New results on B_s mixing and CP violation from LHCb
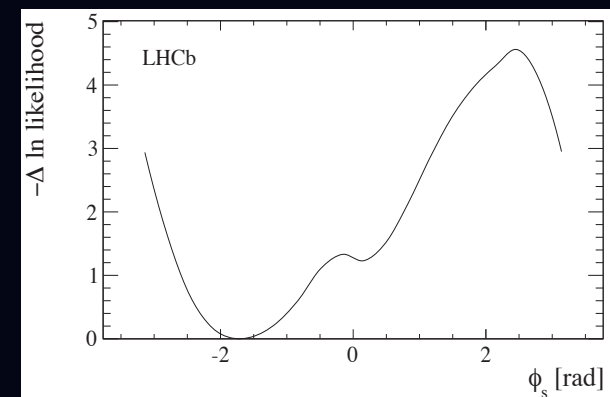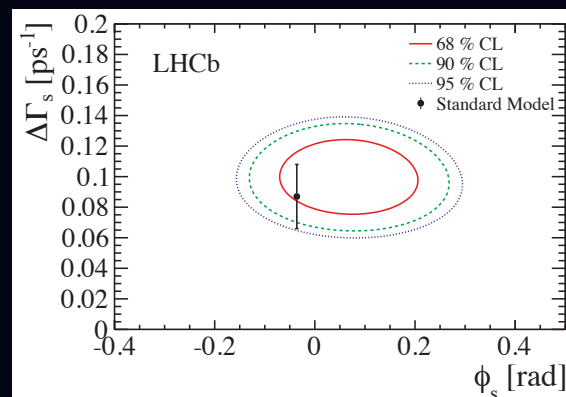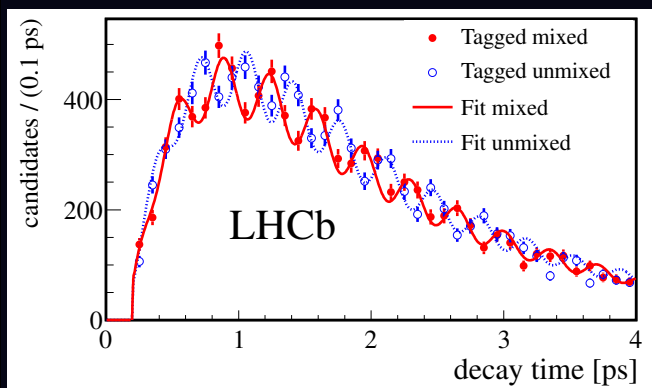
Yuehong Xie

University of Edinburgh & CERN

On behalf of the LHCb Collaboration

Outlines

Matter-antimatter asymmetry and CP violation

LHCb detector and performance

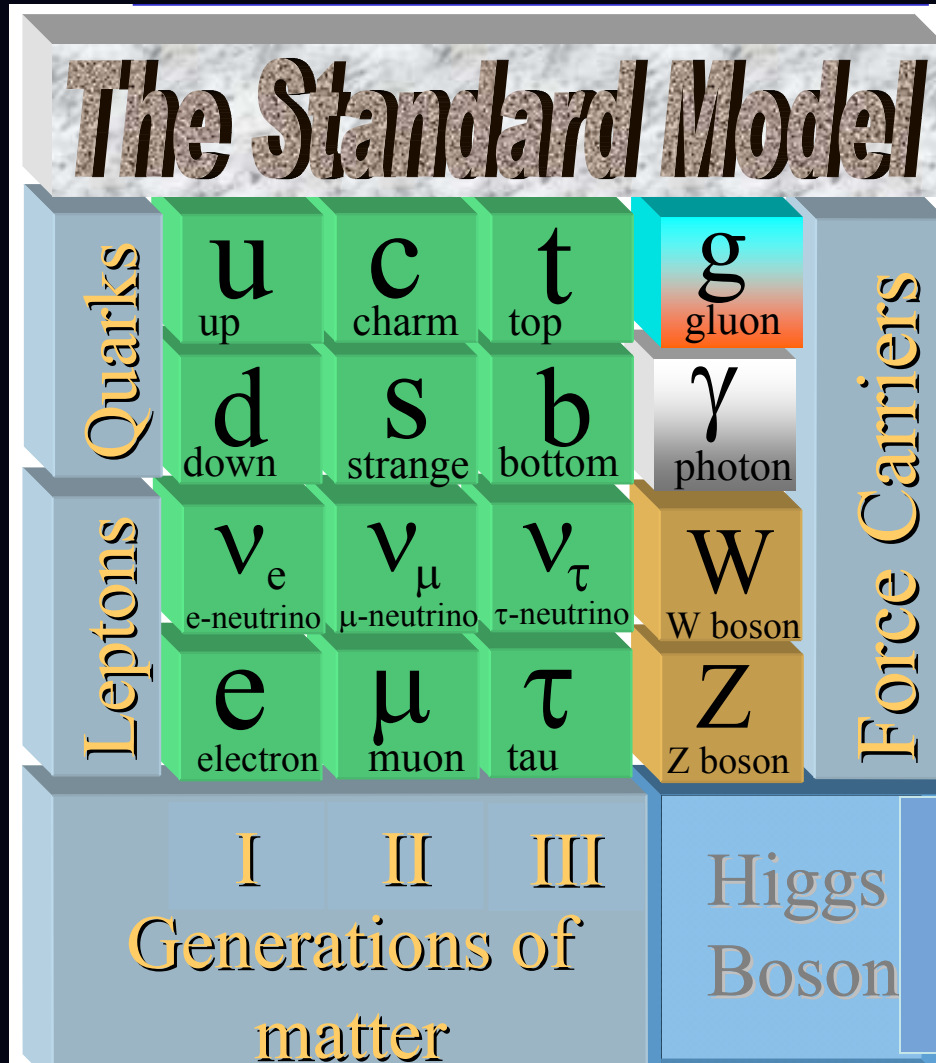Search for new physics in B_s mixing (Δm_s, $\Delta\Gamma_s$, ϕ_s measurements)

Measurement of CP violation in $B_s \rightarrow \phi\phi$

Summary and prospects

Matter-antimatter asymmetry and CP violation

Building blocks and interactions

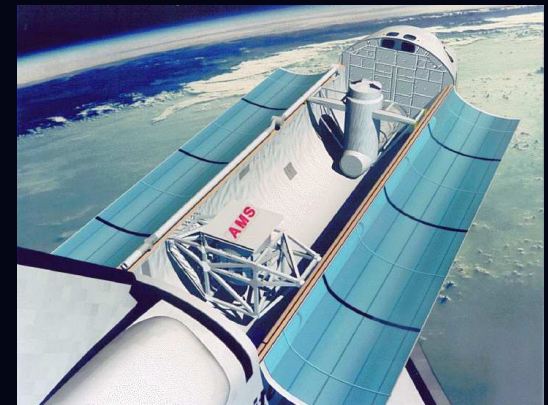# The matter-dominated Universe

Solar system is made up of matter (p, n) only. What about distant galaxies?

No observation of extra γ-rays from particle anti-particle annihilation

No observation of anti-nuclei in primary cosmic rays

The Universe is matter dominated. Why don't we see anti-matter?

It all started with a tiny asymmetry

At **t~10^{-6} s** after the Big Bang, there were 10^{10}-1 antiquarks for every 10^{10} quarks. Some time later the symmetric part annihilated into photons and neutrinos. The asymmetric part survived and turned into the Universe we live in today
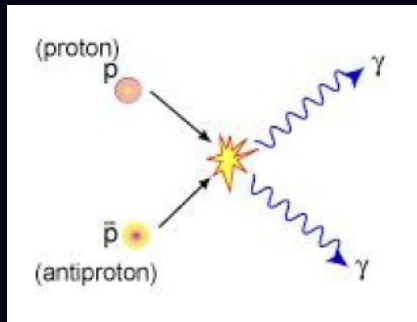
$n_B/n_\gamma \sim 10^{-10}$ today
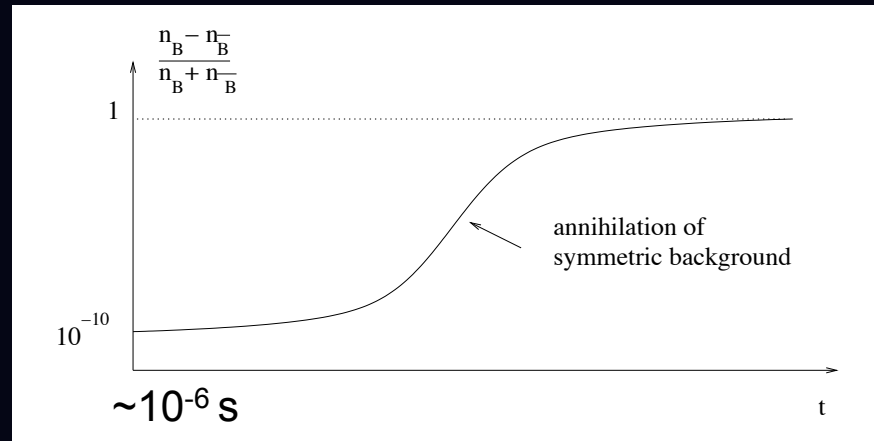
CP violation is a necessary condition for this to have happened (Sakharov conditions)

C: particle ↔ antiparticle; P: mirror operation
CP violation: matter and antimatter behave differently

CKM mechanism of CP violation

$$\mathcal{L}_{SM} = \underbrace{\mathcal{L}_G(\psi, W, \phi)}_{} + \underbrace{\mathcal{L}_H(\phi)}_{} + \underbrace{\mathcal{L}_Y(\psi, \phi)}_{}$$

kinetic energy + gauge IA

Higgs potential → spontaneous symmetry breaking

Yukawa IA → fermion masses

EWSB & diagonalization of Yukawa mass matrix ⇒ CKM quark mixing matrix

$$V_{CKM} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

L.Wolfenstein PRL 51 (1983) 1945

$q = \{u,\ c,\ t\}$

$p = \{d,\ s,\ b\}$

quark decay

W^-

q

gV_{qp}

p

anti-quark decay

W^+

q

gV^*_{qp}

p
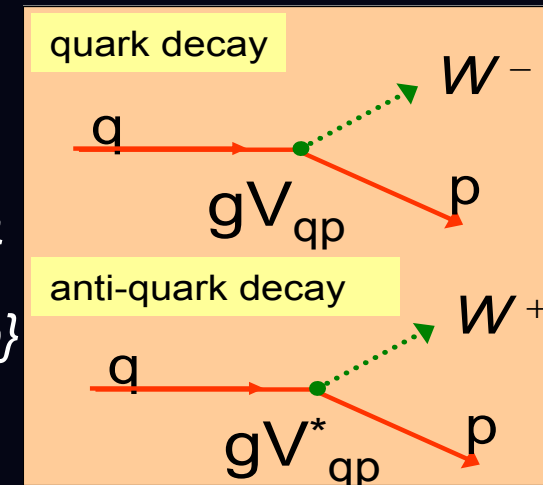
CP violation accommodated by a single complex phase
➤ Quark and anti-quark decays could have different properties
with complex elements

CKM works well but not ultimate

Very impressive achievements from all flavour experiments

2003   2007   2013
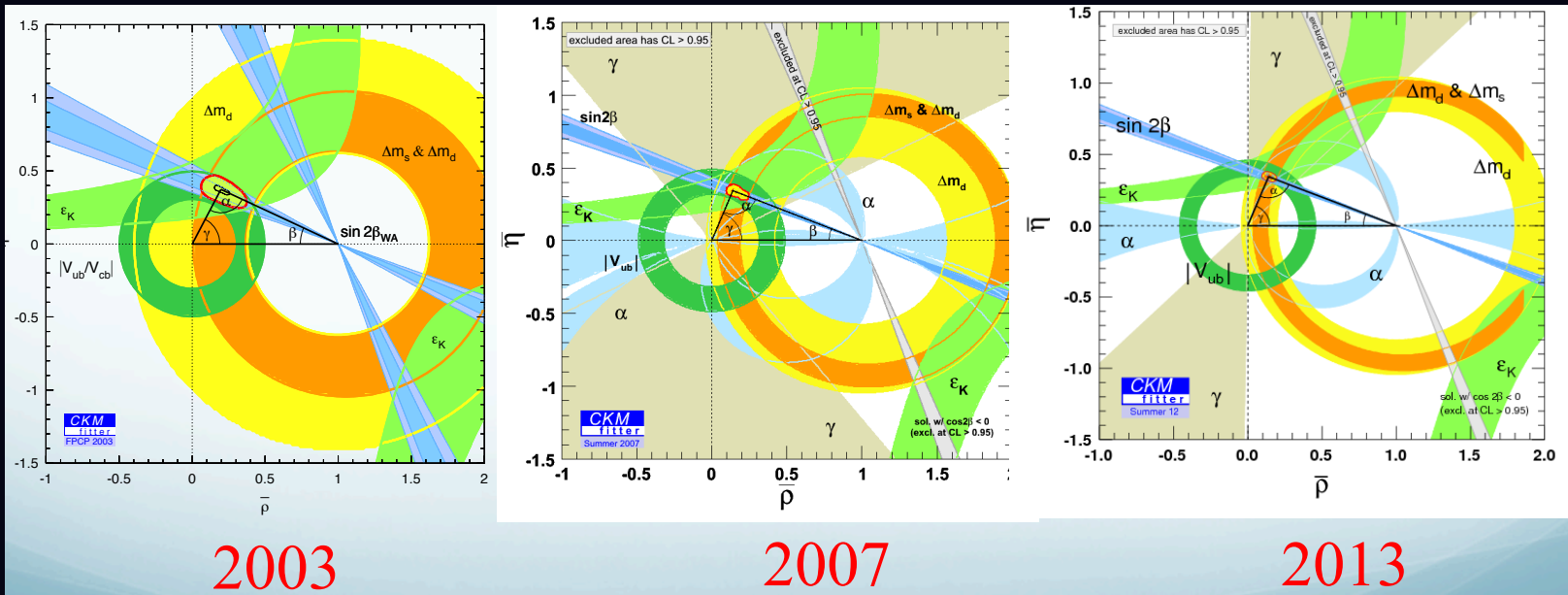
However, the predicted $n_B/n_\gamma \sim 10^{-20}$ is 10 orders of magnitude smaller than the observed $n_B/n_\gamma \sim 10^{-10}$

Require a more fundamental theory of particle interactions which provides extra sources of CP violation

THANKS to the LHC

and everyone who contributed to its excellent performance
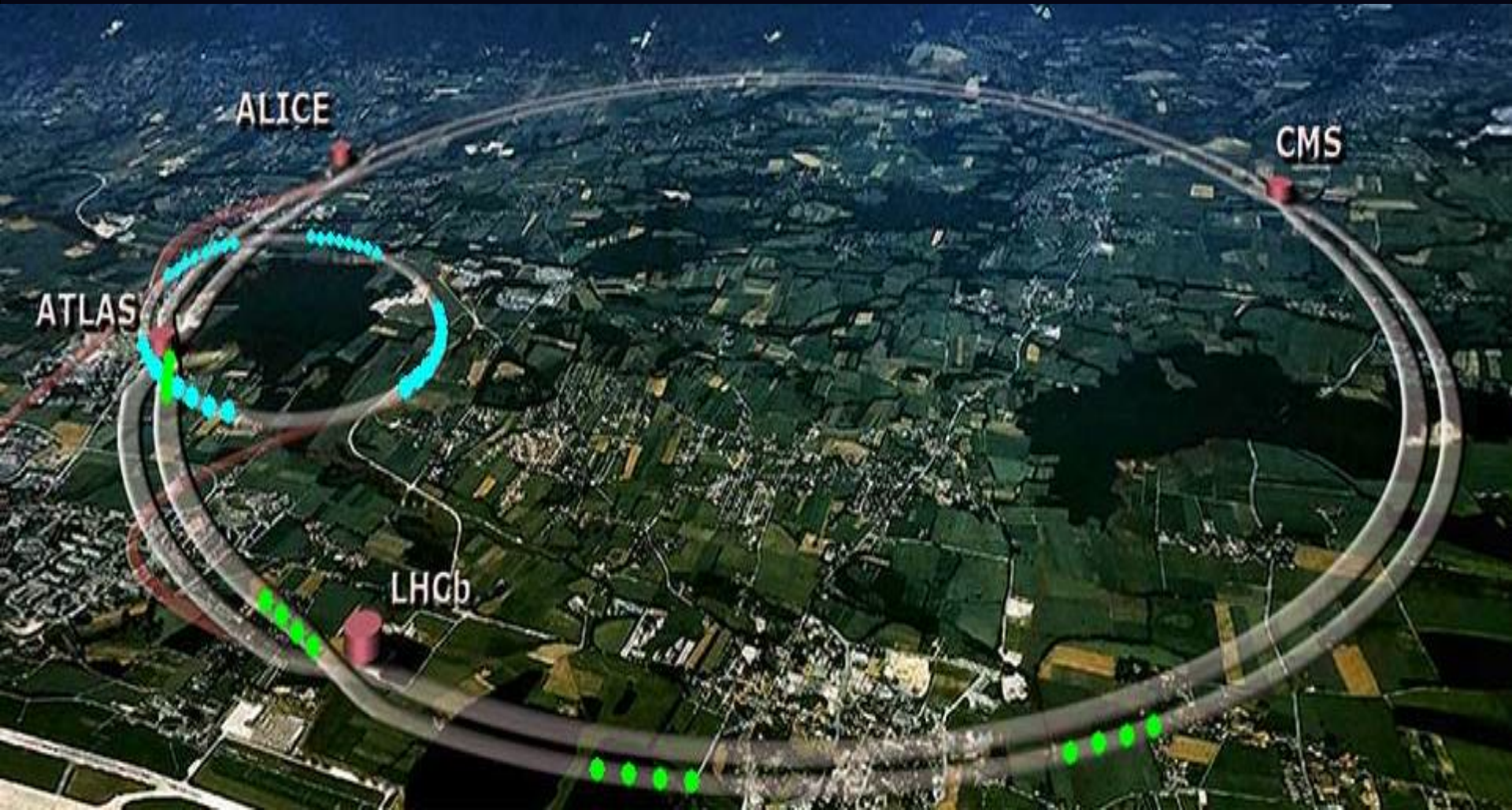
Physics frontiers at the LHC

Energy frontier: ATLAS and CMS

Search for direct production of TeV level new particles

Quantum frontier: LHCb

Test CKM and search for new sources of CP violation

↓

Explore physics up to 100 TeV

↑

Study flavour changing processes and seek footprints of new particles in the quantum loops
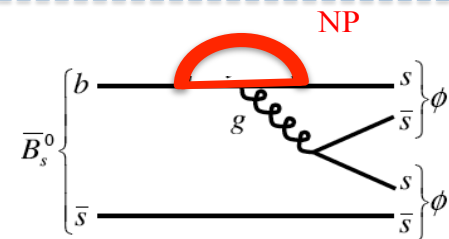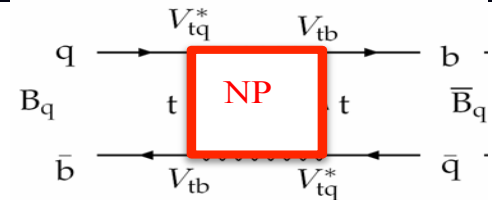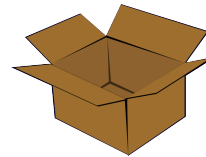
LHCb detector and performance

LHCb detector

RICH Detectors Particle ID

Muon System

Vertex Locator VELO

Proton beam

Collision point

Tracking stations

Calorimeters

LHCb MC
$\sqrt{s}$ = 7 TeV
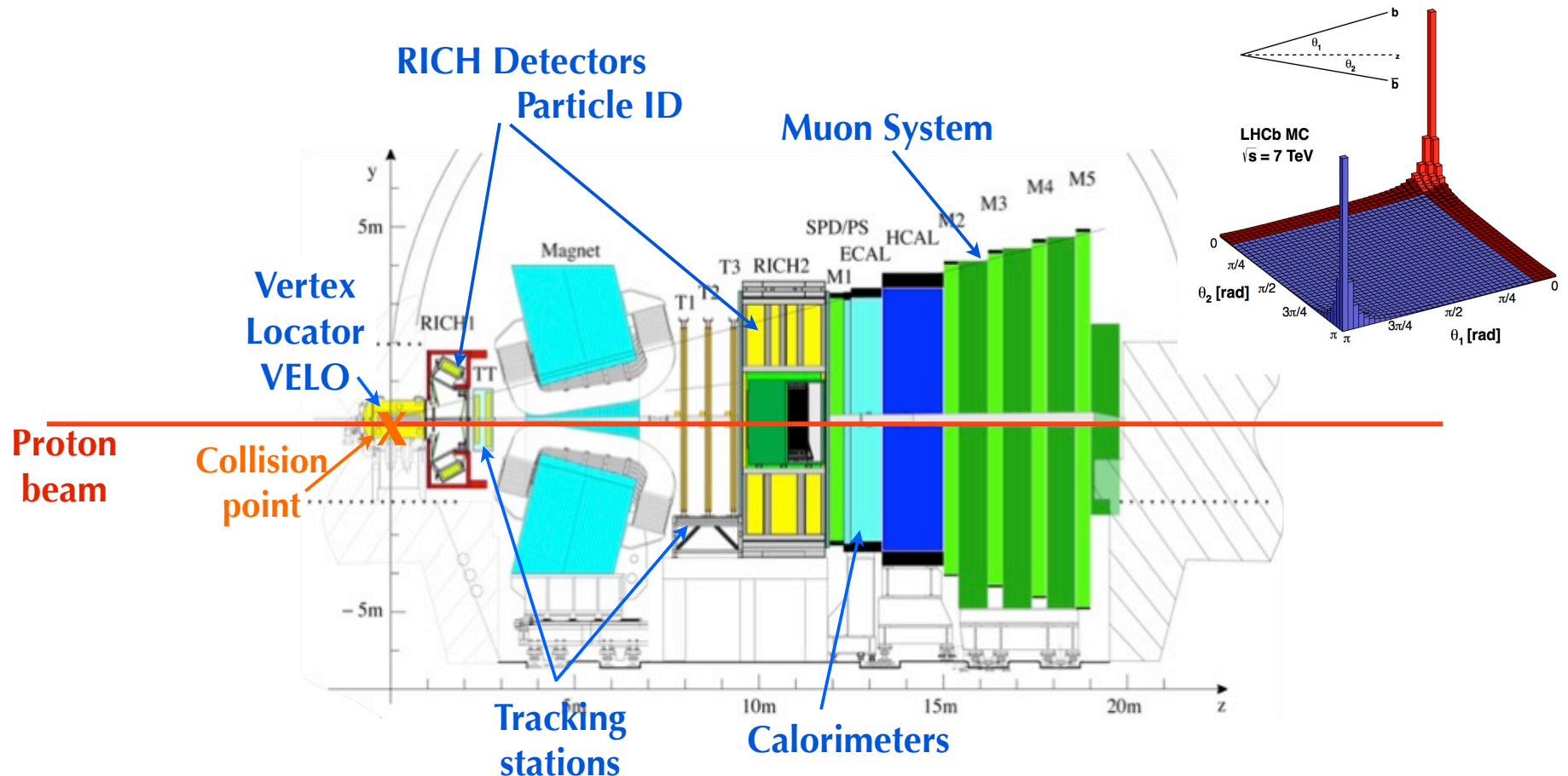
$(pp \rightarrow b\bar{b}X) = (75.3 \pm 5.4 \pm 13.0)\ \mu b\ @\ \sqrt{s} = 7\ TeV$
$(\sim 10^{11}\ b\bar{b}\ pairs\ with\ 1\ fb^{-1})$
in LHCb acceptance [PLB 694 (2012) 209]

All b hadrons produced
B^0, B^+, B_s, B^{**}, Λ_b, Σ_b, ...

Vertex measurements

21 silicon strip detector stations, 8 mm from beam

IP resolution of p_T > 2 GeV/c tracks: 20 μm
Typical decay time resolution: ~ 45 fs
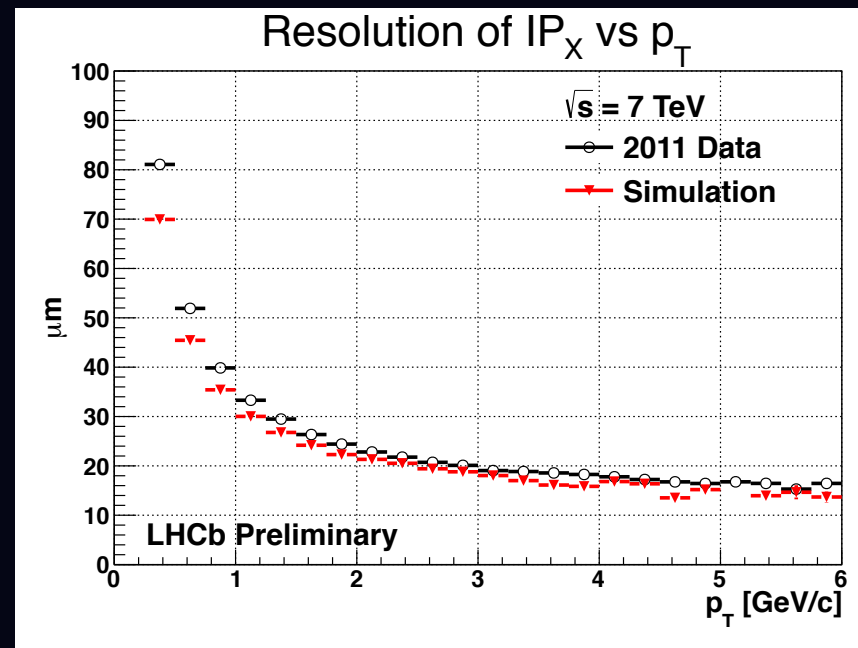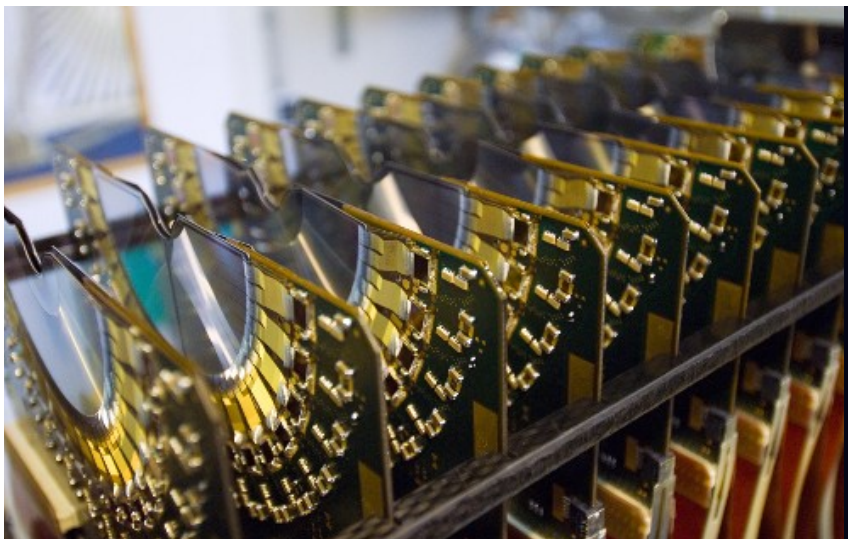
K/π separation

Two Ring Imaging Cherenkov detectors (RICH1, 2)
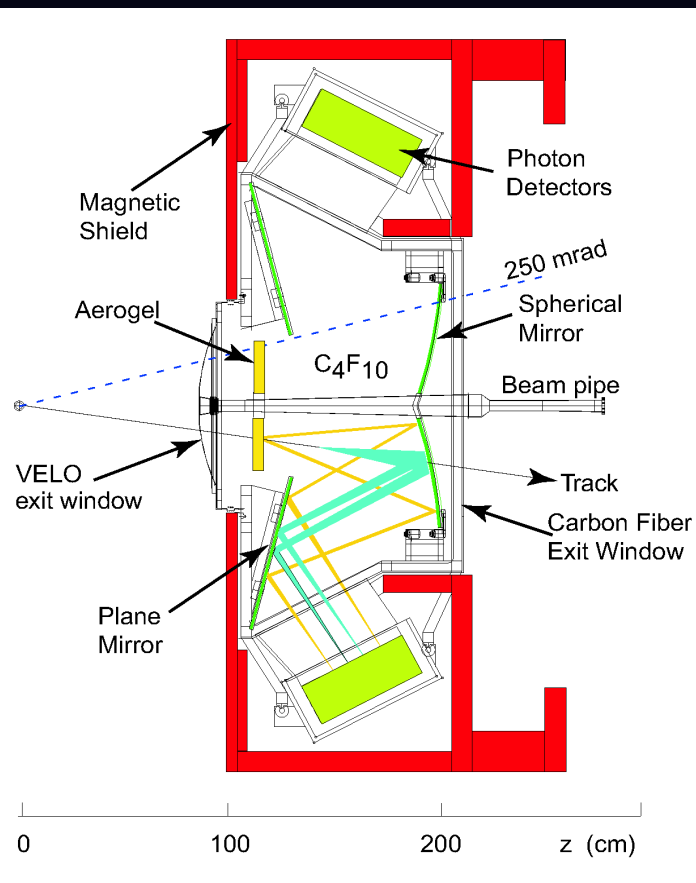
Good K/π separation up to 100 GeV

Kaon eff. ~ 95% with 5% pion contamination
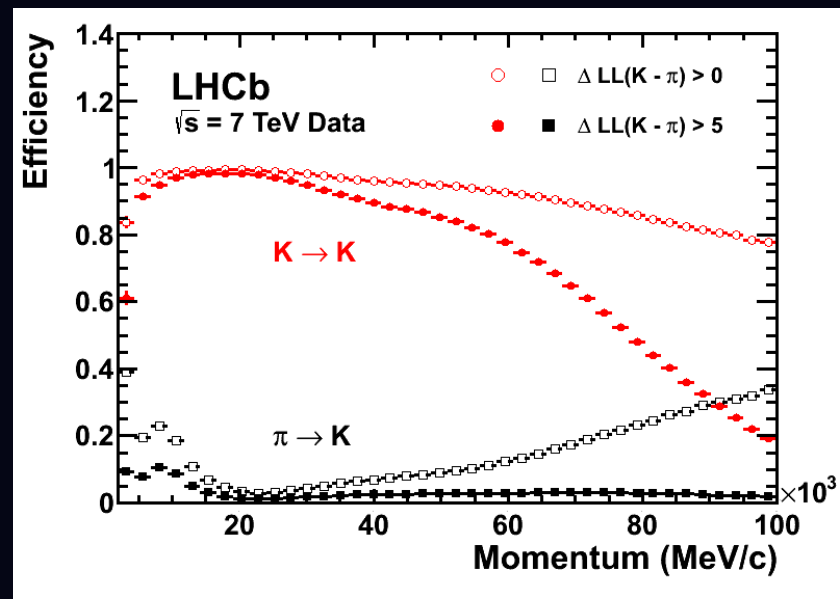
Muon identification

Five multi-wire proportional chamber detectors (interleaved with iron walls) provie trigger and muon identification
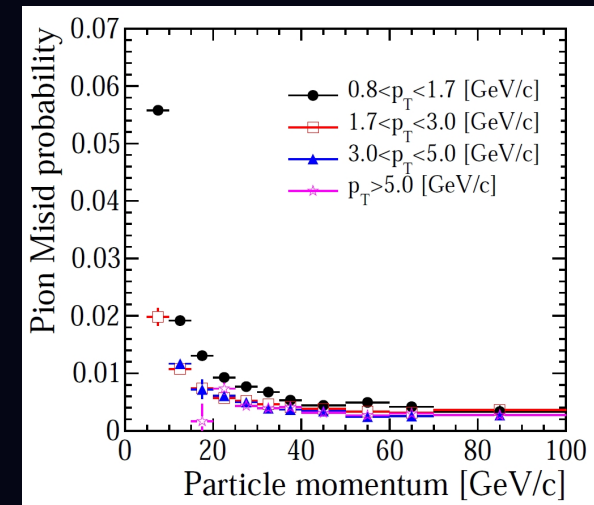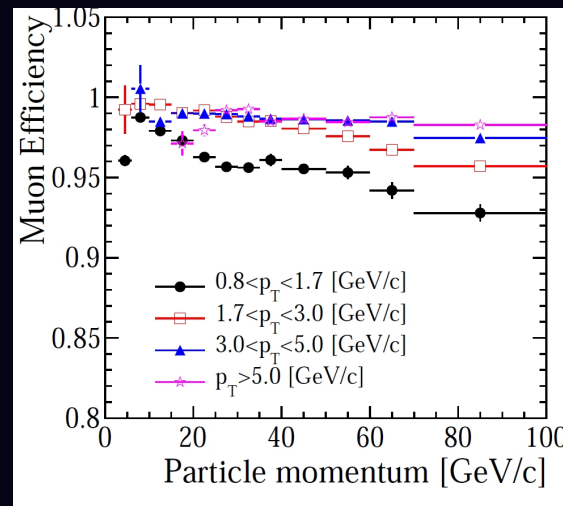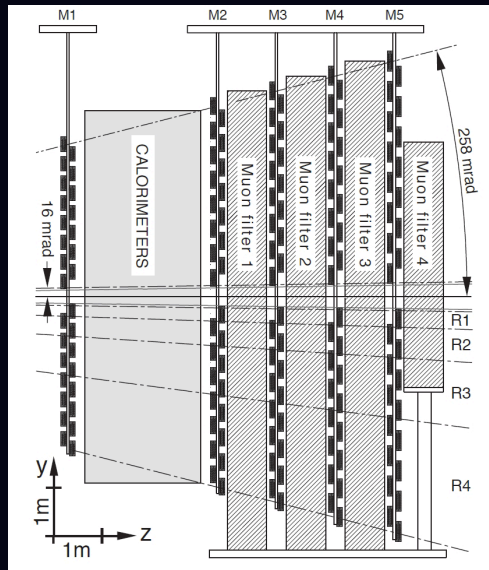
97% muon identification efficiency with 1-3% $\pi \to \mu$ probability

Tracking

4 tracking stations: silicon micro-strips + straw tubes.
Dipole magnet: 4 Tm bending power
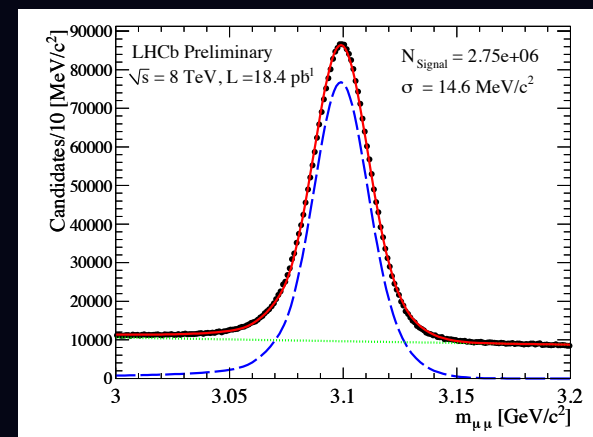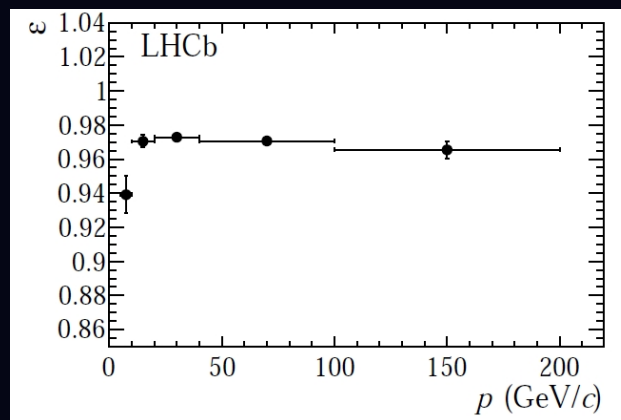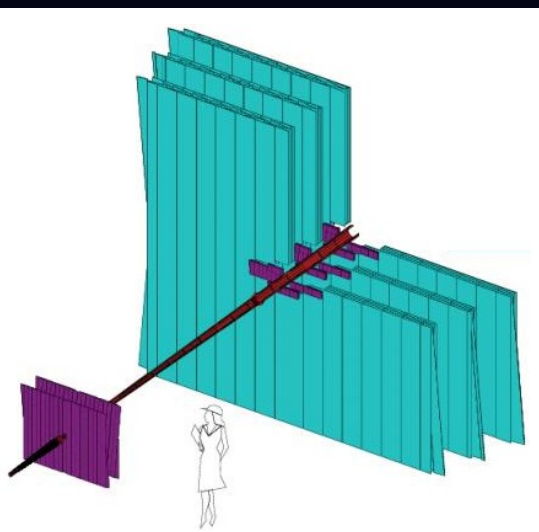
Efficiency > 96% for tracks in acceptance (depending on p, p_T, multiplicity)

$\delta p/p$: 0.4-0.6% (5-100 GeV/c)

J/$\psi \rightarrow \mu\mu$ mass resolution 15 MeV/c^2

The LHCb trigger

40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHZ readout, high E_T/P_T signatures

| 450 kHz $h^{\pm}$ | 400 kHz $\mu/\mu\mu$ | 150 kHz e/γ |

Software High Level Trigger

29000 Logical CPU cores

Offline reconstruction tuned to trigger time constraints

Mixture of exclusive and inclusive selection algorithms

5 kHZ Rate to storage

| 2 kHz Inclusive Topological | 2 kHz Inclusive/ Exclusive Charm | 1 kHz Muon and DiMuon |

- o **Level-0 Trigger: hardware**
  - ➢ use calorimeters and muon system
  - ➢ select high-p_T particles
    - ✓ $p_T(\mu) > O(1)$ GeV/c
    - ✓ $p_T(h,e,\gamma) > O(3)$ GeV/c

- o **High-Level Trigger: software**
  - ➢ HLT1: add VELO information
    - ✓ impact parameter and lifetime
  - ➢ HLT2: global event reconstruction
    - ✓ exclusive & inclusive selections
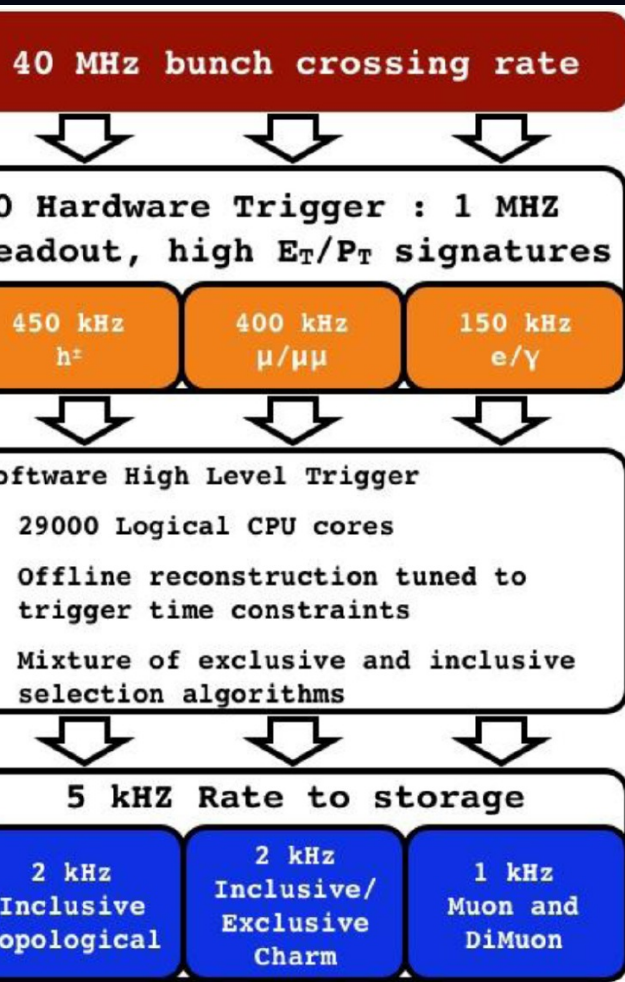
Trigger efficiency: ~90% for dimuon events
~30% for multibody hadronic final states

LHCb data taking
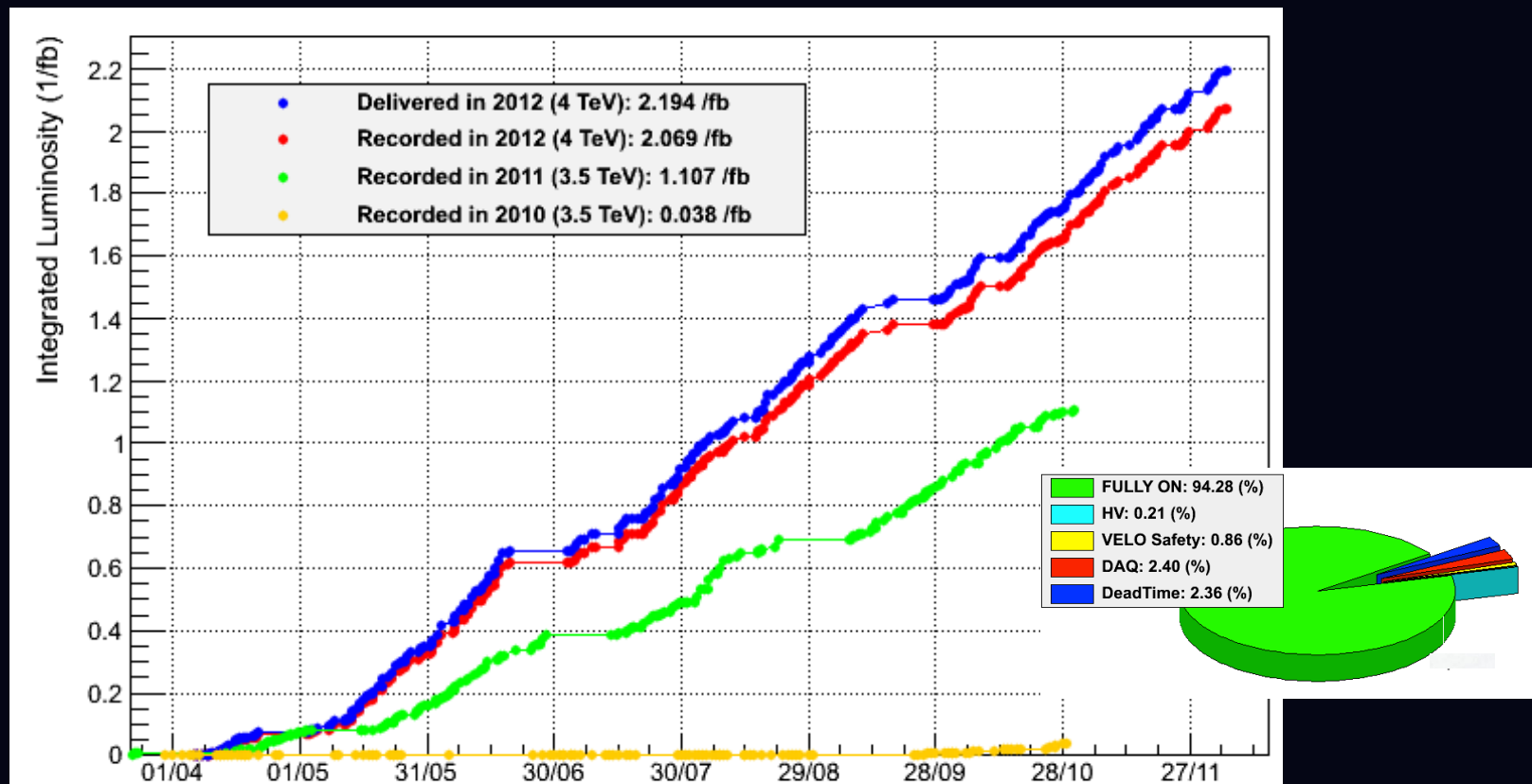
More than 3 fb^{-1} in total @ up to 4×10^{32} cm^{-2} s^{-1}
(design luminosity: 2×10^{32} cm^{-2} s^{-1})

Presented results based on 1.0 fb^{-1} collected in 2011 at 7 TeV

Search for new physics in B_s mixing

$B_s - \overline{B}_s$ mixing

Weak states mix via box diagram : flavour oscillation

t=0

$$\left| B_s \right\rangle = \left| \overline{b}s \right\rangle$$

t>0

$$\left| \overline{B}_s \right\rangle = \left| b\overline{s} \right\rangle$$
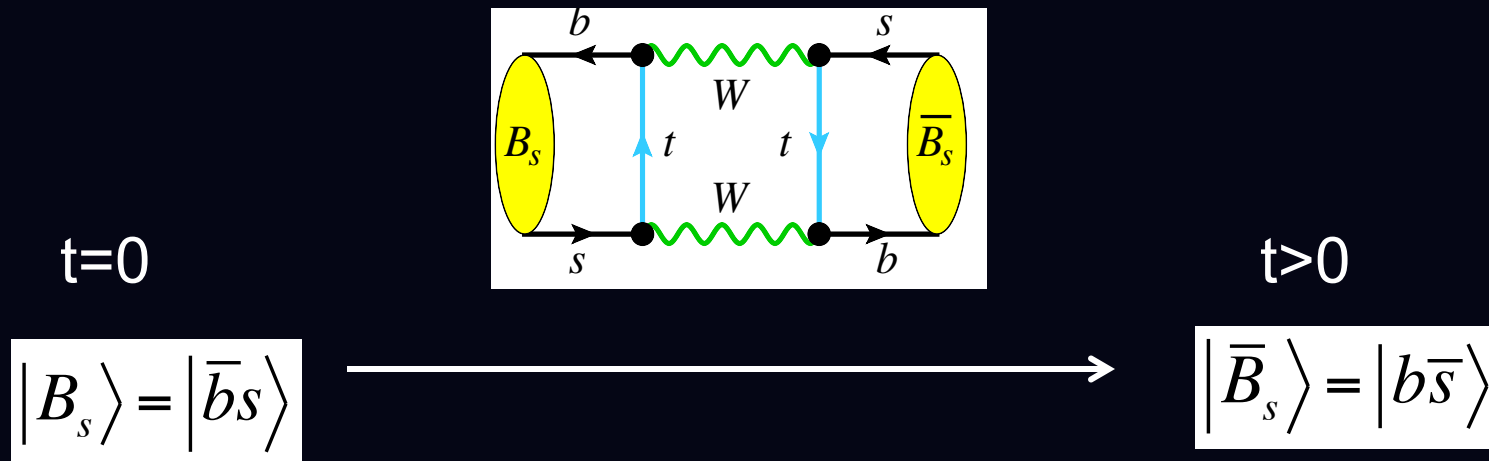
Mass eigenstates are mixtures of weak states

$$\left| B_L^s \right\rangle = p \left| B_s \right\rangle + q \left| \overline{B}_s \right\rangle$$

$$\left| B_H^s \right\rangle = p \left| B_s \right\rangle - q \left| \overline{B}_s \right\rangle$$

Probes for new physics in B_s mixing
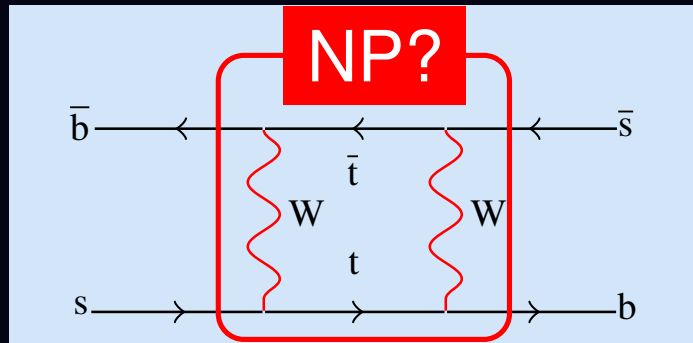
$$i\frac{d}{dt}\begin{pmatrix}|B_s(t)\rangle\\|\bar{B}_s(t)\rangle\end{pmatrix}=\left(\begin{bmatrix}M_{11}&M_{12}\\M_{12}^*&M_{11}\end{bmatrix}-\frac{i}{2}\begin{bmatrix}\Gamma_{11}&\Gamma_{12}\\\Gamma_{12}^*&\Gamma_{11}\end{bmatrix}\right)\begin{pmatrix}|B_s(t)\rangle\\|\bar{B}_s(t)\rangle\end{pmatrix}$$

M_{12} responsible for mixing and sensitive to NP

o CPV in mixing $a^s_{fs} \approx |\Gamma_{12}/M_{12}|\sin\varphi_{12}$, $\varphi_{12}=\arg(-M_{12}/\Gamma_{12})$

o Mass difference: $\Delta m_s = m_H-m_L \approx 2|M_{12}|$

o Decay width difference: $\Delta\Gamma_s = \Gamma_L-\Gamma_H \approx 2|\Gamma_{12}|\cos\varphi_{12}$

o Phase difference between $B\rightarrow f$ and $B\rightarrow\bar{B}\rightarrow f$ (f: CP eigenstate)
  ➢ sensitive to NP in mixing, causing time-dependent CP violation

Measurement of CP violation and the B_s meson decay width difference with $B_s \to J/\psi K^+ K^-$ and $B_s \to J/\psi \pi^+ \pi^-$ decays

LHCb-PAPER-2013-002
arXiv: 1304.2600
Submitted to PRD

Golden channel $B_s \rightarrow J/\psi(\mu^+\mu^-)\phi(K^+K^-)$
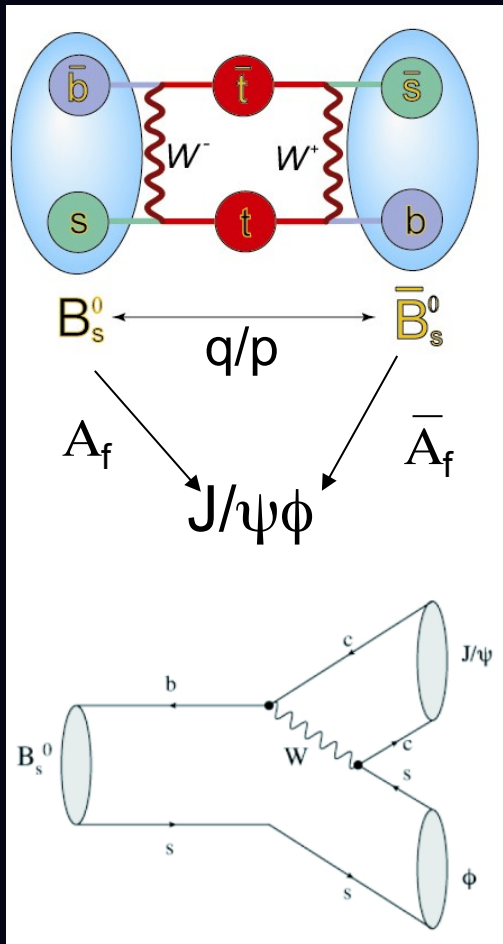
b→cc̄s decay

ϕ_s: relative phase between interfering amplitudes of $B_s \rightarrow J/\psi\phi$ and $B_s \rightarrow \bar{B}_s \rightarrow J/\psi\phi$

$$\phi_s = -\arg(\lambda), \qquad \lambda = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

Also accessing $\Delta\Gamma_s$

Theoretically clean tree-dominating decay

Precise SM prediction from global fit ignoring penguin contribution [J. Charles *et. al*, PRD 84 (2011) 033005]

SM: $\phi_s \approx -2\beta_s = -0.036 \pm 0.002$ (rad)

ϕ_s sensitive to NP in B_s mixing

$$\phi_s = \phi_s^{SM} + \Delta\phi, \qquad \Delta\phi = \arg\left(M_{12}/M_{12}^{SM}\right)$$

Early LHCb results with 0.37 fb⁻¹

[PRL 108 (2012),101803
arXiv: 1112.3183]

Y. Xie principal author

[PRL 108 (2012), 241801,
arXiv: 1202.4717]
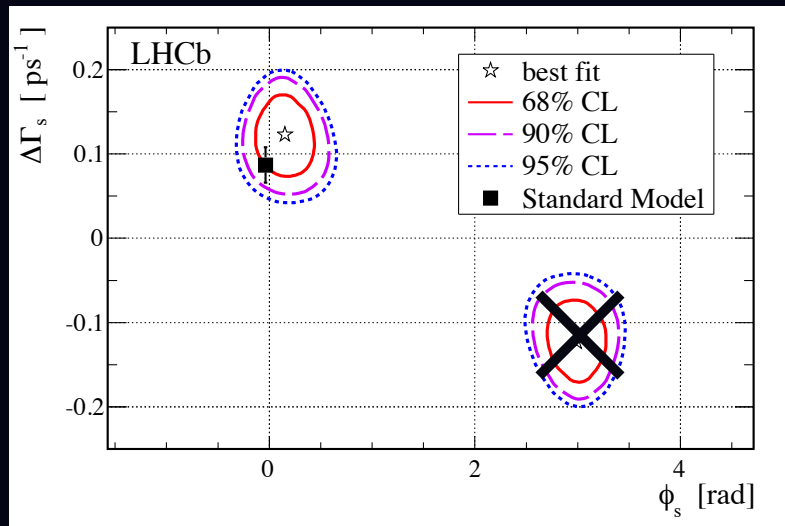
ϕ_s = 0.15 ±0.18 ± 0.06 (rad)

$\Delta\Gamma_s$ = 0.123 ±0.029 ± 0.011 (ps⁻¹)

Most precise measurement of ϕ_s and $\Delta\Gamma_s$ at that time, consistent with SM predictions
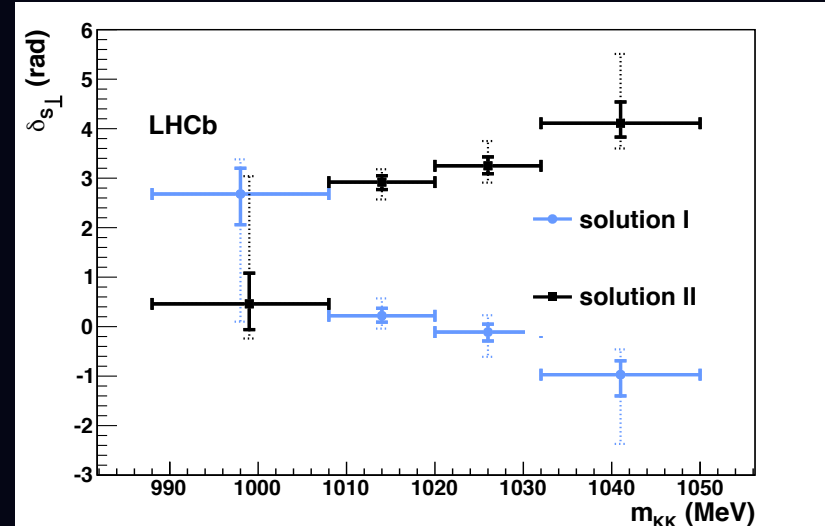
$\Delta\Gamma_s$>0 determined at 4.7σ significance level, following method in
[Y. Xie *et. al,* arXiv: 0908.3627, JHEP 0909 (2009) 074]

Angular analysis

Angular analysis to statistically separate CP eigenstates

K^+K^- in P wave: 0 (CP even), || (CP even), $\perp$ (CP odd)

Helicity angles: $\Omega=(\theta_\mu, \theta_K, \phi_h)$
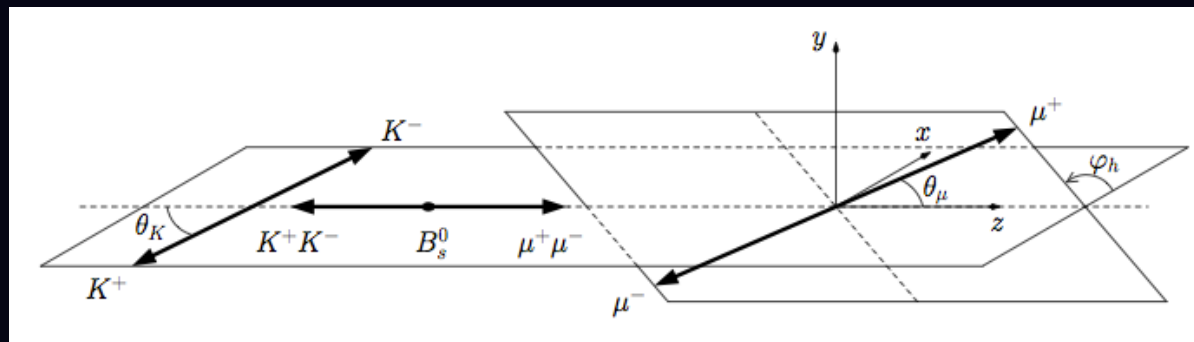
A small CP odd K^+K^- S-wave contribution accounted for

Angular acceptance effect based on simulation. Possible data/simulation differences taken as systematics

Time-dependent angular PDF

k	$f_k(\Omega)$	$h_k(t)$
1	$2\cos^2\theta_K\sin^2\theta_\mu$	$|A_0|^2(t)$
2	$\sin^2\theta_K(1-\sin^2\theta_\mu\cos^2\phi_h)$	$|A_{\parallel}|^2(t)$
3	$\sin^2\theta_K(1-\sin^2\theta_\mu\sin^2\phi_h)$	$|A_{\perp}|^2(t)$
4	$\sin^2\theta_K\sin^2\theta_\mu\sin2\phi_h$	$\mathrm{Im}\{A_{\parallel}^*(t)A_{\perp}(t)\}$
5	$(\sqrt{2}/2)\sin2\theta_K\sin2\theta_\mu\cos\phi_h$	$\mathrm{Re}\{A_0^*(t)A_{\parallel}(t)\}$
6	$-(\sqrt{2}/2)\sin2\theta_K\sin2\theta_\mu\sin\phi_h$	$\mathrm{Im}\{A_0^*(t)A_{\perp}(t)\}$
7	$(2/3)\sin^2\theta_\mu$	$|A_S|^2(t)$
8	$(\sqrt{6}/3)\sin\theta_K\sin2\theta_\mu\cos\phi_h$	$\mathrm{Re}\{A_S^*(t)A_{\parallel}(t)\}$
9	$-(\sqrt{6}/3)\sin\theta_K\sin2\theta_\mu\sin\phi_h$	$\mathrm{Im}\{A_S^*(t)A_{\perp}(t)\}$
10	$(4\sqrt{3}/3)\cos\theta_K\sin^2\theta_\mu$	$\mathrm{Re}\{A_S^*(t)A_0(t)\}$

Depending on physics parameters: ϕ_s, $\Delta\Gamma_s$, Γ_s, Δm_s, $|\lambda|$, $|A_0|^2$, $|A_{\perp}|^2$, $\delta_{\parallel}$, $\delta_{\perp}$, S wave parameters.
(assuming same λ for all CP eigenstates)

Key ingredients

- Theoretical time-dependent CP asymmetry

$$A_{\mathrm{CP}} \equiv \frac{\Gamma\left(\overline{B}_s^0 \to f\right) - \Gamma\left(B_s^0 \to f\right)}{\Gamma\left(\overline{B}_s^0 \to f\right) + \Gamma\left(B_s^0 \to f\right)} = \eta_f \sin\phi_s \sin(\Delta m_s t)$$

- From flavour tagged time-dependent angular analysis

$$A_{\mathrm{CP}} \approx (1 - 2w)\, e^{-\frac{1}{2}\Delta m_s^2 \sigma_t^2}\, \eta_f \sin\phi_s \sin(\Delta m_s t)$$

– ω Probability of getting the initial flavour wrong

– σ_t Decay time resolution

– η_f CP eigenvalue → angular analysis

Essential ingredients: excellent decay time resolution, good flavour tagging performance, precise knowledge of time resolution, mistag rate and Δm_s

Decay time resolution
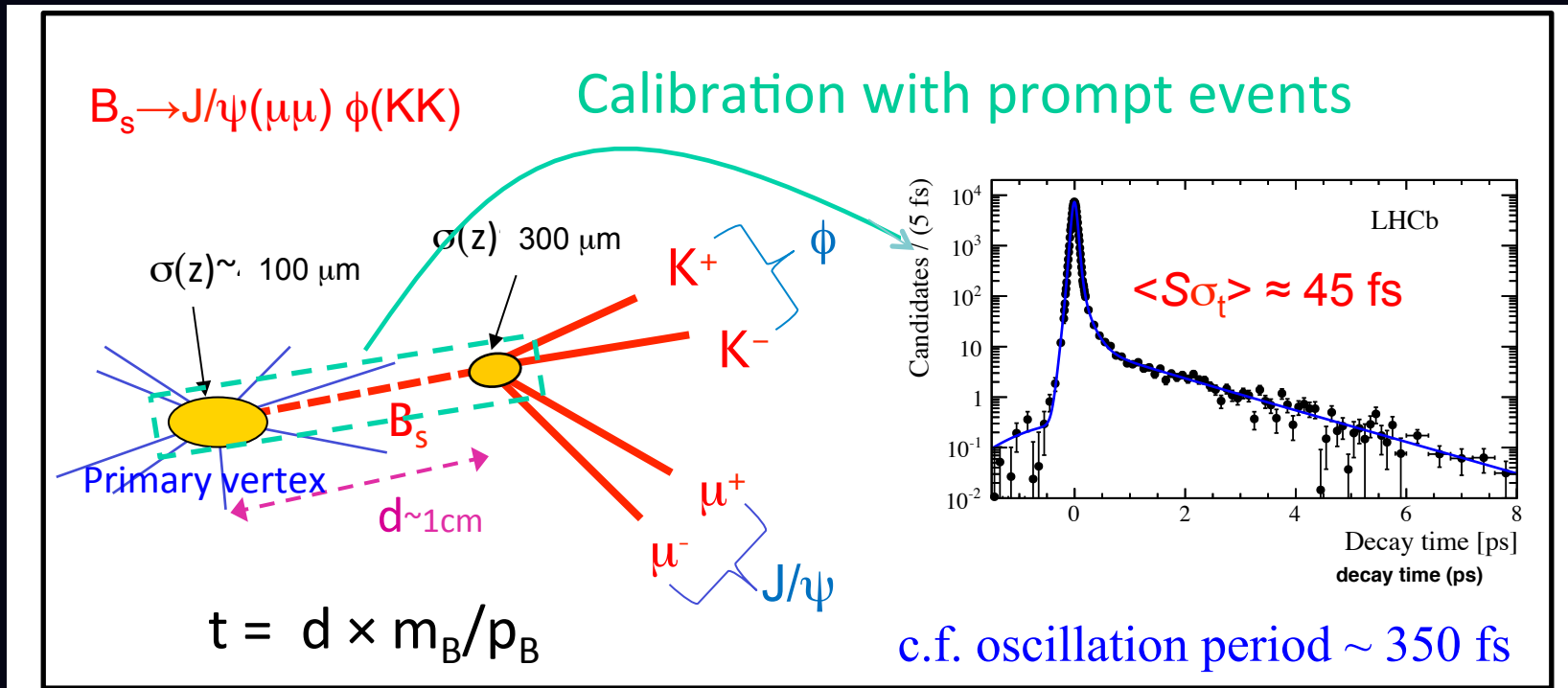
σ_t: event-by-event decay time uncertainty

Calibrated scale factor $S \approx 1.45 \pm 0.06$, $\langle S\sigma_t \rangle \approx 45$ fs

Impact of decay time resolution, $\Delta m_s \approx 17.7$ ps^{-1}
➢ If $\langle S\sigma_t \rangle = 45$ fs, dilution factor $\exp(-\Delta m_s^2 \langle S\sigma_t \rangle^2/2) \approx 0.73$
➢ If $\langle S\sigma_t \rangle = 90$ fs, dilution factor $\exp(-\Delta m_s^2 \langle S\sigma_t \rangle^2/2) \approx 0.28$

Flavour tagging introduction

o Use charge of leptons or hadrons from the decay of the other B meson: opposite-side tagging

o Use charge of kaon produced in the fragmentation: same-side tagging

o Analysis requires precise knowledge of
   ➢ Mistag rate: ω
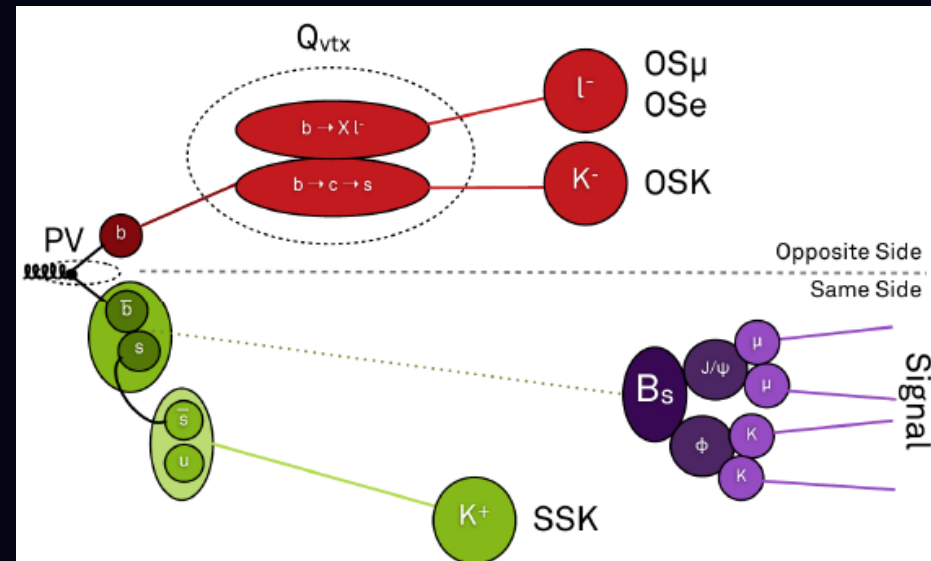
Opposite side tagging performance

o Use control channels for calibration
o Opposite-side tagging:
   ➢ Fit time evolution in
     flavour specific $B^0 \to D^{*-} \mu^+ \nu_\mu$
   ➢ Count correctly/mis-tagged events
     in self tagging $B^+ \to J/\psi K^+$
o OS tagging optimized and calibrated
   on data

algorithm	$\varepsilon(1-2\omega)^2$ [%]
OS	2.29 ± 0.06

[EPJC 72 (2012) 2022, arXiv: 1202.4979]
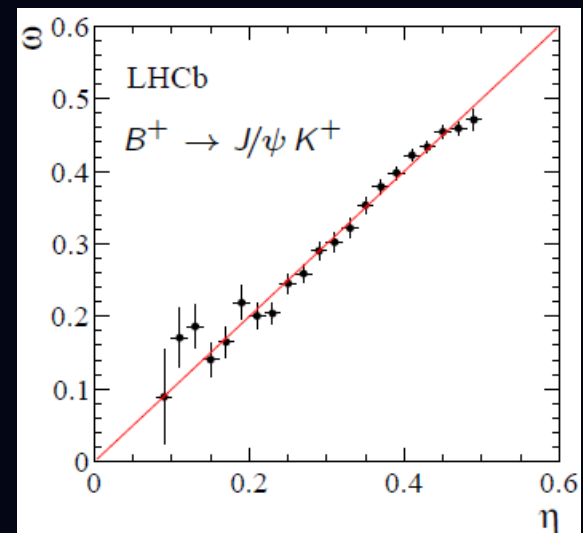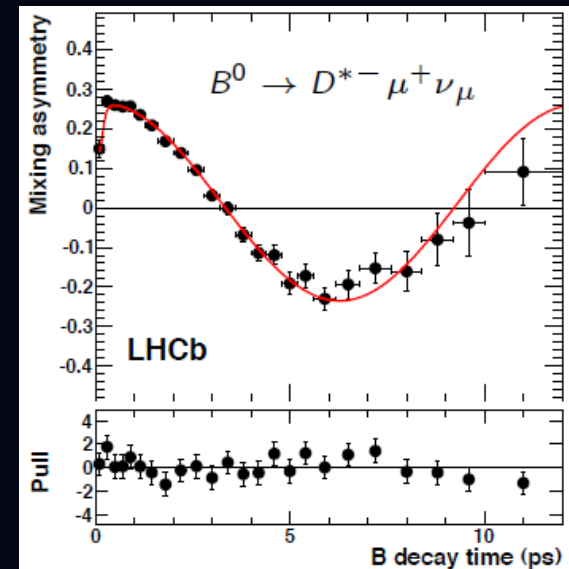
Same side tagging performance

o Use flavour specific control channels to calibrate tagging

o Same-side tagging:
  ➢ Fit time evolution in
    $B_s \rightarrow D_s^- \pi^+$

o SS tagging optimized on MC and calibrated on data

Y. Xie principal author

LHCb preliminary
$\sqrt{s} = 7$ TeV, 1 fb^{-1}
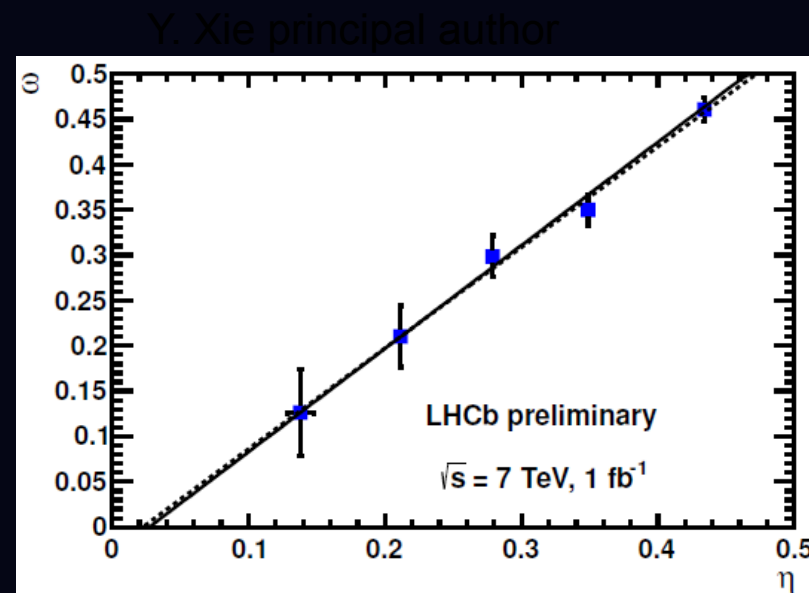
$B_s \rightarrow D_s^- \pi^+$

[LHCb-CONF-2012-033]

algorithm	$\varepsilon(1-2\omega)^2$ [%]
SSK	0.89 ±0.17
OS	2.29 ± 0.06
OS + SSK	3.13±0.12

Event selection with 1.0 fb^{-1}

Very clean sample obtained by exploiting

➢ Excellent muon and kaon identification
➢ Precise tracking and vertexing
➢ Powerful trigger provided by the muon detector
➢ A requirement of t>0.3 ps to remove prompt background

27.6 ± 0.1 k signals
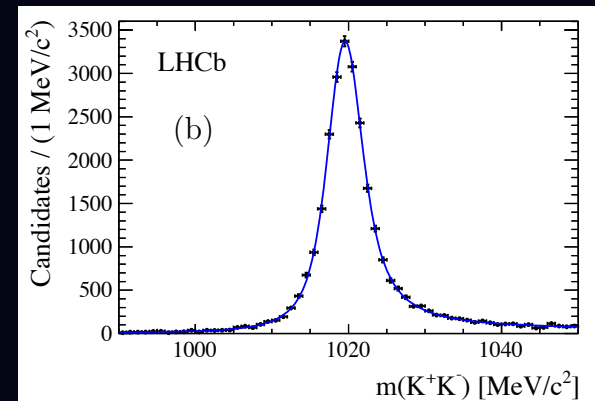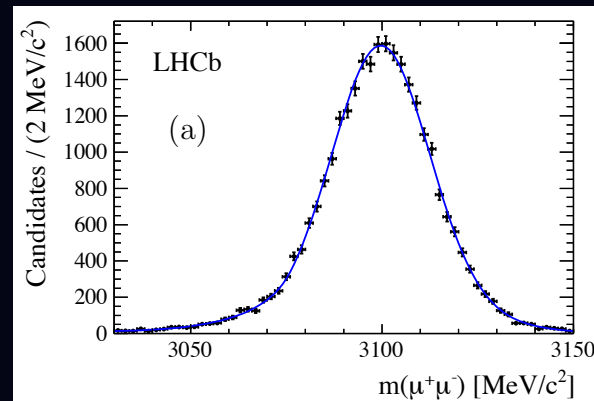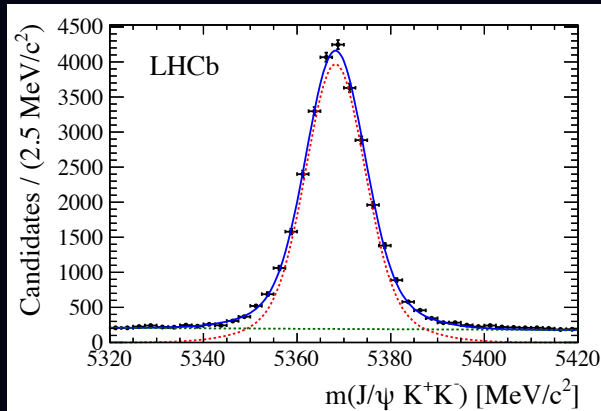
Background subtraction in ML fit

Y. Xie, principal author

Use a sWeight-based method to optimally subtract combinatorial background in maximum likelihood fit

➤ Avoid parameterization in multiple dimension

[Y. Xie, arXiv: 0905.0724]

$$-\ln L\left(\theta\right) = -\alpha \sum_{e=1}^{N_s+N_b} w_e \cdot \ln P_s\left(x_e;\theta\right)$$

θ fit parameters

x t, Ω, σ_t, η

$P_s(x)$ signal PDF

α factor for error correction

w signal weight calculated using J/ψKK mass as discriminating variable [M. Pivk, F. R. Le Diberder, NIMA 555 (2005) 356,]

Background subtracted projections

Total
CP−even
CP−odd
S−wave
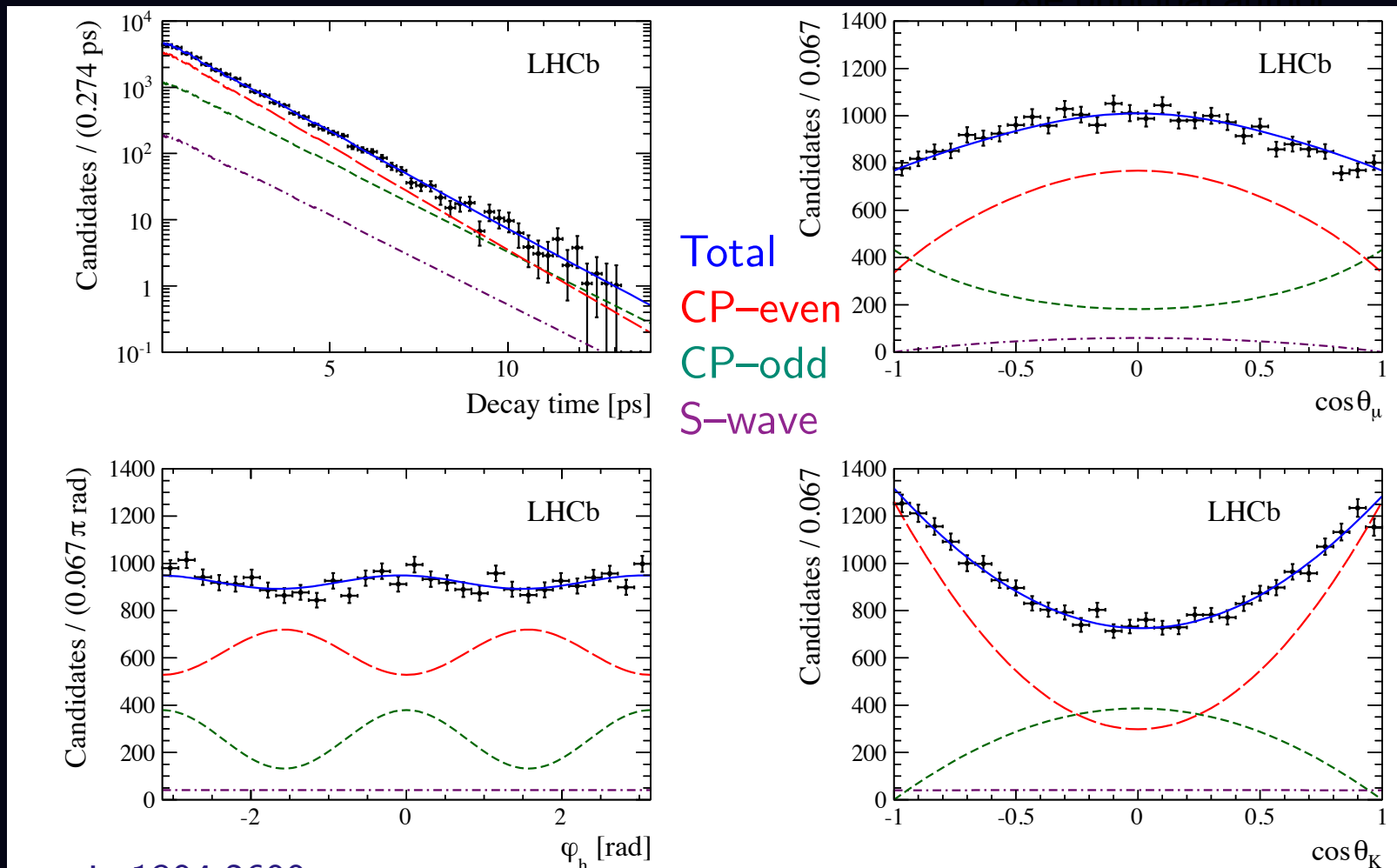
Systematic uncertainties

Source	Γ_s [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	$|A_\perp|^2$	$|A_0|^2$	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	ϕ_s [rad]	$|\lambda|$
Stat. uncertainty	0.0048	0.016	0.0086	0.0061	$^{+0.13}_{-0.21}$	0.22	0.091	0.031
Background subtraction	0.0041	0.002	–	0.0031	0.03	0.02	0.003	0.003
$B^0 \to J/\psi K^{*0}$ background	–	0.001	0.0030	0.0001	0.01	0.02	0.004	0.005
Ang. acc. reweighting	0.0007	–	0.0052	0.0091	0.07	0.05	0.003	0.020
Ang. acc. statistical	0.0002	–	0.0020	0.0010	0.03	0.04	0.007	0.006
Lower decay time acc. model	0.0023	0.002	–	–	–	–	–	–
Upper decay time acc. model	0.0040	–	–	–	–	–	–	–
Length and mom. scales	0.0002	–	–	–	–	–	–	–
Fit bias	–	–	0.0010	–	–	–	–	–
Quadratic sum of syst.	0.0063	0.003	0.0064	0.0097	0.08	0.07	0.009	0.022
Total uncertainties	0.0079	0.016	0.0107	0.0114	$^{+0.15}_{-0.23}$	0.23	0.091	0.038

Statistical uncertainty is dominating the precision for major physics parameters ϕ_s and $\Delta\Gamma_s$

Result

ϕ_s = 0.07 ± 0.09 (stat) ± 0.01(syst) rad

$\Delta\Gamma_s$ = 0.100 ± 0.016 (stat) ± 0.003 (syst) ps^{-1}

SM: $\phi_s \approx -2\beta_s$ = - 0.036 ± 0.002 rad, $\Delta\Gamma_s$ = 0.087 ± 0.021 ps^{-1}

[J. Charles *et. al*, PRD 84 (2011) 033005]   [A. Lenz, U. Nierste, arXiv: 1102.4274
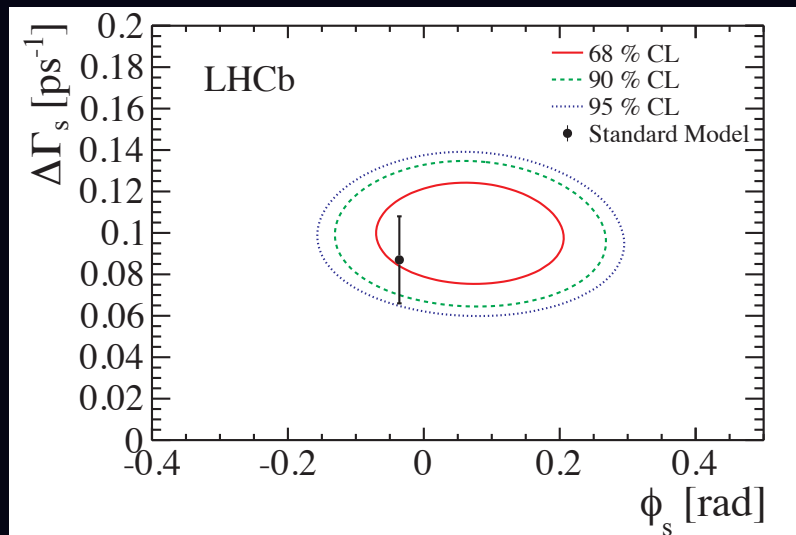
In good agreement with the SM expectation
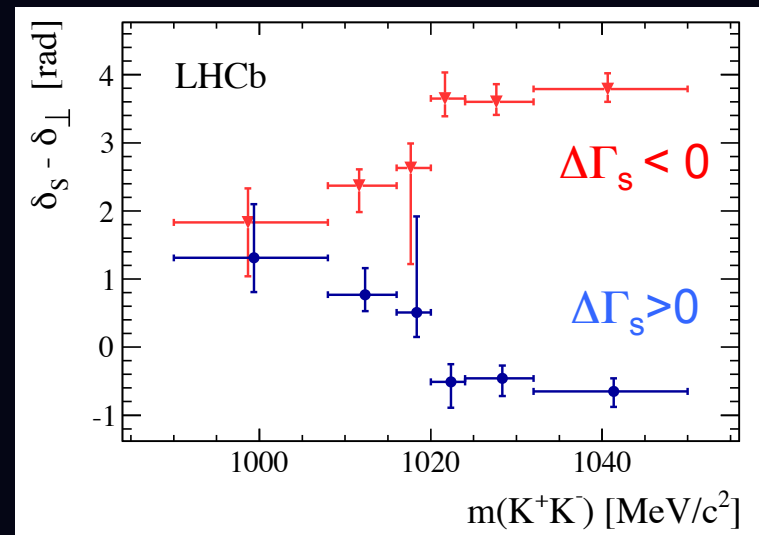
$\Delta\Gamma_s$>0 confirmed

$B_s \to J/\psi\pi^+\pi^-$

Also a b→cc̄s process

97.5% pure CP odd decay

[PRD 86 (2012) 052006, arXiv: 1204.5643]

Γ_s and $\Delta\Gamma_s$ constrained to result from $B_s \to J/\psi K^+K^-$

$$\phi_s = -0.14^{+0.17}_{-0.16} \pm 0.01 \ \text{rad}$$

Combined fit of $B_s \to J/\psi K^+K^-$ and $B_s \to J/\psi\pi^+\pi^-$

$\phi_s^{ccs} = 0.01 \pm 0.07 \pm 0.01$ rad

$\Delta\Gamma_s = 0.106 \pm 0.011 \pm 0.007$ ps^{-1}

[PLB 713 (2012) 378, arXiv: 1204.5675]

7.4 ± 0.1 k signals
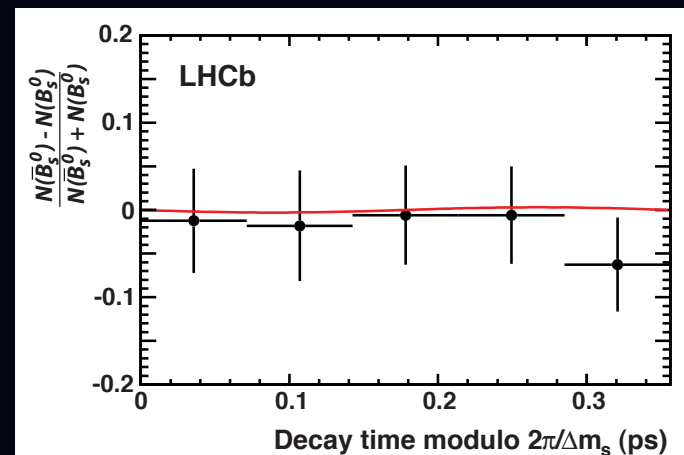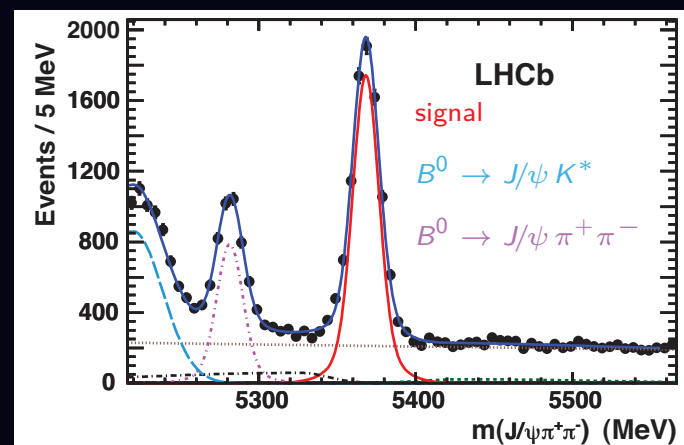
Comparison with other experiments
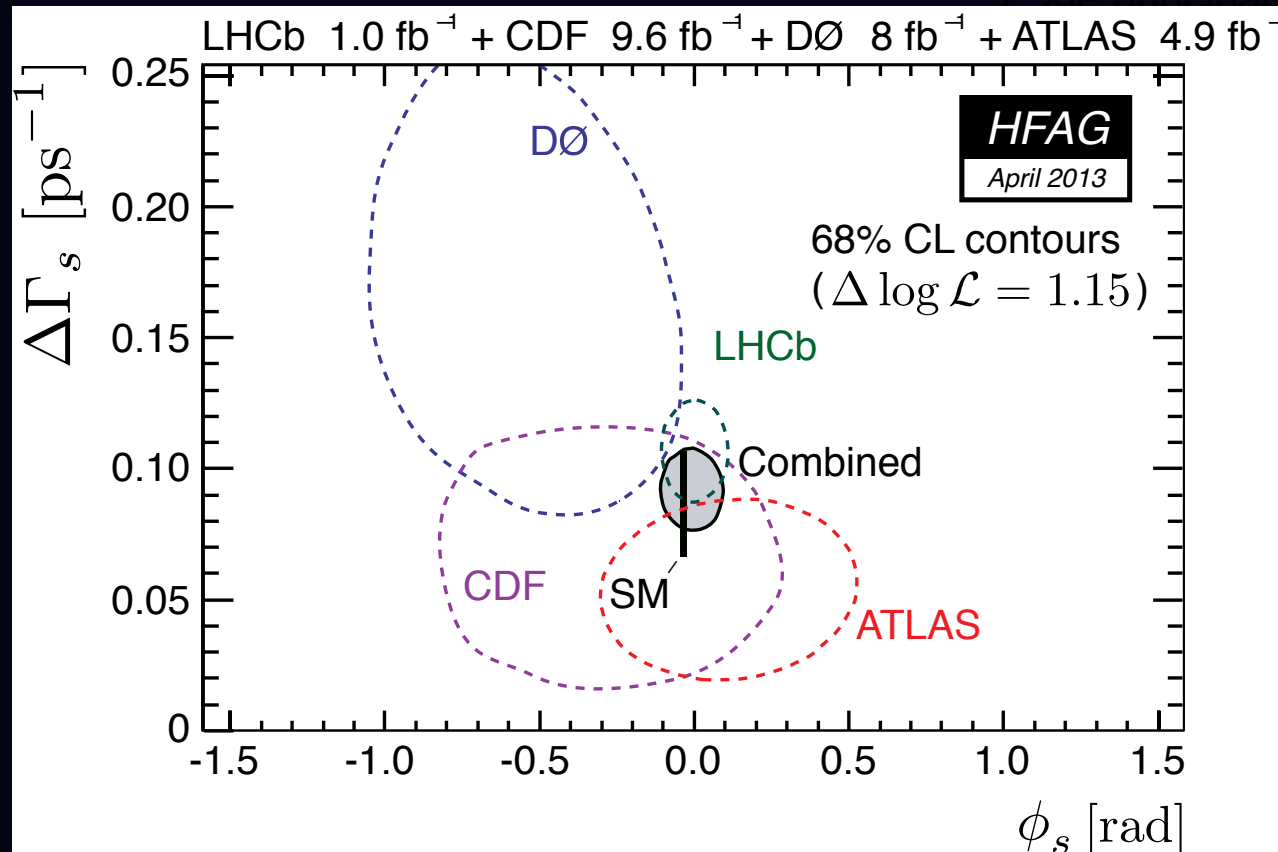
LHCb measurement is most precise and dominating. No big NP effect is observed. Precision improvement crucial for further test of the SM.

Precision measurement of the $B_s - \bar{B}_s$ oscillation frequency with the decay $B_s \rightarrow D_s^- \pi^+$

Flavour specific B_s decays

Allowed: $B_s \rightarrow D_s^- \pi^+$ and $\bar{B}_s \rightarrow D_s^+ \pi^-$

Forbidden: $\bar{B}_s \rightarrow D_s^- \pi^+$ and $B_s \rightarrow D_s^+ \pi^-$

Time-dependent decay rates: mixed decays $(B_s \rightarrow \bar{B}_s)$

$\bar{B}_s(t=0) \rightarrow B_s(t>0) \rightarrow D_s^- \pi^+$ and $B_s(t=0) \rightarrow \bar{B}_s(t>0) \rightarrow D_s^+ \pi^-$

$$R(t) = Ae^{-\Gamma_s t}\left(\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) - \cos(\Delta m_s t)\right)$$

Oscillation frequency Δm_s

Time-dependent decay rates: unmixed decays $(B_s \rightarrow B_s)$

$\bar{B}_s(t=0) \rightarrow \bar{B}_s(t>0) \rightarrow D_s^+ \pi^-$ and $B_s(t=0) \rightarrow B_s(t>0) \rightarrow D_s^- \pi^+$

$$R(t) = Ae^{-\Gamma_s t}\left(\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) + \cos(\Delta m_s t)\right)$$

Oscillation frequency Δm_s

Event selection

Select 34 k $B_s \to D_s^- \pi^+$ signals with 5 D_s^- decay modes exploiting the powerful RICH

$D_s^- \to \phi(K^+K^-)\pi^-$
$D_s^- \to K^{*0}(K^+\pi^-)K^-$
$D_s^- \to K^+K^-\pi^-$ non-resonant
$D_s^- \to K^-\pi^+\pi^-$,
$D_s^- \to \pi^-\pi^+\pi^-$

Topological trigger

2, 3 or 4 track displaced vertex
Large sum of p_T
One track with p_T >1.7 GeV/c
Tracks with large IP and good fit quality
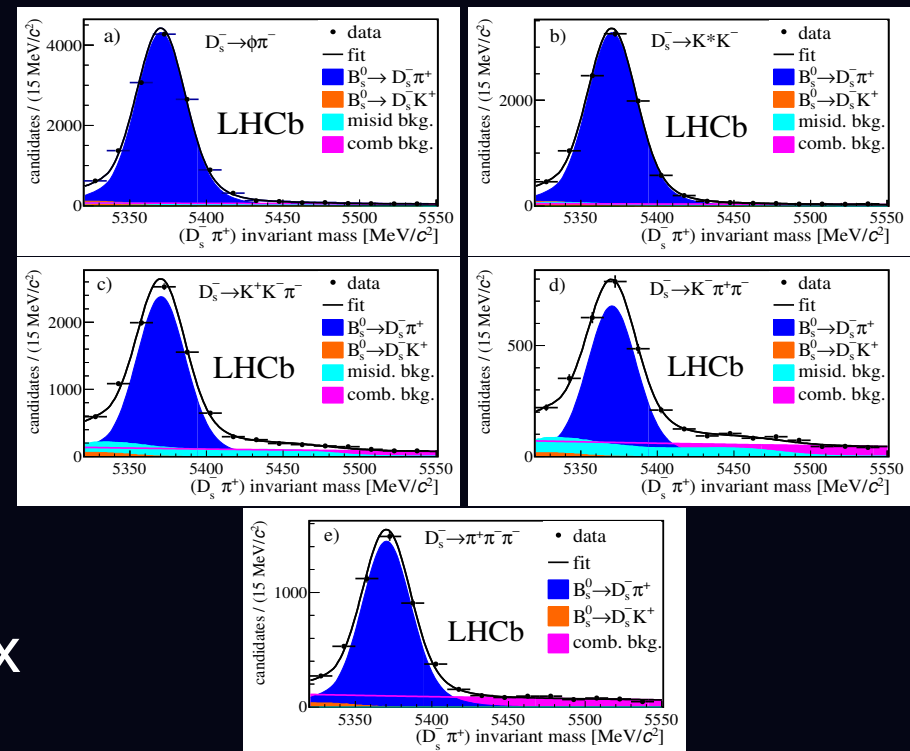
Fit model

For each signal or background component

$$\mathcal{P} = \mathcal{P}_m(m)\,\mathcal{P}_t(t,q|\sigma_t,\eta)\,\mathcal{P}_{\sigma_t}(\sigma_t)\,\mathcal{P}_\eta(\eta),$$

Invariant mass PDF $P_m(m)$

Signal: sum of two Crystal Ball functions
Combinatorial background: exponential function
b-hadron background: shape from simulation

$P_{\sigma t}(\sigma_t)$ and $P_\eta(\eta)$

For proper relative normalization, obtained from data

Decay time model

Signal:

$$\mathcal{P}_t(t|\sigma_t) \propto \left\{ \Gamma_s e^{-\Gamma_s t} \frac{1}{2} \left[\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) + q\left[1 - 2\omega(\eta_{\mathrm{OST}}, \eta_{\mathrm{SST}})\right]\cos(\Delta m_s t) \right] \theta(t) \right\} \otimes G(t, S_{\sigma_t}\sigma_t)\ \mathcal{E}_t(t)\ \epsilon,$$

G(t; 0, Sσ_t):   event-by-event decay time resolution model
Average time resolution: 44 fs

ε_t(t): acceptance function from simulation

ω: mistag rate
$\varepsilon(1-2\omega)^2$: (2.6 ± 0.4)% for OS, (1.2 ± 0.3)% for SS

Combinatorial background: from high mass sideband

b-hadron background: similar to signal
                    ($\Delta\Gamma_s$ = 0 and different Γ_s)
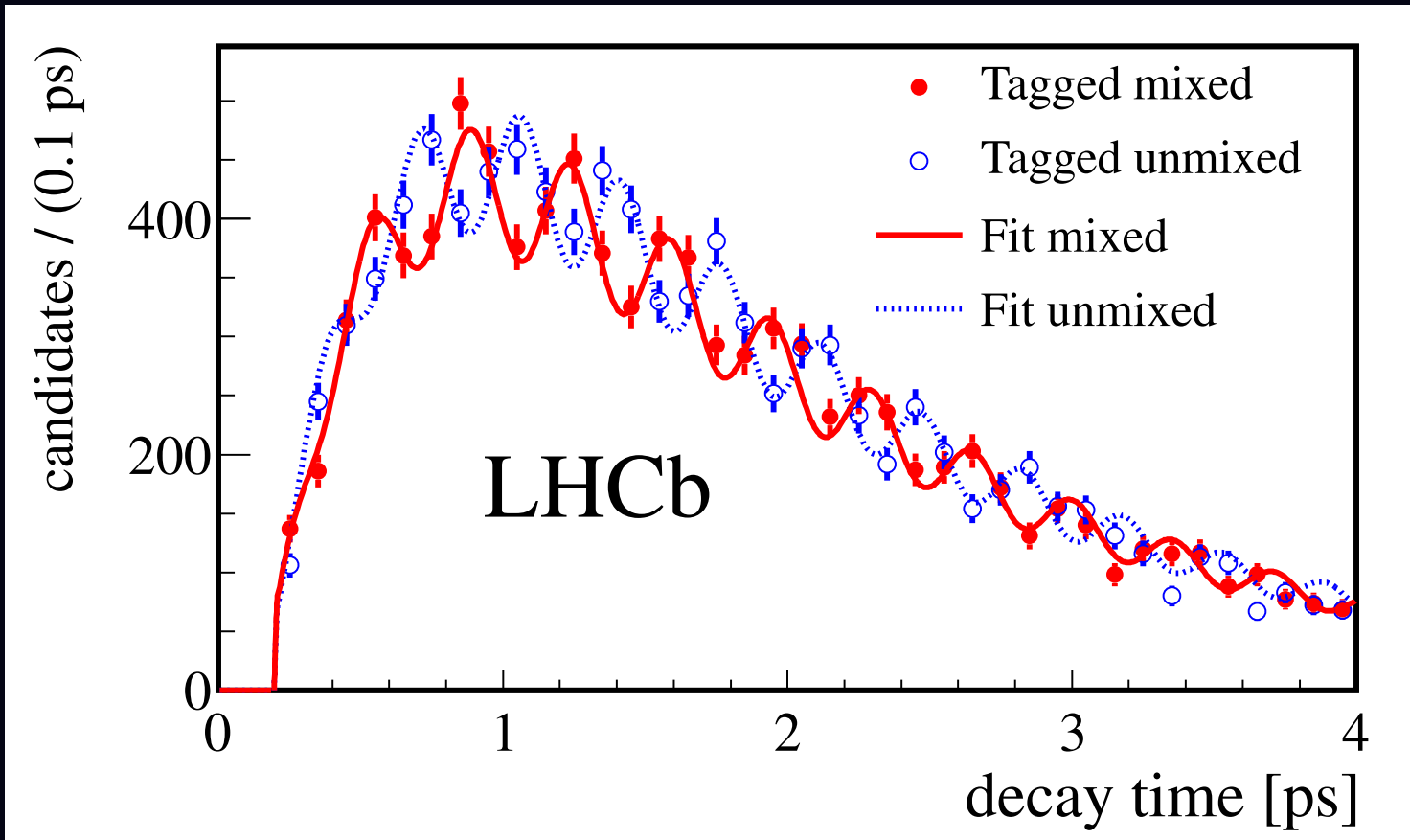
Decay time fit

Very clear oscillation pattern.
A B_s meson on average changes flavour ~9 times.
$(x = \Delta m_s / \Gamma_s \approx 26.9)$

Systematic uncertainties

source	Uncertainty [ps^{-1}]
z-scale *	0.004
Momentum scale	0.004
Decay time bias	0.001
Total	0.006

* z-scale relative uncertainty estimated to be 0.02% by comparing track based alignment and survey

Δm_s result

Most precise measurement to date

$$\Delta m_s = 17.768 \pm 0.023 \text{ (stat)} \pm 0.006 \text{ (syst) ps}^{-1}$$

Consistent with:

LHCb previous measurement with 0.037 fb^{-1}
$\Delta m_s = 17.63 \pm 0.11 \text{ (stat)} \pm 0.02 \text{ (syst) ps}^{-1}$

World average [PDG, PRD 86 (2012) 010001]
$\Delta m_s = 17.69 \pm 0.08 \text{ ps}^{-1}$

SM expectation [A. Lenz, U. Nierste, arXiv: 1102.4274]
$\Delta m_s = 17.3 \pm 2.6 \text{ ps}^{-1}$

Need better precision of hadronic parameters from Lattice QCD

Implication of B_s mixing measurements

excluded area has CL > 0.68

$\Delta \Gamma_s$ & τ_s^{FS}

SM point

Δm_d & Δm_s

ϕ^{Δ}_s-$2\beta_s$

A_{SL} & $a_{SL}(B_d)$ & $a_{SL}(B_s)$

CKM fitter
Winter 2012

New Physics in B_s - $\bar{B}_s$ mixing
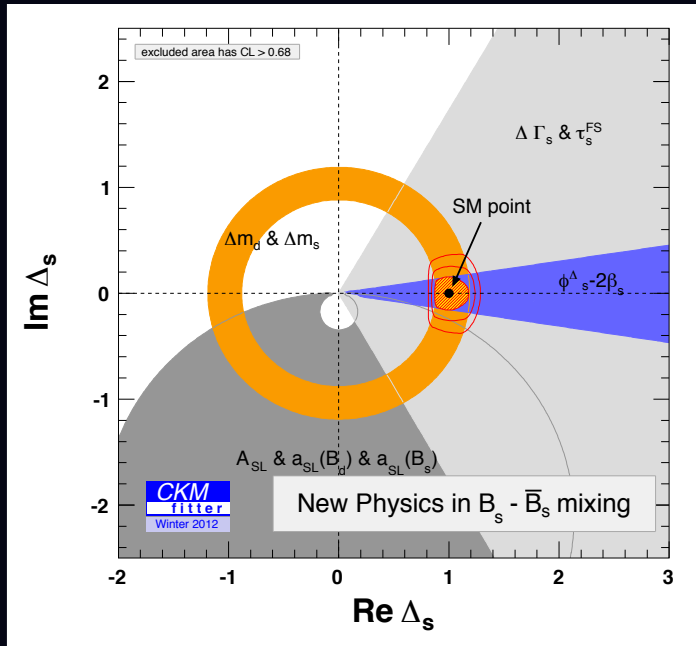
Y. Xie principal author

Model-independent analysis of NP in B_s mixing using LHCb prelimary results of ϕ_s, $\Delta\Gamma_s$ from 1.0 fb^{-1} [LHCb-CONF-2012-002]
Δm_s from 0.34 fb^{-1} [LHCb-CONF-2012-002]

NP contribution in B_s mixing amplitude is limited to at most ~30% at 3σ level.

[A. Lenz *et. al*, PRD 86 (2012) 033008, arXiv: 1203.0238]

New ϕ_s, $\Delta\Gamma_s$ and Δm_s measurements, superseding the preliminary results and consistent with the SM, will be able to put severe constriants on NP contribution in B_s mixing.

First measurement of the CP violating phase in $B_s \to \phi\phi$ decays
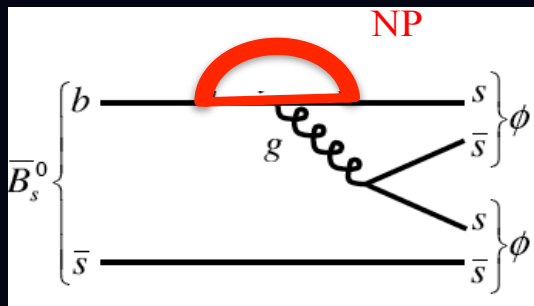
$B_s \rightarrow \phi\phi$

b→s penguin decay. Weak phase $|\phi_s|<0.02$ in SM. Can be affected by NP in decay and/or mixing.

Mixture of CP eigenstates: 3 CP even, 2 CP odd
Angular analysis similar to $B_s \rightarrow J/\psi\phi$

Tagging power
$\varepsilon(1-2\omega)^2 = (3.29 \pm 0.48)\%$

Time resolution ~40 fs

Angular and decay time acceptance from simulation
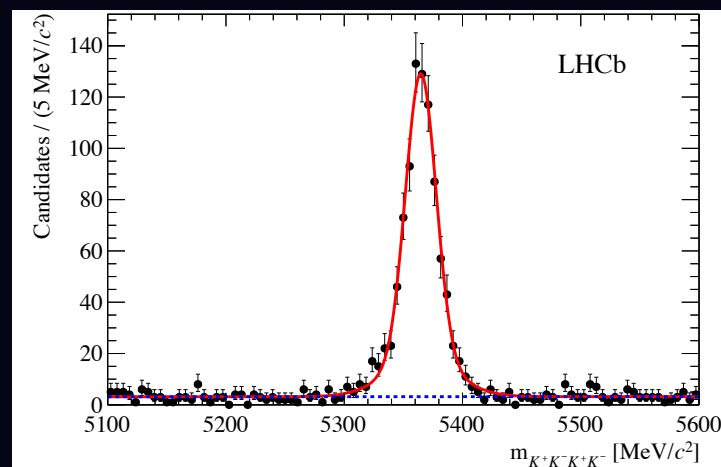
880 ± 31 signals

Background subtracted projections

Use sWeight-based method to subtract background in ML fit
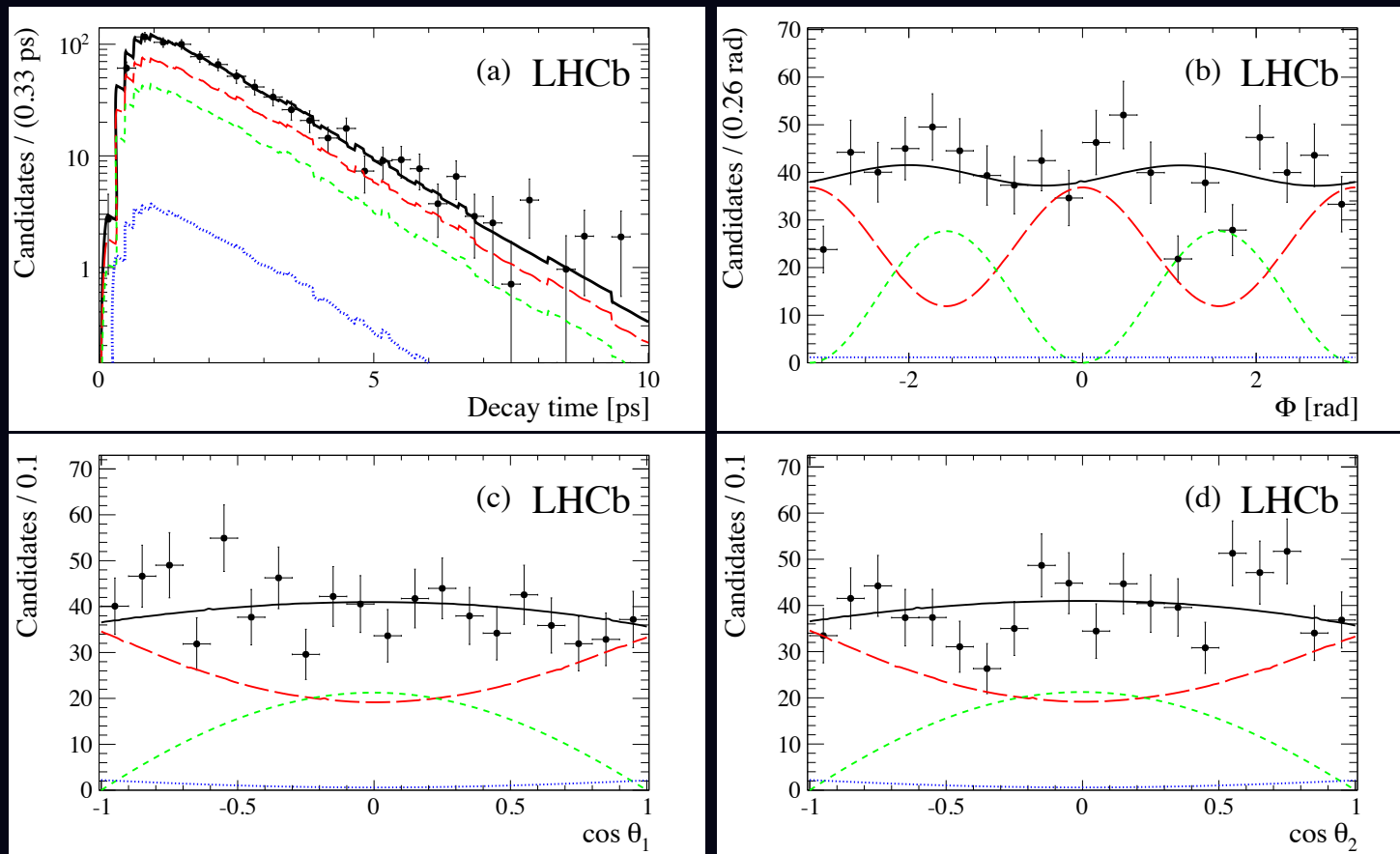
Result

Parameter	Value	$\sigma_{\text{stat.}}$	$\sigma_{\text{syst.}}$
ϕ_s[rad] (68 % CL)		$[-2.37, -0.92]$	0.22
$|A_0|^2$	0.329	0.033	0.017
$|A_\perp|^2$	0.358	0.046	0.018
$|A_{\text{S}}|^2$	0.016	$+0.024$ -0.012	0.009
δ_1 [rad]	2.19	0.44	0.12
δ_2 [rad]	-1.47	0.48	0.10
δ_{S} [rad]	0.65	$+0.89$ -1.65	0.33
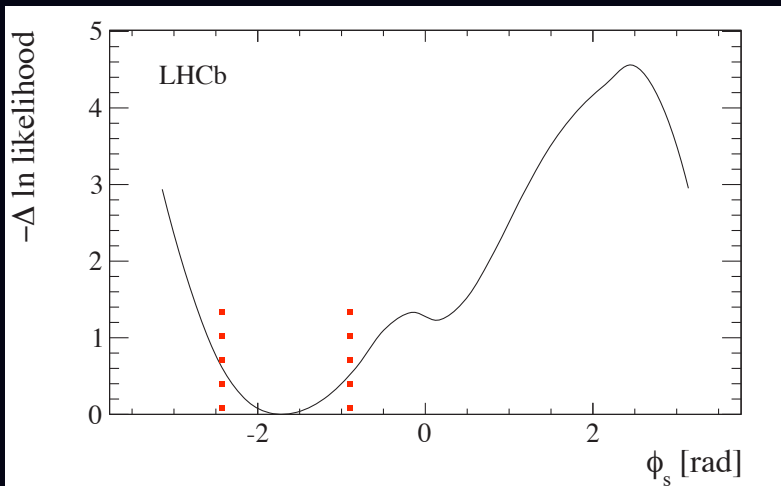
p-value of the SM prediction is 16%

First measurement of CP violating phase in B_s pure penguin decays

Statistical uncertainty dominating

Conclusions

LHCb has produced several new results in the pursuit of new physics in the B_s system:

➤ World's most precise measurement of ϕ_s and $\Delta\Gamma_s$, expected to put severe constraint on NP in B_s mixing

➤ World's most precise measurement of Δm_s, providing an essential ingredient for time-dependent study of B_s decays

➤ First measurement of CP violating phase in B_s penguin decays

Analyses of 2012 data are ongoing and significant precision improvement of these measurements is expected

Timeline of the Universe
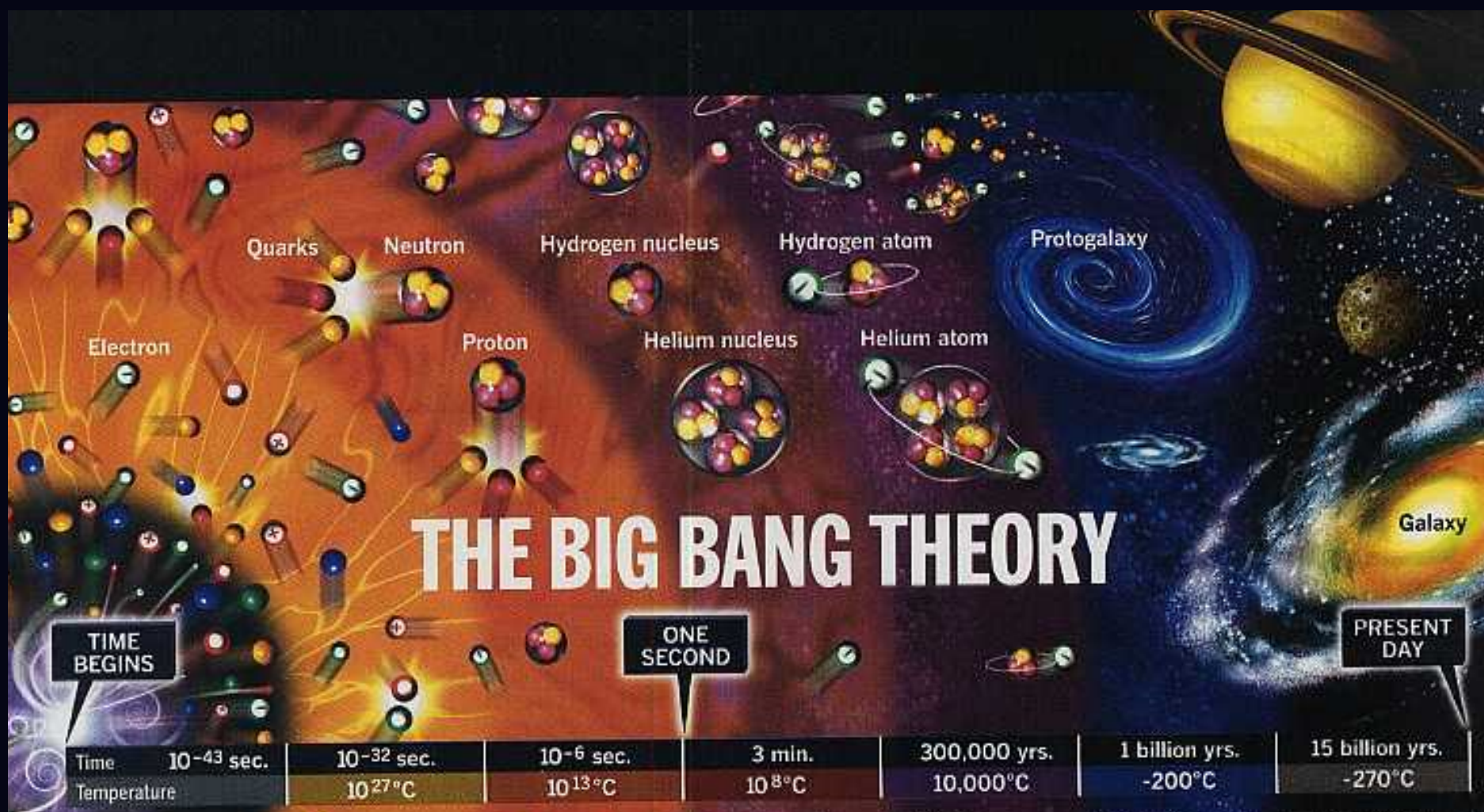
10^{-36}-10^{-6}s: free (anti-)quarks and gluons in plasma state
10^{-6}-1s: plasma cooled, protons & neutrons formed

Sakharov conditions

1) Baryon number violation: obviously needed!

2) Different physics laws for matter and antimatter ("CP violation")

$$\Gamma(X \to Y + B) \neq \Gamma(\bar{X} \to \bar{Y} + \bar{B})$$

Otherwise, baryon asymmetry is washed out by charge and parity conjugate processes

3) Departure from thermal equilibrium

$$\Gamma(X \to Y + B) > \Gamma(Y + B \to X)$$

Otherwise, baryon asymmetry is washed out by reverse processes

CP violation

Charge conjugation: particle ↔ anti-particle
Parity operation: left ↔ right

CP symmetry

Start with **particle**
and **antiparticle**

Change **particle**
into **antiparticle**

Reflect co-ordinates in a
mirror ("parity") gets
back the original result
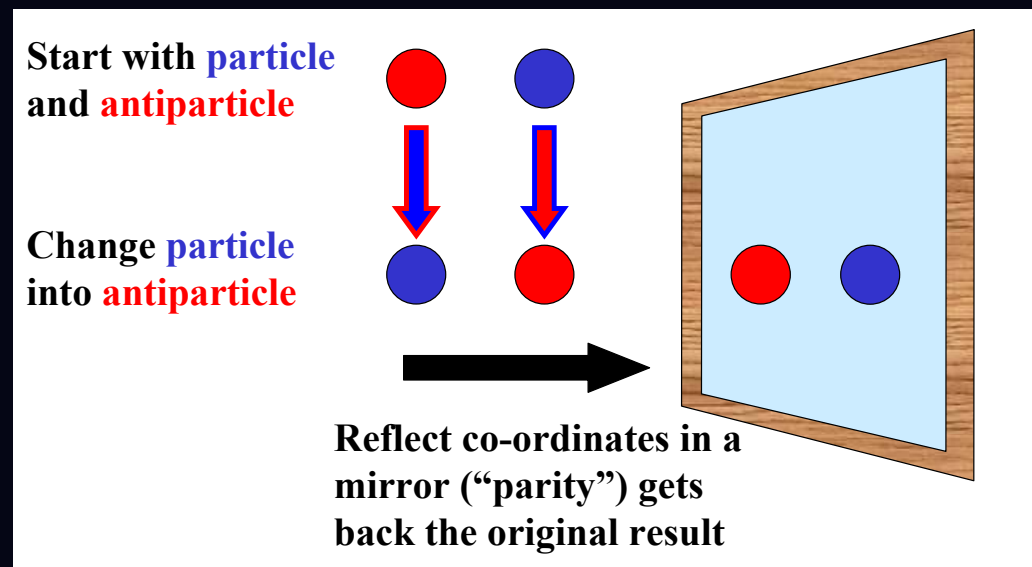
Breaking of this symmetry is called "CP violation"

CP violation has been established in K^0, B^0 and B_s systems

Method to resolve the ambiguity

[Y. Xie et al., JHEP 0909:074, 2009]

Similar to Babar measurement of sign of $\cos(2\beta)$, PRD 71, 032005 (2007)

K$^+$K$^-$ P-wave:

Phase of Breit-Wigner amplitude increases rapidly across $\phi(1020)$ mass region

$$BW(m_{KK}) = \frac{F_r F_D}{m_\phi^2 - m_{KK}^2 - im_\phi\Gamma(m_{KK})}$$

K$^+$K$^-$ S-wave:

Phase of Flatté amplitude for $f_0(980)$ relatively flat (similar for non-resonance)
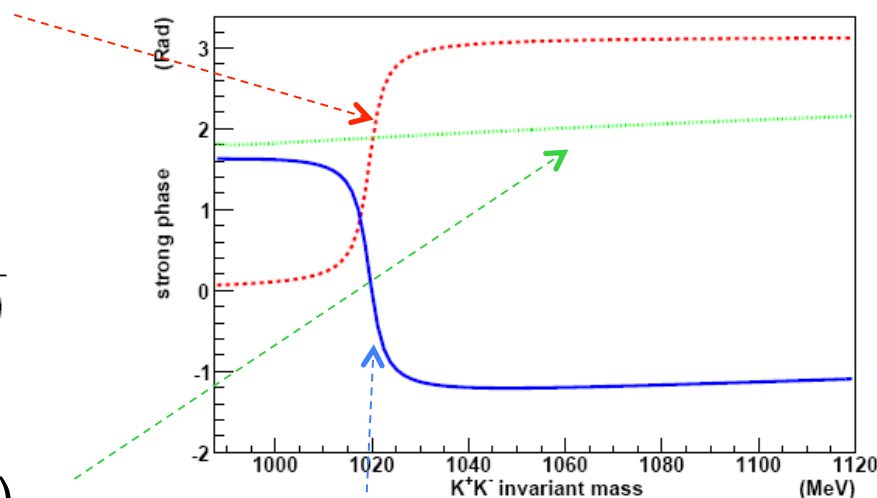
Phase difference between S- and P-wave amplitudes
Decreases rapidly across $\phi(1020)$ mass region

Resolution method: choose the solution with decreasing trend of δ_s-δ_P vs m_{KK} in the $\phi(1020)$ mass region

Time evolution for |λ|=1

$$
|A_0|^2(t) = |A_0|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)\right],
$$

$$
|A_\parallel(t)|^2 = |A_\parallel|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)\right],
$$

$$
|A_\perp(t)|^2 = |A_\perp|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s \sin(\Delta m t)\right],
$$

$$
\Im(A_\parallel(t) A_\perp(t)) = |A_\parallel||A_\perp| e^{-\Gamma_s t}\left[-\cos(\delta_\perp - \delta_\parallel)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right.
$$
$$
\left. -\cos(\delta_\perp - \delta_{-\parallel})\cos\phi_s \sin(\Delta m t) + \sin(\delta_\perp - \delta_\parallel)\cos(\Delta m t)\right],
$$

$$
\Re(A_0(t) A_\parallel(t)) = |A_0||A_\parallel| e^{-\Gamma_s t}\cos(\delta_\parallel - \delta_0)\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right.
$$
$$
\left. +\sin\phi_s \sin(\Delta m t)\right],
$$

$$
\Im(A_0(t) A_\perp(t)) = |A_0||A_\perp| e^{-\Gamma_s t}\left[-\cos(\delta_\perp - \delta_0)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right.
$$
$$
\left. -\cos(\delta_\perp - \delta_0)\cos\phi_s \sin(\Delta m t) + \sin(\delta_\perp - \delta_0)\cos(\Delta m t)\right],
$$

$$
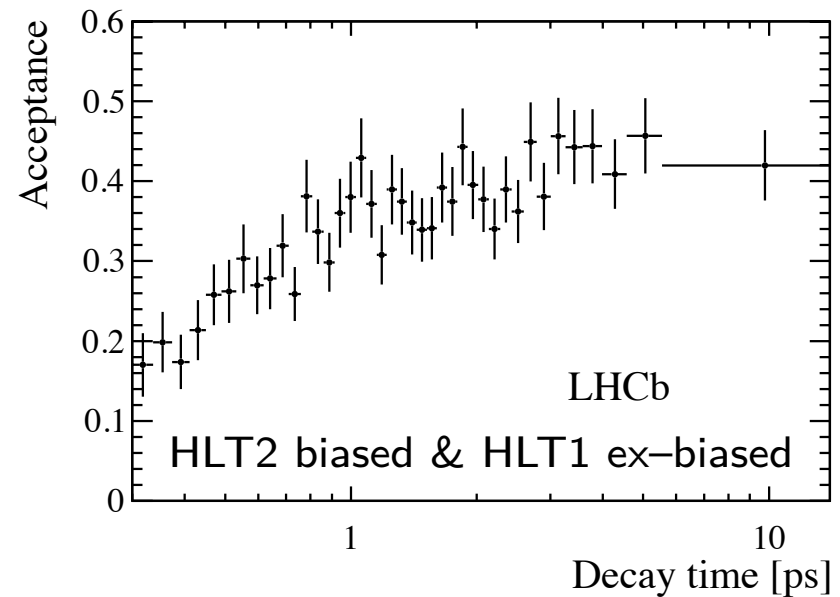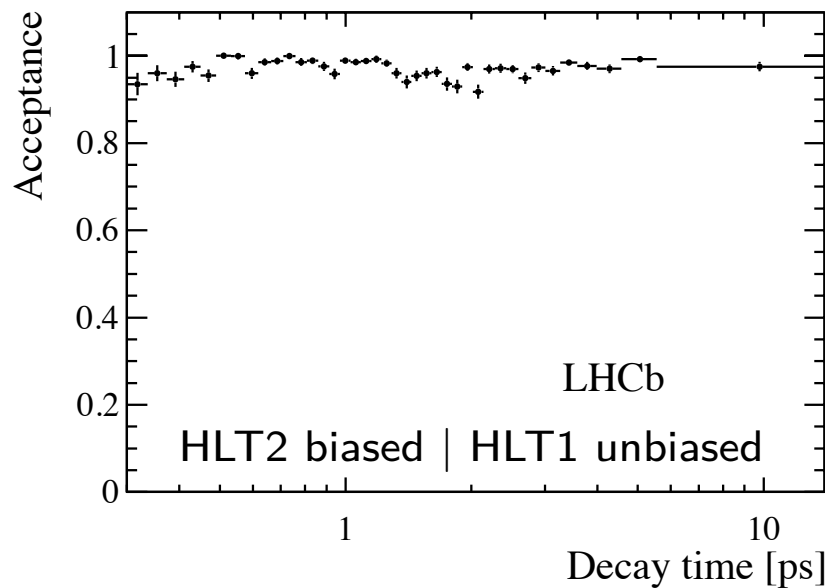|A_s(t)|^2 = |A_s|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s \sin(\Delta m t)\right],
$$

$$
\Re(A_s^*(t) A_\parallel(t)) = |A_s||A_\parallel| e^{-\Gamma_s t}\left[-\sin(\delta_\parallel - \delta_s)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin(\delta_\parallel - \delta_s)\cos\phi_s \sin(\Delta m t)\right.
$$
$$
\left. +\cos(\delta_\parallel - \delta_s)\cos(\Delta m t)\right],
$$

$$
\Im(A_s^*(t) A_\perp(t)) = |A_s||A_\perp| e^{-\Gamma_s t}\sin(\delta_\perp - \delta_s)\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right.
$$
$$
\left. -\sin\phi_s \sin(\Delta m t)\right],
$$

$$
\Re(A_s^*(t) A_0(t)) = |A_s||A_0| e^{-\Gamma_s t}\left[-\sin(\delta_0 - \delta_s)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right.
$$
$$
\left. -\sin(\delta_0 - \delta_s)\cos\phi_s \sin(\Delta m t) + \cos(\delta_0 - \delta_s)\cos(\Delta m t)\right].
$$

Decay time acceptance

- Decay time acceptance arrises from trigger selections.
- Presence of unbiased sample allows data–driven determination of decay time acceptance.

- High decay time acceptance from VELO reconstruction parameterised as $(1 + \beta\tau)$ and obtained obtained from MC.

Angular acceptance

Y. Xie principal author

Angular acceptance effect based simulation. Possible data/simulation differences taken as systematics
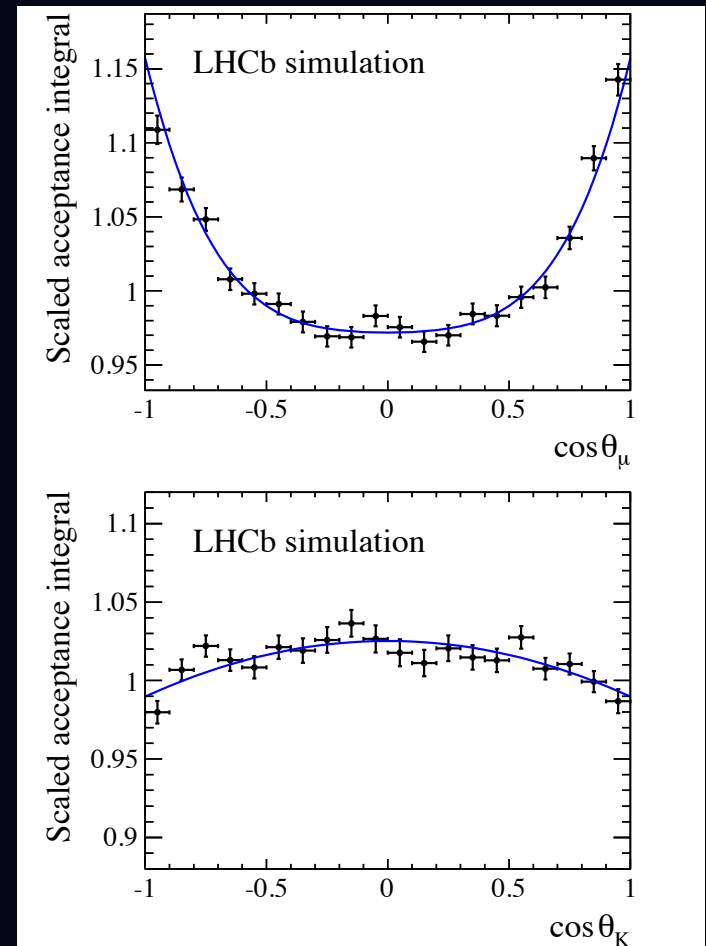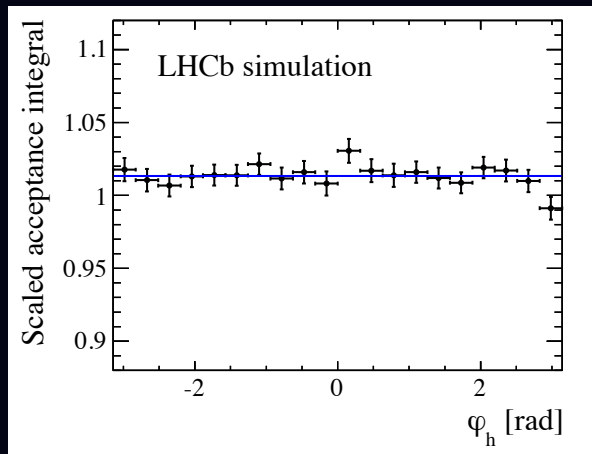
Δm_s from $B_s \rightarrow J/\psi\phi$

Y. Xie principal author

Without constraining Δm_s to measurement in other channels

$$\Delta m_s = 17.70 \pm 0.10 \text{ (stat)} \pm 0.01 \text{ (syst) ps}^{-1}$$
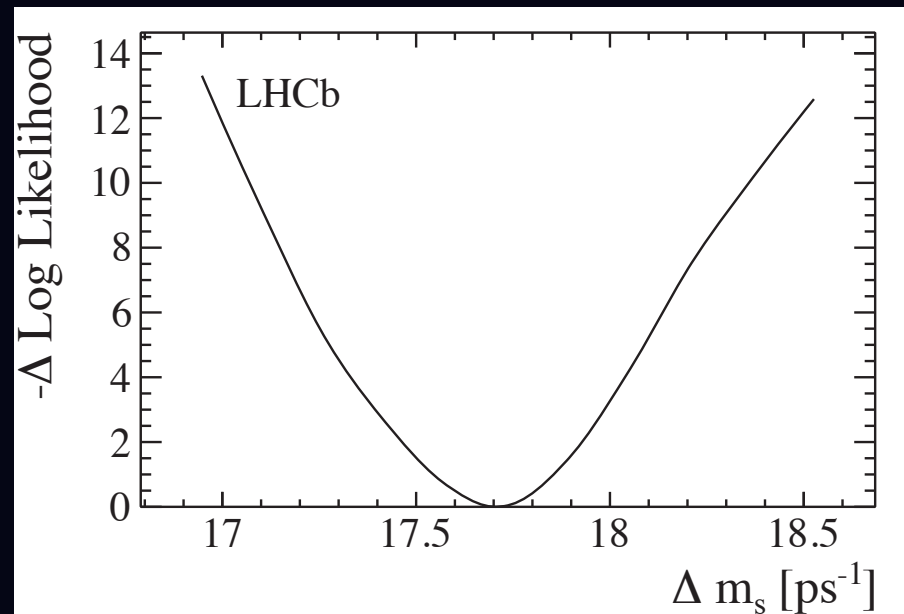
Earlier comparison

Experiment	Dataset [fb^{-1}]	Ref.	ϕ_s [rad]	$\Delta\Gamma_s$ [ps^{-1}]
LHCb ($B_s^0 \to J/\psi\phi$)	0.4	[5]	$0.15 \pm 0.18 \pm 0.06$	$0.123 \pm 0.029 \pm 0.011$
LHCb ($B_s^0 \to J/\psi\pi^+\pi^-$)	1.0	[6]	$-0.019\,^{+0.173+0.004}_{-0.174-0.003}$	$-$
LHCb (combined)	0.4+1.0	[6]	$0.06 \pm 0.12 \pm 0.06$	$-$
ATLAS	4.9	[9]	$0.22 \pm 0.41 \pm 0.10$	$0.053 \pm 0.021 \pm 0.010$
CMS	5.0	[10]	$-$	$0.048 \pm 0.024 \pm 0.003$
D0	8.0	[11]	$-0.55\,^{+0.38}_{-0.36}$	$0.163\,^{+0.065}_{-0.064}$
CDF	9.6	[12]	$[-0.60, 0.12]$ at 68% CL	$0.068 \pm 0.026 \pm 0.009$

$B_s \rightarrow J/\psi\phi$ fit parameters

Y. Xie principal author

Parameter	Value
$\Gamma_s \, [\,\mathrm{ps}^{-1}\,]$	$0.663 \pm 0.005 \pm 0.006$
$\Delta\Gamma_s \, [\,\mathrm{ps}^{-1}\,]$	$0.100 \pm 0.016 \pm 0.003$
$|A_\perp|^2$	$0.249 \pm 0.009 \pm 0.006$
$|A_0|^2$	$0.521 \pm 0.006 \pm 0.010$
$\delta_\parallel \, [\mathrm{rad}]$	$3.30\,^{+0.13}_{-0.21} \pm 0.08$
$\delta_\perp \, [\mathrm{rad}]$	$3.07 \pm 0.22 \pm 0.07$
$\phi_s \, [\mathrm{rad}]$	$0.07 \pm 0.09 \pm 0.01$
$|\lambda|$	$0.94 \pm 0.03 \pm 0.02$

$m(K^+K^-)$ bin $[\,\mathrm{MeV}/c^2\,]$	Parameter	Value	σ_{stat} (asymmetric)	σ_{syst}
$990 - 1008$	F_{S}	0.227	$+0.081, -0.073$	0.020
	$\delta_{\mathrm{S}} - \delta_\perp \, [\mathrm{rad}]$	1.31	$+0.78, -0.49$	0.09
$1008 - 1016$	F_{S}	0.067	$+0.030, -0.027$	0.009
	$\delta_{\mathrm{S}} - \delta_\perp \, [\mathrm{rad}]$	0.77	$+0.38, -0.23$	0.08
$1016 - 1020$	F_{S}	0.008	$+0.014, -0.007$	0.005
	$\delta_{\mathrm{S}} - \delta_\perp \, [\mathrm{rad}]$	0.51	$+1.40, -0.30$	0.20
$1020 - 1024$	F_{S}	0.016	$+0.012, -0.009$	0.006
	$\delta_{\mathrm{S}} - \delta_\perp \, [\mathrm{rad}]$	-0.51	$+0.21, -0.35$	0.15
$1024 - 1032$	F_{S}	0.055	$+0.027, -0.025$	0.008
	$\delta_{\mathrm{S}} - \delta_\perp \, [\mathrm{rad}]$	-0.46	$+0.18, -0.26$	0.05
$1032 - 1050$	F_{S}	0.167	$+0.043, -0.042$	0.021
	$\delta_{\mathrm{S}} - \delta_\perp \, [\mathrm{rad}]$	-0.65	$+0.18, -0.22$	0.06

S-wave parameter systematics

Source	bin 1 F_S	bin 2 F_S	bin 3 F_S	bin 4 F_S	bin 5 F_S	bin 6 F_S
Stat. uncertainty	$+0.081$ -0.073	$+0.030$ -0.027	$+0.014$ -0.007	$+0.012$ -0.009	$+0.027$ -0.025	$+0.043$ -0.042
Background subtraction	0.014	0.003	0.001	0.002	0.004	0.006
$B^0 \to J/\psi K^{*0}$ background	0.010	0.006	0.001	0.001	0.002	0.018
Angular acc. reweighting	0.004	0.006	0.004	0.005	0.006	0.007
Angular acc. statistical	0.003	0.003	0.002	0.001	0.003	0.004
Fit bias	0.009	–	0.002	0.002	0.001	0.001
Quadratic sum of syst.	0.020	0.009	0.005	0.006	0.008	0.021
Total uncertainties	$+0.083$ -0.076	$+0.031$ -0.029	$+0.015$ -0.009	$+0.013$ -0.011	$+0.028$ -0.026	$+0.048$ -0.047

| Source	bin 1 $\delta_S - \delta_\perp$ [rad]	bin 2 $\delta_S - \delta_\perp$ [rad]	bin 3 $\delta_S - \delta_\perp$ [rad]	bin 4 $\delta_S - \delta_\perp$ [rad]	bin 5 $\delta_S - \delta_\perp$ [rad]	bin 6 $\delta_S - \delta_\perp$ [rad]
Stat. uncertainty	$+0.78$ -0.49	$+0.38$ -0.23	$+1.40$ -0.30	$+0.21$ -0.35	$+0.18$ -0.26	$+0.18$ -0.22
Background subtraction	0.03	0.02	–	0.03	0.01	0.01
$B^0 \to J/\psi K^{*0}$ background	0.08	0.04	0.08	0.01	0.01	0.05
Angular acc. reweighting	0.02	0.03	0.12	0.13	0.03	0.01
Angular acc. statistical	0.033	0.023	0.067	0.036	0.019	0.015
Fit bias	0.005	0.043	0.112	0.049	0.022	0.016
C_{SP} factors	0.007	0.028	0.049	0.025	0.021	0.020
Quadratic sum of syst.	0.09	0.08	0.20	0.15	0.05	0.06
Total uncertainties	$+0.79$ -0.50	$+0.39$ -0.24	$+1.41$ -0.36	$+0.26$ -0.38	$+0.19$ -0.26	$+0.19$ -0.23

Examples of NP effects

Little Higgs Model with T-Parity
[M. Blanke *et al*., Acta Phys.Polon.B41:657, 2 010]
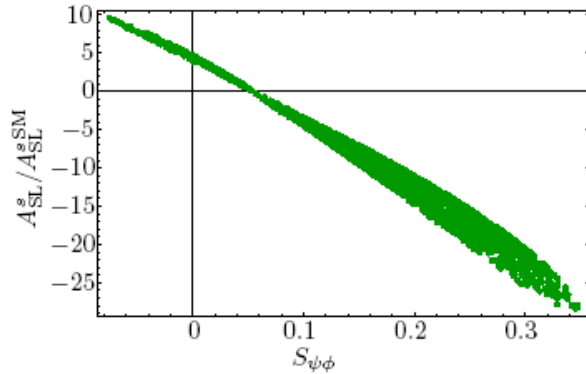
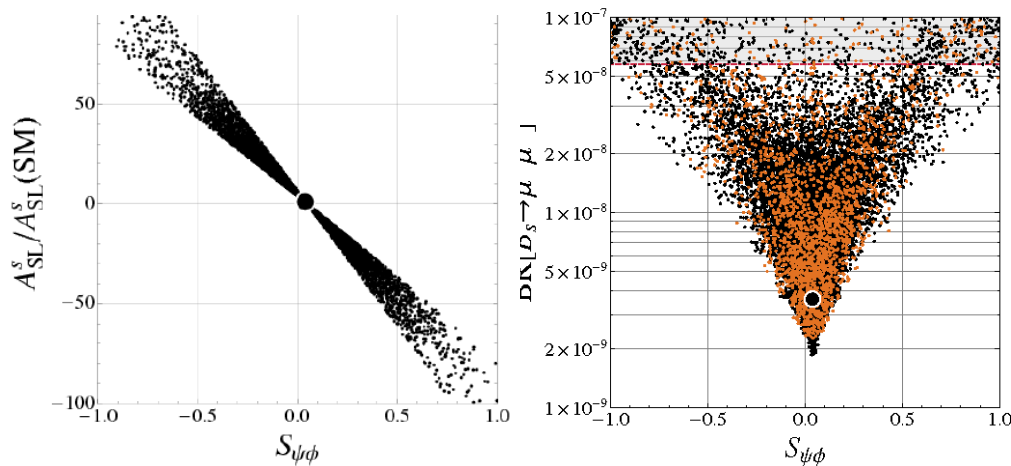Warped Extra Dimension Model
[M. Blanke *et al*., JHEP 0903:001,2009]
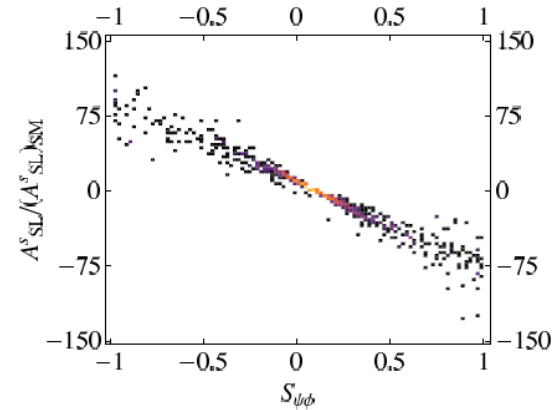
SUSY "AC" Model

MFV SUSY Model
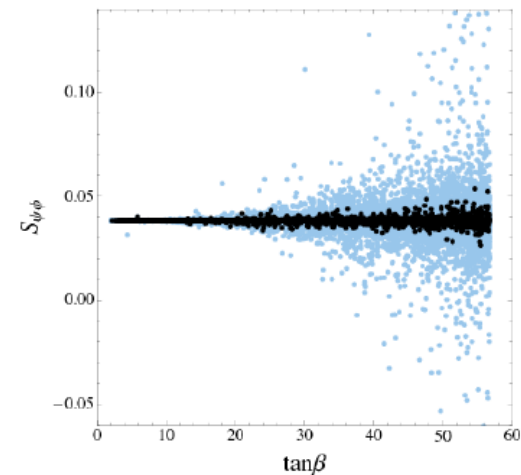
[W. Altmannshofer *et al*., arXiv:0909.1333]

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LHCb physics program

Y. Xie principal author

- Major physics objective: indirect search for new physics effects in loop-mediated processes
  - New physics in B_s mixing: ϕ_s, Γ_s, A_{SL}
  - New physics in $b \to s$ loop decays: $B_s \to \mu^+\mu^-$, $B^0 \to K^*\mu^+\mu^-$, $B_s \to \phi\gamma$, $B_s \to \phi\phi$ ...
  - New physics in D^0 mixing or decays: direct CPV in $D^0 \to K^+K^-/\pi^+\pi^-$, mixing parameters from $\tau(K^+K^-)$, $\tau(\pi^+\pi^-)$ and $\tau(K^+\pi^-)$, …
  - Precision test of CKM mechanism: γ measurements
- Also EW, exotics, spectroscopy, LFV, QCD …

B$_s$ mixing summary table

Y. Xie principal author

Observable	Measurement	Source	SM prediction	References
B_s^0 system				
Δm_s (ps^{-1})	17.719 ± 0.043	HFAG 2012 [43]	17.3 ± 2.6	[214–216]
	$17.725 \pm 0.041 \pm 0.026$	LHCb ($0.34\,\mathrm{fb}^{-1}$) [217]		
$\Delta\Gamma_s$ (ps^{-1})	0.105 ± 0.015	HFAG 2012 [43]	0.087 ± 0.021	[214–216]
	$0.116 \pm 0.018 \pm 0.006$	LHCb ($1.0\,\mathrm{fb}^{-1}$) [137]		
ϕ_s (rad)	$-0.044^{+0.090}_{-0.085}$	HFAG 2012 [43]	-0.036 ± 0.002	[118, 215, 216]
	$-0.002 \pm 0.083 \pm 0.027$	LHCb ($1.0\,\mathrm{fb}^{-1}$) [137]		
a_{sl}^s (10^{-4})	$-17 \pm 91^{+14}_{-15}$	D0 (no A_{SL}^b) [218]	$0.29^{+0.09}_{-0.08}$	[118, 215, 216]
	-105 ± 64	HFAG 2012 (including A_{SL}^b) [43]		
Admixture of B^0 and B_s^0 systems				
A_{SL}^b (10^{-4})	$-78.7 \pm 17.1 \pm 9.3$	D0 [158]	-2.0 ± 0.3	[214–216]
B^0 system				
Δm_d (ps^{-1})	0.507 ± 0.004	HFAG 2012 [43]	0.543 ± 0.091	[210, 215, 216]
$\Delta\Gamma_d/\Gamma_d$	0.015 ± 0.018	HFAG 2012 [43]	0.0042 ± 0.0008	[214–216]
$\sin 2\beta$	0.679 ± 0.020	HFAG 2012 [43]	$0.832^{+0.013}_{-0.033}$	[118, 215, 216]
a_{sl}^d (10^{-4})	-5 ± 56	HFAG 2012 [43]	$-6.5^{+1.9}_{-1.7}$	[118, 215, 216]

Detector performance in a nutshell

Integrated luminosity

2010:
    37 pb^{-1}
2011:
    1.0 fb^{-1}
2012:
    2 fb^{-1} (note number of digits)

Acceptance

pseudorapidity:
    $2 < \eta < 5$

Resolutions

momentum resolution:
    $\Delta p / p = 0.4\,\%$ at 5 GeV/c to 0.6 % at 100 GeV/c
ECAL resolution (nominal):
    $1\,\% + 10\,\% / \sqrt{(E[GeV])}$
impact parameter resolution:
    20 µm for high-pT tracks
invariant mass resolution:
    ~8 MeV/c^2 for $B \rightarrow J/\psi\, X$ decays with constraint on J/ψ mass
    ~22 MeV/c^2 for two-body B decays
    ~100 MeV/c^2 for $B_S \rightarrow \varphi\,\gamma$, dominated by photon contribution
decay time resolution:
    45 fs for $B_S \rightarrow J/\psi\,\varphi$ and for $B_S \rightarrow D_S\,\pi$

Efficiencies

percentage of working detector channels:
    ~ 99 % for all sub-detectors
data taking efficiency:
    > 90 %
data good for analyses:
    > 99 %
trigger efficiencies:
    ~ 90 % for dimuon channels
    ~ 30 % for multi-body hadronic final states
track reconstruction efficiency:
    > 96 % for long tracks
electron ID efficiency:
    ~ 90 % for ~ 5 % e→h mis-id probability
kaon ID efficiency:
    ~ 95 % for ~ 5 % π→K mis-id probability
muon ID efficiency:
    ~ 97 % for 1-3 % π→µ mis-id probability

Physics frontiers at the LHC

Energy frontier: ATLAS and CMS

Search for direct production of TeV level new particles

Quantum frontier: LHCb

Test CKM and search for new sources of CP violation

Explore physics up to 100 TeV

Study flavour changing processes and seek footprints of new particles in the quantum loops