FP*CP* 2016 - *Caltech June 6-9*

Rare decays

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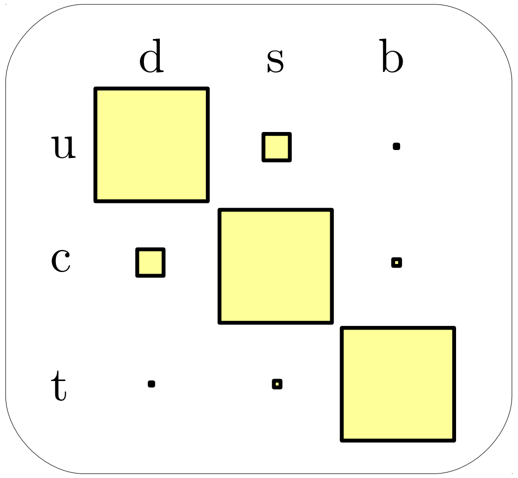
on behalf of the LHCb collaboration

with results from ATLAS and CMS

Rare decays

- The Standard Model is not the full story:
  - Dark matter, hierarchy problem, flavour puzzle, matter-antimatter, gravity, …
  - We have the proof that New Physics is there!
- BSM models can cure (some of) these SM shortcomings
  - they also predict new undetected particles
- The LHC is looking for their direct production (mainly ATLAS and CMS)
- But they can also enter in "SM observables" through competing diagrams
- Measuring very-suppressed SM-processes could allow us to unveil New Physics

$V_{\text{CKM}} =$



Outline

- $B_{(s)}\to\mu\mu$ CMS+LHCb and new ATLAS result
- Other very rare decays in beauty and charm
- Lepton Flavour (Universality) violation tests

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

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

- FCNC + helicity suppressed

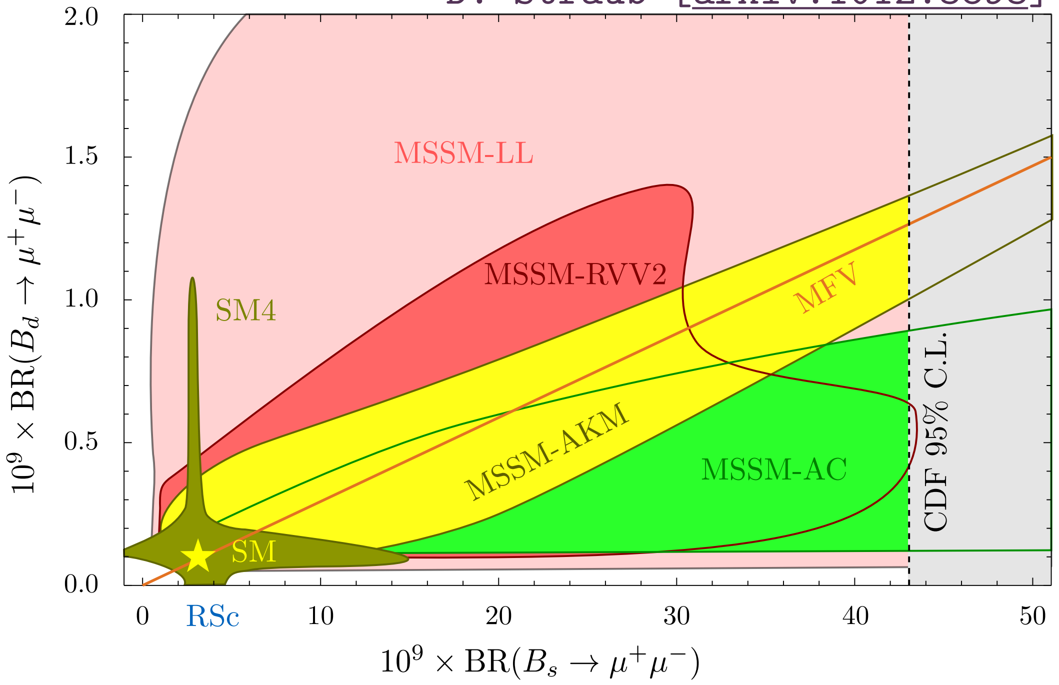
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

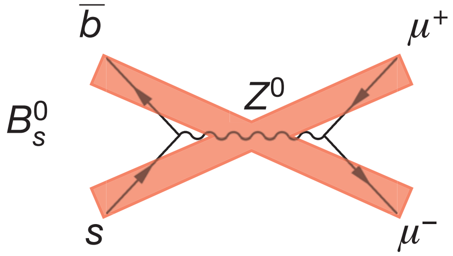
C. Bobeth et al [PRL 112(2014)101801]

- Possible large BR enhancement from (pseudo-)scalar contributions:
  - sensitive to extensions of the Higgs sector
  - also Extra Dimensions, non-MFV SUSY, …

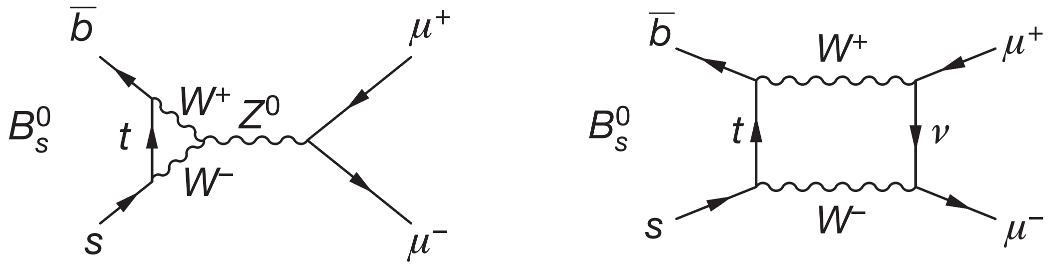
D. Straub [arXiv:1012.3893]



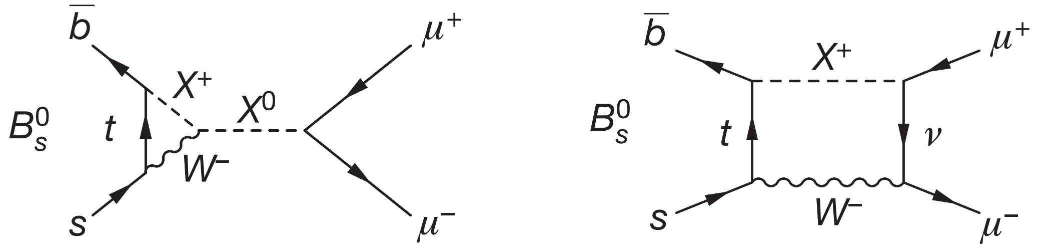
FCNC:



SM processes:

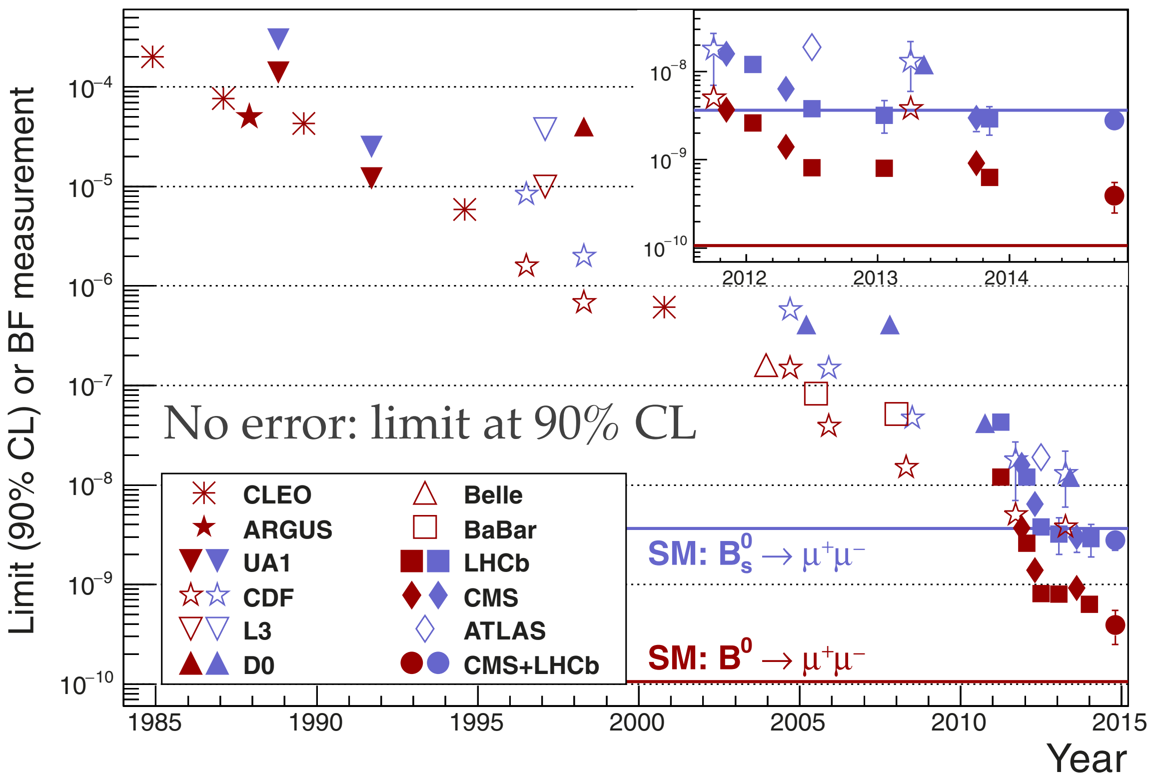


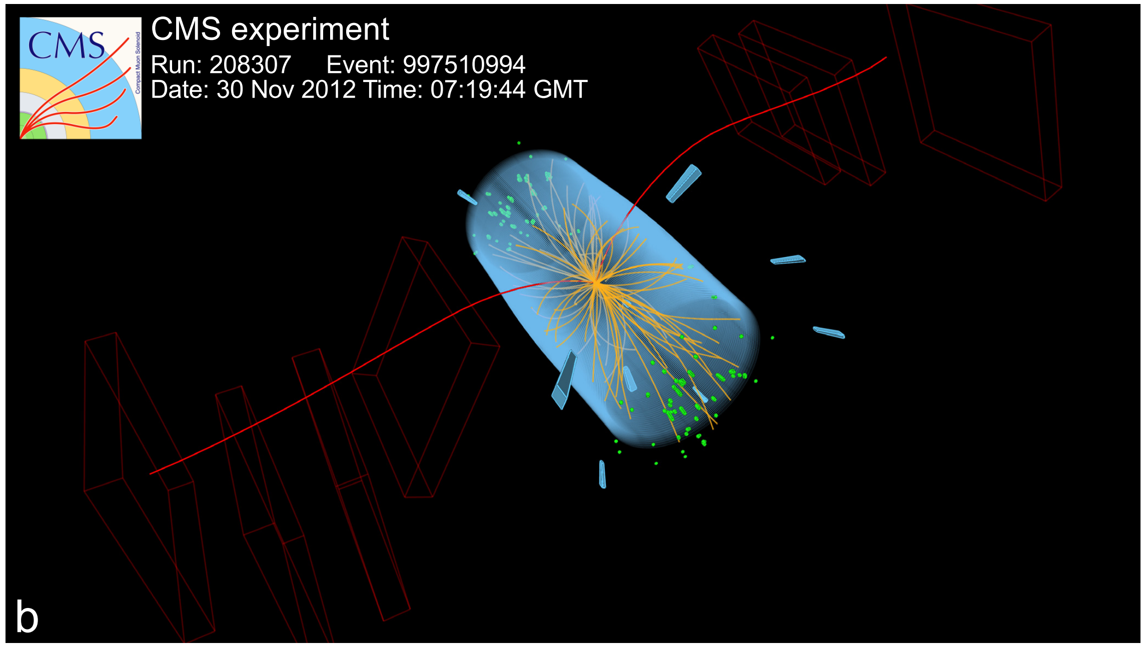
NP processes examples:



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

- The Holy Grail of rare decays
- A quest lasted 30 years and spanning 5 orders of magnitude
- Crucial role of hadron colliders: Tevatron first, now led by LHC
  - Large $pp\to b\bar{b}X$ cross section
  - $\mu\mu$ decay easy to identify despite harsh hadronic environment



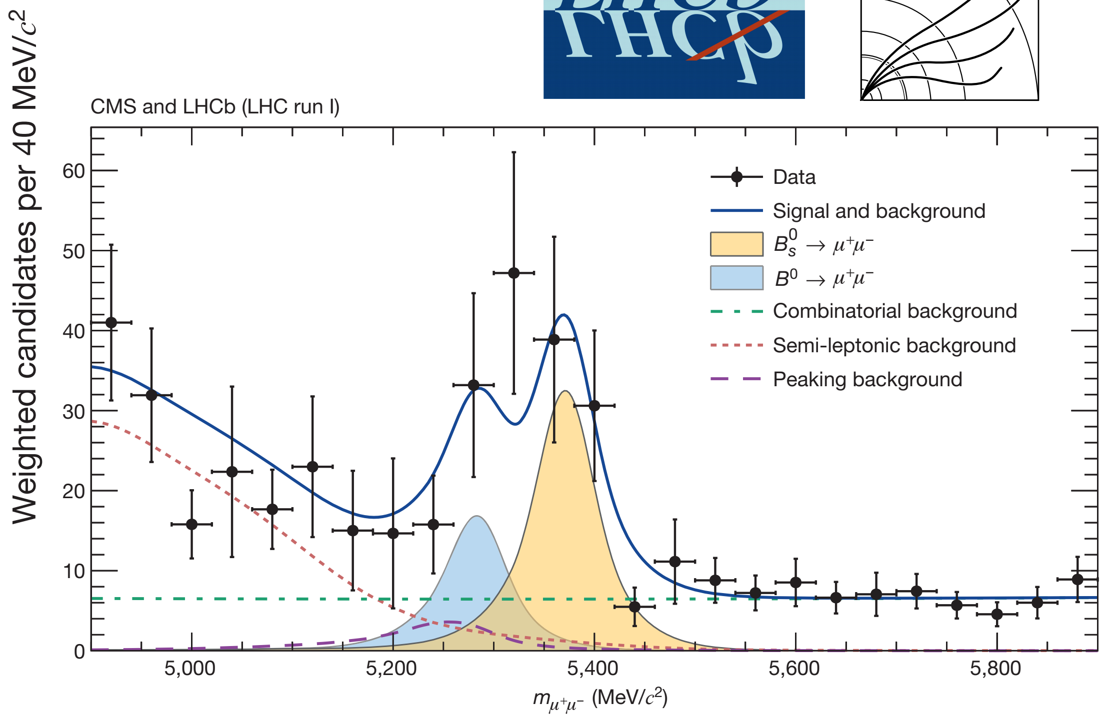


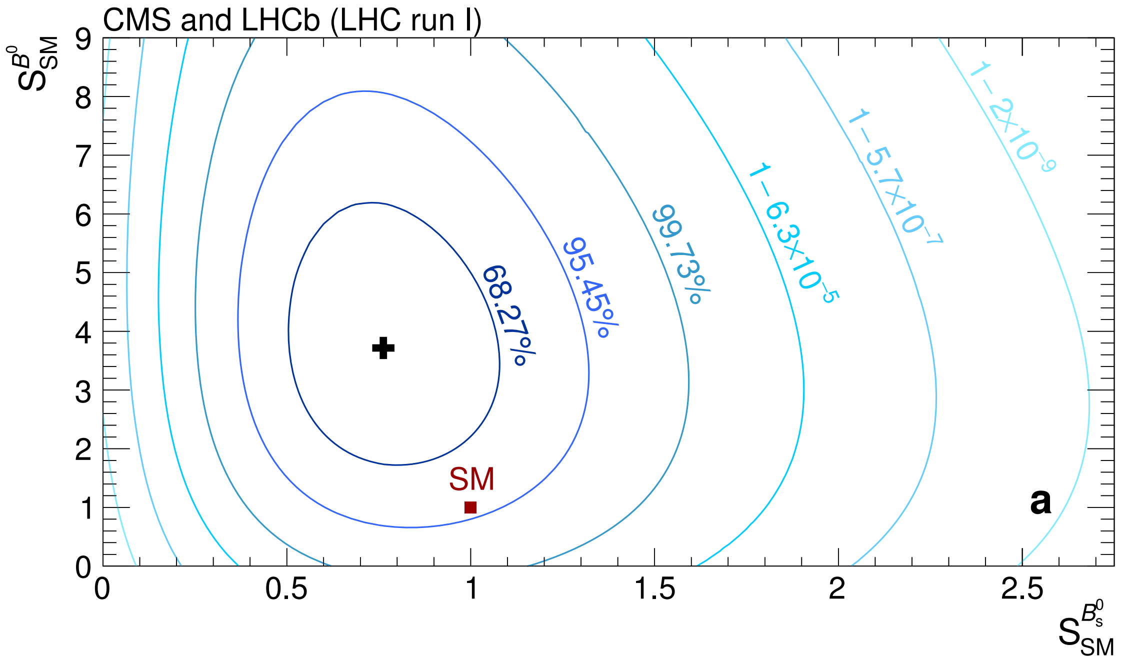
LHCb+CMS result

- LHCb and CMS: world-best sensitivity
- Their Run 1 results combined `[nature:522(2015)68]` gave us:
  - **First observation** of $B_{(s)}\to\mu\mu$ with 6.2σ (1.2σ from SM)
  - **Evidence** for $B^0\to\mu\mu$ with 3.2σ (2.2σ from SM)
  - Measurement ratio $\mathrm{B}^0/\mathrm{B_s}$:

$$\mathcal{R}=0.14^{+0.08}_{-0.06}$$

- ATLAS recently published analysis of full Run 1 dataset: `[ArXiv:1604.04263]` → briefly discussed in this talk





$B_{(s)}\to\mu\mu$ at the LHC

- General strategy:
  - Good quality displaced di-muons
  - $p(\mu\mu)$ pointing back to primary vertex
  - MVA selection using kinematic and geometric features
  - Fit to $m(\mu\mu)$ in bins of MVA to maximise sensitivity
  - Normalisation: $B^+\to J/\psi K^+$ (LHCb uses also $B^0\to K^+\pi^-$)
  - Extraction of f_s/f_d from control channels

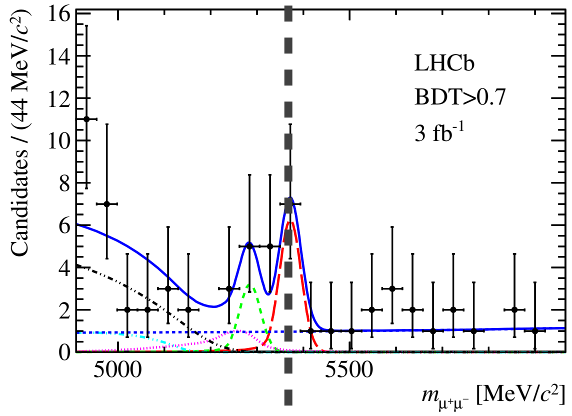
from mass fit

$$\mathcal{B}(B_s^0\to\mu^+\mu^-) = \frac{N_{B_s^0\to\mu^+\mu^-}}{N_{\text{norm.}}}\times\frac{f_d}{f_s}\times\frac{\varepsilon_{\text{norm.}}}{\varepsilon_{B_s^0\to\mu^+\mu^-}}\times\mathcal{B}_{\text{norm.}} = \alpha_{\text{norm.}}\times N_{B_s^0\to\mu^+\mu^-}$$

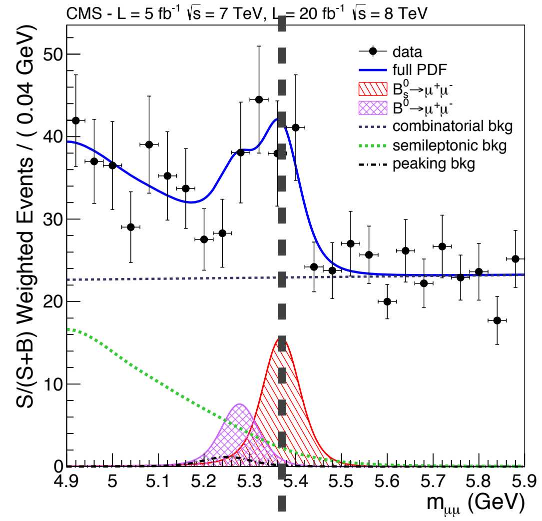
"single-event sensitivity"

$B_{(s)} \to \mu\mu$ in LHC Run 1

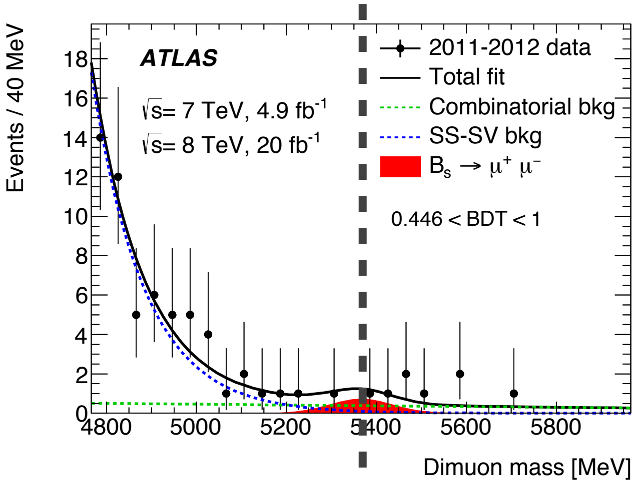
- Mass resolution (separation of bkg and B_d - B_s):
  - LHCb has the best: 25 MeV/c^2 in whole accept.
  - CMS better than ATLAS (depends on η)
- Luminosity:
  - 3 fb^{-1} for LHCb
  - 25 fb^{-1} for ATLAS/CMS
- Trigger on muons p_T:
  - LHCb: single muon $p_T > 1.5$ GeV/c
  - CMS: two muons with $p_T > 4(3)$ GeV/c.
  - ATLAS two muon triggers with generally somewhat higher p_T



[Phys. Rev. Lett. 111(2013)101805]



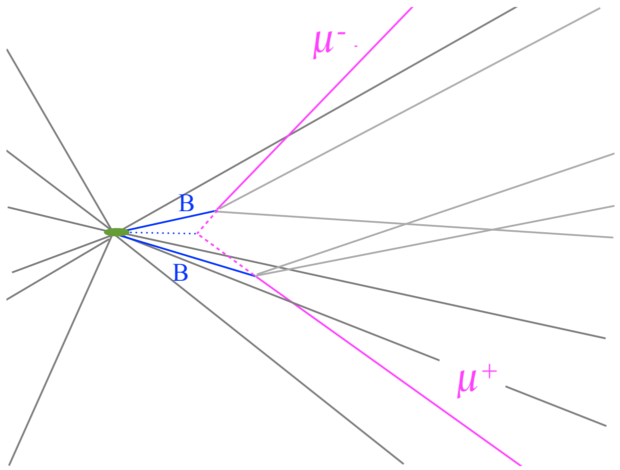
[Phys. Rev. Lett. 111(2013)101804]



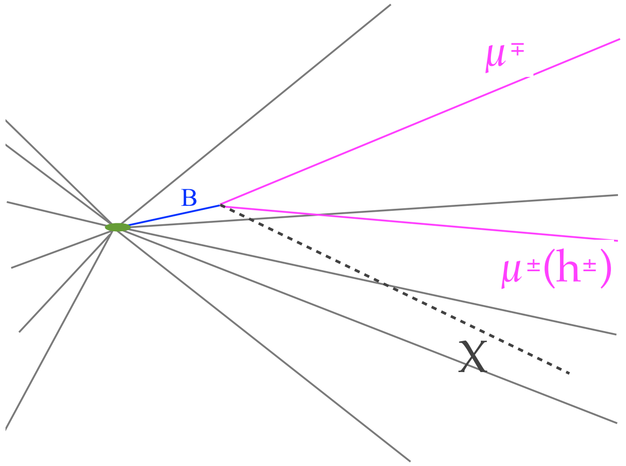
[ArXiv:1604.04263]

$B_{(s)}\to\mu\mu$ backgrounds

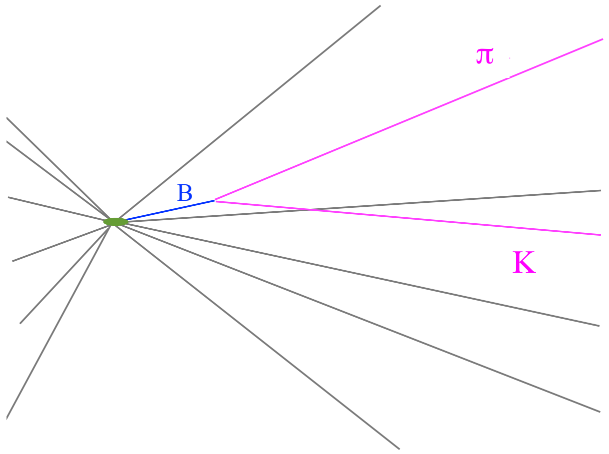
- Mass continuum:
  - Combinatorial background (mainly muons from the two b’s)



- Below B mass:
  - Semi-leptonic with hadron mis-id: $B_s\to K^-\mu^+\nu$, $B^0\to\pi^-\mu^+\nu$, $\Lambda_b\to p\mu^-\nu$
  - Rare penguins: $B^{0,+}\to\pi^{0,+}\mu^+\mu^-,\ldots$
  - Double semilept: $b\to c\mu\nu\to s(d)\mu\mu\nu\nu$



- Peaking background:
  - $B_{(s)}\to h'^+h^-$ with double mis-id



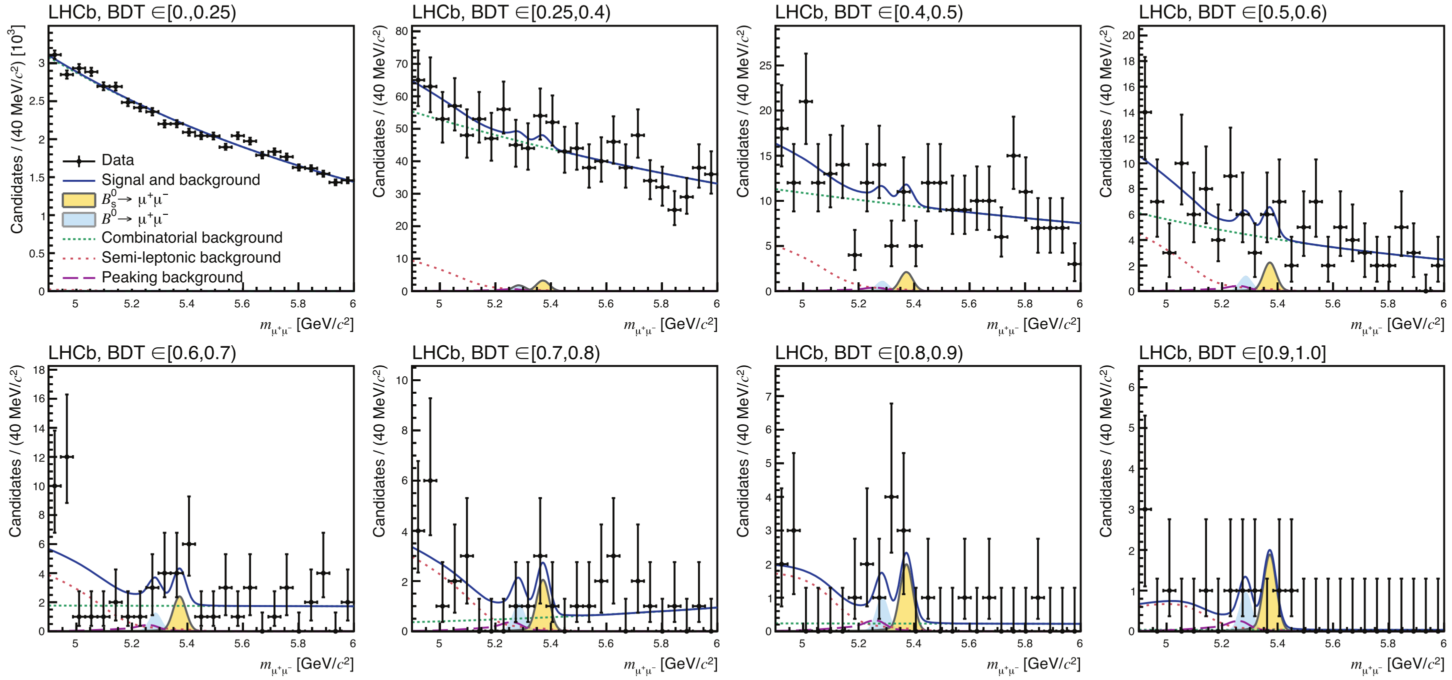
ATLAS selection

- ATLAS used a double MVA selection (with Boosted Decision Trees):
- a BDT to reduce **peaking background** $B_{(s)} \rightarrow h'^{+} h^{-}$
    - based on tracking ID, muon spectrometer and calorimeter info
    - trained on MC and validated on data
    - rejection 7× larger than first paper ($\epsilon_{\text{sig}} = 90\%$)
- a BDT to reduce **combinatorial**
    - based on kinematic, geometry and isolation
    - trained on MC samples of b/c quarks decay chains
    - cut with $\epsilon_{\text{sig}}=54\%$ and background rejection 10^{3}
    - Mass fit in 3 bins of BDT: same strategy as LHCb/CMS

Mass fit in BDT bins

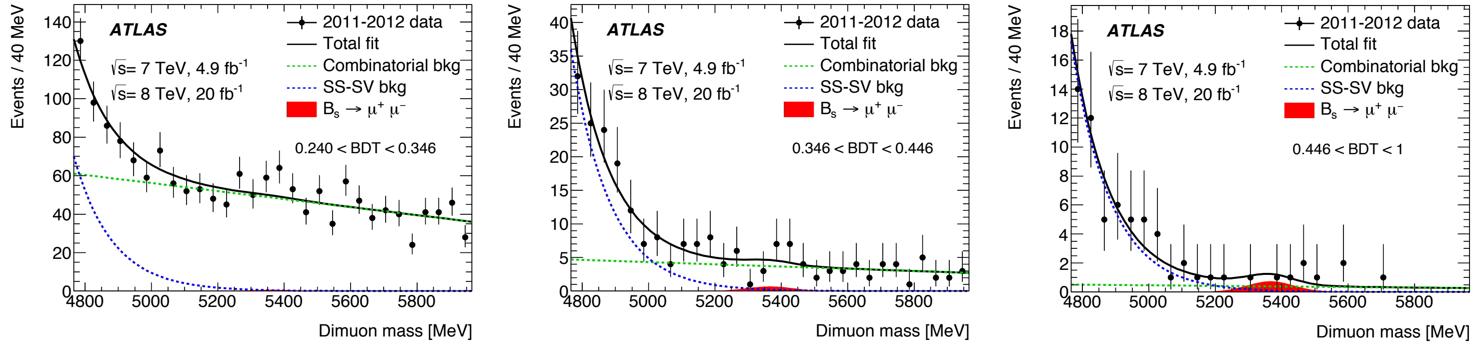
- Simultaneous unbinned mass fit in BDT bins
  - whole stat power
  - handle on background
- For CMS+LHCb
  - combine all bins in same fitter with shared parameters
  - more stability and reliability

Example: 8 BDT categories in LHCb:



[PRL 111(2013)101805]

Example: 3 BDT categories in ATLAS:

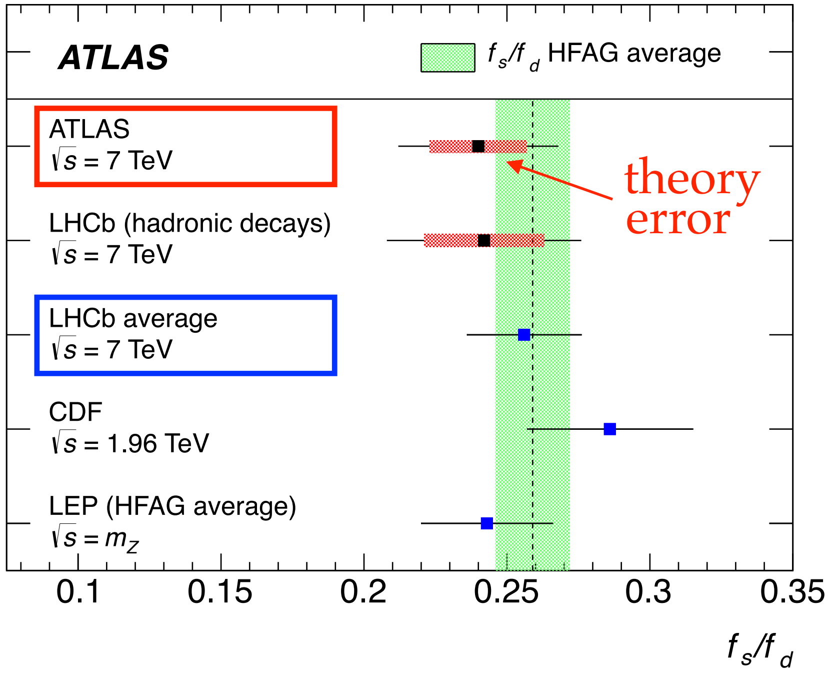


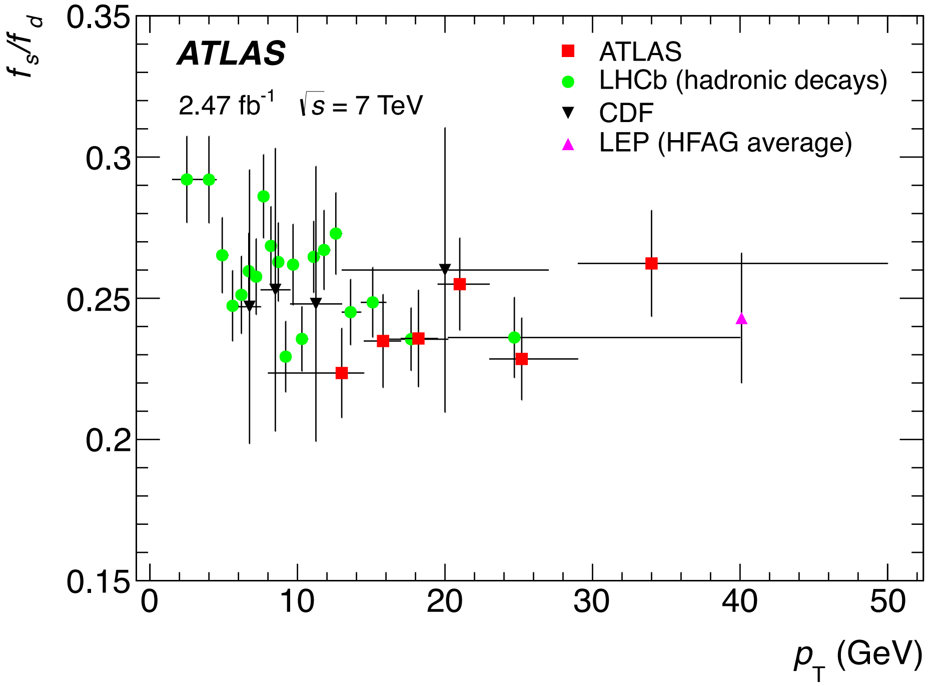
[ArXiv:1604.04263]

f_s/f_d for $B_s\to\mu\mu$

- Normalising $B_s\to\mu\mu$ to $B_u\to J/\psi K^+$ (or $B_d\to K^+\pi^-$)
  - Need probability that a b-quark is bound to either an s- or a d/u-quark
- LHCb measured it with semi-leptonic decays to avoid model dependence [LHCb-CONF-2013-011]
- CMS used LHCb result with additional systematic to account for possible p_T dependence
- ATLAS recently measured it [PRL 115(2015)26]
  - Using $B_d\to J/\psi K^*$ and $B_s\to J/\psi\varphi$
  - pQCD calculation of BF ratio [PRD 89(2014)9]
  - p_T range adapted to its $B_s\to\mu\mu$ analysis

[PRL 115(2015)26]





ATLAS sensitivity

[ArXiv:1604.04263]

- ATLAS sensitivity compared:
  - Single-event sensitivities very similar to LHCb

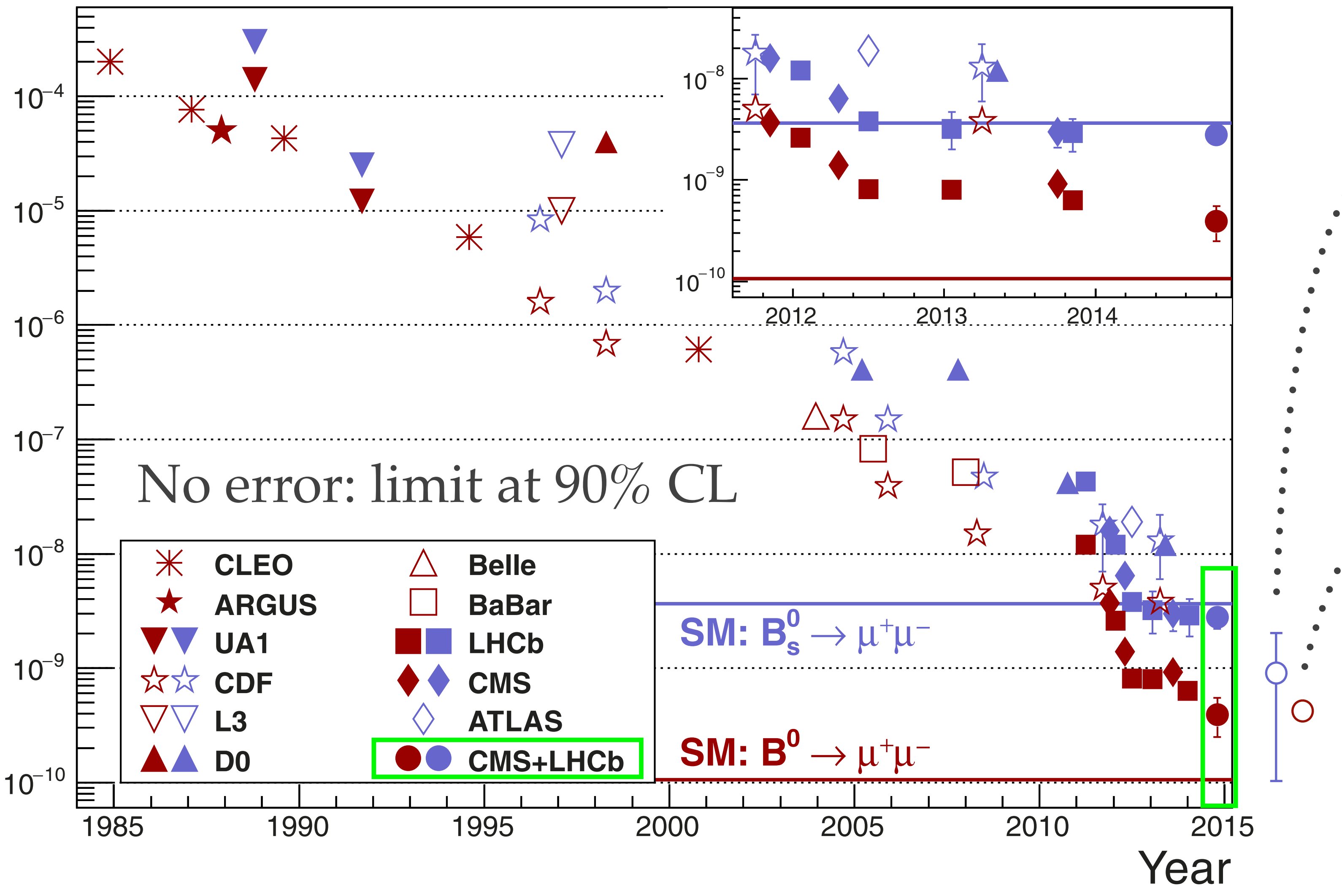
$$(8.9 \pm 1.0) \times 10^{-11} \text{ for } B_s^0 \to \mu^+\mu^-$$
$$(2.21 \pm 0.15) \times 10^{-11} \text{ for } B^0 \to \mu^+\mu^-$$

    - about same number of expected signal events
  - Expected ATLAS sensitivity for SM B_s is 3.1σ
    - It is 5.0σ (4.8σ) for LHCb (CMS)
- ATLAS demonstrated it can play an important role
  - before the LHC the upper limit on B_s was one order of magnitude larger than the SM

ATLAS results

[ArXiv:1604.04263]

[nature:522(2015)68]



- Result for B_s:

  $$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(0.9^{+1.1}_{-0.8}\right) \times 10^{-9}$$

  (syst component is ±0.3)

- Result for B^0:

  $$\mathcal{B}(B^0 \to \mu^+\mu^-) < 4.2 \times 10^{-10}$$

  at 95% conf. level

- Result is compatible with SM at 2.0σ (p=4.8%)

Other very rare decays

$B_{(s)}\to\mu\mu\mu\mu$ at LHCb

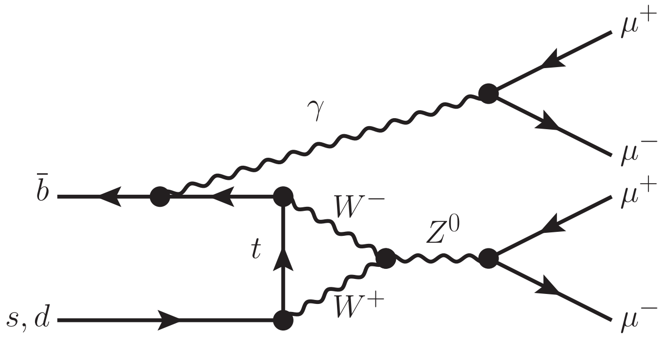
[PRL 110(2013)211801]

- $B_{(s)}\to\mu\mu\mu\mu$ (non resonant) is very suppressed in the SM
    - $B_{(s)}\to\mu\mu\gamma(\mu\mu)$ is less than 10^{-10}
- Significant enhancement can occur in MSSM through sgoldstinos P, S

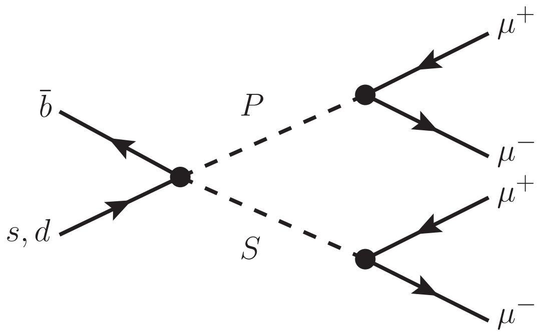
`Demidov et al [PRD 85(2012)077701]`
`Batell et al[PRD 83(2011)054005]`

- HyperCP evidence for $\Sigma^{+}\to p\mu\mu$
    - all 3 events at $m(\mu\mu)$=214.3(5) MeV/c^{2}
    - suggests intermediated state $\Sigma^{+}\to pP^{0}(\mu\mu)$

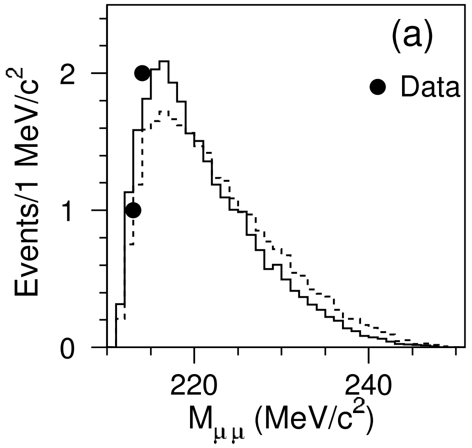
SM:

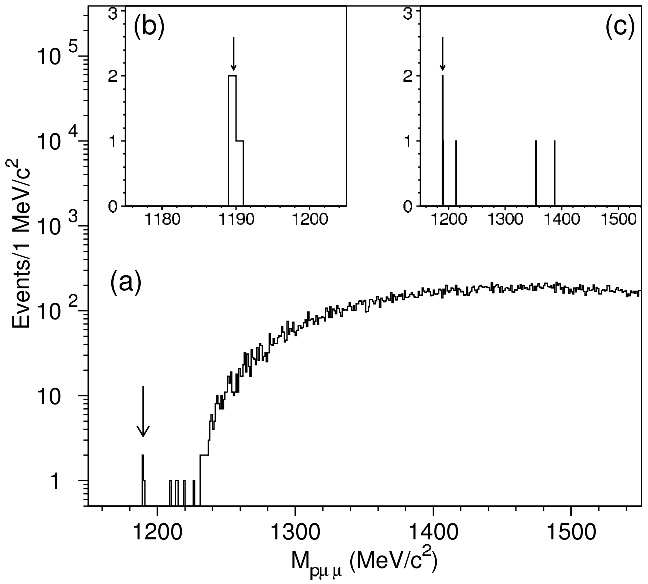


NP:



[PRL 94(2005)021801]





$B_{(s)} \to \mu\mu\mu\mu$ at LHCb

[PRL 110(2013)211801]

- Searched at LHCb with 1 fb^{-1}
- Normalised to $B^0 \to J/\psi K^*$
- Limits at 95%(90%) CL:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\mu^+\mu^-) < 1.6(1.2) \times 10^{-8},$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-\mu^+\mu^-) < 6.6(5.3) \times 10^{-9}.$$

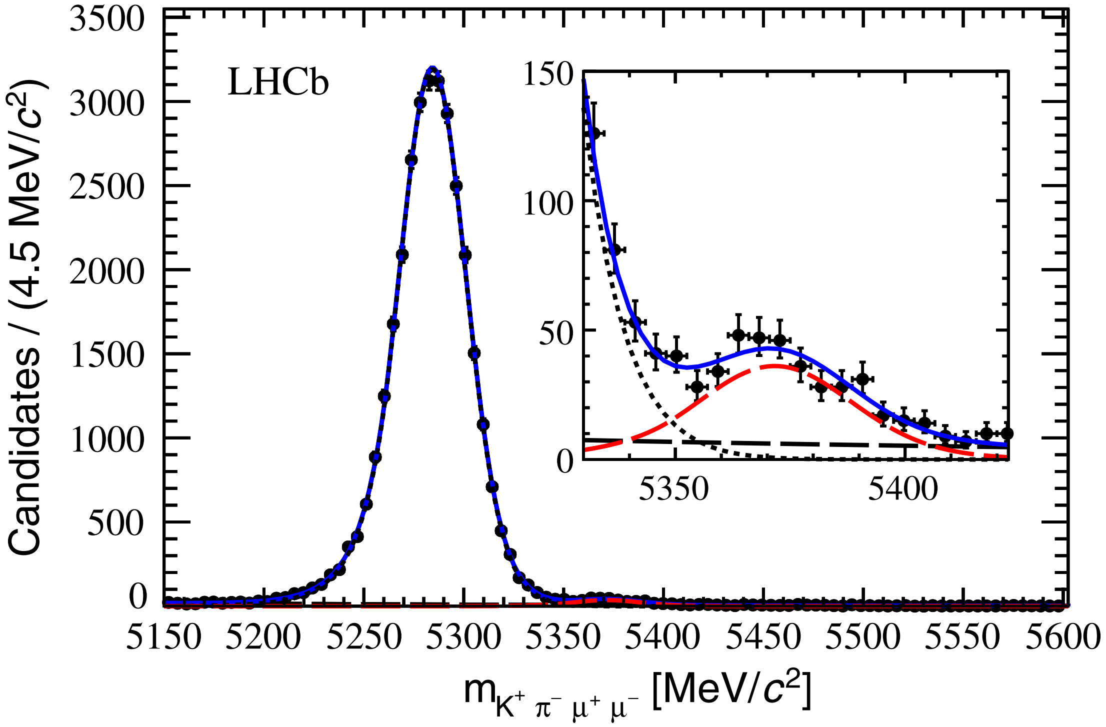
- Following the model in `[PRD 85(2012)077701]` put limit on:

$$\mathcal{B}(B_s^0 \to SP) < 1.6(1.2) \times 10^{-8},$$

$$\mathcal{B}(B^0 \to SP) < 6.3(5.1) \times 10^{-9}.$$

- LHCb plans to measure also $\Sigma^+ \to p\mu\mu$

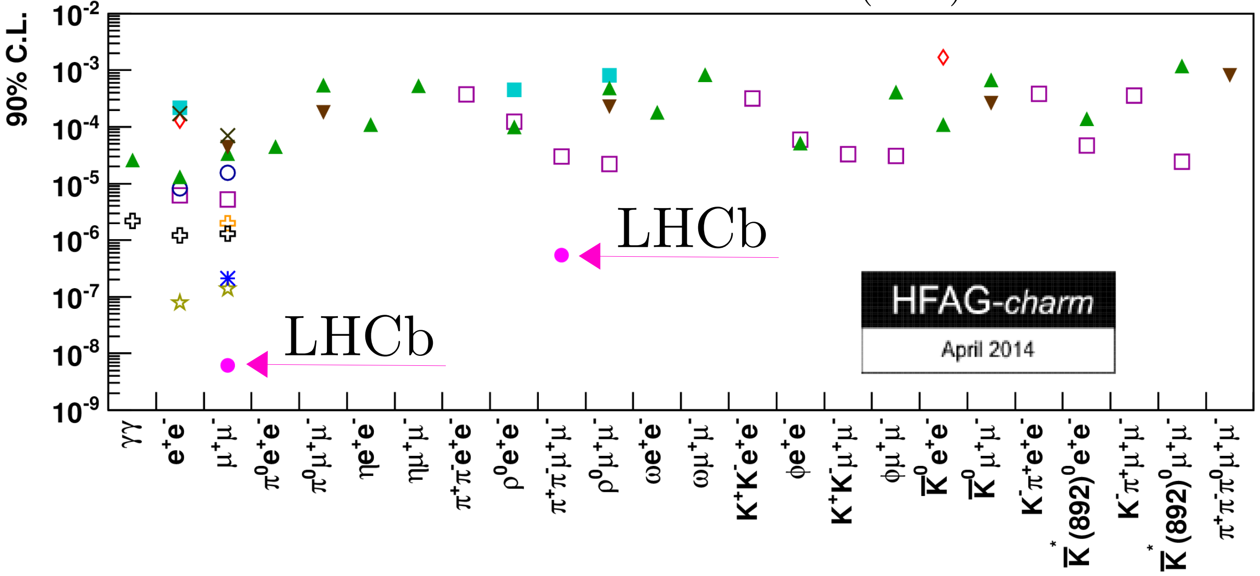
Normalisation channel



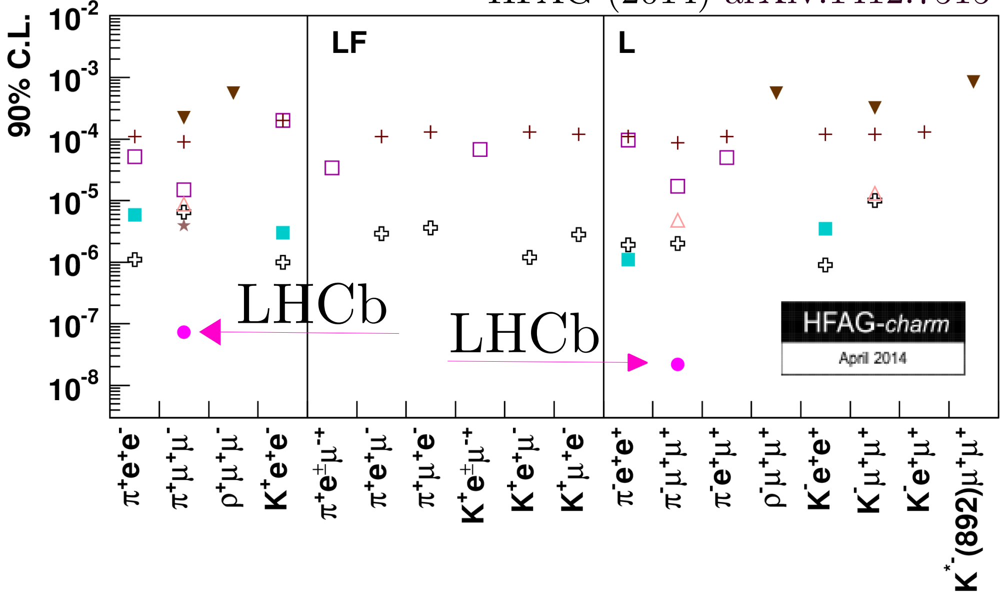
Rare *D* decays at LHCb

- Probe the effects of NP on the coupling of up-type quarks in EW processes
- Very high charm x-section $\sim 5(2)\times 10^{12}$ $D^0(D^+)$ with 3 fb^{-1}

D^0 limits HFAG (2014) arXiv:1412.7515



D^+ limits HFAG (2014) arXiv:1412.7515



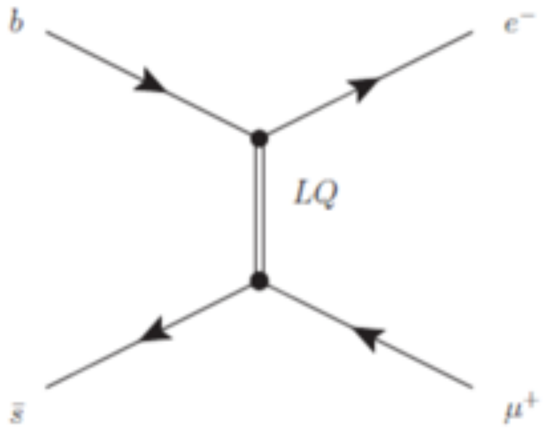
- Search for the rare decay $D^0\to\mu\mu$ [PLB 725(2013)15]
- Search for $D^+_{(s)}\to\pi^+\mu\mu$ and $D^+_{(s)}\to\pi^-\mu\mu$ [PLB 724(2013)203]
- Search for $D^0\to\pi^+\pi^-\mu\mu$ [PLB 728(2014)234]
- LFV test on $\mathscr{B}(D^0\to e\mu) < 1.3\times10^{-8}$ at 90% C.L. [PLB 754 (2016) 167]
- First observation of the decay $D^0\to K^-\pi^+\mu\mu$ [PLB 757(2016)558]

Lepton flavour (universality) violation

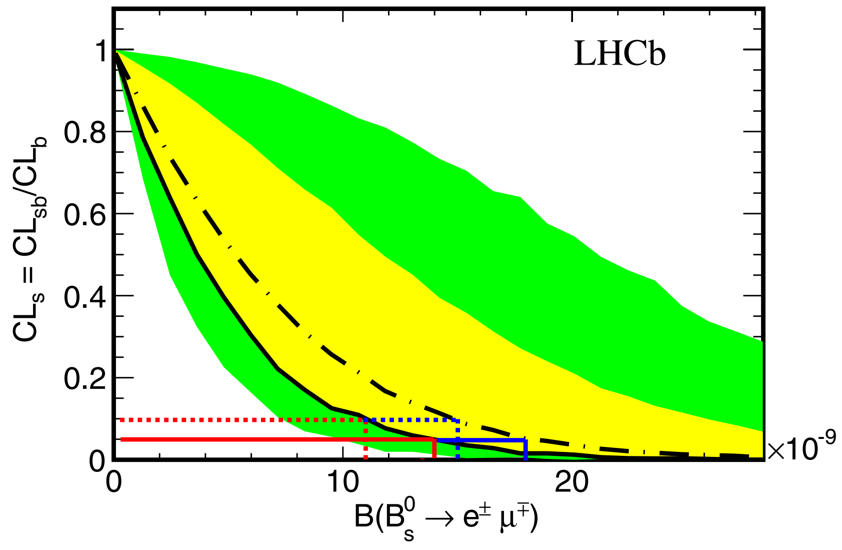
LFV: $B_{(s)}\to\mu e$

[LHCb, PRL 111(2013) 141801]

- LFV decay forbidden in SM, allowed in leptoquarks models
- LHCb measure with 1 fb^{-1} (3 on tape)
  - strategy identical to $B_{(s)}\to\mu\mu$
  - normalised to $B^0\to K^+\pi^-$
  - Upper limit with CLs method
  - LHCb 95% C.L. limits are 20× lower than previous best (from CDF [PRL 102 201901])
    $\mathscr{B}(B_s\to e\mu) < 1.4\times10^{-8}$ and
    $\mathscr{B}(B^0\to e\mu) < 3.7\times10^{-9}$
  - 95% C.L. lower bound on Pati-Salam leptoquark are 2× higher than CDF
    $\mathrm{M_{LQ}}(B_s\to e\mu) > 101\ \mathrm{TeV/c^2}$ and
    $\mathrm{M_{LQ}}(B^0\to e\mu) > 126\ \mathrm{TeV/c^2}$



Heavy singlet Dirac ν, PRD 62 (2000) 036010
SUSY, EPJC 41 (2005) 305
Pati-Salam PRD 10 (1974) 275



LFU tests: R_K

- Look for BSM sources of LFU violation
  e.g. leptoquarks or a Z' coupling more to $\mu\mu$
- $B^+ \to K^+ ll$ processes involve EW loop
- The exclusive BR bears large theoretical uncertainty
- Hadronic effects cancel-out in the ratio:

$$\mathcal{R}_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)} = 1 \pm \mathcal{O}(10^{-3})$$

- Experimental uncertainty can be reduced using a double ratio with the resonant J/ψ channel:

$$\mathcal{R}_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ J/\psi\,(\mu^+ \mu^-))} \frac{\mathcal{B}(B^+ \to K^+ J/\psi\,(e^+ e^-))}{\mathcal{B}(B^+ \to K^+ e^+ e^-)} =$$

$$= \frac{N_{K^+ \mu^+ \mu^-}}{N_{K^+ J/\psi\,(\mu^+ \mu^-)}} \frac{N_{K^+ J/\psi\,(e^+ e^-)}}{N_{K^+ e^+ e^-}} \boxed{\frac{\epsilon_{K^+ J/\psi\,(\mu^+ \mu^-)}}{\epsilon_{K^+ \mu^+ \mu^-}}} \boxed{\frac{\epsilon_{K^+ e^+ e^-}}{\epsilon_{K^+ J/\psi\,(e^+ e^-)}}}$$

→ cancel systematics

LFU tests: R_K

- LHCb result with Run 1 data:

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

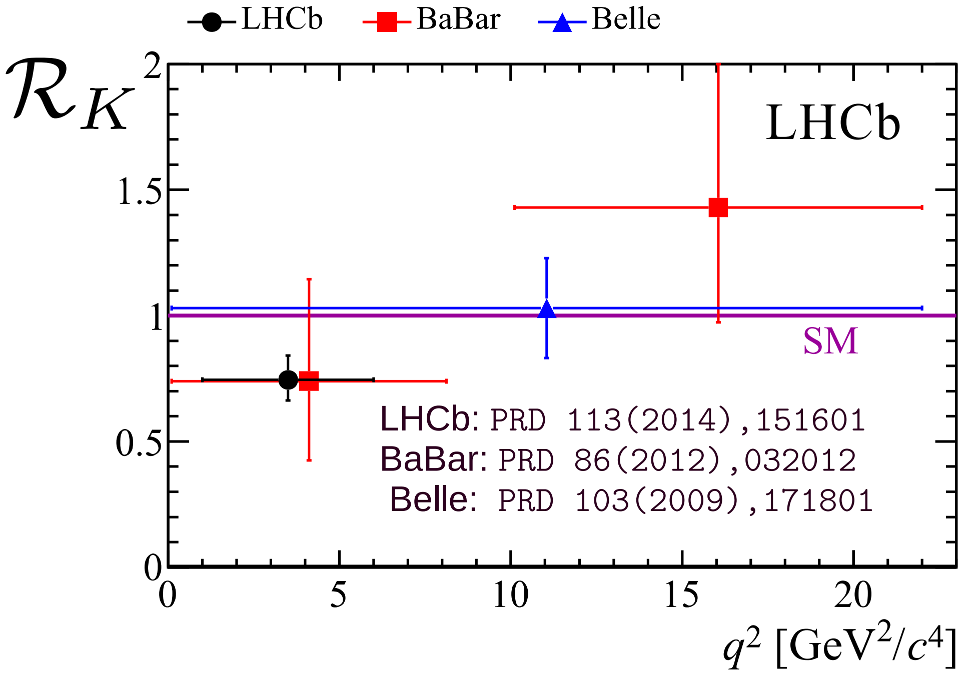
`LHCb: [PRD113(2014),151601]`

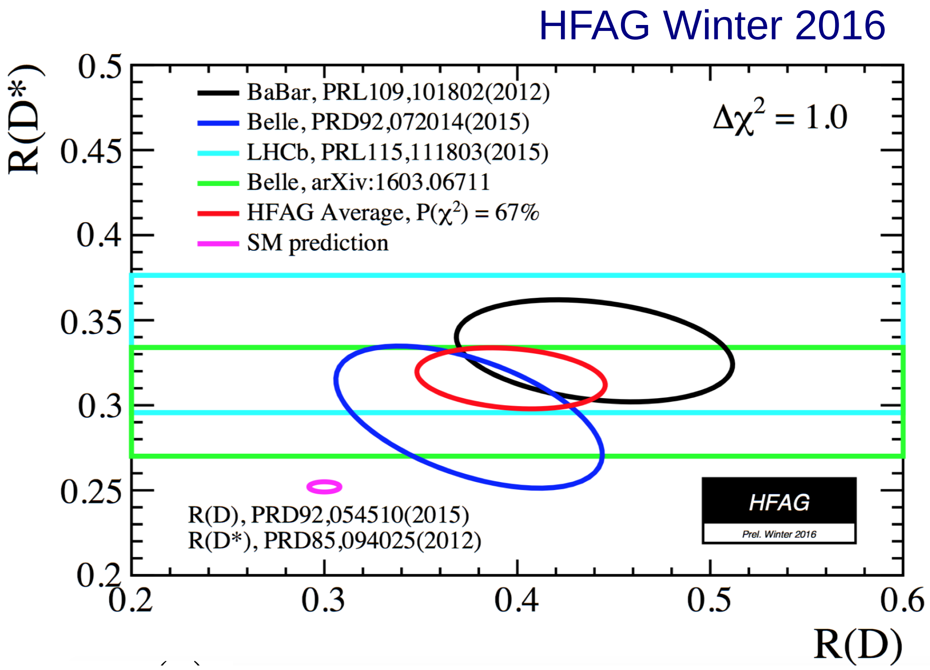
  - **2.6σ deviation**

- Corresponds to effect expected if $B \rightarrow K^* \mu\mu$ $(BR,\ P'_5)$ deviations were due to NP in $\mu\mu$ only `Descotes-Genon et al - [ArXiv:1510.04239]`

- Some models can explain also the 4 sigma deviation in $R(D)$ and $R(D^*)$

`Boucenna et al [ArXiv:1604.03088]`
`Faijfer, Kosnic [ArXiv:1511.06024]`
`Faijfer, Kosnic [ArXiv:1511.06024]`



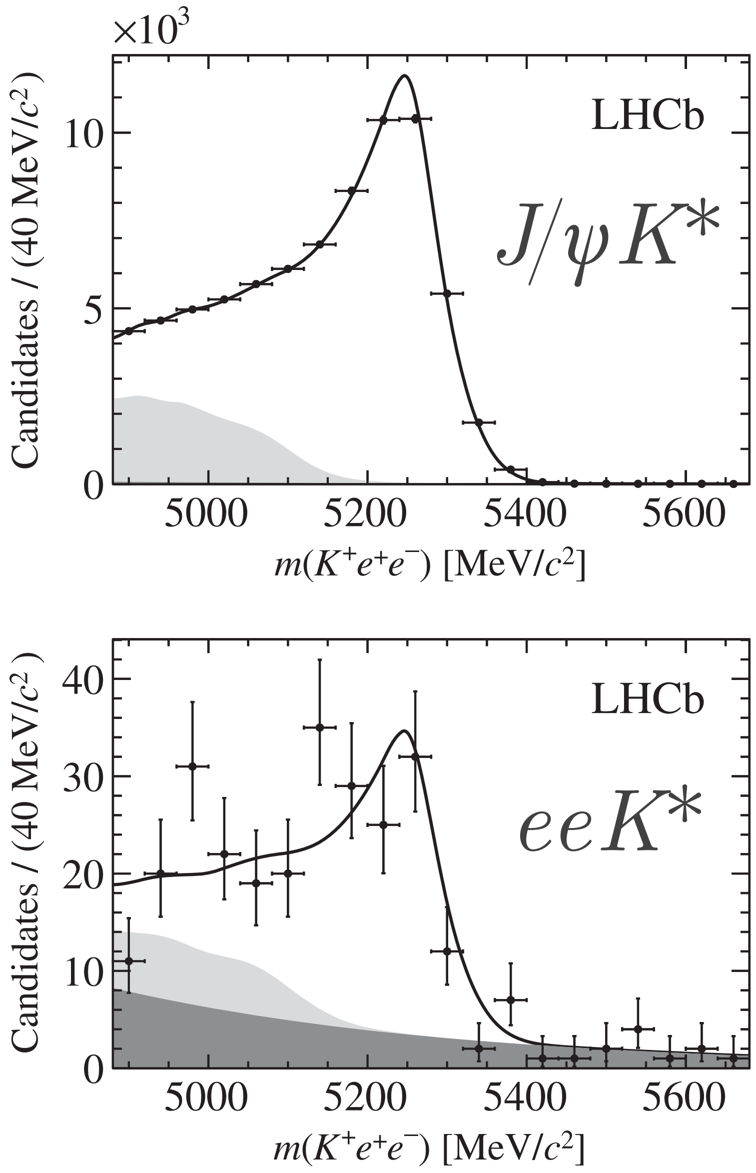


more on R(D(*)) in S.Hirose's talk

LFU tests: R_K

- Electrons: LHCb vs B-factories
  - ~3× worse efficiency on dielectrons/dimuons
  - Larger bremsstrahlung and hard recovery
  - Still LHCb has best sensitivity!
- Future for LHCb:
  - more statistics being collected in Run 2
  - more channels: R_{K^*}, R_φ, $R_{K\pi\pi}$,…
- Belle II and LHCb upgrade will reduce the error by an order of magnitude

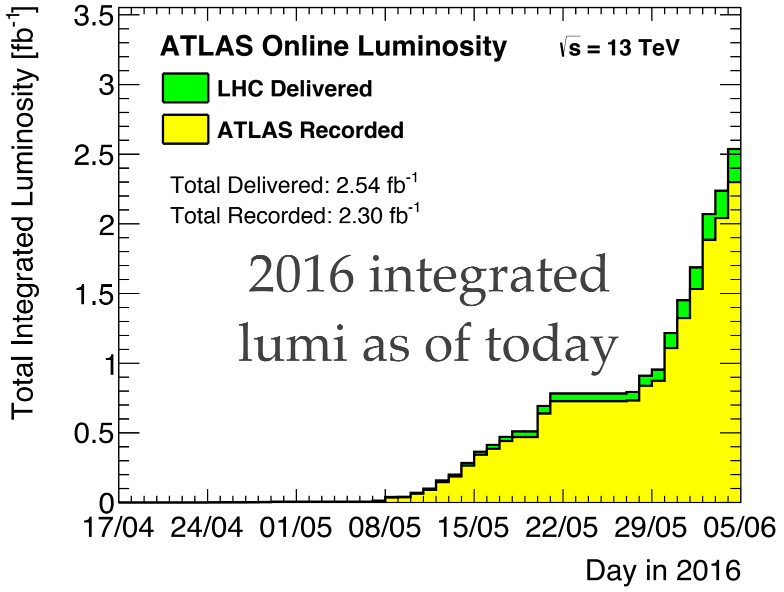
`[LHCb: PRD113(2014),151601]`



LHC Run 2 has started!

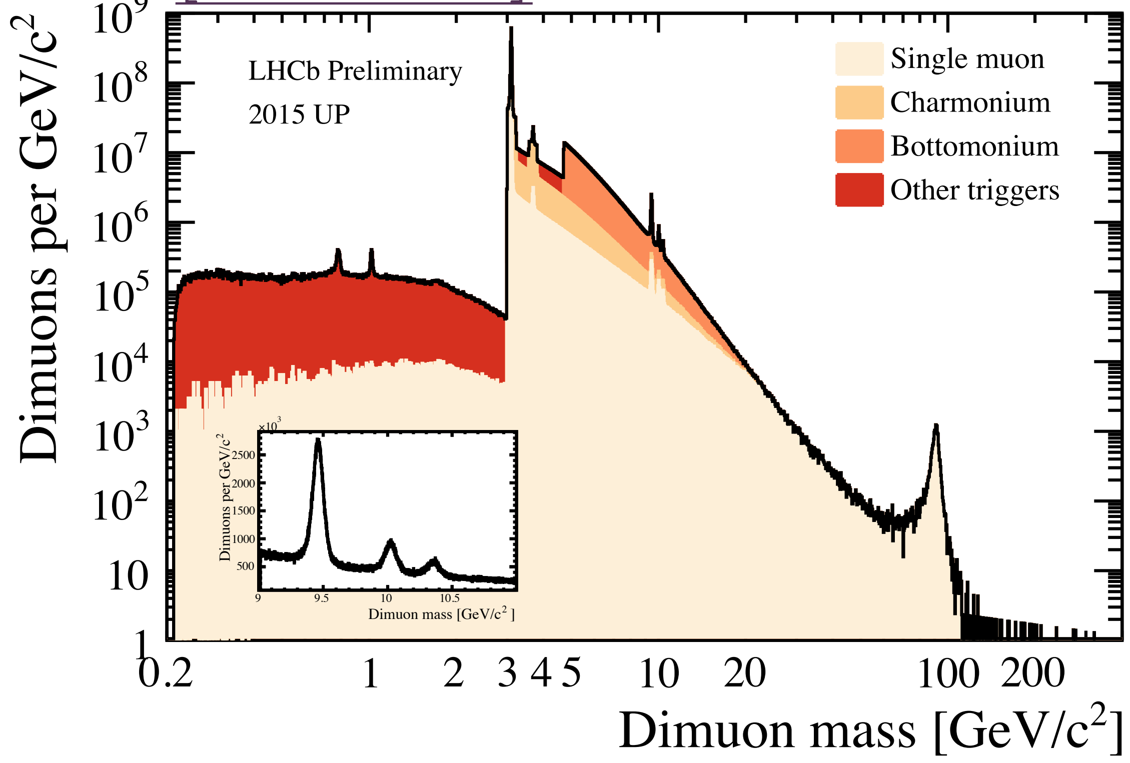
- All results presented are from LHC *Run 1*
- But *Run 2* has already started:
  - ~2× energy → 2× bb cross section
  - By 2018 expect 5 fb^{-1} in LHCb and 100 fb^{-1} in ATLAS/CMS

[LuminosityPublicResult]

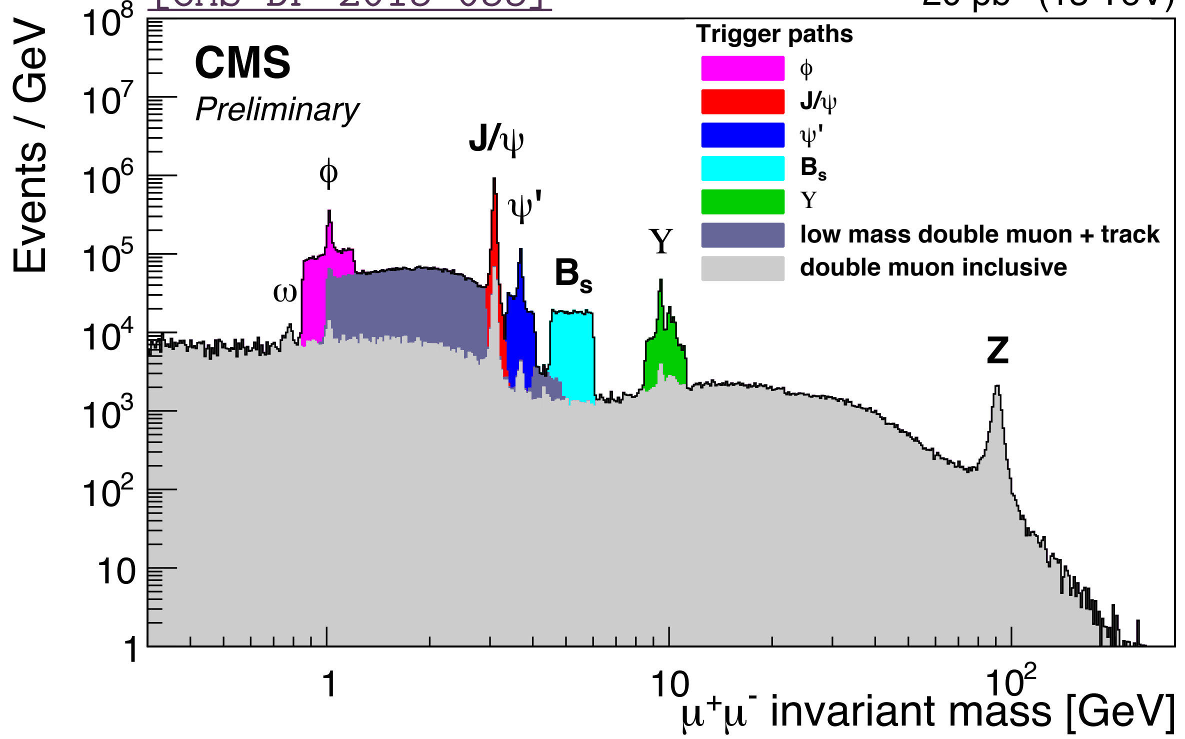


2016 integrated lumi as of today

[LHCbPlots2015]



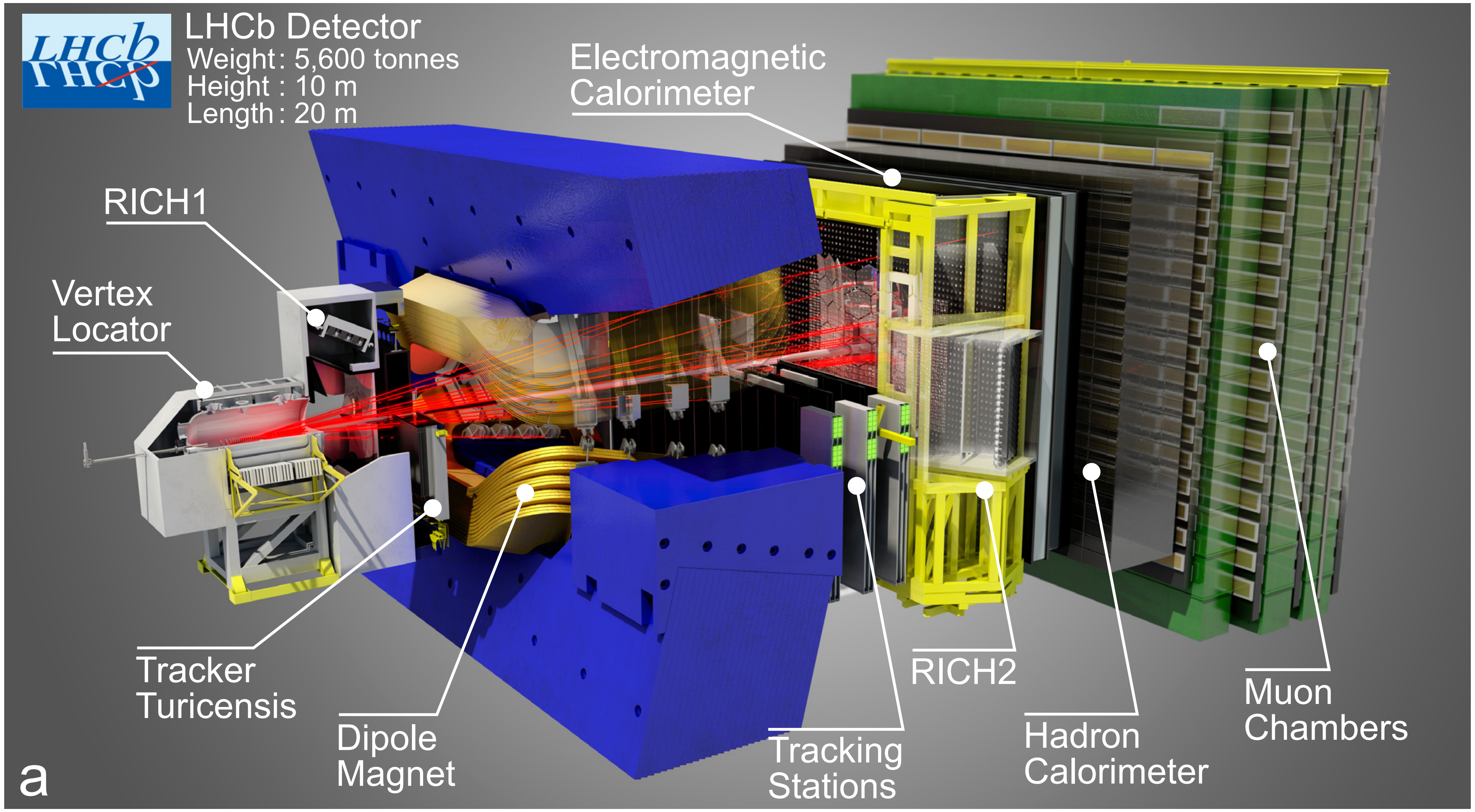
[CMS-DP-2015-055]

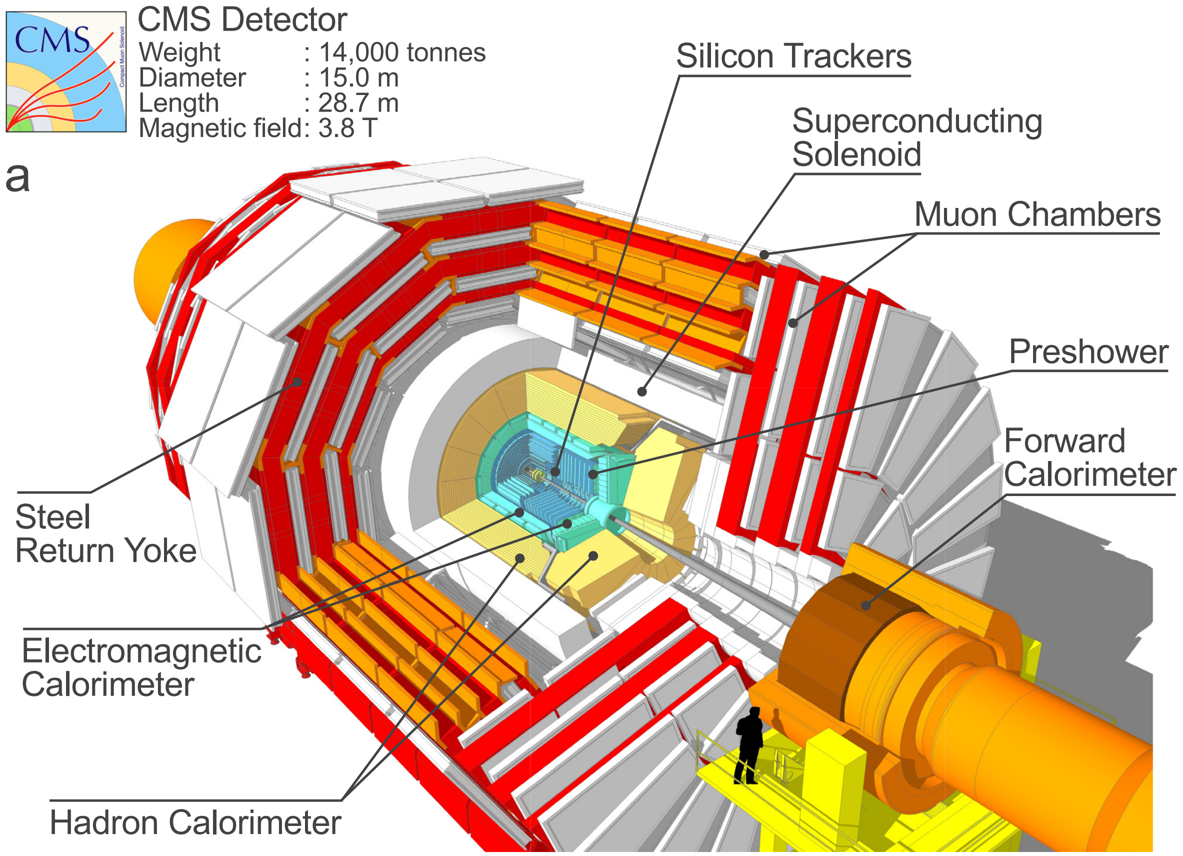


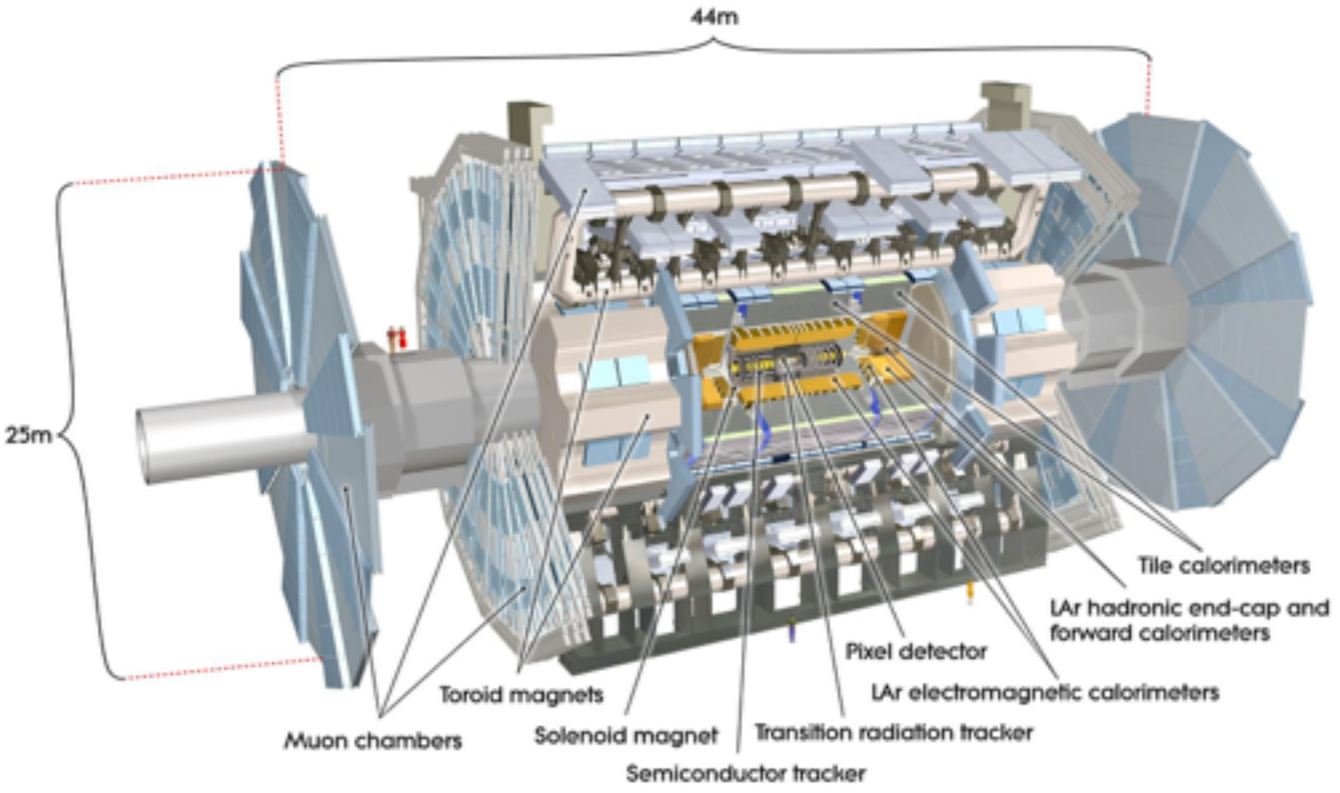
Conclusions

- The LHC is leading the rare decay searches
- ATLAS result on $B_s \to \mu\mu$ completed LHC *Run 1* legacy
  - So far no significant deviation from SM
  - Still a lot of space for NP: eagerly waiting Run 2
- Other (very)-rare decays in B and D decays have complementary sensitivity to BSM
- LFU and LFV tests with B decays are intriguing
- All measurements limited by statistics
  - LHC *Run 2* will tell us more!

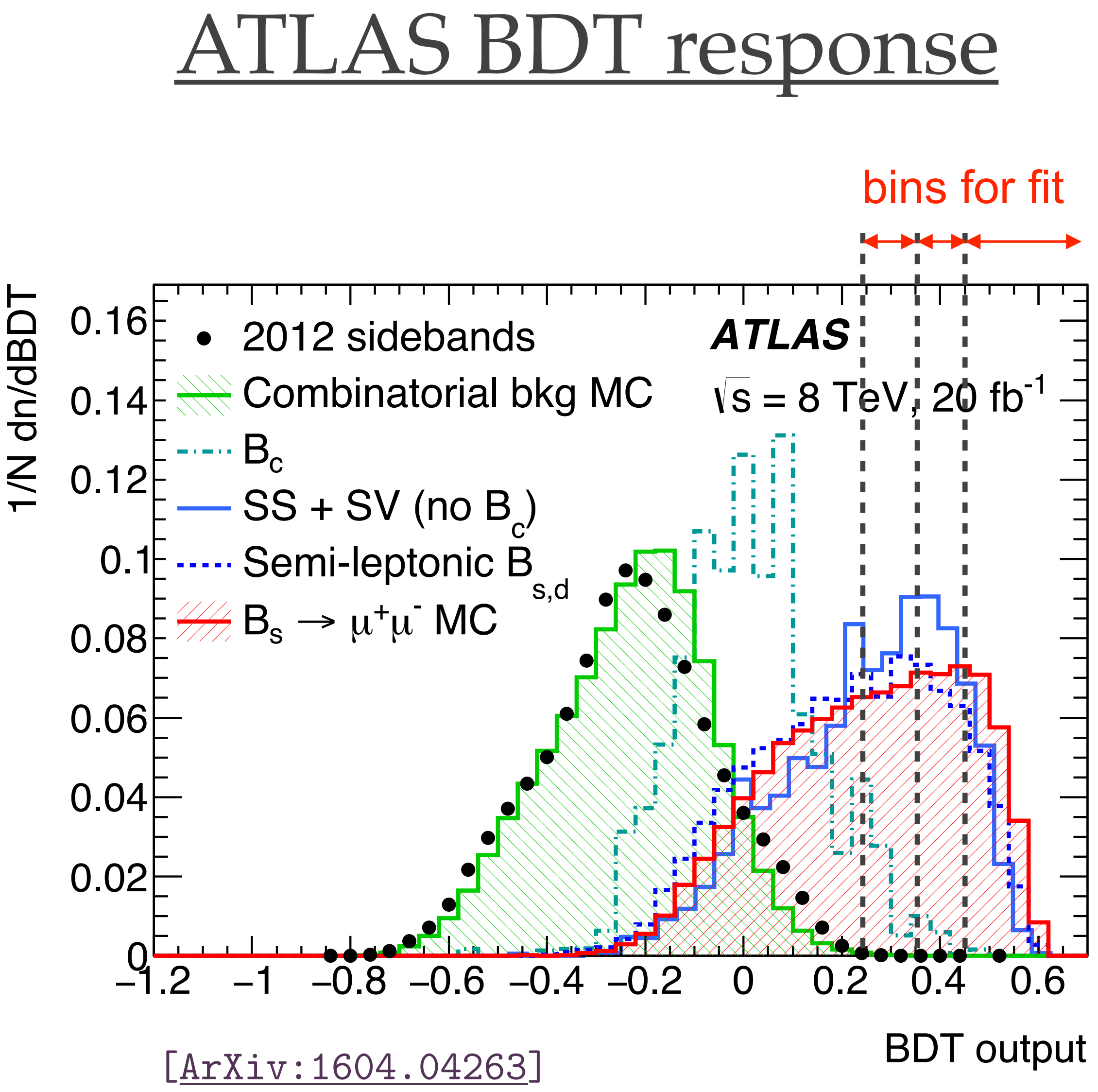
BACKUP


LHCb Detector
Weight: 5,600 tonnes
Height : 10 m
Length : 20 m
Electromagnetic Calorimeter
RICH1
Vertex Locator
Tracker Turicensis
Dipole Magnet
Tracking Stations
RICH2
Hadron Calorimeter
Muon Chambers
a

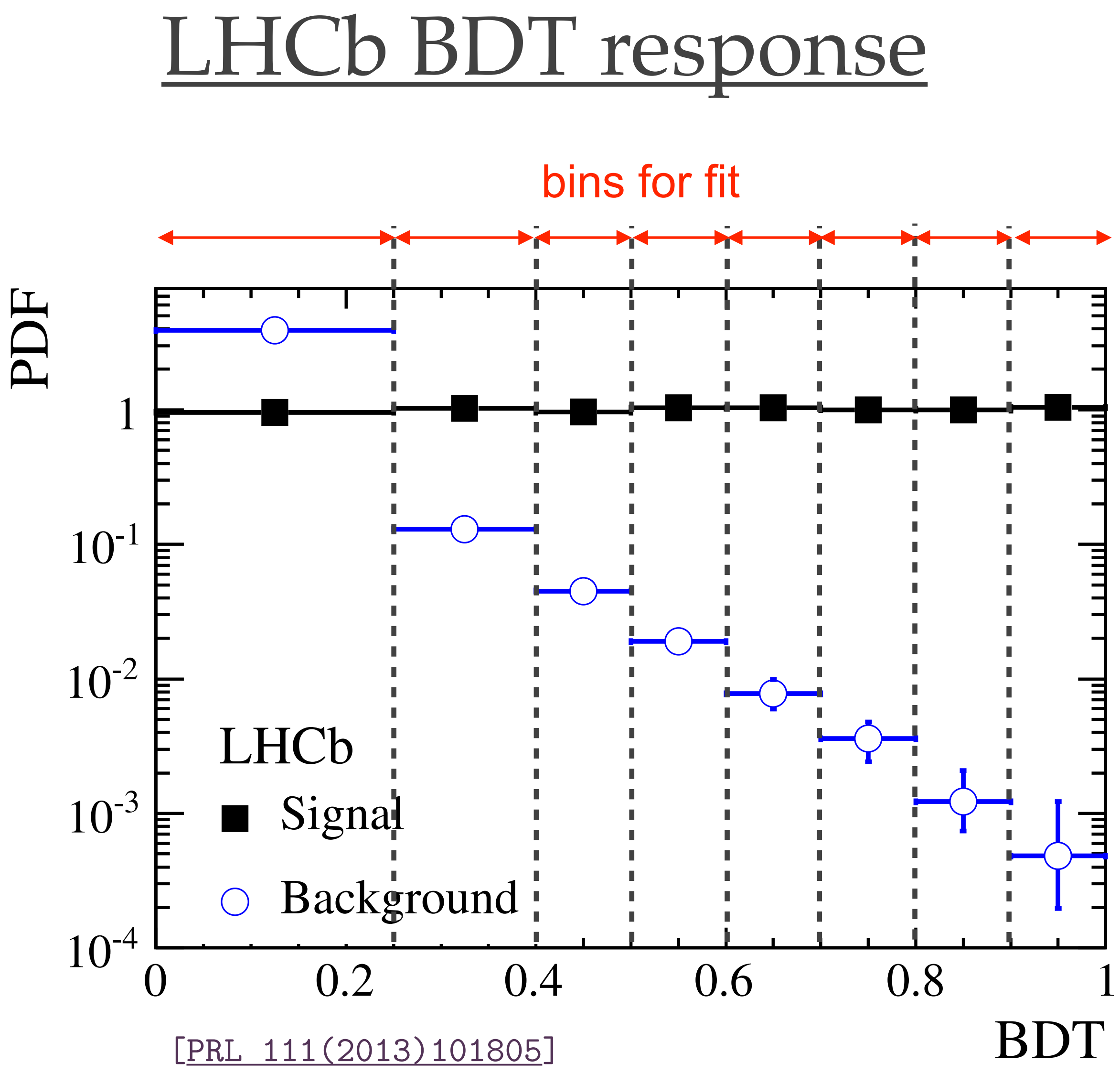

CMS Detector
Weight : 14,000 tonnes
Diameter : 15.0 m
Length : 28.7 m
Magnetic field: 3.8 T
a
Silicon Trackers
Superconducting Solenoid
Muon Chambers
Preshower
Forward Calorimeter
Steel Return Yoke
Electromagnetic Calorimeter
Hadron Calorimeter


44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker

BDT bins

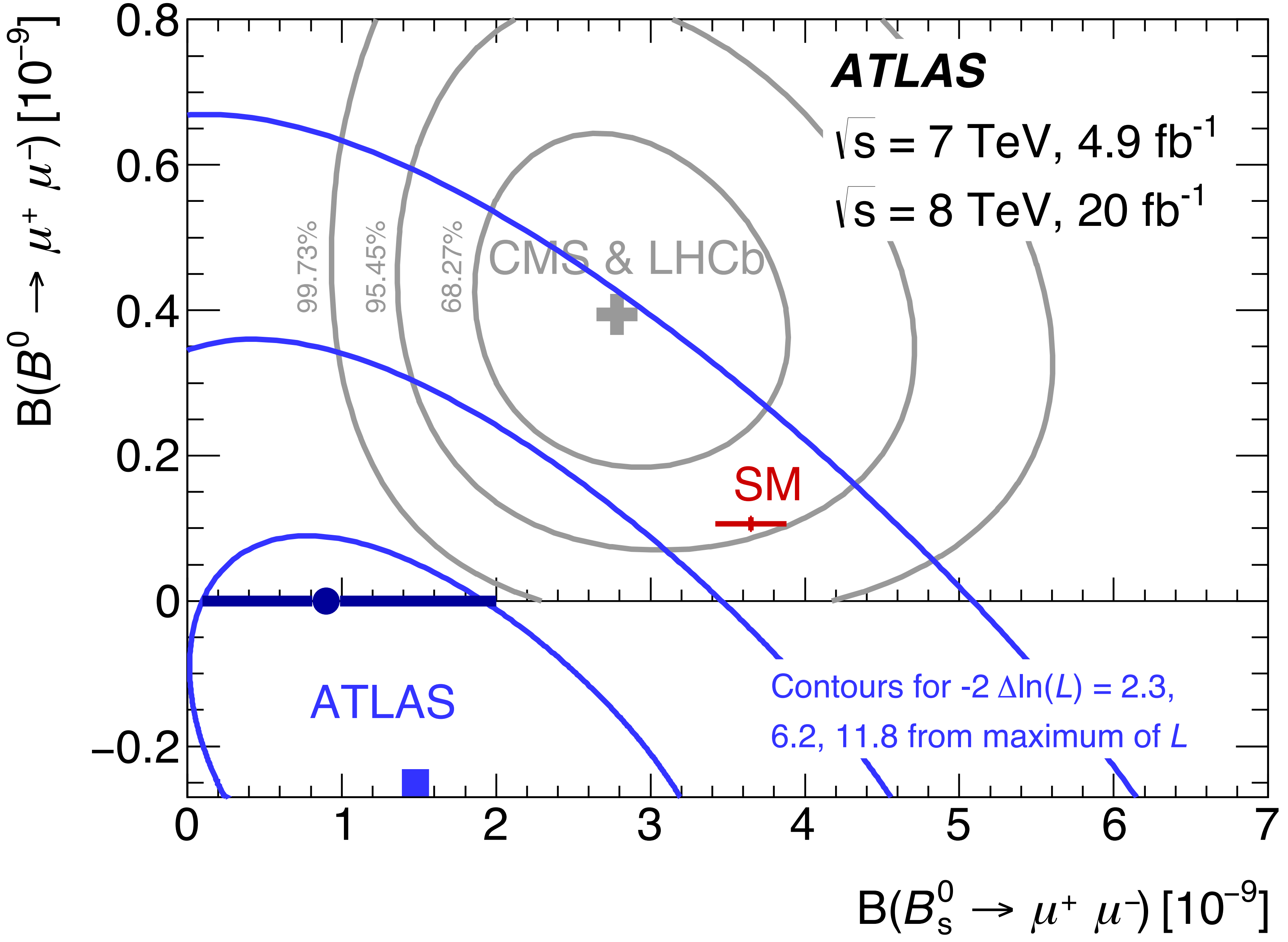


[ArXiv:1604.04263]



[PRL 111(2013)101805]

ATLAS $B_{(s)} \to \mu\mu$ result in 2D

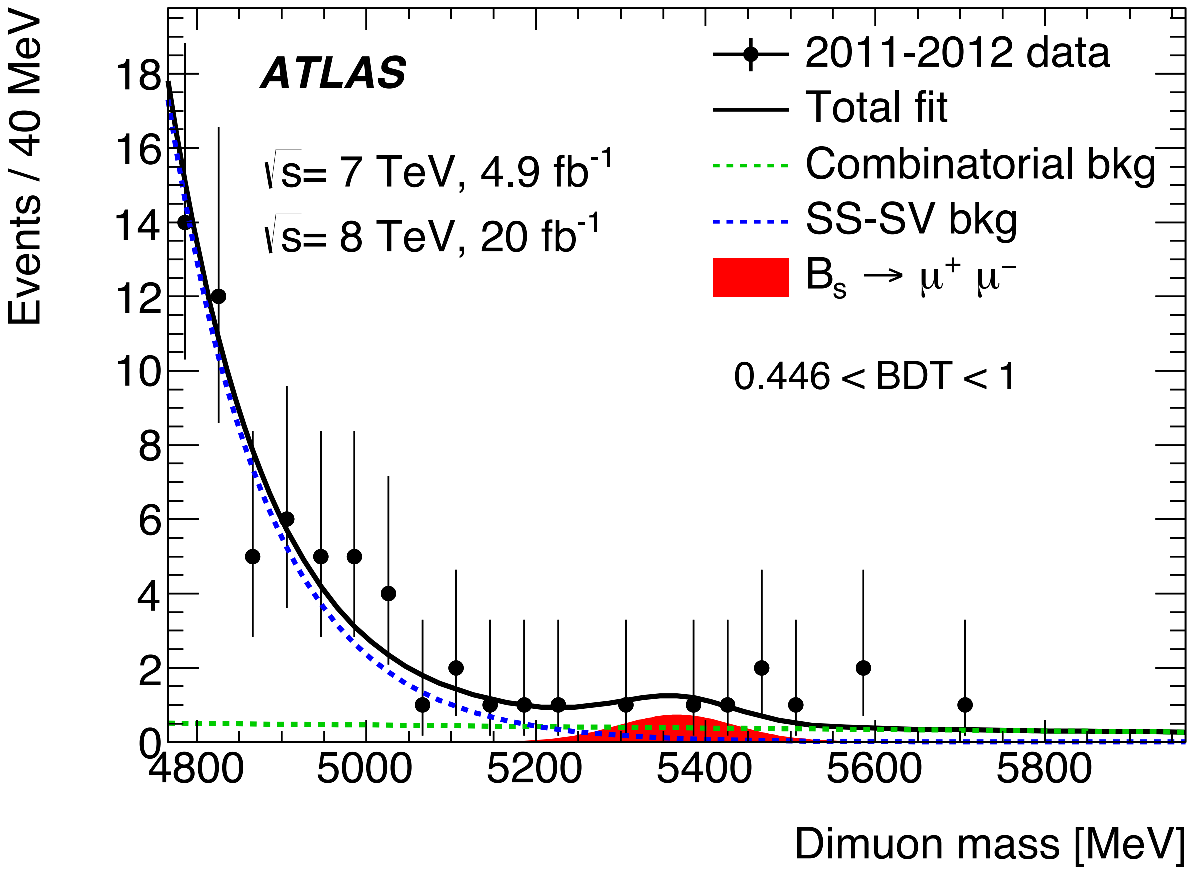


ATLAS trigger

- Normal dimuon trigger (both $p_T > 4$ GeV/c) is pre-scaled in 2012:
  - add a “barrel” trigger
  - and a tighter asymm one ($p_T > 6(4)$ GeV/c)
- 3 trigger categories for 2012:
  - high p_T threshold ($p_T > 6(4)$ GeV/c)
  - 1 muon in barrel and both $p_T > 4$ GeV/c
  - normal dimuon (both $p_T > 4$ GeV/c)

ATLAS mass fit

- Simultaneous ML fit on 3 BDT bins to get N_{Bs} and N_{Bd}
- Mass *shapes*:
  - Signal from MC
  - Combinatorial: linear
  - Below B mass: exponential



$\mu\mu$: CMS vs ATLAS

- ATLAS: superconducting toroid magnets and a set of precise muon chambers —> standalone momentum measurement outside the tracker
- CMS: higher magnetic field in the silicon tracker 4T (pays in jet efficiency) but better µµ resolution