Lecture 1: b quarks at Hadron Colliders

CTEQ Summer School

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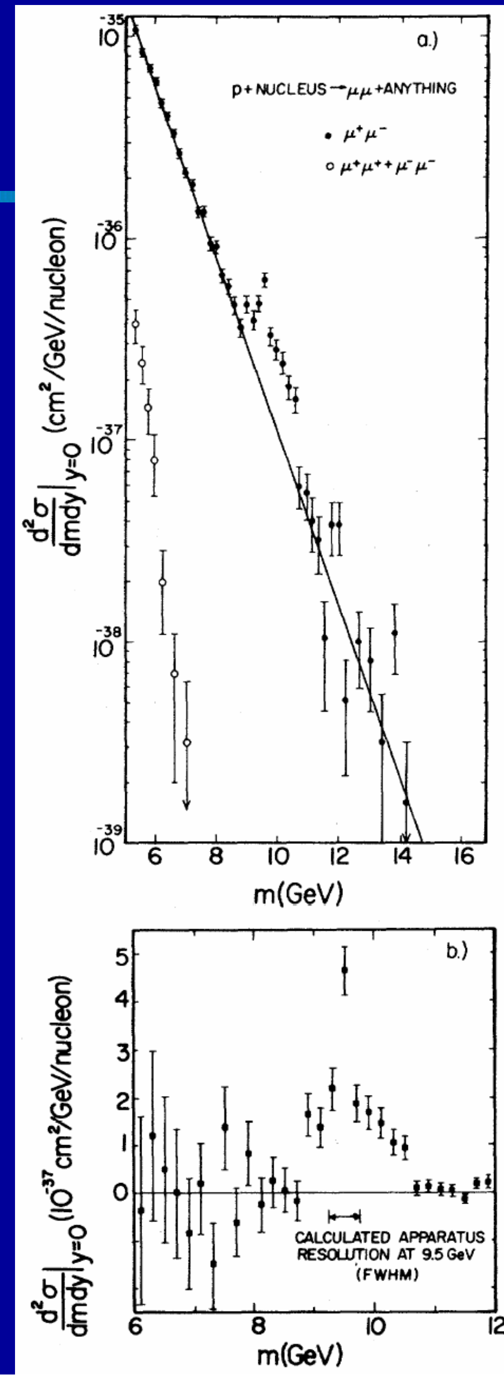
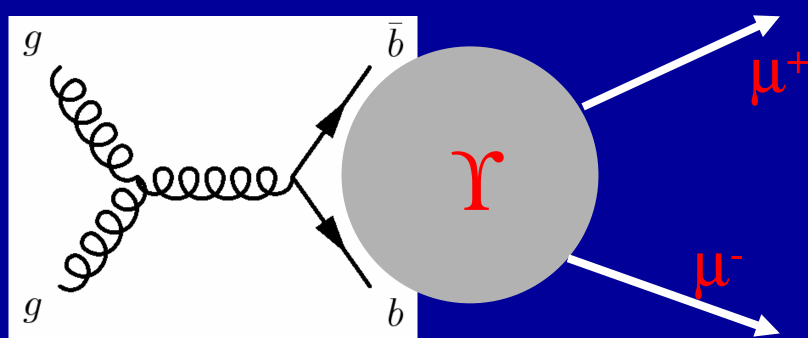
Discovery of b quark

- E288/CFS experiment at Fermilab
  - Search of lepton pairs
    - p+Nucleus → $\mu^+\mu^- + X$
  - 1977: narrow resonance in μ pair mass spectrum

S. W. Herb et Al., Phys. Rev. Lett. 39, 252 – 255 (1977).

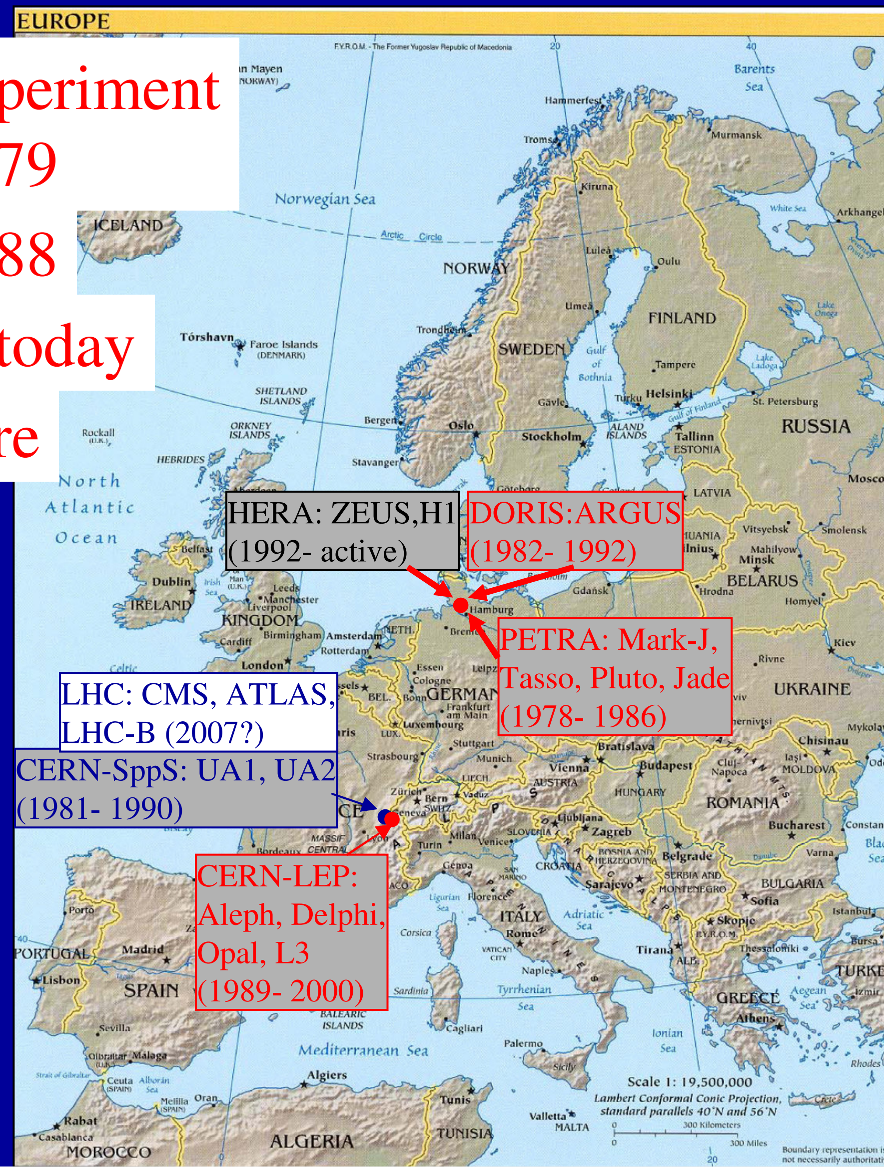
  - In analogy with the J/ψ case this new particle, Υ, can be interpreted as a $b\bar{b}$ bound state





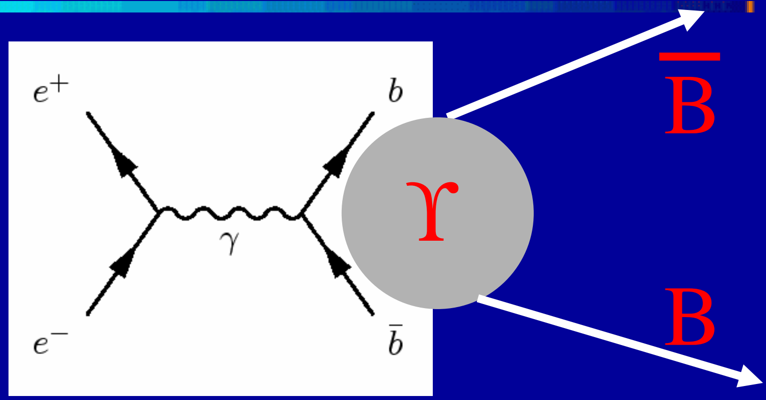
b-production around the world

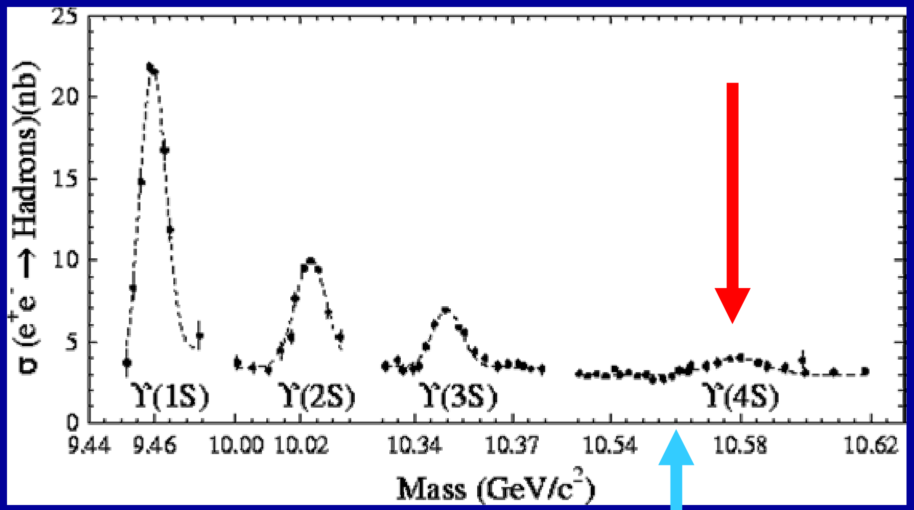
Active experiment
Year ’73-79
Year ’80-88
Year ’89-today
Near future



B-production at e+e-

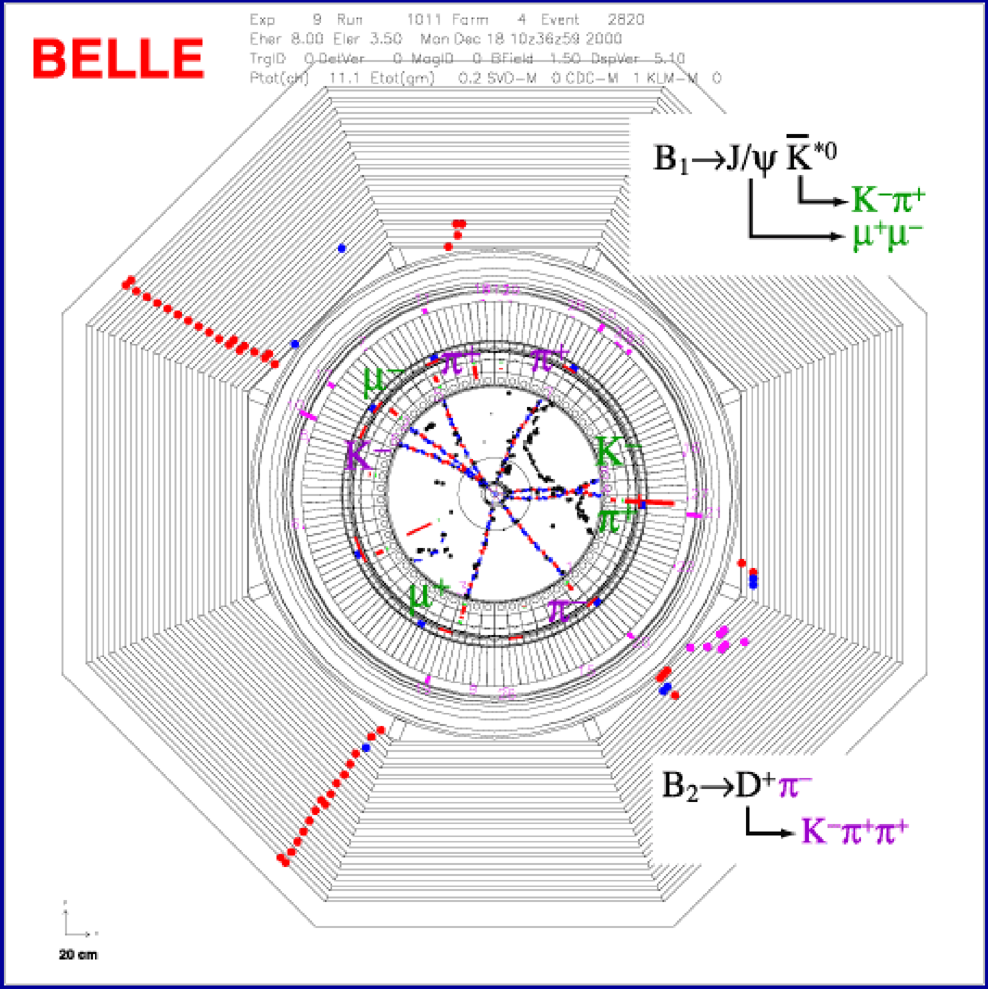
- Production on ϒ(4s) resonance
  - σ ~ 1.1 nb
  - S/N ~ 1/5
  - B's are at rest or have small βγ in asymmetric B factories (~ 0.6)
  - Produce only Bu or Bd in coherent QM state
    - Don't know which is which until decay
- (Z resonance production: LEP)
  - σ ~ 6.5 nb
  - S/N ~ 1/5
  - B's have large boost and are monochromatic
  - Produce all kinds of B's





B-production in e+e-

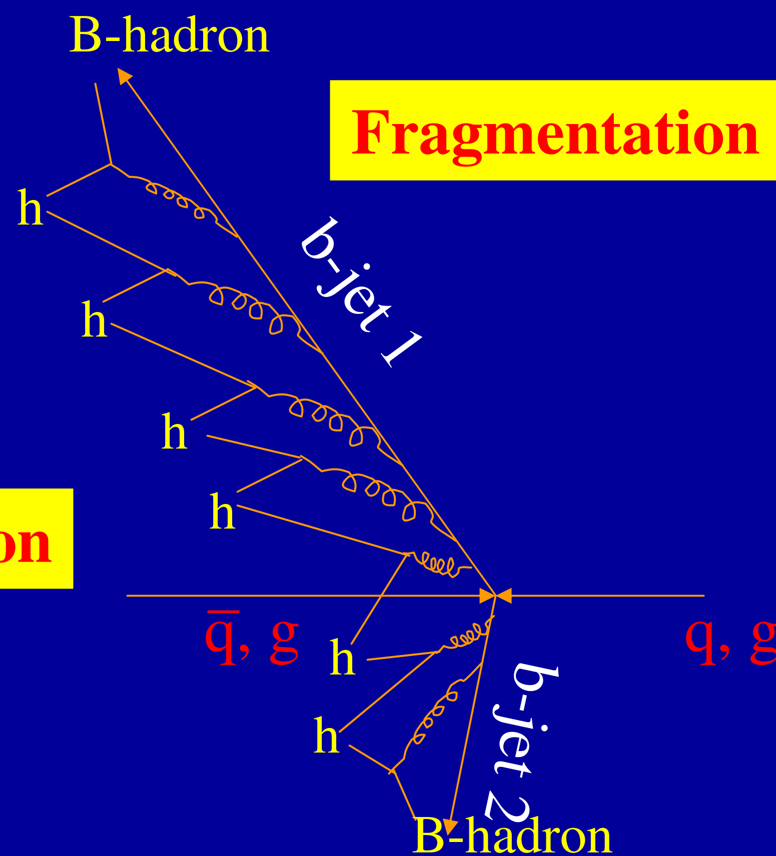
- Typical event properties
  - Low charged multiplicity ~11
  - Collisions/crossing <1



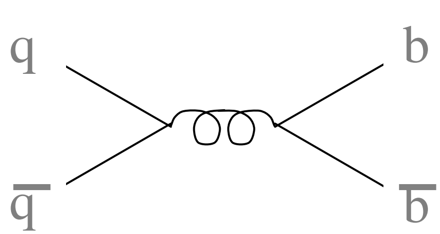
B-production at hadronic machines

- Tevatron → $p\bar{p}$ @ ~ 1.96 TeV CM energy
  - σ ~ 100 μb
  - S/N ~ 1/1000
  - B's are boosted $\beta\gamma$ ~ 1-4
  - Each B's produced in flavor specific state
  - Produce all kind of B's

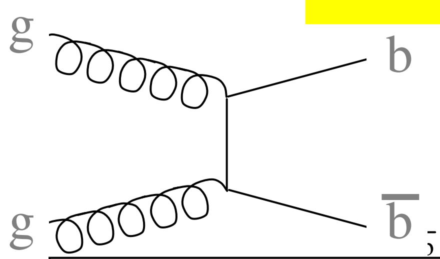
Fragmentation



Production



Flavor creation (annihilation)



Flavor creation (gluon fusion)

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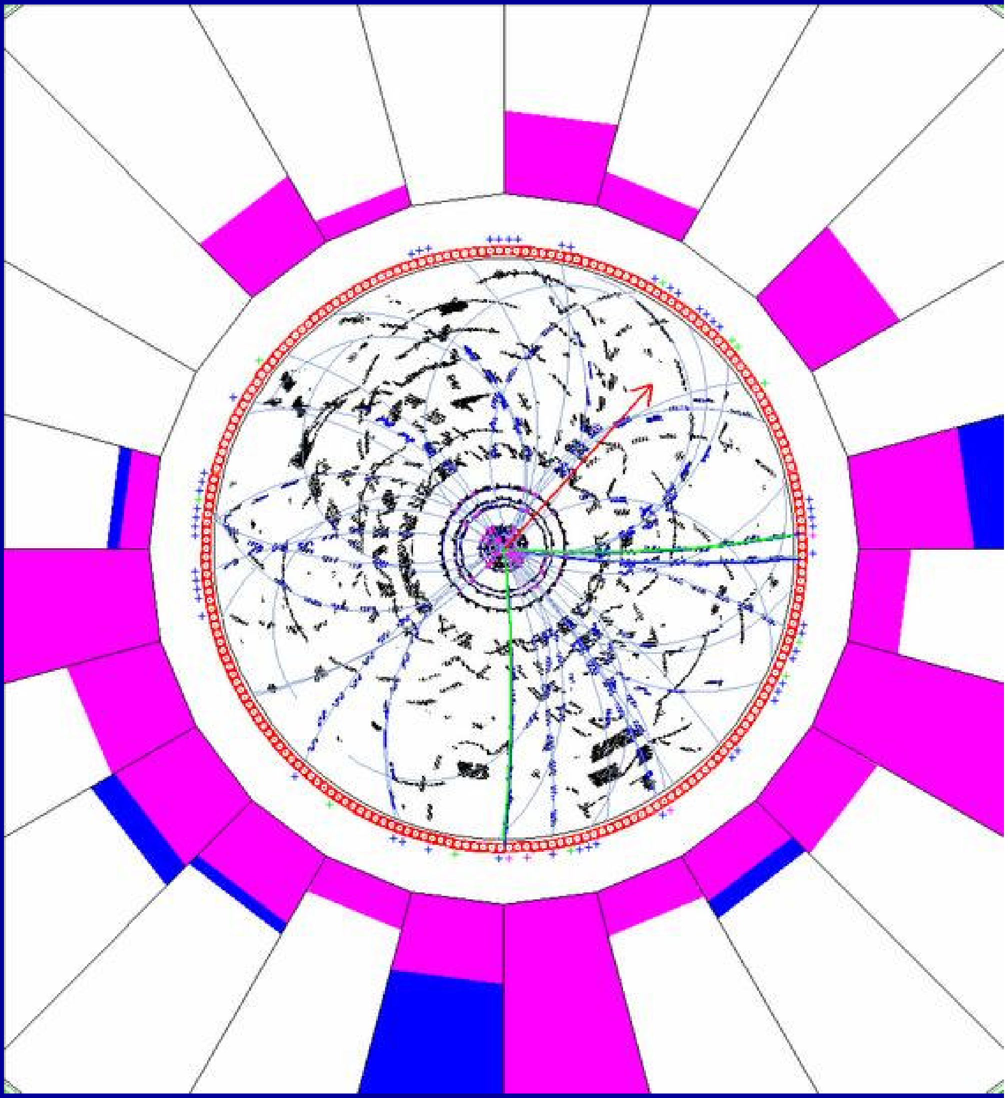
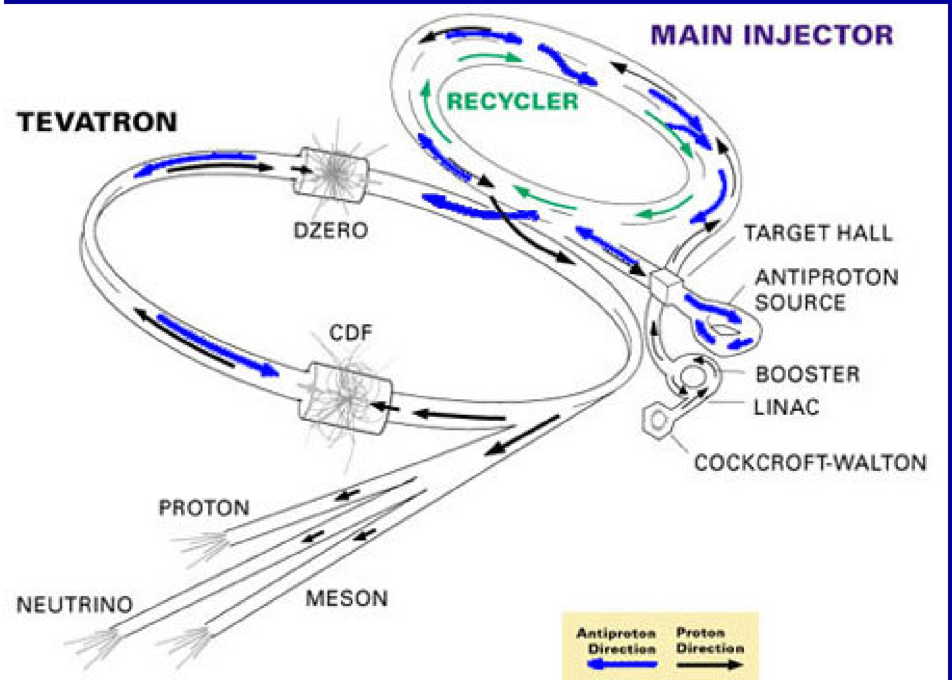
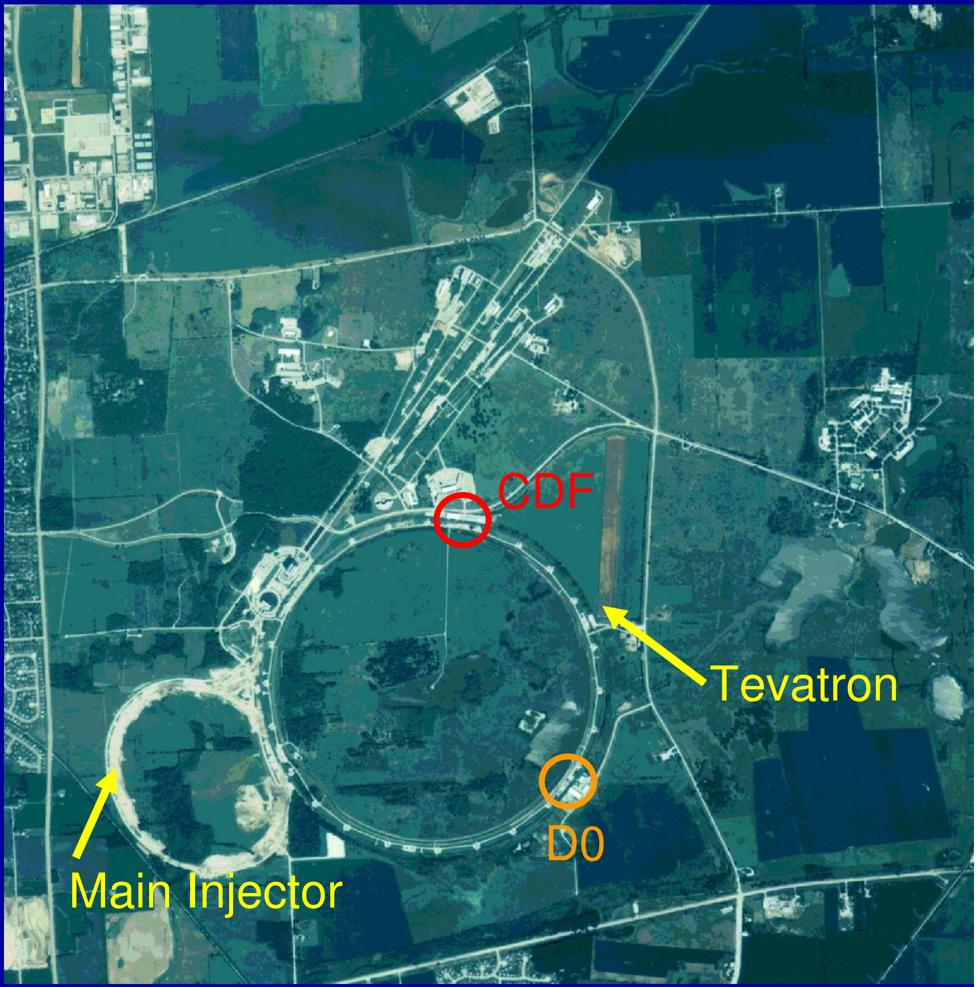
B-production at hadronic machines

- Typical Tevatron event
  - Large charged multiplicity ~ 40
  - Multiple interactions per crossing ~ 1-10
  - Very demanding trigger to exploit efficiently the large sample potentially available



Tevatron for Run II





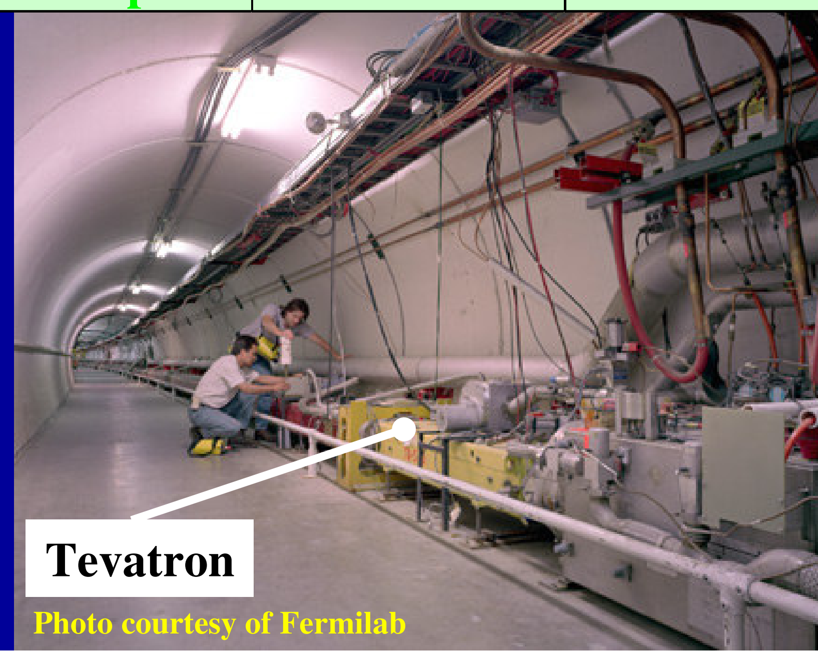
- New Main Injector:
  - Improve p-bar production
- Recycler ring:
  - Additional storage and cooling of p-bars

Tevatron Run II 2001-2009

Tevatron parameters

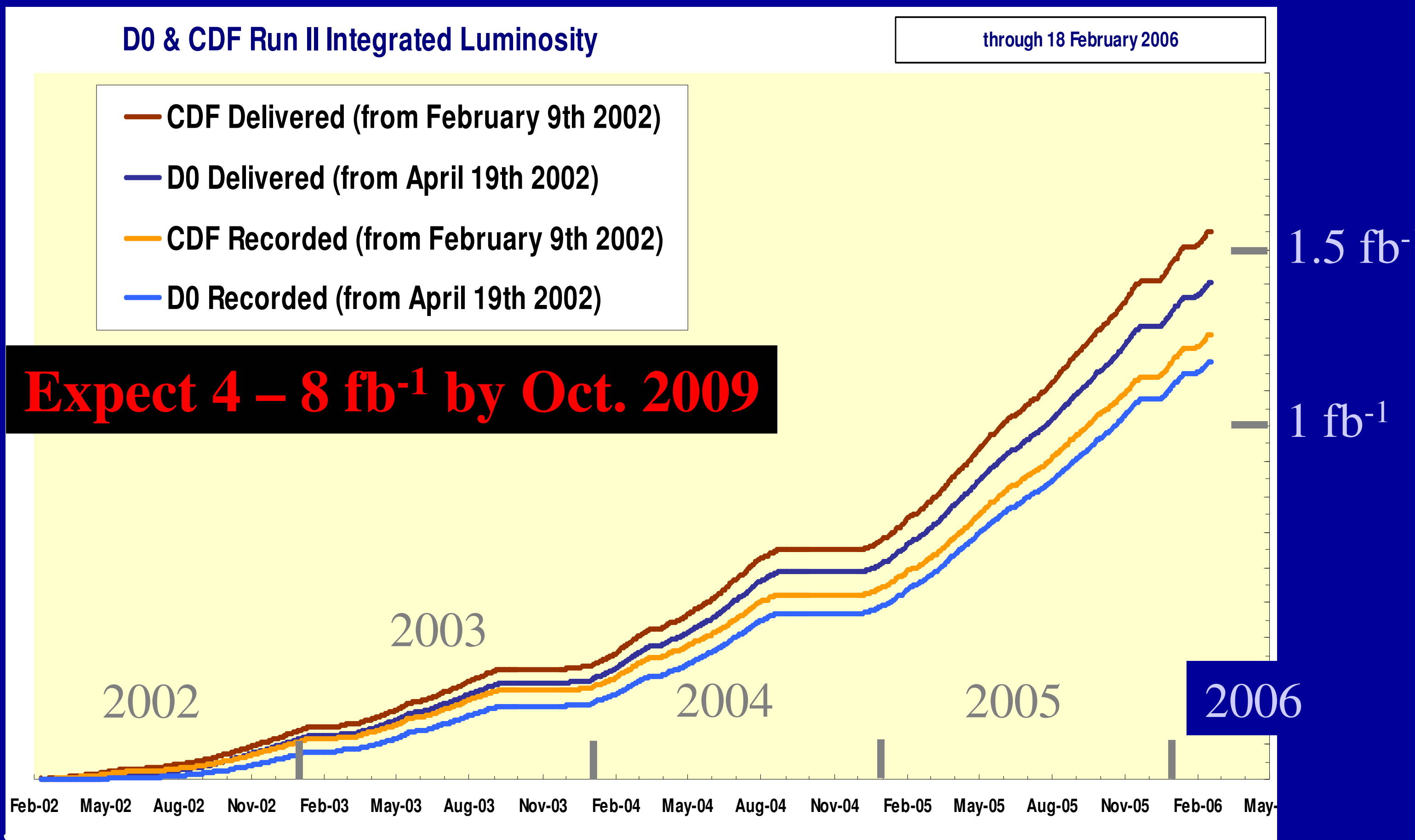
10^{32} cm^{-2}s^{-1} = 10^{-4} pb^{-1}s^{-1}

	Run I	Run II (low)	Run II (high)
Energy/beam	900 GeV	980 GeV	980 GeV
Peak Luminosity	1.6×10^{31}	1.6×10^{32}	2.9×10^{32}
Number of bunches	6	36	36
Bunch spacing	3500 nsec	396 nsec	396 nsec
Interactions/crossing	2.8	5	8.5
Run period	1992-96	2001-06	2007-09
Integral Luminosity	118 pb^{-1}	2 fb^{-1}	8 fb^{-1}

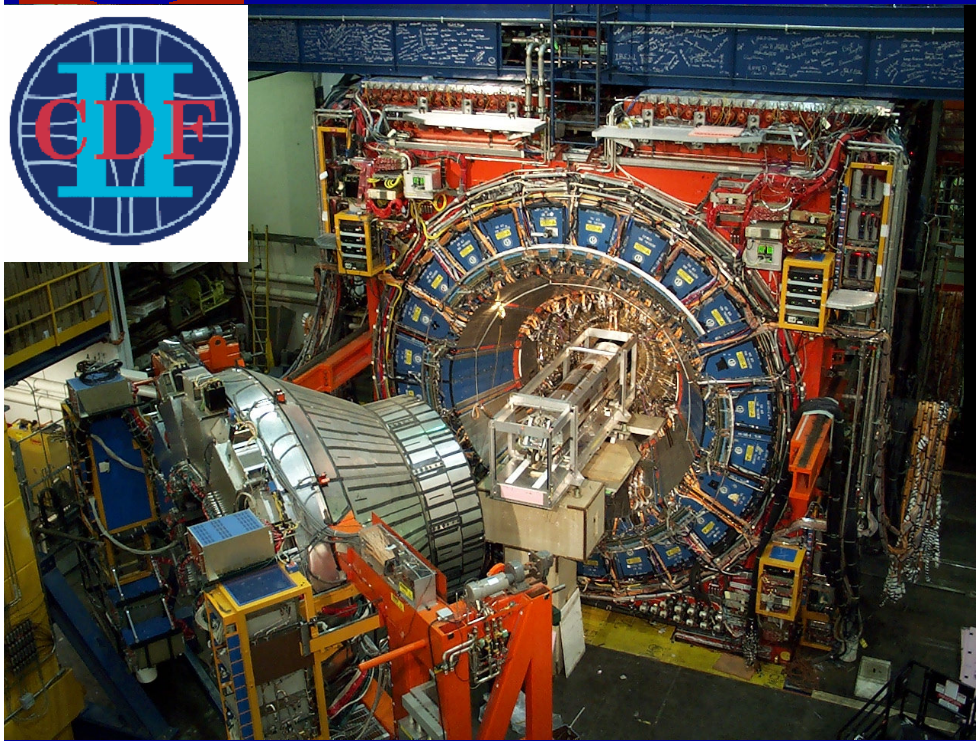


Tevatron performance

- Tevatron delivered more than 1.5 fb^{-1} up to Feb 2006
- Recorded 1.4 fb^{-1}(CDF) / 1.2 fb^{-1} (DØ)
- Now ~ 1.0 fb^{-1} reconstructed and under analysis

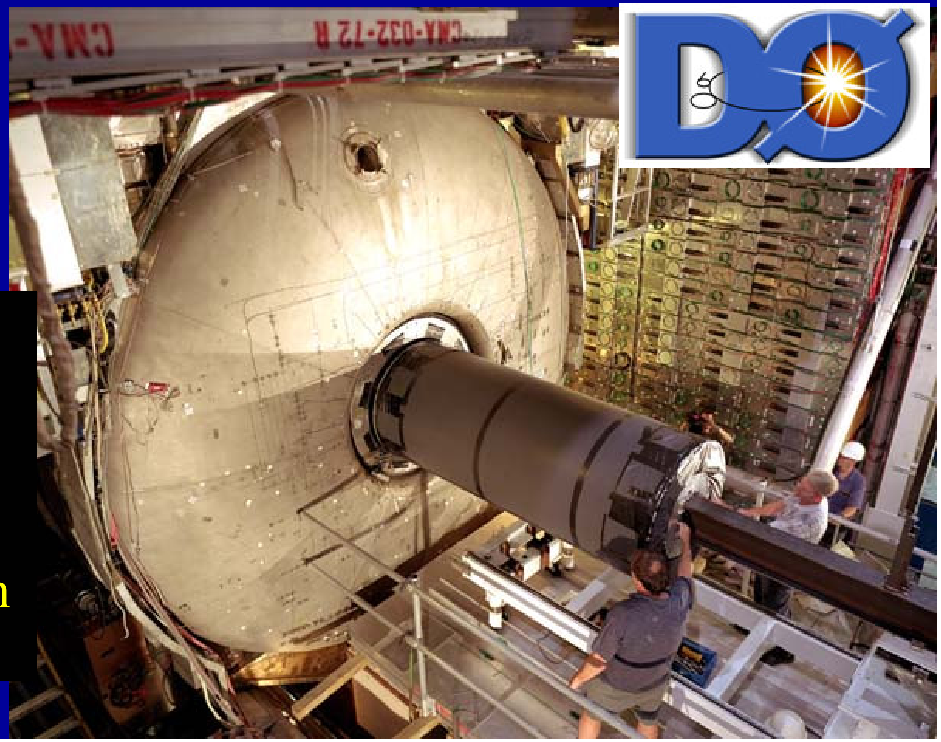


Tevatron Detectors



CDF

- Excellent mass and impact parameter measurement
- Good ability of lepton identification
- Limited PID capability



DØ

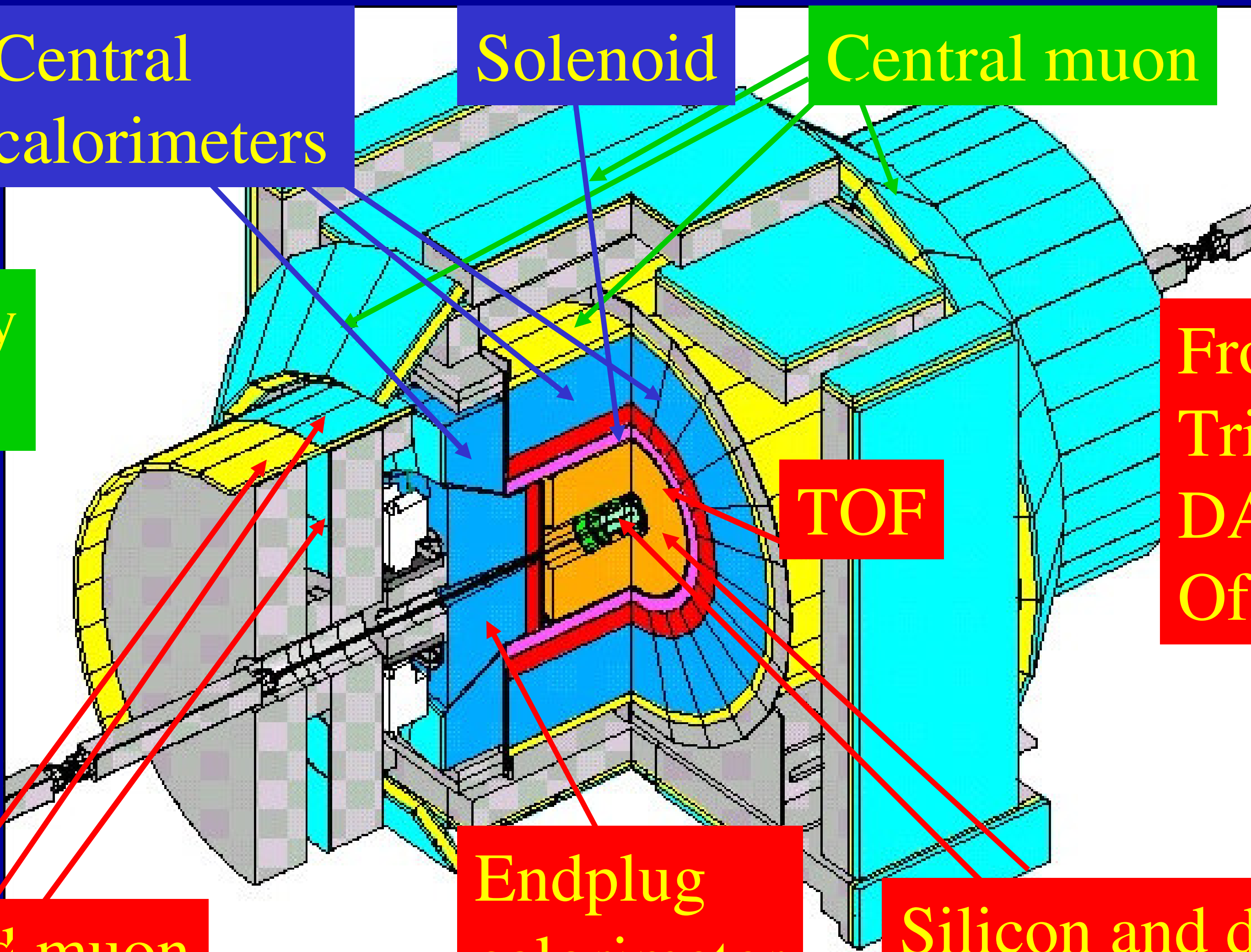
- Extended tracking and muon coverage
- Good electron/mu identification

CDF-II: isometric view

New

Old

Partially new

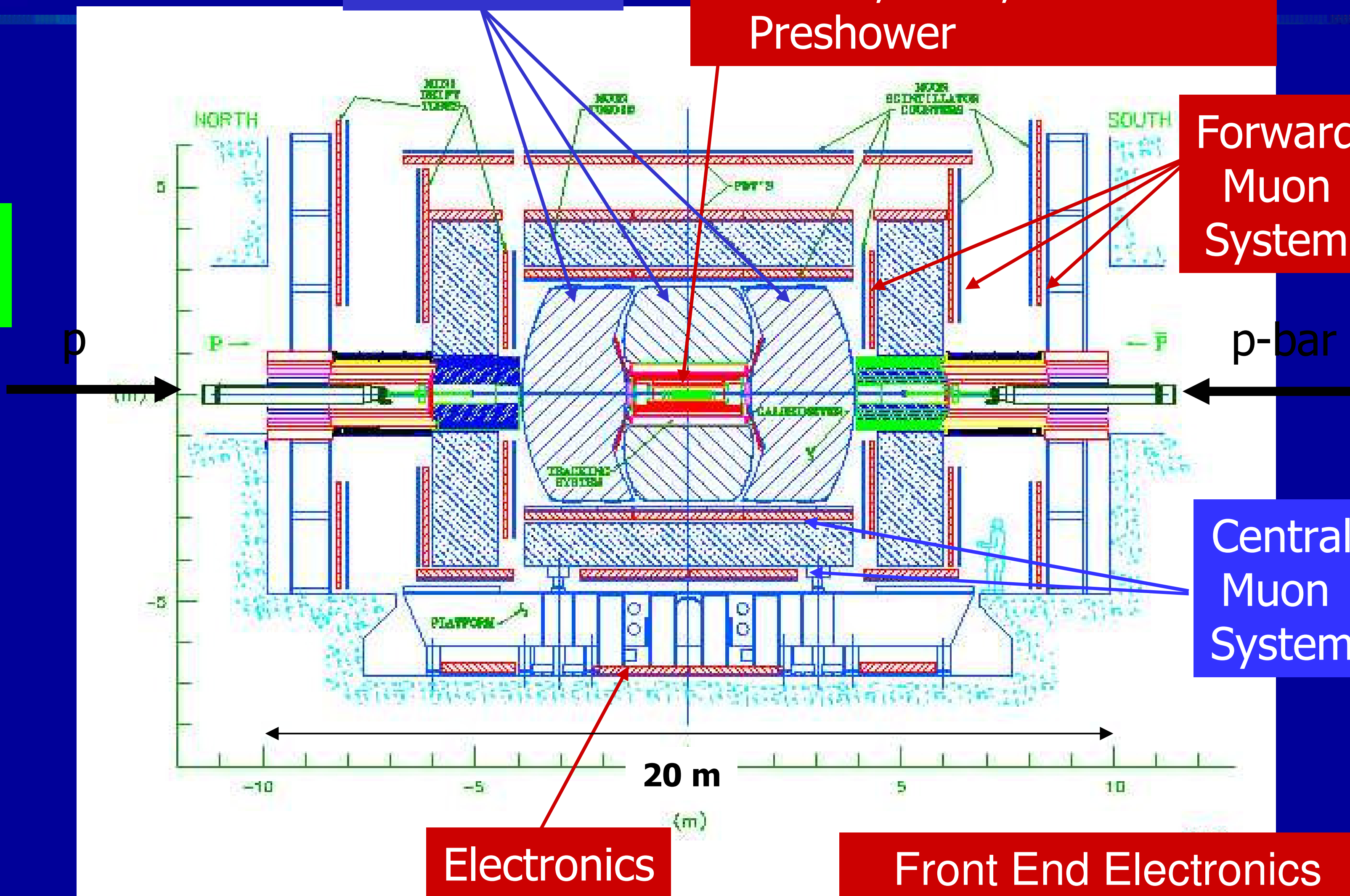


D0: side view

New

Old

Partially New



Front End Electronics
Triggers / DAQ (pipeline)
Online & Offline Software

Key detector features for b physics

- Electron/muon identification
  - Identify semi-leptonic B decays or decays involving $\psi \rightarrow \mu^+ \mu^-$
- Secondary vertices
  - Identify decay vertex
    - Requires high resolution tracking (silicon vertex detector)
- Powerful tracker
  - Find all decay tracks with high efficiency
- Trigger:
  - Identify leptons and detached tracks in times ~ 5 - 20 μs
  - Only way to collect large samples of hadronic B decays
    - Currently implemented only at CDF

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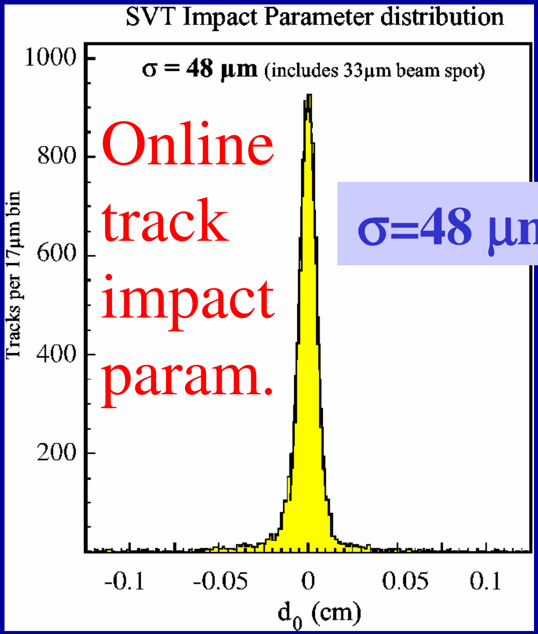
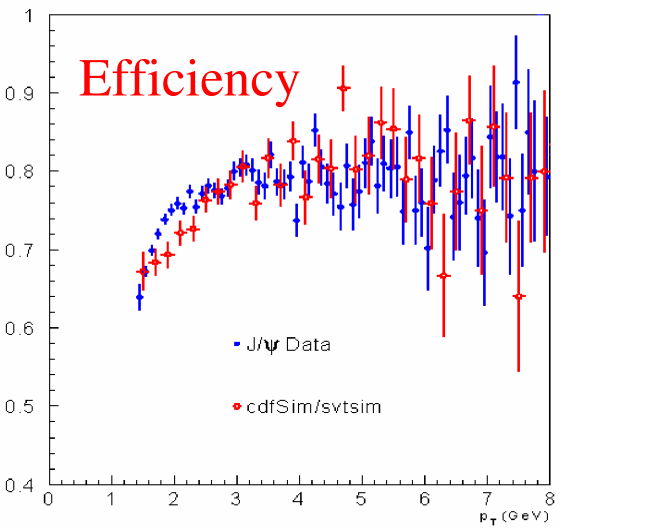
L2 SVT trigger

8 VME crates
Find tracks in Si in 20 μs with offline accuracy

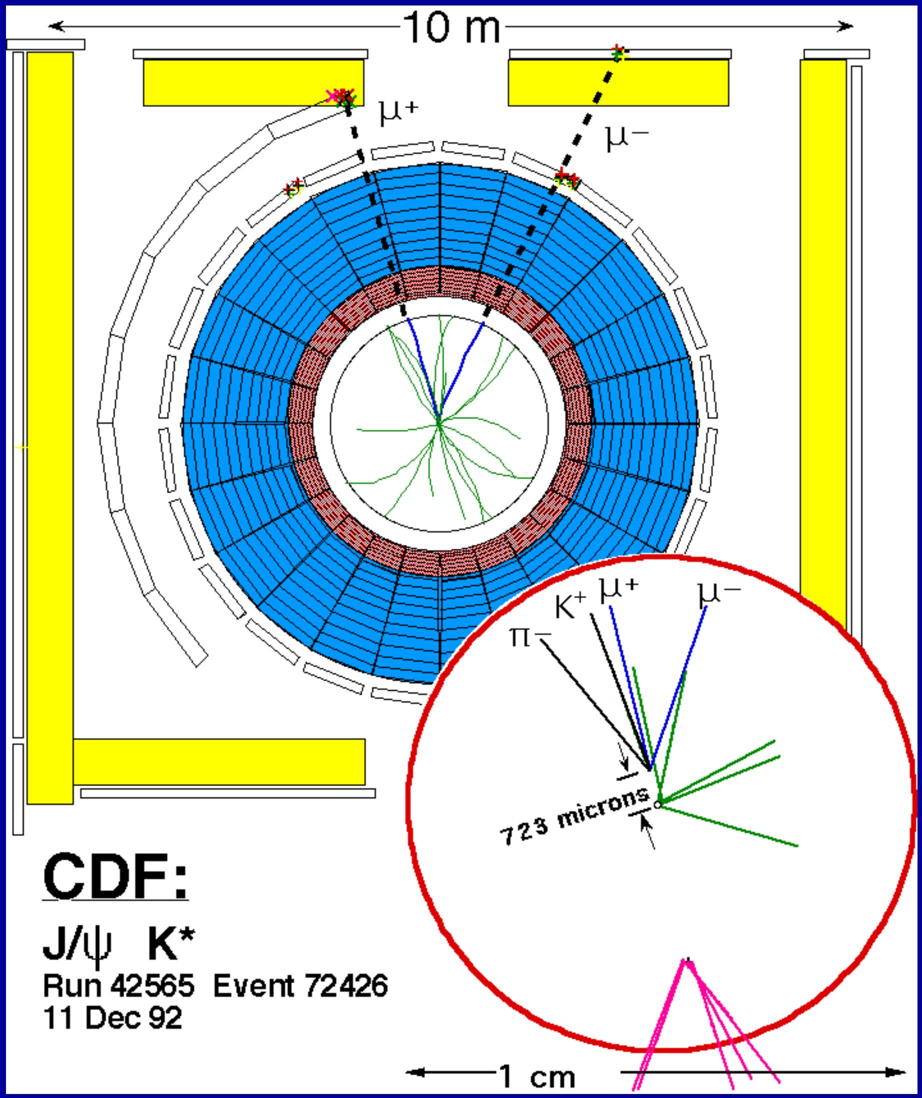


Secondary VerTex L2 trigger

- Online fit of primary Vtx
- Beam tilt aligned
- Observed D resolution
  - 48 μm (33 μm beam spot transverse size)

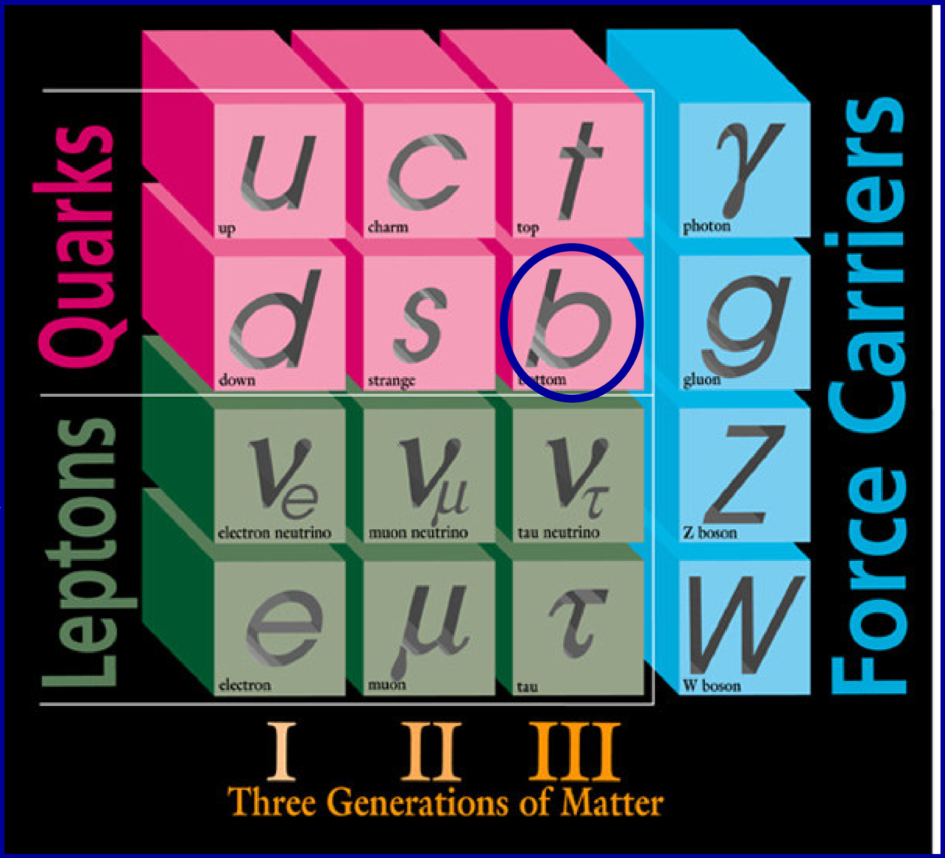


Example of b production event



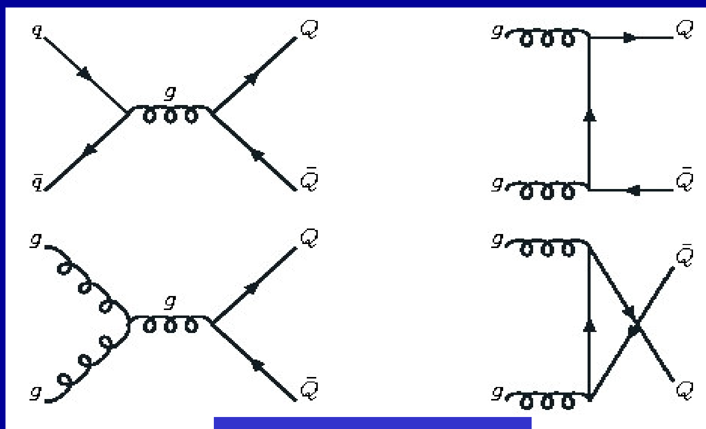
b quark interest

- b is only 3rd generation particle being produced in abundance
  - fundamental probe of SM
    - CKM in particular (see later)
    - Couplings to γ and Z extensively studied at LEP
      - Strong coupling to SM Higgs
- $M_b >> \Lambda_{QCD}$ improves accuracy of many theory predictions
  - No time to explore all of them!
- This lecture:
  - Production x-section/correlations
    - Test QCD
  - B^0 mixing, $\Delta\Gamma$, CPV in mixing
    - Many new recent results



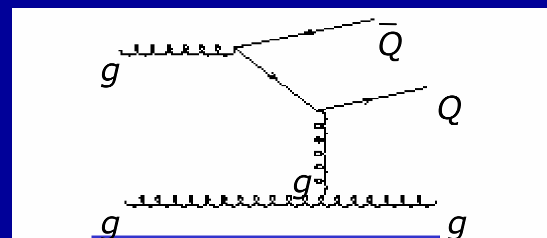
B production

Leading Order

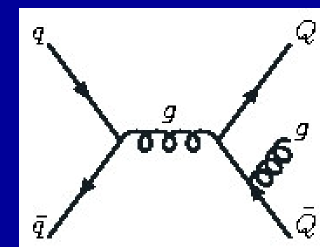


Flavor creation

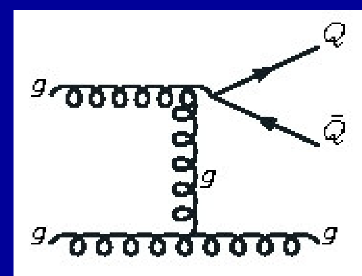
Next to Leading Order



Flavor excitation



other radiative corrections..

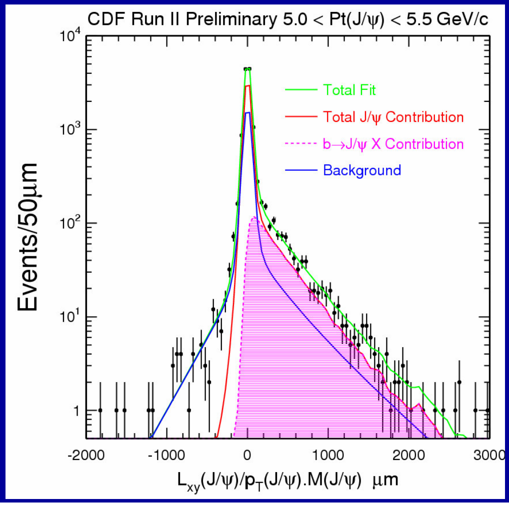


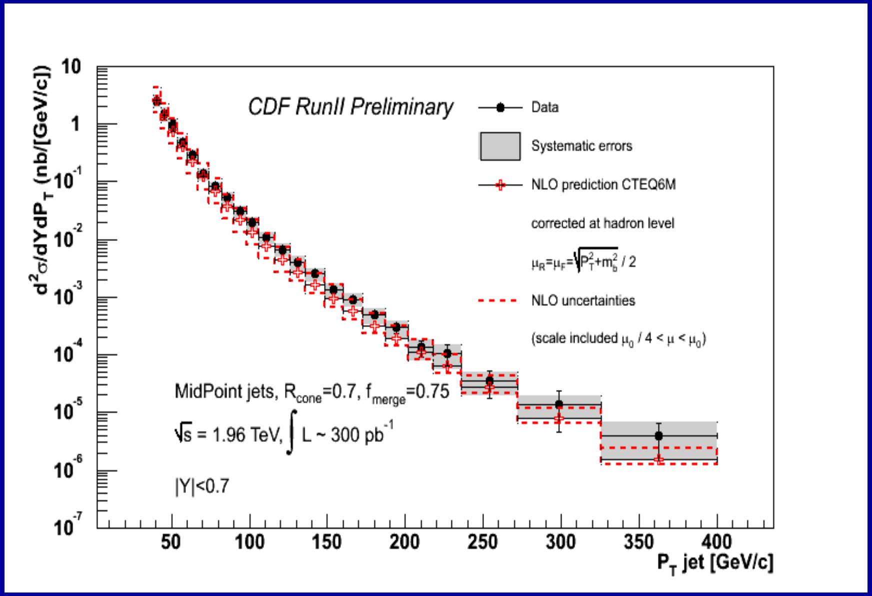
Gluon splitting

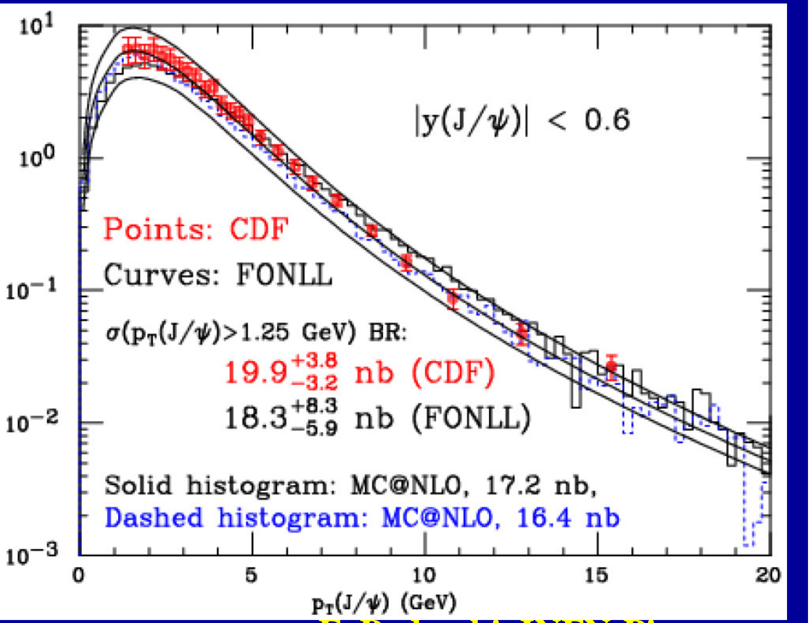
- Big gluon x-section/flux → large NLO contribution
- Large b-mass provides natural cut-off, but introduces additional scale (and potential divergences) in calculations (see Carlo's lectures)

B production

- From J/ψ sample (low pt)
  - Sensitivity up pt=0
  - B-fractions from lifetime analysis
  - Find consistency with FONLL (=NLO + NLL) **after reanalysis of fragmentation**
- From b-tagged jets (hi pt)
  - Compatible also with QCD

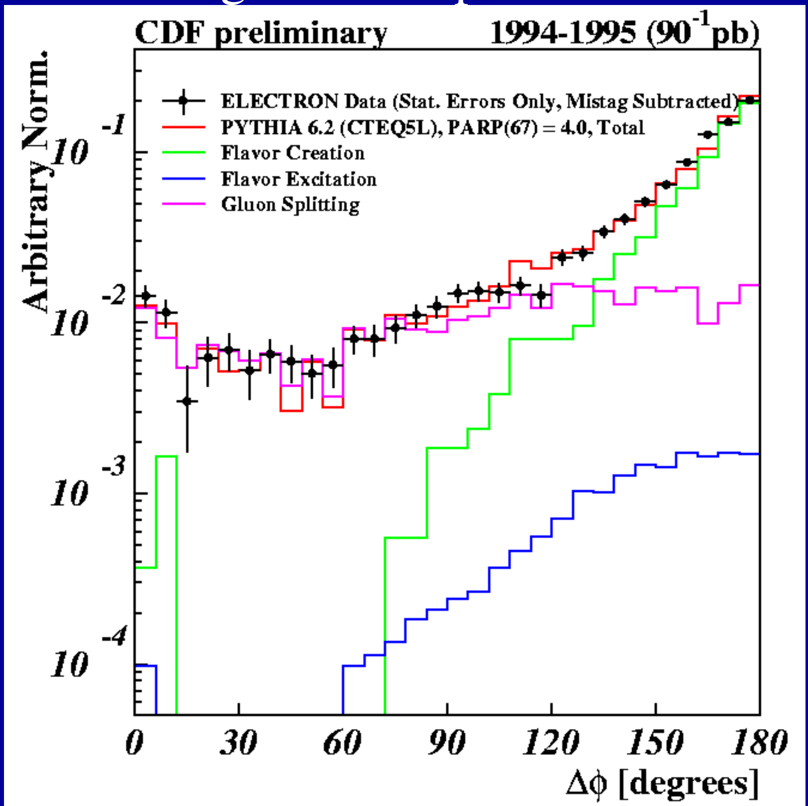


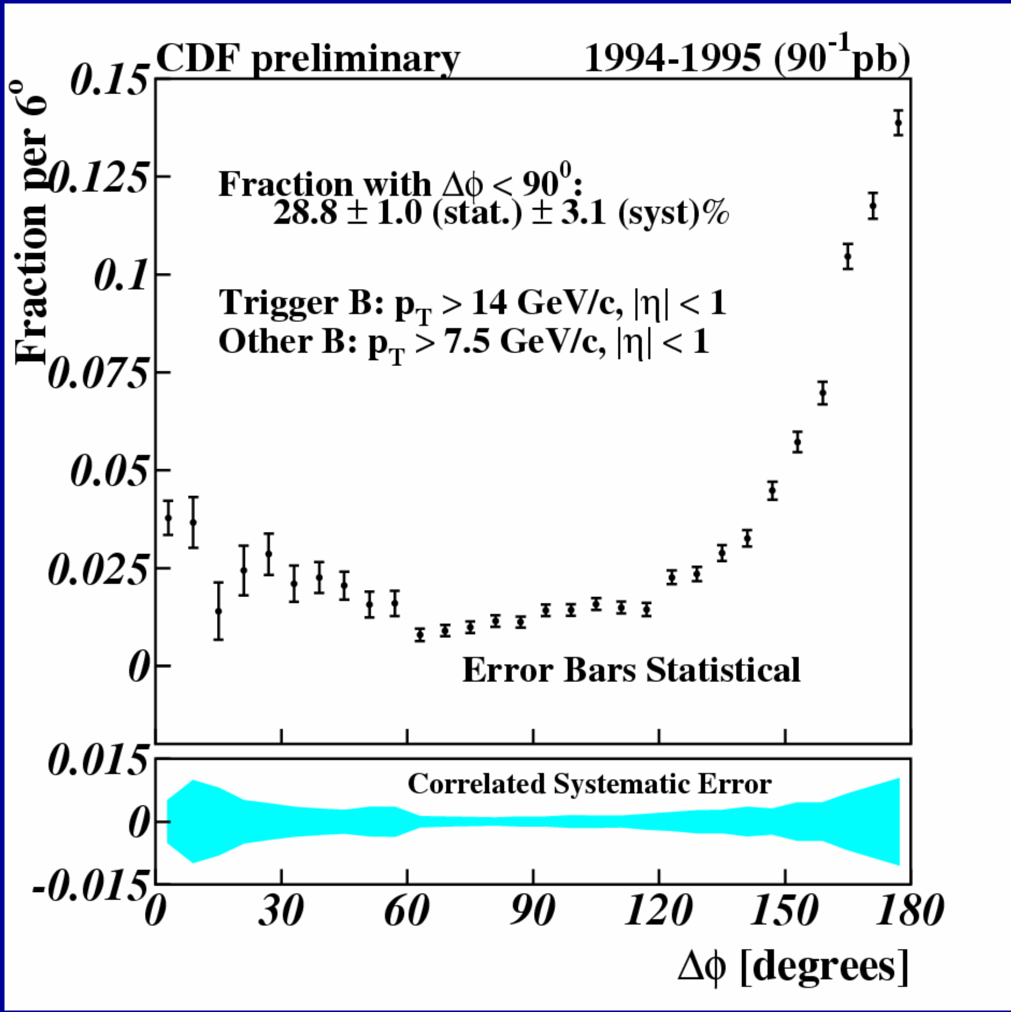




B production correlations

- Double b-tagged semileptonic sample
  - Consistent with significant higher order production





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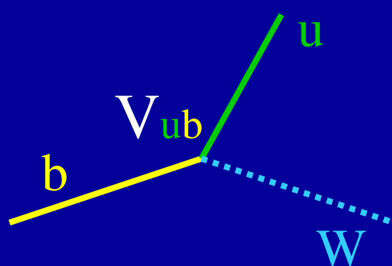
CKM matrix (1)

- CKM matrix describes flavor mixing in weak charged current transitions
  - All up-type quarks (u, c, t) can couple with any down-type quarks with a strength modulated by the elements of the CKM matrix



$$\text{CKM matrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$V_{ub} = |V_{ub}| e^{-i\gamma}$

Only 2 elements are complex*

$V_{td} = |V_{td}| e^{-i\beta}$

$V_{ts} = |V_{ts}| e^{-i\beta_s}$

β_s very small

CKM matrix must be unitary if there are only 3 generations

* Only 1 phase needed, the two phases are related

CKM matrix (2)

- CKM can be expressed in powers of $V_{us} = \lambda = \sin(\theta_{Cabibbo}) \sim 0.22$
  - Wolfenstein representation

A ~ 0.8
ρ ~ 0.2, η ~ 0.4

$$\begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2(1+i\lambda^2\eta) & 1 \end{pmatrix}$$

Measurement of CKM elements allows test of unitarity → triangle is closed

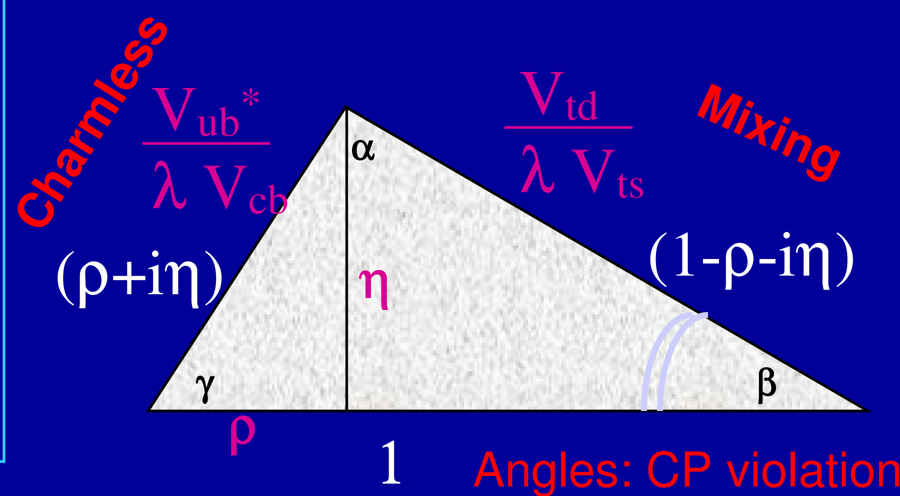
1st, 3rd col.: $V_{ud}V_{ub}^{*}+V_{cd}V_{cb}^{*}+V_{td}V_{tb}^{*}=0$

Other triangles less interesting

Let: $V_{ud} = 1$, $V_{cd} = -\lambda$, $V_{tb} = 1$

$V_{ub}^{*} + V_{td} = \lambda V_{cb}^{*}$ $\quad O(3\%)$

Divide by $A\lambda^3 = \lambda V_{cb}^{*} = -\lambda V_{ts}$



Basic Theory (1)

- 1 state effective theory:

$$H = m - \frac{i\gamma}{2}$$
$$i\frac{d|B(t)>}{dt} = H|B(t)>$$
$$|B(t)> = e^{-imt}e^{-\frac{\gamma t}{2}}|B(0)>$$
$$|<B(0)|B(t)>|^2 = e^{-\gamma t}$$

- 2 state effective theory:
  - M, Γ hermitian
    - CPT invariance: $M_{11} = M_{22}$, $\Gamma_{11} = \Gamma_{22}$
  - Solution reduces to 1 state case after diagonalization of H
    - Eigenvalues:
    - Eigenstates:

$$H = M - \frac{i\Gamma}{2}$$
$$M = \begin{pmatrix} m & m_{12} \\ m_{12}^* & m \end{pmatrix}$$
$$\Gamma = \begin{pmatrix} \gamma & \gamma_{12} \\ \gamma_{12}^* & \gamma \end{pmatrix}$$

$$|B(t)> \;\downarrow\; \begin{pmatrix} |B(t)> \\ |\bar{B}(t)> \end{pmatrix}$$

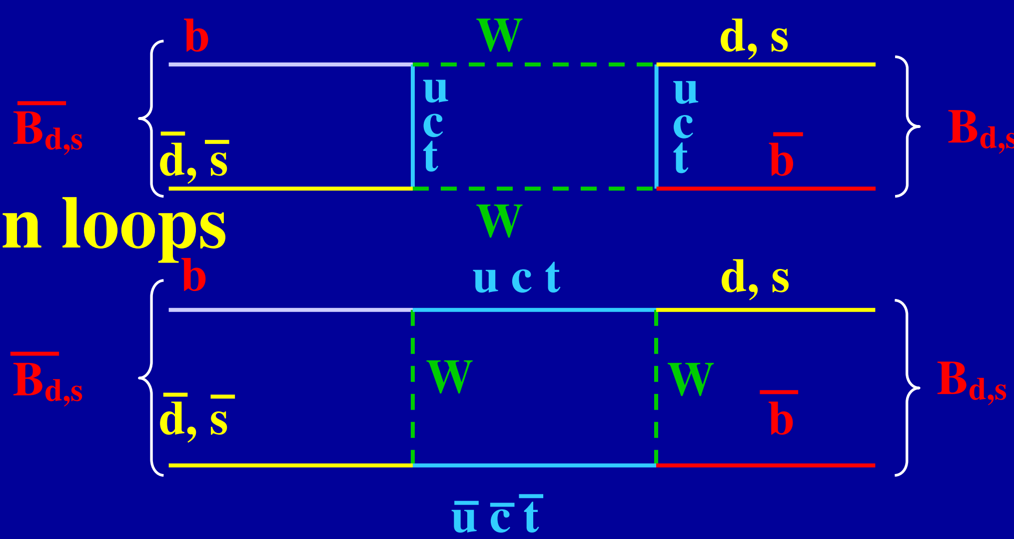
$$\lambda_\pm = (m \pm \Delta m) - \frac{i}{2}(\gamma \pm \Delta\gamma) = m - \frac{i}{2}\gamma \pm \sqrt{(m_{12} - \frac{i}{2}\gamma_{12})(m_{12}^* - \frac{i}{2}\gamma_{12}^*)}$$

$$|B_\pm> = \frac{1}{|p|^2 + |q|^2}(p|B> \pm q|\bar{B}>)$$

Box diagrams

Neutral B's can turn into their antiparticle <u>MIXING</u>

- m_{12} from box diagram
  - Top quark dominant
  - $m_{12} \propto V^2_{td(s)} \propto e^{-2i\beta(s)}$



- **New particles can run in loops besides W and quarks**
- Assuming $m_{12} \gg \Gamma_{21}$:
  - $2|m_{12}| = \Delta m_{s(d)} = [G_F^2 m_t^2 \eta\, F(m_t^2/m_W^2)/6\pi^2]\, m_{Bs(d)} f^2_{Bs(d)} B_{Bs(d)} |V_{ts(d)} V^*_{tb}|^2$

Oscill. Freq. — Known factors — From lattice O(30 %) error — ~ 1

Basic Theory (2)

- Time evolution of |B(0)> and $|\bar{B}(0)>$
  - Assume $\Gamma_{12} << m_{12}$

$$|B(t)> \;=\; e^{-imt}e^{-\frac{\Gamma t}{2}}\left[cos\left(\frac{\Delta mt}{2}\right)|B(0)> -i\frac{q}{p}sin\left(\frac{\Delta mt}{2}\right)|\bar{B}(0)>\right]$$

$$|\bar{B}(t)> \;=\; e^{-imt}e^{-\frac{\Gamma t}{2}}\left[cos\left(\frac{\Delta mt}{2}\right)|\bar{B}(0)> -i\frac{p}{q}sin\left(\frac{\Delta mt}{2}\right)|B(0)>\right]$$

$$\frac{p}{q} \approx \frac{m_{12}-\frac{i}{2}\Gamma_{12}}{|m_{12}|} \approx \frac{m_{12}}{|m_{12}|} = e^{-2i\beta_{(s)}}$$

$$\left|\frac{p}{q}\right|^2 \approx 1+\mathcal{I}m\left(\frac{\Gamma_{12}}{m_{12}}\right) \approx 1+\mathcal{O}(\underset{\text{Bd}}{10^{-3}} - \underset{\text{Bs}}{10^{-5}})$$

Mixing theory

- Neutral mesons time evolution with mixing can be easilty derived from the equations of previous slide:

$$P_{B\to B}(t) = |<B|B(t)>|^2 \;=\; e^{-\Gamma t}\left[cos^2\left(\frac{\Delta mt}{2}\right)\right] = \frac{e^{-\Gamma t}}{2}(1+cos\Delta mt)$$

$$P_{B\to \bar{B}}(t) = |<\bar{B}|B(t)>|^2 \;=\; e^{-\Gamma t}\left[sin^2\left(\frac{\Delta mt}{2}\right)\right] = \frac{e^{-\Gamma t}}{2}(1-cos\Delta mt)$$

- Bd mixing well established $\Delta m_d = 0.507 \pm 0.004\ ps^{-1}$
  - Measurements from LEP, Tevatron and B-Factories
    - Accuracy dominated by BaBar and Belle
- Bs mixing much harder
  - Less signal and much faster (~ x $1/\lambda^2$) oscillation
  - Tevatron has first results NOW!

Mixing measurements

- Steps needed to measure mixing:
  - Select signal in flavor specific final states
  - Identify B type at production: FLAVOR TAG
  - Measure proper decay time and its resolution
  - Parameterize background contributions
  - **Fit time dependence**

$$\#\sigma\ significance\ of\ oscillation = \sqrt{\frac{N_S}{N_S+N_B}}\sqrt{\frac{N_S\epsilon D^2}{2}}\,e^{-\frac{\Delta m_s^2\sigma^2}{2}}$$

Significance from Fourier like analysis

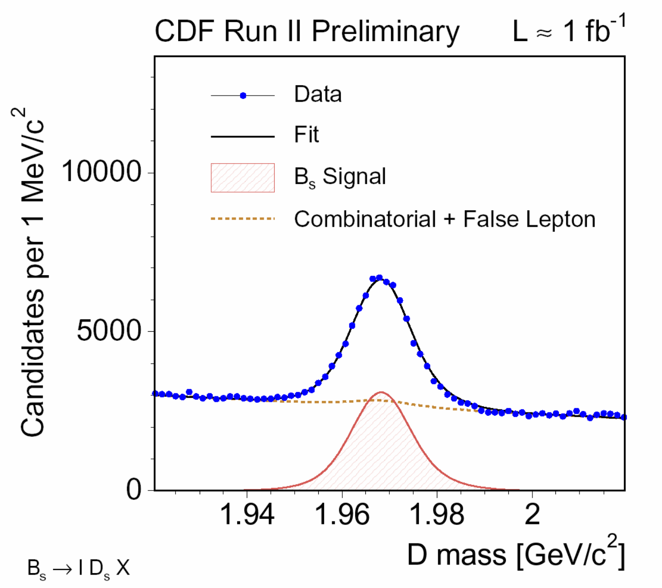
#signal

#background

Tagging power

cτ resolution

CDF Signal Sample for Δm_s

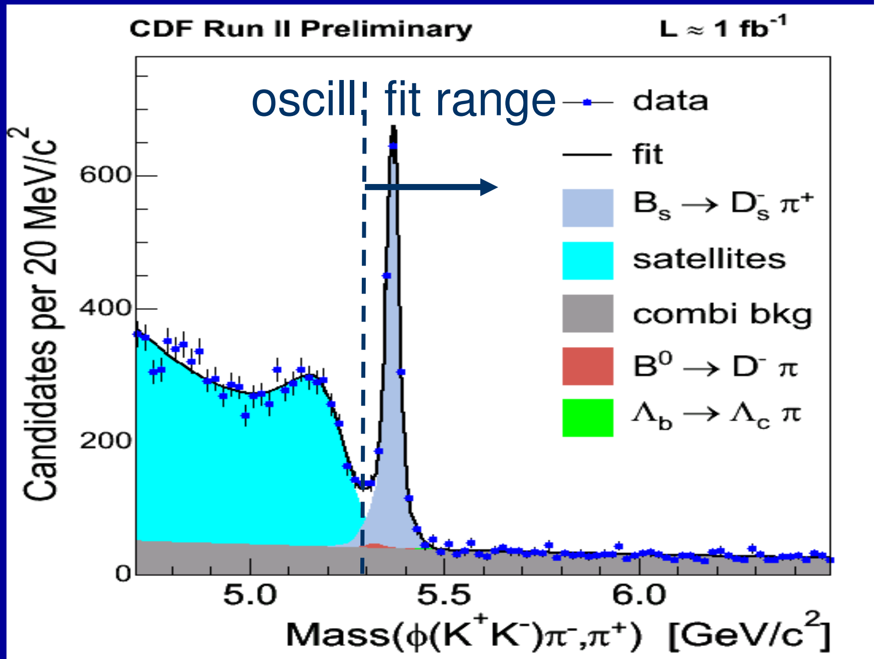


Semileptonic Modes

ℓD_s: $D_s \to \phi\pi$	32 K
ℓD_s: $D_s \to K^*K$	11 K
ℓD_s: $D_s \to \pi\pi\pi$	10 K

~53 K events

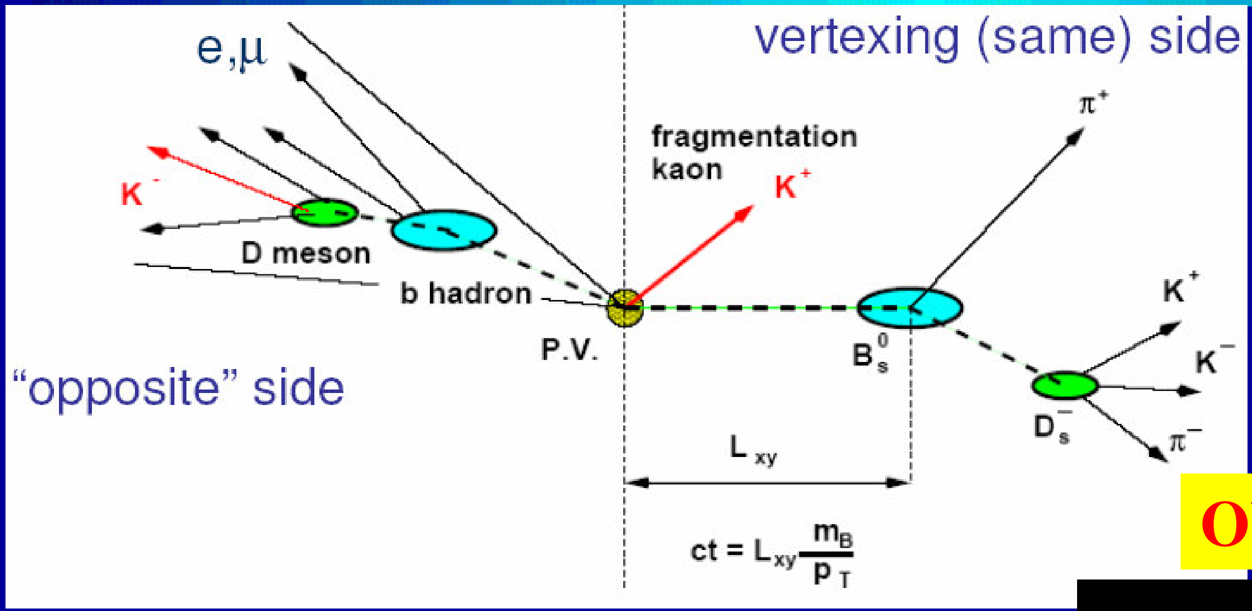
Hadronic Modes	Yield
$B_s \to D_s\pi$ ($\phi\pi$)	1600
$B_s \to D_s\pi$ (K^* K)	800
$B_s \to D_s\pi$ (3π)	600
$B_s \to D_s 3\pi$ ($\phi\pi$)	500
$B_s \to D_s 3\pi$ (K^*K)	200
Total	**3700**



Huge Control Signals

- Hadronic decays:
  - B^+ ($J/\psi K^+$, $D^0\pi$, $D^0 3\pi$): ~ 50 k events
  - B^0($J/\psi K^*$, $D^-\pi$, $D^{*-}\pi$, $D^- 3\pi$, $D^{*-}3\pi$): ~ 60 k events
- Semileptonic decays:
  - lD^0 ($D^0 \rightarrow K\pi$): ~ 540 k events
  - lD^{*-} ($D^{*-} \rightarrow D^0\pi$): ~ 74 k events
  - lD^- ($D^- \rightarrow K\pi\pi$): ~ 300 k events

Flavor tagging



Taggers charaterized by:
Efficiency (**ε**)
Dilution (**D**) = 1-2w
w = prob. wrong tag

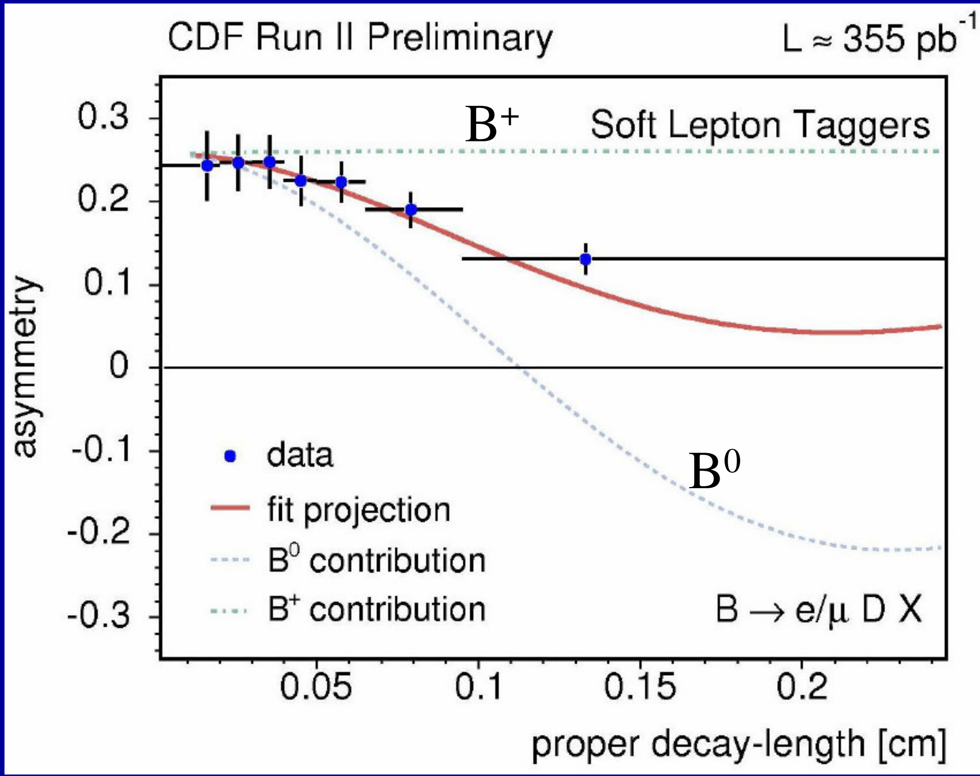
Observed time evolution

$$P_{B\to B}(t) = \frac{e^{-\Gamma t}}{2}(1 + Dcos\Delta mt)$$
$$P_{B\to \bar{B}}(t) = \frac{e^{-\Gamma t}}{2}(1 - Dcos\Delta mt)$$

- Use combined same side and opposite side tags
  - Opposite side: electrons, muons, jet charge
  - Same Side: tag with selected track (kaon) close to reconstructed (signal) B

OST tagger calibration

- Dilution calibration
  - Use the large control samples of B+ and B0
  - Works only for OST
    - SST different for every B type. Must use MC



- Bd mixing by-product and cross-check

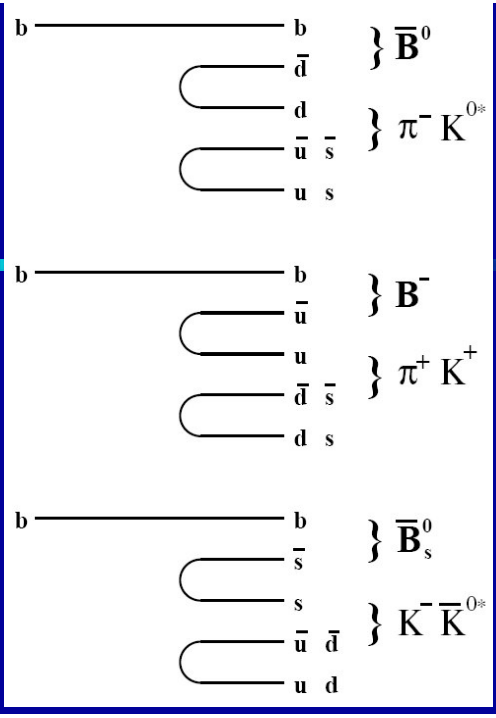
hadronic: $\Delta m_d = 0.536 \pm 0.028\ (\text{stat}) \pm 0.006\ (\text{syst})\ ps^{-1}$

semileptonic: $\Delta m_d = 0.509 \pm 0.010\ (\text{stat}) \pm 0.016\ (\text{syst})\ ps^{-1}$

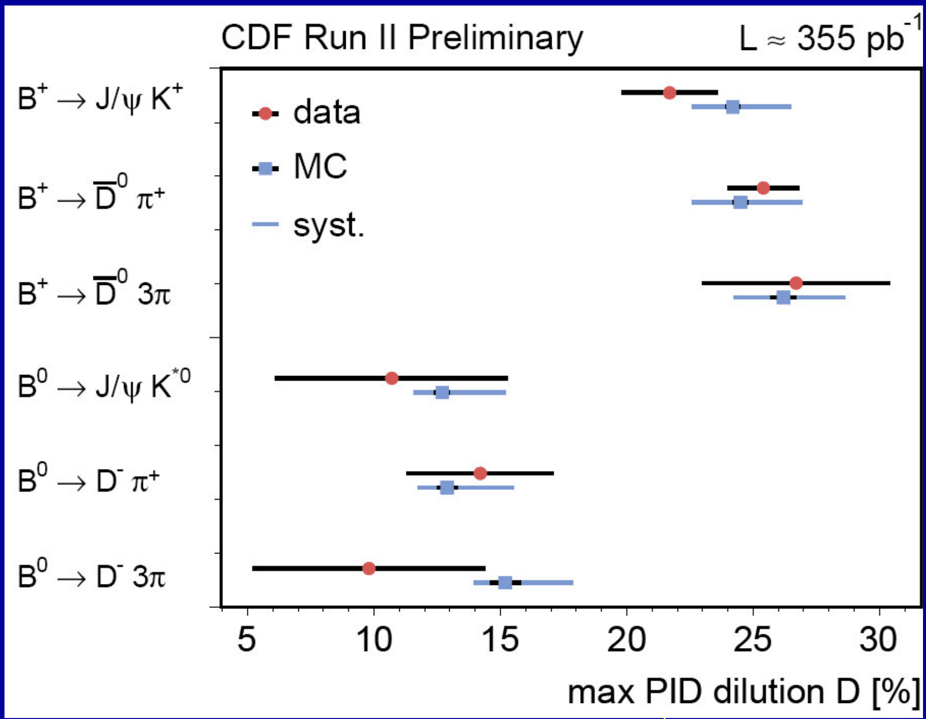
world average: $\Delta m_d = 0.507 \pm 0.004\ ps^{-1}$

SSKT

- Particles closer to B in fragmentation carry information on B type at production



- Bs likely to have a K
- Use TOF/dE/dx for K/π separation
- Tune MC:
  - Reproduce B+, Bd
  - Determine systematics
  - Apply to Bs



Flavor tag summary

	εD^2 Hadronic (%)	εD^2 Semileptonic (%)
Muon	0.48 ± 0.06 (stat)	0.62± 0.03 (stat)
Electron	0.09 ± 0.03 (stat)	0.10 ± 0.01 (stat)
JQ/Vertex	0.30 ± 0.04 (stat)	0.27 ± 0.02 (stat)
JQ/Prob.	0.46 ± 0.05 (stat)	0.34 ± 0.02 (stat)
JQ/High p_T	0.14 ± 0.03 (stat)	0.11 ± 0.01 (stat)
Total OST	1.47 ± 0.10 (stat)	1.44 ± 0.04 (stat)
SSKT	3.42 ± 0.06 (stat)	4.00 ± 0.04 (stat)

Total $\varepsilon D^2 \sim 5\%$

- Opposite side: use combination of tags
- Same side/OST combination assumes independent tagging information

Measuring proper time

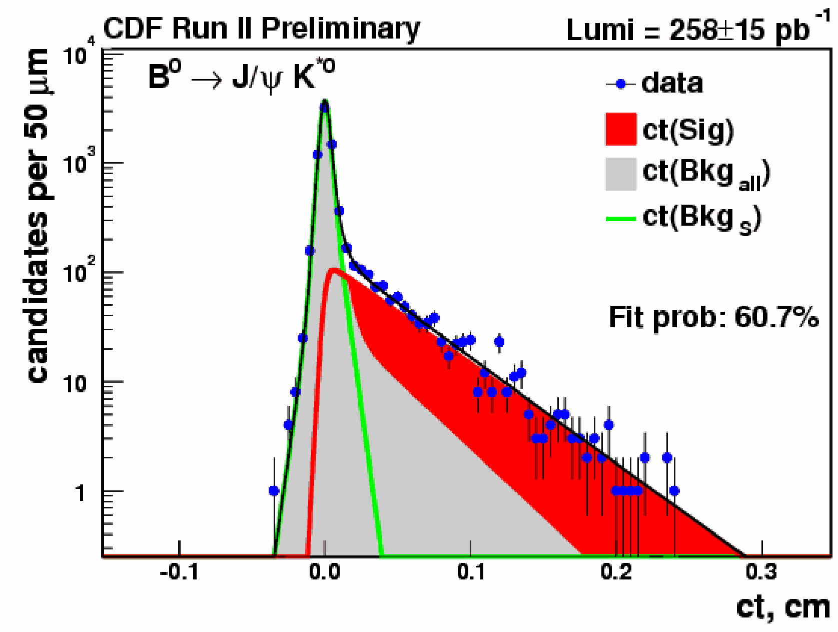
proper decay length → $c\tau = \frac{L}{\gamma\beta} = \frac{L_{xy} M_B}{p_T}$

Flight distance (L); Boost ($\gamma\beta$)

$$\sigma_{ct} = \sigma^0_{ct} \oplus ct \times \frac{\sigma_p}{p}$$

Vertex resolution (~constant)

Momentum resolution (proportional to ct)

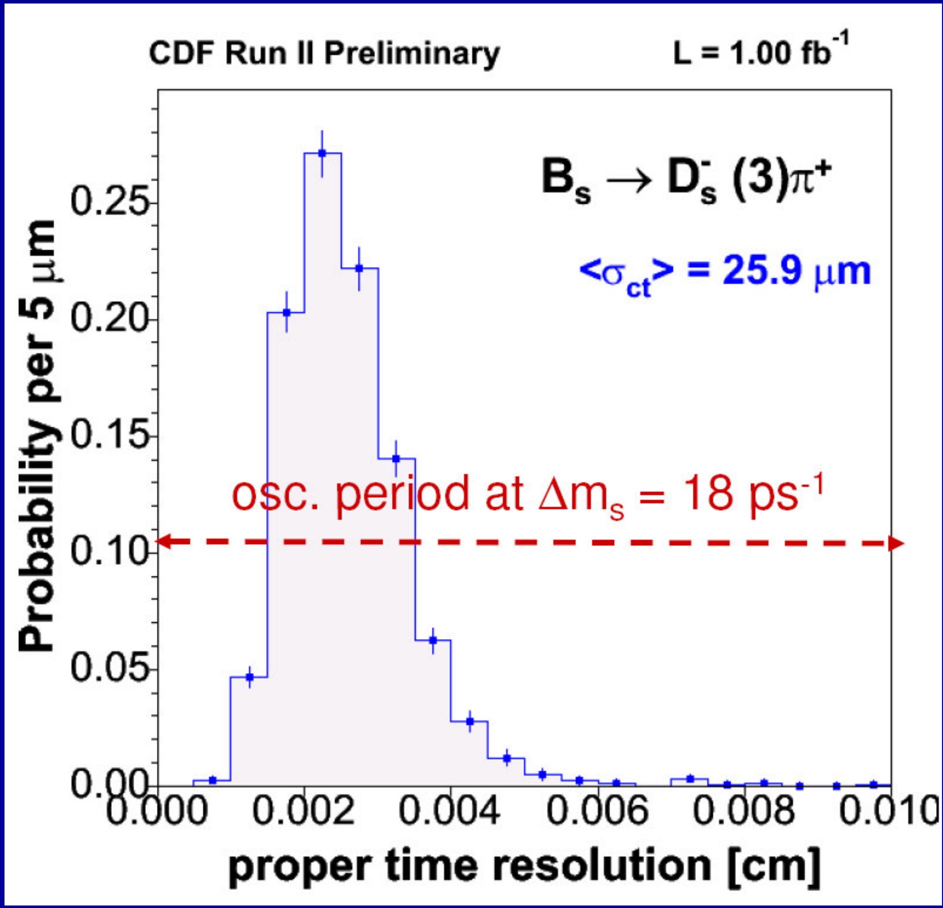


- For fully reconstructed (hadronic) modes $\sigma_{ct} \sim O(30\mu)$ (c.f. $ct \sim 450\mu$)
- For semileptonic modes, missing neutrino causes

$\frac{\sigma_p}{p} \sim O(15\%)$ => Resolution poor at large decay time

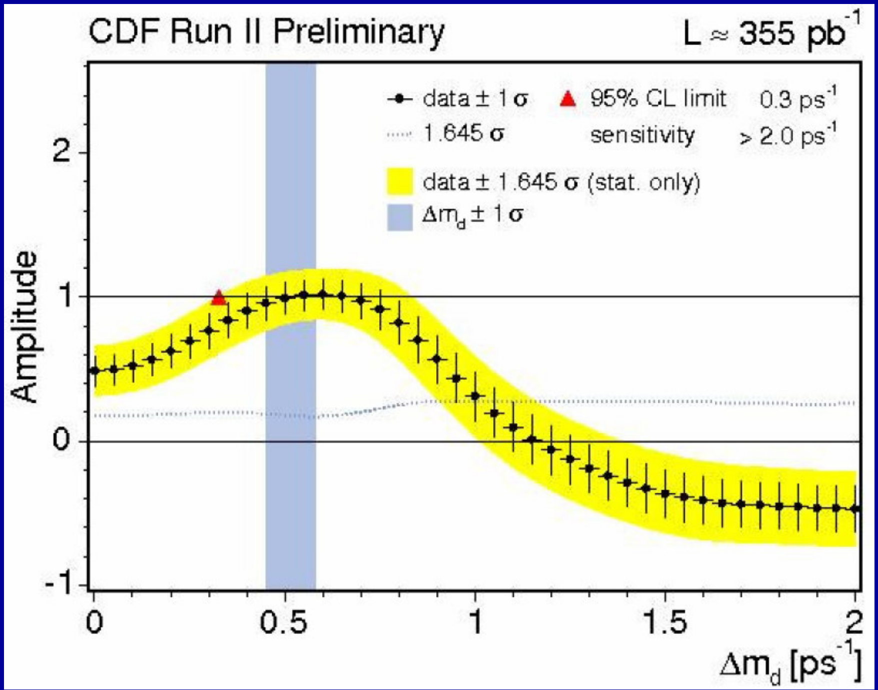
Bs proper time resolution

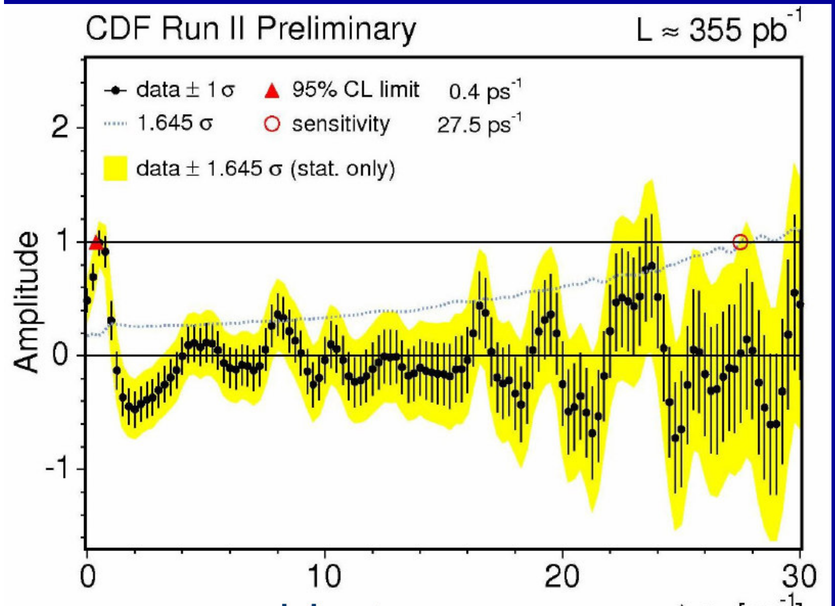
- Average σ_t ~ 87 fs
  - Good sensitivity for $\Delta m_s \sim 20\ ps^{-1}$



Putting all together

- Amplitude scan
  - Fit $e^{-t/\tau}(1\pm A(\omega)\, D\cos \omega t)\otimes G(t)$ for various values of ω
  - $A(\omega) = 1$ for $\omega = \Delta m$
  - Similar to a Fourier transform

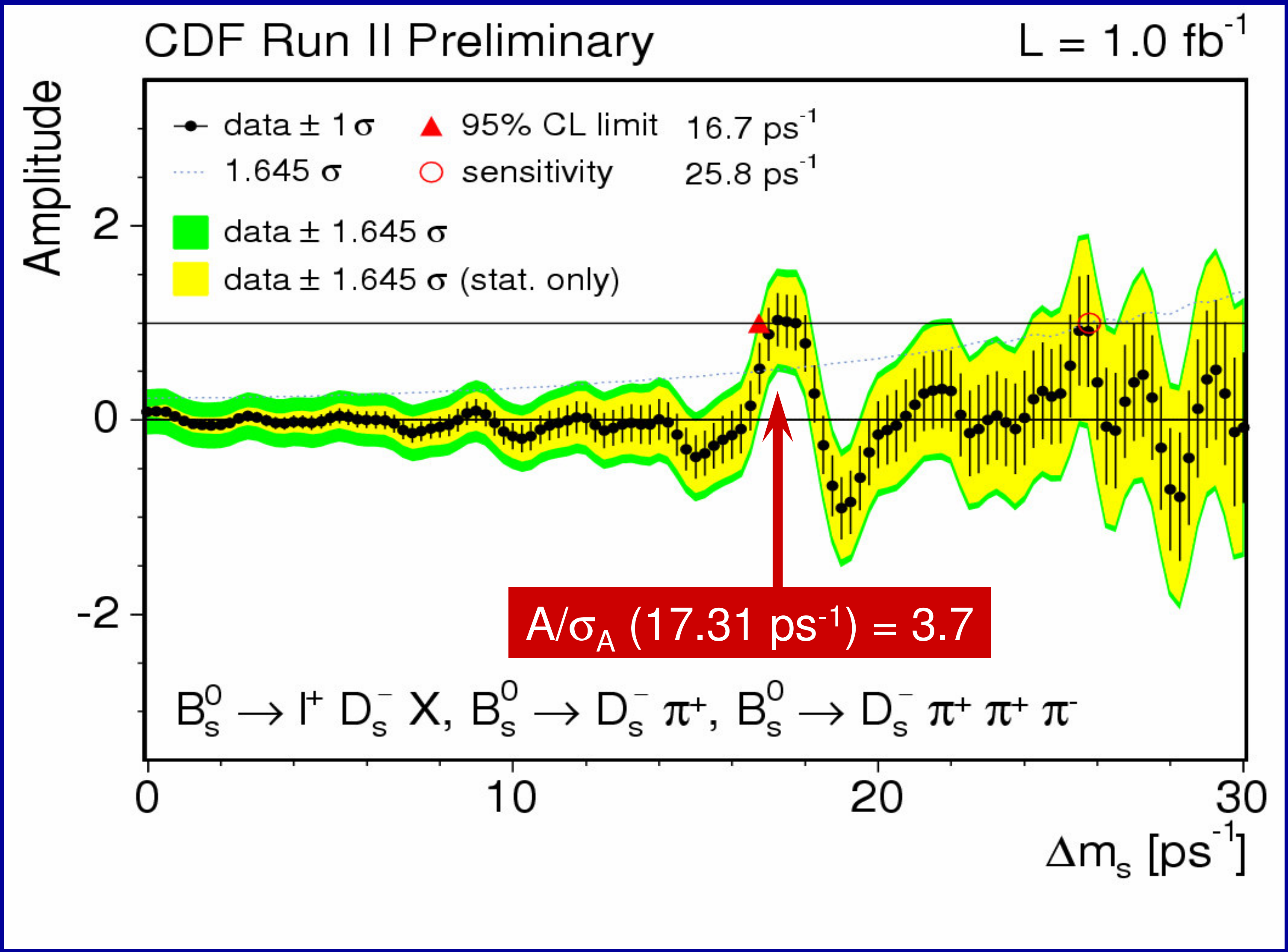




wide Δm_s range

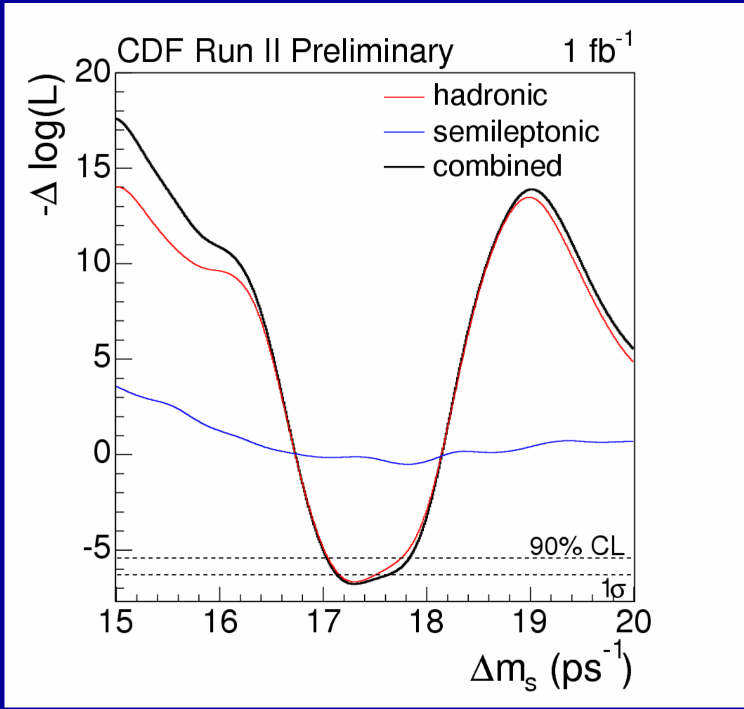
- Test amplitude scan on Bd
  - A=1 at the correct value
  - Shape consistent with model expectations

CDF Bs result

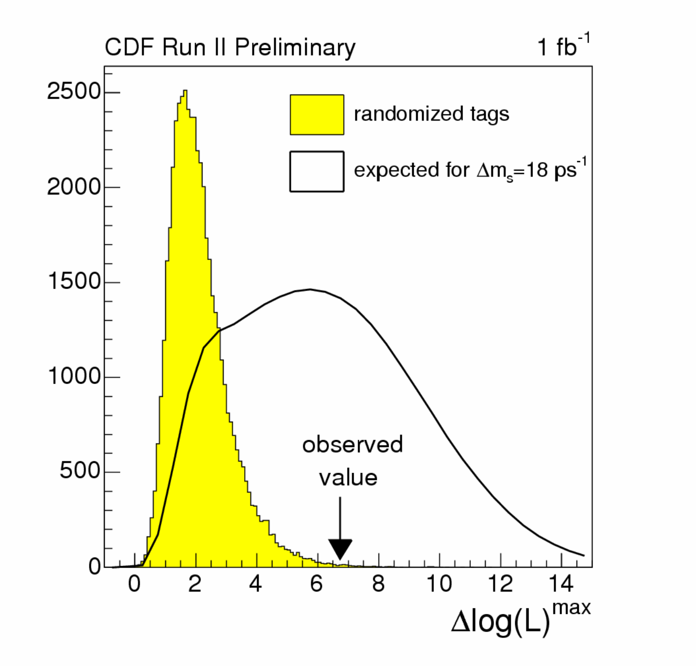


CDF Bs result

- $\Delta m_s = 17.31 + 0.33 - 0.18(\text{stat}) \pm 0.07(\text{sys})$
  - D0 consistent but lower sensitivity



Resolution dominated by hadronic decays



Probability of background fluctuation = 0.2% ~ 3σ

Γ_{12}

ρ_f is phase space factor

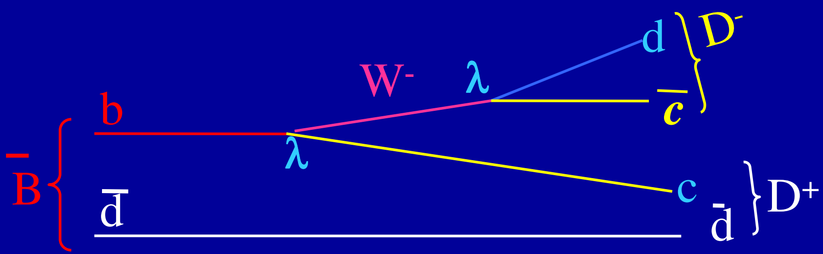
- Γ_{12} from common final states

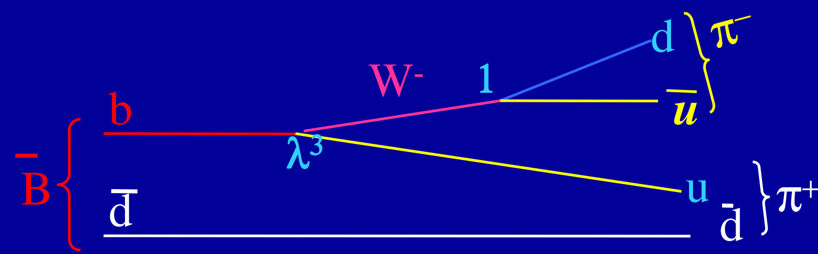
$$\Gamma_{12} = \sum_f < B|f > \rho_f < f|\bar{B} >$$

$\Delta\Gamma = 2\mathrm{Re}\{\Gamma_{12}/ m_{12}\}|m_{12}|$
$= 2 |\Gamma_{12}| \cos\phi$

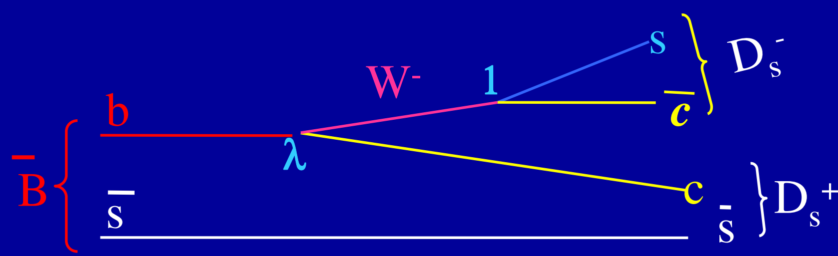
$|\Gamma_{12}/ m_{12}| \sim 5\mathrm{x}10^{-3}$ in SM

- B_d dominated by D^+D^-, $\pi^+\pi^-$, … ,
  - $\Gamma_{12} \sim O(\lambda^4)$, $\Delta\Gamma/\Gamma \sim 3\mathrm{x}10^{-3}$





- B_s dominated by $D_s^+D_s^-$
  - $\Gamma_{12} \sim O(\lambda^2)$, $\Delta\Gamma/\Gamma \sim 0.10$
    - Γ_{12}/m_{12} mostly real:
    $\phi \sim \arg(m^*_{12}) \sim \beta_s$



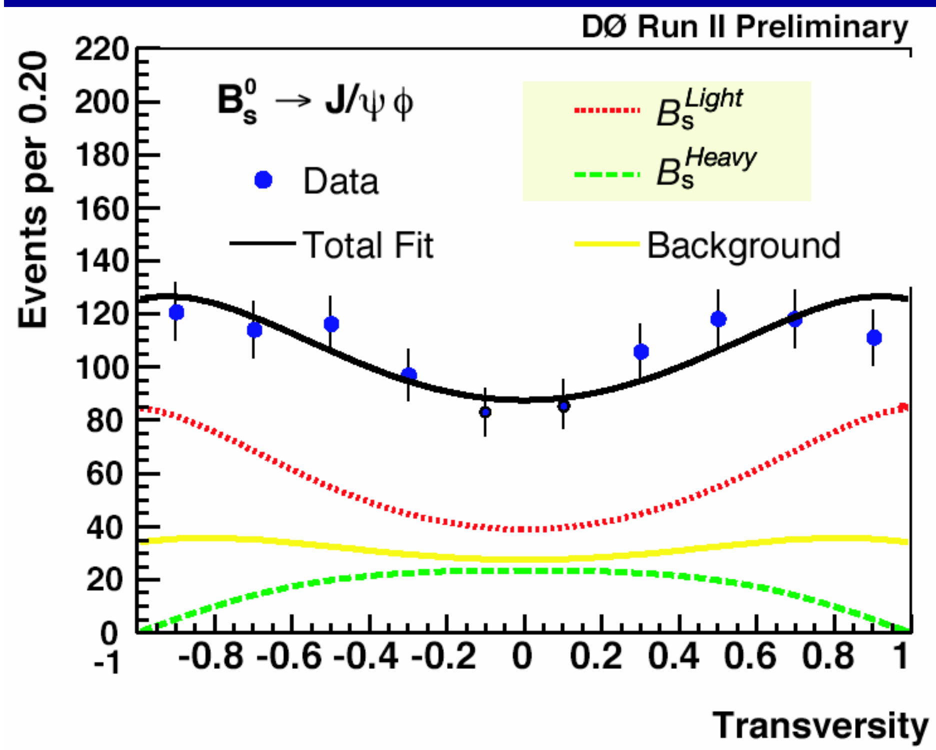
Measurements of $\Delta\Gamma/\Gamma$

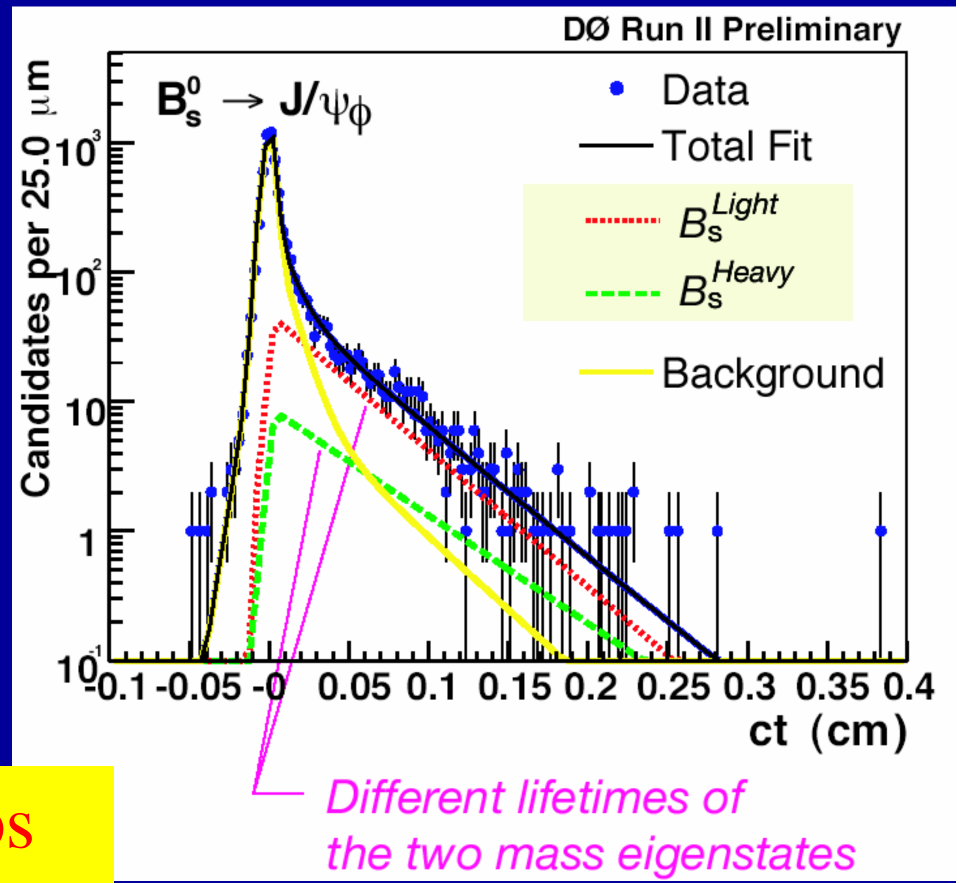
- $\Delta\Gamma_d$ very hard
  - Limits from LEP and B-factories consistent with SM value

- $\Delta\Gamma_s$ feasible at Tevatron with several techniques:
  - Combined lifetime/transversity (angular) analysis of $Bs \to \psi\phi$ decay
    - Found to be ~ 19% CP-odd
  - Measurement of $BR(Bs \to D_s^{+(*)} D_s^{-(*)})$
    - Mostly CP-even (theory expectations > 95%)
  - Combination of flavor specific and CP specific lifetime measurements (e.g. $Bs \to l\nu Ds$ and $Bs \to K+K-$)

DØ transversity analysis

- Update of published analysis with 800 pb^{-1}

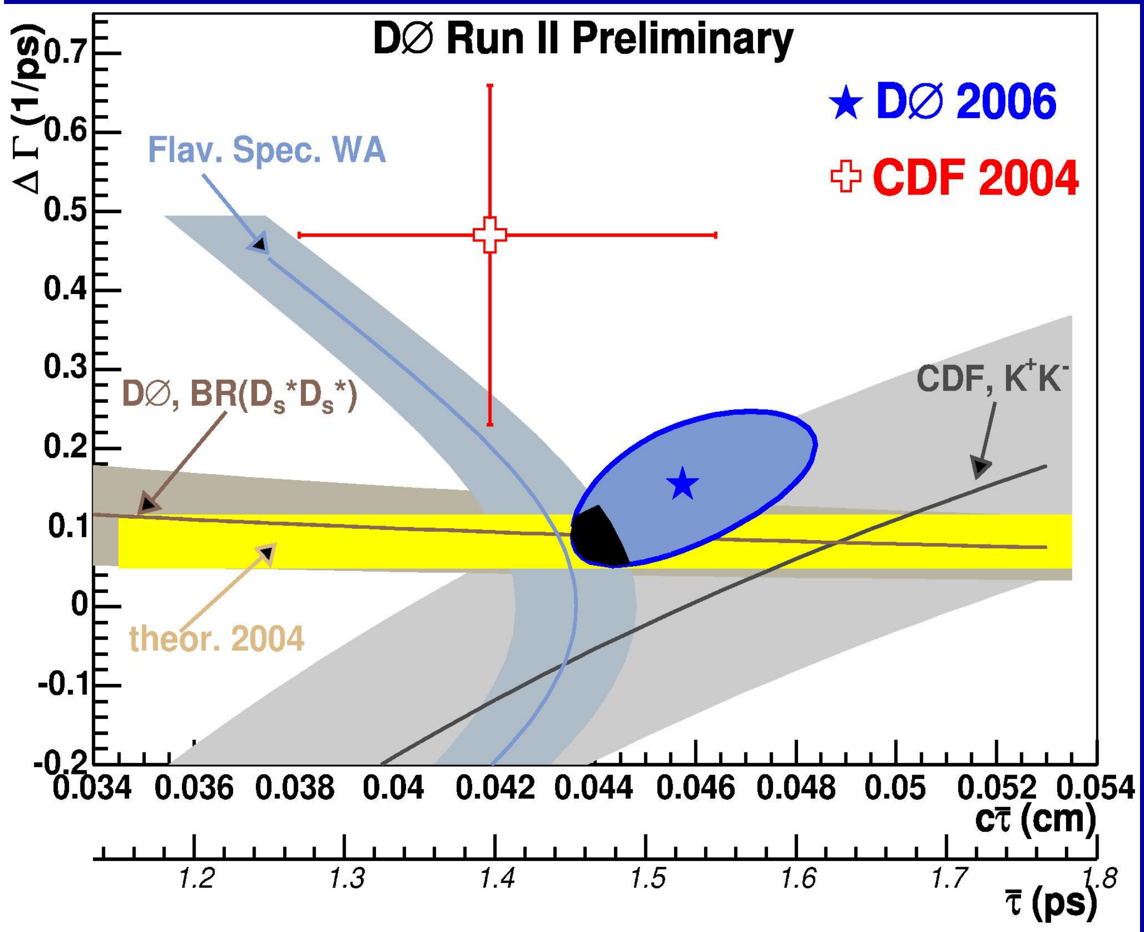




$$\bar{\tau}_{Bs} = 1.53 \pm 0.08^{+0.01}_{-0.03}\ \text{ps}$$

$$\Delta\Gamma_s = 0.15 \pm 0.10^{+0.03}_{-0.04}\ \text{ps}^{-1}$$

Combined $\Delta\Gamma_s$ Results



- **Theoretical prediction (Nierste)**

$$\Delta\Gamma_s = 0.10 \pm 0.03\ \text{ps}^{-1}\left(\frac{f_{B_s}}{250\ \text{MeV}}\right)^2$$

- ***Unofficial world average***

$$\Delta\Gamma_s = 0.097^{+0.041}_{-0.042}\ \text{ps}^{-1}$$

$$\bar{\tau}_s = \frac{1}{\Gamma_s} = 1.461 \pm 0.030\ \text{ps}$$

CPV in mixing

- $|p/q| \neq 1$ → CPV
- Measure asymmetry $A = \frac{N(BB) - N(\bar{B}\bar{B})}{N(BB) + N(\bar{B}\bar{B})} = \frac{N(l^+l^+) - N(l^-l^-)}{N(l^+l^+) + N(l^-l^-)}$
- Expect:

$$N(BB) = N(B \to B)(\bar{B} \to B) = \left(e^{-\Gamma t} cos^2\left(\frac{\Delta m t}{2}\right)\right)\left(\left|\frac{p}{q}\right|^2 e^{-\Gamma t'} sin^2\left(\frac{\Delta m t'}{2}\right)\right)$$

$$N(\bar{B}\bar{B}) = N(\bar{B} \to \bar{B})(B \to \bar{B}) = \left(e^{-\Gamma t} cos^2\left(\frac{\Delta m t}{2}\right)\right)\left(\left|\frac{q}{p}\right|^2 e^{-\Gamma t'} sin^2\left(\frac{\Delta m t'}{2}\right)\right)$$

$$A = \frac{1 - \left|\frac{q}{p}\right|^4}{1 + \left|\frac{q}{p}\right|^4} \approx \mathcal{I}m\left(\frac{\Gamma_{12}}{m_{12}}\right)$$

- SM prediction: Bd: 9×10^{-4}, Bs: 1×10^{-5}
- Bd avg: -0.0030±0.0078 (LEP, CLEO, Belle, BaBar)
- Bs avg: 0.0013±0.0014 (D0 2006)

$|p/q| = 1$ → Mass eigenstates = CP eigenstates

Summary of lecture 1

- B-quark hadrons have been studied for about 30 years
- e+e- storage rings and hadronic machines have complemented each other
  - Now B-factories and Tevatron
- b-hadron production and their basic properties are now known with an unprecedented level of detail
  - Their study has helped develop and test QCD, even in non-perturbative regimes
- Detailed measurements of neutral B meson mixing have become recently available for both species
  - Find overall consistency with Standard Model
  - In conjunction with CP violation measurements (next lecture) further confirm SM and limit possible new physics