Measurements of the Masses, Lifetimes and Decay Modes of Hadrons

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On behalf of the CDF and D0 collaborations

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Rencontres de Moriond QCD and High Energy Interactions

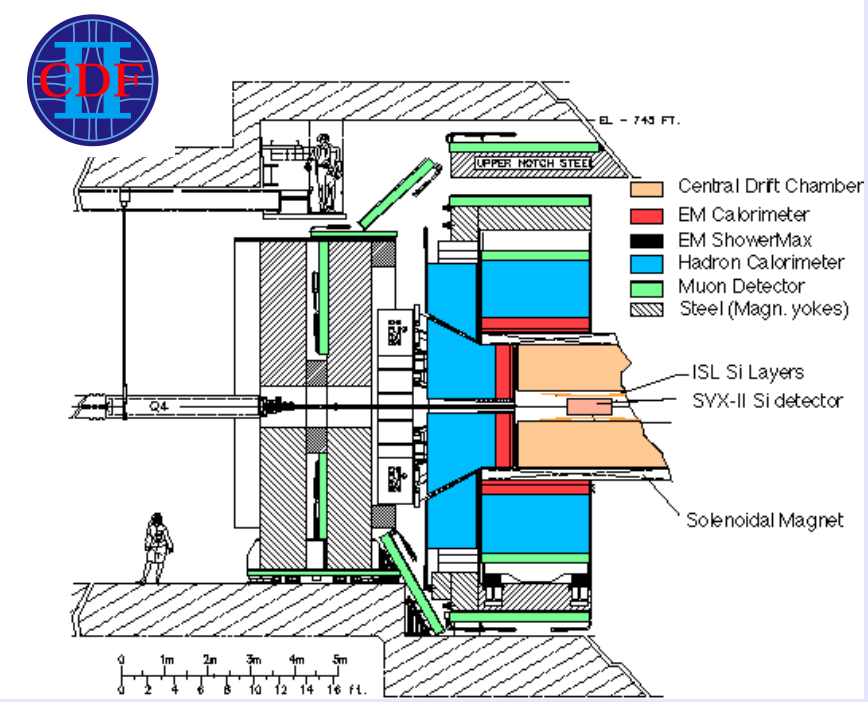
Outline

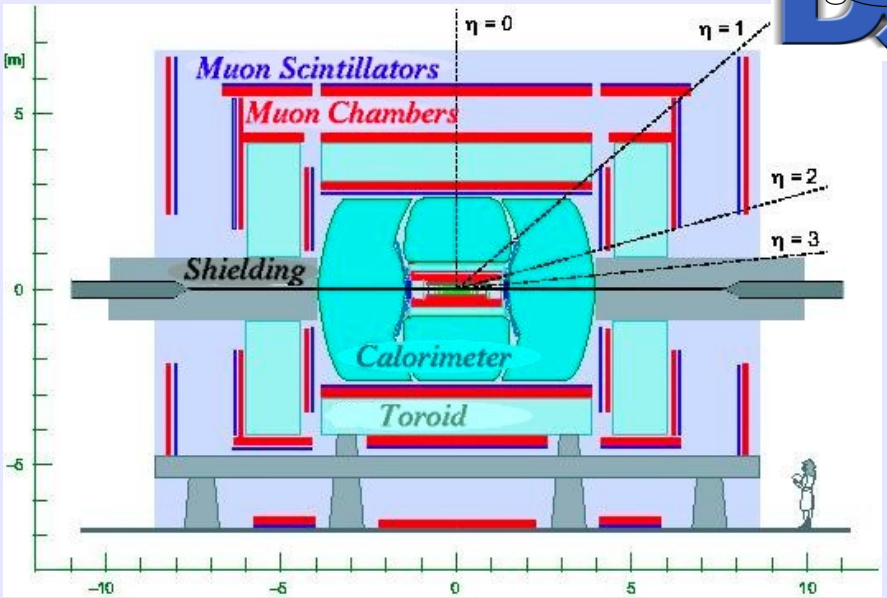
Latest results from **TeVatron CDF** and **D0** experiments

Masses	Ω^-_b
Lifetimes	*b*-hadron lifetimes in decays to J/ψ $B^\pm$ B^0 Λ^0_b
Decay Modes	$\Lambda^0_b \rightarrow \Lambda^+_c \pi^-\pi^+\pi^-$ $B^0_s \rightarrow \phi\phi$

CDF & D0

Tevatron: $p\bar{p}$ @ $\sqrt{s}$ = 1.96 TeV
Peak luminosity: L~3.5 x 10^{32} $cm^{-2}s^{-1}$





- Excellent tracking and mass resolution. $\sigma_{p_T}/p_T^2 \approx 0.0015\,(\mathrm{GeV}/c)^{-1}$

- Trigger on displaced tracks based on the SVT measurement of track impact parameter: large sample of hadronic decays

- Excellent Muon Id and tracking coverage: large samples of semi-leptonic decays

- Regular magnet inversion: smaller systematics in charge sensitive measurements

Masses

Ω^-_b search

Tevatron: observation of new *b*-baryons

Ξ^-_b

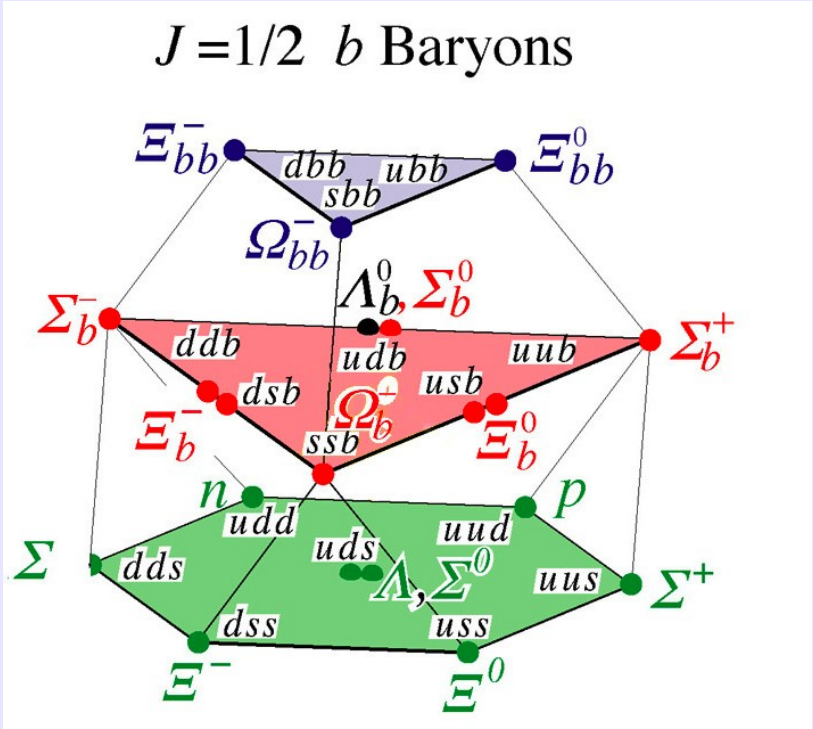
D0 coll. PRL99,052001 (2007)
CDF coll. PRL99,052002 (2007)

$\Sigma^{(*)}_b$

CDF coll. PRL99,202001 (2007)

Ω^-_b

D0 coll. PRL101,232002 (2008)
CDF coll. PRLD80,072003 (2009)



Channel: $\Omega^-_b \to J/\psi\,\Omega^-$ and $J/\psi \to \mu^+\mu^-$

$\Omega^- \to \Lambda K^- \quad \Lambda \to p\pi^-$

Ω_b^- search

D0

- L = 1.3 fb^{-1}
- built on Ξ_b^- discovery
  $m(\Xi_b^-) = 5774 \pm 11 \pm 15$ MeV/c^2

- $N(\Omega_b^-) = 17.8 \pm 4.9 \pm 0.8$
- significance 5.4σ
- $m(\Omega_b^-) = 6165 \pm 10 \pm 13$ MeV/c^2

World's First

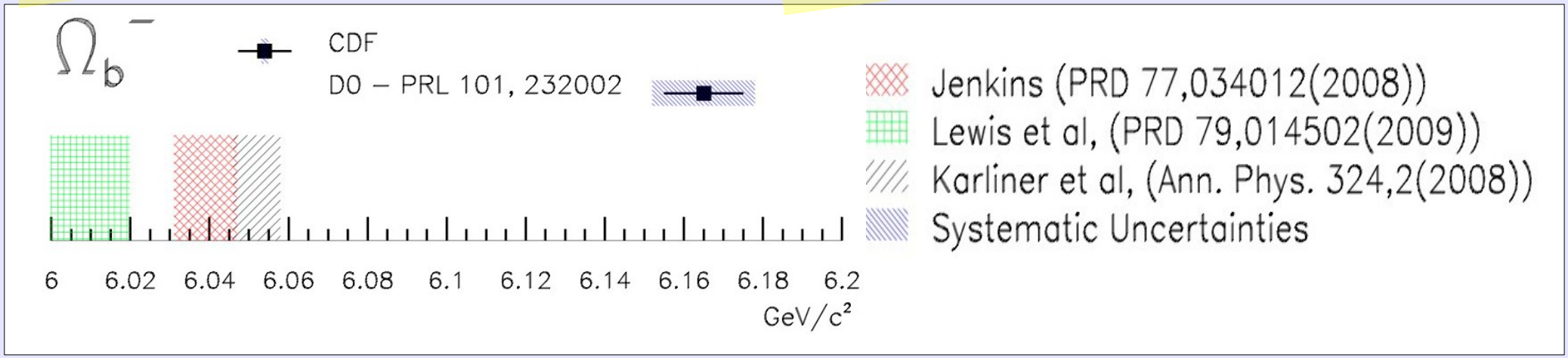
CDFII

- L = 4.2 fb^{-1}
- Ξ_b^- update (from 1.9 fb^{-1}):
  $m(\Xi_b^-) = 5790.9 \pm 2.6 \pm 0.8$ MeV/c^2
  $\tau(\Xi_b^-) = 1.56^{+0.27}_{-0.25} \pm 0.2$ ps

World's Best

- $N(\Omega_b^-) = 16^{+6}_{-4}$
- significance 5.5σ
- $m(\Omega_b^-) = 6054.4 \pm 6.8 \pm 0.9$ MeV/c^2
- $\tau(\Omega_b^-) = 1.13^{+0.53}_{-0.40} \pm 0.02$ ps

World's First



Lifetimes

b-hadron lifetimes in decays to J/ψ

$$B^+ = \underline{u}\,\underline{\bar{b}} \qquad B^0 = \underline{d}\,\underline{\bar{b}} \qquad \Lambda_b^0 = \underline{u\,d}\,\underline{b}$$

b-hadrons Lifetime: largely determined by charged **weak decay of *b* quark**

HQE: "**spectator model**" predicts equal lifetimes for all B hadrons

Several effects change these lifetimes by up to about 10%

$\tau(B^+)/\tau(B^0)$ in $1.04\text{-}1.08$

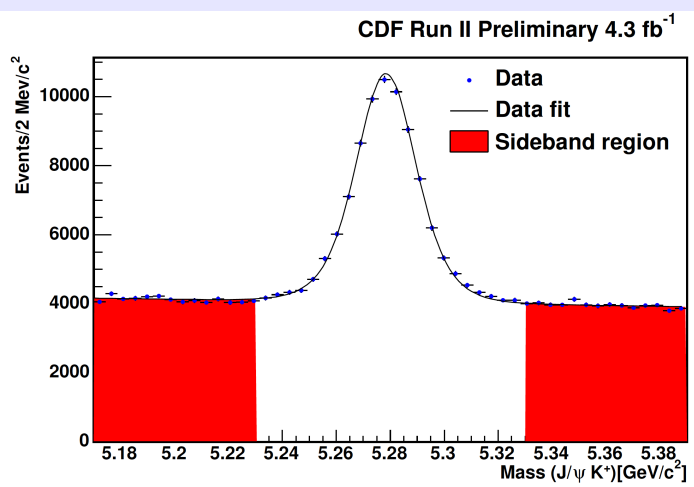
$\tau(\Lambda_b^0)/\tau(B^0)$ in $0.83\text{-}0.93$

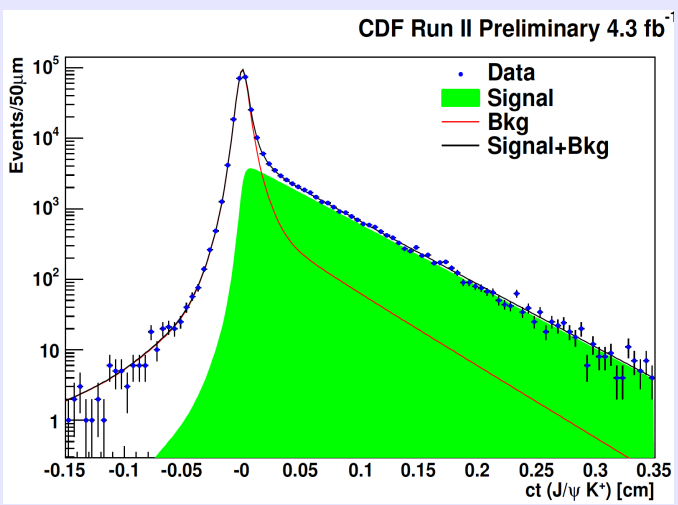
[PLB667(20068), hep-ph/0310241(2004), PRD70,094031]

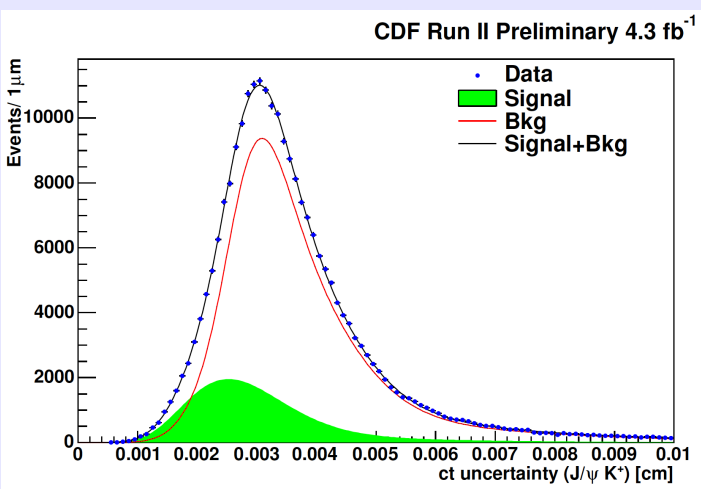
b-hadron lifetimes in decays to J/ψ

2009, **CDFII update** (from 1 fb^{-1} to 4.3 fb^{-1})

- $B^+ \to J/\psi\, K^+$, $B^0 \to J/\psi\, K^{*0}$, $B^0 \to J/\psi\, K^0_s$, **and** $\Lambda^0_b \to J/\psi\, \Lambda^0$
- data collected by **di-muon trigger**: no biasing effects on proper time distribution
- **Un-binned Maximum Likelihood** fit to: **mass**, **proper decay time** and **proper decay time error**
- Similar final states and unified analysis strategy: **partial cancellation** of certain **systematic uncertainties** in the lifetime ratios.





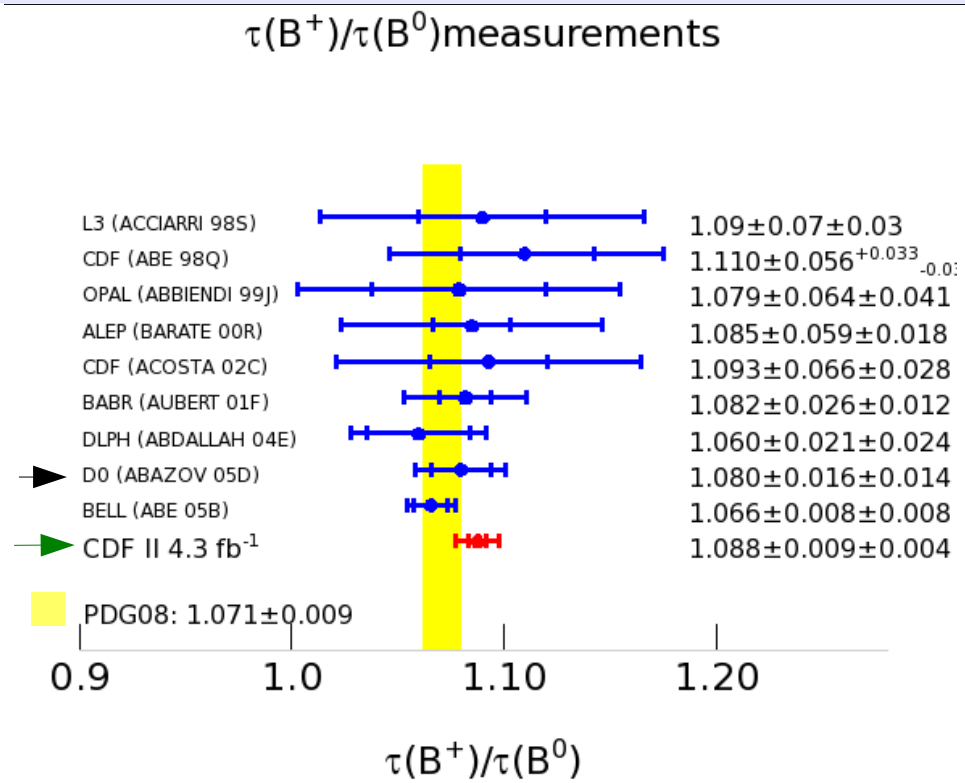


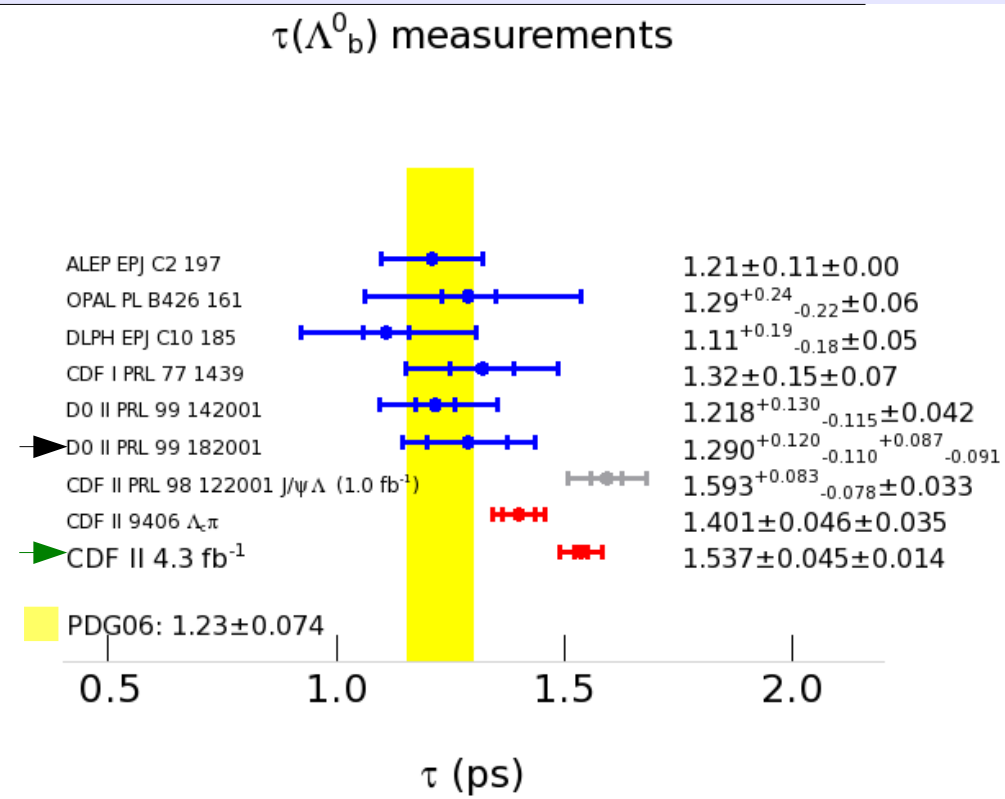
b-hadron lifetimes in decays to J/ψ

Results

World's Best

$$c\tau(B^+) = 491.4 \pm 2.6\ (stat.)\ \pm\ 2.6\ (syst.)\ \mu m,$$
$$c\tau(B^0) = 451.7 \pm 3.0\ (stat.)\ \pm\ 2.5\ (syst.)\ \mu m,$$
$$c\tau(\Lambda_b^0) = 460.8 \pm 13.4\ (stat.)\ \pm\ 4.1\ (syst.)\ \mu m.$$
$$\tau(B^+)/\tau(B^0) = 1.088 \pm 0.009\ (\text{stat.}) \pm 0.004\ (\text{syst.})$$
$$\tau(\Lambda_b^0)/\tau(B^0) = 1.020 \pm 0.030\ (\text{stat.}) \pm 0.008\ (\text{syst.})$$





Decay Modes

$\Lambda^0_b \longrightarrow \Lambda^+_c \pi^-\pi^+\pi^-$

Motivation: - recent observation $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+l^-\nu$ [CDFII PRD79,032001(2009)]
- test of HQET [PLB586(2004)]

2009 CDFII first observation of $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$ (2.4 fb^{-1})
first measurement of relative BR's

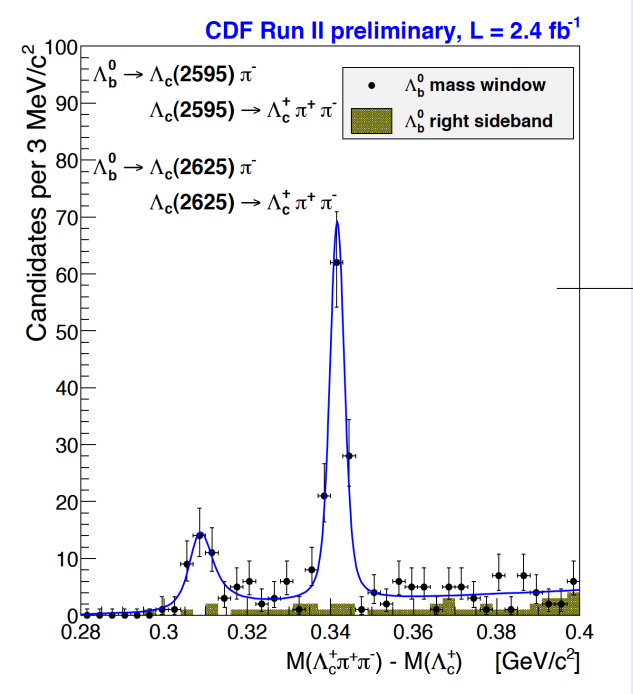
$$\Lambda_b^0 \to A\pi(\pi) \to \Lambda_c^+\pi^-\pi^+\pi^-$$

Strategy

$$\frac{\mathcal{B}(\Lambda_b^0 \to A\pi(\pi) \to \Lambda_c^+\pi^-\pi^+\pi^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-)} = \frac{N(A\pi(\pi))_{\rm obs}}{\sum_i \left[N(i)_{\rm obs} \times \frac{\epsilon_{A\pi(\pi)}}{\epsilon_i}\right]}$$

- $\Lambda_c^+ \to pK^-\pi^+$
- yields from ML fit of mass distributions
- relative efficiencies with simulation

$\Lambda^0_b \longrightarrow \Lambda^+_c \pi^-\pi^+\pi^-$



Yields

$\Lambda^0_b \to \Lambda_c(2595)^+\pi^- \to \Lambda^+_c\pi^-\pi^+\pi^-$	46.6±9.7
$\Lambda^0_b \to \Lambda_c(2625)^+\pi^- \to \Lambda^+_c\pi^-\pi^+\pi^-$	114±13
$\Lambda^0_b \to \Sigma_c(2455)^{++}\pi^-\pi^- \to \Lambda^+_c\pi^-\pi^+\pi^-$	81±15
$\Lambda^0_b \to \Sigma_c(2455)^0\pi^+\pi^- \to \Lambda^+_c\pi^-\pi^+\pi^-$	41.5±9.3
$\Lambda^0_b \to \Lambda^+_c\rho^0\pi^- + \Lambda^+_c 3\pi(other) \to \Lambda^+_c\pi^-\pi^+\pi^-$	610±88

World's First

$$\frac{\mathcal{B}(\Lambda^0_b\to\Lambda_c(2595)^+\pi^-\to\Lambda^+_c\pi^-\pi^+\pi^-)}{\mathcal{B}(\Lambda^0_b\to\Lambda^+_c\pi^-\pi^+\pi^-(all))} = (2.5 \pm 0.6(stat.) \pm 0.5(syst.)) \times 10^{-2}$$

$$\frac{\mathcal{B}(\Lambda^0_b\to\Lambda_c(2625)^+\pi^-\to\Lambda^+_c\pi^-\pi^+\pi^-)}{\mathcal{B}(\Lambda^0_b\to\Lambda^+_c\pi^-\pi^+\pi^-(all))} = (6.2 \pm 1.0(stat.)^{+1.0}_{-0.9}(syst.)) \times 10^{-2}$$

$$\frac{\mathcal{B}(\Lambda^0_b\to\Sigma_c(2455)^{++}\pi^-\pi^-\to\Lambda^+_c\pi^-\pi^+\pi^-)}{\mathcal{B}(\Lambda^0_b\to\Lambda^+_c\pi^-\pi^+\pi^-(all))} = (5.2 \pm 1.1(stat.) \pm 0.8(syst.)) \times 10^{-2}$$

$$\frac{\mathcal{B}(\Lambda^0_b\to\Sigma_c(2455)^0\pi^+\pi^-\to\Lambda^+_c\pi^-\pi^+\pi^-)}{\mathcal{B}(\Lambda^0_b\to\Lambda^+_c\pi^-\pi^+\pi^-(all))} = (8.9 \pm 2.1(stat.)^{+1.2}_{-1.0}(syst.)) \times 10^{-2}$$

$$\frac{\mathcal{B}(\Lambda^0_b\to\Lambda^+_c\rho^0\pi^-+\Lambda^+_c 3\pi(other)\to\Lambda^+_c\pi^-\pi^+\pi^-)}{\mathcal{B}(\Lambda^0_b\to\Lambda^+_c\pi^-\pi^+\pi^-(all))} = (77.3 \pm 3.1(stat)^{+3.0}_{-3.3}(syst)) \cdot 10^{-2}$$

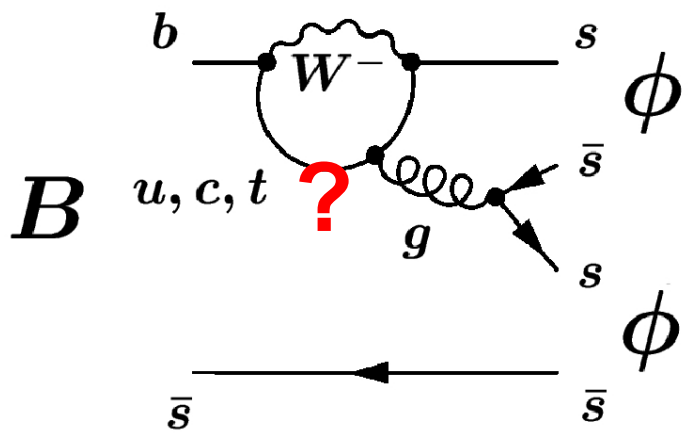
$B^0_s \longrightarrow \phi\phi$

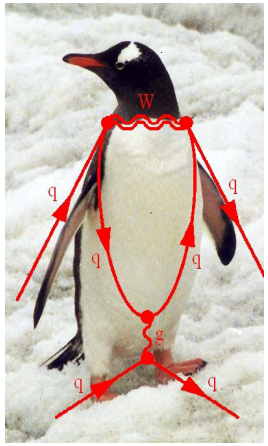
$P \rightarrow VV$

Polarization Amplitudes

$$|A_0|^2 \quad |A_{\parallel}|^2 \quad |A_{\perp}|^2$$

Penguin $b \longrightarrow s$ transition





potentially sensitive to **NP**

"Polarization Puzzle"

SM expectation: $|A_0|^2 \gg |A_{\parallel}|^2 \simeq |A_{\perp}|^2$

- confirmed $b \rightarrow u$ tree-level
- evidence $b \rightarrow d$ penguin

while $b \longrightarrow s$ penguin $\quad |A_0|^2 = 0.50 \pm 0.05 \quad B^+ \rightarrow \phi K^{\star +}$

$|A_0|^2 = 0.484 \pm 0.033 \quad B^0 \rightarrow \phi K^{\star 0}$

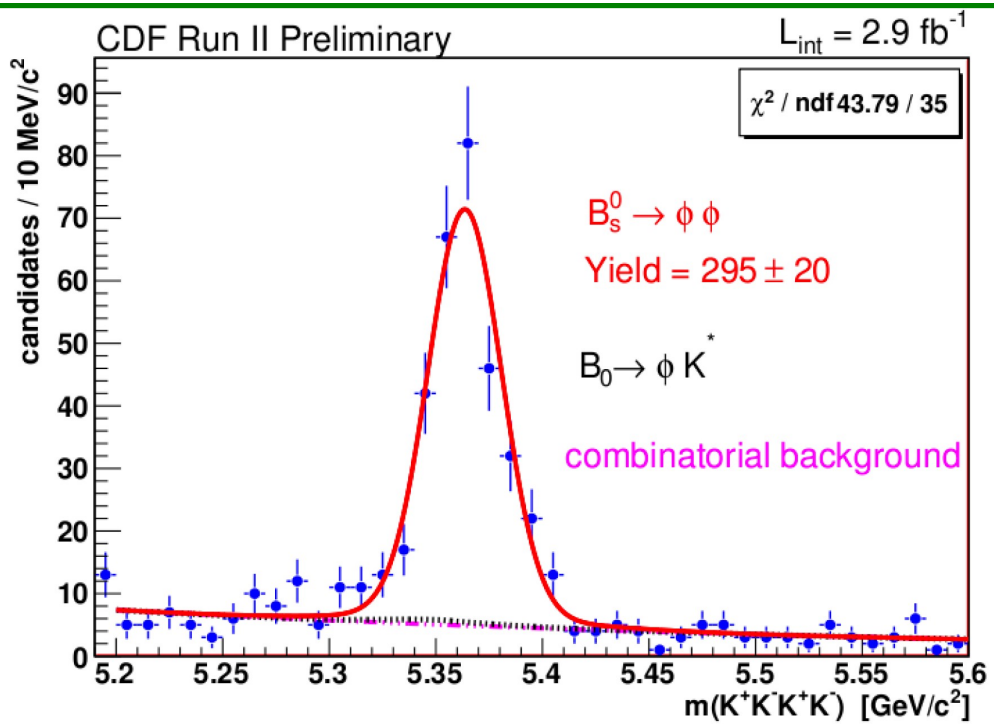
"Ad hoc" **SM** explanations and **NP** still possible.

$B^0_s \longrightarrow \phi\phi$

- CDFII: $B^0_s \rightarrow \phi\phi \rightarrow [K^+K^-][K^+K^-]$ from Hadronic Two Track Trigger
- 2005 CDFII **BR** measurement (180 pb^{-1}), **8 signal events**
  [PRL95,031801(2005)]: BR = (1.4 ± 0.6 ± 0.6) × 10^{-5} World's First

2009, CDFII **BR** update (2.9 fb^{-1})

$$\mathcal{B}(B^0_s \rightarrow \phi\phi) = [2.40 \pm 0.21(\text{stat}) \pm 0.86(\text{syst})] \times 10^{-5}$$



$B^0_s \longrightarrow \phi\phi$

Brand New!

2010, CDFII **first polarization measurement** (2.9 fb^{-1})

Strategy

- **Un-binned Maximum Likelihood** fit to
  - **mass** of reconstructed B^0_s candidates
  - **3 helicity angles** of reconstructed K candidates
- **Time-integrated**: differential decay rate integrated in time
- **Untagged analysis**: no tag *B* flavor at production time
- Fix **CP-violation** phase to **zero**

Control sample (same trigger selection): $B^0_s \to J/\psi\phi \to [K^+K^-][\mu^+\mu^-]$

the results are consistent with other experiment (di-muon trigger, CDFII and D0)

$B^0_s \longrightarrow \phi\phi$

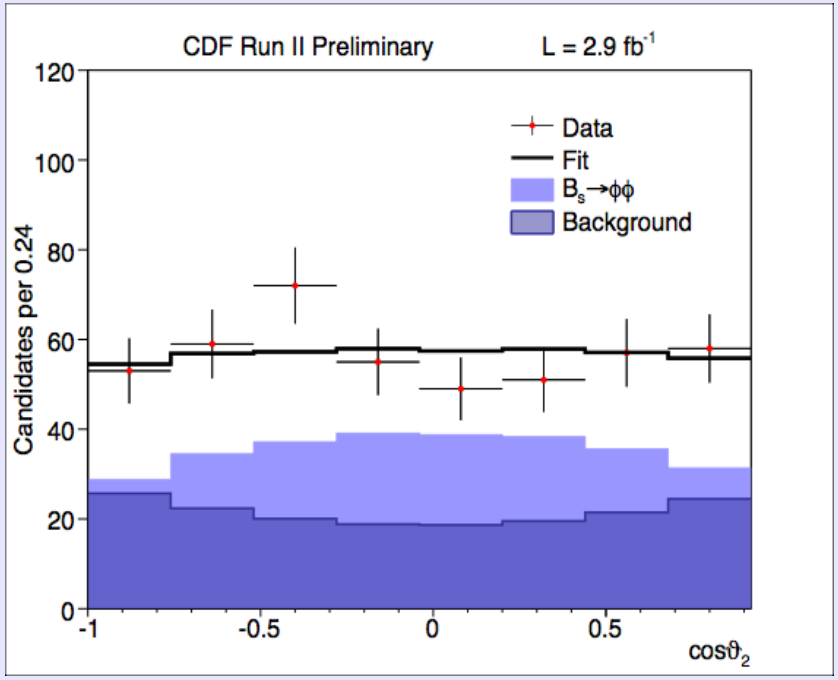
Results

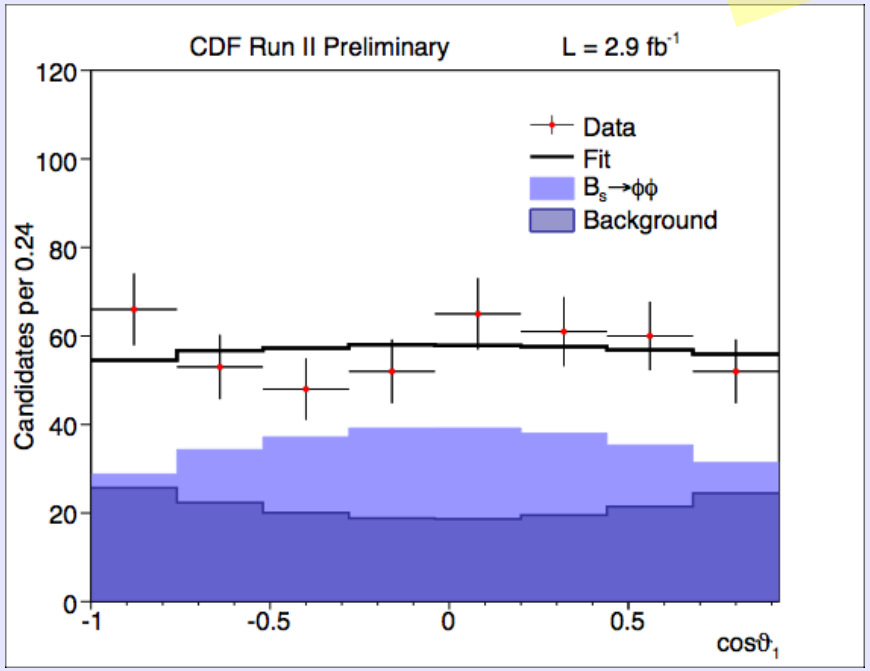
$$
\begin{aligned}
|A_0|^2 &= 0.348 \pm 0.041(\text{stat}) \pm 0.021(\text{syst}) \\
|A_{\|}|^2 &= 0.287 \pm 0.043(\text{stat}) \pm 0.011(\text{syst}) \\
|A_{\perp}|^2 &= 0.365 \pm 0.044(\text{stat}) \pm 0.027(\text{syst}) \\
\cos\delta_{\|} &= -0.91^{+0.15}_{-0.13}(\text{stat}) \pm 0.09(\text{syst})
\end{aligned}
$$

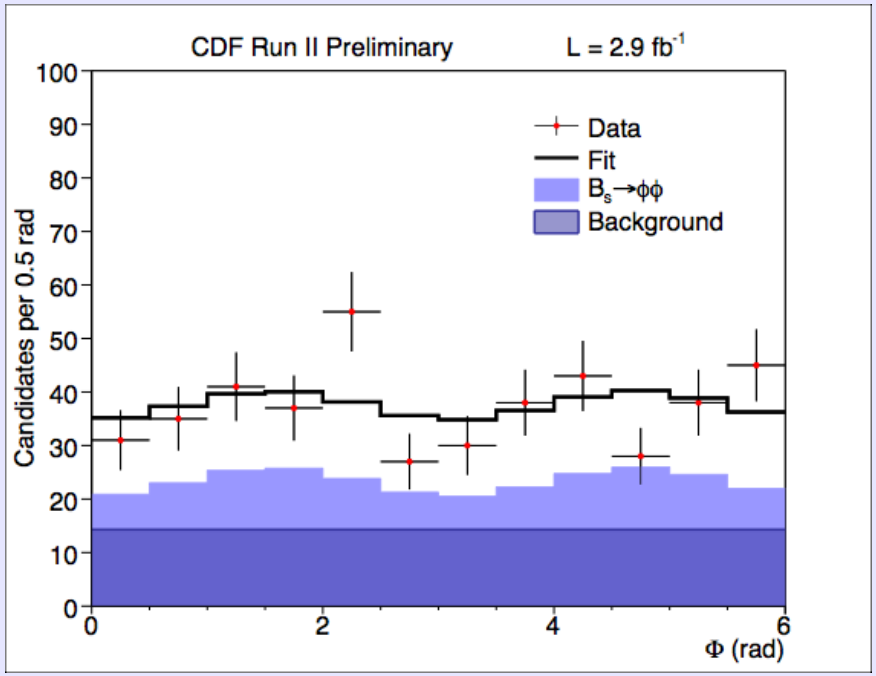
Main systematic sources:

- time integration O(1%)
- non-resonant contribution O(1%)
- $\tau_{L(H)}$ uncertainties O(1%)

World's First







$B^0_s \longrightarrow \phi\phi$

- Expected amplitudes hierarchy disfavored

$$|A_0|^2 \simeq |A_\parallel|^2 \simeq |A_\perp|^2 \text{ instead of } |A_0|^2 \gg |A_\parallel|^2 \simeq |A_\perp|^2$$

- Comparison with various model

	$\lvert A_0\rvert^2$ [%]	$1-\lvert A_0\rvert^2$ [%]
CDF Run II	$34.8 \pm 4.1(\text{stat}) \pm 2.1(\text{syst})$	$65.2 \pm 4.1(\text{stat}) \pm 2.1(\text{syst})$
QCD factorization (2007) [a]	48^{+0+26}_{-0-27}	52^{+0+26}_{-0-27}
QCD factorization (2008) [b]	34 ± 28	66 ± 28
Naive factorization [c]	88.3	11.7
NLO EWP [d]	86.3	13.7
perturbative QCD [e]	$61.9^{+3.6+2.5+0.0}_{-3.2-3.3-0.0}$	$38.1^{+3.6+2.5+0.0}_{-3.2-3.3-0.0}$

[a] Beneke et al., NPB 774 (2007)

[b] Datta et al., hep-ph/0802.0897 (2008)

[c] Xinqiang Li et al. (2005)

[d] D. Du and L. Guo. JPG:NPP 23 (1997)

[e] Ahmed Ali et al., PRD, 65 094023 (2002)

Conclusion

Conclusion

Tevatron has done world's best/first
mass, lifetime and polarization measurements:
key contributions
of the mature Tevatron program in the HF sector
(don't miss the other Tevatron talks of Louise and Dmitri)

World class B physics program
(competitive to B factories results)

Sitting on a goldmine of data:
reaching 8 fb^{-1} of data, further improvements are coming

All CDF and D0 results shown @
http://www-cdf.fnal.gov/physics/new/bottom/bottom.html
http://www-d0.fnal.gov/d0_publications/d0_pubs_list_runII_bytopic.html#b

Backup

B_c lifetime

$$B_c^+ = c\bar{b}$$
$$B_c^- = \bar{c}\,b$$

Significant contributions from
- *c* decay
- *c/b* annihilation to a *W*

Prediction
$$c\tau = 165 \pm 45\ \mu\mathrm{m}$$
[hep-ph/0308214]

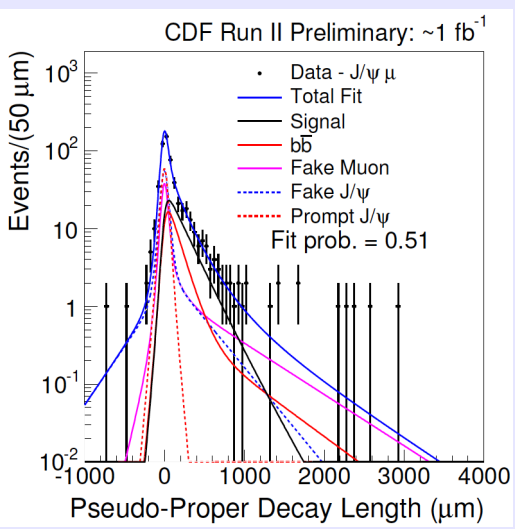
CDFII & D0 measurement in semi-leptonic channel $B_c \to J/\psi + l + X$

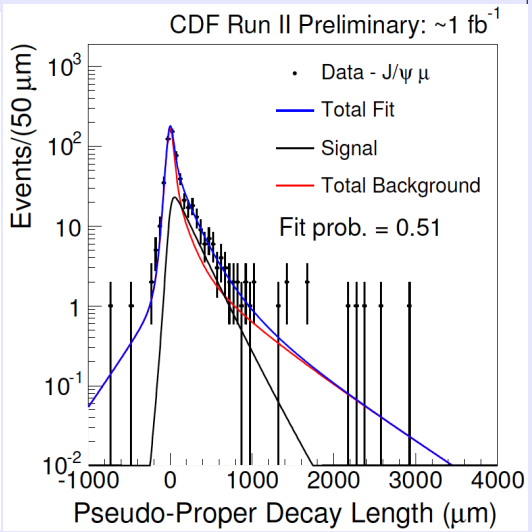
CDFII

- Both muon and electron channels
- Un-binned ML fit to decay-length

$c\tau = 142.5^{+15.8}_{-14.8}$(stat) ± 5.5 (syst) μm

[PRL102,09200]





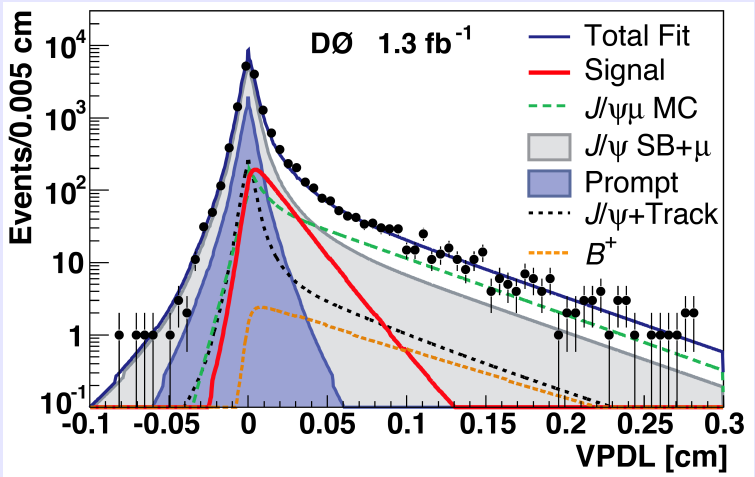
D0

- Muon channels
- Un-binned ML fit to mass & decay length

$c\tau = 134.3^{+11.4}_{-10.8}$(stat) ± 9.6 (syst) μm

[PRL102,09200]

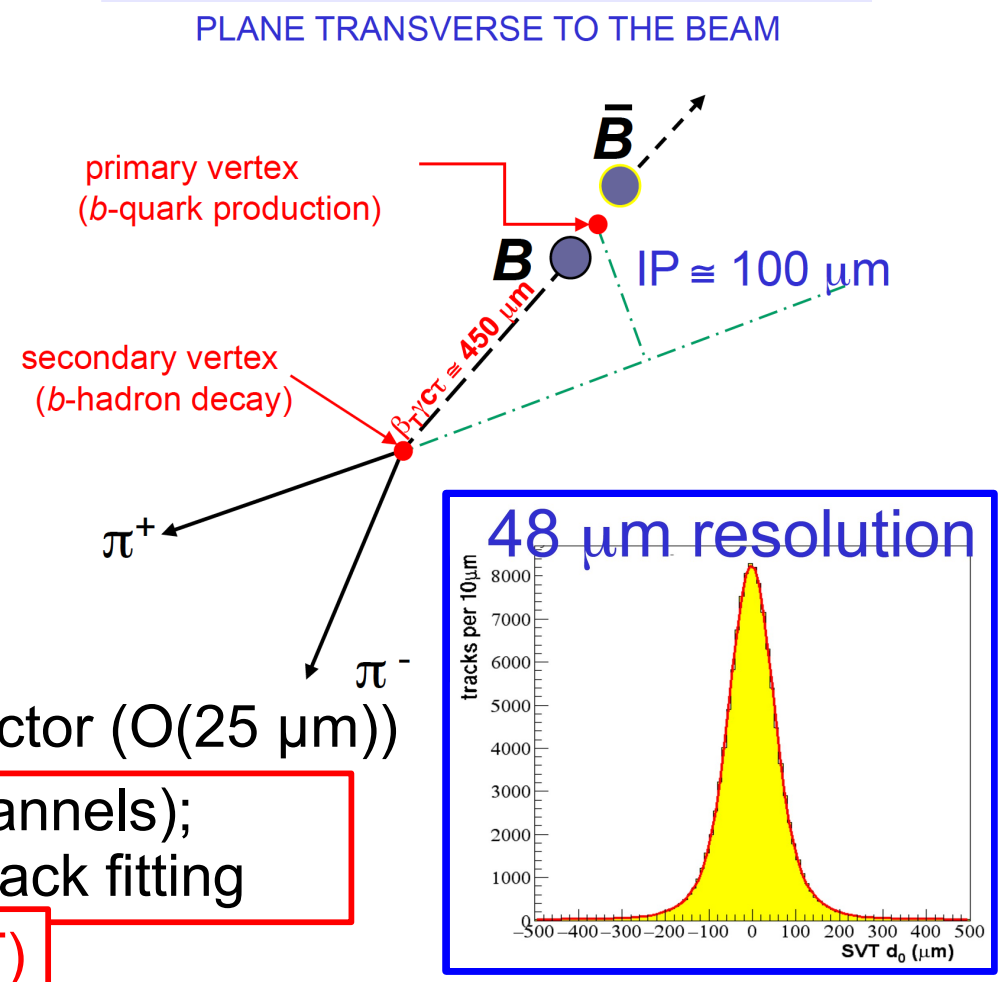
World Best



The Hadronic Trigger

1.5 ps lifetime of *b*-hadrons:
a powerful signature.

Sufficiently boosted *B* fly a path resolvable with vertex detectors before decaying.

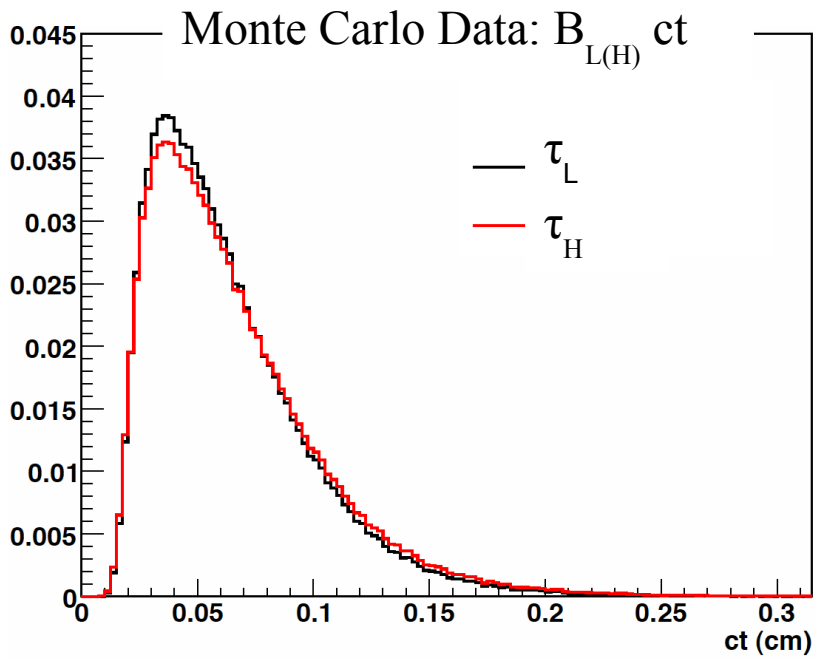


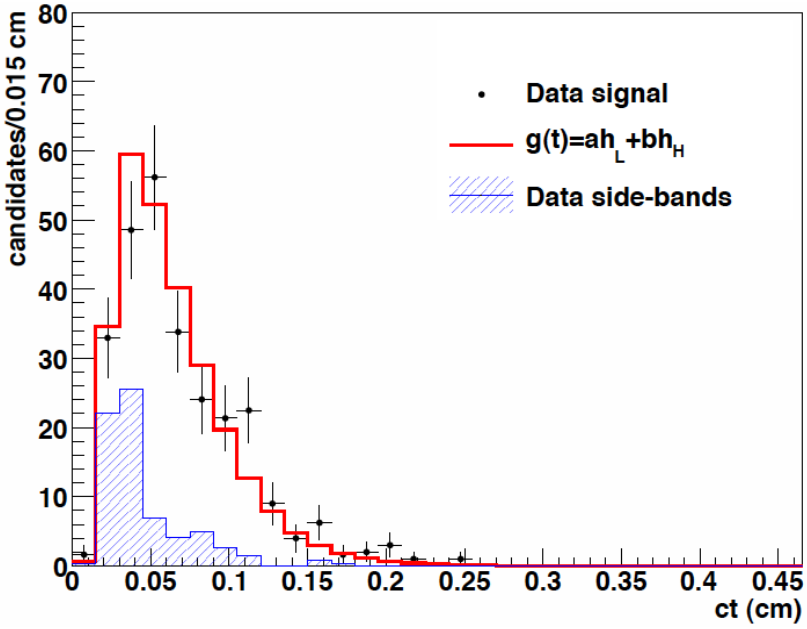
Run I exploited this offline.
Run II in the **trigger**
An experimental challenge:
(1) **high resolution** vertex detector (O(25 μm))
(2) read out silicon (212 000 channels);
(3) do pattern recognition and track fitting

within 25 μs (SVT)

Selections: two tracks with $p_T > 2$ GeV/c,
$L_{xy} > 200$ μm,
120 μm < IP < 1000 μm

Lifetimes with Hadronic Trigger





2 effect:

1) Detector resolution

2) TTT, bias on the observed proper decay length;

it selects events with two displaced tracks:

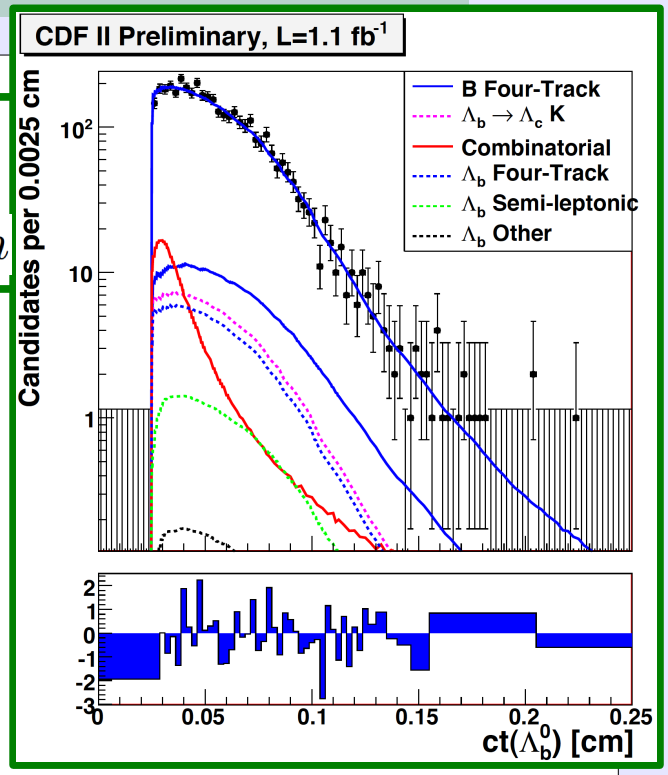
removes both events with the short proper decay lengths, and those with very long ones.

Lifetimes with Hadronic Trigger

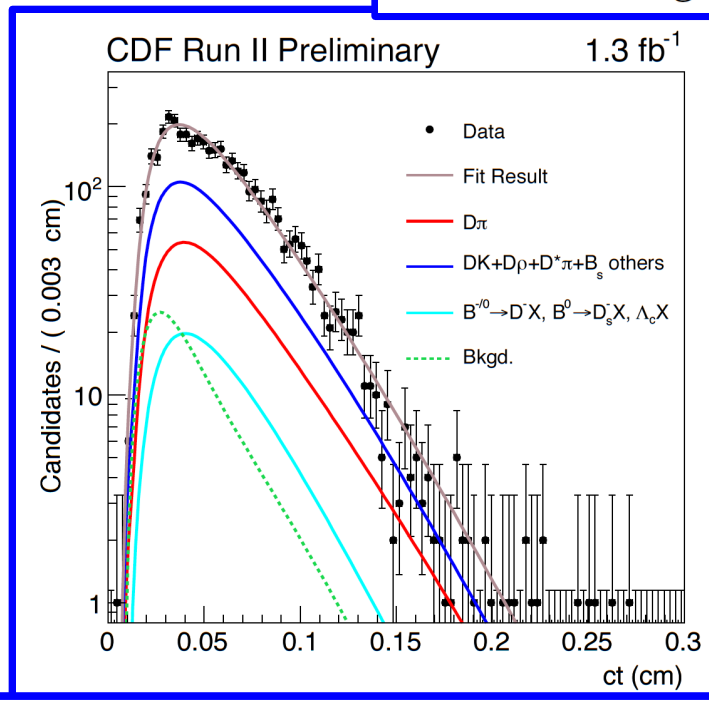
$$\Lambda_b^0 \to \Lambda_c^+ \pi^-$$

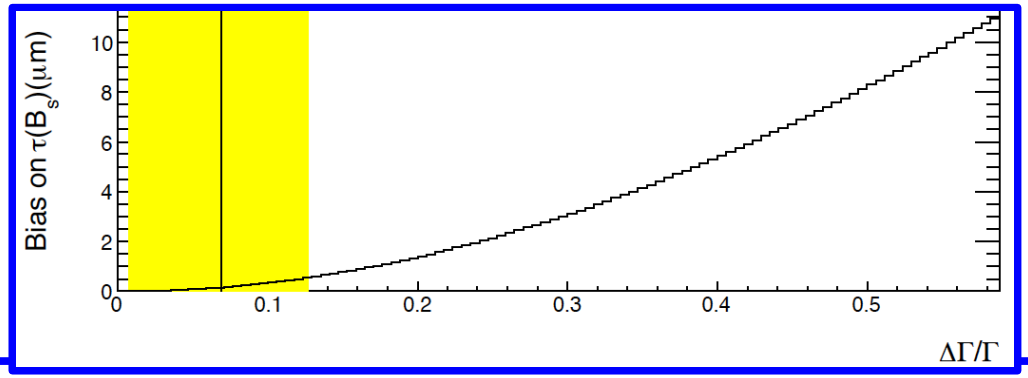
TTT: $c\tau(\Lambda_b^0) = 420.1 \pm 13.7\ (\text{stat}) \pm 10.6\ (\text{syst})\ \mu\text{m}$

di-muon: $c\tau(\Lambda_b^0) = 460.8 \pm 13.4\ (stat.)\ \pm\ 4.1\ (syst.)\ \mu m$



$$B_s \to D_s^- (\phi\pi^-)\pi^+$$





TTT: $c\tau = 455.0 \pm 12.2(\text{stat.}) \pm 8.2(\text{syst.})\ \mu\text{m}$

di-muon: $c\tau_s = 456 \pm 13\ (\text{stat.}) \pm 7\ (\text{syst.})\ \mu\text{m}$

$B^0_s \longrightarrow \phi\phi$: BR

2009, CDFII **BR** updated (2.9 fb^{-1}), **295 signal events**

Strategy

$$\frac{\mathcal{B}(B_s^0 \to \phi\phi)}{\mathcal{B}(B_s^0 \to J/\psi\ \phi)} = \frac{N_{\phi\phi}}{N_{J/\psi\phi}} \cdot \frac{\mathcal{B}(J/\psi \to \mu\mu)}{\mathcal{B}(\phi \to K^+K^-)} \cdot \frac{\varepsilon_{TOT}^{J/\psi\phi}}{\varepsilon_{TOT}^{\phi\phi}} \cdot \varepsilon_{\mu}^{TOT}$$

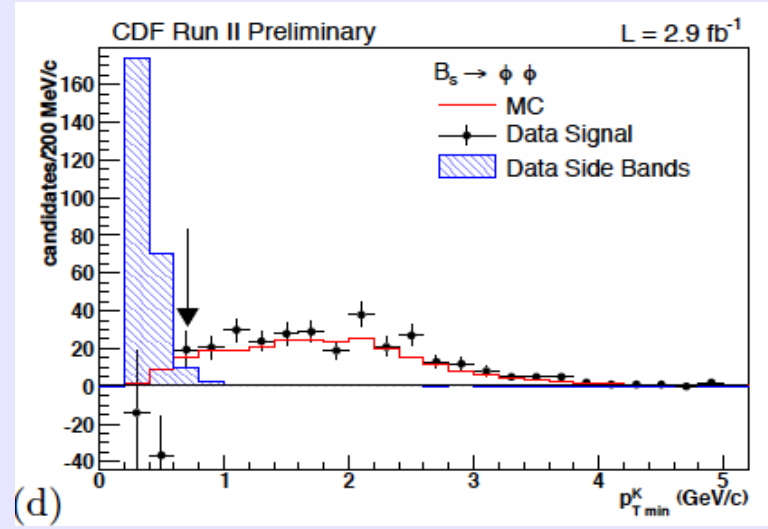
- $\frac{N_{\phi\phi}}{N_{J/\psi\phi}}$: Fit to mass on data
- $\frac{\mathcal{B}(J/\psi \to \mu\mu)}{\mathcal{B}(\phi \to K^+K^-)}$: PDG
- $\frac{\varepsilon_{TOT}^{J/\psi\phi}}{\varepsilon_{TOT}^{\phi\phi}}$: Trigger and selection efficiency from simulation
- ε_{μ}^{TOT}: Muon-ID efficiency from control sample of data

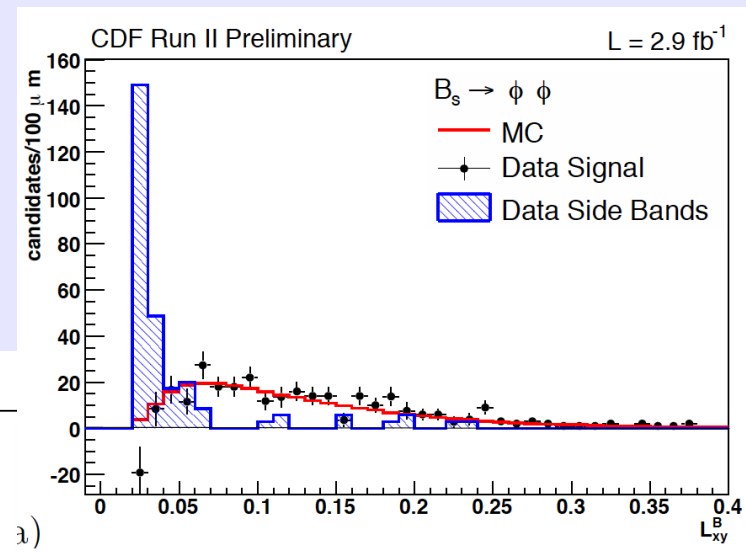
$$\frac{\mathcal{B}(B_s^0 \to \phi\phi)}{\mathcal{B}(B_s^0 \to J/\psi\phi)} = [1.78 \pm 0.14(stat) \pm 0.20(syst)] \cdot 10^{-2}$$

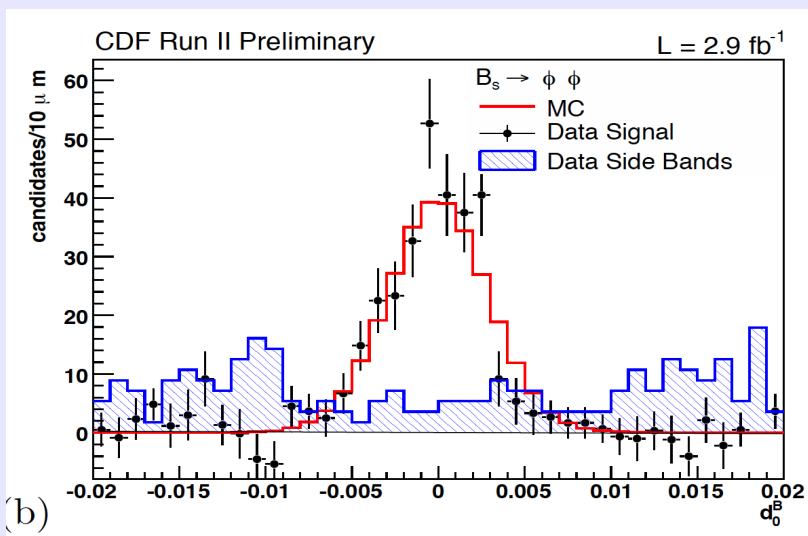
Use $B_s^0 \to J/\psi\phi$ as reference (no e.g. $B_d^0 \to \phi K^\star$): avoid f_s/f_d dependence

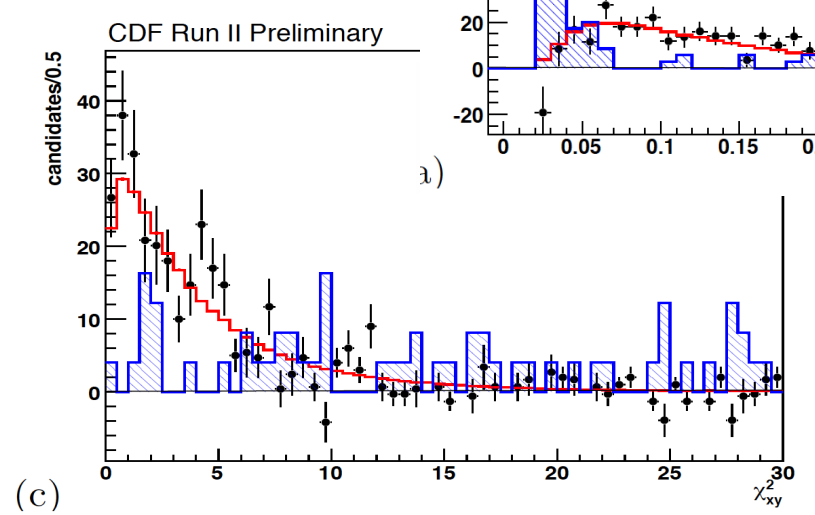
$B^0_s \to \phi\phi$: Off-line selections

Variables		Requirements $B^0_s \to \phi\phi$	Requirements $B^0_s \to J/\psi\phi$
L^B_{xy}	[μm]	> 330	> 290
$p^K_{\mathrm{T\,min}}$	[GeV/c]	> 0.7	
p^ϕ_{T}	[GeV/c]		> 1.4
χ^2_{xy}		< 17	< 15
d^B_0	[μm]	< 65	< 80
$d^{\phi_{\max}}_0$	[μm]	> 85	
$p^{J/\psi}_{\mathrm{T}}$	[GeV/c]		> 2.0







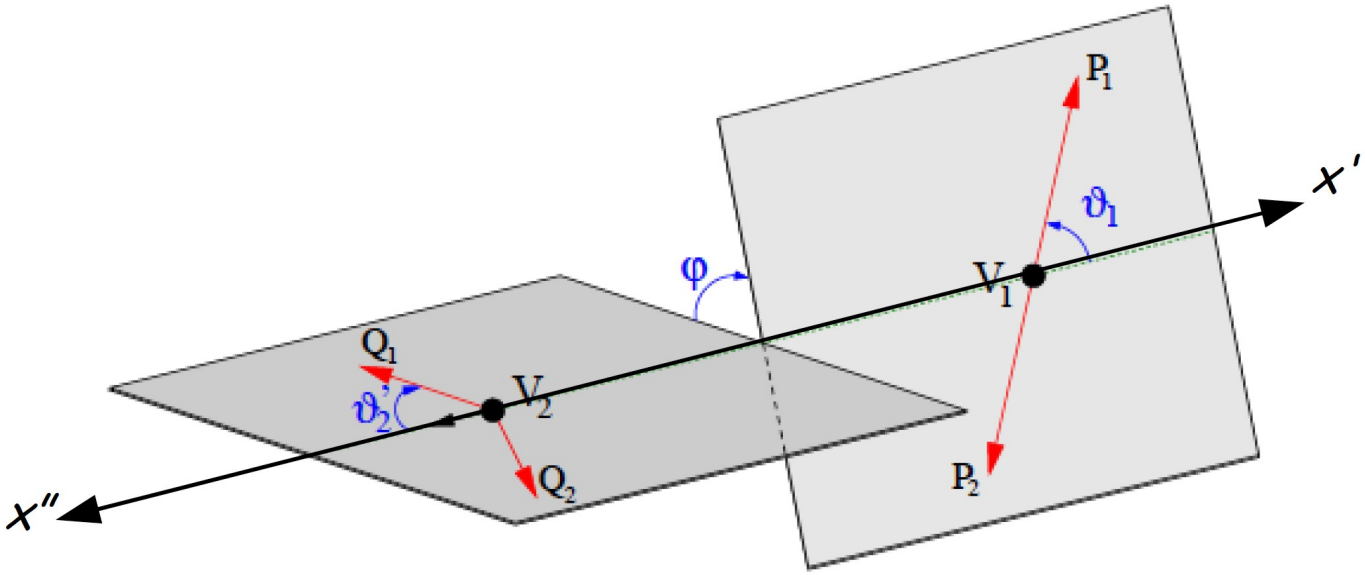


$B^0_s \to \phi\phi$: helicity basis

x' (x") : $\mathbf{p}_{\Phi 1}$ ($\mathbf{p}_{\Phi 2}$) direction in B rest frame

Θ_1 : in Φ_1 rest frame

Θ_2 : in Φ_2 rest frame



Legend

$V_{1/2} = \Phi$

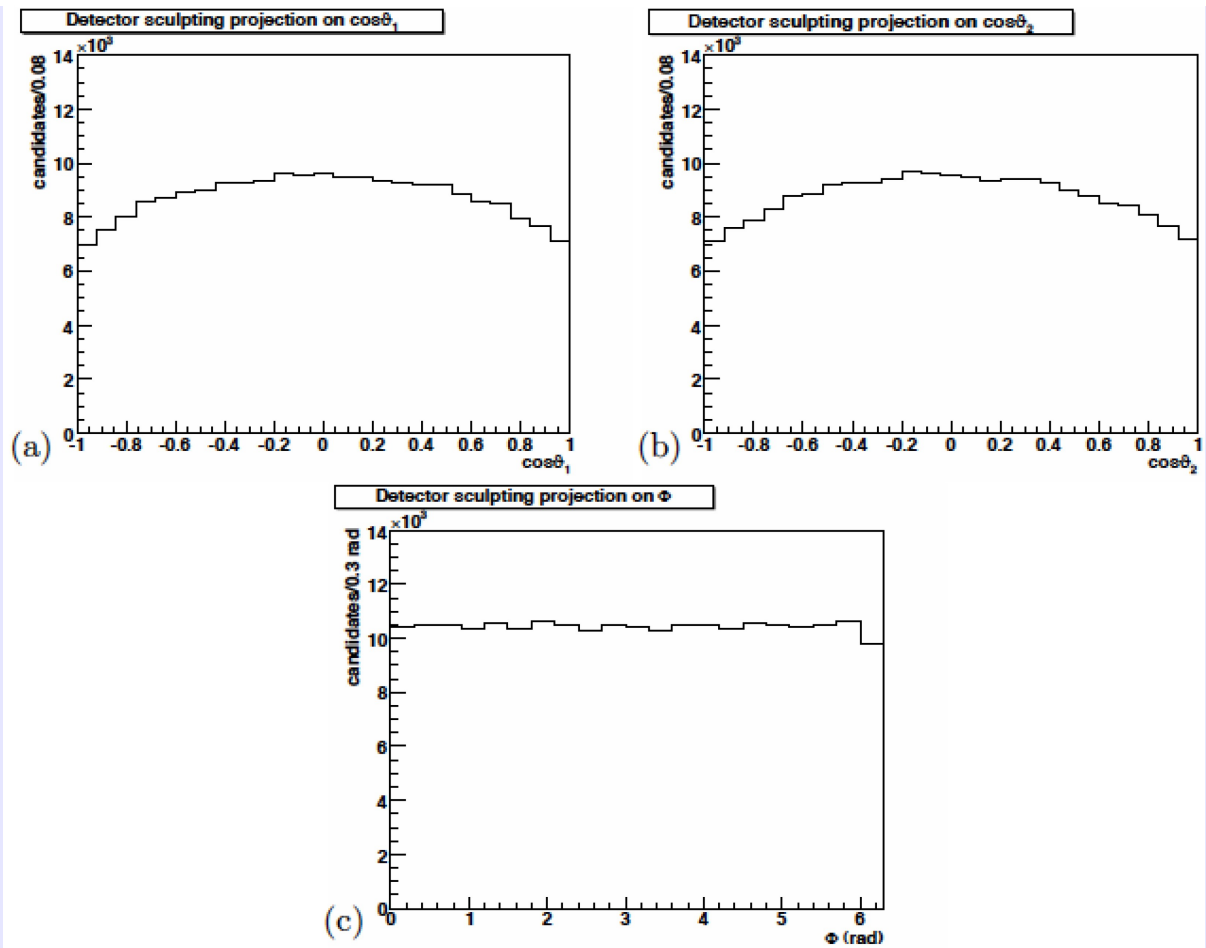
$P_{1/2} = K^{+/-}$

B^0_s->ϕϕ: angular acceptance

- model the **angular acceptance** for both $B_s^0 \to \phi\phi$ and $B_s^0 \to J/\psi\phi$

respectively 400K and 200K events of **PHSP** decay model:

§ it performs the decay using only phase space,
§ it averages all final state spin values without taking into account any spin correlations between the two vectors in the final state
§ it generates uniform angular distribution



$B^0_s \to \phi\phi$: control sample

Control sample (same trigger selection): $B_s^0 \to J/\psi\phi \to [K^+K^-][\mu^+\mu^-]$

	$\lvert A_0\rvert^2$	$\lvert A_\parallel\rvert^2$
TTT Sample Fit	0.534 ± 0.019	0.220 ± 0.025
CDFII [PRL100, 121803 (2008)]	0.531 ± 0.020	0.239 ± 0.029
D0 [PRL102, 032001 (2009)]	0.555 ± 0.027	0.244 ± 0.032

$B^0_s \to \phi\phi$: polarization systematics

	$\lvert A_0\rvert^2$ syst	$\lvert A_\parallel\rvert^2$ syst	$\lvert A_\perp\rvert^2$ syst	$\cos\delta_\parallel$ syst
MC reweight	±0.003	±0.001	±0.002	±0.007
Acceptance binning	±0.001	±0.001	±0.000	±0.004
Acceptance Model	±0.005	±0.002	±0.003	±0.005
Background Model	±0.001	±0.001	±0.002	±0.009
Acceptance ct-dependence	±0.000	±0.001	±0.001	±0.004
Reflection component	±0.008	±0.002	±0.006	±0.019
Non-resonant contribution	±0.013	±0.003	±0.010	±0.084
Satellite peak	±0.004	±0.000	±0.004	±0.020
Acceptance $\Delta\Gamma$-dependence	±0.009	±0.009	±0.016	±0.011
$\tau_{L(H)}$ uncertainties	±0.008	±0.006	±0.017	
total	±0.021	±0.011	±0.027	±0.089

If we want to consider also the CP-violation effects, we obtain

	$\lvert A_0\rvert^2$ syst	$\lvert A_\parallel\rvert^2$ syst	$\lvert A_\parallel\rvert^2$ syst	$\cos\delta_\parallel$ syst
CP-violation	±0.002	±0.001	±0.003	±0.009
total	±0.021	±0.011	±0.027	±0.090