Rare B-decays @LHC

(Results from CMS, ATLAS and LHCb)

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on behalf of CMS collaboration

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In search for New Physics…

Two ways to search for New Physics:

• Produce new **heavy particles beyond SM**, that may have existed in early universe. The production cross-section of those particles are usually very small.

• Measure the observables/parameters of SM processes (usually rare decay processes). Any **significant deviation of these observables from SM prediction** will be hint of NP.

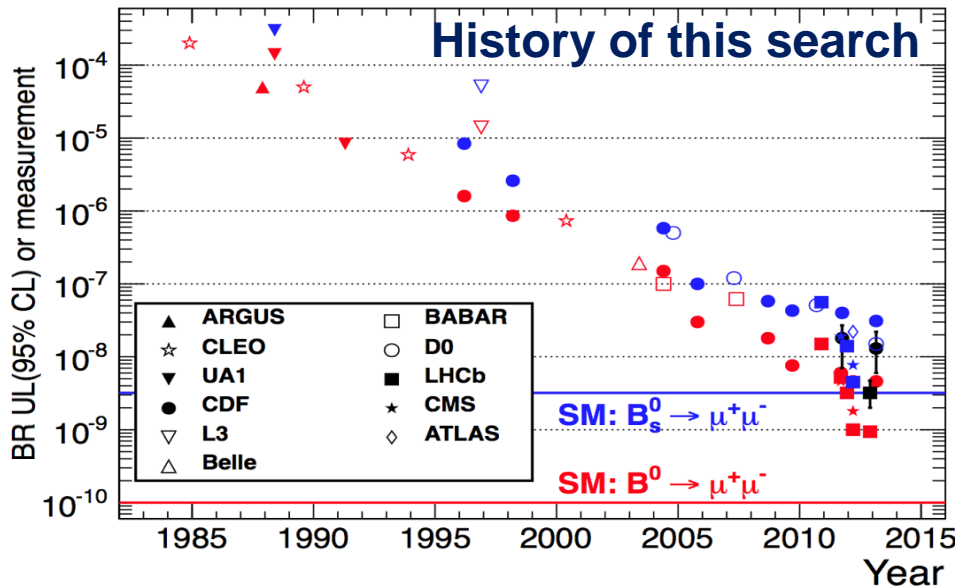**Studying both processes are important and are complementary to each other**

I will show the results of $B_{(S)} \rightarrow \mu^+\mu^-$, $K^{(*)}\mu^+\mu^-$, $K^{(*)}\gamma$ from CMS, ATLAS and LHCb.

SM & NP contributions to $B_{(S)} \rightarrow \mu^+\mu^-$

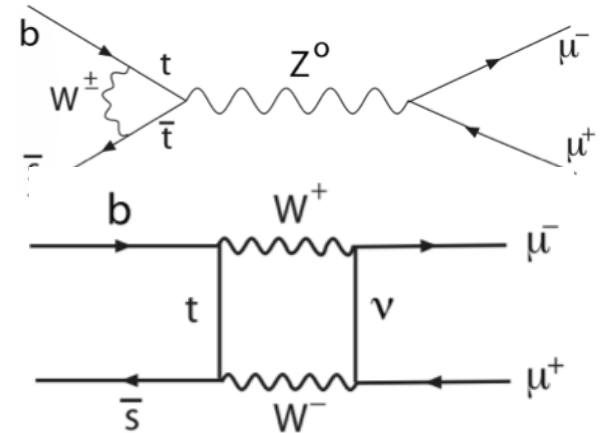- **The golden rare decays: $B_{d/s} \rightarrow \mu\mu$**

  - **Highly suppressed in Standard Model**

  - **Forbidden at tree level, can only proceed through higher-order loop diagrams**

  - **Helicity suppressed, by factor of $(m_\mu/m_B)^2$**

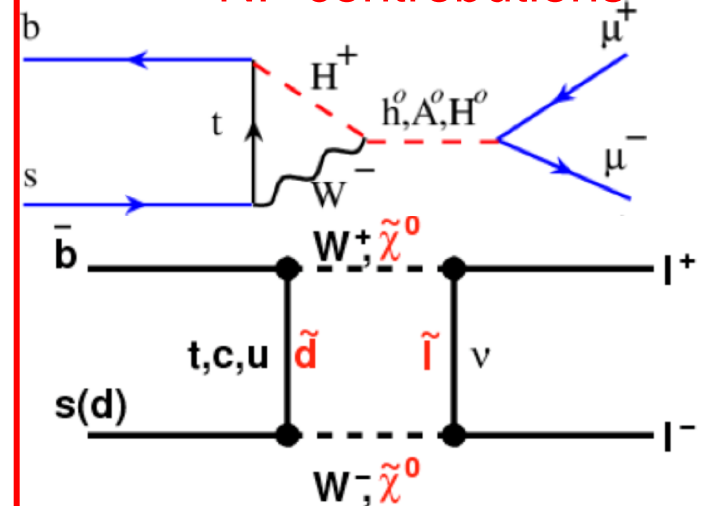 - **Rate is Cabibbo suppressed $|V_{ts(td)}|^2$**

decay	SM
$B_s \rightarrow \mu^+\mu^-$	$3.65 \pm 0.23 \times 10^{-9}$
$B^0 \rightarrow \mu^+\mu^-$	$1.1 \pm 0.1 \times 10^{-10}$

SM process

NP controbutions

History of this search

SM: $B_s^0 \rightarrow \mu^+\mu^-$

SM: $B^0 \rightarrow \mu^+\mu^-$

Legend: ARGUS, CLEO, UA1, CDF, L3, Belle, BABAR, D0, LHCb, CMS, ATLAS

Measurement of $B_{(S)} \rightarrow \mu^+\mu^-$ from CMS

- **B_d and B_s signals [blind analysis]**
  - Crystal Ball, fixed shape
  - normalization floating
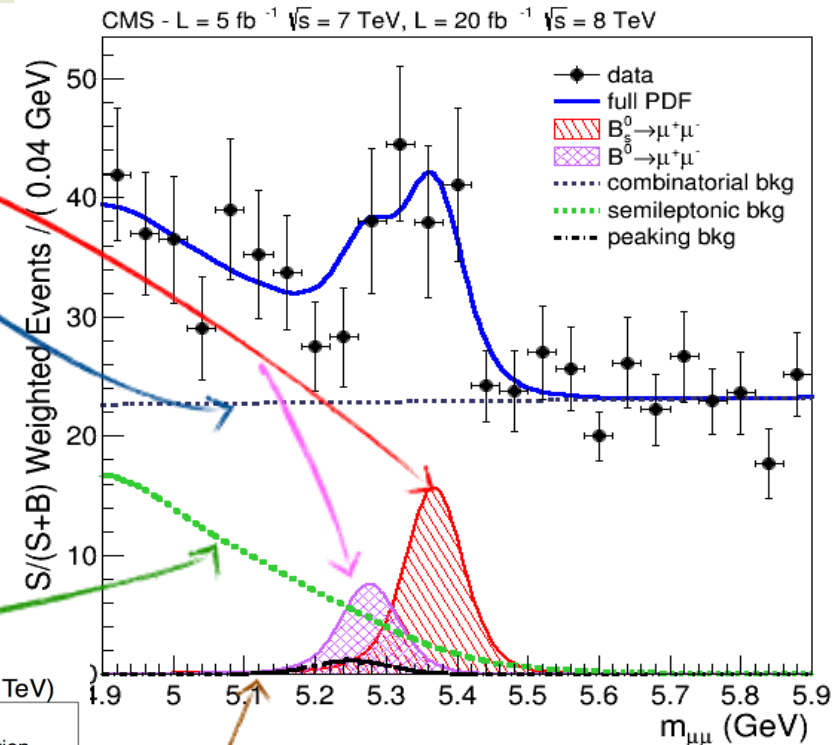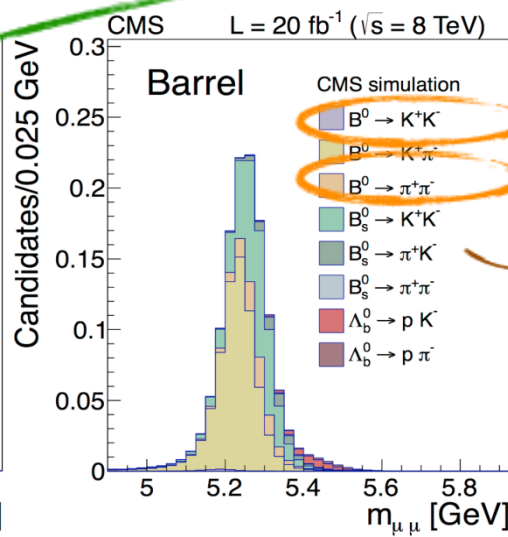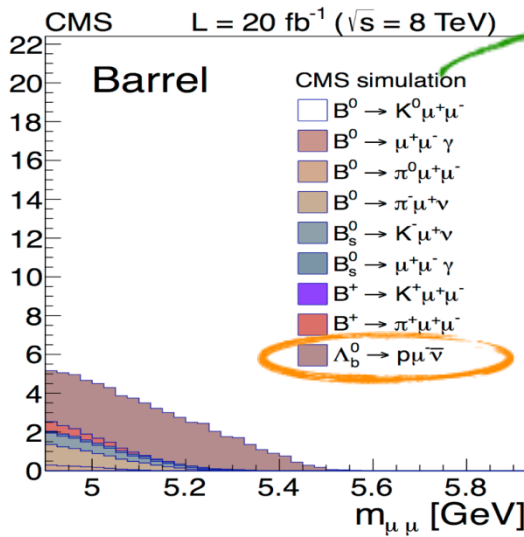- **combinatorial background**
  - first-degree polynomial
- **rare semi-leptonic background ($b \rightarrow q\mu\nu$)**
  - fixed shape, floated normalization
- **rare peaking background**
  - constrained to expectation

CMS - L = 5 fb^{-1} $\sqrt{s}$ = 7 TeV, L = 20 fb^{-1} $\sqrt{s}$ = 8 TeV

- data
- full PDF
- $B^0_s \rightarrow \mu^+\mu^-$
- $B^0_d \rightarrow \mu^+\mu^-$
- combinatorial bkg
- semileptonic bkg
- peaking bkg

$m_{\mu\mu}$ (GeV)

CMS $\quad$ L = 20 fb^{-1} ($\sqrt{s}$ = 8 TeV)

Barrel $\quad$ CMS simulation
- $B^0 \rightarrow K^0\mu^+\mu^-$
- $B^0 \rightarrow \mu^+\mu^-\gamma$
- $B^0 \rightarrow \pi^0\mu^+\mu^-$
- $B^0 \rightarrow \pi^-\mu^+\nu$
- $B^0_s \rightarrow K^-\mu^+\nu$
- $B^0_s \rightarrow \mu^+\mu^-\gamma$
- $B^+ \rightarrow K^+\mu^+\mu^-$
- $B^+ \rightarrow \pi^+\mu^+\mu^-$
- $\Lambda^0_b \rightarrow p\mu^-\bar{\nu}$

$m_{\mu\mu}$ [GeV]

CMS $\quad$ L = 20 fb^{-1} ($\sqrt{s}$ = 8 TeV)

Barrel $\quad$ CMS simulation
- $B^0 \rightarrow K^+K^-$
- $B^0 \rightarrow K^+\pi^-$
- $B^0 \rightarrow \pi^+\pi^-$
- $B^0_s \rightarrow K^+K^-$
- $B^0_s \rightarrow \pi^+K^-$
- $B^0_s \rightarrow \pi^+\pi^-$
- $\Lambda^0_b \rightarrow p K^-$
- $\Lambda^0_b \rightarrow p \pi^-$

$m_{\mu\mu}$ [GeV]

Rare decay backgrounds are normalized, channel by channel, to data size.

PRL 111 (2013) 101804

$\mathcal{BF}$ of $B_{(S)} \rightarrow \mu^+\mu^-$ from CMS
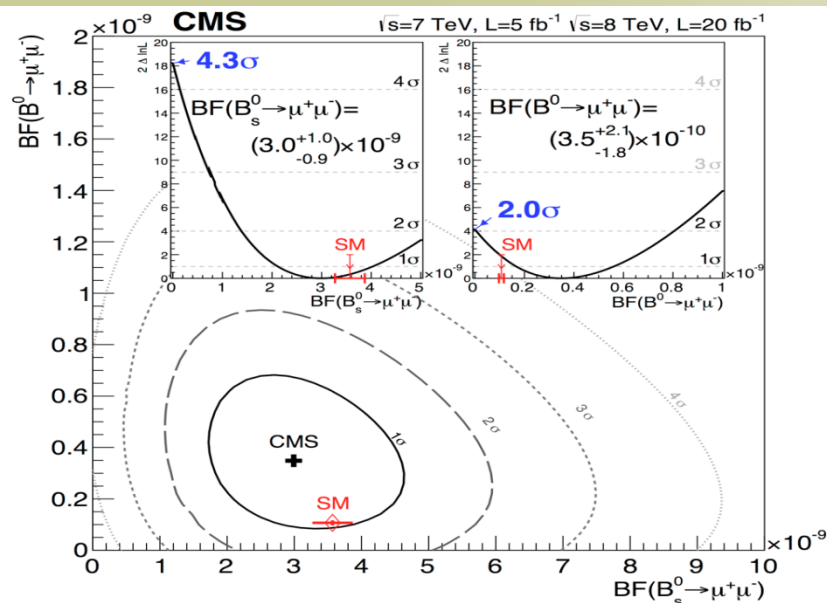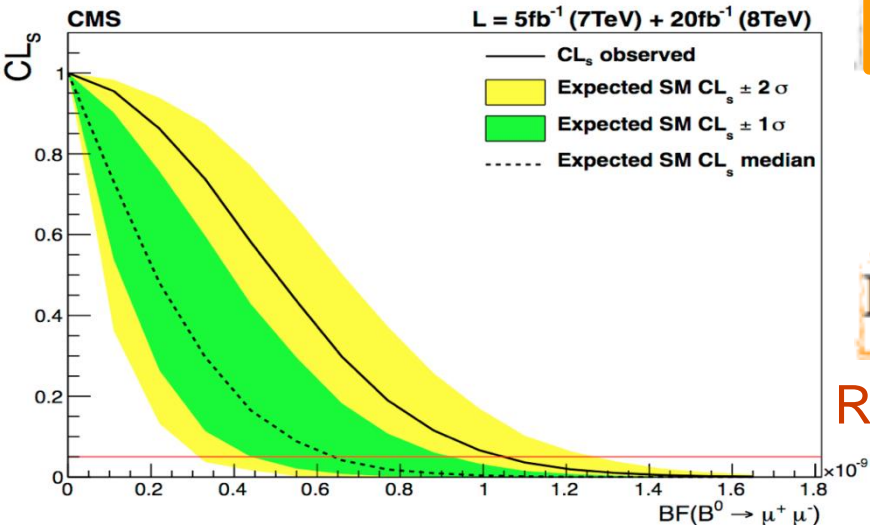

$B_S \rightarrow \mu\mu$
significance: 4.3 σ

$$BR(B_S \rightarrow \mu\mu) = \left(3.0^{+0.9}_{-0.8}\ (stat)^{+0.6}_{-0.4}\ (syst)\right) \times 10^{-9}$$

$B_d \rightarrow \mu\mu$

significance: 2.0 σ

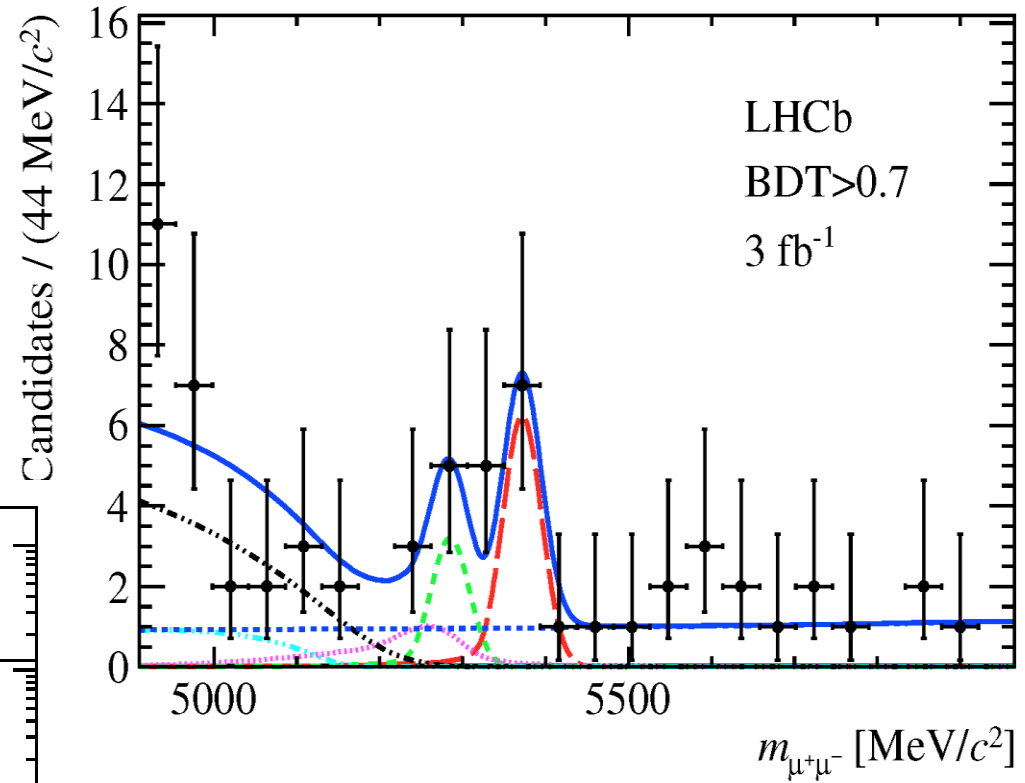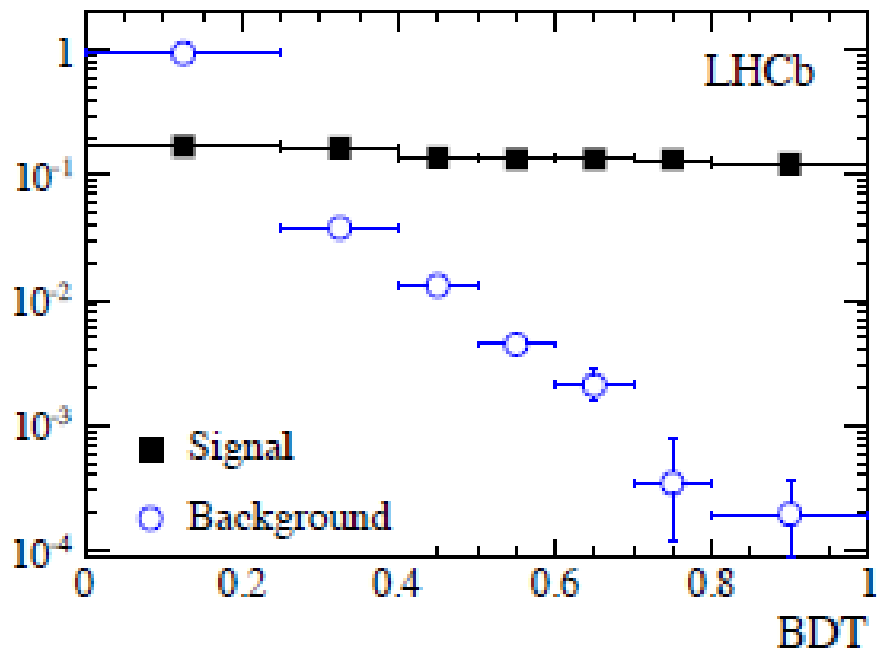$$BR(B_d \rightarrow \mu\mu) = \left(3.5^{+2.1}_{-1.8}\ (stat+syst)\right) \times 10^{-10}$$

upper limit **CLs method, using BDT**

$$BR(B_d \rightarrow \mu\mu) < 1.1 \times 10^{-9}\ @95\%\ CL$$

Results are compatible with SM expectations.

Measurement of $B_{(S)} \rightarrow \mu^+\mu^-$ from LHCb

- **Used full dataset of 3fb⁻¹ (1fb⁻¹ @7TeV, 2fb⁻¹ @8TeV)**
- **Improved BDT, optimized by using $B_{(S)} \rightarrow \mu^+\mu^-$ and bbar -> $\mu^+\mu^- X$ (topology & kinematics)**
- **Observed sensitivity: 4σ**

$$BR(B_s \rightarrow \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}) \times 10^{-9}$$

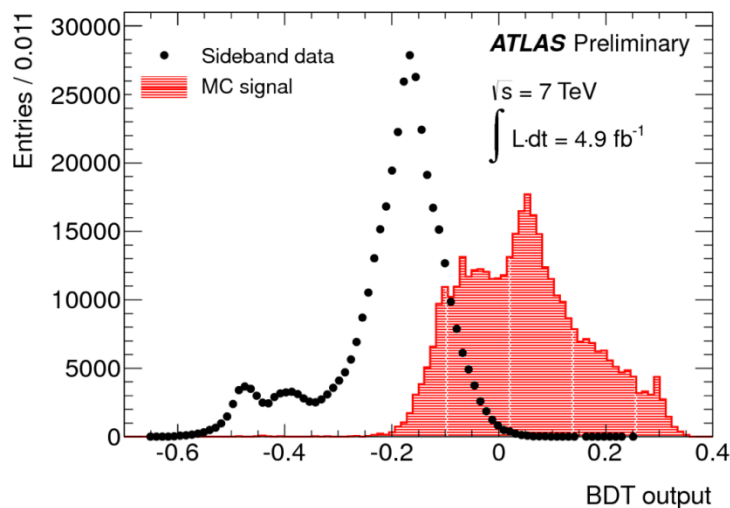$$BR(B^0 \rightarrow \mu^+\mu^-) = (3.7^{+2.4}_{-2.1}) \times 10^{-10}$$

$$BR(B^0 \rightarrow \mu^+\mu^-) < 7 \times 10^{-10} @ 95\% CL$$

PRL 111 (2013) 101805

Measurement of $B_{(S)} \rightarrow \mu^+\mu^-$ from ATLAS

- **Blind analysis: +/- 300MeV around Bs mass is blinded.**

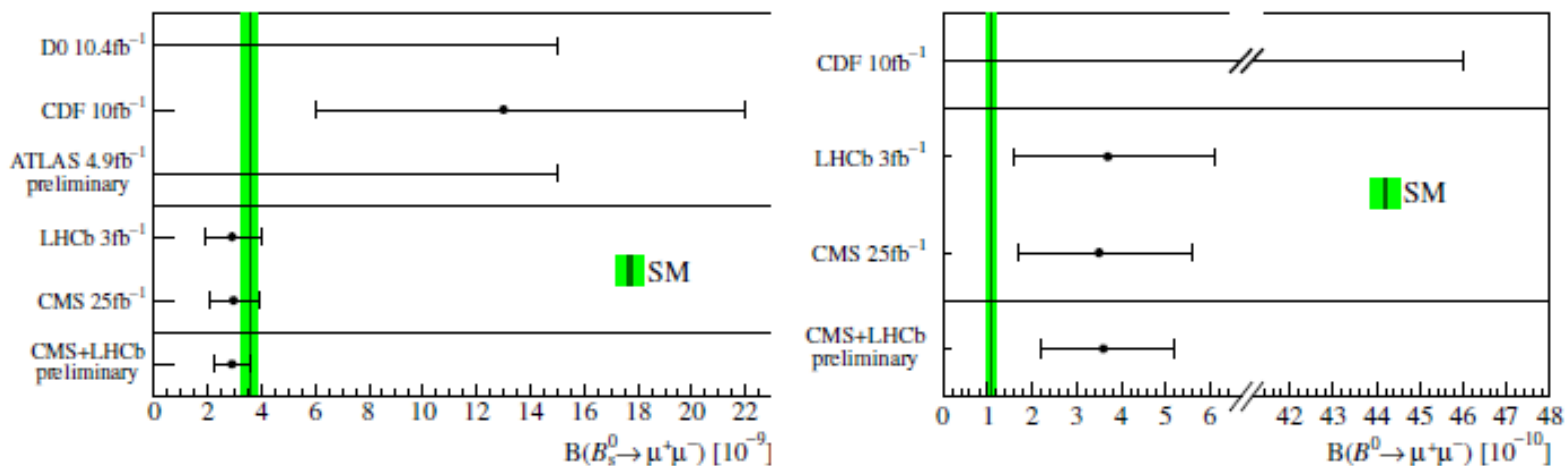| Channel	Blinded/Signal Region	Sideband Regions
$B_s^0 \rightarrow \mu^+\mu^-$	[5066, 5666] MeV	[4766, 5066] MeV
		[5666, 5966] MeV
$B^\pm \rightarrow J/\psi K^\pm$	[5180, 5380] MeV	[4930, 5130] MeV
		[5430, 5630] MeV

- **Signal/Background discrimination: Multivariate analysis BDT based on 13 variables**

bb→μμX dominant background
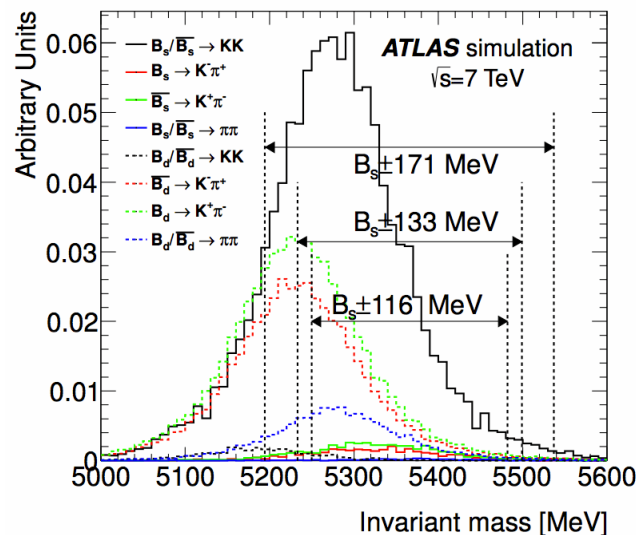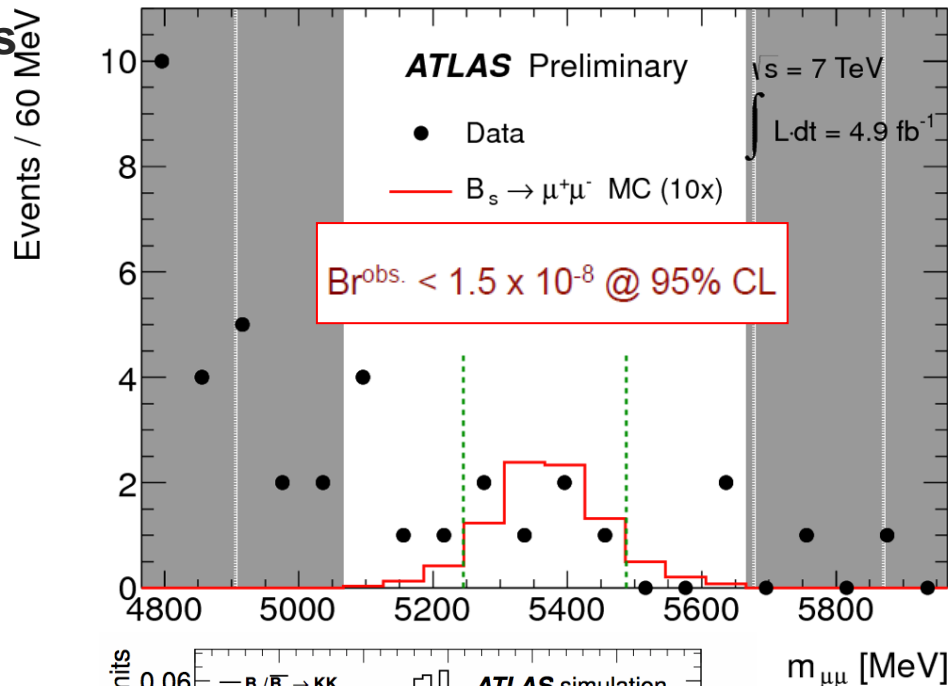
B(S)→ μ⁺μ⁻ from CMS + LHCb

Preliminary combination of results

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.6\ ^{+1.6}_{-1.4}) \times 10^{-10}$$

SM: BR(B$_s$) = (3.65±0.23) 10^{-9}
BR(B^0) = (1.1±0.1) 10^{-10}
PRL 112 101801 (2014)

$B_s^0 \to \mu^+\mu^-$ is observed at more than 5σ
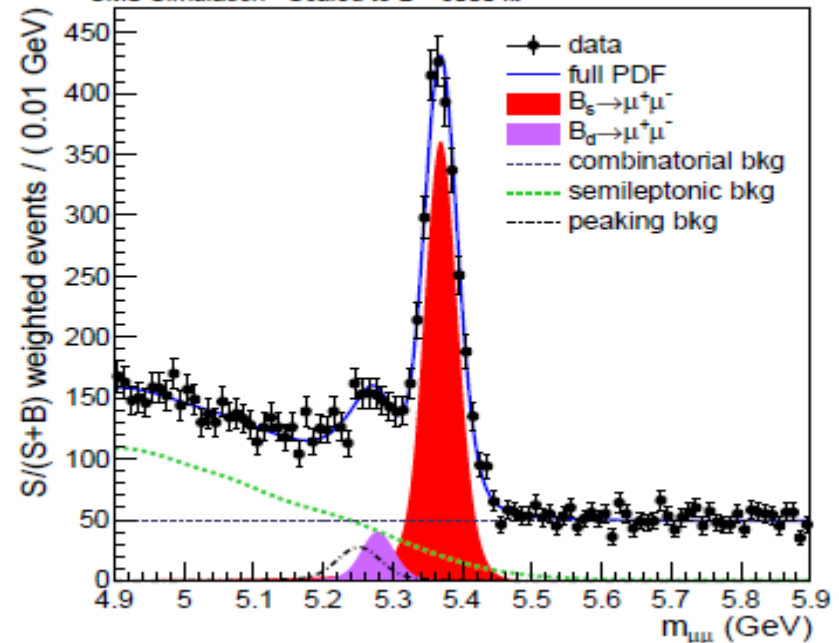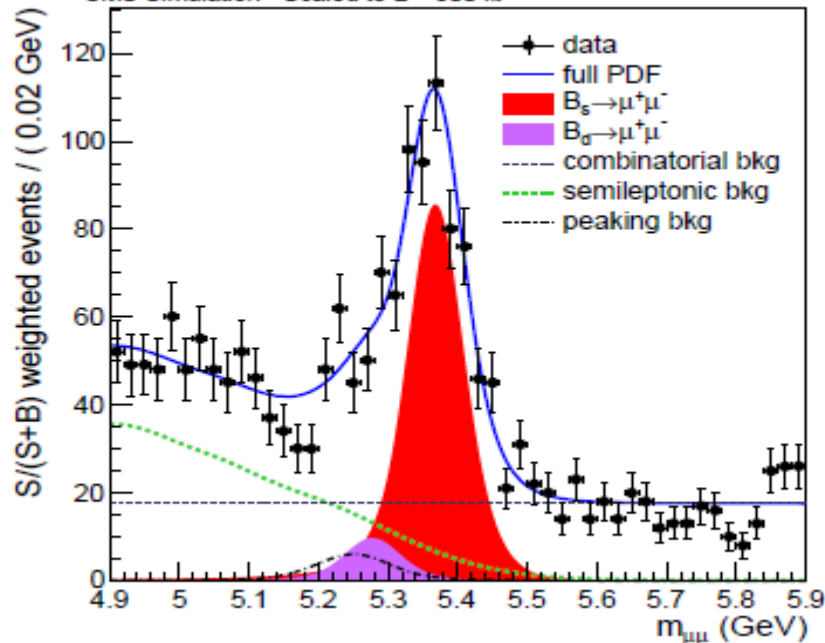
SM (decay-time integrated) expectation:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) \quad = \quad (3.57 \pm 0.30) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) \quad = \quad (1.07 \pm 0.10) \times 10^{-10}$$

(Buras, *et al.*, 2012)

CMS reach for B$_{(S)} \rightarrow \mu^+\mu^-$

L (fb^{-1})	No. of B$_s^0$	No. of B^0	$\delta\mathcal{B}/\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$	$\delta\mathcal{B}/\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)$	B^0 sign.	$\delta\frac{\mathcal{B}(B^0\rightarrow\mu^+\mu^-)}{\mathcal{B}(B_s^0\rightarrow\mu^+\mu)}$
20	16.5	2.0	35%	>100%	0.0–1.5 σ	>100%
100	144	18	15%	66%	0.5–2.4 σ	71%
300	433	54	12%	45%	1.3–3.3 σ	47%
3000	2096	256	12%	18%	5.4–7.6 σ	21%

- **Expectation assuming SM branching fraction and planned detector upgrade**
- **Large pileup will affect the detection efficiency, tightening the selection criteria reduce in background, better determination of peaking backgrounds…**
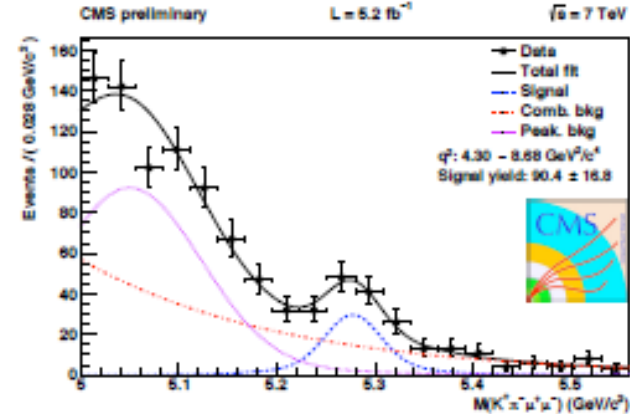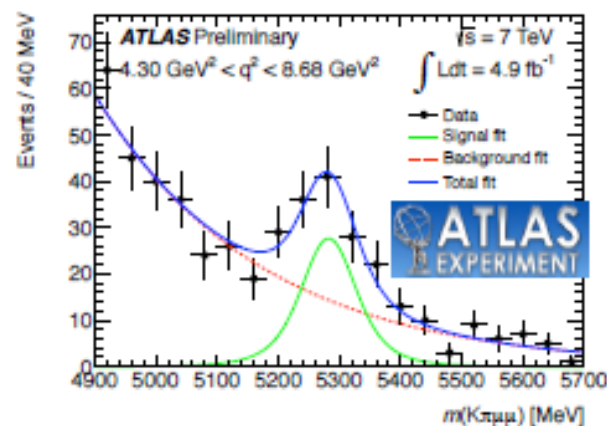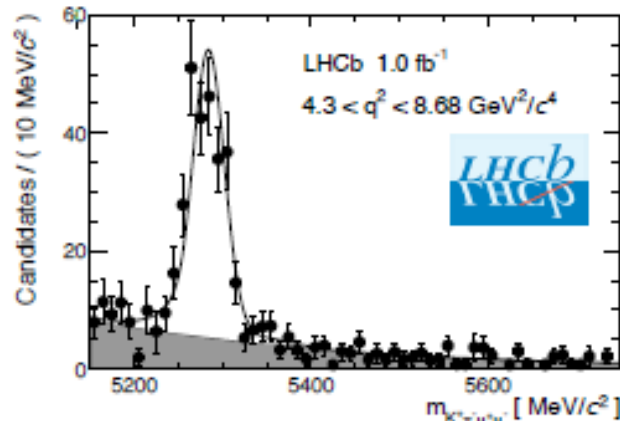
Electroweak penguin decays: B→ X$_s \ell^+ \ell^-$

- **Forbidden at tree level, but allowed via loop diagrams in SM**
- **Sensitive to NP through BSM particles in the loop**
- **Small branching fraction**
- **More precise theoretical prediction**
- **Observables to compare with SM predictions:**
  Branching fraction, A$_{CP}$, A$_{FB}$, P'$_5$, Isospin-asymmetry….

Electroweak penguin decay
$(b \rightarrow sl^+ l^-)$
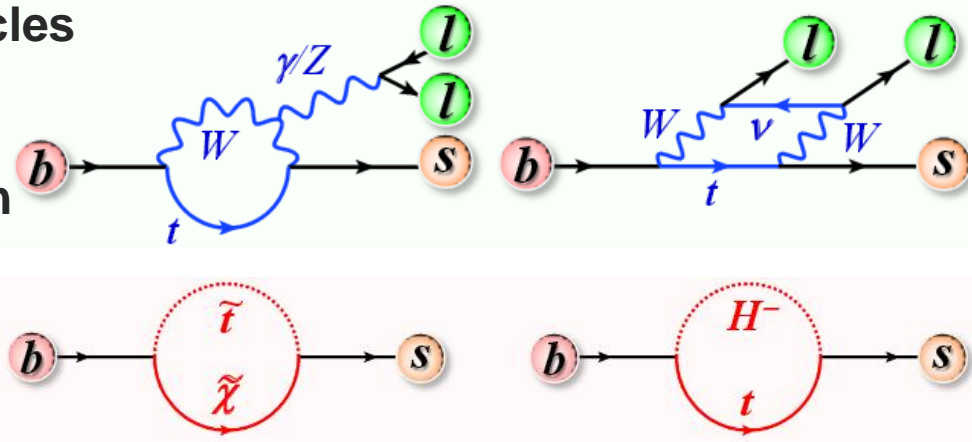
All LHC experiments see clear signals of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

LHCb 1.0 fb^{-1}
$4.3 < q^2 < 8.68$ GeV^2/c^4

ATLAS Preliminary
$\sqrt{s}$ = 7 TeV
4.30 GeV$^2 < q^2 < 8.68$ GeV^2
$\int$ Ldt = 4.9 fb^{-1}
- Data
- Signal fit
- Background fit
- Total fit

CMS preliminary
L = 5.2 fb^{-1}
$\sqrt{s}$ = 7 TeV
- Data
- Total fit
- Signal
- Comb. bkg
- Peak. bkg
q^2: 4.30 – 8.68 GeV^2/c^4
Signal yield: 90.4 ± 16.8

B→ X$\ell^+\ell^-$ @LHC, Belle, BaBar, CDF

# of events	BaBar 433fb^{-1}	Belle 605fb^{-1}	CDF 9.6fb^{-1}	LHCb 1 / 3 fb^{-1}	ATLAS 5fb^{-1}	CMS 5fb^{-1}
$B^0 \to K^{*0} \ell^+\ell^-$	137±44*	247±54*	288±20	2361±56	466±34	415±29
$B^+ \to K^{*+} \ell^+\ell^-$			24±6	162±16		
$B^+ \to K^+ \ell^+\ell^-$	153±41*	162±38*	319±23	4746±81		
$B^0 \to K^0_s \ell^+\ell^-$			32±8	176±17		
$B_s \to \phi \ell^+\ell^-$			62±9	174±15		
$\Lambda_b \to \Lambda \ell^+\ell^-$			51±7	78±12		
$B^+ \to \pi^+ \ell^+\ell^-$		limit		25±7		

Babar arXiv:1204.3933
Belle arXiv:0904.0770
CDF arXiv:1107.3753 + 1108.0695
  + ICHEP 2012

ATLAS (preliminary) [ATLAS-CONF-2013-038]
CMS (preliminary) [CMS-BPH-11-009]

LHCb arxiv:1403.8044 +1305.2168 +1306.2577 +JHEP12(2012)125

*mixture of B^0 and B$^\pm$ and ℓ = e,μ
other experiments: ℓ = μ only

Decay parameters for B→ K*⁰μ⁺μ⁻

- **Decay is characterized by 3 angular variables**

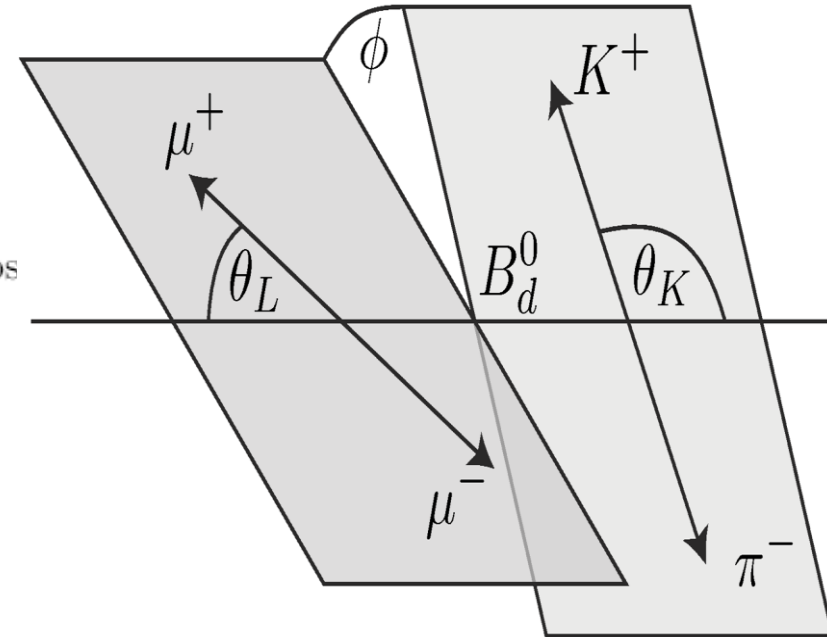$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi\, dq^2}$$

$$=\frac{9}{32\pi}\left[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos\right.$$

$$- F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$

$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$

$$+ S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$

$$\left.+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\right],$$

- **One of the interesting parameter is muon forward-backward asymmetry (A_{FB}) which is sensitive to new physics**

dimuon invariant mass

$$A_{FB}\propto -\mathrm{Re}\left[\left(2C_7^{eff} + \frac{q^2}{m_b^2}C_9^{eff}\right)C_{10}\right]$$
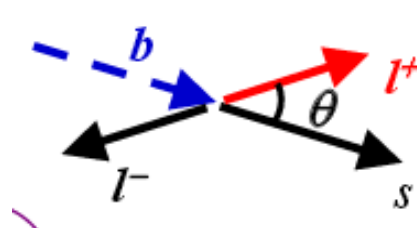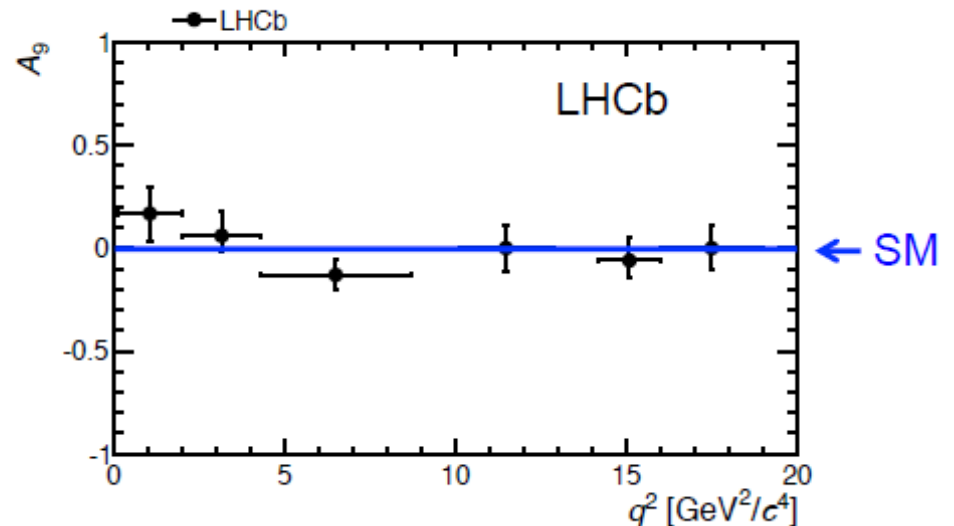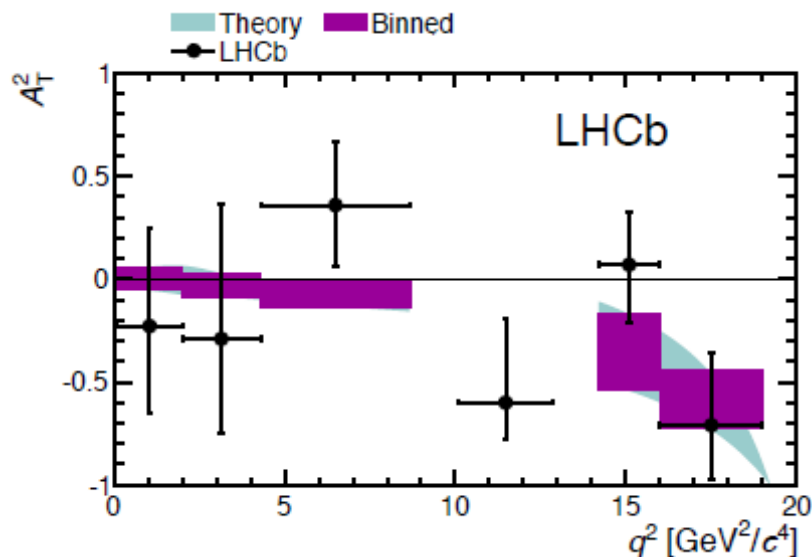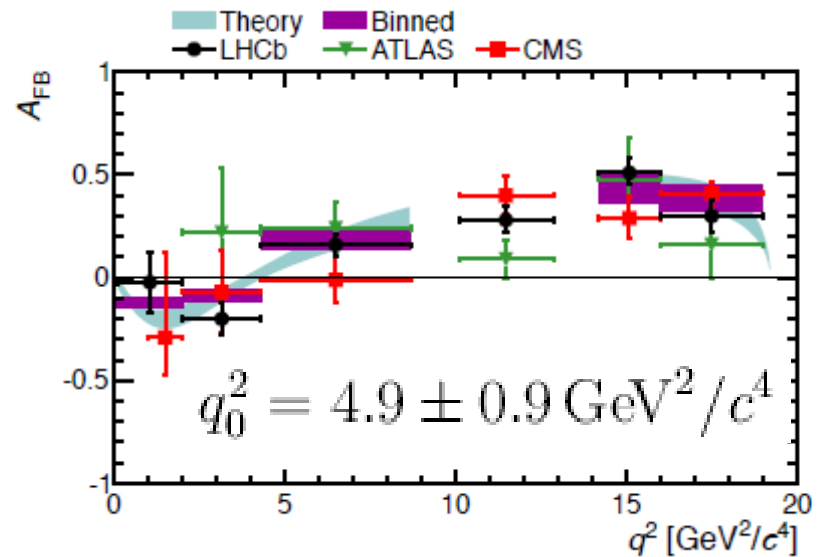
Forward event   **Backward event**
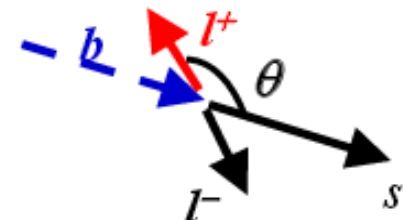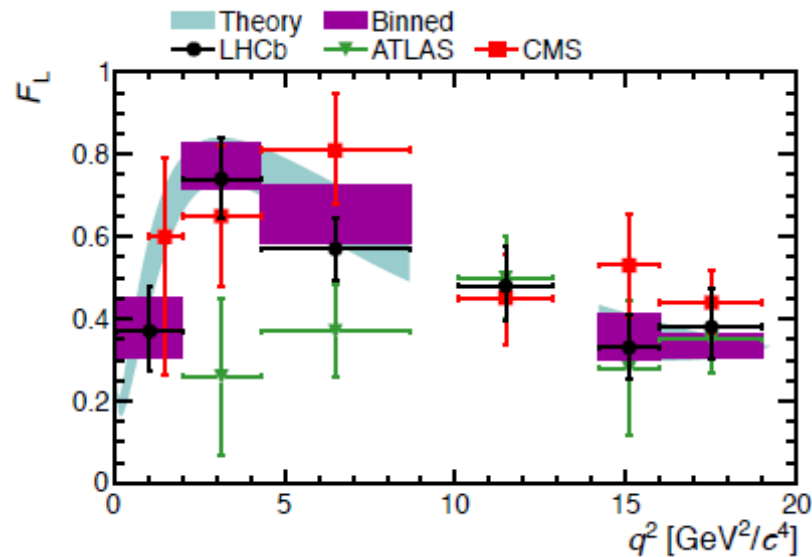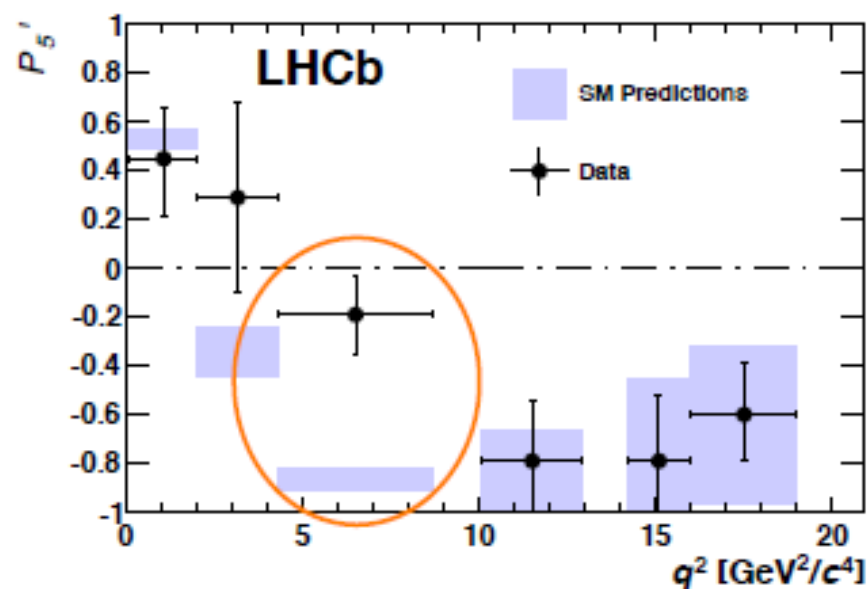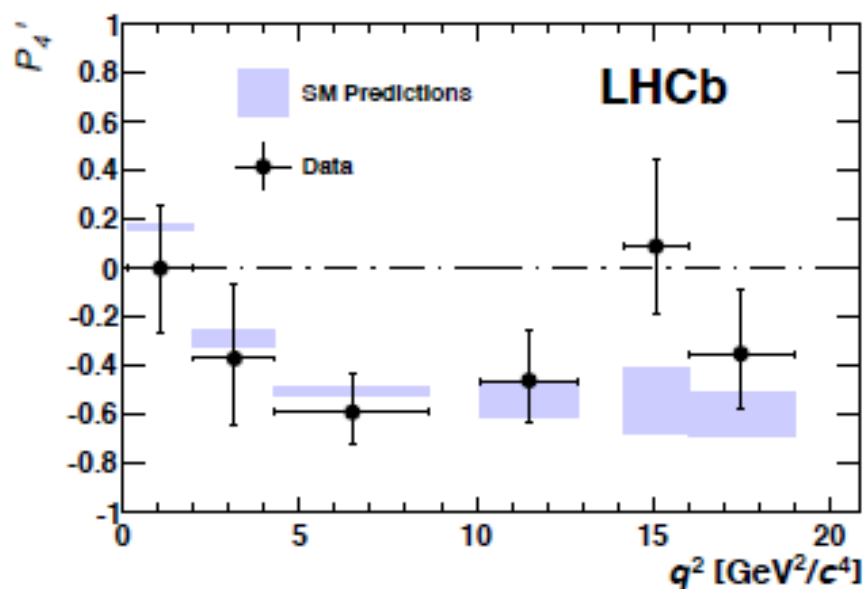
Observables for B$\rightarrow$ K$^{*0}\mu^+\mu^-$ @LHC

ATLAS (prelim.) [ATLAS-CONF-2013-038] , CMS 5.2 fb^{-1} [PLB 727 (2013) 77] , LHCb 1 fb^{-1} [JHEP 08 (2013) 131]

$$q_0^2 = 4.9 \pm 0.9\,\mathrm{GeV}^2/c^4$$

Observables for B$\rightarrow$ K$^{*0}\mu^+\mu^-$ @LHCb

- **Some new observables used by LHCb which are free from hadronic uncertainties are** $P'_{4,5} = S_{4,5} / F_L (1 - F_L)$
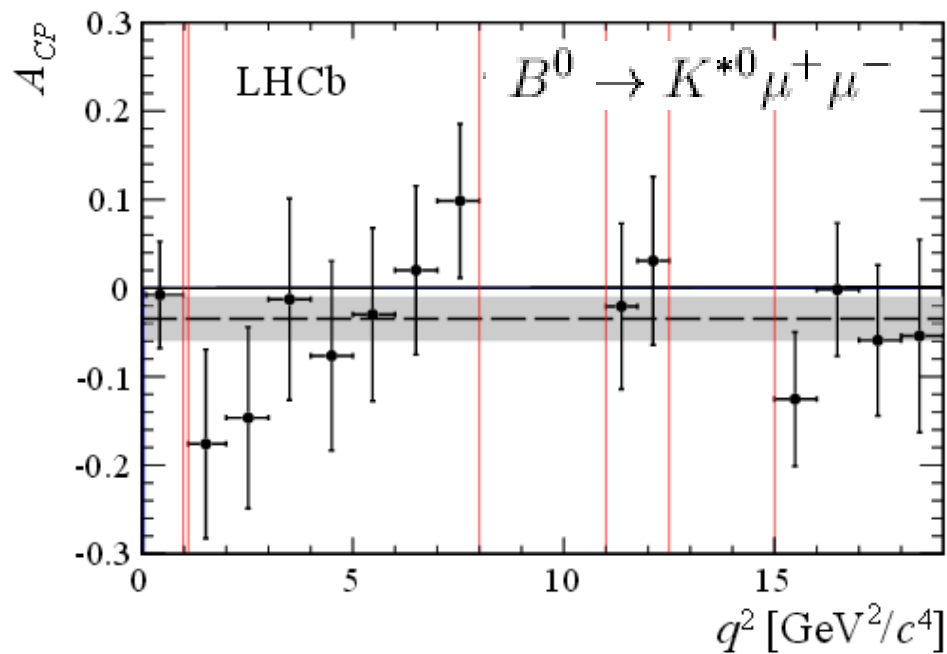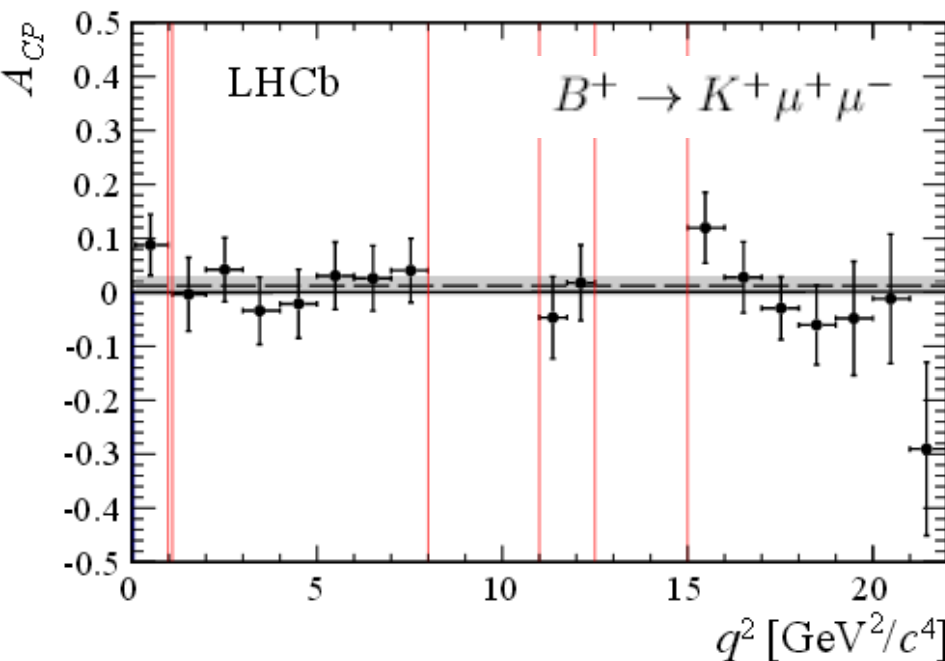

SM predictions from [Decotes-Genon et al. JHEP 05 (2013) 137]

- **There is a local discrepancy of 3.7σ in P'$_5$ parameter. More data will either establish/reject this discrepancy.**

Direct CP violation in B→K$^{(*)}\mu^+\mu^-$ @LHCb

- **Direct CP asymmetry is defined to be** $\quad \mathcal{A}_{CP} \equiv \dfrac{\Gamma(\overline{B} \to \overline{K}^{(*)}\mu^+\mu^-) - \Gamma(B \to K^{(*)}\mu^+\mu^-)}{\Gamma(\overline{B} \to \overline{K}^{(*)}\mu^+\mu^-) + \Gamma(B \to K^{(*)}\mu^+\mu^-)}$

- **Better theoretical prediction due to form-factor cancellation in asymmetry.**

- **LHCb uses 3fb^{-1} data**

$$\mathcal{A}_{CP}(B^0 \to K^{*0}\mu^+\mu^-) = -0.035 \pm 0.024 \pm 0.003,$$
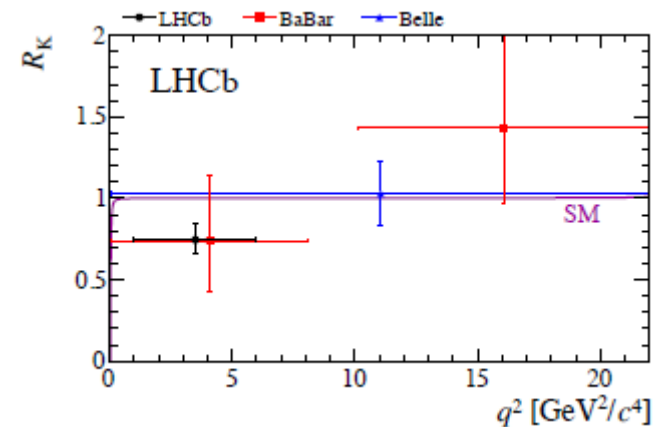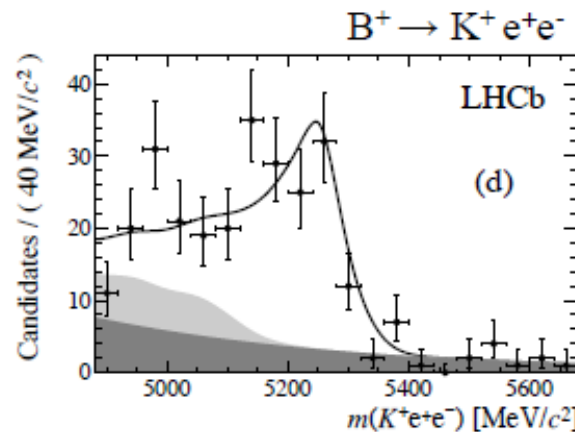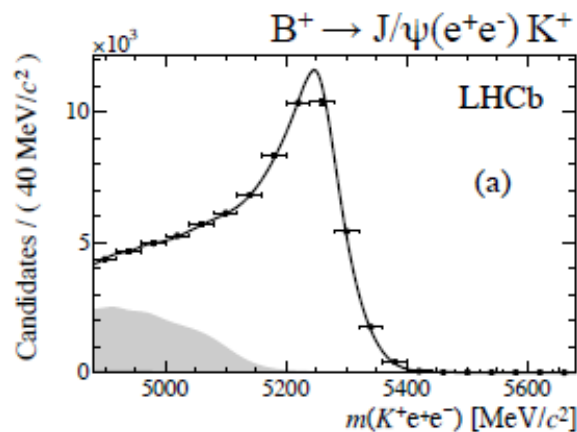$$\mathcal{A}_{CP}(B^+ \to K^+\mu^+\mu^-) = 0.012 \pm 0.017 \pm 0.001,$$

arXiv: 1408:0978

Test of lepton Universality in B⁺→K⁺ℓ⁺ℓ⁻

- **SM requires the three lepton family to have identical coupling to gauge bosons**

- **One can test universality by comparing the results from B⁺–>K⁺μ⁺μ⁻ and B⁺–>K⁺e⁺e⁻**

$$R_{\rm K} = \frac{\int_{q^2=1\,{\rm GeV}^2/c^4}^{q^2=6\,{\rm GeV}^2/c^4} (d\mathcal{B}[B^+ \to K^+\mu^+\mu^-]/dq^2)dq^2}{\int_{q^2=1\,{\rm GeV}^2/c^4}^{q^2=6\,{\rm GeV}^2/c^4} (d\mathcal{B}[B^+ \to K^+e^+e^-]/dq^2)dq^2} \overset{\rm SM}{=} 1 \pm \mathcal{O}(10^{-3})$$

SM: JHEP 12 (2007) 040

In 3fb⁻¹ LHCb determines

$$R_{\rm K} = 0.745^{+0.090}_{-0.074}({\rm stat})^{+0.036}_{-0.036}({\rm syst})$$

(consistent with SM at 2.6σ)

LHCb-PAPER-2014-024 [Preliminary],

Belle [PRL 103 (2009) 171801] ,

BaBar [PRD 86 (2012) 032012]

Observables for B→ Xγ

Photon polarization measured from up-down asymmetry
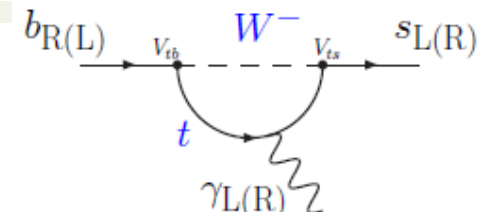
- Asymmetry of photon direction in Kππ rest frame
- Analogously to the Wu experiment

Reconstruct $B^+ \to K^+\pi^+\pi^-\gamma$

- ~13000 signal candidates in 3fb^{-1}
- Several overlapping resonances in $m(K^+\pi^+\pi^-)$

  → data divided in 4 bins in $m(K^+\pi^+\pi^-)$
-

Combining the 4 bins, the photon is observed to be polarized at 5.2σ

- **First observation of photon polarization in $b \to s\gamma$ decays**
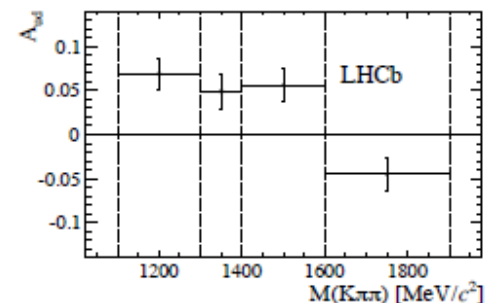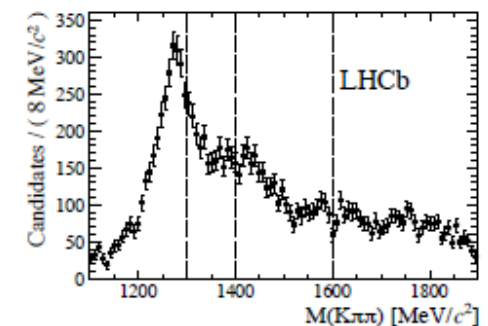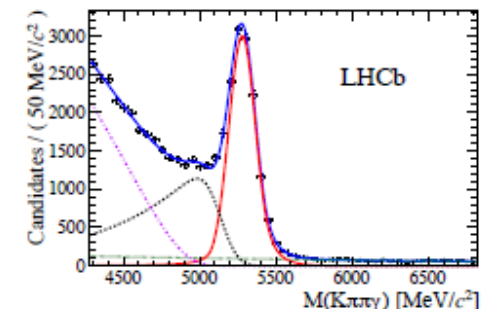
Summary

- **Rare quark decays play an important role in search for New Physics**

- **So far there is no conclusive hint for New Physics, however few observables**

  show some deviation from SM

  –> P'$_5$ in B–>K$^{(*)}\mu^+\mu^-$ in LHCb

  –> Lepton Universality in B–>K$^+$l+l- from LHCb

- **Need more work from theory as well as experimental side.**

- **Many more new results will come soon: B–>K$^{(*)}\mu^+\mu^-$ (CMS, ATLAS, LHCb),**

  B–>$\mu^+\mu^-$ (LHCb + CMS)

STAY TUNED !