LHC searches in rare heavy-flavor decays

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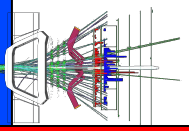
(on behalf of the LHCb collaboration, including results from ATLAS and CMS)

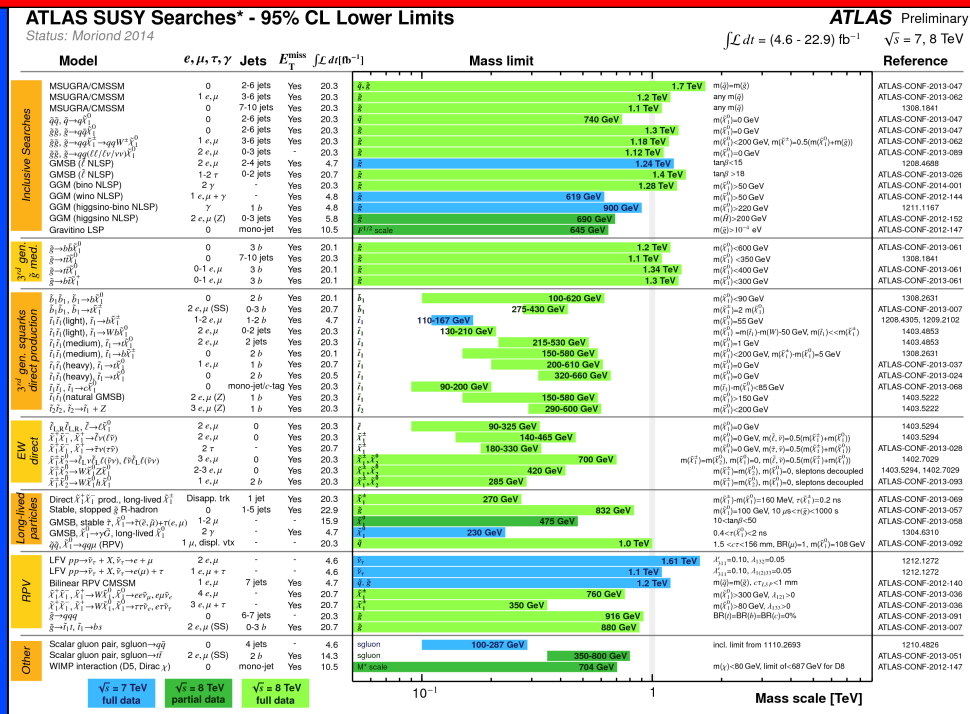
ASTROPARTICLES PHYSICS 2014 – Amsterdam – June 23rd

Waiting for...

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

SUSY & Exotics direct searches

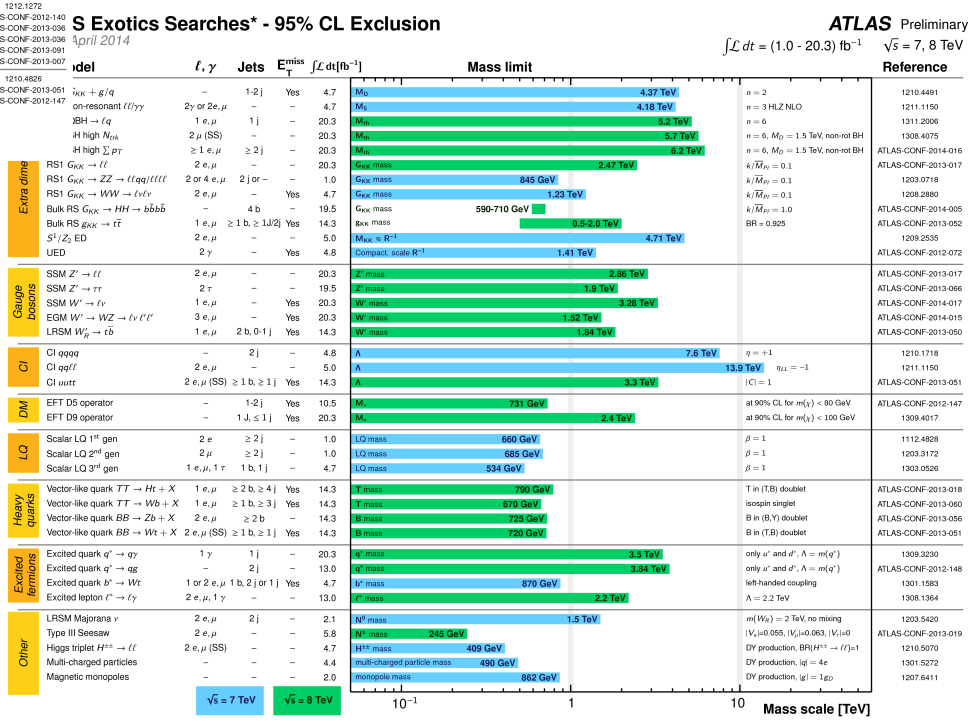




@ ATLAS (CMS similar trend)

SUSY

Exotics



...no New Physics...

Flavor Physics

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

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

Discovery of J/Ψ 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 B0 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 Λ_{NP} ~ 1TeV motivated to tame fine tuning in Higgs sector

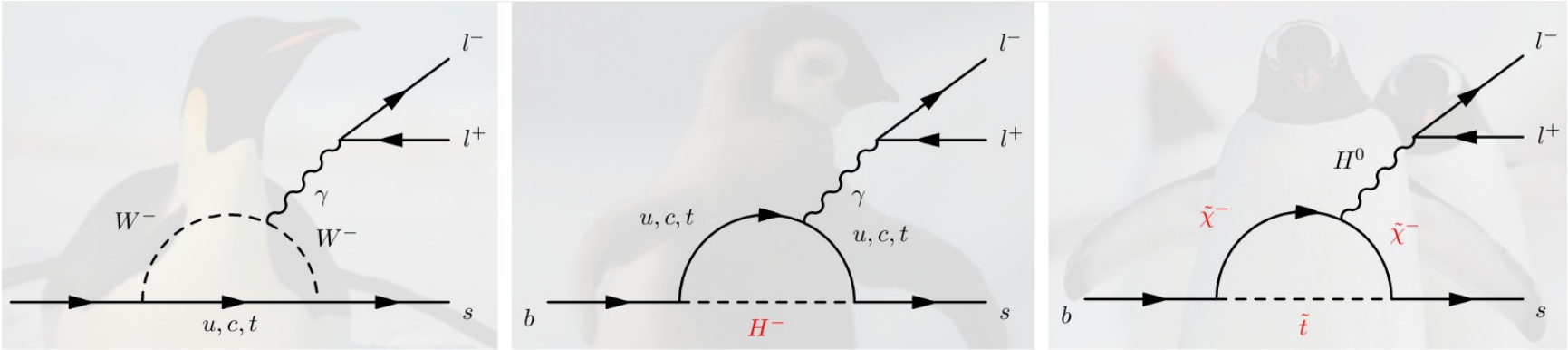
NP at Λ_{NP} ~ 1TeV refuted by flavor measurements (pre LHC) → CKM-like NP couplings (MFV)

LHC pushes NP to >> 1 TeV → 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. $b \to s\ l^+\ l^-$) **forbidden at tree level in SM proceed via penguins/boxes**

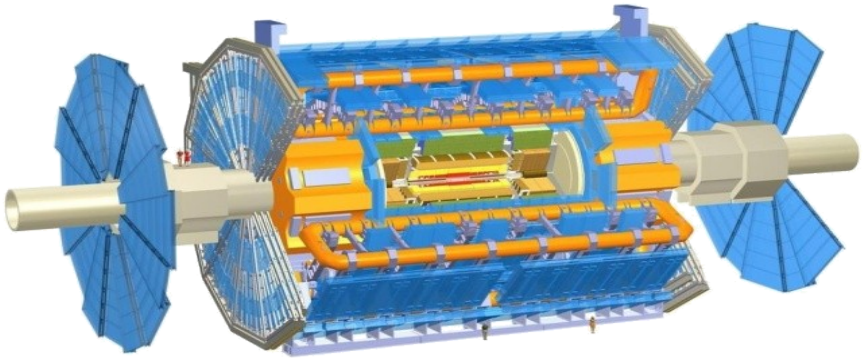
⇒ suppressed by GIM-mechanism

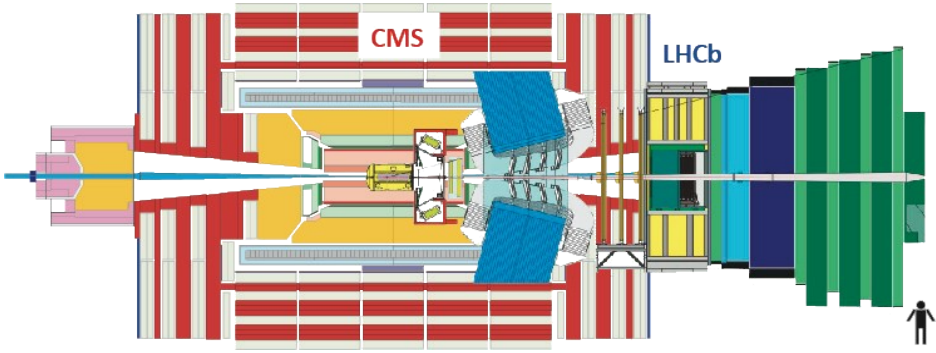
Many extensions of the SM may contribute to these processes involving "new" virtual particles (e.g. charged Higgs , squarks...)

⇒ **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 σ(pp→bbX) cross-section (at 7 TeV):

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

CMS ($28.1 \pm 2.4 \pm 2.0 \pm 3.1$) μb ($p_T(B)>5$ GeV and $|\eta|<2.4$)

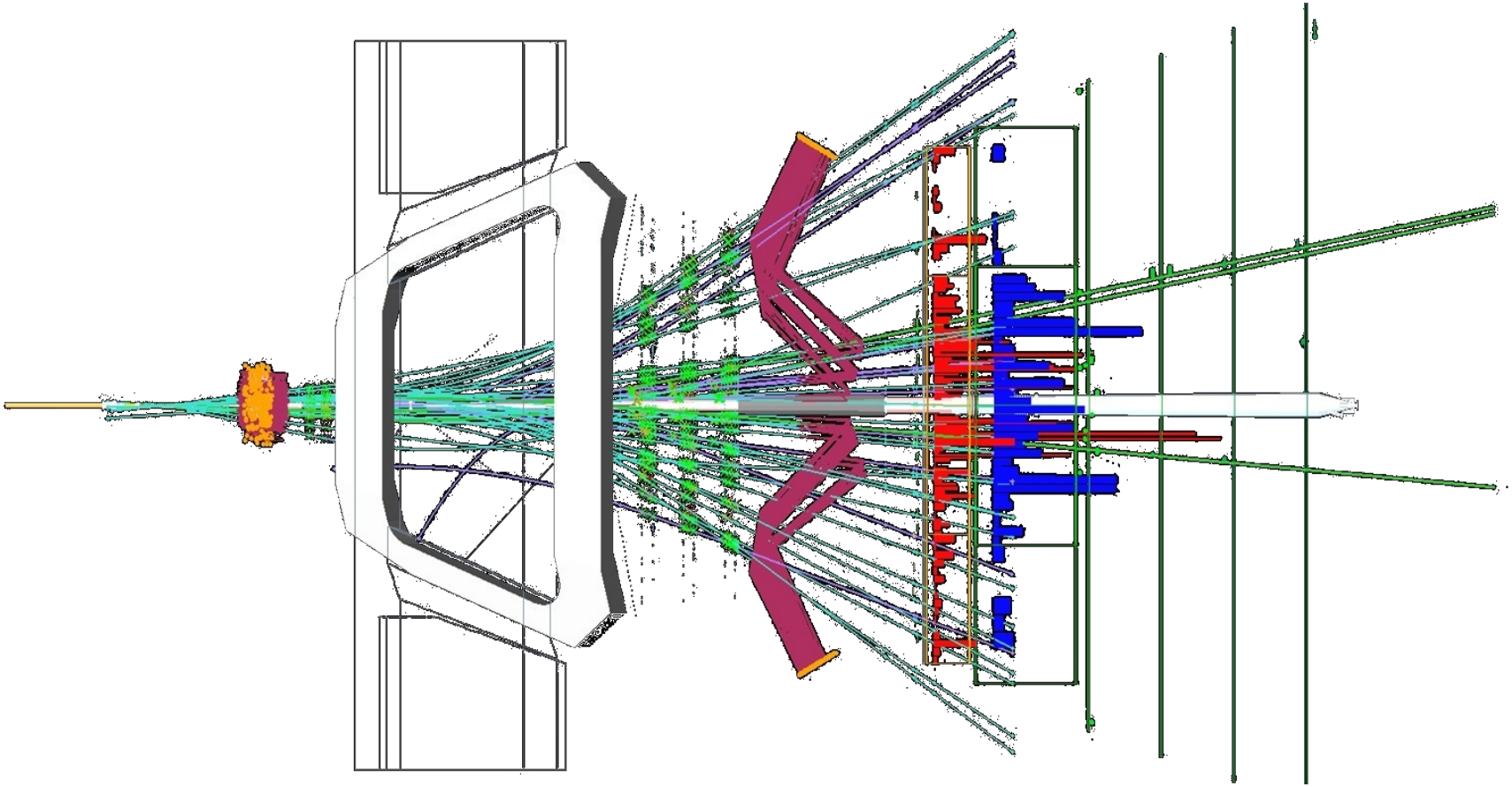
LHCb ($75.3 \pm 5.4 \pm 13.0$) μb ($2<\eta<6$)

[PLB 694 (2010) 209]
[Nucl.Phys. B864 (2012) 341-381]
[Phys.Rev.Lett.106:252001,2011]

Each experiment: O(10^{10})/fb bb pairs on tape

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

B → leptons



$B_{(s)} \to \mu\mu$: Introduction

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

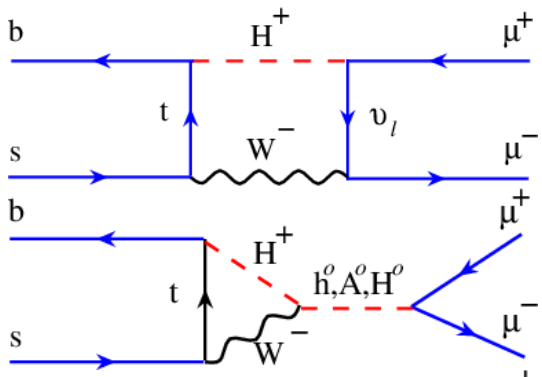
helicity suppression

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

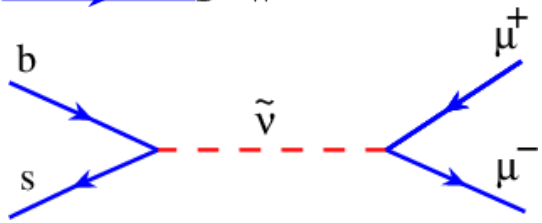
In MSSM:

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

2HDM:

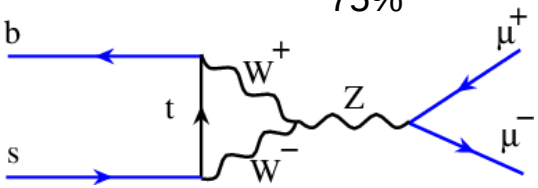


RPV:

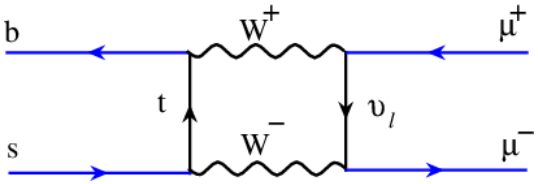


SM contributions:

75%



24%



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

Bobeth et al., arXiv:1311.0903v1

sensitive to contributions in the **scalar/pseudo-scalar sector**

highly interesting to probe **extended Higgs** models and **high tanβ**

limit or measurement of $B_{s,d} \to \mu\mu$ strongly constrain **tanβ vs M_A plane**

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

LHCb

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

with 4.0σ sign.

[PRL 111(2013)101805]

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

with 2.0σ sign.

CMS

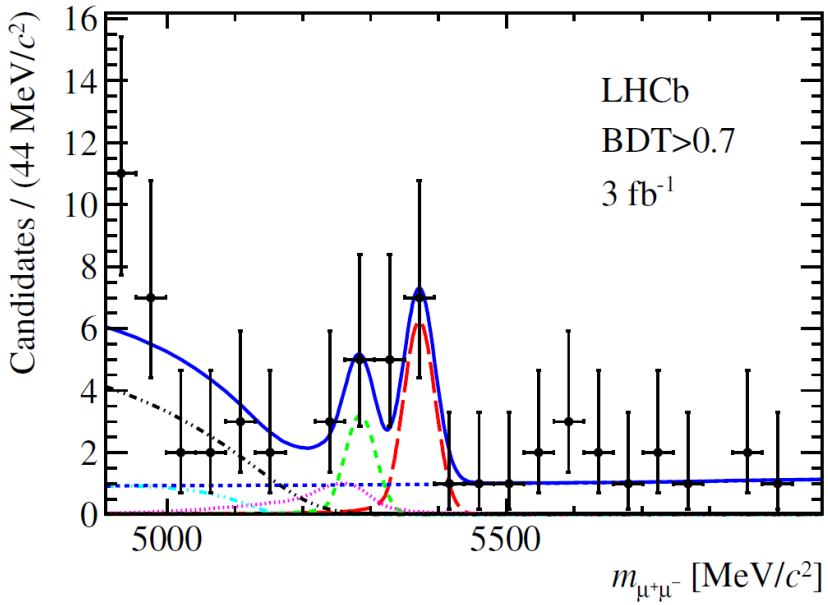
$$\mathrm{BR}(B_s \to \mu\mu) = \left(3.0^{+0.9}_{-0.8}\ (\mathrm{stat})^{+0.6}_{-0.4}\ (\mathrm{syst})\right) \times 10^{-9}$$

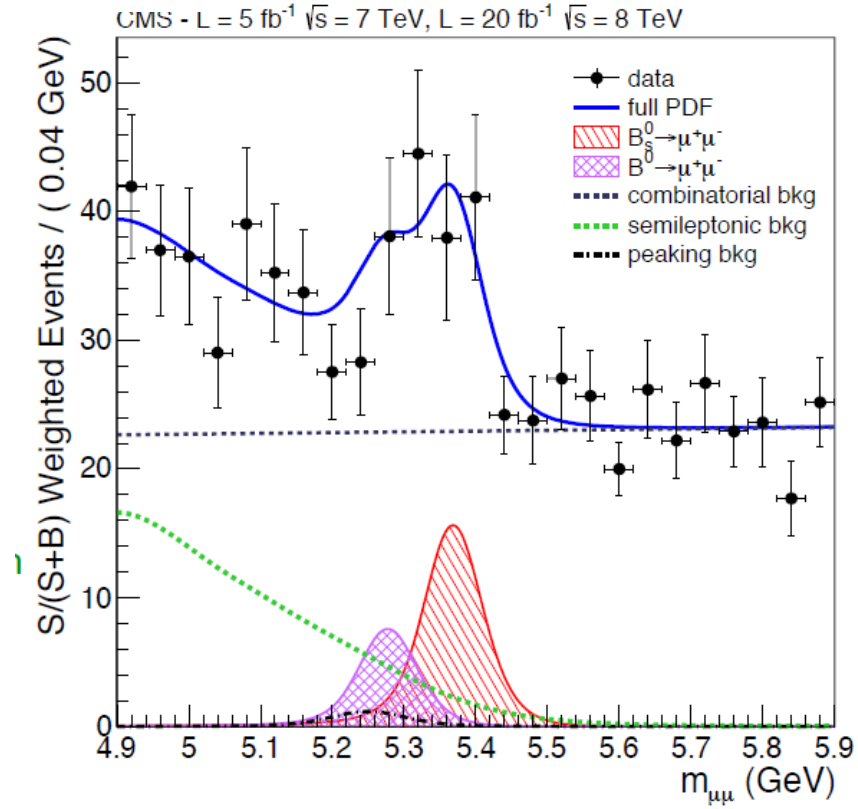
with 4.3σ sign.

[PRL 111(2013)101804]

$$\mathrm{BR}(B_d \to \mu\mu) = \left(3.5^{+2.1}_{-1.8}\ (\mathrm{stat+syst})\right) \times 10^{-10}$$

with 2.0σ sign.





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

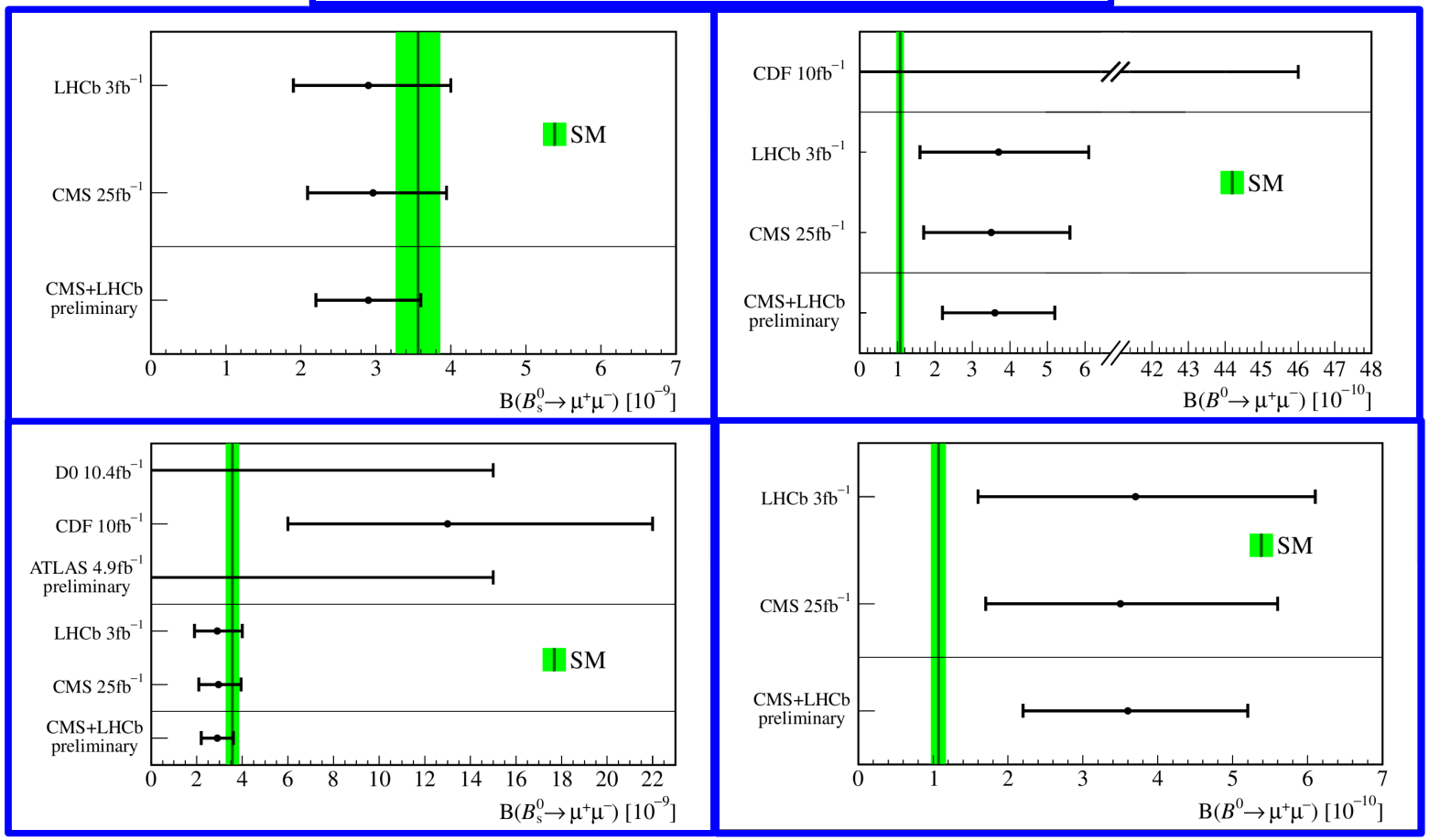
[ATLAS-CONF-2013-076]

Combination LHCb/CMS

Averages

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

[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, BR($B^+ \to J/\psi\ K^+$),…).

Output: combined BF and 2D scans, significances.

Historical Picture

A long way since 1984 at CLEO:

PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1

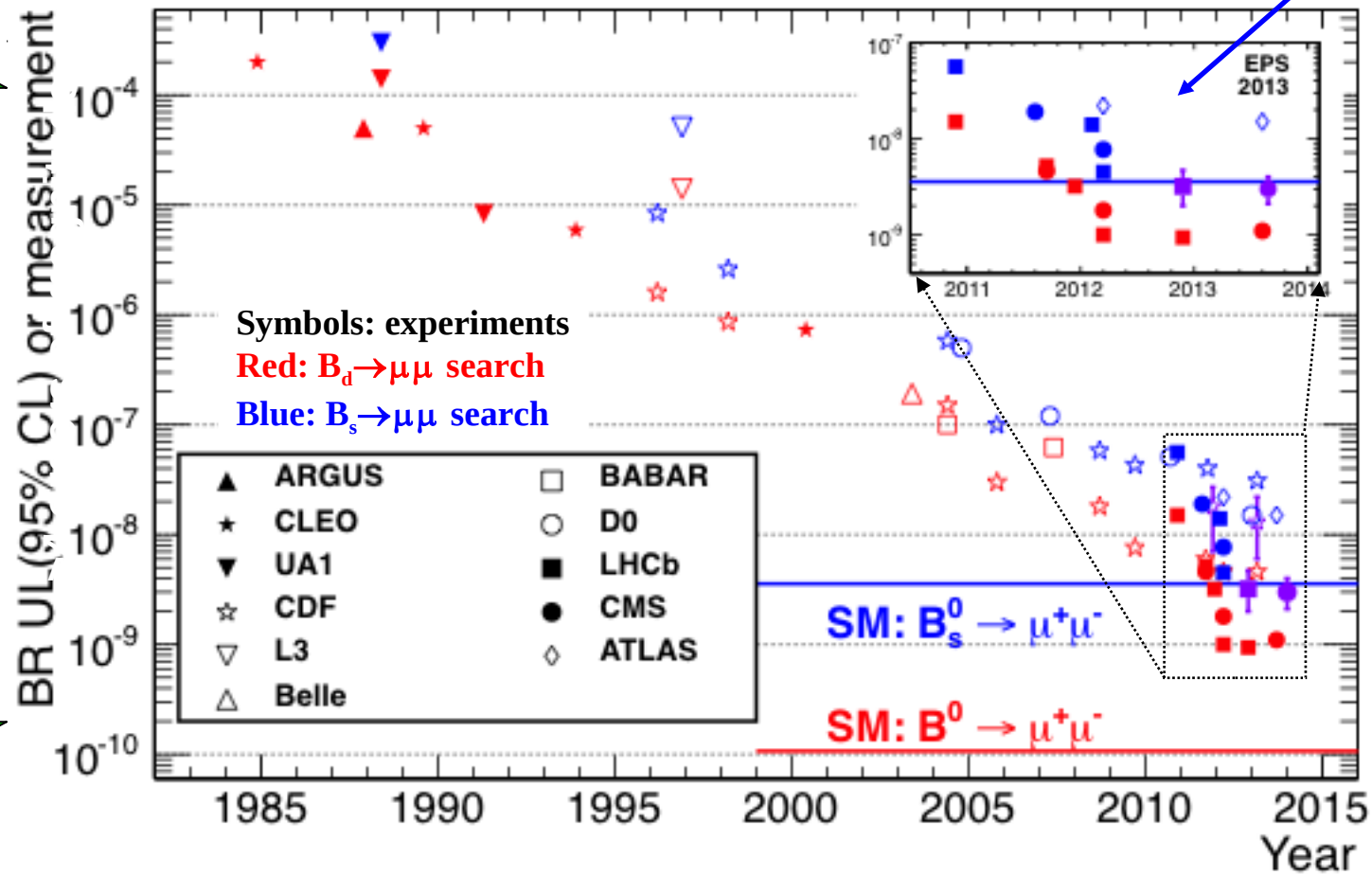
Two-body decays of B mesons

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

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

◇ full Run1 ATLAS update on the way

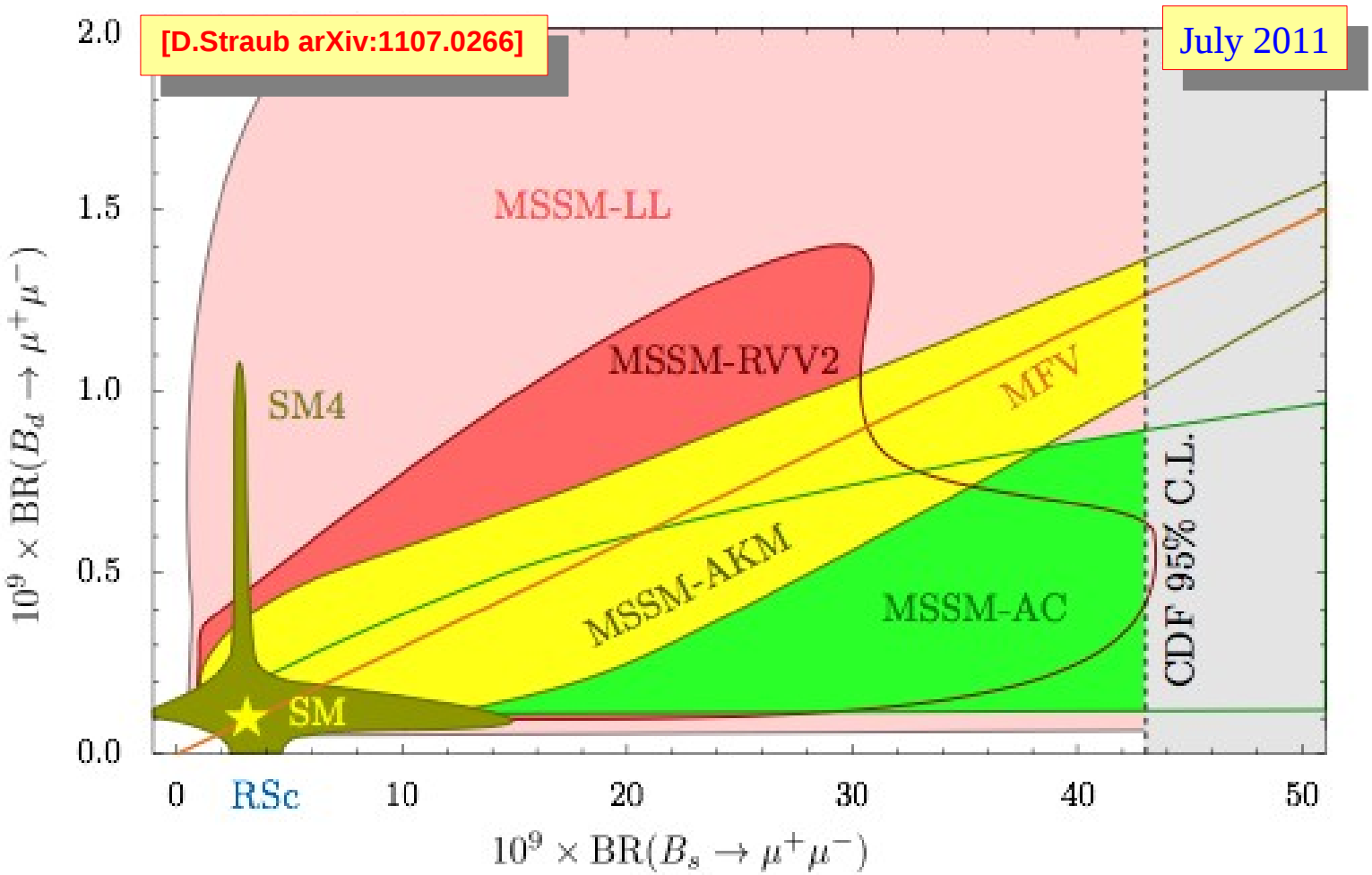


5 orders of magnitude

>25 years

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

Closing up on NP



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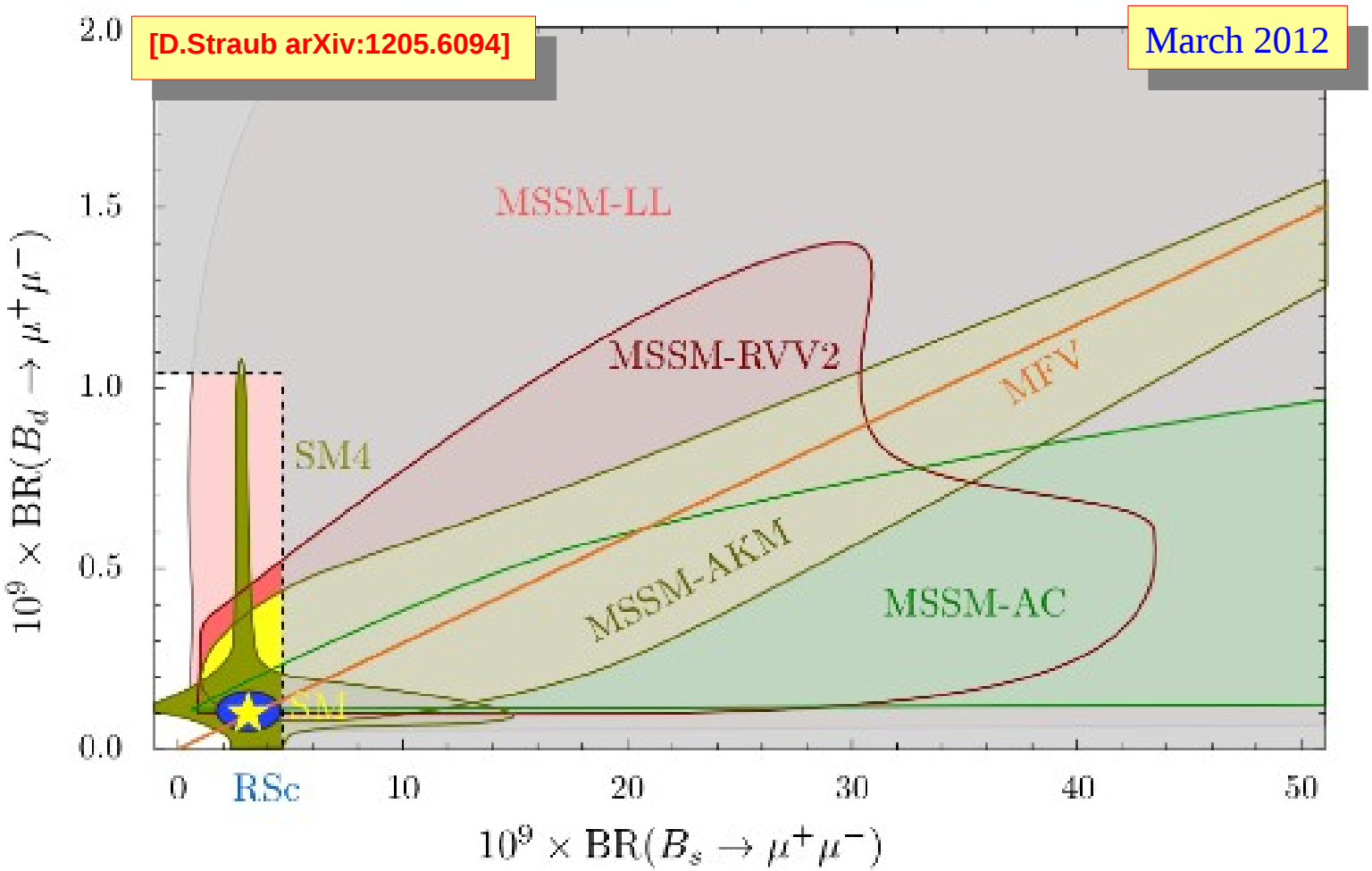
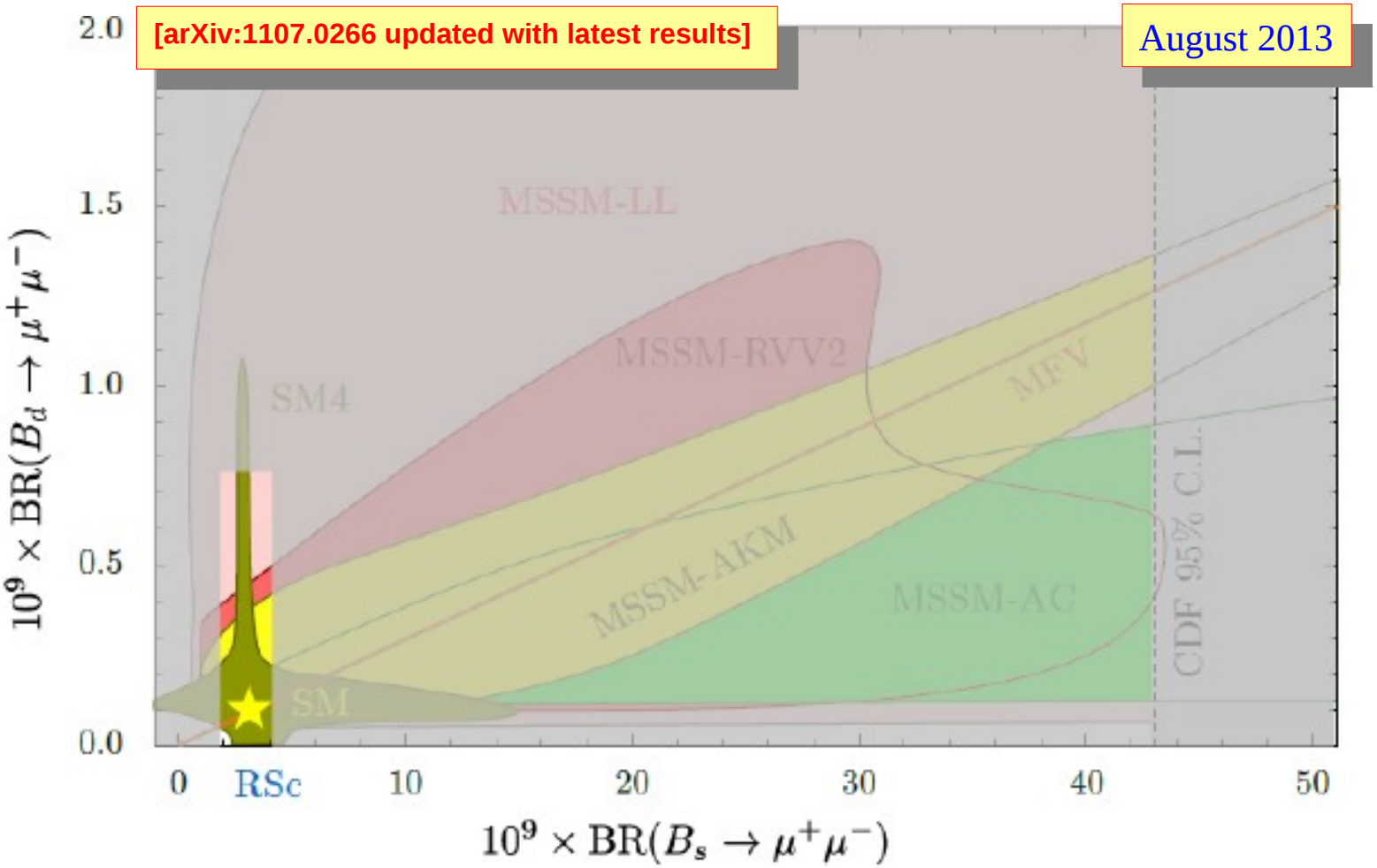


Closing up on NP



*"**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***

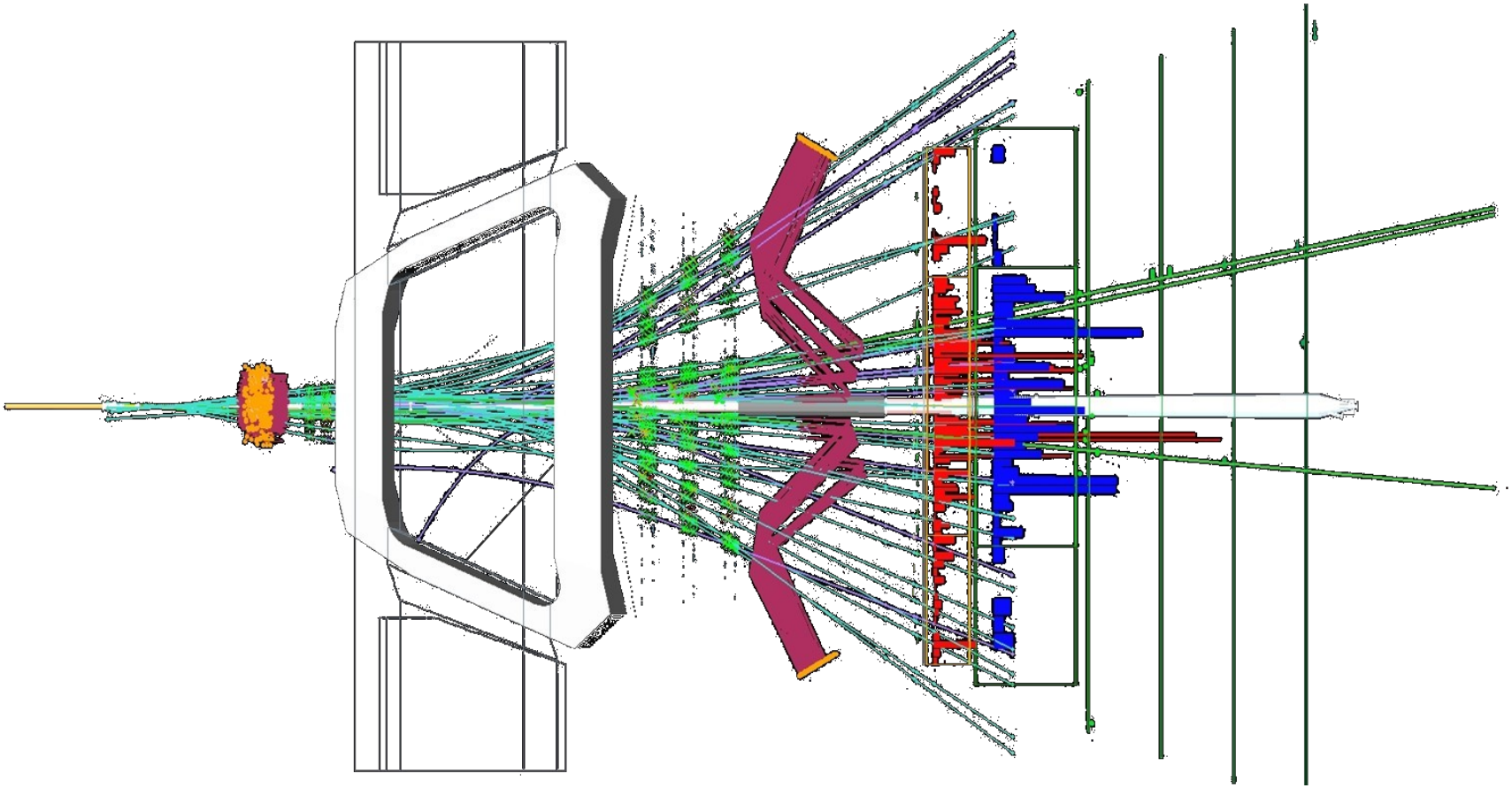
Is there any space for new physics left?

"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 $B_s \to \mu\,\mu$ 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.

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

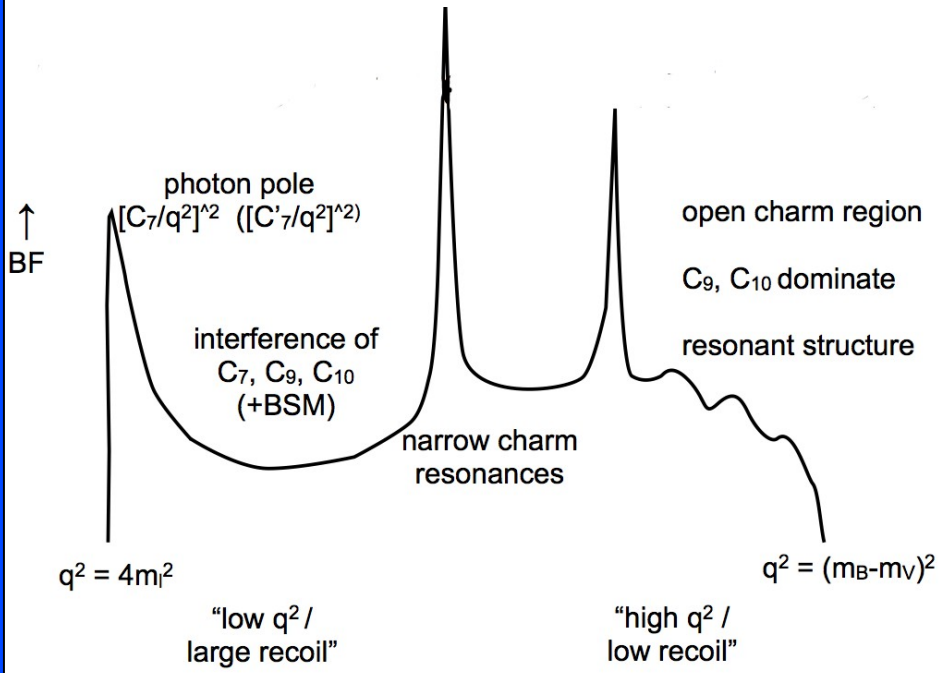


Introduction

If b → 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: O7, O9, O10



Operator $\mathcal{O}_i$	$B \to K^{*0}\mu^+\mu^-$	$B \to \mu^+\mu^-$
$\mathcal{O}_7 \sim m_b(\bar{s}_L\sigma_{\mu\nu}b_R)F_{\mu\nu}$	✓	
$\mathcal{O}_9 \sim (\bar{s}b)_{V-A}(\bar{\ell}\ell)_V$	✓	
$\mathcal{O}_{10} \sim (\bar{s}b)_{V-A}(\bar{\ell}\ell)_A$	✓	✓
$\mathcal{O}_{S,P} \sim (\bar{s}b)_{S+P}(\bar{\ell}\ell)_{S,P}$		✓

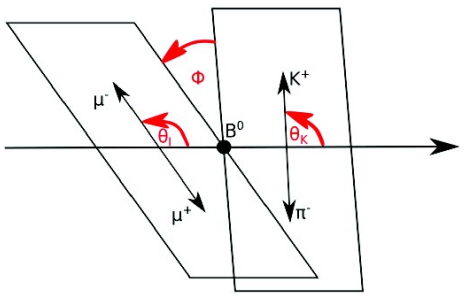
From S. Jaeger at Workshop on b → sll processes, 1-3 April 2014

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

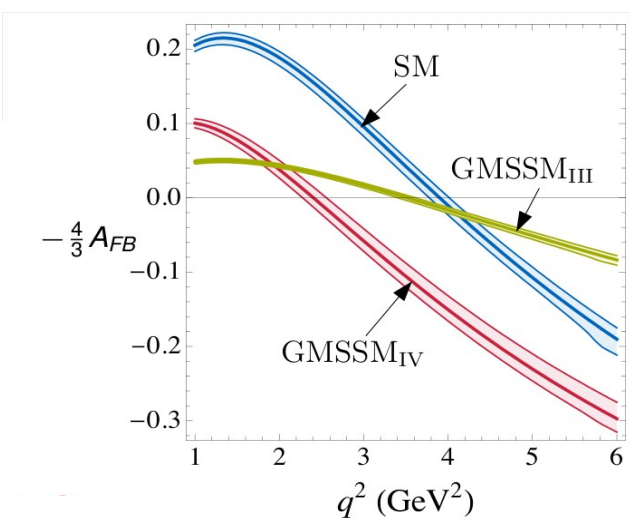
Decay described with 3 angles (θ_l , θ_k , φ) and dimuon mass q^2

Parametrized in terms of **angular observables**

$$\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + \frac{1}{2}(1-F_L)A_T^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi +$$
$$\sqrt{F_L(1-F_L)}P_4'\sin 2\theta_K\sin 2\theta_\ell\cos\phi + \sqrt{F_L(1-F_L)}P_5'\sin 2\theta_K\sin\theta_\ell\cos\phi +$$
$$(1-F_L)A_{Re}^T\sin^2\theta_K\cos\theta_\ell + \sqrt{F_L(1-F_L)}P_6'\sin 2\theta_K\sin\theta_\ell\sin\phi +$$
$$\sqrt{F_L(1-F_L)}P_8'\sin 2\theta_K\sin 2\theta_\ell\sin\phi + (S/A)_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$



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



A_{FB}

Forward-backward asymmetry (θ_l)

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

Branching fractions

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

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]

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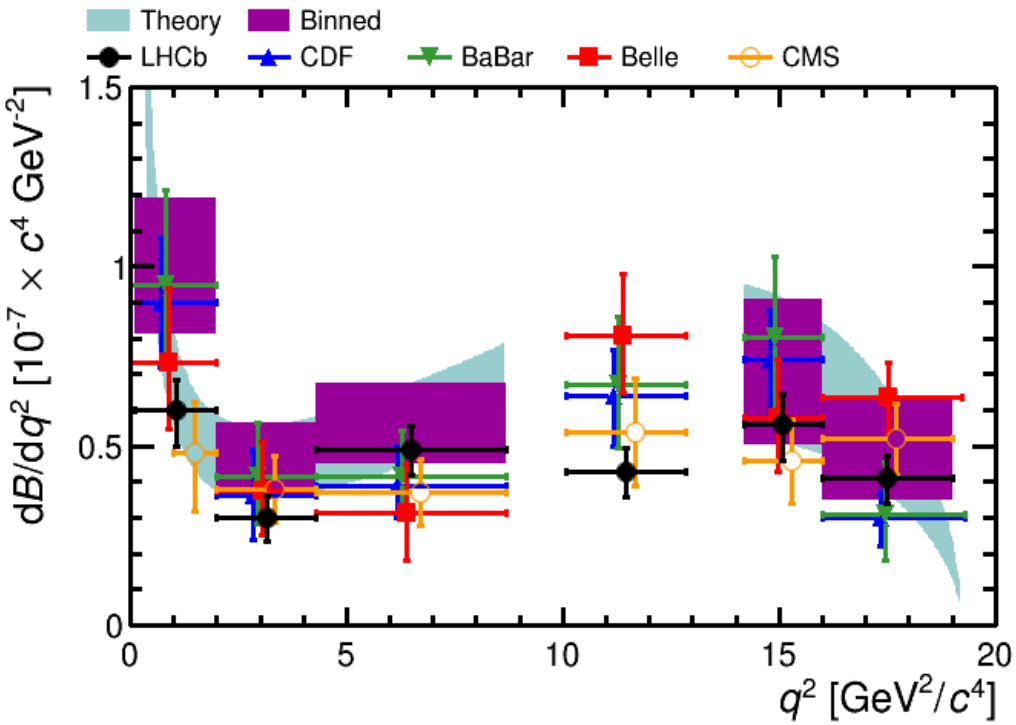
LHCb 883 ± 34 events (1.0 fb^{-1})



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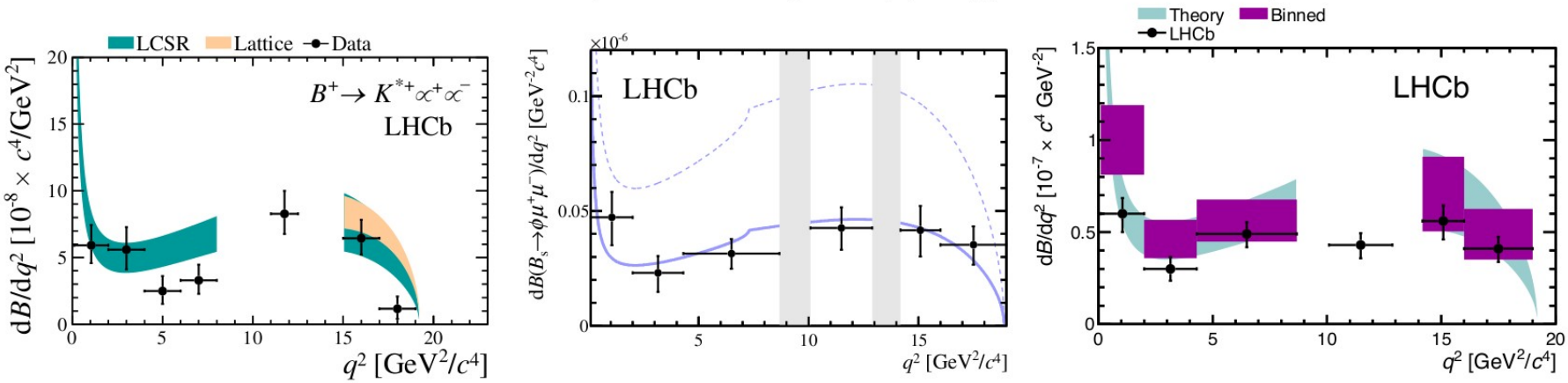
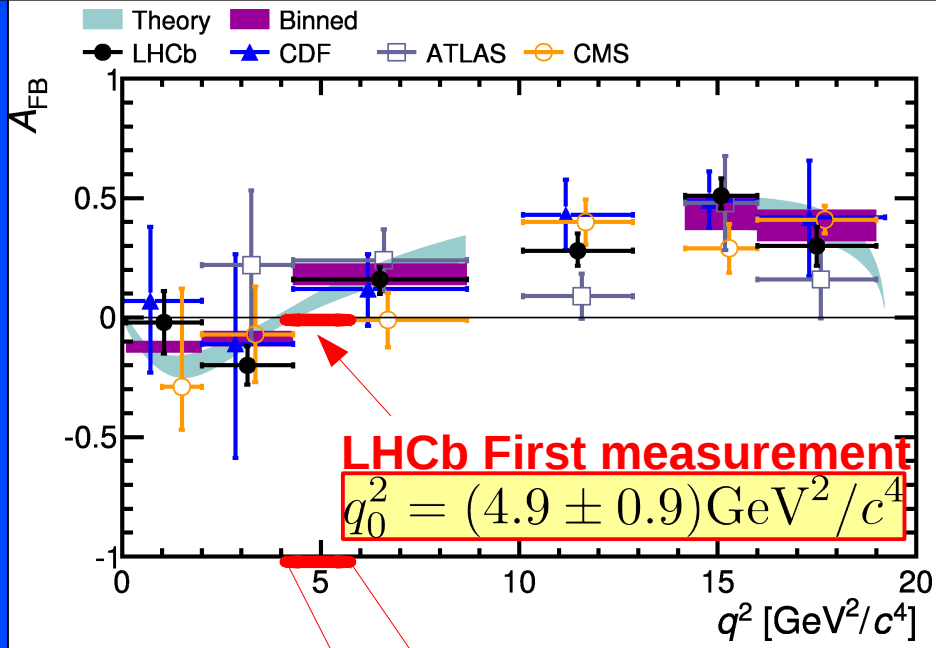
Left: $B^+ \to K^{*+}$, Middle $B_s \to \phi$, Right: $B^0 \to K^{*0}$,



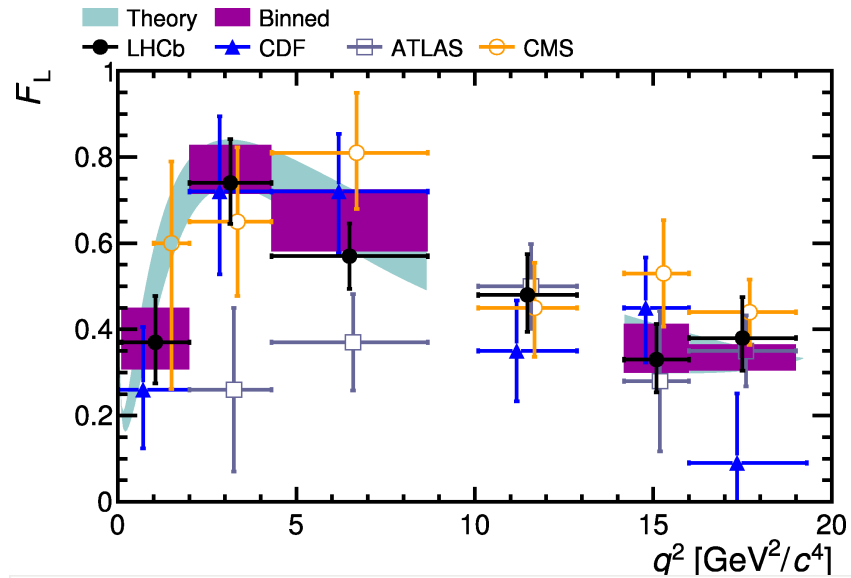
Hint that all BR are on the low side?

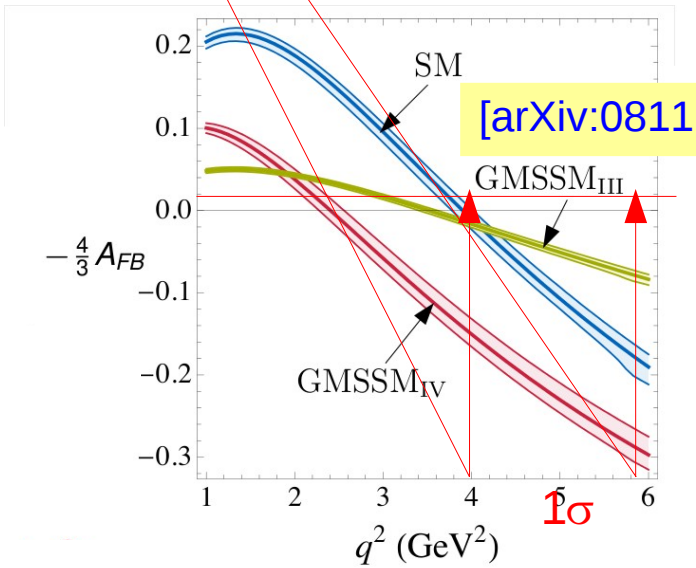
Angular Variables



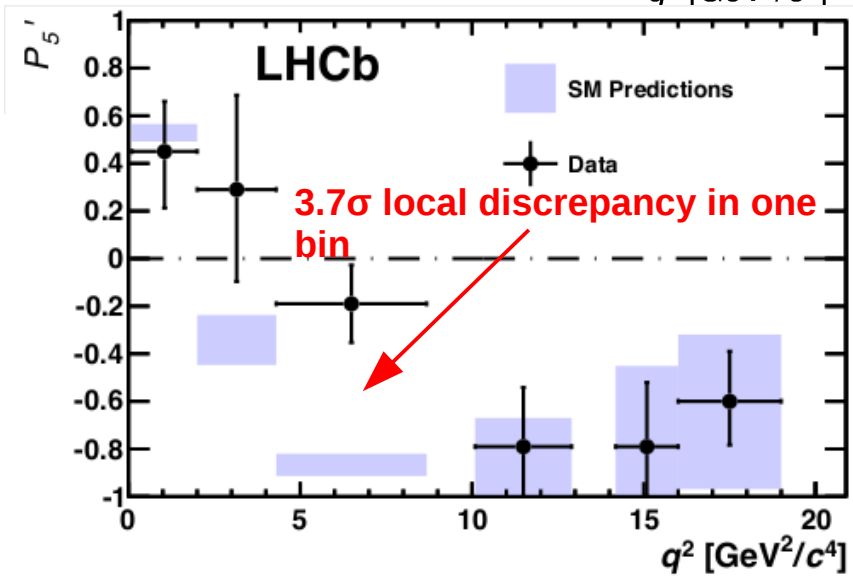
LHCb First measurement

$$q_0^2 = (4.9 \pm 0.9)\mathrm{GeV}^2/c^4$$





[arXiv:0811.1214]



3.7σ local discrepancy in one bin

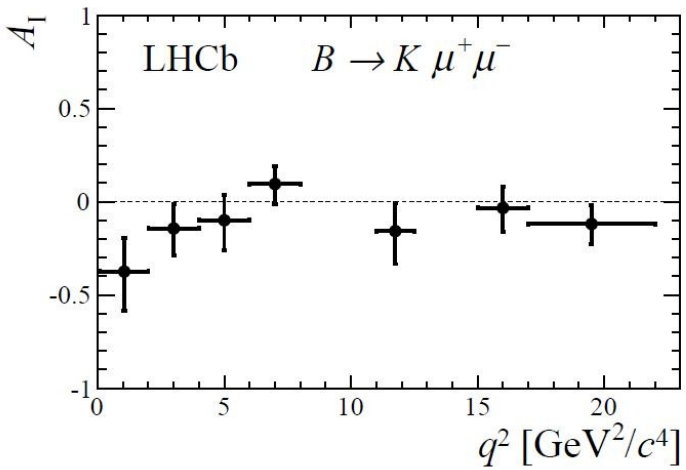
Isospin Asymmetry

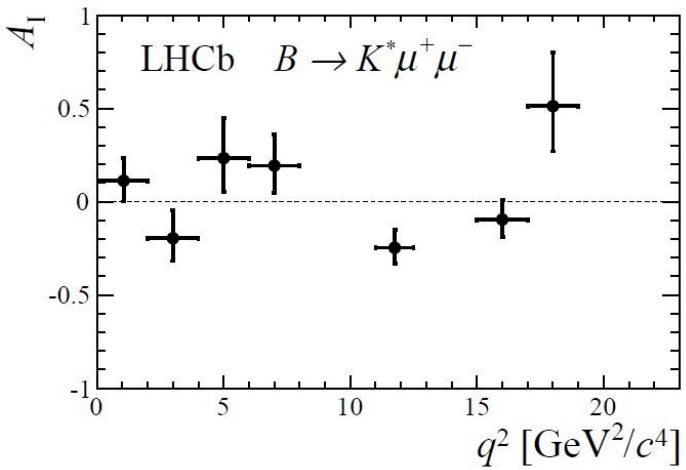
$$A_I = \frac{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) - \frac{\tau_0}{\tau_+}\mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) + \frac{\tau_0}{\tau_+}\mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)}$$

SM prediction is close to zero

$1fb^{-1}$: Deviation from zero over all q^2 at 4.4σ

$3fb^{-1}$: Deviation from zero over all q^2 at 1.5σ





LHCb [arXiv:1403.8044]

Deviations from the SM?

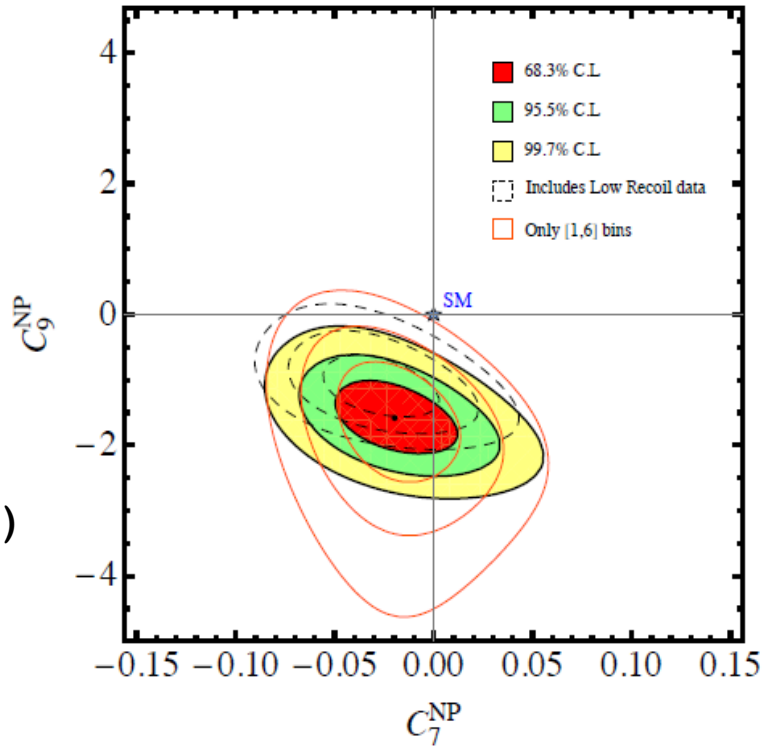
Combine $B_s \to \mu\mu$, $B \to K^{(*)}\mu\mu$, $B \to X_s\gamma$, $B \to K^*\gamma$ measurements to constrain New Physics

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:

~ 35 TeV for O(1) couplings (tree)

~ **7 TeV for CKM-like couplings** (tree)

Straub et al [1308.1501]

Difficult to accommodate within MSSM

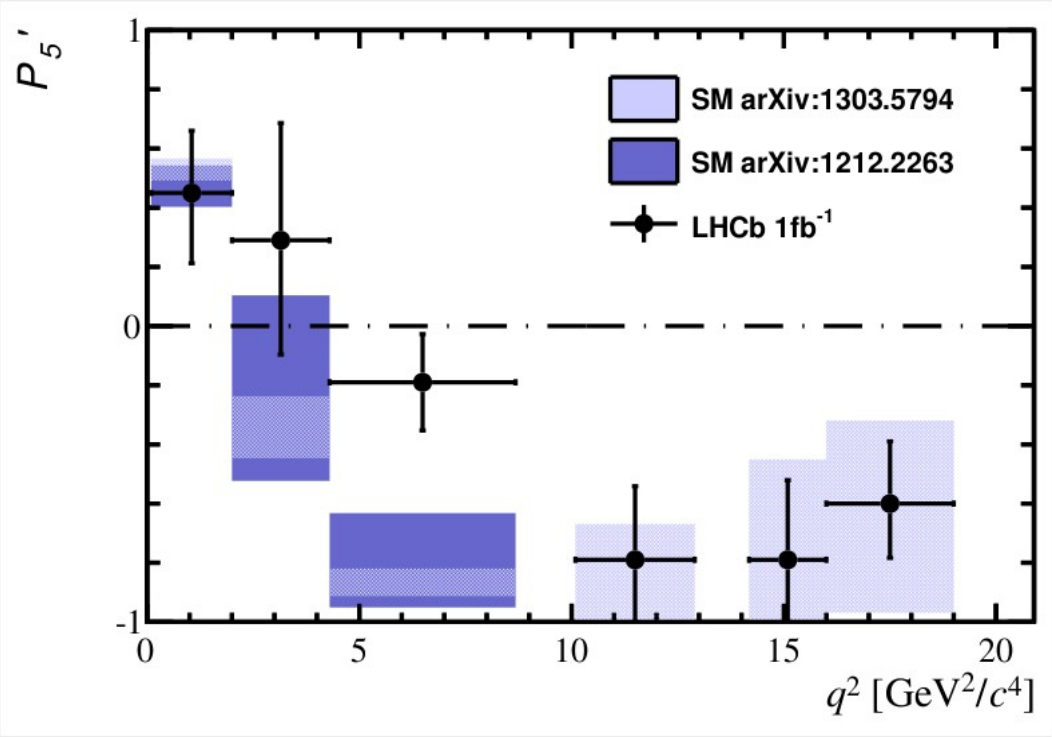
This could happen without affecting the $B_s \to \mu\mu$ branching fraction, which is not sensitive to O_9 (vector) but to O_{10}

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

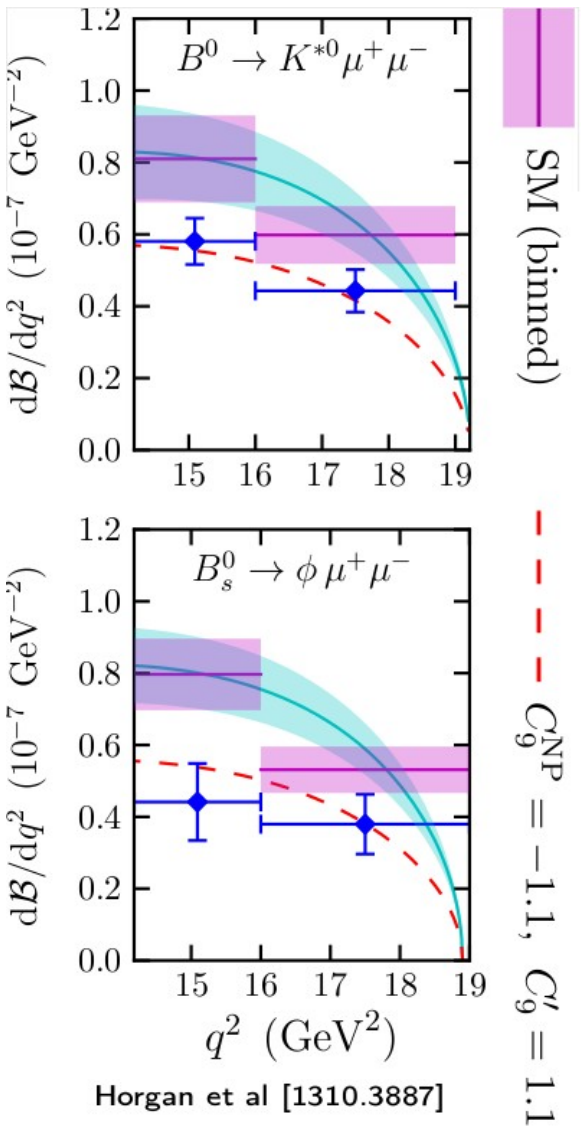
Branching Fraction measurements at high q^2 in tension with SM predictions from the Lattice, and consistent with best fit point for NP from low q^2

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

Lattice QCD predictions + measurements in related channels (e.g b → dμ+ μ-) (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



Horgan et al [1310.3887]

All experiments combined

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

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

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

$$R_H \equiv \frac{\int_{4m_\mu^2}^{q^2_{\max}} dq^2 \frac{d\Gamma(B \to H\mu^+\mu^-)}{dq^2}}{\int_{4m_\mu^2}^{q^2_{\max}} dq^2 \frac{d\Gamma(B \to He^+e^-)}{dq^2}}, \quad H = X_s, K^{(*)},$$

Hiller, Kruger: 0310219

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

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

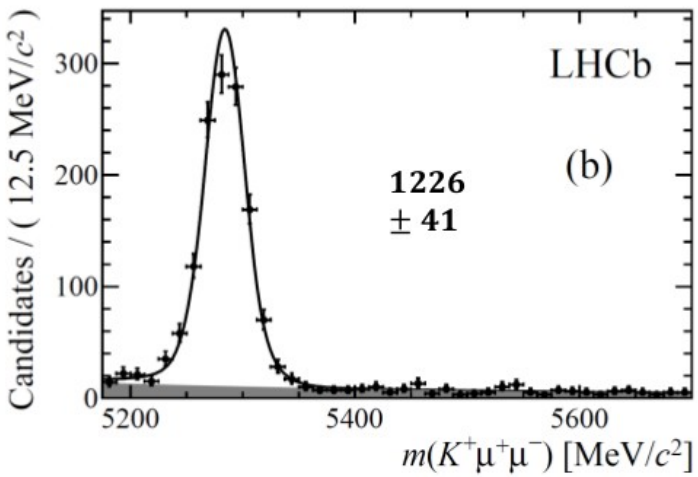
Equality of coupling is concept of lepton-universality.

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

Ke^+e^- vs Km^+m^-

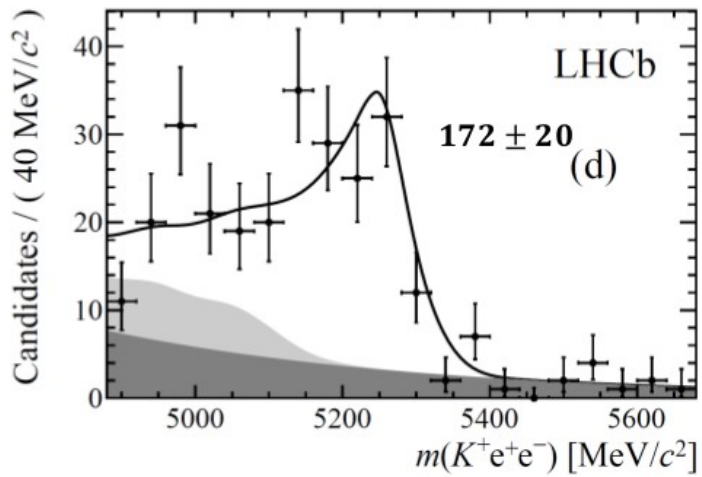
$B^+ \to K^+\mu^+\mu^-$

all events



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

events with a high pT electron



BABAR arXiv: 1204.3933
Belle, arXiV: 0904.0770

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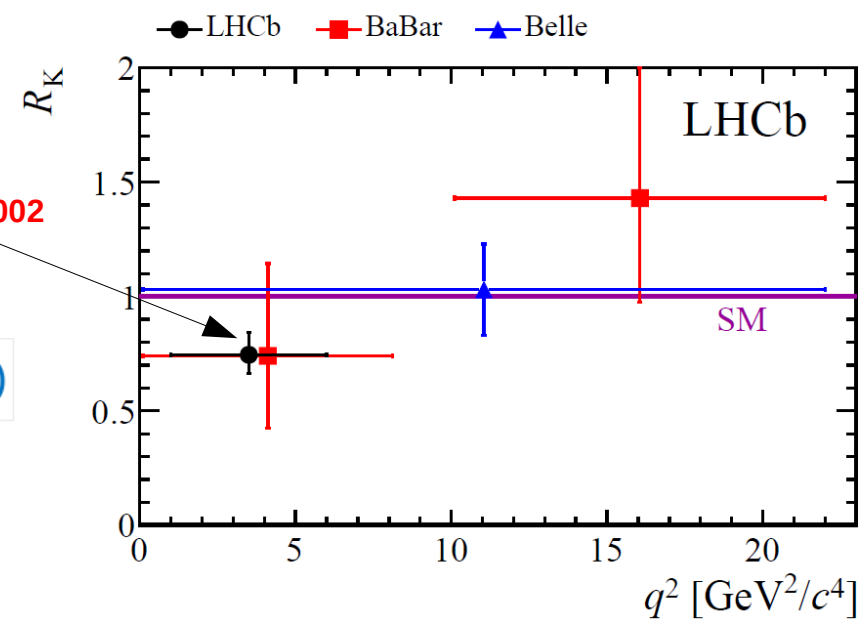
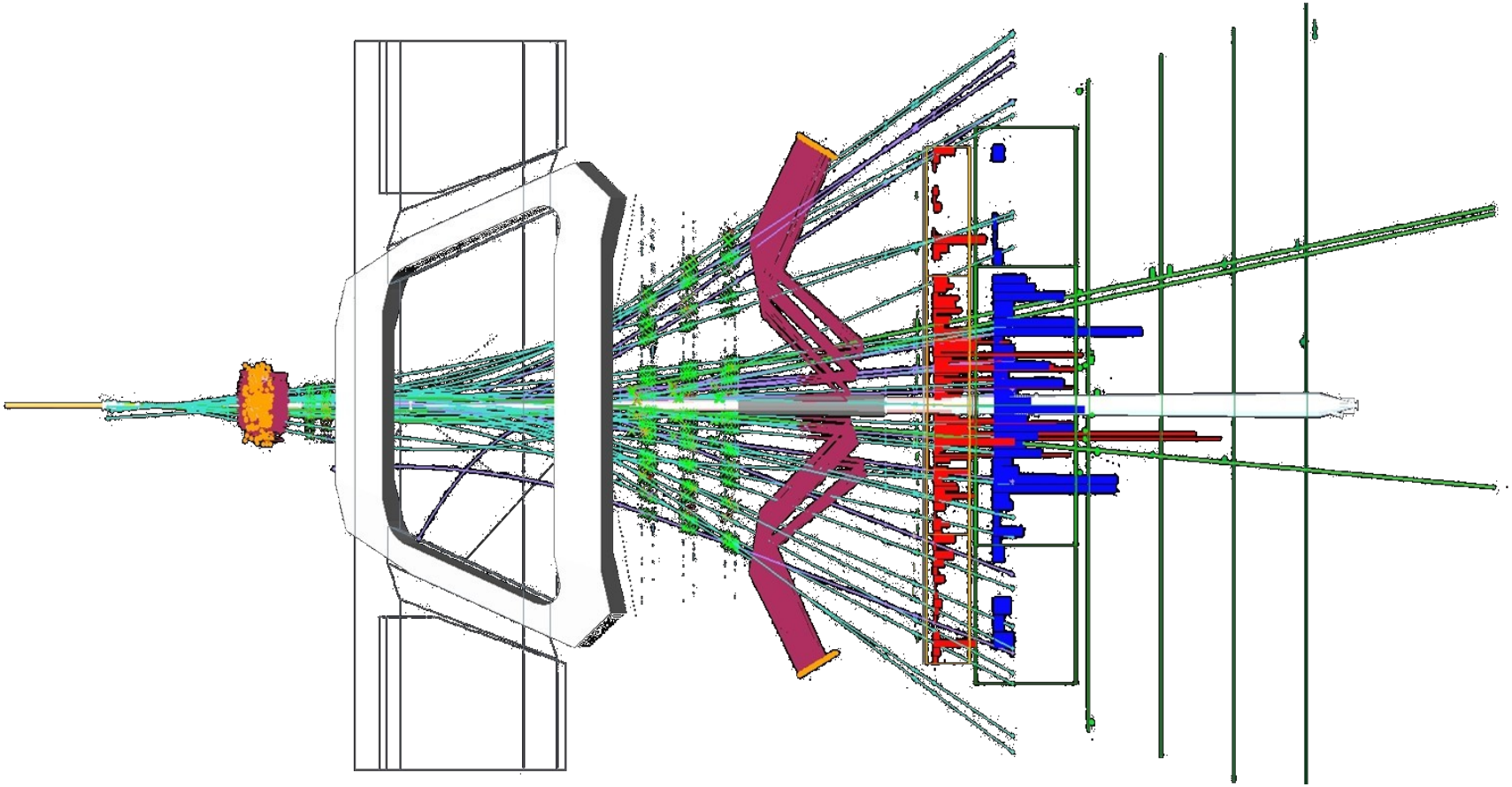


$$R_K = 0.745^{+0.090}_{-0.074}(stat) \pm 0.036(syst)$$

2.6 sigma

$b \rightarrow s\gamma$



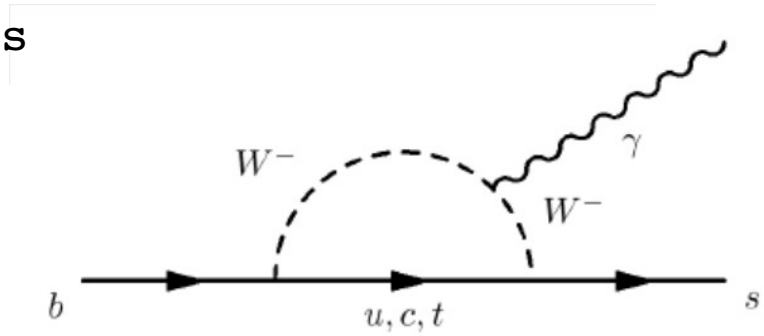
$b \to s\gamma$

LHCb PRL 112 (2014) 161801

b →sγ 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

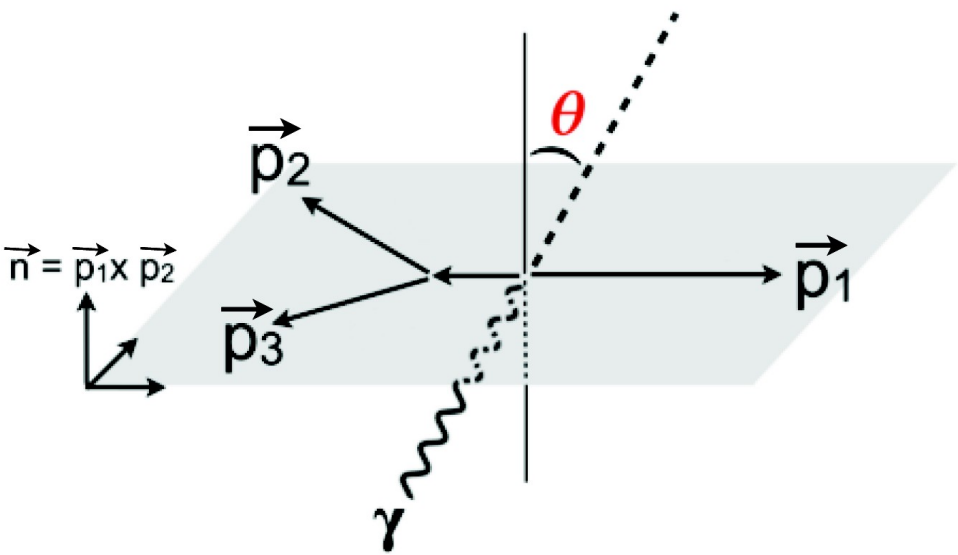
Significant right handed component possible in many NP models



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

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

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



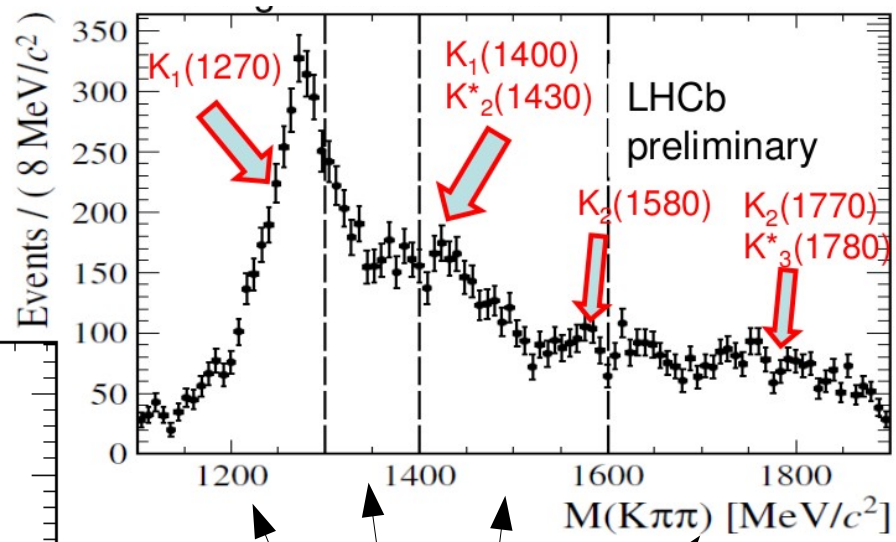
LHCb just updated LHCb-CONF-2013-009 with 3 fb^{-1} of data

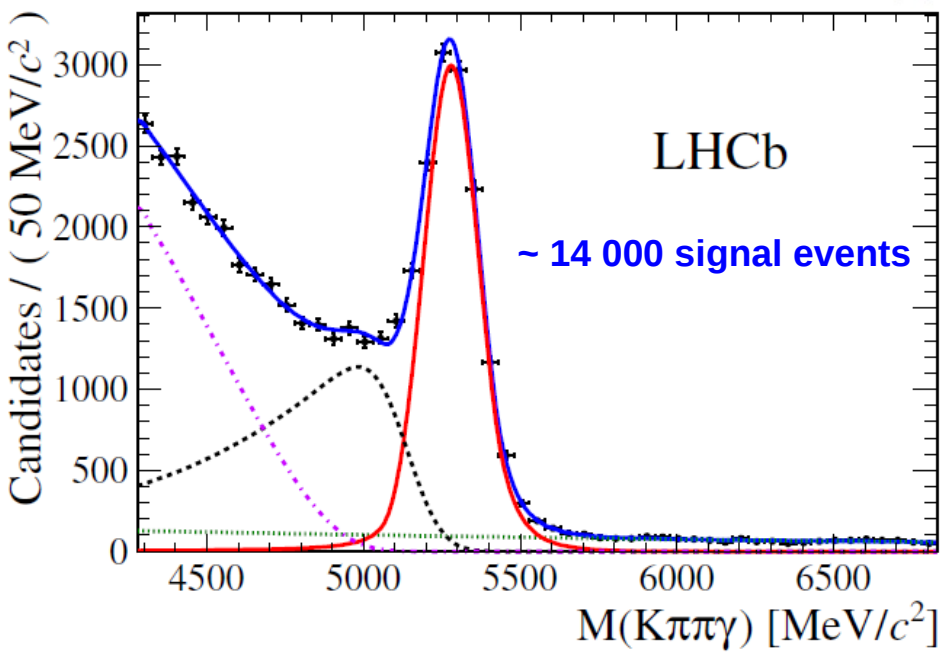
$B^+ \to K^+\pi^-\pi^+\gamma$

Differential decay rate of $B^+ \to K^+\pi^-\pi^+\gamma$ (*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 Kππ spectrum and their interferences



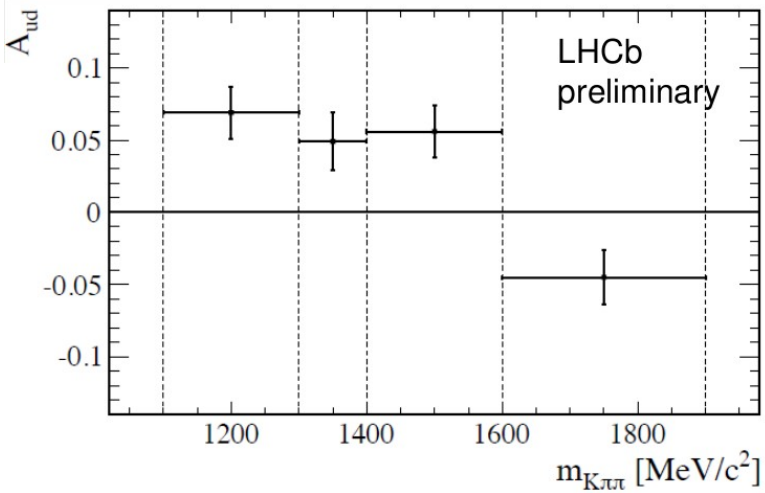


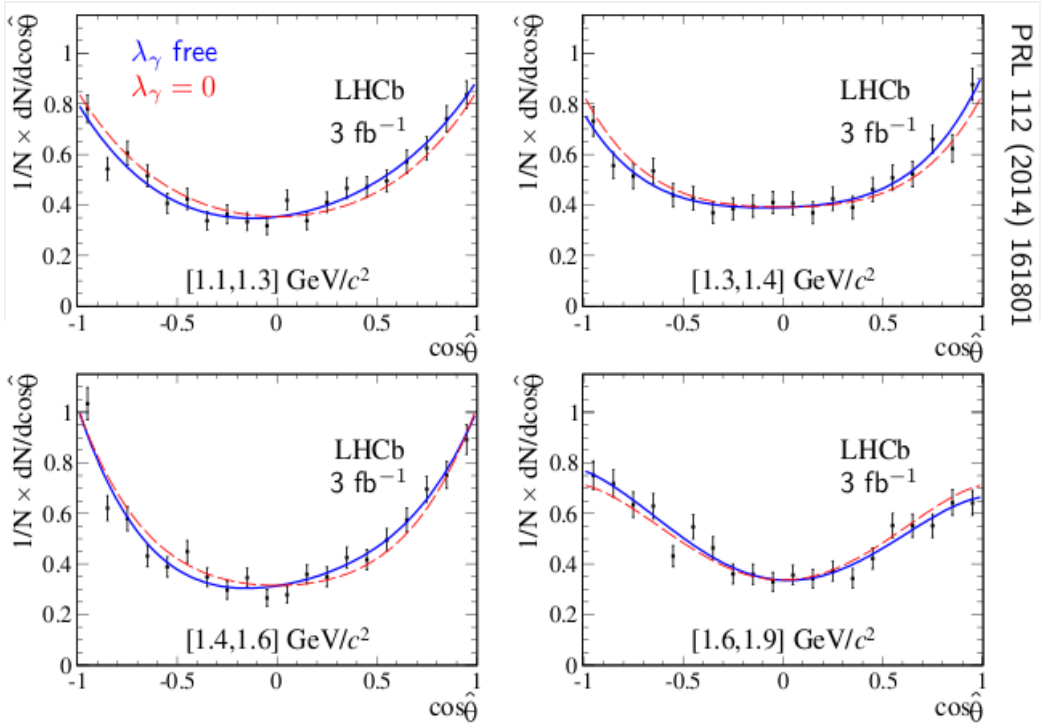
4 bins

Observation of γ polarization

Asymmetry between number of events on each side of the plane

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





Up-down asymmetry proportional to the γ polarisation

5.2σ significance for a non zero up-down asymmetry

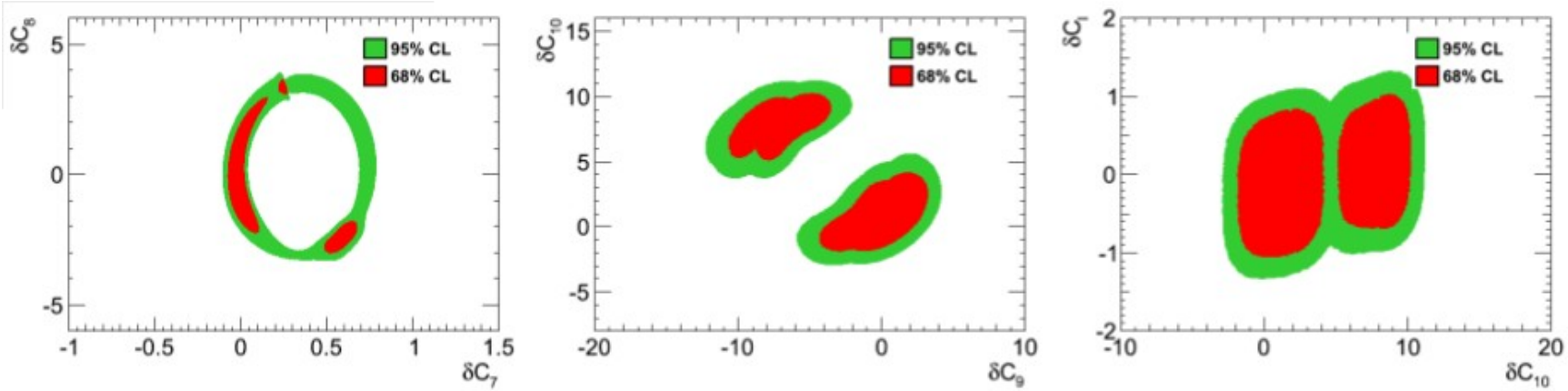
→ first observation of photon polarization in b →sγ transition

Determination of the polarization from A_{ud} and cosθ shape may constrain the effects of NP in the b→sγ sector!

It's crucial to understand the KΠΠ mass structure!

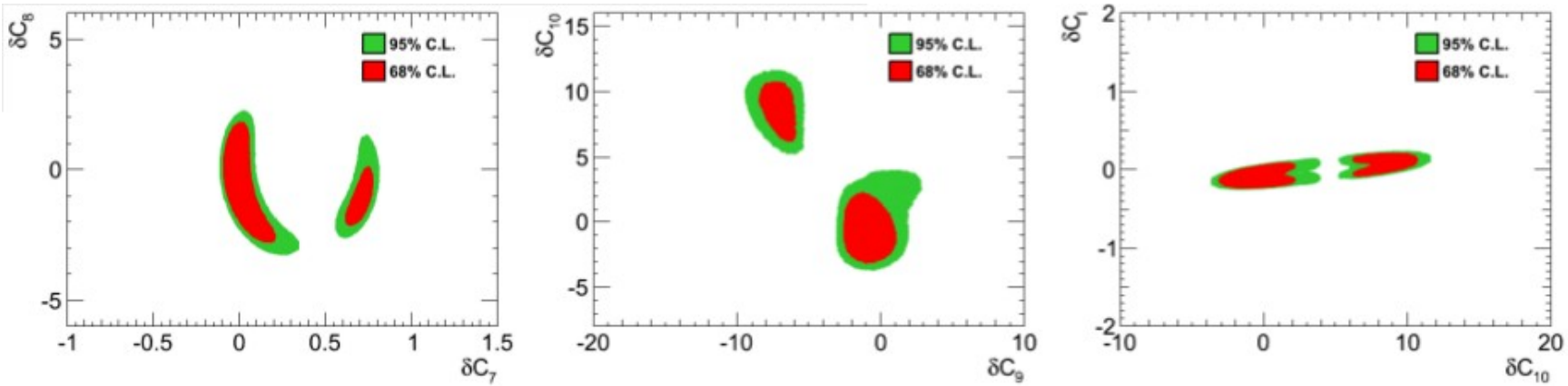
Shrinking the Wilson coeff.

2012



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

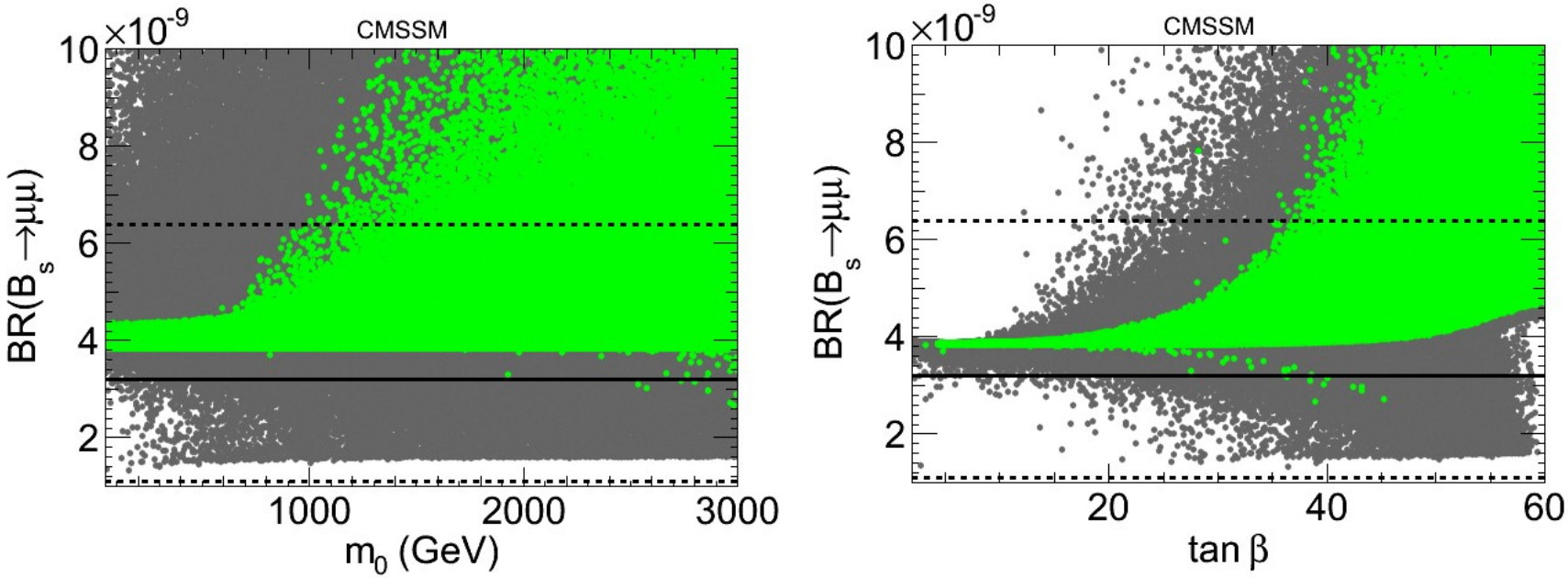
2014



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

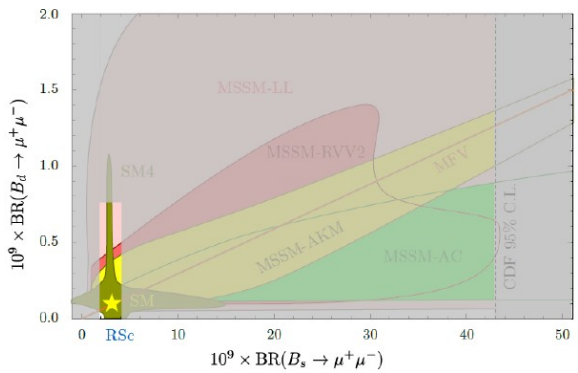
Not true in pMSSM !

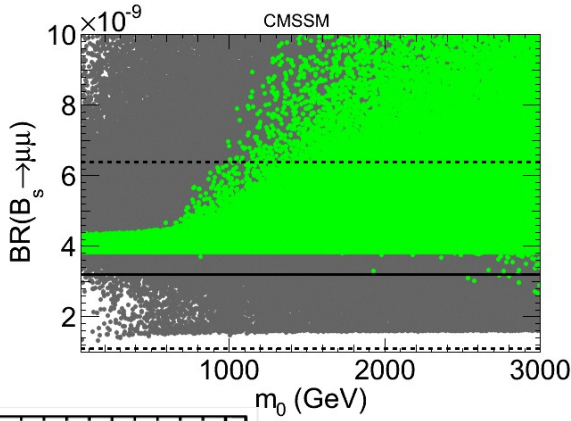
Flat scans over the CMSSM parameters with $\mu > 0$
Solid line: central value of the BR($B_s \to \mu^+ \mu^-$) measurement
Dashed lines: 2σ experimental deviations
Gray points: all valid points
Green points: points in agreement with the Higgs mass constraint

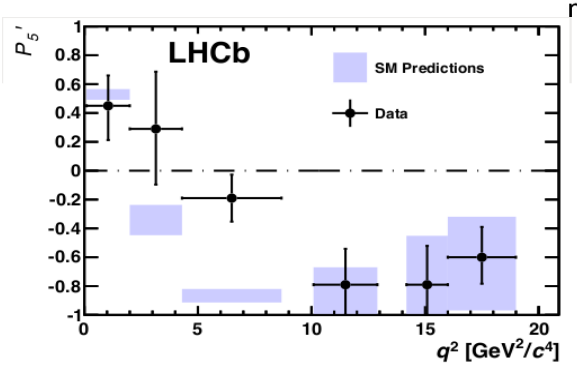
Conclusions

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 -> **1st observation of $B_s \to \mu^+\mu^-$**

More data needed to:

- measure **$B(B_s \to \mu^+\mu^-)/B(B^0 \to \mu^+\mu^-)$**
- measure **effective lifetime for $B_s \to \mu^+\mu^-$**
- search for other **decays as those involving taus** (e.g. **$B^0 \to (K^*)\tau^+\tau-$**)

Coming soon: full combination CMS+LHCb

Latest **$B^0 \to K^*\mu^+\mu^-$** 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.