Bs Mixing at CDF

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Plan

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  - Δms measurement
  - |Vtd|/|Vts| measurement
- Conclusions

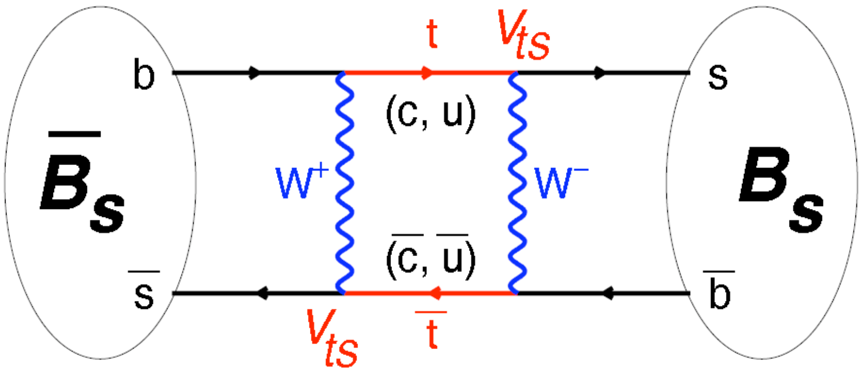
Theory of Bs mixing

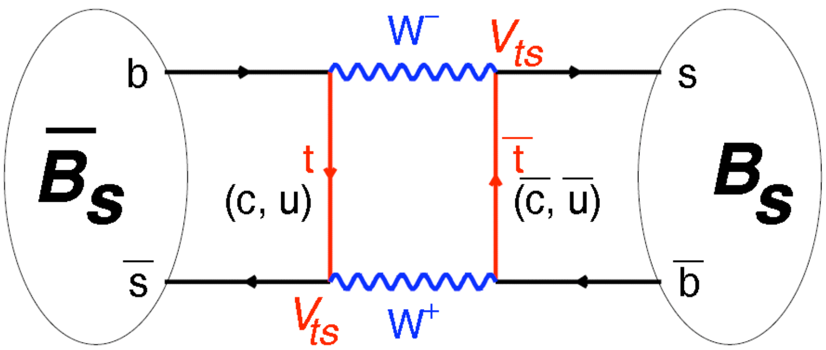
- In SM neutral B mesons can transform to its antiparticles
- Flavor eigenstate is different from mass eigenstate
- Mixture of two mass eigenstates:

(No CP violation case)

$$|B_H\rangle = \frac{1}{\sqrt{2}}\left(|B\rangle + |\overline{B}\rangle\right)$$

$$|B_L\rangle = \frac{1}{\sqrt{2}}\left(|B\rangle - |\overline{B}\rangle\right)$$



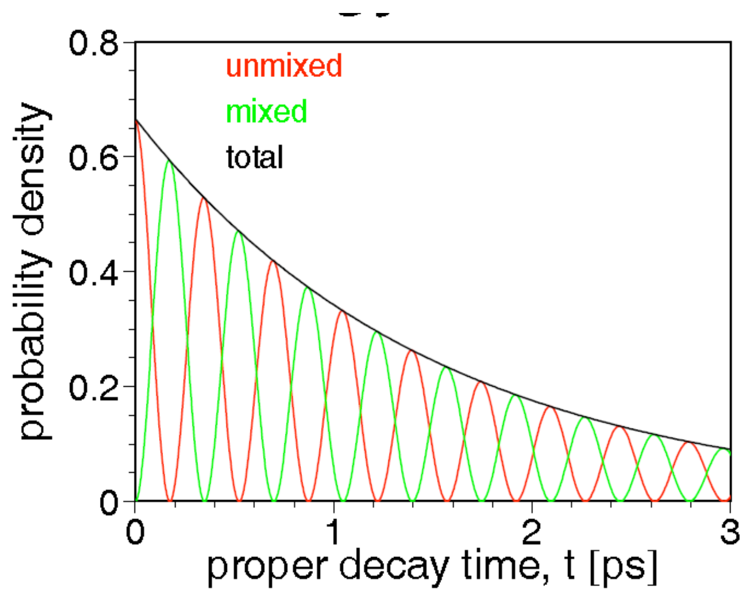


Theory (cont….)

- Behavior in proper time:

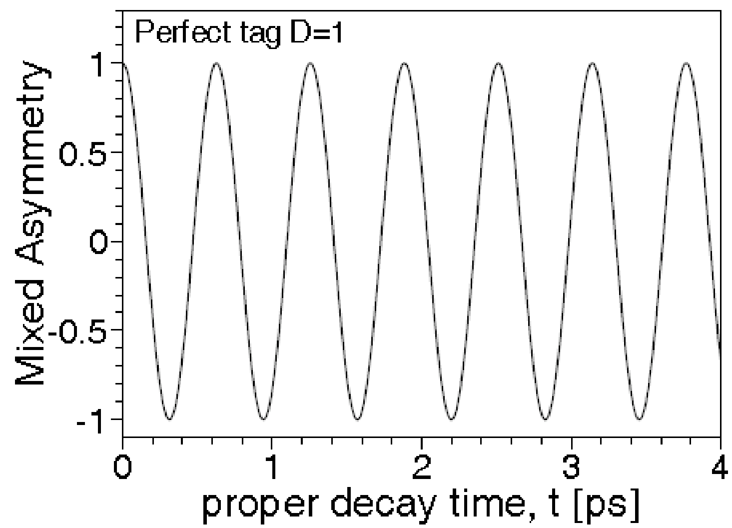
$$P(t)_{B^0\to B^0} = \frac{1}{2\tau}e^{-t/\tau}(1+\cos\Delta m t)$$
$$P(t)_{B^0\to \overline{B^0}} = \frac{1}{2\tau}e^{-t/\tau}(1-\cos\Delta m t)$$

where $\Delta m = m_H - m_L$



- Mixing asymmetry:

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



SM expectation for Δm

- B^0/B_s mix through box diagram:

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

- Uncertainties cancel in ratio:

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

Δm_d measured to high precision:

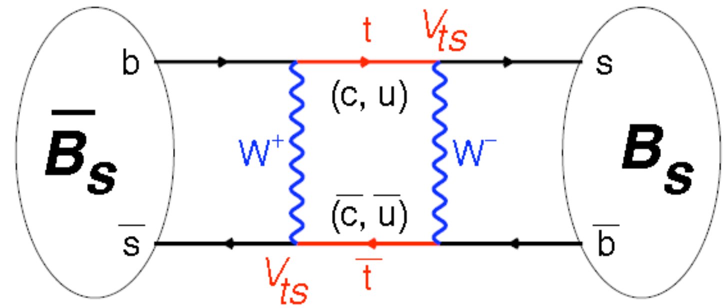
$$\Delta m_d = 0.507 \pm 0.005 \text{ ps}^{-1}$$

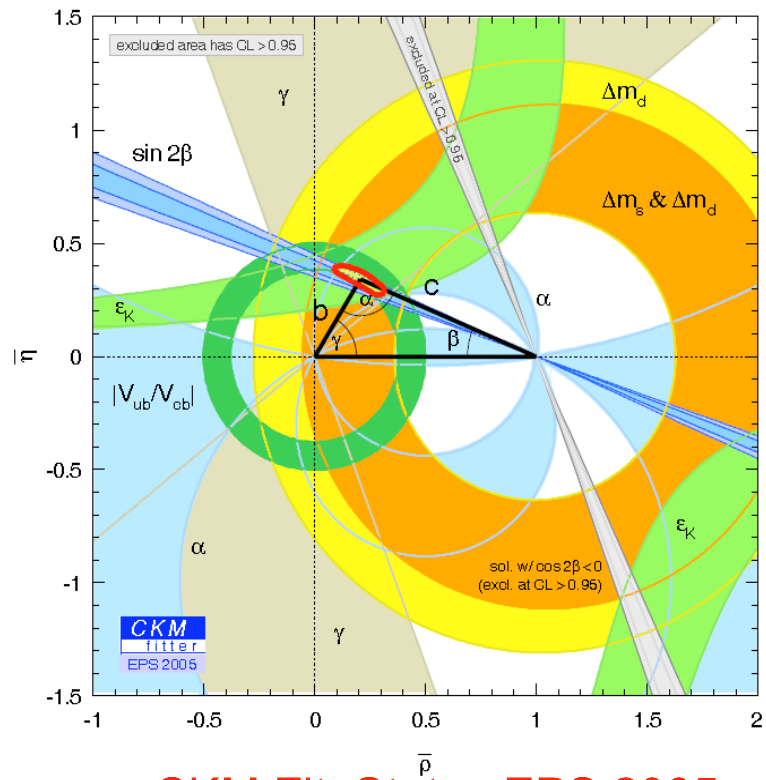
Lattice QCD: $\xi = 1.21\,^{+0.047}_{-0.035} \approx 3.4\%$

M Okamoto, hep-lat/0510113

- Standard Model CKM fit:

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





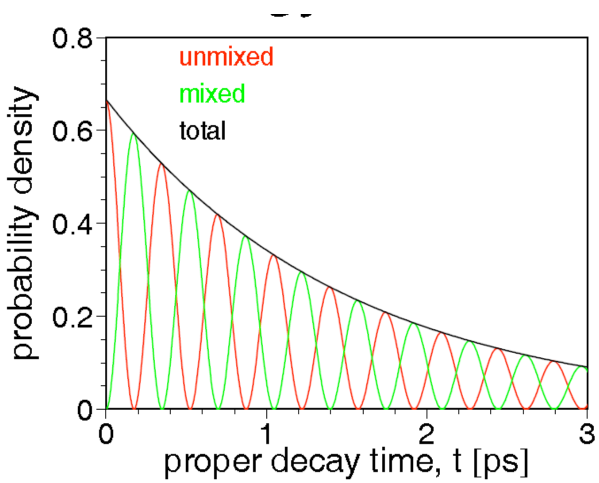
CKM Fit: Status EPS 2005

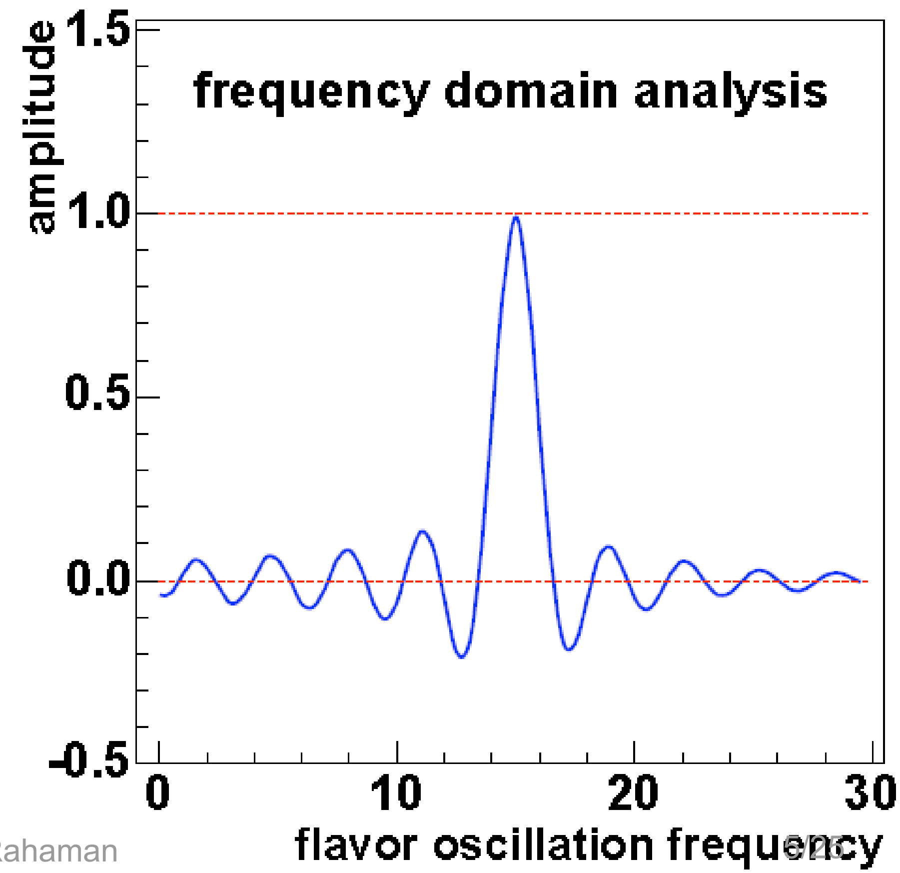
Fourier analysis

NIM A384 (1997) 491

- Unbinned likelihood fit:
  - Introduce artificial amplitude, A

    $p \sim exp(-t/\tau)(1 \pm AD \cos \Delta m t)$
  - Scan Δm for signal: fit amplitude, A
    - A = 1 at mixing frequency
    - A = 0 otherwise
  - Determine Δm when A is consistent with 1





Statistical significance

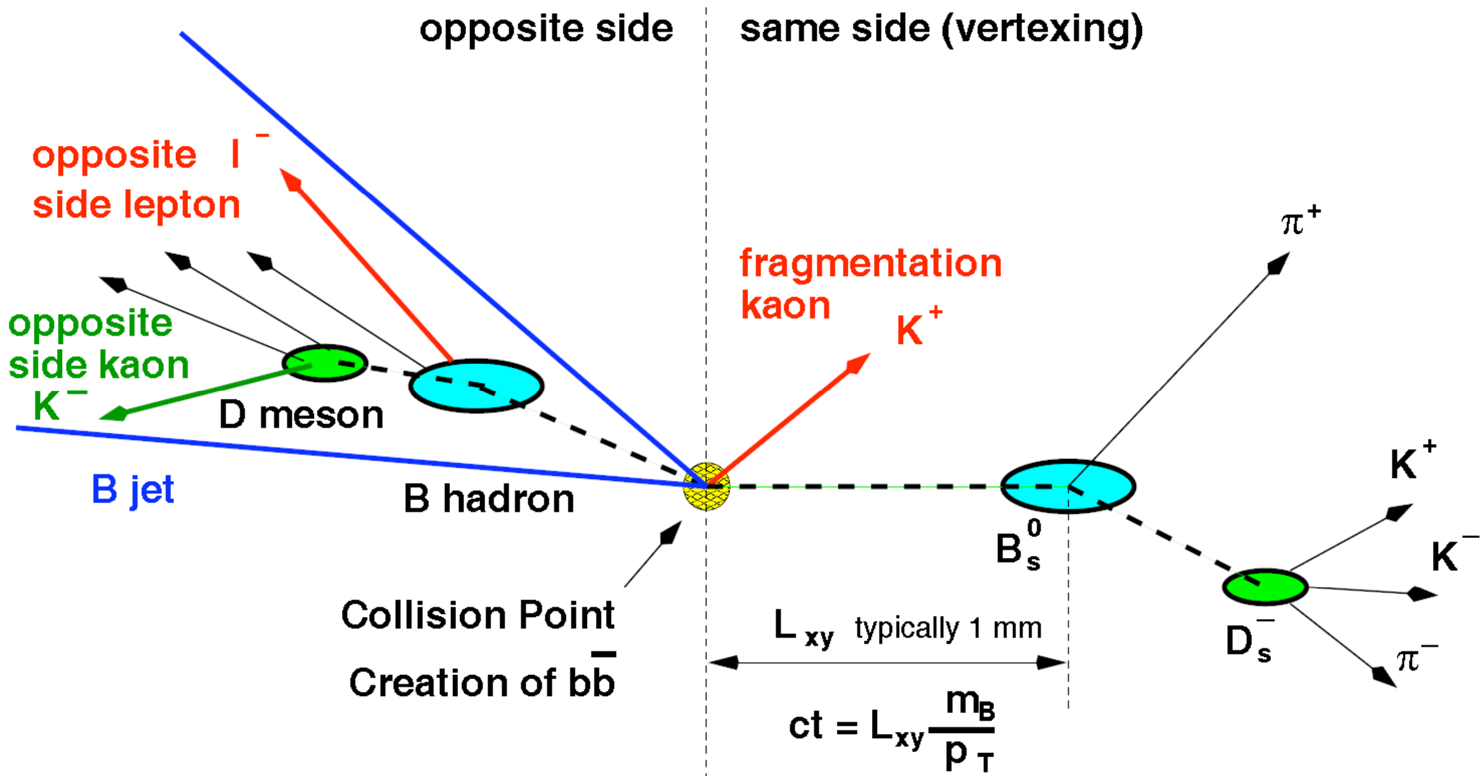
- Statistical power of the analysis:

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

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

- Signal statistics and purity
- Proper decay time resolution:
  - Hadronic: good ct and mass resolution
  - Semileptonic: inferior ct and mass resolution
- Tagging:
  - efficiency $\varepsilon =$ probability to have a tag
  - dilution $D = 1 - 2 \cdot w$, w: mistag probability

Analysis roadmap



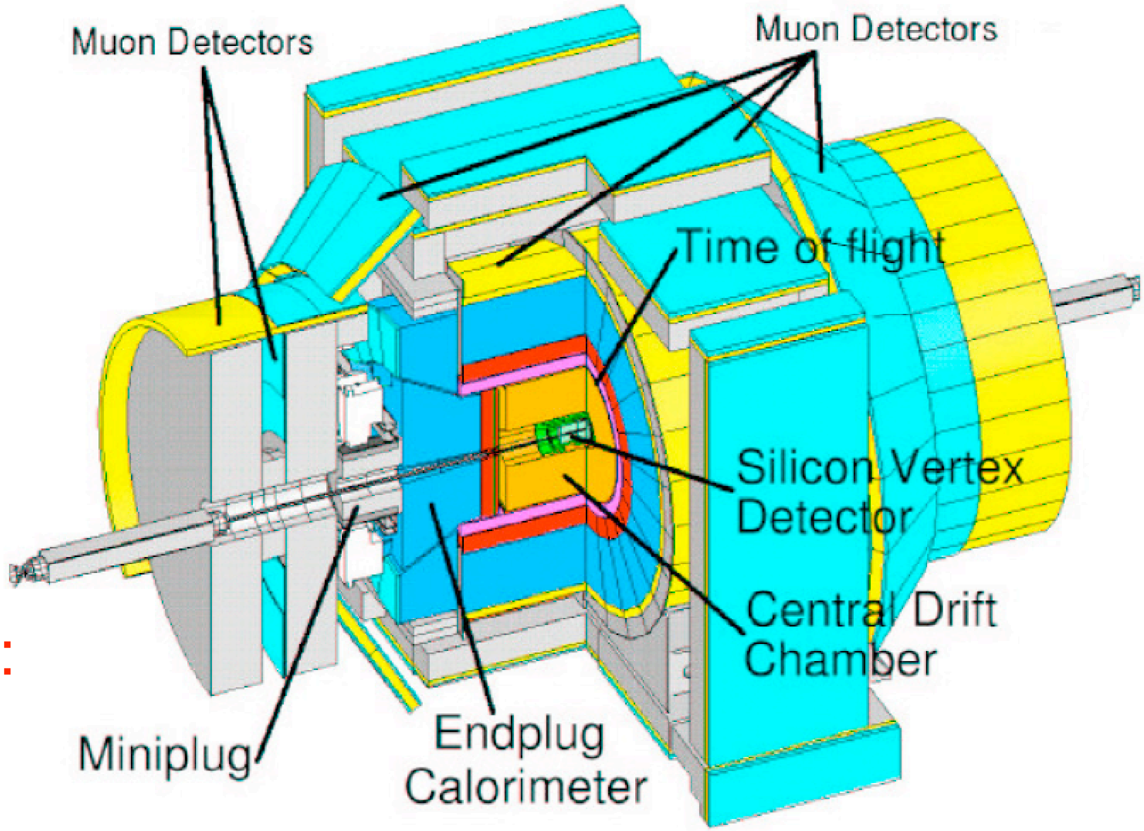
- Ingredients to measure mixing:
  - B reconstruction
  - B flavor at decay: final state
  - B flavor at production: flavor tagging
  - Proper decay length, ct at B rest frame

CDF-II detector

CDF-II detector: multi-purpose detector

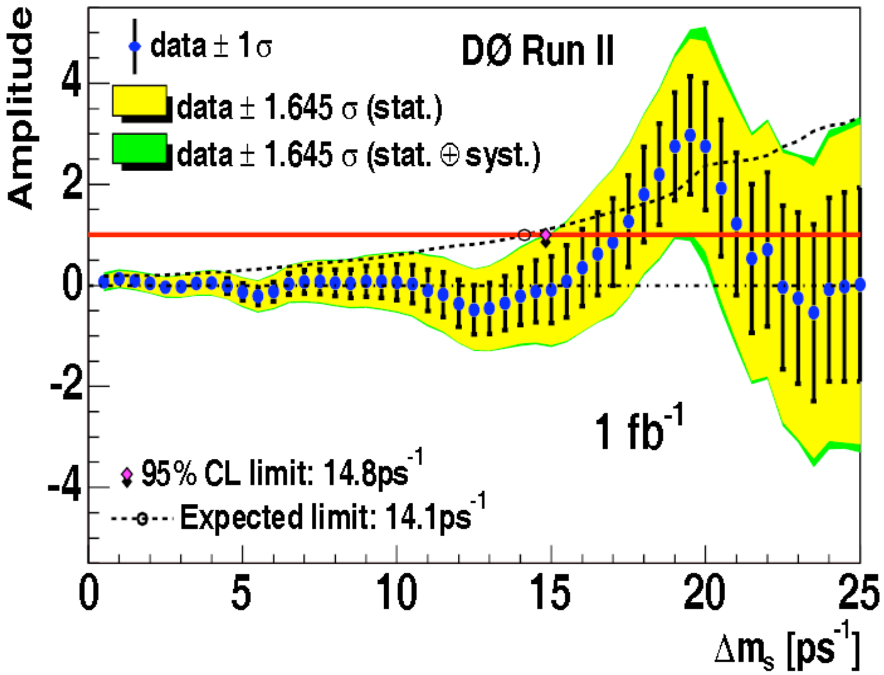
Important features:

- Yield:
  - SVT based triggers
- Momentum resolution:
  - $\sigma(p)/p < 0.1\%$
- Tagging power:
  - dE/dx in COT, TOF
- Proper time resolution:
  - SVXII and L00



Status: before this analysis

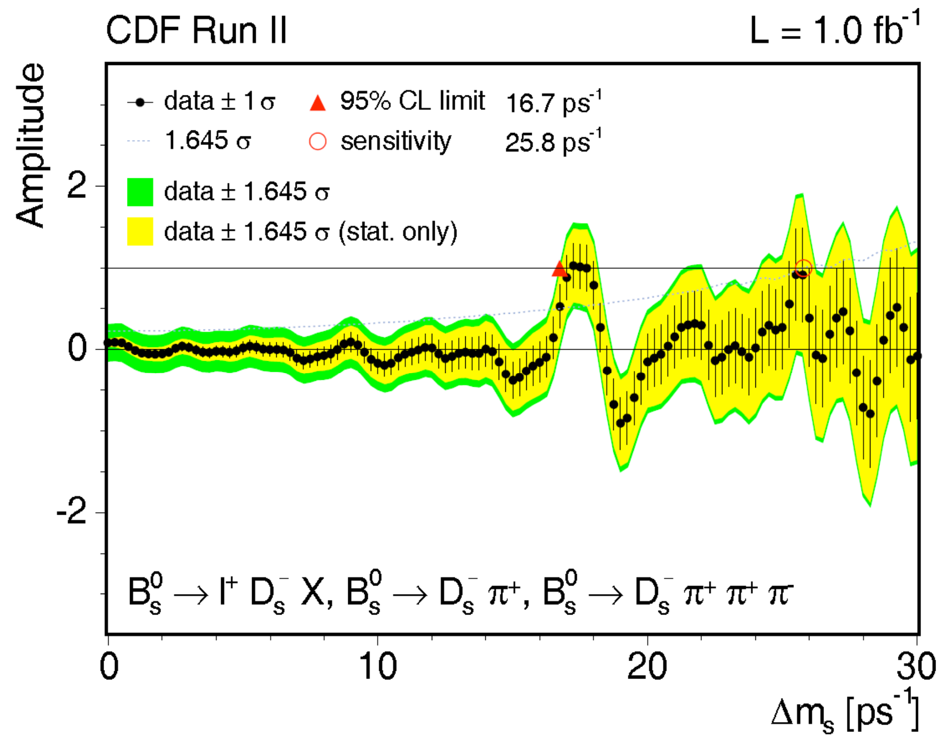
D0 results: PRL 97 (2006) 21802



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

p-value about 5.0%

CDF results: PRL 97 (2006) 062003



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

p-value: 0.2%

This talk:
Improved analysis with same 1 fb^{-1} data

Bs reconstruction

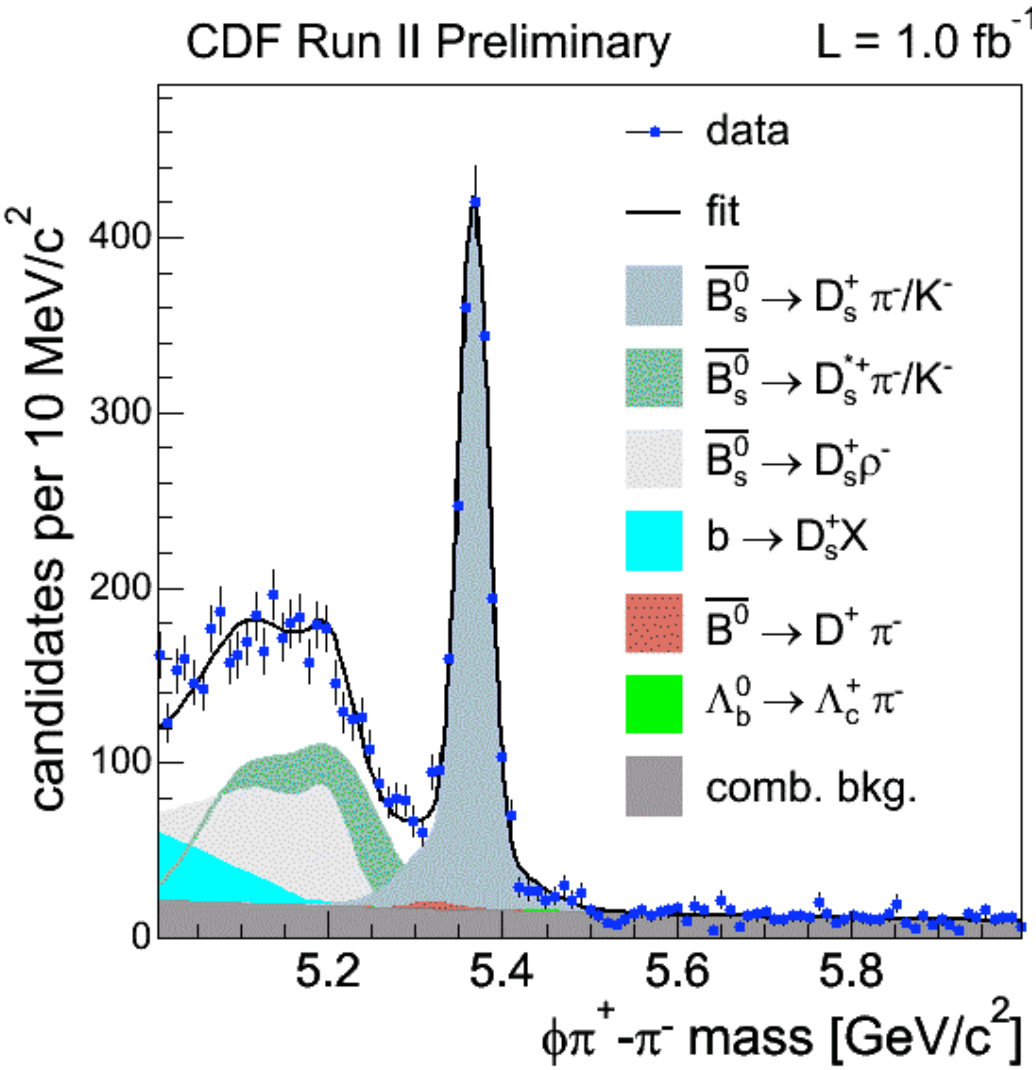
Hadronic modes

- Fully reconstructed:
  - Use PID quantities (dE/dx, ToF)
  - Loose cut based pre-selection
  - Neural Net based final selection

Added partially reconstructed decays

- This improves signal yield

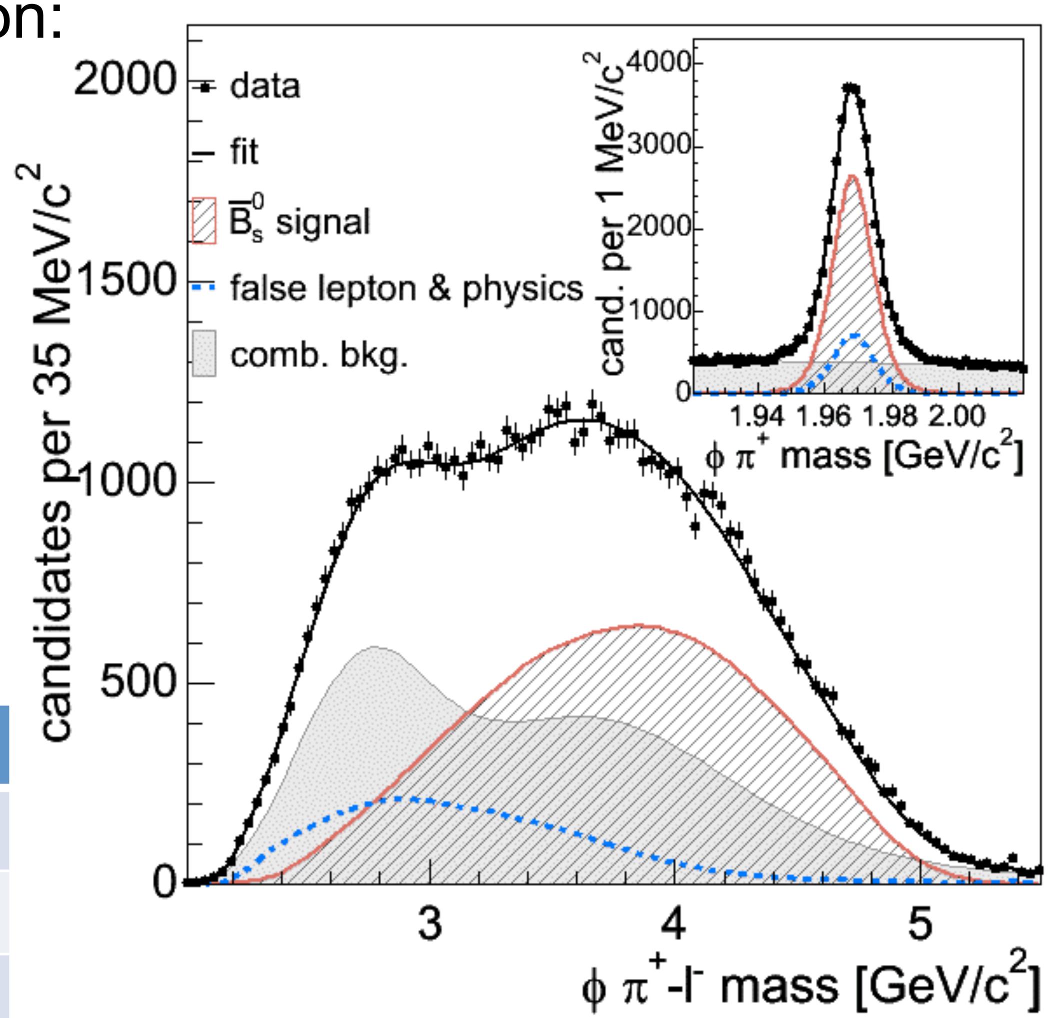
B_s Decay	Signal	April
$D_s(\phi\pi)\pi$	2000	1600
Partially rec.	3100	—
$D_s(K^*K)\pi$	1400	800
$D_s(3\pi)\pi$	700	600
$D_s(\phi\pi)3\pi$	700	500
$D_s(K^*K)3\pi$	600	200
$D_s(3\pi)3\pi$	200	—
Total	8700	3600



Semileptonic modes

- Use PID to improve selection:
  100% S/N improvement in Φπ and K*K modes
- Add new trigger path:
  improved yield 61K from 37K
- Exploit IDs mass in the oscillation fit:
  $\Delta p/p \approx$ 3% at high mass
  $\Delta p/p \approx$ 20% at low mass

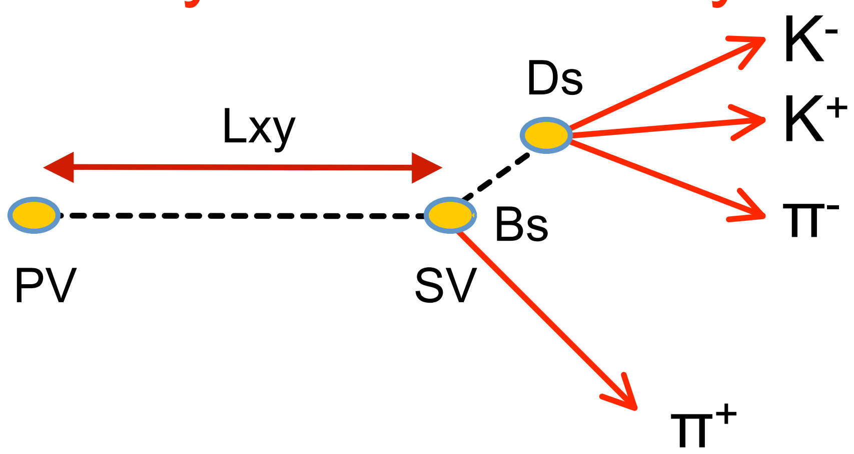
decay modes	candidates
Ds(Φπ)lX	29,600
Ds(K*K)lX	22,000
Ds(3π)lX	9,900



Proper decay time reconstruction

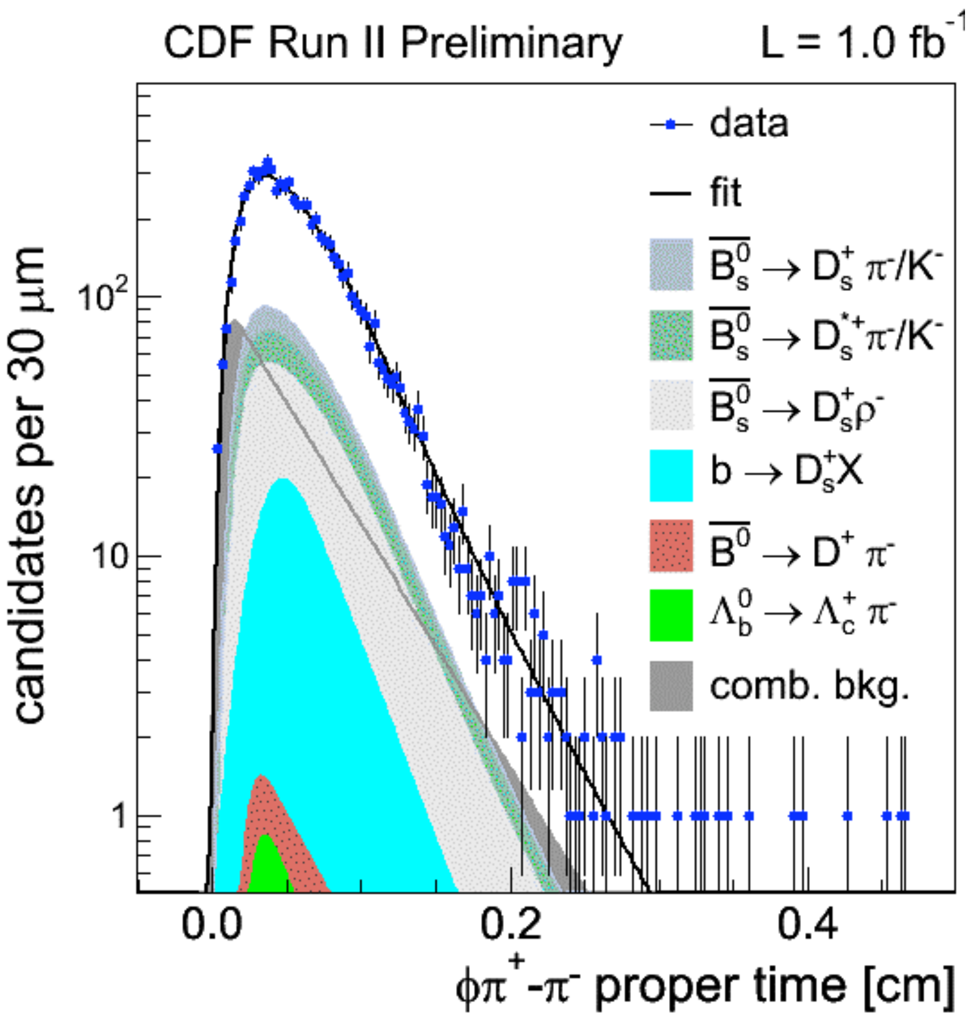
Hadronic mode

- Fully hadronic decay:



The proper decay length is computed from the flight distance in transverse plane, Lxy and the momentum of Bs:

$$ct = L_{xy} \frac{m_{B_s}}{p_T(B_s)}$$



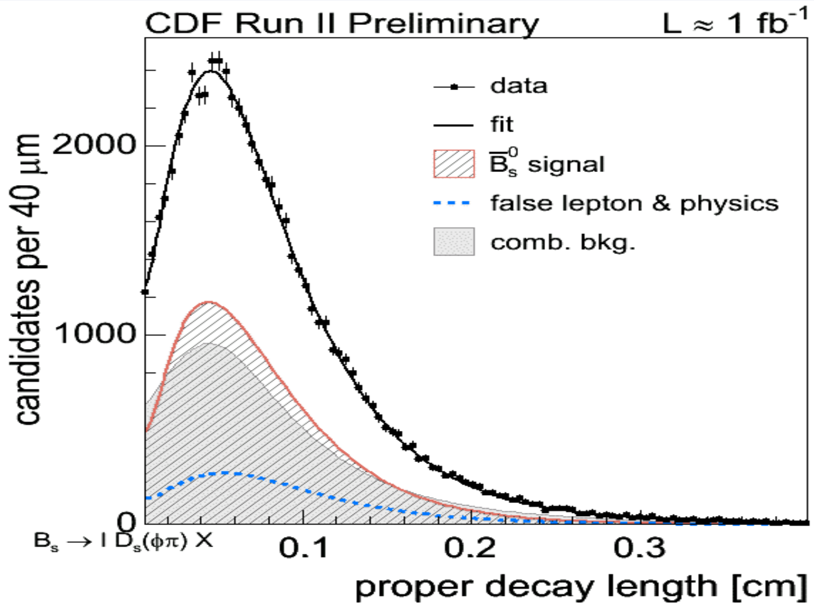
Semileptonic mode

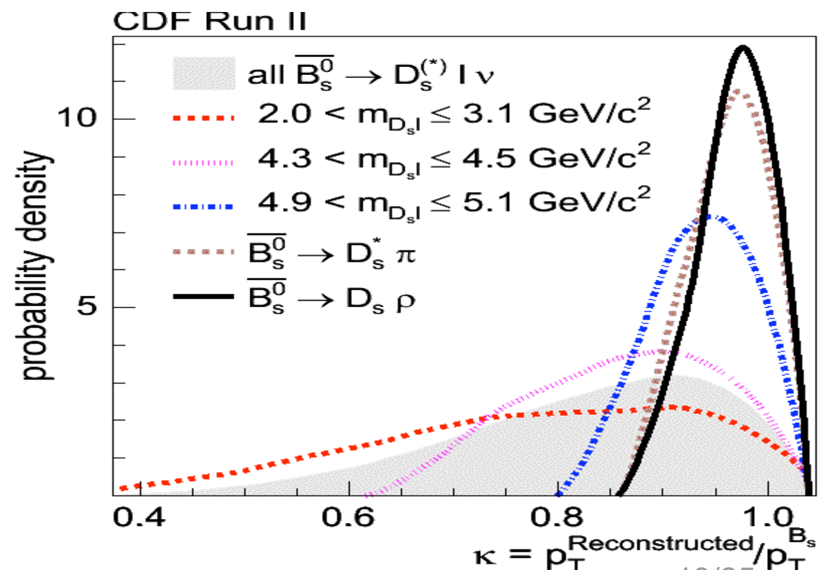
- Semileptonic and partially reconstructed decay:
  - missing momentum, reconstruct (psedo-) proper decay length:

$$ct = L_{xy}\frac{m_{B_s}}{p_T(D_s l)}k$$

  - Correction factor, k from MC

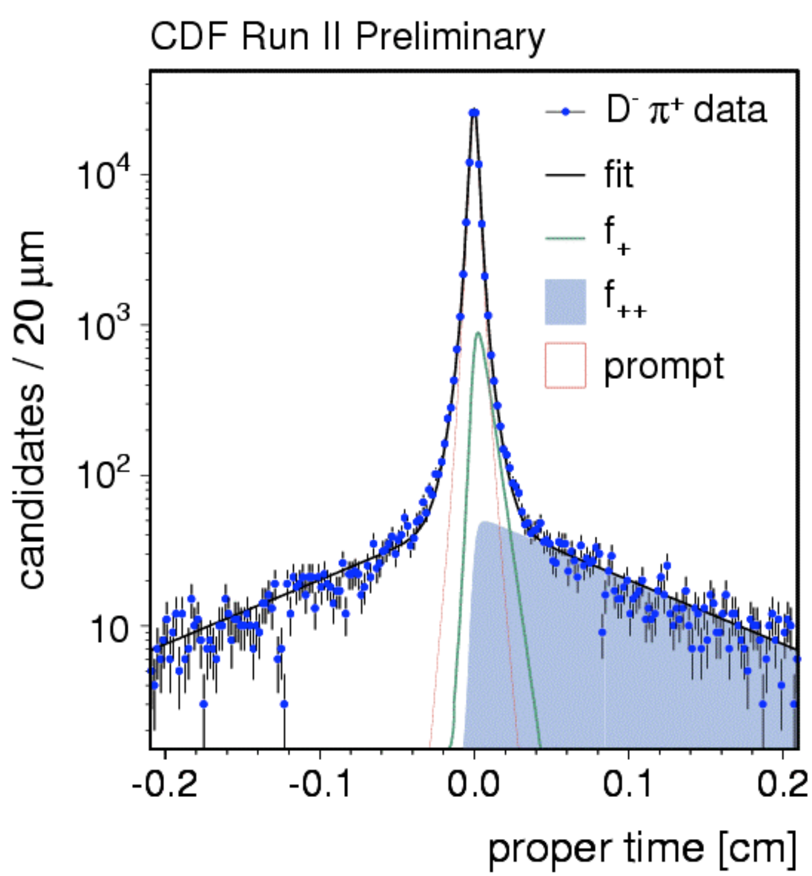
$$k = \frac{p_T(D_s l)}{p_T(B_s)}$$



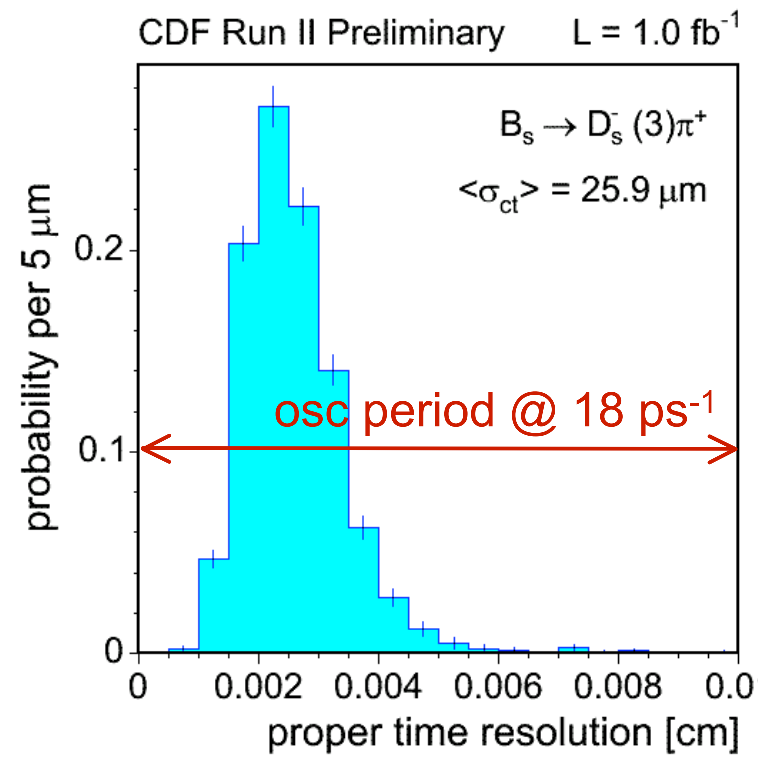


Decay time resolution

- Calibrate proper time resolution:
  - use prompt D^- plus pion sample
  - calibrate by fitting lifetime



- Resolution for hadronic decay:



- Use this information per candidate in the likelihood fit

SVT bias correction

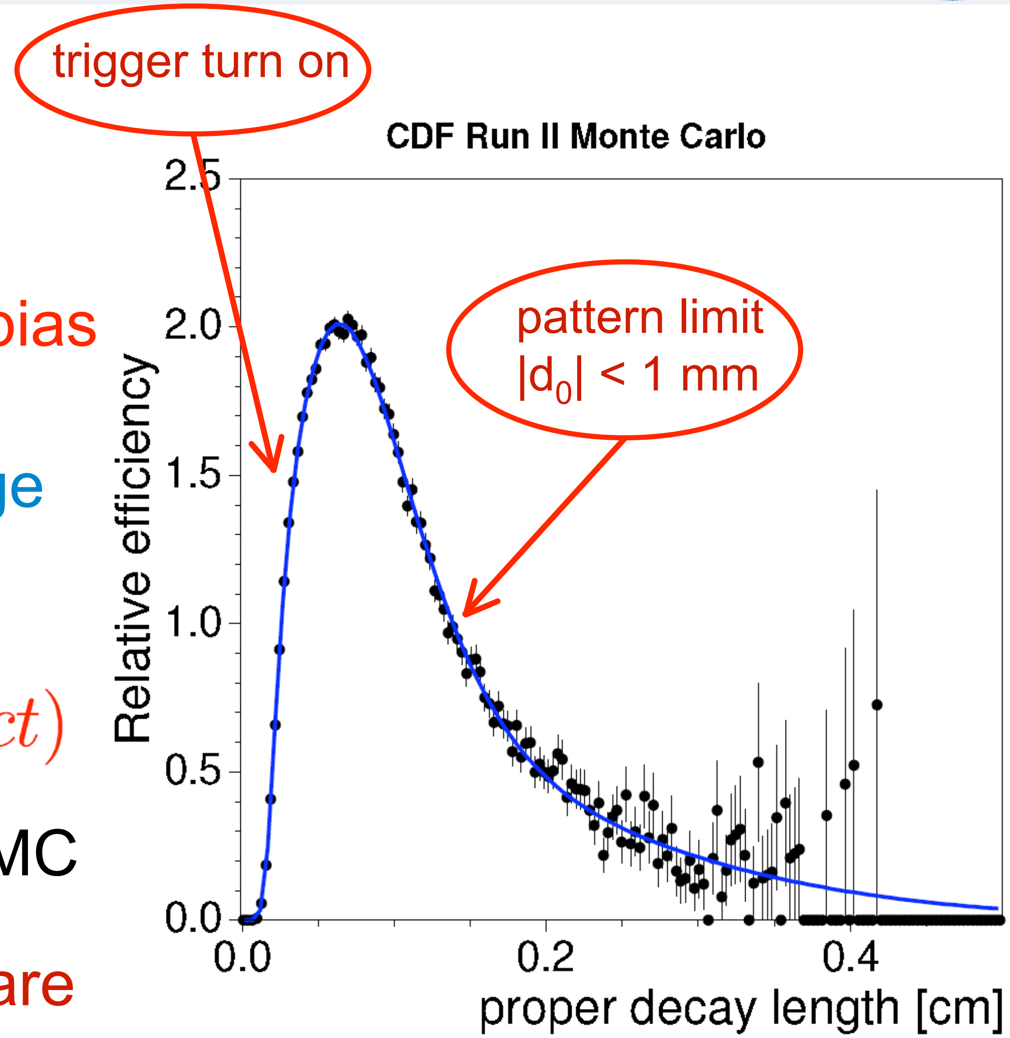
- SVT d_0 cut:

  120 μm < $|d_0|$ < 1 mm

- SVT trigger and selection bias lifetime distribution
- Correct this bias on average using efficiency function

$$P \sim e^{-\frac{k.ct'}{c\tau}} \otimes R(ct', ct).\epsilon(ct)$$

Obtained from MC

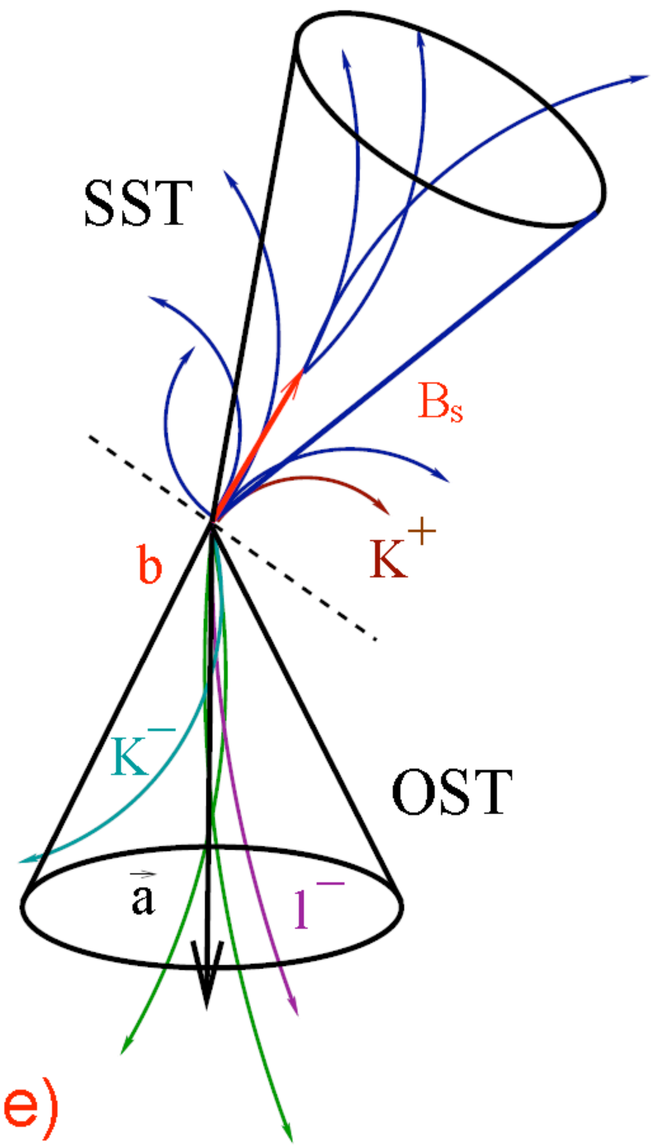


Lifetime measurements are consistent with PDG values

Flavor tagging

Opposite side tag

- Soft lepton tagger:
  - look for $B \rightarrow \ell X$ decay
  - lepton charge gives b-flavor
- Jet charge tagger:
  - look for jet or secondary vertex
  - jet charge indicates b-flavor
- Kaon tagger:
  - look for kaon in OS
  - k-charge gives b-flavor



- Neural Network combines taggers
- OST performs identically on $B_{s,u,d}$
- Calibrate on high stat B^0/B^+ data

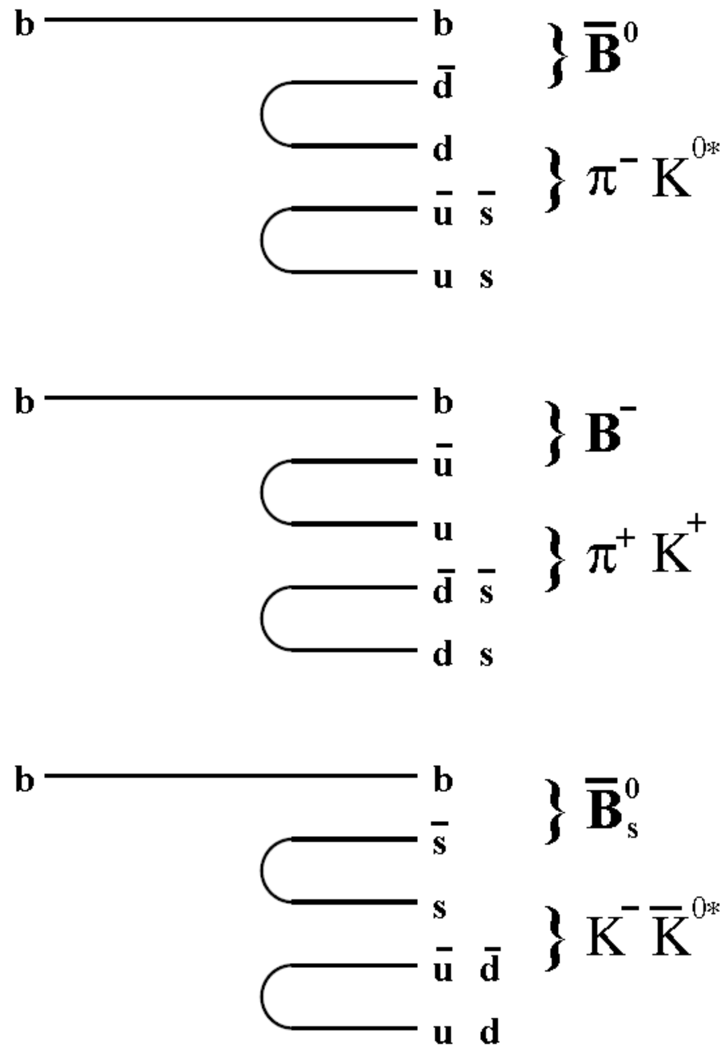
$\varepsilon D^2 = 1.8\%$ (+20% relative increase)

Same side tag

- Exploit charge correlation between b and fragmentation tracks:
  - B^- and B^0 likely to have a pion nearby
  - B_s likely to have a kaon nearby
- Neural Network separates K and π:
  - Use PID quantities: TOF and dE/dx
  - Candidate kinematics: additional power
- SSKT different for $B_{s,u,d}$
- Need to rely on MC simulation
- Data and MC thoroughly compared

Hadronic : $\varepsilon D^2 = 3.5\%$

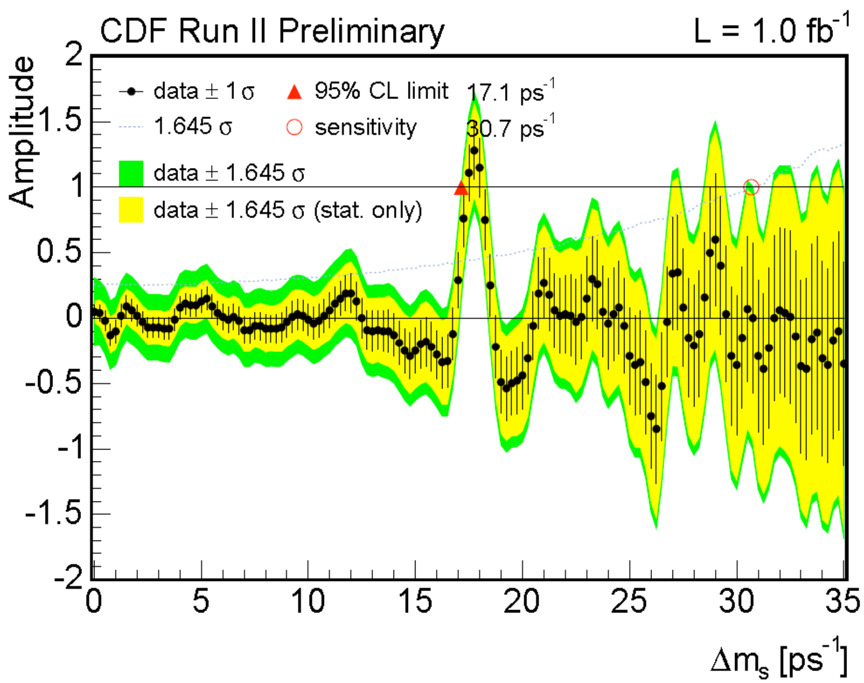
Semileptonic : $\varepsilon D^2 = 4.8\%$



Oscillation analysis

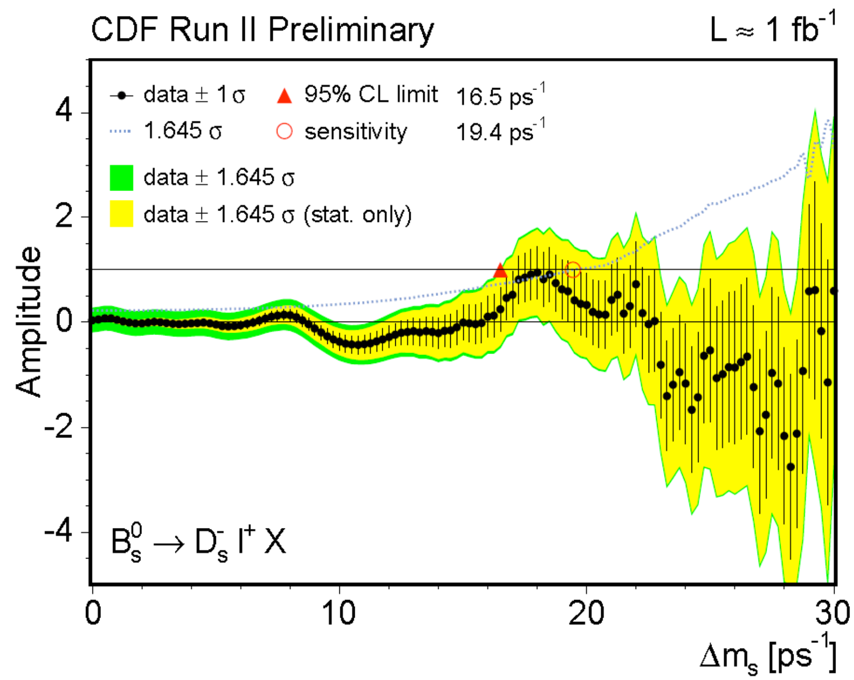
Amplitude scan

Hadronic modes



A = 1.28 ± 0.22

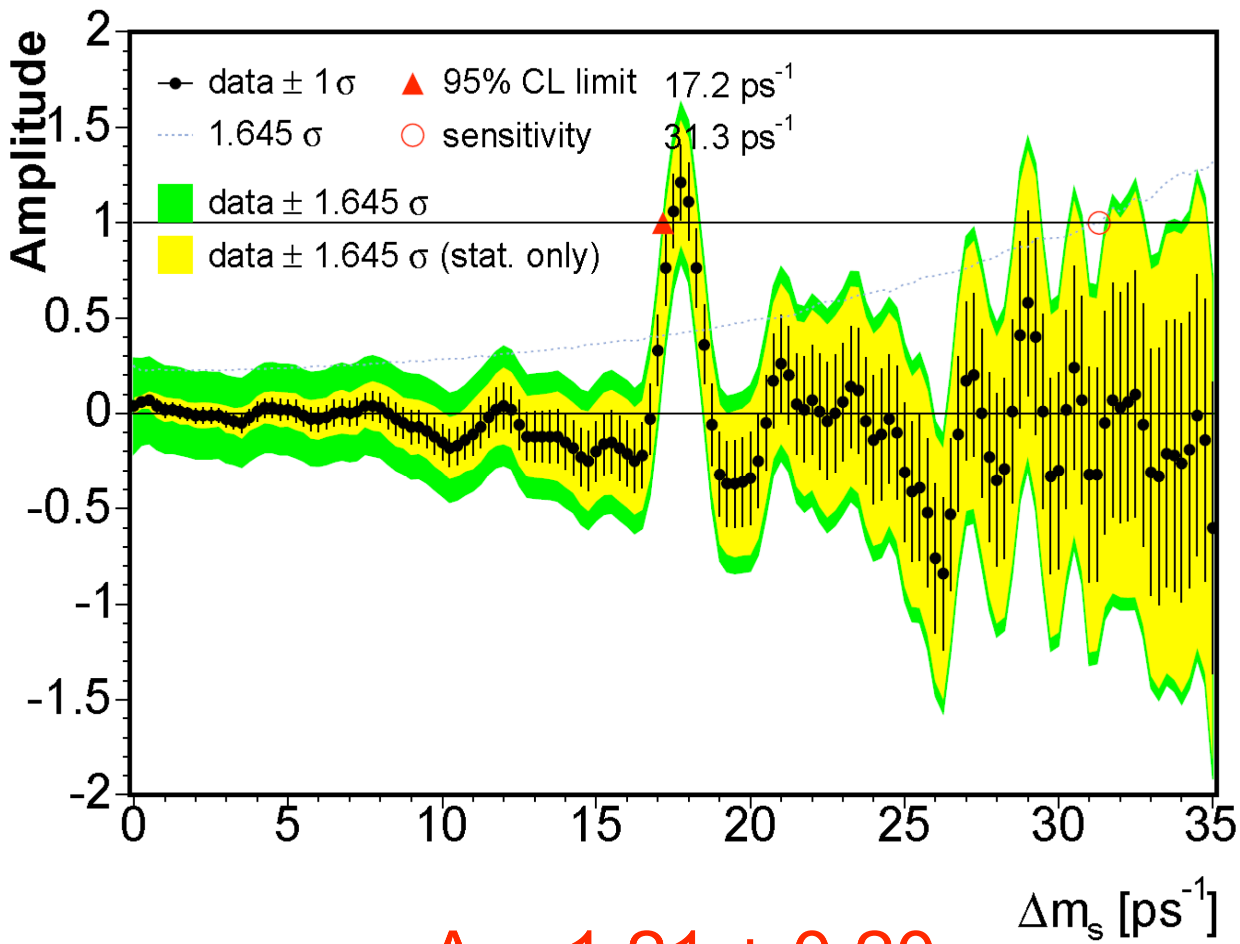
Semileptonic modes



A/σ ≈ 2

Hadronic scan compatible with A=1 at $\Delta m_s \approx 17.75$ ps^{-1}

Combined amplitude scan



A = 1.21 ± 0.20

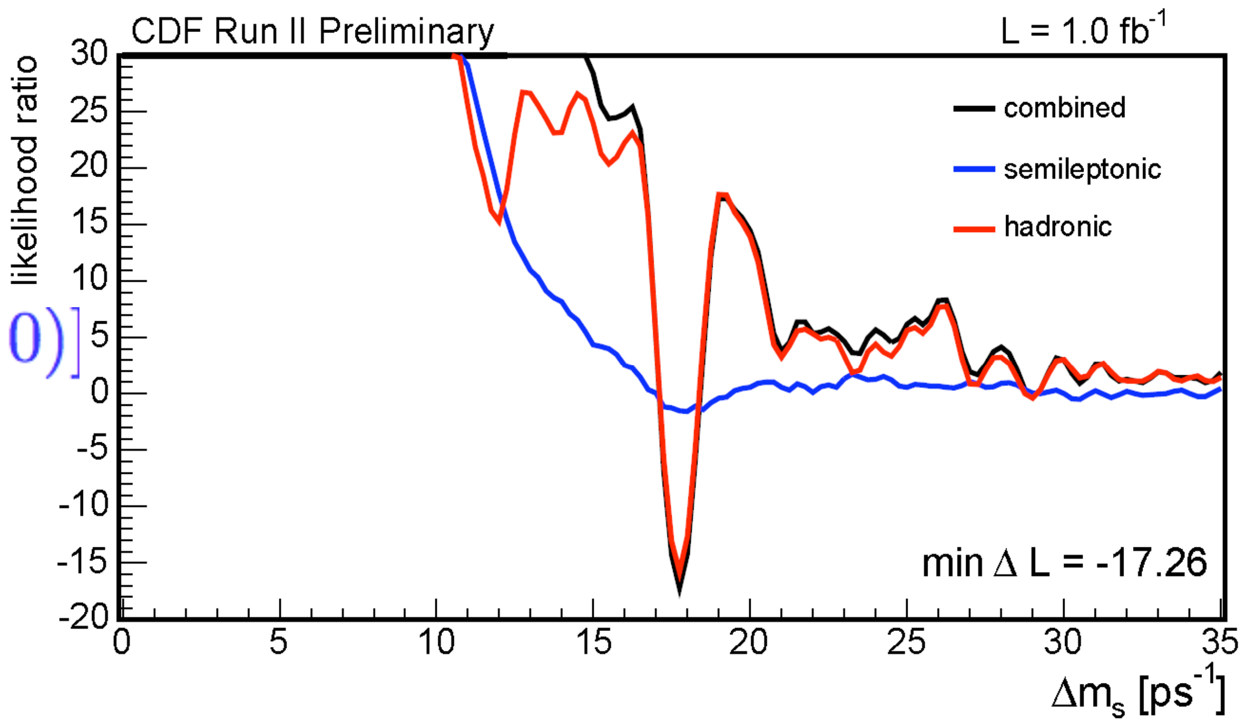
compatible with 1 at Δm_s = 17.75 ps^{-1}

Likelihood profile

Likelihood ratio

$$log[\mathcal{L}(A=1)/\mathcal{L}(A=0)]$$

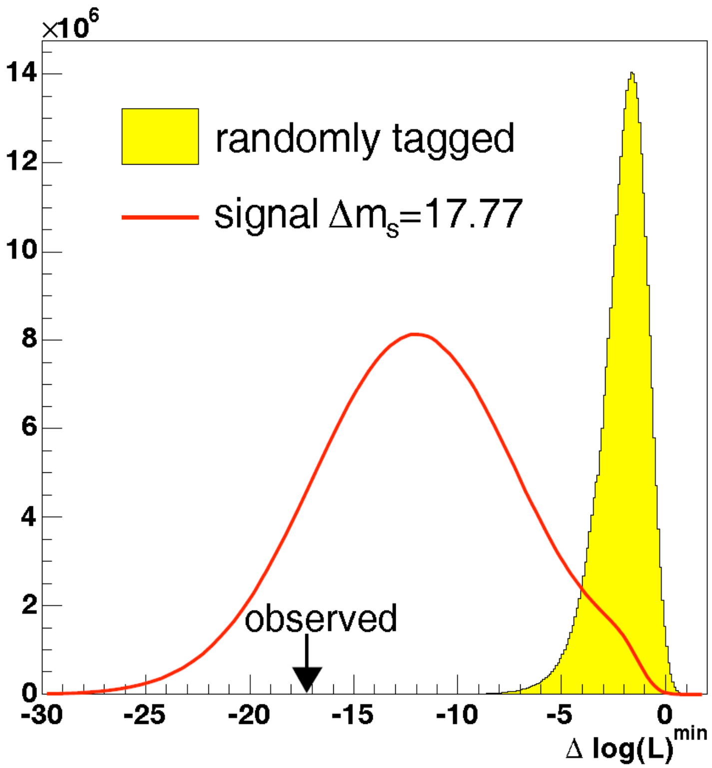
Minimum: -17.26

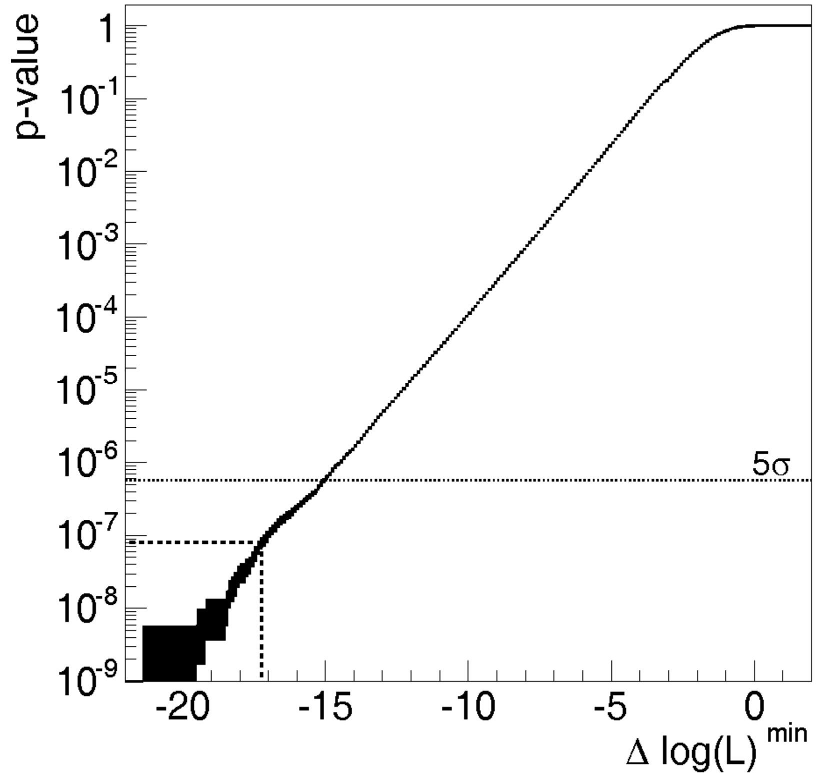


How often can random tags produce a minimum at least as deep ?

Likelihood significance

- Randomize tags decision
- Scan data in Δm_s 1 to 35 ps^{-1} and take the minimum





28 scan out of 350 millions trials

p-value $\approx 8 \times 10^{-8}$ corresponding to 5.4σ

Results

Δm_s measurement

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

Consistent with:

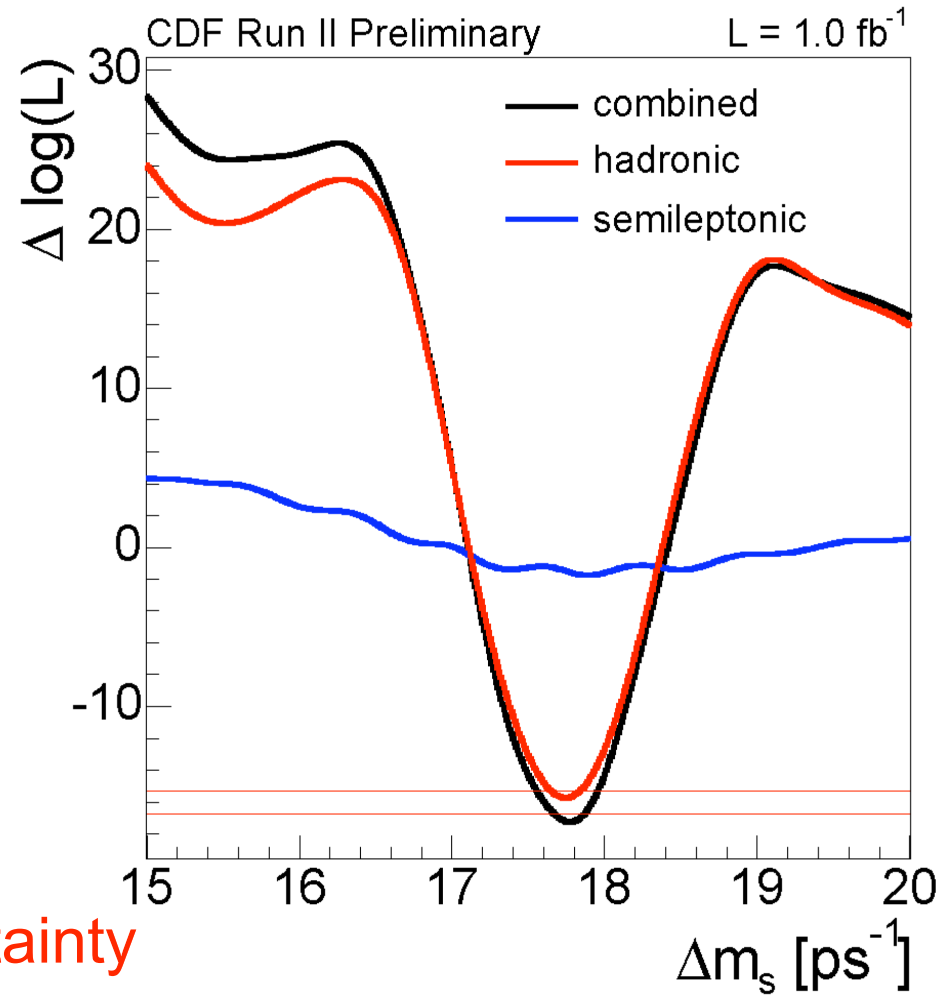
- SM prediction:

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

- CDF previous results:

  $17.31\ ^{+0.33}_{-0.18} \pm 0.07\ ps^{-1}$

  PRL **97**, 062003 (2006)



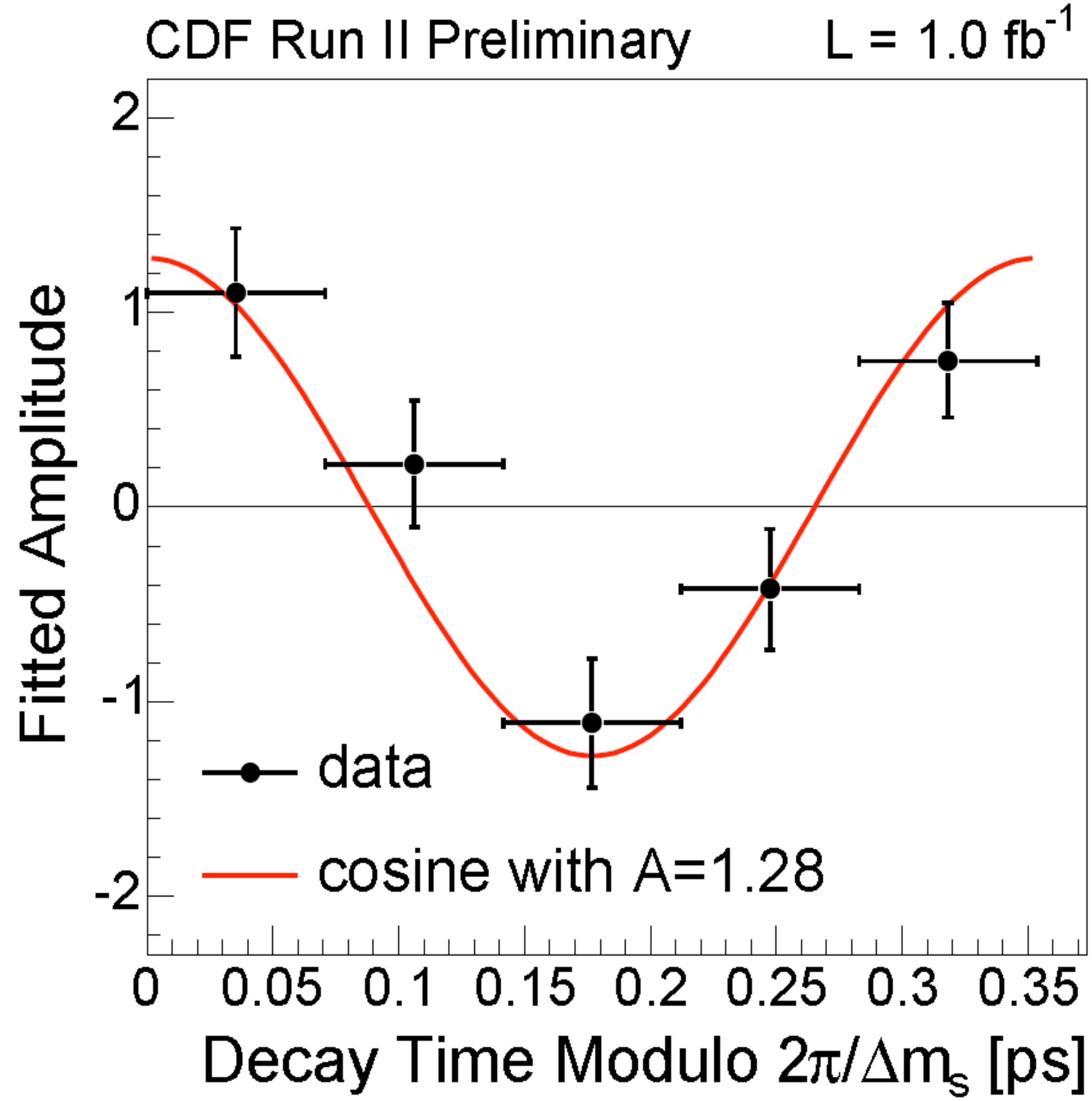
Main systematic: ct scale uncertainty

Asymmetry plot

- Proper decay time folded into a $2\pi/\Delta m_s$ interval
- Fitted A closely matches result of amplitude scan

$$\chi^2 = 4.77$$

$$A = 0 : \chi^2 = 30.5$$



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

- Use theoretical relation:

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

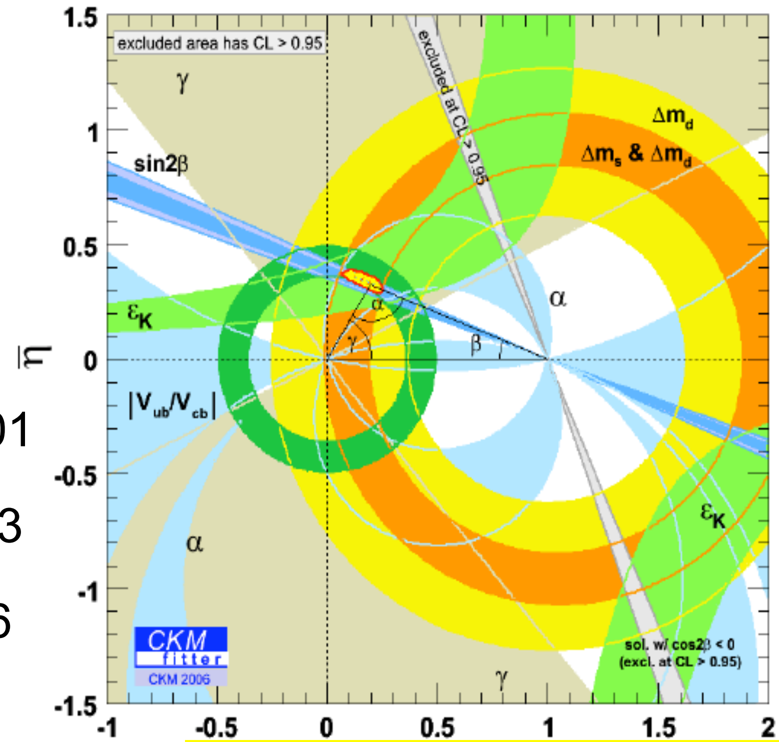
- Inputs:

$$\frac{m_{B_d}}{m_{B_s}} = 0.98390$$ PRL 96 (2006) 202001

$$\xi = 1.21 \,^{+0.047}_{-0.035}$$ hep-lat/0510113

$$\Delta m_d = 0.507 \pm 0.005$$ PDG 2006

Impact on global picture



Karim Trabelsi ckm2006

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

Error dominated by theoretical uncertainty

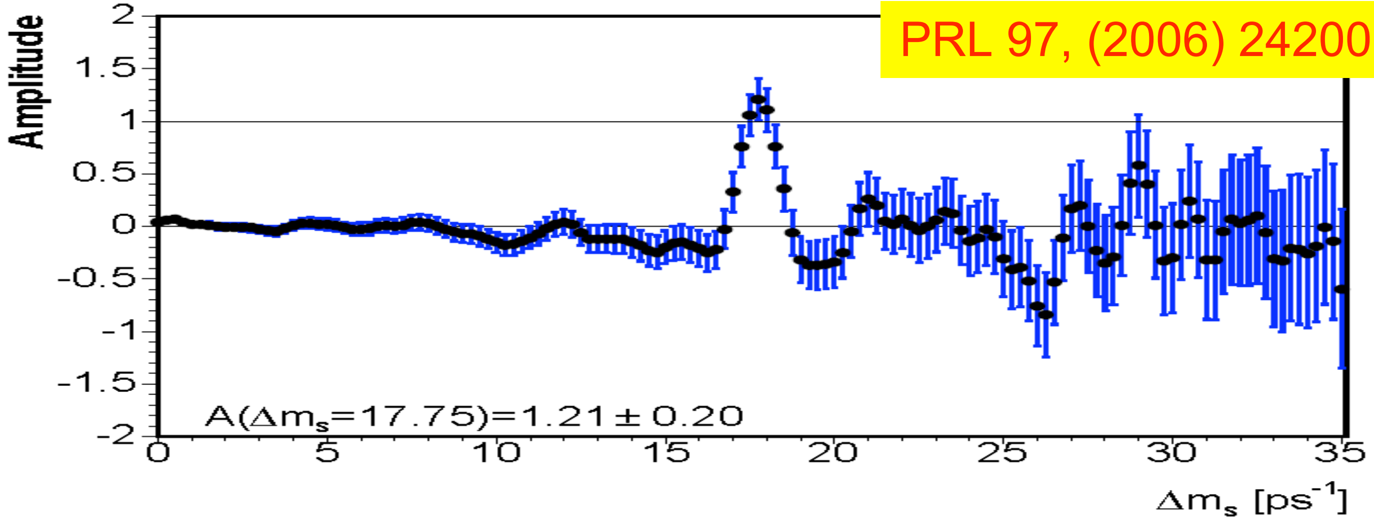
Conclusions

- Observed signal consistent with B_s-$\overline{B}_s$ oscillations
  Significance: 5.4σ corresponding to p-value 8×10^{-8}
- Measured the oscillation frequency:

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

- Most precise measurement of CKM parameters:

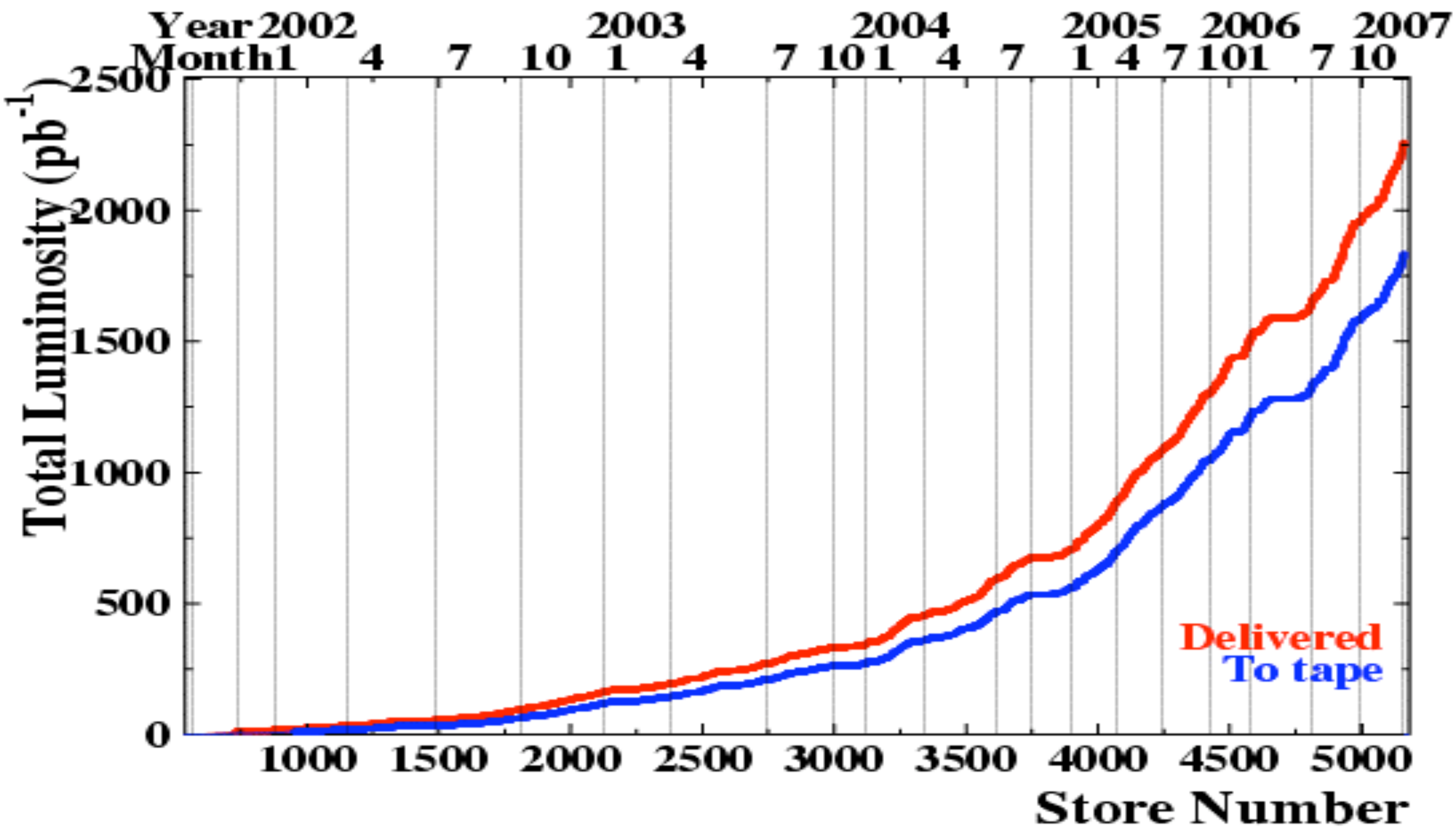
$$\frac{|V_{td}|}{|V_{ts}|} = 0.2060 \pm 0.0007(\mathrm{exp})\ ^{+0.0081}_{-0.0060}(\mathrm{theo})$$



PRL 97, (2006) 242003

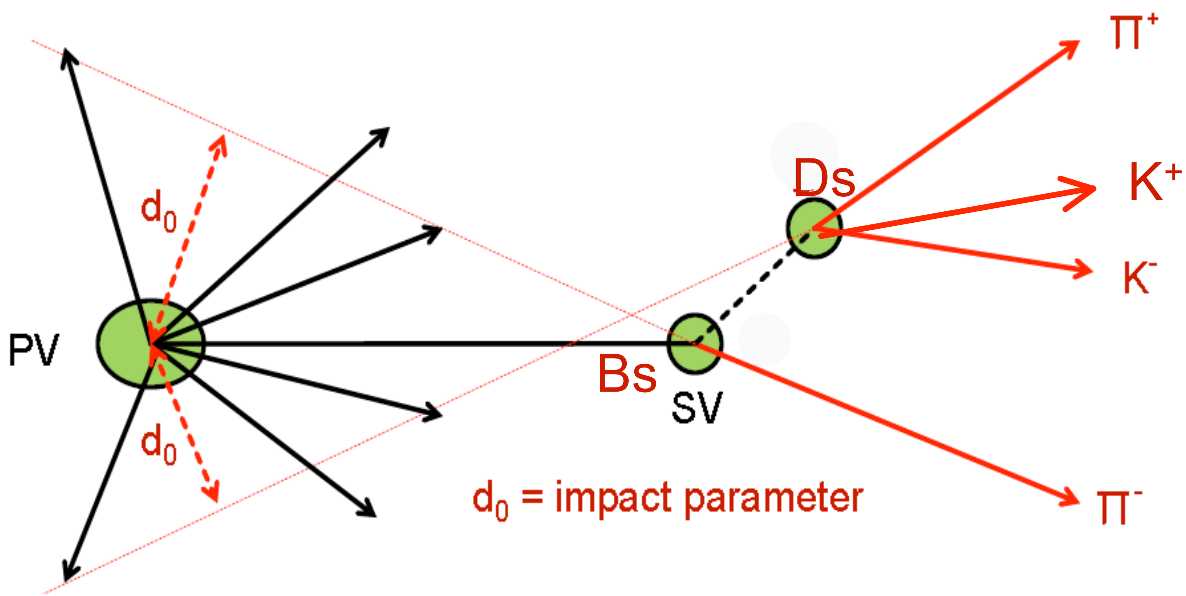
BACK-UP

Data used for this analysis

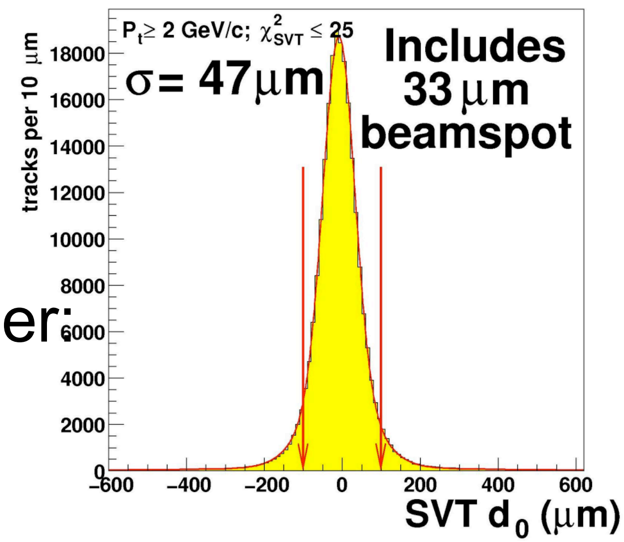


Data used for this analysis is 1 fb^{-1}

Displaced track triggers



Applied at L2 in a tier of three level trigger system



Impact parameter resolution

Hadronic B trigger:

at least two tracks with

- p_T > 2 GeV
- 120 μm < $|d_0|$ < 1 mm
- Lxy > 200 μm
-

Lepton + SVT trigger:

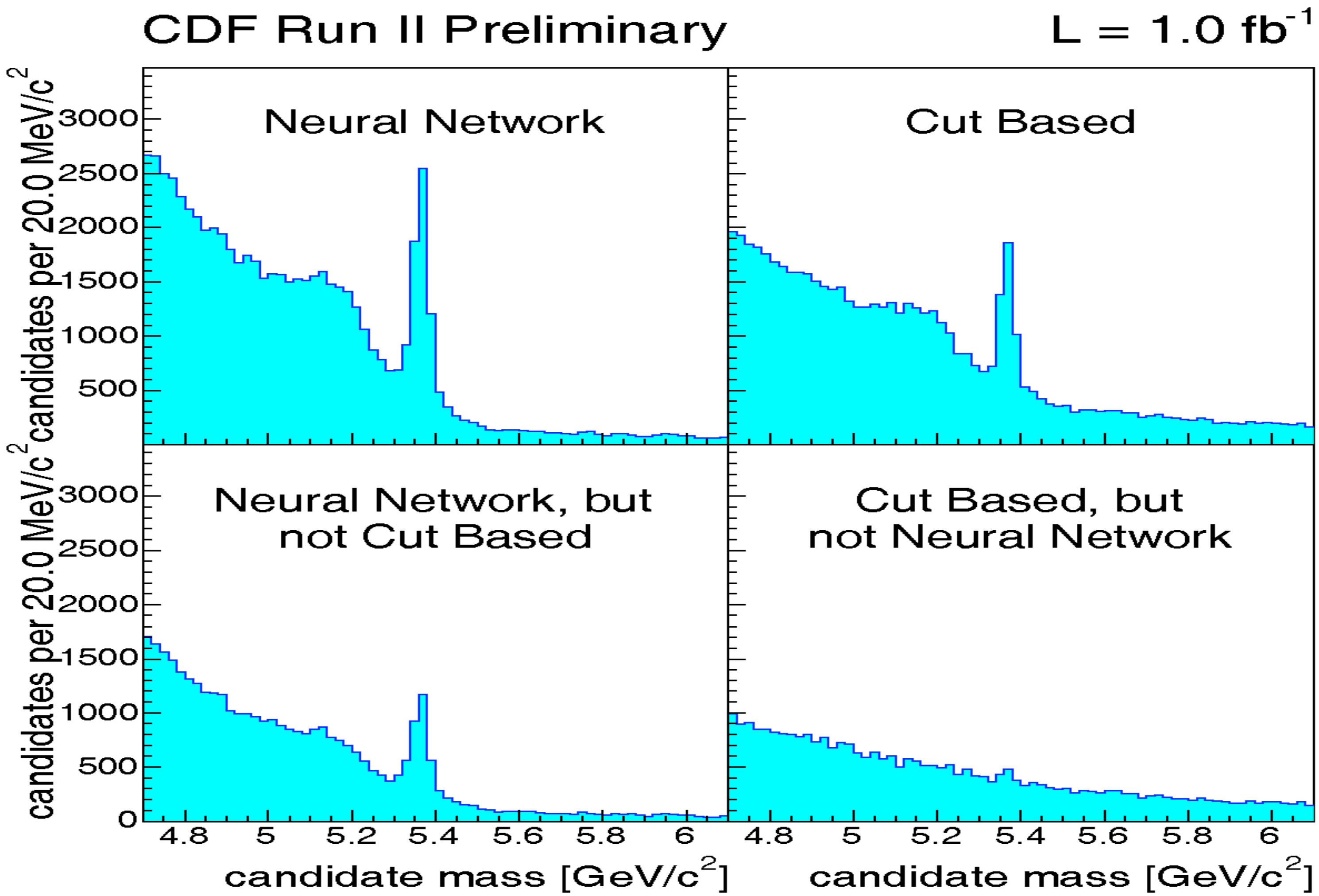
One lepton with

- p_T > 4 GeV

One SVT track with

- p_T > 2 GeV
- 120 μm < $|d_0|$ < 1 mm

Performance of NN selection



Importance of measurement

- Cabbibo-Kobayashi-Maskawa matrix:

Describe mixing between three quark pair families

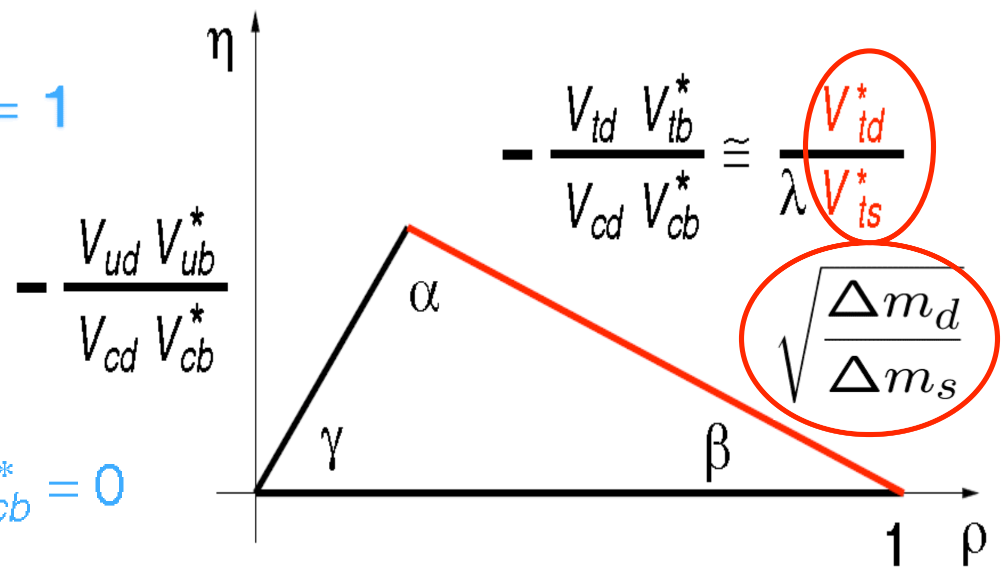
Wolfenstein parameterization:
$(\lambda = 0.2272 \pm 0.0010)$

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- CKM matrix is unitary: $V^\dagger V = 1$
- Orthogonality between first and third column:

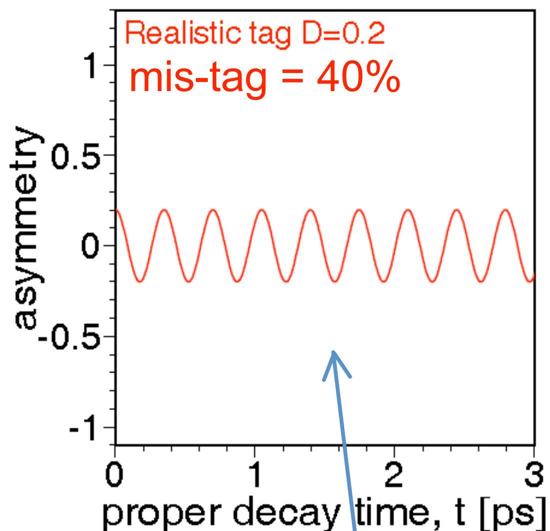
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

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

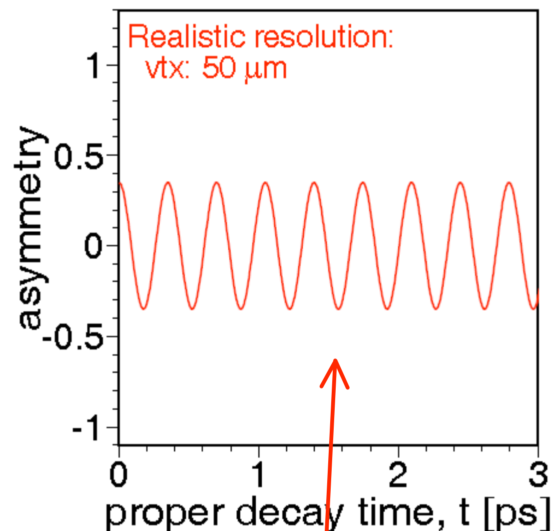


Realistic effects

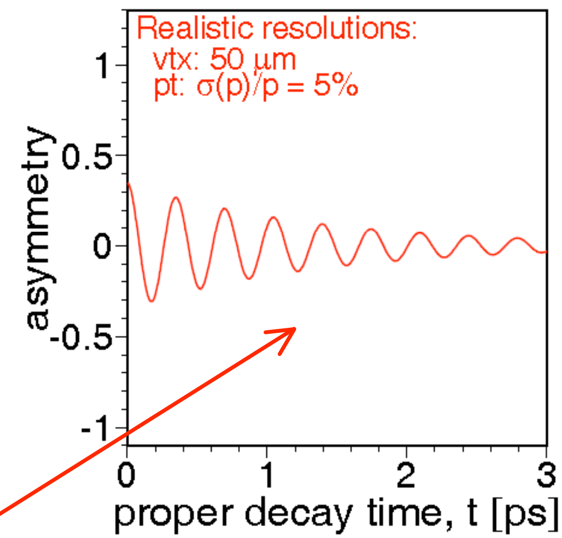
Flavor tagging



Vertex



Vertex and Momentum



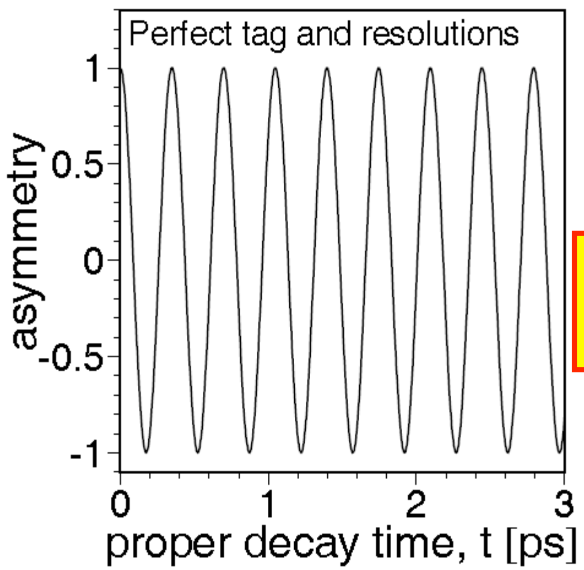
- Statistical power of the analysis:

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

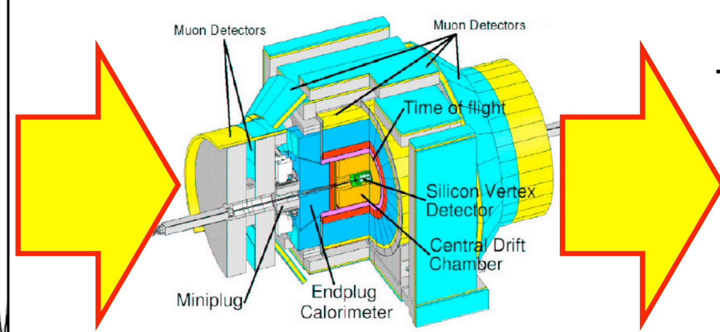
$$\sigma_{ct} = \sqrt{(\sigma_{ct}^0)^2 + \left(ct\,\frac{\sigma_p}{p}\right)^2}$$

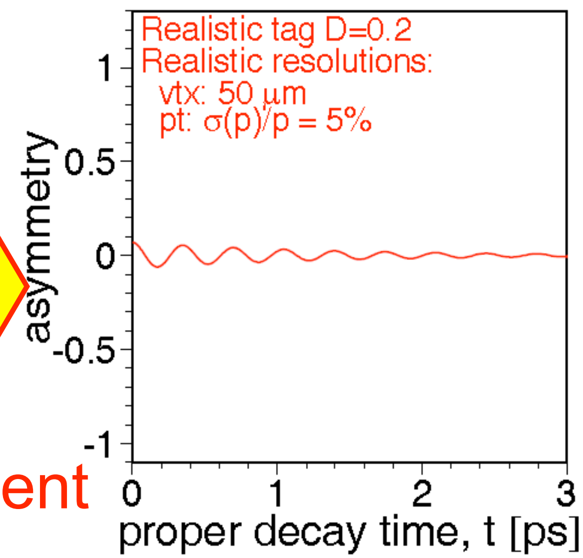
- Tagging: Effective stat scale to εD^2
  - efficiency $\varepsilon =$ probability to have a tag
  - dilution $D = 1 - 2 \cdot w$, w: mistag probability
- Proper decay time resolution
  - hadronic modes provide better accuracy

Measurement layouts



All effects together





Challenging measurement

- Unbinned likelihood fit:
  - Introduce artificial amplitude, A

    $p \sim exp(-t/\tau)(1 \pm AD\cos\Delta mt)$
  - Scan Δm for signal: fit amplitude, A
    - A = 1 at mixing frequency
    - A = 0 elsewhere
  - Measure Δm with A = 1

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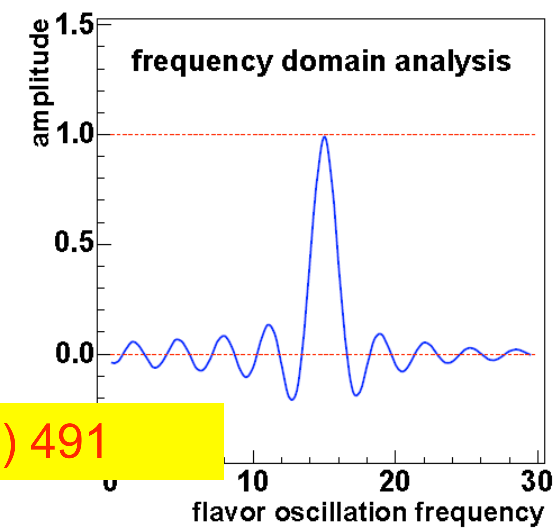
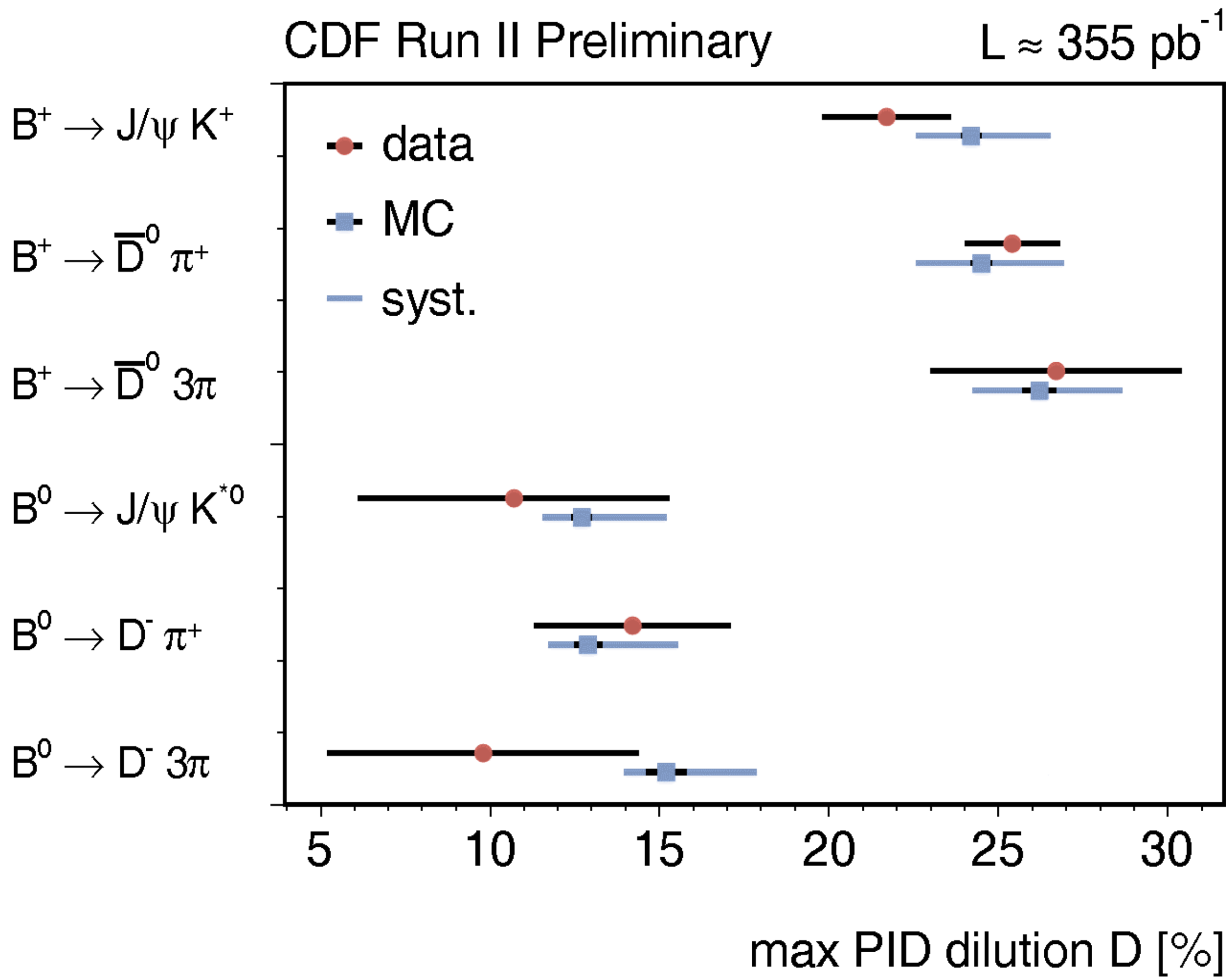


OST tagger performance

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

SSKT: MC Vs data

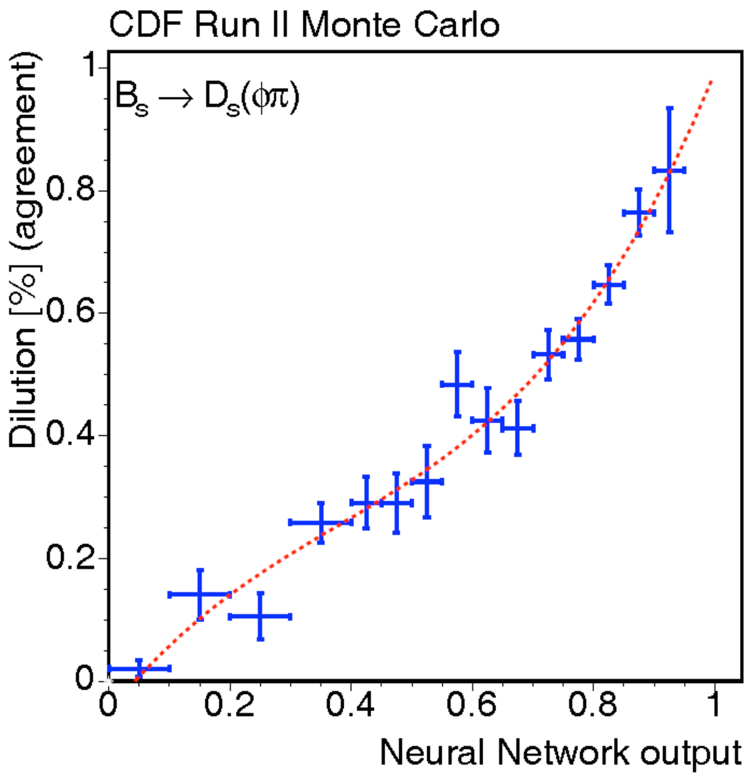


SSKT- Neural network

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

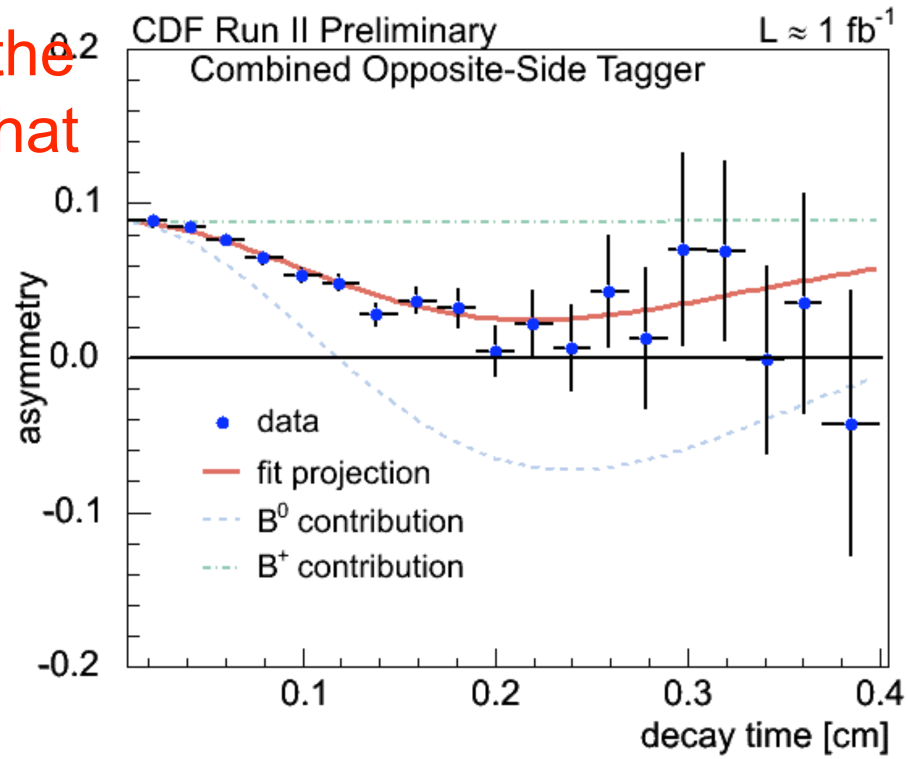
decision: track charge of highest NN tag candidate



Global tagger calibration

Re-calibrate OST by fitting for the amplitude, A given Δmd such that A=1

- important for setting limit but not observation
- by-product Δm_d measurement



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

semileptonic: $\Delta m_d = 0.509 \pm 0.010$ (stat) ± 0.016 (syst) ps^{-1}

world average: $\Delta m_d = 0.507 \pm 0.004$ ps^{-1} (HFAG)