Observation of B_s-$\overline{B}_s$ Oscillations

Christoph Paus
Massachusetts Institute of Technology

Wine and Cheese Seminar
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Overview

- ☞ Theory and some History
- ☞ The Method
- ☞ Equipment Used for the Measurements
- ☞ Our Samples
- ☞ *b* Flavor Tagging
- ☞ Results per Sample
- ☞ Mixing Result Summary
- ☞ Conclusions

Theory and some History

Matter in the Standard Model

Matter build of families of fermion doublets

Leptons $\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L$ $\begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L$ $\begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$

Quarks $\begin{pmatrix} u \\ d' \end{pmatrix}_L$ $\begin{pmatrix} c \\ s' \end{pmatrix}_L$ $\begin{pmatrix} t \\ b' \end{pmatrix}_L$

Weak interaction through $W^\pm$ bosons

In general: weak eigenstates ≠ strong eigenstates

- mixing between families possible
- lower quark doublet components absorb difference
- neutrinos also mix

Cabibbo–Kobayashi–Maskawa Matrix

Example: two families of quark pairs $\rightarrow$ one mixing angle

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix} \quad \text{rotation matrix}$$

Matrix has to be unitary: $V^\dagger V = 1$

Describe mixing between three quark-pair families

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

V is Cabbibo–Kobayashi–Maskawa matrix

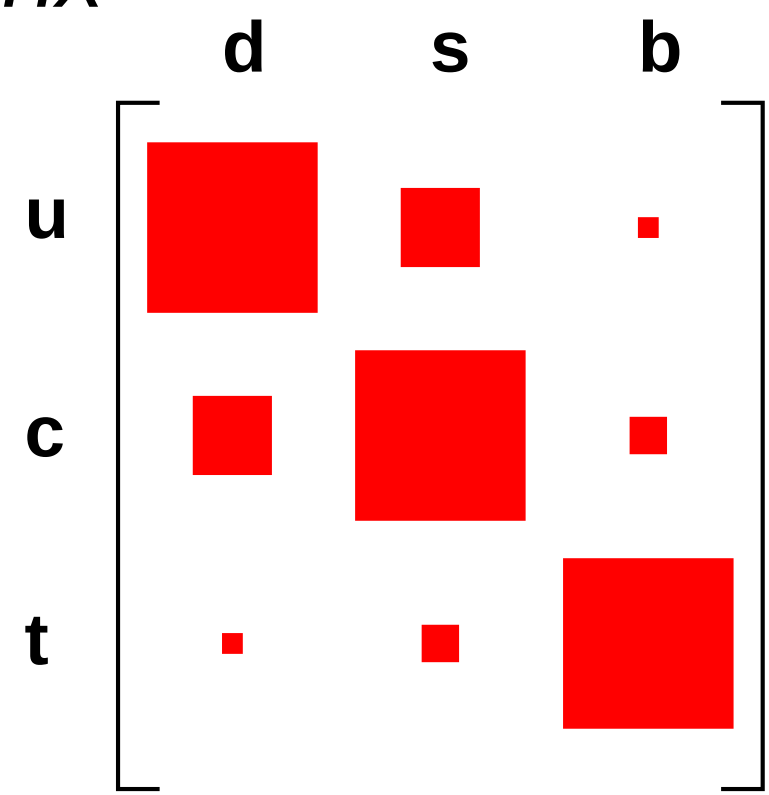
Three families $\rightarrow$ 4 degrees of freedom

- ☞ 3 angles
- ☞ 1 complex phase $\rightarrow$ *CP* violation

CKM Matrix

Matrix structure

- ☞ mostly diagonal
- ☞ crossing of families suppressed
- ☞ the further the less probable
- ☞ values not predicted



Particles are conserved:

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

$\rightarrow$ unitarity condition

Wolfenstein parametrization ($\lambda = 0.2272 \pm 0.0010$):

$$V = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + o(\lambda^4)$$

Least known parameters: ρ and η

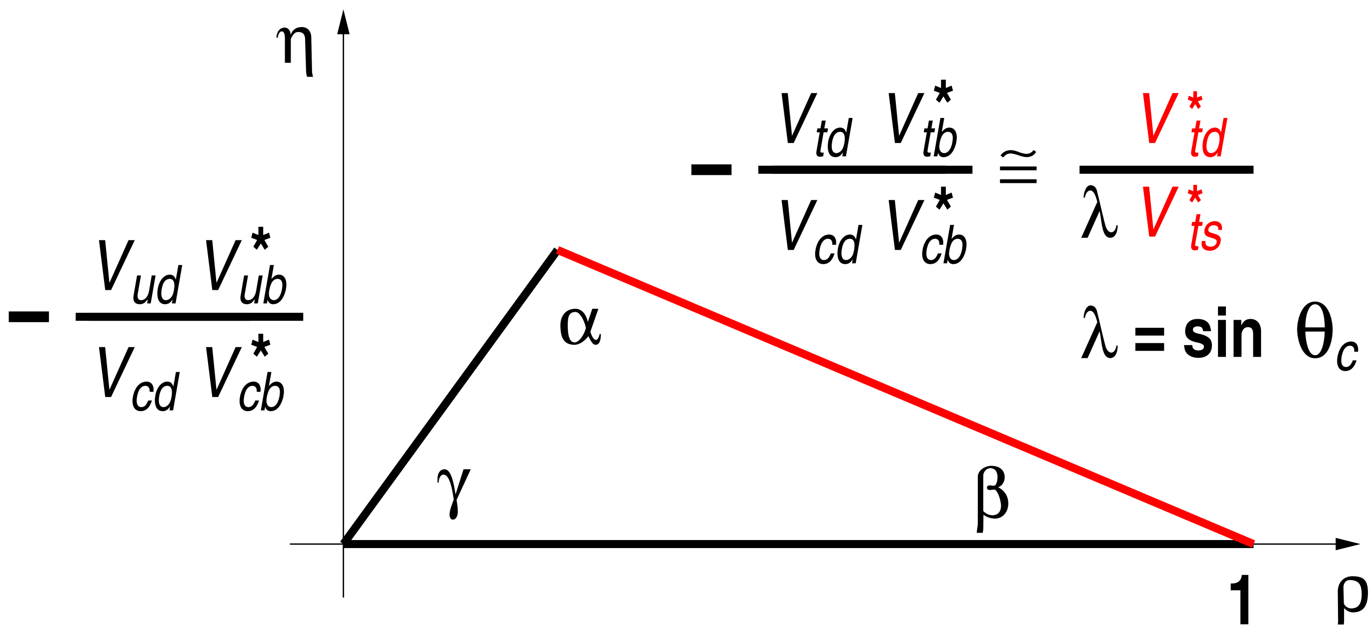
Unitarity Triangle

Unitarity condition: $V^{\dagger}V = 1$

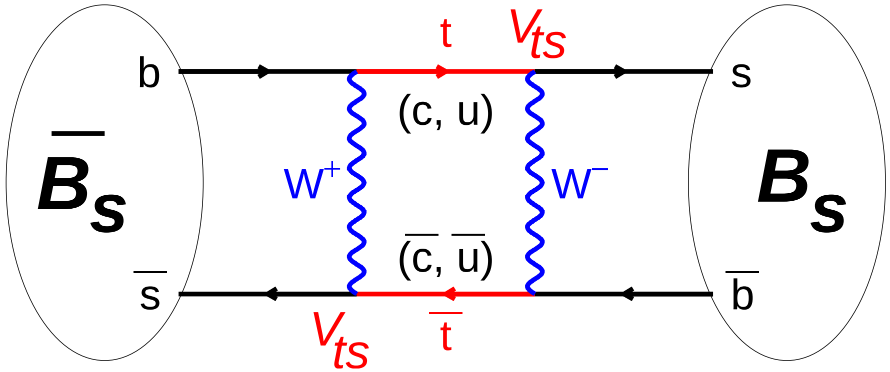
$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

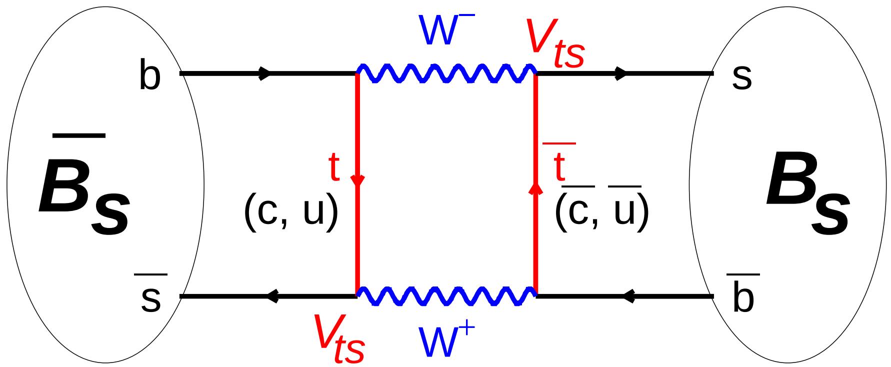
$$\rightarrow V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$

$$\rightarrow 1 + V_{ud}V_{ub}^{*}/V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*}/V_{cd}V_{cb}^{*} = 0$$



Neutral B Meson Mixing





Quark mixing $\rightarrow$ non diagonal Hamiltonian for $\langle \overline{B} | H | B \rangle$

$$H = \begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix} - \frac{i}{2} \begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}$$

Diagonalizing the Hamiltonian results in

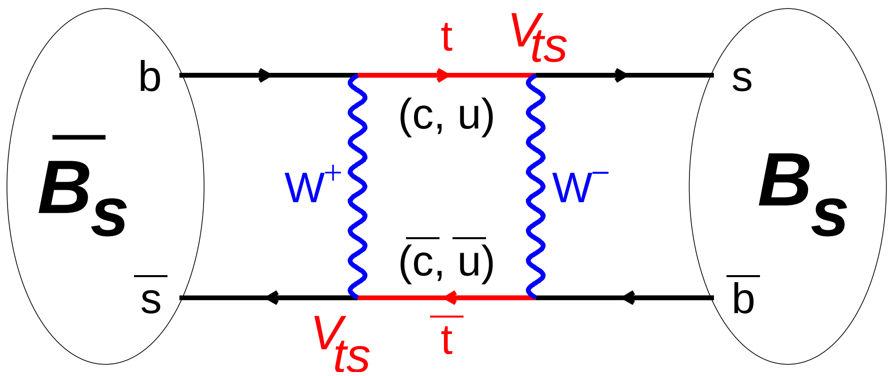
- ☞ two masses: m_H and m_L and $\Delta m = m_H - m_L$
- ☞ two decay widths: Γ_H and Γ_L and $\Delta\Gamma = \Gamma_H - \Gamma_L$
- ☞ remember: $\Gamma = 1/\tau$

Mass and decay width (lifetime) are measurable!!

Theoretical Predictions - Δm

Theory prediction for B^0/B_s^0 mix through box diagram

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



Lattice QCD calculations

$$\hat{B}_{B_d} f_{B_d}^2 = (246 \pm 11 \pm 25)\ \text{MeV}^2$$

Hadronic uncertainties limit

$|V_{td}|$ determination to $\approx 11\%$

In ratio theory uncertainties are reduced

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2} \quad \text{with} \quad \xi = 1.21\,^{+0.047}_{-0.035}$$

Determine $\frac{|V_{ts}|}{|V_{td}|}$ to $\approx 3.4\%$

Unitarity Triangle - Status EPS 2005

Apex $(\bar{\rho}, \bar{\eta})$

Squeezing along side *b*

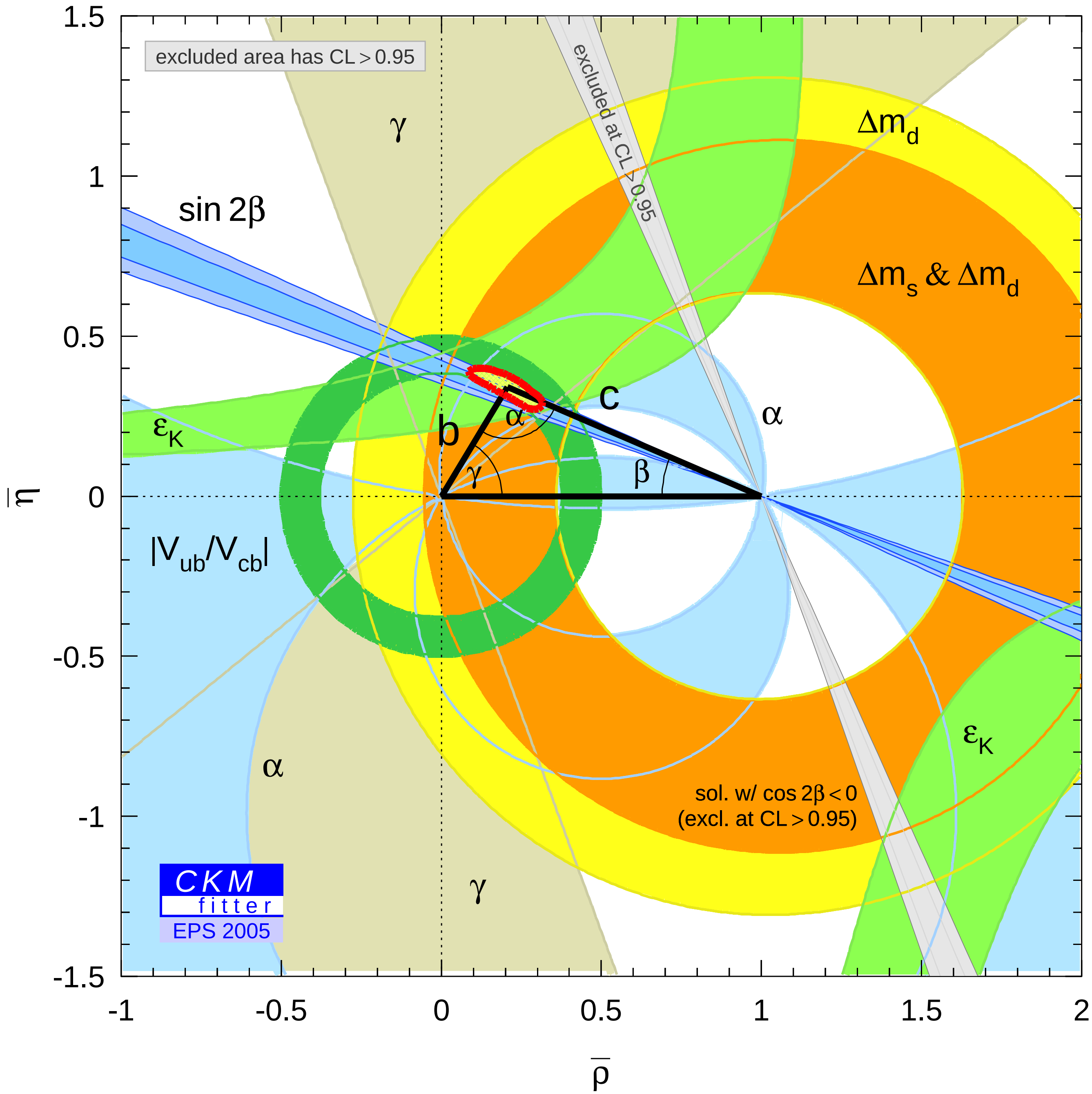
- ☞ $\sin 2\beta$
- ☞ V_{ub}/V_{cb}

Squeezing along side *c*

- ☞ Δm_d
- ☞ Δm_s
- ☞ γ

CKM fit result:

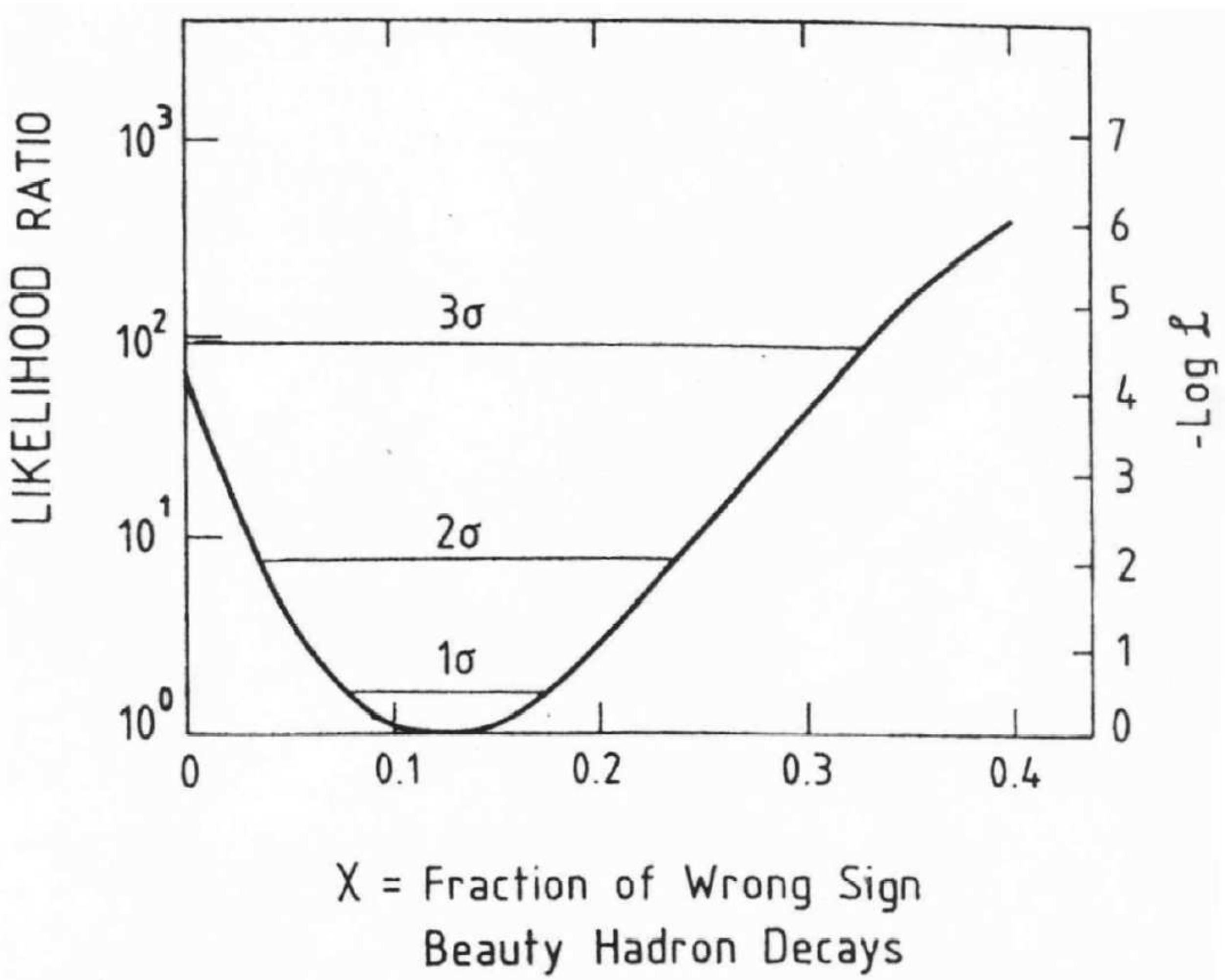
$$\Delta m_s = 18.3\ ^{+6.5}_{-1.5}\ \mathrm{ps}^{-1}$$



First Measurement of B Mixing from UA1

Signature: like sign high p_T leptons

PLB 186 (1987) 247



Result

- ☞ time integrated
  $\overline{\chi} = 0.121 \pm 0.047$
- ☞ implied heavy top

For B_s

- ☞ too fast: $\chi_s = 0.5$

Later Argus/Cleo/LEP/SLD/Tevatron/BaBar/Belle ....

Historic Review: A 20-Year Effort

1987

- first evidence of B mixing from UA1 — PLB 186 (1987) 247
- Argus observes B^0 mixing: UA1 implies large B_s mixing, $m_t > 50\ \mathrm{GeV}/c^2$ — PLB 192 (1987) 245

1989

- CLEO confirms Argus result — PRL 62 (1989) 2233

1990s

- inclusive measurements of B^0 mixing from LEP establish B_s mixing

1993

- first time dependent measurement of Δm_d from Aleph — PLB 313 (1993) 498
- first lower limit on Δm_s from Aleph: $\Delta m_s > 12 \cdot 10^{-4}\ \mathrm{eV}/c^2$ — PLB 322 (1994) 441

1999

- CDF Run I result on Δm_s: $\Delta m_s > 5.8\ \mathrm{ps}^{-1}$ — PRL 82 (1999) 3576

2005

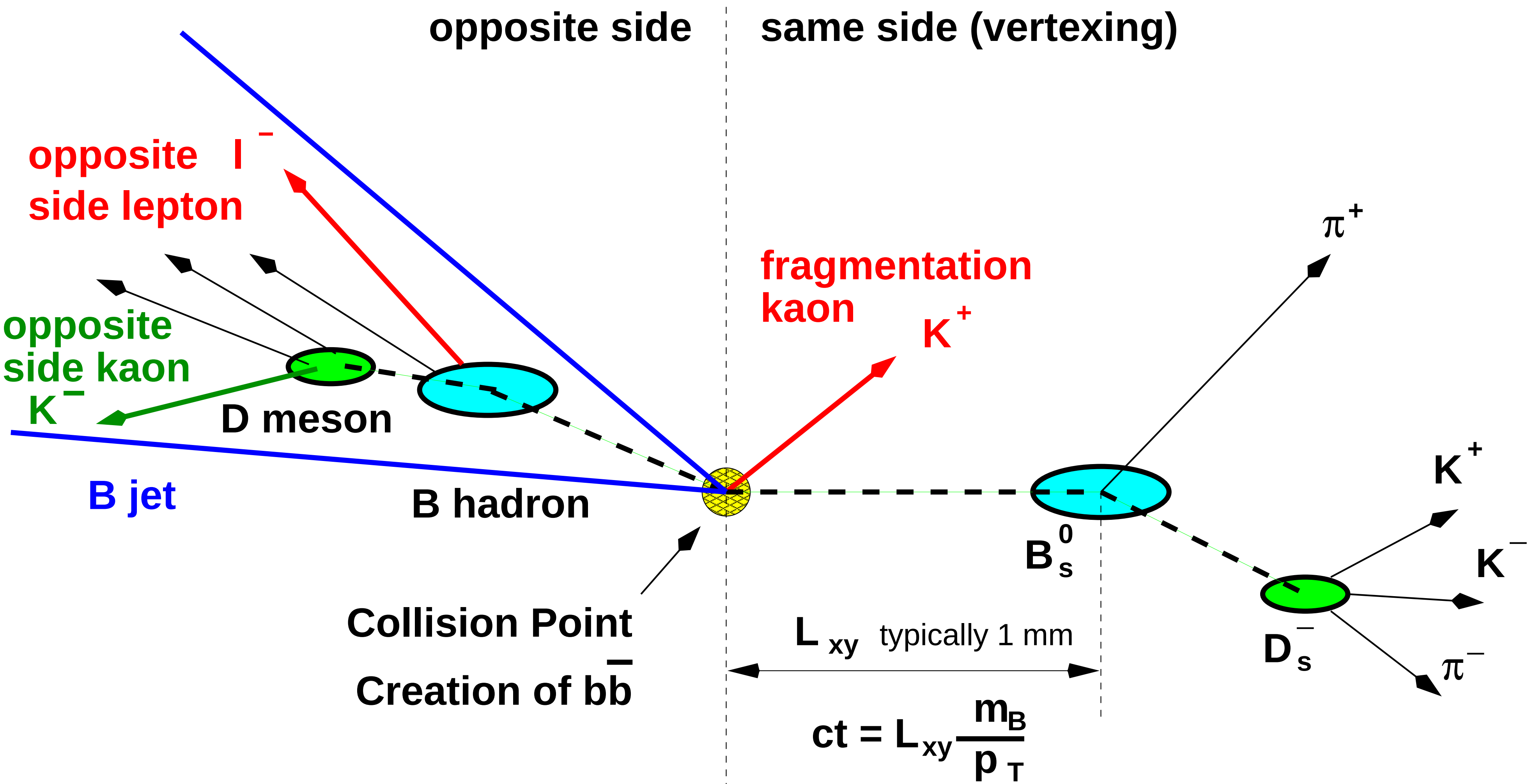
- DØ first result on Δm_s: $\Delta m_s > 5.0\ \mathrm{ps}^{-1}$
- CDF Run II first result on Δm_s: $\Delta m_s > 7.9\ \mathrm{ps}^{-1}$

2006

- D0 reports interval: $\Delta m_s \in [17, 21]\ \mathrm{ps}^{-1}$ at 90% CL — PRL 97 (2006) 021802
- CDF Run II first measurement $\Delta m_s = 17.31^{+0.33}_{-0.18} \pm 0.07\ \mathrm{ps}^{-1}$ — PRL 97 (2006) 062003

The Method

A Picture Book Event

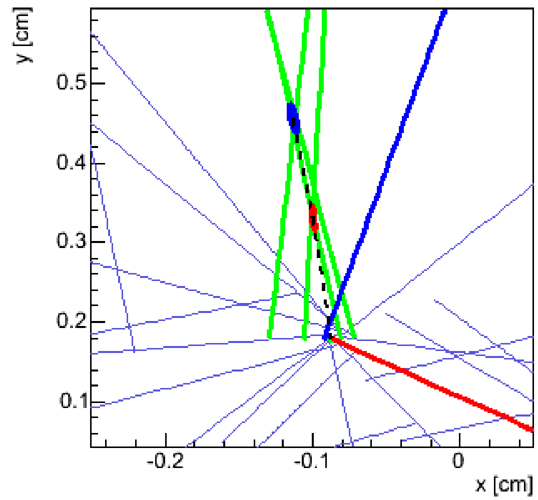


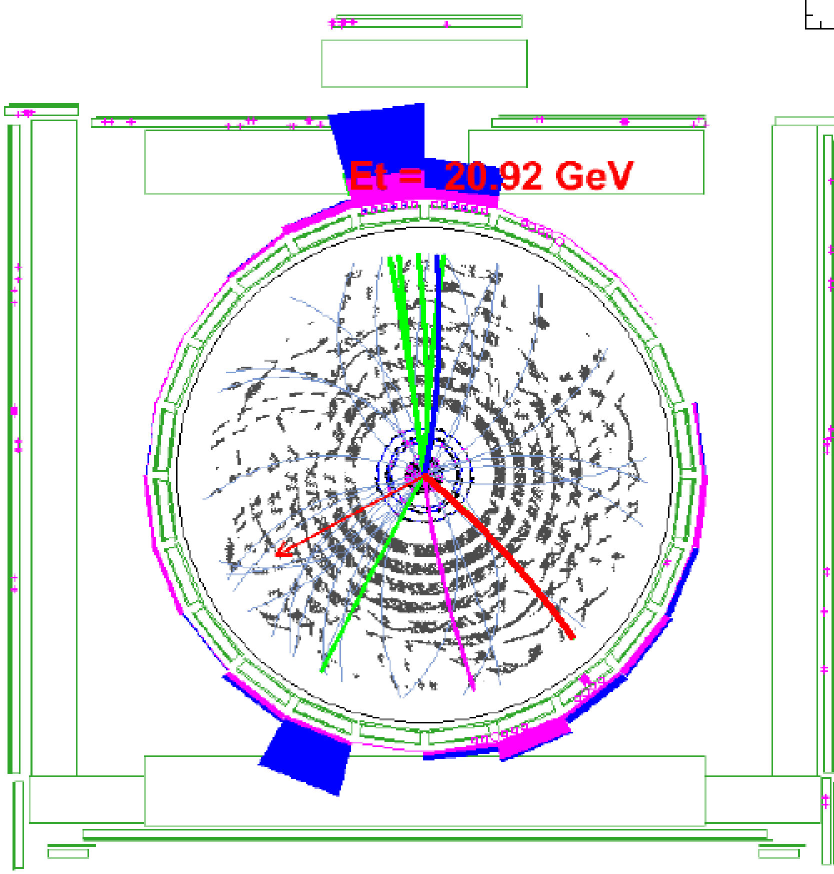
Ingredients to measure mixing

- ☞ proper decay time *ct*, *B* rest frame
- ☞ *B* flavor at decay, final state
- ☞ *B* flavor at production, flavor tagging

An Event Display

Run 204720, Event 109026





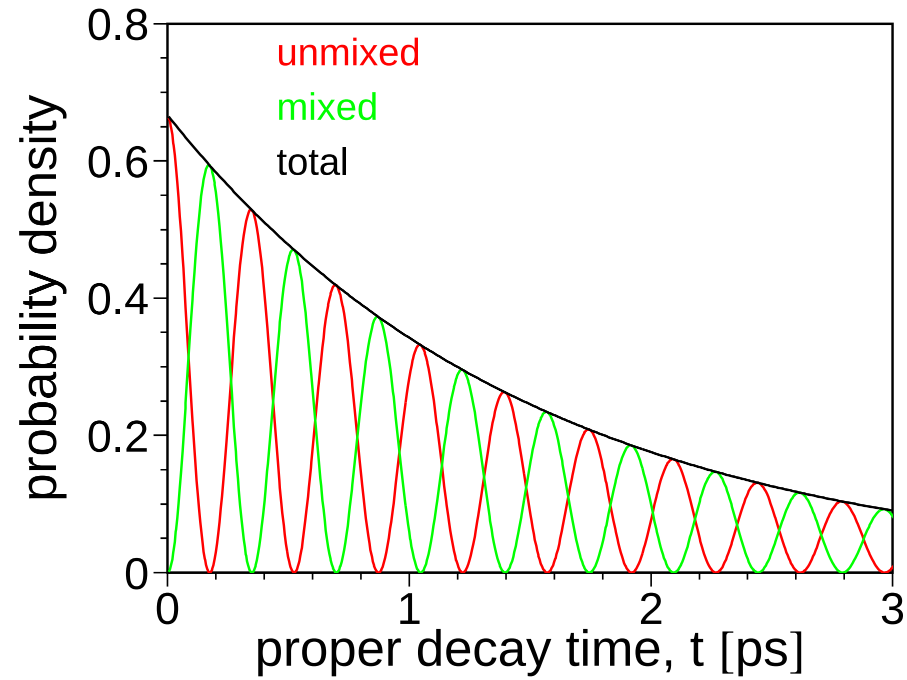
SSKT Track
Tag Muon
Other Track
Candidate Track
Beam Line
Primary Vertex
B Vertex
D Vertex
Path

B Mixing Phenomenology

Behavior in proper time

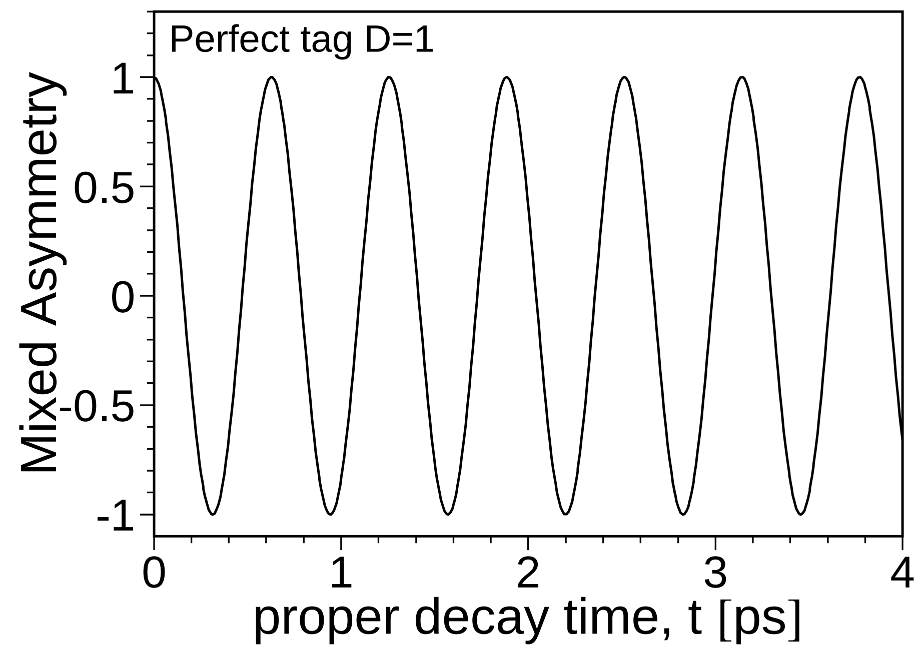
$$P(t)_{B^0 \to B^0} = \frac{1}{2\tau} e^{-t/\tau}(1 + \cos \Delta m t)$$

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



Determine asymmetry

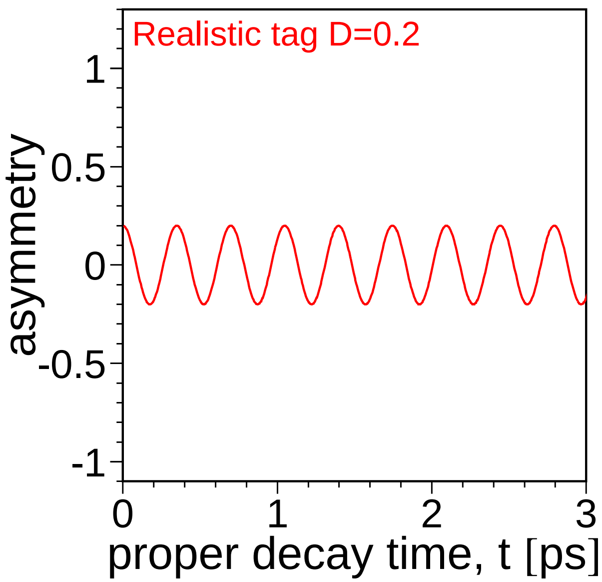
$$A_0(t) = \frac{N(t)_{unmixed} - N(t)_{mixed}}{N(t)_{unmixed} + N(t)_{mixed}} = \cos \Delta m\, t$$



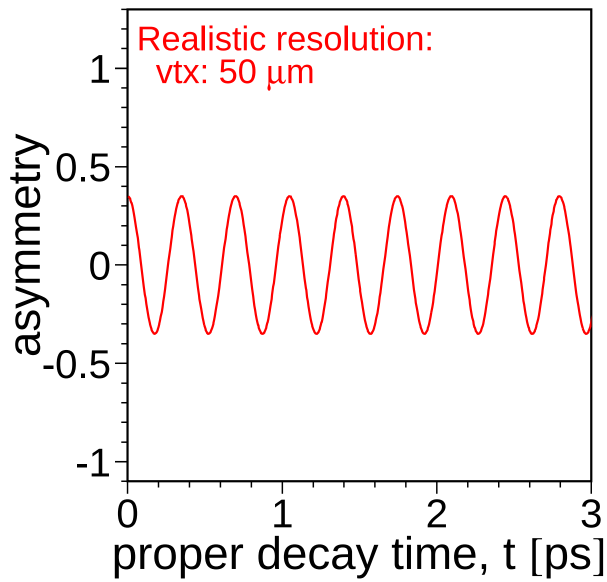
In a perfect world

What Do We See in the End?

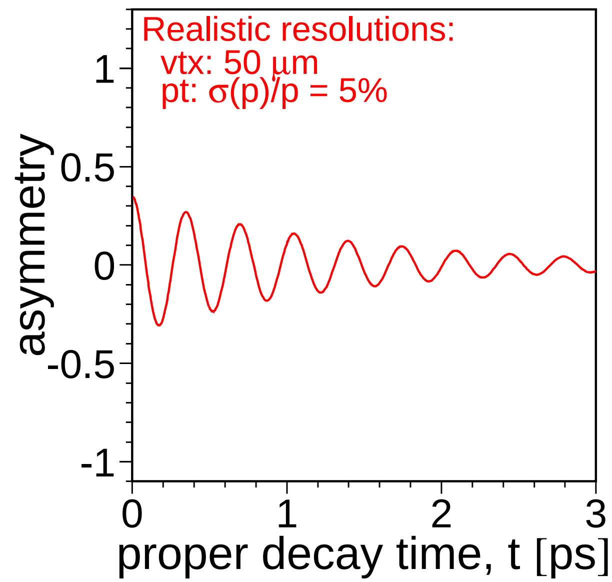
Flavor tagging



Vertex



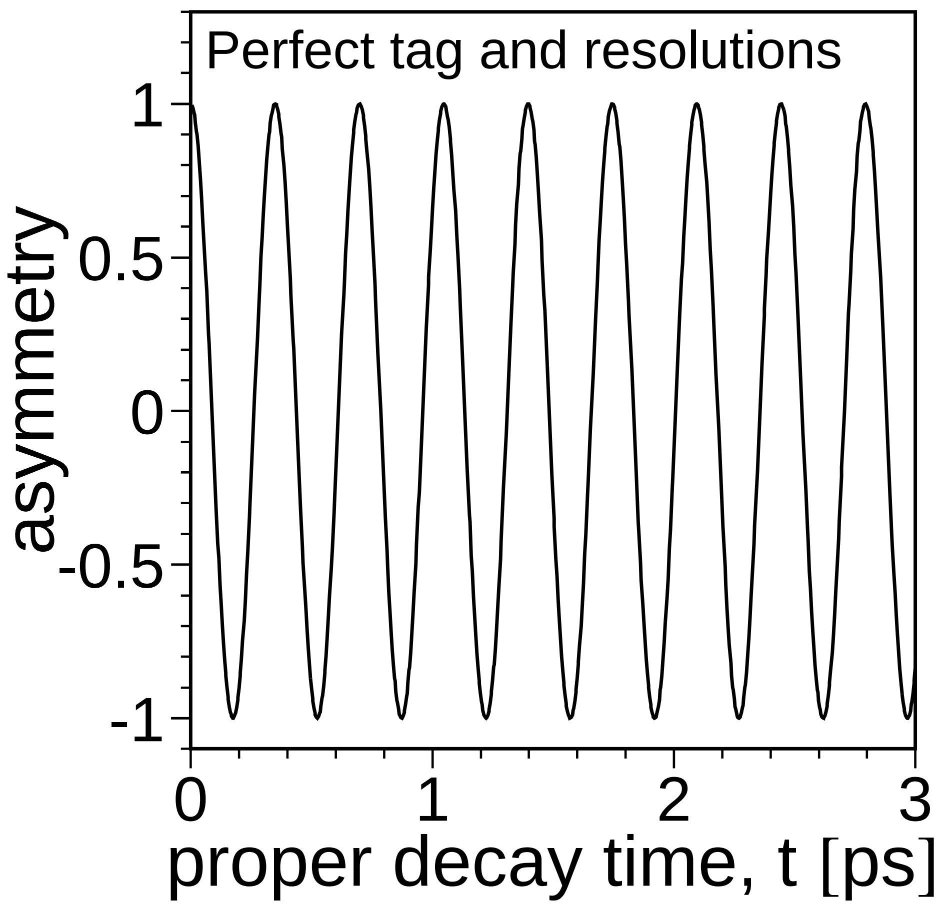
Vertex and Momentum

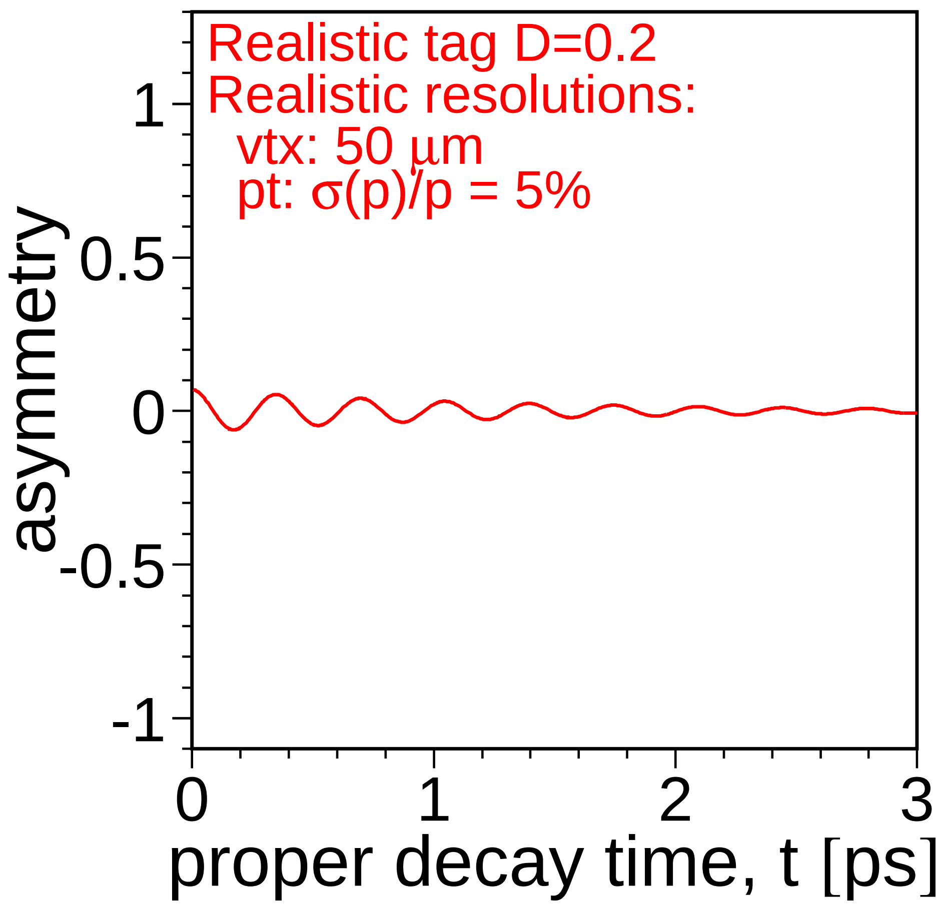


$$1/\sigma_A = \sqrt{\frac{n_S \varepsilon D^2}{2}}\sqrt{\frac{n_S}{n_S+n_B}}\exp\left(-\frac{(\Delta m_s \sigma_{ct})^2}{2}\right)$$

$$\sigma_{ct} = \sqrt{(\sigma_{ct}^0)^2 + \left(ct\,\frac{\sigma_p}{p}\right)^2}$$

Perfect to Realistic



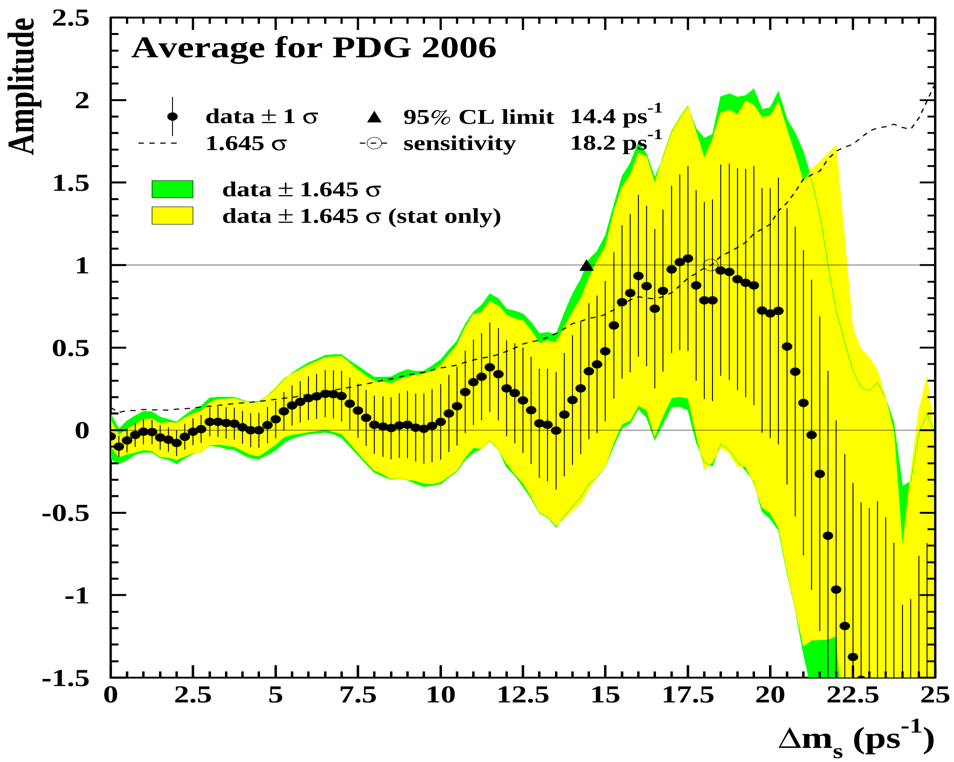


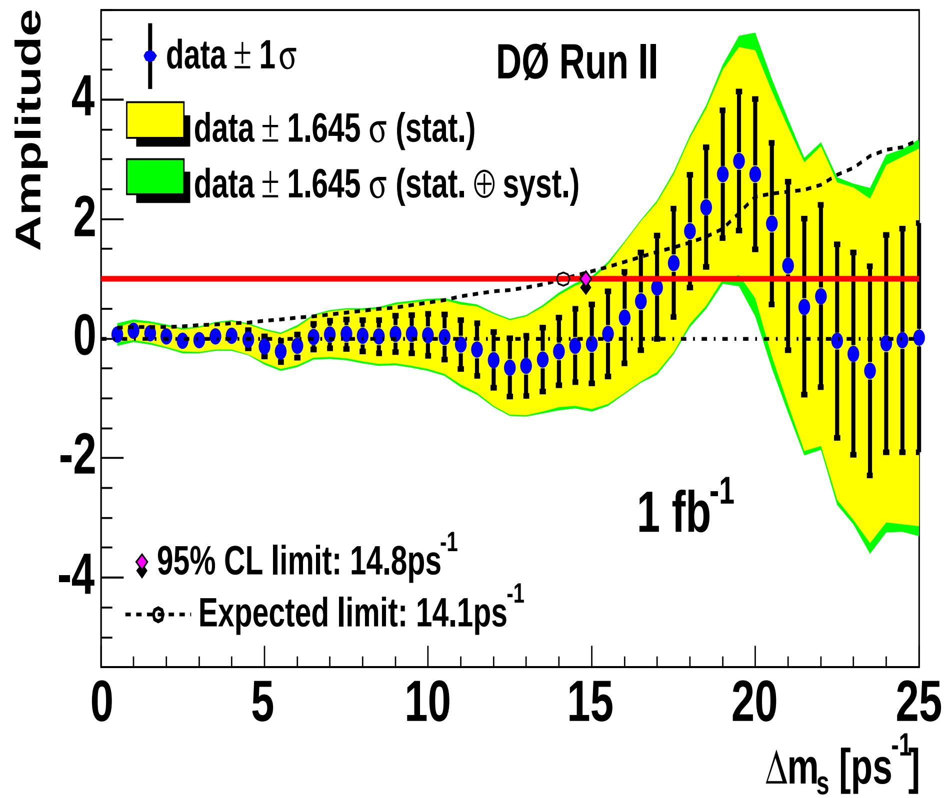
Unbinned likelihood fit: $p \sim exp(-t/\tau)(1 \pm AD \cos \Delta m t)$

- ☞ scan Δm for signal: determine amplitude, A
- ☞ measure Δm_s with $A = 1$

Status: Scanning for B_s Oscillation Signal

Before this analysis





before Spring 2005

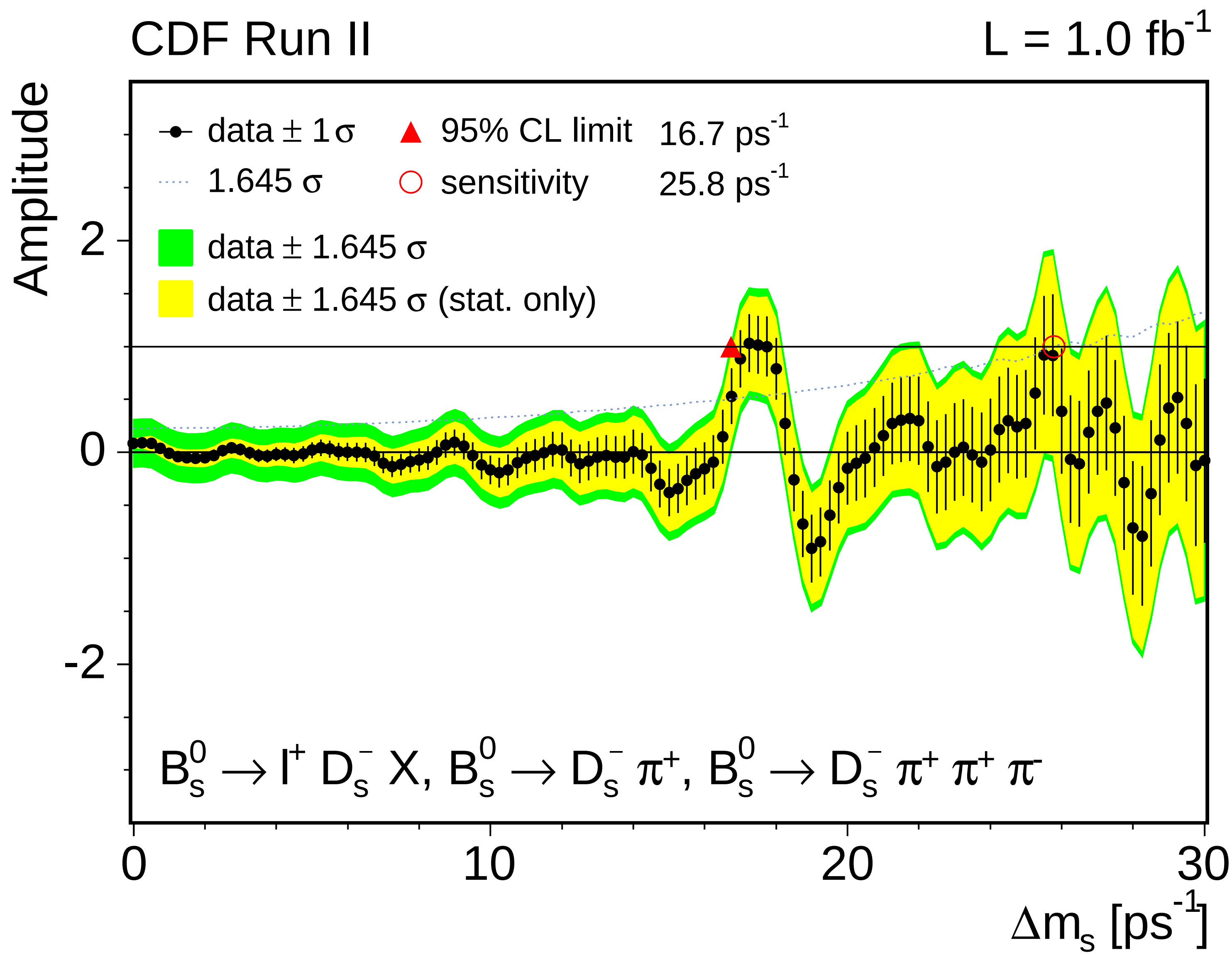
recent DØ result

PRL 97 (2006) 21802

$17\ ps^{-1} < \Delta m_s < 21\ ps^{-1}$ at 90% CL

p-value about 5.0%

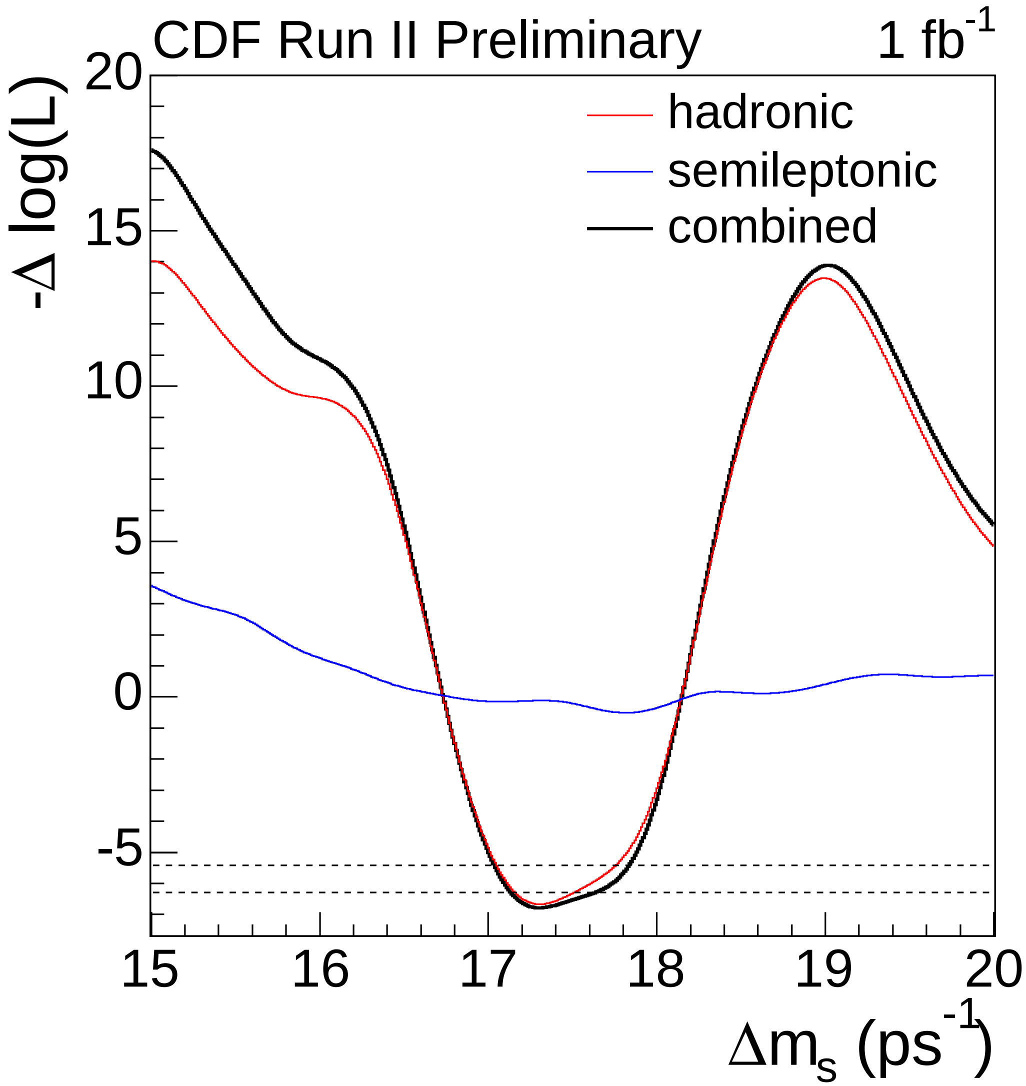
Last CDF Result *PRL 97 (2006) 062003*



$A = 1.03 \pm 0.28\text{(stat)}$ compatible with 1 for $\Delta m_s \sim 17.3\ \text{ps}^{-1}$

Last CDF Result *PRL 97 (2006) 062003*

Signature: minimum of $\log(\mathcal{L}(A=1)) - \log(\mathcal{L}(A=0))$



Minimum: -6.75

p-value: 0.2%

Analysis was blinded

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

Plan After April

Close box again

Refine analysis methods

Go for 5σ

What We Improved

Unchanged

- same data: 1 fb^{-1}

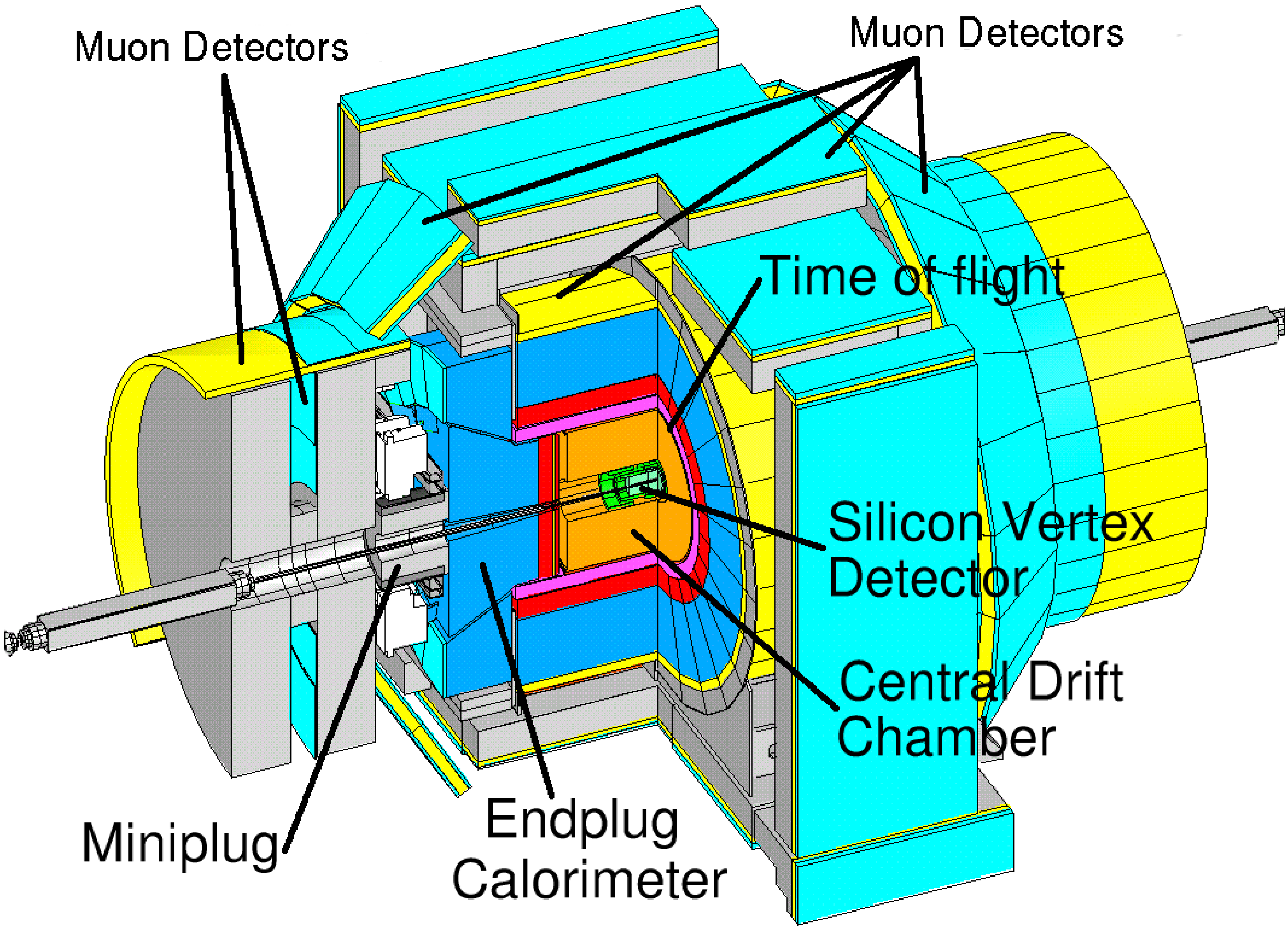
Improvements

- flavor tagging
  - added opposite side kaon tagger
  - applied NN to combine all opposite side taggers
  - applied NN to same side tagger
- signal yields
  - added partially reconstructed decays
  - used particle identification in selection
  - used NN for hadronic selection
  - added trigger path in ℓD_s^-

Added effective statistics of factor of 2.5

Equipment Used for the Measurements

CDF II Detector



CDF II Detector - Key Features

’Deadtimeless’ trigger system

- ☞ 3 level, pipelined, flexible system
- ☞ Silicon Vertex Trigger (SVT) at 2nd level (≈25 kHz)

Charged particle reconstruction

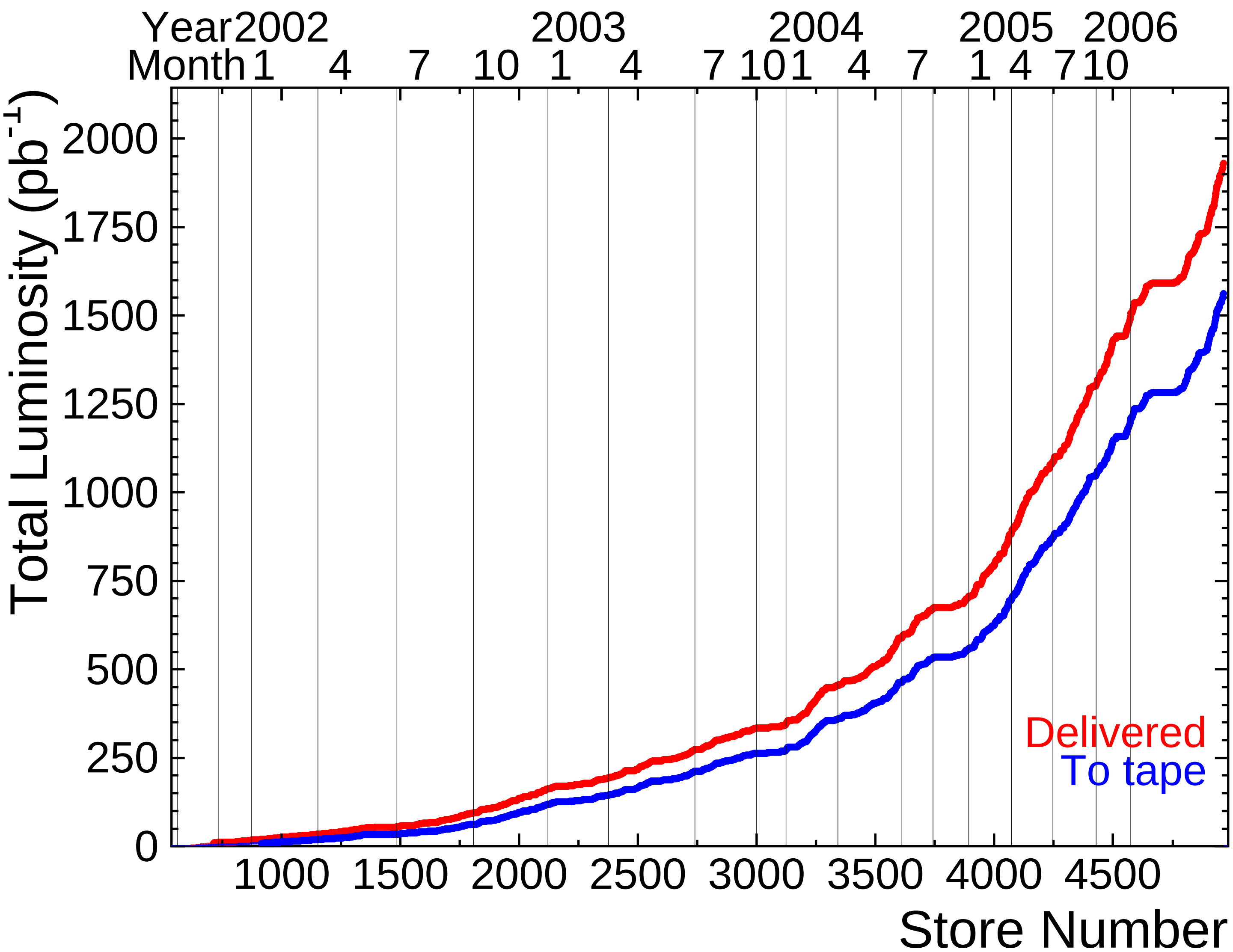
- ☞ redundancy for pattern reco in busy environment
- ☞ excellent momentum resolution: $R = 1.4$m,$B = 1.4$T
- ☞ excellent vertex resolution: L00 at 1.5cm

Particle identification

- ☞ energy loss in drift chamber (dE/dx)
- ☞ Time-of-Flight system at 1.4 m radius
- ☞ electron and muon identification

Our Samples

Sample Luminosity



B_s Mixing Analysis uses: 1 fb^{-1}

now: 1.8 fb^{-1} delivered, 1.6 fb^{-1} on tape

Samples Used in the Analysis

Sample to tune flavor taggers (largest)

- ☞ ℓ+track sample (track is required to be displaced)

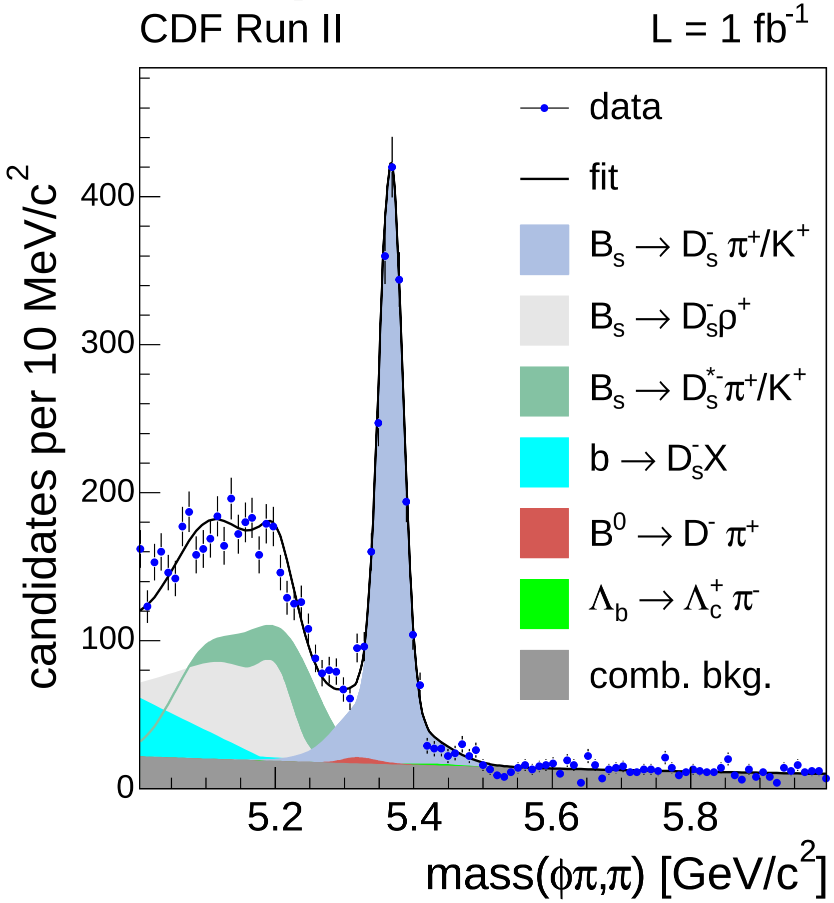
Calibration samples (taggers, vertex resolutions)

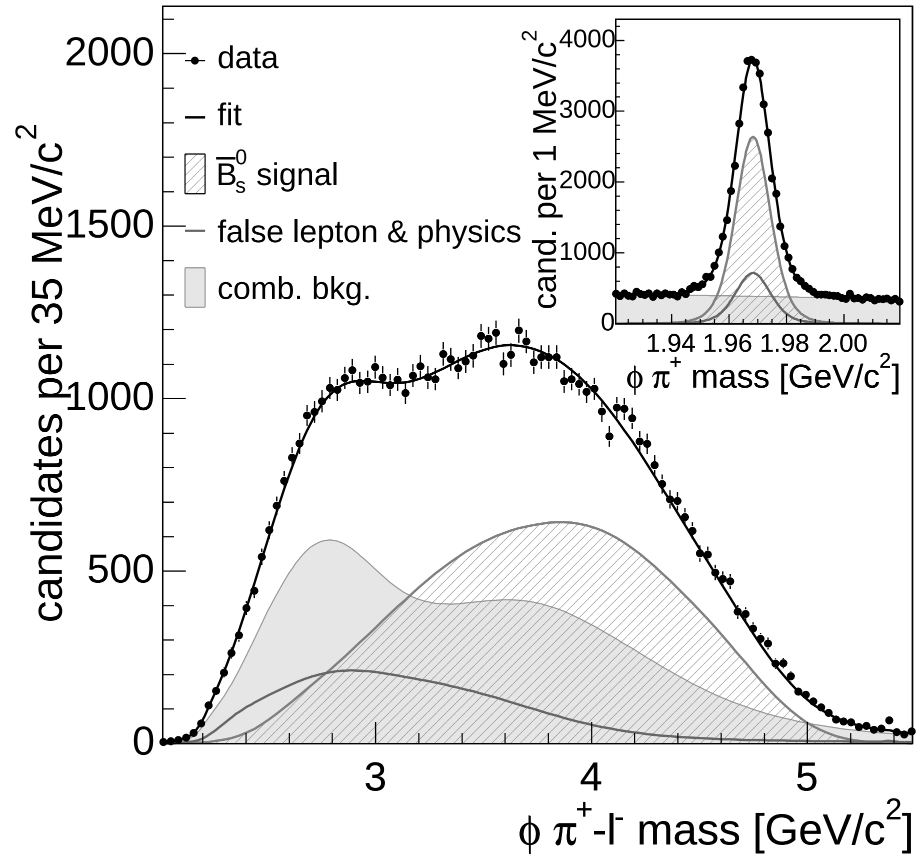
- ☞ $B^+ \to J/\psi K^+, \overline{D}^0\pi^+(\pi^+\pi^-), \overline{D}^0\ell^+X$,
- ☞ $B^0 \to J/\psi K^{*0}, D^-\pi^+(\pi^+\pi^-), D^-\ell^+X, D^{*-}\ell^+X$
- ☞ $B_s \to J/\psi\phi$
- ☞ with $D^{*-} \to D^0\pi^-$, $D^0 \to K^-\pi^+(\pi^+\pi^-)$, $D^- \to K^+\pi^-\pi^-$

Signal samples

- ☞ hadronic: $B_s \to D_s^-\pi^+(\pi^+\pi^-)$
- ☞ semileptonic: $B_s \to D_s^-\ell^+X$
- ☞ with $D_s^- \to \phi\pi^-, K^{*0}K^-, \pi^+\pi^-\pi^-$

Samples - Semileptonic Versus Hadronic





Hadronic $D_s\pi(\pi\pi)$

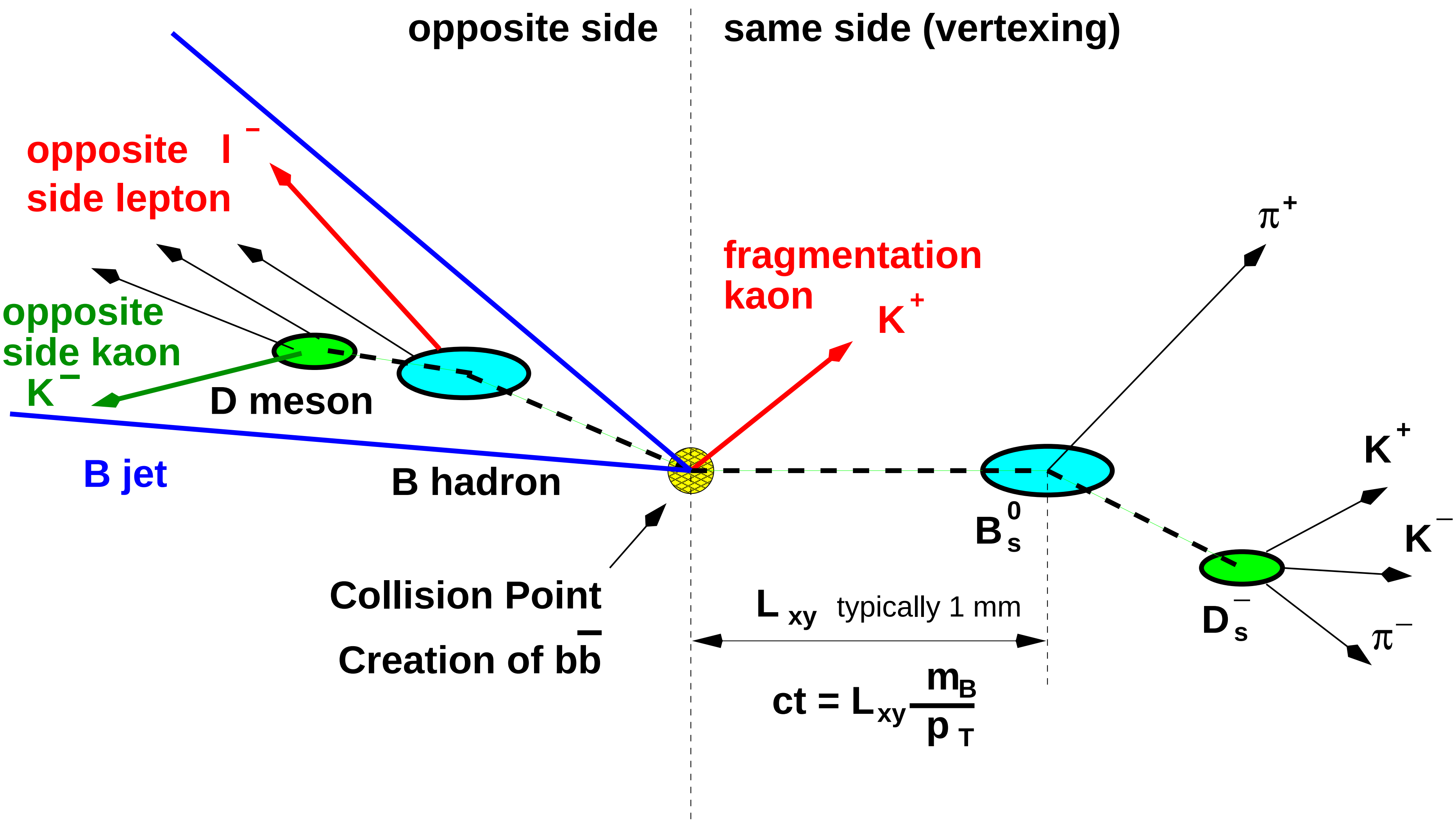
- ☞ reconstruct: $ct = L_{xy}\frac{m^B}{p_T^B}$
- ☞ great ct, mass resolution
- ☞ sample is clean
- ☞ small branching ratio

Semileptonic $\ell D_s X$

- ☞ reconstruct: $ct^* = L_{xy}\frac{m^B}{p_T^{\ell D}}$
- ☞ large branching ratio
- ☞ inferior ct, mass resolution
- ☞ sample composition issue

b Flavor Tagging

Flavor Tagging Introduction



Crucial parameters

☞ efficiency: ε, dilution: $D = 1 - 2p_W$ (p_W prob. for wrong decision)

☞ εD^2 expresses statistical power

Flavor Tagging Introduction

Tagging algorithms used

- opposite side: electron, muon, jet charge, kaon
- same side: pion (B^+, B^0), kaon (B_s)

Tuning the algorithm

- based on huge heavy flavour rich ℓ+track sample
- find dependencies and determine parametrizations
- find optimal point for the algorithm

Calibration of the tagger

- verify algorithms on B^0 and B^+ semileptonic/hadronic samples
- determine scale factor S in

  $B^+ : p \sim exp(-t/\tau)(1 \pm SD)$

  $B^0 : p \sim exp(-t/\tau)(1 \pm SD \cos \Delta m_d t)$
- use single scale factor: should be consistent with 1

Scheme for combination of taggers

OST Flavor Taggers

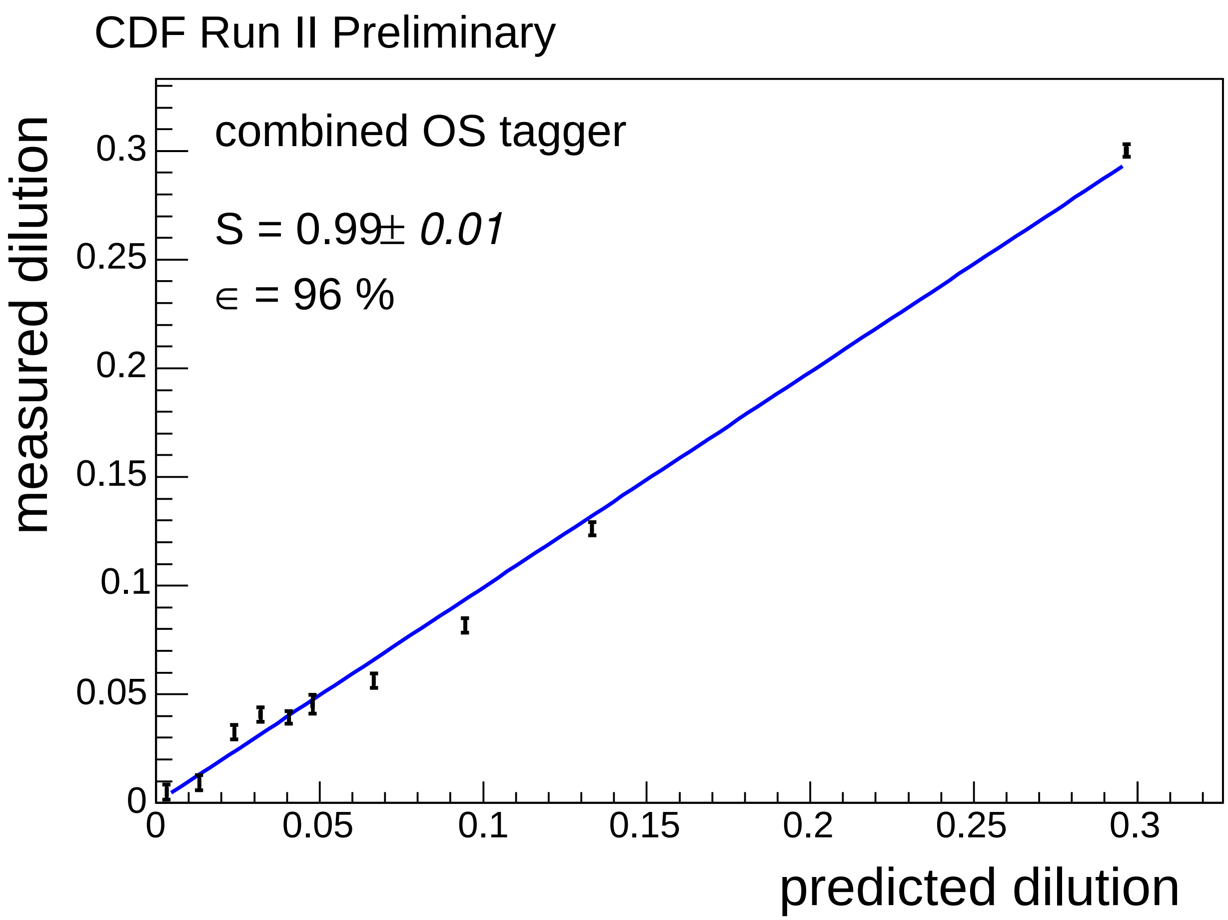
Individual performance and combination (ℓ+track sample)

tagger [%]	efficiency	dilution	εD^2
Muon	4.6 ± 0.0	34.7 ± 0.5	0.58 ± 0.02
Electron	3.2 ± 0.0	30.3 ± 0.7	0.29 ± 0.01
JQT	95.5 ± 0.1	9.7 ± 0.2	0.90 ± 0.03
Kaon	18.1 ± 0.1	11.1 ± 0.9	0.23 ± 0.02
OST old	95.6 ± 0.1	11.9 ± 0.1	1.34 ± 0.03
OST NN	95.8 ± 0.1	12.7 ± 0.2	1.54 ± 0.04

Opposite Side Taggers

- ☞ new kaon tagger
- ☞ not mutually exclusive $\rightarrow$ hierarchical scheme
- ☞ new NN combination: tag decisions as input

OST Flavor Taggers - Neural Network



Linear parametrization works well

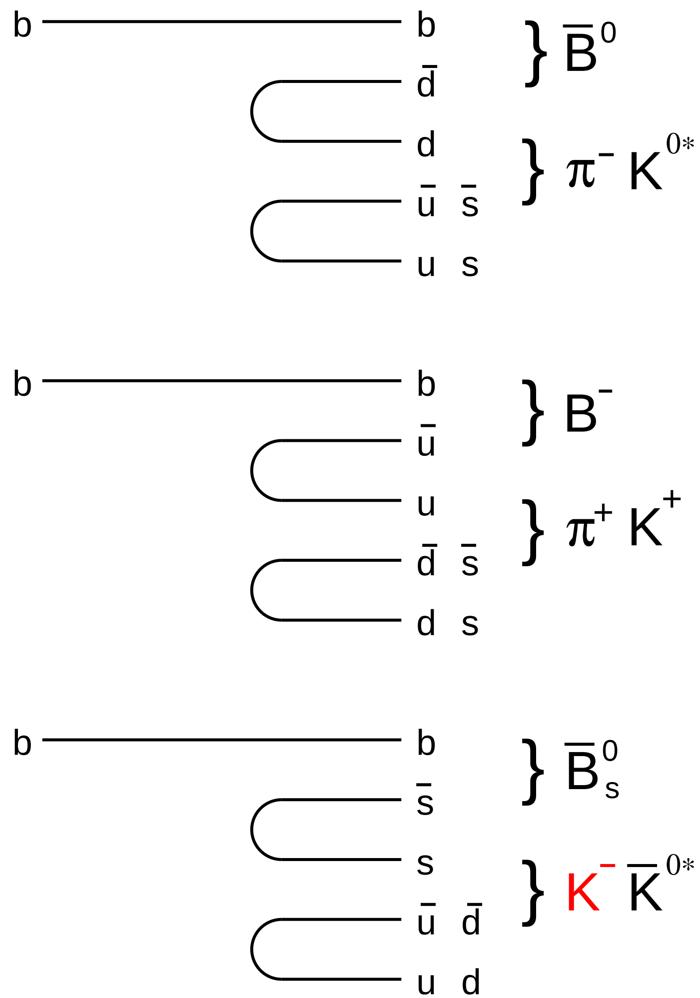
Improvement of εD^2

- hadronic 1.81 ± 0.10% from 1.51%
- semileptonic 1.82 ± 0.04% from 1.54%

Same Side Kaon Tagging

Fragmentation

- $B_{d/u}$ likely accompanied by π^+/π^-
- B_s likely accompanied by a K^+
- processes differ
- no direct transfer $B^+, B^0 \rightarrow B_s$
- need MC to measure tagger dilution



Strategy

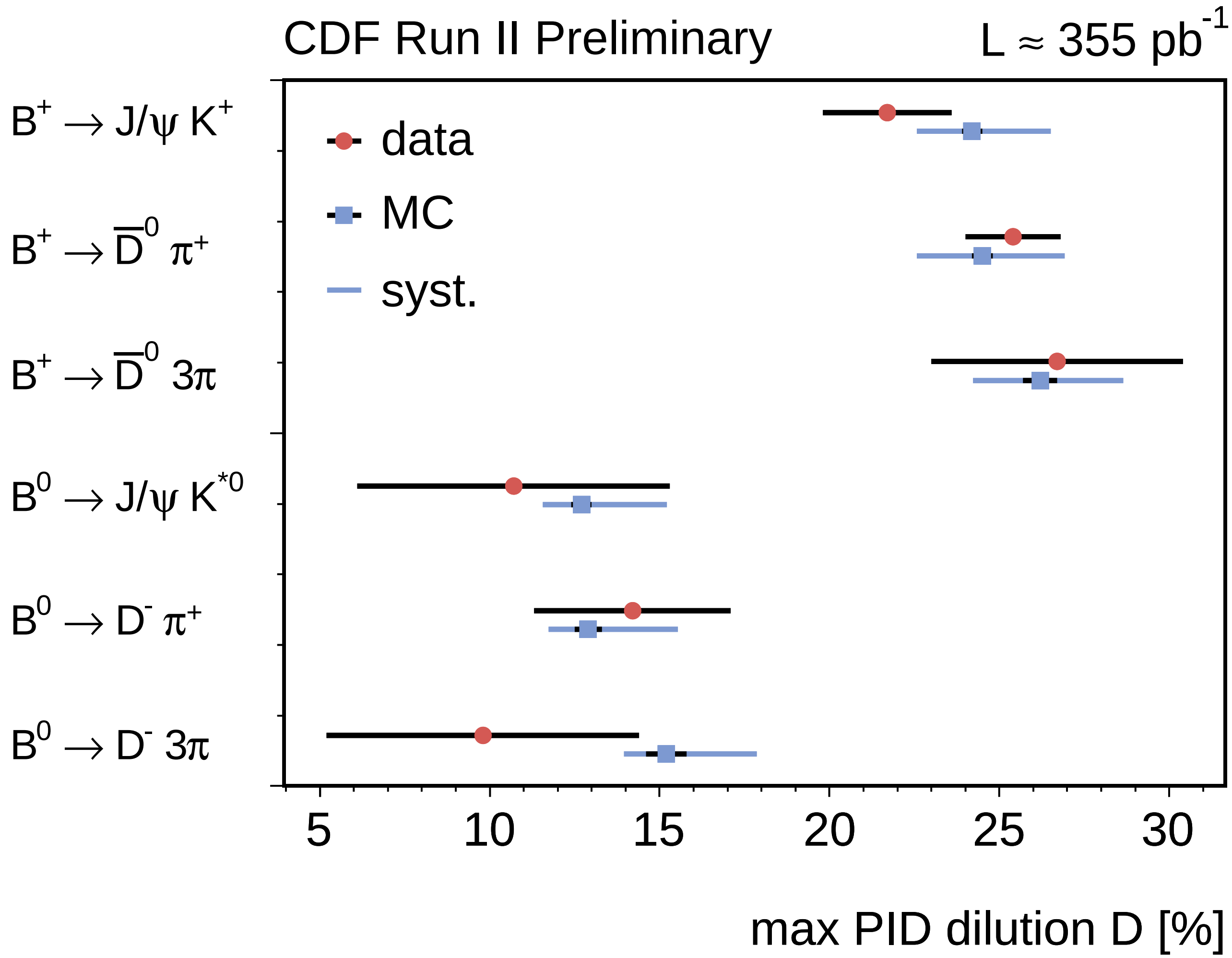
- tune MC with B^+ and B^0
- apply PID to de-weight pions
- use MC to parametrize dilution

ParticleID very important

- significantly improves εD^2
- reduces systematic uncertainty

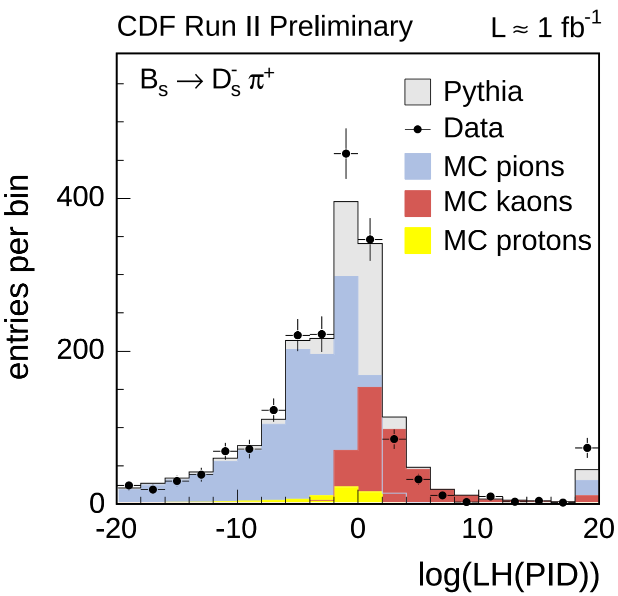
$\rightarrow$TOF (dE/dx) very important!

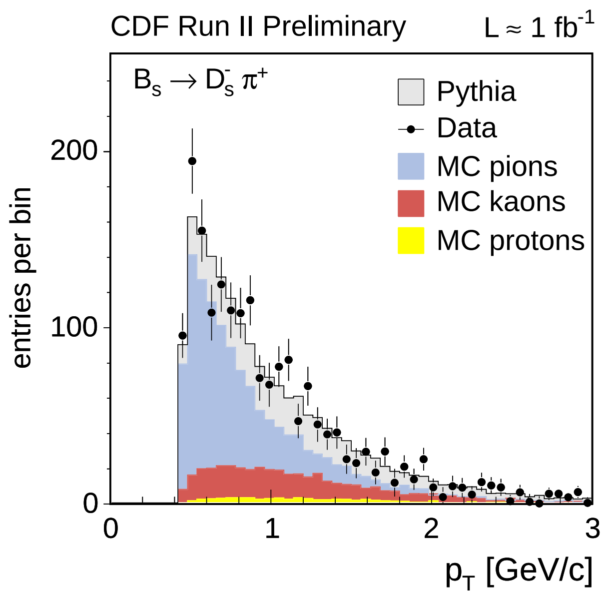
Flavor Tagging - SSKT Calibration: B^+, B^0

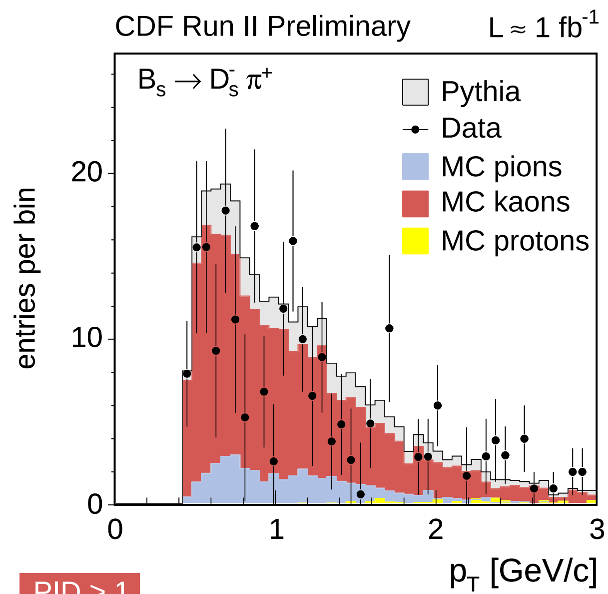


- find good agreement: particle Id and kinematic variables
- use kinematic variables to improve tagger

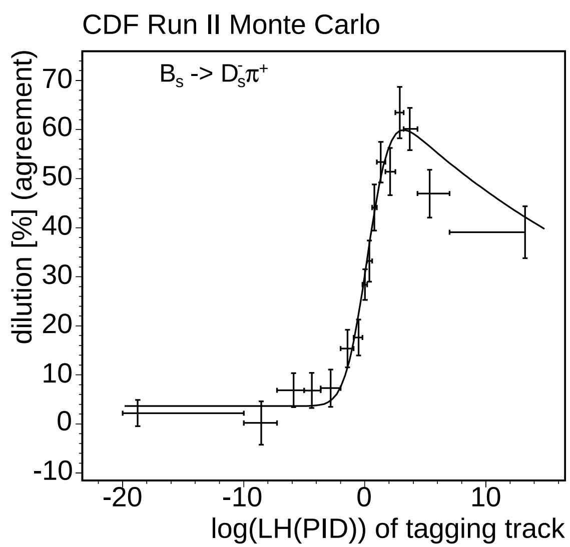
SSKT Particle Id Algorithm





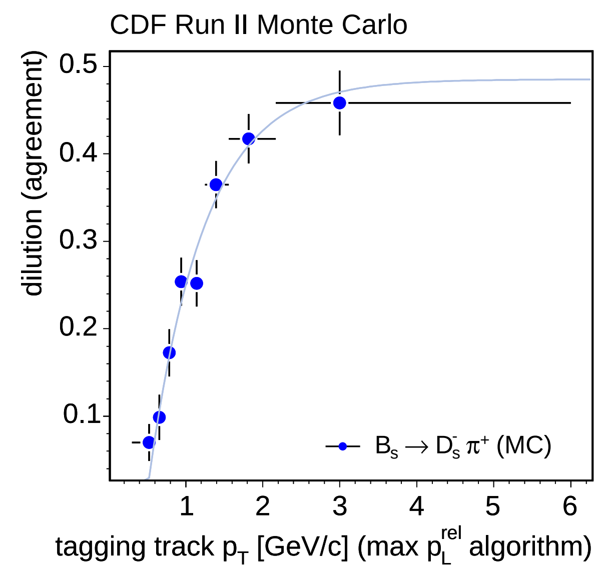


PID > 1



Pid algorithm works well

Kinematic of tag track not used

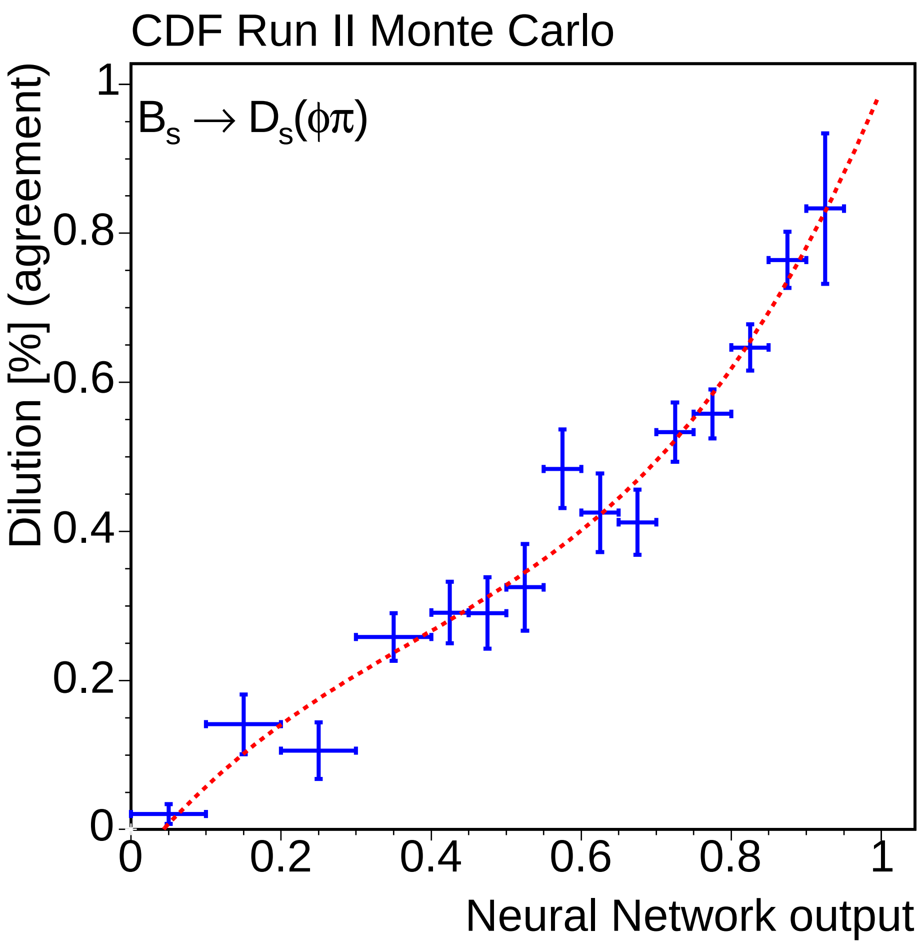


ex.: max. p_L^{rel} algorithm shows dependencies → use it

Neural Network SSKT

Algorithm

- variables: pid, ΔR, p_T, p_L^{rel}, p_T^{rel}, b (bool tags have same charge)
- train: signal - RS kaons, bg - WS kaons, pions and protons
- decision: track charge of highest NN tag candidate



Expected improvement

- MC ≈ 6% relative

Measured improvement

- 0% relative hadronic
  $\to$ $\varepsilon D^2 = 3.5\%$
- 8% relative semileptonic
  $\to$ now $\varepsilon D^2 = 4.8\%$

Results per Sample

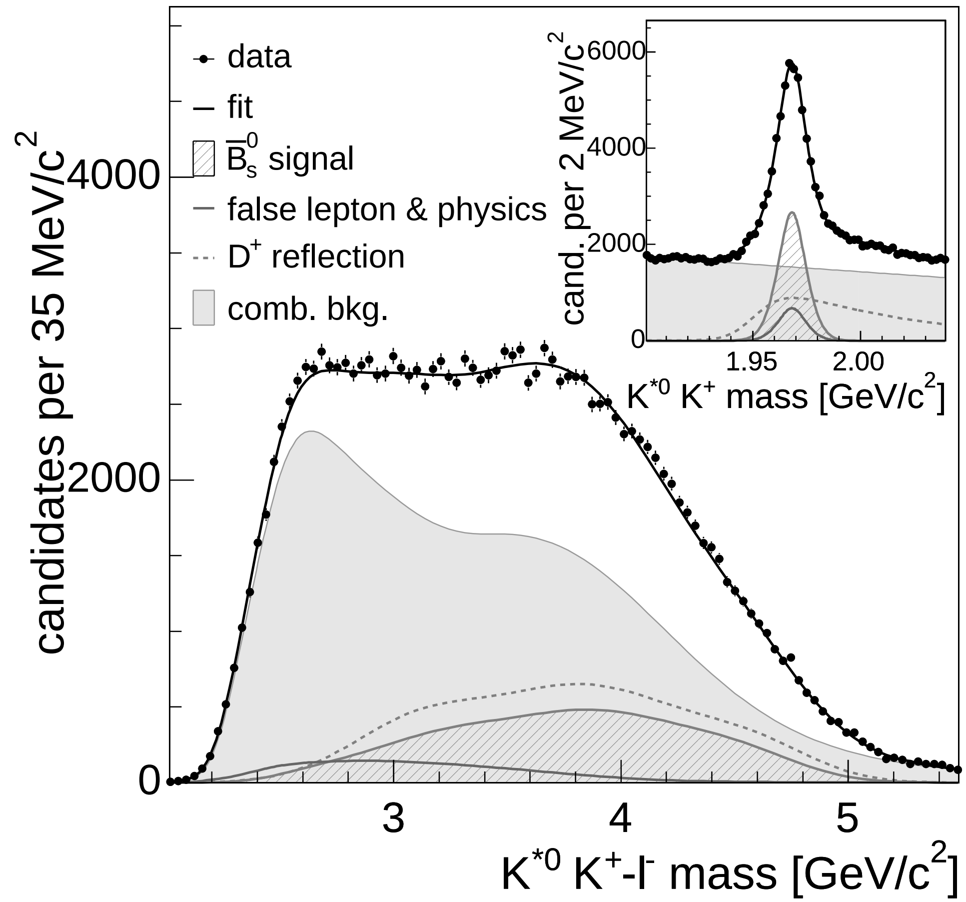
Samples - Semileptonic Selection

Use of particle identification in selection

- standard practice at *B* factories
- applied in hadronic and semileptonic analyses
- using combined Time-of-Flight and dE/dx (see SSKT)

Effects

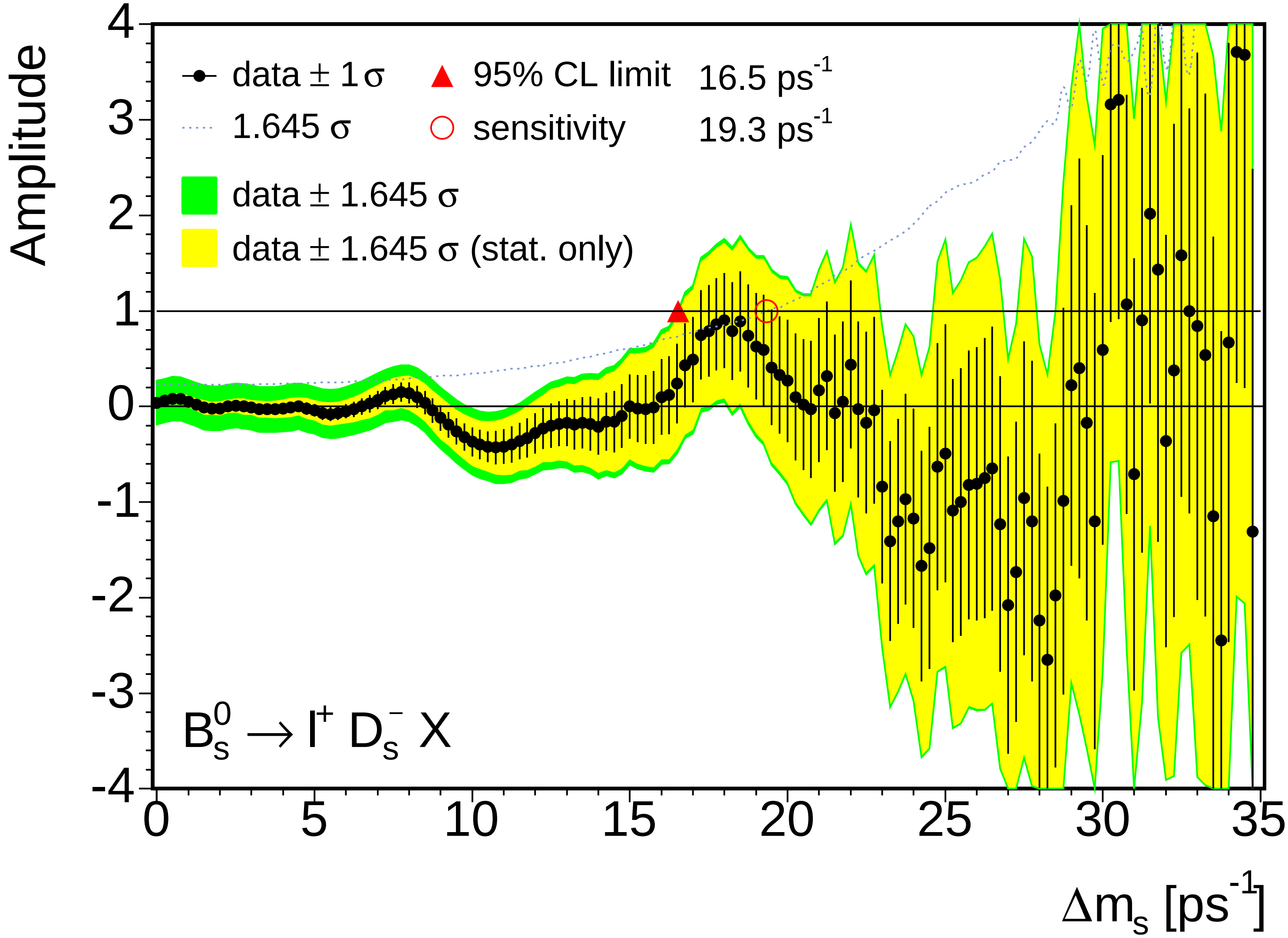
- strongest in $D_s \to K^{*0}K$
- no explicit $D^+ \to K^-\pi^+\pi^+$ rejection (+35%)
- combinatorial background dominated by π



Yields: 62k (was 37k)

- S/Bx2 for $D_s^- \to K^{*0}K^-, \phi\pi^-$
- added trigger paths

Semileptonic Amplitude Scan



A compatible with 1 for $\Delta m_s \sim 17.75\ ps^{-1}$

$A/\sigma_A(\Delta m_s = 17.75\ ps^{-1}) \approx 2$, can set two sided 95% CL limit

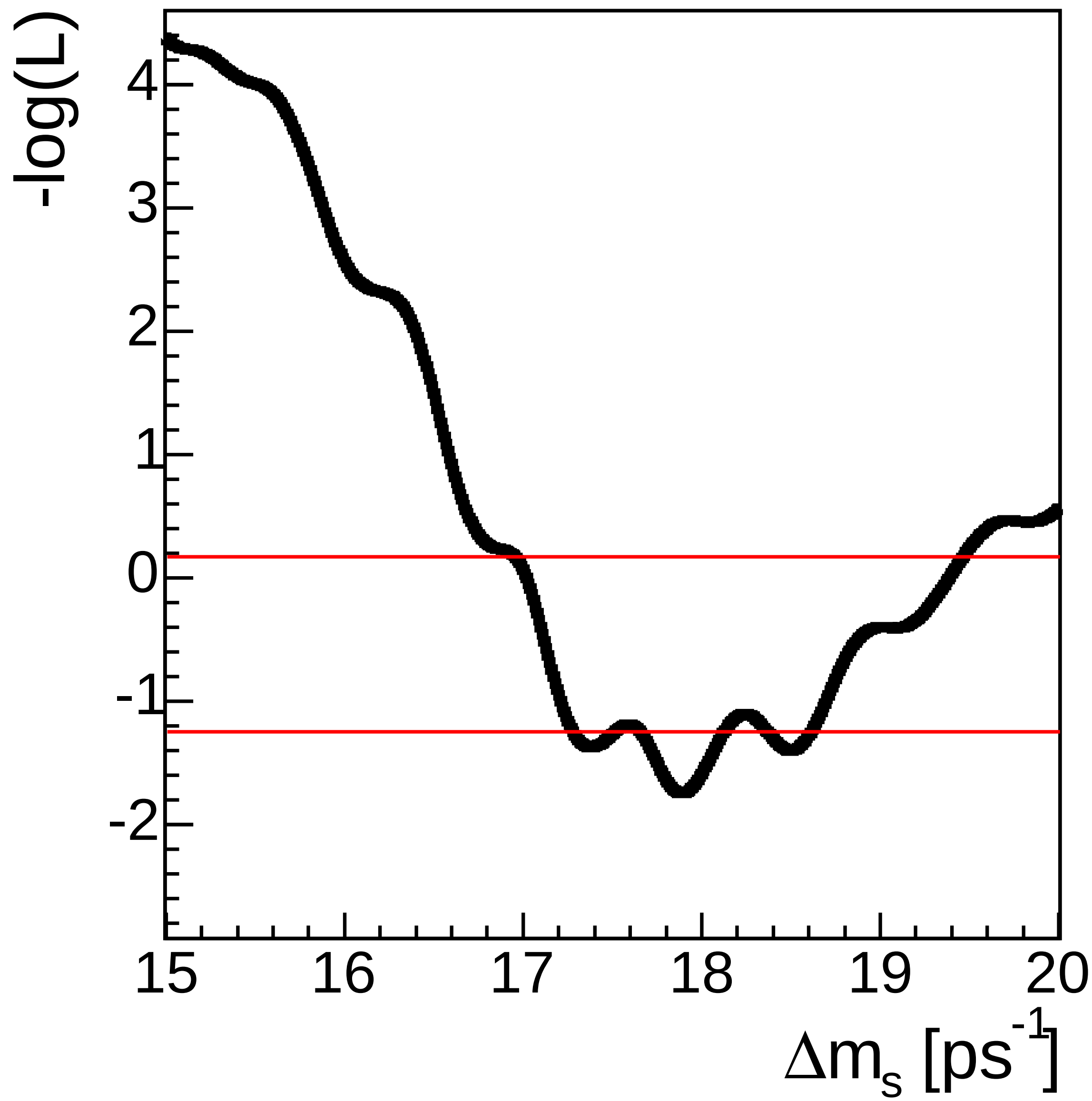
Semileptonic Likelihood Profile

Minimum

17.89 ps^{-1}

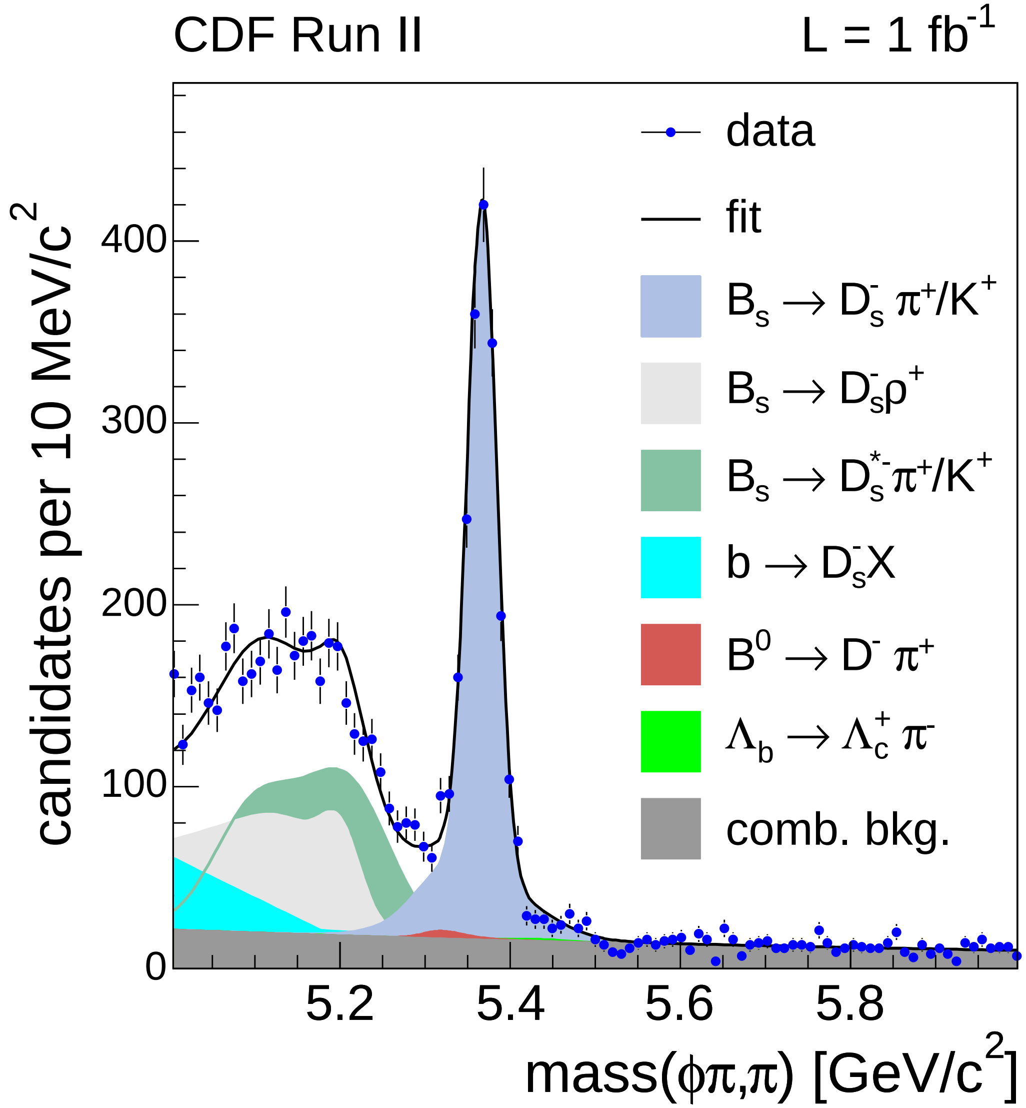
Depth

- ☞ sets 95% CL interval
- ☞ 1σ equiv. to $\pm$ 0.3 ps^{-1}



Samples - Hadronic: $B_s \to D_s^- \pi^+ (\pi^+ \pi^-)$

B_s Modes	Signal	S/B
$(\phi\pi)\pi$	2000(1600)	+13%
partial	3100(–)	–
$(K^{*0}K)\pi$	1400(800)	+35%
$(3\pi)\pi$	700(600)	+22%
$(\phi\pi)3\pi$	700(500)	+92%
$(K^{*0}K)3\pi$	600(200)	+110%
$(3\pi)3\pi$	200(–)	–
total	8700(3700)	–



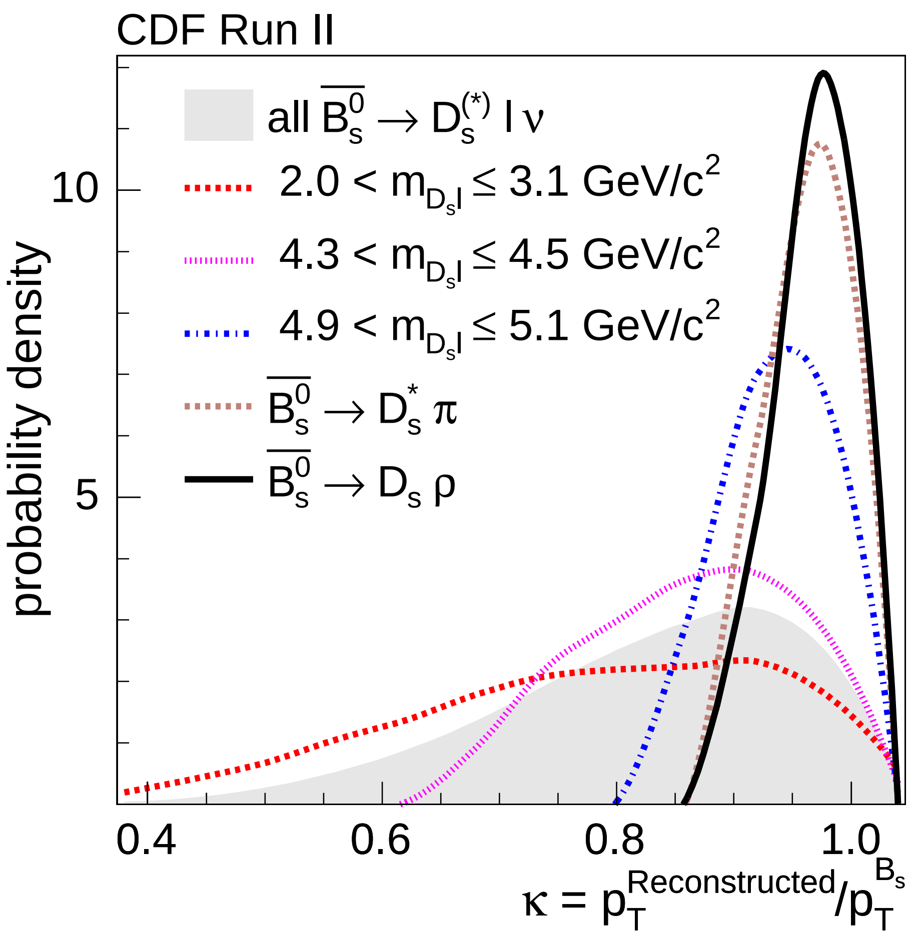
Golden signature

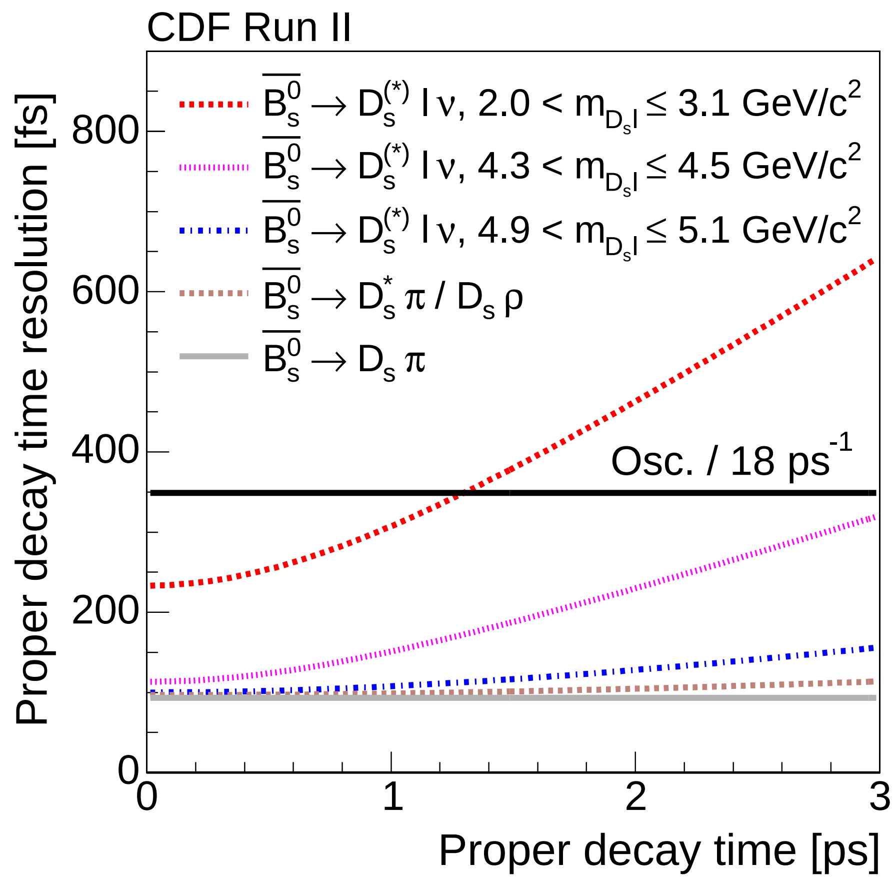
- ☞ $B_s \to D_s^-(\phi\pi^-)\pi^+$

Improvements:

- ☞ partial reconstruction, particle Id, NN in selection

How Good are Partially Reconstructed Decays?



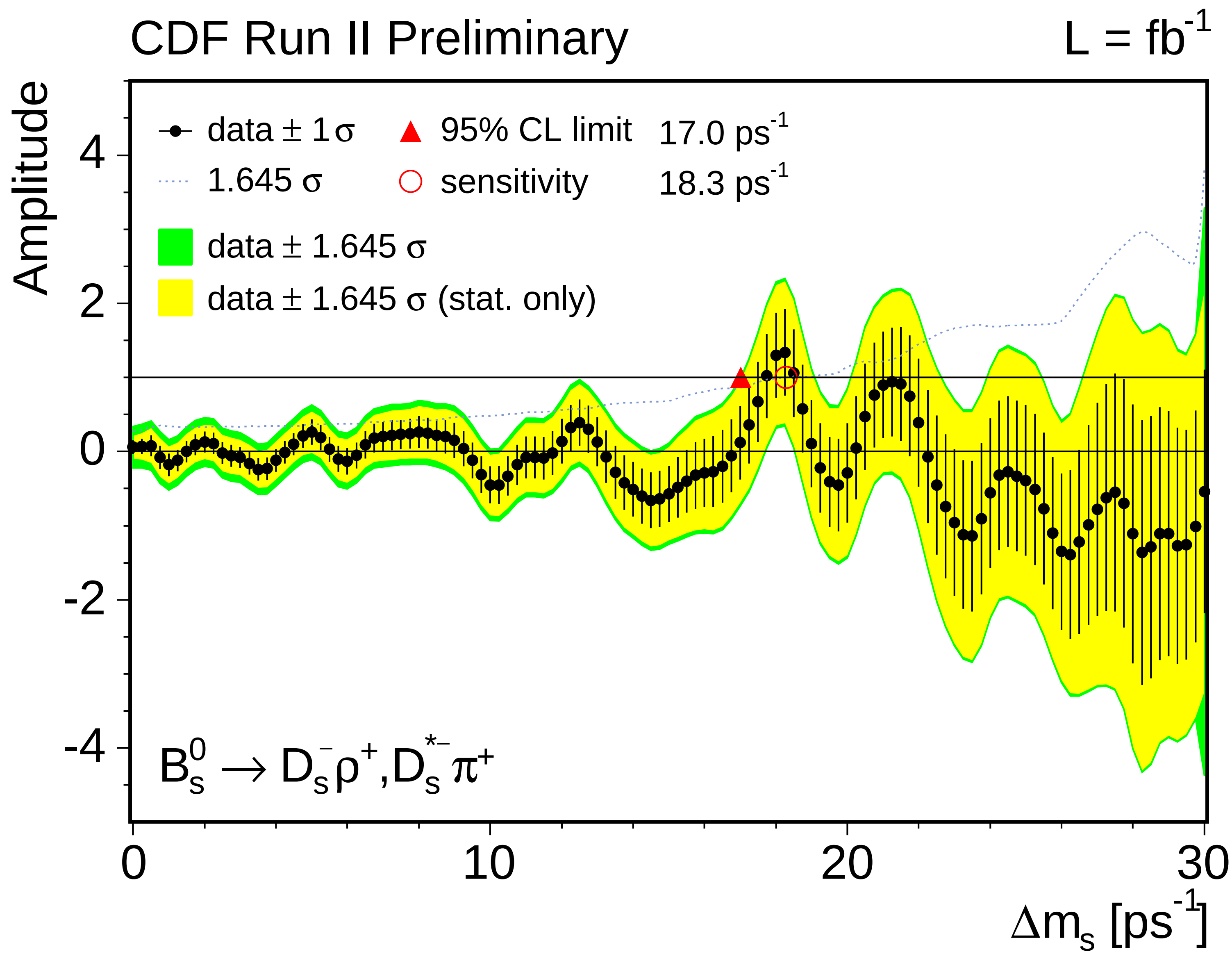


Decay modes: $B_s \to D_s^{*-}(D_s\gamma(\pi^0))\pi^+$, $B_s \to D_s^- \rho^+(\pi^0\pi^-)$

- ☞ need to correct for missing momentum, as semileptonic
- ☞ large reconstructed mass → missing momentum small

Partial reco almost as good as full reco

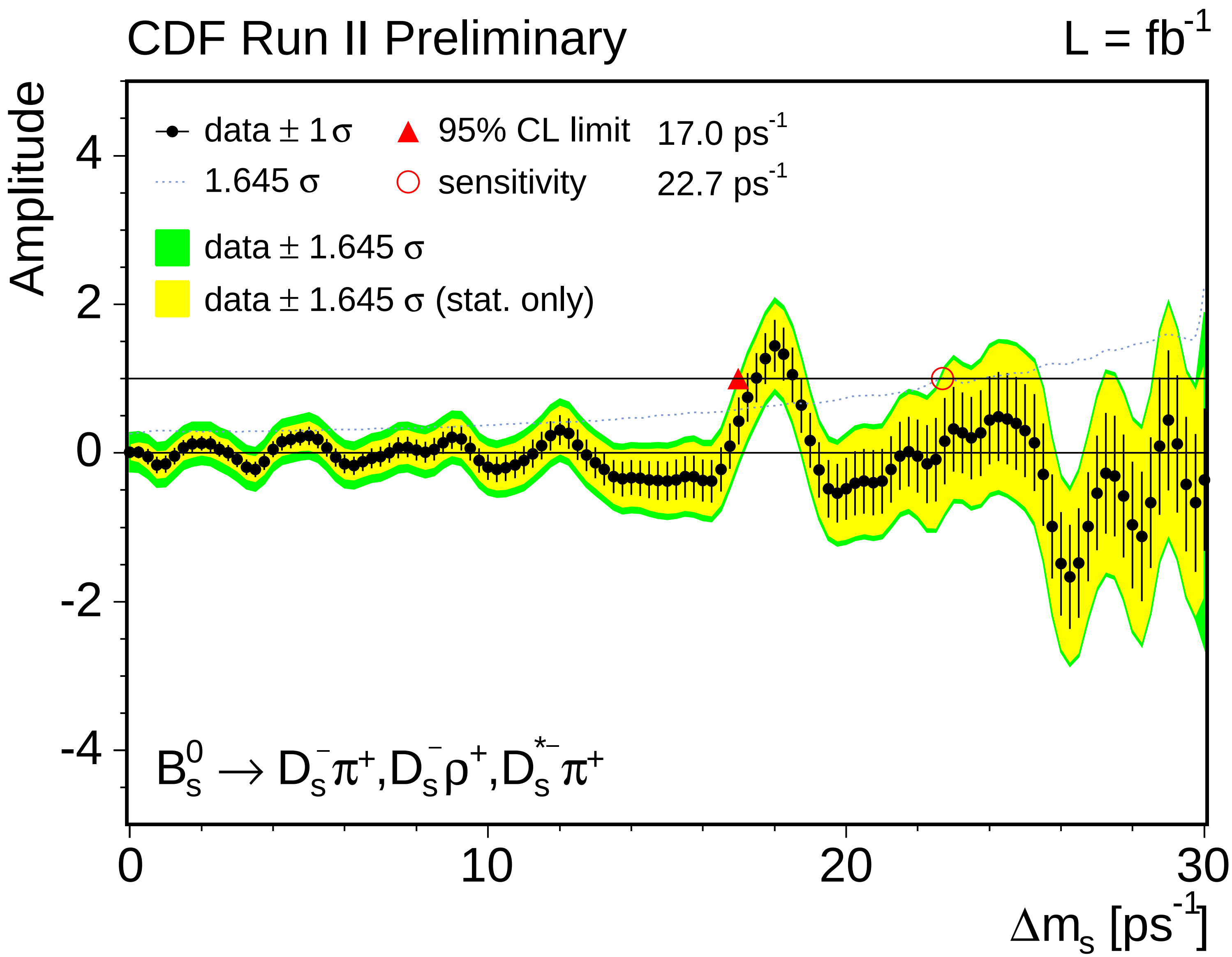
Amplitude Scan Partial Reconstruction Only



$A = 1.02 \pm 0.57(\text{stat})$

consistent with 1 for $\Delta m_s \sim 17.75\ \text{ps}^{-1}$

Amplitude Scan Golden Mode Only



$A = 1.27 \pm 0.34$(stat)

consistent with 1 for $\Delta m_s \sim 17.75$ ps^{-1}

Likelihood Curves - Golden Channel Only

Golden Likelihood

Minimum: –7.4

p-value: 0.15%

→ 3.2σ

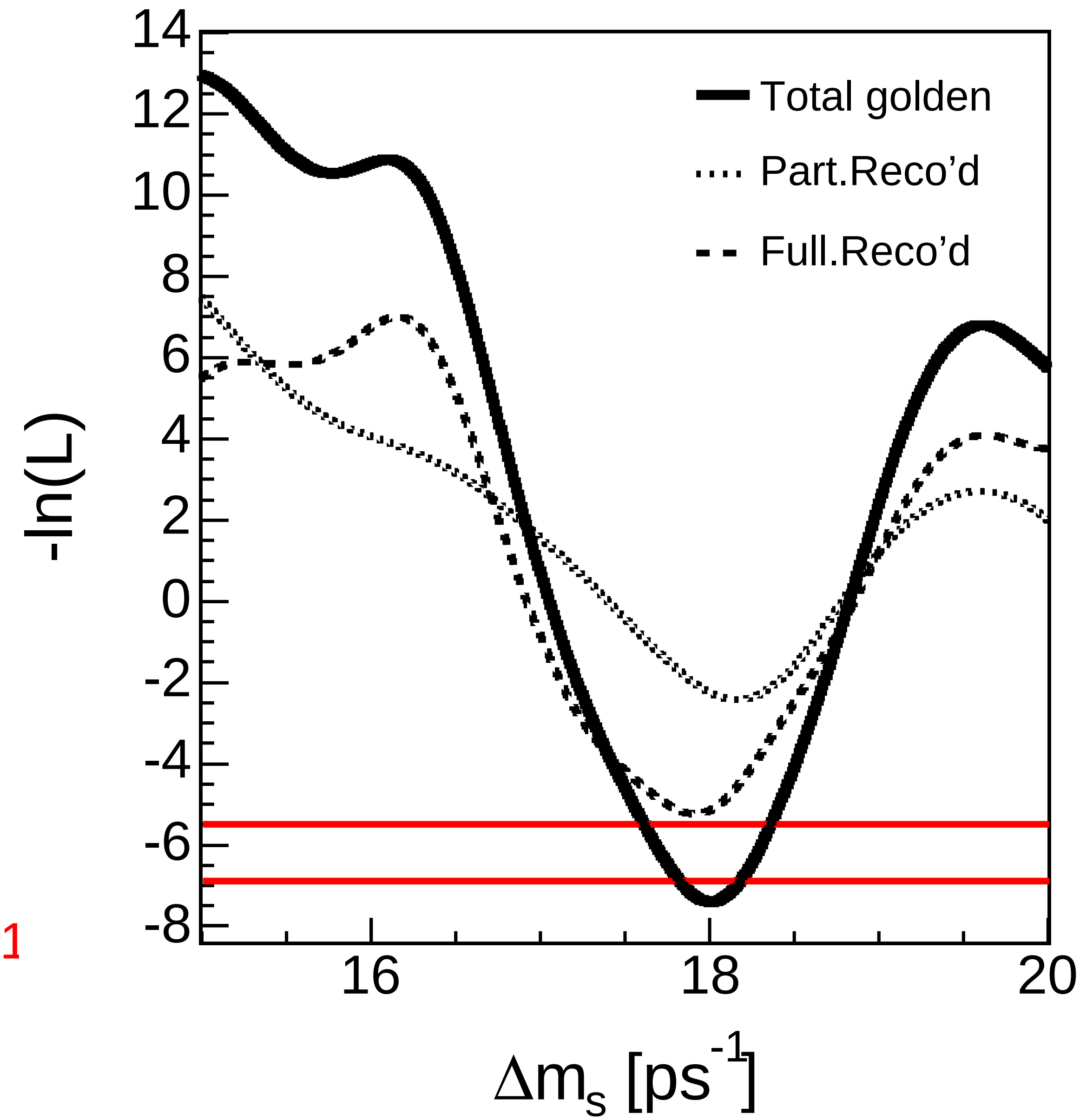
Spring analysis

Minimum: –6.4

p-value: 0.2%

Golden sample

$\Delta m_s = 18.01\,^{+0.17}_{-0.18}\ \mathrm{ps}^{-1}$



Consistent results: full and partial reconstruction

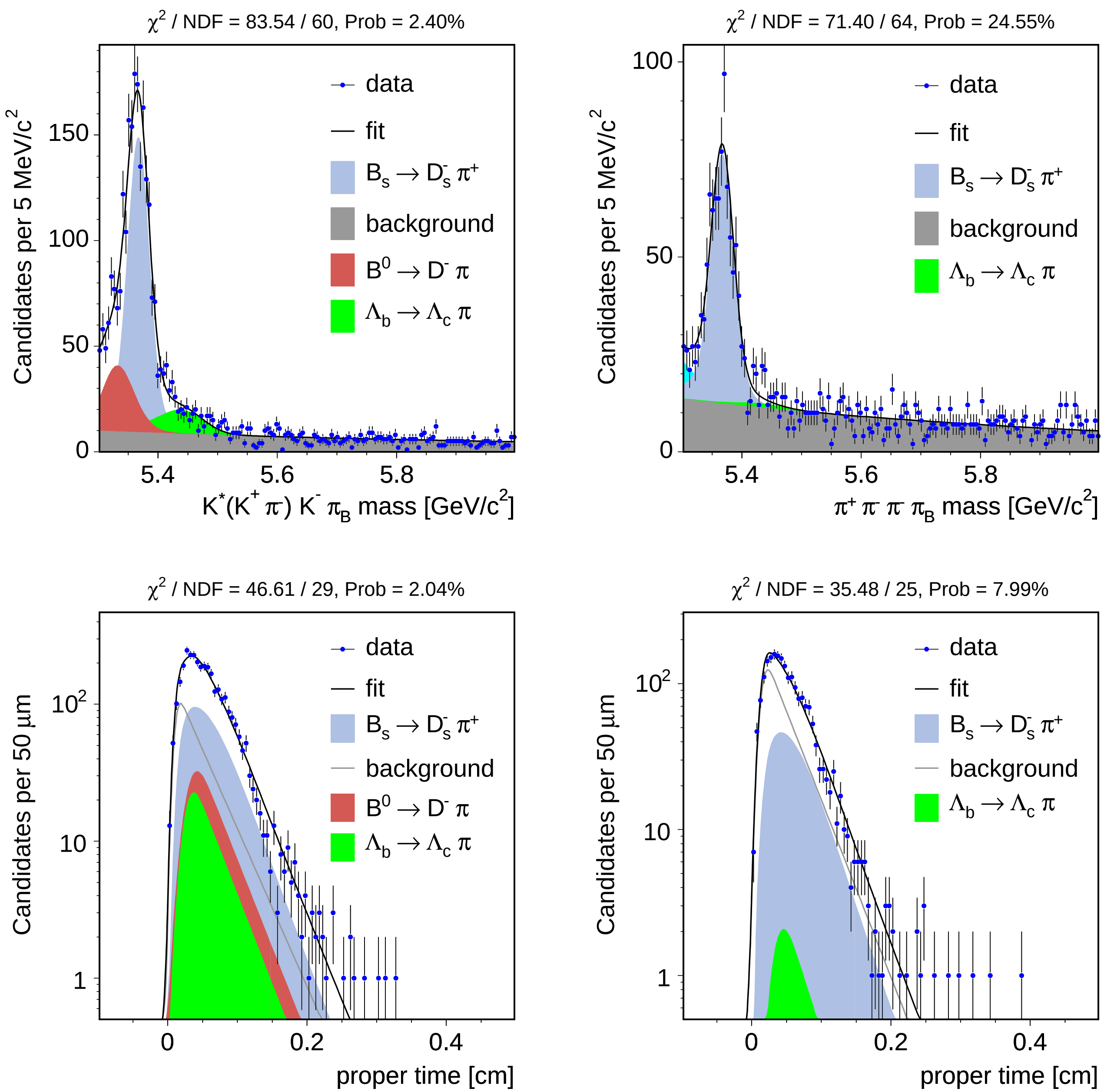
Non-Golden Channels, $B_s \to D_s\pi$

Particle Id

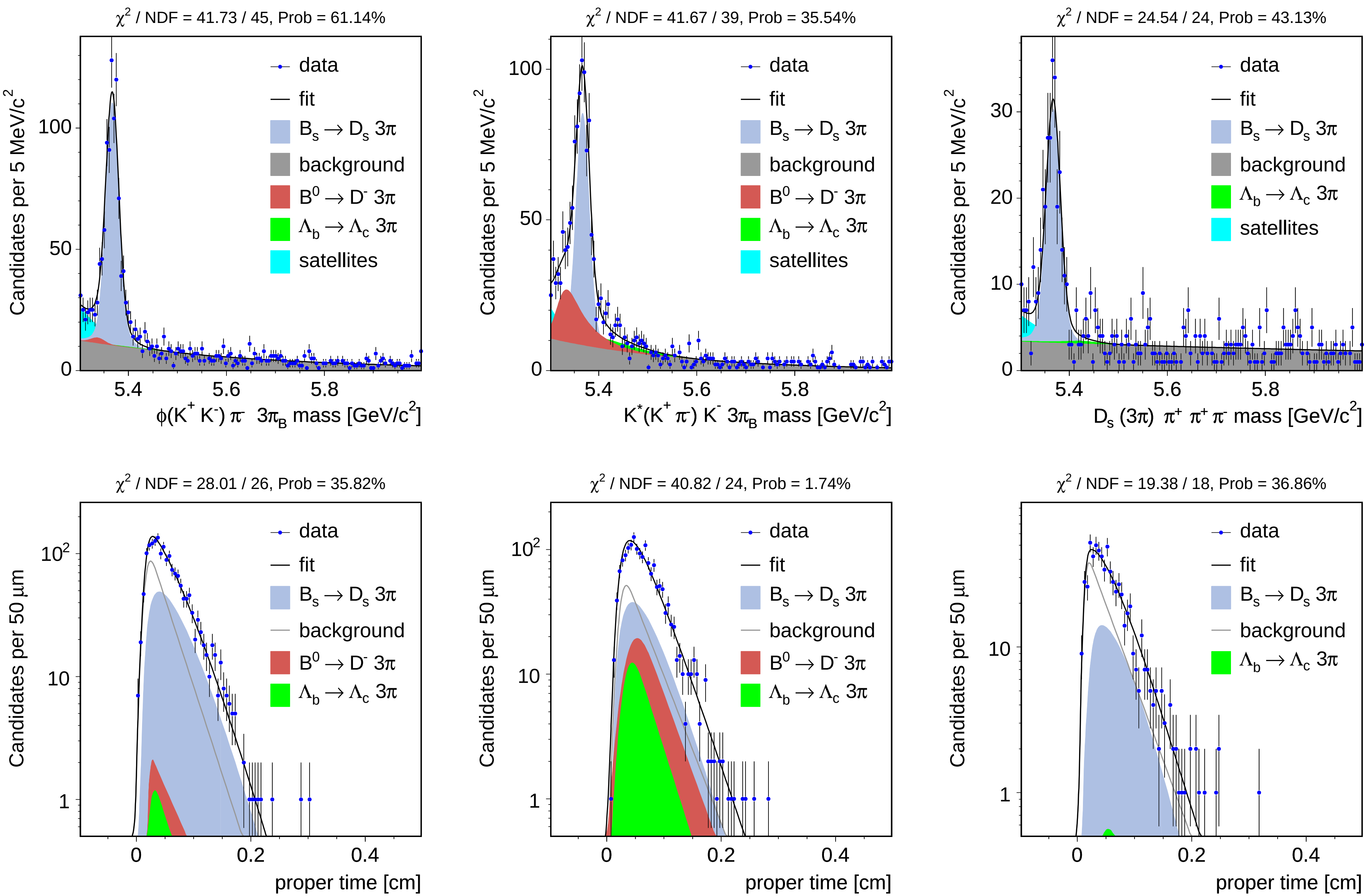
- opt. D^+ rejection
- relax kinematic cuts

Neural Net

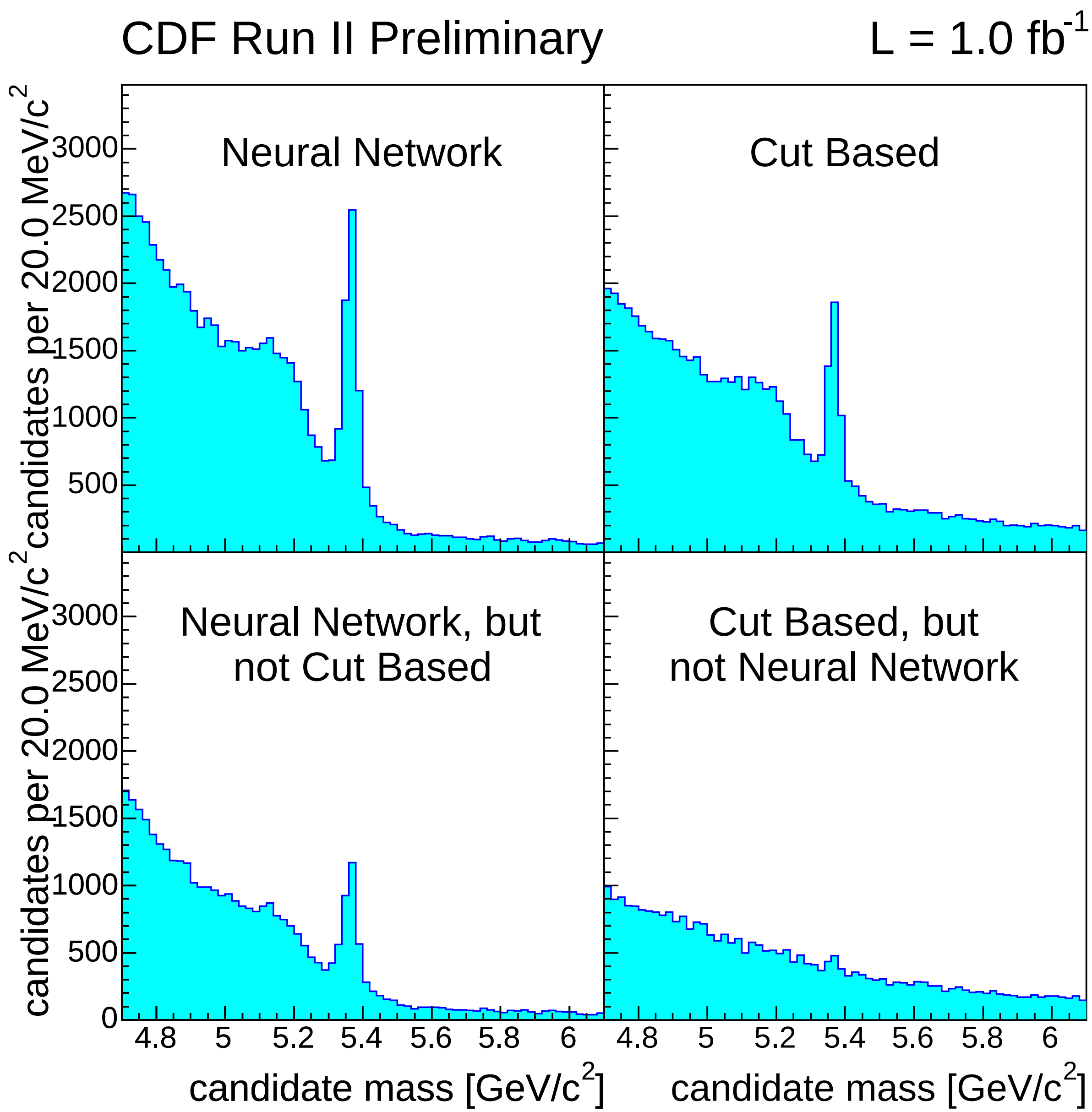
- larger signal at same bg
- add new mode $B_s \to D_s(3\pi)3\pi$



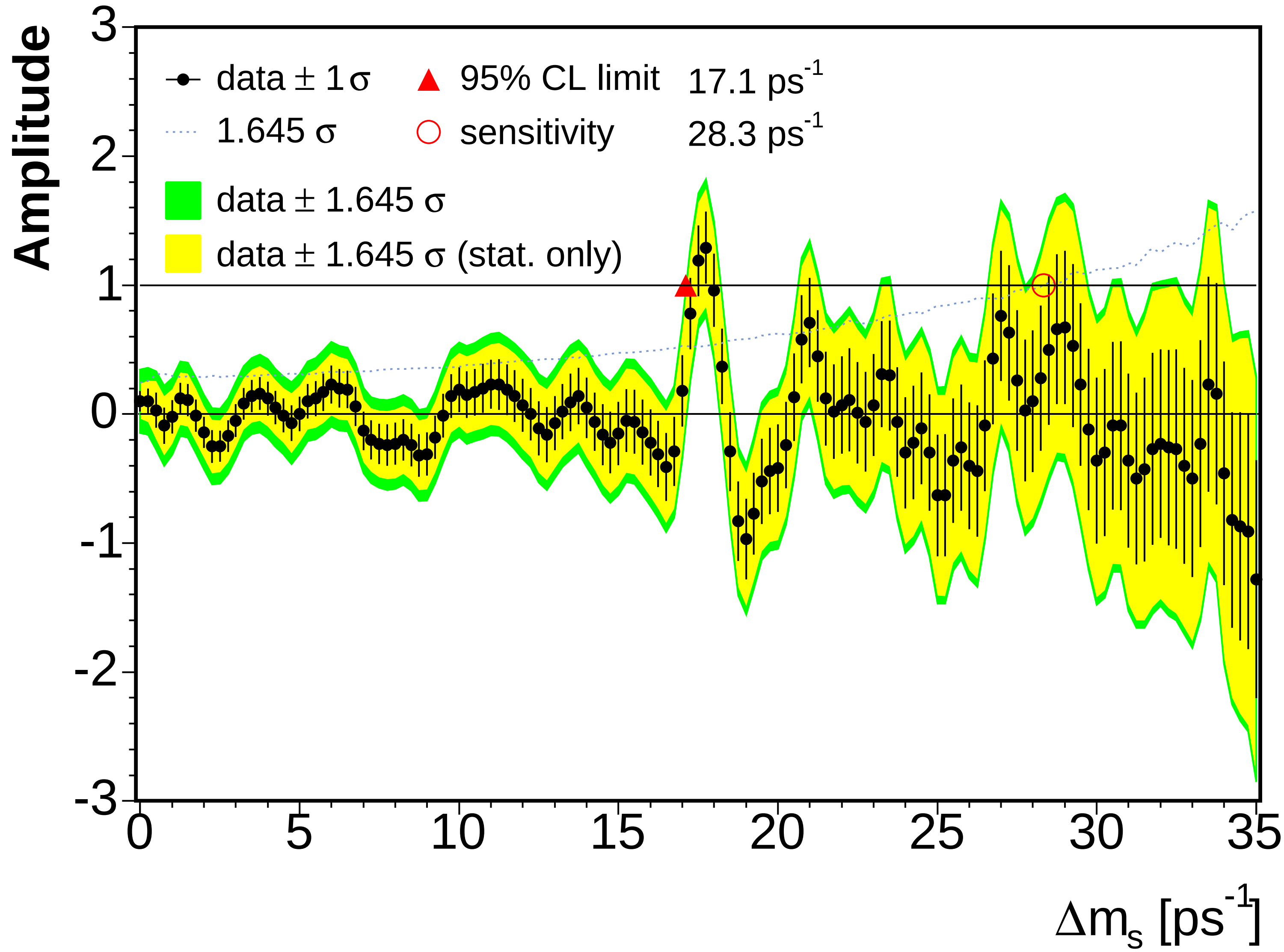
Non-Golden Channels, $B_s \to D_s 3\pi$



Performance of Neural Network Selection



Amplitude Scan Non-Golden Modes



$A = 1.29 \pm 0.29(\text{stat})$

consistent with 1 for $\Delta m_s \sim 17.75\ \text{ps}^{-1}$

Likelihood Curves - Non-Golden Channels

Non-Golden Likelihood

Minimum: –9.6

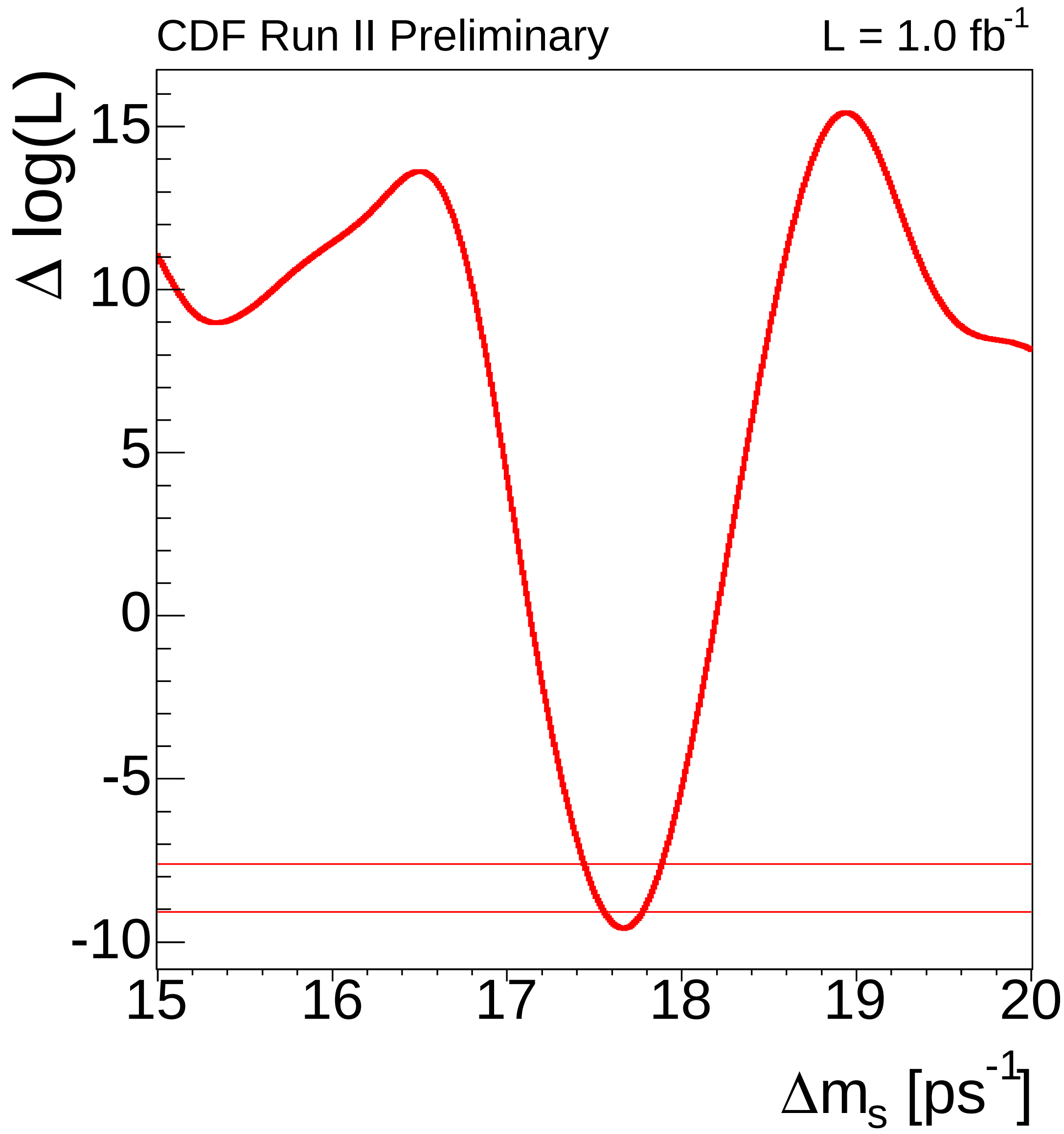
Spring analysis

Minimum: –6.4

p-value: 0.2%

Non-Golden sample

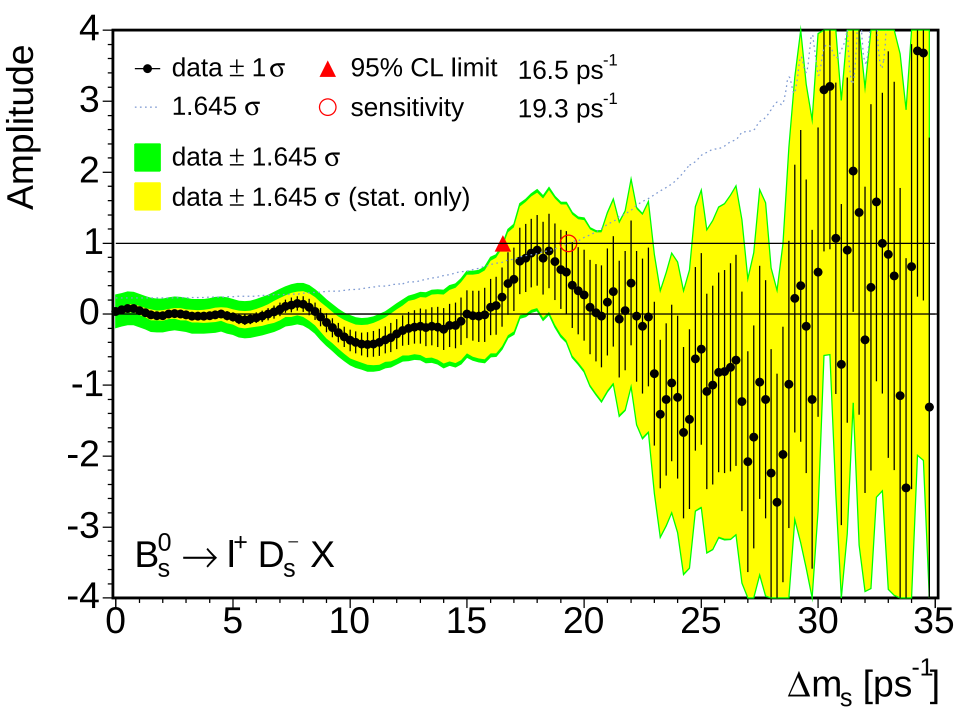
$\Delta m_s = 17.66 \pm 0.11\ \mathrm{ps}^{-1}$



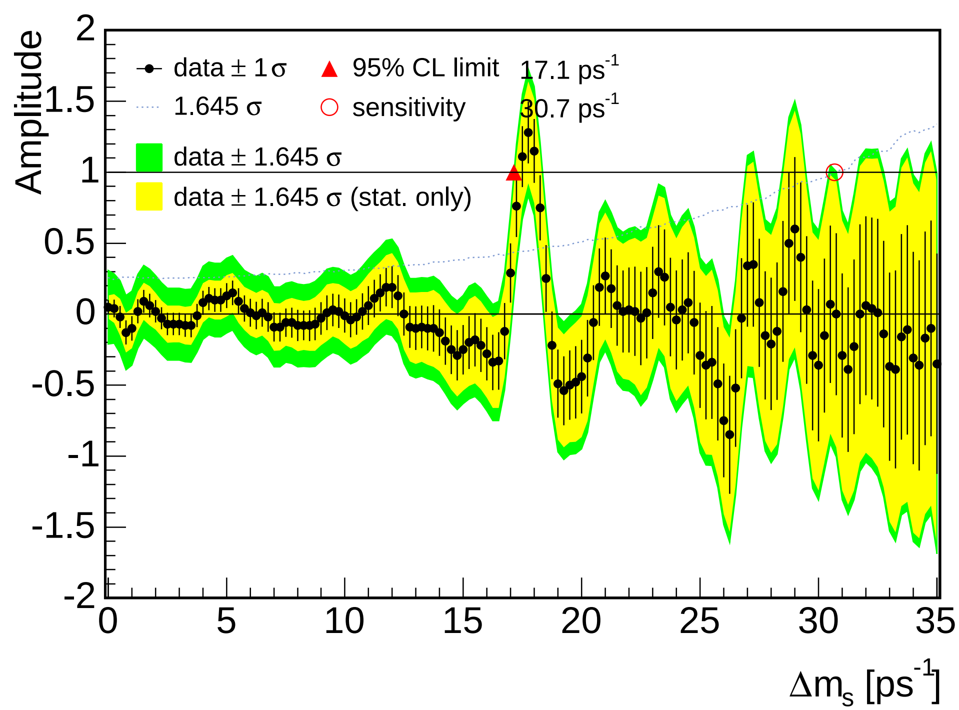
Consistent result with Golden Only

Combined Amplitude Scans

Semileptonic



Hadronic

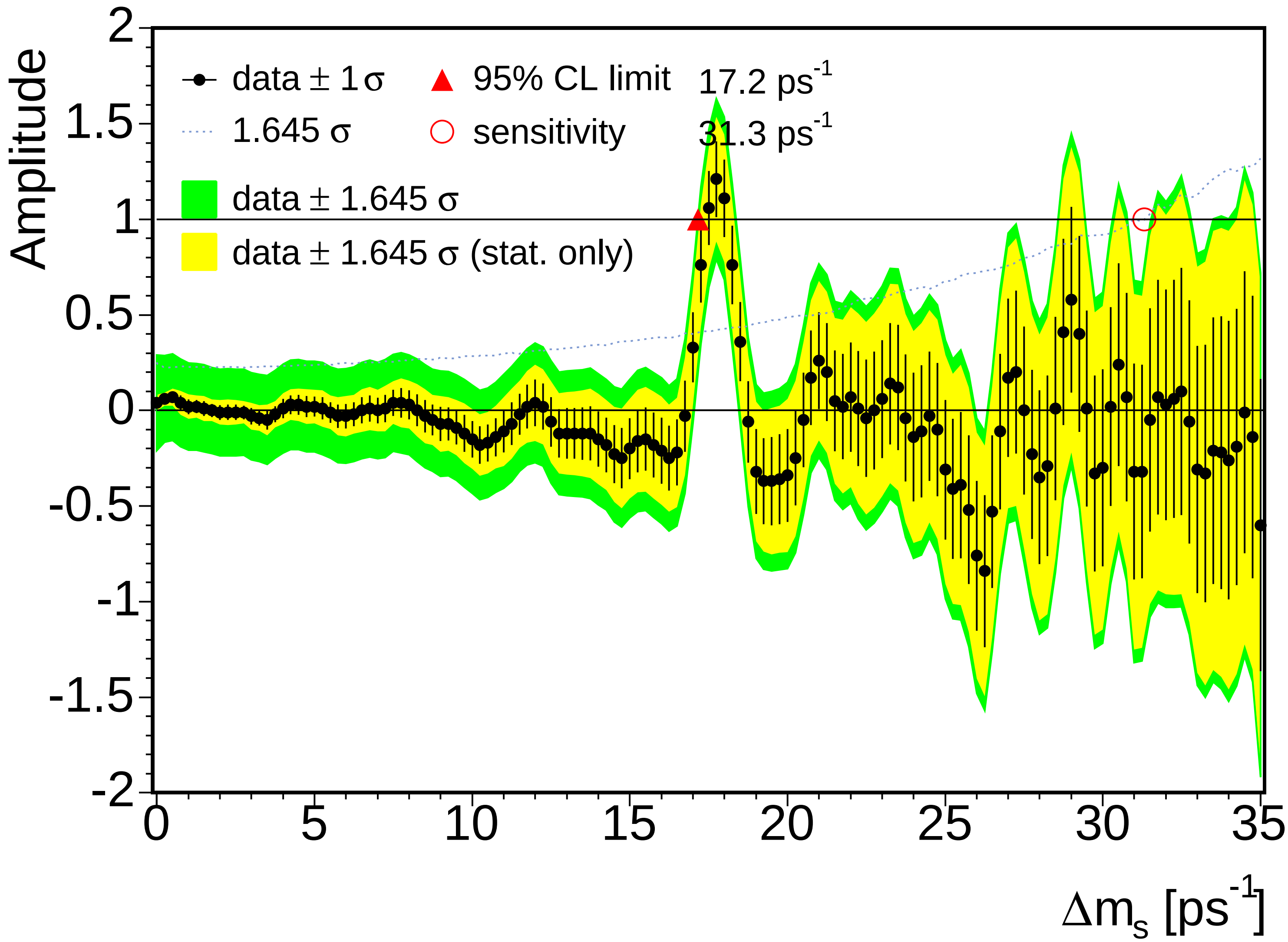


Signal at ≈ 17.75 in hadronic analysis

Note

- world best semileptonic analysis: 19.3 ps^{-1}
- hadronic analysis in different league: 30.7 ps^{-1}

Combined Amplitude Scan



$A = 1.21 \pm 0.20(\text{stat})$ compatible with 1 for $\Delta m_s \sim 17.75\ \text{ps}^{-1}$

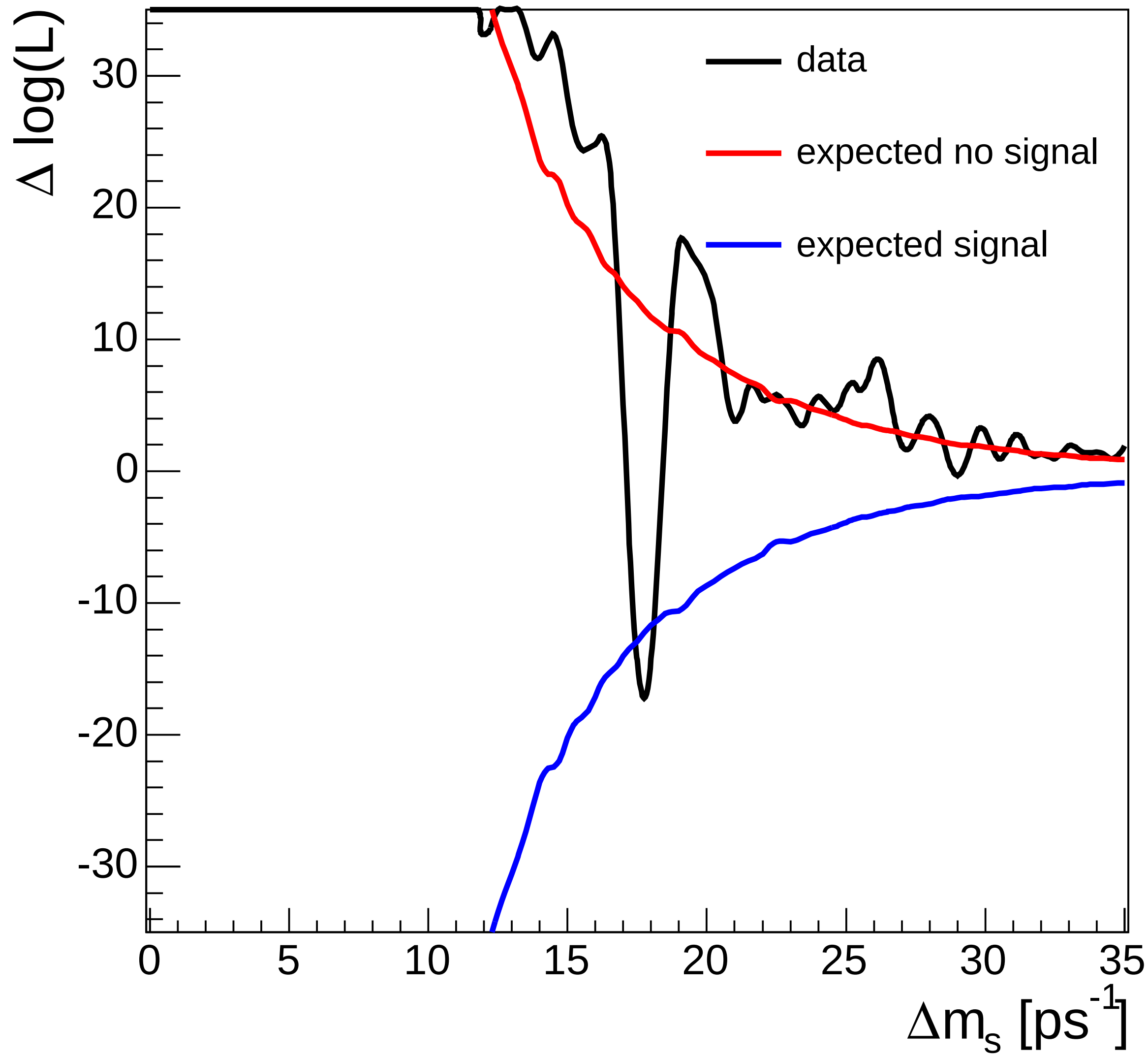
$A/\sigma_A(\Delta m_s = 17.75\ \text{ps}^{-1}) = 6.05$, but what is the *p*-value?

Likelihood Profile

Difference, $-\Delta \log(L)$

$\log(\mathcal{L}(A=1)) - \log(\mathcal{L}(A=0))$

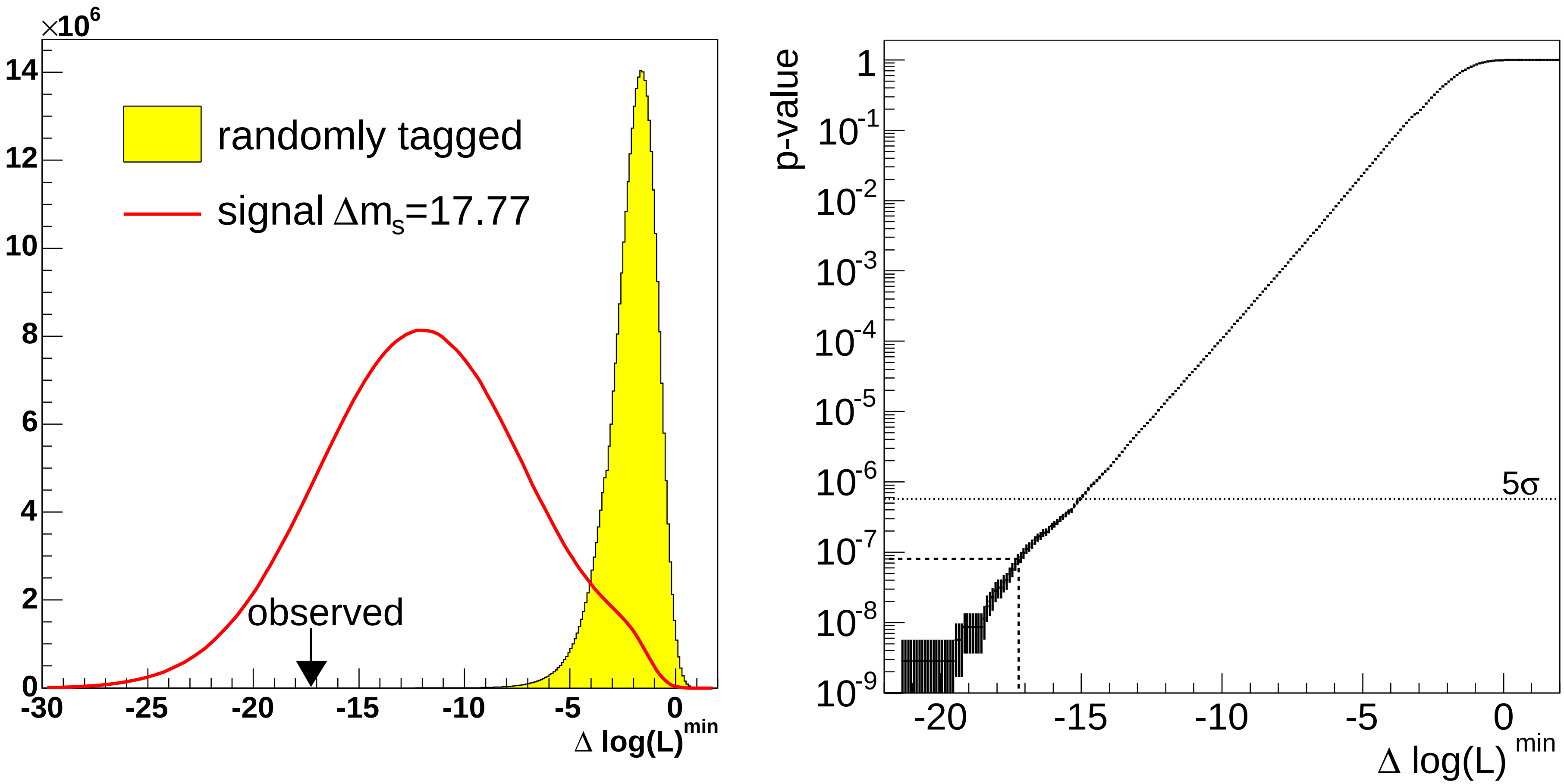
Minimum: –17.26



Key question:

How often can random tags produce a minimum at least as deep?

Likelihood Significance



28 trials out of 350 million

p-value ≈ 8×10^{-8} corresponding to 5.4σ

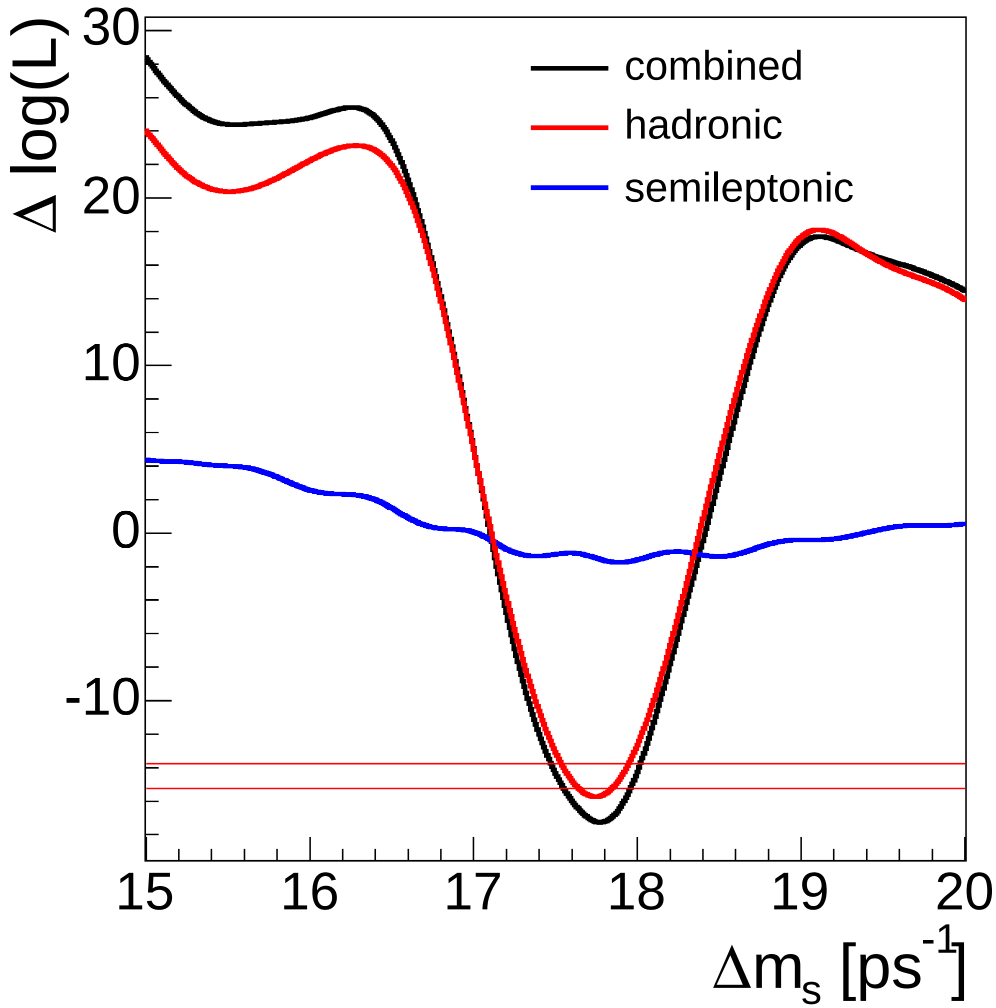
(5 standard deviations is = 5.7×10^{-7})

→ passed observation criterion

Δm_s *Measurement*

$$\Delta m_s = 17.77 \pm 0.10(\text{stat}) \pm 0.07(\text{syst})\ \text{ps}^{-1}$$

was submitted to PRL on Monday



Systematic

- well behaved
- *ct* scale uncertainty
- rest: small

Agrees with SM

$18.3^{+6.5}_{-1.5}\ \text{ps}^{-1}$ EPS 2005

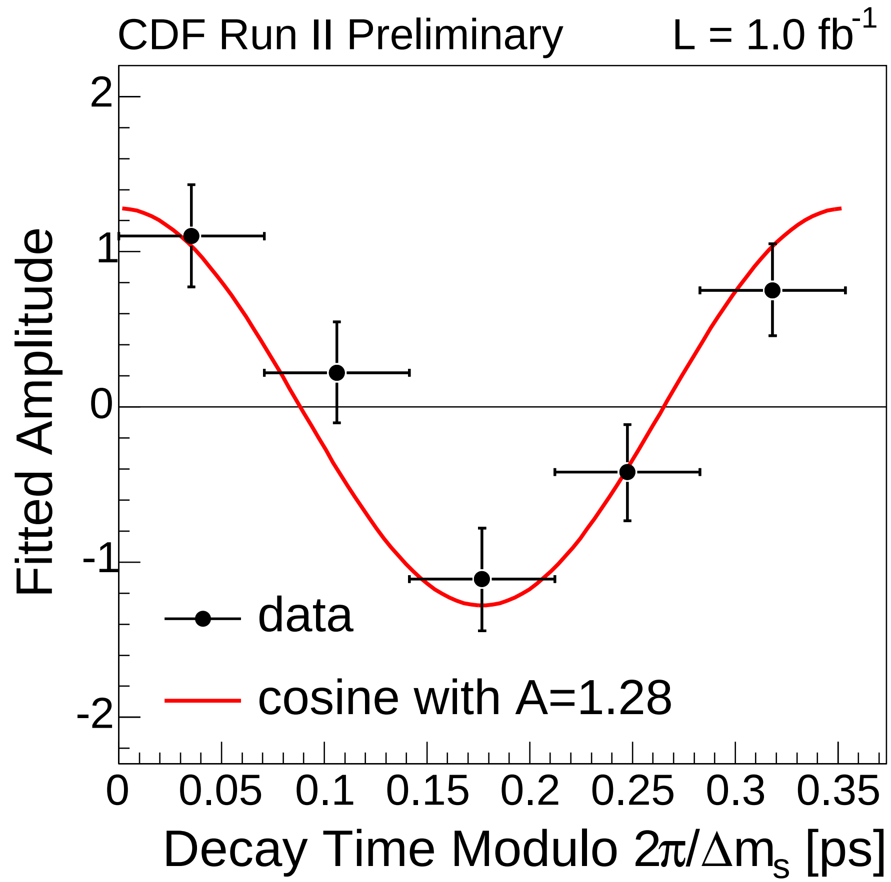
Agrees with 1st result

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

PRL 97 (2006) 62003

Visualizing the Result

$$\Delta m_s = 17.77 \pm 0.10(stat) \pm 0.07(syst)\ ps^{-1}$$



Proper decay time folded onto a 2π interval

Direct Measure of $|V_{td}/V_{ts}|$

Relation between Δm_q and V_{tq}

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

Inputs

- ☞ $\frac{m_{B_d}}{m_{B_s}} = 0.98390$ — PRL 96 (2006) 202001
- ☞ $\xi = 1.21 \,^{+0.047}_{-0.035}$ — M.Okamoto hep-lat/0510113
- ☞ $\Delta m_d = 0.507 \pm 0.005$ — PDG 2006

$$\frac{|V_{td}|}{|V_{ts}|} = 0.2060 \pm 0.0007(\text{exp}) \,^{+0.0081}_{-0.0060}(\text{theo})$$

Best so far

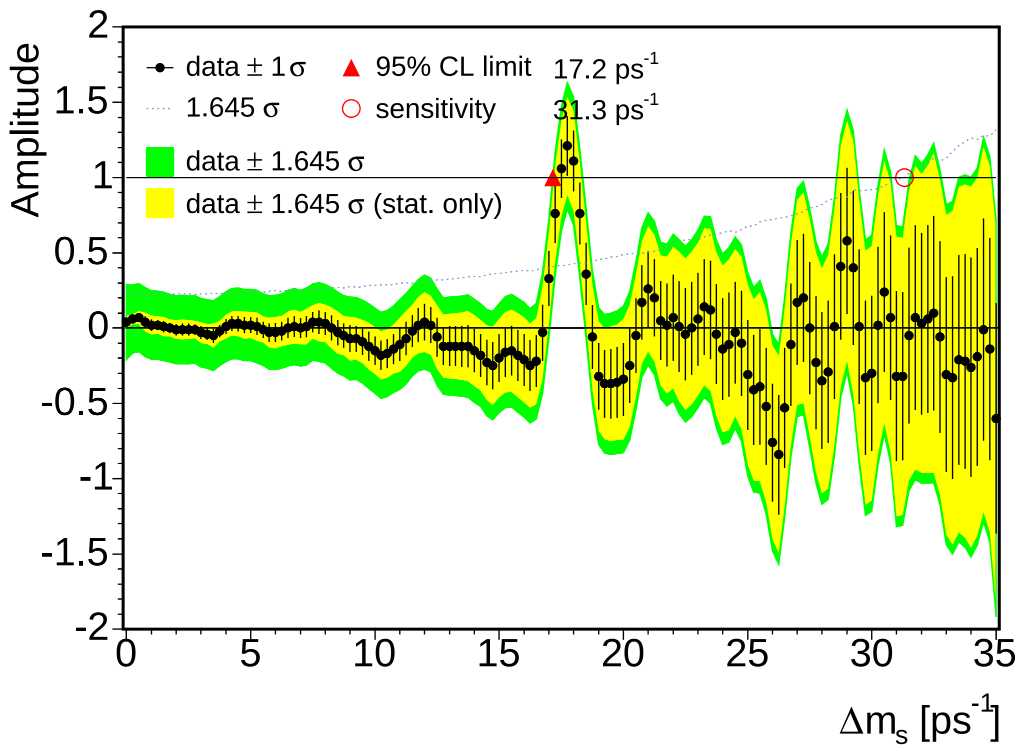
Belle: PRL 96 221601 (2006)

$$\frac{|V_{td}|}{|V_{ts}|} = 0.199 \,^{+0.026}_{-0.025}(\text{exp}) \,^{+0.018}_{-0.016}(\text{theo})$$

Conclusions

Long journey ended

- ☞ 19 years of search to see B_s-$\overline{B}_s$ oscillations
- ☞ found signal consistent with B_s-$\overline{B}_s$ oscillations
- ☞ significance: 5.4σ corresponding to $p = 8 \times 10^{-8}$



$$\Delta m_s = 17.77 \pm 0.10(\text{stat}) \pm 0.07(\text{syst})$$

Accomplishments in the Course of the Analysis

PhD Theses

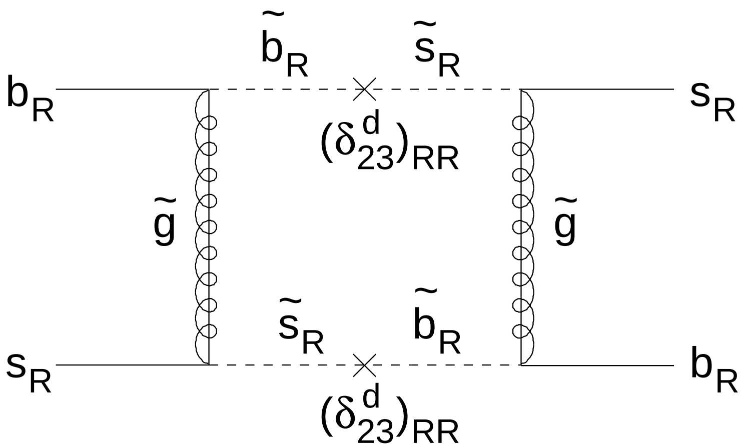
C.Chen	UPenn	Charm Cross Section Measurement
I.Furić	MIT	Reconstruction of $B_s \to D_s^- \pi^+$
A.Bolshov	MIT	Reconstruction of $B_s \to D_s^- 3\pi$
S.DaRonco	Padova	Lifetimes from Exclusive Reconstruction
J.Piedra	Cantabria	B^0 Mixing and Tagger Calibration
G.Giurgu	CMU	Muon Tagging
V.Tiwari	CMU	Electron Tagging
D.Usynin	UPenn	Charged Particle Composition Around B Mesons
G.Salamanna	Rome I	Opposite Side Kaon Tagging
A.Belloni	MIT	SSKT and Neural Network for Hadronic Decays
N.Leonardo	MIT	Likelihood Framework
J.Miles	MIT	Proper Time Resolution and Partial Decays
G.Di Giovanni	Paris	Same Side Kaon Tagging (next gen. analysis)
B.Casal	Cantabria	Neural Network (next gen. analysis)

2006 Tollestrup Award

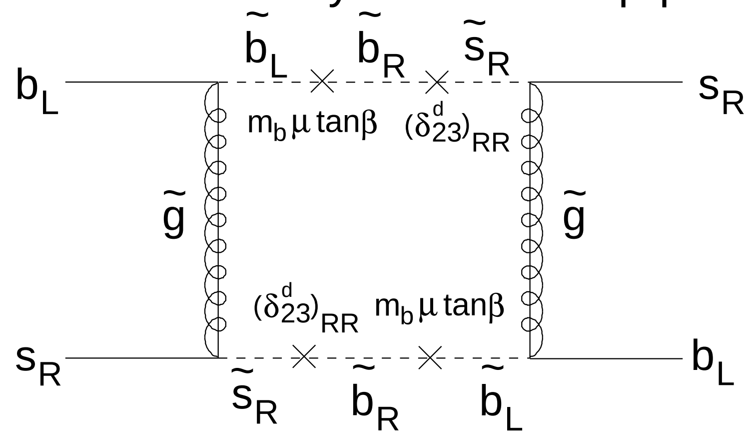
G.Ceballos (Cantabria), I.Furić (Chicago), S.Menzemer (MIT/Cantabria)

The End

New Physics in Loops?



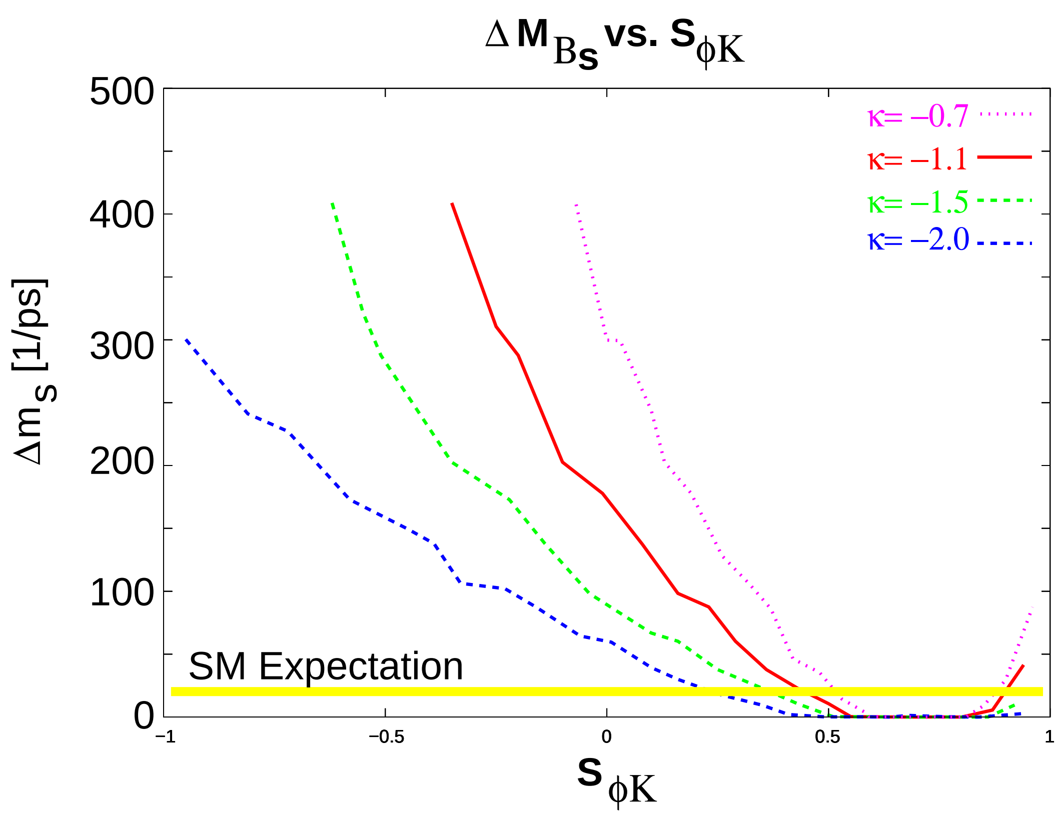
from Murayama et al. hep-ph/0212180



Supersymmetry model

- ☞ gluino in loop
- ☞ squarks in loop
- ☞ describes all data
- ☞ allows very high Δm_s
- ☞ Δm_s excludes models

→ Δm_s sensitive to New Physics



Observables: Neutral B Meson Mixing

For B_s no imaginary matrix element involved

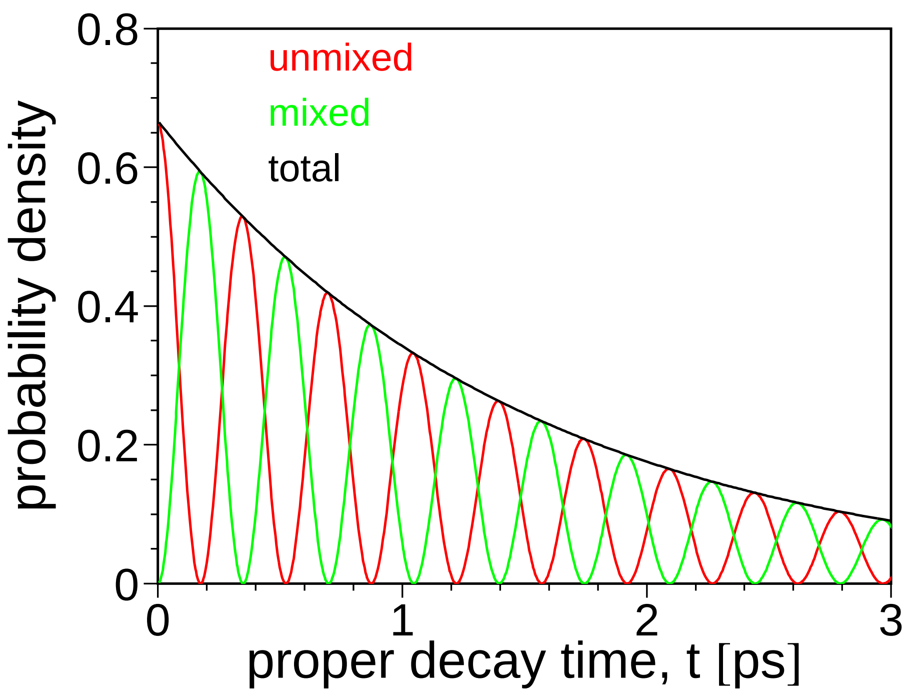
$|B_{s,H}\rangle = \frac{1}{\sqrt{2}}(|B_s\rangle + |\overline{B}_s\rangle)$ *CP* odd $\qquad |B_{s,L}\rangle = \frac{1}{\sqrt{2}}(|B_s\rangle - |\overline{B}_s\rangle)$ *CP* even

Initial particles and anti-particles

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

Behavior in proper time

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

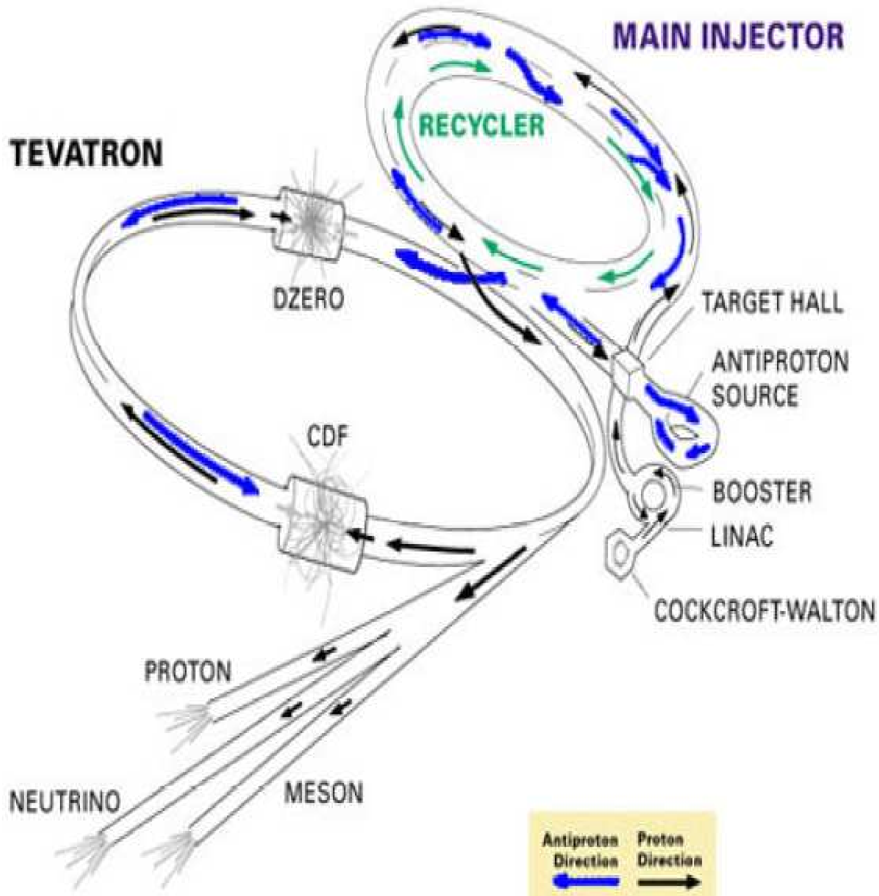


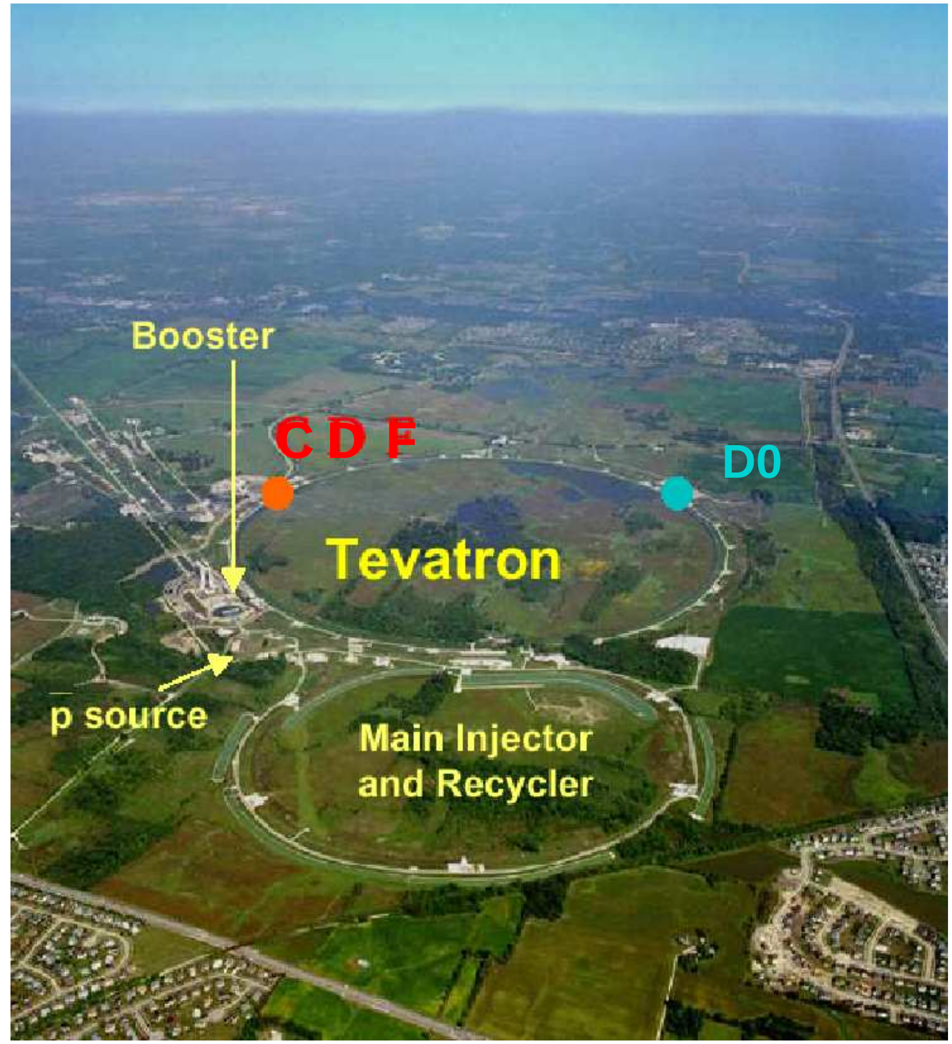
Determine asymmetry

$$A_0(t) = \frac{N(t)_{unmixed} - N(t)_{mixed}}{N(t)_{unmixed} + N(t)_{mixed}} = \cos(\Delta m\, t)$$

Accelerator Setup at Fermilab

Complex accelerator system

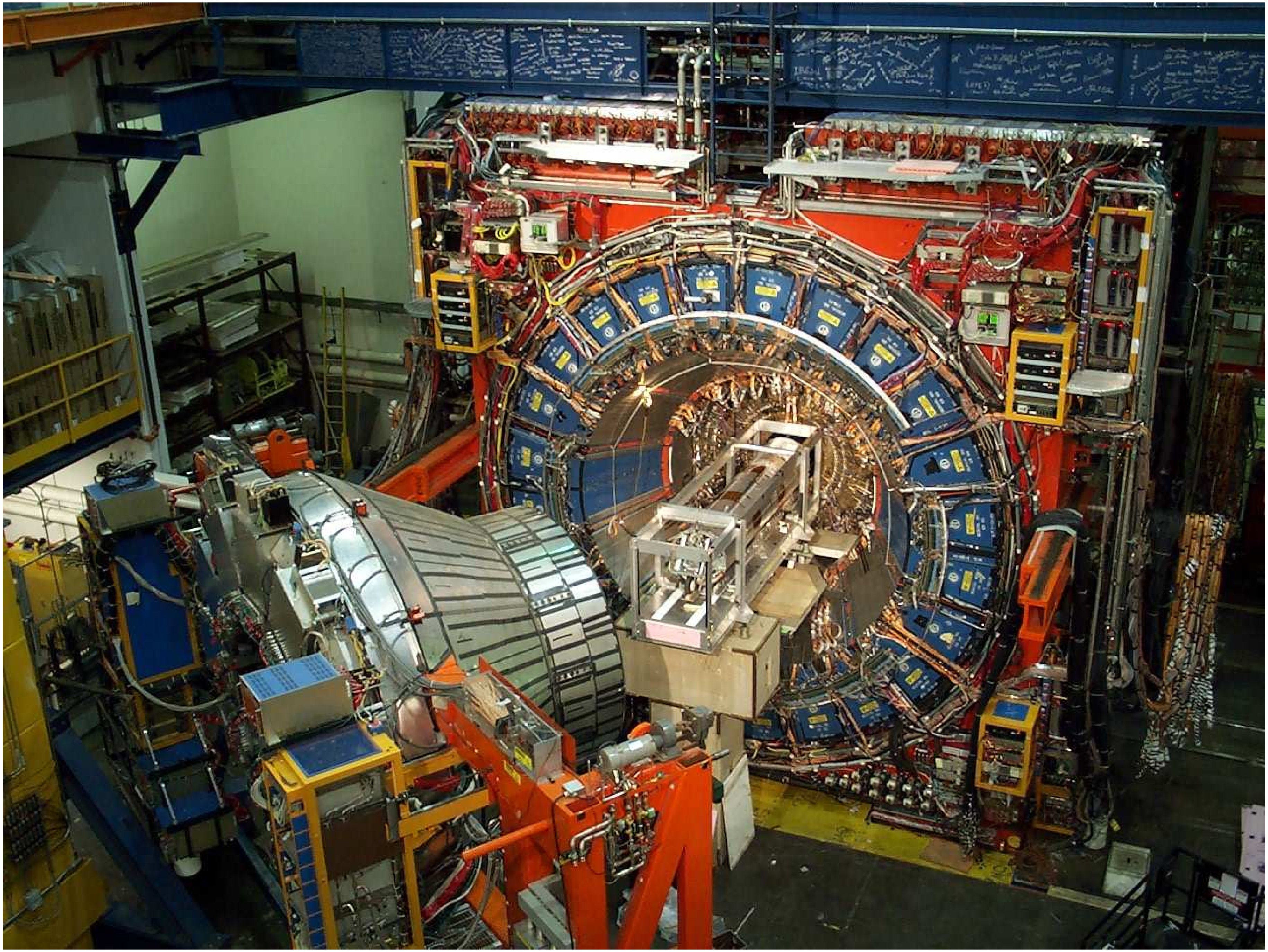




Tevatron Collider

- Tevatron 1 km ring radius, CM energy $\sqrt{s} = 1.96$ TeV
- 36x36 colliding p, $\overline{p}$ bunches, $10^{11}(10^{10})$ $p(\overline{p})$ per bunch

CDF Detector – Opened Up



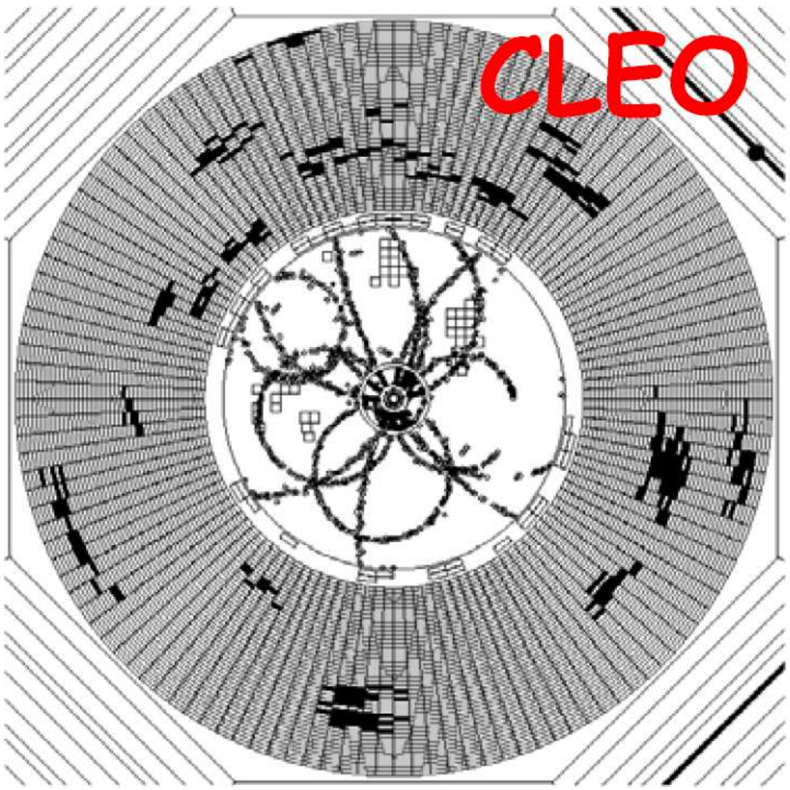
b Production: Tevatron versus B Factories

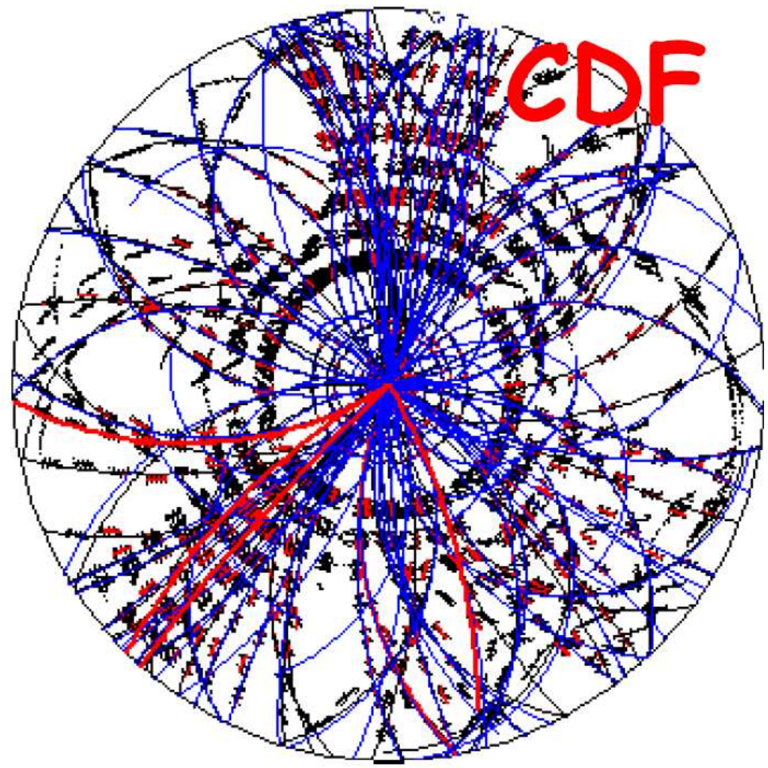
Disadvantages

- $n_{qq} = 1000 \times n_{bb}$
- hostile environment
- second *b* often outside fiducial

Advantages

- larger cross section x10^5
- larger boost x10
- *b* hadrons: B^+, B^0, B_s, B_c, Λ_b, ..



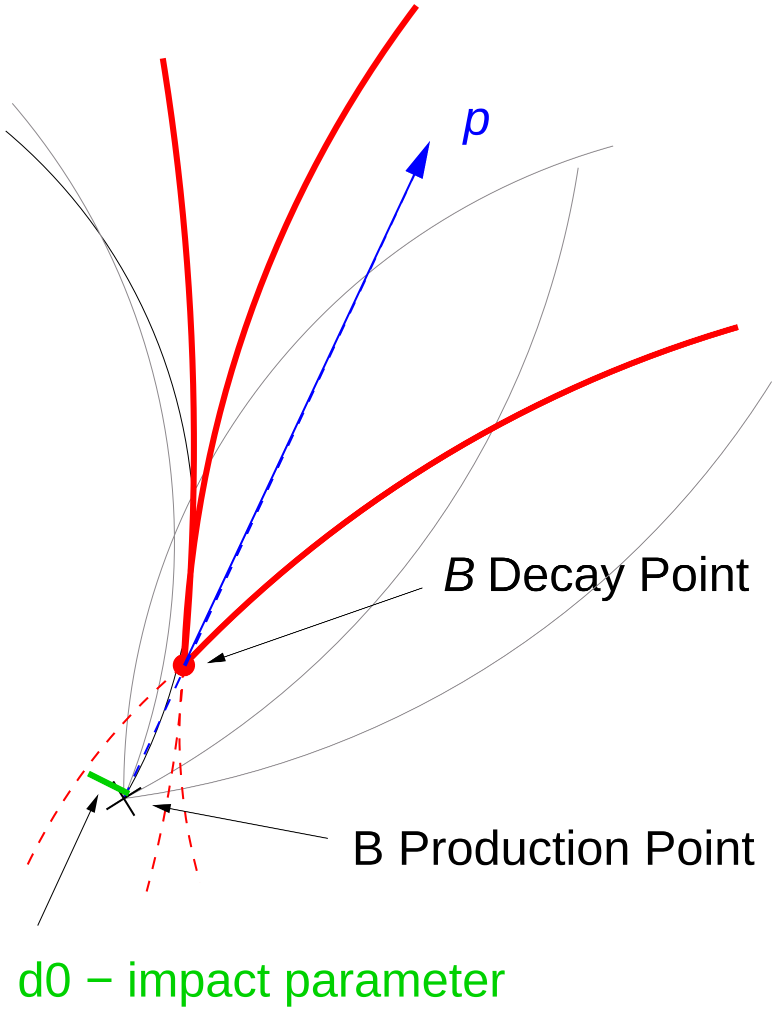


Conclusion

- fast event selection necessary, we call this trigger
- typical rejection factors are 1/50,000

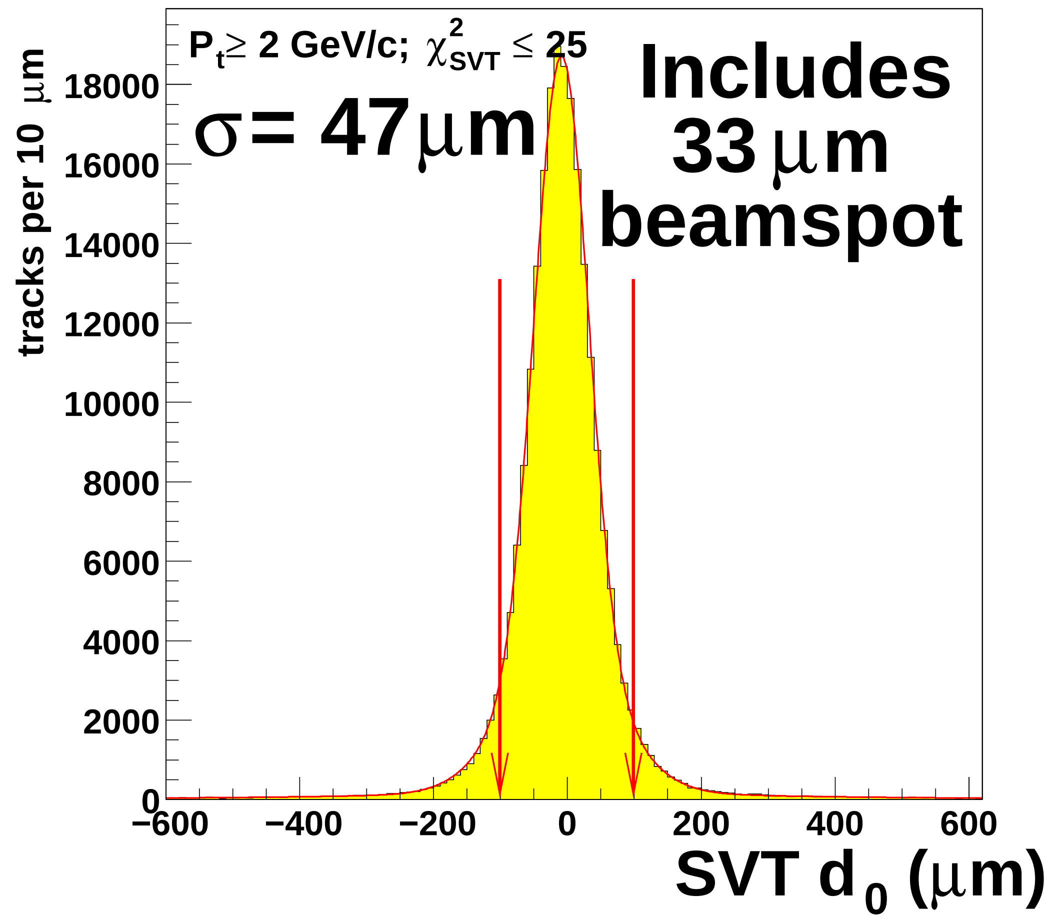
Upgrades: Displaced Track Trigger

Sketch of a B Decay



B Signatures

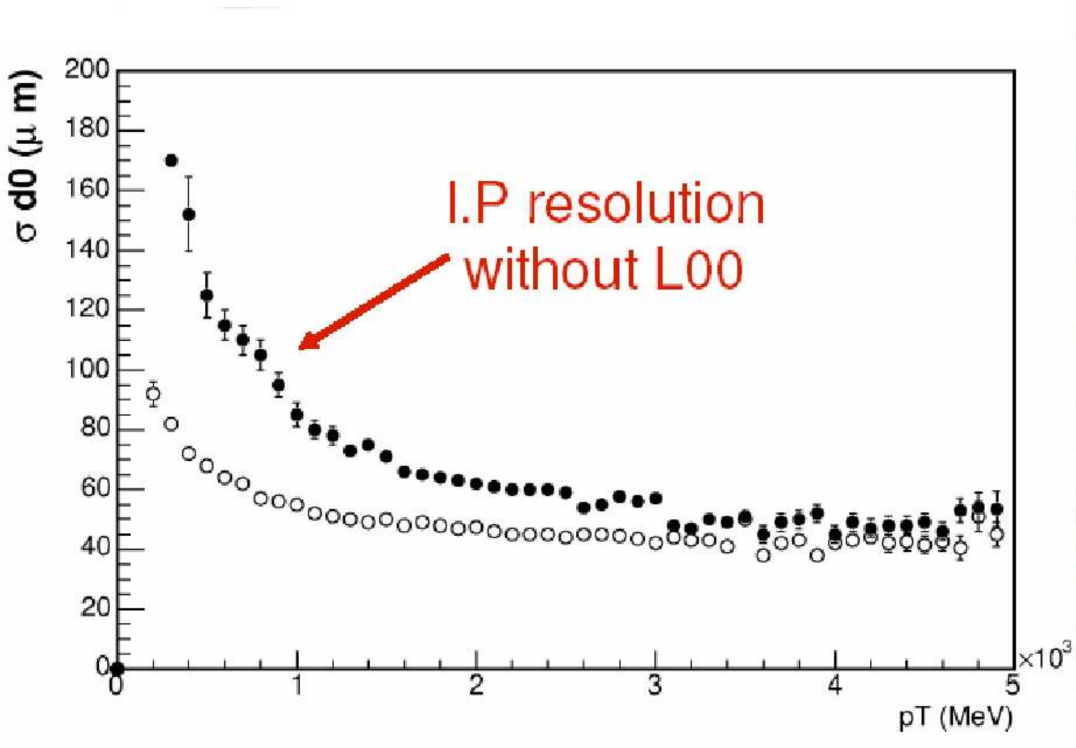
- ☞ electrons, muons
- ☞ high momentum tracks
- ☞ displaced tracks

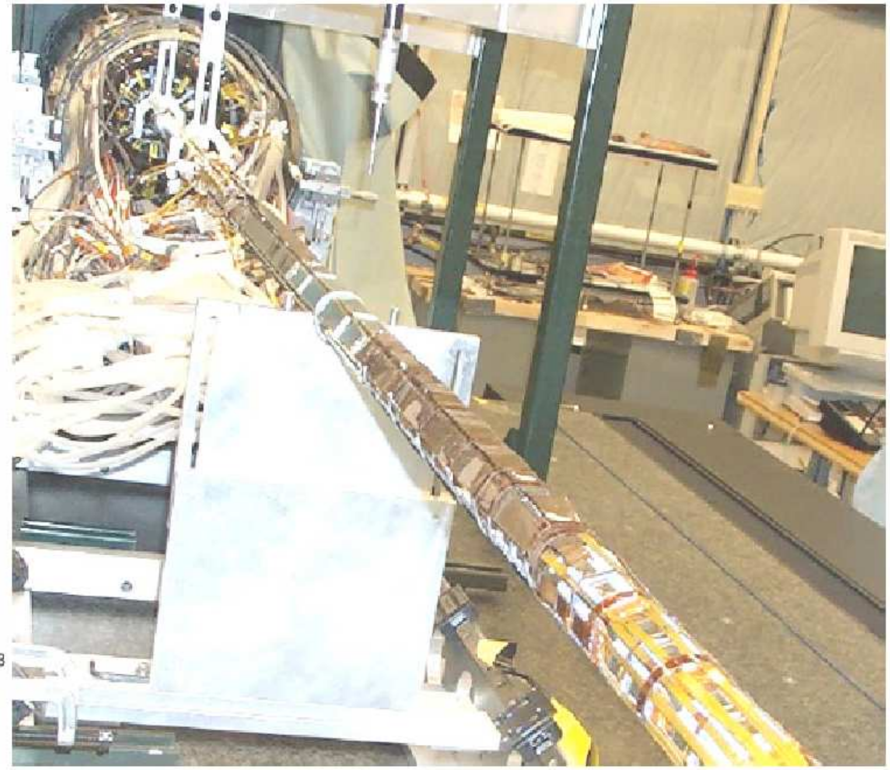


Challenge:

- ☞ fast readout
- ☞ track above 25 kHz

Vertexing - Key Detector

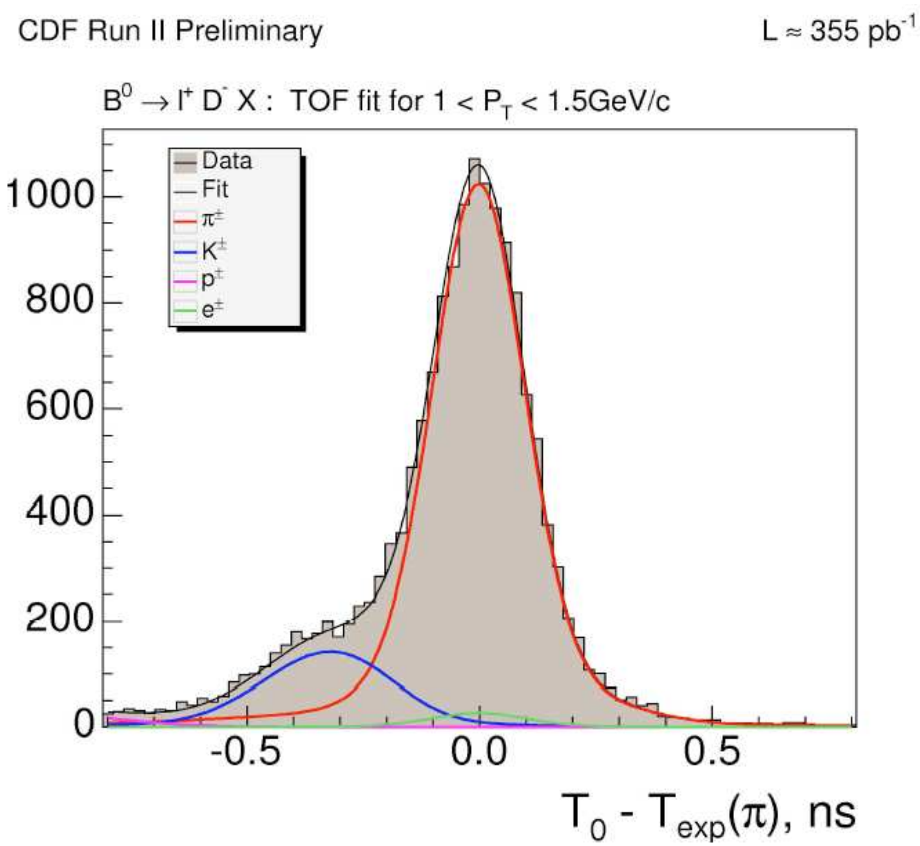




Layer 00

- ☞ innermost silicon layer: mounted on beampipe
- ☞ at distance of about 1.5 cm from the beamline
- ☞ significant boost for vertexing resolution

Flavor Tagging - Key Detector



Time-of-Flight Detector

- ☞ distinguish pions/kaons to $p \approx 1.5$ GeV/c, 100 ps resolution
- ☞ most important information for same side tagger

Unbiased Analysis Upgrade

Upgrade power estimated in an unbiased fashion

Signal Improvements

- ☞ fits of mass spectra provide estimate of $S/\sqrt{S+B}$

Flavor tagging

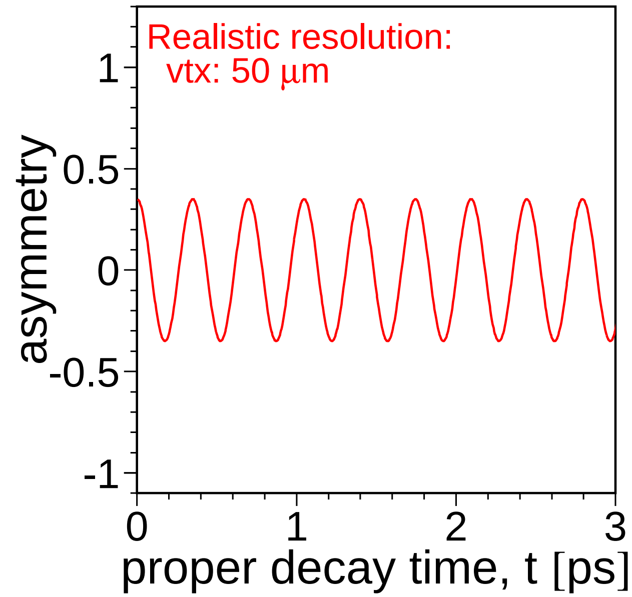
- ☞ OST improvement measured in calibration samples: ℓ+track, B^0/B^+
- ☞ SSKT improvement obtained from Monte Carlo

Proper Time Resolution

Proper Time Resolution - Basics

Significance revisited

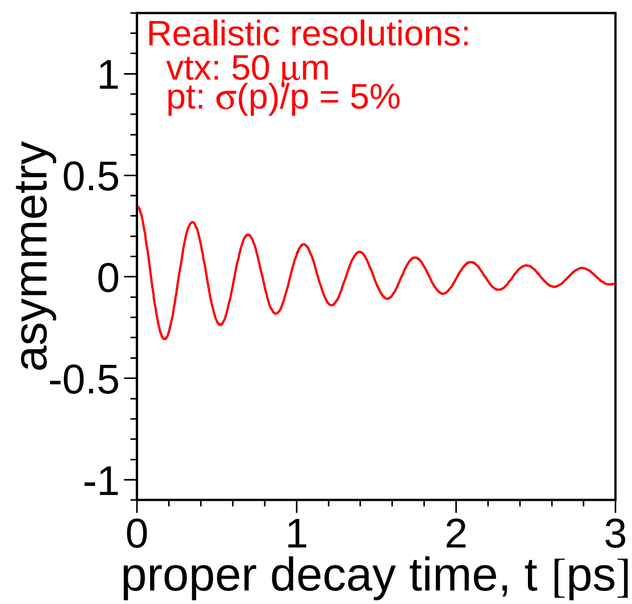
$$1/\sigma = \sqrt{\frac{n_S \varepsilon D^2}{2}} \sqrt{\frac{n_S}{n_S + n_B}} \exp\left(-\frac{(\Delta m_s \sigma_{ct})^2}{2}\right)$$



Reconstructed proper decay time

$$ct = L_{xy}^{B} \frac{m_B}{p_T^B}$$ hadronic

$$ct = L_{xy}^{\ell D} \frac{m_B}{p_T^{\ell D}} \cdot \left\langle \frac{p_T^{\ell D}}{p_T^{B}} \frac{L_{xy}^{B}}{L_{xy}^{\ell D}} \right\rangle_{MC}$$ semileptonic



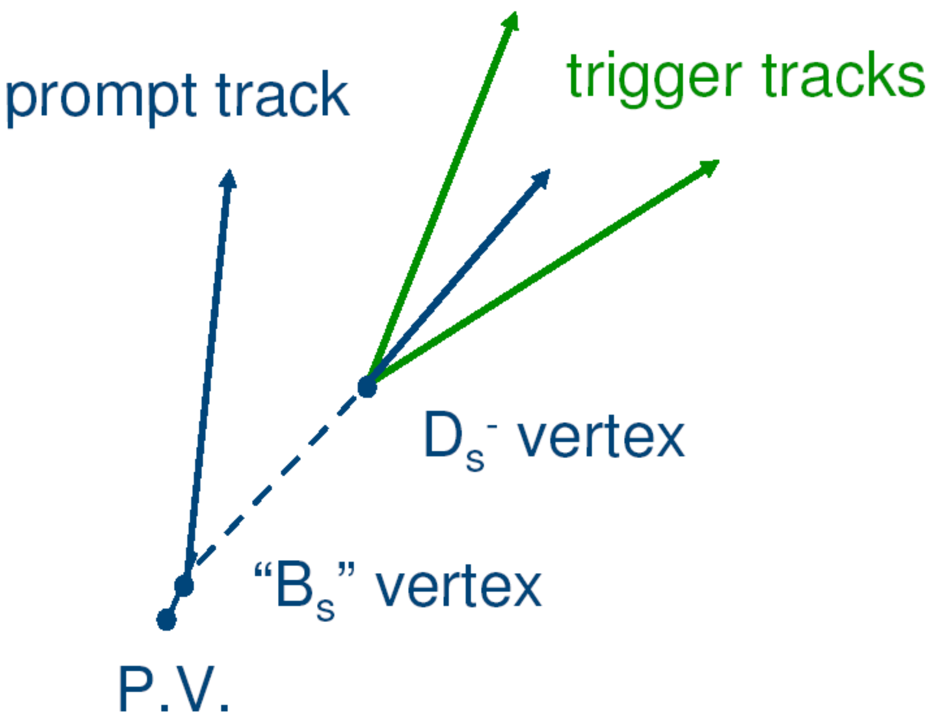
Understanding of resolution

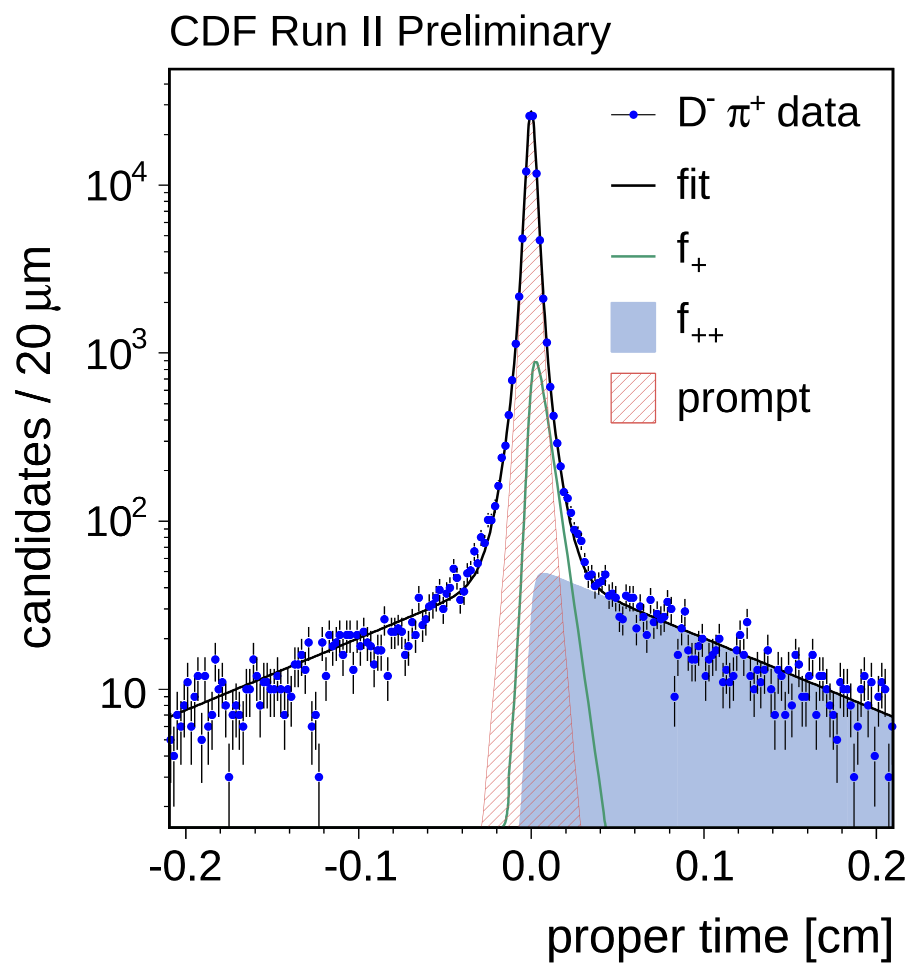
- irrelevant for lifetime measurements
- critical piece for B_s oscillations
- the faster the more important
- calibration on data needed

Proper Decay Time Resolution- Calibration

Use prompt D^+ and track

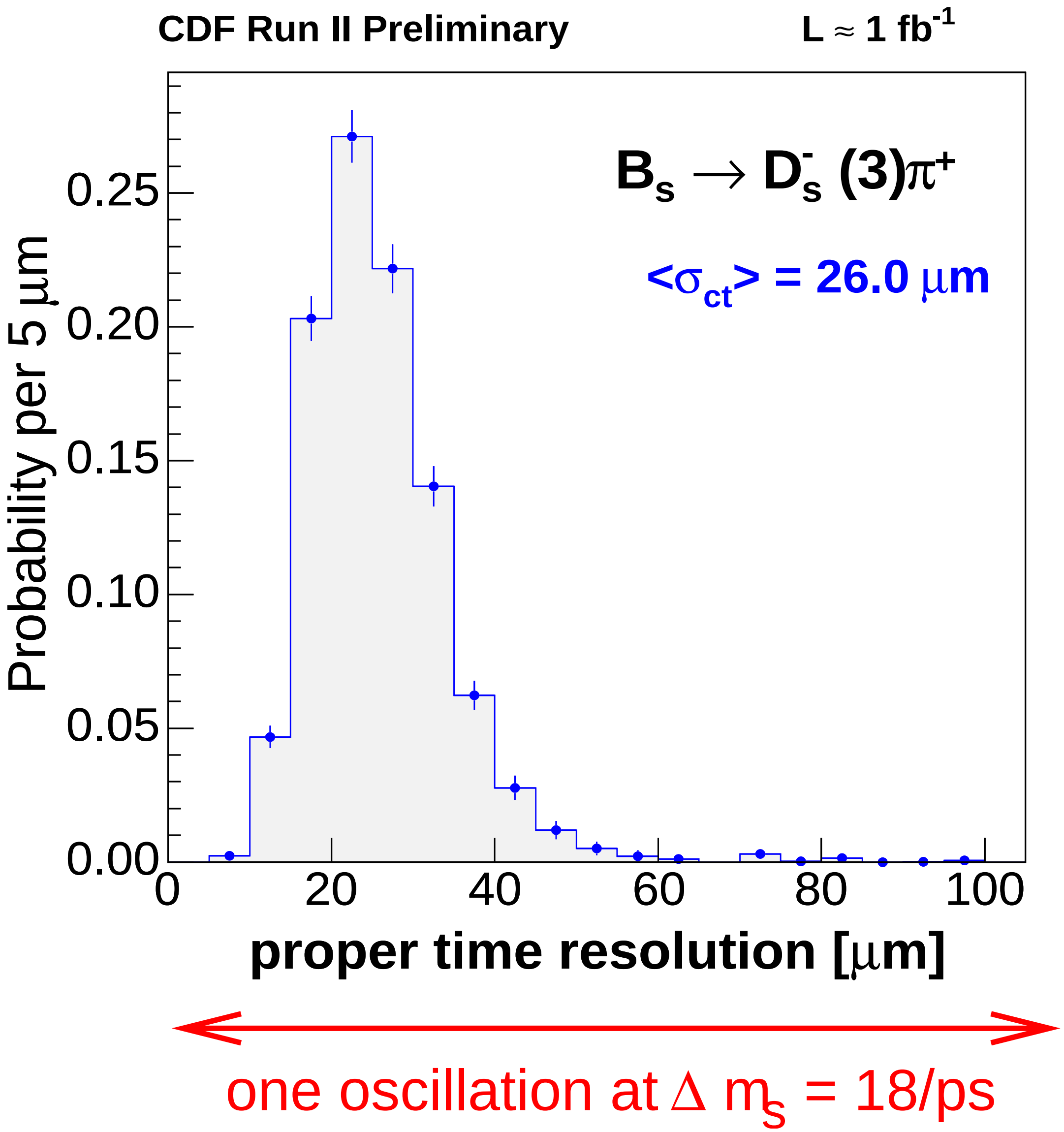
- large sample of prompt D^+
- most tracks from PV
- same topology as signal
- measure of *ct* resolution





Calibrated on our data

Proper Decay Time Resolution - Results



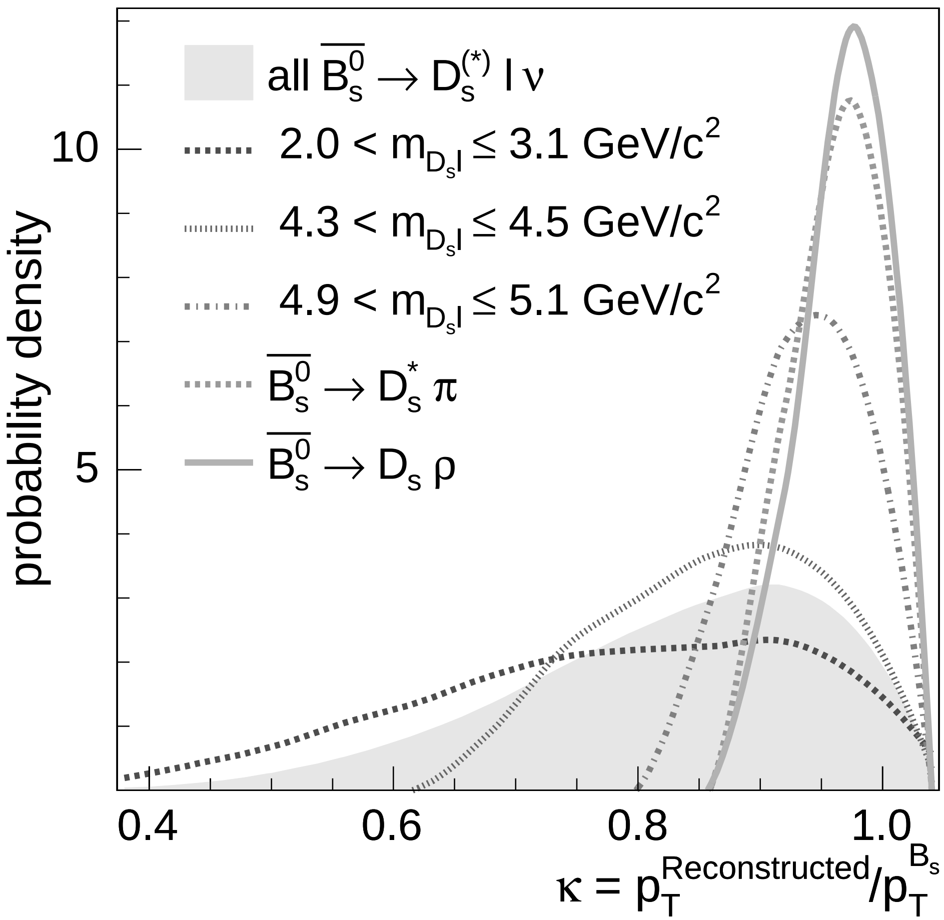
Optimal use of data

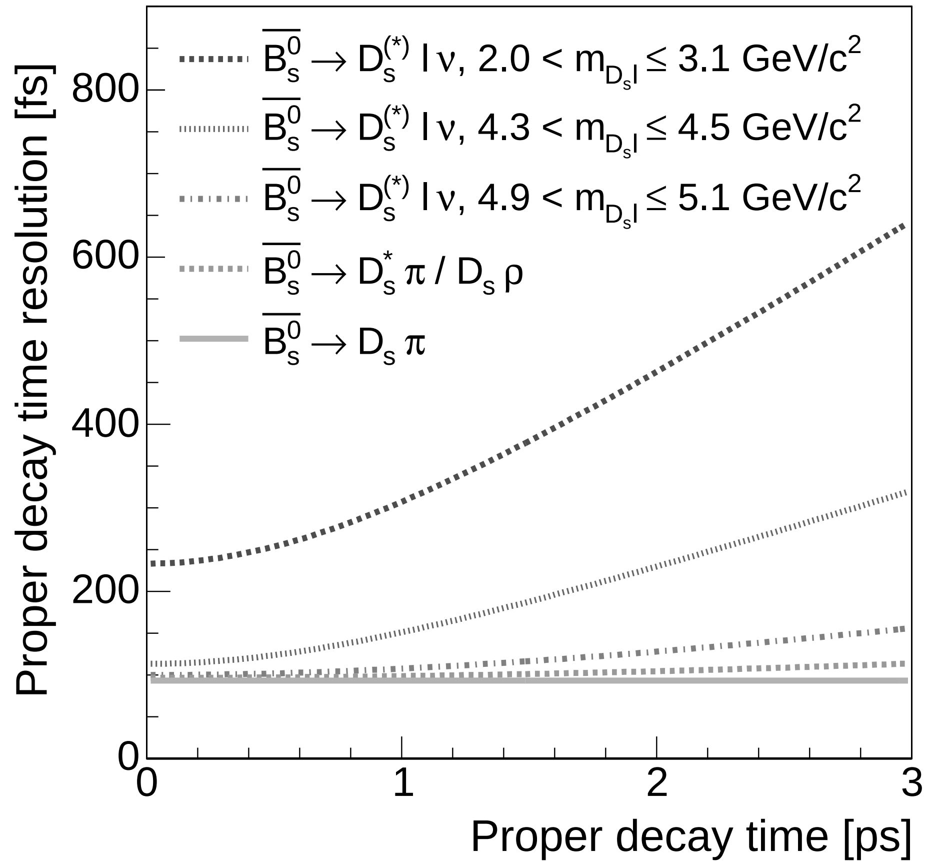
- PV per candidate
- resolution per candidate

Superior resolution

- access to high Δm_s
- CDF plays in a new league

Proper Decay Time Resolution - Results





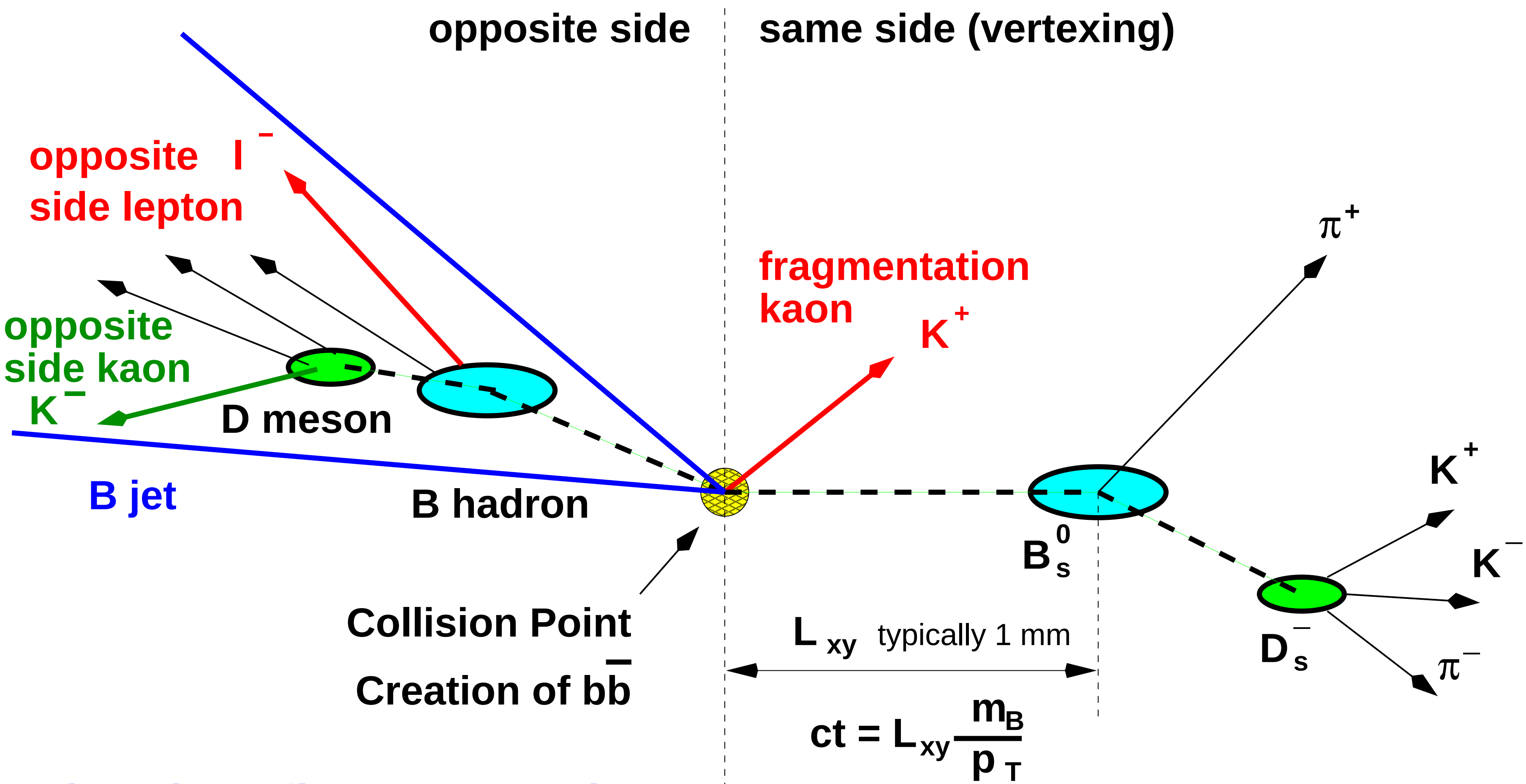
Hadronic $B_s \to D_s(3)\pi$

- ☞ $\sigma_{ct}^0 \sim 26\ \mu m$, 87 fs; $\sigma_p/p < 1\%$

Semileptonic $B_s \to \ell D_s X$

- ☞ $\sigma_{ct}^0 \sim$ 30-70 μm, 100-230 fs; $\sigma_p/p \sim$ 3-20%

Flavor Taggers - Overview

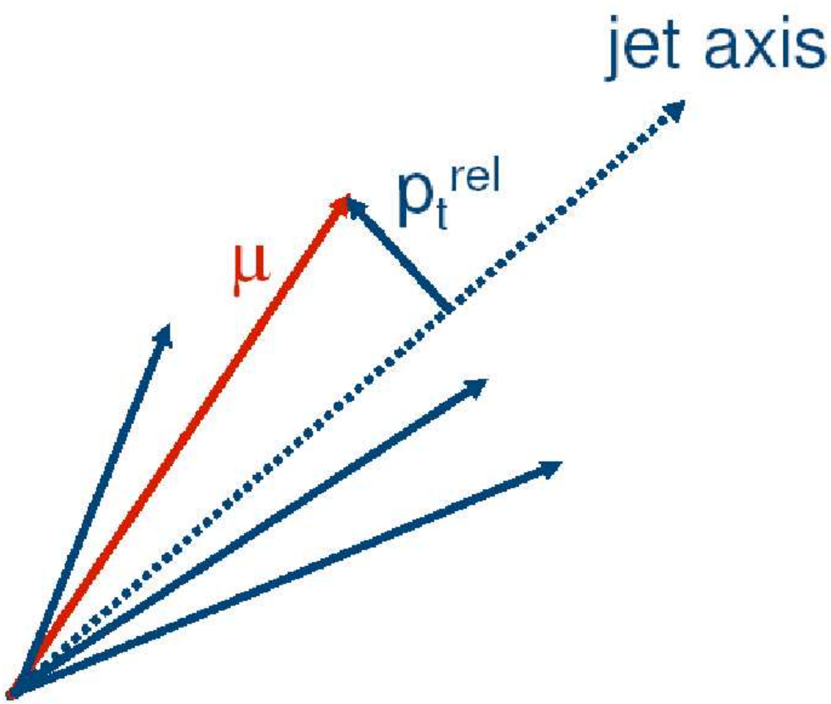


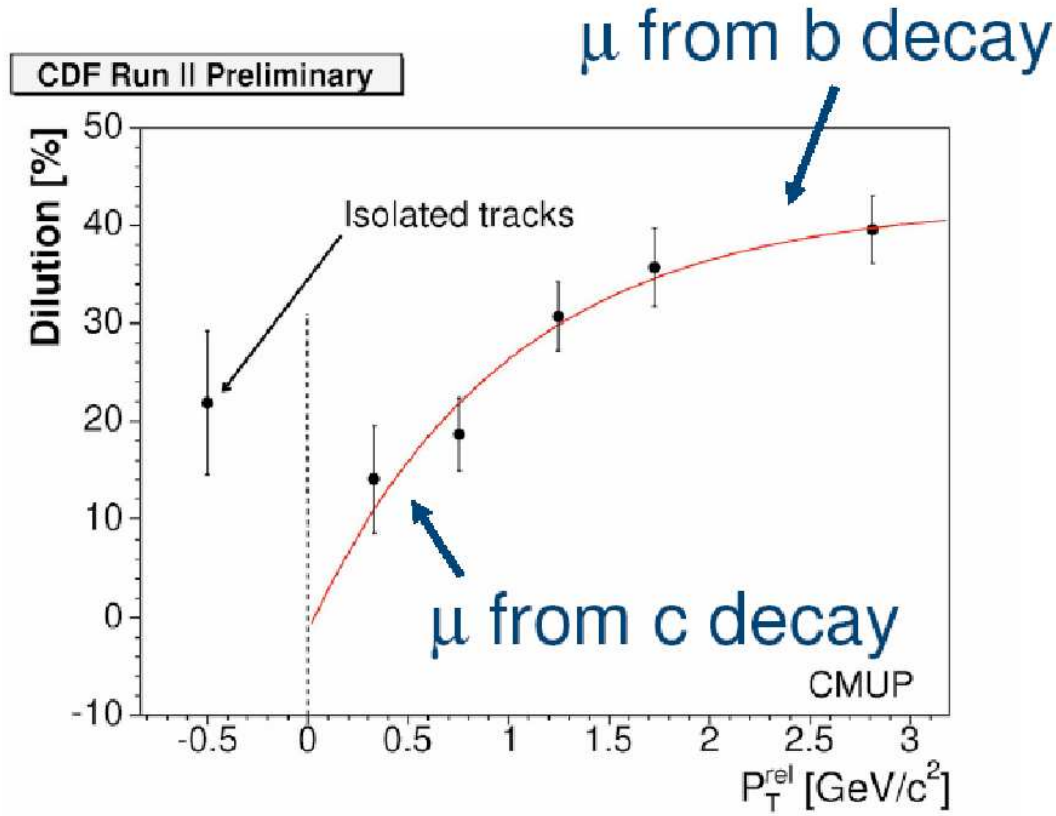
Production flavor tagging

- combine same side and opposite side tags
- opposite side: muon, electron, kaon and jet charge taggers
  jet selection algorithms: vertex, jet probability and highest p_T
- same side: particle ID based Kaon Tagger

Flavor Taggers - Maximize Performance

Parametrize tagger performance in dependent variables: here muon tagger and p_T^{rel}





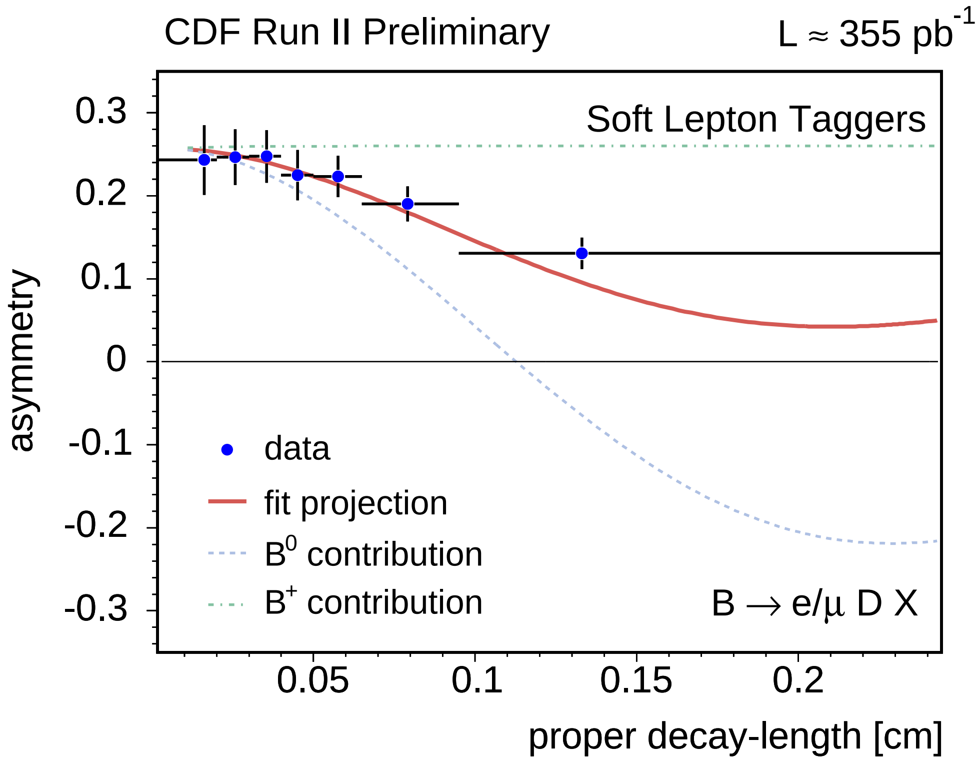
Tune on large B^+, B^0 samples: transfers directly to B_s

$\rightarrow$ each event has predicted dilution

Flavor Taggers - Fit for Tagger Performance

Fit B^+ and B^0

- ℓD and $D\pi(\pi\pi)$ are fit separately
- parameters: D and Δm_d
- depicted: combined ℓD samples with combined lepton tags



B^0 Mixing Result

- $0.536 \pm 0.028(\text{stat}) \pm 0.006(\text{syst})\ \text{ps}^{-1}$ hadronic
- $0.509 \pm 0.010(\text{stat}) \pm 0.016(\text{syst})\ \text{ps}^{-1}$ semileptonic
- $0.507 \pm 0.005\ \text{ps}^{-1}$ PDG 2006

Flavor Taggers - Results

Usage of flavor taggers

- OST: selection of best available OS tag
- OST and SST use disjunct input information
- simple uncorrelated OST/SST combination algorithm

$\varepsilon D^2[\%]$	Hadronic	Semileptonic
Muon	0.48 ± 0.06	0.62 ± 0.03
Electron	0.09 ± 0.03	0.09 ± 0.01
JQ/Vertex	0.30 ± 0.04	0.28 ± 0.02
JQ/JetCharge	0.46 ± 0.05	0.34 ± 0.02
JQ/highPt	0.14 ± 0.03	0.11 ± 0.01
OST	1.47 ± 0.10	1.44 ± 0.04
SSKT	3.42 ± 0.96	4.00 ± 1.12

SSKT improves tagging by factor of 3

Unbinned Likelihood Fit Overview

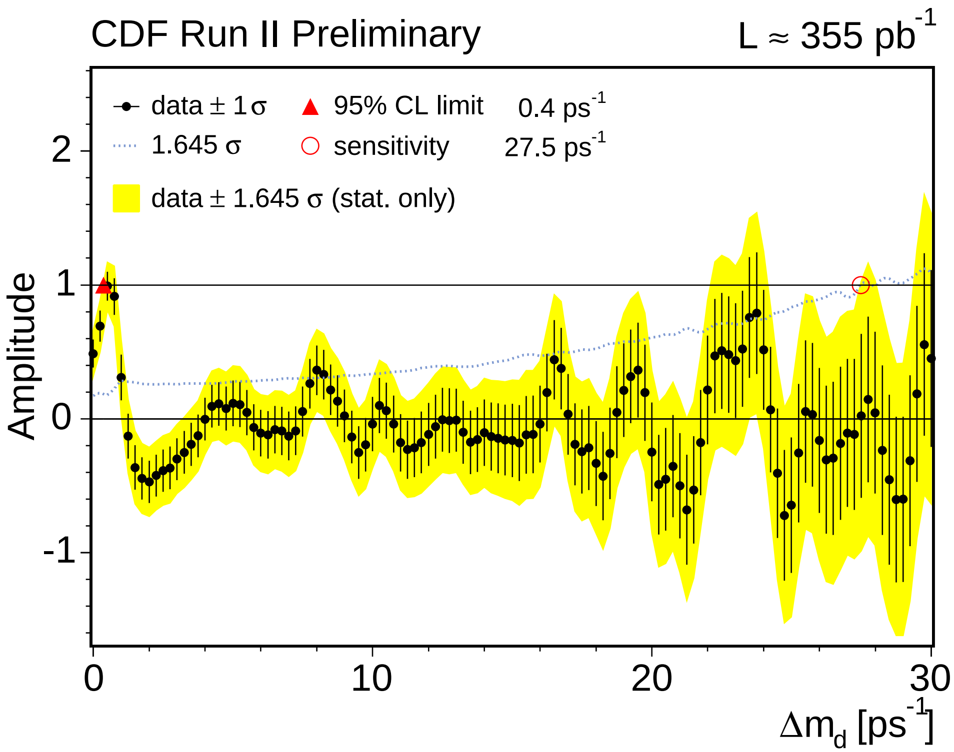
For each sample component and event

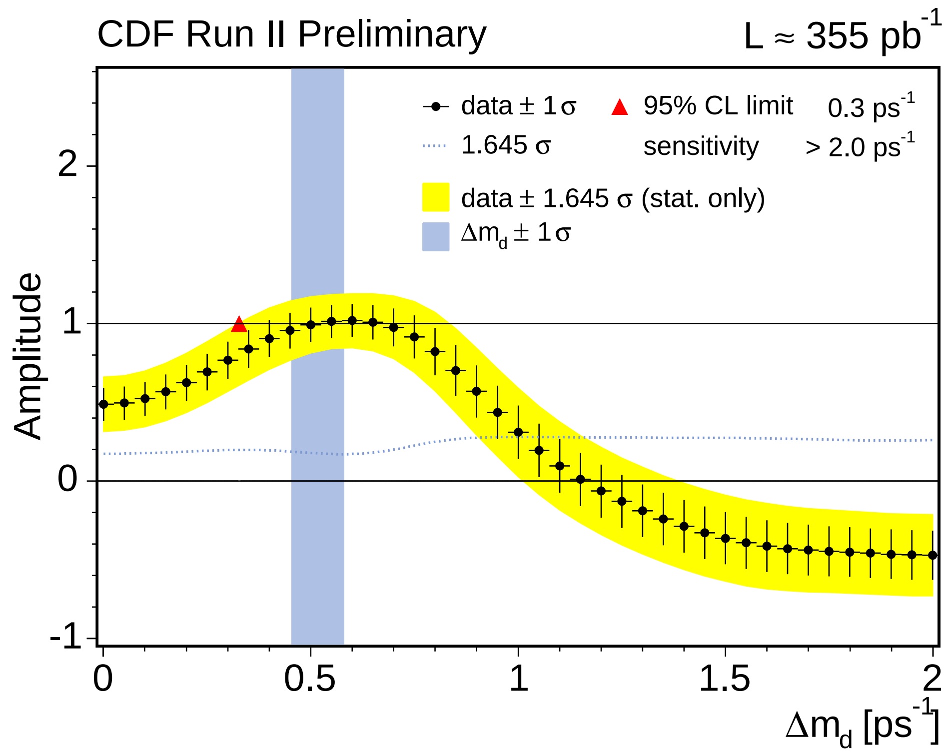
$$L = L_m \cdot L_t \cdot L_{\sigma_t} \cdot L_D$$

Most complex is proper decay time description

$$L_t = \frac{1}{N} \kappa \frac{e^{-\frac{\kappa t'}{\tau}}}{\tau} \frac{1 \pm A S_D D \cos(\Delta m_s \kappa t')}{2}$$
$$\otimes R(t - t'; S_{\sigma_t} \sigma_t) \cdot \varepsilon(t)$$
$$\otimes F(\kappa)$$

Amplitude Scan Method - Using B^0





Unbinned likelihood fit

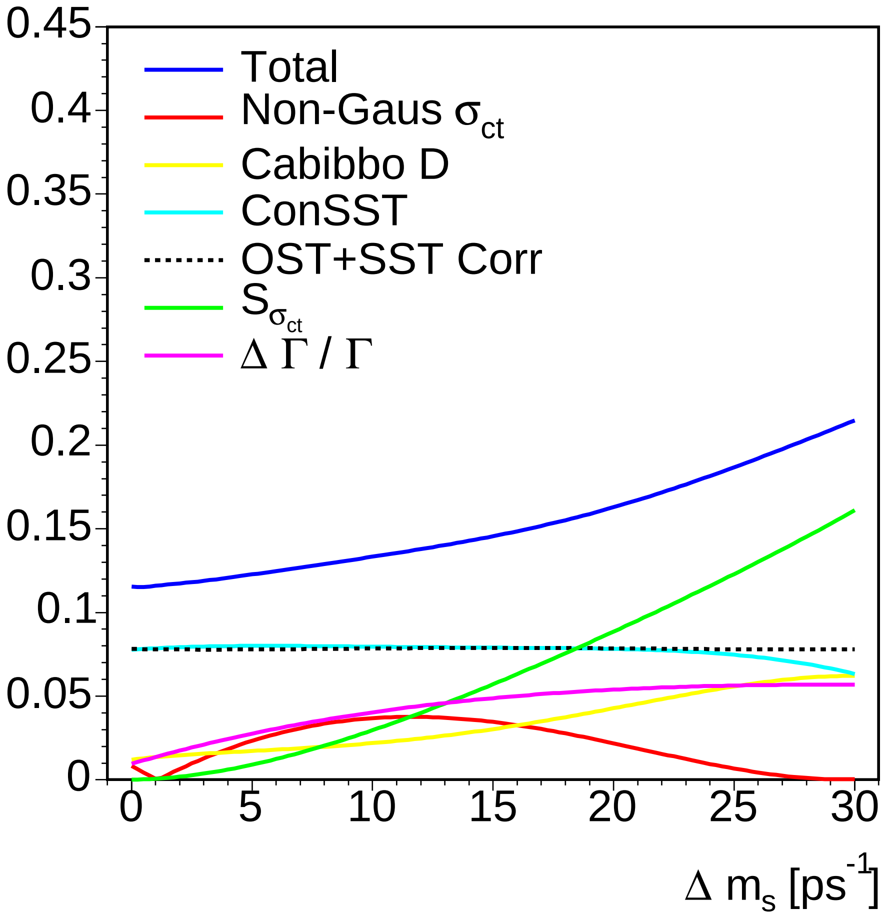
- $p \sim (1 \pm AD\cos(\Delta m t))$
- scan fixed values of Δm
- record A and $\sigma(A)$

Signal ≡ unit amplitude

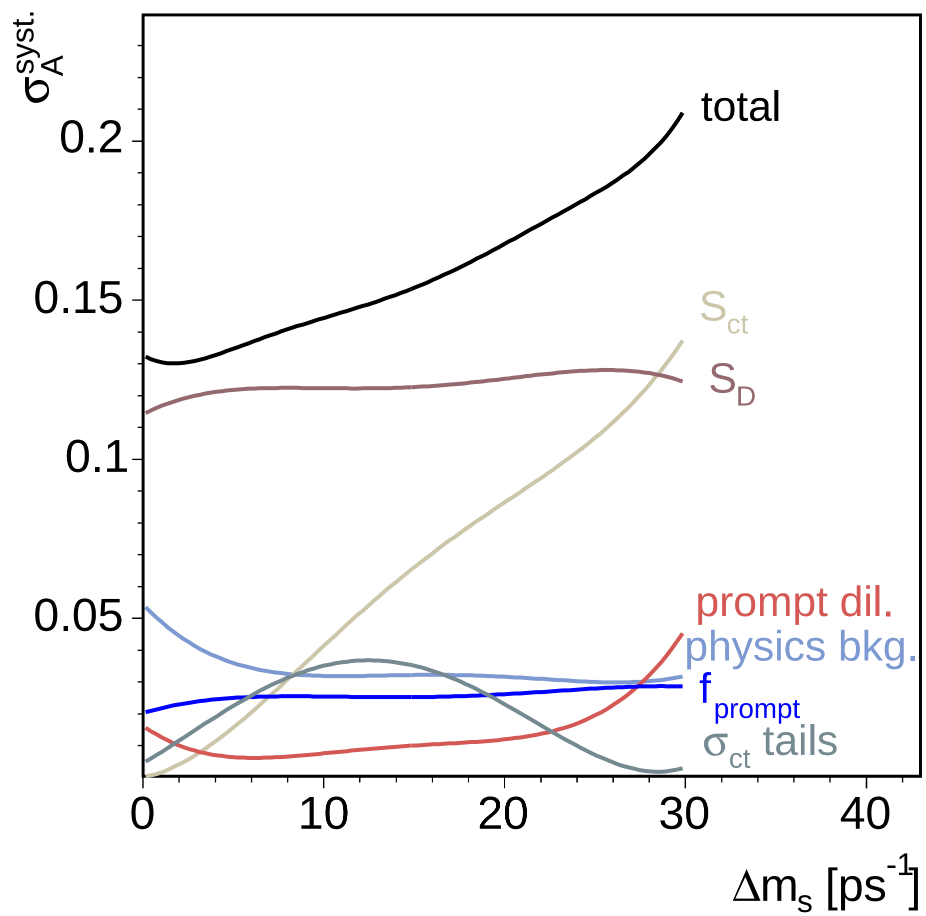
- else A consistent with 0
- exclude Δm @95%*CL* for $(1 - A) > 1.645\sigma(A)$

Systematic Uncertainties on Amplitude

Hadronic



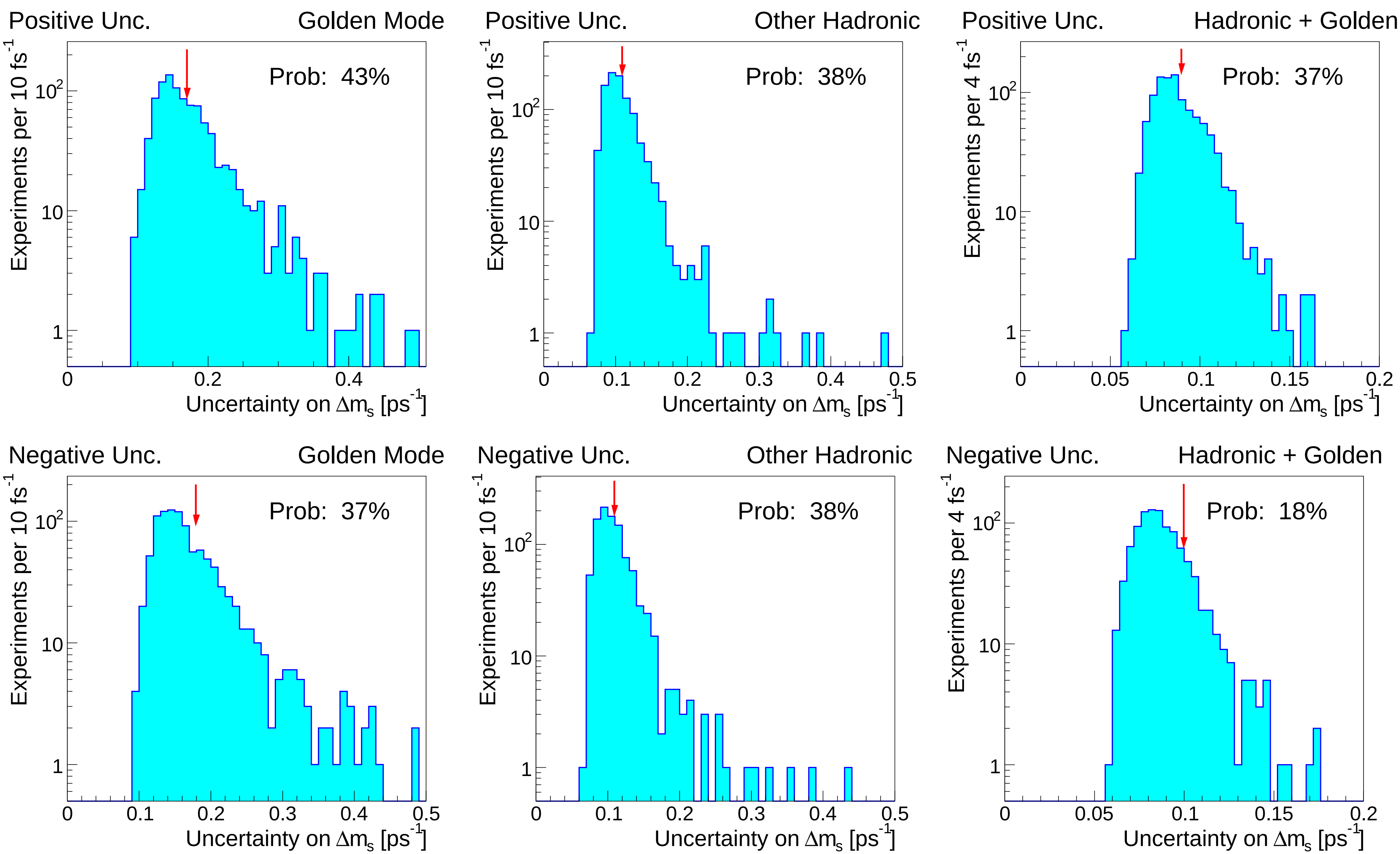
Semileptonic



Systematic uncertainties ~0.15-0.20 at high Δm_s:

→ analysis is statistically limited

Probabilities of Uncertainties



Uncertainties as expected for this sample

Systematic on Δm_s

Relevant systematic uncertainties

- all related to *ct* scale
- common for hadronic and semileptonic samples

Source	Value [ps^{-1}]
SVX alignment	0.04
Track fit bias	0.05
P.V. bias from tagging	0.02
Others	< 0.01
Total	0.07