Physics and recent results from LHCb

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On behalf of the LHCb Collaboration
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Outline

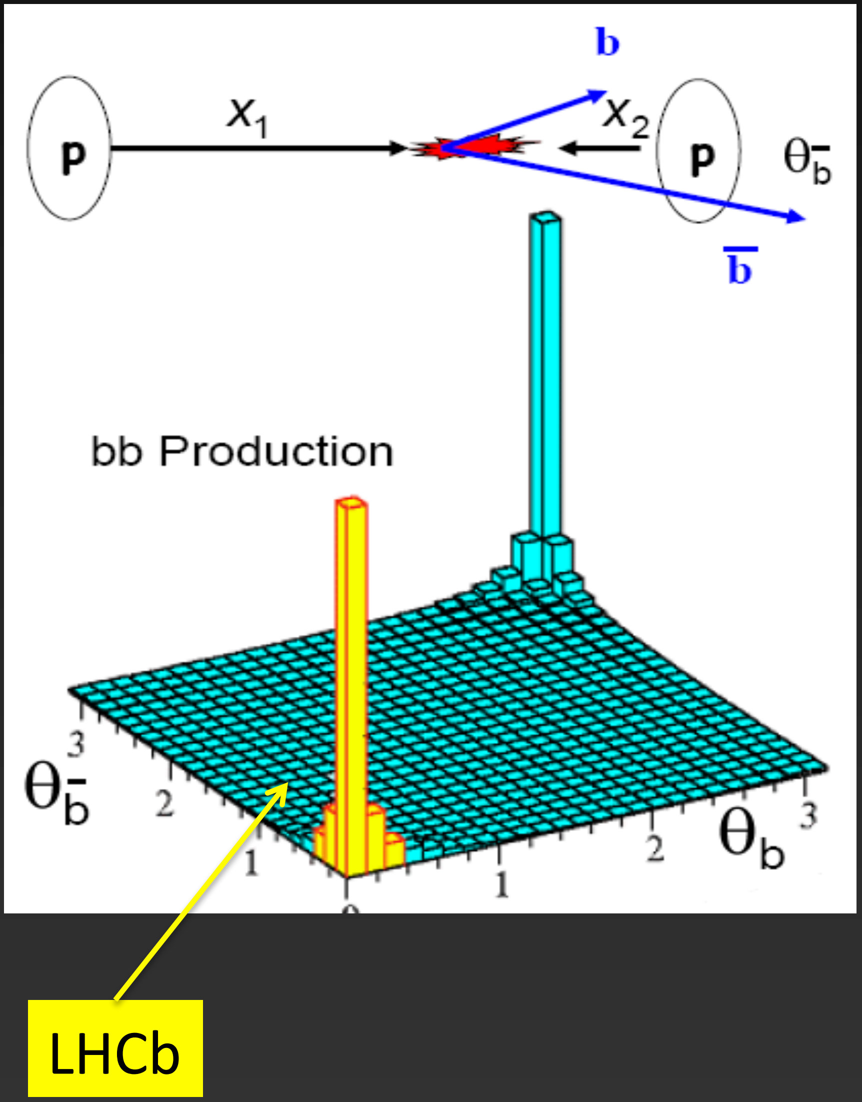
- The LHCb detector
- Physics at LHCb
- A Selection of results:
  - ★Rare decays: $B_{(S)} \to \mu\mu$
  - ★Mixing-induced CP violation in B_s decays
  - ★Charmless B decays
- Upgrade

LHCb

- LHC is a flavour factory !
- Large bb-production cross-section:

  $\sigma_{bb} = (288 \pm 4 \pm 48)\ \mu b$ (7 TeV)

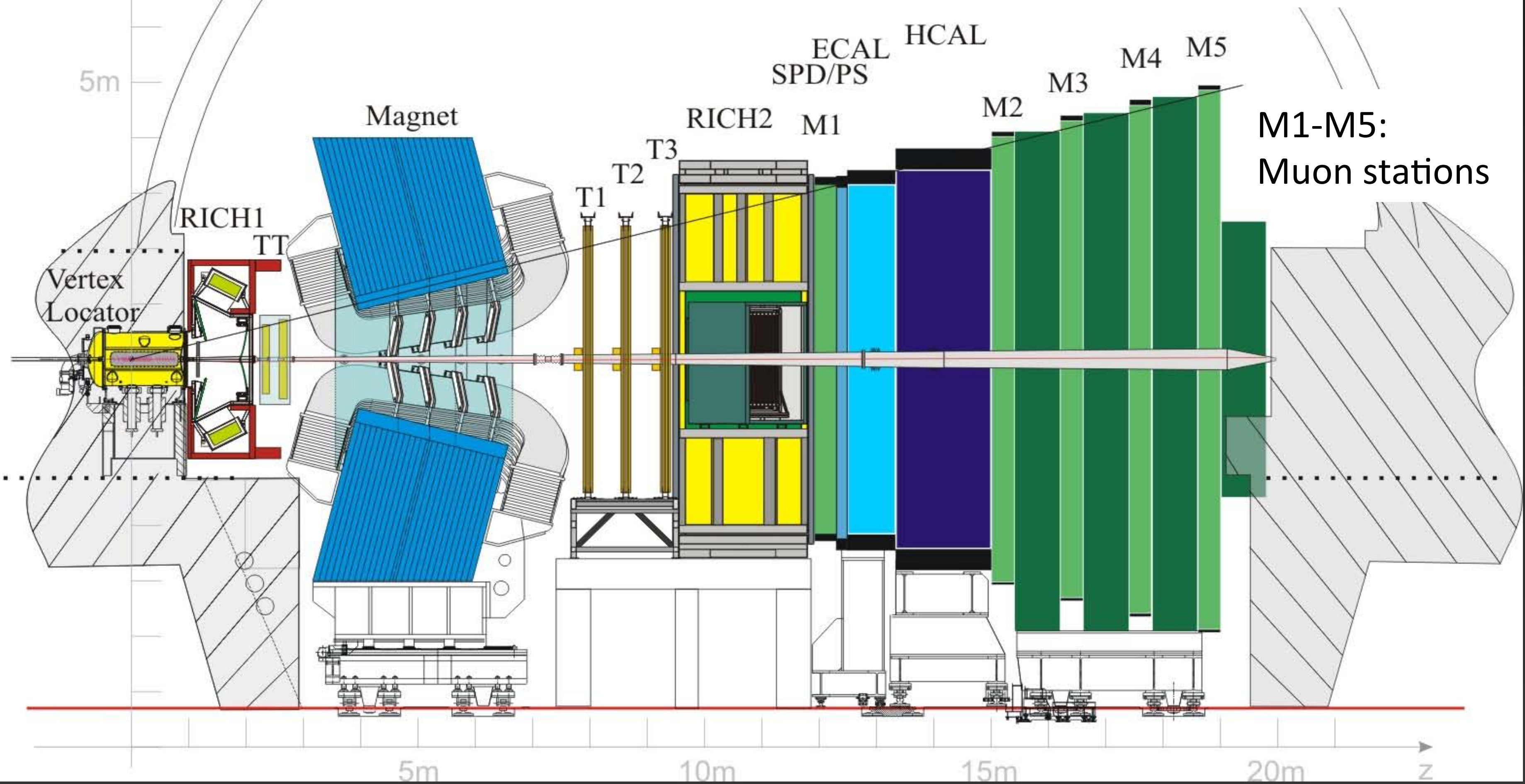
  (LHCb, Eur. Phys. J. C 71 (2011) 1645)
  - ★ correlated in forward/backward direction
  - ★ access to all b-hadrons: B_x , Λ_b etc.
- Large σ_{cc} : not only b-physics but also charm !



LHCb

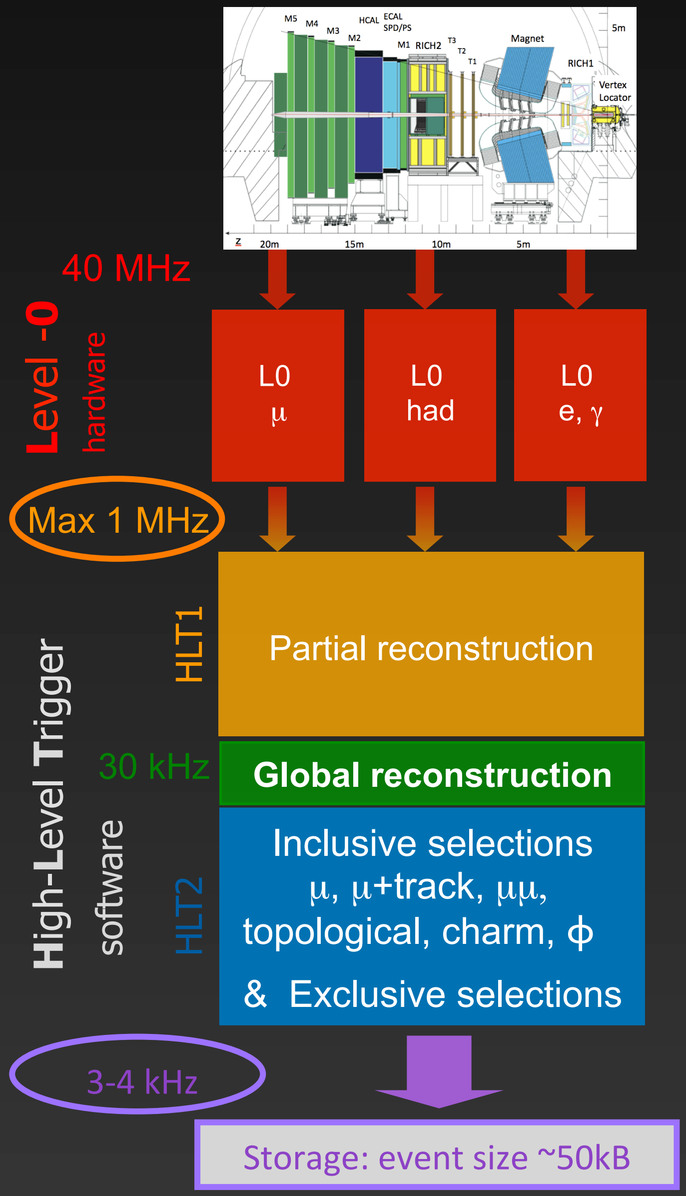
- LHCb: Forward spectrometer
- LHCb acceptance: $2 < \eta < 5$
  ATLAS/CMS: $|\eta| < 2.5$
- typical luminosity: 2-4 x 10^{32} cm^{-2} s^{-1}
- 3-5 x 10^{11} bb events / fb^{-1}

Mass resolutions 7-20 MeV
Muon ID ε = 97%; mis-id rate: 0.7%
Kaon ID ε > 90%; π mis ID < 5%
Time resolution 30-50 fs
Vertex resolution σ_{xy}~ 15µm; σ_z~ 80µm
Track $\Delta p/p$ < 0.4%-0.6%



M1-M5:
Muon stations

The LHCb trigger

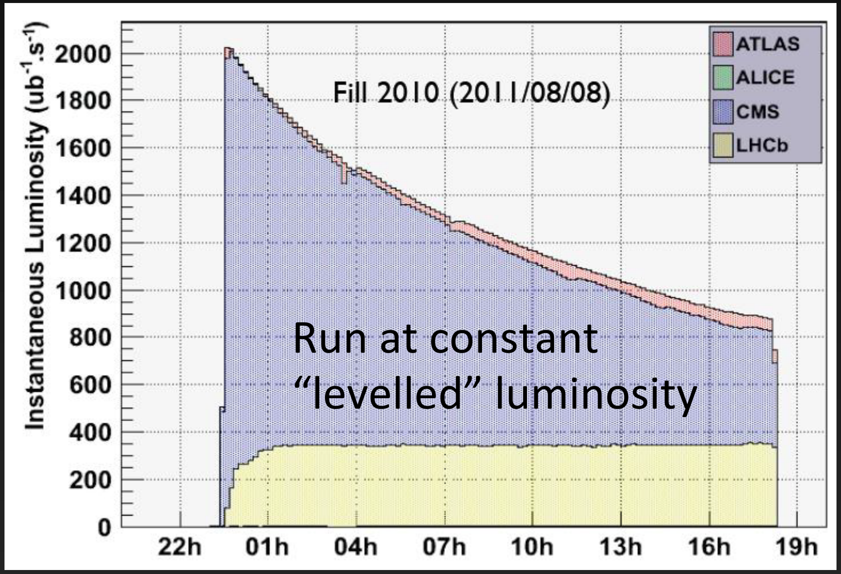


- Level-0 (hardware) trigger:
  - Search for high PT μ, h, e, γ candidates; typical cuts:

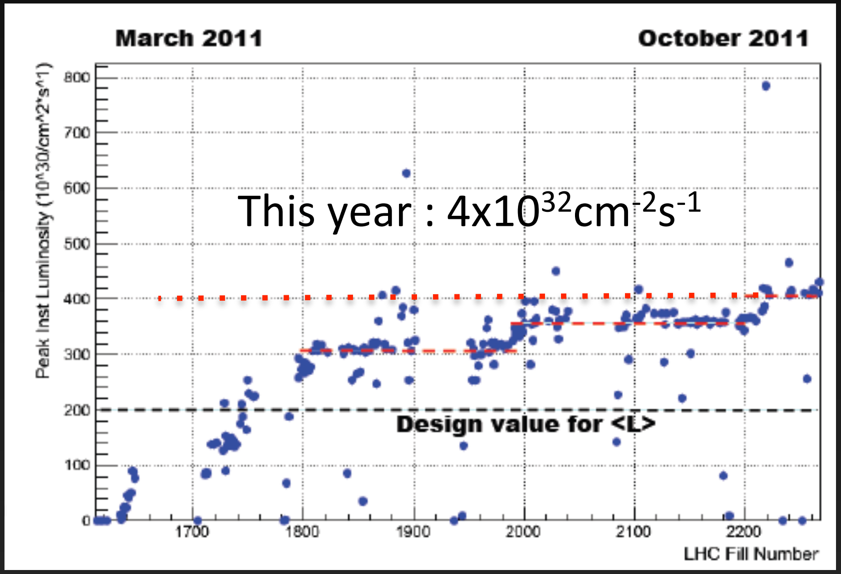
Trigger	had	μ	μμ	$e^{\pm}$	γ	π^0
p_T> (GeV)	3.5	1.4	Σ>1.5	2.6	2.3	4.5

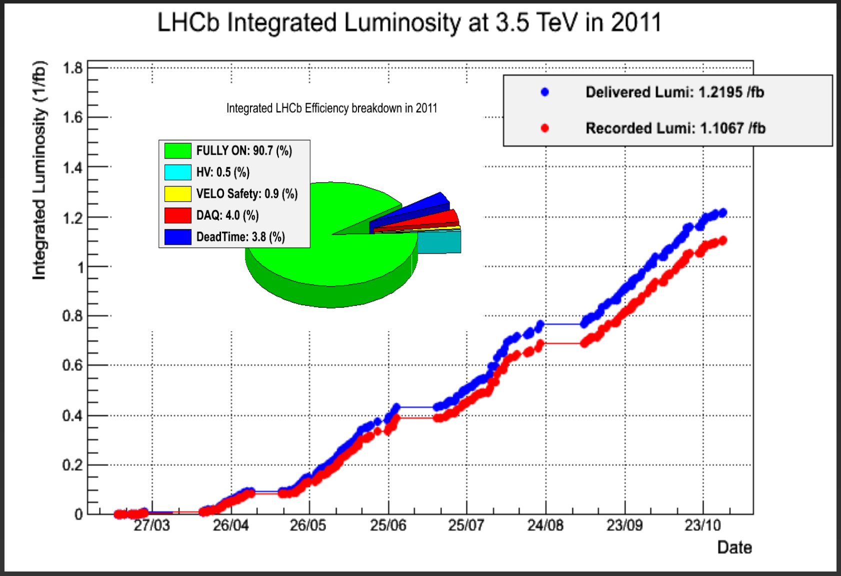
- Higher Level (software) triggers:
  - Event Filter Farm with ~1500 16-core nodes
  - HLT1: Look for high P_T displaced tracks
  - HLT2: Global event reconstruction + selections.
- Typical overall trigger efficiency:
  - ~30% for multibody hadronic
  - ~90% for dimuons.

Data taking

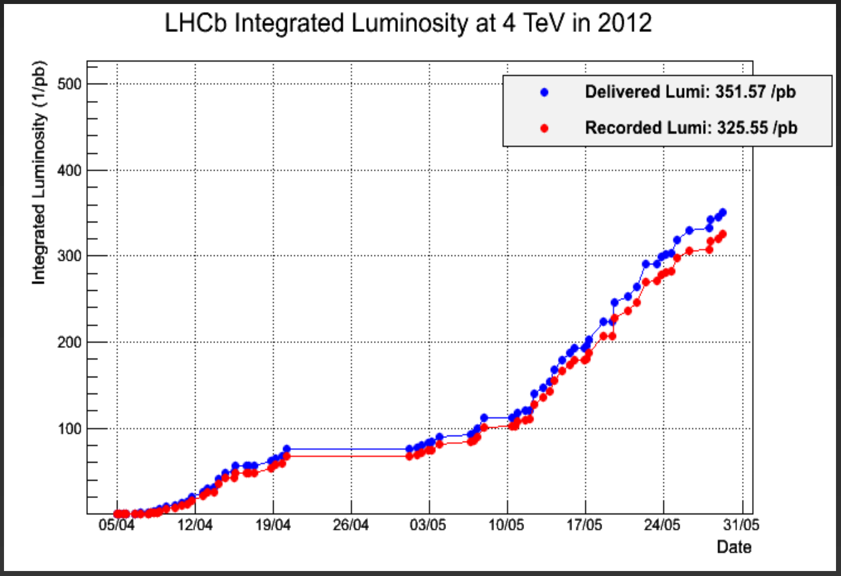


2011





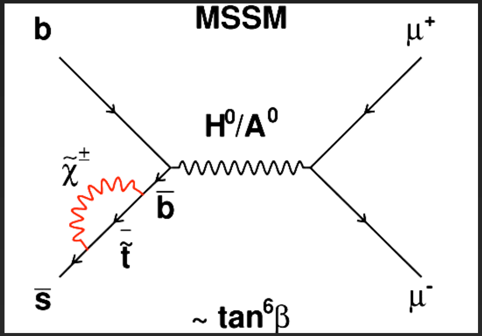
2012



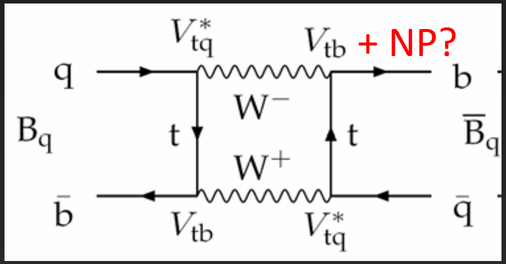
LHCb physics

- Search for potential effects of physics beyond the Standard Model in CP violation and rare decays using charm and beauty hadrons.

- Flavour physics observables have sensitivity to new particles at high mass scales via their indirect effects in loop diagrams



$B_{(s)} \rightarrow \mu\mu$



Phase ϕ_s

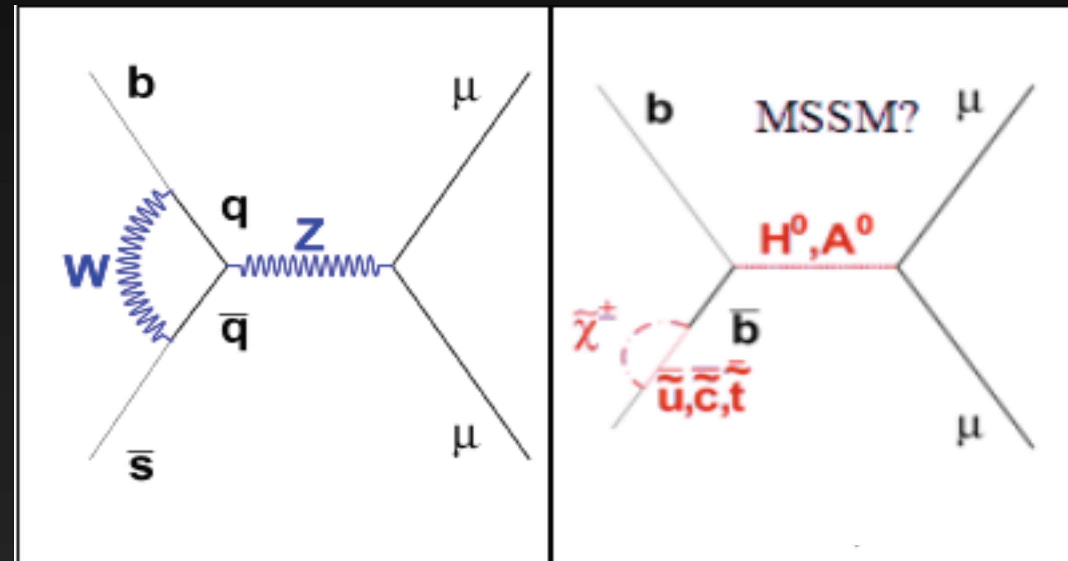
- Improve measurement precision of CKM elements:
  Compare measurements of same quantity, which may or may not be sensitive to NP
  - ★ Extract all CKM angles and sides in many different ways:
    any inconsistency will be a sign of New Physics

LHCb physics

- **B decays to charmonium**
  - ★ Bs mixing parameters
  - ★ CP violation measurements
  - ★ B → J/ψ X and related decays
- **B decays to open charm**
  - ★ CKM angle γ from B → D K family
  - ★ B decays to double charm
  - ★ Rare hadronic B decays
- **Rare decays**
  - ★ Leptonic, electroweak and radiative decays
  - ★ SM forbidden processes
- **Charm physics**
  - ★ Mixing and CP violation
  - ★ Open charm prod. & spectroscopy
  - ★ Rare charm decays
- **Charmless B decays**
  - ★ **Studies of B → h h(') and B → h h(')h(")**
  - ★ B → V V decays
  - ★ Rare charmless B decays
- **Semileptonic B decays**
  - ★ Search for CP violation in mixing
  - ★ Form factors
  - ★ Rare decays
- **B hadrons & quarkonia**
  - ★ Production and spectroscopy of B hadrons and quarkonia
  - ★ Exotic states (talk by Tomasz Skwarnicki)
- **QCD, electroweak & exotica**
  - ★ "Soft" & "hard" QCD
  - ★ Electroweak boson production, PDFs
  - ★ New long-lived particles

$B_{(s)} \to \mu\mu$: introduction

- Very rare FCNC decay
- $BR_{SM} = (3.2 \pm 0.2) \times 10^{-9}$
  (Buras et al., JHEP 10 (2010) 009)



- Can be strongly enhanced in many NP models: e.g. MSSM with large tanβ

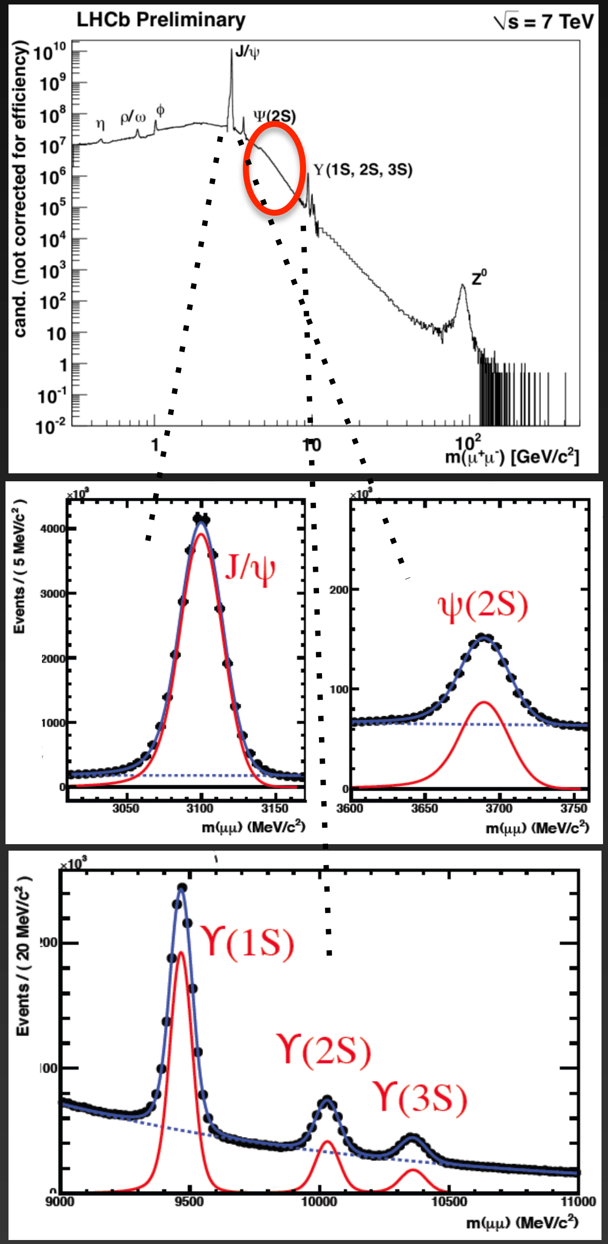
$$BR \propto \frac{\tan^6\beta}{M_A^4}$$

- LHCb has already published an upper limit based on 0.37 fb^{-1}. *(LHCb, PLB 708 (2012) 55)*

- **Present here new updated results based on 1 fb^{-1} of data from 2011**

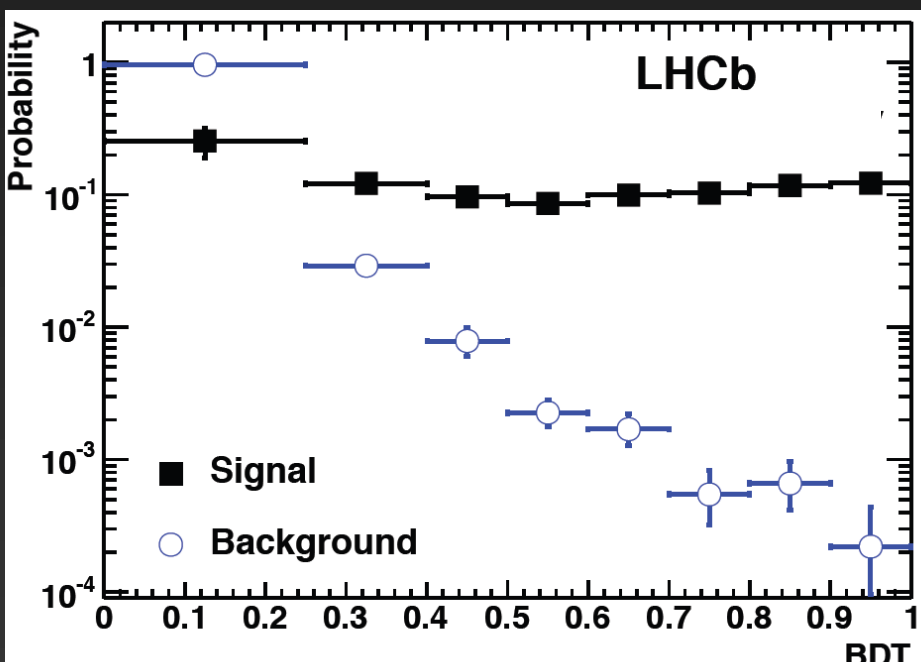
$B_{(s)} \rightarrow \mu\mu$: event selection

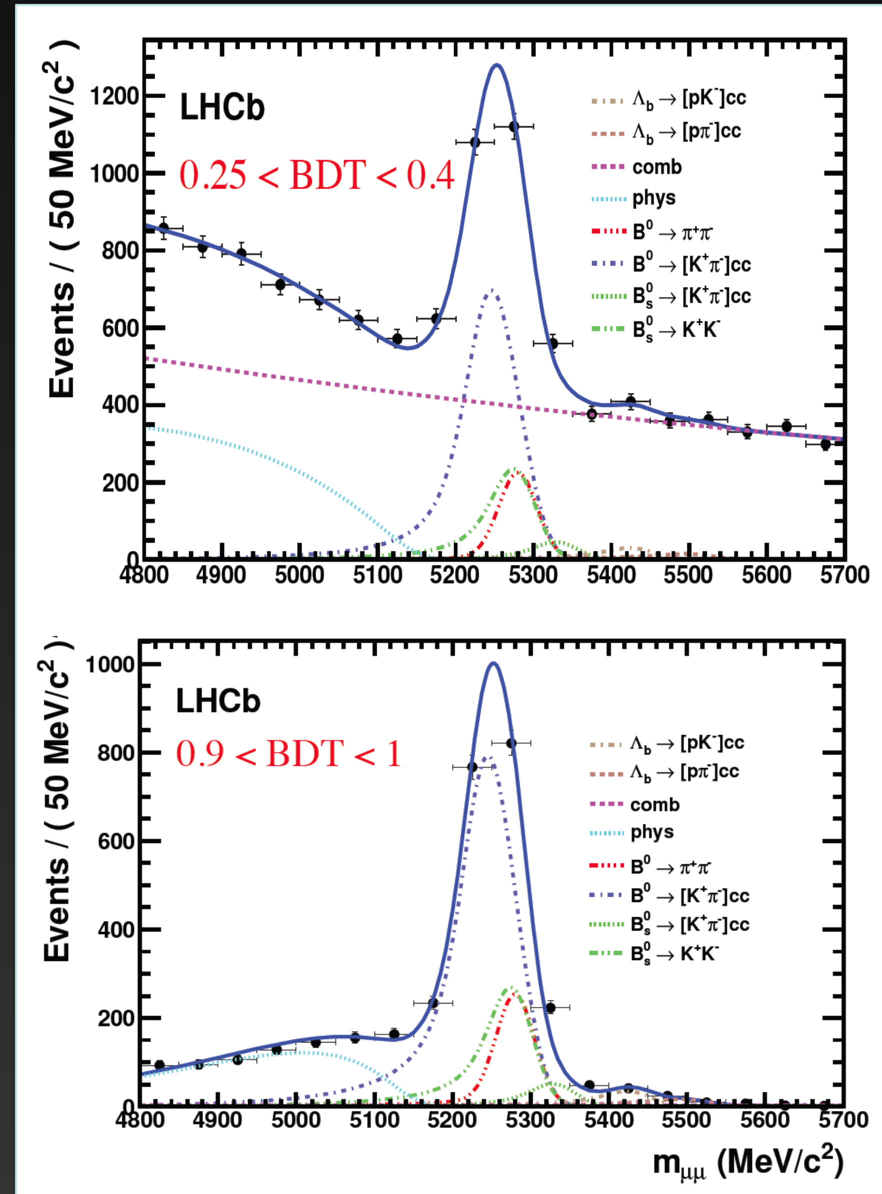
- Signal easy to trigger and reconstruct; however **background rejection is an issue !**
- After simple dimuon selection, the analysis relies on two variables:
  - ★ dimuon mass
  - ★ multivariate discriminant BDT (Boosted Decision Tree) on kinematics and topology
- Mass calibration:
  - ★ central value from $B_s \rightarrow K^+K^-$
  - ★ resolution from linear interpolation of ψ(1S,2S), ϒ(1S,2S,3S)
- $\sigma(m_{Bs}) = 24.8 \pm 0.3 \pm 0.7$ MeV/c^2
  - ★ cross checked also with B->hh control channels
- Blind analysis!



$B_{(s)} \to \mu\mu$: analysis

- BDT is calibrated with data:
- signal: $B_{(s)} \to h^+h'^-$ selected without PID requirements
- background: candidates in Bs mass sidebands





$B_{(s)} \to \mu\mu$: normalization

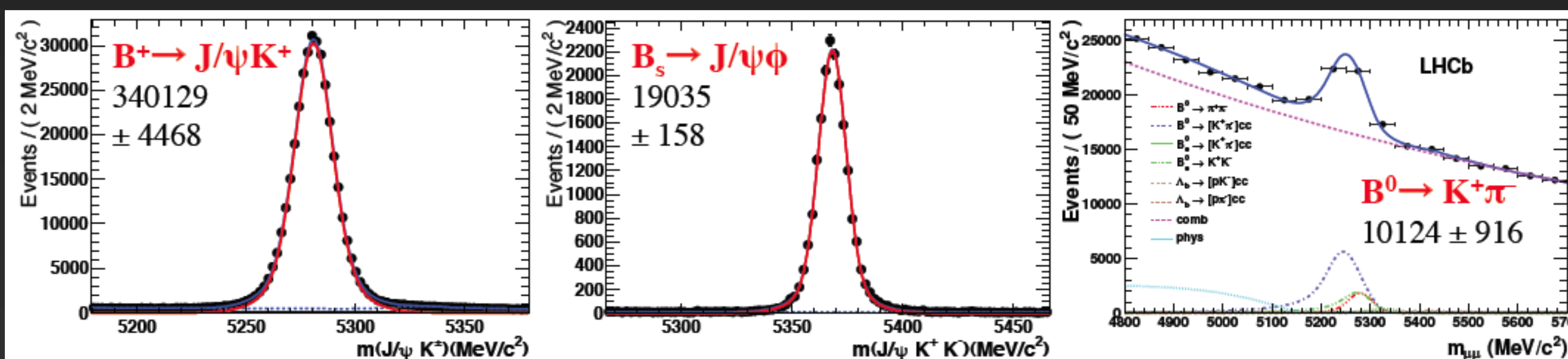
- Brancing fraction normalization:

$$BR_{B_s^0\to\mu\mu} = BR_{norm} \times \frac{N_{B_s^0\to\mu\mu}}{N_{norm}} \times \frac{\varepsilon_{norm}}{\varepsilon_{B_s^0\to\mu\mu}} \times \frac{f_{norm}}{f_s} = \alpha^{norm}_{B_s^0\to\mu\mu} \times N_{B_s^0\to\mu\mu}$$

$$f_s/f_d = 0.267^{+0.021}_{-0.020}$$

measured directly by LHCb
(arXiv:1111.2357, to appear on PRD; Phys. Rev. Lett. 107 (2011) 211801)

- 3 different normalization channels…



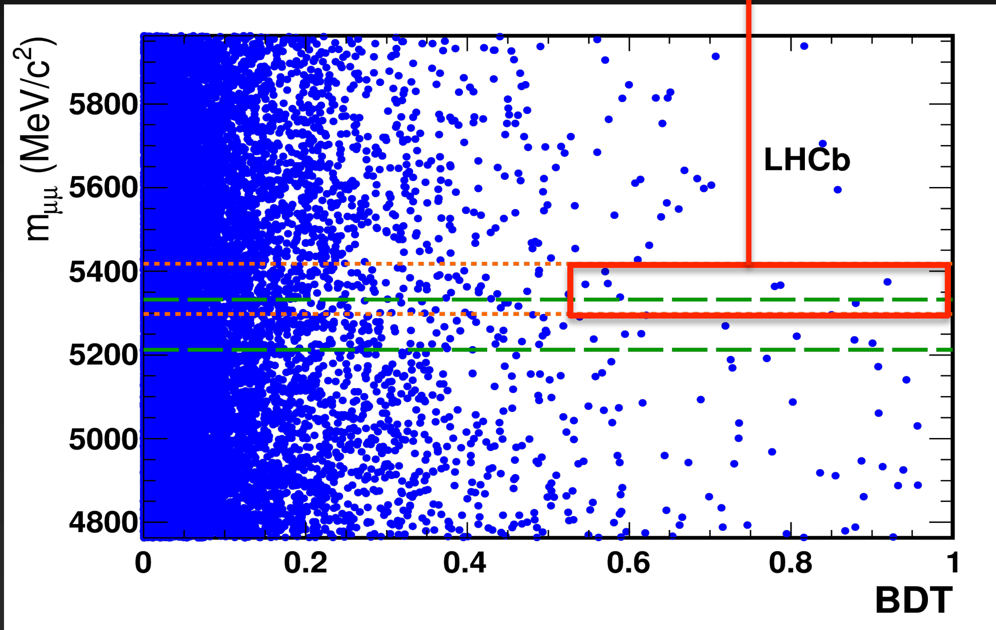
- …give consistent normalization factors; wheighted average gives the **single-event sensitivity:**

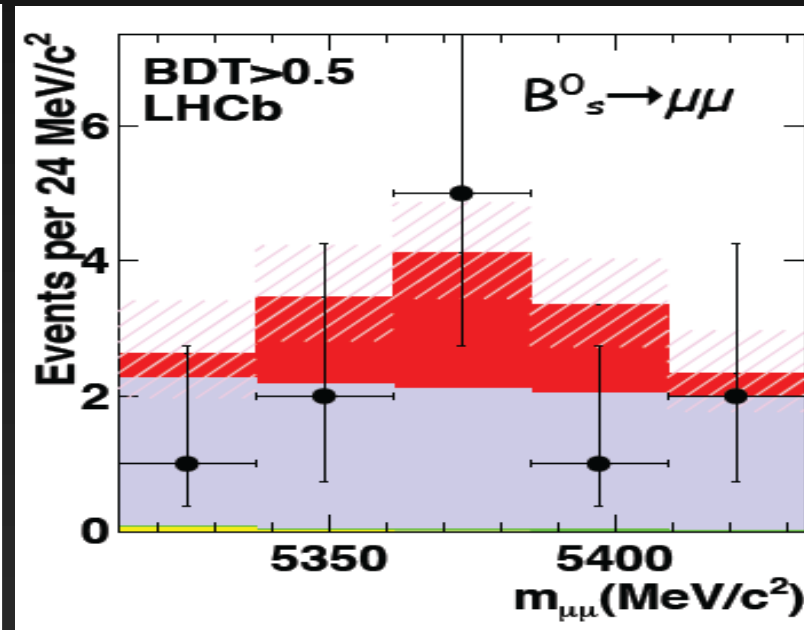
$$\alpha^{norm}_{B_s^0\to\mu\mu} = (0.319 \pm 0.028) \times 10^{-9}$$

$B_{(s)} \to \mu\mu$: results

After unblinding....

$B_s \to \mu\mu$ signal region





Expected combinatorial background

Expected $B \to hh'$ background

Expected $B_s \to \mu\mu$ SM signal

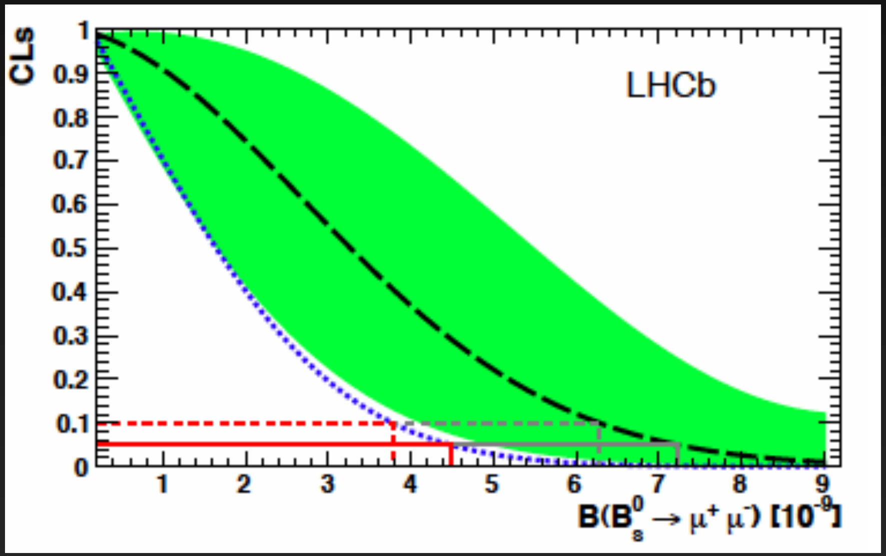
Uncertainty on expectations

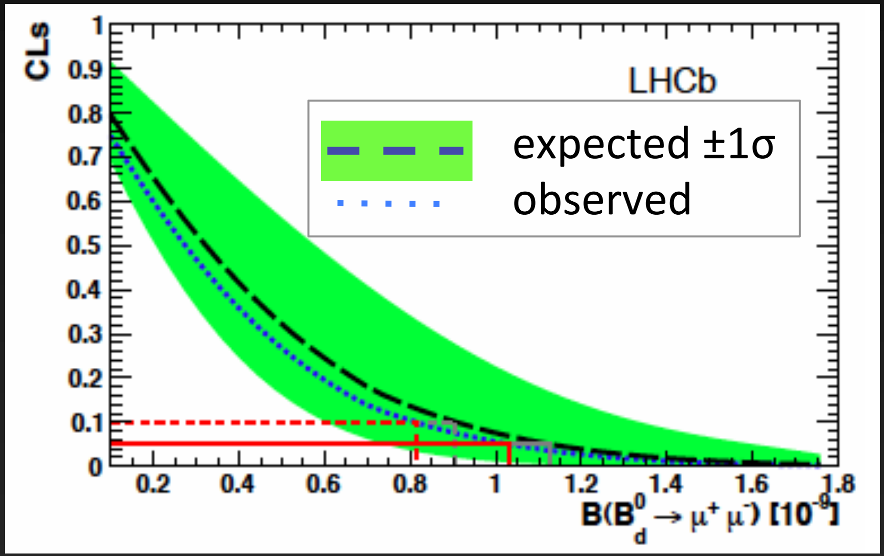
Mass vs BDT :

- 8 bins in BDT and 9 bins in mass
- Estimate signal and background events in each bin using CLs method.

$B_{(s)} \to \mu\mu$: results

arXiv:1203.4493, to appear in PRL





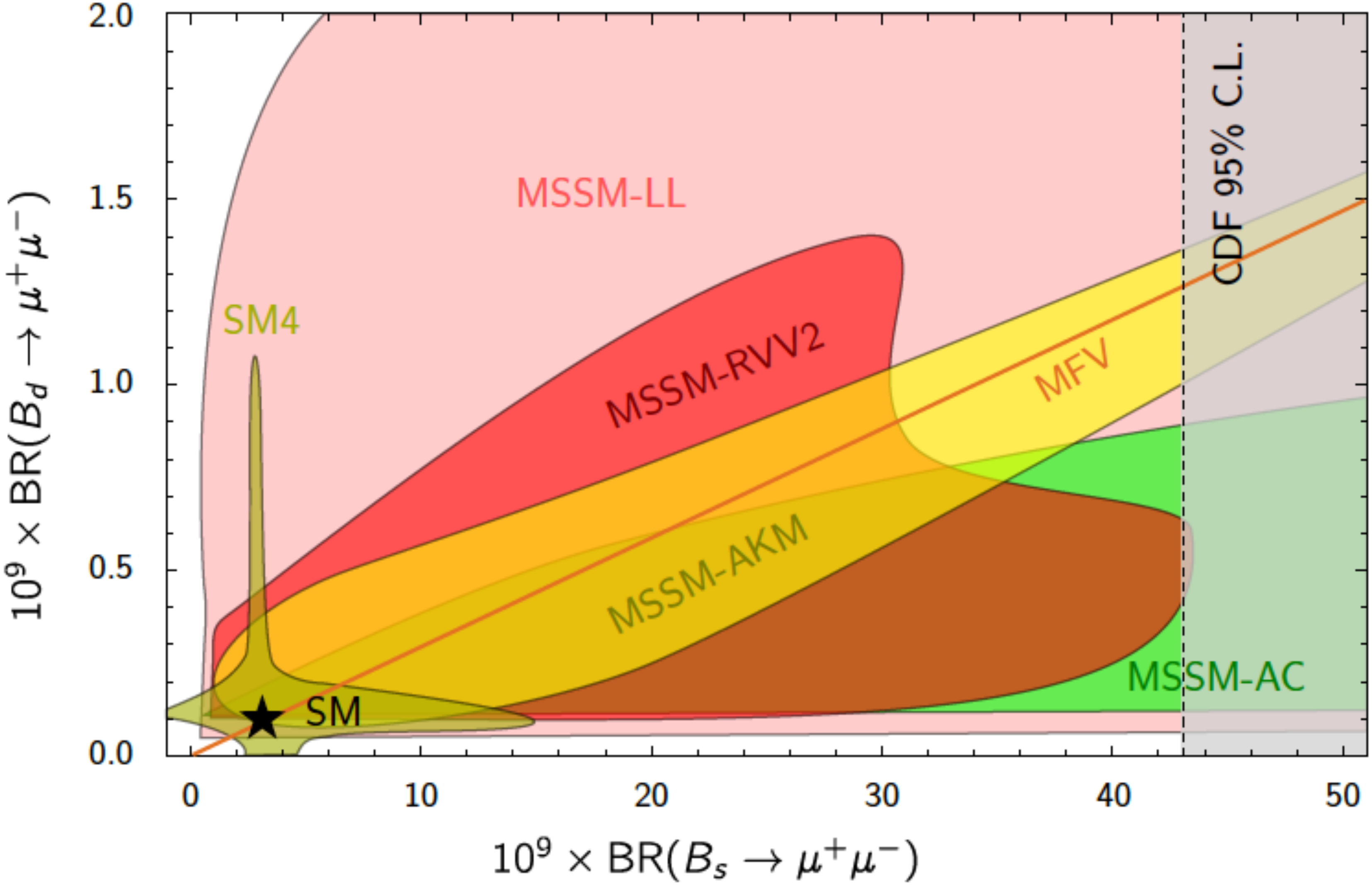
@95% CL: $BR(B_s \to \mu\mu) < 4.5 \times 10^{-9}$ $BR(B^0 \to \mu\mu) < 1.03 \times 10^{-9}$

- New published results from LHCb with 1 fb^{-1}

		CDF	ATLAS	CMS	LHCb	SM
	Luminosity (fb^{-1})	10	2.4	2.4	**1.0**	
$BR(B^0 \to \mu\mu)$	95%CL upper limit ($\times 10^{-9}$)	4.6		1.8	**1.03**	**0.10±0.1**
$BR(B_s \to \mu\mu)$	95%CL upper limit ($\times 10^{-9}$) Value ($\times 10^{-9}$)	31 13^{+9}_{-7}	22	7.7	**4.5** **$0.8^{+1.8}_{-1.3}$**	**3.2±0.2**

Consequences of $B_{(s)} \to \mu\mu$ measurements: before LHCb

David M. Straub, XLVII Rencontres de Moriond Electroweak Sesion, March 7, 2012



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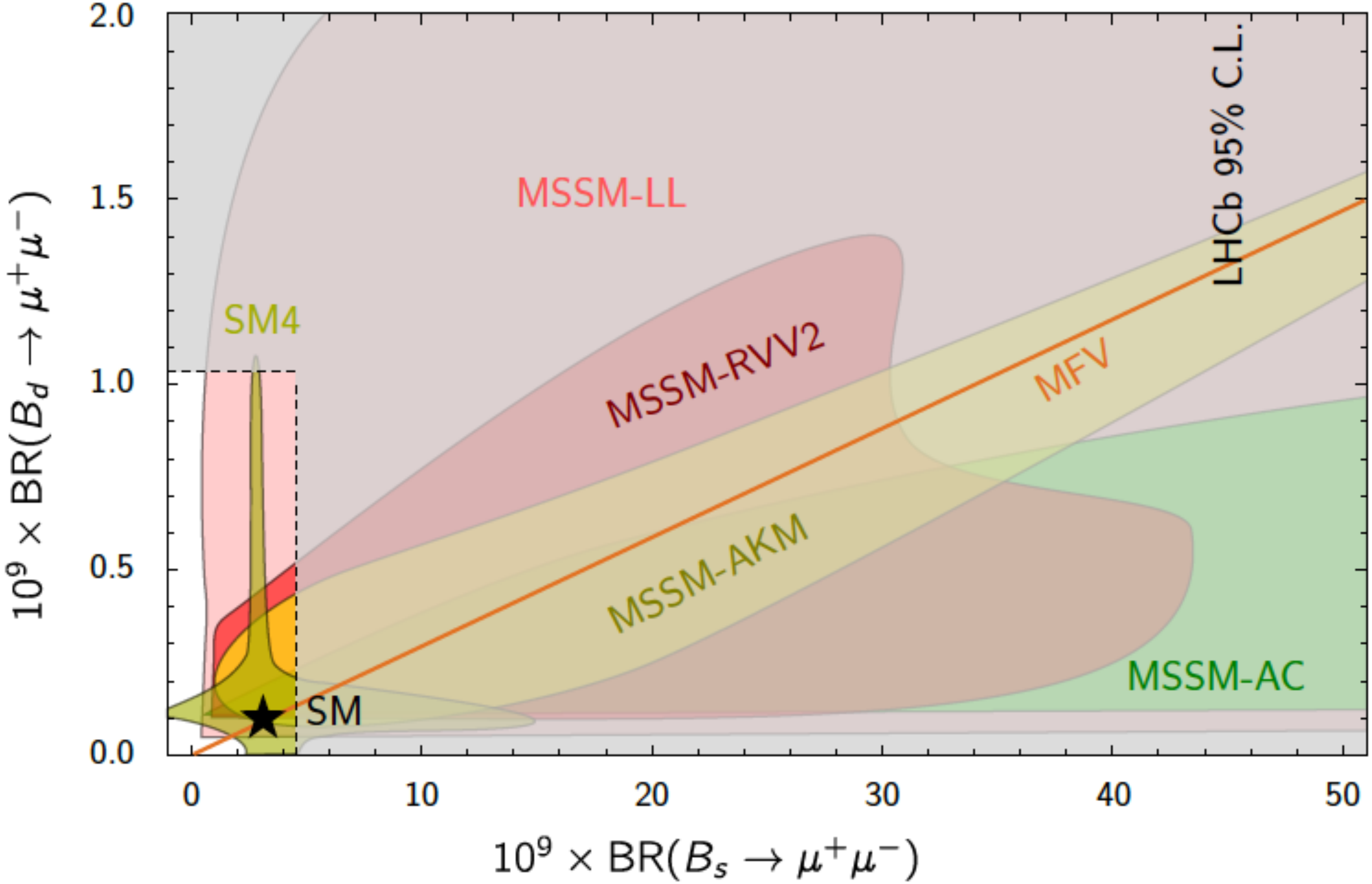
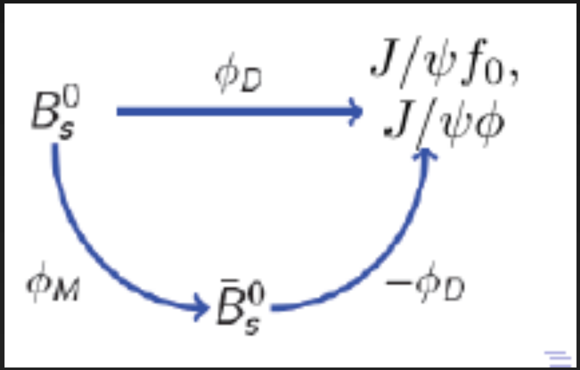


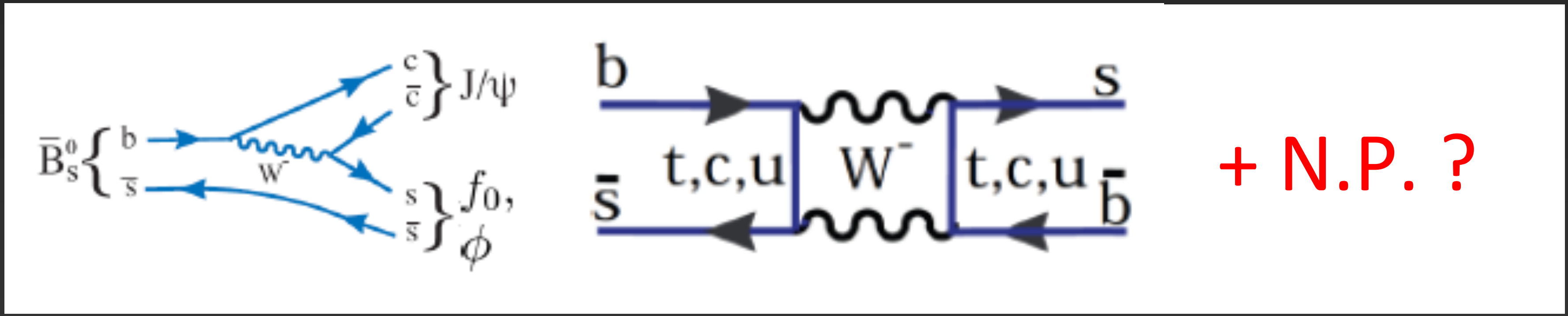
CPV in B_s decays

- CP violation from interference between Bs mixing and decay to the same final state: $\phi_s = \phi_M - 2\phi_D$



- SM predicts a small calue with high precision:
  $\phi_s^{SM} = -2\beta_s = -0.036\pm0.002$ *(PRD 84 (2011) 033005)*
- Mixing phase Sensitive to NP:
  $\phi_s = \phi_s^{SM} + \phi_s^{NP}$

- **Present here the latest measurements of ϕ_s from $B_s \to J/\psi\phi$ and $B_s \to J/\psi\pi\pi$ with 1 fb $^{-1}$ data collected in 2011.**



Ingredients for the measurement

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

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

k	$f_k(\theta,\psi,\varphi)$	N_k	a_k	b_k	c_k	d_k
1	$2\cos^2\psi\,(1-\sin^2\theta\cos^2\phi)$	$\lvert A_0(0)\rvert^2$	1	$-\cos\phi_s$	0	$\sin\phi_s$
2	$\sin^2\psi\,(1-\sin^2\theta\sin^2\phi)$	$\lvert A_\parallel(0)\rvert^2$	1	$-\cos\phi_s$	0	$\sin\phi_s$
3	$\sin^2\psi\sin^2\theta$	$\lvert A_\perp(0)\rvert^2$	1	$\cos\phi_s$	0	$-\sin\phi_s$
4	$-\sin^2\psi\sin 2\theta\sin\phi$	$\lvert A_\parallel(0)A_\perp(0)\rvert$	0	$-\cos(\delta_\perp-\delta_\parallel)\sin\phi_s$	$\sin(\delta_\perp-\delta_\parallel)$	$-\cos(\delta_\perp-\delta_\parallel)\cos\phi_s$
5	$\frac{1}{2}\sqrt{2}\sin 2\psi\sin^2\theta\sin 2\phi$	$\lvert A_0(0)A_\parallel(0)\rvert$	$\cos(\delta_\parallel-\delta_0)$	$-\cos(\delta_\parallel-\delta_0)\cos\phi_s$	0	$\cos(\delta_\parallel-\delta_0)\sin\phi_s$
6	$\frac{1}{2}\sqrt{2}\sin 2\psi\sin 2\theta\cos\phi$	$\lvert A_0(0)A_\perp(0)\rvert$	0	$-\cos(\delta_\perp-\delta_0)\sin\phi_s$	$\sin(\delta_\perp-\delta_0)$	$-\cos(\delta_\perp-\delta_0)\cos\phi_s$
7	$\frac{2}{3}(1-\sin^2\theta\cos^2\phi)$	$\lvert A_S(0)\rvert^2$	1	$\cos\phi_s$	0	$-\sin\phi_s$
8	$\frac{1}{3}\sqrt{6}\sin\psi\sin^2\theta\sin 2\phi$	$\lvert A_S(0)A_\parallel(0)\rvert$	0	$-\sin(\delta_\parallel-\delta_S)\sin\phi_s$	$\cos(\delta_\parallel-\delta_S)$	$-\sin(\delta_\parallel-\delta_S)\cos\phi_s$
9	$\frac{1}{3}\sqrt{6}\sin\psi\sin 2\theta\cos\phi$	$\lvert A_S(0)A_\perp(0)\rvert$	$\sin(\delta_\perp-\delta_S)$	$\sin(\delta_\perp-\delta_S)\cos\phi_s$	0	$-\sin(\delta_\perp-\delta_S)\sin\phi_s$
10	$\frac{4}{3}\sqrt{3}\cos\psi(1-\sin^2\theta\cos^2\phi)$	$\lvert A_S(0)A_0(0)\rvert$	0	$-\sin(\delta_0-\delta_S)\sin\phi_s$	$\cos(\delta_0-\delta_S)$	$-\sin(\delta_0-\delta_S)\cos\phi_s$

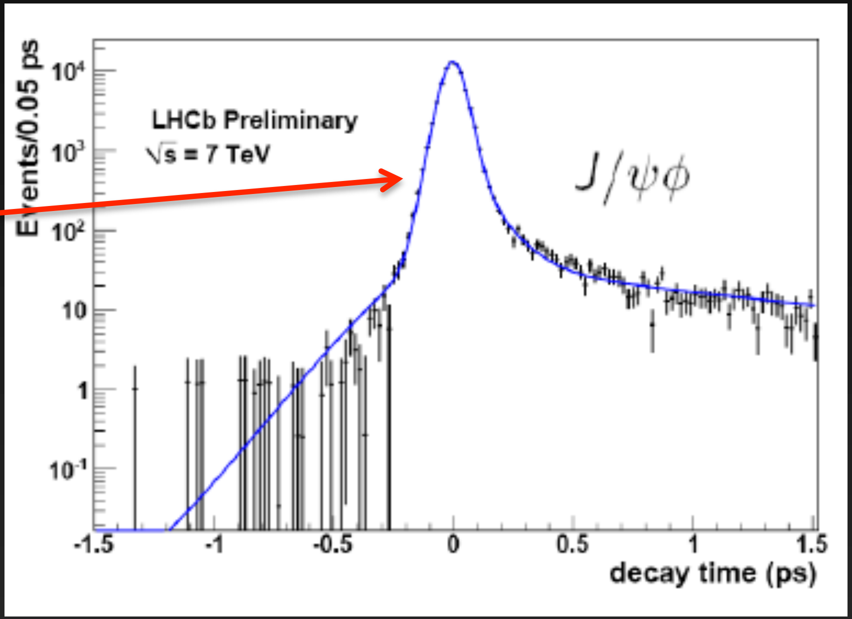
Only this term for $B_s \to J/\psi\pi\pi$

Used to determine the sign of $\Delta\Gamma_s$

- Full angular analysis for **$B_s \to J/\psi\phi$**;
  $B_s \to J/\psi\pi\pi$ is almost purely CP odd ⇒ no angular anaysis needed.
- Measure time dependent amplitudes ⇒ need Δm_s ⇒ excellent time resolution
  Tag B_s flavor: flavor tagging
- 10 physical parameters : Γ_s, $\Delta\Gamma_s$, φ_s, Δm_s 3 amplitude ratios, 3 strong phase differences

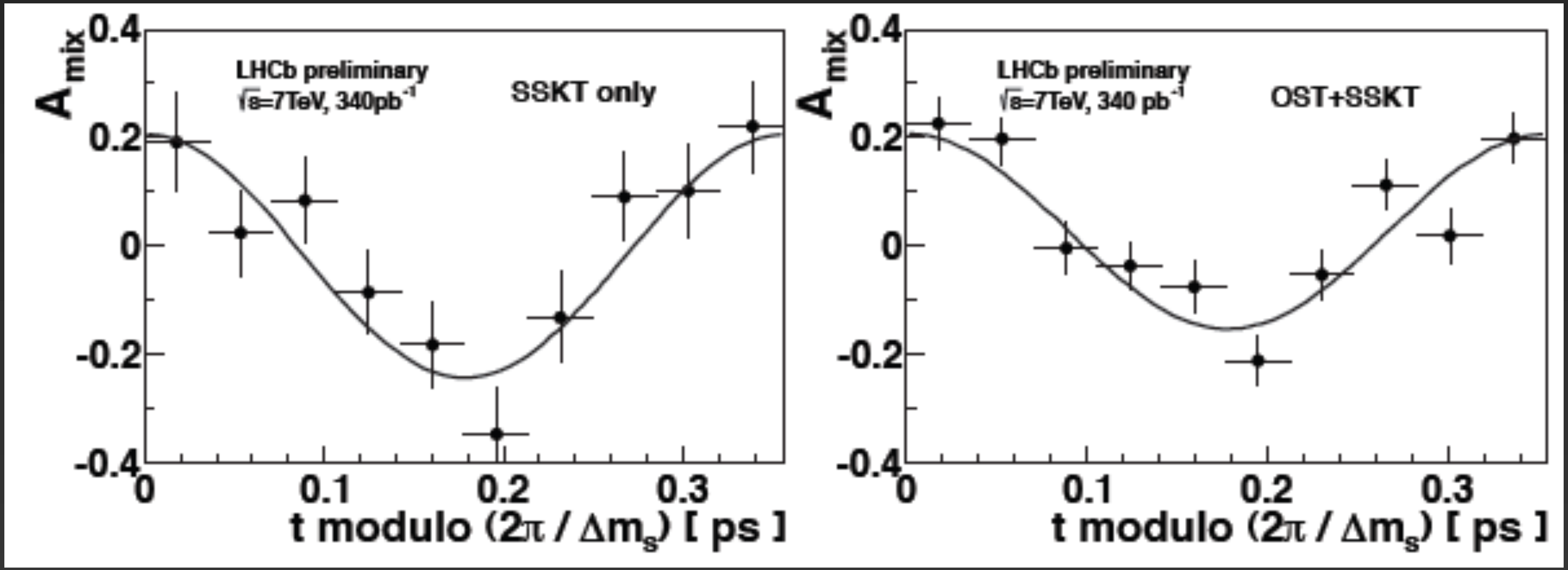
Flavor tagging, time resolution, Δm_s

- Effective tagging power using both SSKT and OST: $\varepsilon_{tag} D^2 = (2.43 \pm 0.08 \pm 0.26)\%$ *(arXiv:1204.5675)*
- Time resolution 45 fs



Two independent measurements of Δm_s

- $\Delta m_s = 17.63 \pm 0.11 \pm 0.02\ ps^{-1}$ *(Phys Lett. B709 (2012) 177).*
- $\Delta m_s = 17.725 \pm 0.041 \pm 0.026\ ps^{-1}$ *(LHCb-CONF-2011-050)*



Signal event samples

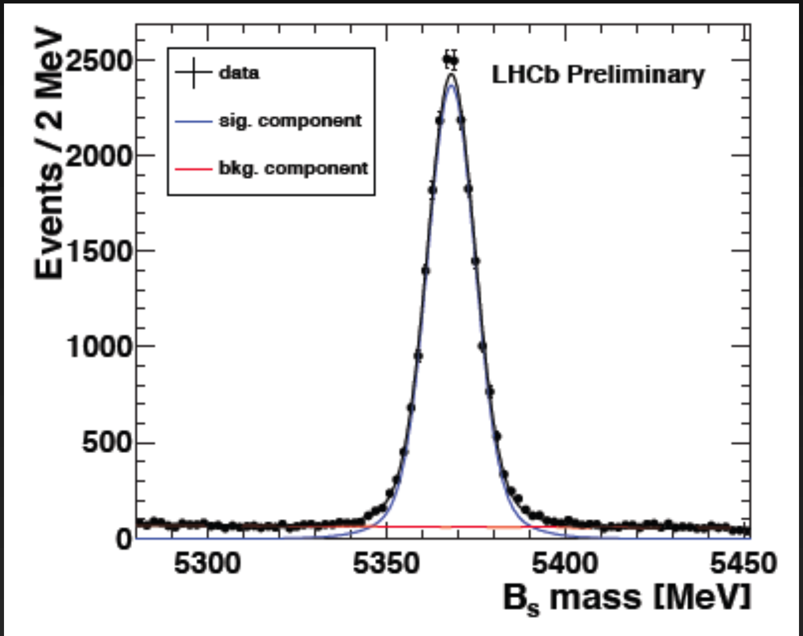
Very clean signals

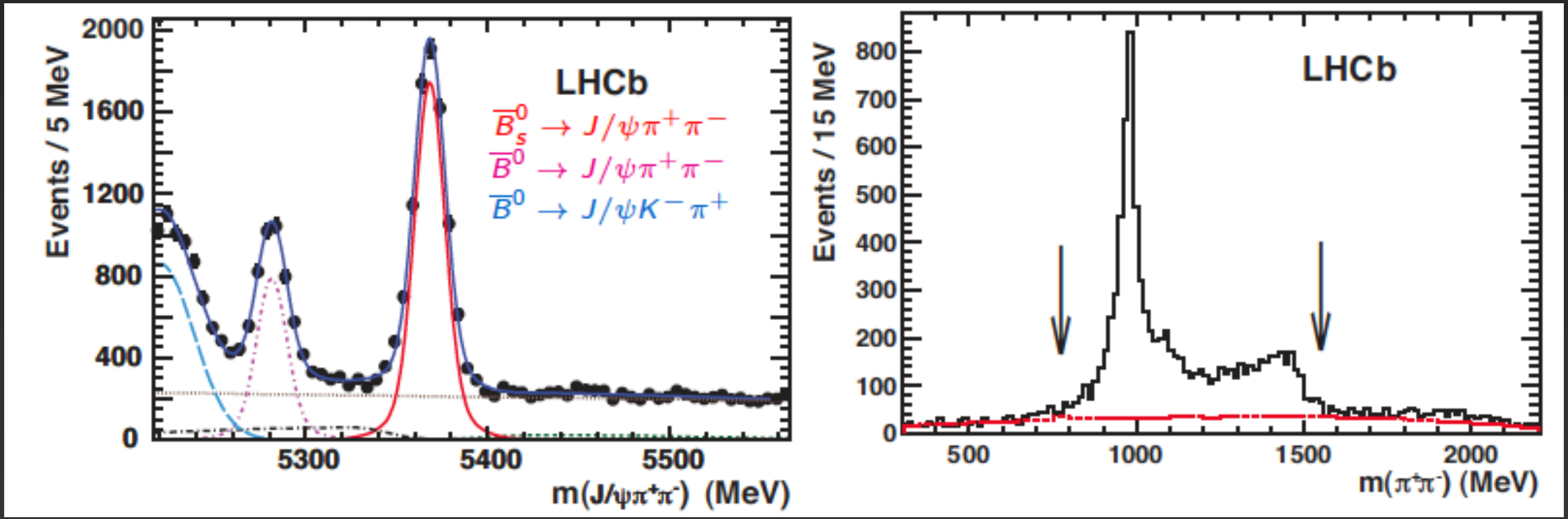
Selected Bs →J/ϕ candidates:

- ~ 21200 signal events (1 fb–1)
- ~ 8 MeV/c² mass resolution

Enlarged $m_{\pi\pi}$ range wrt to previous analysis *(LHCb, PLB 707 (2012) 497)*

- 7421 ± 105 signal and 1717 ± 38 background events within ±20 MeV of $m(B_s)$

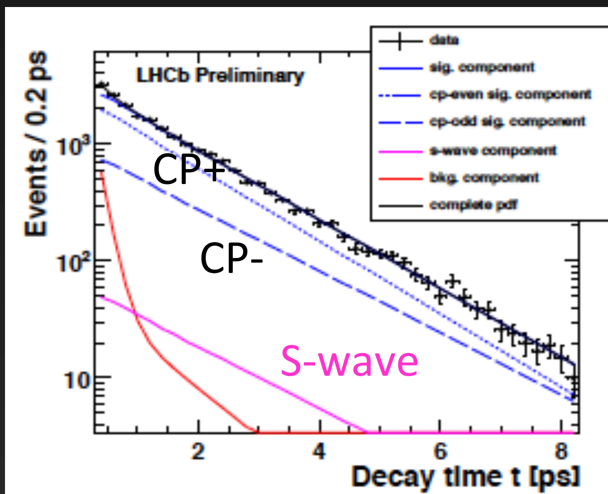


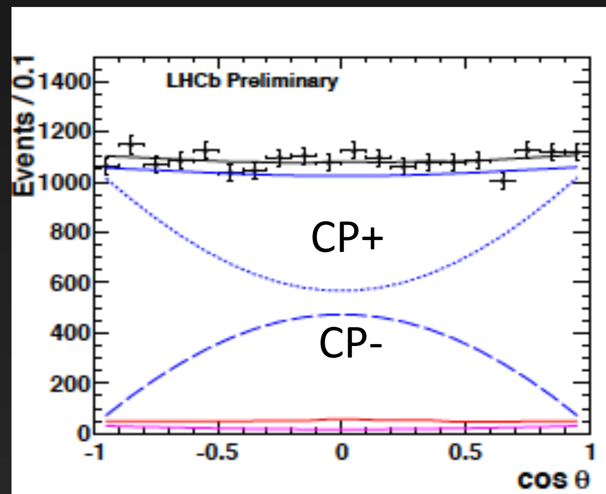


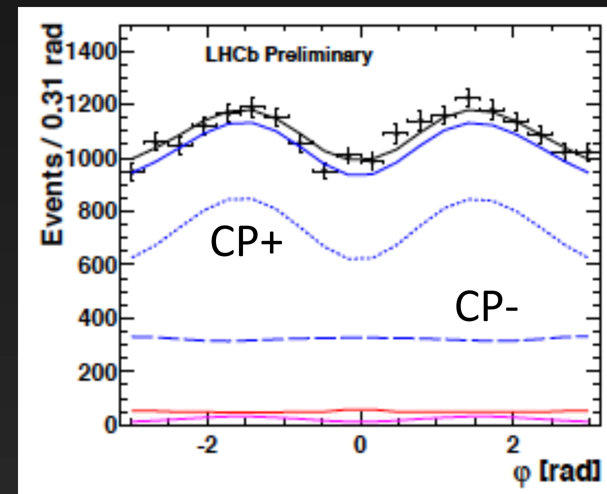
Bs →J/ψϕ angular analysis

- P-wave CP-even (CP+) and CP-odd (CP-) components very cleanly separated.
- S-wave contribution (CP-odd) well visible

(LHCb-CONF-2012-002)

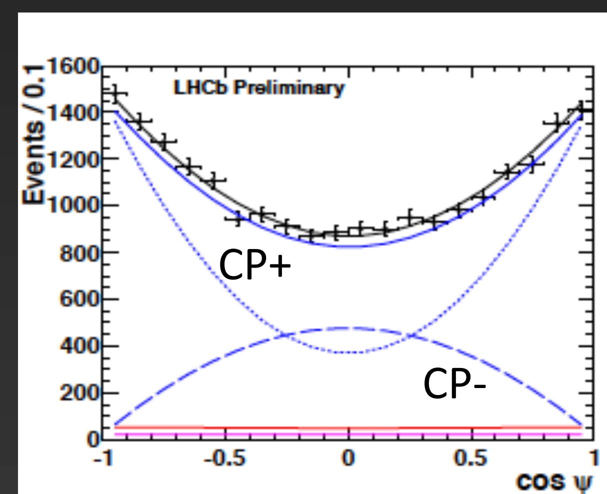




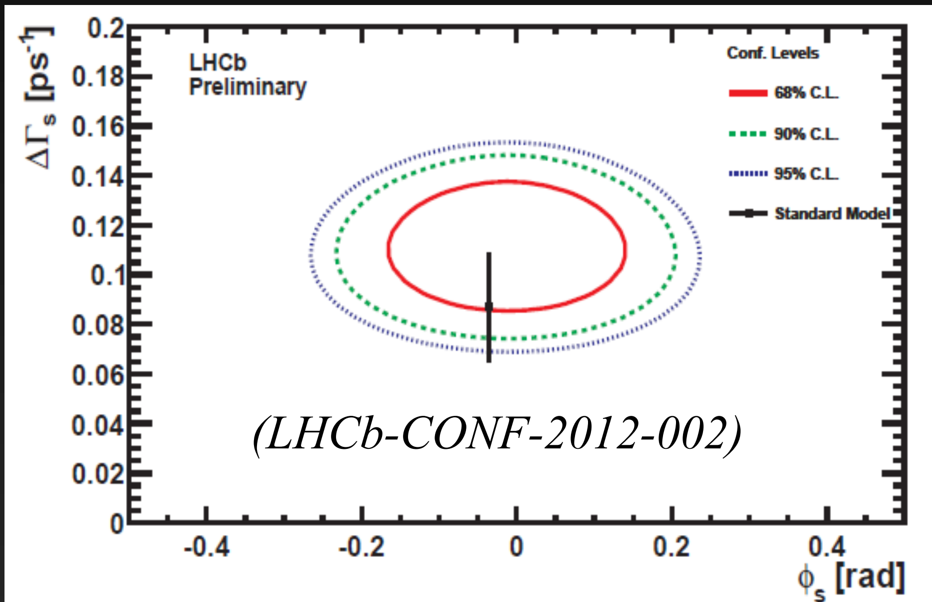


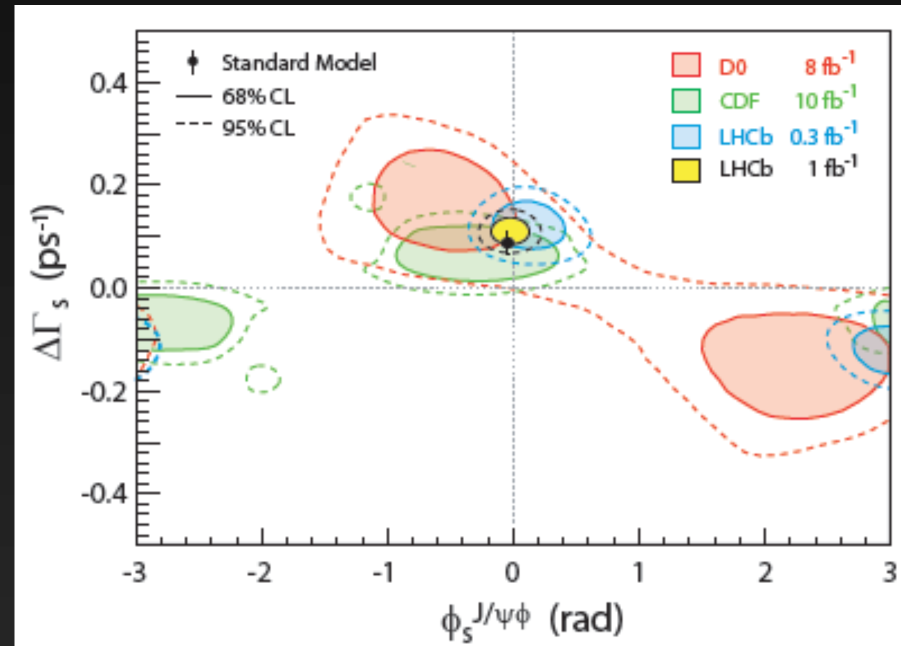
- $\phi_s = 0.001 \pm 0.101 \pm 0.027$
- $\Gamma_s = (0.6580 \pm 0.0054 \pm 0.0066)\ ps^{-1}$
- $\Delta\Gamma_s = (0.116 \pm 0.018 \pm 0.006)\ ps^{-1}$

- First >5σ observation of $\Delta\Gamma_s \neq 0$



Measurement of ϕ_s





- Simultaneous fit to both $B_s \to J/\psi\phi$; $B_s \to J/\psi\pi\pi$
  $\phi_s = -0.002 \pm 0.083$ (stat) ± 0.027 (syst) (preliminary)
- Most precise measurement of ϕ_s to date
- ϕ_s and $\Delta\Gamma_s$ compatible with SM. However experimental error >> theoretical error ! Improvement with more statistics !

Sign of $\Delta\Gamma_s$

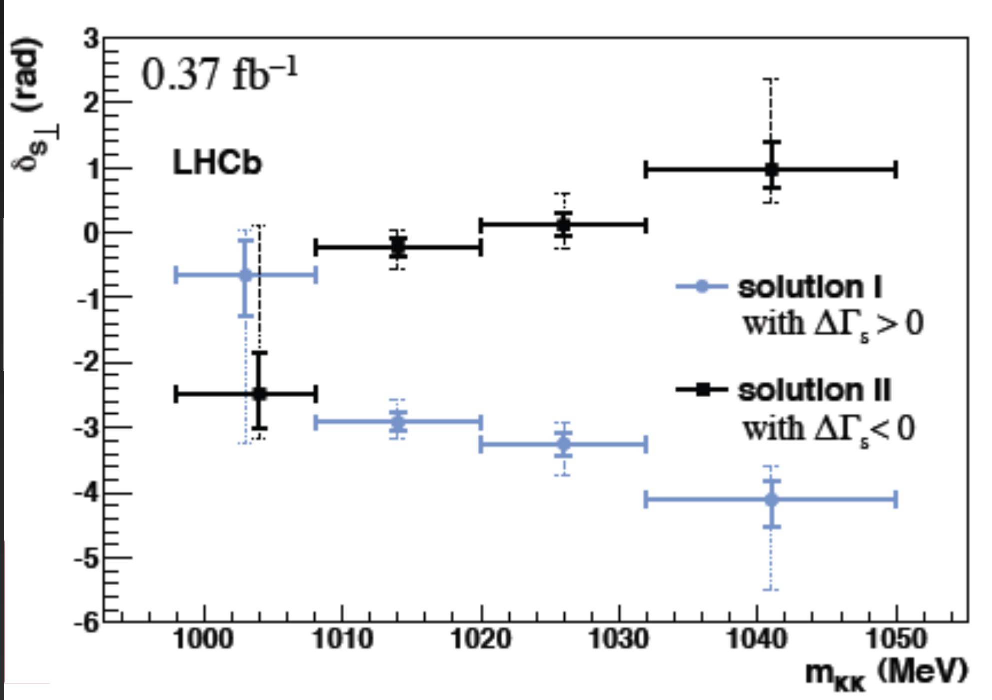
- Decay rates have an intrinsic two-fold ambiguity:
  $(\phi_s, \Delta\Gamma_s, \delta_{//}, \delta_\perp, \delta_s) \Leftrightarrow (\pi-\phi_s, -\Delta\Gamma_s, -\delta_{//}, \pi-\delta_\perp, -\delta_s)$
- Repeat the analysis in larger m(KK) range, not just around mass of φ(1020)

Expect: *(arxiV:0908.3627 (hep-ph))*

- P-wave phases to increase rapidly with m(KK)
- S-wave phase to vary slowly,
- hence $\delta_s - \delta_\perp$ to decrease

Observe:

- solution with $\Delta\Gamma_s > 0$ behaves as expected

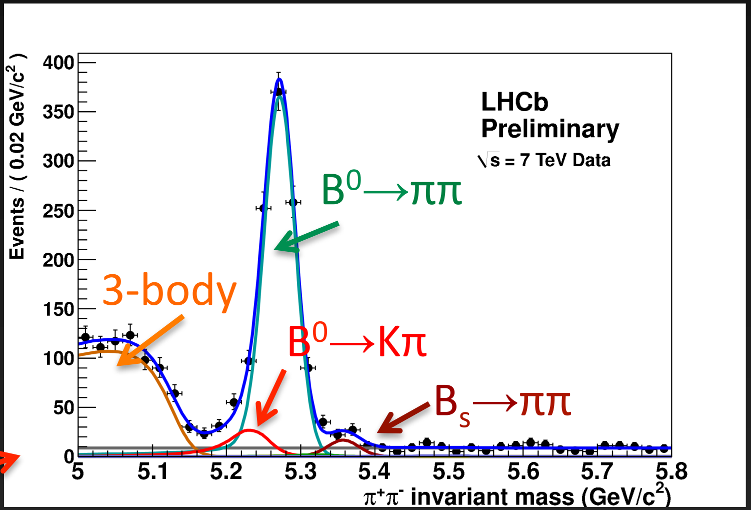


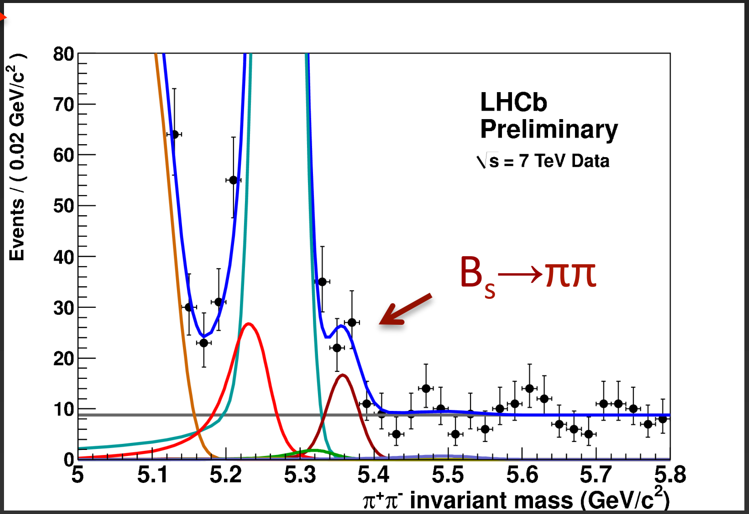
- $\Delta\Gamma_s = \Delta\Gamma_L - \Delta\Gamma_H > 0$ selected at 4.7σ level
- Heavy state lives longer than light state !

(arXiv:1202.4717; subm. to PRL)

Charmless b decays

- Exploits hadronic trigger and π/K/p identification power of RICH
- Physics rich channel:
  - ★ Branching ratios for rare decay modes, e.g. :
    $B_s \to \pi\pi$ first observation !
    $BR(B_s \to \pi\pi) = (0.98^{+0.23}_{-0.19} \pm 0.11) \times 10^{-6}$
    (LHCb-CONF-2011-042)
  - ★ Direct CPV
  - ★ Time dependent CPV





Charmless b decays: direct CPV in B decays

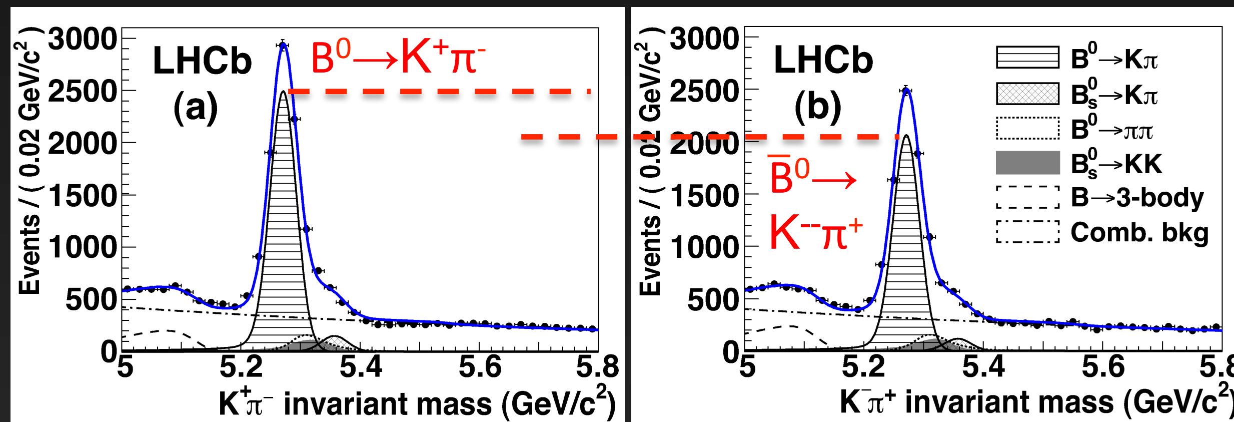
Look for CP asymmetries in $B_{(s)} \to K\pi$ decays. Direct CPV clearly seen !

First observation of direct CPV in B decays at a hadron collider: and most precise measurement to date:

LHCb, Phys. Rev. Lett. 108 (2012) 201601

$A_{CP}(B^0 \to K\pi) =$

$-0.088 \pm 0.011 \pm 0.008$



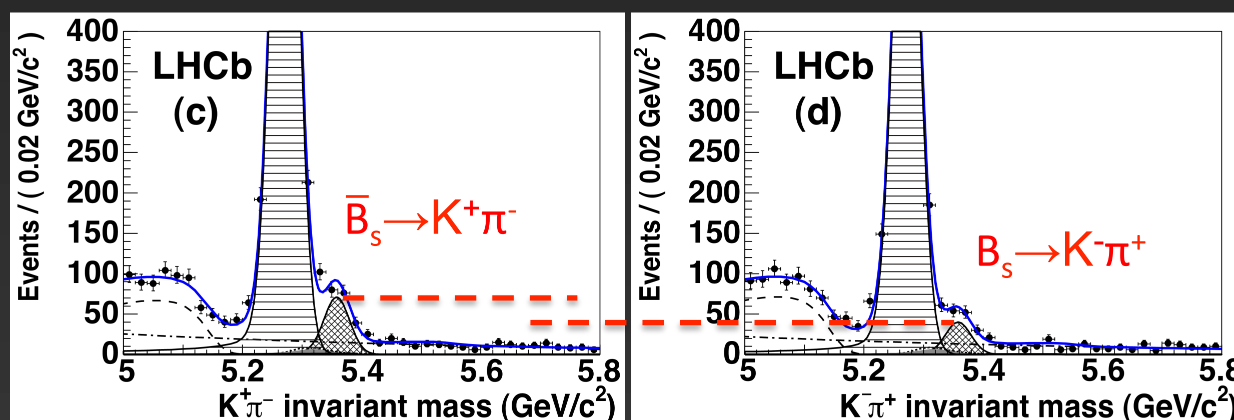
First evidence of direct CPV in B_s decays:

LHCb, Phys. Rev. Lett. 108 (2012) 201601

$A_{CP}(B_s \to K\pi) =$

$+0.27 \pm 0.08 \pm 0.02$

The two above CP asymmetries have opposite sign as expected in the SM



Time dependent CPV in $B^0 \to \pi\pi$ and $B_s \to KK$

- Time dependent CP asymmetries defined as:

$$A_{CP}(t) = \frac{A_f^{\rm dir}\cos(\Delta m t) + A_f^{\rm mix}\sin(\Delta m t)}{\cosh\left(\frac{\Delta\Gamma}{2}t\right) - A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma}{2}t\right)}$$

- With the measurements shown before, give a **test of U-spin symmetry (d ↔ s)** since, in the case of negligible annihilation contributions for Kπ modes:
  - ★ $A_{CP}(B^0 \to K\pi) \approx A^{dir}_{KK}$
  - ★ $A_{CP}(B_s \to K\pi) \approx A^{dir}_{\pi\pi}$ *(Phys. Lett. B459 (1999) 306)*

- Needs flavour tagging. Tagging performance studied with flavour specific Kπ decay modes

Time dependent CPV in $B^0 \to \pi\pi$ and $B_s \to KK$

$B^0 \to \pi\pi$

$A^{dir}_{\pi\pi} = 0.11 \pm 0.2 \pm 0.03$

$A^{mix}_{\pi\pi} = -0.56 \pm 0.17 \pm 0.03$

First measurement at a hadron collider

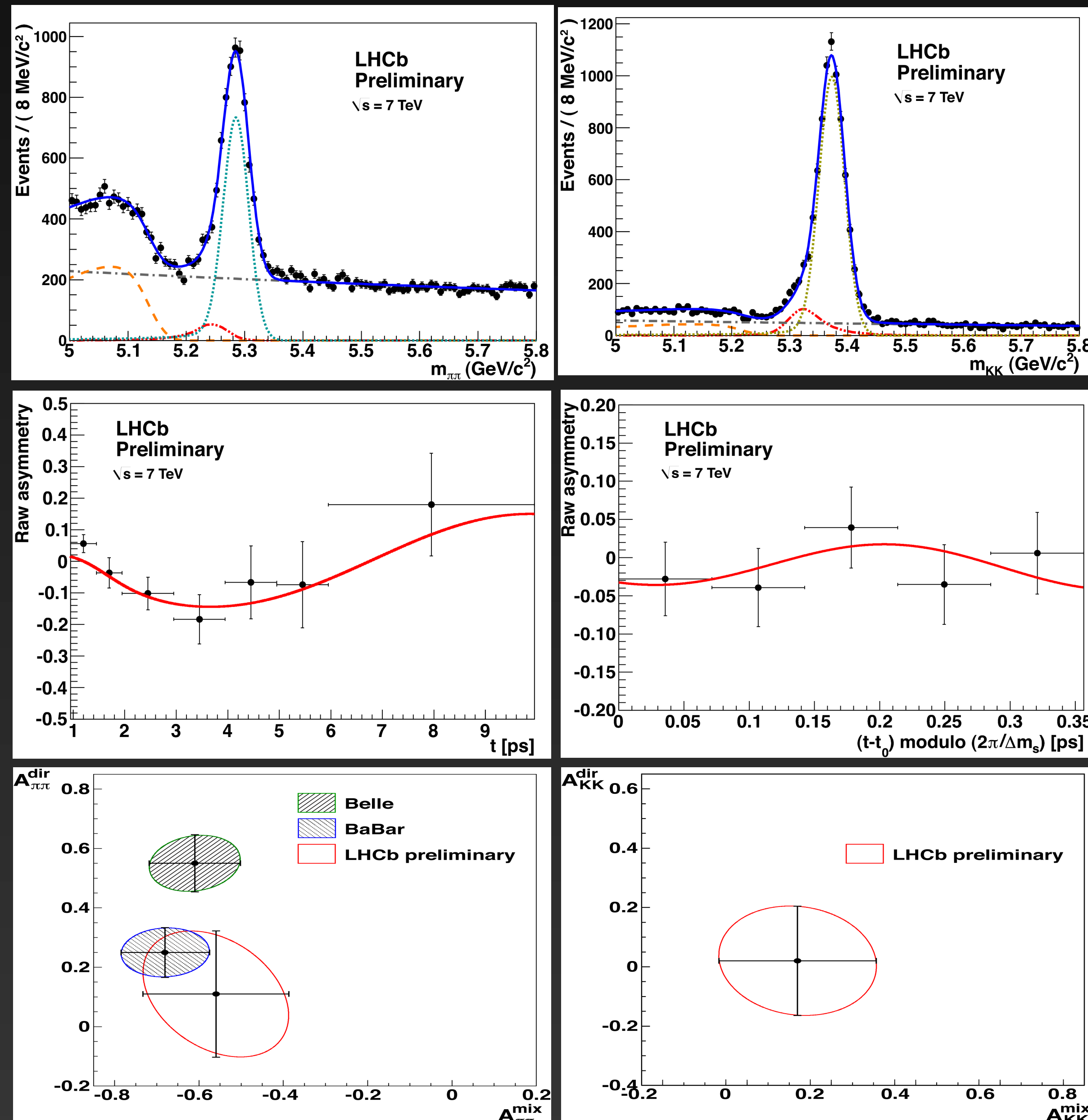
(LHCb-CONF-2012-007)

$B_s \to KK$

$A^{dir}_{KK} = 0.02 \pm 0.18 \pm 0.04$

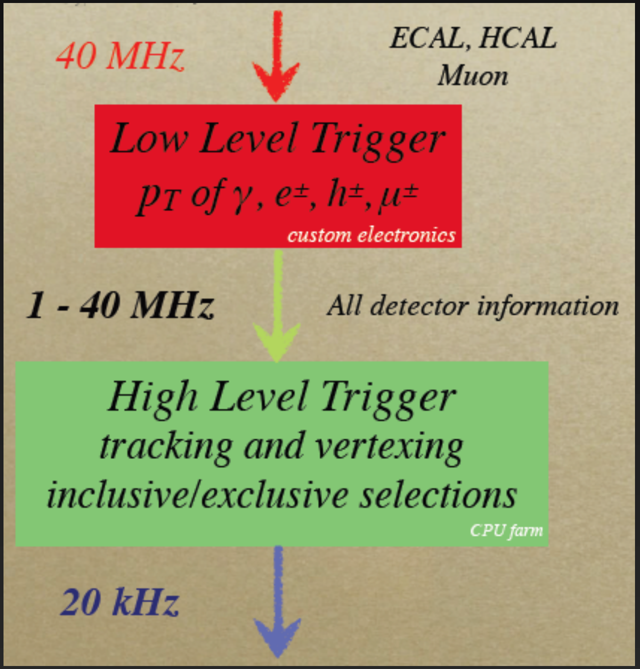
$A^{mix}_{KK} = 0.17 \pm 0.18 \pm 0.05$

First measurement

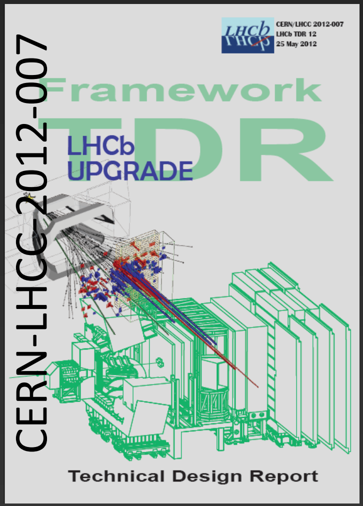


Upgrade

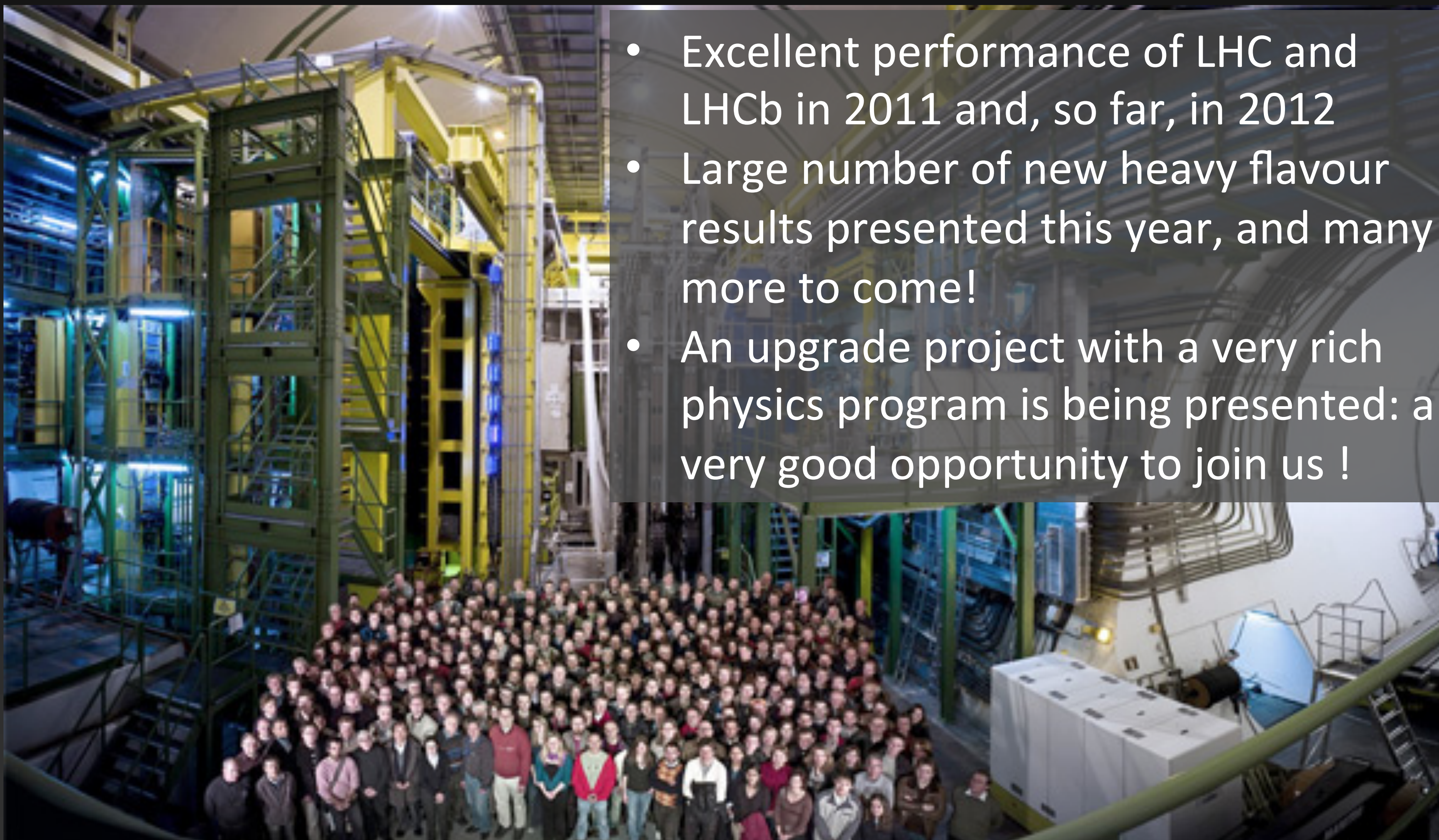
- Reach experimental sensitivities comparable or better than theoretical uncertainties
- Increase the annual yield by a factor 10 for leptonic channels and by a factor 20 for hadronic ones
  - ★ Collect 50 fb^{-1}
  - ★ Constant luminosity of ~ $10^{33} cm^{-2} s^{-1}$ with 25 ns bunch spacing - sub-systems should sustain peak luminosity of $2x10^{33} cm^{-2} s^{-1}$



- Key element of the upgrade: new software trigger (Event Filter Farm) able to "digest" data at an input rate of 40 MHz !
- A LOI already submitted to LHCC and a TDR to be submitted in June
- Installation and commissioning in 2018



Conclusions



- Excellent performance of LHC and LHCb in 2011 and, so far, in 2012
- Large number of new heavy flavour results presented this year, and many more to come!
- An upgrade project with a very rich physics program is being presented: a very good opportunity to join us !

BACKUP SLIDES

Sensitivity to key flavour channels

Type	Observable	Current precision	LHCb (5 fb^{-1})	Upgrade (50 fb^{-1})	Theory uncertainty
Gluonic penguin	$S(B_s \to \phi\phi)$	-	0.08	0.02	0.02
	$S(B_s \to K^{*0}\bar{K}^{*0})$	-	0.07	0.02	< 0.02
	$S(B^0 \to \phi K^0_S)$	0.17	0.15	0.03	0.02
B_s mixing	$2\beta_s\ (B_s \to J/\psi\phi)$	0.16	0.019	0.006	~ 0.003
Right-handed currents	$S(B_s \to \phi\gamma)$	-	0.07	0.02	< 0.01
	$\mathcal{A}^{\Delta\Gamma_s}(B_s \to \phi\gamma)$	-	0.14	0.03	0.02
E/W penguin	$A_T^{(2)}(B^0 \to K^{*0}\mu^+\mu^-)$	-	0.14	0.04	0.05
	$s_0\ A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	-	4%	1%	7%
Higgs penguin	$\mathcal{B}(B_s \to \mu^+\mu^-)$	-	30%	8%	$< 10\%$
	$\frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B_s \to \mu^+\mu^-)}$	-	-	$\sim 35\%$	$\sim 5\%$
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	$\sim 20^\circ$	$\sim 4^\circ$	0.9°	negligible
	$\gamma\ (B_s \to D_s K)$	-	$\sim 7^\circ$	1.5°	negligible
	$\beta\ (B^0 \to J/\psi\, K^0)$	1°	0.5°	0.2°	negligible
Charm CPV	A_Γ	2.5×10^{-3}	2×10^{-4}	4×10^{-5}	-
	$A_{CP}^{dir}(KK) - A_{CP}^{dir}(\pi\pi)$	4.3×10^{-3}	4×10^{-4}	8×10^{-5}	-

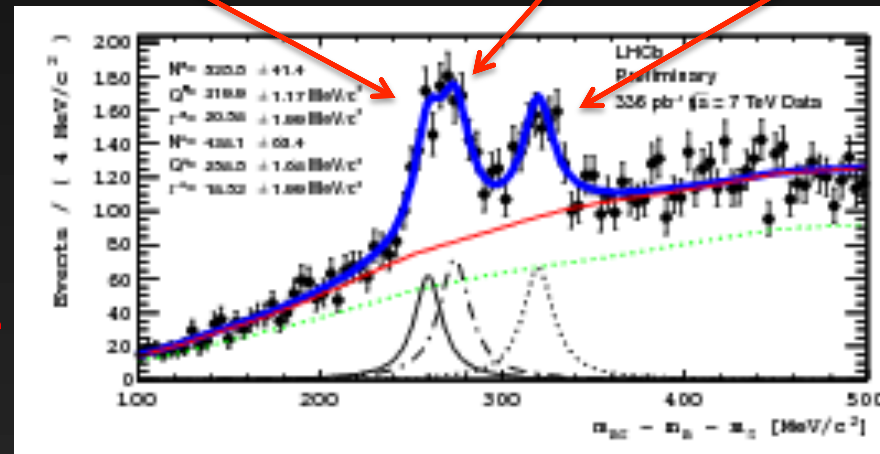
[LHCb-PUB-2011-022]

- Unique potential B_s / b baryon sector
- Charged particle final states far in excess of other facilities

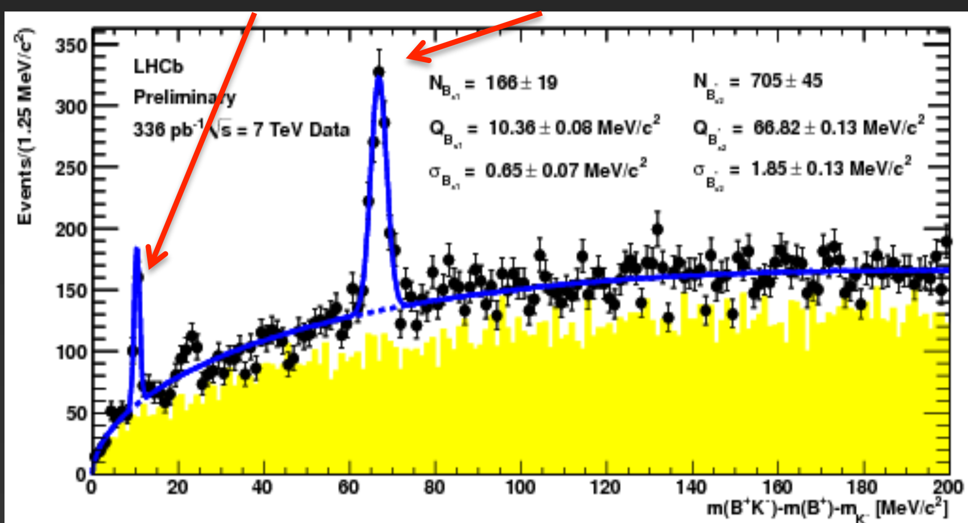
Spectroscopy with LHCb: orbitally excited $B_{(s)}$ states

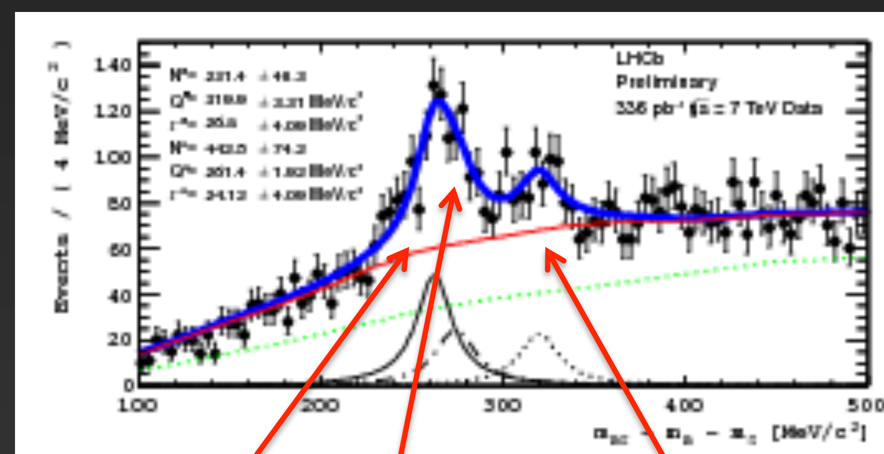
- Important test for HQET and lattice-QCD calculations
- Perform search for $B^{**}_{(s)}$ states in $B^{\pm}K^{\mp}$, $B^{\pm}\pi^{\mp}$ and $B^0\pi^{\pm}$ channels with 0.33 fb^{-1}.
- Results compatible with theoretical calculations
- Masses of B_1^+ and B_2^+ measured for the first time

$B^0_1 \rightarrow B^{*+}\pi^-$ $B^0_2 \rightarrow B^{*+}\pi^-$ $B^0_2 \rightarrow B^+\pi^-$



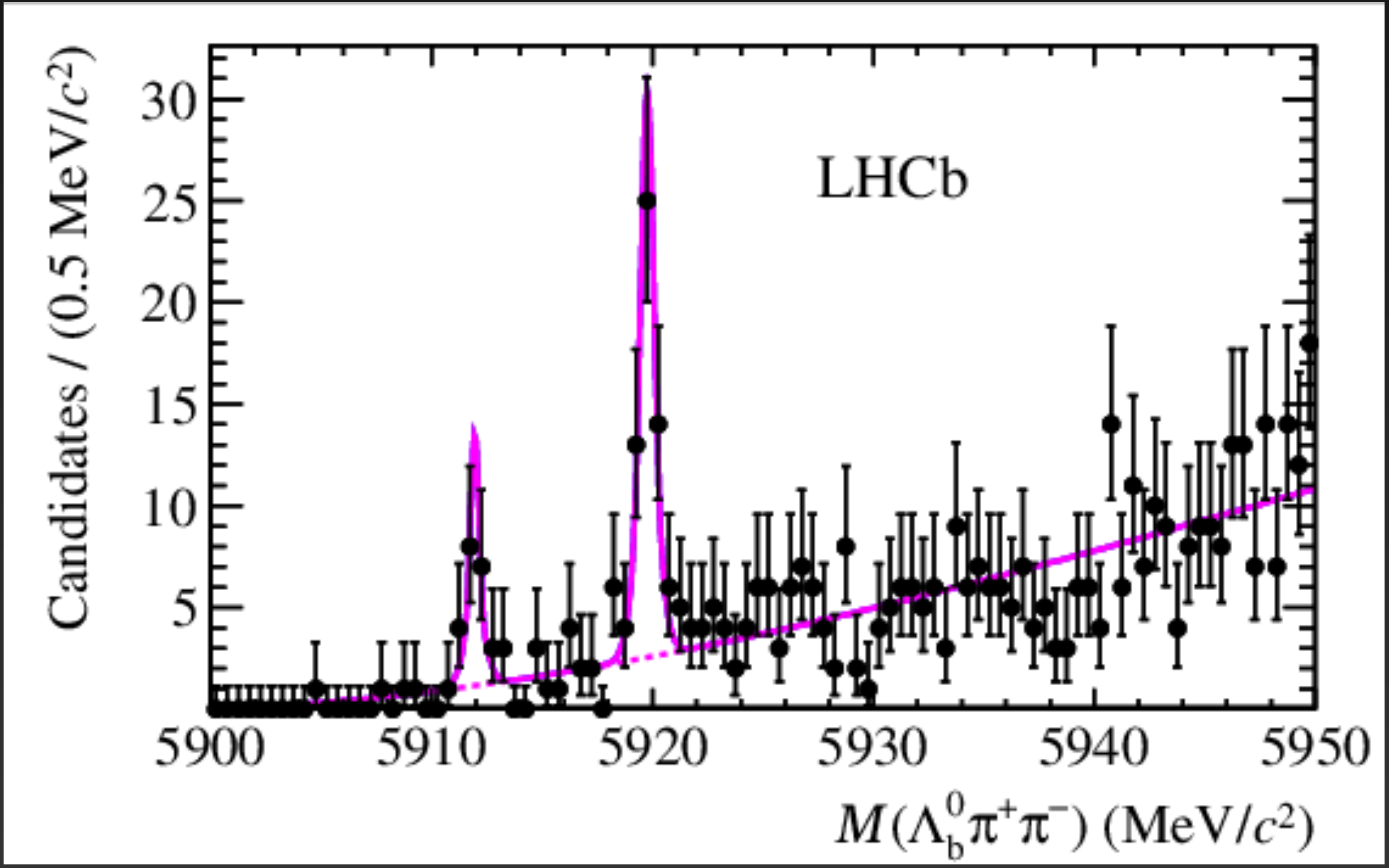
$B^0_{s1} \rightarrow B^{*+}K^-$ $B^{*0}_{s2} \rightarrow B^+K^-$





$B^{+1} \rightarrow B^{*0}\pi^+$ $B^{+2} \rightarrow B^{*0}\pi^+$ $B^{+2} \rightarrow B^0\pi^+$

- First observation of two Λ_b excited states



Direct CPV in $D^0 \to h^+h^-$

LHCb, arXiv:1112.0938
to appear in PRL

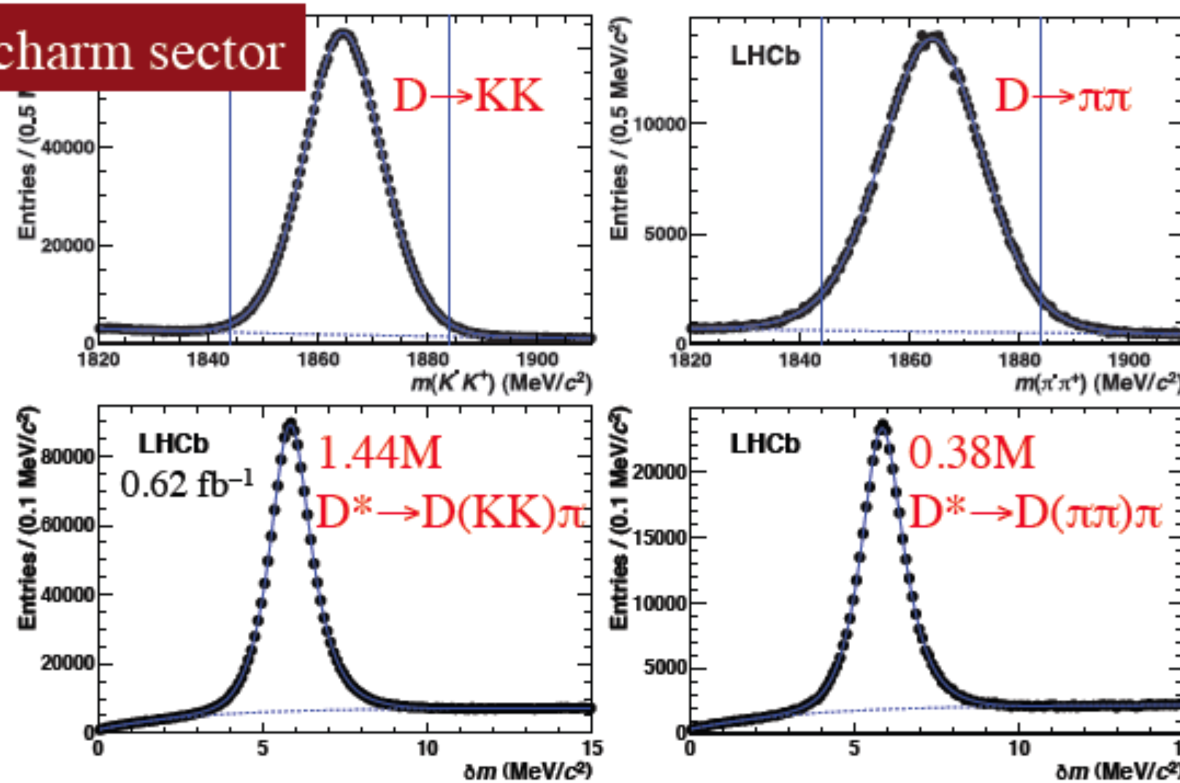
- Using $D^0 \to h^+h^-$ decays tagged with $D^{*+} \to D^0\pi^+$

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-0.82 \pm 0.21 \pm 0.11)\%$$

$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)}$$

First evidence of CPV in charm sector

- To first order
  - $A_{CP}(f)$ not affected by detection asymmetries
  - soft pion detection and D^* production asymmetries cancel in ΔA_{CP}
  - mixing-induced CPV components of $A_{CP}(f)$ largely cancel in ΔA_{CP}
  - U-spin symmetry predicts opposite direct CPV for K^+K^- and $\pi^+\pi^-$



confirmed on Feb 29 by CDF: $(-0.62 \pm 0.21 \pm 0.10)\%$