A promenade through selected LHCb results

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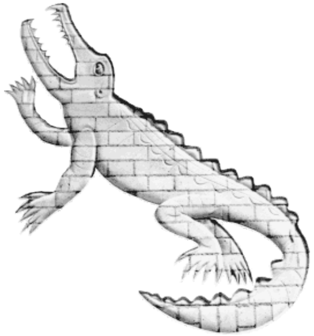
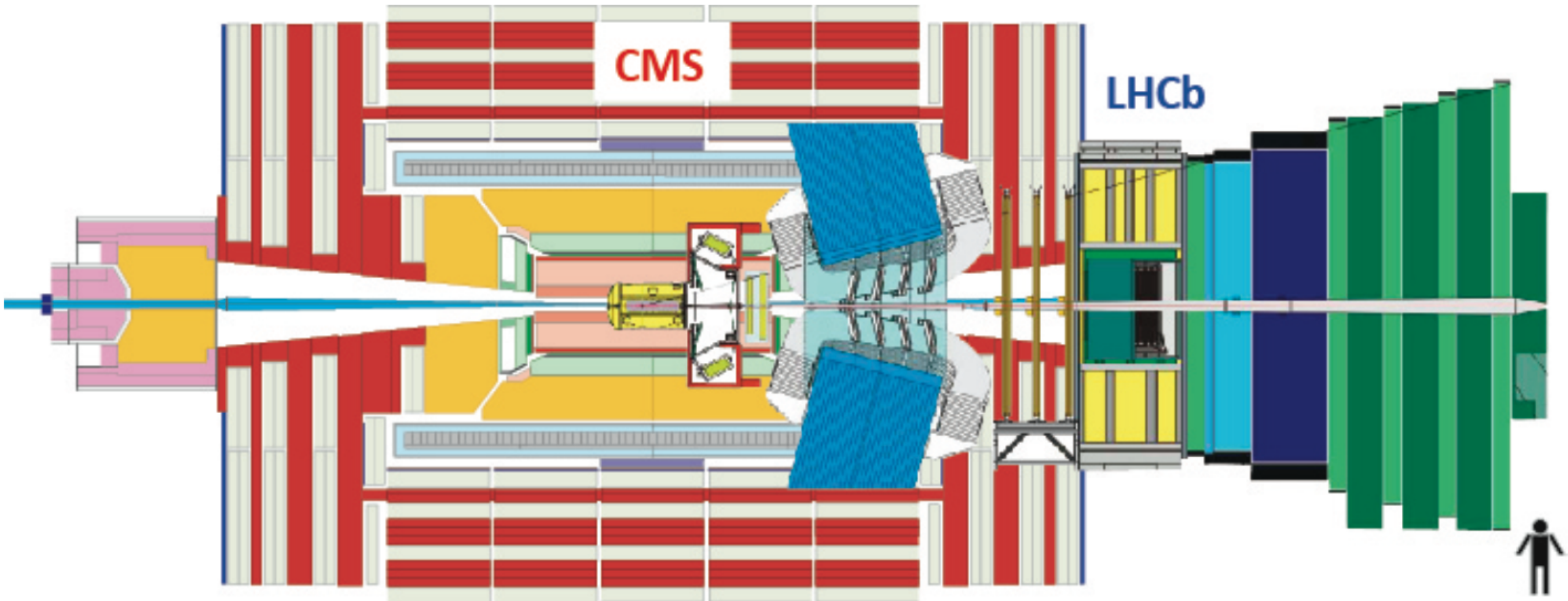
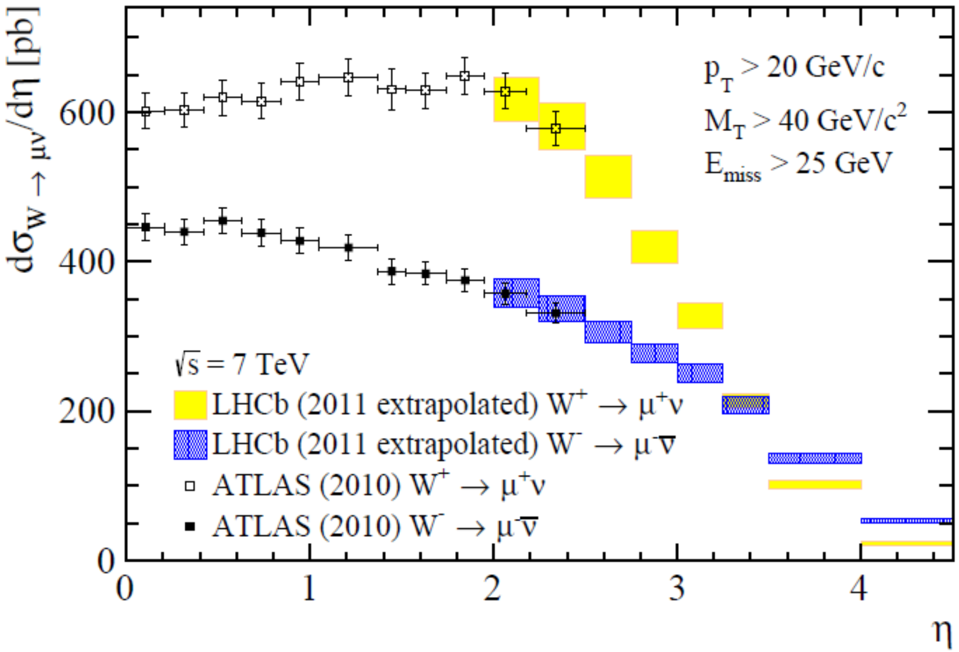
on behalf of the LHCb collaboration



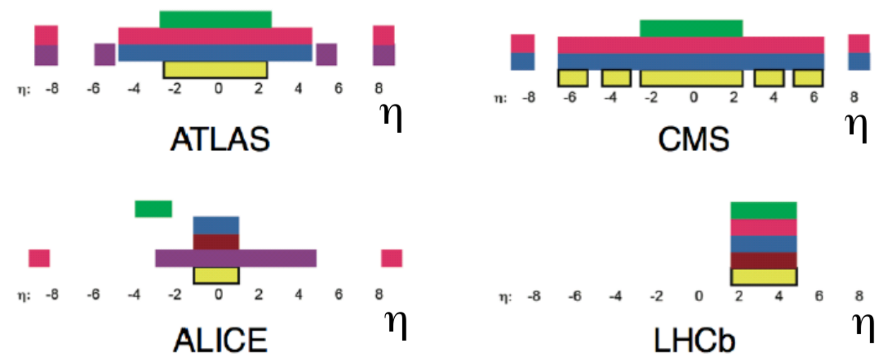


Complementary to GPDs:

- **in geometrical acceptance**
- **in searches for NP, flavour structure complements direct searches**



Preliminary
LHCb-PAPER-2014-033
ATLAS, [PRD 85 (2012) 072004]



tracking, ECAL, HCAL, counters lumi, muon, hadron PID

Complementary to GPDs:

- ► **in geometrical acceptance**
- ► **in searches for NP, flavour structure complements direct searches**

Why LHCb ?

Directly: by producing 'real' new particles and observing their decay.
Reach **limited by available Energy.**

Indirectly: The effect of 'virtual' new particles in loop processes alter decay properties: branching fraction, angular distribution, asymmetries.
Tiny effects, **precision** is crucial.

Direct observation of NP at GPDs

YES → **Need to measure the Flavour structure to distinguish between NP models**

NO → **Flavour sets the scale of NP and guides direct searches with constraints**

Flavour studies required

50 years of flavour

Flavour physics has contributed strongly in the construction of the SM.

Kaon mixing and measurement of $\mathcal{B}(K_L^0 \to \mu^+\mu^-)$

- **GIM mechanism**
- **prediction of the existence of the charm quark**

CP violation

- **prediction of the third quark family**

B mixing

- **mass of the top is very heavy**

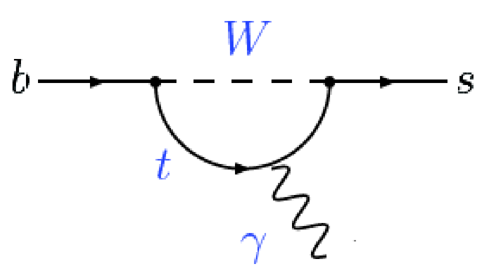
Observation of CPV in Kaon mixing (1964)
Explanation by Kobayashi and Maskawa (1973): need a third quark family!
Directly observed in 1977 (b) and 1995 (t)

Use Operator Product Expansion and an Effective Field Theory

$$H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \sum_i \Big[\underbrace{C_i(\mu) O_i(\mu)}_{\text{left-handed part}} + \underbrace{C_i'(\mu) O_i'(\mu)}_{\substack{\text{right-handed part} \\ \text{suppressed in SM}}} \Big]$$

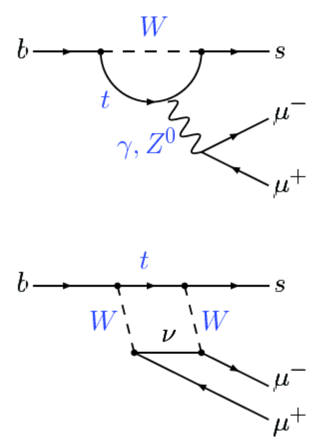
$i = 1,2$	Tree
$i = 3-6,8$	Gluon penguin
$i = 7$	Photon penguin
$i = 9,10$	Electroweak penguin
$i = S$	Higgs (scalar) penguin
$i = P$	Pseudoscalar penguin

$b \to s\gamma$



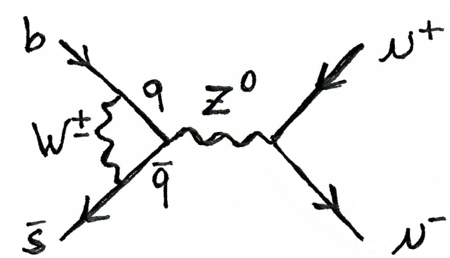
$C_7^{(\prime)}$

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



$C_7^{(\prime)}, C_9^{(\prime)}, C_{10}^{(\prime)}$

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



$C_S^{(\prime)}, C_P^{(\prime)}, C_{10}^{(\prime)}$

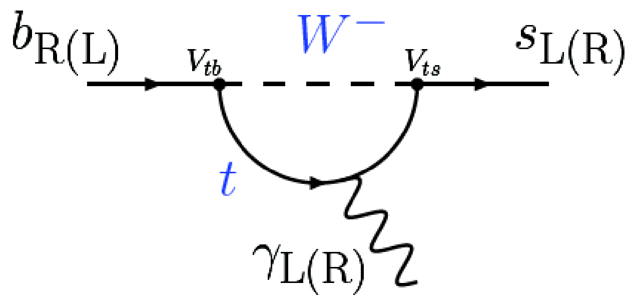
Radiative decays

- $B^0 \to K^*\gamma$ **was the first penguin decay ever observed**

  CLEO, [PRL 71 (1993) 674]

- **From B-factories, inclusive and exclusive $\mathcal{B}(b \to s\gamma)$ are compatible with the SM**

  Why bother?



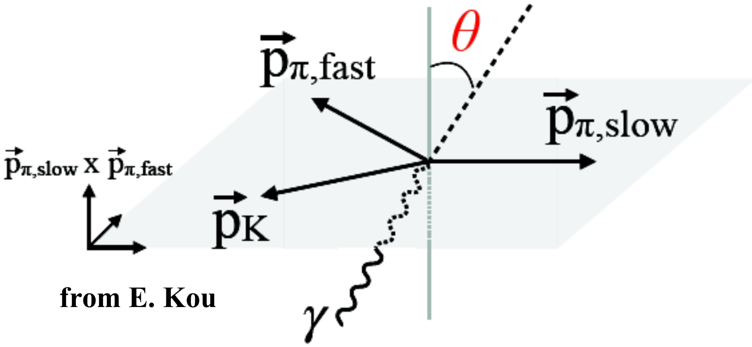
- **Measure photon polarisation:**
  SM, photons are predominantly left-handed with $C_7/C_7' \sim m_b/m_s$

- **Let's try to test** C_7/C_7' **in** $B \to K^{**}\gamma$ **decays such as** $B^+ \to K_1(1270)\gamma$

  Gronau & Pirjol [PRD 66 (2002) 054008]
  Kou et al., [PRD 83 (2011) 094007]

Photon polarisation $B^+ \to K^+\pi^+\pi^-\gamma$

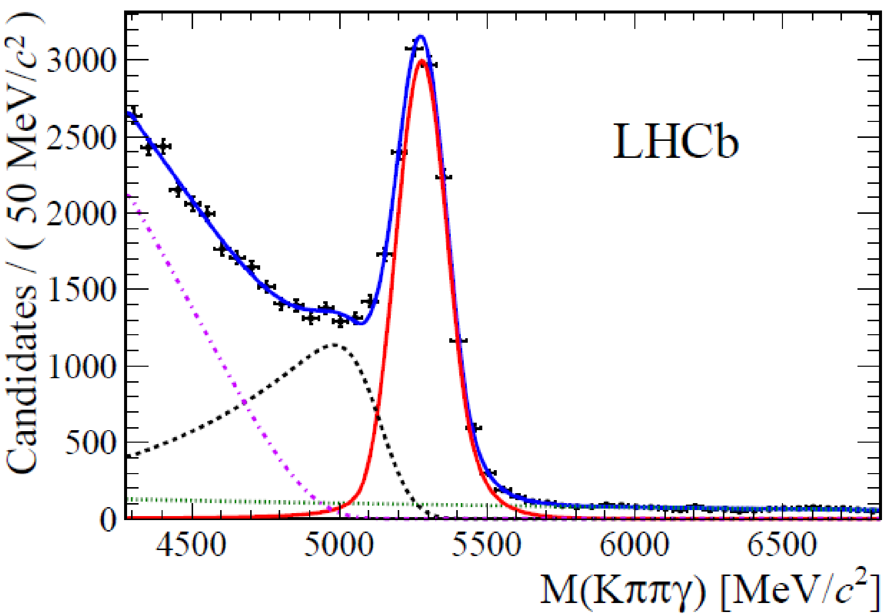
[PRL 112 (2014) 161801]



- **Photon polarisation is inferred from up-down asymmetry of the direction of the photon in the $K\pi\pi$ rest frame. Unpolarised photons would show no asymmetry.**

  Similar to the Wu experiment

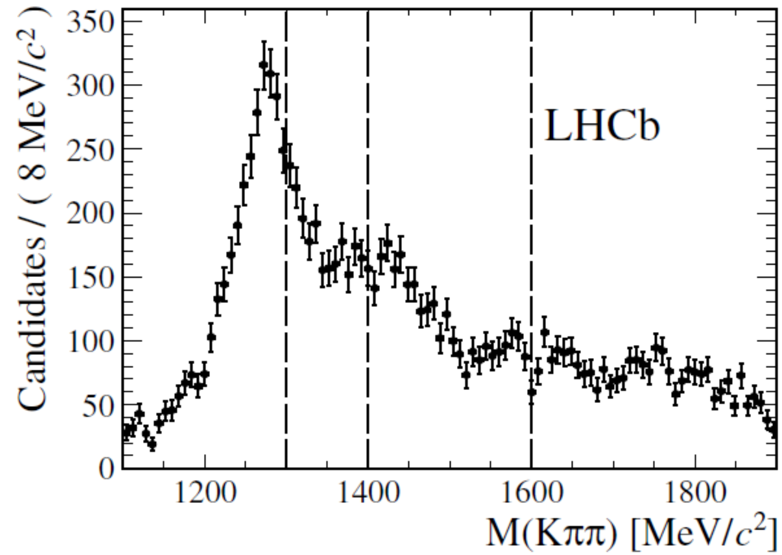
- **LHCb observes about 13'000 $B^+ \to K^+\pi^+\pi^-\gamma$ candidates in 3 fb^{-1}.**



Photon polarisation $B^+ \to K^+\pi^+\pi^-\gamma$

[PRL 112 (2014) 161801]

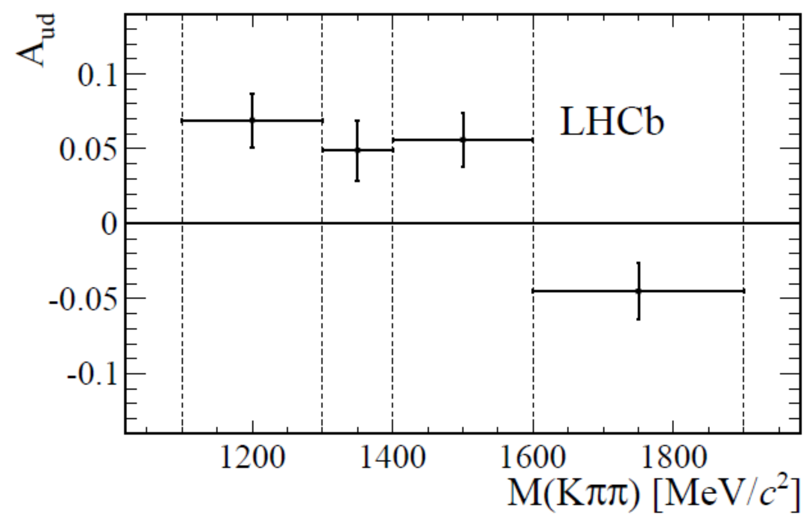
- **Numerous overlapping resonances in the $m(K\pi\pi)$ mass spectra.**
- **No attempt to separate them, divide in 4 mass bins**



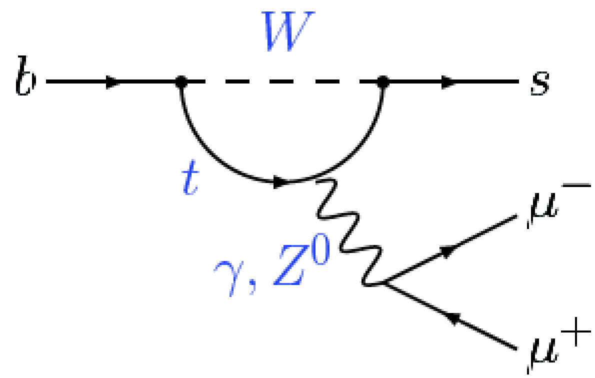
Combining the 4 bins, the photon is observed to be polarised at 5.2 σ

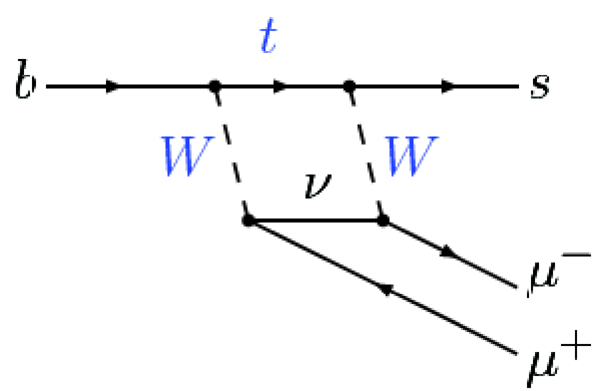
First observation of the photon polarisation in $b \to s\gamma$

- **Unfortunately, understanding of the hadronic system is needed before one can tell its nature (left or right).**



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

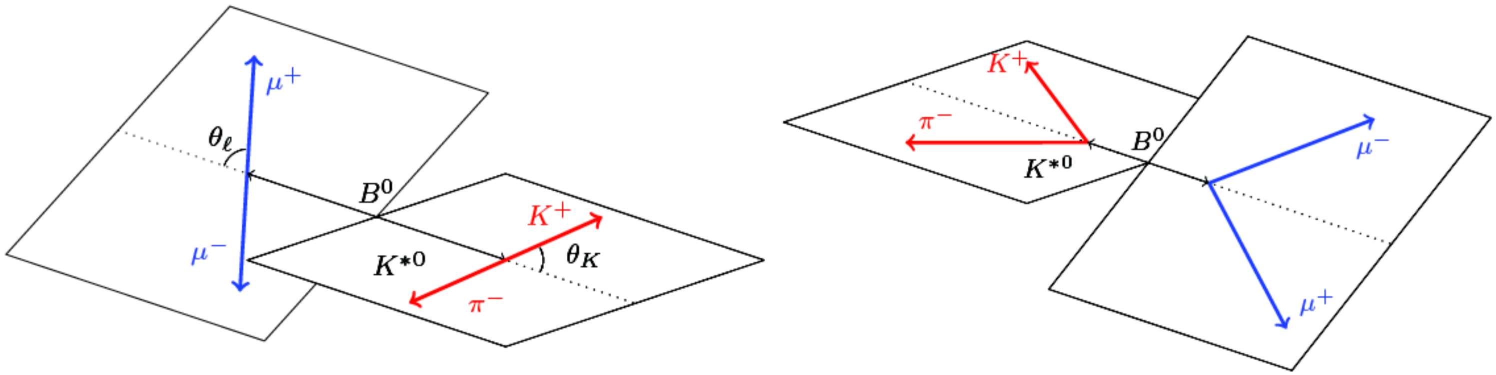




Let's probe for the same physics using virtual photons ...

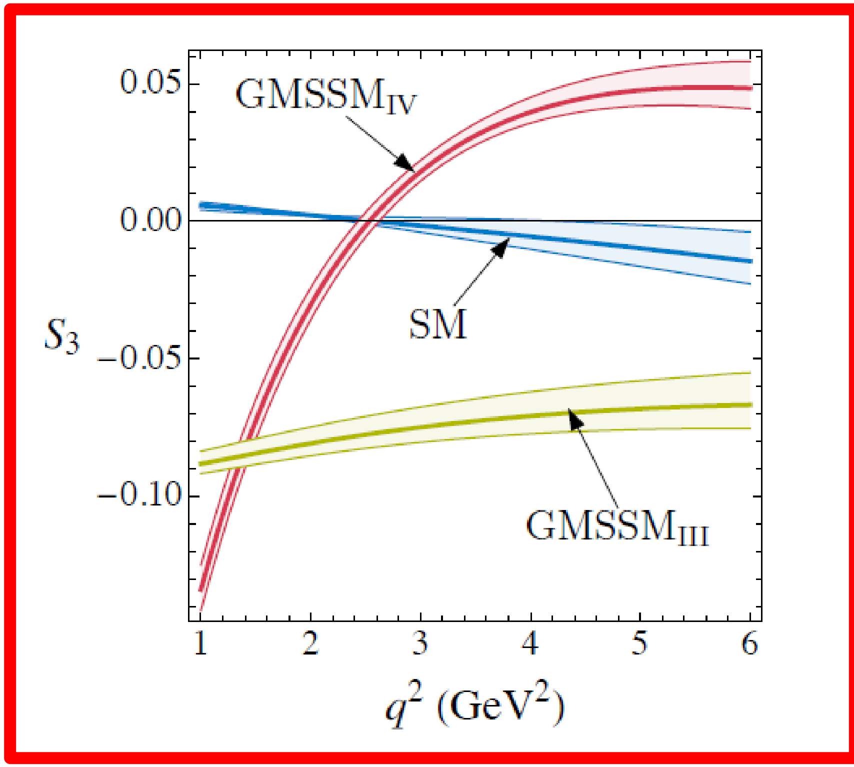
$B^0 \to K^{*0}\mu^+\mu^-$ Angular analysis

Four-particle final state allows for wealth of observables in angular distributions along three angles (θ_l, θ_K, ϕ) and the dimuon invariant mass squared q^2.



Angular distribution depends on 11 terms, sensible to NP:

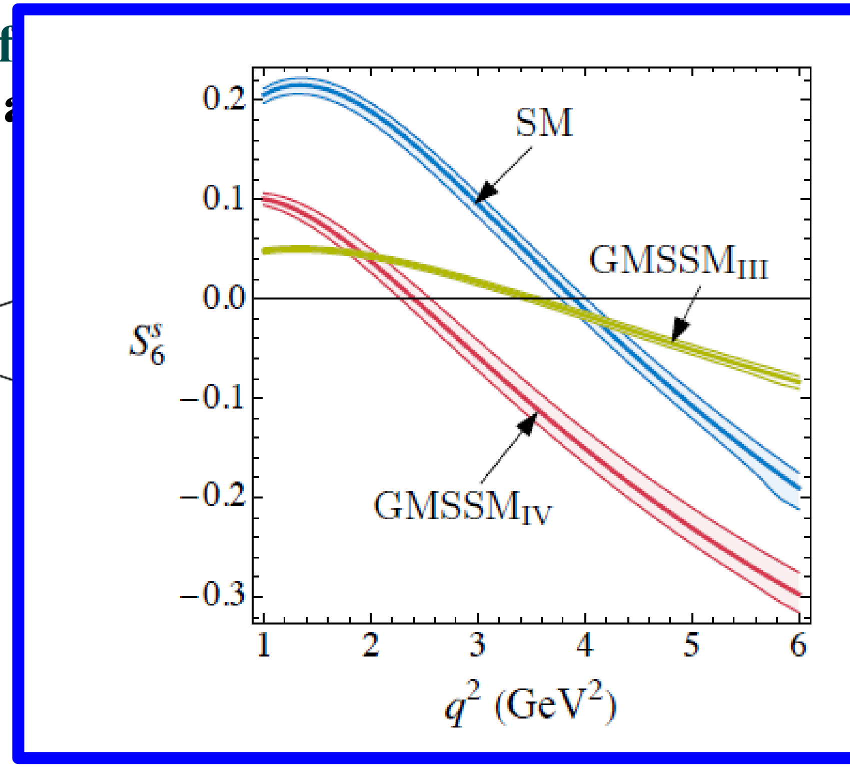
$$\frac{d^4\Gamma[B^0 \to K^{*0}\mu^+\mu^-]}{d\cos\theta_\ell \, d\cos\theta_K \, d\phi \, dq^2} = \frac{9}{32\pi}\Big[J_1^s \sin^2\theta_K + J_1^c \cos^2\theta_K + J_2^s \sin^2\theta_K \cos 2\theta_\ell + J_2^c \cos^2\theta_K \cos 2\theta_\ell + J_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + J_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi + J_5 \sin 2\theta_K \sin\theta_\ell \cos\phi + J_6 \cos^2\theta_K \cos\theta_\ell + J_7 \sin 2\theta_K \sin\theta_\ell \sin\phi + J_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi + J_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi \Big]$$



lth of

K, ϕ)

erms,



$$\frac{d^4\Gamma[B^0 \to K^{*0}\mu^+\mu^-]}{d\cos\theta_\ell \, d\cos\theta_K \, d\phi \, dq^2} = \frac{9}{32\pi}\Big[J_1^s \sin^2\theta_K + J_1^c \cos^2\theta_K + J_2^s \sin^2\theta_K \cos 2\theta_\ell + J_2^c \cos^2\theta_K \cos 2\theta_\ell +$$
$$J_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + J_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi +$$
$$J_5 \sin 2\theta_K \sin\theta_\ell \cos\phi + J_6 \cos^2\theta_K \cos\theta_\ell + J_7 \sin 2\theta_K \sin\theta_\ell \sin\phi +$$
$$J_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi + J_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi \Big]$$

Altmannshofer et al., [JHEP 01 (2009) 019]

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

LHCb, 1 fb^{-1}, [JHEP 08 (2013) 131]

$$\frac{d^4\Gamma[B^0 \to K^{*0}\mu^+\mu^-]}{d\cos\theta_\ell \, d\cos\theta_K \, d\phi \, dq^2} = \frac{9}{32\pi}\Big[J_1^s \sin^2\theta_K + J_1^c \cos^2\theta_K + J_2^s \sin^2\theta_K \cos 2\theta_\ell + J_2^c \cos^2\theta_K \cos 2\theta_\ell +$$

$$J_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + \cancel{J_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi} +$$

$$\cancel{J_5 \sin 2\theta_K \sin\theta_\ell \cos\phi} + J_6 \cos^2\theta_K \cos\theta_\ell + \cancel{J_7 \sin 2\theta_K \sin\theta_\ell \sin\phi} +$$

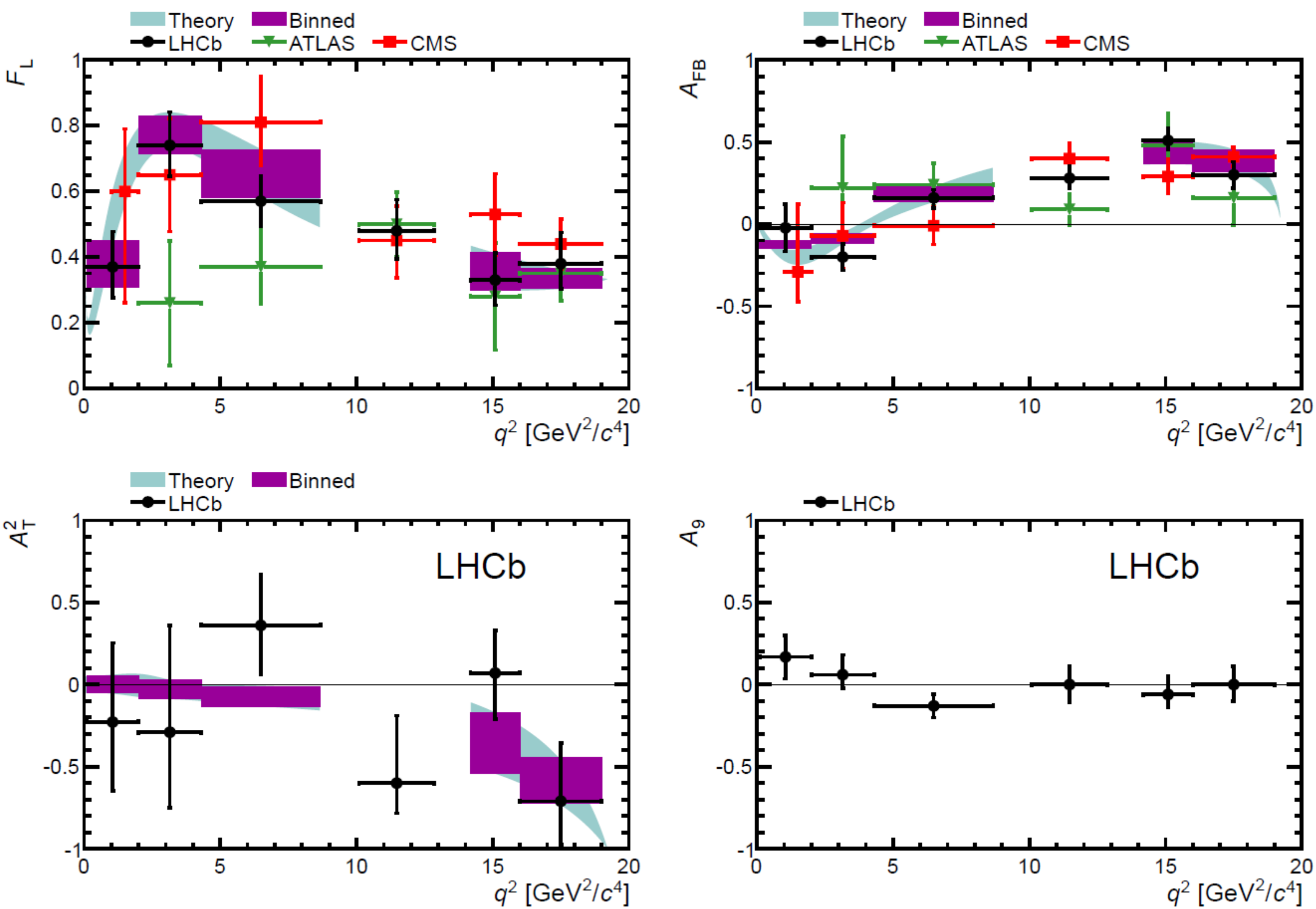
$$\cancel{J_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi} + J_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi \Big]$$

- **Number of terms too large for 1fb^{-1} statistics, simplify by angular folding:** $\phi \to \phi + \pi$ for $\phi < 0$

- **Leaving 4 observables:**

A_{FB} : Dimuon forward-backward asymmetry
F_L : Fraction of the K^{*0} longitudinal polarisation
A^2_T/S_3 : Sensitive to the virtual photon polarisation
A_9 : A CP asymmetry

Angular distributions

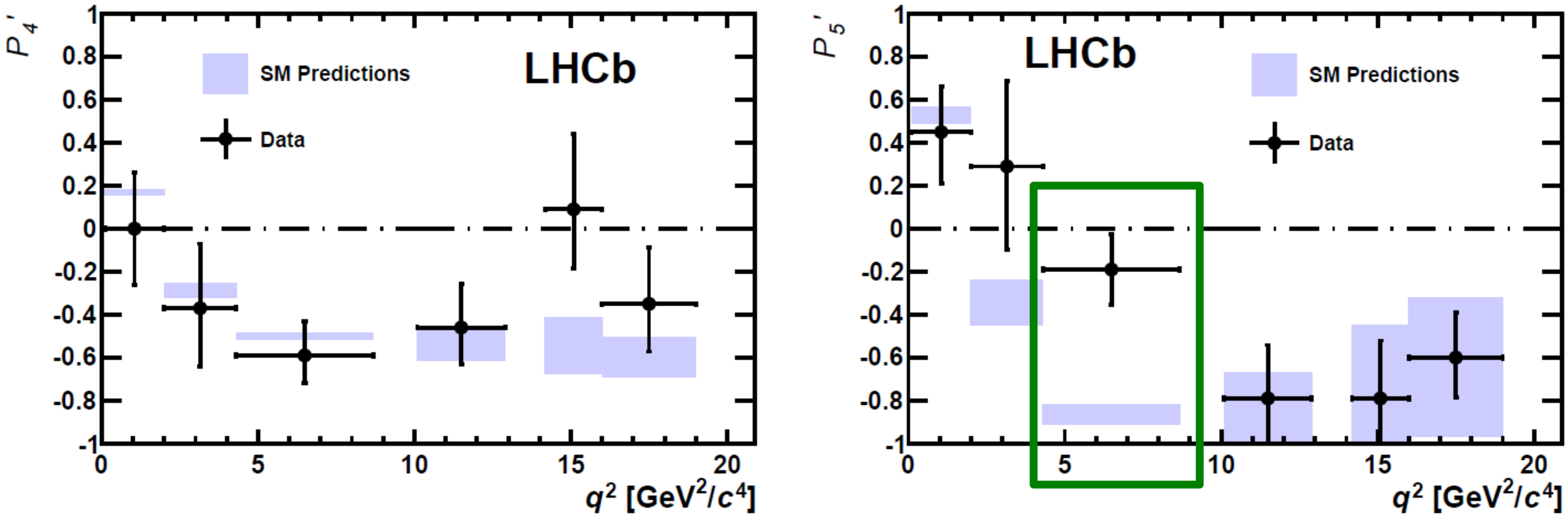


LHCb, 1 fb^{-1}, [JHEP 08 (2013) 131], ATLAS (prelim.), 5 fb^{-1} [ATLAS-CONF-2013-038]
CMS, 5 fb fb^{-1}, [PLB 727 (2013) 77], SM: Bobeth et al. [JHEP 07 (2011) 067] and therein

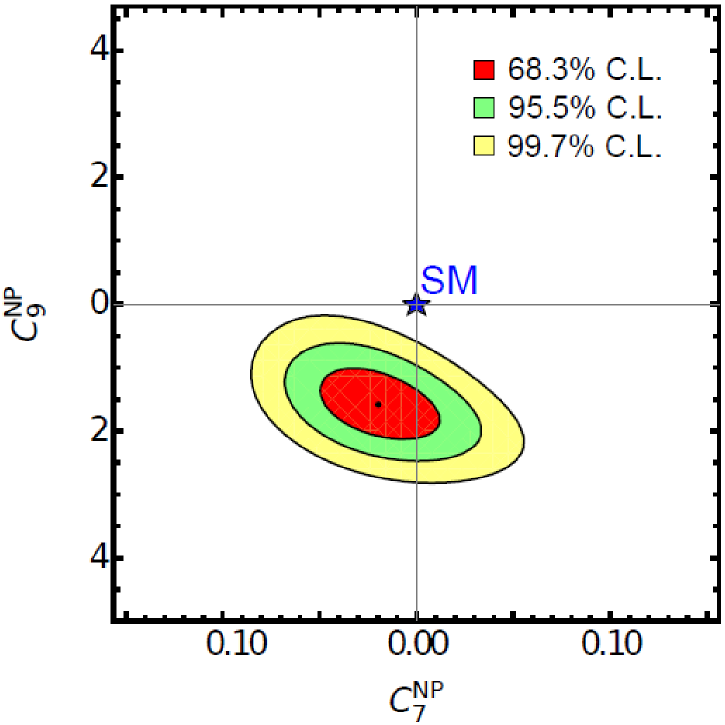
- **Different folding gives access to other terms.**

Observables, where leading form-factor uncertainties cancel:
$P'_{4,5} = S_{4,5}/\sqrt{F_L(1-F_L)}$

LHCb, 1 fb^{-1},[PRL 111 (2013) 191801], **SM: Descotes-Genon et al. [JHEP 05 (2013) 137]**



- **Local discrepancy wrt the SM of 3.7σ in P'_5**
Probability that one bin varies by this much is 0.5%



Descotes-Genon, Matia & Virto:
global fit to the $b \to s\gamma$ and $b \to s\ell^+\ell^-$ data. Fit favours C_9^{NP} = -1.5.

4.5σ from SM

[PRD 88 (2013) 074002]

Altmannshofer & Straub:

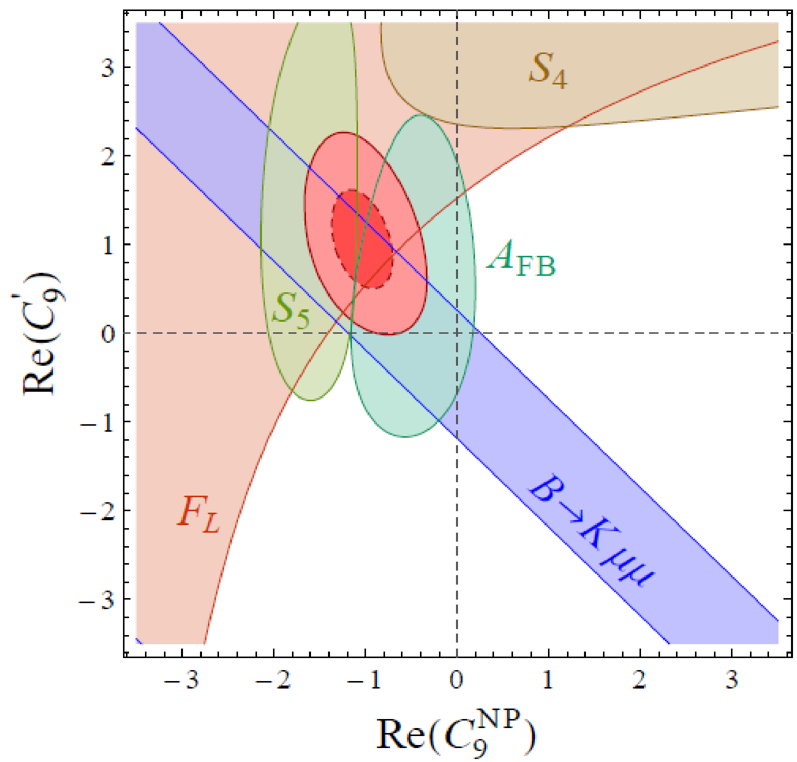
Global analysis, 3σ from SM.

Fit favours negative C_9^{NP} and enhanced C_9'

Difficult to explain within SUSY

Can be explained by a flavour-changing Z' boson with mass O(1TeV)

[EPJC 73 (2013) 2646]



Interpretating ... II

- **Gaul, Goertz & Haish: also favour Z' but with larger mass (7TeV)** [JHEP 01 (2014) 069]
- **Beaujean, Bobeth & van Dyk: by floating the form-factor uncertainties in the fit, the discrepancy to the SM is reduced to 2σ.** [EPJC 74 (2014) 2897]
- **Jaeger & Camalich: investigate form-factor uncertainties and try to address their size.** [JHEP 05 (2013) 043]

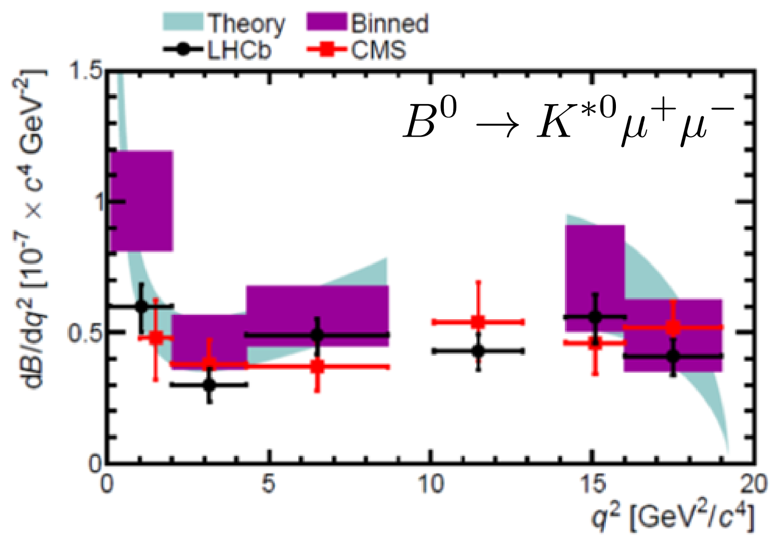
Kinda tension in one observable, fit for the Wilson coefficients allows to combine information.

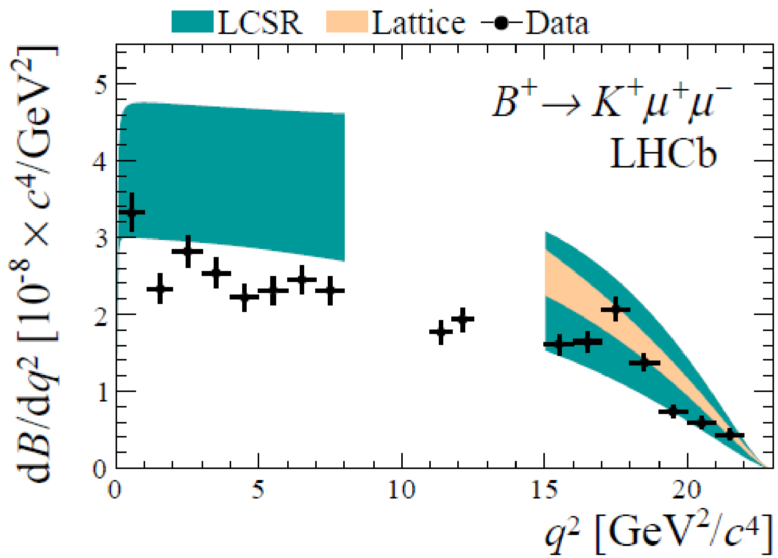
Theory uncertainties seem underestimated: enough to explain away?

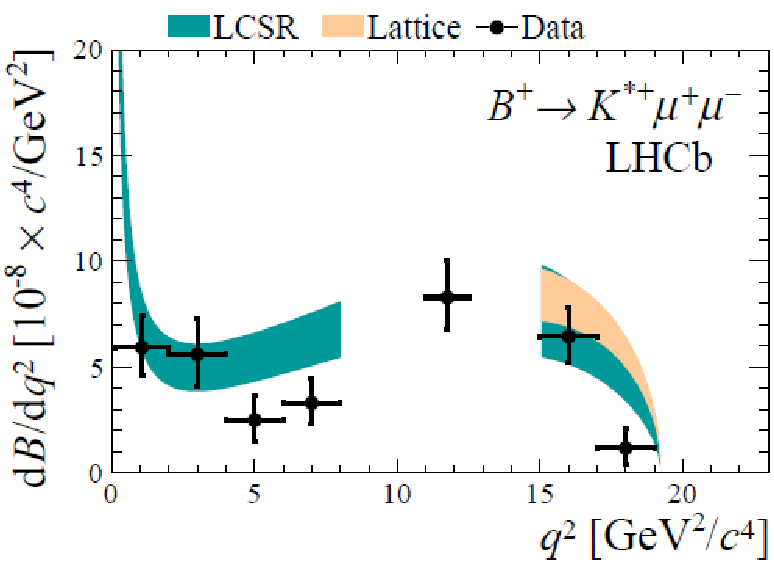
SUSY has trouble accommodating the data, Z' is a candidate.

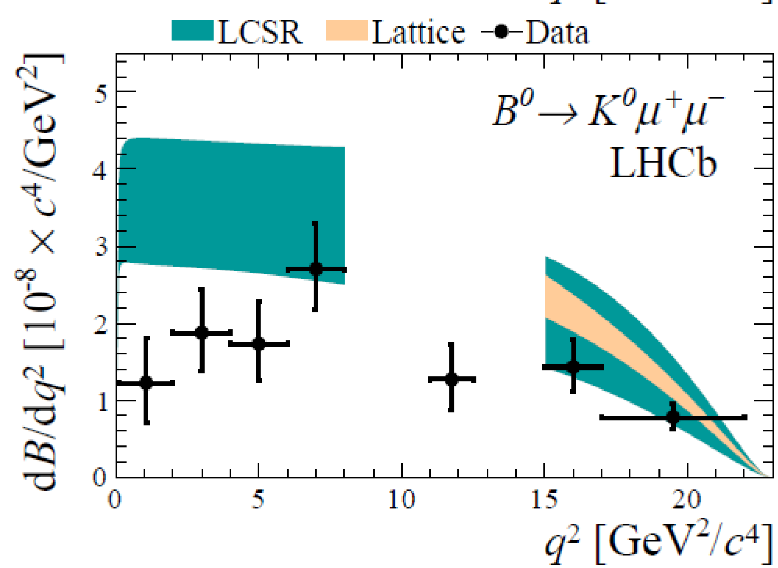
Analysis on $3fb^{-1}$ is coming. Can we go further with current data?

C_9^{NP} = -1.5 leads to a suppression of the rate of the $B \to K^{(*)}\mu^+\mu^-$









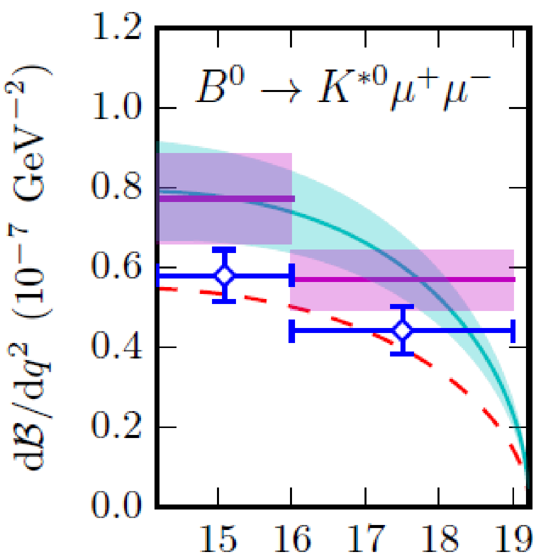
LHCb, 1 fb^{-1} (K*0), [JHEP 08 (2013) 131], LHCb, 3 fb^{-1}, [JHEP 06 (2014) 133], CMS, 5 fb^{-1}, [PLB 727 (2013) 77], SM: [JHEP 07 (2011) 067], [JHEP 01 (2012) 107], Lattice: HPQCD, [PRL 111 (2013) 162002], [PRL 112 (2014) 212003]

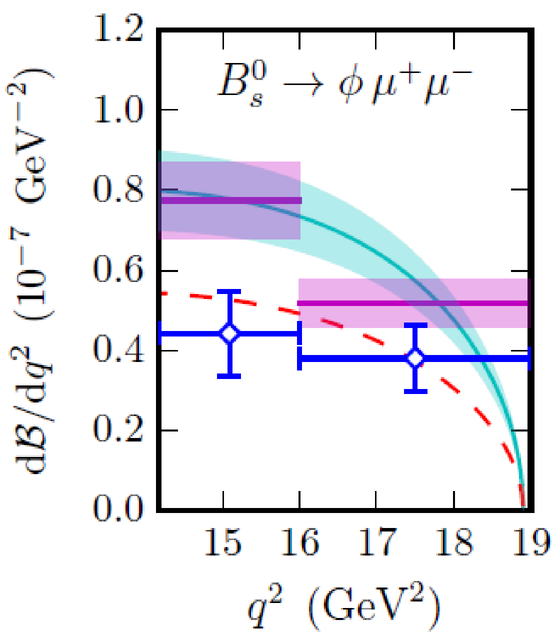
[PRL 112(2014) 212003]

- Horgan et al., perform global analysis of the high-q^2 region (no P5' anomaly!) including $B_s^0 \to \phi\mu^+\mu^-$

obtain C_9^{NP} = -1.0 and C_9'= 1.2:

effect on differential branching fraction:





Data, their average from
CDF, [Public Note 10894]
CMS, 5 fb^{-1}, [PLB 727 (2013) 077]
LHCb, 1 fb^{-1}, [JHEP 08 (2013) 131]

Data, their average from
CDF, [Public Note 10894]
LHCb, 1fb^{-1}, [JHEP 07 (2013) 084]

Lepton universality

$$R_K = 1?$$

$$e, \mu$$

... what if our putative Z' does not couple equally to e and μ ...

Test of lepton universality

In the SM, couplings to all leptons are universal
(apart form tiny Higgs couplings)

[LHCb-PAPER-2014-024]
Preliminary

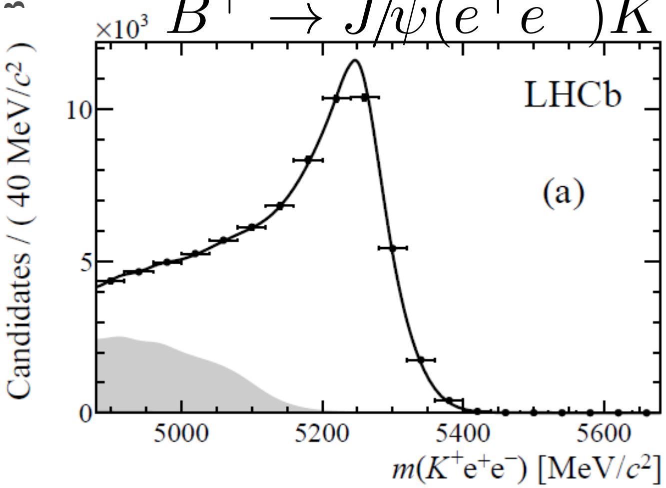
Test lepton universality in $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+e^+e^-$

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

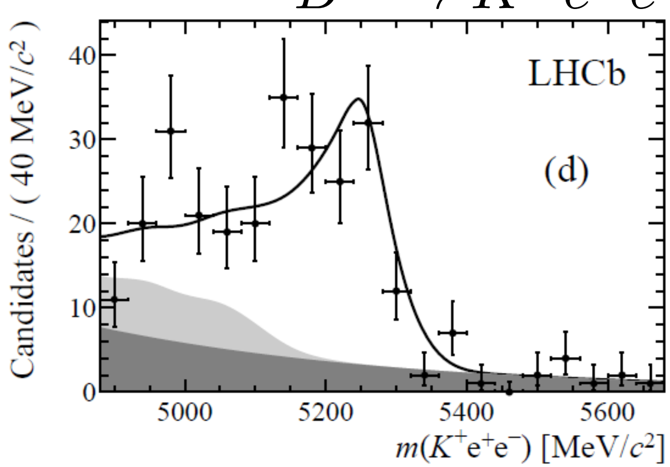
Bobeth et al. [JHEP 12 (2007) 040]

Selection of the $B^+ \to K^+e^+e^-$ decay is experimentally difficult due to the bremstrahlung emission from the electrons.

$B^+ \to J/\psi(e^+e^-)K^+$



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



Candidates triggered by the electrons

Test of lepton universality

[LHCb-PAPER-2014-024]
Preliminary

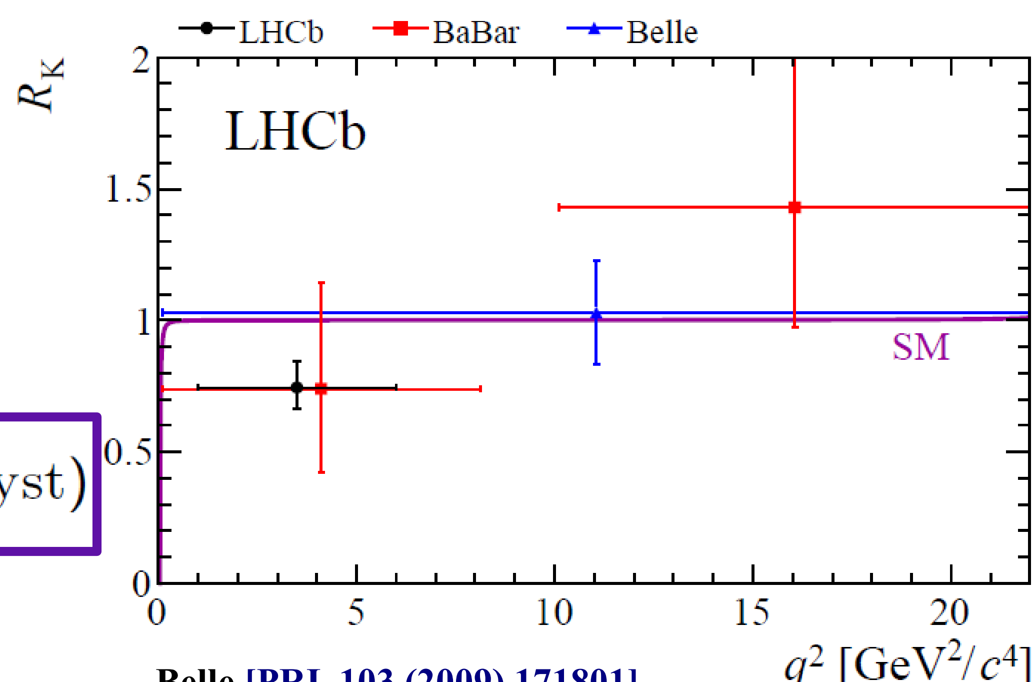
Correct for bremstrahlung loss using calorimeter photons (with E_T > 75 MeV)

Take double ratio to resonant $B^+ \to J/\psi K^+$ to cancel possible systematic bias.

In 3 fb^{-1}, LHCb measures

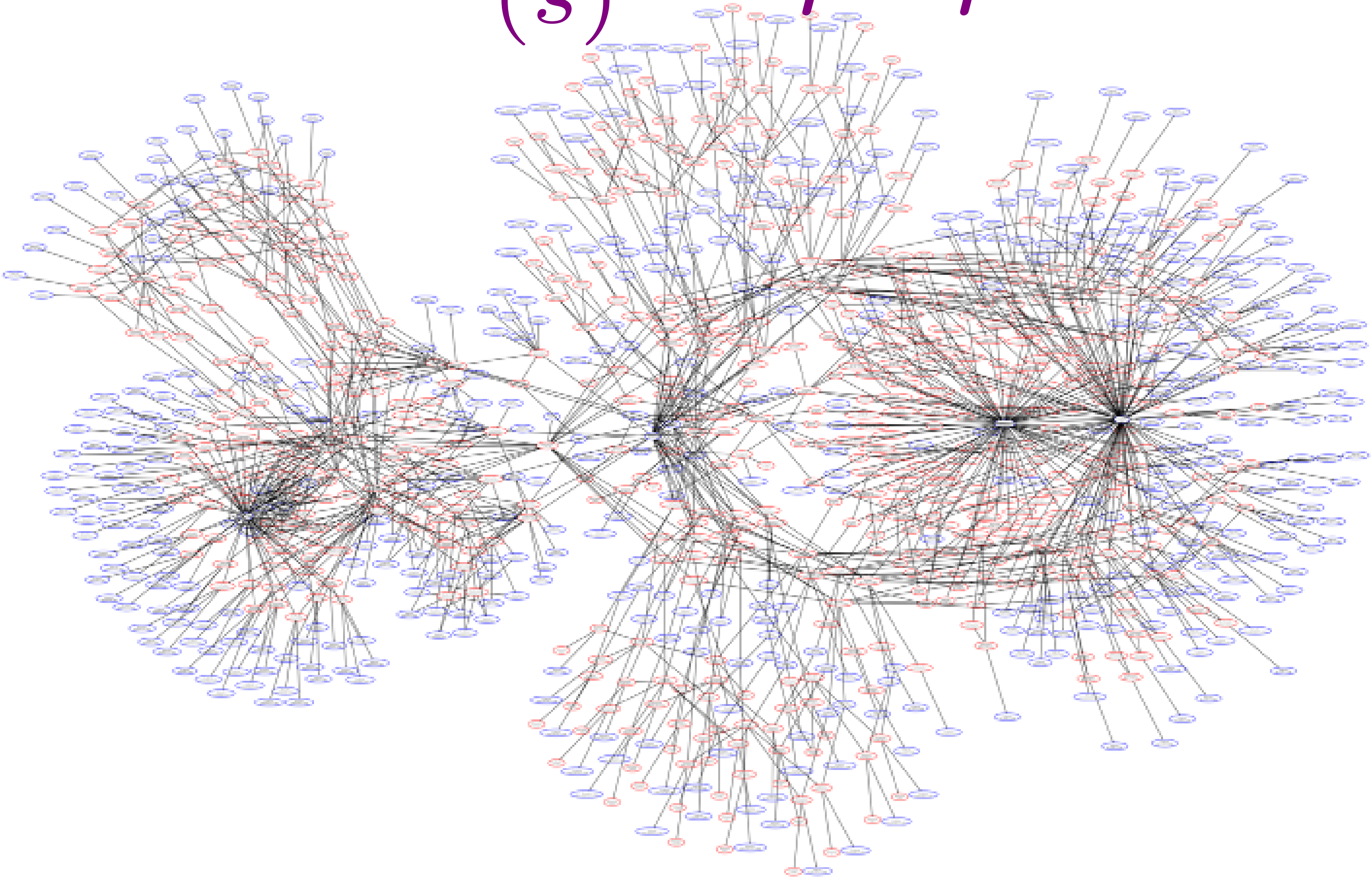
$$R_K = 0.745^{+0.090}_{-0.074}(\text{stat})^{+0.036}_{-0.036}(\text{syst})$$

2.6σ away from the SM.



Belle [PRL 103 (2009) 171801]
Babar [PRD 86 (2012) 032012]

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



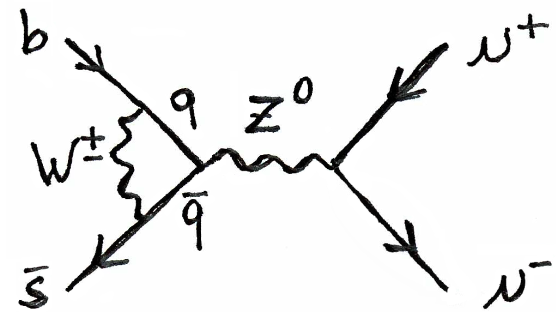
Why (still) $B^0_{(s)} \to \mu^+\mu^-$?

Clean theoretical prediction, GIM and helicity suppressed in the SM

$$\mathcal{B}_{\rm SM}(B^0_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$

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

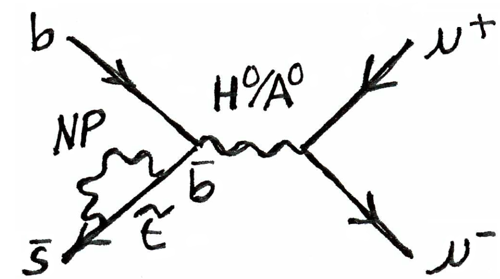
Bobeth et al., [PRL 112 (2014) 101801]



$$\frac{\mathcal{B}(B^0_s \to \mu^+\mu^-)}{|V_{tb}V^\star_{ts}|} \propto |C_{\rm S} - C'_{\rm S}|^2 \left(1 - \frac{4m_\mu}{m_B}\right) + \left|(C_{\rm P} - C'_{\rm P}) + \frac{2m_\mu}{m_B}(C_{10} - C'_{10})\right|^2$$

MFV **NP-only** **NP-only**

Sensitive to contribution from (pseudo) scalar sector.
E.g. models with extended Higgs sector.
in MSSM, branching fraction goes with $\tan^6\beta/m_A^4$

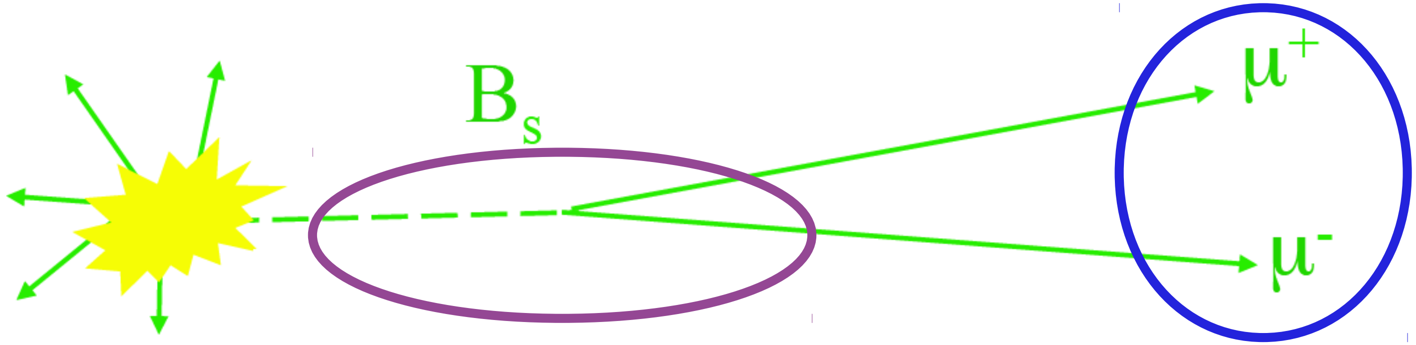


Brings strong constraints on SUSY parameter space.

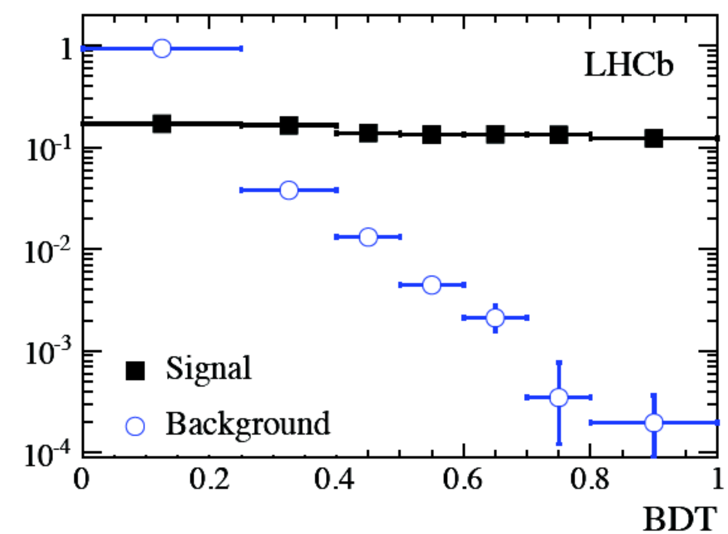
Ratio $\dfrac{\mathcal{B}(B^0_s \to \mu^+\mu^-)}{\mathcal{B}(B^0 \to \mu^+\mu^-)}$ **very precise in SM and in Minimal Flavour Violation.**

Discrimination

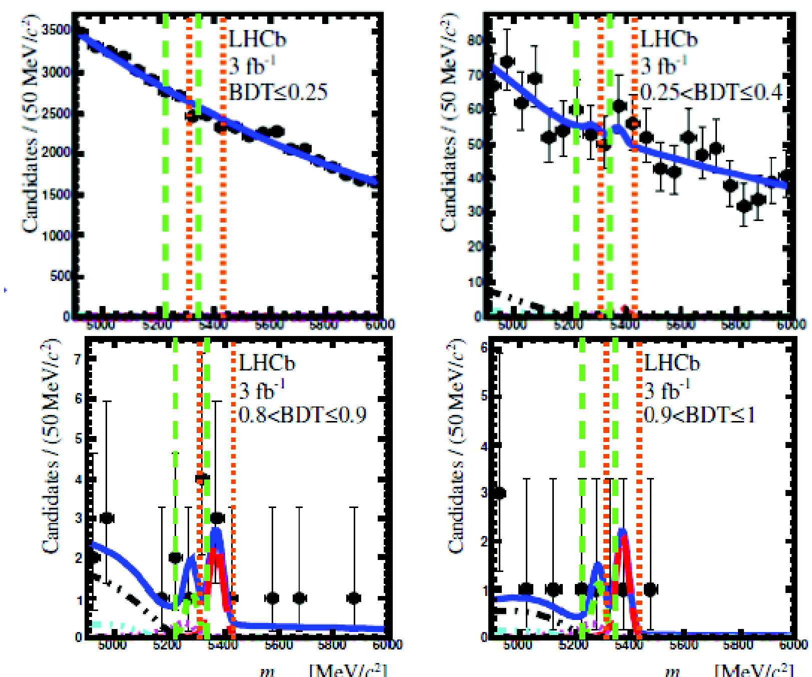
LHCb, 3fb^{-1}, [PRL 111 101805 (2013)]



Topology, kinematics in BDT



Invariant Mass



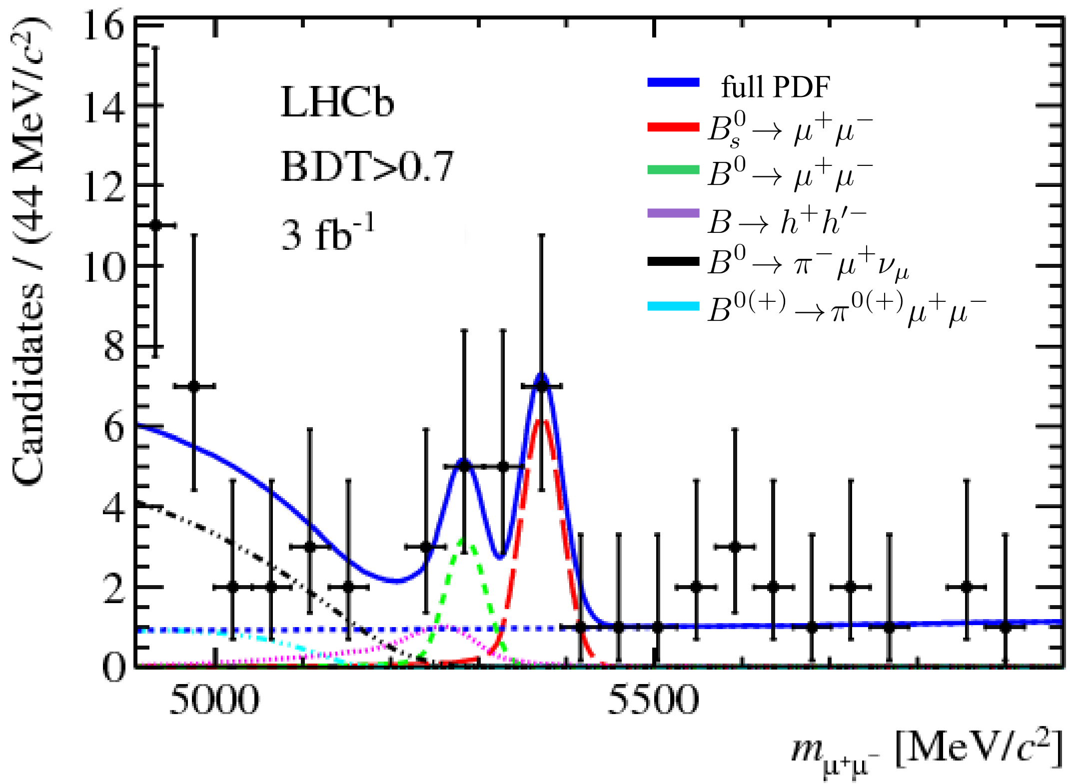
Fit mass in bins of BDT

To get a BF, normalise to $B^+ \to J/\psi(\to \mu^+\mu^-)K^+$ and $B^0 \to K^+\pi^-$

LHCb, 3fb^{-1}, [PRL 111 101805 (2013)]

[PRL 110 (2013) 021801]

LHCb Nov. 2012,
First evidence 3.5σ for
$B_s^0 \to \mu^+\mu^-$ **with 2.1 fb^{-1}.**



Summer 2013,
full dataset, 3 fb^{-1}:
- expected 5.0 σ sensitivity
- improved analysis

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}(\text{stat.})^{+0.3}_{-0.1}(\text{syst.})) \times 10^{-9}$$

Significance of 4.0 σ

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.7^{+2.4}_{-2.1}(\text{stat.})^{+0.6}_{-0.4}(\text{syst.})) \times 10^{-10}$$

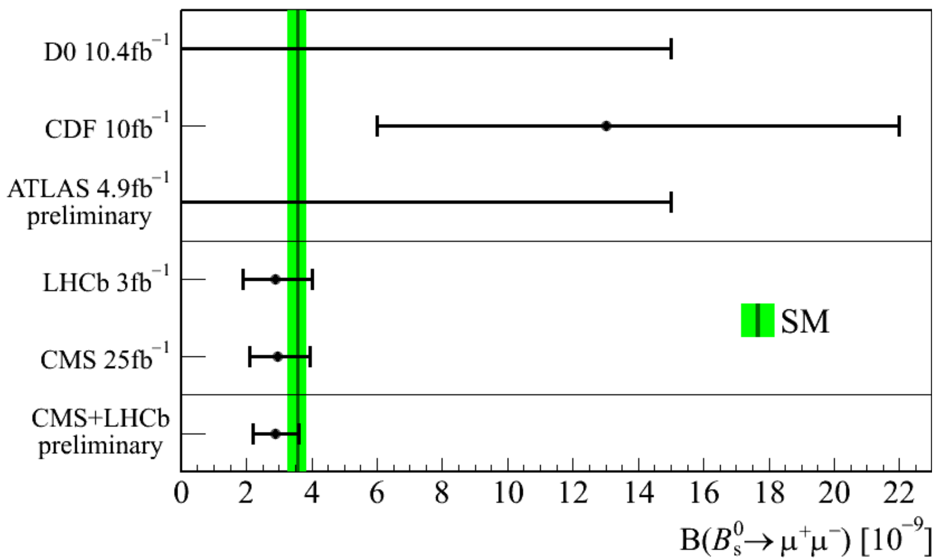
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 7 \times 10^{-10} \text{ at } 95\% \text{ CL}$$

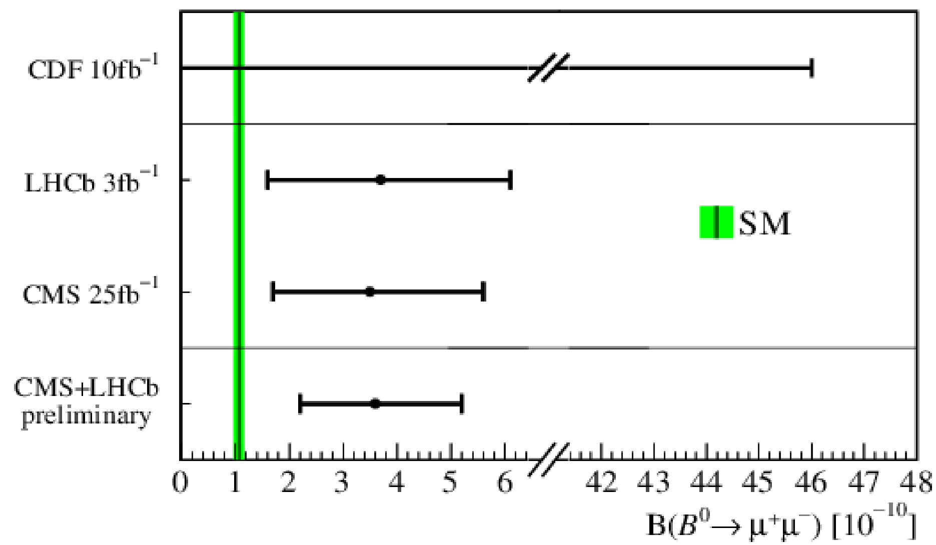
LHCb+CMS Combination

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

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$ **observation**

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10}$$ **not significant**



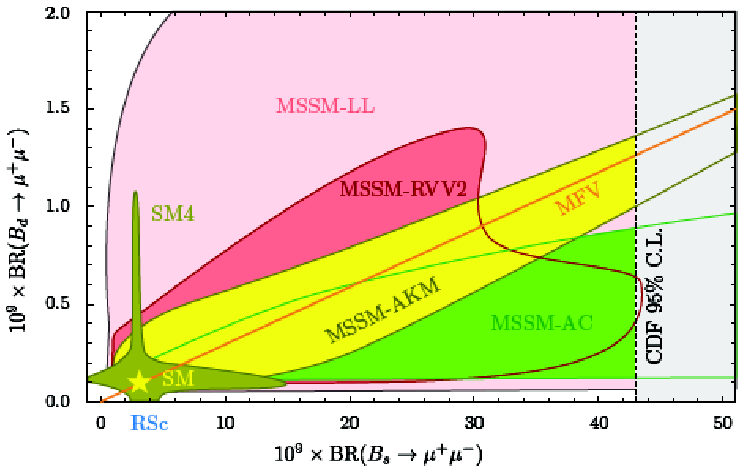


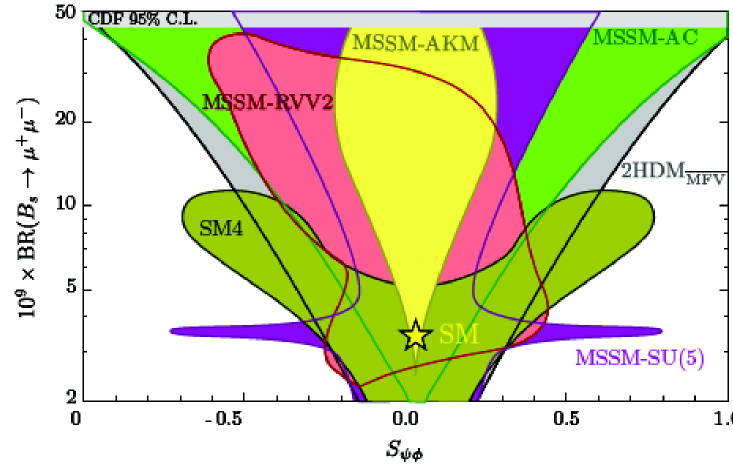
Full combination CMS+LHCb via simultaneous fit close to completion

Correlation with other Flavour observables, CPV in Bs mixing in $B_s^0 \to J/\psi\phi$

Summer 2010:

Straub arXiv:1107.0266



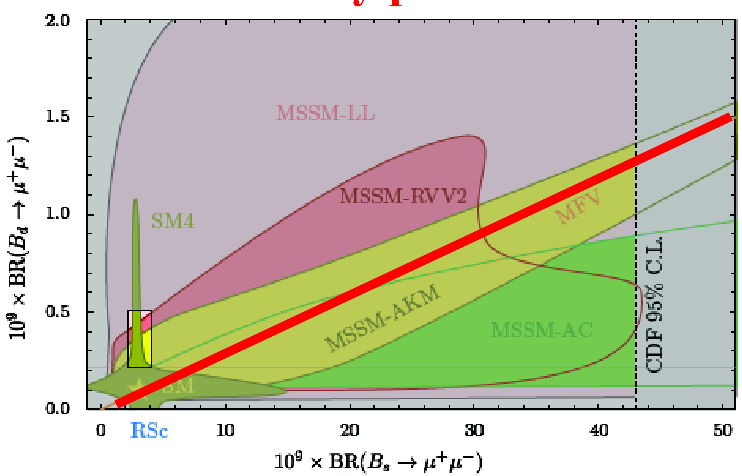


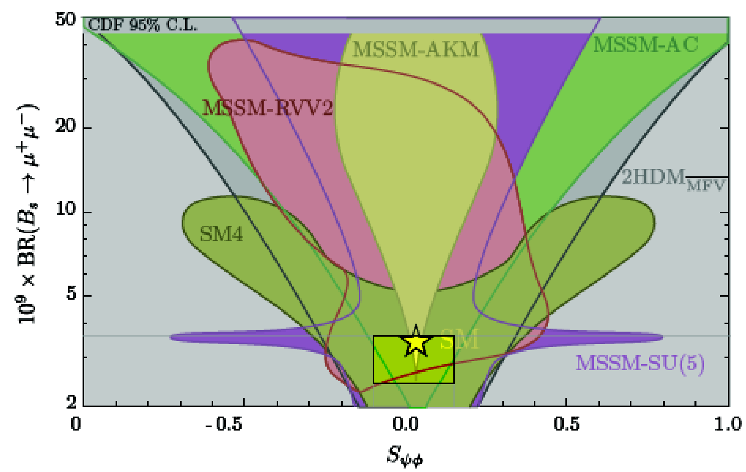
MSSM-LL [PRL75(1995)3985]
SM4 4th generation
MFV Minimal Flavour Violation

Today:

MFV scenario : very precise ratio of BF

Straub arXiv:1107.0266

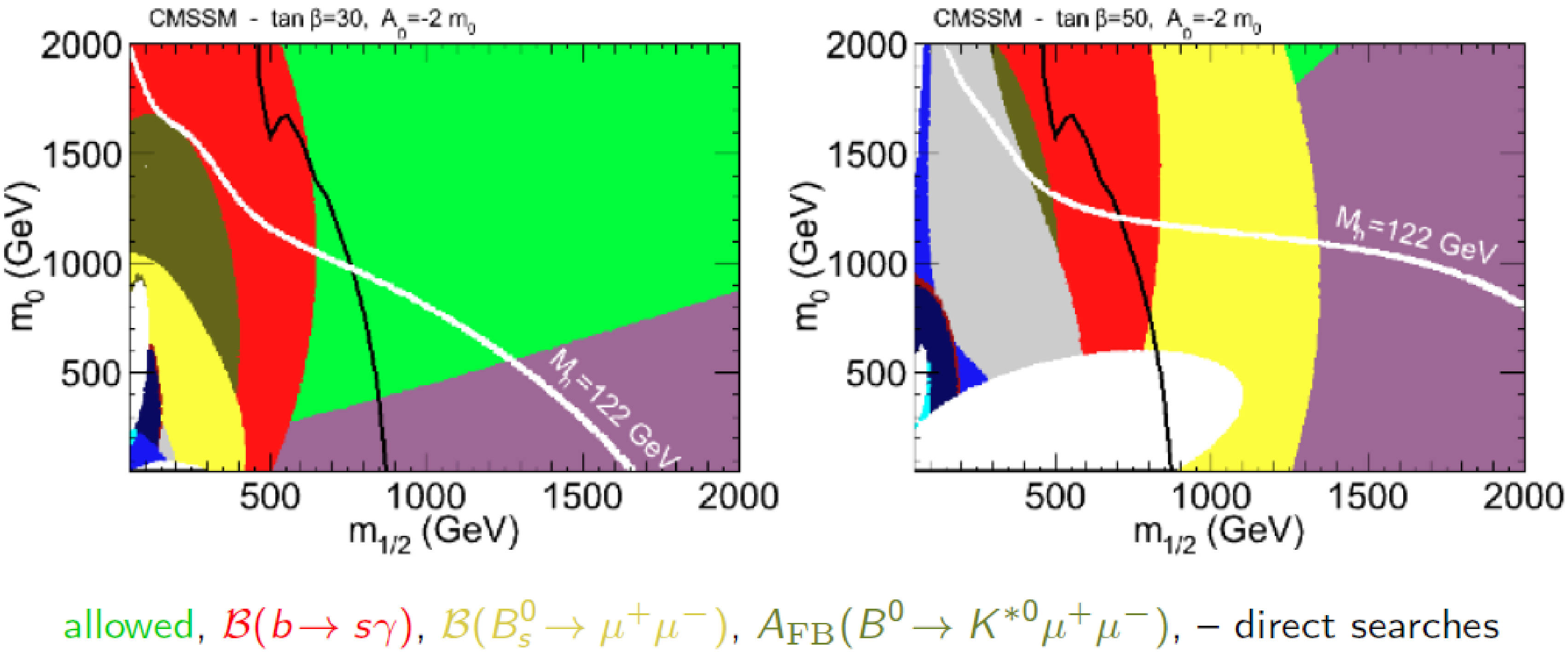




MSSM-RVV2 [Nucl.Phys.B692(2004)50]
MSSM-AKM [JHEP0806(2008)068]
MSSM-AC [PRD68(2003)035017]

Level of the constraints depends on the model and on the phase space.
Example in CMSSM.

Mahmoudi [arXiv:1310.2556]



At high tan β, large constraint coming from $B_s^0 \to \mu^+\mu^-$
At lower value of tanβ, the flavour constraints are comparable to those from direct searches.

Summary

Only a (biased) selection of the LHCb physics has been presented.

Charm, precision CKM measurement, exoticas ... are probing for Physics beyond the SM.

C. Linn, EW Penguin decays
M. Rangel, LFV and LNV decays
S. DeCapua, Exoticas
V. Rives Molina, Radiative decays

Very lively interaction with the theory community.

Importance of the correlations across the observables and decays.
NP is subtle, it might show up only with global analyses.

We haven't struck gold yet. Important updates are coming:
full CMS+LHCb combination for $B^0_{(s)} \to \mu^+\mu^-$
$B^0 \to K^{*0}\mu^+\mu^-$ **on full run I data.**

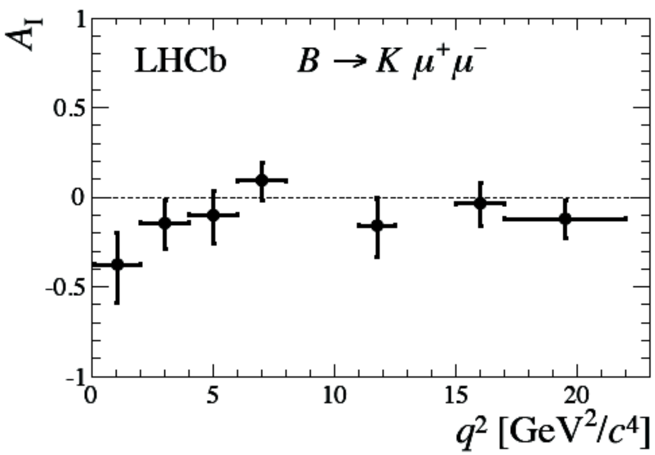
Backup

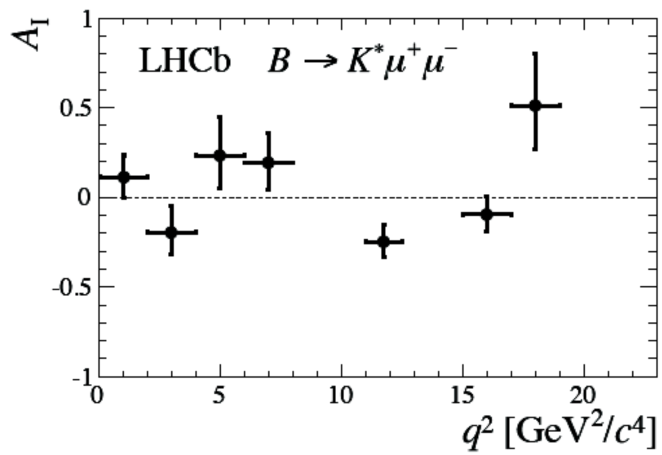
JHEP 06 (2014) 133

- Isospin asymmetry expected to be close to zero in SM

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

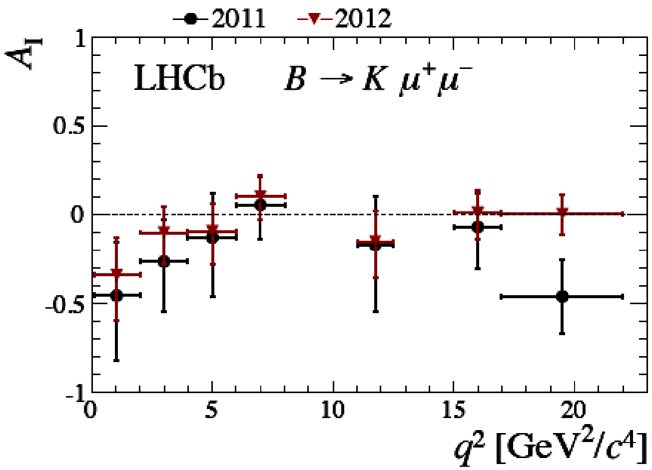
- LHCb measured A_I in two modes:
  - $B^0 \to K^0 \mu^+\mu^-$ vs $B^+ \to K^+ \mu^+\mu^-$
  - $B^0 \to K^{0*} (K^+\pi^-) \mu^+\mu^-$ vs $B^+ \to K^{*+} (K^0\pi^+) \mu^+\mu^-$



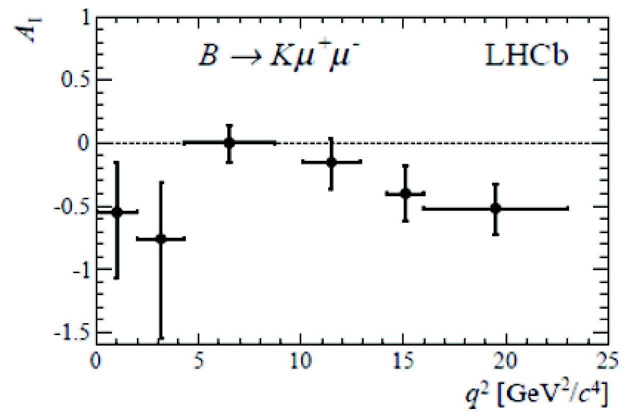


A_I consistent with 0 as expected from SM prediction
(tension in 1fb^{-1} analysis of $B \to K \mu^+\mu^-$ reduced)

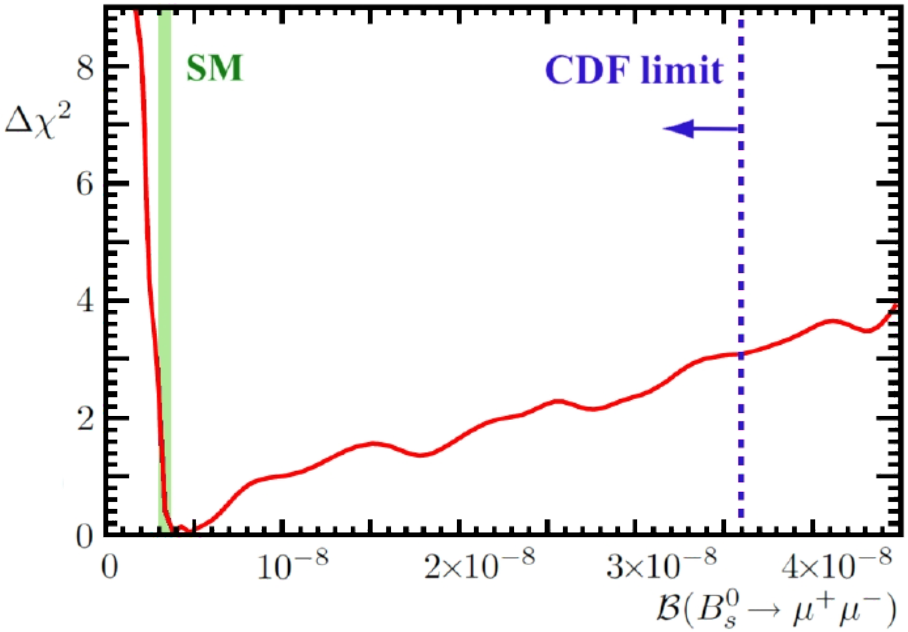
JHEP 06 (2014) 133



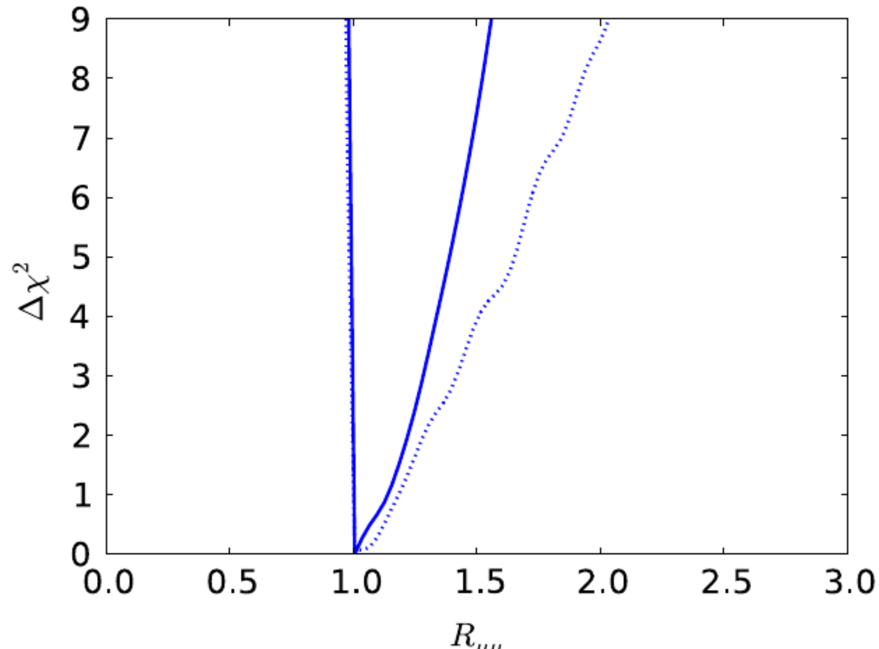
1fb^{-1}
JHEP 07 (2012) 133



- What changed in the meantime?
  - LHCb added another 2 fb^{-1} of data.
  - Previously assumption that equal amounts of B^+ and B^0 are produced at $\Upsilon(4S)$. Now assume isospin symmetry for $B \to J/\psi K^{(*)}$.
  - Reanalysis of 2011 data with identical selection for 2011 and 2012.
  - All these effects reduce the discrepancy.



[Eur.Phys.J.C64(2009)391]



Summer 2014: Buchmueller et al. ,[EPJC 74 (2014) 2922]

Likelihood function for the BF in the NUHM1 (a supersymmetric scenario) from global fit.

Table 3: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the expected sensitivity i given for the integrated luminosity accumulated by the end of LHC Run 1, by 2018 (assuming $5\,\text{fb}^{-1}$ recorded during Ru 2) and for the LHCb Upgrade ($50\,\text{fb}^{-1}$). An estimate of the theoretical uncertainty is also given – this and the potenti sources of systematic uncertainty are discussed in the text.

Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.05	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\, f_0(980))$ (rad)	0.09	0.05	**0.016**	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.18	0.12	**0.026**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.029**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.04**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$	0.20	0.13	**0.030**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.8%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\, A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.14	0.07	**0.024**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\,\%$
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**1.1°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.4°**	negligible
	$\beta(B^0 \to J/\psi\, K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm *CP* violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.5**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.12**	–

Why searching for $B^0_{(s)} \to \mu^+\mu^-$?

PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

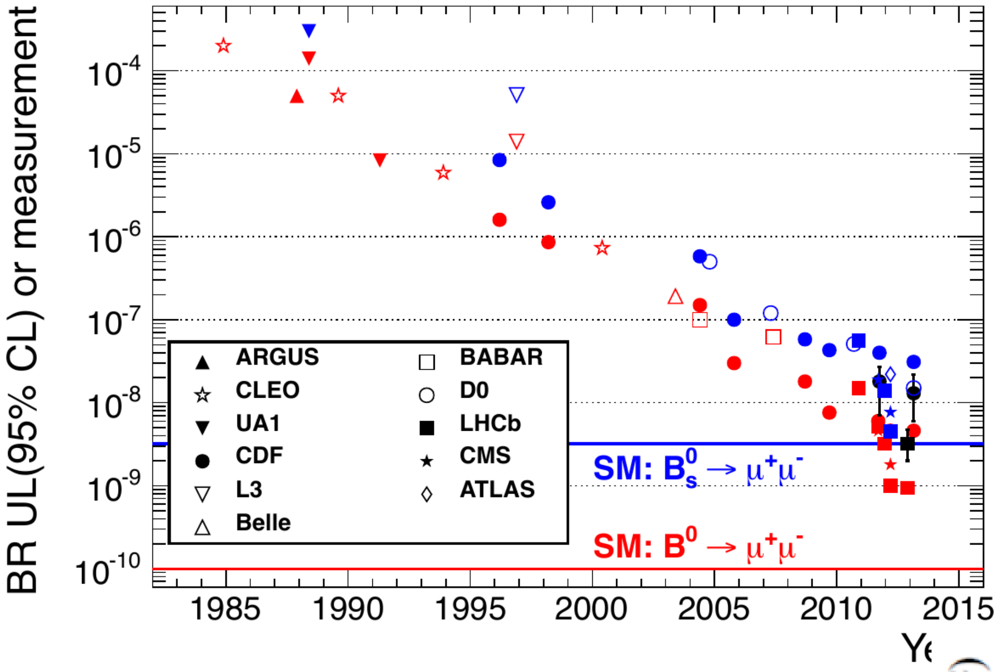
Two-body decays of B mesons

(Received 8 June 1984; revised manuscript received 10 September 1984)

Various exclusive and inclusive decays of B mesons have been studied using data taken with the CLEO detector at the Cornell Electron Storage Ring. The exclusive modes examined are mostly decays into two hadrons. The branching ratio for a B meson to decay into a charmed meson and a charged pion is found to be about 2%. Upper limits are quoted for other final states ψK^-, $\pi^+\pi^-$, $\rho^0\pi^-$, $\mu^+\mu^-$, e^+e^-, and $\mu^\pm e^\mp$. We also give an upper limit on inclusive ψ production and improved charged multiplicity measurements.

tor.[14] For the decay $\overline{B}{}^0 \to \mu^+\mu^-$, we improve our limit by requiring that both muons penetrate the iron and produce signals in drift chambers. We find no such events. After correcting for detection efficiency (33%), we set an upper limit of 0.02% at 90% confidence for this decay. We im-

Search is ongoing since 3 decades!



Nov. 2012,
First evidence at LHCb with 2.1 fb-1.

[PRL 110 (2013) 021801]

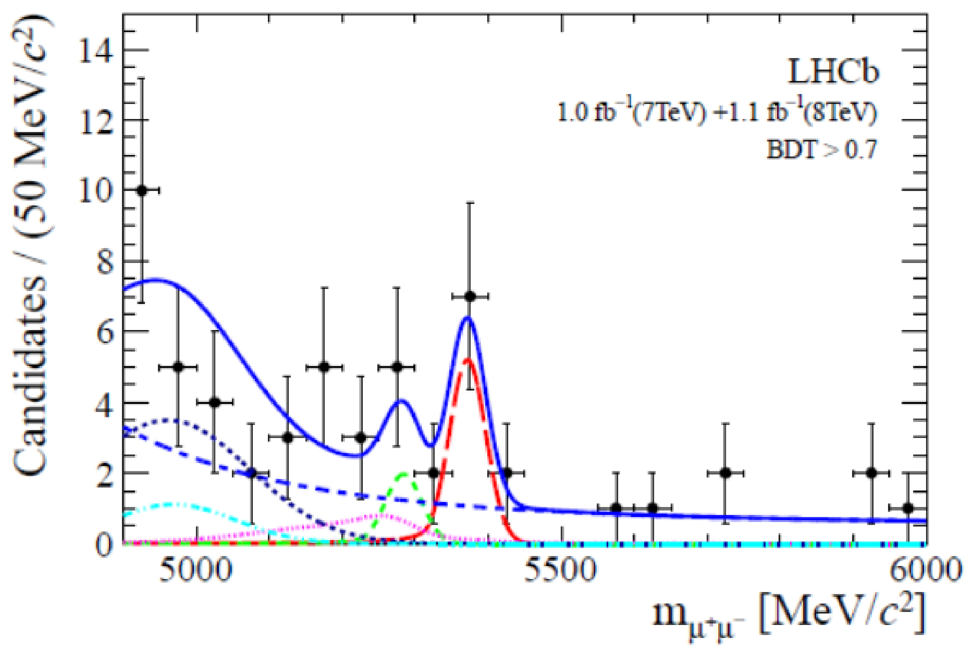
Excess of $B_s^0 \to \mu^+\mu^-$ candidates with a significance of 3.5 standard deviations.

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 3.2^{+1.5}_{-1.2} \times 10^{-9}$$

Today, I present an update on the full dataset at LHCb:
1 fb-1 (2011, 7 TeV) and
2 fb-1 (2012, 8 TeV)

All data consistently reprocessed
All data are blind in m(B(s))+-60 MeV

[PRL 111 101805 (2013)]

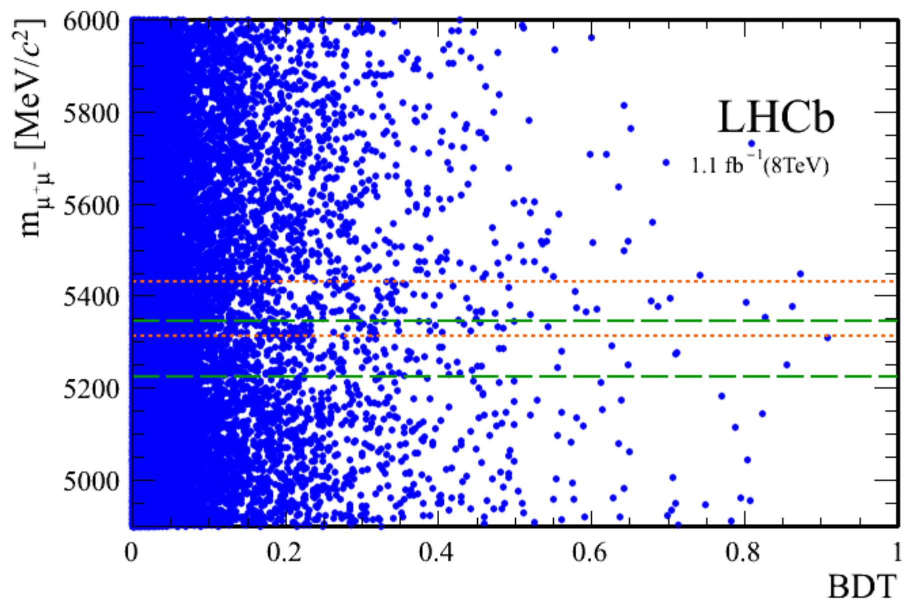


[PRL 111 101805 (2013)]

- **Selection**
  - **opposite-charge muons making a good vertex, separated from the PV, with mμμ in the range [4.9-6] GeV/c²**
  - **loose cut on a MVA discriminant**
  - **similar for normalisation channels**

- **Signal / Background discrimination via classification of** $B_s^0 \to \mu^+\mu^-$ **and** $B^0 \to \mu^+\mu^-$ **candidates in a 2D space**
  - **mass of the μμ pair combination**
  - **multivariate discriminant, BDT**

B: IP, isolation, p_T,..
muons: isolation, IPχ^2 wrt PVs, min(p_T),...



- **Use of control channels to calibrate the expectations**

$$J/\psi \to \mu^+\mu^-,\ \psi(2S) \to \mu^+\mu^- \text{ and } \Upsilon \to \mu^+\mu^-$$
$$B_s^0 \to K^+K^-,\ B^0 \to K^+\pi^- \text{ and } B^0 \to \pi^+\pi^-$$

Analysis strategy II

[PRL 111 101805 (2013)]

- Use of normalisation channels

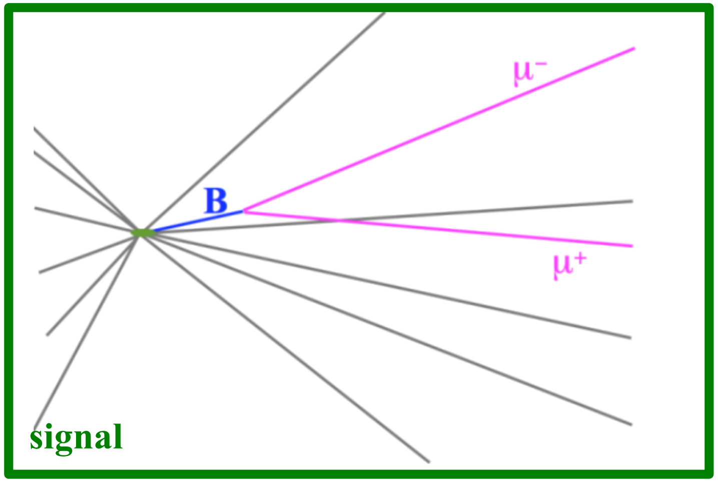
$$B^+ \to J/\psi(\to \mu^+\mu^-)K^+ \text{ and } B^0 \to K^+\pi^-$$

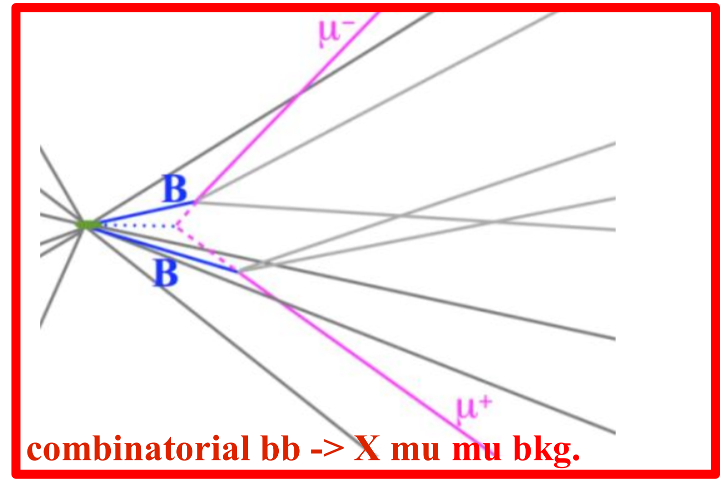
- Background estimation
  - combinatorial bkg from mass sidebands
  - double misidentified
  - detailed study of other exclusive background contributions

- Compare expectations with observed distribution of events
  - and get a BR measurement using a maximum likelihood fit to the invariant mass in bins of BDT
  - in case no signal excess is found, set an upper limit on the branching fraction using the modified frequentist method, Cls, in bins of mass and BDT.

BDT variables

[PRL 111 101805 (2013)]





The BDT training, choice of variables and BDT parameters optimisation on full MC signal and comb. bkg. (7 fb-1 equ.)

Choose kinematic and topological variables BDT so that the discrimination is maximal without inducing correlation with invariant mass.

B candidate

- proper time
- IP
- pT
- isolation
- Angle betw. the p(B) and $P_{thtrust}$
- Angle betw. μ+ in the B rest frame and $P_{thtrust}$ in the B rest frame

$P_{thtrust}$ is the sum of momenta of all tracks consistent with originating from the decay of the other b hadron

Muons

- min IP significance
- distance of closest approach
- isolation
- polarization angle
- |η(μ1)-η(μ2)|
- |φ(μ1)- φ(μ2)|

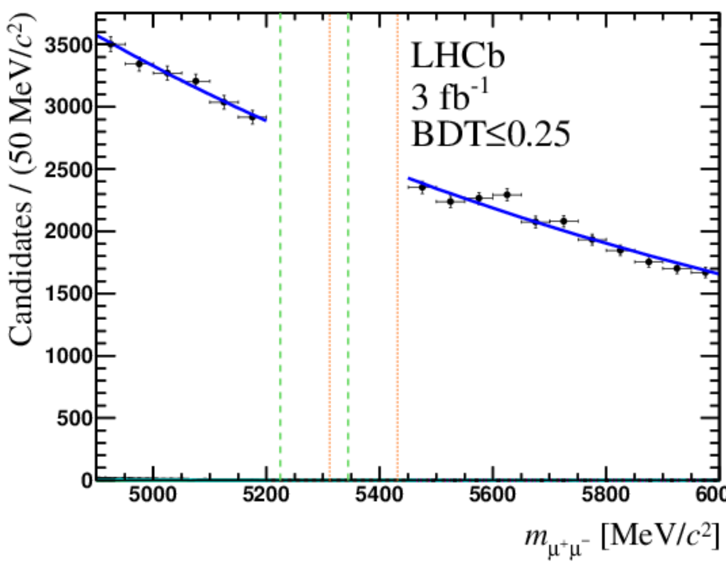
Discriminant calibration

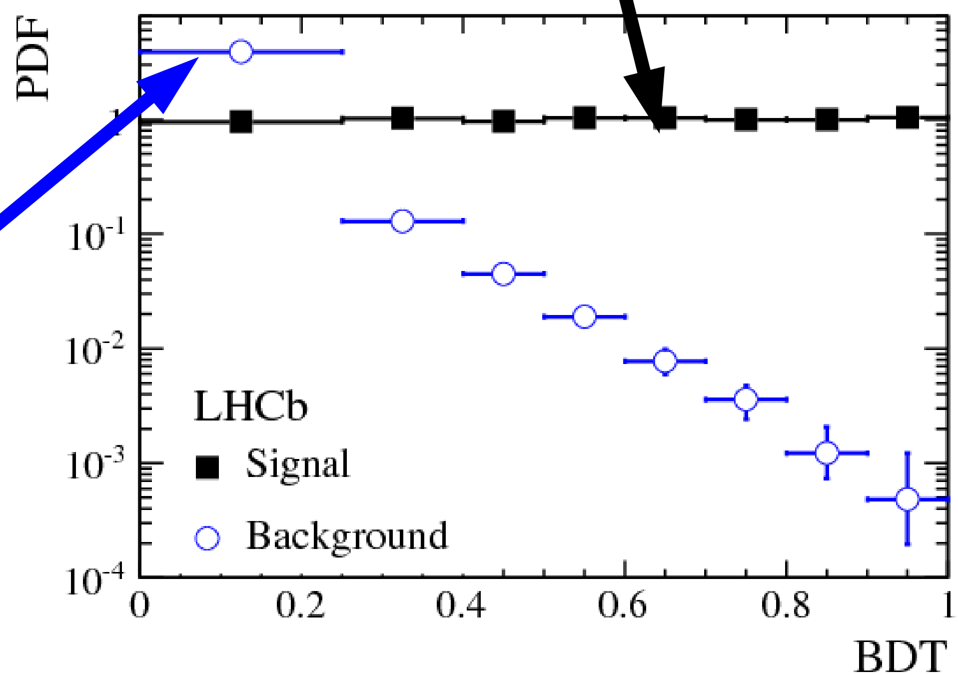
[PRL 111 101805 (2013)]

- **The BDT is trained using simulation.**
  But it is calibrated from data.

signal PDF is obtained from channels with same topology, $B \to h^+ h'^-$

background PDF is obtained from fit to the mass sidebands.

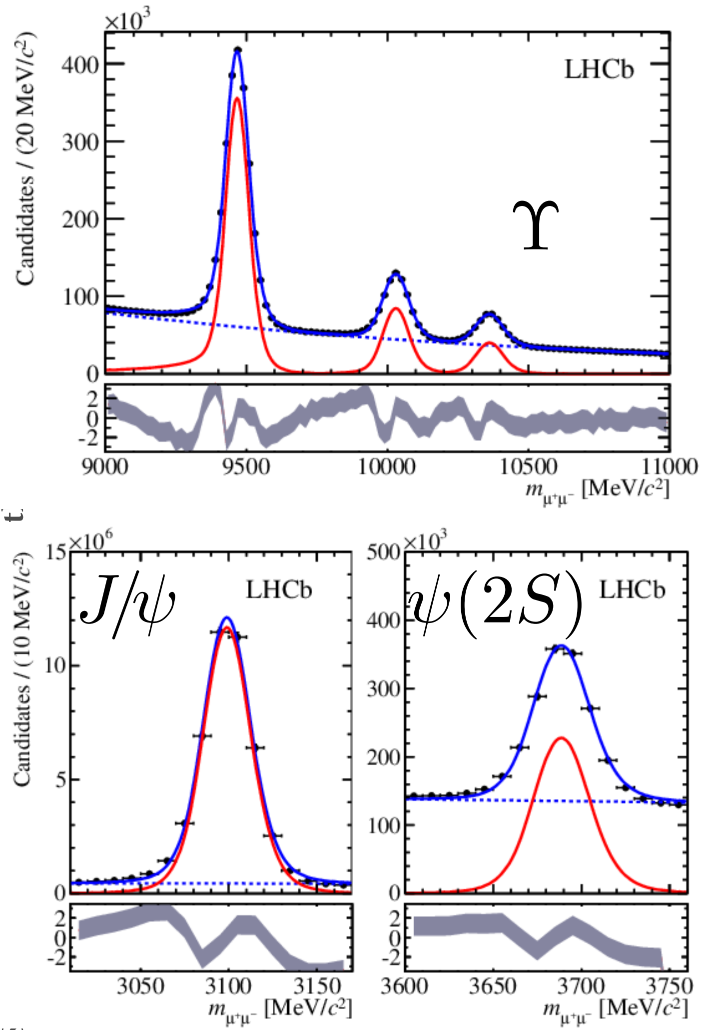




invariant mass calibration

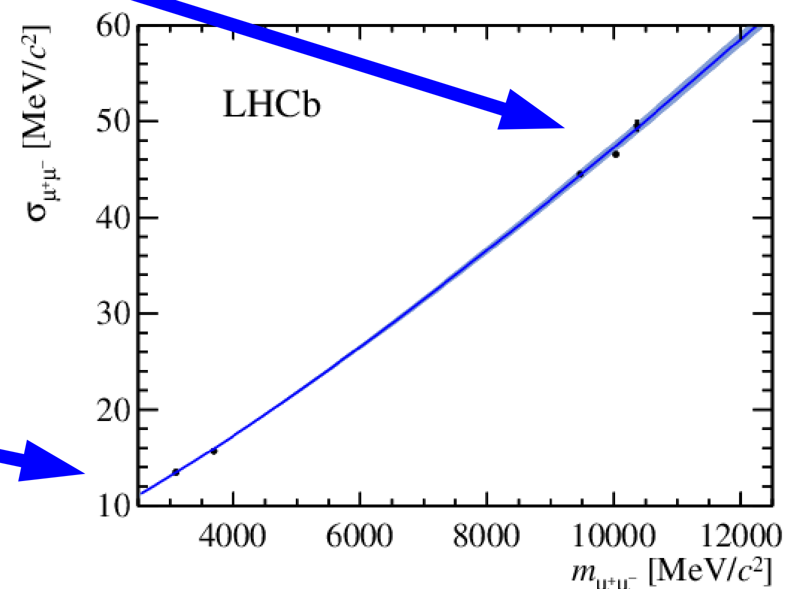
[PRL 111 101805 (2013)]

- **Invariant mass mean from exclusive B->hh**
- **Invariant mass resolution: 2 methods:**
  - ► **from exclusive B->hh**
  - ► **interpolation from** J/ψ, $\Psi(2S)$ and Υ



$$\sigma_{B^o} = (22.83 \pm 0.07 \pm 0.42)\ \mathrm{MeV/c^2}$$

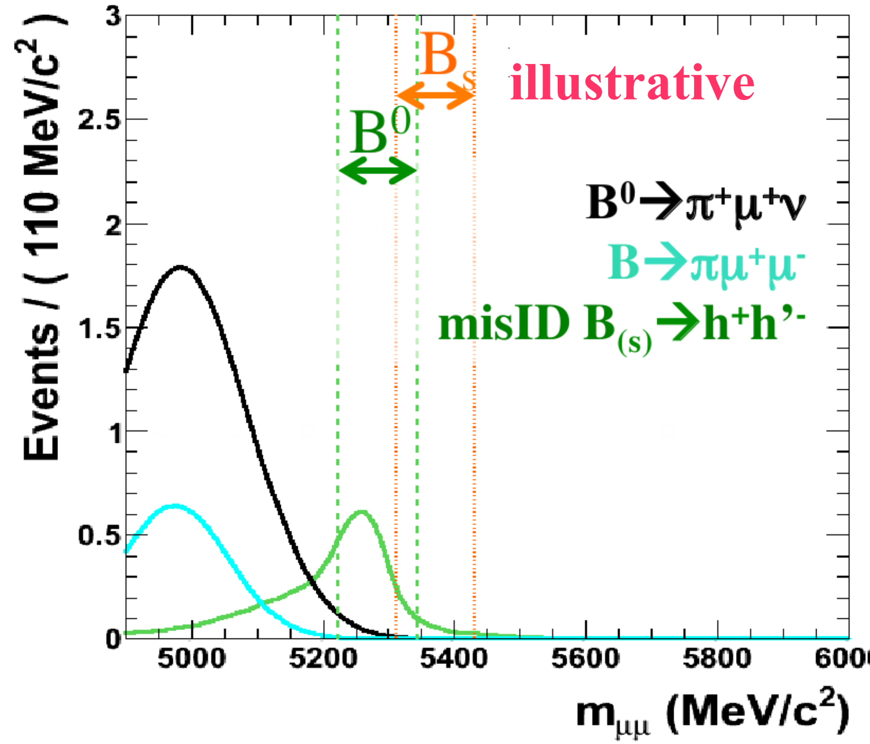
$$\sigma_{B_S} = (23.24 \pm 0.08 \pm 0.44)\ \mathrm{MeV/c^2}$$



Other backgrounds

[PRL 111 101805 (2013)]

- **Main background source is combinatorial from $bb \to \mu^+\mu^- X$**



- **contribution in the signal window:** $B^0_{(s)} \to h^+h'^-$ **with both hadrons misidentified as muons.**

  Mis-id probability from data with tag-and-probe: $\epsilon(hh \to \mu\mu) \sim 10^{-5}$
  Mass shape from simulation

- **contribution at lower mass sideband: decays with one hadron misidentified, or two muons coming from the same vertex.**

$B^0 \to \pi^-\mu^+\nu_\mu$	$B^{0(+)} \to \pi^{0(+)}\mu^+\mu^-$
$B^0_s \to K^-\mu^+\nu_\mu$	included in the final fit

$\Lambda^0_b \to p\mu^-\overline{\nu}_\mu$ $\quad$ $B^+_c \to J/\psi\mu^+\nu_\mu$

Normalisation I

[PRL 111 101805 (2013)]

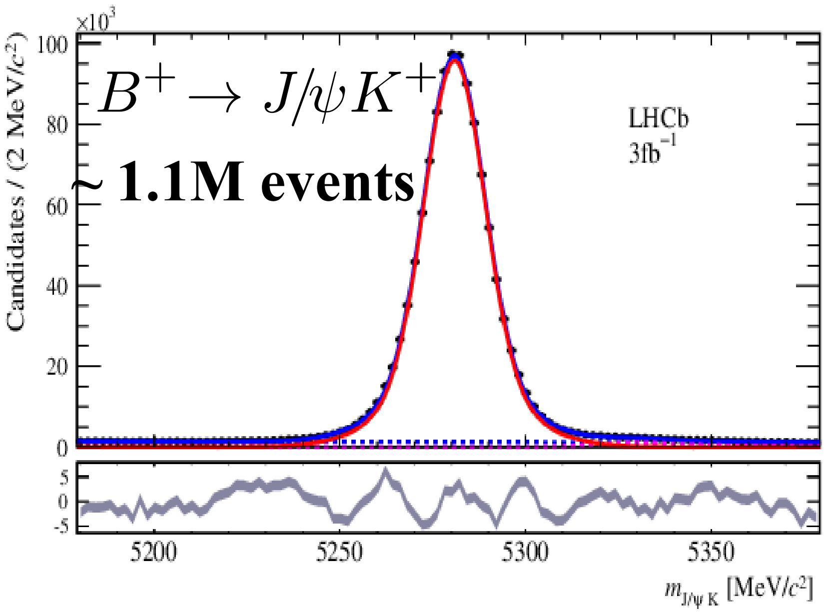
$$\mathcal{B} = \mathcal{B}_{\rm norm} \times \frac{\epsilon^{\rm rec}_{\rm norm}\epsilon^{\rm sel}_{\rm norm}}{\epsilon^{\rm rec}_{\rm sig}\epsilon^{\rm sel}_{\rm sig}} \times \frac{\epsilon^{\rm trig}_{\rm norm}}{\epsilon^{\rm trig}_{\rm sig}} \times \frac{f_{\rm norm}}{f_s} \times \frac{\mathcal{N}^{\rm obs}_{\rm sig}}{\mathcal{N}^{\rm obs}_{\rm norm}} = \alpha \times \mathcal{N}^{\rm obs}_{\rm sig}$$

PDG

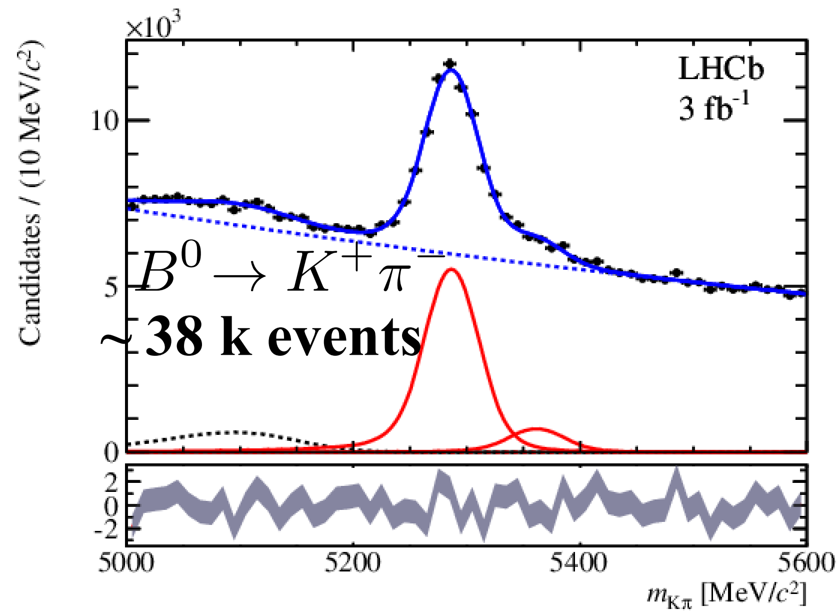
from MC
check on data

from data

- **2 normalisation channels** $B^+ \to J/\psi(\to \mu^+\mu^-)K^+$ and $B^0 \to K^+\pi^-$



same trigger, 1 track more



same topology, different trigger

Normalisation II

[PRL 111 101805 (2013)]

$$\mathcal{B} = \mathcal{B}_{\rm norm} \times \frac{\epsilon^{\rm rec}_{\rm norm}\epsilon^{\rm sel}_{\rm norm}}{\epsilon^{\rm rec}_{\rm sig}\epsilon^{\rm sel}_{\rm sig}} \times \frac{\epsilon^{\rm trig}_{\rm norm}}{\epsilon^{\rm trig}_{\rm sig}} \times \frac{f_{\rm norm}}{f_s} \times \frac{\mathcal{N}^{\rm obs}_{\rm sig}}{\mathcal{N}^{\rm obs}_{\rm norm}} = \alpha \times \mathcal{N}^{\rm obs}_{\rm sig}$$

- **Ratio of probability for a b-quark to hadronise into a given meson, fu= fd**

- **b fragmentation measured at LHCb at 7 Tev via 2 methods:**

  Ratio of B0 → D- K+/π+ and Bs → Ds- π+ [JHEP 04 (2013) 001]

  B → D+Xμ and Bs → DsXμ [PRD 85 (2012) 032008]

- **Recently updated using new B(Ds →KKπ) from CLEO, Babar and Belle and new B lifetime:**

$$\frac{f_s}{f_d} = 0.259 \pm 0.015$$

[LHCb-CONF-2013-011]

- **Stability of fd/fs for 7 and 8 TeV checked with**

$$B^+ \to J/\psi K^+ \text{ and } B^0 \to J/\psi \phi$$

Normalisation III

[PRL 111 101805 (2013)]

$$\mathcal{B} = \mathcal{B}_{\text{norm}} \times \frac{\epsilon^{\text{rec}}_{\text{norm}}\epsilon^{\text{sel}}_{\text{norm}}}{\epsilon^{\text{rec}}_{\text{sig}}\epsilon^{\text{sel}}_{\text{sig}}} \times \frac{\epsilon^{\text{trig}}_{\text{norm}}}{\epsilon^{\text{trig}}_{\text{sig}}} \times \frac{f_{\text{norm}}}{f_s} \times \frac{\mathcal{N}^{\text{obs}}_{\text{sig}}}{\mathcal{N}^{\text{obs}}_{\text{norm}}} = \alpha \times \mathcal{N}^{\text{obs}}_{\text{sig}}$$

- **2 normalisation channels** $B^+ \to J/\psi(\to \mu^+\mu^-)K^+$ and $B^0 \to K^+\pi^-$

- **The two normalisation channels give compatible results and are averaged:**

$$\alpha_{B^0_s} = (9.01 \pm 0.62) \times 10^{-11}$$
$$\alpha_{B^0} = (2.40 \pm 0.09) \times 10^{-11}$$

- **SM expectations in the signal mass windows:**

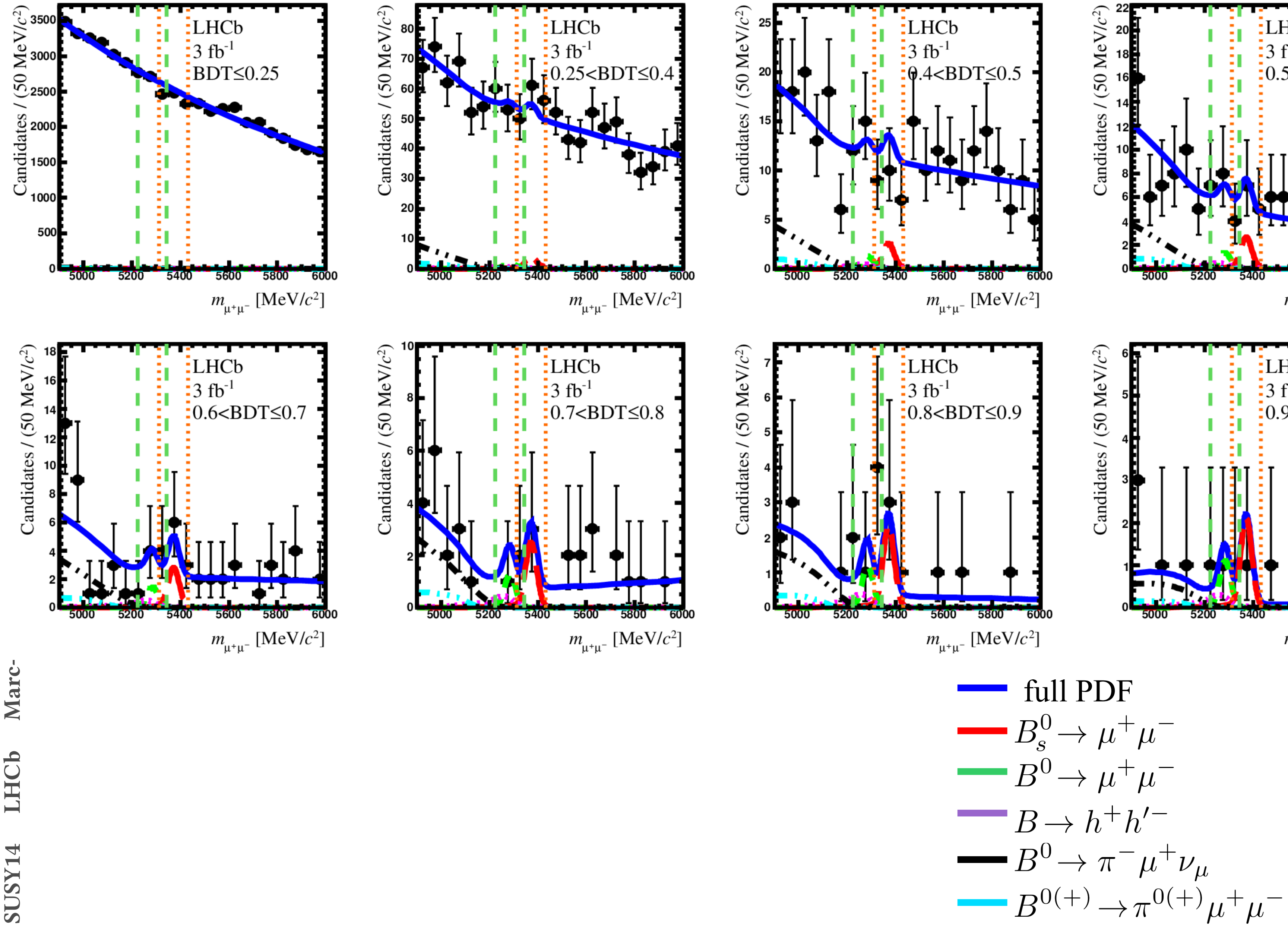
$$40 \pm 4 \ B^0_s \to \mu^+\mu^- \quad \text{and} \quad 4.5 \pm 0.4 \ B^0 \to \mu^+\mu^-$$

[PRL 111 101805 (2013)]

- **Simultaneous unbinned likelihood fit to the mass spectrum in 8 BDT bins.**
- **Free parameters:** $\mathcal{B}(B_s^0 \to \mu^+\mu^-), \mathcal{B}(B^0 \to \mu^+\mu^-)$ **and combinatorial background.**
- **All other signal parameters Gaussian constrained (mass mean, resolution, distribution in BDT bins).**
- **Yields of exclusive background are Gaussian constrained within their expectations.**
- **Systematics from variation of the exclusive mass shape, inclusion of** $\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$ **.**

Fit in 8 bins

[PRL 111 101805 (2013)]



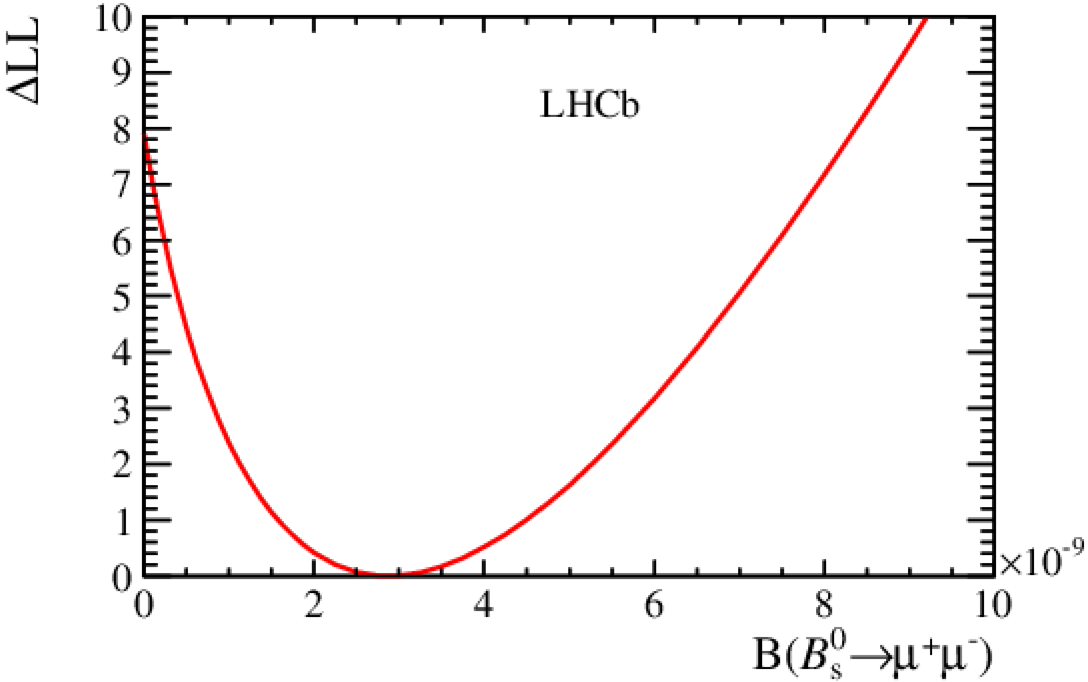
[PRL 111 101805 (2013)]

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}(\text{stat.})^{+0.3}_{-0.1}(\text{syst.})) \times 10^{-9}$$

Significance of 4.0 σ (expected 5.0 σ)

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.7^{+2.4}_{-2.1}(\text{stat.})^{+0.6}_{-0.4}(\text{syst.})) \times 10^{-10}$$

Significance of 2.0 σ



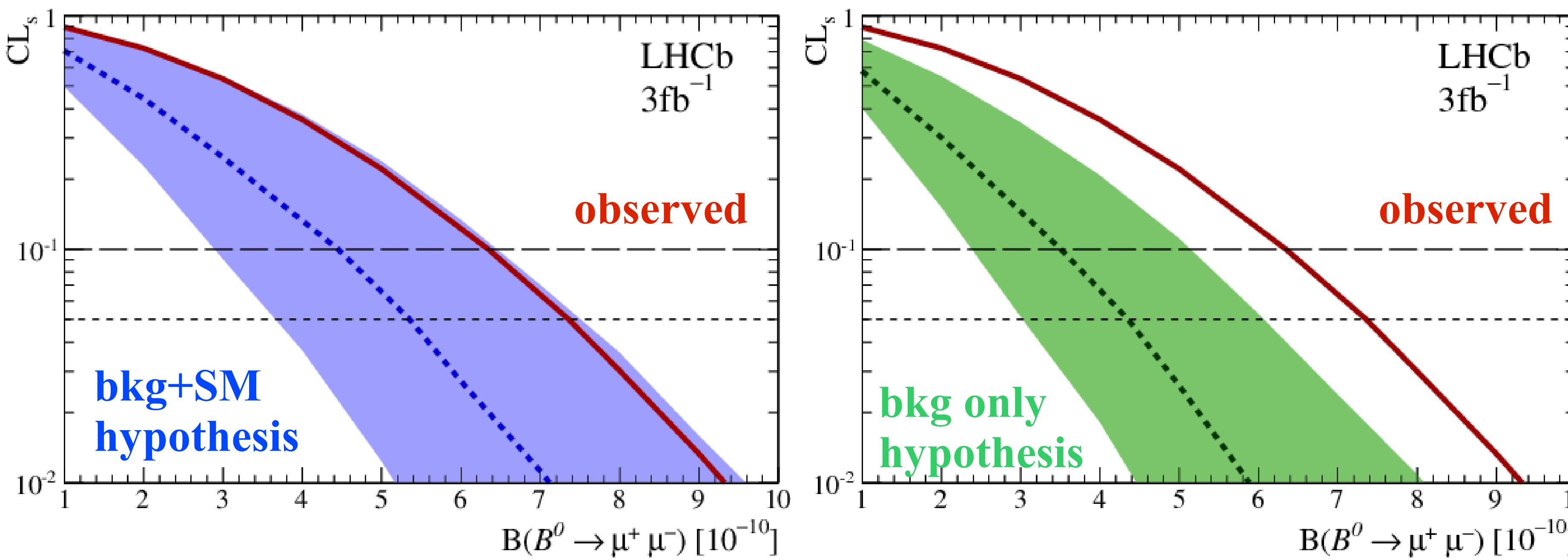
Correlation between the the BFs of 3.3%

Scan of the profile-likelihood ratio for B(Bs->mumu).
All other parameters can float within uncertainties.

limit on $\mathcal{B}(B^0 \to \mu^+\mu^-)$

[PRL 111 101805 (2013)]

- CLs method defines CLs = CLs+b / CLb
- 95% CL limit such that CLs = 0.05



Limit at 95%CL	
Expected bkg+SM	5.4×10^{-10}
Expected bkg only	4.4×10^{-10}
observed	7.4×10^{-10}

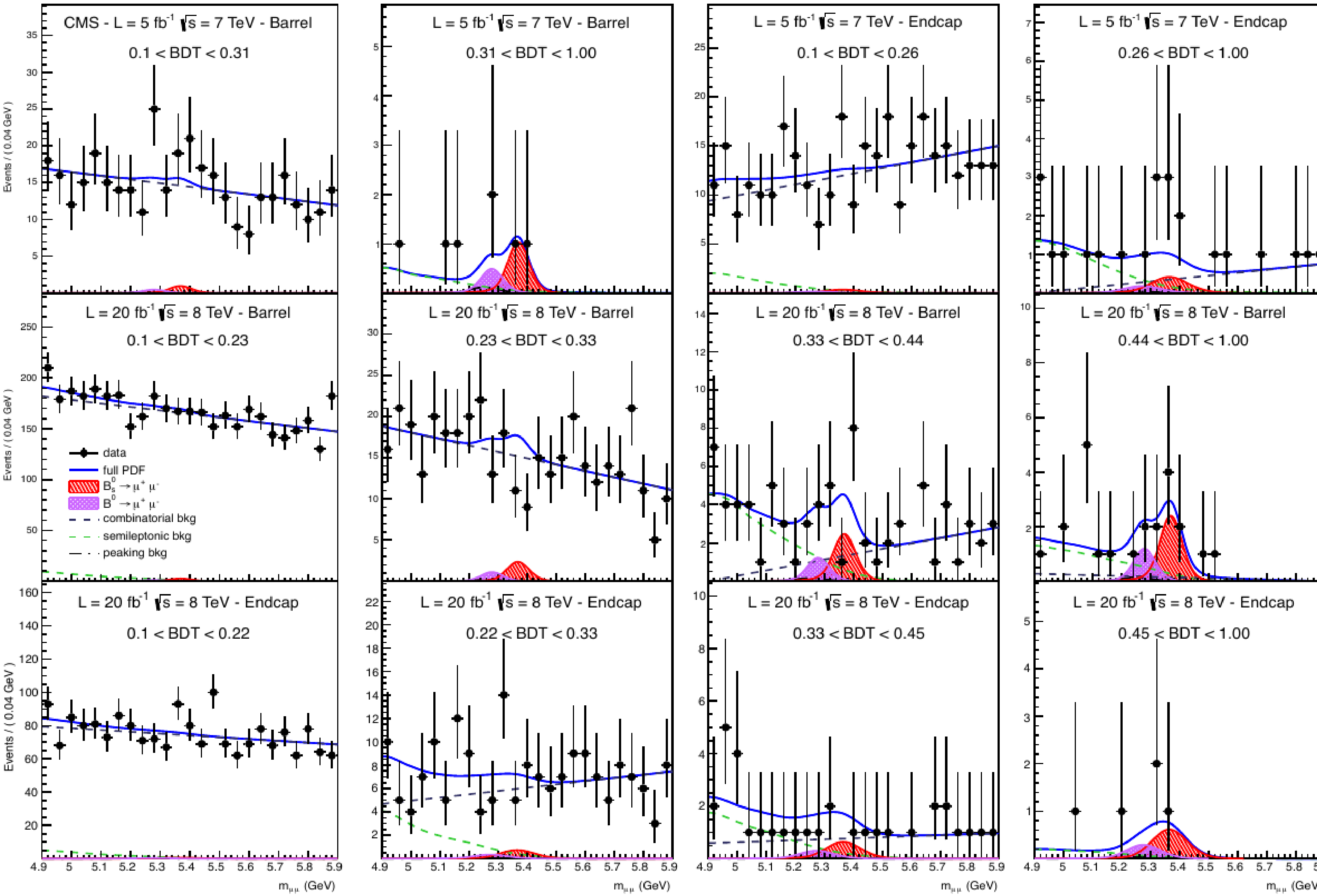
[PRL 111 101804 (2013)]

Last analysis very close to the LHCb one, significant improvement.
Main differences:

- Much more data, 5fb-1 (7TeV) + 20fb-1 (8TeV)
- Only one normalisation channel
- Separation of the data in detector region
  Barrel (2 muons with $\eta < 1.4$) mass reso. 40MeV
  End-cap (at least 1 muon) mass reso. 60 MeV
  and per data-taking period.
- BDT is trained on data for the combinatorial bkg.

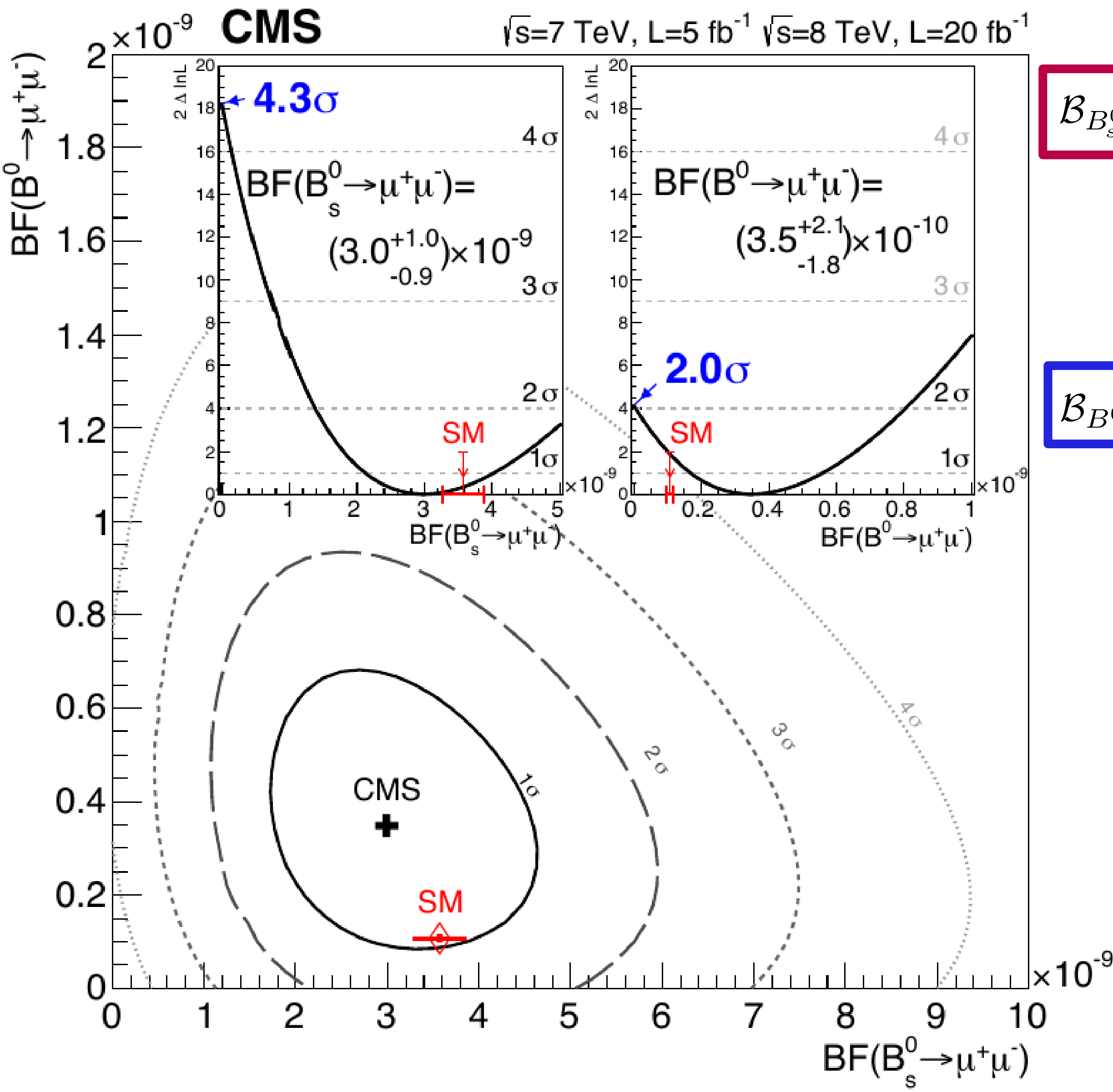
CMS Fit

[PRL 111 101804 (2013)]



CMS result

[PRL 111 101804 (2013)]



$$\mathcal{B}_{B_s^0} = (3.0^{+0.9}_{-0.8}(\text{stat.})^{+0.6}_{-0.4}(\text{syst.})) \times 10^{-9}$$

Significance of 4.3 σ

(expected 4.8 σ)

$$\mathcal{B}_{B^0} = (3.5^{+2.1}_{-1.8}(\text{stat.+syst.})) \times 10^{-10}$$

Significance of 2.0 σ

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

- **Simple preliminary average.**

- **Only one correlated uncertainty, fs/fd, as both experiments use $B^+ \to J/\psi K^+$ for normalisation. Extract the fs/fd uncertainty.**

- **CMS used an outdated value of fs/fd, rescale to latest update.**

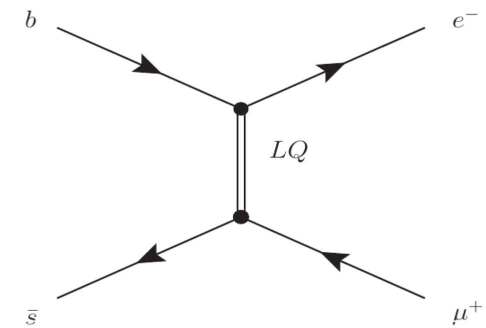
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.96\,^{+0.97}_{-0.85} \pm 0.17) \times 10^{-9} \qquad (2.87\,^{+1.09}_{-0.95} \pm 0.17) \times 10^{-9}$$

CMS **LHCb**

- **Use pseudo-experiment with variable-width Gaussian to model asymmetric uncertainties.**

Search for $B^0_{(s)} \to e^\pm \mu^\mp$

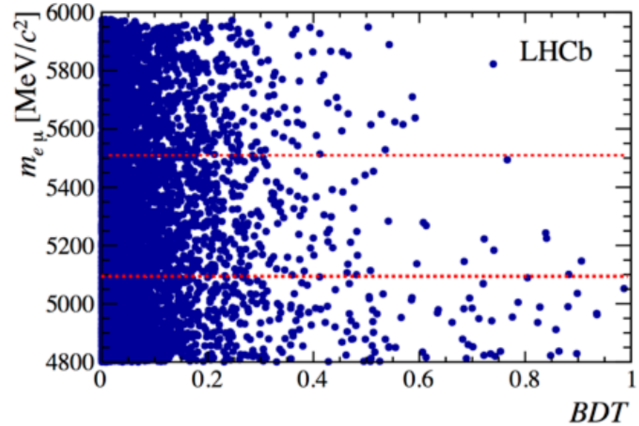
[arxiv:1307.4889], subm. PRL



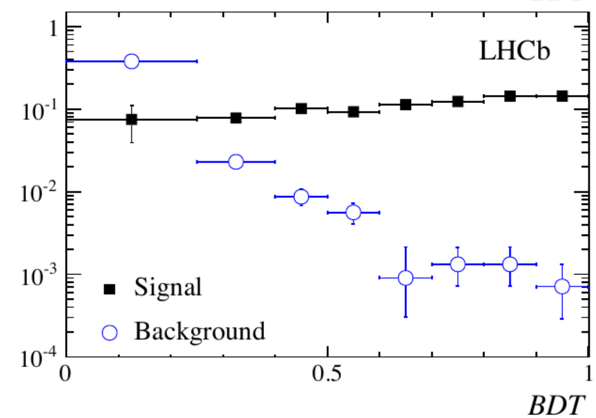
- **Direct search for LFV decays, forbidden in the SM (BF ~10^{-54})**

- **Can be enhanced in NP, in particular LeptoQuark model.**

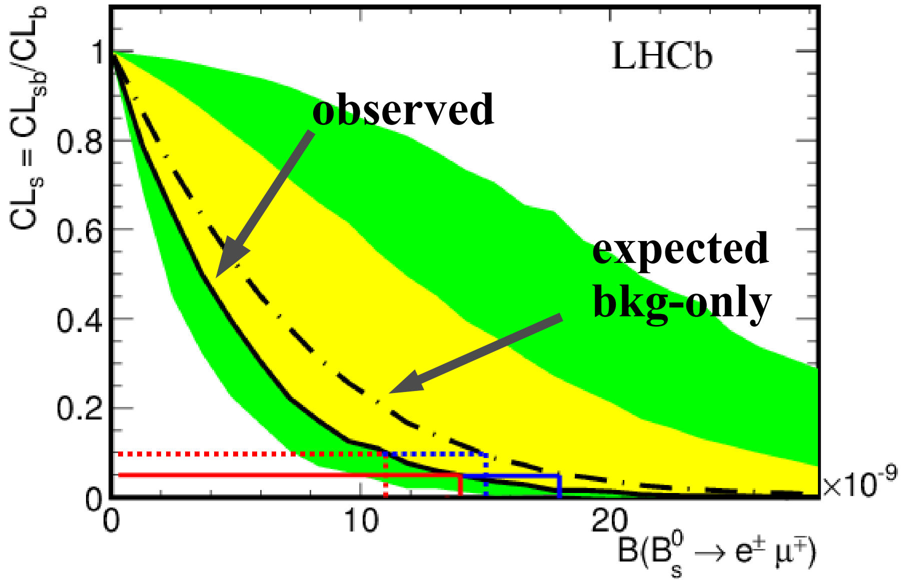
- **Lower bounds can be set on the mass of Pati-Salam lepto-quark.**
  [PRD 50 (1994) 6843]

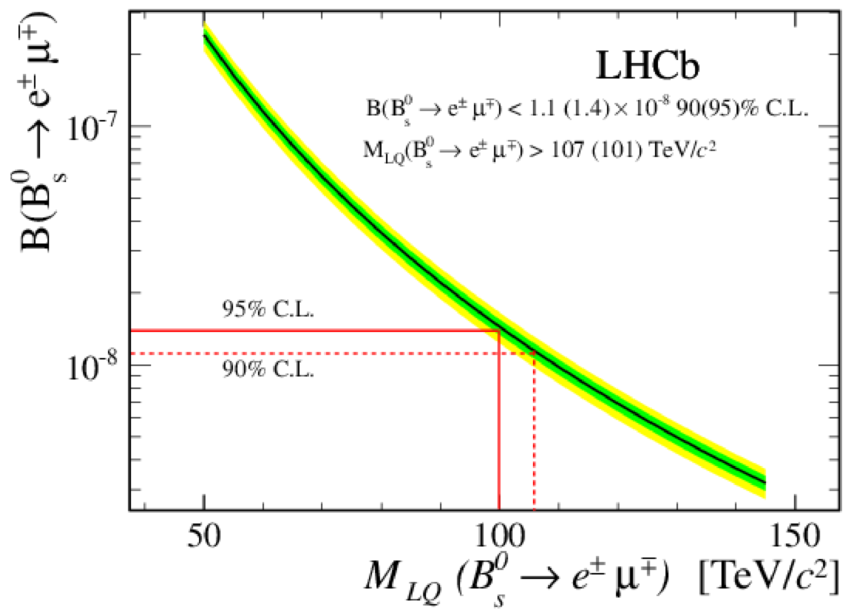


- **Blind analysis of 1fb-1 of 7 Tev LHCb data**
- **use $m_{e\mu}$ and a DBT discriminant**
  normalisation to $B^0 \to K\pi$
  Cls method to set limit



[arxiv:1307.4889], subm. PRL





95% CL limits	$B^0_s \to e^\pm \mu^\mp$	$B^0 \to e^\pm \mu^\mp$
LHCb (1fb-1)	1.4 x 10^{-8}	3.7 x 10^{-8}
CDF (2fb-1)	20.6 x 10^{-8}	79 x 10^{-8}

[PRL 102 (2009) 201901]

Lower bounds on the lepto-quark mass at 95% CL:

$$m_{\rm LQ}(B^0_s \to e^\pm \mu^\mp) > 101\ {\rm TeV}/c^2$$
$$m_{\rm LQ}(B^0 \to e^\pm \mu^\mp) > 126\ {\rm TeV}/c^2$$

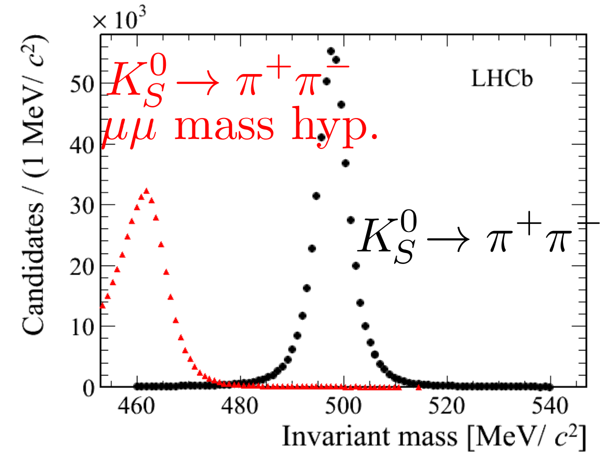
Search for $K_S^0 \to \mu^+\mu^-$

[JHEP 01 (2013) 090]

[Nucl.Phys.B366 (1991) 189]
[JHEP0401(2004) 009]

- Yet unobserved FCNC decay with $\mathcal{B}_{\rm SM} = (5.0 \pm 1.5) \times 10^{-12}$

- $K_L^0 \to \mu^+\mu^-$ and $K_S^0 \to \mu^+\mu^-$ receive different contributions, hence the fact that $\mathcal{B}(K_L^0 \to \mu^+\mu^-)$ is SM-like does not necessarily imply that $\mathcal{B}(K_S^0 \to \mu^+\mu^-)$ is. Enhancement up to 10^{-10} is possible.

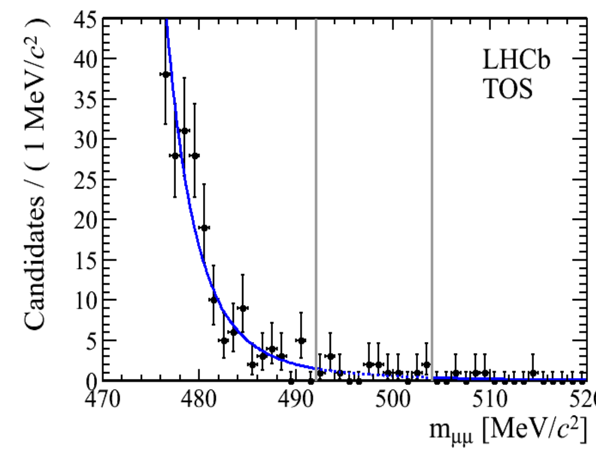


- Previous result dates from 1973

$$\mathcal{B}(K_S^0 \to \mu^+\mu^-) < 3.2 \times 10^{-7}$$

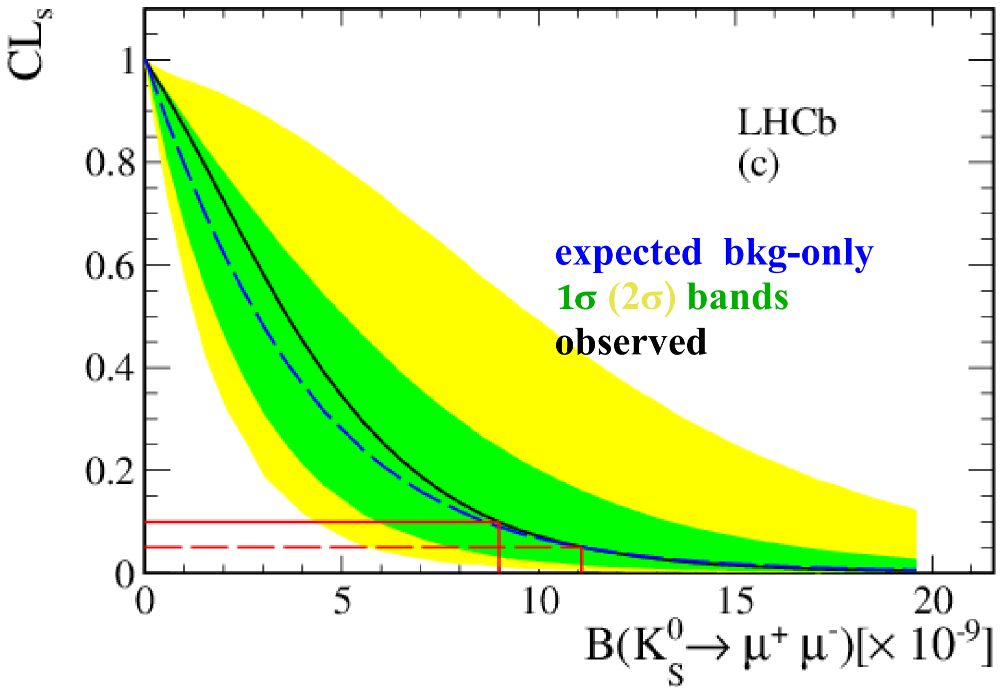
[Phys.Lett.B44(1973)217]

- Peaking background from $K_S^0 \to \pi^+\pi^-$
Good mass resolution helps containing it.

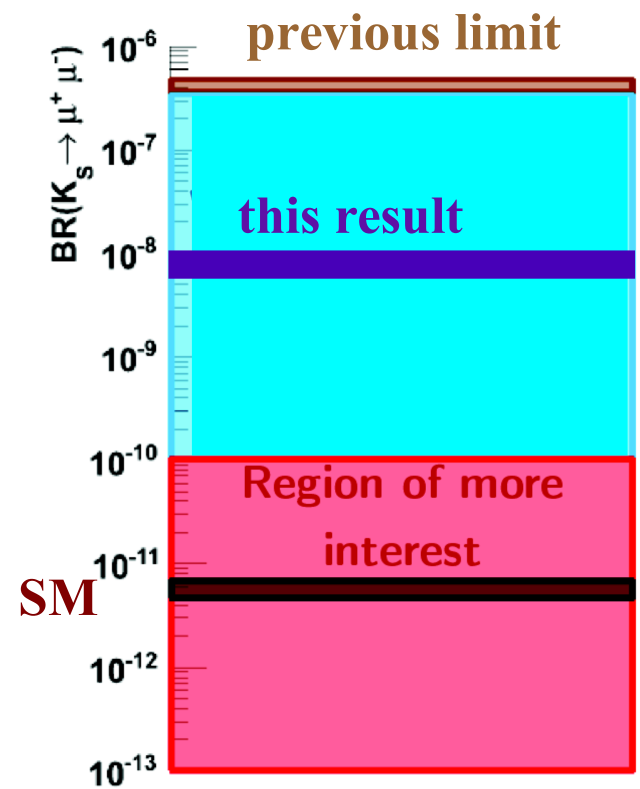


- Discrimination through a BDT (geometrical and kinematic), trained and calibrated on data.
Normalisation to $K_S^0 \to \pi^+\pi^-$

[JHEP 01 (2013) 090]



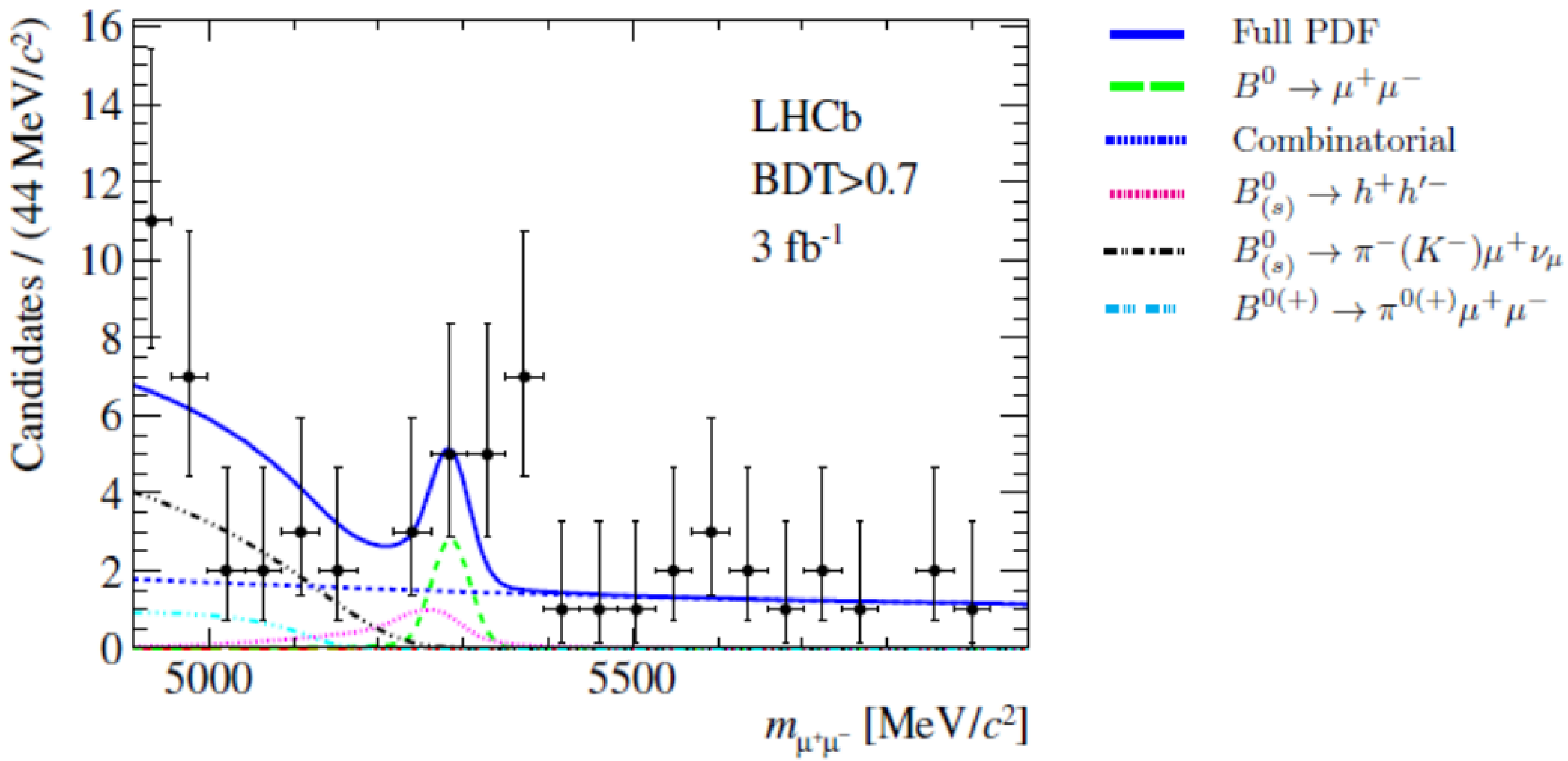
Use the CLs Method to determine an upper limit on the branching fraction



$$\mathcal{B}(K_S^0 \to \mu^+\mu^-) < 9 \times 10^{-9} \text{ at } 90\% \text{ CL}$$
$$\mathcal{B}(K_S^0 \to \mu^+\mu^-) < 11 \times 10^{-9} \text{ at } 95\% \text{ CL}$$

New world best limit, a factor 35 lower than the previous result.

- Fit without Bs signal



- Neutral B_s^0 mesons undergo mixing:

$$\langle \Gamma(B_s^0(t) \to f) \rangle \equiv R_H^f e^{-\Gamma_H^s t} + R_L^f e^{-\Gamma_L^s t}$$

- Experimental observable is the time integrated B:

$$B(B_s^0 \to f)_{\text{exp}} \equiv \frac{1}{2} \int_0^\infty \langle \Gamma(B_s^0(t) \to f) \rangle dt$$

- Theoretical definition for the prediction:

$$B(B_s^0 \to f)_{\text{theo}} \equiv \frac{\tau_{B_s^0}}{2} \langle \Gamma(B_s^0(t) \to f) \rangle \Big|_{t=0}$$

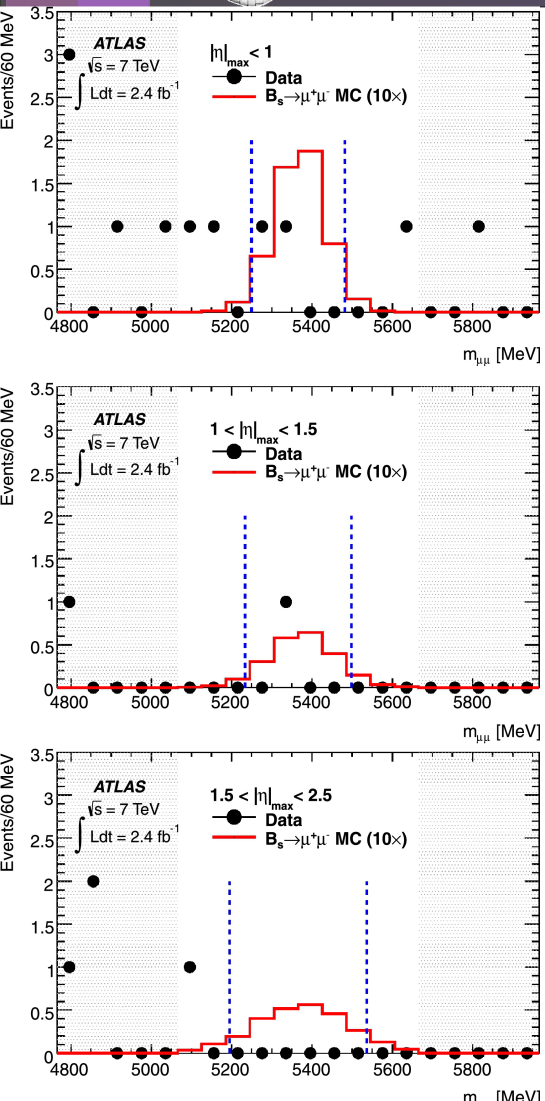
- Time integrated prediction:

$$B(B_s^0 \to \mu^+\mu^-)_{\text{exp}}^{\text{SM}} = (3.56 \pm 0.30) \times 10^{-9}$$

De Bruyn et al., PRL 109, 041801 (2012), uses $\Delta\Gamma_s$ from LHCb-CONF-2012-002

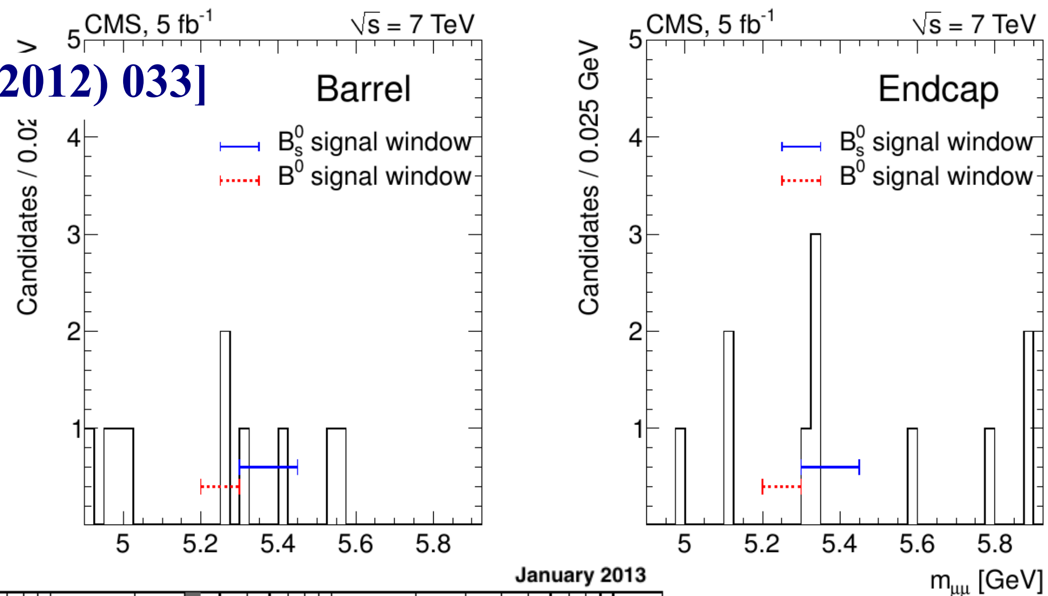
	Scenarios	Implications
✗	$\mathcal{B}(B_s^0 \to \mu^+\mu^-) >> SM$	NP is discovered. Can be SUSY, Extradimension, ...
✗	$\mathcal{B}(B_s^0 \to \mu^+\mu^-) << SM$	NP is discovered. But MSSM does not survive.
?	$\frac{\mathcal{B}(B_s^0 \to \mu^+\mu^-)}{\mathcal{B}(B^0 \to \mu^+\mu^-)} \neq SM$	MFV is ruled out. CP violation in NP is not gouverned by CKM.
✓	$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = SM$	Any model is valid. Major constraints on NP.

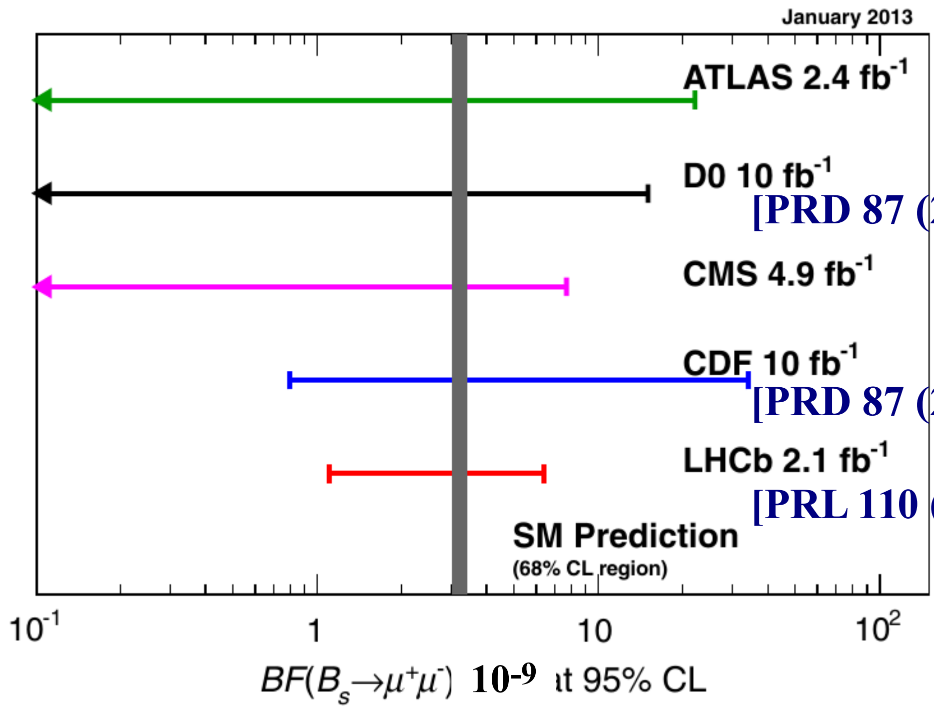
$B^0_{(s)} \to \mu^+\mu^-$ status



ATLAS 2.4 fb-1
[PLB 713 (2012) 387]

CMS 5 fb-1
[JHEP 04 (2012) 033]

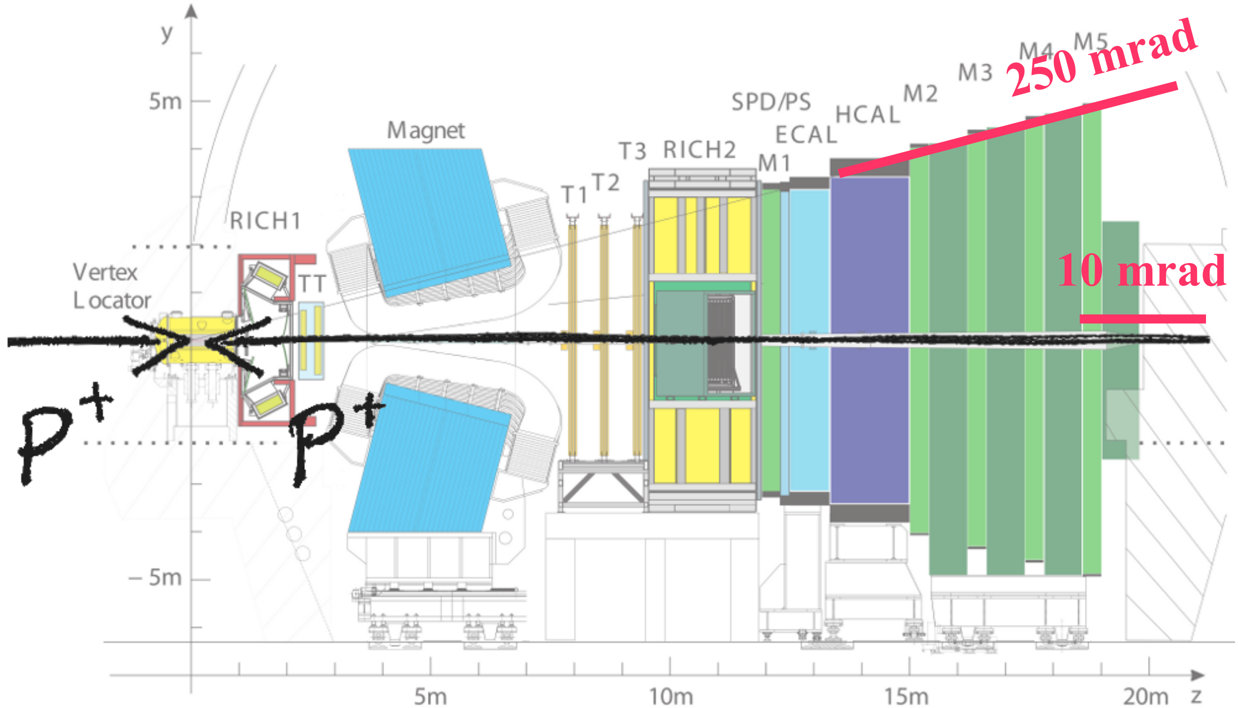




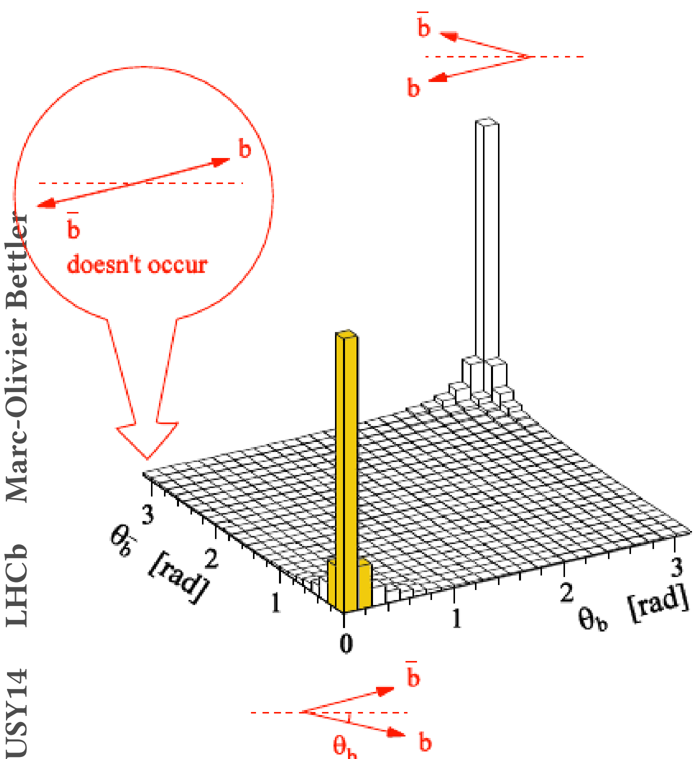
[PRD 87 (2013) 072006]
[PRD 87 (2013) 072003]
[PRL 110 (2013) 021801]

LHC experiment optimised for Heavy Flavour physics

Forward spectrometer



[JINST 3 S08005 (2008)]



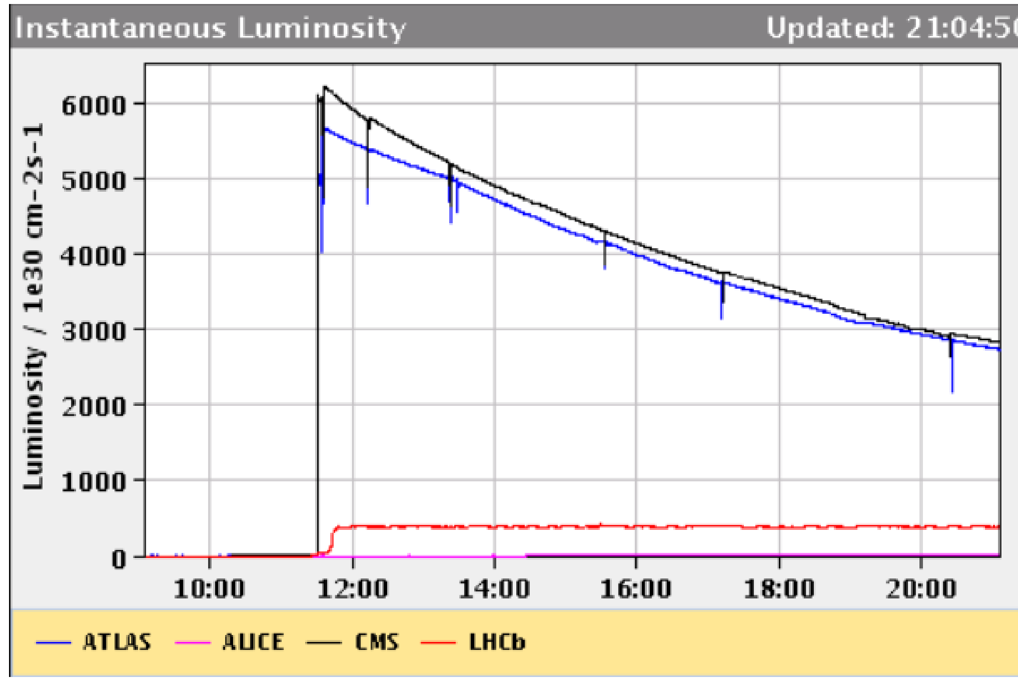
Forward spectrometer, acceptance: 2 < eta < 5

Huge bb production cross-section

B particles fly ~O(cm) before to decay.

The LHCb physics program calls for measurement accuracy.

Running at a constant luminosity of 4 10^{32} cm^{-2} s^{-1} thanks to luminosity leveling
This is twice the design luminosity.

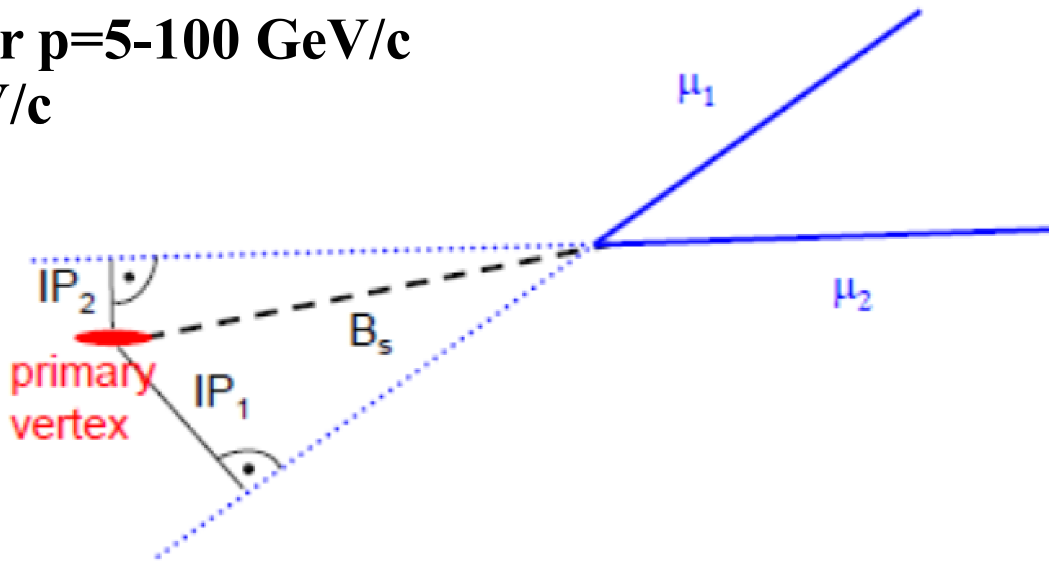


Interactions per crossing <μ>~1.7
This is about four times the design!

Large muon trigger efficiency:

- **L0 single muon pT>1.76 GeV/c, dimuon sqrt(pT1xpT2)>1.6GeV/c**
- **HLT: IP and invariant mass cut**
- **Global trigger efficiency for Bs/d→mumu : ~90%**

Excellent momentum and IP resolution:
- **$\delta p/p$ ~0.4% to 0.6% for p=5-100 GeV/c**
- **$\sigma(IP)$ = 25 µm @ 2GeV/c**



Excellent muon identification:
- **Use muon chambers information**
+ global PID likelihood (RICH, CALO, MUON)

- **$\varepsilon(\mu \rightarrow \mu)$~98%, $\varepsilon(\pi \rightarrow \mu)$~0.6%, $\varepsilon(K \rightarrow \mu)$~0.4%, $\varepsilon(p \rightarrow \mu)$~0.3%**