First B_s Mixing Results from CDF II

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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

Unitarity Triangle - Who Measures What?

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

Squeezing along side *b*

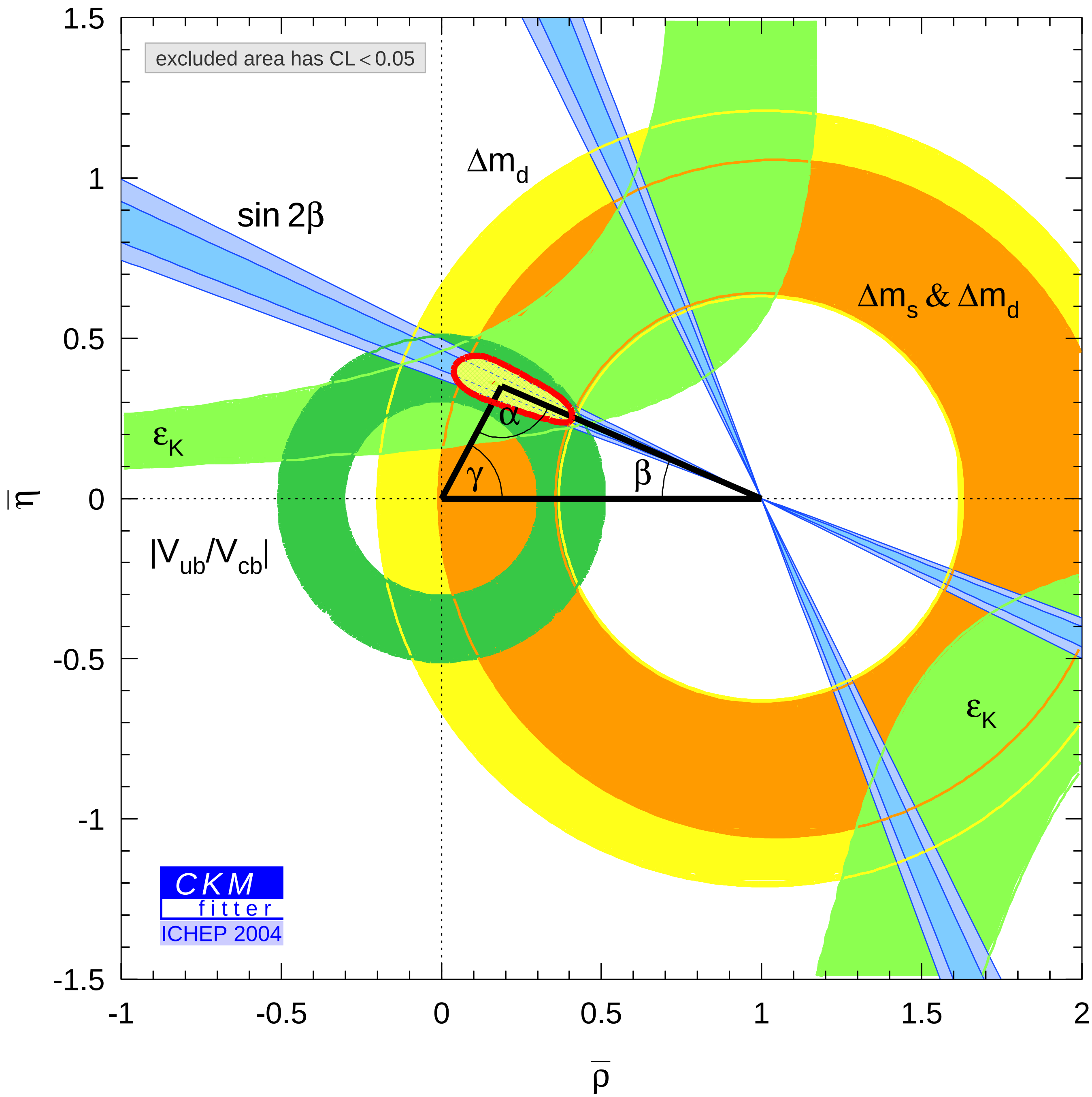
- + $\sin 2\beta$
- + V_{ub}/V_{cb}

Squeezing along side *c*

- + Δm_d
- + Δm_s

CKM fit result:

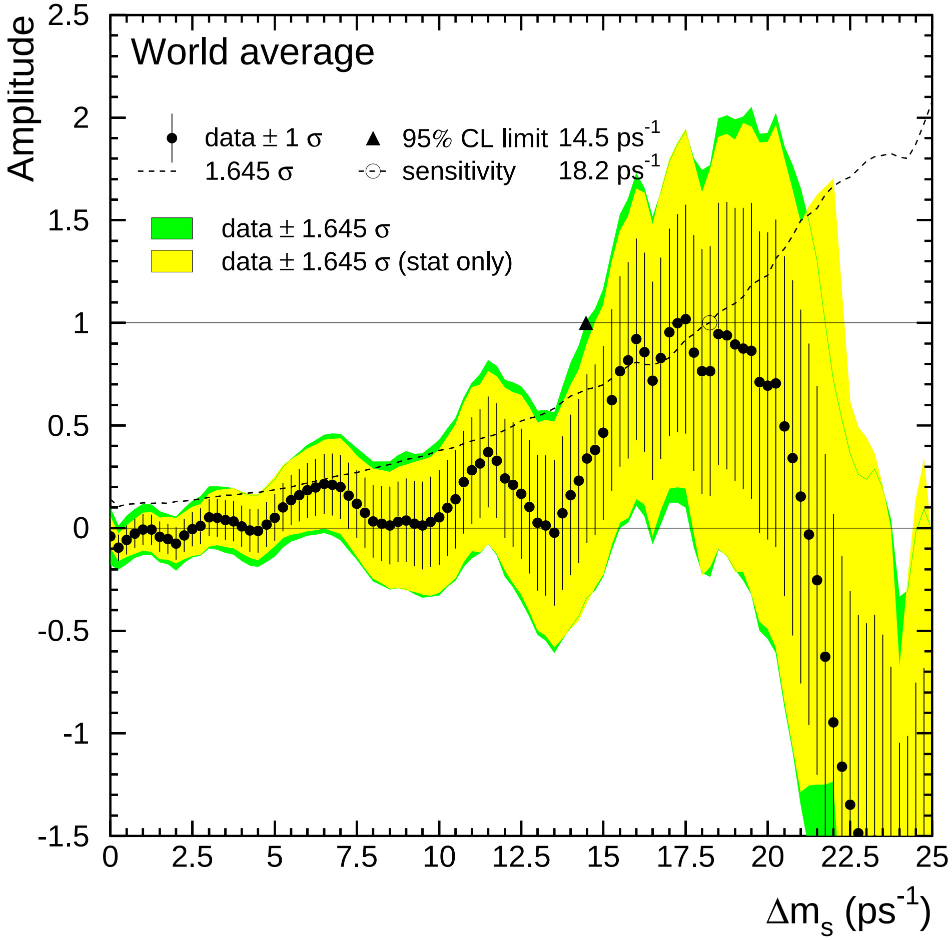
$$\Delta m_s = 17.8\,^{+6.7}_{-1.6}\mathrm{ps}^{-1}$$

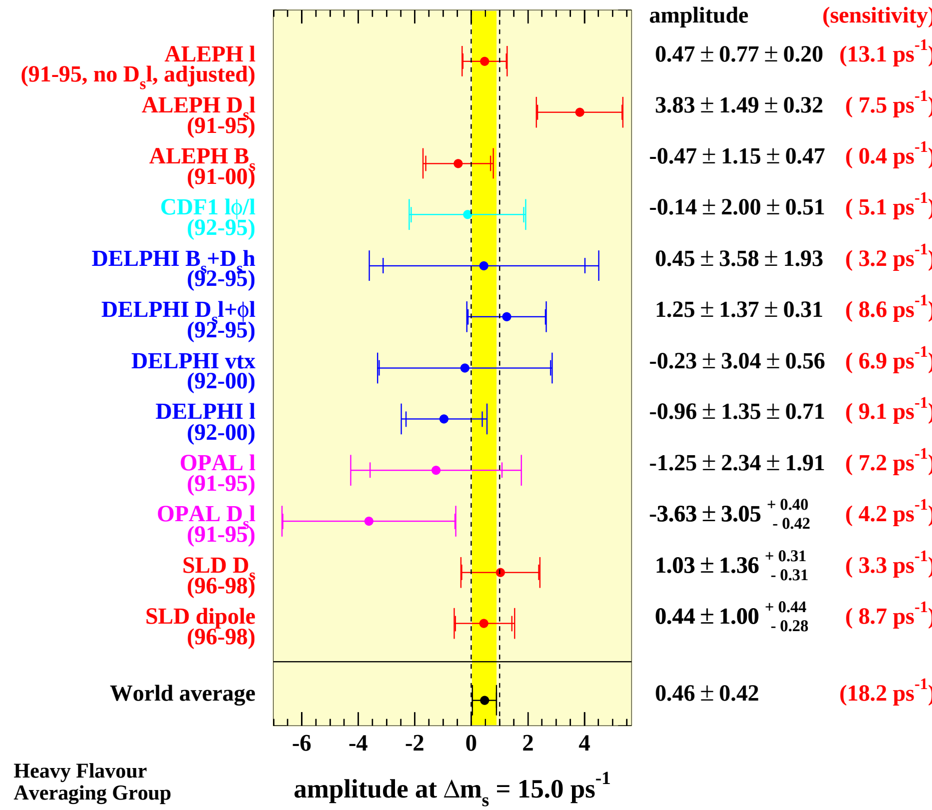


Present Experimental Results

Summary at 95% CL

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

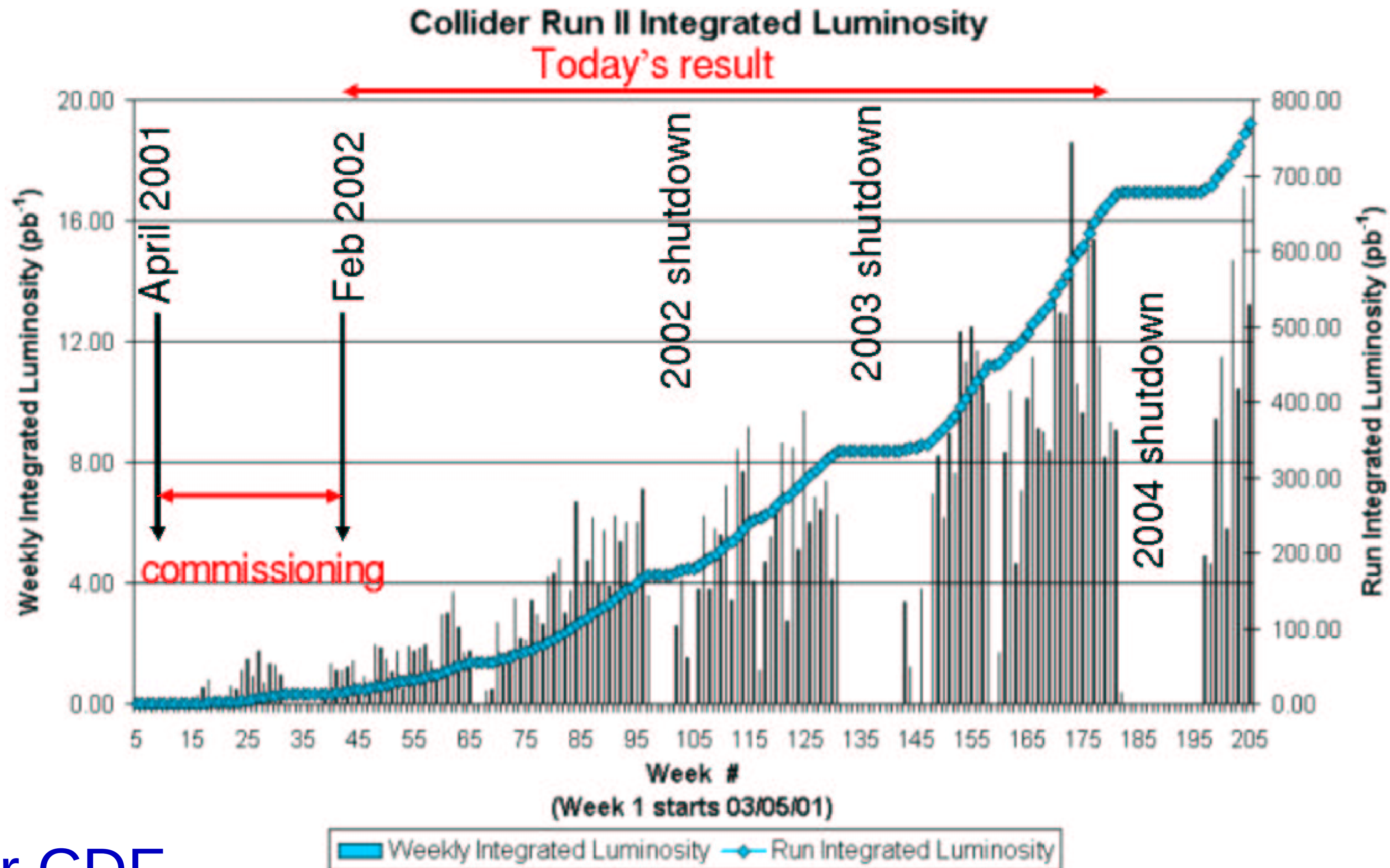




B_s mixing frequency more than 30 times faster than for B^0

→ experimental challenge

Tevatron Performance: Data Delivered



For CDF

+ delivered luminosity (2002-2005): 1 fb^{-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, $|Y| < 1$)

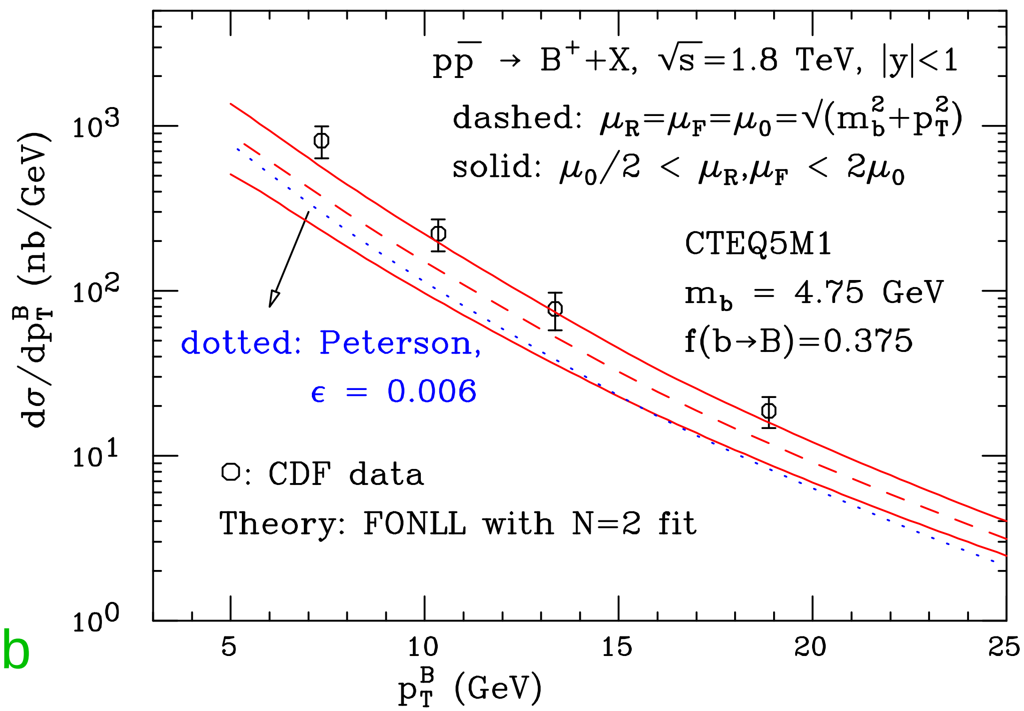
- single inclusive (B^+): $3.6 \pm 0.6\ \mu$b
- Peterson fragmentation:
  $\varepsilon_b = 0.002$
- $\sigma_{data}/\sigma_{theory} = 1.7$

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

- single inclusive (D^+): $4.3 \pm 0.7\ \mu$b

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

- single inclusive (D^0): $9.3 \pm 1.1\ \mu$b

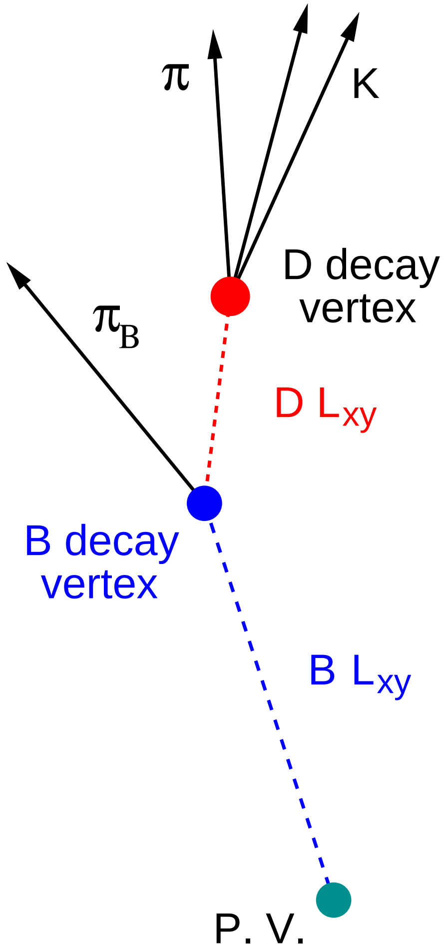


Difficulties for mixing

- 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

Run II Upgrades: Hadronic Trigger

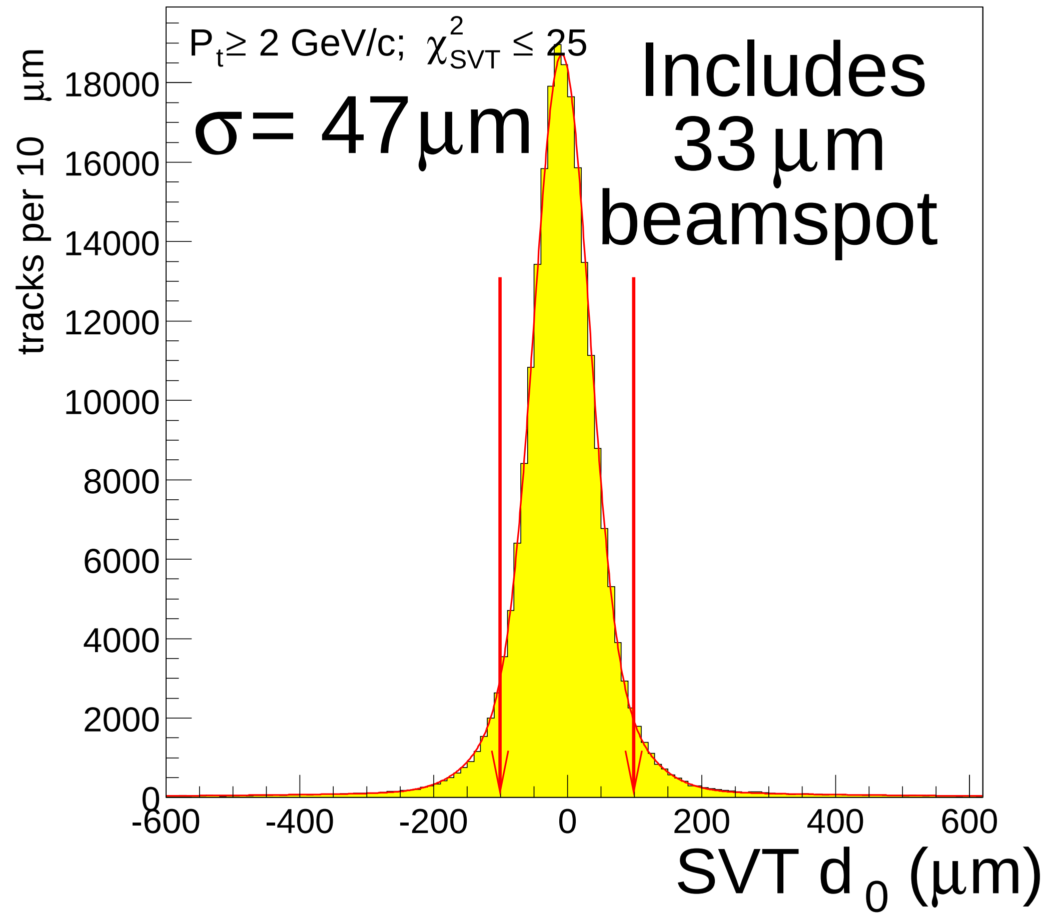
Run I: only e, μ trigger



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 $\Delta\Gamma \neq 0$

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

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

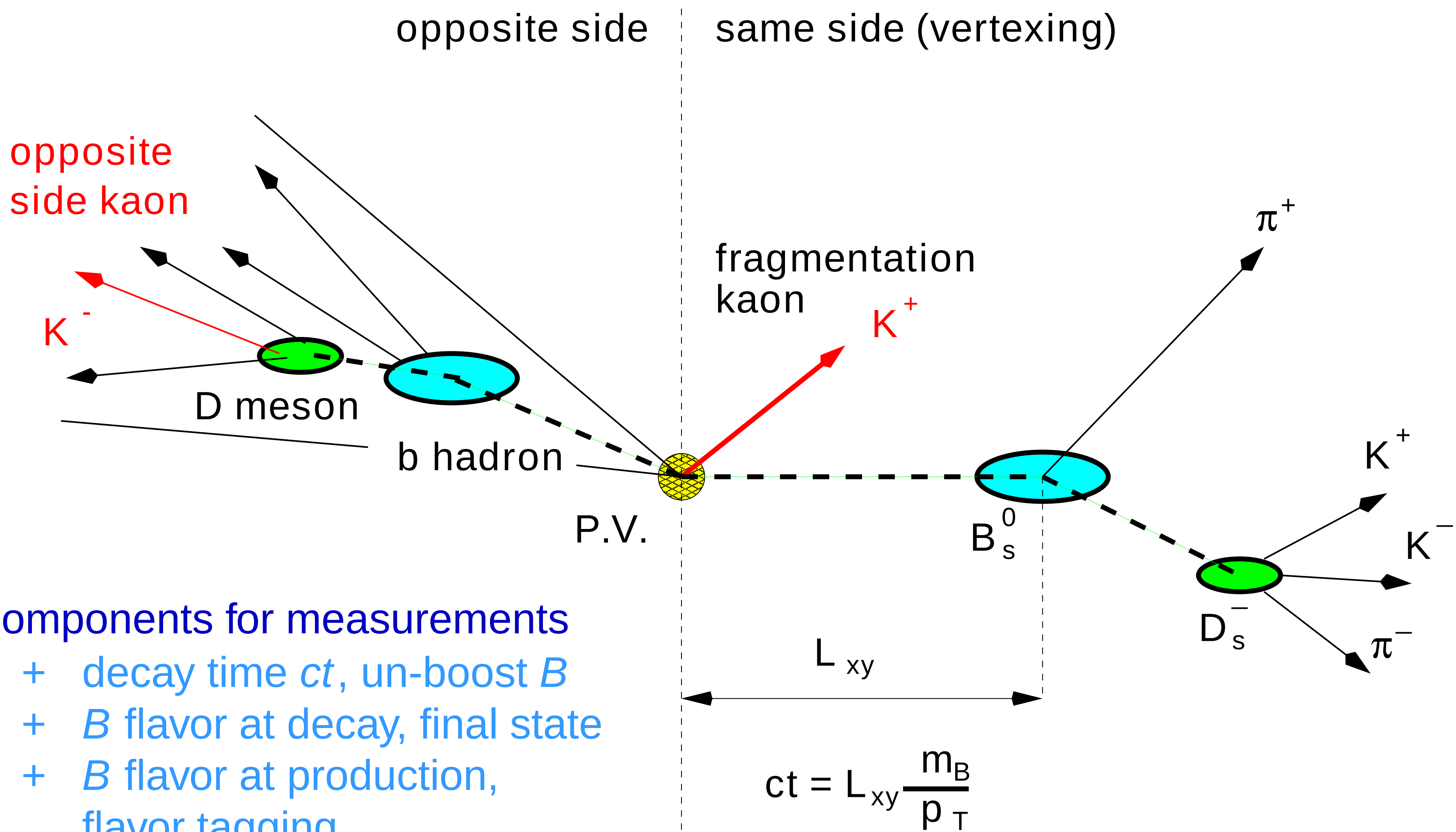
$$P(t)_{B^0\to\overline{B^0}} = \frac{1}{2\tau}e^{-t/\tau}(1 - \cos\Delta m t) \qquad P(t)_{B^0\to B^0} = \frac{1}{2\tau}e^{-t/\tau}(1 + \cos\Delta m t)$$

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

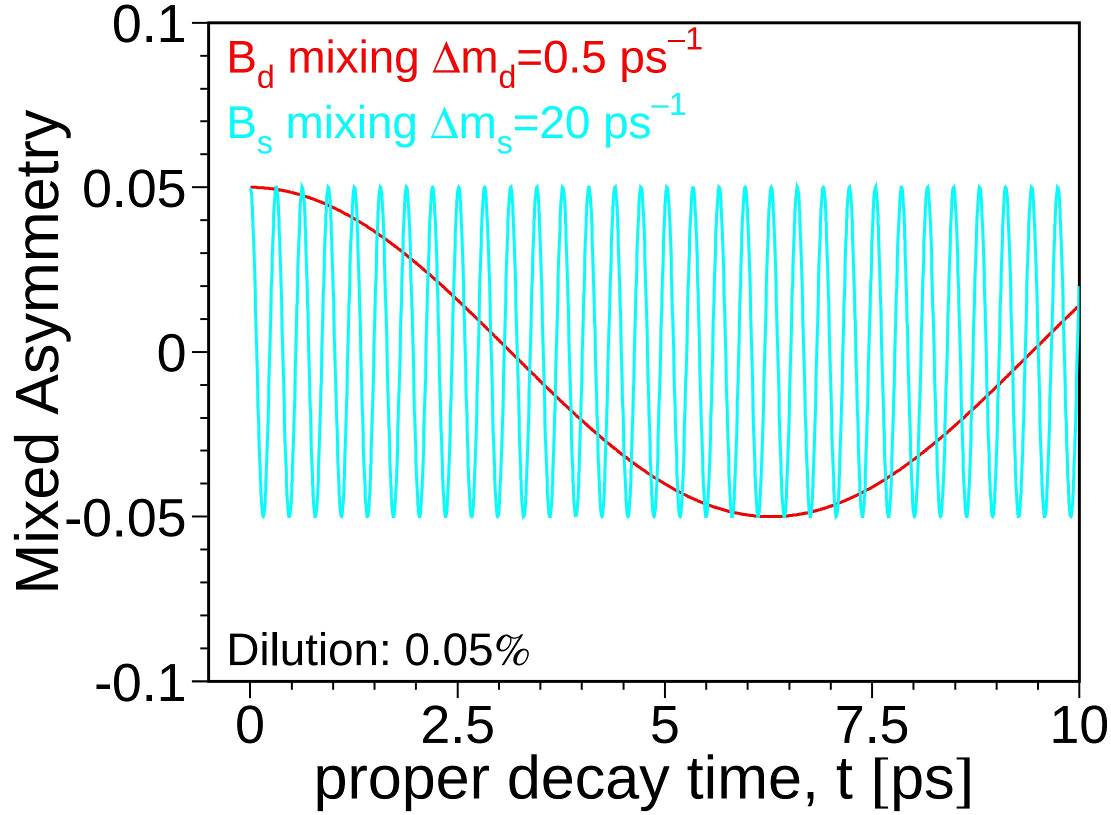
$$A_0^{meas}(t) \equiv \frac{N(t)_{RS} - N(t)_{WS}}{N(t)_{RS} + N(t)_{WS}} = D\cos(\Delta m_s t) \quad \text{with} \quad D = 2P - 1 = \text{dilution}$$

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 $\sigma(ct)$

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

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

B_s *Mixing Analysis - Road Map*

Samples

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

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

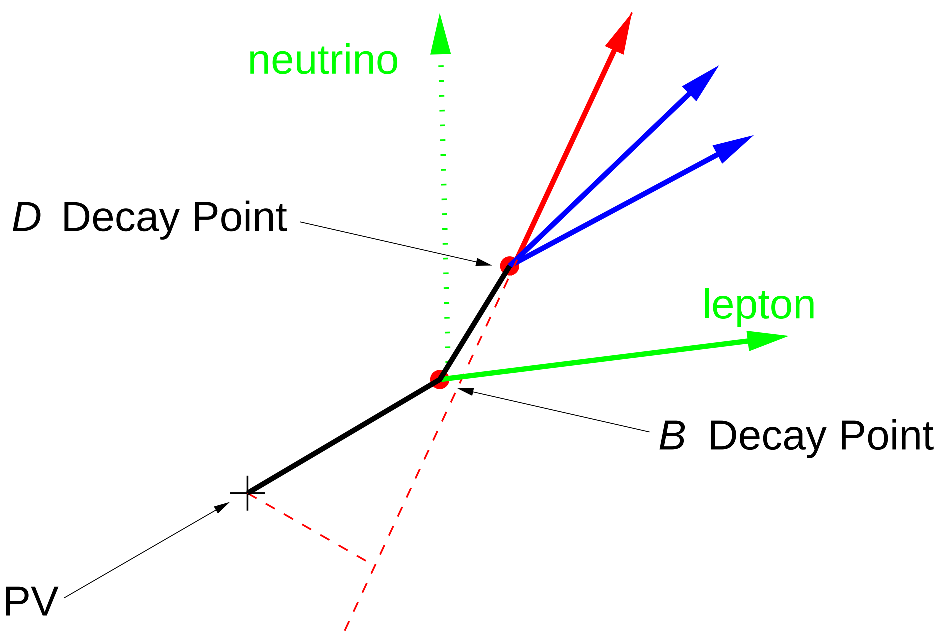
SVT Based Triggers

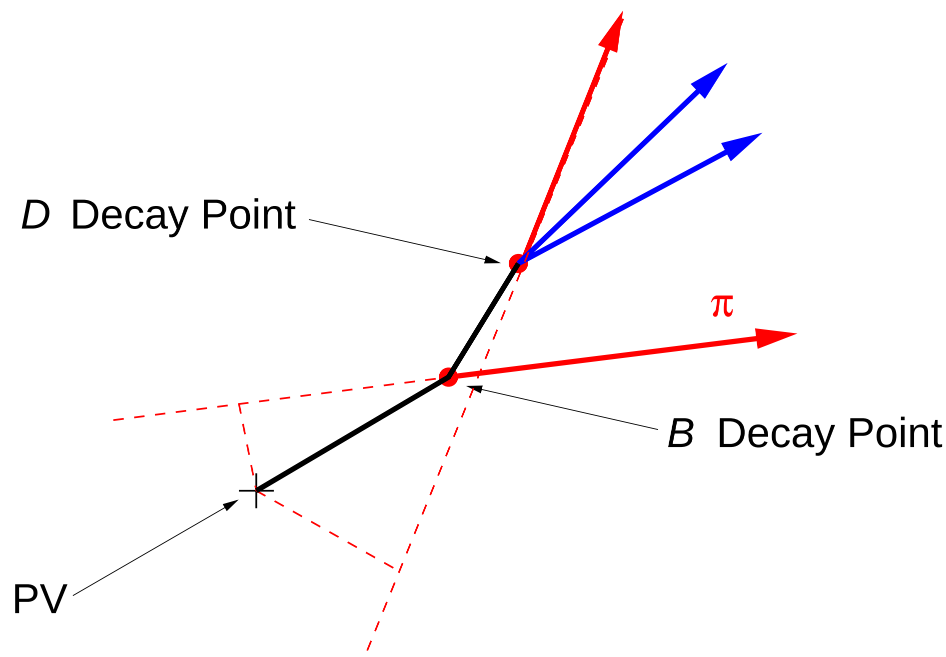
Semileptonic: $B_s \to l^+ D_s^- X$

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

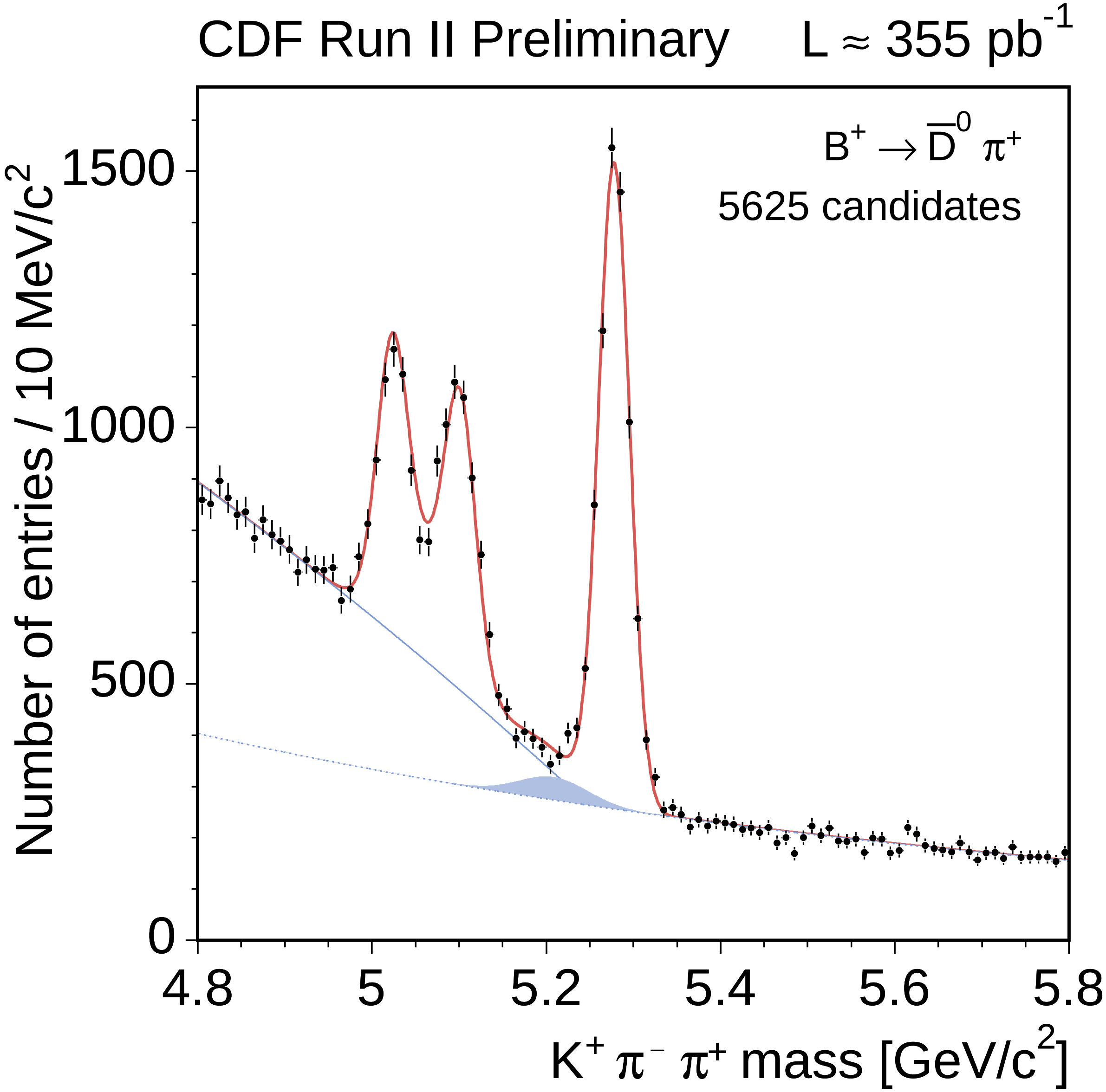
Hadronic: $B_s \to D_s^- \pi^-$

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

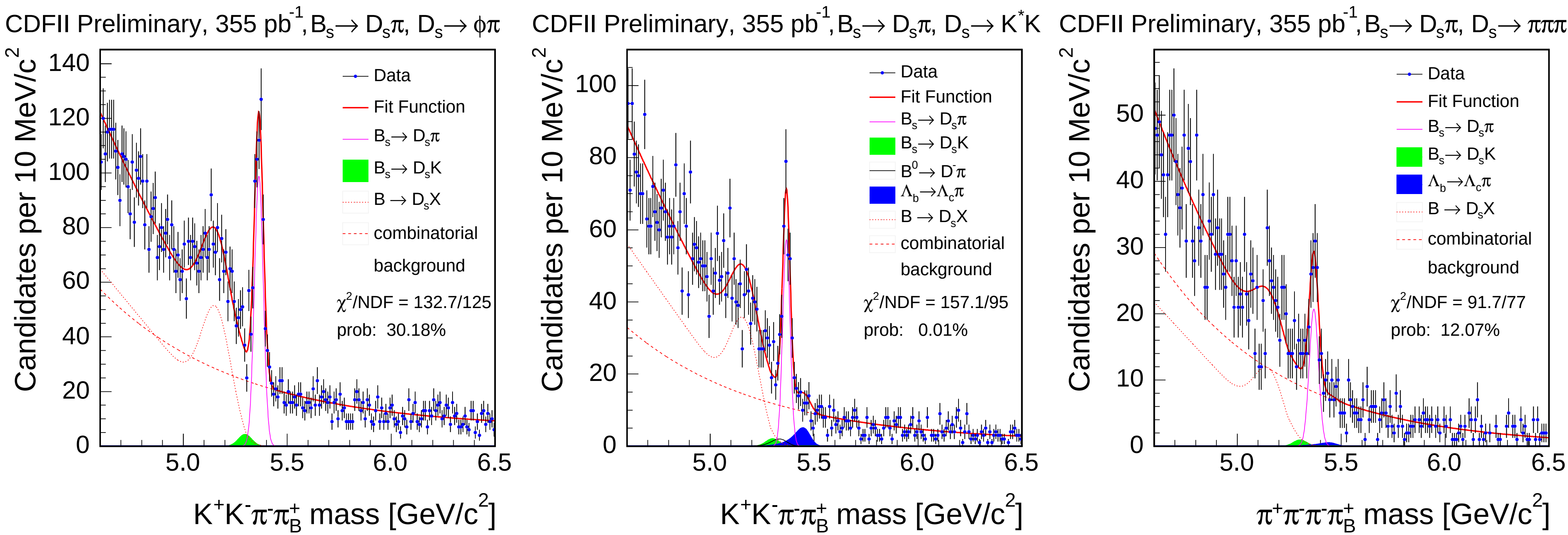




Hadronic Decay Signals $B^+ \rightarrow \overline{D}^0 \pi^+$



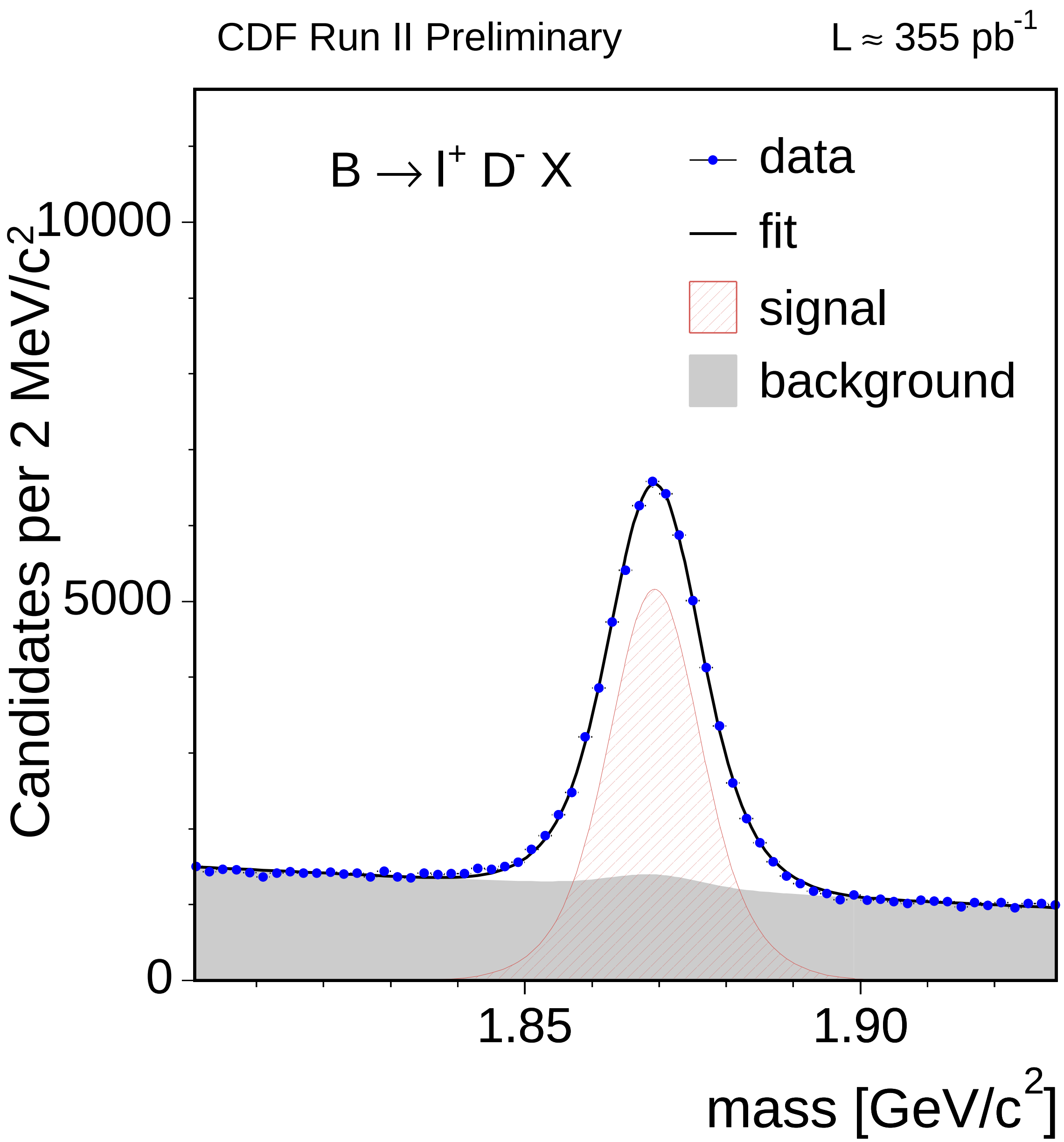
Hadronic Decay Signals $D_s^- \pi^+$



Decent samples of fully reconstructed B_s

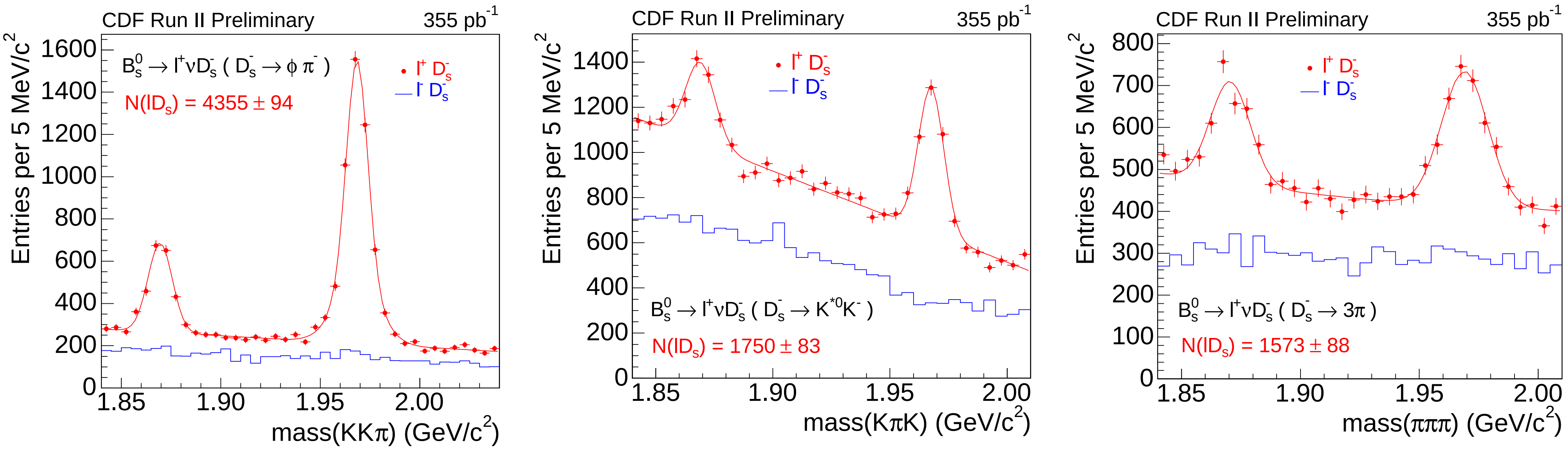
about 900 events

Semileptonic Decay Signals $B \to l^- D^+ X$



Very large sample: about 56k events

Semileptonic Decay Signals lD_s^-X

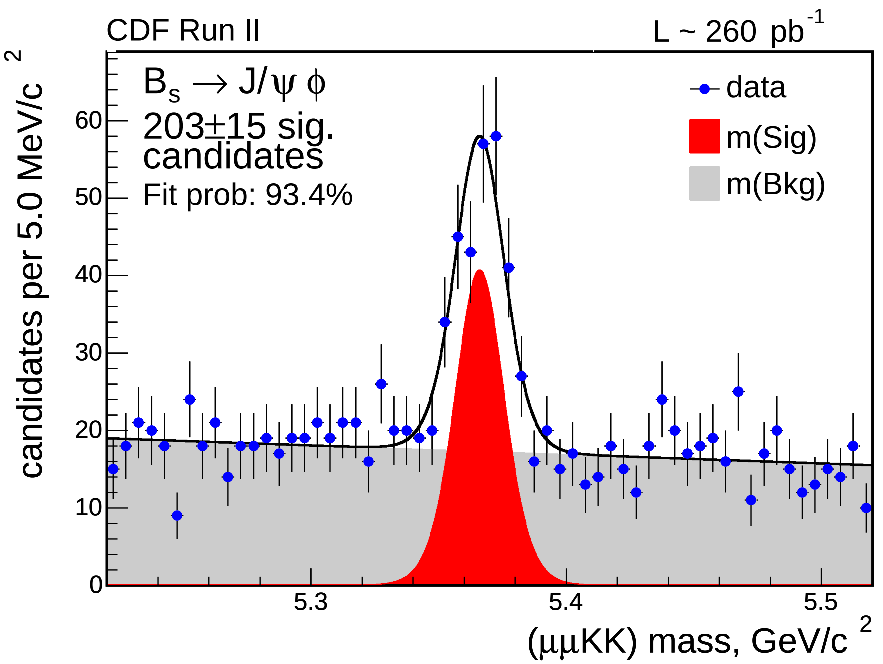


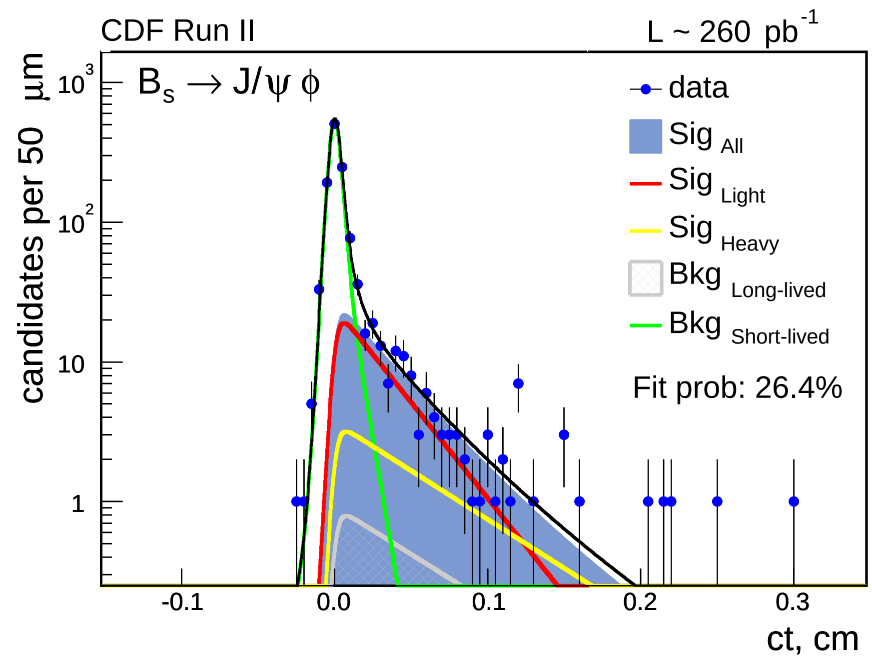
Very decent samples of fully reconstructed B_s

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*

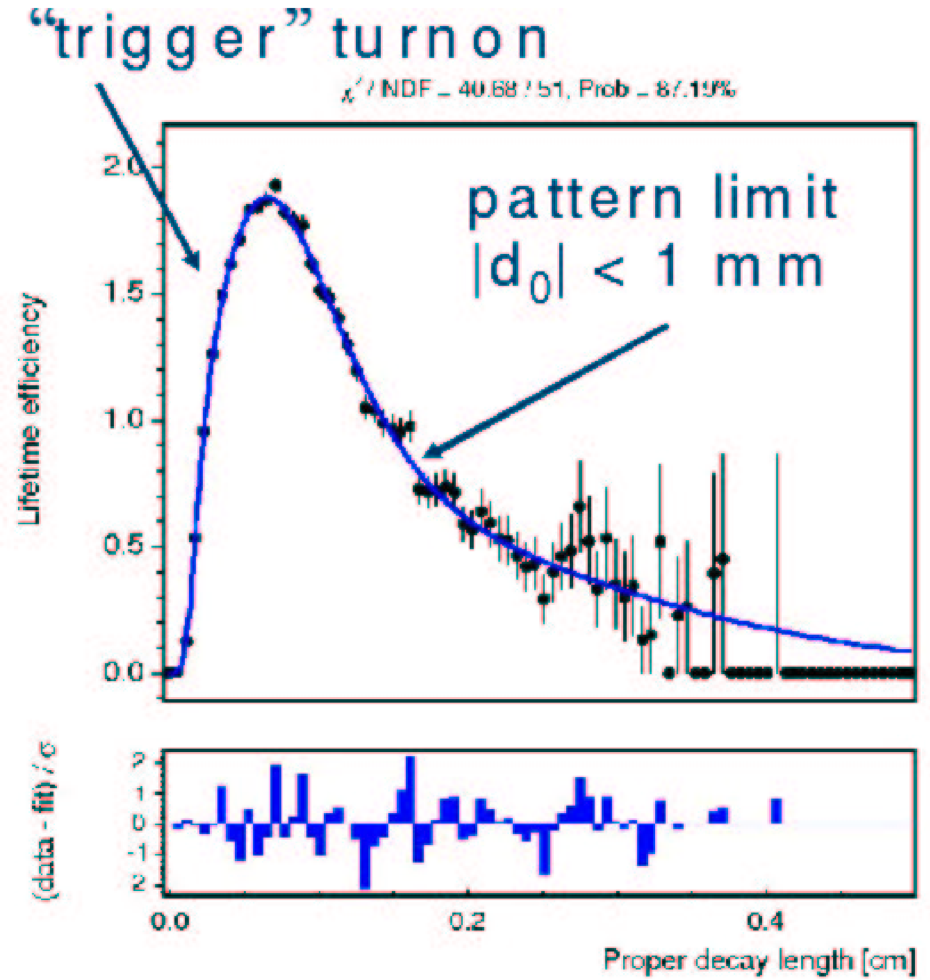
+ two SVT tracks
+ turnon: $d_0 > 120\ \mu$m
+ turnoff: $d_0 < 1$ mm and pattern limit
+ selection increases bias

Adjust probability density

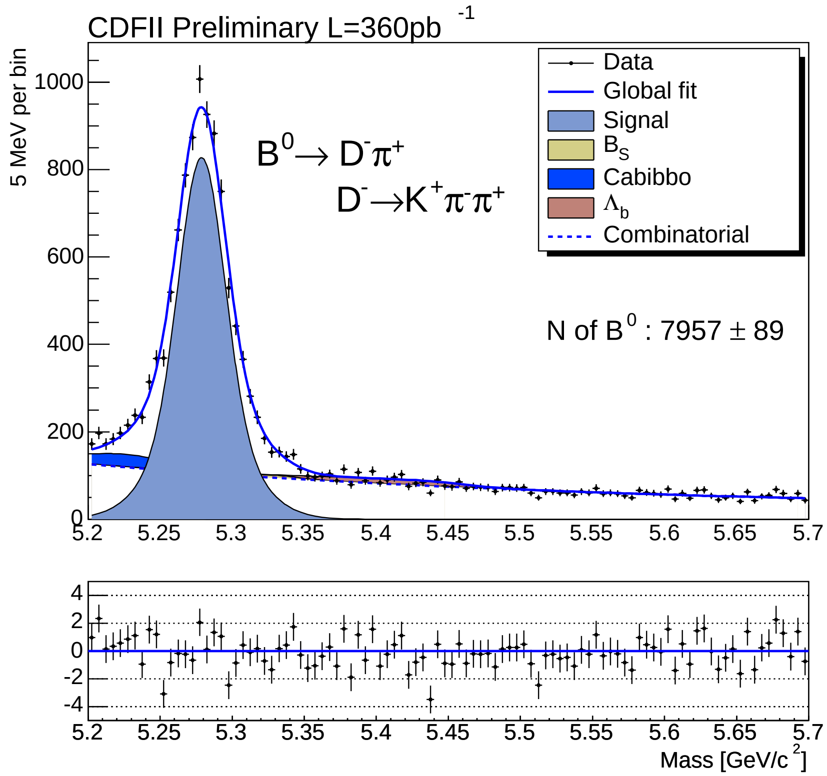
+ $p(t) = N(e^{-t/\tau} \times G(\sigma_{ct}))\ \ \varepsilon(t)$
+ background more complex, still from mass sideband

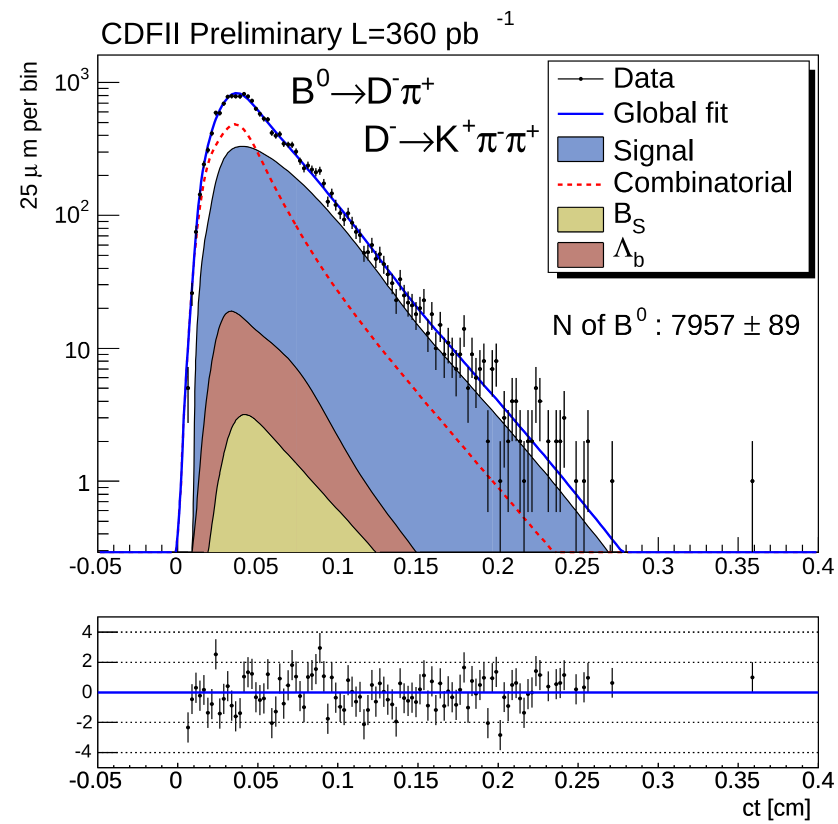
Do we care for mixing?

+ bias cancels!
+ very small effect on mixing



Hadronic Decays Dπ – Lifetimes





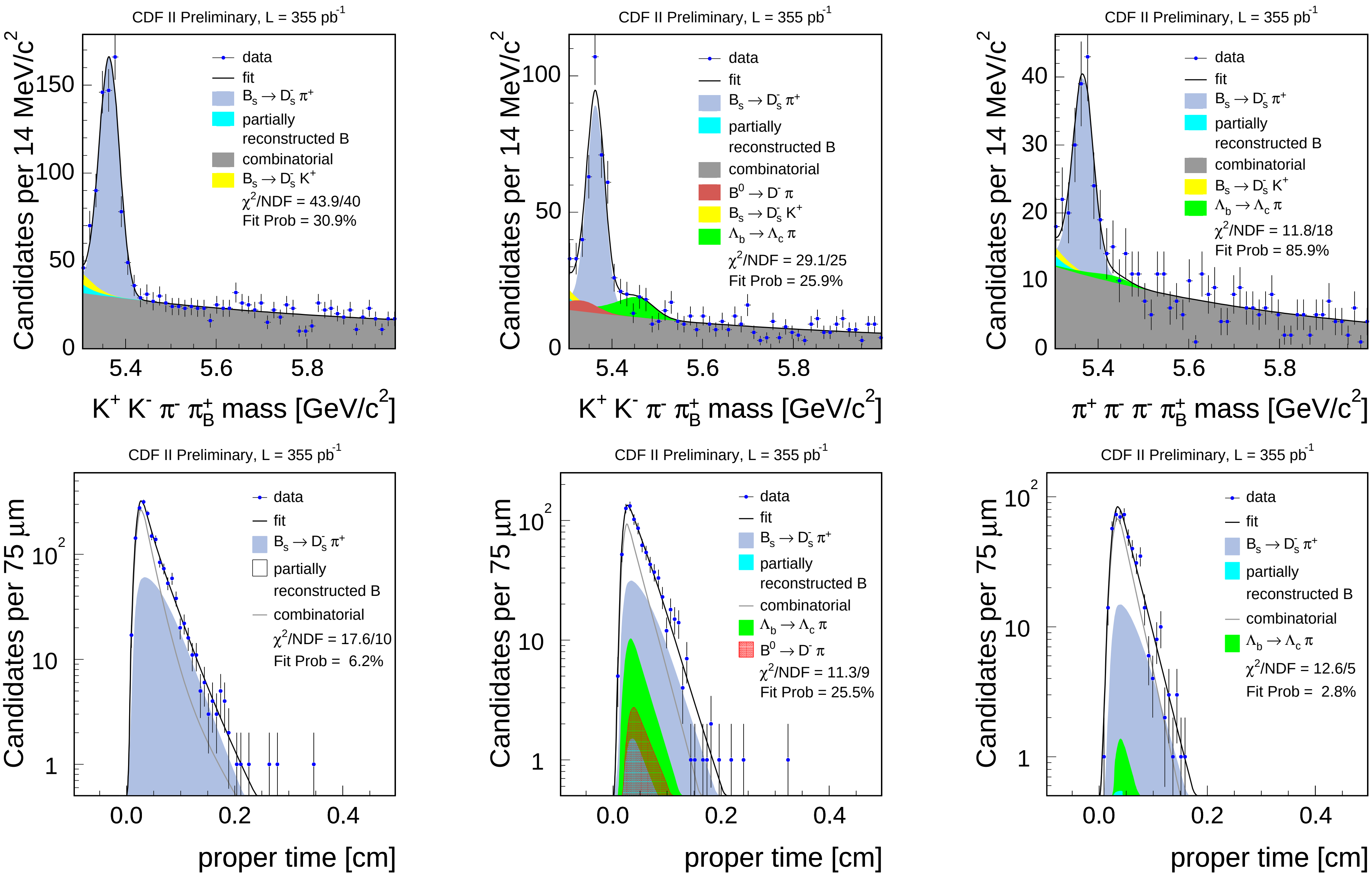
Measure lifetimes of B^+ and B^0 → then B_s

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

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

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

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

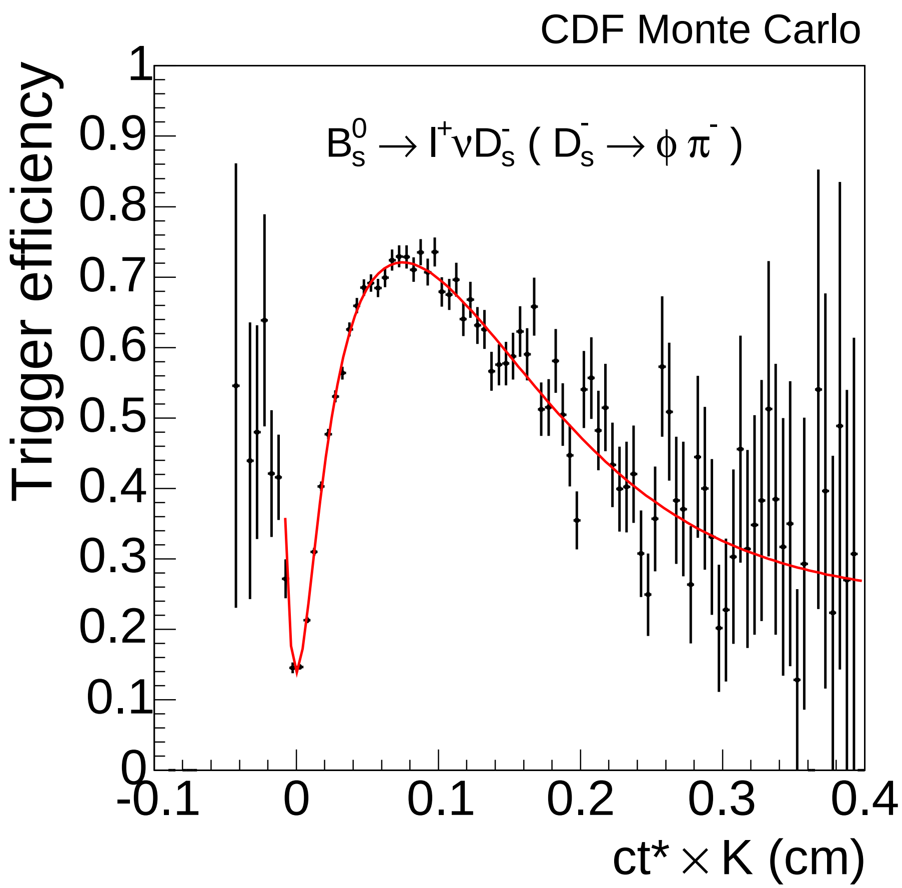


$D_s^- \to \phi \pi^-$ | $D_s^- \to K^{*0} K^-$ | $D_s^- \to \pi^+ \pi^- \pi^-$

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



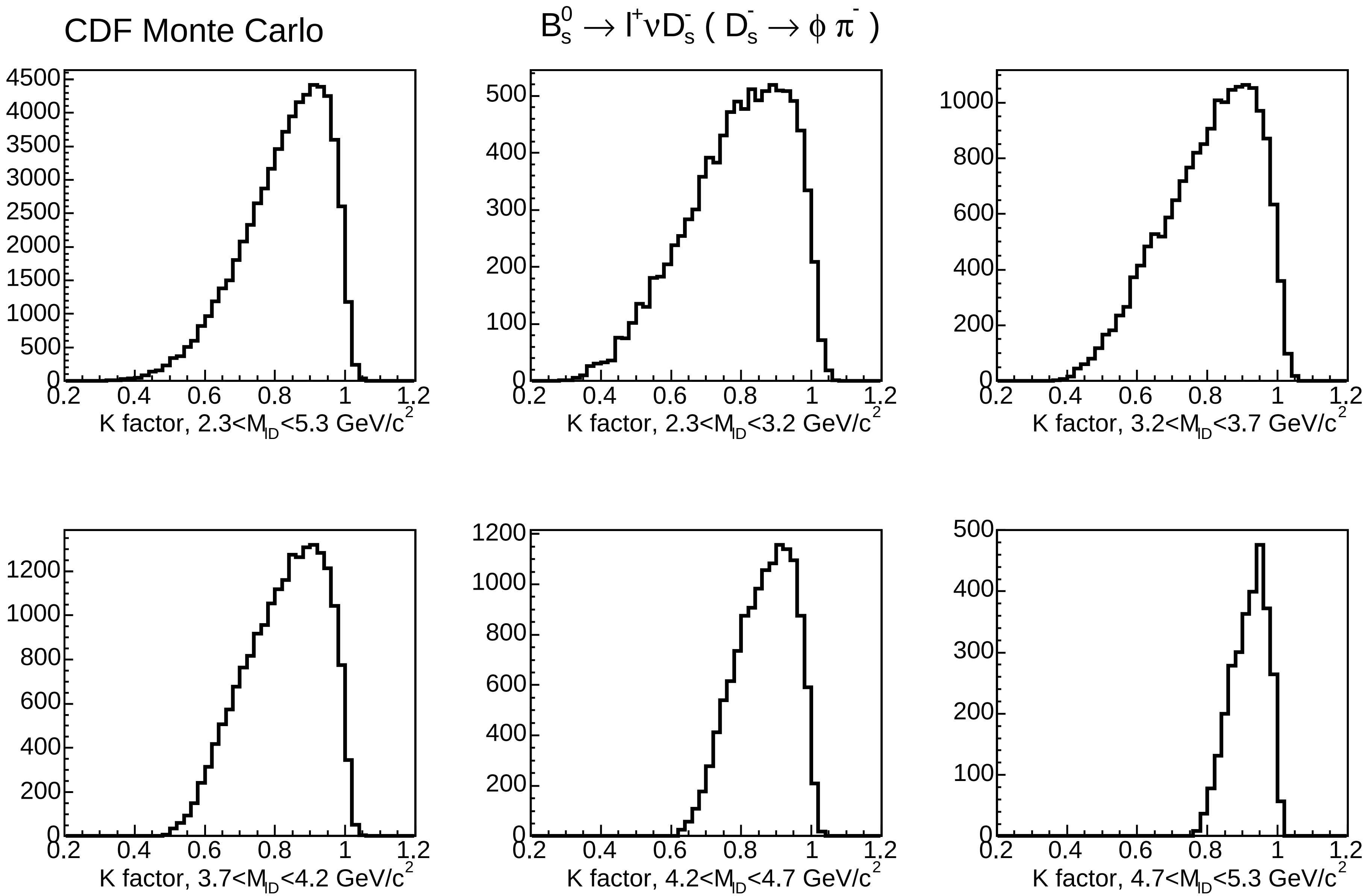
Corrrect missing momentum

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

Incomplete reconstruction

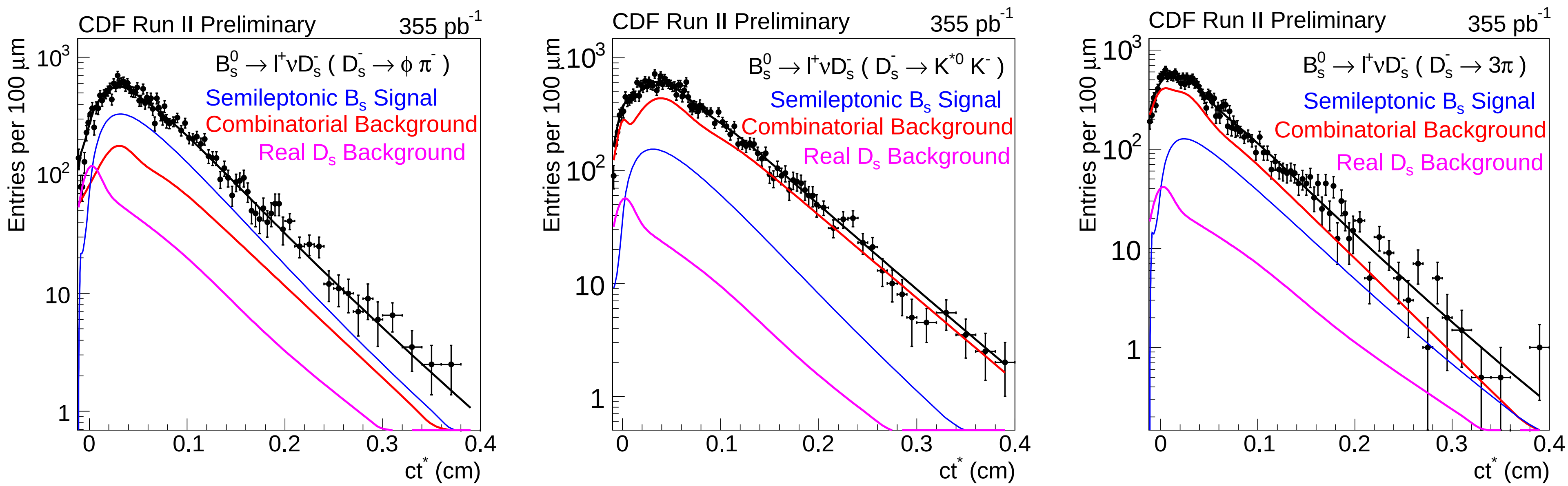
- + cross talk B^+, B^0
- + B background, $B \rightarrow D_s D$ ..
- + prompt *D* background

Lifetimes in Semileptonic Channels - K Factor



Bin fit in *lD* mass: highest mass → highest sensitivity

Semileptonic Decay $l^+D_s^-X$ – 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

Significance

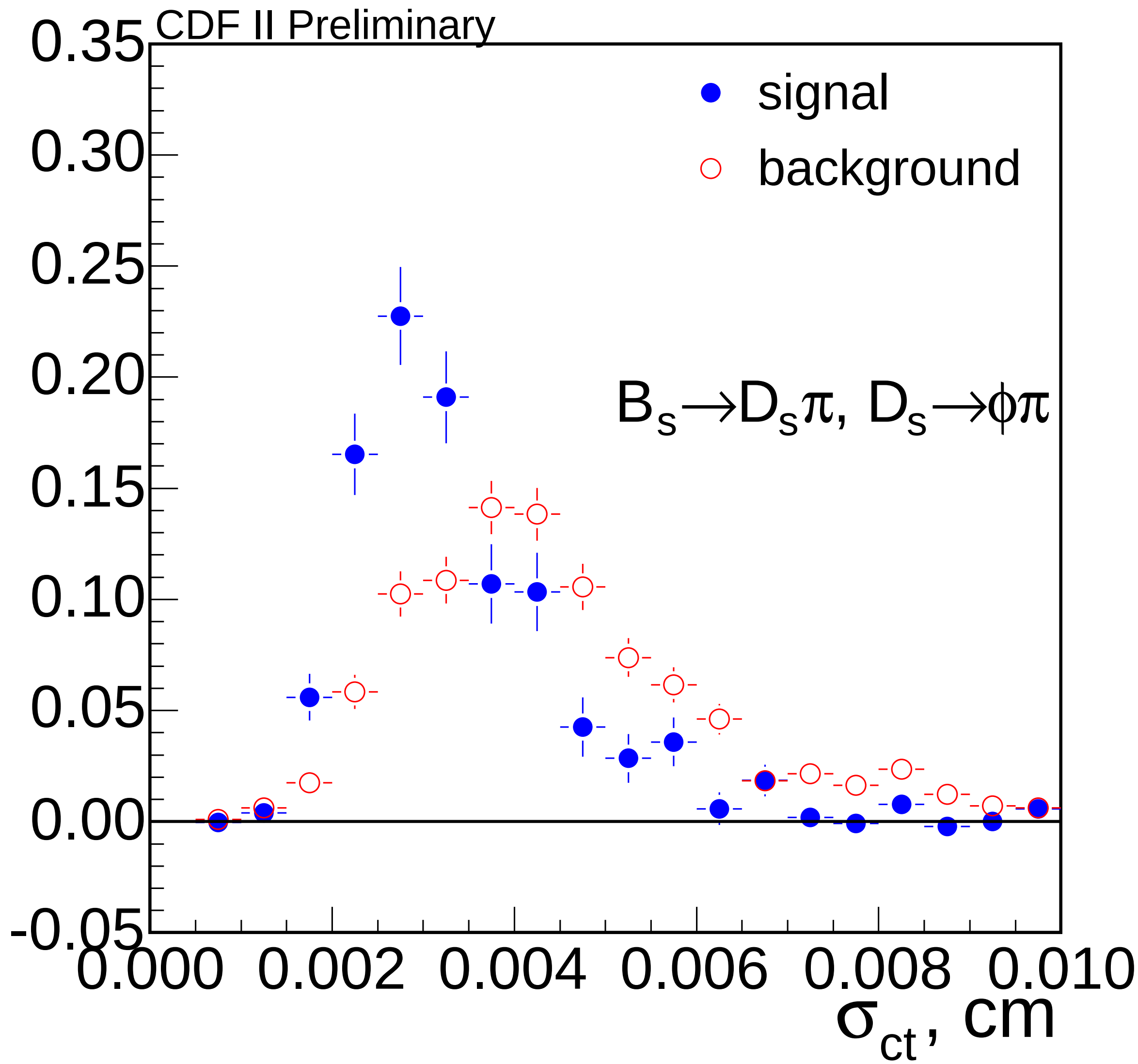
$$\propto \exp\left(-\frac{(\Delta m_s \sigma_{ct})^2}{2}\right)$$

Limit depends on σ_{ct}

- is it accurate?

Vertex fitter measures

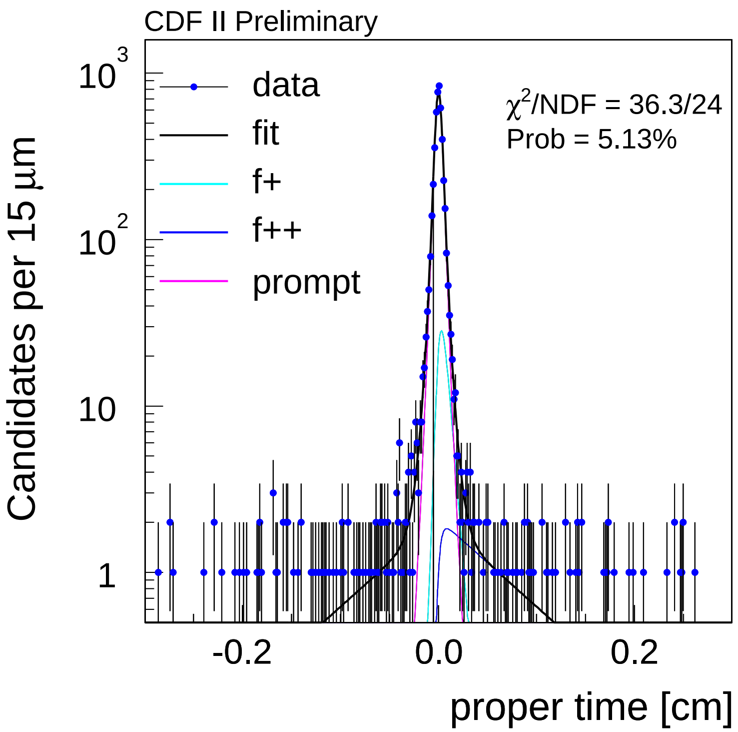
- $L_{xy}, p_T \rightarrow \sigma_{L_{xy}}, \sigma_{p_T}$
- $\sigma_{L_{xy}}, \sigma_{p_T}$ from track uncertainties

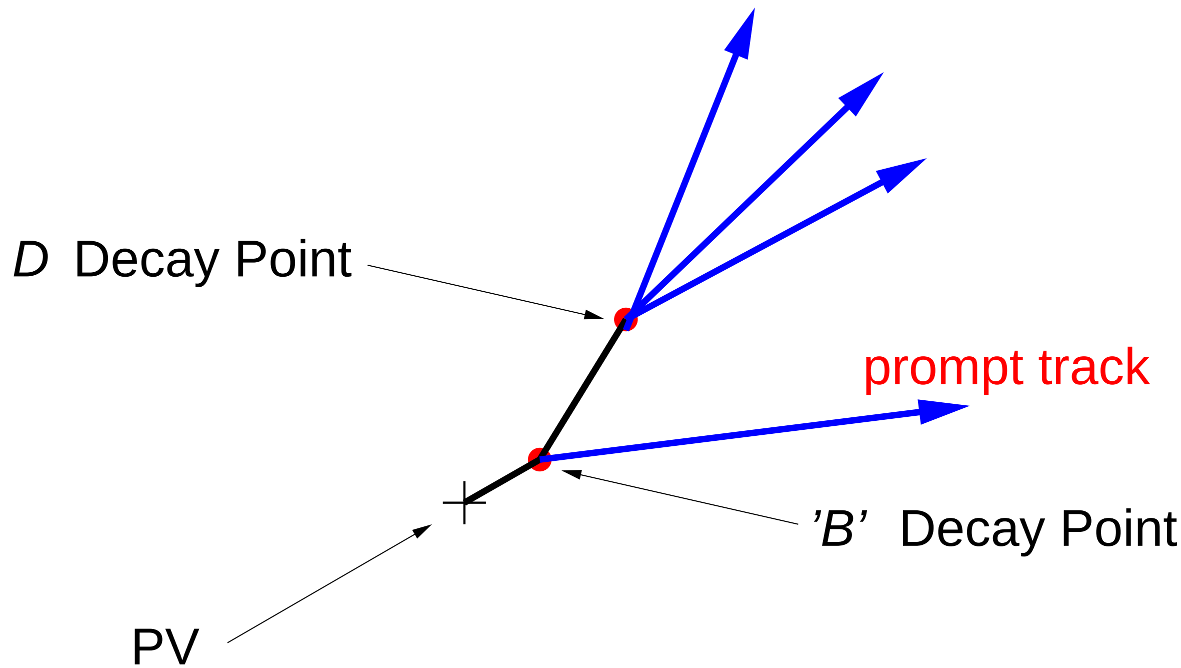


Track uncertainties: where do they come from?

- simply derived from hit resolutions
- hit resolutions are very tricky and need to be measured

Calibration of Proper Time Scale Uncertainty



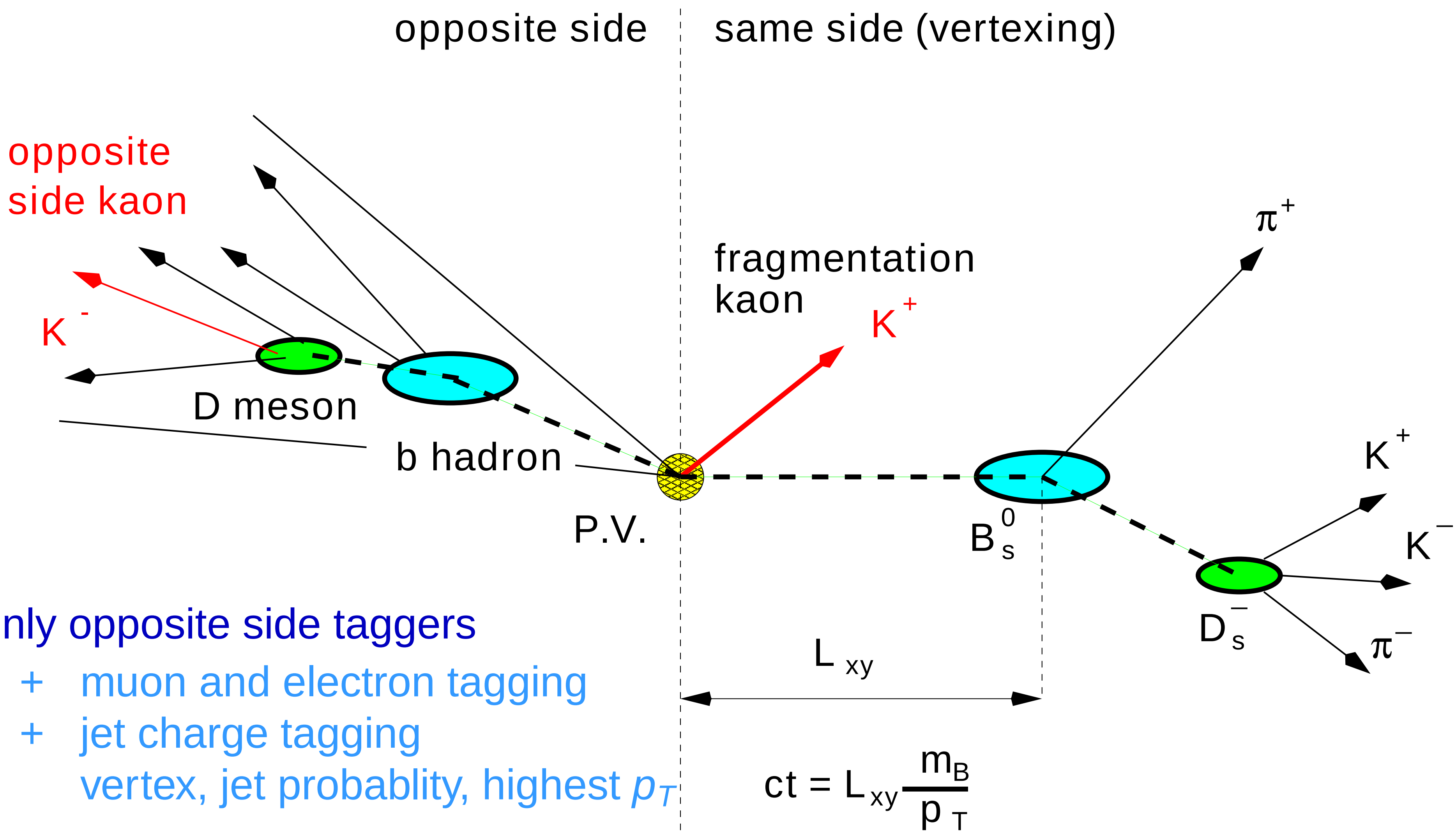


Create unbiased calibration sample

- 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 $\rightarrow$ 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

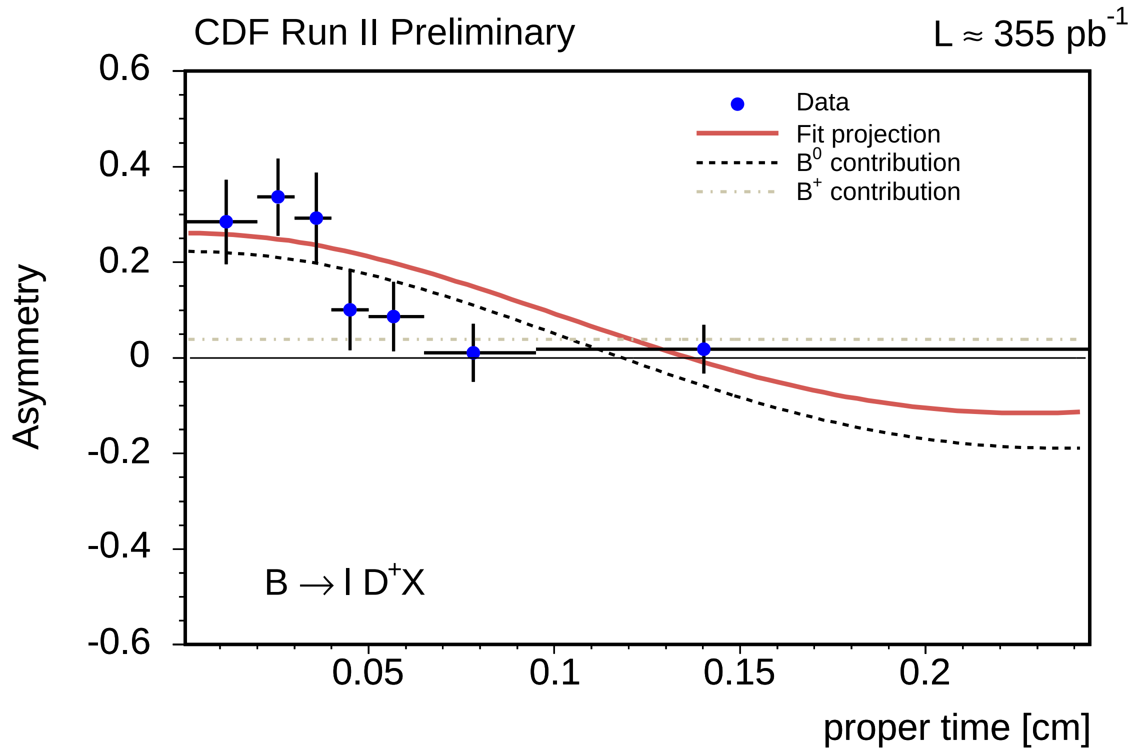
Fitting separately

- hadronic decays
- semileptonic decays

Measure

- Δm_d
- tagger performance

Sample picture: lD^+X SMT



Mixing results

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

Tagger Performance

Measure of tagger performance: εD^2

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

Tagger Combination

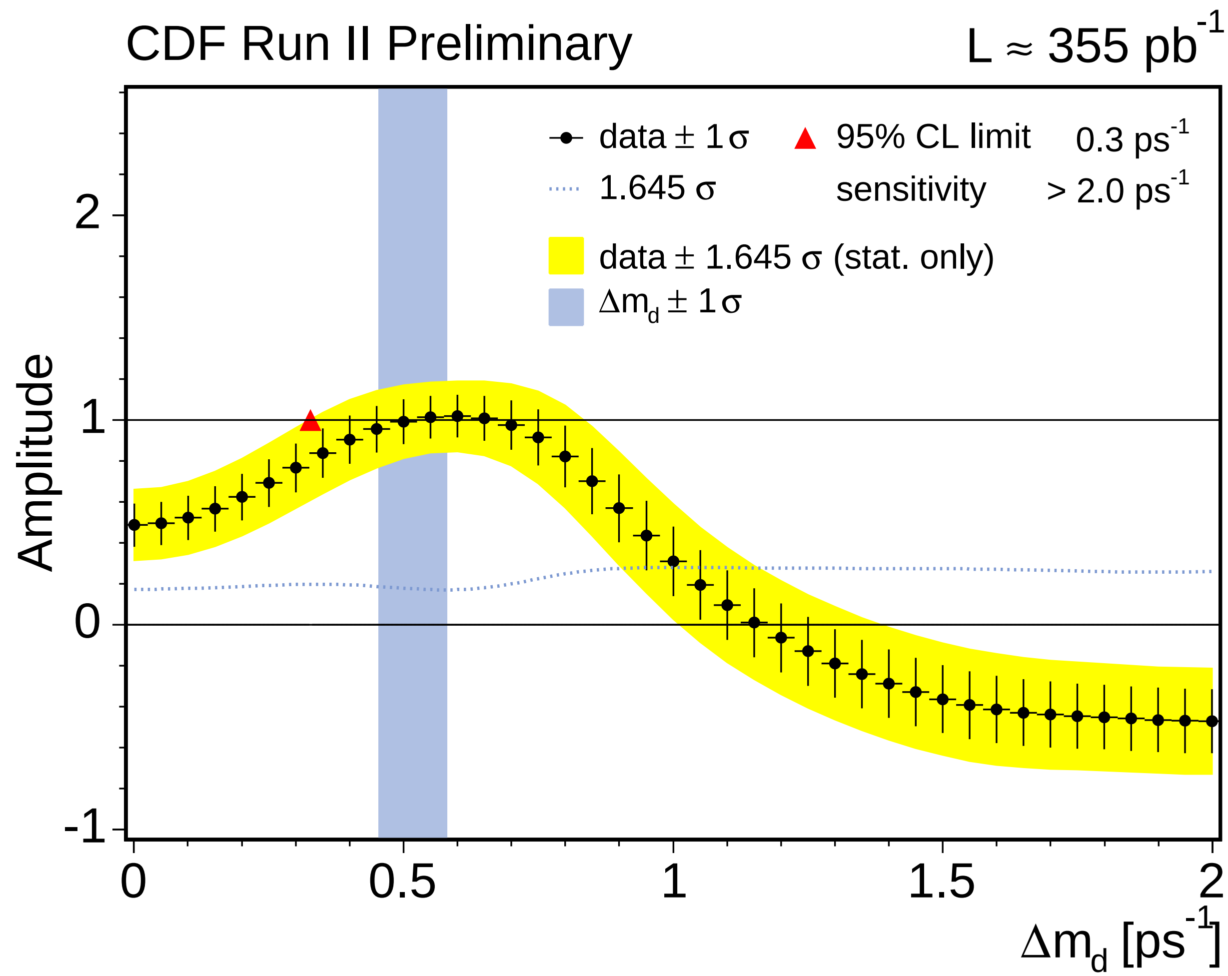
- taggers are ordered by performance
- exclusive taging decision, use best available tagger

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



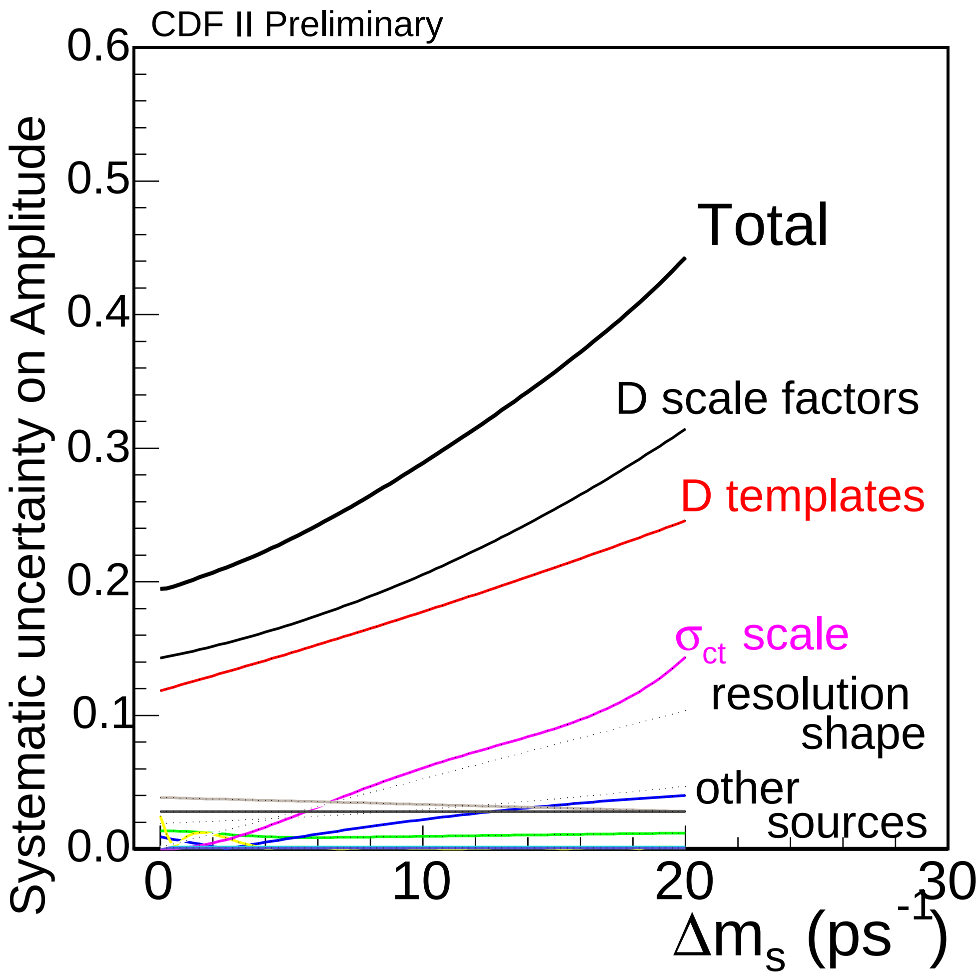
Perform unbinned likelihood fit

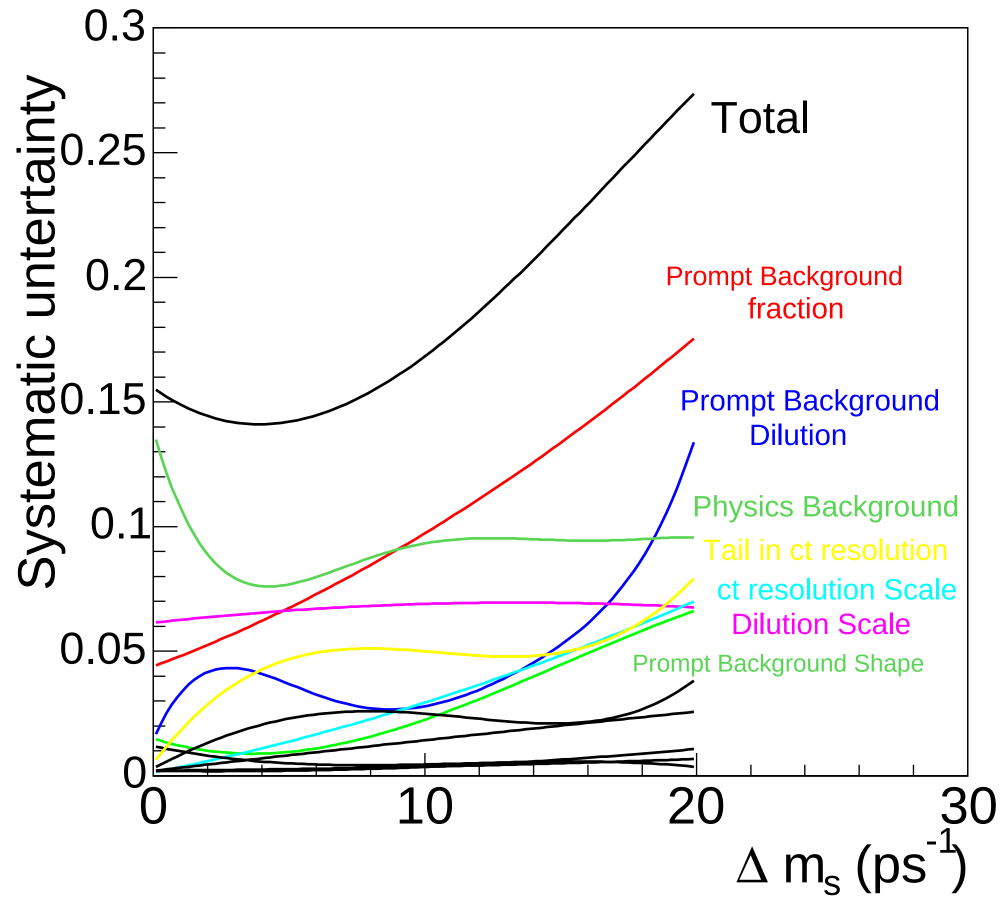
+ $p \sim (1 \pm A S_D D_i \cos(\Delta m_s))$
+ scan fixed values of Δm_s
+ record A and $\sigma(A)$

Signal ≡ unit amplitude

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

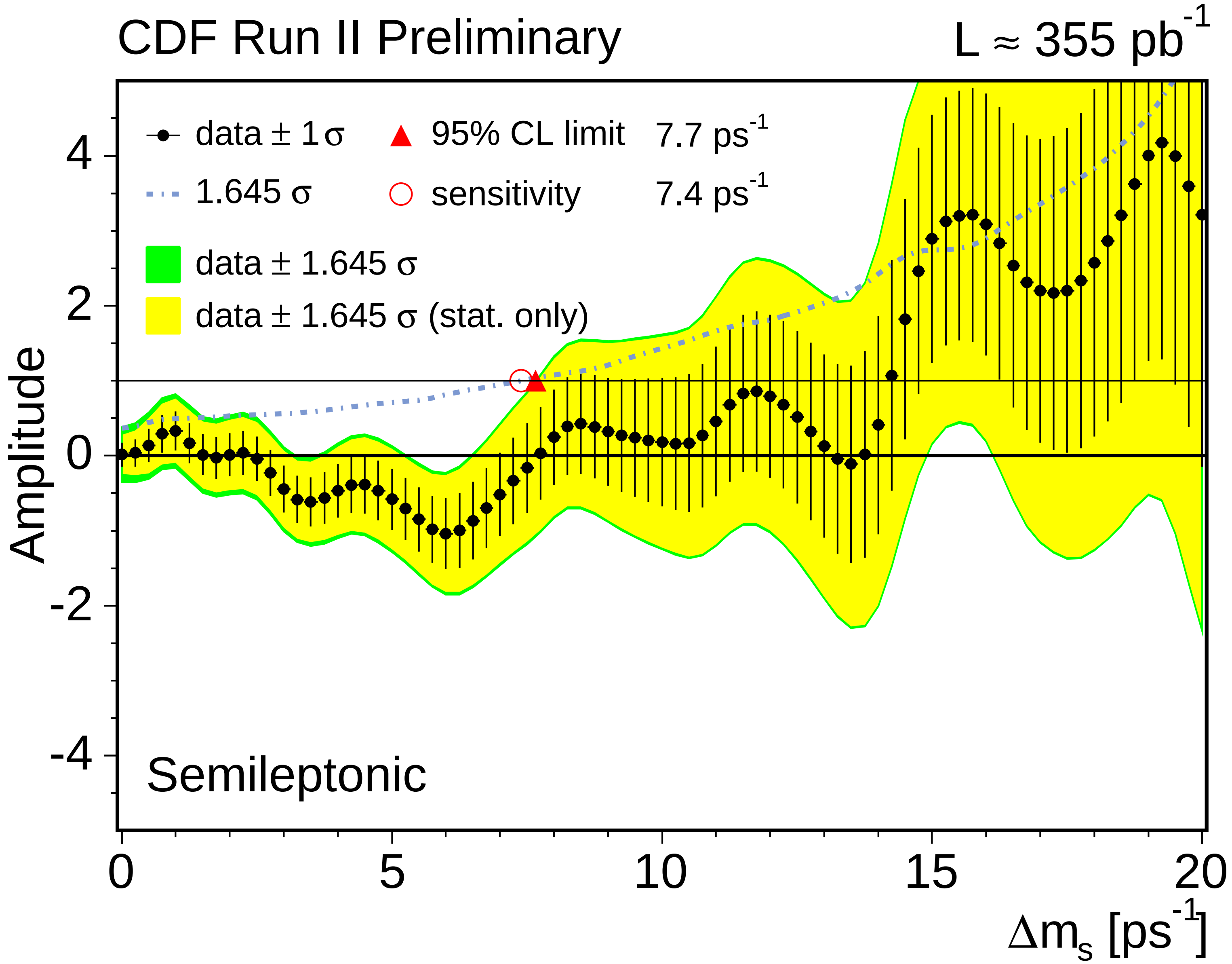
Systematic Uncertainties





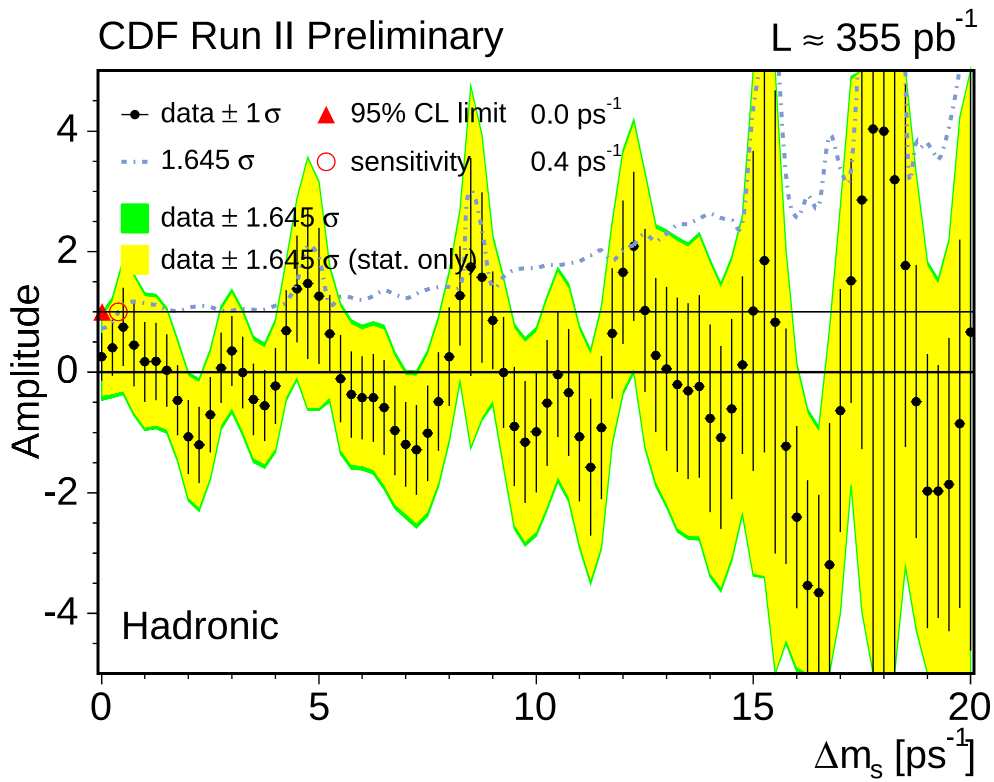
+ absolute errors on amplitude are shown
+ systematic very small compared to statistical uncertainty
+ dominant systematics limited by sample size → will improve

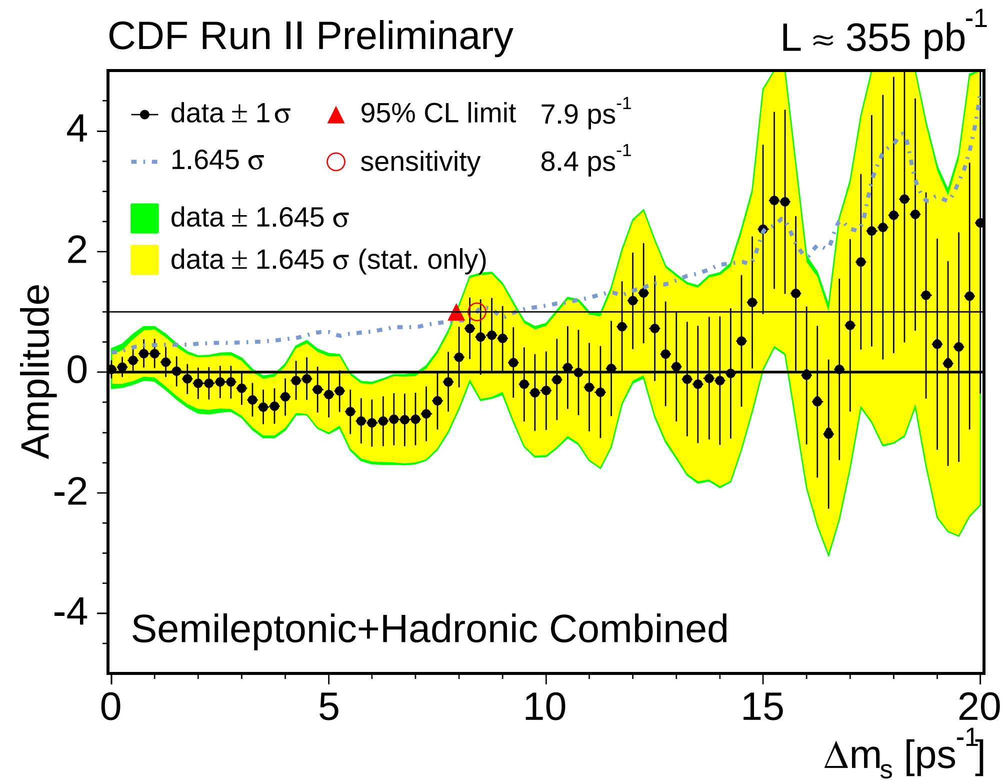
Semileptonic Result



sensitivity: 7.4 ps^{-1} lower limit: 7.7 ps^{-1} at 95% CL

Hadronic and Combined Result

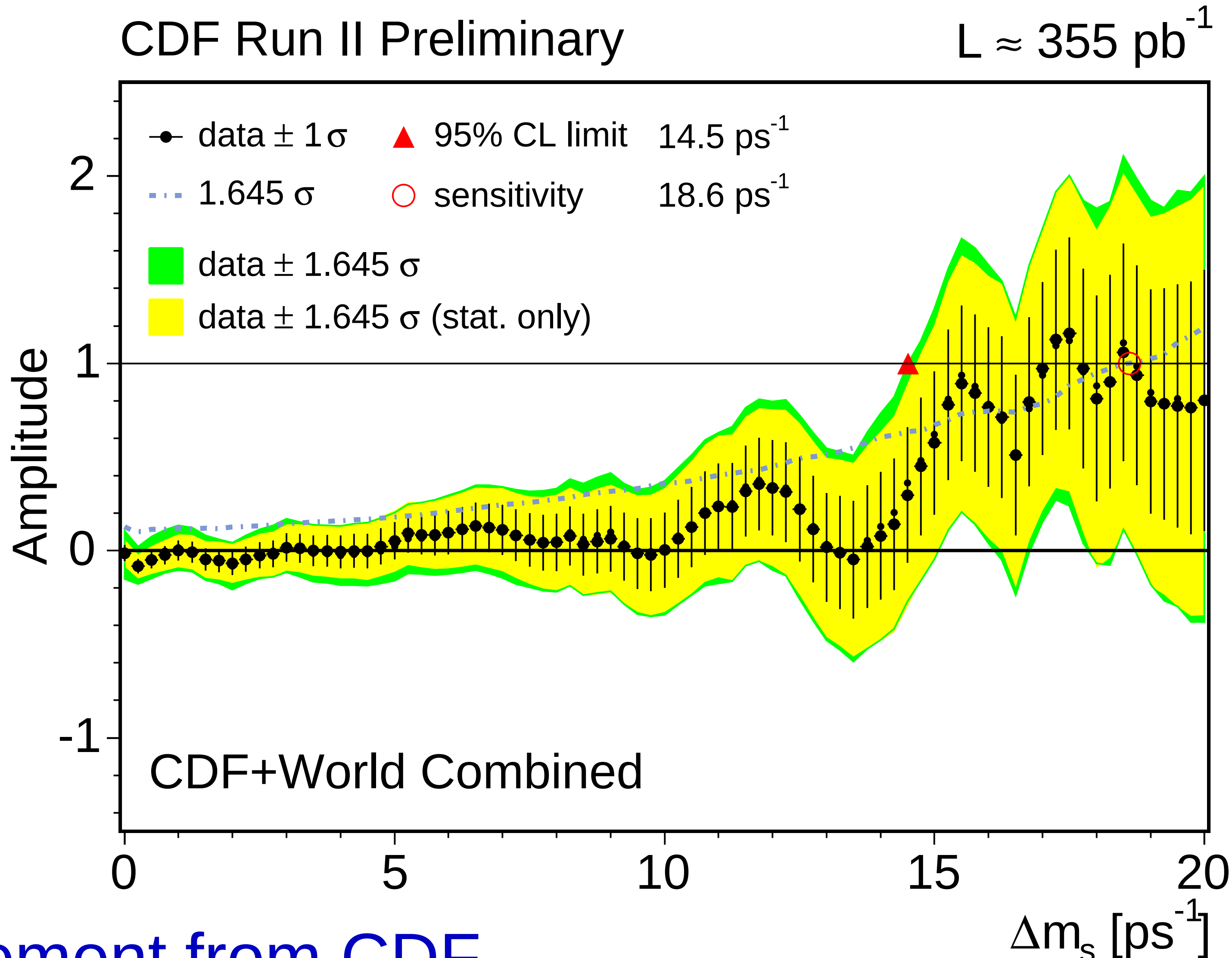




Comments

- 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 $\Delta m_s < 7.9\ \mathrm{ps}^{-1}$ 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}

Summary

First B_s mixing analysis is completed

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

Implemented *ct* bias correction

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

Prospects

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

Backup Slides

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

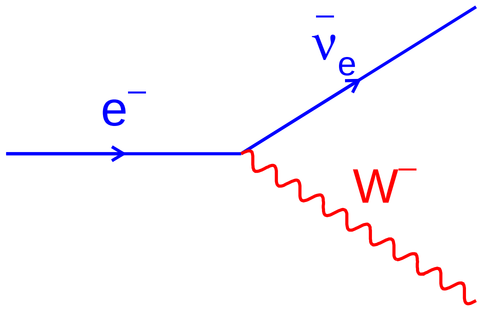
Matter in the Standard Model

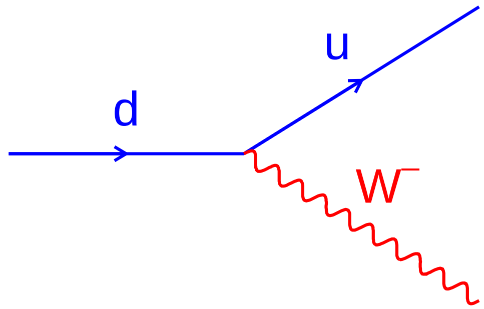
Matter build in families of weak isospin fermion doublets

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

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

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

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

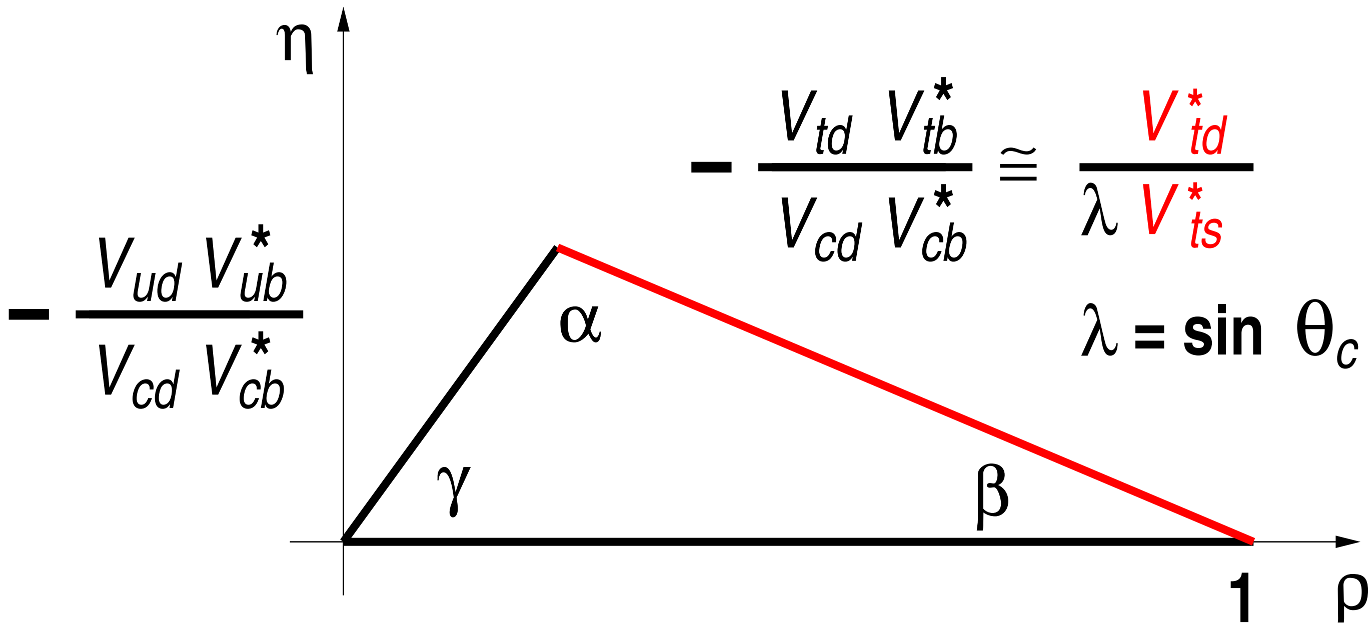
Least known parameters: ρ and η

Unitarity Triangle

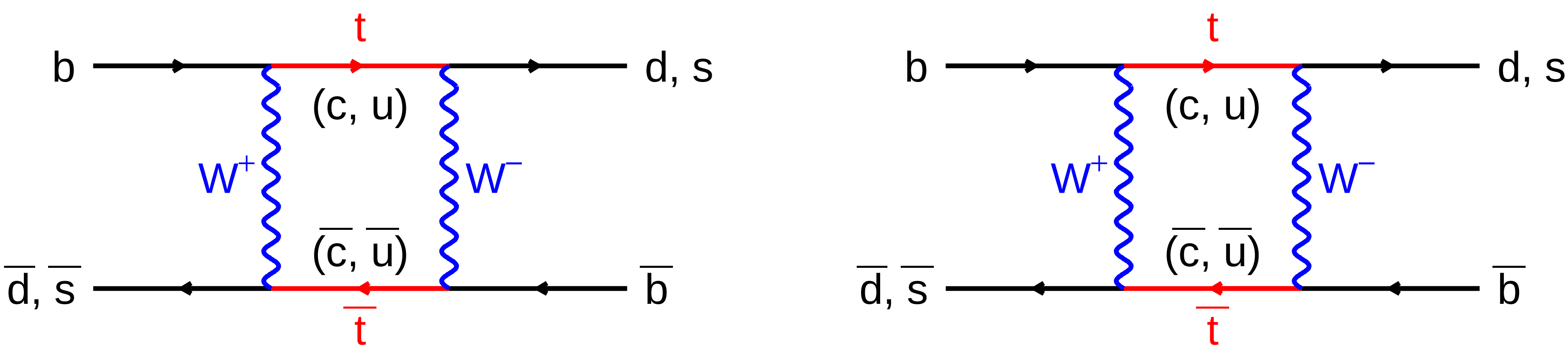
Unitarity condition: $VV^\dagger = 1$ $\qquad V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$

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

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



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:

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

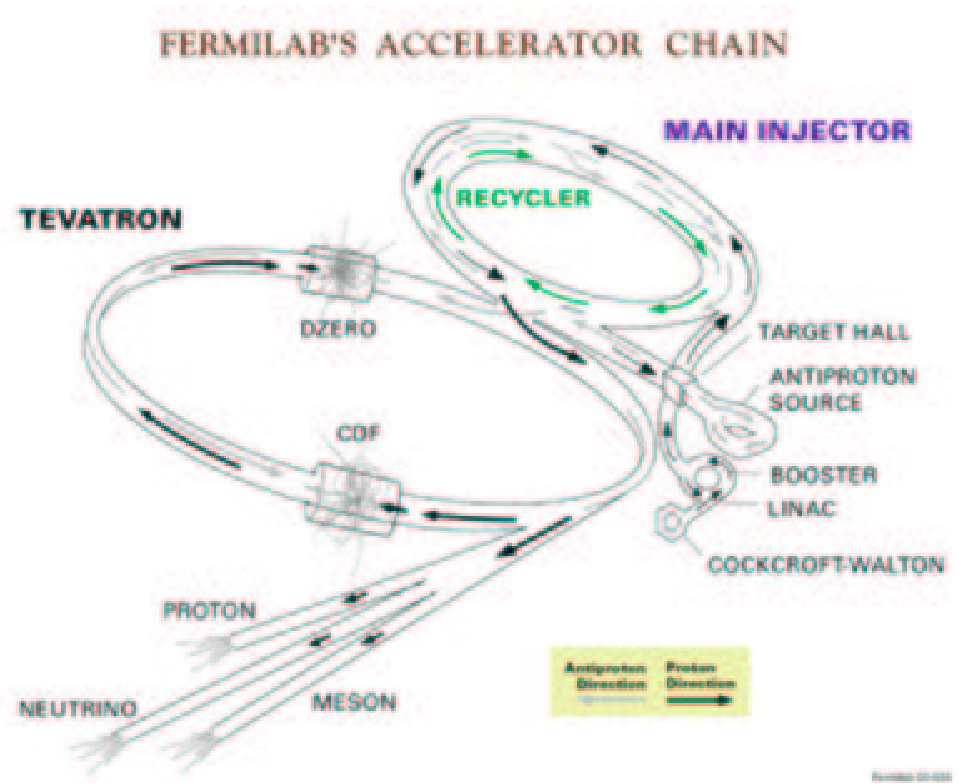
Hadronic uncertainties limit $|V_{td}|$ determination to $\approx$ 15%

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%

Tevatron Collider



Main injector

+ new Tevatron injection stage
+ accelerate and deliver higher intensity of protons
+ more efficient $\bar{p}$ transfer
+ $\bar{p}$ 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

b Hadron Production in Comparison

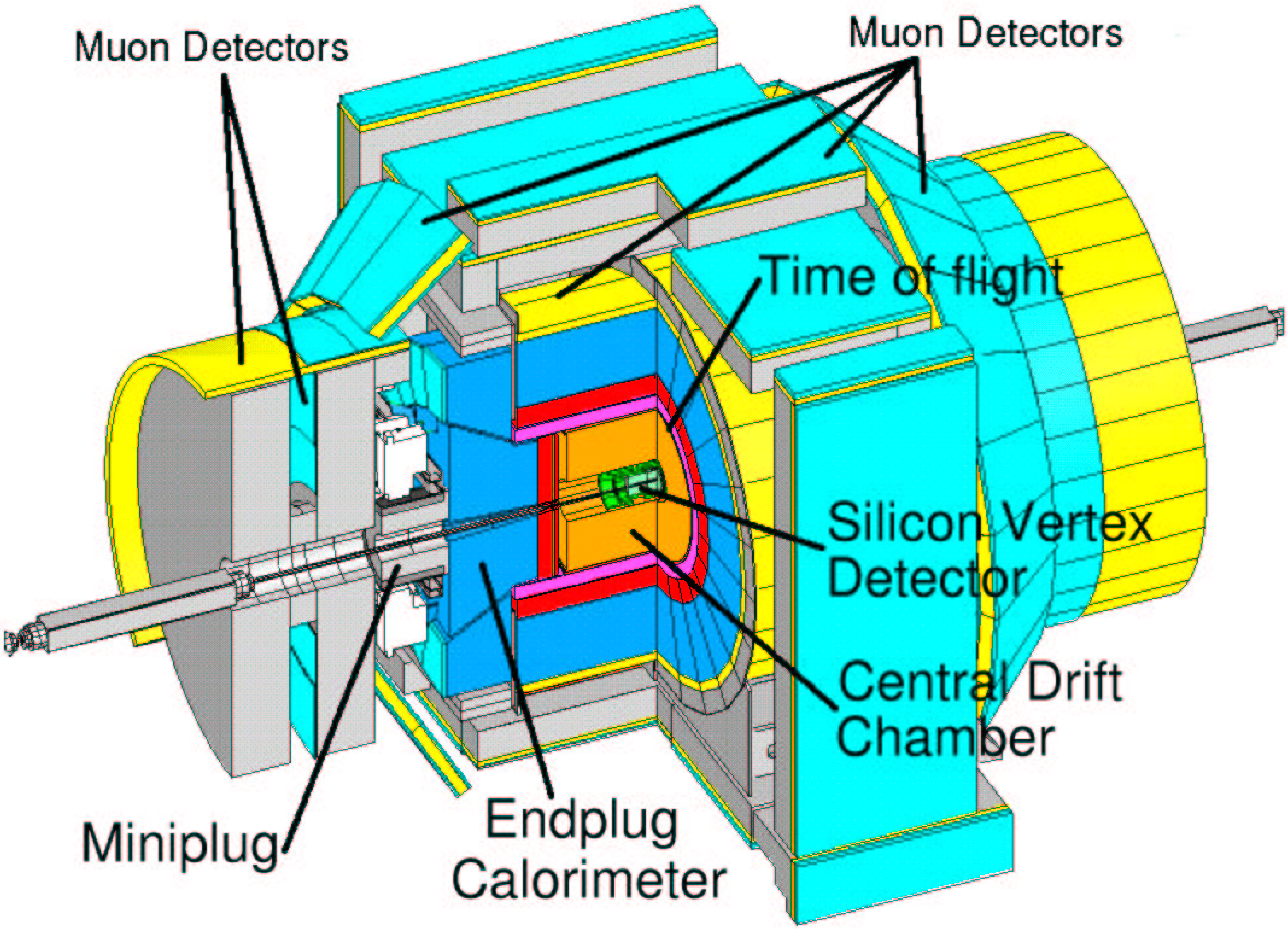
Accelerator	CESR,DORIS	LEP,SLC	PEPII,KEKB	Tevatron
Detector	Argus,CLEO	ADLO,SLD	BaBar,Belle	CDF,DØ
$\sigma(b\bar{b})$	$\sim$ 1 nb	$\sim$ 6 nb	$\sim$ 1 nb	$\sim$ 50 μb
$\sigma(b\bar{b}) : \sigma(had)$	0.26	0.22	0.26	0.001
b hadrons	B^0, B^+	all	B^0, B^+	all
Boost $<\beta\gamma>$	0.06	6	$\sim$ 0.5	2-4
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



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

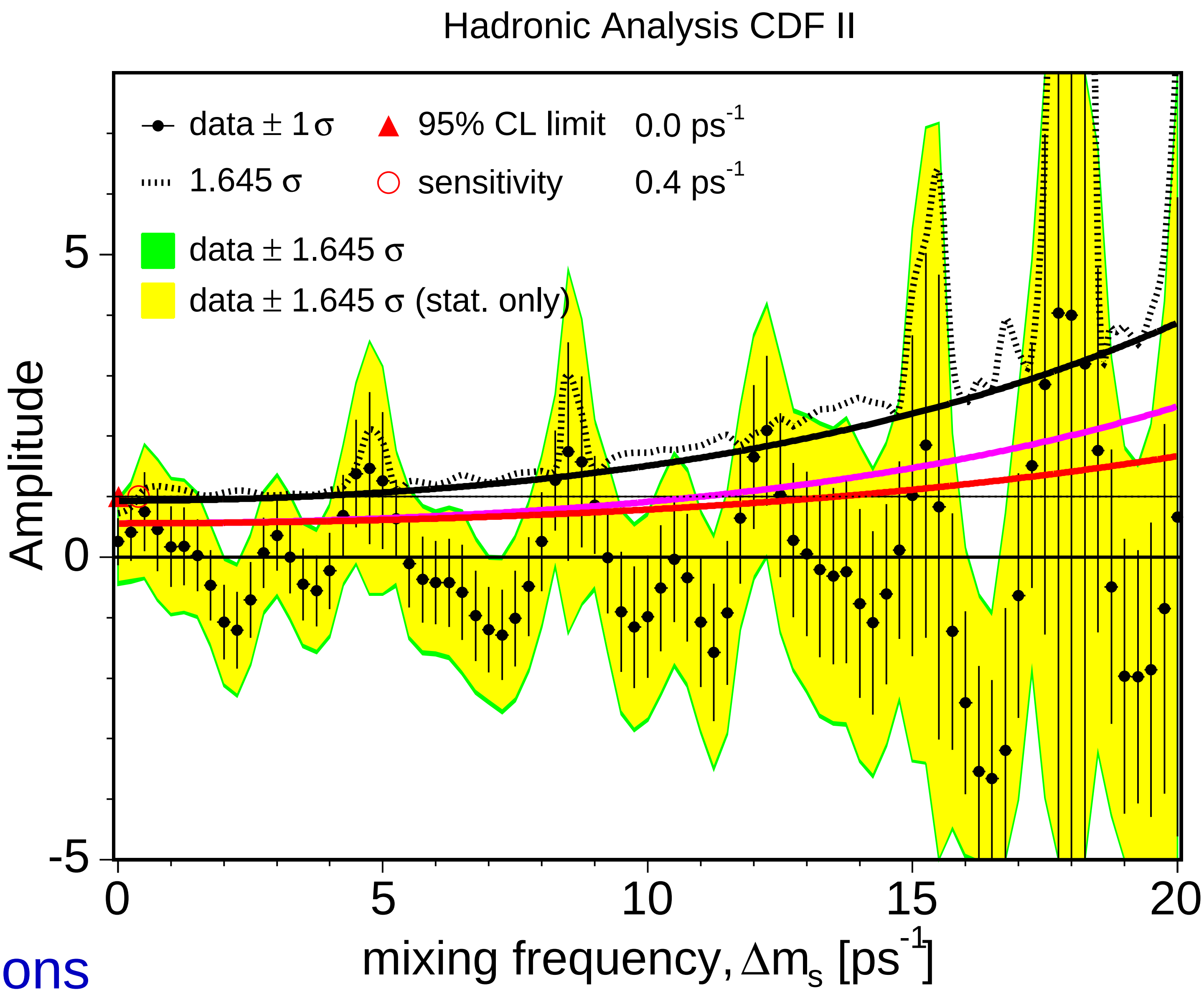
Improve proper time resolution

+ 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%

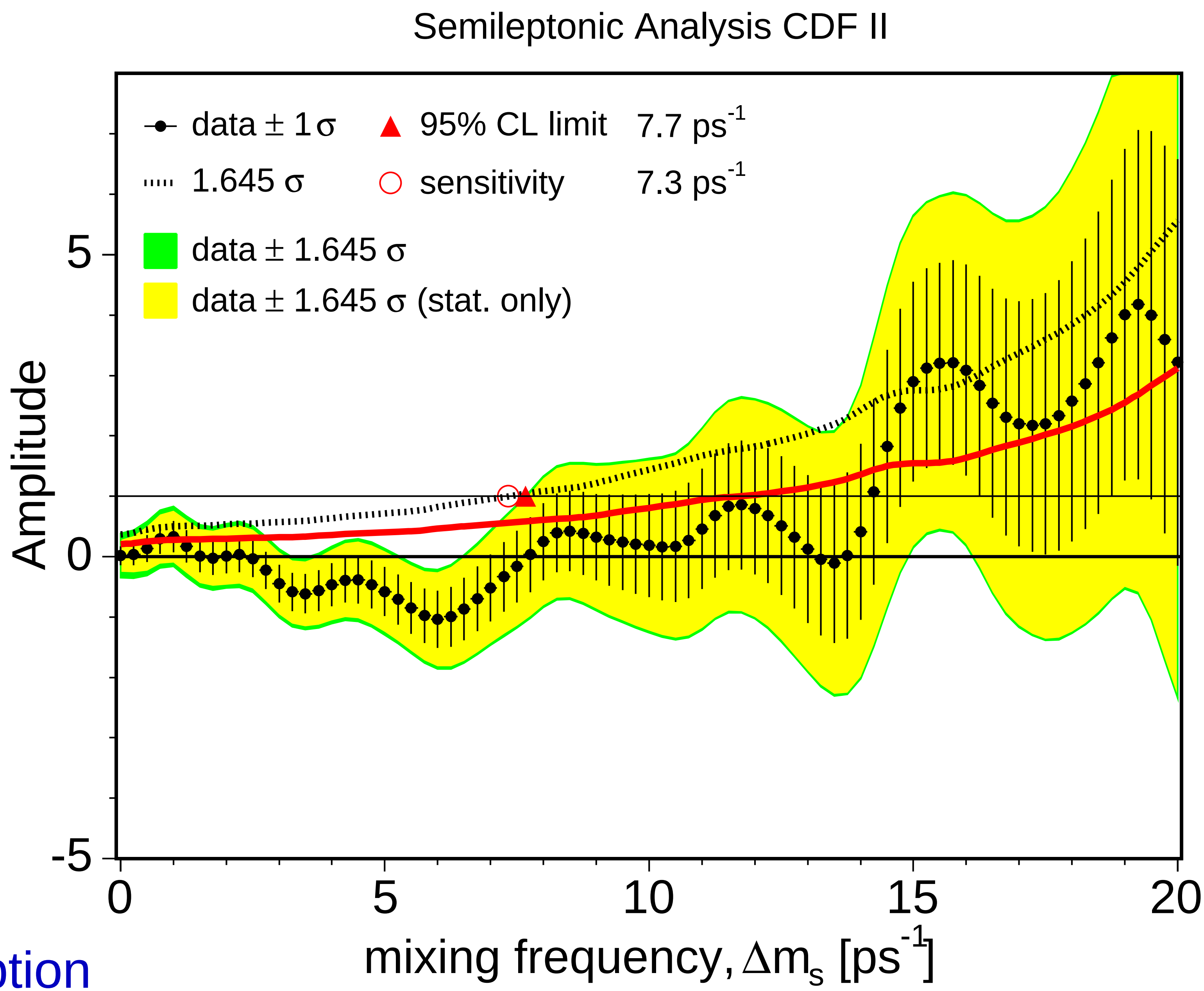
Improvements: Hadronic



Assumptions

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

Improvements: Semileptonics



Assumption

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