Beauty(ful) and Charm(ing) physics with CDF II

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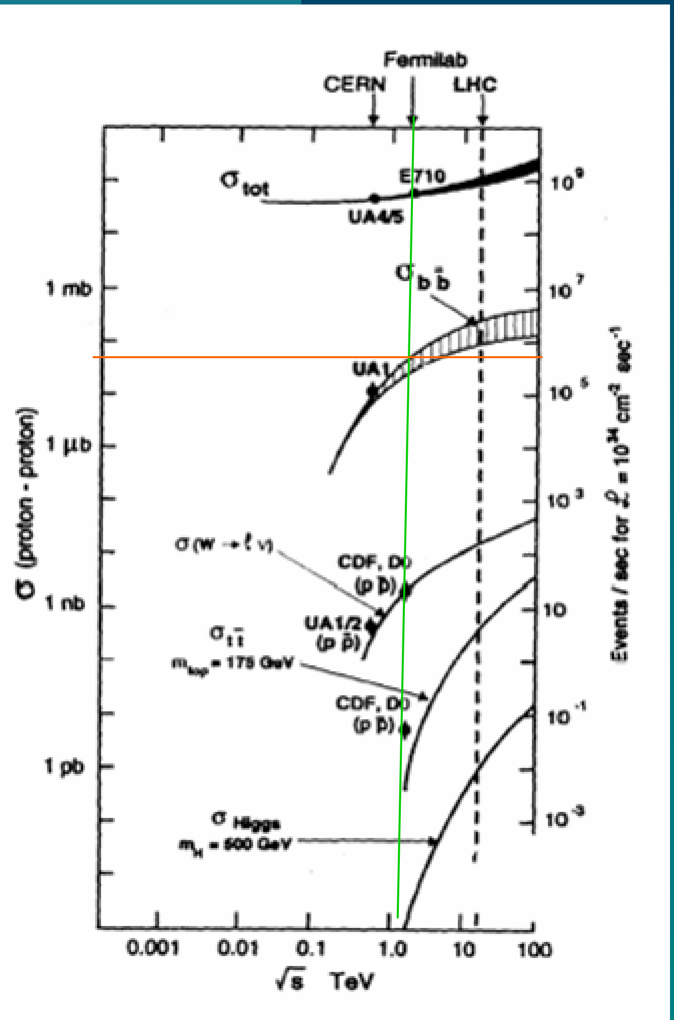
Introduction: why?

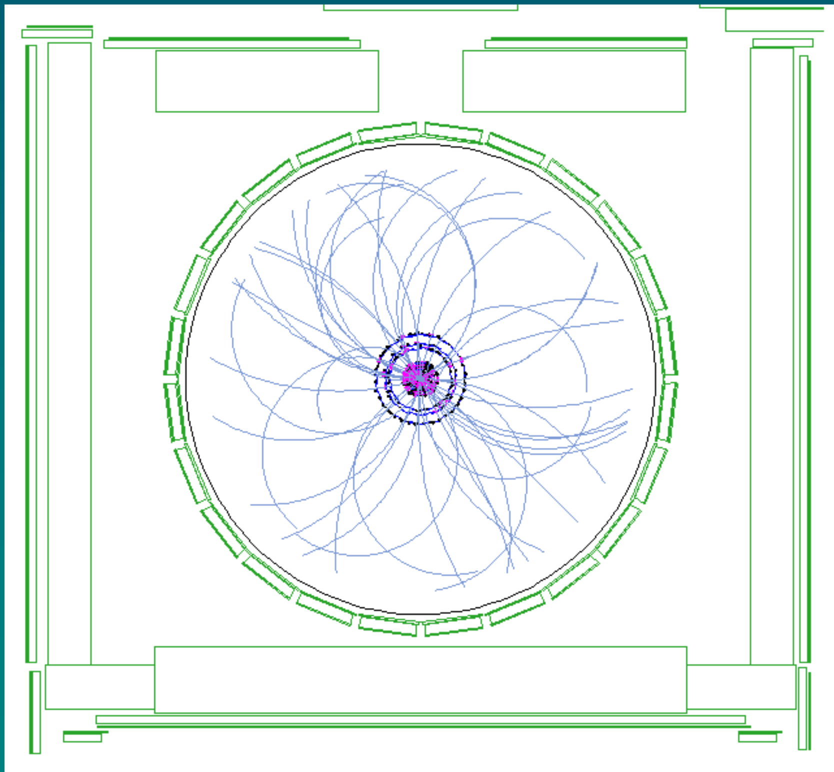
- CDF is known in the physics community for having discovered the top quark, and running at the world's largest energy accelerator
- Does it make sense to study low-energy events, a field dominated by dedicated experiments running at b factories?

Introduction: why b physics at Tevatron



- Extremely high cross section
- Access to heavy states (B_s,Λ_b)
- Relatively "clean" events

σ(bb):
- TeV ≈ 50 μb, cc ×10
- ϒ(4S) ≈ 1 nb
- Z0 ≈ 7 nb

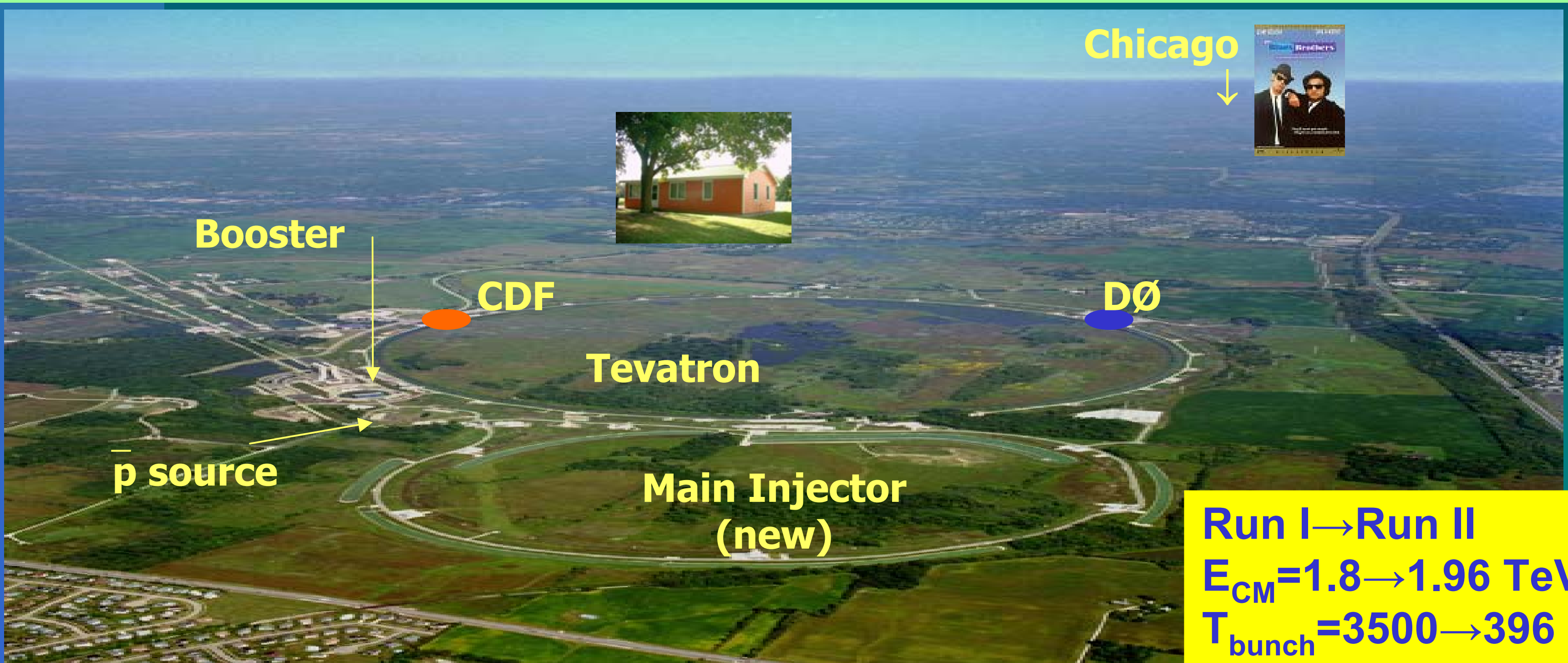


Introduction: why b physics at Tevatron

- However:
  - Luminosity factor 1000 lower than b-factories
  - Not optimal calorimetry (and PID)
  - Large backgrounds (important combinatorics, trigger issues)
- Not obvious *a priori*: more details, please!

The accelerator

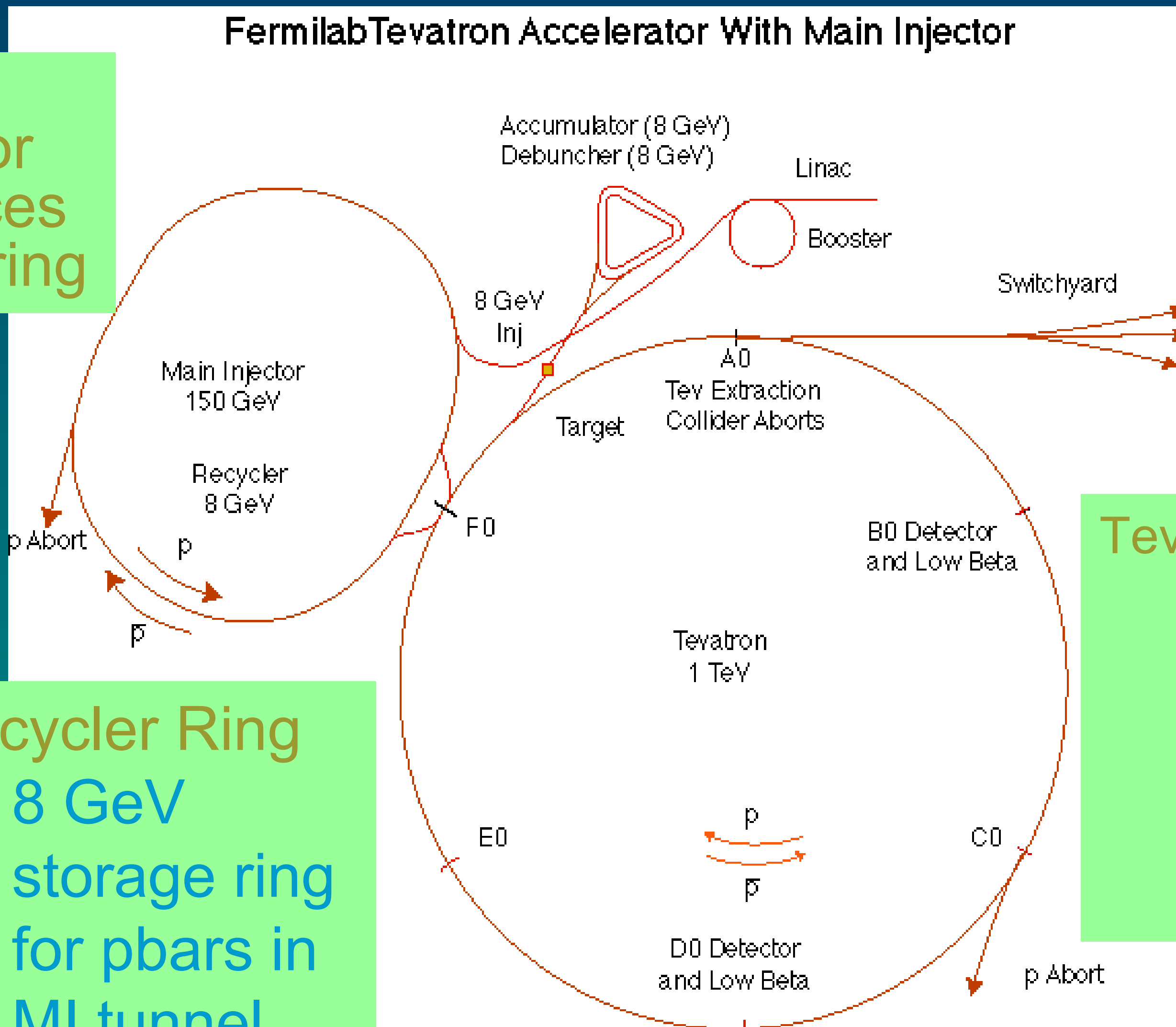
- The Tevatron is the largest-energy accelerator ever built.
- It serves two collider experiments (CDF and D0), plus several fixed targets (KTeV, NuTeV, DoNuT etc.)
- From 2001 it started phase 2 to increase collider luminosity



Run I→Run II
E_{CM}=1.8→1.96 TeV
T_{bunch}=3500→396 ns

Changes between Run I -> Run II

- Main injector replaces main ring



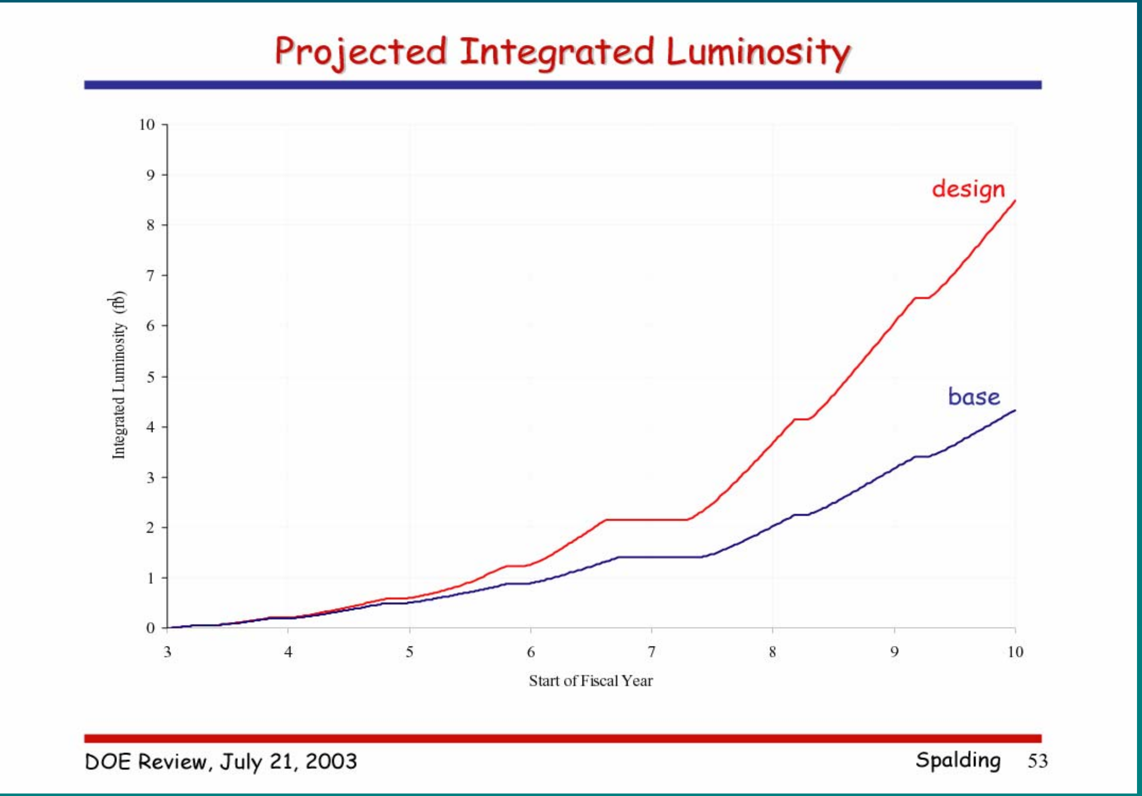
Recycler Ring
- 8 GeV storage ring for pbars in MI tunnel

Tevatron
- # bunches: 6x6 -> 36x36
- Two-stage collimation system

Initial and revised luminosity goals

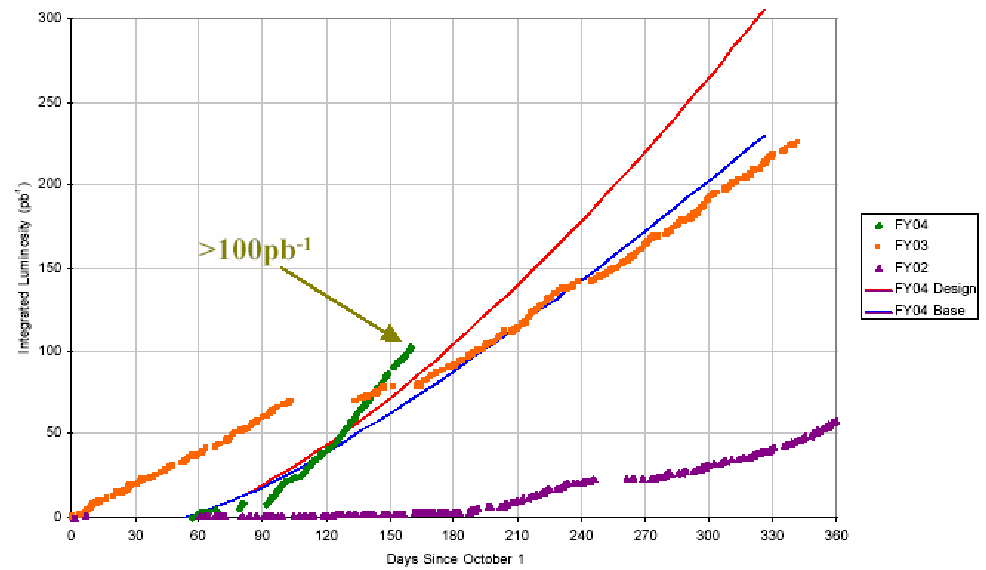
- Initial planning for RunII was to achieve instantaneous luminosities of $2x10^{32}$, for an integrated luminosity of 2 fb^{-1} over a 2-3 year period and 15 fb^{-1} before LHC.

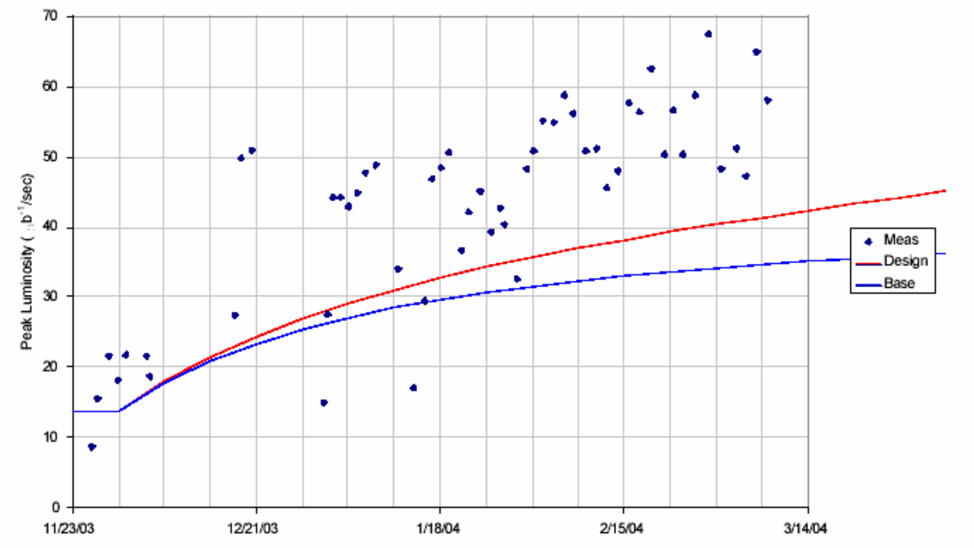
- First goals were not reached, schedule revised by DOE reviews (oct. 2002, july 2003)



The progress of Tevatron luminosity

- 1.5 years after that looks like the accelerator is much better understood, performances exceed (revised) expectations, still far from design goals

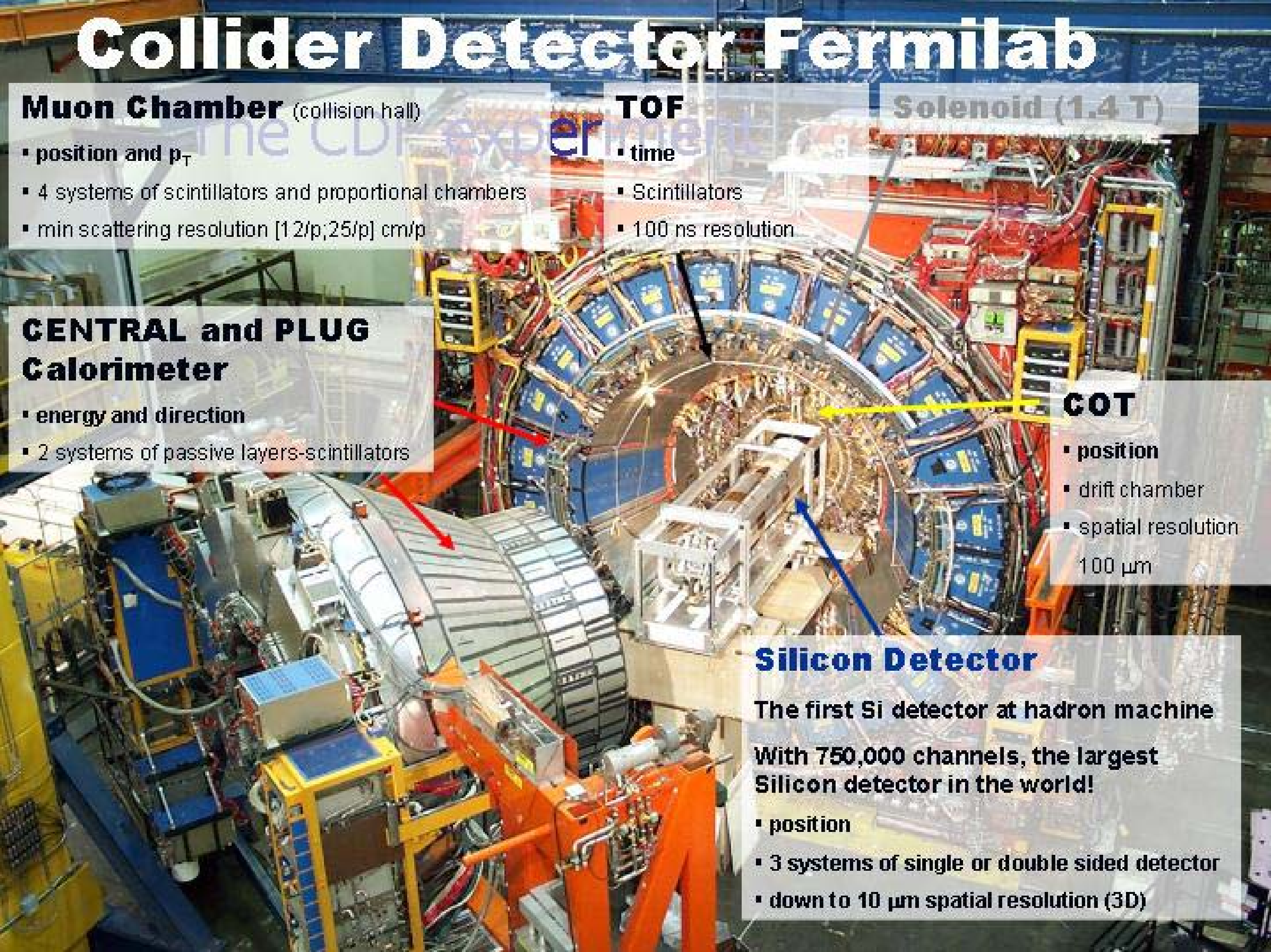




Reasons for improvements

Fight for better Tevatron

	10/02	03/03	09/03	02/04	$\bar{p}$/p only
Record Luminosity, e30	36	41	50	63	n/a
Protons/bunch	170e9	205e9	245e9	245e9	same
Pbars/bunch	22e9	23e9	25e9	30e9	same
P-loss at 150 GeV	14%	10%	8%	5%	5%
Pbar-loss at 150	9%	4%	2%	2%	2%
P-loss on ramp	6%	5%	5%	4%	3% *
Pbar-loss on ramp	8%	11%	8%	6%	2%
Pbar-loss in squeeze	5%	2%	3%	1%	0%
… at the beginning of store:					
Pbar lifetime at HEP, hr	~40	~35	~35	~30	~900
Proton lifetime at HEP, hr	~90	~60	~20	~100	~300 *
Eff.emittance lifetime, hr	~14	~26	~31	~16	n/a
Luminosity lifetime, hr	~10	~13	~10	~9	n/a



Collider Detector Fermilab
Muon Chamber (collision hall)
▪ position and p_T
▪ 4 systems of scintillators and proportional chambers
▪ min scattering resolution [12/p;25/p] cm/p
TOF
▪ time
▪ Scintillators
▪ 100 ns resolution
Solenoid (1.4 T)
CENTRAL and PLUG Calorimeter
▪ energy and direction
▪ 2 systems of passive layers-scintillators
COT
▪ position
▪ drift chamber
▪ spatial resolution 100 μm
Silicon Detector
The first Si detector at hadron machine
With 750,000 channels, the largest Silicon detector in the world!
▪ position
▪ 3 systems of single or double sided detector
▪ down to 10 μm spatial resolution (3D)

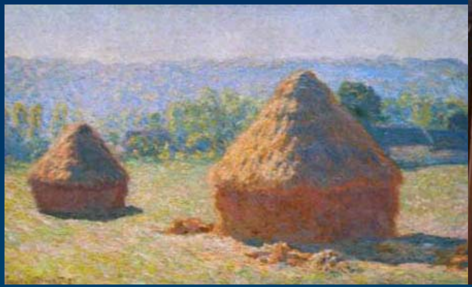
Trigger issues

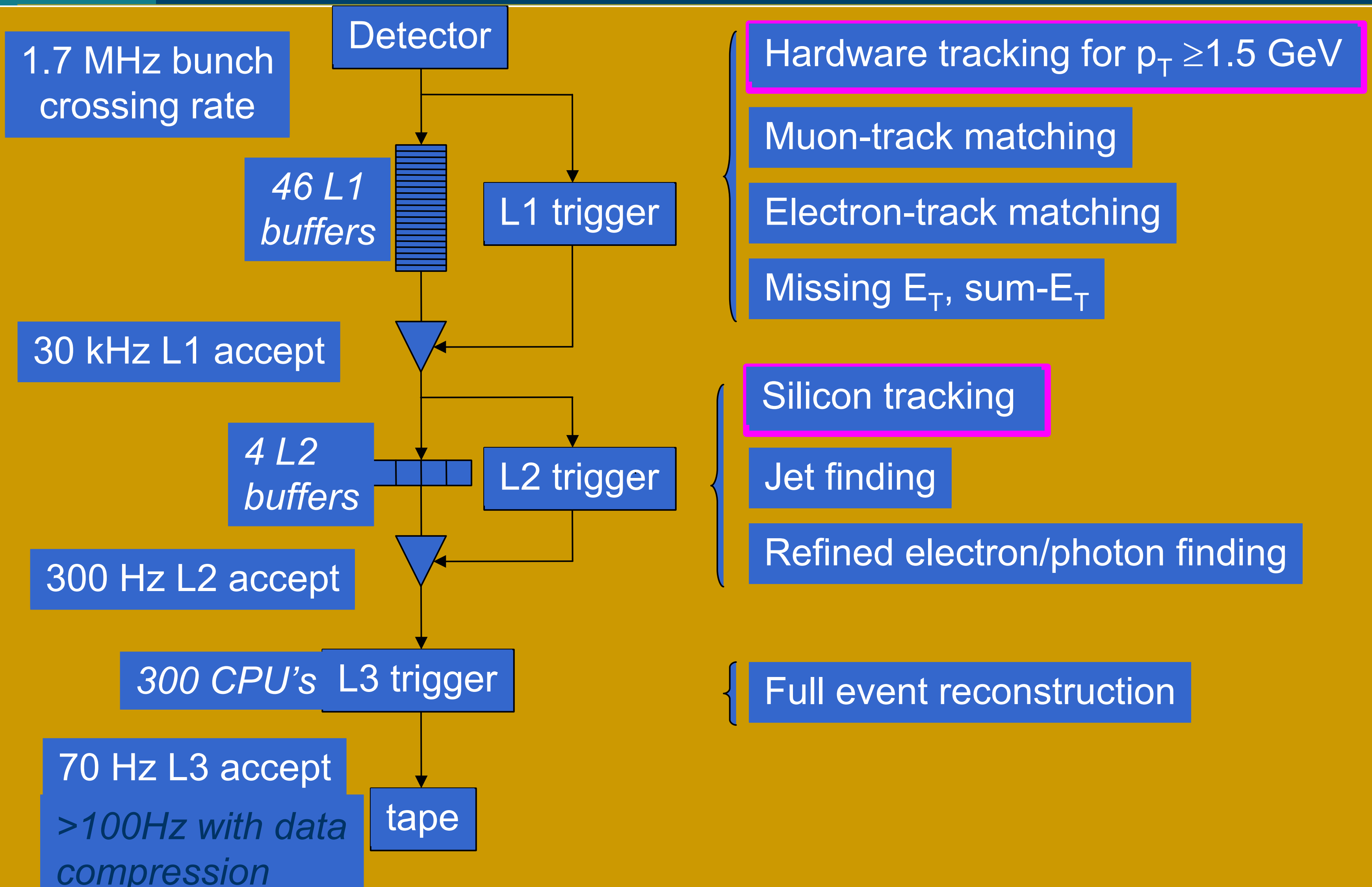
1.7 MHz events in central region
Only 70 Hz can be stored on tape

Process	Cross-section	Event Rate
Inelastic pp	60 mb	6 MHz
pp→bb (b p_T>6 GeV, |η|<1)	10 μb	1 kHz
pp→WX→ℓνX	5 nb	0.4 Hz
pp→ZX→ℓℓX	0.5 nb	0.04 Hz
pp→tt→WWbb→ℓν bbX	2 pb	0.0002 Hz
pp→WH→ℓνbb (M_H=120GeV)	15 fb	15 10-7 Hz

Assume L =100x10^{30} cm^{-2}s^{-1}, ℓ=electron or muon

Finding needles in haystacks: the CDF trigger





Strategies to trigger on Heavy Flavors

Traditional

- Di-lepton - dilepton sample
  - pT(μ/e)>1.5/4.0 GeV/c
  - J/ψ modes, masses, lifetime, x-section
  - Yield 2x Run I (low Pt threshold, increased acceptance)

New!

- lepton + displaced track - semileptonic sample
  - pT(e/μ)>4 GeV/c 120 μm<d0(Trk)<1mm, pT(Trk)>2 GeV/c
  - Semileptonic decays, Lifetimes, flavor tagging.
  - B Yields 3x Run I

New!

- Two displaced vertex tracks - hadronic sample
  - pT(Trk)>2 GeV/c, 120 μm<d0(Trk)<1mm, S pT>5.5 GeV/c
  - Branching ratios, Bs mixing, …

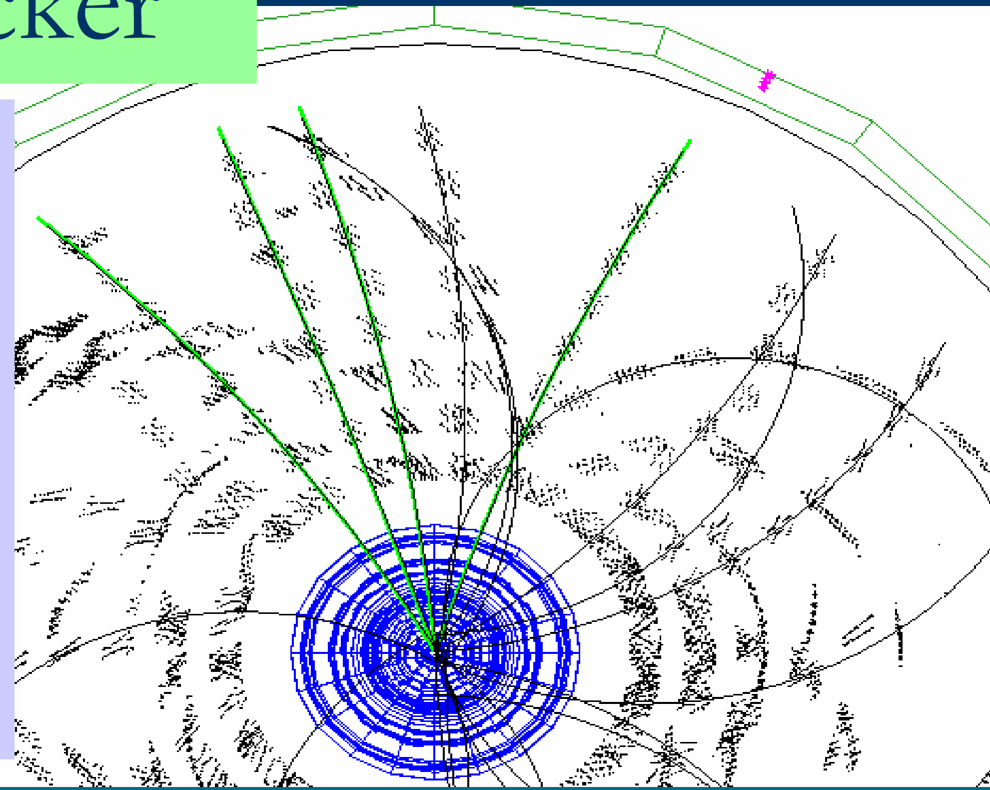
eXtremely Fast Tracker

Heart of CDF Run II trigger

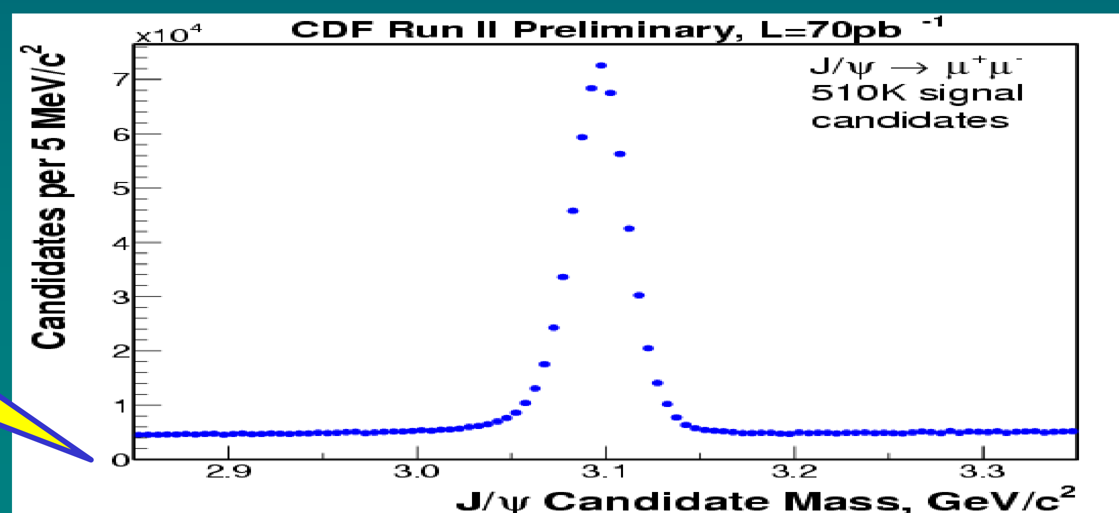
L1 tracks p_T>1.5GeV every 132ns
Efficiency=96% σ(Φ)=5mr
$\sigma(p_T)=(1.74\ p_T)\%$

L1 electron = L1 track + EM cluster
L1 muon = L1 track + muon stub

L1 high p_T lepton triggers for W/Z
L1 low p_T lepton/track triggers for B

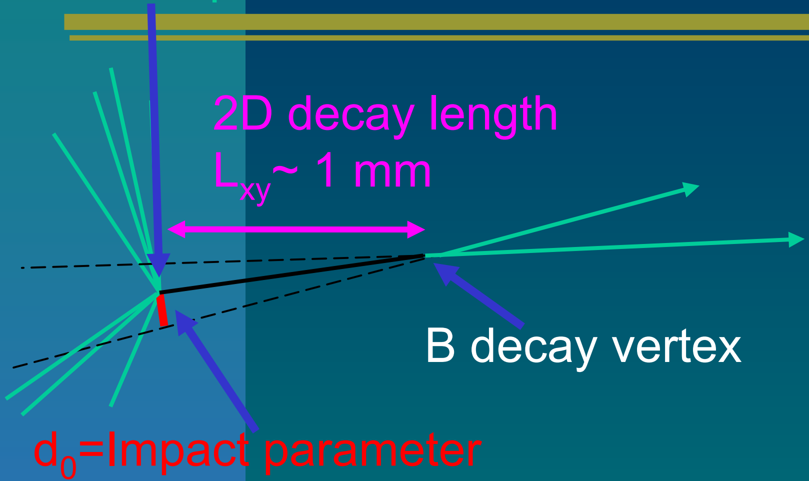


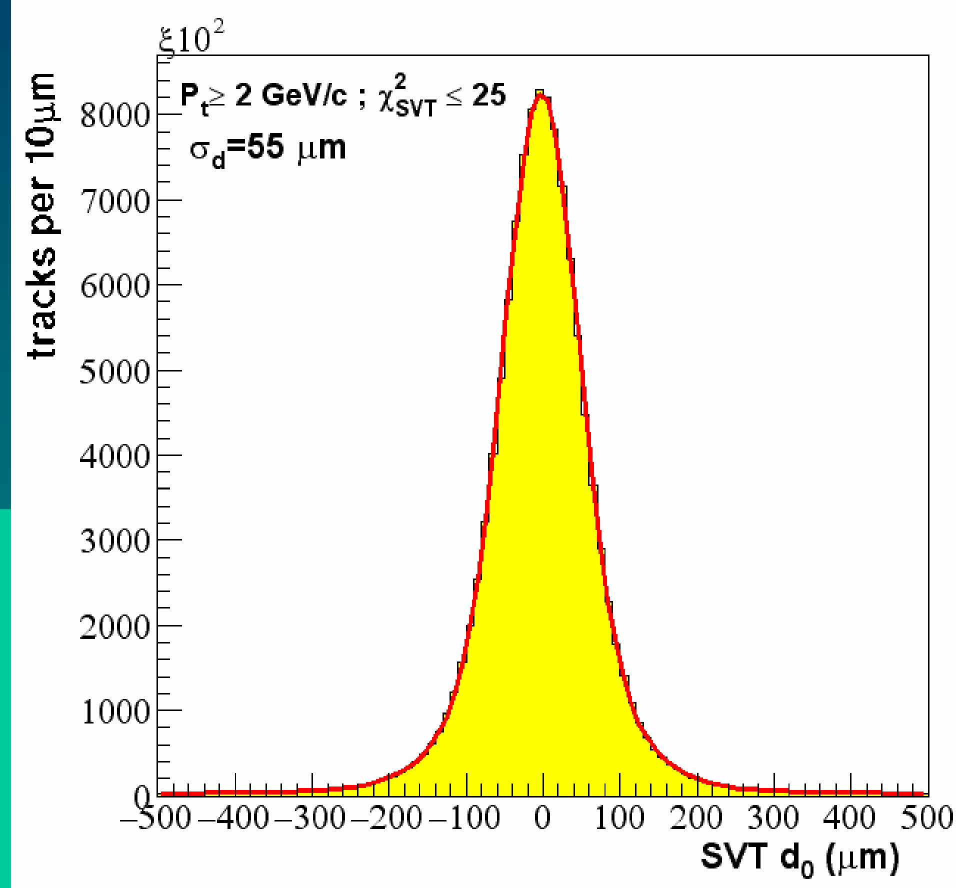
Low p_T di-muon trigger:
2 L1 muons p_T>1.5 GeV
Collect J/Ψ's for calibration and B physics



The SVT

Exploit long b, c lifetimes in Trigger
L1 track + Si hits = Impact parameter @L2
A first at a hadron collider!
CDF is a charm/ B Factory!





Lepton (e, μ) + displaced track

Lepton: p_T>4 GeV

Track: p_T>2 GeV, d_0>120 μm

Semi-leptonic B decays ($B \rightarrow \ell \nu X$)

Displaced two track trigger

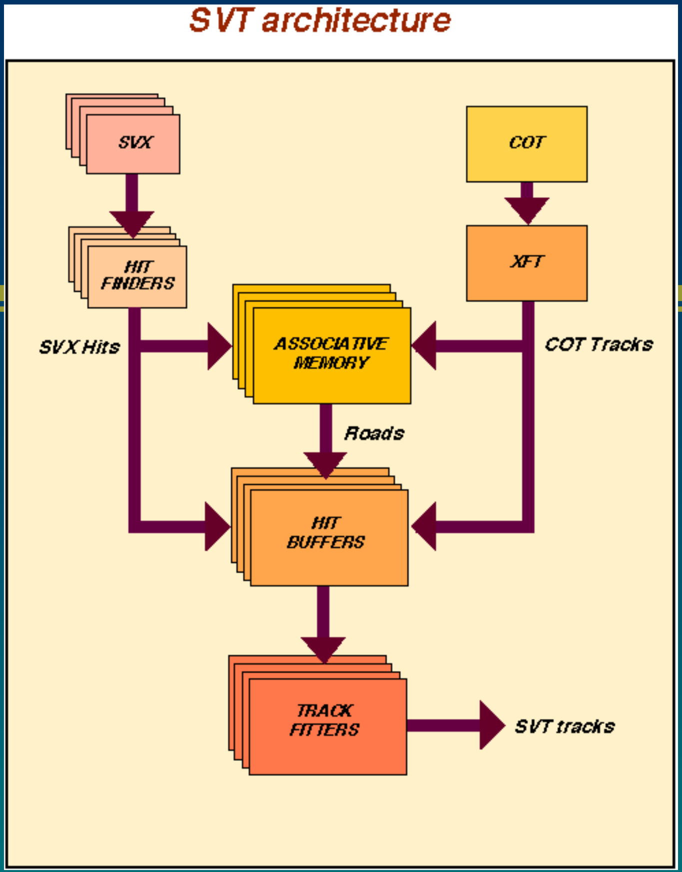
Tracks: p_T>2 GeV, d_0>120 μm

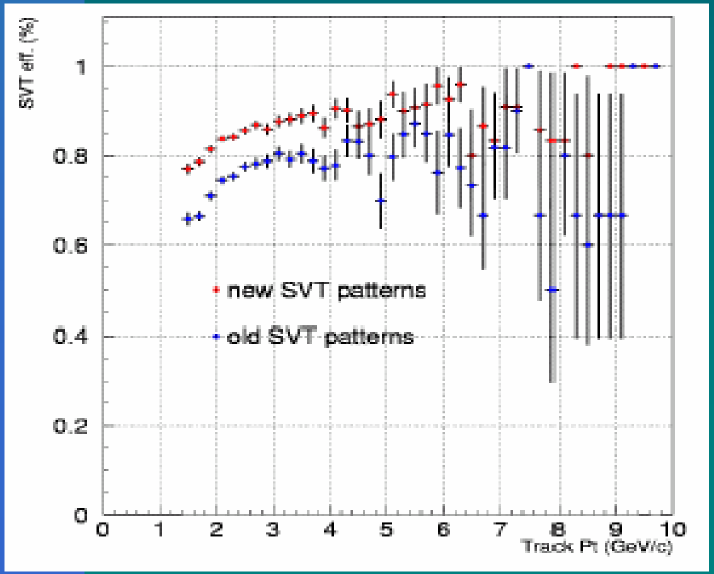
Σp_T>5.5 GeV

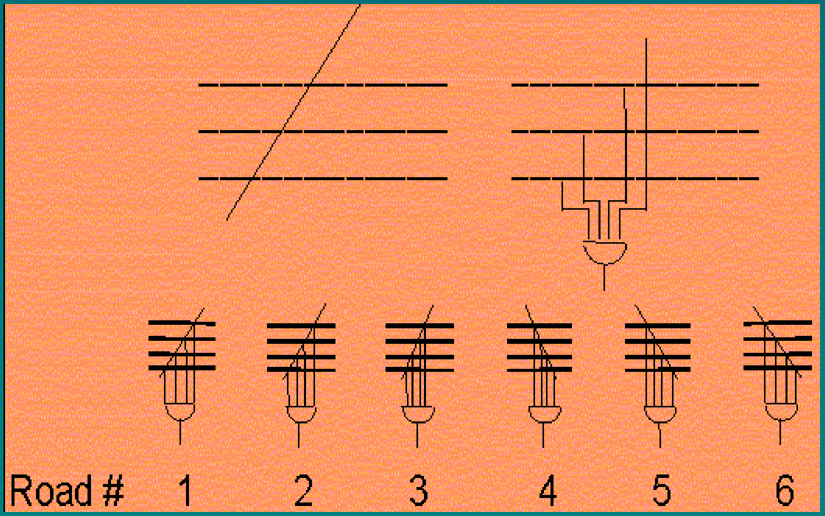
Fully hadronic B decays ($B \rightarrow hh'$, $B_s \rightarrow D_s \pi$, $D \rightarrow K\pi$ …)

The SVT

The Silicon Vertex tracker allows reconstructing track parameters (including impact parameter) on-line. Based on an associative memory, pre-defined roads stored and compared to detecor information.



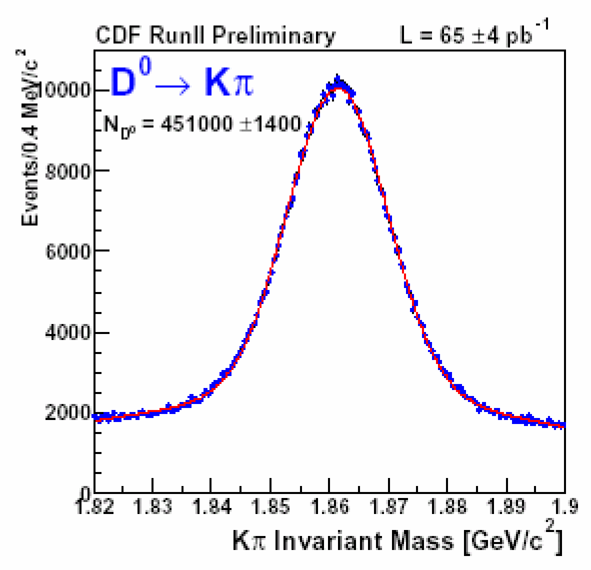


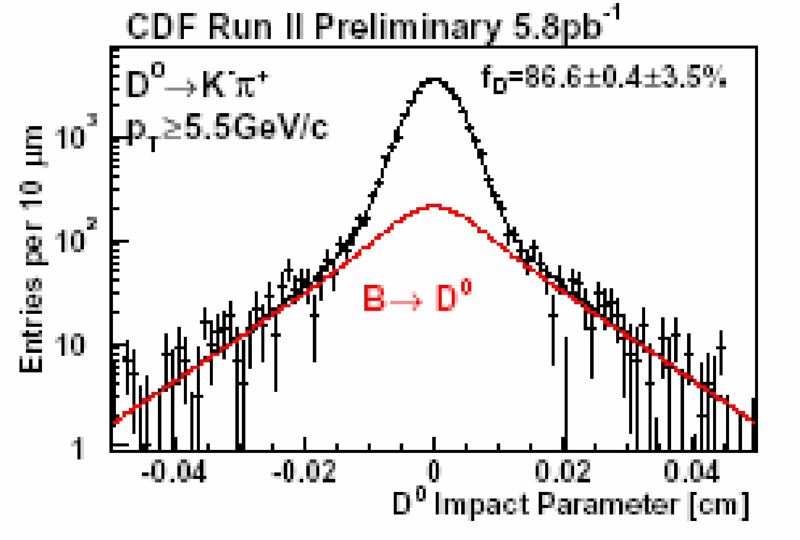


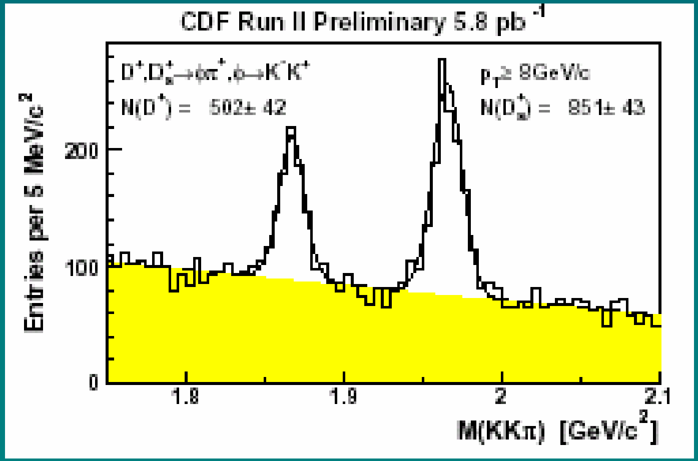
Now we know what the C in CDF stands for… (K.Pitts, LP’03)

- Two-Track Trigger :

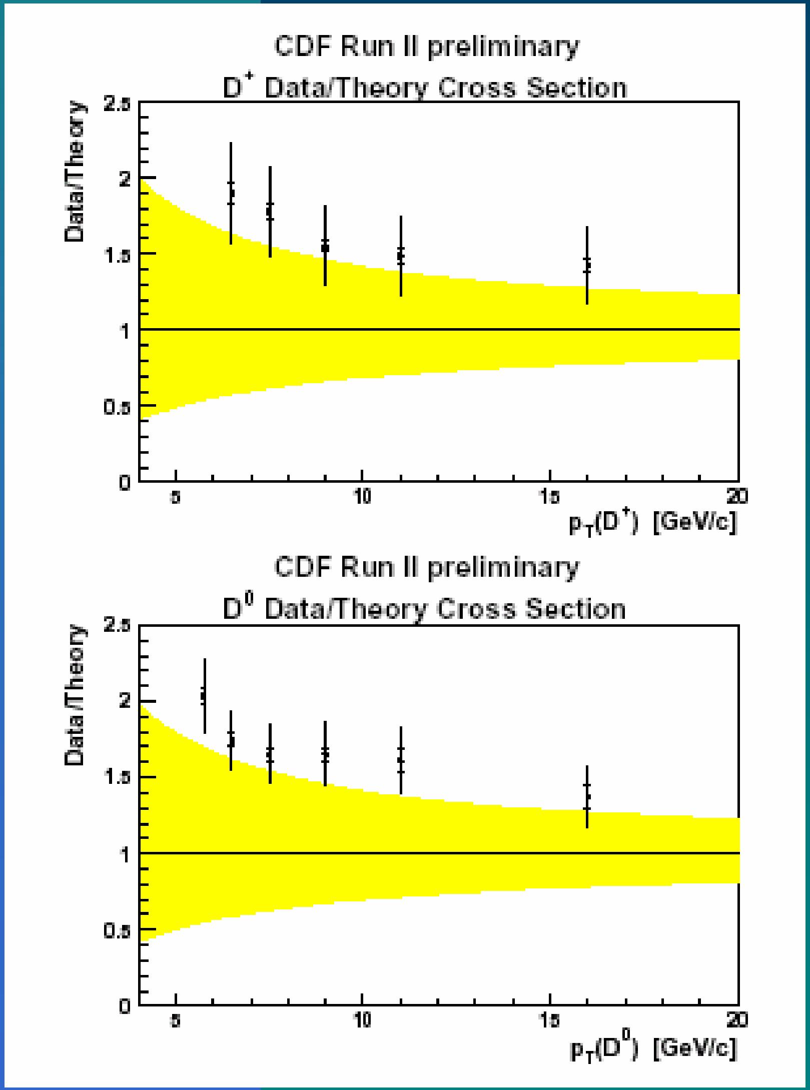
p_T>2 GeV, d_0>100m, Σp_t>5.5 GeV selects a huge sample of D^0 (prompt or from B)







Charm cross section



Done with few runs (syst. lim)

- $\sigma(D^0)$pT>5.5 GeV =13.3 ± 0.2 ±1.5 μb
- $\sigma(D^*)$pT>6.0 GeV =5.2 ± 0.1 ± 0.8 μb
- $\sigma(D^+)$pT>6.0 GeV =4.3 ± 0.1 ± 0.7 μb
- $\sigma(D^+_s)$pT>8 GeV =0.75 ± 0.05±0.22 μb

Agrees with Cacciari Nason JHEP 0309, 006 (2003), but on the high side

Cabibbo-suppressed decays and asymmetries

D0 decays other than Kπ seen in mass plot.

Γ(D0->KK)/Γ(D0->Kπ)=9.38±0.18±0.10%

Γ(D0->ππ)/Γ(D0->Kπ)=3.686±0.076±0.036%

compare with FOCUS (2003)

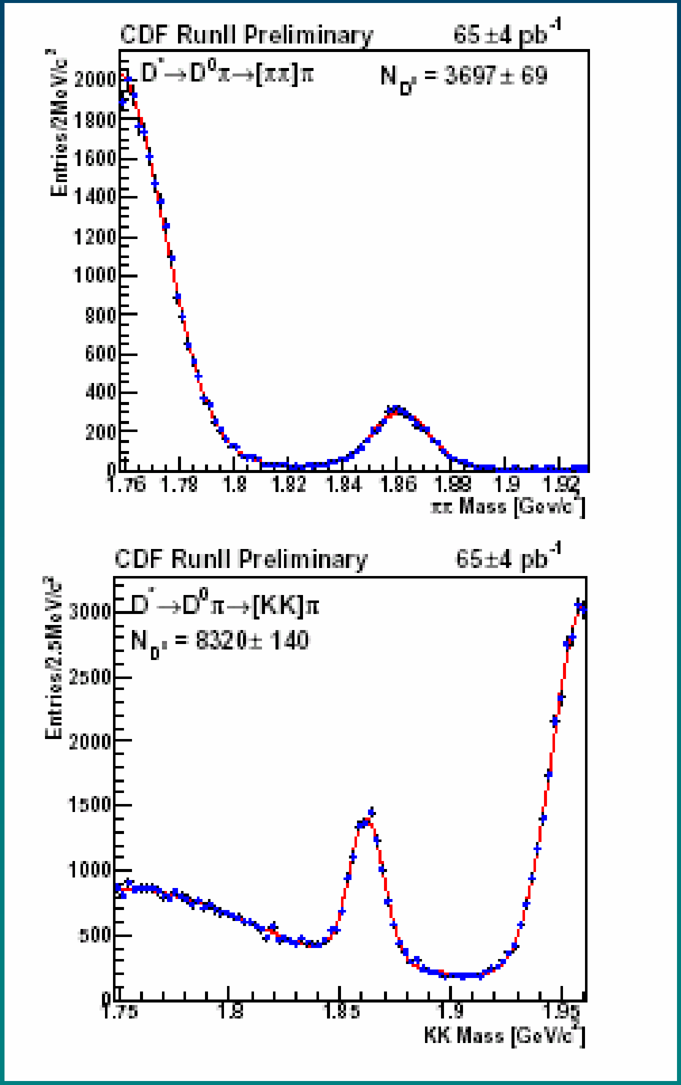
Γ(D0->KK)/Γ(D0->Kπ)=9.93±0.14±0.14%

Γ(D0->ππ)/Γ(D0->Kπ)=3.53±0.12±0.06%

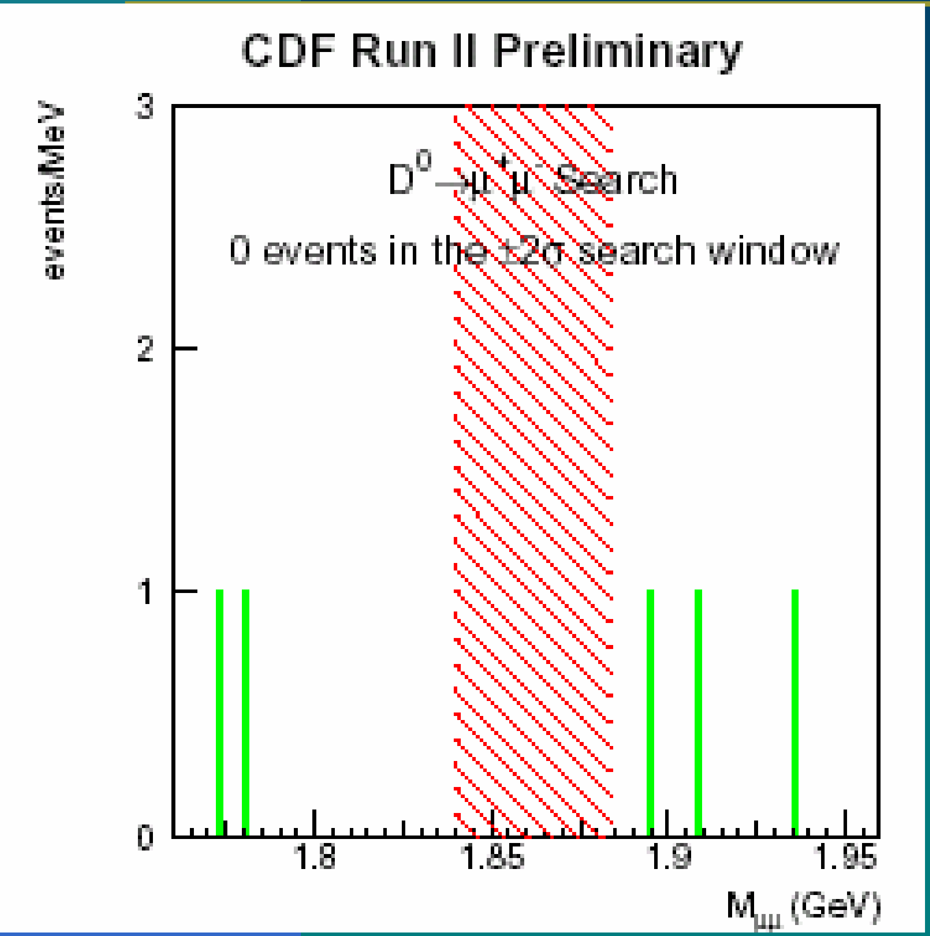
CP asymmetry: tagging the soft π from D* decays.

A(D0->KK) = 2.0 ±1.7± 0.6 %

A(D0->ππ) = 3.0 ± 1.9 ± 0.6 %



FCNC D^0-> μ μ decays



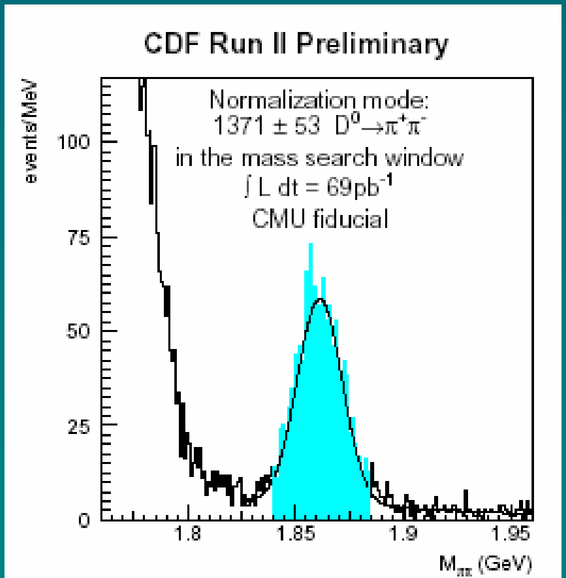
SM Br is 3 x 10^{-13}

Can grow by 10^7 in R-violating SUSY

D0->ππ used as reference sample

0 events observed, 1.8±0.7 from BG

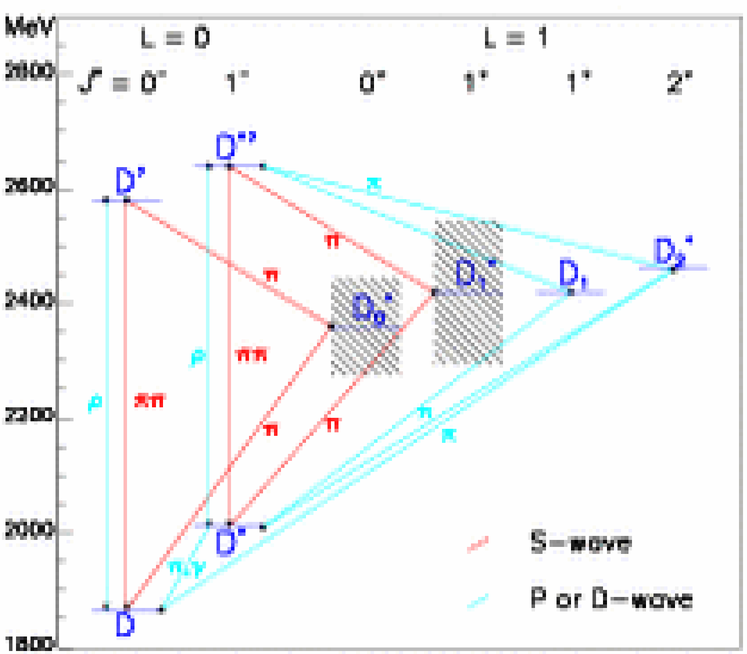
BR(D0->μμ)< 2.4 x 10^{-6} at 90% CL (improves PDG by a factor 2)

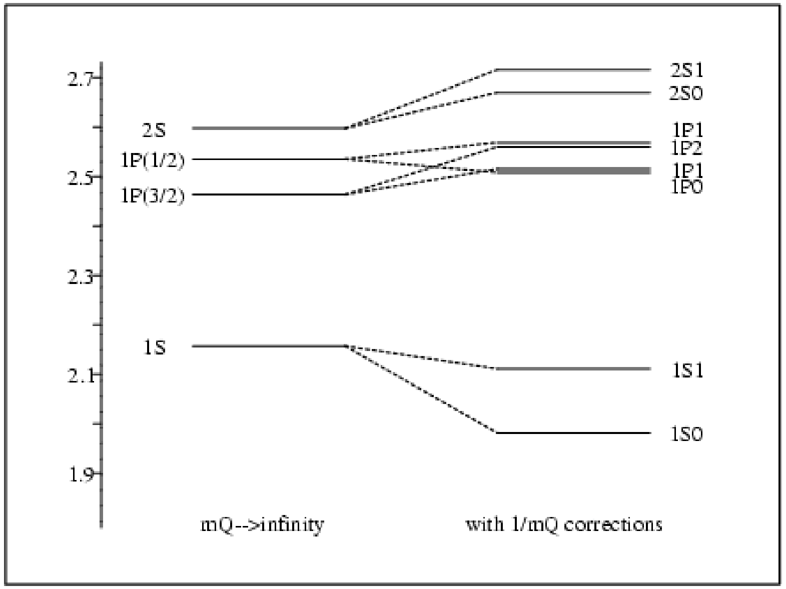


Orbitally-excited charm mesons

Total angular momentum of a meson: $J=s_q+s_Q+L$. Depending on relative spin orientation, 4 P-wave mesons (L=1)

In heavy quark limit, masses of mesons with same $j_q=s_q+L$ are degenerate. $1/m_Q$ corrections introduce hyperfine splitting, particularly visible for $j_q=3/2$ states, decaying via a suppressed D-wave, (width ≅ 20 MeV). Width of $j_q=1/2$ states is about 200 MeV.





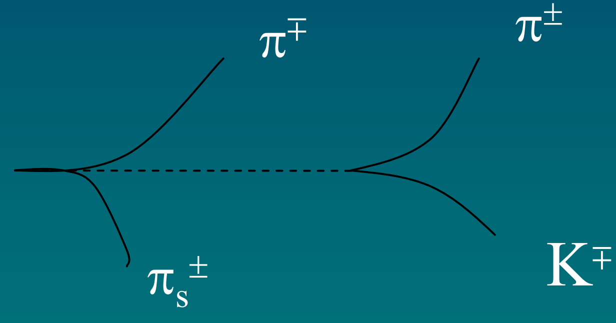
Decay topology

J=3/2 narrow resonances: $D_1(2420)$ and $D_2^*(2460)$. Mass is known with a precision of about 2 MeV and width with about 5 MeV. Studied in CDF in the decay

$D^{**} \to D^* \pi^{\mp}$

$\to D^0 \pi^{\pm}$

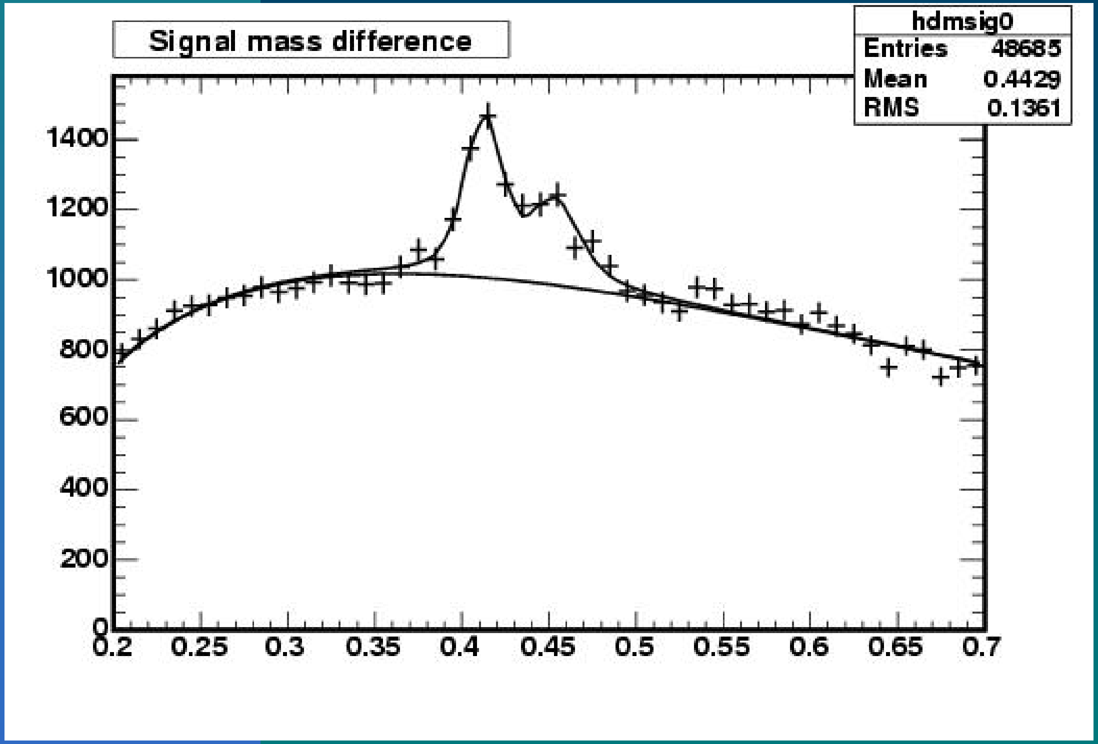
$\to K^{\pm} \pi^{\mp}$



two strong and a weak decay, giving rise to a displaced vertex from the D^0.

These kind of events are observed for the first time in RunII due to the impact parameter trigger done thanks to the SVT.

D** signals: 7000 and 4000 events



D** candidates are created combining the D* candidates with all tracks (assumed π) with opposite charge and Pt>1.5 GeV

Detector resolution is much better in the mass difference D**-D*, where the two peaks are clearly resolved

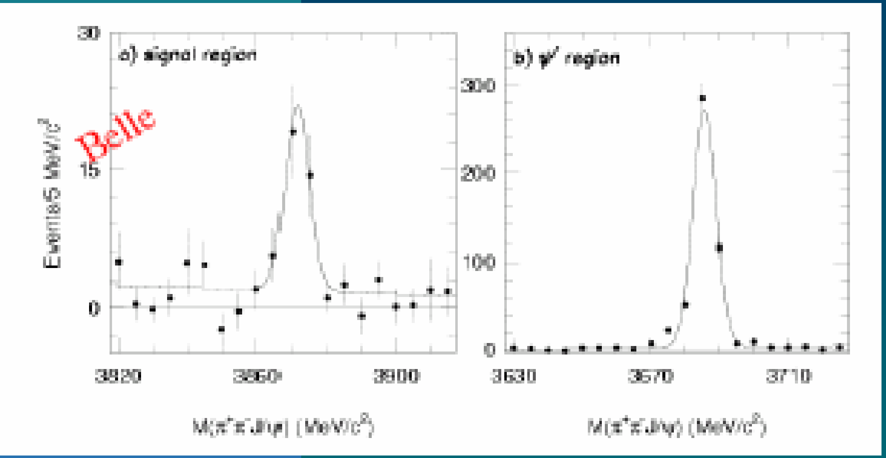
Fitted with 2 BWxGaus

Plus BG described as $e^{-am}\, m^b \sqrt{(m-m_\pi)}$

Errors on masses ≈ 1 MeV

(PDG: 2 MeV)

X(3872) confirmed by CDF

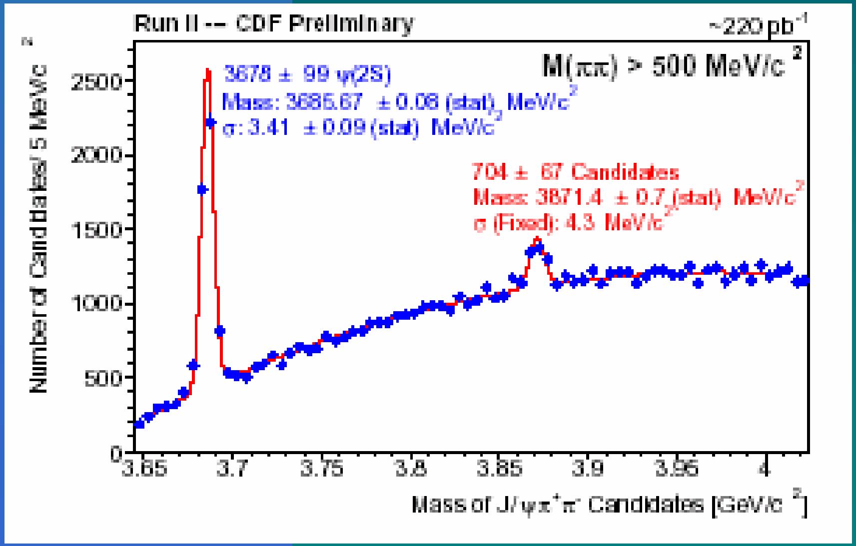


- New unexpected narrow state observed by Belle in J/Ψππ

M(X) = 3872.0 ± 0.6 ± 0.5 MeV

- CDF has 2M J/Ψ
- We observe a 11σ signal with mass

M(X) = 3871.4 ± 0.7 ± 0.4 MeV



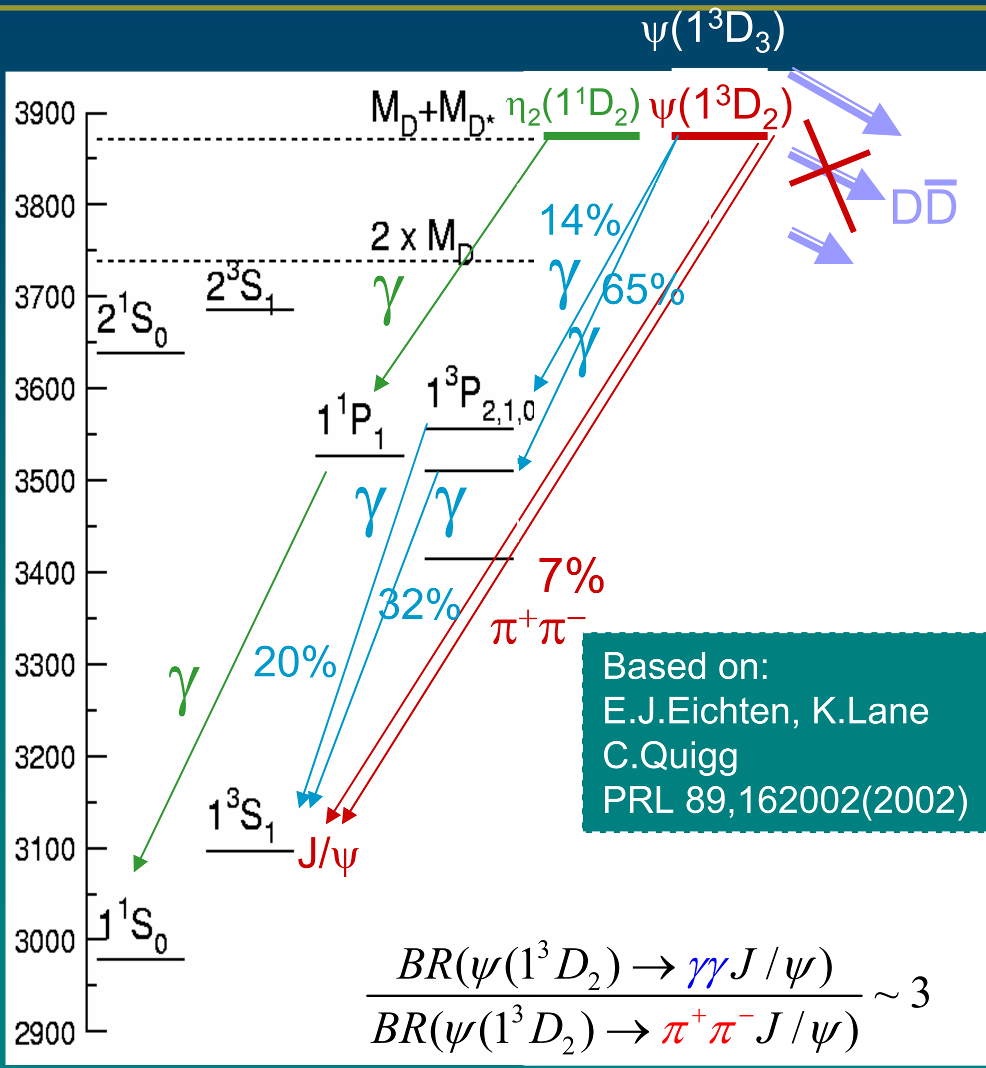
What is it?

•Charmonium?

•DD molecule?

Possible explanations

- A $\psi(1^3D_2)$ state:
  - Because D-states have negative parity, spin-2 states cannot decay to $D\bar{D}$
  - They are narrow as long as below the DD* threshold
  - $\eta_2(1^1D_2)$ preferentially decays to $h_c(1^1P_1)$. Decays to $\pi^+\pi^- J/\psi$ would be of magnetic type and are suppressed.
  - Some models predict large widths for $\psi(1^3D_2) \to \pi^+\pi^- J/\psi$
  - All models predict even larger widths for $\psi(1^3D_2) \to \gamma\, \chi_c(1^3P_{2,1})$ Should easily see $\psi(1^3D_2) \to \gamma\gamma\, J/\psi$.
- Discovery is very recent.



B production from J/Ψ

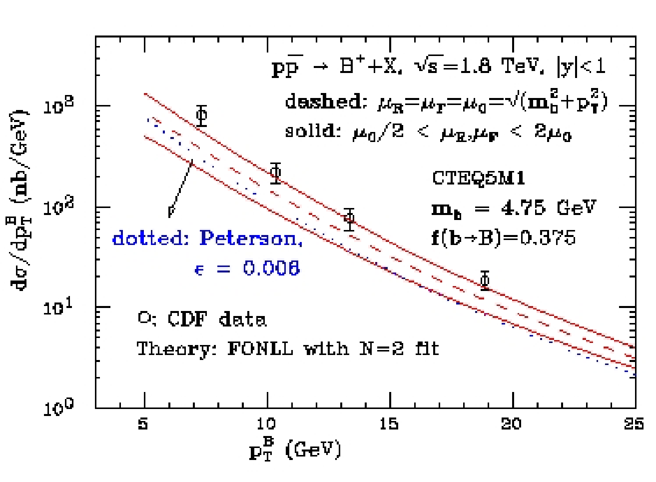
- RunI b cross-section ~ 3x NLO QCD
- theoretical approaches: new physics, Next-to-Leading-log resummations, non perturbative fragmentation function from LEP, new factorization schemes… discrepancy reduced to **1.7 ± 0.5(theo) ± 0.5(exp)** (see M.Cacciari in two weeks)
- Only top 10% in Pt of the total x-section measured
- New measurements to lower $p_T(B)$:
- Inclusive J/Psi cross section up to PT(J/Psi)=0 (first time hadron collider)

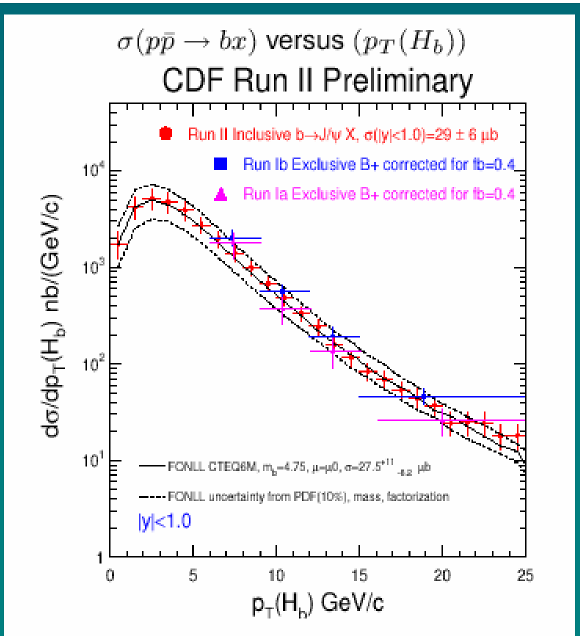
$\sigma(pp \to J/\Psi\ X)_{|y(J/\Psi)|<0.6} = (4.08 \pm 0.02\ (stat)\ ^{+0.60}_{-0.48}\ (syst))\ \mu b$

- Bottom Quark Production cross-section

$\sigma(pp \to b\ X)_{|y|<1.0} = (29.4 \pm 0.06\ (stat) \pm 6.2(sys))\ \mu b$

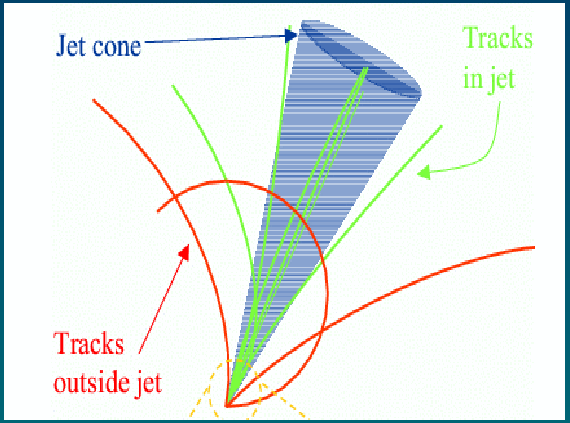
FONLL $\sigma(pp \to b\ X)_{|y(|<1.0} = (27.5\ ^{+11}_{-8.2})\ \mu b$

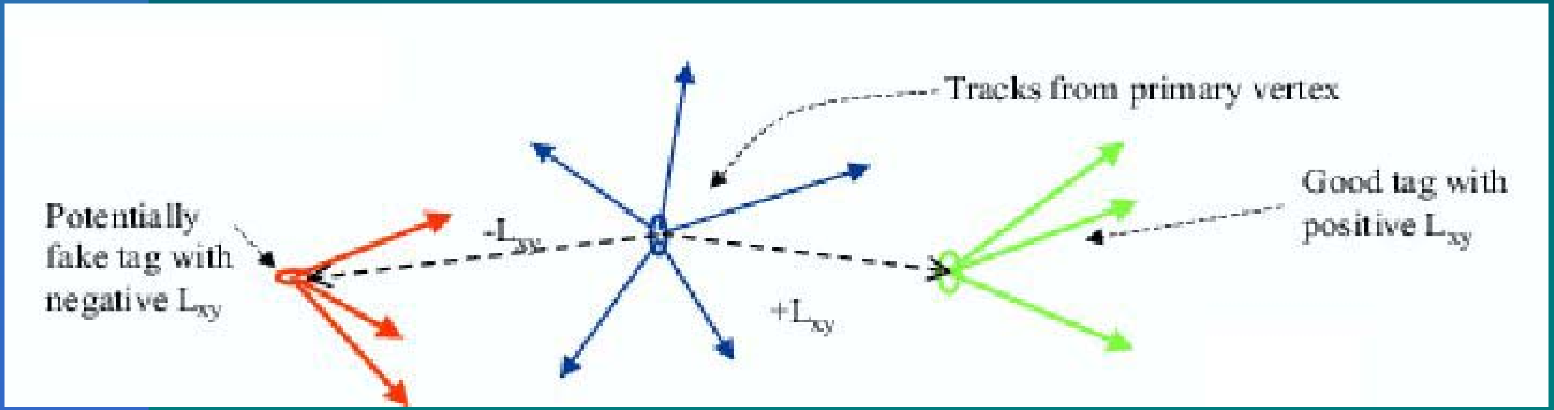




B production from secondary vertex (Monica)

- Search for high-pt secondary verteces inside a jet (midpoint with R<0.7) , if ≥ 2 tracks with large impact parameter



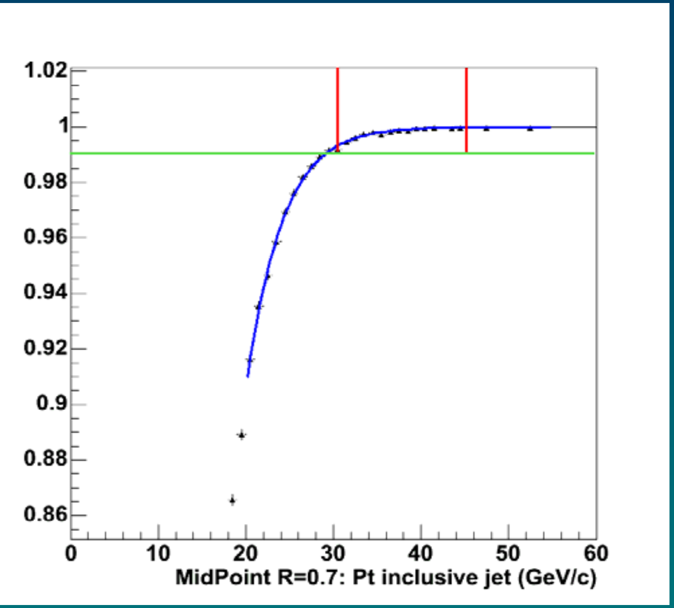


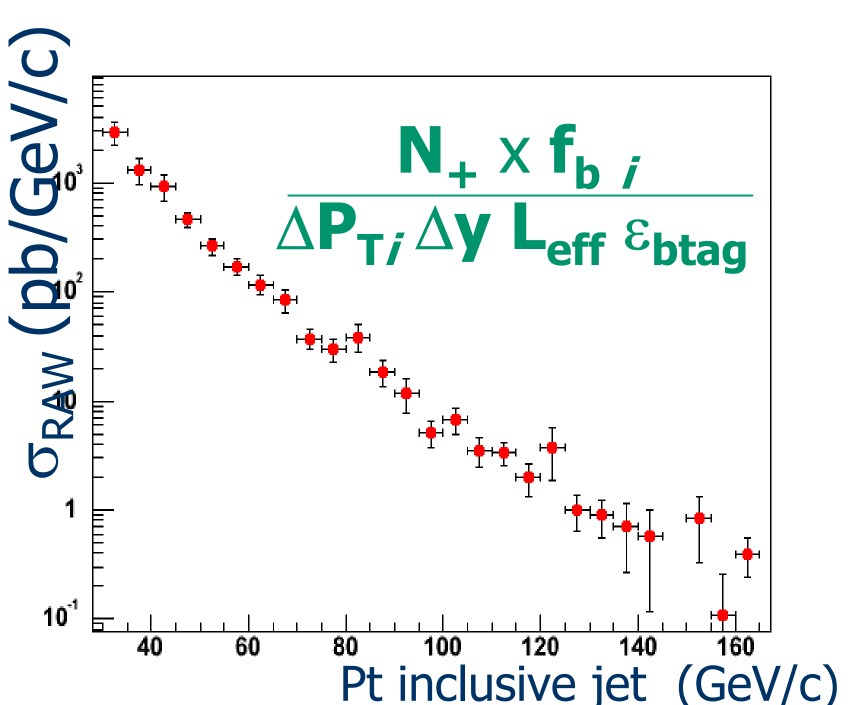
Positive tags for efficiency, negative tags for background estimation

B production: samples and first results

Inclusive sample Datasets:
ST05, Jet20, Jet50, Jet70, Jet100

Each sample used in P_t range where ε>99%

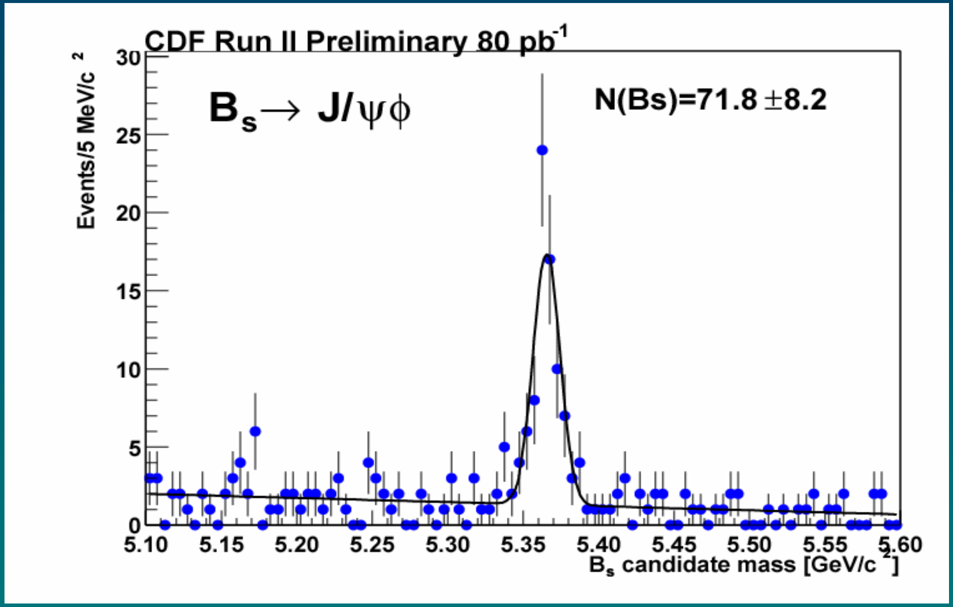




Preliminary cross section using efficiency and b jet fraction from MC

Measuring B masses

- Measure masses using fully reconstructed $B \to J/\psi X$ modes
- High statistics $J/\psi \to \mu^+\mu^-$ and $\psi(2s) \to J/\psi \pi^+\pi^-$ for calibration.
- Systematic uncertainty from tracking momentum scale
  - *Magnetic field*
  - *Material (energy loss)*
- B^+ and B^0 consistent with world average.
- **B_s measurements are world's best.**

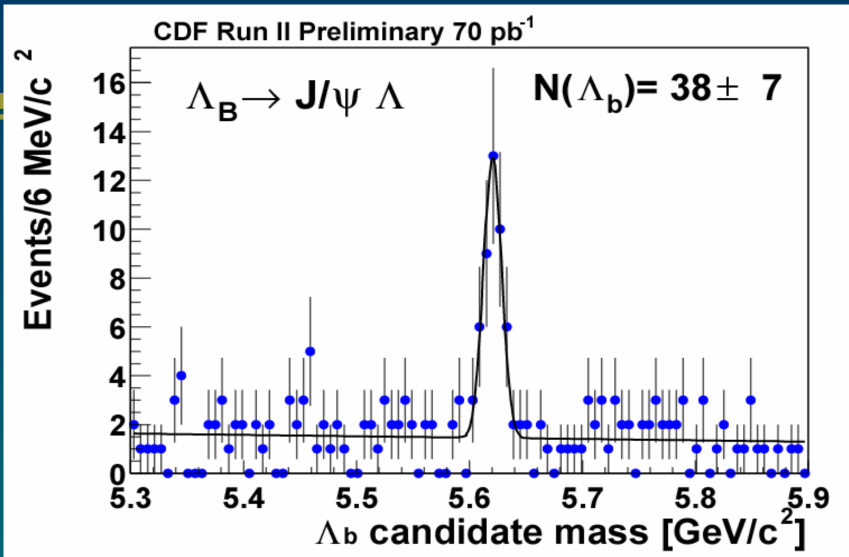


CDF result: $M(B_s)=5365.5 \pm 1.6$ MeV
World average: $M(B_s)=5369.6 \pm 2.4$ MeV

Λ_b and Λ_c

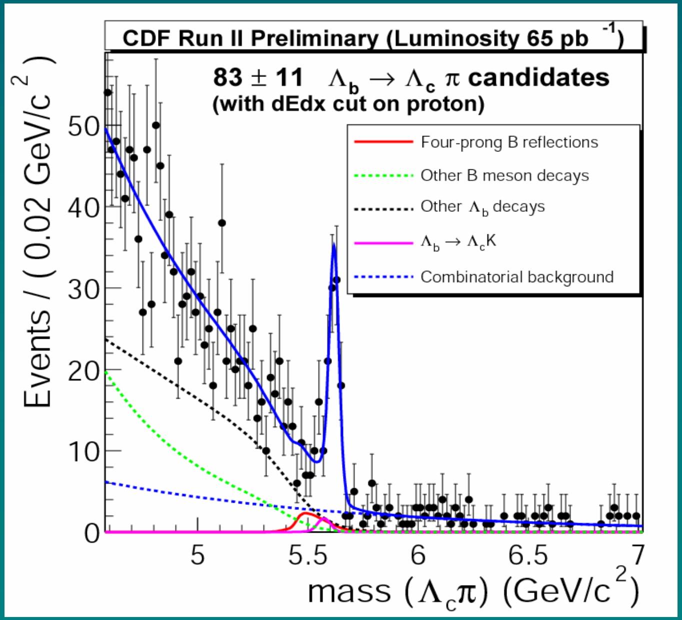
Λ_b mass measured in J/Ψ mode best world measurement

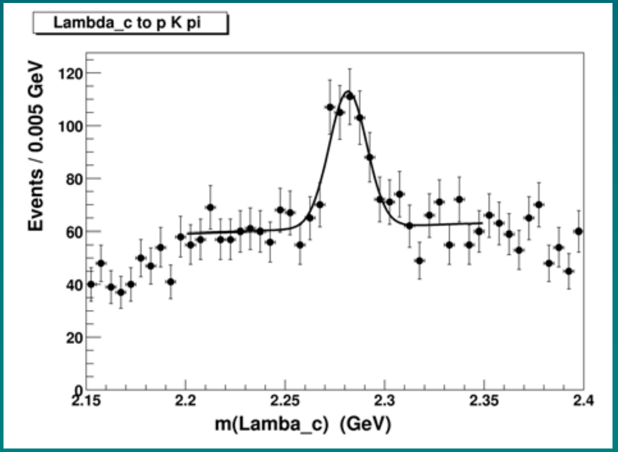
- CDF result: M(Λb)=5620.4 ±2.0 MeV
- World average: M(Λb)=5624.4 ±9.0 MeV



Also seen in $\Lambda_c\pi$ mode, will be used for mass soon

BR($\Lambda_b \rightarrow \Lambda_c \pi^{\pm}$) = (6.0 ±1.0(stat) ± 0.8(sys) ± 2.1(BR)) x 10^{-3}





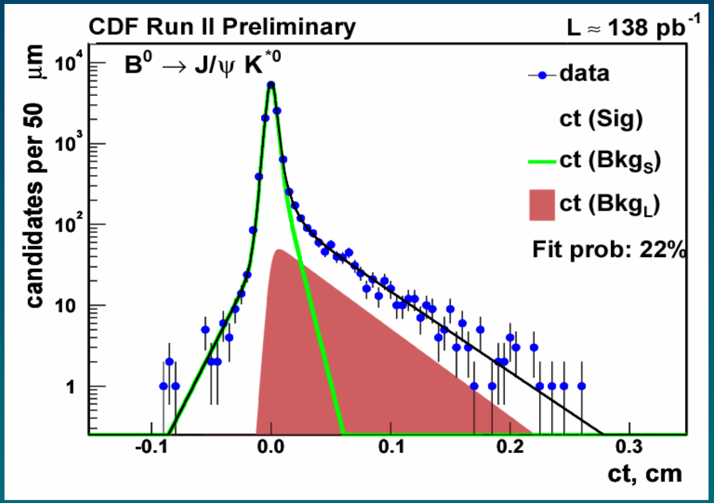
Lifetimes

- Exclusive J/Ψ modes

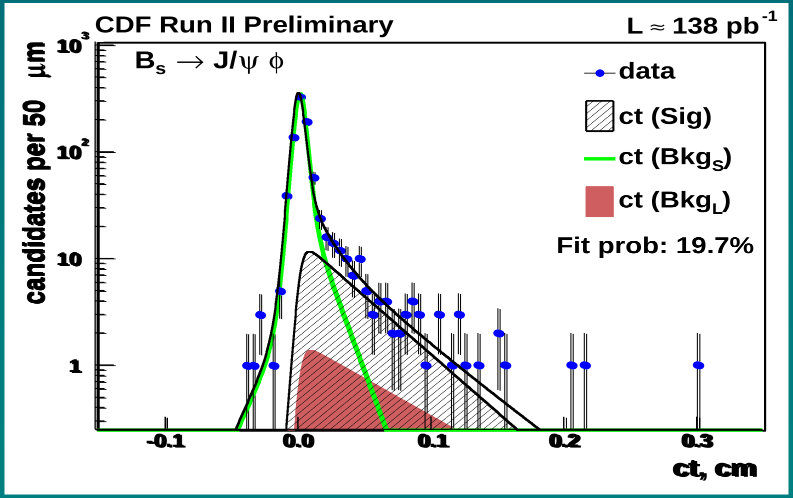
$\tau(B^0)$ **1.63 ± 0.05(*stat.*) ± 0.04 (*syst.*) ps**

$\tau(B^+)$ **1.51 ± 0.06(*stat.*) ± 0.02 (*syst.*) ps**

$\tau(B_s)$ **1.33 ± 0.14(*stat.*) ± 0.02 (*syst.*) ps**



$$ct = \frac{L_{xy}}{\beta\gamma} = \frac{L_{xy} m_B}{p_T}$$

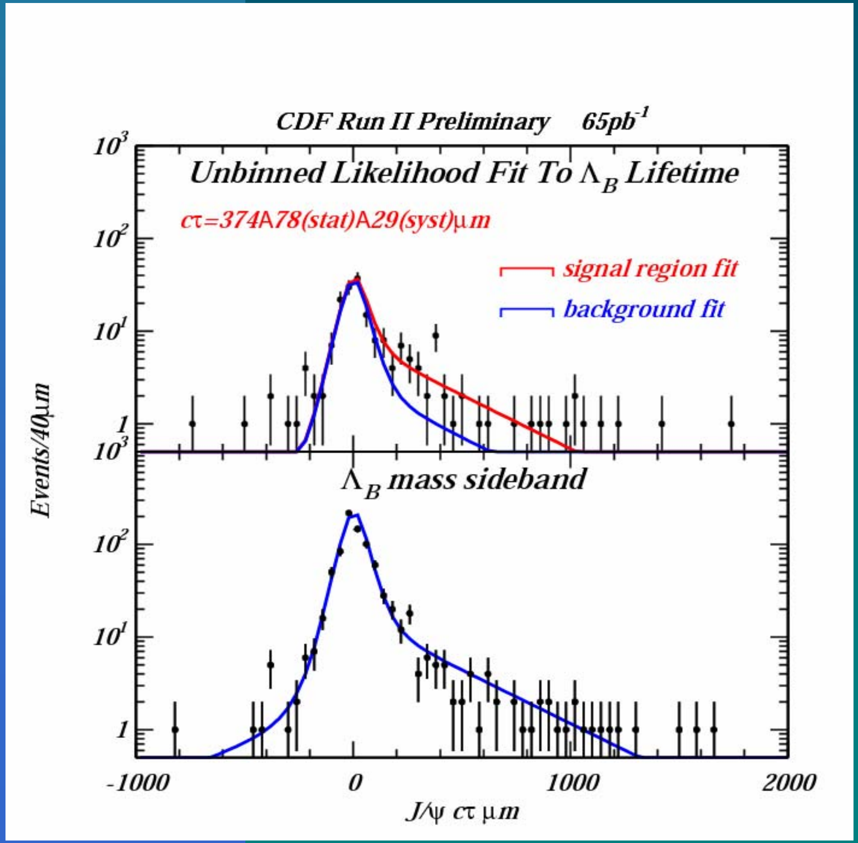


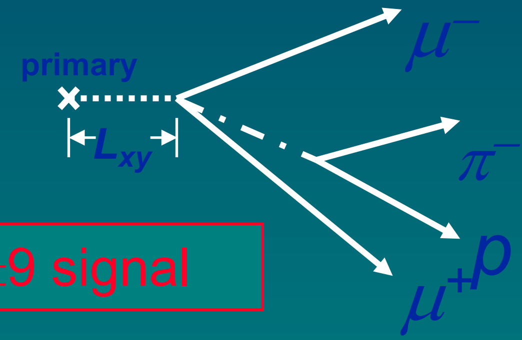
$B_s \to J/\psi\ \Phi$ with $J/\psi \to \mu^+\mu^-$ and $\Phi \to K^+K^-$

$B^+ \to J/\Psi K^+$, $B^0 \to J/\Psi K^{*0}$ check technique, systematics

Λ_b lifetimes

- Use <u>fully reconstructed</u> $\Lambda_b \to J/\psi \Lambda$ $\quad J/\psi \to \mu^+\mu^-$ and $\Lambda \to p\pi^-$
  - Previous LEP/CDF measurements: semileptonic $\Lambda_b \to \Lambda_c l \nu$





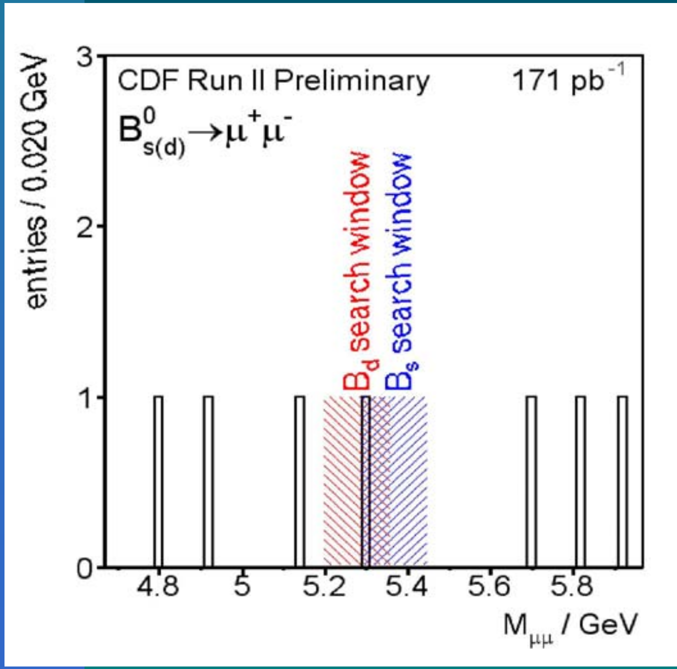
46±9 signal

$$\tau(\Lambda_b) = 1.25 \pm 0.26(stat.) \pm 0.10(syst.)\,\text{ps}$$

First lifetime from fully reconstructed Λ_b decay!

Also for beauty: rare B->μμ decays

- BR(Bs $\rightarrow \mu\mu$) ~ 10^{-9} in SM (SUSY physics two orders of magnitude enhancement)
- Blind analysis optimized for 300-400 pb^{-1} (~ 1 ± 0.3 expected bkg)

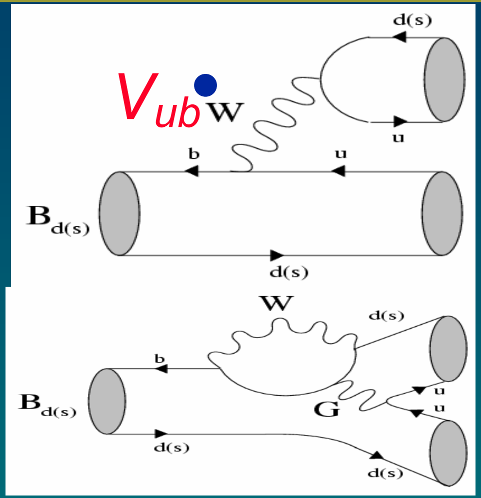


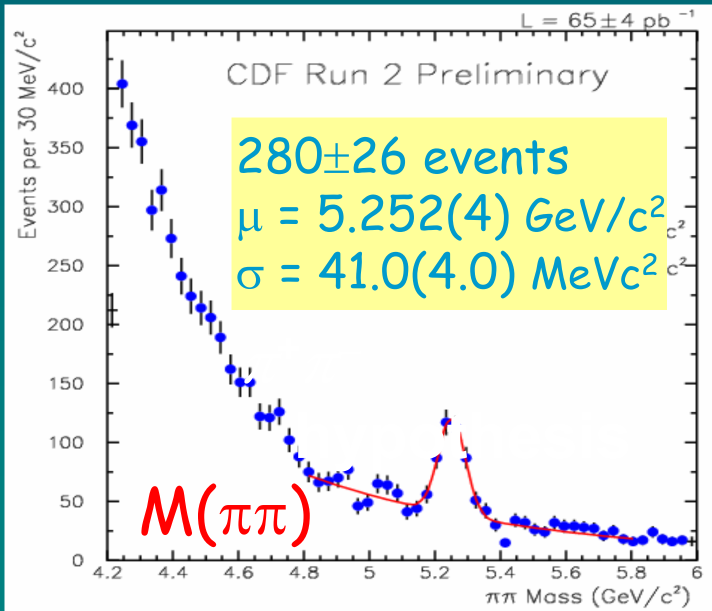
Limits at 90% C.L.
BR(Bs->MuMu) < 5.8 E-7
BR(Bd->MuMu) < 1.5 E-7

- B_s factor 3 better than best published limit (Run I)
- B_d slightly better than Belle's at LP03: 1.6 E^{-7}@90%CL

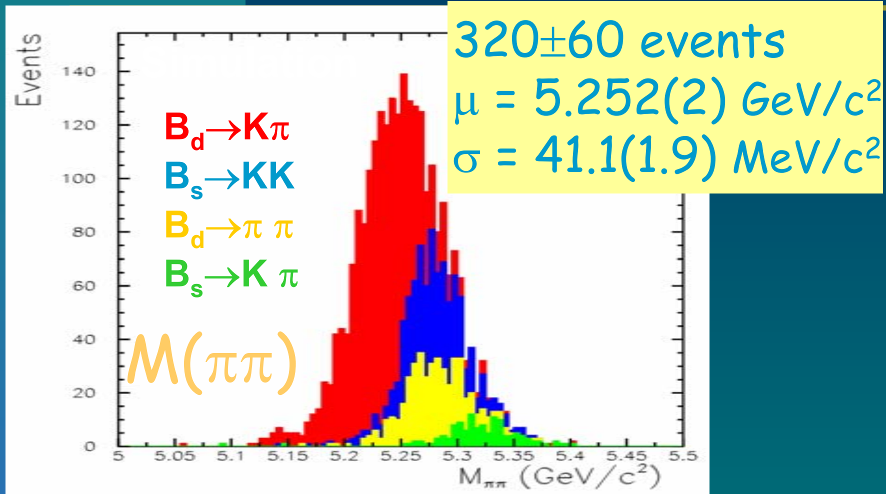
Finding beauty in only two tracks

- charmless two-body decays
  - longer term B_s modes help extract unitarity angle γ
- Signal is a combination of:
  - $B^0 \rightarrow \pi^+\pi^-$ BR~5x10^{-6} } Υ(4s),Tevatron
  - $B^0 \rightarrow K^+\pi^-$ BR~2x10^{-5}
  - $B_s \rightarrow K^+K^-$ BR~5x10^{-5} } Tevatron
  - $B_s \rightarrow \pi^+K^-$ BR~1x10^{-5}
- Requirements
  - Displaced track trigger
  - Good mass resolution
  - Particle ID (*dE/dx*)



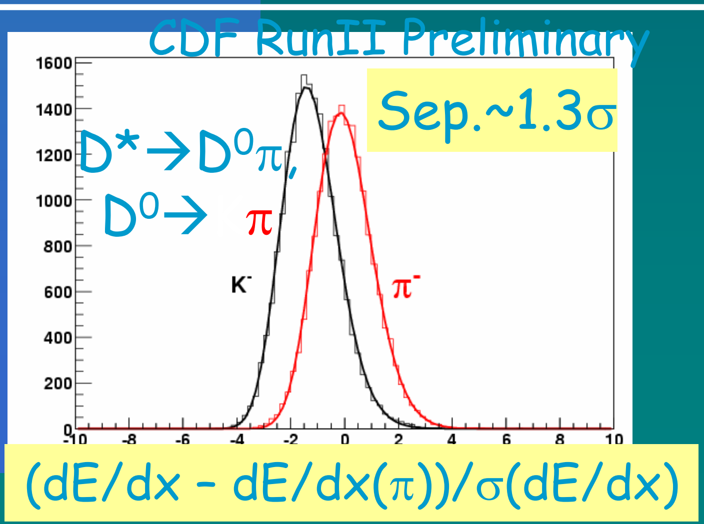


Composition of the B->hh peak



mode	Yield (65 pb^{-1})
$B^0 \to K\pi$	148±17(stat.)±17(syst)
$B^0 \to \pi\pi$	39±14(stat.)±17(syst)
$B_s \to KK$	90±17(stat.) ±17(syst)
$B_s \to K\pi$	3±11(stat.) ±17(syst)

kinematics & *dE/dx* to separate contributions



First observation of $B_s \to K^+K^-$!!

Result:
$$\frac{f_s BR(B_s \to KK)}{f_d BR(B^0 \to K\pi)} = 0.74 \pm 0.20 \pm 0.22$$

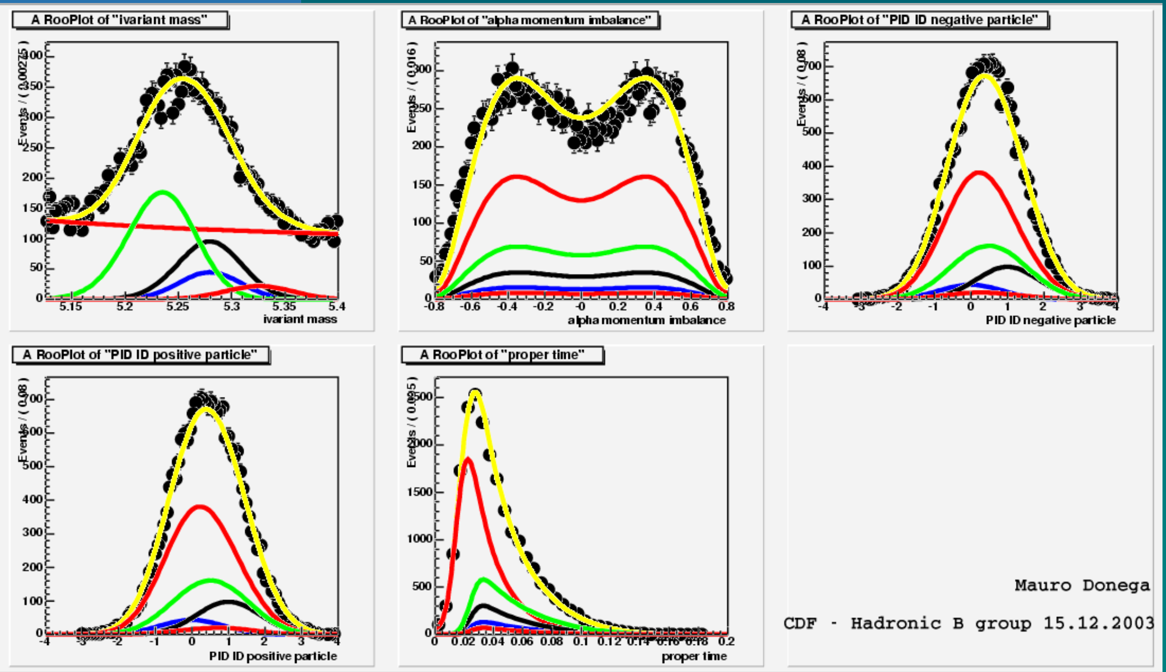
Measure A_{CP}

$$\frac{N(\overline{B}\to K^-\pi^+) - N(B\to K^+\pi^-)}{N(\overline{B}\to K^-\pi^+) + N(B\to K^+\pi^-)} = 0.02 \pm 0.15 \pm 0.02$$

More involved: using B->hh for $\Delta\Gamma_s$ (Mauro)

- $\Delta\Gamma_s/\Delta m_s = -3\pi/2\, m_b^2/m_t^2 \eta(\Delta\Gamma_s)/\eta(\Delta m_s)$
- SM: $\Delta\Gamma_s/\Delta m_s = 3.7^{+0.8}_{-1.5}\ 10^{-3}$
- LQCD: $\Delta\Gamma_s/\Gamma_s = 0.12 \pm 0.06$
- Present 95% C.L. limit: $\Delta\Gamma_s/\Gamma_s < 0.54$

CKM-independent QCD factors



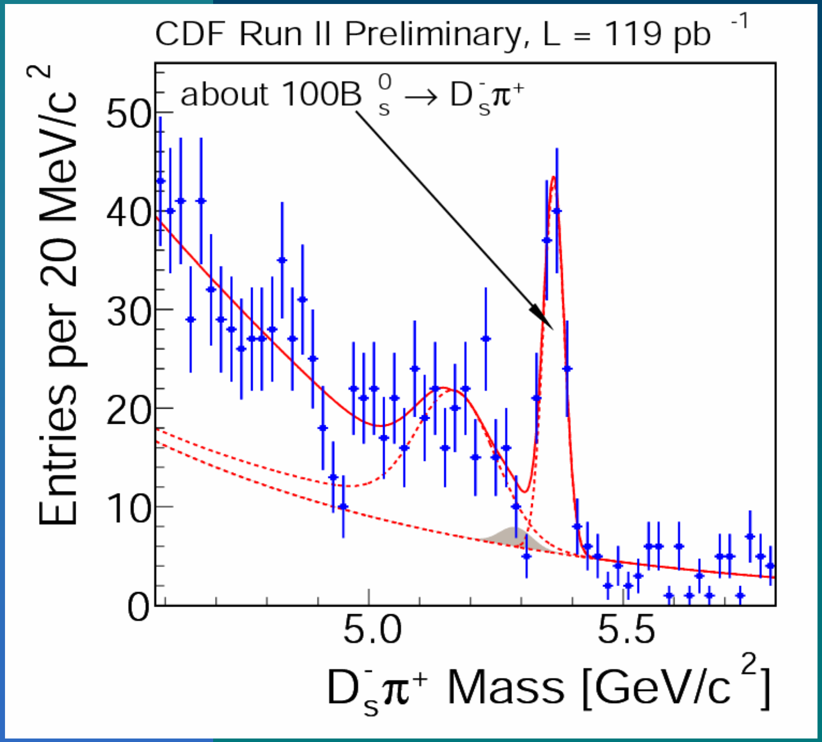
Disentangle on a statistical basis contributions to the B->hh peak, then fit lifetimes for the different charges

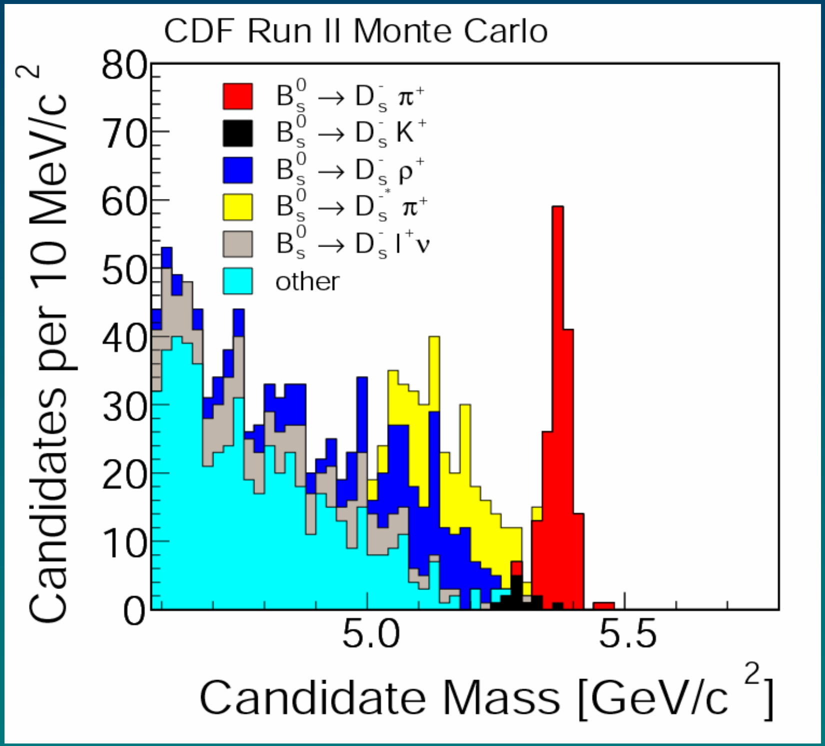
Expected sensitivity:

•0.29 at 500 pb^{-1}

•0.10 at 2 fb^{-1}

Bs: signal reconstruction in Ds π





$$BR(B_s \rightarrow D_s \pi^{\pm}) = (4.8 \pm 1.2 \pm 1.8 \pm 0.8 \pm 0.6) \times 10^{-3}$$

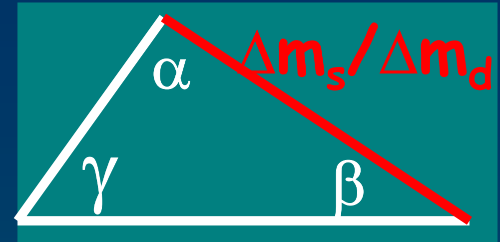
(Stat) *(BR)* *(sys)* *(f_s/f_d)*

New measurement !

Previous limit set by OPAL: BR ($B_s \rightarrow D_s \pi^{\pm}$) < 13%

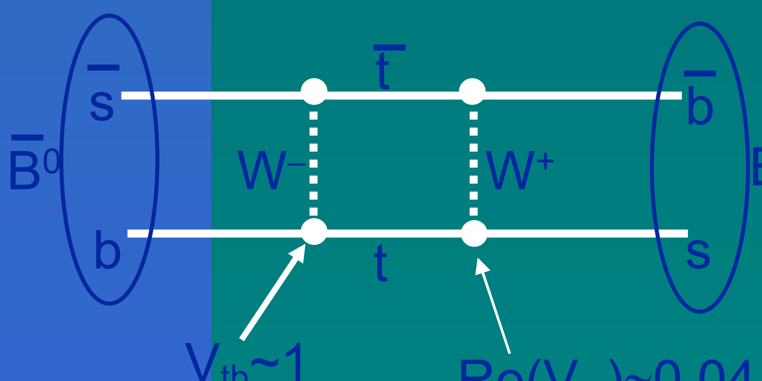
BR result uses less data than shown in plot.

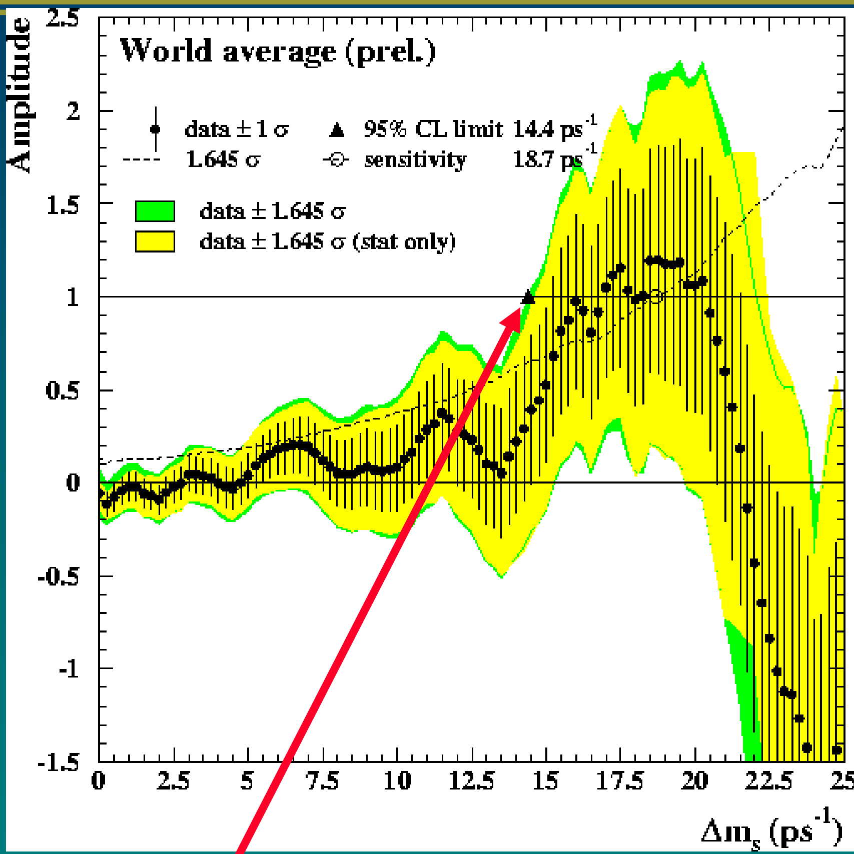
Towards B_s Mixing



- **Measurement of Δm_s helps improve our knowledge of CKM triangle.**
- Combined world limit on B_s mixing
  - $\Delta m_s > 14.4 ps^{-1}$ @95%CL
  - **B_s fully mixes in <0.15 τ**
- B_s oscillation much faster than B_d because of coupling to top quark:

$Re(V_{ts}) \approx 0.040 > Re(V_{td}) \approx 0.007$



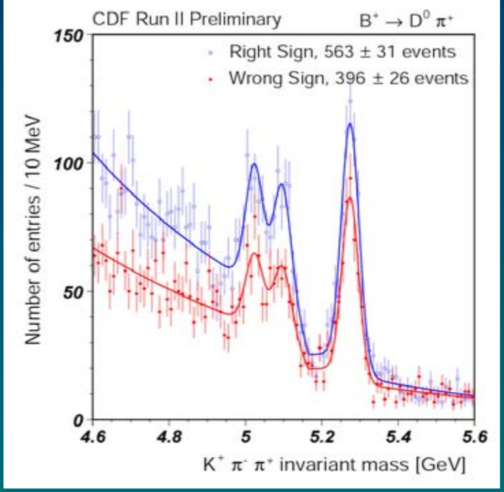


Combined limit comes from 13 measurements from LEP, SLD & CDF Run I

Ingredients for Bs mixing

- **B_s reconstruction (Bs->D_s π)**
- **Flavor tagging (B_s or B_s at time of production?)**
  - Tagging "dilution": D=1-2w
  - Power proportional to: εD^2

Typical power (one tag):
εD^2 = O(1%) at Tevatron
εD^2 = O(10%) at PEPII/KEKB



Results:
- Same-side (B^+) εD^2=(2.1±0.7)%
  (B^+/ B^0/ B_s correlations different)
- Muon tagging εD^2=(0.7±0.1)%

- **Proper decay time**

$$ct = \frac{L_{xy}}{(\beta\gamma)} = \frac{L_{xy} m_B}{p_T}$$

uncertainty →

$$\sigma_{ct} = \frac{m_B}{p_T}\sigma_{L_{xy}} \oplus ct\left(\frac{\sigma_{p_T}}{p_T}\right)$$

  - Crucial for fast oscillations (i.e. B_s)

Bs: expected sensitivities

- Current performance:
  - S=1600 events/fb^{-1} (*i.e.* $\sigma_{effective}$ for produce+trigger+recon)
  - S/B = 2/1
  - εD^2 = 4%
  - σ_t = 67fs

2σ sensitivity for Δm_s=15ps^{-1} with ~0.5fb^{-1} of data

surpass the current world average

- With "modest" improvements
  - S=2000 fb (improve trigger, reconstruct more modes)
  - S/B = 2/1 (unchanged)
  - εD^2 = 5% (kaon tagging)
  - σ_t = 50fs (event-by-event vertex + L00)

5σ sensitivity for Δm_s=18ps^{-1} with ~1.7fb^{-1} of data (2005?)
5σ sensitivity for Δm_s=24ps^{-1} with ~3.2fb^{-1} of data (2007?)

Δm_s=24ps^{-1} "covers" the expected region based upon indirect fits.

Final remarks

- CDF has a huge program in charm and beauty physics- I just scratched the surface
- despite non-dedicated, it plays a major role in the field
- best for light (charm->largest sample in the world) and heavy (B_s, Λ) states
- B_s oscillations will be seen in Run II (unless something really strange over there)
- Most of this success is due to the craziness of few people who believed more than 10 years ago to the possibility of reconstructing on-line tracks at trigger level… any idea for the LHC?