$B_s - \bar{B}_s$ - Oscillation @ CDF II

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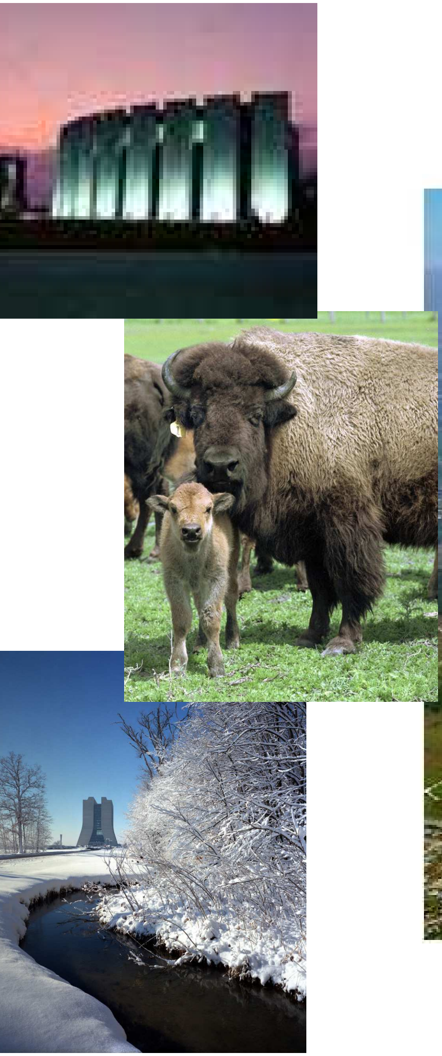
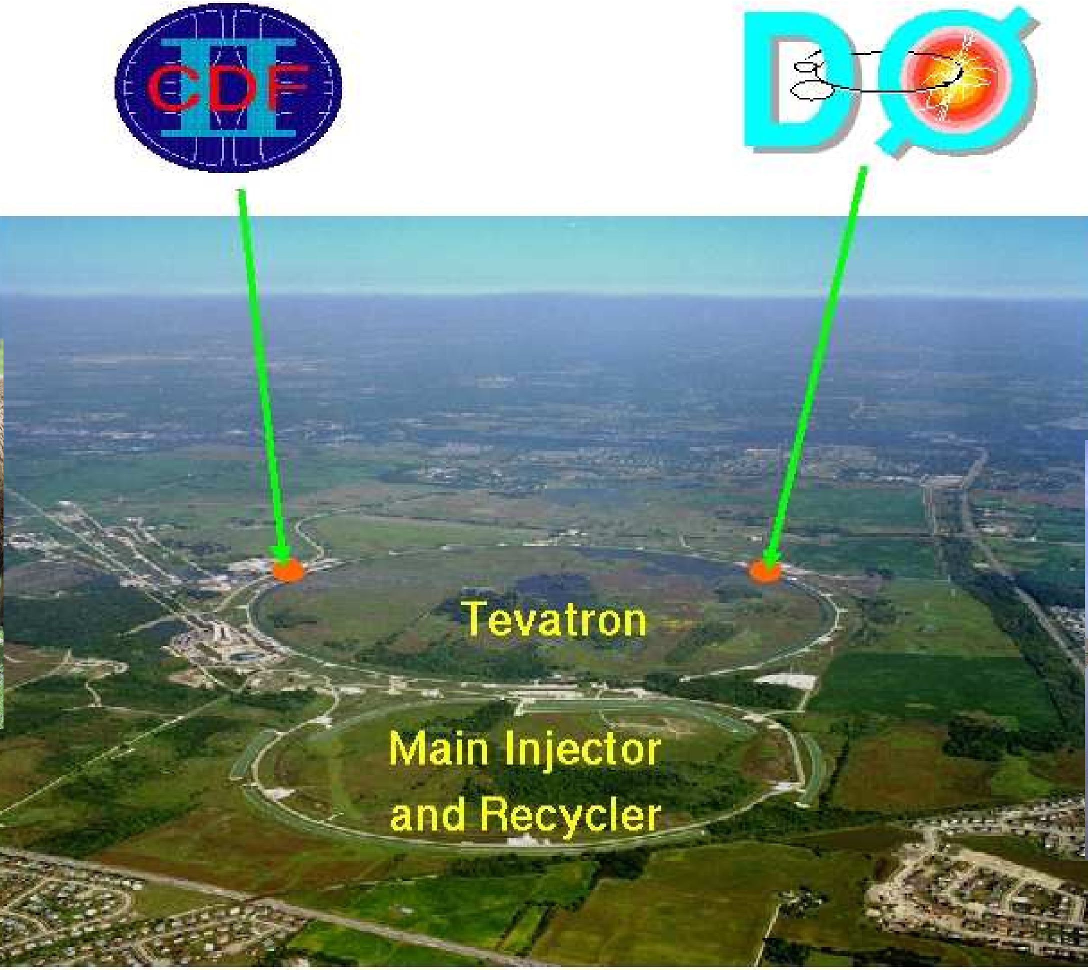
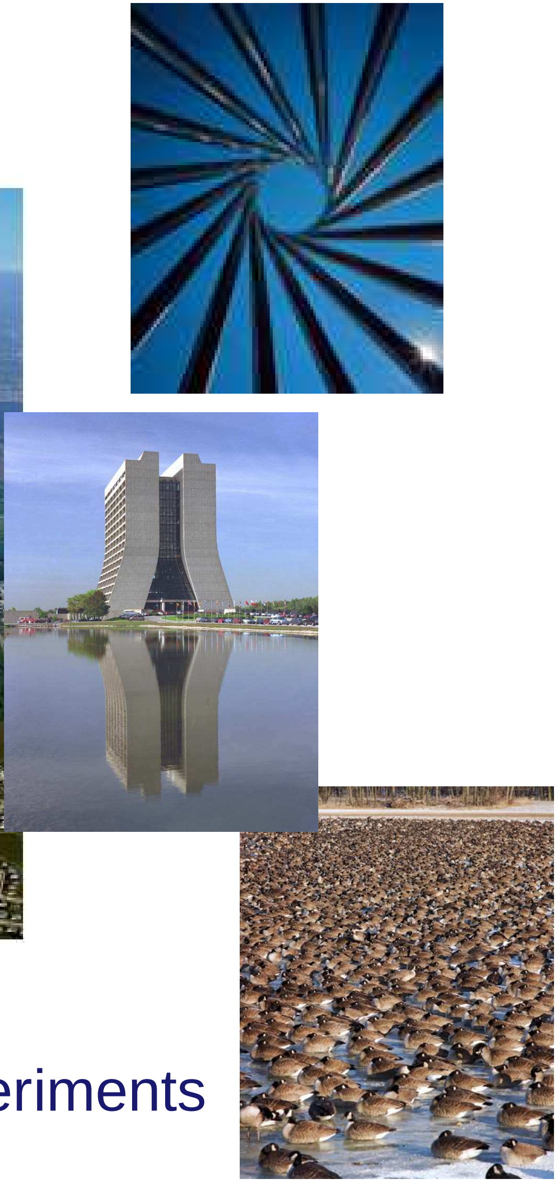
for the CDF Collaboration

DESY, 13/14th June 2006

Tevatron





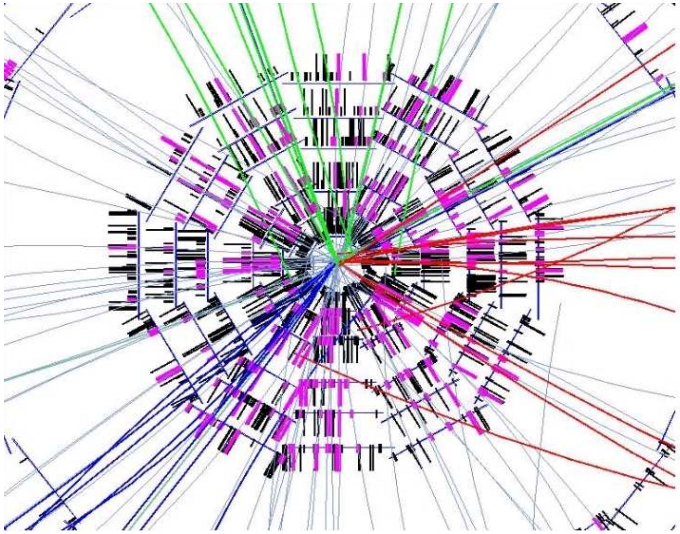


$p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV observed by two experiments

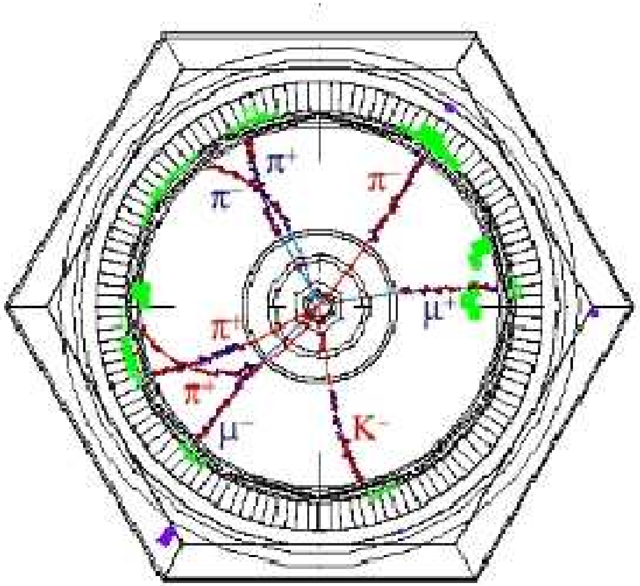
CDF & D0

B Physics @ Hadron Colliders

+ Large cross section
  $\sigma(p\bar{p} \rightarrow bX) \approx 100\ \mu b$
  $\leftrightarrow B$ factories: $\approx$ 1 nb
+ High center-of-mass energy
+ Heavy & excited B's,
  e.g. B_s, $B_c, \Lambda_b, \Xi_b, B^{**}, B_s^{**}$, ...

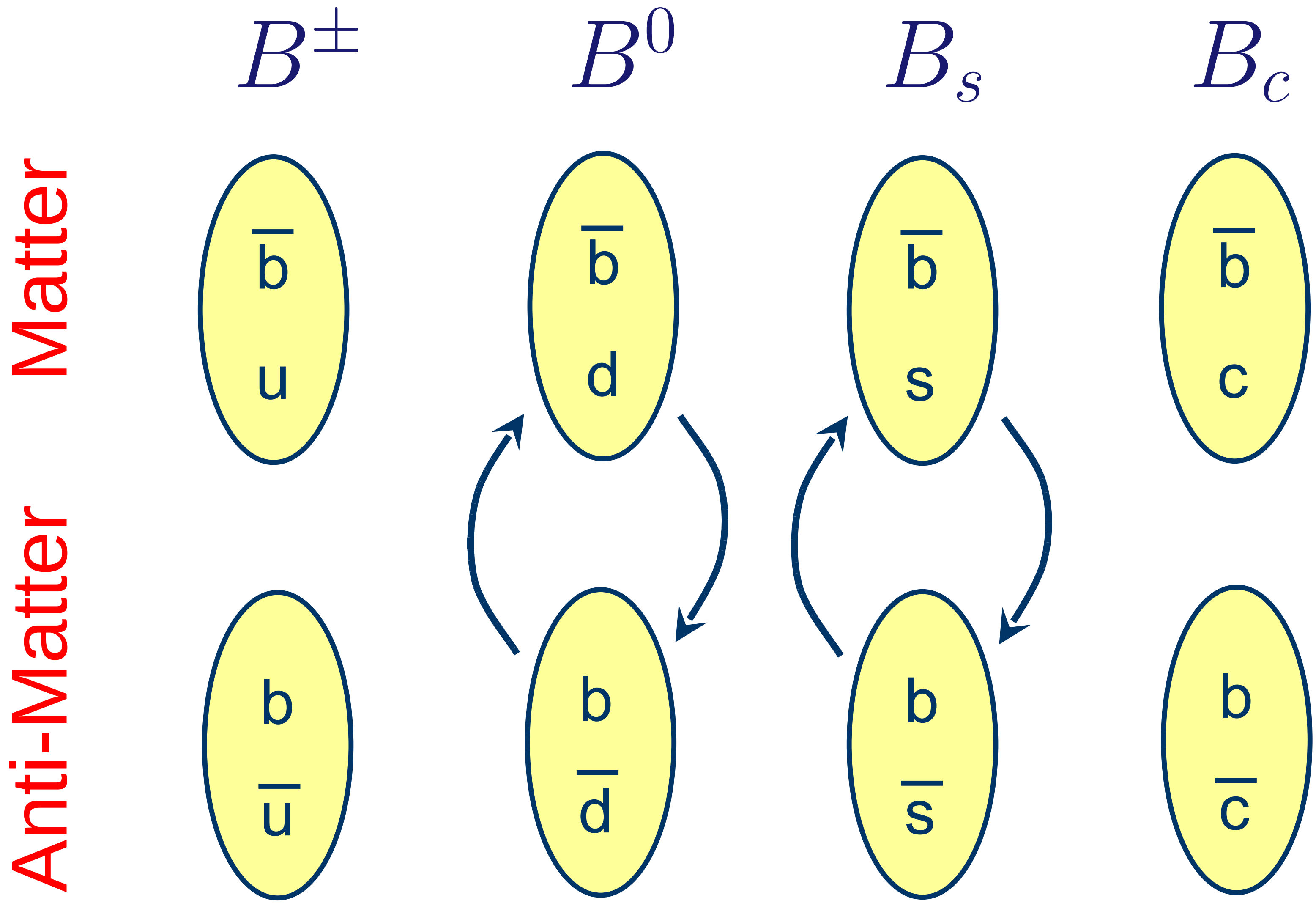

event @ CDF

- $\sigma(p\bar{p} \rightarrow X)$ O(10^3) higher
  $\longrightarrow$ require excellent trigger
- High track density
- Boost in longitudinal direction
  $\longrightarrow$ less opposite side B's
  $\longrightarrow$ lower (OS) tagging performance



event @ BABAR

B Mesons

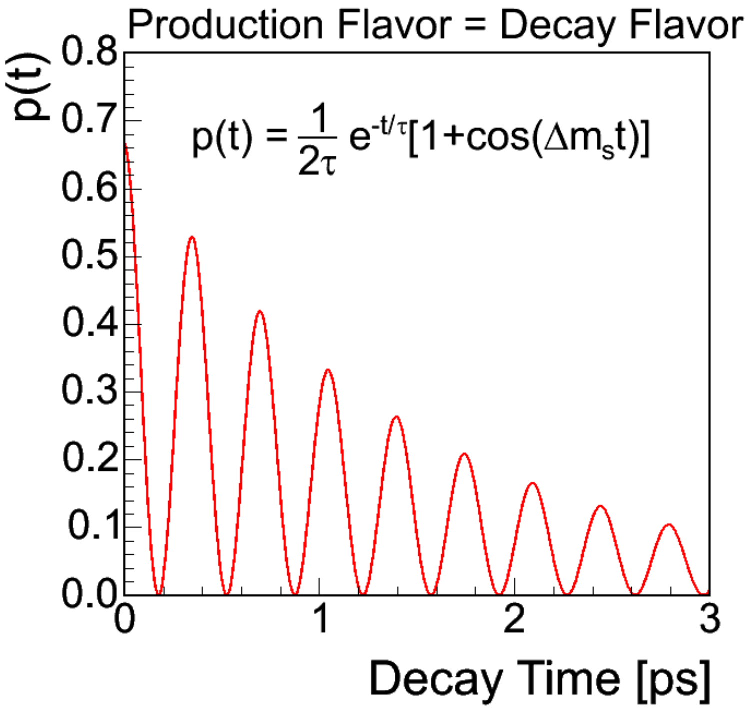


	$B^{\pm}$	B^{0}	B_s	B_c
Matter	$\bar{b}$ u	$\bar{b}$ d	$\bar{b}$ s	$\bar{b}$ c
Anti-Matter	b $\bar{u}$	b $\bar{d}$	b $\bar{s}$	b $\bar{c}$

Neutral B Meson Mixing

Two-state mixing system:

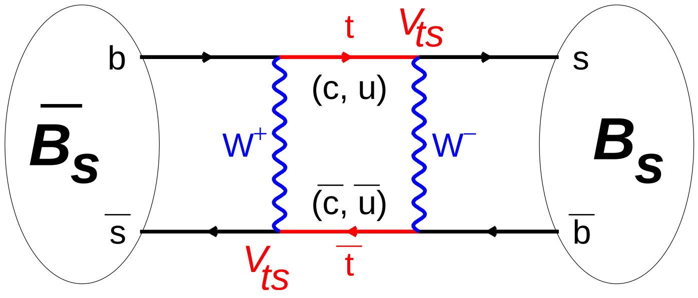
- “heavy” and “light” mass eigenstates
- B $(\bar{b}s)$ and $\overline{B}$ $(b\bar{s})$ weak eigenstates:
  $|B_s\rangle = \frac{1}{\sqrt{2}}(|B_{s,H}\rangle + |B_{s,L}\rangle)$
  $|\overline{B}_s\rangle = \frac{1}{\sqrt{2}}(|B_{s,H}\rangle - |B_{s,L}\rangle)$
- B_H and B_L may have different mass and decay width
  - Δm = $M_H - M_L$
  - $\Delta\Gamma = \Gamma_H - \Gamma_L$
- Solution in proper time ($\Delta\Gamma$ = 0)
  $P(t)_{B_s \to B_s} = \frac{1}{2\tau} e^{-t/\tau}(1 + \cos \Delta m_s t)$
  $P(t)_{B_s \to \overline{B}_s} = \frac{1}{2\tau} e^{-t/\tau}(1 - \cos \Delta m_s t)$

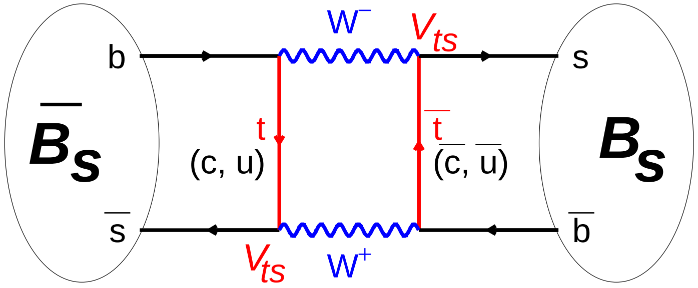


Standard Model Prediction

CKM Matrix: transformation from mass to weak quark eigenstates

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





- Access to fundamental SM Parameters:

$$\Delta m_s = \frac{G_F^2 M_W^2 \eta S(m_t^2/m_W^2)}{6\pi^2} m_{B_s} f_{B_{B_s}}^2 |V_{ts}^* V_{tb}|^2$$

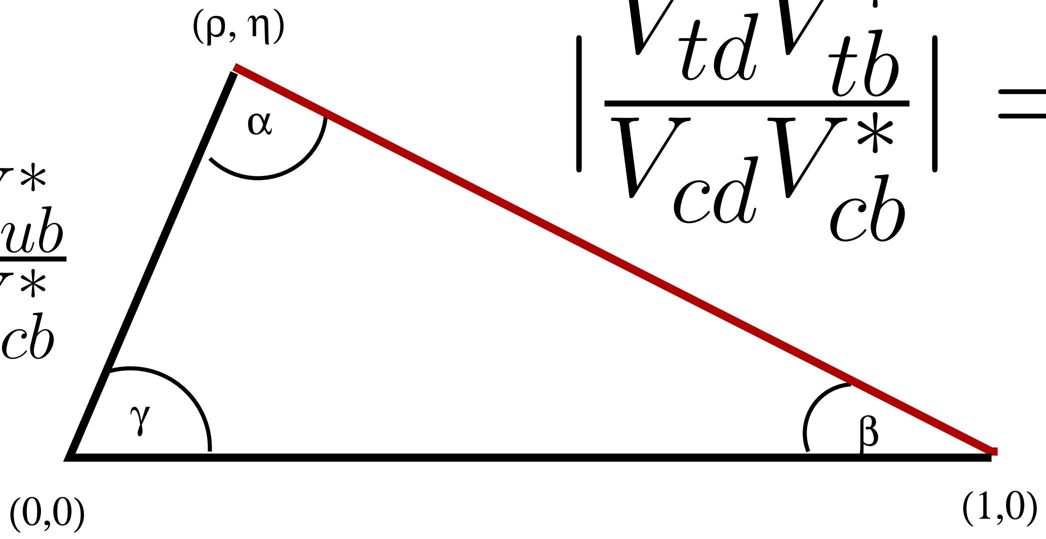
- Hadronic uncertainties cancel in ratio: $\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2}$

improved lattice QCD: ξ = 1.210 $^{+0.047}_{-0.035}$ (hep/lat-0510113)

Unitarity Triangle

CKM Matrix Unitarity Relation

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



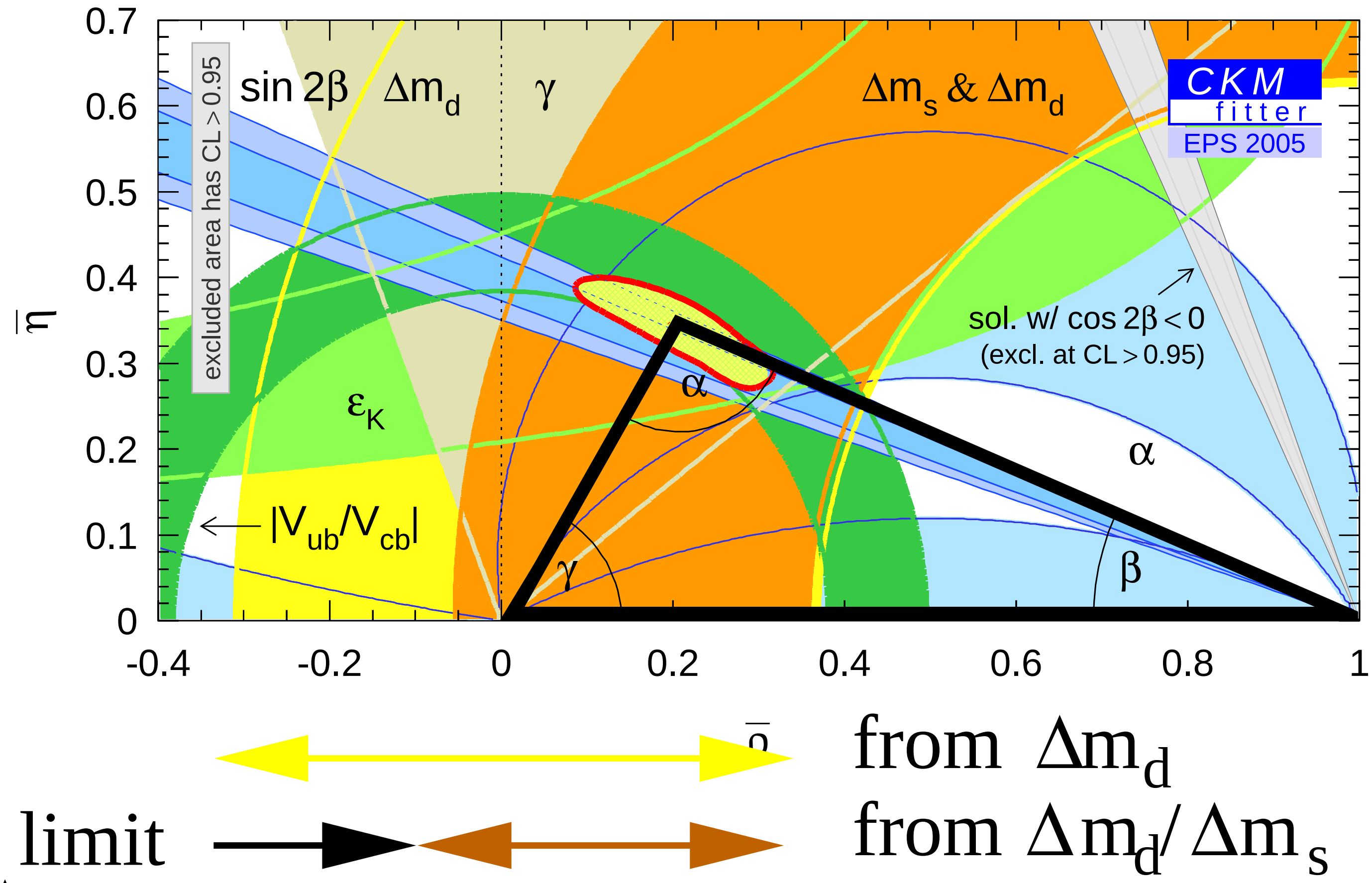
$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

$$\left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right| = \frac{|V_{td}|}{|V_{ts}|} \times \frac{1}{|V_{cd}|}$$

$$\frac{\Delta m_d}{\Delta m_s}$$

Unitarity Triangle Fit

- Many measurements from kaon and bottom physics constraint the triangle → indirect measurements of Δm_s
- CKM fit result: Δm_s: 18.3 $^{+6.5}_{-1.5}$ (1σ), $^{+11.4}_{-2.7}$(2σ) ps^{-1}

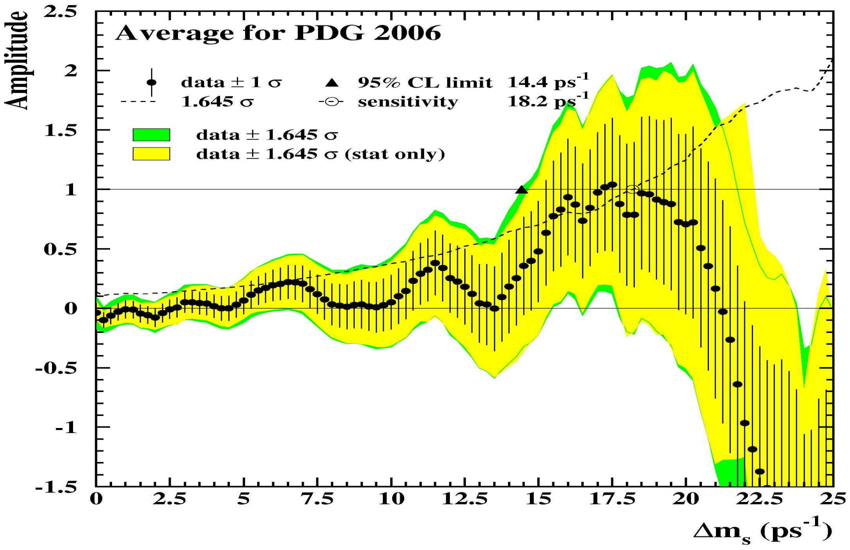


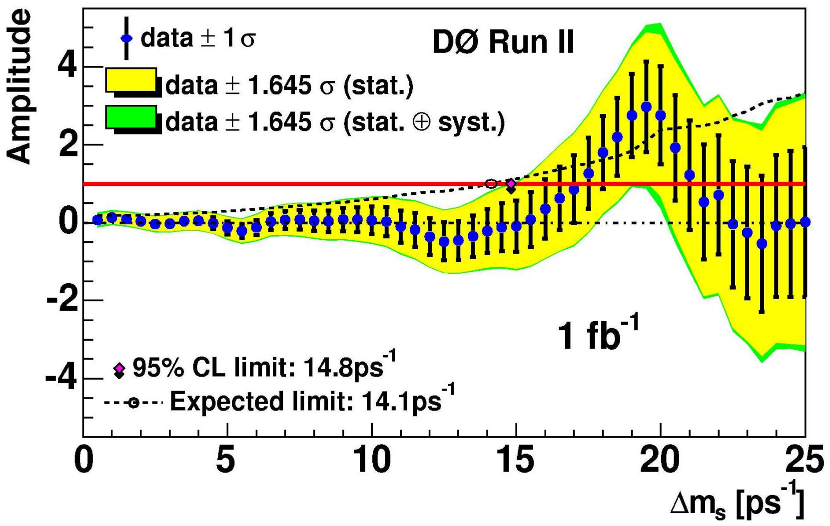
from Δm_d

Lower limit on Δm_s

from $\Delta m_d / \Delta m_s$

Direct Δm_s Measurements

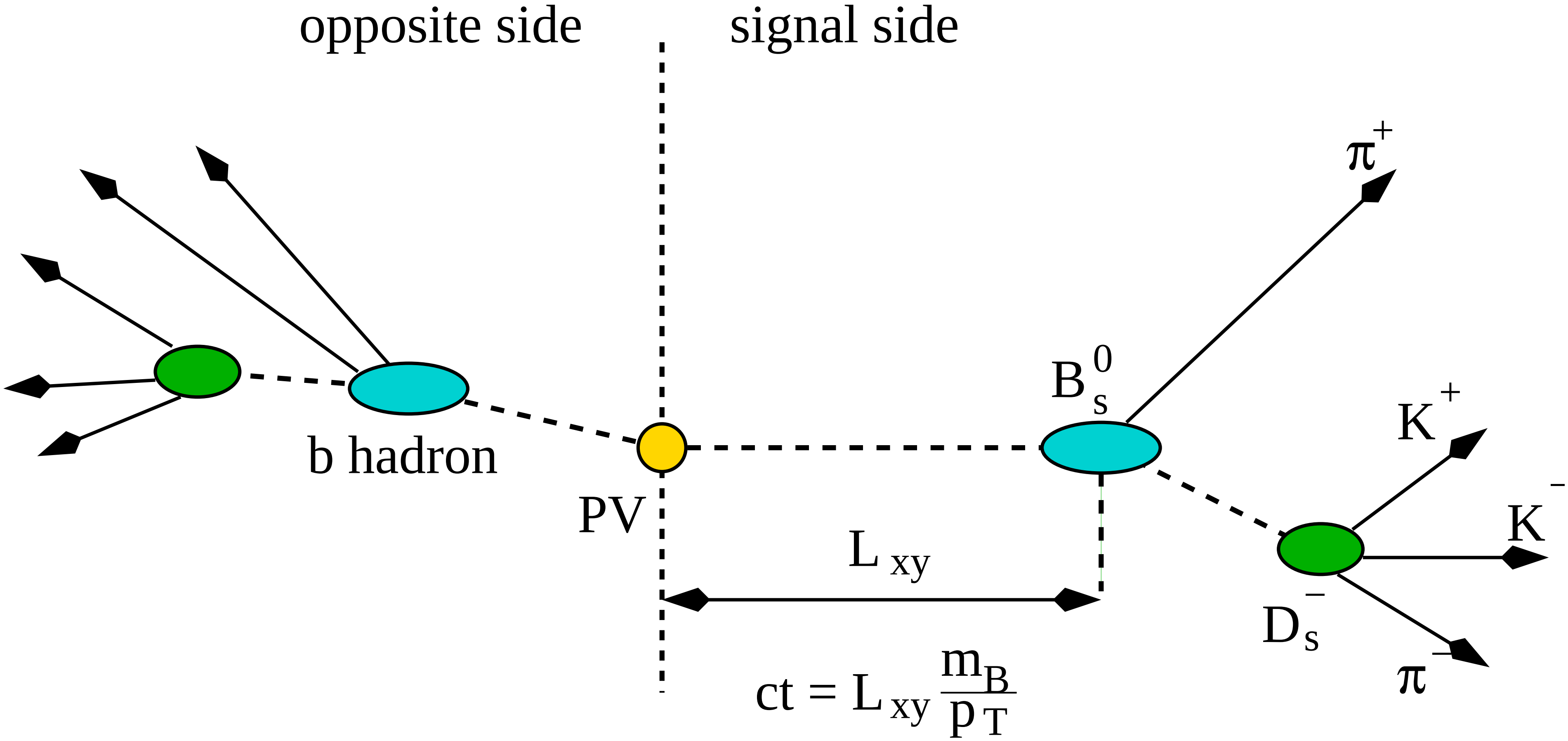




- Limit: $\Delta m_s \geq$ 14.4 ps^{-1}
- Sensitivity:
  Δm_s = 18.2 ps^{-1}

- Limit: $\Delta m_s \geq$ 14.8 ps^{-1}
- Sensitivity:
  Δm_s = 14.1 ps^{-1}
- Boundaries from direct fit:
  17 < Δm_s < 21 ps^{-1} @ 90% CL
  (hep-ex/0603029)

$B_s - \bar{B}_s$ Mixing Analysis



1) B_s selection & reconstruction

2) Measurement of proper decay time ct & ct resolution

3) Flavor tagging (main challenge at hadron colliders)

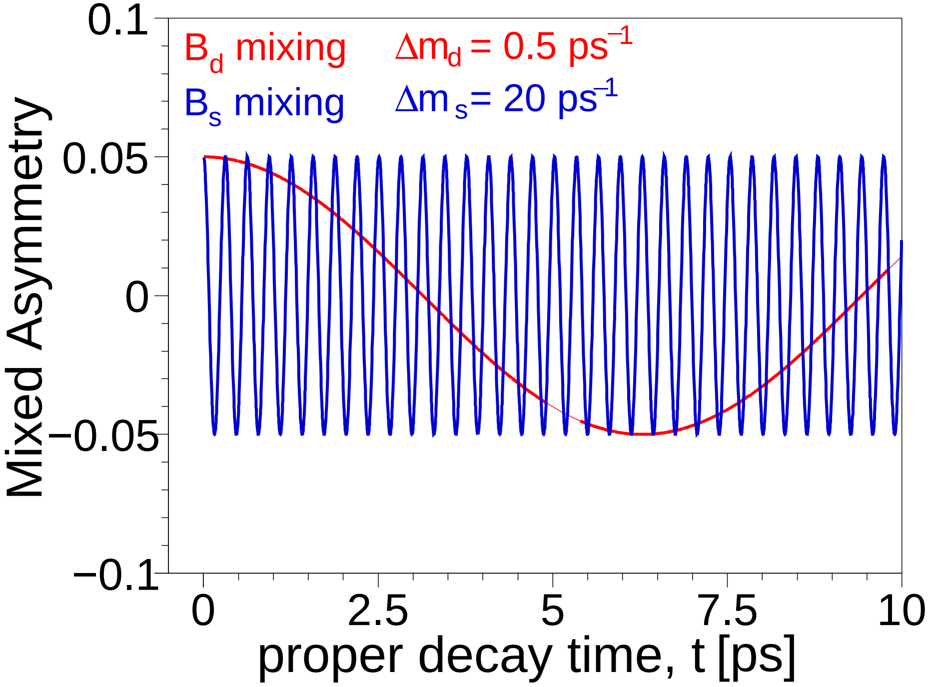
Why is it so difficult?

B_s Mixing is very very fast!

Challenges:

- High vertex resolution
- High momentum resolution
- Large statistics
- Good tagging

Very complex analysis!



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

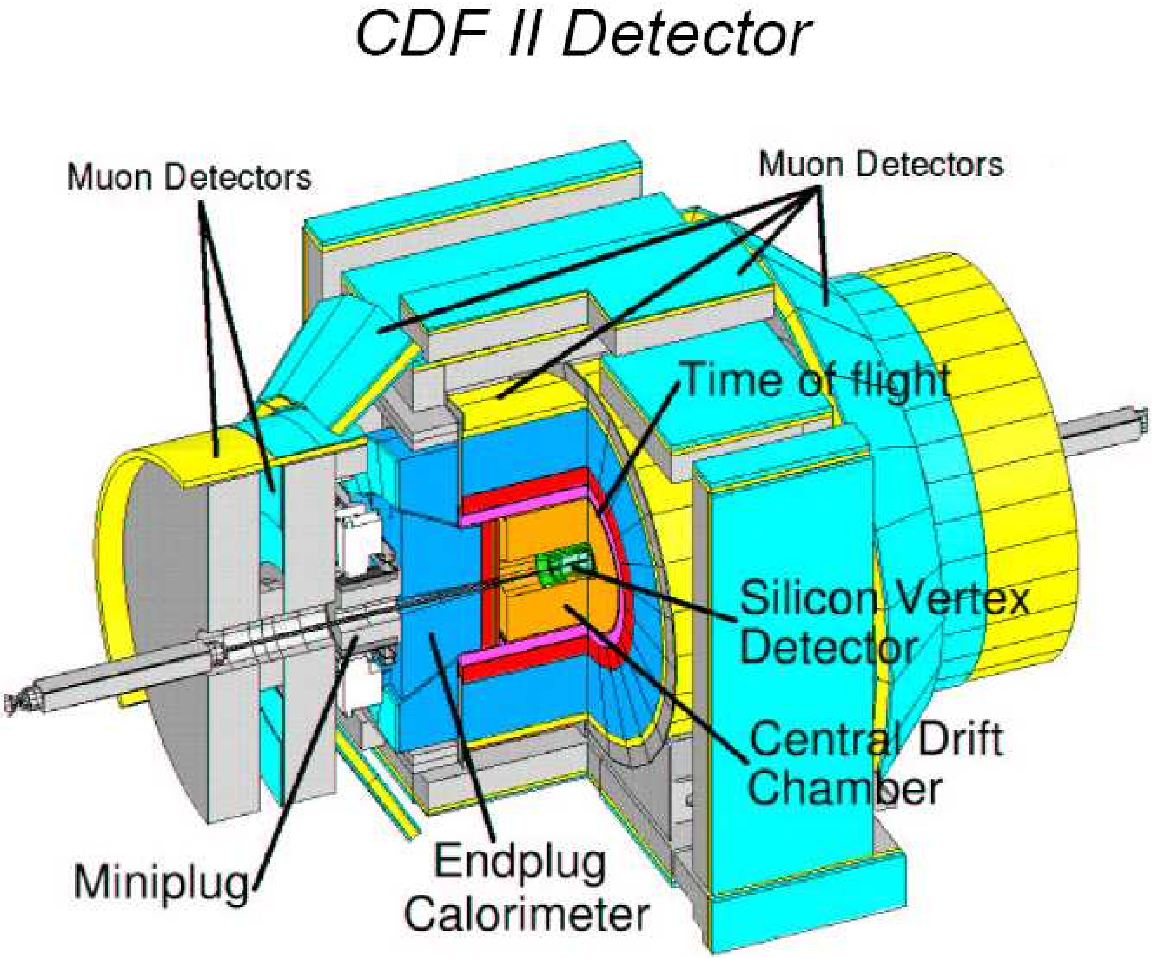
ϵD^2: tagging performance (efficiency ϵ and dilution D = 1-2*P$_{mistag}$),

$\sigma(ct)$: proper time resolution, for high Δm_s, $\sigma(ct)$ is crucial!

S,B: signal and background yields

The CDF II Detector

- multi-purpose detector
- excellent momentum resolution $\frac{\sigma(p)}{p} < 0.1\%$



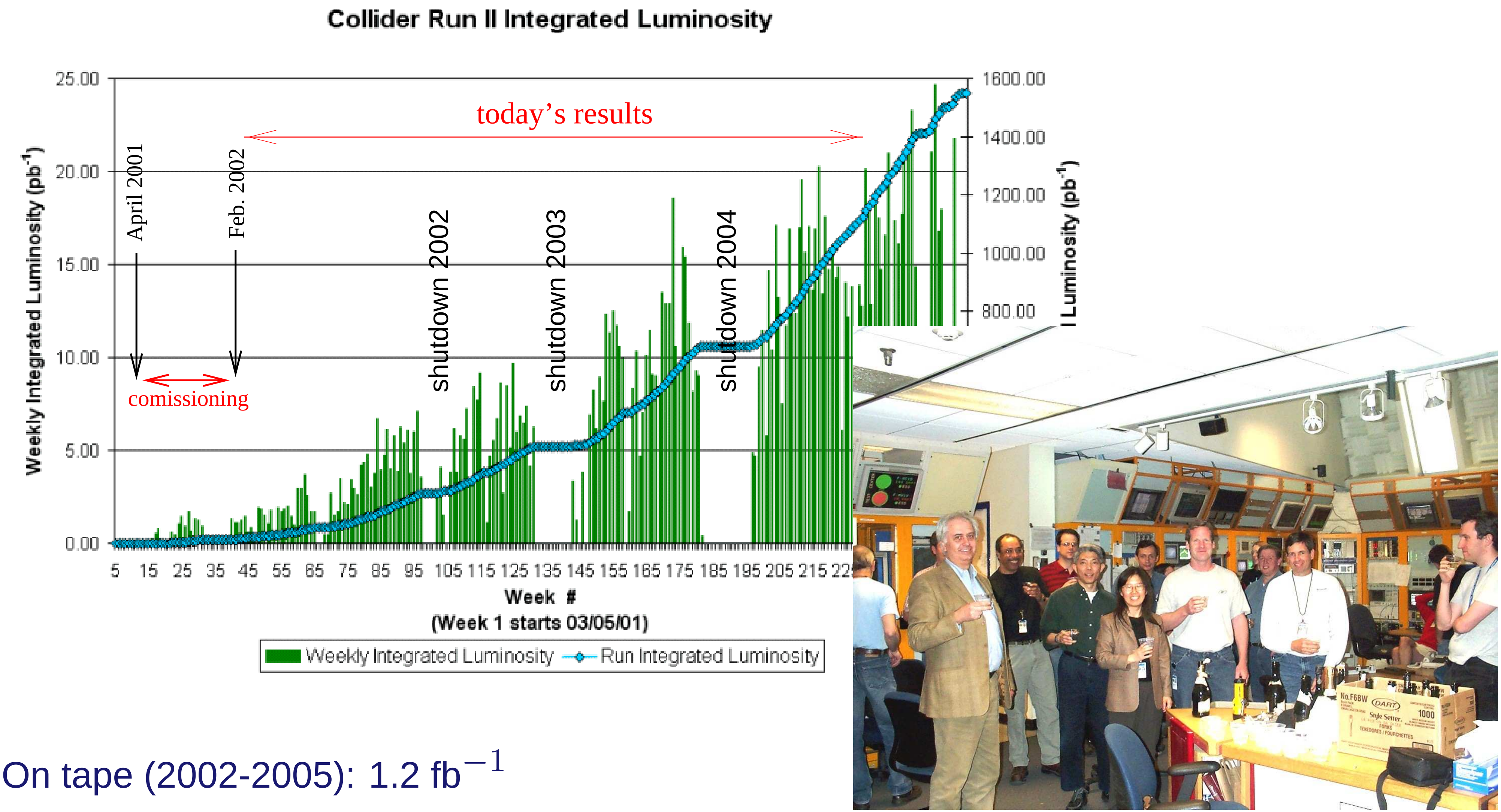
- Yields:

  - SVT based trigger
- Tagging Power:

  - TOF, dE/dx in COT
- Proper time resolution:

  - SVXII, L00

Tevatron Performance



On tape (2002-2005): 1.2 fb^{-1}

Used for this analysis: 1 fb^{-1};

Celebrating first 1 fb^{-1}

Signal Reconstruction

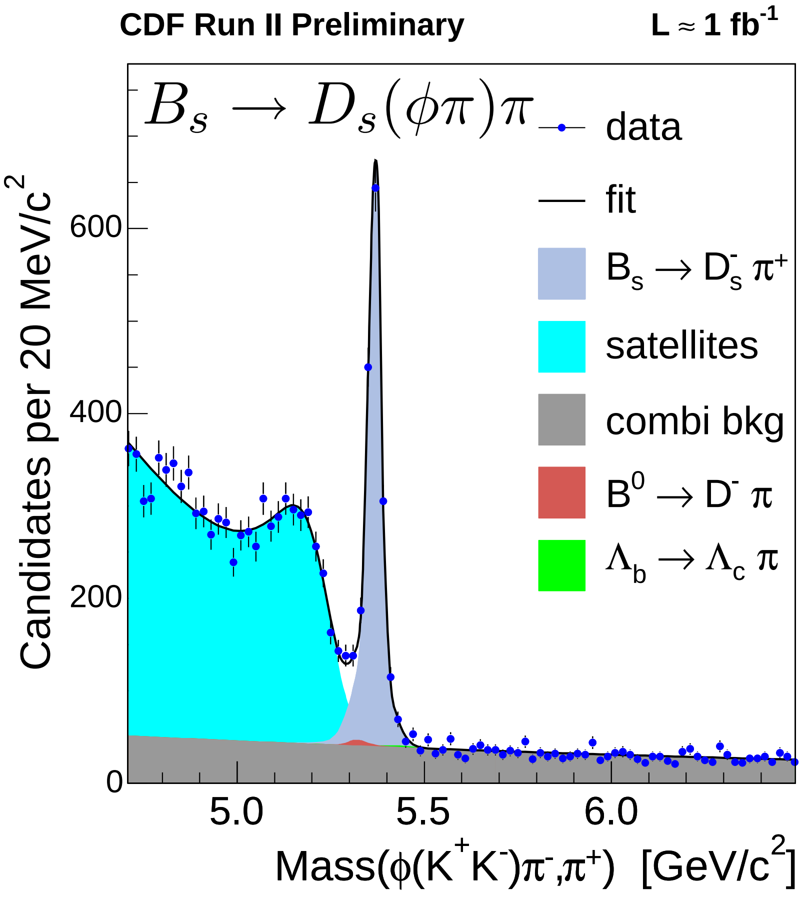
$$\sqrt{\frac{S\epsilon D^2}{2}\frac{S}{S+B}e^{-\frac{(\Delta m_s\sigma_{ct})^2}{2}}}$$

Hadronic B_s Decays

Fully reconstructed B_s decays (Two Displaced Track Trigger)

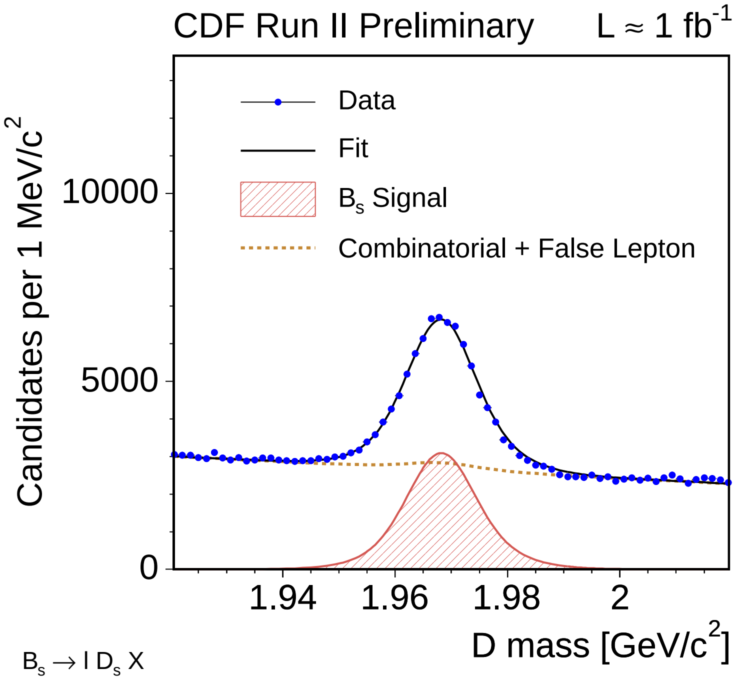
Decay	Candidates
$B_s \rightarrow D_s\pi, D_s \rightarrow \phi\pi$	1.500
$B_s \rightarrow D_s\pi, D_s \rightarrow K^*K$	800
$B_s \rightarrow D_s\pi, D_s \rightarrow \pi\pi\pi$	600
$B_s \rightarrow D_s 3\pi, D_s \rightarrow \phi\pi$	400
$B_s \rightarrow D_s 3\pi, D_s \rightarrow K^*K$	200

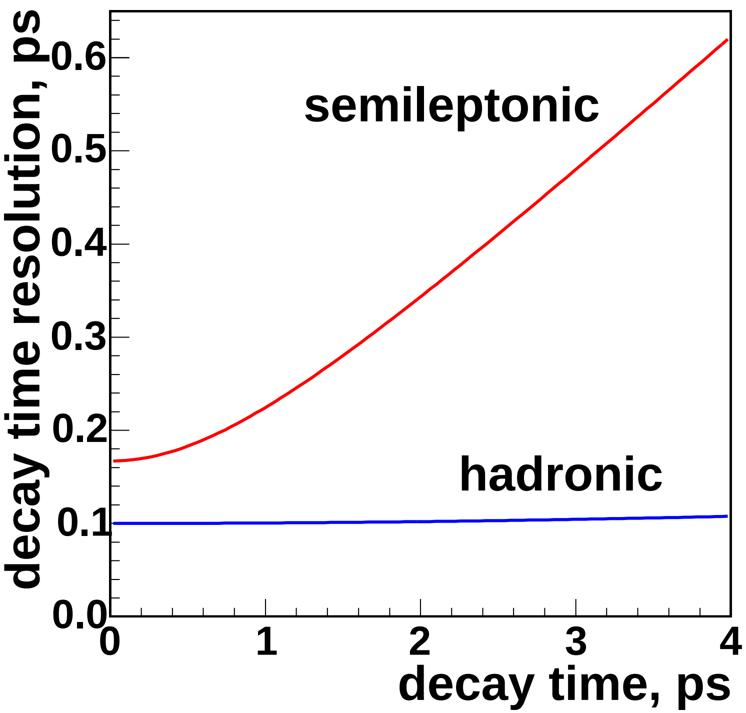
$\sim$ 3.600 B_s candidates



Low background under B_s mass peak

$B_s \to \ell D_s X$ Decays





$\sim$ 37.000 semileptonic B_s candidates

High statistic, but worse ct-resolution:

$$ct = \frac{L_{xy}}{\gamma\beta} = \frac{L_{xy} M(B)}{p_T(B)} = \frac{L_{xy} M(B)}{p_T(\ell D)} * K$$ (K from Monte Carlo);

$$\sigma_{ct} = \sqrt{\left(\frac{\sigma_{L_{xy}}}{\gamma\beta}\right)^2 + \left(\frac{\sigma_{\gamma\beta}}{\gamma\beta} * ct\right)^2}$$

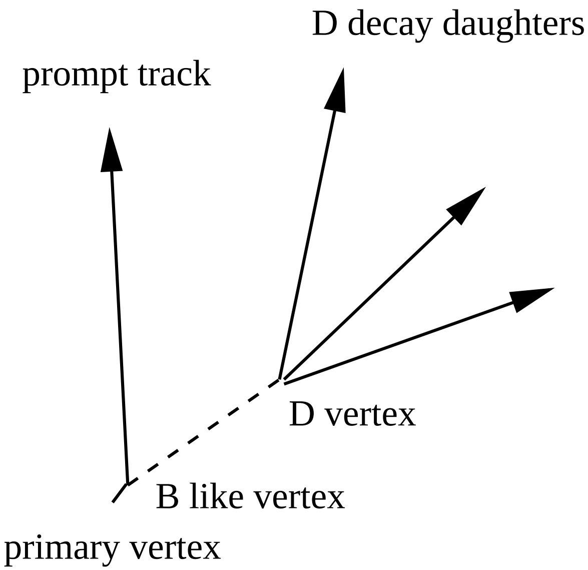
Proper Decay Time Resolution

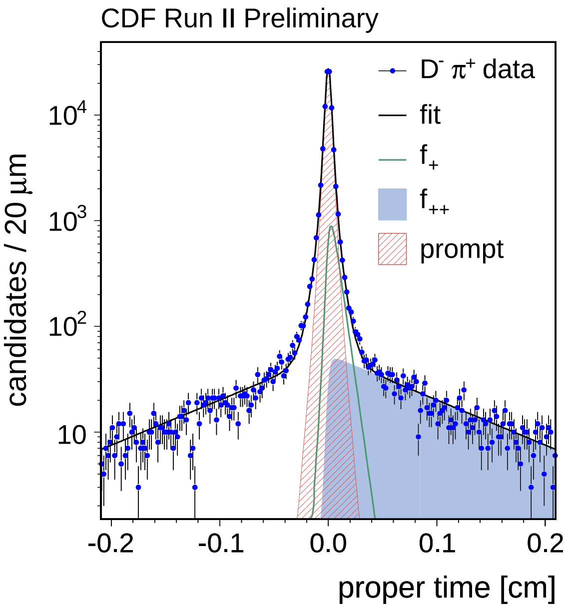
$$\sqrt{\frac{S\epsilon D^2}{2}\frac{S}{S+B}e^{-\frac{(\Delta m_s \sigma_{ct})^2}{2}}}$$

ct Resolution

Critical aspect of the analysis, limiting factor at high Δm_s

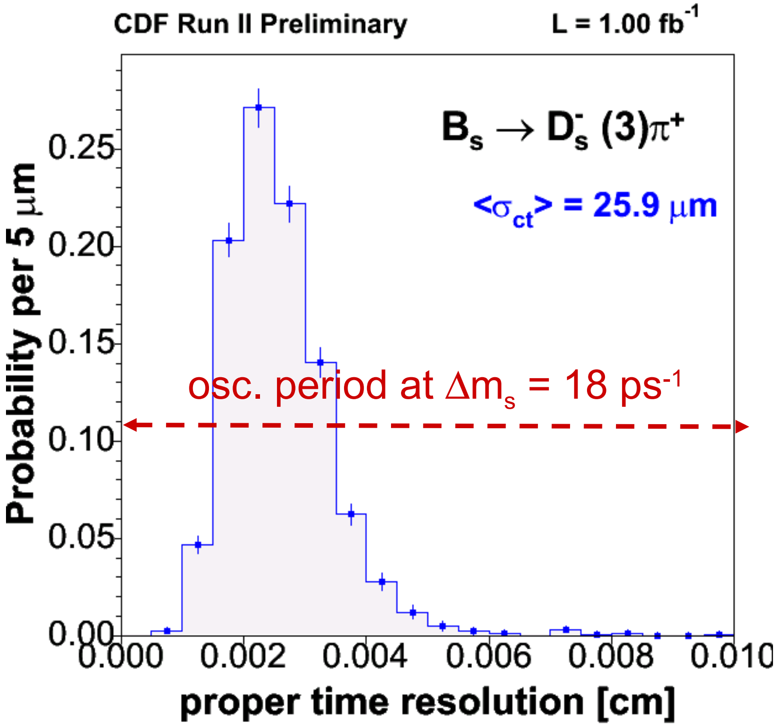
σ_{ct} is determined from data





- Use prompt charm sample (huge cross-section)
- Prompt D + track(s) mimic B_s decay topology
- Calibrate ct resolution as function of several variables (isolation, vertex χ^2, B momentum ...)

Proper Time Resolution



- average uncertainty hadronic sample $\approx 26\ \mu$m
- average uncertainty semileptonic sample $\approx 40\ \mu$m
- use ct resolution per candidate $\Leftrightarrow$ valuable events get higher weight assigned

Very good performance thanks to innermost silicon layer (L00)!

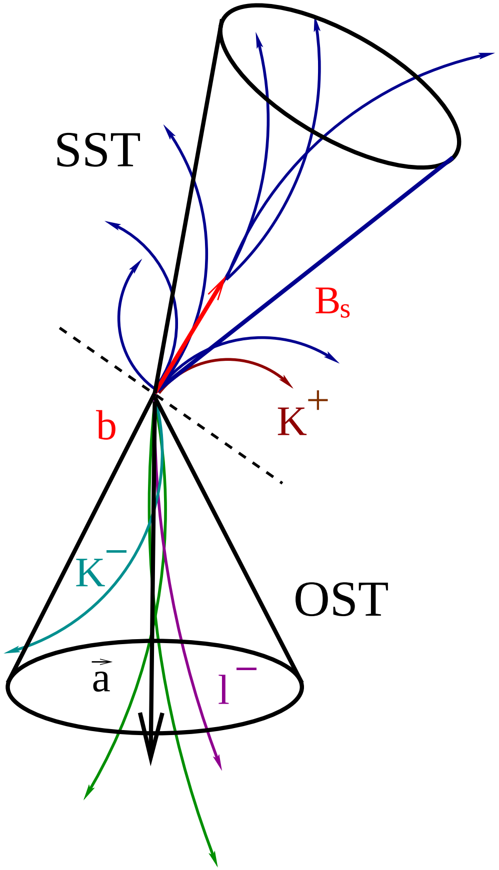
Flavor Tagging

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

Opposite Side Tagging

B mesons produced in pairs $\longrightarrow$ production flavors correlated

- Jet Charge Tagging (high efficiency, low purity)
  Weighted sum of fragmentation and decay tracks of the opposite side B
- Lepton Tagging (high purity, low efficiency)
  Semileptonic decay of opposite side B
  ($\approx 20\%$ B's mix before the decay)
- Kaon tagging (not yet used)
  Favored transition: $b \longrightarrow c \longrightarrow s$



Often opposite side B not in detector acceptance

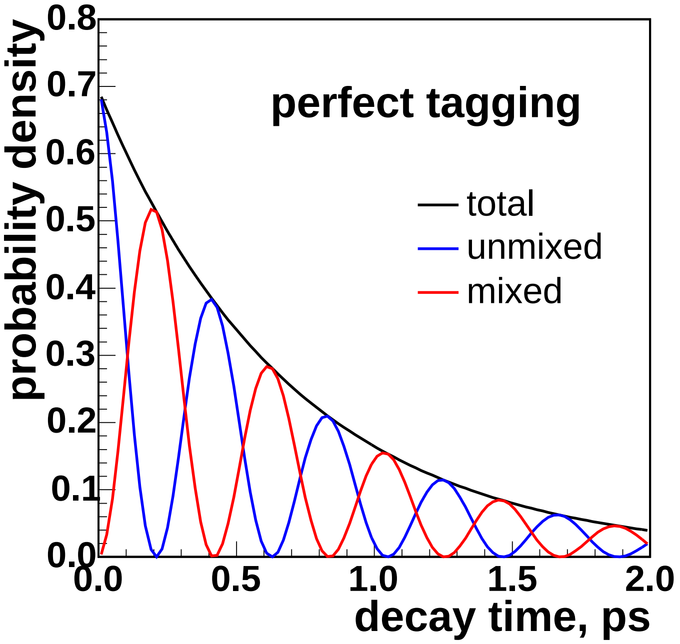
Additional gain in tagging performance:

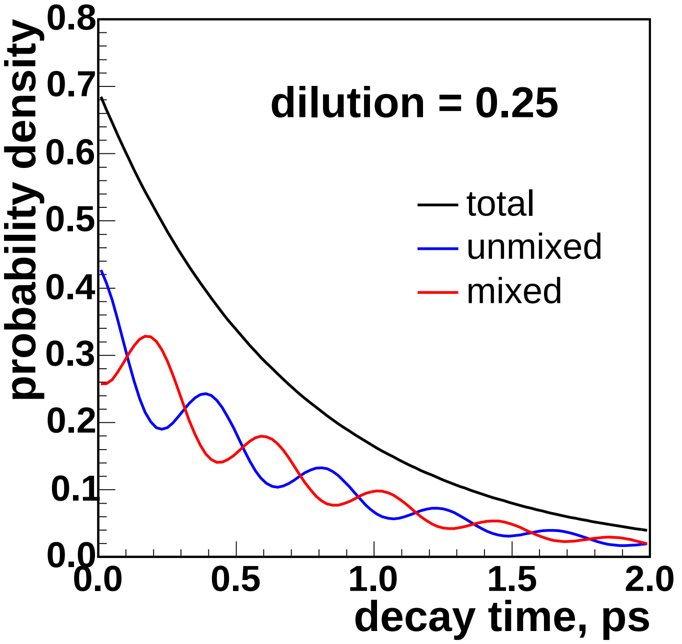
+ Classification of events (dilution parameterization)

+ Combination of all opposite side tagging information

Effect of Imperfect Tagging

Dilution dampens the observed oscillation!





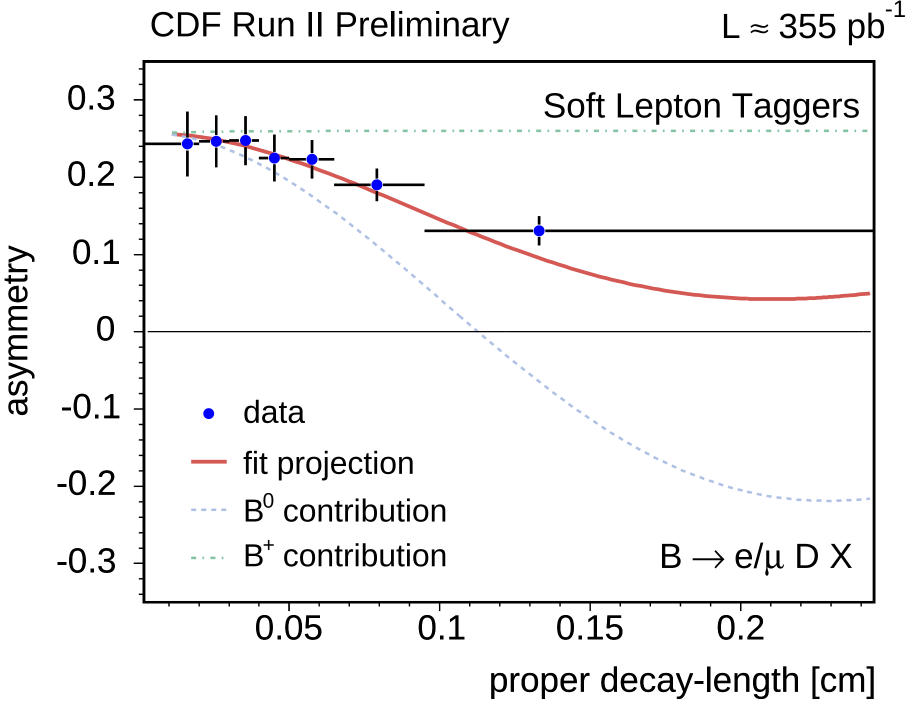
$\mathcal{D}$ = 25% $\longrightarrow$ 62.5% of the events are correctly tagged.

$$\mathcal{A}(t) \equiv \frac{N(t)_{mixed} - N(t)_{unmixed}}{N(t)_{mixed} + N(t)_{unmixed}} = \mathcal{D}\cos(\Delta m_s t)$$

(in this example: Δm_s = 2.5 ps $^{-1}$)

OST in B^+ & B^0

- Important test of the fitter (complex unbinned Likelihood Fit)
- Calibration of opposite side taggers
  (opposite side B independent of signal side)

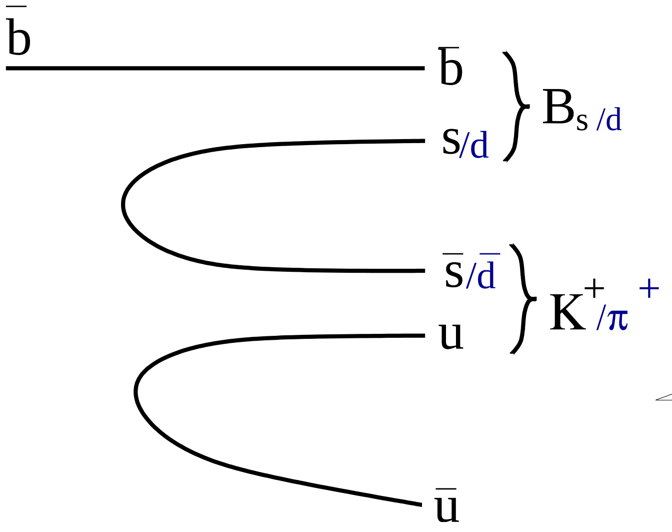


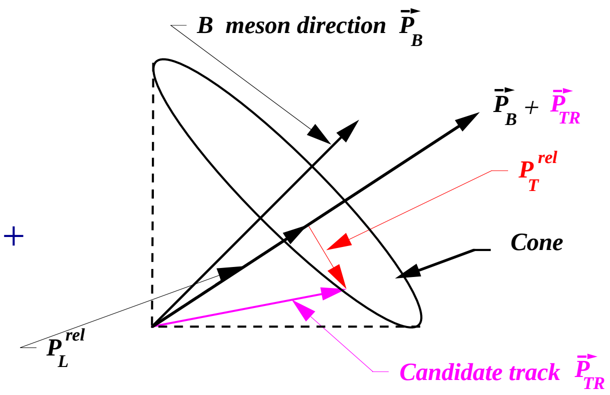
$\epsilon D^2(semil.)$ = 1.44 ± 0.04 % $\epsilon D^2(hadr.)$ = 1.47 ± 0.10 %

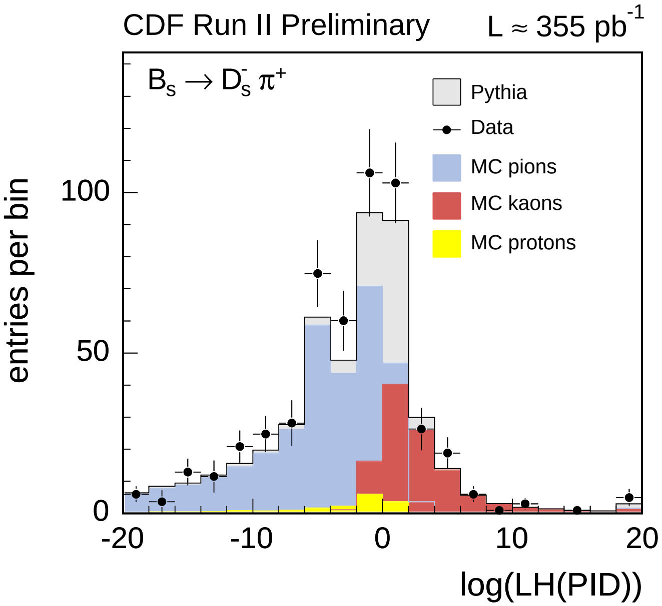
$\Delta m_d(semil.)$ = 0.509 $\pm$ 0.019 ps^{-1} $\Delta m_d(hadr.)$ = 0.536 $\pm$ 0.029 ps^{-1}

Δm_d consistent with PDG, B factories perform way better

Same Side Tagger (I)







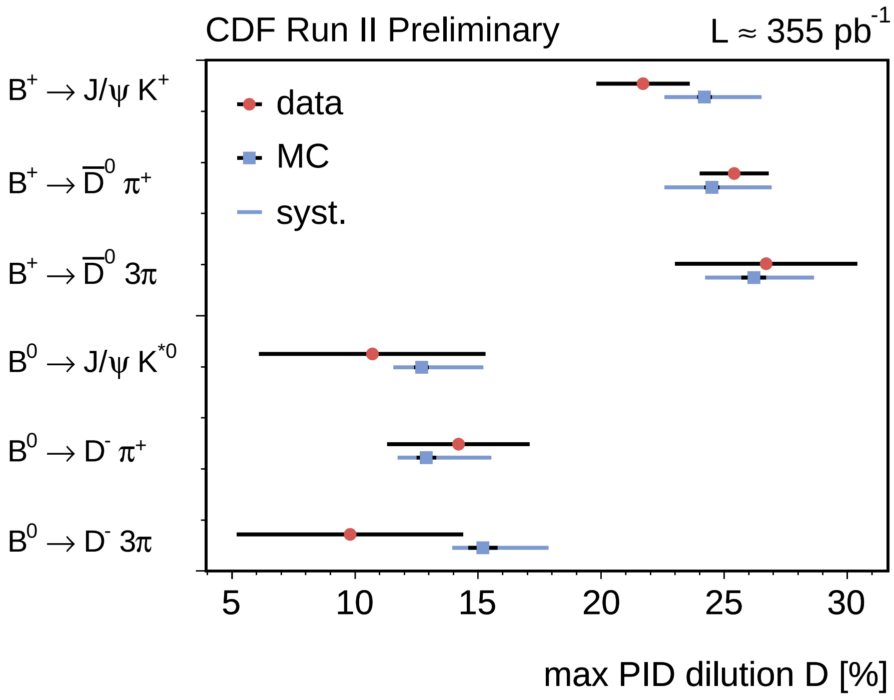
- Charge of closest fragmentation track correlated to B production flavor
- Particle identification helps to select tagging kaons (for B_s)
- SSKT performance can NOT be determined on data (till B_s oscillation can be resolved)

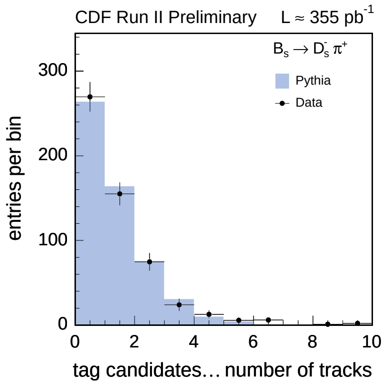
  Understanding of Monte Carlo crucial!

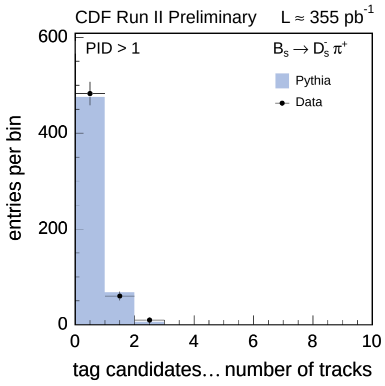
Same Side Tagger (II)

- Data Monte Carlo comparison of B candidate and tagging track candidate quantities (momentum, track multiplicity, ...)
- Different tagging algorithms test different fragmentation properties (select by momentum, by kaon probability track ...)

Very good agreement in all algorithms and decay modes!



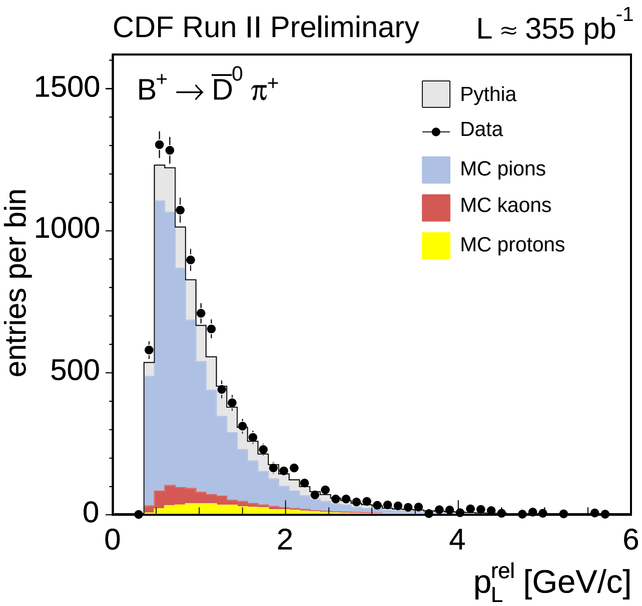


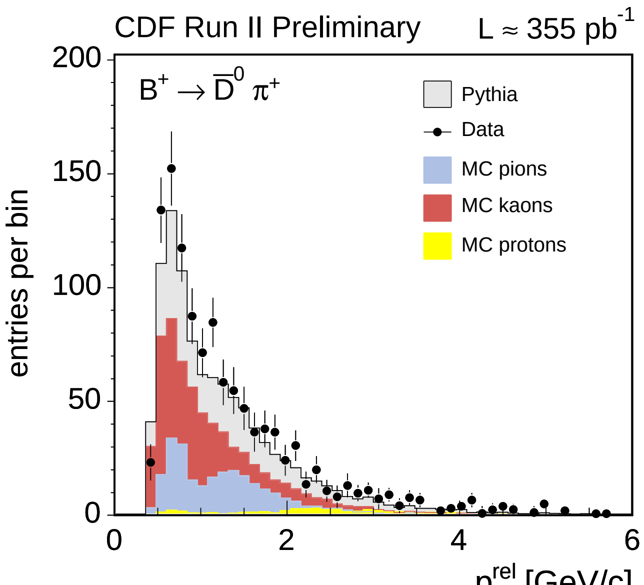


track multiplicity with and w/o cut on PID

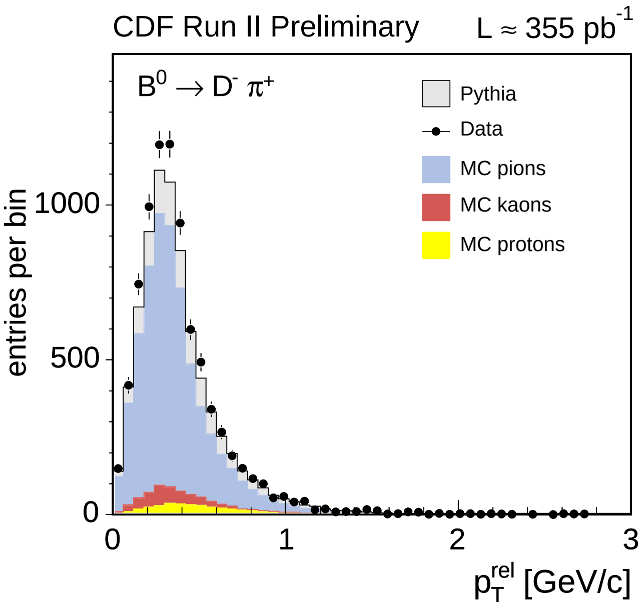
$B_s \to D_s \pi$

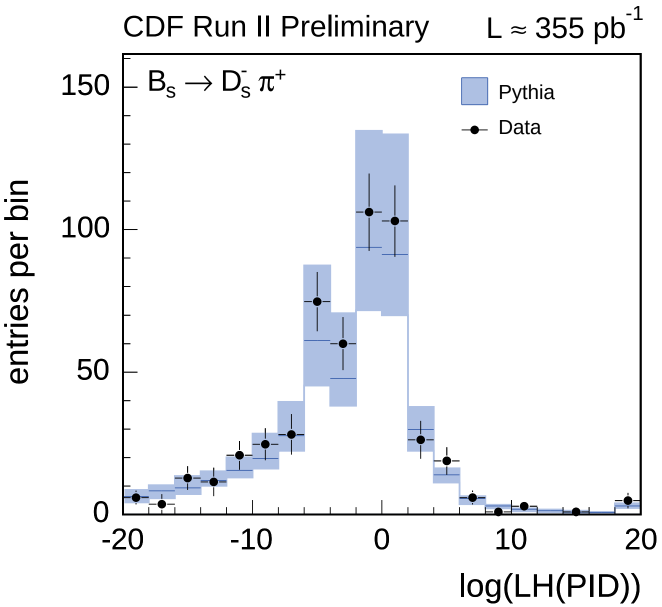
Same Side Tagger (III)





PID > 1



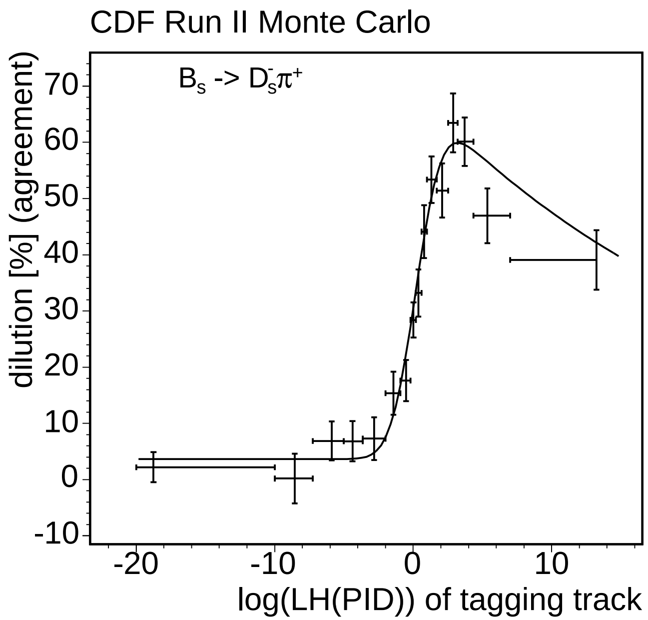


Same Side Tagger (IV)

Systematic studies:

- Fragmentation
- Production mechanisms
- Particle ID resolution
- kaon/proton/pion rates
- B^{**} rates (for B^{+}, B^{0})
- Data/MC agreement

Tagging dilution as function of kaon probability



Dilution: $D = 28.3^{+3.2}_{-4.2}$ %

Tagging performance: ϵD^2 = $4.0^{+0.9}_{-1.2}$ %

Tagging performance enlarged by × 3-4!

(results based on first 365 pb^{-1})

Analysis Methods & Results

Fourier Analysis

Two domains to fit for oscillation:

Time domain:

- Fit for Δm_s in
  $P(t) \sim (1 \pm D \cos \Delta m_s t)$

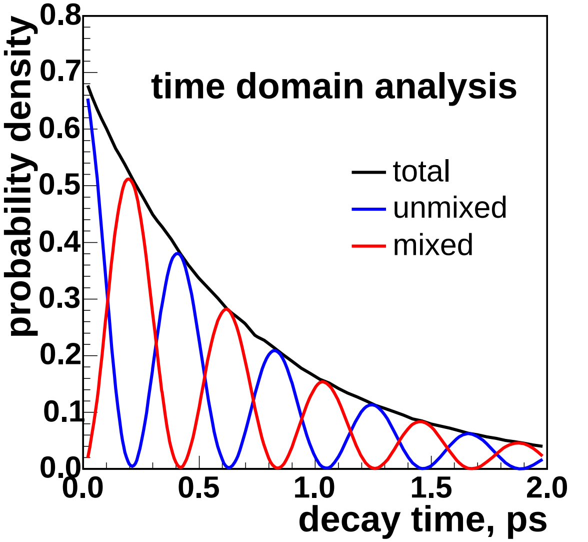
Frequency domain: amplitude scan

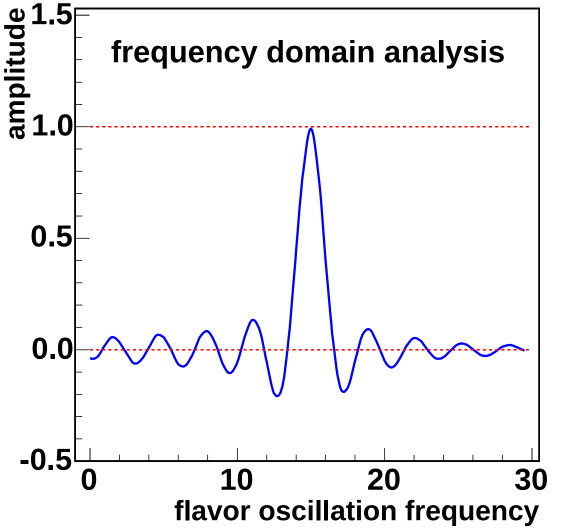
- Introduce amplitude:
  $P(t) \sim (1 \pm \mathcal{A} D \cos \Delta m_s t)$
- Fit for $\mathcal{A}$ at different Δm_s

$\Rightarrow$ Obtain frequency spectrum

- True $\Delta m_s \Rightarrow \mathcal{A} = 1$, else $\mathcal{A} = 0$
- Traditionally used for B_s mixing search

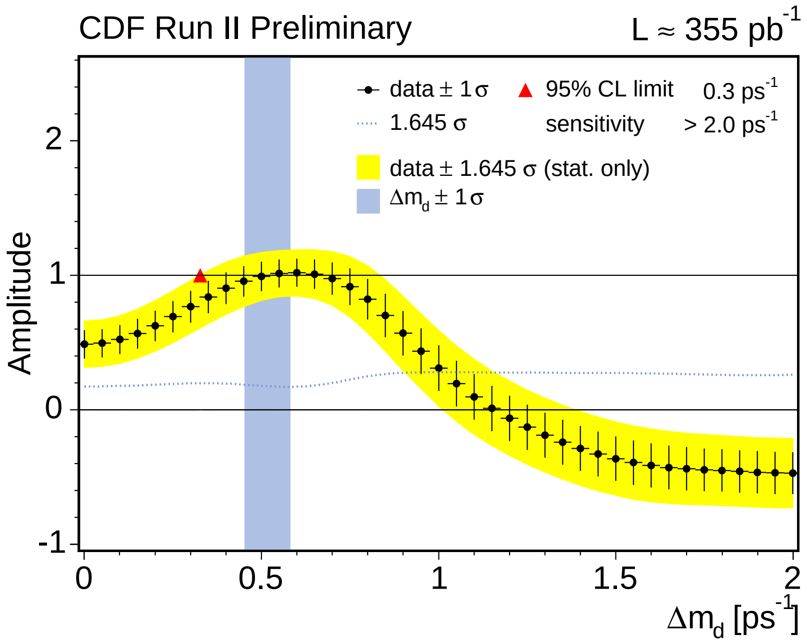
$\Rightarrow$ Easy to combine experiments



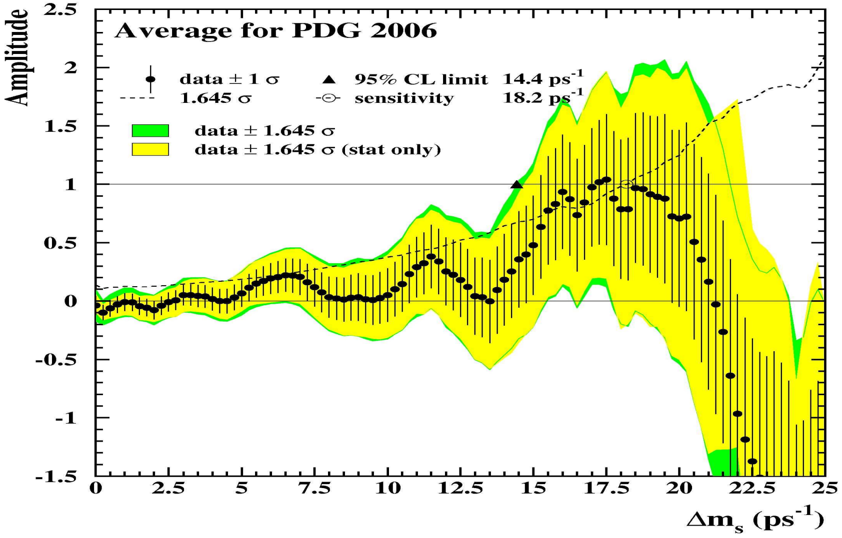


Amplitude Scan Notation

Test of amplitude scan on B^0 data



2006 world combined B_s scan



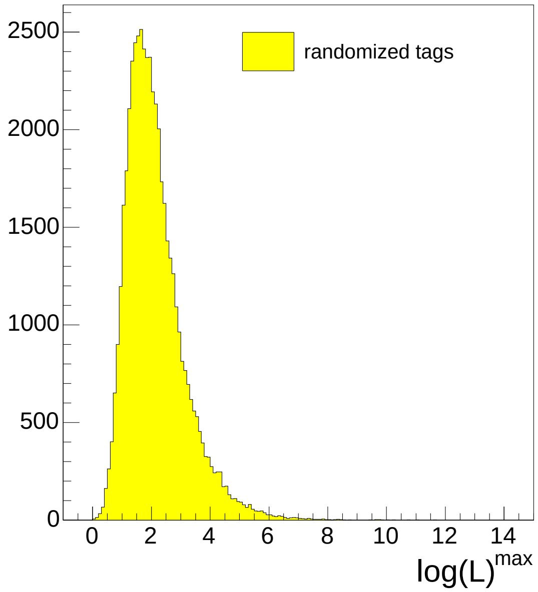
- Amplitude uncertainties from unbinned likelihood fit
- Yellow: 1.645σ around data points defines 95% CL region
- Δm values, where $\mathcal{A} + 1.645\sigma < 1$ are excluded at 95% CL
- Dashed line: 1.645σ as a function of Δm
- Sensitivity: Δm, where $1.645\sigma = 1$ first

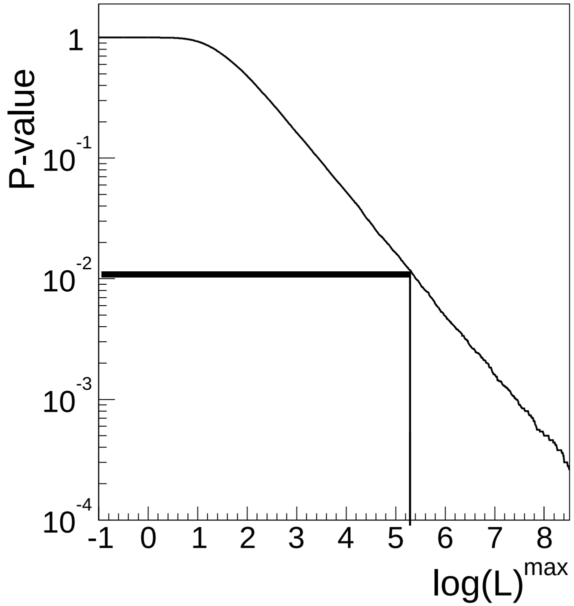
H.G. Moser, A. Roussarie, Nucl Instr. Meth. A **384**

Predefined Unblinding Procedure

Before un-blinding the data sample, we decided what to do:

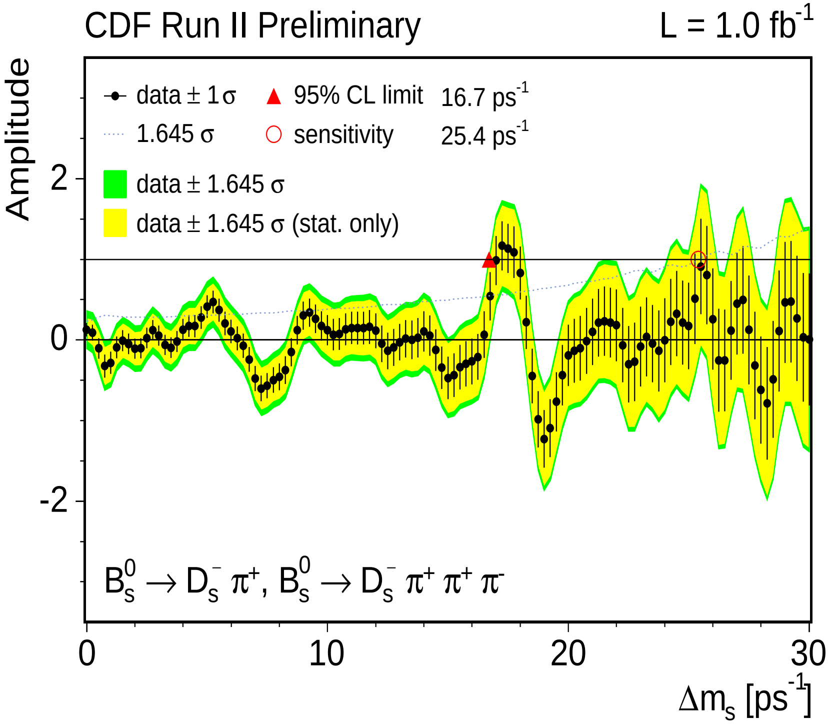
- Figure of merit: $\log(L) = \log[L(A=1,\Delta m_s)/L(A=0)]$
- P-value: probability that random tags mimics such a signature
- If P-value $>$ 1%: use amplitude scan & set 95% C.L. on Δm_s
- If P-value $<$ 1%: fit for Δm_s



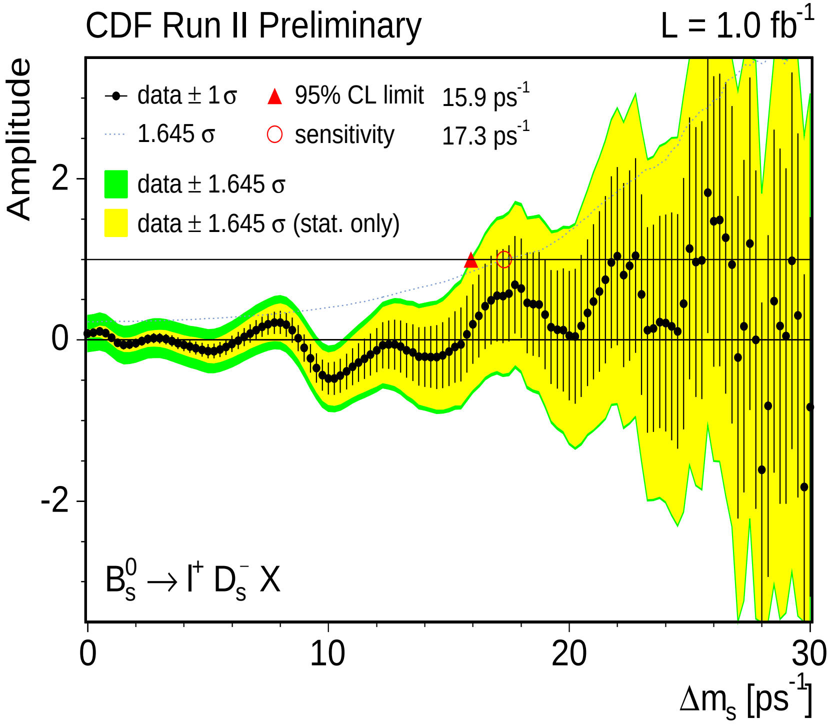


Amplitude Scans

Hadronic

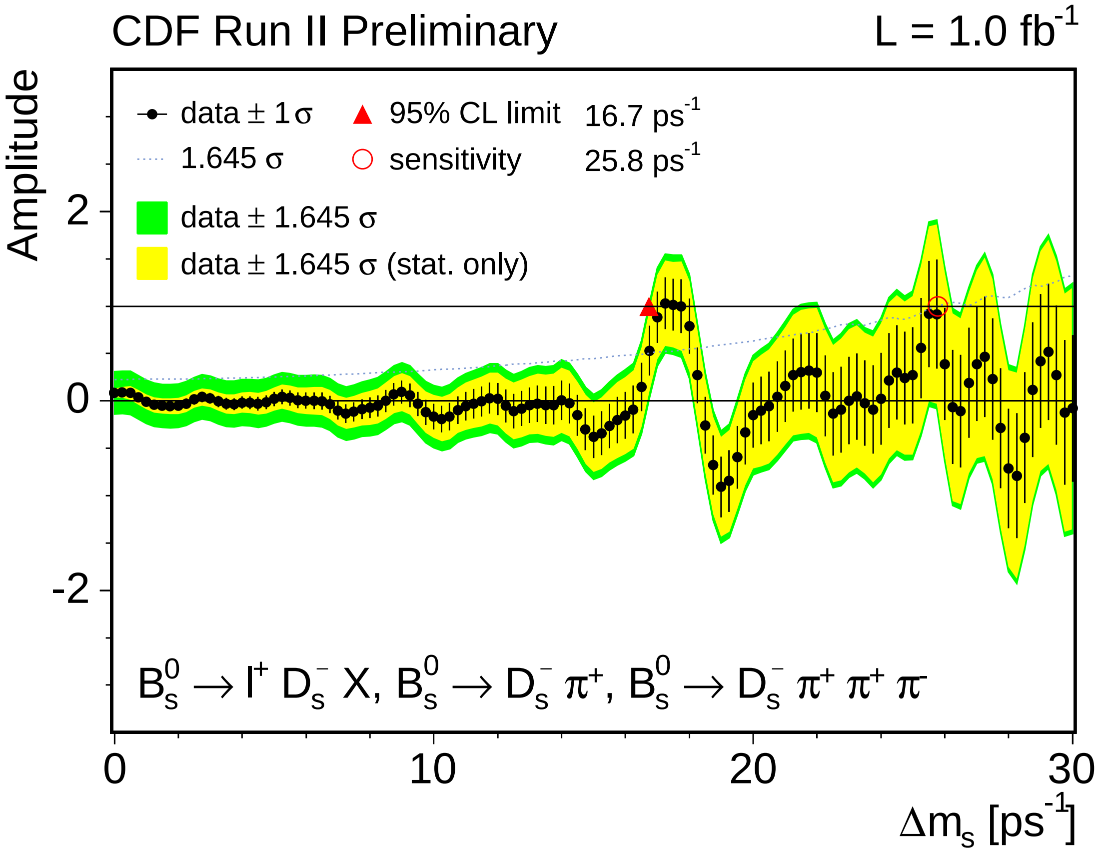


Semileptonic



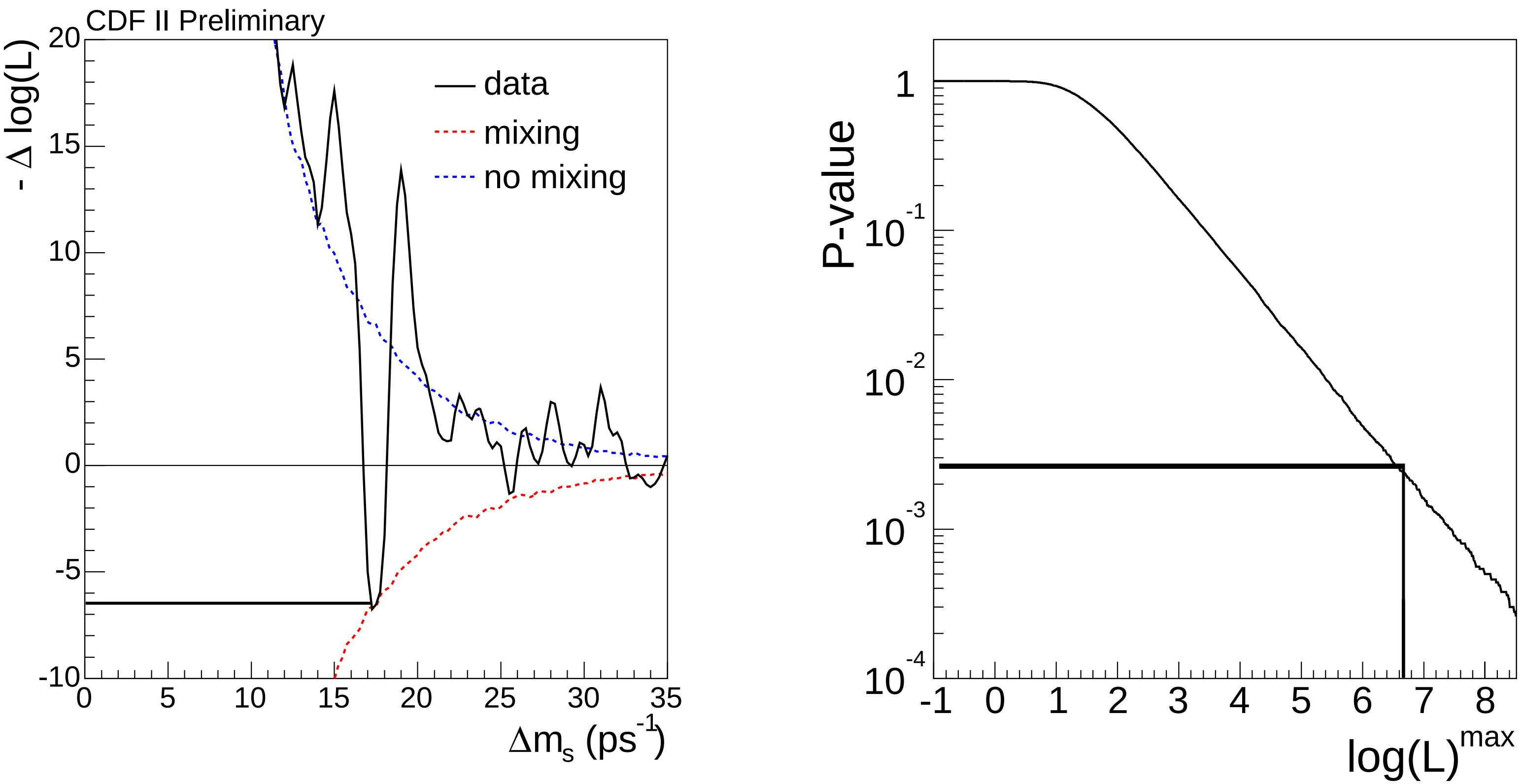
Combined Amplitude Scan

$\mathcal{A}$ compatible with 1 for $\Delta m_s \sim 17.25$ ps^{-1}!



$$\mathcal{A}/\sigma_{\mathcal{A}}(\Delta m_s = 17.25\ \text{ps}^{-1}) \sim 3.7$$

Likelihood Scan



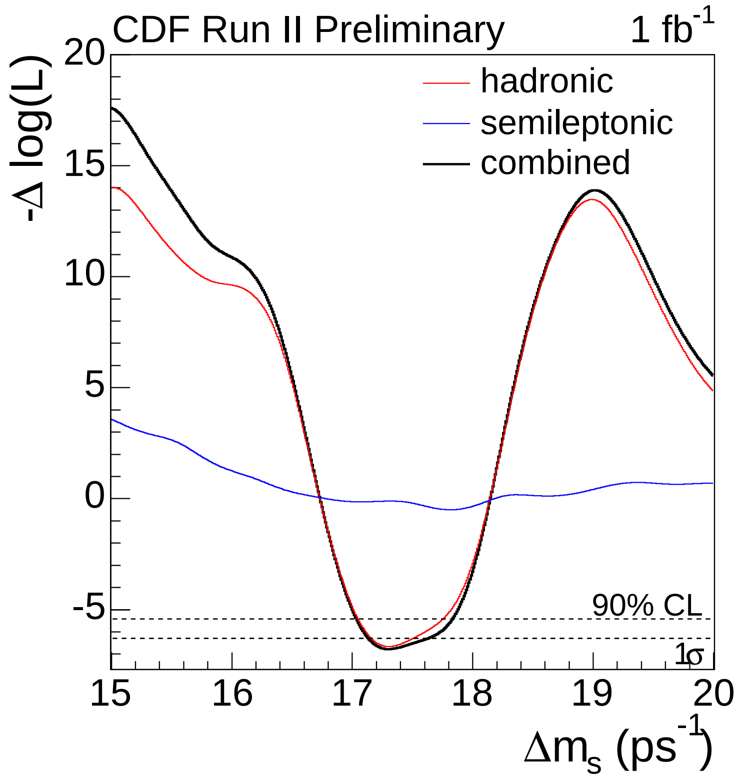
How often can random tags produce a LH minimum this deep?

→ P-value(6.75): 0.2 %

Δm_s Measurement

Δm_s in [17.01, 17.84] ps^{-1} @ 90% C.L.

Δm_s in [16.96, 17.91] ps^{-1} @ 95% C.L.



$$\Delta m_s = 17.31^{+0.33}_{-0.18}(stat.) \pm 0.07(syst.)\text{ps}^{-1}$$

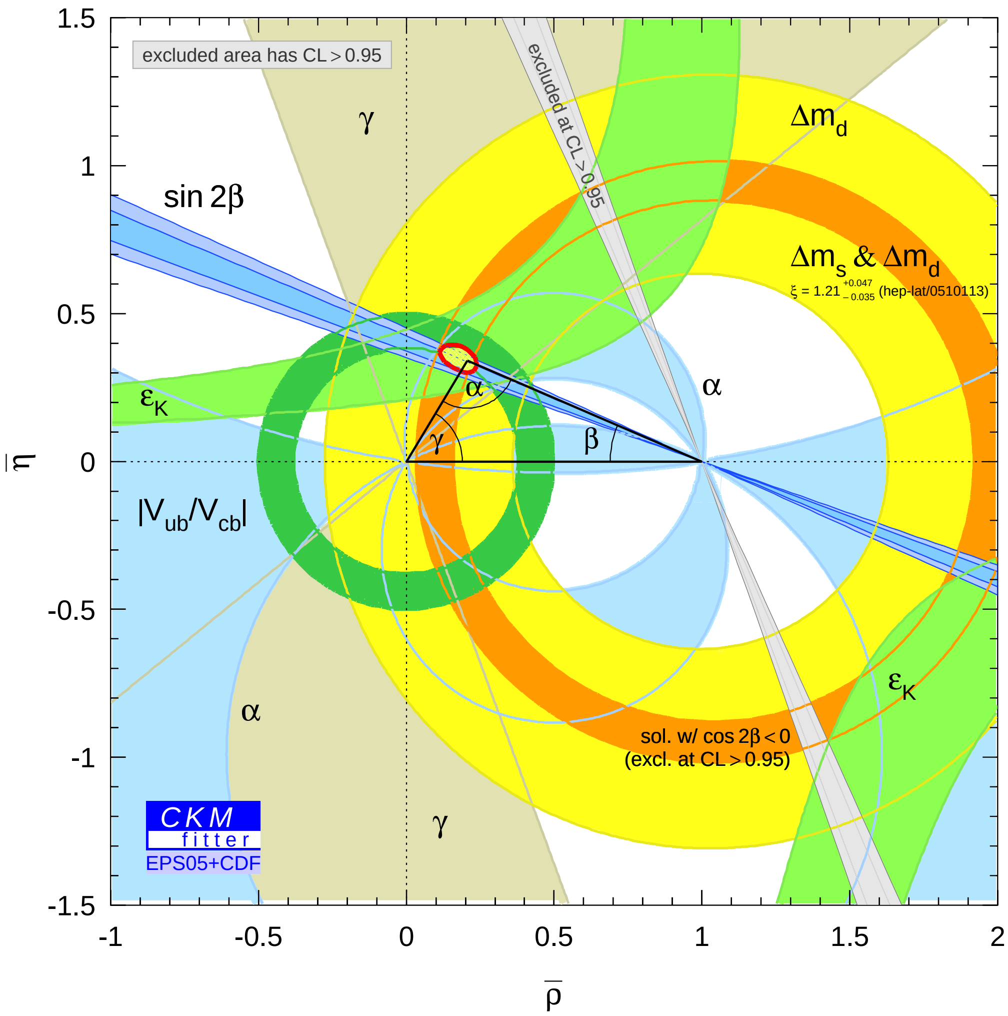
Systematic dominated by uncertainties on ct.

$|V_{td}|/|V_{ts}|$ Measurement

Input	Value	Source
$\frac{m(B^0)}{m(B_s)}$	0.98320	PDG
ξ	$1.21^{+0.047}_{-0.035}$	Lattice 2005
Δm_d	0.505 ± 0.005	PDG
Δm_s	$17.310^{+0.34}_{-0.19}$	this analysis

$|V_{td}|/|V_{ts}| =$

$0.208\ ^{+0.001}_{-0.002}$(exp.) $^{+0.008}_{-0.006}$ (theo.)



Belle measurement $b \to d\gamma$:

$|V_{td}|/|V_{ts}| = 0.199\ ^{+0.026}_{-0.025}$(exp.) $^{+0.018}_{-0.015}$(theo.)

Summary & Outlook

- Δm_s measurement → important test of CKM mechanism
- First direct Δm_s measurement from CDF:

$$\Delta m_s = 17.31^{+0.33}_{-0.18}(stat.) \pm 0.07(syst.)\text{ps}^{-1}$$

$$|V_{td}|/|V_{ts}| = 0.208\ ^{+0.001}_{-0.002}\text{(exp.)}\ ^{+0.008}_{-0.006}\text{(theo.)}$$

(probability for random fluctuation $\leq$ 0.2%)

- Potential for further improvements:
  - partial reconstructed hadronic B_s
  - combined OST (NN)
  - improved SS(K)T
  - ...