LHCb results and plans

Umberto Marconi, I.N.F.N. Bologna
on behalf of the LHCb Collaboration

Planck'12, Warsaw, May 2012

Strategy for NP search at LHCb

- **Measure rare processes.**
  - Measure FCNC transitions, where New Physics is more likely to emerge, and compare results to SM predictions.
- **Measure CP symmetry violation to improve measurement precision of CKM elements.**
  - Extract CKM-UT angles and sides in many different ways: any inconsistency will be a sign of New Physics.
  - Compare measurements of same quantity, which may or may not be sensitive to NP: e. g. NP-free determinations of CKM-UT angle γ to be compared to γ from loop.

b and c hadrons production at LHC

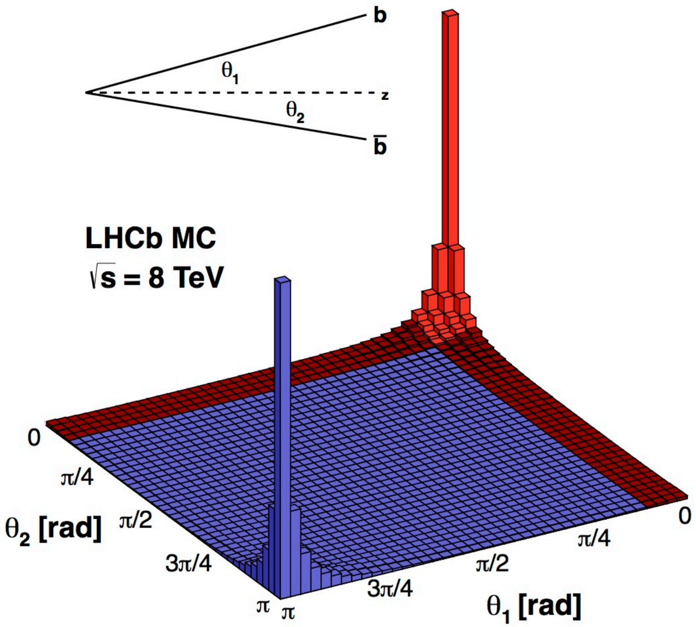
The beauty cross-sections given by PYTHIA (PYTHIA8 and CTEQ6 NLO) are:
251.8 μb at 7 TeV; 291.6 μb at 8 TeV; 527.3 μb at 14 TeV.

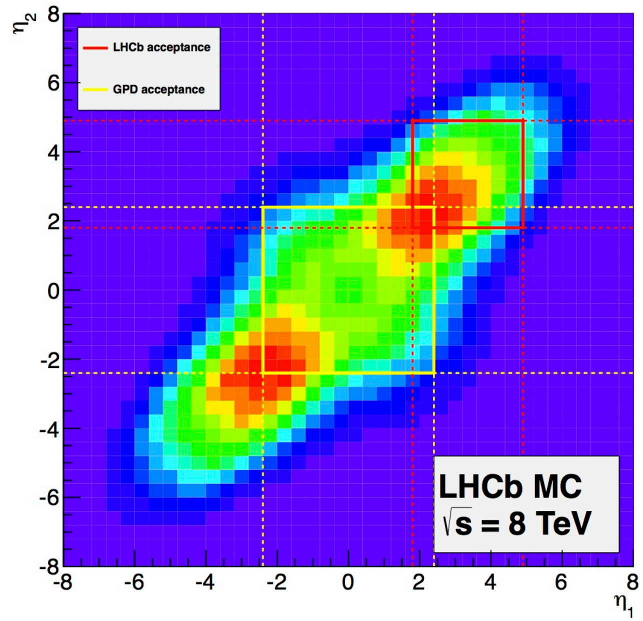
LHCb measurement in the acceptance, at 7 TeV:

$\sigma(pp \rightarrow bbX) = (75.3 \pm 5.4 \pm 13.0)$ μb, PLB 694 (2010) 209,

corresponding to **$\sigma(pp \rightarrow bbX)_{4\pi} = 284 \pm 20 \pm 49$ μb.**

σ_{inel}= 60 mb and σ_{cc}= 6 mb.





1.8 < η < 4.9 for LHCb

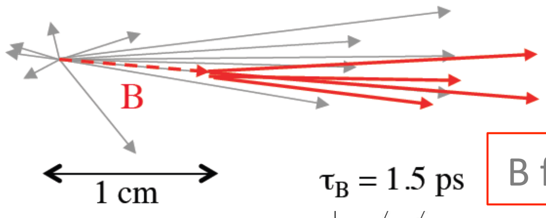
The LHCb detector

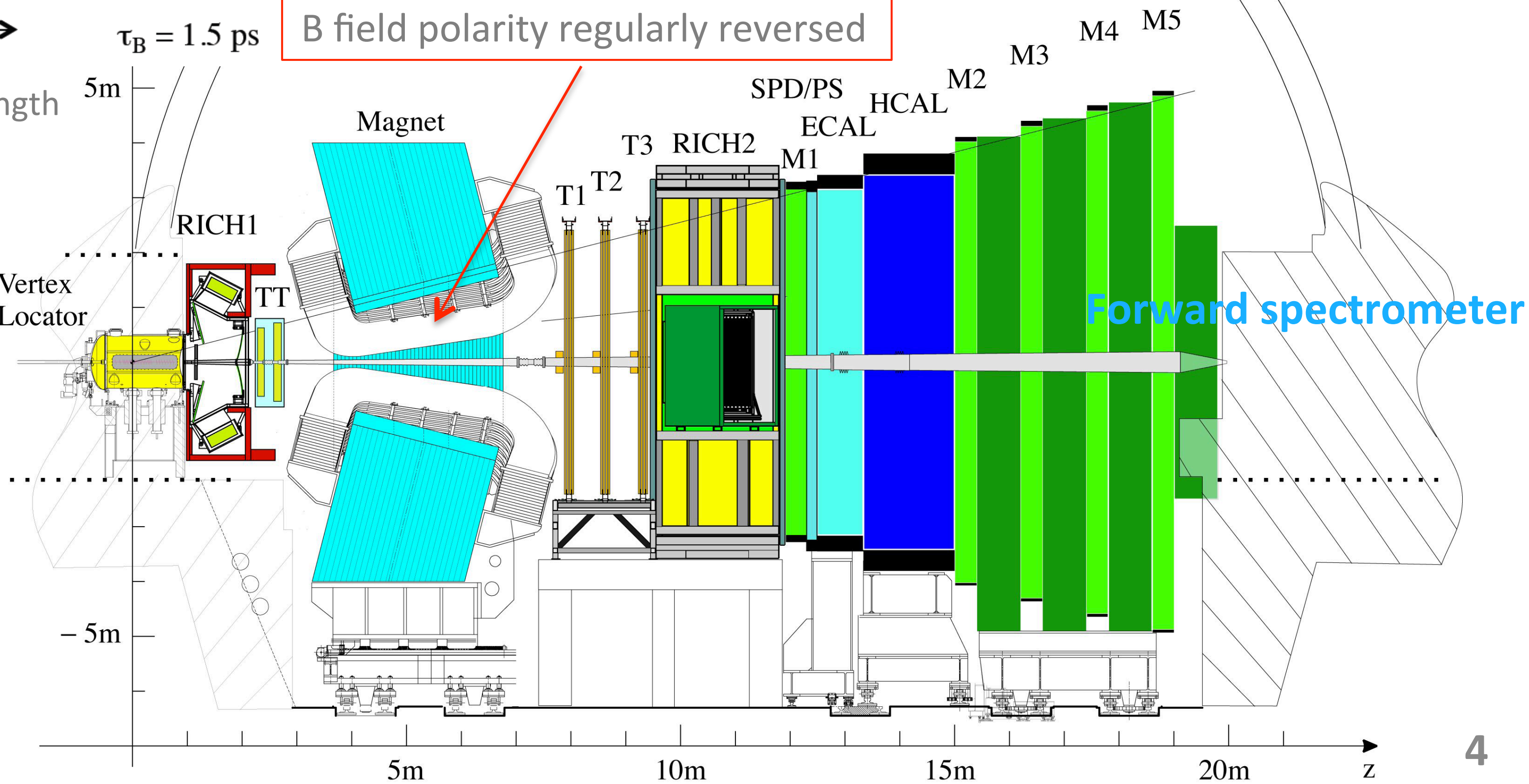
Experiment optimized for B physics requires:

- Precision tracking and vertexing (mass, proper time).
- Excellent particle identification: e, γ, μ, **π**, K, p
- Efficient trigger for hadronic and leptonic modes.

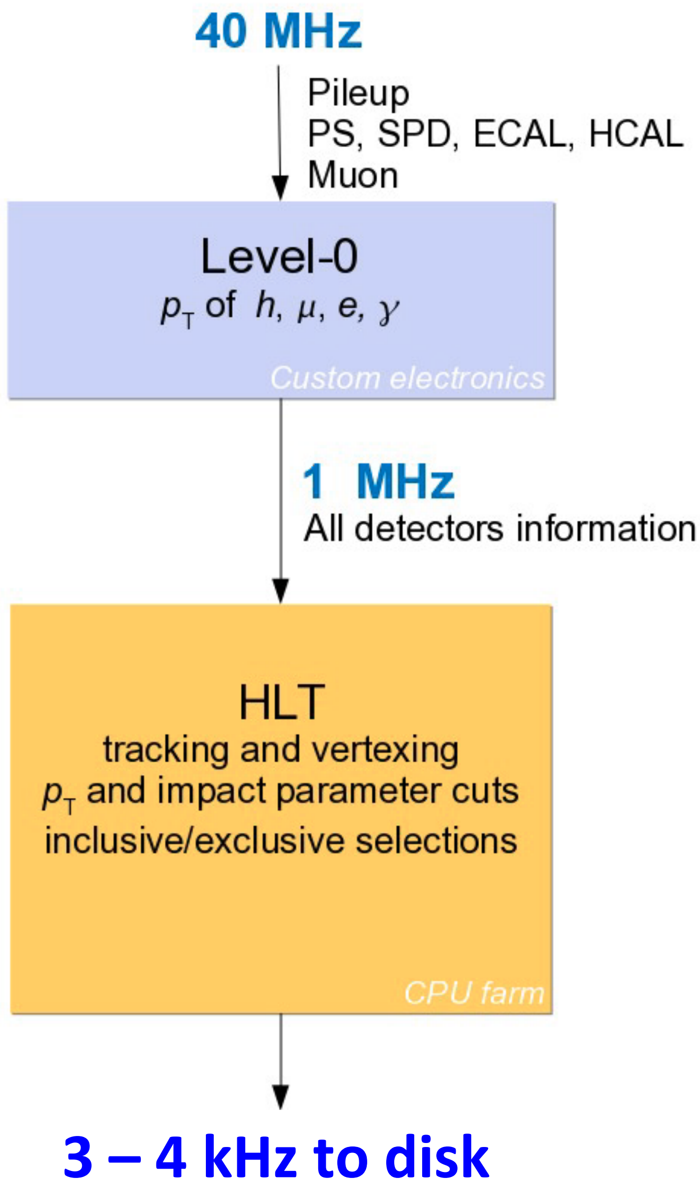
LHCb performance:

- Decay time resolution **Δ**t: 30-50 fs
- **Δ**p/p = 0.35-0.55%, $1 < p < 100$ Gev/c
- **Δ**m = 10-20 MeV/c^2
- MUON ID:
  ε(μ/μ) = 95%, mis-ID **ε**(**π**/μ) ~ 1%
- RICH ID **π**/K:
  ε(K/K) = 95%, mis-ID **ε**(**π**/K) ~ 10%



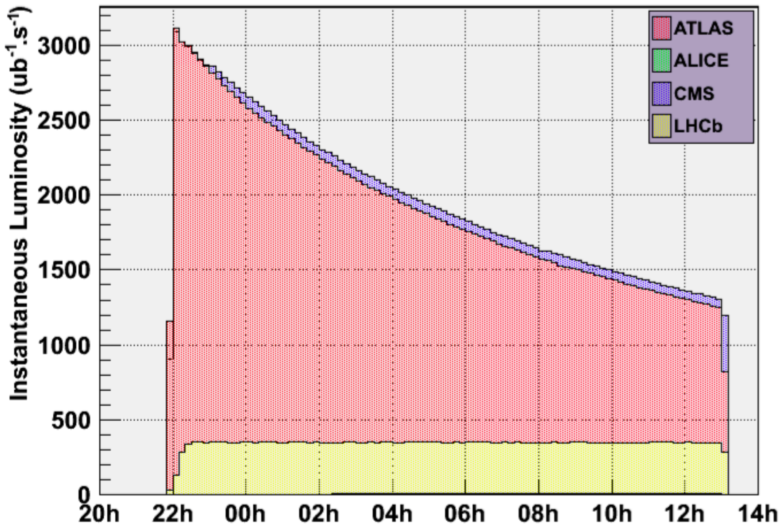


Trigger architecture



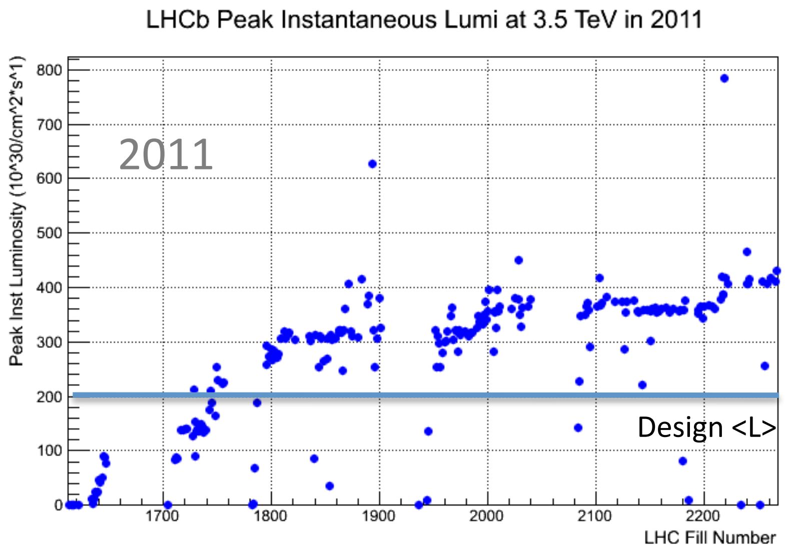
Running Conditions

Instantaneous luminosity leveling



Leveling is obtained through vertical beam displacements.

Recorded instantaneous luminosity

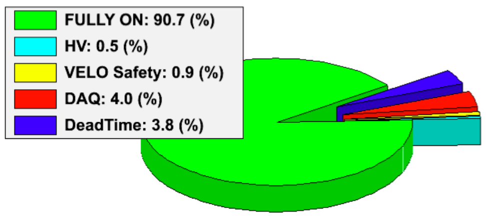


LHCb luminosity per fill typically $3–4 \times 10^{32}$ cm^{-2}s^{-1}

The average instantaneous <L> is a factor 2. above the design value !

2011 integrated luminosity of 1.1 fb^{-1}
10^{15} x 75.3 x 10^{-6} ~ 10^{11} beauty.

Target of 1.5 fb^{-1} recorded in 2012

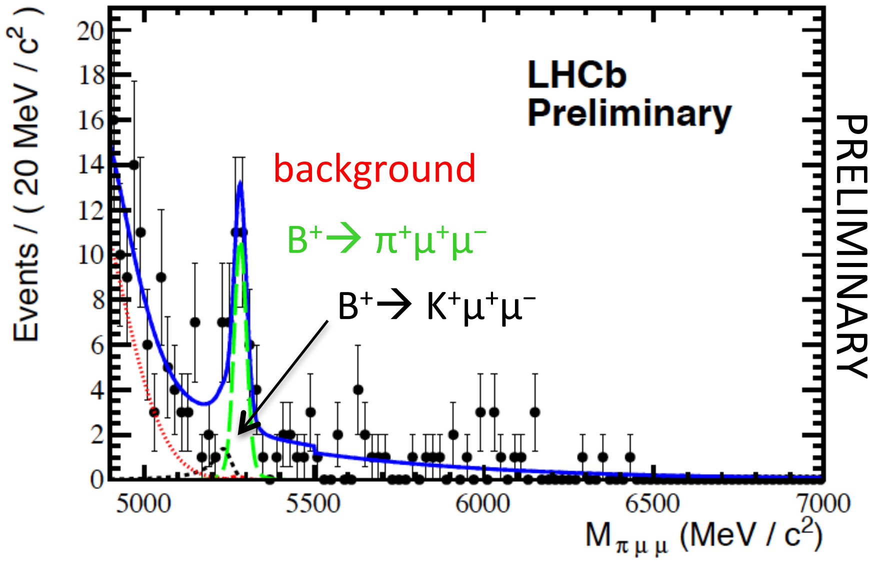


91% data-taking efficiency

$B^+ \rightarrow \pi^+\mu^+\mu^-$
The rarest B decay ever observed

LHCb-CONF-2012-006

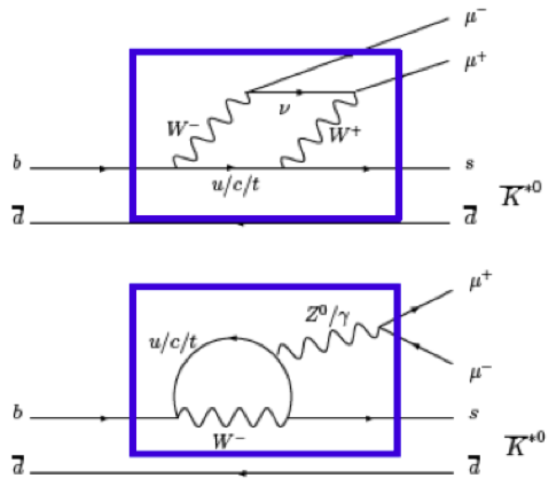
- It is a $b \rightarrow d\,\mu^+\mu^-$ flavour changing neutral current process.
- $b \rightarrow d\,\mu^+\mu^-$ is suppressed by a factor $|V_{td}/V_{ts}|$ relative to $b \rightarrow s\,\mu^+\mu^-$:
  This suppression does not necessarily apply to NP beyond the SM.
- The predicted SM branching fraction $\mathbf{B(B^+ \rightarrow \pi^+\mu^+\mu^-)_{SM} = (1.96 \pm 0.21)\times 10^{-8}}$
  Communications in Theoretical Physics 50 (2008) 696
- The best published limit is $\mathbf{B(B^+ \rightarrow \pi^+\mu^+\mu^-) < 6.9\times 10^{-8}}$ at 90% C.L. by Belle full dataset.
  Phys. Rev. D78 (2008) 011101, arXiv:0804.3656
- 21 ± 3 $B^+ \rightarrow \pi^+\mu^+\mu^-$ events expected in 1.0 fb^{-1}, given the SM prediction.
- A signal yield of $25.3\,^{+6.7}_{-6.4}$ is extracted from the fit, corresponding to a 5.2σ observation.
- The LHCb measurement:
  $\mathbf{(2.4 \pm 0.6\,(stat) \pm 0.2\,(syst))\times 10^{-8}}$
  in good agreement with the SM.



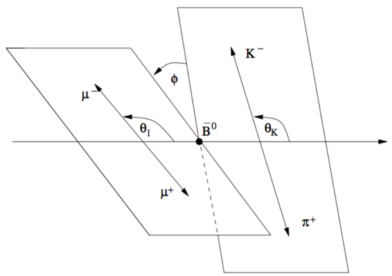
$B_d \rightarrow K^*(K^+\pi^-)\mu^+\mu^-$ ($1fb^{-1}$)

LHCb-CONF-2012-008

- It is a $b \rightarrow s\,\mu^+\mu^-$ FCNC process, with a vector in the final state: a reach phenomenology.
- The decay can be described by three angles (θ_l,θ_K,ϕ) and by the squared di-muon invariant mass (q^2).
- Angular observables in this decay have been previously measured by BaBar, Belle, CDF.
- The LHCb fit of the differential amplitude, in the angles and in bins of q^2, allow to access:
- F_L , the longitudinal polarization of the K*
- A_{FB} of the leptonic system
- T-odd CP A_{IM} asymmetry
- The transverse asymmetry $S_3 = 0.5\times(1-F_L) \times A_T^2$



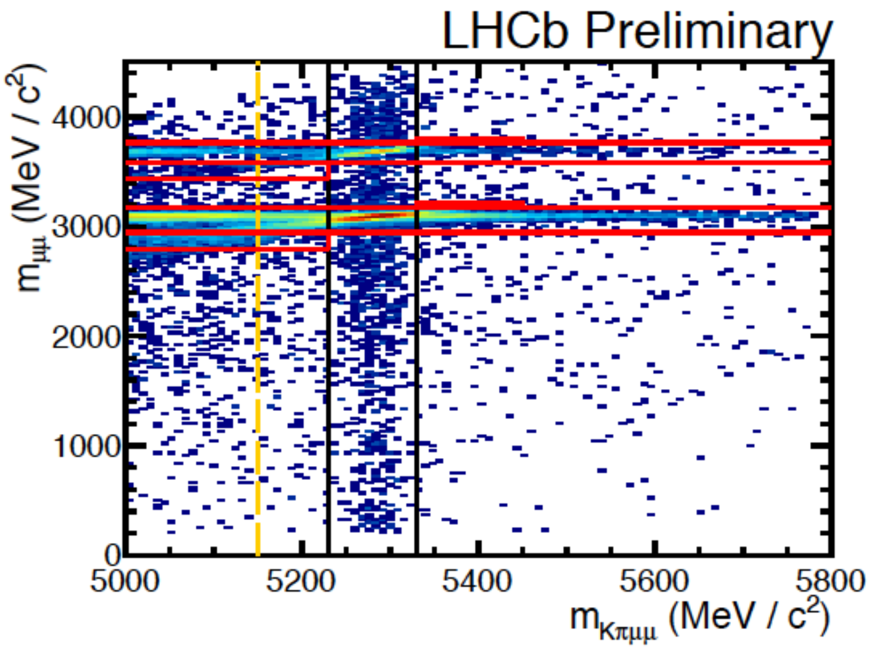
$$\frac{1}{\Gamma}\frac{d^4\Gamma}{d\cos\theta_\ell\, d\cos\theta_K\, d\hat{\phi}\, dq^2} = \frac{9}{16\pi}\Big[F_L\cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K) + F_L\cos^2\theta_K(2\cos^2\theta_\ell - 1) + \frac{1}{4}(1-F_L)(1-\cos^2\theta_K)(2\cos^2\theta_\ell - 1) + S_3(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\cos 2\hat{\phi} + \frac{4}{3}A_{FB}(1-\cos^2\theta_K)\cos\theta_\ell + A_{Im}(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\sin 2\hat{\phi}\Big]$$



$B_d \to K^*(K^+\pi^-)\mu^+\mu^-$ signal selection

LHCb-CONF-2012-008

The $K^+\pi^-\mu^+\mu^-$ versus $\mu^+\mu^-$ invariant mass distribution for candidates in the data sample.



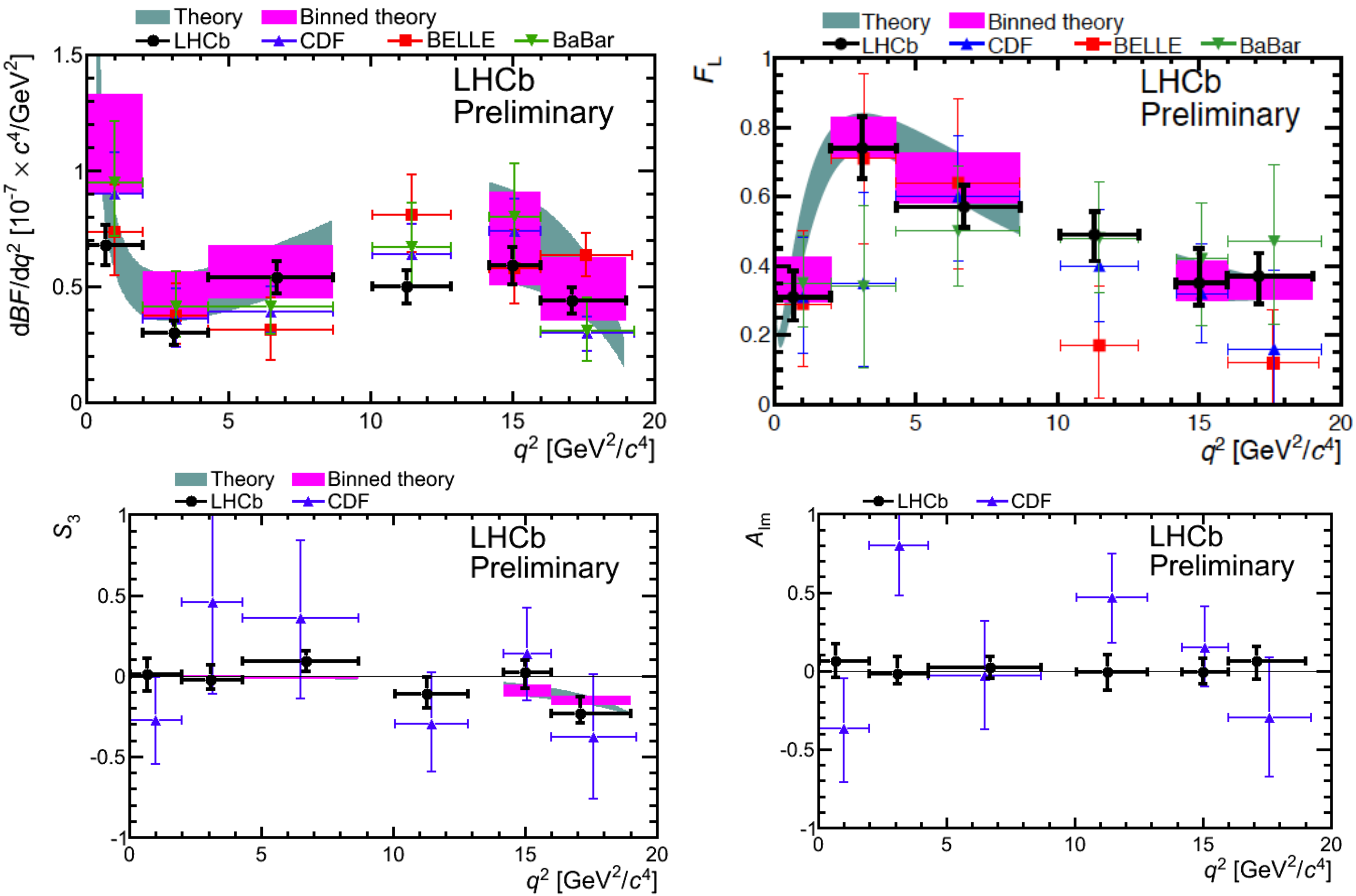
q^2 (GeV^2/c^4) range	Signal Yield	Background Yield
$4m_\mu^2 < q^2 < 2.00$	162.4 ± 14.2	27.7 ± 3.8
$2.00 < q^2 < 4.30$	71.4 ± 10.7	37.1 ± 4.1
$4.30 < q^2 < 8.68$	270.5 ± 18.8	58.8 ± 5.5
$10.09 < q^2 < 12.90$	167.0 ± 14.9	41.7 ± 4.5
$14.18 < q^2 < 16.00$	113.0 ± 11.7	17.1 ± 3.0
$16.00 < q^2 < 19.00$	115.0 ± 12.4	23.9 ± 3.6
$1.00 < q^2 < 6.00$	195.2 ± 16.9	75.8 ± 6.0
$4m_\mu^2 < q^2 < 19.00$	900.0 ± 34.4	206.2 ± 10.3

The signal and background yields resulting from a fit to the $K^+\pi^-\mu^+\mu^-$ invariant mass distributions of the candidates in the six q^2-bins used in the analysis.

The red lines limit the cc-bar resonance regions that are removed in the analysis.
The black lines indicate a ±50MeV/c^2 window around the reconstructed B_d mass.

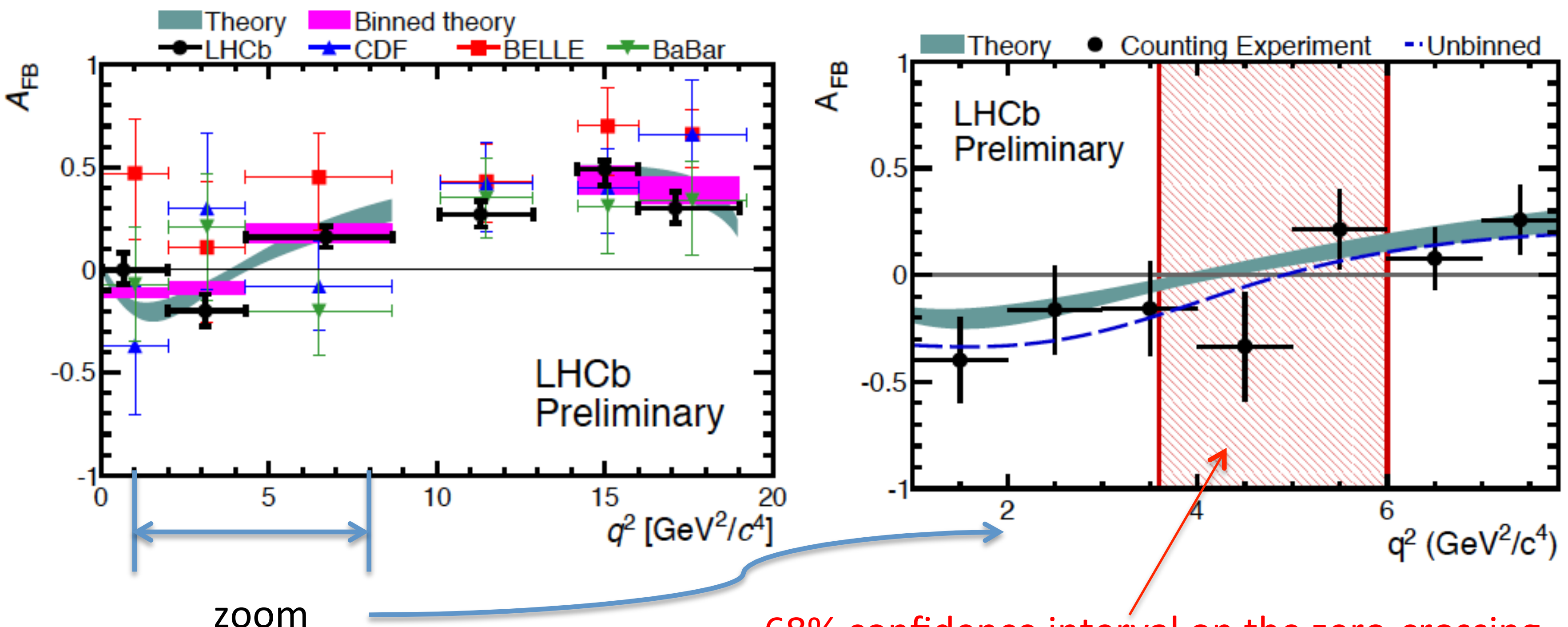
The BDT selection uses information about the kinematic properties of B^0 meson, B^0 vertex quality, track quality, impact parameter and Particle Identification (PID) of the kaon, the pion and the muons.

$B_d \to K^*(K^+\pi^-)\mu^+\mu^-$ results



LHCb-CONF-2012-008

A_{FB} zero crossing point $B_d \rightarrow K^*(K^+\pi^-)\mu^+\mu^-$



LHCb-CONF-2012-008

68% confidence interval on the zero-crossing point observed in the data.

The SM predictions for q^2_0 is the range: 4.0 - 4.3 GeV^2/c^4

The LHCb results is: $q^2_0 = (4.9^{+1.1}_{-1.3})$ GeV^2/c^4

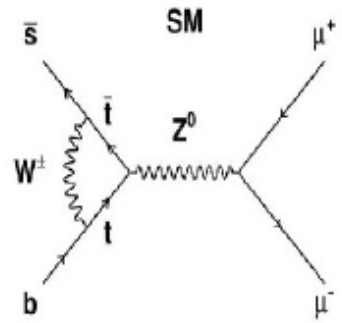
Theory prediction:
C. Bobeth, G. Hiller, D. van Dyk, JHEP 07, 067 (2011)
Measurements:
BaBar: S.Akar Lake Louise (2012)
Belle: Phys.Rev.Lett. 103, 171801 (2009)
CDF :Phys. Rev. Lett. 108, 081807 (2012)

Results are in good agreement with Standard Model predictions.

$B_{(s)} \rightarrow \mu^+\mu^-$ (1fb^{-1})

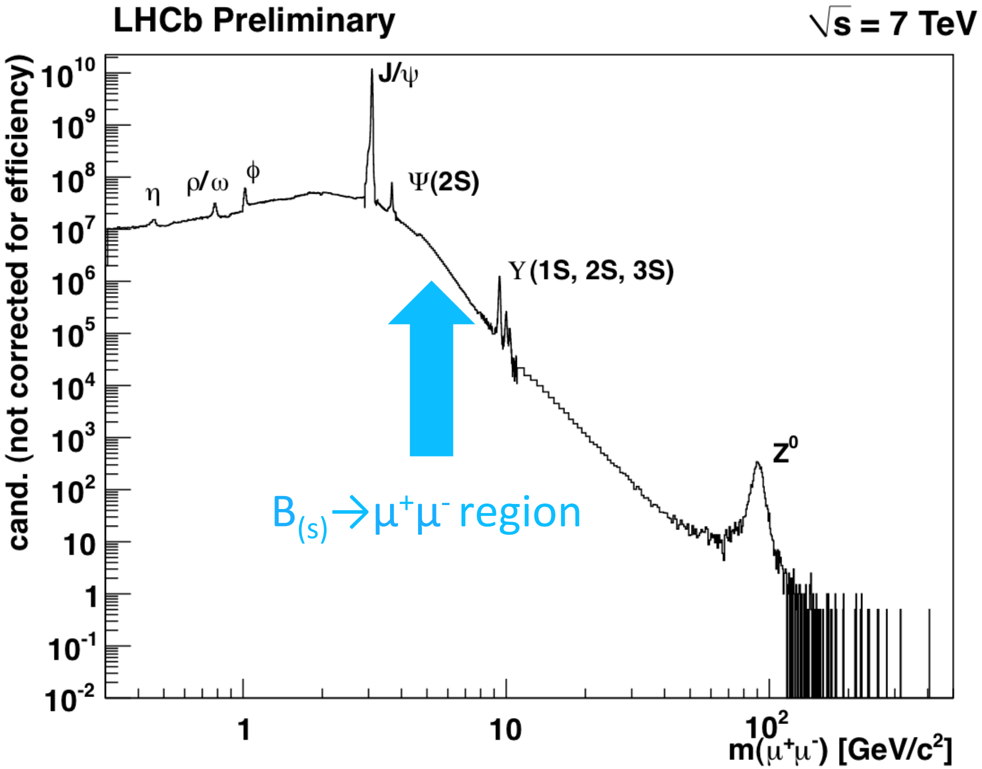
- Very rare in Standard Model, due to the absence of tree-level FCNC, helicity suppression, CKM suppression:
- BR_{SM} ($B_s \rightarrow \mu^+\mu^-$)= $(3.2 \pm 0.2)\times10^{-9}$
- BR_{SM} ($B_d \rightarrow \mu^+\mu^-$)= $(0.10 \pm 0.01)\times10^{-9}$

  Buras et al., JHEP 10 (2010) 009
  E.Gamiz et al. Phys. Rev. D 80 (2009) 104503

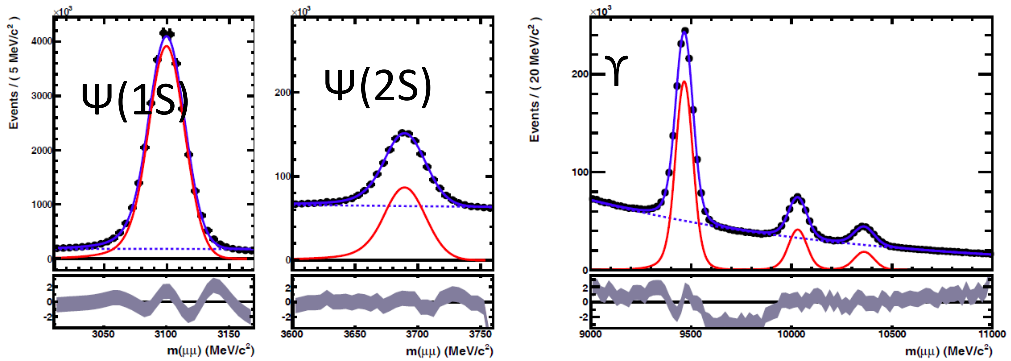


- The SM BRs can be enhanced in NP models.
- $B_{(s)} \rightarrow \mu^+\mu^-$ decays are relatively easy to trigger and reconstruct. The main issue for the analysis is the background rejection.
- Classification of events in 2D space:
  Invariant di-muon mass of high quality muon tracks and Boosted Decision Tree (BDT) multivariate discriminant on kinematics and topology variables.
- Control channels used for the expectation for signal and background.

Di-muon invariant mass

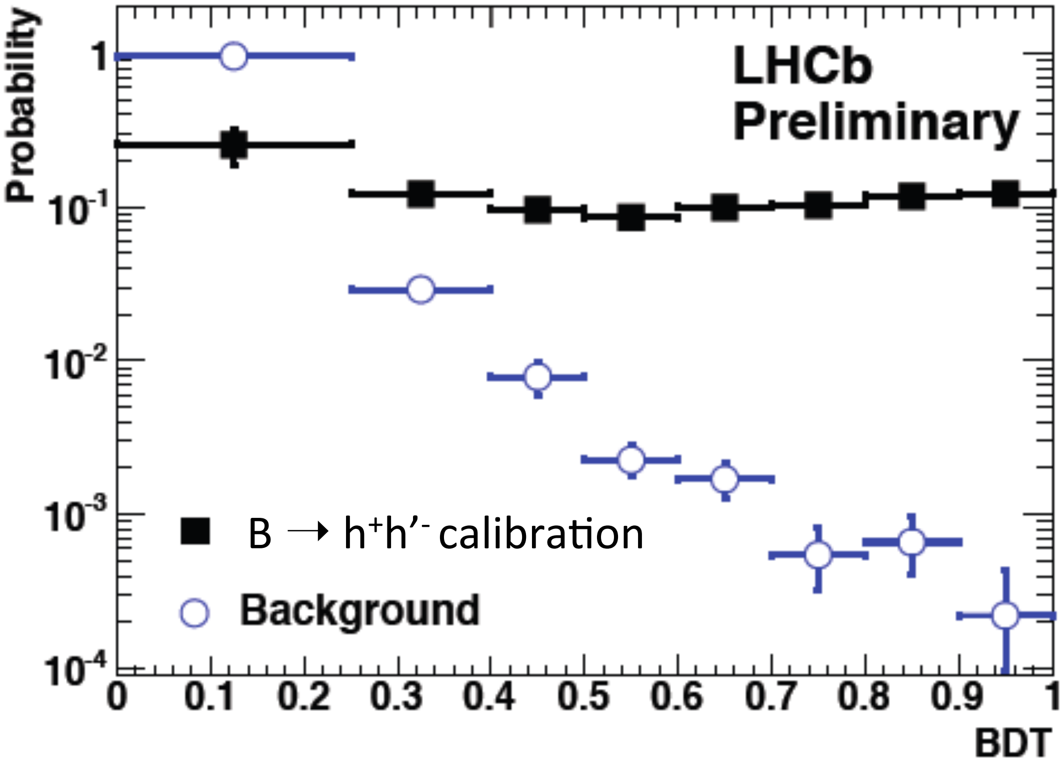


Mass resolution measured in data from di-muon resonances:
ψ(1S), ψ(2S), ϒ(1S), ϒ(2S), ϒ(3S)
$\sigma(m) = 24.8 \pm 0.3 \pm 0.7$ MeV/c^2
Central value from charmless two body decays $B \to h^+h'^-$

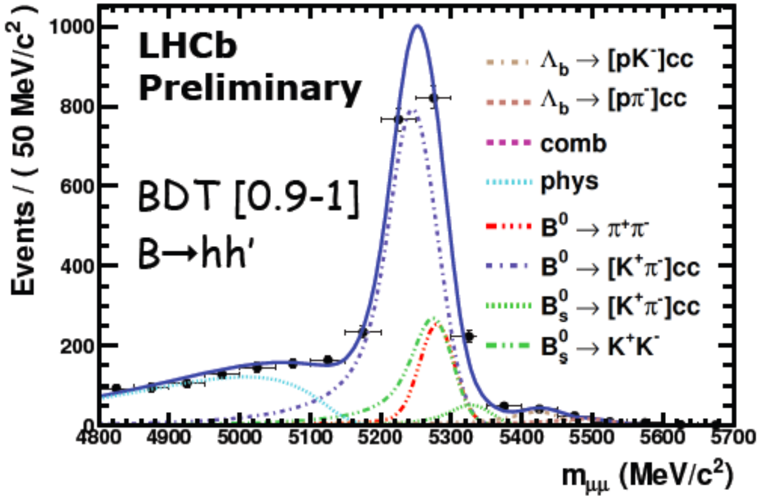


BDT selection

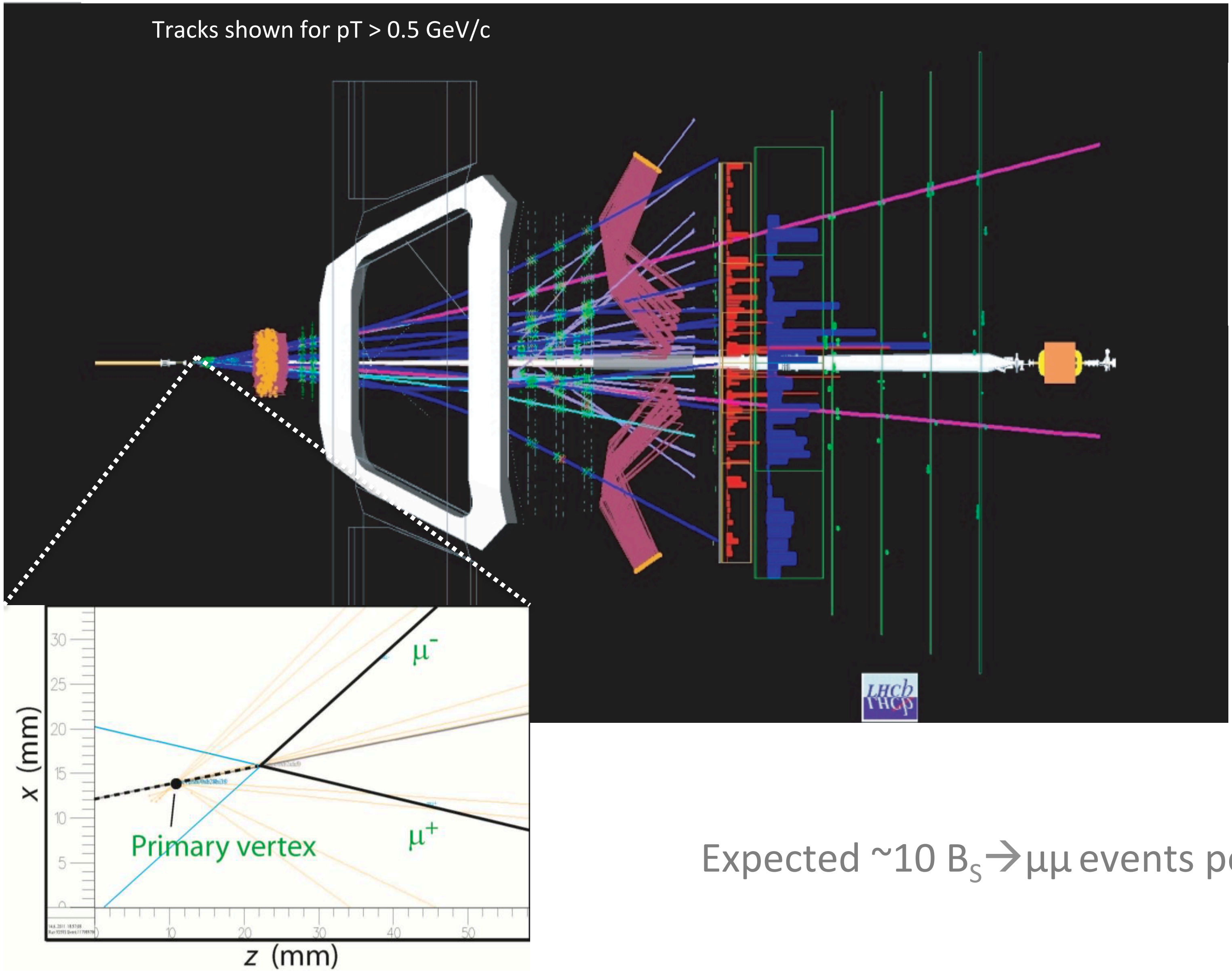
BDT trained using MC simulated samples of $B_s \rightarrow \mu^+\mu^-$ and bb $\rightarrow \mu^+\mu^-$ X background.
Signal distribution taken from data using $B_{(s)} \rightarrow h^+h'^-$.
Background distribution from the sidebands of the $\mu\mu$ invariant mass distribution in the $B_{(s)}$ mass window.



Signal distribution from B $\rightarrow$ $h^+h'^-$



$B_s \rightarrow \mu^+\mu^-$ candidate ?



$m(\mu^+\mu^-) = 5.374$ GeV/c^2
$p_T(\mu^+) = 2.3$ GeV/c
$p_T(\mu^-) = 3.5$ GeV/c

BDT = 0.92
Decay length = 11.5 mm
Proper time = 3.5 ps

Expected ~10 $B_s \rightarrow \mu\mu$ events per fb-1

$B_{(s)} \rightarrow \mu^+\mu^-$

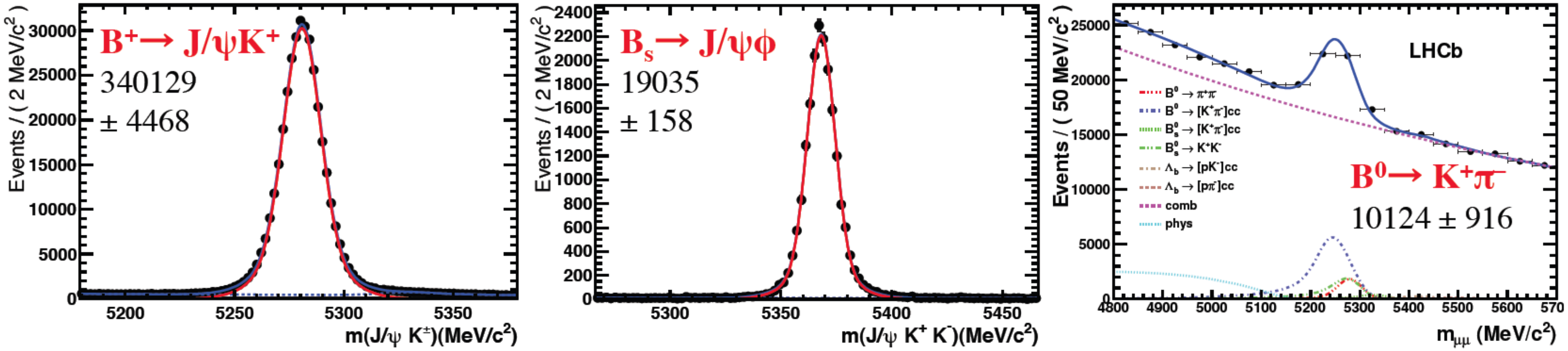
LHCb-PAPER-2012-007
arXiv:1203.4493

Branching fraction normalization:

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

LHCb measurement of B_S fraction: $f_s/f_d = 0.267^{+0.021}_{-0.020}$ → arXiv:1111.2357, to appear in PRD; PRL 107 (2011) 211801

Three complementary normalization channels

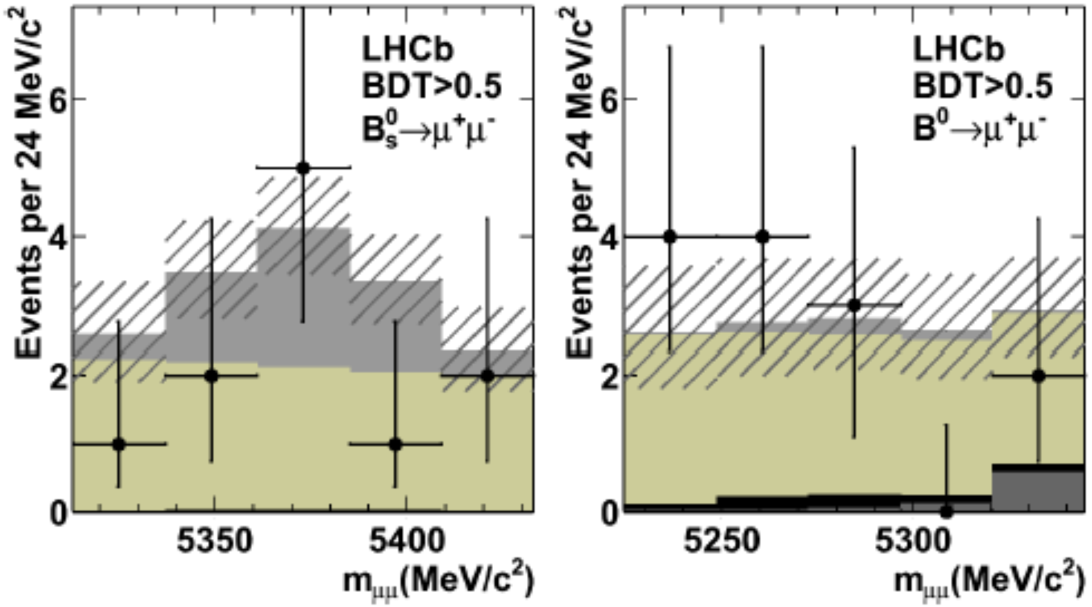


Single event sensitivity (weighted average)

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

$B_{(s)} \to \mu^+\mu^-$

LHCb-PAPER-2012-007
arXiv:1203.4493

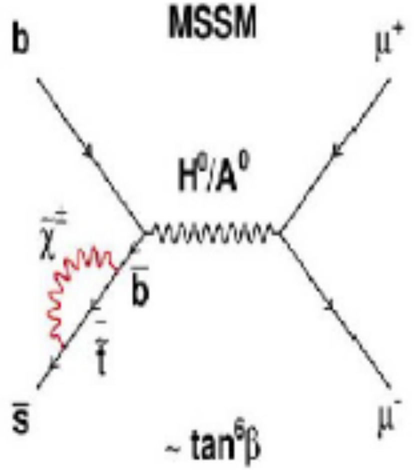


Mode	Limit	at 90 % CL	at 95 % CL
$B_s^0 \to \mu^+\mu^-$	Exp. bkg+SM	6.3×10^{-9}	7.2×10^{-9}
	Exp. bkg	2.8×10^{-9}	3.4×10^{-9}
	Observed	3.8×10^{-9}	4.5×10^{-9}
$B^0 \to \mu^+\mu^-$	Exp. bkg	0.91×10^{-9}	1.1×10^{-9}
	Observed	0.81×10^{-9}	1.0×10^{-9}

$B(B_s \to \mu^+\mu^-) = (0.8^{+1.8}_{-1.3}) \times 10^{-9}$

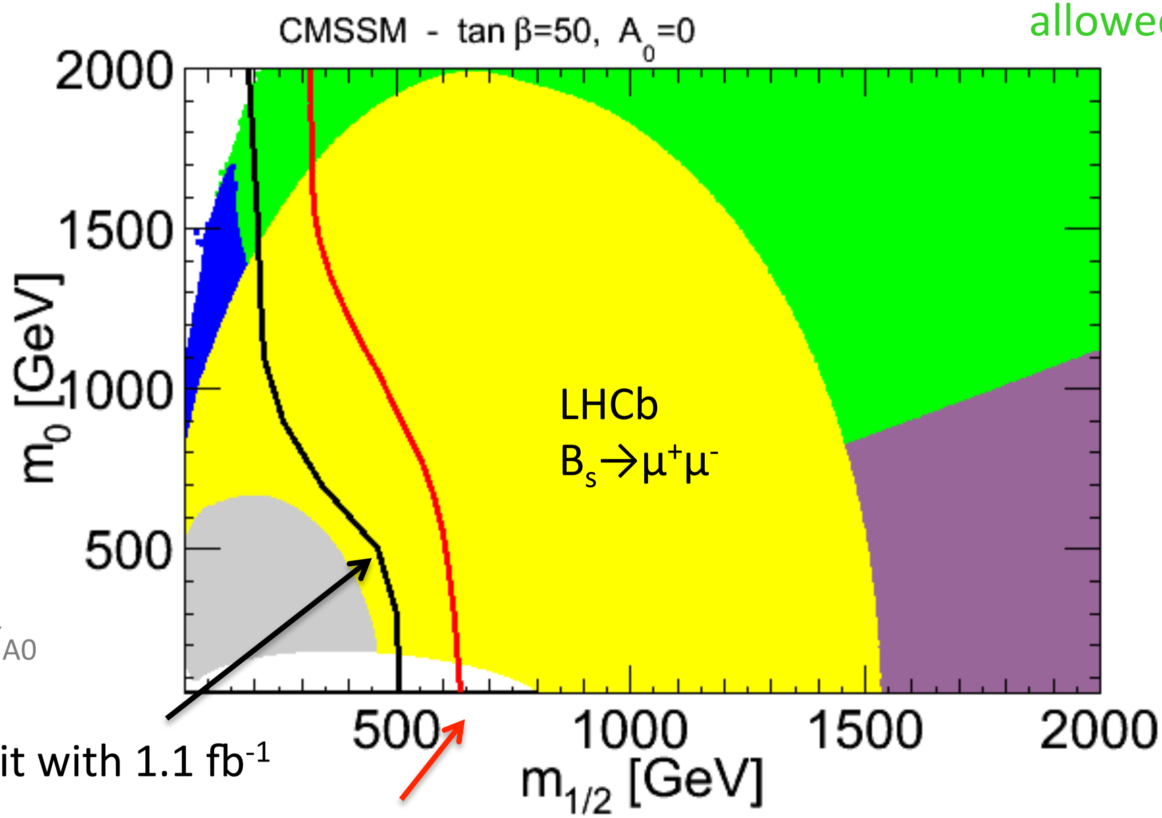
$B_{(s)} \rightarrow \mu^+\mu^-$ implications

Complementarity of direct and indirect searches



$BR(B_{(s)} \rightarrow \mu^+\mu^-)_{MSSM} \propto \tan(\beta)/M^4_{A0}$

allowed



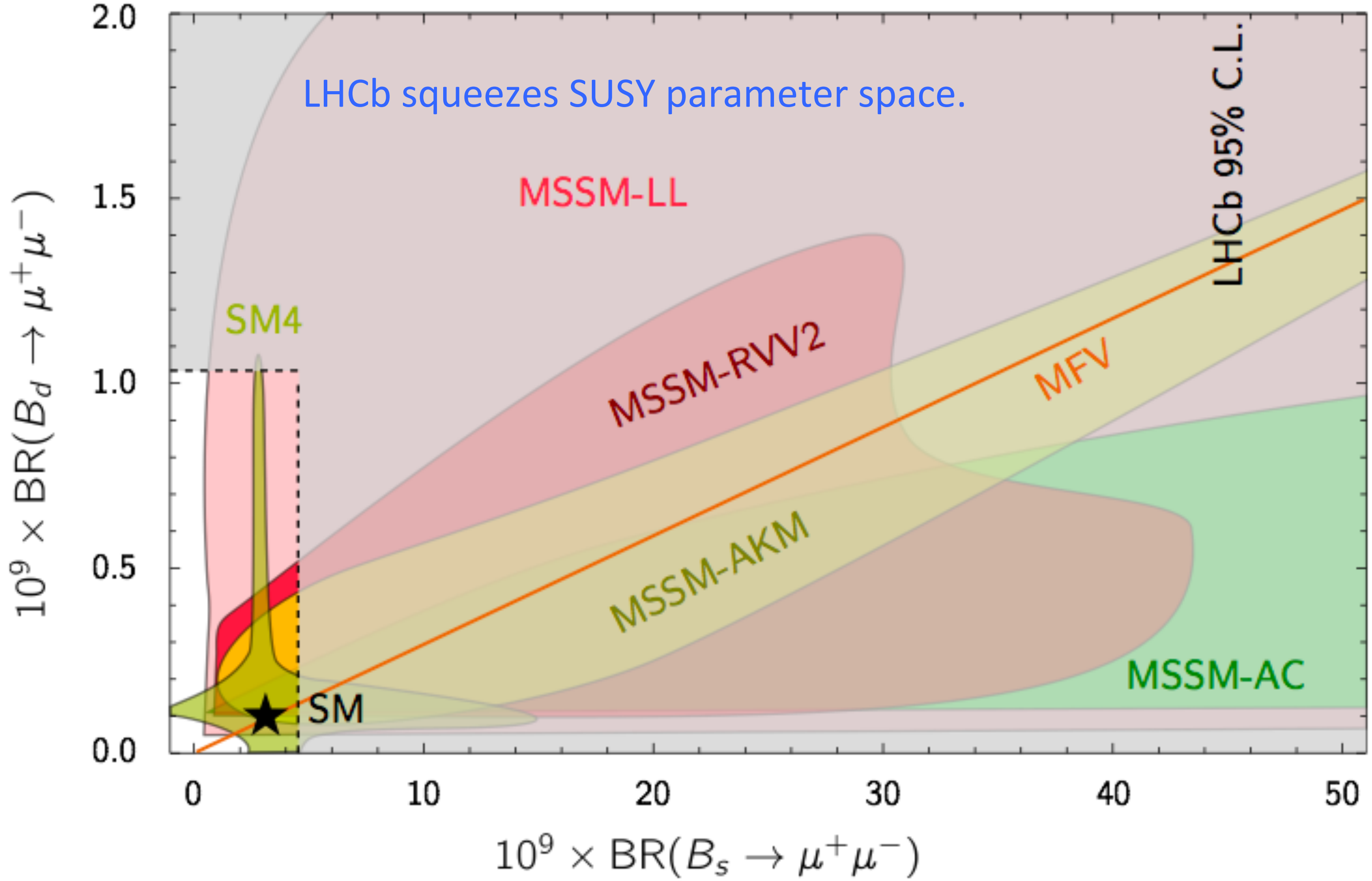
CMS exclusion limit with 1.1 fb^{-1}

CMS exclusion limit with 4.4 fb^{-1}

N. Mahmoudi at Moriond (2012)

$B_{(s)} \to \mu^+\mu^-$ implications

Minimal Supersymmetric Standard Model for $BR(B_d \to \mu^+\mu^-)/BR(B_S \to \mu^+\mu^-)$



David Straub, Rencontres de Moriond EW, La Thuile (2012)

Mixing-induced CPV in $B_s \to J/\psi\phi$

- $B_S \to J/\psi\phi$ is the counterpart of $B^0 \to J/\psi K^0$
- We aim to measure ϕ_s: the phase difference between the $B_S \to J/\psi\phi$ decay amplitudes with or without oscillation.
- ϕ_s possibly sensitive to New Physics contributions to B_S mixing:
  $\phi_s = (\phi_s)_{SM} + (\phi_s)_{NP}$

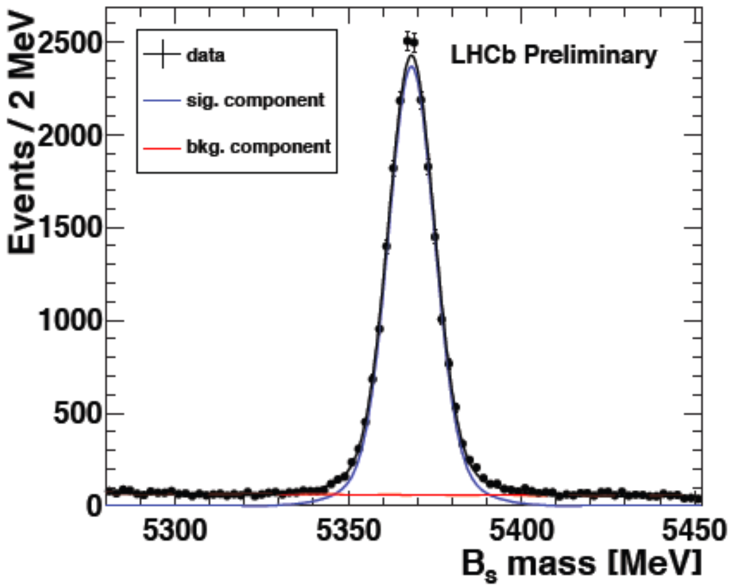
$$(\phi)_{SM} = -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = -0.036 \pm 0.002$$

- Important differences between B_S and B^0 cases:
  $\Delta M_S >> \Delta M_d$: excellent proper time resolution to resolve oscillations.
  $\Delta\Gamma s >> \Delta\Gamma d$: access to $\cos(\phi_s)$ in addition to $\sin(\phi_s)$
  $B_S \to J/\psi$ KK final state is a mixture of CP-even and CP-odd eigenstates, with 4 contributing amplitudes:
  KK in P-wave state: final state is CP-odd or CP-even
  KK in S-wave state: final state is CP-odd

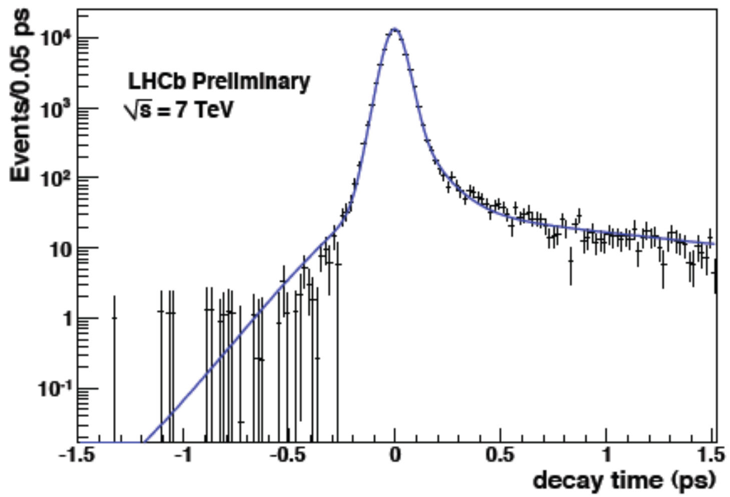
J. Charles et al. PRD 84 (2011) 033005

$B_S \rightarrow J/\psi\phi$ signals and resolutions

$B_S \rightarrow J/\psi\phi$ mass resolution



Proper time resolution



$B_S \rightarrow J/\psi\phi$ candidates:

- Require t > 0.3 ps
- 8 MeV/c^2 mass resolution.
- 21200 signal events (1 fb^{-1}).

Time resolution

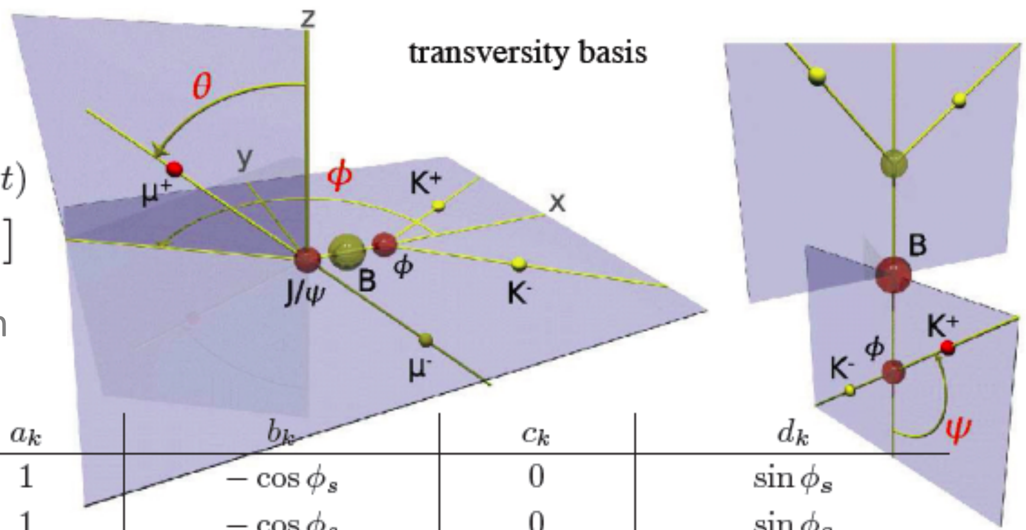
- Apply selection without decay length or impact parameter cuts (trigger + offline)
- Calibrate per-event estimate of proper time error from fit to prompt peak.
- **45 fs time resolution.**

$B_s \rightarrow J/\psi\phi$ decay rates

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

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

c_k and d_k get opposite signs for anti-meson



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	$-\sin(\delta_0-\delta_S)\sin\phi_s$	$\cos(\delta_0-\delta_S)$	$-\sin(\delta_0-\delta_S)\cos\phi_s$

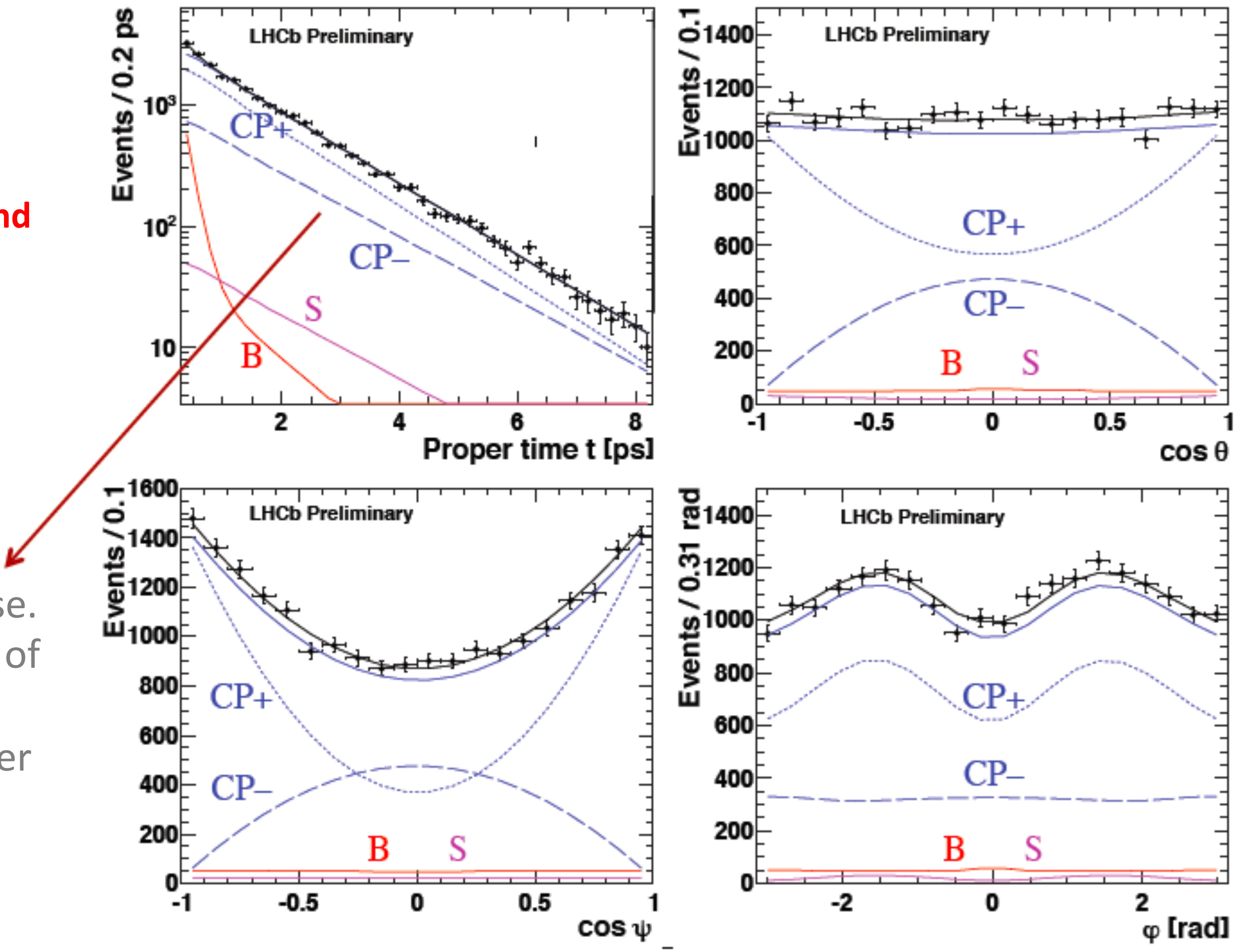
δ_0 set to 0

10 parameters: ϕ_S, Γ_S, $\Delta\Gamma_S$, ΔM_S, 3 amplitudes and 3 strong phases

$B_s \rightarrow J/\psi\phi$ fits (1.0 fb^{-1})

LHCb-CONF-2012-002

CP = +1: CP-even final state
CP = -1: CP-odd final state
S : J_{KK} =0, S-wave CP-odd
B : combinatorial background



Similar to the K_s K_L case.
First >5σ observation of non zero $\Delta\Gamma_S$
CP=-1 state lives longer than CP=+1 state.

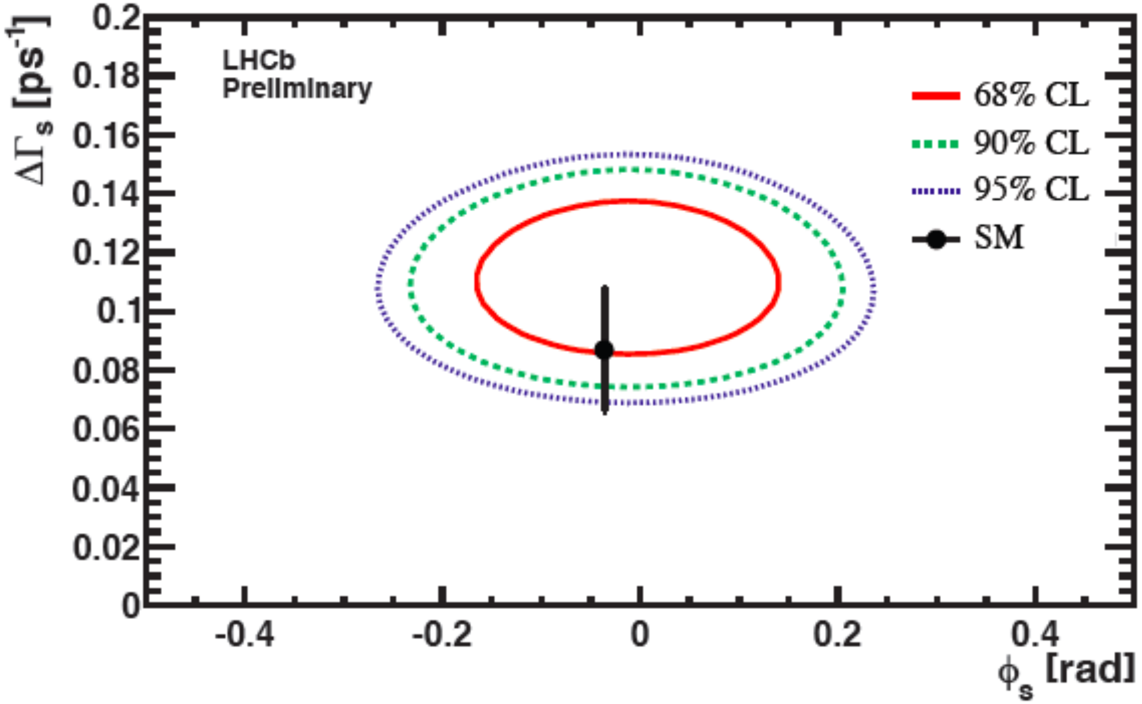
CPV in $B_S \rightarrow J/\psi\phi$

LHCb-CONF-2012-002

Fit of the tagged and the untagged rates as a function of B_S mass, proper time and angles.

Parameter	Value	Stat.	Syst.
Γ_s [ps^{-1}]	0.6580	0.0054	0.0066
$\Delta\Gamma_s$ [ps^{-1}]	0.116	0.018	0.006
$\|A_\perp(0)\|^2$	0.246	0.010	0.013
$\|A_0(0)\|^2$	0.523	0.007	0.024
F_S	0.022	0.012	0.007
$\delta_\perp$ [rad]	2.90	0.36	0.07
$\delta_\parallel$ [rad]	[2.81, 3.47]		0.13
δ_s [rad]	2.90	0.36	0.08
ϕ_s [rad]	-0.001	0.101	0.027

δ_0 set to 0
ΔM_S constrained to LHCb measurement
ΔM_S = (17.725 ± 0.041 ± 0.026) ps^{-1}
LHCb-CONF-2011-050



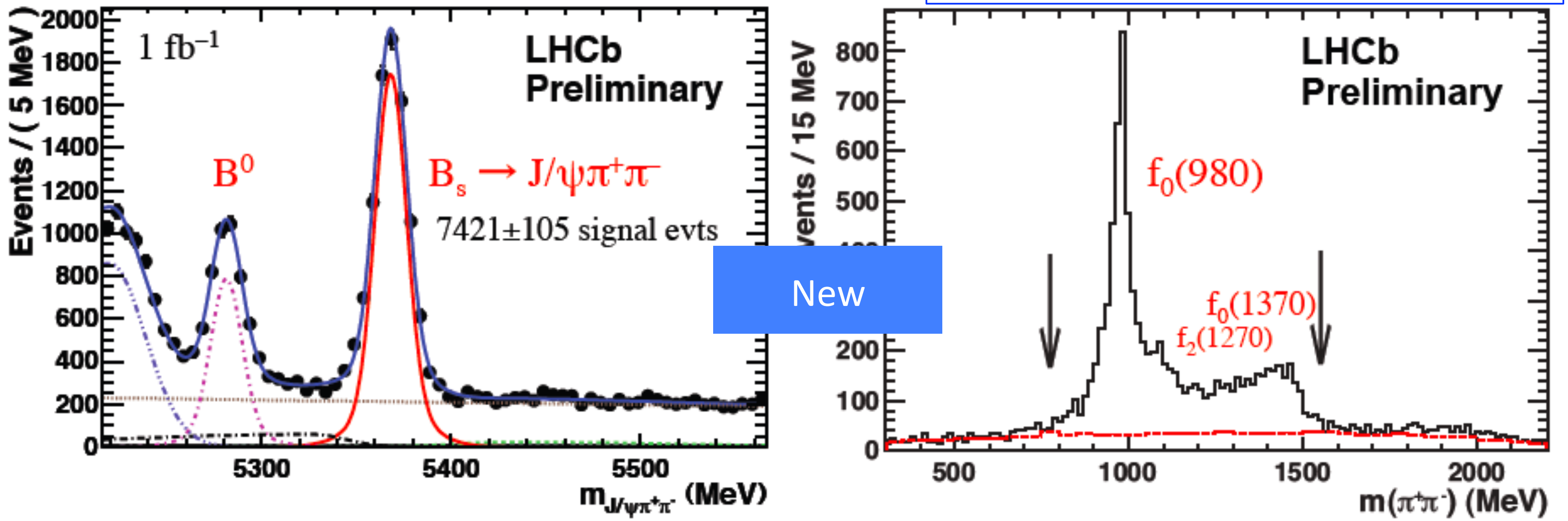
ϕ_S and $\Delta\Gamma_S$ are compatible with the SM prediction

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

"Amplitude analysis to determine CP content of J/ψππ".
LHCb-PAPER-2012-005
arXiv:1204.5643
submitted to PRD
"Tagged time-dependent analysis of J/ψππ".
LHCb-PAPER-2012-006
arXiv:1205.0918
submitted to PLB

Mass window $775 < m(\pi\pi) < 1550\ MeV/c^2$
Angular analysis shows CP-fraction > 97.7% at 95% C.L.

$\phi_s = -0.02 \pm 0.17 \pm 0.02$

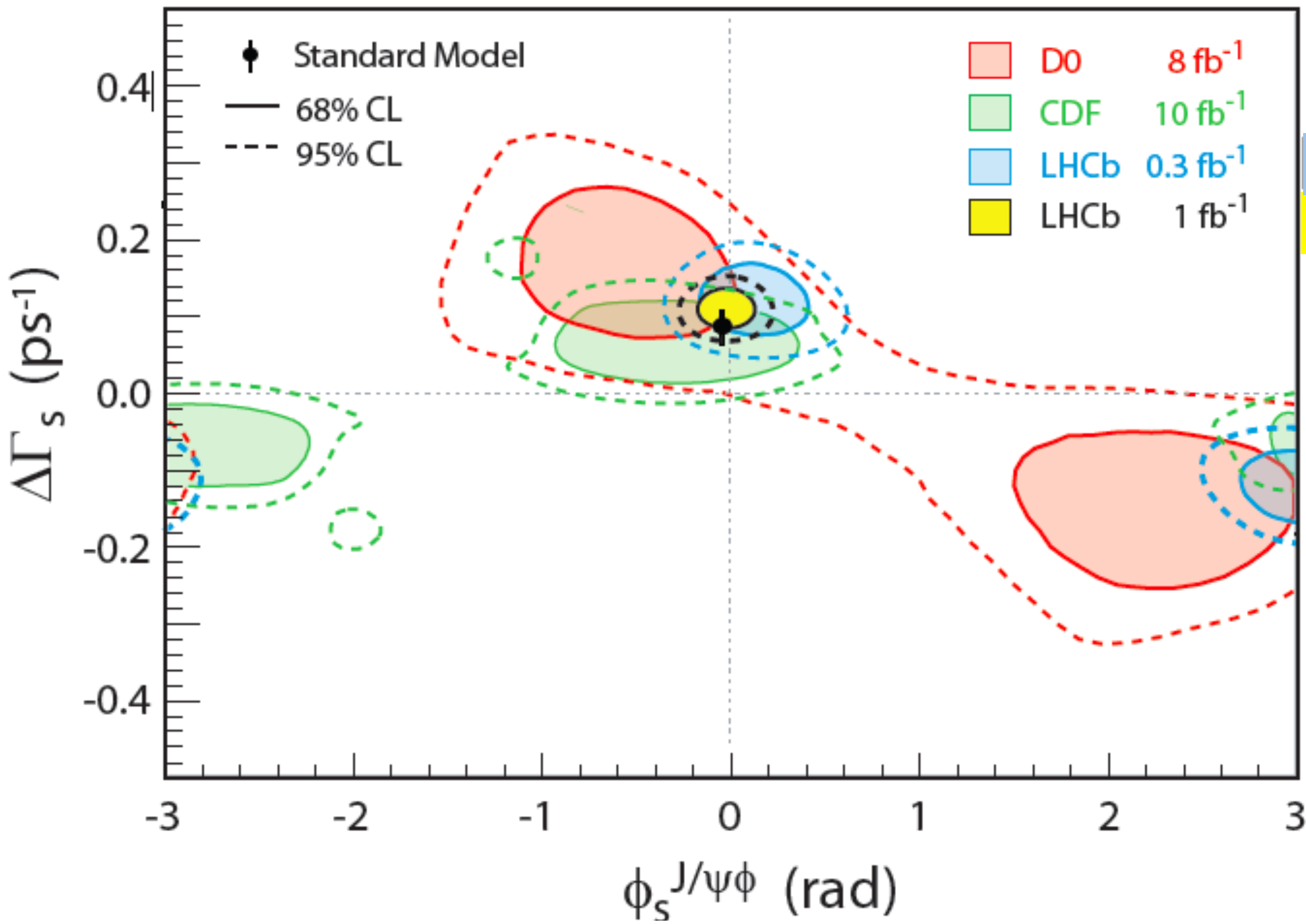


Combined 1 fb^{-1} results of the $B_s \to J/\psi\phi$ and $B_s \to J/\psi\pi^+\pi^-$:

$$\phi_s = -0.002 \pm 0.083 \pm 0.027$$

CPV in $B_s \rightarrow J/\psi\phi$

Just for illustration purposes …



PRD 85 (2012) 032006

CDF note 10778

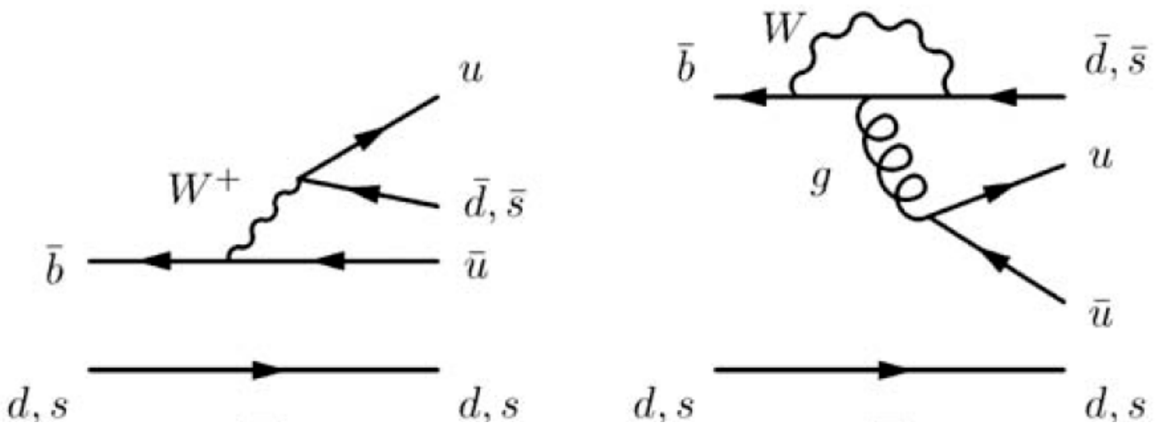
arXiv:1112.3183

LHCb-CONF-2012-002

LHCb result with the 2011 dataset corresponding to $1 fb^{-1}$

LHCb with $0.37\ fb^{-1}$

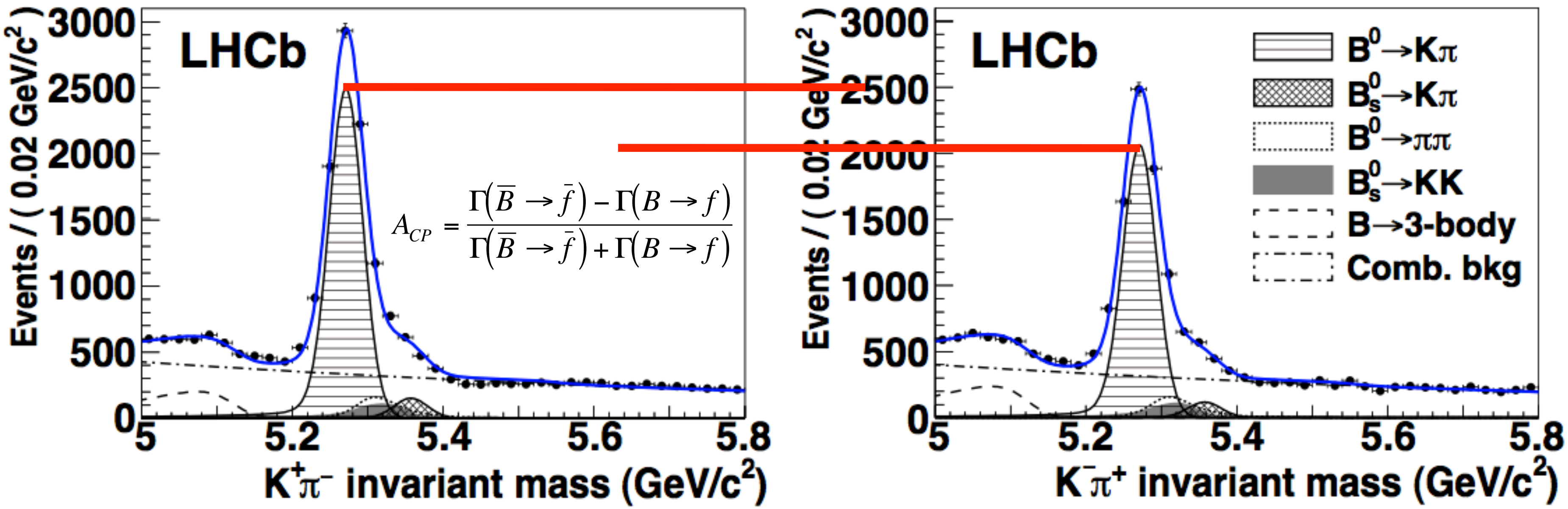
Charmless two bodies b-hadron decays



- Decay amplitudes from tree and penguin diagrams.
- Tree-penguin interference allows to look for direct CPV.
- Sensitive to V_{ub} so to the CKM-UT angle γ.
- New Physics possibly contributes to penguin loops.

Direct CPV in $B^0 \to K\pi$ (0.32 fb^{-1})

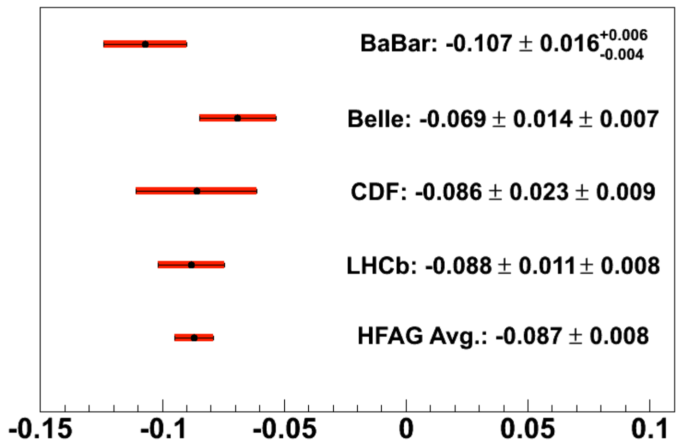
arXiv:1202.6251 (accepted by PRL) 13250 ± 150 $B^0 \to K\pi$



$$A_{CP} = \frac{\Gamma(\bar{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\bar{B} \to \bar{f}) + \Gamma(B \to f)}$$

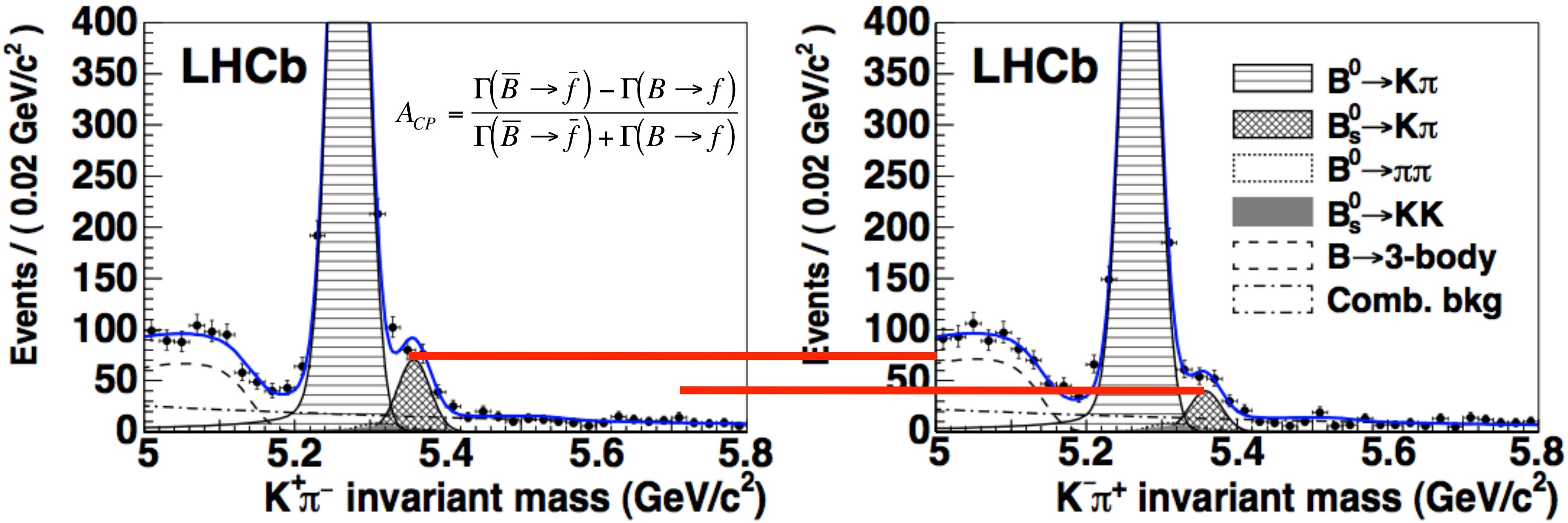
$$A_{CP}(B^0 \to K\pi) = -0.088 \pm 0.011\,(\text{stat}) \pm 0.008\,(\text{syst})$$

- First observation of CP violation at an hadron collider (> 6σ)



Direct CPV in $B_s \rightarrow \pi K$ ($0.32\ fb^{-1}$)

arXiv:1202.6251 (accepted by PRL) $314 \pm 27\ B_s \rightarrow \pi K$



$$A_{CP}(B_s^0 \to K\pi) = 0.27 \pm 0.08\,(\mathrm{stat}) \pm 0.02\,(\mathrm{syst})$$

First evidence of CP violation in B_s decays (3.3σ)

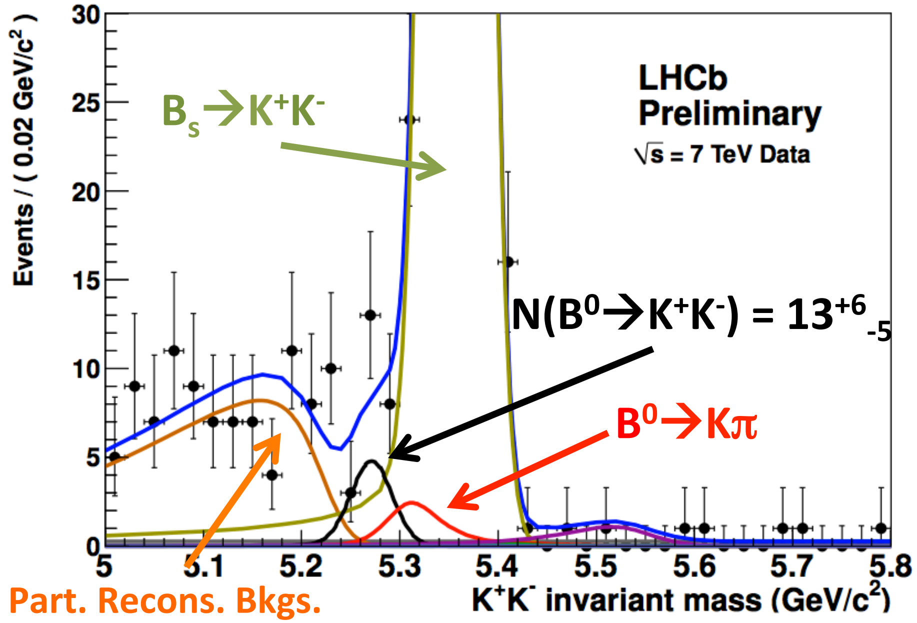
$A_{CP}(B_s \to \pi K) = 0.39 \pm 0.15 \pm 0.08$ CDF [Phys. Rev. Lett. 106 (2011) 181802]

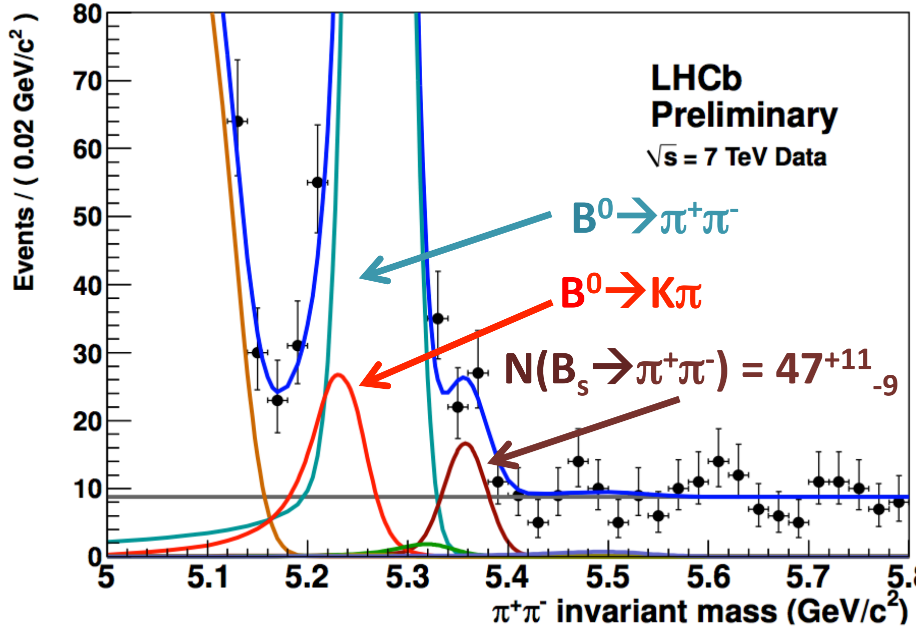
$$A_{CP}(B_s \to \pi K) \approx A_{dir}^{\pi\pi} = \begin{cases} 0.25 \pm 0.08 \pm 0.02 & \text{BaBar [arXiv:0807.4226]} \\ 0.55 \pm 0.08 \pm 0.05 & \text{Belle [PRL 98 (2007) 211801]} \end{cases}$$

Assuming U-spin symmetry

Annihilation topologies in B→h⁺h'⁻

LHCb-CONF-2011-042





$$\mathcal{BR}(B^0 \to K^+K^-) = (0.13^{+0.06}_{-0.05} \pm 0.07) \times 10^{-6}$$

$$\mathcal{BR}(B^0_s \to \pi^+\pi^-) = (0.98^{+0.23}_{-0.19} \pm 0.11) \times 10^{-6}$$

First observation of $B_s \to \pi^+\pi^-$ decay with a significance of 5.3σ

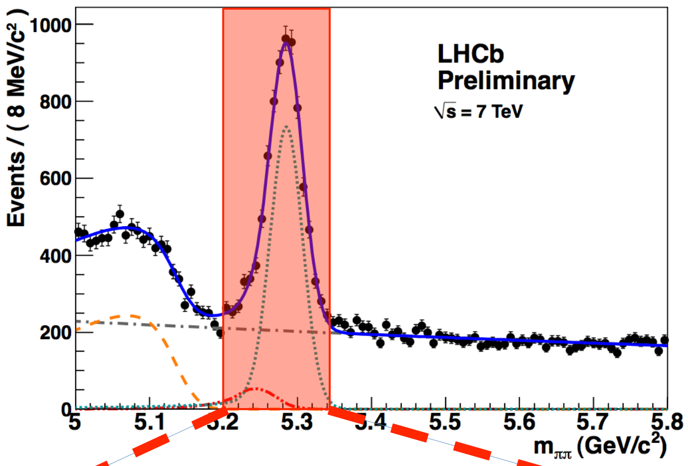
PRELIMINARY

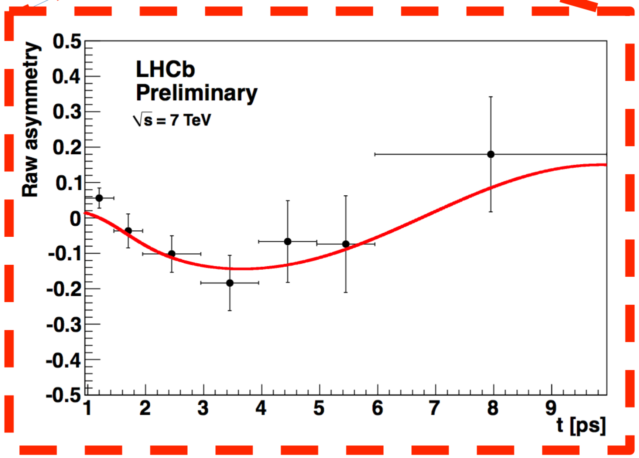
$BR(B^0 \to K^+K^-) = 0.13^{+0.10}_{-0.09} \times 10^{-6}$ HFAG Average

$BR(B_s \to \pi^+\pi^-) = (0.57 \pm 0.15 \pm 0.10) \times 10^{-6}$ CDF [arXiv:1111.0485v2]

Time-dependent CPV B→π⁺π⁻ (0.69 fb⁻¹)

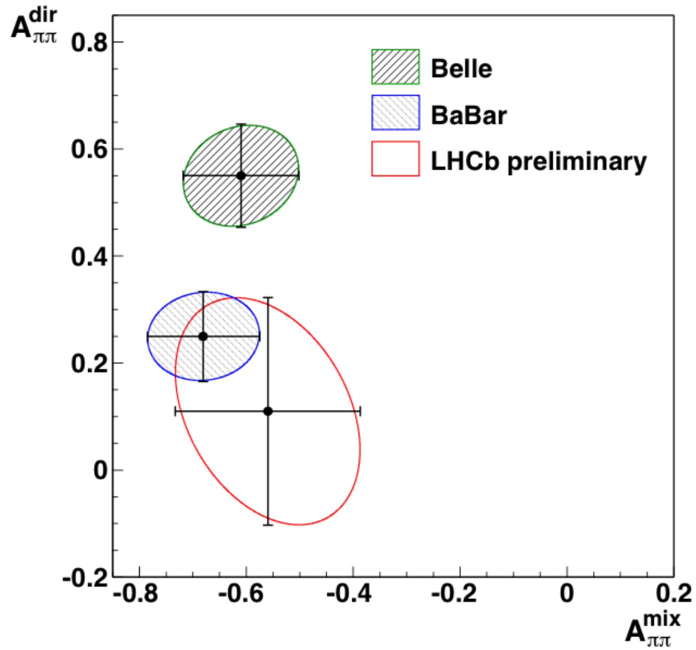
~ 5400 $B^0 \to \pi^+\pi^-$





First time-dependent CP asymmetry plot of $B^0 \to \pi^+\pi^-$ decay at a hadron collider

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



LHCb-CONF-2012-007

PRELIMINARY

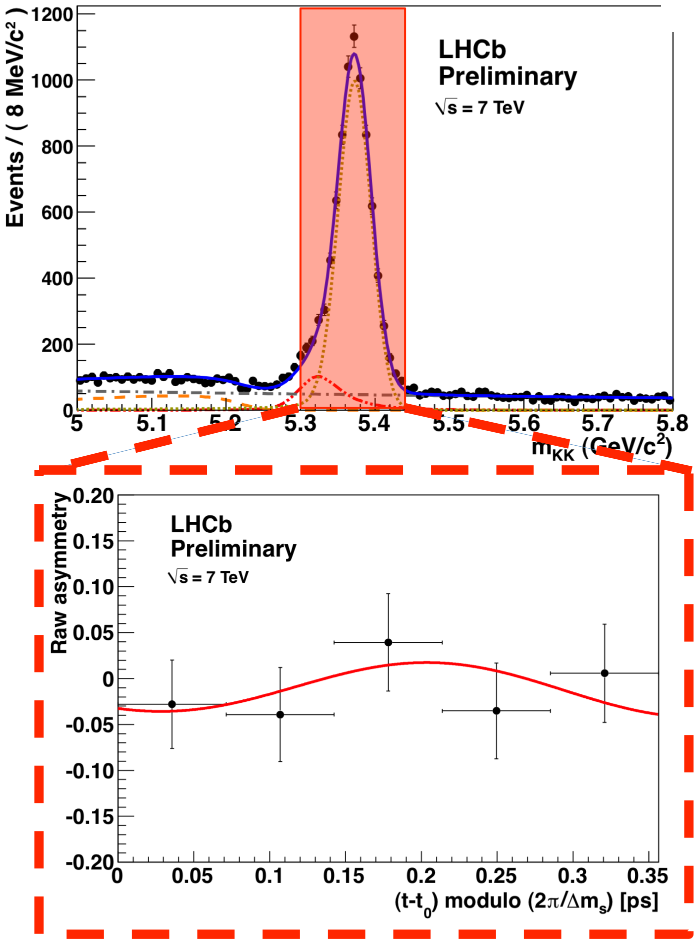
$$A_{\pi\pi}^{\rm dir} = 0.11 \pm 0.21 \pm 0.03$$
$$A_{\pi\pi}^{\rm mix} = -0.56 \pm 0.17 \pm 0.03$$
$$\rho(A_{\pi\pi}^{\rm dir}, A_{\pi\pi}^{\rm mix}) = -0.34.$$

A_{mix} is the first evidence of mixing-induced CP violation at an hadron collider (3.2σ)

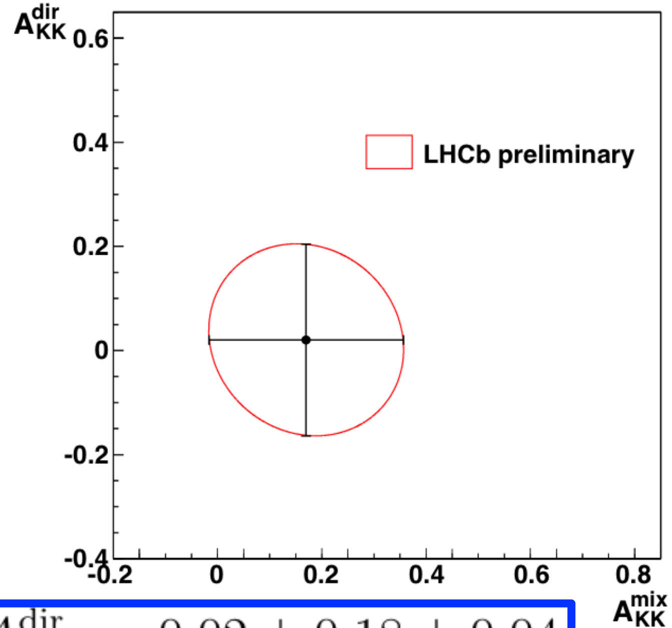
Time-dependent CPV $B_s \rightarrow K^+K^-$ (0.69 fb^{-1})

~7100 $B_s \rightarrow K^+K^-$

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



First time-dependent CP asymmetry plot of $B_s \rightarrow K^+K^-$ decay ever



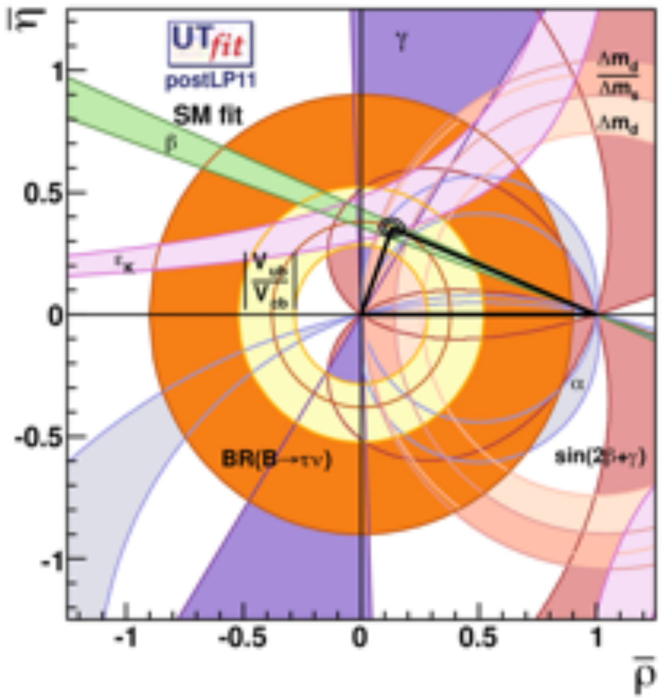
LHCb-CONF-2012-007

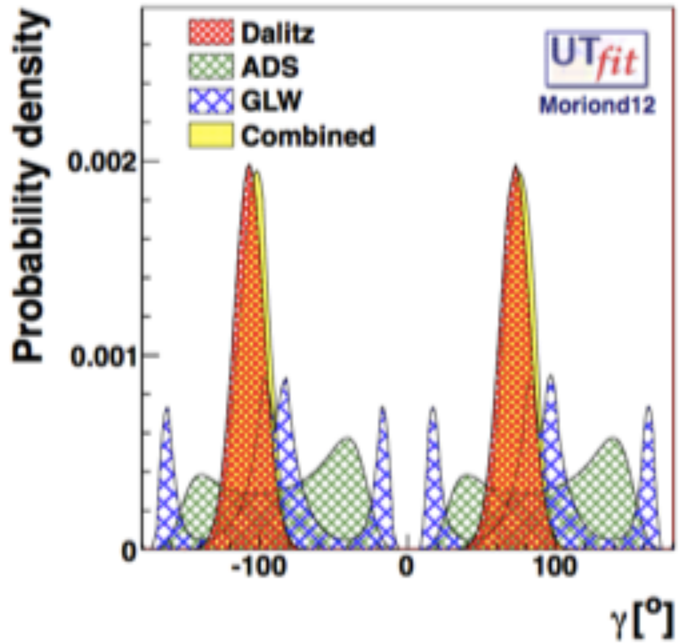
PRELIMINARY

$$A_{KK}^{\rm dir} = 0.02 \pm 0.18 \pm 0.04$$
$$A_{KK}^{\rm mix} = 0.17 \pm 0.18 \pm 0.05$$
$$\rho(A_{KK}^{\rm dir}, A_{KK}^{\rm mix}) = -0.10.$$

- First measurement ever of time-dependent CP asymmetries of the $B_s \rightarrow K^+K^-$ decay
- No evidence of CP violation effect

γ measurements





γ_{Comb} is the combination of the available results including all the data available after Moriond 2012 (thus with updates of LHCb analyses to 1 fb-1).

γ_{SM} is the fit prediction from the SM using post LP11 results.

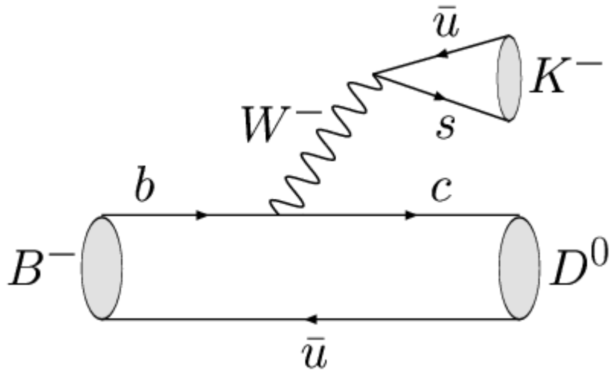
$$\gamma_{comb} = (75.5 \pm 10.5)^\circ$$

$$\gamma_{SM} = (68.5 \pm 3.2)^\circ$$

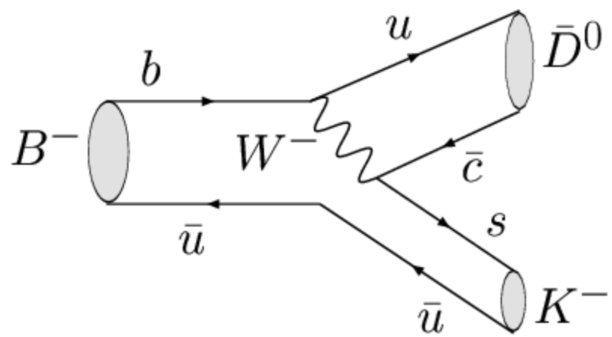
γ from B→DK

- γ plays a unique role in flavour physics:
  It is the only CP violating parameter that can be measured through tree decays.
- It is a benchmark Standard Model reference point.

$A(B^- \to D^0 K^-) \propto V_{cb}V^*_{us}$



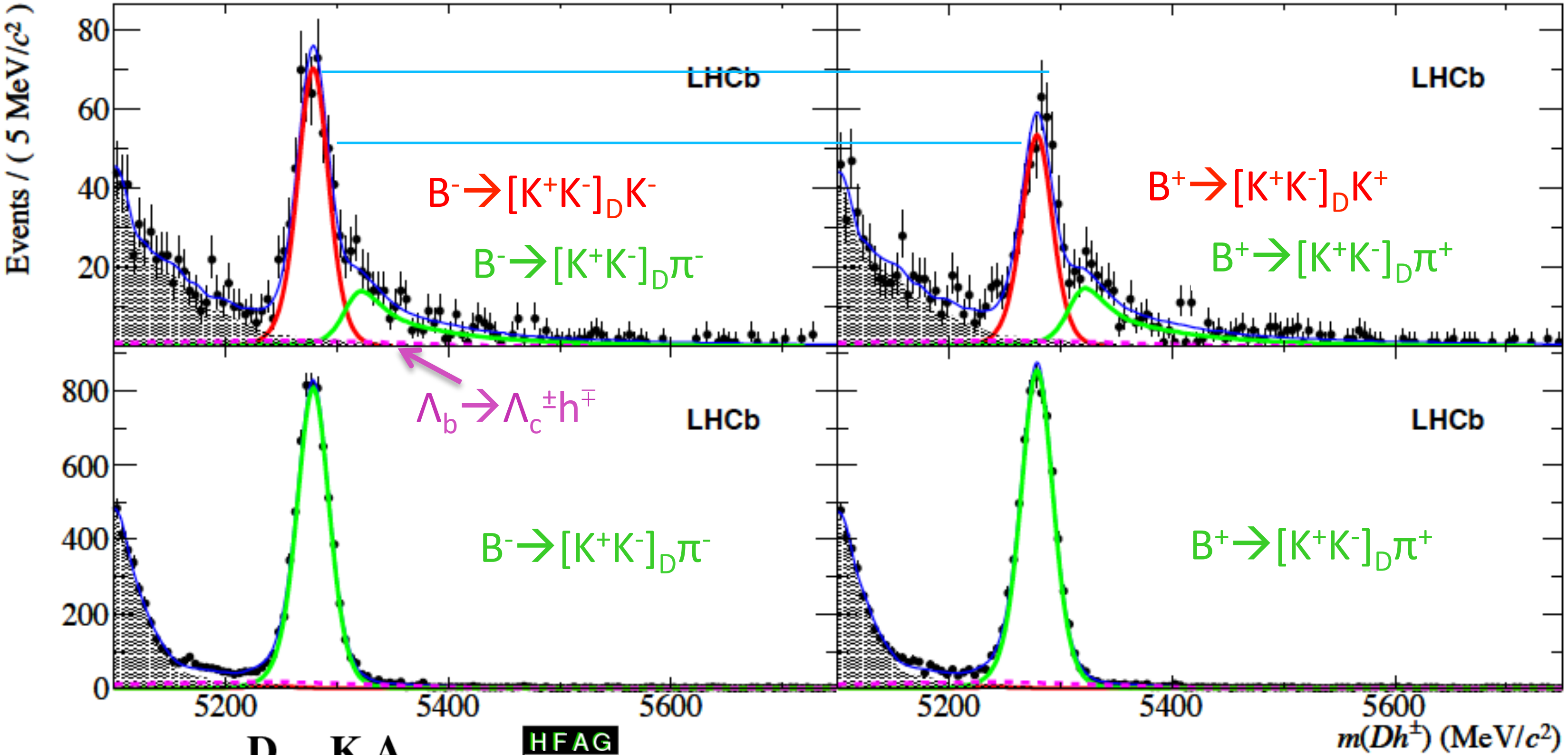
$A(B^- \to \bar{D}^0 K^-) \propto \mathbf{V_{ub}}V^*_{cs}$



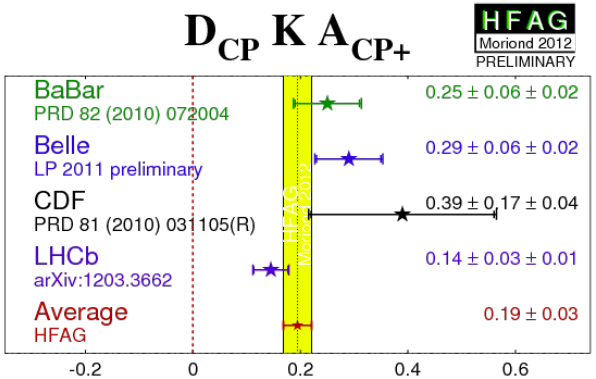
Variants use different B or D decays and require a final state common to both D^0 and D^0-bar

Latest results on $B \rightarrow D_{CP}K$ (GLW)

5.8 σ evidence for direct CP violation in $B^{\pm} \rightarrow D(K^{+}K^{-})K^{\pm}$



LHCb arXiv:1203.3662
Submitted to PLB



$$A_h^f = \frac{\Gamma(B^- \to [f]_D h^-) - \Gamma(B^+ \to [f]_D h^+)}{\Gamma(B^- \to [f]_D h^-) + \Gamma(B^+ \to [f]_D h^+)},$$

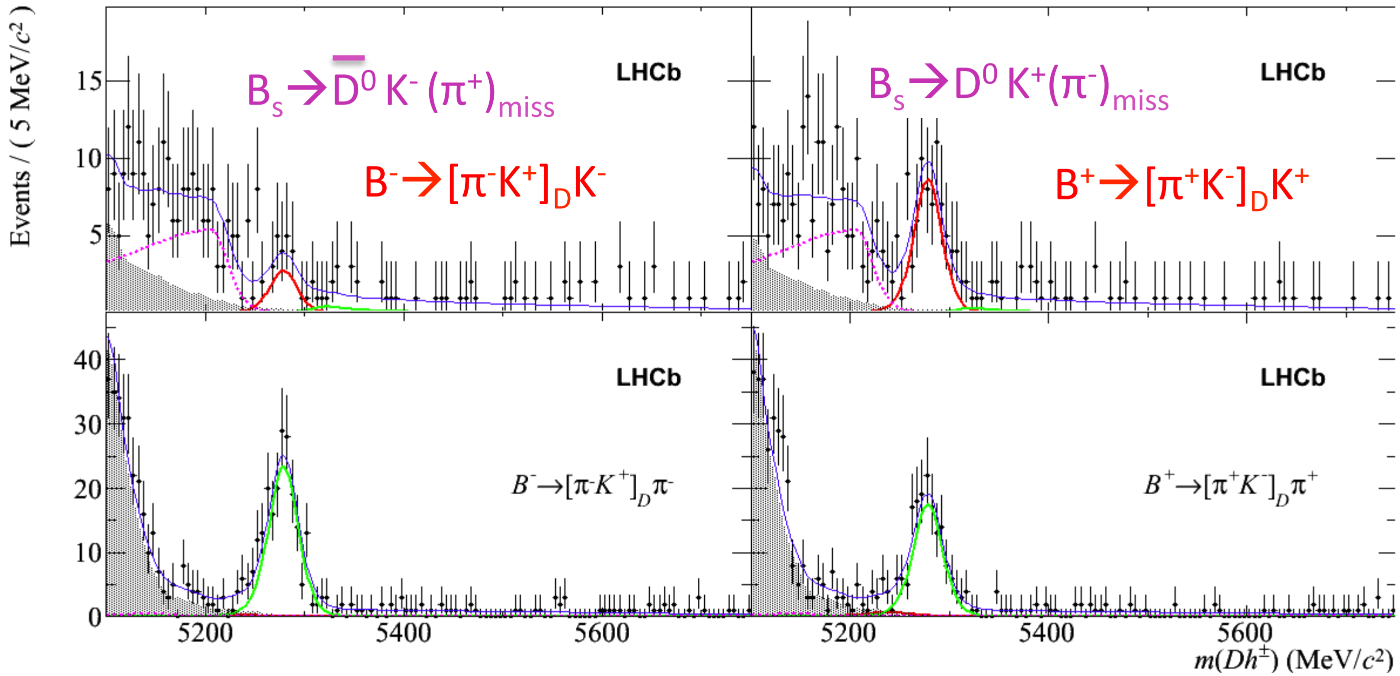
D → KK, ππ, CP egeinstates:
M. Gronau and D. London, Phys. Lett. B253 (1991) 483;
M. Gronau and D. Wyler, Phys. Lett. B265 (1991) 172.

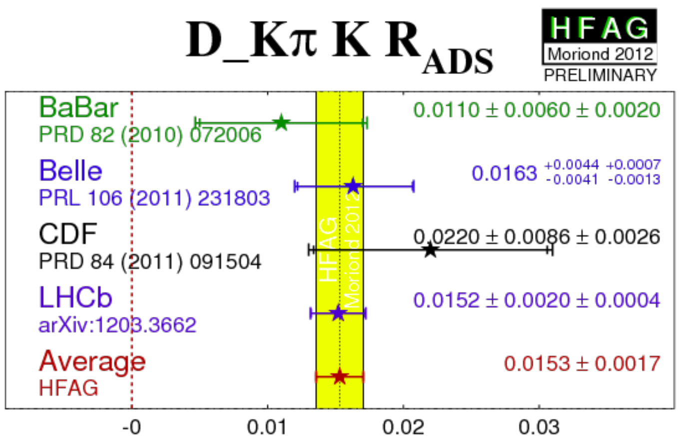
Latest results on B→D(πK)K (ADS)

First observation of suppressed mode $B^{\pm} \to [\pi^{\pm}K^{\mp}]_D K^{\pm}$

Evidence for direct CP violation

LHCb arXiv:1203.3662
Submitted to PLB





$$R^f_{K/\pi} = \frac{\Gamma(B^- \to [f]_D K^-) + \Gamma(B^+ \to [f]_D K^+)}{\Gamma(B^- \to [f]_D \pi^-) + \Gamma(B^+ \to [f]_D \pi^+)},$$

The favoured, b → c decay to be followed by a doubly Cabibbo-suppressed D decay, and the suppressed b → u decay to precede a favoured D decay. The amplitudes of such combinations are of similar total magnitude and hence large interference can occur.

D. Atwood, I. Dunietz, and A. Soni , Phys. Rev. Lett. 78 (1997) 3257;
D. Atwood, I. Dunietz, and A. Soni,, Phys. Rev. D63 (2001) 036005,

Evidence of CPV in charm

LHCb PRL 108 (2012) 111602

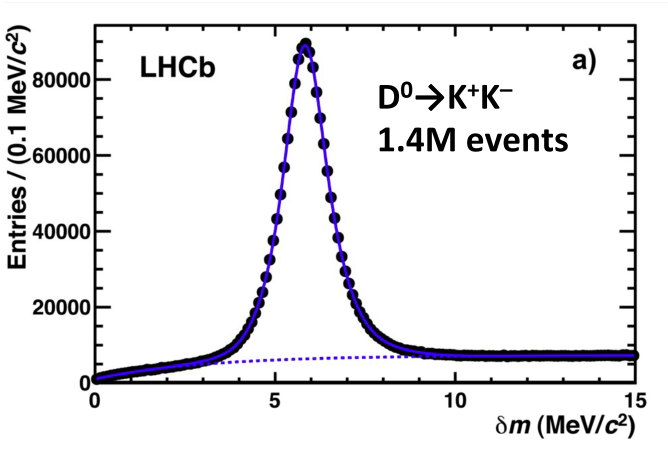
Measurement of CP asymmetry at pp collider requires knowledge of production and detection asymmetries; e.g. for $D^0 \rightarrow f$, where D meson flavour is tagged by $D^{*+} \rightarrow D^0 \pi^+$ decay

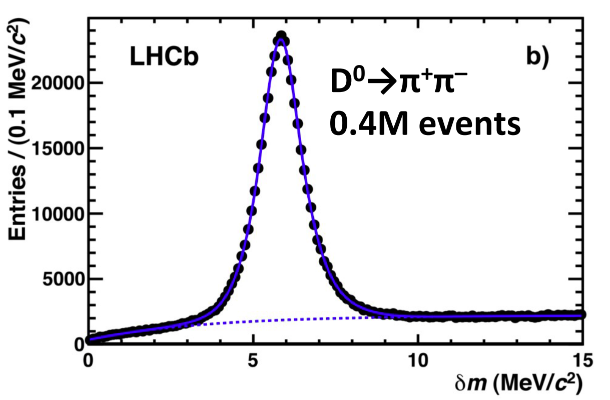
$$A_{\rm raw}(f) = A_{CP}(f) + A_{\rm D}(f) + A_{\rm D}(\pi_{\rm s}^{+}) + A_{\rm P}(D^{*+}).$$

Final state detection asymmetry $A_D(f)$ vanishes for CP eigenstate

Cancel asymmetries by taking difference of raw asymmetries in two different final states.

$$\Delta A_{CP} = A_{\rm raw}(K^{-}K^{+}) - A_{\rm raw}(\pi^{-}\pi^{+}).$$

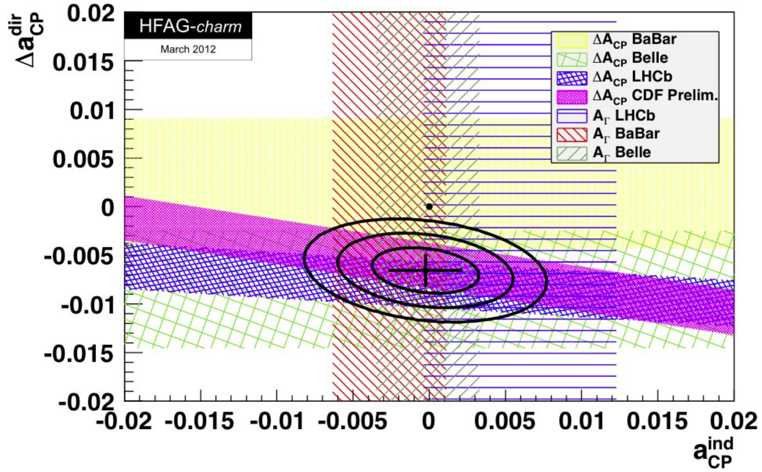




0.62/fb

Evidence of CPV in charm

Result, based on 0.62/fb of 2011 data
ΔA_{CP} = [−0.82 ±0.21(stat.) ± 0.11(syst.)]%



LHCb PRL 108 (2012) 111602

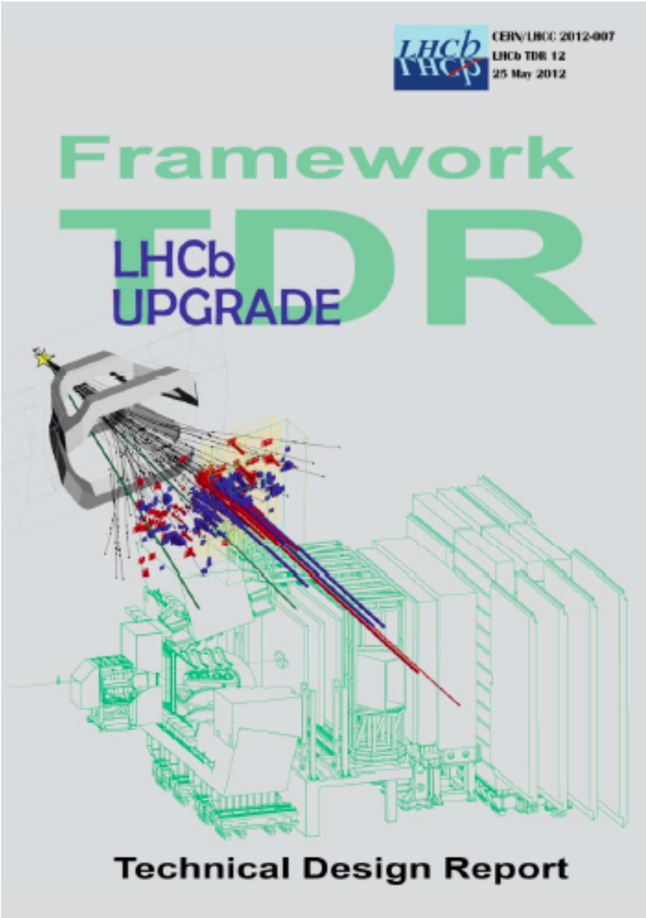
ΔA_{CP} related mainly to direct CP violation:
The contribution from indirect CPV suppressed by difference in mean decay time.

$$\Delta A_{CP} \equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$$
$$= [a_{CP}^{\rm dir}(K^-K^+) - a_{CP}^{\rm dir}(\pi^-\pi^+)] + \frac{\Delta\langle t\rangle}{\tau} a_{CP}^{\rm ind}.$$

Evidence for CPV in charm

- Implications of the LHCb Evidence for Charm CP Violation. arXiv:1111.4987
- Direct CP violation in two-body hadronic charmed meson decays. arXiv: 1201.0785
- CP asymmetries in singly-Cabibbo-suppressed D decays to two pseudoscalar mesons. arXiv:1201.2351
- Direct CP violation in charm and flavor mixing beyond the SM. arXiv:1201.6204
- New Physics Models of Direct CP Violation in Charm Decays. arXiv:1202.2866
- Repercussions of Flavour Symmetry Breaking on CP Violation in D-Meson Decays. arXiv:1202.3795
- On the Universality of CP Violation in Delta F = 1 Processes. arXiv:1202.5038
- The Standard Model confronts CP violation in $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$. arXiv:1203.3131
- A consistent picture for large penguins in $D^0 \to \pi^+\pi^-$, K^+K^-. arXiv:1203.6659
- …
- … and many others!
  Further experimental input needed to clarify whether CPV is SM or NP

LHCb upgrade



- Run at a nominal luminosity of:

  $L=1. \times 10^{33}\ cm^{-2}s^{-1}$

- Exploit a fully flexible HLT (software trigger), selecting events synchronously with the BX clock, at 40 MHz.
  - Increase signal efficiency for leptonic channels by a factor 5 and for hadronic channels up to a factor 10.
- Accumulate 50 fb^{-1} over 10 years starting from 2018
- For reasons of flexibility and to allow for possible evolutions of the trigger, LHCb decided to design those detectors that need replacement for the upgrade such that they can sustain a minimal luminosity of $L=2.\times10^{33}\ cm^{-2}\ s^{-1}$.

CERN/LHCC 2012-007, LHCb TDR 12, 25 May 2012

LHCb sensitivity to key channels

CERN/LHCC 2012-007, LHCb TDR 12, 25 May 2012 | 5 fb^{-1} | 50 fb^{-1}

Type	Observable	Current precision	LHCb 2018	Upgrade (50 fb^{-1})	Theory uncertainty
B_s^0 mixing	$2\beta_s$ $(B_s^0 \to J/\psi\ \phi)$	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s$ $(B_s^0 \to J/\psi\ f_0(980))$	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\mathrm{fs}}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$	–	0.13 %	0.03 %	0.02 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\ A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	8 %	2.5 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %	~ 10 %
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	γ $(B \to D^{(*)}K^{(*)})$	$\sim 20^\circ$ [19]	4°	0.9°	negligible
	γ $(B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	β $(B^0 \to J/\psi\ K_S^0)$	0.8° [18]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–

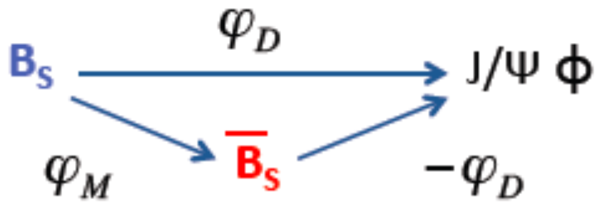
Summary

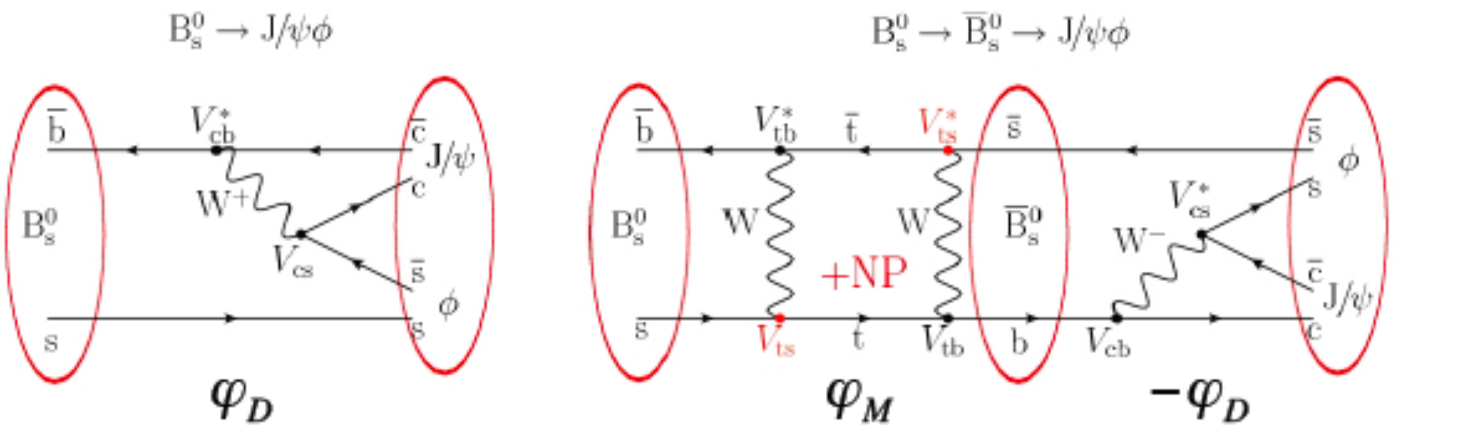
- Concept of LHCb definitely proved.
  - Dedicated experiment for heavy flavour physics exploiting a forward spectrometer at a hadron collider.
- Many world leading results already with 2011 data and many more to come.
  - Significant increase in available samples with 2012 data.
- Standard Model still survives.
  - Now on probing regions where new physics effects might appear.
- LHCb plan the upgrade to be installed in 2018.
  - Essential next step forward for flavour physics.

Spares

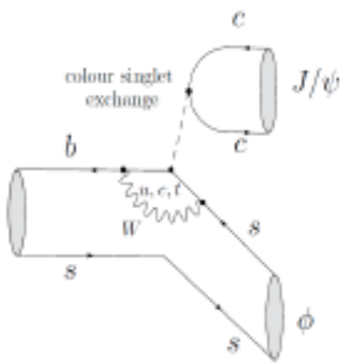
Mixing-induced CPV in $B_S \to J/\psi\phi$

The interfering amplitudes





$$\Phi_{SM} = \varphi_M - \varphi_D - \varphi_D = 2\arg\left(V_{ts}^{*}V_{tb}\right) - 2\arg\left(V_{cb}^{*}V_{cs}\right) + \delta_{Penguin} \cong -2\beta_S$$



Penguin contribution to the decay amplitude

$\sim A\lambda^4(\rho + i\eta)$

Standard Model

$$\beta_s = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

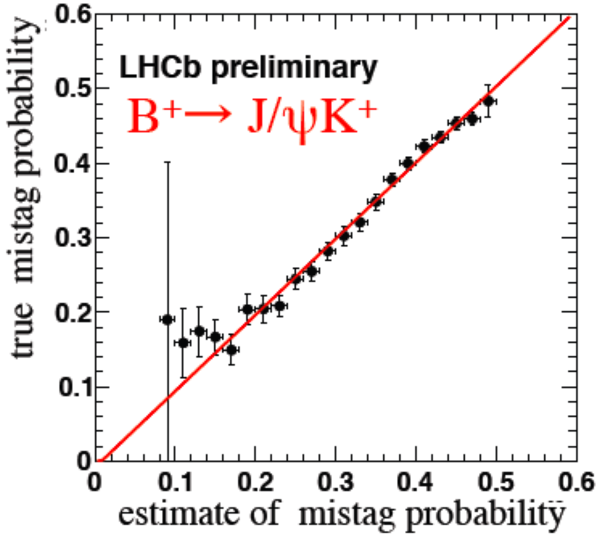
$\beta_S = 0.018 \pm 0.001$

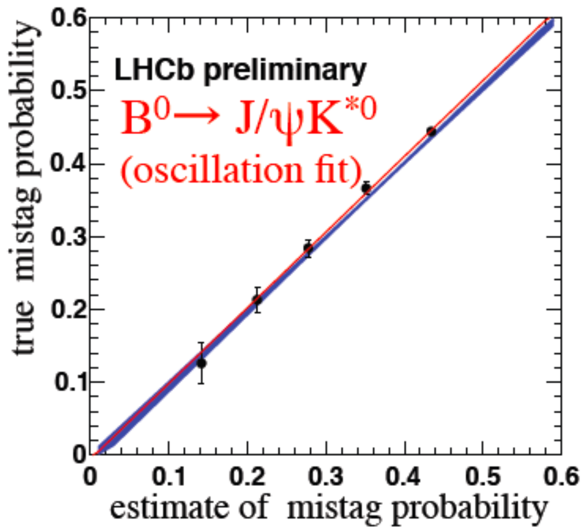
Tagging

- Tag the initial B_s flavour state with the other b-hadron.
- Electron, muon, kaon, or inclusively reconstructed vertex.
- Per-event mistag-probability from neural network trained on MC.
- Calibration of the per-event mistag probability using flavour specific decays similar to $B_s \to J/\psi\phi$

LHCb, arXiv:1202.4979
Submitted to EPJC

LHCb-CONF-2012-002



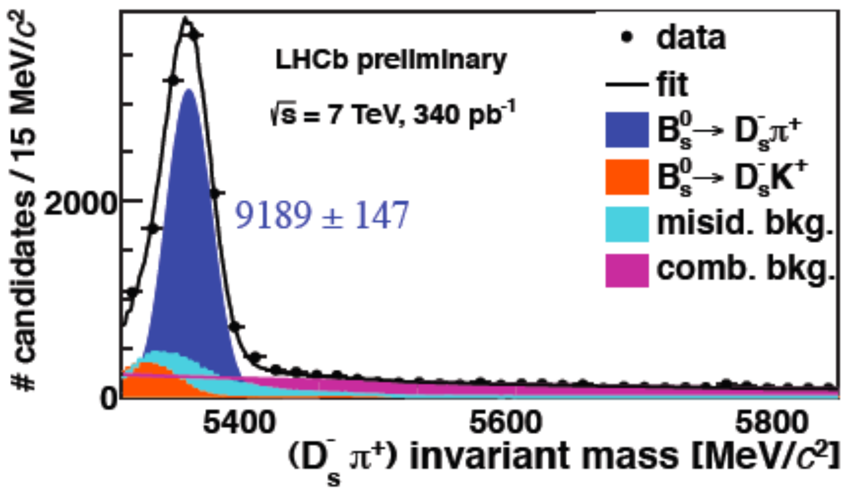


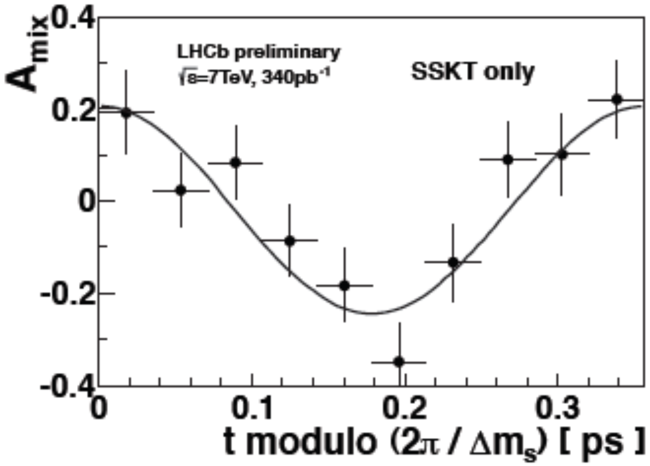
Tagging power for $B_s \to J/\psi\phi$: $\varepsilon D^2 = (2.29 \pm 0.07 \pm 0.26)\%$
To be added yet: "same-side" tagging, using charged kaon produced in association with B_s.

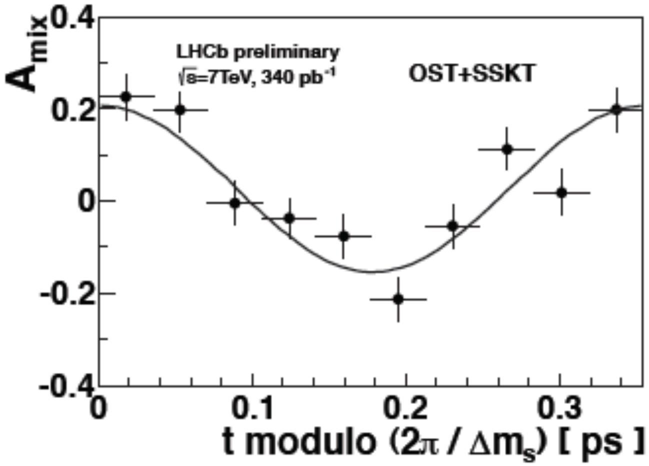
Same side tagging and ΔM_S

- ΔM_S analysis done with $B_S \rightarrow D_S^- (K^- K^+ \pi^-) \pi^+$
- Same Side Kaon Tagging global calibration tested with D_S^- decays: $\varepsilon D^2 = (1.3 \pm 0.4)\%$
- For the future: optimization and per-event calibration with ΔMs oscillations.
- Opposite Side Tagging per event calibration done with $B^0 \rightarrow D^- \pi^+$, ΔM_d oscillation: $\varepsilon D^2 = (3.1 \pm 0.8)\%$
- $\Delta M_S = (17.725 \pm 0.041 \pm 0.026)\ ps^{-1}$ using a combination of the opposite-side and same-side tagging algorithms.

340 pb^{-1}







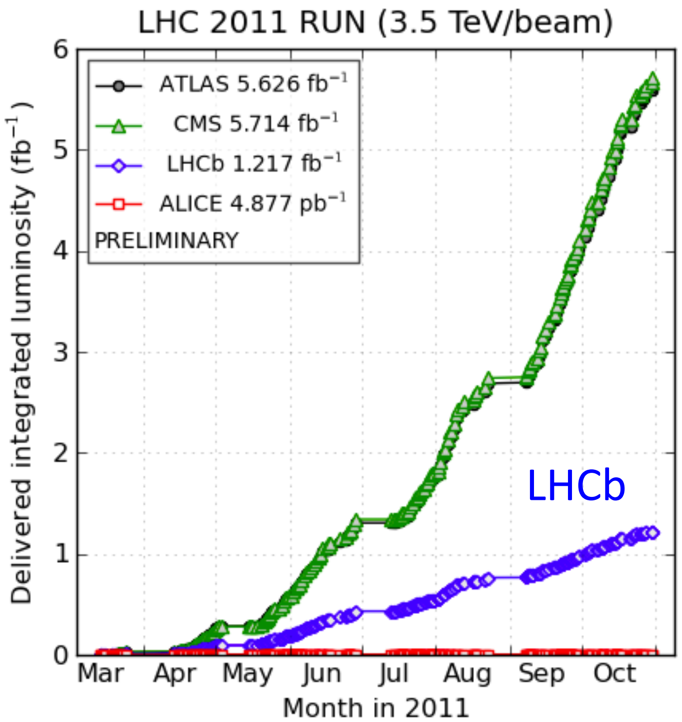
LHCb published
$\Delta M_S = (17.63 \pm 0.11 \pm 0.01)\ ps^{-1}$

independent of "2010" result
$\Delta m_s = 17.63 \pm 0.11 \pm 0.01\ ps^{-1}$
LHCb, PLB 709 (2012) 177

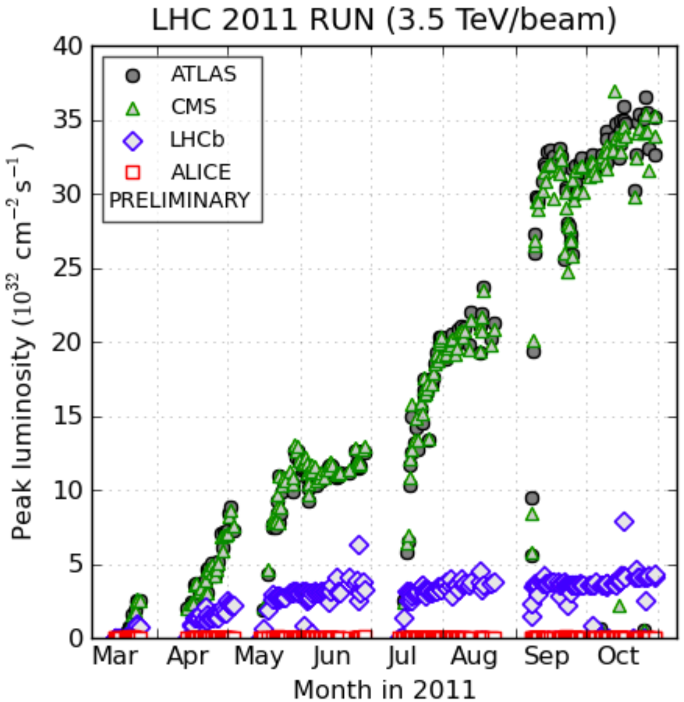
LHCb-CONF-2011-050

LHCb performance in 2011

Integrated luminosity



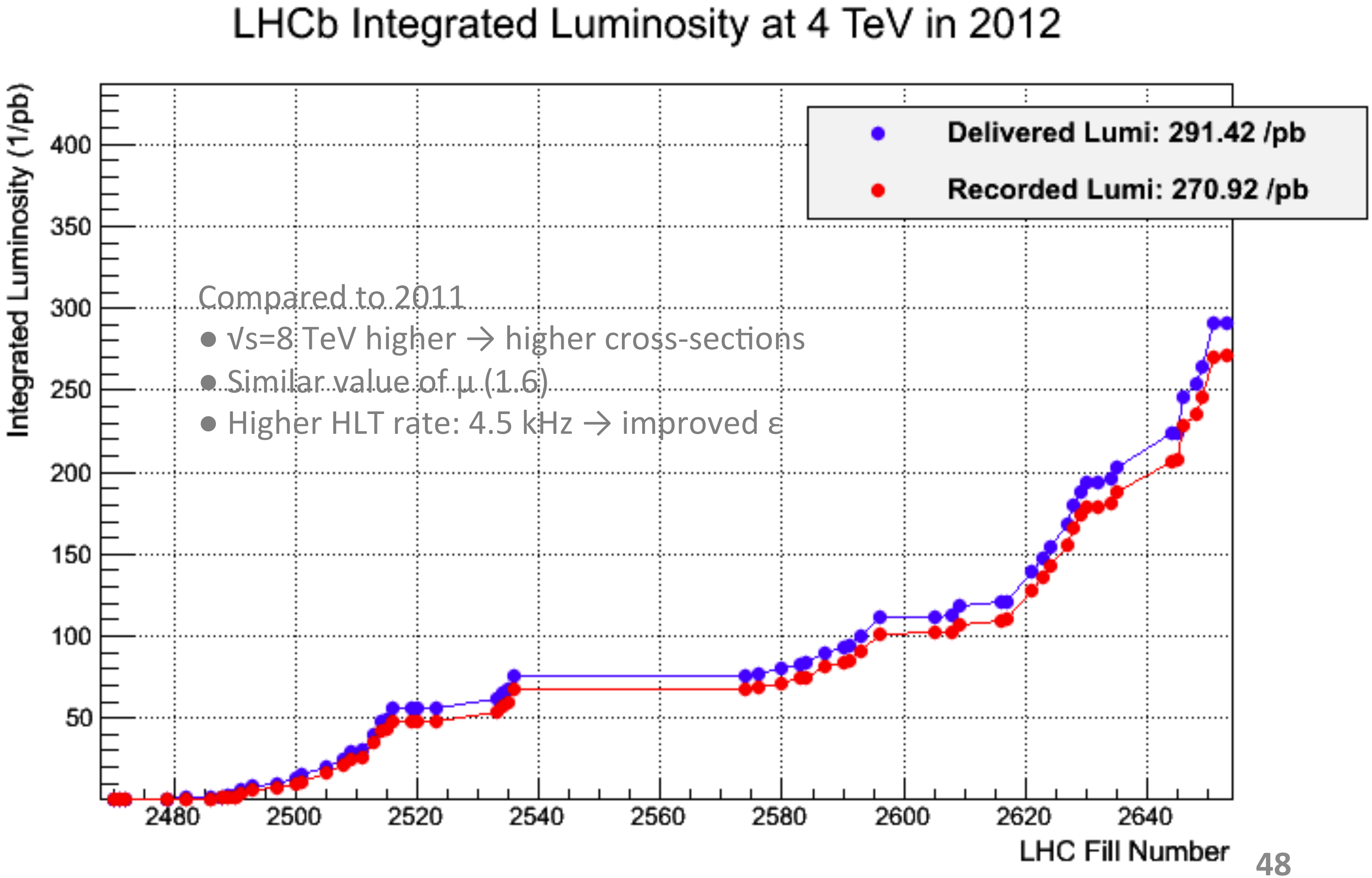
Peak instantaneous luminosity



Delivered luminosity: 1.2195 fb^{-1}
Recorded luminosity: 1.1067 fb^{-1}
Average #interactions/visible event (μ) ~ 1.5
c.f. design value ~ 0.4;
2010 data taking up to 2.5

What does ∫Ldt = 1/fb mean?
10^{15} x 75.3 x 10^{-6} ~ 10^{11} beauty produced
LHCb has world's largest data sample for any channel where the efficiency is not too small.
BaBar and Belle combined: 10^9 BB-bar recorded.

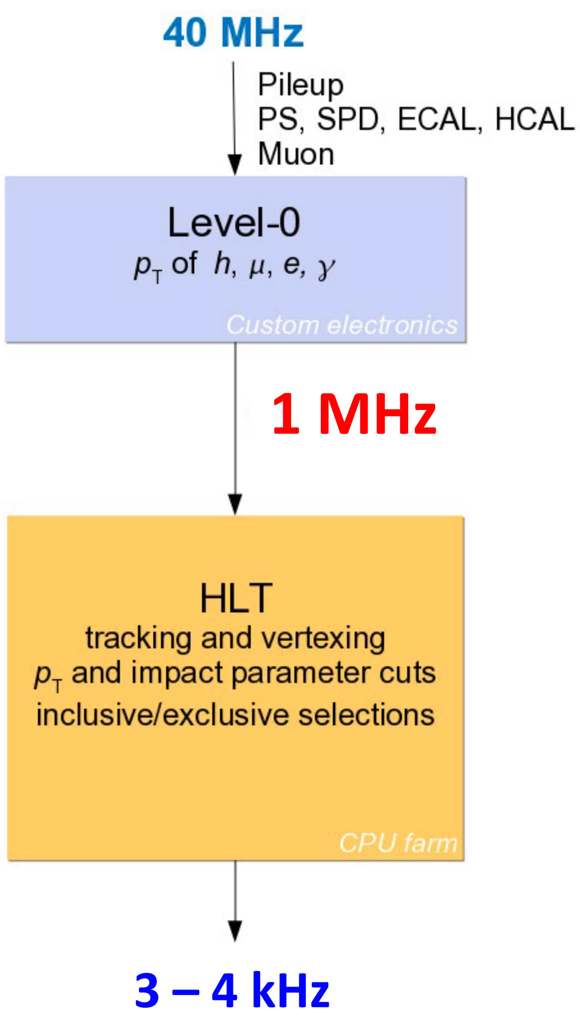
2012 data taking (so far)



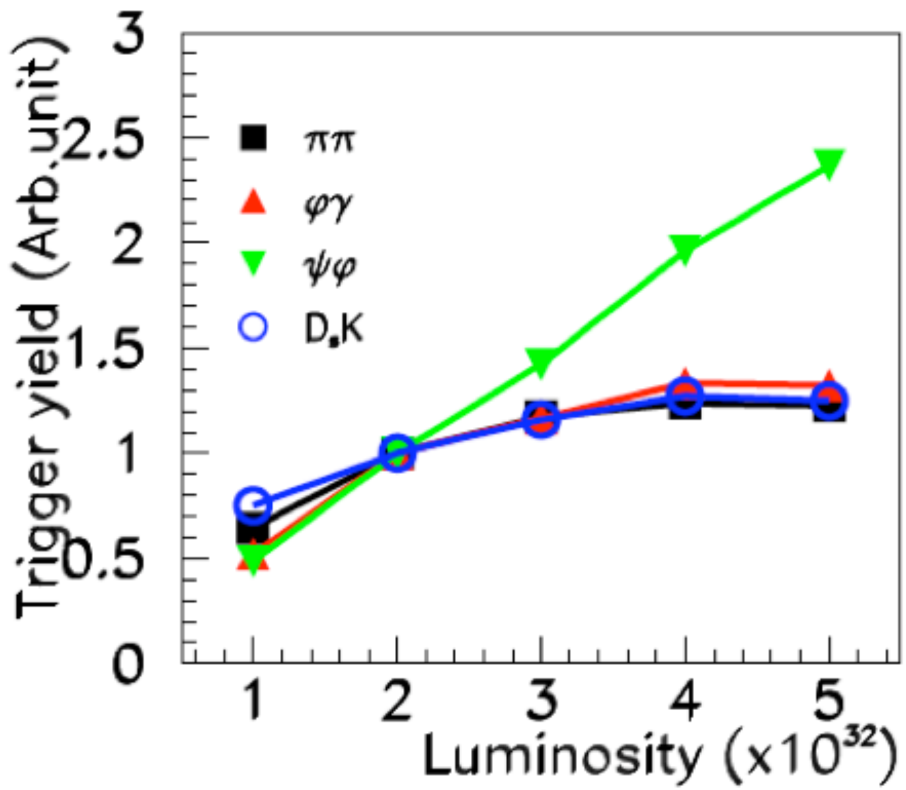
Compared to 2011

- √s=8 TeV higher → higher cross-sections
- Similar value of μ (1.6)
- Higher HLT rate: 4.5 kHz → improved ε

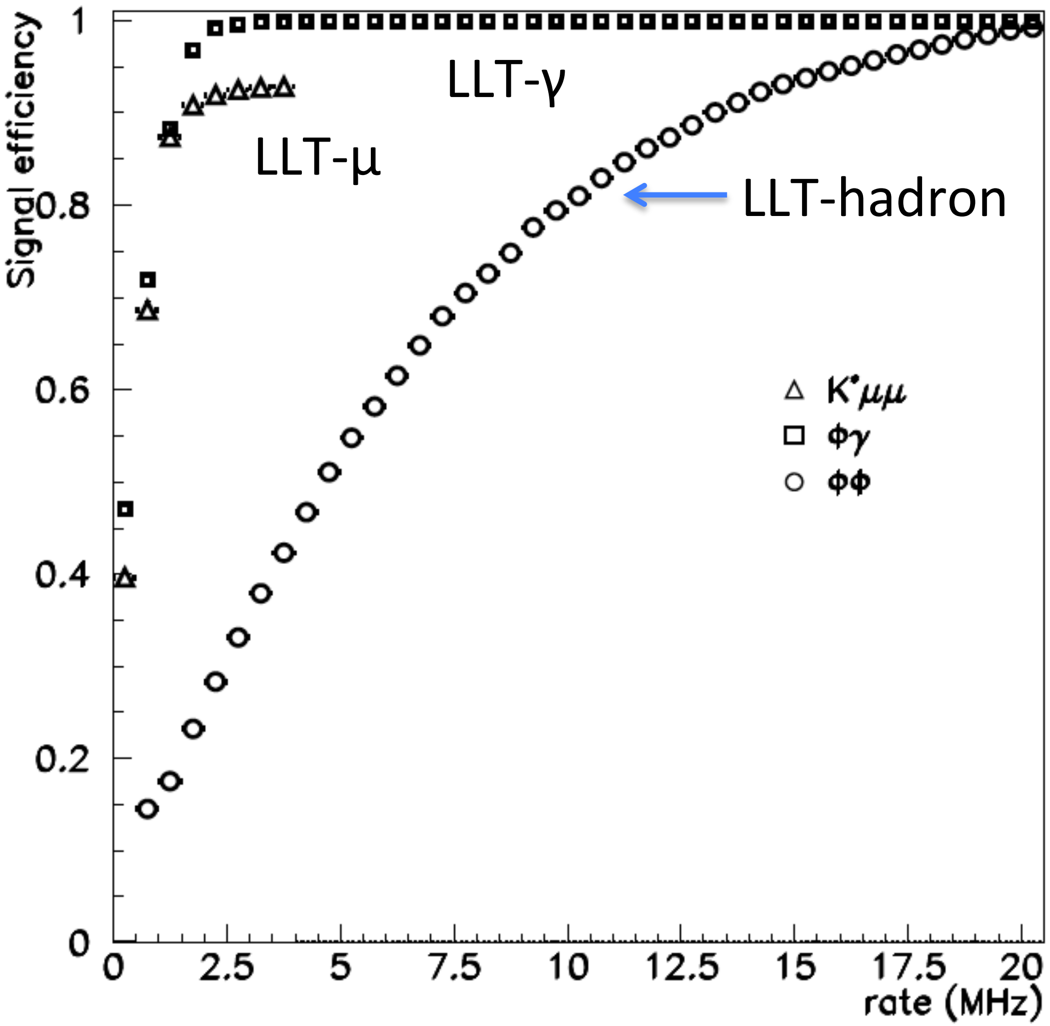
The present L0 trigger architecture



1 MHz L0 trigger rate limitation



LLT efficiency vs LLT output rate



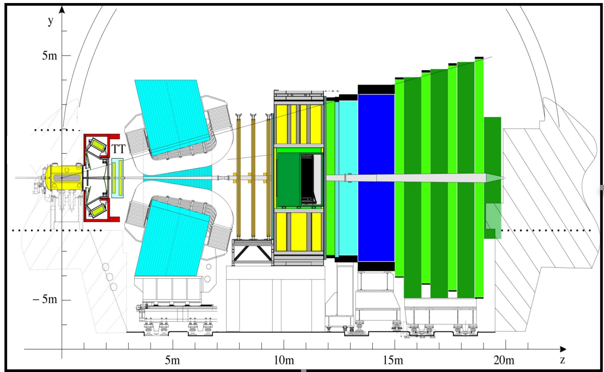
LLT efficiency

LLT-rate (MHz)	1	5	10
$B_s \to \phi\phi$	0.12	0.51	0.82
$B^0 \to K^*\mu\mu$	0.36	0.89	0.97
$B_s \to \phi\gamma$	0.39	0.92	1.00

Relative rates LLT-μ : LLT-hadron: LLT-e/γ = 1:3:1.

Trigger: the key to higher luminosity

All the sub-detectors information to the readout at 40 MHz



40 MHz

LLT
p_T of h,μ, e/γ

Custom electronics

40 MHz

LLT trigger rate 10 – 30 MHz

Bandwidth presently limited to 1MHz

READ-OUT
TELL40
Custom electronics

FCTS

40 MHz

HLT
Tracking and vertexing
p_T and impact parameter cuts
Inclusive/exclusive selections
Event Filter Farm

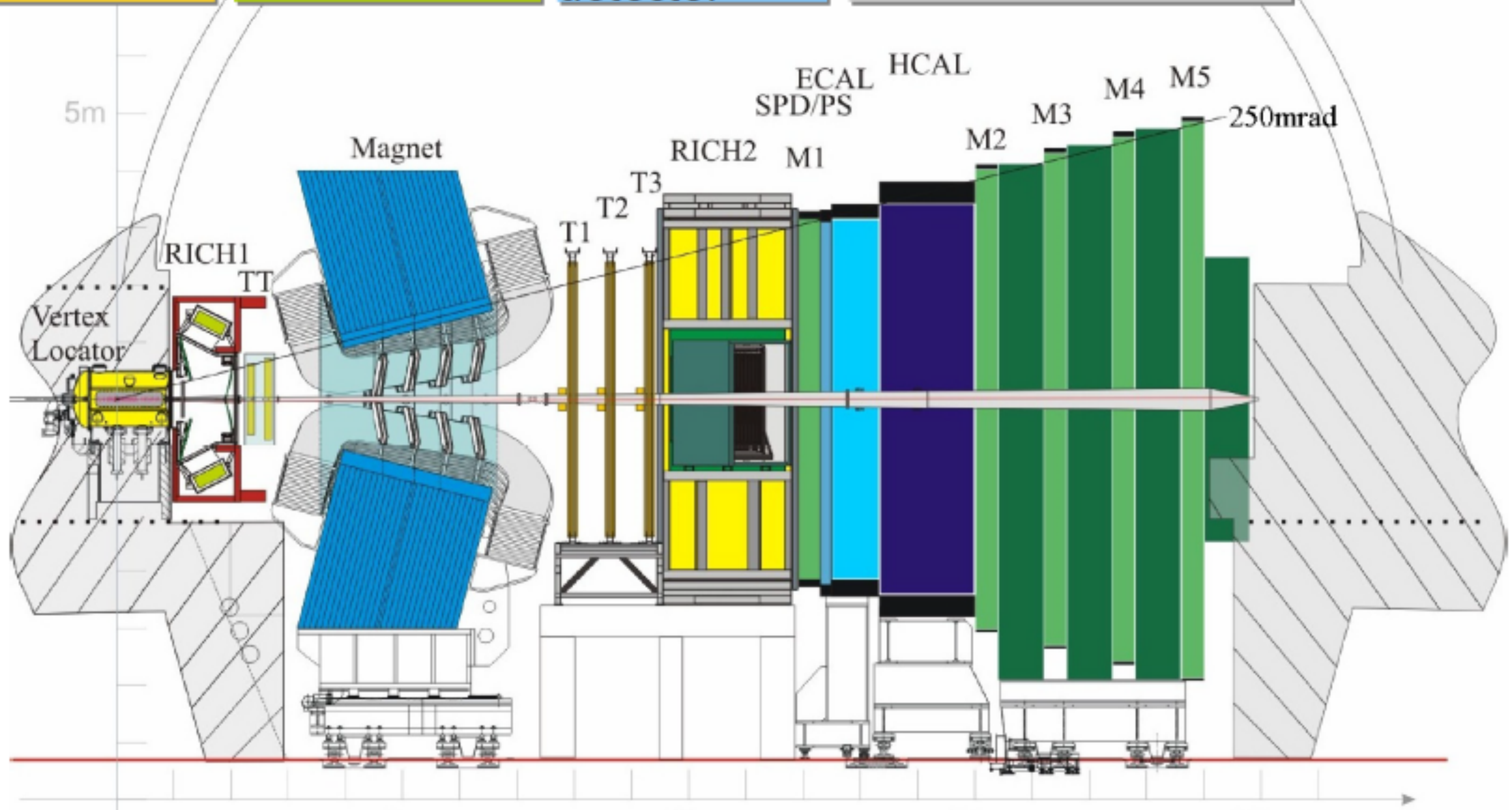
Detector modifications

VELO
New pixel system

TRACKING
New TT and IT

RICH
New photon detector

CALO + MUON
Remove M1, SPD, PS



Replace all the front-end electronics + DAQ network