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Particle Physics

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Flavour Physics

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Outline

- **Part I: Introduction**
  - what is (quark) flavour physics and why is it so exciting?
  - how we got here: brief history of flavour physics in the 20th century

- **Part II: Particle-Antiparticle Mixing**
  - a short summary of the formalism (don't worry, I'm an experimentalist …)
  - introduce experimental facilities and techniques

- **Part III: Precision tests of the Standard Model**
  - CP violating observables: sin 2β, CKM angle γ, $B^0_s\overline{B}^0_s$ mixing phase ϕ_s
  - rare decays: search for $B^0_{(s)} \to \mu^+ \mu^-$, angular observables in $B^0 \to K^{*0} \mu^+ \mu^-$

$P^0\bar{P}^0$ Mixing

Applies for all neutral meson systems ($K^0\bar{K}^0$, $D^0\bar{D}^0$, $B^0\bar{B}^0$, $B^0_s\bar{B}^0_s$)

- different phenomenologies due to different mass and lifetime differences
- flavour mixing through box diagrams → coupled system

$$\left|\psi(t)\right\rangle = a(t)\left|P^0\right\rangle + b(t)\left|\bar{P}^0\right\rangle$$

- time evolution described by two-component Schrödinger equation

$$-i\frac{\partial}{\partial t}\begin{pmatrix}a(t)\\b(t)\end{pmatrix} = H\begin{pmatrix}a(t)\\b(t)\end{pmatrix}$$

- with an effective Hamiltonian H
  - H is not Hermitian since it does not include decay products
- decompose H into Hermitian parts:

$$M \equiv \frac{1}{2}\left(H+H^\dagger\right) \quad ; \quad \frac{1}{2}\Gamma \equiv \frac{1}{2i}\left(H-H^\dagger\right)$$

$$H = M - \frac{i}{2}\Gamma = \begin{pmatrix}M_{11} & M_{12}\\M_{21} & M_{22}\end{pmatrix} - \frac{i}{2}\begin{pmatrix}\Gamma_{11} & \Gamma_{12}\\\Gamma_{21} & \Gamma_{22}\end{pmatrix}$$

$P^0\bar{P}^0$ Mixing (ii)

- **assume CPT is conserved: particle/antiparticle have same mass/lifetime**

$$\left.\begin{array}{l} M \equiv M_{11} = M_{22} \\ \Gamma \equiv \Gamma_{11} = \Gamma_{22} \end{array}\right\} \Rightarrow H = \begin{pmatrix} M - \frac{i}{2}\Gamma & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & M - \frac{i}{2}\Gamma \end{pmatrix}$$

- Eigenvalues

$$\omega_{H,L} = M - \frac{i}{2}\Gamma \pm \sqrt{\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)\left(M_{12}^* - \frac{i}{2}\Gamma_{12}^*\right)} \equiv m_{H,L} - \frac{i}{2}\Gamma_{H,L}$$

- Eigenstates (labeled by their mass, H for "heavy", L for "light")

$$|P_{H,L}\rangle = p\,|P^0\rangle \mp q\,|\bar{P}^0\rangle \qquad \textbf{with} \qquad \frac{q}{p} = -\sqrt{\frac{H_{21}}{H_{12}}} = -\sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}$$

- **these are states with well-defined mass and decay width**

$$|P_H(t)\rangle = \left(p \cdot |P^0\rangle - q \cdot |\bar{P}^0\rangle\right) \cdot e^{-im_H t} \cdot e^{-\Gamma_H t/2}$$

$$|P_L(t)\rangle = \left(p \cdot |P^0\rangle + q \cdot |\bar{P}^0\rangle\right) \cdot e^{-im_L t} \cdot e^{-\Gamma_L t/2}$$

$P^0\bar{P}^0$ Mixing (iii)

- time evolution of initially pure flavour states

$$\left|P^0_{(t=0)}(t)\right\rangle = g_+(t)\cdot\left|P^0\right\rangle + \frac{q}{p}\cdot g_-(t)\cdot\left|\bar{P}^0\right\rangle$$

$$\left|\bar{P}^0_{(t=0)}(t)\right\rangle = g_+(t)\cdot\left|\bar{P}^0\right\rangle + \frac{p}{q}\cdot g_-(t)\cdot\left|P^0\right\rangle$$

with:

$$g_\pm(t) = \frac{1}{2}\left(e^{-\omega_L t} \pm e^{-\omega_H t}\right)$$

$$= \frac{1}{2}\, e^{-iMt}\, e^{-\Gamma t/2}\left(e^{+i\Delta m t/2} e^{+\Delta\Gamma t/4} \pm e^{-i\Delta m t/2} e^{-\Delta\Gamma t/4}\right)$$

$$\boxed{\begin{aligned} \Delta m &\equiv m_H - m_L > 0 \\ \Delta\Gamma &\equiv \Gamma_H - \Gamma_L \end{aligned}}$$

- mixing probabilities as a function of time t:

$$\mathrm{Prob}_{(P^0\to P^0)}(t) = \mathrm{Prob}_{(\bar{P}^0\to\bar{P}^0)}(t) = \left|g_+(t)\right|^2 = \frac{1}{2}\, e^{-\Gamma\cdot t}\left\{\cosh\left(\frac{\Delta\Gamma}{2}\cdot t\right) + \boxed{\cos\left(\Delta m\cdot t\right)}\right\}$$

$$\mathrm{Prob}_{(P^0\to\bar{P}^0)}(t) = \left|\frac{q}{p}\right|^2\cdot\left|g_-(t)\right|^2 = \frac{1}{2}\cdot\left|\frac{q}{p}\right|^2\cdot e^{-\Gamma\cdot t}\cdot\left\{\cosh\left(\frac{\Delta\Gamma}{2}\cdot t\right) - \boxed{\cos\left(\Delta m\cdot t\right)}\right\}$$

$$\mathrm{Prob}_{(\bar{P}^0\to P^0)}(t) = \left|\frac{p}{q}\right|^2\cdot\left|g_-(t)\right|^2 = \frac{1}{2}\cdot\left|\frac{p}{q}\right|^2\cdot e^{-\Gamma\cdot t}\cdot\left\{\cosh\left(\frac{\Delta\Gamma}{2}\cdot t\right) - \boxed{\cos\left(\Delta m\cdot t\right)}\right\}$$

$P^0\bar{P}^0$ Mixing (iv)

- observable time-dependent asymmetries

$$a_{mix}(t) \equiv \frac{N(P^0 \to P^0) - N(P^0 \to \bar{P}^0)}{N(P^0 \to P^0) + N(P^0 \to \bar{P}^0)} = \frac{\cos(\Delta m \cdot t) + \delta \cdot \cosh(\Delta\Gamma \cdot t/2)}{\cosh(\Delta\Gamma \cdot t/2) + \delta \cdot \cos(\Delta m \cdot t)}$$

$$\bar{a}_{mix}(t) \equiv \frac{N(\bar{P}^0 \to \bar{P}^0) - N(\bar{P}^0 \to P^0)}{N(\bar{P}^0 \to \bar{P}^0) + N(\bar{P}^0 \to P^0)} = \frac{\cos(\Delta m \cdot t) - \delta \cdot \cosh(\Delta\Gamma \cdot t/2)}{\cosh(\Delta\Gamma \cdot t/2) - \delta \cdot \cos(\Delta m \cdot t)}$$

with

$$\delta \equiv \frac{1 - |q/p|^2}{1 + |q/p|^2}$$

$\delta \neq 0 \Leftrightarrow$ CP violation in mixing

- assume for now that CP is conserved in mixing, i.e. $\delta = 0$

$$a_{mix}(t) = \bar{a}_{mix}(t) = \frac{\cos(\Delta m \cdot t)}{\cosh(\Delta\Gamma \cdot t/2)} = \frac{\cos(x \cdot \Gamma \cdot t)}{\cosh(y \cdot \Gamma \cdot t)} \quad \text{with} \quad \left\{ \begin{array}{l} x = \Delta m / \Gamma \\ y = \Delta\Gamma / 2\Gamma \end{array} \right.$$

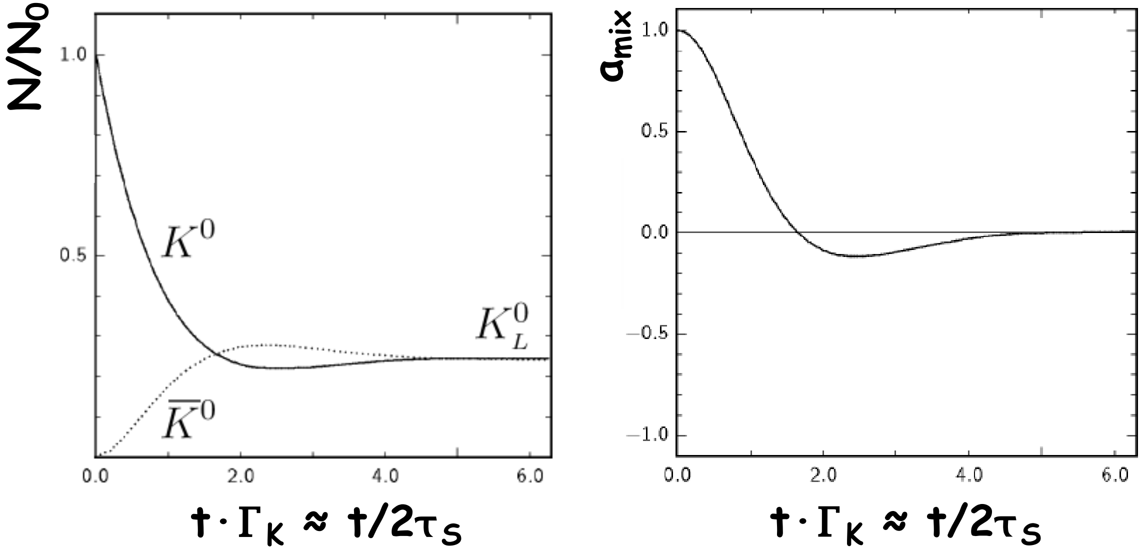
- oscillation frequency x: mass difference
- damping parameter y: lifetime difference

} between the two weak Eigenstates

Mixing: $K^0\overline{K}^0$ and $D^0\overline{D}^0$

$K^0\overline{K}^0$

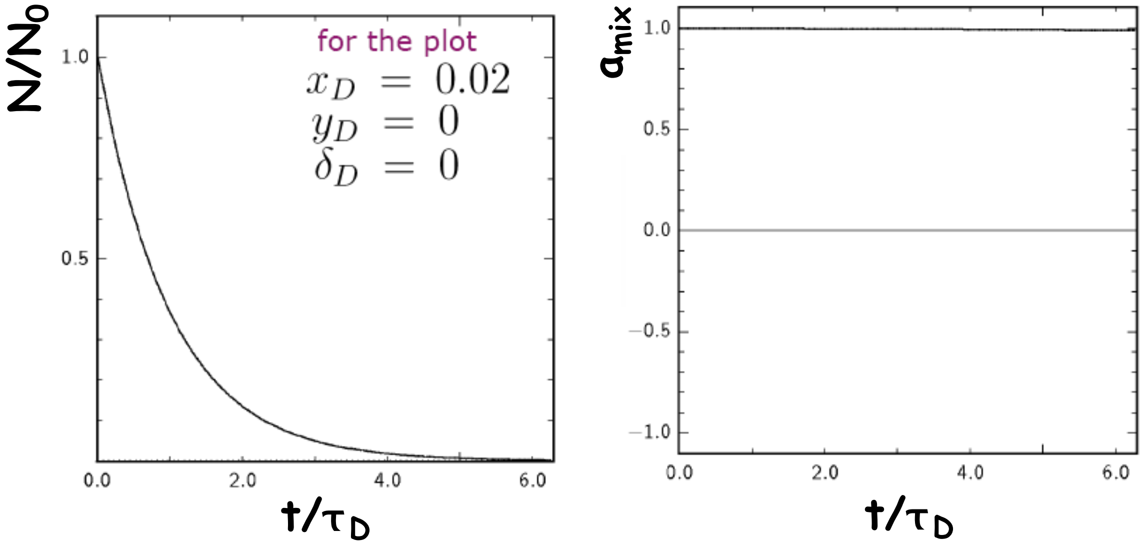
- $x_K \approx 0.95$
- $y_K \approx -0.996$ ($\tau_L \gg \tau_S$)
- strong damping, only K_L left after about one oscillation



$D^0\overline{D}^0$

- $x_D \approx 0.008$
- $y_D \approx 0.007$
- mixing very small, e.g. time-integrated probability

$$\chi_D = \frac{x_D^2 + y_D^2}{2\,(1 + x_D^2)} \approx 3 \times 10^{-5}$$



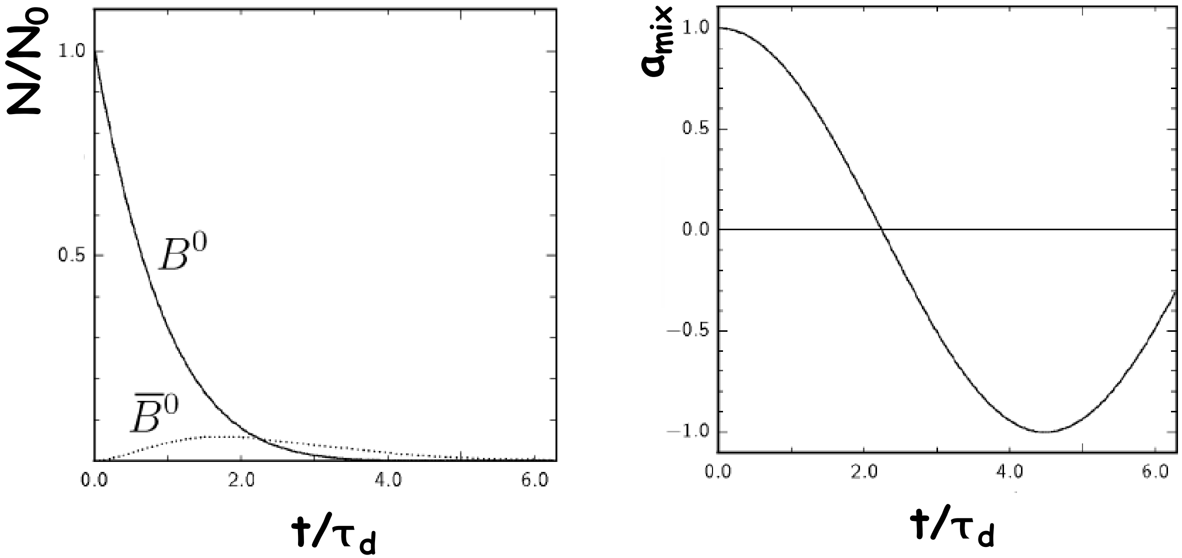
- 2007: first evidence @ B factories; 2012: first observation @ LHCb

Mixing: $B^0\bar{B}^0$ and $B^0_s\bar{B}^0_s$

$B^0\bar{B}^0$

- $x_d \approx 0.7$
- $y_d \approx 0$
- significant mixing:

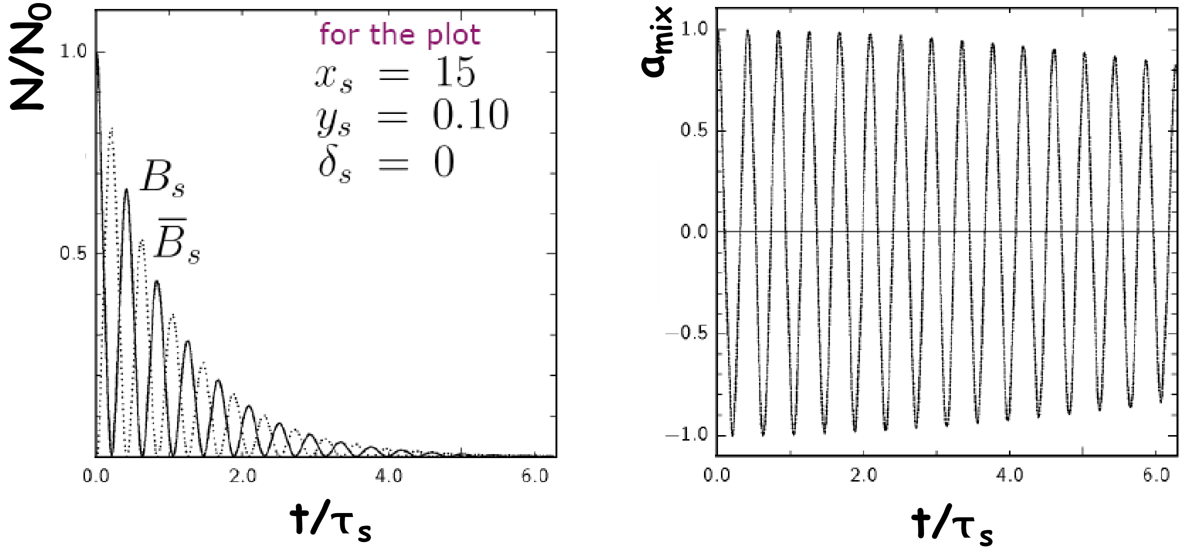
$$\chi_d = \frac{x_d^2}{2\,(1+x_d^2)} \approx 18\,\%$$



$B^0_s\bar{B}^0_s$

- $x_s \approx 26$
- $y_s \approx 0.07$
- very fast oscillation, complete mixing:

$$\chi_s = \frac{x_s^2 + y_s^2}{2\,(1+x_s^2)} \approx 50\,\%$$



for the plot

$$x_s = 15 \quad y_s = 0.10 \quad \delta_s = 0$$

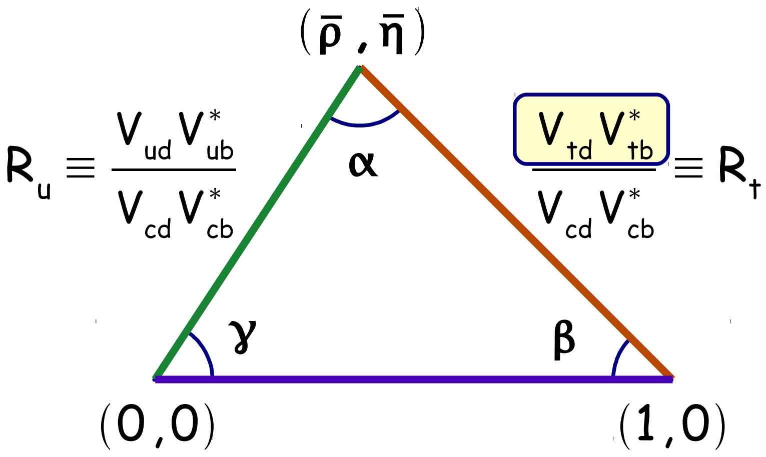
$B^0\bar{B}^0$ Oscillations

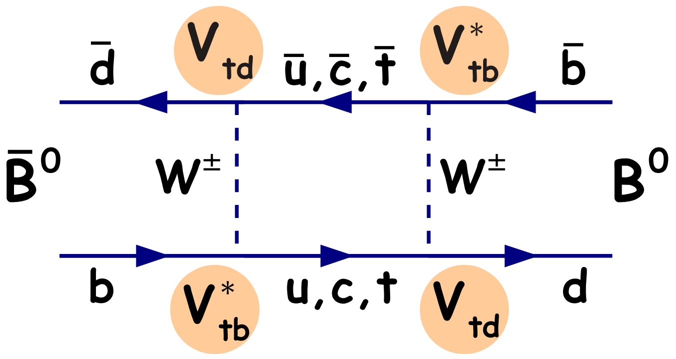
$B^0\bar{B}^0$ oscillation frequency → length of R_t side of the Unitarity Triangle

- $B^0\bar{B}^0$ transitions due to the off-diagonal elements of the effective Hamiltonian

$$H_{12} = M_{12} - (i/2)\,\Gamma_{12}$$

- M_{12}: dispersive part of the amplitude, transitions via <u>off-shell</u> intermediate states
  - dominated by t-box: $M_{12} \propto (V_{td}V_{tb}^*)^2$
- Γ_{12}: "absorptive part of the amplitude, transitions via <u>on-shell</u> intermediate states
  - dominated by c-box: $\Gamma_{12} \ll M_{12}$



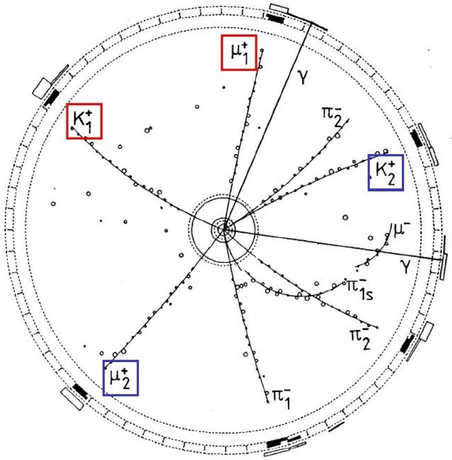


$$\Rightarrow \quad \boxed{\Delta m = 2\left|M_{12}\right| \propto \left|V_{td}\right|^2 \cdot \left|V_{tb}\right|^2}$$

$B^0\bar{B}^0$ Oscillations

First observation of time-integrated asymmetry by Argus (1987)

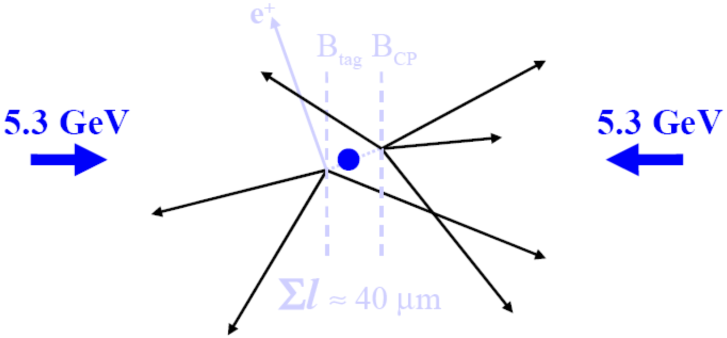
$$e^+e^- \rightarrow \Upsilon(4s) \rightarrow B^0\bar{B}^0$$



- look at semi-leptonic decays, count fraction of like-sign dimuon events → gives integrated mixing probability

But: impossible to observe oscillation pattern at Argus

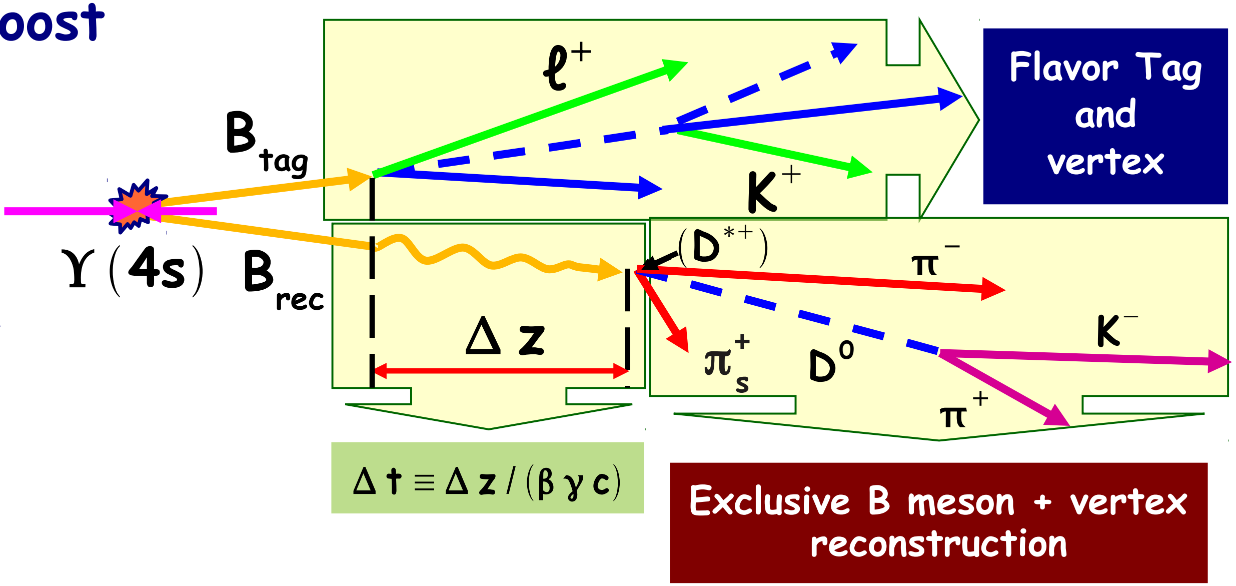
- symmetric beam energies → lab frame = $\Upsilon(4s)$ rest frame
  - $m_{\Upsilon(4s)} = 10.58$ GeV → $p_B = 340$ MeV → $\beta\gamma = 0.064$
  - mean B decay length $c\tau_B \cdot \beta\gamma \sim 30\ \mu m$, too small to resolve
- $B^0\bar{B}^0$ produced in coherent quantum state, oscillate in phase until one decays
  - need to measure difference of decay times to observe oscillation pattern
  - but $B^0\bar{B}^0$ produced back-to-back, cannot reconstruct position of production vertex



B Factories

High-luminosity e^+e^- colliders with asymmetric beam energies

- produce $\Upsilon(4s)$ with Lorentz boost
- Babar: 9 GeV e^- + 3.1 GeV
  - $\beta\gamma = 0.56$, $\langle\Delta z\rangle = 260\ \mu m$
- Belle: 8 GeV e^- + 3.5 GeV e^+
  - $\beta\gamma = 0.425$, $\langle\Delta z\rangle = 200\ \mu m$



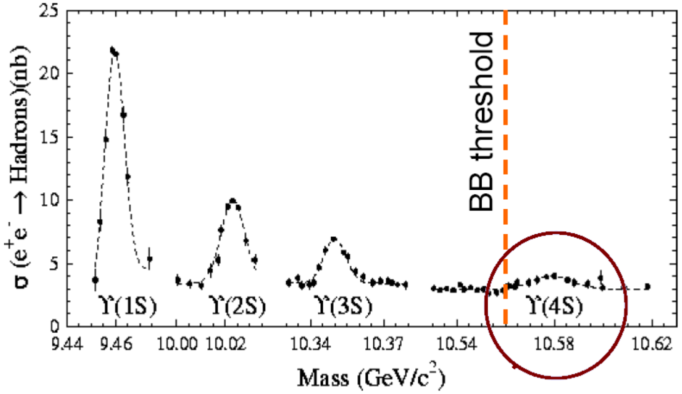
Reconstruction strategy:

- reconstruct B_{rec} fully → B_{rec} decay vertex, momentum and flavour at decay
- assign remaining final-state particles to B_{tag} decay (no full reconstruction)
  - reconstruct B_{tag} decay vertex → fixes t=0 for oscillation measurement
  - infer flavour of B_{tag} at its decay → fixes flavour of B_{rec} at t=0
- B_{rec} oscillated (not oscillated) if opposite (same) flavour at t=0 and decay
- calculate oscillation time from B_{rec} momentum and Δz of decay vertices

B factories

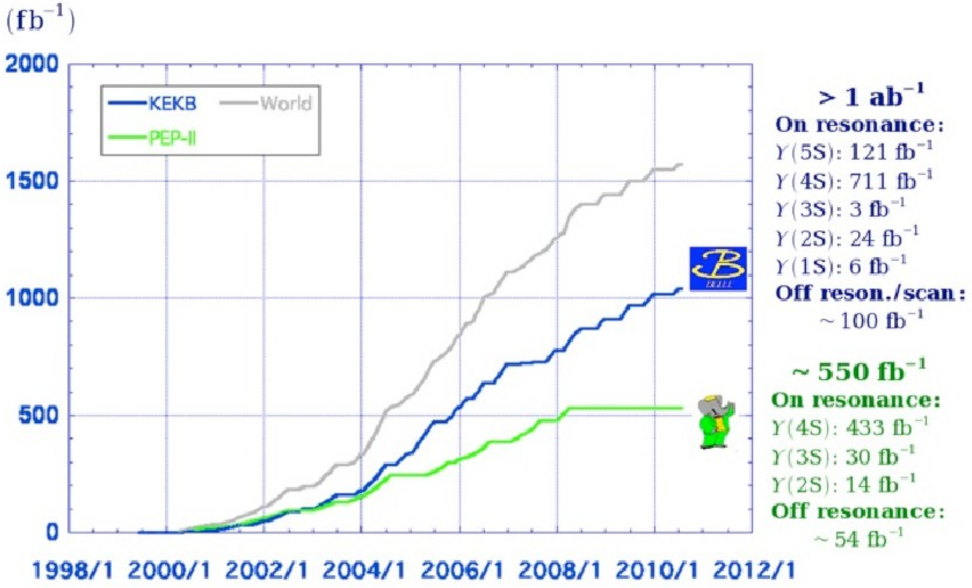
Υ(4s) resonance: bound $b\bar{b}$ state just above $B\bar{B}$ threshold

- decays ~ 50% to B^+B^- and ~ 50% to $B^0\bar{B}^0$
- $\sigma_{b\bar{b}} \approx 1$ nb → with 1 fb^{-1} produce 10^6 $B\bar{B}$ pairs
- $\sigma_{b\bar{b}} / \sigma_{tot} \approx 0.25$ → large fraction of B events
- "clean" events → only tracks from B decays



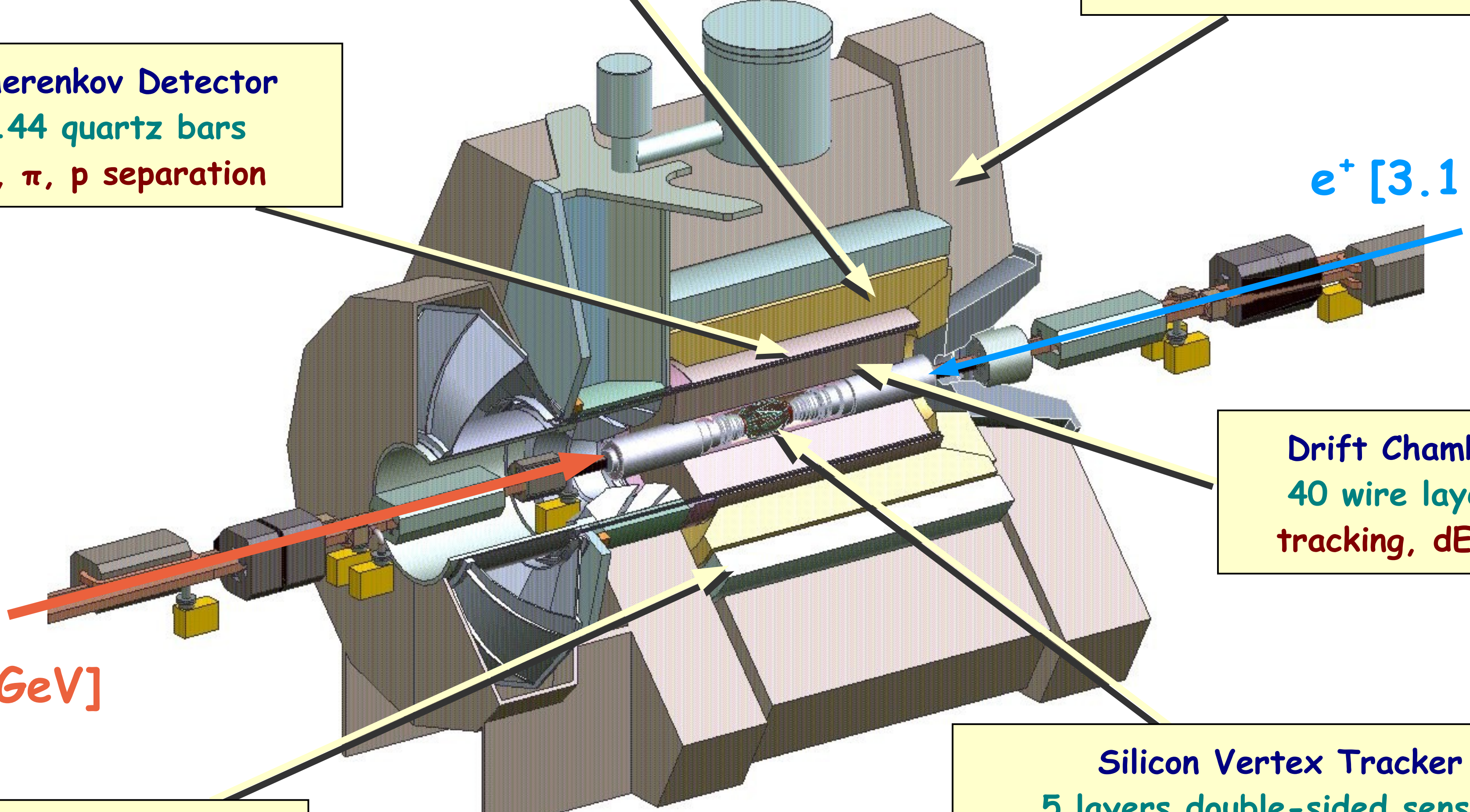
Need highest possible luminosity to beat small production cross section

- PEP-II ring at SLAC, California
  - peak luminosity 12×10^{33} $cm^{-2}s^{-1}$
  - integrated luminosity: 553 fb^{-1}
- KEK-B ring at KEK, Japan
  - peak luminosity 21×10^{33} $cm^{-2}s^{-1}$
  - integrated luminosity: 1040 fb^{-1}



Babar

[NIM A479 (2002) 1]



Electromagnetic Calorimeter
6580 CsI crystals
$e^{\pm}$ ID, π^0 and γ reconstruction

Instrumented Flux Return
12-18 layers of RPC/LST
μ ID

Cherenkov Detector
144 quartz bars
K, π, p separation

e^+ [3.1 GeV]

Drift Chamber
40 wire layers
tracking, dE/dx

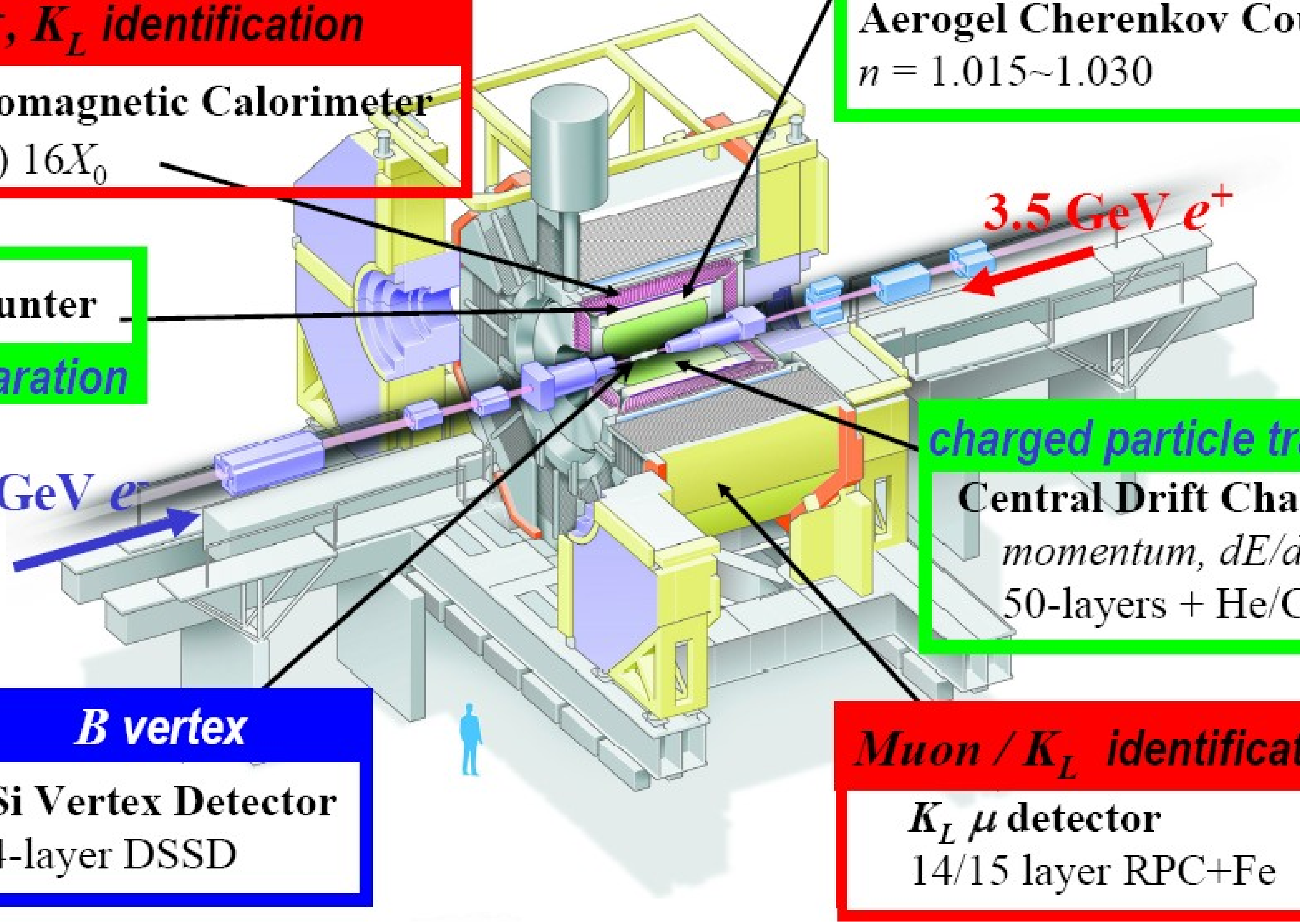
e^- [9 GeV]

Silicon Vertex Tracker
5 layers double-sided sensors
vertexing, tracking (+ dE/dx)

1.5T Magnet

Belle

[NIM A479 (2002) 117]



γ, π^0 reconstruction
e^{+-}, K_L identification

Electromagnetic Calorimeter
CsI(Tl) $16X_0$

K/π separation

Aerogel Cherenkov Counter
$n = 1.015{\sim}1.030$

TOF counter
K/π separation

charged particle tracking

Central Drift Chamber
momentum, dE/dx
50-layers + He/C_2H_6

B vertex

Si Vertex Detector
4-layer DSSD

Muon / K_L identification

K_L μ detector
14/15 layer RPC+Fe

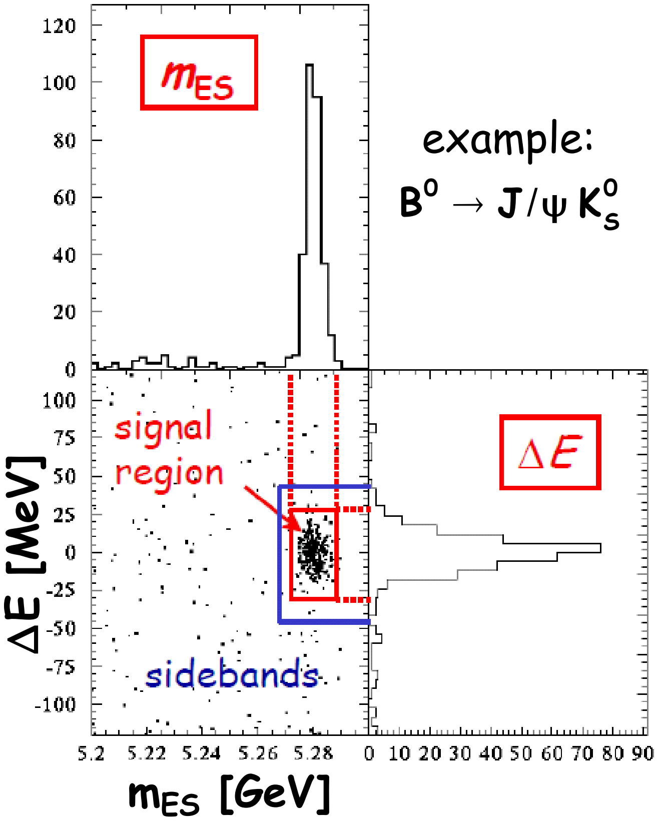
Event Selection

Kinematic variables: exploit precisely known beam energy

- **energy conservation in center-of-mass frame**

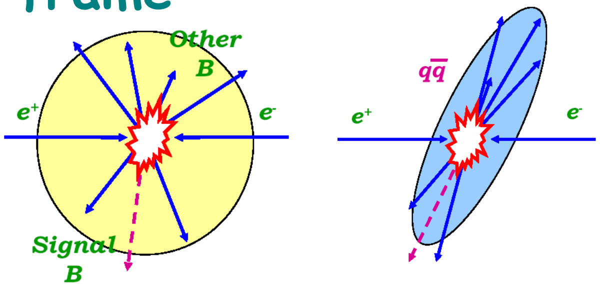
$$E_B^* = \frac{\sqrt{s}}{2} = E_{\text{beam}}^* \quad \left\{ \begin{array}{l} \Delta E \equiv E_B^* - E_{\text{beam}}^* = 0 \\ m_{ES} \equiv \sqrt{(E_{\text{beam}}^*)^2 - (\vec{p}_B^{\,*})^2} \end{array} \right.$$

- **m_{ES}: "energy-substituted" invariant mass**
  - E^*_{beam}: beam energy, known to ~ 2.5 MeV
  - E^*_B: energy of B meson, only known to ~ 10–40 MeV from detector resolution



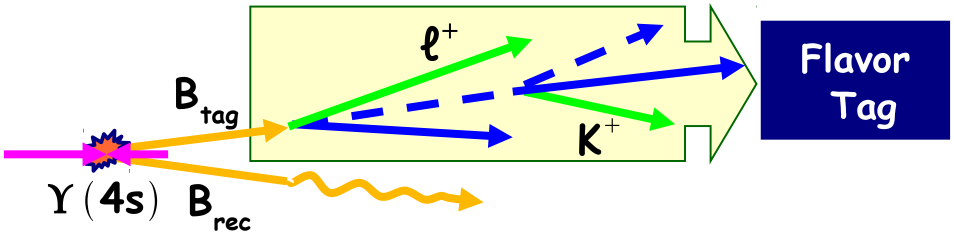
Event shape:

- **B mesons produced almost at rest in center-of-mass frame**
  → decay products isotropically distributed
- **light quarks produced with high momenta**
  → boost along flight direction → jet-like topology



Flavour Tagging

Infer flavour of B_{rec} at t=0 from decay properties of B_{tag}



- **lepton tag ($b \to c\, \ell^- \bar{\nu}$)**
  - small wrong-tag fraction < 5%
  - contamination of wrong-sign leptons from b→c→s cascade decays small
  - clean identification of $e^\pm$, $\mu^\pm$
  - low efficiency: BF only 11% each
- **kaon tag ($b \to c \to s$)**
  - high efficiency: 66% of B^0 decay to K^+
  - but significant wrong-tag fraction:
  - 13% of B^0 have a K^- in the decay chain
  - contamination from mis-identified π^+
- **inclusive tags (e.g. decay vertex charge)**
  - typically use neural-net techniques
  - high efficiency, high wrong-tag fraction

efficiency ε:
fraction of reconstructed events for which flavour tag is obtained

wrong-tag fraction ω:
fraction of tagged events for which tagging decision is wrong

figure of merit:
effective tagging power

$$\varepsilon \cdot D^2 = \varepsilon \cdot (1 - 2\omega)^2$$

total tagging power at B factories, combining all algorithms

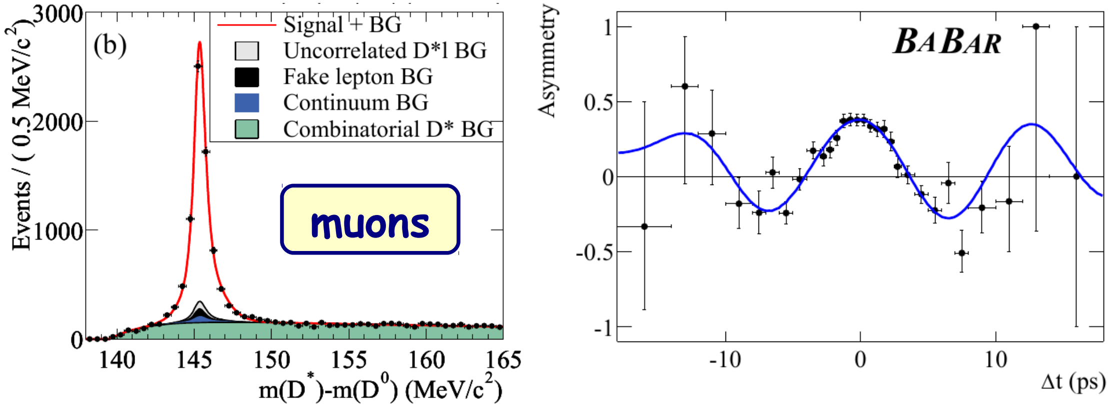
$$\varepsilon \cdot D^2 \approx 30\%$$

B_{rec} Reconstruction

Semi-leptonic decays:

- $B^0 \rightarrow D^{*-} \ell^+ \nu_\ell$ with $D^{*-} \rightarrow \bar{D}^0 \pi^-$
- reasonable branching fraction
- clean event sample
    - soft pion from $D^{*-} \rightarrow \bar{D}^0 \pi^-$
- but neutrino not reconstructed
- B flavour from lepton charge

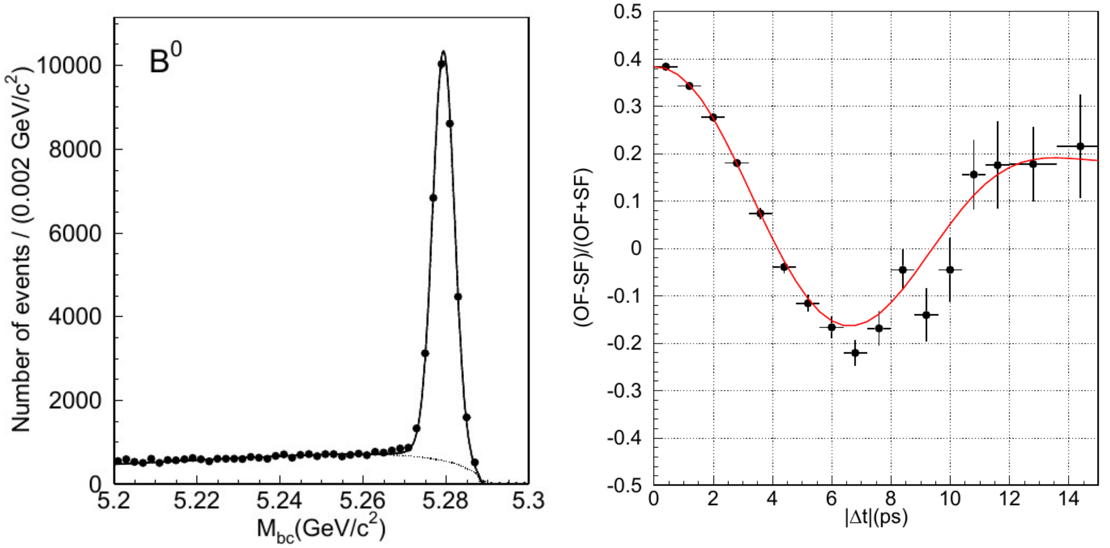
[PRD 67 (2003) 072002]



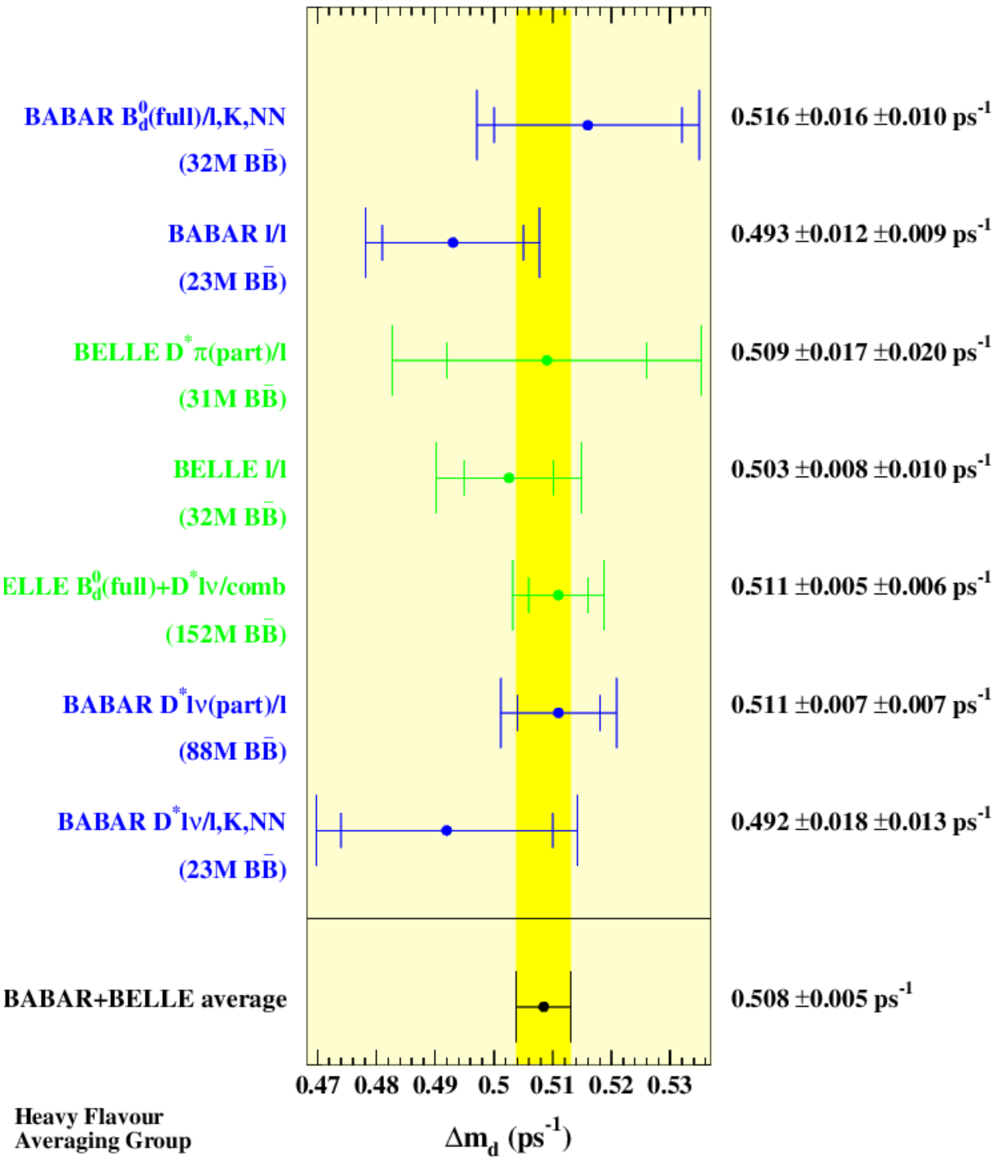
Hadronic decays:

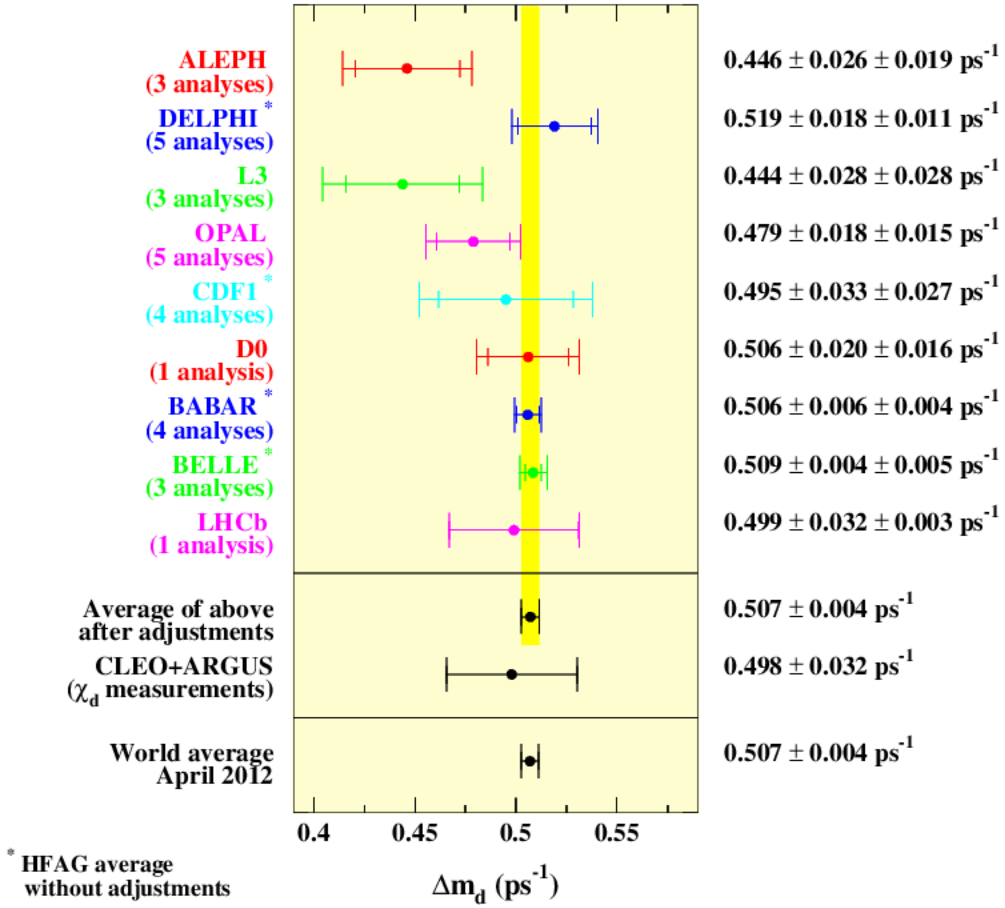
- $B^0 \rightarrow D^{*-} \pi^+$ with $D^{*-} \rightarrow \bar{D}^0 \pi^-$
- $B^0 \rightarrow J/\psi K^{*0}$ with $K^{*0} \rightarrow K^+ \pi^-$
- clean event samples
- all particles reconstructed
- but small branching fractions
- B flavour from charge of fast pion ($D^{*-} \pi^+$) or Kaon (J/ψ K^{*0})

[PRD 71 (2005) 072003]



Results Δm_d



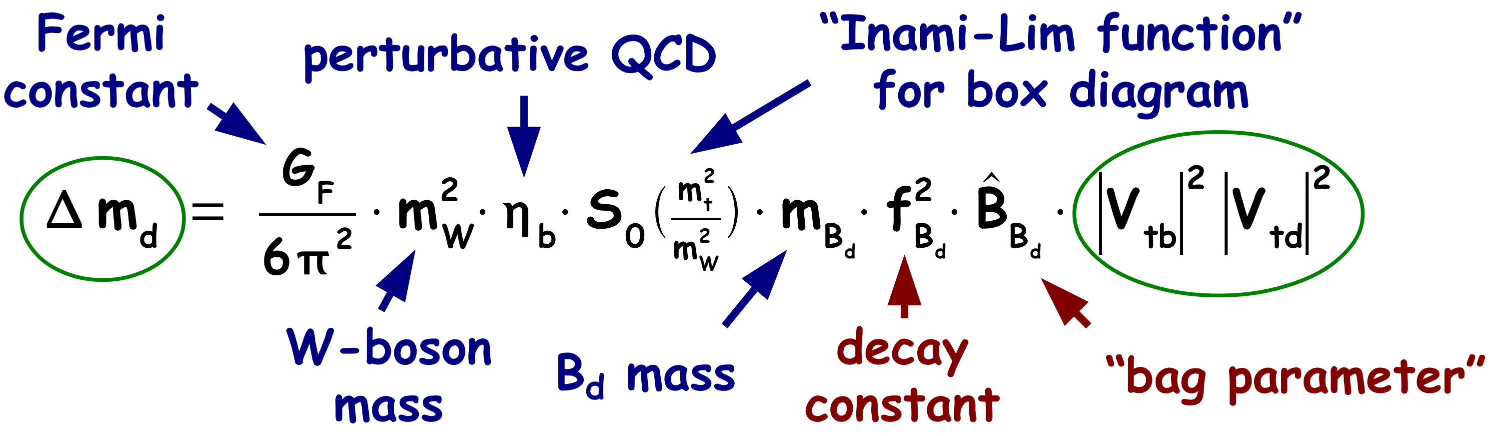


Heavy Flavour Averaging Group

[http://www.slac.stanford.edu/xorg/hfag/]

Theory Uncertainties

Uncertainty on $|V_{tb}|^2\cdot|V_{td}|^2$ dominated by non-perturbative QCD factors



Fermi constant

perturbative QCD

"Inami-Lim function" for box diagram

$$\boxed{\Delta m_d} = \frac{G_F}{6\pi^2}\cdot m_W^2\cdot \eta_b\cdot S_0\left(\frac{m_t^2}{m_W^2}\right)\cdot m_{B_d}\cdot f_{B_d}^2\cdot \hat{B}_{B_d}\cdot \boxed{|V_{tb}|^2\,|V_{td}|^2}$$

W-boson mass

B_d mass

decay constant

"bag parameter"

- best determination of $f_{B_d}^2$ and $\hat{B}_{B_d}$ from lattice QCD → uncertainty ~ 10 %

Theory uncertainties partially cancel in the ratio $\Delta m_d / \Delta m_s$

- uncertainty from lattice QCD ~ 3%
- still measure R_t side of unitarity triangle, since $|V_{tb}|^2\cdot|V_{ts}|^2$ hardly depends on ρ and η
- measure Δm_s from $B^0_s\overline{B}{}^0_s$ oscillation frequency
- B^0_s not produced at the $\Upsilon(4s)$ → hadron colliders

$$\frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d}}{m_{B_s}}\cdot\boxed{\frac{f_{B_d}^2\,\hat{B}_{B_d}}{f_{B_s}^2\,\hat{B}_{B_s}}}\cdot\frac{|V_{tb}|^2\,|V_{td}|^2}{|V_{tb}|^2\,|V_{ts}|^2}$$

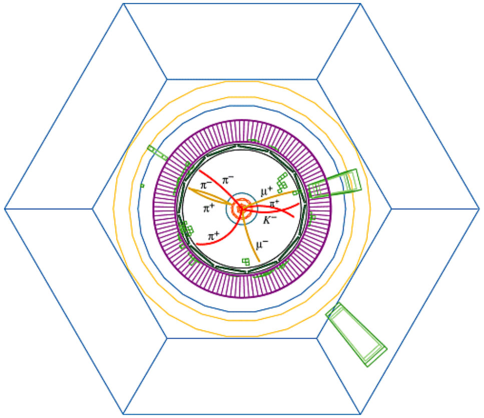
$b\bar{b}$ Production at Hadron Colliders

Advantages and disadvantages with respect to $e^+e^- \to \Upsilon(4s)$ B factories

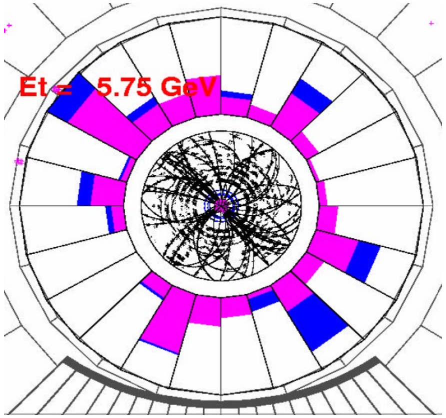
- all species of b hadrons produced:
  $B^\pm$, B^0, B^0_s, B^+_c, Λ_b
- $\sigma_{b\bar{b}}$ much higher than at B factories
- $\sigma_{b\bar{b}}/\sigma_{tot}$ much smaller than at B factories
- large number of additional particles from underlying hadronic interaction

Facility	$\sqrt{s}$	$\sigma_{b\bar{b}}$ [nb]	$\sigma_{b\bar{b}}/\sigma_{tot}$
e^+e^- @ $\Upsilon(4s)$	10.58 GeV	1	0.25
HERA-B pA	42 GeV	~ 30	10^{-6}
Tevatron $p\bar{p}$	1.96 TeV	5×10^3	10^{-3}
LHC pp	7 TeV	3×10^5	10^{-2}
LHC pp	14 TeV	6×10^5	10^{-2}

- selective and efficient trigger vital
- exploit features of B decays:
  - B mesons heavy → decay products have large transverse momentum p_T
  - B mesons live long → decay products have large impact parameters with respect to primary vertex



$B^0 \to J/\psi K^0_S$ event in BaBar

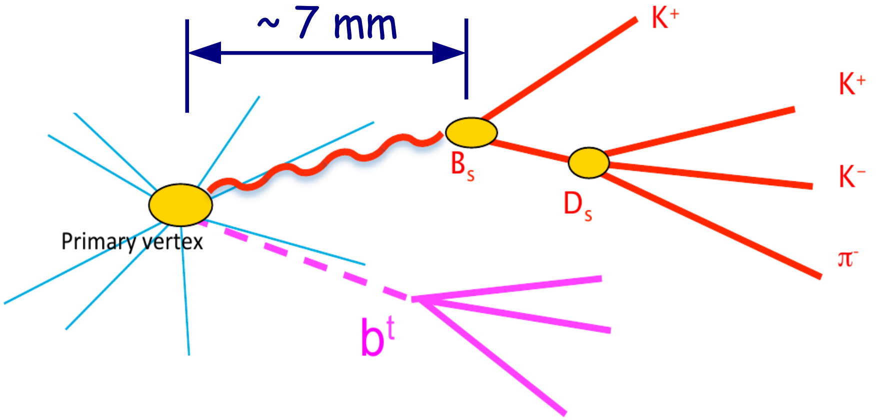


$J/\psi \to \mu^+\mu^-$ event in CDF

$b\bar{b}$ Production at Hadron Colliders

$b\bar{b}$ pair is not created in a coherent quantum state

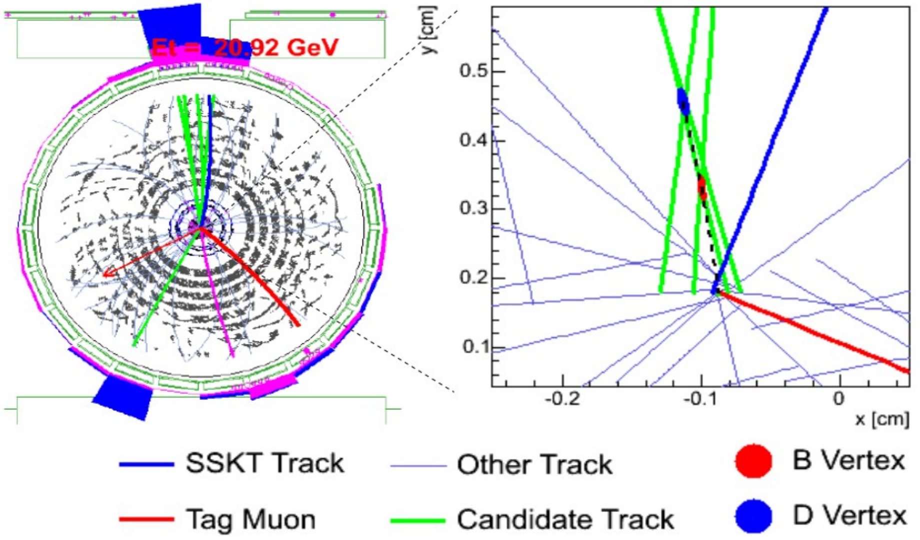
- reference for oscillation measurement: primary vertex, B flavour at production
- primary vertex reconstruction: excellent precision due to large number of charged tracks from underlying event



Flavour tagging: more challenging due to the many extra tracks

- "opposite side tagging" a la B factories (lepton, kaon, vertex charge)
- in addition "same side tagging": charge of a kaon from b fragmentation chain or from B^{**} decays
  - select kaon close to B in phase space
- combined tagging power

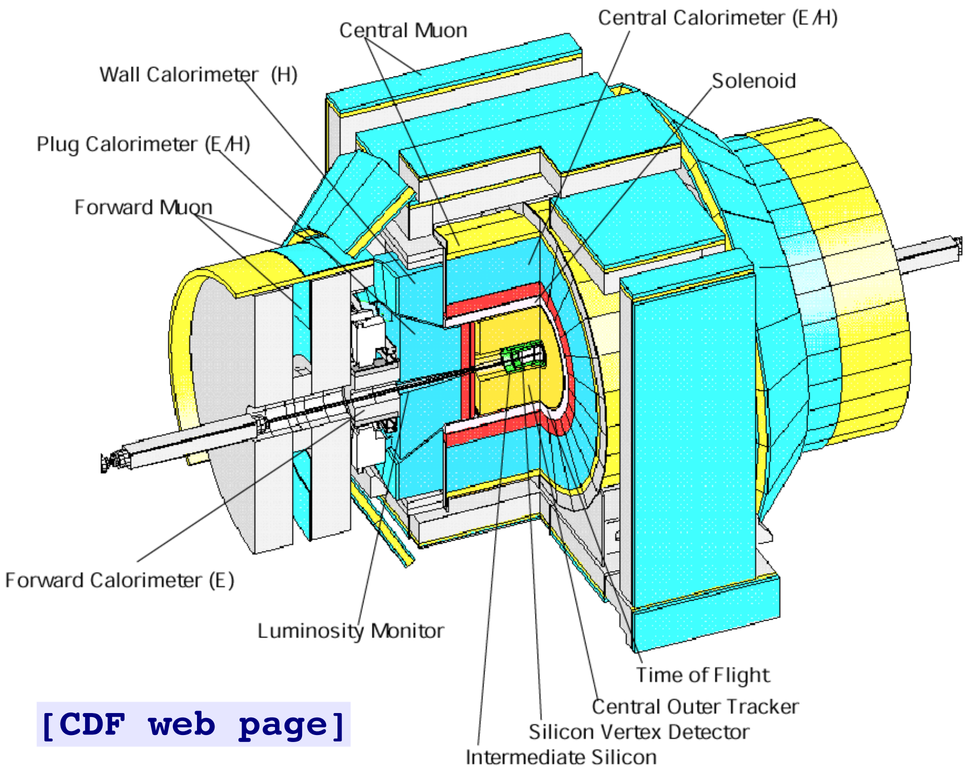
$$\boxed{\varepsilon \cdot D^2 = \text{few } \%}$$



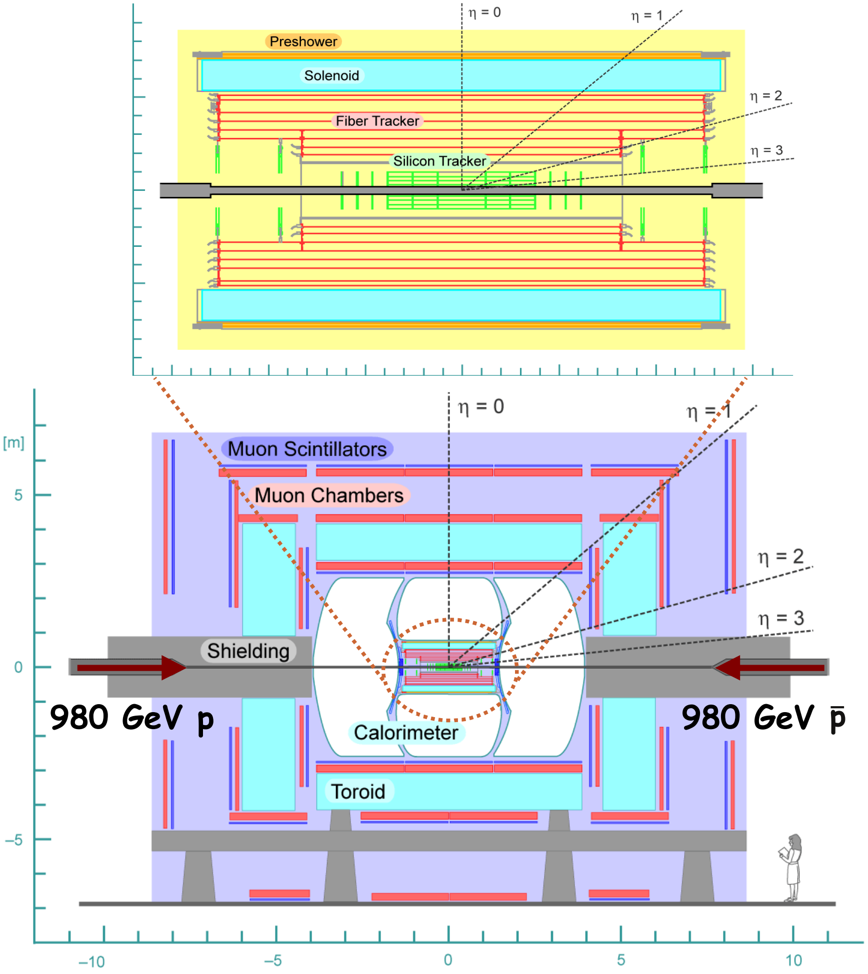
Tevatron: CDF and D0

Typical general-purpose detectors

- **main focus: high-energy frontier, top-quark physics and Higgs searches**
- **but also significant B-physics programme**
  - e.g. first observation of $B^0_s\overline{B}^0_s$ oscillation
  - main limitations: trigger, π/K separation



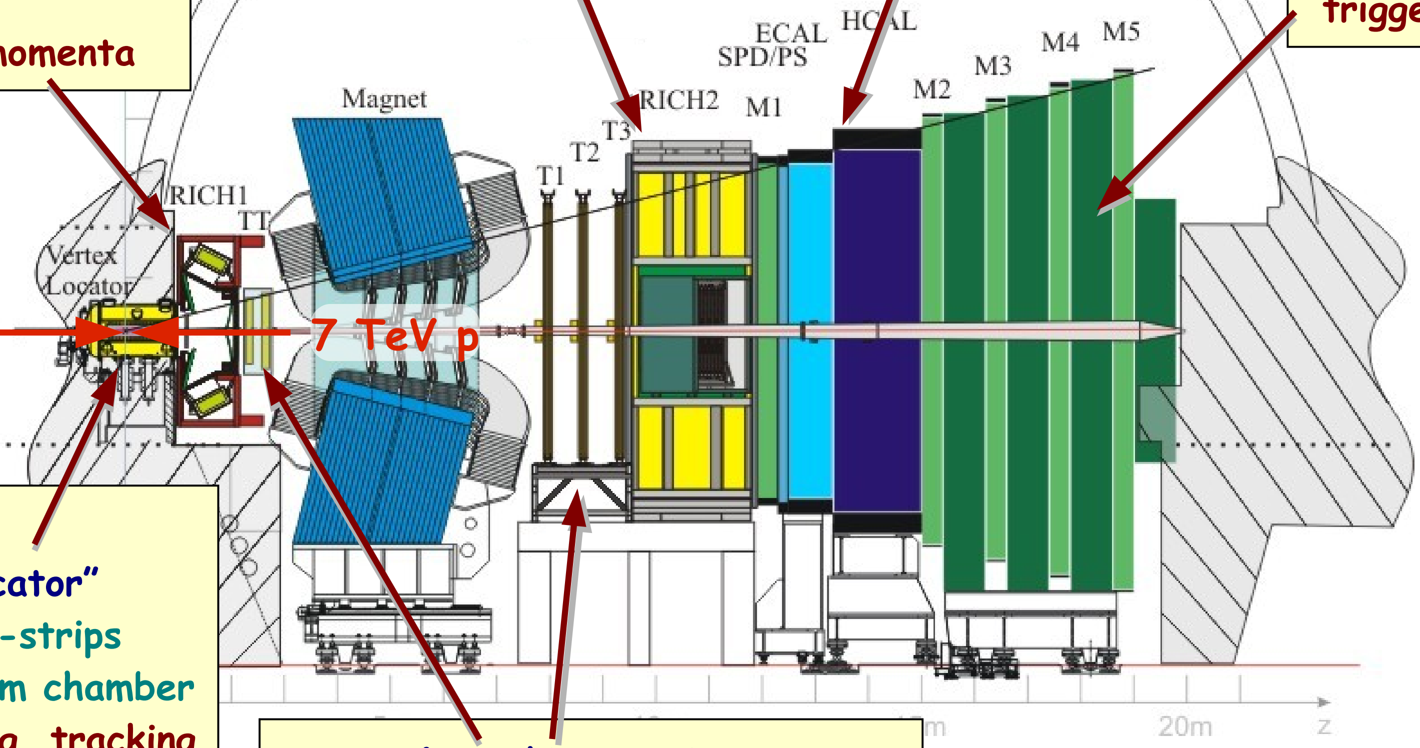
[CDF web page]



D0, [NIM A565 (2006) 463]

LHCb

Dedicated experiment for heavy flavour physics at the LHC



RICH1
Aerogel and C4F10 radiators
K/π-ID at low momenta

RICH2
CF4 radiator
K/π -ID at high momenta

Calorimeters
scintillating fibres
trigger, e/γ/π^0-ID

5 muon stations
drift tubes
trigger, μ-ID

2011: 3.5+3.5 TeV
2012: 4+4 TeV

7 TeV p

7 TeV p

"Vertex Locator"
Silicon micro-strips
inside LHC vacuum chamber
trigger, vertexing, tracking

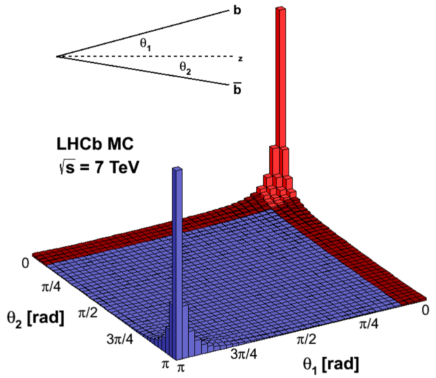
4 tracking stations
Silicon strips, straw drift tubes
tracking, momentum reconstruction

[JINST 3 (2008) S08005]

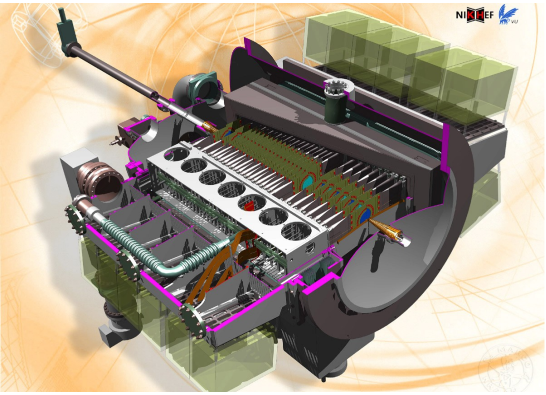
LHCb

Key features that distinguish LHCb from general purpose detectors

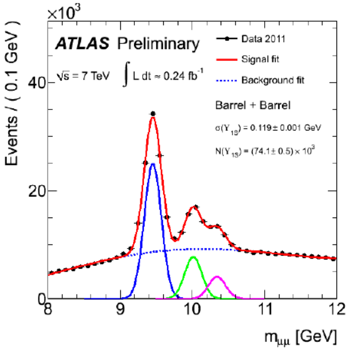
- **forward geometry**
  - large acceptance, $b\bar{b}$ production forward peaked
  - large Lorentz boost, helps with proper-time resolution
  - lower p_T trigger thresholds than at central detectors

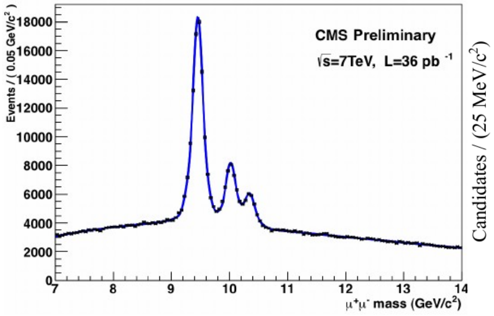


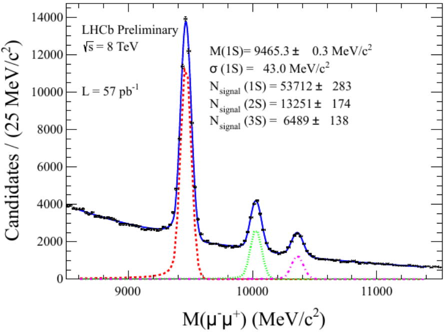
- **vertex detector inside LHC vacuum vessel**
  - impact parameter resolution to identify tracks from B decays (→ trigger)
  - proper-time resolution, e.g. to resolve fast $B^0_s\bar{B}^0_s$ oscillations



- **tracking system**
  - momentum and invariant mass resolution to fight combinatorial backgrounds

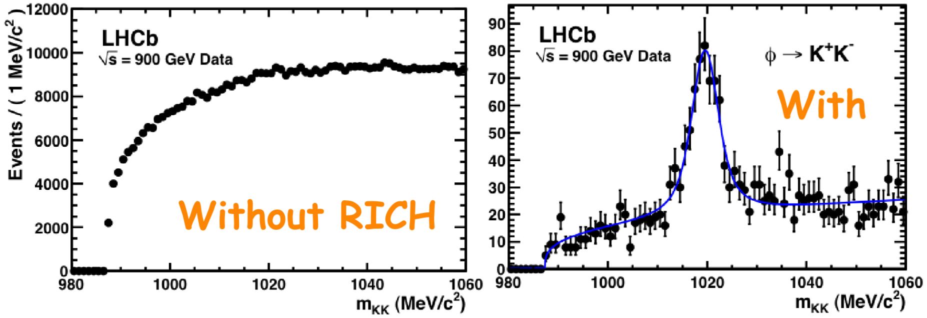




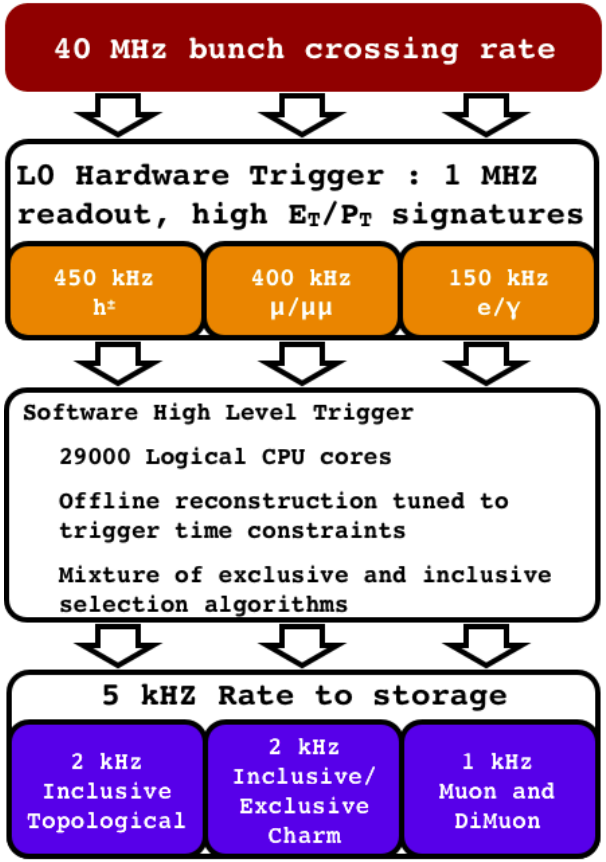


LHCb

- **two RICH detectors for**
  - efficient K/π separation from few GeV for flavour tagging up to 100 GeV, e.g. to separate $B^0 \rightarrow \pi\pi$, $B^0_{(s)} \rightarrow K\pi$, $B^0_s \rightarrow KK$



- **flexible, selective and efficient trigger, also for hadronic final states**
  - **hardware level (L0):**
    - high-pT track segments in muon system
    - high-ET clusters (e,h,γ) in calorimeters
  - **software level (HLT):**
    - multi-processor computing farm
    - access to full detector data
  - **combined efficiency:**
    - 90 % for dimuon channels (e.g. J/psi)
    - 30 % for fully hadronic final states



40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHZ readout, high E_T/P_T signatures

450 kHz h±	400 kHz μ/μμ	150 kHz e/γ

Software High Level Trigger

29000 Logical CPU cores

Offline reconstruction tuned to trigger time constraints

Mixture of exclusive and inclusive selection algorithms

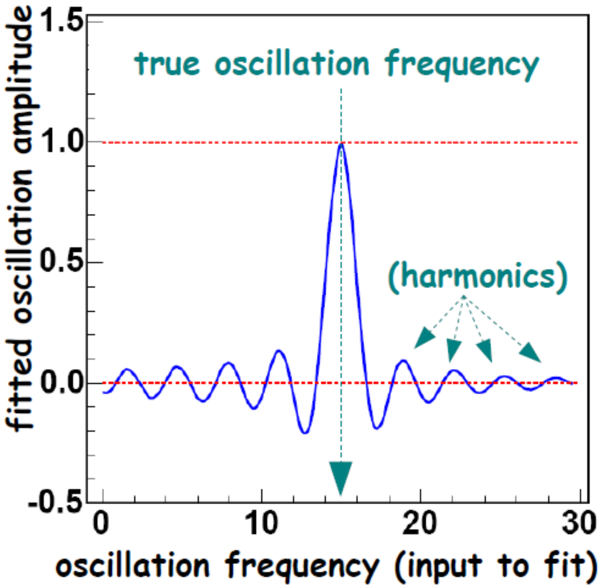
5 kHZ Rate to storage

2 kHz Inclusive Topological	2 kHz Inclusive/ Exclusive Charm	1 kHz Muon and DiMuon

Back to Δm_s: Amplitude Scan

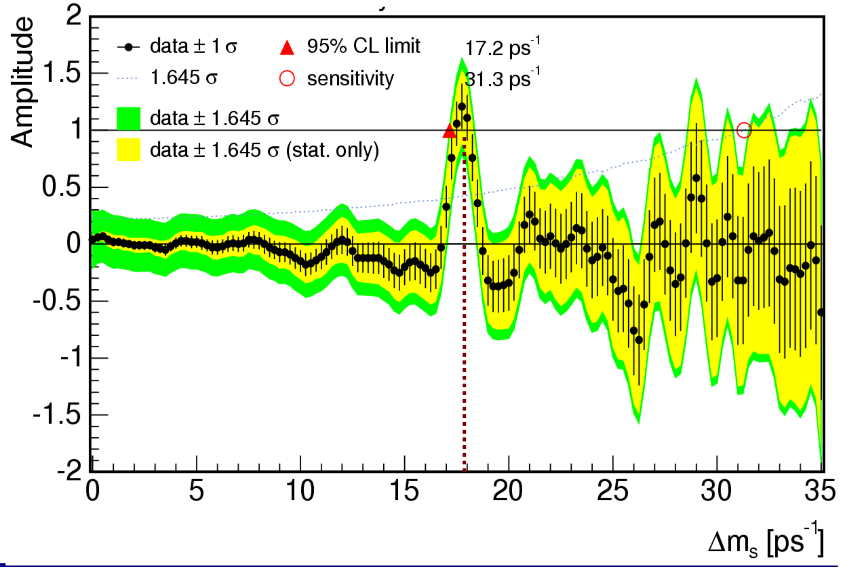
Perform frequency-domain analysis

- **scan over oscillation frequency, fit amplitude *A* as a function of the assumed frequency**
- **normalize to the expected signal amplitude**
  → *A*=1 at true mixing frequency, *A*~0 elsewhere
- **useful method for combining results from different experiments when no clear signals observed**
- **similar method applied for Higgs searches now**



CDF (2006, 1fb^{-1})

- **clear signal at Δm_s = 17.75 ps^{-1}**
  → statistical significance A/σ_A = 6.05
- **lower limit at 95 % CL: Δm_s = 17.2 ps^{-1}**
  → frequency below which $A+1.645\cdot\sigma_A < 1$
- **sensitivity: 31.3 ps^{-1}**
  → value for which $1.645\cdot\sigma_A = 1$



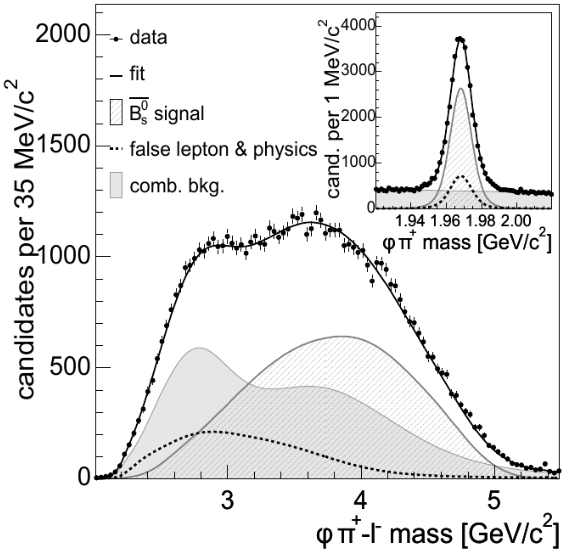
Δm_s at CDF

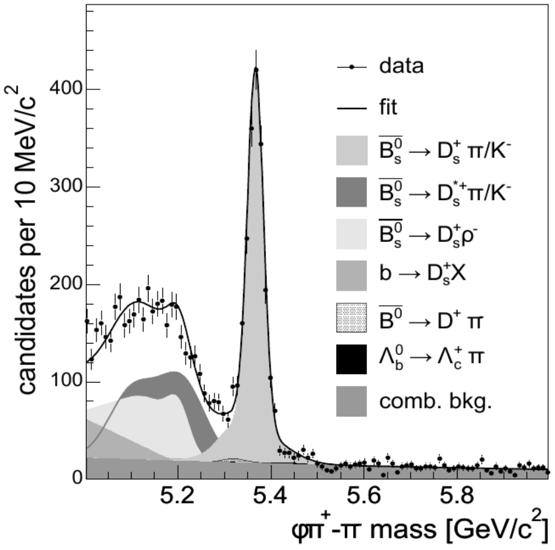
Semi-leptonic decays:

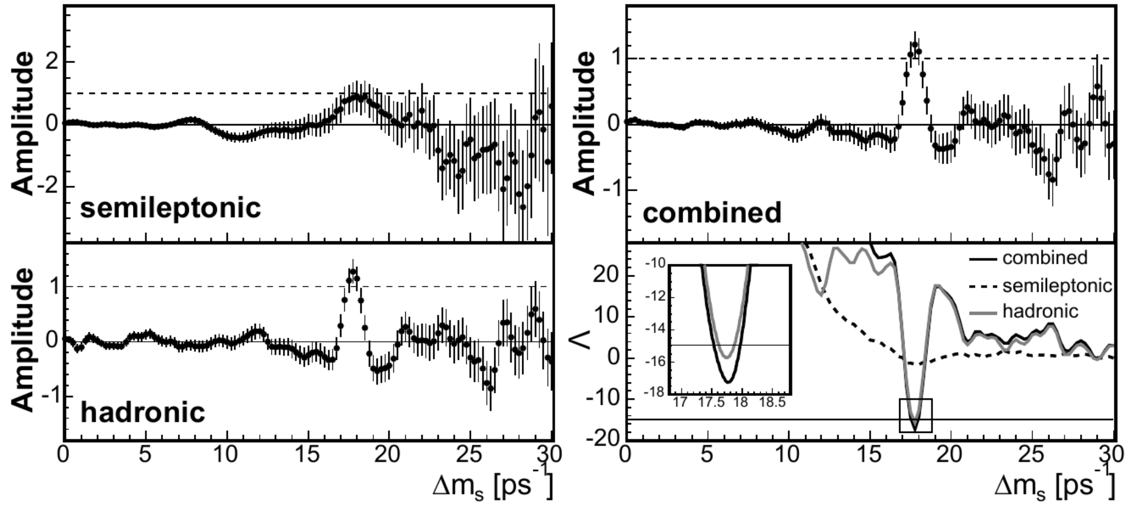
- $B^0_s \rightarrow D^-_s \ell^+ \nu_\ell$ with
  $D_s^- \rightarrow \phi\,\pi^-$, $K^{*0} K^-$ or $\pi^-\pi^+\pi^-$
- B flavour from lepton charge
- reasonable branching fraction
- but neutrino not reconstructed
  - limits proper time resolution

Hadronic decays:

- $B^0_s \rightarrow D^-_s \pi^+$, $B^0_s \rightarrow D^-_s 3\pi$ with
  $D_s^- \rightarrow \phi\,\pi^-$, $K^{*0} K^-$ or $\pi^-\pi^+\pi^-$
- B flavour from fast pion charge
- smaller branching fraction
- but all particles reconstructed







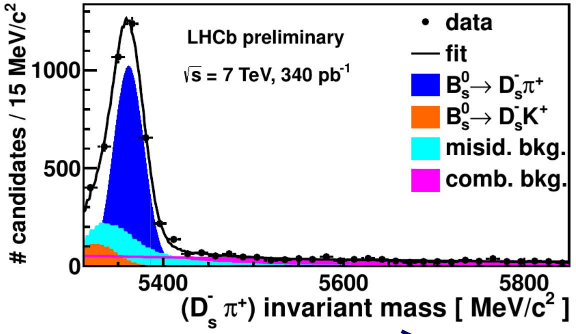
$$\Delta m_s = 17.75 \pm 0.10(\text{stat}) \pm 0.07(\text{syst})\ \text{ps}^{-1}$$

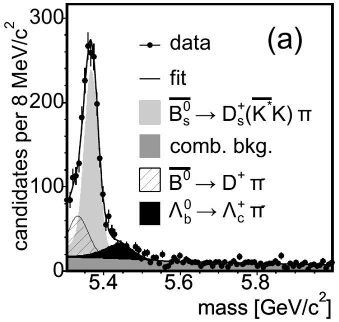
[PRL 97 (2006) 242003]

Δm_s at LHCb

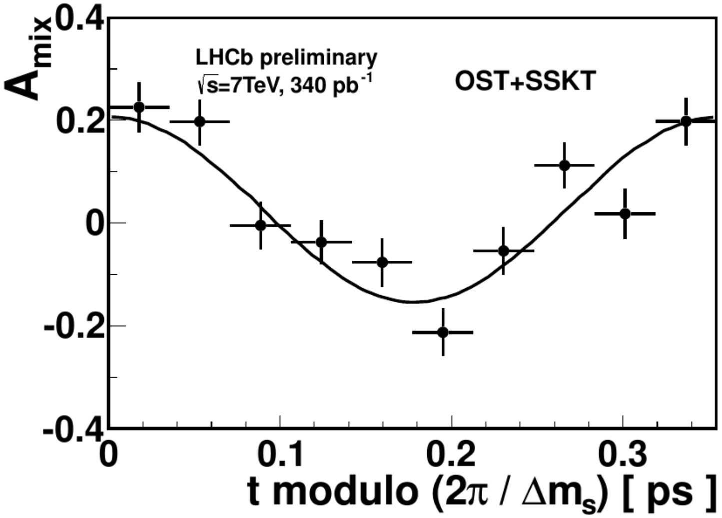
Analysis strategy inspired by CDF

- but look only at fully reconstructed hadronic decays $B^0_s \to D^-_s \pi^+$ to fully exploit excellent proper-time resolution
- employ opposite-side tagging and same-side kaon tagging algorithms





	LHCb	CDF
signal event yields $B^0_s \to D^-_s \pi^+$	9200 in 0.34 fb^{-1}	4100 in 1 fb^{-1}
proper time resolution	45 ps	87 ps
tagging power opposite side	3.2 %	1.8 %
tagging power same side	1.3 %	3.7 %



$$\Delta m_s = 17.725 \pm 0.041 \pm 0.026 \text{ ps}^{-1}$$

`[LHCb-CONF-2011-050]` `preliminary`