B_d and B_s Oscillations at the TeVatron

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On behalf of the DØ and CDF Collaborations

B-Physics at Hadron Colliders

+ Large production rates

$\sigma(p\bar{p} \rightarrow bX, |y| < 0.6) \approx 18\mu b$

10^3 higher than at $\Upsilon(4S)$

+ Heavy and excited B states currently uniquely at Tevatron:

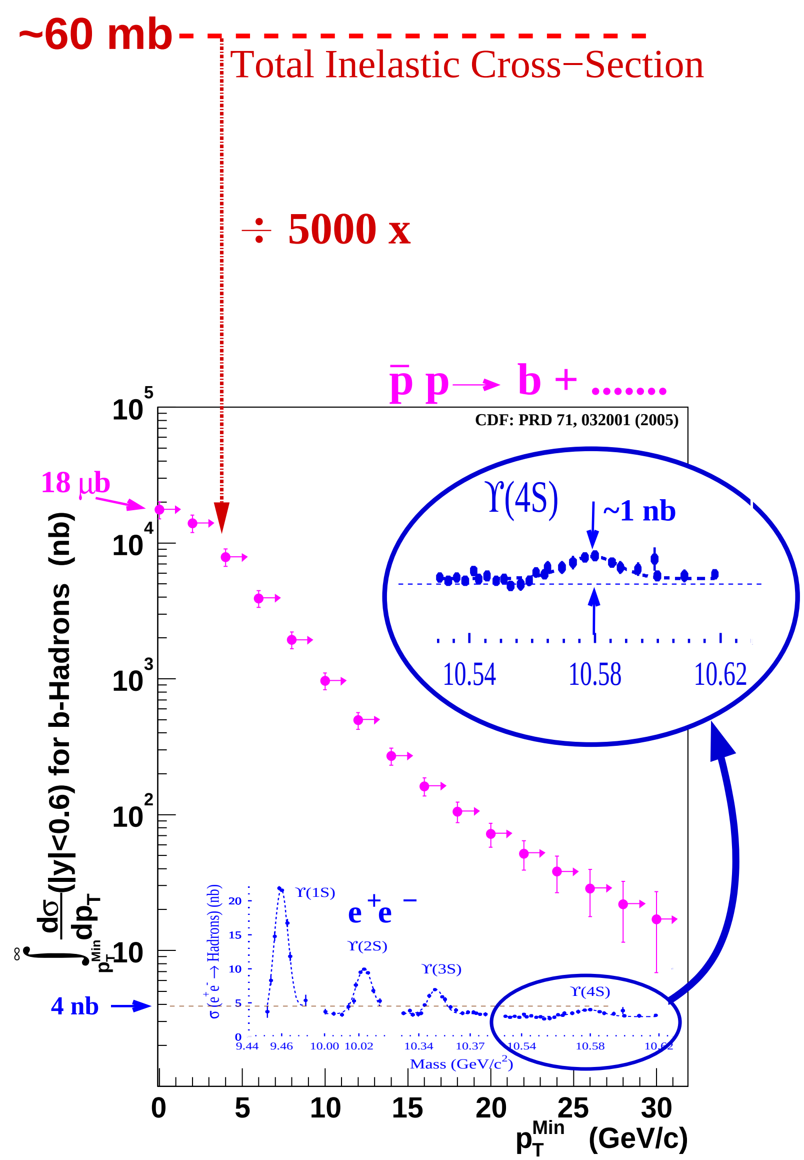
$B_s, B_c, \Lambda_b, \Xi_b, B^{**}, B_s^{**}$, ...

+ But QCD background is 10^3 higher than signal

Triggers are critical

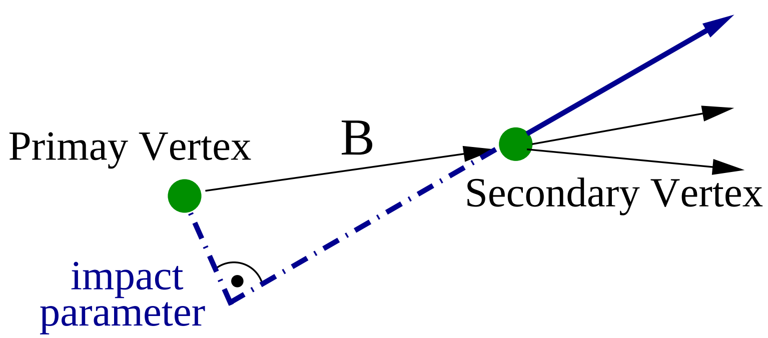
+ Event signature polluted by many fragmentation tracks;

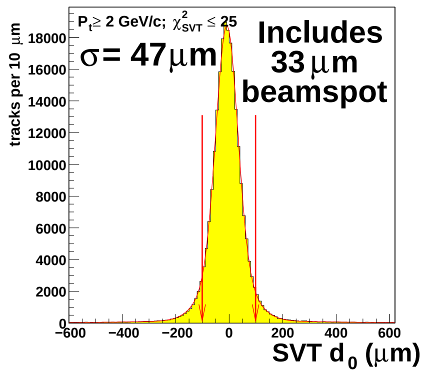
High precision vertex tracker + dedicated reconstruction algorithms needed



B Triggers

- *B* decays to $J/\psi \rightarrow \mu^+\mu^- \rightarrow$ Di-muon trigger (CDF/DØ)
  - easy trigger
  - clean environment
- Semileptonic *B* decays $\rightarrow$ Single lepton trigger (DØ) + displaced track (CDF)
  - large branching ratio
  - missing momentum (neutrino & neutrals)



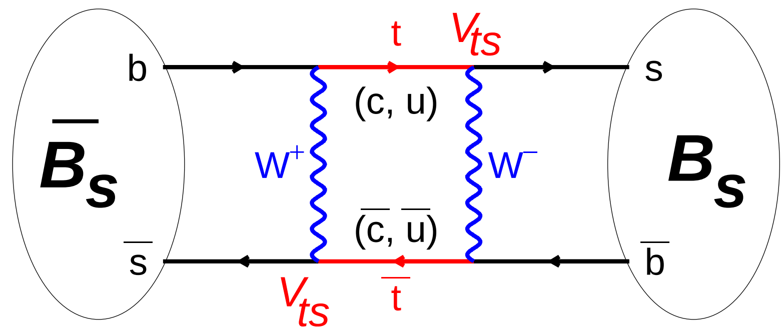


- Fully hadronic *B* decays $\rightarrow$ Two Track trigger (CDF)
  - requires displaced track trigger
  - requires fast online tracking

Theoretical Predictions for Δm

B^0/B^0_s mix through box diagram:

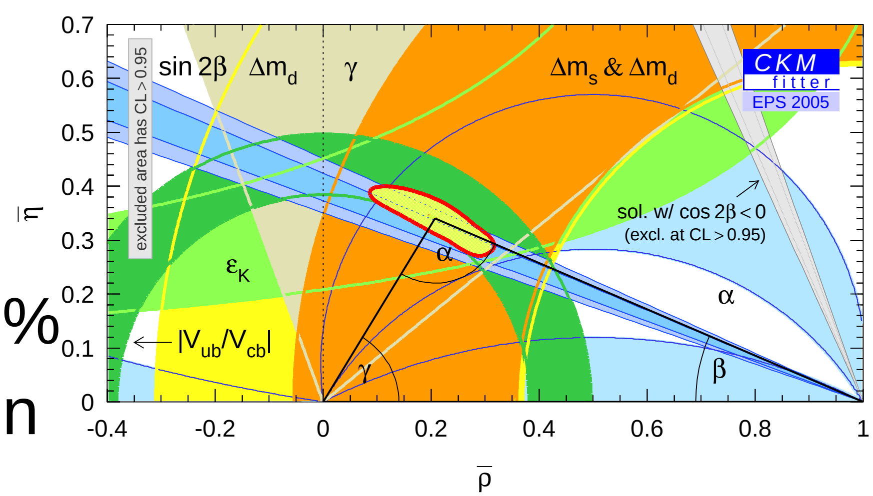
$$\Delta m_q \propto m_{B_q} \hat{B}_{B_q} f^2_{B_q} \left| V_{tb} V^*_{tq} \right|^2$$
$$q = s, d$$



Uncertainties cancel in ratio:

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

with $\xi^2 = 1.21 \pm 0.02 \, ^{+0.035}_{-0.014}$



- + measure $\frac{\Delta m_s}{\Delta m_d} \Rightarrow$ find $\frac{|V_{ts}|^2}{|V_{td}|^2}$ to 2.5%
- + Δm_d measured to high precision
- + B_s Mixing hasn't been seen!
- + Standard Model CKM fit:

$$\Delta m_s = 18.3 \, ^{+6.5}_{-1.5} \text{ ps}^{-1}$$

- + potential new physics discovery

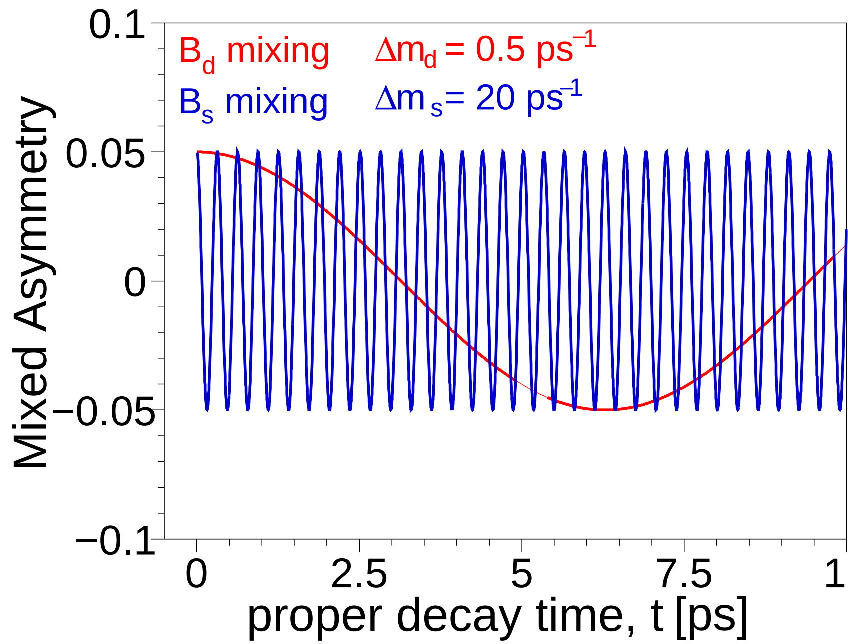
Δm_s Measurement

Why is this measurement so difficult?:

B_s Mesons Mix much faster than *B_d* Mesons!

In order to measure:

$$\mathcal{A}_{mix}(t) = \frac{N_{unmix}(t) - N_{mix}(t)}{N_{unmix}(t) + N_{mix}(t)} = \mathcal{D} * cos(\Delta m_s t)$$



Significance $\propto \varepsilon\mathcal{D}^2 \frac{S}{\sqrt{S+B}} e^{-\Delta m_s^2 \sigma_t^2/2}$

We need to:

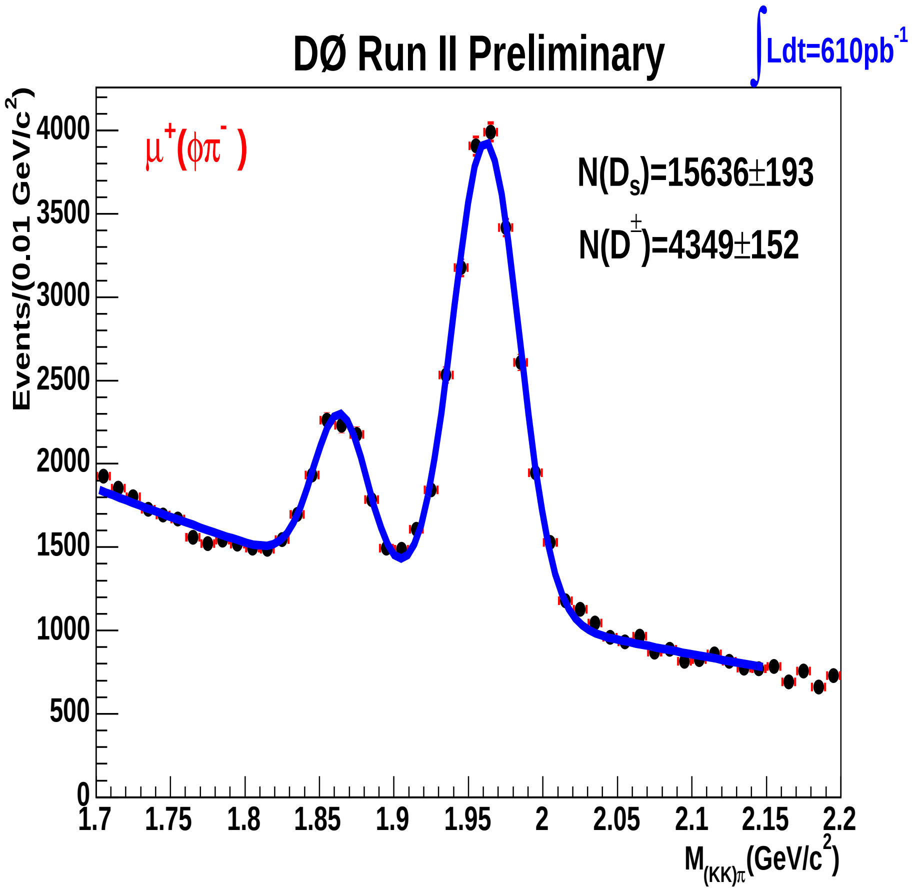
- + Reconstruct B_s signal in:
  - + hadronic modes
  - + semileptonic modes
- + Proper decay length resolution: fully reconstructed modes provide better accuracy
- + Tag the production flavor (the -key- problem in a hadron collider!): tagging power $\varepsilon\mathcal{D}^2$

  Efficiency: $\varepsilon = \frac{N_{wrong}+N_{right}}{N}$; Dilution: $\mathcal{D} = 1 - 2\frac{N_{wrong}}{N_{wrong}+N_{right}} = \frac{N_{right}-N_{wrong}}{N_{wrong}+N_{right}}$

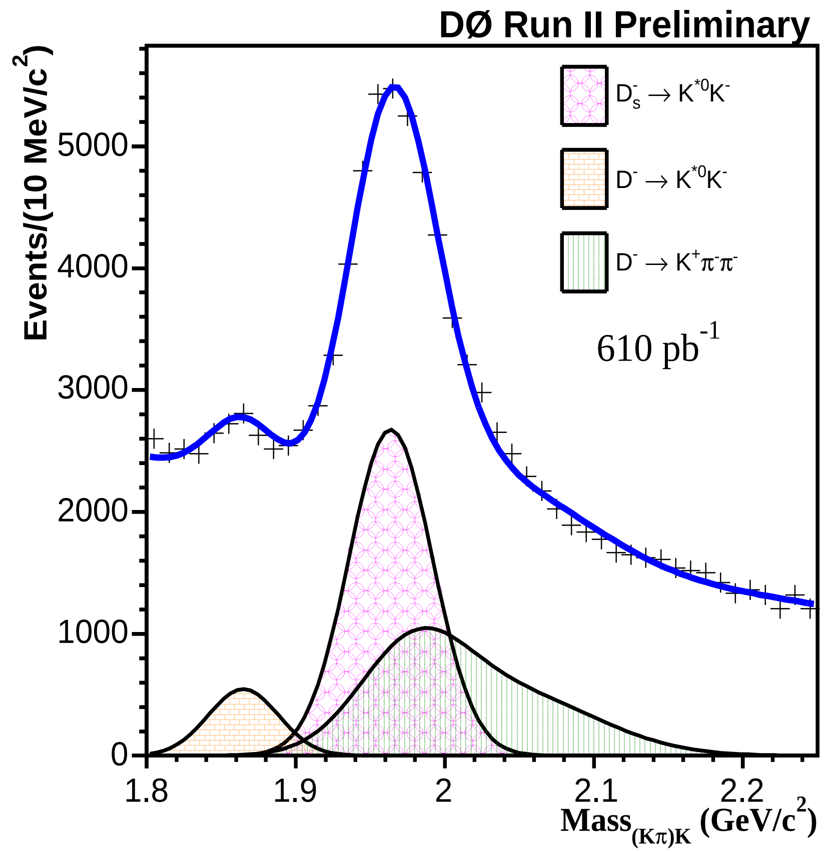
Reconstructed $B \to lDX$ Candidates (DØ)

DØ exploits high statistics μ trigger semileptonic decays: worse proper time resolution, but high statistics

$$ct = \frac{L_{xy}}{\gamma\beta};\ \gamma\beta = \frac{p_T(B)}{M(B)} = \frac{p_T(\ell D)}{M(B)} * K \text{ (K from MC)};\ \sigma_{ct} = \left(\frac{\sigma_{L_{xy}}}{\gamma\beta}\right) \oplus \left(\frac{\sigma_{\gamma\beta}}{\gamma\beta}\right) * ct$$



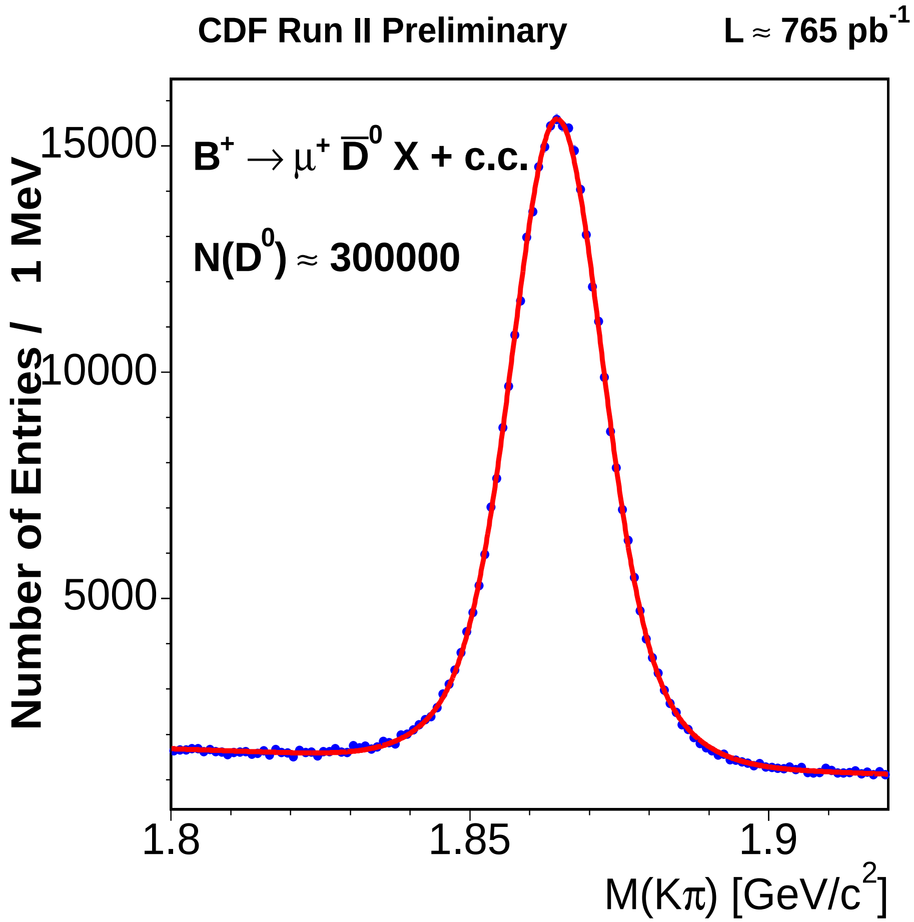
$D_s \to \phi\pi, \phi \to K^+K^-$



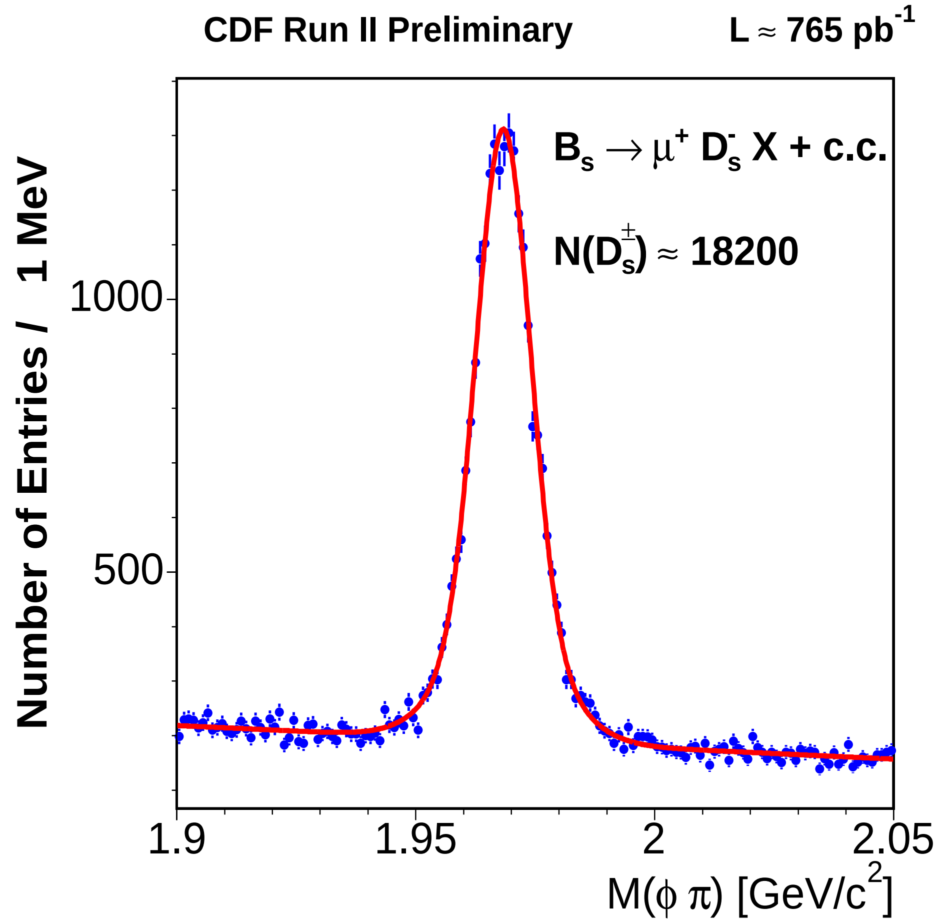
$D_s \to K^*K, K^* \to K\pi$

Reconstructed $B \to lDX$ Candidates (CDF)

The most recent analysis uses semileptonic modes collected by the Two Track Trigger, new analysis in progress with ~ 765 pb^{-1}



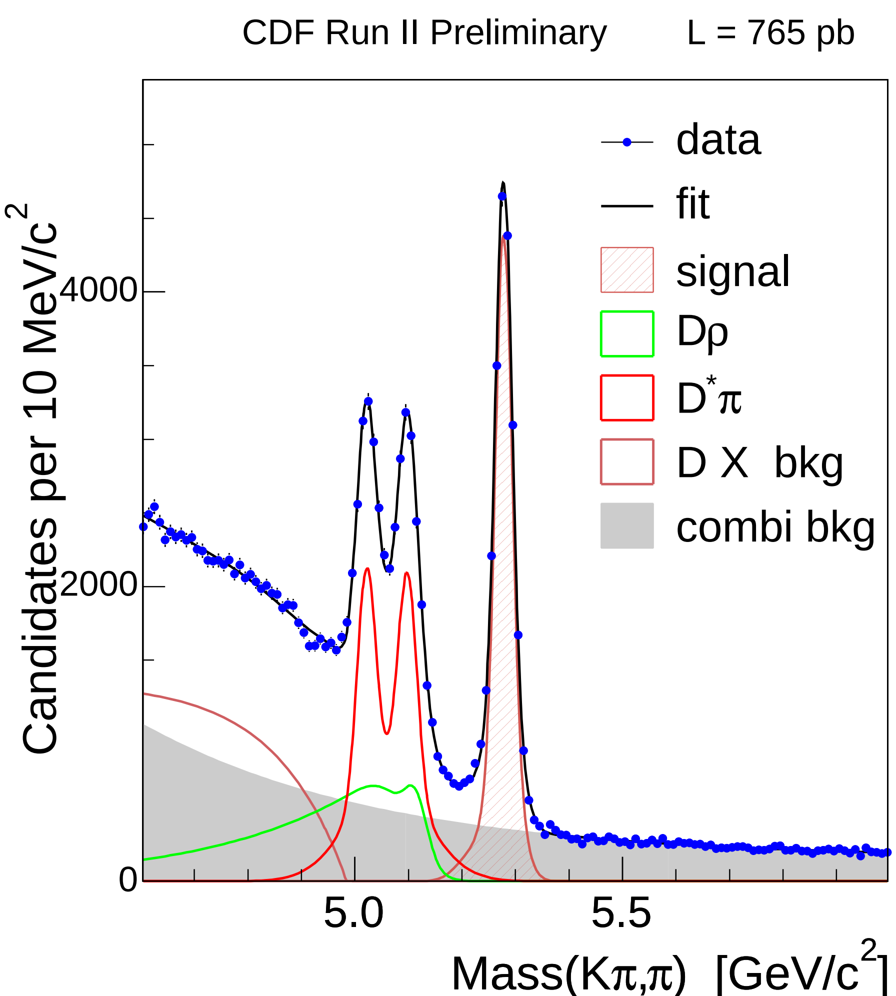
$B^+ \to \mu^+ \overline{D}^0 (K\pi) X$



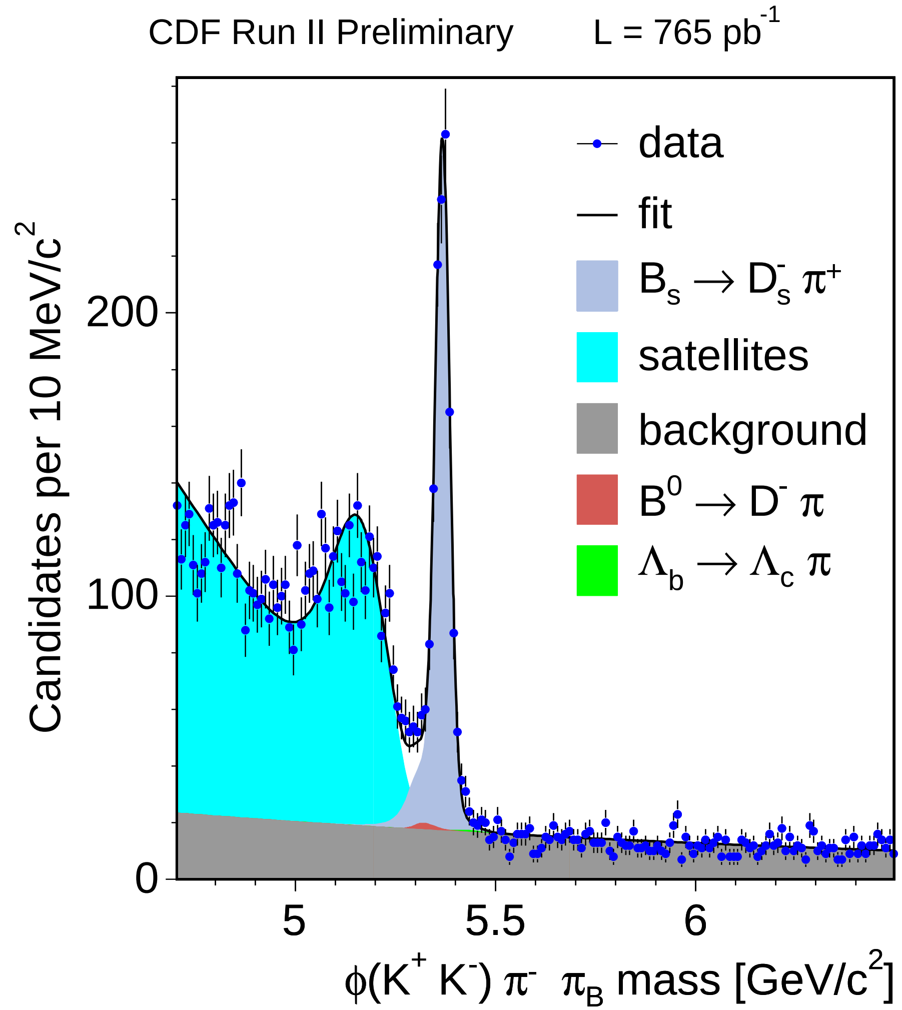
$B_s \to \mu^+ D_s^- (\phi\pi) X$

Fully Hadronic Decays (CDF)

More than 2300 B_s signal candidates with ~ 765 pb^{-1}



$B^+ \to \overline{D}^0(K\pi)\pi^+$



$B_s \to D_s^-(\phi\pi)\pi^+$

Proper Decay Time Reconstruction

Algorithm:

- + measure transverse momenta p_T of all decay products
- + measure the decay length L_{xy} from the P.V. to decay vertex
- + boost meson back to its rest frame

Fully reconstructed decays $B_s \to D_s(3)\pi$

- + all daughters reconstructed
- + formula for proper decay time: $ct = L_{xy}\frac{m_B}{p_T}$

Inclusively reconstructed decays $B_s \to \ell\nu D_s X$

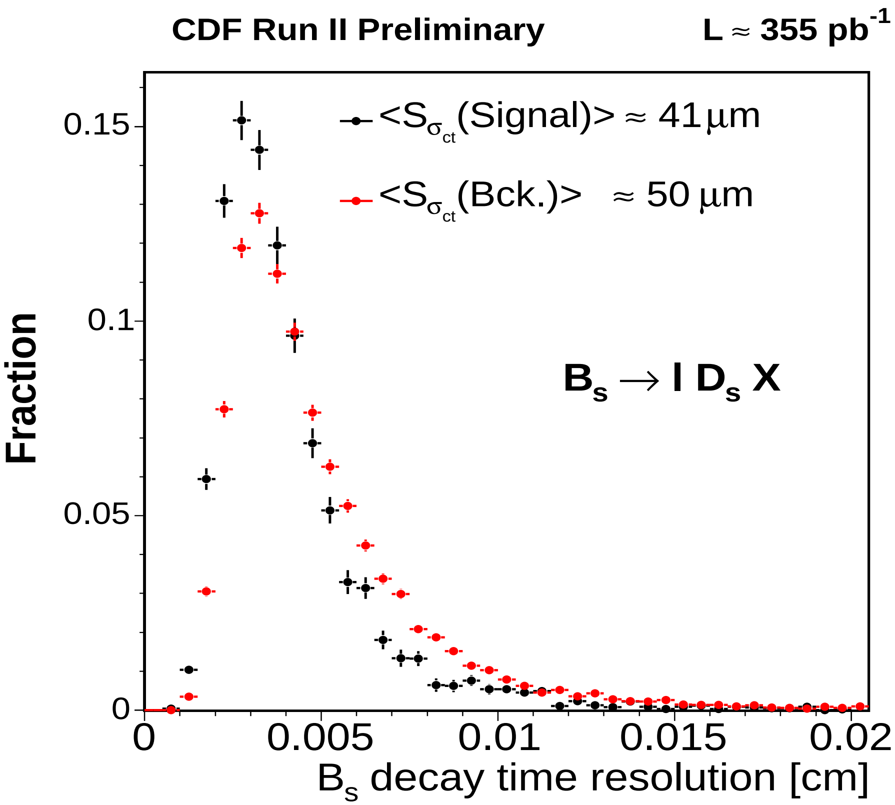
- + some decay products escape detection (ν, neutrals, etc)
- + missing momentum $\Rightarrow$ increased ct error (σ_{ct})
- + formula for proper decay time:

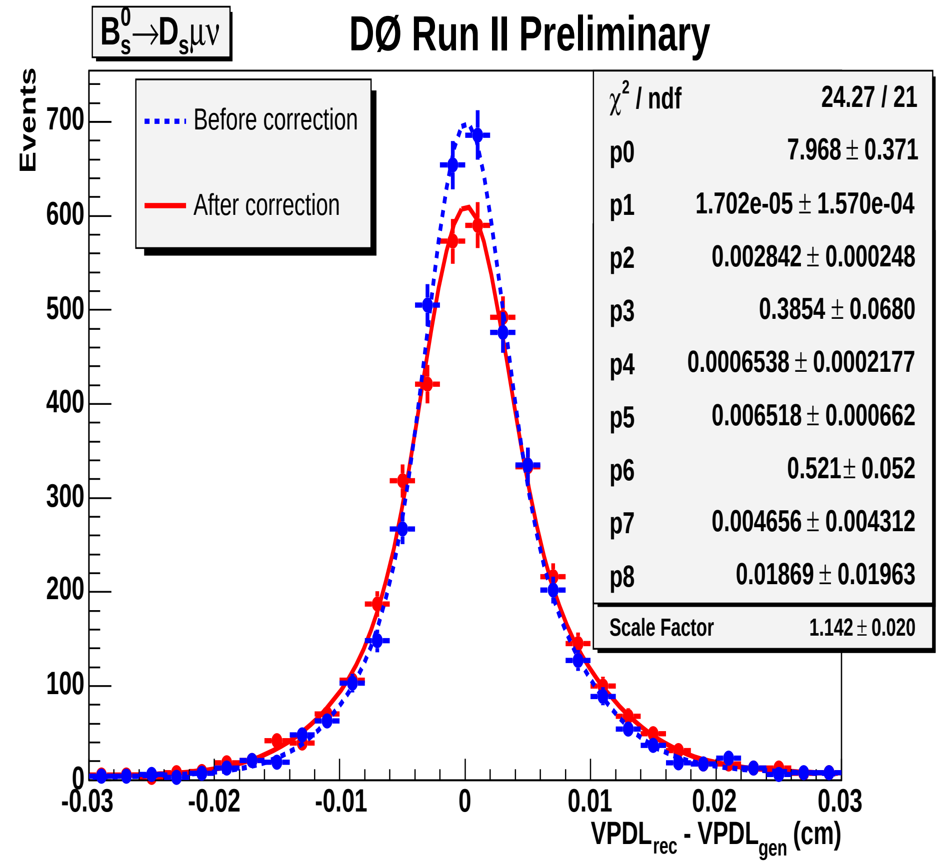
$$ct = L_{xy}\frac{m_B}{p_T} \cdot K, \quad \text{where } K = \left\langle \frac{p_T^{\ell D}}{p_T^B} \right\rangle \text{ from MC}$$

σ_{ct} Resolution Studies

The proper decay length resolution is the limiting factor at high Δm_s

Studies on this topic play a very important role!





σ_{ct}: signal/background (CDF)

σ_{ct}: before/after tuning (DØ)

B Flavor Tagging

Opposite Side Tagging:

- Jet-Charge-Tagging: (used at CDF/DØ)
  sign of the weighted average charge of opposite B-Jet

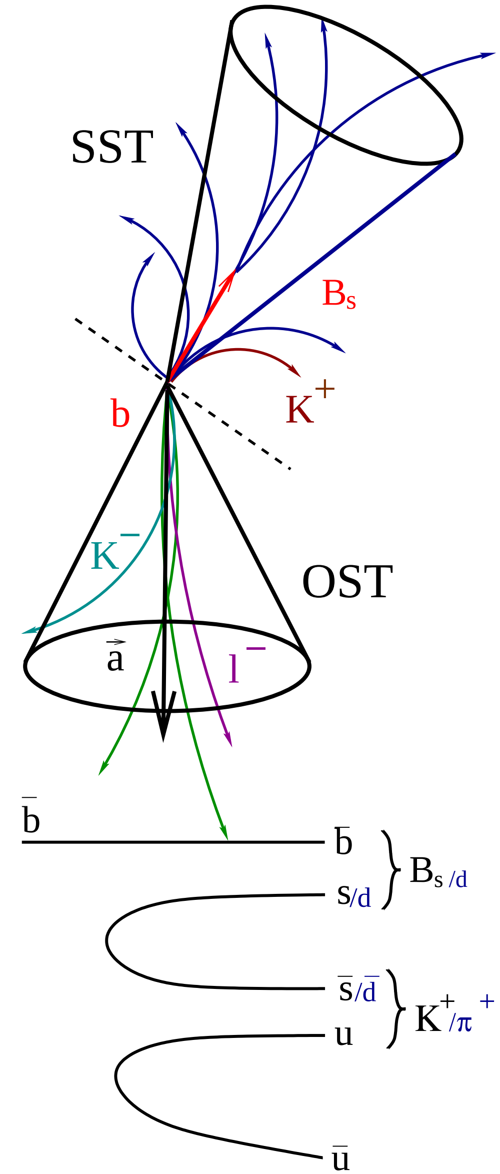
- Soft-Lepton-Tagging: (used at CDF/DØ)
  identify soft lepton (e, μ) from semileptonic decay of opposite B: $b \to l^- X$ (BR $\approx$ 20%),

  Dilution due to $\bar{b} \to \bar{c} \to l^- X$ and oscillation

- Kaon-Tagging: (in progress at CDF)
  due to b$\to$c$\to$s it is more likely that a $\bar{B}$ meson contains a K^- than a K^+ in the final state (particle ID is mandatory)

Same Side Tagging : (in progress at CDF)

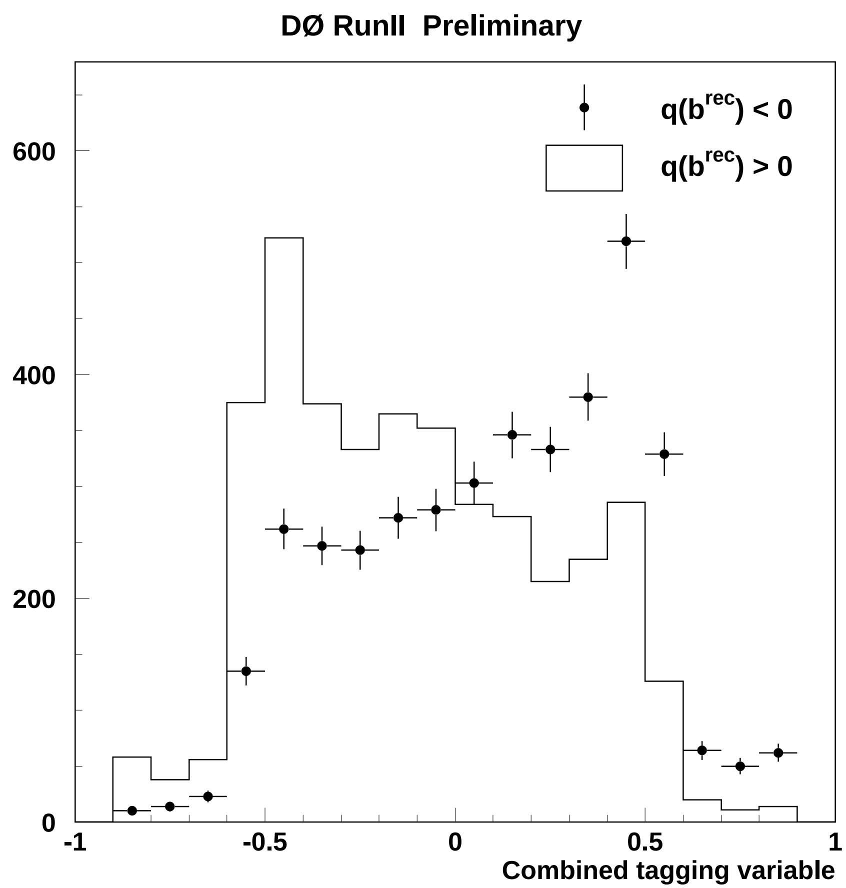
- $B_{s/d}$ is likely to be accompanied close by a K^+/π^+ (particle ID is mandatory)



Opposite Side Taggers at DØ

Combined Tagger:

- + Soft Muon
- + Soft Electron
- + Secondary vertex



Tagger	εD^2 (%)
Muon	1.27±0.13
Electron	0.28±0.06
Sec. Vert.	0.54±0.08
Combined ($\|d\| > 0.3$)	1.94±0.14

Tagging performance measured in $\mu D^{0/*}$ candidates

Opposite Side Taggers at CDF

tagger	εD^2 hadronic (%)	εD^2 semileptonic (%)
muon	0.56±0.09±0.03	0.55±0.05±0.02
electron	0.26±0.05±0.02	0.31±0.03±0.01
JQ/vertex	0.23±0.07±0.01	0.25±0.03±0.01
JQ/displaced	0.35±0.08±0.02	0.37±0.05±0.02
JQ/high-p_T	0.15±0.06±0.02	0.08±0.02±0.01
combined	1.55±0.16±0.05	1.55±0.08±0.03

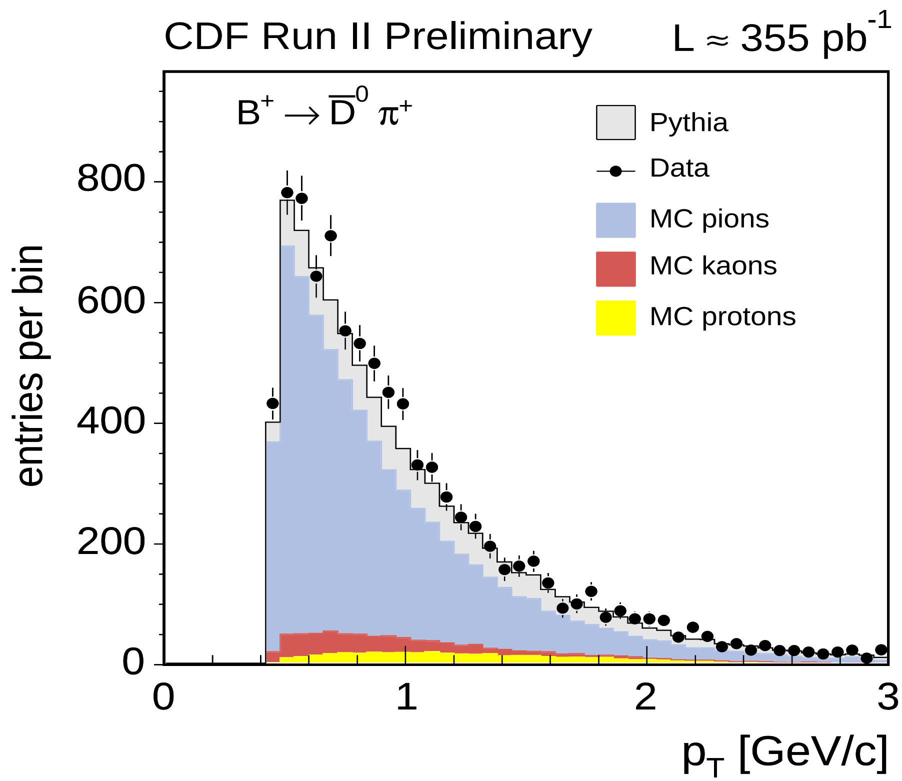
+ Taggers are mutually exclusive
+ 3 different jet types in Jet Charge (JQ) tagger
+ Performance on hadronics and semileptonics consistent within errors

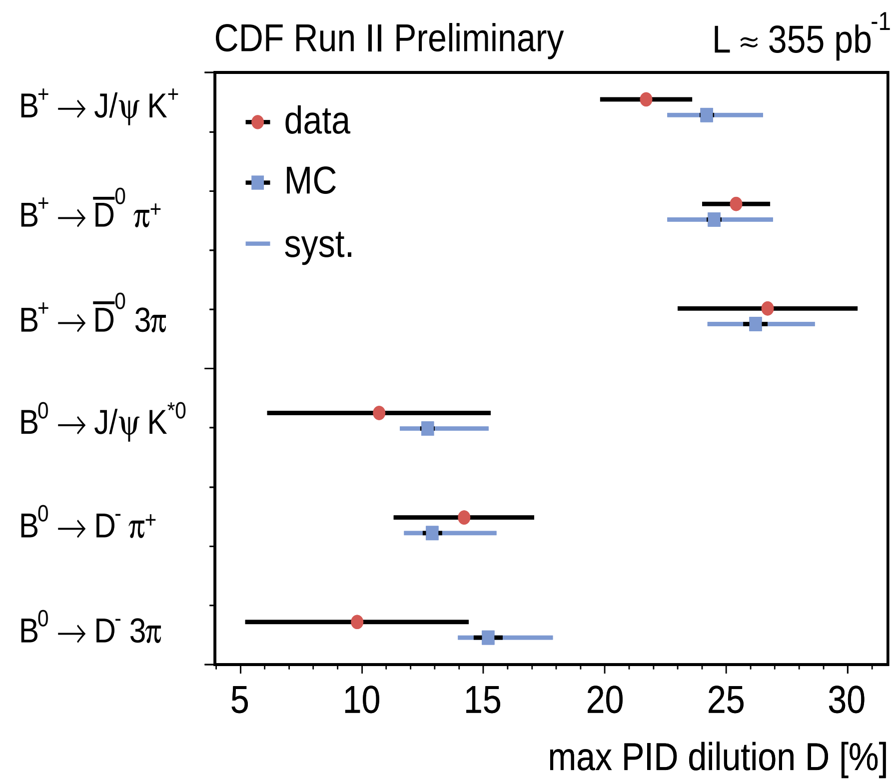
Same Side Kaon Tagger at CDF (I)

Have to rely on Monte Carlo for prediction of SS(K)T performance for B_s decays!

+ Extensive data/MC comparisons on all tagging related quantities
+ Different tagging algorithms probe different aspects of the fragmentation

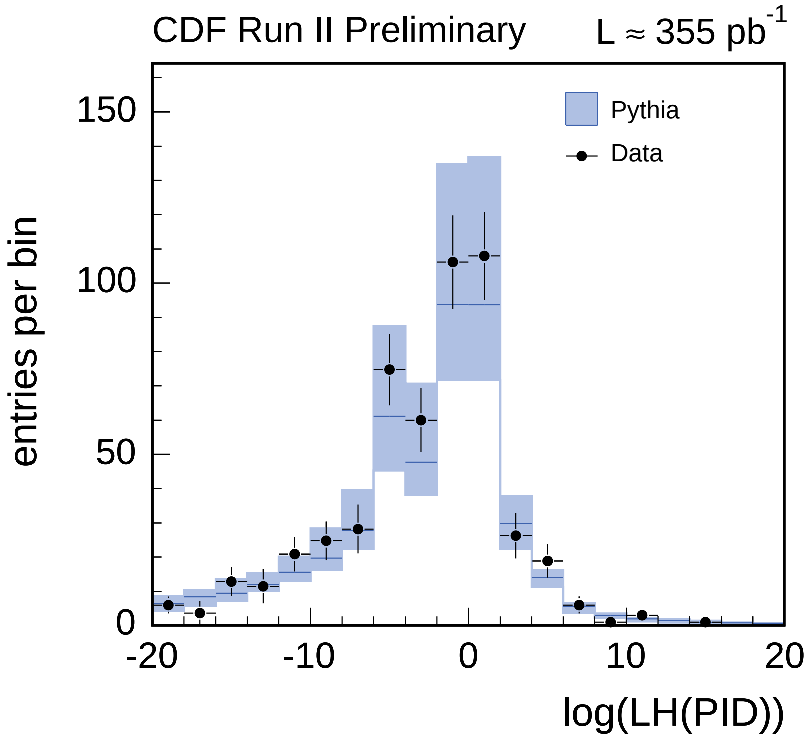
Very good agreement in high statistics B^+ and B^0 modes in all checks!





Same Side Kaon Tagger at CDF (II)

Small discrepancies covered by systematics



Systematic studies cover:

- \+ Fragmentation Model
- \+ $b\bar{b}$ Production Mechanisms
- \+ B^{**} content
- \+ Detector/PID resolution
- \+ Multiple interactions
- \+ PID content around B
- \+ Data/MC agreement

Select the most likely kaon track (PID *) as tagging track

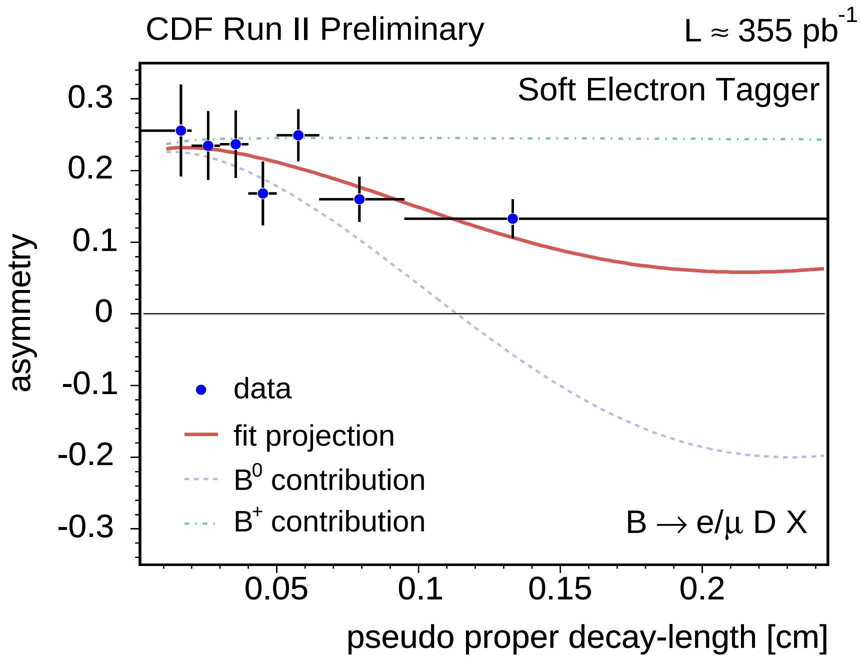
Final evaluation of the tagging performance in progress

*) TOF & dE/dx are used for particle identification

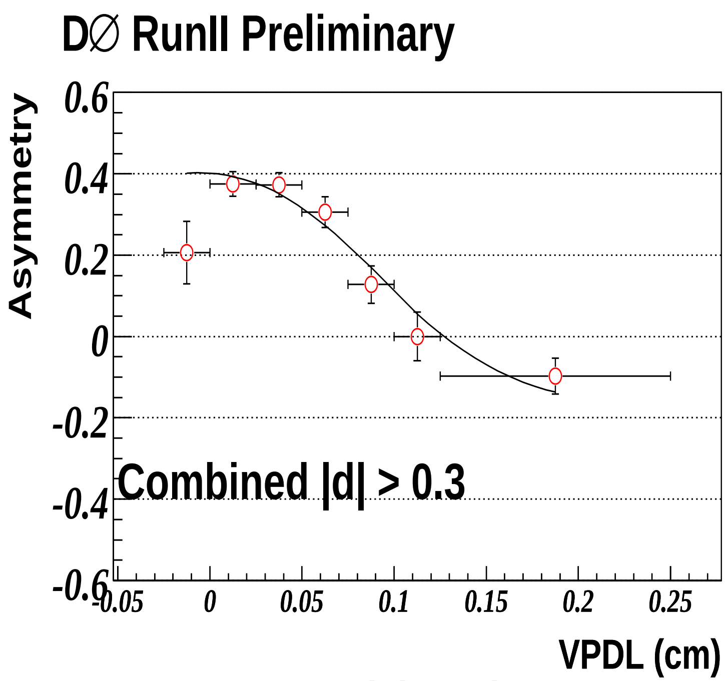
Crucial Test of the Whole "Machinery": B_d Mixing

- For setting limit on Δm_s, knowledge of tagger performance is crucial $\rightarrow$ measure tagging dilution in kinematically similar B^0/B^+ samples (for OST)
- Δm_d and Δm_s fit is very complex, $>$ 1000 parameters
  - combining several B flavor and several decay modes
  - combining several taggers
  - mass and lifetime templates for various backgrounds

Δm_d measurement is very important to test the fitter



CDF: Soft Electron Tagger



DØ: Combined Tagger

Δm_d Measurement

Combined taggers (semileptonic channels) DØ:

$$\Delta m_d = 0.498 \pm 0.026(syst) \pm 0.016(stat) ps^{-1}$$

Combined opposite side taggers (semileptonic channels) CDF:

$$\Delta m_d = 0.511 \pm 0.020(syst) \pm 0.014(stat) ps^{-1}$$

Combined opposite side taggers (hadronic channels) CDF:

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

Results consistent with world average ($\Delta m_d = 0.508 \pm 0.004$)

The whole framework ready to fit for B_s Oscillations...

Fourier analysis

Two domains to fit for oscillation:

- \+ time: fit for a cos-wave
- \+ frequency: examine f-spectrum

Time domain approach:

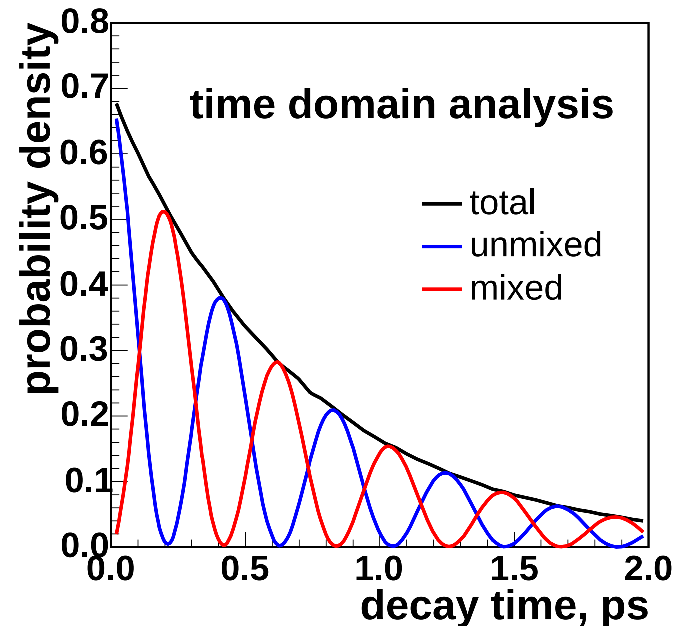
- \+ good old method
- \+ fit for Δm_s in $P(t) \sim (1 \pm D \cos \Delta m_s t)$

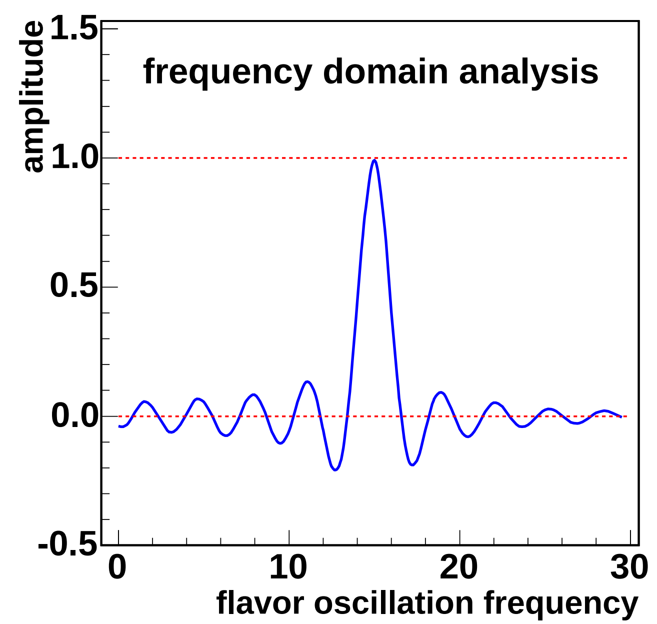
Frequency domain approach:

- \+ introduce amplitude:

  $P(t) \sim (1 \pm \mathcal{A} D \cos \Delta m_s t)$

- \+ fit for $\mathcal{A}$ at different Δm_s
- $\Rightarrow$ obtain frequency spectrum
- \+ method is called amplitude scan
- \+ traditionally used for B_s mixing search
- $\Rightarrow$ easy to combine experiments
- \+ true $\Delta m_s \Rightarrow \mathcal{A} = 1$, else $\mathcal{A} = 0$

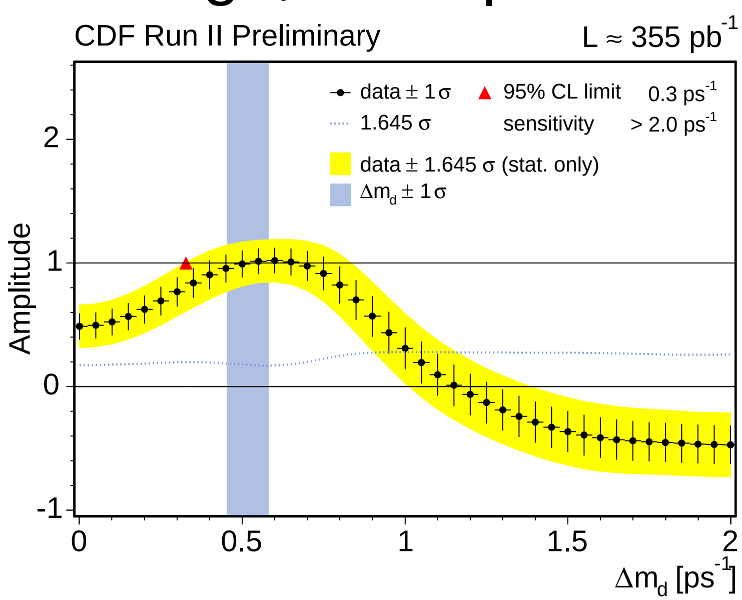




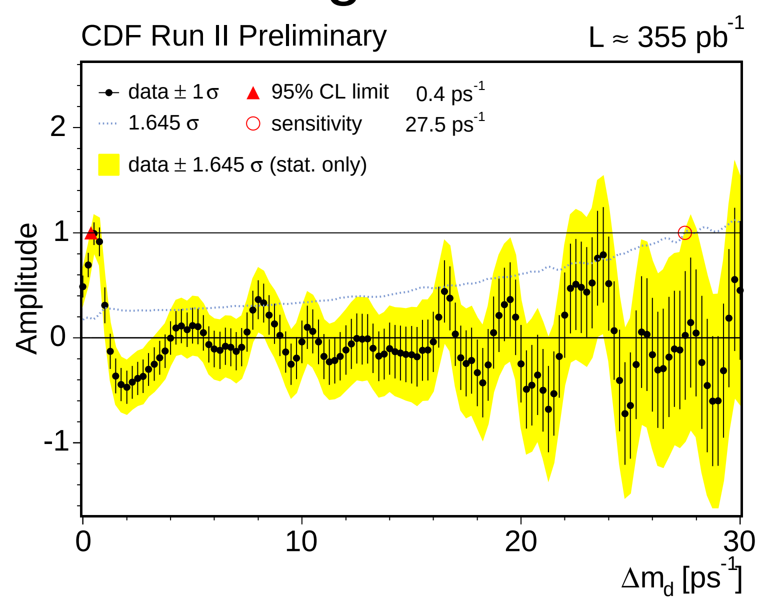
Amplitude scan notations

Example of B^0 mixing:

- + amplitude error bars: come from unbinned likelihood fit
- + yellow: 1.645σ around data points defines 95% CL region
- + Δm values where $\mathcal{A} + 1.645\sigma < 1$ are excluded at 95% CL
- + dashed line: 1.645σ as a function of Δm
- + sensitivity: the Δm where $1.645\sigma = 1$
- + on average, we expect to observe mixing within sensitivity

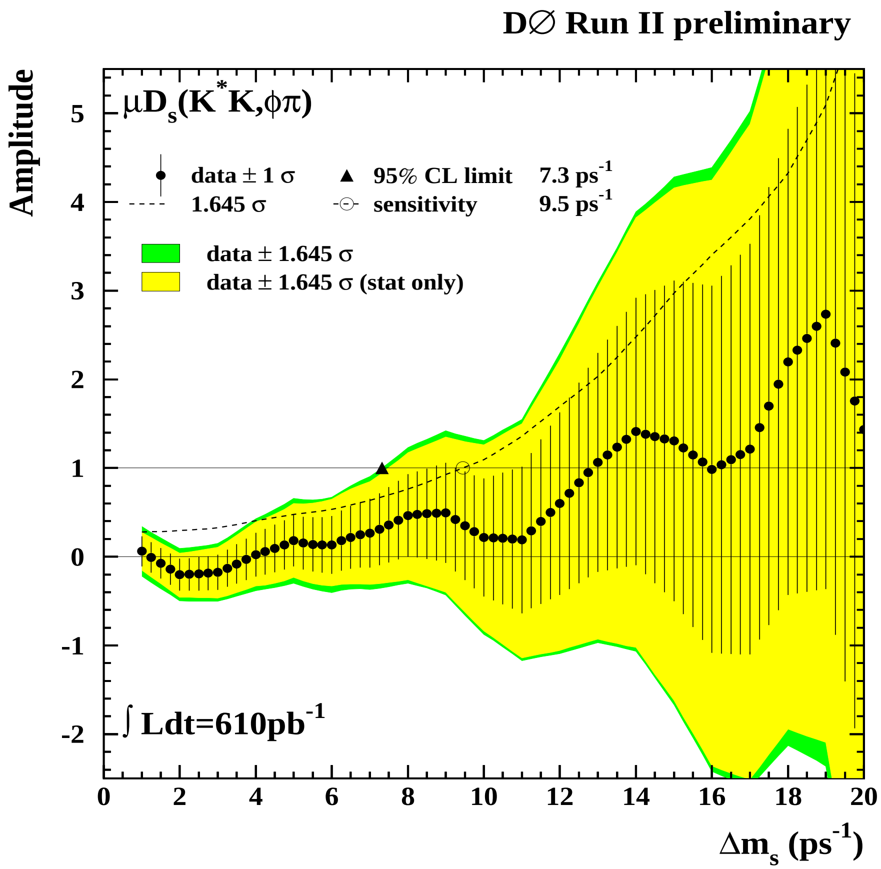


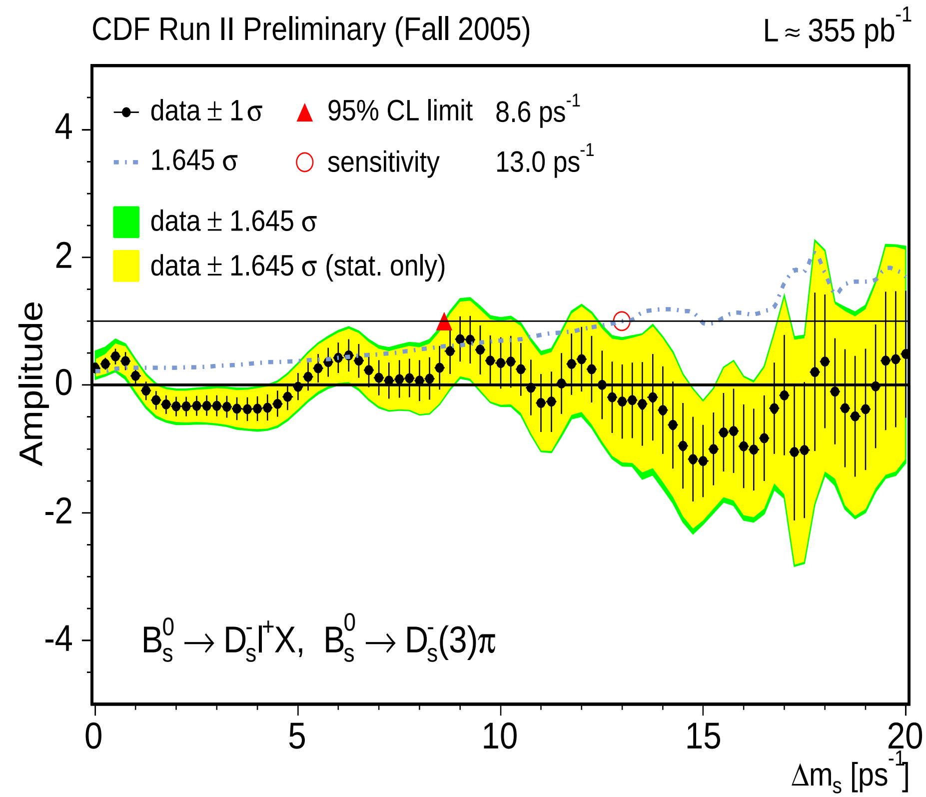
narrow range $\mathcal{A}$ scan



same analysis, wider $\mathcal{A}$ range

B_s Mixing Limits in Run II





DØ:
Observed Limit at 95% C.L.: 7.3 ps^{-1}
(Sensitivity: 9.5 ps^{-1})

CDF:
Observed Limit at 95% C.L.: 8.6 ps^{-1}
(Sensitivity: 13.0 ps^{-1})

World Average:
Observed Limit at 95% C.L.: 16.6 ps^{-1} (Sensitivity: 20.0 ps^{-1})

Coming Improvements

DØ:

- Addition of other taggers
- Use of other semileptonic decay modes
- Use of hadronic decay modes
- Unbinned fitting procedure (!!)

CDF:

- Improved selection in hadronic modes using Neural Networks
- Use partially reconstructed hadronic modes
- Use semileptonic events from other triggers
- Improve vertex resolution
- Use Same-Side Kaon tagger (!!!)

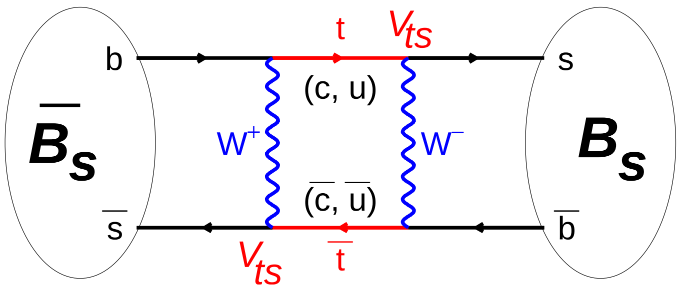
Use all the data in our hands!!!

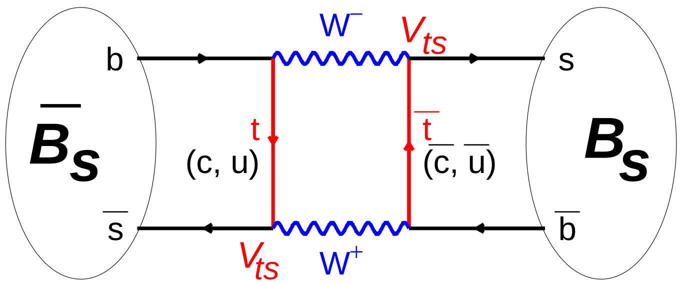
Summary

- Tevatron experiments are in unique position to exploit B_s system
- Δm_d results are quite robust and consistent with world average
- Δm_s results:
  - limit at 7.3 (8.6) ps^{-1} at DØ(CDF)
  - sensitivity at 9.5 (13.0) ps^{-1} at DØ(CDF)
- Effect on the World 2004 results:
  - limit $14.6 \rightarrow 16.6$ ps^{-1}
  - sensitivity $18.2 \rightarrow 20.0$ ps^{-1}
- Significant potential for improvements!!!

Back Up Slides

Neutral B Meson Mixing

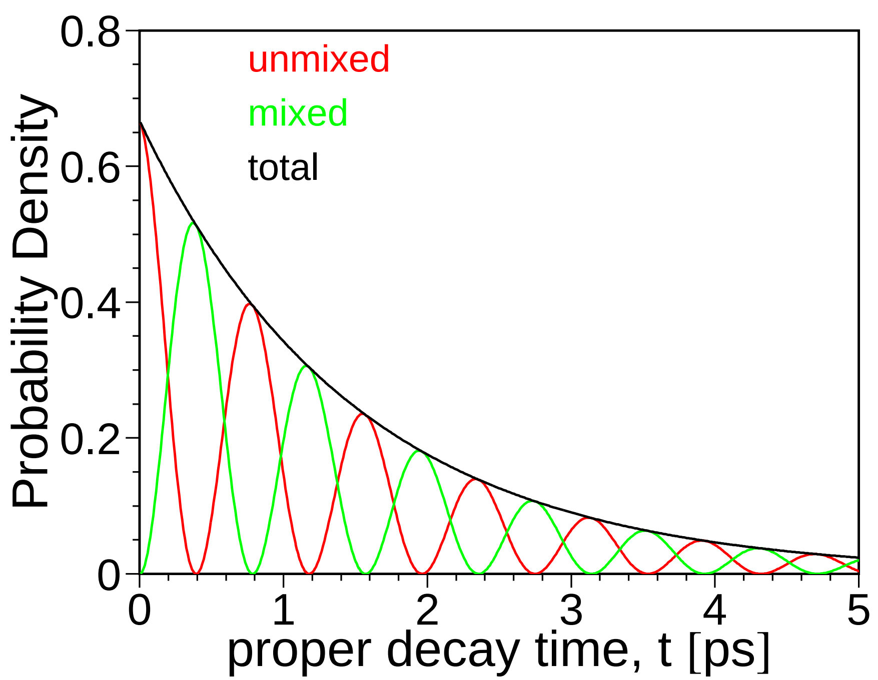




Two-state mixing system

- "heavy" and "light" weak eigenstates
- B and $\overline{B}$ mass eigenstates

$$|B_s\rangle = \frac{1}{\sqrt{2}}(|B_{s,H}\rangle + |B_{s,L}\rangle)$$
$$|\overline{B}_s\rangle = \frac{1}{\sqrt{2}}(|B_{s,H}\rangle - |B_{s,L}\rangle)$$



Solution in proper time

$$P(t)_{B^0\to B^0} = \frac{1}{2\tau}e^{-t/\tau}(1+\cos\Delta m t)$$
$$P(t)_{B^0\to \overline{B^0}} = \frac{1}{2\tau}e^{-t/\tau}(1-\cos\Delta m t)$$

- mixing par. $\Delta m = m_H - m_L$

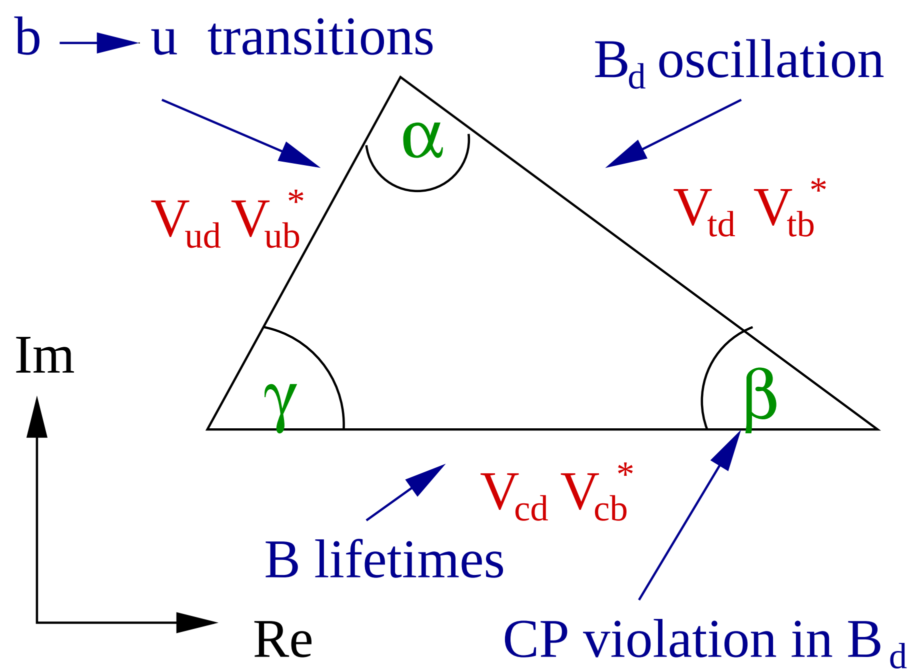
CKM Matrix

What is the origin of flavor symmetry breaking?
$\rightarrow$ quark mixing, CKM matrix

quark mass eigenstates
$\neq$ weak interaction eigenstates

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$V * V^{\dagger} = 1$$



CKM elements not predicted by SM
B decays measure 5 CKM elements

Goal: Measure sides/angles of CKM triangle sides in all possible ways

Δm_s: World Average