



# **LHC searches in rare heavy-flavor decays**



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(on behalf of the LHCb collaboration, including  
results from ATLAS and CMS)**

# Waiting for...



I'll show you the results of a match between  
direct and indirect searches at the LHC

# SUSY & Exotics direct searches

## ATLAS SUSY Searches\* - 95% CL Lower Limits

Status: Moriond 2014

ATLAS Preliminary

$\int \mathcal{L} dt = (4.6 - 22.9) \text{ fb}^{-1}$   $\sqrt{s} = 7, 8 \text{ TeV}$

Model	$\epsilon, \mu, \tau, \gamma$	Jets	$E_{T}^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	Reference
<b>Inclusive Searches</b>						
MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	1.7 TeV	ATLAS-CONF-2013-047
MSUGRA/CMSSM	1 e, $\mu$	3-6 jets	Yes	20.3	1.2 TeV	ATLAS-CONF-2013-062
MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	1.1 TeV	1306.1941
MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	740 GeV	ATLAS-CONF-2013-047
$\tilde{g}, \tilde{g} \rightarrow q\bar{q}, \tilde{g} \rightarrow t\bar{t}$	0	2-6 jets	Yes	20.3	1.3 TeV	ATLAS-CONF-2013-047
$\tilde{g}, \tilde{g} \rightarrow q\bar{q}, \tilde{g} \rightarrow t\bar{t}, \tilde{g} \rightarrow W\gamma$	1 e, $\mu$	3-6 jets	Yes	20.3	1.16 TeV	ATLAS-CONF-2013-062
$\tilde{g}, \tilde{g} \rightarrow q\bar{q}, \tilde{g} \rightarrow t\bar{t}, \tilde{g} \rightarrow W\gamma, \tilde{g} \rightarrow WZ$	2 e, $\mu$	0-3 jets	Yes	20.3	1.12 TeV	ATLAS-CONF-2013-069
GMSB ( $\tilde{L}$ NLSP)	2 e, $\mu$	2-4 jets	Yes	4.7	1.24 TeV	1206.4969
GMSB ( $\tilde{L}$ NLSP)	1.2 e, $\mu$	0-2 jets	Yes	20.7	1.4 TeV	ATLAS-CONF-2013-026
GGM (bino NLSP)	2 $\gamma$	-	Yes	20.3	1.28 TeV	ATLAS-CONF-2014-001
GGM (wino NLSP)	1 e, $\mu, \tau, \gamma$	-	Yes	4.8	619 GeV	ATLAS-CONF-2012-144
GGM (higgsino-bino NLSP)	1.2 e, $\mu$	1 $\gamma$	Yes	4.8	800 GeV	1211.1167
GGM (higgsino NLSP)	2 e, $\mu$ (Z)	0-3 jets	Yes	5.8	600 GeV	ATLAS-CONF-2012-152
Gravitino LSP	0	mono-jet	Yes	10.5	645 GeV	ATLAS-CONF-2012-147
<b>3<sup>rd</sup> gen. &amp; med.</b>						
$\tilde{g} \rightarrow b\bar{b}, \tilde{g} \rightarrow t\bar{t}$	0	7-10 jets	Yes	20.1	1.2 TeV	ATLAS-CONF-2013-061
$\tilde{g} \rightarrow t\bar{t}, \tilde{g} \rightarrow b\bar{b}$	0	7-10 jets	Yes	20.1	1.1 TeV	1306.1941
$\tilde{g} \rightarrow t\bar{t}, \tilde{g} \rightarrow b\bar{b}$	0.1 e, $\mu$	3 $\gamma$	Yes	20.1	1.34 TeV	ATLAS-CONF-2013-061
$\tilde{g} \rightarrow t\bar{t}, \tilde{g} \rightarrow b\bar{b}$	0.1 e, $\mu$	3 $\gamma$	Yes	20.1	1.3 TeV	ATLAS-CONF-2013-061
<b>3<sup>rd</sup> gen. squarks direct production</b>						
$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t\bar{t}$	0	2 b	Yes	20.1	$\tilde{t}_1$	$m(\tilde{t}_1) > 90 \text{ GeV}$
$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t\bar{t}, \tilde{t}_1 \rightarrow Wb$	2 e, $\mu$ (SS)	0, 3 b	Yes	20.7	$\tilde{t}_1$	$m(\tilde{t}_1) > 2 m(\tilde{t}_1)$
$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t\bar{t}, \tilde{t}_1 \rightarrow Wb, \tilde{t}_1 \rightarrow t\bar{t}$	1.2 e, $\mu$	1, 2 b	Yes	4.7	$\tilde{t}_1$	1208.4905, 1209.2102
$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t\bar{t}, \tilde{t}_1 \rightarrow Wb, \tilde{t}_1 \rightarrow t\bar{t}$	2 e, $\mu$	0, 2 jets	Yes	20.3	$\tilde{t}_1$	1403.4853
$\tilde{t}_1 \tilde{t}_1$ (medium), $\tilde{t}_1 \rightarrow t\bar{t}$	2 e, $\mu$	2 jets	Yes	20.3	$\tilde{t}_1$	1403.4853
$\tilde{t}_1 \tilde{t}_1$ (medium), $\tilde{t}_1 \rightarrow t\bar{t}, \tilde{t}_1 \rightarrow Wb$	0	2 b	Yes	20.1	$\tilde{t}_1$	1306.2631
$\tilde{t}_1 \tilde{t}_1$ (heavy), $\tilde{t}_1 \rightarrow t\bar{t}$	1 e, $\mu$	1 b	Yes	20.7	$\tilde{t}_1$	ATLAS-CONF-2013-037
$\tilde{t}_1 \tilde{t}_1$ (heavy), $\tilde{t}_1 \rightarrow t\bar{t}$	0	2 b	Yes	20.5	$\tilde{t}_1$	ATLAS-CONF-2013-024
$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t\bar{t}$	0	mono-jet+tag	Yes	20.3	$\tilde{t}_1$	ATLAS-CONF-2013-068
$\tilde{t}_1 \tilde{t}_1$ (natural GMSB)	2 e, $\mu$ (Z)	1 b	Yes	20.3	$\tilde{t}_1$	1403.5222
$\tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow t\bar{t} + Z$	3 e, $\mu$ (Z)	1 b	Yes	20.3	$\tilde{t}_2$	1403.5222
<b>EW direct</b>						
$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t\bar{t}$	2 e, $\mu$	0	Yes	20.3	$\tilde{t}_1$	$m(\tilde{t}_1) > 90 \text{ GeV}$
$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t\bar{t}, \tilde{t}_1 \rightarrow Wb$	2 e, $\mu$	0	Yes	20.3	$\tilde{t}_1$	1403.5294
$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t\bar{t}, \tilde{t}_1 \rightarrow Wb$	2 e, $\mu$	0	Yes	20.7	$\tilde{t}_1$	1403.5294
$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t\bar{t}, \tilde{t}_1 \rightarrow Wb$	3 e, $\mu$	0	Yes	20.3	$\tilde{t}_1$	ATLAS-CONF-2013-028
$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t\bar{t}, \tilde{t}_1 \rightarrow Wb$	2-3 e, $\mu$	0	Yes	20.3	$\tilde{t}_1$	1402.7029
$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t\bar{t}, \tilde{t}_1 \rightarrow Wb$	1 e, $\mu$	2 b	Yes	20.3	$\tilde{t}_1$	1403.5294, 1402.7029
$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t\bar{t}, \tilde{t}_1 \rightarrow Wb$	2 e, $\mu$	2 b	Yes	20.3	$\tilde{t}_1$	ATLAS-CONF-2013-033
<b>Long-lived particles</b>						
Direct $\tilde{t}_1 \tilde{t}_1$ prod., long-lived $\tilde{t}_1$	Disapp. trk	1 jet	Yes	20.3	$\tilde{t}_1$	ATLAS-CONF-2013-069
Stable, stopped $\tilde{t}_1$ -hadron	0	1-9 jets	Yes	22.9	$\tilde{t}_1$	ATLAS-CONF-2013-067
GMSB, stable $\tilde{t}_1, \tilde{t}_1 \rightarrow t\bar{t}, \tilde{t}_1 \rightarrow Wb, \tilde{t}_1 \rightarrow t\bar{t}$	1.2 $\mu$	-	Yes	4.7	$\tilde{t}_1$	10-nanb-50
GMSB, $\tilde{t}_1 \rightarrow t\bar{t}$ , long-lived $\tilde{t}_1$	2 $\gamma$	-	Yes	4.7	$\tilde{t}_1$	1304.6310
$\tilde{g}, \tilde{g} \rightarrow q\bar{q}$ (RPV)	1 $\mu$ , displ. vtx	-	Yes	20.3	$\tilde{g}$	ATLAS-CONF-2013-092
<b>RPV</b>						
LFV $\tilde{g} \rightarrow t\bar{t} + X, \tilde{g} \rightarrow t\bar{t} + \mu$	2 e, $\mu$	-	Yes	4.6	$\tilde{g}$	1212.1272
LFV $\tilde{g} \rightarrow t\bar{t} + X, \tilde{g} \rightarrow t\bar{t} + \tau$	1 e, $\mu, \tau$	-	Yes	4.6	$\tilde{g}$	1212.1272
Bi-linear RPV CMSSM	1 e, $\mu$	7 jets	Yes	4.7	$\tilde{g}$	ATLAS-CONF-2012-140
$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t\bar{t}, \tilde{t}_1 \rightarrow Wb, \tilde{t}_1 \rightarrow t\bar{t}$	4 e, $\mu$	-	Yes	20.7	$\tilde{t}_1$	ATLAS-CONF-2013-038
$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t\bar{t}, \tilde{t}_1 \rightarrow Wb, \tilde{t}_1 \rightarrow t\bar{t}$	3 e, $\mu, \tau$	-	Yes	20.7	$\tilde{t}_1$	ATLAS-CONF-2013-036
$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t\bar{t}, \tilde{t}_1 \rightarrow Wb, \tilde{t}_1 \rightarrow t\bar{t}$	0	6-7 jets	Yes	20.3	$\tilde{t}_1$	ATLAS-CONF-2013-091
$\tilde{g} \rightarrow t\bar{t}, \tilde{g} \rightarrow b\bar{b}$	2 e, $\mu$ (SS)	0-3 b	Yes	20.7	$\tilde{g}$	ATLAS-CONF-2013-007
Scalar gluon pair, sgluon $\rightarrow \tilde{g}$	0	4 jets	Yes	4.6	sgluon	incl. limit from 1110.2693
Scalar gluon pair, sgluon $\rightarrow \tilde{g}$	2 e, $\mu$ (SS)	2 $\gamma$	Yes	14.3	sgluon	ATLAS-CONF-2013-051
WIMP interaction (D5, Dirac $\chi$ )	0	mono-jet	Yes	10.5	$\tilde{g}$ scale	ATLAS-CONF-2012-147

@ ATLAS (CMS similar trend)

SUSY

## S Exotics Searches\* - 95% CL Exclusion

April 2014

ATLAS Preliminary

$\int \mathcal{L} dt = (1.0 - 20.3) \text{ fb}^{-1}$   $\sqrt{s} = 7, 8 \text{ TeV}$

Model	$\ell, \gamma$	Jets	$E_{T}^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	Reference
<b>idell</b>						
$\tilde{g} \rightarrow g\bar{g}$	-	1-2 j	Yes	4.7	$M_{\tilde{g}}$	4.37 TeV
gluon-sansant ( $\ell\ell\gamma\gamma$ )	2 $\gamma$ or 2 e, $\mu$	-	Yes	4.7	$M_{\tilde{g}}$	4.38 TeV
$\tilde{g}H \rightarrow f\bar{f}$	1 e, $\mu$	1 j	-	20.3	$M_{\tilde{g}}$	5.2 TeV
H high $N_{eff}$	2 $\mu$ (SS)	-	-	20.3	$M_{\tilde{g}}$	5.7 TeV
H high $\Delta p_T$	$\geq 1 e, \mu \geq 2 j$	-	-	20.3	$M_{\tilde{g}}$	6.2 TeV
$\tilde{g} \rightarrow t\bar{t}$	2 e, $\mu$	-	-	20.3	$M_{\tilde{g}}$	2.47 TeV
Bulk RS $\tilde{g}_{KK} \rightarrow t\bar{t}$	1 e, $\mu$	$\geq 1 b, \geq 1 W$	Yes	14.3	$M_{\tilde{g}_{KK}}$	590-710 GeV
$\tilde{g}_{KK} \rightarrow t\bar{t}$	2 e, $\mu$	-	-	5.0	$M_{\tilde{g}_{KK}}$	0.5-2.0 TeV
UED	2 $\gamma$	-	Yes	4.8	Compact scale $R^{-1}$	4.71 TeV
<b>Gauge bosons</b>						
$\tilde{Z} \rightarrow \ell\ell$	2 e, $\mu$	-	-	20.3	$Z'$ mass	2.86 TeV
$\tilde{Z} \rightarrow \tau\tau$	2 $\tau$	-	-	19.5	$Z'$ mass	1.9 TeV
$\tilde{W} \rightarrow f\bar{f}$	1 e, $\mu$	-	Yes	20.3	$W'$ mass	3.26 TeV
EGM $W' \rightarrow WZ$	3 e, $\mu$	-	Yes	20.3	$W'$ mass	1.32 TeV
LRS $W'_2 \rightarrow t\bar{t}$	1 e, $\mu$	2 b, 0-1 j	Yes	14.3	$W'$ mass	1.59 TeV
<b>CI</b>						
CI $q\bar{q}q$	-	2 j	-	4.8	A	7.6 TeV
CI $q\bar{q}\ell\ell$	2 e, $\mu$	-	-	5.0	A	13.9 TeV
CI $u\bar{u}t\tau$	2 e, $\mu$ (SS) $\geq 1 b, \geq 1 j$	Yes	14.3	A	3.8 TeV	
<b>DM</b>						
EFT D5 operator	-	1-2 j	Yes	10.5	M <sub>DM</sub>	731 GeV
EFT D9 operator	-	1, 3, 5 j	Yes	20.3	M <sub>DM</sub>	2.4 TeV
Scalar LQ 1 <sup>st</sup> gen	2 e $\geq 2 j$	-	-	1.0	LQ mass	660 GeV
Scalar LQ 2 <sup>nd</sup> gen	2 $\mu$ $\geq 2 j$	-	-	1.0	LQ mass	685 GeV
Scalar LQ 3 <sup>rd</sup> gen	1 e, $\mu, \tau$ 1 b, 1 j	-	-	4.7	LQ mass	934 GeV
<b>Heavy quarks</b>						
Vector-like quark $TT \rightarrow Ht + X$	1 e, $\mu$	$\geq 2 b, \geq 4 j$	Yes	14.3	T mass	790 GeV
Vector-like quark $TT \rightarrow Wb + X$	1 e, $\mu$	$\geq 1 b, \geq 3 j$	Yes	14.3	T mass	970 GeV
Vector-like quark $BB \rightarrow Zb + X$	2 e, $\mu$	$\geq 2 b$	-	14.3	B mass	725 GeV
Vector-like quark $BB \rightarrow Wt + X$	2 e, $\mu$ (SS) $\geq 1 b, \geq 1 j$	Yes	14.3	B mass	720 GeV	
<b>Excited fermions</b>						
Excited quark $q^* \rightarrow q\gamma$	1 $\gamma$	1 j	-	20.3	$q^*$ mass	1.5 TeV
Excited quark $q^* \rightarrow qZ$	-	2 j	-	13.0	$q^*$ mass	1.84 TeV
Excited quark $b^* \rightarrow Wt$	1 or 2 e, $\mu$ , 1 b, 2 j or 1 $\gamma$	Yes	4.7	$b^*$ mass	870 GeV	
Excited lepton $\ell^* \rightarrow \ell\gamma$	2 e, $\mu, \tau, 1 \gamma$	-	-	13.0	$\ell^*$ mass	2.2 TeV
<b>Other</b>						
LRS Majorana $\nu$	2 e, $\mu$	2 j	-	2.1	$M_{\tilde{\nu}}$ mass	1.5 TeV
Type III Seesaw	2 e, $\mu$	-	-	5.8	$M_{\tilde{\nu}}$ mass	245 GeV
Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	2 e, $\mu$ (SS)	-	-	4.7	$H^{\pm\pm}$ mass	409 GeV
Multi-charged particles	-	-	-	4.4	multi-charged particle mass	490 GeV
Magnetic monopoles	-	-	-	2.0	monopole mass	862 GeV

Exotics

\*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1 $\sigma$  theoretical signal cross section uncertainty.

...no New Physics...

\*Only a selection of the available mass limits on new states or phenomena is shown.

# Flavor Physics

Flavor Physics has played a central role in the development of the Standard Model:

**c-quark** inferred from measurements showing suppression of  $K^0 \rightarrow \mu\mu$  rate compared to  $K \rightarrow \mu\nu$  (GIM 1970)

Discovery of  $J/\Psi$  in 1974 (SLAC, BNL)

**t,b-quarks** inferred from CPV in K sector (KM of CKM 1973)  
Limit on t-quark mass  $> 50$  GeV from  $B_0$  mixing (ARGUS 1987)

Discovery of the t-quark in 1995 (D0, CDF)

**Weak neutral current** inferred from neutrino scattering in Gargamelle (1973)

Discovery of the  $Z^0$  boson in 1983 (UA1,UA2)

**Flavor Physics can play a central role in reaching beyond the SM!**

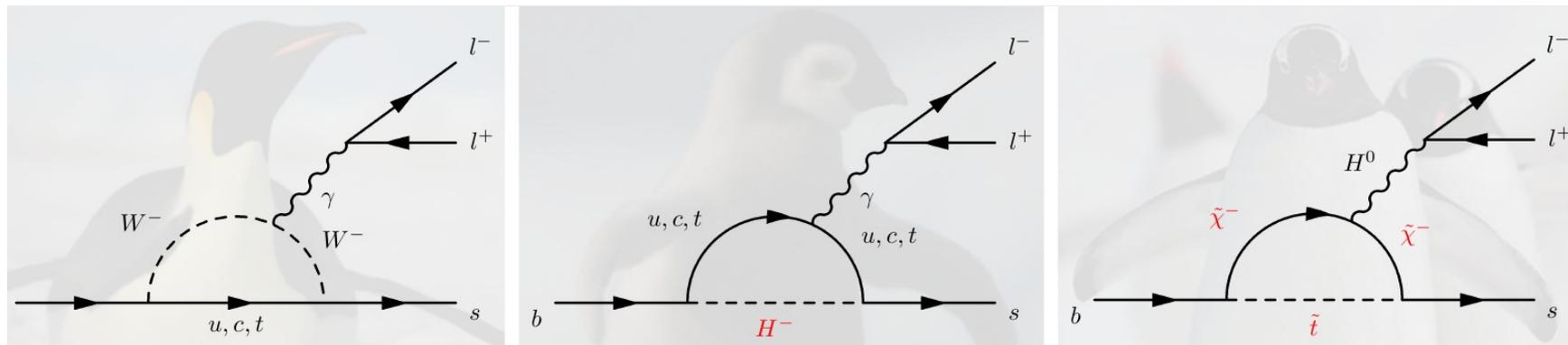
NP at  $\Lambda_{NP} \sim 1\text{TeV}$  **motivated** to tame fine tuning in Higgs sector

NP at  $\Lambda_{NP} \sim 1\text{TeV}$  **refuted** by flavor measurements (pre LHC)  $\rightarrow$  CKM-like NP couplings (MFV)

**LHC pushes NP to  $\gg 1$  TeV  $\rightarrow$  MFV constraints are lifted  
Increase chance to see new physics in flavor**

# FCNC to the rescue?

Naturalness' loss = Flavor's gain?



New Physics indirect searches via FCNC processes (e.g.  $b \rightarrow s l^+ l^-$ ) **forbidden at tree level in SM proceed via penguins/boxes**

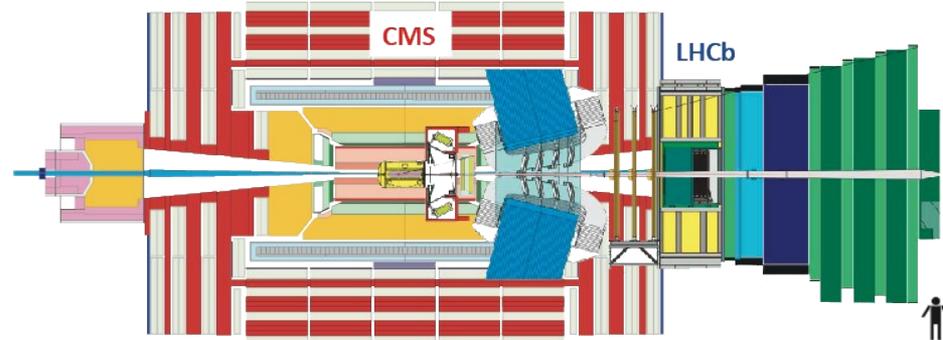
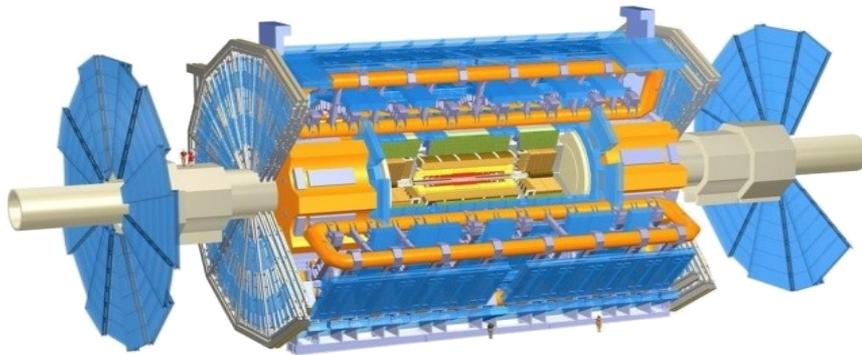
⇒ suppressed by GIM-mechanism

Many extensions of the SM may contribute to these processes involving **"new" virtual particles** (e.g. charged Higgs, squarks...)

⇒ **can access higher energy scales than direct searches**

# The tools

**ATLAS** and **CMS** largely in central region ( $|\eta| < 2.4$ ), **LHCb**  
forward region ( $2 < \eta < 5$ )



**Measured  $\sigma(pp \rightarrow bbX)$  cross-section (at 7 TeV):**

ATLAS ( $32.7 \pm 0.8^{+4.5}_{-5.8}$ )  $\mu\text{b}$  ( $p_T(B) > 9\text{GeV}$  and  $|\eta| < 2.5$ )

CMS ( $28.1 \pm 2.4 \pm 2.0 \pm 3.1$ )  $\mu\text{b}$  ( $p_T(B) > 5\text{ GeV}$  and  $|\eta| < 2.4$ )

LHCb ( $75.3 \pm 5.4 \pm 13.0$ )  $\mu\text{b}$  ( $2 < \eta < 6$ )

[PLB 694 (2010) 209]

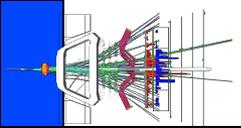
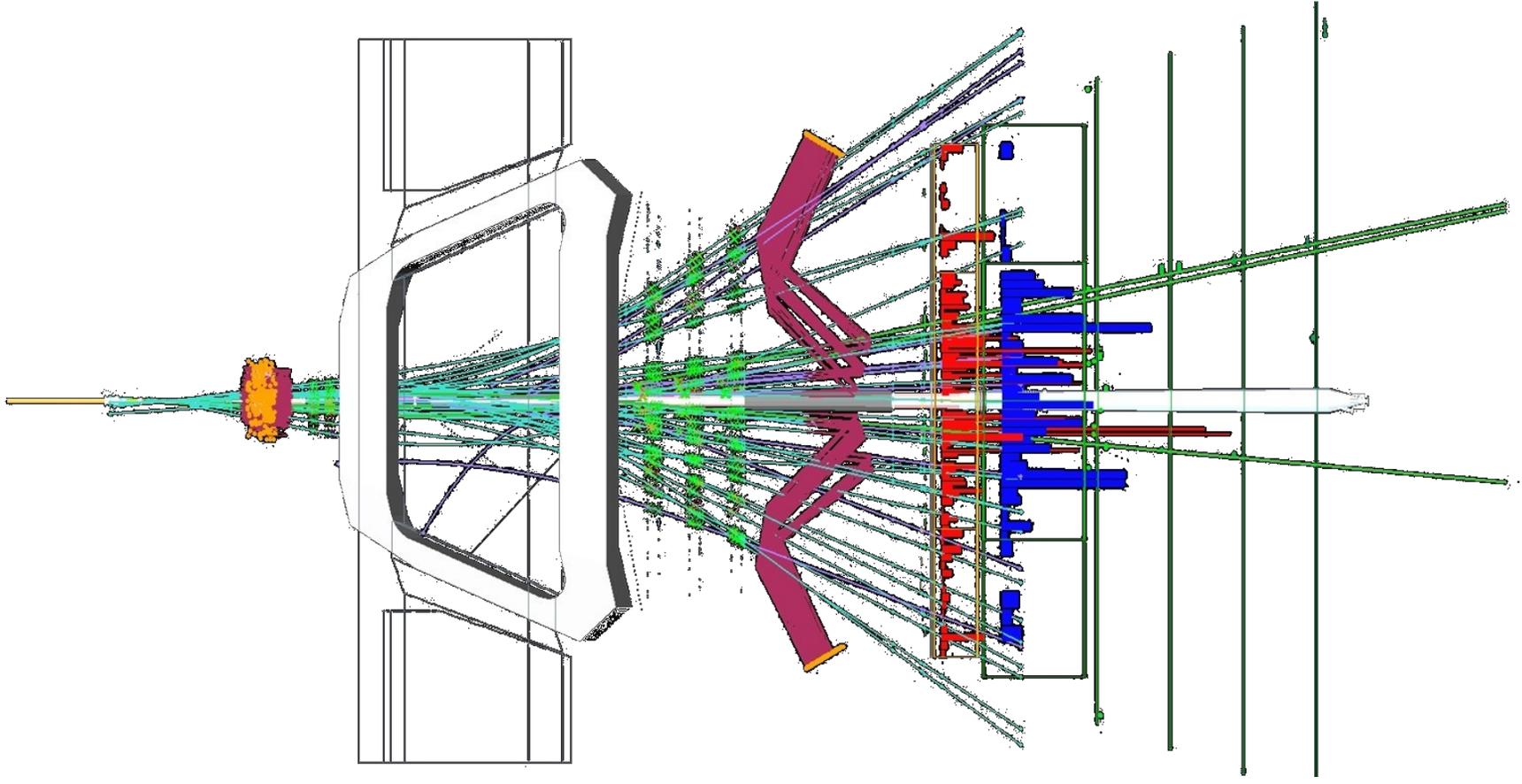
[Nucl.Phys. B864 (2012) 341-381]

[Phys.Rev.Lett.106:252001,2011]

**Each experiment:  $0(10^{10})/\text{fb}$   $bb$  pairs on tape**

Compare to **combined BaBar and Belle data sample** of  $\sim 10^9$   $B^0 B^0$   
pairs. For any channel where the (trigger, reconstruction,  
stripping, offline) efficiency is not too small, LHC have the  
world's largest data sample.. **the right place to look for very  
rare B decays.**

# B $\rightarrow$ leptons



# $B_{(s)} \rightarrow \mu\mu$ : Introduction

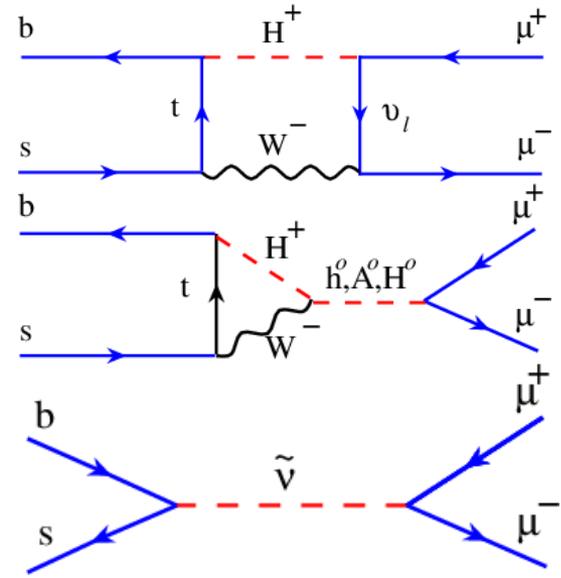
$$BR(B_q^0 \rightarrow \ell^+ \ell^-) = \left( \frac{G_F^2 \alpha^2}{64 \pi^3} \right) \cdot |V_{tb}^* V_{tq}|^2 \cdot \tau_{B_q} \cdot f_{B_q}^2 \cdot M_{B_q}^3 \cdot \sqrt{1 - 4 \frac{m_\ell^2}{M_{B_q}^2}} \longrightarrow \text{helicity suppression}$$

$$\times \left\{ \left| 2 \frac{m_\ell}{M_{B_q}} (C_{10} - C'_{10}) + (C_P - C'_P) \right|^2 + \left( 1 - 4 \frac{m_\ell^2}{M_{B_q}^2} \right) |C_S - C'_S|^2 \right\}$$

In MSSM:

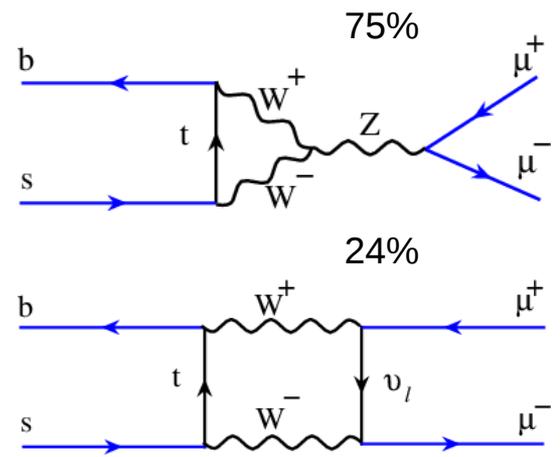
$$C_{S,P}^{MSSM} \propto \frac{m_b^2 m_\mu^2 \tan^6 \beta}{M_A^4}$$

2HDM:



RPV:

SM contributions:



Mode	SM
$B_s \rightarrow \mu^+ \mu^-$	$3.65 \pm 0.23 \times 10^{-9}$
$B^0 \rightarrow \mu^+ \mu^-$	$1.06 \pm 0.09 \times 10^{-10}$

Bobeth et al., arXiv:1311.0903v1

sensitive to contributions in the **scalar/pseudo-scalar sector**  
 highly interesting to probe **extended Higgs** models and **high  $\tan\beta$**   
 limit or measurement of  $B_{s,d} \rightarrow \mu\mu$  strongly constrain  **$\tan\beta$  vs  $M_A$  plane**

# $B_{(s)} \rightarrow \mu\mu$ : finally, the signs

LHCb

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

with  $4.0\sigma$  sign.

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

with  $2.0\sigma$  sign.

[PRL 111(2013)101805]

CMS

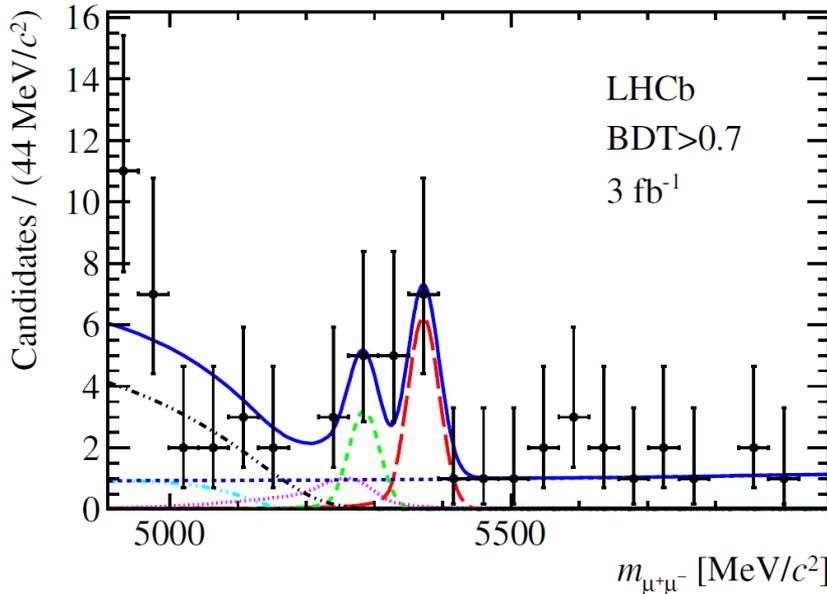
$$\text{BR}(B_s \rightarrow \mu\mu) = (3.0_{-0.8}^{+0.9} (stat)_{-0.4}^{+0.6} (syst)) \times 10^{-9}$$

with  $4.3\sigma$  sign.

$$\text{BR}(B_d \rightarrow \mu\mu) = (3.5_{-1.8}^{+2.1} (stat+syst)) \times 10^{-10}$$

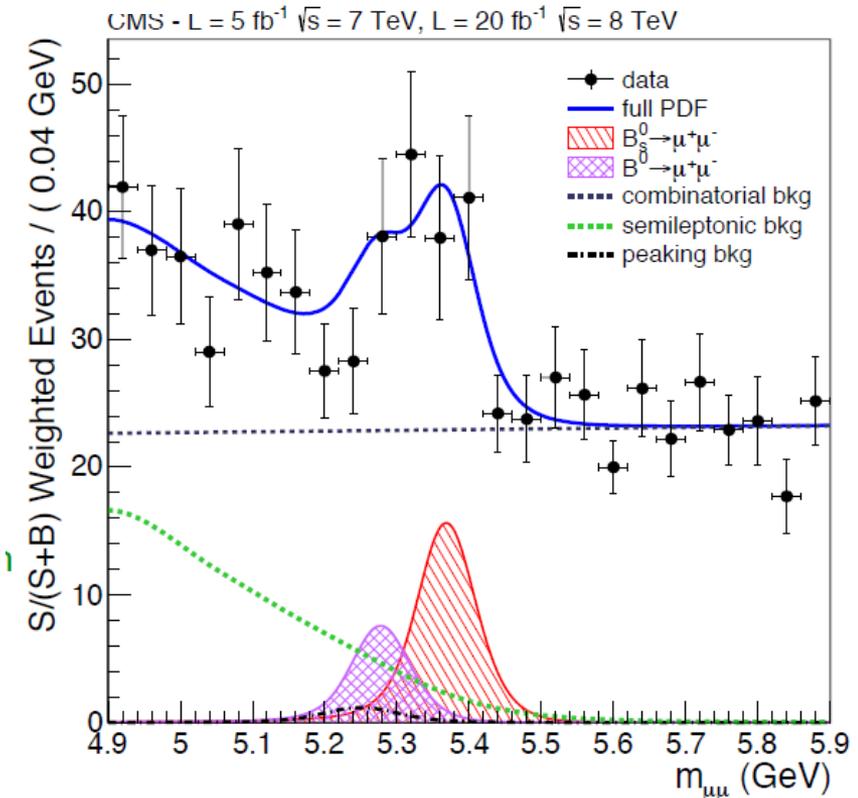
with  $2.0\sigma$  sign.

[PRL 111(2013)101804]



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

[ATLAS-CONF-2013-076]



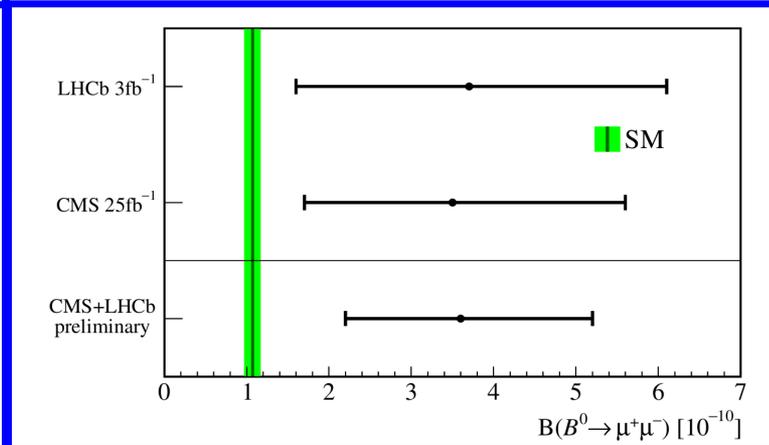
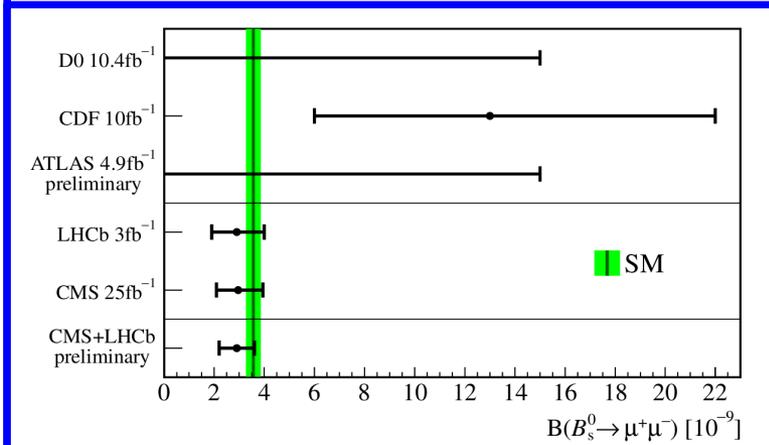
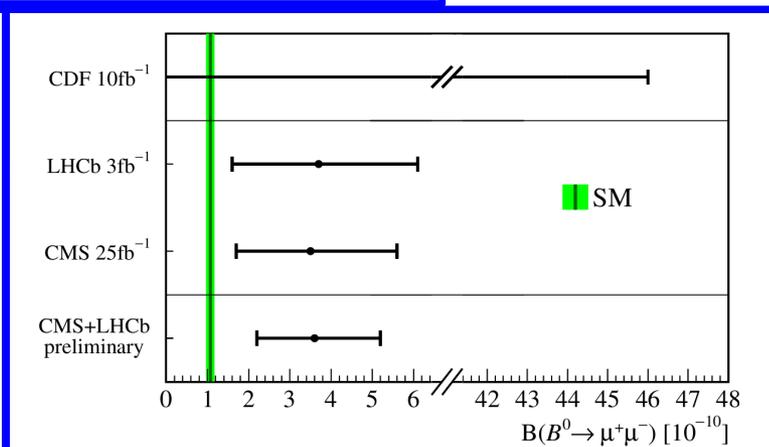
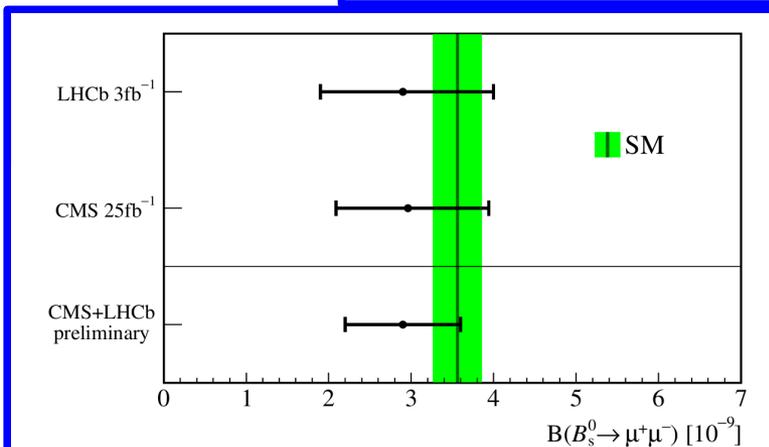
# Combination LHCb/CMS

## Averages

$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (2.9 \pm 0.7) \cdot 10^{-9}$$

$$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = 3.6_{-1.4}^{+1.6} \cdot 10^{-10}$$

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



**Soon :** combined fit to the CMS/LHCb data, sharing of all PDFs and correlated parameters ( $f_s/f_d$ ,  $\text{BR}(B^+ \rightarrow J/\psi K^+)$ , ...).

**Output:** combined BF and 2D scans, significances.

A long way since 1984 at CLEO:

PHYSICAL REVIEW D

VOLUME 30, NUMBER 11

1 DECEMBER 1

## Two-body decays of $B$ mesons

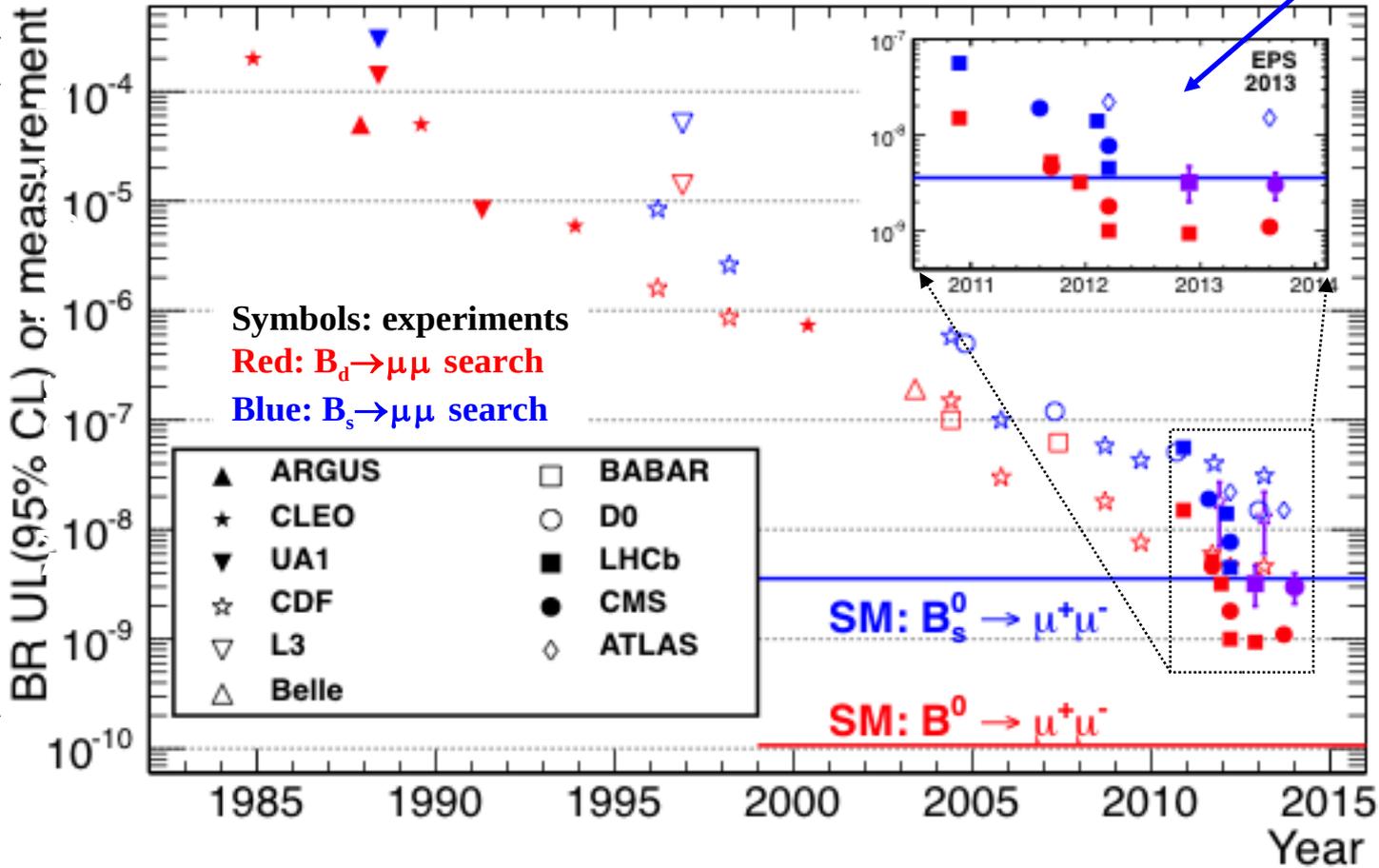
### B. Search for exclusive $\bar{B}^0$ decays into two charged leptons

Our search for the  $\pi^+\pi^-$  final state is not sensitive to the mass of the final-state particles, provided that they are light, since the mass enters only in the energy constraint. Therefore, the upper limit of 0.05% applies for any final-state particles with a pion mass or less. When the final-state particles are leptons the limits are improved by using the lepton identification capabilities of the CLEO detector.<sup>14</sup> For the decay  $\bar{B}^0 \rightarrow \mu^+\mu^-$ , we improve our limit by requiring that both muons penetrate the iron and produce signals in drift chambers. We find no such events. After correcting for detection efficiency (33%), we set an upper limit of 0.02% at 90% confidence for this decay. We im-

# 25 years of $B_{(s)} \rightarrow \mu\mu$

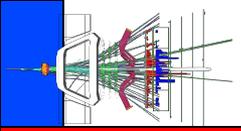
◇ full Run1 ATLAS update on the way

5 orders of magnitude

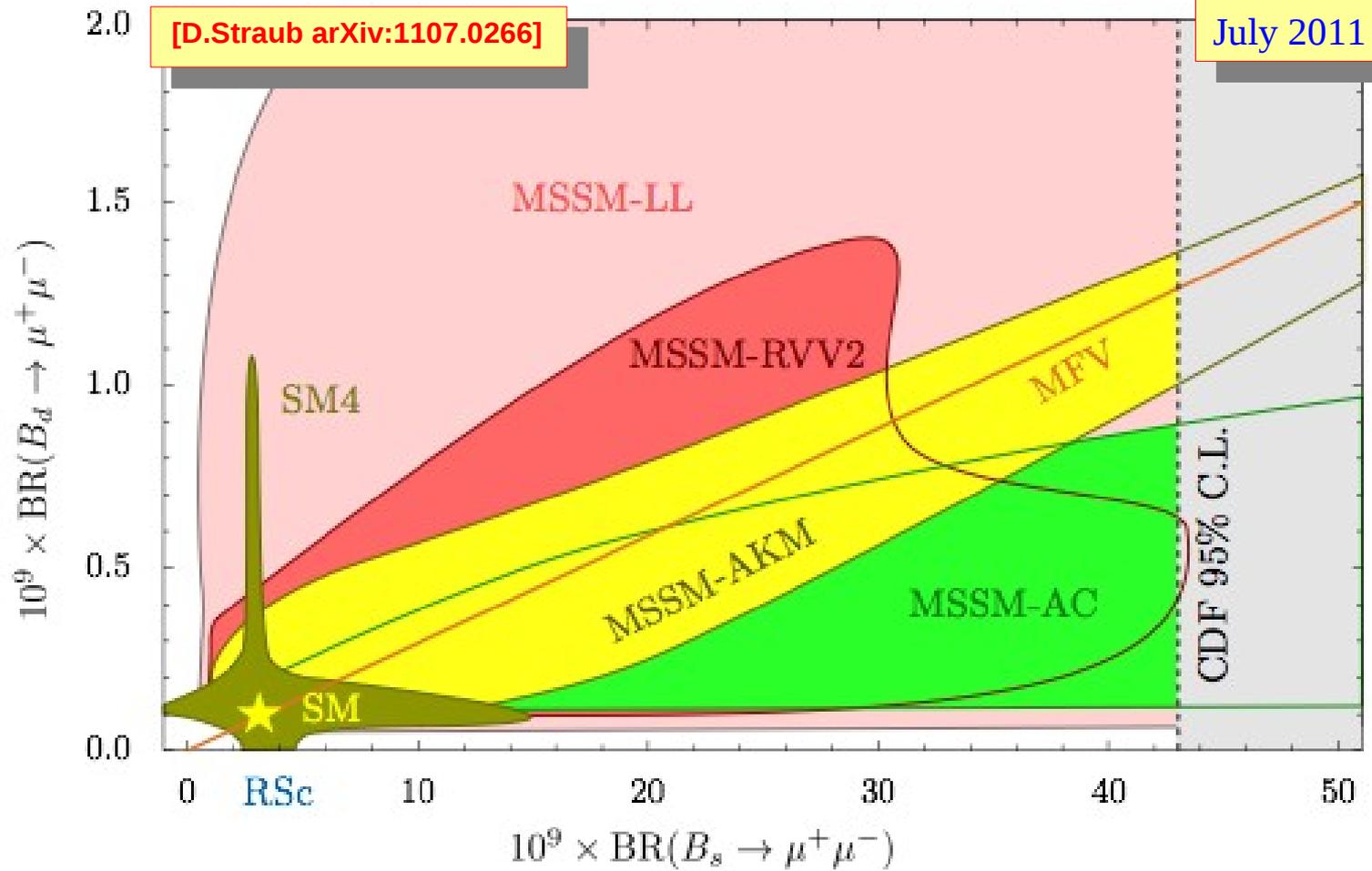


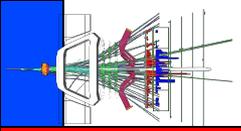
>25 years

Crucial role of hadronic colliders, Tevatron first, and now LHC



# Closing up on NP

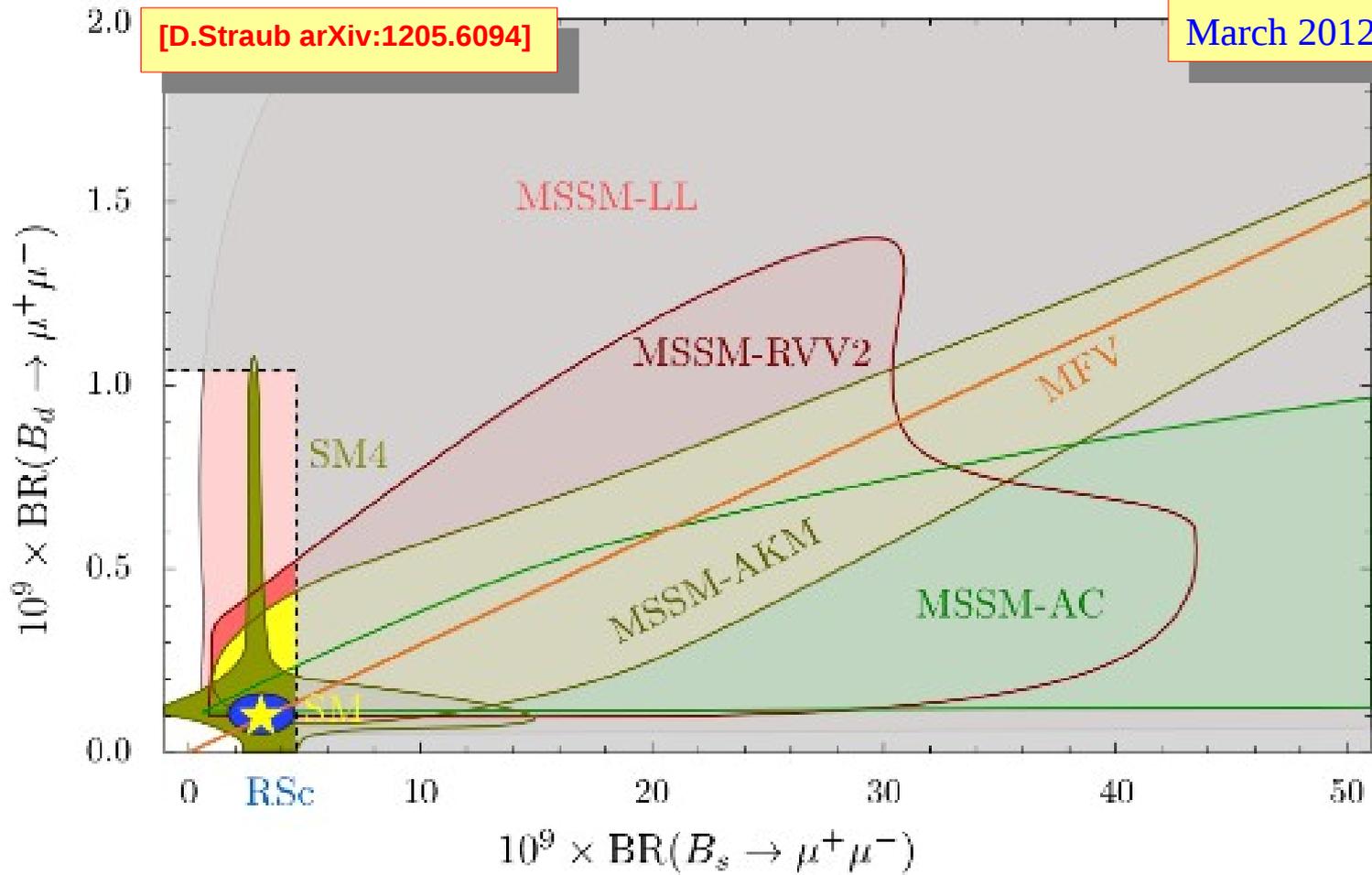


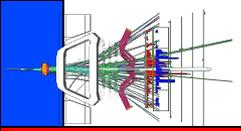


# Closing up on NP

[D.Straub arXiv:1205.6094]

March 2012

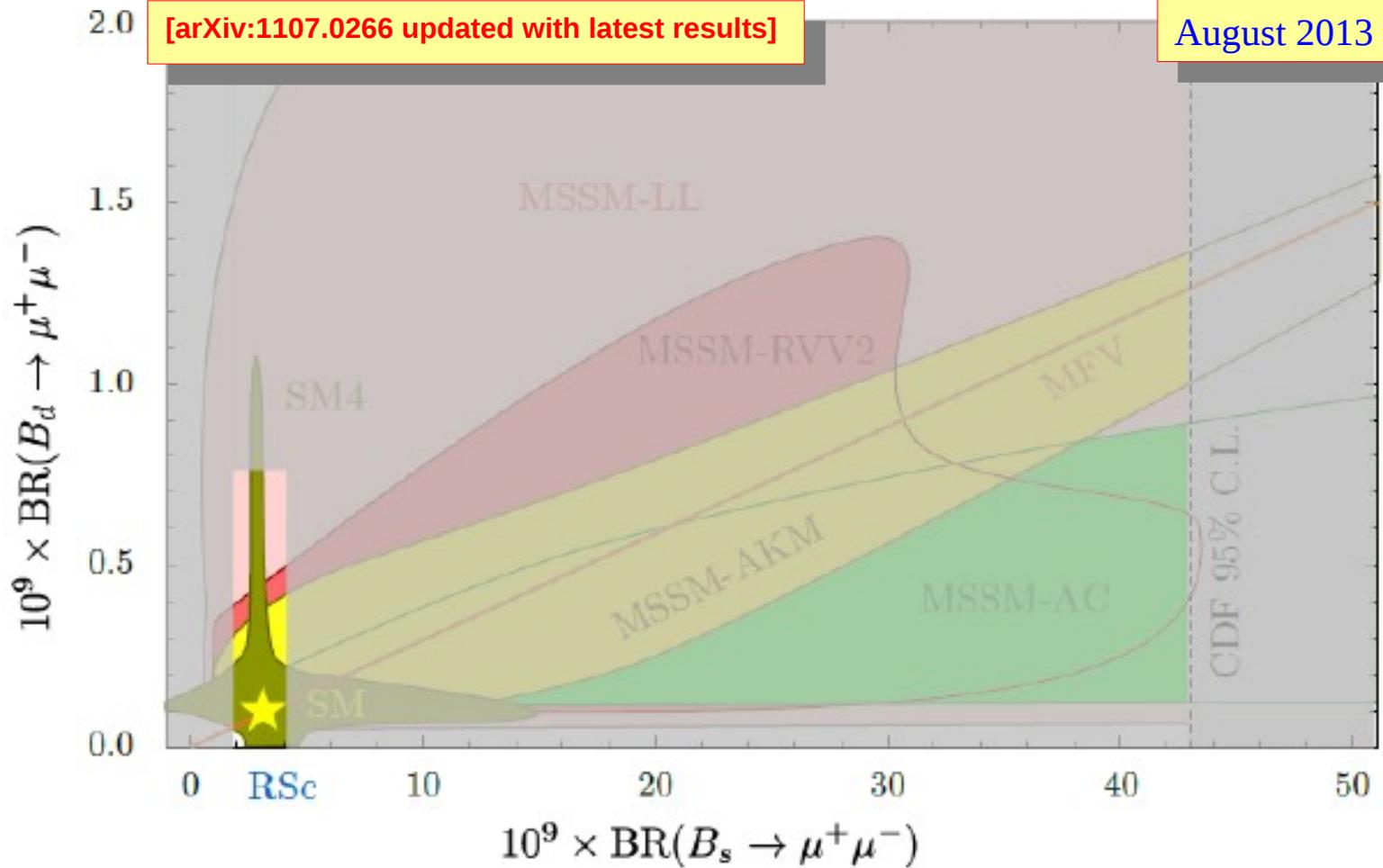




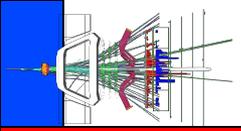
# Closing up on NP

[arXiv:1107.0266 updated with latest results]

August 2013



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



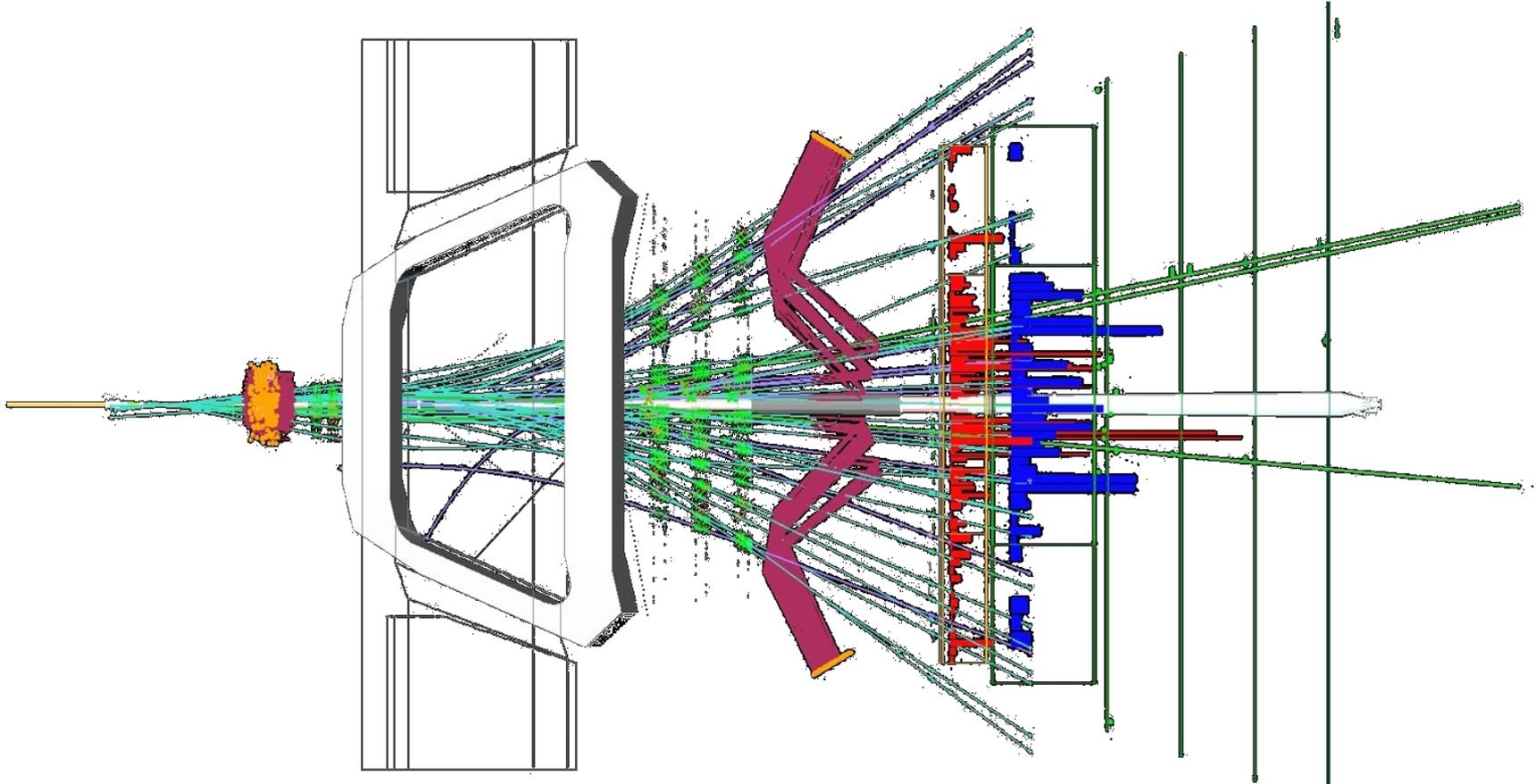
## Is there any space for new physics left?

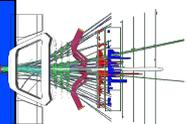
“The success of the LHCb experiment has so far been a nightmare for all flavour physicists that were hoping to see signs of new physics popping up in  $B_s$  and  $B^0$  mixing and the rare  $B_s \rightarrow \mu \mu$  decay. This situation might have changed with the latest measurements [1,2]”

[Gauld, Goertz, Haisch, arXiv:1310.1082]

[1,2] are discussed in the next slides.

$$b \rightarrow x l^+ l^-$$



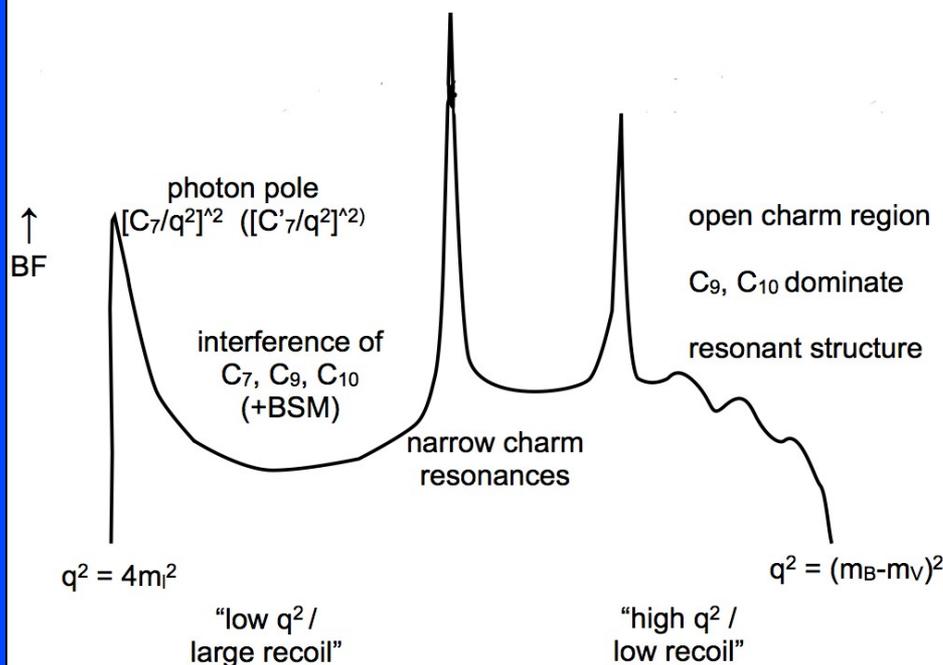


# Introduction

If  $b \rightarrow s/d l^+ l^-$  FCNC processes represent a very rich environment, three/four-particles final states are special as:

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

**Sensitive to magnetic, vector, and axial semileptonic penguin operators:  $O_7, O_9, O_{10}$**



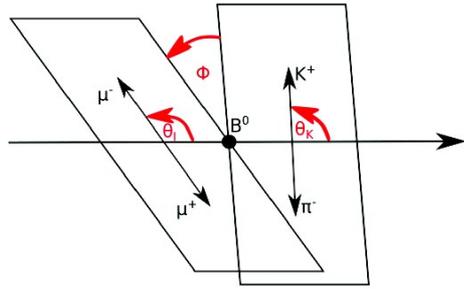
Operator $O_i$	$B \rightarrow K^{*0} \mu^+ \mu^-$	$B \rightarrow \mu^+ \mu^-$
$O_7 \sim m_b (\bar{s}_L \sigma_{\mu\nu} b_R) F_{\mu\nu}$	✓	
$O_9 \sim (\bar{s}b)_{V-A} (\bar{\ell}\ell)_V$	✓	
$O_{10} \sim (\bar{s}b)_{V-A} (\bar{\ell}\ell)_A$	✓	✓
$O_{S,P} \sim (\bar{s}b)_{S+P} (\bar{\ell}\ell)_{S,P}$		✓

From S. Jaeger at Workshop on  $b \rightarrow sll$  processes, 1-3 April 2014

# $B \rightarrow K^* \mu^+ \mu^-$

Decay described with 3 angles ( $\theta_1$ ,  $\theta_K$ ,  $\phi$ ) and dimuon mass  $q^2$   
 Parametrized in terms of **angular observables**

$$\frac{1}{\Gamma} \frac{d^3(\Gamma + \bar{\Gamma})}{d \cos \theta_\ell d \cos \theta_K d \phi} = \frac{9}{32\pi} \left[ \frac{3}{4}(1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4}(1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell \right.$$



$$\begin{aligned} & - F_L \cos^2 \theta_K \cos 2\theta_\ell + \frac{1}{2}(1 - F_L) A_T^{(2)} \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi + \\ & \sqrt{F_L(1 - F_L)} P'_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + \sqrt{F_L(1 - F_L)} P'_5 \sin 2\theta_K \sin \theta_\ell \cos \phi + \\ & (1 - F_L) A_{Re}^T \sin^2 \theta_K \cos \theta_\ell + \sqrt{F_L(1 - F_L)} P'_6 \sin 2\theta_K \sin \theta_\ell \sin \phi + \\ & \left. \sqrt{F_L(1 - F_L)} P'_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + (S/A)_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right] \end{aligned}$$

$\phi \rightarrow \phi + \pi$  for  $\phi < 0$

$A_{FB}$

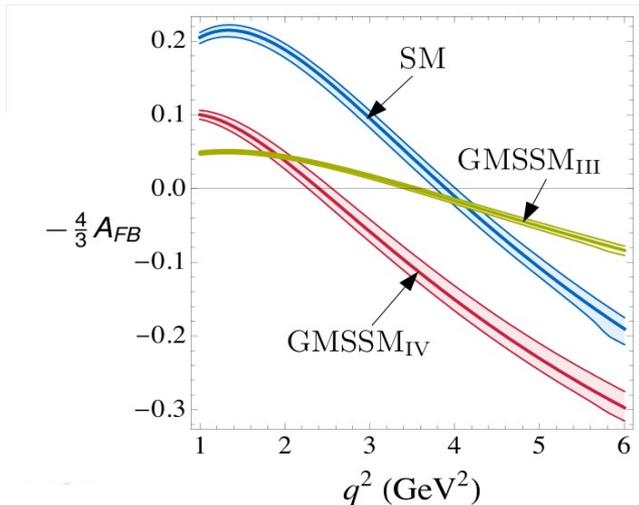
Forward-backward asymmetry ( $\theta_1$ )

$F_L$

fraction of  $K^{*0}$  longitudinally polarized

$S_9$

T-odd CP



Hadronic form factors uncertainties under control at low  $q^2$

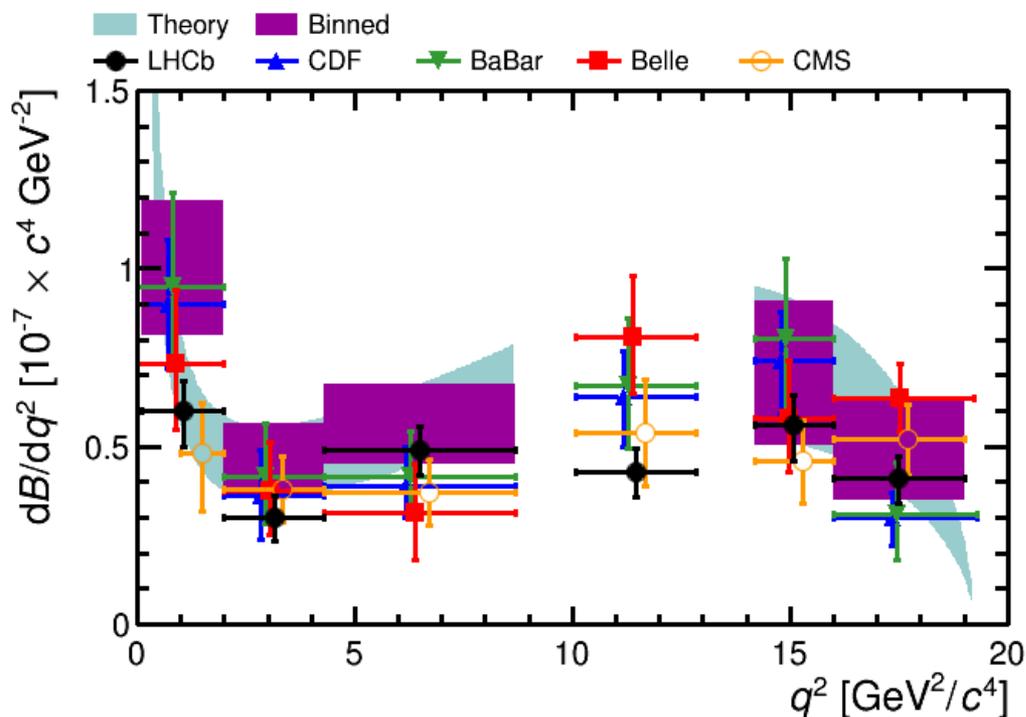
Zero asymmetry @  $q^2 = 4.36^{+0.33}_{-0.31} \text{ (GeV/c}^2\text{)}^2$

# Branching fractions

LHCb: Differential branching fraction in bins of dimuon invariant mass  $q^2$  determined with normalization to  $B^0 \rightarrow J/\psi K^{*0}$

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

CMS  $415 \pm 30$  events ( $5.2 \text{ fb}^{-1}$ )  
ATLAS  $466 \pm 34$  events ( $4.9 \text{ fb}^{-1}$ )  
LHCb  $883 \pm 34$  events ( $1.0 \text{ fb}^{-1}$ )



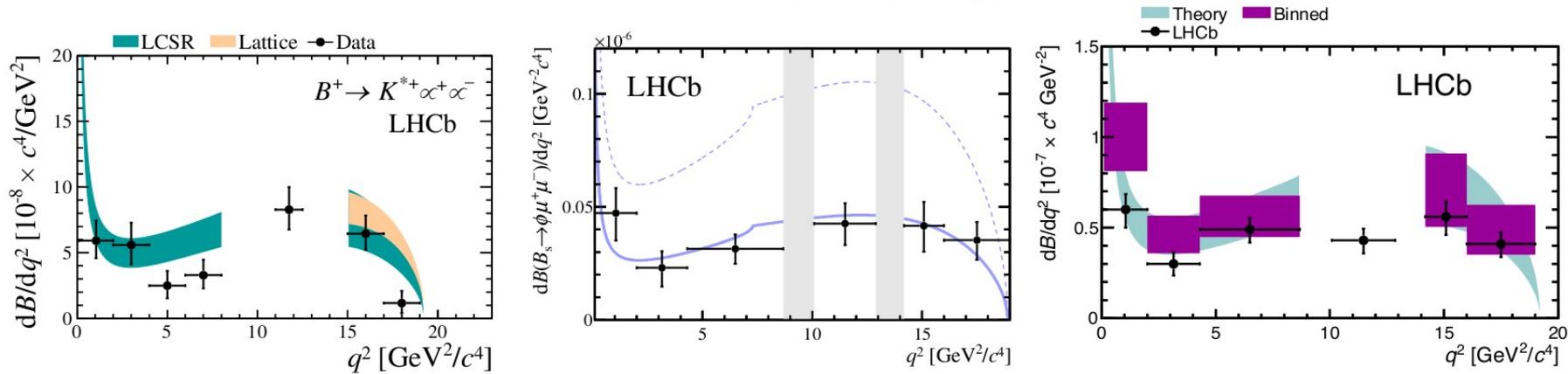
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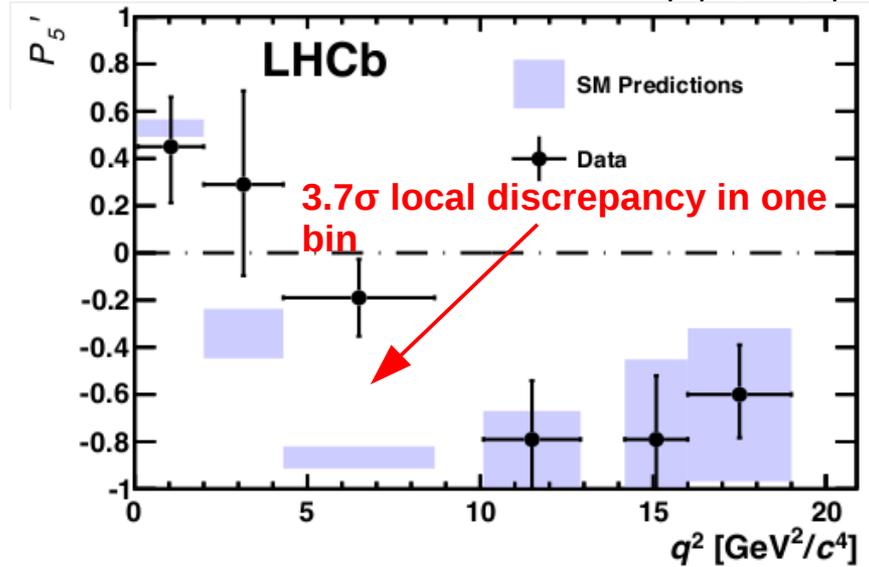
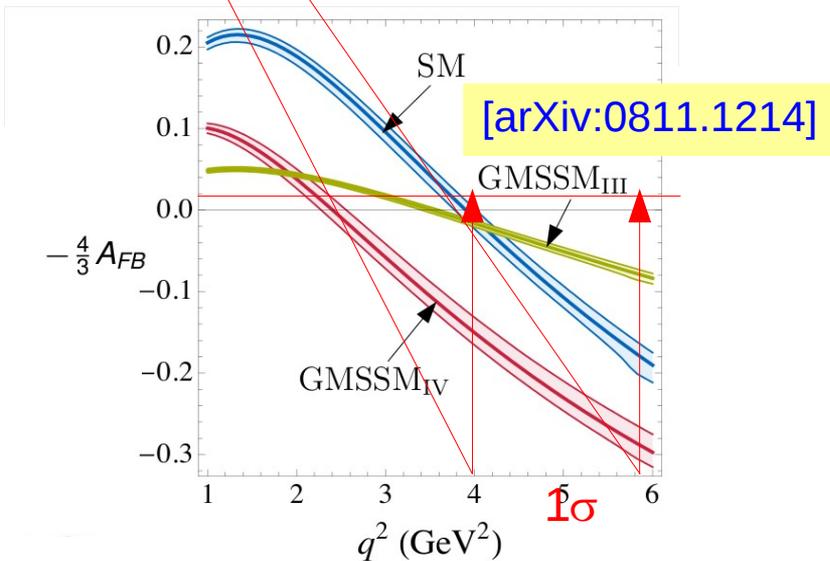
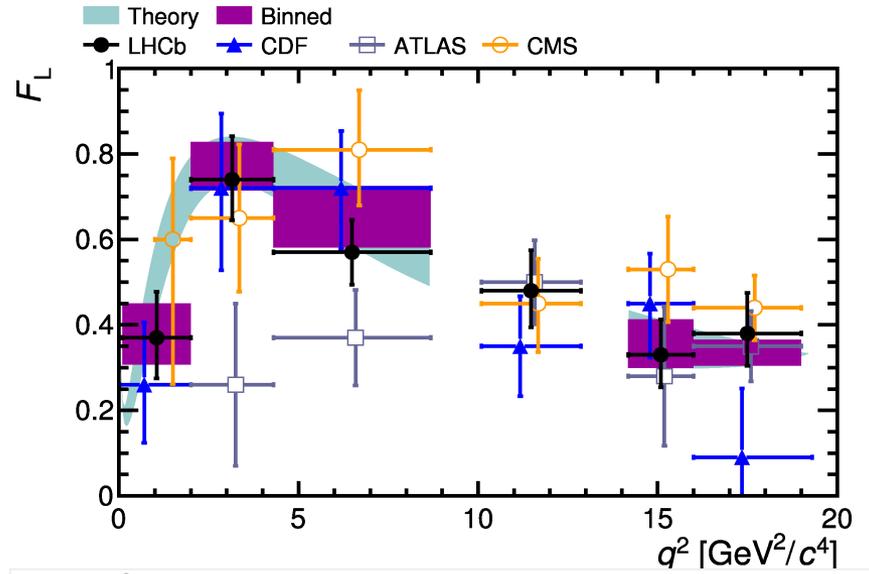
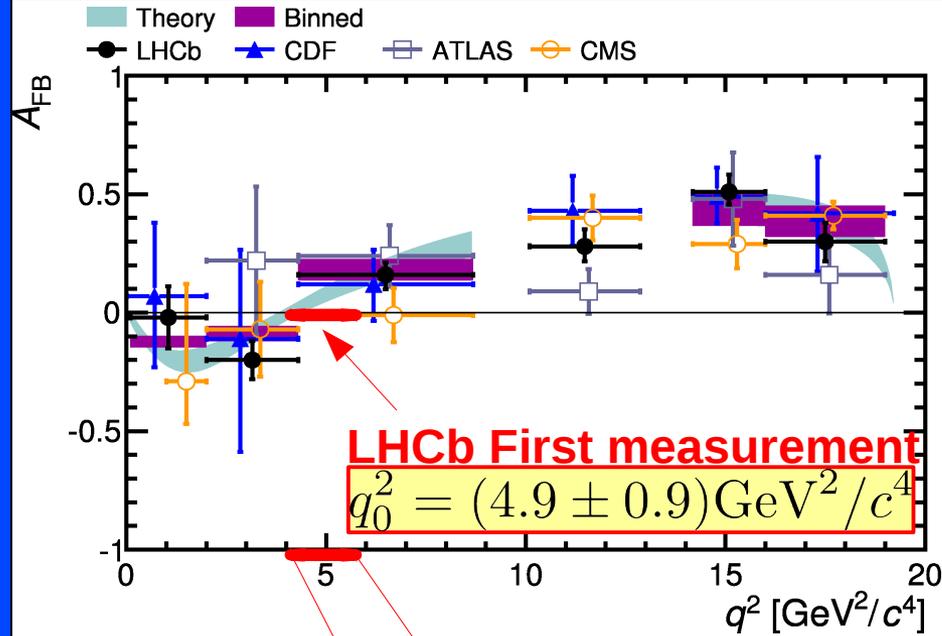
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Left:  $B^+ \rightarrow K^{*+}$ , Middle  $B_s \rightarrow \phi$ , Right:  $B^0 \rightarrow K^{*0}$ ,



Hint that all BR are on the low side?

# Angular Variables



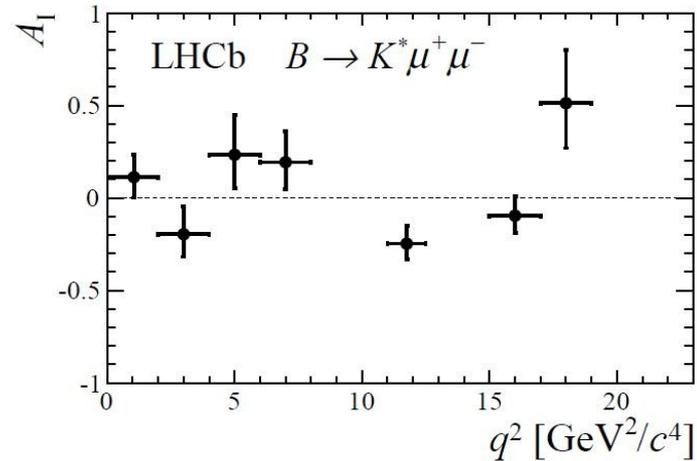
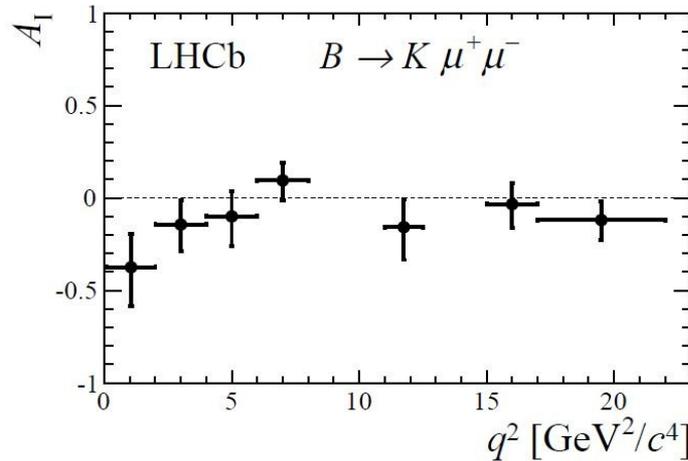
# Isospin Asymmetry

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

SM prediction  
is close to  
zero

$1\text{fb}^{-1}$  :  
Deviation from  
zero over all  
 $q^2$  at 4.40

$3\text{fb}^{-1}$  :  
Deviation from  
zero over all  
 $q^2$  at 1.50



LHCb [arXiv:1403.8044]

# Deviations from the SM?

Combine  $B_s \rightarrow \mu\mu$ ,  $B \rightarrow K^{(*)}\mu\mu$ ,  $B \rightarrow Xs \gamma$ ,  $B \rightarrow K^*\gamma$  measurements to constrain New Physics

**Indicate significant deviation in di-leptonic vector operator ( $C_9$ )**

Descote-Genon et al. [arXiv:1307.5683]]

Numerous theory papers:

Descotes-Genon et al [1307.5683], Beaujean et al [1310.2478],  
Gauld et al [1308.1959], Hurth et al [1312.5267],  
Straub et al [1308.1501], Horgan et al [1310.3887],  
Altmannshofer et al [1403.1269], Biancofiore et al [1403.2944]...

**Consistent with  $Z'$  of mass:**

$\sim 35$  TeV for  $O(1)$  couplings (tree)

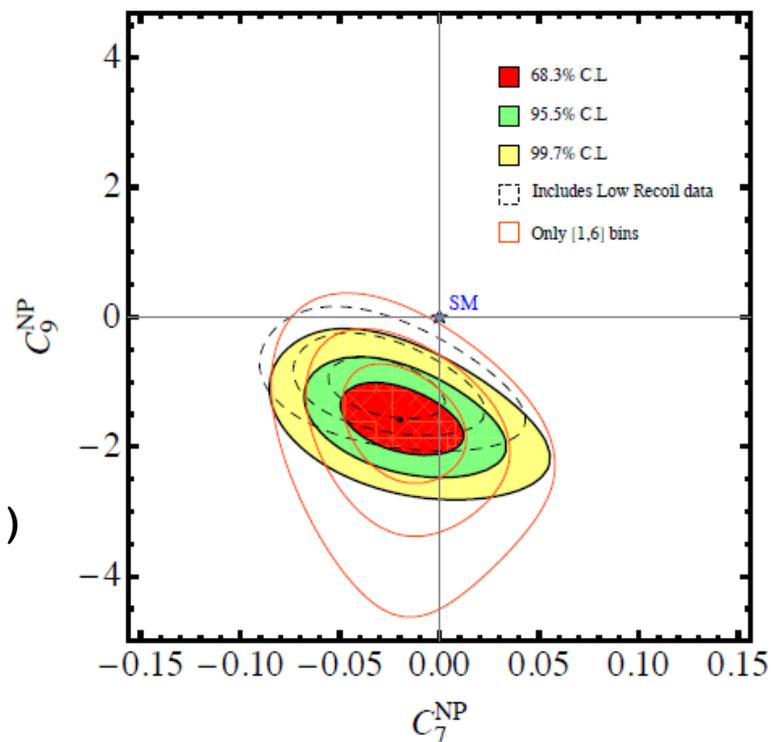
$\sim 7$  TeV for **CKM-like couplings** (tree)

Straub et al [1308.1501]

Difficult to accommodate within MSSM

**This could happen without affecting the  $B_s \rightarrow \mu\mu$  branching fraction, which is not sensitive to  $O_9$  (vector) but to  $O_{10}$**

**Demonstrates the power of these searches!**

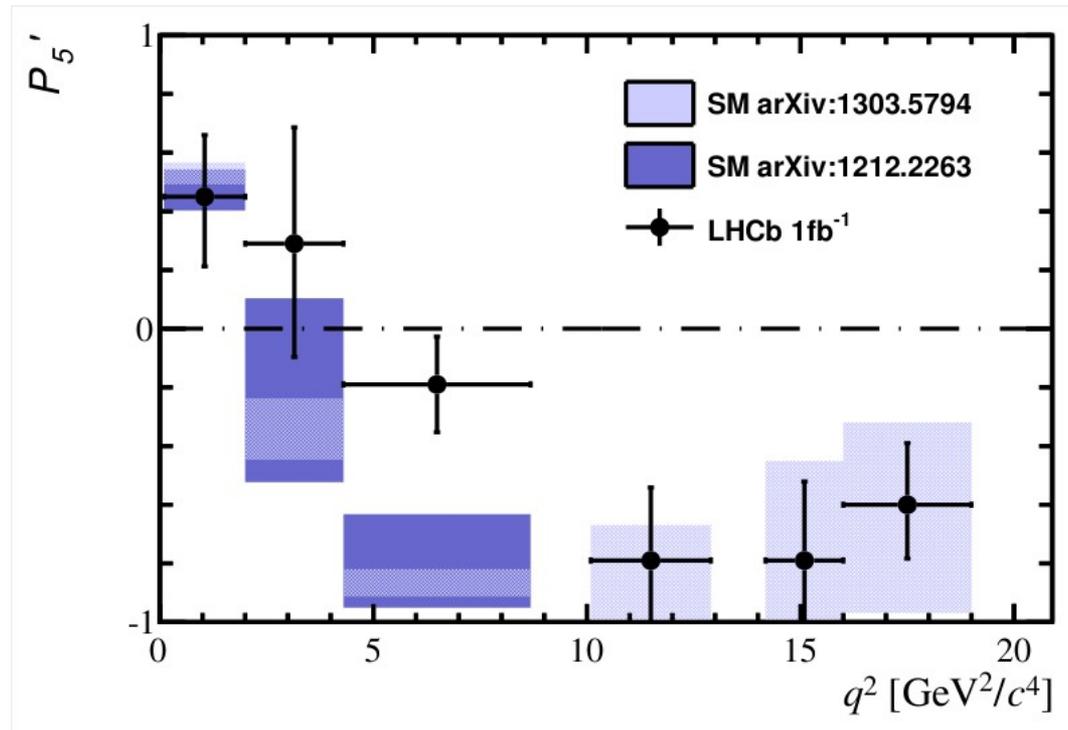


# ...or theory problems...

Unfortunately not that simple...

**Observables are theoretically clean  
at leading order**

But! Uncertainties of higher order  
corrections can potentially dilute the  
significance  $P'_5$



# Something new

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

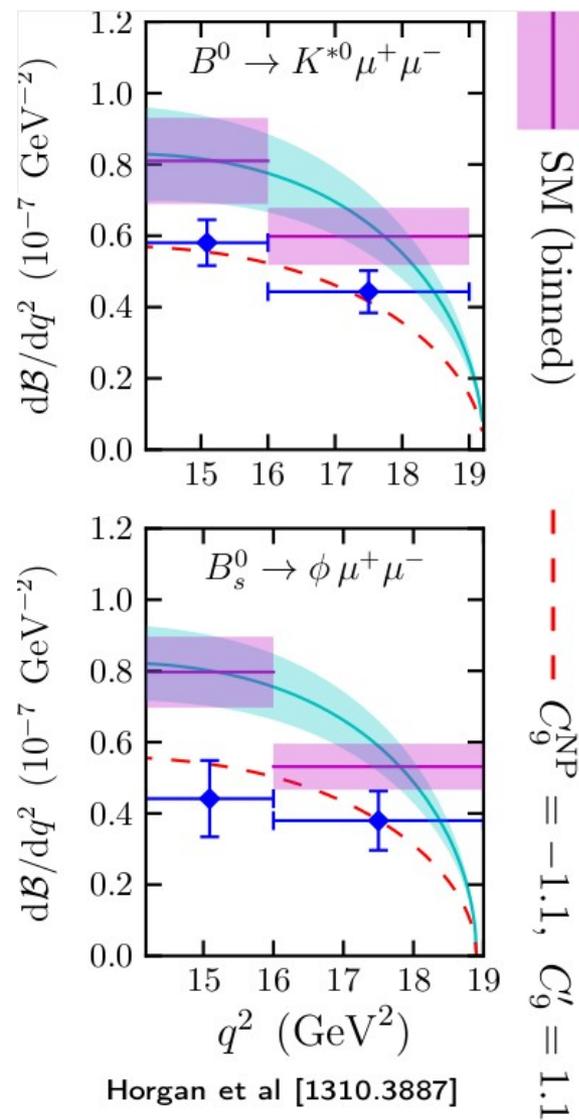
→ NP or unaccounted QCD effects?

**Something new? or something new to understand?**

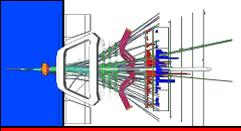
Lattice QCD predictions + measurements in related channels (e.g  $b \rightarrow d\mu + \mu^-$ ) (to reveal information on MFV nature of NP) can help clarify the situation at high  $q^2$

The data can help us understand QCD effects and test extent of applicability of OPE and factorization

See: Zwicky-Lyon: arXiv:1406.0566



All experiments combined



# $se^+e^-$ vs $sm^+m^-$

Measurements of different dilepton final states in  $b \rightarrow sll$  can test the lepton and flavor couplings simultaneously.

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

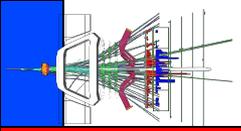
$$R_H \equiv \frac{\int_{4m_\mu^2}^{q_{\max}^2} dq^2 \frac{d\Gamma(B \rightarrow H \mu^+ \mu^-)}{dq^2}}{\int_{4m_\mu^2}^{q_{\max}^2} dq^2 \frac{d\Gamma(B \rightarrow H e^+ e^-)}{dq^2}}, \quad H = X_s, K^{(*)}, \quad \text{Hiller, Kruger: 0310219}$$

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

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

Equality of coupling is concept of lepton-universality.

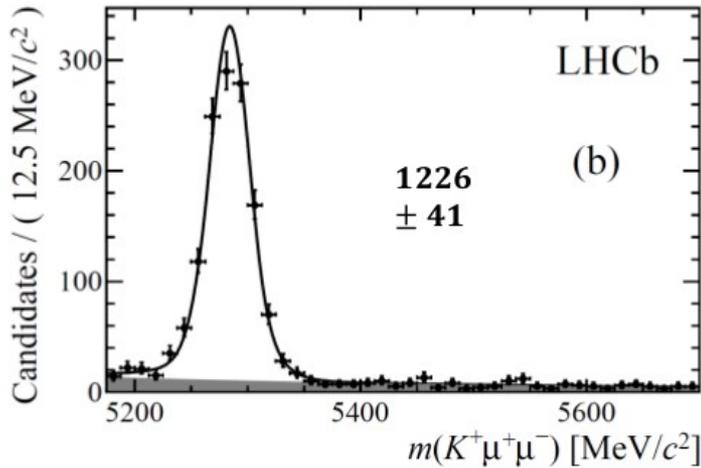
Enhancement possible for either muon or electron modes from anything which breaks lepton universality, for example R-parity violating models.



# $Ke^+e^-$ vs $K\mu^+\mu^-$

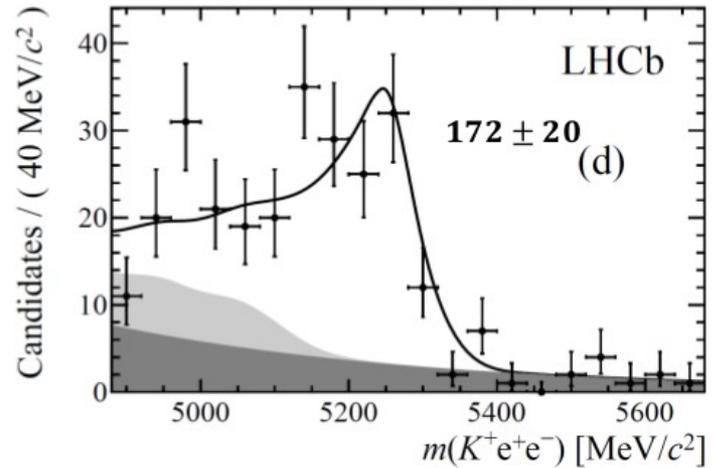
$B^+ \rightarrow K^+\mu^+\mu^-$

all events



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

events with a high  $p_T$  electron



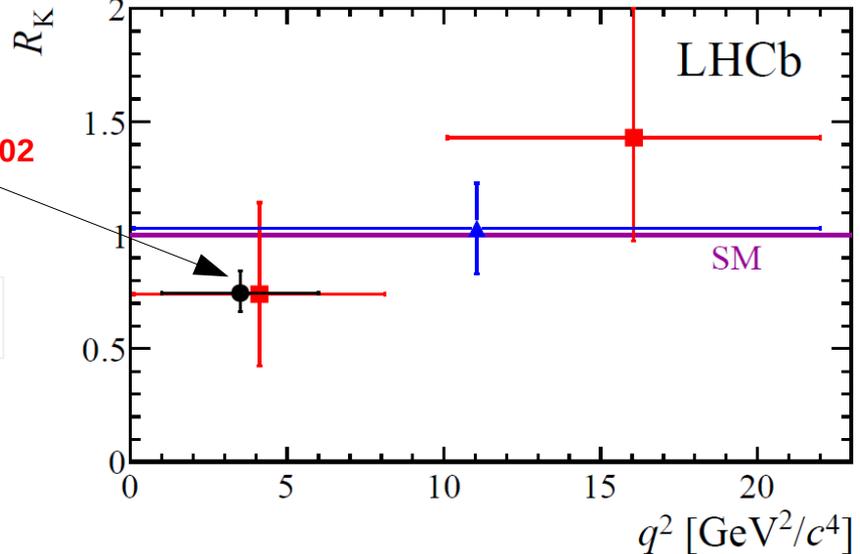
● LHCb    ■ BaBar    ▲ Belle

BABAR arXiv: 1204.3933  
Belle, arXiv: 0904.0770

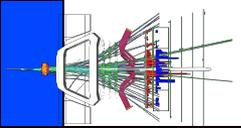
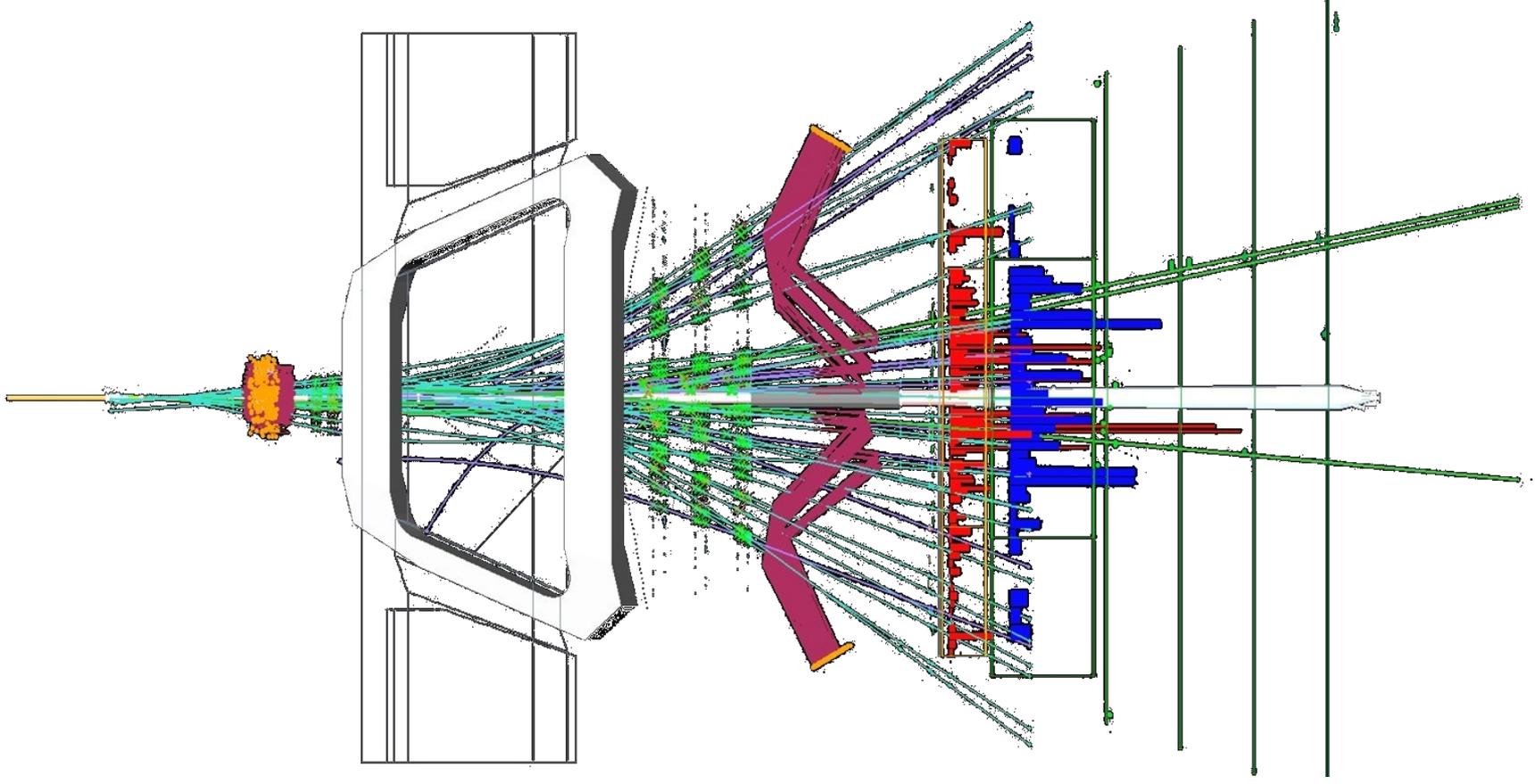
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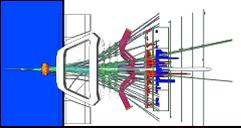
$$R_K = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$$

2.6 sigma



$$b \rightarrow s\gamma$$



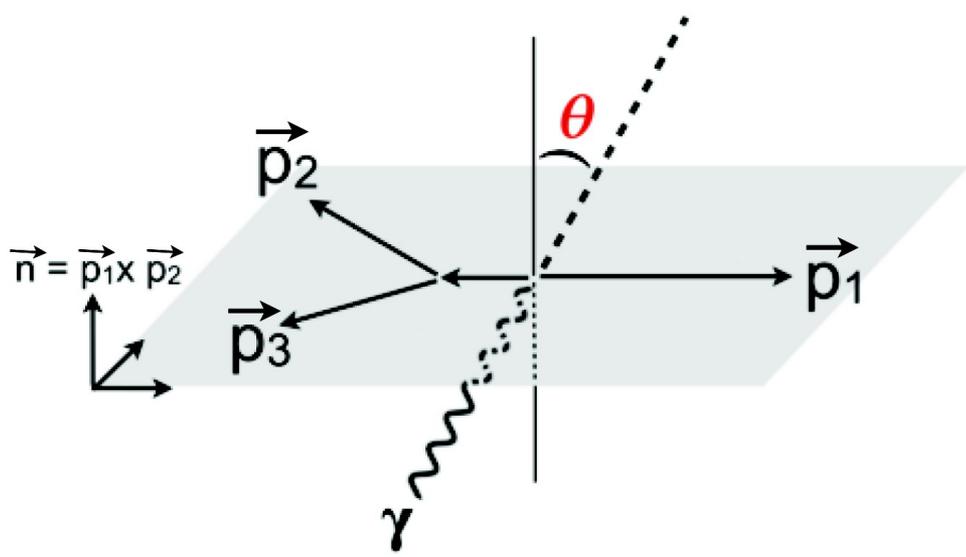


# $b \rightarrow s \gamma$

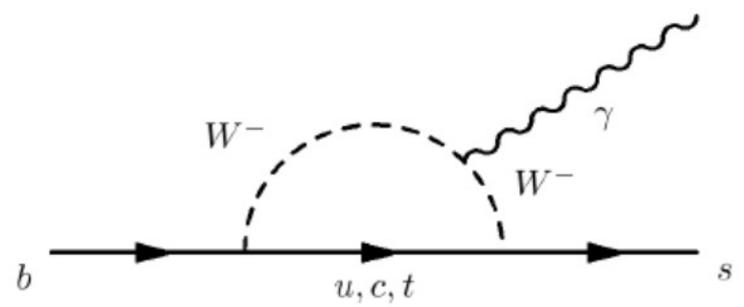
$b \rightarrow s \gamma$  FCNC are sensitive to NP through the presence of new physics particle that can enter the electroweak penguin diagram

Photons are predominantly left handed in SM

Significant right handed component possible in many NP models



LHCb PRL 112 (2014) 161801

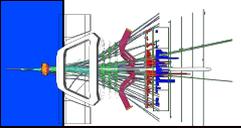


The **up-down asymmetry** is proportional to the **photon polarization**

$$A_{ud} \propto \lambda \gamma$$

$$A_{ud} = \frac{\int_0^1 d\cos\theta \frac{d\Gamma}{d\cos\theta} - \int_{-1}^0 d\cos\theta \frac{d\Gamma}{d\cos\theta}}{\int_{-1}^1 d\cos\theta \frac{d\Gamma}{d\cos\theta}}$$

LHCb just updated **LHCb-CONF-2013-009** with  $3 \text{ fb}^{-1}$  of data

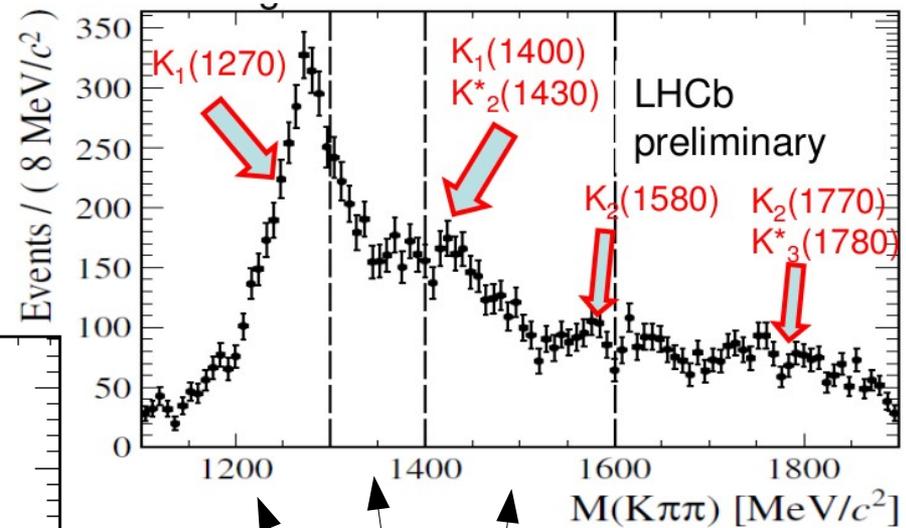
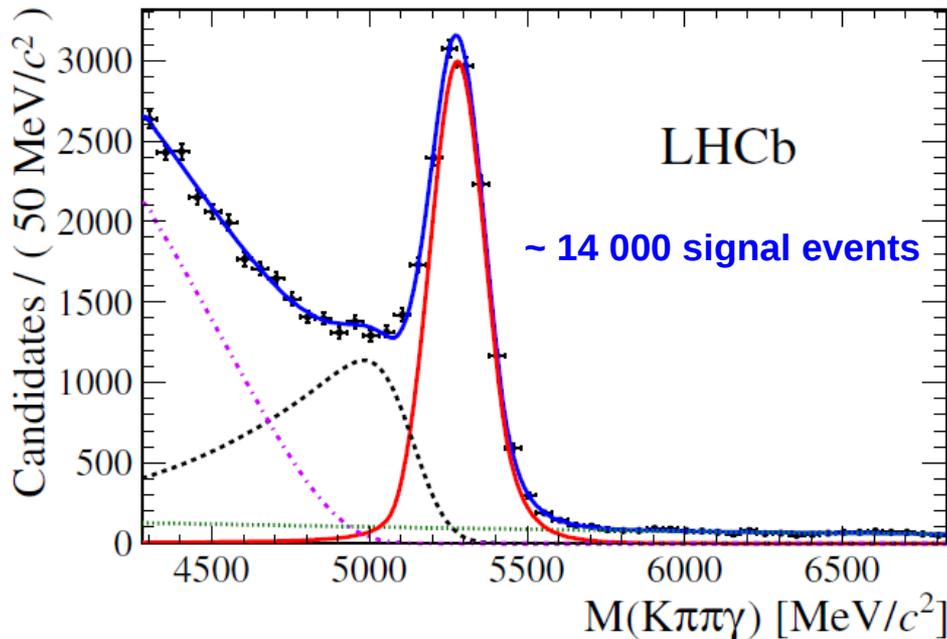


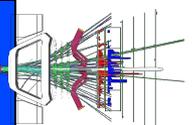
# $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$

Differential decay rate of  $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$  (Gronau, et al. PRD66 (2002) 054008) :

$$\frac{d\Gamma}{ds ds_{13} ds_{23} d\cos\theta} \propto \sum_{i=0,2,4} a_i(s, s_{13}, s_{23}) \cos^i \theta + \lambda_\gamma \sum_{j=1,3} a_j(s, s_{13}, s_{23}) \cos^j \theta$$

Depends on the resonances in the  $K\pi\pi$  spectrum and their interferences

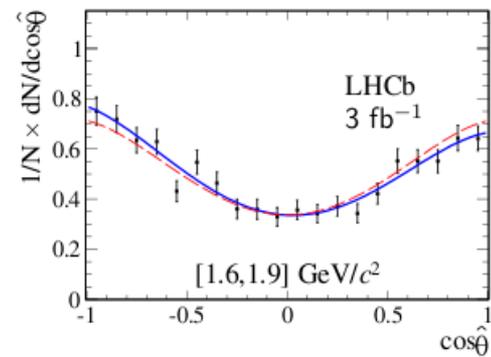
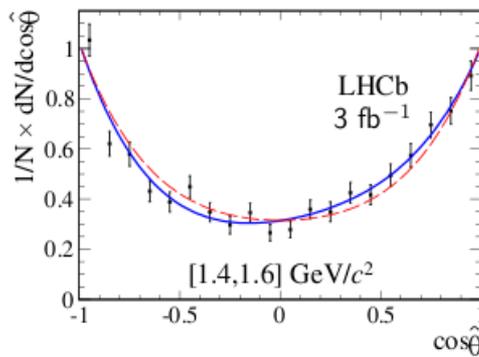
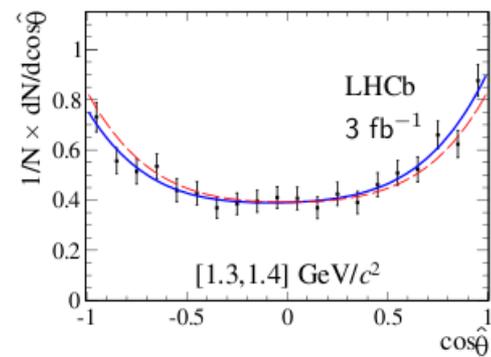
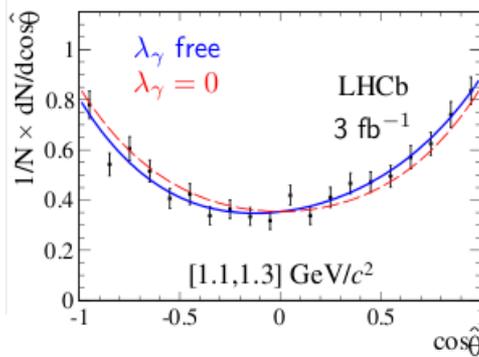
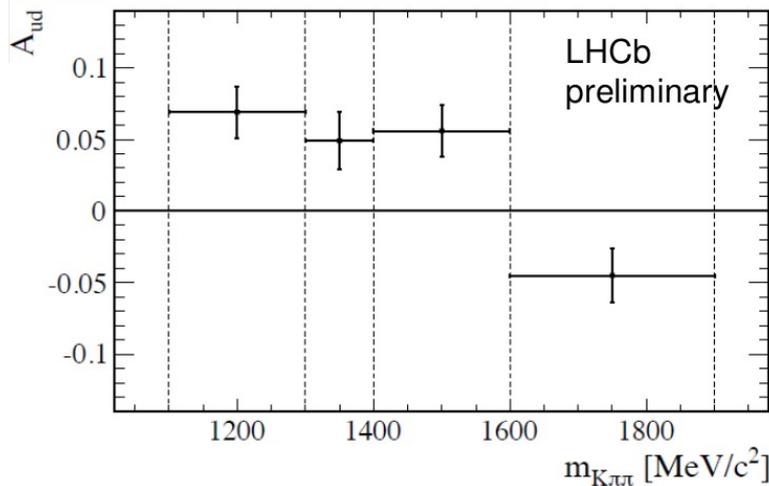




# Observation of $\gamma$ polarization

Asymmetry between number of events on each side of the plane

$$A_{ud} = \frac{\int_0^1 d\cos\theta \frac{d\Gamma}{d\cos\theta} - \int_{-1}^0 d\cos\theta \frac{d\Gamma}{d\cos\theta}}{\int_{-1}^1 d\cos\theta \frac{d\Gamma}{d\cos\theta}}$$



PRL 112 (2014) 161801

Up-down asymmetry proportional to the  $\gamma$  polarisation

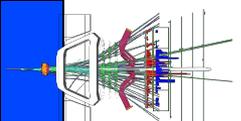
**5.2 $\sigma$  significance for a non zero up-down asymmetry**

**→ first observation of photon polarization in  $b \rightarrow s\gamma$  transition**

Determination of the polarization from  $A_{ud}$  and  $\cos\theta$  shape

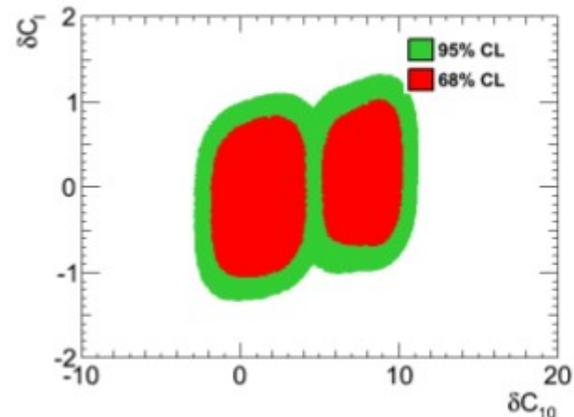
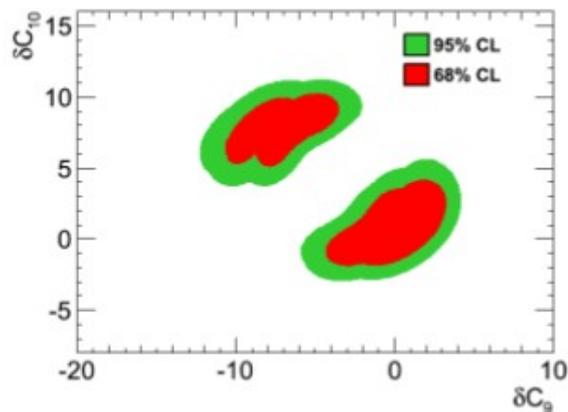
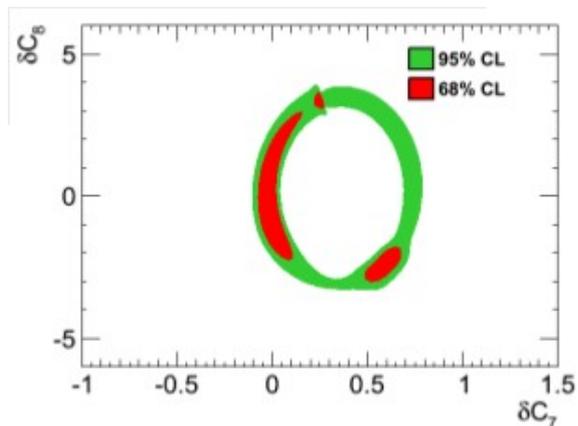
may constrain the effects of NP in the  $b \rightarrow s\gamma$  sector!

It's crucial to understand the  $K\pi\pi$  mass structure!



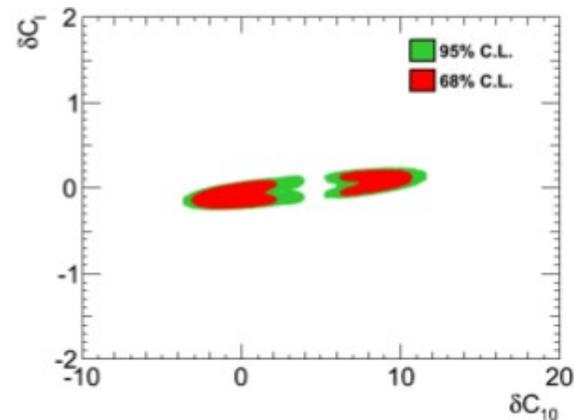
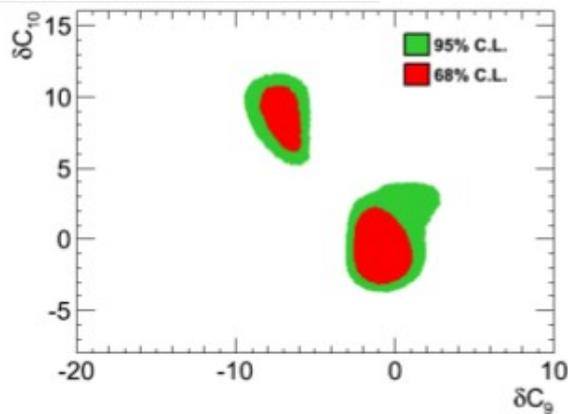
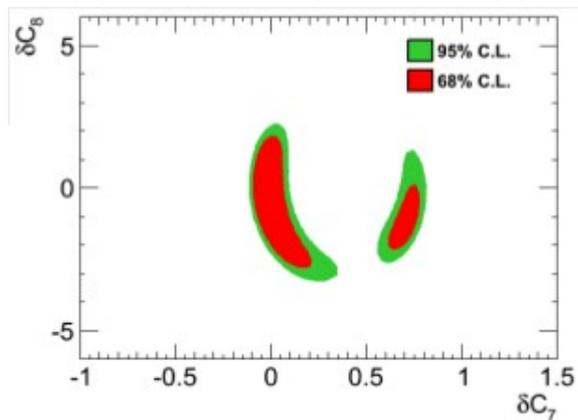
# Shrinking the Wilson coeff.

2012

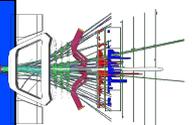


2014

T. Hurth, FM, Nucl.Phys. B865 (2012) 461

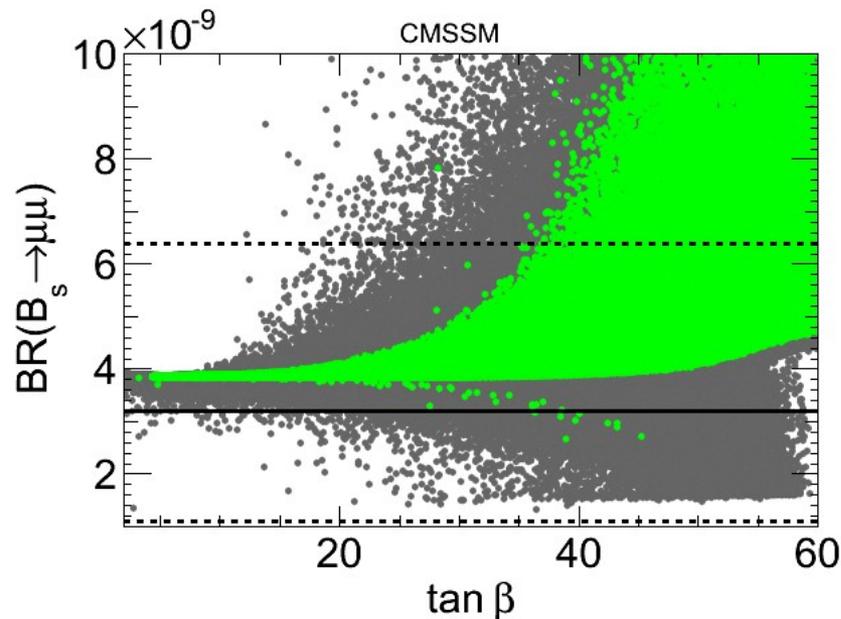
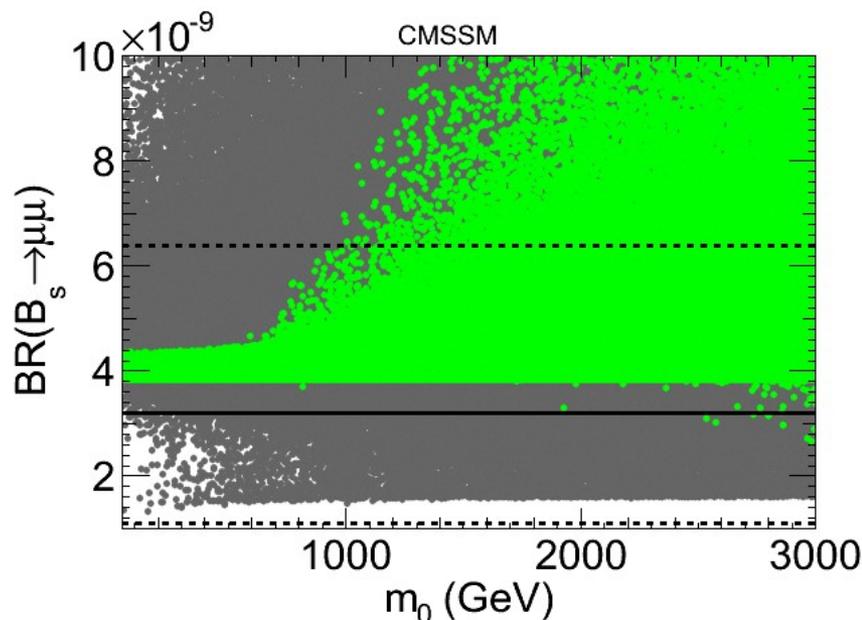


T. Hurth, FM, JHEP 1404 (2014) 097



# Can we really kill any model?

A. Arbey, M. Battaglia, N. Mahmoudi, D. Martinez Santos, Phys.Rev. D87 (2013) 035026



**$BR(B_s \rightarrow \mu^+ \mu^-)$  smaller than SM and the Higgs mass constraint cannot be satisfied simultaneously!!!**

**Not true in pMSSM !**

Flat scans over the CMSSM parameters with  $\mu > 0$

Solid line: central value of the  $BR(B_s \rightarrow \mu^+ \mu^-)$  measurement

Dashed lines:  $2\sigma$  experimental deviations

Gray points: all valid points

Green points: points in agreement with the Higgs mass constraint

# Conclusions

Rare decays are powerful ways to search for NP beyond the SM

LHCb strongly performing and very well positioned in this field, but other experiments highly contribute to the fun

CMS and LHCb results -> 1<sup>st</sup> observation of  $B_s \rightarrow \mu^+ \mu^-$

More data needed to:

measure  $B(B_s \rightarrow \mu^+ \mu^-) / B(B^0 \rightarrow \mu^+ \mu^-)$

measure effective lifetime for  $B_s \rightarrow \mu^+ \mu^-$

search for other decays as those involving taus (e.g.  $B^0 \rightarrow (K^*) \tau^+ \tau^-$ )

Coming soon: full combination CMS+LHCb

Latest  $B^0 \rightarrow K^* \mu^+ \mu^-$  analysis results

defined and measured cleaner angular observables

some tension with SM, more data and improved theory error needed

Rare decays essential part of LHC upgrade & Belle II physics program

Update on full stat of many analyses eagerly awaited for.

