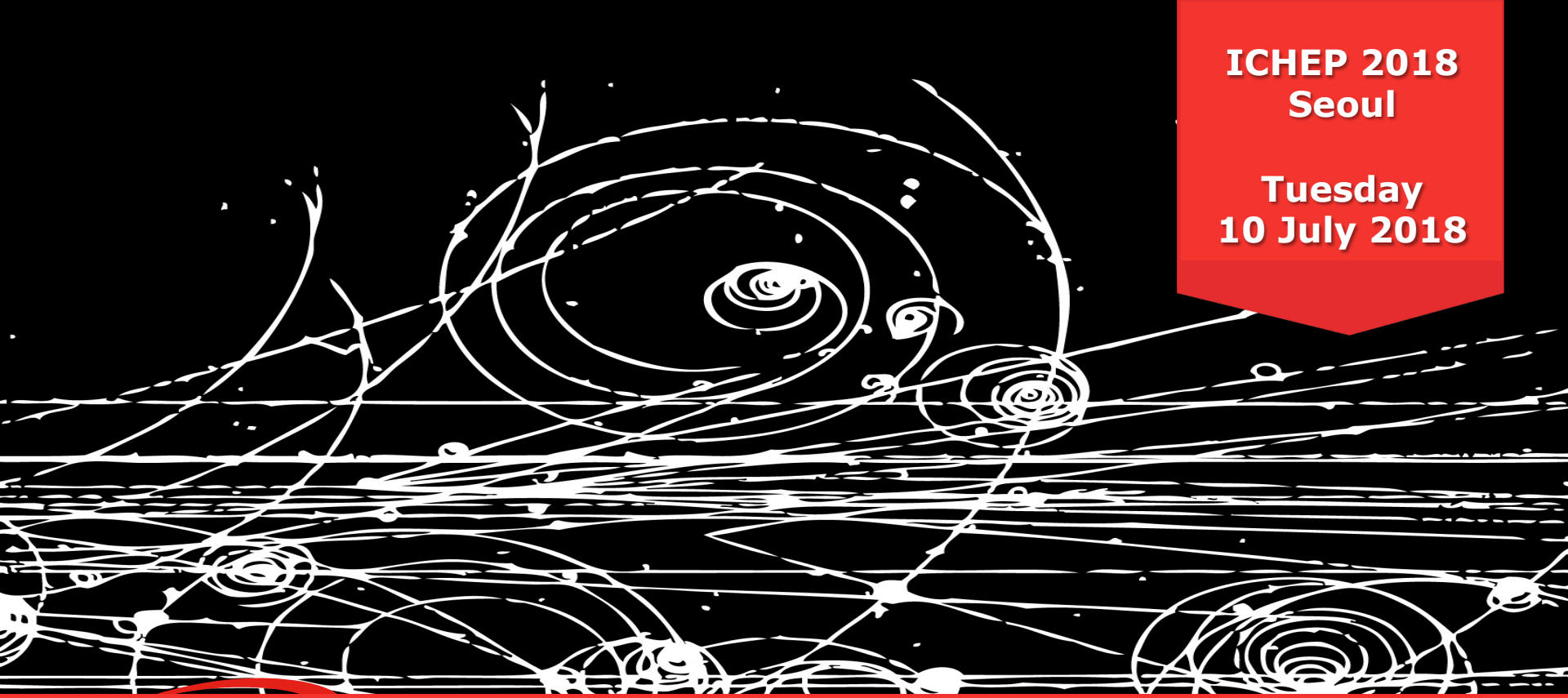


ICHEP 2018
Seoul

Tuesday
10 July 2018

Rare decays of B, D, and K mesons

Niels Tuning

on behalf of LHCb with material from ATLAS, BaBar, Belle, BESIII, CMS, KOTO, NA62

Rare decays have a track record

- $K^0 \to \mu\mu$: predicted charm quark
  - $m_c < 5$ GeV
  - J/ψ discovered 4 years later

Weak Interactions with Lepton-Hadron Symmetry*

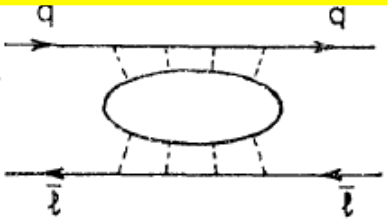
S. L. Glashow, J. Iliopoulos, and L. Maiani†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139
(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Milis theory is discussed.

splitting, beginning at order $G(G\Lambda^2)$, as well as contributions to such unobserved decay modes as $K_2 \to \mu^+ + \mu^-$, $K^+ \to \pi^+ + l + \bar{l}$, etc., involving neutral lepton

We wish to propose a simple model in which the divergences are properly ordered. Our model is founded in a quark model, but one involving four, not three, fundamental fermions; the weak interactions are medi-

new quantum number $\mathcal{C}$ for charm.



Phys.Rev. D2 (1970) 1285

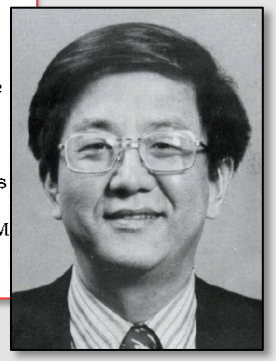
Rare Decay Modes of the K-Mesons in Gauge Theories

M. K. GAILLARD* and BENJAMIN W. LEE†
National Accelerator Laboratory, Batavia, Illinois 60510

our attention on the Weinberg-Salam model. In this model, $K \to \mu\bar{\mu}$ is suppressed due to a fortuitous cancellation. To explain the small K_L-K_S mass difference and nonsuppression of $K_L \to \gamma\gamma$, it is found necessary to assume $m_p/m_p' \ll 1$ where m_p is the mass of the p-quark and m_p' the mass of the charmed quark, and $m_p' < 5$ GeV. We

in the limit of chiral SU(3) × SU(3) symmetry, where m_c is the average mass of the charmed pseudoscalar mesons. If this is correct, we expect m_c to be less than, say, 10 GeV. The experimental implications of the existence of charmed mesons have already been discussed by GIM

Phys.Rev. D10 (1974) 897

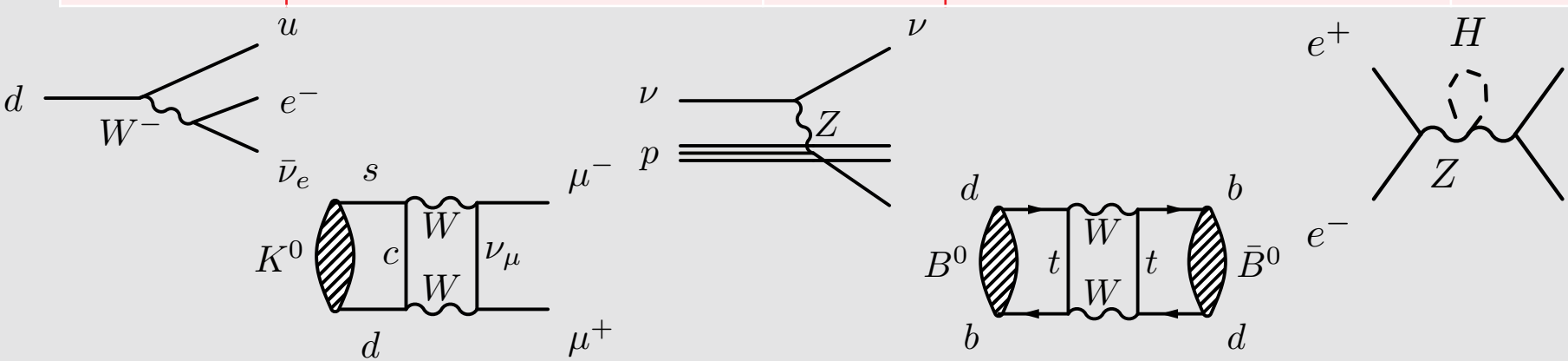


B.W. Lee

Heavy Flavour = Precision search for NP

- Historical record of indirect discoveries:

Particle	Indirect			Direct		
ν	β decay	Fermi	1932	Reactor ν-CC	Cowan, Reines	1956
W	β decay	Fermi	1932	$W \to e\nu$	UA1, UA2	1983
c	$K^0 \to \mu\mu$	GIM	1970	J/ψ	Richter, Ting	1974
b	CPV $K^0 \to \pi\pi$	CKM, 3rd gen	1964/72	Υ	Ledermann	1977
Z	ν-NC	Gargamelle	1973	$Z \to e^+e^-$	UA1	1983
t	B mixing	ARGUS	1987	$t \to Wb$	D0, CDF	1995
H	e^+e^-	EW fit, LEP	2000	$H \to 4\mu/\gamma\gamma$	CMS, ATLAS	2012
?	**What's next ?**		?			?



Heavy Flavour = Precision search for NP

- Direct discoveries rightfully higher valued:

Particle	Indirect			Direct		
ν	β decay	Fermi	1932	Reactor ν-CC	Cowan, Reines	1956
W	β decay	Fermi	1932	$W \to e\nu$	UA1, UA2	1983
c	$K^0 \to \mu\mu$	GIM	1970	J/ψ	Richter, Ting	1974
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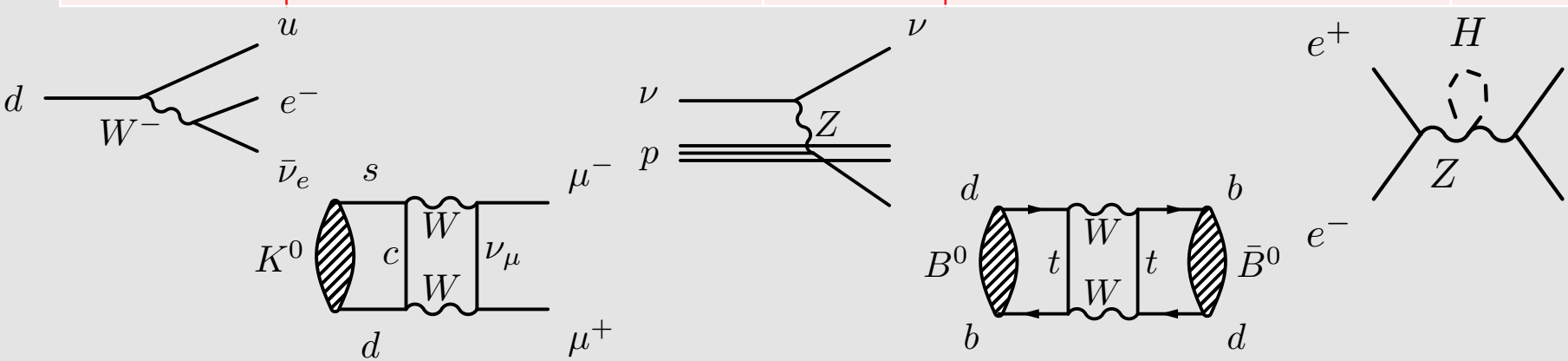
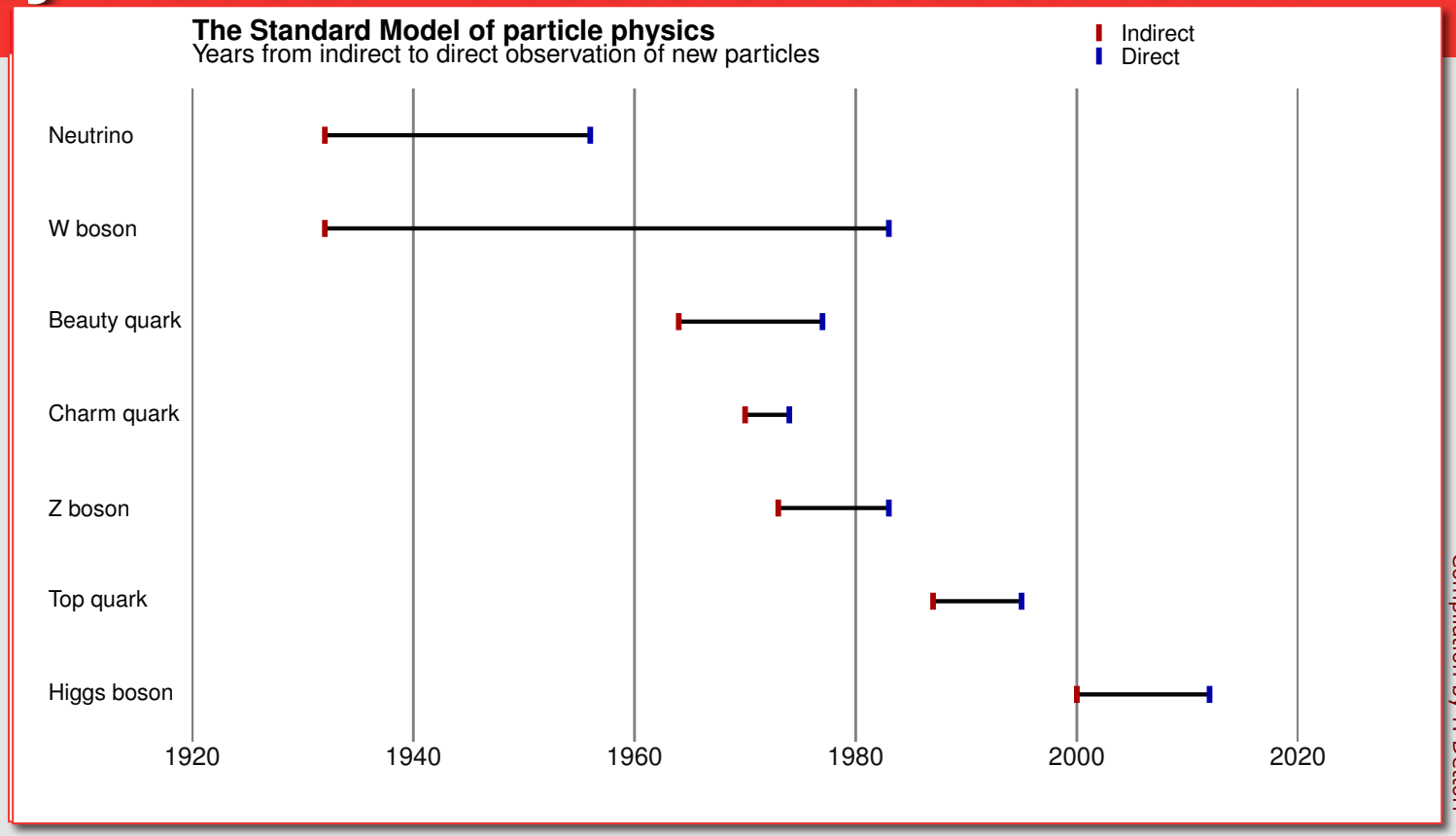
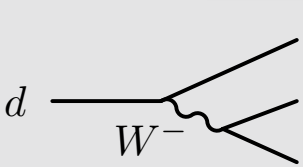
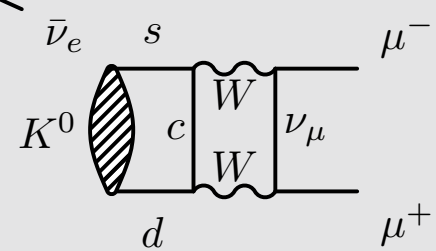


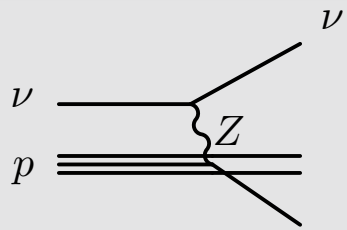
Heavy Flavour = Precision search for NP

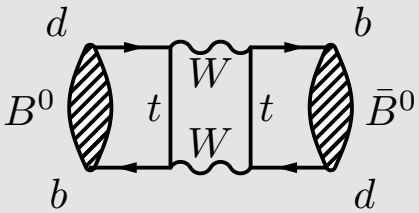


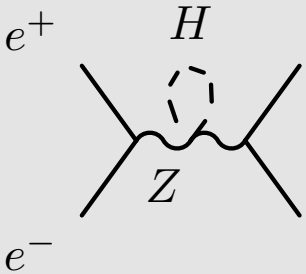
Compilation by F. Dettori





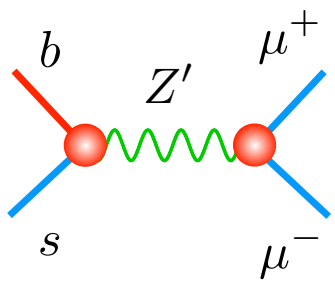






Heavy Flavour = Precision search for NP

- Depending on your model, sensitive to multi-TeV scales, eg:



$$\mu_{B_s\to\mu^+\mu^-} \simeq 1 \pm \frac{4\pi}{g^2\,|V_{tb}^* V_{ts}|^2}\,\frac{v^2}{\Lambda^2}$$

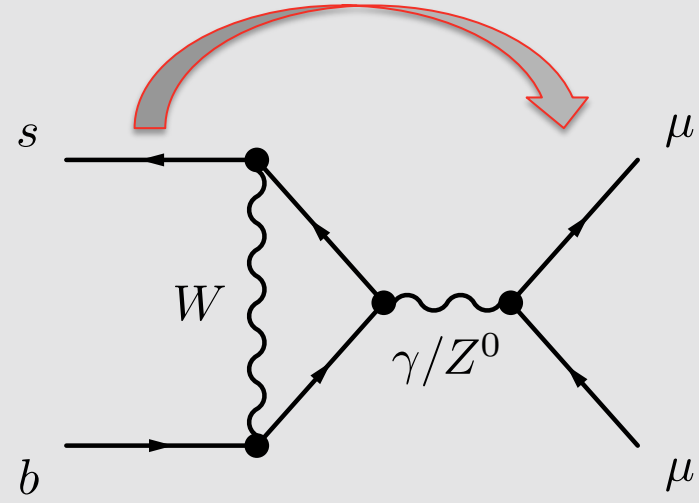
$\mu_{B\to\mu\mu}$ is ratio BR^{exp}/BR^{SM}

$$\Lambda \gtrsim \frac{v}{\sqrt{0.2}} \times \begin{cases} \dfrac{\sqrt{4\pi}}{g\,|V_{tb}^* V_{ts}|} \\ 1 \end{cases} \simeq \begin{cases} 50\,\text{TeV}\,, & \text{anarchic tree} \\ 0.6\,\text{TeV}\,, & \text{MFV loop} \end{cases}$$

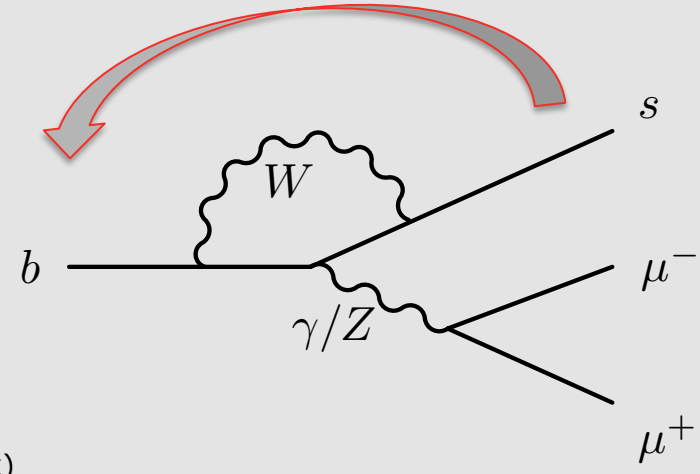
From Uli Haisch, 31 Aug 2016
arXiv:1510.03341

Two types

- Fully leptonic



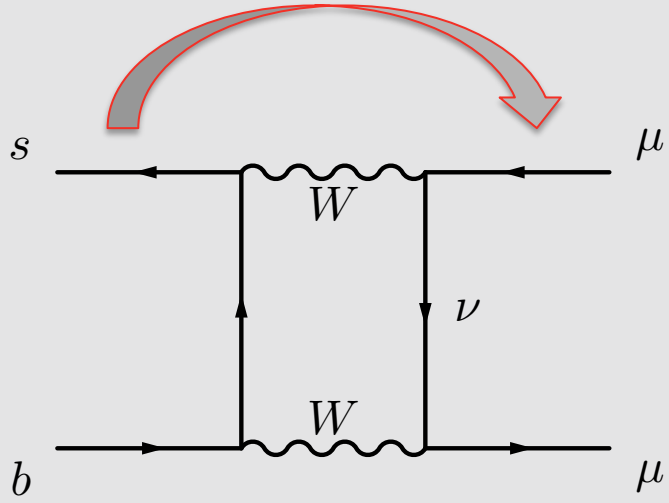
- "Half-leptonic"



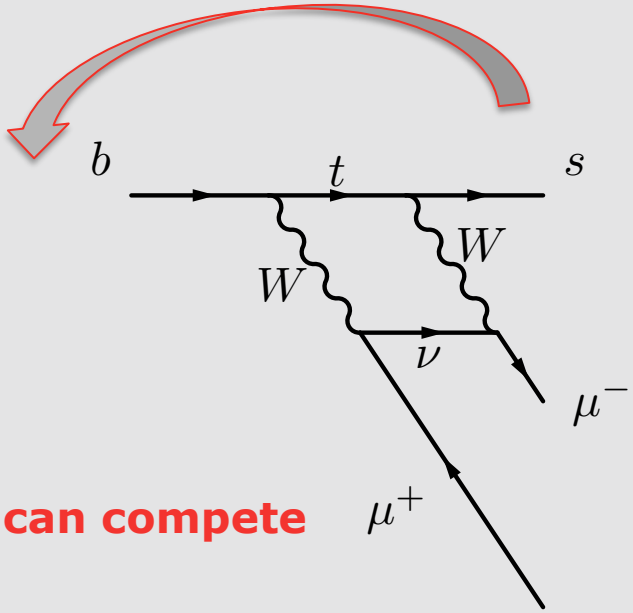
- **It's all about FCNC EW Penguins**
  - (= Flavour Changing Neutral Current - Electro Weak)
- **Suppressed in the SM, so NP effects can compete**

Two types

- Fully leptonic



- "Half-leptonic"



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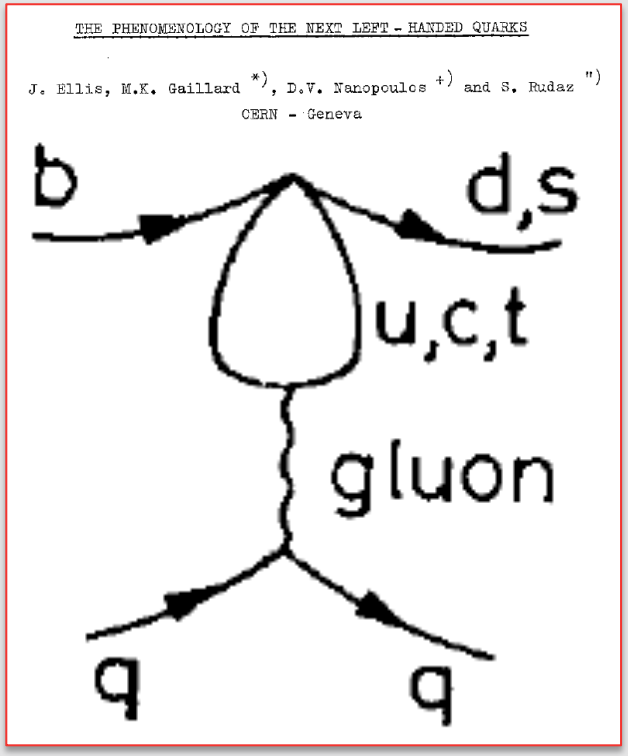
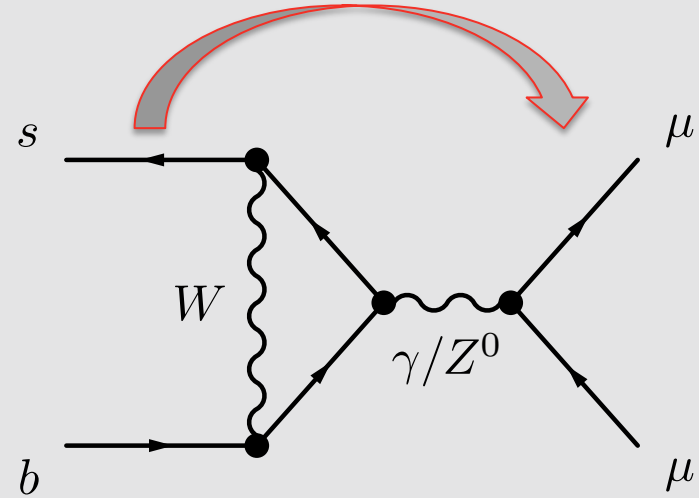
Two types

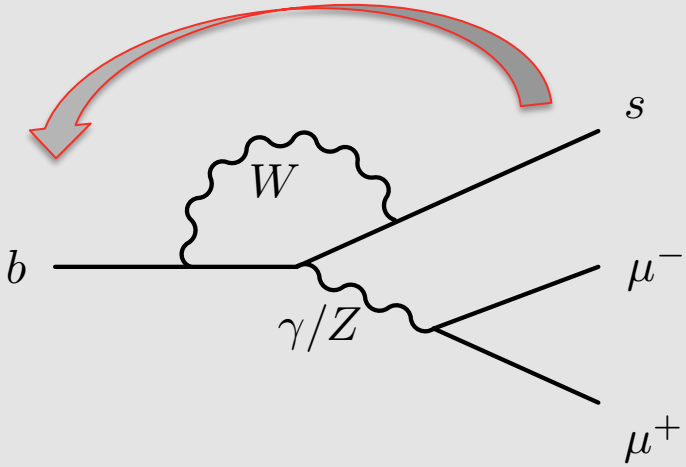
The first penguin:


THE PHENOMENOLOGY OF THE NEXT LEFT - HANDED QUARKS

J. Ellis, M.K. Gaillard *), D.V. Nanopoulos +) and S. Rudaz ")
CERN - Geneva

Nucl. Phys. B131 (1977) 285





- **It's all about FCNC EW Penguins**
  - (= Flavour Changing Neutral Current - Electro Weak)
- **Suppressed in the SM, so NP effects can compete**

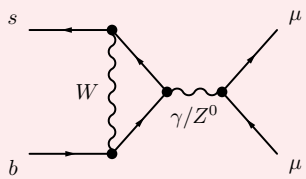
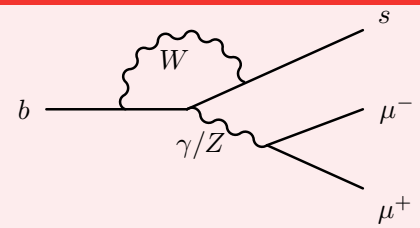
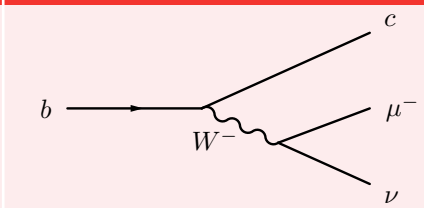
Outline: A wealth of sensitive probes!

- Rare Strange and Charm
  - Leptonic: $K_S^0 \to \mu^+\mu^-$ $D^0 \to \mu^+\mu^-$ $D^0 \to e^+\mu^-$
  - FCNC: $K^{+/0} \to \pi^{+/0}\nu\nu$ $D^0 \to h^+h^-\mu^+\mu^-$
  - Baryonic: $\Sigma^+ \to p\mu^+\mu^-$ $\Lambda_c^+ \to p\mu^+\mu^-$

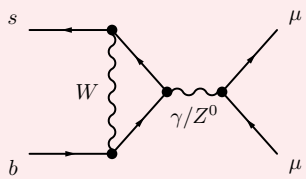
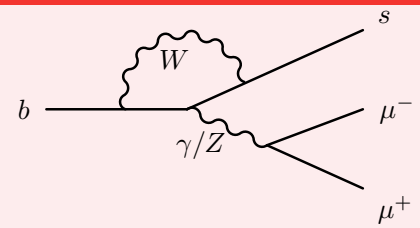
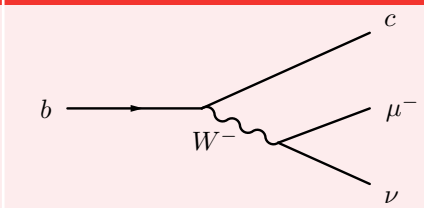
- Rare Beauty
  - Leptonic: $B^0_{(s)} \to \mu^+\mu^-$ $B^0_s \to \tau^+\tau^-$ $B^0 \to e^+\mu^-$
  - FCNC: $B^0 \to K^*\mu^+\mu^-$ $B^0_s \to (\varphi)K^{0*}\mu^+\mu^-$
  - Baryonic: $\Lambda_b^0 \to \Lambda^0\mu^+\mu^-$
  - Semi-leptonic: $B^0 \to D^{(*)}\mu^+\nu$ $B_c^+ \to J/\psi\ \mu^+\nu$

- Observables:
  - *Branching fraction*
  - *Decay rate*
  - *Angular distributions*

Outline

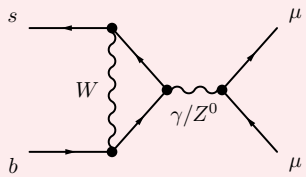
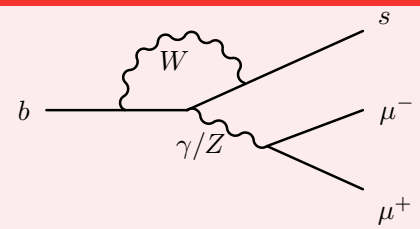
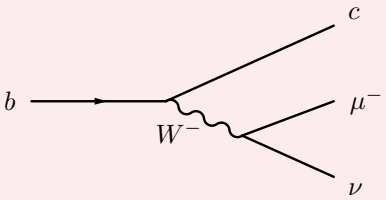
	Flavour Changing Neutral Current			Charged Current
	Leptonic	**Mesonic**	**Baryonic**	**Semi-leptonic**
				
Strange	$K_S^0 \to \mu^+\mu^-$	$K^+ \to \pi^+\nu\nu$ $K^0 \to \pi^0\nu\nu$	$\Sigma^+ \to p\mu^+\mu^-$	
Charm	$D^0 \to \mu^+\mu^-$ $D^0 \to e^+\mu^-$	$D^0 \to h^+h^-\mu^+\mu^-$ $J/\psi \to D^0e^+e^-$	$\Lambda_c^+ \to p\mu^+\mu^-$	
Beauty	$B^0_{(s)} \to \mu^+\mu^-$ $B^0_{(s)} \to \tau^+\tau^-$ $B^0_{(s)} \to e^+\mu^-$	$B^0 \to K^{(*)}\mu^+\mu^-/e^+e^-$ $B^+ \to K^{(*)}\mu^+\mu^-/e^+e^-$ $B^0_s \to \varphi\mu^+\mu^-$ $B^0_s \to K^*\mu^+\mu^-$	$\Lambda_b \to \Lambda\,\mu^+\mu^-$	$B^0 \to D^{(*)}\mu^+\nu\,/\,\tau^+\nu$ $B_c^+ \to J/\psi\mu^+\nu\,/\,\tau^+\nu$

Outline

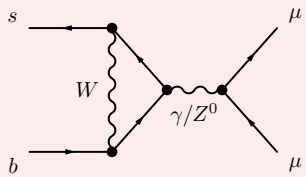
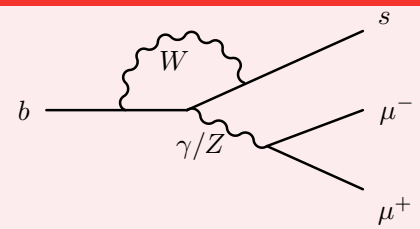
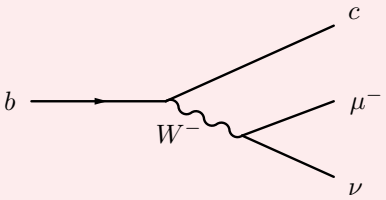
	Flavour Changing Neutral Current			Charged Current
	Leptonic	**Mesonic**	**Baryonic**	**Semi-leptonic**
				
Strange	$K_S^0 \to \mu^+\mu^-$	$K^+ \to \pi^+\nu\nu$ $K^0 \to \pi^0\nu\nu$	$\Sigma^+ \to p\mu^+\mu^-$	
Charm	$D^0 \to \mu^+\mu^-$ $D^0 \to e^+\mu^-$	$D^0 \to h^+h^-\mu^+\mu^-$ $J/\psi \to D^0e^+e^-$	$\Lambda_c^+ \to p\mu^+\mu^-$	
Beauty	$B^0_{(s)} \to \mu^+\mu^-$ $B^0_{(s)} \to \tau^+\tau^-$ $B^0_{(s)} \to e^+\mu^-$	$B^0 \to K^{(*)}\mu^+\mu^-/e^+e^-$ $B^+ \to K^{(*)}\mu^+\mu^-/e^+e^-$ $B^0_s \to \varphi\mu^+\mu^-$ $B^0_s \to K^*\mu^+\mu^-$	$\Lambda_b \to \Lambda\,\mu^+\mu^-$	$B^0 \to D^{(*)}\mu^+\nu / \tau^+\nu$ $B_c^+ \to J/\psi\mu^+\nu / \tau^+\nu$

Lepton Flavour Non-Universality

References

	Flavour Changing Neutral Current			Charged Current
	Leptonic	**Mesonic**	**Baryonic**	**Semi-leptonic**
				
Strange	*LHCb, 1706.00758*	*NA62, Moriond 2018* *KOTO, ICHEP 2018*	*LHCb, 1712.08606*	
Charm	*LHCb, 1305.5059,* *LHCb, 1512.00322*	*LHCb, 1707.08377* *LHCb, 1806.10793* *BESIII, 1710.02278* *BESIII, 1802.09752* *BESIII, 1802.04057*	*LHCb, 1712.07938*	
Beauty	*CMS, 1307.5025* *LHCb&CMS, 1411.4413* *LHCb, 1703.05747* *LHCb, 1710.04333* *LHCb, 1703.02508*	*BaBar, 1204.3933 (RK)* *BaBar, 1508.07960 (Ang)* *Belle, 0904.0770 (RK)* *Belle, 1612.05014 (Q5')* *CMS, 1507.08126 (Ang, B^0)* *CMS, 1710.02846 (Ang, B^0)* *CMS, 1806.00636 (Ang, B^+)* *ATLAS, 1805.04000 (B^0)* *LHCb, 1403.8044 (BR(B^0))* *LHCb, 1406.6482 (R_K)* *LHCb, 1512.04442 (Ang)* *LHCb, 1506.08777 (BR(B_s))* *LHCb, 1612.06764 (phase)* *LHCb, 1612.07818 (scalar search)* *LHCb, 1705.05802 (R_K*)* *LHCb, 1804.07167 (B_s^0)*	*LHCb, 1503.07138* *LHCb, 1701.08705* *LHCb, 1703.00256*	*BaBar, 1205.5442* *Babar, 1303.0571* *Belle, 1607.07923* *Belle, 1612.00529* *Belle, 1709.00129* *Belle, 1803.06444* *LHCb, 1506.08614* *LHCb, 1708.08856* *LHCb, 1709.02505*

References

	Flavour Changing Neutral Current			Charged Current
	Leptonic	**Mesonic**	**Baryonic**	**Semi-leptonic**
				
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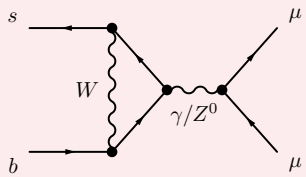
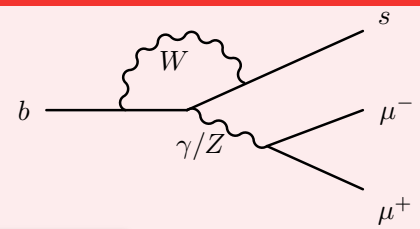
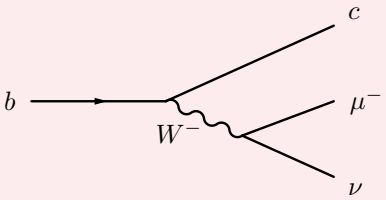
New since ICHEP'16

References

	Flavour Changing Neutral Current			Charged Current
	Leptonic	**Mesonic**	**Baryonic**	**Semi-leptonic**
				
Strange	*LHCb, 1706.00758*	*NA62, Moriond 2018* *KOTO, ICHEP 2018*	*LHCb, 1712.08606*	
Charm	*LHCb, 1305.5059,* *LHCb, 1512.00322*	*LHCb, 1707.08377* *LHCb, 1806.10793* *BESIII, 1710.02278* *BESIII, 1802.09752* *BESIII, 1802.04057*	*LHCb, 1712.07938*	
Beauty	*CMS, 1307.5025* *LHCb&CMS, 1411.4413* *LHCb, 1703.05747* *LHCb, 1710.04333* *LHCb, 1703.02508*	*BaBar, 1204.3933 (RK)* *BaBar, 1508.07960 (Ang)* *Belle, 0904.0770 (RK)* *Belle, 1612.05014 (Q5')* *CMS, 1507.08126 (Ang, B^0)* *CMS, 1710.02846 (Ang, B^0)* *CMS, 1806.00636 (Ang, B^+)* *ATLAS, 1805.04000 (B^0)* *LHCb, 1403.8044 (BR(B^0))* *LHCb, 1406.6482 (R_K)* *LHCb, 1512.04442 (Ang)* *LHCb, 1506.08777 (BR(B_s))* *LHCb, 1612.06764 (phase)* *LHCb, 1612.07818 (scalar search)* *LHCb, 1705.05802 (R_K*)* *LHCb, 1804.07167 (B_s^0)*	*LHCb, 1503.07138* *LHCb, 1701.08705* *LHCb, 1703.00256*	*BaBar, 1205.5442* *Babar, 1303.0571* *Belle, 1607.07923* *Belle, 1612.00529* *Belle, 1709.00129* *Belle, 1803.06444* *LHCb, 1506.08614* *LHCb, 1708.08856* *LHCb, 1709.02505*

New in 2018

Strange

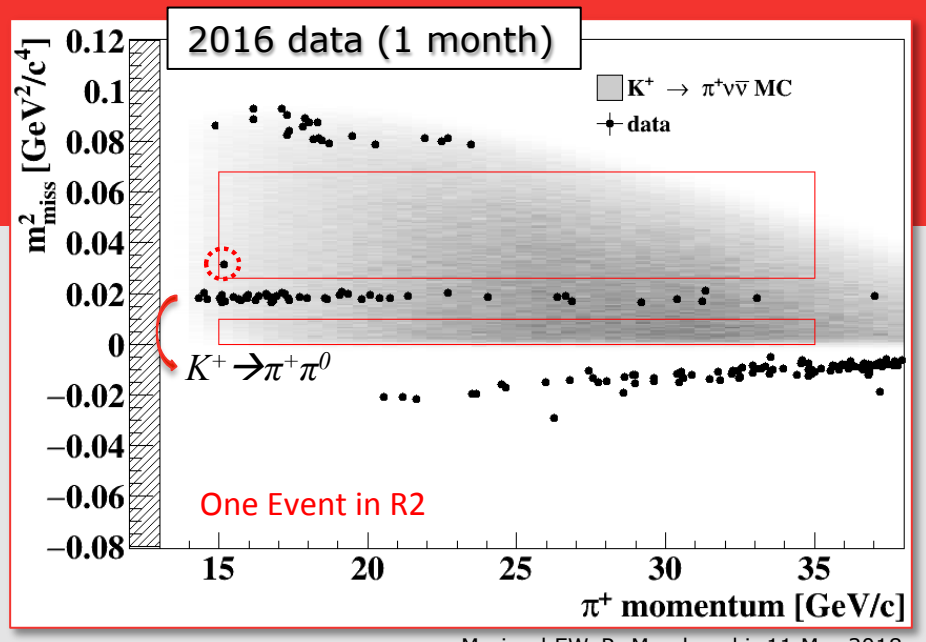
- NA62
  - $K^+ \to \pi^+ \nu\nu$ (preliminary)
  - Observed 1 event
    - expect 0.27 signal + 0.15 bkgd

$$B\left(K^+ \to \pi^+ \nu\bar{\nu}\right) < 14 \times 10^{-10} (95\%\ \mathrm{CL})$$

$$B\left(K^+ \to \pi^+ \nu\bar{\nu}\right) < 10 \times 10^{-10} (\mathrm{expected})$$

$$B\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(1.5^{+1.3}_{-0.5}\right) \times 10^{-10} (\mathrm{E787/E949,\ BNL})$$

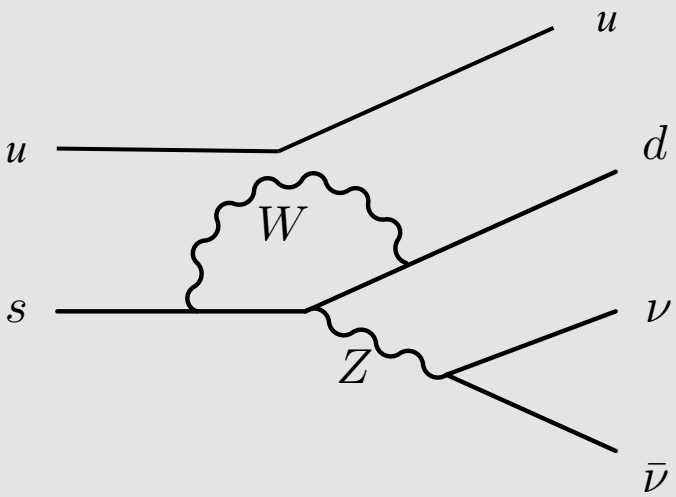
$$B\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(0.84 \pm 0.10\right) \times 10^{-10} (\mathrm{SM,\ A.\ Buras})$$



Moriond EW, R. Marchevski, 11 Mar 2018

20 SM events expected before LS2 (2019)

- KOTO
  - $K^0 \to \pi^0 \nu\nu$ (preliminary)



- Relatively new field within LHCb
  - $K_S^0 \to \mu^+\mu^-$
  - $\Sigma^+ \to p\mu^+\mu^-$

Strange

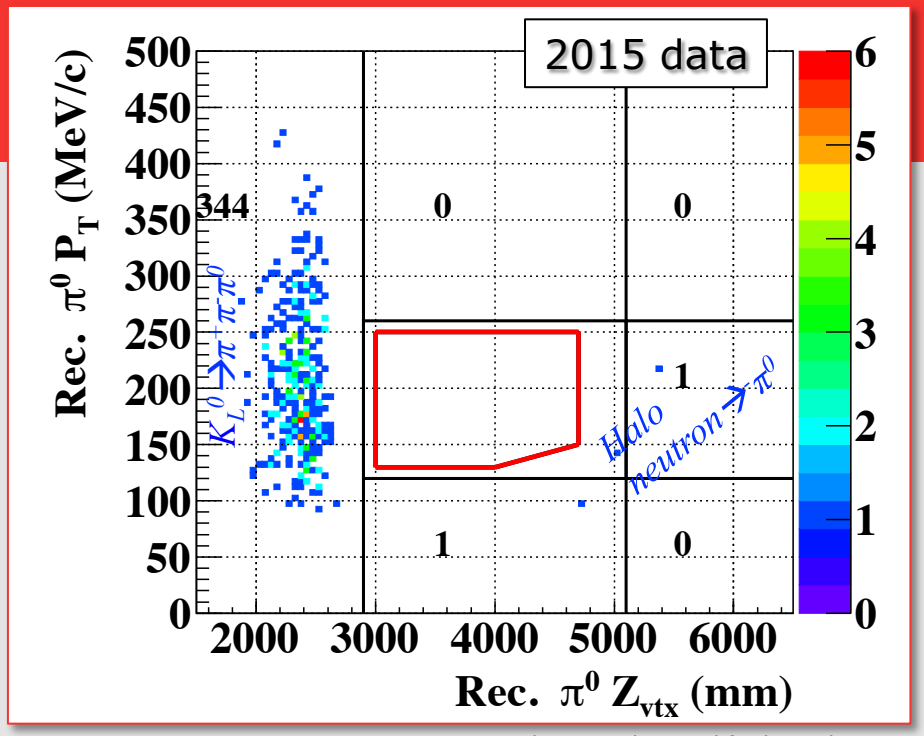
- NA62
  - $K^+ \to \pi^+ \nu\nu$ (preliminary)

- KOTO
  - $K^0 \to \pi^0 \nu\nu$ (preliminary)
  - Observed 0 event
    - expect 0.40 ± 0.18 bkgd

$$B\left(K_L^0 \to \pi^0 \nu\bar{\nu}\right) < 30 \times 10^{-10} (90\%\ \mathrm{CL})$$

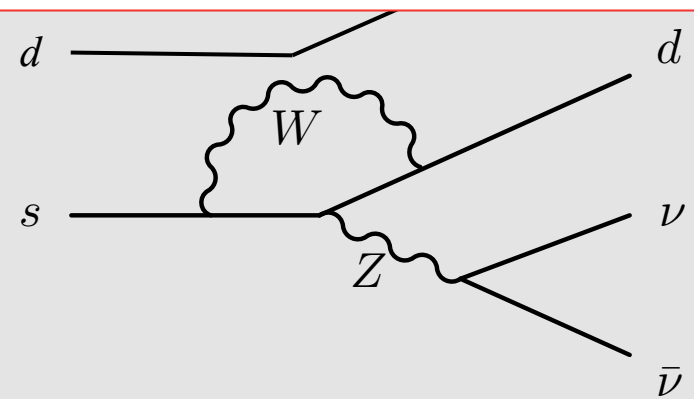
$$B\left(K_L^0 \to \pi^0 \nu\bar{\nu}\right) = 0.3 \times 10^{-10} (\mathrm{SM})$$

- Relatively new field within LHCb
  - $K_S^0 \to \mu^+\mu^-$
  - $\Sigma^+ \to p\mu^+\mu^-$



ICHEP 2018, K. Shiomi and B. Beckford, 6 July 2018

Expect B<12 x 10^{-10} with full 2015-2018 data



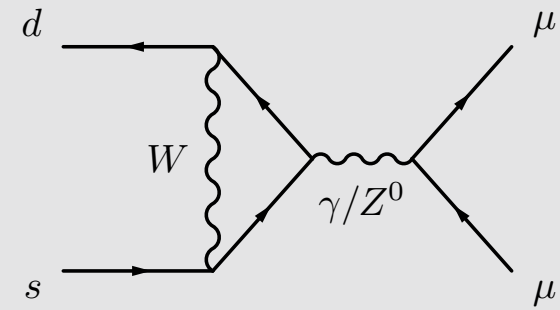
Strange

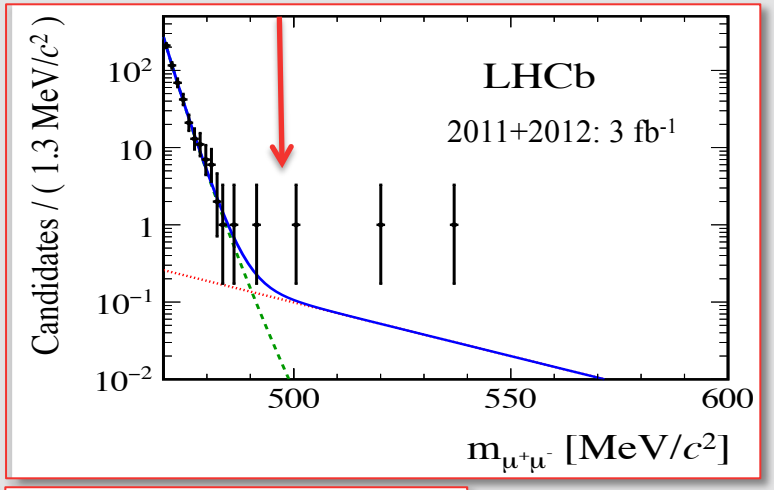
- NA62
  - $K^+ \to \pi^+ \nu\nu$
- KOTO
  - $K^0 \to \pi^0 \nu\nu$ (preliminary)
- Relatively new field within LHCb
  - $K_S^0 \to \mu^+\mu^-$

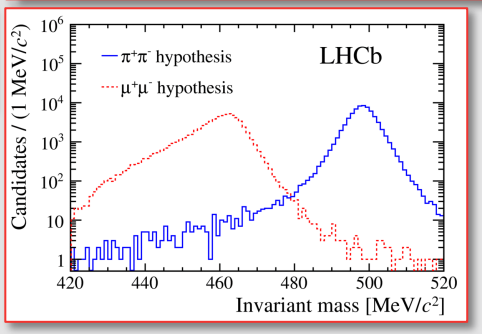
$$\mathcal{B}(K_S^0 \to \mu^+\mu^-) < 0.8\ (1.0) \times 10^{-9} \text{ at } 90\%\ (95\%) \text{ CL.}$$

LHCb, JHEP05 (2018) 024

  - $\Sigma^+ \to p\mu^+\mu^-$



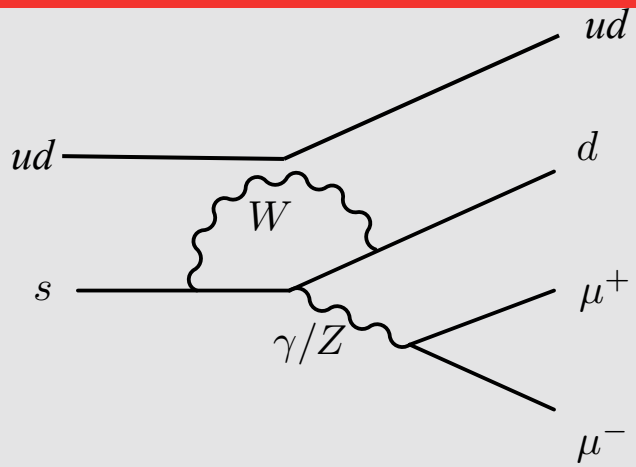




Largest bkgd $K_S^0 \to \pi^+\pi^-$: well separated

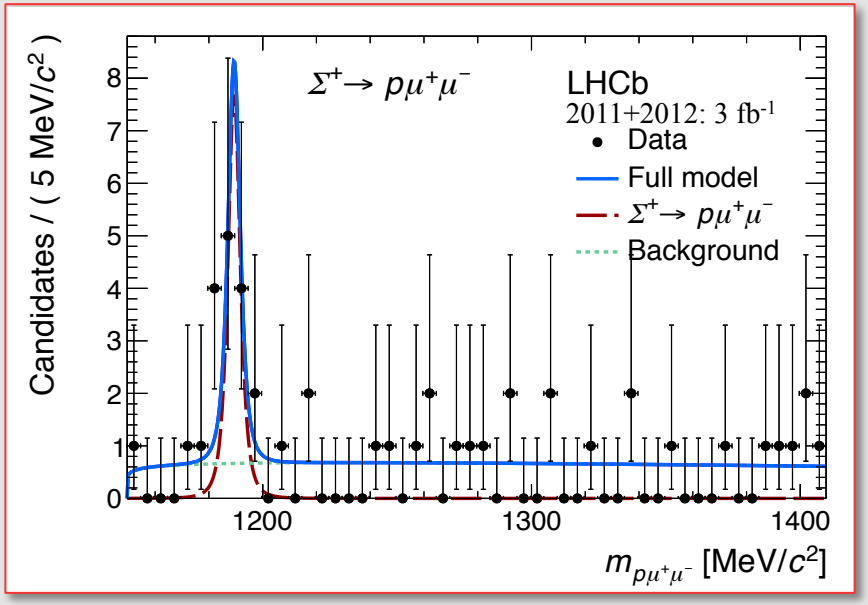
Strange

- NA62
  - $K^+ \to \pi^+ \nu\nu$



- KOTO
  - $K^0 \to \pi^0 \nu\nu$ (preliminary)

- Relatively new field within LHCb
  - $K_S^0 \to \mu^+\mu^-$
  - $\Sigma^+ \to p\mu^+\mu^-$
    - 4.1 σ significance



$$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (2.2\,^{+1.8}_{-1.3}) \times 10^{-8}$$

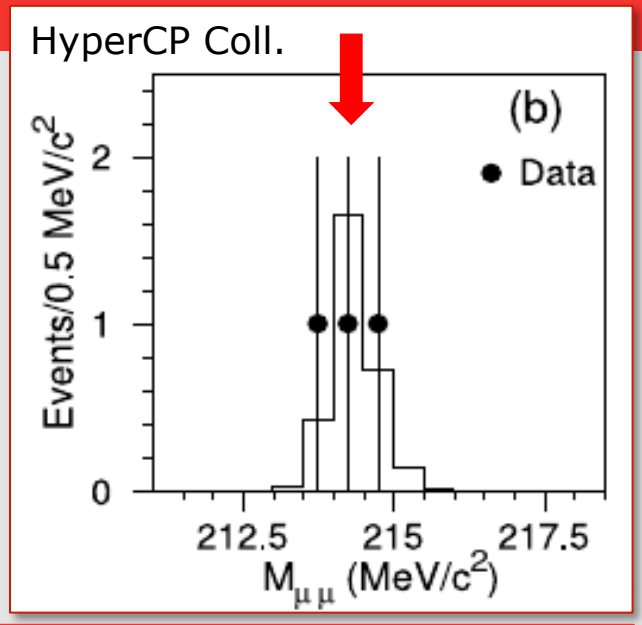
LHCb, PRL 120 (2018) 221803

Strange

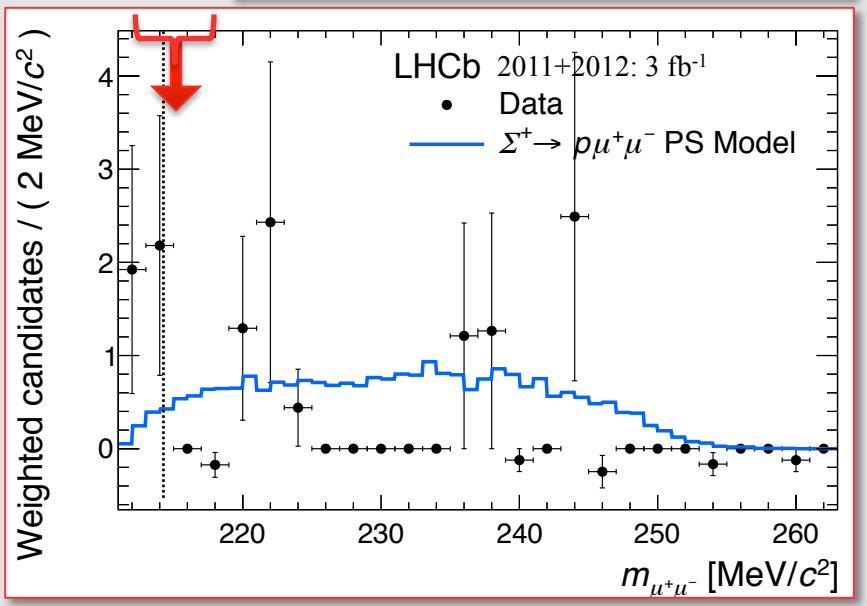
$\Sigma^+ \to pX(\to \mu^+\mu^-)$?

- NA62
  - $K^+ \to \pi^+\nu\nu$
- KOTO
  - $K^0 \to \pi^0\nu\nu$ (preliminary)
- Relatively new field within LHCb
  - $K_S^0 \to \mu^+\mu^-$
  - $\Sigma^+ \to p\mu^+\mu^-$
    - Check HyperCP (E871) events
    - Fit at m=214.3 MeV:

$$\mathcal{B}(\Sigma^+ \to pX^0(\to \mu^+\mu^-)) < 1.4 \times 10^{-8}\ (1.7 \times 10^{-8})$$



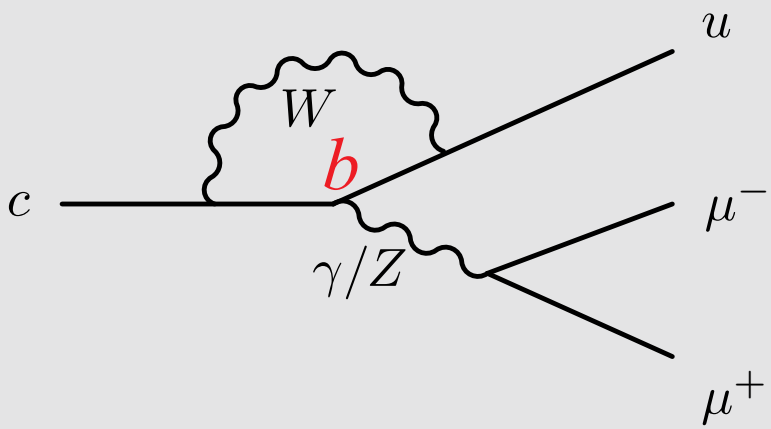
HyperCP, PRL 94 (2005) 021801



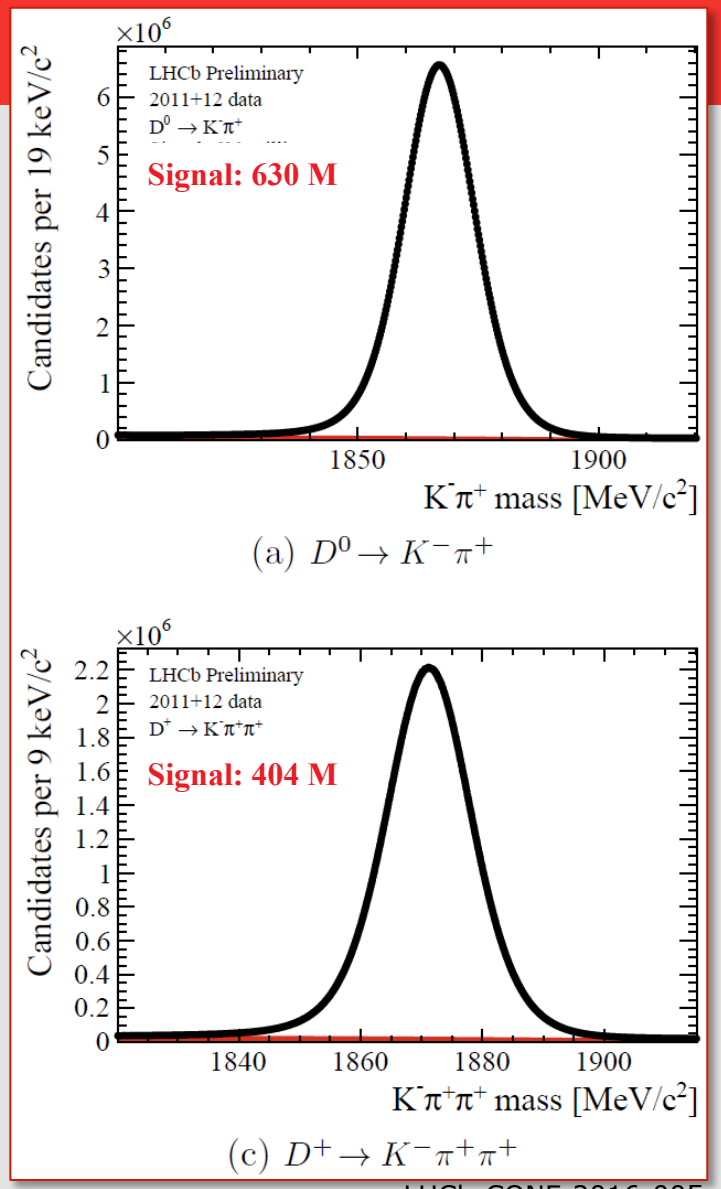
LHCb, PRL 120 (2018) 221803

Charm

- Probing the up-quark sector



- Enormous data set
  - 10^9 *D*-decays in Run-I

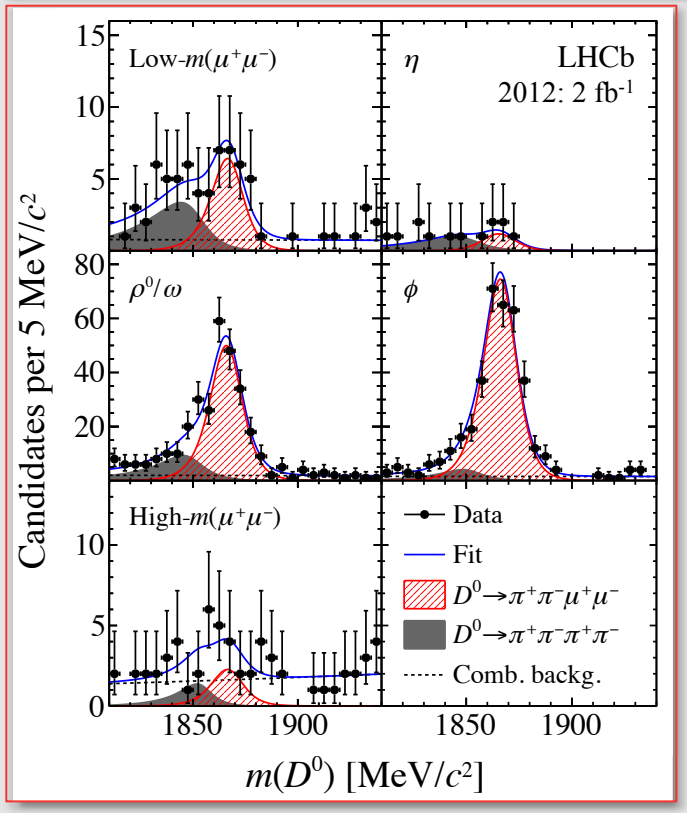


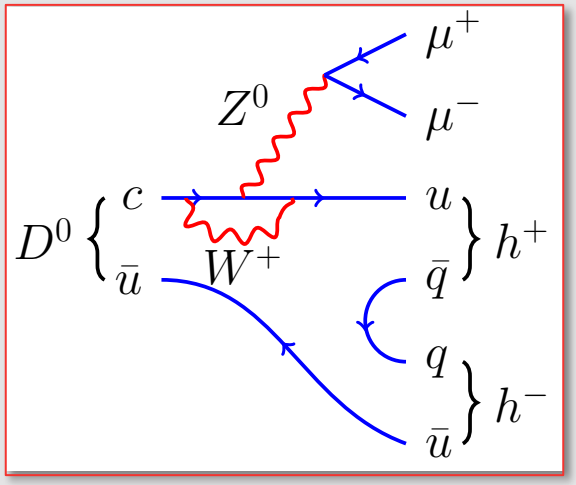
LHCb-CONF-2016-005

Charm: $D^0 \to h^+h^-\mu^+\mu^-$

- Search with 2 fb^{-1} of Run-1 data
  - Exploited $D^{*+} \to D^0\pi^+$ decays to suppress comb bkgd
  - Rarest charm decay ever observed

$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97) \times 10^{-7},$$
$$\mathcal{B}(D^0 \to K^+K^-\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16) \times 10^{-7}.$$





LHCb, PRL 119 (2017) 181805, arXiv:1707.08377

Charm: $D^0 \to h^+h^-\mu^+\mu^-$

- Search with 2 fb^{-1} of Run-1 data
  - Exploited $D^{*+} \to D^0\pi^+$ decays to suppress comb bkgd
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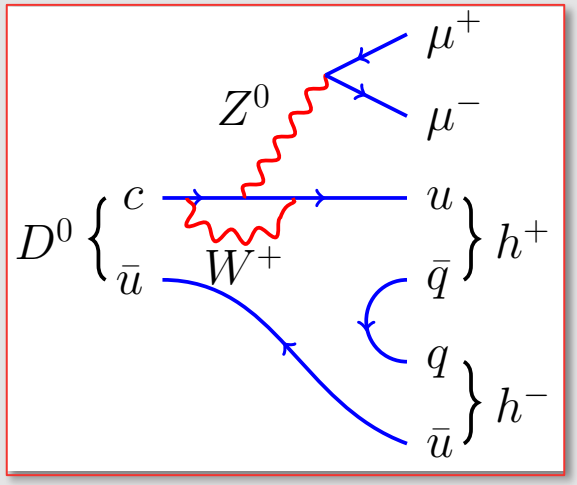
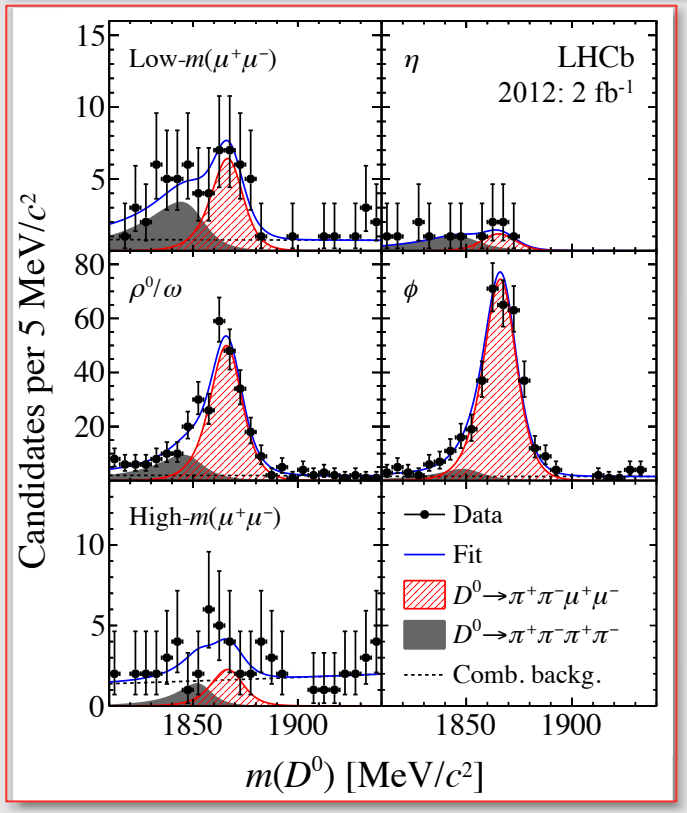
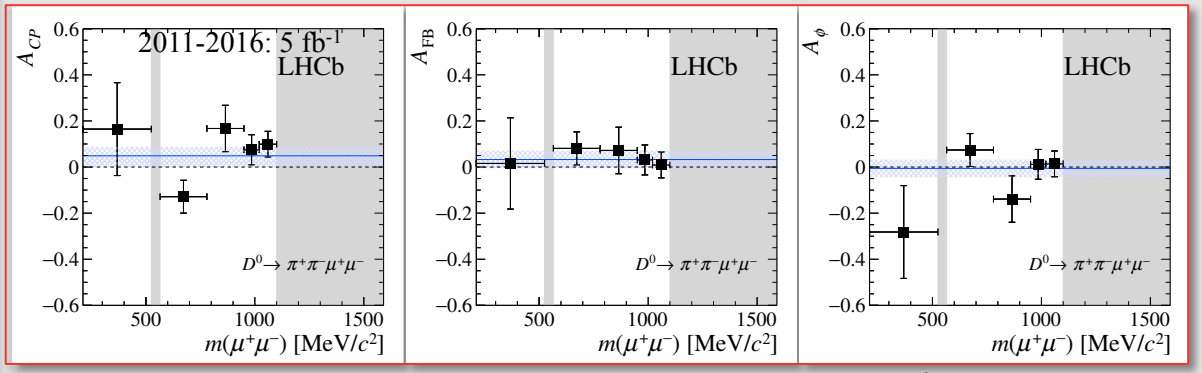
$$\mathcal{B}(D^0 \to K^+K^-\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16) \times 10^{-7}.$$





LHCb, PRL 119 (2017) 181805, arXiv:1707.08377

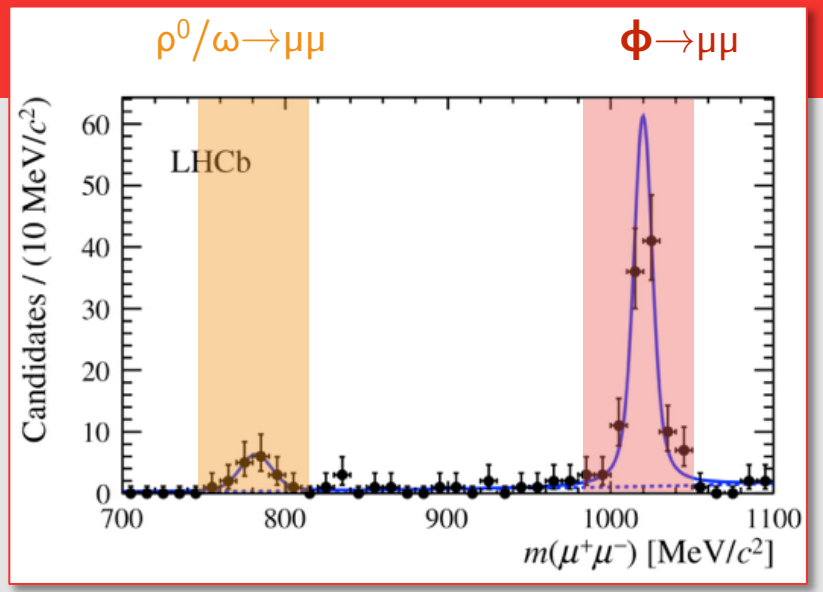


LHCb, arXiv:1806.10793

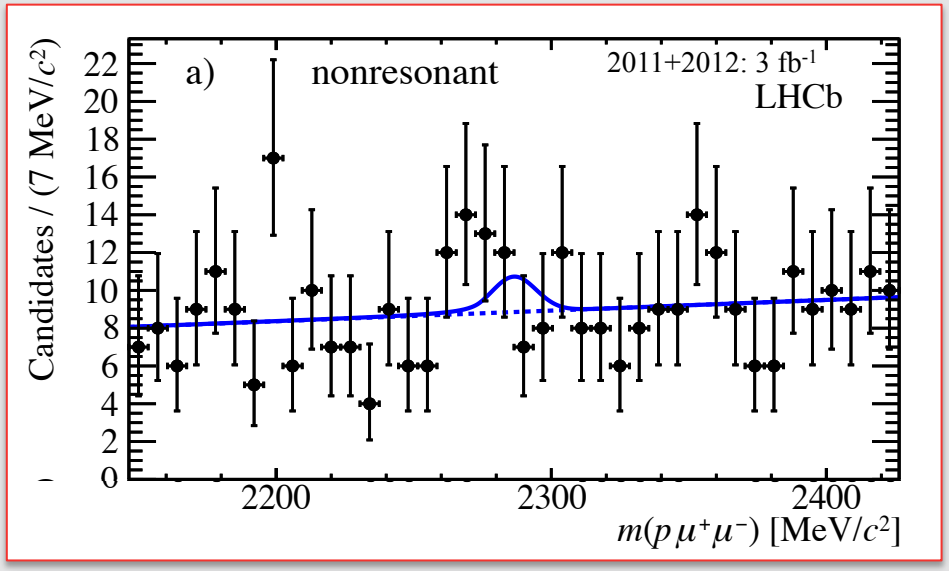
- Added Run-2 for angular analysis
  - All asymmetries consistent with zero

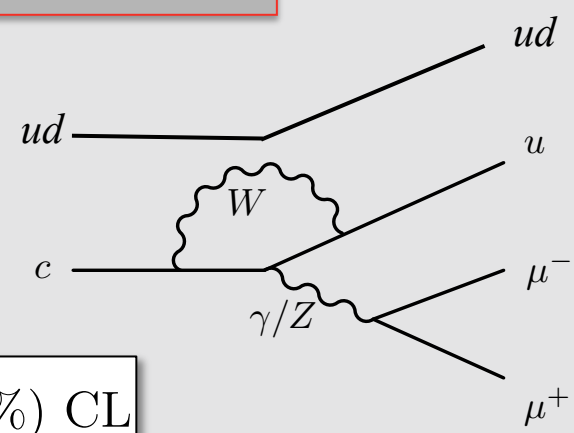
Charm: $\Lambda_c^+ \to p\mu^+\mu^-$

- Interesting region:
  - Non-resonant m($\mu^+\mu^-$) region
  - exclude w(782) and φ(1020) region



- No significant excess observed:



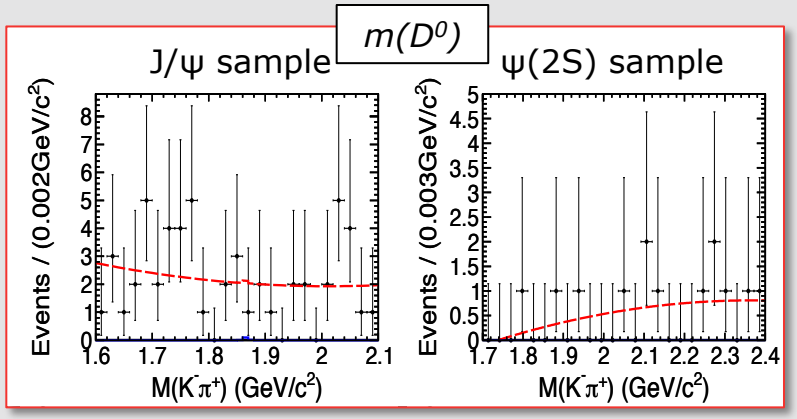


$$\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 7.7\ (9.6) \times 10^{-8} \quad \text{at} \quad 90\%\ (95\%)\ \text{CL}$$

LHCb, PRD 97 (2018) 091101, arXiv:1712.07938

Charm: $\psi \to D^0 e^+ e^-$ and $D \to h(h) e^+ e^-$ at BESIII

- $\psi \to D^0 p e^+ e^-$ No significant excess observed:



$$\mathcal{B}(J/\psi \to D^0 e^+ e^-) < 8.5 \times 10^{-8}$$
$$\mathcal{B}(\psi(3686) \to D^0 e^+ e^-) < 1.4 \times 10^{-7}$$

BESIII, Phys. Rev. D96,111101 (RC) (2017)

- Many searches at BESIII:
  - $\psi(2S) \to \Lambda_c^+ p e^+ e^-$

$$B(\psi(2S) \to \Lambda_c^+ p e^+ e^-) < 1.7 \times 10^{-6} (90\% \text{ CL})$$

BESIII, Phys. Rev. D 97, 091102(RC)(2018)

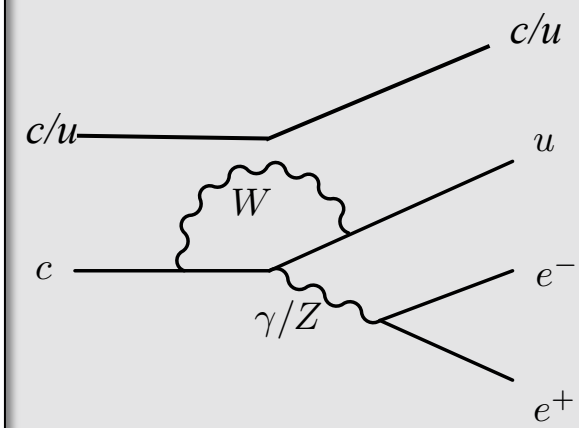
  - $D^0 \to h^+ h^- e^+ e^-$
  - $D^+ \to h^+ e^+ e^-$

BESIII, Preliminary

	$\mathcal{B}[\times 10^{-6}]$
$D^+ \to K^+ e^+ e^-$	< 1.2
$D^+ \to K^- e^+ e^+$	< 0.6
$D^+ \to \pi^+ e^+ e^-$	< 0.3
$D^+ \to \pi^- e^+ e^+$	< 1.2

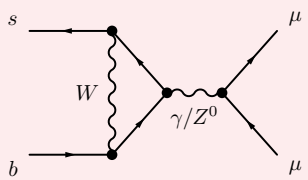
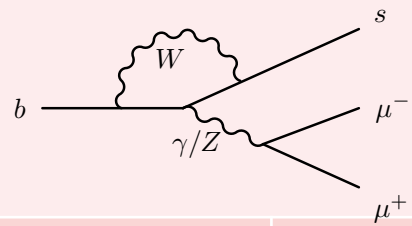
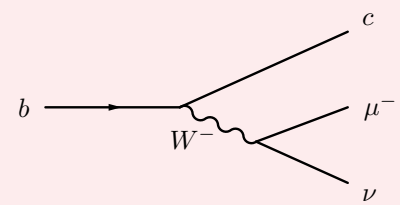
BESIII, Phys. Rev. D 97, 072015 (2018)

Signal decays	$\mathcal{B}$ ($\times 10^{-5}$)
$D^+ \to \pi^+ \pi^0 e^+ e^-$	<1.4
$D^+ \to K^+ \pi^0 e^+ e^-$	<1.5
$D^+ \to K_S^0 \pi^+ e^+ e^-$	<2.6
$D^+ \to K_S^0 K^+ e^+ e^-$	<1.1
$D^0 \to K^- K^+ e^+ e^-$	<1.1
$D^0 \to \pi^+ \pi^- e^+ e^-$	<0.7
$D^0 \to K^- \pi^+ e^+ e^{-\dagger}$	<4.1
$D^0 \to \pi^0 e^+ e^-$	<0.4
$D^0 \to \eta e^+ e^-$	<0.3
$D^0 \to \omega e^+ e^-$	<0.6
$D^0 \to K_S^0 e^+ e^-$	<1.2
† in $M_{e^+e^-}$ regions:	
$[0.00, 0.20)$ GeV/c^2	<3.0 $(1.5^{+1.0}_{-0.9})$
$[0.20, 0.65)$ GeV/c^2	<0.7
$[0.65, 0.90)$ GeV/c^2	<1.9 $(1.0^{+0.5}_{-0.4})$



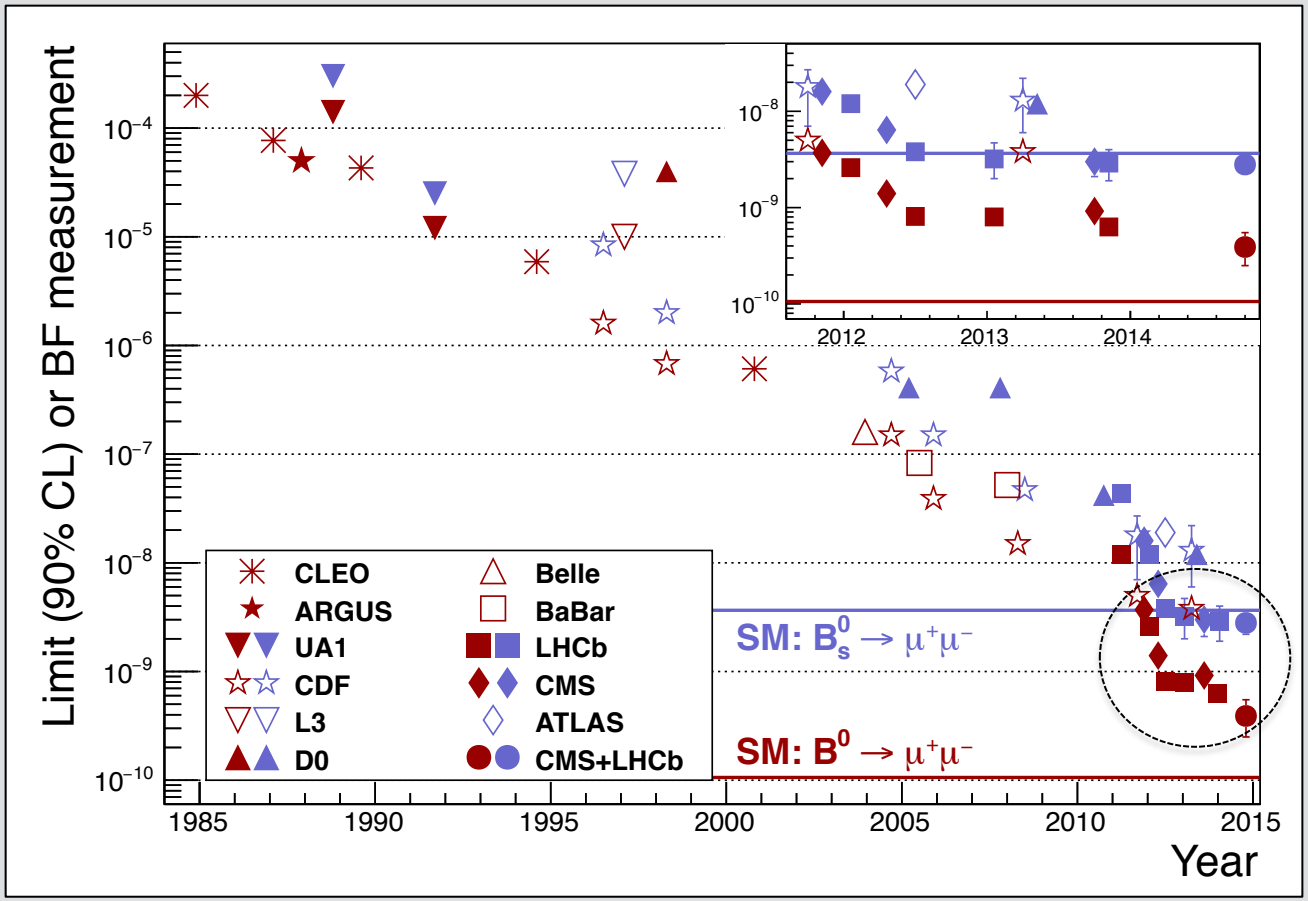
Non-resonant, short distance

Outline

	Flavour Changing Neutral Current			
	Leptonic	**Mesonic**	**Baryonic**	**Semi-leptonic**
				
Strange	$K_S^0 \to \mu^+\mu^-$	$K^+ \to \pi^+\nu\nu$ $K^0 \to \pi^0\nu\nu$	$\Sigma^+ \to p\mu^+\mu^-$	
Charm	$D^0 \to \mu^+\mu^-$ $D^0 \to e^+\mu^-$	$D^0 \to h^+h^-\mu^+\mu^-$ $J/\psi \to D^0e^+e^-$	$\Lambda_c^+ \to p\mu^+\mu^-$	
Beauty	$B^0_{(s)} \to \mu^+\mu^-$ $B^0_{(s)} \to \tau^+\tau^-$ $B^0_{(s)} \to e^+\mu^-$	$B^0 \to K^{(*)}\mu^+\mu^-/e^+e^-$ $B^+ \to K^{(*)}\mu^+\mu^-/e^+e^-$ $B^0_s \to \varphi\mu^+\mu^-$ $B^0_s \to K^*\mu^+\mu^-$	$\Lambda_b \to \Lambda\,\mu^+\mu^-$	$B^0 \to D^{(*)}\mu^+\nu\,/\,\tau^+\nu$ $B_c^+ \to J/\psi\mu^+\nu\,/\,\tau^+\nu$

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

- Historical endeavour!

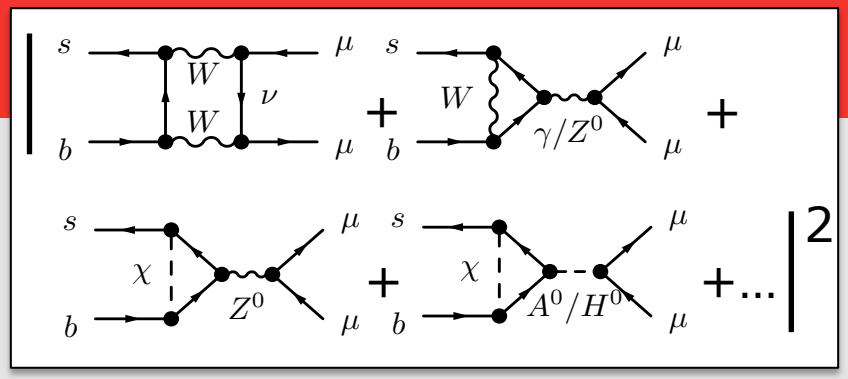


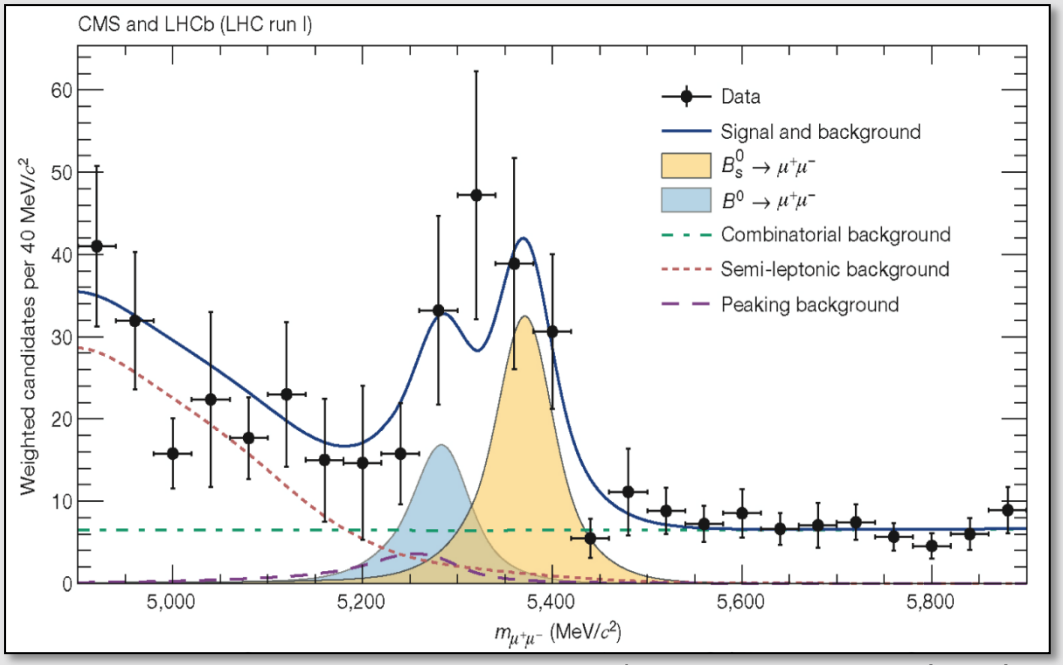
CMS & LHCb, Nature 522, 68–72 (2015)

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

- *"Golden channel for SUSY"*

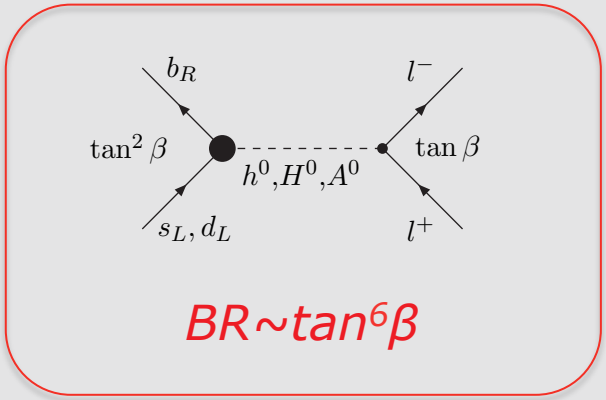
- Decay discovered in 2015





CMS & LHCb, Nature 522, 68–72 (2015)

$$\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-) = \left(2.8\,^{+0.7}_{-0.6}\right) \times 10^{-9}$$
$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = \left(3.9\,^{+1.6}_{-1.4}\right) \times 10^{-10}$$

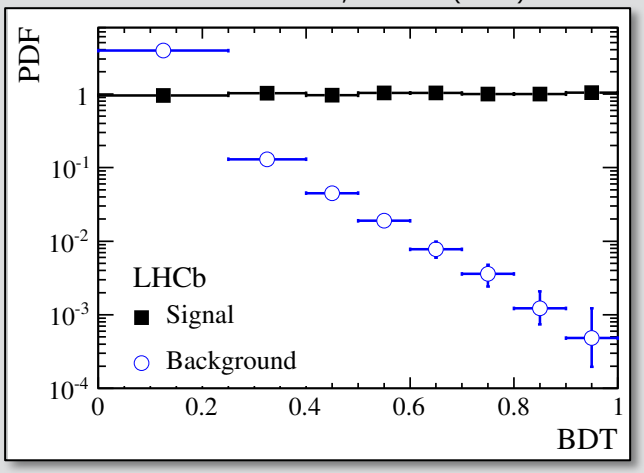


A.Buras et al., Nucl.Phys.B659 (2003) 3

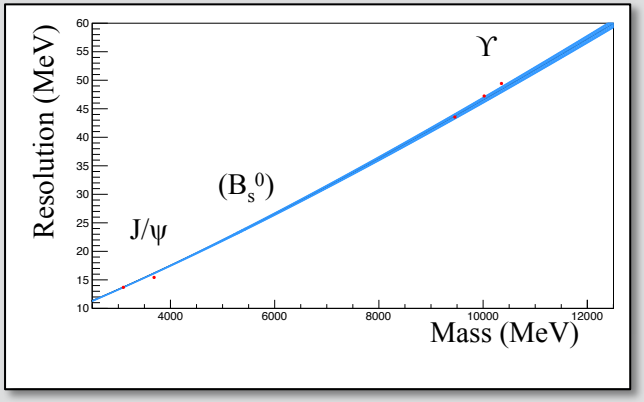
$B^0_{(s)} \to \mu^+\mu^-$

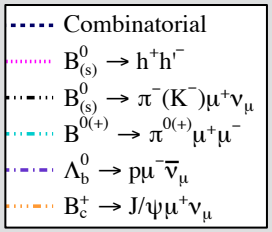
- Challenge: huge amount of events with two muons!
  - Background: BR($B \to X\mu^+$) = 10^{-1}
  - Signal: BR($B_s^0 \to \mu^+\mu^-$) < 10^{-8}

LHCb, PRL 111 (2013) 101805



- Analysis largely data driven:
  - BDT event selection
    - Mainly lifetime
    - Calibrate efficiency on data with $B \to \pi\pi$ decays
  - Mass resolution
    - Interpolate between $J/\psi \to \mu\mu$ and $\Upsilon \to \mu\mu$
  - Backgrounds
    - $b \to \mu + b \to \mu$
    - Semileptonic B^0, B_s^0, B_c^+ and Λ_b^0 decays
    - Misidentified $B \to \pi\pi$





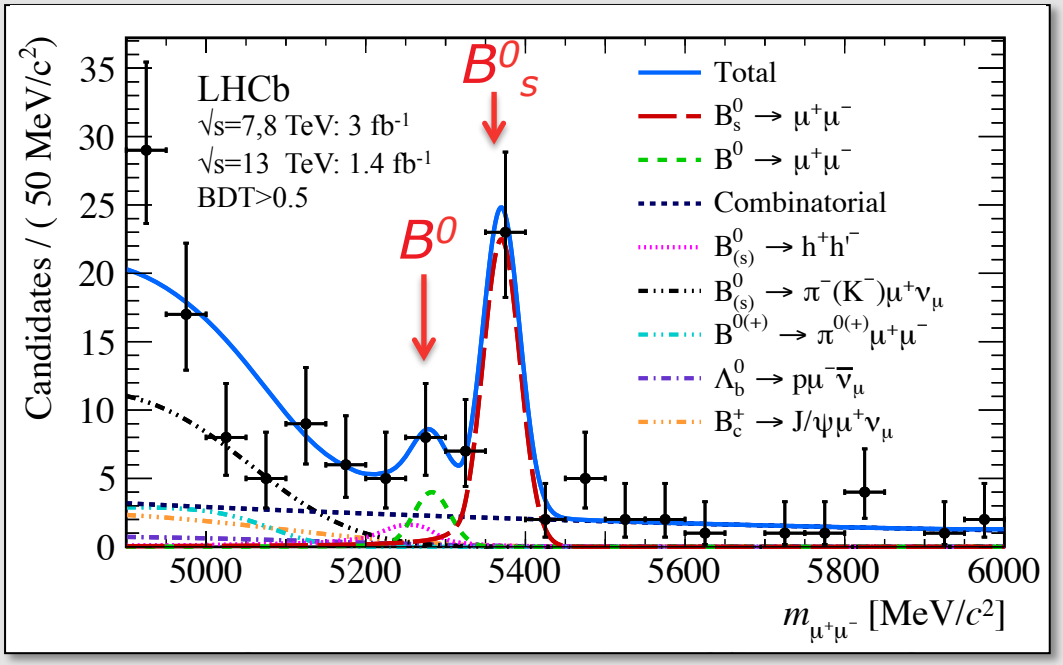
- Largest systematic uncertainty:
  - Relative production of B_s^0 wrt B^0 mesons, f_s/f_d

LHCb coll., JHEP04 (2013) 001
LHCb coll., PRD85 (2012) 032008
Fleischer, Serra, NT, PRD 82, 034038

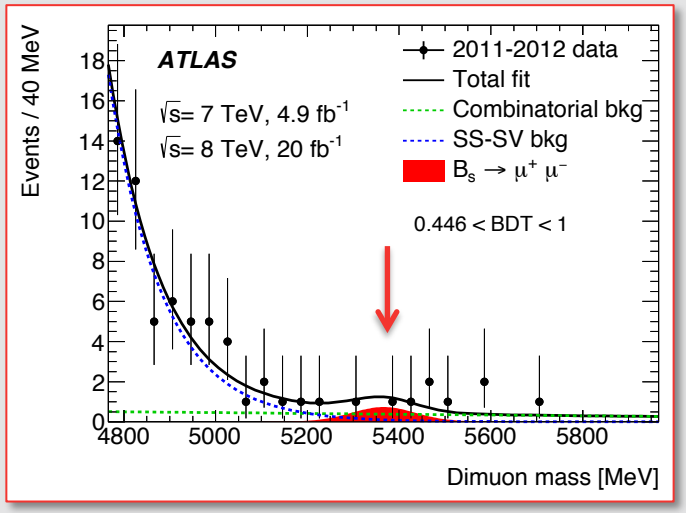
$B^0_{(s)} \rightarrow \mu^+\mu^-$: Update 2017

- *"Golden channel for SUSY"*

- Update 2017 with 1.4 fb^{-1} Run-2
  - 7.8σ significance



LHCb, PRL 118 (2017) 191801, arXiv:1703.05747



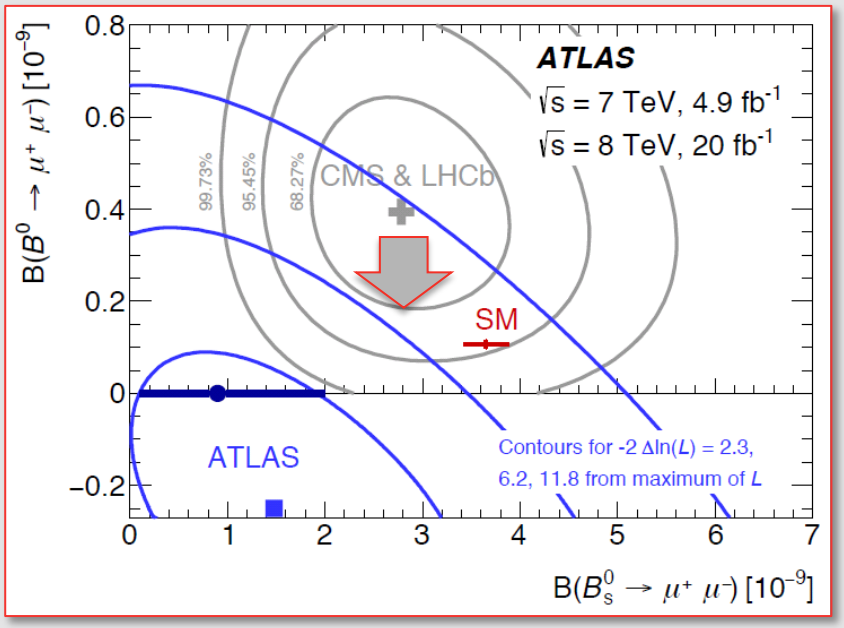
ATLAS, EPJ C76 (2016) 513

$$B\left(B_s^0 \rightarrow \mu^+\mu^-\right) = \left(3.0 \pm 0.6^{+0.3}_{-0.2}\right) \times 10^{-9}$$

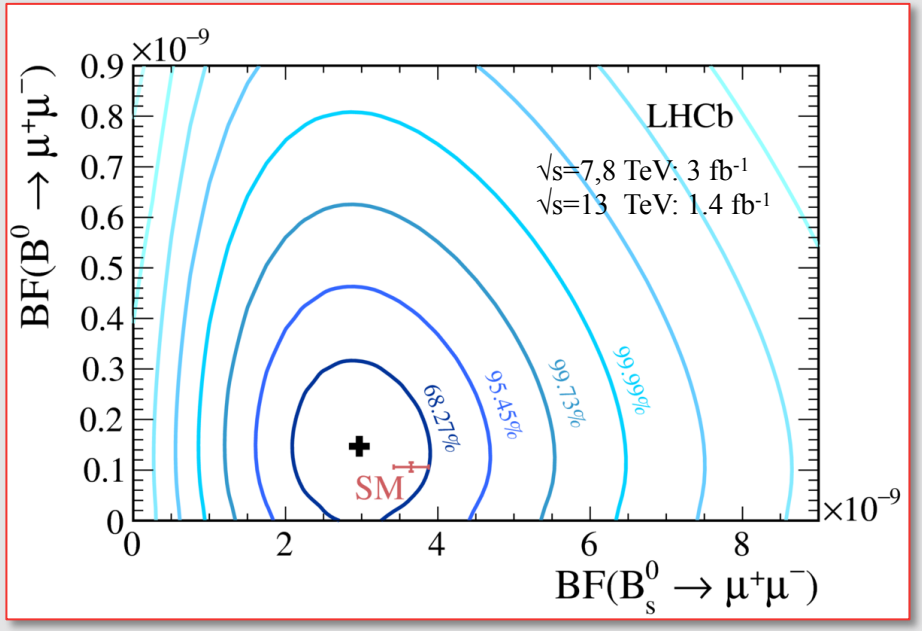
$$B\left(B^0 \rightarrow \mu^+\mu^-\right) < 3.4 \times 10^{-10} (95\%CL)$$

$B^0 \rightarrow \mu^+\mu^-$ and $B^0_s \rightarrow \mu^+\mu^-$: Update 2017

- BR($B^0 \rightarrow \mu\mu$): the next search
  - 1.6σ above SM prediction



ATLAS, EPJ C76 (2016) 513

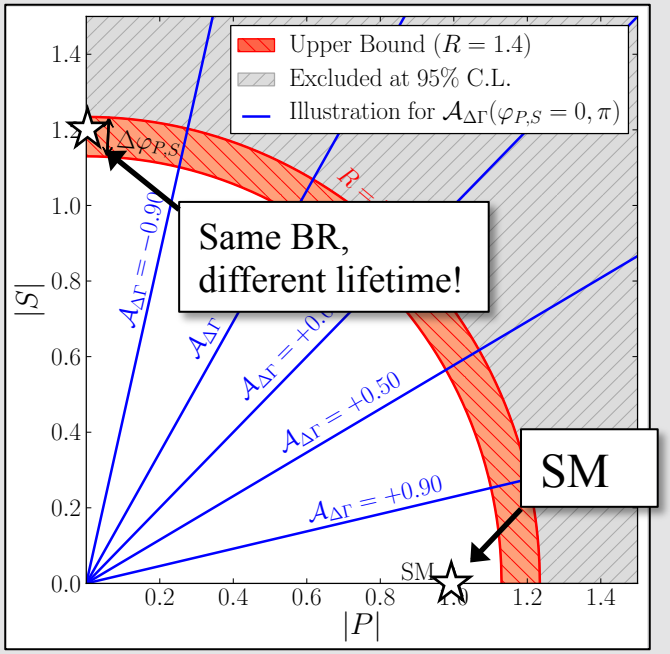


LHCb, PRL 118 (2017) 191801, arXiv:1703.05747

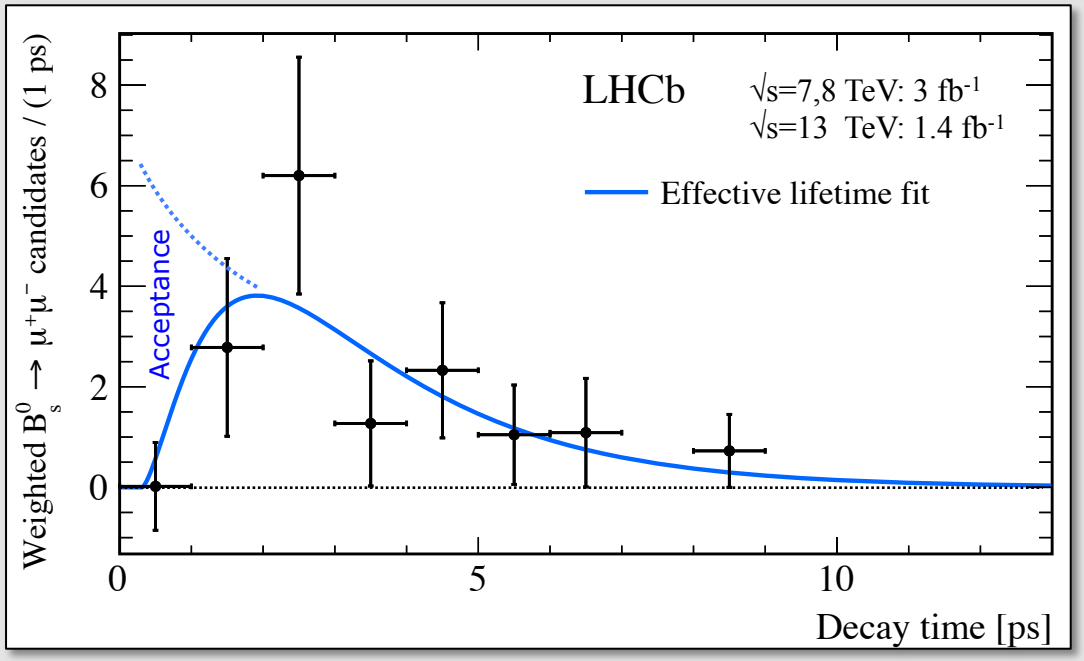
$B^0_s \rightarrow \mu^+\mu^-$: effective lifetime

- More observables accessible
- New Physics (i.e. scalar couplings) can lead to different CP structure of final state
  - Affects the mix of long and short-living B_s^0 mesons

$$\tau(B_s^0 \rightarrow \mu^+\mu^-) = 2.04 \pm 0.44 \pm 0.05\,\text{ps}$$



De Bruyn, Fleischer, NT, et al., PRL109 (2012) 041801

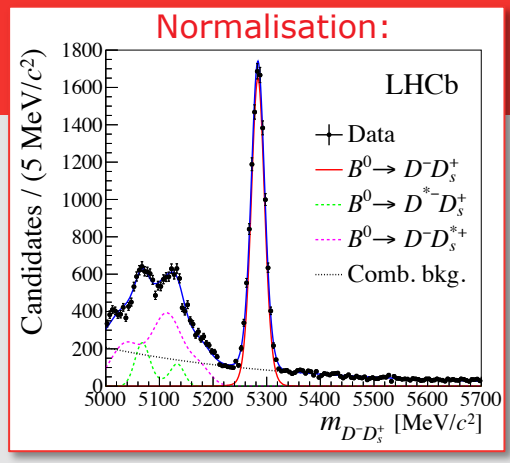


LHCb, PRL 118 (2017) 191801

$B^0_s \to \tau^+\tau^-$: First limit

- Analogous to $B^0_s \to \mu^+\mu^-$
- Helicity suppression less severe, BR x 200
- Enhanced by NP coupling to 3rd generation?

- Analysis:
  - Select $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$
  - Exploit intermediate $\rho^0 \to \pi^-\pi^+$
  - Normalisation $B^0 \to D_s^-\left(K^-K^+\pi^-\right)D^+\left(K^-\pi^+\pi^+\right)$



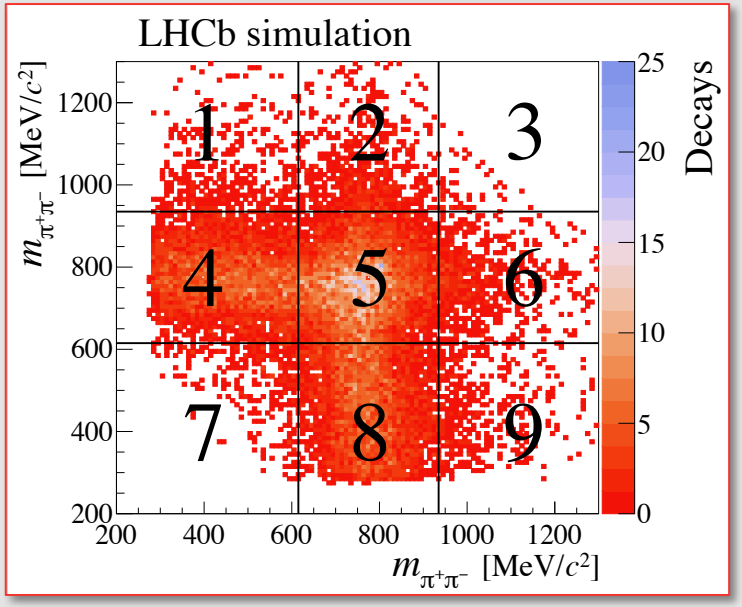
$$\text{LHCb: } B\left(B_s^0 \to \tau^+\tau^-\right) < 5.2\times10^{-3}(90\%\ \text{CL})$$

$$\text{LHCb: } B\left(B^0 \to \tau^+\tau^-\right) < 1.6\times10^{-3}(90\%\ \text{CL})$$

$$\text{BaBar: } B\left(B^0 \to \tau^+\tau^-\right) < 4.1\times10^{-3}(90\%\ \text{CL})$$

2011+2012: 3 fb^{-1}

BaBar, PRL 96 (2006) 241802



LHCb, PRL 118 (2017) 281802

$$\text{SM: } B\left(B_s^0 \to \tau^+\tau^-\right) = (7.7\pm0.5)\times10^{-7}$$

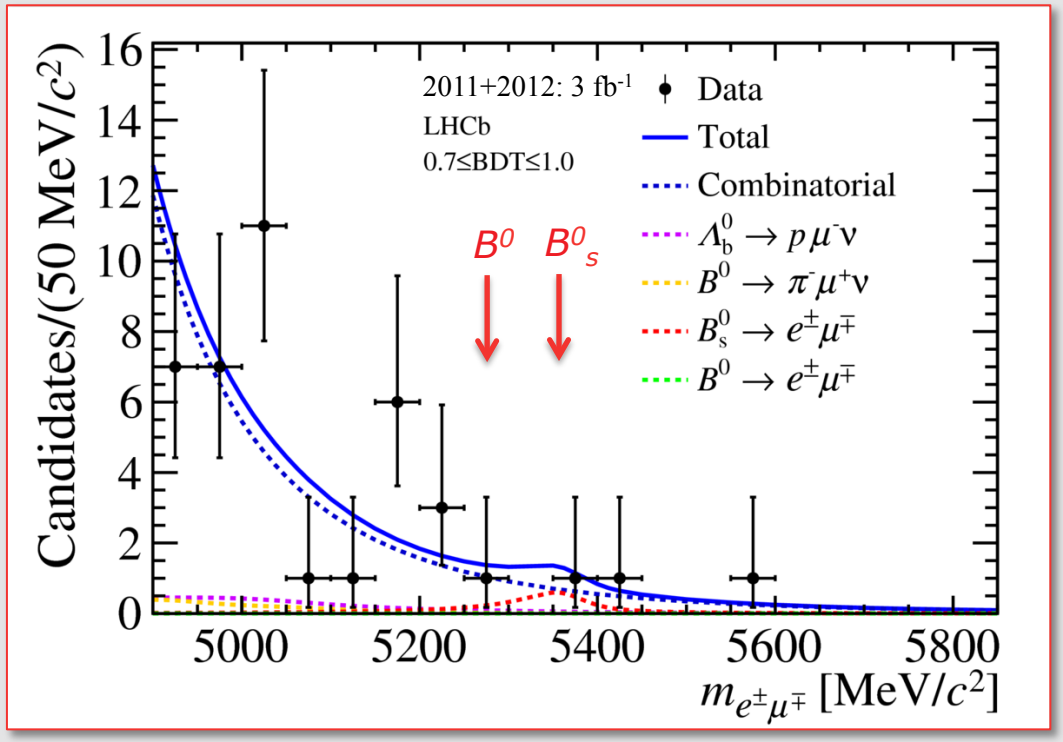
$$\text{SM: } B\left(B^0 \to \tau^+\tau^-\right) = (2.2\pm0.2)\times10^{-7}$$

Bobeth et al., PRL 112 (2014) 101801

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

- Lepton Flavour Violation?
- Forbidden in SM

$$B\left(B_s^0 \rightarrow e^+\mu^-\right) < 6.0 \times 10^{-9} (90\%\ \mathrm{CL})$$
$$B\left(B^0 \rightarrow e^+\mu^-\right) < 1.0 \times 10^{-9} (90\%\ \mathrm{CL})$$

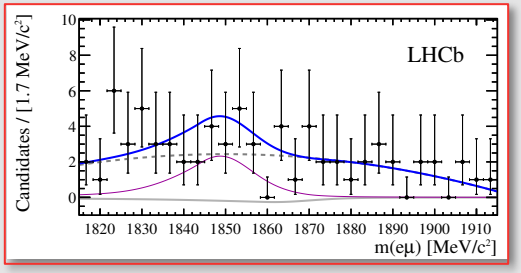


LHCb, JHEP 03 (2018) 078, arXiv:1710.04111

- $D^0 \rightarrow e^+\mu^-$
  - -7±15 events

$$\mathcal{B}(D^0 \rightarrow e^\pm\mu^\mp) < 1.3 \times 10^{-8} \text{ at } 90\%\ \mathrm{CL}$$

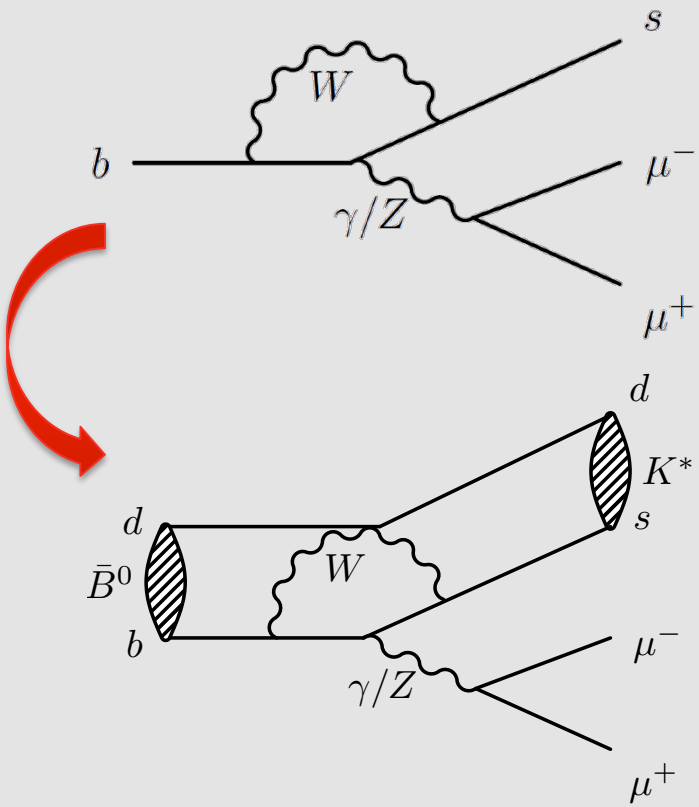
LHCb, Phys.Lett. B754 (2016) 167



See also next talk on charged lepoton flavour

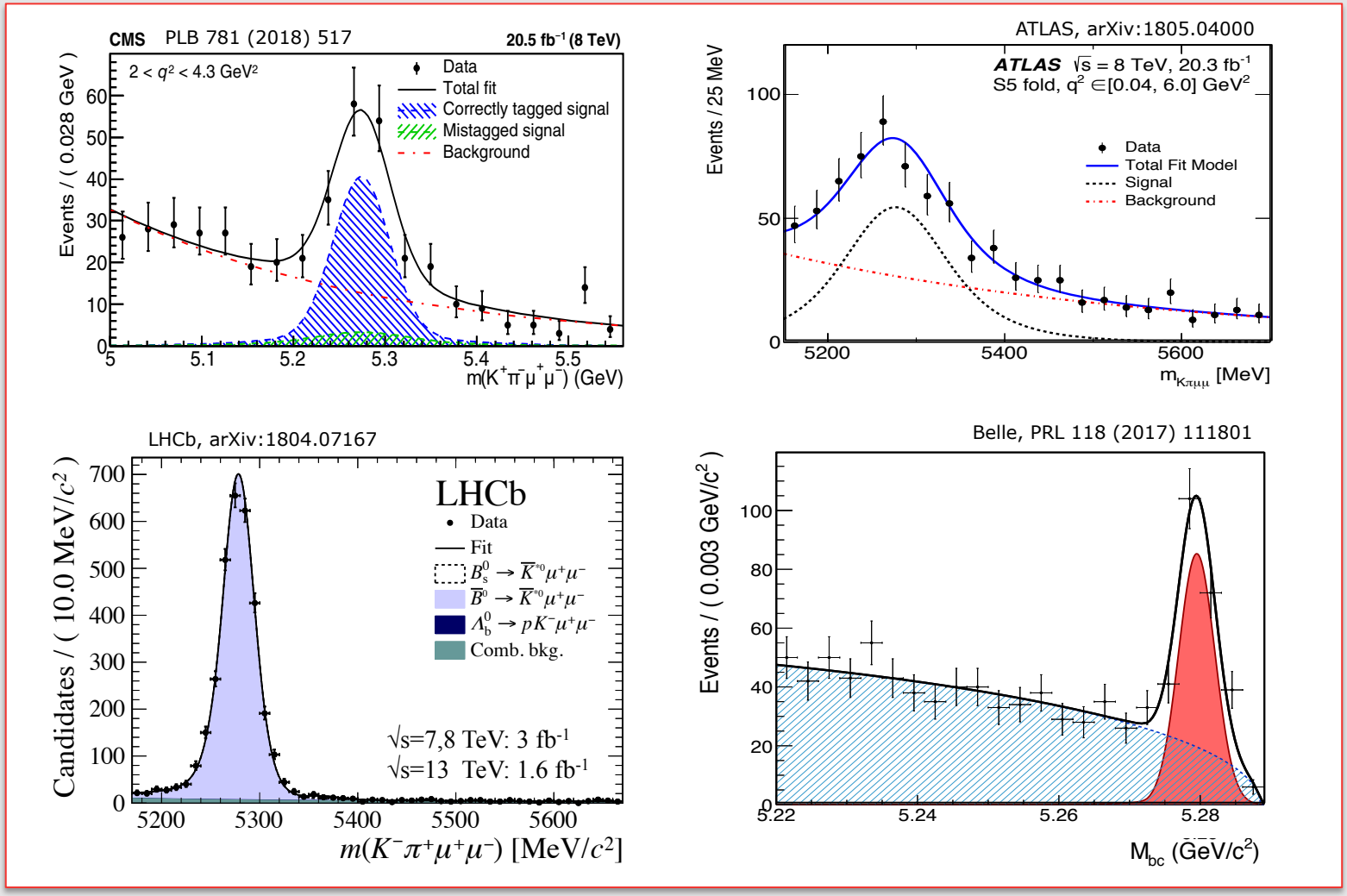
More Flavour Changing Neutral Currents: $B^0 \rightarrow K^* \mu\mu$

- Similar loop diagram!
- More observables
  - Invariant mass of μμ-pair
  - Angles of *K* and *μ*



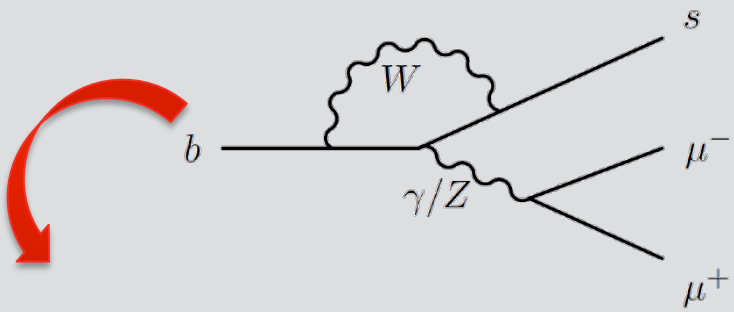
$B^0 \to K^*\mu^+\mu^-$: Joint effort

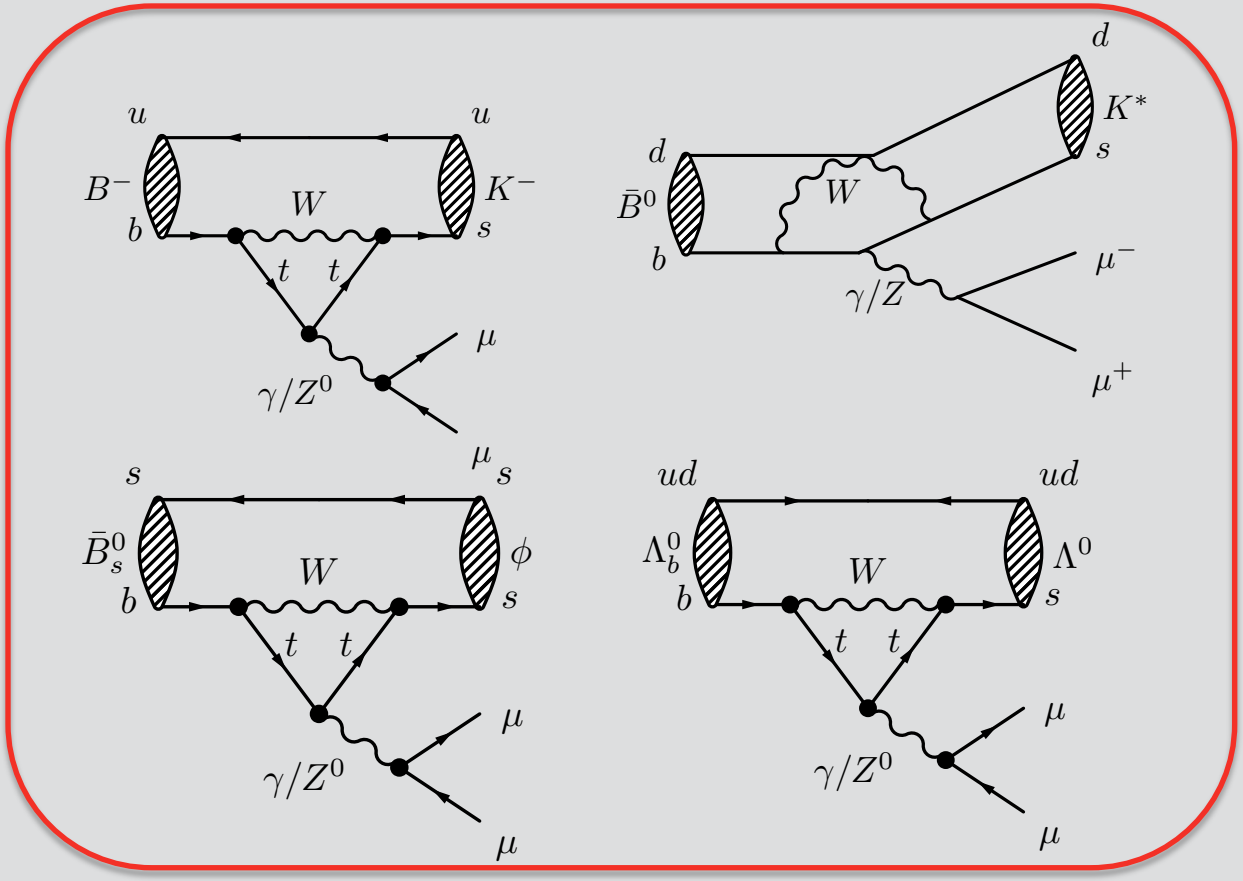
- Analysis efforts by Belle, LHCb, CMS, ATLAS



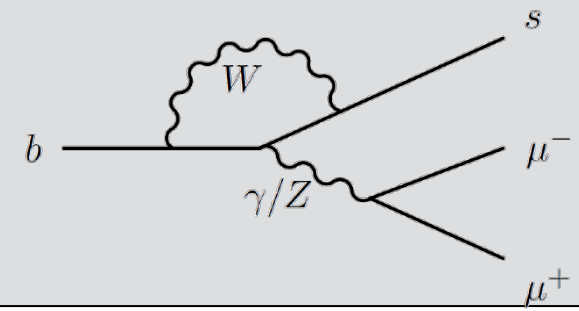
Decay rates: *b→ sll*

- Study same process with different hadrons:

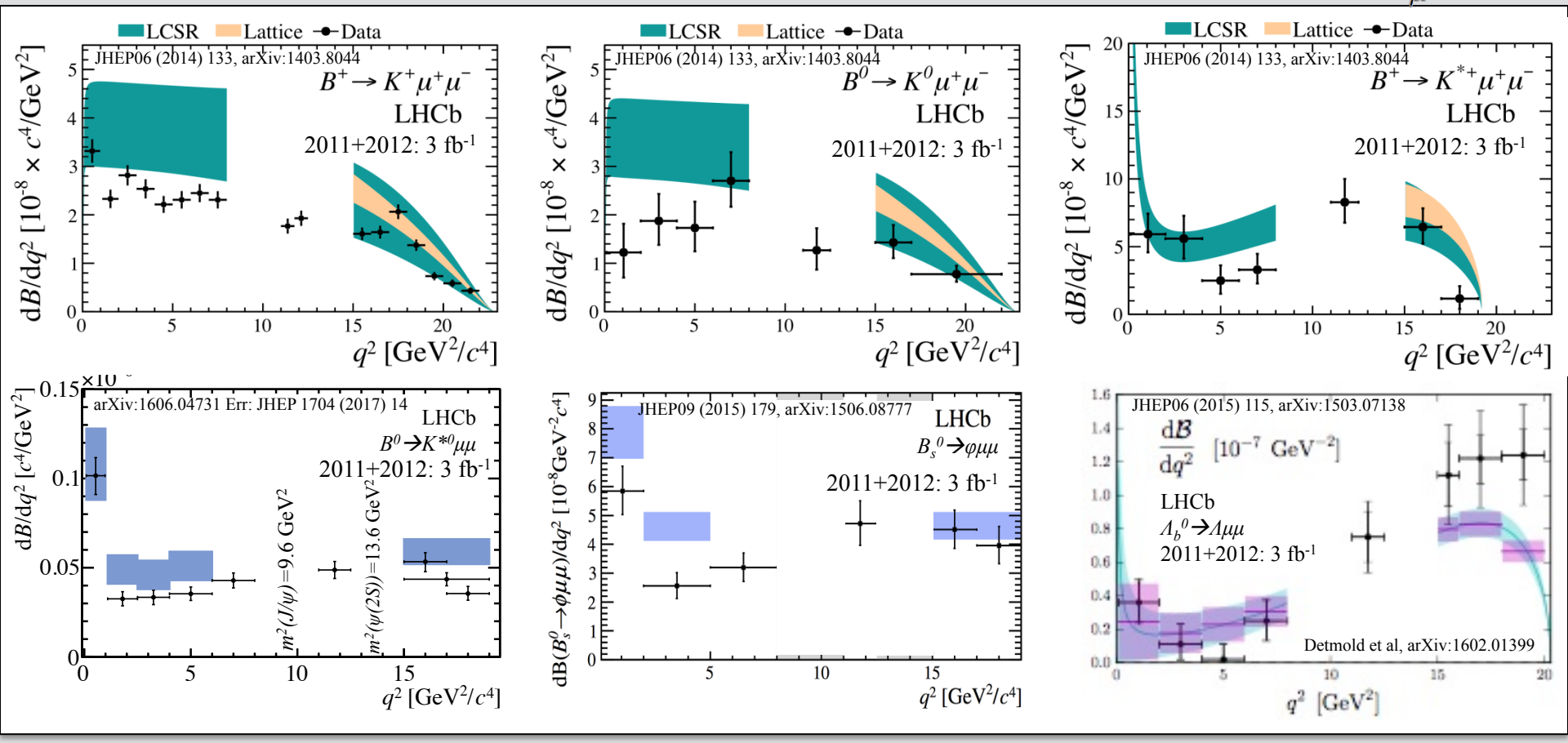




Decay rates: $b \to s ll$

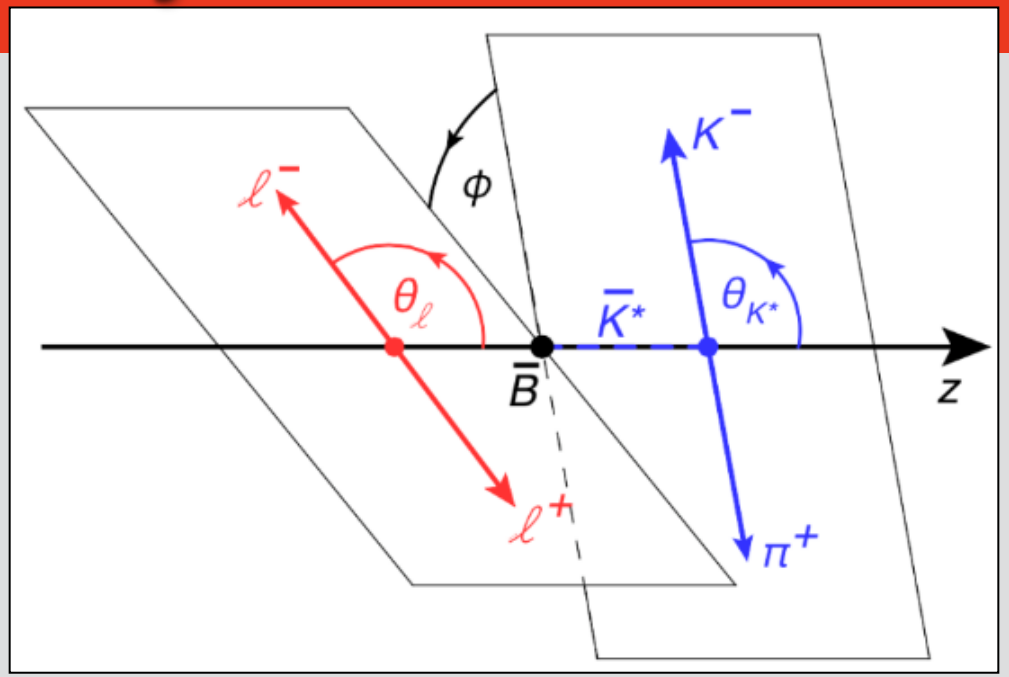


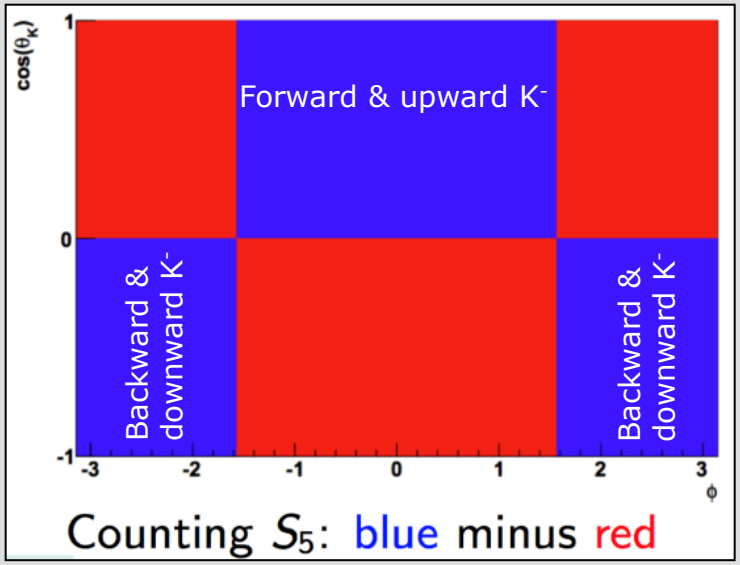
- Decay rate is consistently low:



$B^0 \rightarrow K^{0*}\mu^+\mu^-$: angular analysis

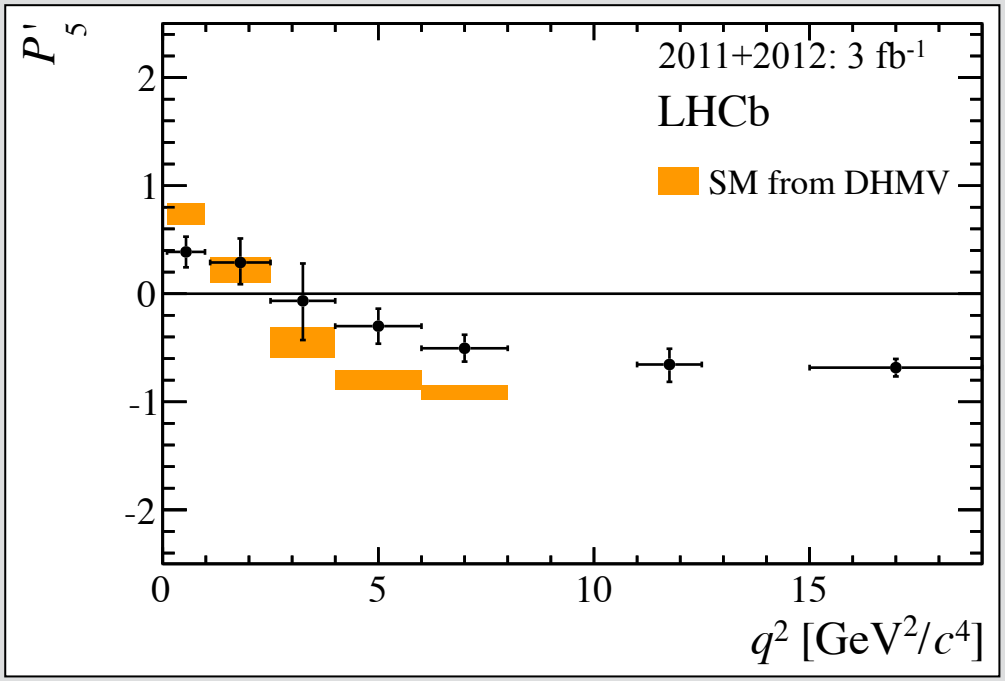
- Similar loop diagram!
- More observables
  - Invariant mass of μμ-pair
  - Angles of *K* and *μ*
- For example: P_5':
  - asymmetry of red and blue:
    - (corrected for $\sqrt{F_L(1-F_L)}$)





$B^0 \rightarrow K^{0*}\mu^+\mu^-$: P_5'

- Similar loop diagram!
- More observables
  - Invariant mass of μμ-pair
  - Angles of *K* and *μ*
- Debate on SM calculation
  - Non-perturbative "charm loop" effects?



LHCb, JHEP02 (2016) 104, arXiv:1512.04442

$B^0 \rightarrow K^{0*}\mu^+\mu^-$: P_5'

- Similar loop diagram!
- More observables
  - Invariant mass of μμ-pair
  - Angles of *K* and *μ*
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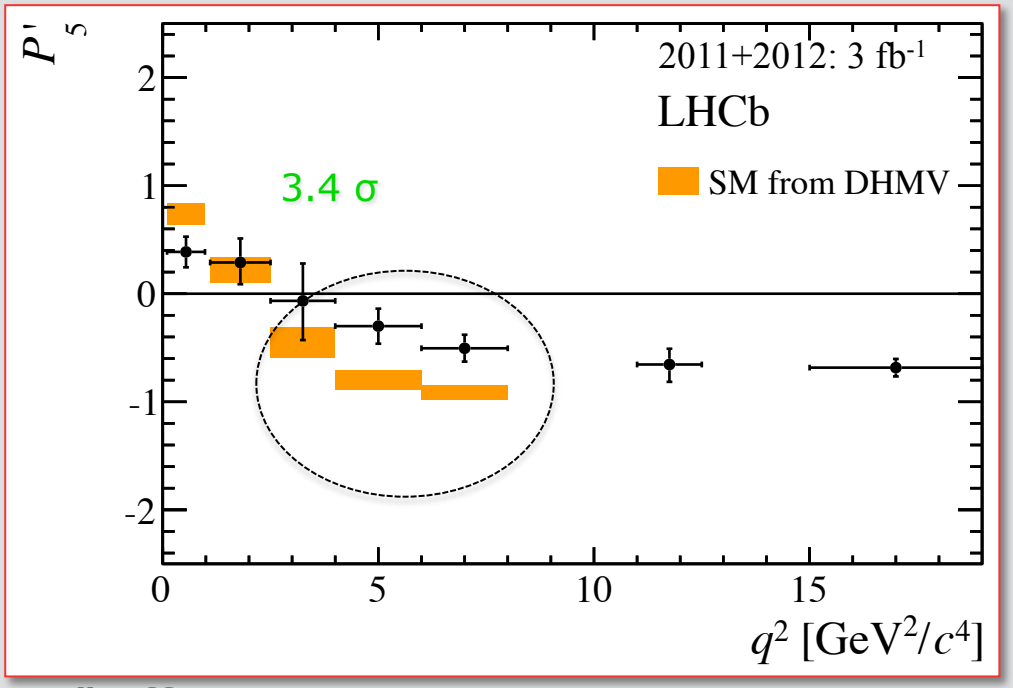
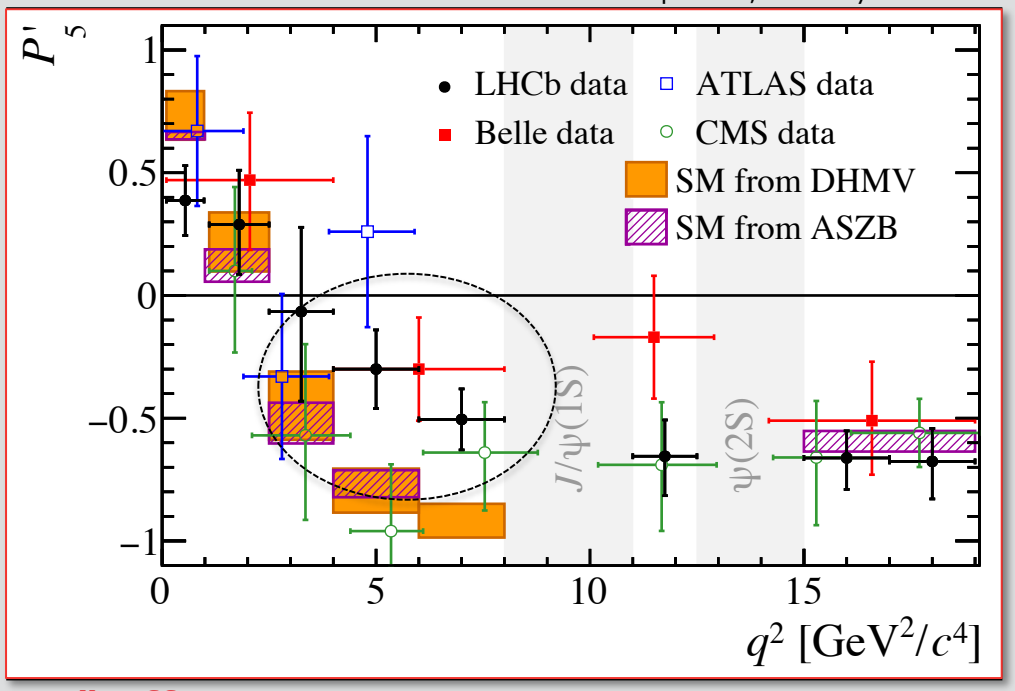


LHCb, JHEP02 (2016) 104, arXiv:1512.04442

$B^0 \rightarrow K^{0*}\mu^+\mu^-$: P_5' Joint effort!

- Similar loop diagram!
- More observables
  - Invariant mass of μμ-pair
  - Angles of *K* and *μ*
- Debate on SM calculation
  - Non-perturbative "charm loop" effects?

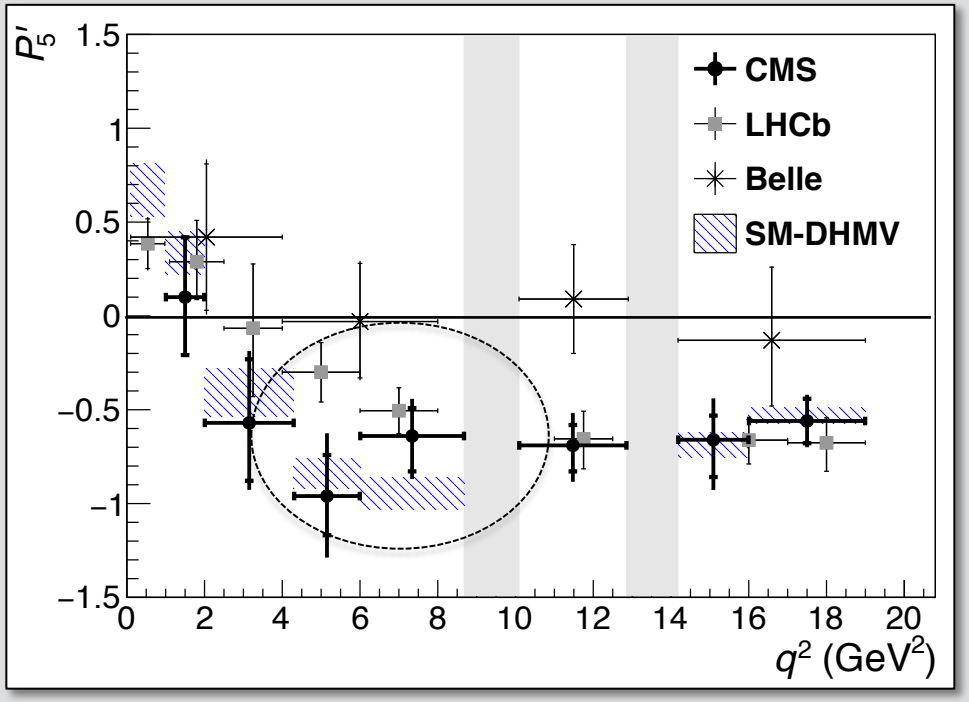
Private compilation, courtesy T. Blake



- LHCb, JHEP02 (2016) 104
- Belle, PRL 118 (2017) 111801
- ATLAS-CONF-2017-023
- CMS, PLB 81 (2018) 517

$B^0 \rightarrow K^{0*}\mu^+\mu^-$: P_5' Joint effort!

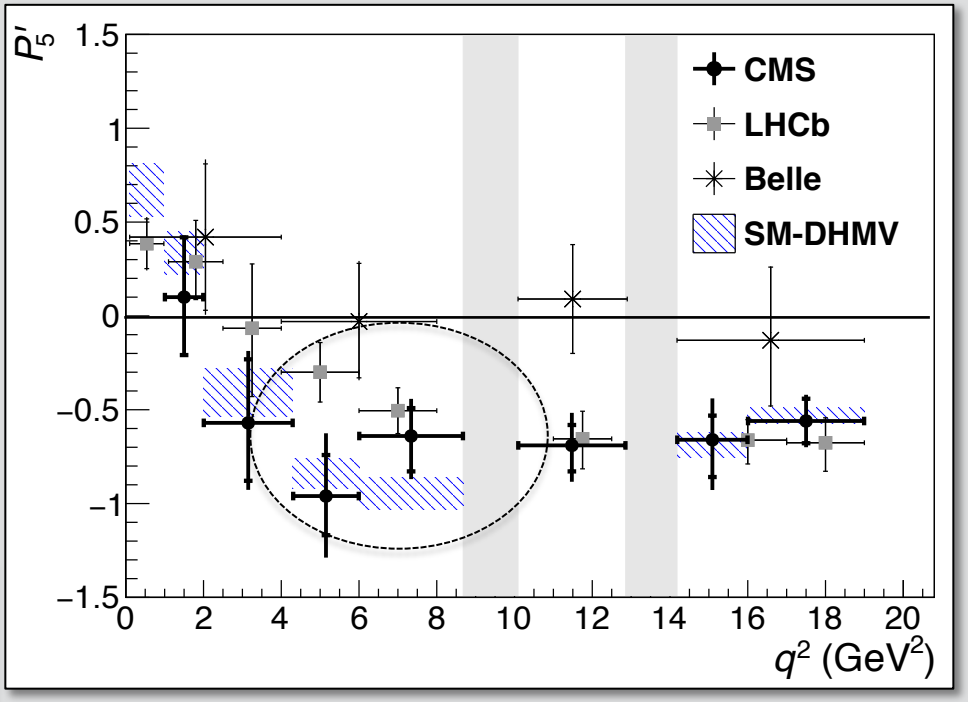
- Similar loop diagram!
- More observables
  - Invariant mass of μμ-pair
  - Angles of *K* and *μ*
- Debate on SM calculation
  - Non-perturbative "charm loop" effects?



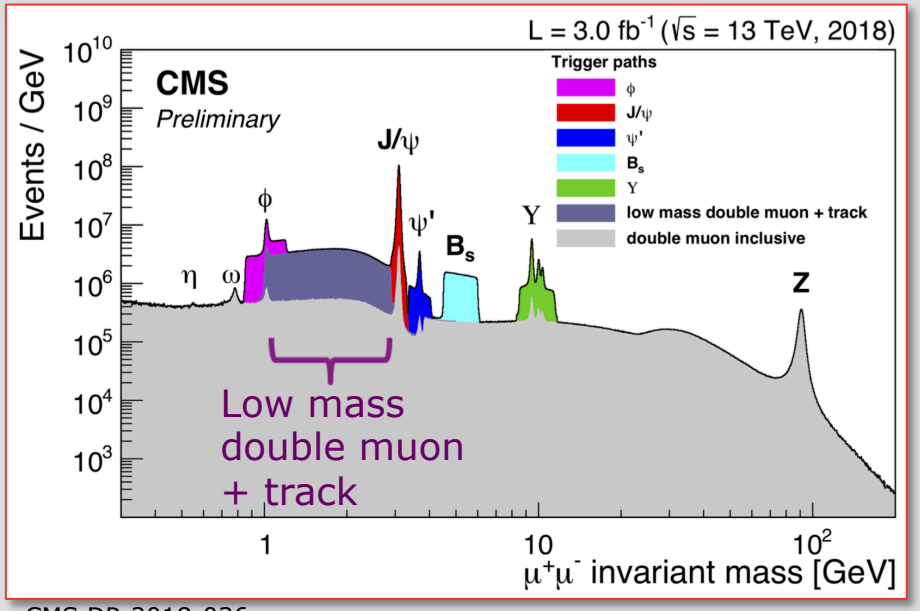
● CMS, PLB 781 (2018) 517
■ LHCb, JHEP02 (2016) 104
✧ Belle, PRL 118 (2017) 111801

$B^0 \rightarrow K^{0*}\mu^+\mu^-$: P_5' Joint effort!

- Similar loop diagram!
- More observables
  - Invariant mass of μμ-pair
  - Angles of *K* and *μ*



● CMS, PLB 781 (2018) 517
■ LHCb, JHEP02 (2016) 104
✧ Belle, PRL 118 (2017) 111801



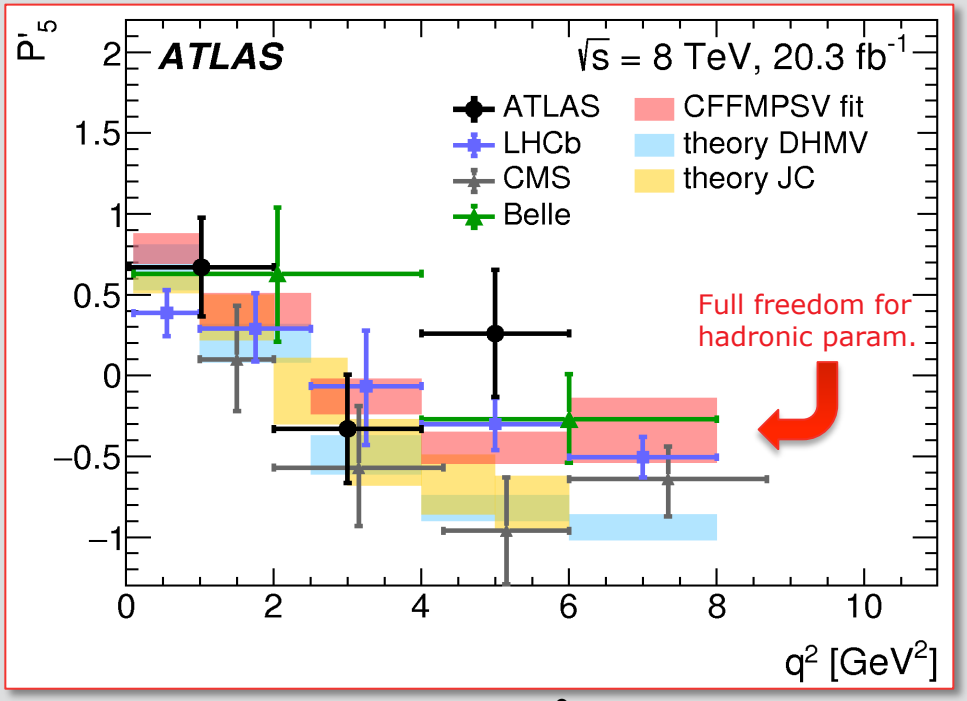
CMS DP-2018-036

- CMS: Dedicated trigger is collecting larger statistics!

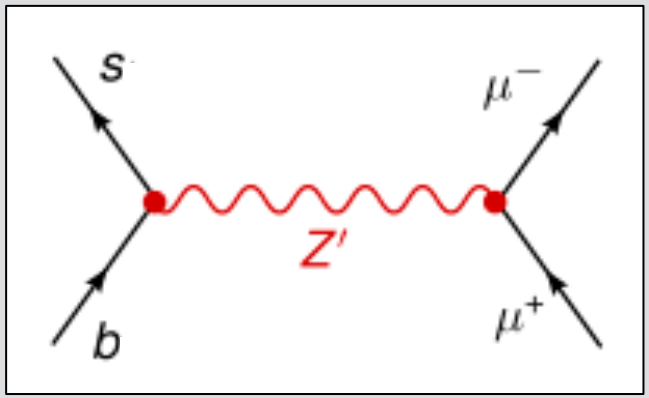
CMS DP-2016/059

$B^0 \rightarrow K^{0*}\mu^+\mu^-$: P_5'

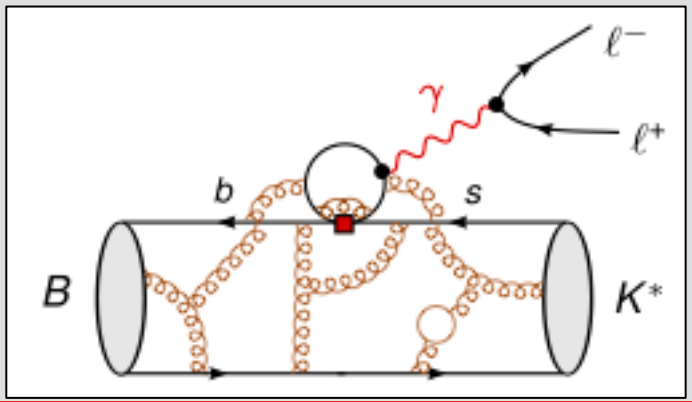
- Similar loop diagram!
- More observables
  - Invariant mass of μμ-pair
  - Angles of *K* and *μ*
- Debate on SM calculation
  - Non-perturbative "charm loop" effects?



- ATLAS, arXiv:1805.04000
- LHCb, JHEP02 (2016) 104
- Belle, PRL 118 (2017) 111801



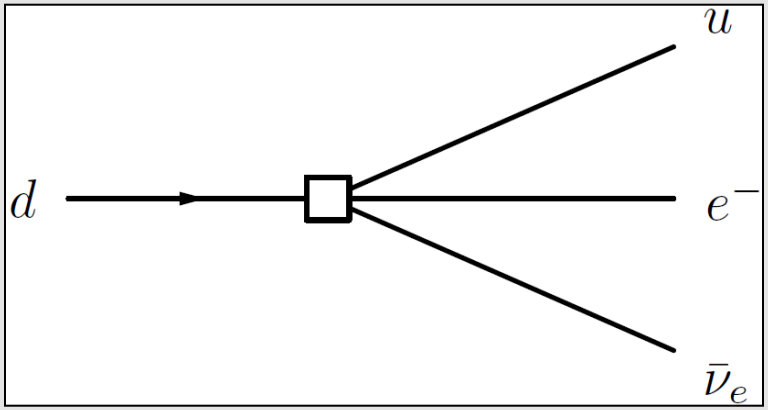
or

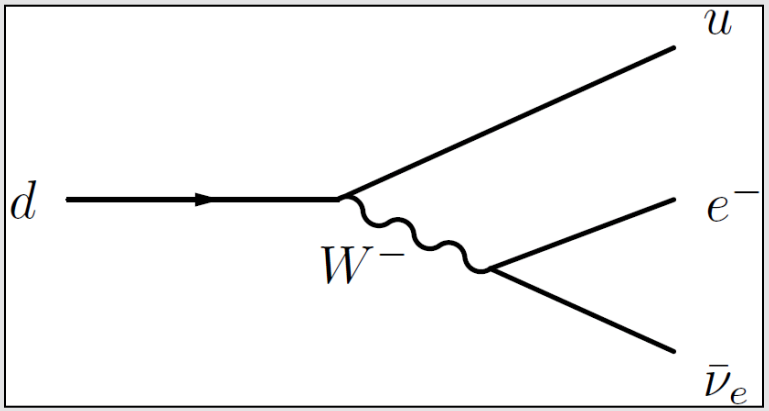


?

Intermezzo: Effective couplings

- Historical example



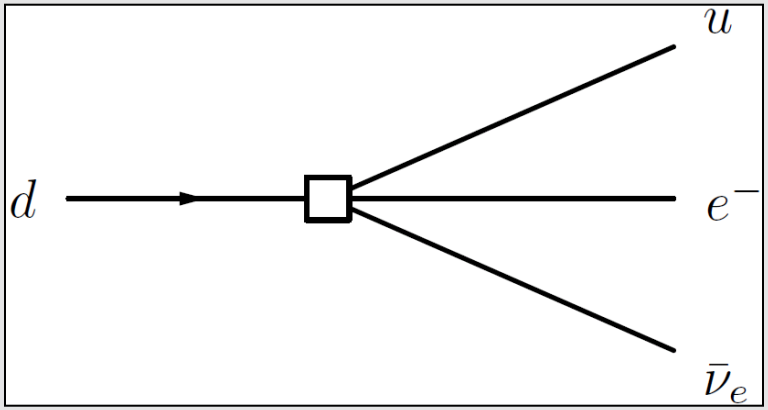


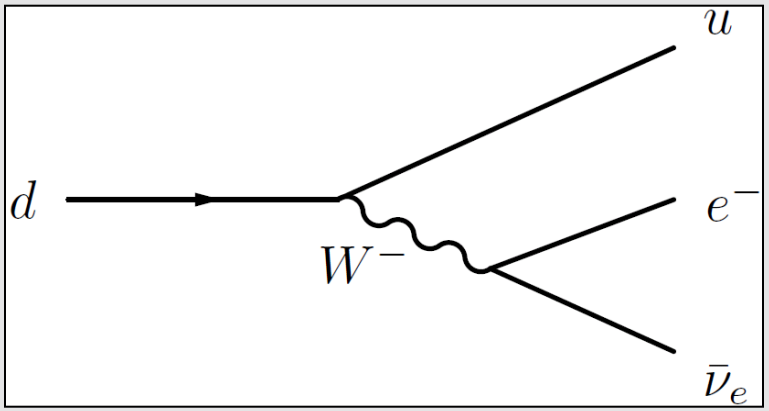
$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$

- Both are correct, depending on the energy scale you consider

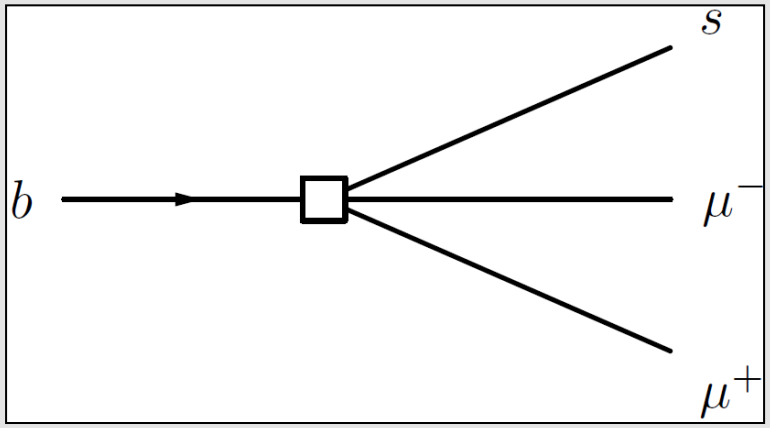
Intermezzo: Effective couplings

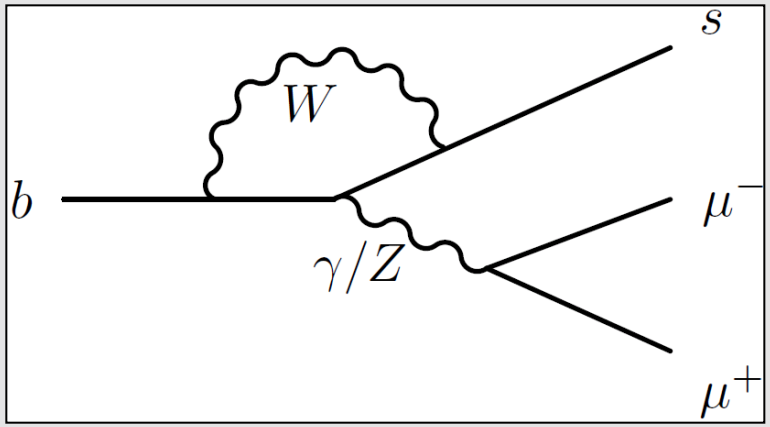
- Historical example





- Analog: Flavour-changing neutral current



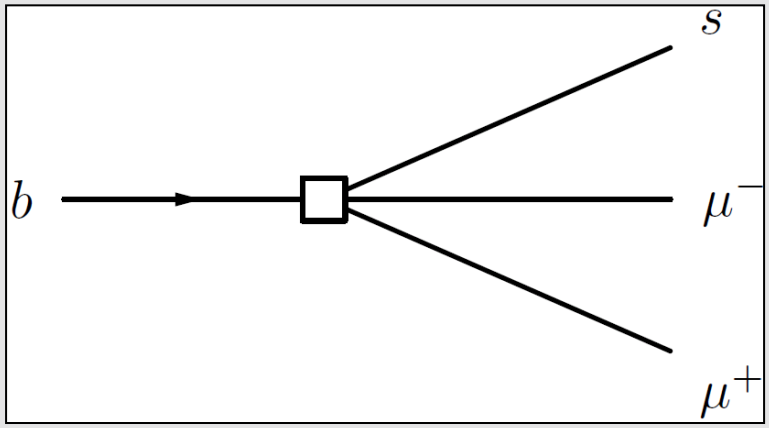


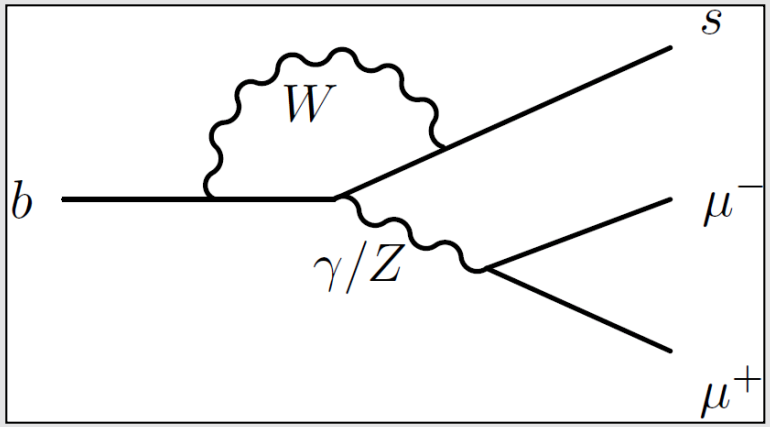
Intermezzo: Effective couplings

- Effective coupling can be of various "kinds"
  - Vector coupling
  - Axial coupling
  - Left-handed coupling (V-A)
  - Right-handed (to quarks)
  - …

$$\mathcal{H}_{\text{eff}} = \frac{G_{\text{F}}}{\sqrt{2}} V_{\text{CKM}} \sum_i C_i(\mu) Q_i$$

- Analog: Flavour-changing neutral current





Intermezzo: Effective couplings

- Effective coupling can be of various "kinds"
  - Vector coupling: C_9
  - Axial coupling: C_{10}
  - Left-handed coupling (V-A): C_9-C_{10}
  - Right-handed (to quarks): C_9', C_{10}', …
  - …

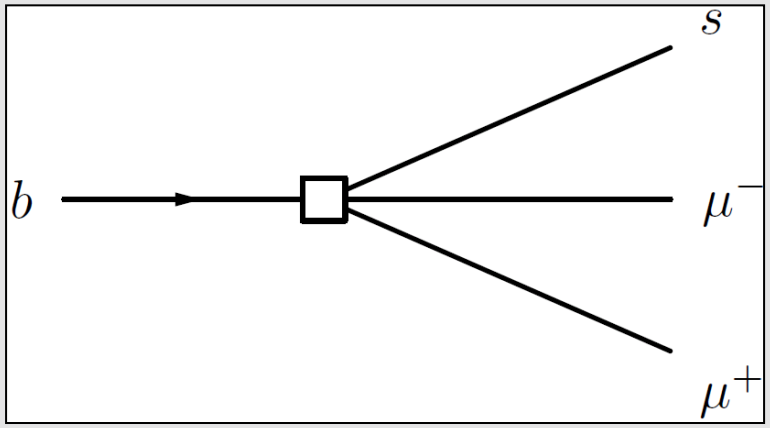
$$\mathcal{H}_{\rm eff} = \frac{G_{\rm F}}{\sqrt{2}} V_{\rm CKM} \sum_i C_i(\mu) Q_i$$

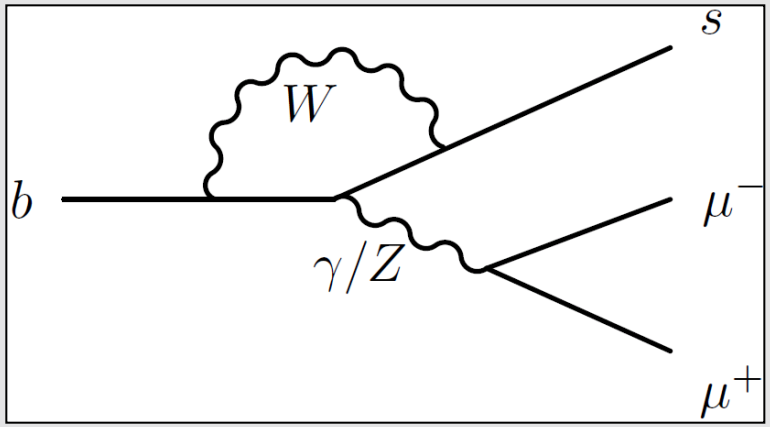
See e.g. Buras & Fleischer, hep-ph/9704376

Semi–Leptonic Operators (fig. 11f):

$$Q_{9V} = (\bar{s}b)_{V-A}(\bar{\mu}\mu)_V \qquad Q_{10A} = (\bar{s}b)_{V-A}(\bar{\mu}\mu)_A$$

- Analog: Flavour-changing neutral current





Intermezzo: Effective couplings

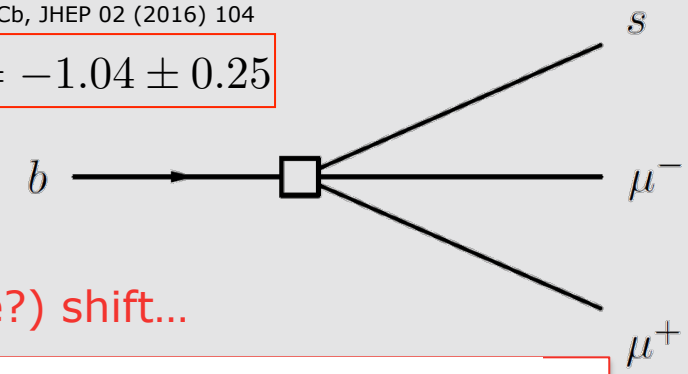
Model independent fits:

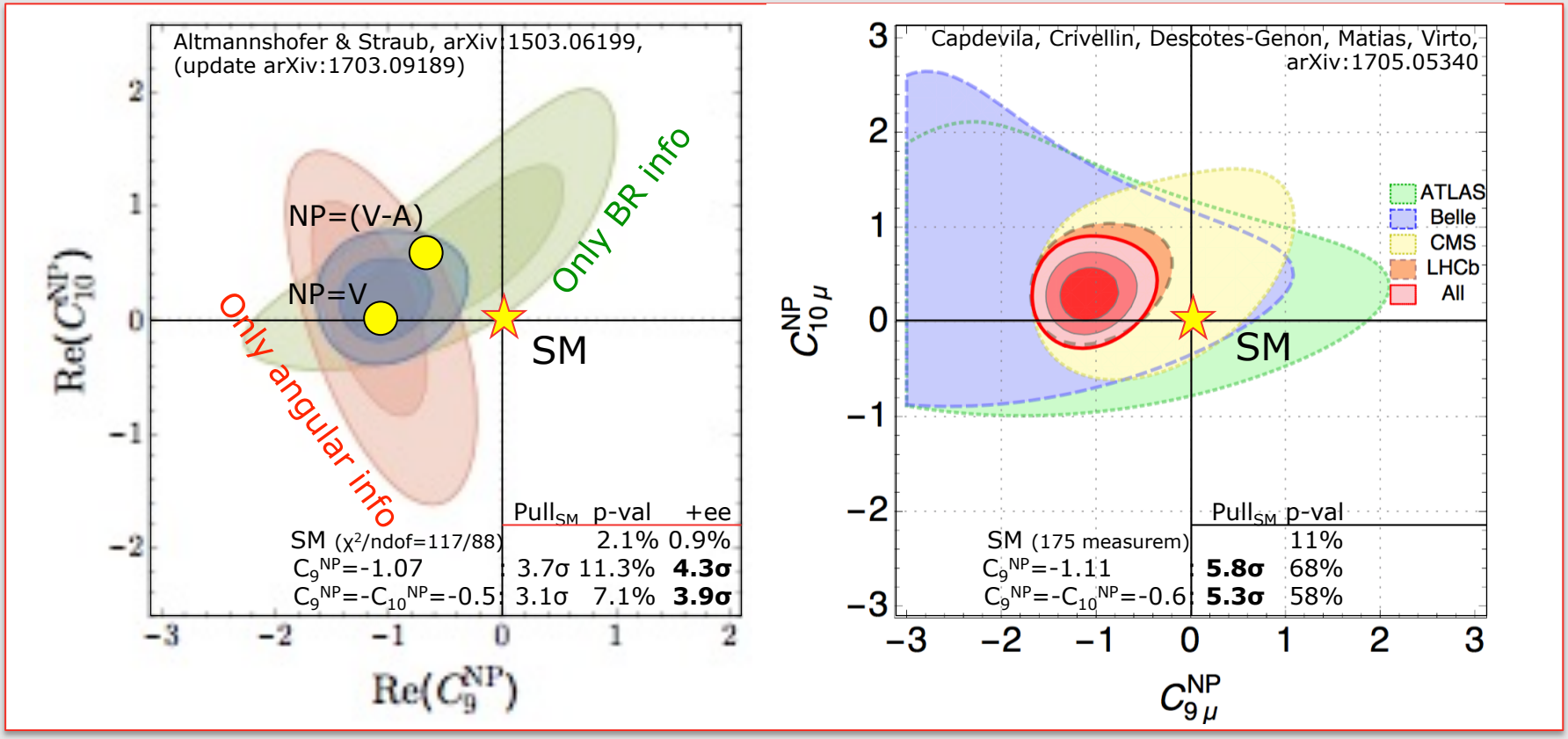
- C_9^{NP} deviates from 0 by >4σ
- Independent fits by many groups favour:
  - C_9^{NP}=-1 or
  - C_9^{NP}=-C_{10}^{NP}

➢ *All* measurements (175) agree with a single (simple?) shift…

LHCb, JHEP 02 (2016) 104

$$\Delta\mathrm{Re}(\mathcal{C}_9) = -1.04 \pm 0.25$$

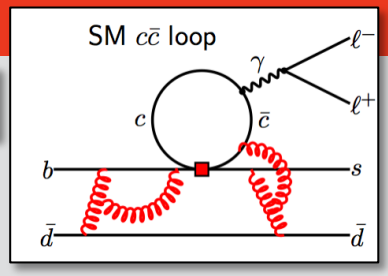


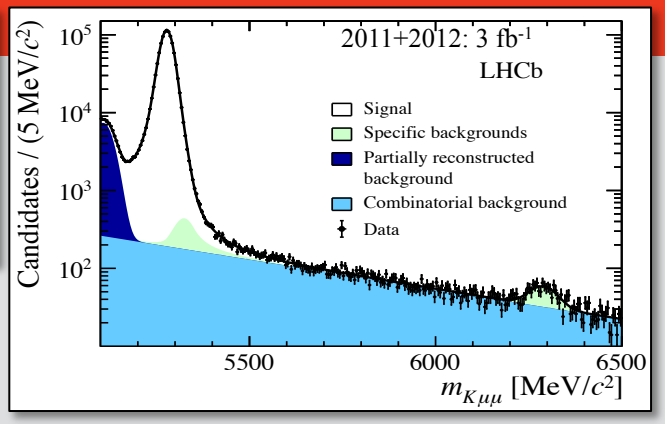


$B^+ \to K^+\mu^+\mu^-$: in detail

LHCb Coll., EPJ C77 (2017) 161

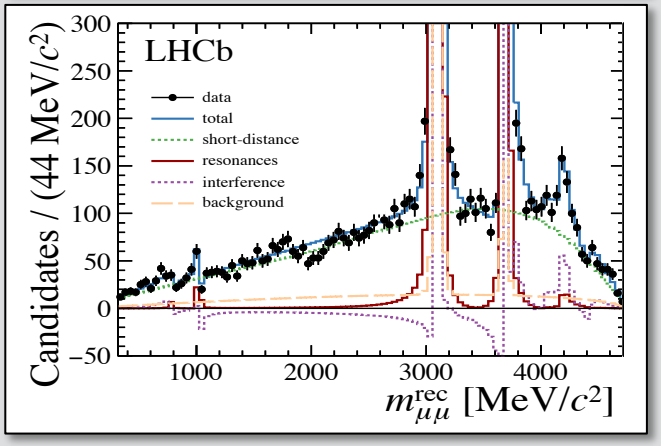
$$\mathcal{B}(B^+ \to K^+\mu^+\mu^-) = (4.37 \pm 0.15\,(\text{stat}) \pm 0.23\,(\text{syst})) \times 10^{-7}$$



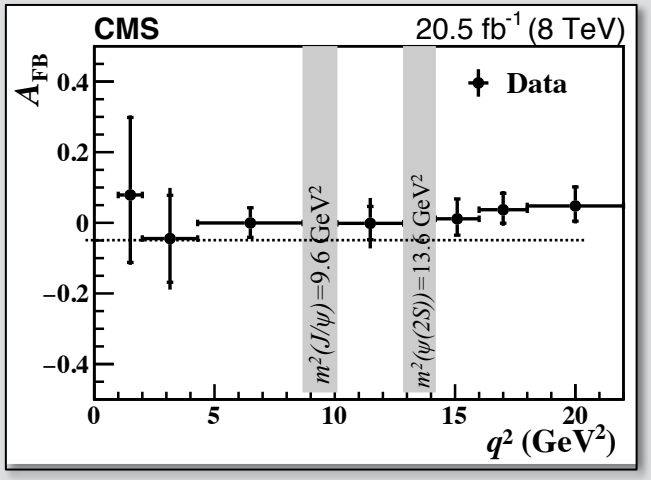


- Contributions from b→sll
  - *$B^+ \to K^+\mu^+\mu^-$*
- Contributions from b→scc
  - *e.g. $B^+ \to K^+\varphi$, $B^+ \to K^+J/\psi$, $B^+ \to K^+\psi(2S)$, …*
- Understand interference
  - Positive or negative?
  - More general: phase difference? ±90^0
    - Small interference

Resonance	Phase [rad]
J/ψ	-1.66 ± 0.05
$\psi(2S)$	-1.93 ± 0.10



- Angular analysis:
  - Consistent with no assymetry



CMS, arXiv:1806.00636

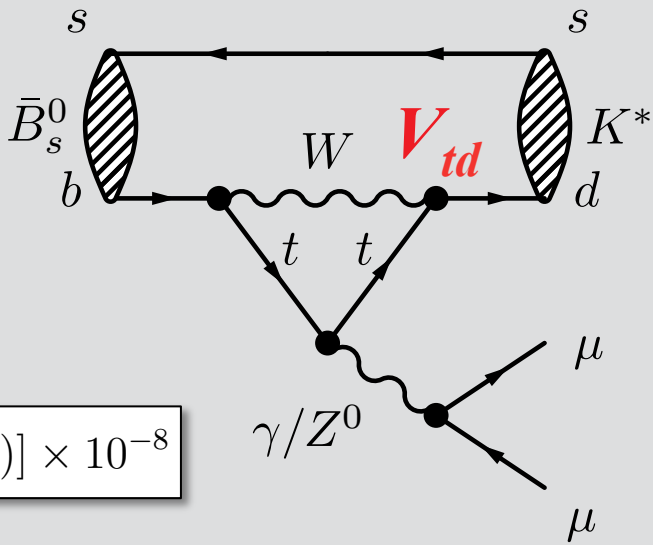
$B^0_s \to K^{0*}\mu^+\mu^-$

- Study analogous $b \to d\mu^+\mu^-$ transition:
  - Also observed in

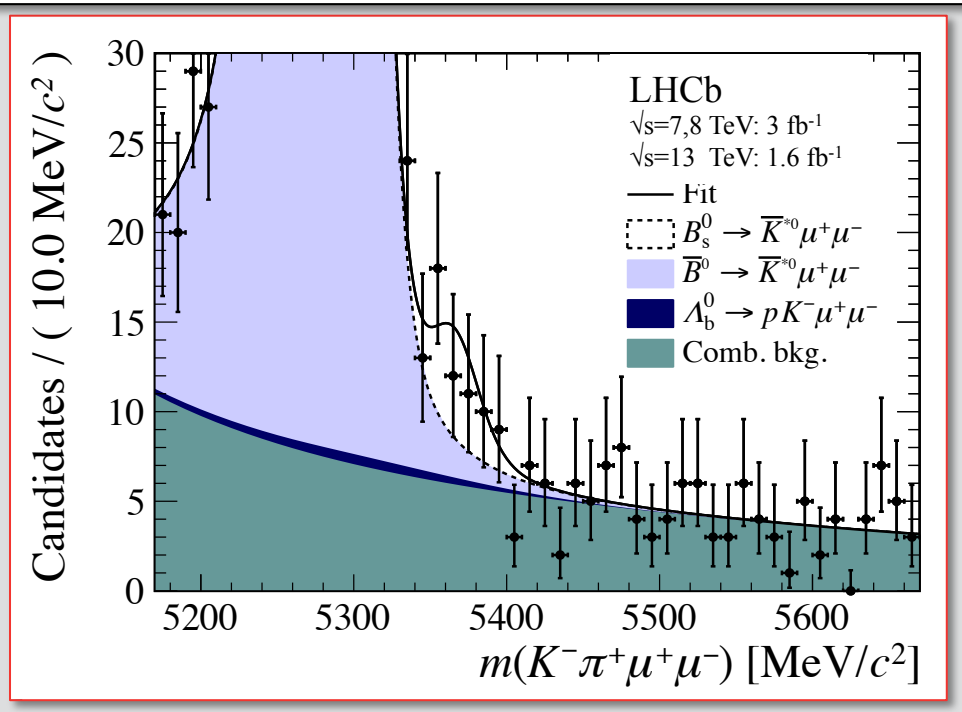
LHCb, JHEP 10 (2015) 034
LHCb, PLB 743 (2015) 46
LHCb, JHEP 04 (2016) 029

$$B^+ \to \pi^+\mu^+\mu^-, B^0 \to \pi^+\pi^-\mu^+\mu^-, \Lambda_b^0 \to p\pi^+\mu^+\mu^-$$

  - Similar EW penguin as $b \to s\mu^+\mu^-$
  - Observed 38 ± 12 events (3.4σ)
  - Consistent with suppression due to $|V_{td}|/|V_{ts}|$

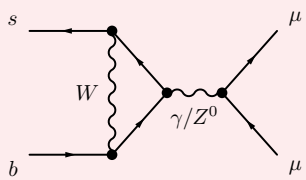
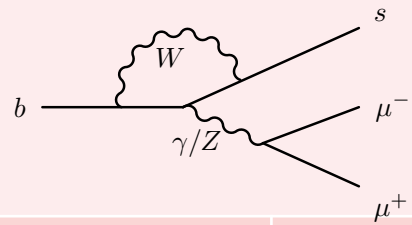
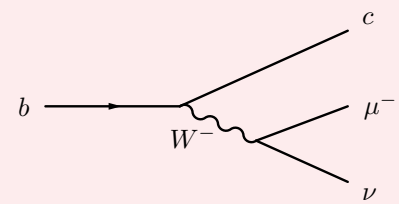


$$\mathcal{B}(B^0_s \to \overline{K}^{*0}\mu^+\mu^-) = [2.9 \pm 1.0\,(\text{stat}) \pm 0.2\,(\text{syst}) \pm 0.3\,(\text{norm})] \times 10^{-8}$$



LHCb, arXiv:1804.07167

Outline

	Flavour Changing Neutral Current			
	Leptonic	**Mesonic**	**Baryonic**	**Semi-leptonic**
				
Strange	$K_S^0 \to \mu^+\mu^-$	$K^+ \to \pi^+\nu\nu$ $K^0 \to \pi^0\nu\nu$	$\Sigma^+ \to p\mu^+\mu^-$	
Charm	$D^0 \to \mu^+\mu^-$ $D^0 \to e^+\mu^-$	$D^0 \to h^+h^-\mu^+\mu^-$ $J/\psi \to D^0e^+e^-$	$\Lambda_c^+ \to p\mu^+\mu^-$	
Beauty	$B^0_{(s)} \to \mu^+\mu^-$ $B^0_{(s)} \to \tau^+\tau^-$ $B^0_{(s)} \to e^+\mu^-$	$B^0 \to K^{(*)}\mu^+\mu^-/e^+e^-$ $B^+ \to K^{(*)}\mu^+\mu^-/e^+e^-$ $B^0_s \to \varphi\mu^+\mu^-$ $B^0_s \to K^*\mu^+\mu^-$	$\Lambda_b \to \Lambda\,\mu^+\mu^-$	$B^0 \to D^{(*)}\mu^+\nu / \tau^+\nu$ $B_c^+ \to J/\psi\mu^+\nu / \tau^+\nu$

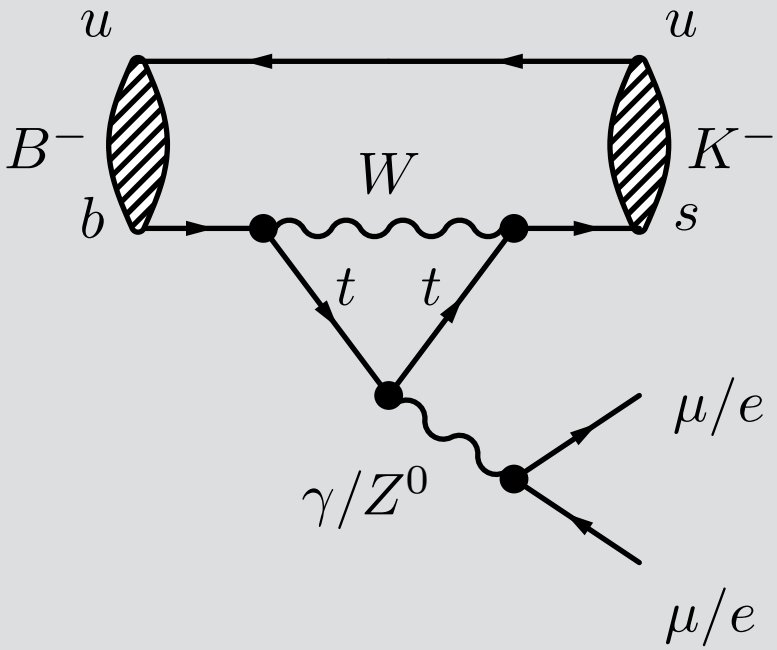
Lepton Flavour Non-Universality

R_K : $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+e^+e^-$

- Similar loop diagram!

- Measure ratio μ/e
- SM expectation: R_K=1

$$R_K = \frac{\Gamma(B^+ \to K^+\mu^+\mu^-)}{\Gamma(B^+ \to K^+e^+e^-)}$$



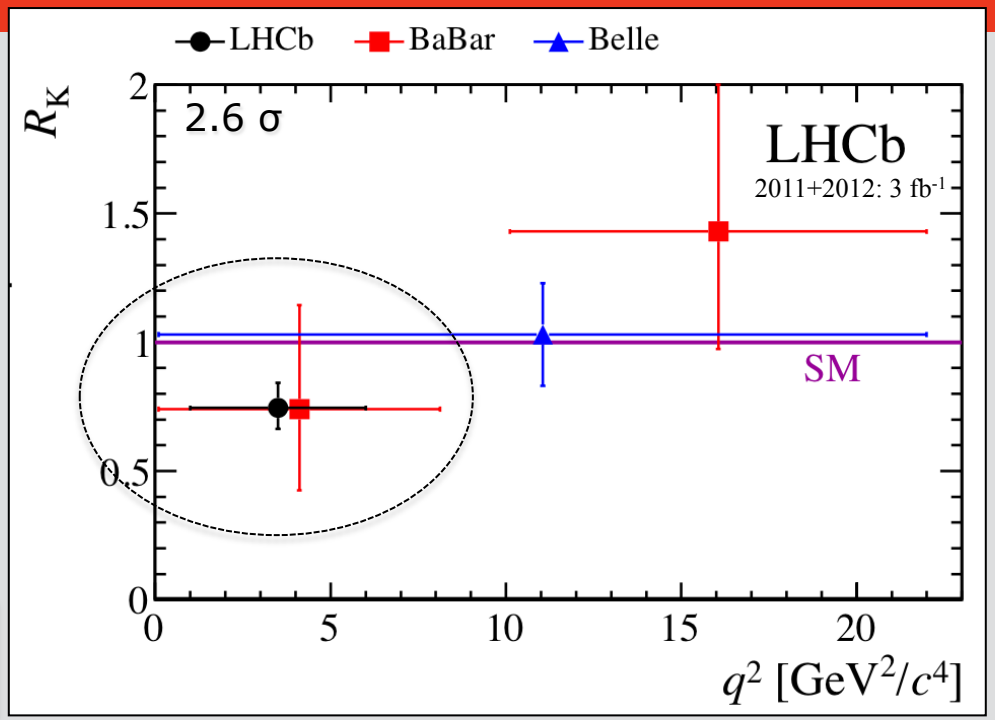
R_K : $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+e^+e^-$

- Similar loop diagram!

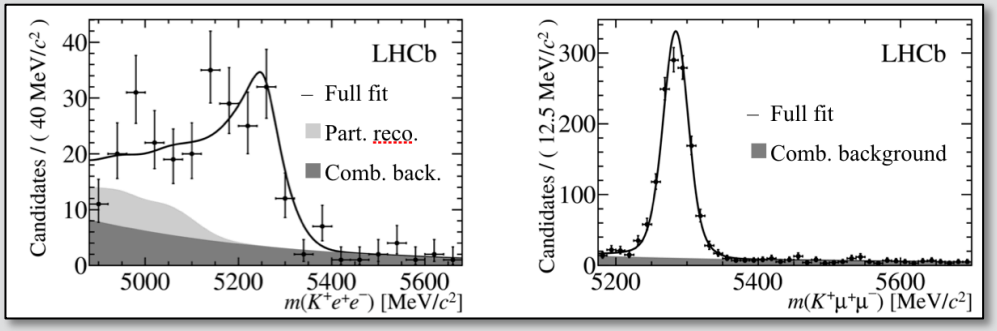
- Measure ratio μ/e
- SM expectation: R_K=1

$$R_K = \frac{\Gamma(B^+ \to K^+\mu^+\mu^-)}{\Gamma(B^+ \to K^+e^+e^-)}$$

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



LHCb,PRL 113 (2014) 151601

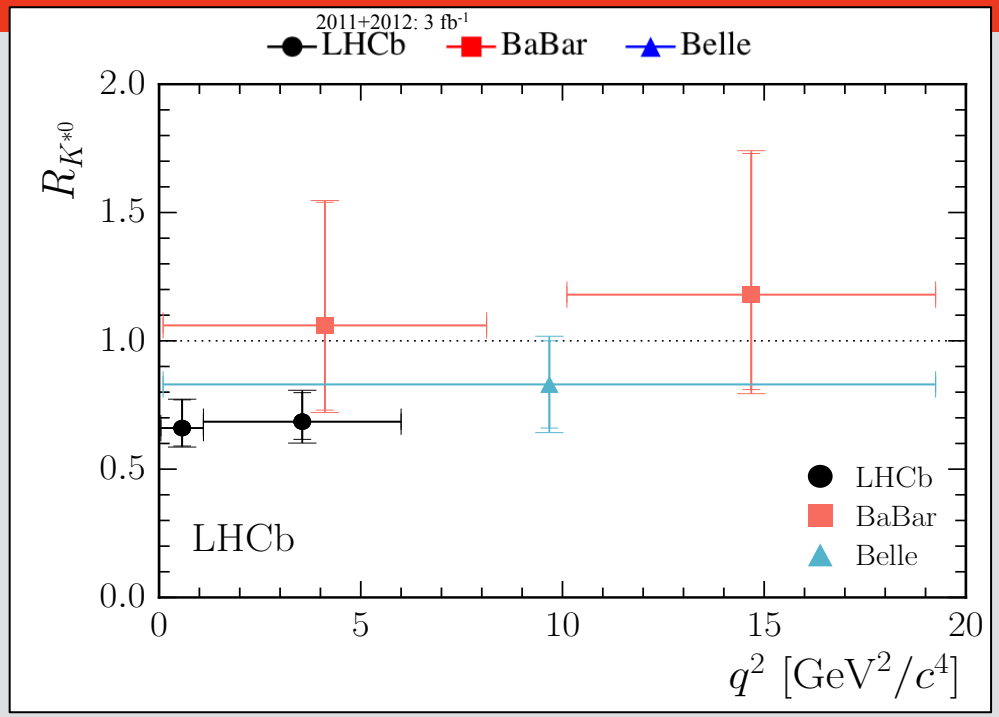


- **Lepton flavour "non-universal" ?**

R_{K*}: $B^0 \to K^{0*}\mu^+\mu^-$ and $B^0 \to K^{0*}e^+e^-$

- Similar loop diagram!
- Measure ratio μ/e
- SM expectation: $R_{K*}=1$

➢ Extra bin at low q^2…
  - $q^2 \sim 0$ not helicity suppressed



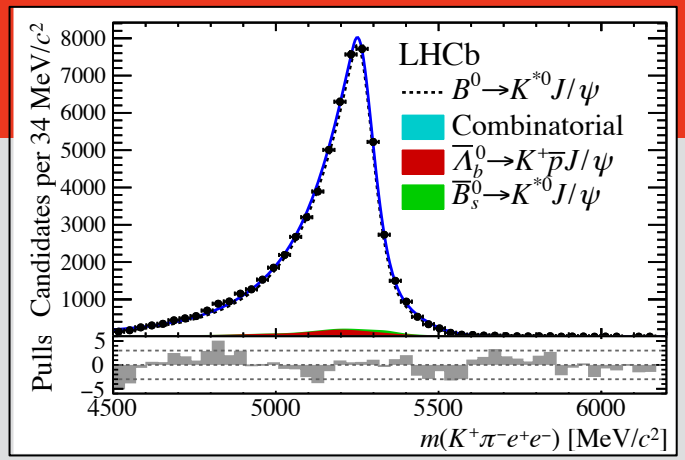
LHCb Coll., JHEP 1708 (2017) 055

$$R_{K^{*0}} = \begin{cases} 0.66\,^{+\,0.11}_{-\,0.07}\,(\text{stat}) \pm 0.03\,(\text{syst}) & \text{for } 0.045 < q^2 < 1.1\ \text{GeV}^2/c^4 \\ 0.69\,^{+\,0.11}_{-\,0.07}\,(\text{stat}) \pm 0.05\,(\text{syst}) & \text{for } 1.1 \quad < q^2 < 6.0\ \text{GeV}^2/c^4 \end{cases}$$

➢ **Lepton flavour "non-universal" ?**

R_{K^*} : Analysis

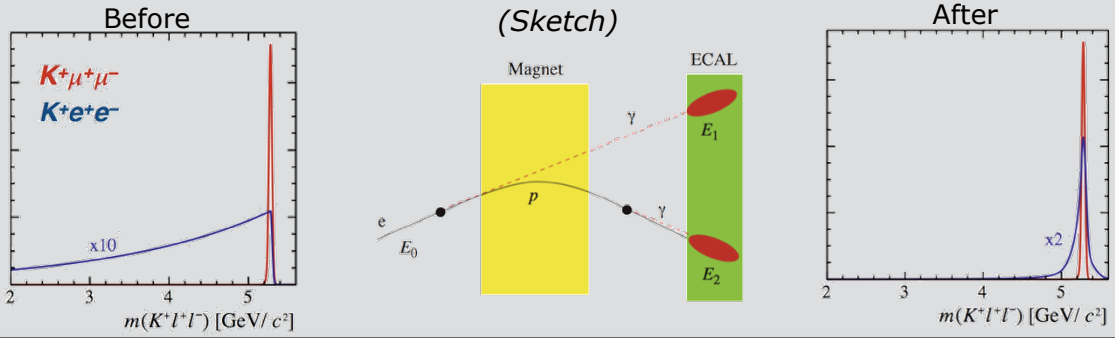
LHCb Coll., JHEP 1708 (2017) 055



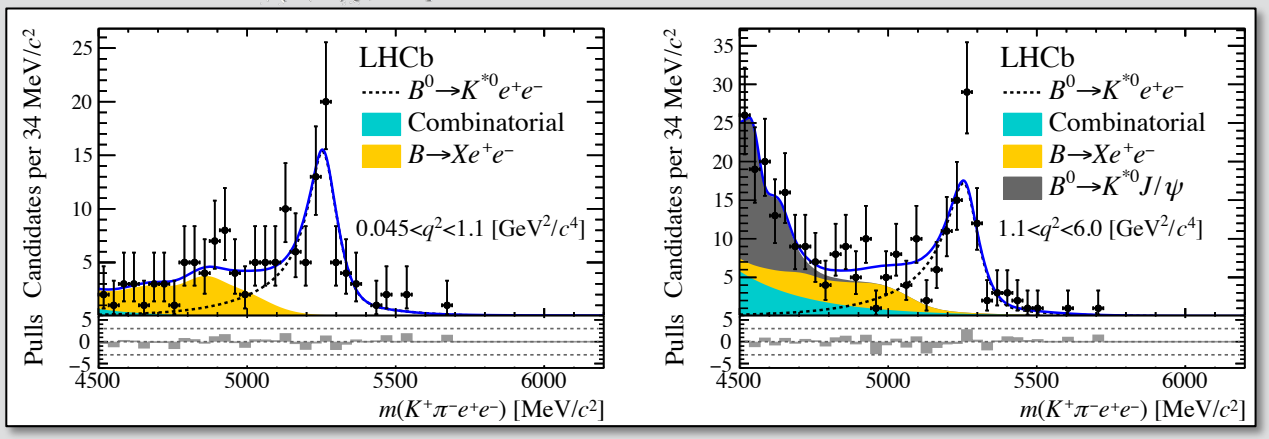
- Double ratio:

$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))}$$

- Bremstrahlung correction



- Statistically dominated by $B^0 \to K^{0*}ee$

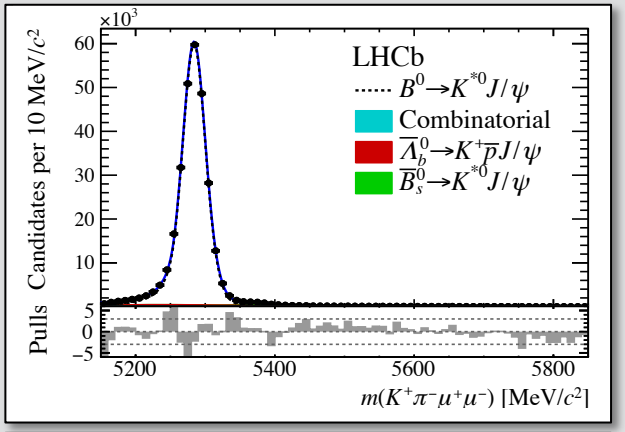


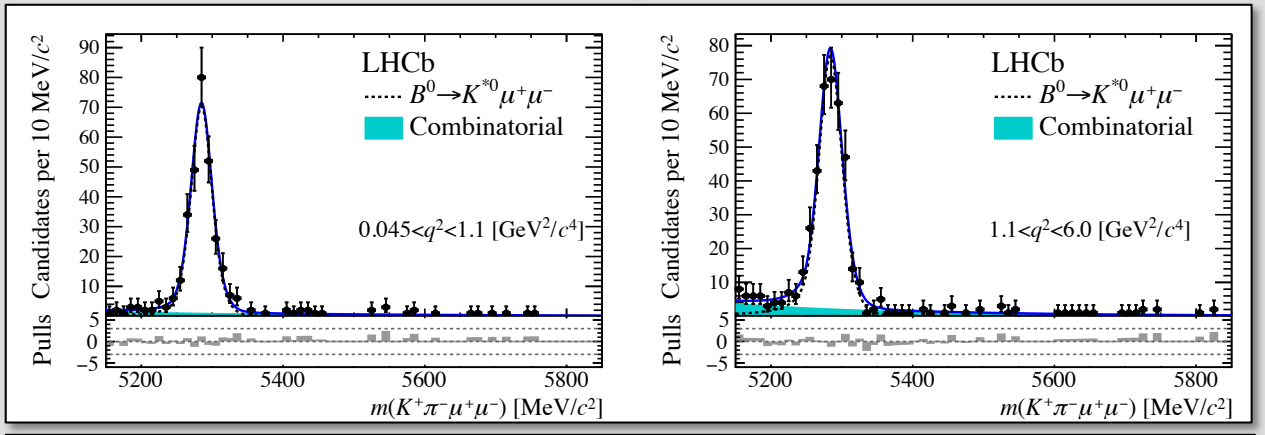
LHCb Coll., JHEP 1708 (2017) 055

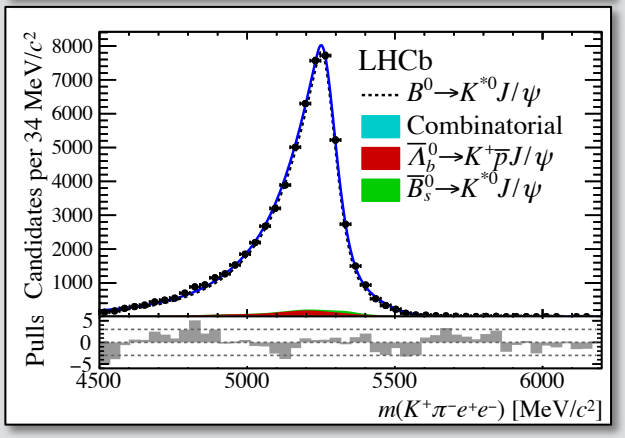
R_{K^*} : Analysis

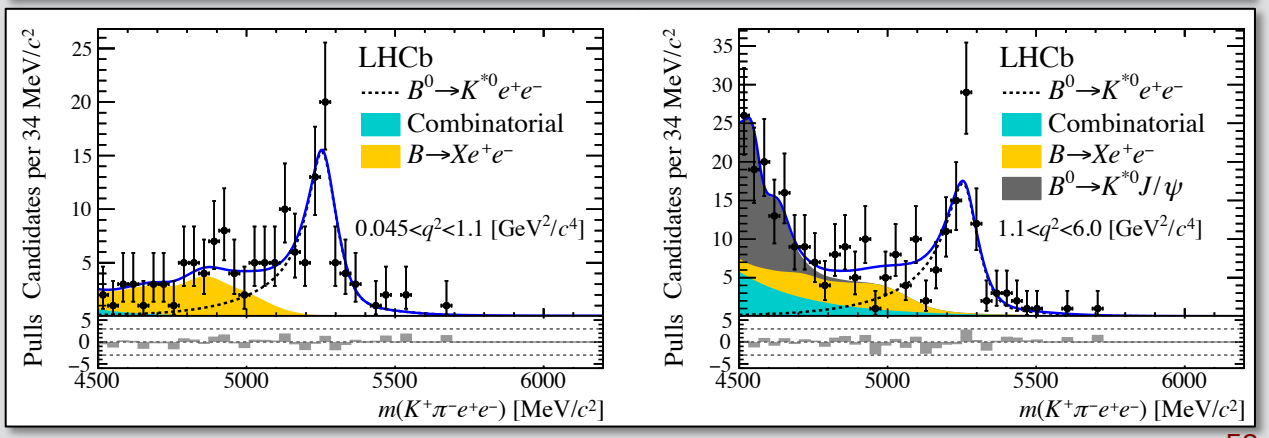
- Event yields:

	$B^0 \to K^{*0}\ell^+\ell^-$		$B^0 \to K^{*0}J/\psi(\to \ell^+\ell^-)$
	low-q^2	central-q^2	
$\mu^+\mu^-$	285^{+18}_{-18}	353^{+21}_{-21}	274416^{+602}_{-654}
e^+e^- (L0E)	55^{+9}_{-8}	67^{+10}_{-10}	43468^{+222}_{-221}
e^+e^- (L0H)	13^{+5}_{-5}	19^{+6}_{-5}	3388^{+62}_{-61}
e^+e^- (L0I)	21^{+5}_{-4}	25^{+7}_{-6}	11505^{+115}_{-114}









LHCb Coll., JHEP 1708 (2017) 055

R_{K^*} : Cross checks

- Check with J/ψ
  - Unity with 4.5% at 1σ
- Check with ψ(2S)
  - Unity within 2% at 1σ
- Check BR($B^0 \to K^*\gamma(\to ee)$)
  - Agrees within 15% at 2σ

$$r_{J/\psi} = \frac{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))} = 1.043 \pm 0.006(\text{stat}) \pm 0.045(\text{syst})$$

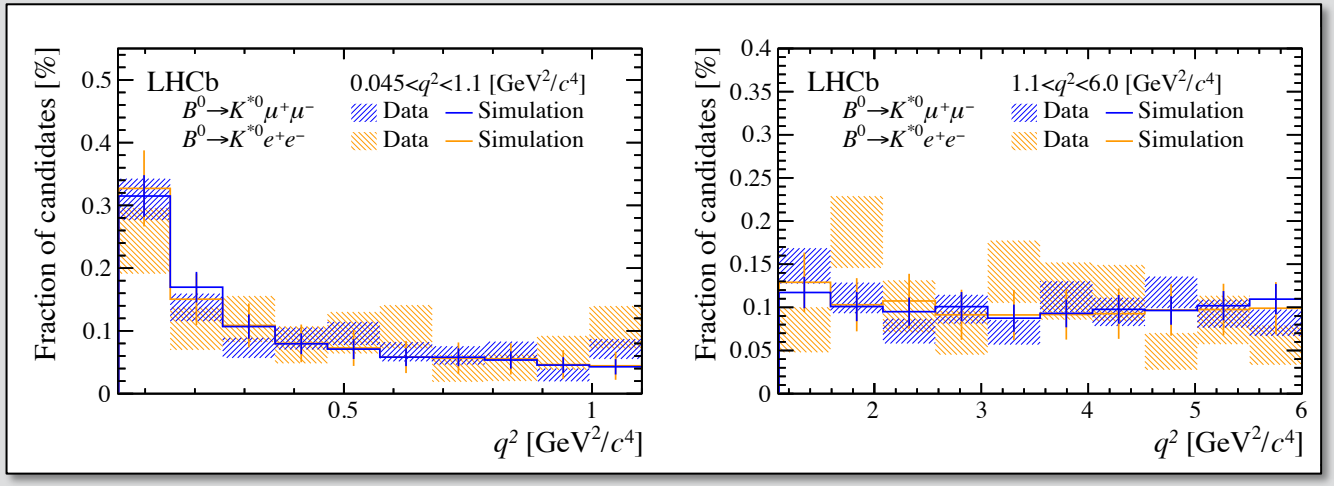
$$R_{\psi(2S)} = \frac{\mathcal{B}(B^0 \to K^{*0}\psi(2S)(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^0 \to K^{*0}\psi(2S)(\to e^+e^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))}$$

$$r_\gamma = \frac{\mathcal{B}(B^0 \to K^{*0}\gamma)}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))}$$

- Cross checked with earlier $d\Gamma/dq^2(B^0 \to K^*\mu\mu)$
  - Consistent

LHCb Coll., JHEP 1611 (2016) 47
Erratum: JHEP 1704 (2017) 14

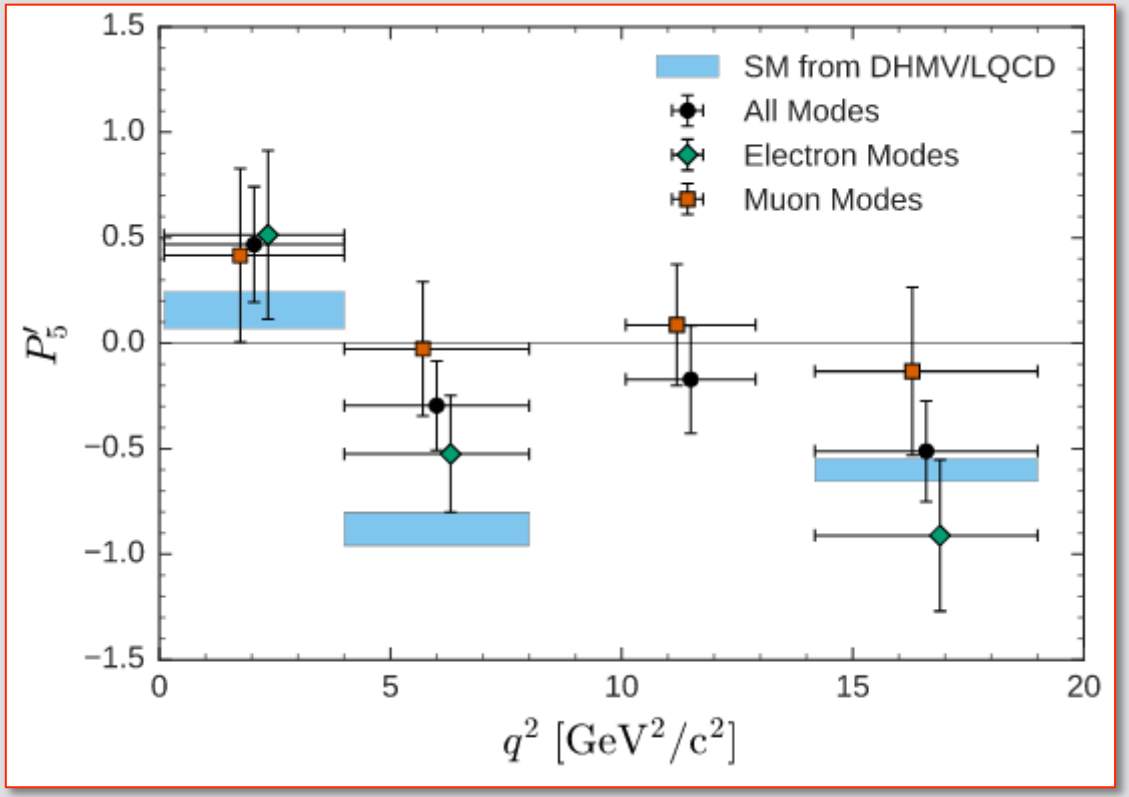
- Data vs simulation:



$B^0 \to K^{0*} e^+ e^-$: Difference in angular analysis?

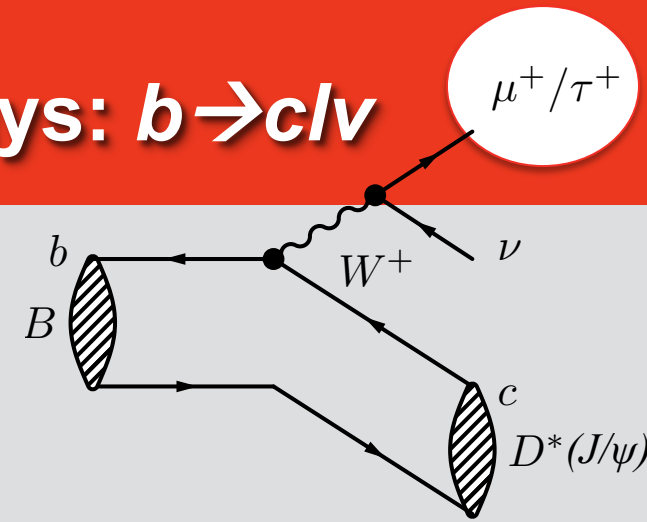
- So, decay rate different between $\mu^+\mu^-$ and e^+e^- final state?
- What about angular distribution?
  - P_5' deviates in $\mu^+\mu^-$ final state

➢ P_5' for $B^0 \to K^{0*} e^+ e^-$ seems in better agreement with expectations:



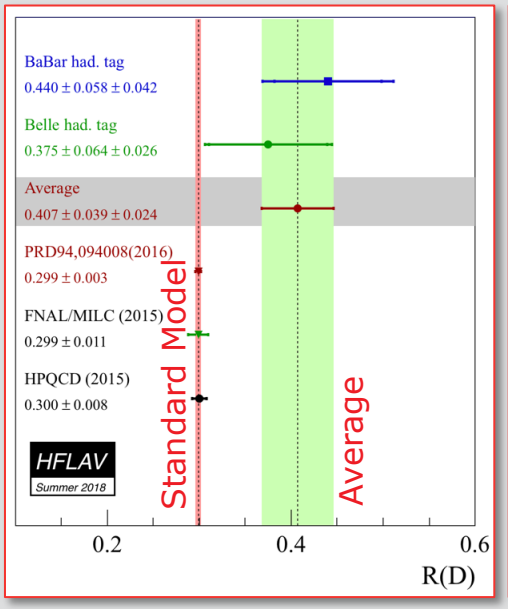
Belle, PRL 118 (2017) 111801

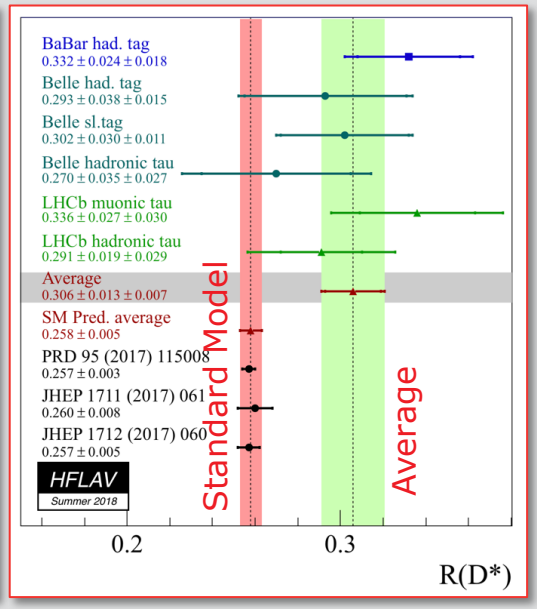
More LFNU? Semileptonic decays: $b \to c l \nu$

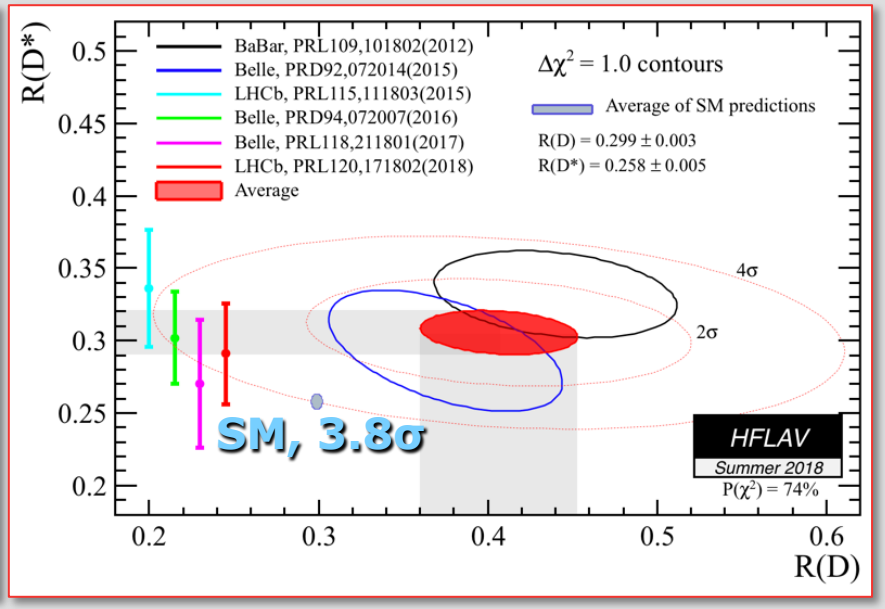


- $B^0 \to D^{(*)} l \nu$ Measured ratio τ/μ
  - Multiple experiments: Belle, BaBar, LHCb
  - Multiple c-modes: D, D^*, J/ψ
  - Multiple tau final states: μ, 1-prong, 3-prong
  - Multiple tags: semileptonic, hadronic

See talks by Ph.Urquijo and S.Fajfer







$$\mathcal{R}(J/\psi) = 0.71 \pm 0.17\,(\text{stat}) \pm 0.18\,(\text{syst})$$

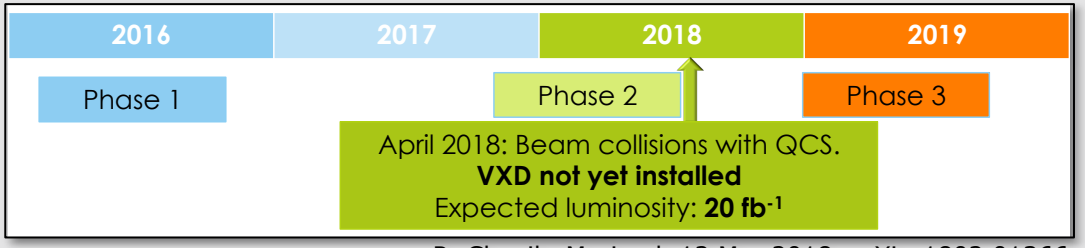
LHCb Coll. arXiv:1711.05623

Outlook

2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	203+
		Run III						Run IV					Run V	
LS2						**LS3**					**LS4**			
LHCb 40 MHz UPGRADE I		$L = 2 \times 10^{33}$			**LHCb Consolidate: Upgr Ib**			$L = 2 \times 10^{33}$ $50\ fb^{-1}$			**LHCb UPGRADE II**		$L=1\text{-}2 \times 10^{34}$ $300\ fb^{-1}$	
ATLAS Phase I Upgr		$L = 2 \times 10^{34}$			**ATLAS Phase II UPGRADE**			**HL-LHC** $L = 5 \times 10^{34}$			**ATLAS**		**HL-LHC** $L = 5 \times 10^{34}$	
CMS Phase I Upgr		$300\ fb^{-1}$			**CMS Phase II UPGRADE**						**CMS**		$3000\ fb^{-1}$	
Belle II	$5\ ab^{-1}$		$L = 8 \times 10^{35}$		$50\ ab^{-1}$									

LHC schedule: Frederick Bordry, Jun 2015

- Belle II
  - $L=5 \times 10^{33}\ cm^{-2}s^{-1}$ achieved!
  - Physics with VXD in 2019

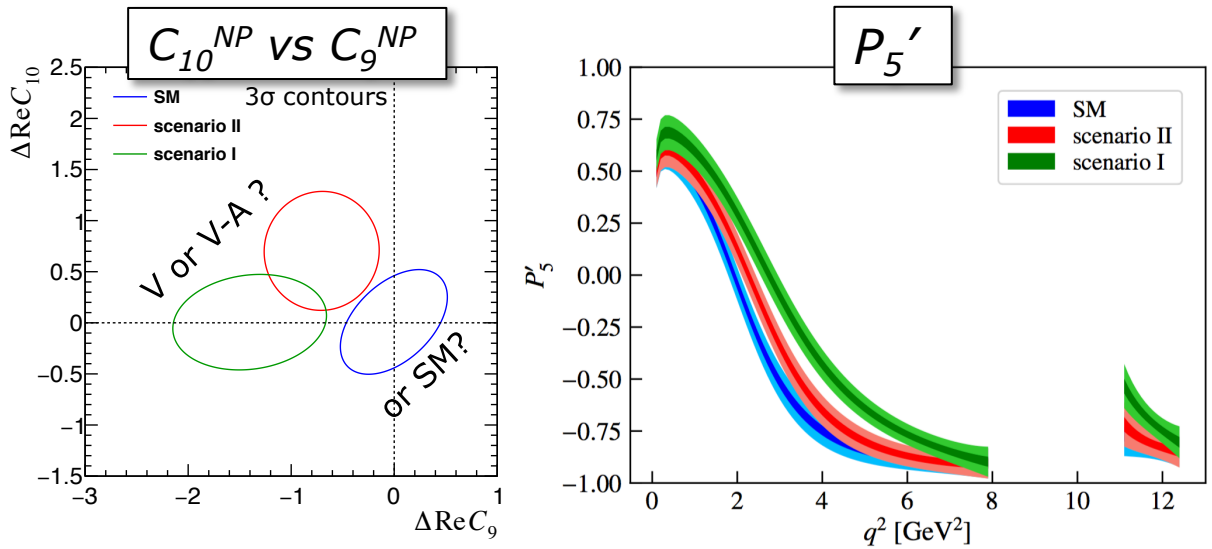


R. Cheaib, Moriond, 12 Mar 2018, arXiv:1802.01366

Outlook

2019	2020	2021	2022	2023
		Run III		
LS2				
LHCb 40 MHz UPGRADE I		$L = 2 \times 10^{33}$		
ATLAS Phase I Upgr		$L = 2 \times 10^{34}$		
CMS Phase I Upgr		$300\ fb^{-1}$		
Belle II	$5\ ab^{-1}$		$L = 8 \times 10^{35}$	

Sensitivity to New Physics at end of Run-3

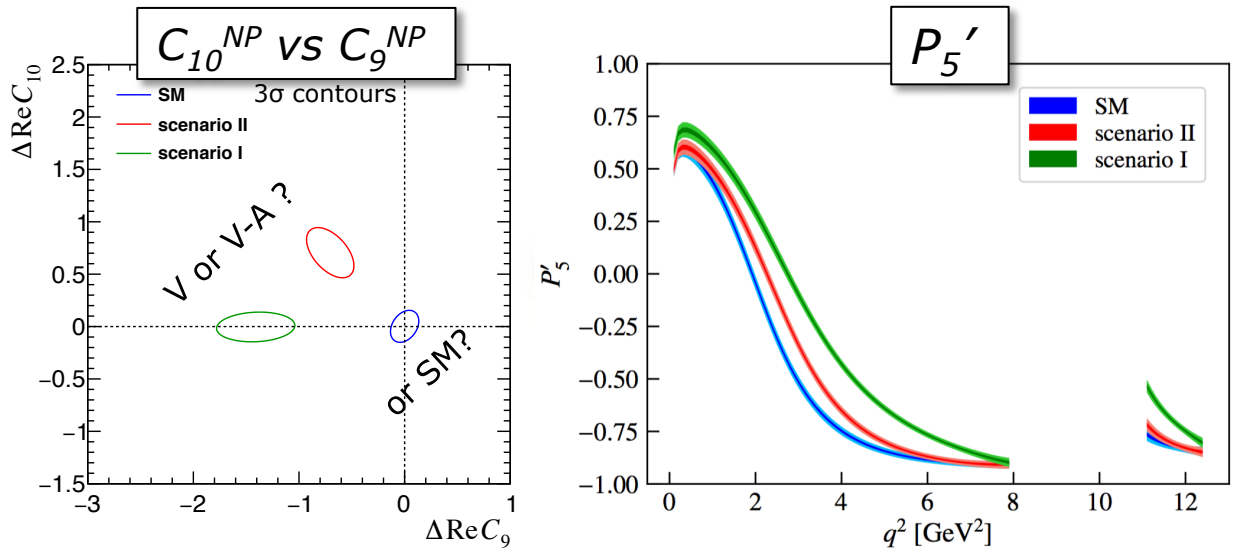


LHCb, "*Physics Case for Upgrade II*" (in preparation)

- LHCb
  - Fully exploit HL-LHC for flavour physics
    - x10 with respect to Upgrade I
  - Consolidate in LS3; major upgrade in LS4
    - Expression of Interest issued in 2017
  - Feasibility study performed by LHC experts & Physics case in preparation

Outlook

Sensitivity to New Physics with Upgrade II data set



2030	2031	2032	203+
		Run V	
LS4			
LHCb UPGRADE II		L=1-2x 10^{34} 300 fb^{-1}	
ATLAS		**HL-LHC** L = 5 x 10^{34}	
CMS		3000 fb^{-1}	

LHC schedule: Frederick Bordry, Jun 2015

LHCb, "*Physics Case for Upgrade II*" (in preparation)

- LHCb
  - Fully exploit HL-LHC for flavour physics
    - x10 with respect to Upgrade I
  - Consolidate in LS3; major upgrade in LS4
    - Expression of Interest issued in 2017
  - Feasibility study performed by LHC experts & Physics case in preparation

Conclusions

- Precision measurements to scrutinize the Standard Model
- Precision measurements only way to reach very high mass scales
- Precision measurements are not yet precise enough

Shahram Rahatlou (Monday):

"Leptoquarks are kind of trending right now."

See for example: D. Buttazzo, A. Greljo, G. Isidori, D. Marzocca, *B-physics anomalies: a guide to combined explanations,* JHEP 1711 (2017) 044, arXiv:1706.07808

Backup slides

The need for more precision

Imagine if Fitch and Cronin had stopped at the 1% level, how much physics would have been missed"

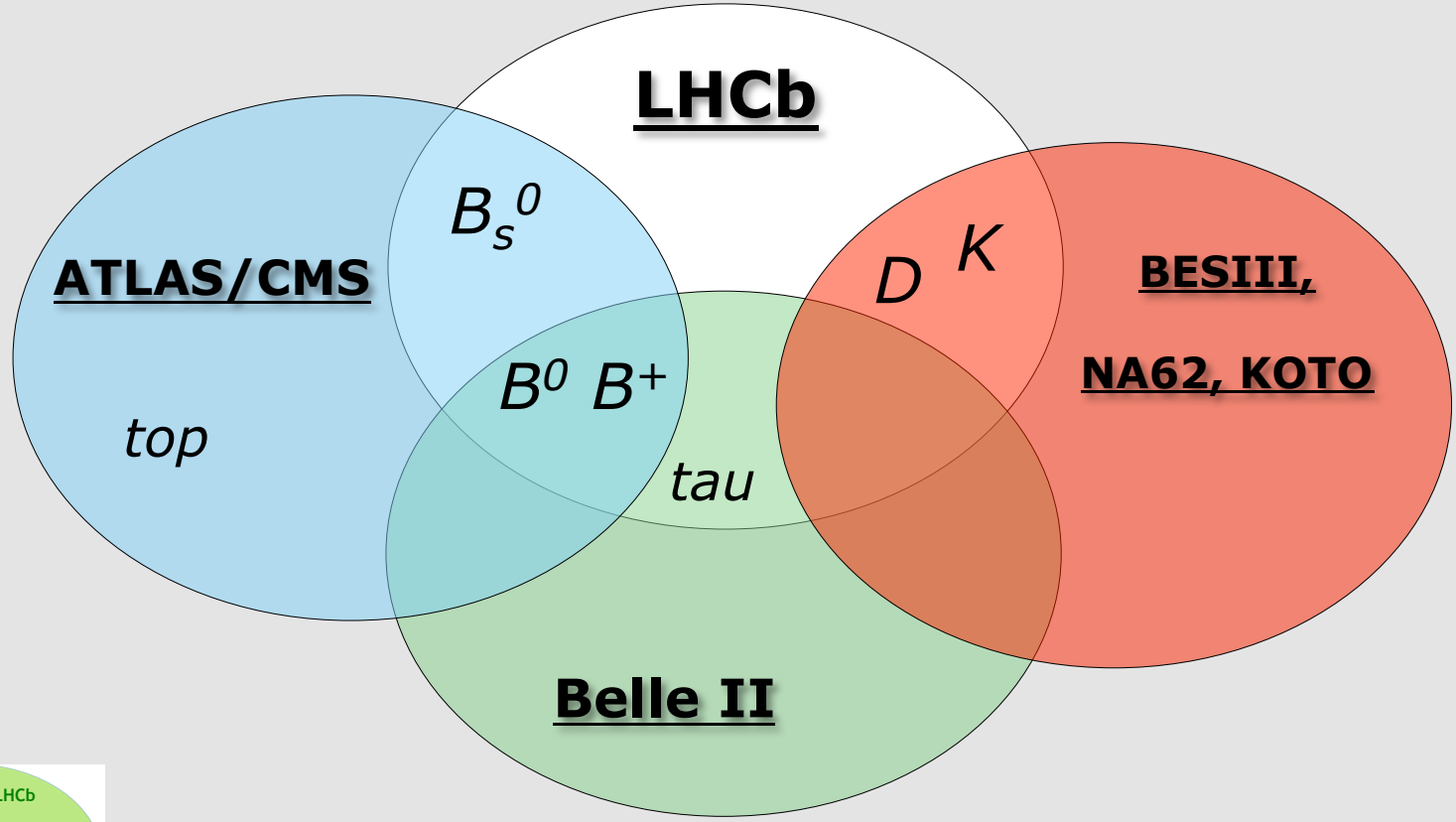
– A.Soni

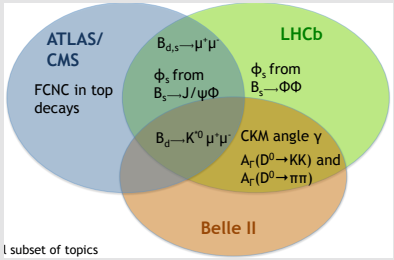
- "A special search at Dubna was carried out by Okonov and his group. They did not find a single $K_L^0 \to \pi^+\pi^-$ event among 600 decays into charged particles (Anikira et al., JETP 1962). At that stage the search was terminated by the administration of the lab. The group was unlucky."

– L.Okun

(remember: $B(K_L^0 \to \pi^+\pi^-) \sim 2\ 10^{-3}$)

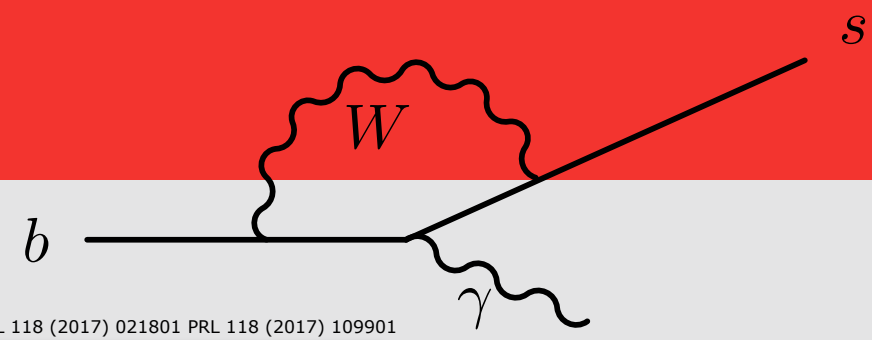
Playing field: heavy flavour





Sketch adopted from Marie-Hélène Schune ECFA2013, 1 Oct 2013

Radiative B decays



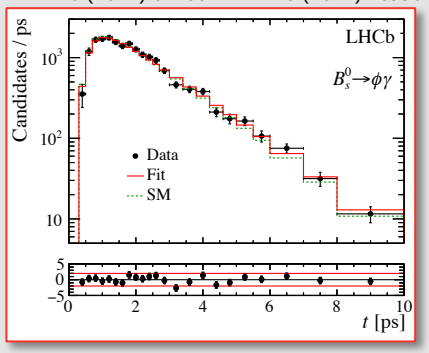
LHCb:

- $B_s^0 \to \phi\gamma_R$: photon polarization
  - Lifetime sensitive to photon polarization
  - A^Δ: $\mathcal{P}(t) \propto e^{-\Gamma_s t}\{\cosh(\Delta\Gamma_s t/2) - \mathcal{A}^\Delta \sinh(\Delta\Gamma_s t/2)\}$

$$\mathcal{A}^\Delta = -0.98\,^{+0.46}_{-0.52}\,^{+0.23}_{-0.20}$$

$$\mathcal{A}^\Delta_{\rm SM} = 0.047\,^{+0.029}_{-0.025}$$

PRL 118 (2017) 021801 PRL 118 (2017) 109901

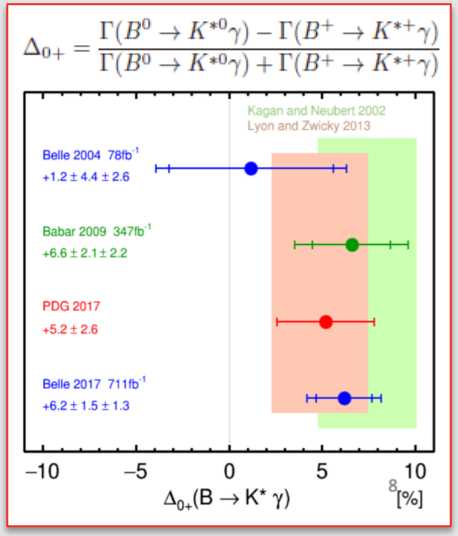


Belle:

- $B^0 \to K^{0*}\gamma$ and $B^+ \to K^+\gamma$: isospin asymmetry at 3.1σ

$$\Delta_{0+} = (+6.2 \pm 1.5 \pm 0.6 \pm 1.2)\%$$

Belle, Phys.Rev.Lett. 119 (2017) 191802



- $B^0 \to K_S^0\eta\gamma_R$: photon polarization, time-dependent

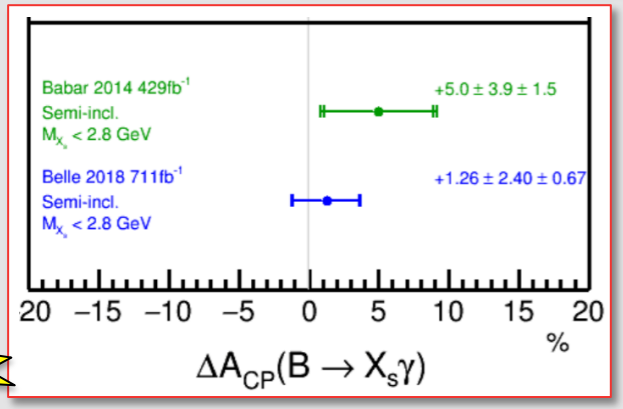
$$\mathcal{S} = -1.32 \pm 0.77(\text{stat.}) \pm 0.36(\text{syst.})$$
$$\mathcal{A} = -0.48 \pm 0.41(\text{stat.}) \pm 0.07(\text{syst.})$$

Belle, PRD97,092003 (2018)

- $B^0 \to X_s\gamma$: isospin asymmetry, incl. ΔA_{CP}

$$\Delta_{0-} = (+1.70 \pm 1.39 \pm 0.87 \pm 1.15)\%$$
$$\Delta A_{CP} = (+1.26 \pm 2.40 \pm 0.67)\%,$$

New

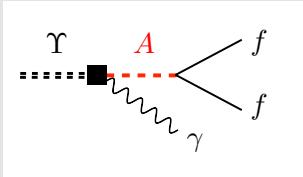


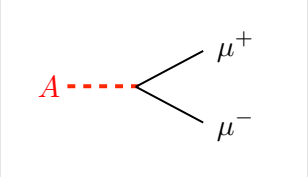
BELLE-CONF-1801

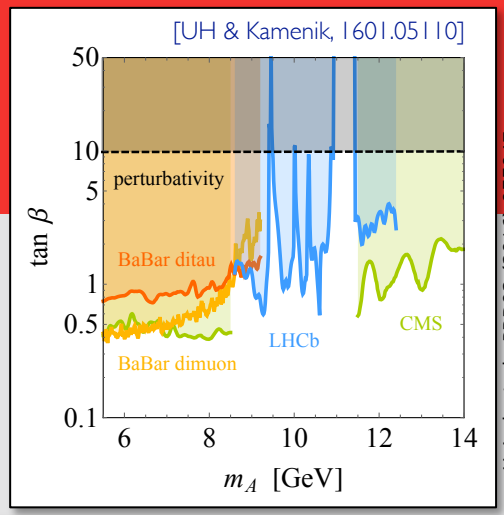
Searches

Dark photons, Majorana, light scalars

- Light scalars
  - A→μμ

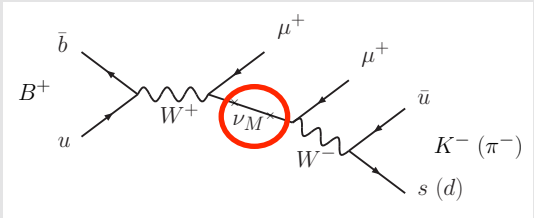


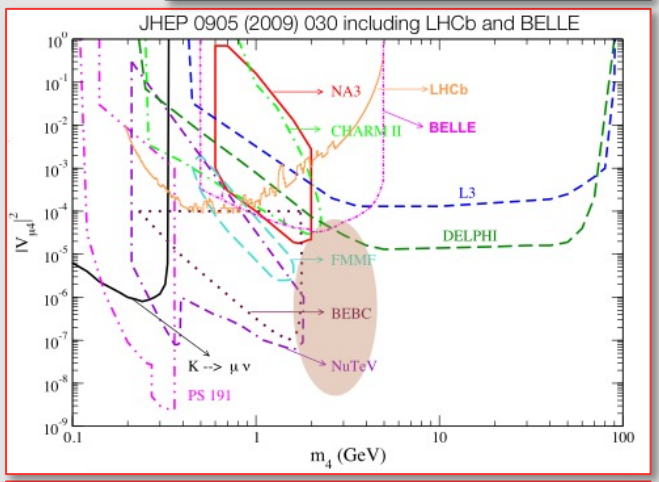




Haisch et al., PRD93 (2016) 055047

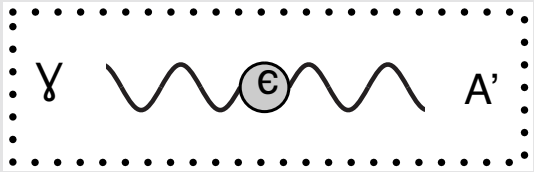
- Majorana neutrino's
  - $B^+ \to \pi^- \mu^+ \mu^+$

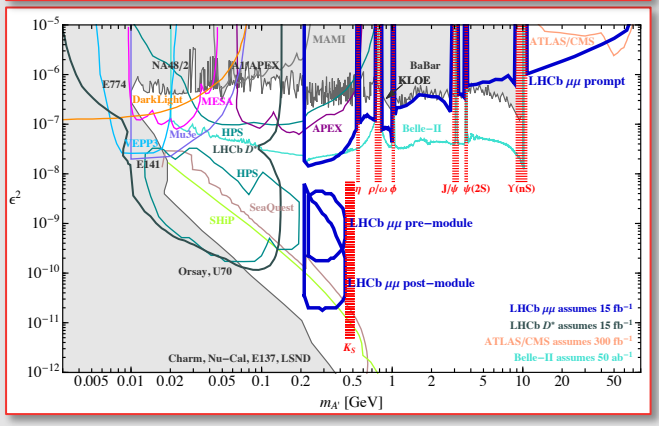




Atre et al., JHEP 0905 (2009) 030

- Dark photons
  - $D^{*0} \to D^0 \gamma$, $A \to \mu\mu$

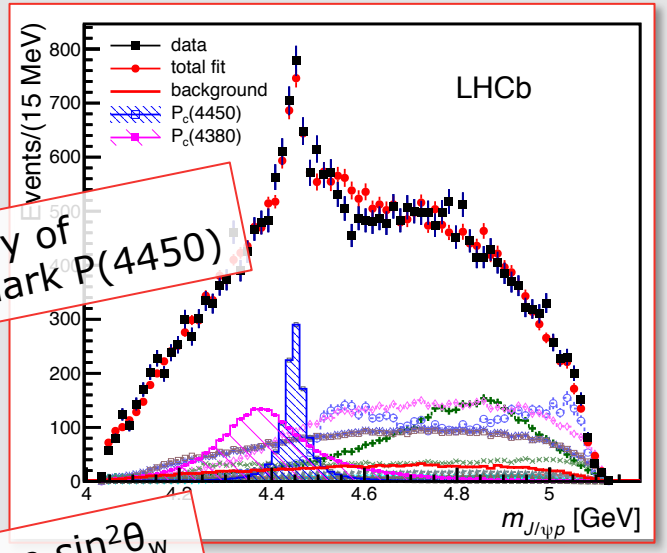




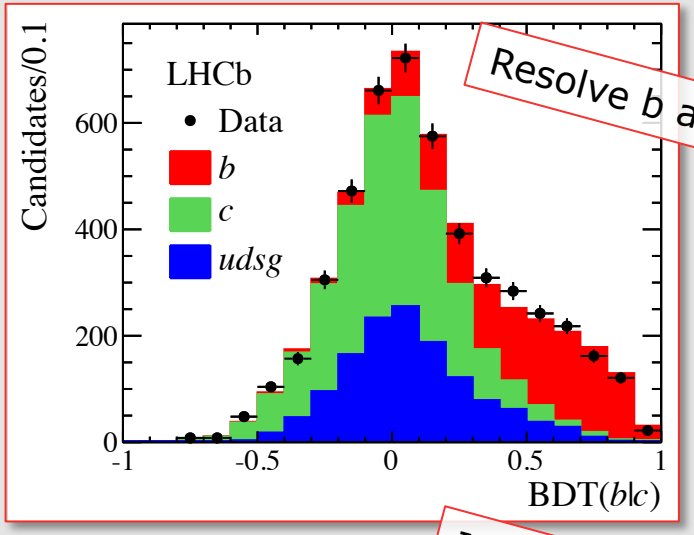
Ph.Ilten et al PRL 116 (2016) 251803

LHCb = more than flavour

pdfs, jets, heavy-ion, EW, exotic states…

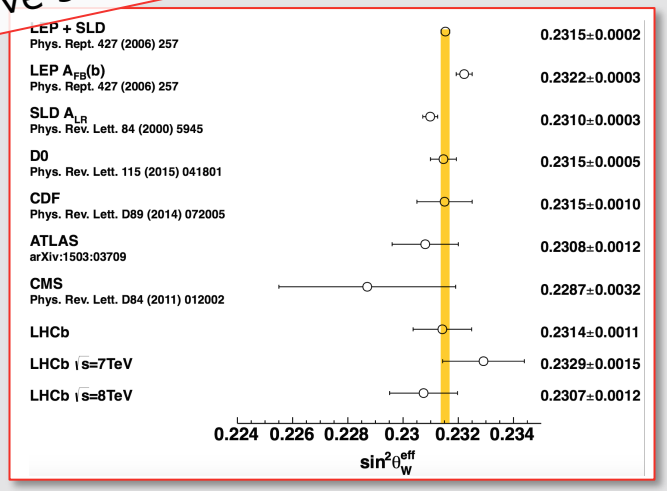


Discovery of pentaquark P(4450)

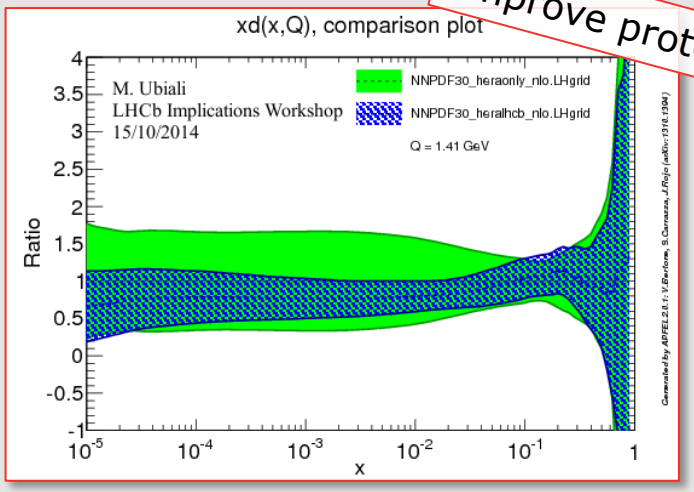


Resolve b and c jets

Impressive $\sin^2\theta_W$



Improve proton pdf's



What NP could it be?

- If interpreted as NP signals, both set of anomalies are <u>not in contradiction</u> among themselves & with existing low- & high-energy data.
  <u>Taken together,</u> they point out to NP coupled mainly to 3rd generation, with a flavor structure connected to that appearing in the SM Yukawa couplings

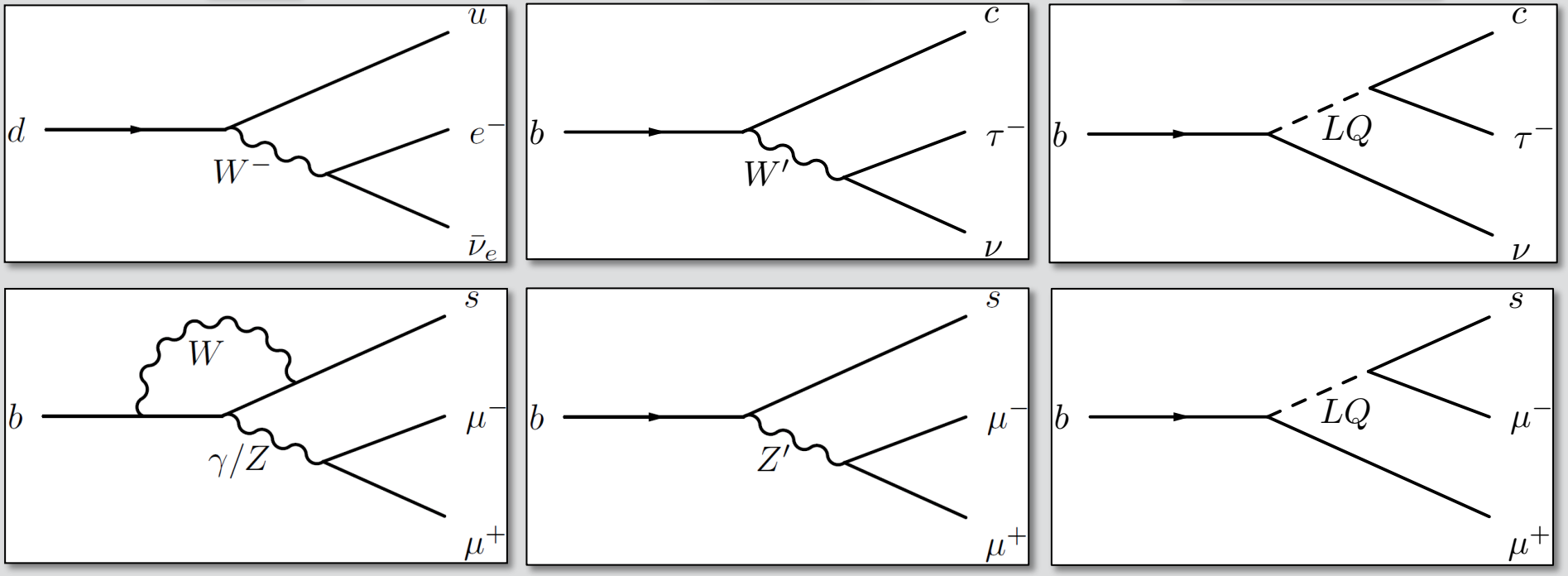
G. Isidori, *Implications workshop*, CERN, 10 Nov 2017
https://indico.cern.ch/event/646856/timetable/

- Indirect measurements
- What are the (anomalous) measurements?
  - FCNC: b→sll
  - LFNU: b→sll and b→clv
- What are the interpretations?

Model building

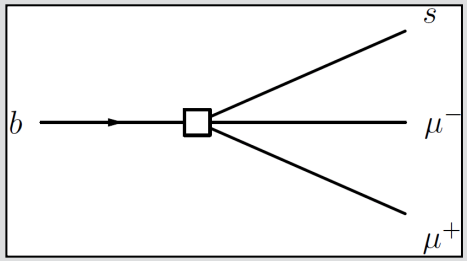
- Most popular models: Z' or Leptoquark

SM | SU(2)' | Leptoquark



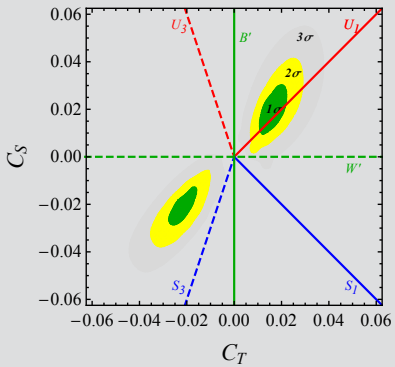
Model building

- Step 1: Effective theory

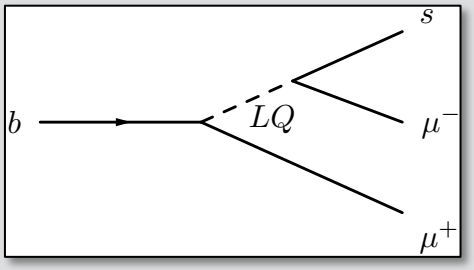


$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} - \frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T\ (\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + C_S\ (\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right]$$

Observable	Experimental bound	Linearised expression
$R^{\tau\ell}_{D^{(*)}}$	1.237 ± 0.053	$1 + 2C_T(1 - \lambda^q_{sb}V^*_{tb}/V^*_{ts})(1 - \lambda^\ell_{\mu\mu}/2)$
$\Delta C^\mu_9 = -\Delta C^\mu_{10}$	-0.61 ± 0.12 [36]	$-\frac{\pi}{\alpha_{\rm em}V_{tb}V^*_{ts}}\lambda^\ell_{\mu\mu}\lambda^q_{sb}(C_T + C_S)$
$R^{\mu e}_{b\to c} - 1$	0.00 ± 0.02	$2C_T(1 - \lambda^q_{sb}V^*_{tb}/V^*_{ts})\lambda^\ell_{\mu\mu}$
$B_{K^{(*)}\nu\bar{\nu}}$	0.0 ± 2.6	$1 + \frac{2}{3}\frac{\pi}{\alpha_{\rm em}V_{tb}V^*_{ts}C^{\rm SM}_\nu}(C_T - C_S)\lambda^q_{sb}(1 + \lambda^\ell_{\mu\mu})$
$\delta g^Z_{\tau_L}$	-0.0002 ± 0.0006	$0.033C_T - 0.043C_S$
$\delta g^Z_{\nu_\tau}$	-0.0040 ± 0.0021	$-0.033C_T - 0.043C_S$
$\lvert g^W_\tau / g^W_\ell \rvert$	1.00097 ± 0.00098	$1 - 0.084C_T$
$\mathcal{B}(\tau \to 3\mu)$	$(0.0 \pm 0.6) \times 10^{-8}$	$2.5 \times 10^{-4}(C_S - C_T)^2(\lambda^\ell_{\tau\mu})^2$



- Step 2: Simplified models



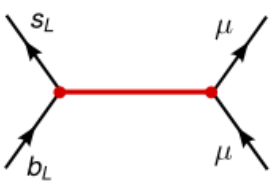
$SU(2)_L$-singlet vector leptoquark, $U^\mu_1 \equiv (\mathbf{3}, \mathbf{1}, 2/3)$

$$\begin{aligned}\mathcal{L}_U &= -\frac{1}{2}U^\dagger_{1,\mu\nu}U^{1,\mu\nu} + M^2_U U^\dagger_{1,\mu}U^\mu_1 + g_U(J^\mu_U U_{1,\mu} + \text{h.c.})\\ J^\mu_U &\equiv \beta_{i\alpha}\ \bar{Q}_i\gamma^\mu L_\alpha\ .\end{aligned}$$

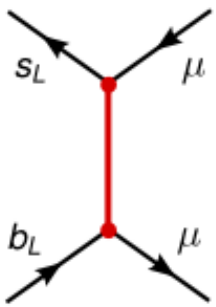
Model building

- Many models! See e.g.:

➢ Possible BSM models

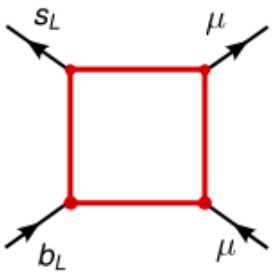


- Heavy Z' model
- $SU(2)_L$ singlet or triplet
- arXiv:1403.1269, 1501.00993, 1503.03477, 1611.02703, ...



- Leptoquark model
- Spin 0 or 1
- arXiv:01511.01900, 1503.01084, 1704.05835, 1512.01560, 1511.06024, 1408.1627, ...

arXiv:1706.07808



- Other new heavy scalars/vectors also leptoquark possible
- arXiv:01509.05020, 1608.07832, 1704.05438, 1607.01659, 1704.07845, hep-ph/0610037, ...

ICHEP 2018 @Seoul

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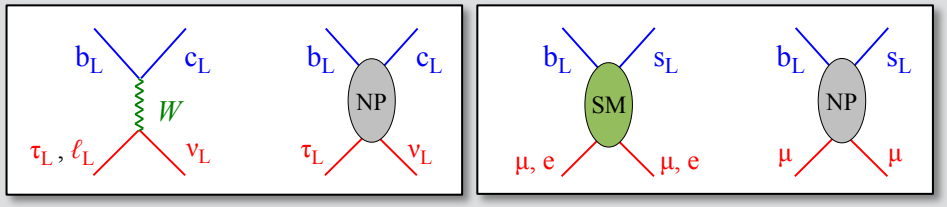
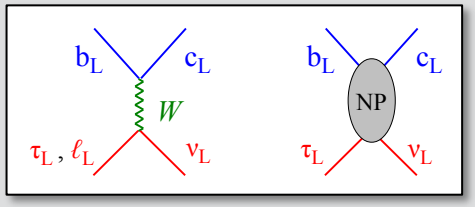
Courtesy, Geng CHEN, ICHEP 2018 , 7 July 2018

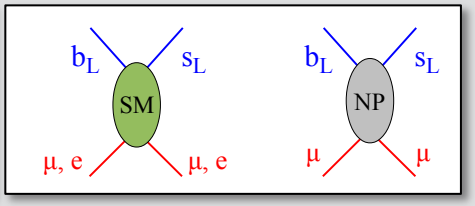
Model building

- Ingredients
  - NP: large coupling $b \to c\tau\nu$
    - Large coupling to 3rd gen leptons
    - Left-handed coupling (no RH neutrino)
  - NP: small (non-vanishing) coupling $b \to s\mu\mu$
    - Small coupling to 2nd gen leptons
    - Left-handed coupling (from C_9)



Model building





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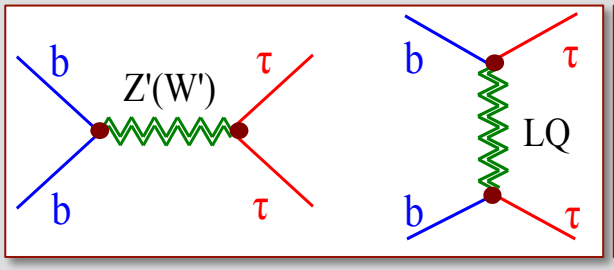
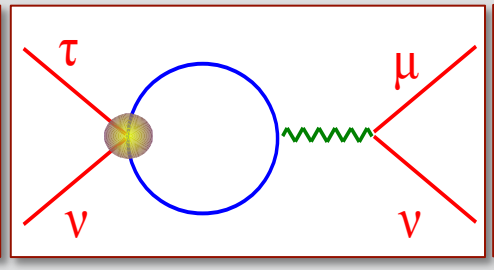
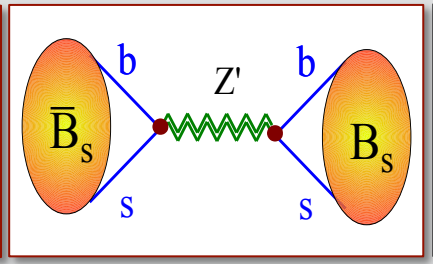
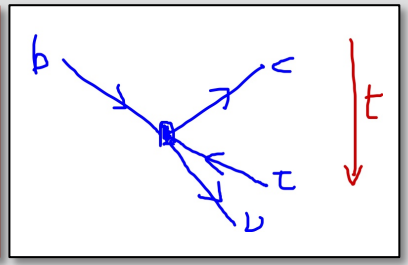








G.Isidori J.M.Camalich

- Experimental constraints
  - High p_T searches (No $\tau\tau$ resonance: no s-channel Z')
  - Radiative constr. $\tau \to \mu\nu\nu$
  - B_s^0 mixing (No tree level NP: small bs implies large $\tau\nu$)
  - B_c^+ lifetime (Scalar LQ increases BR($B_c^+ \to \tau^+\nu$))

} Vector LQ favoured over Scalar LQ or Z'

Model building

$SU(2)_L$-singlet vector leptoquark emerges as a particularly simple and successful framework.

Buttazzo, Greljo, Isidori, Marzocca, B-physics anomalies: a guide to combined explanations, JHEP 1711 (2017) 044

- Many more experimental handles; predictions can be checked!
- Universal for all b→cτν:
  - Accurate R(D*), R(J/ψ), …

$$\frac{R_D}{(R_D)_{SM}} = \frac{\Gamma(B\to D^*\tau\nu)/\Gamma_{SM}}{\Gamma(B\to D^*\mu\nu)/\Gamma_{SM}} = \frac{\Gamma(B_c\to\psi\tau\nu)/\Gamma_{SM}}{\Gamma(B_c\to\psi\mu\nu)/\Gamma_{SM}} = \frac{\Gamma(\Lambda_b\to\Lambda_c\tau\nu)/\Gamma_{SM}}{\Gamma(\Lambda_b\to\Lambda_c\mu\nu)/\Gamma_{SM}} = \dots$$

- Strong coupling to *tau's:*
  - Measure e.g. $B^0\to K^*\tau\tau$
- LFNU linked with LFV:
  - Look for e.g. $B^0\to K^*\tau\mu$
  - $BR(\tau\to\mu\mu\mu)\sim 10^{-9}$

	μμ (ee)	ττ	νν	τμ	μe
$b\to s$	R_K, R_{K^*} O(20%)	$B\to K^{(*)}\tau\tau$ → 100×SM	$B\to K^{(*)}\nu\nu$ O(1)	$B\to K\,\tau\mu$ → ~10^{-6}	$B\to K\,\mu e$???
$b\to d$	$B_d\to\mu\mu$, $B\to\pi\,\mu\mu$, $B_s\to K^{(*)}\mu\mu$ O(20%) [$R_K=R_\pi$]	$B\to\pi\,\tau\tau$ → 100×SM	$B\to\pi\,\nu\nu$ O(1)	$B\to\pi\,\tau\mu$ → ~10^{-7}	$B\to\pi\,\mu e$???

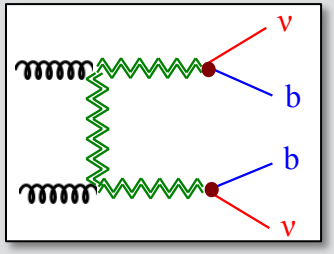
- c, u symmetry:
  - Study suppressed semileptonic

$$\frac{\Gamma(B\to\pi\,\tau\nu)/\Gamma_{SM}}{\Gamma(B\to\pi\,\mu\nu)/\Gamma_{SM}} = \frac{\Gamma(\Lambda_b\to p\,\tau\nu)/\Gamma_{SM}}{\Gamma(\Lambda_b\to p\,\mu\nu)/\Gamma_{SM}} = \frac{\Gamma(B_s\to K^*\tau\nu)/\Gamma_{SM}}{\Gamma(B_s\to K^*\mu\nu)/\Gamma_{SM}} = \dots = \frac{R_D}{(R_D)_{SM}}$$

- B_s mixing
  - O(1-10%) effect on Δm_s

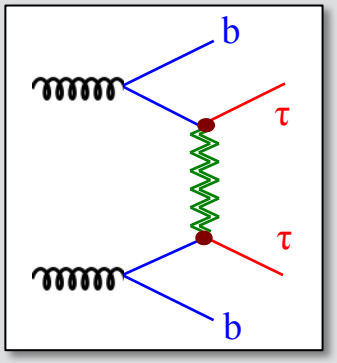
Model building

- Many more experimental handles; predictions can be checked!
- High p_T signatures?
  - LQ pairs

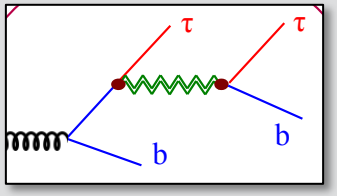


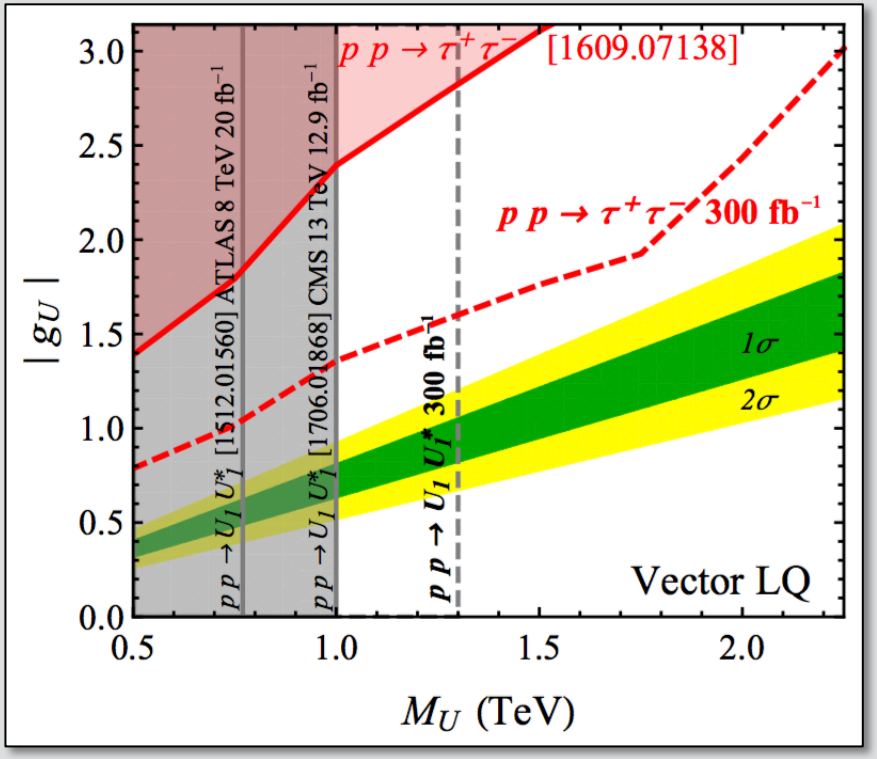
  - LQ t-channel in $bb \to \tau\tau$

Reachable during HL-LHC



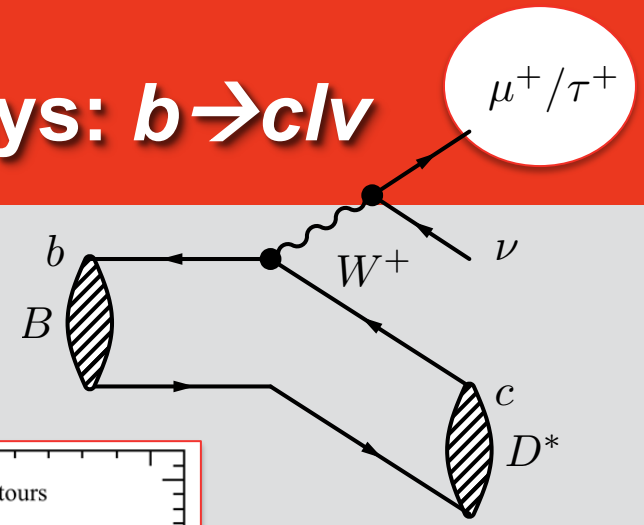
  - Single production channel (dominant?)





Buttazzo, Greljo, Isidori, Marzocca, B-physics anomalies: a guide to combined explanations JHEP 1711 (2017) 044

More LFNU? Semileptonic decays: *b→clν*



- Surprises possible in tree-level decays?

$$\mathcal{R}(D^*) \equiv \mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu)$$