
# Rare FCNC b decays

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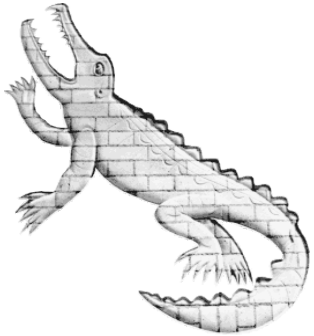
**Cavendish Lab. Cambridge**

**on behalf of the LHCb collaboration,**
**including results from**
**ATLAS, CMS, BaBar, Belle and CDF.**

MARIE CURIE ACTIONS



# Heavy Flavour: Two main ways to New Physics

SM

**CP violation**

extra source must exist

New Physics

**Rare decays**

potential smoking gun

FCNC decays:
- forbidden at tree level
- proceed via loop, box diagrams

Virtual NP particles can contribute in loops

Indirect probe can access higher energy scale than direct searches

## $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ decays

**Last LHCb result, first evidence for the $B_s$ mode**

## $b \to s\ell^+\ell^-$ decays

**Angular analysis, isospin asymmetry, CP asymmetry in** $B^0 \to K^{*0}\mu^+\mu^-$

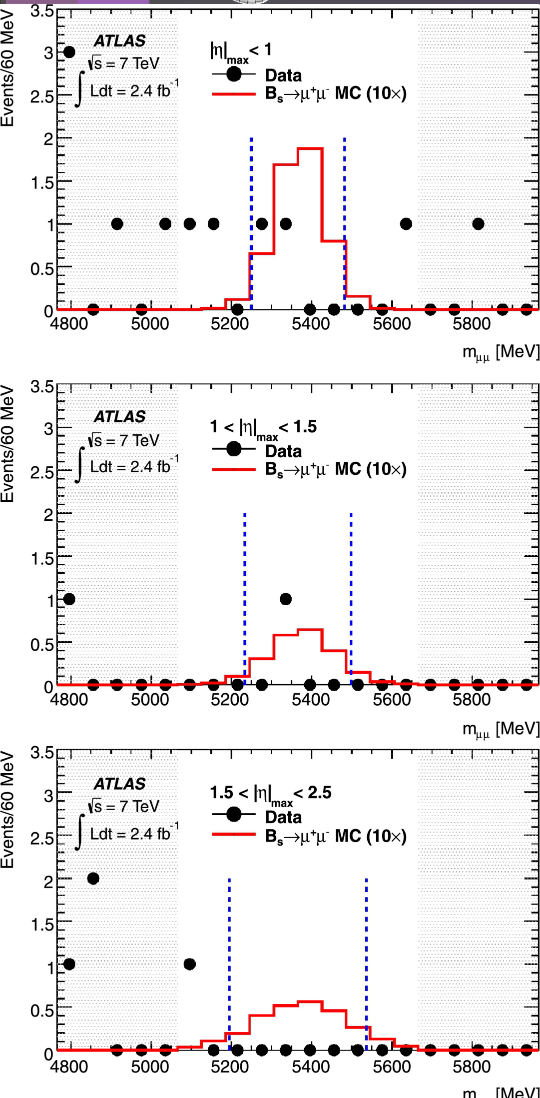
**Angular analysis of** $B_s^0 \to \phi\mu^+\mu^-$

**Branching fraction of** $B^0 \to K^{*0}e^+e^-$

**Branching fraction of** $\Lambda_b^0 \to \Lambda\mu^+\mu^-$

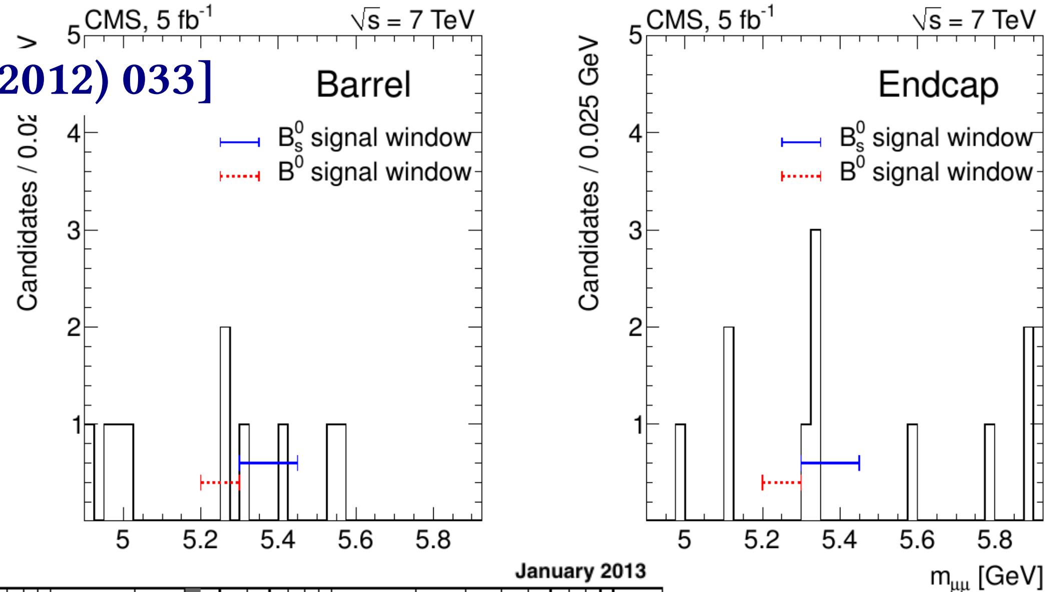
$$B_s^0 \to \mu^+\mu^- \text{ and}$$
$$B^0 \to \mu^+\mu^- \text{ decays}$$

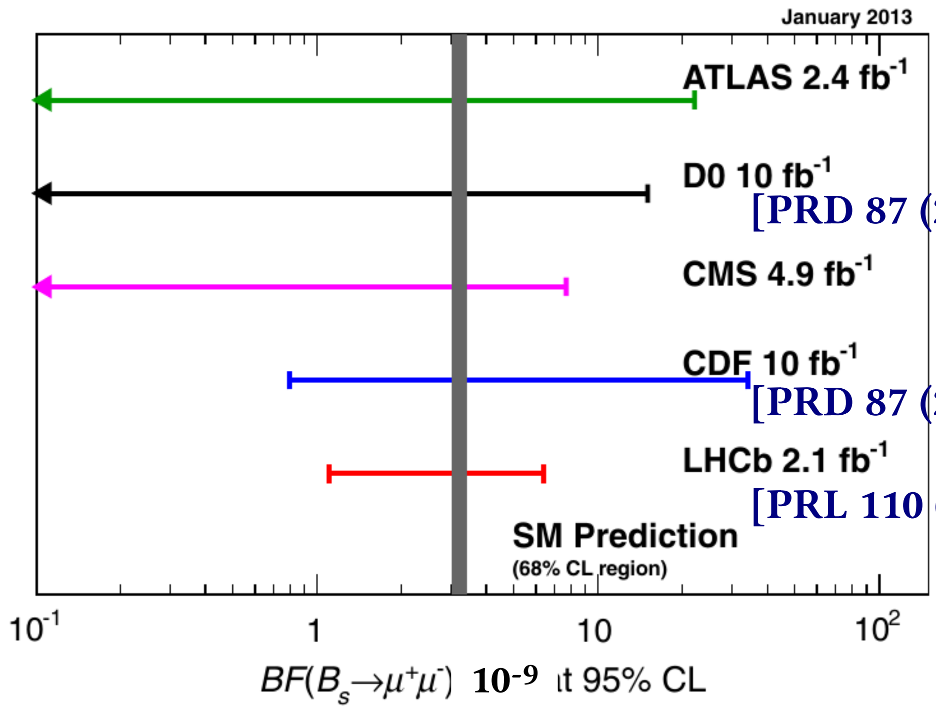
# $B^0_{(s)} \to \mu^+\mu^-$ status




**ATLAS 2.4 fb$^{-1}$**
[PLB 713 (2012) 387]

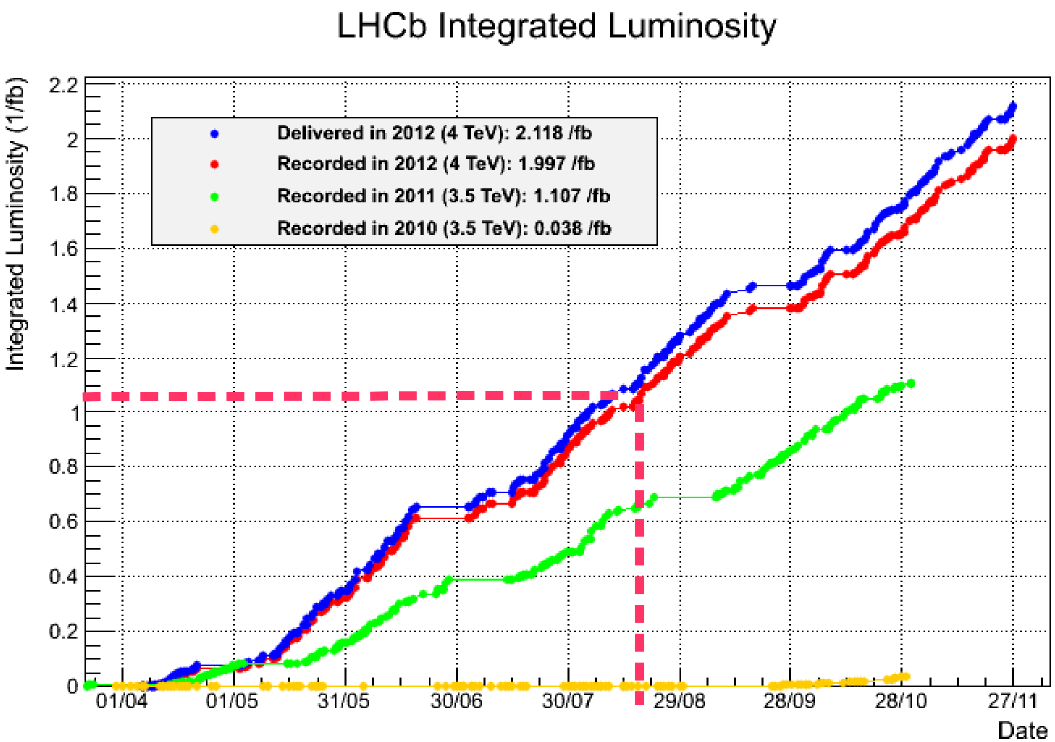
**CMS 5 fb$^{-1}$**
[JHEP 04 (2012) 033]




[PRD 87 (2013) 072006]
[PRD 87 (2013) 072003]
[PRL 110 (2013) 021801]

LHCb [PRL 110 (2013) 021801]



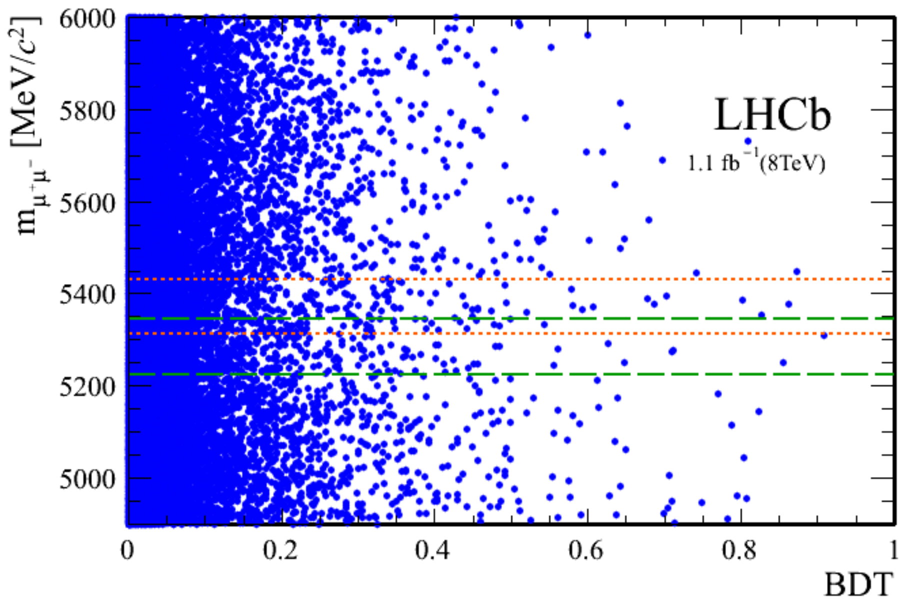

**Analysis combining two datasets:**

- **1.0 $fb^{-1}$ of data taken in 2011 at $\sqrt{s}$=7TeV (re-analysed with improvements)**
- **1.1 $fb^{-1}$ of data taken in 2012 at $\sqrt{s}$=8TeV (50% of available statistics)**

# Analysis strategy

LHCb [PRL 110 (2013) 021801]

- Classification of $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ candidates in a 2D space
  - mass of the μμ pair combination
  - multivariate discriminant, BDT
    B: IP, isolation, $p_T$,..
    muons: isolation, IP$\chi^2$ wrt PVs, min($p_T$),...




- Use of control channels to calibrate the expectations

  $J/\psi \to \mu^+\mu^-$, $\psi(2S) \to \mu^+\mu^-$ and $\Upsilon \to \mu^+\mu^-$

  $B_s^0 \to K^+K^-$, $B^0 \to K^+\pi^-$ and $B^0 \to \pi^+\pi^-$

- Use of normalisation channels

  $B^+ \to J/\psi(\to \mu^+\mu^-)K^+$ and $B^0 \to K^+\pi^-$

- Compare expectations with observed distribution of events
  - to set a limit on the branching fraction
  - to get a branching fraction measurement via a fit

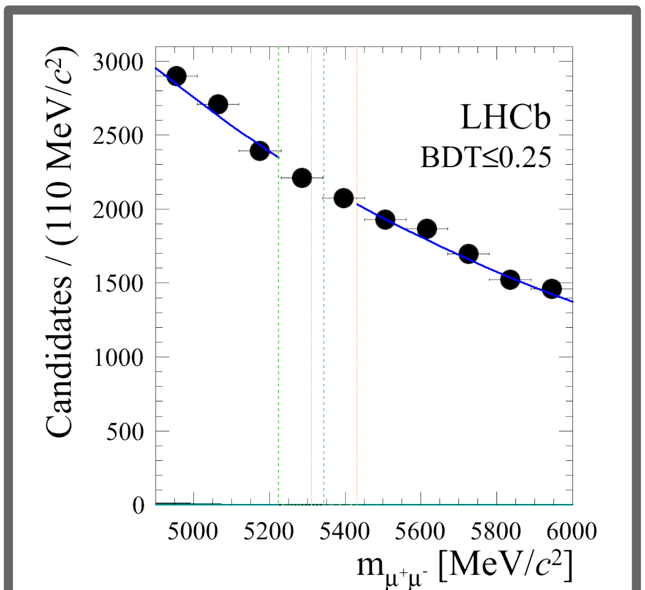
# Discriminant calibration

LHCb [PRL 110 (2013) 021801]

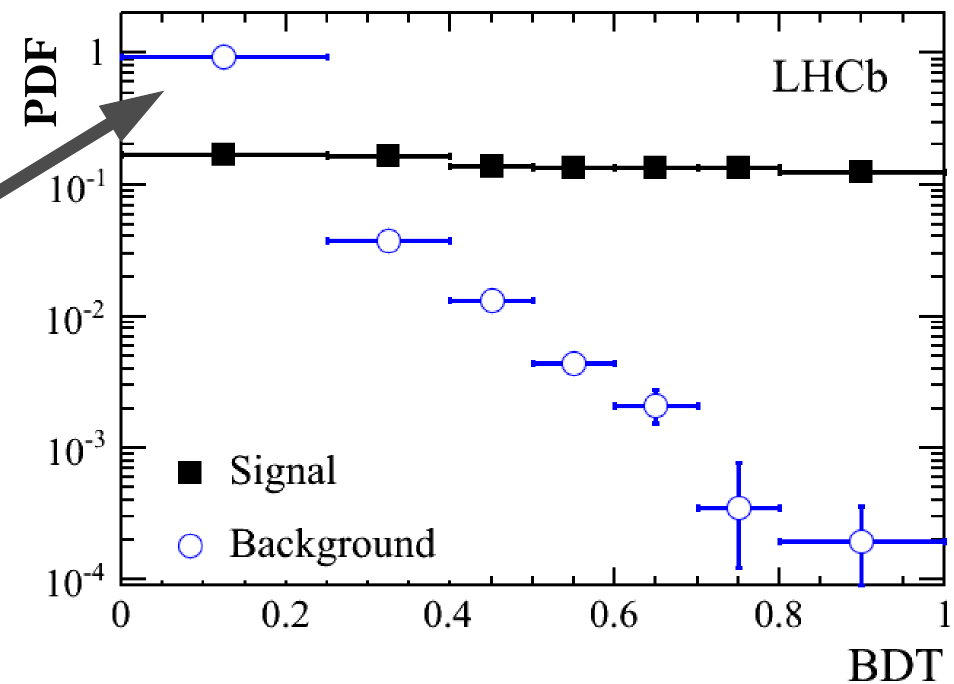
- The signal mass distribution is modeled as a Gaussian (with a radiative tail). The parameters of this model are determined from data using control channels. mass resolution $\sigma = 25.0 \pm 0.4\,\mathrm{MeV}/c^2$

- The BDT is trained using simulation. But it is calibrated from data.

background PDF is obtained from fit to the mass sidebands.




signal PDF is obtained from channels with same topology, $B \to h^+ h'^-$



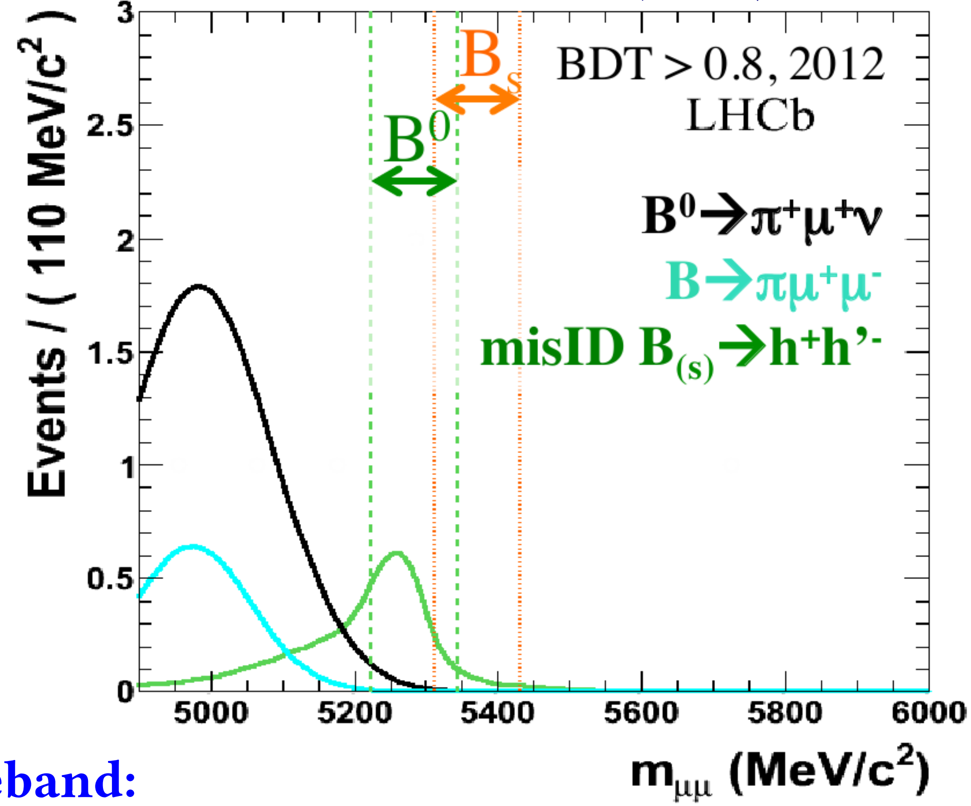
# Other backgrounds

LHCb [PRL 110 (2013) 021801]

Main background source is combinatorial from bb -> μ+μ-X

- contribution in the signal window:

$B^0_{(s)}$ -> $h^+h'^-$ with both hadrons misidentified.
Mis-id from data, folded with simulation spectra.




- contribution to the lower mass sideband:

mass shape different from exponential, could bias the interpolation of not considered.

Three components added to the fit: $B^0$ -> $\pi^-\mu^+\nu$, $B^{+(0)}$ -> $\pi^{+(0)}\mu^+\mu^-$ and $B^0_{(s)}$ -> $h^+h'^-$

# Normalisation

LHCb [PRL 110 (2013) 021801]

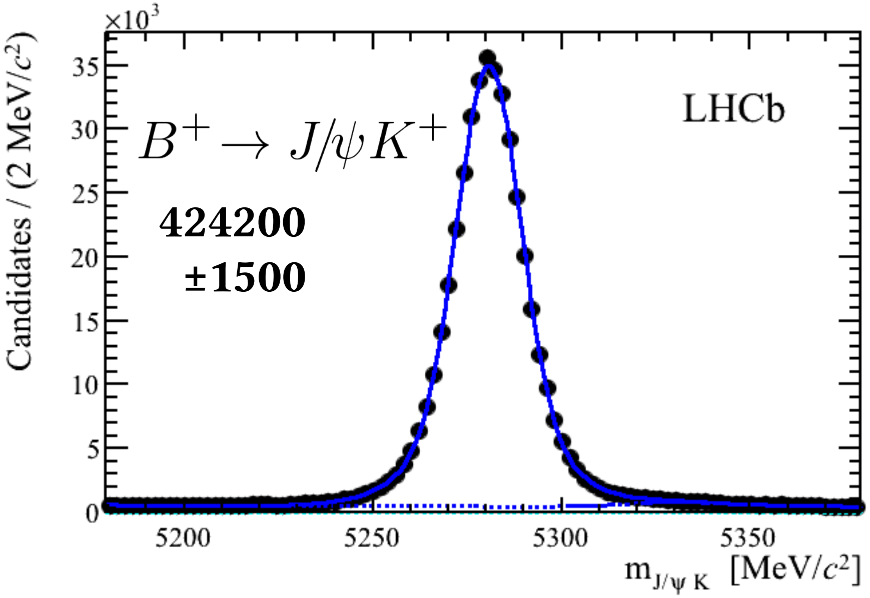
**normalisation to** $B^+ \to J/\psi(\to \mu^+\mu^-)K^+$ and $B^0 \to K^+\pi^-$

$$\mathcal{B} = \mathcal{B}_{\rm norm} \times \frac{\epsilon^{\rm rec}_{\rm norm}\epsilon^{\rm sel}_{\rm norm}}{\epsilon^{\rm rec}_{\rm sig}\epsilon^{\rm sel}_{\rm sig}} \times \frac{\epsilon^{\rm trig}_{\rm norm}}{\epsilon^{\rm trig}_{\rm sig}} \times \frac{f_{\rm norm}}{f_s} \times \frac{\mathcal{N}^{\rm obs}_{\rm sig}}{\mathcal{N}^{\rm obs}_{\rm norm}} = \alpha \times \mathcal{N}^{\rm obs}_{\rm sig}$$

**PDG**

**from MC**
**check on data**

**from data**




**b fragmentation measured at LHCb**

$$\frac{f_s}{f_d} = 0.256 \pm 0.020 \text{ at } 7\,\text{TeV}$$

[JHEP 04 (2013) 001]

**stability checked on 8 TeV data.**

$$\alpha_{B^0_s} = (2.52 \pm 0.23) \times 10^{-10}$$
$$\alpha_{B^0} = (6.45 \pm 0.30) \times 10^{-11}$$

**for the 8 TeV dataset.**

# Result for the BF of $B_s^0 \to \mu^+\mu^-$

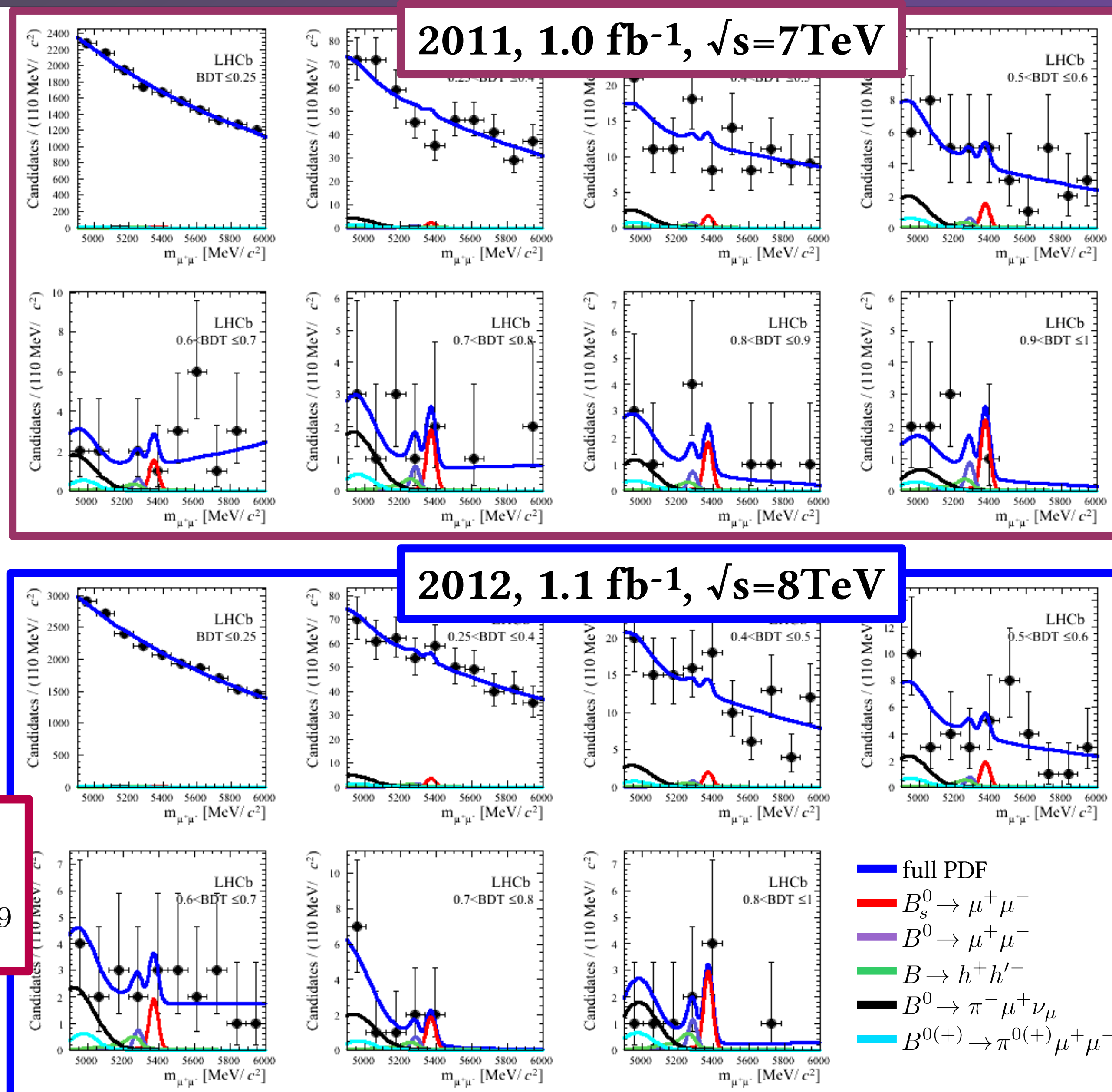
Simultaneous unbinned likelihood fit to 15 BDT bins.

Combinatorial bkg, $B_s$ and $B^0$ yield free.

All other parameters Gaussian constrained.

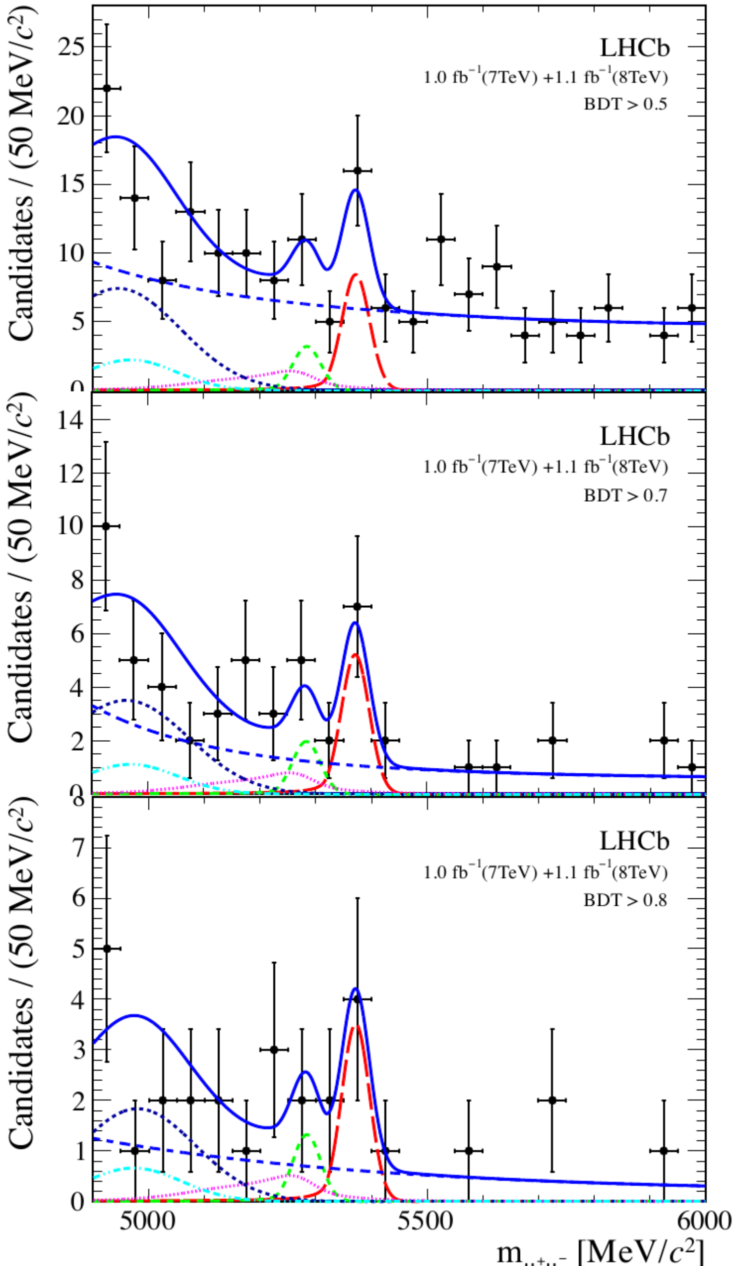
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) =$$
$$3.2^{+1.4}_{-1.2}(\text{stat})^{+0.5}_{-0.3}(\text{syst}) \times 10^{-9}$$

LHCb
[PRL 110 (2013) 021801]



# Result for the BF of $B_s^0 \to \mu^+\mu^-$

LHCb [PRL 110 (2013) 021801]




**Excess of $B_s^0 \to \mu^+\mu^-$ candidates with a significance of 3.5 standard deviations.**
**(p-value bkg-only hyp.: $5 \cdot 10^{-4}$)**

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 3.2^{+1.5}_{-1.2} \times 10^{-9}$$

**First evidence of this decay!**

**compatible with the SM prediction, after correction for $\Delta\Gamma_s \neq 0$ :**

$$\mathcal{B}_{\rm SM}(B_s^0 \to \mu^+\mu^-) = (3.54 \pm 0.30) \times 10^{-9}$$

[EPJ C72 (2012) 2172][PRL 109 (2012) 041801]

**For the $B^0$ mode, not significant excess is found, an upper limit on the BF is set:**

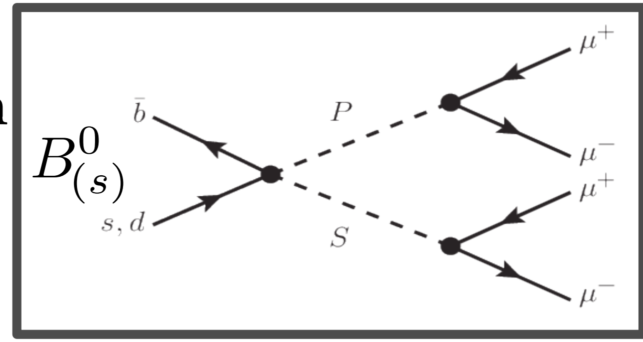
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 9.4 \times 10^{-10} \text{at } 95\% \text{ CL.}$$

[LHCb-PAPER-2012-049] Acc. PRL

**In the SM:**

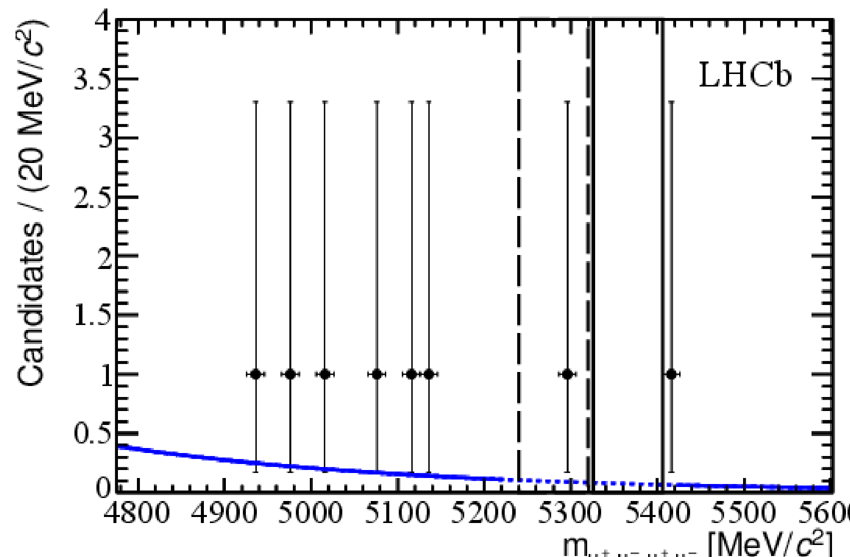
**non-resonant** $\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-\gamma(\to \mu^+\mu^-)) < 10^{-10}$
[PRD70 (2004) 114028]

**resonant** $\mathcal{B}(B^0_{(s)} \to J/\psi\phi) = (2.3 \pm 0.9) \times 10^{-8}$
**use as control channel, removed from search**




**In MSSM, could stem through new scalar S and pseudoscalar P sgoldstinos particles. (HyperCP motivated: P = 214.3 MeV)**
[PRD85 (2012) 077701] [PRL 94 (2004) 021801]

**No excess over background expectation.**

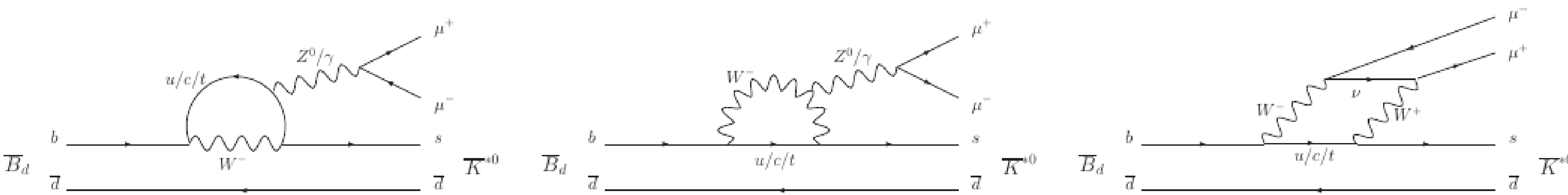



**First experimental search**
**Limit are set at 95% CL:**

$$\mathcal{B}(B^0_s \to 4\mu) < 1.6 \times 10^{-8}$$
$$\mathcal{B}(B^0 \to 4\mu) < 6.6 \times 10^{-9}$$

# $b \to s\ell^+\ell^-$ decays

# $b \to s\ell^+\ell^-$ decays

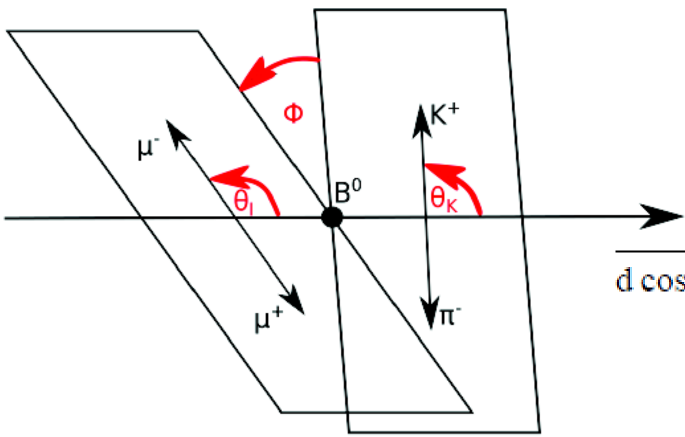



**$b \to s\ell^+\ell^-$ FNCN processes represent a very rich environment:**

- **Four-particles final states allow for a wealth of angular observables**
- **Experimentally clean signatures**
- **Rate, angular distributions and asymmetries sensitive to NP**
- **theoretically well predicted**

$$B^0 \to K^{*0}\mu^+\mu^- \qquad B_s^0 \to \phi\mu^+\mu^- \qquad B^0 \to K^{*0}e^+e^-$$

**Four-particle final state fully described by three angles ($\theta_l$, $\theta_K$, $\phi$) and the dimuon invariant mass squared $q^2$.**

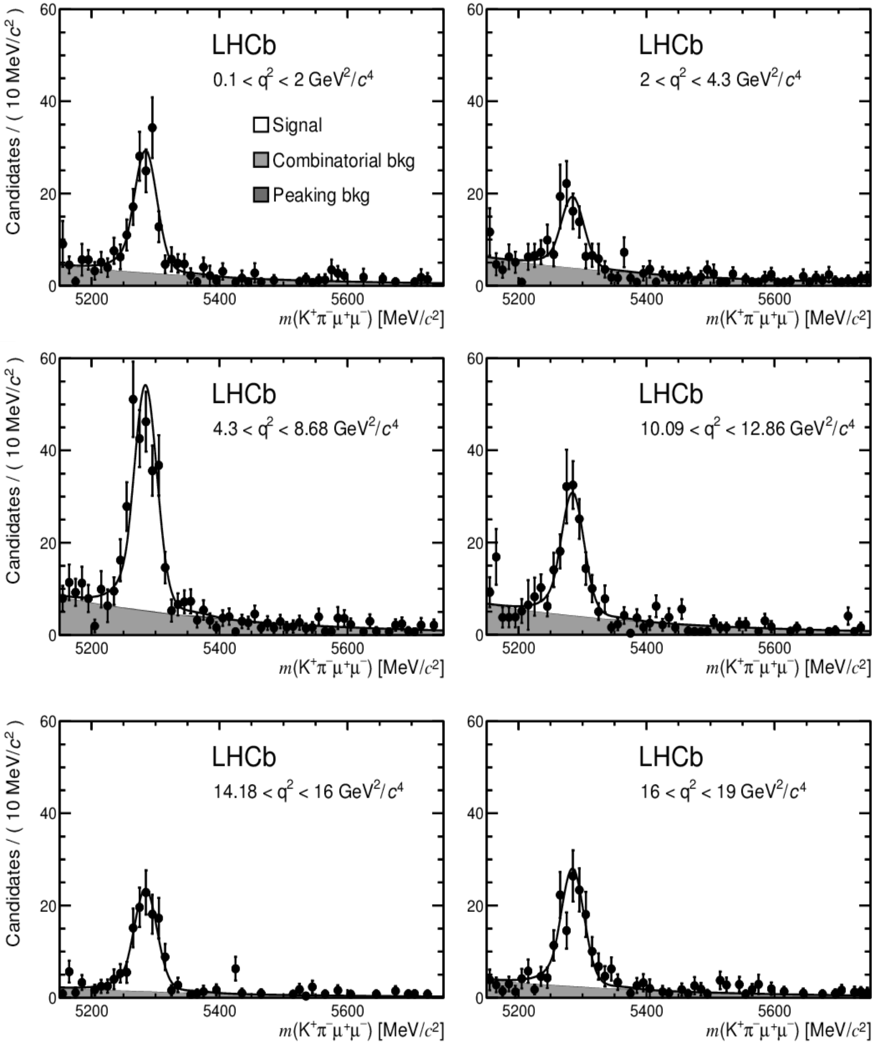



**apply folding,** $\phi \to \phi + \pi$ for $\phi < 0$

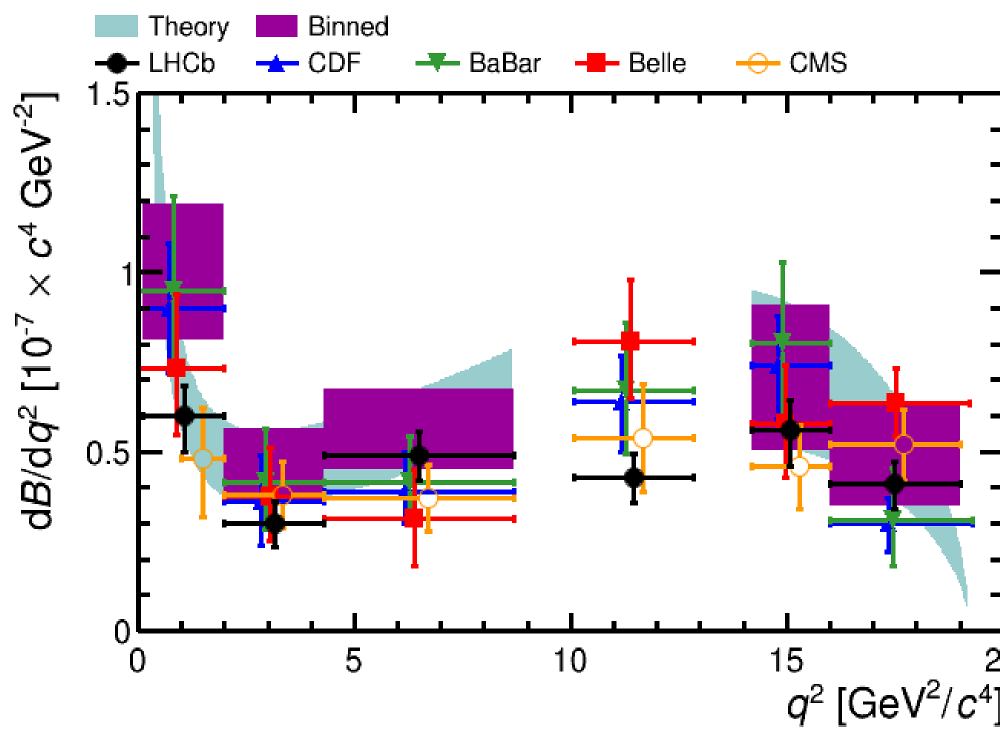
$$\frac{d^4(\Gamma + \bar{\Gamma})}{d\cos\theta_\ell \, d\cos\theta_K \, d\phi \, dq^2} \propto F_L \cos^2\theta_K + \frac{3}{4}(1 - F_L)(1 - \cos^2\theta_K) + F_L \cos^2\theta_K (2\cos^2\theta_\ell) + \frac{1}{4}(1 - F_L)(1 - \cos^2\theta_K)(2\cos^2\theta_\ell - 1) + S_3(1 - \cos^2\theta_K)(1 - \cos^2\theta_\ell)\cos 2\phi + \frac{4}{3}A_{FB}(1 - \cos^2\theta_K)\cos\theta_\ell + S_9(1 - \cos^2\theta_K)(1 - \cos^2\theta_\ell)\sin 2\phi$$

Four angular observables $F_{\rm L}, S_3(A_{\rm T}^2), A_{FB}(A_{\rm T}^{\rm Re}), A_9$ in bins of $q^2$.

# $d\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)/dq^2$




LHCb [PAPER-2013-019] Subm. JHEP
CMS [BPH-11-009]
CDF [PRL 108 (2012) 081807]
Belle [PRL 103 (2009) 171801]
BaBar [PRD 86 (2012) 032012]
Theory (SM) [JHEP 1107 (2012) 067]




**Differential branching fraction in bins of dimuon invariant mass $q^2$ determined with normalisation to $B^0 \to J/\psi K^{*0}$**

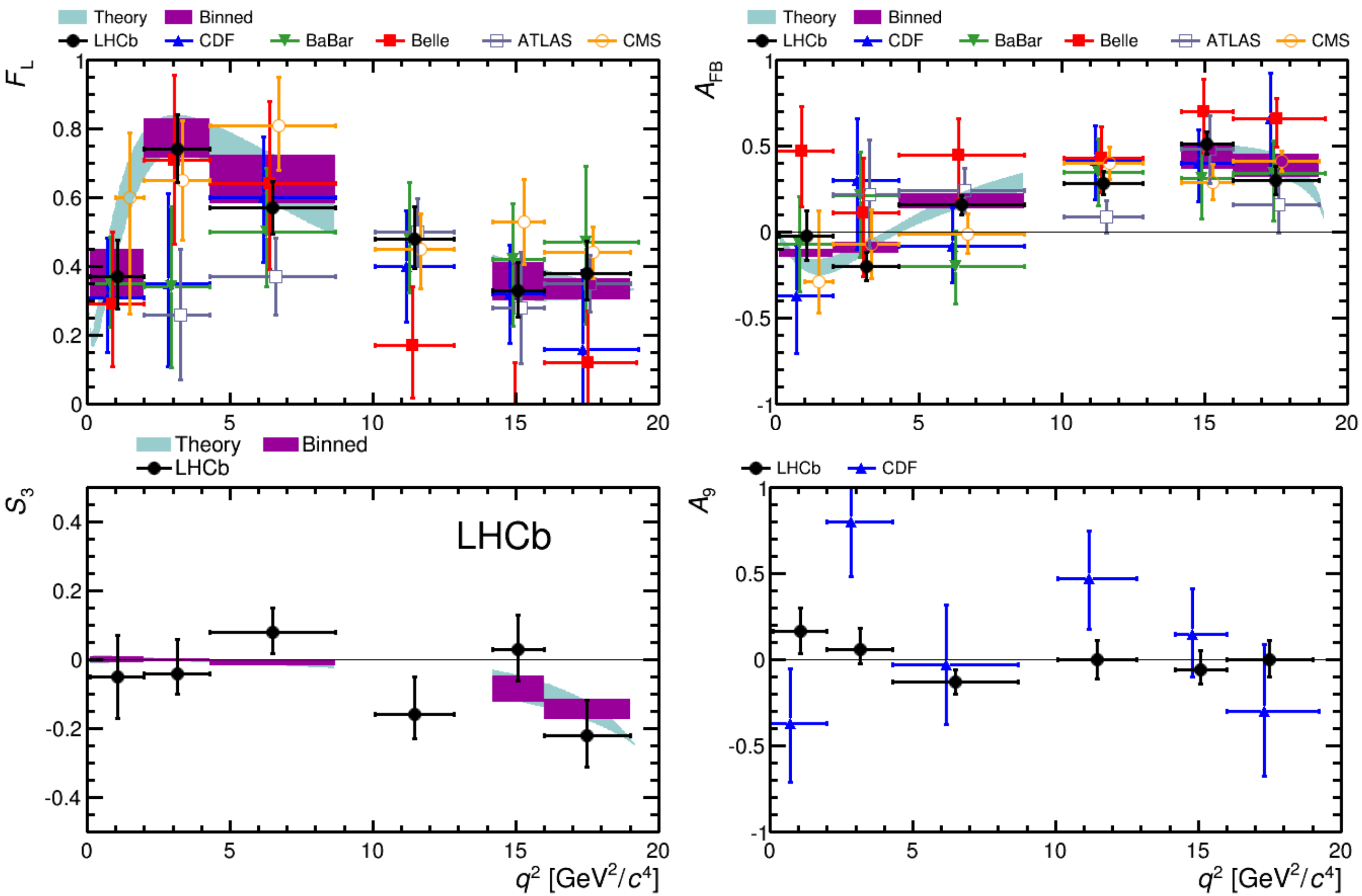
# $B^0 \to K^{*0}\mu^+\mu^-$ angular observables

**In the SM, AFB has a zero-crossing point.**
**SM predicts $q^2_0$ value ranging 4.0-4.3 GeV$^2$/c$^4$**

[Eur.Phys.J. C41 (2005) 173][JHEP 1201 (2012) 107]
[Eur.Phys.J. C47 (2006) 625]

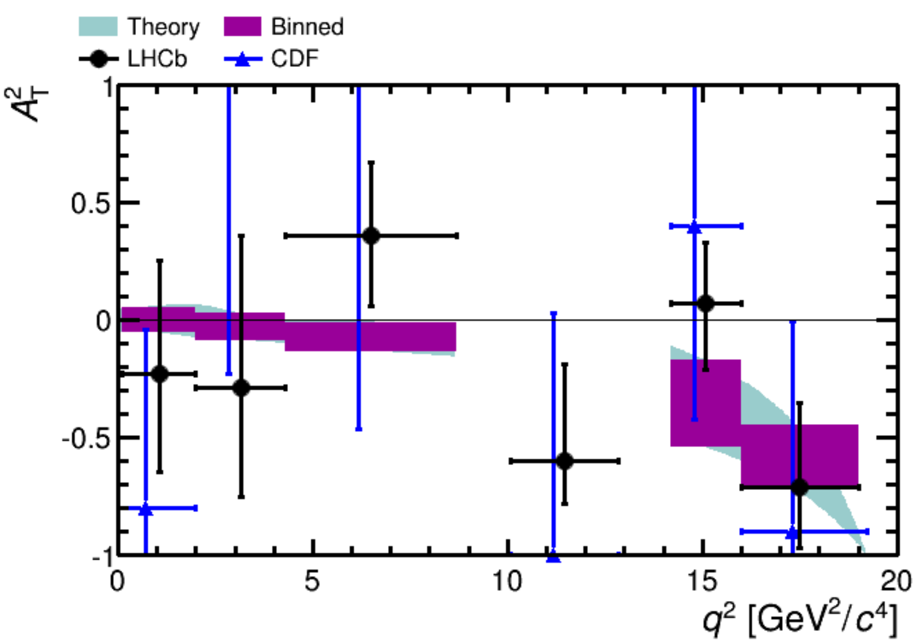
**First measurement at** $q_0^2 = (4.9 \pm 0.9)\mathrm{GeV}^2/c^4$

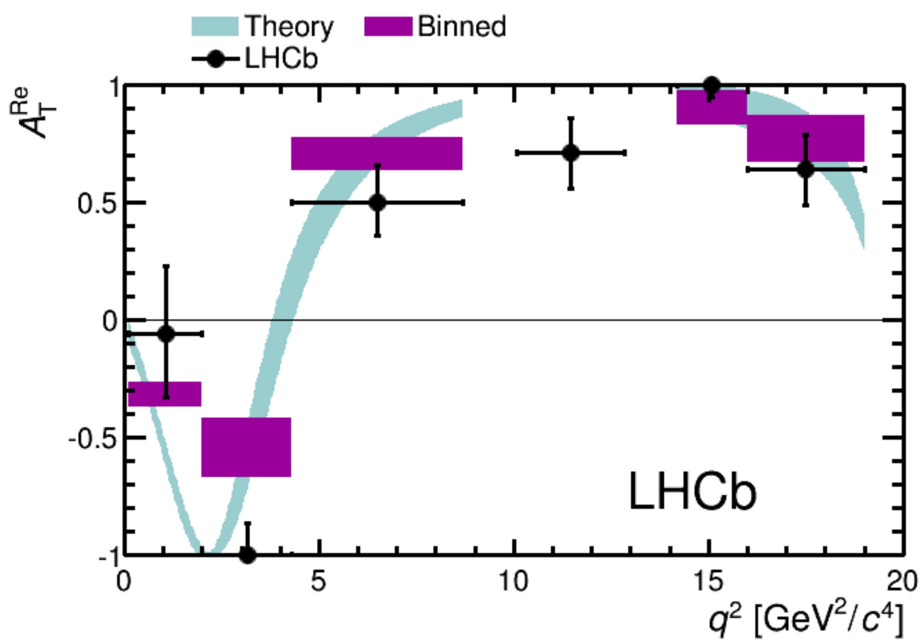
**LHCb** [PAPER-2013-019] **Subm. JHEP**
**CMS** [BPH-11-009]
**ATLAS** [CONF-2013-038]
**CDF** [PRL 108 (2012) 081807]
**Belle** [PRL 103 (2009) 171801]
**BaBar** [PRD 86 (2012) 032012]
**Theory (SM)** [JHEP 1107 (2012) 067]



# $B^0 \to K^{*0}\mu^+\mu^-$ angular observables

**LHCb [PAPER-2013-019] Subm. JHEP**
**CDF [PRL 108 (2012) 081807]**



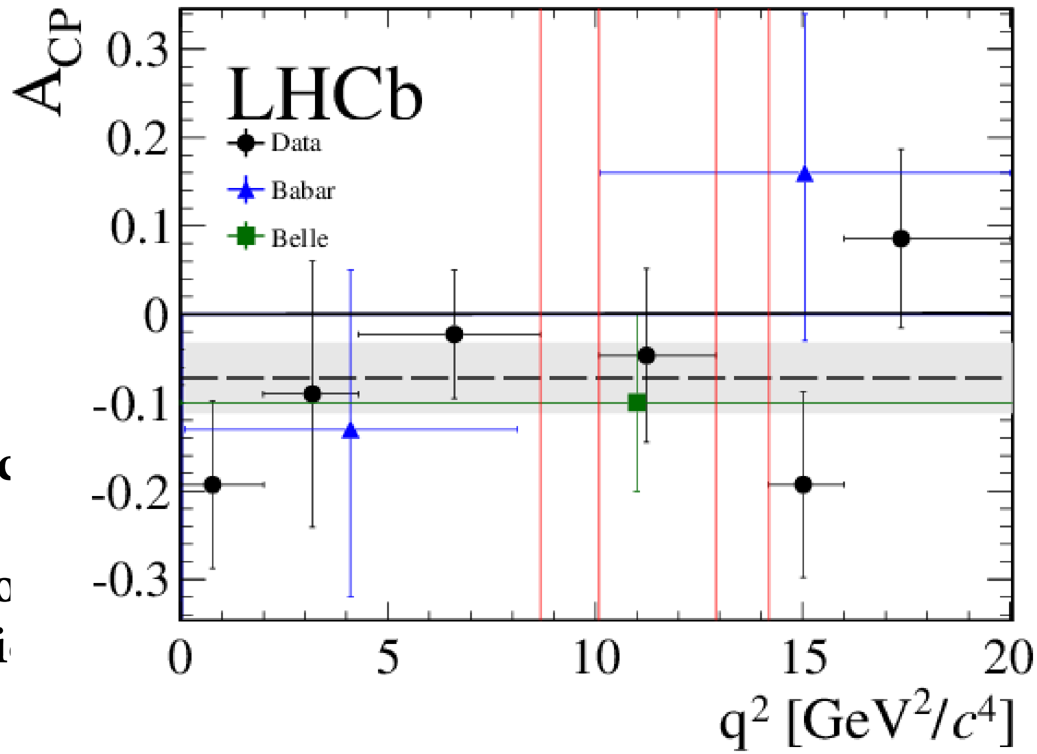

**Another expression of the decay bring up alternative observables $A_T^2$ and $A_T^{Re}$, theoretically very clean.**
**Second angular fit to determine these transverse amplitudes.**

# $B^0 \to K^{*0}\mu^+\mu^-$ $CP$ asymmetry

**LHCb**
**[PRL110 (2013) 031801]**

$$A_{\mathcal{CP}} = \frac{\Gamma(\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-) - \Gamma(B^0 \to K^{*0}\mu^+\mu^-)}{\Gamma(\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-) + \Gamma(B^0 \to K^{*0}\mu^+\mu^-)}$$

**Clean SM prediction O(10$^{-3}$), up to 0.15 beyond SM**
**[JHEP 01 (2009) 019]**
**[JHEP 11 (2011) 122]**




**Ratio of 2 magnet polarities to canc detector asymmetries and $B^0 \to J/\psi K^{*0}$ as control channel to account for production asymmetri**

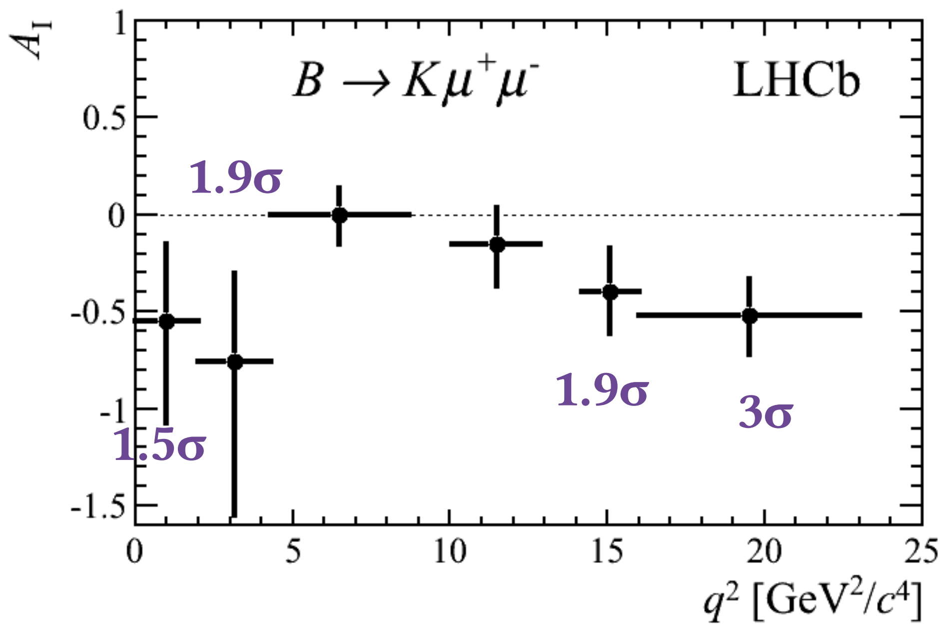
$$A_{\mathcal{CP}} = -0.072 \pm 0.040 \text{ (stat)} \pm 0.005 \text{ (syst)}$$

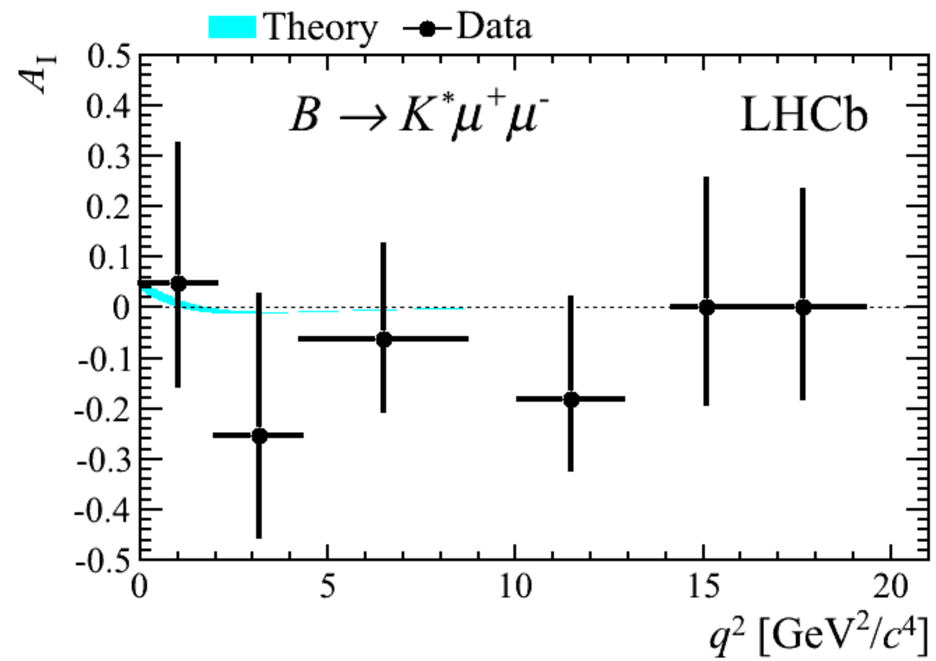
**Compatible with less precise measurements by Belle and BaBar.**
**[PRL 103 (2009) 171801]** **[PRD 86 (2012) 032012]**

# $B \to K^{(*)}\mu^+\mu^-$ isospin asymmetry

LHCb [JHEP 07 (2012) 133]

$$A_{\rm I} = \frac{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) - \Gamma(B^+ \to K^{(*)+}\mu^+\mu^-)}{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) + \Gamma(B^+ \to K^{(*)+}\mu^+\mu^-)}$$



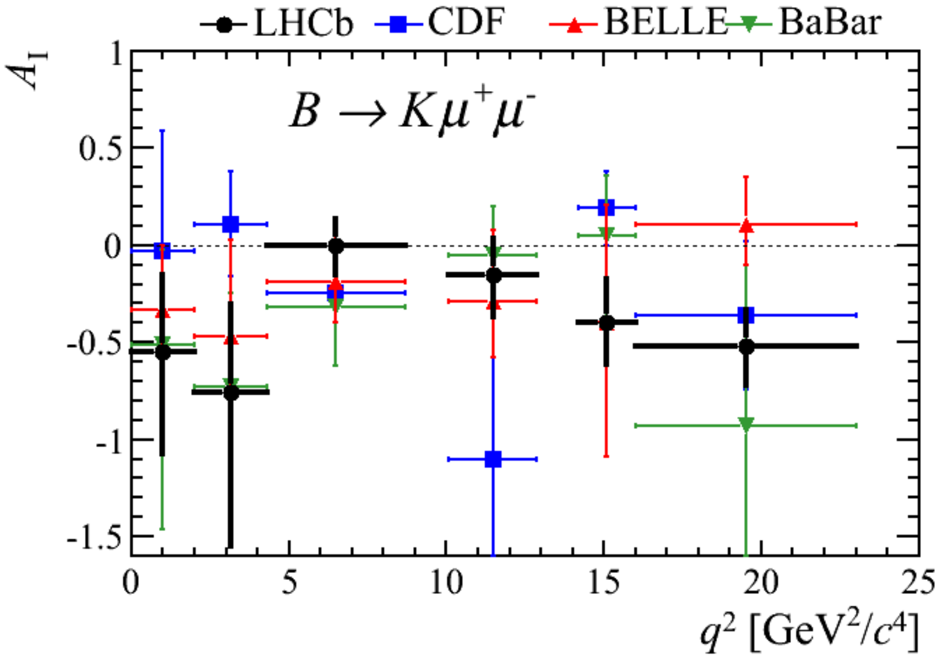



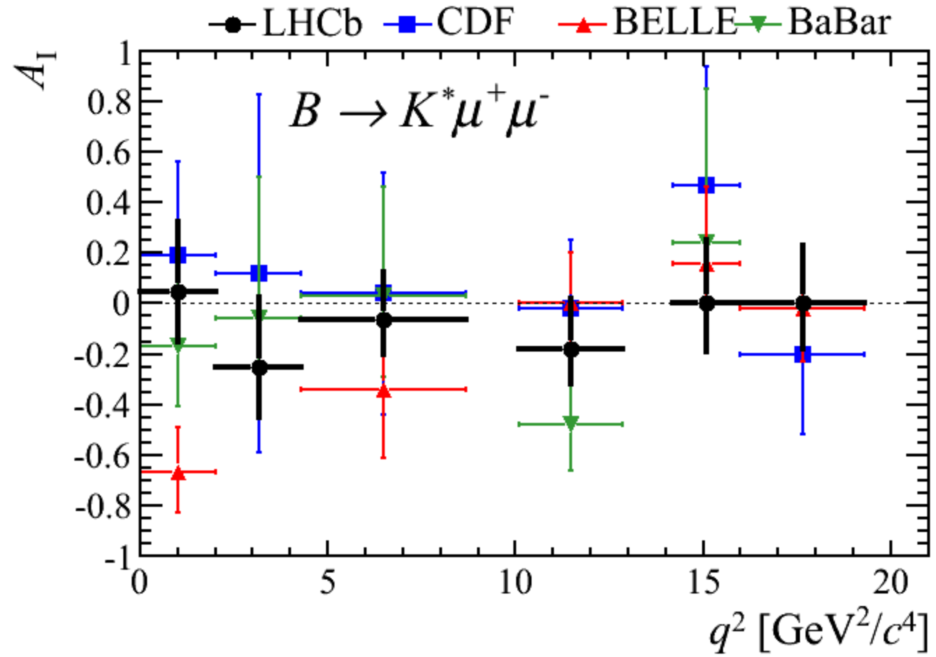

Deviation from zero over all $q^2$ at 4.4σ.
SM prediction is close to zero.

Consistent with zero and with SM.

LHCb [JHEP 07 (2012) 133]

$$A_{\mathrm{I}} = \frac{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) - \Gamma(B^+ \to K^{(*)+}\mu^+\mu^-)}{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) + \Gamma(B^+ \to K^{(*)+}\mu^+\mu^-)}$$




**Deviation from zero over all $q^2$ at 4.4σ.**

**SM prediction is close to zero.**

**Consistent with zero and with SM.**

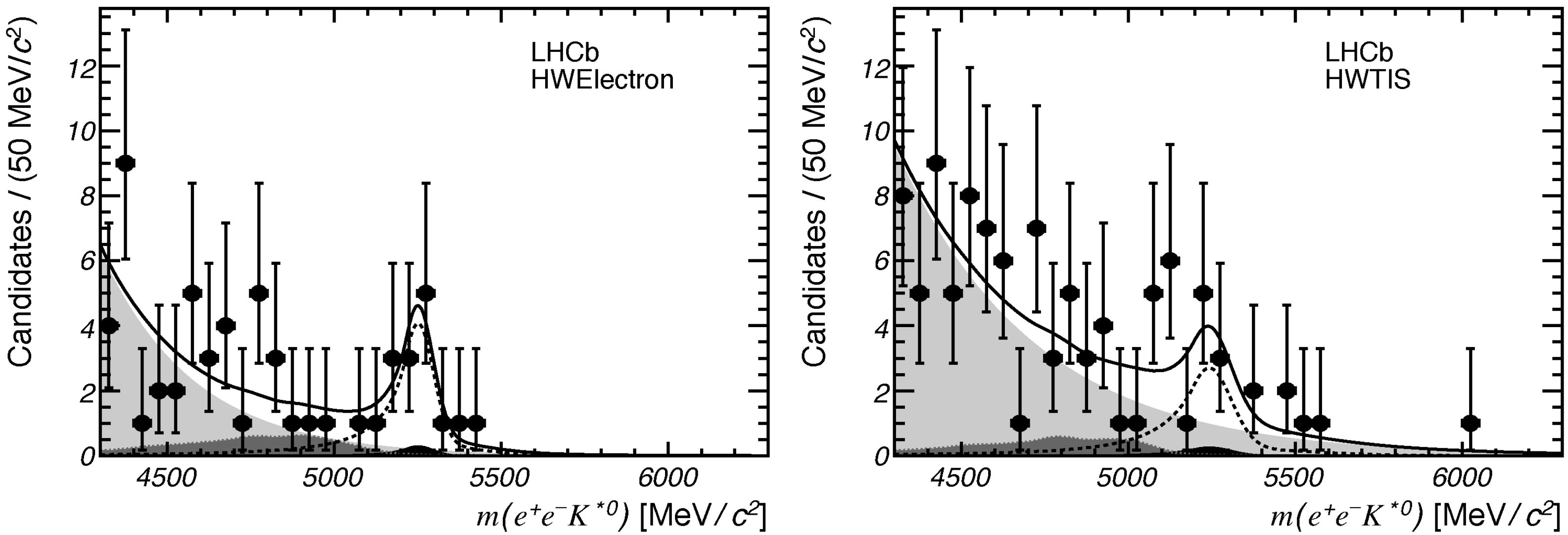
BaBar [PRL102 (2009) 091803]
Belle [PRL103 (2009) 171801]
CDF [arXiv:1301.2244]

**Compatible with previous measurement by BaBar, Belle and CDF.**

# $B^0 \to K^{*0} e^+ e^-$

[LHCb-PAPER-2013-005] Acc. JHEP

**Complementary to the dimuon mode: probing very low q².**



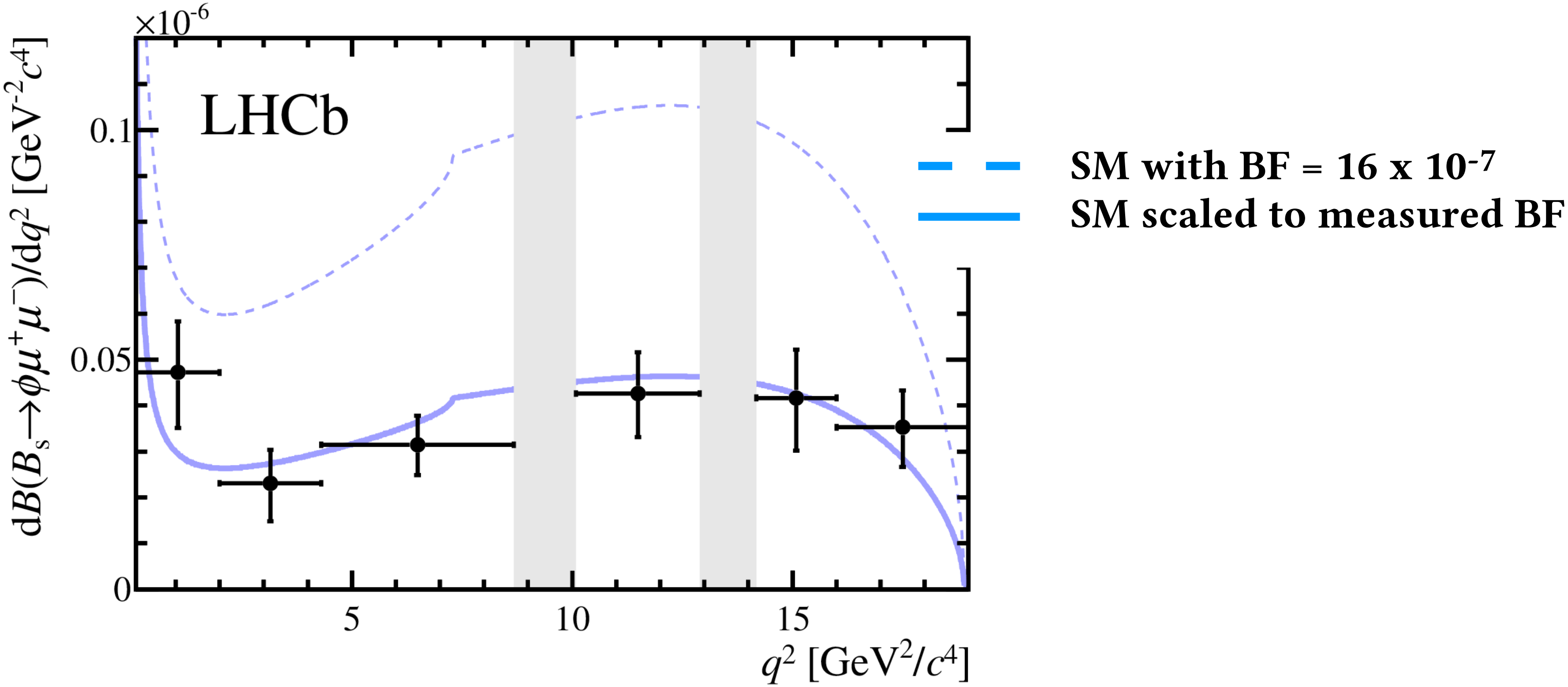

$$\mathcal{B}(B^0 \to K^{*0} e^+ e^-)^{0.03-1\ \mathrm{GeV}/c^2} = (3.1^{+0.9+0.2}_{-0.8-0.3} \pm 0.2(\mathcal{B})) \times 10^{-7}$$

**normalising to** $B^0 \to K^{*0} J/\psi(\to e^+ e^-)$

**In agreement to SM prediction.**

**First step towards angular analysis, that should be possible with current LHCb data set.**

[LHCb-PAPER-2013-017] Subm. JHEP




$$\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-) = (7.07^{+0.64}_{-0.59}(\text{stat}) \pm 0.17(\text{syst}) \pm 0.71(\mathcal{B})) \times 10^{-7}$$

**normalised to** $B_s^0 \to J/\psi\phi$ [PRD87 (2013) 072004]

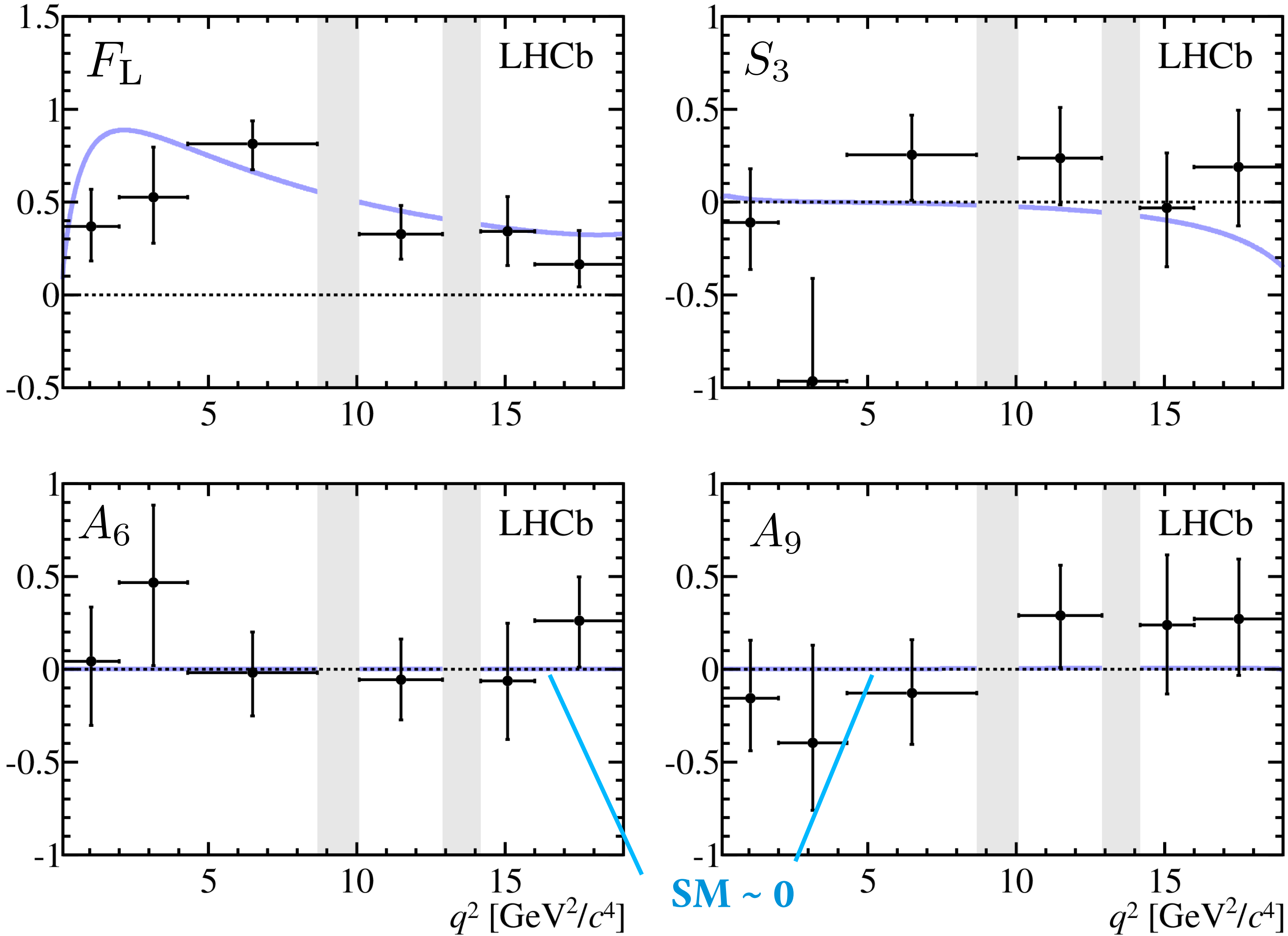
**compatible with previous CDF measurements.** [PRL 107 (2011) 201802] [CDF public 10894 (2012)]

**Theory prediction range [14.5, 19.2] x $10^{-7}$ with uncertainties 20-30%**

# $B_s^0 \to \phi\mu^+\mu^-$ angular observables

**Observations compatible with SM.**

**[LHCb-PAPER-2013-017] Subm. JHEP**




**SM predictions computed from**

**[JHEP 01 (2009) 019]**

**[PRD 71 (2005) 014029 ]**

# NEW! $\mathcal{B}(\Lambda_b^0 \to \Lambda\mu^+\mu^-)$

**LHCb-PAPER-2013-025**

**Preliminary**

**$\Lambda_b^0$ (u, d, b) is a baryon:**

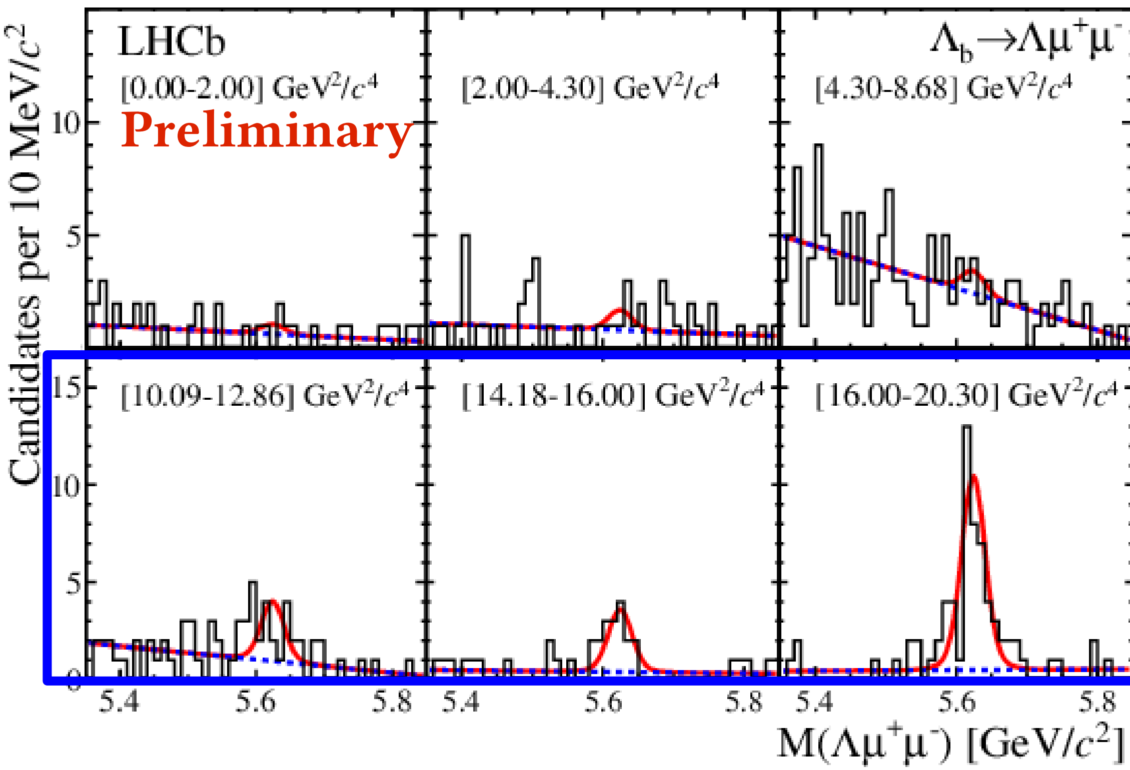
- **non-zero initial spin: probe helicity structure**
- **theory side in need for constraint**

**Normalised to $\Lambda_b^0 \to \Lambda J/\psi(\to \mu^+\mu^-)$**

$$\mathcal{B}(\Lambda_b^0 \to \Lambda\mu^+\mu^-) = (0.96 \pm 0.16(stat) \pm 0.13(syst) \pm 0.21(\mathcal{B})) \times 10^{-6}$$

**Based on 78 ± 12 signal decays.**

**Compatible with SM and previous measurement by CDF [PRL 107 (2011) 201802]**




**Differential branching fraction in bins of q².**

**Significant evidence only for $q^2 > m^2_{J/\psi}$**

# NEW! $\Lambda_b^0 \to \Lambda\mu^+\mu^- d\mathcal{B}/dq^2$

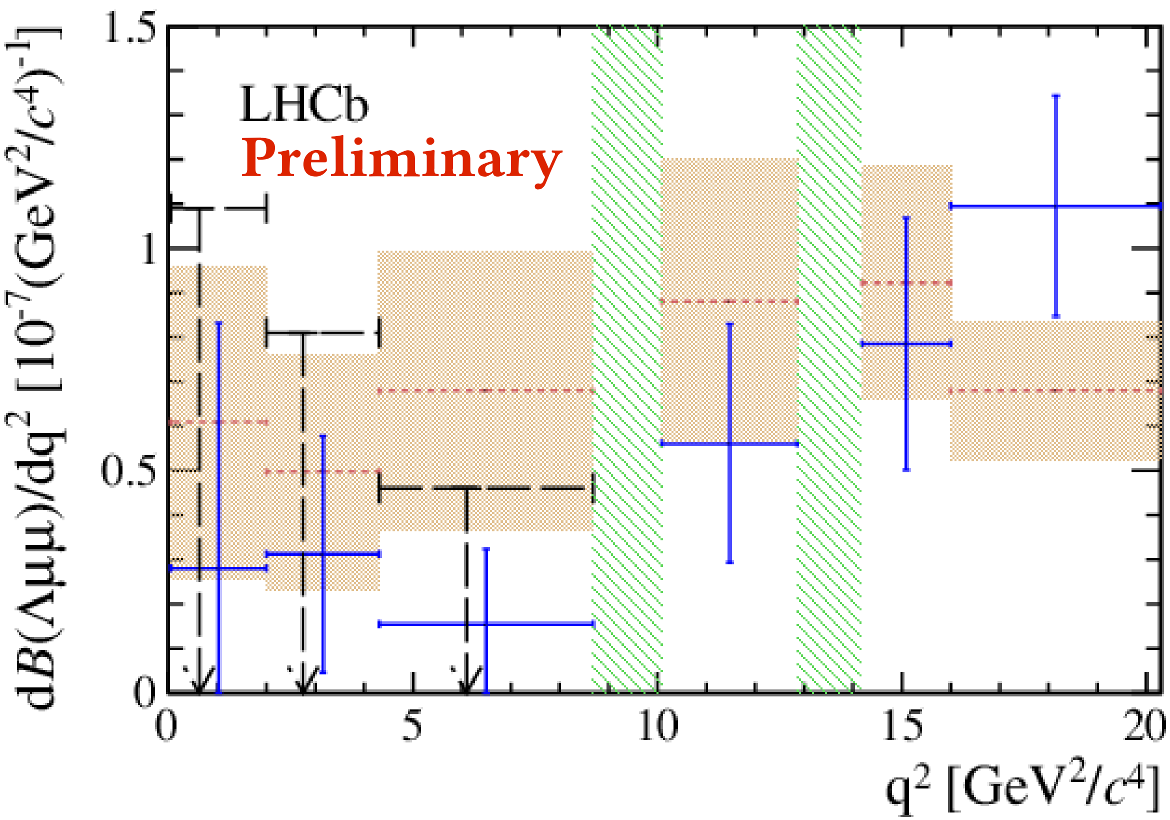
**LHCb-PAPER-2013-025**

**Preliminary**



**Differential branching fraction in bins of $q^2$.**

**Significant evidence only for $q^2 > m^2_{J/\psi}$ : limits are computed for the lower bins.**




**Compatible with previous measurement by CDF [PRL 107 (2011) 201802]**

**Binned SM**
**[PRD87 (2012) 074502]**

$d\mathcal{B}/dq^2$

limit on $d\mathcal{B}/dq^2$ at 90 % CL.

# Conclusions

**Glorious first two years of LHC data for Rare Decays in Heavy Flavour physics!**

**Healthy competition in the search for $B^0_{(s)} \to \mu^+\mu^-$, first evidence by LHCb.**

**Impressive results in the $b \to s\ell^+\ell^-$ sector. Many additional and complementary observables still to measure.**

**Coming soon:**
**Update on full stat of the $B^0_{(s)} \to \mu^+\mu^-$ analyses by all players.**
**Many new rare decays analyses in the pipeline.**