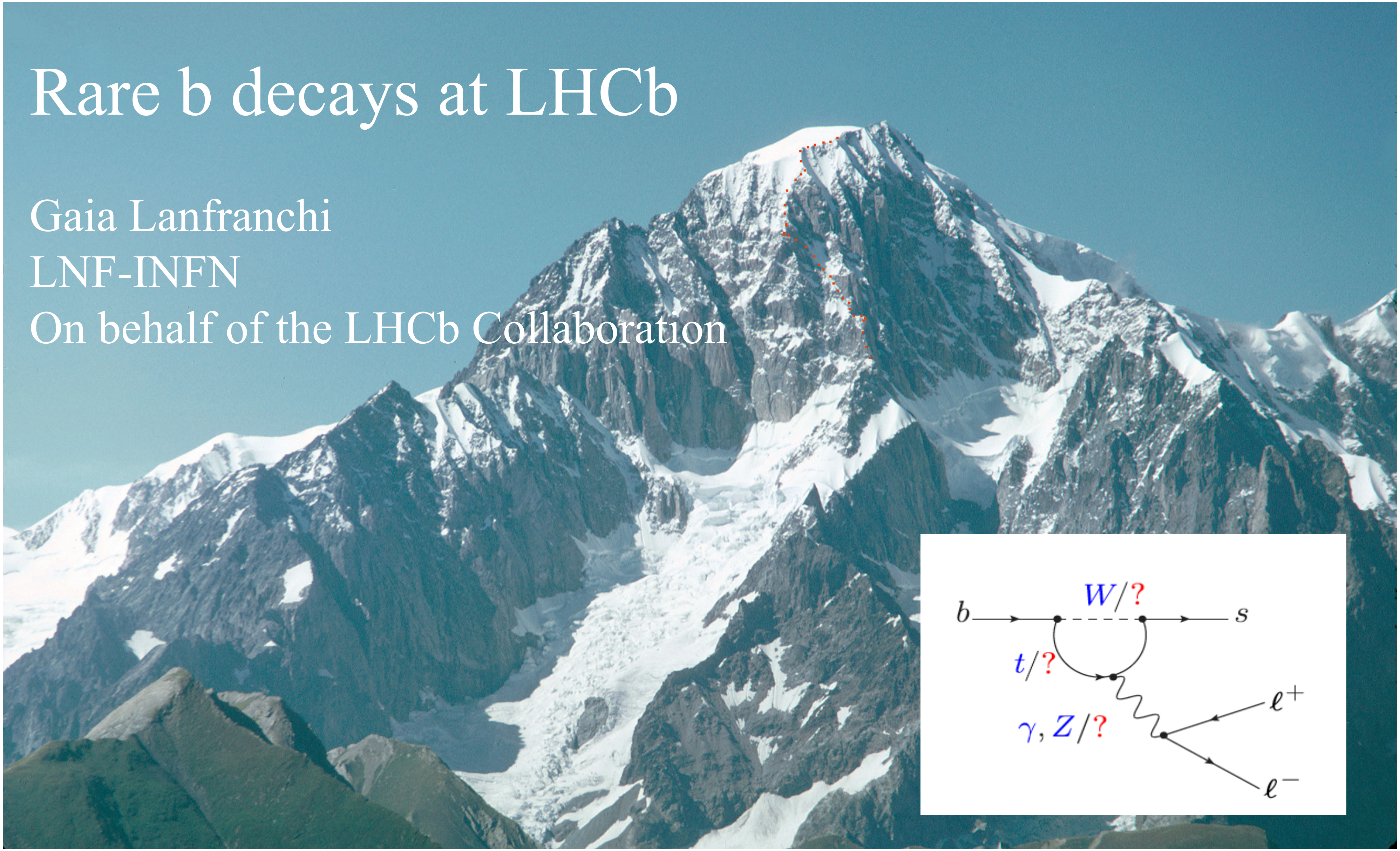
Rare b decays at LHCb

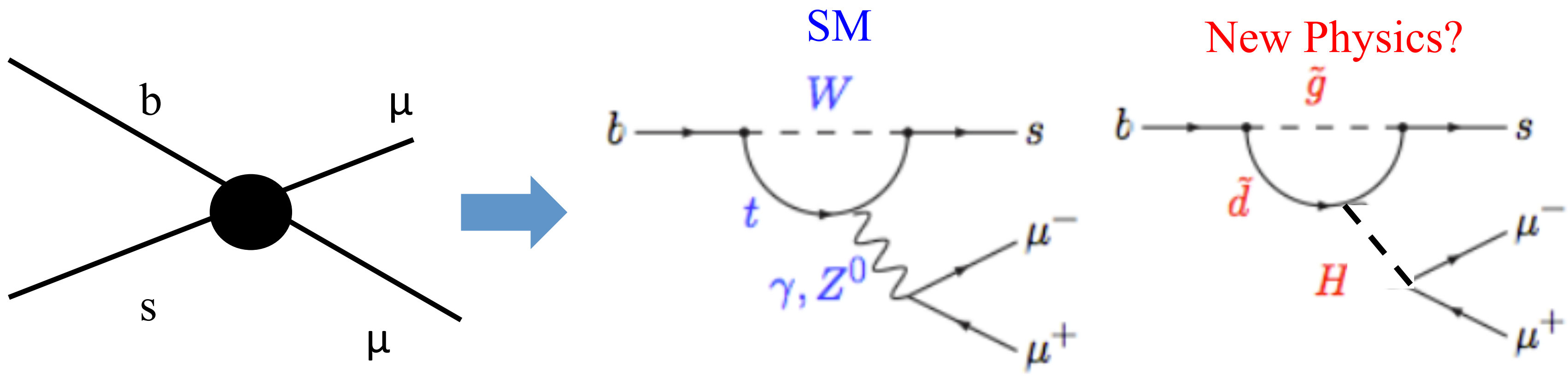
Gaia Lanfranchi
LNF-INFN
On behalf of the LHCb Collaboration



Les Rencontres de Physique de la Vallee d'Aoste, La Thuile 2015

Why to study rare B decays?

Rare FCNC b decays are sensitive to quantum corrections from degrees of freedom **at** or **above** the electroweak scale.



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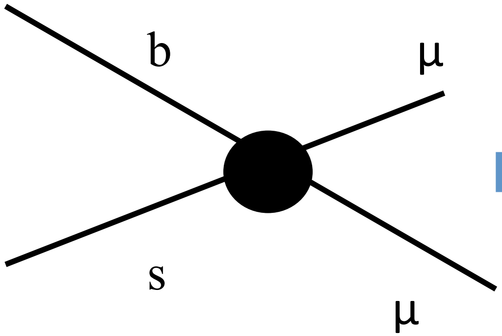
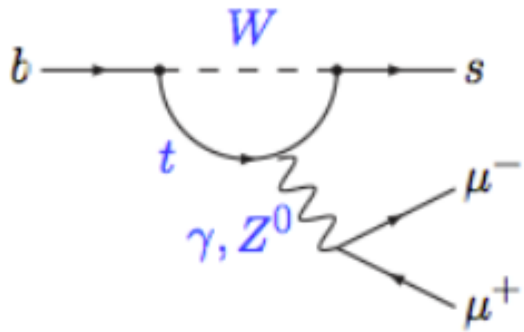
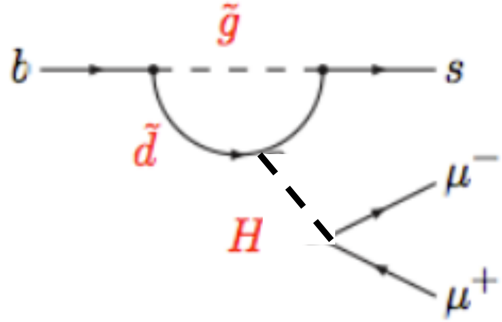


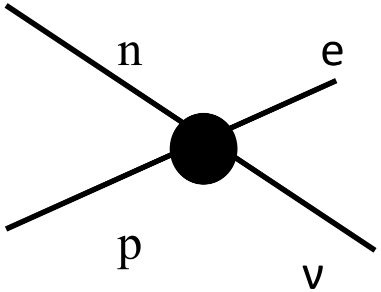
SM

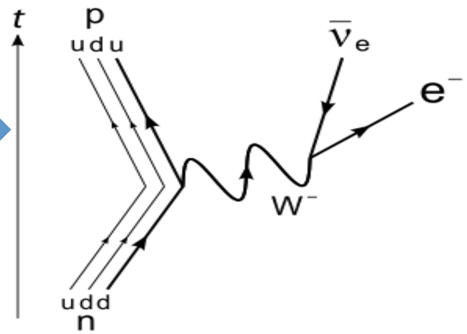


New Physics?



Nothing different from what was done at the dawn of the electroweak theory:





1934: Fermi's theory of the nuclear beta decay (only S & V currents)
1936: Gamow-Teller transitions (also T and A are possible)
1957: Mme Wu experiment: The parity is violated in weak interactions
1957: Feynman-Gellmann: V-A theory
1968: Glashow, Weinberg and Salam: birth of the Standard Model

Why to study rare B decays?

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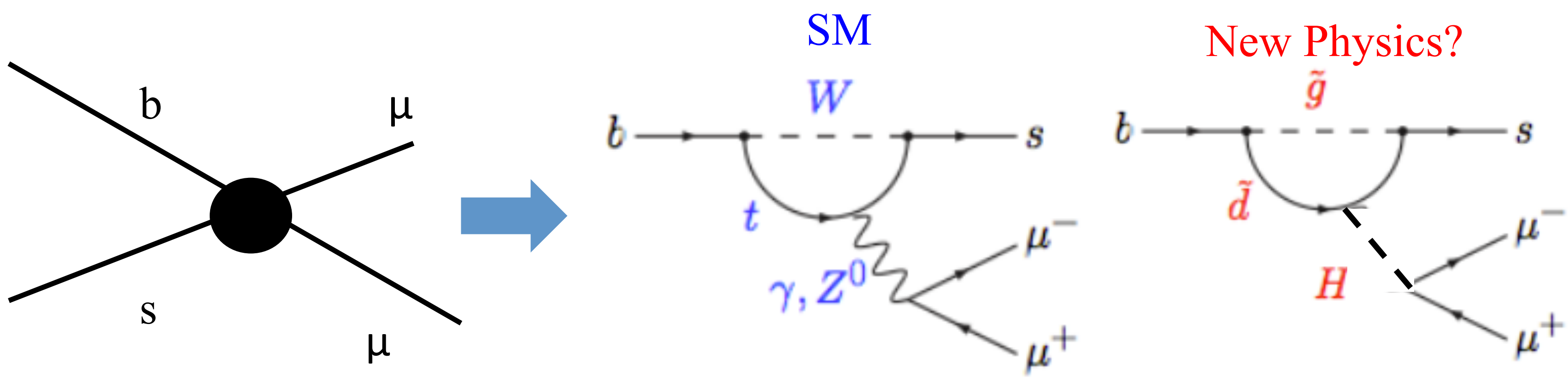


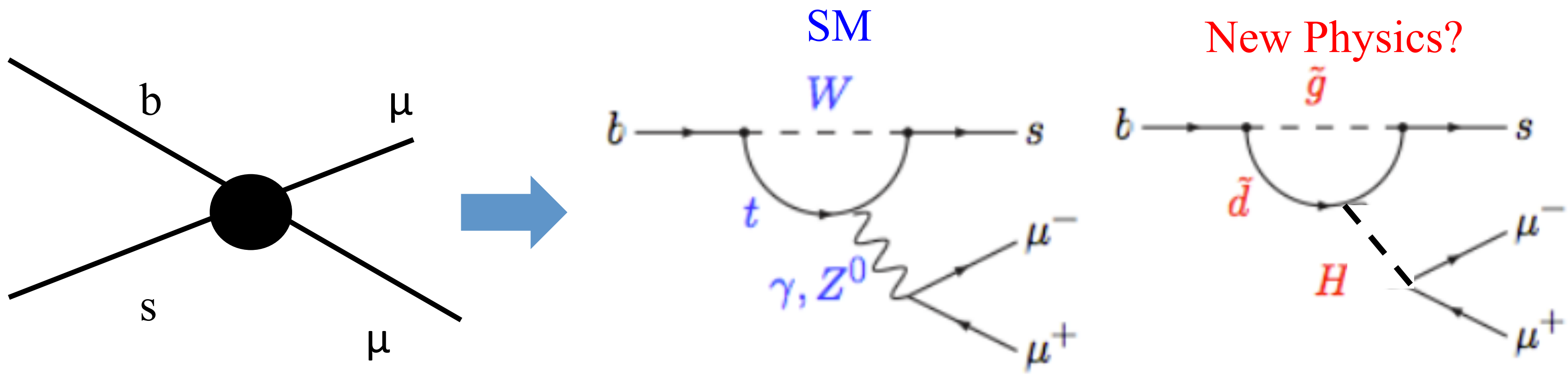
We describe FCNC processes by an effective Hamiltonian in the form of Operator Product Expansion to identify the types of operators that enter in the transitions:

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

$i = 1,2$	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

Why to study rare B decays?

Rare FCNC b decays are sensitive to quantum corrections from degrees of freedom **at** or **above** the electroweak scale.



NP can modify the Wilson coefficients (C_i) affecting observable quantities as angular distributions and decay rates in B→ $K^{(*)}\mu\mu$ decays (C_7, C_9, C_{10}), decay rates in B→ μμ decays (C_s, C_p) and photon polarization (C'_7)

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

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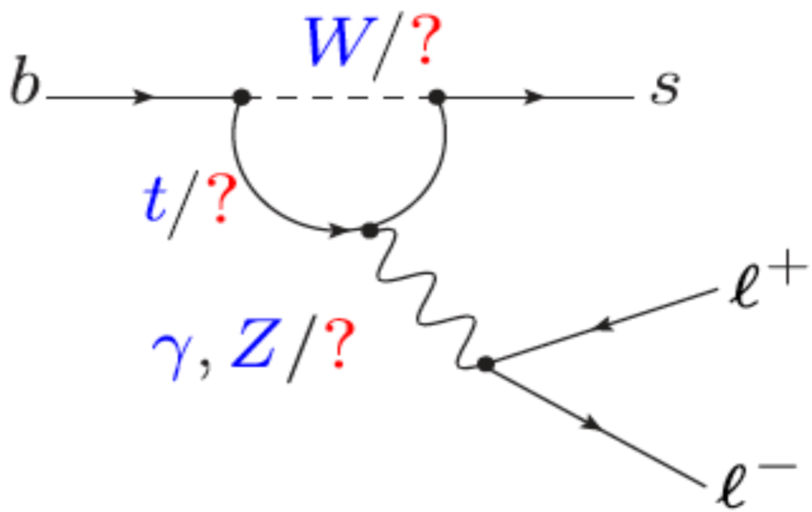
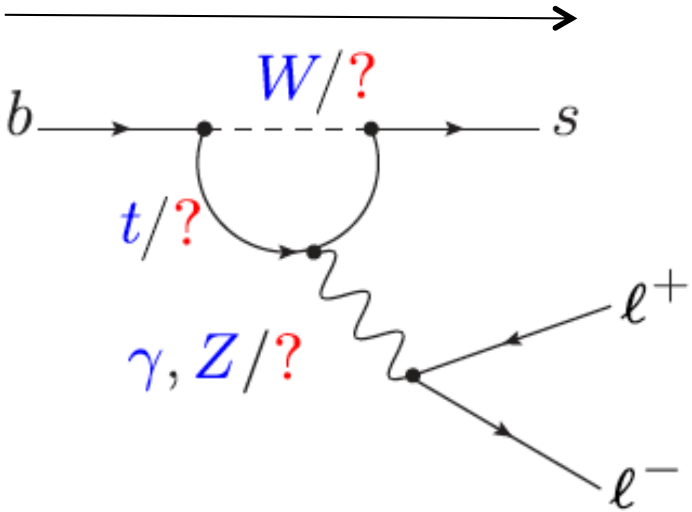
…You will see that, despite the variety of topics,
today we will be talking always about (almost) the same diagram
(in different flavors)….



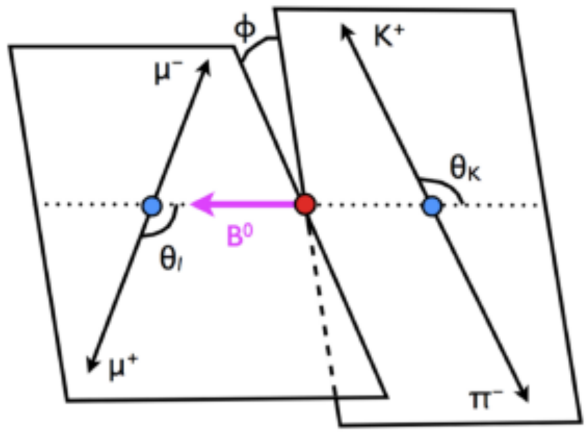
Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ decays



Angular distribution of the $B^0 \to K^{*0}\mu^+\mu^-$ decay is sensitive to the virtual photon polarisation and new left- and right-handed (axial) vector currents.

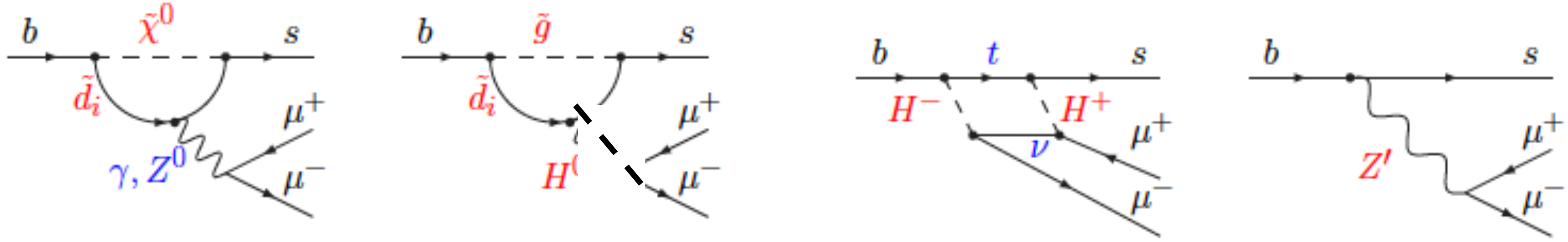
Decay described by three angles (θ_l, θ_K, ϕ) and the dimuon invariant mass squared q^2.

3 angles, 12 different J_i coefficients (which contain the information from Wilson coefficients) due to 6 complex numbers that define the K^{*0} spin amplitudes.
(see spares slides for complete description)

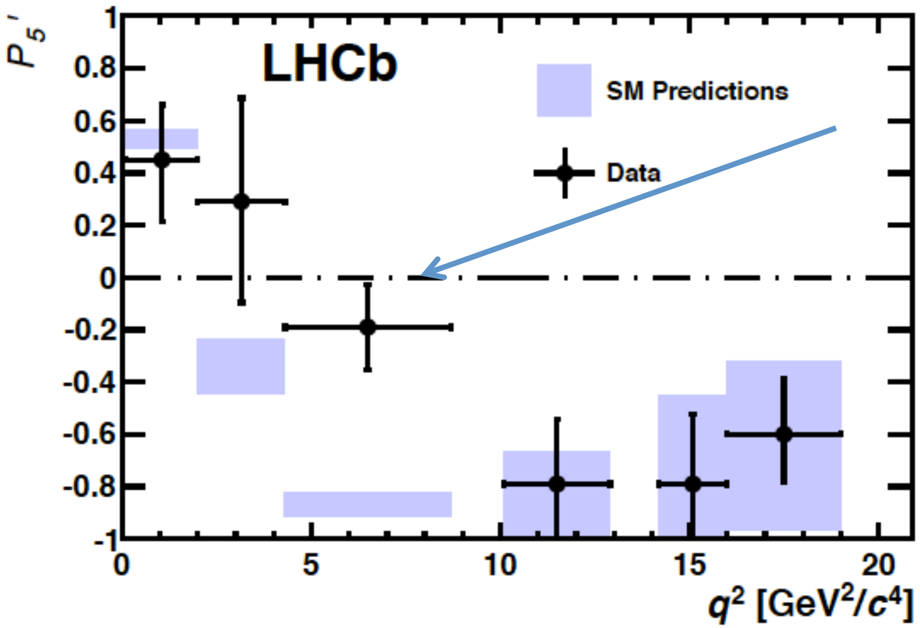


Puzzling deviations: P'_5 in $B^0 \to K^{*0} \mu^+ \mu^-$

In 2013, the observation by LHCb of a tension with the SM in $B \to K^*\mu\mu$ angular observables has received considerable attention from theorists and it was shown that the tension could be softened by assuming the presence of new physics (NP).



LHCb, Phys.Rev.Lett. 111 (2013) 191801



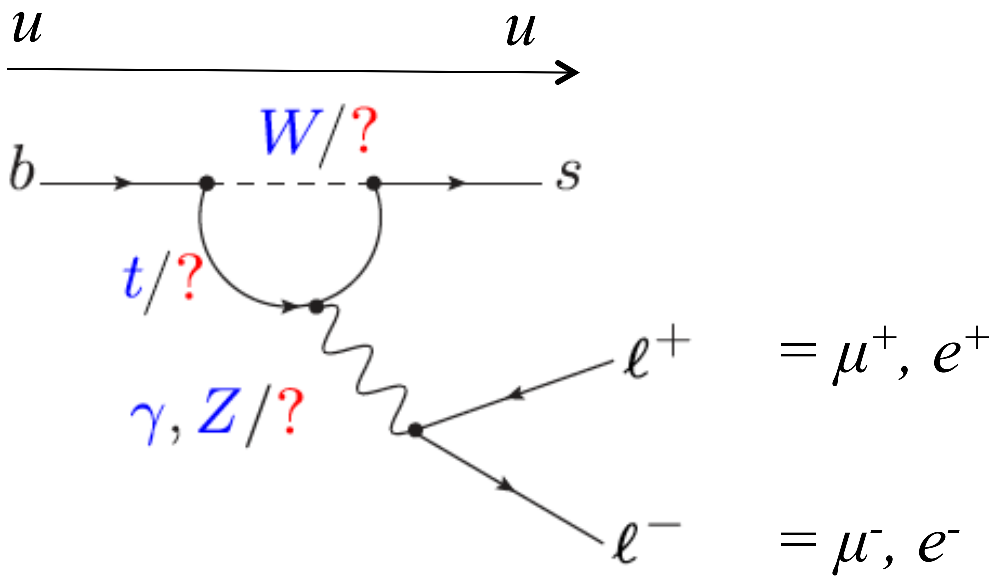
-3.7 σ discrepancy in the reqion
$4.3 < q^2 < 8.68$ GeV^2/c^4
[probability that at least one bin varies by this much is 0.5%]

Can be explained by a negative NP contribution to the Wilson coefficient C_9, namely $C_9=C_9(SM)-1.5$

Descotes-Genon, Virto, Matias PRD 88 (2013) 074002
D. Van Dyck, C. Bobeth, F. Beaujean arXiv 1310.2478
Altmannshofer, Straub (arXiv 1308.1501)

Puzzling deviations: $R_k = BR(B^+ \to K^+\mu^+\mu^-)/BR(B^+ \to K^+e^+e^-)$

In 2014, another tension with the SM has been observed by LHCb, namely a suppression of the ratio R_K of $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+ e^+ e^-$ branching fractions at low di-lepton invariant mass $\to$ test of lepton universality



In SM this ratio is expected to differ from unity only due to tiny Higgs penguin contributions and difference of phase space:

$$\boxed{R_K\,(SM) = 1.0003 \pm 0.0001}$$

Bobeth et al., JHEP 12 (2007) 040

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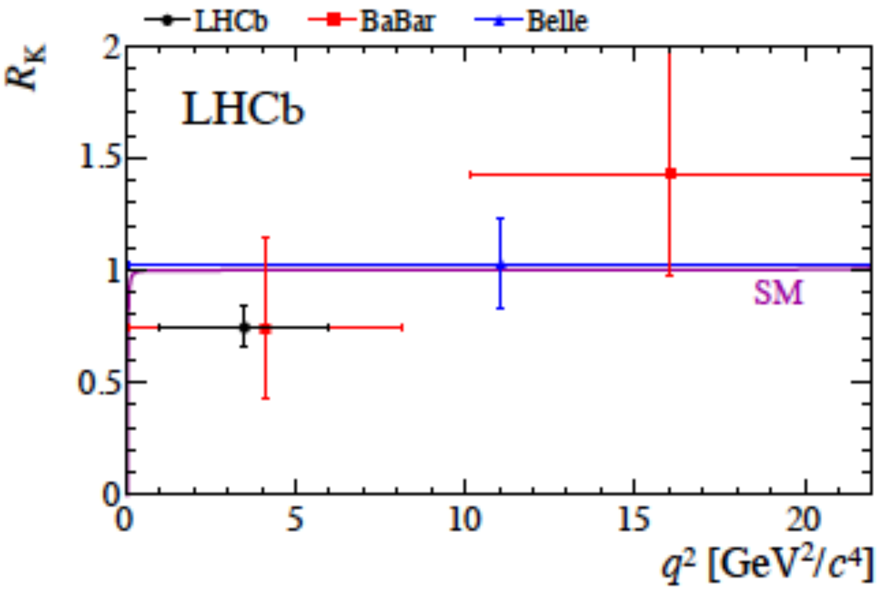


LHCb, PRL 113 (2014) 151601
Belle, PRL 103 (2009) 171801
Babar, PRD 86 (2012) 032012

With 3 fb^{-1} LHCb measures:

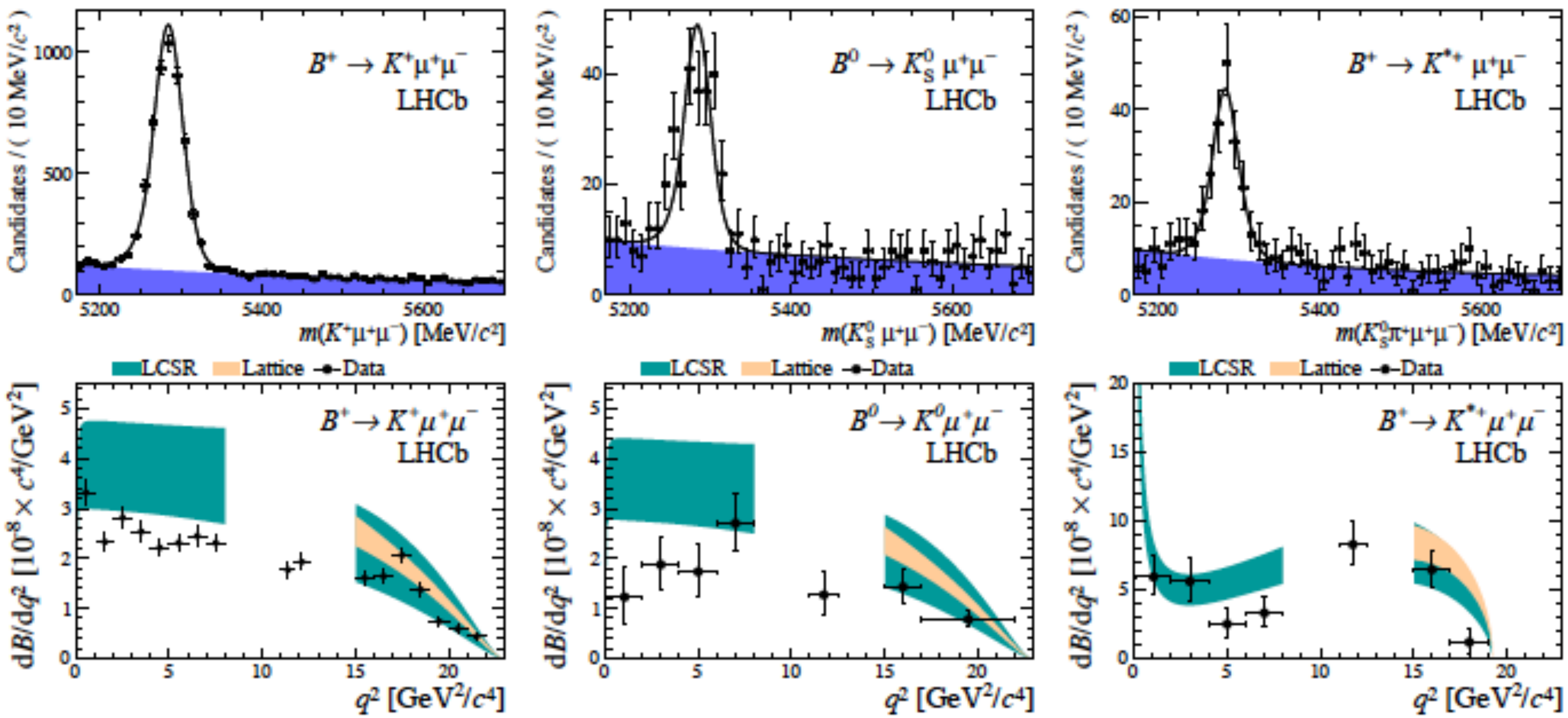
$$R_K = 0.745^{+0.090}_{-0.074}\,(\text{stat})\,^{+0.036}_{-0.036}\,(\text{syst})$$

which is (in)consistent with SM at 2.6 σ

Puzzling deviations: BR($B^0 \rightarrow K^{*0}\mu^+\mu^-$), BR ($B^0 \rightarrow K_S\mu^+\mu^-$), BR($B^+ \rightarrow K^{*+}\mu^+\mu^-$)

Finally, also branching ratio measurements of $B^0 \rightarrow K^*\mu^+\mu^-$, $B^0 \rightarrow K_S\mu^+\mu^-$ and $B^+ \rightarrow K^{*+}\mu^+\mu^-$ decays published recently seem to be too low compared to the SM predictions when using state-of-the art form factors from lattice QCD or light-cone sum rules (LCSR).

LHCb, JHEP 06 (2014) 133



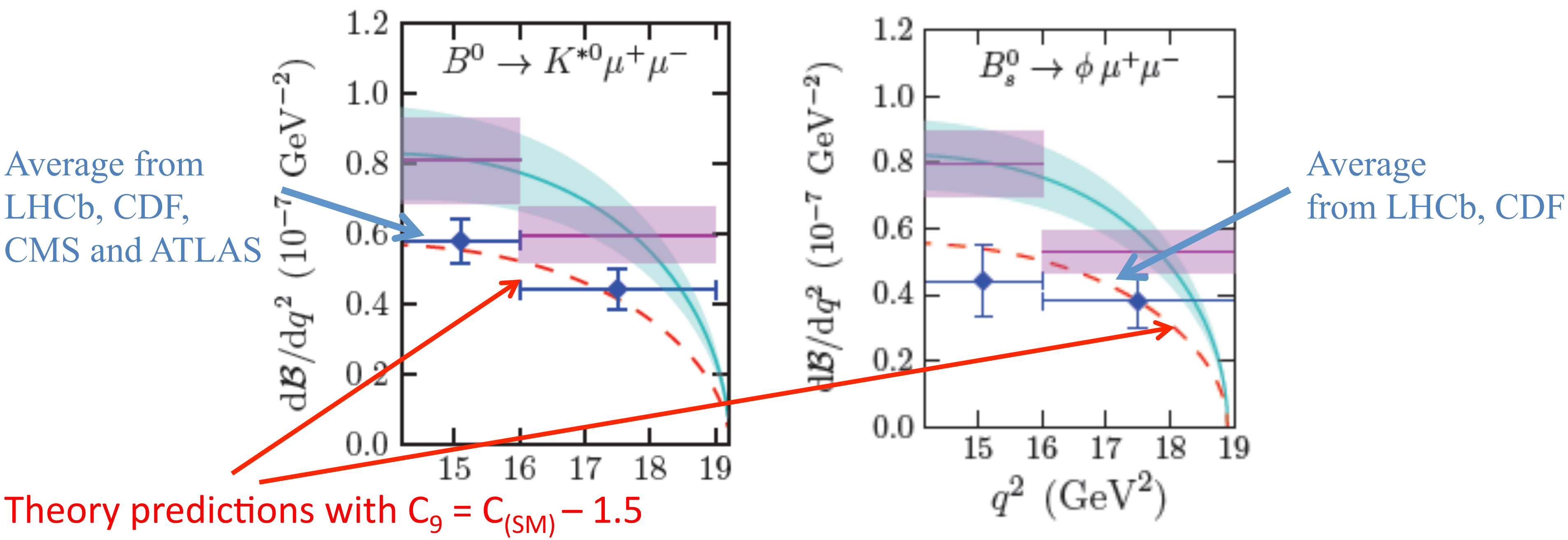
Behavior also seen in $B_s \rightarrow \phi\mu^+\mu$, **LHCb,** JHEP 07 (2013) 084

SM predictions based on: JHEP 07 (2014) 067, JHEP 01 (2012) 107, PRL 111 (2013) 162002, PRL 112 (2014) 212003

Puzzling deviations: BR($B^0 \to K^{*0}\mu^+\mu^-$), BR ($B^0 \to K_S\mu^+\mu^-$), BR($B^+ \to K^{*+}\mu^+\mu^-$)

Average of the $B^0 \to K^*\mu\mu$ and $B^0{}_s \to \phi\,\mu\mu$ decay rates measured by LHCb, CMS, ATLAS and CDF in the high-q^2 range:

Zwicky et al,Phys.Rev. D71 (2005) 014029,
Horgan et al., Phys.Rev. D89 (2014) 094501
Horgan et al., Phys. Rev. Lett. 112 (2014) 212003

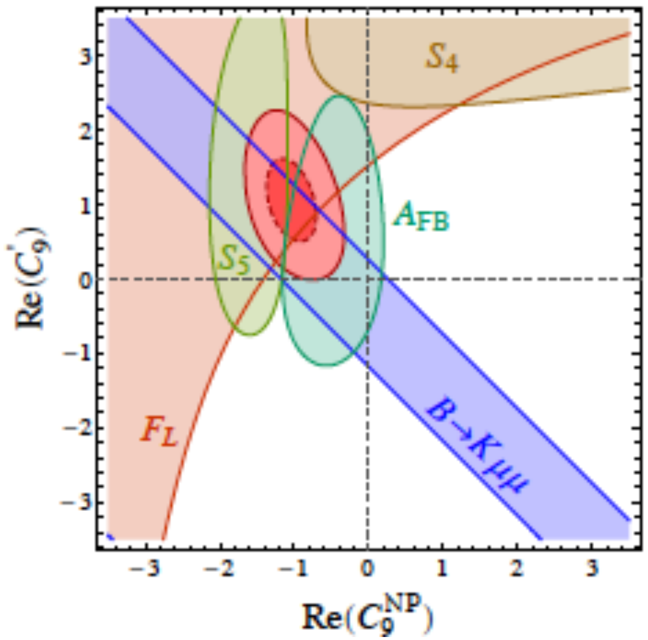


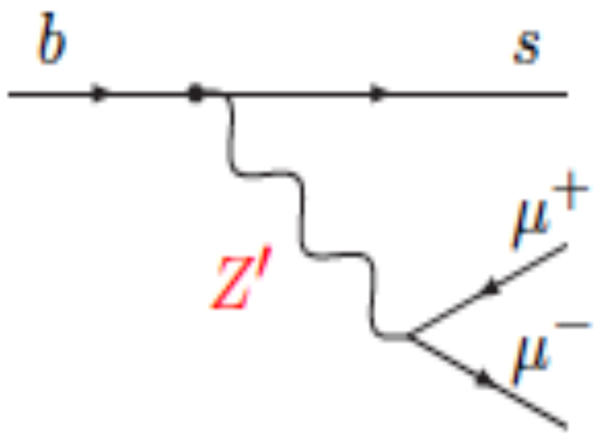
LHCb: JHEP 06 (2014) 133, JHEP 08 (2013)131, JHEP 07 (2013) 084
CDF: Public note 10894, CMS: arXiv: 1308.3409 ATLAS: ATLAS-CONF-2013-038

Interpretation

Assuming new physics in $B \rightarrow K^{(*)}\mu\mu$ only, a consistent description of these anomalies seems possible:

G. Hiller and M. Schmaltz, PRD90 (2014) 054014
D. Ghosh et al., arXiv:1408.4097 [hep-ph].
T. Hurth at al., arXiv:1410.4545 [hep-ph].
S. L. Glashow et al., arXiv:1411.0565 [hep-ph].





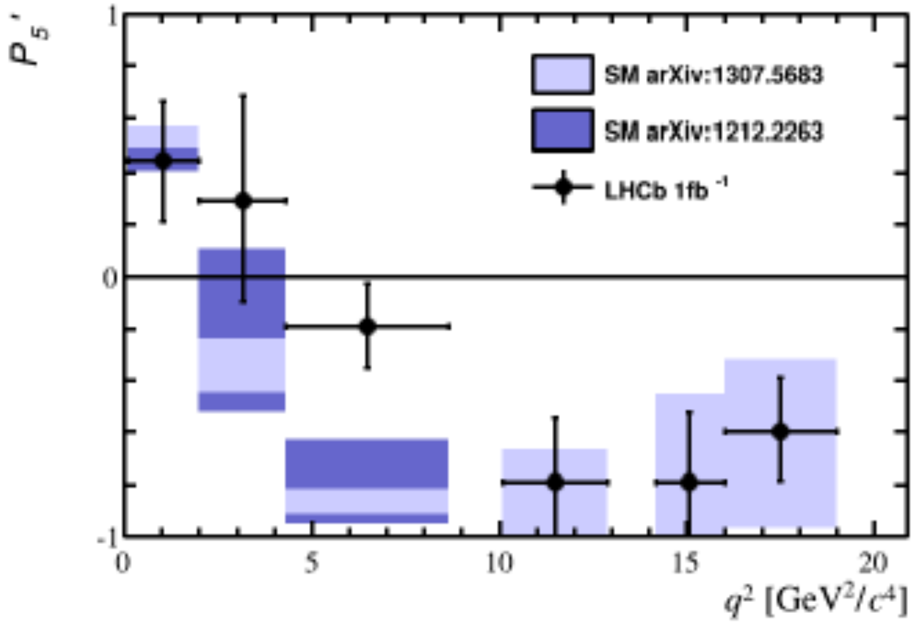
Difficult to explain data in SUSY scenarios or using partial compositeness (why only C_9?)
Data can be described using **Z' with flavour violating couplings**, but mass must be o(**7 TeV**) to avoid direct limits and limits from mixing (Δm_s).

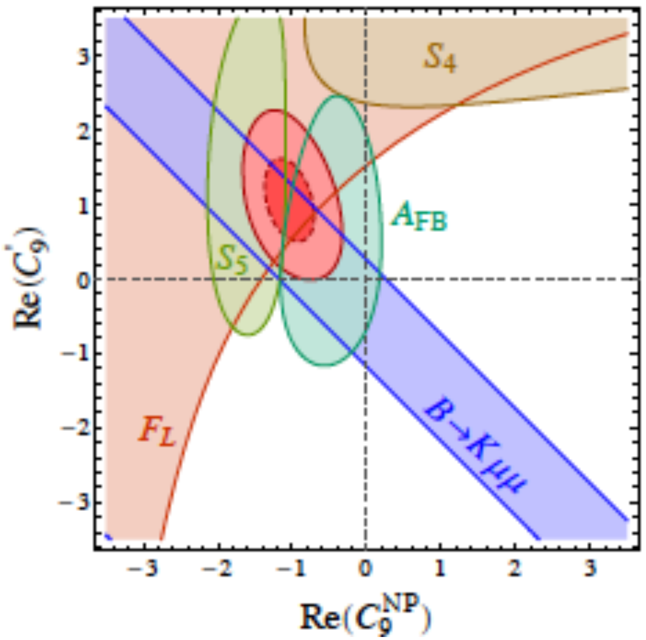
Fox et al., PRD 84 (2011) 115006, Buras et al. JHEP 11 (2014) 121
Altmannshofer et al. PRD 89 (2014) 095033

PS: NA62 will probe the same underlying physics with $K \rightarrow \pi\nu\nu$ decays

Interpretation

However, while R_K is theoretically extremely clean, predicted to be 1 to an excellent accuracy in the SM, the **other observables are plagued by sizable hadronic uncertainties**,
[different treatments of (factorisable/non-factorisable) corrections can give large variation of P'_5]





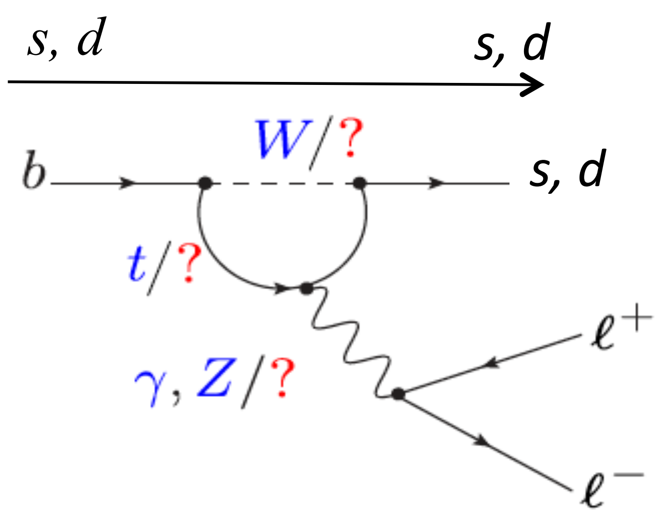
A lot to be done still both on experimental and theoretical sides

Descotes-Genon, Virto, Matias PRD 88 (2013) 074002
D. Van Dyk, C. Bobeth, F. Beaujean EPJC 74 (2014) 2893
Altmannshofer, Straub, EPJC 73 (2013) 2646, JHEP 01 (2014) 069
Jaeger, Camalich JHEP 05 (2013) 043

Study of the rare $B^0_{(s)} \to \pi^+ \pi^- \mu^+ \mu^-$ decays

LHCb, arXiv: 1502.05104, to appear in PLB 743 (2015) 46

$B_s^0 \to f_0\mu^+\mu^-$: dominated by "penguin" and "box" $b \to s$ transition in SM. Potentially sensitive to non-SM contributions, access similar physics of $B^0 \to K^{*0}\mu^+\mu^-$ and $B_s^0 \to \phi\mu^+\mu^-$

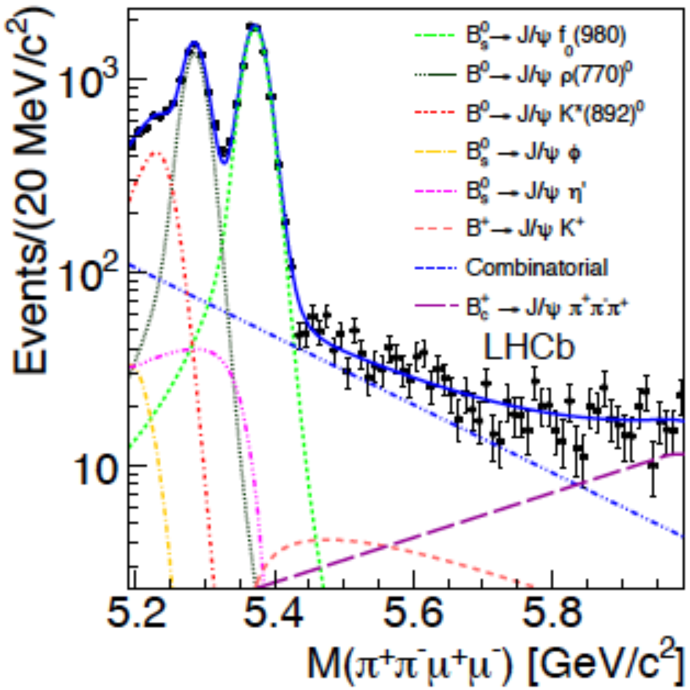


$B^0 \to \rho\mu^+\mu^-$: dominated by "penguin" and "box" $b \to d$ transition in SM. Potentially sensitive to non-SM contributions, complementary w.r.t. $B_s^0 \to f_0\mu^+\mu^-$

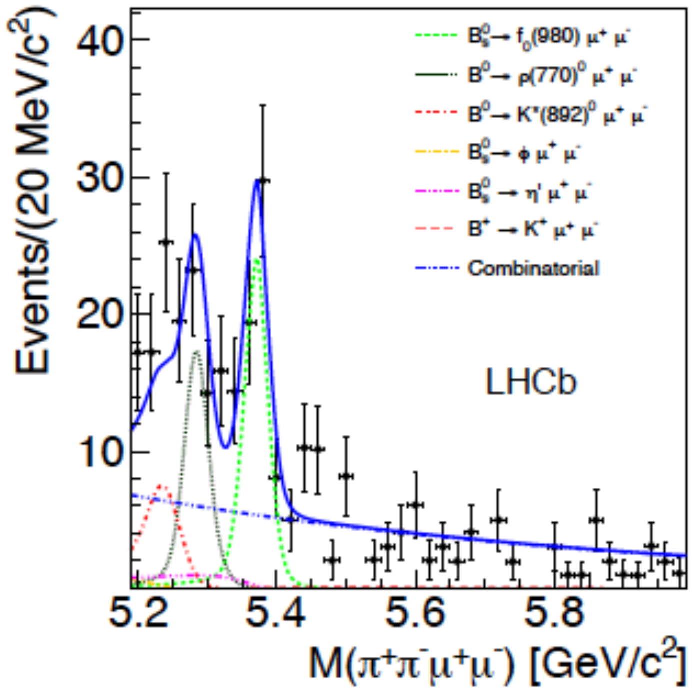
Study of the rare $B^0_{(s)} \to \pi^+ \pi^- \mu^+ \mu^-$ decays

LHCb, arXiv: 1502.05104, to appear in PLB 743 (2015) 46

Resonant channel: $B^0_{(s)} \to J/\psi\, \pi^+ \pi^-$



Signal channel: $B^0_{(s)} \to \pi^+ \pi^- \mu^+ \mu^-$



LHCb sees first evidence for $B^0_s \to \pi^+\pi^-\mu^+\mu^-$ (7.3 σ) and $B^0 \to \pi^+\pi^-\mu^+\mu^-$ (4.8 σ)

NB: $b \to d$ transitions are suppressed by $|V_{td}/V_{ts}|^2$ w.r.t. $b \to s$ in SM;

Study of the rare $B^0_{(s)} \to \pi^+ \pi^- \mu^+ \mu^-$ decays

LHCb, arXiv: 1502.05104, to appear in PLB 743 (2015) 46

The results for the decay rates:

$$\mathcal{B}(B_s^0 \to \pi^+\pi^-\mu^+\mu^-) = (8.6 \pm 1.5\,(\text{stat}) \pm 0.7\,(\text{syst}) \pm 0.7\,(\text{norm})) \times 10^{-8}$$
$$\mathcal{B}(B^0 \to \pi^+\pi^-\mu^+\mu^-) = (2.11 \pm 0.51\,(\text{stat}) \pm 0.15\,(\text{syst}) \pm 0.16\,(\text{norm})) \times 10^{-8}$$

are compatible with SM expectations..

$\mathrm{Br}(B_s^0 \to f_0(980)\mu^+\mu^-)$	
$\left(5.21^{+3.23}_{-2.06}\right) \times 10^{-7}$	[PRD79,014013]
$\left(9.5^{+3.1}_{-2.6}\right) \times 10^{-8}$	[PRD81,074001]
$(1.67 \pm 0.61) \times 10^{-7}$	[PRD81,074001]
$(0.81 - 2.02) \times 10^{-8}$	[PRD80,016009]
$(0.63 - 3.37) \times 10^{-9}$	[PRD80,016009]
$\mathrm{Br}(B^0 \to \rho(770)^0\mu^+\mu^-)$	
$\left(5.0^{+2.1}_{-2.6}\right) \times 10^{-8}$	[PRD56,5452] [HEP-PH/9609503]
$\left(8.6^{+3.4}_{-4.5}\right) \times 10^{-8}$	[PRD53,3672] [HEP-PH/9609503]

.. but SM predictions differ up to two orders of magnitude among each other!!

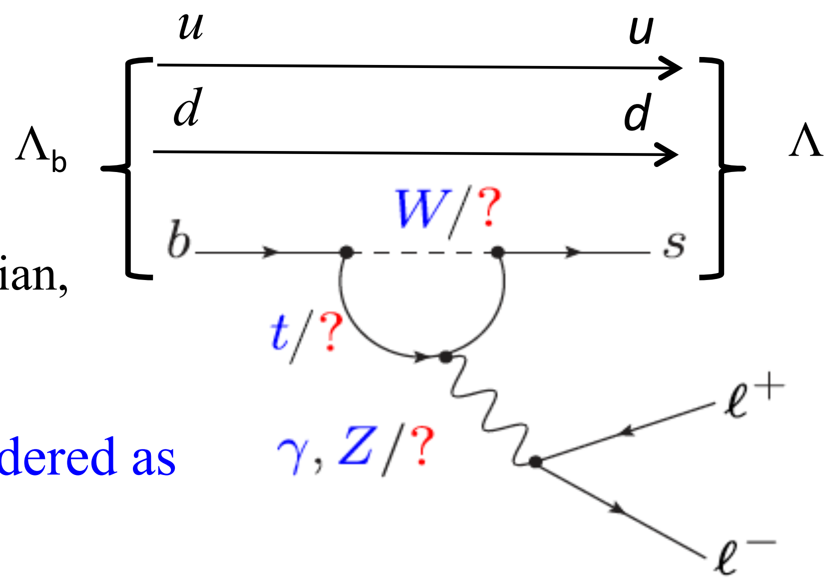
We need input from the theory community.

Differential branching fraction and angular analysis of $\Lambda_b \to \Lambda\, \mu^+\mu^-$ decays

[to be submitted to JHEP]

New

Same b $\to$ s quark level transition as for $B^0 \to K^{*0}\, \mu^+\mu^-$



Unique features:

1) Λ_b baryon has non-zero spin:

$\rightarrow$potential to improve the limited understanding of the helicity structure of the underlying Hamiltonian, which cannot be extracted from mesonic decays.

2) composition of the Λ_b baryon may be considered as the combination of a heavy quark with a light di-quark system:

$\rightarrow$the hadronic physics differs significantly from that of the B meson decay.

3) Λ baryon decays weakly: (vs K^{*0} that decays strongly)

$\rightarrow$ complementary information to that available from meson decays

T. Gutsche et al., PRD87 (2013) 074031, arXiv:1301.3737v2
D. Van Dyk et al., arXiv.1410.2115

Differential branching fraction and angular analysis of $\Lambda_b \to \Lambda\, \mu^+\mu^-$ decays

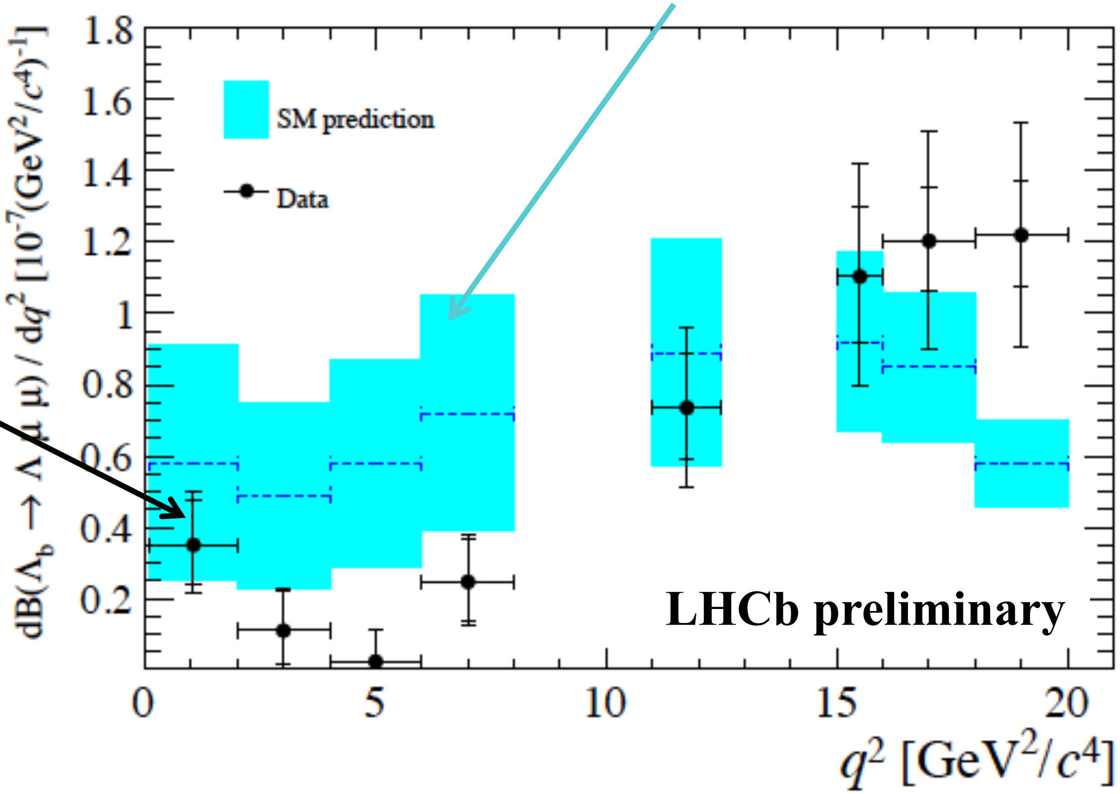
[to be submitted to JHEP]

New

3 fb^{-1} data analyzed.

Inner error: stat + syst
Outer error: including normalization

SM predictions: PRD 87 (2013) 07450



→ **signal seen for the first time** with a significance > 3 σ between $\mathbf{0.1 < q^2 < 2\ GeV^2/c^4}$ and **between charmonium** resonances;

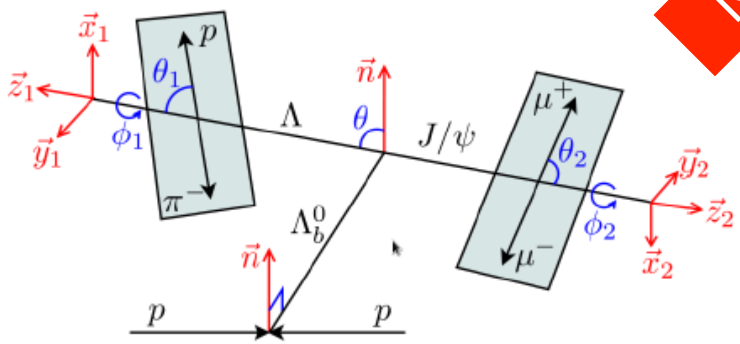
→ **no significant signal** observed in the $\mathbf{1.1 < q^2 < 6.0\ GeV^2/c^4}$ range.

→ **uncertainty** in the decay rate within $\mathbf{15 < q^2 < 20\ GeV^2/c^4}$ is reduced by **a factor of ~ 3** w.r.t previous LHCb measurement.

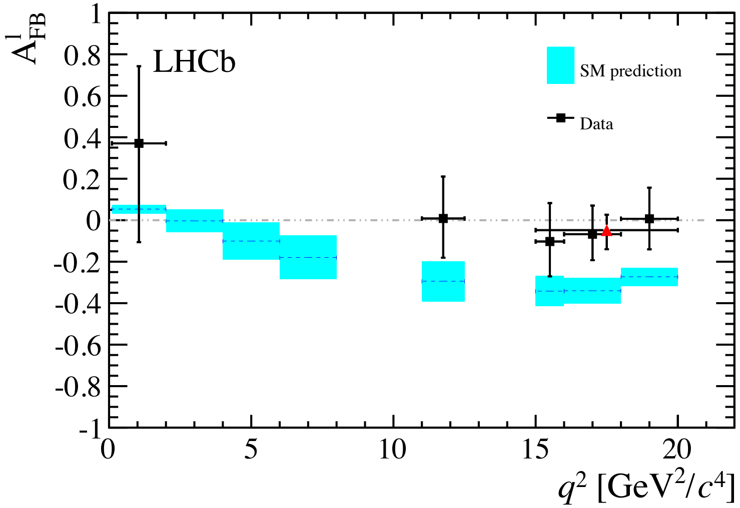
Differential branching fraction and angular analysis of $\Lambda_b \rightarrow \Lambda \mu^+\mu^-$ decays

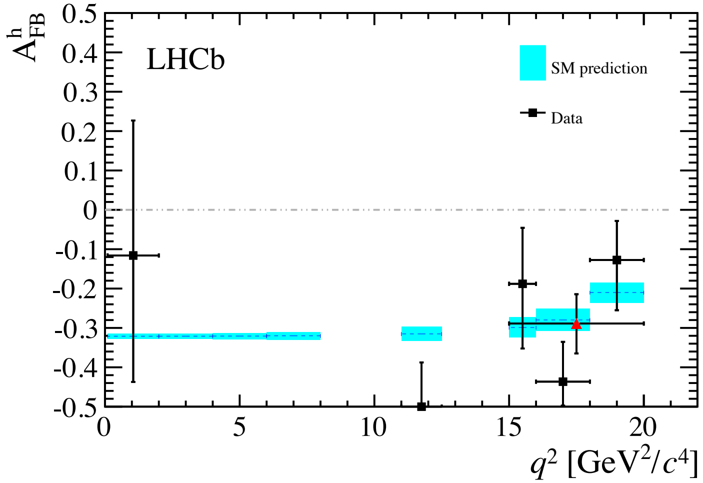
[to be submitted to JHEP]

New



Measurement of the forward-backward asymmetry for the lepton $\mathbf{A^l_{FB}}$ (same as $B^0 \rightarrow K^{*0} \mu^+\mu^-$) and for the hadron side $\mathbf{A^h_{FB}}$





S. Meinel, arXiv 1401.2685, Proceedings of Lattice2013

Computed at the leading order of HQET (accurate up to corrections $o(m_b/\Lambda)$).

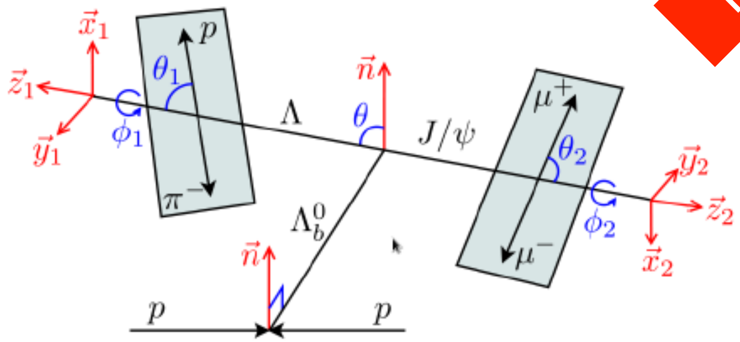
$A_{FB}{}^l$ is compatible with SM predictions at 2 σ level

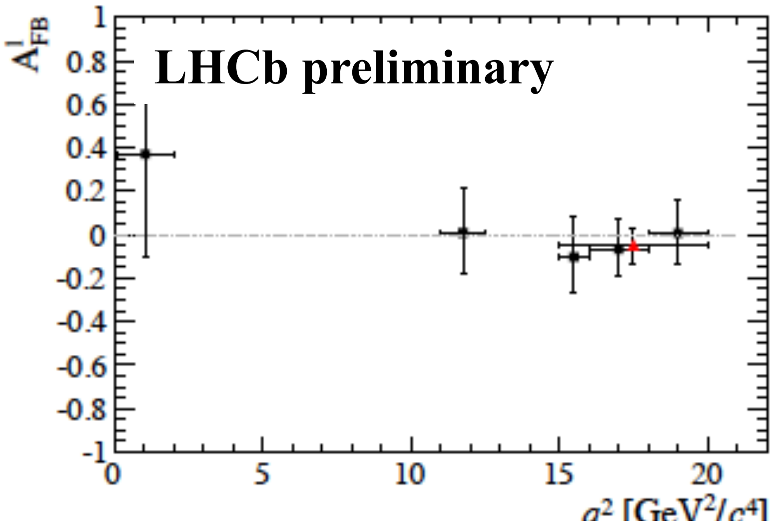
$A_{FB}{}^h$ is fully compatible with SM predictions

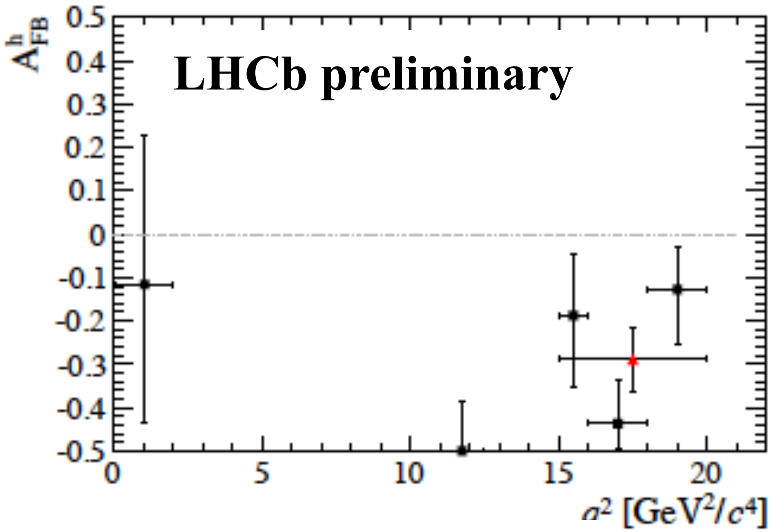
Differential branching fraction and angular analysis of $\Lambda_b \to \Lambda\, \mu^+\mu^-$ decays

[to be submitted to JHEP]

Measurement of the forward-backward asymmetry for the lepton $\mathbf{A^l_{FB}}$ (same as $B^0 \to K^{*0}\, \mu^+\mu^-$) and for the hadron side $\mathbf{A^h_{FB}}$





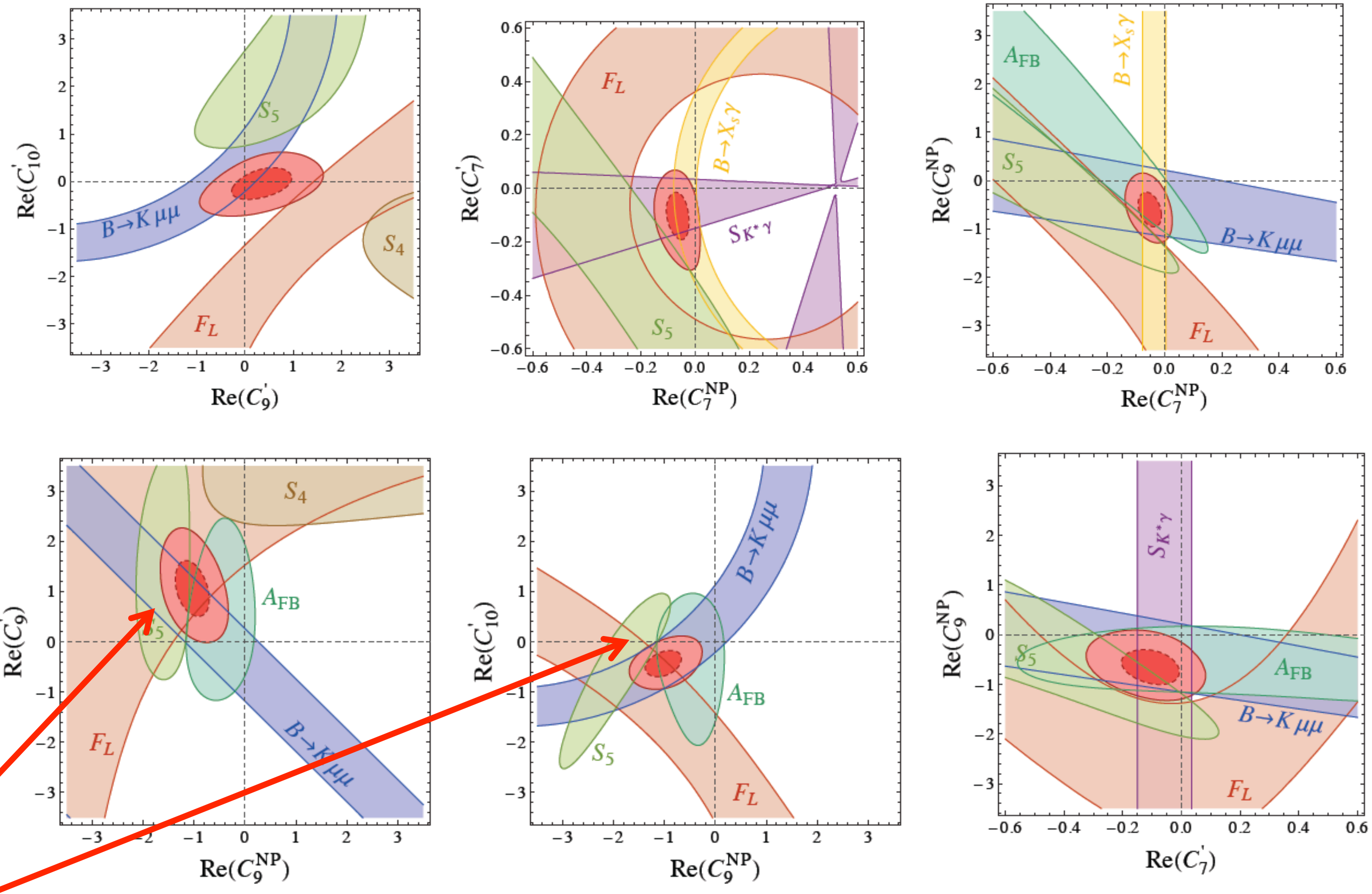


for $15<q^2<20$ GeV^2/c^4

$$A^{\ell}_{FB} = -0.05\ \pm 0.09\ (\text{stat})\ \pm 0.03\ (\text{sys})$$
$$A^{h}_{FB} = -0.29\ \pm 0.07\ (\text{stat})\ \pm 0.03\ (\text{sys})$$

The DNA of the Wilson coefficients

Straub, Altmannshofer arXiv:1308.1501



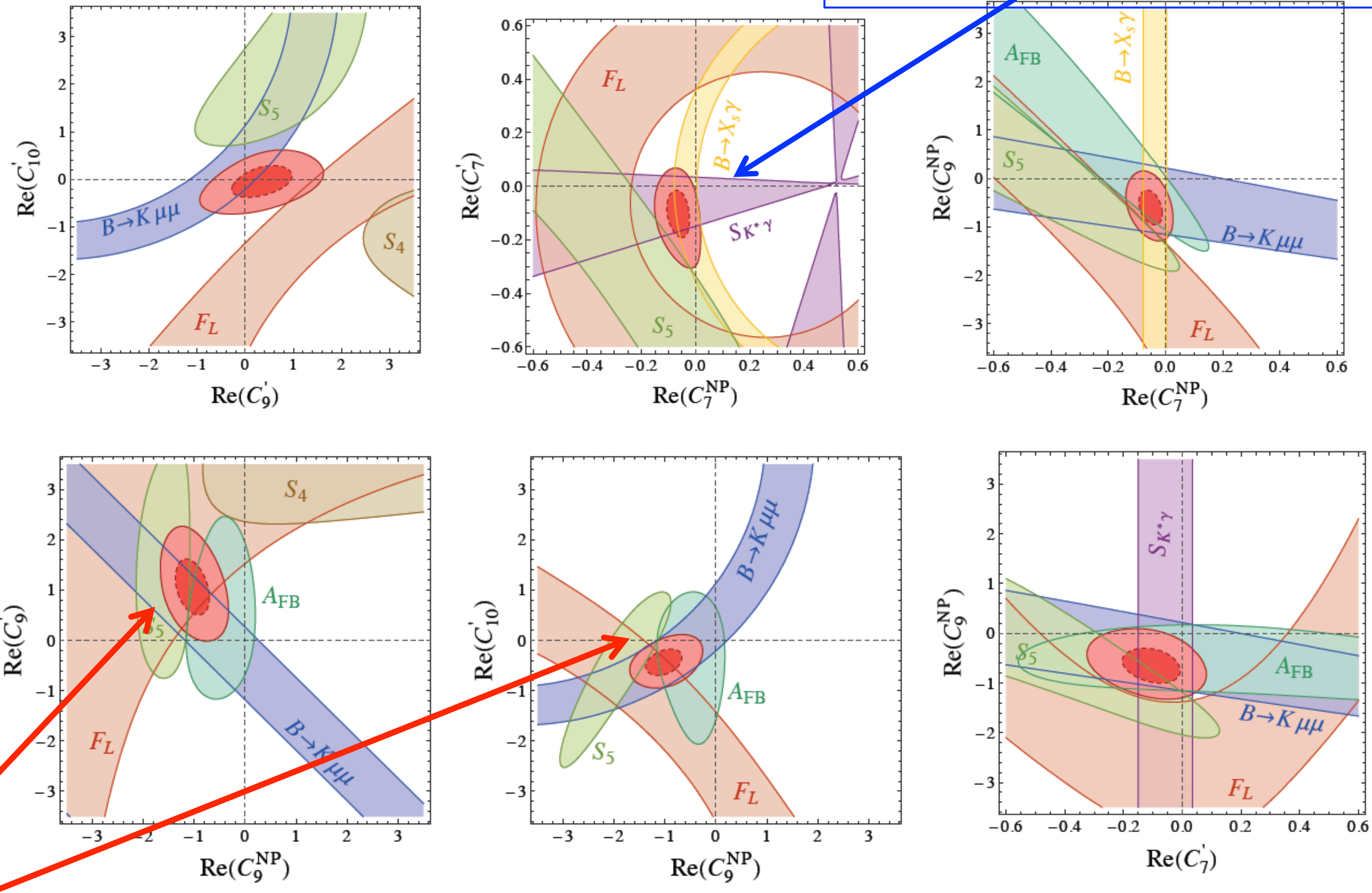
Hints that
C_9(NP) is negative

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

The DNA of the Wilson coefficients

Straub, Altmannshofer arXiv:1308.1501

C_7' compatible with zero (so far)
[in the assumption that Im(C_7') =0]



C_9(NP) is negative

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

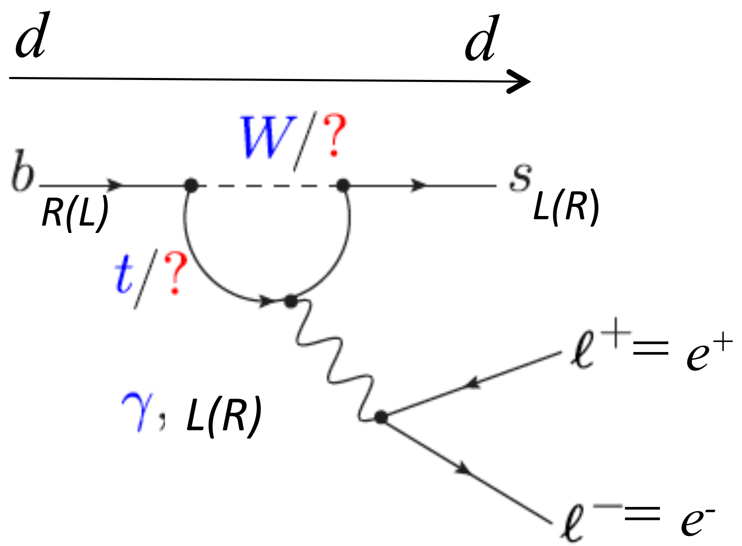
Angular analysis of $B^0 \rightarrow K^{*0} e^+e^-$ decays

LHCb paper, arXiv 1501.03038

New

In the SM, photons from $b \rightarrow s\,\gamma$ decays are predominantly left-handed ($C_7/C_7' \sim m_b/m_s$), due to the charged current interaction.

Several models beyond the SM predict the photon to acquire a significant right-handed component due to the exchange of a heavy fermions in the electroweak penguin loop.



Everett et al. JHEP(2002) 022, Foster et al. PRB641 (2006) 452
Lunghi et al. JHEP 04 (2007) 058, Goto et al. PRD77 (2008) 095010

A 3D angular analysis (like $B^0 \rightarrow K^{*0}\mu^+\mu^-$) at the photon pole (q^2 = [0.0004,1] GeV^2/c^4) allows to assess the photon polarization in $b \rightarrow s\,\gamma$ transition

Grossman et al. JHEP06 (2000) 029
Jager et al., JHEP05 (2013) 043

Angular analysis of $B^0 \to K^{*0} e^+e^-$ decays

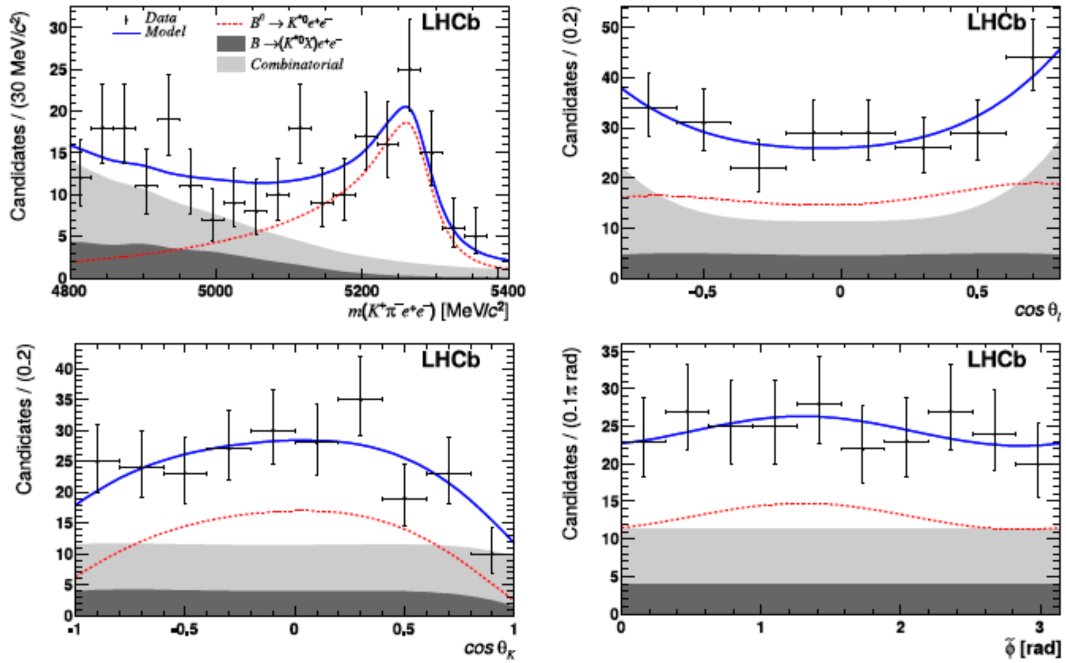
LHCb paper, arXiv 1501.03038

New

Angular analysis as $B^0 \to K^{*0}\mu^+\mu^-$
Measured observables:

$$
\begin{aligned}
F_L &= 0.16 \pm 0.06 \pm 0.03 \\
A_T^{Re} &= +0.10 \pm 0.18 \pm 0.05 \\
\rightarrow A_T^{(2)} &= -0.23 \pm 0.23 \pm 0.05 \\
\rightarrow A_T^{Im} &= +0.14 \pm 0.22 \pm 0.05
\end{aligned}
$$

Quantities related to photon polarization
Kruger et al. PRD71 (2005) 094009
Beciveric et al. NPB854 (2012) 321



Consistent with SM expectations
[adapted from Jager et al. JHEP 05 (2013) 043]

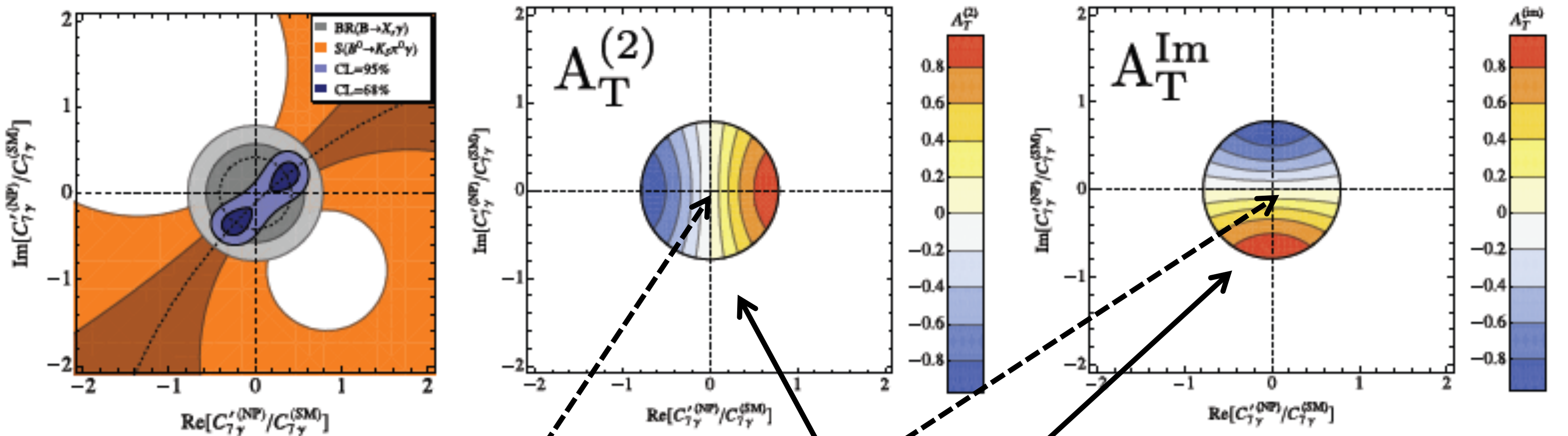
$$
\begin{aligned}
F_L &= 0.10^{+0.11}_{-0.05} \\
A_T^{Re} &= -0.15^{+0.04}_{-0.03} \\
\rightarrow A_T^{(2)} &= +0.03^{+0.05}_{0.04} \\
\rightarrow A_T^{Im} &= (-0.2^{+1.2}_{-1.2}) \times 10^{-4}
\end{aligned}
$$

Angular analysis of $B^0 \rightarrow K^{*0} e^+ e^-$ decays

LHCb paper, arXiv 1501.03038

New

Theory predictions on C_7/C_7' based on the B-factories results



Assumptions: $C_7 = C_7(SM)$,
C_7' = free to vary

Becirevic *et al.* JHEP 08 (2012) 090

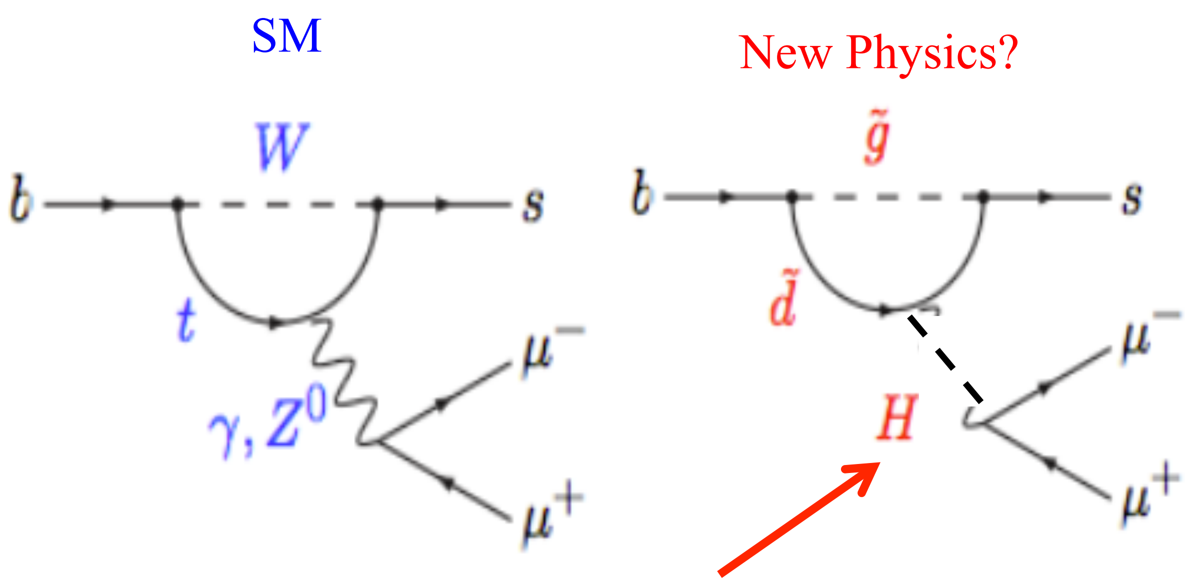
$$
\begin{aligned}
F_L &= 0.16 \pm 0.06 \pm 0.03 \\
A_T^{Re} &= +0.10 \pm 0.18 \pm 0.05 \\
\rightarrow A_T^{(2)} &= -0.23 \pm 0.23 \pm 0.05 \\
\rightarrow A_T^{Im} &= +0.14 \pm 0.22 \pm 0.05
\end{aligned}
$$

3σ contours based on B factories results

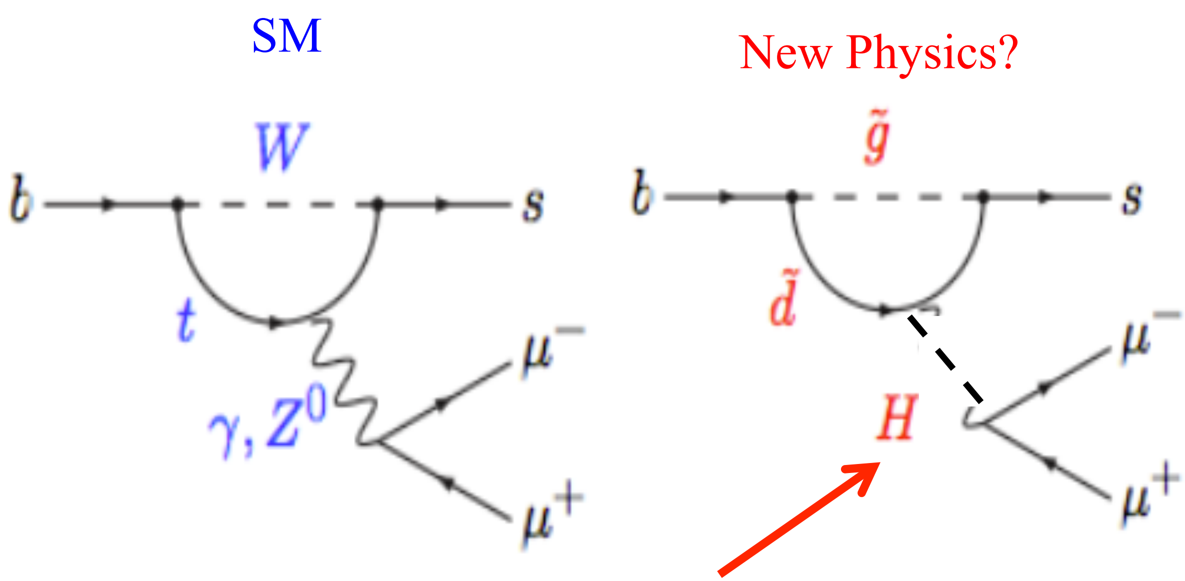
[BaBar PRD78 (2008) 071102,
Belle PRD74 (2006) 111104]

(Unfortunately) everything is consistent with the SM predictions.

Rare Decays and the Higgs
(or how rare processes can test non-SM Higgs sectors)

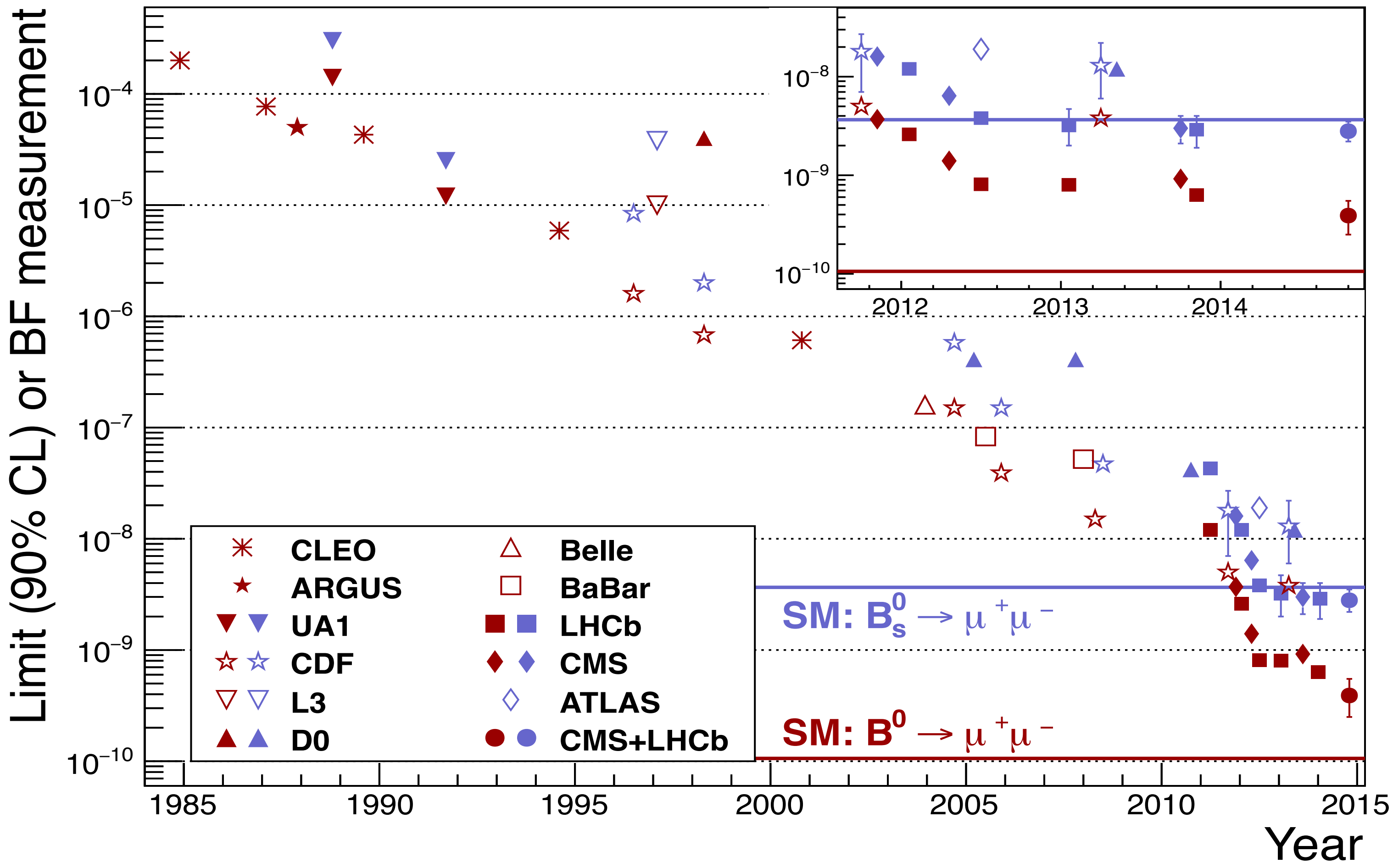


Rare Decays and the Higgs
(or how rare processes can test non-SM Higgs sector)



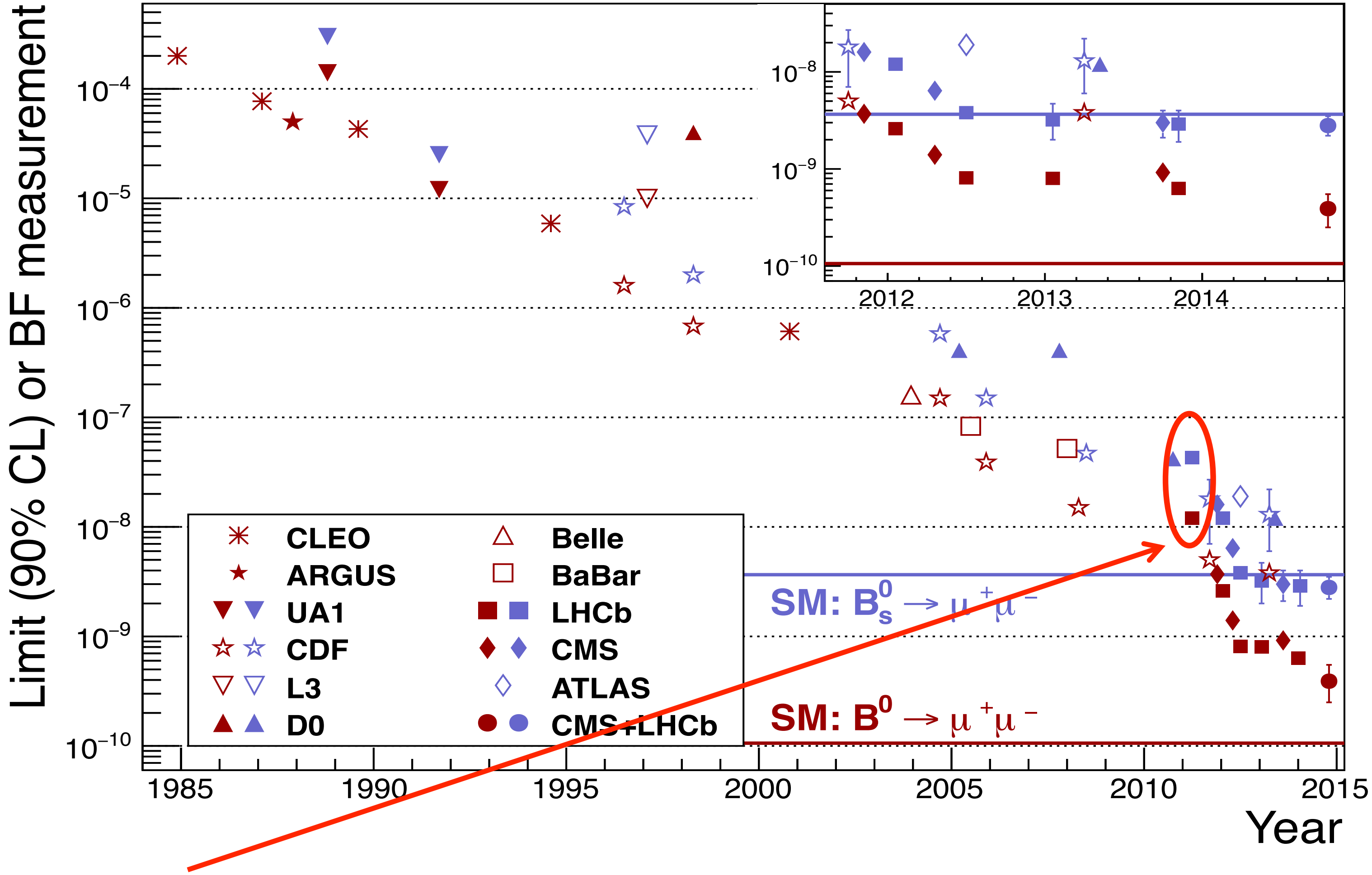
You can recognize here the main diagrams that drive the $B^0_{(s)} \rightarrow \mu^+\mu^-$ decays…

$B^0 \to \mu^+\mu^-$ and $B^0_s \to \mu^+\mu^-$: a story 30 years long



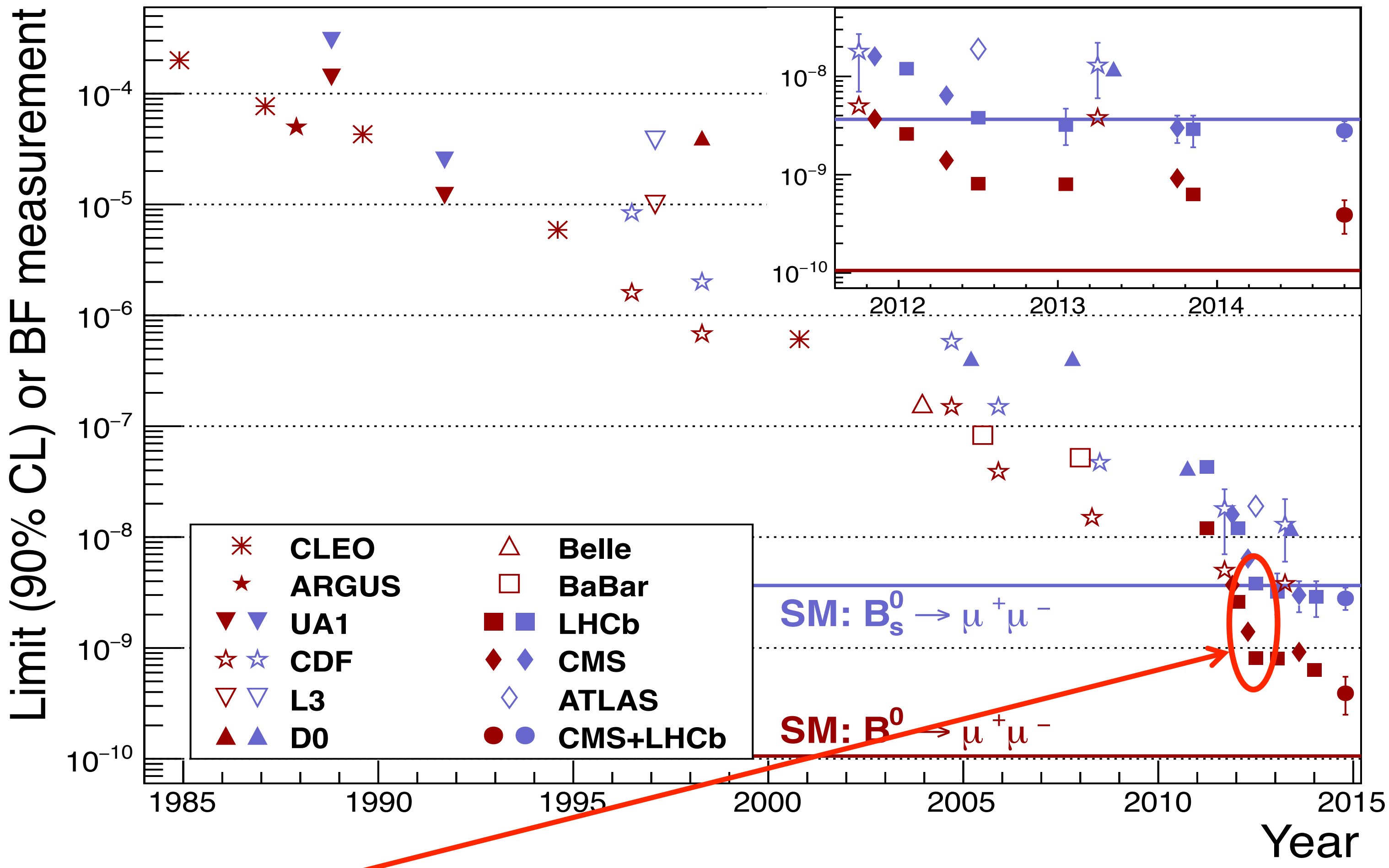
$B^0 \to \mu^+\mu^-$ and $B^0_s \to \mu^+\mu^-$: a story 30 years long

LHCb, 10 months old, 37 pb^{-1} ($33\ pb^{-1}$ collected in 15 days!)



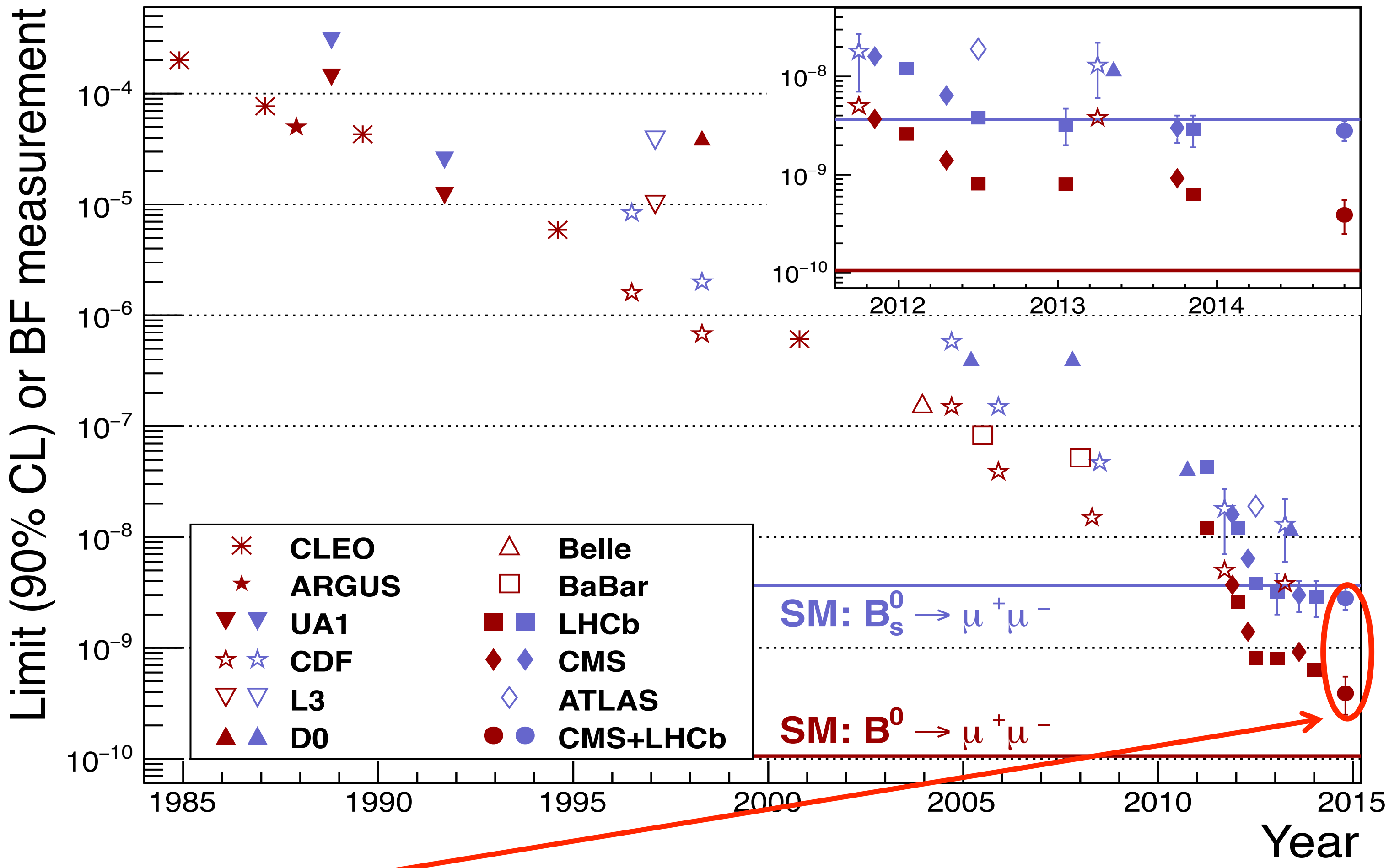
La Thuile 2011: LHCb presents its first results based on 37 pb^{-1} (competitive with CDF with 3.7 fb^{-1})

$B^0 \rightarrow \mu^+\mu^-$ and $B^0_s \rightarrow \mu^+\mu^-$: a story 30 years long



November 2012: LHCb publishes the first evidence for the $B^0_s \rightarrow \mu^+\mu^-$
[PRL 110 (2013) 021801]

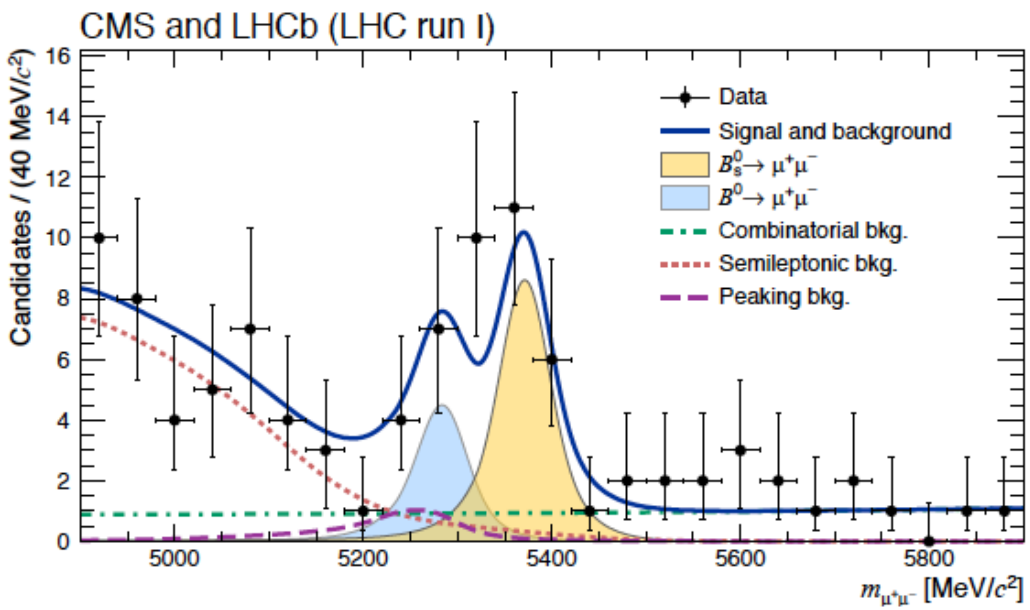
$B^0 \to \mu^+\mu^-$ and $B^0_s \to \mu^+\mu^-$: a story 30 years long

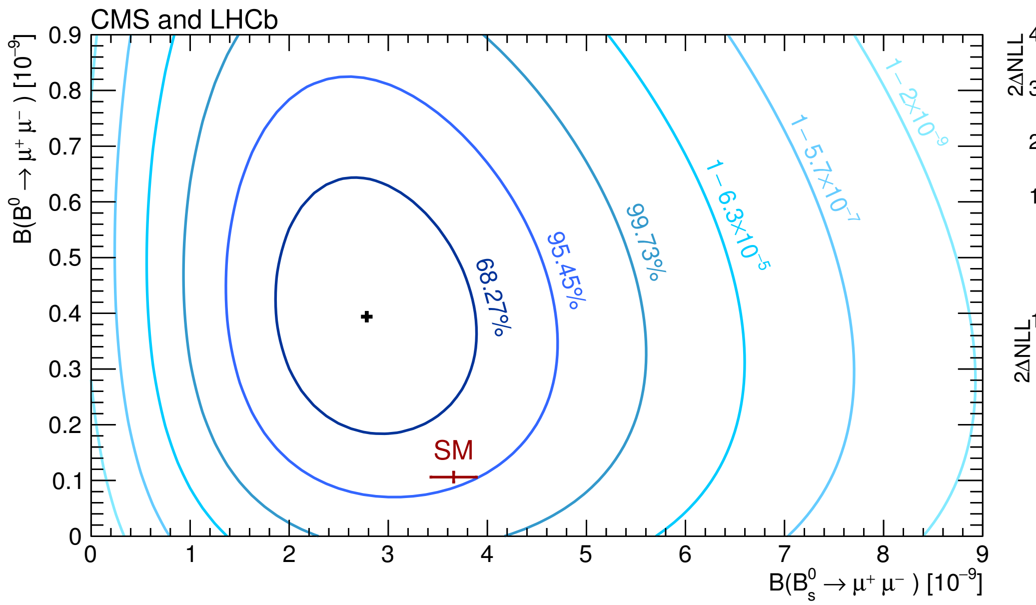


November 2014: CMS and LHCb publish the observation for the $B^0_s \to \mu^+\mu^-$ and the evidence for the $B^0 \to \mu^+\mu^-$ [arXiv:1411.4413, submitted to Nature]

Another puzzling deviation: BR($B_d \to \mu^+\mu^-$)

LHCb and CMS, arXiv:1411.4413





Results:

$BR(B^0) = (3.94\,^{+1.58}_{-1.41}\,^{+0.31}_{-0.24}) \times 10^{-10}$ 3.2σ observed (0.8σ expected)

$BR(B^0_s) = (2.79\,^{+0.66}_{-0.60}\,^{+0.26}_{-0.19}) \times 10^{-9}$ 6.2σ observed (7.6σ expected)

Theory predictions:

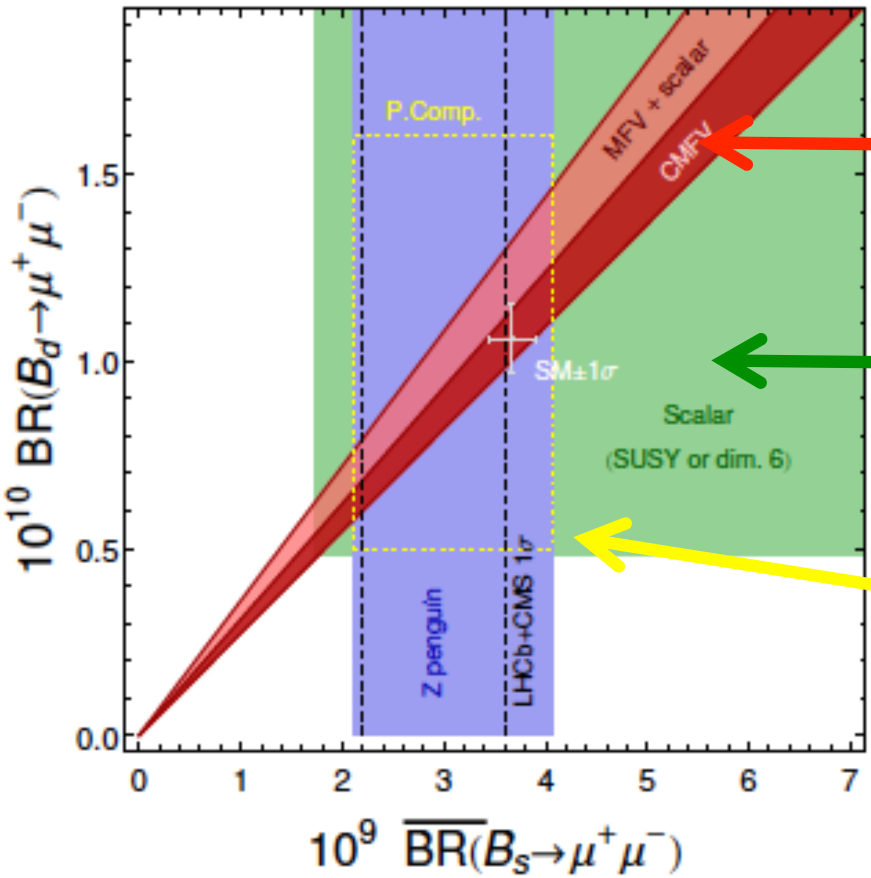
$BR(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$

$BR(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$ **Bobeth et al, PRL 112 (2014) 101801**

Compatibility with the SM predictions: 2.2 σ for B^0 and 1.2 σ for B_s

BR($B^0 \to \mu^+\mu^-$) and BR($B^0 \to \mu^+\mu^-$) in a model independent approach:

LHCb+CMS $B^0 \to \mu^+\mu^-$
result out of scale

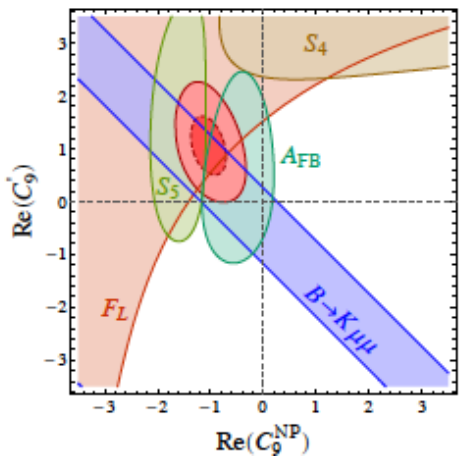


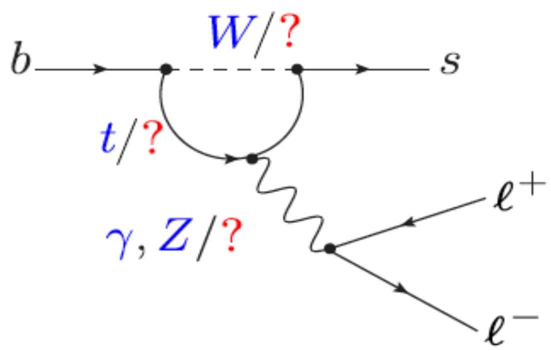
- $B_s \to \mu\mu$ vs. $B_d \to \mu\mu$: powerful test of Minimal Flavour Violation
- Beyond MFV: scalar operators (e.g. SUSY) unconstrained by other processes
- Z penguins beyond MFV: size constrained by $b \to s\ell^+\ell^-$ processes (notably $B \to K^*\mu^+\mu^-$)

D. Straub, CKM 2014

Conclusions

- LHCb with three years of data taking has performed a major step forward in constraining Wilson coefficients related the the b rare decays realm.
- Only hints of discrepancy so far, to be confirmed with more data.
- New results still based on Run I dataset coming soon:
  - Full angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ with full dataset
  - Measurement of the photon polarization in $B_s^0 \to \phi\gamma$ decays
  - Differential BR of $B^+ \to \pi^+\mu^+\mu^-$ decays
  - Differential BR of $B_s^0 \to \phi\, \mu^+\mu^-$
  - R_{K*} and R_ϕ
  - ….





.. And many more during Run II !

SPARES

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

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_K\, d\cos\theta_l\, d\phi} = \frac{9}{32\pi}\Big[J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K + (J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_l$$

$$+J_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + J_4\sin 2\cancel{\theta_K \sin 2\theta_l}\cos\phi + J_5\sin 2\cancel{\theta_K\sin\theta_l}\cos\phi$$

$$+(J_{6s}\sin^2\theta_K + J_{6c}\cos^2\theta_K)\cos\theta_l + J_7\cancel{\sin 2\theta_K}\sin\theta_l\sin\phi + J_8\sin 2\cancel{\theta_K\sin 2\theta_l}\sin\phi$$

$$+J_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big], \qquad (1)$$

- Large number of terms simplified by angular folding, e.g. $\phi \to \phi + \pi$ if $\phi < 0$ to cancel terms in $\cos\phi$ and $\sin\phi$, or integration.

Angular analysis of $B^0 \rightarrow K^{*0} \mu^+\mu^-$ decays

$$
\begin{aligned}
\frac{d^4\Gamma}{dq^2\, d\cos\theta_K\, d\cos\theta_l\, d\phi} = \frac{9}{32\pi}\Big[& J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K + (J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_l \\
& + J_3 \sin^2\theta_K \sin^2\theta_l \cos 2\phi + \cancel{J_4 \sin 2\theta_K \sin 2\theta_l \cos\phi} + \cancel{J_5 \sin 2\theta_K \sin\theta_l \cos\phi} \\
& + (J_{6s}\sin^2\theta_K + J_{6c}\cos^2\theta_K)\cos\theta_l + \cancel{J_7 \sin 2\theta_K \sin\theta_l \sin\phi} + \cancel{J_8 \sin 2\theta_K \sin 2\theta_l \sin\phi} \\
& + J_9 \sin^2\theta_K \sin^2\theta_l \sin 2\phi \Big], \qquad (1)
\end{aligned}
$$

J_i terms depend on the complex spin amplitudes $A_0^{L,R}, A_\parallel^{L,R}, A_\perp^{L,R}$

$$
J_3 = \frac{1}{2}\beta_\ell^2 \left[|A_\perp^L|^2 - |A_\parallel^L|^2 + |A_\perp^R|^2 - |A_\parallel^R|^2 \right]
$$

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

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_K\, d\cos\theta_l\, d\phi} = \frac{9}{32\pi}\Big[J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K + (J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_l$$
$$+ J_3 \sin^2\theta_K \sin^2\theta_l \cos 2\phi + \cancel{J_4 \sin 2\theta_K \sin 2\theta_l \cos\phi} + \cancel{J_5 \sin 2\theta_K \sin\theta_l \cos\phi}$$
$$+ (J_{6s}\sin^2\theta_K + J_{6c}\cos^2\theta_K)\cos\theta_l + \cancel{J_7 \sin 2\theta_K \sin\theta_l \sin\phi} + \cancel{J_8 \sin 2\theta_K \sin 2\theta_l \sin\phi}$$
$$+ J_9 \sin^2\theta_K \sin^2\theta_l \sin 2\phi\Big], \qquad (1)$$

J_i terms depend on the complex spin amplitudes $A_0^{L,R}, A_\parallel^{L,R}, A_\perp^{L,R}$

$$J_3 = \frac{1}{2}\beta_\ell^2\left[|A_\perp^L|^2 - |A_\parallel^L|^2 + |A_\perp^R|^2 - |A_\parallel^R|^2\right]$$

The spin amplitudes depend on the Wilson coefficients via form factors q^2 dependent;

$$A_\perp^{L(R)} = N\sqrt{2\lambda}\left\{\left[(C_9^{\text{eff}} + C_9^{\prime\text{eff}}) \mp (C_{10}^{\text{eff}} + C_{10}^{\prime\text{eff}})\right]\frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2}(C_7^{\text{eff}} + C_7^{\prime\text{eff}})T_1(q^2)\right\}$$

Angular analysis of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decays

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_K\, d\cos\theta_l\, d\phi} = \frac{9}{32\pi}\Big[J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K + (J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_l$$
$$+J_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + \cancel{J_4\sin 2\theta_K\sin 2\theta_l\cos\phi} + \cancel{J_5\sin 2\theta_K\sin\theta_l\cos\phi}$$
$$+(J_{6s}\sin^2\theta_K + J_{6c}\cos^2\theta_K)\cos\theta_l + \cancel{J_7\sin 2\theta_K\sin\theta_l\sin\phi} + \cancel{J_8\sin 2\theta_K\sin 2\theta_l\sin\phi}$$
$$+J_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big], \qquad (1)$$

J_i terms depend on the complex spin amplitudes $A_0^{L,R}, A_{\|}^{L,R}, A_{\perp}^{L,R}$

$$J_3 = \frac{1}{2}\beta_\ell^2\left[|A_\perp^L|^2 - |A_\|^L|^2 + |A_\perp^R|^2 - |A_\|^R|^2\right]$$

The spin amplitudes depend on the Wilson coefficients via form factors q^2 dependent;

$$A_\perp^{L(R)} = N\sqrt{2\lambda}\left\{\left[(C_9^{\mathrm{eff}} + C_9^{\prime\mathrm{eff}}) \mp (C_{10}^{\mathrm{eff}} + C_{10}^{\prime\mathrm{eff}})\right]\frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2}(C_7^{\mathrm{eff}} + C_7^{\prime\mathrm{eff}})T_1(q^2)\right\}$$

Build CP averaged observables:

$S_i = (J_i + J_i) / (\Gamma + \Gamma)$

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

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_K\, d\cos\theta_l\, d\phi} = \frac{9}{32\pi}\Big[J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K + (J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_l$$
$$+ J_3 \sin^2\theta_K \sin^2\theta_l \cos 2\phi + \cancel{J_4 \sin 2\theta_K \sin 2\theta_l \cos\phi} + \cancel{J_5 \sin 2\theta_K \sin\theta_l \cos\phi}$$
$$+ (J_{6s}\sin^2\theta_K + J_{6c}\cos^2\theta_K)\cos\theta_l + \cancel{J_7 \sin 2\theta_K \sin\theta_l \sin\phi} + \cancel{J_8 \sin 2\theta_K \sin 2\theta_l \sin\phi}$$
$$+ J_9 \sin^2\theta_K \sin^2\theta_l \sin 2\phi\Big], \qquad (1)$$

J_i terms depend on the complex spin amplitudes $A_0^{L,R}, A_\parallel^{L,R}, A_\perp^{L,R}$

$$J_3 = \frac{1}{2}\beta_\ell^2\left[|A_\perp^L|^2 - |A_\parallel^L|^2 + |A_\perp^R|^2 - |A_\parallel^R|^2\right]$$

The spin amplitudes depend on the Wilson coefficients via form factors q^2 dependent;

$$A_\perp^{L(R)} = N\sqrt{2\lambda}\left\{\left[(C_9^{\mathrm{eff}} + C_9'^{\mathrm{eff}}) \mp (C_{10}^{\mathrm{eff}} + C_{10}'^{\mathrm{eff}})\right]\frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2}(C_7^{\mathrm{eff}} + C_7'^{\mathrm{eff}})T_1(q^2)\right\}$$

Build CP averaged observables**:**

$S_i = (J_i + J_i) / (\Gamma + \Gamma)$

Build observables where form factors uncertainties cancel at leading order:

$P'_i = S_i/\sqrt{(F_L (1-F_L))}$

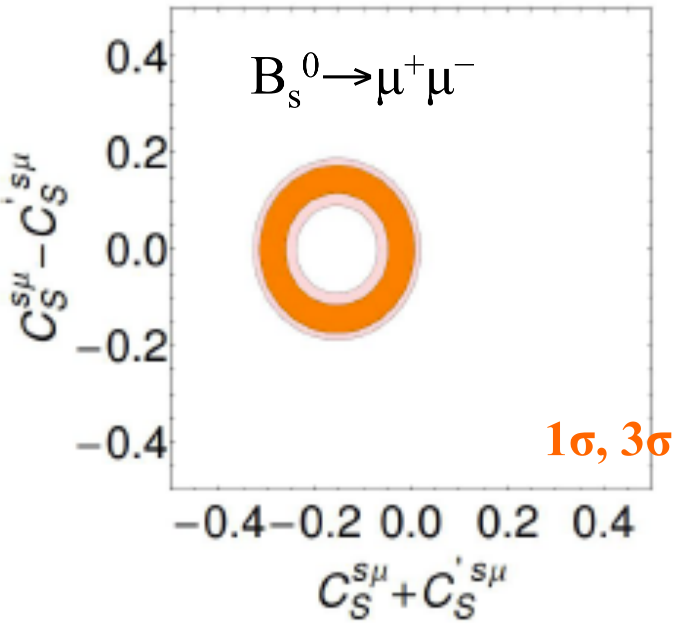
BR($B_s^0 \to \mu^+\mu^-$) and BR($B^0 \to \mu^+\mu^-$): constraints on Wilson coefficients

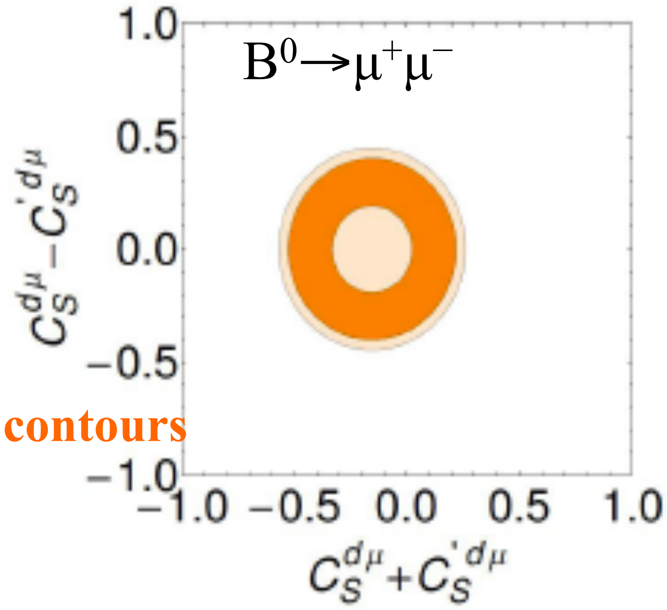
$$BR(B_s \to \mu^+\mu^-) \propto m_\mu^2 \left(\left| (C_{10}^{SM} + \cancel{C_{10}^{NP}} - \cancel{C'_{10}}) - \frac{m_{B_s}}{2m_\mu}(C_{SP} + C'_{SP}) \right|^2 + \left| \frac{m_{B_s}}{2m_\mu}(C_{SP} - C'_{SP}) \right|^2 \right)$$

If we neglect NP in $C^{(')}_{10}$ BRs are proportional to the squared sum/difference of C_S and C_P.

Constraints on the $C^{(')}_S$ Wilson coeff. from the measured BRs (pre-combination)

Alonso et al. arXiv: 1407.7044





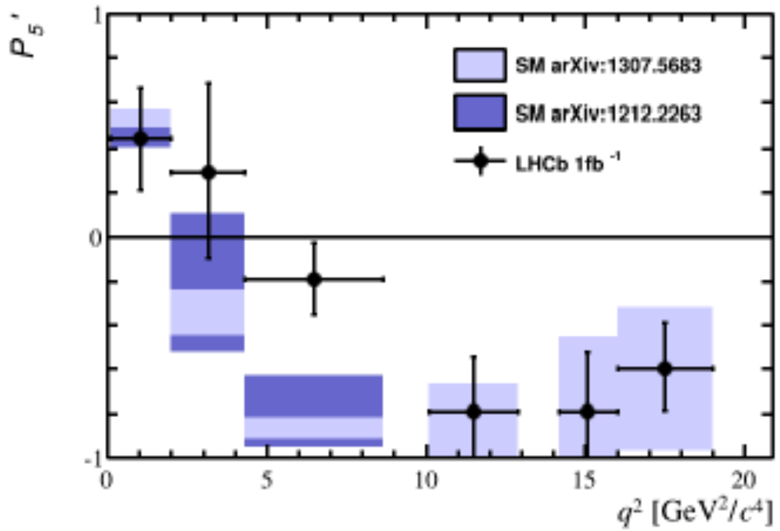
1σ, 3σ contours

The **radius** of the rings is proportional to the **measured branching fractions,**
The **width** of the rings is proportional to the experimental **accuracy.**
→ improving the experimental accuracy in these modes reduces the width of the ring, other observables are required to break the degeneracy (effective lifetime)

Rare decays with ew-penguins: prospects

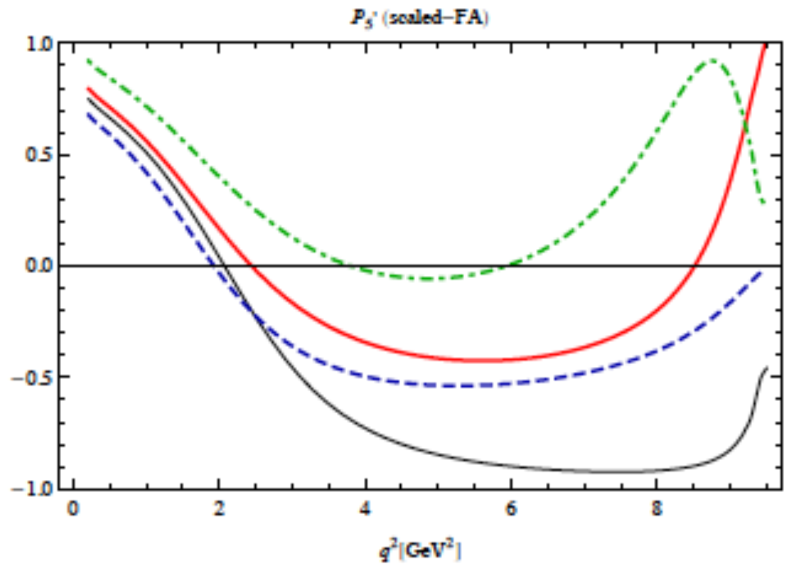
	$3\,\text{fb}^{-1}$ (7+8 TeV)	2015	Run II	Upgrade
$B^0 \to K^{*0}\mu^+\mu^-$	2.6k†	$1.4 - 2.1$k	8.5k	34 k
$B^+ \to K^+\mu^+\mu^-$	4746 ± 81	$2.6 - 3.9$k	15.4k	61.6 k
$B^+ \to \pi^+\mu^+\mu^-$	100	$50 - 80$	320	1280
$B^+ \to K^+e^+e^-$ $(1 < q^2 < 6)$	256^{+25}_{-23}	$140 - 210$	830	3320

† with enlarged q^2 windows for $3\,\text{fb}^{-1}$ analysis



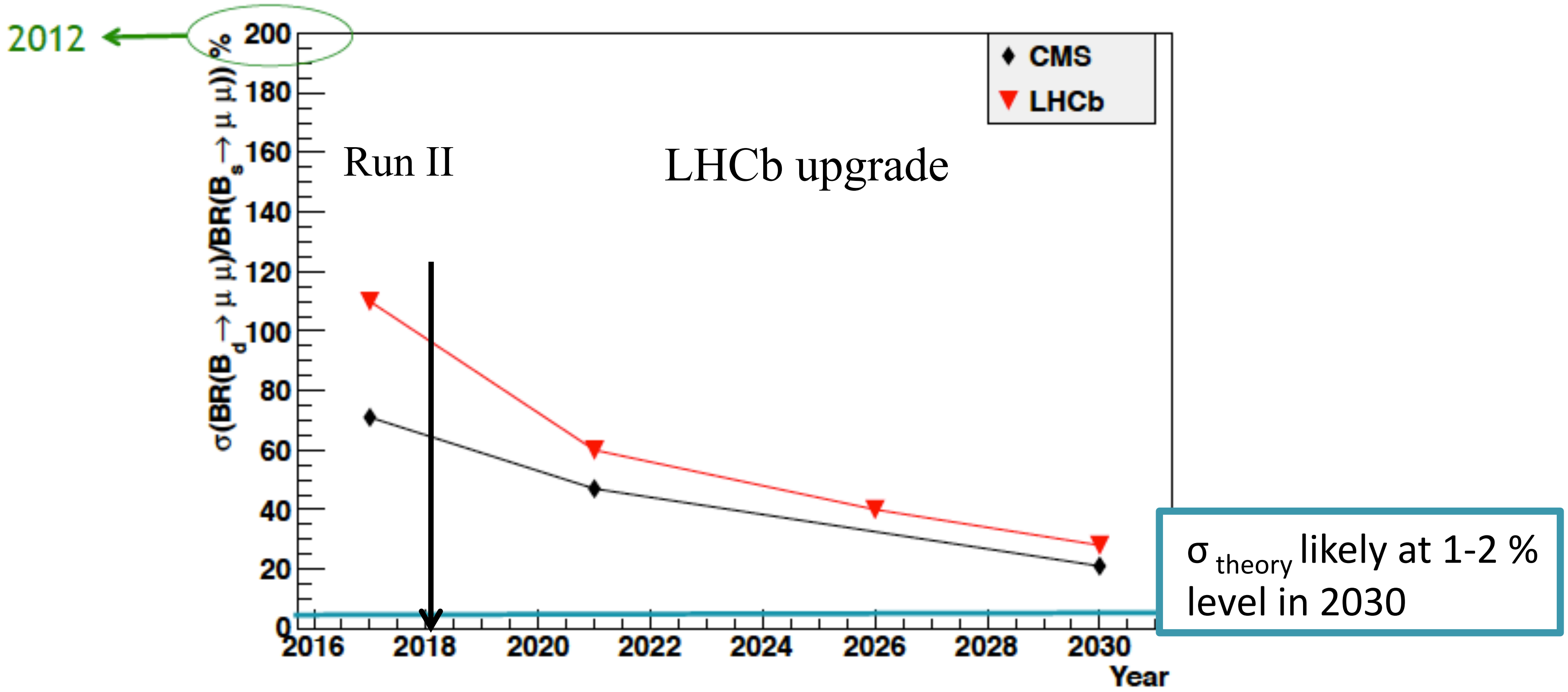
By 2028 the statistical uncertainty on each point will be reduced by a factor 3-4

Zwicky & Lyon in [arXiv:1406.0566]



Will we be able to control the hadronic uncertainties at the same level?

Expected precision on $R = BR(B^0 \to \mu^+\mu^-)/BR(B_s^0 \to \mu^+\mu^-)$



Main limiting factor will be the control of the peaking backgrounds
(pure particle identification problem)

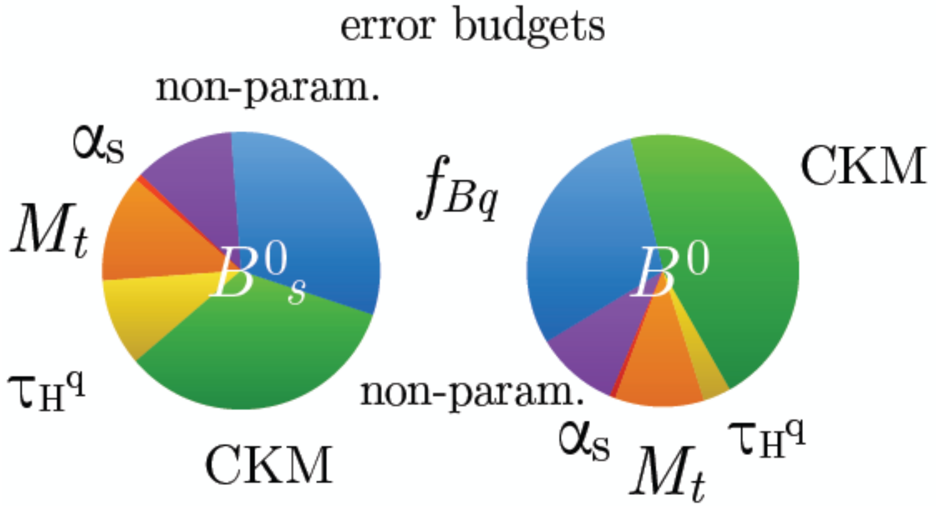
Theory predictions: error budget

$BR(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$ (6.3%)
$BR(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$ (8.5%)

Bobeth et al. '13

$B_s^0 \to \mu^+\mu^-$	f_{B_s}	CKM	τ_H^s	M_t	α_s	other param.	**non-param.**	$\sum$
	4.0%	4.3%	1.3%	1.6%	0.1%	$< 0.1\%$	1.5%	6.4%
$B^0 \to \mu^+\mu^-$	f_{B_d}	CKM	τ_H^s	M_t	α_s	other param.	**non-param.**	$\sum$
	4.5%	6.9%	0.5%	1.6%	0.1%	$< 0.1\%$	1.5%	8.5%

- $f_{B_s} = 227.4(4.5)$ MeV
  [FLAG '13, arXiv:1310.8555]
- V_{cb} from recent inclusive fit
  [Gambino, Schwanda '13, arXiv:1307.4551]
- $f_{B_d} = 190.5(4.2)$ MeV
  [FLAG '13, arXiv:1310.8555]



The uncertainty of CKM matrix elements is now larger than the uncertainty on $f_{Bs,d}$

Theory predictions: error budget

$BR(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$ (6.4%)
$BR(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$ (8.5%)

$B_s^0 \to \mu^+\mu^-$	f_{B_s}	CKM	τ_H^s	M_t	α_s	other param.	**non-param.**	$\sum$
	4.0%	4.3%	1.3%	1.6%	0.1%	< 0.1%	1.5%	6.4%
$B^0 \to \mu^+\mu^-$	f_{B_d}	CKM	τ_H^s	M_t	α_s	other param.	**non-param.**	$\sum$
	4.5%	6.9%	0.5%	1.6%	0.1%	< 0.1%	1.5%	8.5%

$R = BR(B^0 \to \mu^+\mu)/ BR(B_s^0 \to \mu^+\mu) = 0.0295^{+0.0028}_{-0.0025}$ (+8.7% - 7.7%)

The theoretical uncertainty on R is due:

- 8 % uncertainty from CKM elements ;
- 3.7 % uncertainty from f_{Bs}/f_{Bd}
- 1.4 % uncertainty on the B_s lifetime

These uncertainties do not cancel in the ratio.