Recent B Physics Results from the Tevatron

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HEP Seminar
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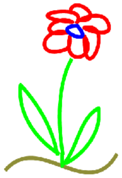
- **Introduction: Flavour Physics**
- **Fermilab, Tevatron and CDF**
- **Recent CDF Results: B Hadron Lifetimes**
- **B_s Oscillation Measurement**
- **CP Violation: B -> hh**
- **Discovery of Σ_b Baryon**
- **Conclusions**

Note: Focus on CDF results



Annalen der Physik 17
(1905)

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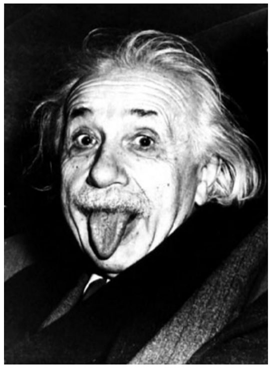
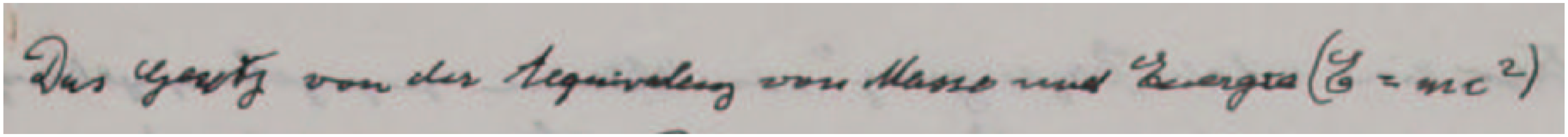
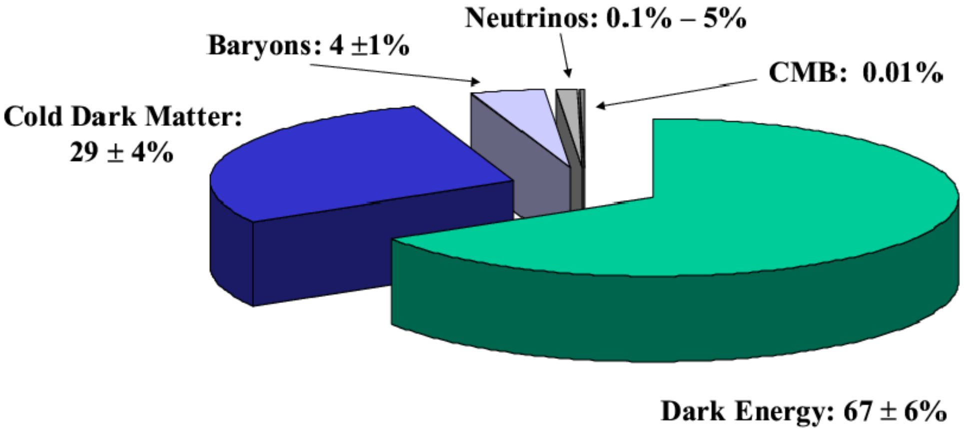


$$\boxed{E = mc^2}$$



Das Gesetz von der Aequivalenz von Masse und Energie ($E = mc^2$)

Mass & Energy



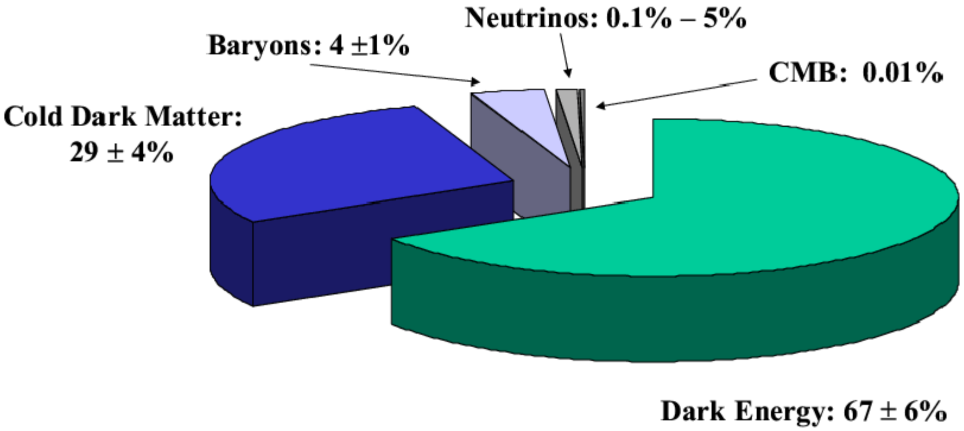
Composition of Universe:

Don't know 95% of
content of universe

Dark energy <=>
Dark matter <=>

?

Mass & Energy



Composition of Universe:

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Dark energy <=>
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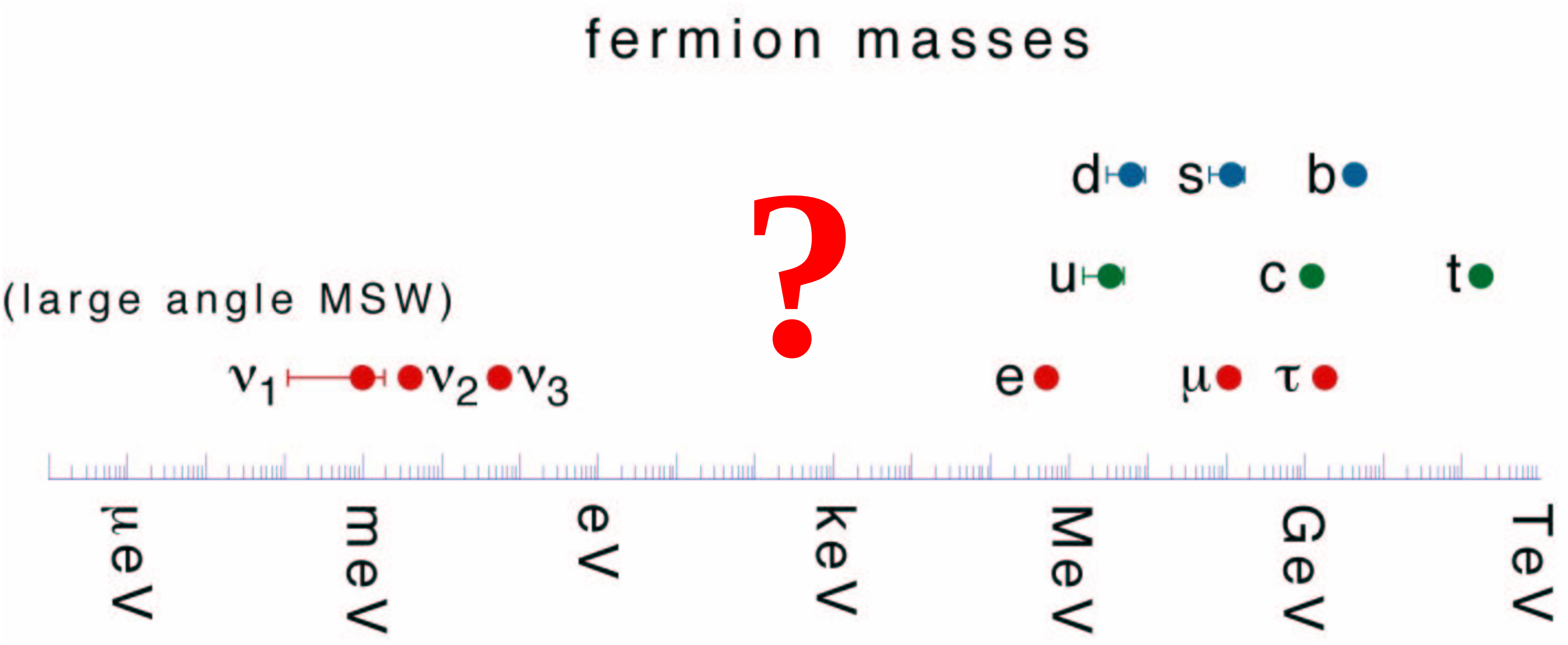
?

Mass & Energy

- **Particle Physics:**



The 5. Quark: Bottom or Beauty

- 1977: Discovery of b quarks in hadronic collisions at Fermilab (Lee-on)
- Υ resonance = bound $|b\bar{b}\rangle$ state
- Today established B meson states:

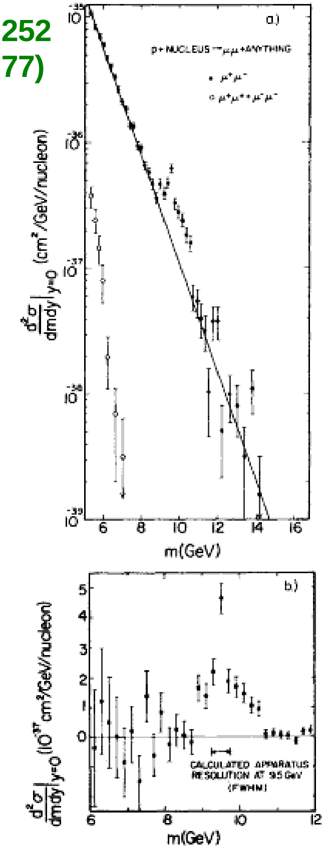
Mesons: $\bar{B}^0 = |b\bar{d}\rangle, \;\; B^- = |b\bar{u}\rangle, \;\; \bar{B}^0_S = |b\bar{s}\rangle$

$B^-_c = |b\bar{c}\rangle$

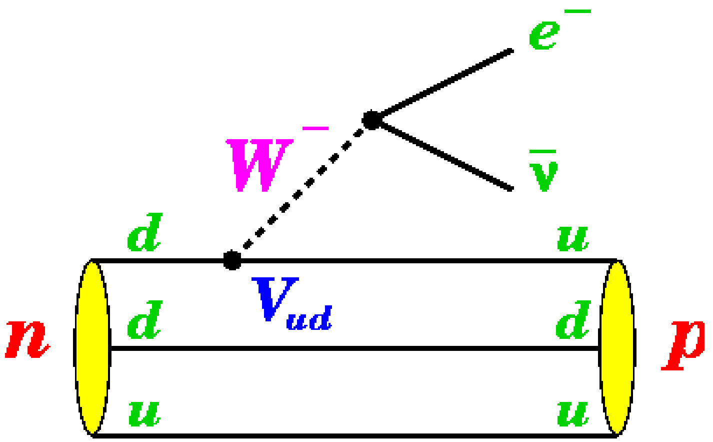
Baryons: $\Lambda^0_b = |bdu\rangle$

- Rest mass: 5.3 - 6.5 GeV (~6 x mass of proton)
- All B hadrons decay via weak interaction

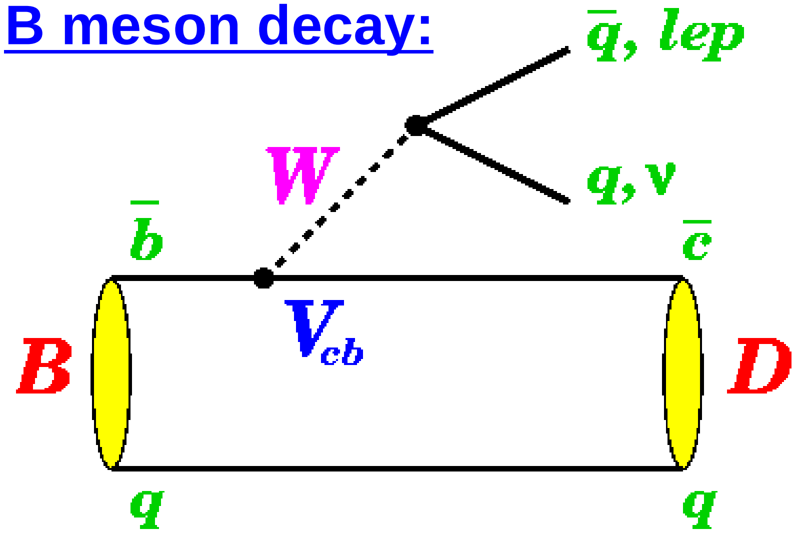
PRL 39, 252 (1977)



Neutron beta decay: $n \rightarrow p\, e^-\, \bar{\nu}_e$



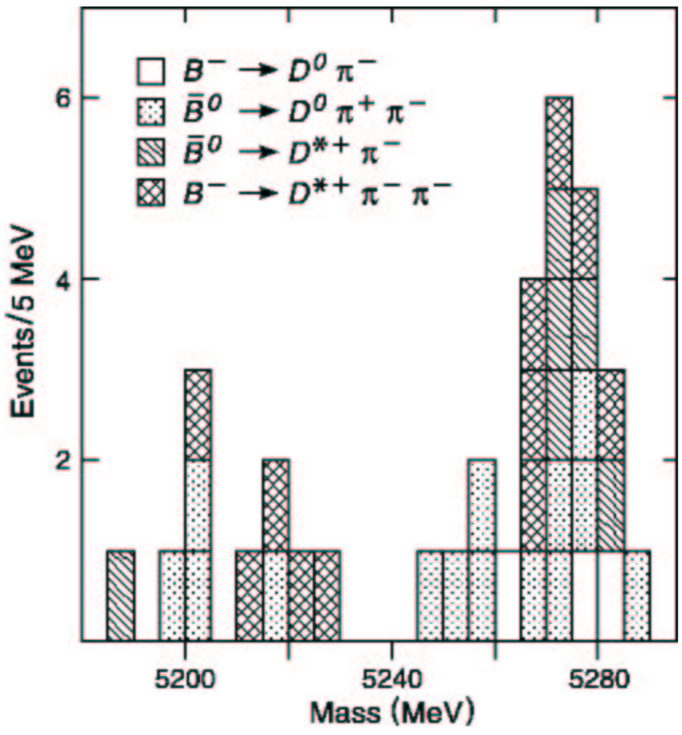
B meson decay:



A Brief History of Time

First fully reconstructed B mesons:

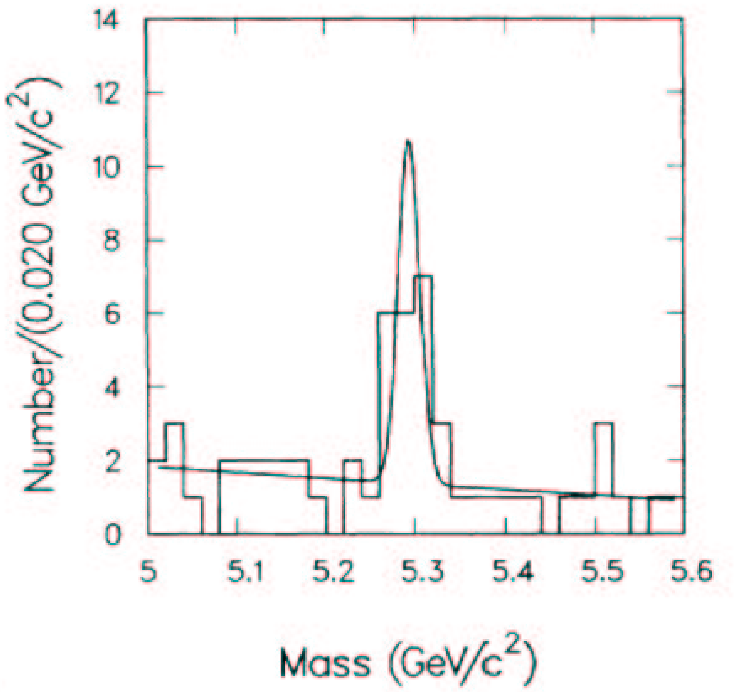
CLEO 1983



First fully reconstructed B mesons at a hadron collider:

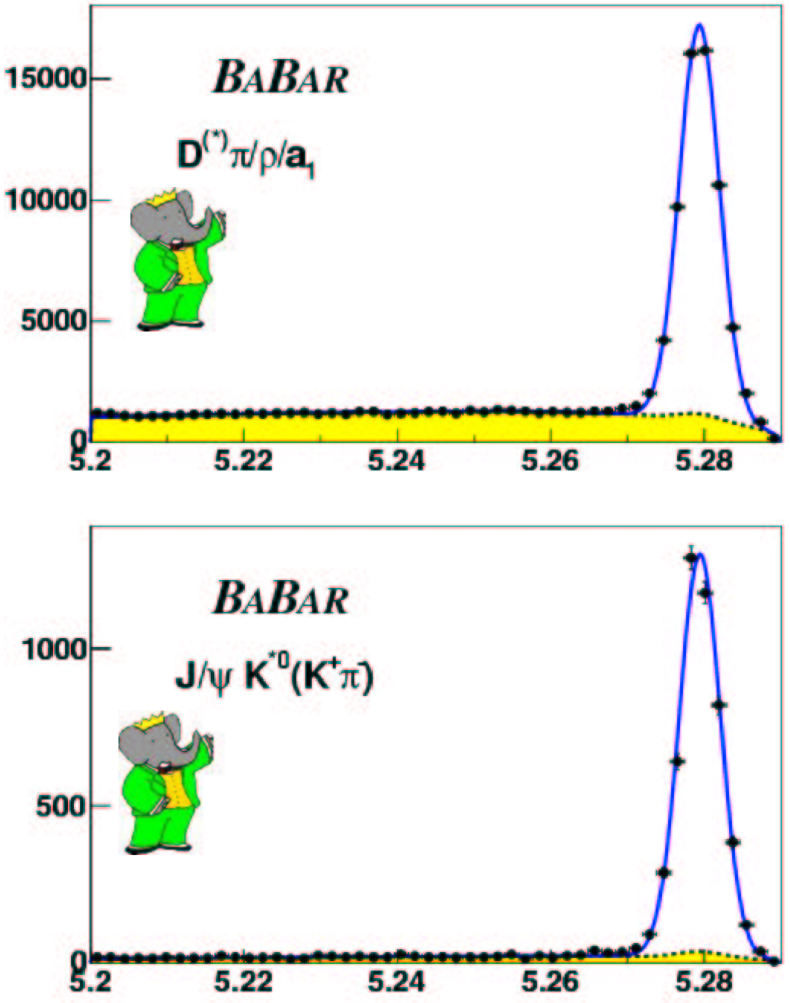
CDF 1992

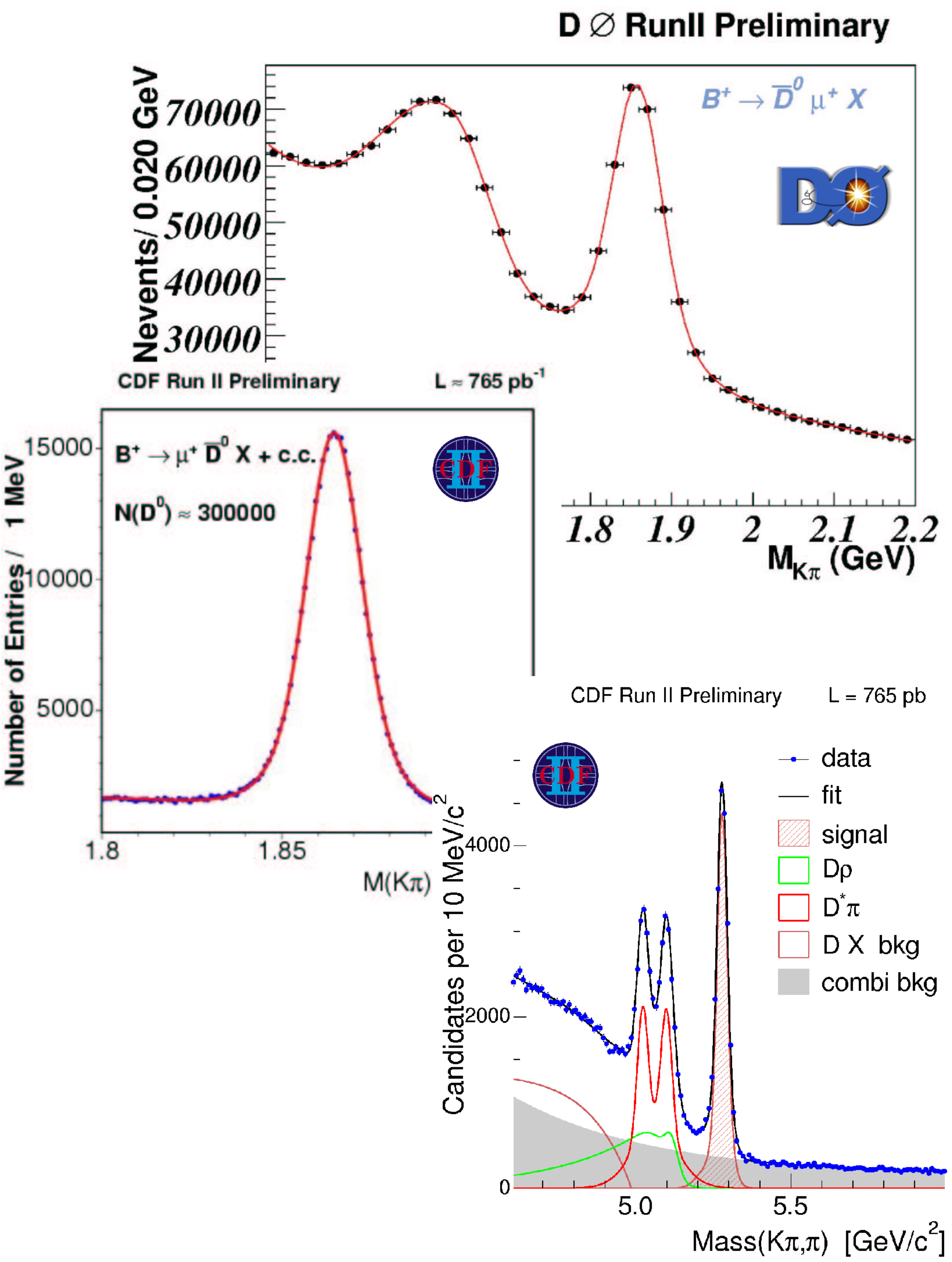
$B^+ \to J/\psi\ K^+$



PRL 68, 3403 (1992)

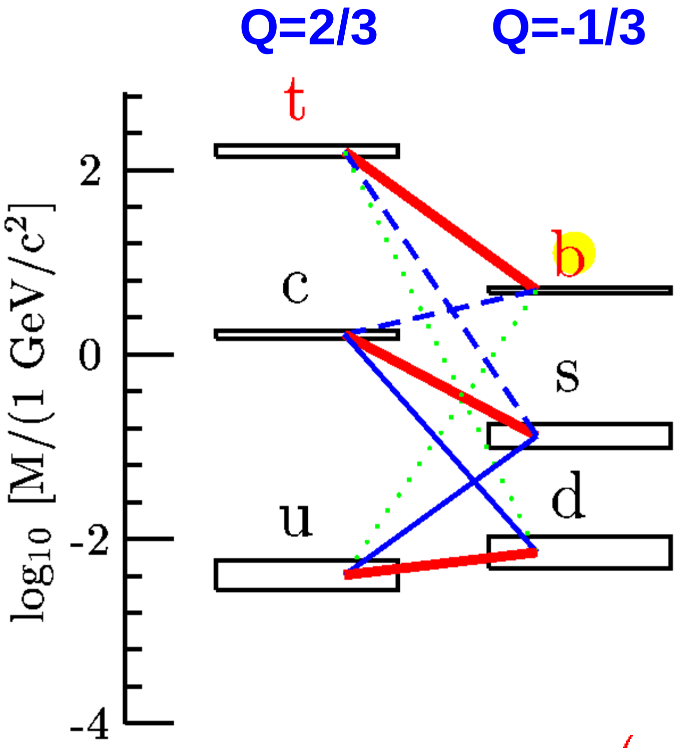
Nowadays ...


15000
10000
5000
0
BABAR
D(*)π/ρ/a1
5.2
5.22
5.24
5.26
5.28
1000
500
0
BABAR
J/ψ K*0(K+π)
5.2
5.22
5.24
5.26
5.28

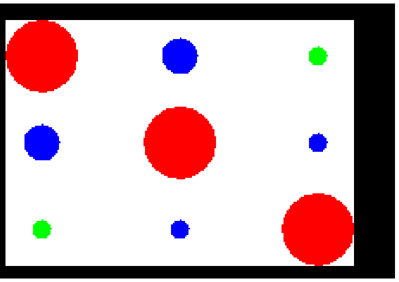

D ∅ RunII Preliminary
Nevents/ 0.020 GeV
70000
60000
50000
40000
30000
B+ → D̄0 μ+ X
1.8
1.9
2
2.1
2.2
MKπ (GeV)
CDF Run II Preliminary
L ≈ 765 pb-1
Number of Entries / 1 MeV
15000
10000
5000
B+ → μ+ D̄0 X + c.c.
N(D0) ≈ 300000
1.8
1.85
M(Kπ)
CDF Run II Preliminary
L = 765 pb
Candidates per 10 MeV/c2
4000
2000
0
data
fit
signal
Dρ
D*π
D X bkg
combi bkg
5.0
5.5
Mass(Kπ,π) [GeV/c2]

Quark Transitions

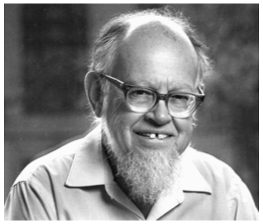
Quark spectrum:



Quark transition described by CKM matrix V_{CKM}:



Wolfenstein: $$V_{\mathrm{CKM}} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$



Particular importance of b quark: Couples to all other quarks directly or via loops

Quark Transitions

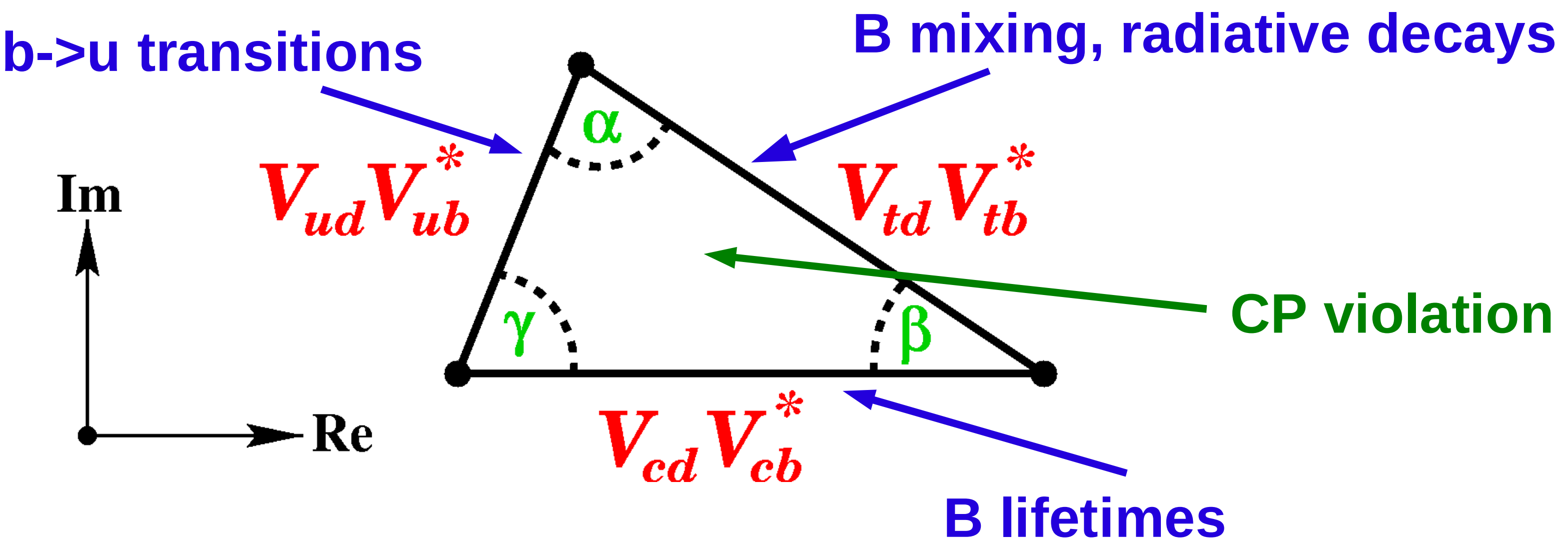
- Individual CKM matrix elements are not predicted by SM => have to be measured
- B decays determine 5 CKM matrix elements

$$V = \begin{pmatrix} V_{ud} & V_{us} & \boxed{V_{ub}} \\ V_{cd} & V_{cs} & \boxed{V_{cb}} \\ \boxed{V_{td}} & \boxed{V_{ts}} & \boxed{V_{tb}} \end{pmatrix}$$

- Unitarity of CKM matrix ([redacted])

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

- **CKM triangle:**



b->u transitions

B mixing, radiative decays

$V_{ud}V_{ub}^*$

$V_{td}V_{tb}^*$

$V_{cd}V_{cb}^*$

CP violation

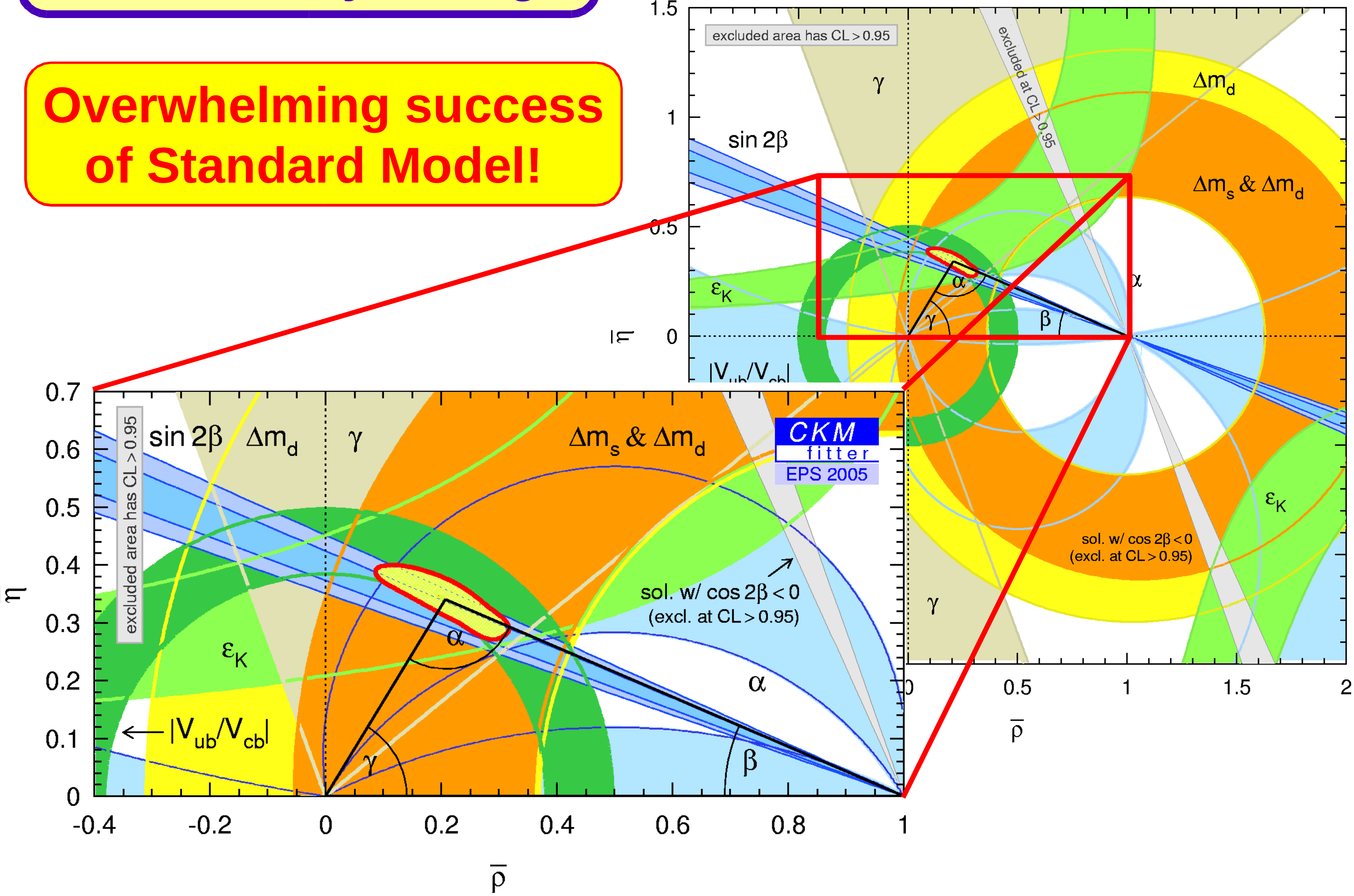
B lifetimes

Our Program Today

- B Hadron Lifetimes
- B_s Oscillation Measurement
- CP Violation: B -> hh
- Discovery of Σ_b Baryon

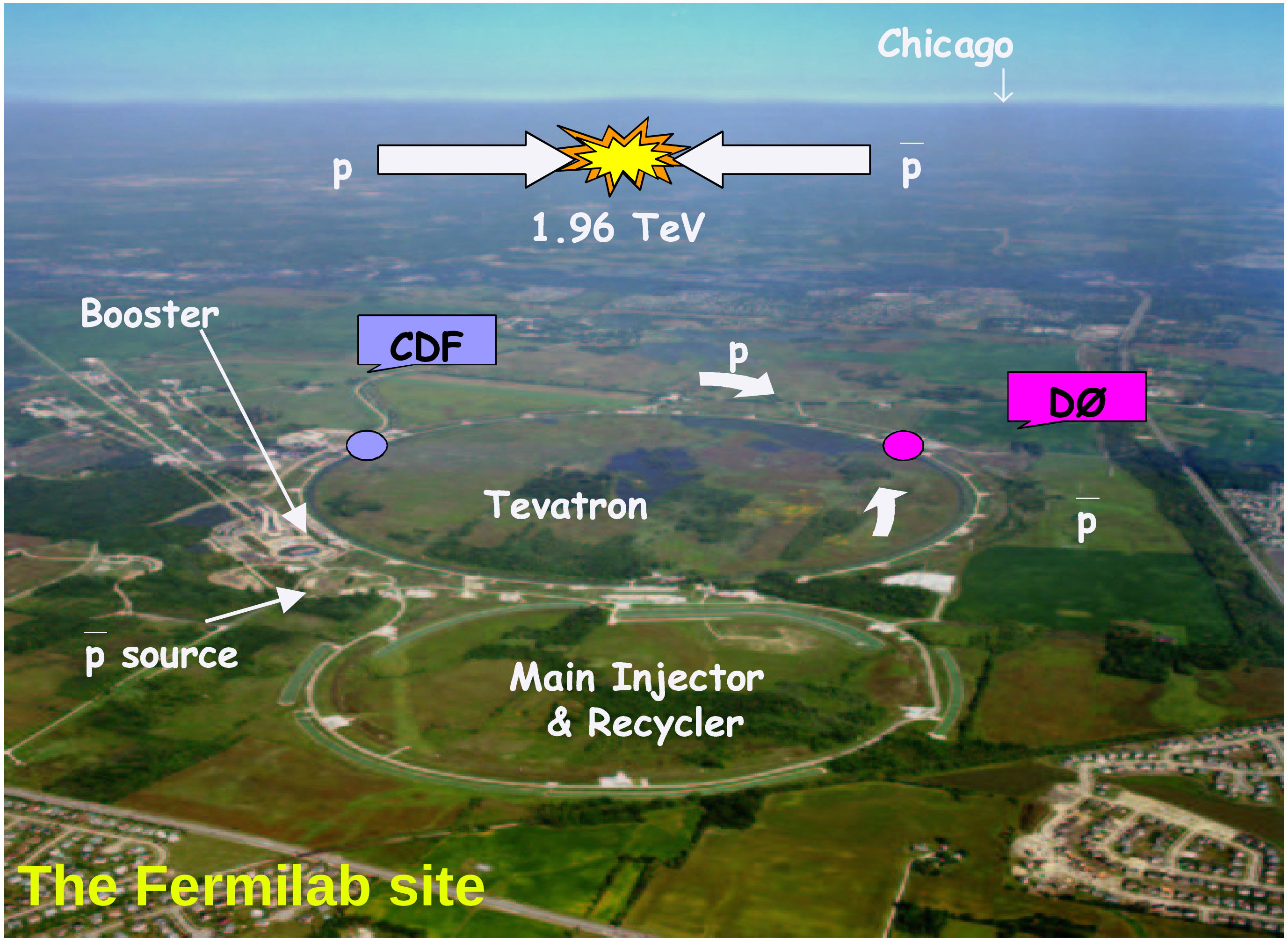
CKM Unitarity Triangle

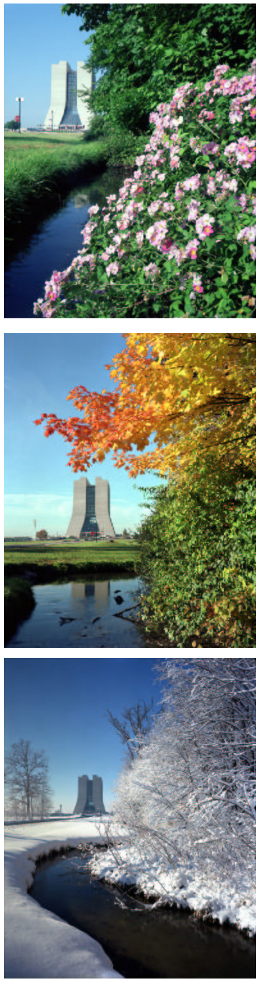
Overwhelming success of Standard Model!

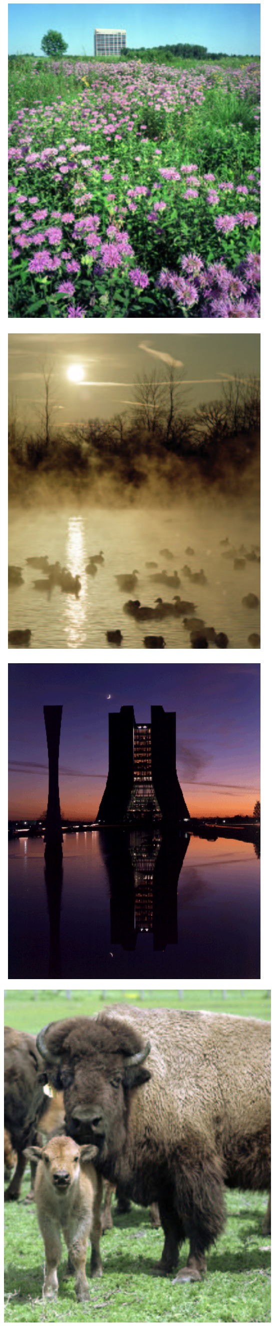


Fermilab, Tevatron and CDF

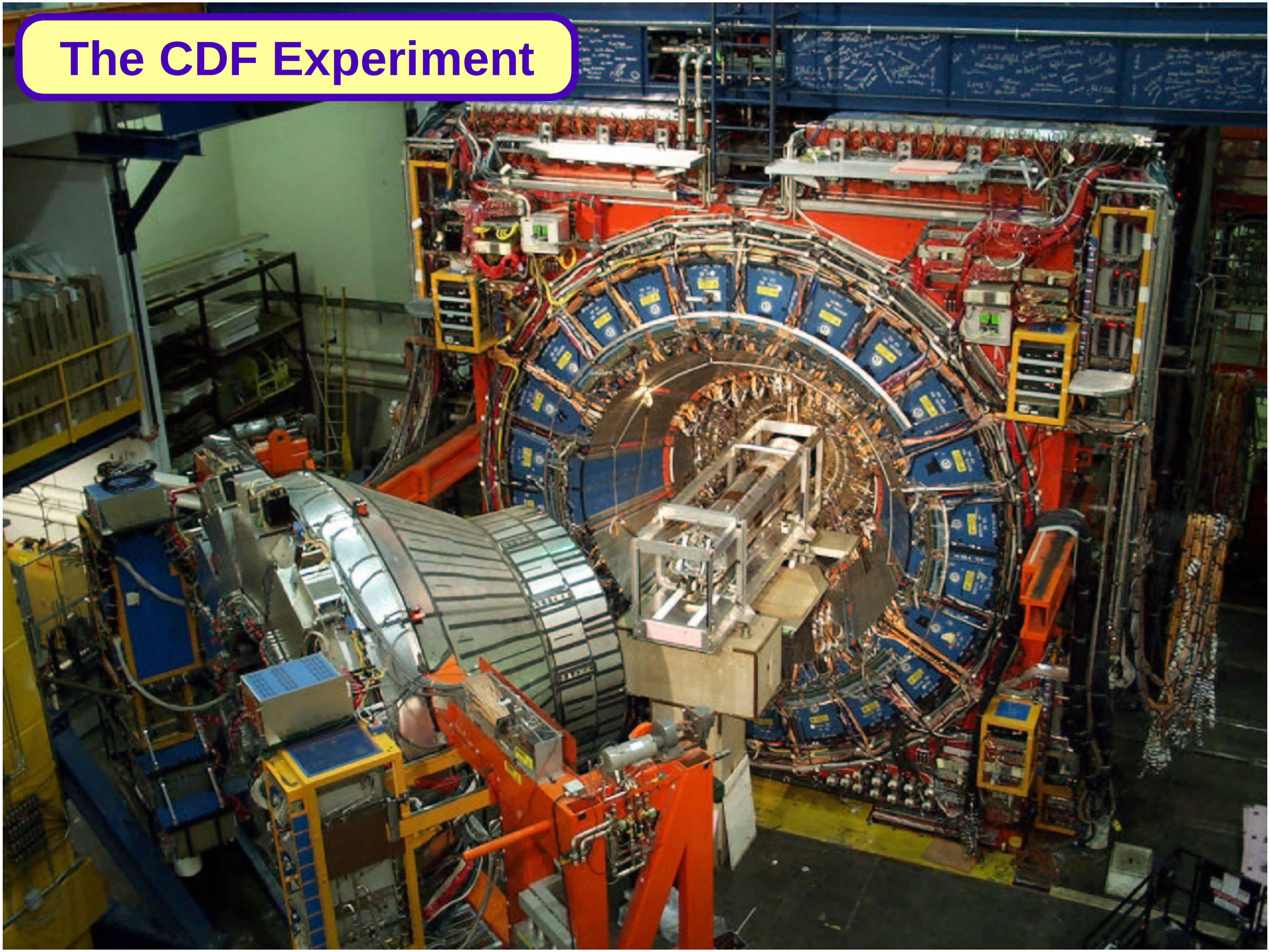
Fermilab


Chicago
p
$\bar{p}$
1.96 TeV
Booster
CDF
p
DØ
Tevatron
$\bar{p}$
$\bar{p}$ source
Main Injector
& Recycler
The Fermilab site





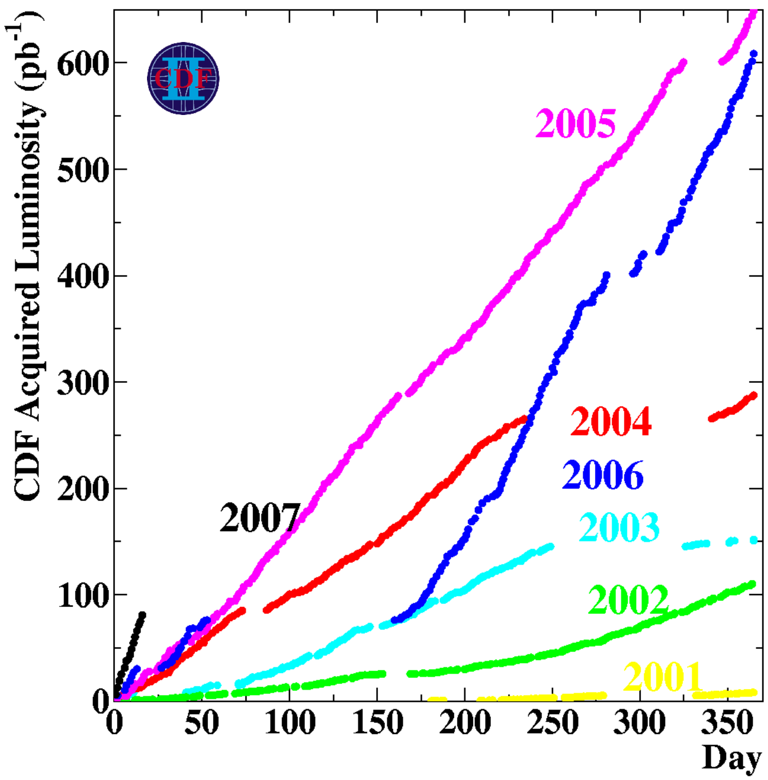
The CDF Experiment

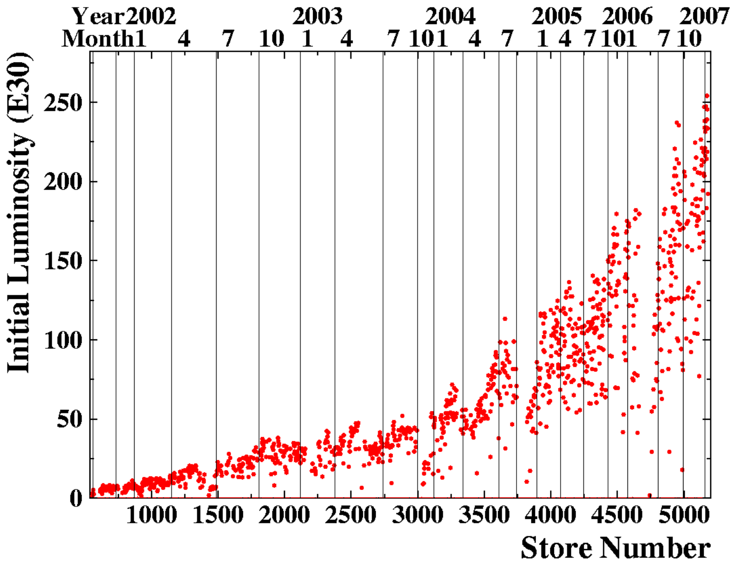


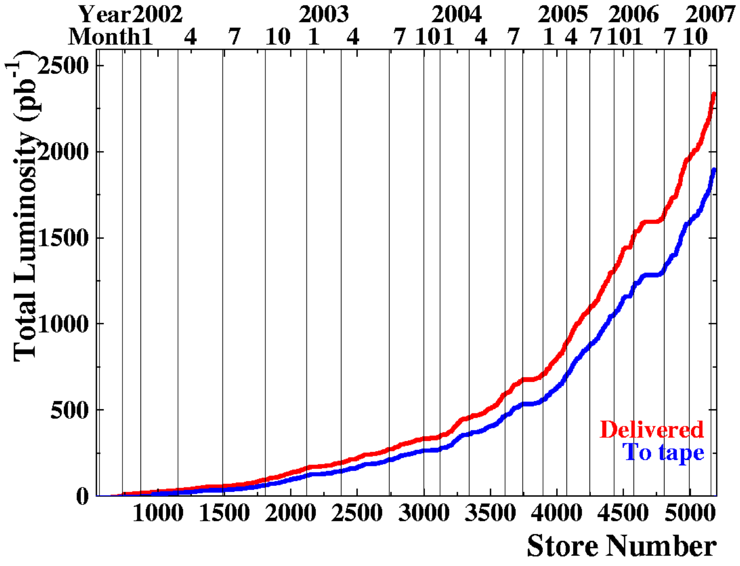
Tevatron Performance

From Record to Record

- Dec. 2006: Best TeV month:
  - Record monthly int. lumi 136.3 pb^{-1}
  - Record weekly int. lumi 39.6 pb^{-1}
- Record initial luminosity:
  $27.8 \times 10^{31}\ sec^{-1}\, cm^{-2}$ (Jan 19, 2007)
- >1.8 fb^{-1} on tape (~ 2.3 fb^{-1} delivered)
- ~1-1.4 fb^{-1} used for analysis



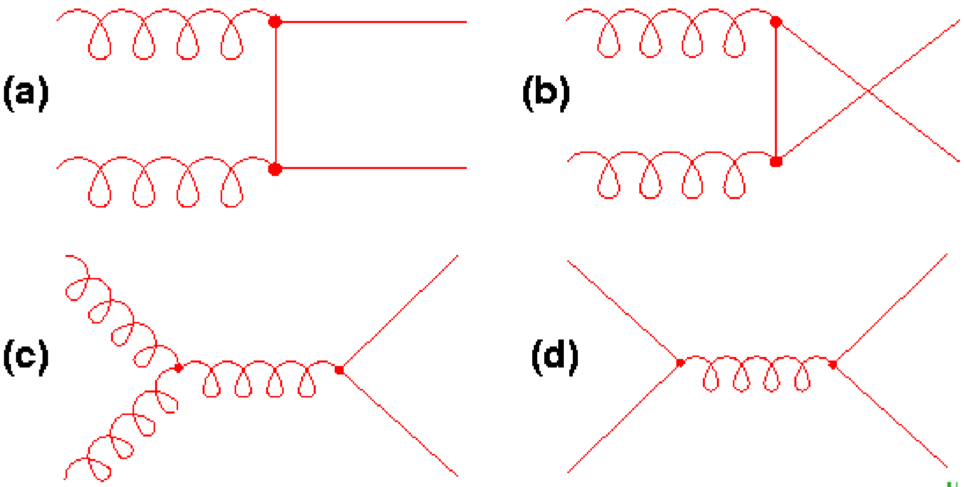




Production of B Hadrons

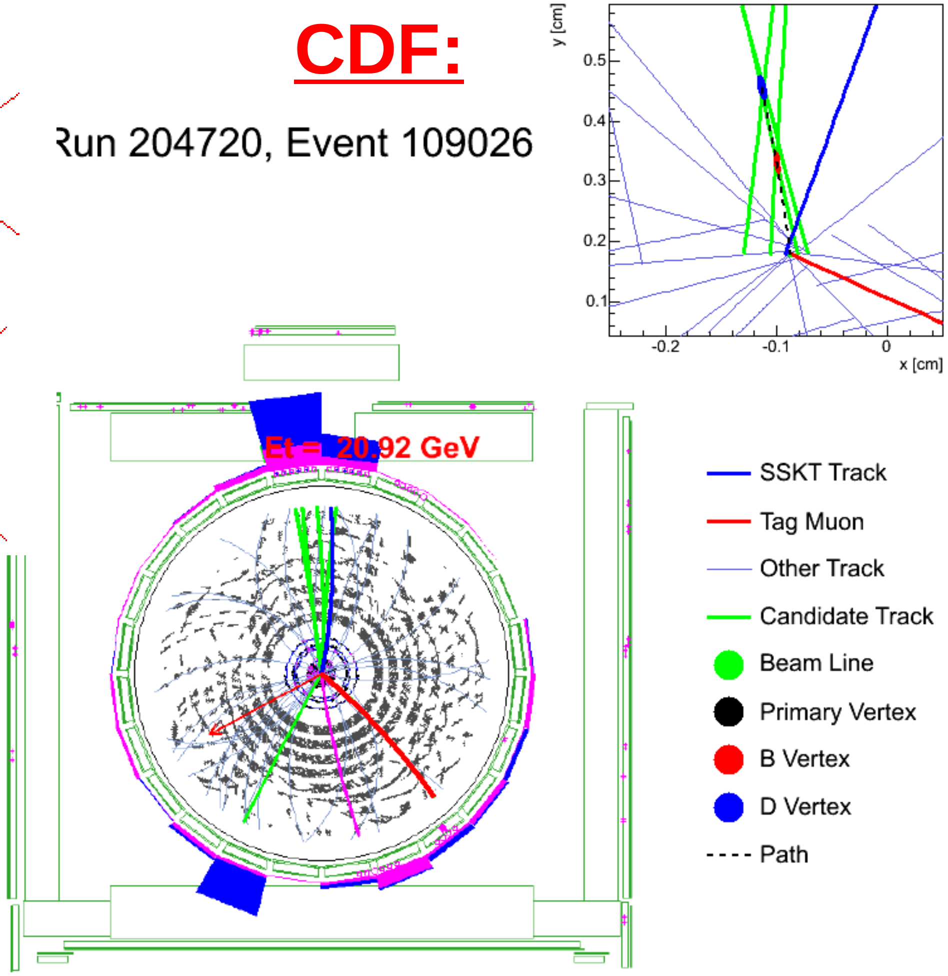
Tevatron: $p\bar{p} \rightarrow b\bar{b}X$

- Lowest order $\mathcal{O}(\alpha_s^2)$ diagrams for $b\bar{b}$ production
  - (a)-(c) gluon-gluon fusion
  - (d) quark-antiquark annihilation



CDF:

Run 204720, Event 109026



—	SSKT Track
—	Tag Muon
—	Other Track
—	Candidate Track
●	Beam Line
●	Primary Vertex
●	B Vertex
●	D Vertex
----	Path

Current Players:

CDF & D0

The Future: LHCb, ~~BTeV~~

(Atlas, CMS)

B Physics at the Tevatron

Advantage of B Physics at the Tevatron:

- **All B hadrons are produced:**

  $B^0, B^+, B_s^+, B_c^+, \Lambda_b^0$

- **Enormous cross section:**
  - B Factory: $\sigma(\Upsilon(4S) \to B\bar{B}) \sim 1\ \text{nb}$
  - Tevatron:

    $\sigma(p\bar{p} \to b, |y| < 0.6) \sim 20\mu b$

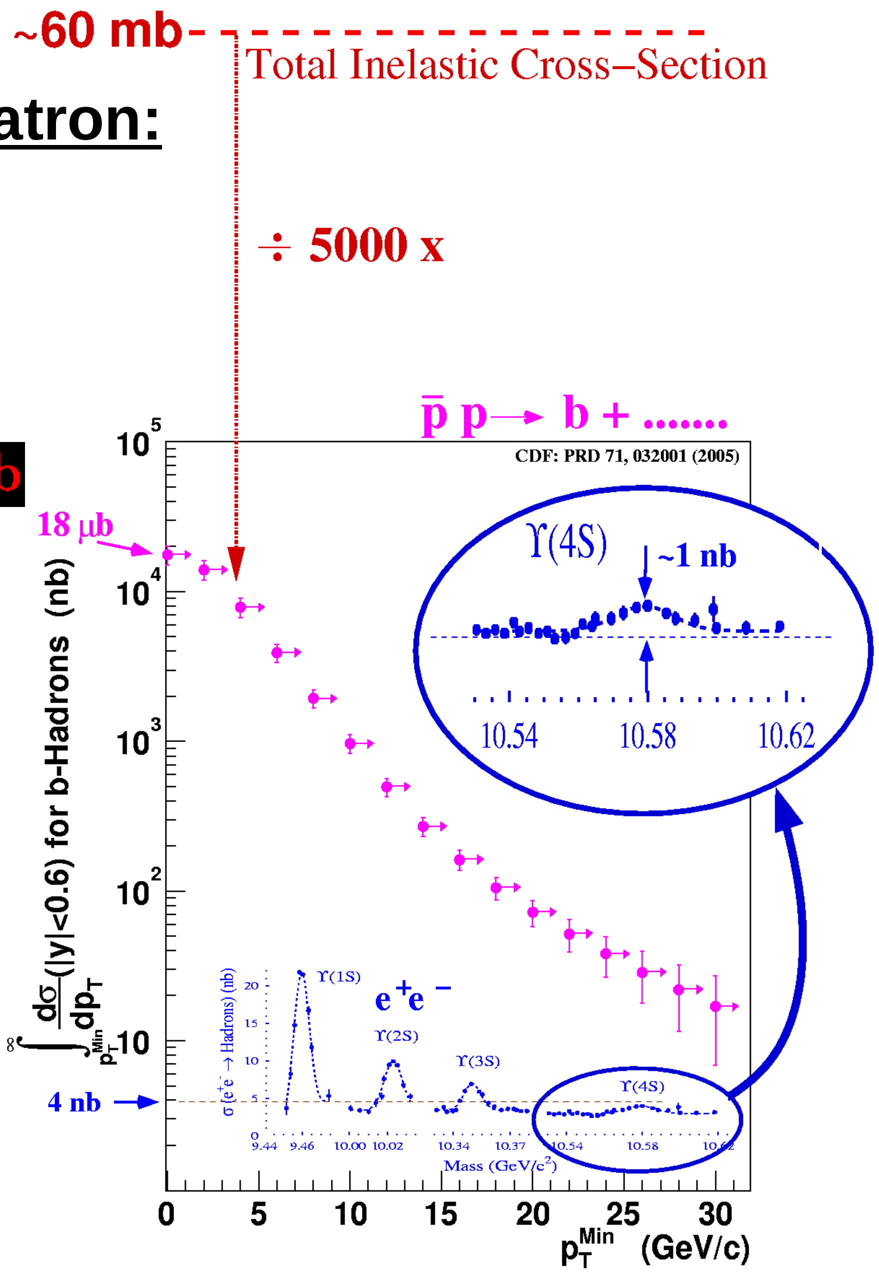
However:

- **Total inelastic cross section:**

  $\sigma(\text{total})/\sigma(b) > 10^3$

➔ **Need to enrich events with B's**

➔ **It's all about the trigger!**



Trigger for B Physics

- **Lepton Trigger:**

➔ **Dilepton trigger: J/ψ -> μ μ**

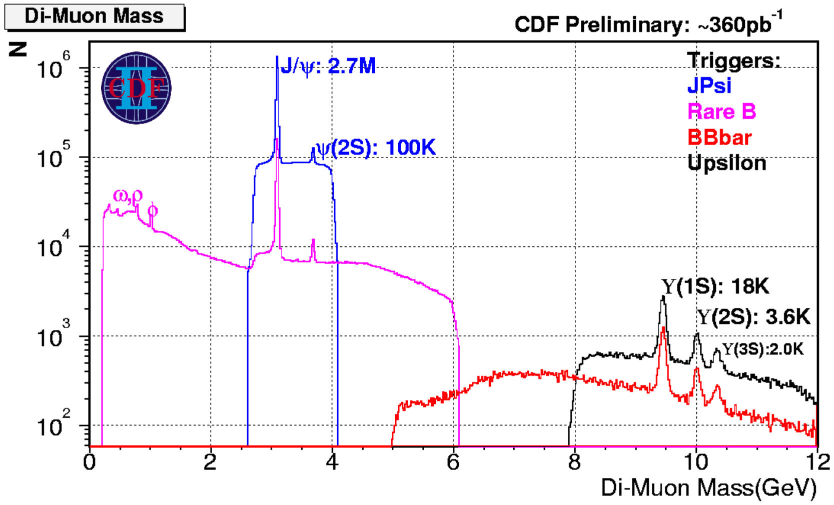
➔ **Single lepton: Semileptonic B decays**

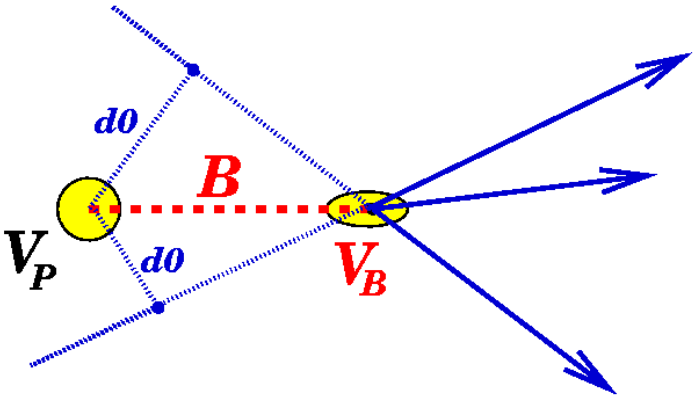
➔ **Lepton+displaced track: Semilept. B's**

- **Hadronic track trigger: CDF (D0)**

(exploit 'long' B lifetime)

Dimuon trigger data



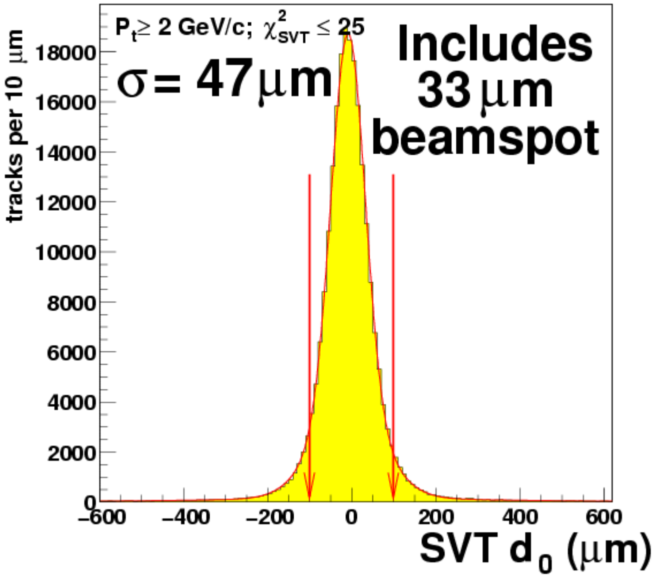


Level 1: Fast track trigger (XFT) finds charged track with p_T > 1.5 GeV/c

Level 2: Link tracks into silicon; require track impact parameter > 100 μm (SVT)

Access to hadronic B decay modes

SVT impact parameter resolution:



Trigger for B Physics

Used in Σ_b and B -> hh analyses!

Di-muon

$J/\psi \to \mu\mu$

$B \to \mu\mu$

Two muons with:

$p_T(\mu) > 1.5$ GeV/c

One displaced track + lepton (e, μ)

$B \to l \nu X$

Lepton:

$p_T(e) > 4.0$ GeV/c,

$p_T(\mu) > 1.5$ GeV/c

Track:

$p_T > 2$ GeV/c, $d_0 > 120\ \mu$m

Two displaced tracks

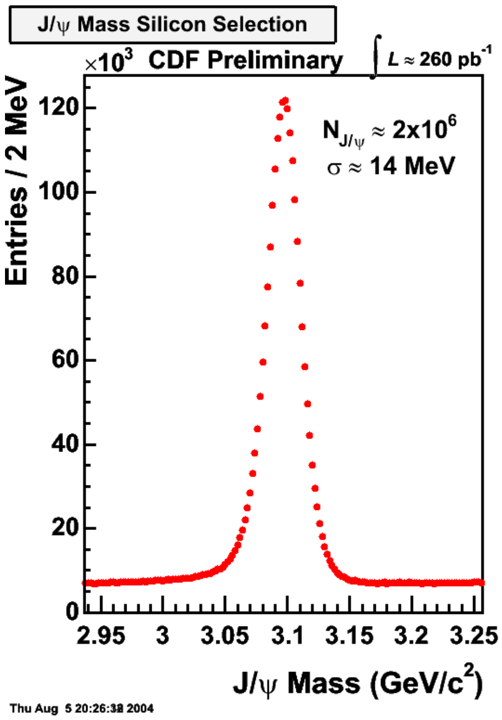
$B \to hh$

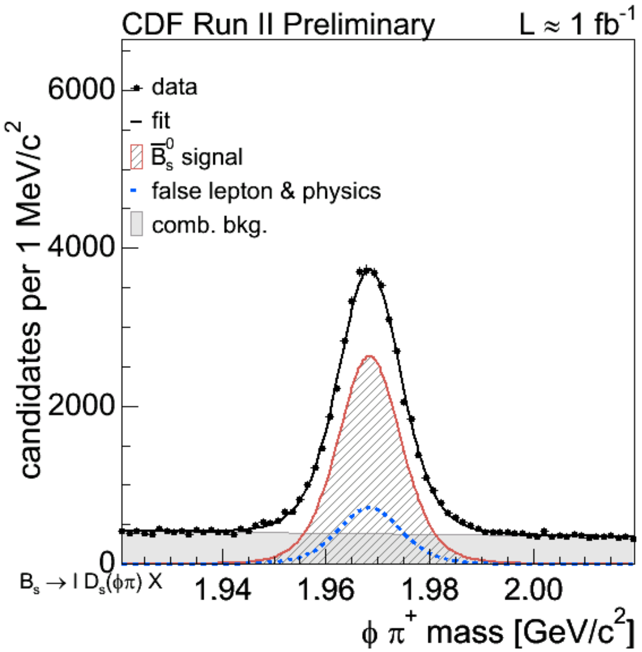
Two tracks with:

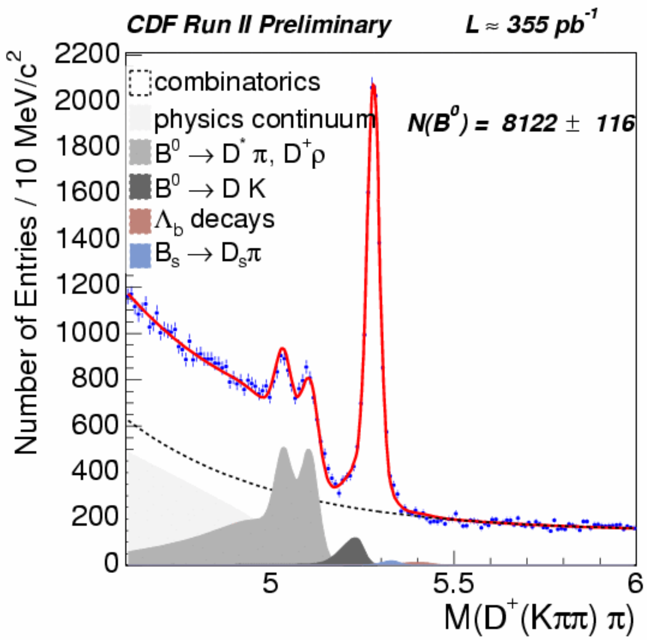
$p_T > 2.0$ GeV/c

$\Sigma p_T > 5.5$ GeV/c

$d_0 > 100\ \mu$m

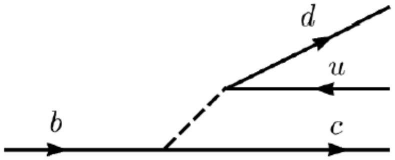




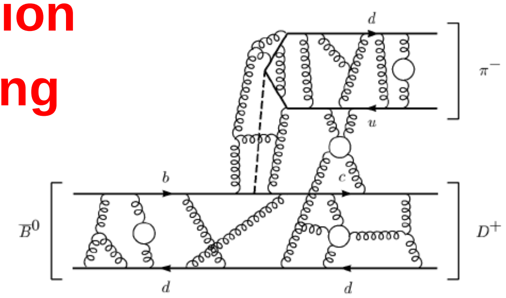


Recent CDF Results: B Lifetimes

B Hadron Lifetimes

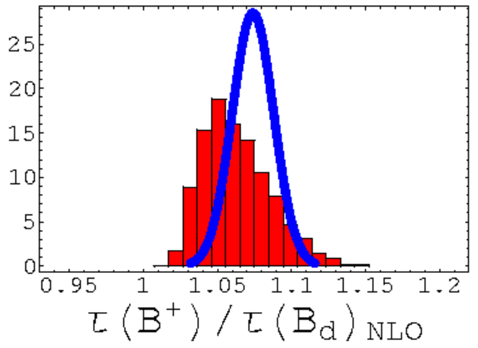


- **Lifetimes of b hadron study interplay between strong and weak interaction**
- **Important testbed for understanding non-perturbative effects in QCD**
- **Heavy quark expansion predicts values for weakly decaying hadrons**

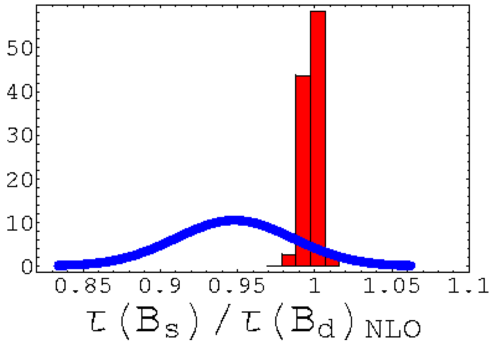


-- NLO theory

-- experiment



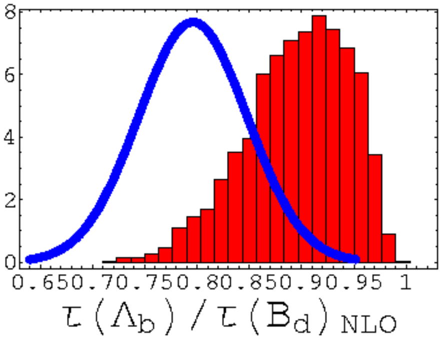
$$\Gamma = \frac{G_F^2 m_b^5}{192\pi^3}|V_{cb}|^2 \cdot \left[A_0 + A_2\left(\frac{\Lambda_{QCD}}{m_b}\right)^2 + A_3\left(\frac{\Lambda_{QCD}}{m_b}\right)^3 + \cdots\right]$$



Theoretical lifetime predictions:

- $\tau(B^+)/\tau(B^0) = 1.06 \pm 0.02$
- $\tau(B_s^0)/\tau(B^0) = 1.00 \pm 0.01$
- $\tau(\Lambda_b^0)/\tau(B^0) = 0.88 \pm 0.05$

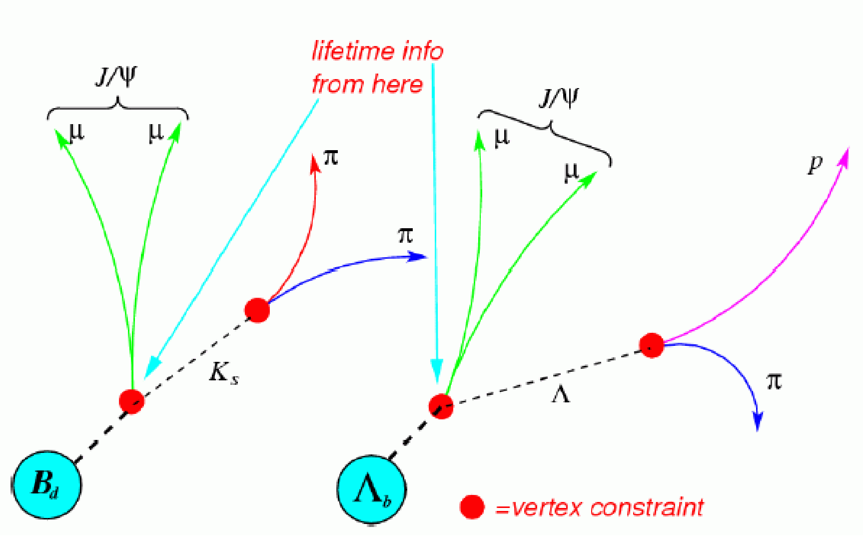
C. Tarantino *et al* hep-ph/0310241

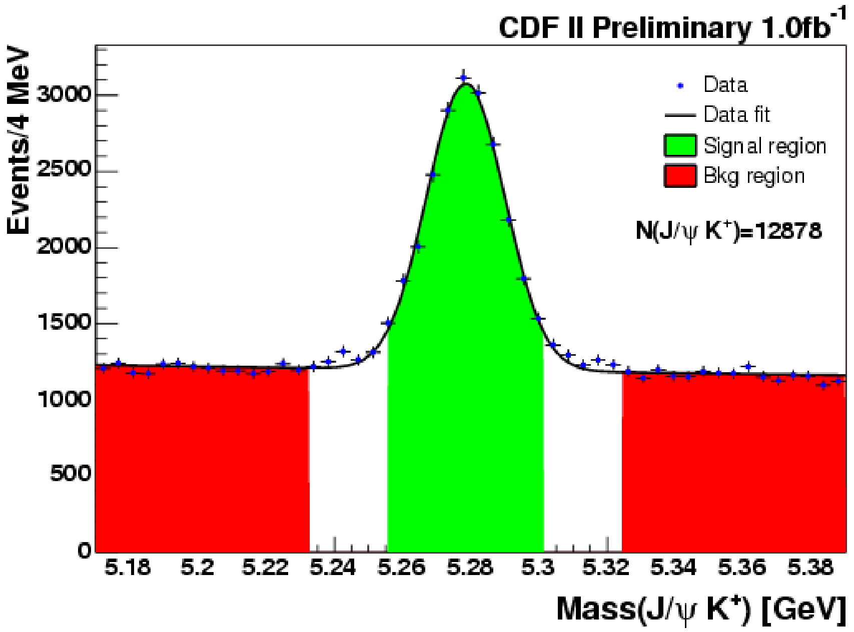


B Hadron Lifetimes

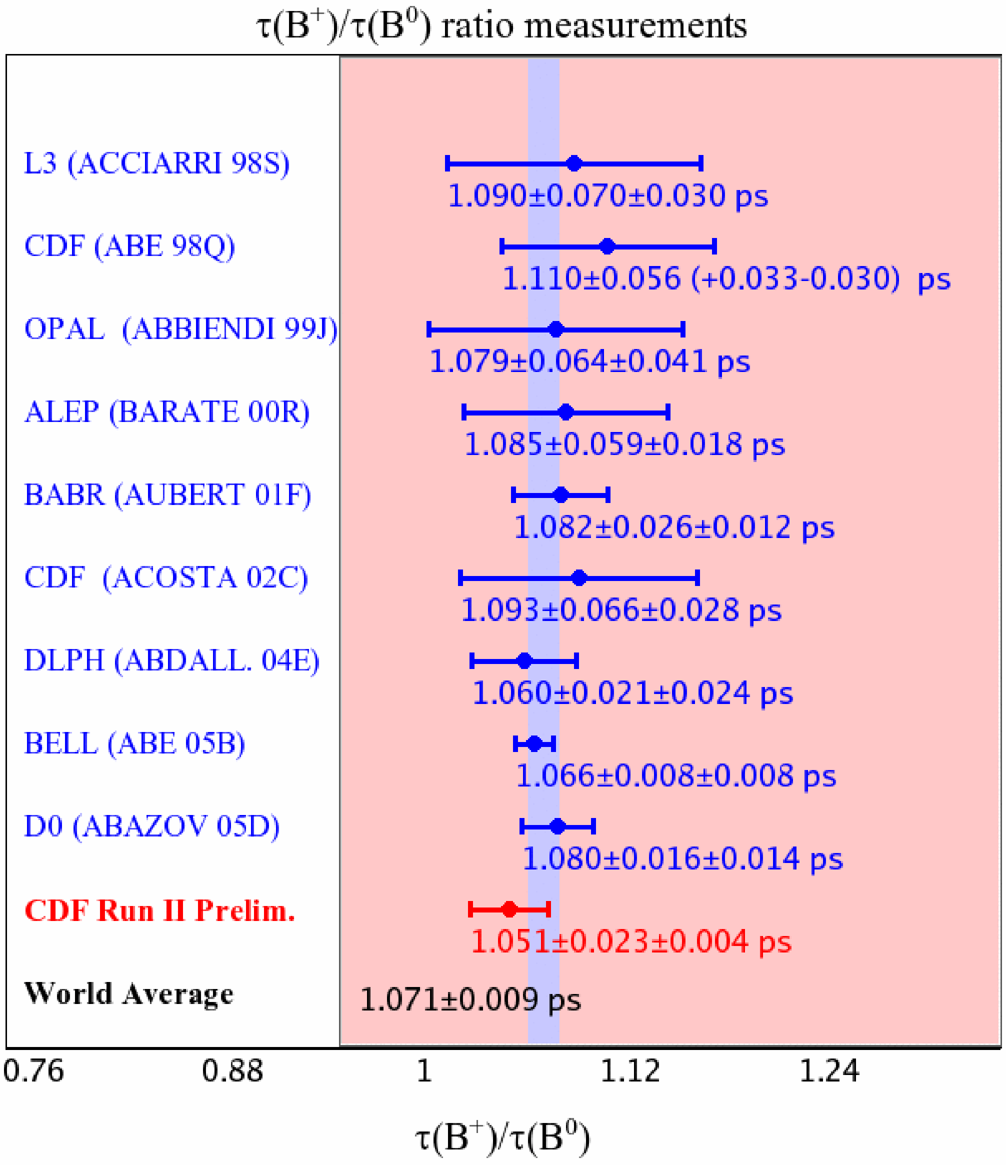
Compreh. analysis of B lifetimes

- Use 1.0 fb^{-1} dimuon trigger data
- Measure lifetime in fully reconstructed B -> J/ψ X decays
  - $B^+ \to J/\psi K^+$ (13k)
  - $B^0 \to J/\psi K^{0*}$ (4.8k)
  - $B^0 \to J/\psi K^0_s$ (3.6k)
  - $\Lambda^0_b \to J/\psi \Lambda$ (0.5k)
  - $B^0_s \to J/\psi \phi$ (1.1k)
- Fully reconstructed decay
  - No missing momentum
- Take lifetime info from J/ψ vertex
- Large B hadron signals





B^0/B^+ Lifetimes



$\tau(B^+) =$

$(1.630 \pm 0.016 \pm 0.011)$ ps

$\tau(B^0) =$

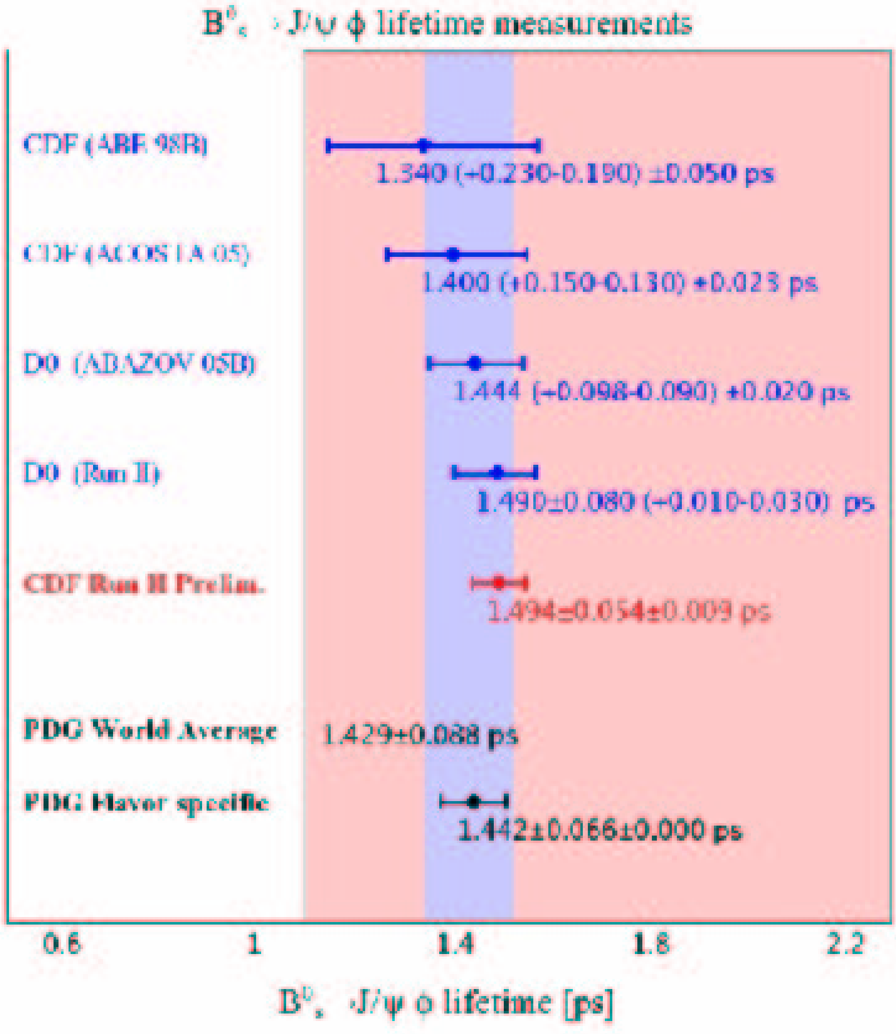
$(1.551 \pm 0.019 \pm 0.011)$ ps

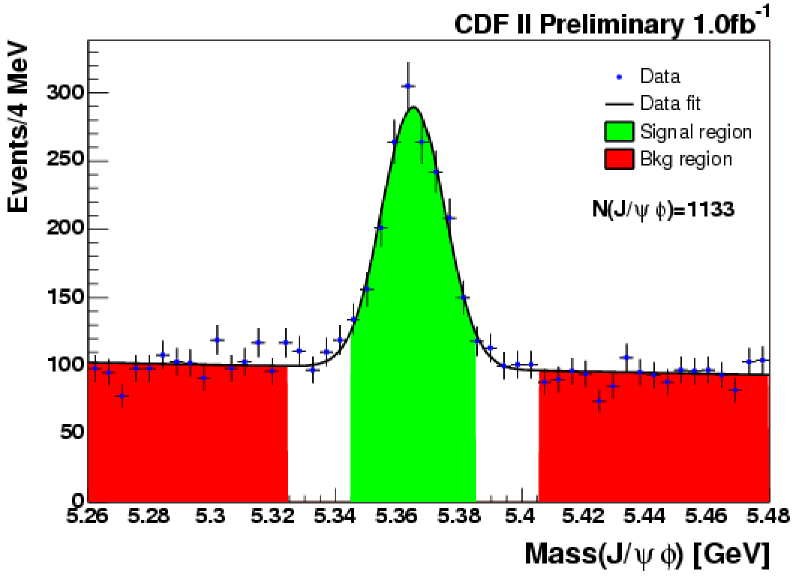
$\tau(B^+) / \tau(B^0) =$

$(1.051 \pm 0.023 \pm 0.004)$

Very good agreement with world average and with theoretical predictions

B_s^0 Lifetime





$\tau(B_s^0) =$

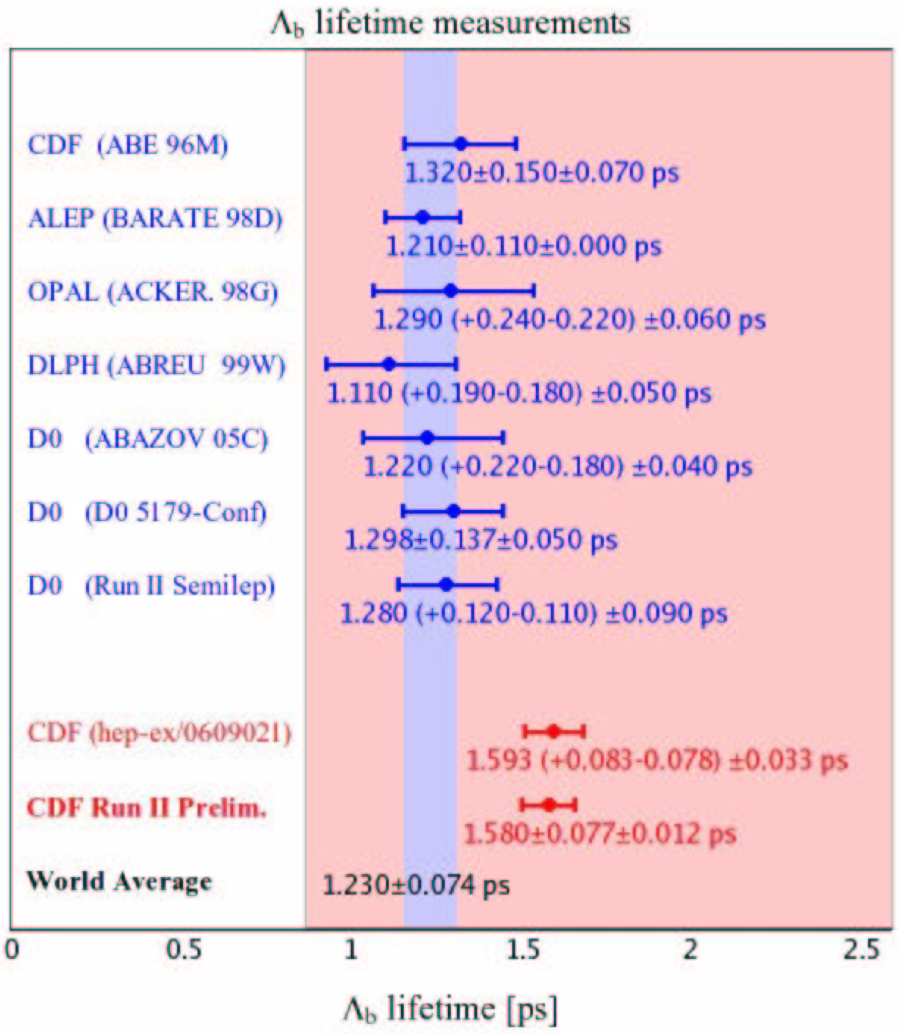
$(1.494 \pm 0.054 \pm 0.009)$ ps

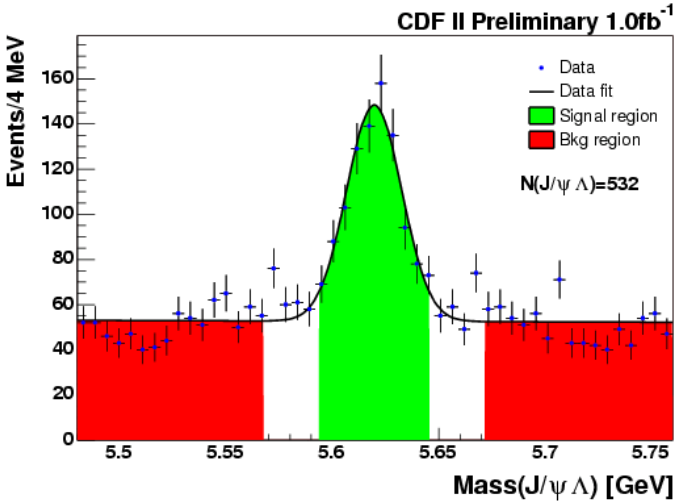
$\tau(B_s^0) / \tau(B^0) =$

$(0.963 \pm 0.047 \pm 0.005)$

Very good agreement with world average and with theoretical predictions

Λ_b Lifetime





$\tau(\Lambda_b)$ =

$(1.580 \pm 0.077 \pm 0.012)$ ps

$\tau(\Lambda_b) / \tau(B^0)$ =

$(1.018 \pm 0.062 \pm 0.007)$

Surprise: ~3σ above world average and above theoretical predictions

=> Measure Λ_b lifetime in hadronic mode $\Lambda_b \to \Lambda_c \pi$

Observation of B_s Oscillations

B_S Meson Oscillations

Two-State Quantum Mechanical System

$B_s^0(\bar{b}s)$ & $\bar{B}_s^0(b\bar{s})$ **Common decay modes! => 2-state QM system**

Eigenstates of 2-state system (neglect CP violation)

Light (CP-even) $$|B_{s,L}^0\rangle = \frac{|B_s^0\rangle - |\bar{B}_s^0\rangle}{\sqrt{2}}$$ m_L, Γ_L **mass & width**

Heavy (CP-odd) $$|B_{s,H}^0\rangle = \frac{|B_s^0\rangle + |\bar{B}_s^0\rangle}{\sqrt{2}}$$ m_H, Γ_H

$$m_s = \frac{m_H + m_L}{2} \sim 5.37\,\mathrm{GeV}/c^2 \qquad \tau = \frac{2}{\Gamma_L + \Gamma_H} \sim 1.5\,\mathrm{ps}$$

$$\Delta m_s = m_H - m_L \qquad \Delta\Gamma_s = \Gamma_L - \Gamma_H$$

Start (t=0) with particle →

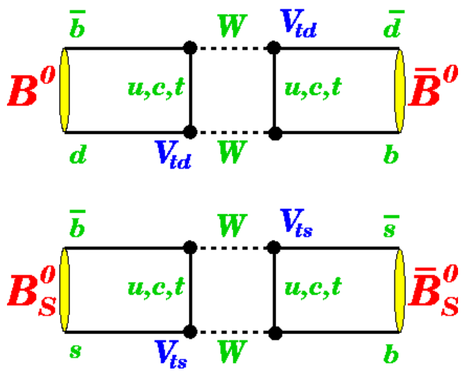
$$|\psi(0)\rangle = |B_s^0\rangle = \frac{B_{s,L} - B_{s,H}}{\sqrt{2}} \quad (\Delta\Gamma = 0)$$

$$|\langle \bar{B}_s^0 | \psi(t)\rangle|^2 = \frac{\Gamma e^{-\Gamma t}}{2}[1 - \cos(\Delta m_s t)]$$

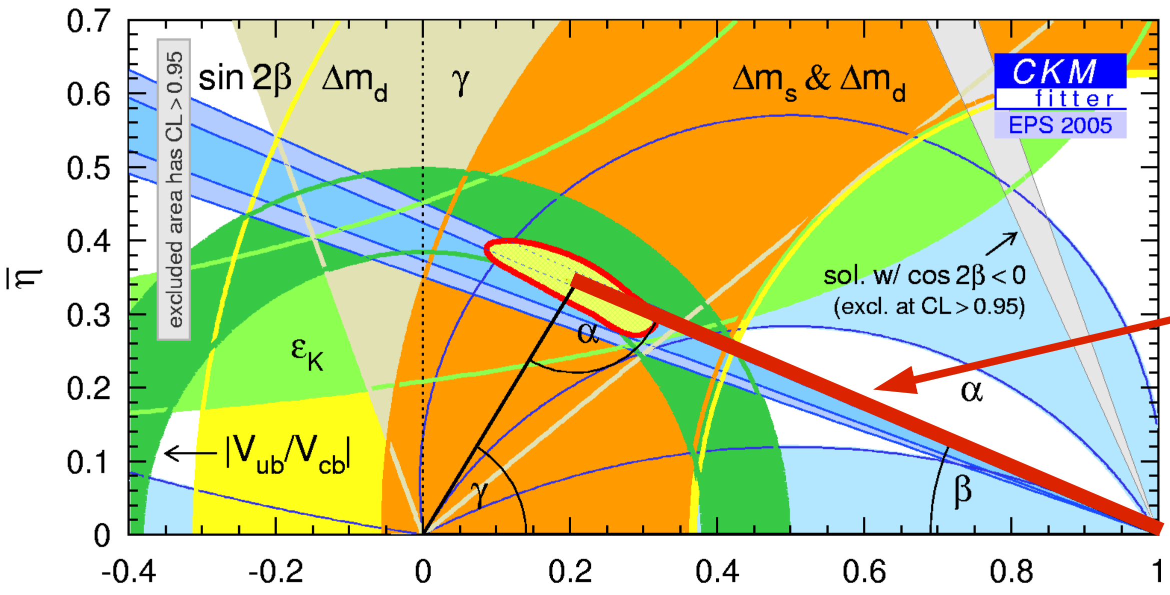
← **Antiparticle exists at time t!**

Δm_s is oscillation frequency

B_S Meson Oscillations



Why are we interested in B_S mixing?



- $\frac{|V_{td}|}{|V_{ts}|}$

- **Theory:** In Standard Model

CKM element

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_B (f_B^2 B_B) \eta_B m_t^2 F\left(\frac{m_t^2}{m_W^2}\right) |V_{tb}^* V_{td}|^2$$

Experiment

Lattice QCD

Better to measure:

$$\frac{\Delta m_S}{\Delta m_d} = \frac{m_{B_S^0}}{m_{B^0}} \frac{f_{B_S^0}^2 B_{B_S^0}}{f_{B^0}^2 B_{B^0}} \frac{|V_{ts}|^2}{|V_{td}|^2}$$

from
lattice QCD

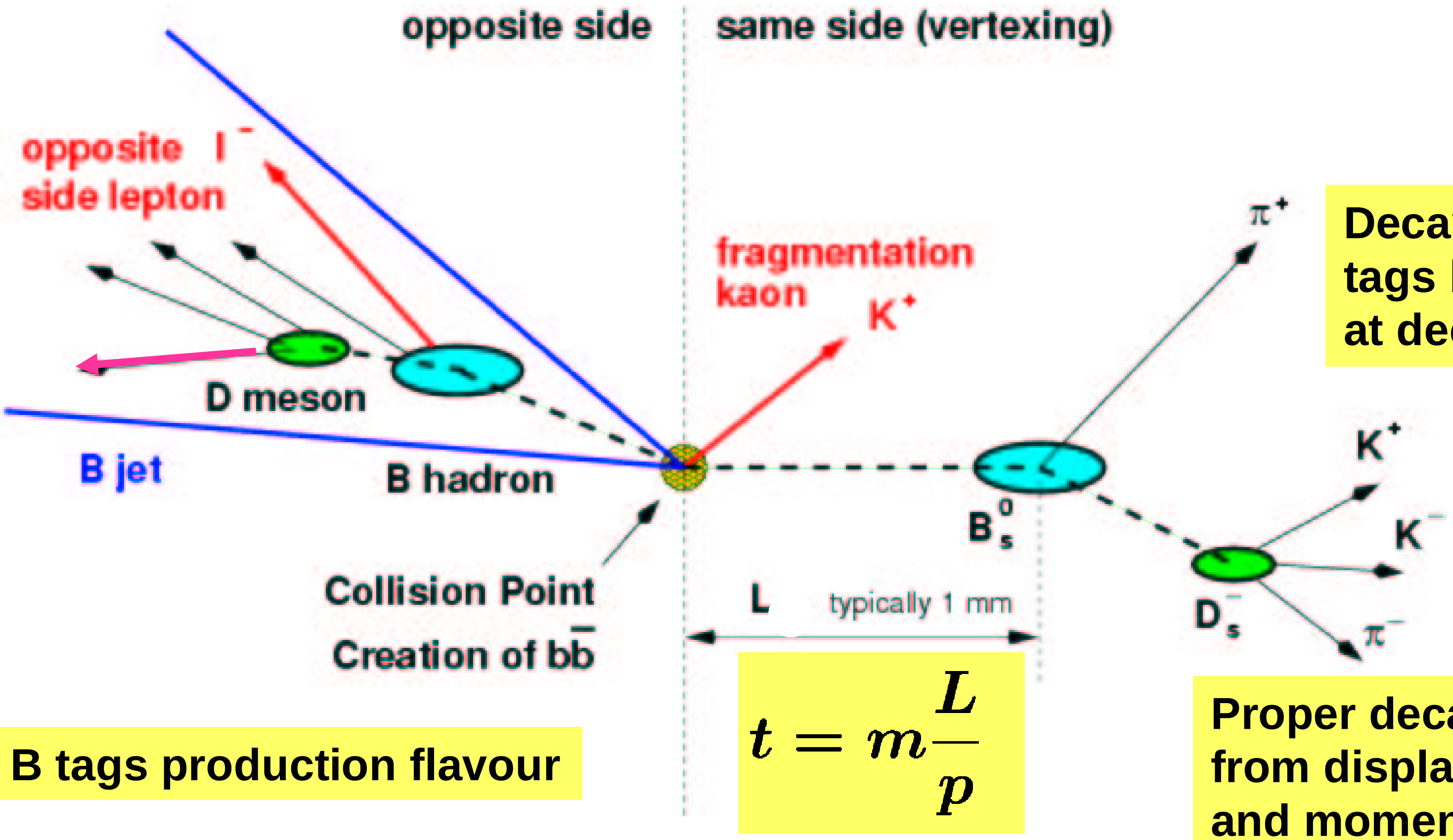
Analysis Strategy

What do we need for measurement of B_S mixing?

(1) B signal reconstruction (semileptonic & fully reconstructed)

(2) Determination of B decay time from decay length and momentum

(3) Determination of B production flavour ("flavour tagging")



Decay mode tags b flavour at decay

2^{nd} B tags production flavour

$$t = m\frac{L}{p}$$

Proper decay time from displacement (L) and momentum (p)

Measurement of B_s Mixing

- Two domains to measure oscillation:

Time domain:

- Fit for Δm_s in $\mathcal{P}_{\text{mix}}(t) \sim (1 - \mathcal{D}\cos \Delta m_s\, t)$

Frequency domain:

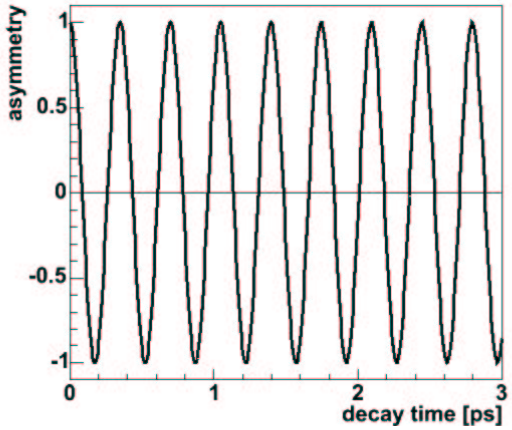
- Fourier transform [redacted]
- "Amplitude scan" method

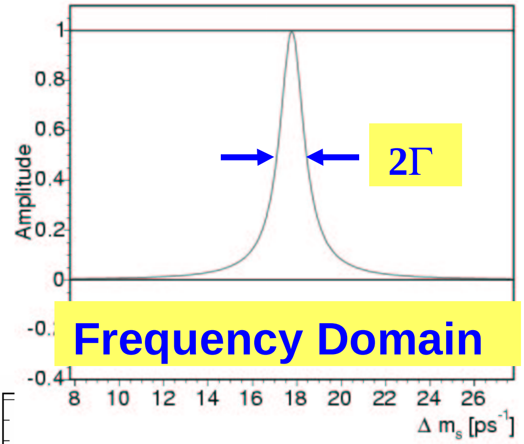
Introduce amplitude $\mathcal{A}$

$$\mathcal{P}_{\text{mix}}(t) \sim (1 - \mathcal{D}\,\mathcal{A} \cos \Delta m_s\, t)$$

- Fit for $\mathcal{A}$ at different Δm_s :
- $\mathcal{A}$ = 1 for mixing at true Δm_s
- $\mathcal{A}$ = 0 else in case of no mixing

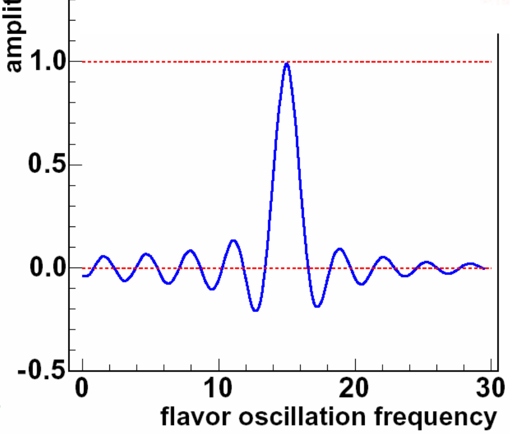
Time Domain





Frequency Domain

In reality: expected amplitude

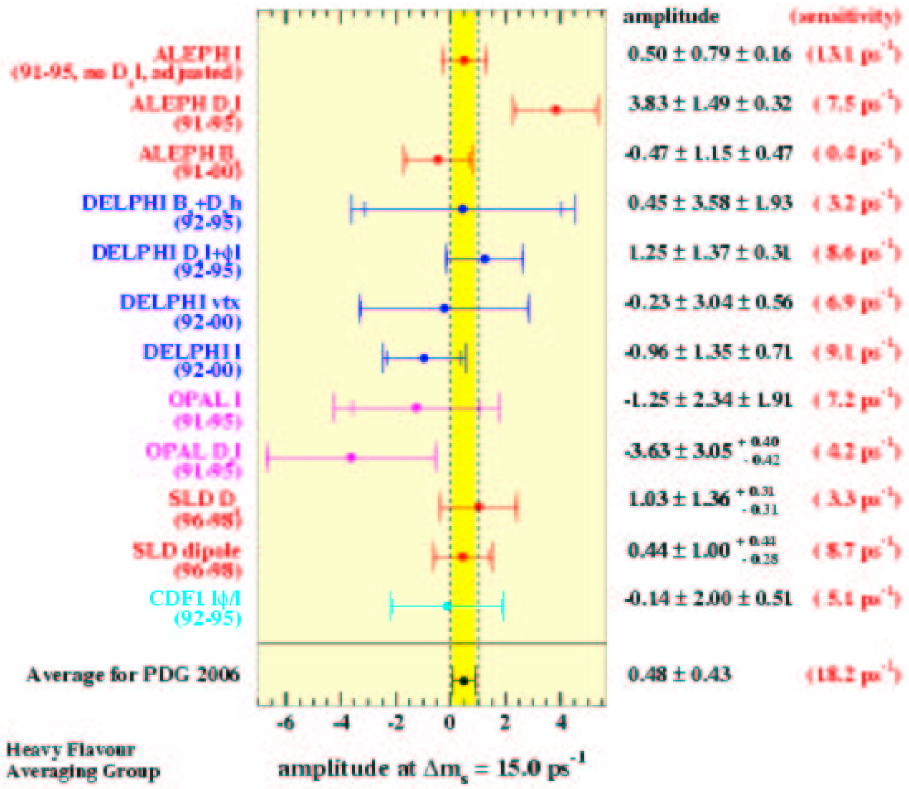


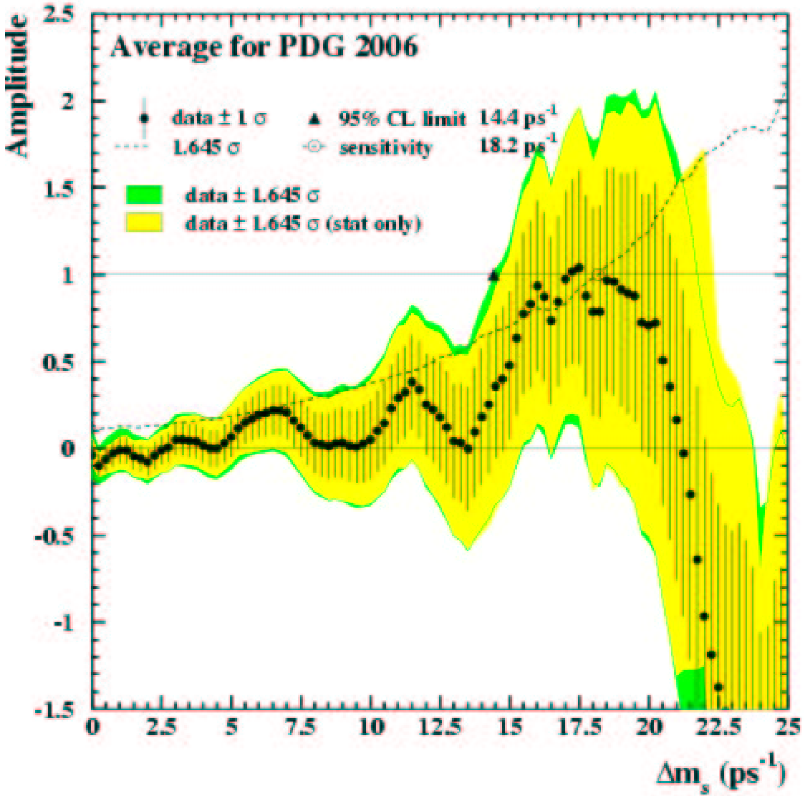
Some History

Beginning of 2006: Published results on B_S mixing:

Results from LEP, SLD, CDF I

$\Delta m_s > 14.4\ ps^{-1}$ 95% CL





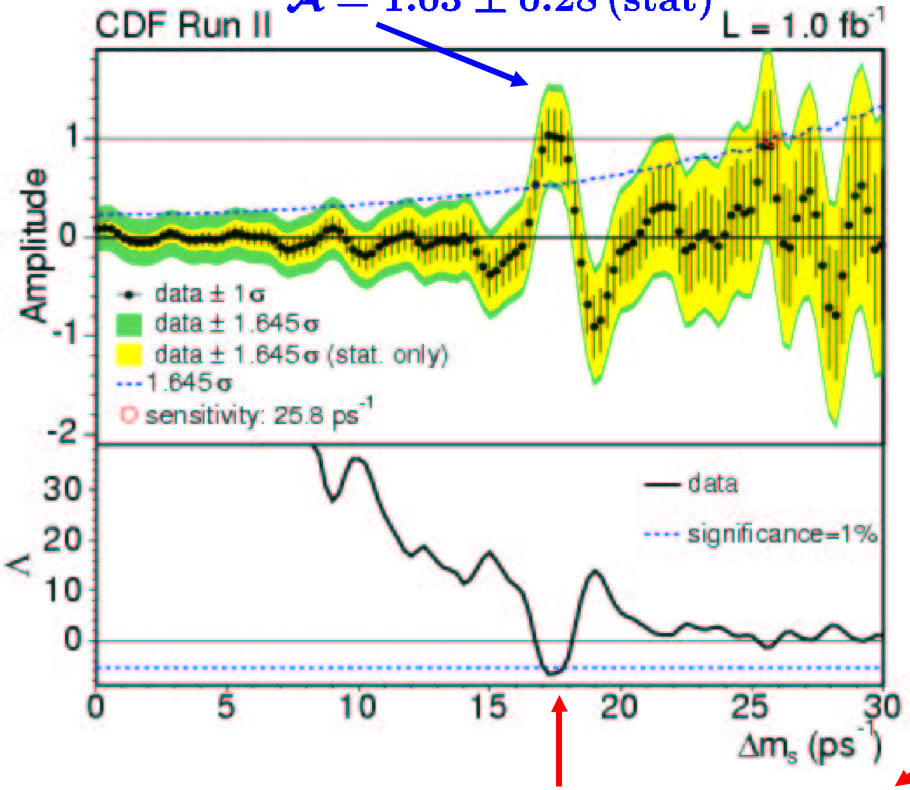
Some History

Reported at DESY in summer '06

April 2006: Result from CDF Collaboration

A. Abulencia *et al.*, *Phys. Rev. Lett.*, **97**, 062003 (2006)

$\mathcal{A} = 1.03 \pm 0.28\ (\text{stat})$



Probability that random fluctuations mimic this signal is 0.2% (3σ)

Assuming signal hypothesis: measure Δm_s

$$\Delta m_s = 17.31^{+0.33}_{-0.18}\,(\text{stat.}) \pm 0.07\,(\text{syst.})\ \text{ps}^{-1}$$

Since then goal has been to observe signal with > 5σ significance

Improvements since then

- Same data set (1 fb^{-1})
- Proper decay time resolution unchanged
- Signal selection
  - Neural network selection for hadronic modes
  - Add partially reconstructed hadronic decays
  - Use particle id (TOF, dE/dx) (separate kaons from pions)
    - Looser kinematic criteria possible due to lower background
  - Additional trigger selection criteria allowed
- Production Flavor tag
  - Opposite-side tags combined using neural network
    - Also added opposite-side kaon tag
  - Neural network combines kinematics and PID in same-side Kaon tag

Improvements since then

Example: Fully reconstructed signal $B_s^0 \to D_s^- \pi^+$

Cleanest decay sequence

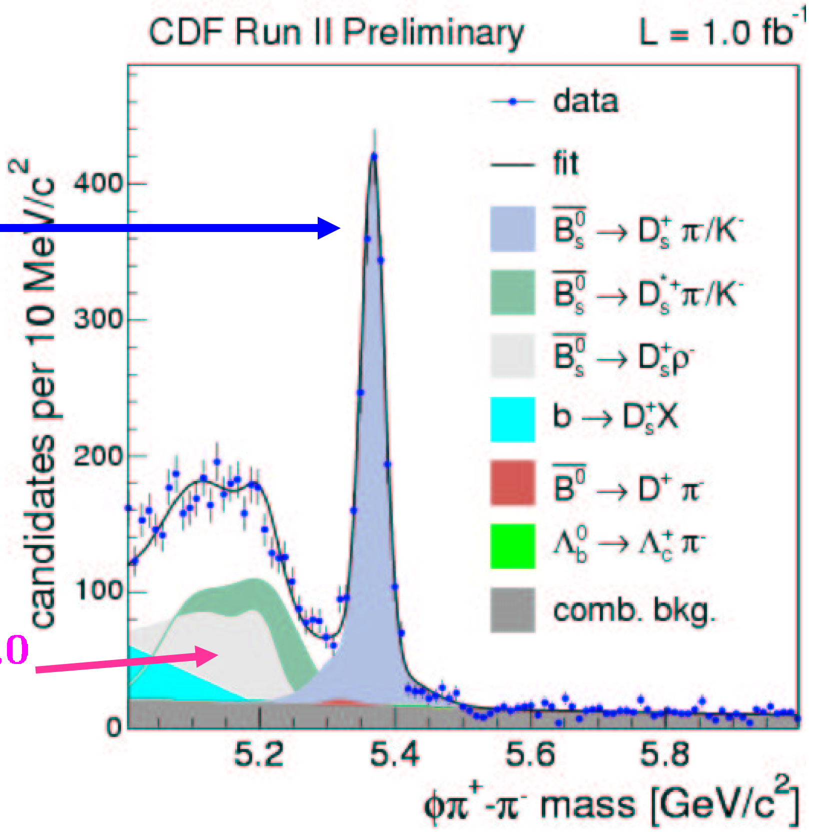
$\bar{B}_s^0 \to D_s^+ \pi^-$

$D_s^+ \to \phi \pi^+$

$(D_s^+ \to K^{*0} K^+, \pi^+ \pi^- \pi^+)$

Add partially reconstructed decays:

$D_s^{*+} \pi^-$ $D_s^+ \rho^-$ missing γ or π^0



Also use 6 body modes:

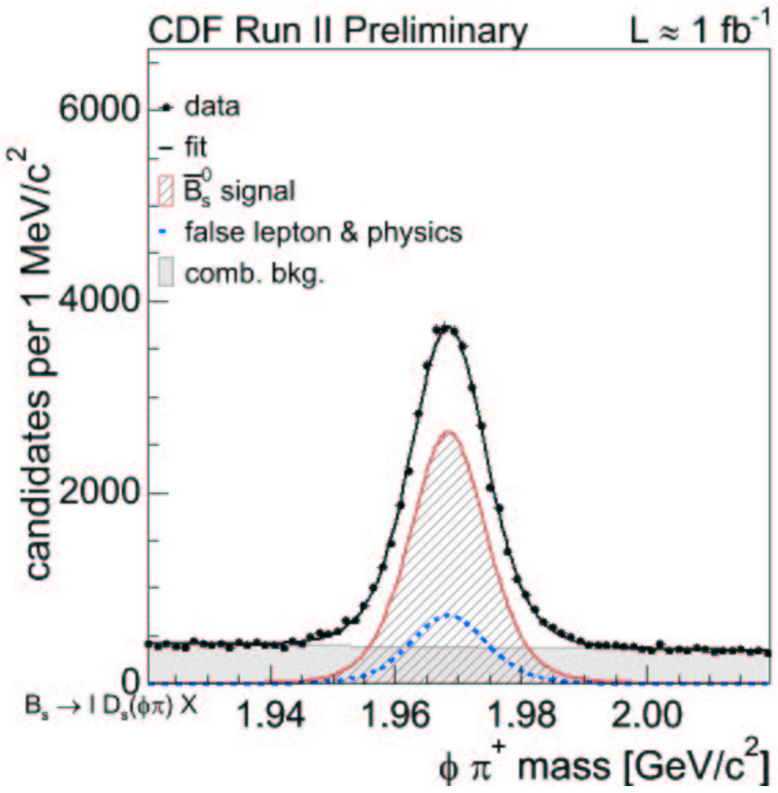
$$\bar{B}_s^0 \to D_s^+ \pi^- \pi^+ \pi^-,\ D_s^+ \to \phi \pi^+, K^{*0} K^+, \pi^+ \pi^- \pi^+$$

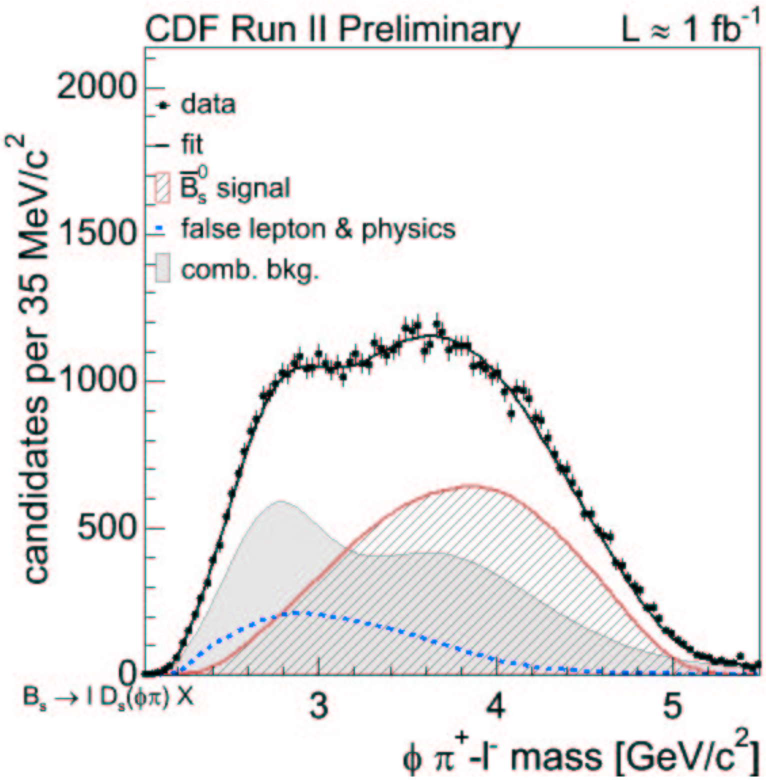
Hadronic signal increased from 3600 to 8700

Improvements since then

Semileptonic Signals: $B_s^0 \rightarrow D_s^- \ell^+ \nu$

$\bar{B}_s^0 \rightarrow D_s^{(*)+} \ell^- \bar{\nu}_\ell \quad D_s^+ \rightarrow \phi\pi^+, K^{*0}K^+, \pi^+\pi^-\pi^+$



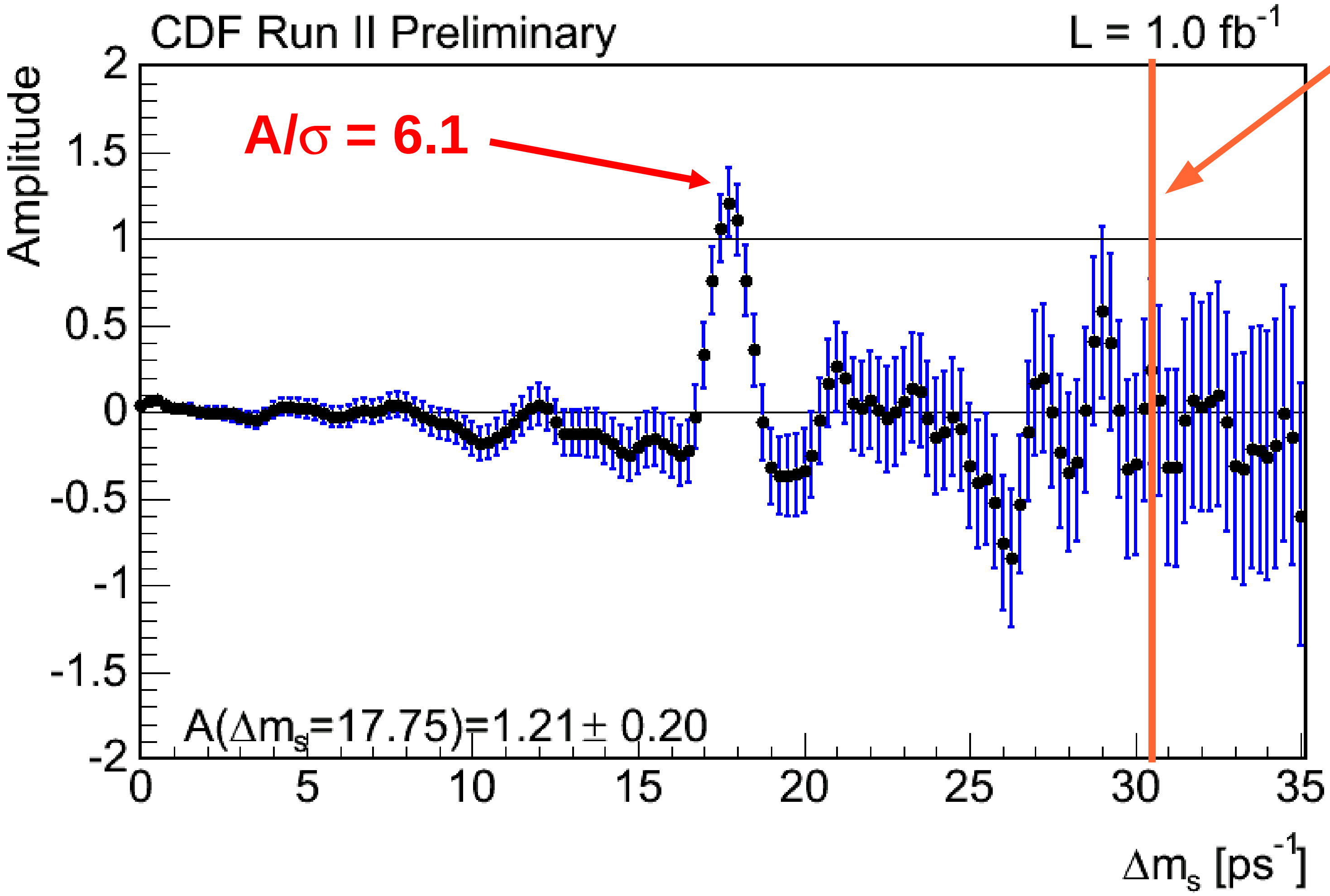


Semileptonic signal increased from 37000 to 61500

Result: Amplitude Scan

Hadronic & Semileptonic: Combined

Sensitivity:
31.3 ps^{-1}

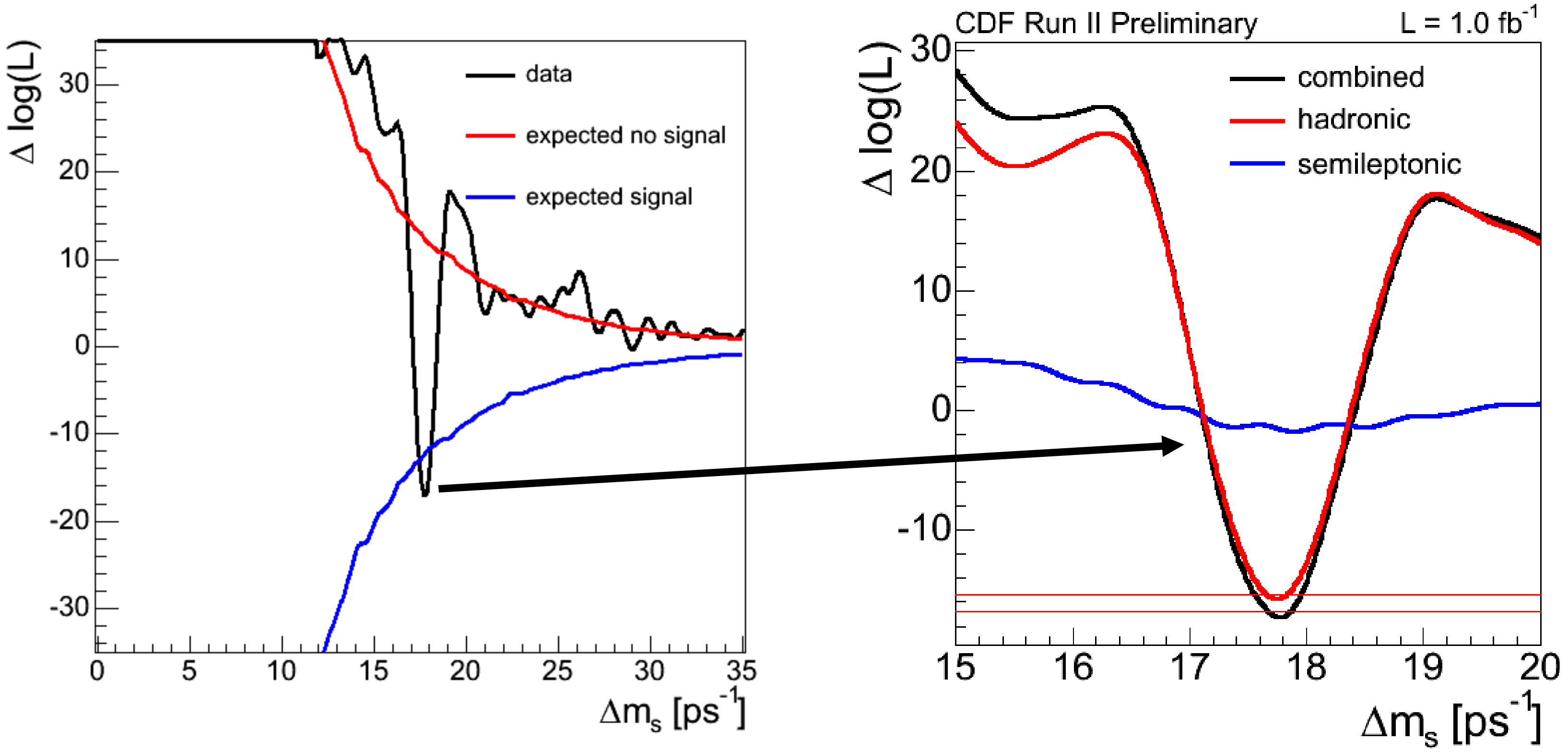


A/σ = 6.1

Result: Fit for Oscillation

Measured Value of Δm_s

Hypothesis of A=1 compared to A=0

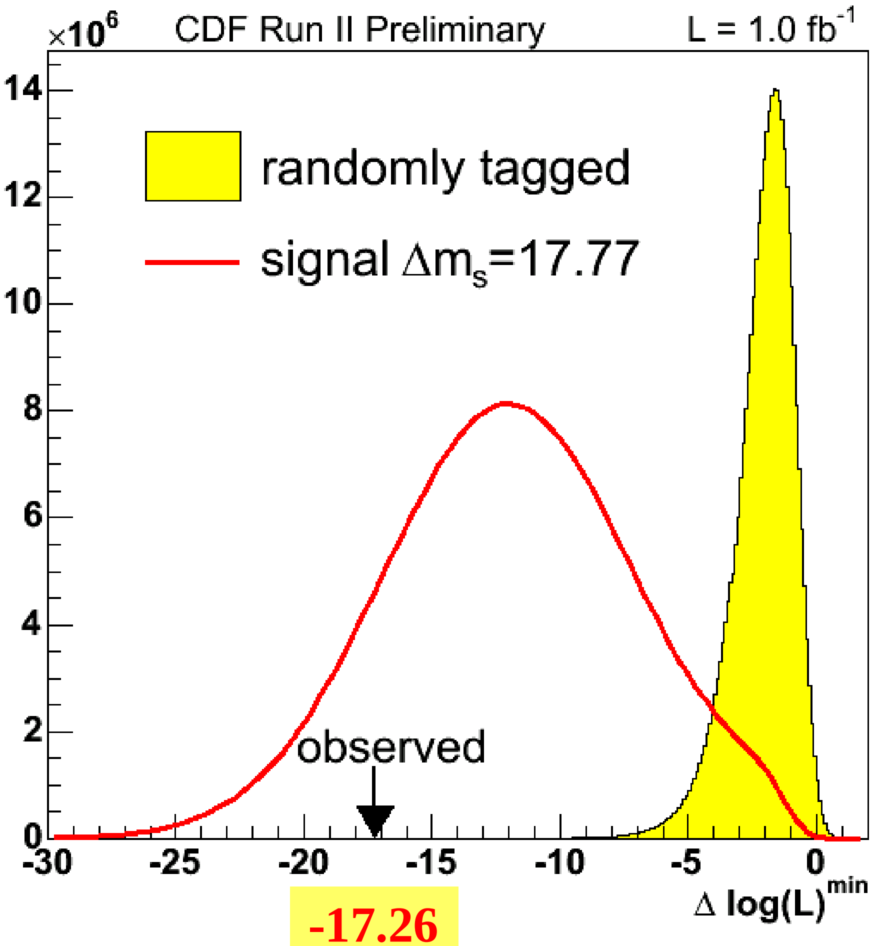


$$\Delta m_s = 17.77 \pm 0.10\,(\mathrm{stat.}) \pm 0.07\,(\mathrm{syst.})\ \mathrm{ps}^{-1}$$

Corresponds to frequency of 3 trillion times a second

Significance of Result

Probability of Fluctuation:



-17.26

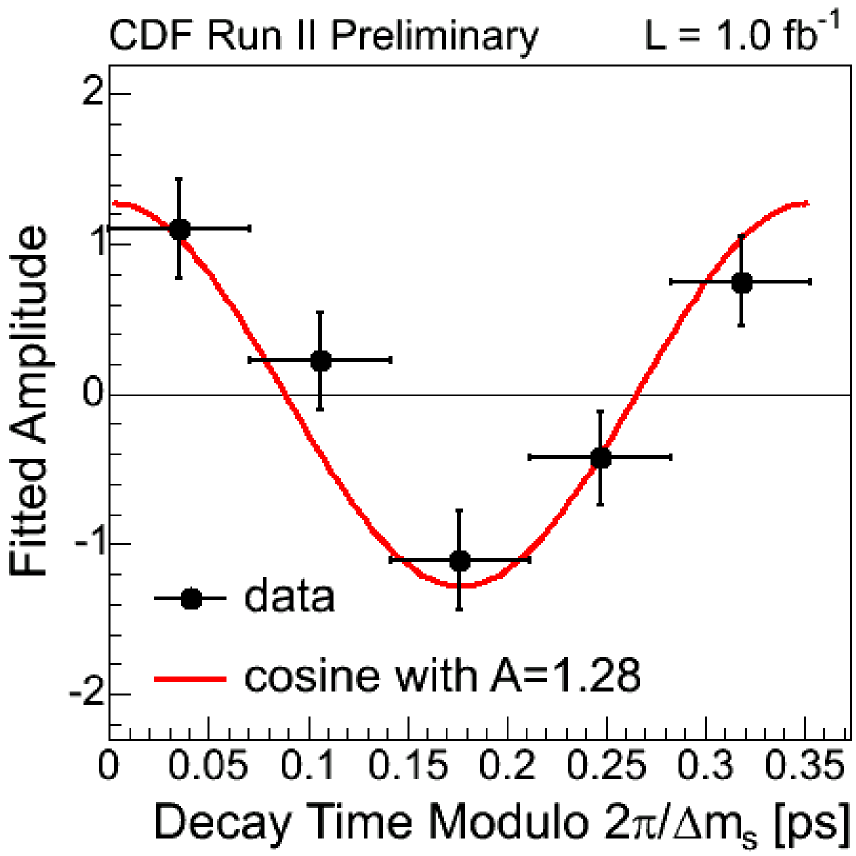
Probability of random fluctuation determined from data

28 of 350 million random trials have L < -17.26

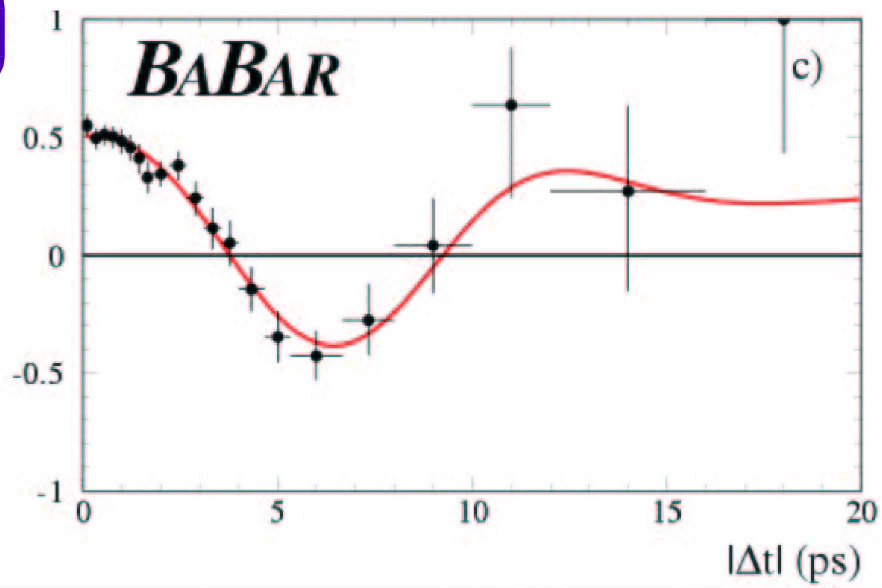
Probability = 8×10^{-8} (5.4σ)

Have exceeded standard threshold to claim observation

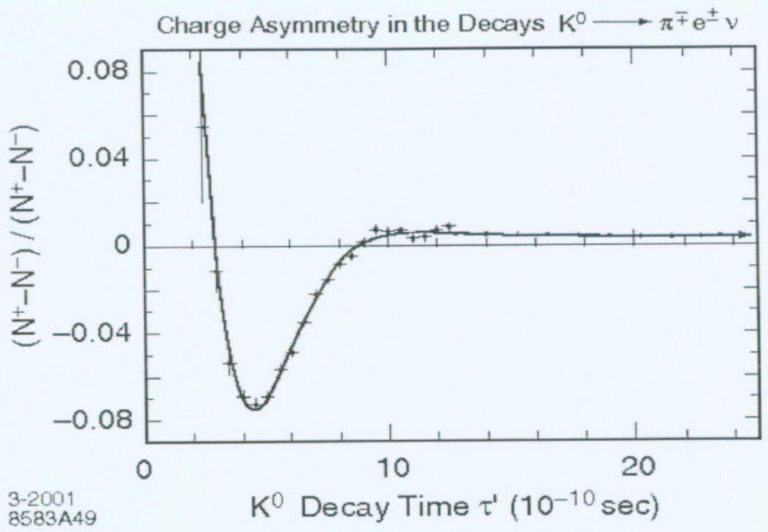
Oscillation in Time Domain



2006: B_s^0 oscillation: ~0.3 ps



2002: B^0 oscillation: ~10 ps



1974: K^0 oscillation: ~1000 ps

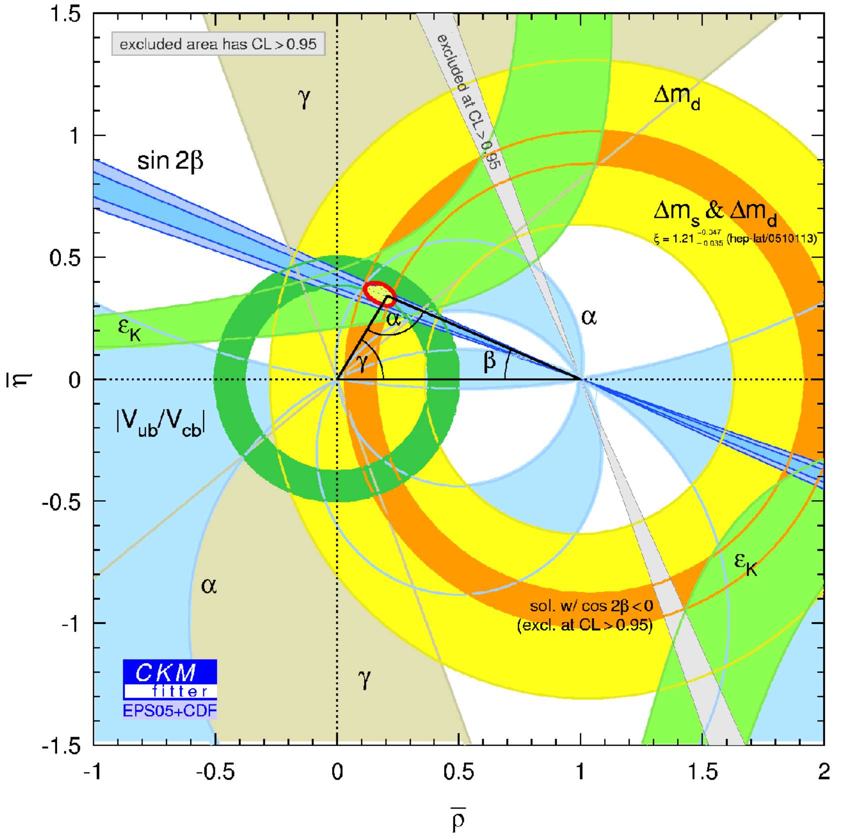
Measurement of CKM Matrix Elements

Determination of $|V_{ts}|$ / $|V_{td}|$:

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2}$$

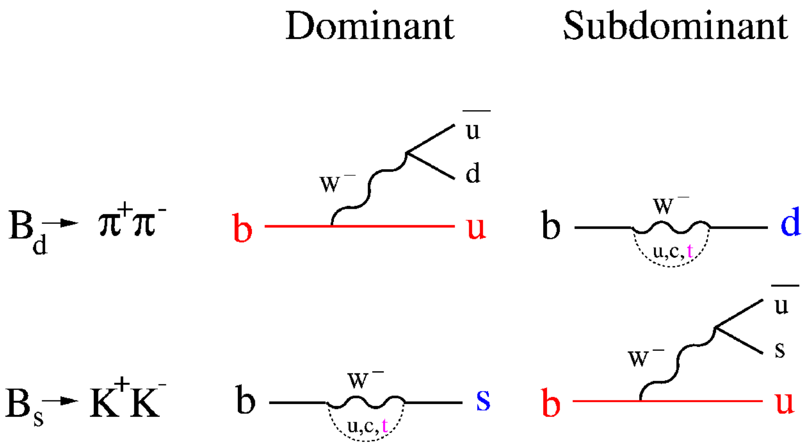
$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.2060 \pm 0.0007\,(\text{exp.})^{+0.0081}_{-0.0060}\,(\text{theo.})$$

The new world order:

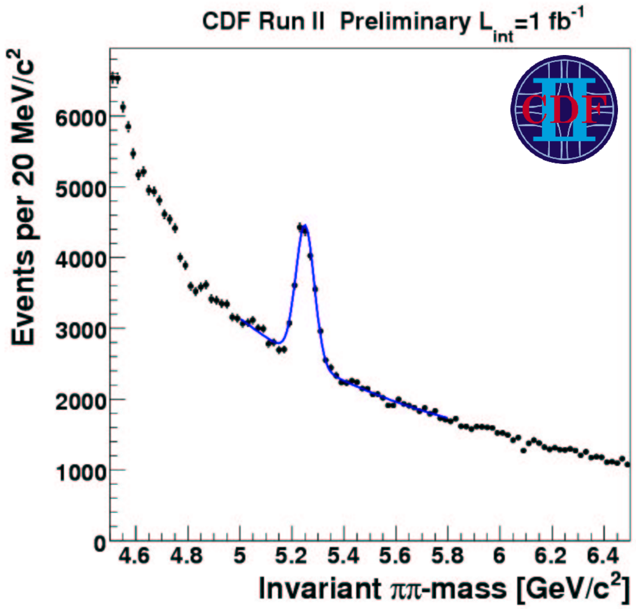


CP Violation: B -> hh

Charmless *B -> hh*



- CDF performed comprehensive analysis of charmless 2-body decays *B -> hh* (1 fb^{-1} of data)
- Joint study of B^0 and B_s decays into ππ/Kπ/KK can shed light on SU(3) symmetry breaking
- Important to disentangle tree versus penguin contributions
- Remember: Direct CP violation in B decays first observed in B^0 -> K π
- CDF uses 2-track hadronic trigger to collect large dataset of B -> hh
- Observe signal with offline confirmation of trigger cuts: ~8500 B -> hh events in 1 fb^{-1} of data
- **Primary analysis goals:**
  - Measure $A_{CP}(B^0 \rightarrow K^+\pi^-)$
  - Measure rare decays: $BR(B_s^0 \rightarrow K^-\pi^+)$



Charmless *B -> hh*

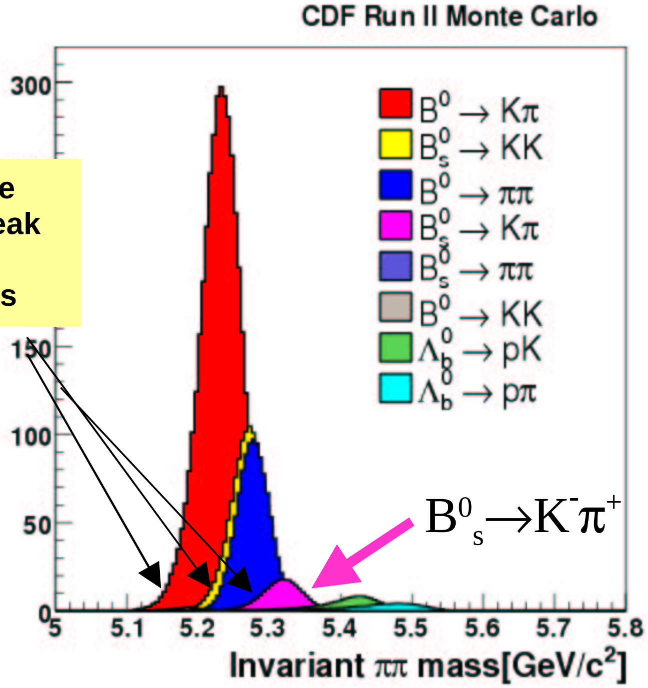
- **Optimize cuts using signal MC and sideband backgrounds:**

2 sets: - Measure CP asymmetry in B -> K π (loose selection)

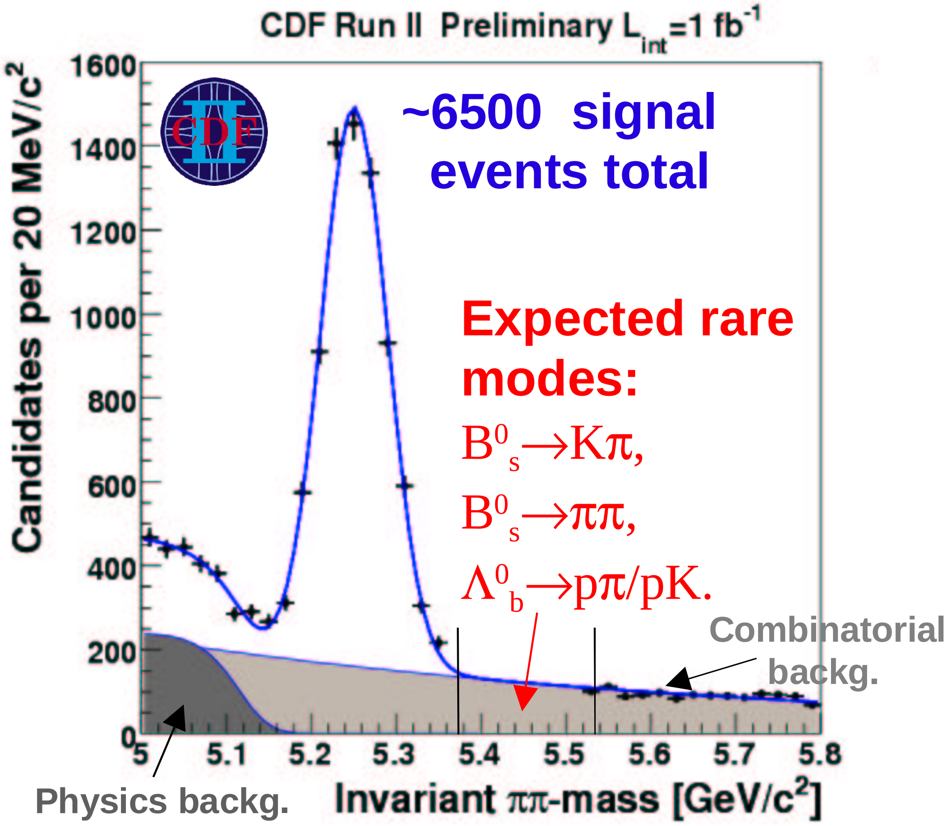
- Search for rare decays B_s -> Kπ & measure BR (tighter select.)

- **Despite excellent mass resolution (~22 MeV) modes overlap**
- **BR measurements sensitive to shape of mass resolution: radiative tails**

FSR tail on the left of each peak affects BR measurements



$B^0_s \to K^-\pi^+$



~6500 signal events total

Expected rare modes:

$B^0_s \to K\pi$,

$B^0_s \to \pi\pi$,

$\Lambda^0_b \to p\pi/pK$.

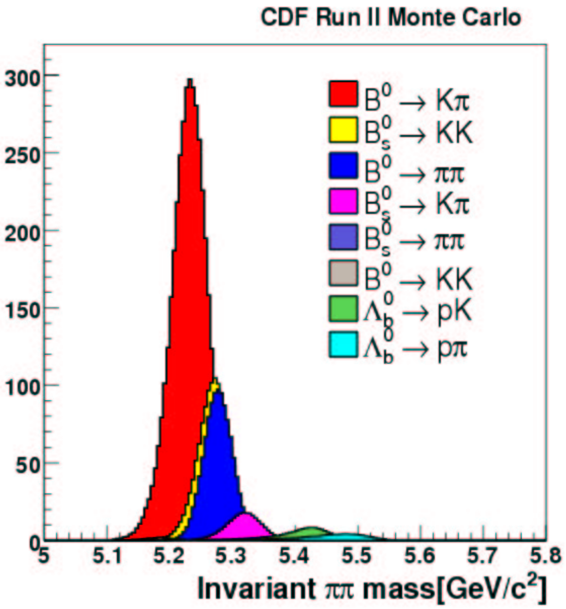
Combinatorial backg.

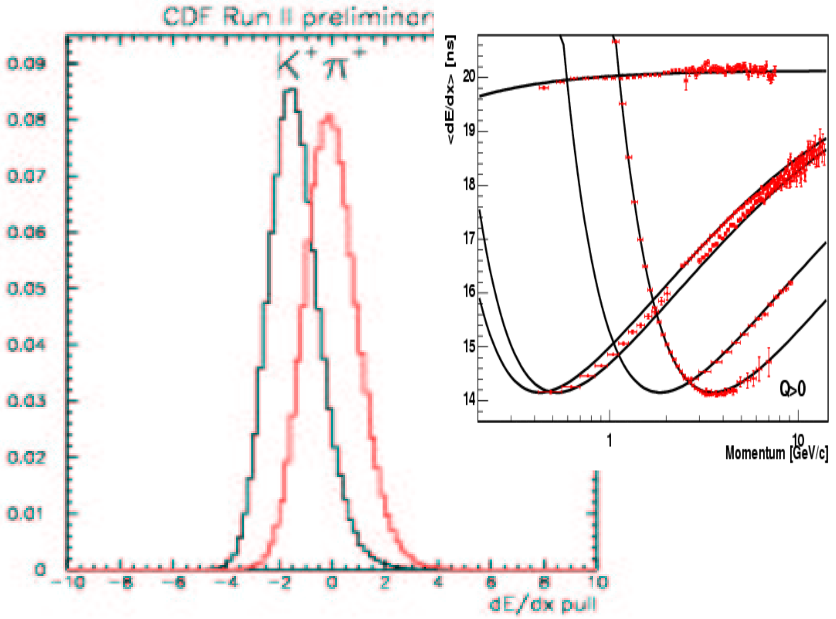
Physics backg.

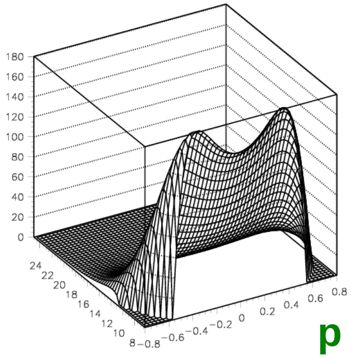
Charmless *B -> hh*

- Disentangle overlapping modes by
  - Invariant mass information: m(ππ)
  - Kinematic discriminates

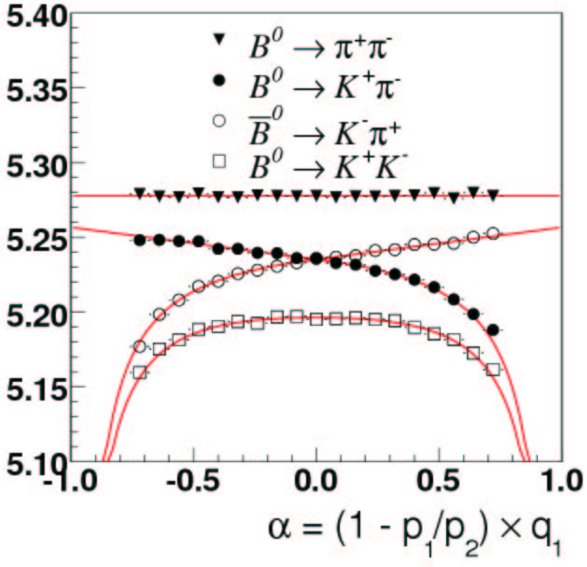
    $\alpha = (1-p_{min}/p_{max})q_{min}$ signed momentum imbalance
  - PID through dE/dx
- Use 1.5 mio D* -> $D^0\pi$, D^0 -> Kπ to accurately calibrate dE/dx over tracking volume & time





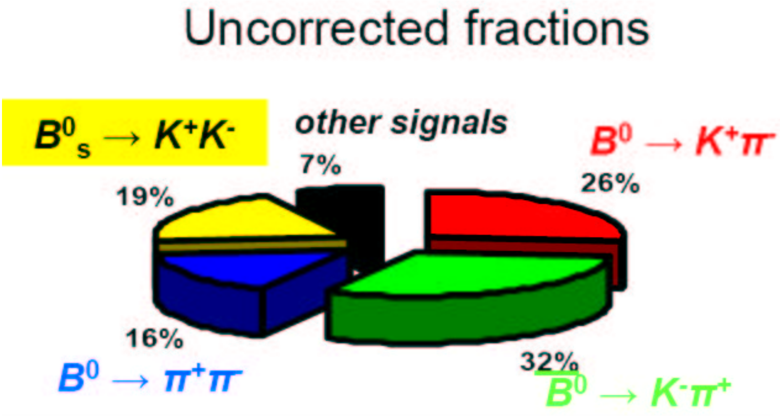


p imbalance

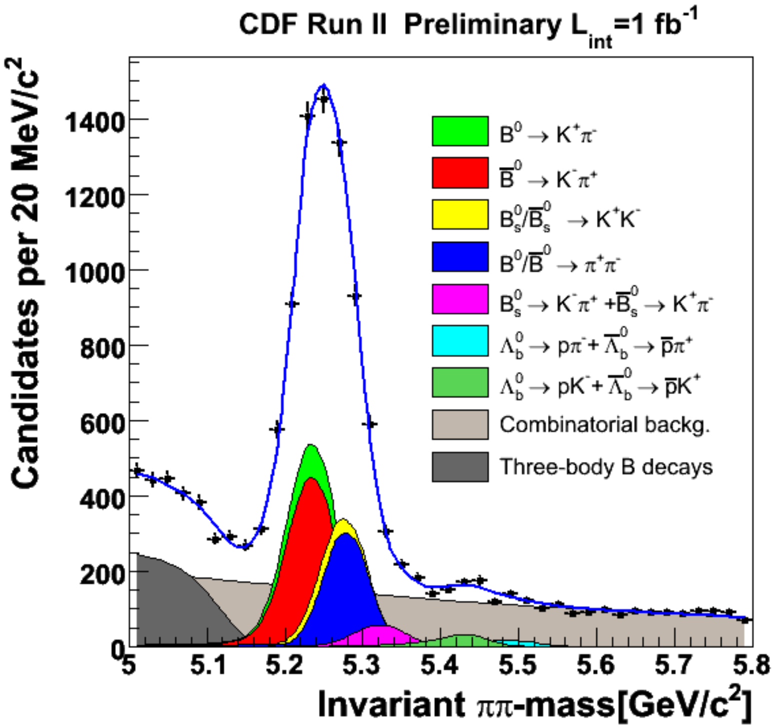


CP Violation: $B^0 \to K^+ \pi^-$

Measurement of "raw" assymetry $A_{CP}(B^0 \to K^+\pi)$



parameter	fraction	yield
$B^0 \to \pi^+\pi^- + \text{c.c.}$	(0.160 ± 0.009)	1121 ± 63
$B^0 \to K^+\pi^- + \text{c.c.}$	(0.577 ± 0.010)	4045 ± 84
$B^0_s \to K^+K^- + \text{c.c.}$	(0.186 ± 0.009)	1307 ± 64



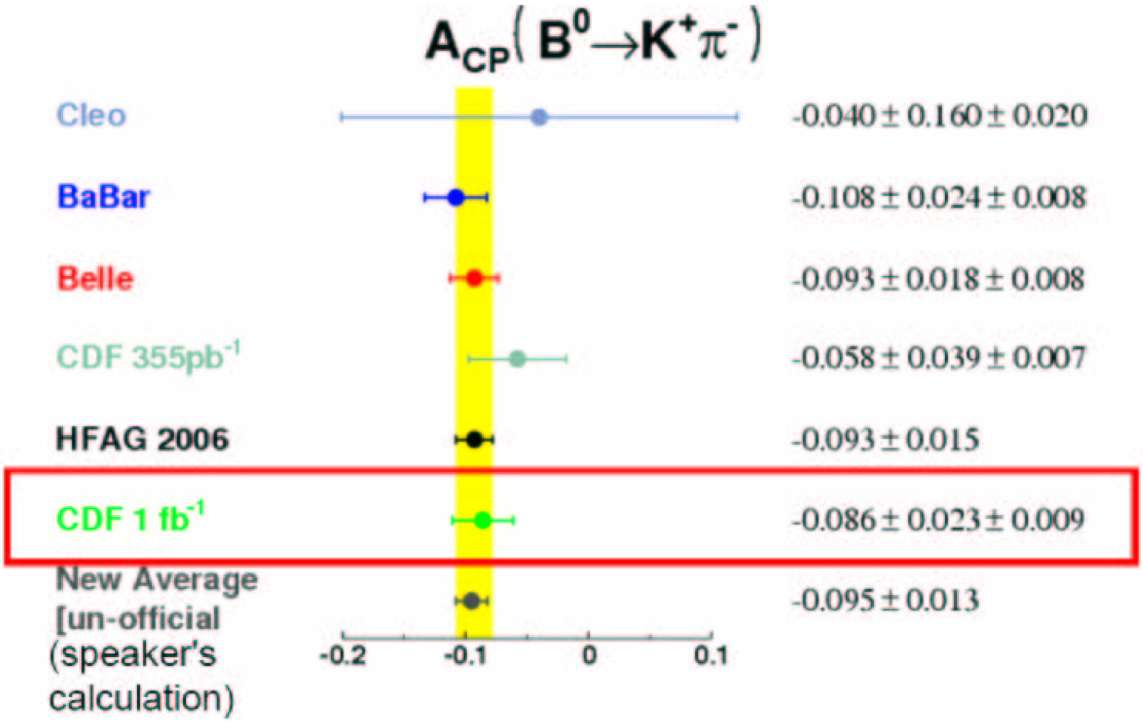
$B^0 \to h^+h^-$ yield like B factories, and unique large sample of $B_s^0 \to h^+h^-$

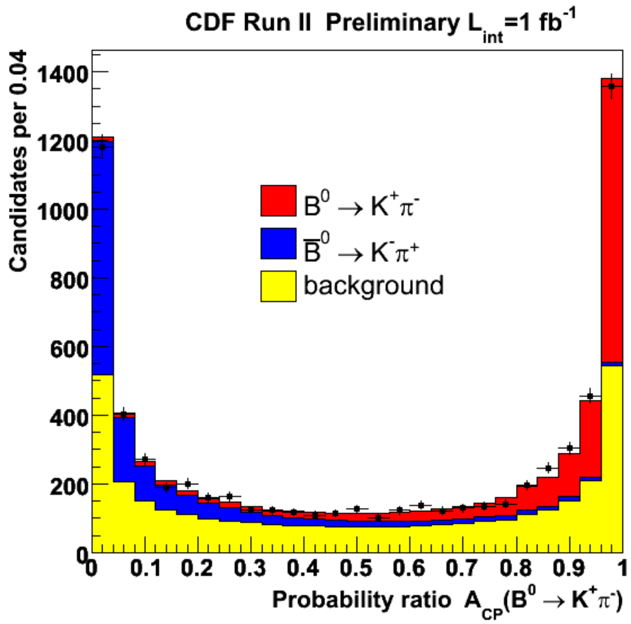
$$A_{CP}\Big|_{raw} = \frac{N_{raw}(\overline{B}^0 \to K^-\pi^+) - N_{raw}(B^0 \to K^+\pi^-)}{N_{raw}(\overline{B}^0 \to K^-\pi^+) + N_{raw}(B^0 \to K^+\pi^-)} = -0.092 \pm 0.023$$

CP Violation: $B^0 \to K^+ \pi^-$

After correcting for K^+/K^- interaction rate asymmetry and evaluating systematic effects, find:

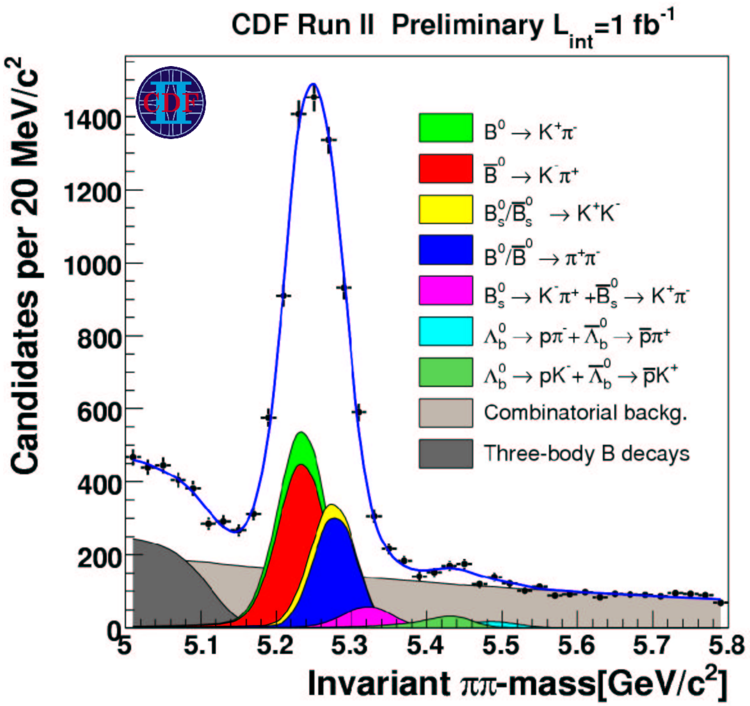
$$A_{CP} = \frac{N(\overline{B}^0 \to K^-\pi^+) - N(B^0 \to K^+\pi^-)}{N(\overline{B}^0 \to K^-\pi^+) + N(B^0 \to K^+\pi^-)} = -0.086 \pm 0.023\ (stat.) \pm 0.009\ (syst.)$$



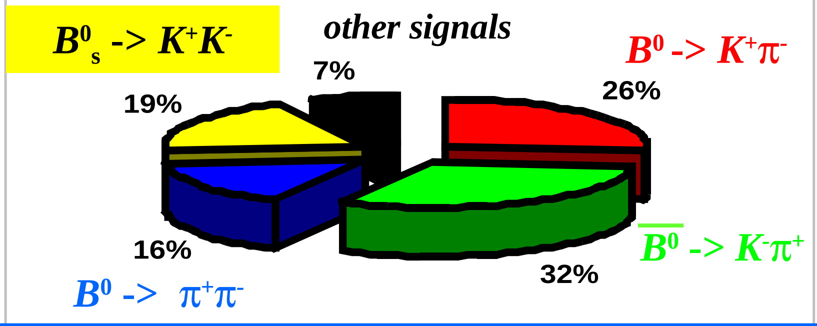


Second best single measurement of $A_{CP}(B^0 \to K^+\pi^-)$!

$B^0 \to \pi^+\pi^-$ & $B_s^0 \to K^+K^-$



Uncorrected fractions



parameter	fraction	yield
$B^0 \to \pi^+\pi^-$ + c.c.	(0.160 ± 0.009)	1121 ± 63
$B^0 \to K^+\pi^-$ + c.c.	(0.577 ± 0.010)	4045 ± 84
$B_s^0 \to K^+K^-$ + c.c.	(0.186 ± 0.009)	1307 ± 64

$$\frac{BR(B^0 \to \pi^+\pi^-)}{BR(B^0 \to K^+\pi^-)} = 0.259 \pm 0.017\ (stat.) \pm 0.016\ (syst.)$$

$$\frac{f_s \cdot BR(B_s^0 \to K^+K^-)}{f_d \cdot BR(B^0 \to K^+\pi^-)} = 0.324 \pm 0.019\ (stat.) \pm 0.041\ (syst.)$$

Using HFAG (Aug'06):

[redacted]

(good agreement with B factories)

$BR(B^0_s \to K^+K^-)$ and $BR(B^0 \to \pi^+\pi^-)$ are becoming high precision measurement.

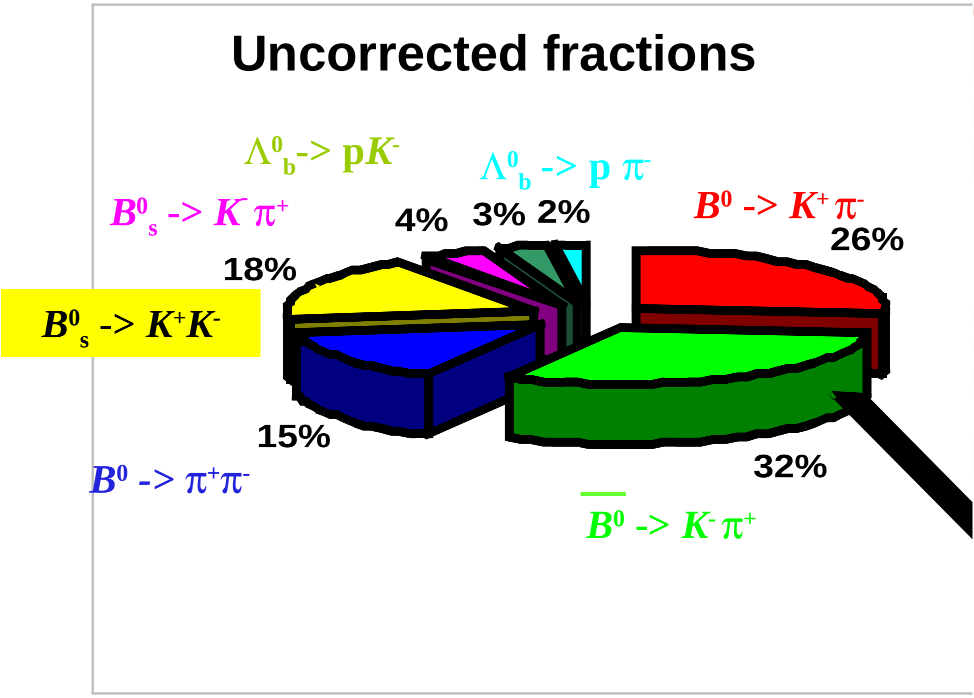
Theoretical expectations are not completely in agreement.

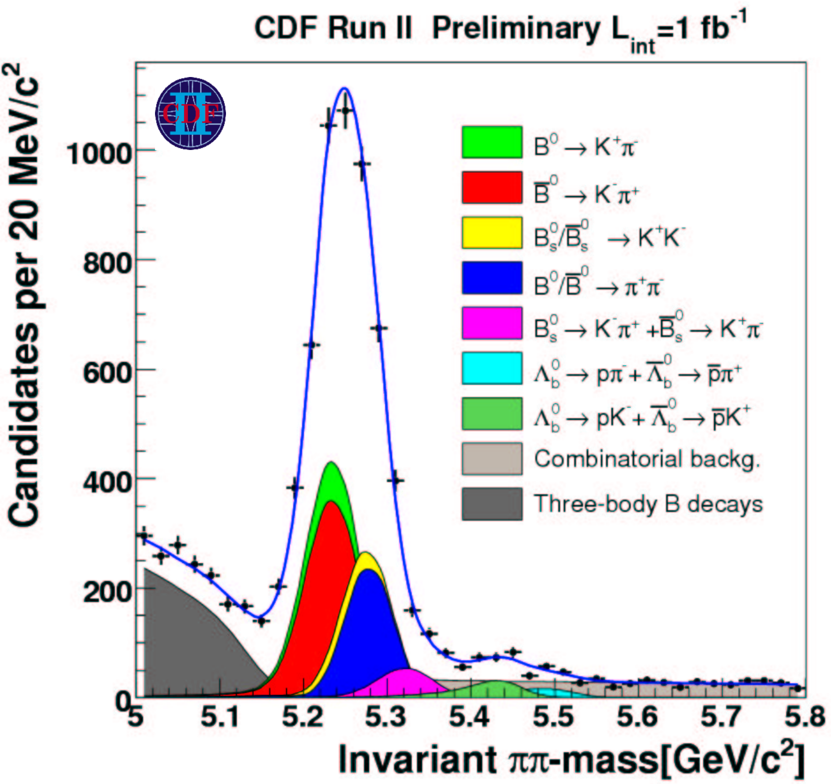
[Matias et al. PRL97, 061801, 2006] $BR(B^0_s \to K^+K^-)/BR(B^0 \to K^+\pi^-) \sim 1$

[Khodjamirian et al. PRD68:114007, 2003] predict large SU(3) breaking ~2 <--- Disfavored by CDF.

Charmless *B -> hh*

Search for rare modes:


Uncorrected fractions


CDF Run II Preliminary L_{int}=1 fb^{-1}

New rare modes observed

🟪 $N_{\rm raw}(B^0_s \to K^-\pi^+) = 230 \pm 34\ (stat.) \pm 16\ (syst.)$ (8σ)

🟦 $N_{\rm raw}(\Lambda^0_b \to p\pi^-) = 110 \pm 18\ (stat.) \pm 16\ (syst.)$ (6σ)

🟩 $N_{\rm raw}(\Lambda^0_b \to pK^-) = 156 \pm 20\ (stat.) \pm 11\ (syst.)$ (11σ)

Charmless B -> hh

First observation: B_s^0 -> $K^- \pi^+$

$$N_{\rm raw}(B_s^0 \to K^-\pi^+) \;=\; 230 \pm 34\;(stat.) \pm 16\;(syst.)$$

$$\frac{f_s \cdot BR(B_s^0 \to K^-\pi^+)}{f_d \cdot BR(B^0 \to K^+\pi^-)} \;=\; 0.066 \pm 0.010\;(stat.) \pm 0.010\;(syst.)$$

Using HFAG: [redacted]

[Beneke&Neubert NP B675, 333(2003)]: ~[7-10] $\cdot 10^{-6}$
[Yu, Li, Yu, PRD71: 074026 (2005)]: ~[6-10]$\cdot 10^{-6}$
[Williamson, Zupan. PRD74 (2006) 014003]: ~4.9 $\cdot 10^{-6}$

Upper limits: B_s^0 -> $\pi^+\pi^-$ & B^0 -> K^+K^-

$$\frac{f_s \cdot BR(B_s^0 \to \pi^+\pi^-)}{f_d \cdot BR(B^0 \to K^+\pi^-)} \;=\; 0.007 \pm 0.004\;(stat.) \pm 0.005\;(syst.)$$

1.5 σ

$$\frac{BR(B^0 \to K^+K^-)}{BR(B^0 \to K^+\pi^-)} \;=\; 0.020 \pm 0.008\;(stat.) \pm 0.006\;(syst.)$$

1.5 σ

Both modes are annihilation-dominated decays. B^0 same resolution as B factories.

Using HFAG:

[redacted] (< 0.7 $\cdot 10^{-6}$ @ 90% C.L.)

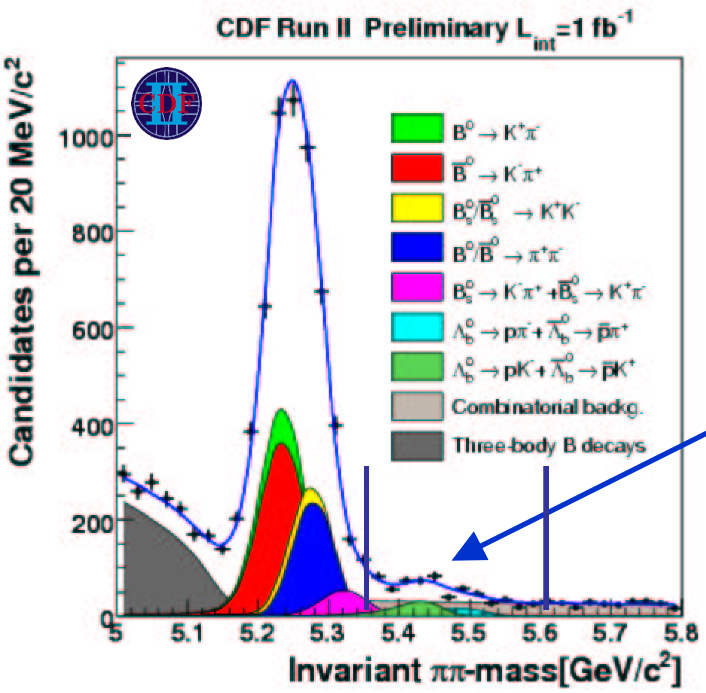
Expected [0.01 - 0.2] $\cdot 10^{-6}$ [Beneke&Neubert NP B675, 333(2003)]

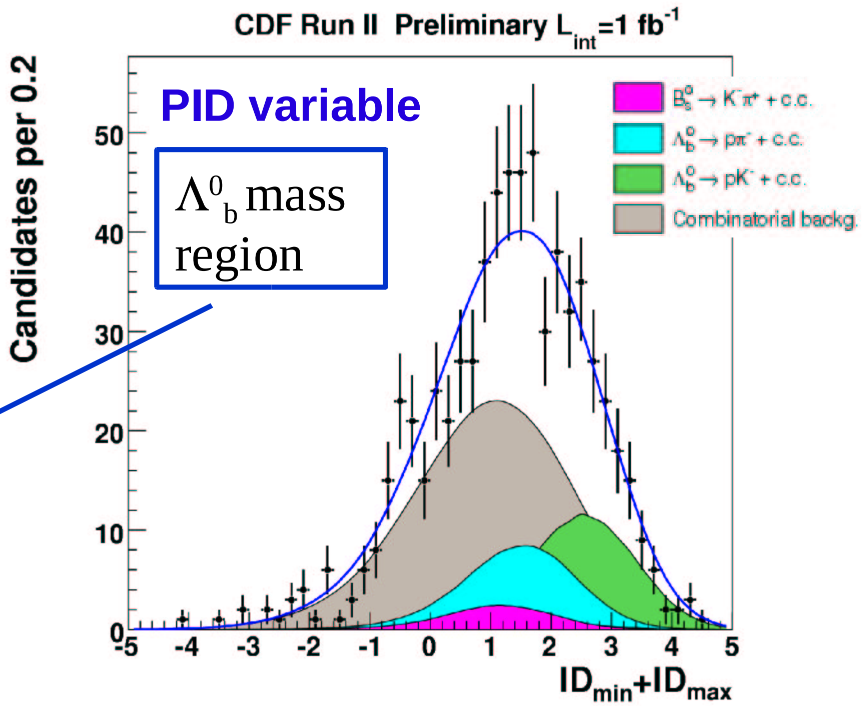
[redacted] (<1.36 $\cdot 10^{-6}$ @ 90% C.L.)

Expected: [0.007 - 0.08] $\cdot 10^{-6}$ [Beneke&Neubert NP B675, 333(2003)]
Expected: 0.42 ± 0.06 [Ying Li et al. hep-ph/0404028]

Charmless *B -> hh*

First observations: $\Lambda_b^0 \to p\,\pi^-$ & $\Lambda_b^0 \to p\,K^-$





$$N_{\text{raw}}(\Lambda_b^0 \to pK^-) = 156 \pm 20\ (stat.) \pm 11\ (syst.)$$

11 σ

$$N_{\text{raw}}(\Lambda_b^0 \to p\pi^-) = 110 \pm 18\ (stat.) \pm 16\ (syst.)$$

6 σ

$$\frac{BR(\Lambda_b^0 \to p\pi^-)}{BR(\Lambda_b^0 \to pK^-)} = 0.66 \pm 0.14\ (stat.) \pm 0.08\ (syst.)$$

Observation of Σ_b Baryon

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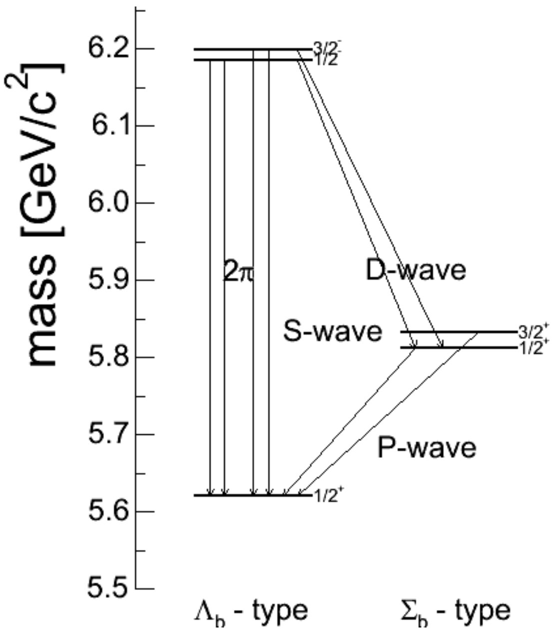


Motivation:

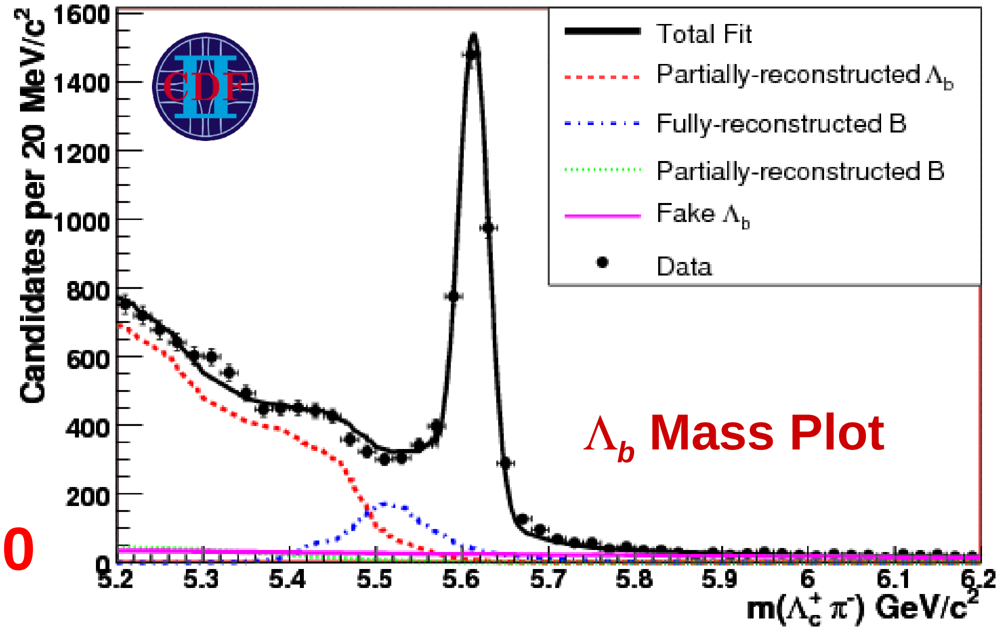
- Λ_b only established *B* baryon
- Next accessible baryons:

$$\Sigma_b: b\{qq\},\ q = u,d;\ J^P = S_Q + s_{qq} \rightarrow = 3/2^+ (\Sigma_b^*)$$

$$\rightarrow = 1/2^+ (\Sigma_b)$$

- HQET well tested for meson systems; check predictions for *Qqq* systems

- Baryon spectroscopy tests Lattice QCD & potential quark models



CDF with 1.1 fb^{-1}, world's largest sample of Λ_b: ~2800

Observation of Σ_b Baryon

Search Strategy:

Use 2 track trigger to reconstruct:

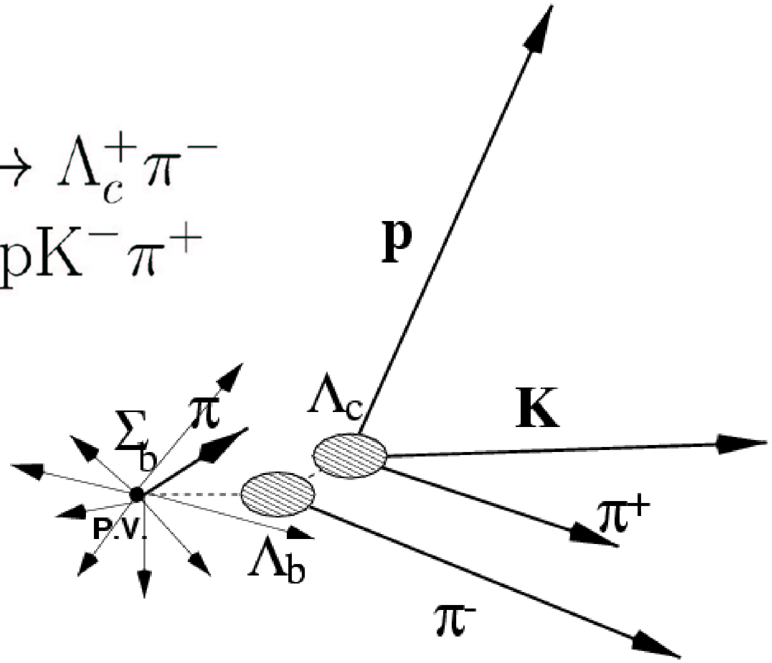
$$\Lambda_b^0 \to \Lambda_c^+ \pi^-$$

$$\Lambda_c^+ \to pK^- \pi^+$$

- **Σ_b decays at primary vertex**
- **Combine Λ_b with a prompt track to form a Σ_b candidate**
- **Separate Σ_b^- and Σ_b^+:**

$$\Sigma_b^{(*)-} \to \Lambda_b^0 \pi^- \to \Lambda_c^+ \pi^- \pi^-$$

$$\Sigma_b^{(*)+} \to \Lambda_b^0 \pi^+ \to \Lambda_c^+ \pi^- \pi^+$$



- **Search for resonances in mass diff.:**

  $Q = m(\Lambda_b\pi) - m(\Lambda_b) - m_\pi$

- **Optimize Σ_b cuts with Σ_b signal region blinded: $30 < Q < 100$ MeV/c^2**

Σ_b backgrounds:

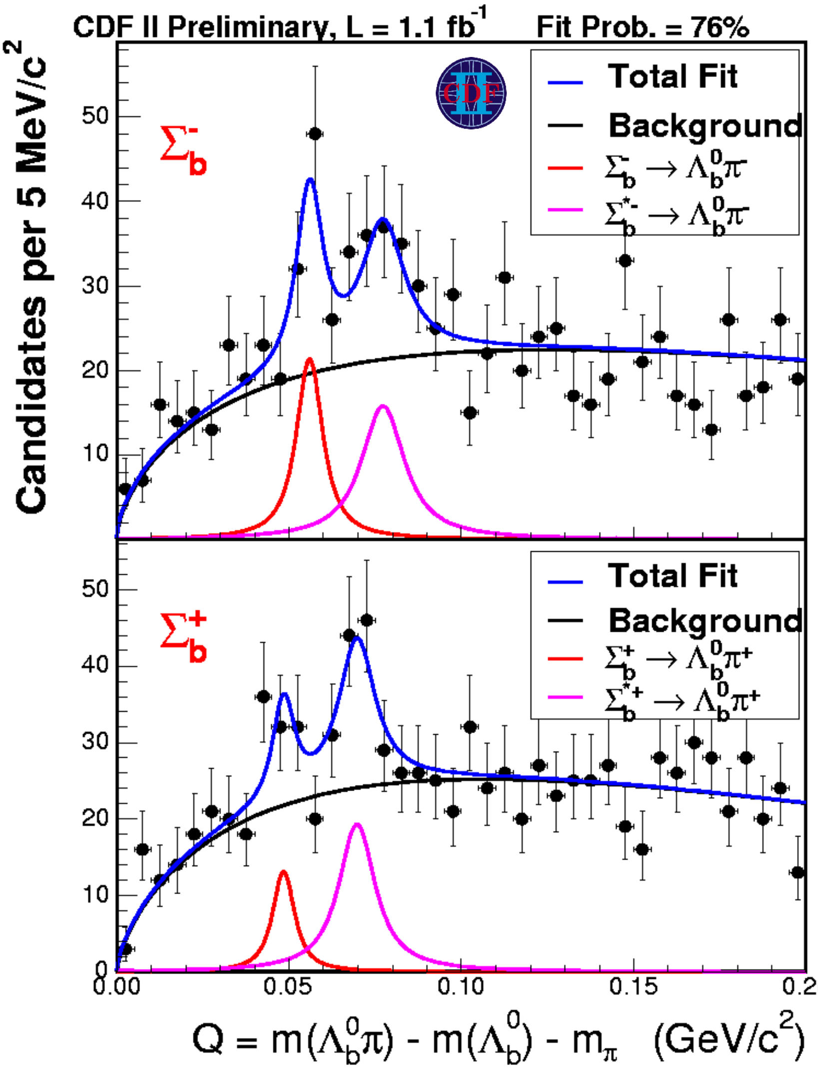
- **Λ_b hadronization + underlying event – Dominant!**
- ***B* meson hadronization**
- **Combinatorial background**

Fix background contributions from data or PYTHIA MC

Observation of Σ_b Baryon

- **Observe signals consistent with lowest lying charged Σ_b states**
- **With unbinned likelihood fit, measure number of events**

$$N(\Sigma_b^-) = 60^{+14.8}_{-13.8}\ (\text{stat})\ ^{+8.4}_{-4.0}\ (\text{syst})$$
$$N(\Sigma_b^+) = 29^{+12.4}_{-11.6}\ (\text{stat})\ ^{+5.0}_{-3.4}\ (\text{syst})$$
$$N(\Sigma_b^{*-}) = 74^{+18.2}_{-17.4}\ (\text{stat})\ ^{+15.6}_{-5.0}\ (\text{syst})$$
$$N(\Sigma_b^{*+}) = 74^{+17.2}_{-16.3}\ (\text{stat})\ ^{+10.3}_{-5.7}\ (\text{syst})$$



Determine mass difference values:

$$m(\Sigma_b^-) - m(\Lambda_b^0) - m_\pi = 55.9^{+1.0}_{-1.0}\ (\text{stat})\ \pm 0.1\ (\text{syst})\ \text{MeV}/c^2$$
$$m(\Sigma_b^+) - m(\Lambda_b^0) - m_\pi = 48.4^{+2.0}_{-2.3}\ (\text{stat})\ \pm 0.1\ (\text{syst})\ \text{MeV}/c^2$$
$$m(\Sigma_b^*) - m(\Sigma_b) = 21.3^{+2.0}_{-1.9}\ (\text{stat})\ ^{+0.4}_{-0.2}\ (\text{syst})\ \text{MeV}/c^2$$

Conclusions

- **Tevatron offers rich heavy flavour program**
- **Some recent results include**
  - **Lifetimes: Λ_b^0 lifetime measured ~3σ higher than world avg.**
  - **Mixing: Observation of B_S^0 oscillations**
  - **CP violation:**
    - **New results from charmless B -> hh decays**
    - **Competitive measurement of $A_{CP}(B^0 \to K^+\pi)$**
    - **Observation of rare charmless Λ_b^0 decay modes**
  - **Observation of Σ_b baryon states**


As part of their campaign to proactively incentivise their members,

the philosophers club initiated a food for thought program.