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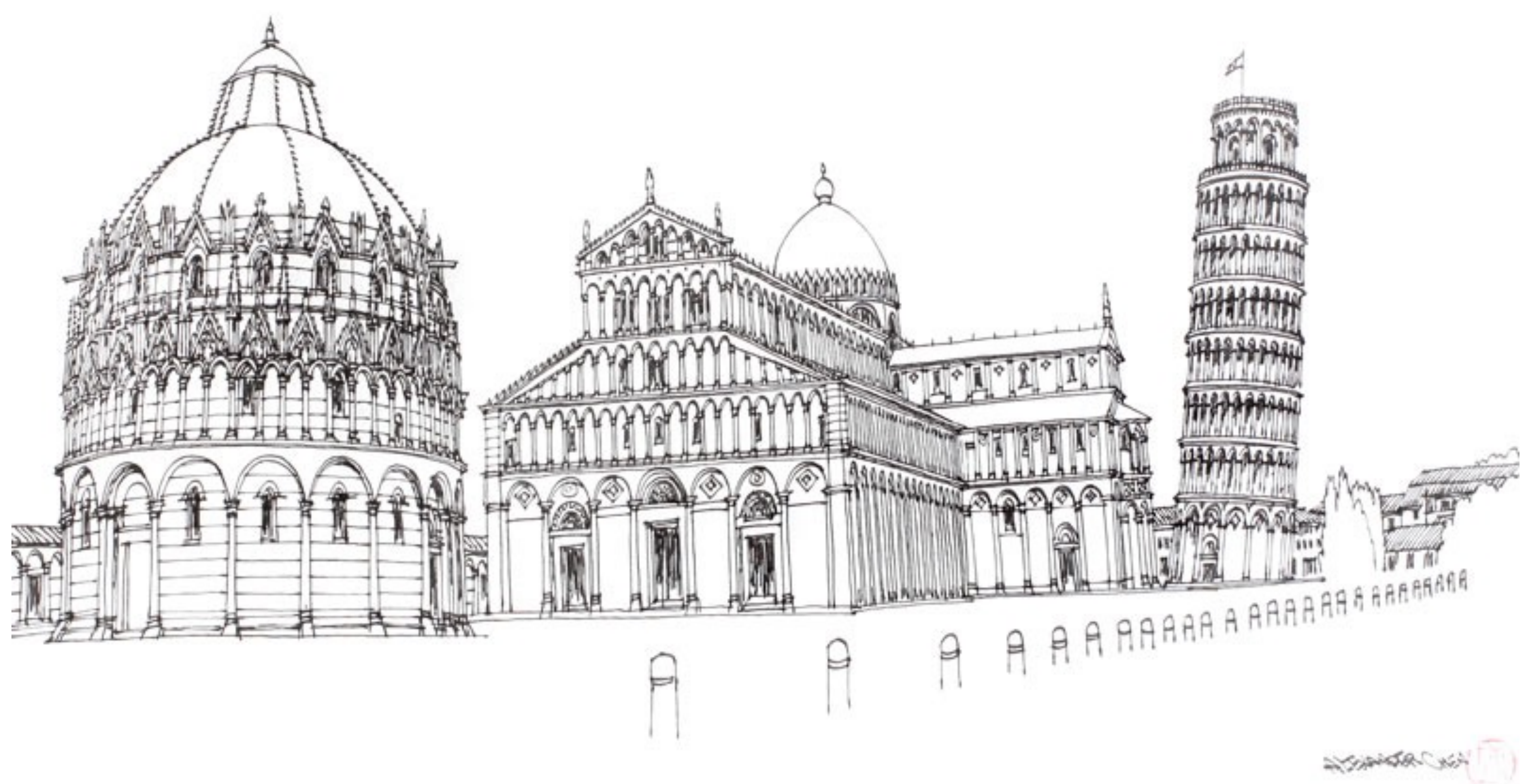
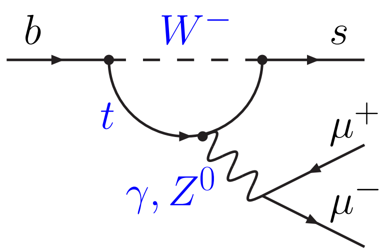
on behalf of
ATLAS CMS and LHCb Collaborations

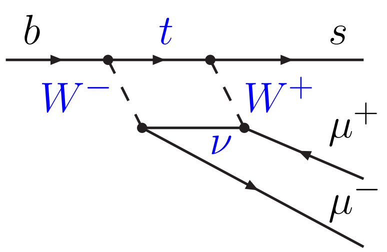
Rare beauty and charm decays



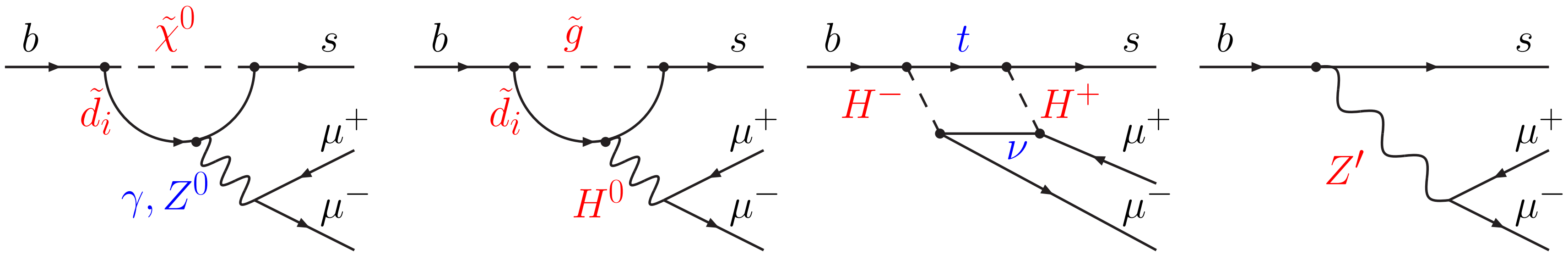
Why rare decays

- **Flavor Changing Neutral Current transitions** only occur at loop order (and beyond) in the SM





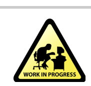
- New particles can contribute at loop or tree level enhancing/suppressing decay rates, introducing new sources of CP violation or modifying the angular distribution of final-state particles

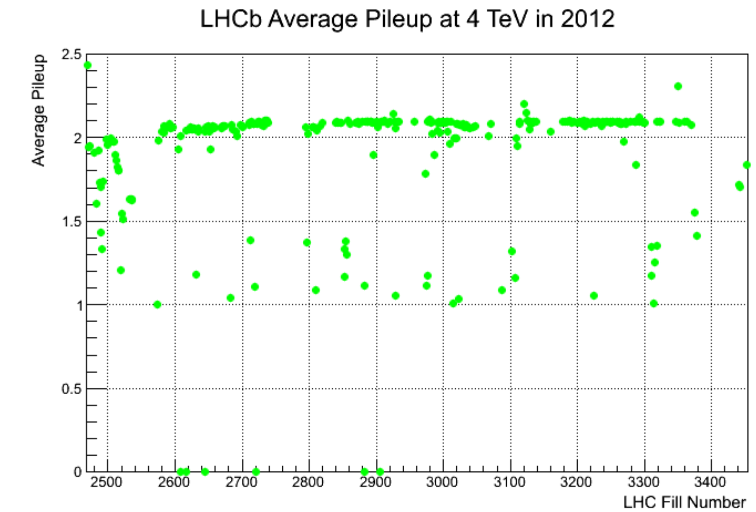


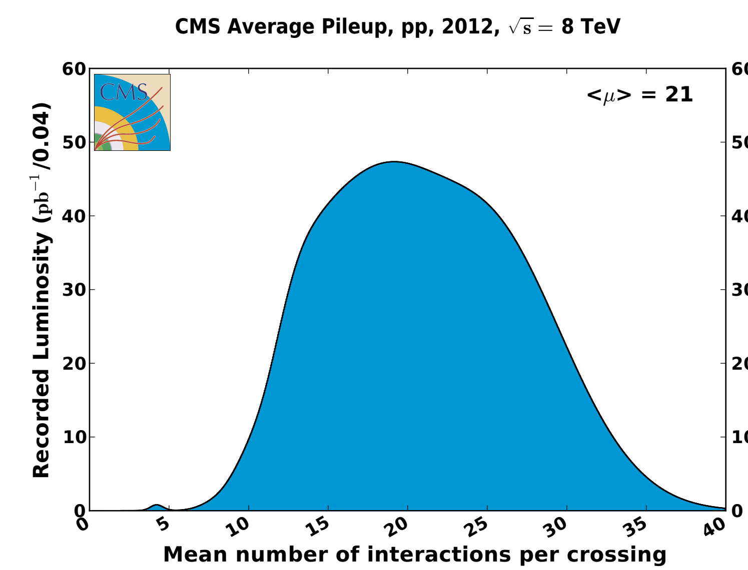
- Information about physics beyond the SM can be found studying rare decays properties:
  - the branching ratios of $B_{s,d} \to \mu\mu$
  - selected observables in $B \to K(^*)\mu\mu$
  - the rate of decays such as $B \to Ml^+l^-$ with different leptons in the final state
  - LFV and very rare decays
  - photon polarization and radiative B decays

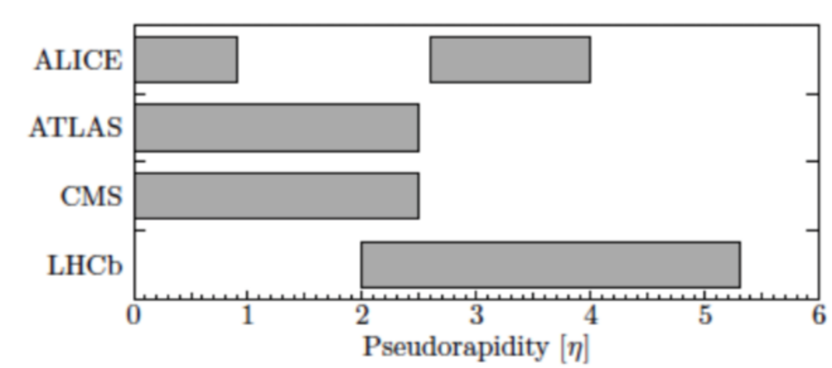
Rare decays analyses in RunI

- Benchmark channels explored/being explored by the three experiments
- Physics of rare-decays is obviously LHCb bread&butter
  - particle ID detectors
  - access to low p_T objects
  - low pileup environment
- CMS and ATLAS:
  - mainly limited to multi-muon triggers with few GeV thresholds
  - complement |η| region covered by LHCb (not so important for rare decays)
  - 20 fb^{-1} data collected, while LHCb has 3fb^{-1}

	ATLAS	CMS	LHCb
$B^0_{(s)} \to \mu\mu$	✓	✓	✓
$B^0 \to K^*\mu\mu$		 ✓	✓
Lepton Univ.	-	-	✓
LFV	✓	-	✓✓✓✓✓…
rare radiative decays	-	-	✓✓✓

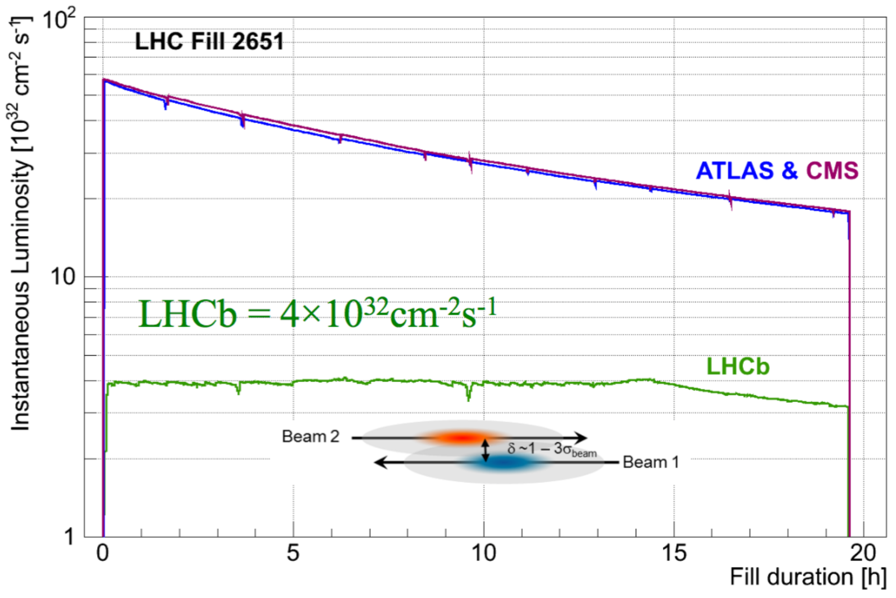






What do we expect from RunII

- **Cross section** for B-physics processes is almost **doubled** wrt RunI
  - factor 2 in the collected statistics
- LHC expected to deliver **~100 fb^{-1} in RunII**
  - LHCb lumi-leveling → collect about 5 fb^{-1}
  - ATLAS and CMS can fully exploit the luminosity delivered by LHC
    - however, this implies higher event rate
      - **main limitation will be the trigger step**
      - higher PU → more combinatorial/backgrounds



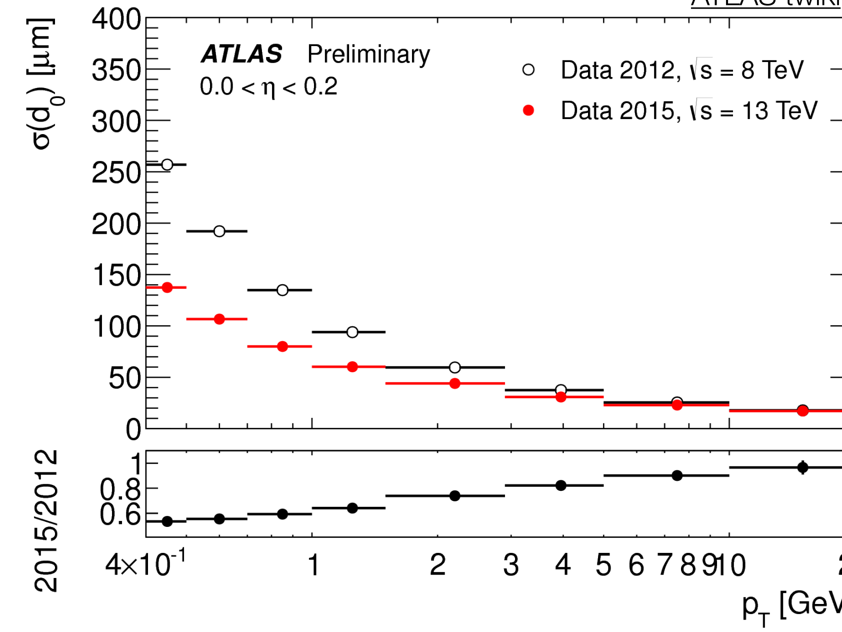
- Higher statistics than in RunI will allow to
  - improve statistical uncertainty on already pursued measurements
  - access to new decay modes (very rare decays)
  - **RunII will significantly improve reach of new physics searches**
  - results will probably come out not before the end of this year

Detector improvements - ATLAS

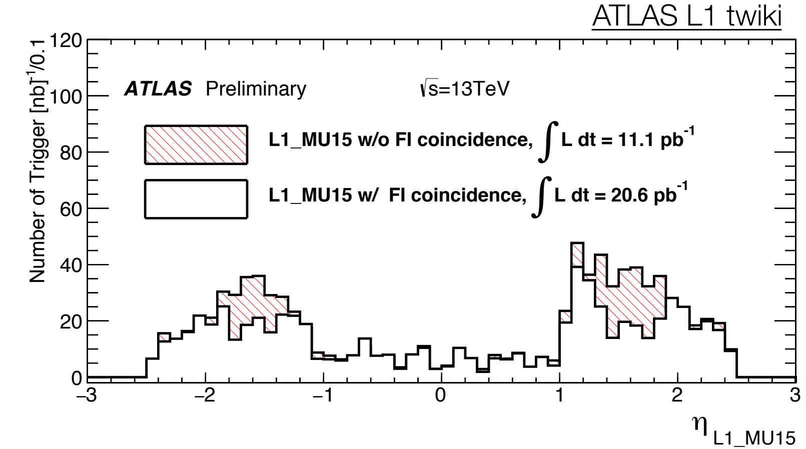
- Insertable **B-Layer**
  - new 4th layer for Pixel detector close to beam pipe (33.25 mm radius)
  - **up to a factor of 2 improvement in impact parameter resolution for low p_T tracks**
    - improvement in lifetime precision
  - significant improvement in b-tagging efficiency for jets and move to offline-style tagging algorithms

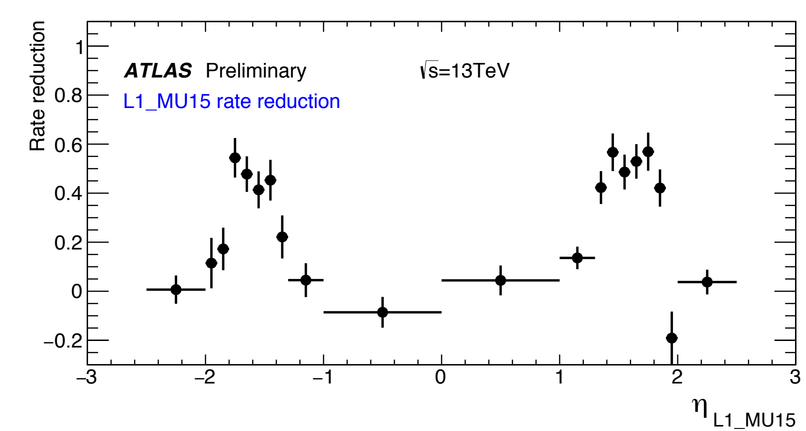
- **Muon system** updates
  - installation of new chambers
  - improvements and overhaul of readout electronics
  - **new Thin Gap Chamber (TGC) coincidence layer added to minimize fakes at high pseudorapidity**
  - extra coincidence with sections of tile calorimeter (2016)

ATLAS twiki



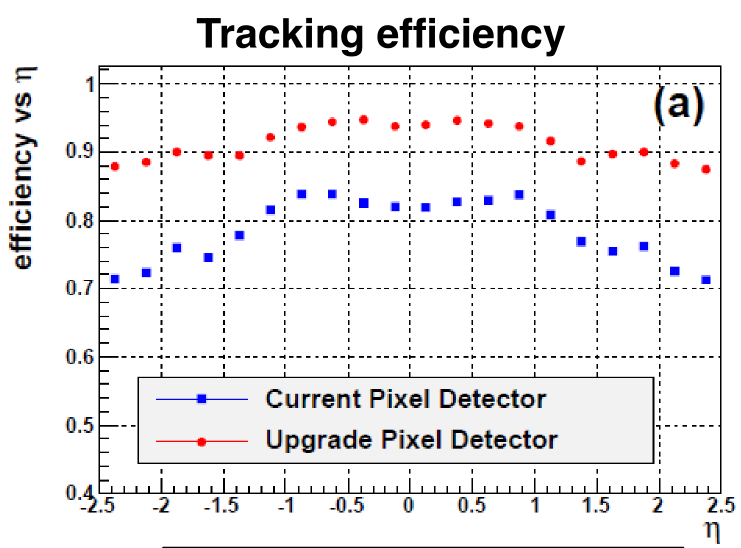
ATLAS L1 twiki





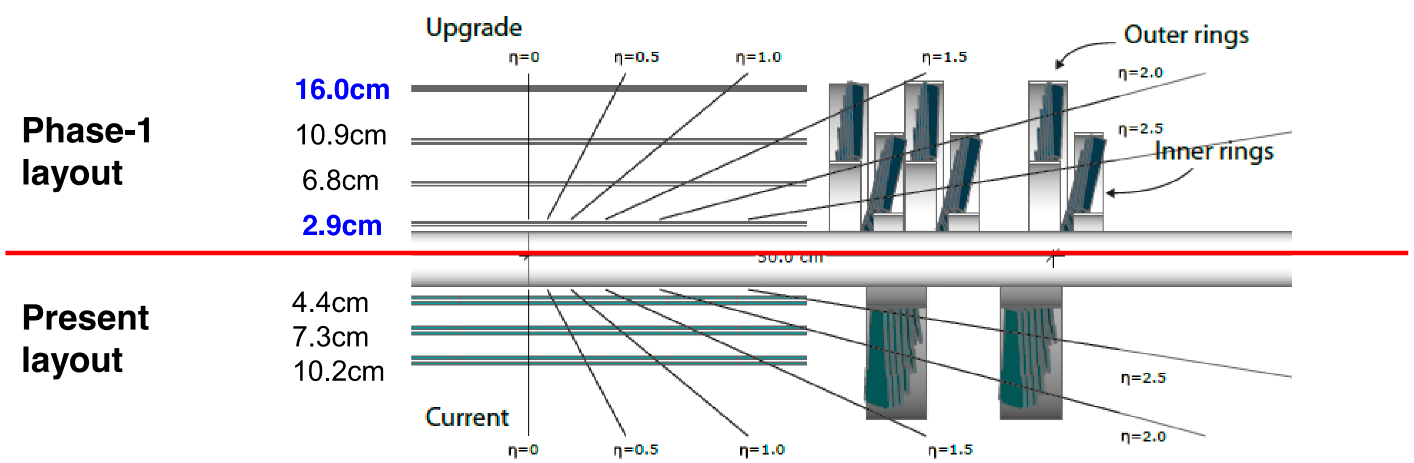
Detector improvements - CMS

- **New pixel detector** to be installed during extended year-end technical stop 2016/2017
  - additional 4th barrel layer and 3rd disk → 4 hit coverage will provide more robust tracking
  - smaller radius of inner layer → better vertex resolution and b-tagging efficiency
  - lower material budget → lower multiple scattering
  - new improved readout chip → recover hit inefficiency



ttbar sample, 50 pileup events

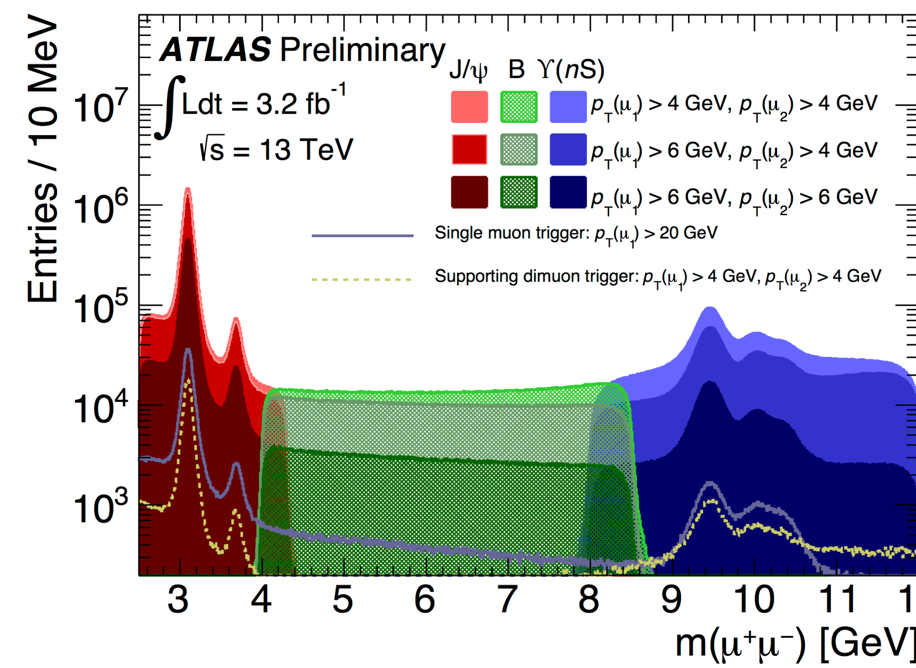
CMS-TALK @VCI2016

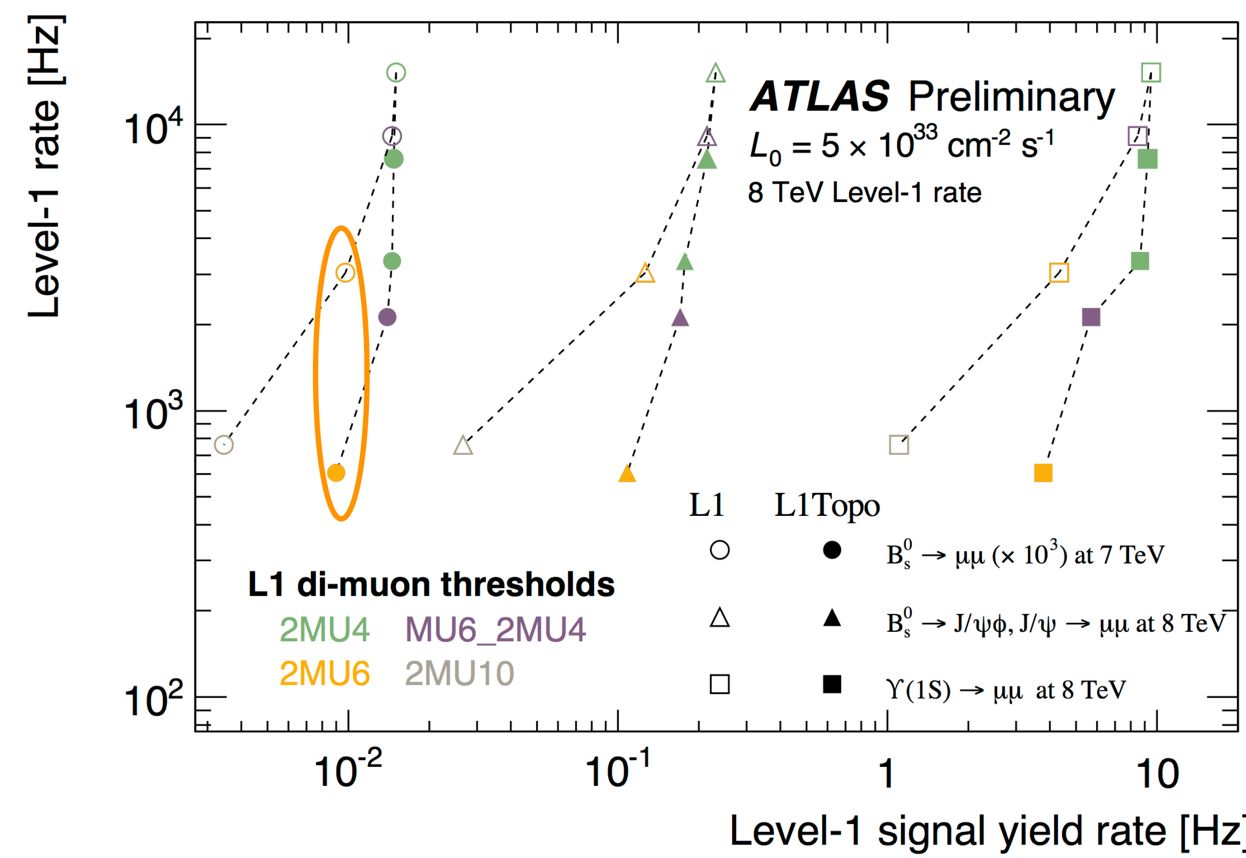


Trigger in RunII- ATLAS

Trigger results ATLAS

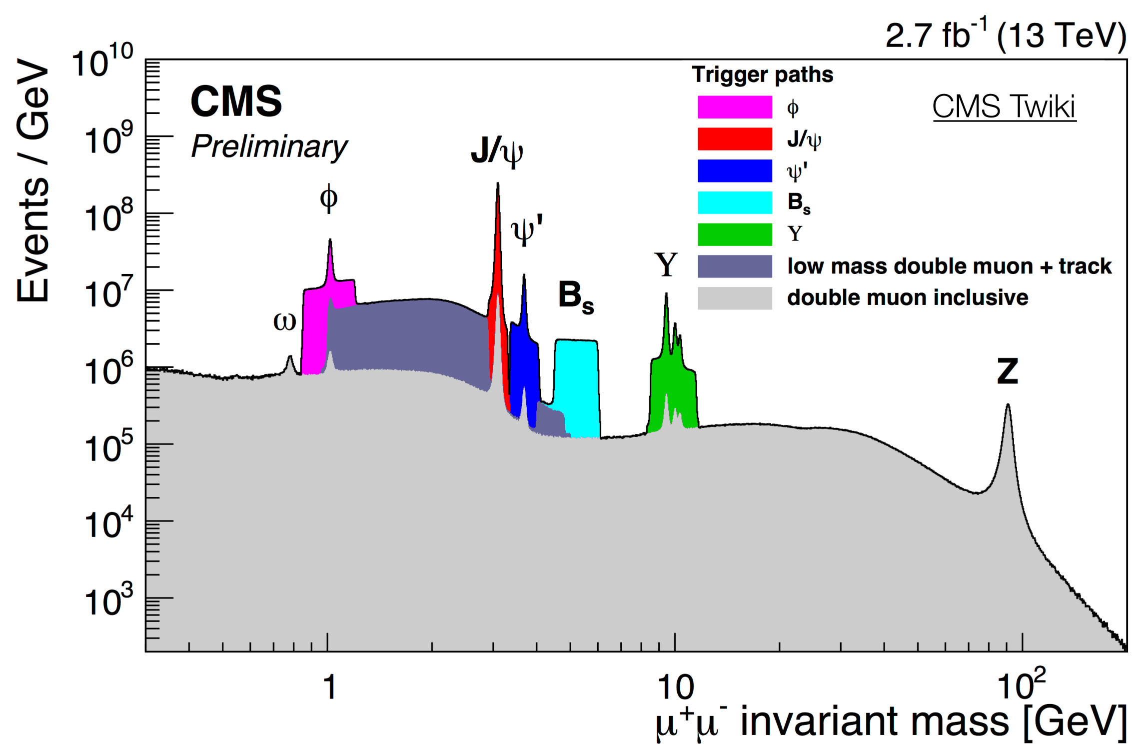
- Dedicated B-physics triggers delivering good yields
  - in 2015, managed to keep Mu4Mu6 unprescaled for the entire run
  - in 2016 additional requirements are applied to keep low thresholds
- In 2016, inclusion of **L1 topological trigger**
  - new inputs to L1 trigger system providing information on event topology
  - expect significant improvements for B-physics performance
    - helping maintaining low thresholds
    - commissioning ongoing through early 2016
- **Fast TracK trigger**
  - tracking reconstruction between L1 and HLT
  - track quality similar to offline reconstruction with significantly reduced processing time





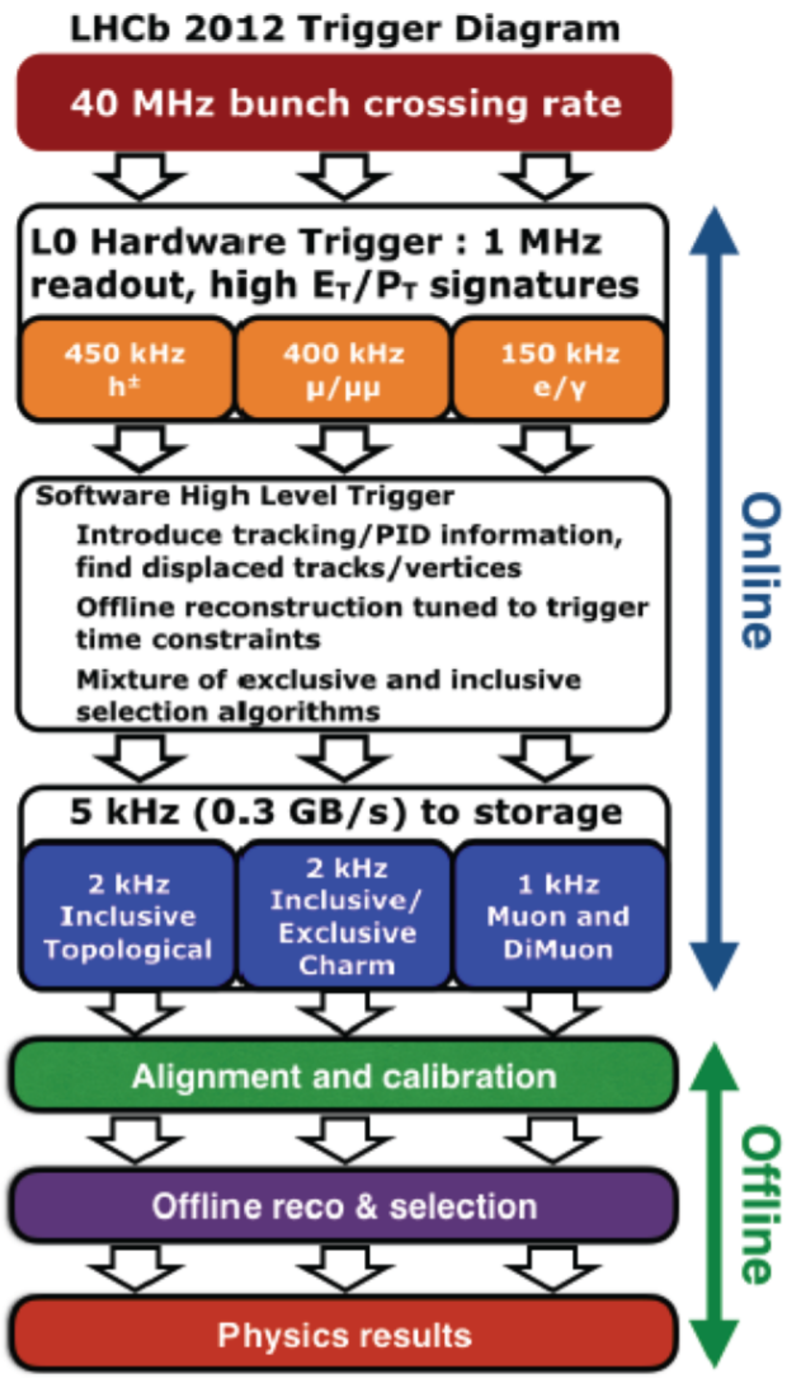
Trigger in RunII - CMS

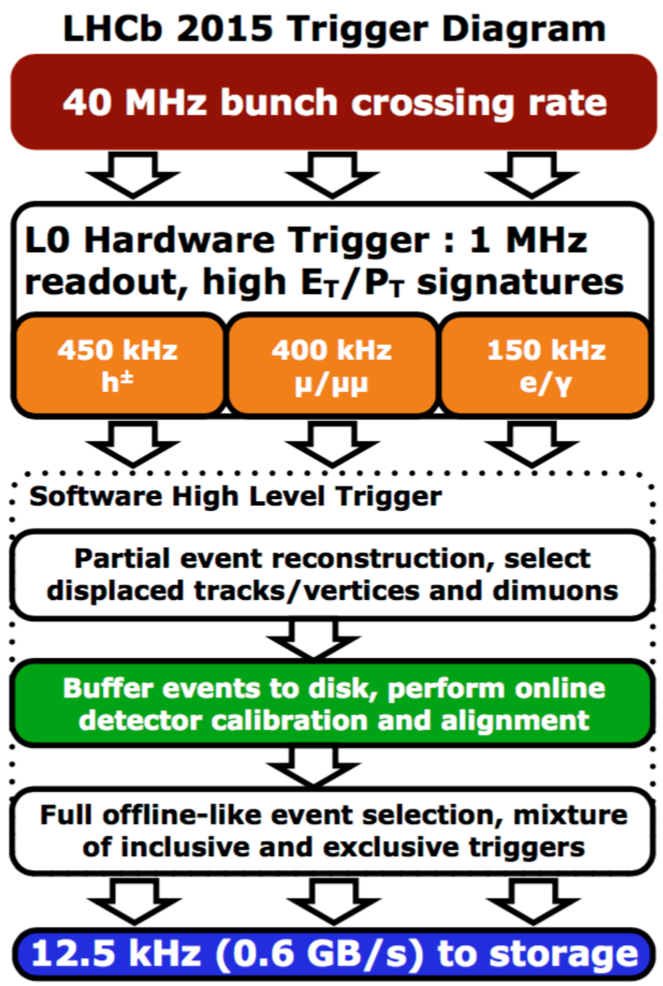
- Completely **renewed hardware trigger** (L1) from 2016
  - possibility to introduce more complex topological requirements (ΔR)
  - will allow to apply invariant mass selections already at this step
  - could be beneficial to reduce rate of low p_T dimuon seeds
- HLT selections based on **multi-muons paths**
  - work ongoing to further improve tuning of the online selections (adding further requirements)
  - in 2015, lowest p_T unprescaled dimuon paths had two muons with p_T > 4 GeV each



Trigger in RunII - LHCb

- Same hardware trigger (L0)
  - not thresholds
- **Completely revised HLT**
  - improved trigger farm able to write to storage 12.5 kHz instead of 5 kHz
  - same reconstruction online as offline
  - need “online” calibrations and alignments
    - split in HLT1 and HLT2
    - events buffered after HLT1
    - alignment and calibration run on dedicated HLT1 samples
    - HLT2 performs full event reconstruction





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

- FCNC in the SM, helicity and CKM suppressed

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{SM} = (3.66 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-)_{SM} = (1.06 \pm 0.09) \times 10^{-10}$$

PRL 112 (2014) 101801

- **Theoretically very clean process** (virtually no long-distance contributions)
  - Particularly sensitive to FCNC scalar currents and Z penguins
- **Experimental signature also very clean**
  - 2 muons in the final state
  - suitable also for CMS and ATLAS
- One of the most promising channels to reveal new physics contributions

	ATLAS arXiv:1604.04263	**CMS** PRL 111 (2013) 101804	**LHCb** PRL 111 (2013) 101805
muon p_T	4 - 6 GeV	4 GeV (2011) 3 GeV (2012)	0.25 GeV
dimuon mass resolution	60 to 120 MeV (η dependent)	from 32 to 75 MeV (η dependent)	~ 23 MeV
sensitivity	3.1σ	4.8σ	5.0σ

CMS + LHCb combined analysis

Nature 522, 68, 2015

- Simultaneous fit to invariant masses distributions
  - nuisance parameters shared between CMS and LHCb
  - $B^+ \to J/\psi K^+$ decay used as reference channel

  - **Branching fraction** results

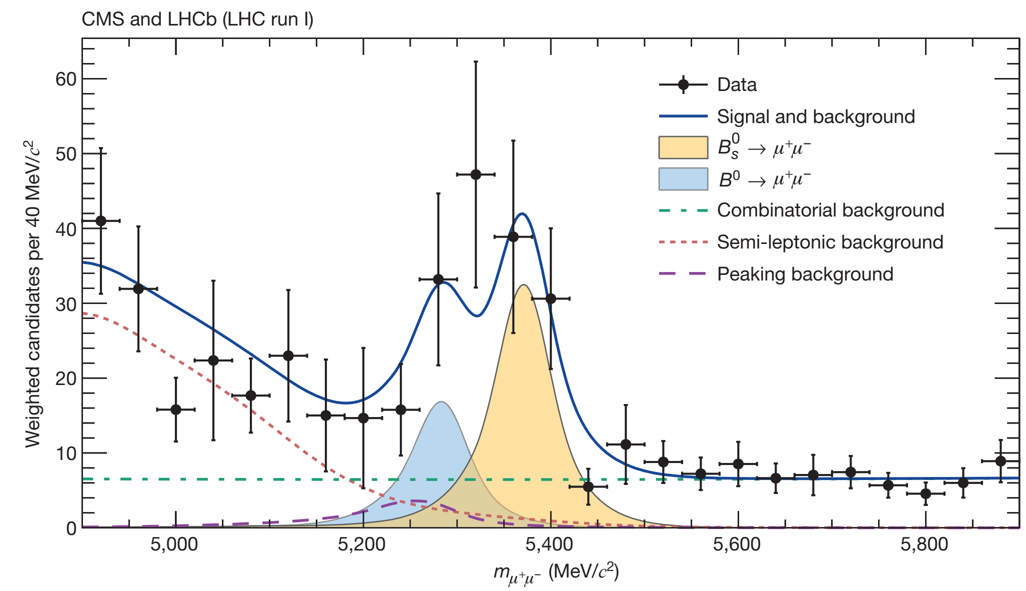
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$$

  compatibile with the SM at 1.2σ for B^0_s and 2.2 for B^0

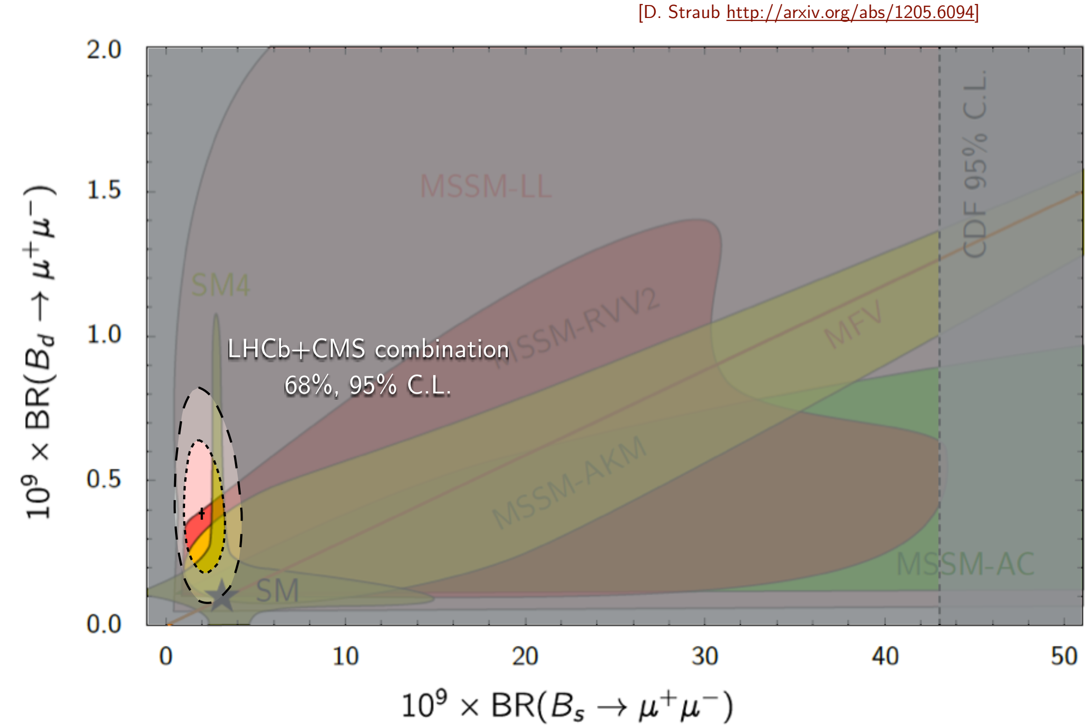
  - Results for the **ratio of branching fractions**

$$\mathcal{R} = \frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)} = 0.14^{+0.06}_{-0.08}$$

  within 2.3σ of SM prediction



[D. Straub http://arxiv.org/abs/1205.6094]

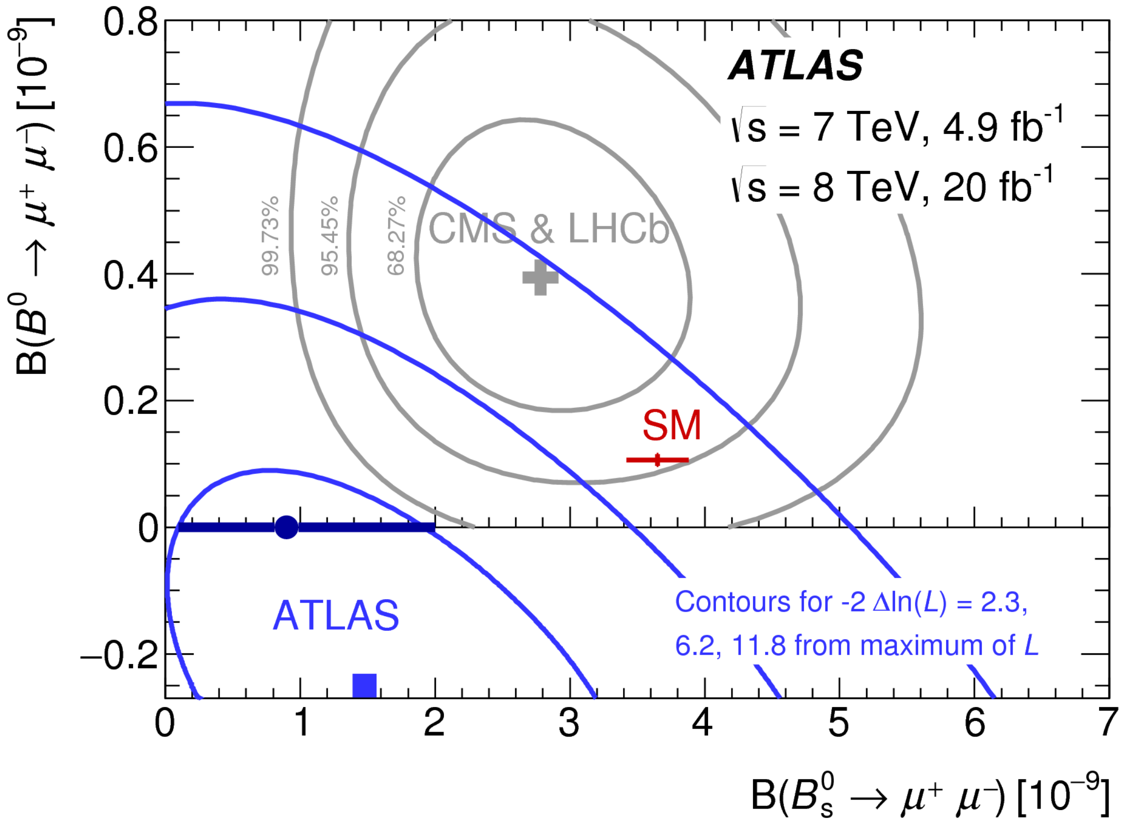


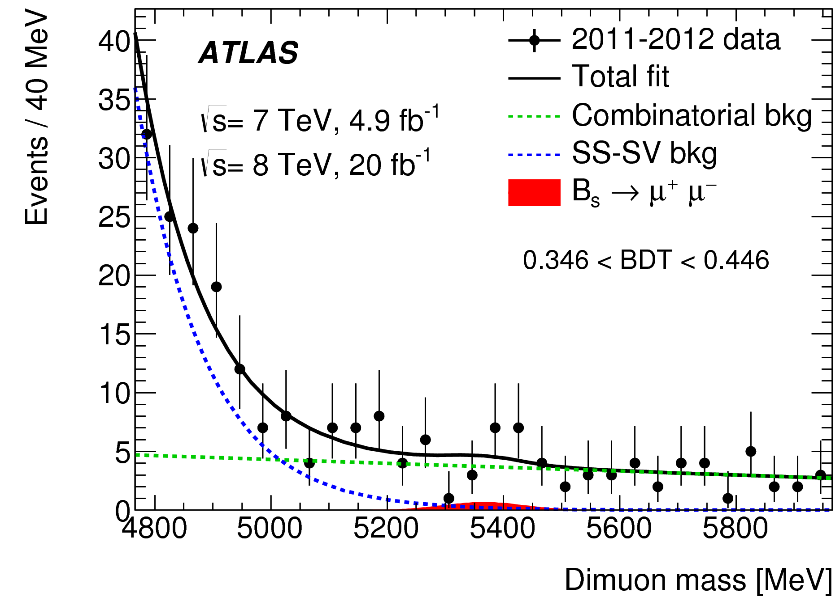
$B^0_{(s)} \rightarrow \mu^+\mu^-$ from ATLAS

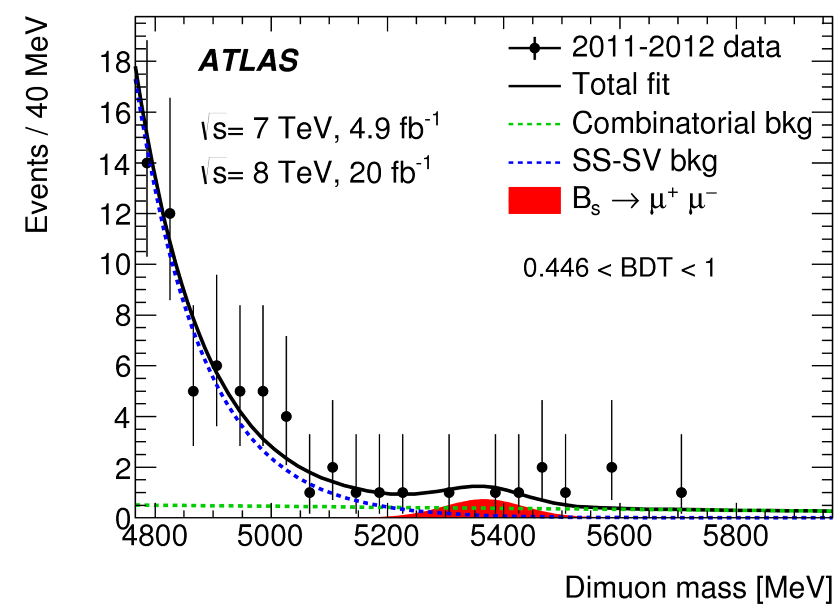
arXiv:1604.04263

- Recent results from ATLAS on full Run1 statistics
  - similar analysis strategy as CMS and LHCb
  - precision comparable to individual CMS and LHCb measurements

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (0.9^{+1.1}_{-0.8}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 4.2 \times 10^{-10} \text{ @95\% } CL$$







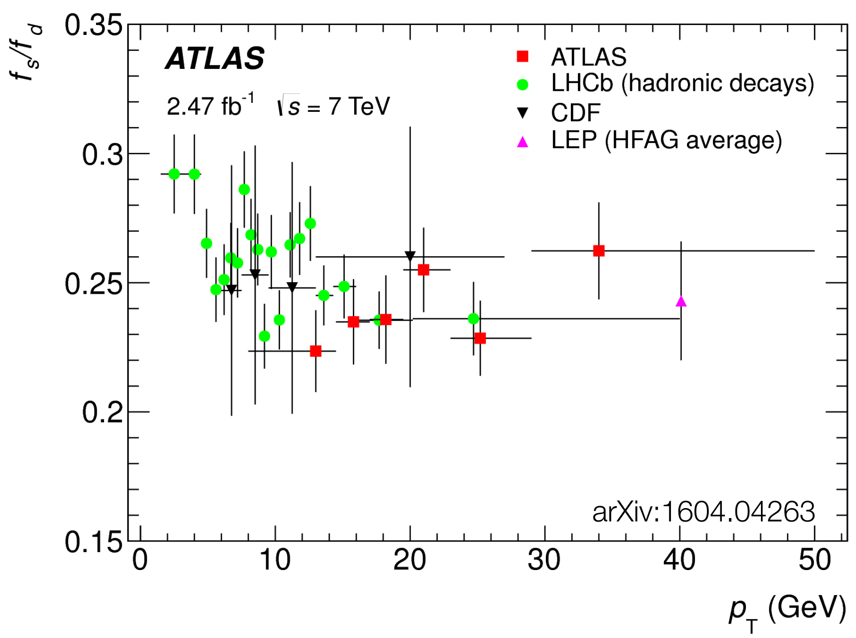
$B^0_{(s)} \to \mu^+\mu^-$ in RunII

- Absence of large enhancements over SM BR does not mean these rare modes are becoming less interesting
    - we simply excluded scenarios with large scalar FCNC's and entered into a regime where different type of amplitudes (Z-penguins, Z', ...) can affect these decays
        - **there is still large room for NP!**

- Measurement of the **branching fractions**
    - production cross-section approximately doubled
    - present theoretical uncertainty ~ 6% likely will decrease to 2-3% in the next few years
    - improve measured precision as theoretical precision increases
    - trigger thresholds will be the main limitation for ATLAS and CMS

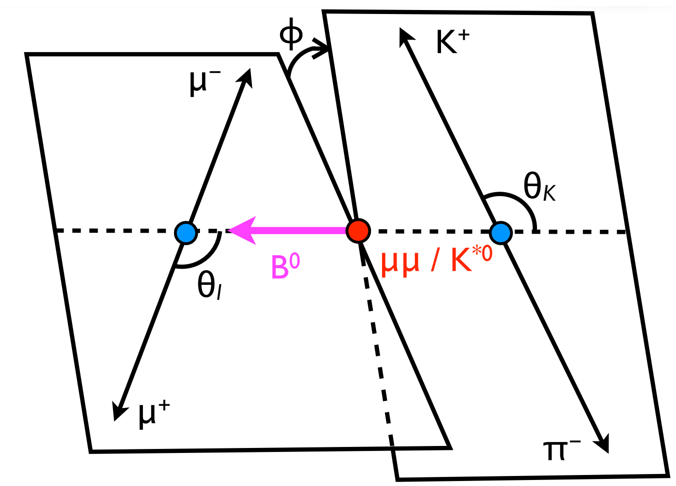
- $B^0_s \to \mu^+\mu^-$ **effective lifetime**
    - sensitive to the asymmetry parameter
    - independent probe of new physics

- f_s/f_d measured by ATLAS and LHCb so far, measurement from CMS would be interesting



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

- Decay mode that gives access to large number of observables: branching fractions, CP asymmetries and angular observable
  - branching fraction ~ $4.5 \cdot 10^{-7}$
  - sensitive to new vector or axial-vector currents and virtual photon polarization
  - the decay is fully described by three angles (θ_l, θ_K, ϕ) and the dimuon invariant mass squared (q^2)
  - the observables depend on form-factors for the $B \rightarrow K^*$ transition plus the underlying short distance physics (Wilson coefficients)



$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}}\bigg|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-\boxed{F_{\mathrm{L}}})\sin^2\theta_K + \boxed{F_{\mathrm{L}}}\cos^2\theta_K +$$

$$+\tfrac{1}{4}(1-\boxed{F_{\mathrm{L}}})\sin^2\theta_K\cos 2\theta_l$$

$$-\boxed{F_{\mathrm{L}}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$

$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + \boxed{S_5}\sin 2\theta_K\sin\theta_l\cos\phi$$

$$+\tfrac{4}{3}\boxed{A_{\mathrm{FB}}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$

$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

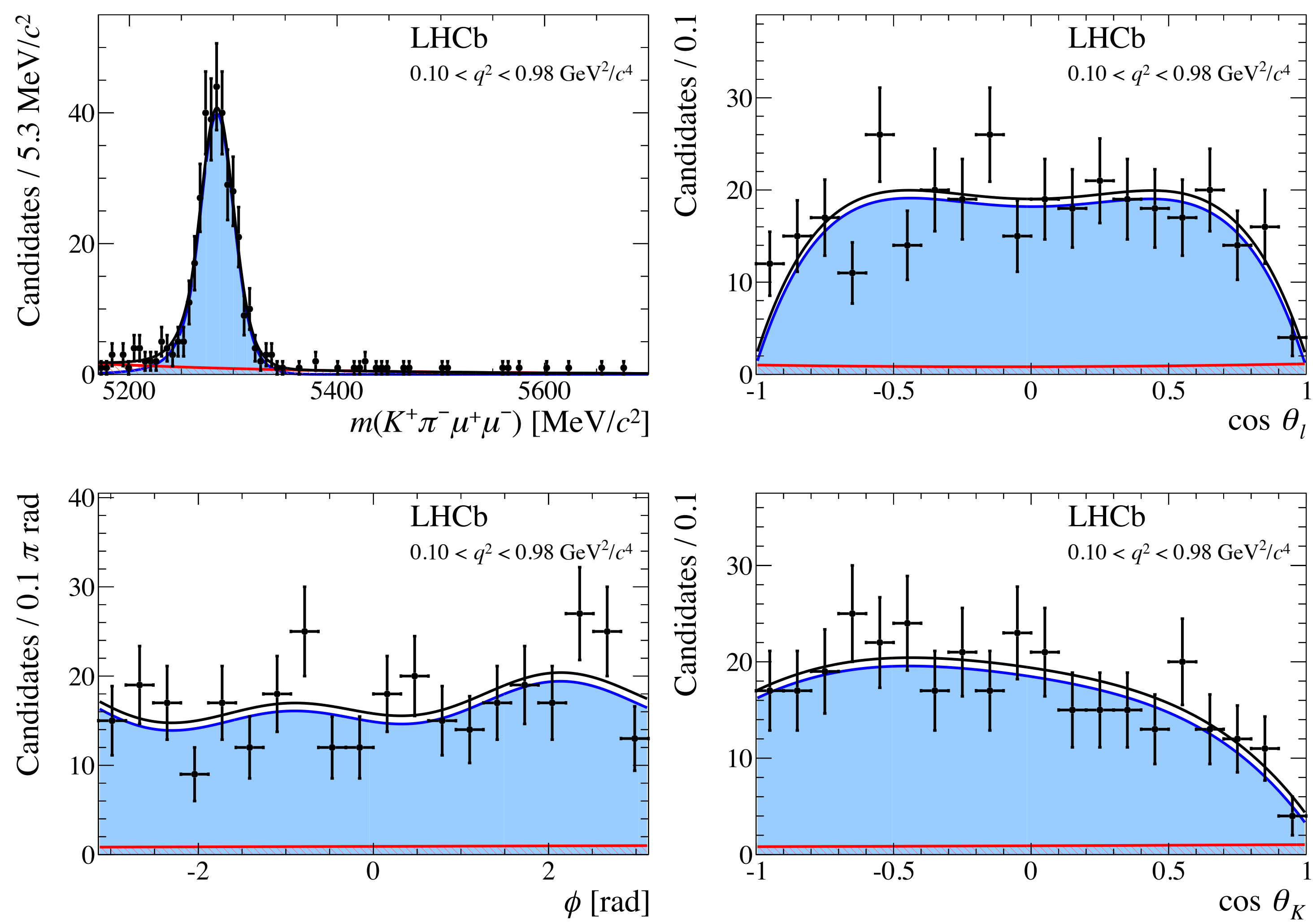
fraction of longitudinal polarisation of the K*

forward-backward asymmetry of the dilepton system

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

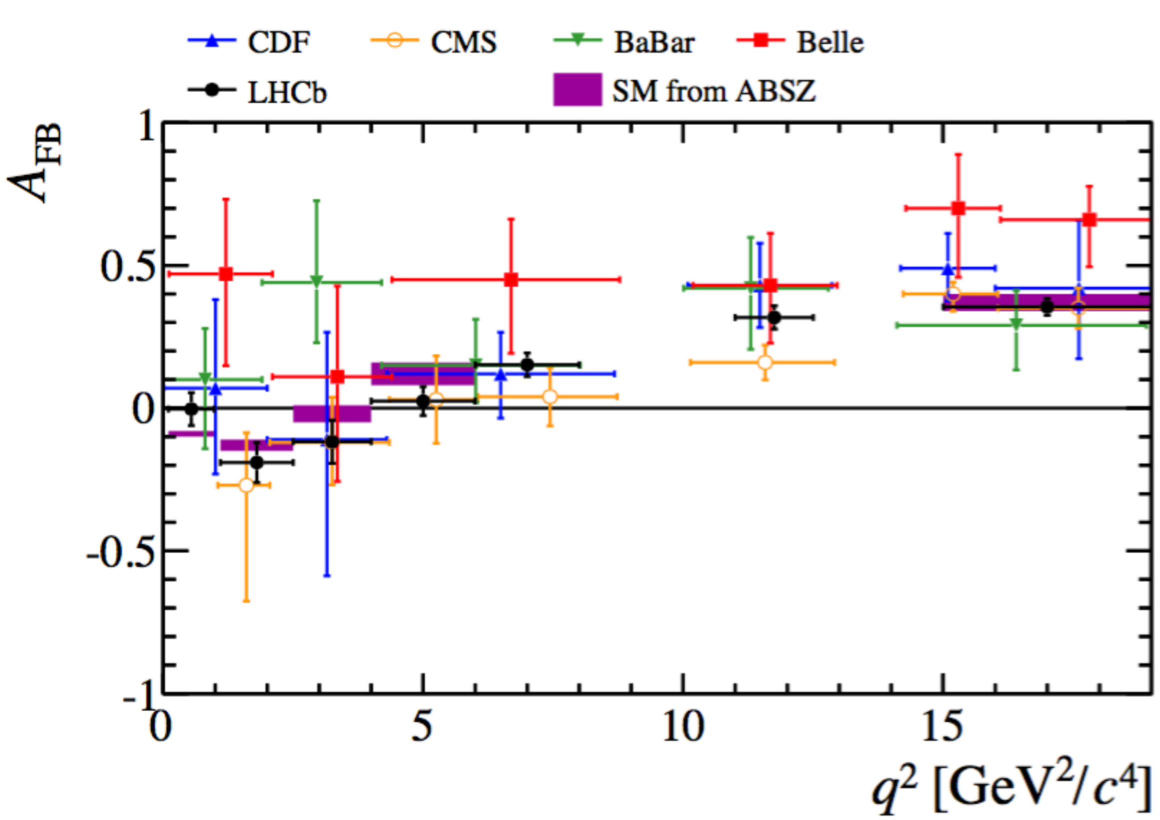
- **LHCb** has performed the full angular analysis of the decay with the full RunI statistics
  - full set of CP-averaged angular terms and their correlations is extracted
- **CMS** published analysis integrates over the ϕ angle PLB 753 (2016) 424
  - lower event yields due to higher p_T thresholds and combinatorial background
  - does not measure the full set of observables
  - full angular analysis on RunI data ongoing
- **ATLAS** analysis on full Run1 data ongoing

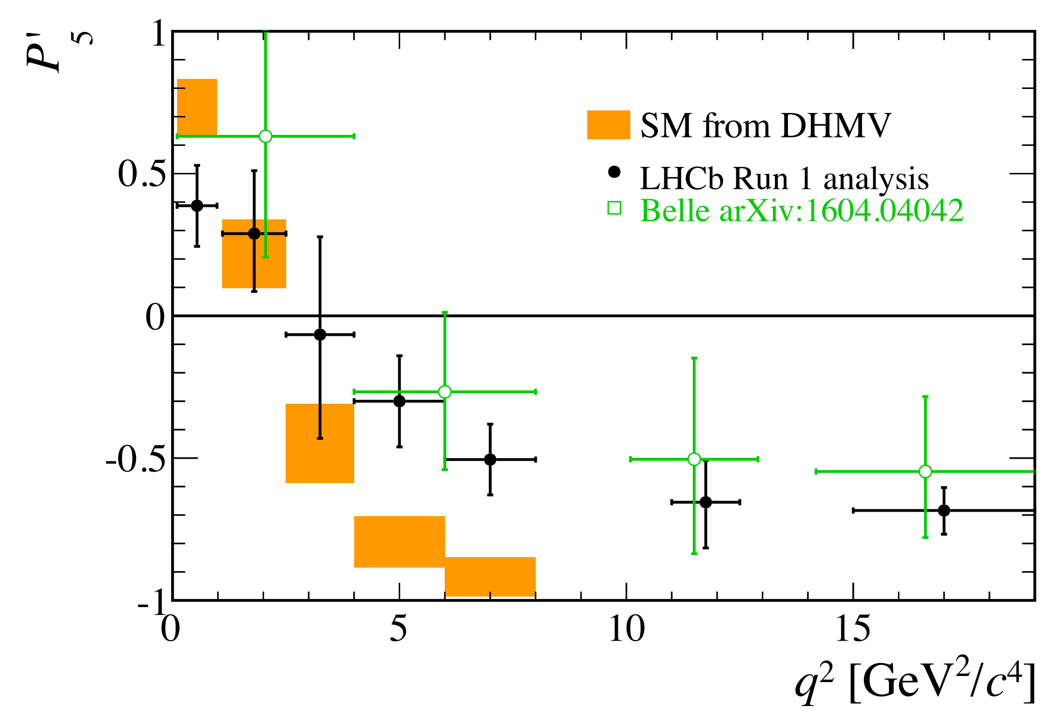
JHEP 02 (2016) 104



$B^0 \rightarrow K^{*0}\,\mu^+\mu^-$ results

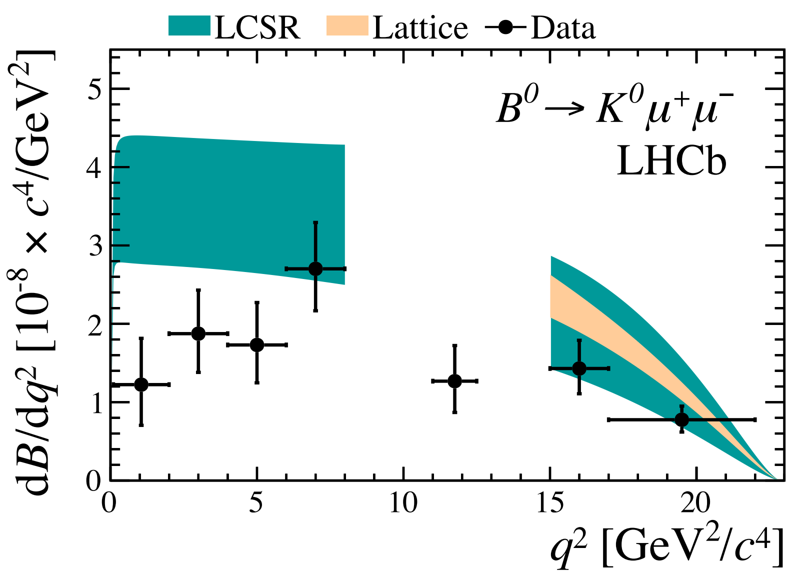
- Results for A_{FB} and F_L available from LHCb, CMS, Babar, CDF and Belle
- Results from full angular analysis only available from LHCb and a recent measurement from Belle
  - present data show some “tension” with SM predictions especially in the P_5’ parameter
  - P_5’ is one of the form-factor free observables $P_5' = \dfrac{S_5}{\sqrt{F_L(1-F_L)}}$
    - deviation from SM prediction at level of 2.8 and 3.0 standard deviations in the q^2 bins (4-6)(6-8) GeV/c^2

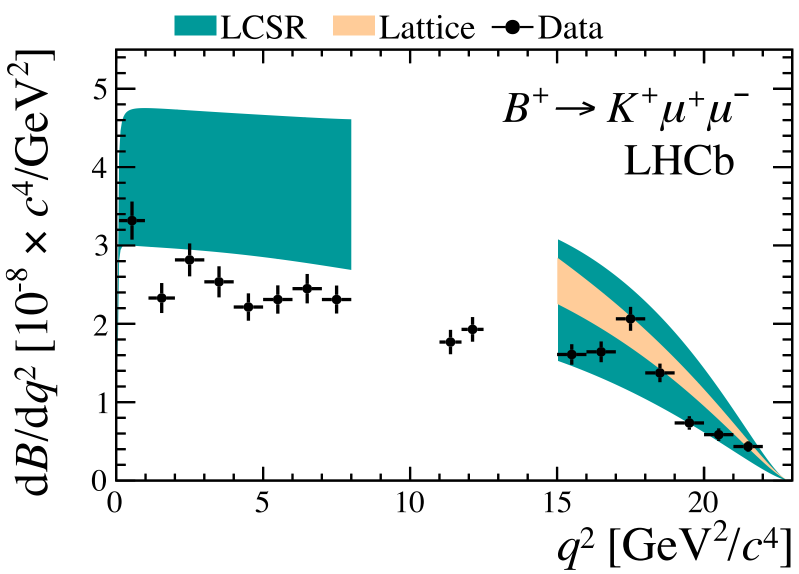


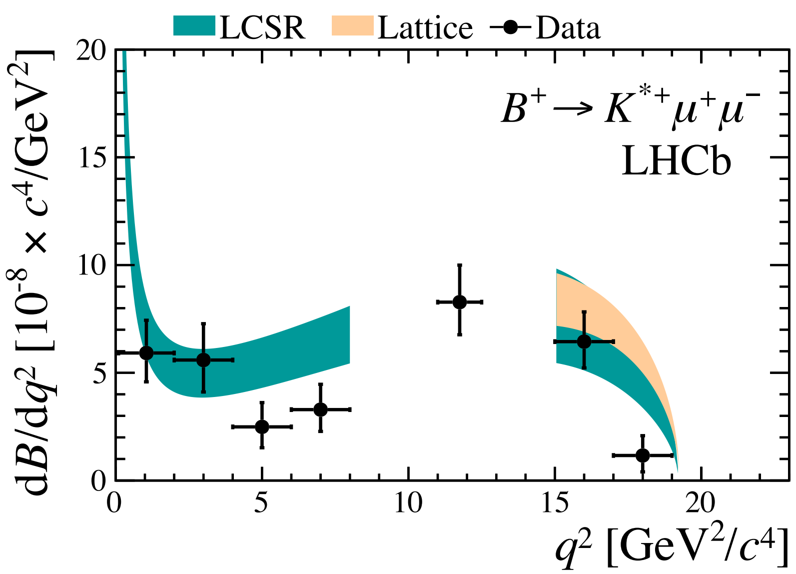


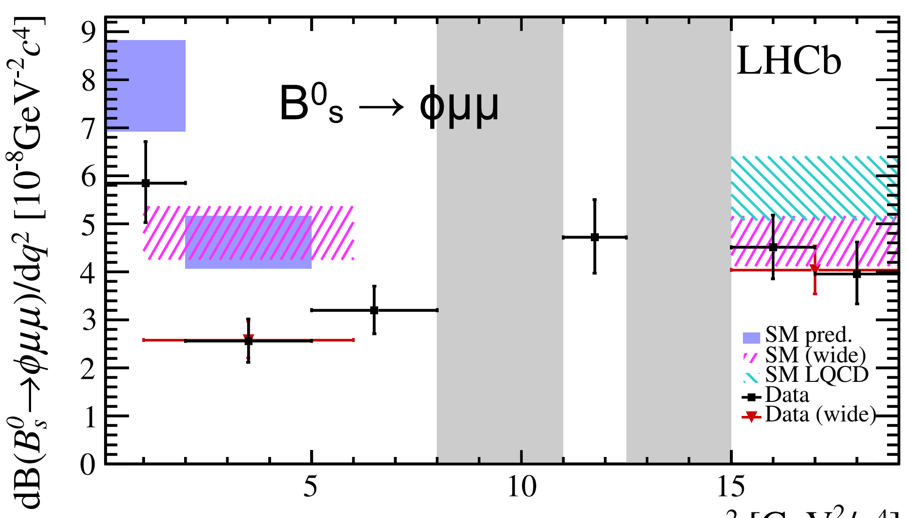
Other branching fraction measurements

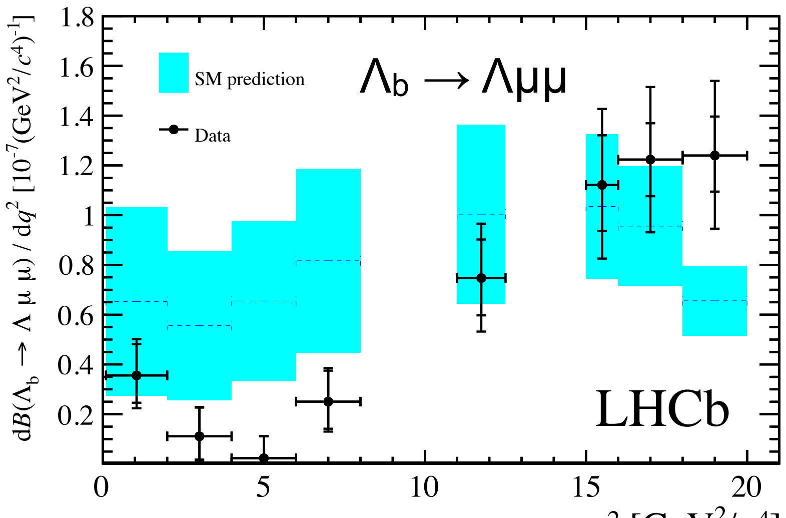
- Anomalies present also in other b→sμμ channels







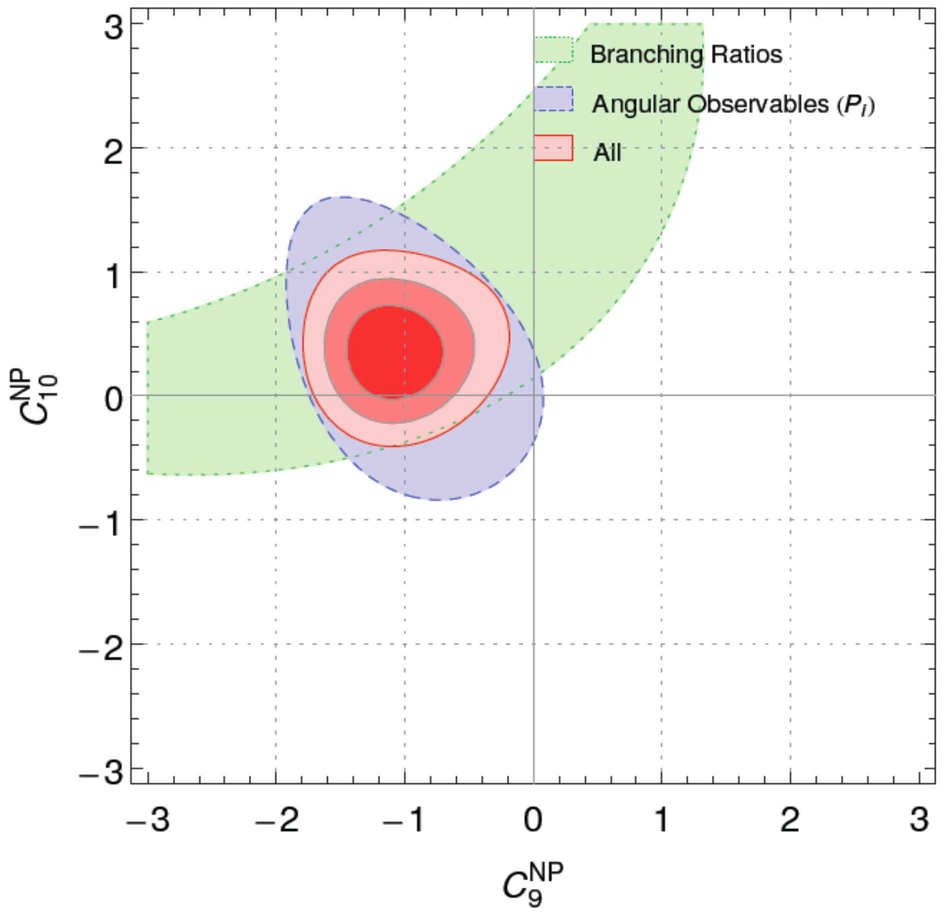




Wilson coefficient fits

- Some deviations are observed in different exclusive modes and different type of observables (angular and BR)
- Reduced tension in all the observables with a unique fit of non-standard short-distance Wilson coefficients

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{tq}^* \sum_i (\mathcal{C}_i \mathcal{O}_i + \mathcal{C}_i' \mathcal{O}_i')$$

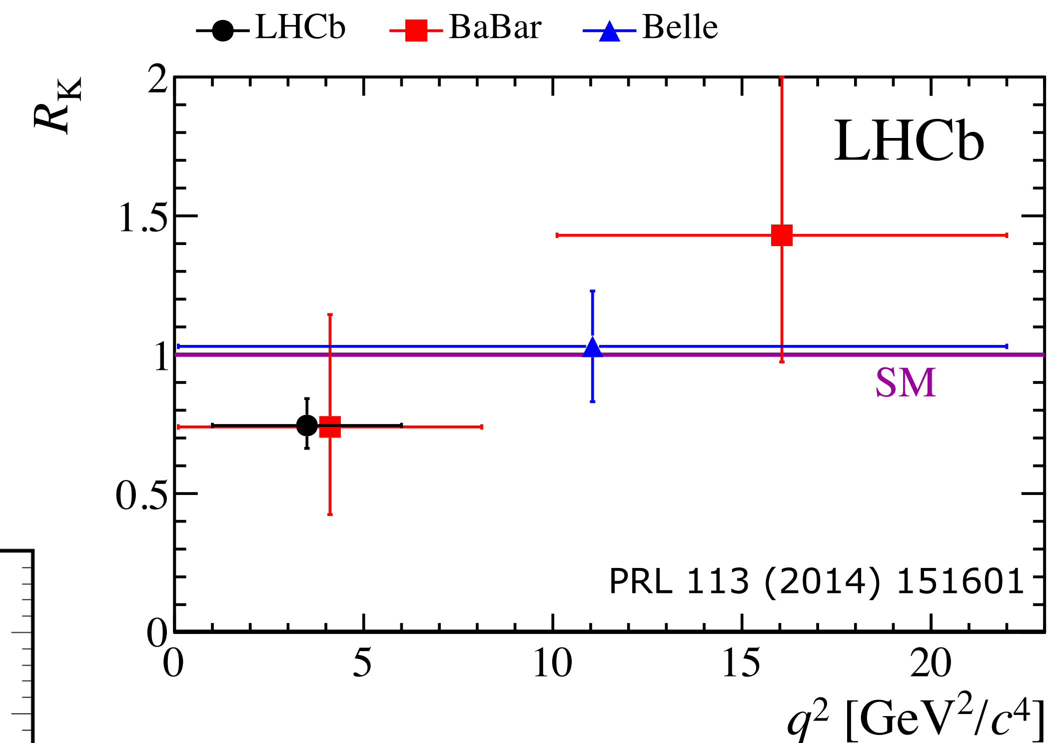


Descotes-Genon, Matias, Virto '13, '15
Altmannshofer & Straub '13, '15
Beaujean, Bobeth, van Dyk '13
Horgan et al. '13

Lepton Universality

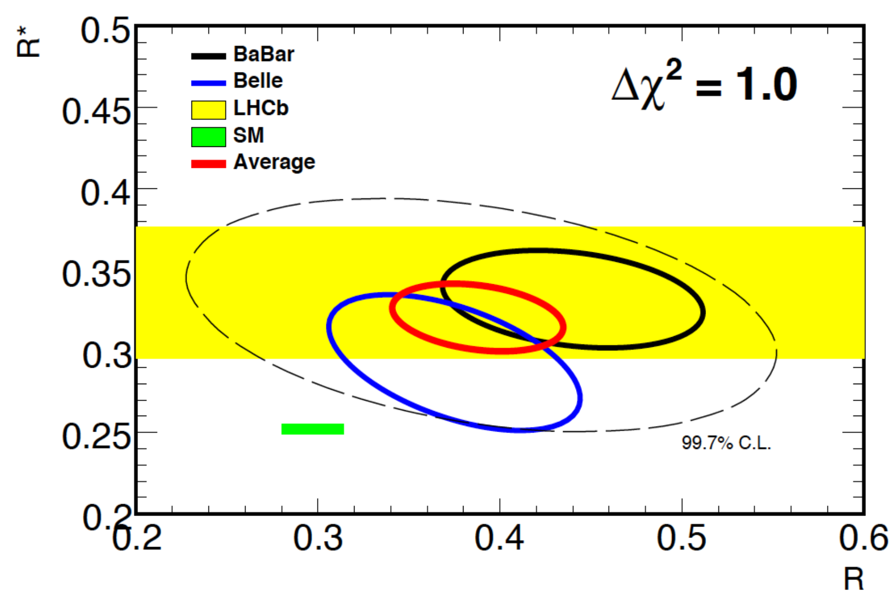
- In the SM, ratios $R_K = \frac{\int d\Gamma[B^+ \to K^+\mu^+\mu^-]/\mathrm{d}q^2 \cdot \mathrm{d}q^2}{\int d\Gamma[B^+ \to K^+e^+e^-]/\mathrm{d}q^2 \cdot \mathrm{d}q^2}$ expected to be 1 in SM with uncertainty O(10^{-3})
  JHEP 12 (2007) 040
  PRL 112 (2014) 149902
  - precise theory prediction due to cancellation of hadronic uncertainties
  - experimentally more challenging due to differences in electron/muon reconstruction (larger Bremsstrahlung of electrons)
- In RunI, LHCb measured $R_{\mathrm{K}} = 0.745\,^{+0.090}_{-0.074}\,^{+0.036}_{-0.036}$

  in the range $1 < q^2 < 6$ GeV^2, consistent with the SM at 2.6σ



- Tension also seen in the measurement of

$$R(X) = \frac{\Gamma(B \to X\tau\bar{\nu})}{\Gamma(B \to X\ell\bar{\nu})}$$



$b \to sll$ decays in RunII

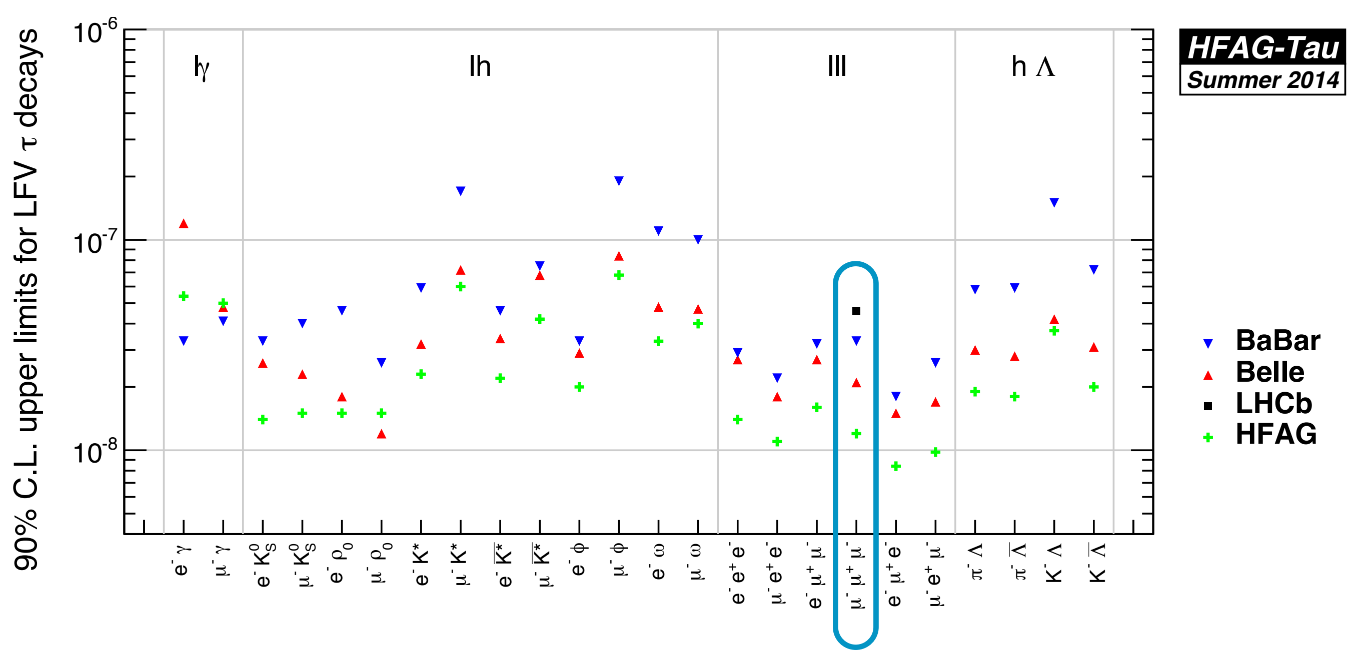
- RunII data will improve statistical precision of the current experimental measurements
  - **LHCb** will repeat full angular analyses and BR measurements at 13 TeV
  - **ATLAS and CMS**:
    - sensitivity reach difficult to predict since full angular analyses on RunI data are still ongoing
    - significant effort ongoing to maintain low trigger thresholds
    - eventually, higher statistics could give access to complementary decay channels
      - $\Lambda_b \to \Lambda\mu^+\mu^-$
      - $B_s \to \phi\mu^+\mu^-$

- Decays with electrons in the final states reasonably investigated only by LHCb

Lepton Flavor Violating decays

- LFV allowed in the SM in the context of massive neutrinos (BR ~10^{-40} or less, beyond experimental sensitivity)
- Beyond the SM theories can significantly enhance LFV decay branching fractions
- Measurements mostly published by LHCb

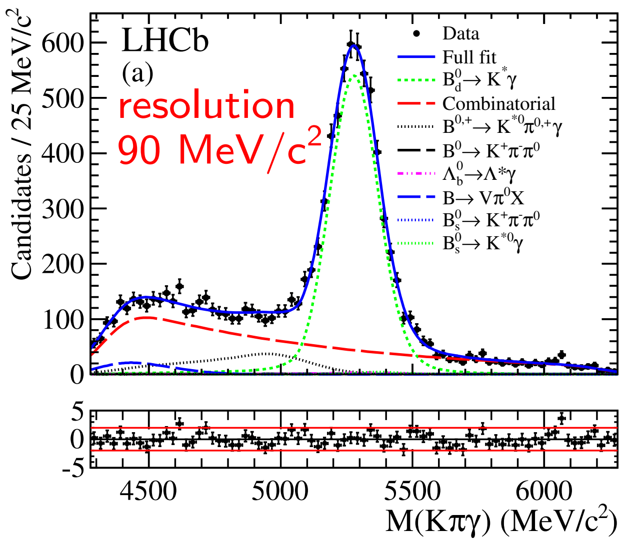
BR	LHCb	data sample	ATLAS
$B^0_s \rightarrow e^+\mu^-$	< 1.4 x 10^{-8} @95% CL	1.0 fb^{-1} 7 TeV	-
$B^0 \rightarrow e^+\mu^-$	< 3.7 x 10^{-9} @95% CL	1.0 fb^{-1} 7 TeV	-
$D^0 \rightarrow e^+\mu^-$	<1.3 x10^{-8} @90% CL	3.0 fb^{-1}	-
$\tau^- \rightarrow \mu^-\mu^+\mu^-$	< (4.1 - 6.8) x 10^{-8} @90% CL	3.0 fb^{-1}	< 3.76 x 10^{-7} @90% CL (20fb^{-1})



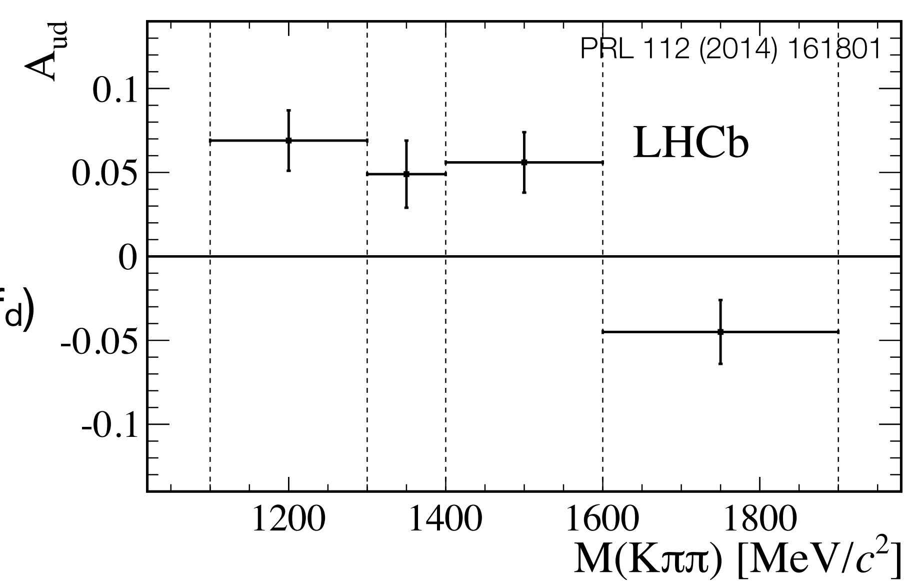
Results from LHC experiments would be competitive if ready by the end of RunII (before Belle2 results)

Radiative B decays

- Loop-driven B decays are very sensitive to the presence of new physics BSM
  - the SM photon in $b \rightarrow s\gamma$ is predominantly left-handed whilst the right-handed contribution can be significantly enlarged due to new physics
- Reconstruction of low p_T photons is experimentally challenging:
  - LHCb: - energy determined from the total cluster energy in the calorimeter
    - photon reconstruction dominates mass resolution
  - CMS and ATLAS: conversion to e^+e^- pairs, very low efficiency



- Publications from LHCb only
  - observation of photon polarization through the decay $B^{\pm} \rightarrow K^{\pm}\pi^{\mp}\pi^{\pm}\gamma$
  - measurement of the ratio of BF
    $B(B^0 \rightarrow K^{*0}\gamma)/B(B_s \rightarrow \phi\gamma) = 1.23 \pm 0.06(\text{stat}) \pm 0.04(\text{syst}) \pm 0.10(f_s/f_d)$
    in agreement with theoretical expectations
    Nucl. Phys. B867 (2013) 1



Rare charm decays

- Rare charm decays proceed via highly suppressed $c \rightarrow u\mu^+\mu^-$ FCNC process
  - in the SM short distance contributions $O(10^{-9})$ but long-distance (tree diagrams involving resonances such as $D \rightarrow XV$ ($\rightarrow \mu^+\mu^-$), where V is a ϕ, ρ^0 or ω vector meson) increase branching fraction to $O(10^{-6})$
  - sensitivity to NP therefore is greatest in regions of the dimuon mass spectrum away from resonances
  - however **angular asymmetries sensitive to NP both in the vicinity and away from resonances**
    - could be as large as O(1%)

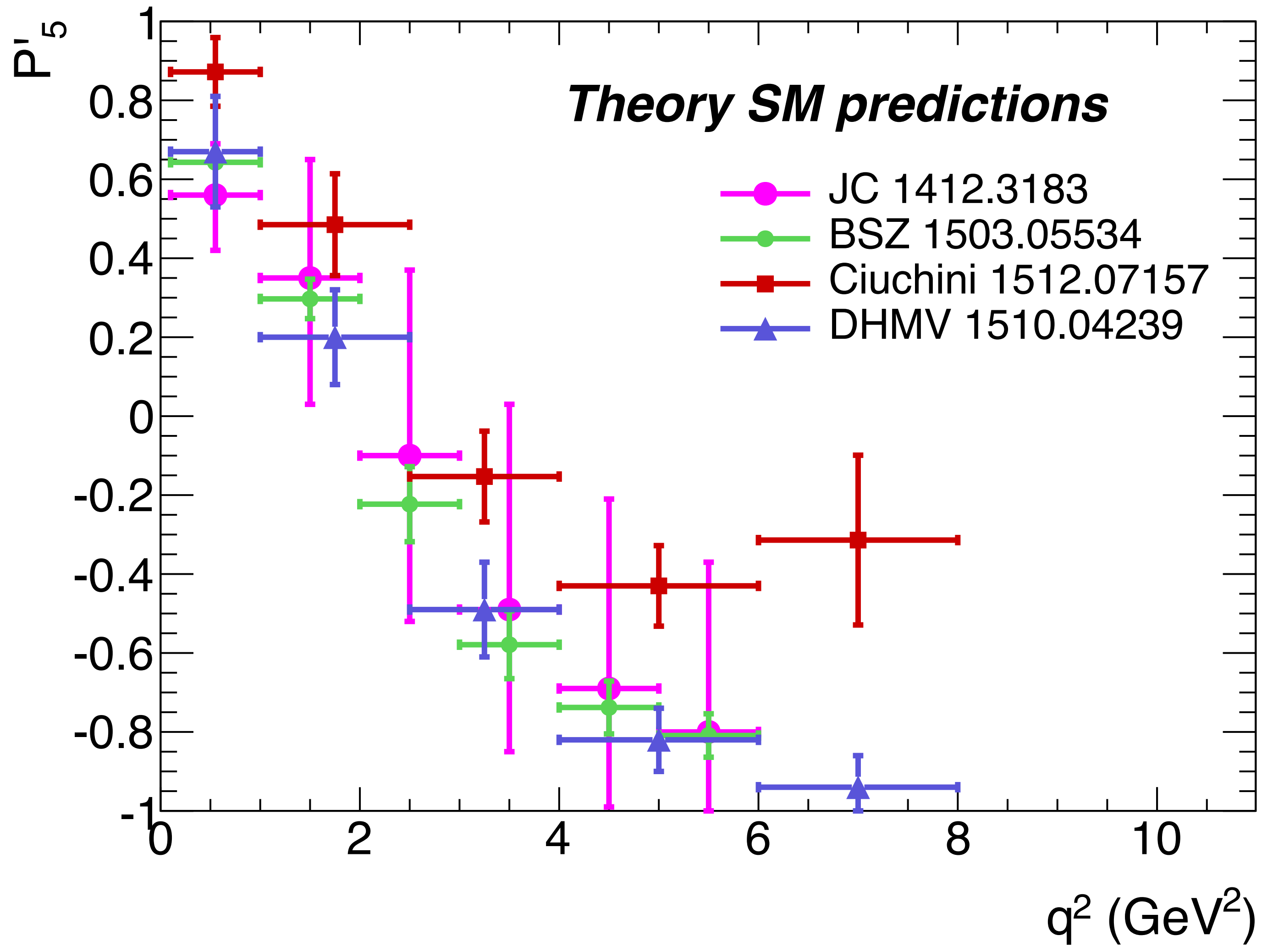
- Measurements from LHCb only for different decay channels, **no significant deviations from SM**
  - first measurement of BF of $D^0 \rightarrow K^-\pi^+\mu^+\mu^-$ in the ρ/ω region — arXiv:1510.08367
  - $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ — PLB728 (2014) 234
  - $D^+_s \rightarrow \pi^+\mu^+\mu^-$ — PLB724 (2013) 203
  - $D^0 \rightarrow \mu\mu$ — PLB725 (2013) 16
  - …

Conclusions

- **Rare decays are a fundamental portal to access new physics effects**
- The RunI of the LHC is showing some tension with SM predictions in the flavor sector
- **Precise measurements in RunII are fundamental to prove these deviations and help building a comprehensive picture**
    - ATLAS and CMS will play an important role alongside LHCb
    - coordination between the three experiments would be beneficial to cover the interesting topics and in view of possible combinations of the results

backup

P_5’ predictions



$B^0_{(s)} \rightarrow \mu^+\mu^-$ from the individual experiments

ATLAS

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (0.9^{+1.1}_{-0.8}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 4.2 \times 10^{-10} @95\% CL$$

CMS

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.1 \times 10^{-9} @95\% CL$$

LHCb

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 7.4 \times 10^{-10} @95\% CL$$