Flavour Physics (III)
History and recent progress at LHC

Summer Institute 2013

17 - 23 August 2013, Jirisan National Park, Korea

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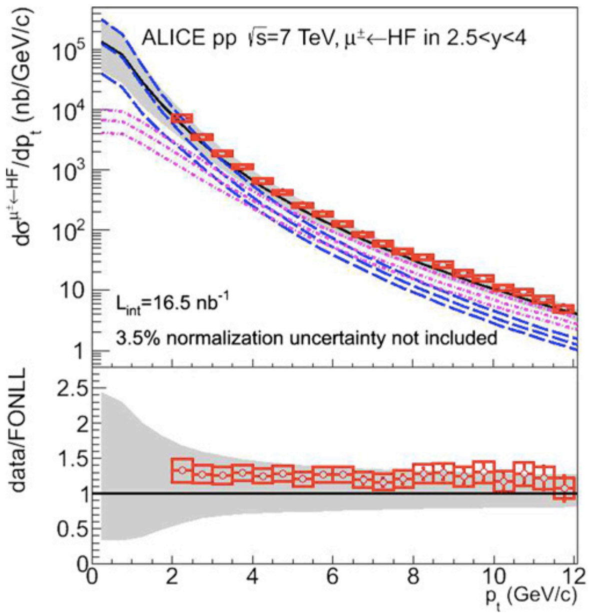
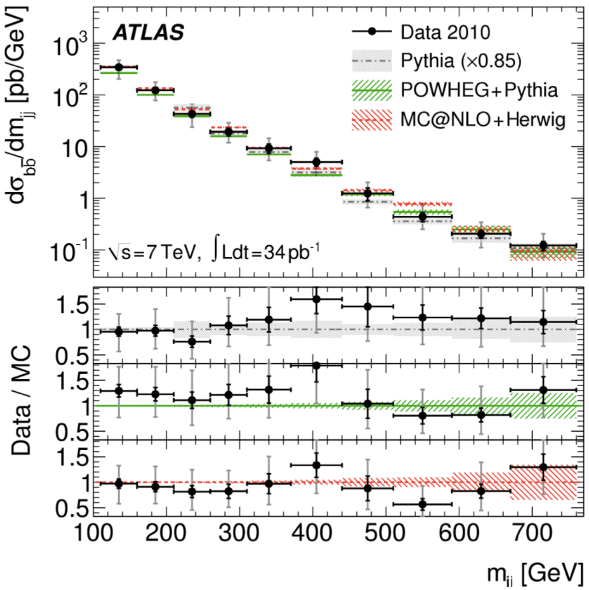
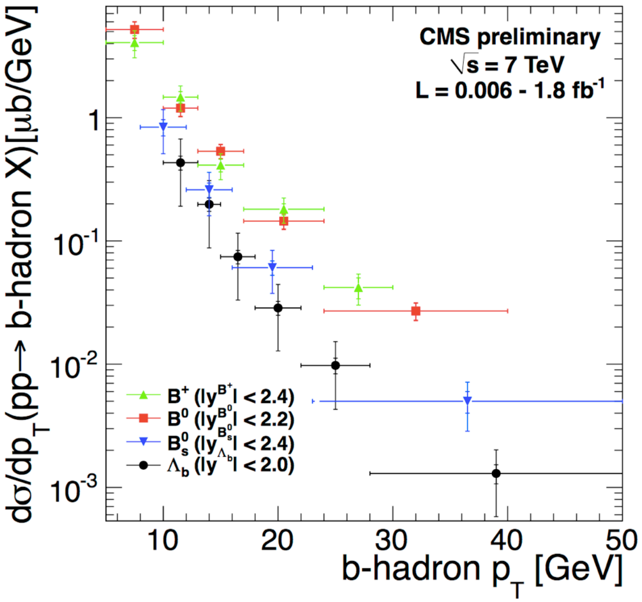
Flavour Physics at Hadron Machines

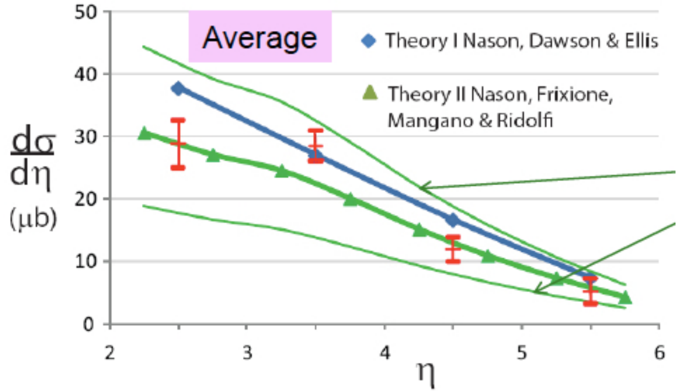
Large b-$\overline{b}$ cross section at LHC

$\sigma_{b\overline{b}}$ was one of the very early measurements at LHC









Generally in good agreement with QCD predictions

Flavour Physics at Hadron Machines

B_s^0-$\overline{B}_s^0$ oscillations: a bench mark measurement

Measure time dependent rates for

$$B_s^0{}_{\text{initial}} \Rightarrow \overline{B}_s^0{}_{\text{at } t} \qquad \propto \cos \Delta m_s \times t$$

Flavour Physics at Hadron Machines

B_s^0-$\overline{B}_s^0$ oscillations: a bench mark measurement

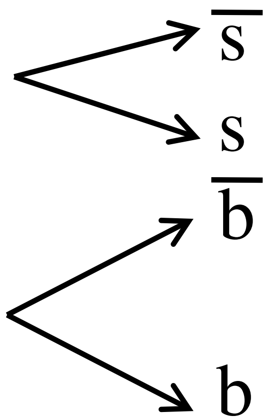
flavour tagging of the initial state

$B_s^0{}_{initial}$

Flavour Physics at Hadron Machines

B_s^0-$\overline{B}_s^0$ oscillations: a bench mark measurement

flavour tagging of the initial state



K^+ same side tag

B_s^0 initial

↳l^-X, c→s→K^-, secondary vertex charge

opposite side tag

Flavour Physics at Hadron Machines

B_s^0-$\overline{B}_s^0$ oscillations: a bench mark measurement

flavour tagging of the initial state

$\overline{s}$ K^+ same side tag

flavour tagging of the final state

s

$\overline{b}$ $B_s^0{}_{\text{initial}} \Rightarrow \overline{B}_s^0{}_{\text{at } t}$

b

↳ l^-X, $c \rightarrow s \rightarrow K^-$, secondary vertex charge

opposite side tag

Flavour Physics at Hadron Machines

B_s^0-$\overline{B}_s^0$ oscillations: a bench mark measurement

flavour tagging of the initial state

$\overline{s}$ K^+ same side tag

s

$\overline{b}$ $B_s^0{}_{\text{initial}} \Rightarrow \overline{B}_s^0{}_{\text{at } t}$ $(\rightarrow D_s^+\pi^-)$

flavour tagging of the final state

↳ $K^+K^-\pi^+$

b

↳ l^-X, $c \rightarrow s \rightarrow K^-$, secondary vertex charge

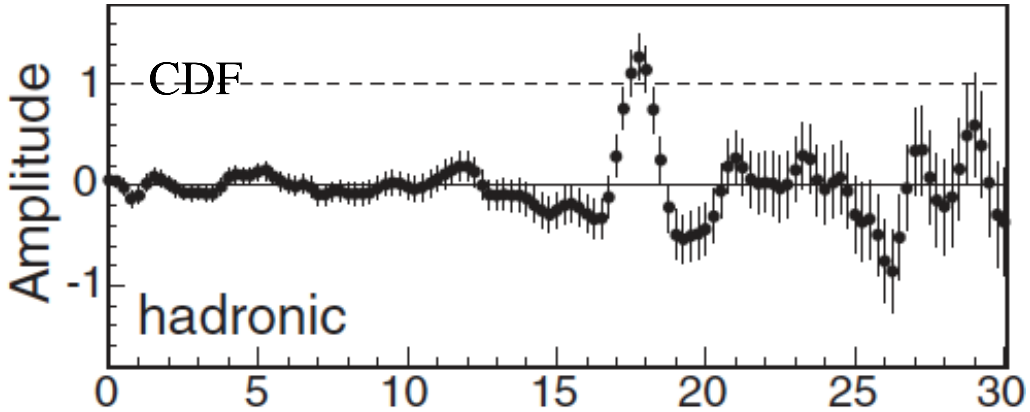
opposite side tag

Flavour Physics at Hadron Machines

B_s^0-$\overline{B}_s^0$ oscillations: a bench mark measurement

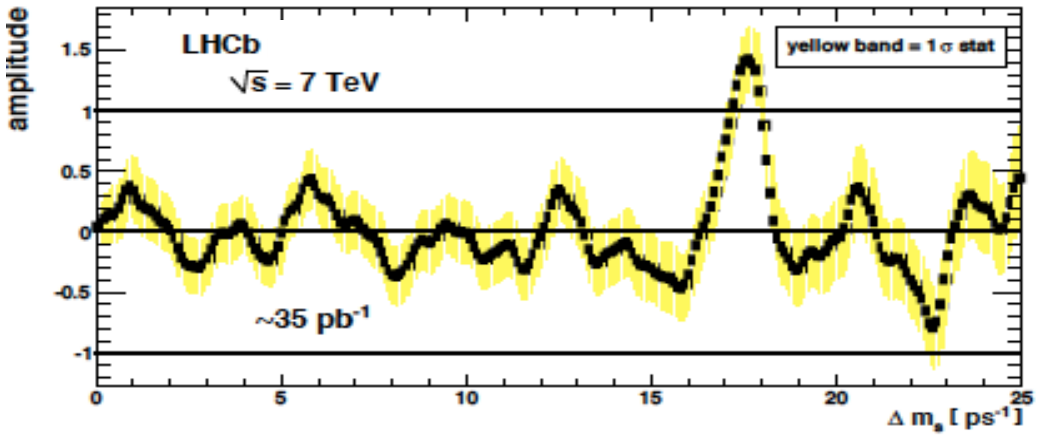
Time dependent rate $A \times \cos \Delta m_s \times t \otimes \sigma_t$-effect

Fit the decay time distribution for different Δm_s with A as a parameter:
$A = 1$ at the correct Δm_s, once the tagging is correctly taken into account



CDF:
1 fb^{-1}

PhysRevLett.97.242003



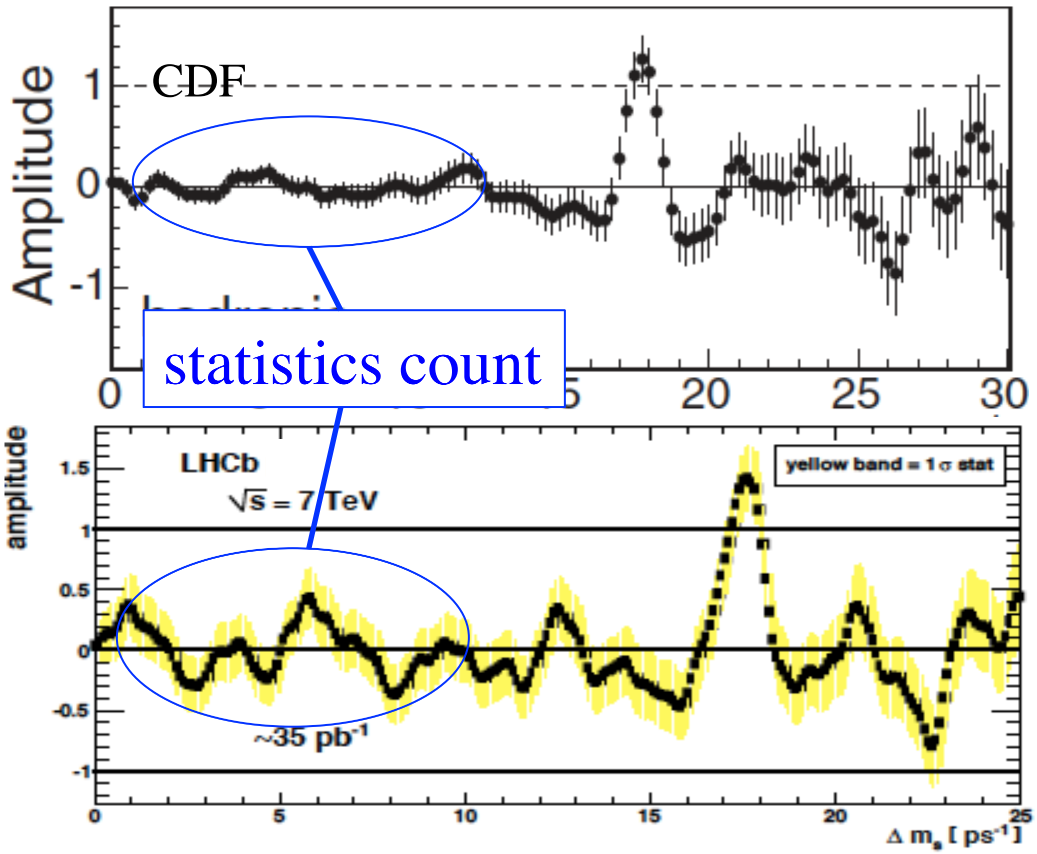
LHCb:
36 pb^{-1}

Phys Lett B709 177

Flavour Physics at Hadron Machines

B_s^0-$\overline{B}_s^0$ oscillations: a bench mark measurement

Time dependent rate $A \times \cos \Delta m_s \times t \otimes \sigma_t$-effect



CDF:
1 fb^{-1}
5600 signal

LHCb:
36 pb^{-1}
1350 signal

Flavour Physics at Hadron Machines

B_s^0-$\overline{B}_s^0$ oscillations: a bench mark measurement

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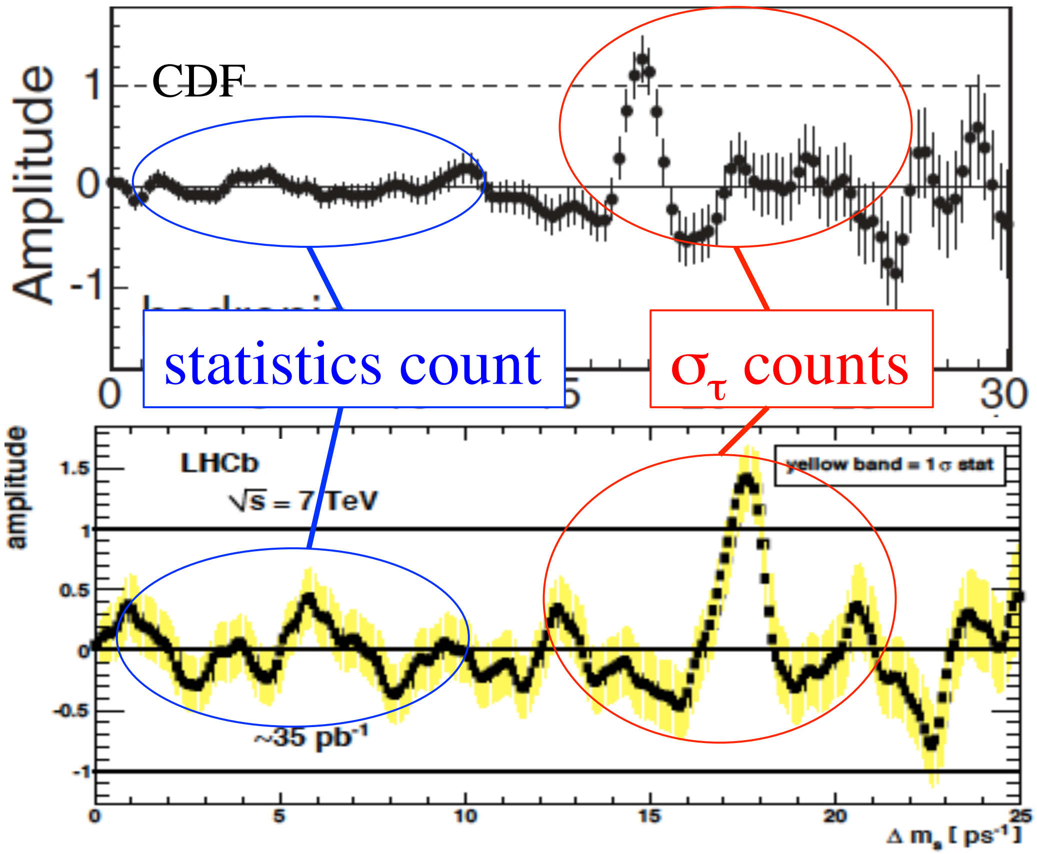


CDF:
1 fb^{-1}
5600 signal, σ_τ=87 fs

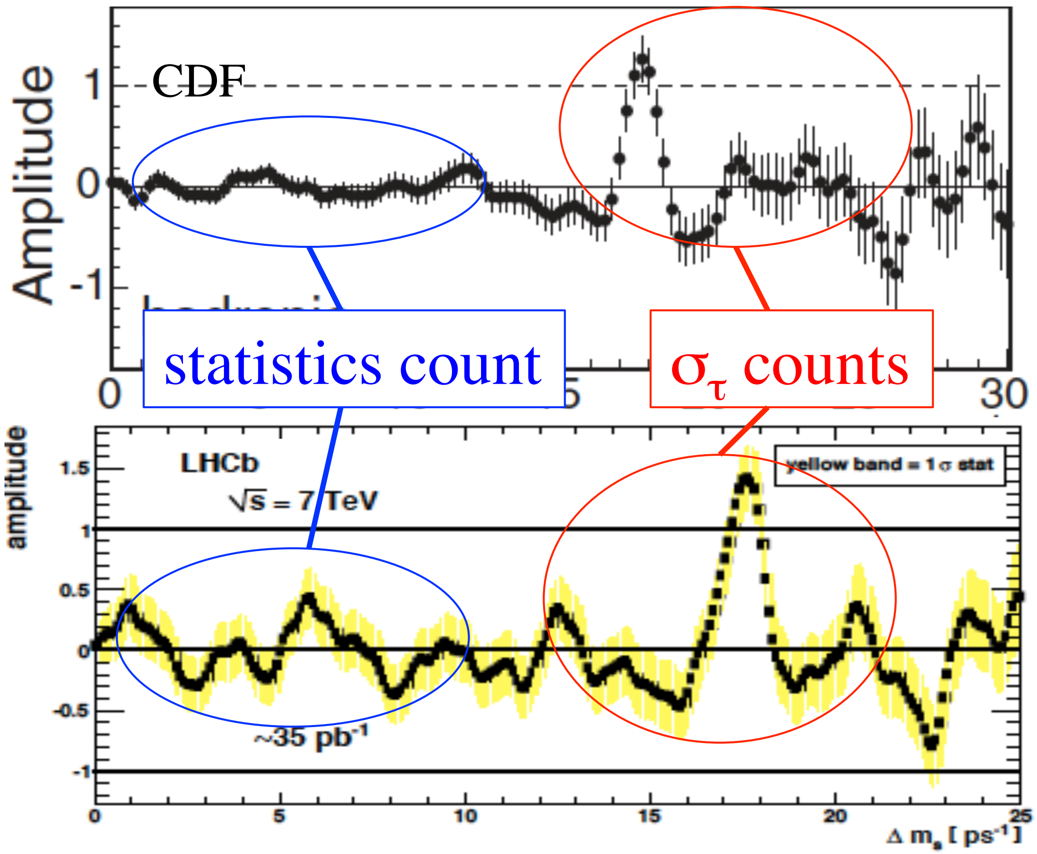
LHCb:
36 pb^{-1}
1350 signal, σ_τ=36 or 44 fs

Flavour Physics at Hadron Machines

B_s^0-$\overline{B}_s^0$ oscillations: a bench mark measurement

Time dependent rate $A \times \cos \Delta m_s \times t \otimes \sigma_t$-effect

$A = 1$ at the correct Δm_s, once the tagging is correctly taken into account



CDF:
1 fb^{-1}
5600 signal, σ_τ=87 fs
$\Delta m_s = 17.77 \pm 0.10 \pm 0.07\ ps^{-1}$

LHCb:
36 pb^{-1}
1350 signal, σ_τ=36 or 44 fs
$\Delta m_s = 17.63 \pm 0.11 \pm 0.04\ ps^{-1}$

Flavour Physics at Hadron Machines

B_s^0-$\overline{B}_s^0$ oscillations: a bench mark measurement

Time dependent rate $A \times \cos \Delta m_s \times t \otimes \sigma_t$-effect

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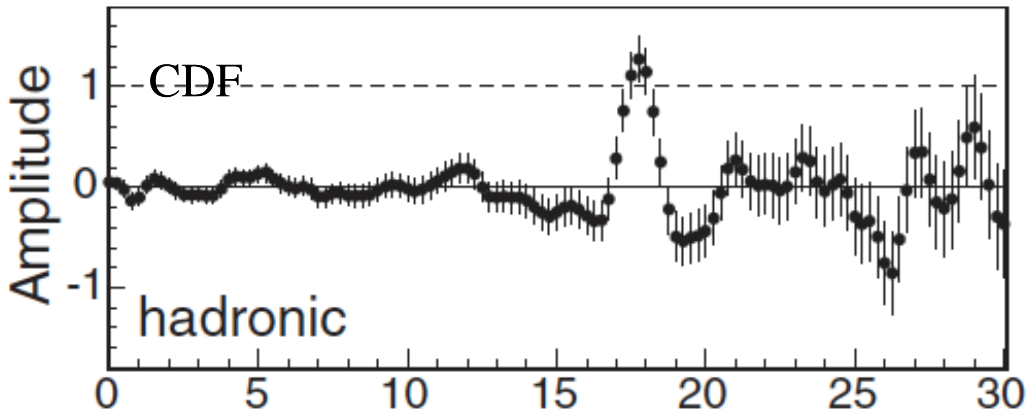

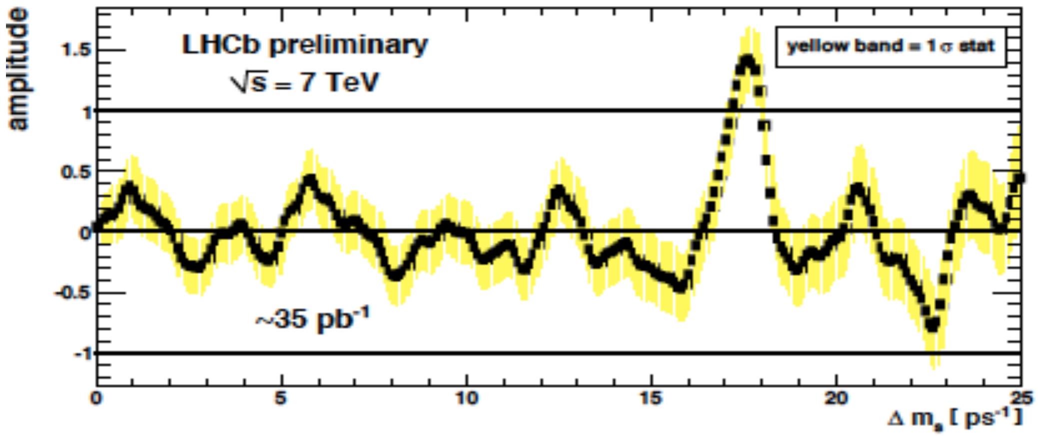

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1350 signal, σ_τ=36 or 44 fs
$\Delta m_s = 17.63 \pm 0.11 \pm 0.04$ ps^{-1}

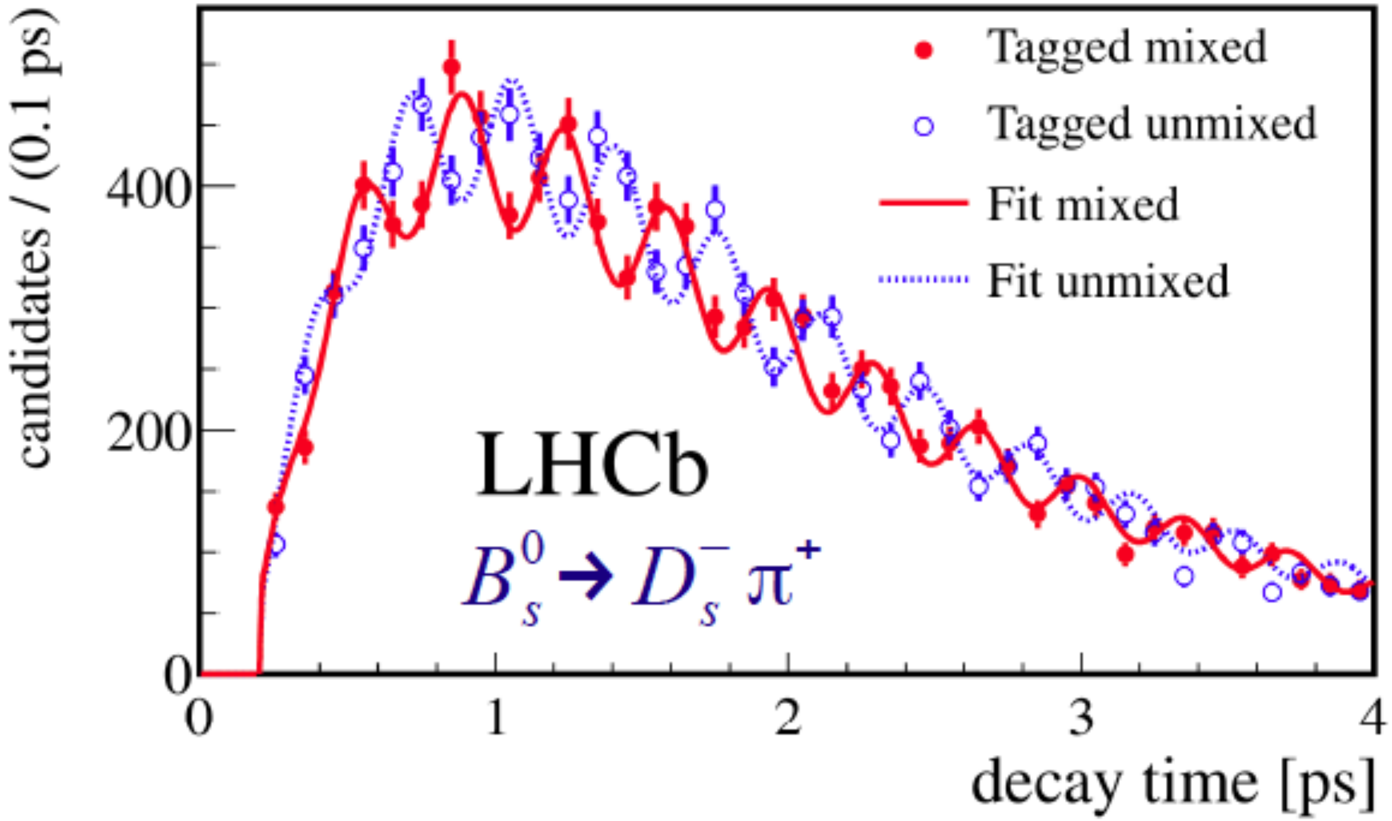
$\beta\gamma c\tau_B \approx 1$cm

Flavour Physics at Hadron Machines

- State of the art B_s-$\overline{B}_s$ oscillation: LHCb with 1 fb^{-1}

B_s at $t = 0 \rightarrow \overline{B}_s$ at t

B_s at $t = 0 \rightarrow B_s$ at t



Oscillation is clearly visible

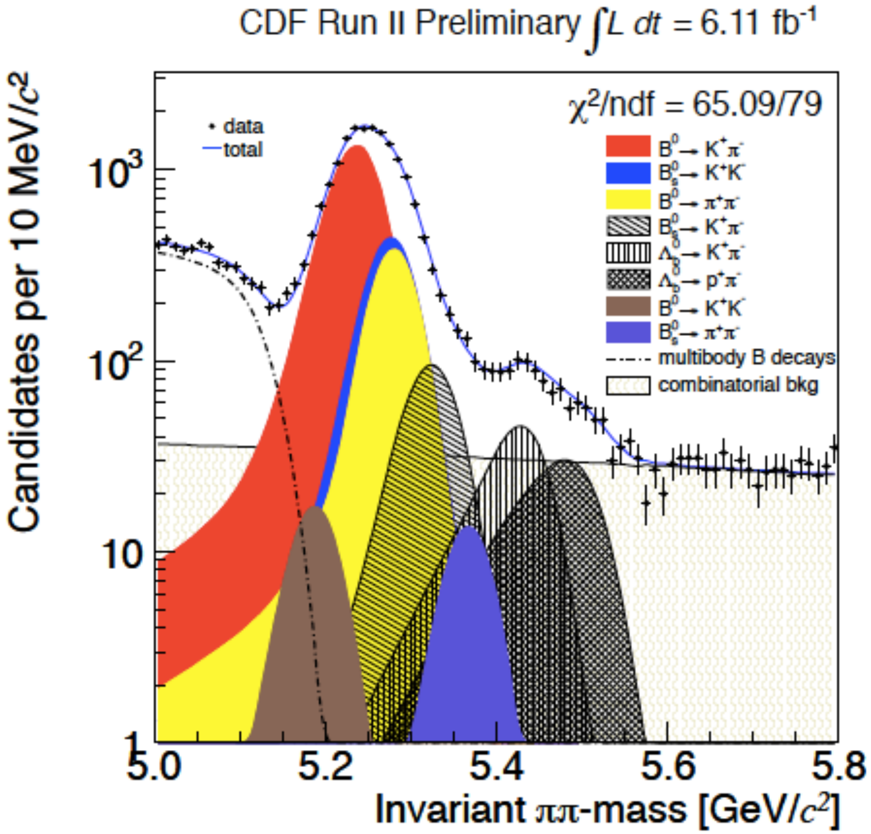
New J.Phys. 15 (2013) 053021

Flavour Physics at Hadron Machines

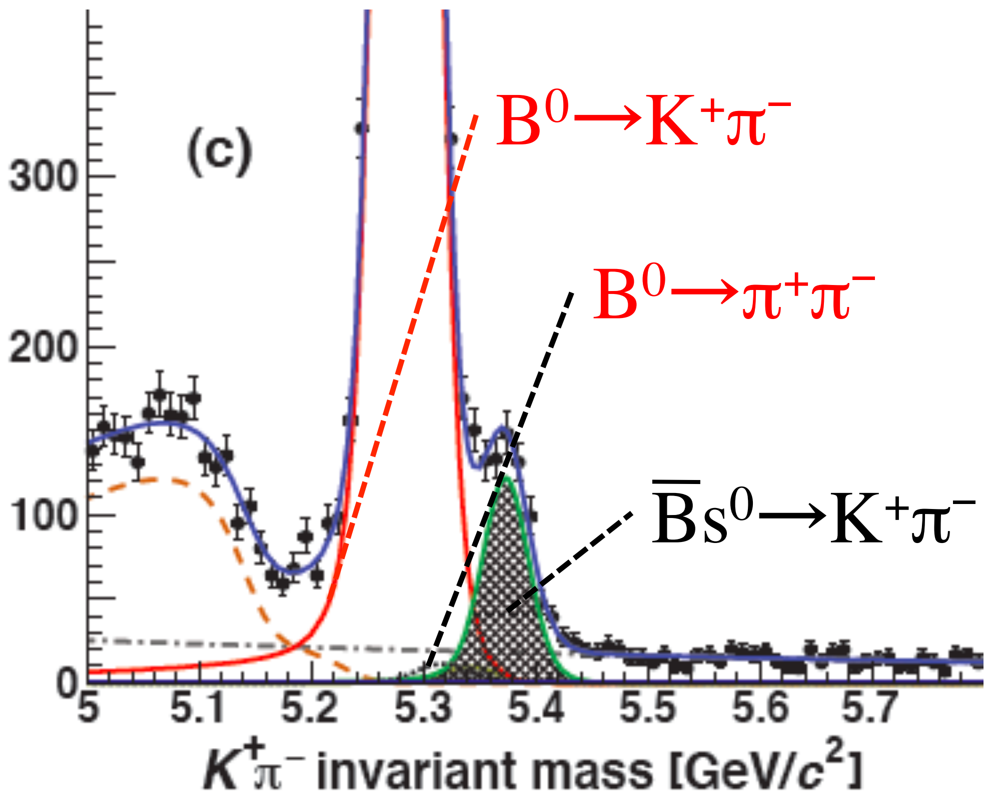
Hadron identification is important for hadronic final states

$B \rightarrow hh'$ as an example

CDF with little hadron PID
(ATLAS/CMS will be similar)



LHCb with with PID



Public Note 10498

Flavour Physics at Hadron Machines

CP violation in the $B\to hh'$ decay amplitude: LHCb 1 fb^{-1}

$A_{CP}(B_d\to K^+\pi^-)$

BABAR	$-0.107\pm0.016_{-0.004}^{+0.006}$
BELLE	$-0.069\pm0.014\pm0.007$
CDF	$-0.083\pm0.013\pm0.003$
LHCb	$-0.080 \pm 0.007 \pm 0.003$

$A_{CP}(B_s\to K^-\pi^+)$

CDF	$0.22 \pm 0.07 \pm 0.02$
LHCb	$0.27 \pm 0.04 \pm 0.01$

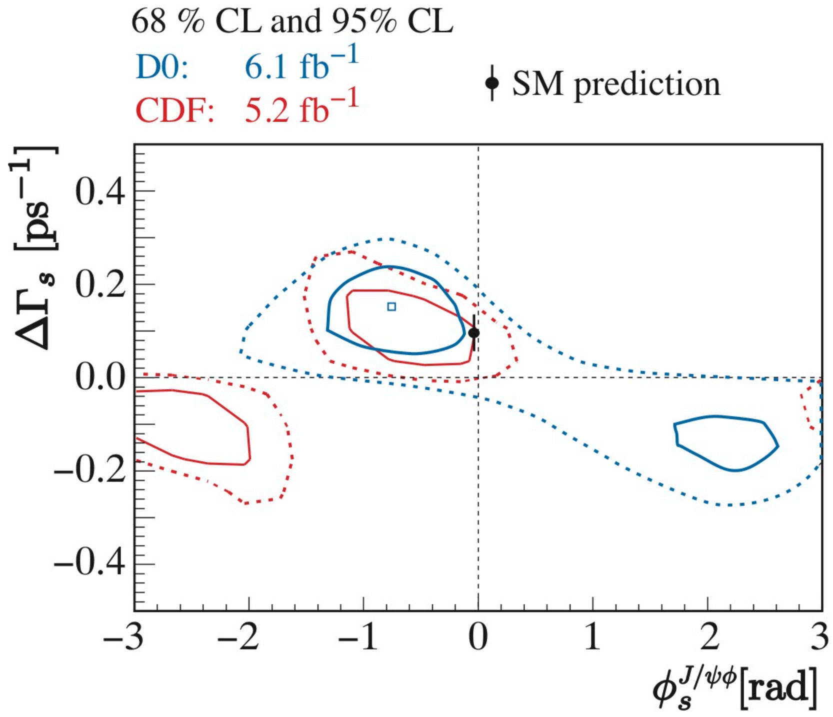
LHCb Phys. Rev. Lett.110 (2013) 221601

Flavour Physics at Hadron Machines

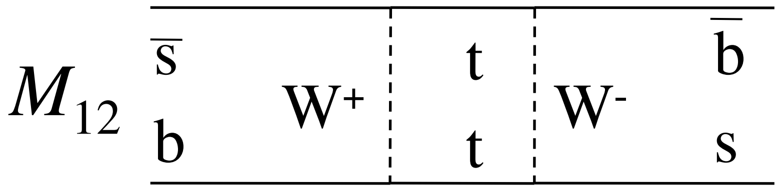
- Large b-$\overline{\text{b}}$ cross sections ($\sqrt{s}$ of LHC)
- High statistics (7-8 TeV full data: close to 30 fb^{-1} each for ATLAS and CMS and 3 fb^{-1} for LHCb)
- Vertex resolutions (ATLAS**, CMS**, LHCb***)
- Momentum resolutions (ATLAS**, CMS**, LHCb***)
- Particle identification
  muons and electrons (ATLAS, CMS, LHCb)
  hadron (LHCb)
- Trigger
  muons and electrons (ATLAS, CMS, LHCb)
  hadron (LHCb)

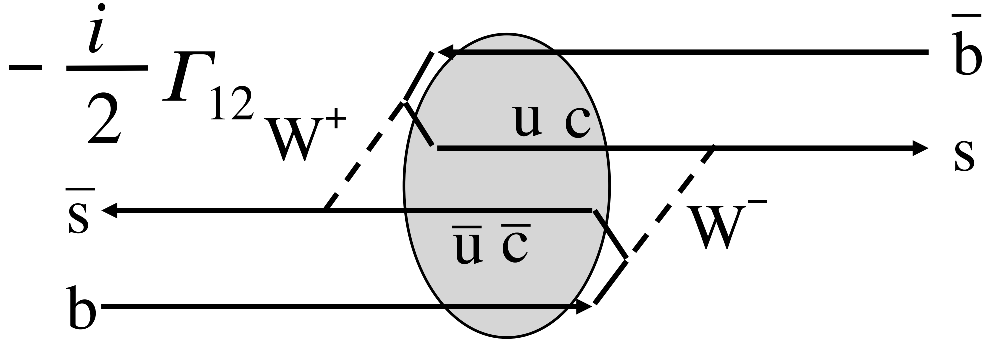
CP violation in $B_s \to J/\psi\phi$

- Recall the past result

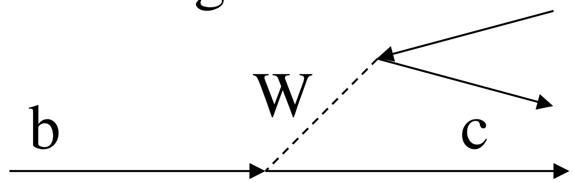


- relevant SM diagrams





Tree diagram



CP violation in $B_s \rightarrow J/\psi\phi$

- Time dependent decay rate studies for $B_s \rightarrow J/\psi\phi$ decays
  - need to distinguish $J/\psi\phi_{CP=+1}$ and $J/\psi\phi_{CP=-1}$ states from **the angular distributions of the final states**: additional complication

$$L_{J/\psi-\phi} = 0 \text{ or } 2\text{: CP} = +1\,,\ L_{J/\psi-\phi} = 1\text{: CP} = -1$$

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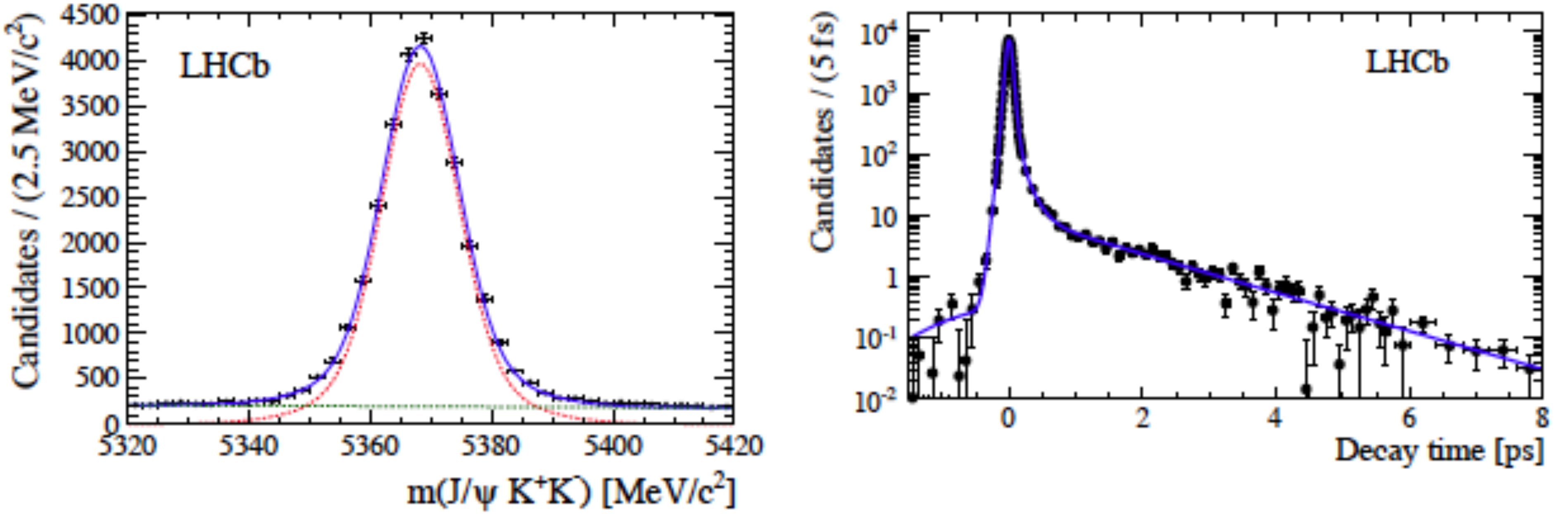
example using LHCb : Phys. Rev. D 87, 112010 (2013)



Reconstructed mass

Decay time distribution

CP violation in $B_s \to J/\psi\phi$

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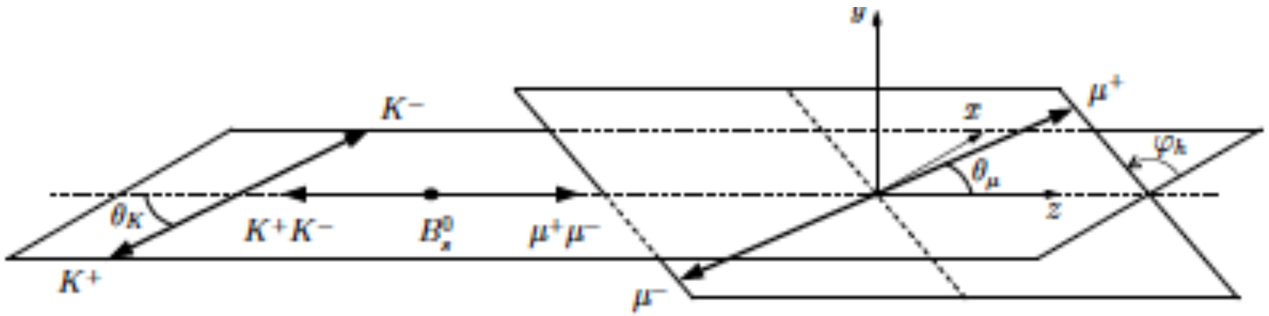

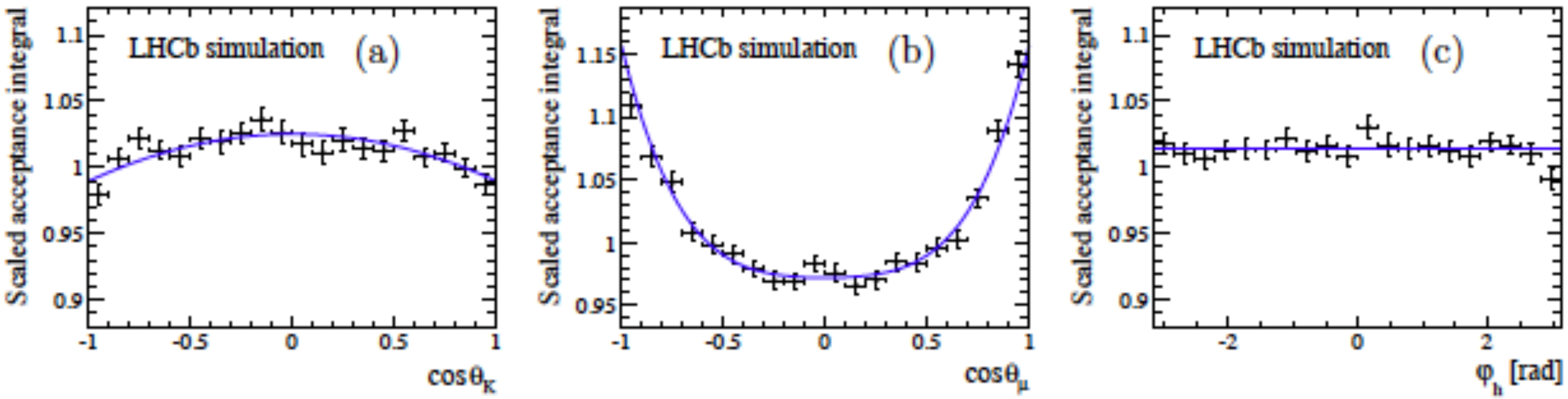

Detector acceptance for the decay angles has to be well understood.

LHCb : Phys. Rev. D 87, 112010 (2013)

CP violation in $B_s \to J/\psi\phi$

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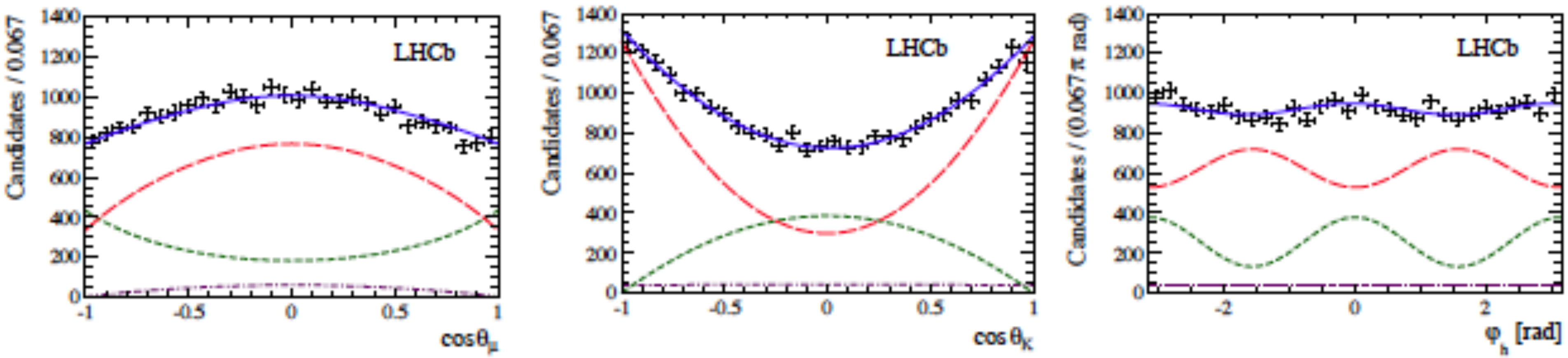


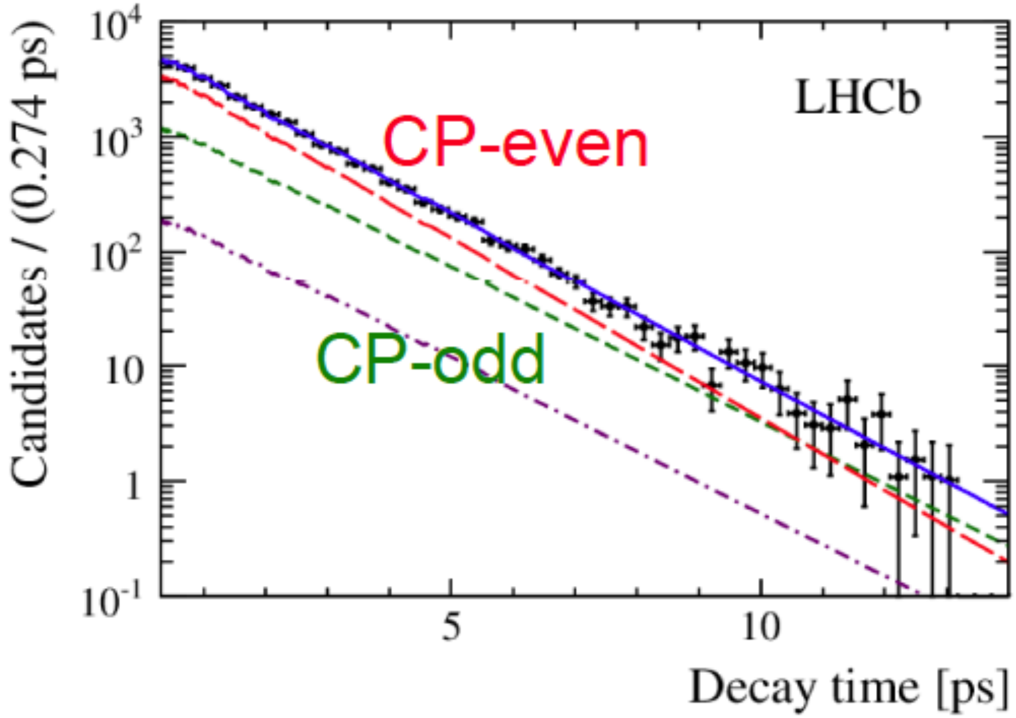
Experimental decay time distribution for $B_s^0 + \overline{B}_s^0$ contribution from the CP = +1 and −1 final states

LHCb : Phys. Rev. D 87, 112010 (2013)

CP violation in $B_s \to J/\psi\phi$

- Time dependent decay rate studies for $B_s \to J/\psi\phi$ decays
  - need to distinguish $J/\psi\phi_{CP=+1}$ and $J/\psi\phi_{CP=-1}$ states from **the angular distributions of the final states**: additional complication

$B_s^0 + \overline{B}_s^0$ decay time distributions projected out for CP=+1 and = −1 states



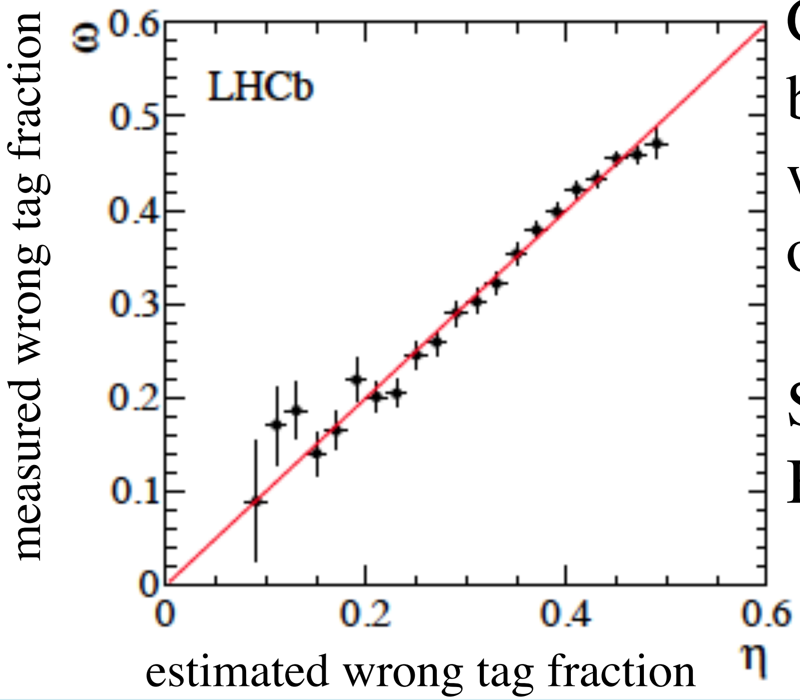
Both are practically exponential decays → CP violation is small

CP=+1 state decays faster
Another phase shift study shows
CP=+1 state is lighter
As predicted by the SM.

LHCb : Phys. Rev. D 87, 112010 (2013)

CP violation in $B_s \to J/\psi\phi$

- Time dependent decay rate studies for $B_s \to J/\psi\phi$ decays
  - need to distinguish $J/\psi\phi_{CP=+1}$ and $J/\psi\phi_{CP=-1}$ states from **the angular distributions of the final states**:
  - **with initial flavour tag**, unique solution on CP violation parameter $\phi_S^{J/\psi\phi}$ and decay width difference $\Delta\Gamma = \Gamma_L - \Gamma_H$ measurements. Calibration of flavour tag needed.



Comparison of the flavour estimate, based on leptons, kaons and vertex charges, with the calibration data $B^+ \to J/\psi K^+$ for the opposite flavour tag.

Similar work for the same sign kaon tag $B_s \to D_s\pi$ necessary

LHCb : Phys. Rev. D 87, 112010 (2013)

CP violation in $B_s \to J/\psi\phi$

- Time dependent decay rate studies for $B_s \to J/\psi\phi$ decays
  - need to distinguish $J/\psi\phi_{CP=+1}$ and $J/\psi\phi_{CP=-1}$ states from **the angular distributions of the final states**:
  - **with initial flavour tag**, unique solution on CP violation parameter $\phi_S^{J/\psi\phi}$ and decay width difference $\Delta\Gamma = \Gamma_L - \Gamma_H$ measurements.

fitting rather complicated PDF…

$$\frac{\mathrm{d}^4\Gamma(B_s^0 \to J/\psi K^+K^-)}{\mathrm{d}t\,\mathrm{d}\Omega} \propto \sum_{k=1}^{10} h_k(t)\, f_k(\Omega)\,.$$

$$h_k(t) = N_k e^{-\Gamma_s t}\left[a_k \cosh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + b_k \sinh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + c_k \cos(\Delta m_s t) + d_k \sin(\Delta m_s t)\right],$$

k	$f_k(\theta_\mu, \theta_K, \varphi_h)$	N_k	a_k	b_k	c_k	d_k
1	$2\cos^2\theta_K \sin^2\theta_\mu$	$\lvert A_0\rvert^2$	1	D	C	$-S$
2	$\sin^2\theta_K\,(1-\sin^2\theta_\mu\cos^2\varphi_h)$	$\lvert A_\parallel\rvert^2$	1	D	C	$-S$
3	$\sin^2\theta_K\,(1-\sin^2\theta_\mu\sin^2\varphi_h)$	$\lvert A_\perp\rvert^2$	1	$-D$	C	S
4	$\sin^2\theta_K\sin^2\theta_\mu\sin 2\varphi_h$	$\lvert A_\parallel A_\perp\rvert$	$C\sin(\delta_\perp-\delta_\parallel)$	$S\cos(\delta_\perp-\delta_\parallel)$	$\sin(\delta_\perp-\delta_\parallel)$	$D\cos(\delta_\perp-\delta_\parallel)$
5	$\frac{1}{2}\sqrt{2}\sin 2\theta_K\sin 2\theta_\mu\cos\varphi_h$	$\lvert A_0 A_\parallel\rvert$	$\cos(\delta_\parallel-\delta_0)$	$D\cos(\delta_\parallel-\delta_0)$	$C\cos(\delta_\parallel-\delta_0)$	$-S\cos(\delta_\parallel-\delta_0)$
6	$-\frac{1}{2}\sqrt{2}\sin 2\theta_K\sin 2\theta_\mu\sin\varphi_h$	$\lvert A_0 A_\perp\rvert$	$C\sin(\delta_\perp-\delta_0)$	$S\cos(\delta_\perp-\delta_0)$	$\sin(\delta_\perp-\delta_0)$	$D\cos(\delta_\perp-\delta_0)$
7	$\frac{2}{3}\sin^2\theta_\mu$	$\lvert A_S\rvert^2$	1	$-D$	C	S
8	$\frac{1}{3}\sqrt{6}\sin\theta_K\sin 2\theta_\mu\cos\varphi_h$	$\lvert A_S A_\parallel\rvert$	$C\cos(\delta_\parallel-\delta_S)$	$S\sin(\delta_\parallel-\delta_S)$	$\cos(\delta_\parallel-\delta_S)$	$D\sin(\delta_\parallel-\delta_S)$
9	$-\frac{1}{3}\sqrt{6}\sin\theta_K\sin 2\theta_\mu\sin\varphi_h$	$\lvert A_S A_\perp\rvert$	$\sin(\delta_\perp-\delta_S)$	$-D\sin(\delta_\perp-\delta_S)$	$C\sin(\delta_\perp-\delta_S)$	$S\sin(\delta_\perp-\delta_S)$
10	$\frac{4}{3}\sqrt{3}\cos\theta_K\sin^2\theta_\mu$	$\lvert A_S A_0\rvert$	$C\cos(\delta_0-\delta_S)$	$S\sin(\delta_0-\delta_S)$	$\cos(\delta_0-\delta_S)$	$D\sin(\delta_0-\delta_S)$

CP violation in $B_s \to J/\psi\phi$

- Time dependent decay rate studies for $B_s \to J/\psi\phi$ decays
  - need to distinguish $J/\psi\phi_{CP=+1}$ and $J/\psi\phi_{CP=-1}$ states from **the angular distributions of the final states**:
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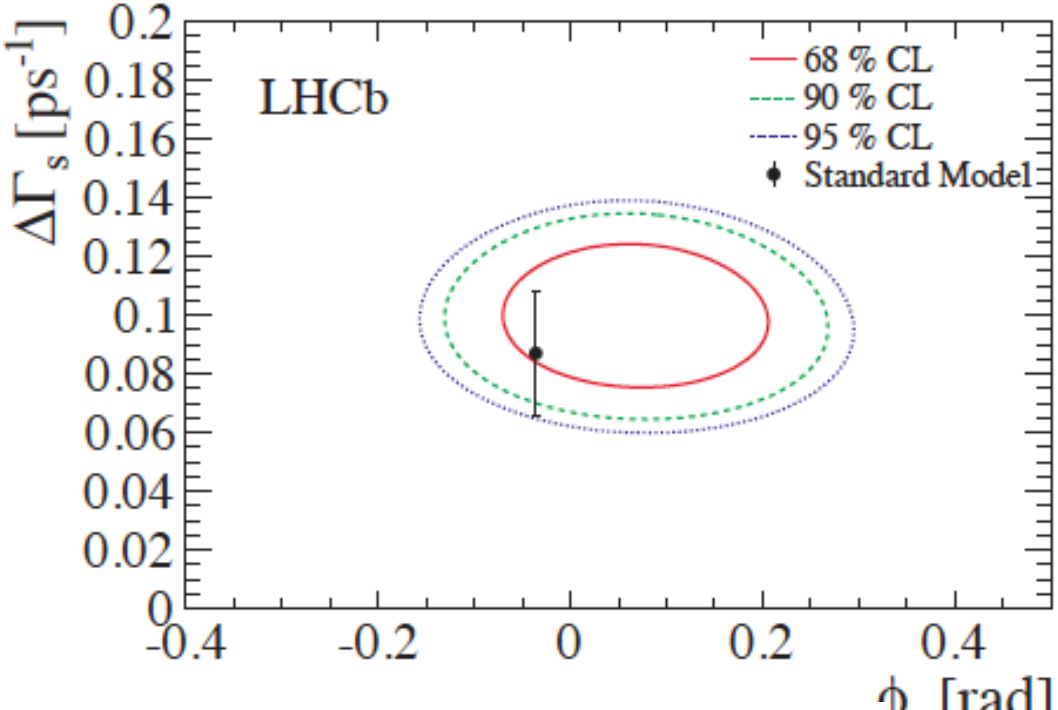
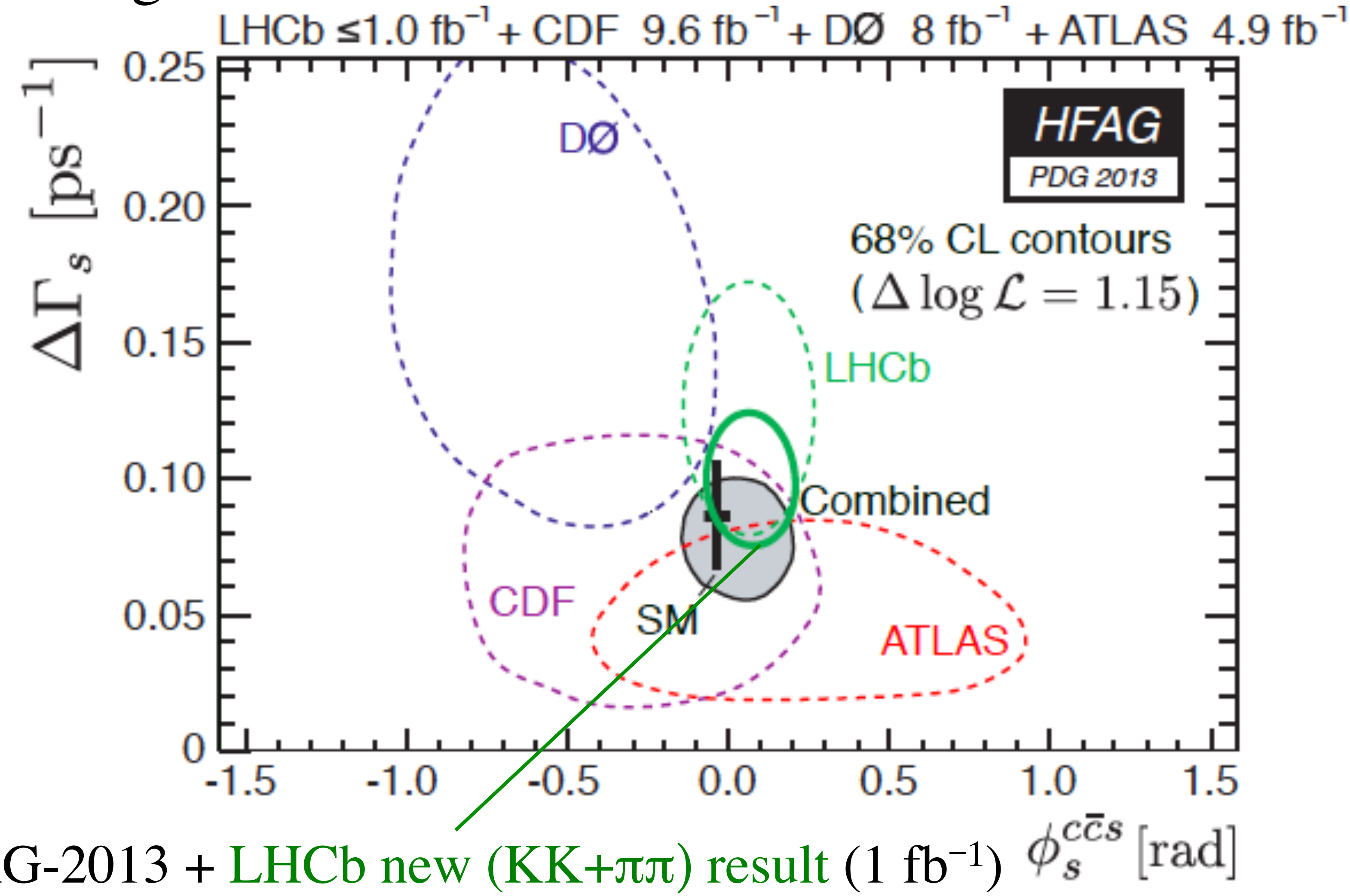


Result by combining $B_s \to J/\psi(KK)$ and $J/\psi(\pi\pi)$ 1 fb^{-1}

LHCb : Phys. Rev. D 87, 112010 (2013)

CP violation in $B_s \to J/\psi\phi$

- Good agreement with the Standard Model



HFAG-2013 + LHCb new (KK+ππ) result (1 fb^{-1})

CP violation in $B_s \to J/\psi\phi$

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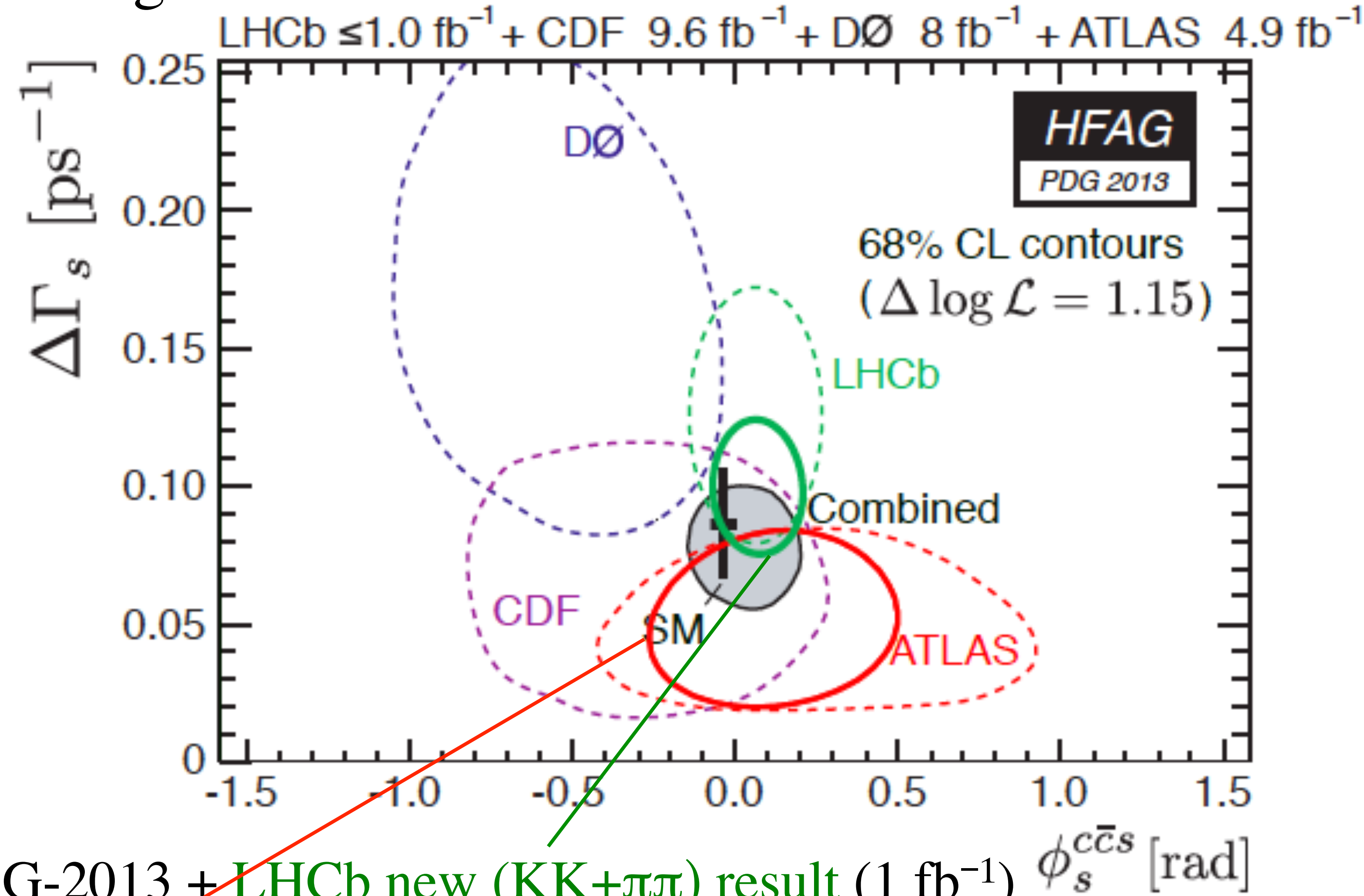

HFAG-2013 + LHCb new (KK+ππ) result (1 fb^{-1})
NB: Updated ATLAS result with the flavour tag (4.9 fb^{-1})

CP violation in B-$\bar{\text{B}}$ oscillations

- Measured by the flavour specific decay modes, e.g. semileptonic decays: inclusively or semi-exclusively

  Inclusive signature
  $h_b\, h_{\bar{b}} \rightarrow l^- l^+$ (no oscillation) or $l^{\pm} l^{\pm}$ (with oscillation)

  Inclusive signature
  $h_b\, B_s \rightarrow l^- l^+ D_s^-$ (n.o,) or $l^- l^- D_s^+ + X$ (w.o.)

- CPV is $a_{SL} = \dfrac{N(l^+l^+) - N(l^-l^-)}{N(l^+l^+) + N(l^-l^-)} \neq 0$

CP violation in B-$\bar{B}$ oscillations

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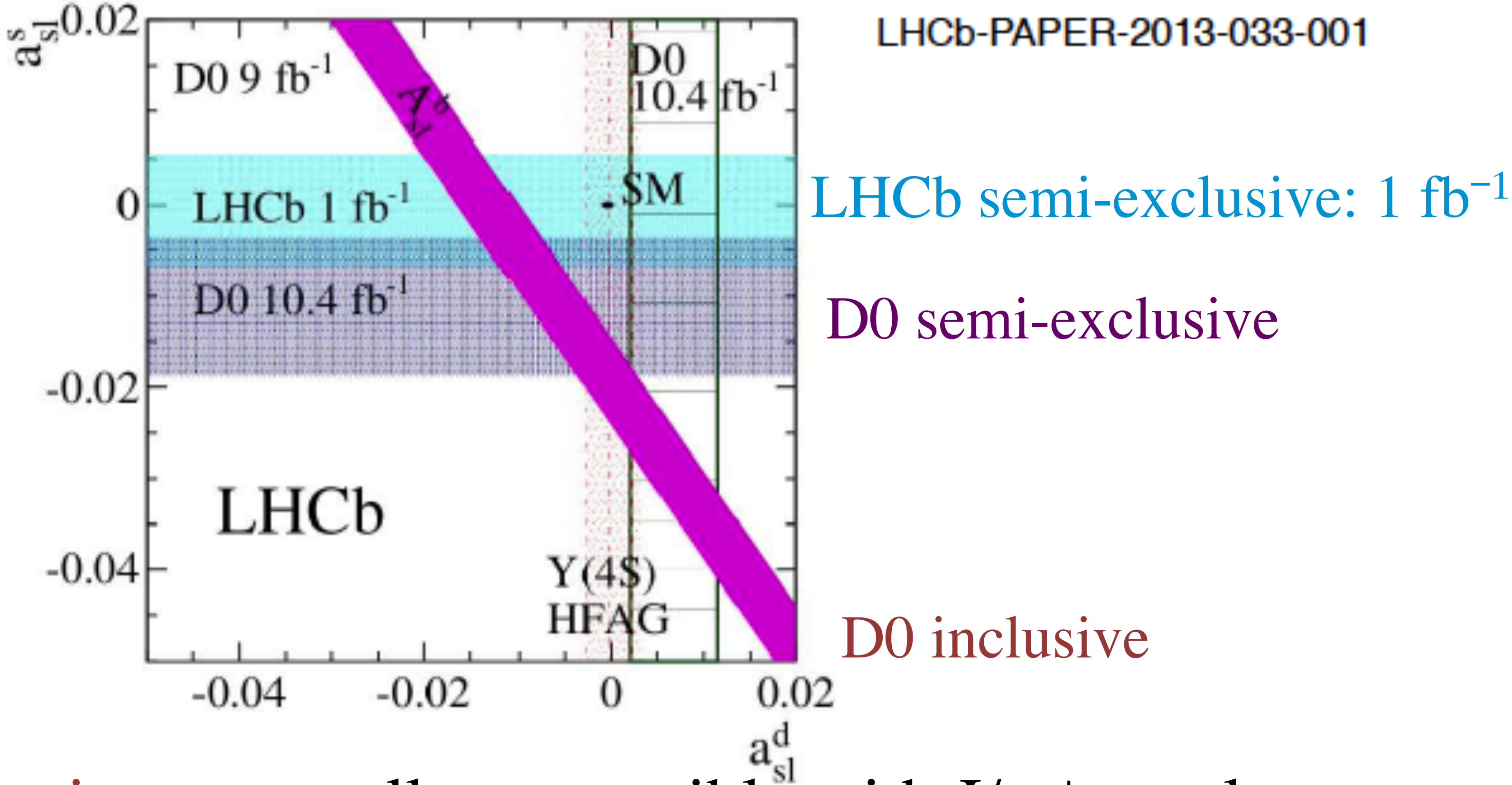
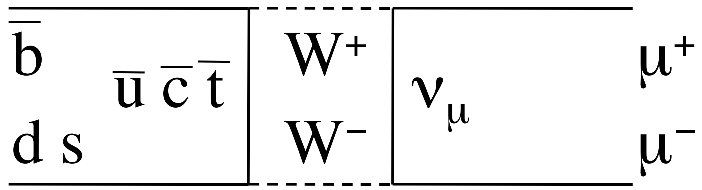


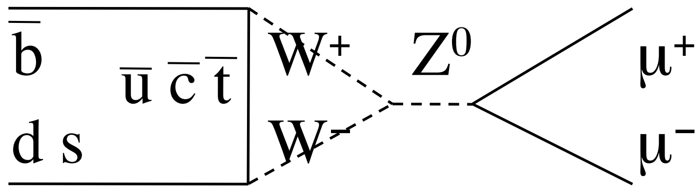
D0 inclusive: not really compatible with J/ψϕ results

→further studies at LHC essential

$B_s, B_d \rightarrow \mu^+\mu^-$

- Very rare decays



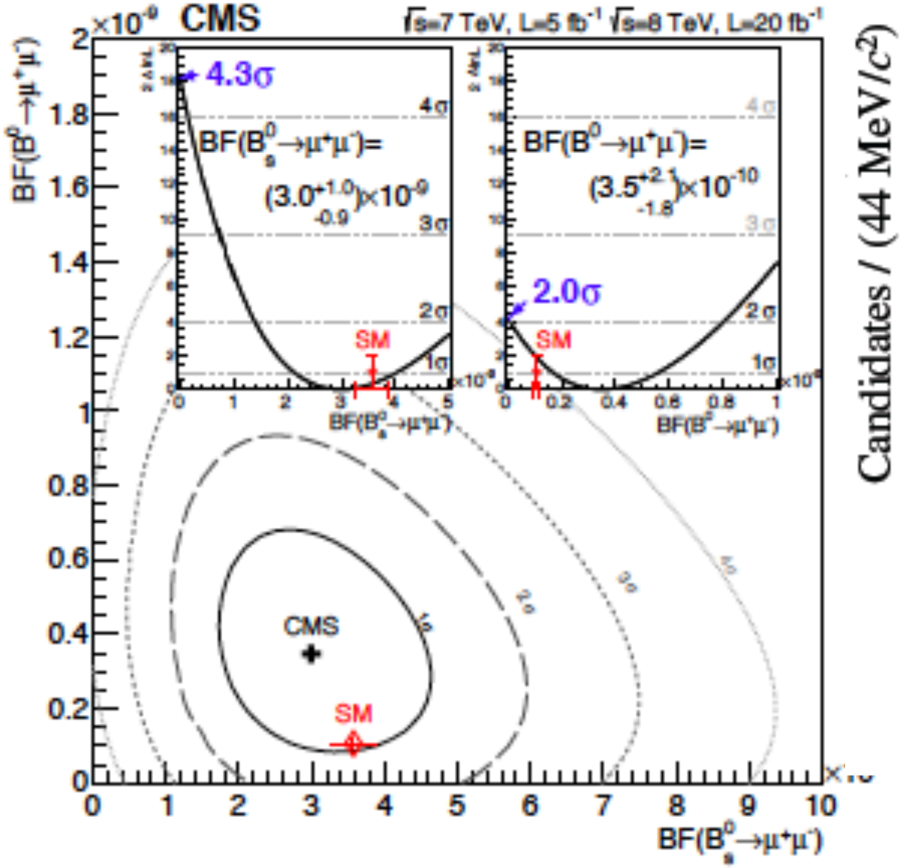


Loop suppressed and helicity suppressed decays
New particles in the loop can easily change
the branching fractions

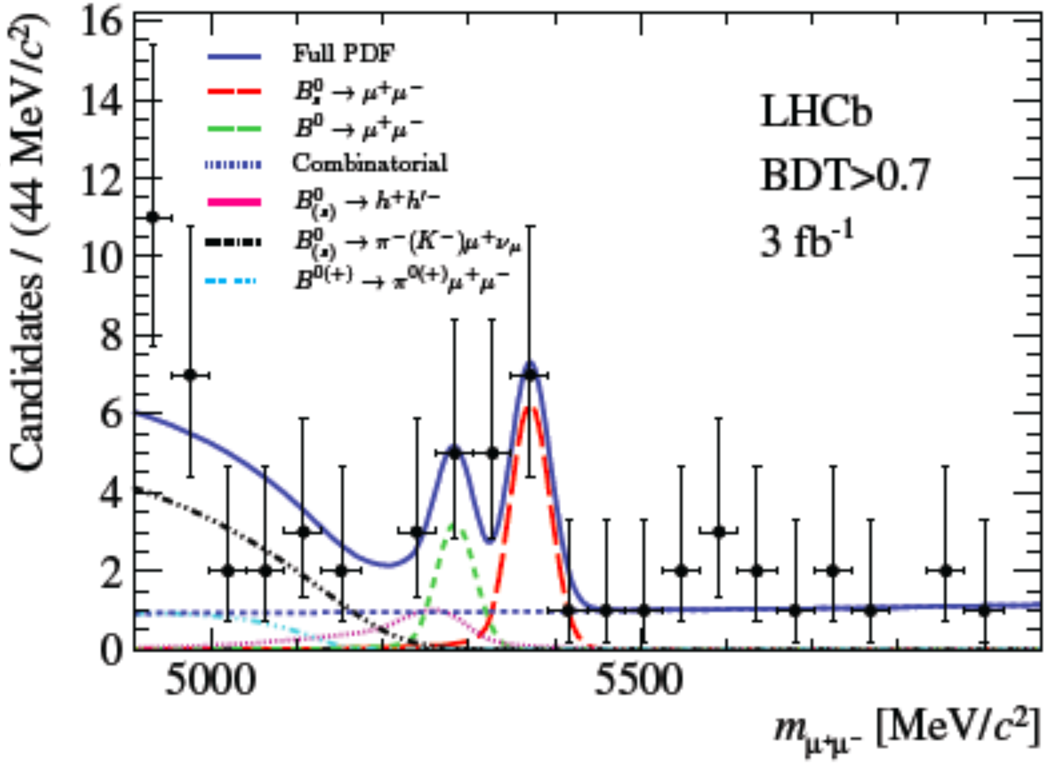
- Analysis exploits variables characteristic for the two body decays and muon identification: can be calibrated using $B \rightarrow \pi\pi$ and $J/\psi \rightarrow \mu\mu$ decays data
- ATLAS/CMS are competitive with LHCb

$B_s, B_d \to \mu^+\mu^-$

- CMS and LHCb results with 7-8 TeV full statistics



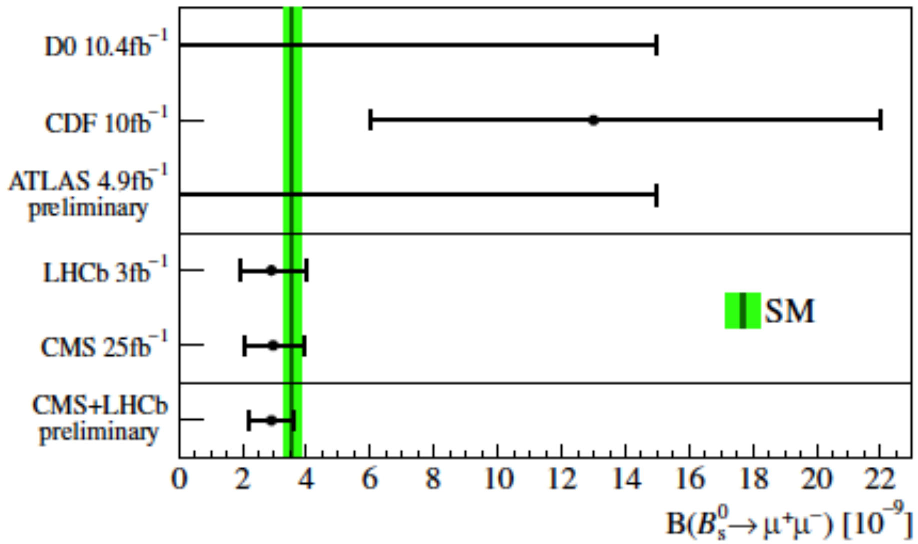
CERN-PH-EP/2013-129

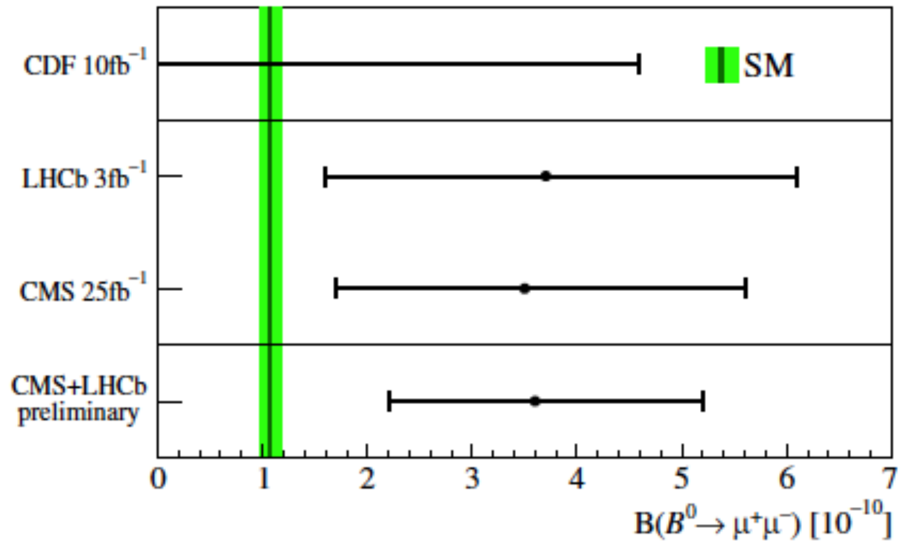


[arXiv:1307.5024]

B_s, $B_d \to \mu^+\mu^-$

- Combined result





CMS-LHCb combined

LHCb-CONF-2013-012

CMS-PAS-BPH-13-007

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9},$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.6\,^{+1.6}_{-1.4}) \times 10^{-10},$$

$B_s \to \mu^+\mu^-$ observed, in agreement with the Standard Model

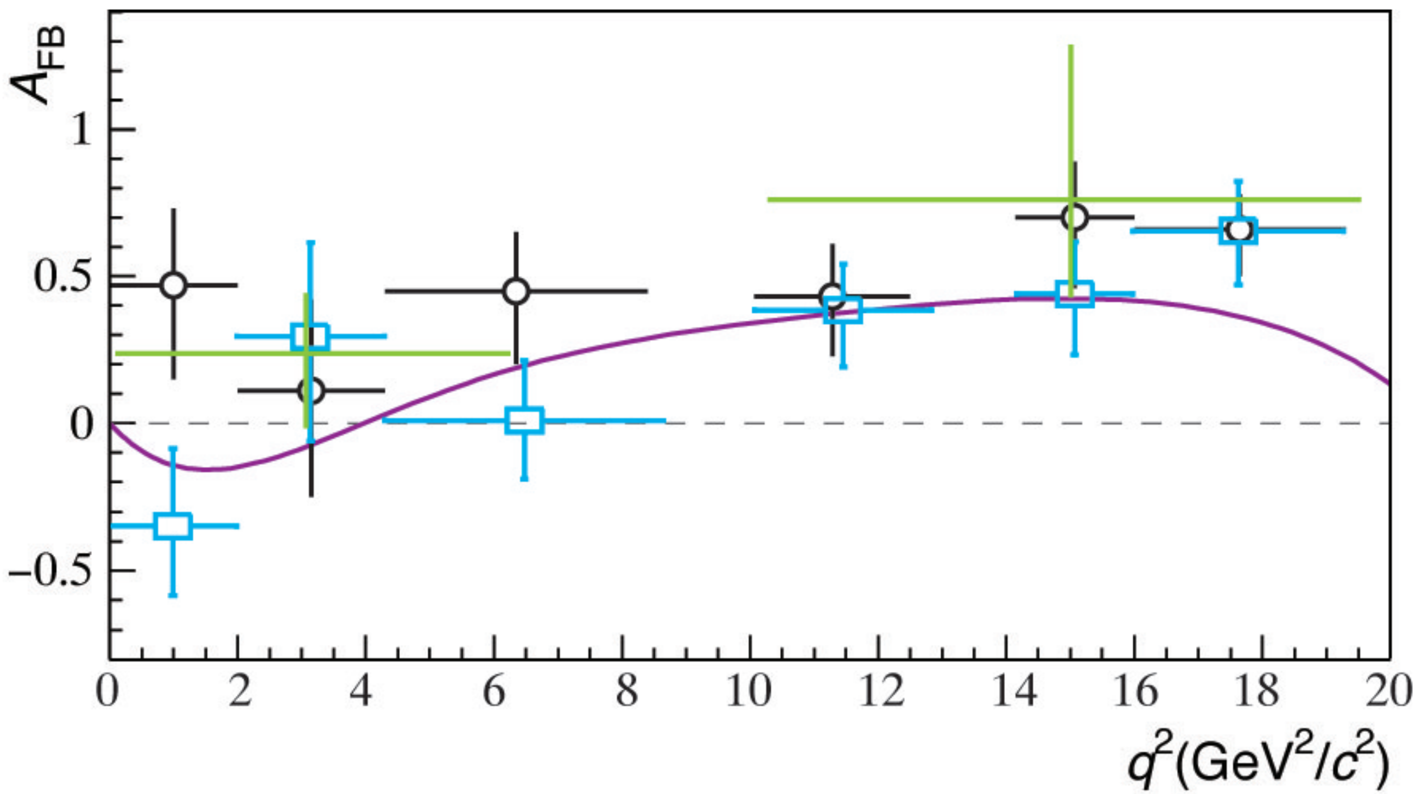
$B_d \to \mu^+\mu^-$ still insignificant, in agreement with the Standard Model

- LHCb also studied $B \to e^\pm\mu^\mp$: 1fb^{-1} [arXiv:1307.4889]
  $B^0 < 2.8(3.7)\times10^{-9}$, $B_s < 1.1(1.4)\times10^{-8}$ 90(95)%CL

$B^0 \rightarrow K^{*0}\mu^+\mu^-$ decays

- Recall previous forward-backward asymmetry results

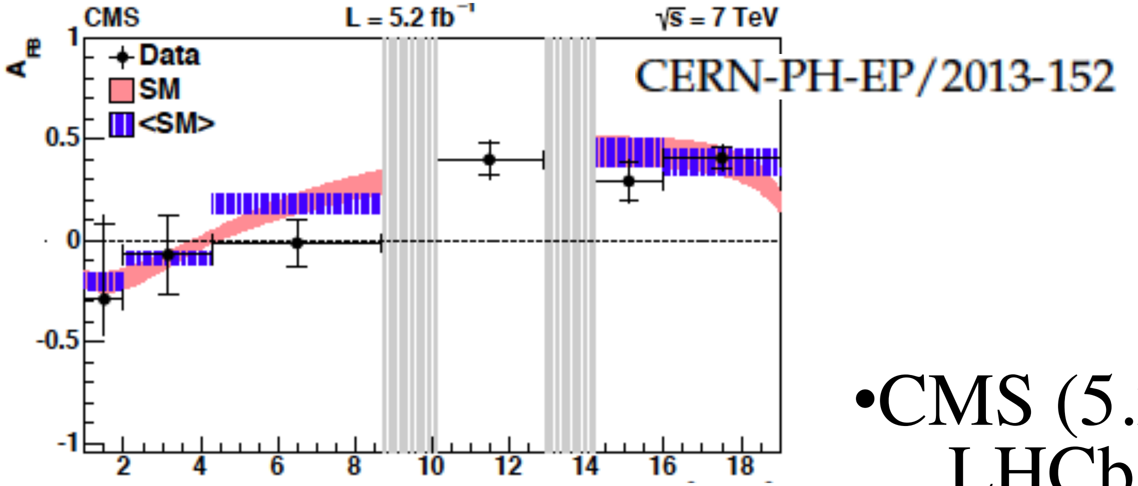
BELLE (PRL2009)
BABAR (PRD2009)
CDF (PRL2011)

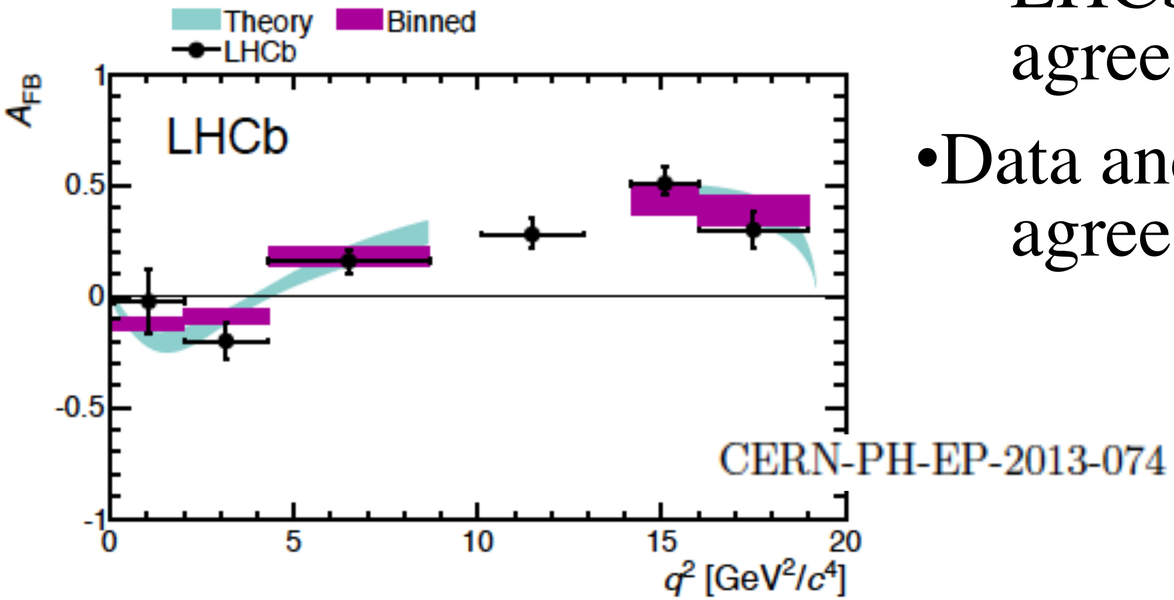


Standard model

$B^0 \rightarrow K^{*0}\mu^+\mu^-$ decays

- Most recent CMS and LHCb results on A_{FB}





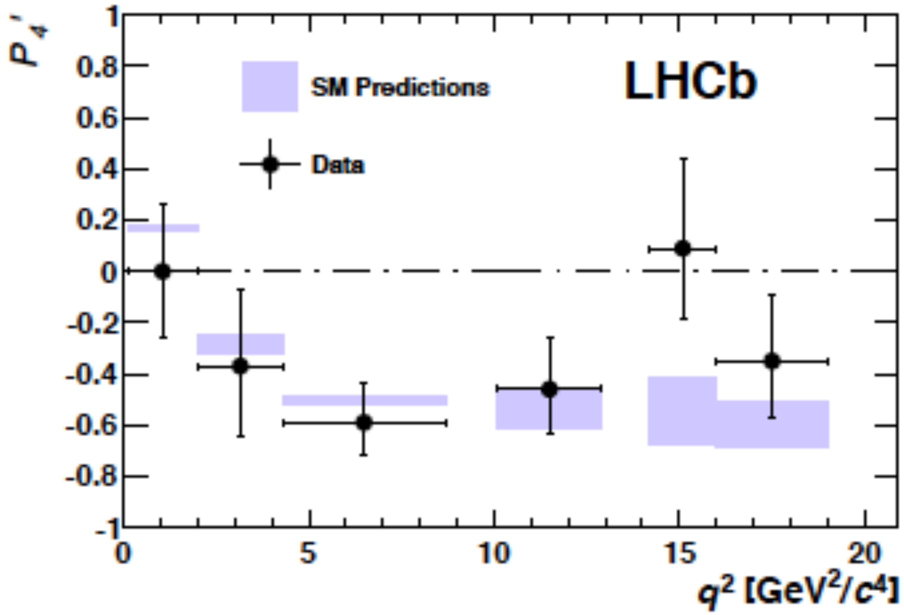
- CMS ($5.2\ fb^{-1}$) and LHCb ($1\ fb^{-1}$) results agree each other
- Data and the SM prediction agree each other

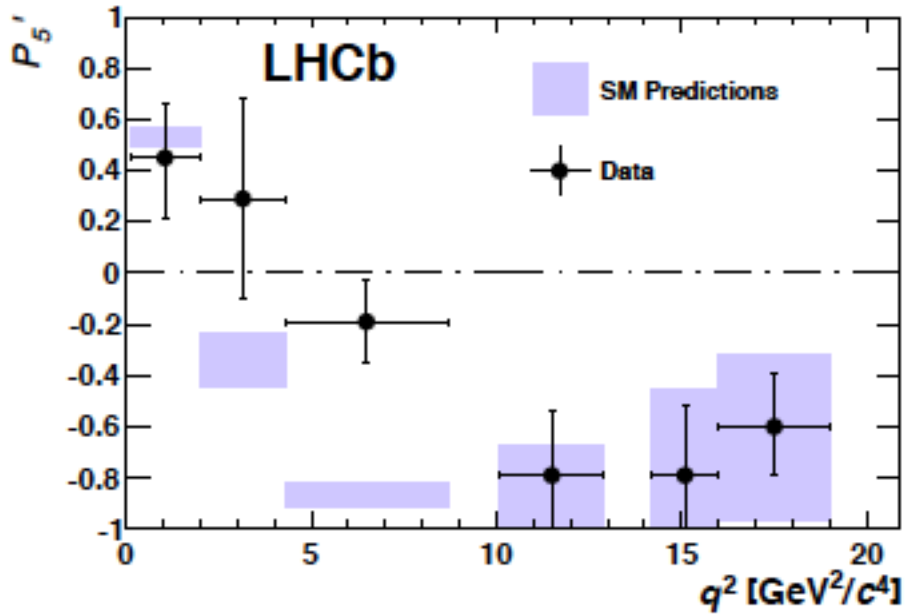
$B^0 \to K^{*0}\mu^+\mu^-$ decays

- LHCb also studied another set of variables

$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi\, dq^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big],$$

$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}.$$





In general, all the measurements agree with the SM prediction.

Only one point out of 24 is off by 3.7σ

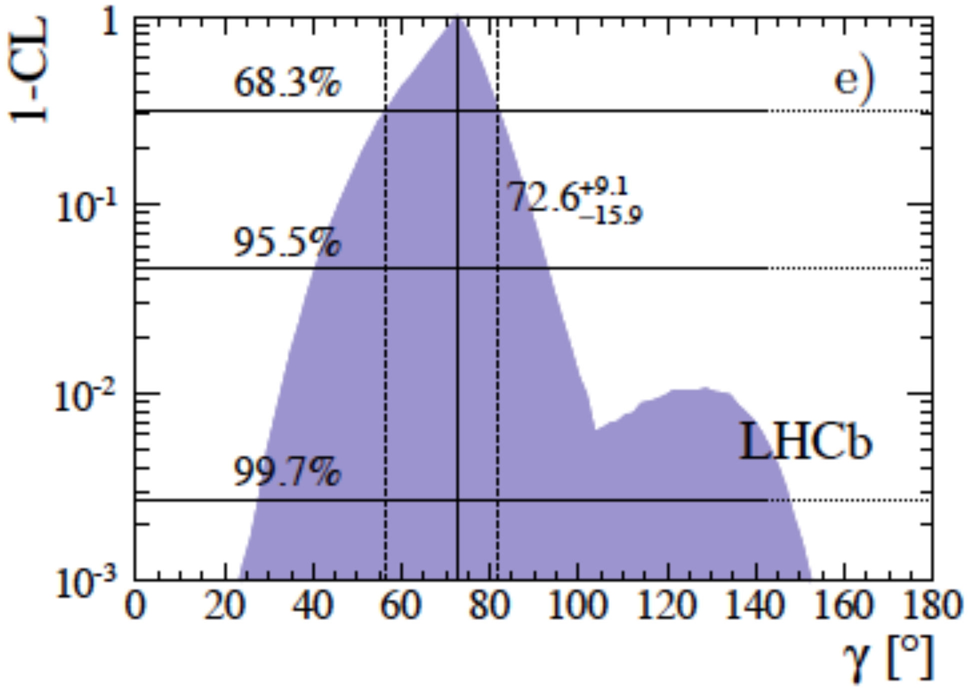
CERN-PH-EP-2013-146

Angle γ (ϕ_3) measurements

- Used decay modes:
  - $B^{\pm}\to D(\to K_S\pi^+\pi^-, \to K_S K^+K^-)K^{\pm}$
  - $B^{\pm}\to D(\to \pi^+\pi^-, \to K^+K^-)K^{\pm}$, $D(\to \pi^+\pi^-, \to K^+K^-)\pi^{\pm}$
  - $B^{\pm}\to D(\to K^+\pi^-, \to K^-\pi^+)K^{\pm}$, $D(\to K^+\pi^-, \to K^-\pi^+)\pi^{\pm}$
  - $B^{\pm}\to D(\to K^+\pi^-\pi^+\pi^-, \to K^-\pi^+\pi^+\pi^-)K^{\pm}$,
    $D(\to K^+\pi^-\pi^+\pi^-, \to K^-\pi^+\pi^+\pi^-)\pi^{\pm}$

Angle γ (ϕ_3) measurements

- Combining all the decay modes

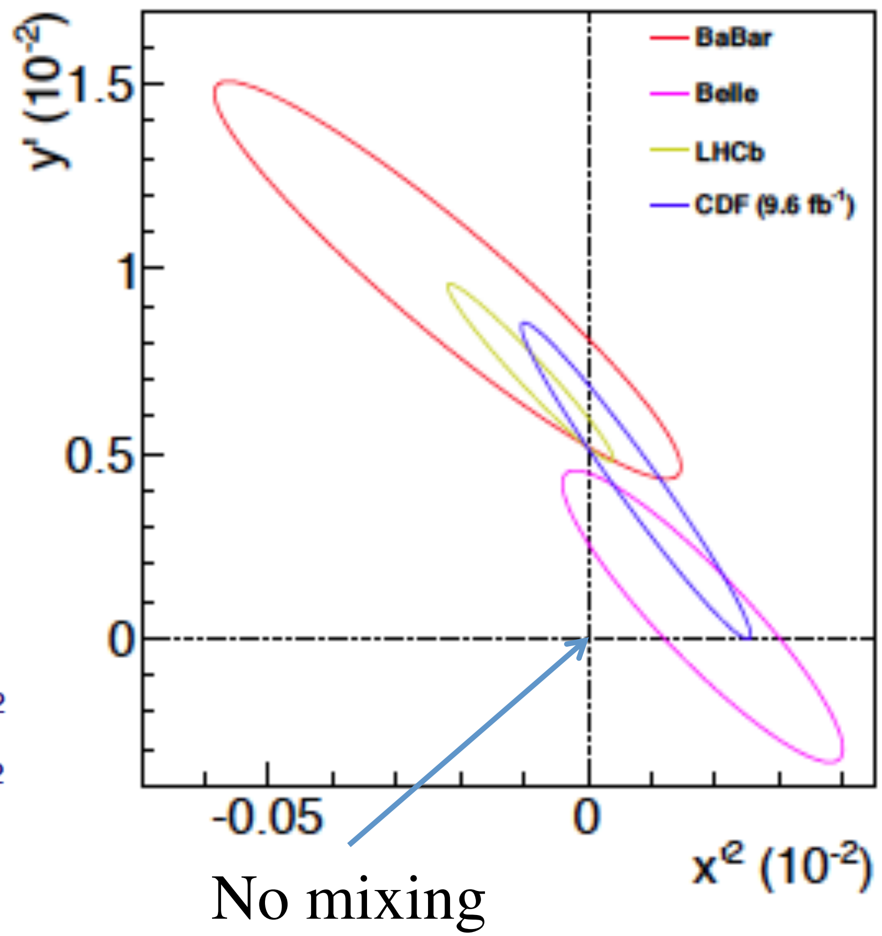


$\gamma = 72.6^{\circ}\,{}^{+9.1^{\circ}}_{-15.9^{\circ}}$ 68% CL with LHCb 1 fb^{-1} data

Cf. Pre-LHC average = $(68\ {}^{+10}_{-11})^{\circ}$ (PDG 2012)

Interesting development in D decays

- D-$\overline{\text{D}}$ mixing confirmed
  No-mixing excluded. The SM predictions have large uncertainties
  x: mixing via mass-matrix
  y: mixing via decay-matrix



CDF: 6.1 σ; CDF Public Note 10990,

LHCb: 9.1 σ; Phys. Rev. Lett 110 (2013) 101802

Babar: 3.9 σ; Phys. Rev. Let 98 (2007) 211802

Belle: 2.0 σ; Phys. Rev. Lett 96 (2006) 151801

Interesting development in D decays

- $D\text{-}\overline{D}$ mixing confirmed
  No-mixing excluded.
- CP violation in D decay amplitudes
  $\Delta A_{CP} = A_{CP}(D\rightarrow K^+K^-) - A_{CP}(D\rightarrow \pi^+\pi^-)$

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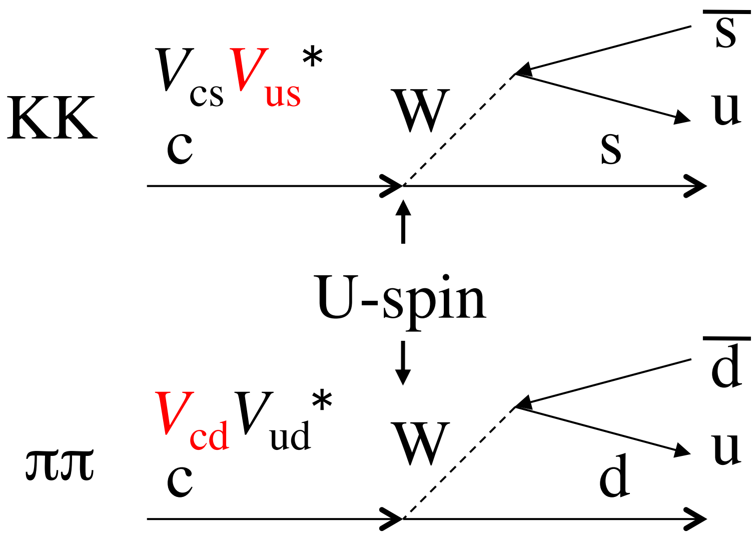
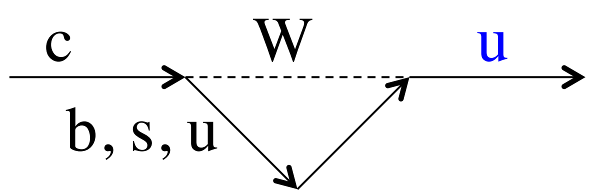
- CP violation in D decay amplitudes
  $\Delta A_{CP} = A_{CP}(D \rightarrow K^+K^-) - A_{CP}(D \rightarrow \pi^+\pi^-)$
  naïve SM expectation: $A_{CP}(K^+K^-)$ and $A_{CP}(\pi^+\pi^-)$ have opposite signs and expected to be small, $\leq 10^{-3}$



+

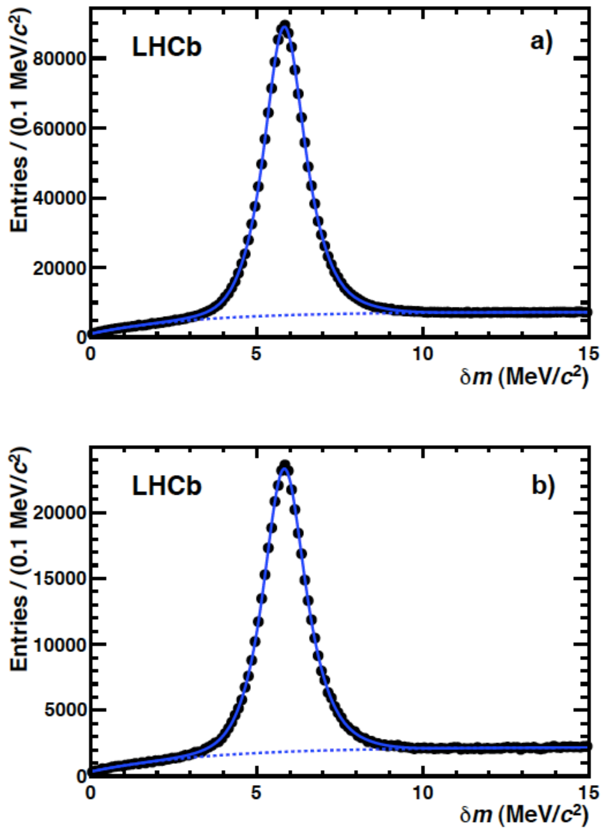


$V_{ub}V_{cb}^* \{F(m_b) - F(m_d)\}$
$+ V_{cs}V_{us}^*\{F(m_s) - F(m_d)\}$

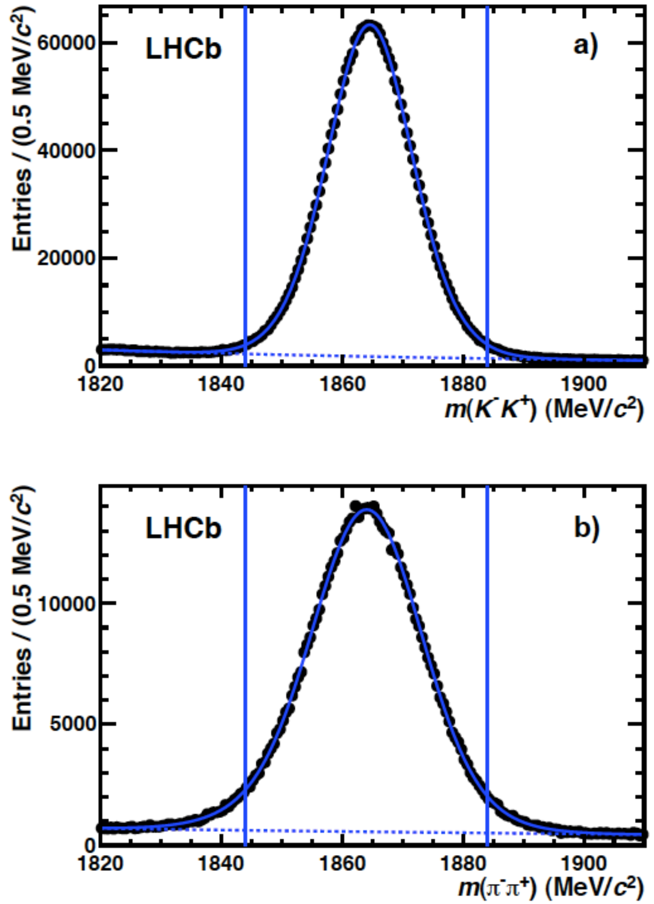
Interesting development in D decays

- Clean D signal with LHCb

$m(D^{*+} - D^0)$

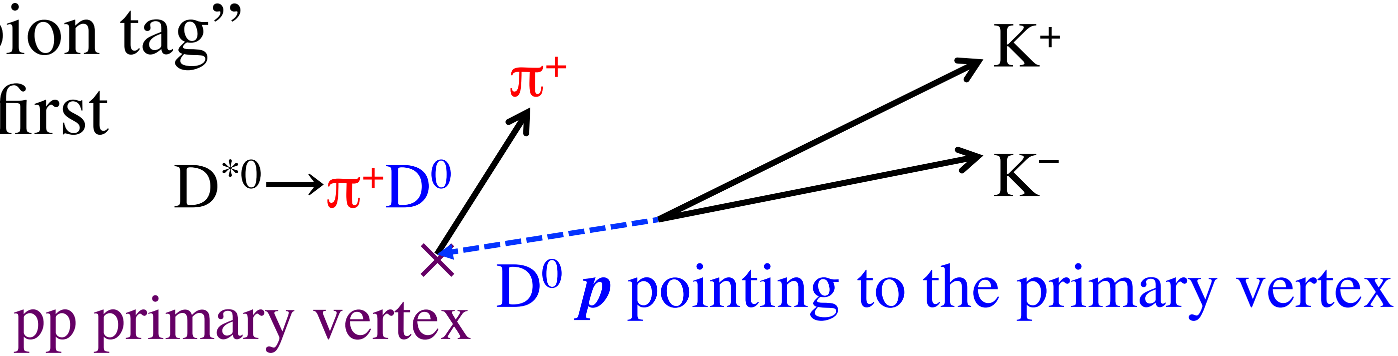


D^0 mass

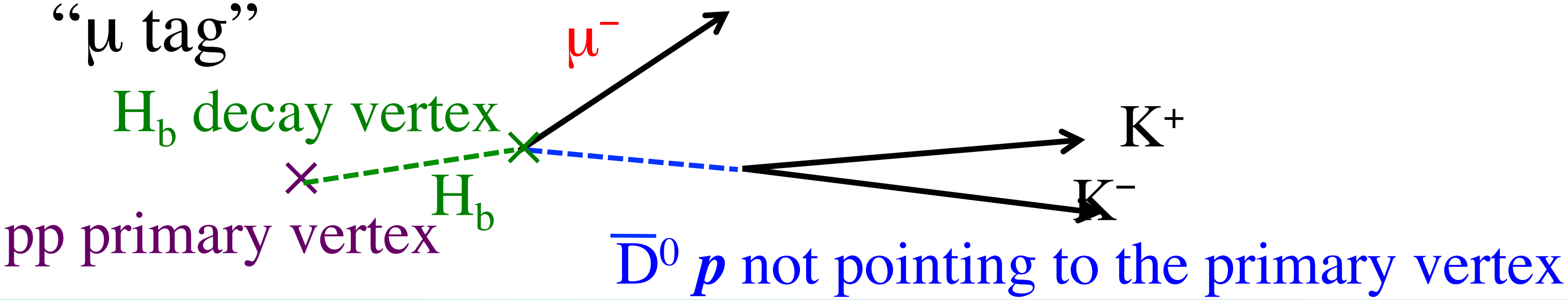


Interesting development in D decays

- Charm quarks produced at the pp primary vertex
  - $D^{*\pm}$ from the primary vertex
  - Initial flavour tag with $D^{*+}\rightarrow D^0\pi^+$ and $D^{*-}\rightarrow \bar{D}^0\pi^-$ "slow pion tag"
  - Utilised first



- Charm quarks from the b-hadron decay vertex
  - D meson from semileptonic b-hadron decays vertex
  - initial flavour tag with $h_{\bar{b}}\rightarrow D^0 l^+ X$ and $h_b\rightarrow \bar{D}^0 l^- X$ "μ tag"



Interesting development in D decays

- D-$\overline{\text{D}}$ mixing confirmed
  No-mixing excluded.
- CP violation in D decay amplitudes
  $\Delta A_{CP} = A_{CP}(D \to K^+K^-) - A_{CP}(D \to \pi^+\pi^-)$
  LHCb result with slow-pion tagged "D" from the prompt $D^{*\pm}$ (0.6 fb^{-1}) generated an excitement
  $\Delta A_{CP} = (-8.2 \pm 2.1 \pm 1.1)\times 10^{-3}$ PRL108.111602
  followed by
  CDF $(-6.2 \pm 2.1 \pm 1.0)\times 10^{-3}$ PRL109.111801
  Belle $(-8.7 \pm 4.1 \pm 0.6)\times 10^{-3}$ arXiv:1212.1975

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  Belle $(-8.7 \pm 4.1 \pm 0.6)\times 10^{-3}$ arXiv:1212.1975
  The latest LHCb results with 1 fb^{-1} LHCb-CONF-2013-003 and PLB 723 (2013) 33
  $\Delta A_{CP} = (-3.4 \pm 1.5 \pm 1.0)\times 10^{-3}$ slow-pion tag
  $\Delta A_{CP} = (4.9 \pm 3.0 \pm 1.4)\times 10^{-3}$ μ tagged from $B\rightarrow \overset{(-)}{D}{}^0 \mu^{+(-)} X$
  average = $(-1.5 \pm 1.6)\times 10^{-3}$

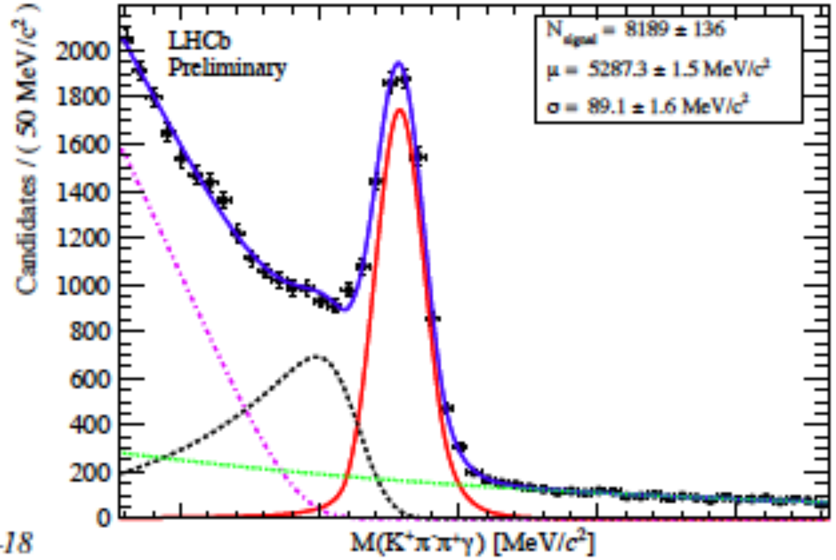
Interesting development in D decays

- D-$\overline{D}$ mixing confirmed
  No-mixing excluded.
- CP violation in D decay amplitudes
  $\Delta A_{CP} = A_{CP}(D \to K^+K^-) - A_{CP}(D \to \pi^+\pi^-)$
  Inconclusive whether CPV is >>10^{-3}
  if ~10^{-3}, could be within the SM

Some final states wit a photon

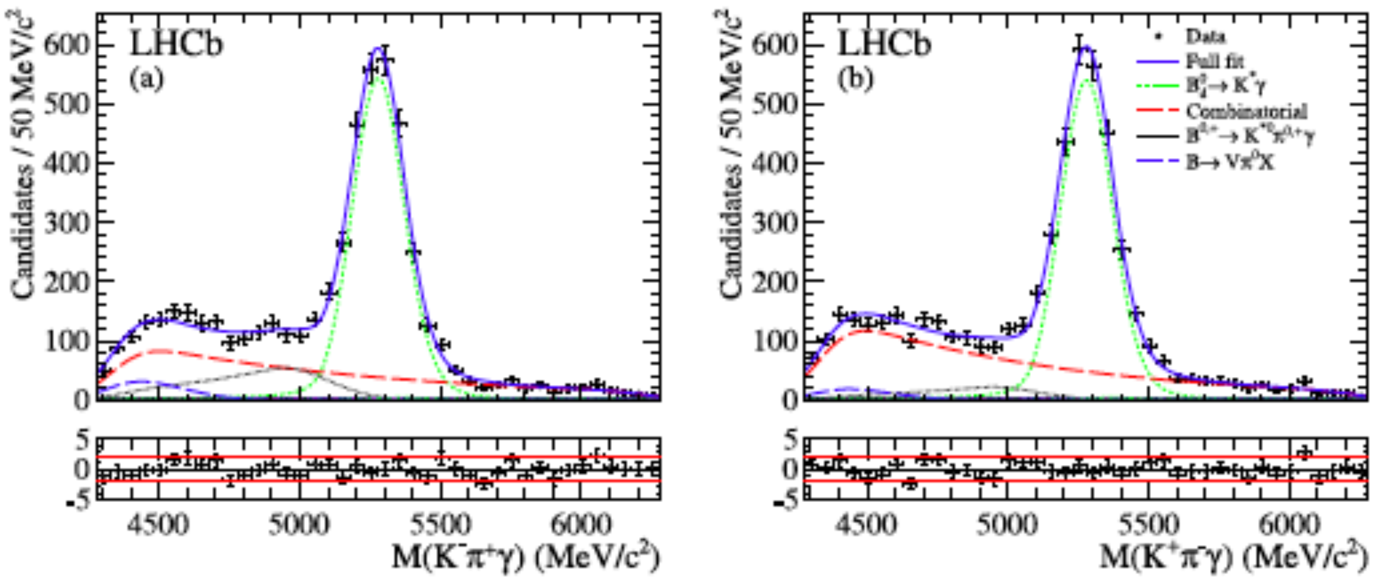
- $B^{\pm}\to K^{\pm}\pi^{+}\pi^{-}\gamma$

LHCb-CONF-2013-009



- $B_d\to K^{*0}\gamma$, $B_s\to \phi\gamma$

Nuclear Physics B 867 (2013) 1–18



⇒to study the Lorentz structure in the electric penguin diagrams

There are more results not mentioned

- Many many c- and b-hadron decay modes first observed including B_c
- Spectroscopy
  c- and b-hadrons
  exotics (X, Y, Z, ⋯)
  mass and lifetime
- And non flavour physics
  parton density in the forward region
  QCD
  new particle production in the forward region
  ⋮

Near future

- Analysis with 7-8 TeV full data set within the next years.
- At 13-14 TeV, further gain in statistics from higher b-$\bar{b}$ cross section (×~2)
  - LHCb: ~four times increases in "effective" statistics by the end of 2017 compared with the 7-8 TeV full statistics
  - ATLAS and CMS: depends on how they can cope with higher luminosities (very much on the decay modes)
- More and more sophisticated analysis methods are being developed.
- Belle II will become online in ~2016
- LHCb Major upgrade during the 2018-2019 long-shutdown to boost the statistics by $\gtrsim 10$

Also important to remember

- Results will come from
  - the kaon system in rare decays ($K^+\to\pi^+\nu\nu$) and CPV ($K_L\to\pi^0\nu\nu$)
  - charge lepton violating μ decays; $\to 3e$, $\to e\gamma$, μ-e conversion and, and τ decays, $\to 3\mu$, $\to \mu\gamma$, $\to e\gamma$
  - Flavour conserving quantities such as neutron electric dipole moment and $(g-2)_\mu$
- i.e. flavour should be considered more globally.
- Accurate Standard Model predictions are essential in the precision measurements. Strong interactions are still the most problematic issue in many measurements ⇒ help from our theory friends are always needed!
- By the way, axions have not been discovered so far, and $\theta_{QCD} < 10^{-10}$ appears to me as another "fine tuning"…

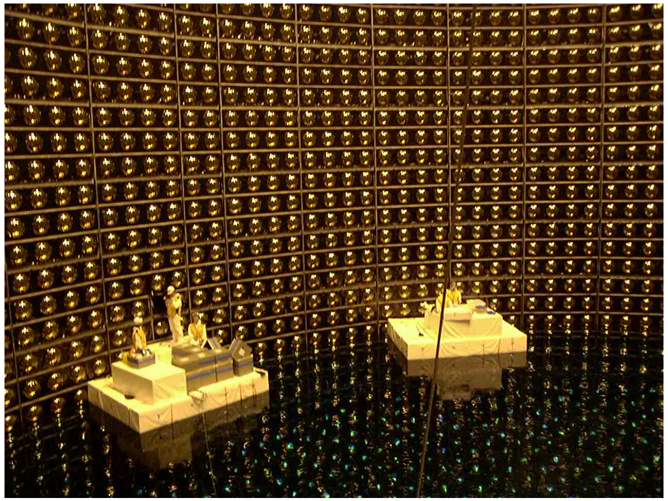
Epilogue

- There exists solid observations for physics beyond the Standard Model

Epilogue

- There exists solid observations for physics beyond the Standard Model
  Neutrino oscillations

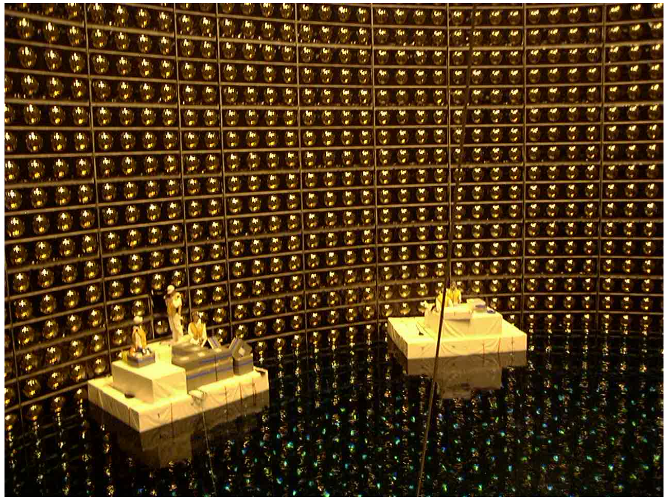
S-KAMIOKANDE



Epilogue

- There exists solid observations for physics beyond the Standard Model
  Neutrino oscillations
  Dark matter

S-KAMIOKANDE

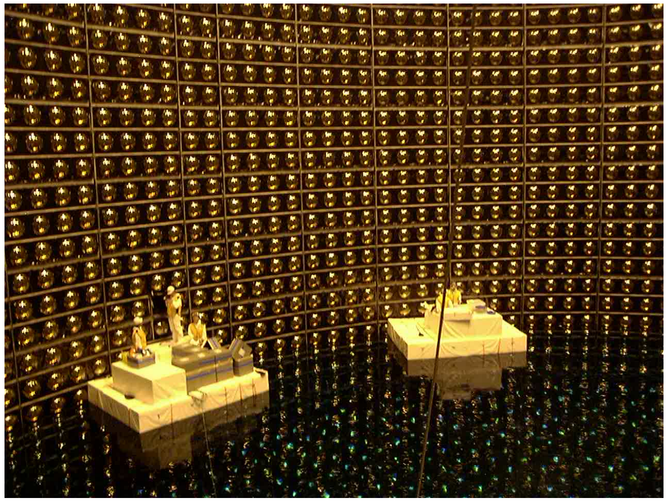


Bullet Galaxy Clusters

Epilogue

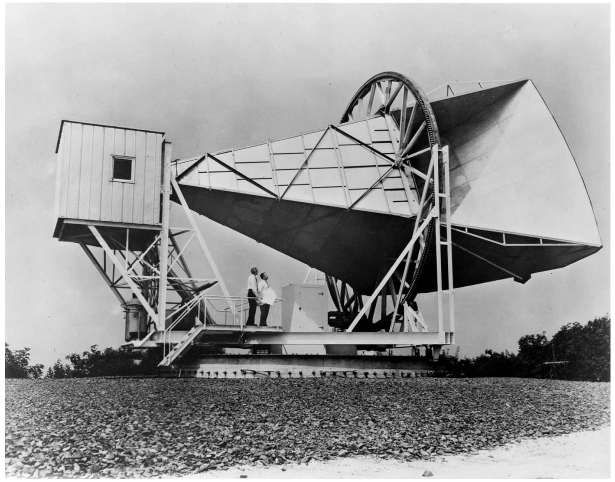
- There exists solid observations for physics beyond the Standard Model
  - Neutrino oscillations
  - Dark matter
  - $N_B \,/\, N_\gamma = 10^{-10}$

S-KAMIOKANDE



Bullet Galaxy Clusters

The Horn Antenna
Bell Telephone Laboratory



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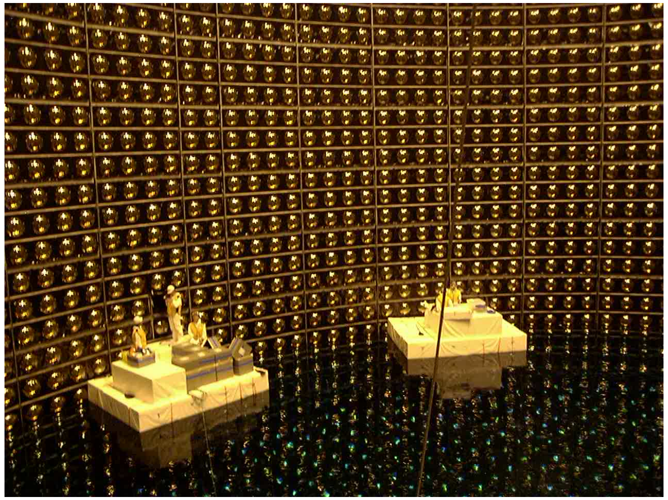

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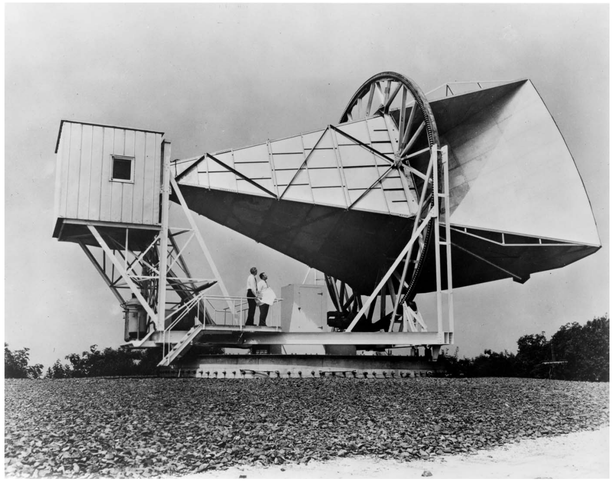

- And there is (was?) strong theoretical anticipation that new physics is just around the corner

Epilogue

- CP violation & rare decays made essential contributions to establish the flavour structure of the SM in the past
- Main motivation of flavour related measurements now is to search for new physics: with e.g. rare decays, CPV, etc.
- In B and D sector, LHC starts to lead the way. Possibility of large new physics contribution in the B_s sector has already been eliminated
- Despite of cosmological "proof" for new physics as well as the neutrino mass, and many clever theoretical works, we have little idea where the energy threshold of new physics.
- We need to observe a clear sign of new physics, directly or indirectly, in particle physics, to know this. And I am afraid there is no obvious road for a discovery

Epilogue

- There are many motivated people working in the broad field. Since there is no obvious road, pursuits must be carried away as wide as possible.
- And the exploitation at LHC has just started!

Epilogue

In any case,

Exciting time is ahead of us all.

My standard joke of the past years…

My hope, expectation and possible realities matrix for 2014 at LHC

ATLAS CMS high p_T physics	BSM	Only SM	BSM	
LHCb flavour physics	Only SM	BSM	BSM	
Particle Physics	☺	☺	☺	

Oh, no more space left…

Particle Physics in LHC Era, T. Nakada — XXVIII Encontro Nacional de Física de Partículas e Campos, Brazil, 2007 — 62/63