# LHCb results on flavour anomalies

- Introduction
- Lepton Universality in pengiuns
- Angular distributions
- More Lepton Universality in trees

**On behalf of the LHCb collaboration**

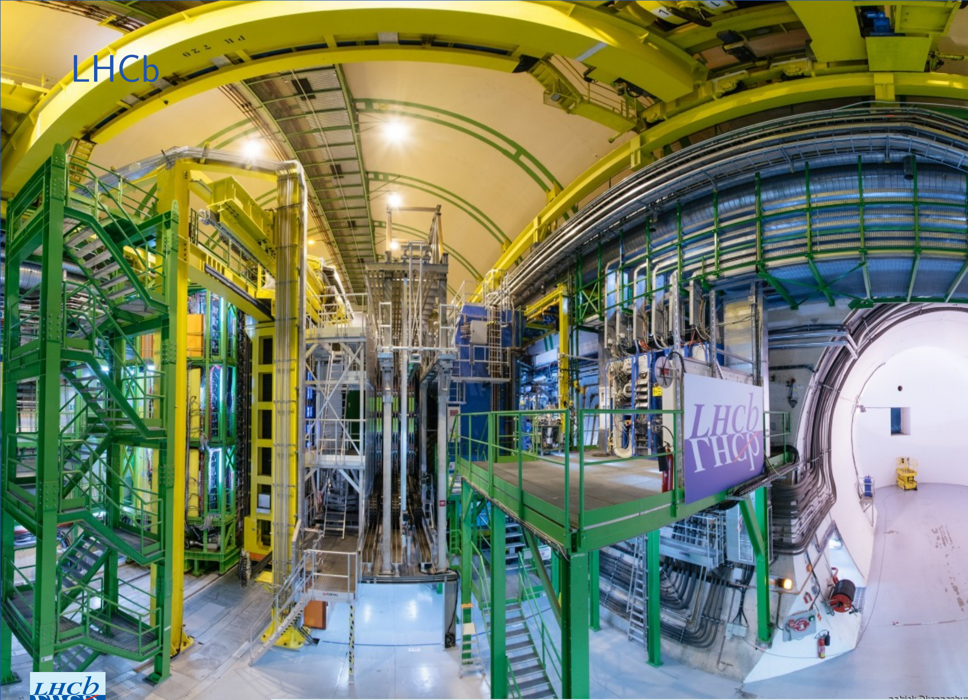
Since many theorists speak after me, I leave interpretation (mostly) aside.

**22/10/2018 — Workshop on high-energy implications of flavour anomalies**

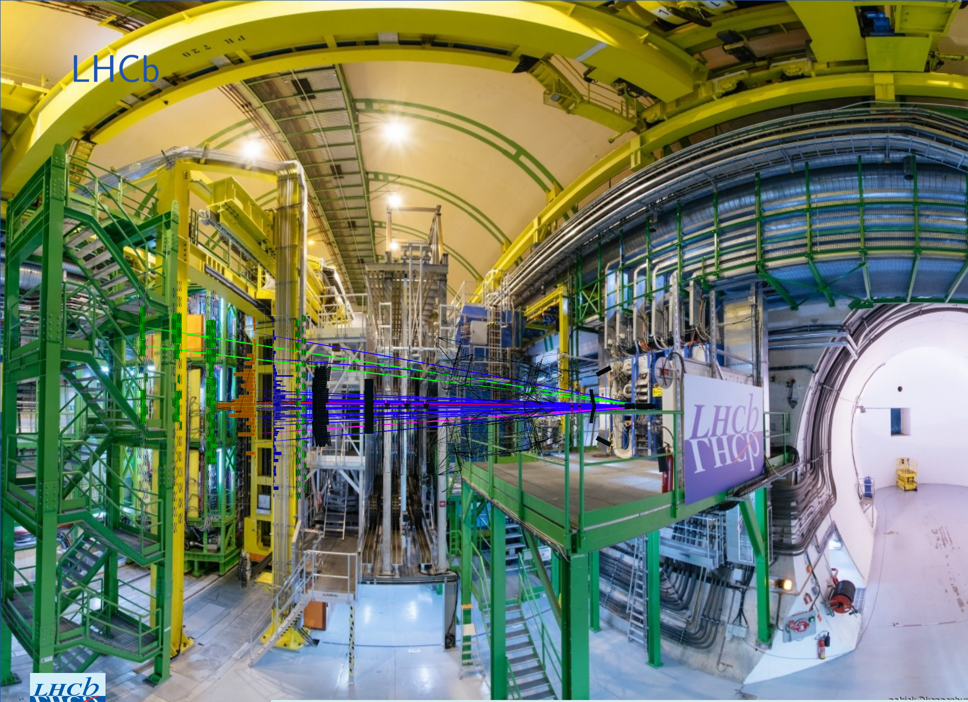

**Patrick Koppenburg**

Nikhef

# LHCb

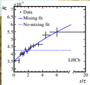


# LHCb

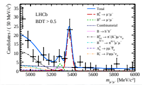


# LHCb Physics Programme

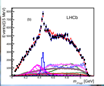
CKM and *CP* violation with *b* and *c* hadrons

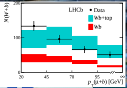



Rare decays of *b* hadrons and *c* hadrons

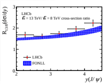



Spectroscopy in *pp* interactions and *B* decays

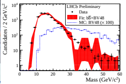



Electroweak and QCD measurements in the forward acceptance



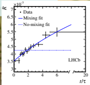

Heavy quark production

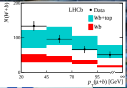



Exotica searches

# LHCb Physics Programme

CKM and *CP* violation with *b* and *c* hadrons

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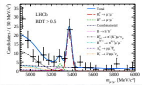


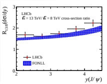


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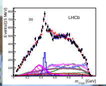
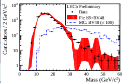



Exotica searches



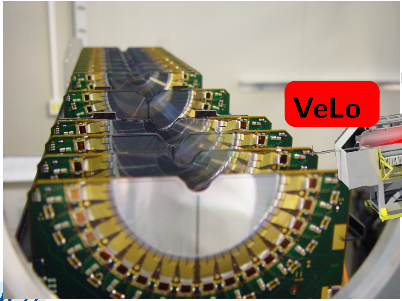
# LHCb Detector

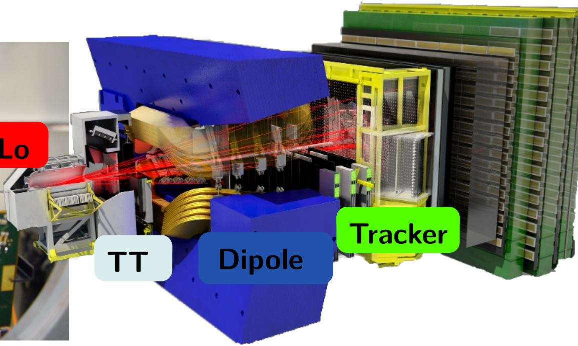
Forward detector: many $b$ hadrons produced forward at LHC, $(144 \pm 1 \pm 21)$ µb in acceptance at 13TeV [PRL 118 (2017) 052002]

- Warm dipole magnet. Polarity can be reversed

✔ Good momentum and position resolution

  - Vertex detector gets 8mm to the beam





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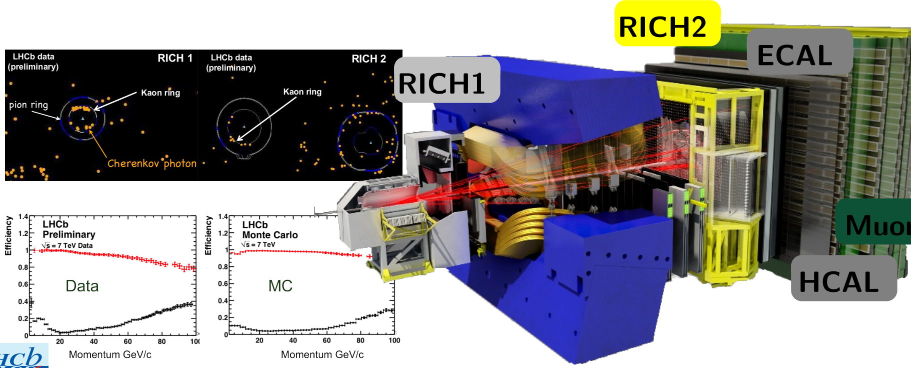
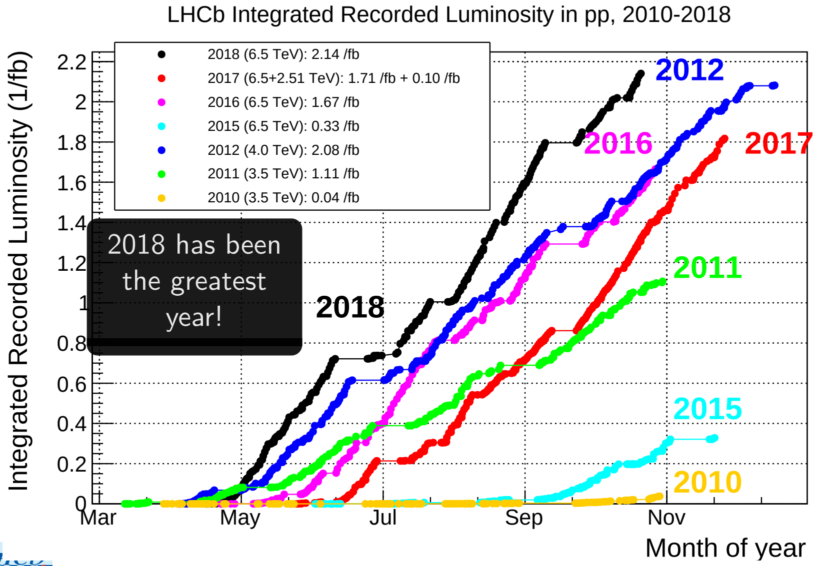
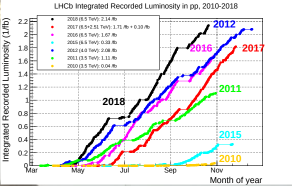
- Warm dipole magnet. Polarity can be reversed
- ✔ Good momentum and position resolution, high efficiency
- ✔ Excellent Particle ID



# Integrated luminosity



# PARTY TIME!




2018 has been the greatest year!

Integrated luminosity counters in 2018 [1/pb]

| | Recorded | Delivered | Efficiency |
|---|---|---|---|
| Current Fill | 8.44 | 9.50 | 88.84 |
| Annual | 2000.00 | 2233.27 | 89.55 |
| Mag DOWN | 1055.69 | 1174.06 | 89.92 |
| Mag UP | 942.76 | 1057.56 | 89.14 |
| 2010-2018 | 9036.17 | 9957.67 | 90.75 |

09 Oct.: 2 $\mathrm{fb}^{-1}$

Integrated luminosity counters in 2018 [1/pb]

| | Recorded | Delivered | Efficiency |
|---|---|---|---|
| Current Fill | 10.64 | 12.85 | 82.81 |
| Annual | 2035.84 | 2275.60 | 89.46 |
| Mag DOWN | 1055.69 | 1174.06 | 89.92 |
| Mag UP | 978.60 | 1099.89 | 88.97 |
| 2010-2018 | 9072.02 | .0000.00 | 90.72 |

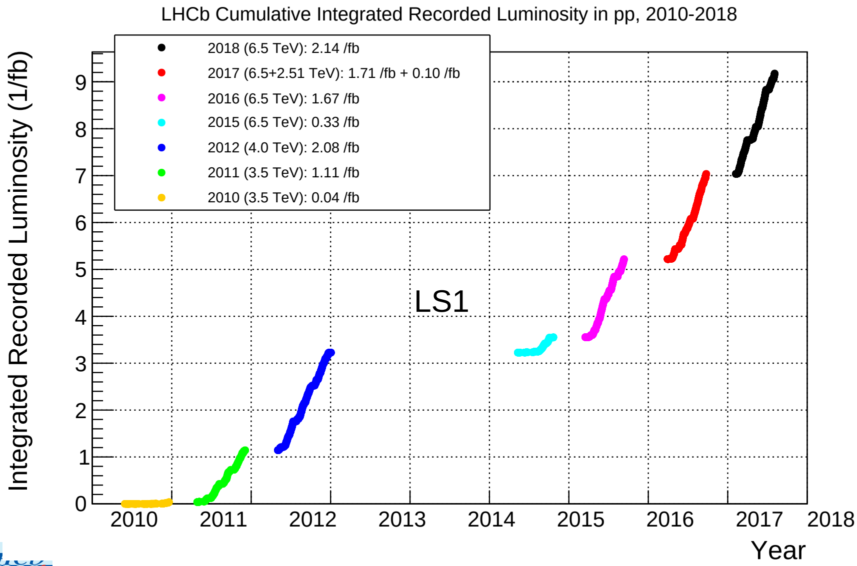
17 Oct.: 10 $\mathrm{fb}^{-1}$

Integrated luminosity counters in 2018 [1/pb]

| | Recorded | Delivered | Efficiency |
|---|---|---|---|
| Current Fill | 3.5 | 4.1 | 86.1 |
| Annual | 2082.0 | 2327.4 | 89.5 |
| Mag DOWN | 1055.7 | 1174.1 | 89.92 |
| Mag UP | 1024.7 | 1151.7 | 88.97 |
| 2010-2018 | 9118.1 | 10051.8 | 90.71 |

18 Oct.: 2.082 $\mathrm{fb}^{-1}$

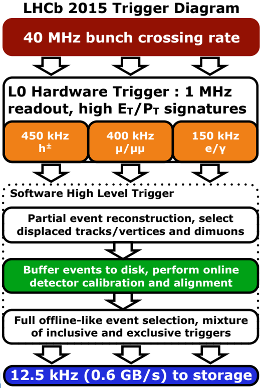
# Integrated luminosity

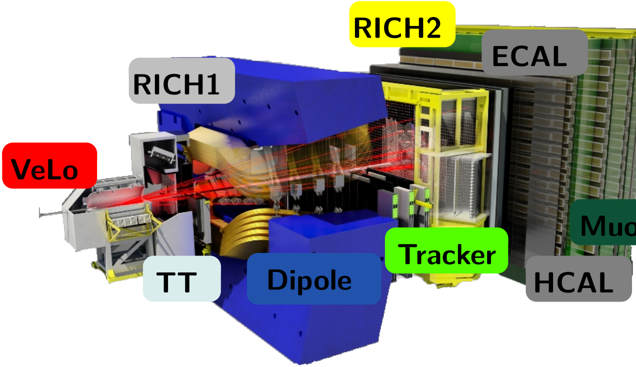


# LHCb Trigger in Run 2

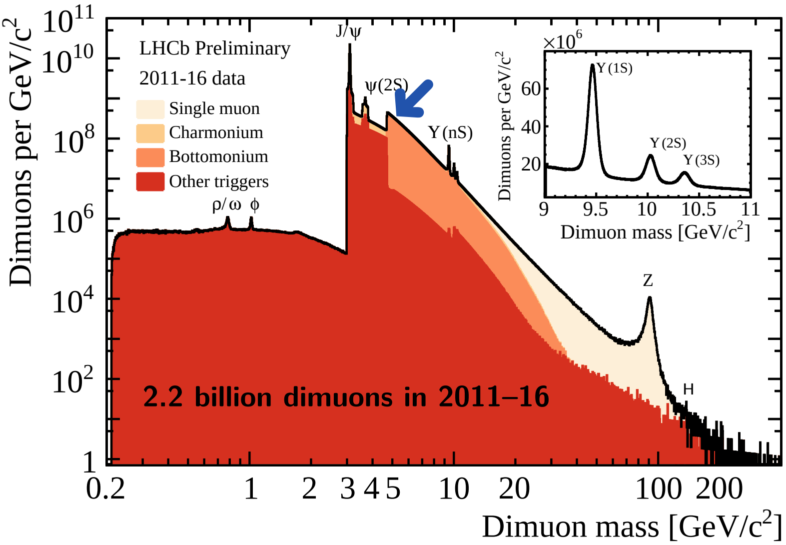
Versatile two stage trigger

- Hardware-based L0 trigger: moderate $p_{\mathrm{T}}$ cuts ➜ 1 MHz
  - ➜ Whole data sent to trigger farm
- Calibrate in real-time ➜ 12 kHz output (some reduced size)



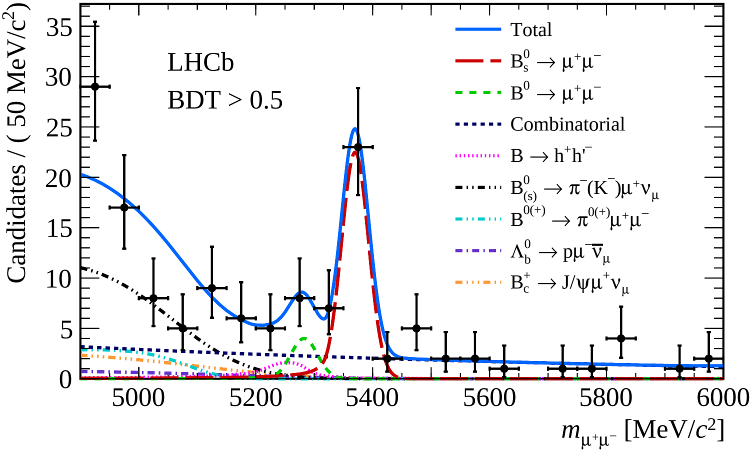



# Dimuon mass distribution



# Observation of the decay $B_s^0 \to \mu^+\mu^-$

Run 2



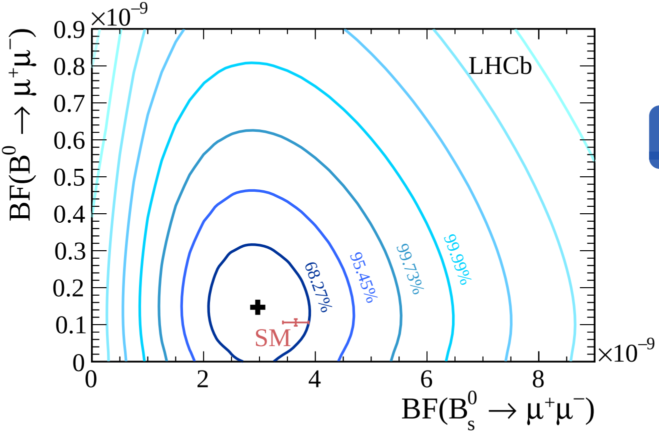

Mass plot shows candidates with BDT$>$ 0.5.

The significances are 7.8$\sigma$ for $B_s^0 \to \mu^+\mu^-$ and 1.6$\sigma$ for $B^0 \to \mu^+\mu^-$.

[LHCb, Phys. Rev. Lett. 118 (2017) 191801, arXiv:1703.05747]

# Observation of the decay $B_s^0 \to \mu^+\mu^-$

Run 2




No anomaly!

The results $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6\,^{+0.3}_{-0.2}) \times 10^{-9}$ and $\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.5\,^{+1.2}_{-1.0}\,^{+0.2}_{-0.1}) \times 10^{-10}$ are consistent with the SM.

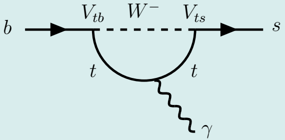
[Bobeth et al., PRL 112 101801 (2014)]

# Flavour Anomalies

Flavour anomalies

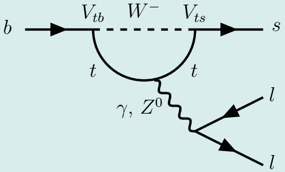
# Flavour Anomalies

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



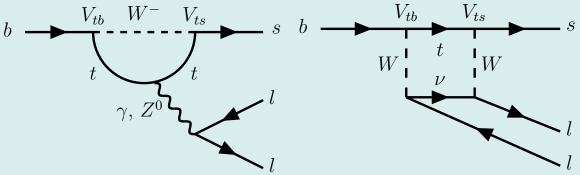

- Start with $b \to s\gamma$

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




- Start with $b \to s\gamma$, pay a factor $\alpha_{\rm EM}$
  - ➜ Decay the $\gamma$ into 2 leptons

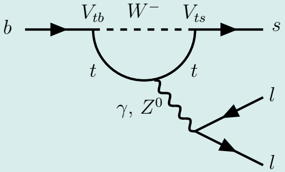
# $b \to s\ell^+\ell^-$

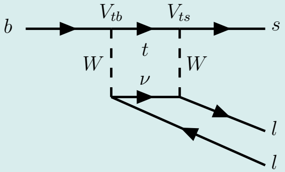



- Start with $b \to s\gamma$, pay a factor $\alpha_{\rm EM}$
  - ➜ Decay the $\gamma$ into 2 leptons
  - Add an interfering box diagram
  - ➜ $b \to s\ell^+\ell^-$, very rare in the SM
    $\mathcal{B}(B \to K^*\ell^+\ell^-) = (1.8 \pm 0.2) \cdot 10^{-6}$

    [Huber et al., Nucl.Phys.B802:40-62,2008]

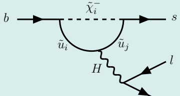
# $b \to s\ell^+\ell^-$



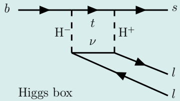




- Start with $b \to s\gamma$, pay a factor $\alpha_{\mathrm{EM}}$
  - ➜ Decay the $\gamma$ into 2 leptons
  - Add an interfering box diagram
  - ➜ $b \to s\ell^+\ell^-$, very rare in the SM
- Sensitive to Supersymmetry, Any 2HDM, Fourth generation, Extra dimensions, Leptoquarks, Axions ...

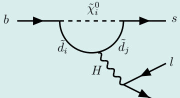
✔ Ideal place to look for new physics



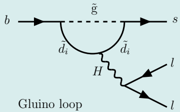

Chargino loop



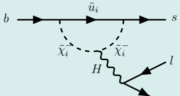

Higgs box




Neutralino loop

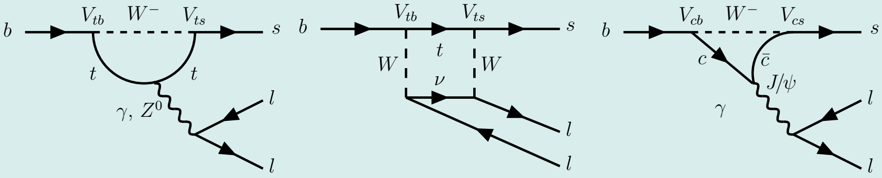



Gluino loop

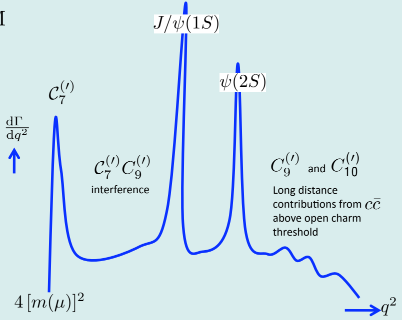



Chargino loop

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

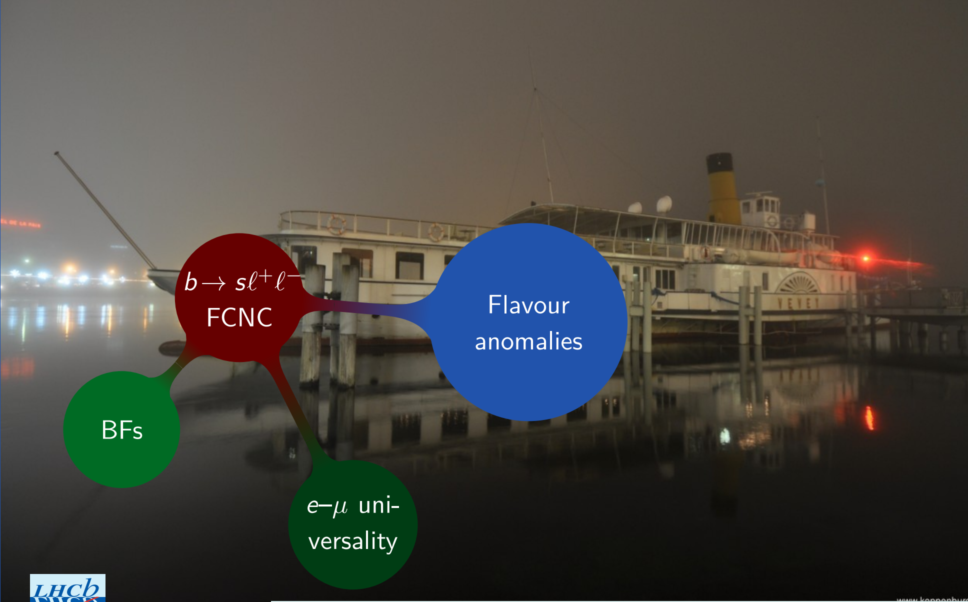



- Start with $b \to s\gamma$, pay a factor $\alpha_{\rm EM}$
  - ➜ Decay the $\gamma$ into 2 leptons
  - Add an interfering box diagram
  - ➜ $b \to s\ell^+\ell^-$, very rare in the SM
- ✗ But beware of long-distance effects:
  - Tree $b \to c\bar{c}s$, $(c\bar{c}) \to \ell\ell$
  - ✔ Can be removed by mass cuts
  - ✗ ✔ Interferes elsewhere




(c) Jaeger

# Flavour Anomalies



# Model-Independent $b \to s\ell^+\ell^-$

$$R_X = \frac{\int_{4m_\mu^2}^{q^2_{\text{max}}} \mathrm{d}s \frac{d\Gamma\left(B \to X\mu^+\mu^-\right)}{\mathrm{d}s}}{\int_{4m_\mu^2}^{q^2_{\text{max}}} \mathrm{d}s \frac{d\Gamma\left(B \to Xe^+e^-\right)}{\mathrm{d}s}} \stackrel{\text{SM}}{=} \begin{cases} 1.000 \pm 0.001 & X = K \\ 0.991 \pm 0.002 & X = K^* \end{cases}$$

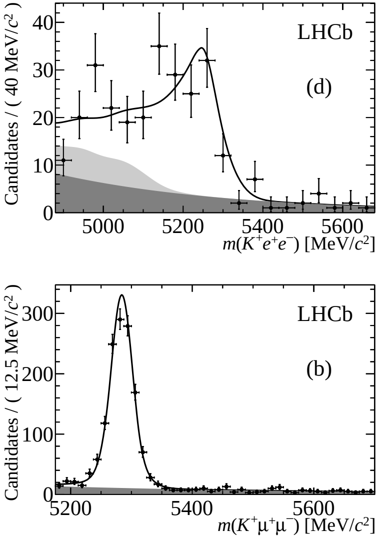
[Hiller & Krüger, PRD69 (2004) 074020]

**Lepton universality is an accidental symmetry of the gauge Lagrangian**

↓

**May be violated at some level.**

# Lepton universality with $B^+ \to K^+\ell^+\ell^-$



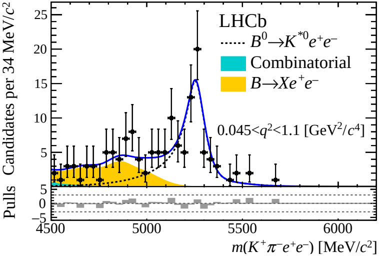

- Measure ratio $R_K$ of $B^+ \to K^+\mu^+\mu^-$ to $B^+ \to K^+e^+e^-$ in $1 < q^2 < 6\ \text{GeV}^2$
  - ✔ Signal clearly visible in $K^+\mu^+\mu^-$
- See
  - $254\ ^{+29}_{-27}$ $B^+ \to K^+e^+e^-$ and
  - $1226 \pm 41$ $B^+ \to K^+\mu^+\mu^-$
- Build a double ratio $R_K =$

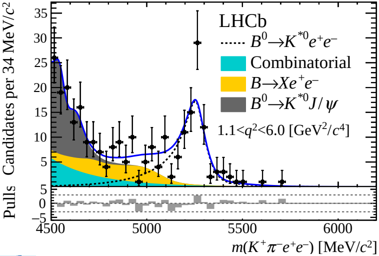
$$\left(\frac{\mathcal{N}_{K^+\mu^+\mu^-}}{\mathcal{N}_{K^+e^+e^-}}\right)\left(\frac{\mathcal{N}_{J/\psi(e^+e^-)K^+}}{\mathcal{N}_{J/\psi(\mu^+\mu^-)K^+}}\right)$$

$$= 0.745\ ^{+0.090}_{-0.074} \pm 0.036$$

✔ $2.6\sigma$ from unity

# Lepton universality in $B^0 \to K^{*0}\ell^+\ell^-$

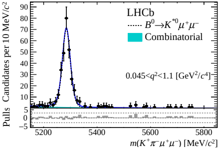


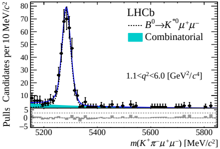




Measure ratio $R_{K^*}$ of $B^0 \to K^{*0}\mu^+\mu^-$ to $B^0 \to K^{*0}e^+e^-$ in $0.045 < q^2 < 1.1$ and $1.1 < q^2 < 6$ GeV$^2$

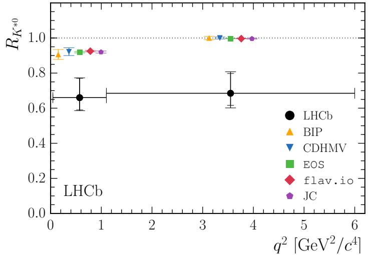
- ✔ Signal clearly visible in $K^{*0}\mu^+\mu^-$
- Yields entering the double ratio:

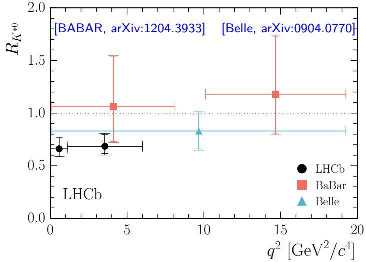
| | $B^0 \to K^{*0}\ell^+\ell^-$ | | $B^0 \to J/\psi K^{*0}$ |
|---|---|---|---|
| | low- $q^2$ | central- $q^2$ | |
| $\mu^+\mu^-$ | $285 \pm 18$ | $353 \pm 21$ | $274416\,^{+602}_{-654}$ |
| $e^+e^-$ | $89\,^{+11}_{-10}$ | $111\,^{+14}_{-13}$ | $43468 \pm 222$ |



# Lepton universality in $B^0 \to K^{*0}\ell^+\ell^-$




Measure ratio $R_{K^*}$ of $B^0 \to K^{*0}\mu^+\mu^-$ to $B^0 \to K^{*0}e^+e^-$ in $0.045 < q^2 < 1.1$ and $1.1 < q^2 < 6$ GeV$^2$

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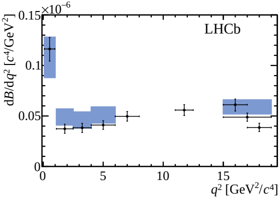
Build a double ratio $R_K =$

$$\left(\frac{\mathcal{N}_{K^{*0}\mu^+\mu^-}}{\mathcal{N}_{K^{*0}e^+e^-}}\right)\left(\frac{\mathcal{N}_{J/\psi(e^+e^-)K^{*0}}}{\mathcal{N}_{J/\psi(\mu^+\mu^-)K^{*0}}}\right)$$

$$= \begin{cases} 0.66\,^{+0.11}_{-0.07} \pm 0.03 & 0.045 < q^2 < 1.1 \\ 0.69\,^{+0.11}_{-0.07} \pm 0.05 & 1.1 < q^2 < 6.0 \end{cases}$$

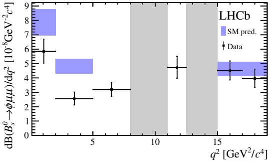
This about 2 to 2.5$\sigma$ from the SM, depending on predictions. [BIP, EPJC 76 440] [CDHMV, JHEP04(2017)016] [EOS, PRD 95 035029] [flav.io, EPJC 77 377] [JC, PRD93 014028]

# BFs too low in $b \to s\mu^+\mu^-$ decays?



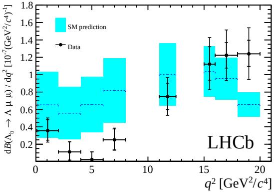

$B^0 \to K^{*0}\mu^+\mu^-$

[JHEP 11 (2016) 047]



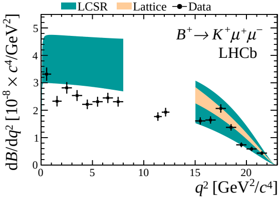

$B_s^0 \to \phi\mu^+\mu^-$

[JHEP 09 (2015) 179]



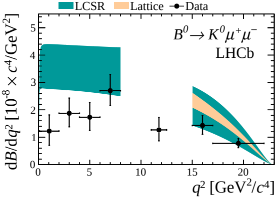

$\Lambda_b^0 \to \Lambda\mu^+\mu^-$

[JHEP 06 (2015) 115]



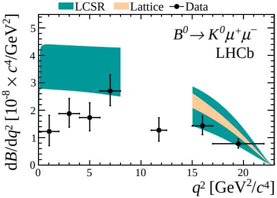

$B^+ \to K^+\mu^+\mu^-$

[JHEP 06 (2014) 133]




$B^0 \to K^0\mu^+\mu^-$

[JHEP 06 (2014) 133]

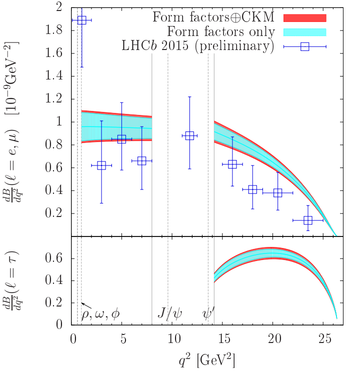


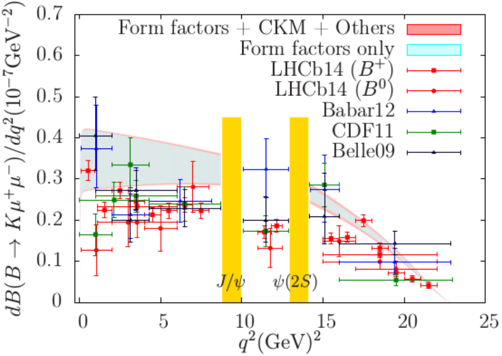

$B^+ \to K^{*+}\mu^+\mu^-$

[JHEP 06 (2014) 133]


LHCb
Lattice
Sum
Rules

# $B \to h\ell^+\ell^-$ form factors from MILC



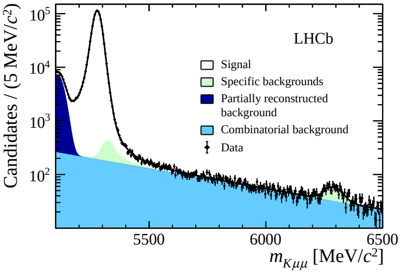



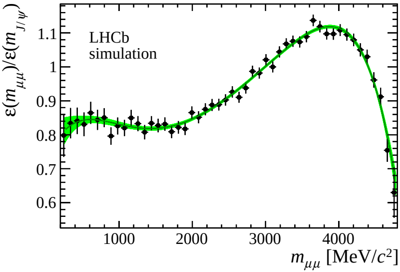

$B^+ \to \pi^+\ell^+\ell^-$ [JHEP 10 (2015) 034] and $B \to K\ell^+\ell^-$ [JHEP 06 (2014) 133] are all below the lattice computations.

# PHASES IN $B^+ \to K^+\ell^+\ell^-$

Use a large sample of ($\sim$ 1M) $B^+ \to K^+\mu^+\mu^-$ decays including $B^+ \to J/\psi K^+$ and $B^+ \to \psi(2S)K^+$ to deterimine the interfrence of SD $B^+ \to K^+\mu^+\mu^-$ and dimuons from resonances.

- The $q^2$ distribution is used. The efficiency is determined from simulation.
- Included resonances: $\rho(770)$, $\omega(782)$, $\phi(1020)$, $J/\psi$, $\psi(2S)$, $\psi(3770)$, $\psi(4040)$, $\psi(4160)$ [PRL 111 (2013) 112003], $\psi(4415)$

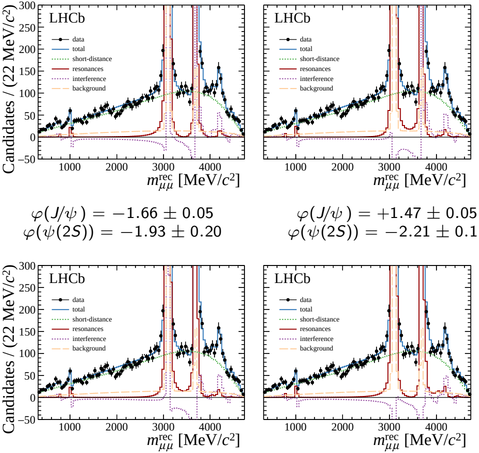


# Phases in $B^+ \to K^+\ell^+\ell^-$

Four fits match the data, all with a $J/\psi$ −short-distance phase difference consistent with $\pm\frac{\pi}{2}$

- ➜ the interference with the short-distance component far from the pole masses is small




$\varphi(J/\psi) = -1.66 \pm 0.05$
$\varphi(\psi(2S)) = -1.93 \pm 0.20$

$\varphi(J/\psi) = +1.47 \pm 0.05$
$\varphi(\psi(2S)) = -2.21 \pm 0.11$

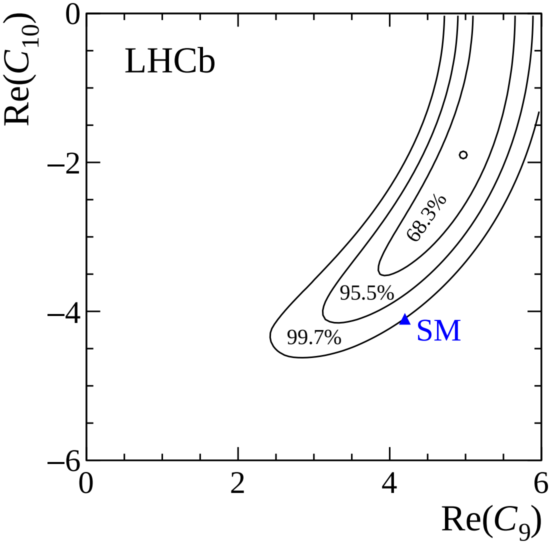
$\varphi(J/\psi) = -1.50 \pm 0.05$
$\varphi(\psi(2S)) = +2.08 \pm 0.11$

$\varphi(J/\psi) = +1.63 \pm 0.05$
$\varphi(\psi(2S)) = +1.80 \pm 0.10$

The BF is measured over the whole $q^2$ range:

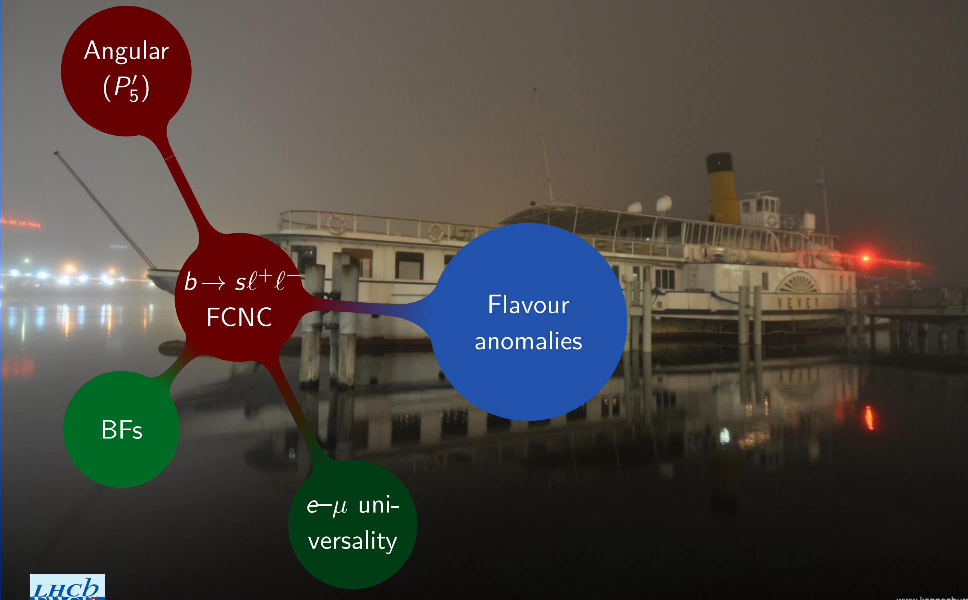
$$\mathcal{B}(B^+ \to K^+\mu^+\mu^-) = (4.37 \pm 0.15 \pm 0.23) \times 10^{-7}$$

# Phases in $B^+ \to K^+\ell^+\ell^-$




The Wilson coefficients $C_9$ and $C_{10}$ are also fitted for, leading to a deviation from the SM expectation at $3\sigma$

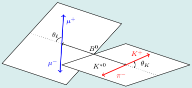
# Flavour Anomalies



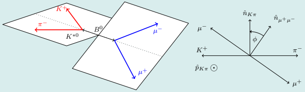
# $B \to K^* \ell^+ \ell^-$ Angular Distributions

A lot of information in the full $\theta_\ell$, $\theta_K$ and $\phi$ distributions

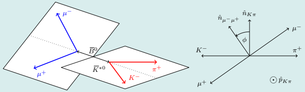
$$\frac{1}{\Gamma}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\hat{\phi}\,\mathrm{d}q^2} = \frac{9}{32\pi}\Bigg[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K$$
$$+\frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell - F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell$$
$$+S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi$$
$$+S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi$$
$$+S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Bigg]$$




(a) $\theta_K$ and $\theta_\ell$ definitions for the $B^0$ decay




(b) $\phi$ definition for the $B^0$ decay



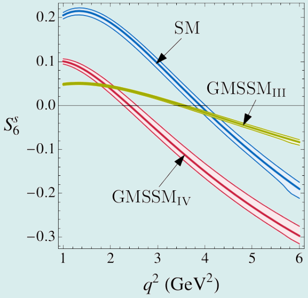

(c) $\phi$ definition for the $\overline{B}^0$ decay

**→ Many observables depending on $q^2 = m^2_{\ell\ell}c^4$**

# $B \to K^* \ell^+ \ell^-$ Angular Distributions

A lot of information in the full $\theta_\ell$, $\theta_K$ and $\phi$ distributions

$$\frac{1}{\Gamma}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\hat{\phi}\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K$$
$$+\frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell - F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell$$
$$+S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi$$
$$+S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi$$
$$+S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$



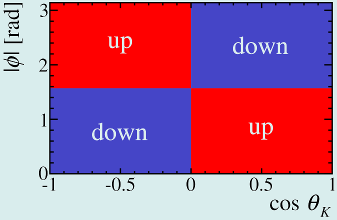

[Altmannshofer et al., JHEP 0901:019,2009] [Krüger & Matias, Phys.Rev.D71:094009] [Egede et al., JHEP 0811:032,2008] [Ali et al., Phys.Rev.D61:074024]

→ **Forward-backward asymmetry** $S_6 = \frac{4}{3}A_{\mathrm{FB}}$

# $B \to K^* \ell^+ \ell^-$ Angular Distributions

A lot of information in the full $\theta_\ell$, $\theta_K$ and $\phi$ distributions

$$\frac{1}{\Gamma}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\hat{\phi}\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K$$
$$+\frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell - F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell$$
$$+ S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi$$
$$+ S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi$$
$$+ S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$




Definition of $S_5$

$$\rightarrow \quad P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

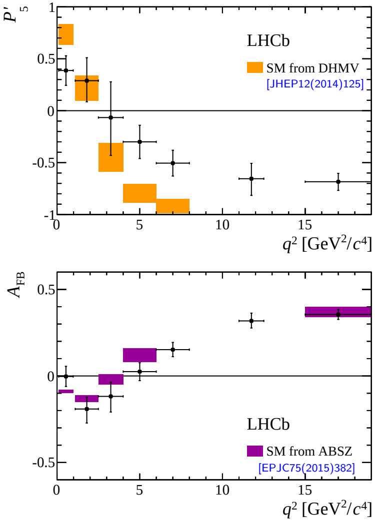
[Descotes-Genon et al., JHEP, 1305 137]

[Altmannshofer et al., JHEP 0901:019,2009] [Krüger & Matias, Phys.Rev.D71:094009] [Egede et al., JHEP 0811:032,2008] [Ali et al., Phys.Rev.D61:074024]

# Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$

Update of [JHEP 08 (2013) 131] and [PRL 111 (2013) 191801] to 3 $\text{fb}^{-1}$. S-wave is taken into account, we have finer bins, and no $\varphi$ folding is needed.

- **Max Likelihood fit:** 4D fit to $m(K^+\pi^-)$ and three angles in bins of $q^2$.
- Observables consistent with SM, except $S_5$
- $P_5' = S_5/\sqrt{F_L(1-F_L)}$ has a local discrepancy in two bins
- $A_{\text{FB}}$ seems to show a trend, but is consistent with SM

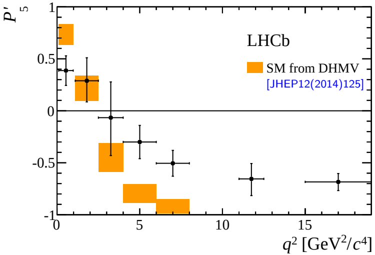


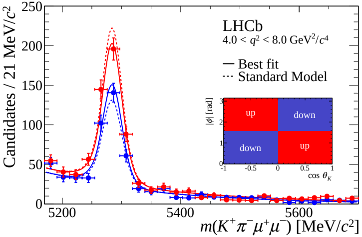
# Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$

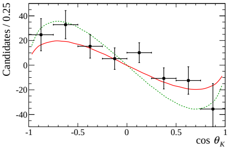
## What is $P_5'$?

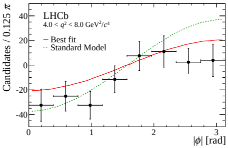
It is an asymmetry built with $\cos\theta_K$ and $|\phi|$, shown in the sketch. (integrating over one of the two gets zero).

The discrepancy with the SM prediction is visible in both angular distributions.

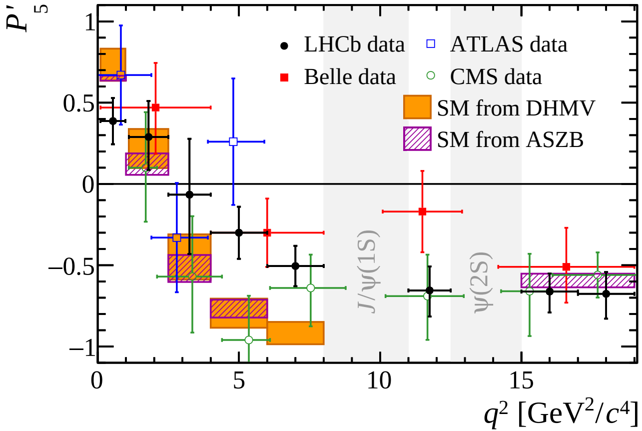


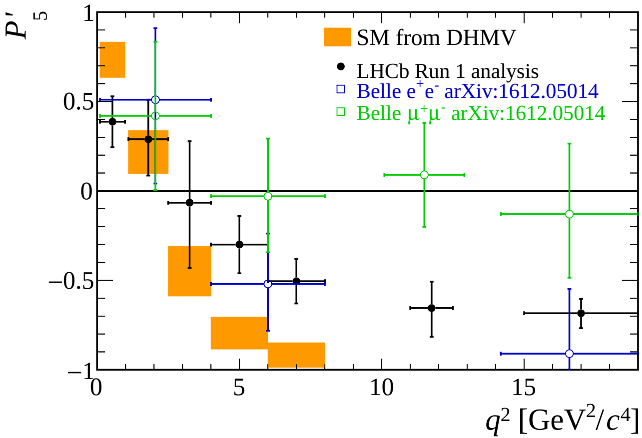



# All $P_5'$ measurements




LHCb [JHEP 02 (2016) 104], Belle [PRL 118 (2017) 111801]
CMS [PLB 781 (2018) 517], ATLAS [arXiv:1805.04000]

# All $P_5'$ measurements



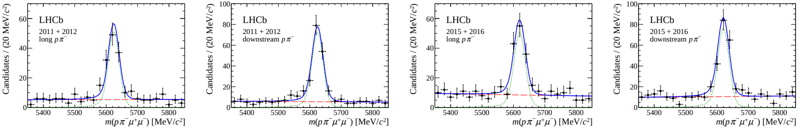

LHCb [JHEP 02 (2016) 104], Belle [PRL 118 (2017) 111801]

# Angular moments in $\Lambda_b^0 \to \Lambda\mu^+\mu^-$

Run 2

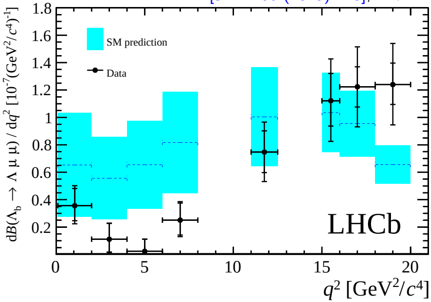
First $b \to s\ell^+\ell^-$ analysis with Run 2 data (bar $B \to \mu^+\mu^-$)

- Find 300 $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ in Run 1 and 300 in 2015–16.




- The data is at high $q^2$, above the $J/\psi$ [JHEP 06 (2015) 115].
  - ➜ Here we look above the $\psi(2S)$ $(15 < q^2 < 20\,\mathrm{GeV}^2/c^4)$

[JHEP 06 (2015) 115], 1 fb$^{-1}$

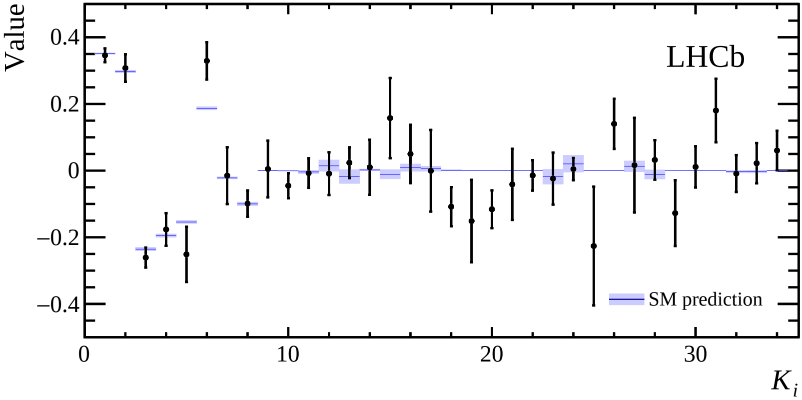


# Angular moments in $\Lambda_b^0 \to \Lambda\mu^+\mu^-$

Run 2

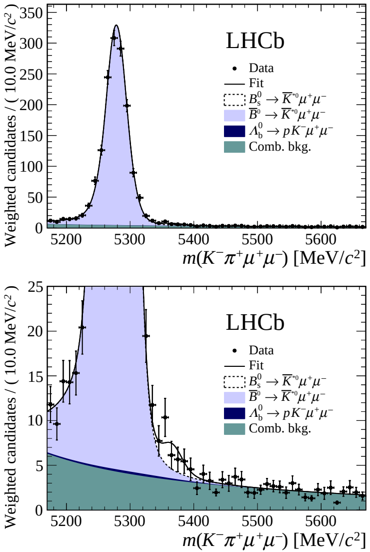
First $b \to s\ell^+\ell^-$ analysis with Run 2 data (bar $B \to \mu^+\mu^-$)

- Find 300 $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ in Run 1 and 300 in 2015–16.
- The moments are consistent with the SM ($K_6$ is $2.6\sigma$ away)



# Evidence for $B_s^0 \to \overline{K}^{*0}\mu^+\mu^-$

Run 2




Search for the Cabibbo-suppressed $b \to d\ell^+\ell^-$ FCNC decay $B_s^0 \to \overline{K}^{*0}\mu^+\mu^-$

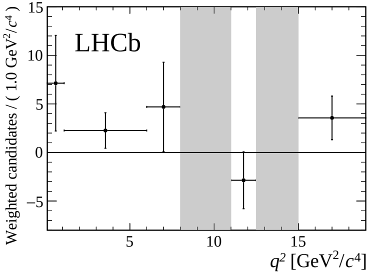
Using 4.6 $\text{fb}^{-1}$ 2011–16 data we find

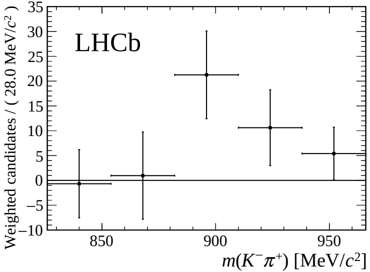
- 4200 $\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-$ and $38 \pm 12$ $B_s^0 \to \overline{K}^{*0}\mu^+\mu^-$ ($3.4\sigma$) decays (shown weighted by purity)

$$\mathcal{B}(B_s^0 \to \overline{K}^{*0}\mu^+\mu^-) = (2.9 \pm 1.0 \pm 0.2 \pm 0.3(\mathcal{B})) \times 10^{-8}$$

# Evidence for $B_s^0 \to \overline{K}^{*0}\mu^+\mu^-$

Run 2



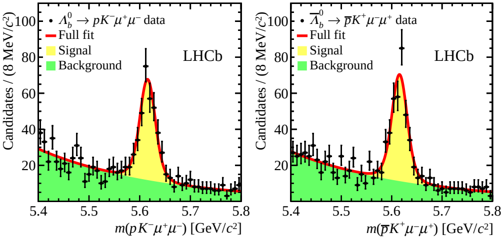

Search for the Cabibbo-suppressed $b \to d\ell^+\ell^-$ FCNC decay $B_s^0 \to \overline{K}^{*0}\mu^+\mu^-$

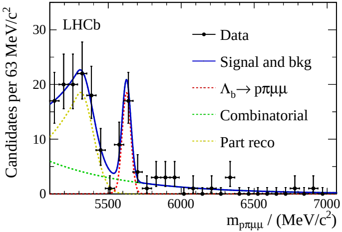
Using 4.6 fb$^{-1}$ 2011–16 data we find

- 4200 $\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-$ and $38 \pm 12$ $B_s^0 \to \overline{K}^{*0}\mu^+\mu^-$ (3.4$\sigma$) decays

  $\mathcal{B}(B_s^0 \to \overline{K}^{*0}\mu^+\mu^-) = (2.9 \pm 1.0 \pm 0.2 \pm 0.3(\mathcal{B})) \times 10^{-8}$
- Too little data to say anything about $q^2$ and $K^+\pi^-$ mass

# $\Lambda_b^0 \to pK^-\mu^+\mu^-$ AND $\Lambda_b^0 \to p\pi^-\mu^+\mu^-$




$600 \pm 44$ $\Lambda_b^0 \to pK^-\mu^+\mu^-$ with $3\,\text{fb}^{-1}$

[JHEP 06 (2017) 108]

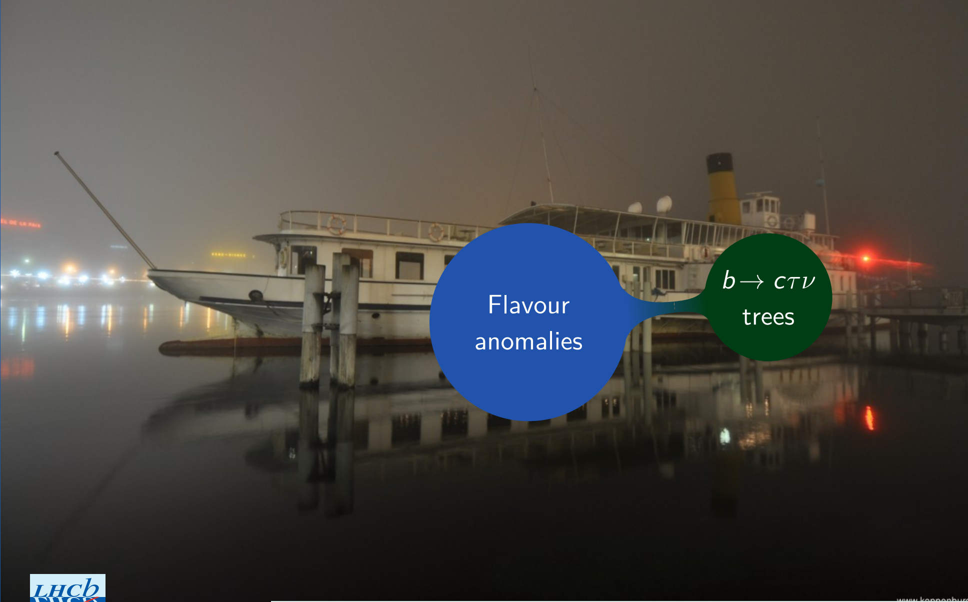
$22 \pm 6$ $\Lambda_b^0 \to p\pi^-\mu^+\mu^-$

[JHEP 04 (2017) 029]

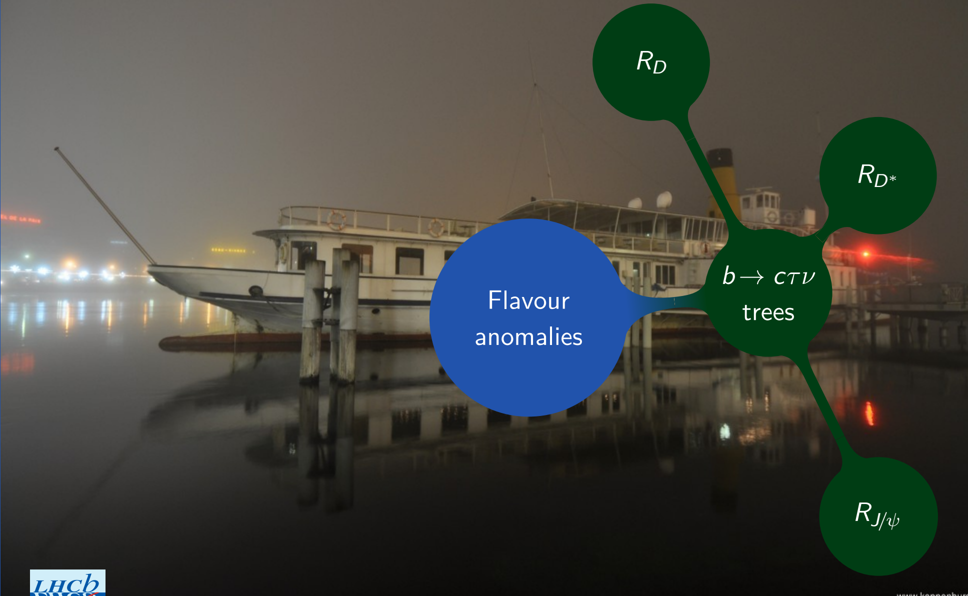
Branching fraction of the Cabibbo-suppressed decay:

$$\mathcal{B}(\Lambda_b^0 \to p\pi^-\mu^+\mu^-) = \left(6.9 \pm 1.9 \pm 1.1\,^{+1.3}_{-1.0}\right) \times 10^{-8}$$

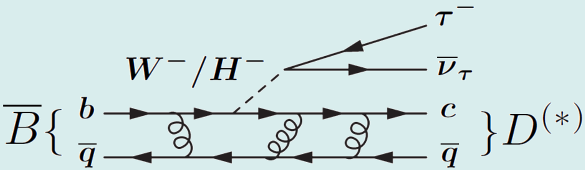
# Flavour Anomalies



# Flavour Anomalies



# $\bar{B} \to D^{(*)}\tau\nu$




$\tau$ versus $\mu$,$e$ lepton universality can be tested with:

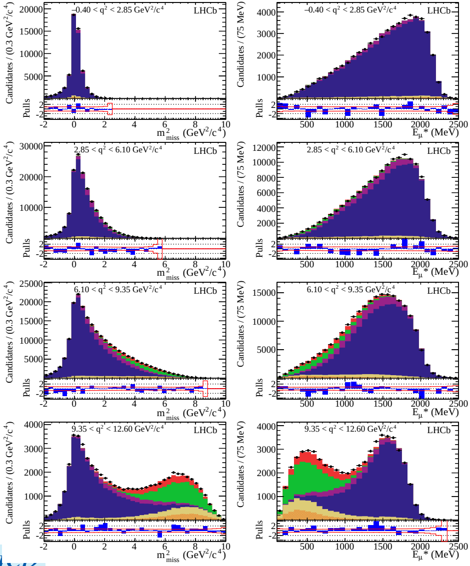
$$R(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau\nu)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell\nu)} \quad \ell = \mu, e,$$

which is well predicted in the SM ($\neq 1$ due to phase-space, etc. . . ) [Kamenik et al., PRD 78 014003], [Fajfer et al., PRD 85 094025], [BABAR, PRD 88 072012]

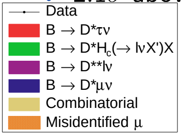
$$R(D^*) \stackrel{\text{SM}}{=} 0.252 \pm 0.003,$$

$$R(D) \stackrel{\text{SM}}{=} 0.297 \pm 0.017$$

# $\overline{B}^0 \to D^{*+}\tau\nu$ AT LHCb




- $B^0 \to D^{*+}\tau^-\overline{\nu}$ with $\tau^- \to \mu^-\nu\overline{\nu}$ and $B^0 \to D^{*+}\mu^-\overline{\nu}$: same final state.
- Disentangled by kinematical variables : $q^2$, $E^*_\mu$, $m^2_{\text{miss}}$.
- A template fit in $q^2$ bins determines signal yields
- Get $36300 \pm 1600$ $B \to D^{*+}\mu^-\overline{\nu}$ decays and $R_{D^*} = 0.336 \pm 0.027 \pm 0.030$
  - ➜ $2.1\sigma$ above the SM

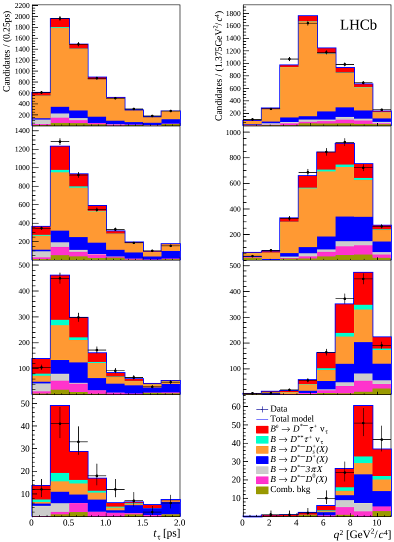


# $B^0 \to D^{*-}\tau^+\nu_\tau$ WITH $\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\overline{\nu}_\tau$

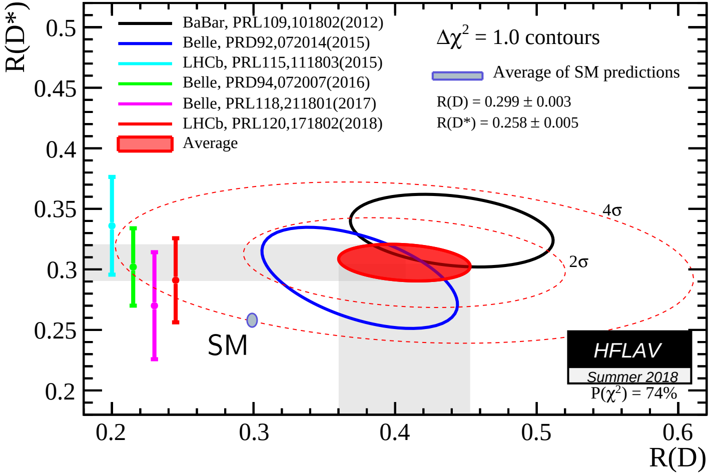
Signal and backgrounds are determined by a three-dimensional binned fit to $t_\tau$, $q^2$ and BDT output.

- signal yield: $1273 \pm 85$.
- Normalised to $B^0 \to D^{*-}\pi^+\pi^-\pi^+$ [PRD 87 (2013) 092001], yielding $\mathcal{B}(B \to D^*\tau^+\nu_\tau) = (1.40 \pm 0.09 \pm 0.12 \pm 0.10)\%$

$\mathcal{R}(D^*) = 0.286 \pm 0.019 \pm 0.025 \pm 0.021$, $1\sigma$ above the SM ($0.252 \pm 0.003$ [Faijfer et al.]) and consistent with the world average.



# $B \to D^{(*)}\tau\nu$ HFLAV AVERAGE




BABAR [PRL 109 101802 (2012)] [PRD 88 072012 (2013)] Belle [PRD 92 072014 (2015)] [PRD 94 072007 (2016), arXiv:1607.07923] [PRL 118 211801 (2017)] [PRD 97 012004 (2018)] LHCb [PRL 115 (2015) 111803] [PRL 120 (2018) 171802]. Theory [Na et al., PRD 92 054410 (2015)], [Faijfer et al., PRD 85 094025 (2012)]

# Study of $B_c^+ \to J/\psi\,\tau^+\nu_\tau$

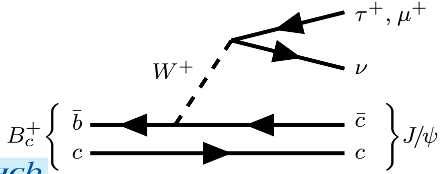
LHCb measured $R(D^{*+})$ with $\tau^+ \to \mu^+\nu\overline{\nu}$ and $\tau^+ \to \pi^+\pi^-\pi^+$

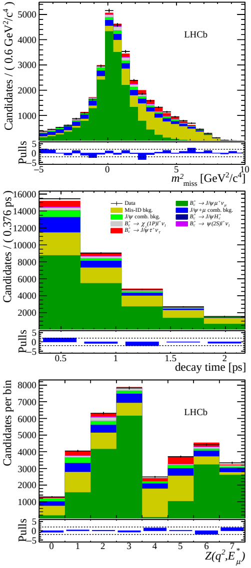
[PRL 115 (2015) 111803]

[PRL 120 (2018) 171802]

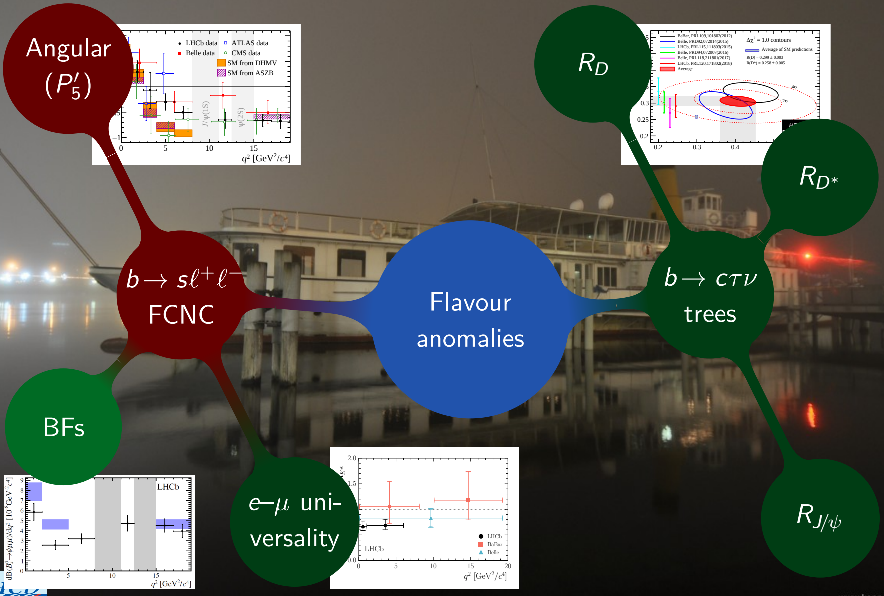
What about $B_c^+ \to J/\psi\,\tau^+(\mu^+\nu\overline{\nu})\nu$?

- Three-dimensional template fit in missing mass ($m_{\text{miss}}$),decay time ($\tau$) and coarse $E^*, q^2$ bins ($Z$)
- ✔ Surprising signal excess ($3\sigma$)
- Measure $R(J/\psi) = 0.71 \pm 0.17 \pm 0.18$, which is $2\sigma$ above the SM

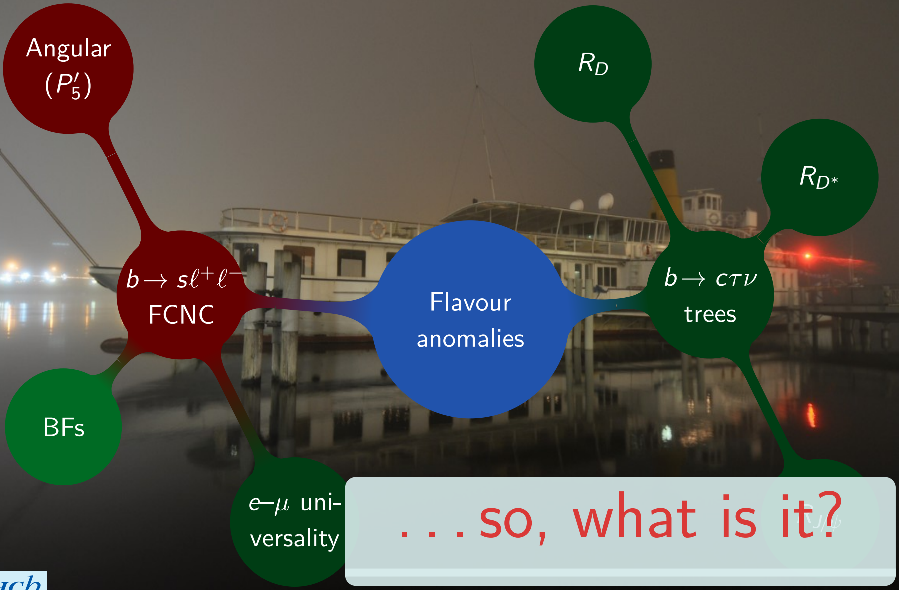


# Flavour Anomalies



# Flavour Anomalies



# QCD and Statistics?


LIVE
breakyourownnews.com
BREAKING NEWS
NEW PHYSICS IN LEPTONS
FABIOLA GIANOTTI
16:36
THIS CHANGES HOW WE SEE THE UNIVERSES SAYS CERN DIRECTOR DR. GIANOTTI.

# Flavour Anomalies

We need a better precision in QCD.

Flavour anomalies

QCD

Lattice

Sum rules

# Flavour Anomalies

It could be new vector bosons (but beware of $B\overline{B}$ mixing)

$Z', W'$

Flavour anomalies

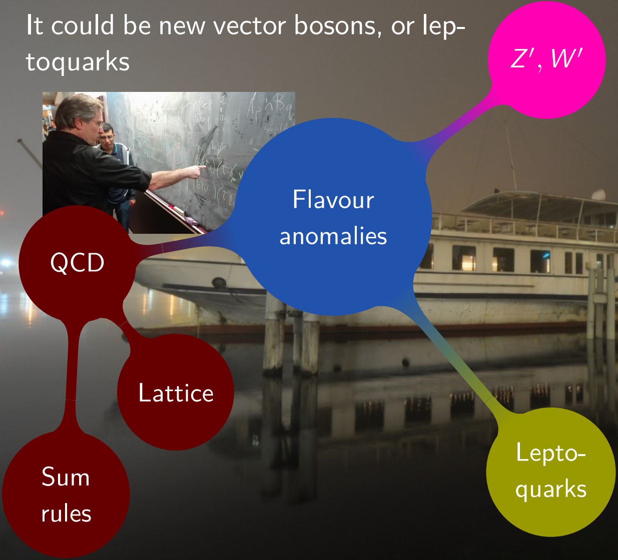
QCD

Lattice

Sum rules

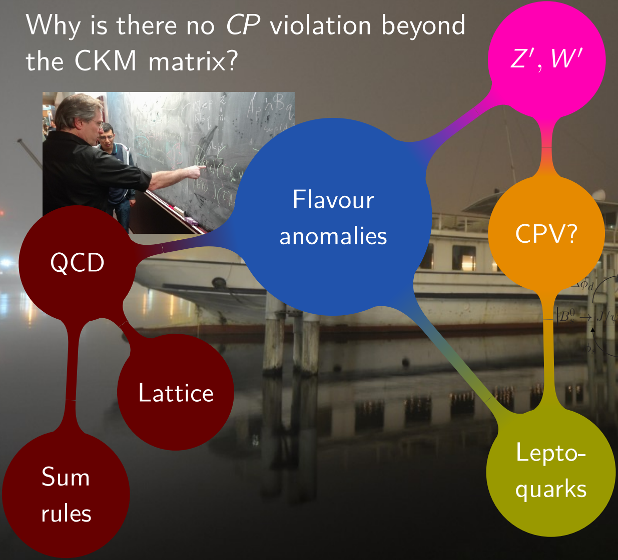
# Flavour Anomalies

It could be new vector bosons, or leptoquarks



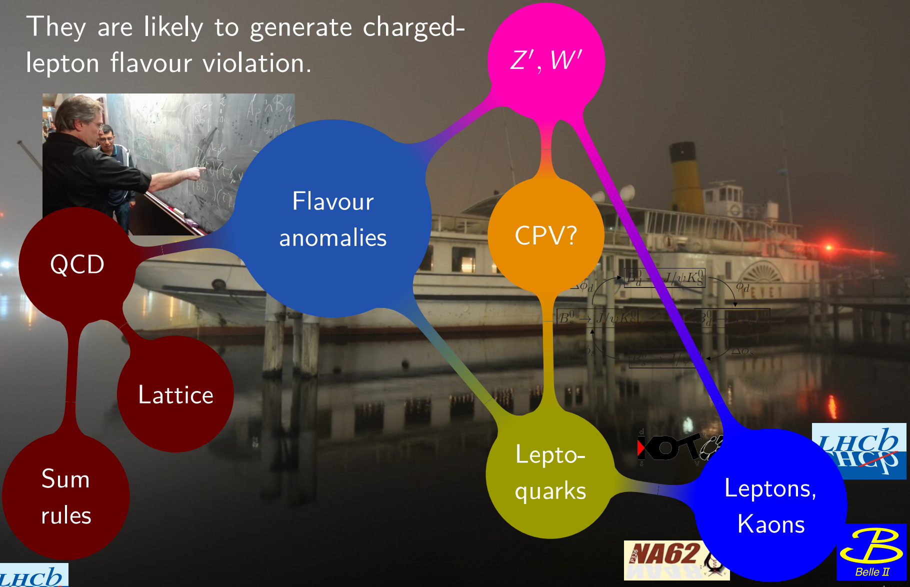
# Flavour Anomalies

Why is there no *CP* violation beyond the CKM matrix?



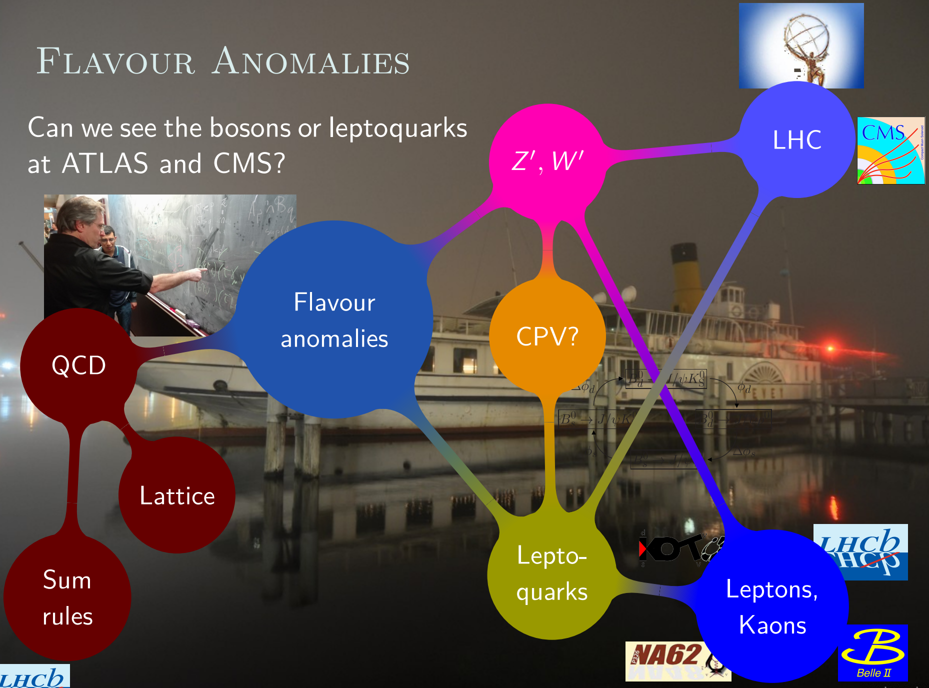
# Flavour Anomalies

They are likely to generate charged-lepton flavour violation.



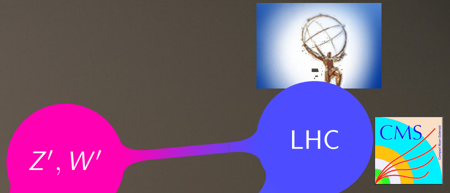
# Flavour Anomalies

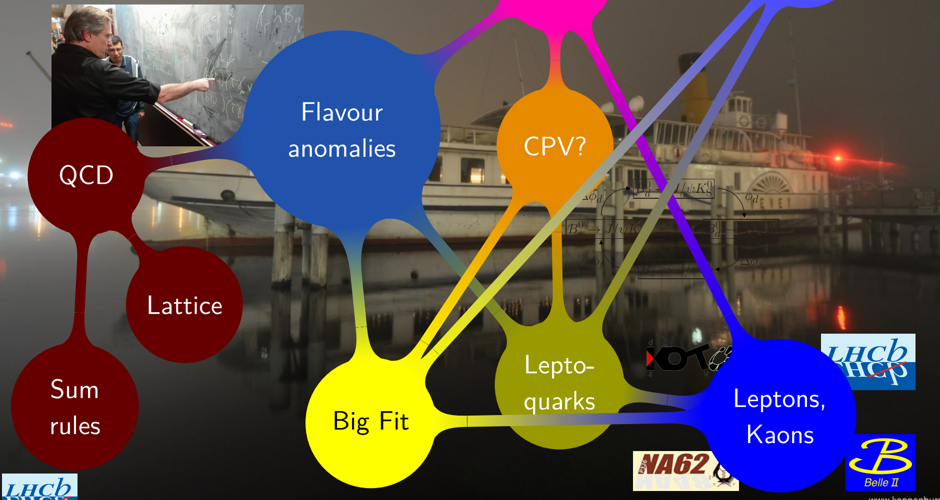
Can we see the bosons or leptoquarks at ATLAS and CMS?



# Flavour Anomalies

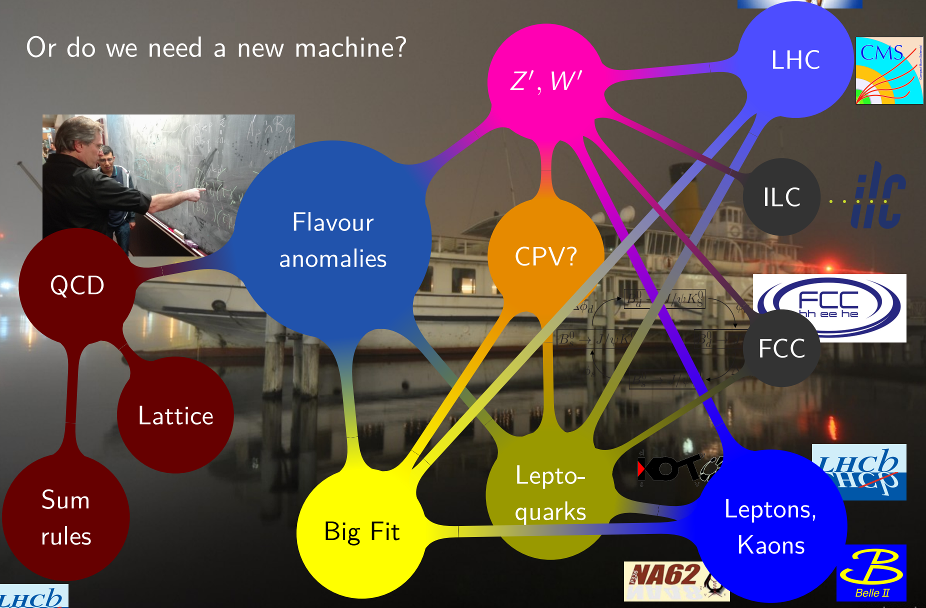
Throw all data at a big fit of everything



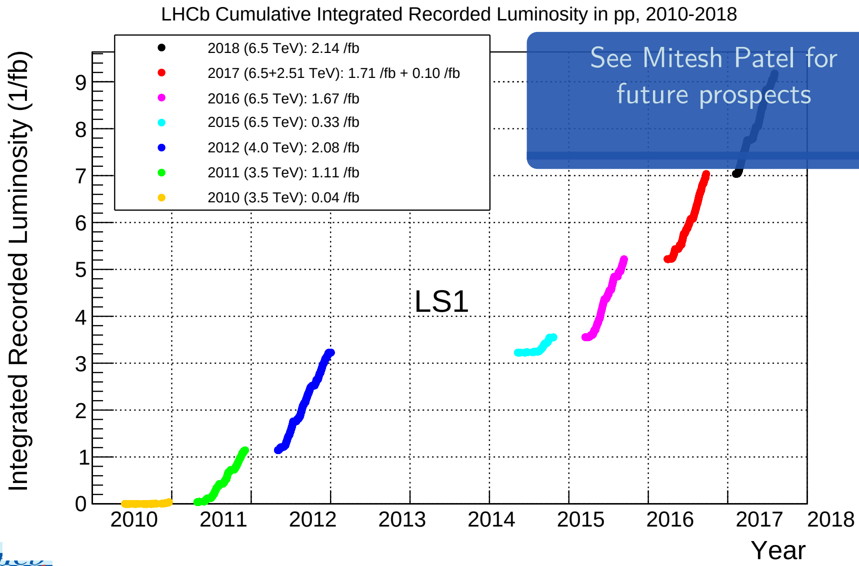



# Flavour Anomalies

Or do we need a new machine?



# Integrated luminosity



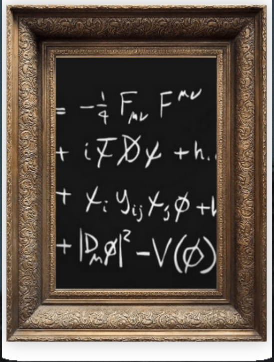

See Mitesh Patel for future prospects

# Conclusion

BSM searches and flavour physics yield null results, except (maybe)

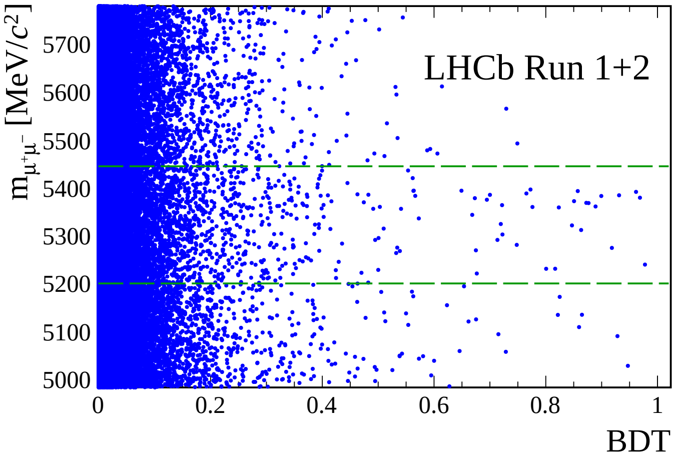
- $b \to s\ell^+\ell^-$ loop transitions, hinting toward a new vector current
- ...that would not be $e$–$\mu$ symmetric
- $b \to c\tau\nu$ tree transitions yield too many $\tau$ leptons.

➜ Leptoquarks, vector bosons, supersymmetry, or SM?



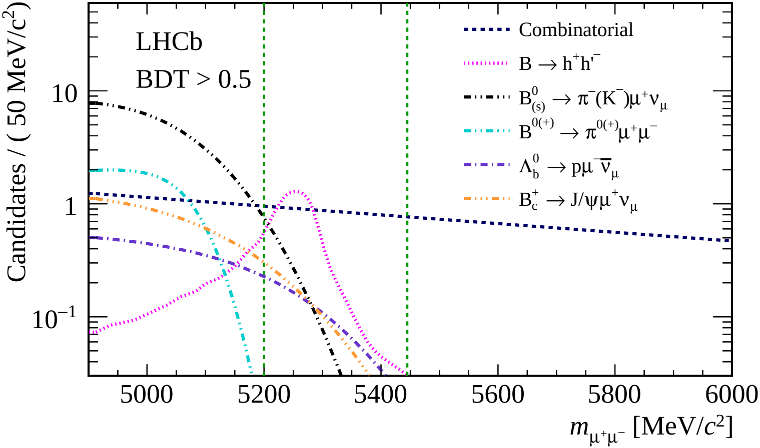

# Backup

# Observation of the decay $B_s^0 \to \mu^+\mu^-$



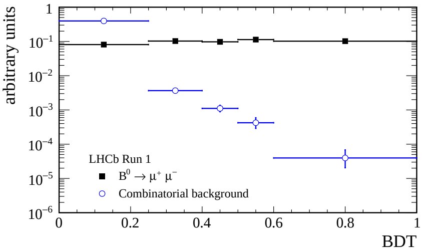

A $B \to \mu^+\mu^-$ search using 2011–2016 data is done with a mass fit in bins of BDT output.

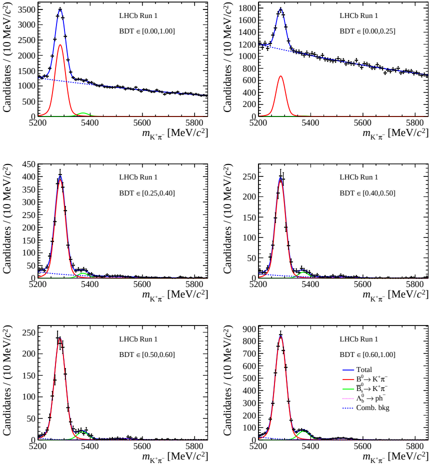
# Observation of the decay $B_s^0 \to \mu^+\mu^-$




The BDT is optimised to fight combinatorial and specific backgrounds.

# Observation of the decay $B_s^0 \to \mu^+\mu^-$

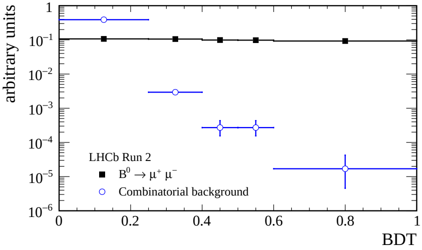


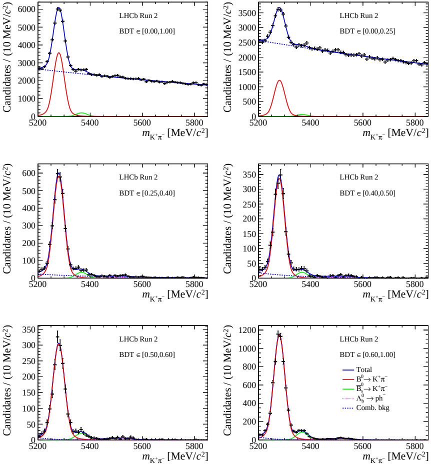




The BDT is calibrated using $B \to h^+ h'^-$ decays, which have the same topology.

Here for Run 1

# Observation of the decay $B_s^0 \to \mu^+\mu^-$

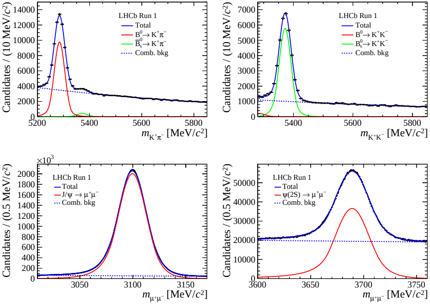


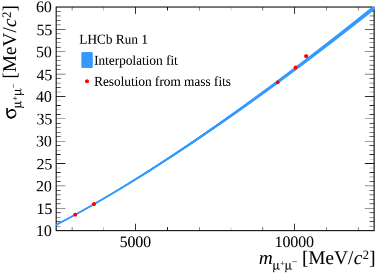



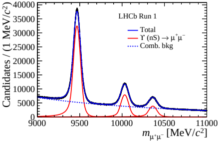

The BDT is calibrated using $B \to h^+ h'^-$ decays, which have the same topology.

Here for Run 2

# Observation of the decay $B_s^0 \to \mu^+\mu^-$



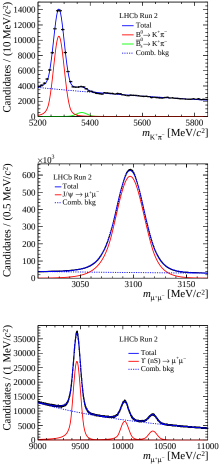



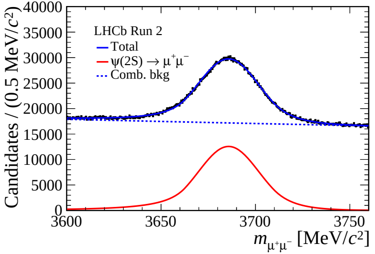




The mass resolution is calibrated using the decays $J/\psi \to \mu^+\mu^-$, $\psi(2S) \to \mu^+\mu^-$ and $\Upsilon([1,2,3]S) \to \mu^+\mu^-$ and interpolated to 23 MeV/$c^2$ at the $B_s^0$ mass.

This is checked with $B^0 \to K^+\pi^-$ and $B_s^0 \to K^+K^-$.

# Observation of the decay $B_s^0 \to \mu^+\mu^-$

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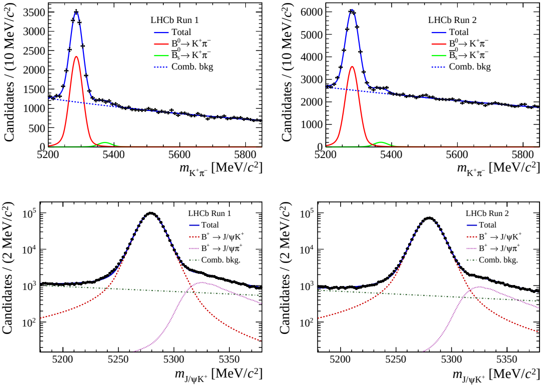
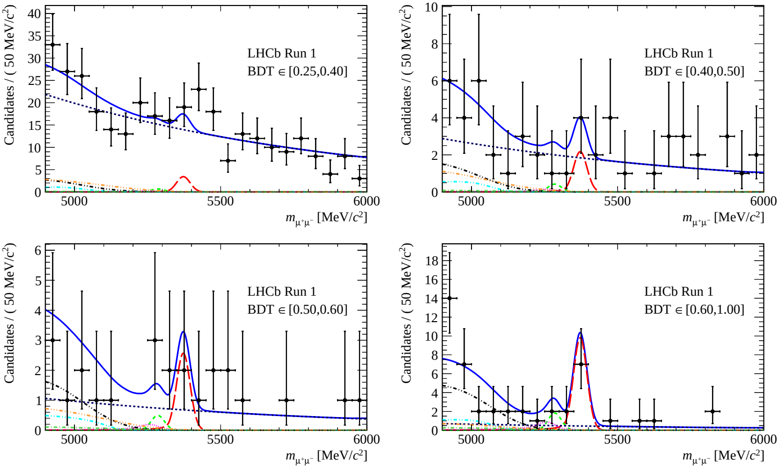
# Observation of the decay $B_s^0 \to \mu^+\mu^-$



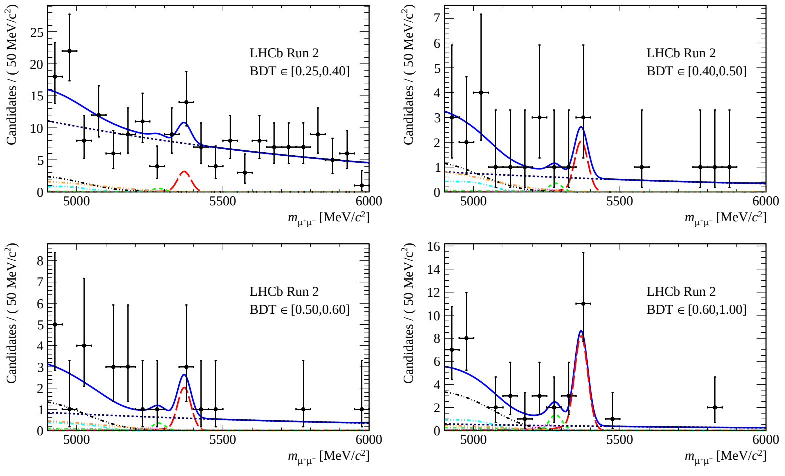

$B^0 \to K^+\pi^-$ and $B^+ \to J/\psi K^+$ are used to normalise the $B \to \mu^+\mu^-$ branching fractions. The factors are $a^{\text{norm}}_{B_s^0 \to \mu^+\mu^-} = (5.7 \pm 0.4) \times 10^{-11}$ and $a^{\text{norm}}_{B^0 \to \mu^+\mu^-} = (1.60 \pm 0.04) \times 10^{-11}$.

# Observation of the decay $B^0_s \to \mu^+\mu^-$




Mass fits are performed in bins of BDT output, separately for Run 1 and Run 2 data.

# Observation of the decay $B_s^0 \to \mu^+\mu^-$

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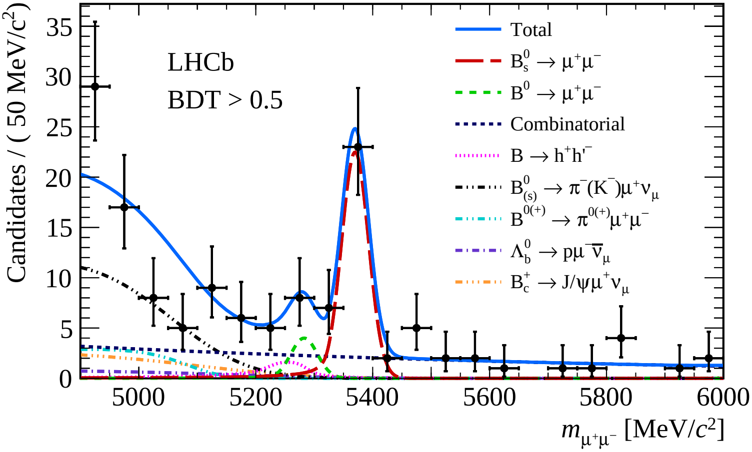
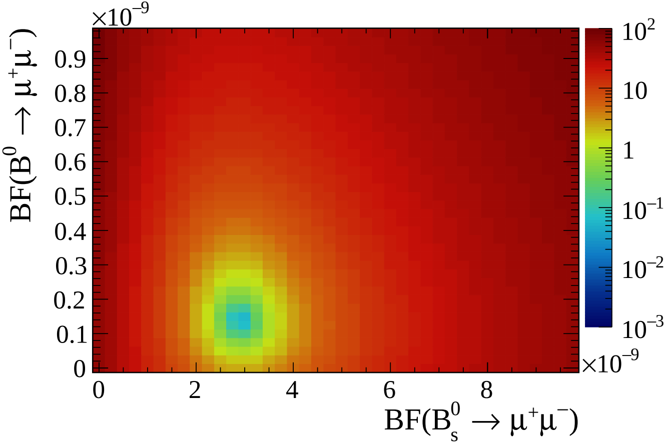



Mass plot shows candidates with BDT$>$ 0.5.
The significances are $7.8\sigma$ for $B_s^0 \to \mu^+\mu^-$ and $1.6\sigma$ for $B^0 \to \mu^+\mu^-$.

# Observation of the decay $B_s^0 \to \mu^+\mu^-$

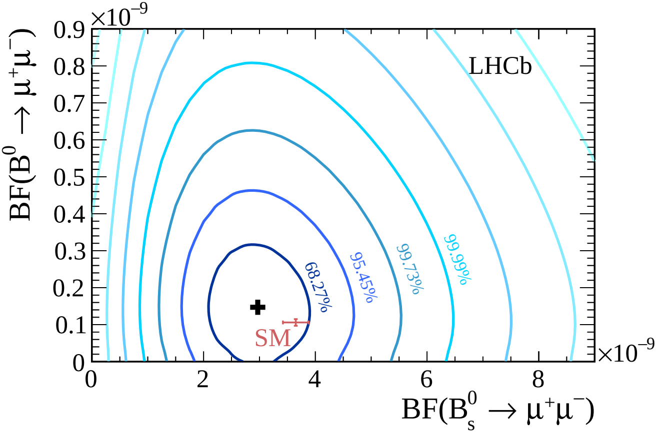



The results $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6\,^{+0.3}_{-0.2}) \times 10^{-9}$ and $\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.5\,^{+1.2}_{-1.0}\,^{+0.2}_{-0.1}) \times 10^{-10}$ are consistent with the SM.

[Bobeth et al., PRL 112 101801 (2014)]

[LHCb, Phys. Rev. Lett. 118 (2017) 191801, arXiv:1703.05747]

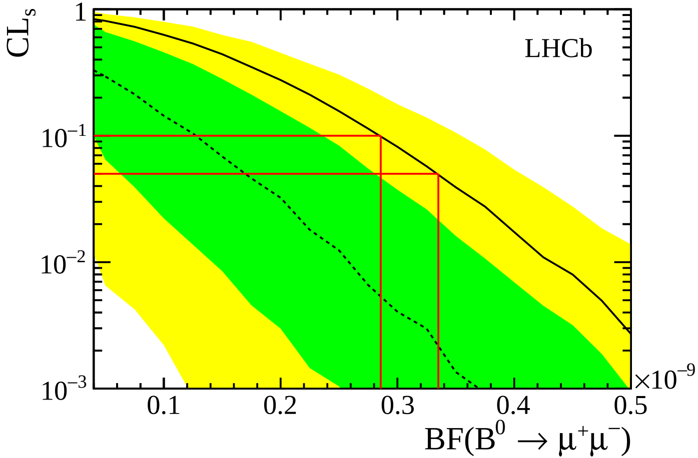
# Observation of the decay $B_s^0 \to \mu^+\mu^-$




The results $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6\,^{+0.3}_{-0.2}) \times 10^{-9}$ and $\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.5\,^{+1.2}_{-1.0}\,^{+0.2}_{-0.1}) \times 10^{-10}$ are consistent with the SM.

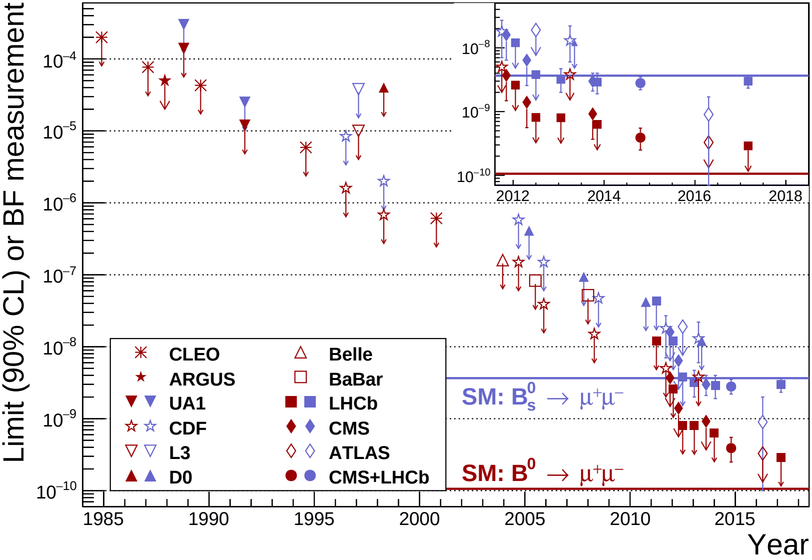
[Bobeth et al., PRL 112 101801 (2014)]

# Observation of the decay $B_s^0 \to \mu^+\mu^-$




As no excess of $B^0 \to \mu^+\mu^-$ is found, a limit at $3.4 \times 10^{-10}$ at 95% confidence level is set.

# $B_s^0 \to \mu^+\mu^-$ race toward the SM



# $B \to \mu^+\mu^-$ EFFECTIVE LIFETIME

The effective lifetime allows the extraction of

$$\mathcal{A}_{\Delta\Gamma}\, y_s = \frac{(1-y_s^2)\tau_{\mu^+\mu^-} - (1+y_s^2)\tau_{B_s^0}}{2\tau_{B_s^0} - (1-y_s^2)\tau_{\mu^+\mu^-}}$$

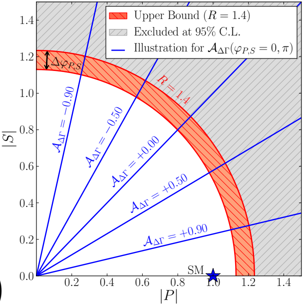
$$\text{with } y_s = \frac{1}{2}\tau_{B_s^0}\Delta\Gamma_s = 0.075 \pm 0.010 \quad \text{[HFAG]}$$

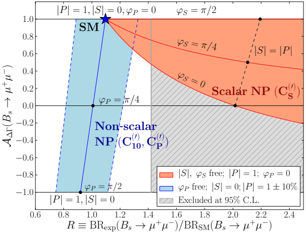
This gives sensitivity to the (pseudo-) scalar operators $\mathcal{O}_{P,S}$ with Wilson coefficients $P$ and $S$ ($=1,0$ in SM):

$$R \equiv \frac{\mathrm{BR}(B_s^0 \to \mu^+\mu^-)_{\rm exp}}{\mathrm{BR}(B_s^0 \to \mu^+\mu^-)_{\rm SM}} = \left[\frac{1+\mathcal{A}_{\Delta\Gamma} y_s}{1-y_s^2}\right]\left(|P|^2 + |S|^2\right)$$

$$= \left[\frac{1+y_s\cos 2\varphi_P}{1-y_s^2}\right]|P|^2 + \left[\frac{1-y_s\cos 2\varphi_S}{1-y_s^2}\right]|S|^2,$$

LHCb expects $\mathcal{O}(500)$ events with 50 fb$^{-1}$, as many as for $\tau_{\rm eff}(B_s^0 \to KK)$ [Phys.Lett. B707 (2012) 349-356, arXiv:1111.0521]

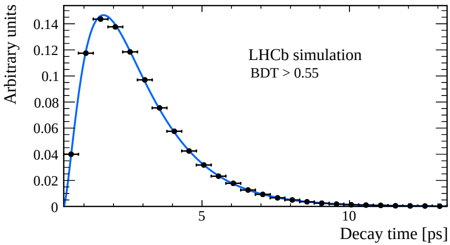


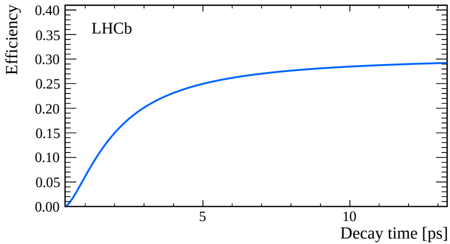



# $B_s^0 \to \mu^+\mu^-$ EFFECTIVE LIFETIME

For the first time the effective lifetime of $B_s^0 \to \mu^+\mu^-$ is measured, as proposed by [De Bruyn, PK, et al., PRL 109, 041801 (2012)].

- Only candidates with BDT$>$ 0.55 are used.
- The time acceptance is taken from simulation.



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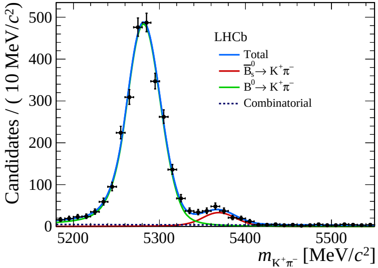
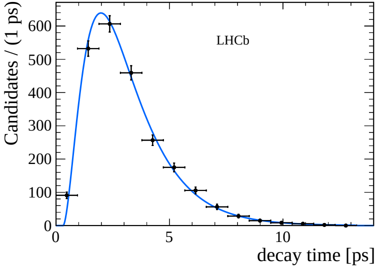
- Only candidates with BDT$>$ 0.55 are used.
- The time acceptance is taken from simulation.
- The time acceptance is validated using $B^0 \to K^+\pi^-$, yielding $1.52 \pm 0.03$ ps, consistent with the $B^0$ lifetime.



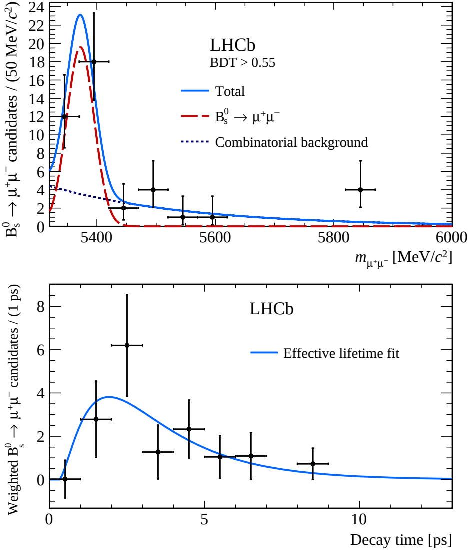



# $B_s^0 \to \mu^+\mu^-$ EFFECTIVE LIFETIME

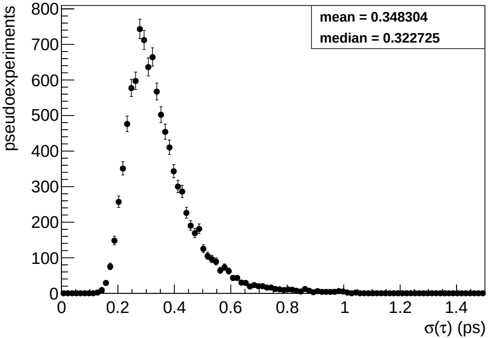
For the first time the effective lifetime of $B_s^0 \to \mu^+\mu^-$ is measured, as proposed by [De Bruyn, PK, et al., PRL 109, 041801 (2012)].

- Only candidates with BDT$>$ 0.55 are used.
- The time acceptance is taken from simulation.
- Using the sPlot technique: $\tau^{\text{eff}}_{B_s^0 \to \mu^+\mu^-} = 2.04 \pm 0.44 \pm 0.5$ ps

➜ Consistent with $A^{\mu^+\mu^-}_{\Delta\Gamma} = 1\ (-1)$ at $1\sigma\ (1.4\sigma)$ level



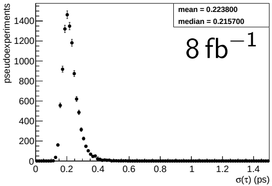
# Expected sensitivity for lifetime

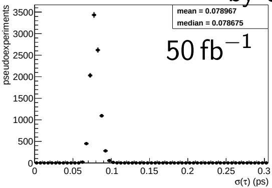


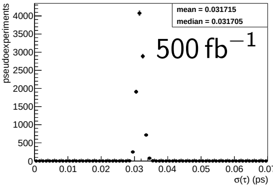

The expected sensitivity for this analysis was 0.32 ps but we got unlucky with 0.44 ps.

Extrapolating assuming an unchanged analysis we expect 0.079 ps for 50 $\mathrm{fb}^{-1}$ and 0.032 ps for 300 $\mathrm{fb}^{-1}$.

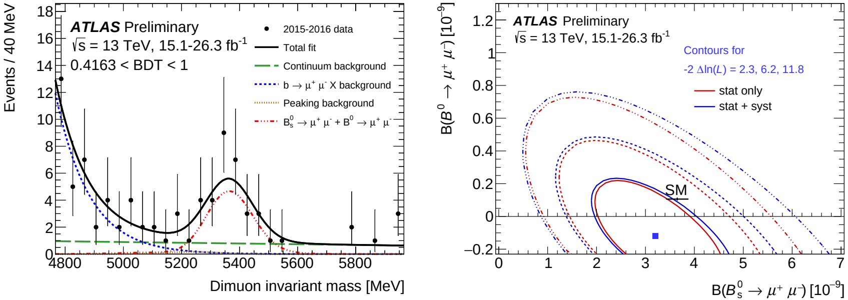
This would allow disentangling the $B_{s\mathrm{H}}$ anb $B_{s\mathrm{L}}$ states by $6\sigma$



# $B^0_{(s)} \to \mu^+\mu^-$ with Run 2 data

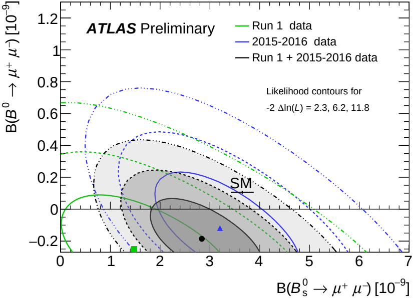


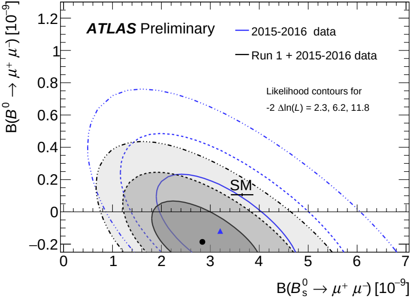

ATLAS now also see $B^0_s \to \mu^+\mu^-$:

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.2\,^{+1.0}_{-0.9}\,^{+0.5}_{-0.3}) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (-1.3 \pm 2.1) \times 10^{-10} < 4.3 \times 10^{-10}\ (95\%\ \text{C.L.})$$

# $B^0_{(s)} \to \mu^+\mu^-$ with Run 2 data



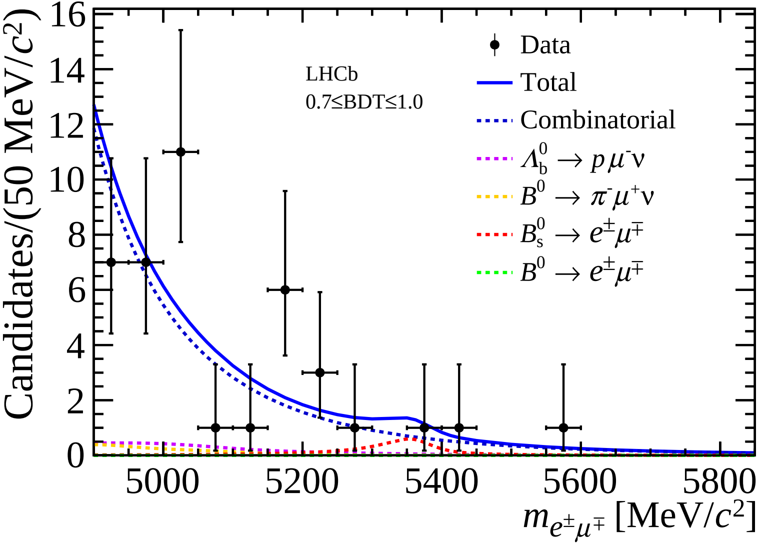




Combining with the Run 1 result [EPJC 76 (2016) 513]:

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (2.80.7) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (-1.9 \pm 1.6) \times 10^{-10} < 2.1 \times 10^{-10} \text{ (95\% C.L.)}$$

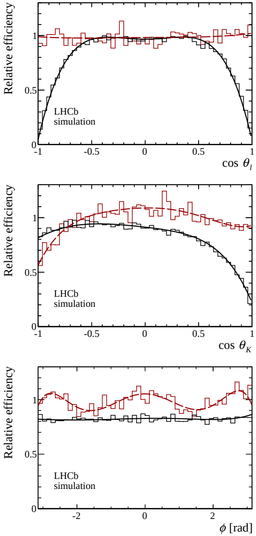
# SEARCH FOR $B_s^0 \to e^{\pm}\mu^{\mp}$

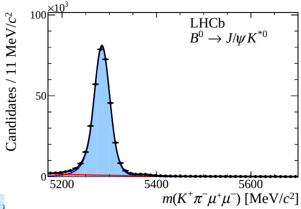


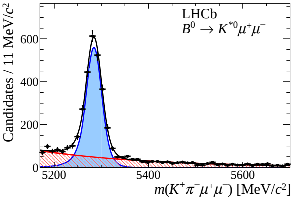
# Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$

Update of [JHEP 08 (2013) 131] and [PRL 111 (2013) 191801] to 3 $\text{fb}^{-1}$. S-wave is taken into account, we have finer bins, and no $\varphi$ folding is needed.

- Angular acceptance obtained from MC and validated on $B^0 \to J/\psi K^*$ decays.



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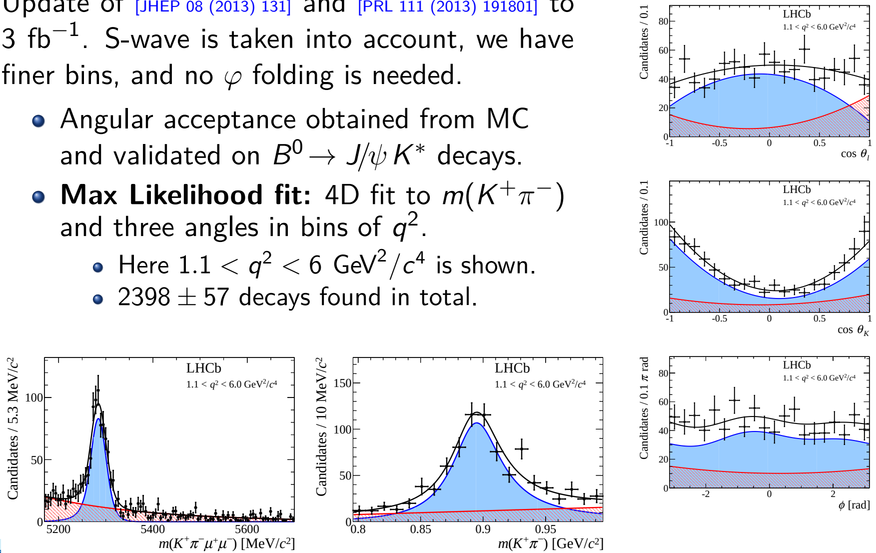

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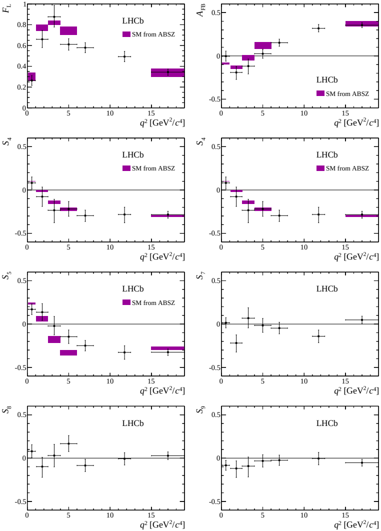

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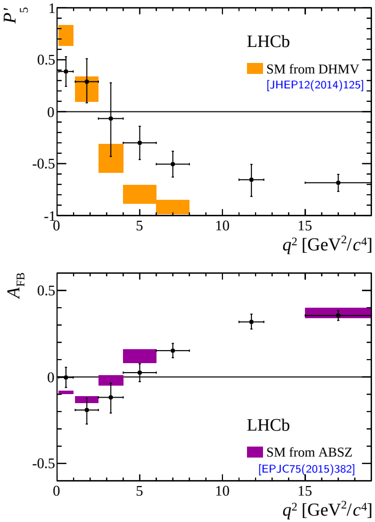

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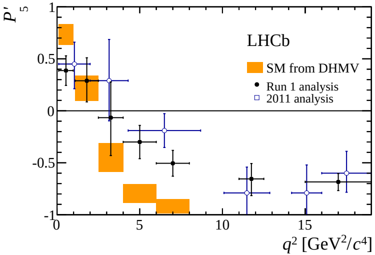


Comparison of $P_5'$ between the 1 $\text{fb}^{-1}$ analysis [PRL 111 (2013) 191801] and the 3 $\text{fb}^{-1}$ update [JHEP 02 (2016) 104]

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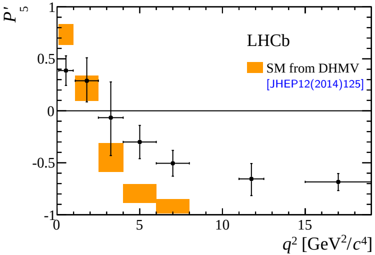
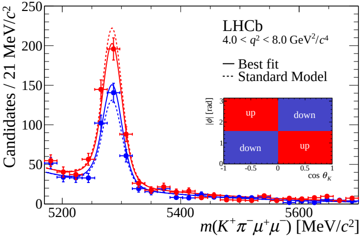
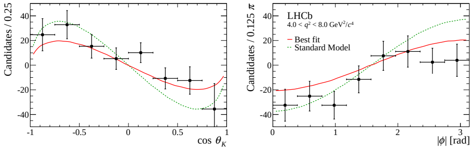
## What is $P_5'$?

It is an asymmetry built with $\cos\theta_K$ and $|\phi|$, shown in the sketch. (integrating over one of the two gets zero).

The discrepancy with the SM prediction is visible in both angular distributions.



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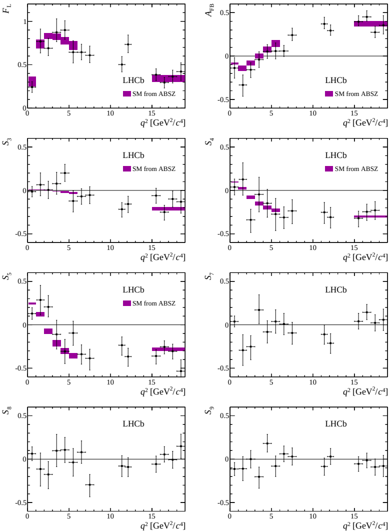
On top of the maximum likelihood method, the paper adds two more methods

**Method of moments:** Counting method, less precise but more stable: Allows for 1 GeV$^2/c^4$ bins.

- Important test for QED corrections: They would generate tensor currents not affecting this method [Gratrex, Hopfer, Zwicky PRD93 054008].



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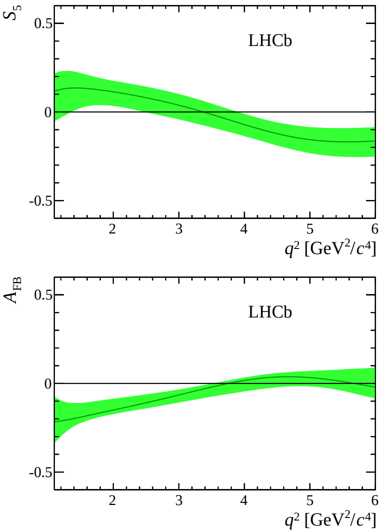
**Method of moments:** Counting method, less precise but more stable: Allows for 1 $\mathrm{GeV}^2/c^4$ bins.

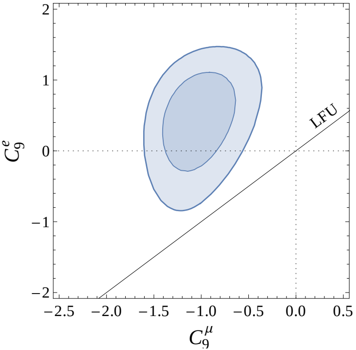
**Fit to decay amplitudes:** Modelling the $q^2$ dependence of the amplitudes one can fit for zero-crossing points more precisely

$$q_0^2(A_{\mathrm{FB}}) \in [3.40, 4.87]\,\mathrm{GeV}^2/c^4$$

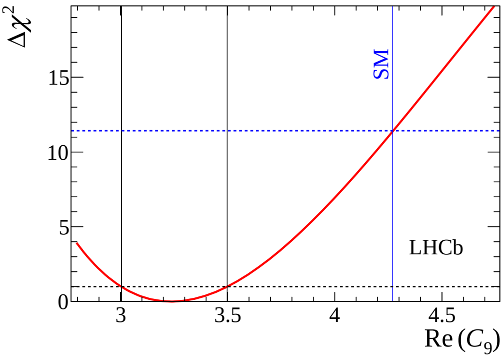
at 68% C.L.



# Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$



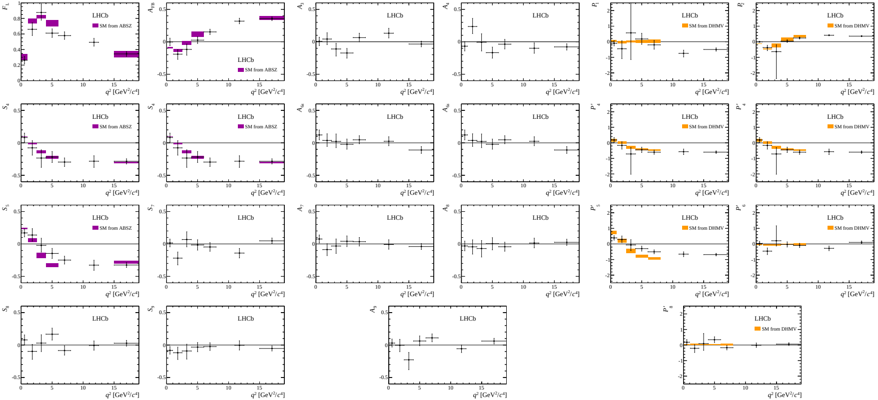

[Altmannshofer, Straub, EPJC 75 382 (2015)]




Using EOS software [Bobeth et al, JHEP 1007 098], we fit the likelihood fit results for a modified $C_9$ (vector coupling) Wilson coefficient and get

$$\Delta C_9 = -1.04 \pm 0.25 \quad (3.4\sigma)$$

# ANGULAR ANALYSIS OF $B^0 \to K^{*0}\mu^+\mu^-$




*CP*-averaged observables

*CP*-asymmetric observables

Optimised observables

All observables obtained from the maximum likelihood fit

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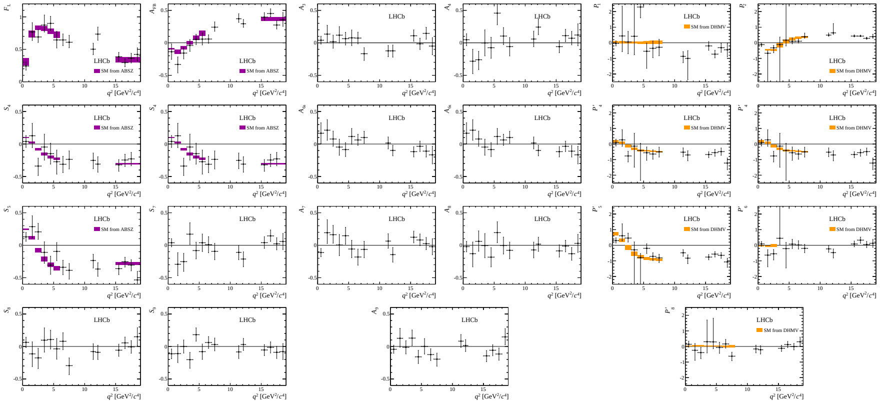


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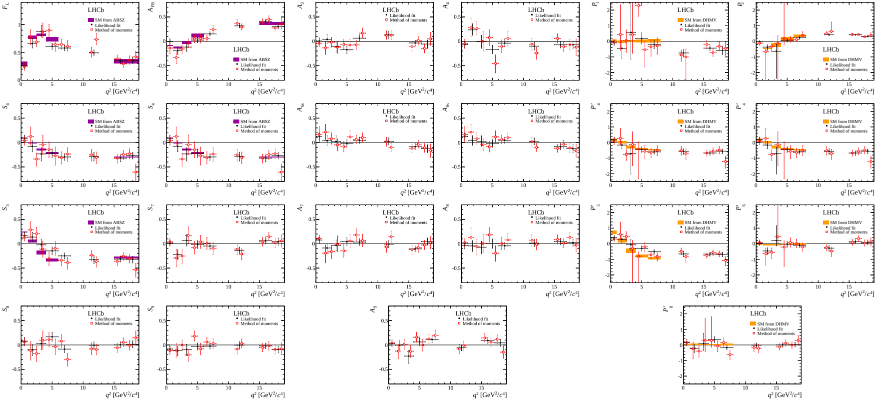
All observables obtained from the moment analysis

# Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$

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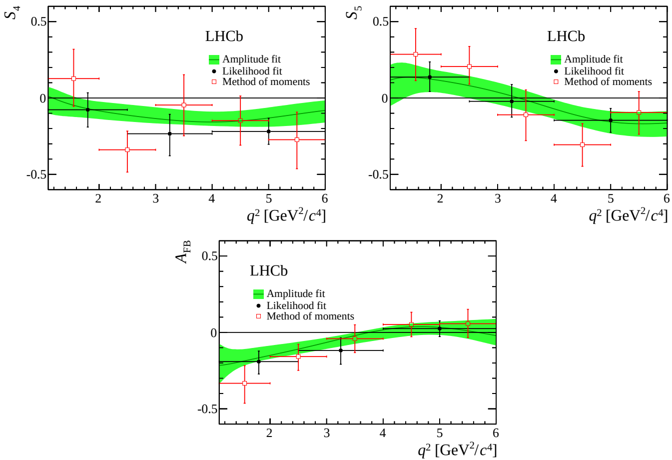
Comparison of likelihood fit and moments

# ANGULAR ANALYSIS OF $B^0 \to K^{*0}\mu^+\mu^-$




Observables determined by fitting the $q^2$-dependent amplitudes

# $R(D^*)$ with $\tau \to \ell\nu\overline{\nu}$

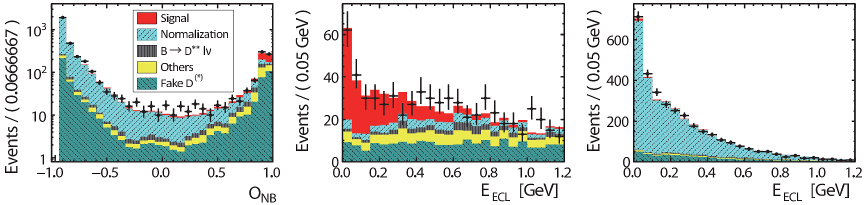
Using 772 million $B\overline{B}$ pairs, Belle compare $\overline{B}^0 \to D^{*+}\tau^-(\ell^-\nu_\tau\overline{\nu}_\ell)\overline{\nu}_\tau$ and $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_\ell$

- $D^{*+} \to D^0\pi^+$ with 10 decay modes for $D^0$
- $D^{*+} \to D^+\pi^0$ with 5 decay modes for $D^+$

They measure

$$R(D^*) = 0.302 \pm 0.030 \pm 0.011$$

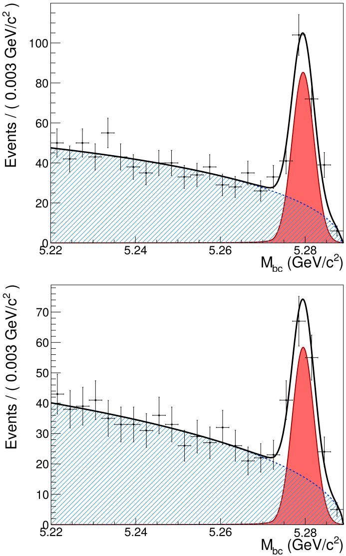
which is $1.6\sigma$ above the SM prediction.



# $B^0 \to K^{*0}\ell^+\ell^-$ ANGULAR ANALYSIS

Belle do an angular analysis of $P'_{(4,5)}$ as LHCb [JHEP 02 (2016) 104]. $A_{\rm FB}$ and $\mathrm{d}\Gamma/\mathrm{d}q^2$ were published in [PRL 103 171801 (2009)]

- Split sample in muons ($185 \pm 17$ decays) and electrons ($127 \pm 15$)



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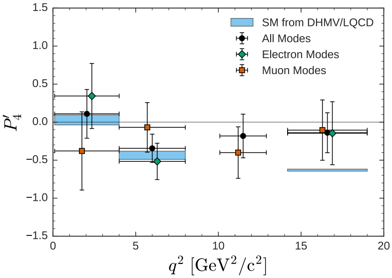
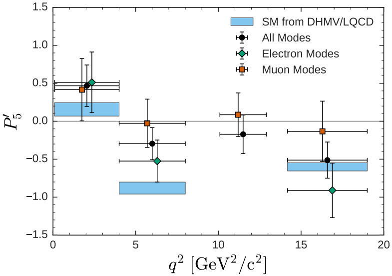
- Electrons are closer to the SM.



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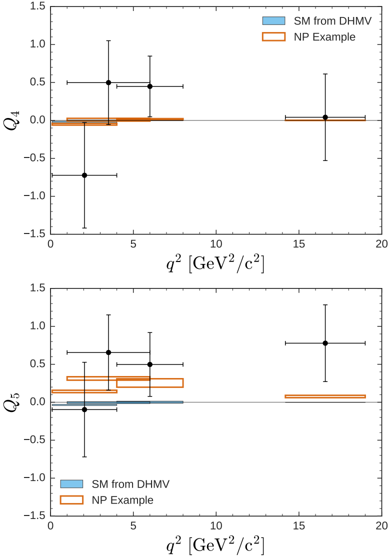
- This can be shown as LFU-violating variables $Q_{4,5} = P^{\mu}_{4,5} - P^{e}_{4,5}$



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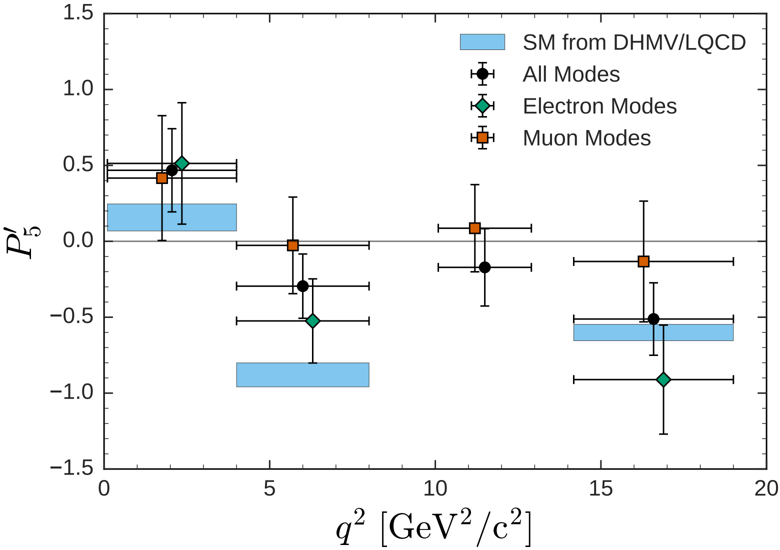

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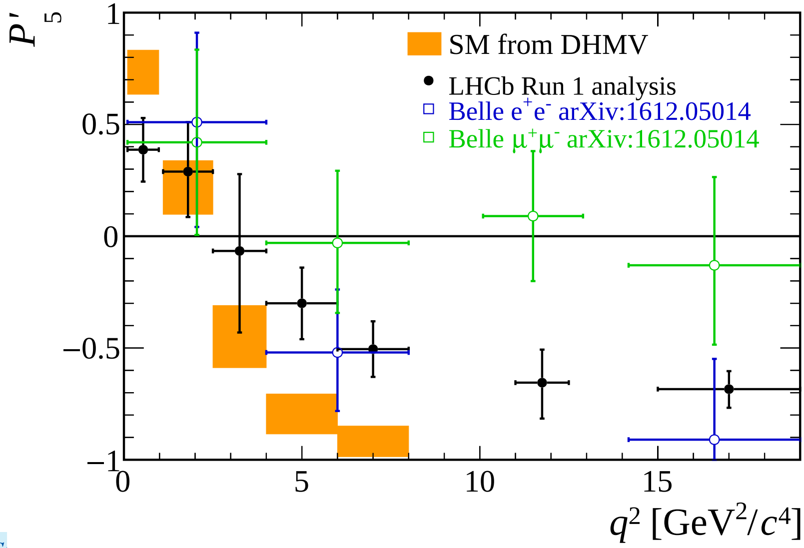
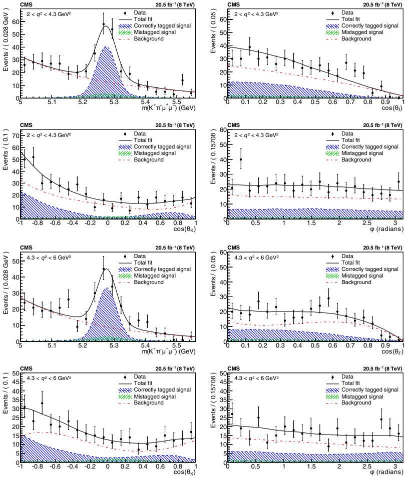
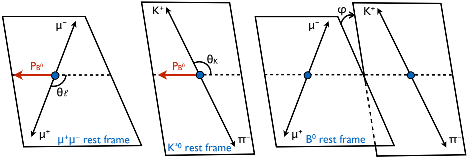


# $B^0 \to K^{*0}\mu^+\mu^-$ at CMS

CMS also study the $P_5'$ variable using $20.5\,\mathrm{fb}^{-1}$ at 8TeV.

- See 1400 decays
- $B^0$ flavour is obtained from $K^\pm\pi^\mp$ combination closest to $K^*(892)^0$ mass.



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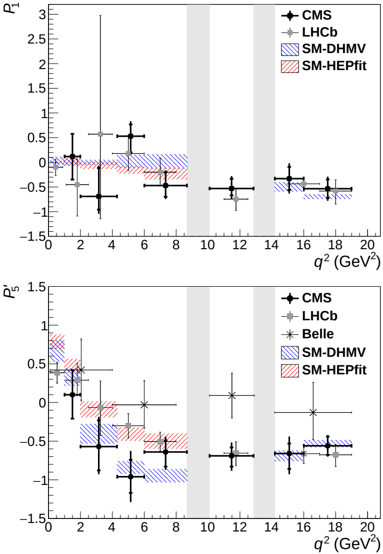
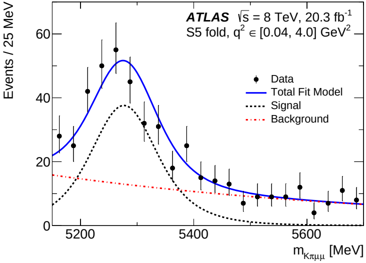
- CMS measurement of $P_5'$ is closer to the SM than LHCb and Belle
  - ✗ "SM-HEPfit" is not a prediction but a fit to the LHCb data [Ciuchini et al., JHEP 1606 (2016) 116]



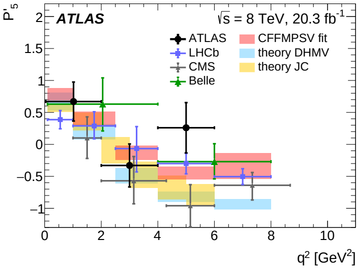
[ATLAS, arXiv:1805.04000]

# $B \to K^{*}\mu^{+}\mu^{-}$ at with 8TeV data

ATLAS see $342 \pm 39$ $B \to K^{*}\mu^{+}\mu^{-}$ in 0.04–6 $\text{GeV}^2/c^2$ range with 20.3 fb at 8TeV




- Their $P_5'$ result pulls in the same direction as LHCb
- Predictions: DHMV [Descotes-Genon et al.,JHEP 12 (2014) 125, arXiv:1407.8526] , JC [Jäger & Camalich, JHEP 05 (2013) 043, arXiv:1212.2263] [Jäger & Camalich, PRD 93 014028 (2016), arXiv:1412.3183]
- CFFMPSV is not a prediction but an SM fit to data. [Ciuchini et al., JHEP 06 (2016) 116, arXiv:1512.07157]
- Experiment: [LHCb, JHEP 02 (2016) 104, arXiv:1512.04442] [Belle, arXiv:1604.04042] [CMS, PLB 781 (2018) 517, arXiv:1710.02846]



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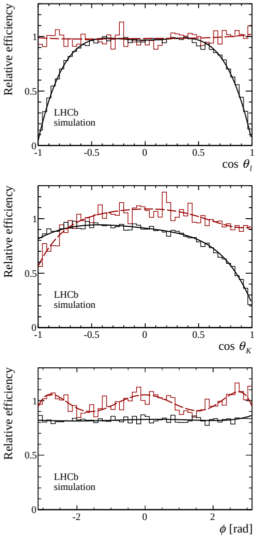


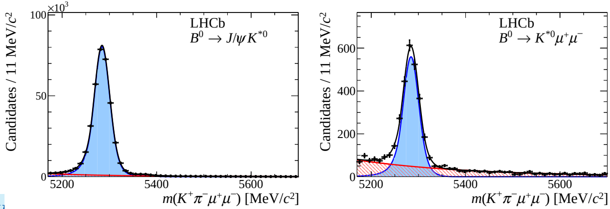

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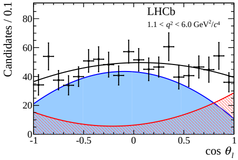


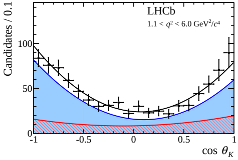


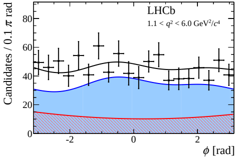


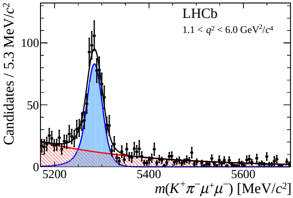


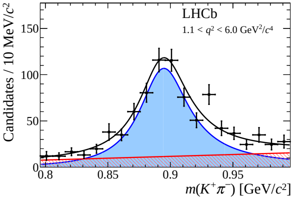

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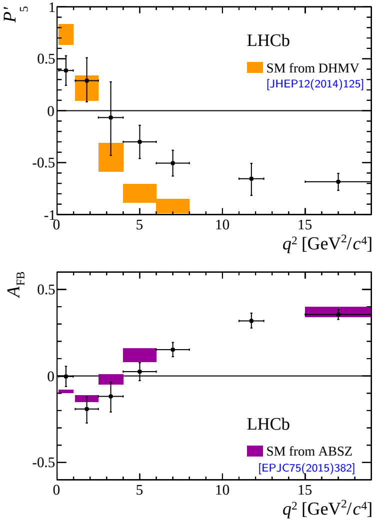

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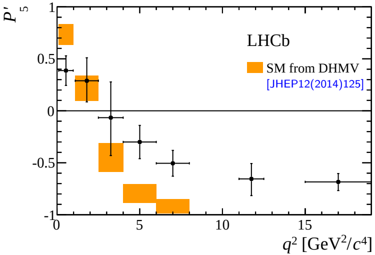
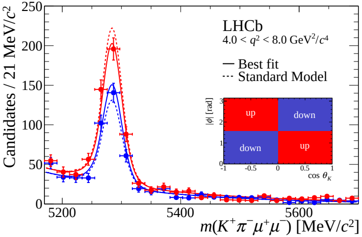
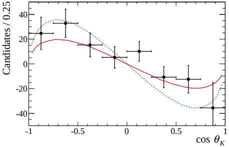
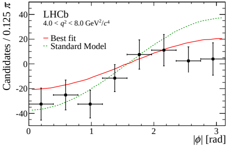


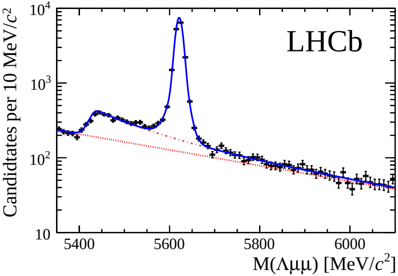



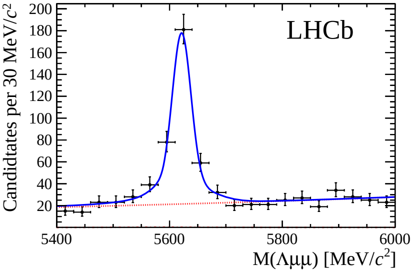



[LHCb, JHEP 06 (2015) 115, arXiv:1503.07138]

# BF and angular analysis of $\Lambda_b^0 \to \Lambda\mu^+\mu^-$




- Study $\Lambda_b^0 \to \Lambda\mu^+\mu^-$, complementary to $B^0 \to K^{*0}\mu^+\mu^-$ as baryons have non-zero spin and $\Lambda$ decay weakly
- Reconstruct $\Lambda$ as long and downstream ➜ calibrate to $\Lambda_b^0 \to J/\psi\,\Lambda$
- Find 345 $\Lambda_b^0 \to \Lambda\mu^+\mu^-$
  - Five times more than in 1 fb$^{-1}$ [PLB 725 (2013) 25]

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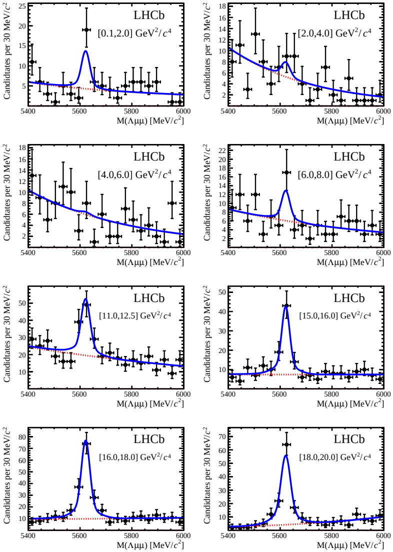
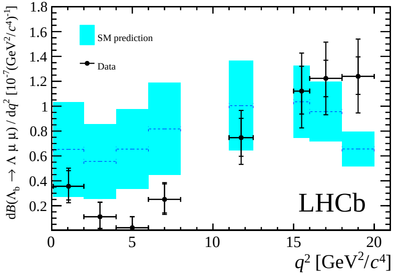
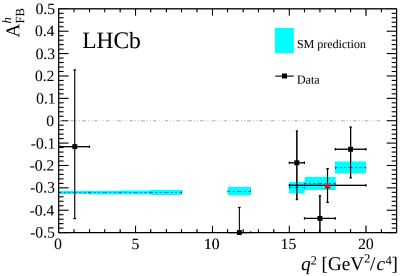



- Find 345 $\Lambda_b^0 \to \Lambda\mu^+\mu^-$
- Hint at very low $q^2$, significant only for high $q^2$
  - CDF also saw nothing at low $q^2$ [PRL 107 201802 (2011)]

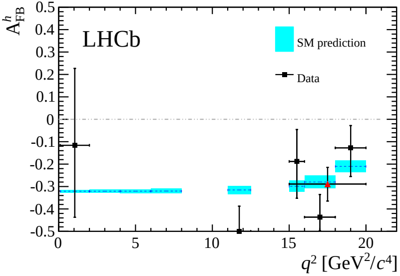
$$\mathcal{B} = (1.18\,^{+\,0.09}_{-\,0.08} \pm 0.03 \pm 0.27) \times 10^{-7}$$

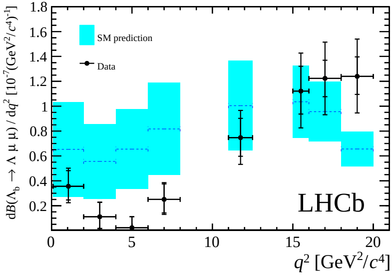


# BF and angular analysis of $\Lambda_b^0 \to \Lambda\mu^+\mu^-$

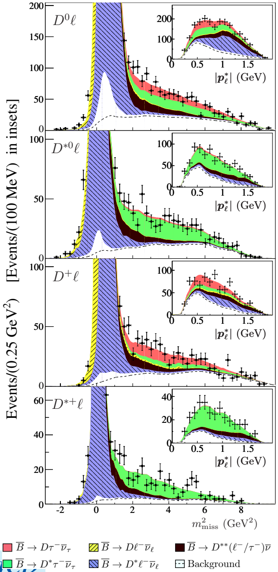



- Find 345 $\Lambda_b^0 \to \Lambda\mu^+\mu^-$
- Angular analysis: Measure $A_{\text{FB}}$ of dimuon and baryonic system.
  - Some hint of an excess in $A_{\text{FB}}^{\ell}$ at high $q^2$



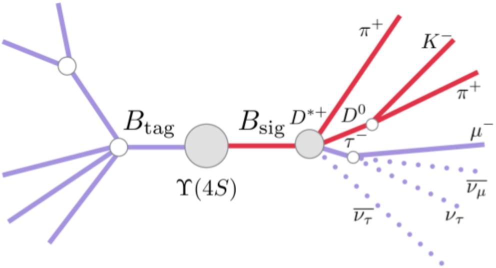



# EVIDENCE FOR A $B \to D^{(*)}\tau\nu$ EXCESS

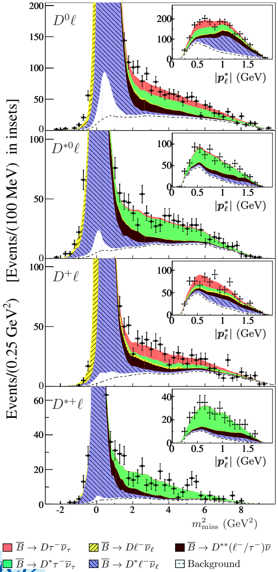



BaBar investigate $B^{0,+} \to D^{(*)}\tau\nu$ with $\tau \to \ell\nu\overline{\nu}$ and compare to $B^{0,+} \to D^{(*)}\ell\nu$

- Full sampe of 471 million $B\overline{B}$ pairs
- The other $B$ meson is fully reconstructed in 1680 final states
- Signal combines a $\ell = e, \mu$ to a $D^{(*)}$



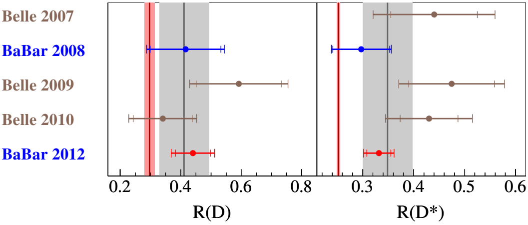
# Evidence for a $B \to D^{(*)}\tau\nu$ excess




BaBar investigate $B^{0,+} \to D^{(*)}\tau\nu$ with $\tau \to \ell\nu\overline{\nu}$ and compare to $B^{0,+} \to D^{(*)}\ell\nu$

- Full sampe of 471 million $B\overline{B}$ pairs
- The other $B$ meson is fully reconstructed in 1680 final states
- Signal combines a $\ell = e, \mu$ to a $D^{(*)}$

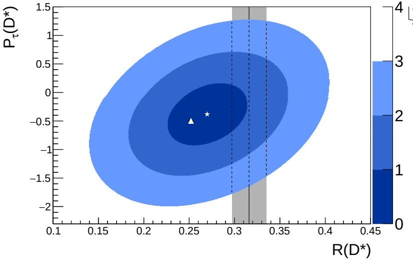
➜ Fit missing mass $m_{\rm miss}$ and momentum of lepton $|p^*_\ell|$



# $R(D^*)$ WITH $\tau^+ \to (\pi^+, \rho^+)\overline{\nu}$

Using 772 million $B\overline{B}$ pairs, Belle compare $\overline{B}^0 \to D^{*+}\tau^-(\ell^-\nu_\tau\overline{\nu}_\ell)\overline{\nu}_\tau$ and $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_\ell$

- 15 decay modes for $D^0$ and $D^+$
- 4 decay modes for $D^{*+}$ and $D^{*0}$
- $\tau \to \pi^+\overline{\nu}$ and $\tau \to \rho^+\overline{\nu}$




They measure

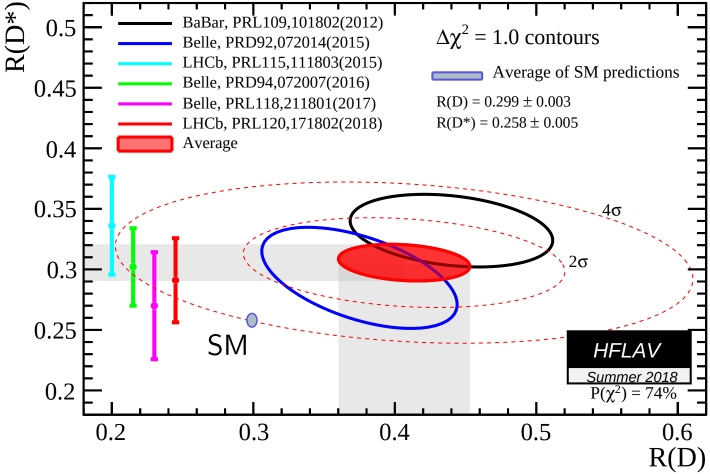
$$R(D^*) = 0.270 \pm 0.035 \, {}^{+\,0.028}_{-\,0.025}$$

$$\tau \text{ polarisation:} \quad P_\tau = -0.38 \pm 0.51 \, {}^{+\,0.21}_{-\,0.16}$$

where the $\tau$ polarisation is the asymmetry of $\pm\frac{1}{2}$ helicities. The SM predicts [M. Tanaka, R. Watanabe, PRD82 034028]

$$P_\tau = -0.497 \pm 0.013$$

# $B \to D^{(*)}\tau\nu$ HFLAV AVERAGE




BABAR [PRL 109 101802 (2012)] [PRD 88 072012 (2013)] Belle [PRD 92 072014 (2015)] [PRD 94 072007 (2016), arXiv:1607.07923] [PRL 118 211801 (2017)] [PRD 97 012004 (2018)] LHCb [PRL 115 (2015) 111803] [PRL 120 (2018) 171802]. Theory [Na et al., PRD 92 054410 (2015)], [Faijfer et al., PRD 85 094025 (2012)]

# First $K^+ \to \pi^+ \nu\overline{\nu}$ decay

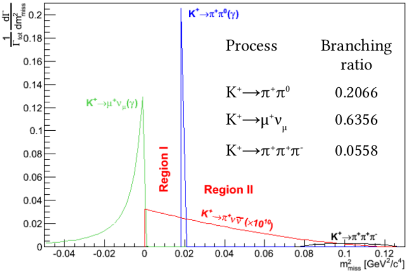
Search for $K^+ \to \pi^+ \nu\overline{\nu}$

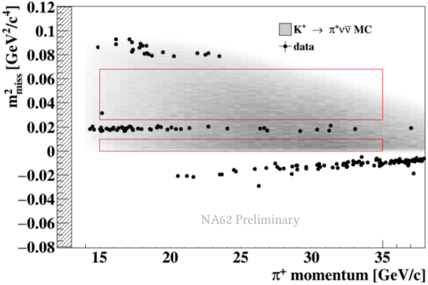
Signature is a $\pi^+$ with missing energy $m^2_{\text{miss}} = (p_{K^+} - p_{\pi^+})^2$

See one candidate in signal box
➜ Set 90% CL

$$\mathcal{B}(K^+ \to \pi^+ \nu\overline{\nu}) < 11 \times 10^{-10}$$

Consistent with SM expectation $(8.4\pm1.0)\pm10^{-11}$ [Buras, Buttazzo, Girrbach, Knegjens, JHEP 1511 (2015) 033].



# LEPTON-UNIVERSALITY IN $D^{0,+} \to \pi^{0,+}\mu\nu$

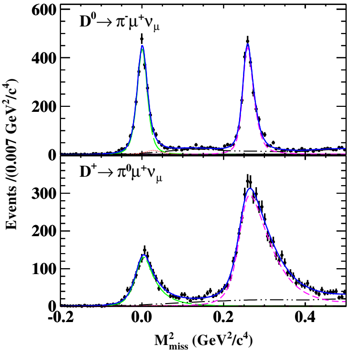
Using $2.93\,\mathrm{fb}^{-1}$ data at 3.773 GeV BESIII study $D^{0,+} \to \pi^{-,0}\mu^+\nu$

$$\mathcal{B}(D^0 \to \pi^-\mu^+\nu) = (0.267 \pm 0.007 \pm 0.007)\%$$
$$\mathcal{B}(D^+ \to \pi^0\mu^+\nu) = (0.342 \pm 0.011 \pm 0.010)\%$$

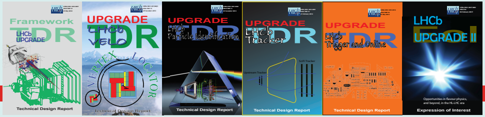
They combine with existing electronic BFs [CLEO, PRD80 (2009) 032005 ] [BESIII,PRD92 (2015) 072012] to get

$$\mathcal{R}(D^0 \to \pi^-\ell^+\nu) = 0.905 \pm 0.027 \pm 0.023$$
$$\mathcal{R}(D^+ \to \pi^0\ell^+\nu) = 0.942 \pm 0.037 \pm 0.027$$

which are 1.9 and $0.6\sigma$ below the SM expectation of 0.97.



# LHCb Upgrade




$\mathcal{L} = 2{\cdot}10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ requires some new detectors and 40 MHz read-out clock new electronics

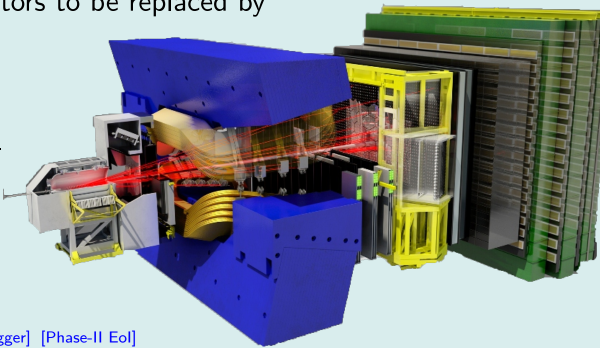
**Velo:** New pixel vertex detector

**Trackers:** New scintillating fibre tracker. The upstream tracker is also replaced

**PID:** Hybrid photodetectors to be replaced by multi-anode PMTs

→ 50 $\mathrm{fb}^{-1}$ by Run 4.

✔ We are preparing another upgrade for Run 5
→ 300 $\mathrm{fb}^{-1}$



[Upgrade TDR] [Velo] [PID] [Sci-Fi] [Trigger] [Phase-II EoI]

# LHCb Trigger in Run 3


## LHCb 2015 Trigger Diagram

**40 MHz bunch crossing rate**

⇩ ⇩ ⇩

**L0 Hardware Trigger : 1 MHz readout, high $E_T/P_T$ signatures**

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

⇩ ⇩ ⇩

**Software High Level Trigger**

- Partial event reconstruction, select displaced tracks/vertices and dimuons
- ⇩ Buffer events to disk, perform online detector calibration and alignment
- ⇩ Full offline-like event selection, mixture of inclusive and exclusive triggers

⇩ ⇩ ⇩

**12.5 kHz (0.6 GB/s) to storage**

→

## LHCb Upgrade Trigger Diagram

**30 MHz inelastic event rate (full rate event building)**

⇩ ⇩ ⇩

**Software High Level Trigger**

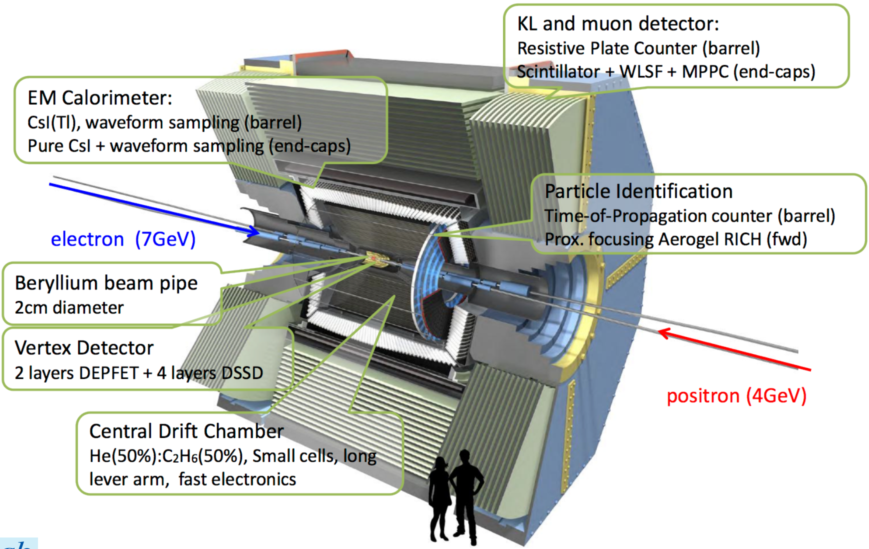
- Full event reconstruction, inclusive and exclusive kinematic/geometric selections
- ⇩ Buffer events to disk, perform online detector calibration and alignment
- ⇩ Add offline precision particle identification and track quality information to selections

  Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers

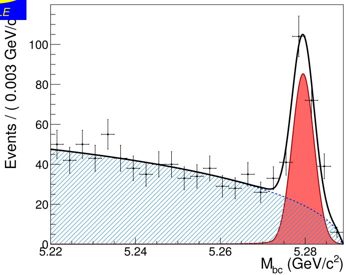
⇩ ⇩ ⇩

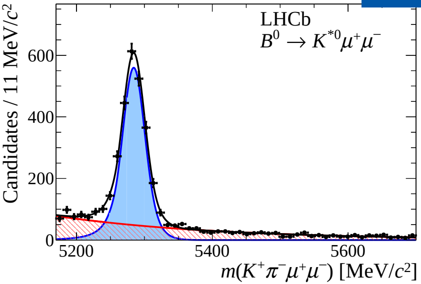
**2-5 GB/s to storage**

# Belle II


KL and muon detector:
Resistive Plate Counter (barrel)
Scintillator + WLSF + MPPC (end-caps)
EM Calorimeter:
CsI(Tl), waveform sampling (barrel)
Pure CsI + waveform sampling (end-caps)
electron (7GeV)
Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (fwd)
Beryllium beam pipe
2cm diameter
Vertex Detector
2 layers DEPFET + 4 layers DSSD
positron (4GeV)
Central Drift Chamber
He(50%):C2H6(50%), Small cells, long
lever arm, fast electronics

# Belle versus LHCb




Example: $B^0 \to K^{*0}\mu^+\mu^-$

✔ Two handles: $B$ mass and $B$ energy in $\Upsilon(4S)$ frame ($\Delta E$)

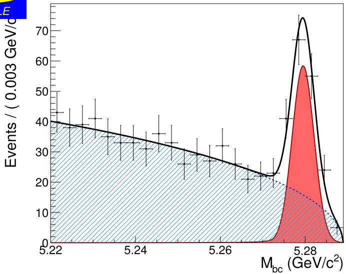
185 signal decays with 711 fb$^{-1}$

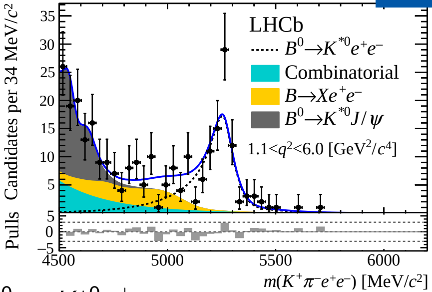
✔ Two handles: $B$ mass and pointing to PV

2400 signal decays with 3 fb$^{-1}$ at 7–8 TeV

Conversion factor: 5 ab$^{-1}$ $\leftrightarrow$ 1 fb$^{-1}$ (at 13 TeV)

# Belle versus LHCb




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

✔ Electron channels are as "easy" as muonic

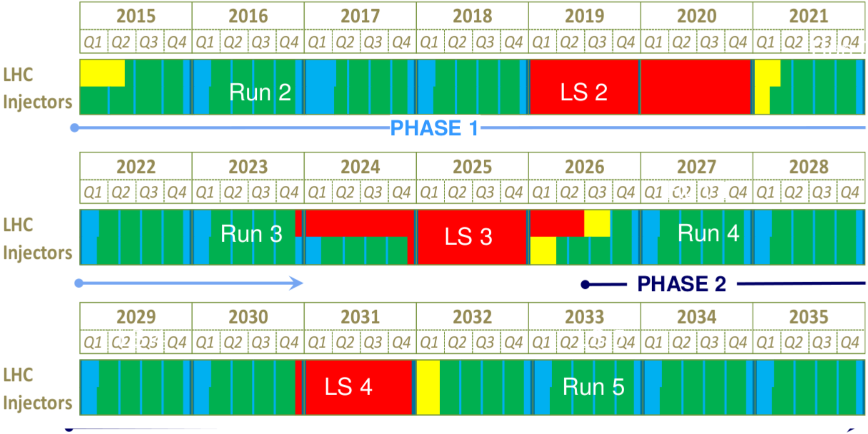
127 signal decays with $711\,\mathrm{fb}^{-1}$

✗ Bremsstrahlung makes electrons much more difficult

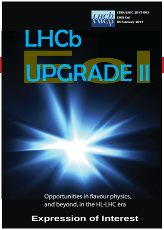
200 signal decays with $3\,\mathrm{fb}^{-1}$ at 7–8 TeV

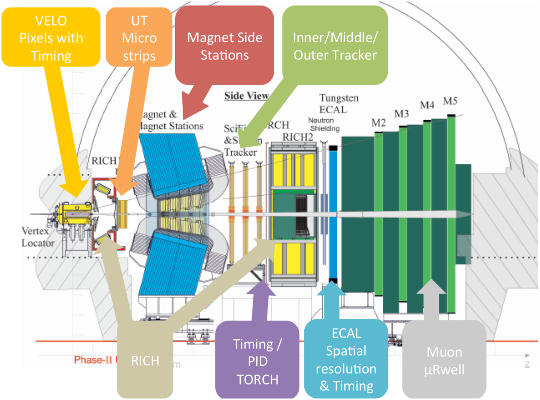
Conversion factor: $1\,\mathrm{ab}^{-1} \leftrightarrow 1\,\mathrm{fb}^{-1}$ (at 13 TeV, upgraded)

# LHC schedule



# EoI for Phase-II Upgrade




We have experessed an interest for a Phase-II upgrade [CERN-LHCC-2017-003] .

We are now writing the physics case.

| Luminosity increments | Run 1 2010–12 | Run 2 2015–18 | Run 3 2021–24 | Run 4 2026–30 | Run 5 2032–35 |
|---|---|---|---|---|---|
| $\Delta\mathcal{L}$ [$\mathrm{fb}^{-1}$] | +3 | +6 | +14 | +27 | +250 |
| Total $\mathcal{L}$ [$\mathrm{fb}^{-1}$] | 3 | 9 | 23 | 50 | 300 |