Towards B_s oscillations at CDF

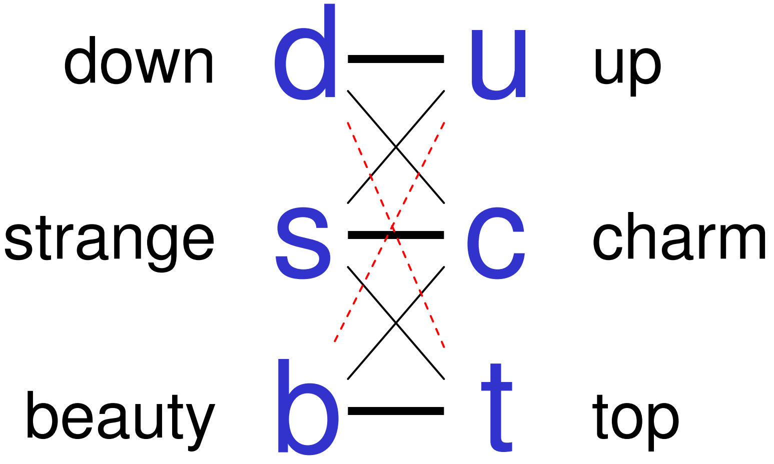
Rudolf Oldeman

University of Liverpool

The B_s particle

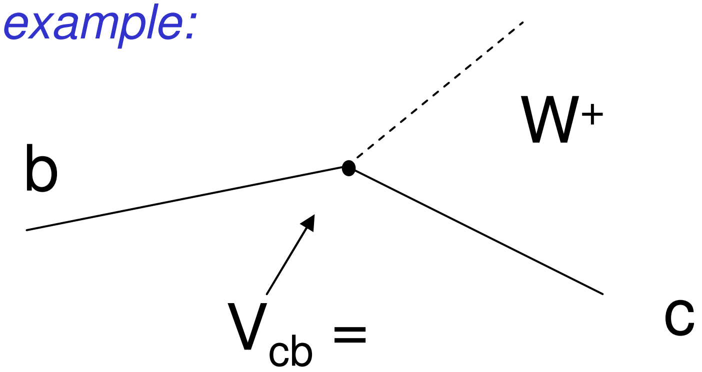
B_s: $\bar{b}\ s$ $\bar{B}_s$: $b\ \bar{s}$

Quarks can transform
into each other via the $W^\pm$ boson



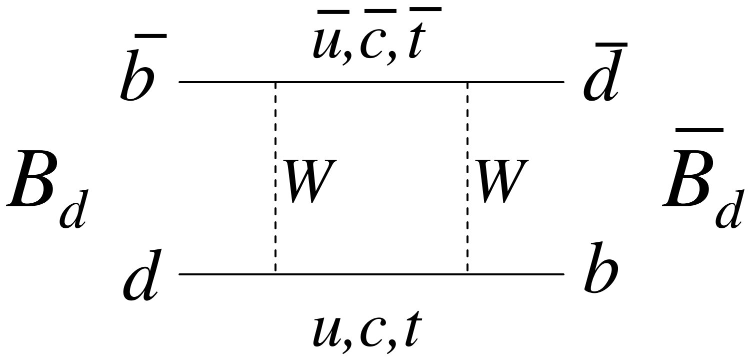
charge: -1/3 2/3

For example:



V_{cb} =
Coupling strength from
b-quark to c-quark

B_d and B_s oscillations



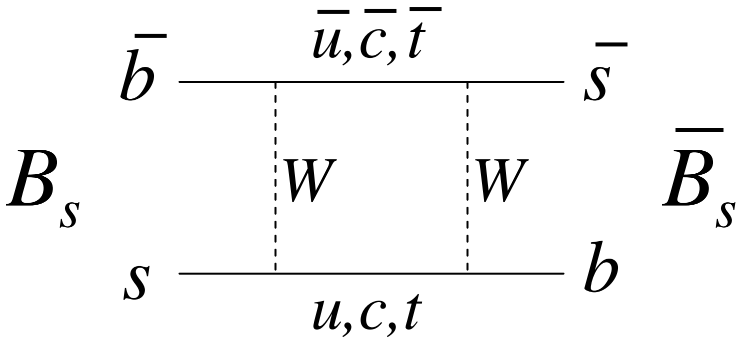
B_d mixing $\propto V_{td}^2$

$\Rightarrow$slow:

Δm_d=0.502±0.007ps^{-1}

$\Rightarrow$large mixing phase:

sin2β=0.736±0.049



B_s mixing $\propto V_{ts}^2$

$\Rightarrow$fast:

$\Delta m_s \approx$18ps^{-1}?

$\Rightarrow$small mixing phase:

sin2$\beta_s \approx$0.02?

Δm_s in the Standard Model

top-W loop factor
2.463

NLO QCD
J_5=1.627

$$\Delta m_s^{SM} = \frac{G_F^2}{12\pi^2} M_W^2 m_{B_s} f_{B_s}^2 (V_{tb}V_{ts}^*)^2 \eta_{2B} S_0\left(\frac{m_t}{M_W}\right) \alpha_s^{-6/23}\left[1+\frac{\alpha_s(m_b)}{4\pi}J_5\right]B^{LL}(m_b)$$

decay constant
lattice QCD
f_{Bs}=230±30 MeV

NLO QCD
η_{2B}=0.551

Bag parameter
lattice QCD
$B^{LL}(m_b)$=0.872±0.005

Δm_s in the Standard Model

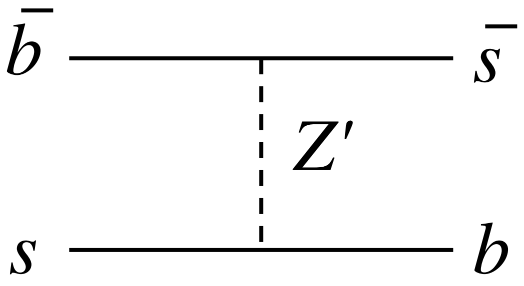
easier to express as a ratio with Δm_d

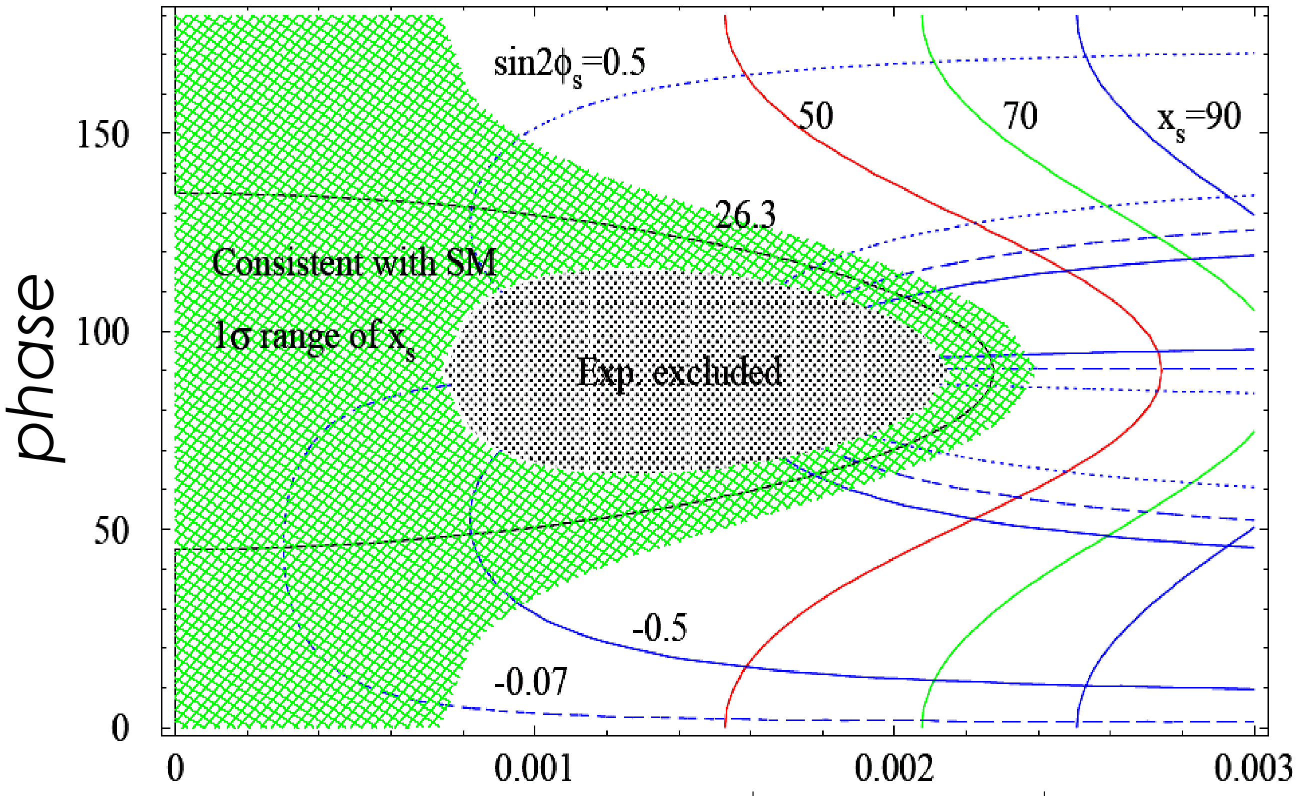
$$\frac{\Delta m_s}{\Delta m_d} = \xi \frac{m_{B_s}}{m_{B_d}} \frac{|V_{ts}|^2}{|V_{td}|^2} \quad \text{with} \quad \xi = \frac{f_{B_s}\sqrt{\hat{B}_{B_s}}}{f_{B_d}\sqrt{\hat{B}_{B_d}}} = 1.24 \pm 0.07$$

we find $\Delta m_s = 18.0 \pm 3.7\,\mathrm{ps}^{-1}$ *(or $x_s = \Delta m_s / \Gamma_s = 26.3 \pm 5.5$)*

New physics in B_s oscillations

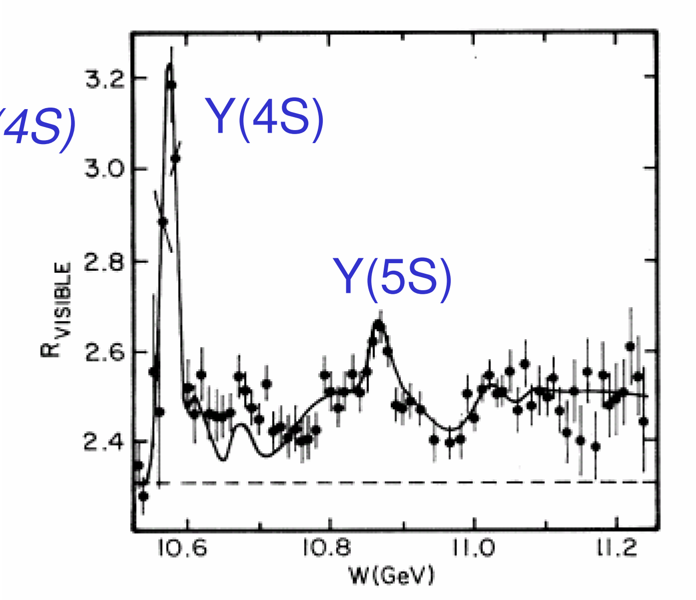
- Heavy Z' with FCNC.





$$\text{magnitude} \propto \left| \frac{m_Z}{m_{Z'}} B_{sb}^{LL} \right|$$

Producing heavy B hadrons



$\Upsilon(4S)$: B^+ / B^0 only

B_s at $\Upsilon(5S)$: $\approx$ 10x smaller cross-section than B_d at $\Upsilon(4S)$

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

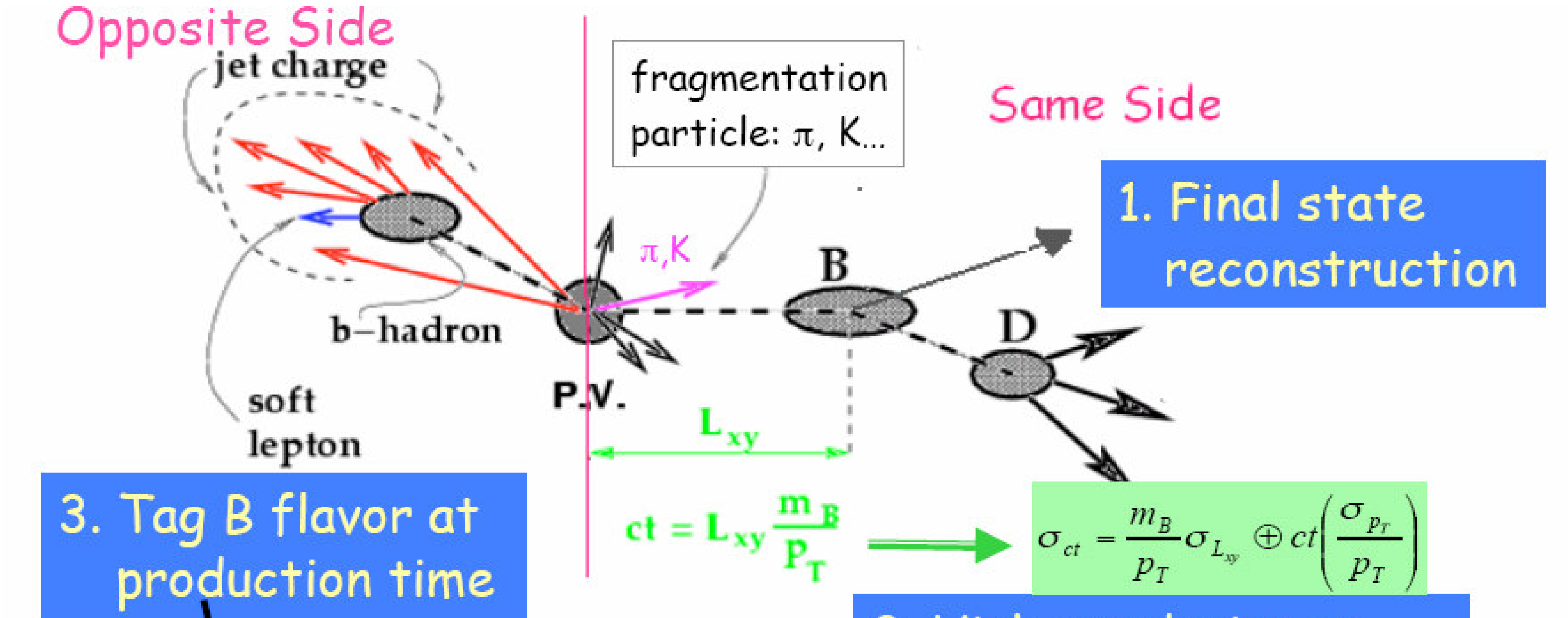
➡ Fixed target $E_{cm} > 2m(B_s)$
- Tried unsuccessfully at HERA-B *$\sigma(b\bar{b})/\sigma(\text{total}) \approx 10^{-6}$*

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

Production ratio at high energy:

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

Observing B_s oscillations



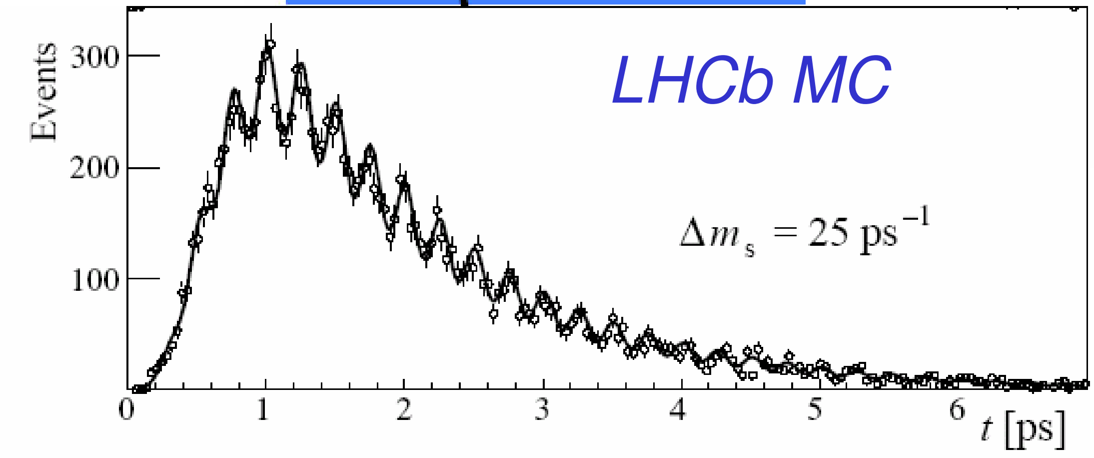
1. Final state reconstruction

$$ct = L_{xy}\frac{m_B}{P_T}$$

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

2. High resolution on proper decay length

3. Tag B flavor at production time

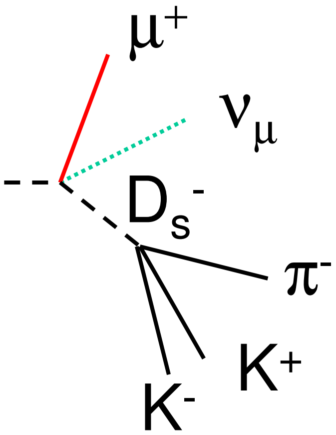


several full oscillations in 1 lifetime

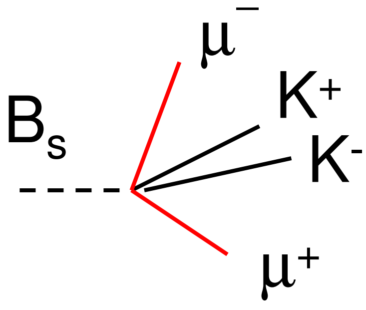
Reconstructing B-decays

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

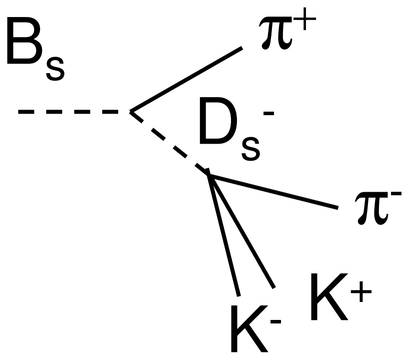
- Semi-leptonic B decays
  - Pro: large branching ratios → large yields
  - Con: missing neutrino



- B decays to J/ψ
  - Pro:muon provides easy trigger
  - Con: same for B_s and $\overline{B}_s$

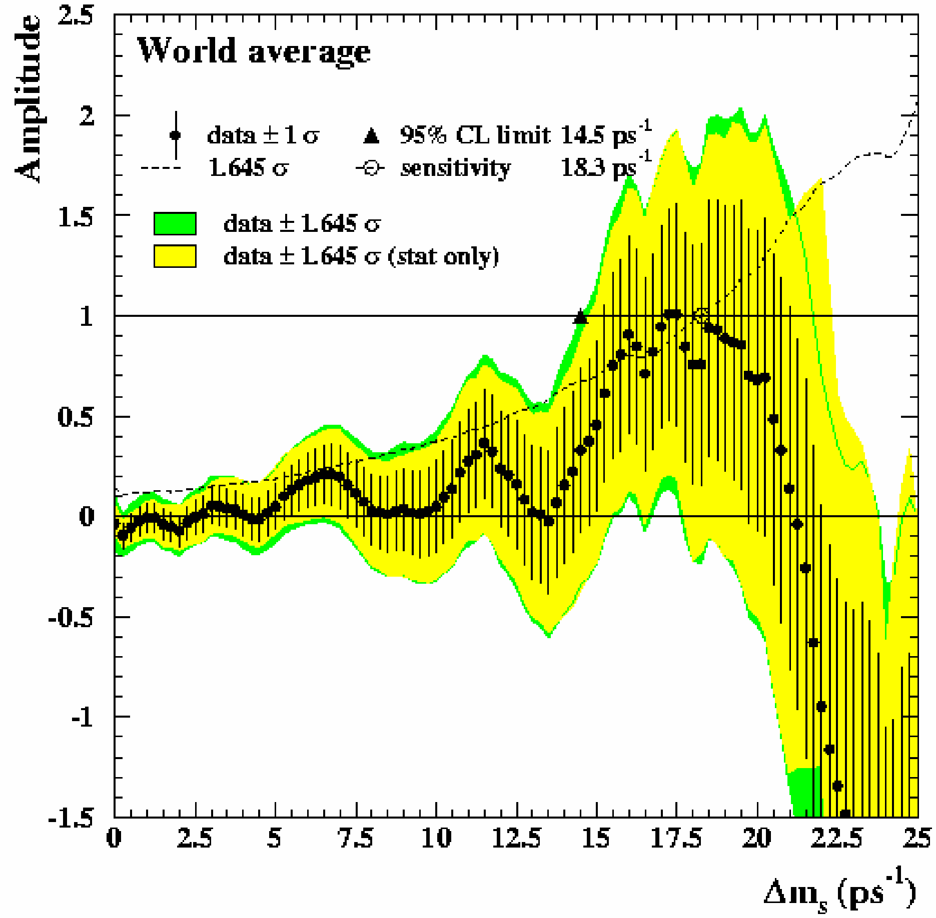


- Fully hadronic B decays
  - Pro: fully reco. & flavour eigenstate
  - Con: requires silicon track trigger



Current status of B_s mixing

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



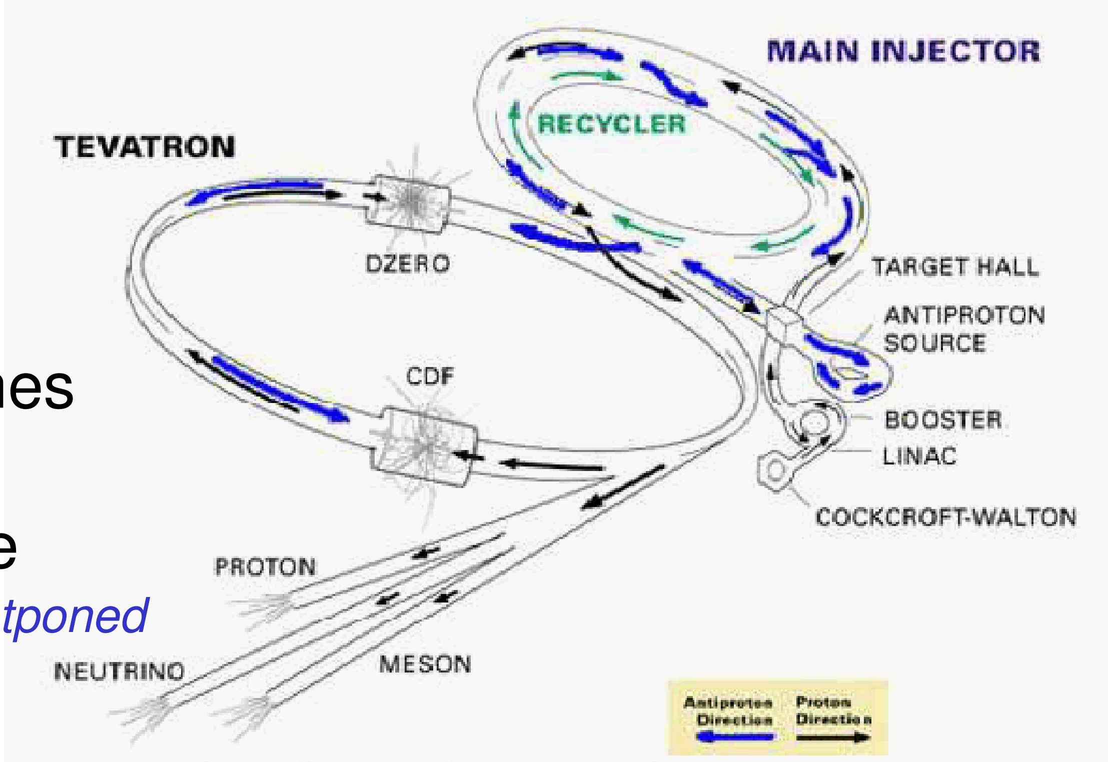
Most analyses used partially reconstructed decays

Poor sensitivity at high Δ m_s

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

⇒ for Δ m_s > 15ps^{-1}
σ(ct) above 70fs hurts!

$p\bar{p}$ collisions at the Tevatron



980+980GeV collisions

36 p bunches x 36 $\bar{p}$ bunches

396 ns bunch crossing time

132 ns upgrade indefinitely postponed

At present luminosities ≈3 interaction/bunch crossing

Anticipate up to 10 in future

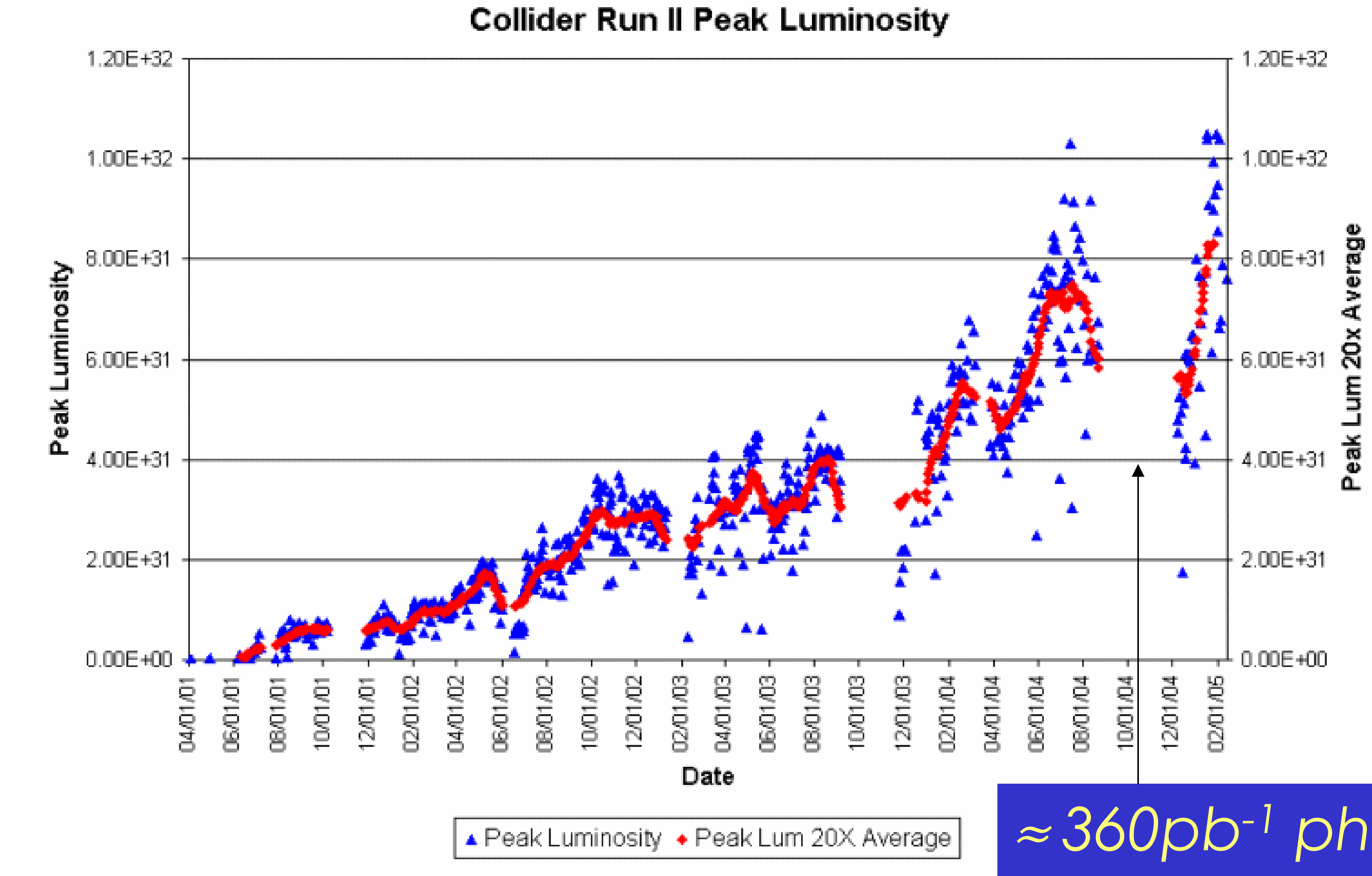
Interaction region: ≈ 30 cm long

Need a long silicon detector

≈ 30 µm transverse size

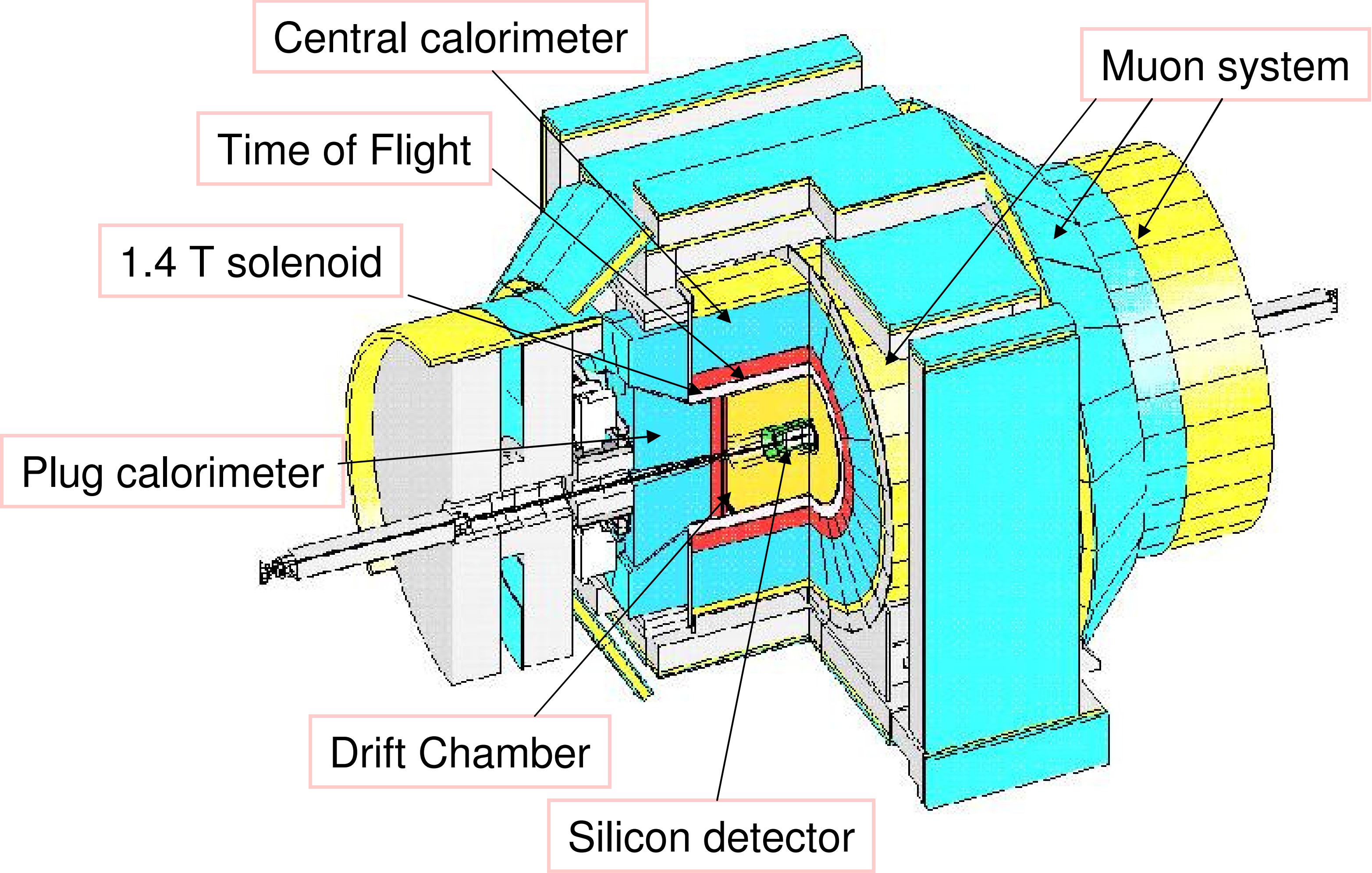
Small compared to ct(B) ≈ 450 µm

Tevatron performance



$\approx 360 pb^{-1}$ physics quality data

The CDFII detector



The Central Outer Tracker (COT)

30k read out wires
96 layers

4 axial superlayers (12 wires)
4 stereo superlayers (±35 mrad)
Inside 1.4 Tesla solenoid

1.4 meter outer radius

200 μm single wire resolution

$$\frac{\Delta p_T}{p_T} = (0.7 \oplus 0.1 \cdot p_T)\%$$

dE/dx for e/π/K/p separation
1.2σ π/K for p_T>2 GeV

The CDF silicon system

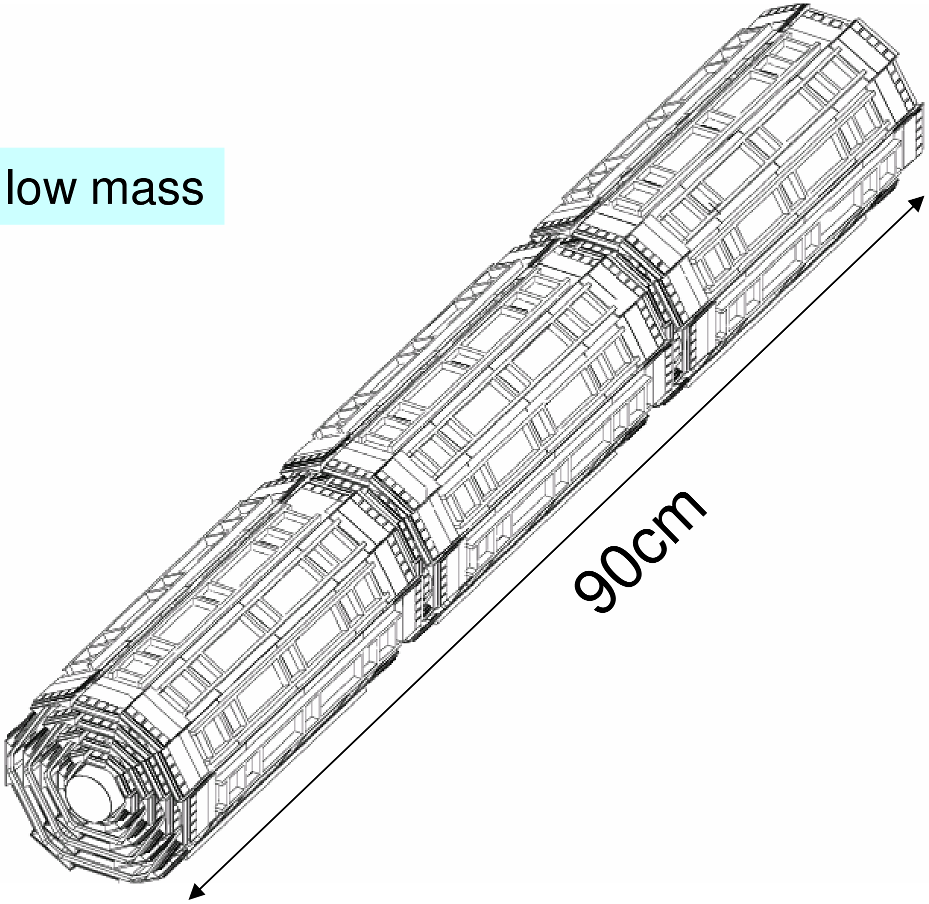
Layer00: 2 cm from the beam-pipe

Single-sided, radiation-hard, low mass

SVXII 5 layers, double sided

ISL 1.5 layer, double sided

750k channels



Impact parameter resolution:13+40/p_T μm

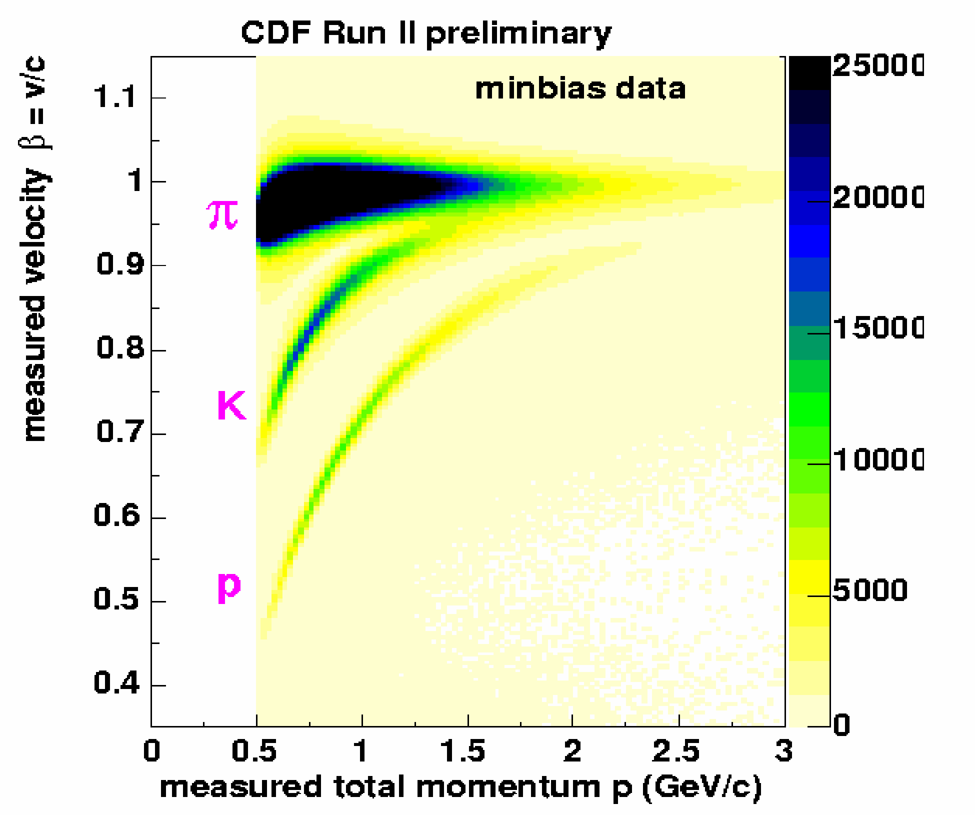
Uses SVXIII chip:
simultaneous readout & recording

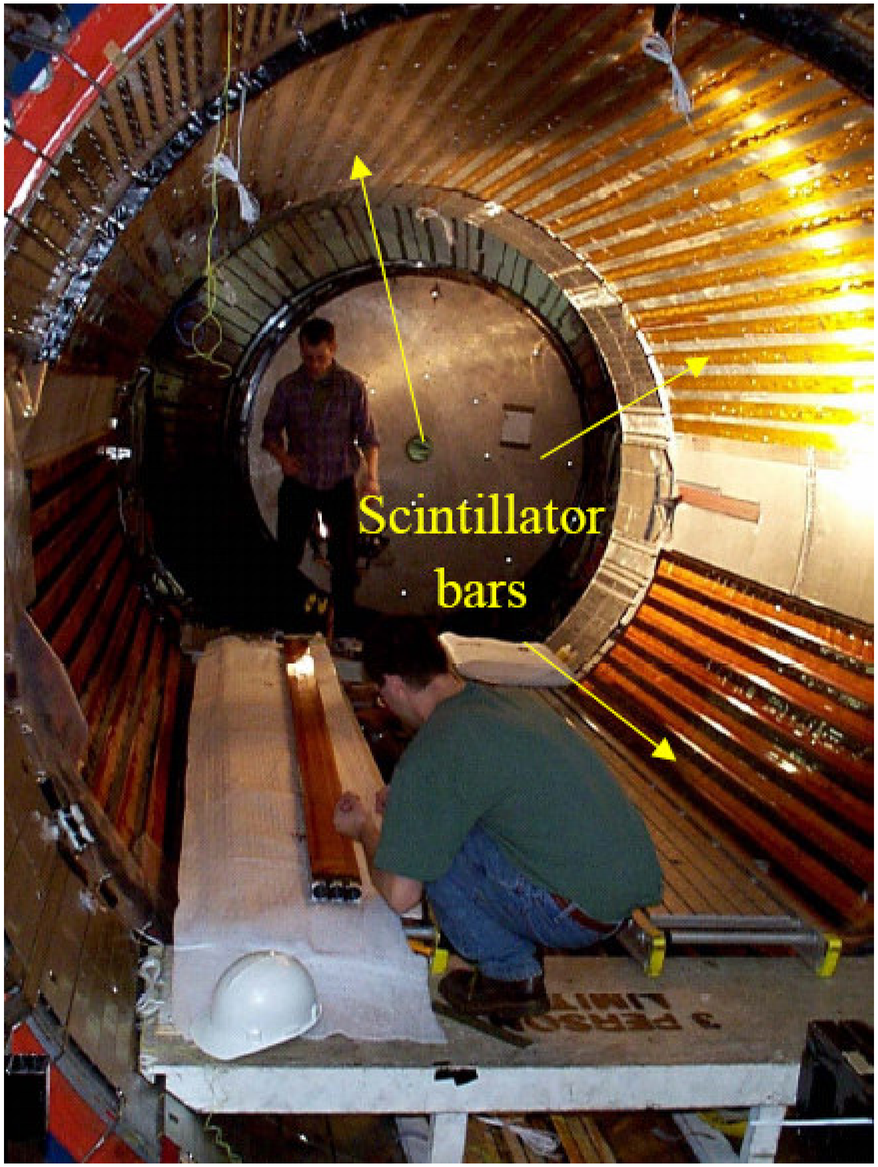
The Time-of-Flight detector (TOF)

4x4 cm scintillator bars, 3 m long (216)

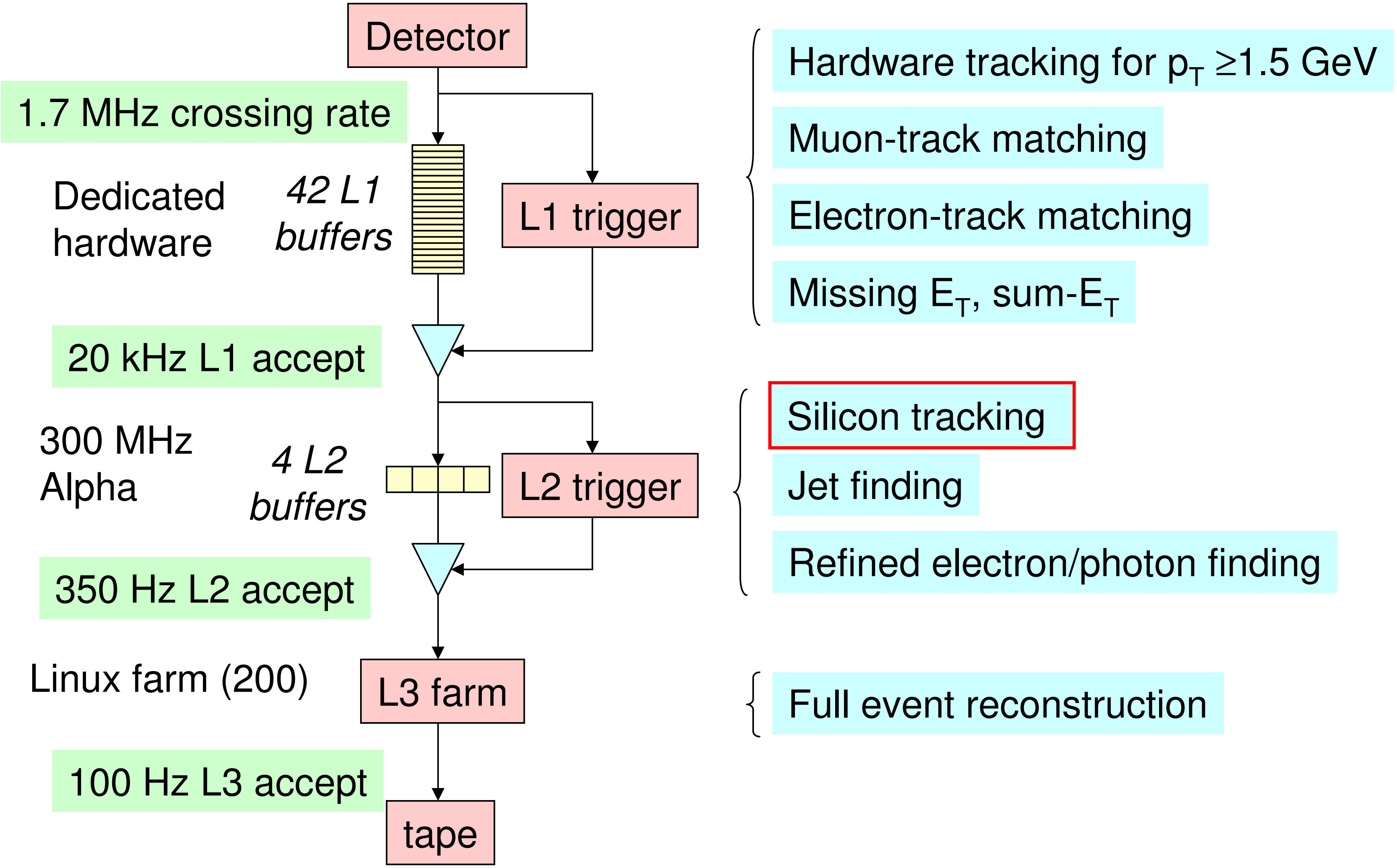
100 ps timing resolution
2σ π /K separation for $p_T \leq 1.6$GeV

Readout on both sides of the bar





The three-level trigger



Detector

1.7 MHz crossing rate

Dedicated hardware

42 L1 buffers

L1 trigger

20 kHz L1 accept

300 MHz Alpha

4 L2 buffers

L2 trigger

350 Hz L2 accept

Linux farm (200)

L3 farm

100 Hz L3 accept

tape

- Hardware tracking for $p_T \geq 1.5$ GeV
- Muon-track matching
- Electron-track matching
- Missing E_T, sum-E_T

- Silicon tracking
- Jet finding
- Refined electron/photon finding

- Full event reconstruction

The eXtremely Fast Tracker (XFT)

Provides a list of tracks p_T>1.5GeV
Every (132ns) clock cycle

Finds segments in 4 axial SL

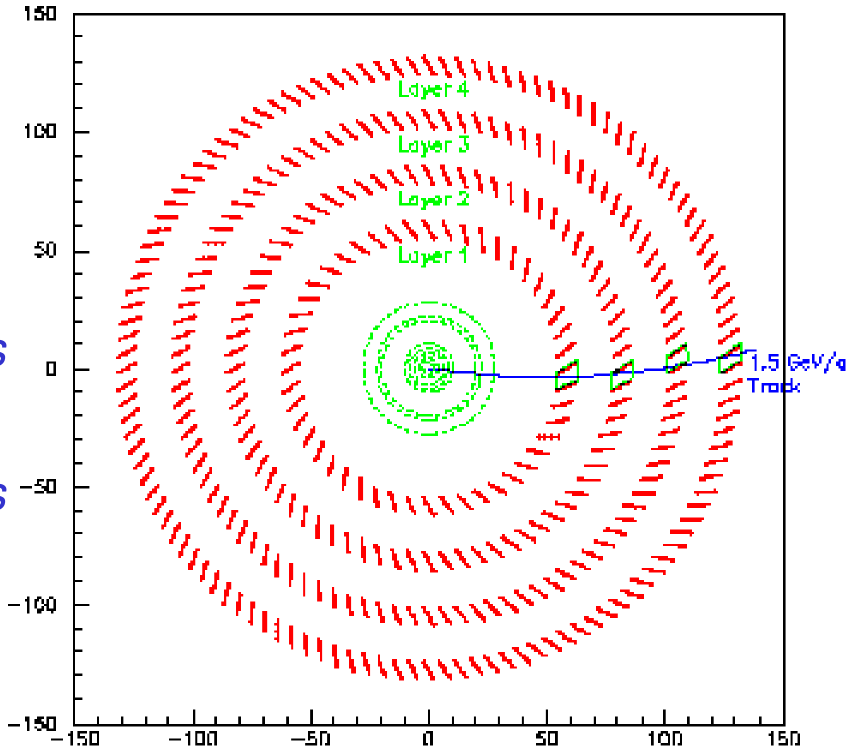
Compare to pre-programmed patterns

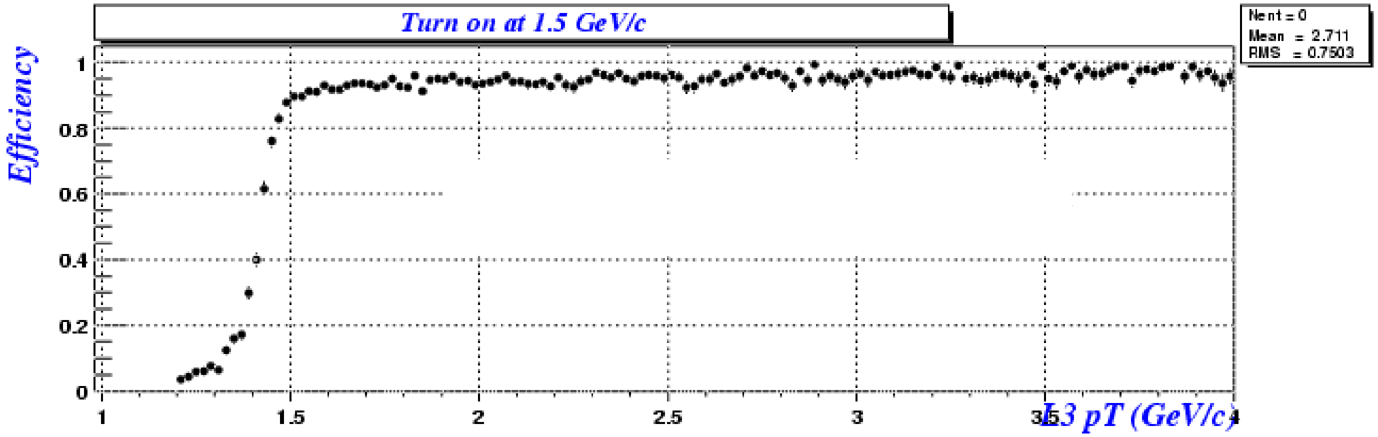
Links segments to tracks

Compare to pre-programmed patterns

Efficiency >95% for p_T>2GeV

No stereo tracking





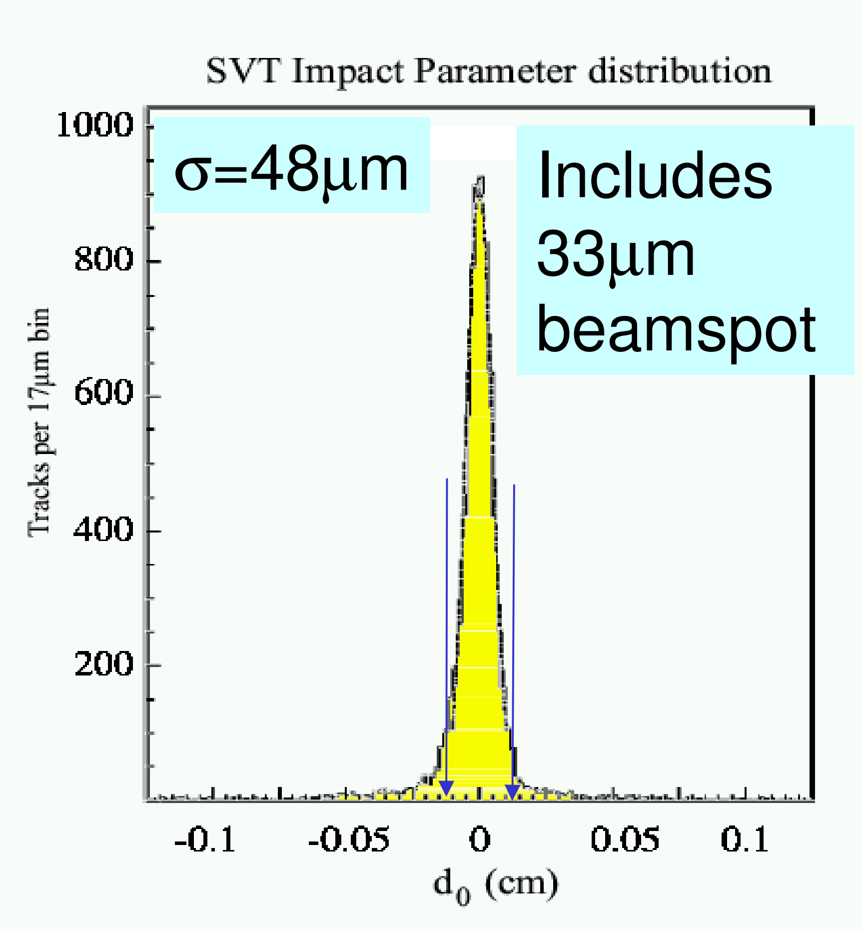
Triggering on displaced tracks

Read out Silicon detector
& Reconstruct tracks at 10’s of kHz!

Silicon Vertex Tracker (SVT)

Trigger on 2 displaced tracks
($|d_0| \geq 120\mu m$, $p_T \geq 2GeV$)

Trigger rejection >500



σ=48μm

Includes 33μm beamspot

SVT makes hadronic B_s decays possible at CDF

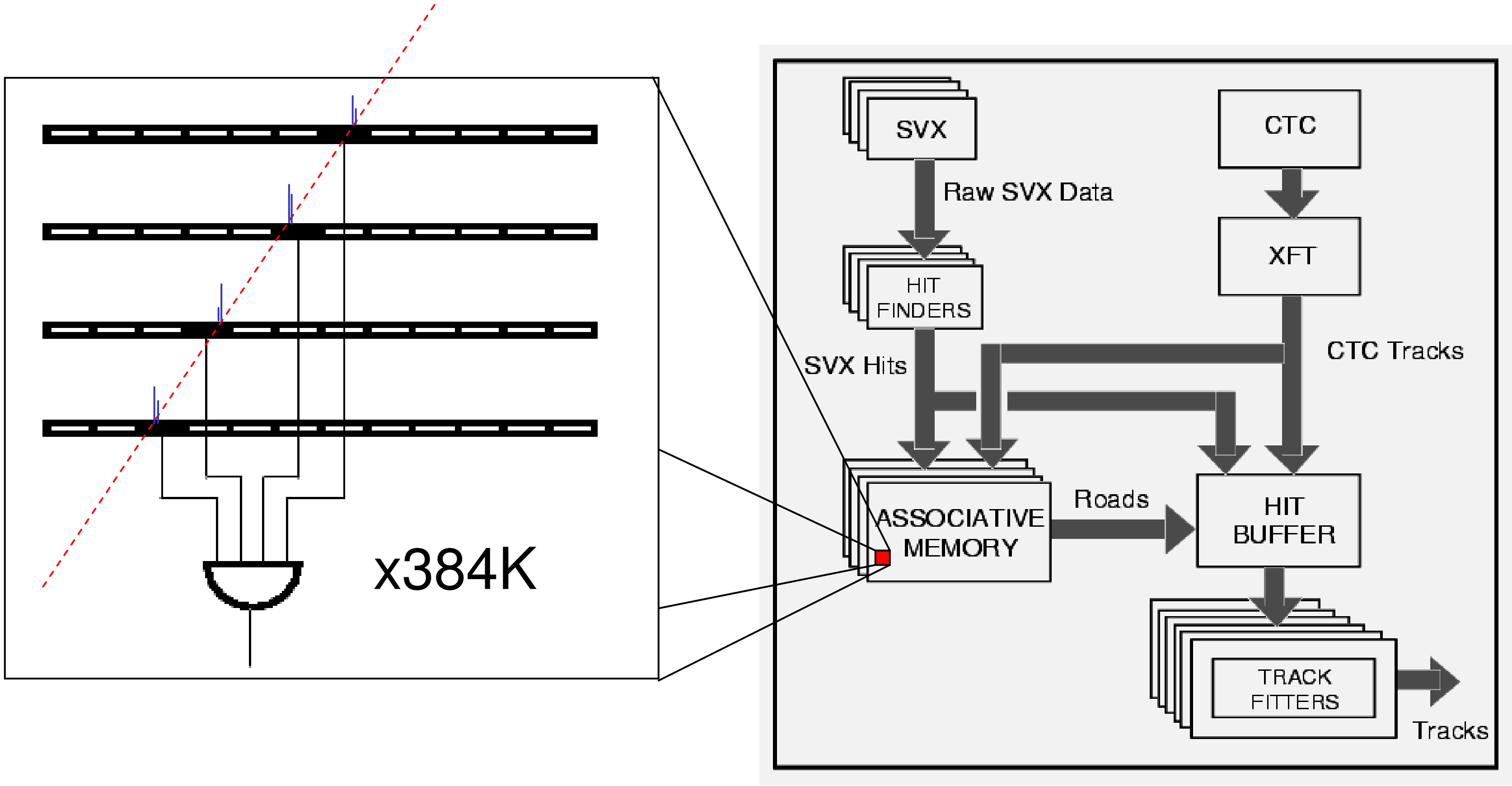
SVT working principle

Step 1

Low-resolution hits fire one of 384K pre-programmed patterns

Step 2

Fit track to high-resolution hits corresponding to fired pattern



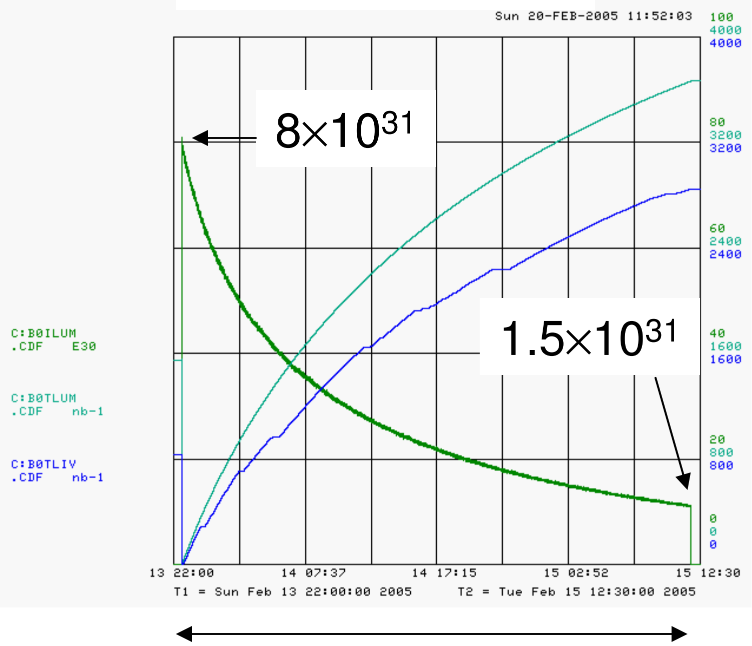
Dynamic prescaling (DPS)

Trigger is designed for peak luminosity

Average luminosity ≈ 50% of peak

Fill the available L1 bandwidth with B physics!

Typical store:



37hours

3 versions of the two-track trigger

High-p_T : $p_{T1}, p_{T2} > 2.5\text{GeV}$, $\Sigma p_T > 6.5$, $Q_1 \neq Q_2$

Fixed prescale 2

Nominal: $p_{T1}, p_{T2} > 2.0\text{GeV}$, $\Sigma p_T > 5.5$, $Q_1 \neq Q_2$

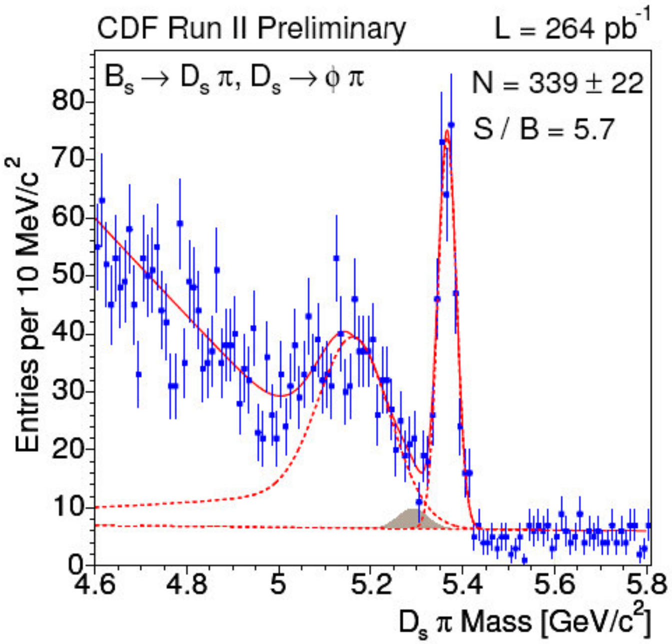
Live for $L<6x10^{31}$

Low-p_T : $p_{T1}, p_{T2} > 2.0\text{GeV}$

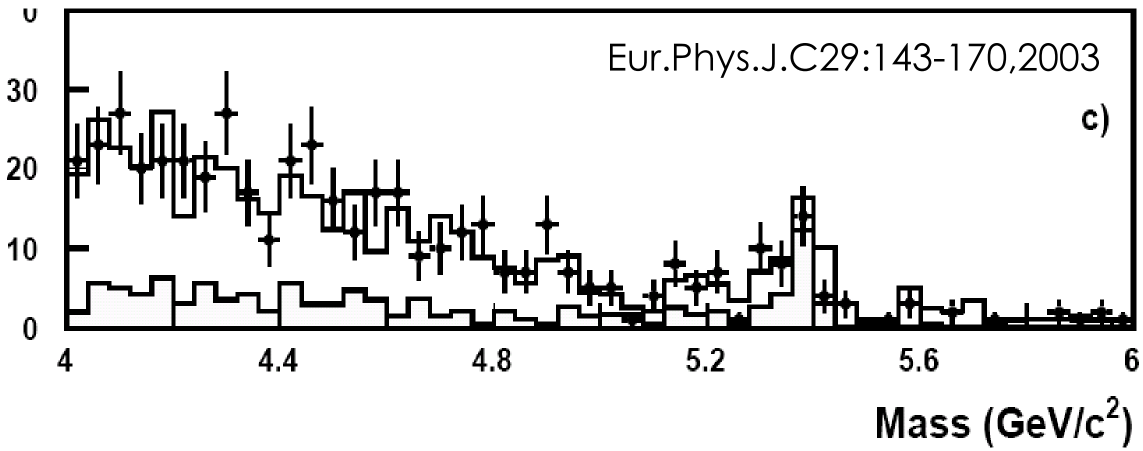
Live for $L<4x10^{31}$

B_s yields at CDF

Channel (add. modes are considered)	Yield/ 250 pb^{-1}	S/B
$B_s \rightarrow D_s\pi(D_s \rightarrow \phi\pi)$	320	5.7
$B_s \rightarrow D_s 3\pi(D_s \rightarrow \phi\pi)$	90	1.0
$B_s \rightarrow D_s\pi(D_s \rightarrow K^* K)$ *	200	1.3
$B_s \rightarrow D_s\pi(D_s \rightarrow 3\pi)$	115	1.75
$B_s \rightarrow l\nu D_s X(D_s \rightarrow \phi\pi)$	2400	3.5

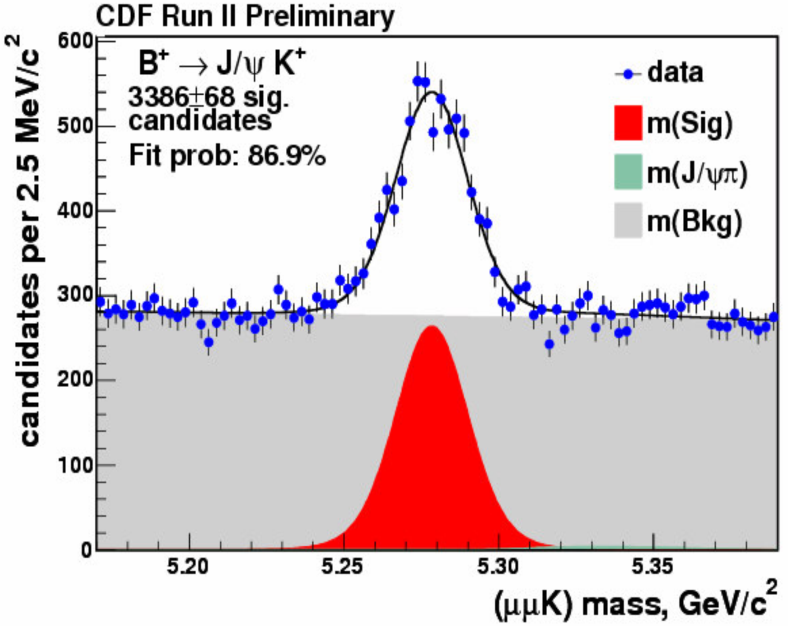


Compare to e.g. ALEPH *all exclusive channels combined*:


Eur.Phys.J.C29:143-170,2003

$B^+ \rightarrow J/\psi\, K^+$, $B^0 \rightarrow J/\psi\, K^{*0}$ lifetimes

- Simultaneous mass-lifetime fit
- Mass-sidebands give good background estimate

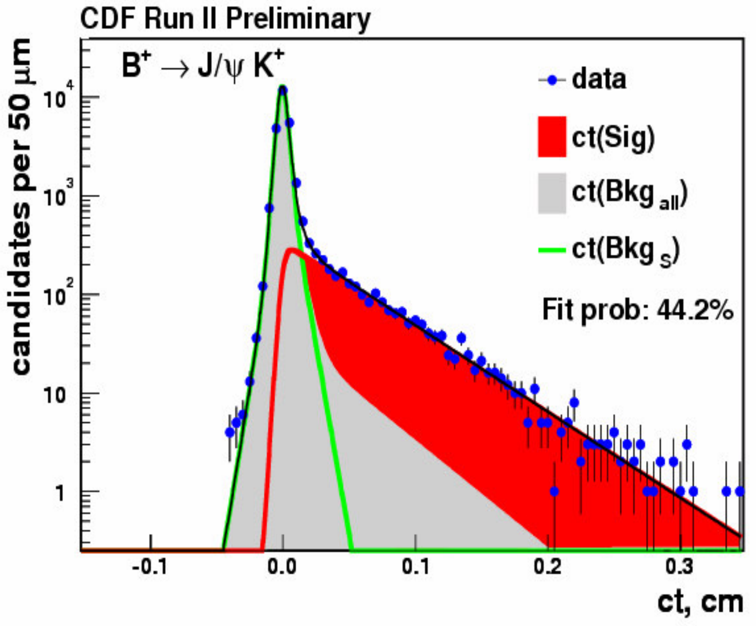


$$\tau_{B+} = 1.662 \pm 0.033\,(stat.) \pm 0.008(syst.)\,\text{ps}$$

PDG2004: 1.671±0.018ps

$$\tau_{B^0} = 1.539 \pm 0.051\,(stat.) \pm 0.008(syst.)\,\text{ps}$$

PDG2004: 1.536±0.014ps



Confirms theoretical prediction

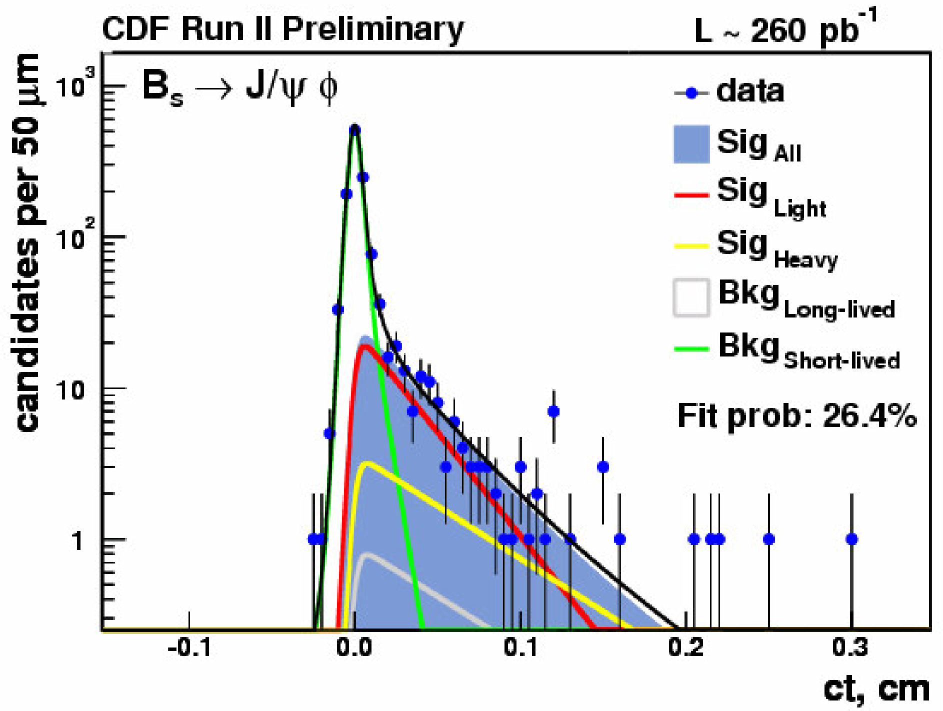
$$\frac{\tau(B^+)}{\tau(B_d)} = 1.06 \pm 0.02$$

Lifetime difference in $B_s \to J/\psi\ \phi$

- Both the J/ψ and the ϕ are vector-mesons
  - spin 1 ⇒ polarization degree of freedom
- Three components in VV final state:
  - A_0 : longitudinal component *CP even*
  - $A_\parallel$: transverse parallel component *CP even*
  - $A_\perp$: transverse perpendicular comp. *CP odd*
- Standard model prediction:
  - CP-even = short lived
  - CP-odd = long lived
  - $\Delta\Gamma/\Gamma=0.12\pm0.06$
- New physics can only(?) ***decrease*** $\Delta\Gamma$

CDF $\Delta\Gamma/\Gamma$ result

Fit CP odd
and CP even
components
to **two** lifetimes



$$
\begin{aligned}
A_0 &= 0.784 \pm 0.039 \pm 0.007\\
A_{||} &= (0.510 \pm 0.082 \pm 0.013)e^{(1.94 \pm 0.36 \pm 0.03)i}\\
|A_\perp| &= 0.354 \pm 0.098 \pm 0.003\\
\tau_L &= 1.05\ ^{+0.16}_{-0.13} \pm 0.02\ \mathrm{ps}\\
\tau_H &= 2.07\ ^{+0.58}_{-0.46} \pm 0.03\ \mathrm{ps}\\
\Delta\Gamma/\Gamma &= 0.65\ ^{+0.25}_{-0.33} \pm 0.01
\end{aligned}
$$

Previous World Average:
$\Delta\Gamma/\Gamma = 0.07 \pm 0.08$

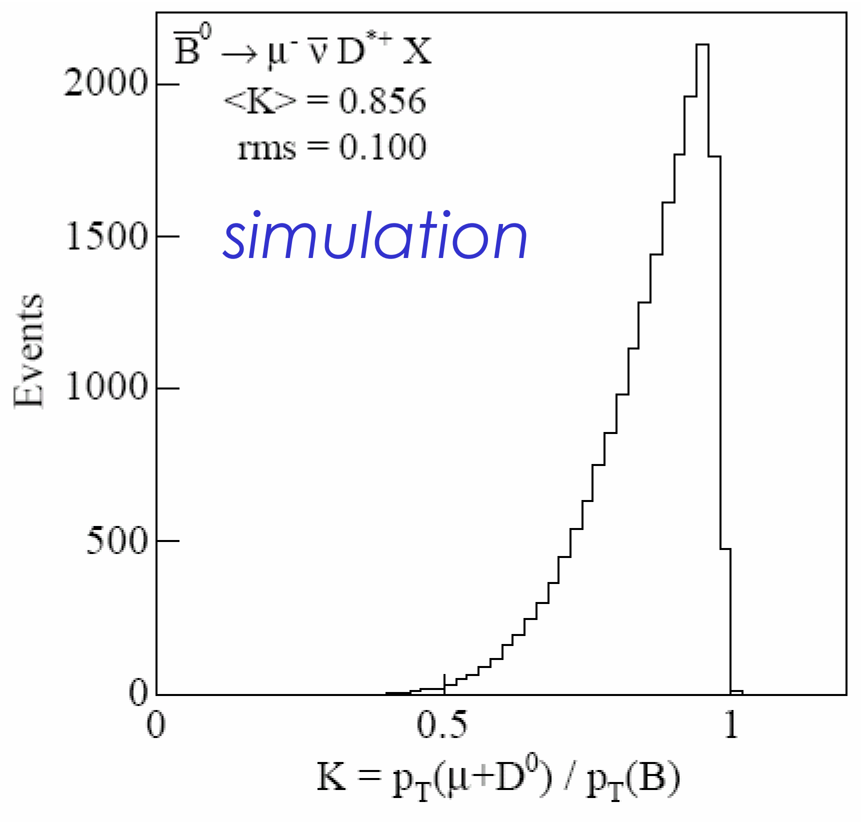
almost 2σ above SM!

Lifetimes in semileptonic B decays

- Signature: 8 GeV lepton (e/μ) + charm meson

Missing neutrino

incomplete proper time reconstruction



Backgrounds:

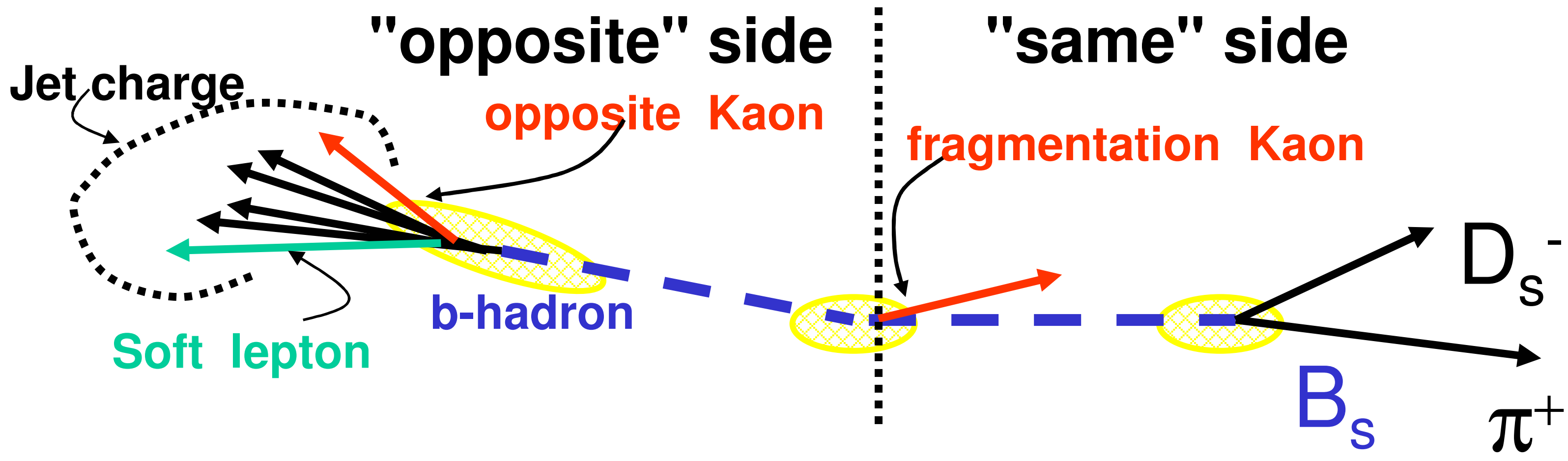
- c + fake lepton
- c + $\bar{c} \to$ e/μ
- b + $\bar{b} \to$ e/μ
- $B \to c\bar{c} \to$ e/μ
- $B \to c + \tau \to$ e/μ
- etc

$\tau(B^+) = 1.653 \pm 0.029 \pm 0.029$

$\tau(B^0) = 1.473 \pm 0.036 \pm 0.052$

Flavour tags at CDF

Oscillations: flavour at production ≠ flavour at decay



Depends on subtleties of b-bbar correlations

Depends on subtleties of fragmentation

Current MC generators unable to predict flavour tagging properties

⇒ Require data to optimize and to calibrate

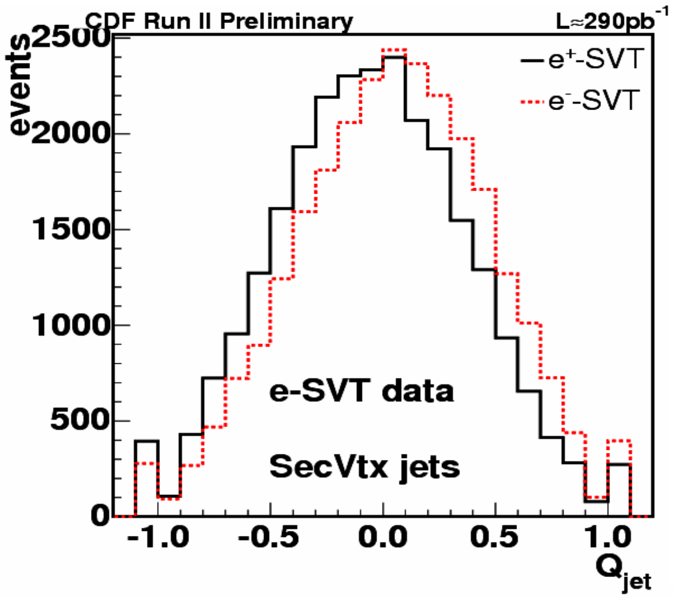
Flavour tag basics

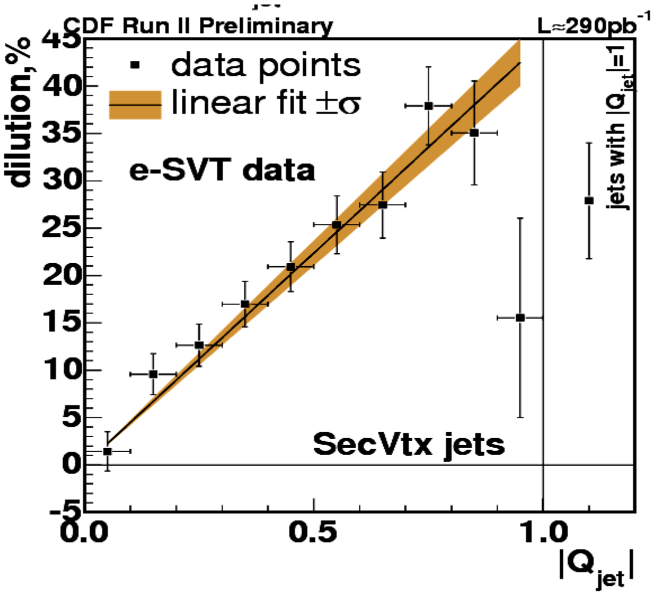
- Effectiveness of flavour tag:
- Efficiency ε
  - Not all events have a muon, opp. side jet etc.
- Accuracy, expressed as 'dilution factor' D
  - D = 1.0 – 2W (W=fraction of wrong tags)
  - Perfect tag has W=0, D=1.0
  - Random tag has W=0.5, D=0.0
- *Statistical power scales as* $\varepsilon \boldsymbol{D^2}$
- Knowing D event-by-event helps
  - Give more weight to high-D events

Opposite side jet-charge tag

$$Q_{jet} = \frac{\sum_i q^i P_T^i (2 - T_P^i)}{\sum_i P_T^i (2 - T_P^i)}$$

P_T transverse momentum; T_P: probability to be primary track



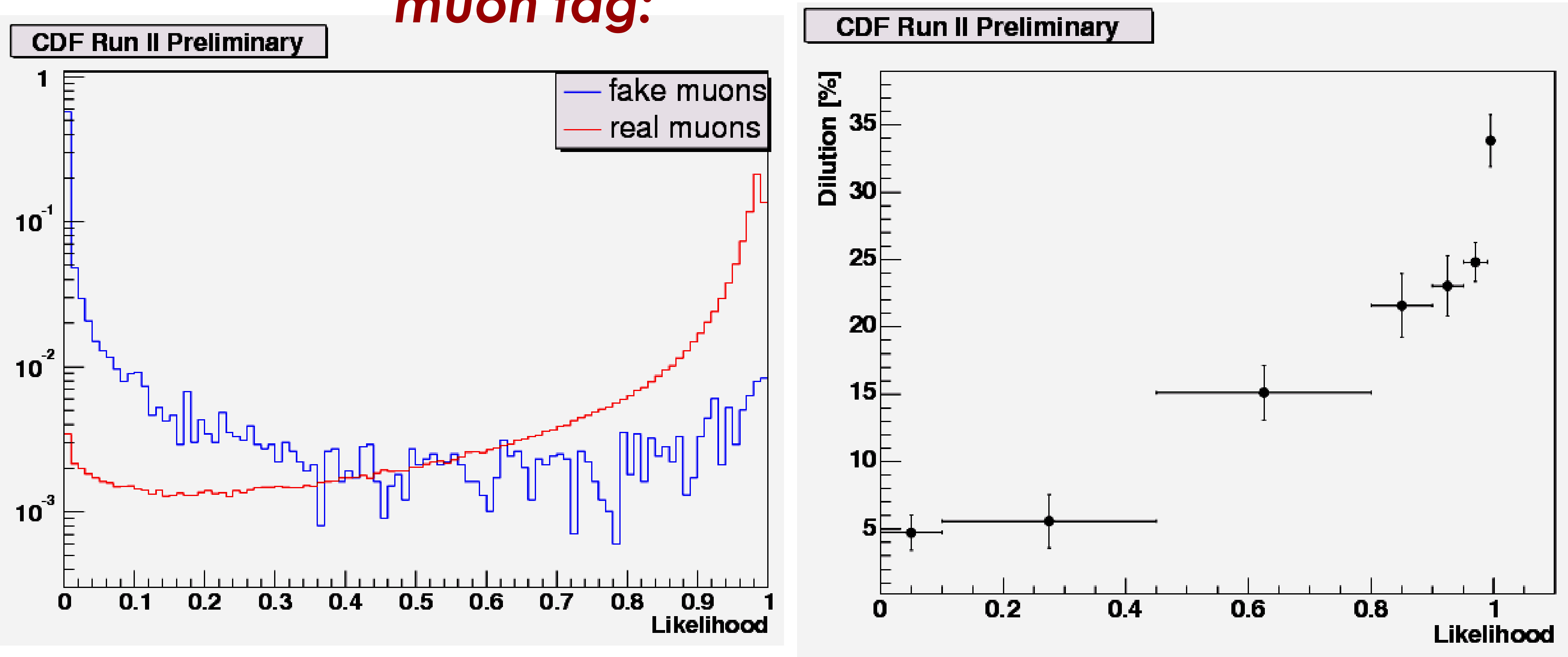


jet type	efficiency	dilution	ϵD^2
SecVtx jets	10.9±0.1%	18.2±0.5%	0.361± 0.018%
$J_p < 0.12$ jets	15.2±0.1%	11.6±0.5%	0.206± 0.017%
the rest	56.3±0.2%	5.1±0.2%	0.149± 0.011%
combined	82.3±0.2%	9.3±0.2%	0.715± 0.027%

Opposite side lepton tag

- Based on a lepton-likelihood variable
  - 5 variables for muon tag $\varepsilon D^2 = 0.70 \pm 0.04\,\%$
  - 9 variables for electron tag $\varepsilon D^2 = 0.37 \pm 0.03\,\%$

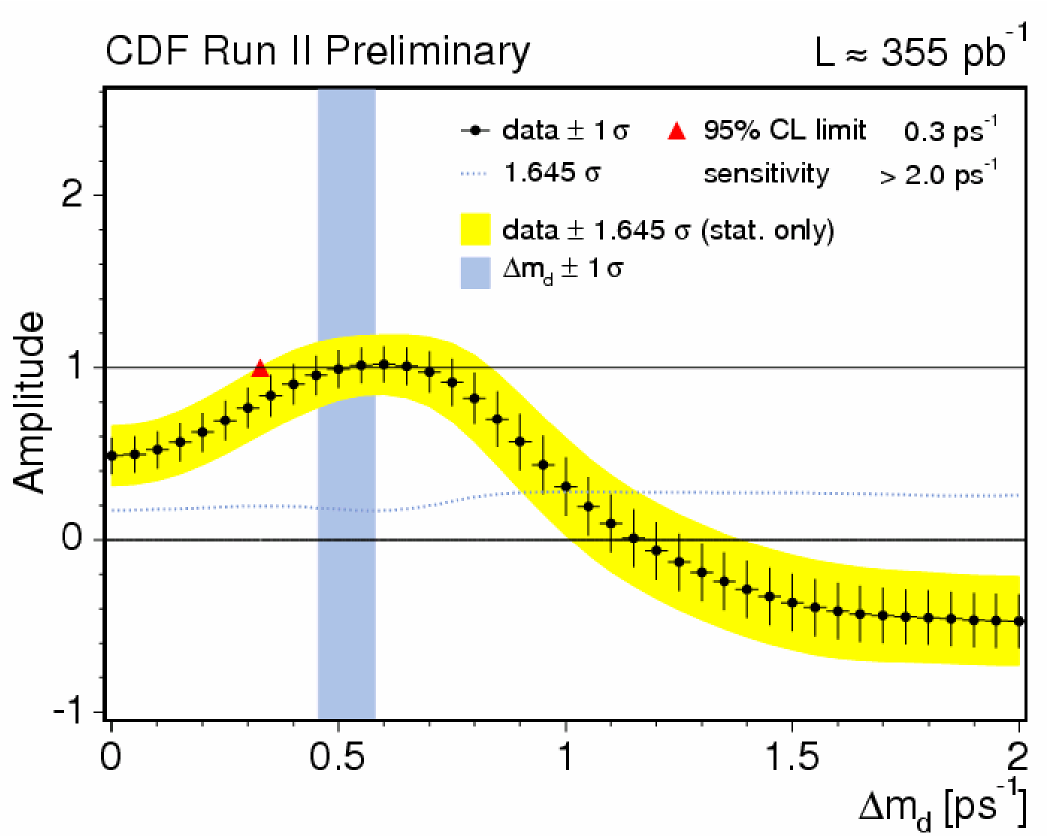
muon tag:



B_d oscillation analysis

6.2K $B_d \rightarrow D^- \pi^+$
2.2K $B_d \rightarrow J/\psi\ K^{*0}$

opposite-side tags only



full unbinned likelihood fit

closest thing to B_s oscillation analysis

$\Delta m_d = 0.503 \pm 0.063 \pm 0.015$

PDG2004: $\Delta m_d = 0.502 \pm 0.007\ ps^{-1}$

B_s oscillation sensitivity estimate

- First CDF B_s oscillation result will only be based on well-understood opposite side tags
  - $\varepsilon D^2 \approx 0.7\%$ (JQ) + 0.7% (μ) + 0.4% (e) =1.8%

significance:

$$S = \sqrt{\frac{N\varepsilon D^2}{2}}\sqrt{\frac{S}{S+B}}\,e^{-\frac{(\sigma_{ct}\Delta m_s)^2}{2}}$$

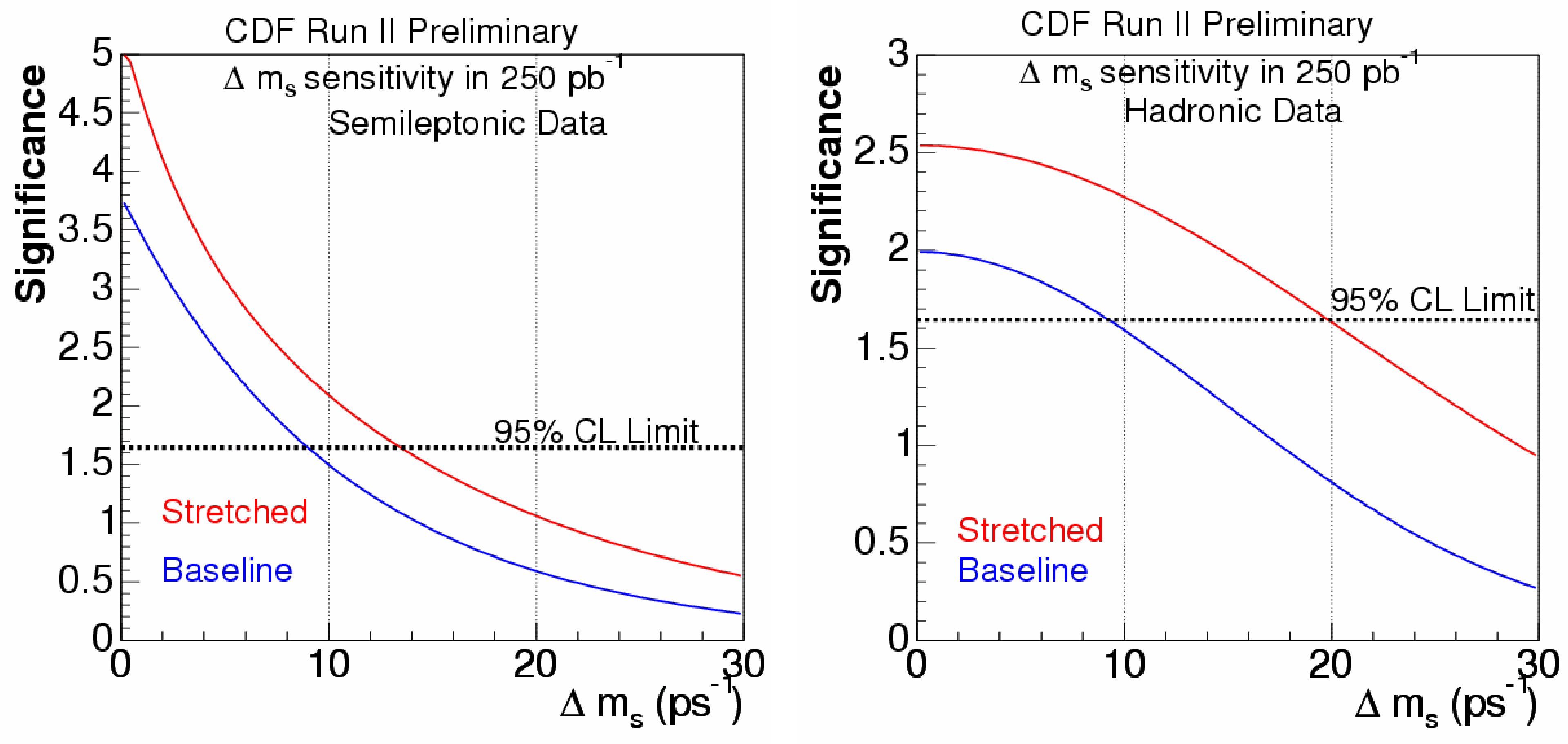
	hadronic	semileptonic	
N	≈700	≈2500	*(250pb^{-1})*
σ_{ct}	70-100fs	70-100fs ⊕ 0.15ct	

CDF B_s oscillation projections

Prepared for summer 2004 – still mostly valid

baseline = $\varepsilon D^2 = 1.6\%$, $\sigma_{ct} = 67fs$

stretched = $\varepsilon D^2 = 2.6\%$, $\sigma_{ct} = 47fs$



Outlook for summer

- yields:
  - more data
  - new channels
- proper time resolution
  - full use of L00 / event-by-event vertexing
- tagging:
  - improving existing tagging algorithms
  - implementing opposite side Kaon tag
  - implementing same-side Kaon tag

Two possible outcomes

No B_s oscillations in SM-allowed range

check
double-check
triple-check
check again
confirm
reconfirm
check reconfirmation

and then..

celebrate new physics!

B_s oscillations observed compatible with SM

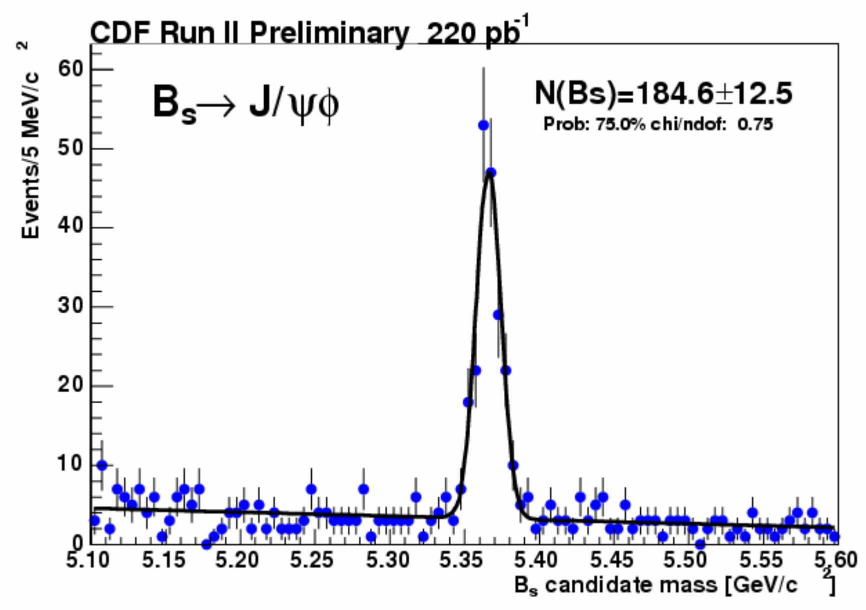
1. B_s and B_d oscillation parameters combined to give precision measurement of V_{td}.
2. Start of a new physics program using B_s oscillations for even more profound searches for new physics

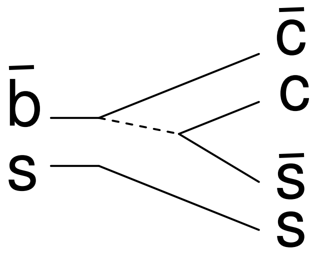
$B_s \to J/\psi\ \phi$

Well established:

"easy" final state
With $J/\psi \to \mu^+\mu^-$

Used for measuring B_s mass, lifetime



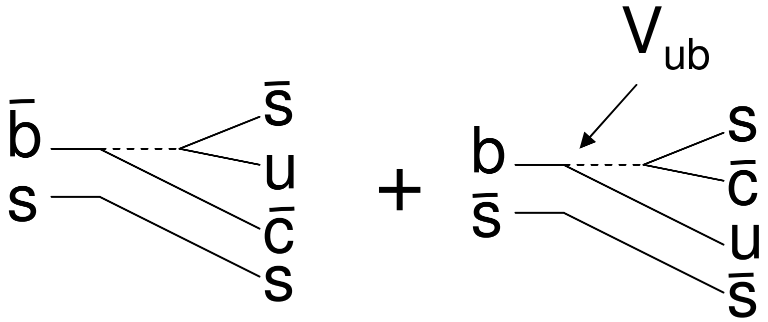


Directly measures B_s mixing phase as CP asymmetry

SM prediction O(1%)

$B_s \rightarrow D_s K$

Two diagrams → quantum interference → CP asymmetry



Robust measurement of the phase of V_{ub} *(also called γ)*

Compare with indirect measurements of γ

Possible new physics scenario: