First B_s Mixing Results from CDF II

Christoph Paus

Massachusetts Institute of Technology

Nuclear and Particle Physics Colloquium

May 9, 2005

Outline

Introduction

- + matter/antimatter puzzle and B_s oscillations
- + tests of the Standard Model with b hadrons

  $\rightarrow$ or find new physics with b hadron decays

Experimental setup

- + Tevatron accelerator
- + CDF detector

Analysis

- + signal reconstruction
- + calibrations: lifetimes, flavor tagging, B^0 mixing
- + Δm_s amplitude scan

Summary and Outlook

The CP Puzzle and the CKM Matrix

Matter/antimatter asymmetry

- why so much matter?
- Sakharov says: *CP* must be violated
- *CKM* matrix describes *CP* violation in SM
- amount too small to explain matter/antimatter asymmetry
- good spot for new physics

Sakharov's Conditions (1966)

- proton must decay
- universe had a thermal non-equilibrium phase
- *CP* must be violated

Measure *CKM* matrix elements

- unitarity condition $VV^\dagger = 1$
- derive unitarity triangle

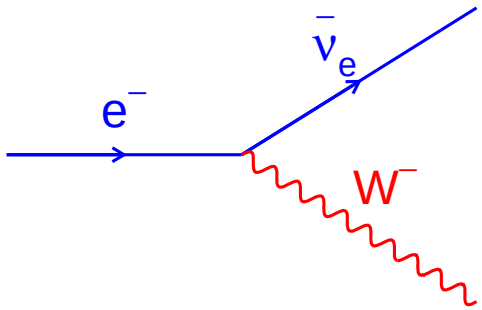
Matter in the Standard Model

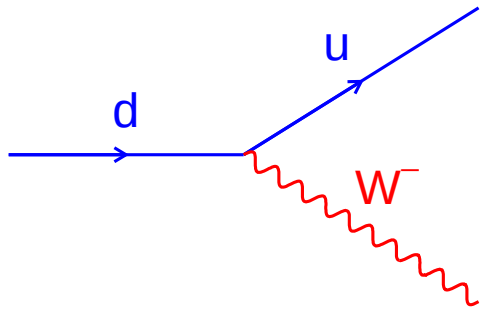
Matter build in families of weak isospin fermion doublets

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

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

Weak interaction through $W^\pm$ bosons





In general: weak eigenstates ≠ mass eigenstates

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

CKM Matrix

General form to describe mixing between quark 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 the Cabibbo–Kobayashi–Maskawa matrix

Wolfenstein parametrization ($\lambda = 0.224 \pm 0.012$):

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

Least known parameters: ρ and η

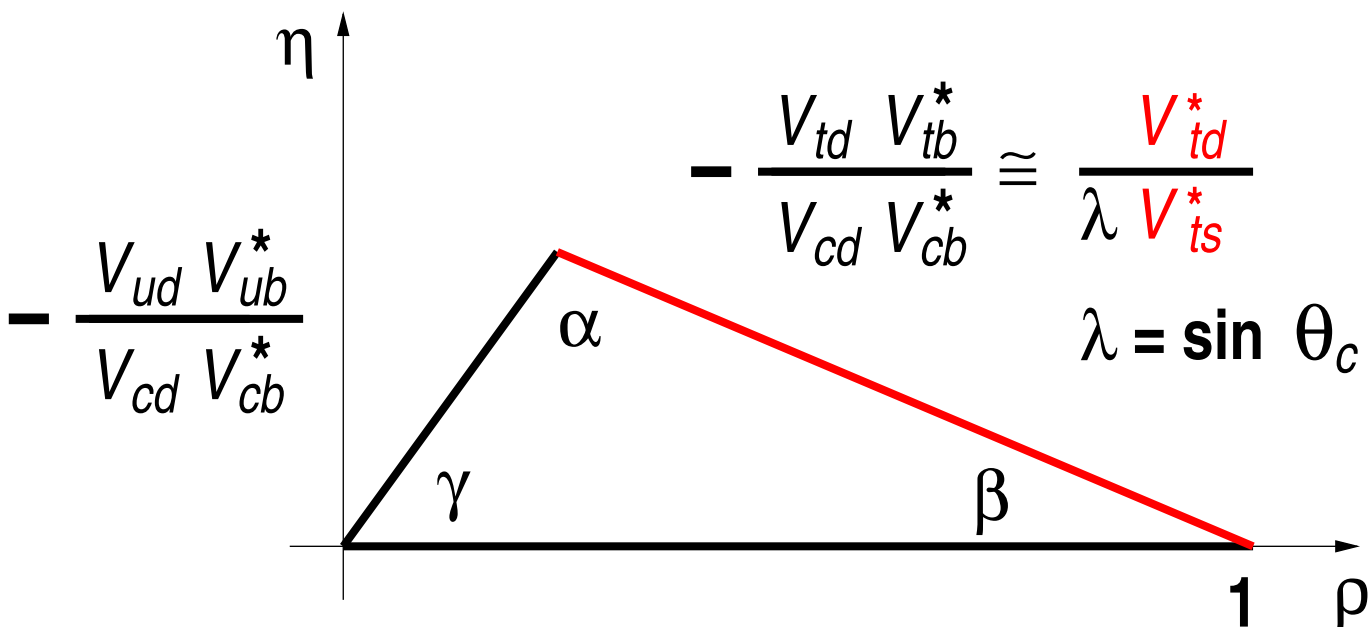
Unitarity Triangle

Unitarity condition: $VV^\dagger = 1$

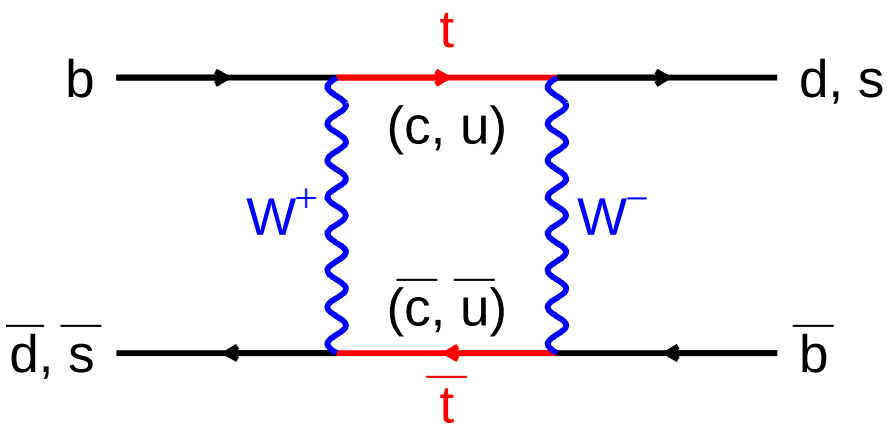
$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

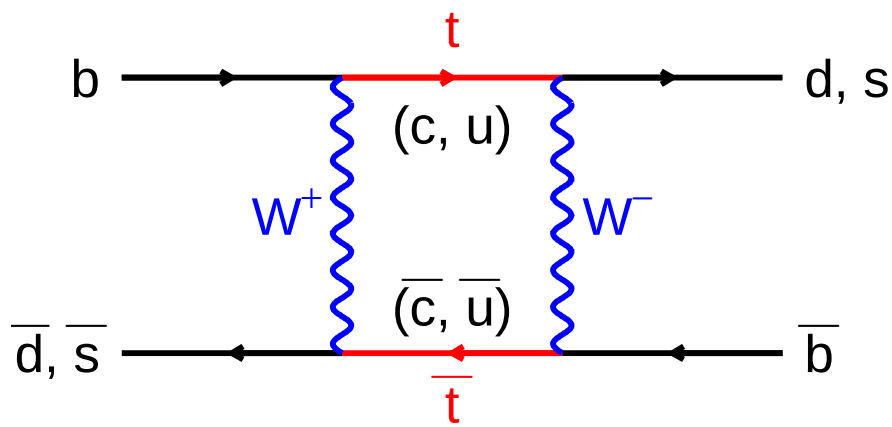
$$\rightarrow V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

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



Neutral B Meson Mixing





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

$$\Delta m_q = \frac{G_F^2}{6\pi}\eta_B m_{B_q}\hat{B}_{B_q} f_{B_q}^2 m_W^2 S\left(\frac{m_t^2}{m_W^2}\right)\left|V_{tb}V_{tq}^*\right|^2$$

Lattice QCD calculations:

$$\hat{B}_{B_d} f_{B_d}^2 = (228 \pm 30 \pm 10)\ \mathrm{MeV}^2$$

Hadronic uncertainties limit $|V_{td}|$ determination to $\approx$ 15%

In ratio most theory uncertainties cancel

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}}\xi^2 |V_{ts}|^2/|V_{td}|^2 \quad \text{with} \quad \xi^2 = 1.21 \pm 0.04 \pm 0.05$$

Determine $|V_{ts}|^2/|V_{td}|^2$ to $\approx$ 5%

Unitarity Triangle - Who Measures What?

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

Squeezing along side *b*

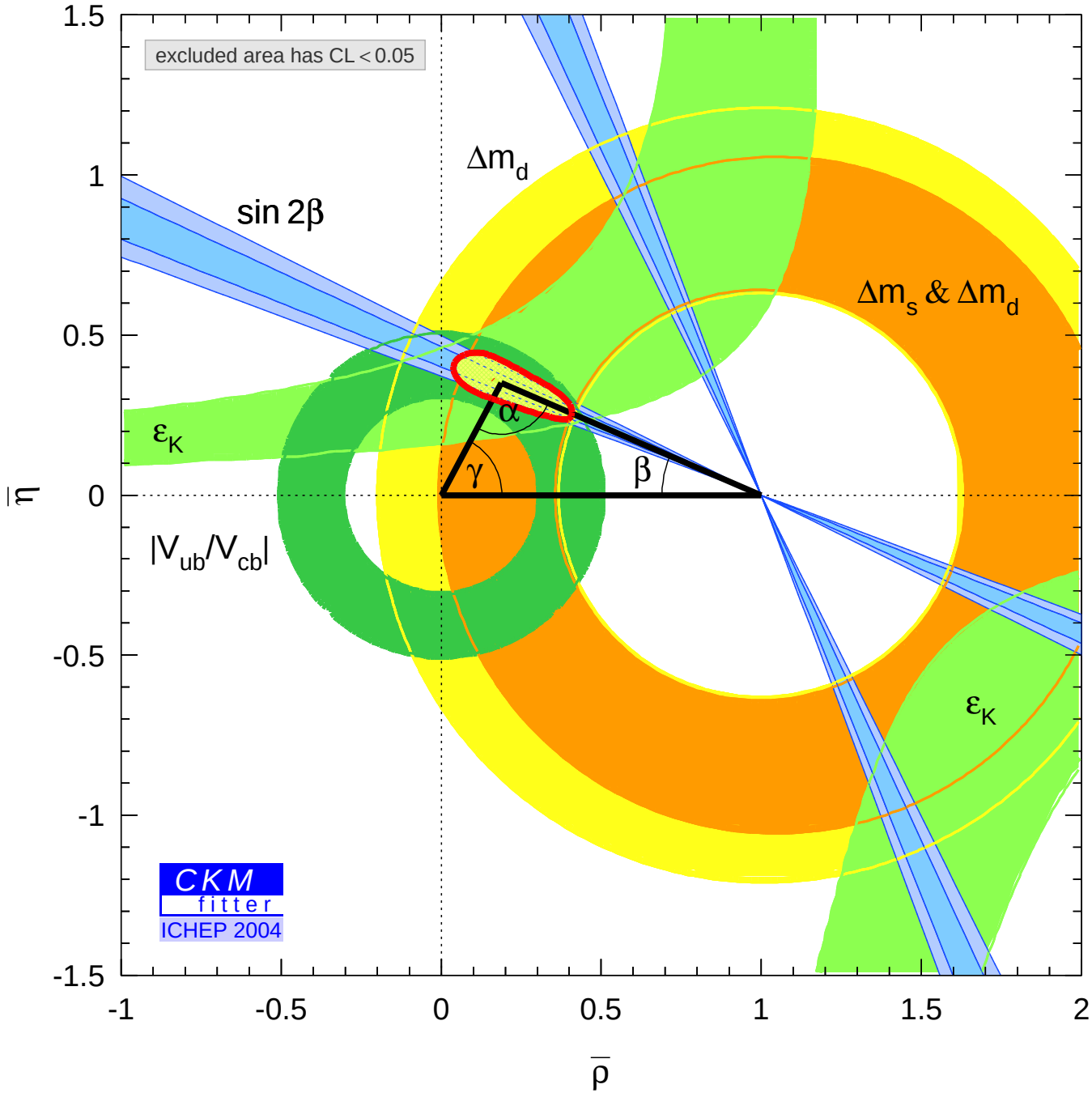
+ $\sin 2\beta$
+ V_{ub}/V_{cb}

Squeezing along side *c*

+ Δm_d
+ Δm_s

CKM fit result:

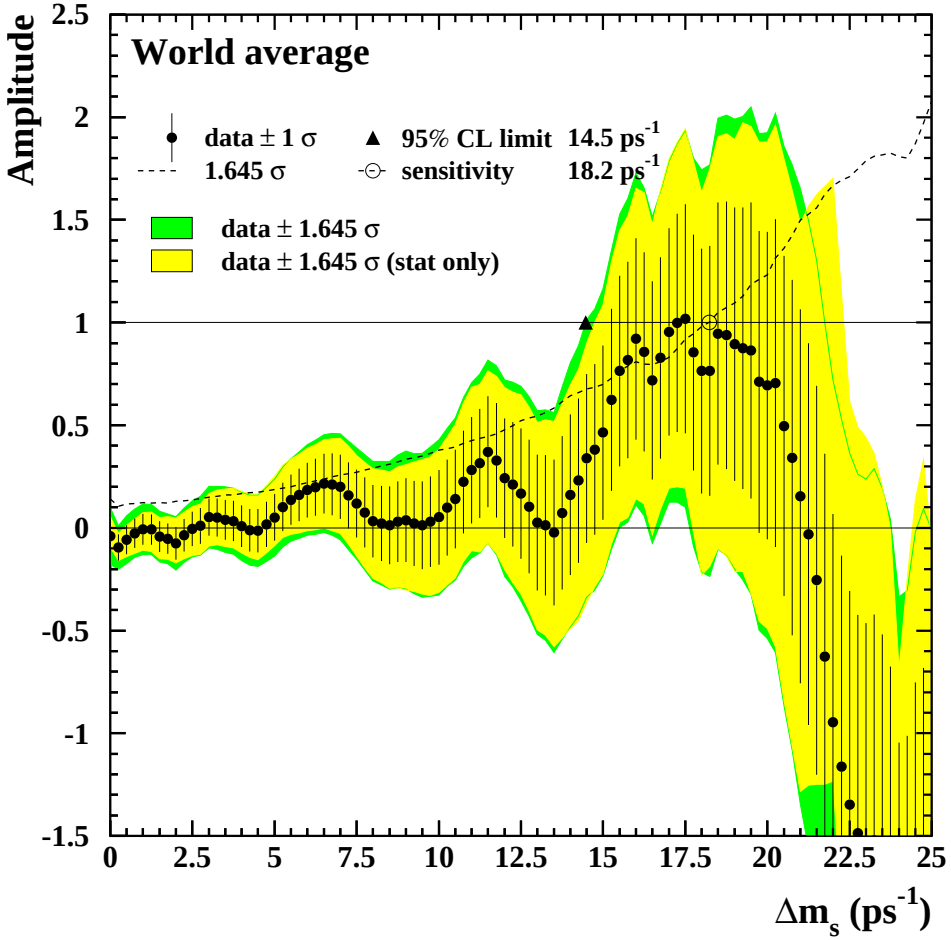
$\Delta m_s = 17.8\,^{+6.7}_{-1.6}\,\mathrm{ps}^{-1}$

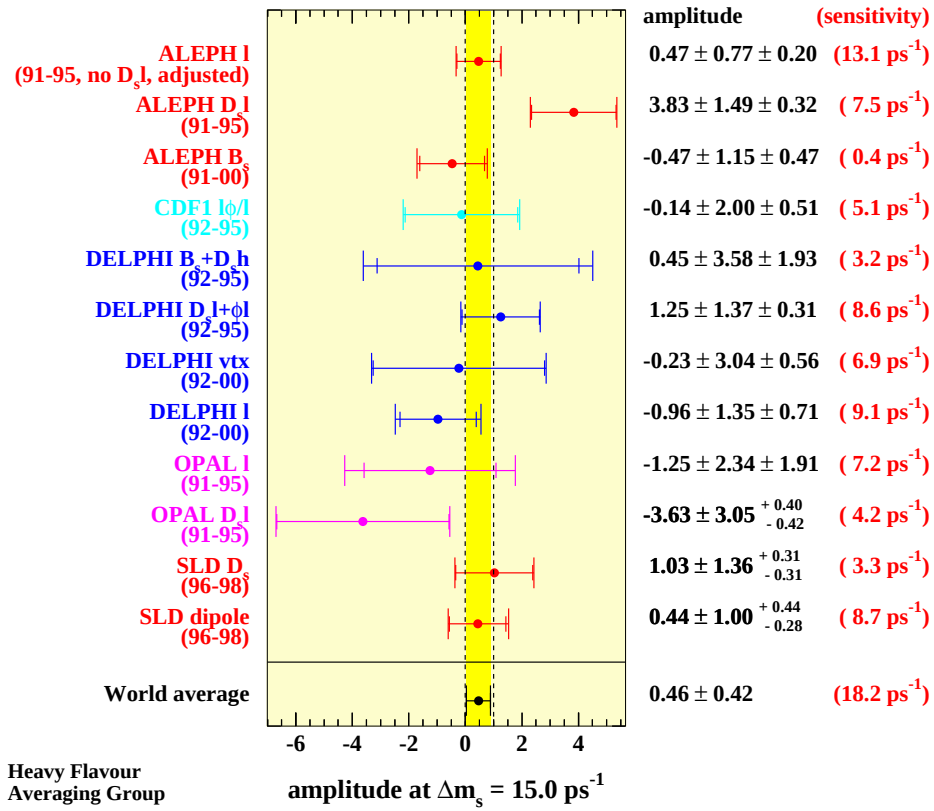


Present Experimental Results

Summary at 95% CL

- + limit: 14.5 ps^{-1}
- + sensitivity: 18.3 ps^{-1}
- + data: LEP, SLD, CDF Run I





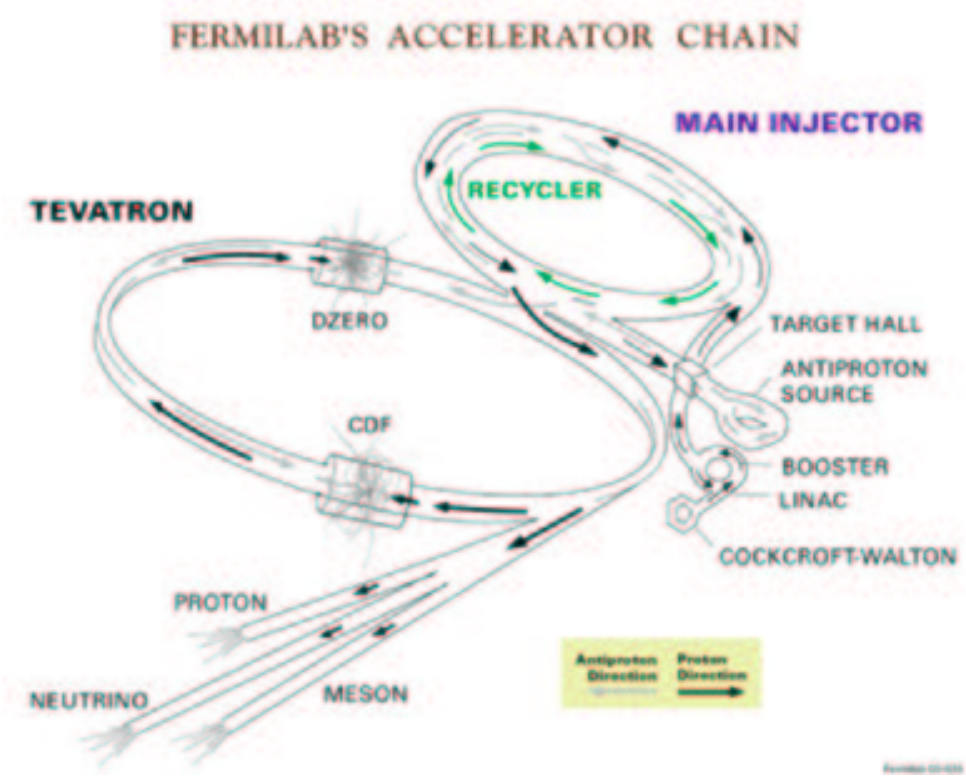
B_s mixing frequency more than 30 times faster than for B^0

→ experimental challenge

Tevatron Collider

Main injector

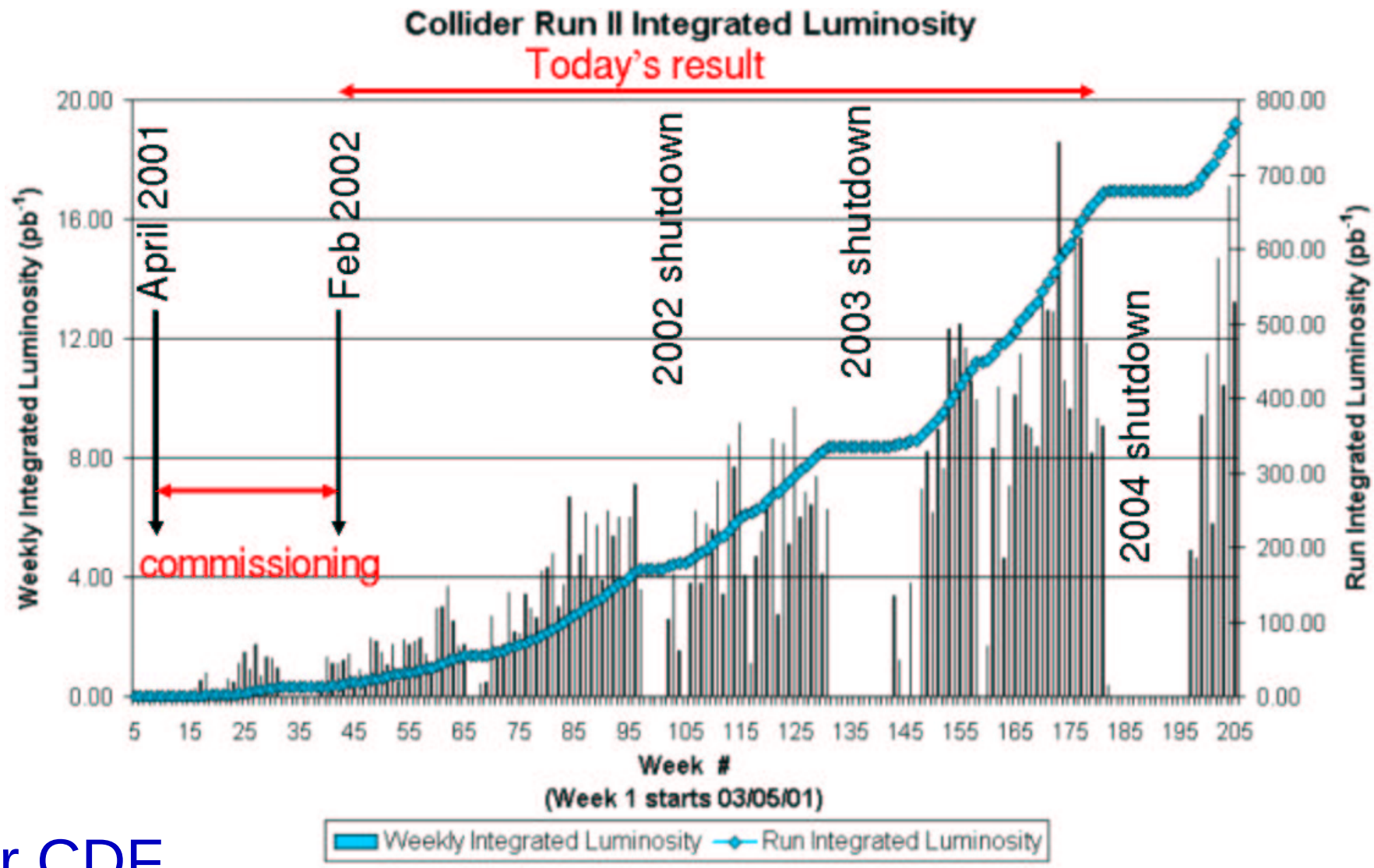
- + new Tevatron injection stage
- + accelerate and deliver higher intensity of protons
- + more efficient $\overline{p}$ transfer
- + $\overline{p}$ recycler (in progress)



Overall improvements:

- + higher collision rate: 396 ns (36×36 bunches)
  $\rightarrow$ 5-10 higher instantaneous luminosity than Run I
- + higher center-of-mass energy
  Run I – 1.8 TeV $\rightarrow$ Run II – 1.96 TeV

Performance: Data Taking



For CDF

+ delivered luminosity (2002-2004): 700 pb^{-1}
+ 350 pb^{-1} used for analyses shown in following

Bottom/Charm Production in $p\bar{p}$

Compare $\sigma(b\bar{b})$:

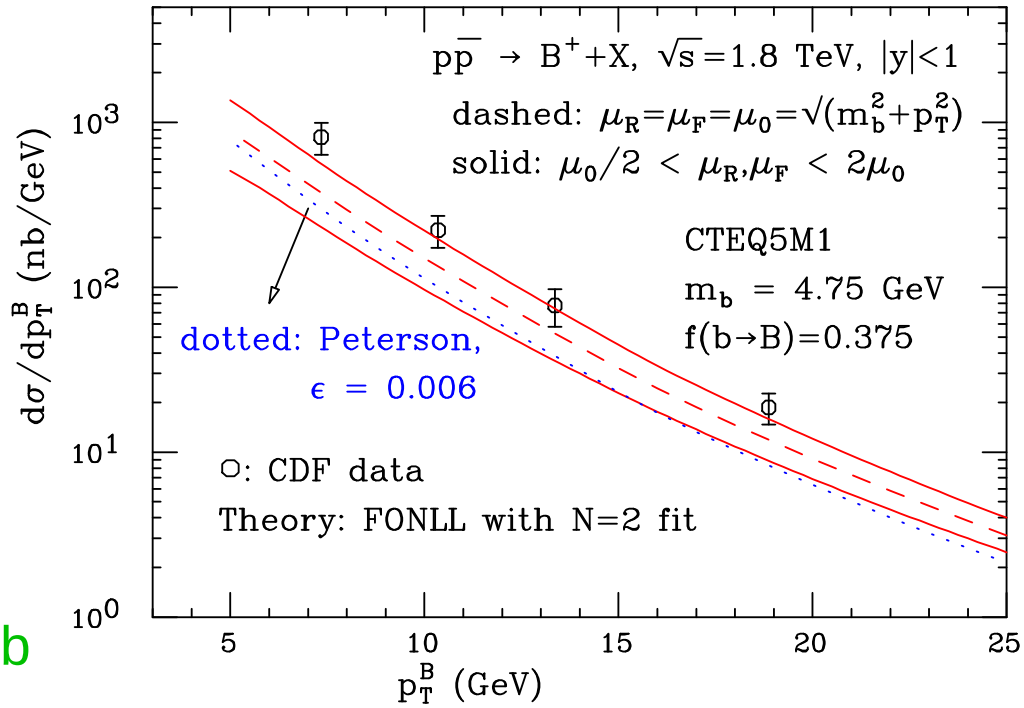
$\Upsilon(4S)$ $\approx$ 1 nb (only B^0, B^+)

Z^0 $\approx$ 7 nb

$p\bar{p}$ $\approx$ 100 μb

Light quark σ(inelastic) 10^3 larger

at $p\bar{p}$ it is all about the trigger



Run I: $B^+ \to J/\psi K^+$ ($p_T > 6$ GeV, $|Y| < 1$)

+ single inclusive (B^+): 3.6 ± 0.6 μb
+ Peterson fragmentation:
  $\varepsilon_b = 0.002$
+ $\sigma_{\text{data}}/\sigma_{\text{theory}} = 1.7$

Run II: $D^+ \to K\pi\pi$ ($p_T > 6$ GeV, $|Y| < 1$)

+ single inclusive (D^+): 4.3 ± 0.7 μb

Run II: $D^0 \to K\pi$ ($p_T > 6$ GeV, $|Y| < 1$)

+ single inclusive (D^0): 9.3 ± 1.1 μb

Difficulties for mixing

+ messy environment (many tracks)
+ boost in longitudinal direction
  $\to$ loose opposite side B (80%)
+ less flavor tagging info
  $\to$ $\varepsilon D^2 \approx 1\%$ *vs* 30% at BaBelle

b Hadron Production in Comparison

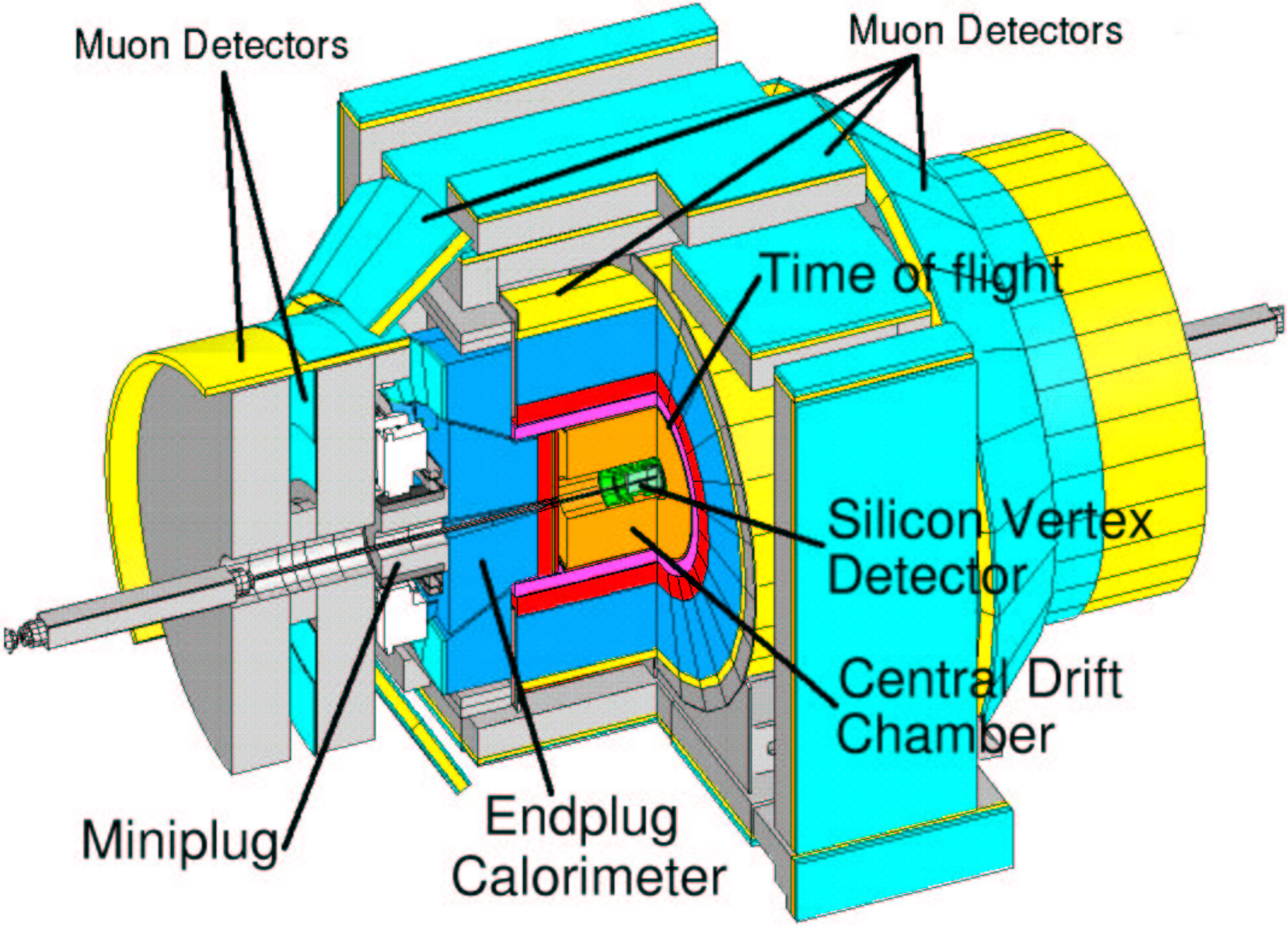
Accelerator	CESR,DORIS	LEP,SLC	PEPII,KEKB	Tevatron
Detector	Argus,CLEO	ADLO,SLD	BaBar,Belle	CDF,DØ
$\sigma(b\bar{b})$	~ 1 nb	~ 6 nb	~ 1 nb	~ 50 μb
$\sigma(b\bar{b}) : \sigma(had)$	0.26	0.22	0.26	0.001
b hadrons	B^0, B^+	all	B^0, B^+	all
Boost $< \beta\gamma >$	0.06	6	~ 0.5	2-4
Production	B at rest	$b\bar{b}$ btb	boosted	$b\bar{b}$ not btb
Pile up	no	no	no	yes
Trigger	inclusive	inclusive	inclusive	selective

Evaluation

+ experimentally LEP/SLC at Z ideal – but expensive
+ Babar and Belle produce ”cheap”, many, but only B^0, B^+
+ Tevatron has largest cross section and produces all b hadrons, but high background, $\sigma_{q\bar{q}} \sim 10^3$ larger

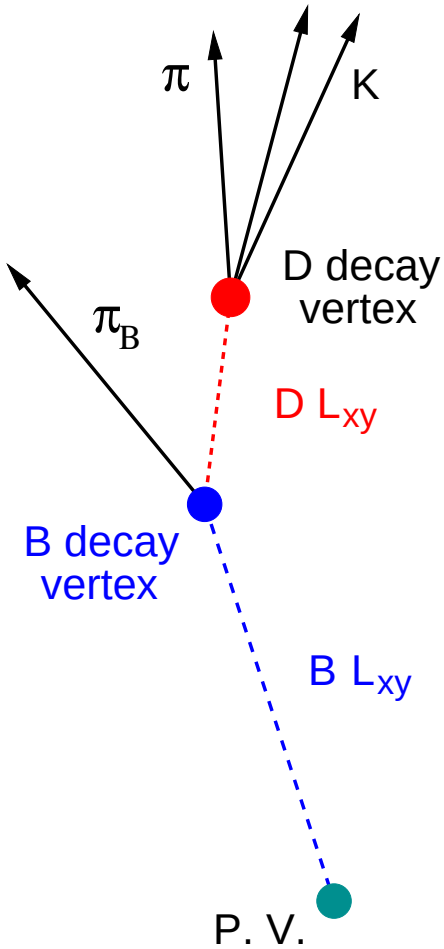
In $p\bar{p}$ at Tevatron it’s about the trigger

CDF II Detector

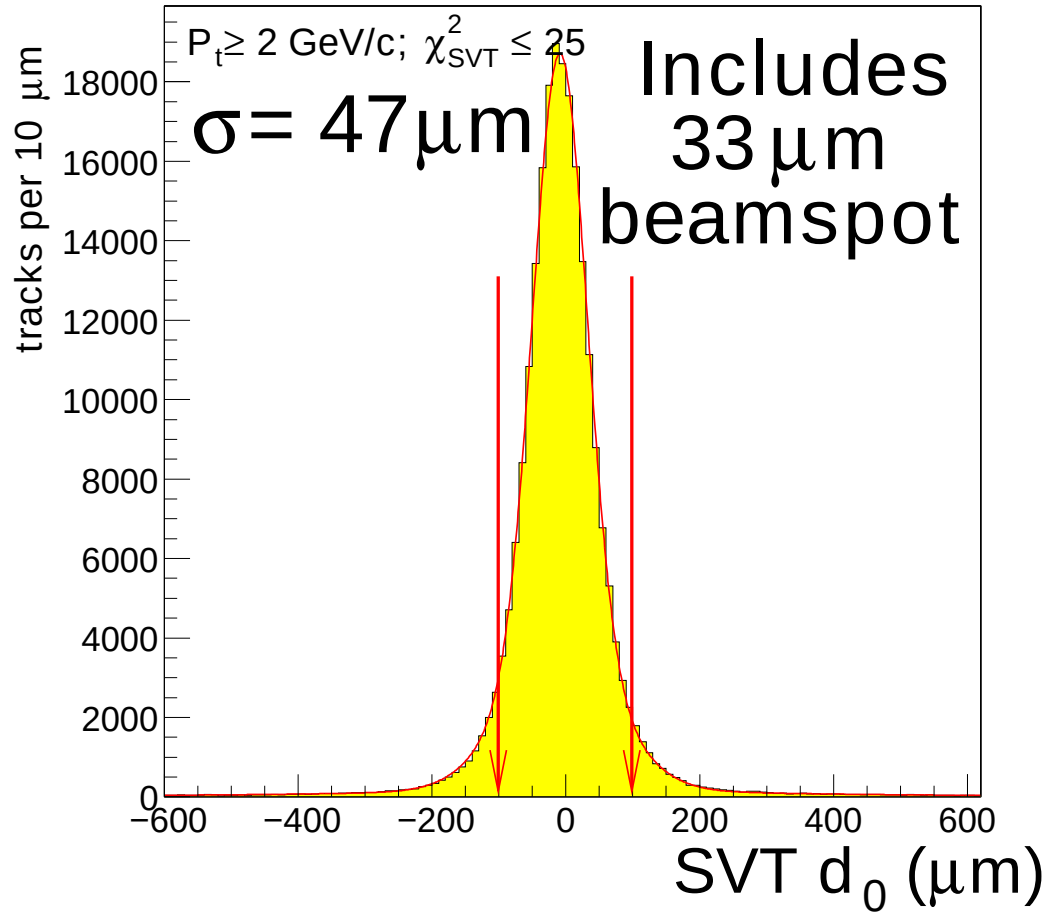


Run II Upgrades: Hadronic Trigger

Run I: only e, μ trigger



Level1 track trigger: high p_T
Level2 track trigger: large d_0
Improves Run I sensitivity by 4-5 orders of magnitude



Challenge:

- \+ fast silicon readout (SVX)
- \+ track at 10 kHz (SVT)
- \+ charm dominated

B Mixing Phenomenology

Neutral *B* mesons: mixtures of two mass eigenstates[1]

$$|B_H>=\frac{1}{\sqrt{2}}(|B>+|\overline{B}>) \qquad |B_L>=\frac{1}{\sqrt{2}}(|B>-|\overline{B}>)$$

Heavy and Light states have different mass and width

$$\Delta m = m_H - m_L (> 0 \text{ by def.}) \qquad \Delta\Gamma = \Gamma_H - \Gamma_L$$

Time evolution with $\Delta\Gamma \neq 0$

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

With $\Delta\Gamma = 0$ $(\Delta\Gamma_d/\Gamma_d < 0.01, \Delta\Gamma_s/\Gamma_s < 0.20)$

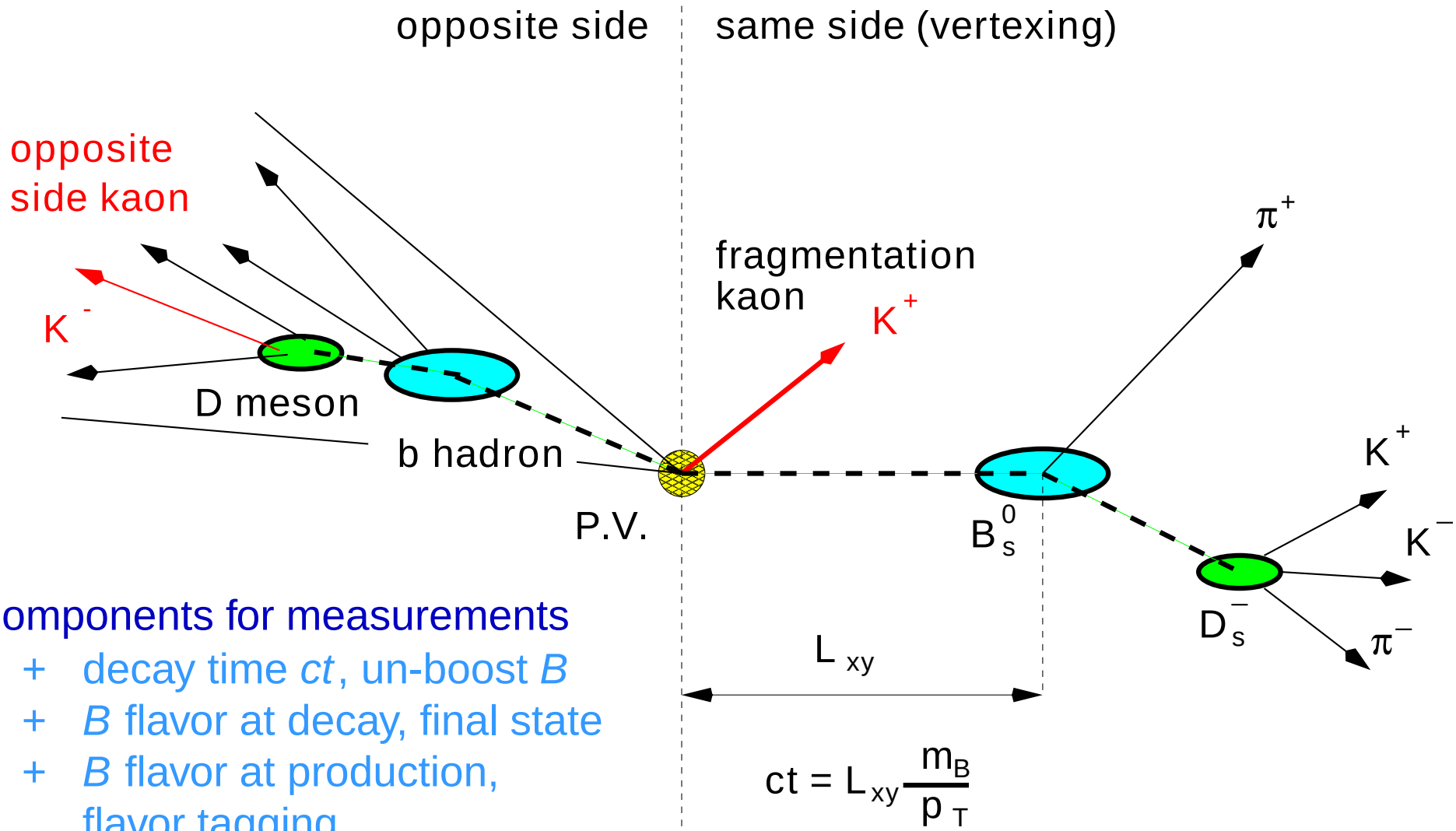
$$P(t)_{B^0\to\overline{B^0}} = \frac{1}{2\tau}e^{-t/\tau}(1 - \cos\Delta m t) \qquad P(t)_{B^0\to B^0} = \frac{1}{2\tau}e^{-t/\tau}(1 + \cos\Delta m t)$$

Determine asymmetry

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

[1] Assume no *CP* violation.

B_s Mixing: Experimental Building Blocks



Components for measurements

- + decay time *ct*, un-boost *B*
- + *B* flavor at decay, final state
- + *B* flavor at production, flavor tagging

Measure asymmetry in dependence of time

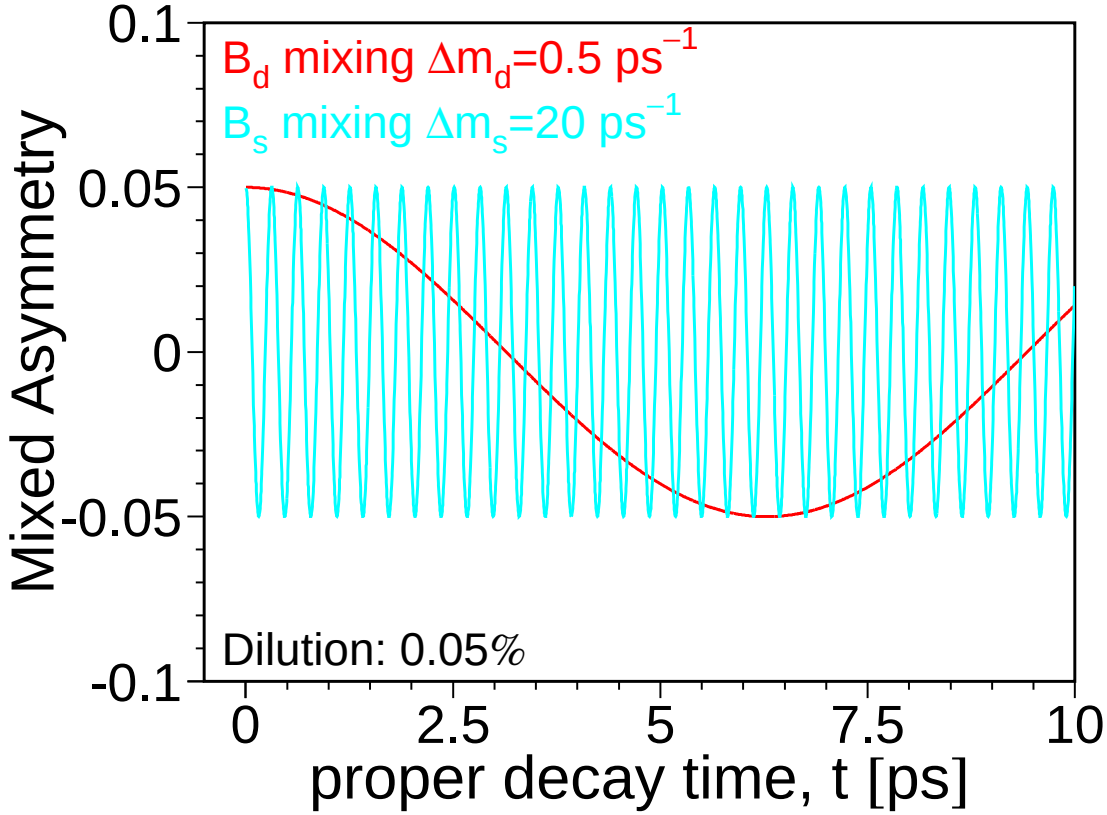
$$A_0^{meas}(t) \equiv \frac{N(t)_{RS} - N(t)_{WS}}{N(t)_{RS} + N(t)_{WS}} = D\cos(\Delta m_s t) \quad \text{with} \quad D = 2P - 1 = \text{dilution}$$

Why is that so difficult?

B_s mixing
- \+ very fast

Challenge
- \+ precise vertex
- \+ precise momentum
- \+ many events
- \+ tagging essential

Very tricky!



The larger Δm_S the more crucial $\sigma(ct)$

$$\text{significance} = \sqrt{\frac{n_S \varepsilon D^2}{2}} \exp\left(-\frac{(\Delta m_S \sigma_{ct})^2}{2}\right)$$

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

B_s *Mixing Analysis - Road Map*

Samples

- + confirm SVT based triggers for the samples
- + reconstruct B signals (B^+, B^0, B_s)
- + optimise $s/\sqrt{S+B}$

Lifetimes

- + SVT and analysis sculpts proper time distribution
- + develop correction for proper time sculpting
- + fit lifetimes for B^+, B^0, B_s

Flavor Taggers

- + calibrate opposite side taggers to parametrize dilution
- + use B^+, B^0 samples
- + use calibrated tagger dilution in fit for mixing

Amplitude scan for B_s mixing with unbinned likelihood

- + test on B^0 sample
- + proper time resolution per candidate
- + tagging power per candidate

Samples

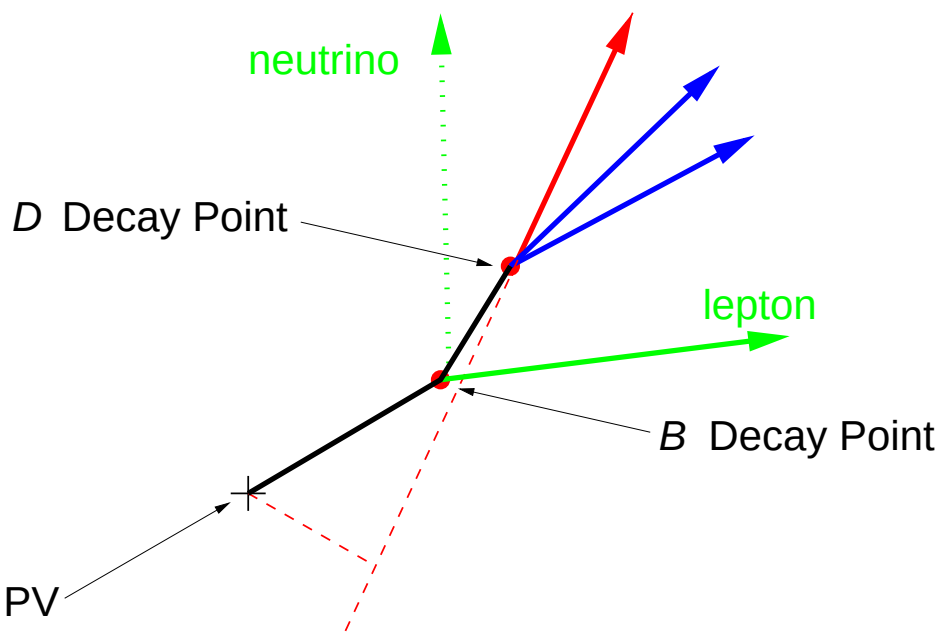
SVT Based Triggers

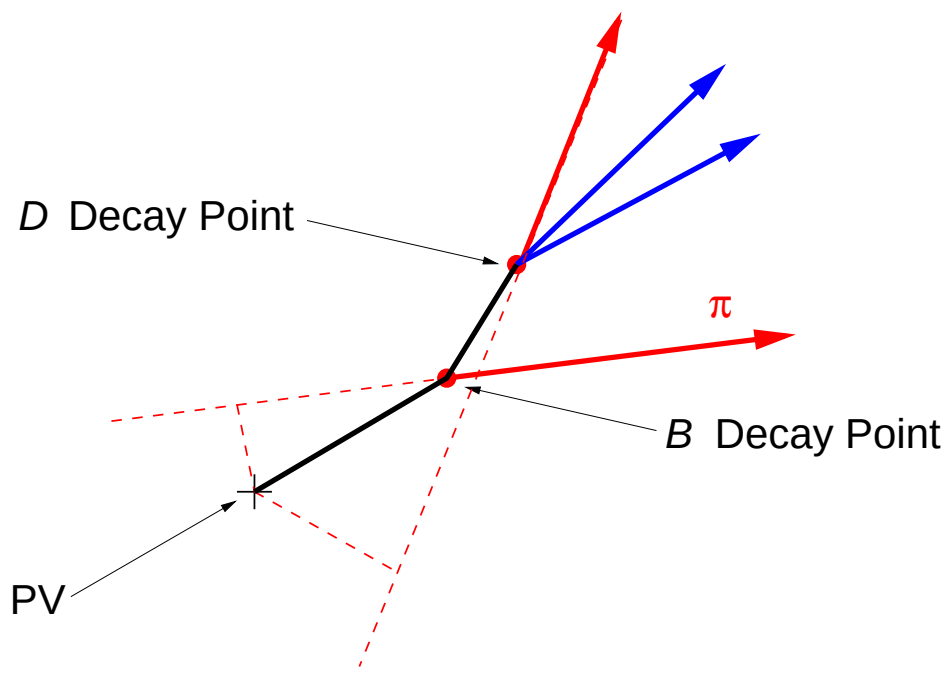
Semileptonic: $B_s \to \ell^+ D_s^- X$

- + one lepton, one SVT track
- + $p_T^{\ell} > 4$ GeV
- + $p_T^{track} > 2$ GeV
- + $p_{T,1} + p_{T,2} > 5.5$ GeV
- + $120\mu\text{m} < d_0^{track} < 1\text{mm}$

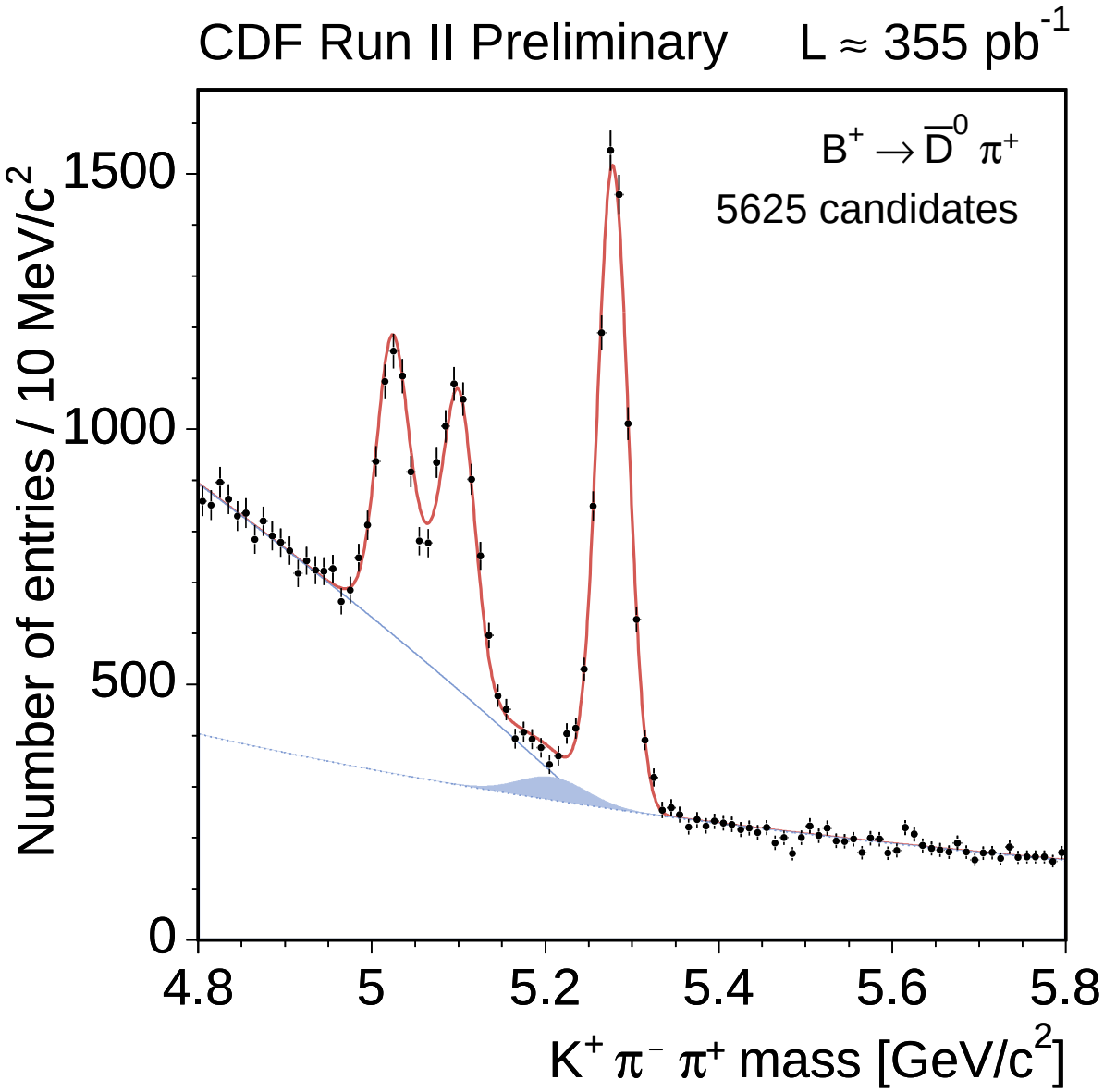
Hadronic: $B_s \to D_s^- \pi^-$

- + two SVT tracks
- + $p_T > 2$ GeV
- + $p_{T,1} + p_{T,2} > 5.5$ GeV
- + opposite charge
- + $120\mu\text{m} < d_0 < 1\text{mm}$
- + $L_{xy} > 200\mu\text{m}$

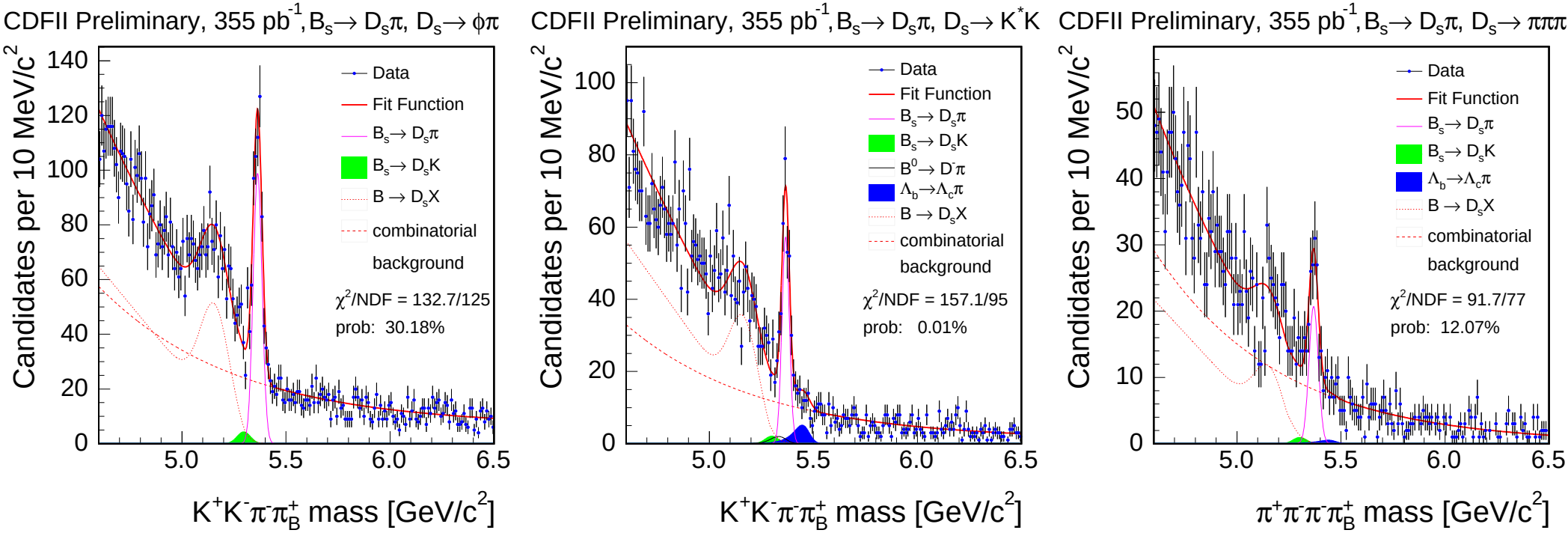




Hadronic Decay Signals $B^+ \to \bar{D}_s^0 \pi^+$



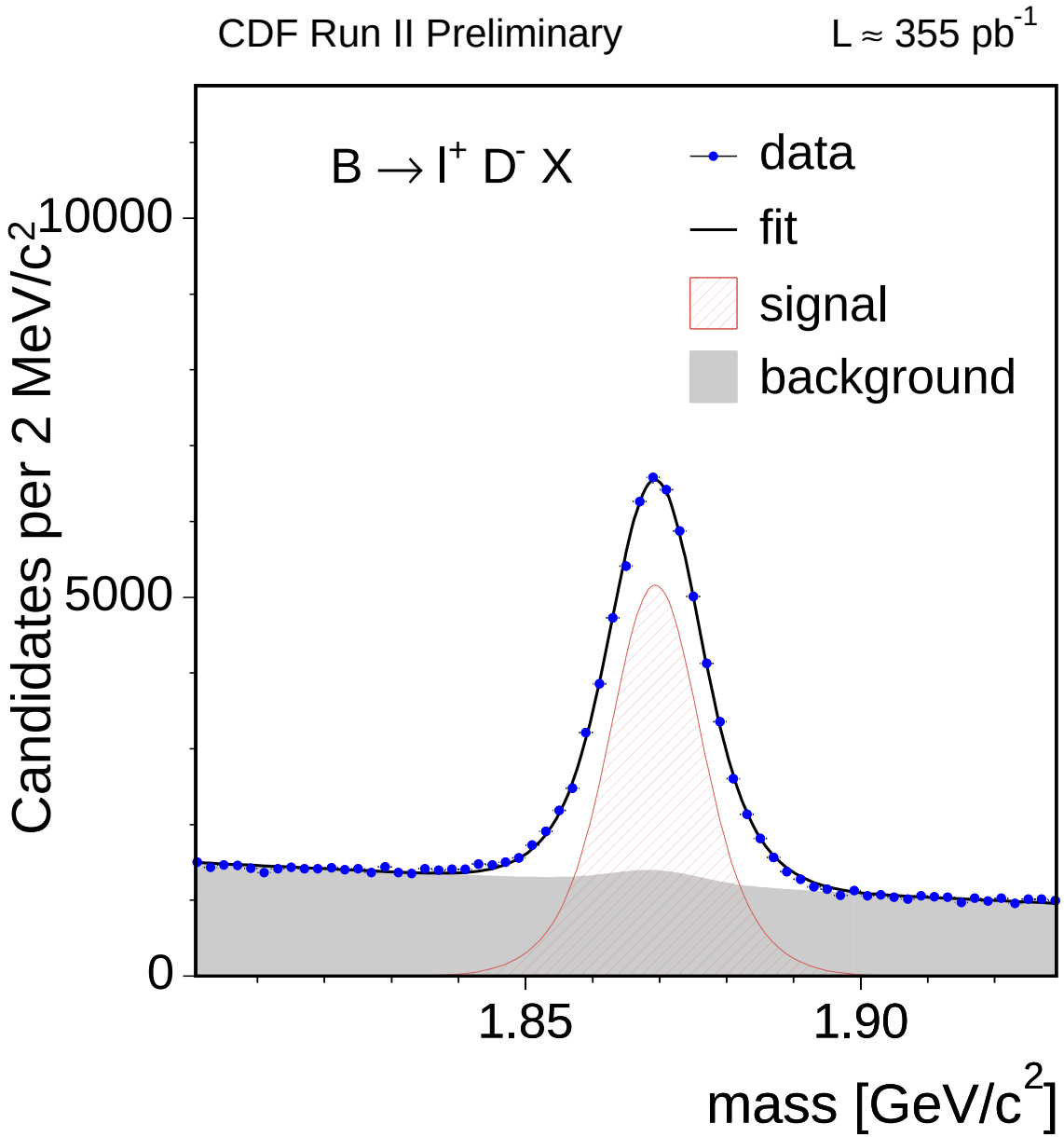
Hadronic Decay Signals $D_s^- \pi^+$



Decent samples of fully reconstructed B_s

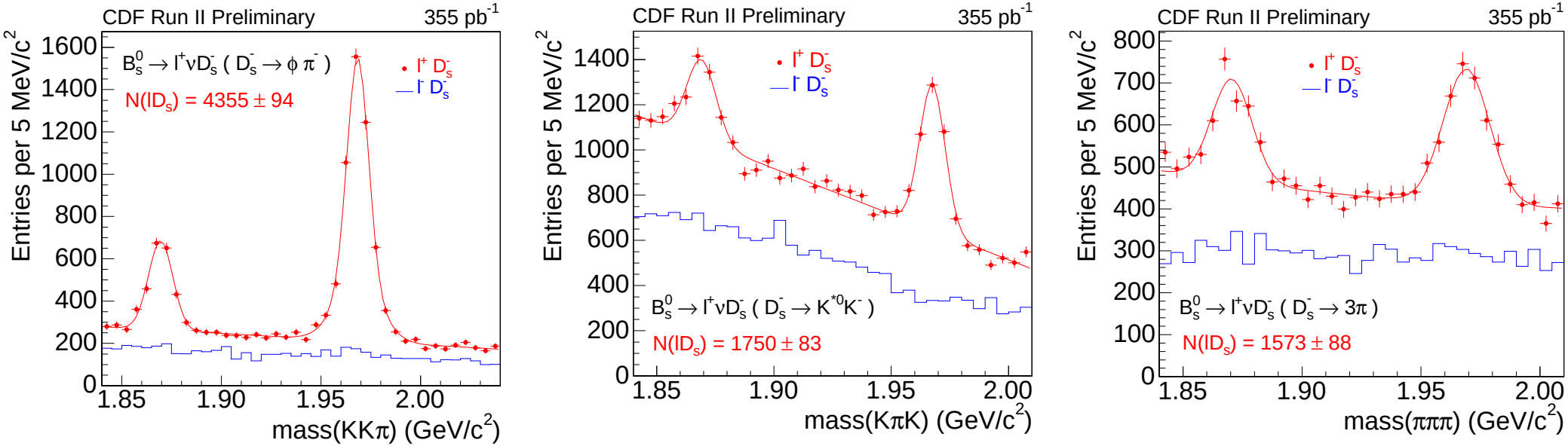
about 900 events

Semileptonic Decay Signals $B^+ \to \ell D^+ X$



Very large sample: about 56k events

Semileptonic Decay Signals $\ell D_s^- X$

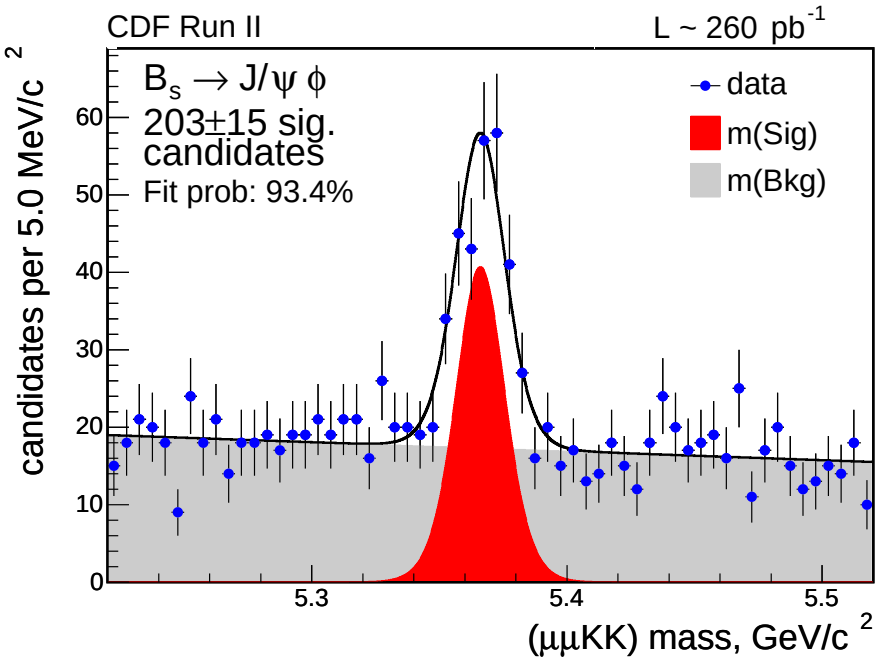


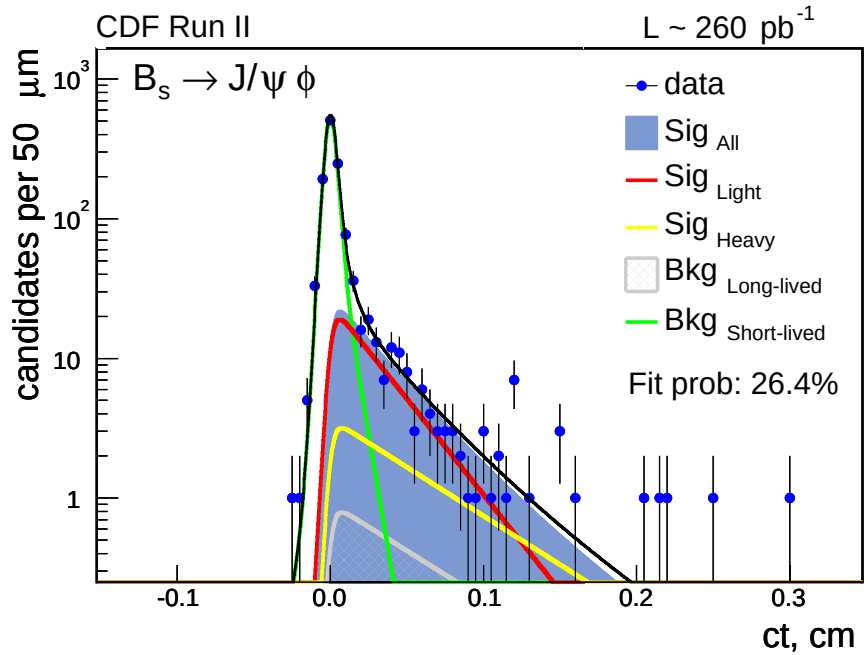
Very decent samples of fully reconstructed B_s

about 7800 events (8.7 times hadronic B_s sample)

Lifetimes

Classic Lifetime Measurement





Analysis sketch ($B_s \to J/\psi\phi$)

- \+ reconstruct p_T, mass, and L_{xy} $\to$ calculate proper time $ct = \frac{L_{xy} m}{p_T}$
- \+ no cuts that bias ct $\to$ signal probability: $p(t) = Ne^{-t/\tau} \times G(\sigma_{ct})$
- \+ background from mass sidebands
- \+ extract $c\tau$ from combined mass and ct fit

Lifetimes in Hadronic Channels

Bias in *ct*

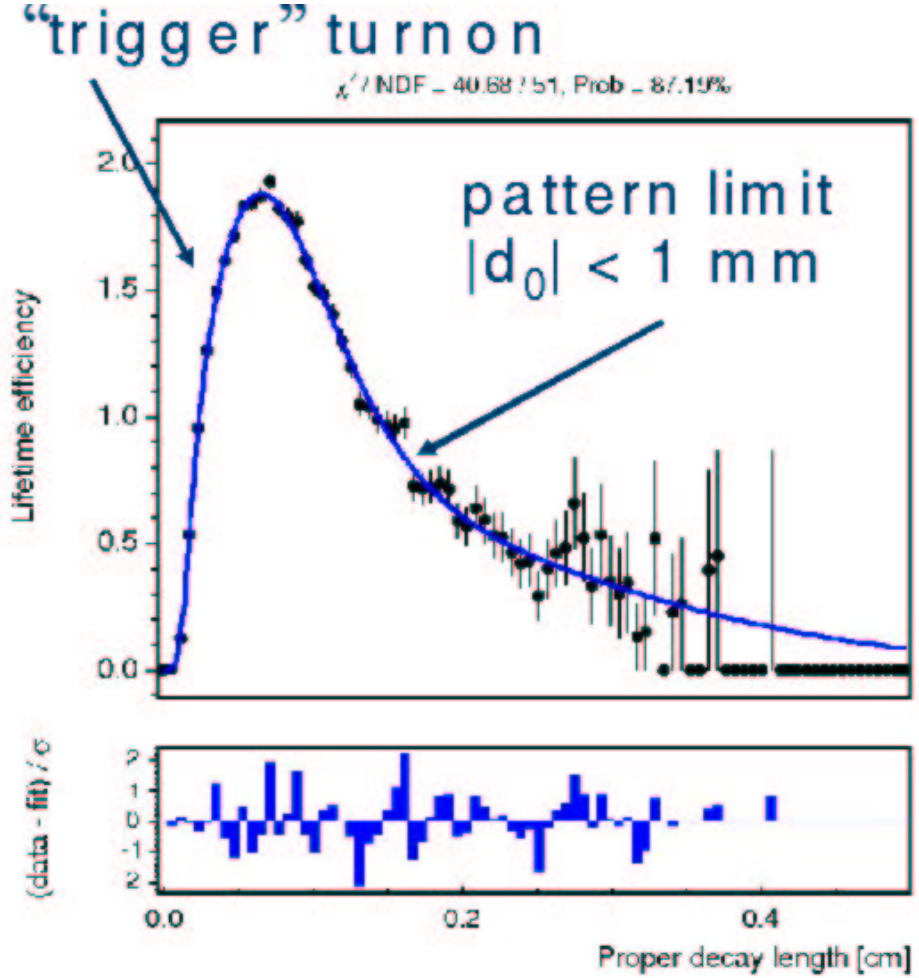
- + two SVT tracks
- + turnon: $d_0 > 120\ \mu$m
- + turnoff: $d_0 < 1$ mm and pattern limit
- + selection increases bias

Adjust probability density

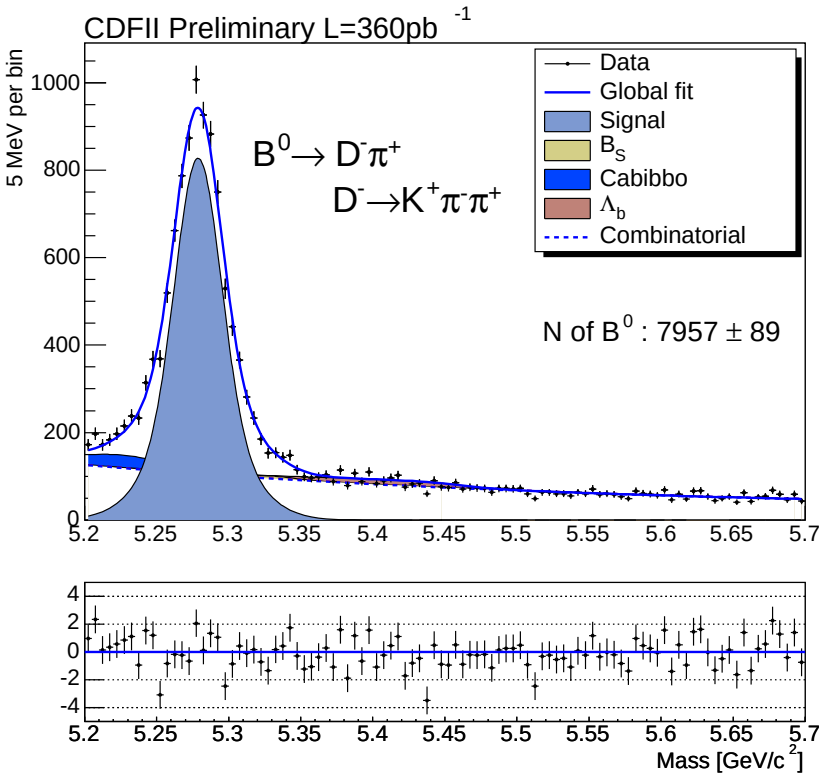
- + $p(t) = N(e^{-t/\tau} \times G(\sigma_{ct}))\ \ \varepsilon(t)$
- + background more complex, still from mass sideband

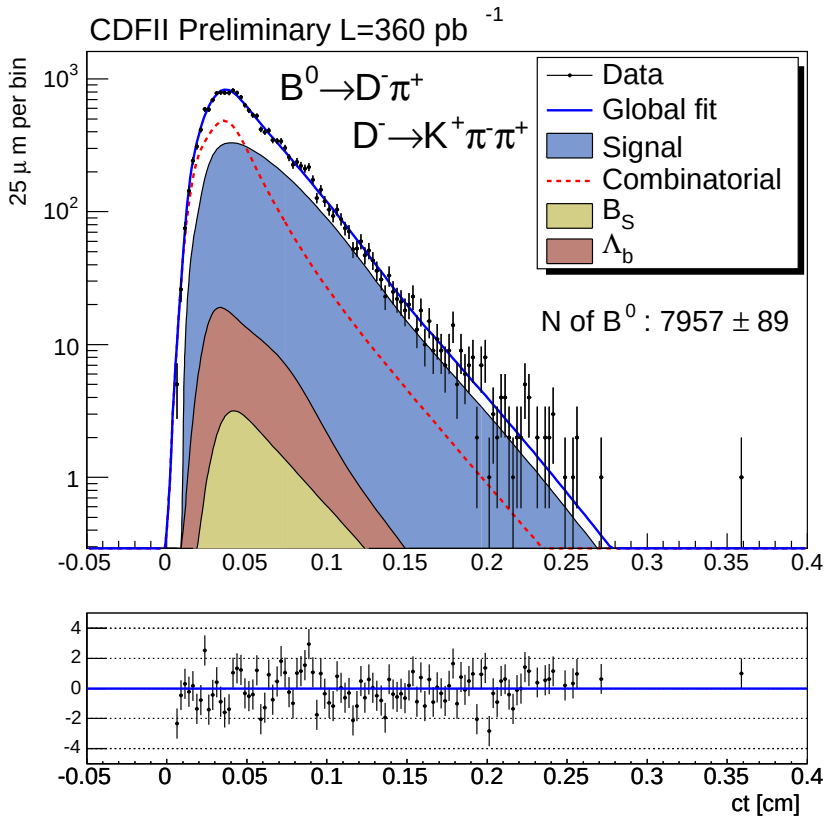
Do we care for mixing?

- + bias cancels!
- + very small effect on mixing



Hadronic Decay $D_s^-\pi^+$ – Lifetimes





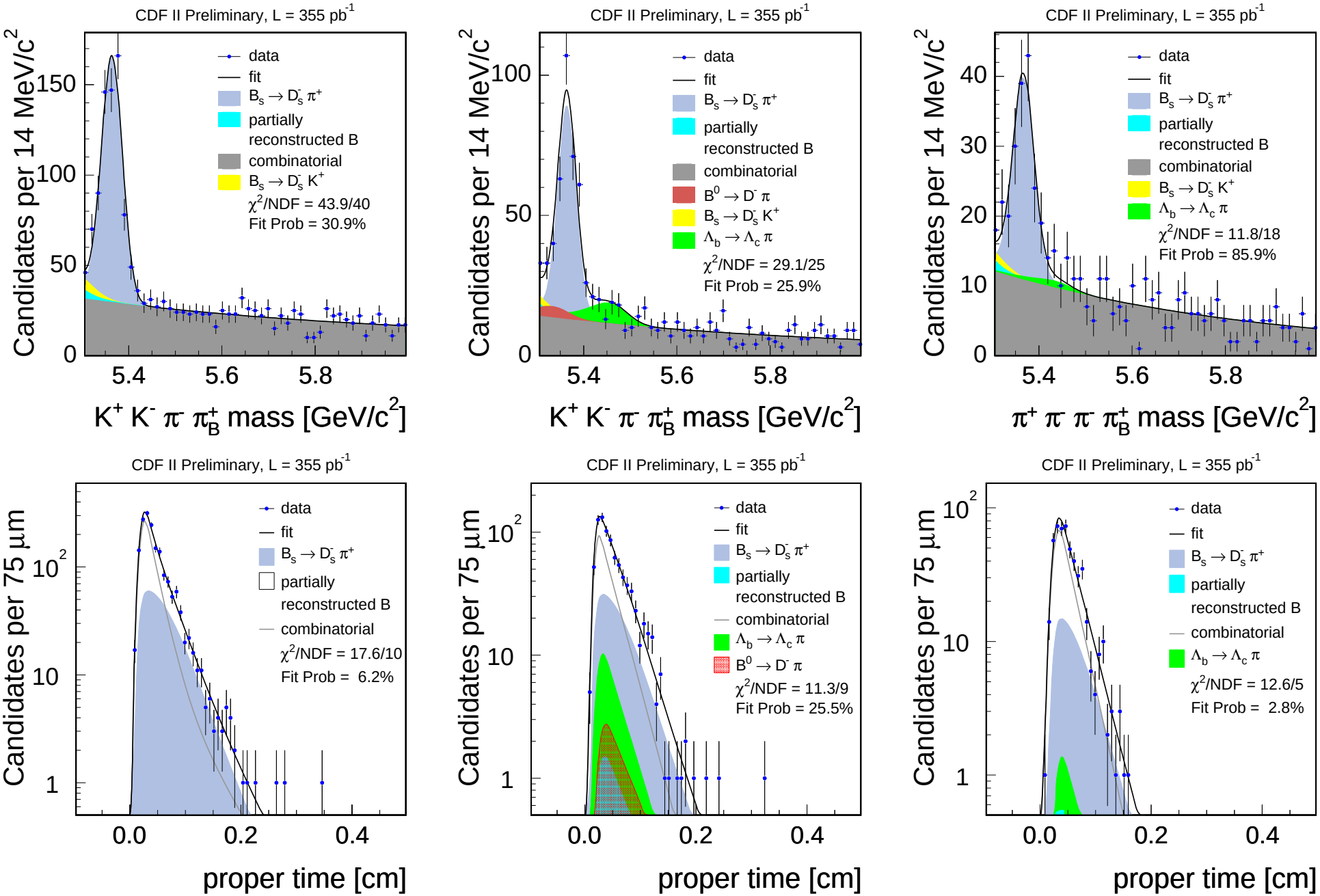
Measure lifetimes of B^+ and B^0 → then B_s

$$c\tau(B^+) = 498 \pm 8(stat) \pm 4(syst)\ \mu\text{m}$$

$$c\tau(B^0) = 453 \pm 7(stat) \pm 4(syst)\ \mu\text{m}$$

$$c\tau(B_s) = 479 \pm 29(stat) \pm 5(syst)\ \mu\text{m}$$

Hadronic Decay $D_s^- \pi^+$ – Lifetimes



Lifetimes in Semileptonic Channels

Bias in *ct* (see hadronic)

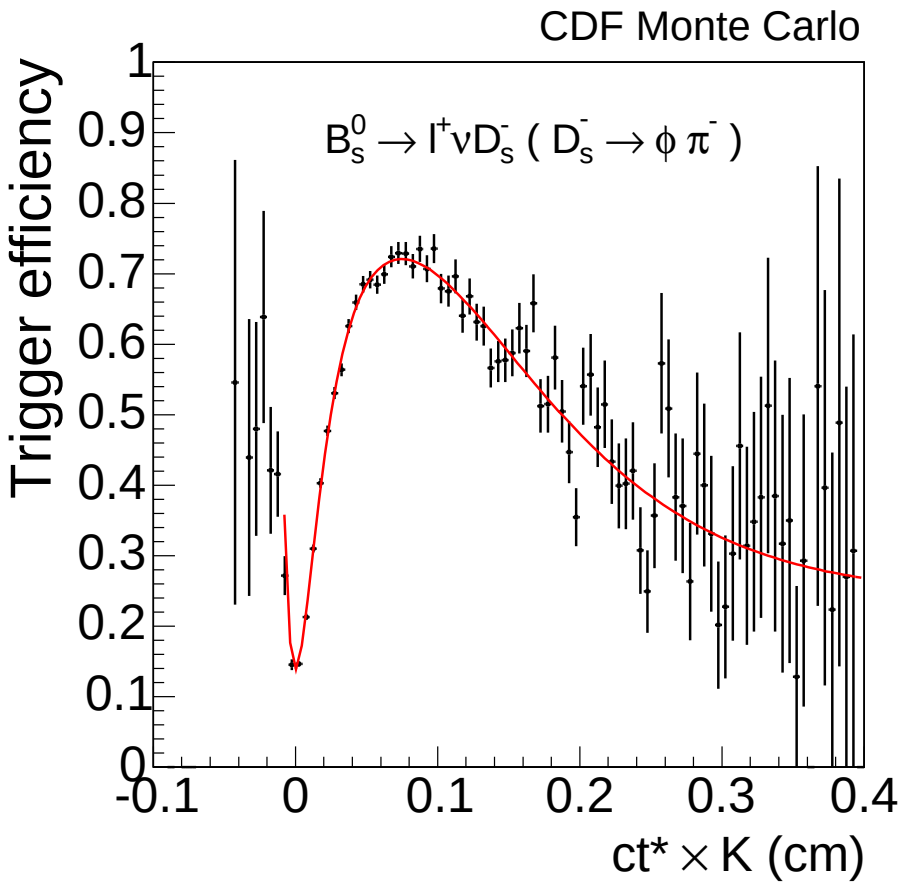
- + one SVT track
- + turnon: $d_0 > 120\ \mu$m
- + turnoff: $d_0 < 1$ mm and pattern limit
- + selection increases bias

Corrrect missing momentum

- + from Monte Carlo (K factor)
- + bin in ℓDX mass

Incomplete reconstruction

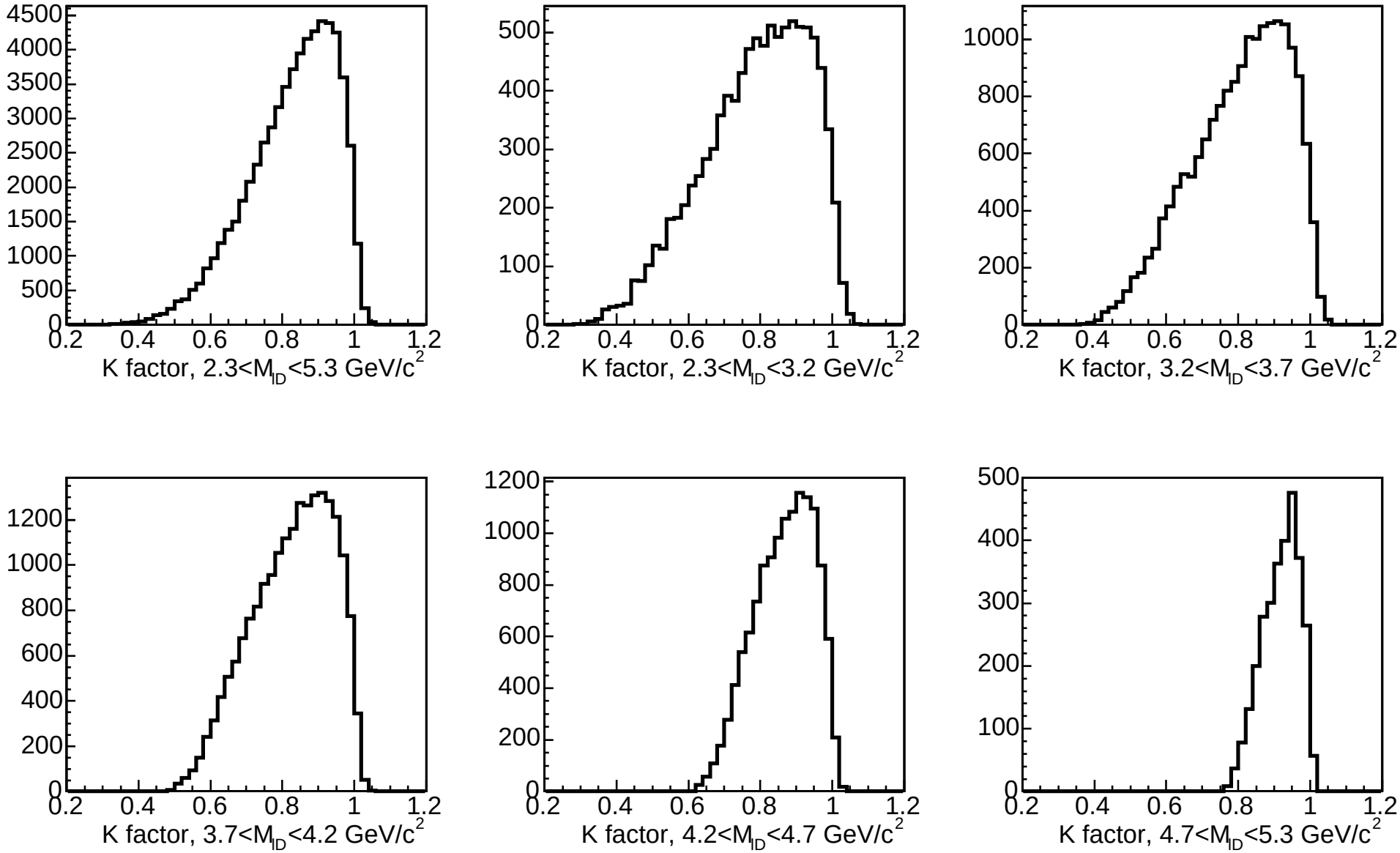
- + cross talk B^+, B^0
- + prompt *D* background



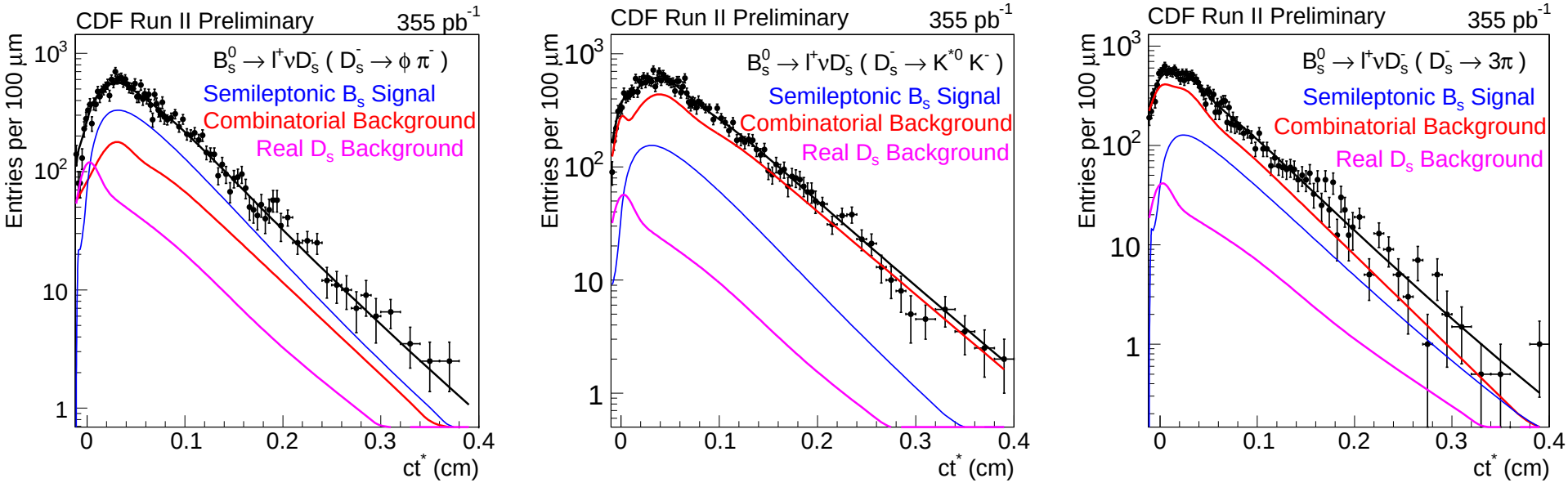
Lifetimes in Semileptonic Channels - K Factor

CDF Monte Carlo

$B_s^0 \rightarrow l^+ \nu D_s^-$ ($D_s^- \rightarrow \phi \pi^-$)



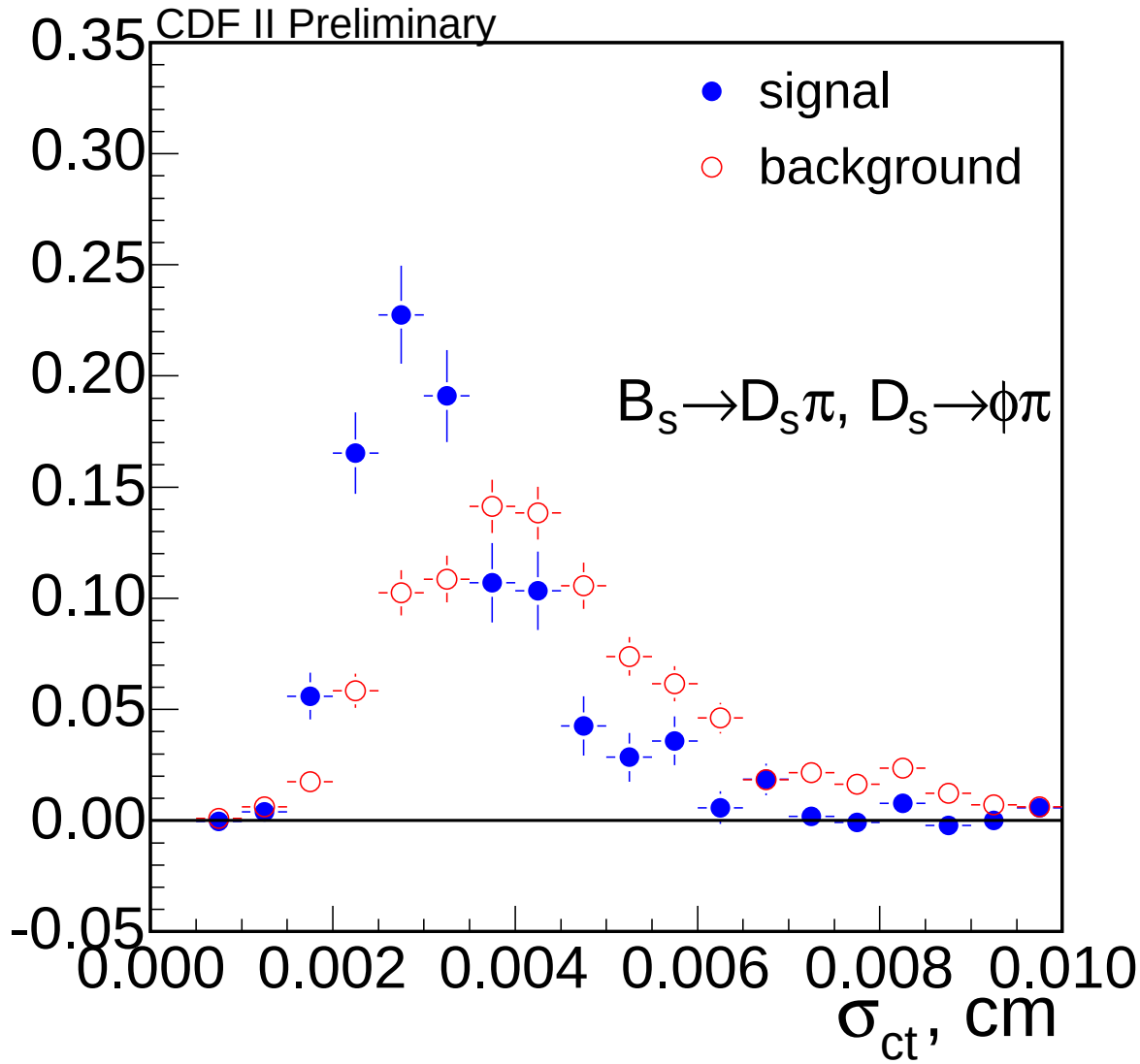
Semileptonic Decay $\ell^+ D_s^- X$ – Lifetimes



Measurement not yet complete only statistical uncertainty

- B^+, B^0 lifetimes within 20 μm of world average
- $c\tau(B_s) = 445 \pm 9.5(stat)\ \mu$m
- $c\tau(B_s) = 438 \pm 17(tot)\ \mu$m – world average

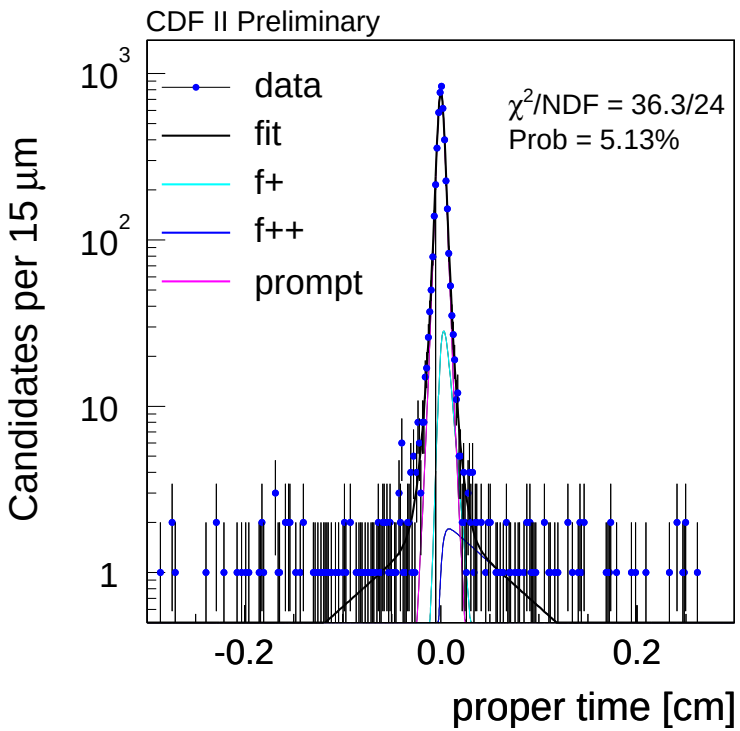
Proper Time Resolution

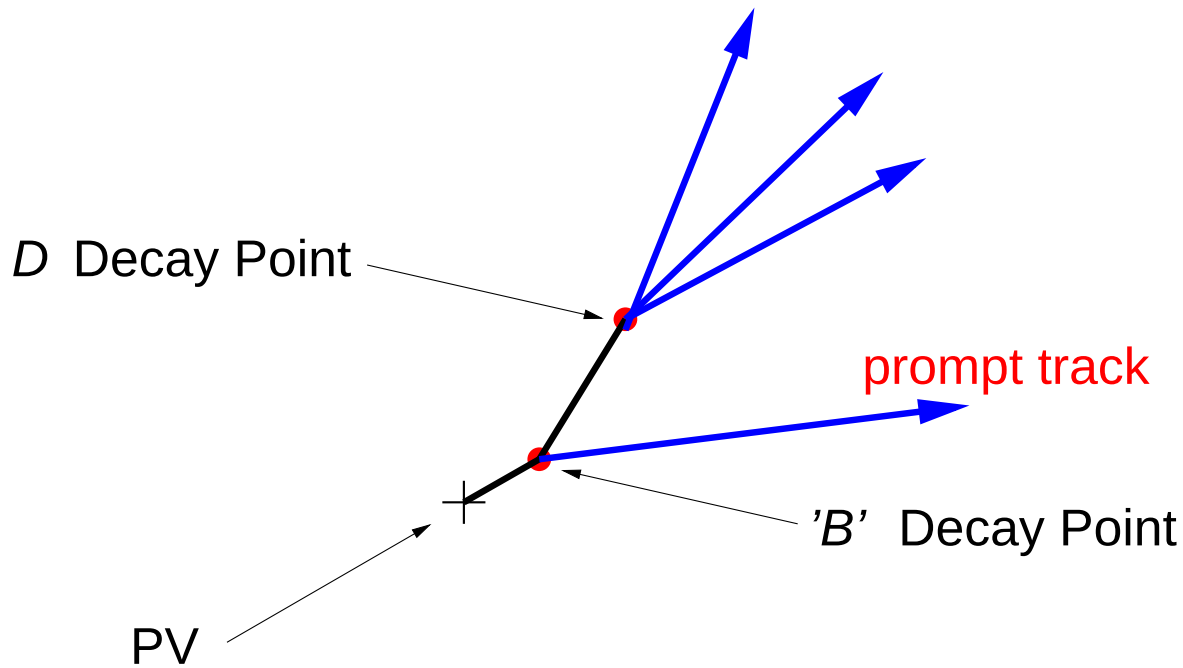


Vertex fitter measures

- L_{xy}, p_T and corresonding uncertainties
- but the errors are not reliable → scale factor already applied

Calibration of Proper Scale Uncertainty



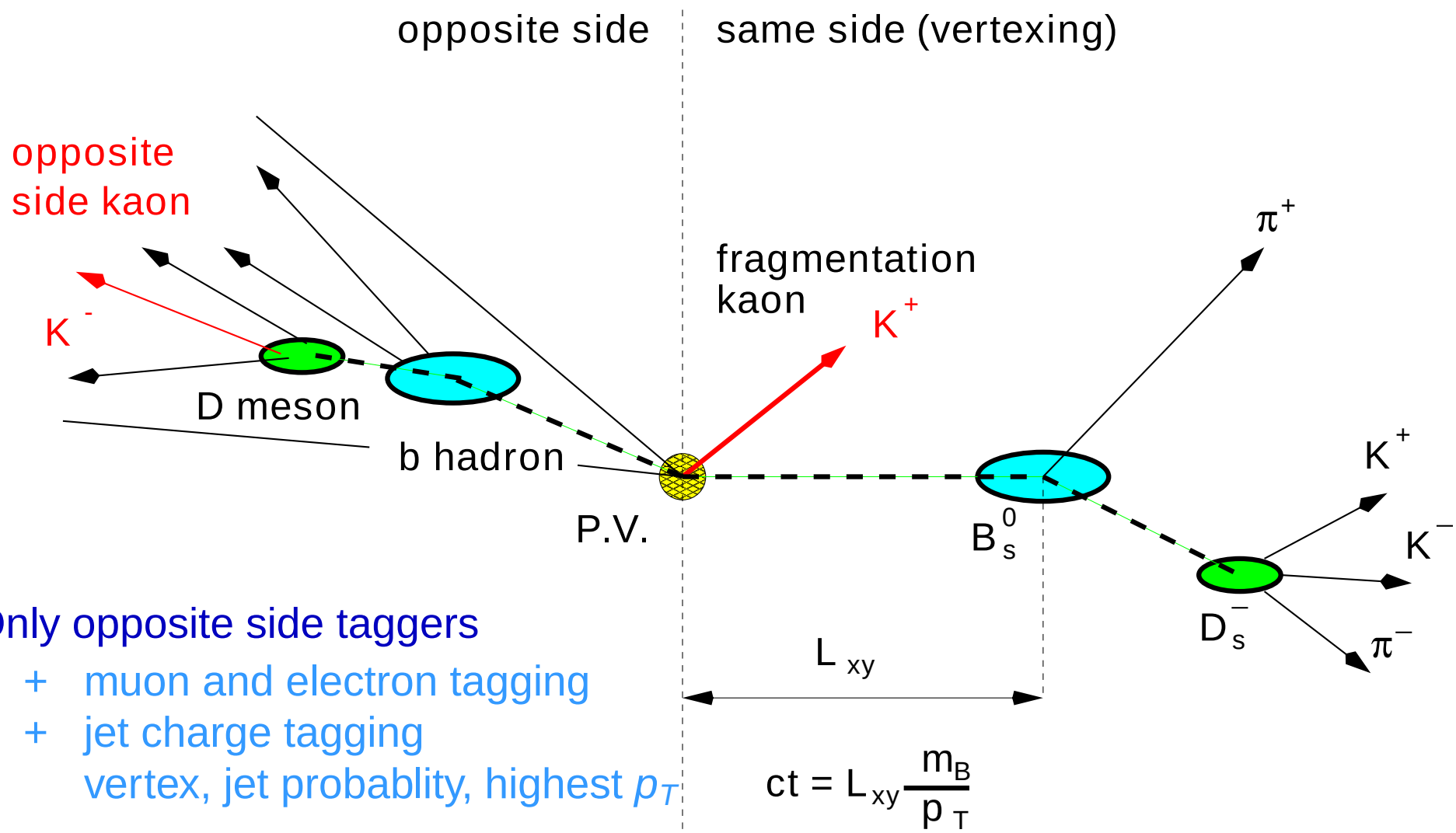


Create unbiased calibration sample

- \+ hadronic trigger dominated by prompt *D*
- \+ require *D* to trigger and add unbiased track (not triggered)
- \+ scale factor applied to uncertainty of each event
- \+ primary vertex position has to be zero → extract scale factor
- \+ long lived background accounted for in fit

Flavor Taggers

Tagging B Production Flavor



Only opposite side taggers

- \+ muon and electron tagging
- \+ jet charge tagging
  vertex, jet probablity, highest p_T

Measure asymmetry in dependence of time

$$A_0^{meas}(t) \equiv \frac{N(t)_{RS} - N(t)_{WS}}{N(t)_{RS} + N(t)_{WS}} = D\cos(\Delta m_s t) \quad \text{with} \quad D = 2P - 1 = \text{dilution}$$

Measuring Δm_d and Tagger Performance

Fitting separately

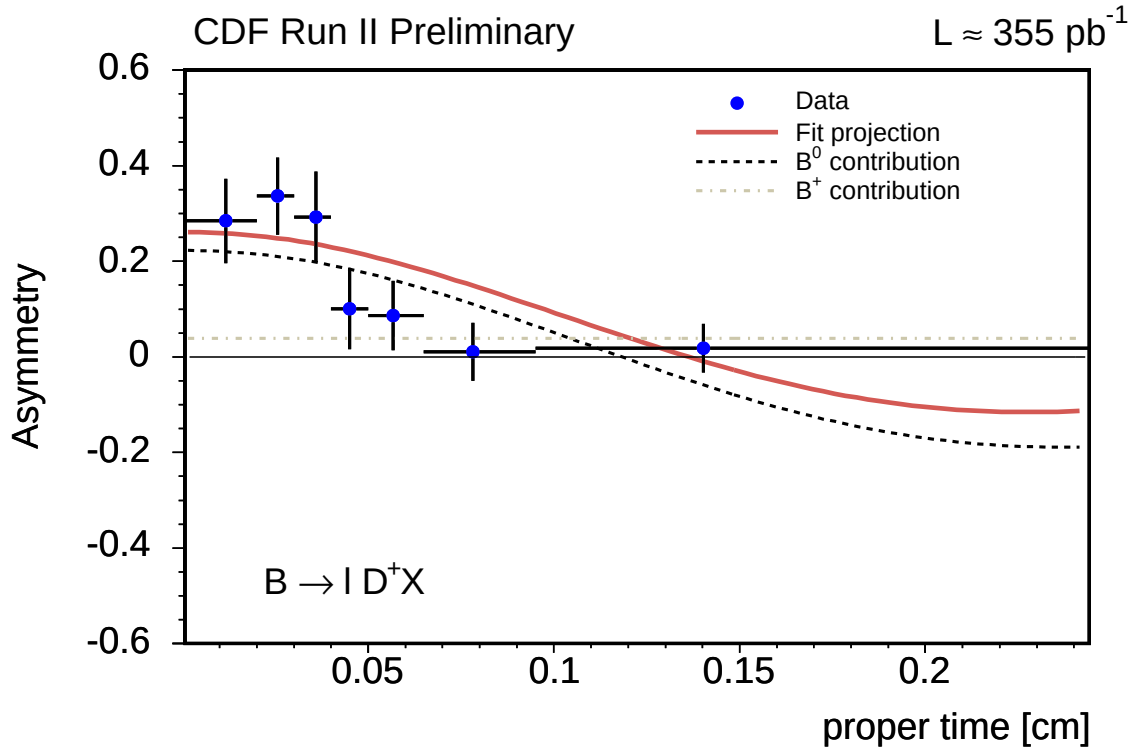
+ hadronic decays
+ semileptonic decays

Measure

+ Δm_d
+ tagger performance

Sample picture: $\ell D^+ X$

SMT



Mixing results

+ $\Delta m_d^{had} = 0.503 \pm 0.063 \pm 0.015\ \mathrm{ps}^{-1}$
+ $\Delta m_d^{semi} = 0.497 \pm 0.028 \pm 0.015\ \mathrm{ps}^{-1}$
+ $\Delta m_d^{HFAG} = 0.502 \pm 0.007\ \mathrm{ps}^{-1}$

Tagger Performance

Measure of tagger performance: εD^2

- ε if the efficiency
- D is the dilution: $D = 2P - 1$

Tagger Combination

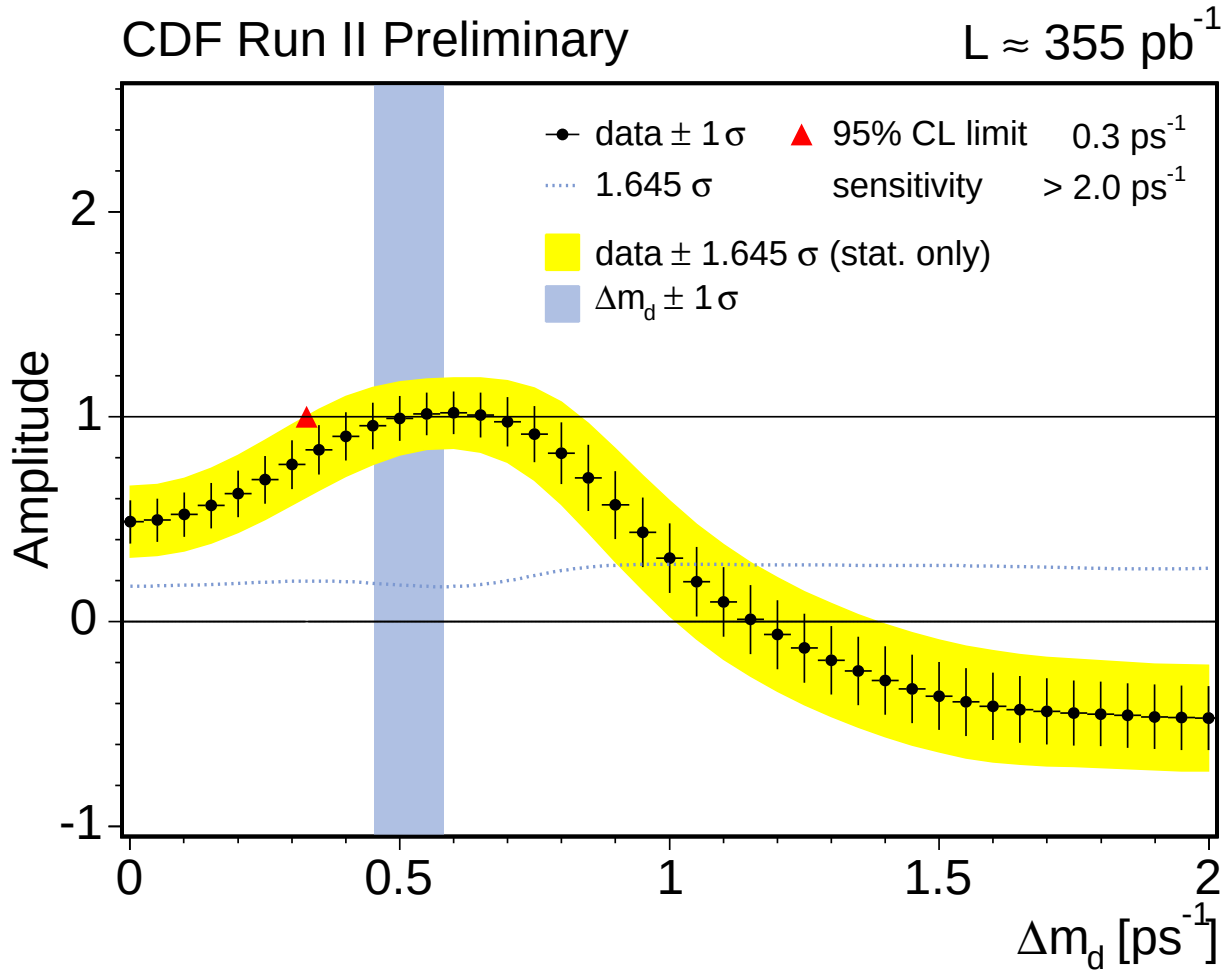
- taggers are ordered by performance
- exclusive taging decision, use best available tagger

Corresponding performances

[%]	εD^2 hadronic	εD^2 semileptonic
Muon	$0.46 \pm 0.11 \pm 0.03$	$0.577 \pm 0.047 \pm 0.034$
Electron	$0.18 \pm 0.06 \pm 0.02$	$0.293 \pm 0.033 \pm 0.017$
JQ/Vertex	$0.14 \pm 0.07 \pm 0.01$	$0.263 \pm 0.035 \pm 0.021$
JQ/Prob.	$0.11 \pm 0.06 \pm 0.01$	$0.150 \pm 0.026 \pm 0.015$
JQ/High p_T	$0.24 \pm 0.09 \pm 0.01$	$0.157 \pm 0.027 \pm 0.015$
Total	1.12 ± 0.18	1.429 ± 0.093

Amplitude Scan

Amplitude Scan Method - Using B^0



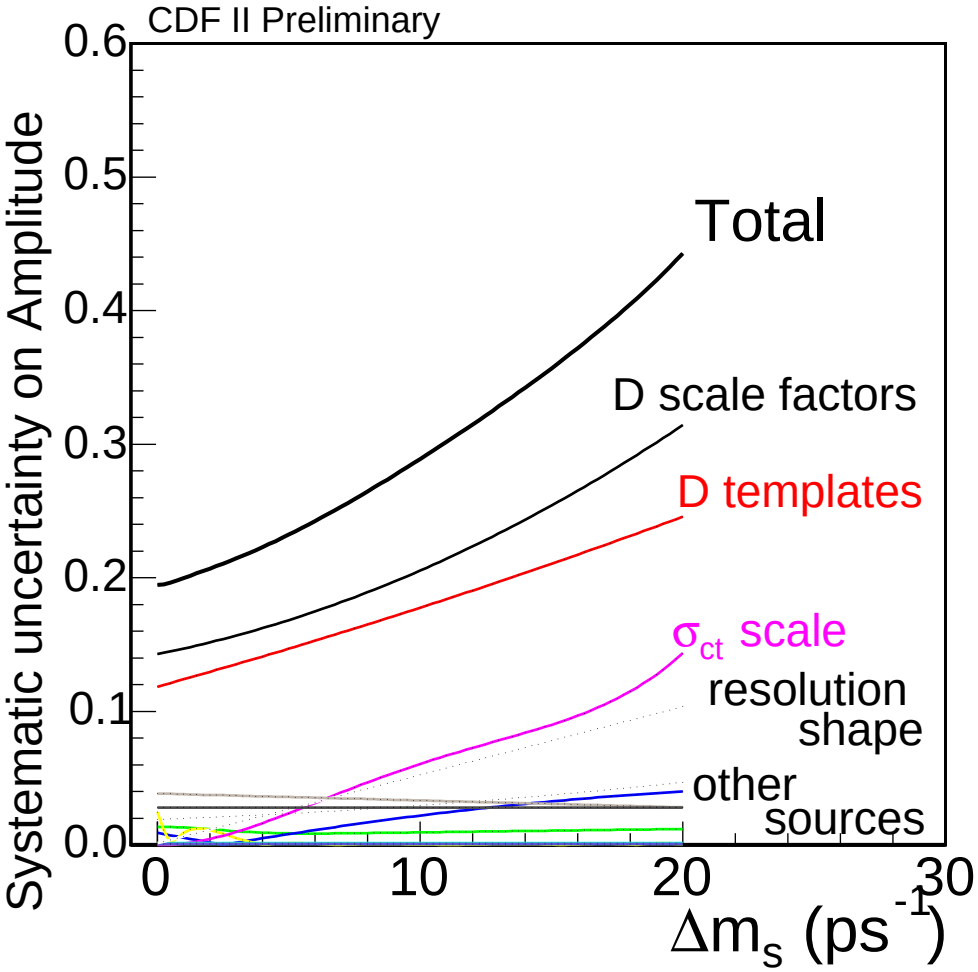
Perform unbinned likelihood fit

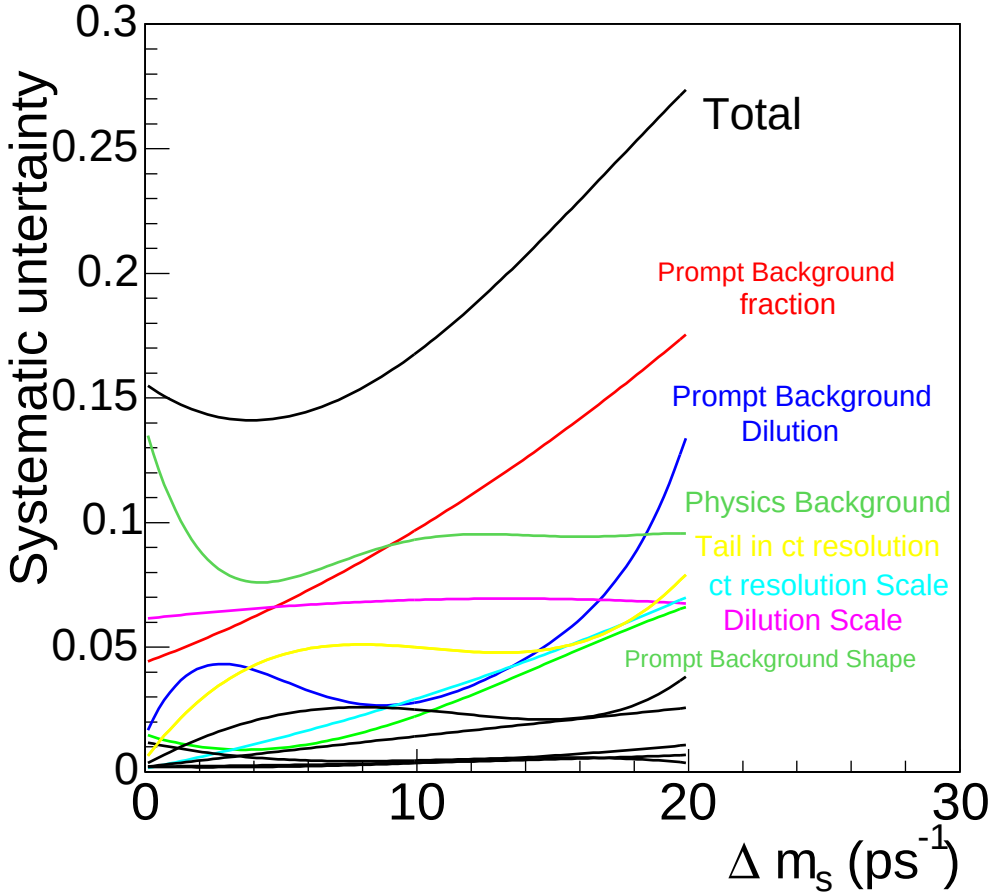
- $p \sim (1 \pm A S_D D_i \cos(\Delta m_s))$
- scan fixed values of Δm_s
- record A and $\sigma(A)$

Signal ≡ unit amplitude

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

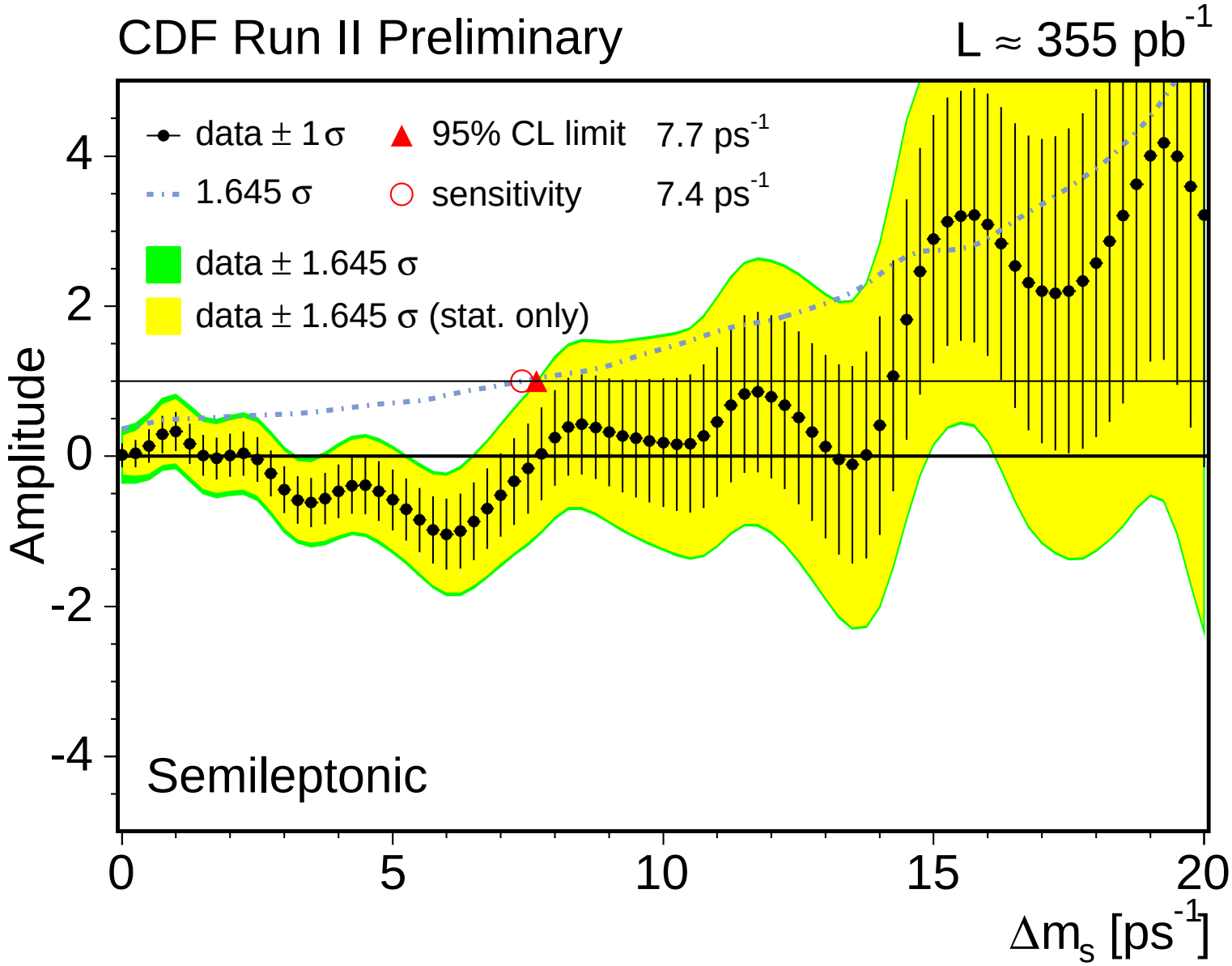
Systematic Uncertainties





+ absolute errors on amplitude are shown
+ systematic very small compared to statistical uncertainty
+ dominant systematics limited by sample size → will improve

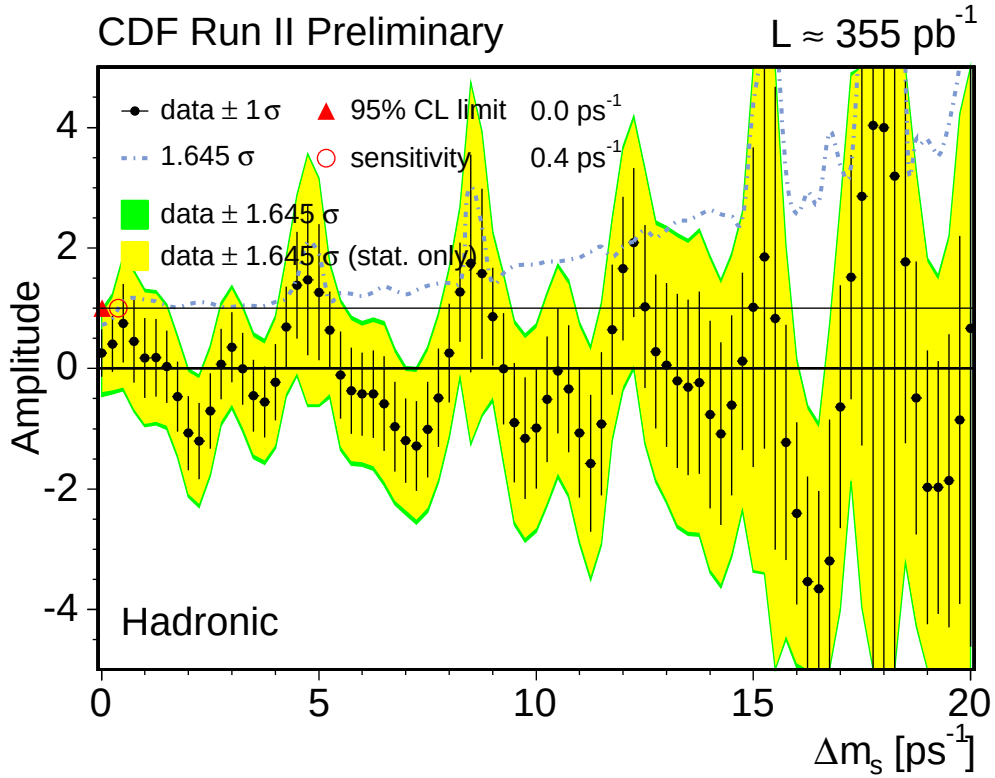
Semileptonic Result

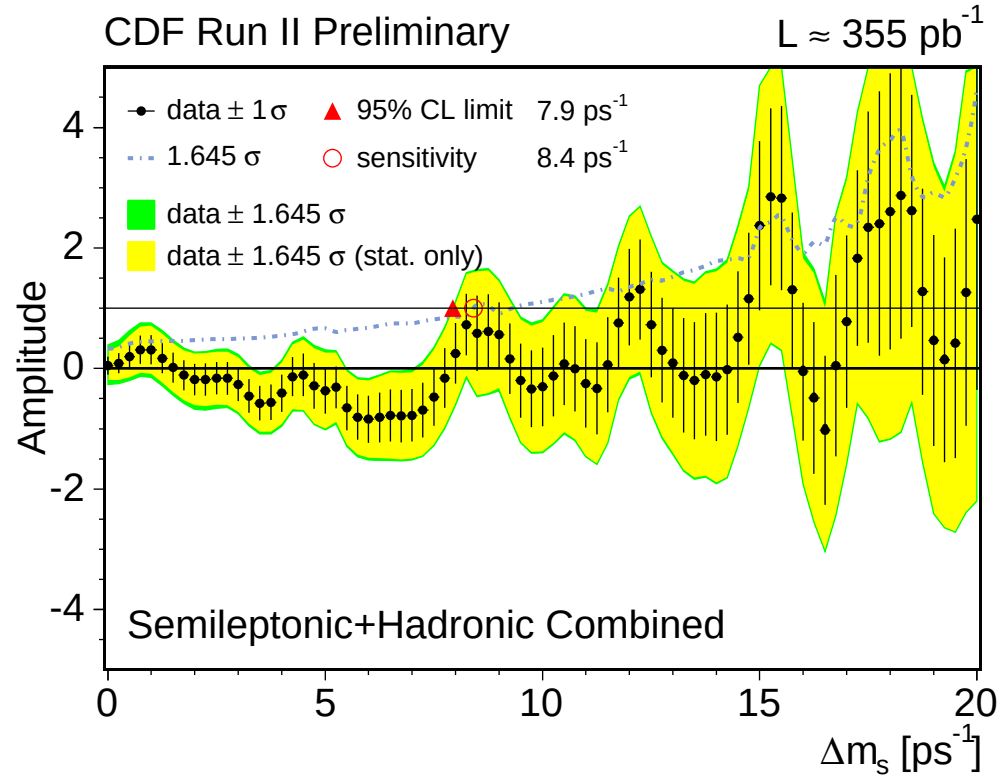


sensitivity: 7.4 ps^{-1}

lower limit: 7.7 ps^{-1} at 95% CL

Hadronic and Combined Result

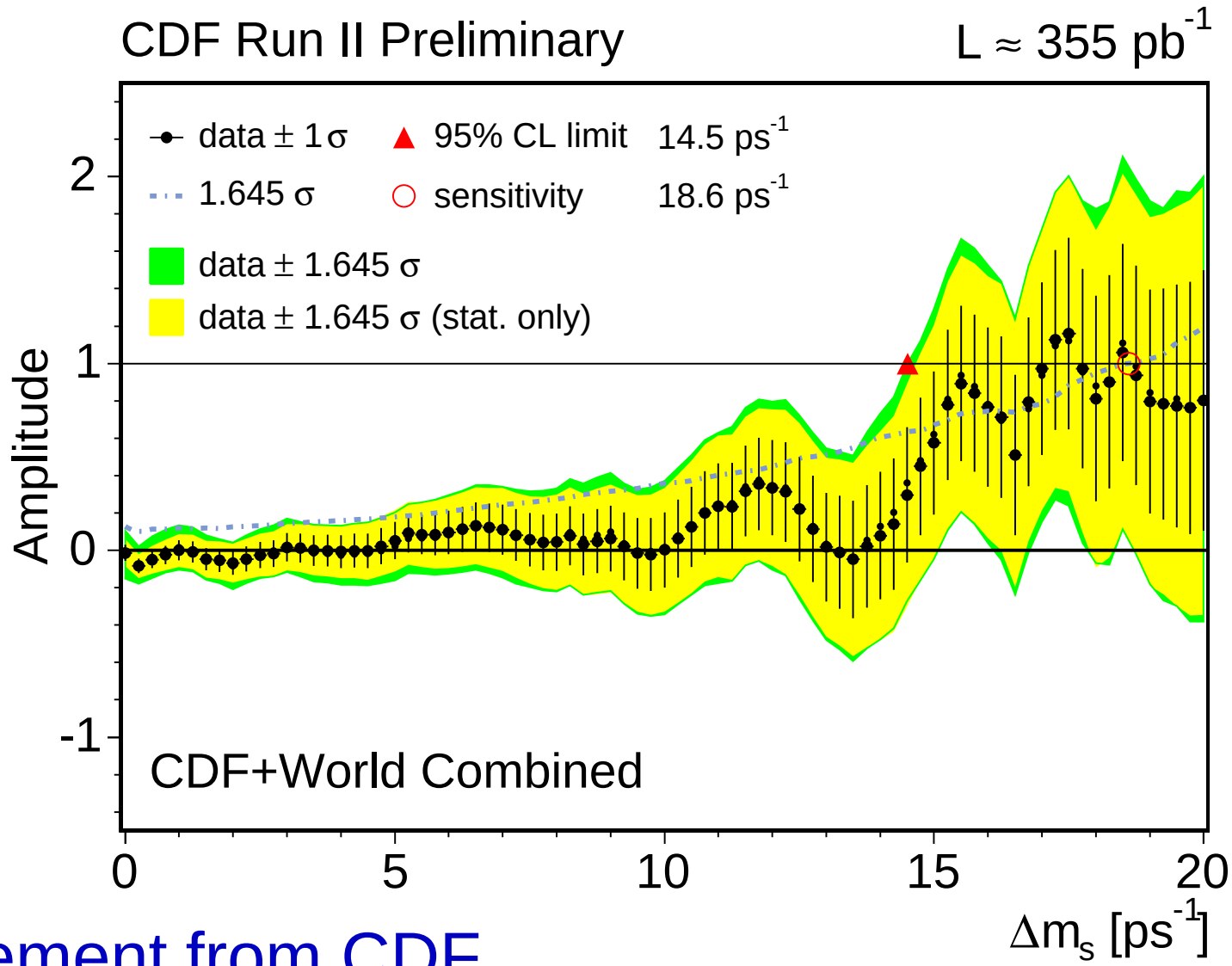




Comments

- + hadronic sample alone has no sensitive (statistics)
- + but helps semileptonic sample in high Δm_s region
- + sensitivity moves from 7.4 ps^{-1} to 8.4 ps^{-1}
- + new limit $\Delta m_s < 7.9$ ps^{-1} at 95% confidence level

CDF II and World Combined Average



Improvement from CDF

- \+ limit stays the same
- \+ sensitivity moves from 18.1 ps^{-1} to 18.6 ps^{-1}

Improvements

Statistical power of the sample

- + add same side koan tagger
- + add more B_s decay channels (ex. $B_s \to D_s^- \pi^+ \pi^+ \pi^-$)
- + gather more data

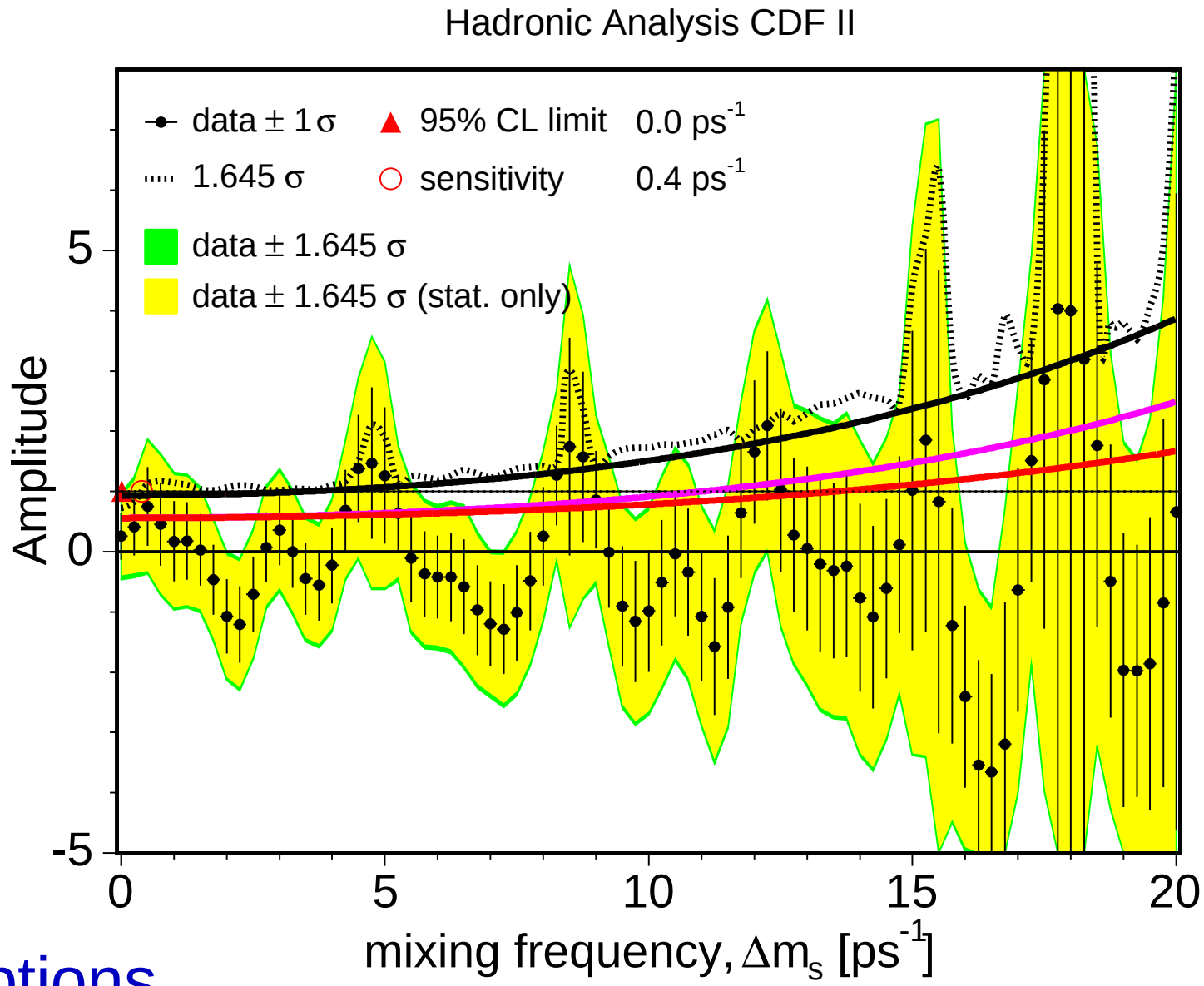
Improve proper time resolution

- + average primary vertex $\to$ primary vertex per candidate
- + improve reconstruction of innermost layer (Layer 00)
- + treat large silicon clusters more carefully

For illustration of improvements

- + increase statistical power by factor of 4
- + improve ct resolution by 20%

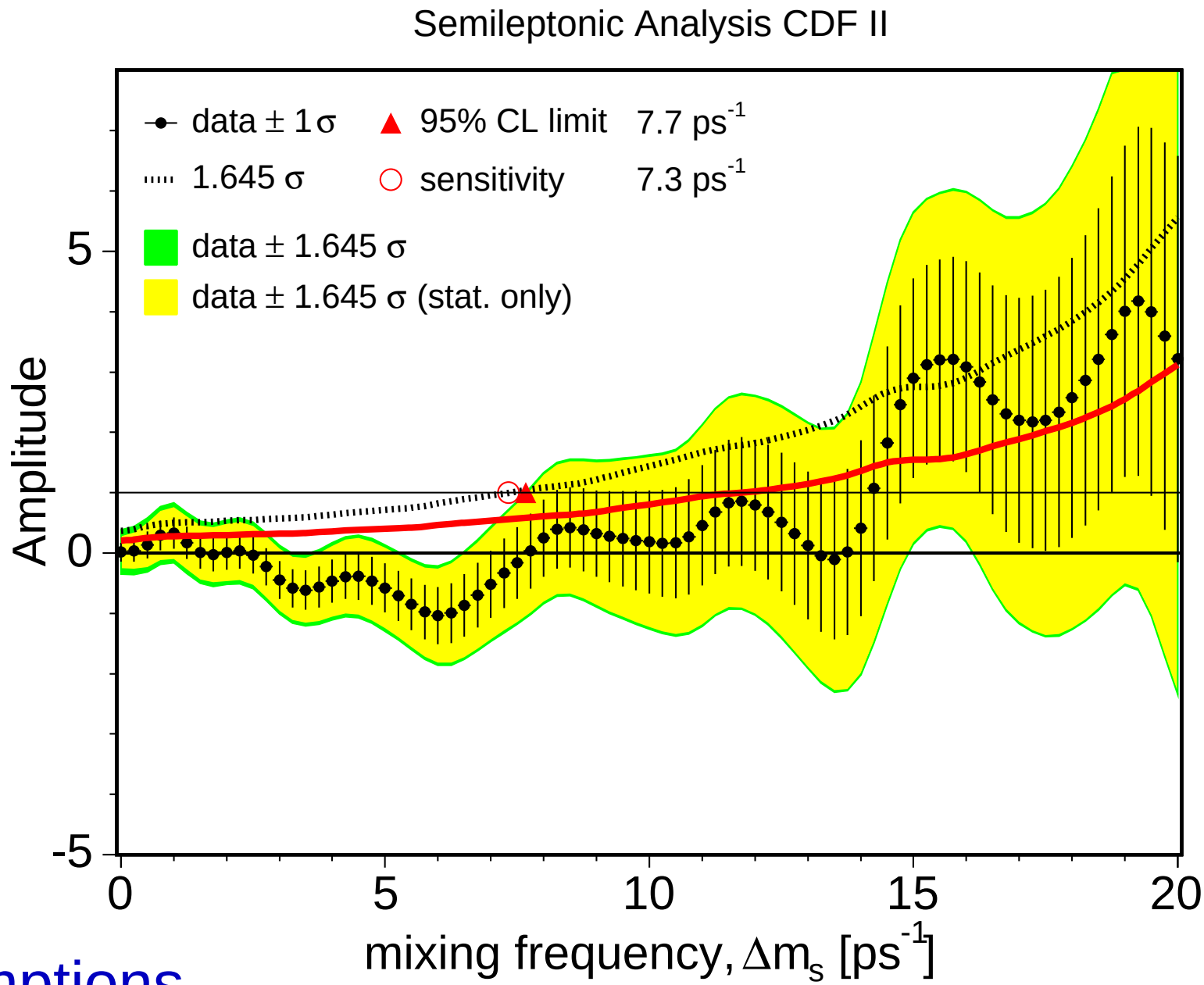
Improvements: Hadronic



Assumptions

+ increase statistical power by factor of 4 (new data, taggers)
+ improve *ct* resolution by 20% (primary vertex per candidate)

Improvements: Semileptonics



Assumptions

+ increase statistical power by factor of 4 (new data, taggers)

Summary

First B_s mixing analysis is completed

- + sensitivity: $\Delta m_s < 8.4\ \mathrm{ps}^{-1}$ at 95% confidence level
- + exclude: $\Delta m_s < 7.9\ \mathrm{ps}^{-1}$ at 95% confidence level
- + used semileptonic and hadronic samples
- + displaced track trigger (SVT) was crucial
- + byproduct: $c\tau(B_s) = 479 \pm 29(stat) \pm 5(syst)\ \mu\mathrm{m}$

Implemented *ct* bias correction

- + displaced track trigger bias modeled from MonteCarlo
- + very small effect on mixing

Prospects

- + statistical power of tagger (same side kaon tagger)
- + proper time resolution: primary vertex per candidate