Rare decays at LHC
LHCb, CMS and ATLAS results

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Interplay between
Particle &
Astroparticle physics
2014

Motivation

The Standard Model (SM) is an **exhaustive theory** able to explain the particles interactions and make many **predictions** with a very high precision ...

… still suffers of a series of theoretical and cosmological **problems**

hierarchy problem: how to get from Planck scale (10^{19} GeV) to EW scale (100 GeV) without “fine tuning” quantum corrections?

flavor puzzle: unexplained **hierarchical structure of the Yukawa coupling**

matter-antimatter asymmetry: from current measurements baryogenesis can only generate 10^{-20}, but 10^{-10} is needed

no good candidate for **dark matter**

neutrino oscillations, …. **gravity**

Standard Model (SM) is likely to be the **low-energy limit of a more fundamental theory**, with new degrees of freedom. Expect New Physics (NP).

Motivation (2)

What is a “rare decay”

A decay that is **forbidden** by a symmetry of the Standard Model (SM) or **highly suppressed** to such an extent that it cannot be observed In any plausible experiment (e.g. charged lepton flavor violation, Baryon number violation)

A decay that occurs in the Standard Model only at **loop level** (**FCNC** forbidden at tree level, e.g. penguin or box diagrams) and for which the BF and/or differential distributions of final state particles may be sensitive to new physics

Rare decays is a **rich soil** to look at if we want to test the standard model and/or find new physics beyond it

Two complementary ways to look for NP:

direct searches [ATLAS and CMS]: NP particles decays

indirect searches [ATLAS, CMS, and LHCb]: discrepancies from the SM predictions due to NP contribution (we “already observe” NP, but difficult to distinguish from SM)

Outline

Search for SM forbidden decay

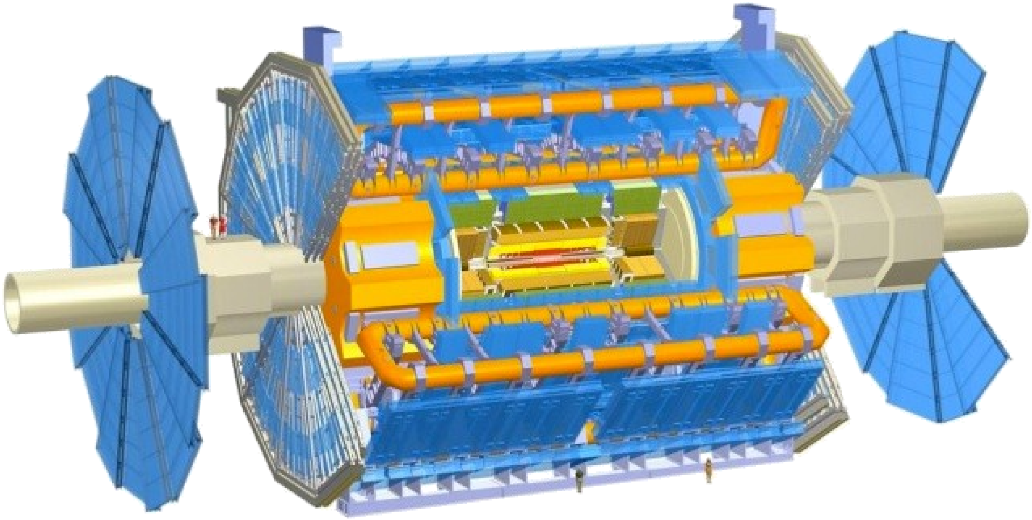
- Search for heavy Majorana neutrinos in B mesons decays

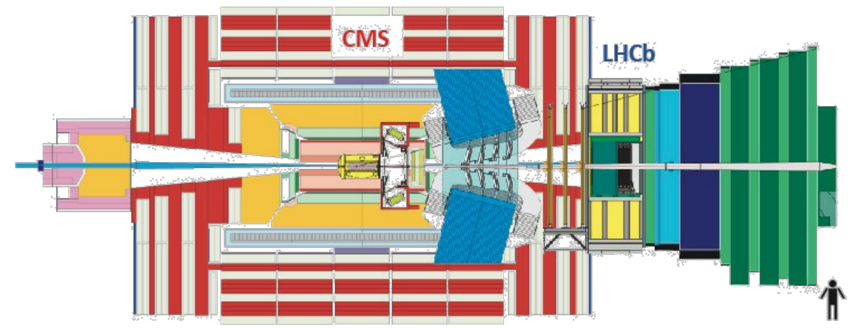
Study of SM-allowed rare decays

- $B_s \rightarrow \mu^+\mu^-$ and $B_d \rightarrow \mu^+\mu^-$
- $B^0 \rightarrow K^{*0} \mu^+\mu^-$ decay: BF and angular analysis
- Photon polarization in $b \rightarrow s \gamma$ transition

The tools

ATLAS and CMS largely in central region (|η|<2.4), LHCb forward region (2<η<5)

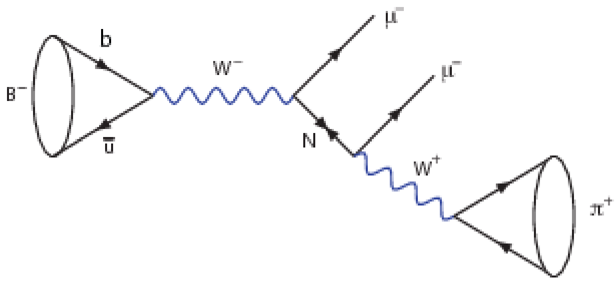




Measured σ(pp→bbX) cross-section (at 7 TeV):
ATLAS ($32.7 \pm 0.8^{+4.5}_{-5.8}$) μb (pT(B) > 9GeV and |η| < 2.5) [PLB 694 (2010) 209]
CMS (28.1 ± 2.4 ± 2.0 ± 3.1) μb (pT(B) > 5 GeV and |η| < 2.4) [Nucl.Phys. B864 (2012) 341-381]
LHCb (75.3 ± 5.4 ± 13.0) μb (2<η<6) [Phys.Rev.Lett.106:252001,2011]

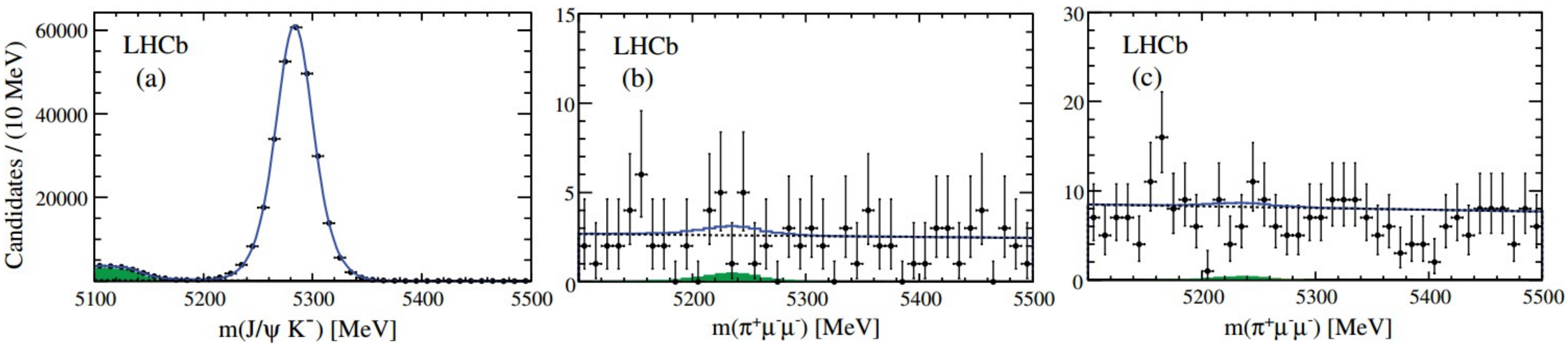
Each experiment: O(10^{10})/fb bb pairs on tape
Compare to combined BaBar and Belle data sample of ~10^9 B^0B^0 pairs. For any channel where the (trigger, reconstruction, stripping, offline) efficiency is not too small, LHC have the **world's largest data sample**… the right place to look for very rare B decays.

Search for Majorana neutrinos in $B^- \rightarrow \pi^+\mu^-\mu^-$



- Forbidden LNV decay decay, probes Majorana neutrino **masses** between **250 MeV and 5000 MeV**
- Search valid for neutrino **lifetimes** between **1 ps and 1000 ps**
- Measurement with all the **3 fb^{-1} LHCb** data
- **Normalised** to $B^- \rightarrow J/\psi K^-$
- Combinatorial background from sidebands fit, peaking background from simulation

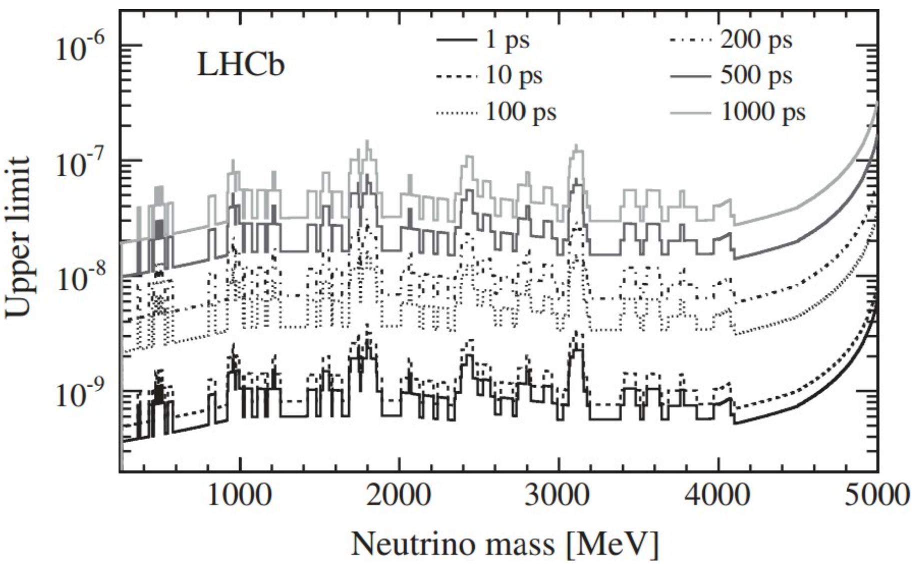
PRL 112, 131802 (2014)

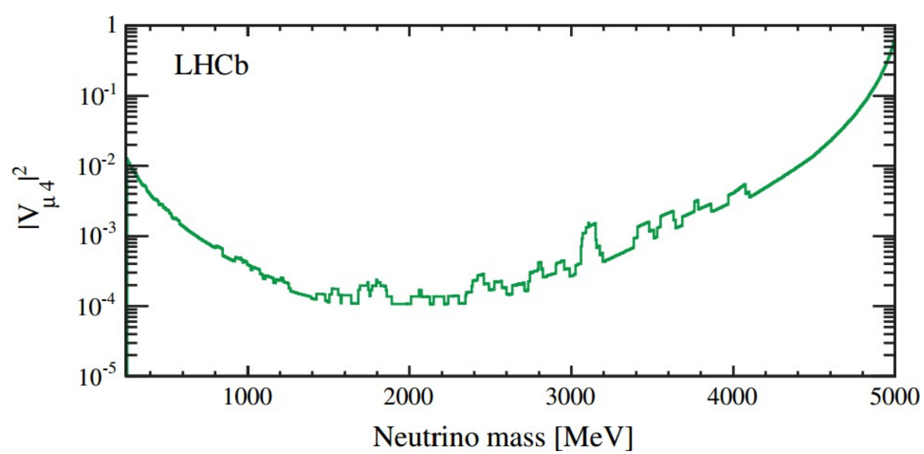


Search for Majorana neutrinos in $B^- \to \pi^+\mu^-\mu^-$

- No signal observed → **limit as a function of m_ν and τ_ν** using CL_S method
- **$BF(B^- \to \pi^+\mu^-\mu^-) < 4.0\cdot10^{-9}$ at 95% CL**
- From BF limit it is possible to extract a limit on the fourth generation coupling $|V_{\mu4}|^2$, as a function of neutrino mass (A. Atre et al., JHEP 05(2009)030)

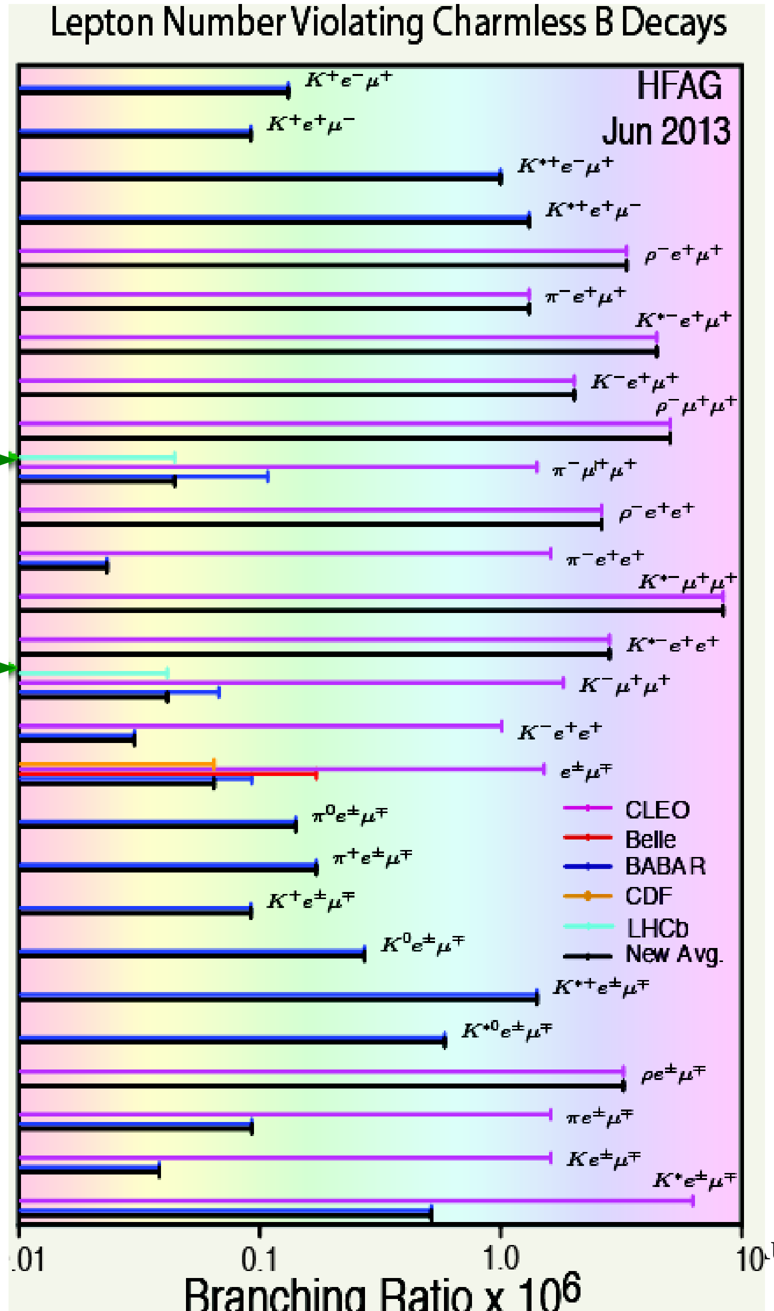
PRL 112, 131802 (2014)





Search for Majorana neutrinos in $B^- \rightarrow \pi^+\mu^-\mu^-$

LHCb



In the $B^- \rightarrow \pi^+\mu^-\mu^-$ and $B^- \rightarrow K^+\mu^-\mu^-$ decays, LHCb lower in a sizable way the previous BABAR limits

$$B_{d,s} \to \mu^+\mu^-$$

$B_{s(d)} \to \mu^+\mu^-$

B^0 and $B_s \to \mu^+\mu^-$ decays are both **GIM (loop) and helicity suppressed**

Sensitive to contributions from (pseudo)scalar sector. Interesting **probe to NP models** with extended Higgs sectors (e.g. MSSM, 2HDM, . . .)

Very **precise prediction** in the SM

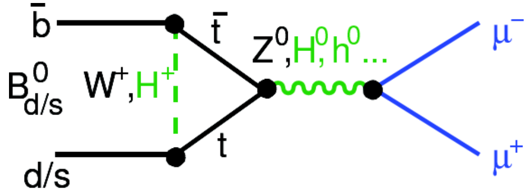
$B_s \to \mu^+\mu^-$	$(3.65 \pm 0.23) \times 10^{-9}$
$B^0 \to \mu^+\mu^-$	$(1.06 \pm 0.09) \times 10^{-10}$

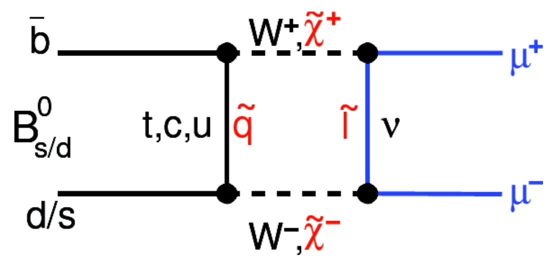
Bobeth, et al., Phys. Rev. Lett. 112, 101801 (2014)

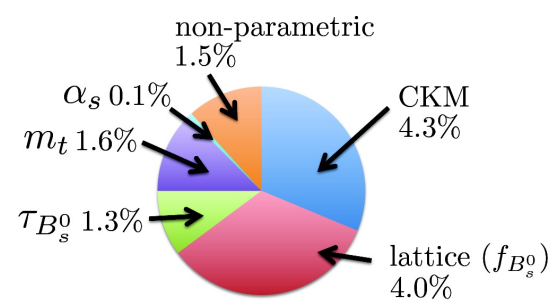
In the Minimal SUSY Model

$$\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm MSSM} \propto \frac{m_b^2 m_\mu^2 \tan^6\beta}{m_A^4}$$

Very sensitive to the β and m_A parameters







Bobeth et al. PRL 112 101801 (2014)

Theory error budget

$B_{s(d)} \rightarrow \mu^+\mu^-$ at CMS

PRL 111 (2013) 101805

Normalise to $B^+ \rightarrow J/\Psi\, K^+$

Use **multivariate classier** (BDT) and tight particle identication requirements

Selection cuts differentiated for barrel and endcap region (all other pairs).

BDT stable versus event multiplicity

In the figure events are weighted with S/sqrt(S+B)

25 fb-1: 4.3σ / 95% CL

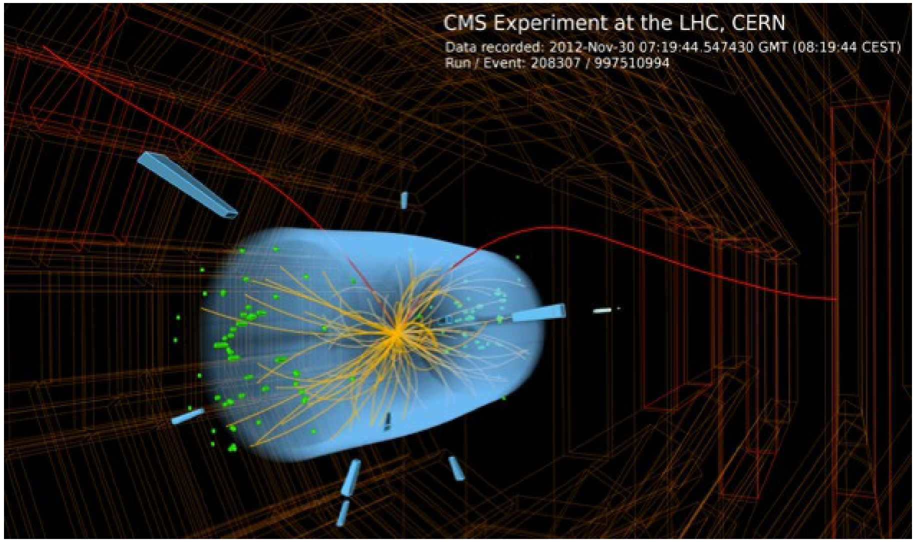
$$\mathcal{B}(B_s \to \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.1 \times 10^{-9}$$

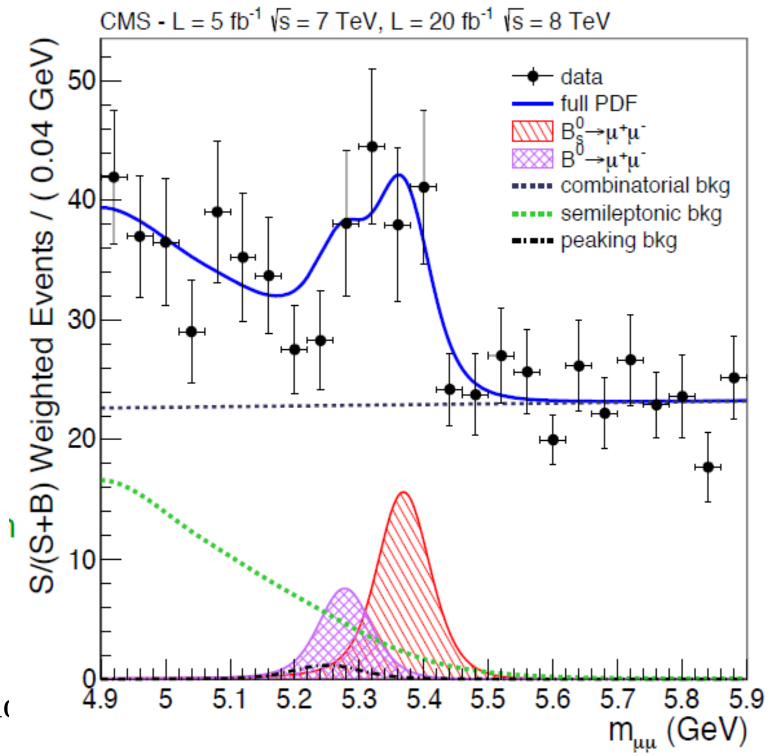
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.5^{+2.1}_{-1.8}) \times 10^{-10}$$

ATLAS: $B(Bs \rightarrow \mu+\ \mu-) < 1.5 \times 10^{-8}$

[ATLAS-CONF-2013-076]

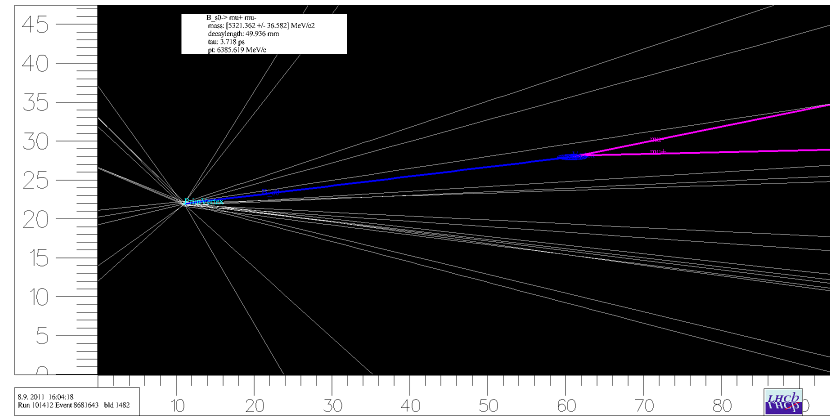
$B_s \rightarrow \mu^+\mu^-$ event reconstructed by CMS detector



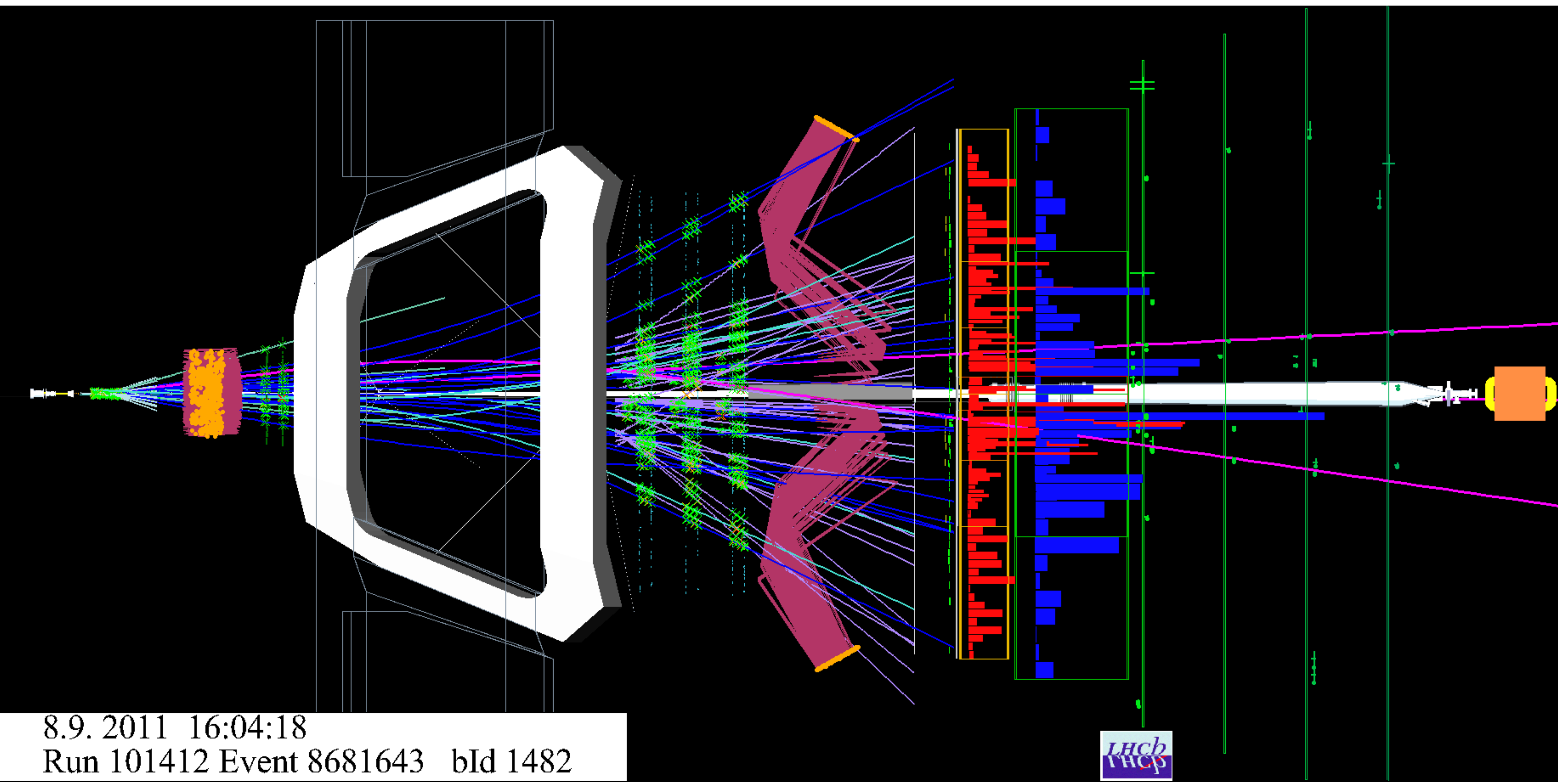


$B_{s(d)} \to \mu^+\mu^-$ at LHCb

Secondary vertex reconstruction



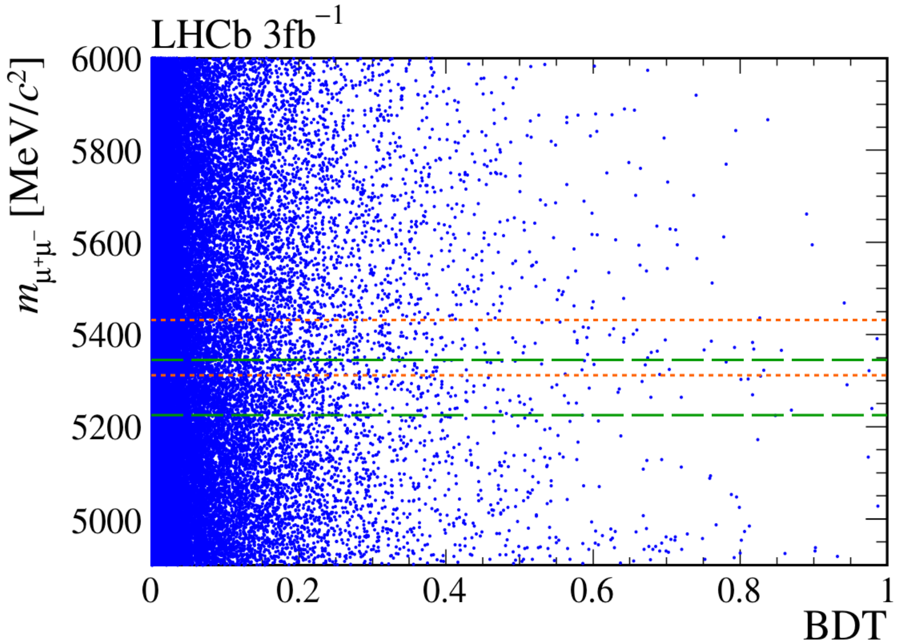
A typical Bs $\to \mu\mu$ decay candidate event



$B_{s(d)} \to \mu^+\mu^-$ at LHCb

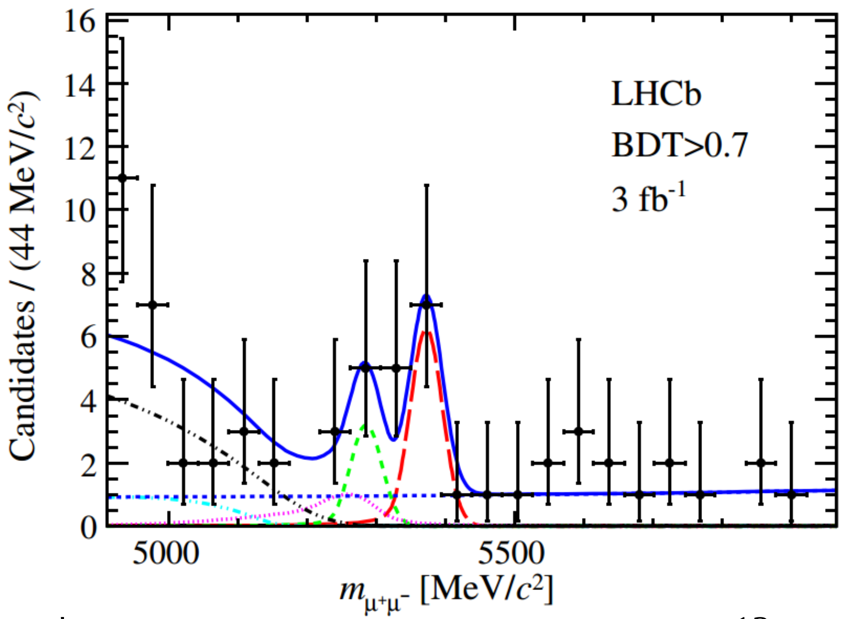
PRL 111 (2013) 101805

- **Normalise** to $B_s \to J/\Psi\ \Phi$, $B^+ \to J/\Psi\ K^+$, $B^0 \to K\pi$
- **Background rejection** key for rare decay searches → use **multivariate classifiers (BDTs)** and tight particle identification requirements
- BDT calibrated on B → hh and the $\mu^+\mu^-$ mass. All points in mass window are used in result, but only BDT > 0.7 shown below
- Search in a two dimensional plane of invariant mass and BDT (blind analysis)
- Unbinned maximum likelihood (UML) fit in case of signal, CLs method for the limits



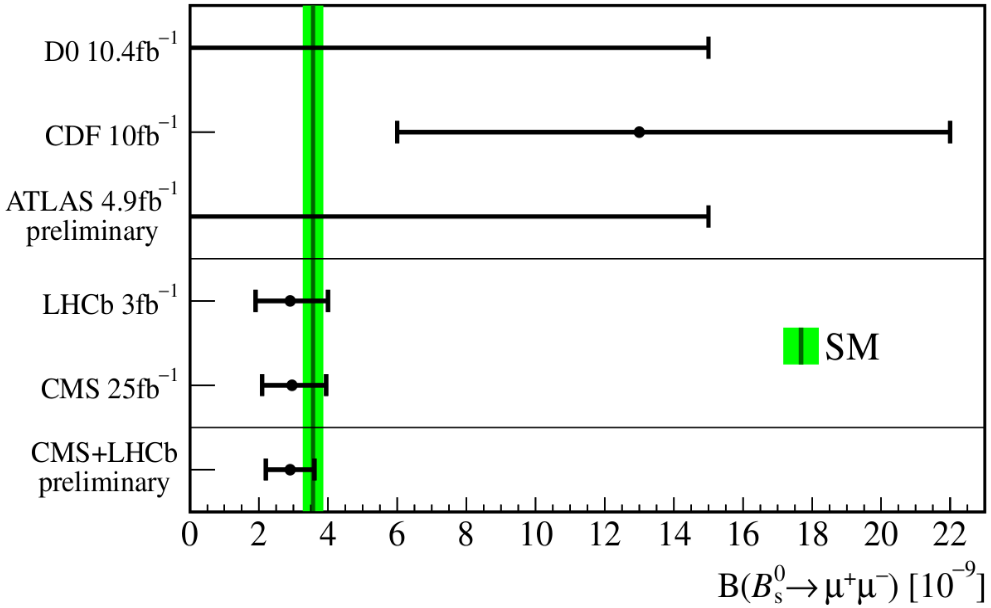
3 fb^{-1}, 4σ / 2σ significance

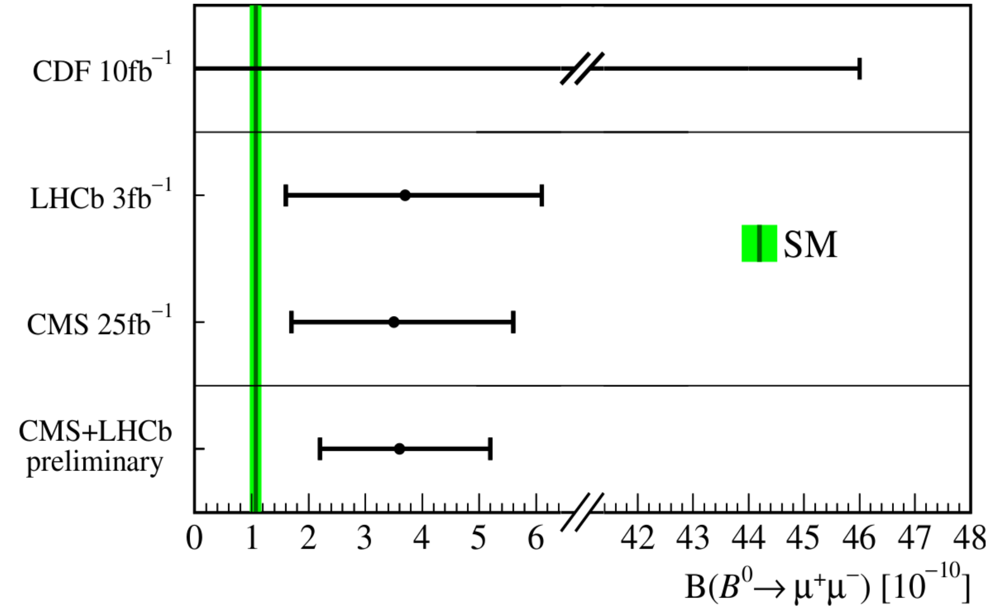
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 2.9^{+1.1}_{-1.0}(stat)^{+0.3}_{-0.1}(syst) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = 3.7^{+2.4}_{-2.1}(stat)^{+0.6}_{-0.4}(syst) \times 10^{-10}$$



$B_s \to \mu^+\mu^-$: CMS+LHCb average

[LHCb-CONF-2013-012, CMS-PAS-BPH-13-007]





Naive combination (central value, no significance assessment)

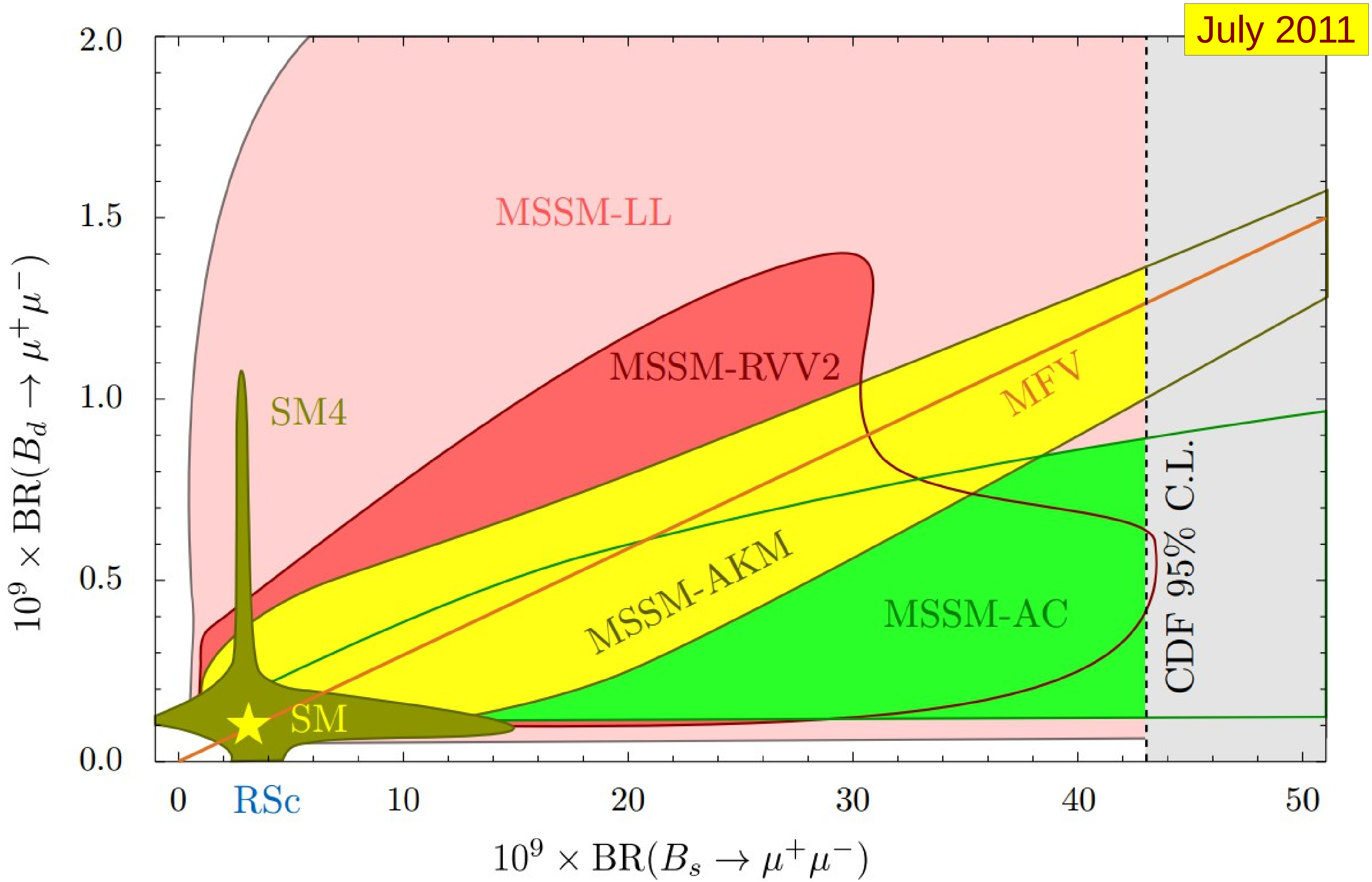
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 2.9 \pm 0.7 \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = 3.6^{+1.6}_{-1.4} \times 10^{-10}$$

Work is ongoing to do a **full combination** of LHCb and CMS measurements: combined fit to the two datasets, sharing of all PDFs etc.

$B_s \to \mu^+\mu^-$ in excellent agreement with SM prediction, $B_d \to \mu^+\mu^-$ shows small excess (still < 2σ)

$B_s \to \mu^+\mu^-$: closing up on NP

D.Straub arXiv:1205.6094



$B_s \rightarrow \mu^+\mu^-$: closing up on NP

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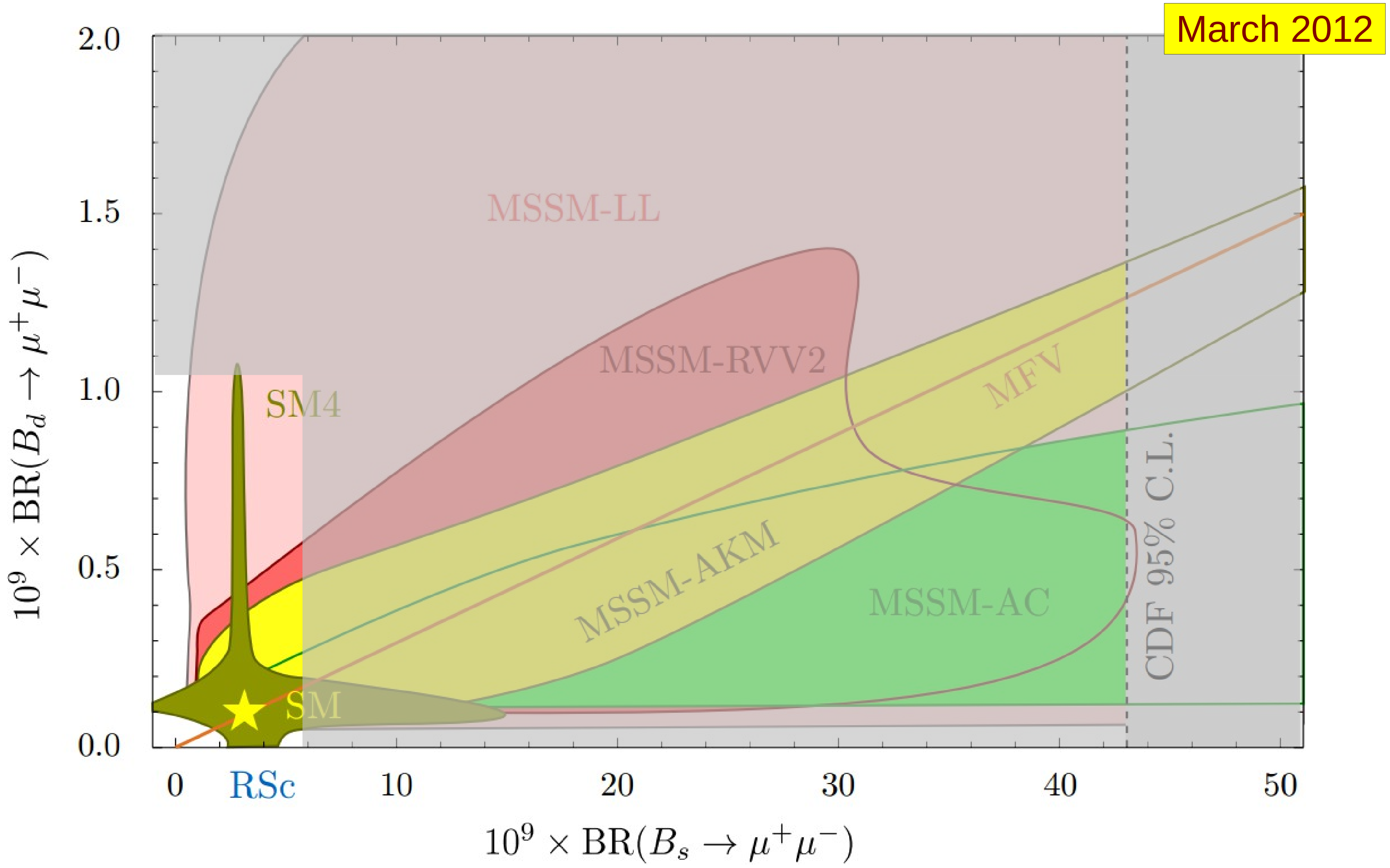

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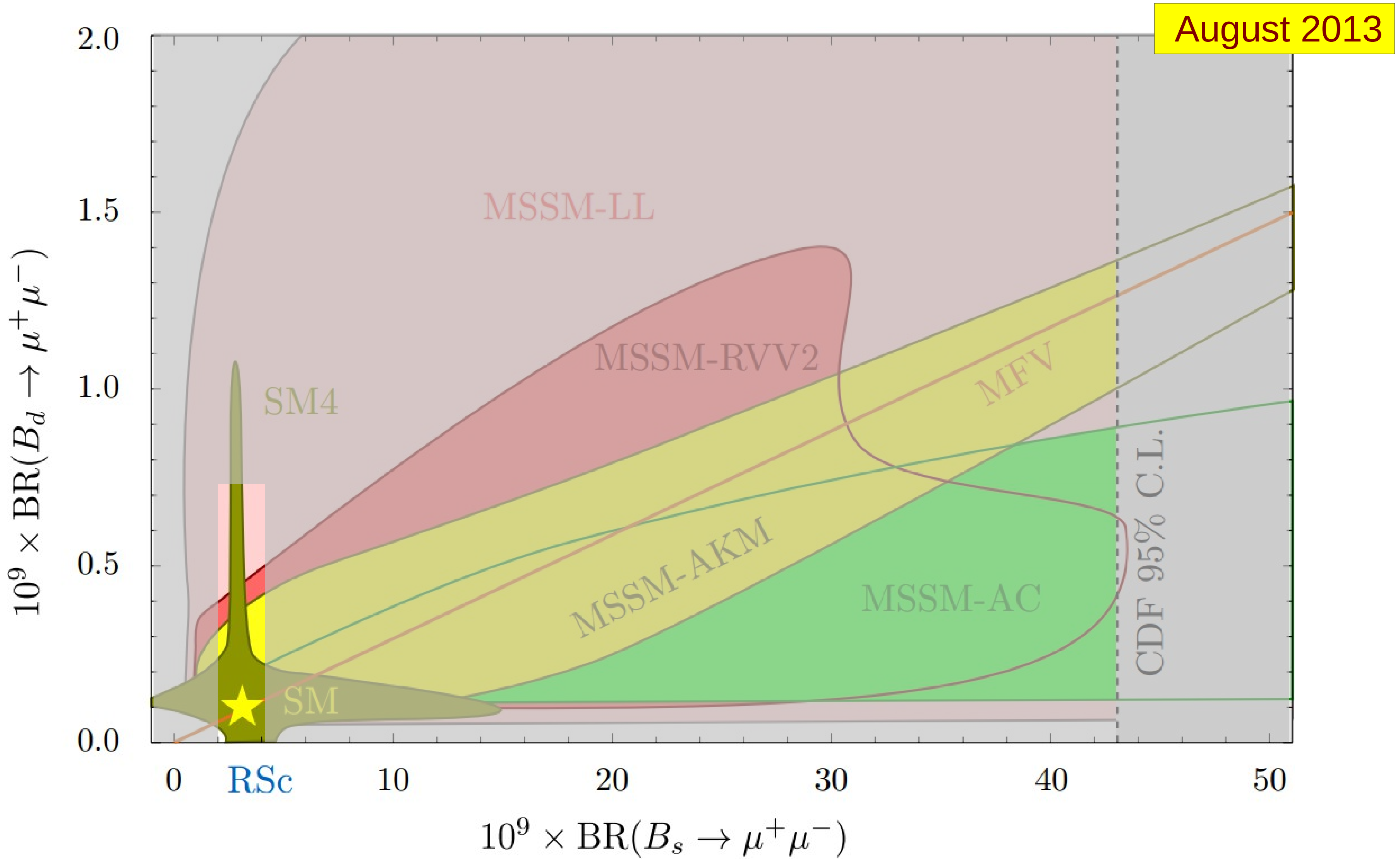


*"**The value of a negative result […]** Arguably, this year's most significant result from CERN was a negative one. […] This kind of result doesn't generate the same media attention that comes with a discovery, but by focusing theoretical attention in the right place it can be very positive for the evolution of the field" Rolf Heuer*

$$B \to s\, l^+ l^-$$

$B \to s\,\mu^+\mu^-$ Introduction

$b \to s/d\, l^+l^-$ FCNC processes represent a **very rich environment**.

The three/four particles final states are **special** as:

- They allow for a **wealth of angular observables, rates and asymmetries sensitive to NP**
- Experimentally **clean signatures**
- Theoretically **well predicted**

Sensitive to magnetic, vector, and axial semileptonic penguin operators: O7, O9, O10

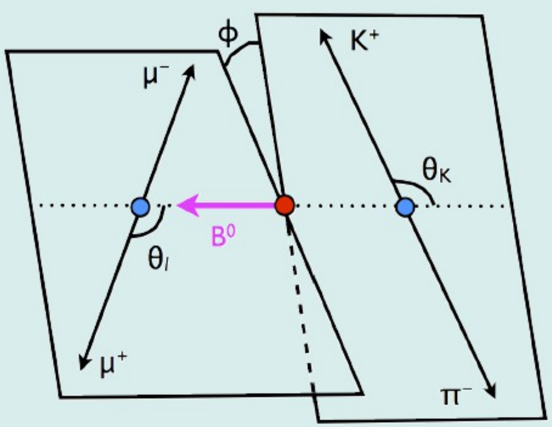
$B \to K^* \mu^+\mu^-$ at LHCb

JHEP 08 (2013) 131

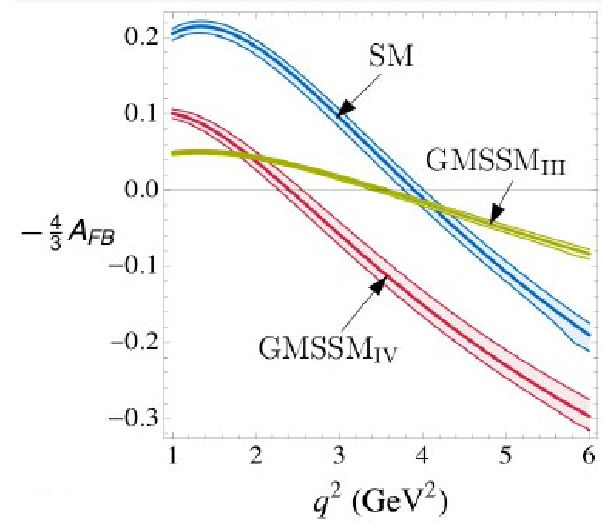
Decay described in three angles (θ_l, θ_K, φ) and dimuon mass q^2

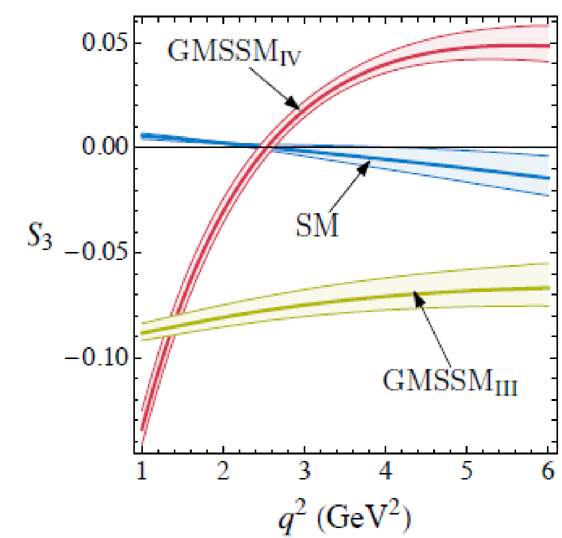
Fit to θ_l, θ_K, φ and q^2 to extract the interesting parameters

$$\frac{1}{\Gamma}\frac{d^4\Gamma}{d\cos\theta_\ell\, d\cos\theta_K\, d\hat{\phi}\, dq^2} = \frac{9}{16\pi}\Big[F_L\cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K) + F_L\cos^2\theta_K(2\cos^2\theta_\ell-1) + \frac{1}{4}(1-F_L)(1-\cos^2\theta_K)(2\cos^2\theta_\ell-1) + S_3(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\cos 2\hat{\phi} + \frac{4}{3}A_{FB}(1-\cos^2\theta_K)\cos\theta_\ell + S_9(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\sin 2\hat{\phi}\Big]$$



Altmannshofer et al.
[JHEP 01 (2009) 019





- Forward-backward asymmetry $\mathbf{S_6 = 4/3\, A_{FB}}$
- Transverse asymmetry $\mathbf{S_3 = (1-F_L)A_T^2}$
- Fraction of longitudinal K* polarization $\mathbf{F_L}$
- CP asymmetry $\mathbf{S_9}$

B → K* μ⁺μ⁻ at LHCb

JHEP 08 (2013) 131

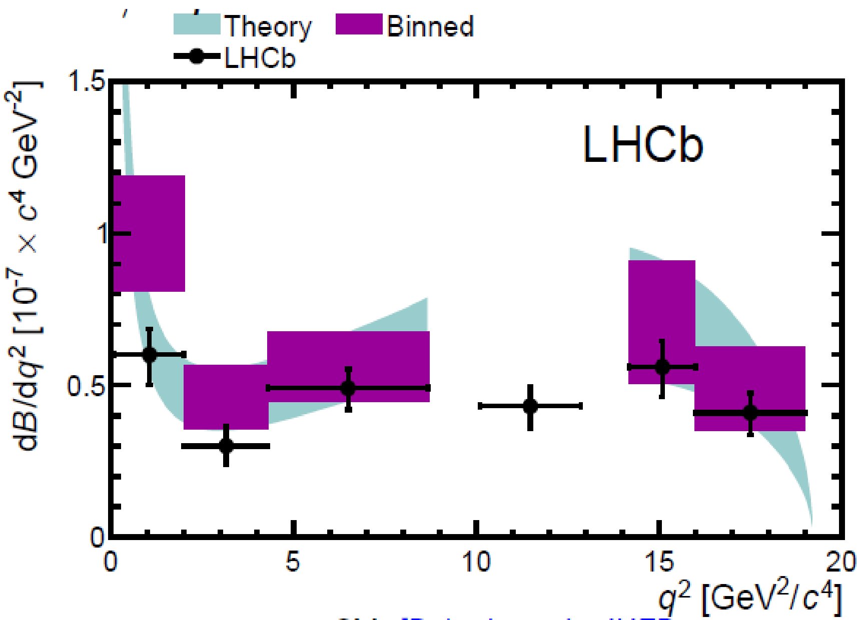
Select B → K* $\mu^+\mu^-$ using **BDT selection**

Cut on J/Ψ and Ψ(2S): these events are used to study systematic effects

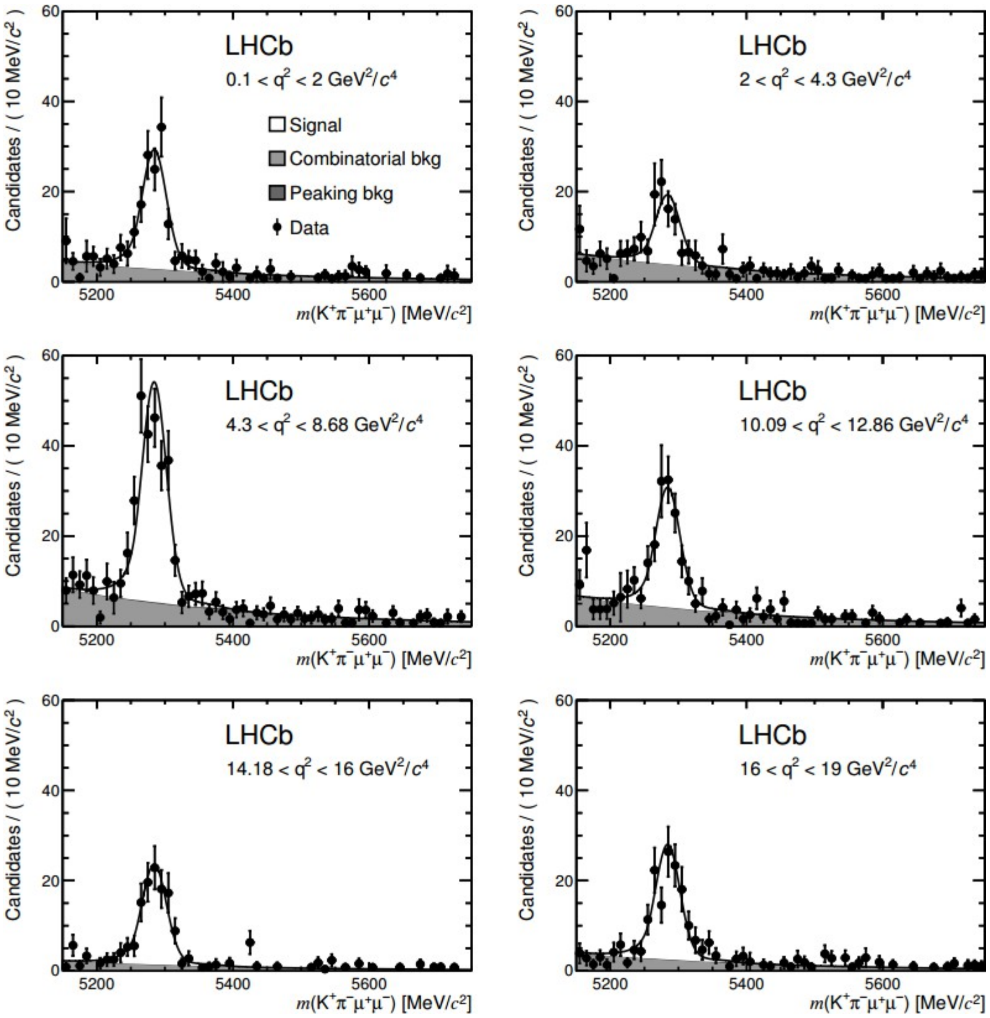
Normalize to $B^0 \rightarrow J/\Psi K^*$

Observe **883 ± 34 events in 1 fb^{-1}**

Bin in $q^2 = m(\mu^+\mu^-)^2$ in order to measure all the quantities as a function of q^2



SM: [Bobeth et al., JHEP 1107:067,2011]



B → K* μ⁺μ⁻ at ATLAS and CMS

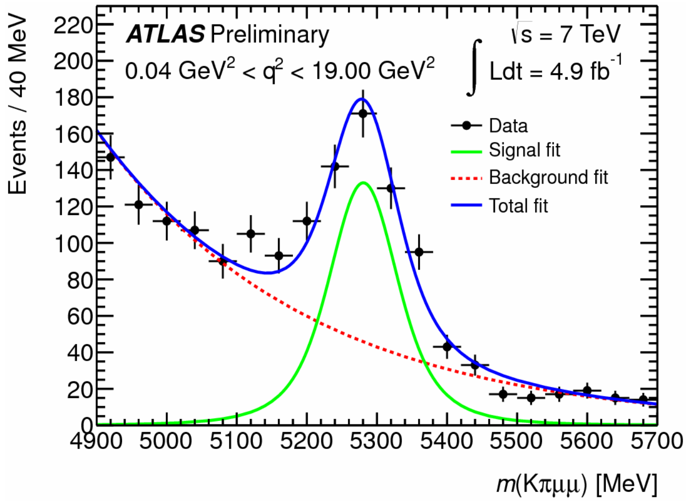
Integrating over two of three angles

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\phi} = \frac{1}{2\pi}\left(1 + S_3\cos 2\phi + A_9 \sin 2\phi\right) \ ,$$

$$\frac{1}{\Gamma}\frac{d\Gamma}{\mathrm{d}\cos\theta_K} = \frac{3}{2}F_\mathrm{L}\cos^2\theta_K + \frac{3}{4}(1-F_\mathrm{L})(1-\cos^2\theta_K) \ ,$$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell} = \frac{3}{4}F_\mathrm{L}(1-\cos^2\theta_\ell) + \frac{3}{8}(1-F_\mathrm{L})(1+\cos^2\theta_\ell) + A_\mathrm{FB}\cos\theta_\ell$$

ATLAS [CONF-2013-038]

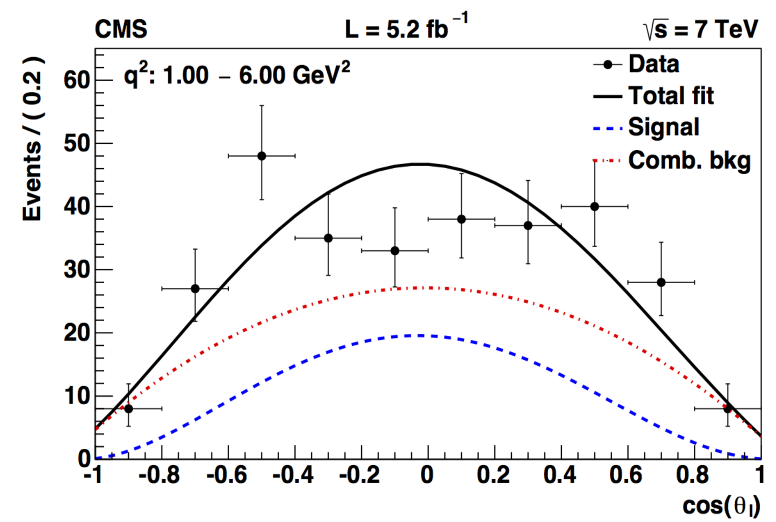


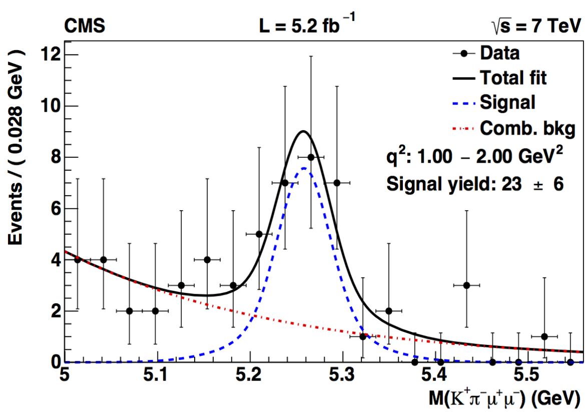
Cut out J/ψ and ψ(2S)

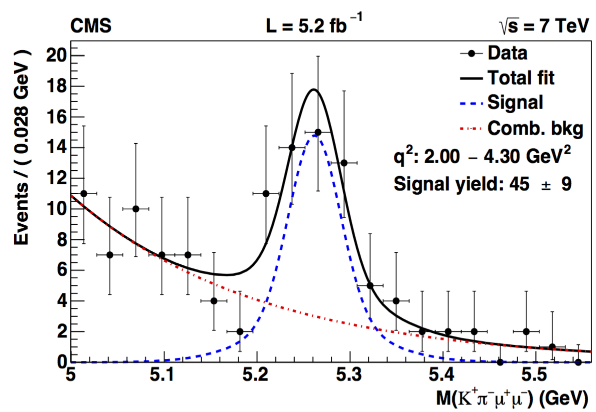
CMS observe 415±30 events in 5.2 fb^{-1} (2011)

ATLAS 466±34 in 4.9 fb^{-1}

CMS [PLB 727 (2013) 77, arXiv:1308.3409]





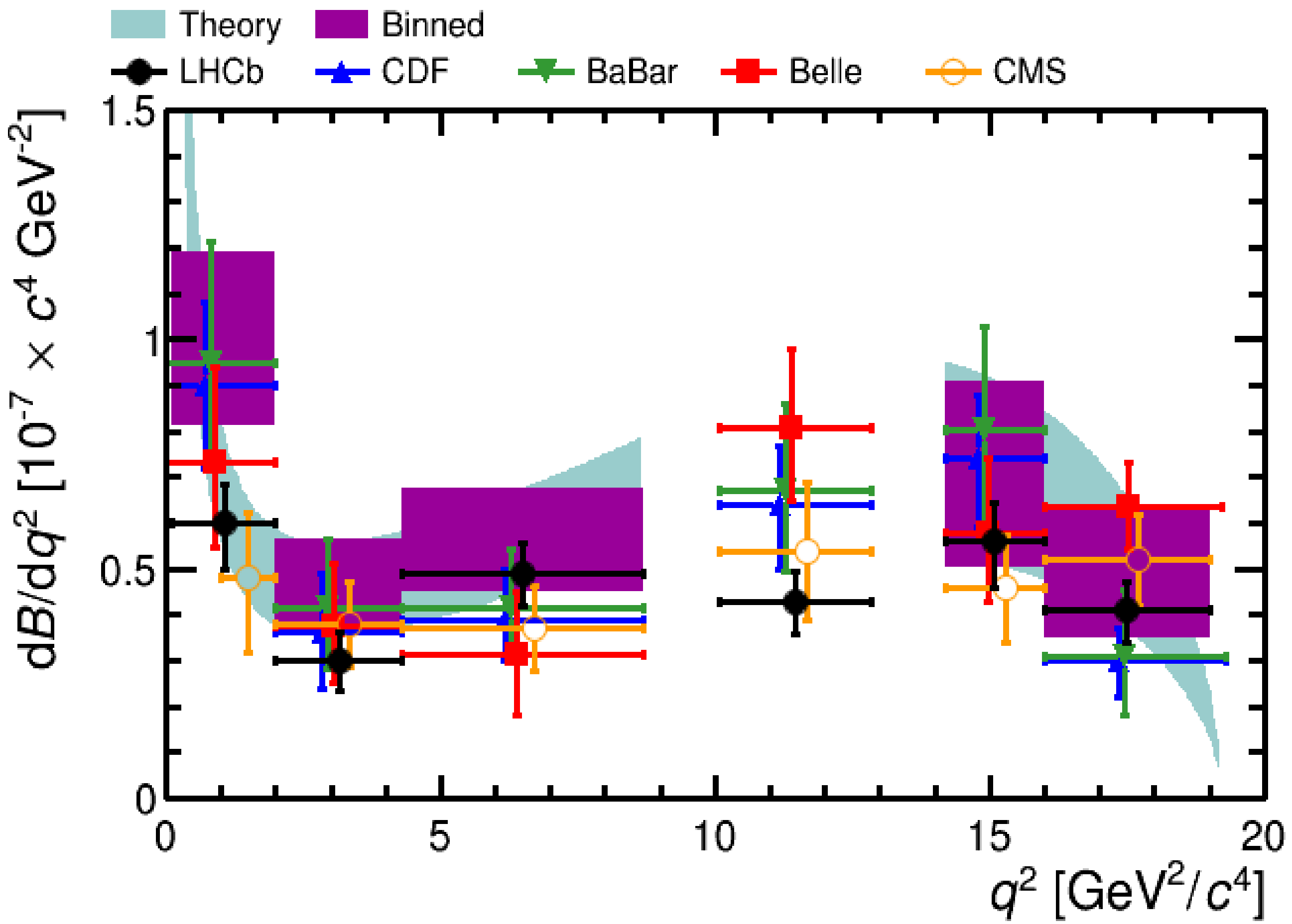


B→K* μ⁺μ⁻ branching fractions

Comparison of all the BF measurements

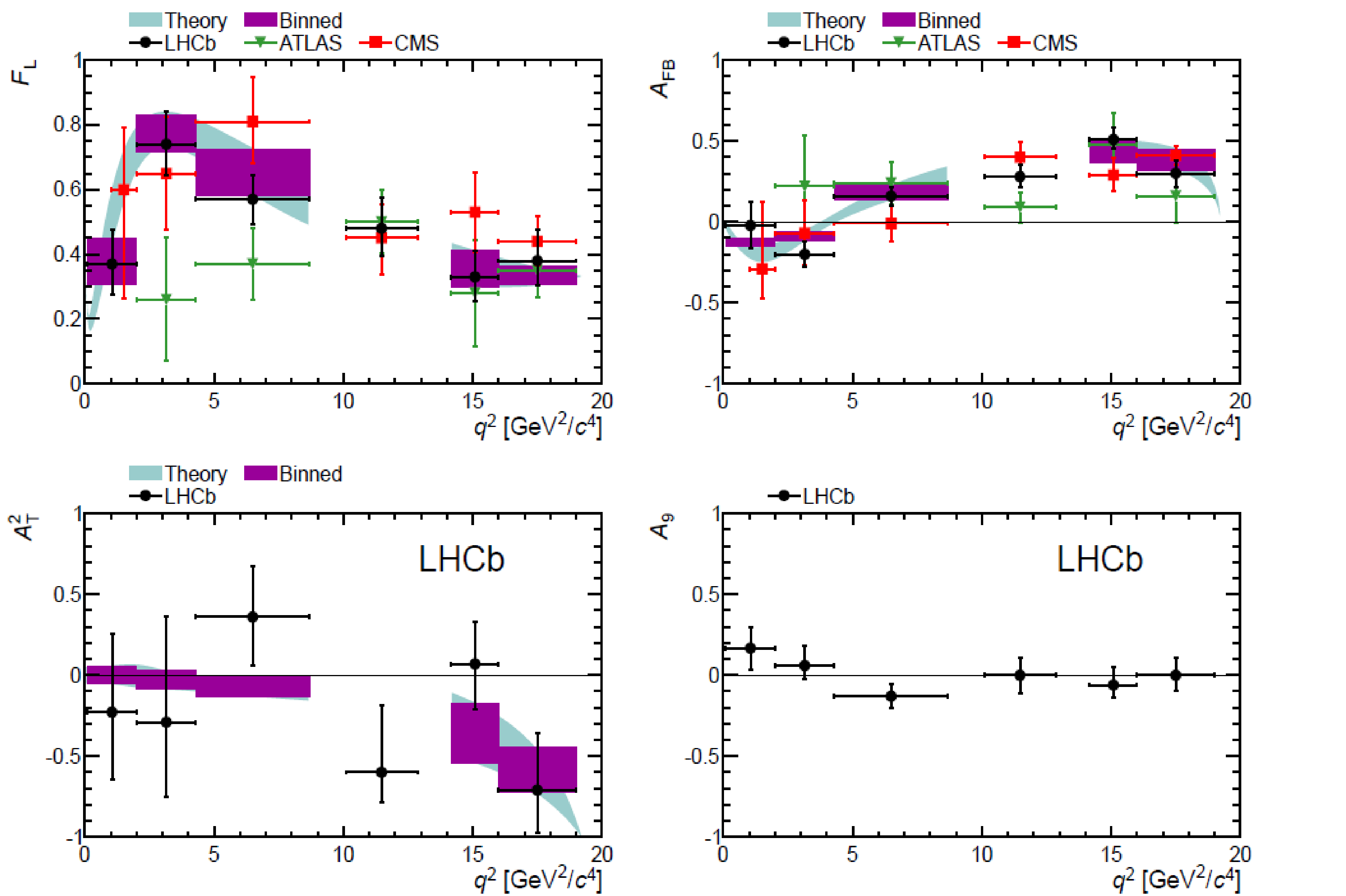
No evident discrepancy with SM

LHCb [JHEP 08 (2013) 131, arXiv:1304.6325]
CMS [PLB 727 (2013) 77, arXiv:1308.3409]
CDF [CONF Note 10894]
Belle [PRL 103 (2009) 171801]
BaBar [PRD 86 (2012) 032012]
ATLAS [CONF-2013-038]
Theory (SM) [JHEP 1107 (2011) 067]



B→K* μ+μ- angular distribution

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



Theory prediction from Bobeth et al. [JHEP 07 (2011)] and references therein.

P'$_5$ anomaly

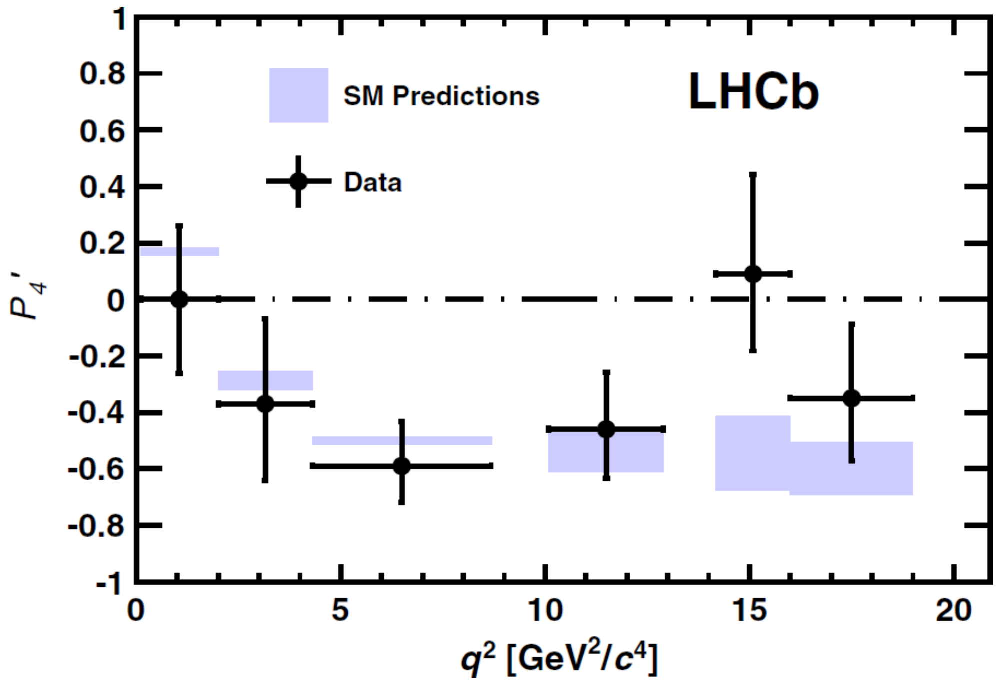
PRL 111 191801 (2013)

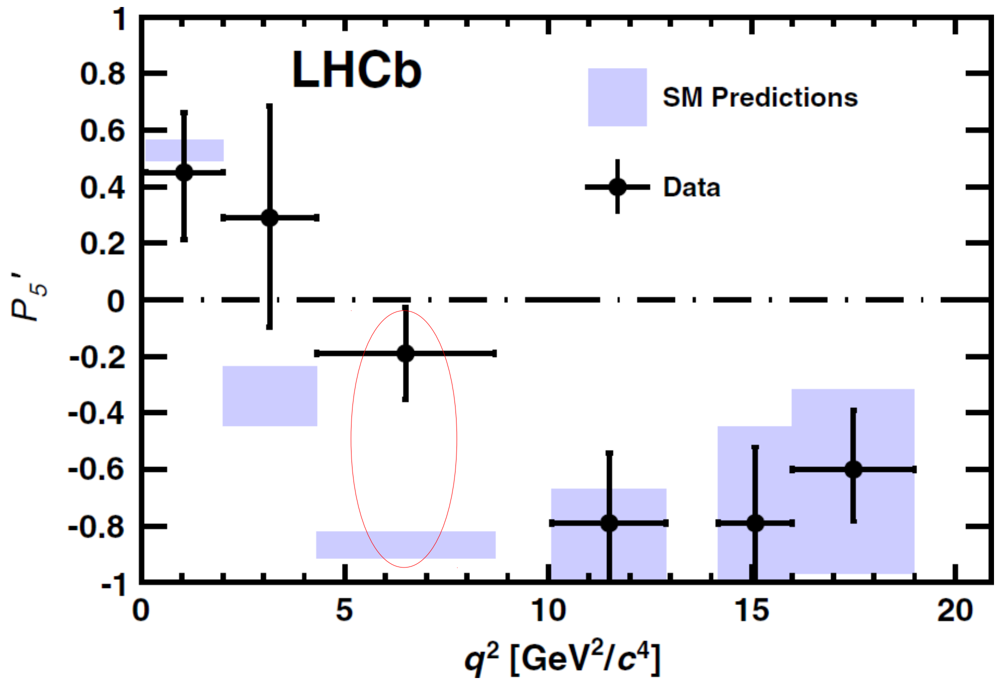
LHCb also measured

$$P'_{4,5} = \frac{S_{4,5}}{\sqrt{F_L(1-F_L)}}$$

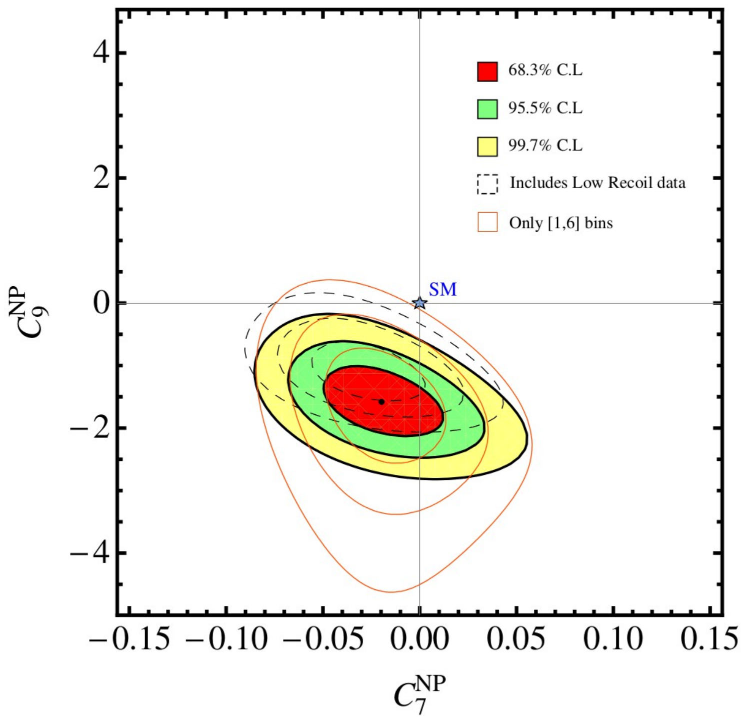
which are quite f**ree from form-factor uncertainties** [Decotes-Genon et al. JHEP 05 (2013) 137]

Local discrepancy in P'$_5$ at 3.7σ (probability that at least one bin varies by this much is 0.5%



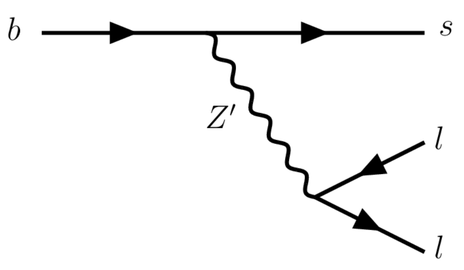


P'$_5$ anomaly



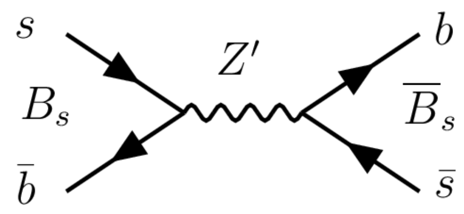
Many theoretical papers to understand data

Altmannshofer & Straub perform a global analysis and find discrepancies at the level of 3σ. Data best described by **modified C_9**, by introducing a **flavour-changing Z' boson** at O(1TeV or higher). [EPJC 73 2646 (2013), Gaul, Goertz & Haisch, JHEP 01 (2014) 069]



Data could be also explained by floating **form-factor uncertainties**. In this way the discrepancy can be reduced to ≈ 2σ. [Jaeger & Camalich, JHEP 05 (2013) 043]

Lattice QCD predictions + **measurements in related channels** can help clarify the situation



Differential BFs of $B \rightarrow K^{(*)} \mu^+\mu^-$

[arXiv:1403.8044]

Reconstruct $B^+ \rightarrow K^+\mu^+\mu^-$

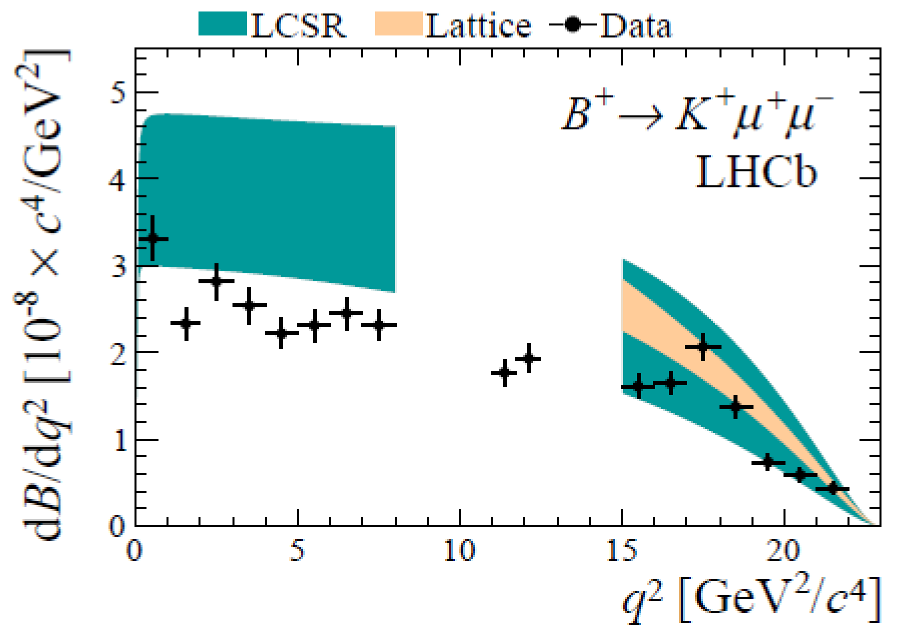
$B^+ \rightarrow K^+ J/\psi$ is taken as normalisation mode.

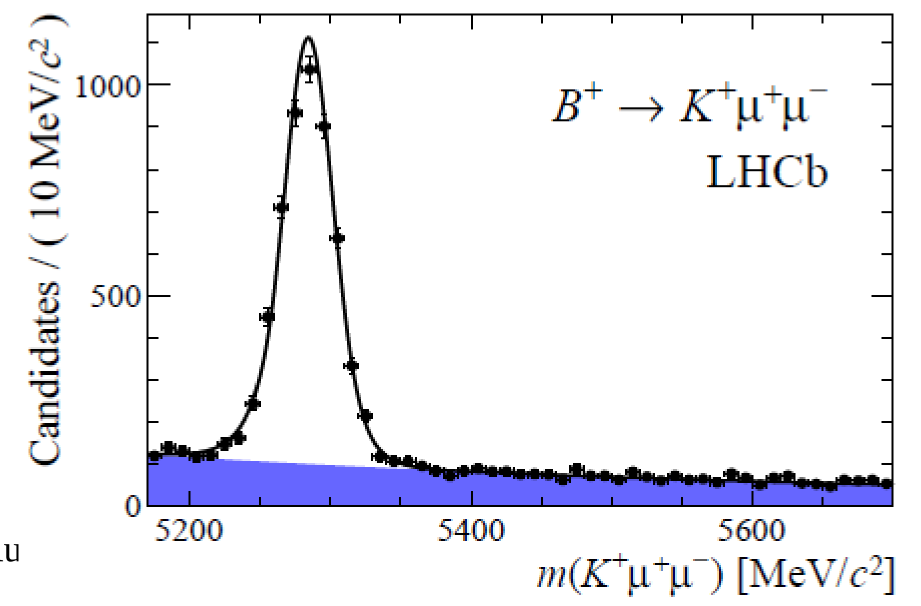
Removing the charmonia, one gets the mass plot

. . . and the differential branching fraction versus $q^2 = m^2(\mu^+\mu^-)$

Standard Model prediction from
JHEP 07 (2011) 067], [JHEP 01 (2012) 107]

Lattice input from
[PRL 111 (2013) 162002], [arXiv:1310.3887]





Differential BFs of $B \to K^{(*)} \mu^+\mu^-$

[arXiv:1403.8044]

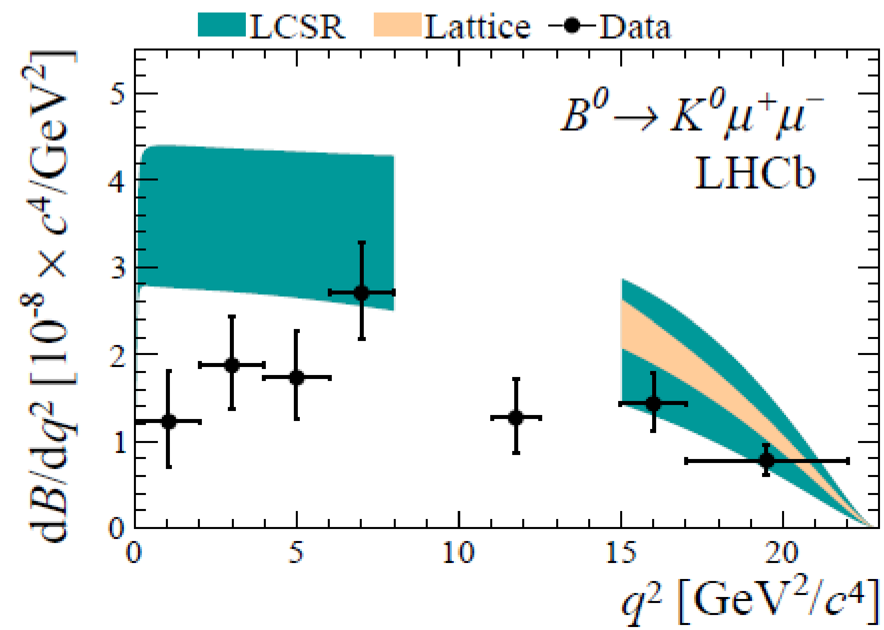
Reconstruct $B^0 \to K^0\mu^+\mu^-$ (K^0 from $K_S \to \pi^+\pi^-$)

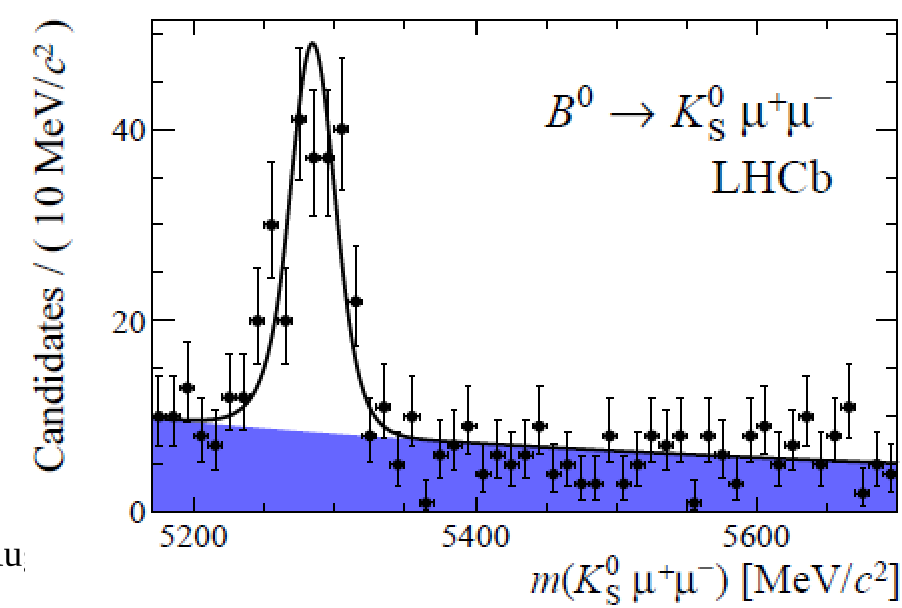
$B^0 \to K_S J/\psi$ is taken as normalisation mode.

Much lower statistics due to high K_S lifetime.

The theoretical expectation of dB/dq^2 is the same up to $\tau_{B^0} = \tau_{B^+}$

The BFs are compatible with the SM expectation, but on the low side

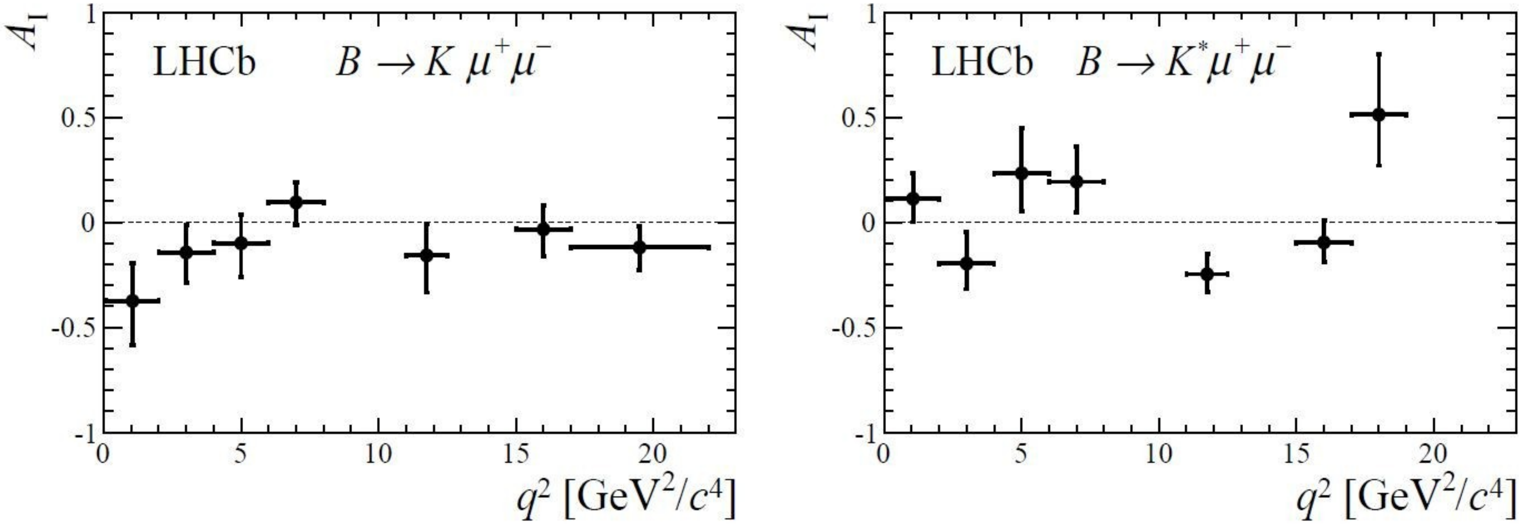




B→K(*) μ⁺μ⁻ isospin asymmetry

[arXiv:1403.8044]

$$A_I = \frac{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) - \frac{\tau_0}{\tau_+}\mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) + \frac{\tau_0}{\tau_+}\mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)}$$



SM prediction is close to zero

The isospin asymmetry is compatible with zero at the 1.5σ level

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

LHCb: arXiv:1406.6482

Measurements of **different dilepton** final states in $b \to s\, l^+l^-$ can test the lepton and flavor couplings simultaneously.

Consider the **ratio of decay rates** for $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+e^+e^-$

$$R \equiv \frac{\int_{4m_\mu^2}^{q^2_{\max}} dq^2 \frac{d\Gamma(B^+ \to K^+\mu^+\mu^-)}{dq^2}}{\int_{4m_e^2}^{q^2_{\max}} dq^2 \frac{d\Gamma(B^+ \to K^+e^+e^-)}{dq^2}}$$

Hiller, Kruger: 0310219

Enable **more precise** predictions than the O(30%) theoretical error in the single BR!

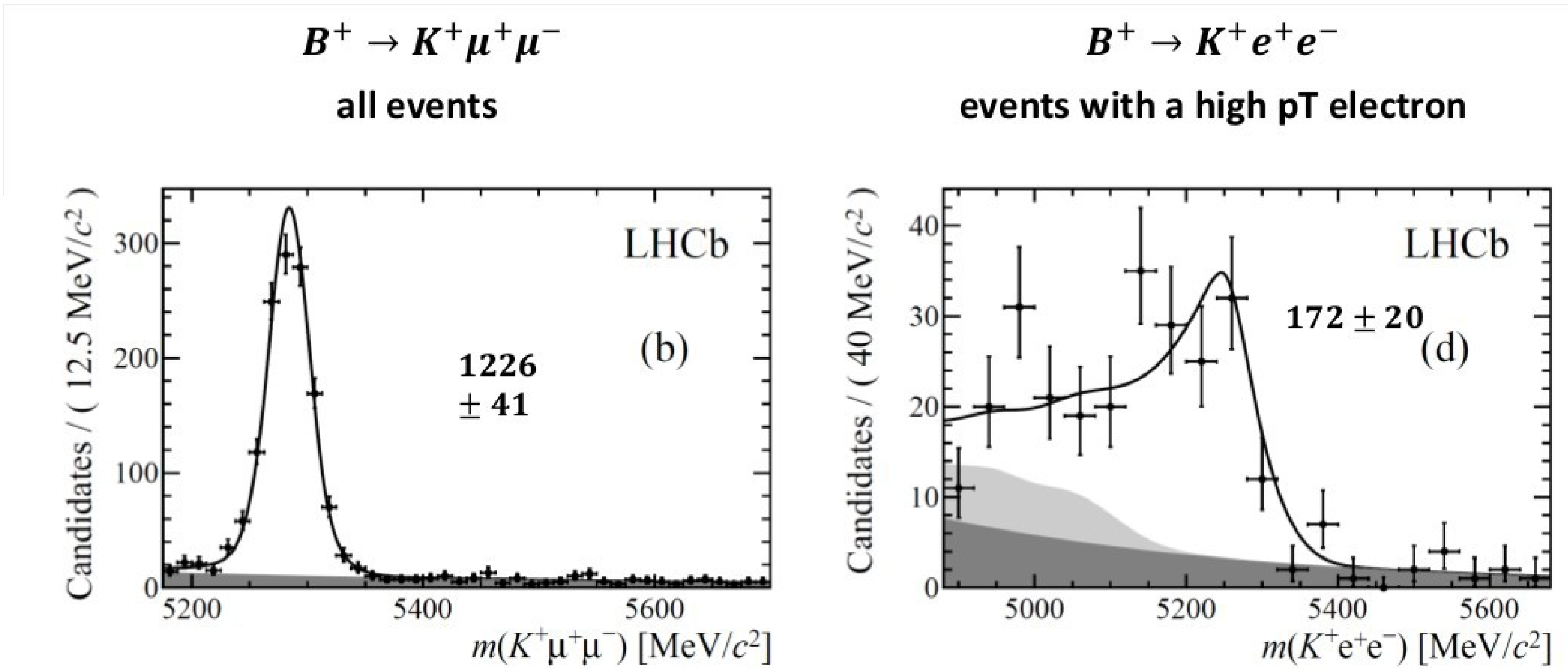
Standard model: $R_H^{SM} = 1 + O(m_\mu^2/m_b^2)$

Equality of coupling is concept of **lepton universality.**

Enhancement for either muon or electron modes can come from anything which breaks lepton universality, for example **R-parity violating models**.

LHCb: arXiv:1406.6482

$B^+ \to K^+ \mu^+\mu^-$ vs $B^+ \to K^+ e^+e^-$ at LHCb



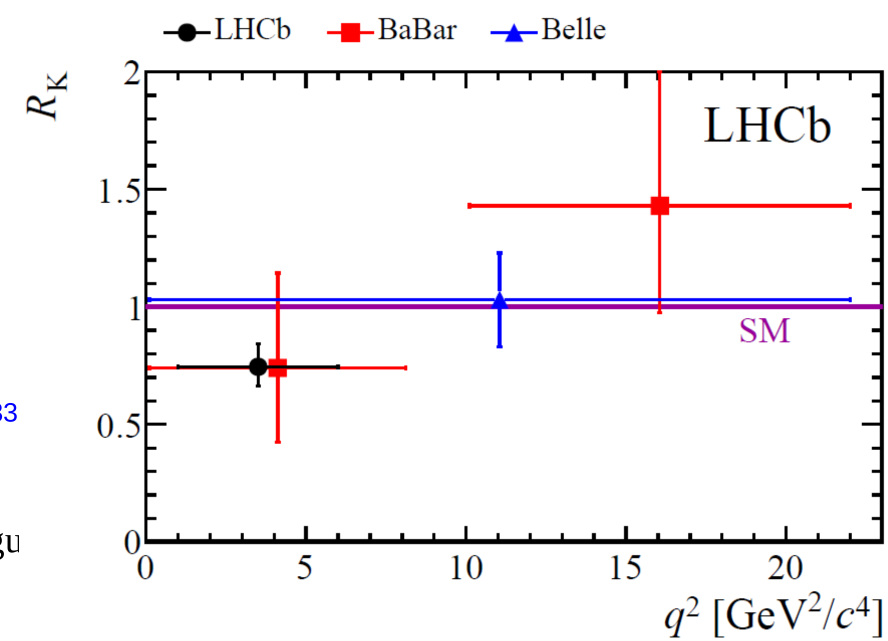
e^+e^- peak very large and distorted because the energy degradation (Bremsstrahlung emission) and pore EC resolution

Trigger based on muons signature → much more $B^+ \to K^+ \mu^+\mu^-$ events

$$R_K = 0.745^{+0.090}_{-0.074}(stat) \pm 0.036(syst)$$

(2.6 σ from 1)

BABAR arXiv: 1204.3933
Belle, arXiV: 0904.0770
LHCb: arXiv:1406.6482



$$b \to s\,\gamma$$

b → s γ transition

No tree diagram → suppressed

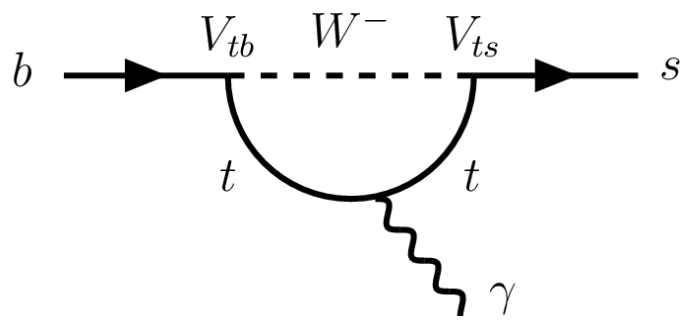
First penguin ever observed (92) by CLEO

Experiment (WA): BF = (3.40 ± 0.21) · 10^{-4}

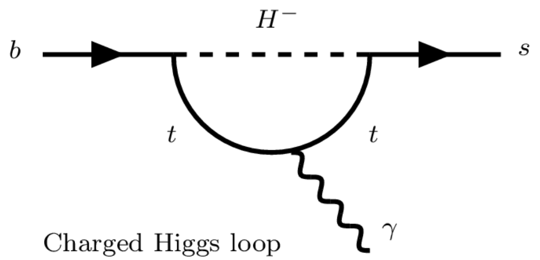
SM: BF = (3.15 ± 0.23) · 10^{-4}
[Misiak et al., hep-ph/0609232]

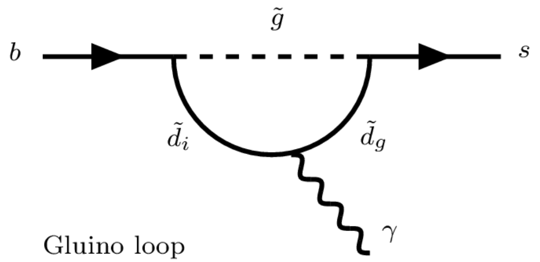
Strong **constraint** on New Physics

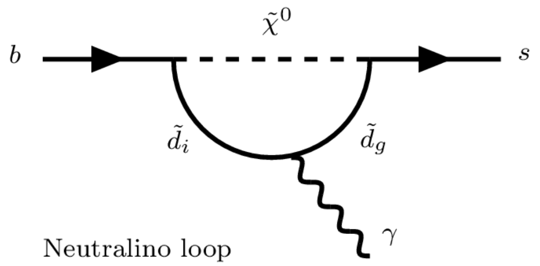
SM diagram



NP contributions





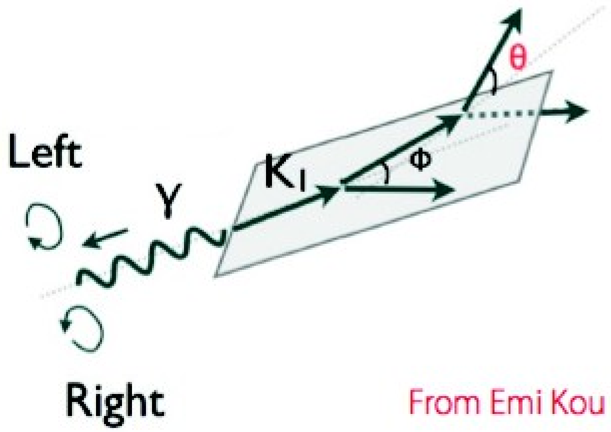


Photon polarization in b → sγ transition

Polarisation so far **unobserved**.

The SM predicts the photon in b → s is left-handed (charged current interaction). Naively

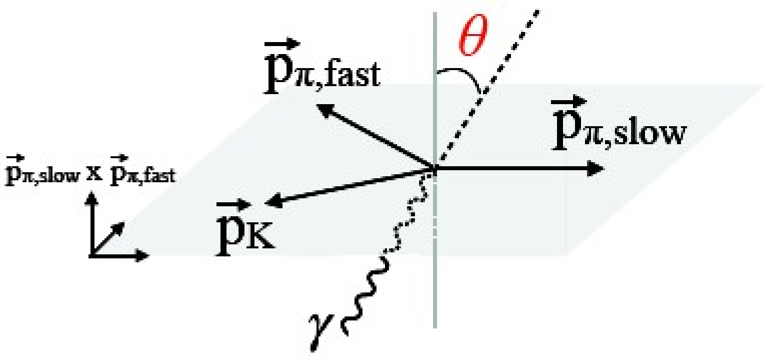
$$r = \frac{C'_{7\gamma}}{C_{7\gamma}}, \qquad r_{SM} \simeq \frac{m_s}{m_b}$$



Gluons contribute a few percent
[Ball & Zwicky PLB642:478,2006]

Right-handed operators could contribute

Photon polarization can be measured studying
$B^+ \to K^{**}(K^+\pi^+\pi^-)\,\gamma$
[Gronau & Pirjol, PRD 66 (2002) 054008]



Can infer the photon polarisation from the **up-down asymmetry** of the photon direction in the $K^+\pi^+\pi^-$ rest-frame. Unpolarised photons would have no asymmetry

$$\mathcal{A}_{ud} \equiv \frac{\int_0^1 d\cos\theta \frac{d\Gamma}{d\cos\theta} - \int_{-1}^0 d\cos\theta \frac{d\Gamma}{d\cos\theta}}{\int_{-1}^1 d\cos\theta \frac{d\Gamma}{d\cos\theta}}$$

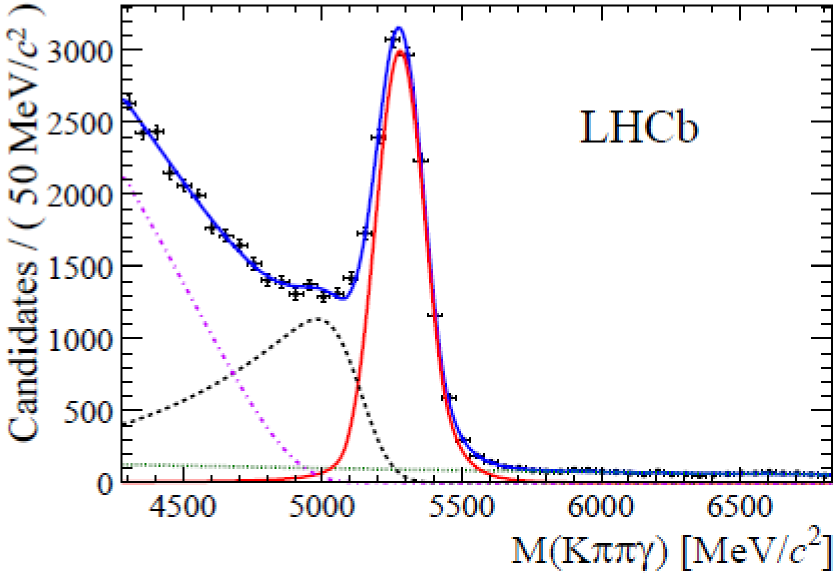
$B^+ \to K^+\pi^+\pi^- \gamma$ at LHCb

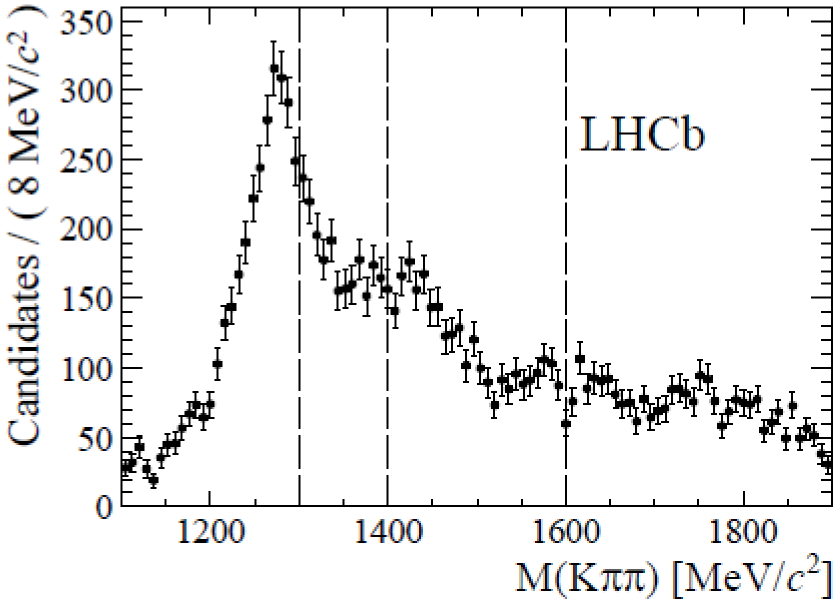
[PRL 112 (2014) 161801]

At **LHCb** we look at $B^+ \to K^+\pi^+\pi^- \gamma$ decays using calorimeter photons.

Observe **13000 signal candidates** in 3 fb^{-1}

There are a large number of overlapping resonances in the $m(K^+\pi^+\pi^-)$ mass spectra. No attempt is made to separate these in the analysis, we simply bin in 4 bins of $m(K^+\pi^+\pi^-)$.





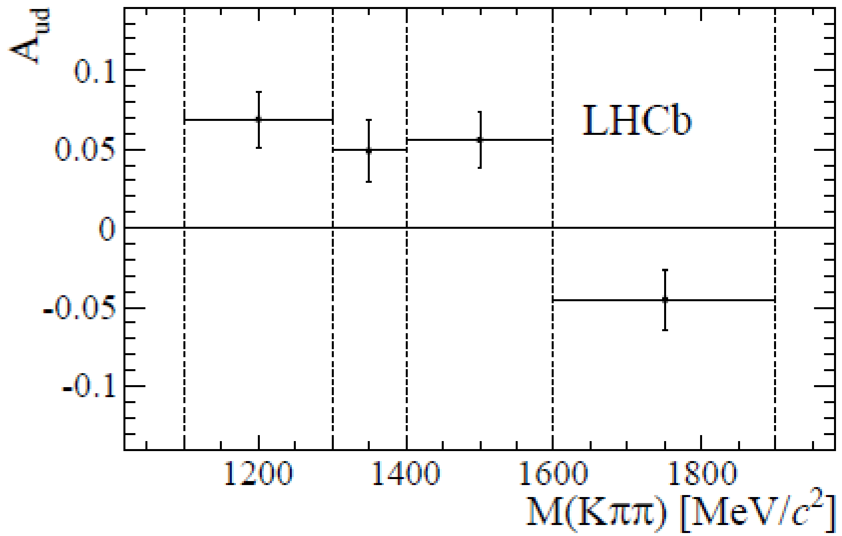
$B^+ \to K^+\pi^+\pi^- \gamma$ at LHCb

[PRL 112 (2014) 161801]

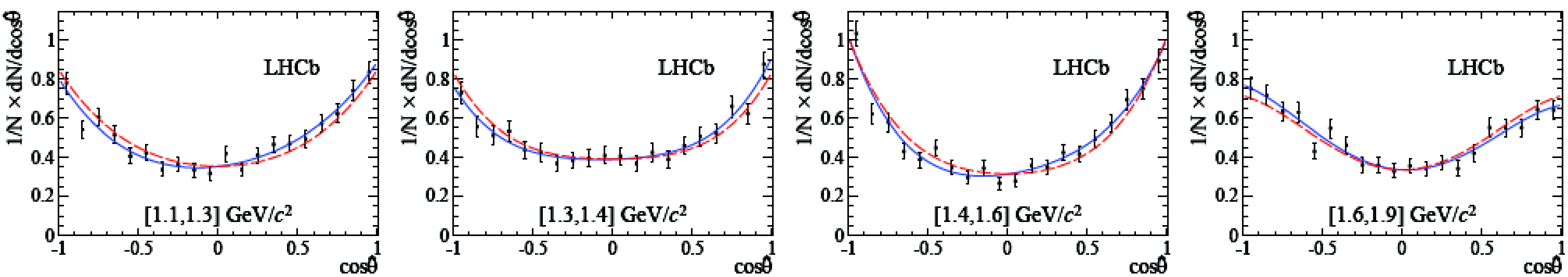
Combining the 4 bins, the photon is observed to be polarised at **5.2σ**.

Unfortunately you need to understand the hadronic system to know if the polarisation is left-handed, as expected in the SM.

First observation of photon polarisation in $b \to s$ decays



Best Fit, Fit with (C'7 – C7)/(C'7 + C7) = 0



Conclusions

Rare decays are **powerful way to search for new physics** beyond the Standard Model

$B_s \to \mu^+\mu^-$ and $b \to s$ transitions **do not highlight large SUSY effects**. Severe constraints to NP models

Interesting **deviation** from the SM in $B \to K^*\mu\mu$

Many analyses are still to be updated with the full Run I datasest. Many new results to come

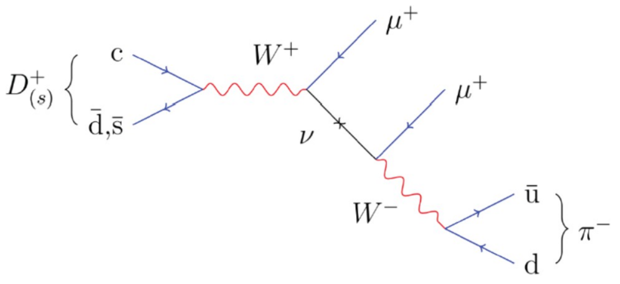
Thank you for the attention!

Spares

Search for Majorana neutrinos in $D^+_{(s)} \to \pi^-\mu^+\mu^+$

PLB 274, 203-212, (2013)

$D^+_{(s)} \to \pi^-\mu^+\mu^+$ decay can occur via leptonic mixing via a **Majorana neutrino** exchange.



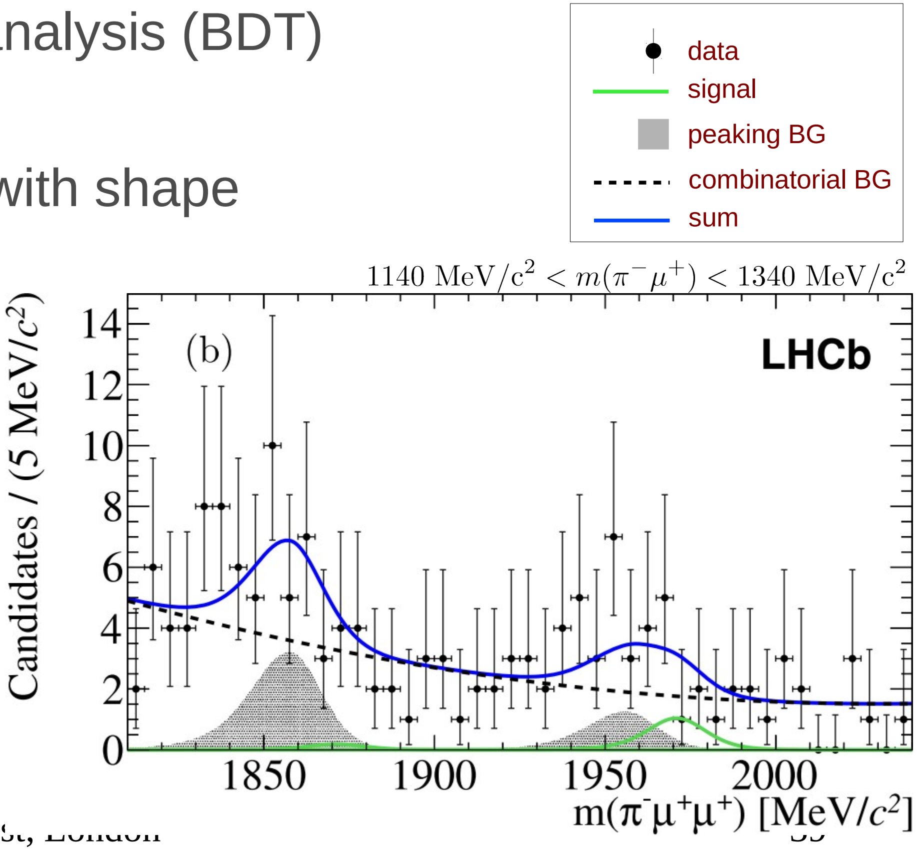
Previous limits was from BaBar 2×10^{-6} and 1.4×10^{-5} for $D^+ \to \pi^-\mu^+\mu^+$ and $D^+_s \to \pi^-\mu^+\mu^+$ respectively

Normalise to $D^+ \to \pi^-\mu^+\mu^+$

Event **selection** with PID cut and multivariate analysis (BDT) using geometric and kinematic variables

Peaking **background** from $D^+ \to \pi^-\pi^+\pi^+$ (gray) with shape extracted from data

Fit in **bins** of $m(\pi^-\mu^+)$ to improve statistical significance



$D^+_{(s)} \to \pi^-\mu^+\mu^+$ decay can occur via leptonic mixing via a **Majorana neutrino** exchange.

Limits are 2.2×10^{-8} and 1.2×10^{-7} for $D^+ \to \pi^-\mu^+\mu^+$ and $D^+_s \to \pi^-\mu^+\mu^+$ respectively

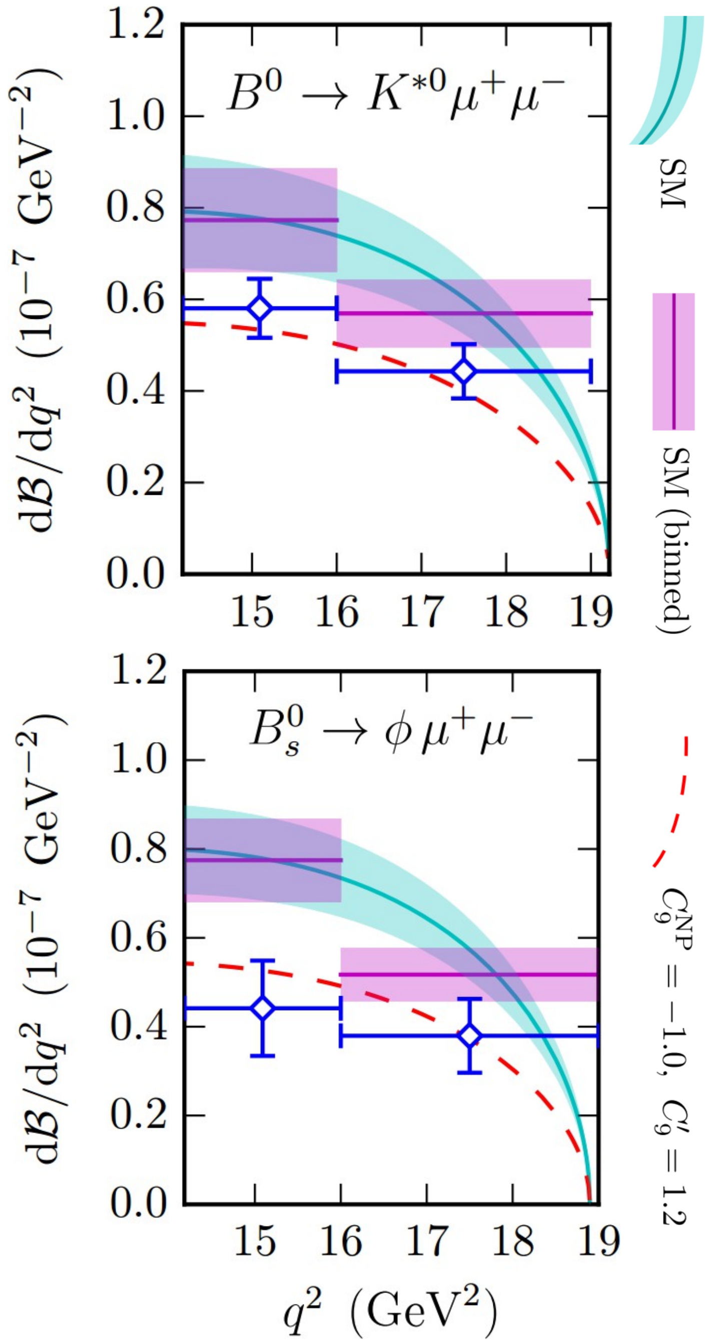
Something new

[arXiv:1403.8044]

Branching Fraction measurements at high q^2 in **tension with SM** predictions from the Lattice, and consistent with best fit point for NP from low q^2

→ NP or unaccounted QCD effects?
Something new? or something new to understand?

Lattice QCD predictions + measurements in related channels (e.g b → d μ+ μ−) (to reveal information on MFV nature of NP) can help clarify the situation at high q^2



See: Zwicky-Lyon: arXiv:1406.0566