Results from LHCb

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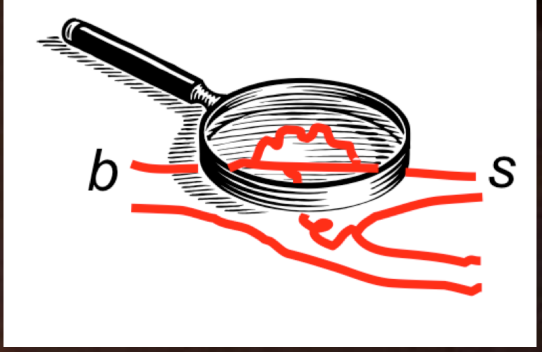


Perugia, March 1st, 2016

Why flavour physics?

Any physics model (SM or NP) has to deal with the observed flavour structure

In SM this is through the Yukawa couplings to the Higgs field and the weak force; misalignment of these gives structure of CKM matrix

wide range: $m_u = O(10^{-15}) m_t$, $|V_{ub}| = O(10^{-3})|V_{tb}|$ **Why???**

Any physics model NP model with new flavoured particles or flavour breaking interactions must "hide" behind SM interactions

NP mass scale very large (>100TeV)

or

NP mimics Yukawa couplings (Minimal Flavour Violation)

Both choices can be argued to be un-natural

What?

Rare decays: electroweak penguins

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

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

Lepton universality

$BF(B \to K\mu^+\mu^-)/BF(B \to Ke^+e^-)$

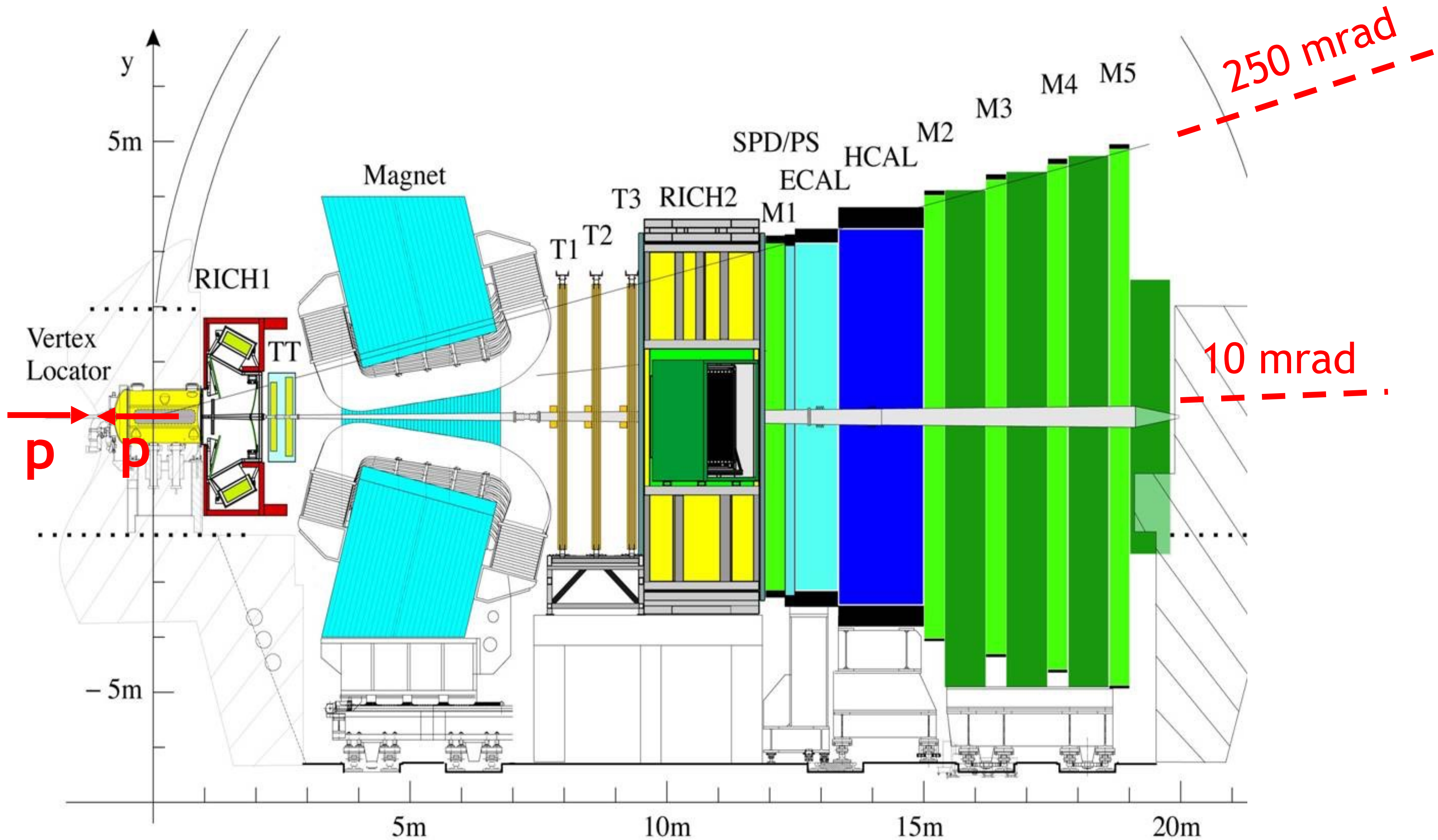
$BF(B \to D^*\tau\nu)/BF(B \to D^*\mu\nu)$

CKM and CP violation

The case of V_{ub} and V_{cb}

Angles

How?



B/D mesons boost ~10 mm

excellent tracking to reconstruct heavy quarks decay chains

Select kaons, pions, protons and muons

excellent PID: RICH+CALO+MUON

Trigger: decay of interest range from

- precision CP violation in charm → kHz
- B decays with 10^{-10} branching fraction → 10 nHz

Large cross section and acceptance, smooth data taking:

RUN I = 1fb^{-1} (7TeV)+2 fb^{-1} (8TeV)

RUN II = 0.3 fb^{-1} (13TeV) + …

The first observation of $B_s \to \mu^+\mu^-$

LETTER

doi:10.1038/nature14474

Observation of the rare $B_s^0 \to \mu^+\mu^-$ decay from the combined analysis of CMS and LHCb data

The CMS and LHCb collaborations*

Nature 522 (2015) 68
13 May 2015

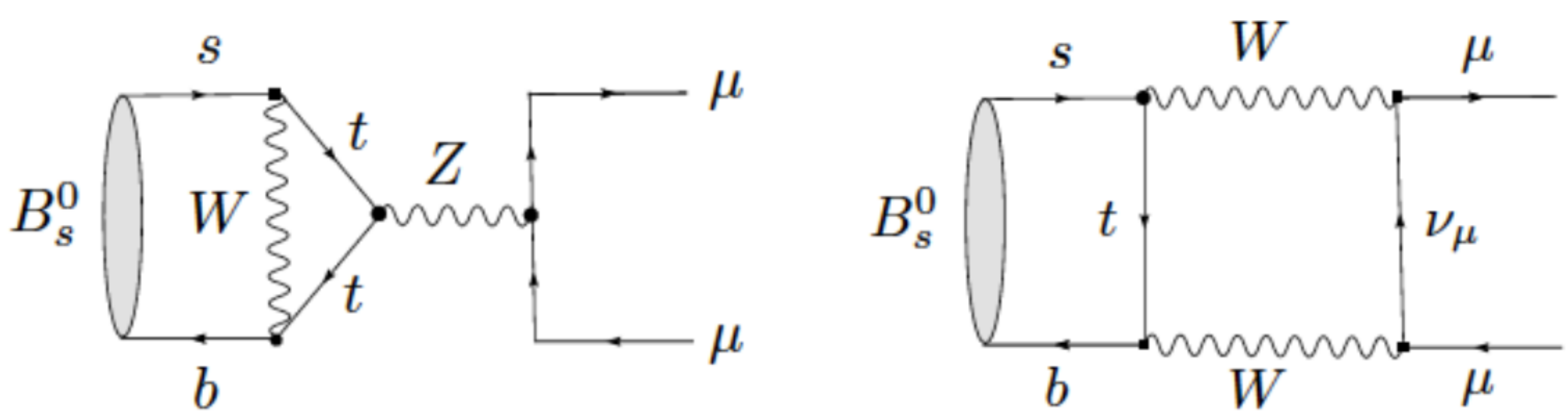
Why to search for NP in $B^0_{s,d} \to \mu^+\mu^-$?

1) Because they are very suppressed in SM

- they can proceed only from loop contributions related to penguin and box topologies, the Higgs diagram is negligible in SM, as it goes as $\sim (m_B/m_W)^2$

- they are helicity suppressed: $\Gamma \sim m^2_\mu$

… hence very sensitive to small perturbations due to BSM contributions



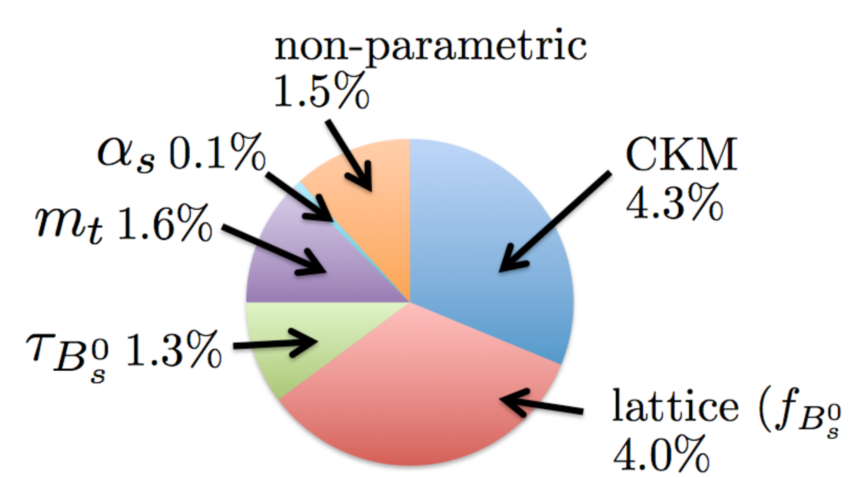
2) Because they are clean theoretically

- only leptons present in the final state, the hadronic sector is very simple and described by a single non-perturbative parameter, the $B_{s(d)}$ decay constant f_{Bs} (f_{Bd})

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

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

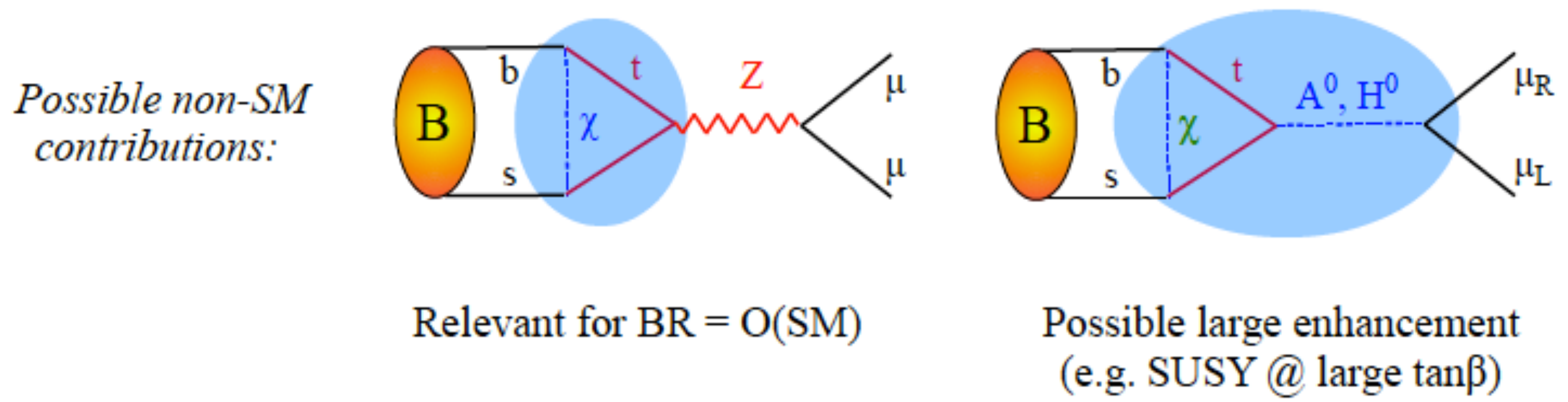
BR($B^0_s \to \mu^+\mu^-$) error budget



Bobeth et al. PRL 112 101801 (2014)

Why to search for NP in $B^0_{s,d} \rightarrow \mu^+\mu^-$?

3) Because they are sensitive to contributions from the extended Higgs sector



this is gone

BR in the OPE

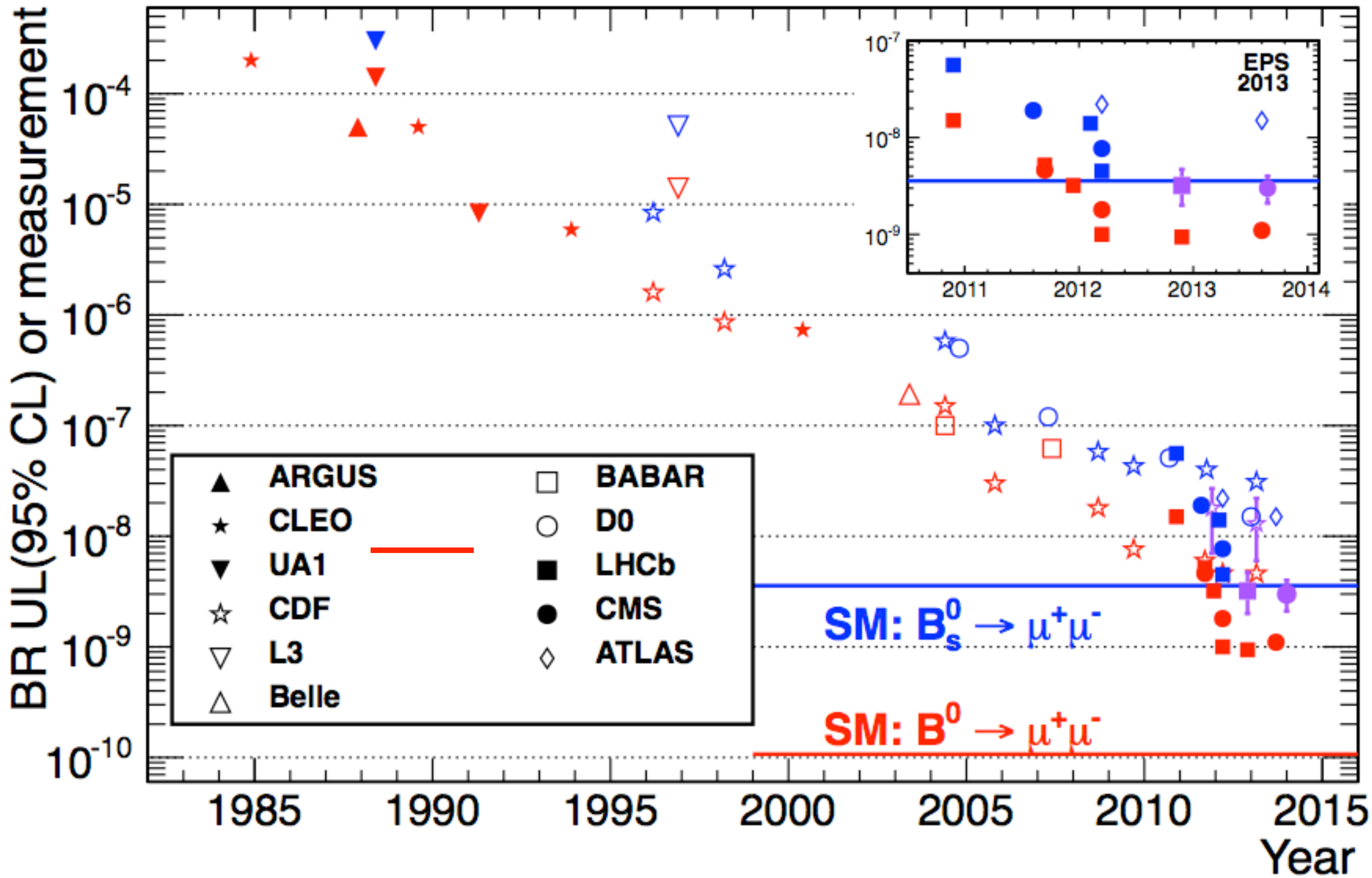
$$\mathcal{B}(B^0_q \to \mu^+\mu^-) \approx \frac{G_F \alpha^2 M^3_{B^0_q} f^2_{B^0_q} \tau_{B^0_q}}{64\pi^3 \sin^4\theta_W} |V_{tb}V^*_{tq}|^2 \left(1 - \frac{4m^2_\mu}{M^2_{B^0_q}}\right)^{1/2} M_{B^0_q} \times$$
$$\left[\left(1 - \frac{4m^2_\mu}{M^2_B}\right)|\mathcal{C}_S - \mathcal{C}'_S|^2 + |(\mathcal{C}_P - \mathcal{C}'_P) + \frac{2m_\mu}{M_B}(\mathcal{C}_{10} - \mathcal{C}'_{10})|^2\right]$$

The Wilson coefficients C_i encode short-distance physics from SM and **from possible NP effects**, computed perturbatively: in SM C_{10} only is different from zero, MSSM $C_{S,P} \sim \tan^3\beta / M_A^2$

4) The B^0/B^0_s ratio is also powerful to discriminate among NP models: a deviation from the value predicted by SM, $\sim(V_{td}/V_{ts})^2$, would indeed also imply the breaking of the Minimal Flavour Violation hypothesis

Matteo Palutan, INFN-LNF

$B_s \to \mu^+\mu^-$: a story 30 years long



LHCb hunt for $B^0_s \to \mu^+\mu^-$ during RUN I

We published five papers in 2.5 years

- Search for the rare decays $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$
arXiv:1103.2465 [hep-ex], Phys.Lett. B699 (2011) 330-340 – 100 citations

- Search for the rare decays $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$
arXiv 1112.1600 [hep-ex], Phys.Lett. B708 (2012) 55-67 – 51 citations

- Strong constraints on $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ decays,
arXiv:1203.4493 [hep-ex], Phys.Rev.Lett. 108 (2012) 231801 – 231 citations

- First evidence for the decay $B^0_s \to \mu^+\mu^-$
arXiv: 1211.2674 [hep-ex], Phys.Rev.Lett. 110 (2013) 2, 021801 – 328 citations

presented 13/11/2012 in a CERN seminar (M. P.)

- Measurement of the $B^0_s \to \mu^+\mu^-$ branching ratio and search for $B^0 \to \mu^+\mu^-$ decay at the LHCb experiment,
arXiv: 1307.5024 [hep-ex], Phys.Rev.Lett. 111 (2013) 101805 - 189 citations

+ discovery paper with CMS: Nature 522 (2015) 68

Strong points for $B_s \to \mu^+\mu^-$ at LHCb

1) Run the experiment at 4×10^{32} cm^{-2}s^{-1} with 1262 colliding bunches

twice the design luminosity with half number of bunches

⟶ 4 times more collisions per crossing than design: $<\mu>_{8TeV}\sim1.7$

⟶ higher occupancy in the detector, challenging for the trigger

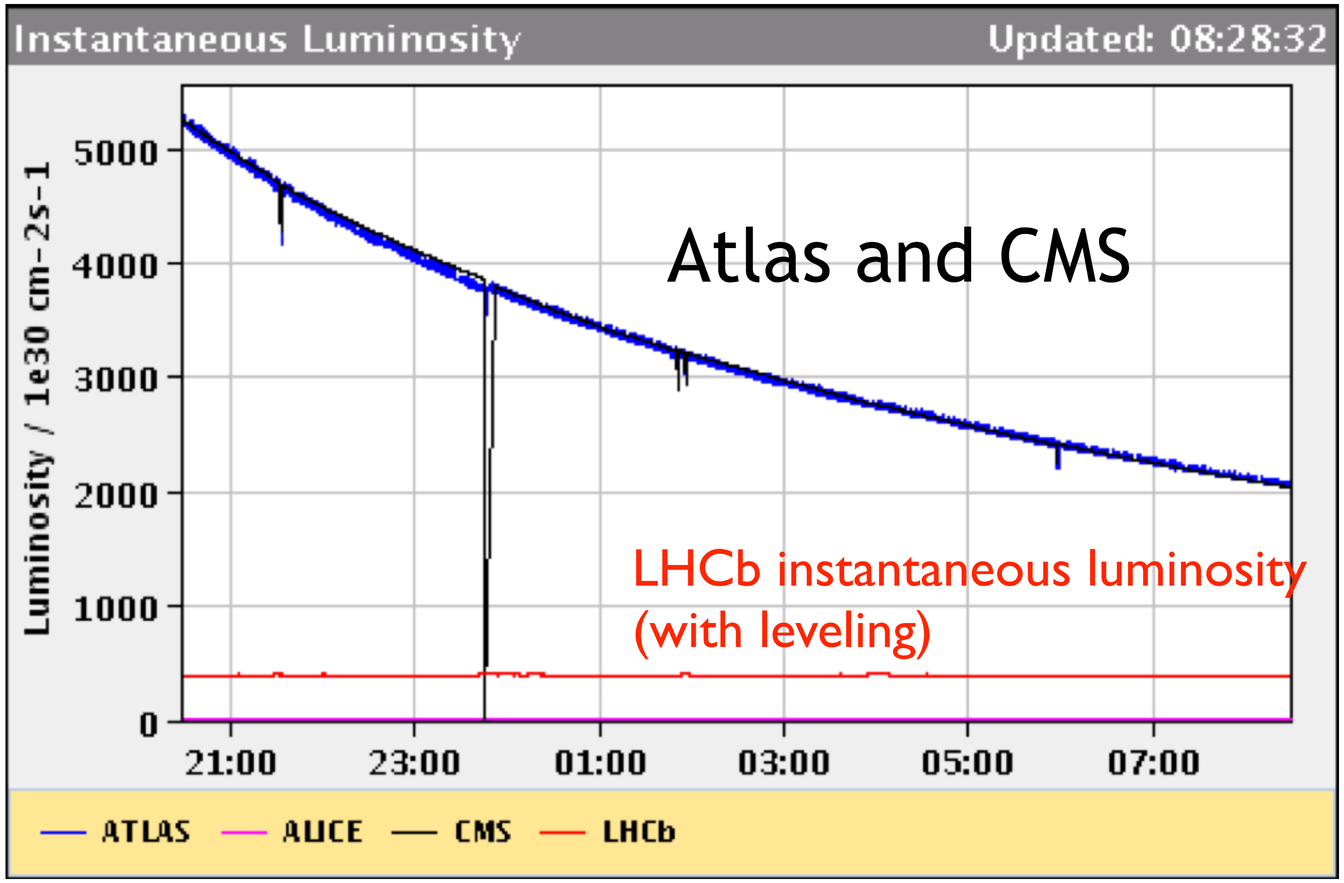
in total 3fb^{-1} acquired during RUN I

2) Large cross section

$\sigma(pp\to bbX)$ @ 7 TeV ~ 300 μb → at L = 4 x10^{32} cm^{-2} s^{-1} 120,000 bb /s produced

3) Large acceptance, efficient muon trigger

- acceptance × reconstruction efficiency for signal is ~10%
- L0: single muon p_T>1.76 GeV/c, dimuon sqrt($p_{T1} * p_{T2}$)>1.6GeV/c
- HLT: IP and invariant mass cuts
- overall trigger efficiency ~90%

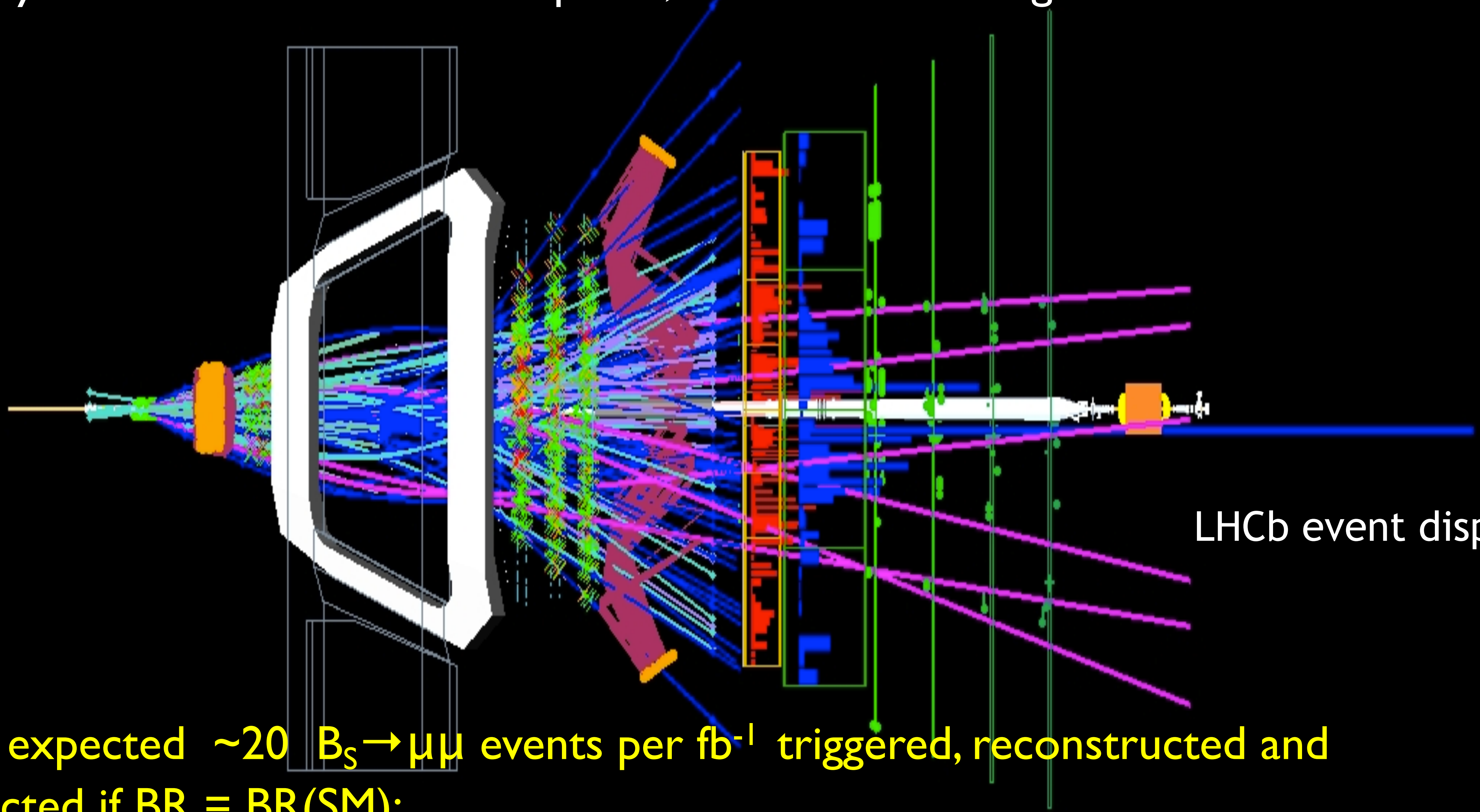


4) Large boost:

→ average flight distance of B mesons ~ 1 cm

… But in a harsh environment

- σ(pp, inelastic) @ $\sqrt{s}$=7 TeV ~ 80 mb
  - ~100 tracks per event in LHCb pileup conditions
  - only 1/300 event contains a b quark , and we are looking for BR~3 10^{-9}



LHCb event display

We expected ~20 $B_S \to \mu\mu$ events per fb^{-1} triggered, reconstructed and selected if BR = BR(SM):

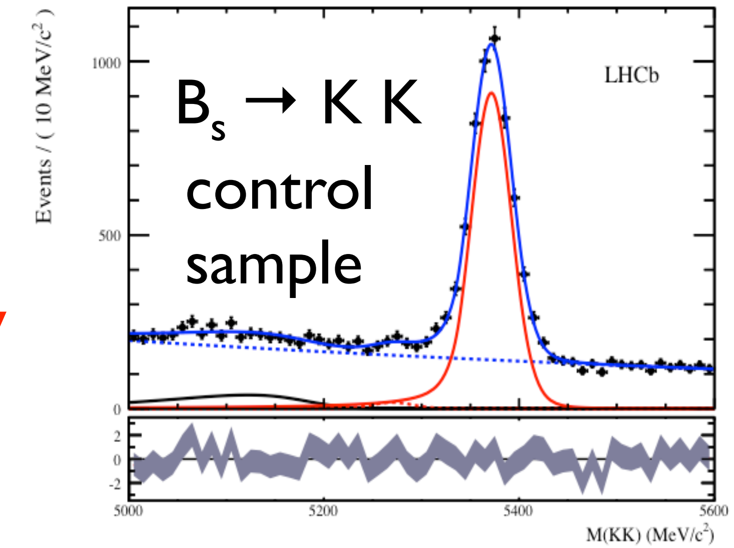
Our problem was clearly the background….

How to reduce the background ?

1) Very good momentum resolution:

→ To have a narrow dimuon mass region where to look for the signal and separate B_s from B^0

→ **$\delta p/p \sim 0.4\% - 0.6\%$ for $p = (5 - 100)$ GeV/c → $\sigma(M) \sim 24$MeV**



2) Good muon identification:

→ To reduce the amount of hadrons misidentified as muons

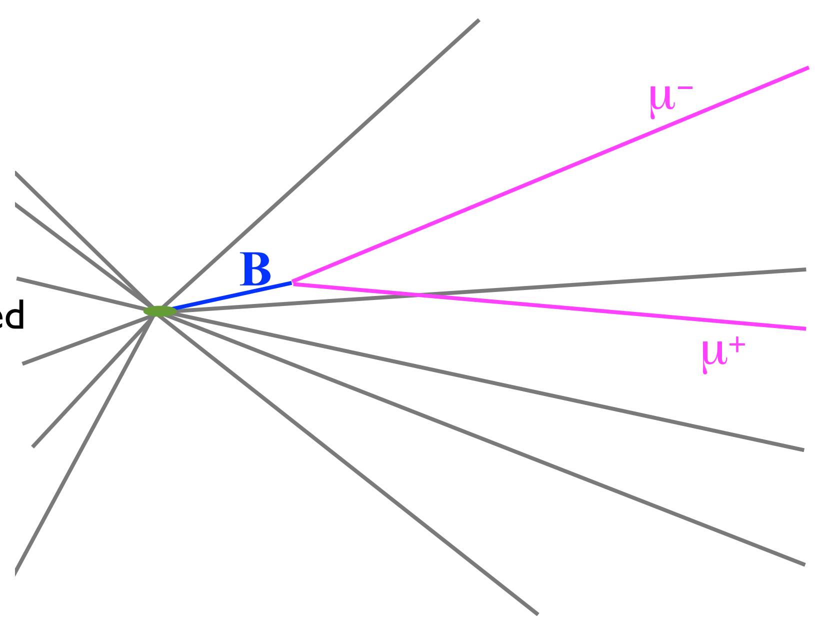
→ **$\varepsilon(\mu\rightarrow\mu) \sim 98\%$, $\varepsilon\pi\rightarrow\mu \sim 0.6\%$, $\varepsilon(K\rightarrow\mu) \sim 0.3\%$, $\varepsilon(p\rightarrow\mu) \sim 0.3\%$**

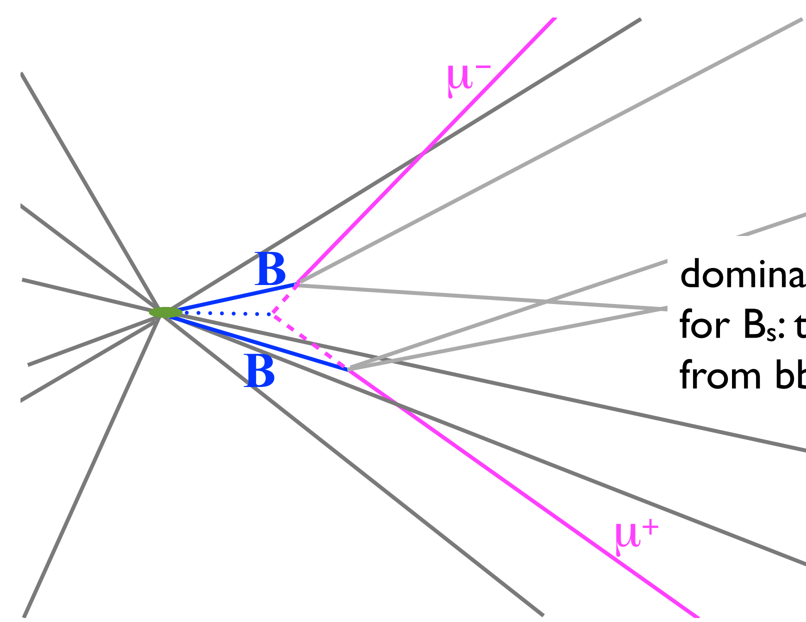
3) Excellent vertex and IP resolution:

→ To separate a displaced secondary vertex from the tracks coming from the primary vertex

→ **$\sigma(IP) \sim 25$ µm @ $p_T = 2$ GeV/c**

signal: 2 muons from a single well reconstructed secondary vertex





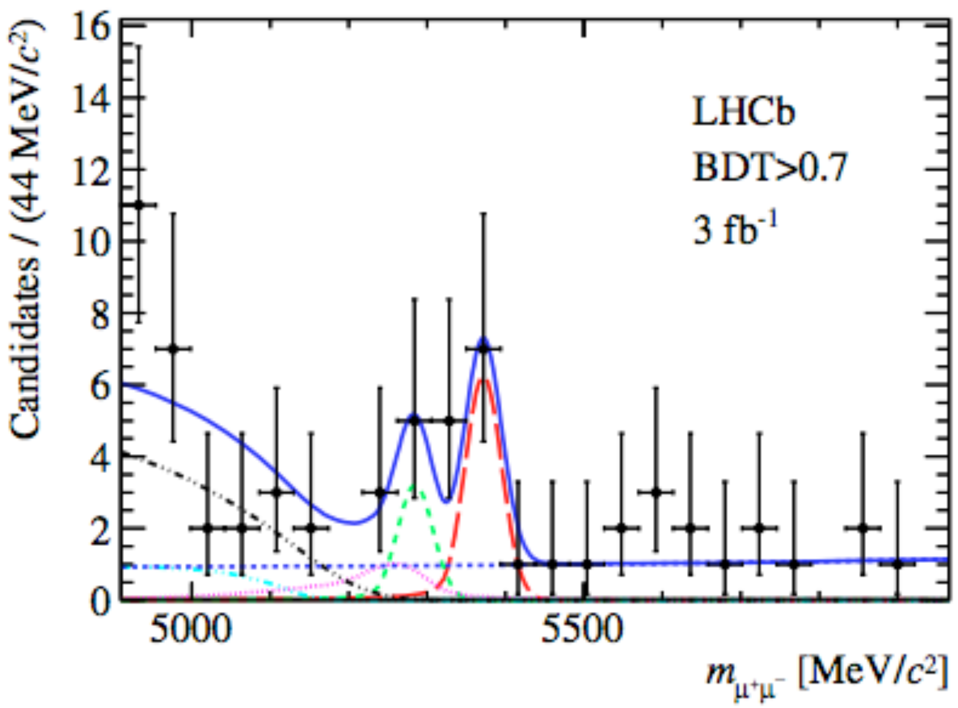
dominant background for B_s: two real muons from bb → $\mu^+\mu^-X$

$B_s \to \mu^+\mu^-$ results at EPS2013

- During EPS 2013 we presented our result based on the full RUN I dataset, 3fb^{-1}; our colleagues/competitors of CMS did the same, using 25 fb^{-1} of data

Nov. 2012: LHCb found the first evidence of the $\mathcal{B}(B^0_s \to \mu^+\mu^-)$ with 2.1fb^{-1}

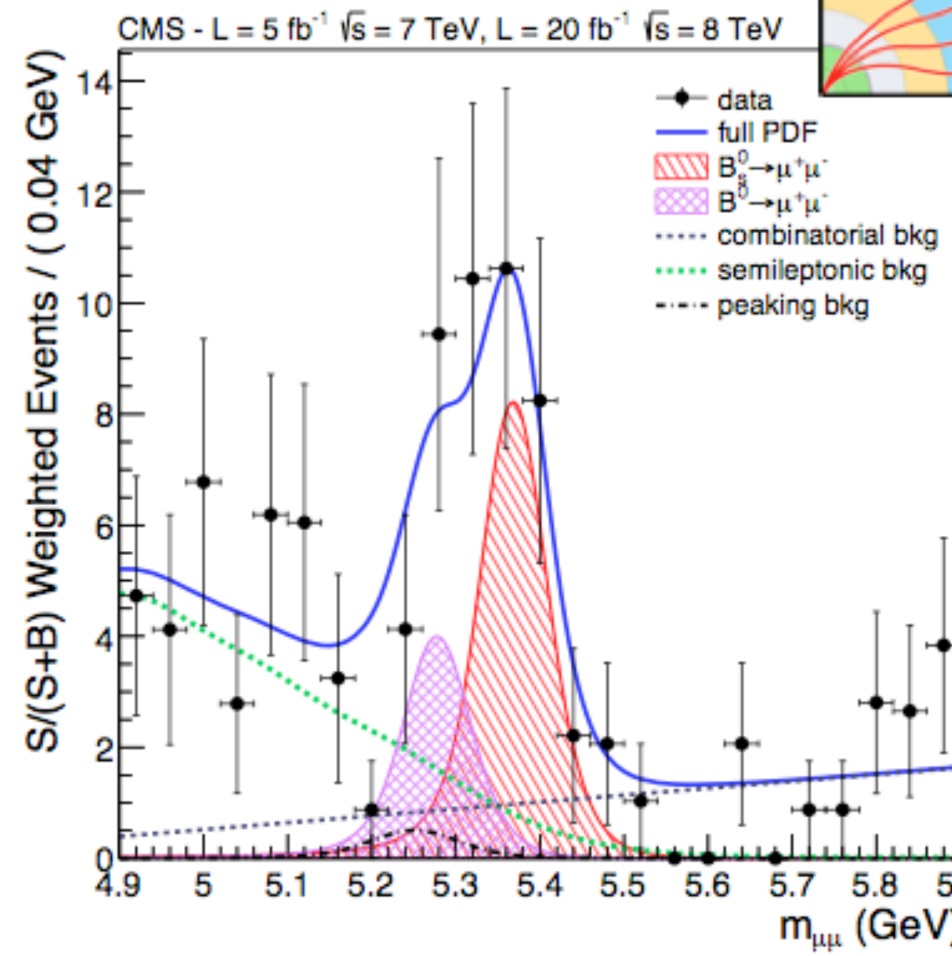
[PRL 111 (2013) 101805]



$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = 2.9^{+1.1}_{-1.0} \times 10^{-9} \quad (4.0\sigma)$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = 3.7^{+2.4}_{-2.1} \times 10^{-10} \quad (2.0\sigma)$$

[PRL 111 (2013) 101804]



$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = 3.0^{+1.0}_{-0.9} \times 10^{-9} \quad (4.3\sigma)$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = 3.5^{+2.1}_{-1.8} \times 10^{-10} \quad (2.0\sigma)$$

Combined CMS and LHCb results

Nature 522 (2015) 68

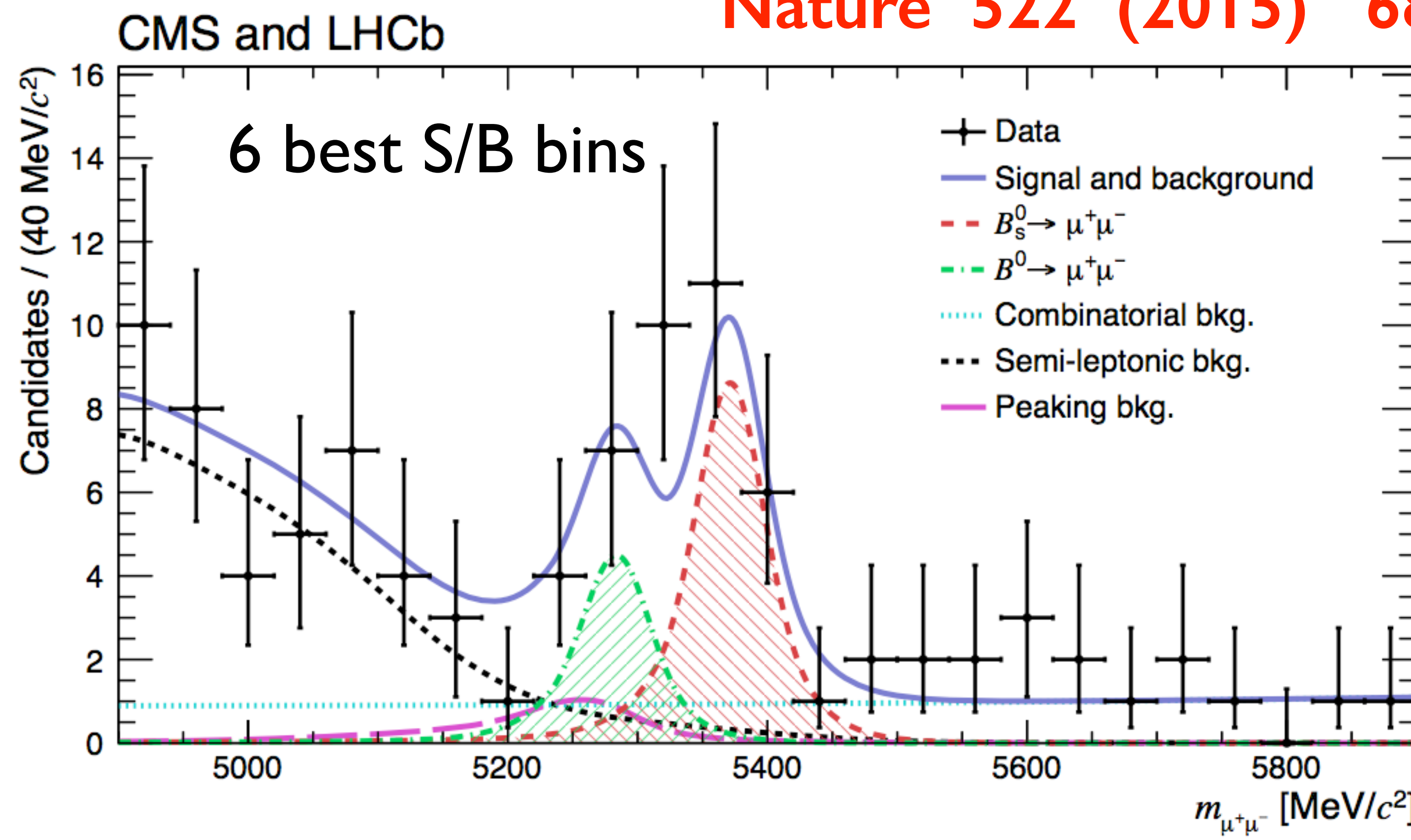
- Full simultaneous fit of CMS and LHCb data

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$$

B^0_s 1.2σ below SM

B^0 2.2σ above SM



- Statistical significance (Wilks' theorem):

▸ 6.2 σ for the $B^0_s \to \mu^+\mu^-$

(Expected SM 7.6 σ)

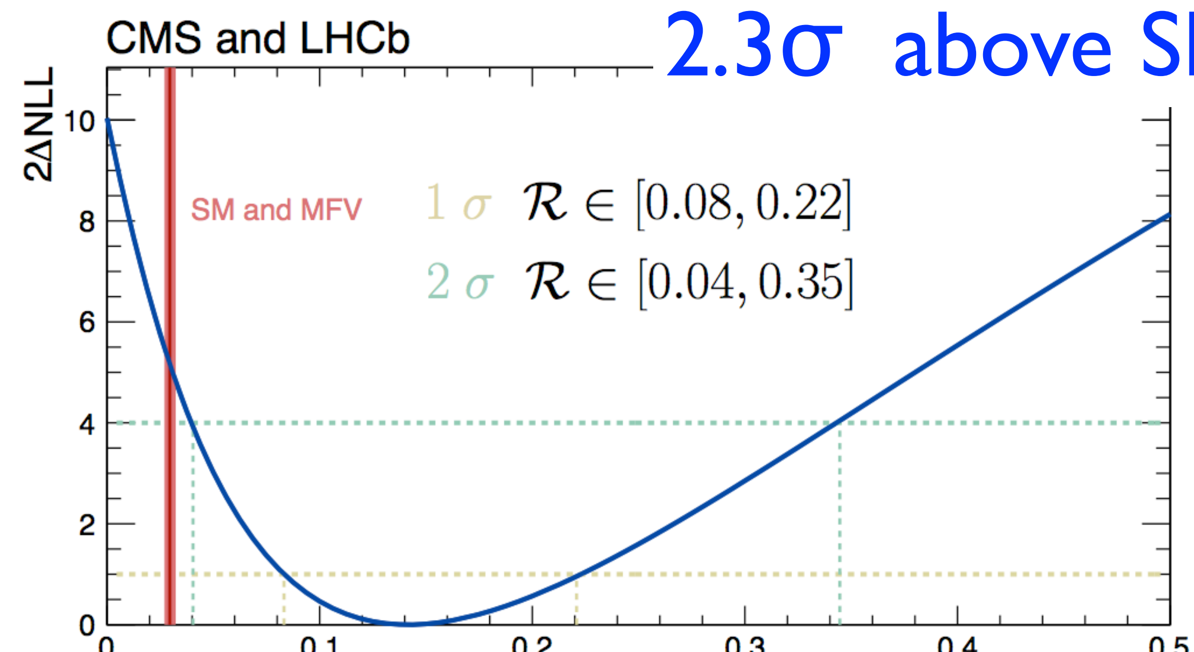
✦ First **observation**

▸ 3.2 σ for the $B^0 \to \mu^+\mu^-$

(Expected SM 0.8 σ)

B^0/B^0_s ratio

2.3σ above SM

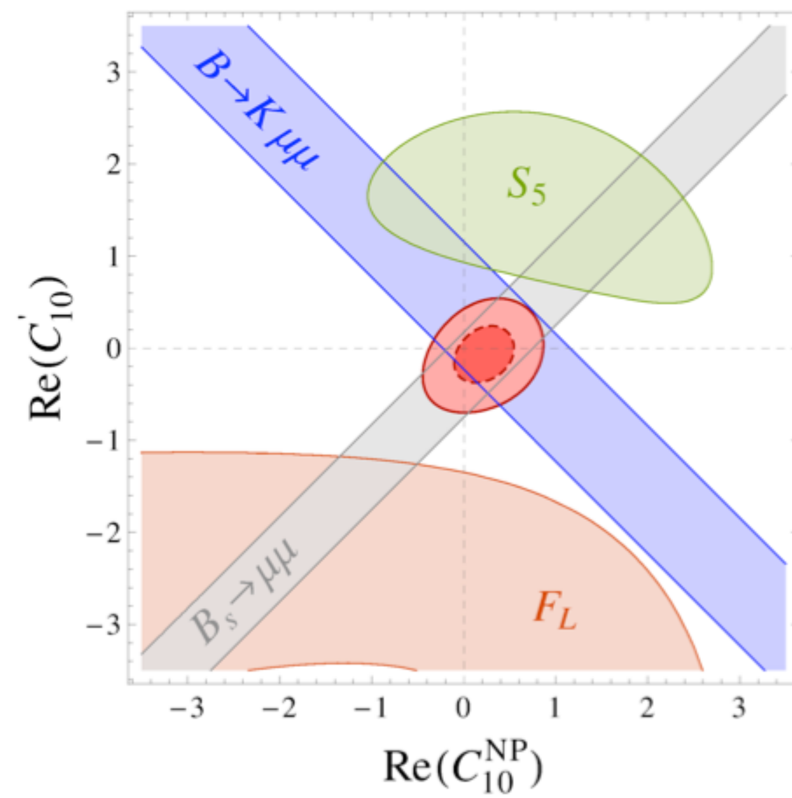


Matteo Palutan, INFN-LNF

Theory implications

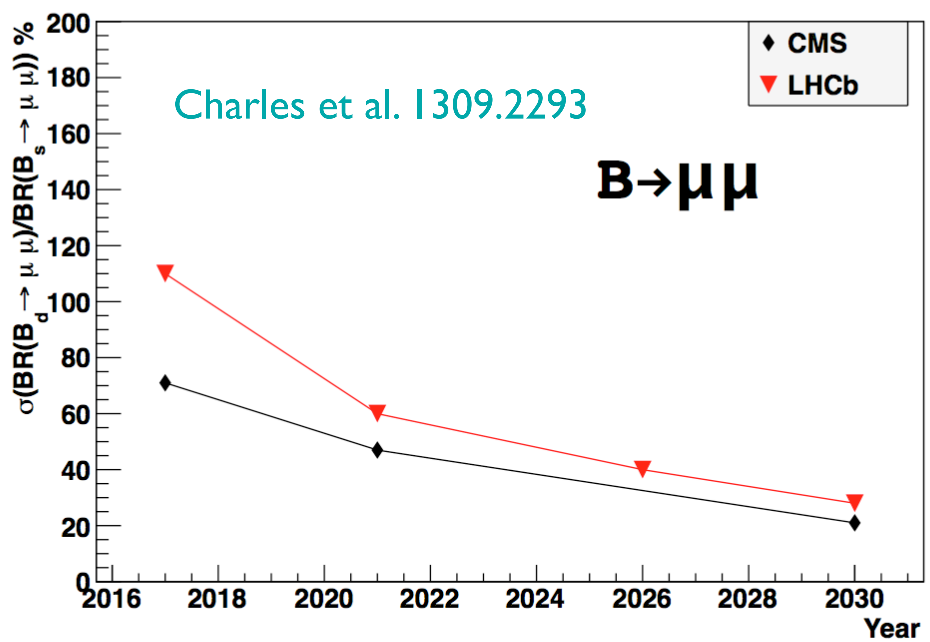
1) Model dependent constraints: Latest results on $B^0_{(s)} \to \mu^+\mu^-$ strongly constrain the parameter space for many NP models, complementing direct searches from ATLAS/CMS: in particular, large $\tan\beta$ with light pseudo-scalar Higgs in CMSSM is strongly disfavored

Althmanshofer et al. 1308.1501



2) Model independent constraints: the precision achieved now is such that $B^0_{(s)} \to \mu^+\mu^-$ sensitivity to (Z,γ) penguin cannot longer be considered sub-leading, and starts to compete with the golden mode $B^0 \to K^*\mu^+\mu^-$

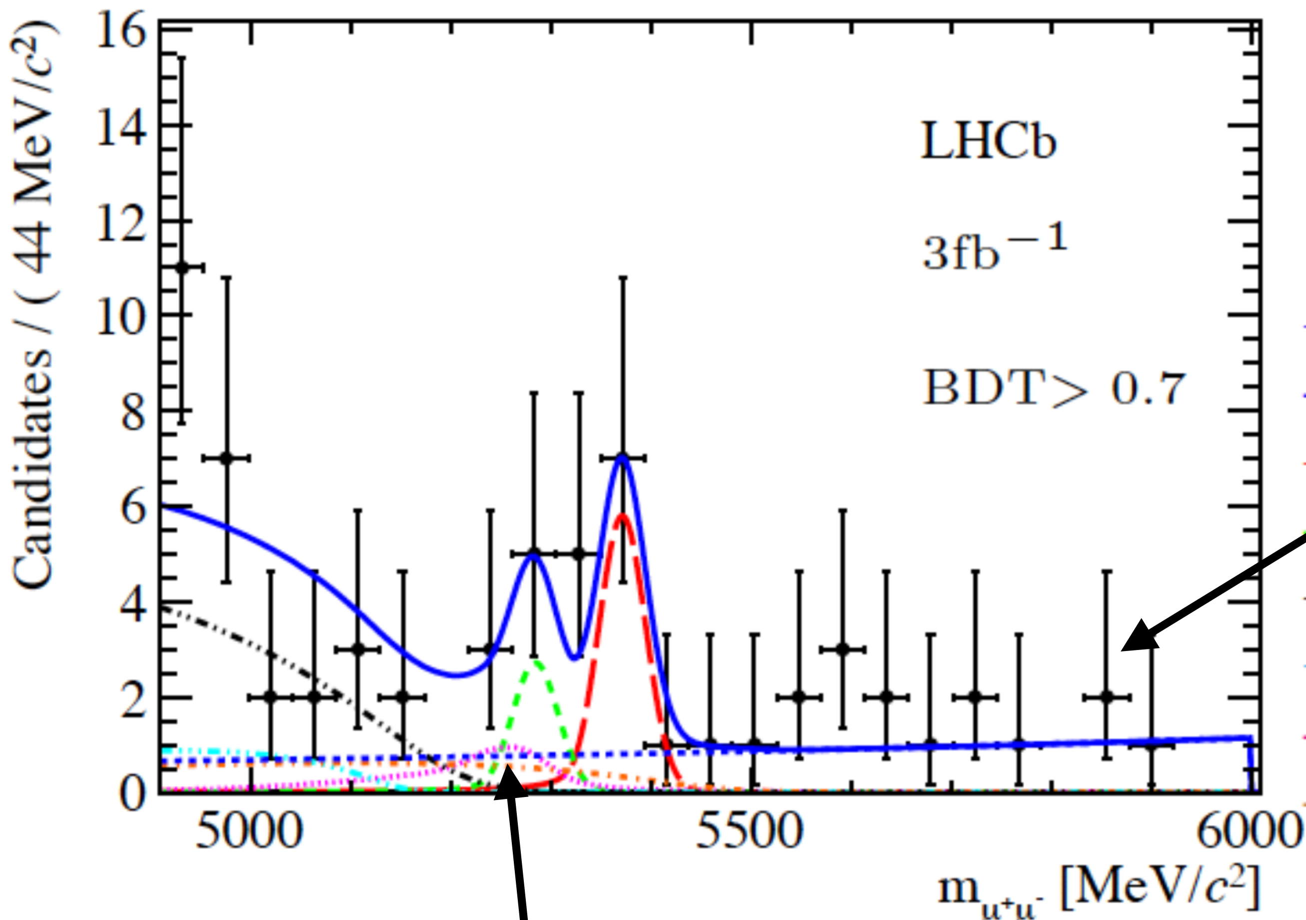
Charles et al. 1309.2293



3) B^0/B^0_s ratio fixed by MFV to SM value $\sim(V_{td}/V_{ts})^2$: it is therefore very relevant to clarify the experimental picture on B^0

The next frontier: $B_d \rightarrow \mu^+\mu^-$

B^0/B^0_s ratio fixed by MFV to SM value $\sim(V_{td}/V_{ts})^2$: it is therefore very relevant to clarify the experimental picture on B^0



We can do better!

Combinatorial: a better muon isolation algorithm is being developed

Exclusive backgrounds: optimisation of the Particle ID selection can give a much better rejection power on $B_{d,s} \rightarrow h^+h'^-$ decays with both hadrons misidentified as muons, and which peak in the Bd mass window

EW penguins measurements

($B_d \to K^{*}\mu^{+}\mu^{-}$ and friends)

Recent measurements

⇛ Branching fractions:

$B^{0,\pm} \to K^{0,\pm}\mu^-\mu^+$ LHCb, Mar 14

$B^0 \to K^*\mu^-\mu^+$ CMS, Jul 15

$B_s^0 \to \phi\mu^-\mu^+$ LHCb, Jun 15

$B^\pm \to \pi^\pm\mu^-\mu^+$ LHCb, Sep 15

$\Lambda_b \to \Lambda\mu^-\mu^+$ LHCb, Mar 15

$B \to \mu^-\mu^+$ CMS+LHCb, Jun 15

⇛ CP asymmetry:

$B^\pm \to \pi^\pm\mu^-\mu^+$ LHCb, Sep 15

⇛ Isospin asymmetry:

$B \to K\mu^-\mu^+$ LHCb, Mar 14

⇛ Lepton Universality:

$B^\pm \to K^\pm\ell\bar{\ell}$ LHCb, Jun 14

⇛ Angular:

$B^0 \to K^*\ell\bar{\ell}$ LHCb, Jan 15

$B^\pm \to K^{*,\pm}\ell\bar{\ell}$ BaBar, Aug 15

$B_s^0 \to \phi\ell\bar{\ell}$ LHCb, Jun 15

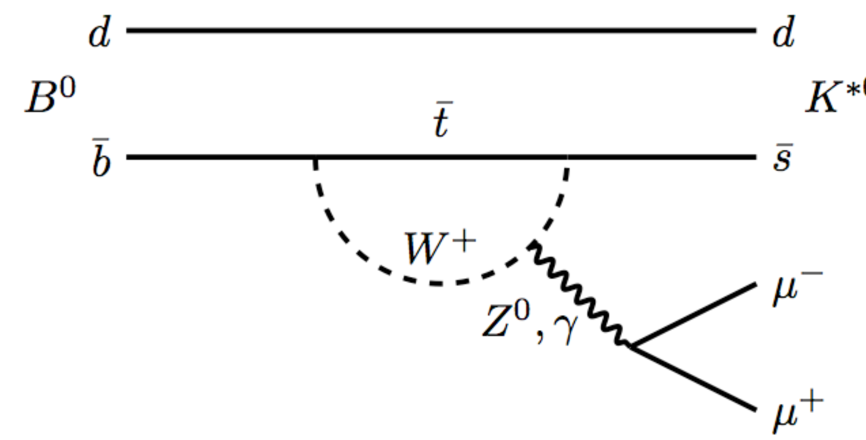
$\Lambda_b \to \Lambda\mu^-\mu^+$ LHCb, Mar 15

$> 2\ \sigma$ deviations from SM

great interest, big effort...

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

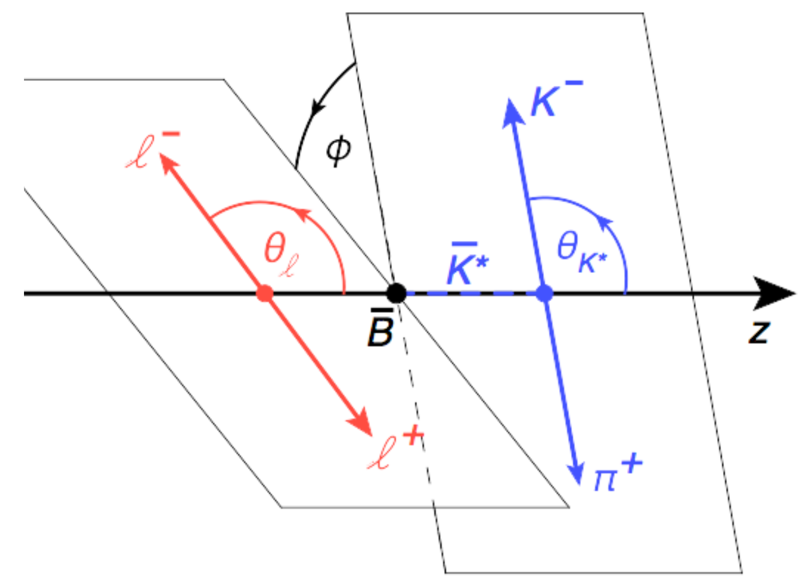
- $B^0 \to K^*\mu^+\mu^-$ is the golden mode to test new vector (-axial) couplings in $b \to s$ transitions: sensitivity to O_7, O_9 and O_{10} and their primed counterparts.



- $K^* \to K\pi$ is self tagged, hence angular analysis ideal to test helicity structure

- Decay described by 3 helicity angles and $q^2 = m(\mu^+\mu^-)$

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_l$$
$$-F_\mathrm{L}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\tfrac{4}{3}A_\mathrm{FB}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$



1st analysis on the full angular distribution

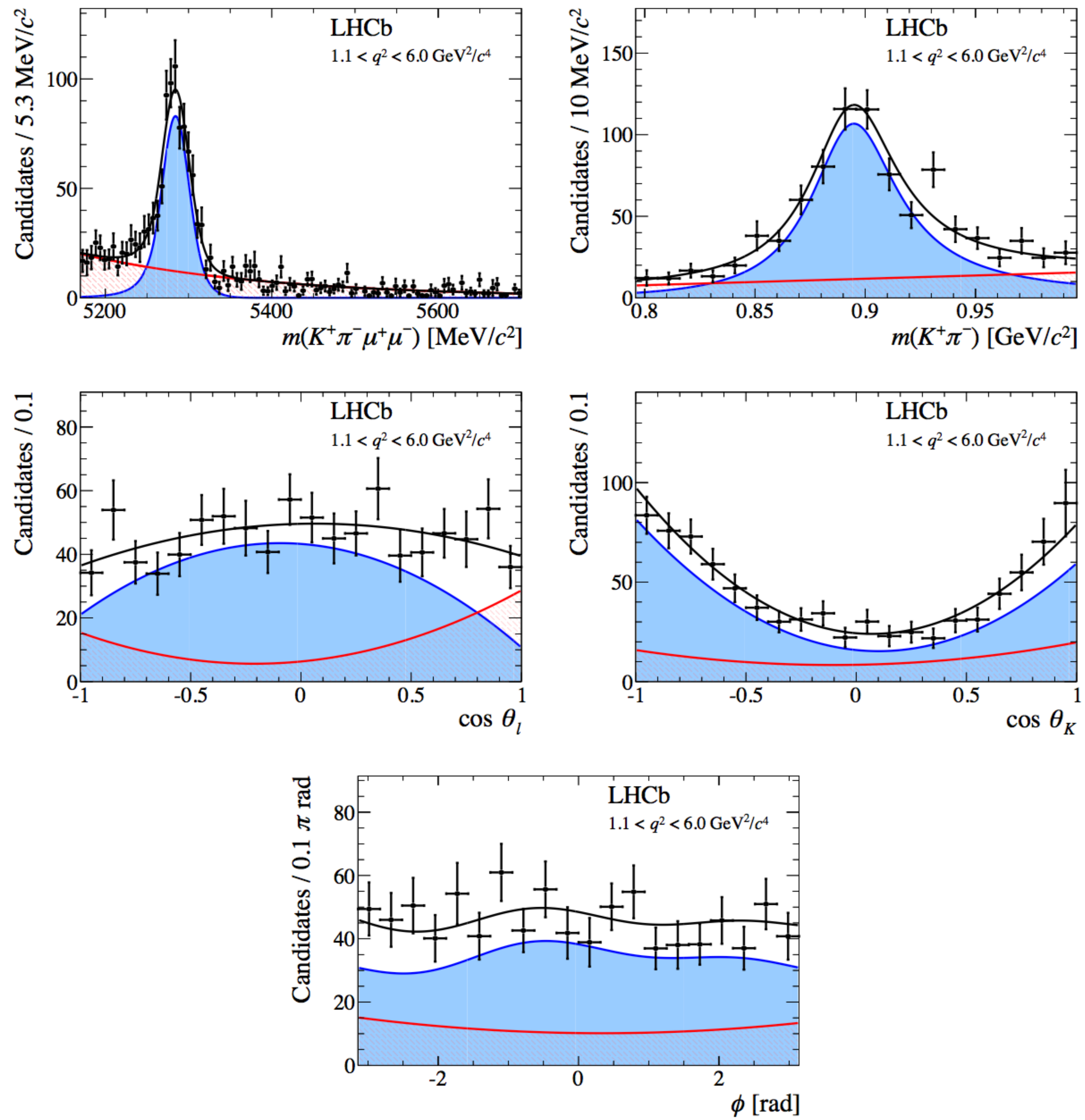
where $S_i = (I_i + \bar{I}_i) \Big/ \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} + \frac{\mathrm{d}\bar{\Gamma}}{\mathrm{d}q^2}\right)$ and the I_i are bilinear combinations of the decay amplitudes

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

JHEP 02 (2016) 104

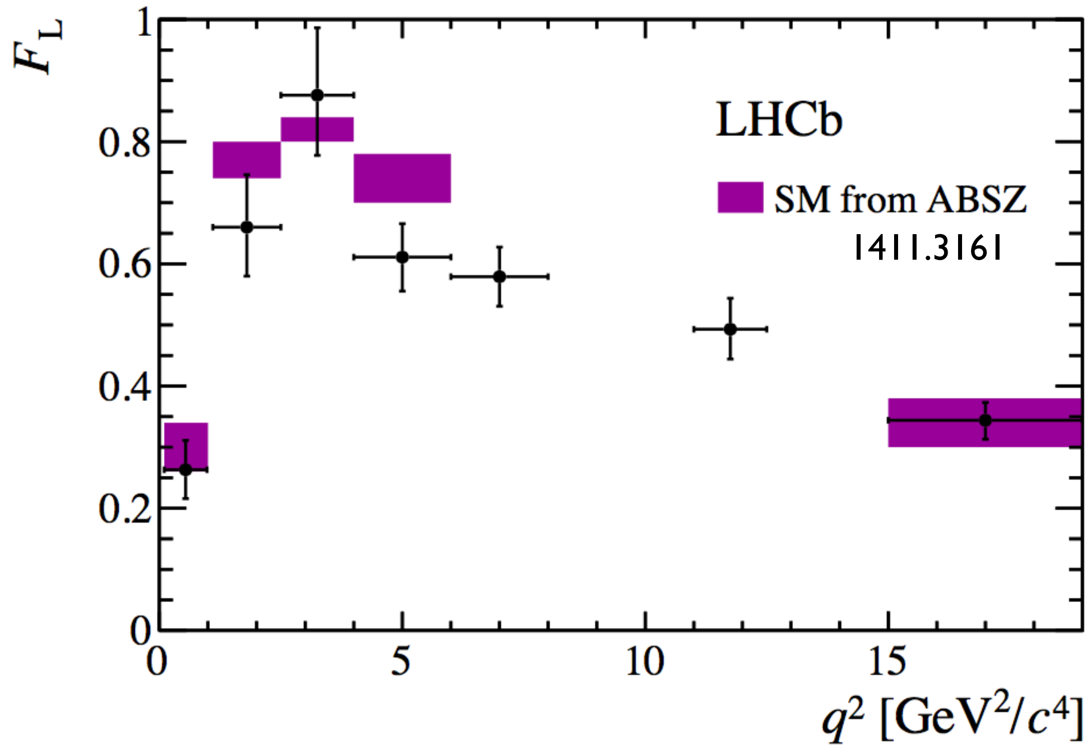
Likelihood fit results projected in the region $1.1<q^2<6.0\ GeV^2/c^4$, 624 ± 30 signal events

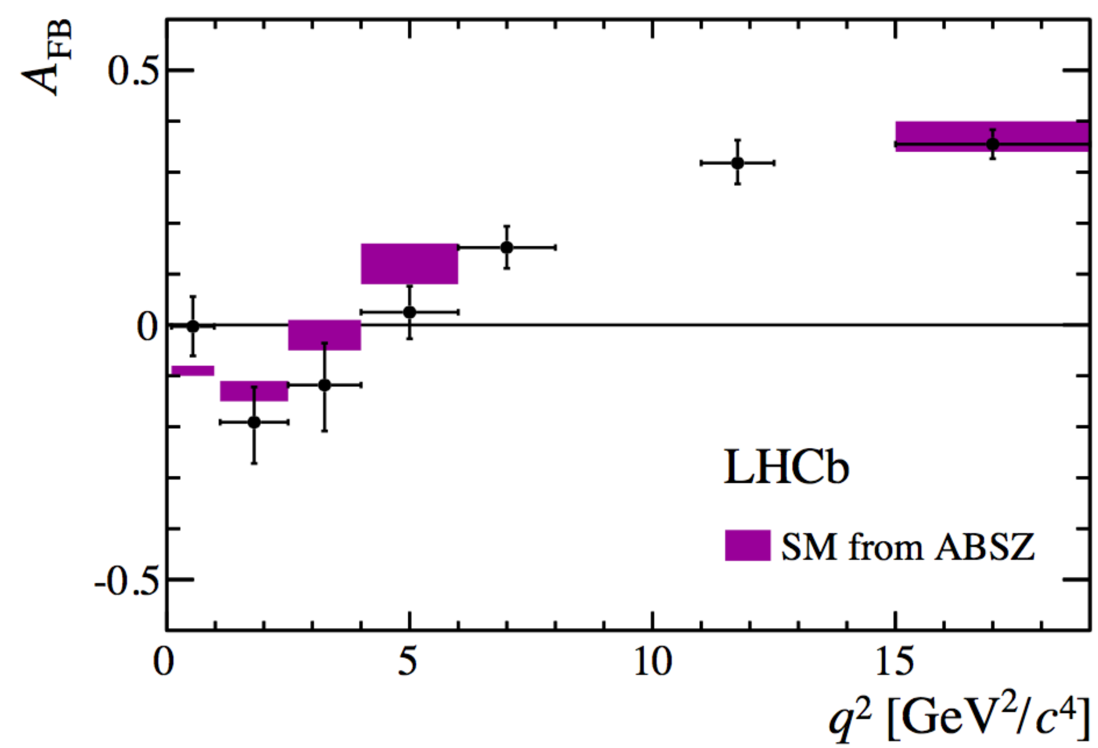
A total of 2400 signal events are observed for $0.1<q^2<19.0\ GeV^2/c^4$

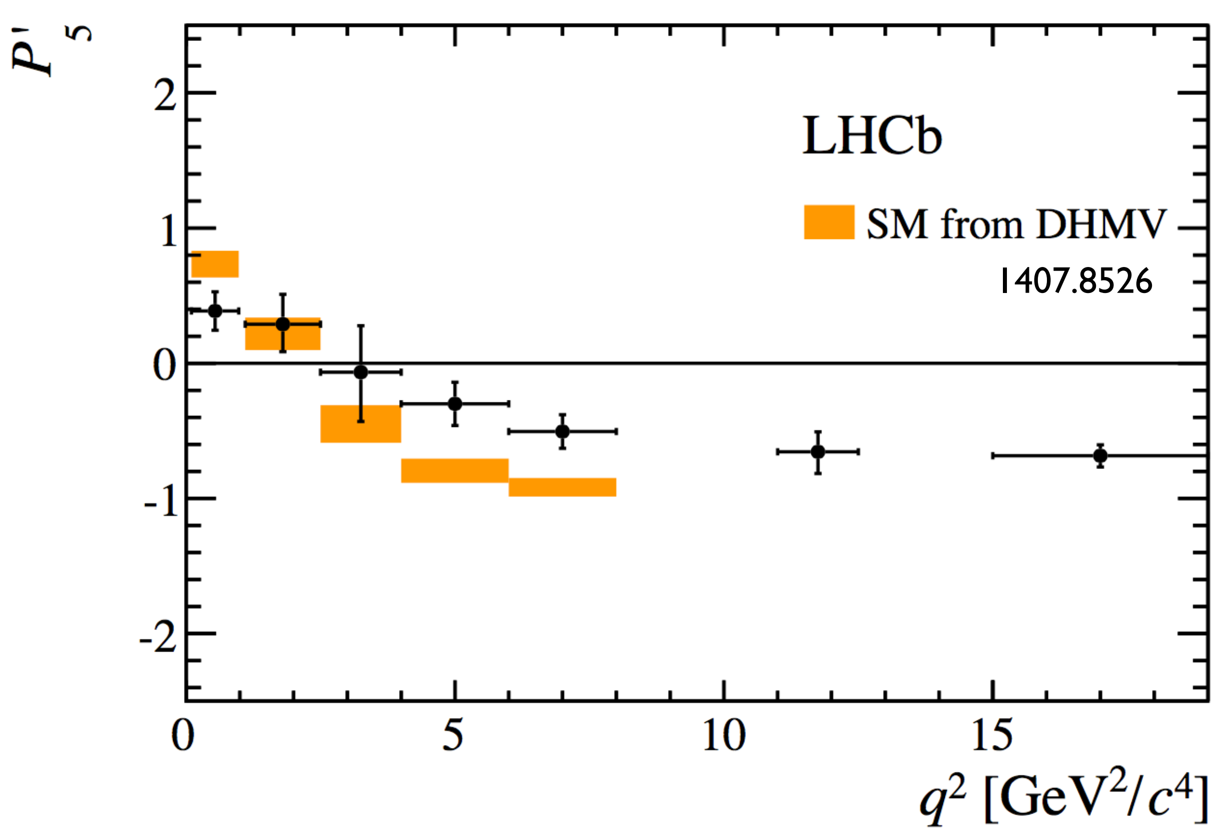


$B^0 \to K^{*0}\mu^+\mu^-$ angular observables (3 fb^{-1})

JHEP 02 (2016) 104







Angular variables with reduced uncertainty (1207.2753):

$$P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_L(1-F_L)}}$$

Tension in P'_5 is confirmed: two bins deviate both by ~3σ from SM prediction

$B^0 \to K^{*0}\mu^+\mu^-$ angular observables (3 fb^{-1})

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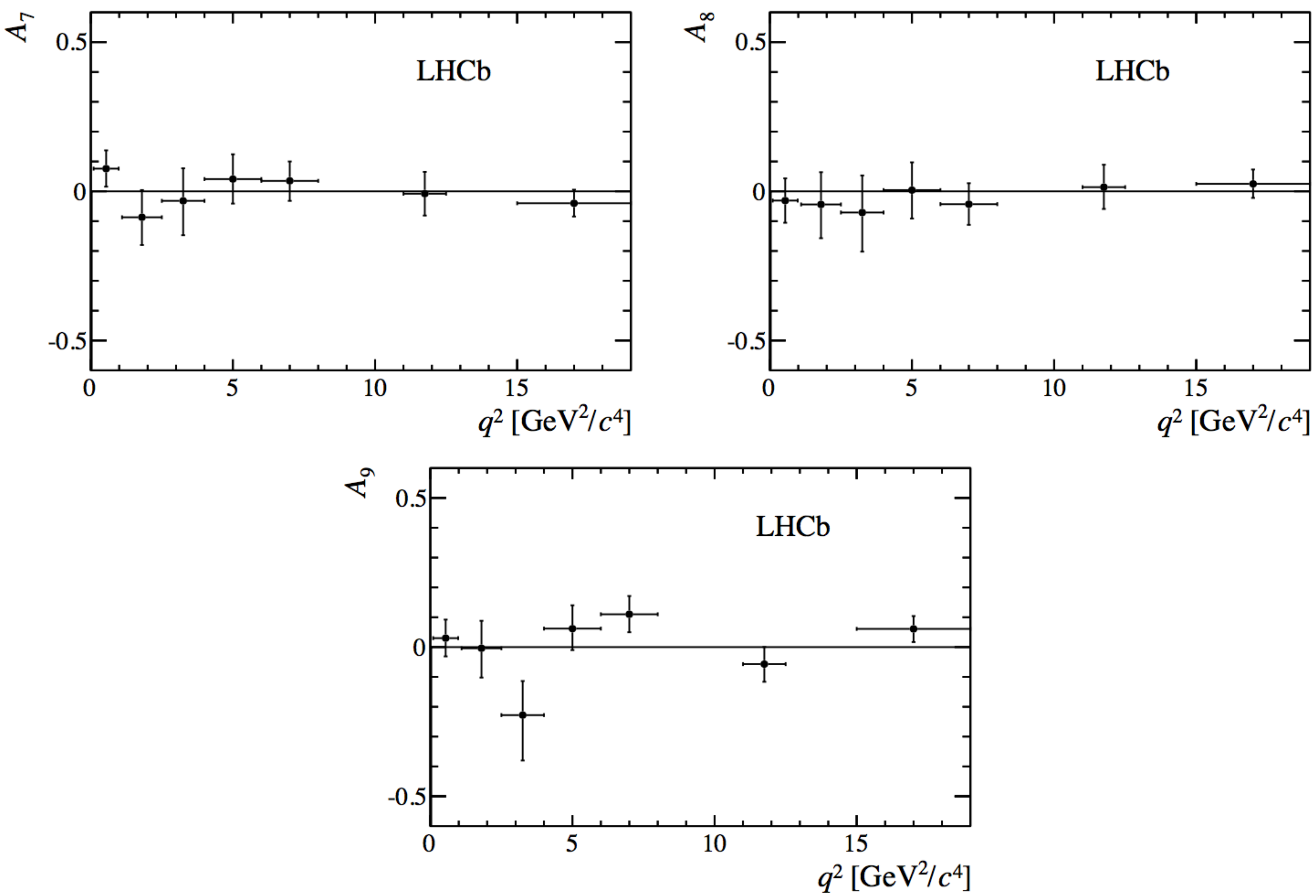


For the first time, also the CP asymmetry terms A_i are extracted from the difference btw B and B angular spectra

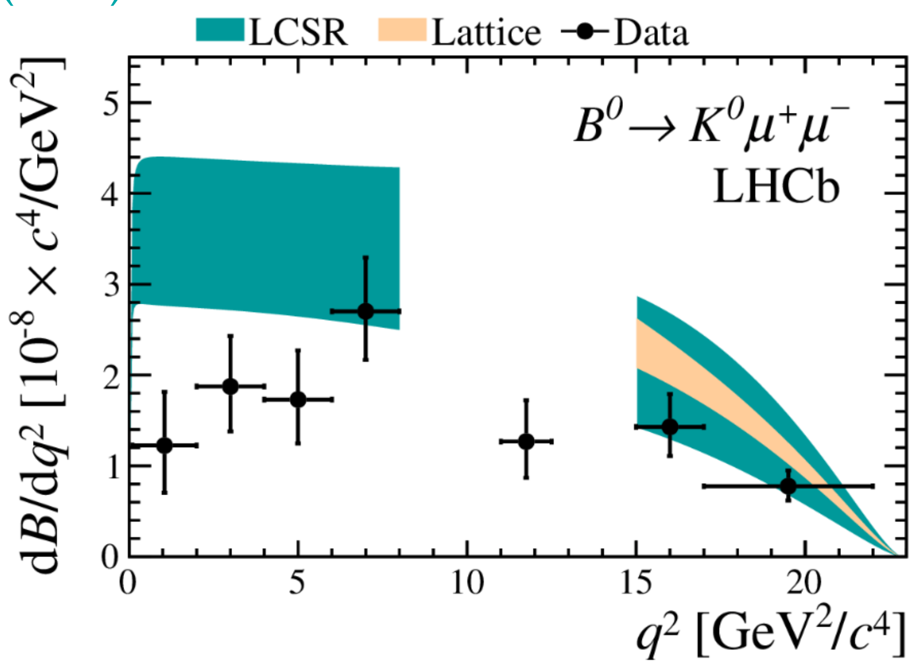
$$A_i = (I_i - \bar{I}_i) \Big/ \left(\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2} \right)$$

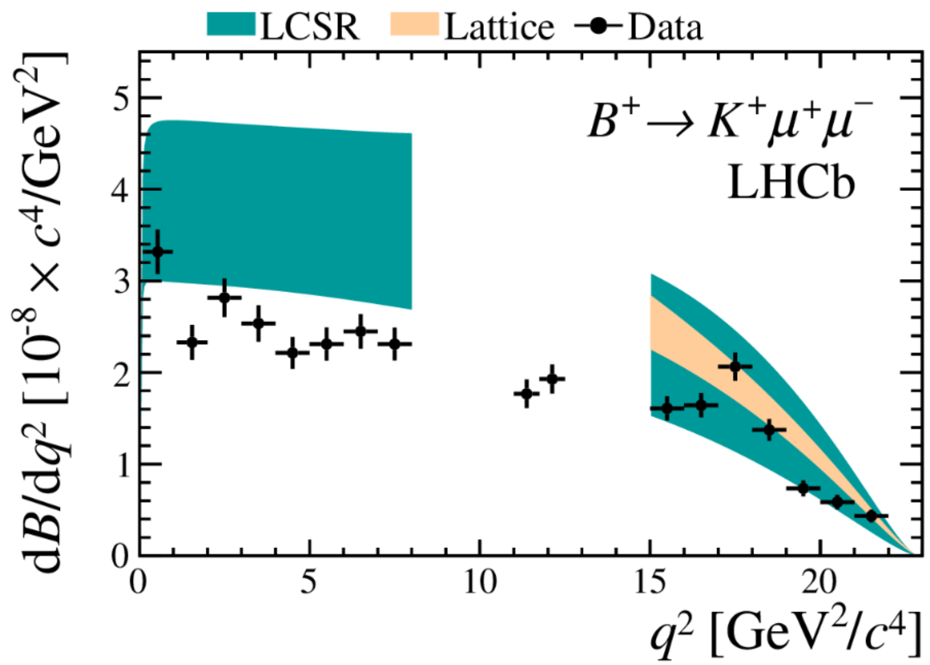
In presence of non-standard CP violation of right-handed currents $A_{7,8,9}$ can be enhanced (±15% to ± 35% effects)

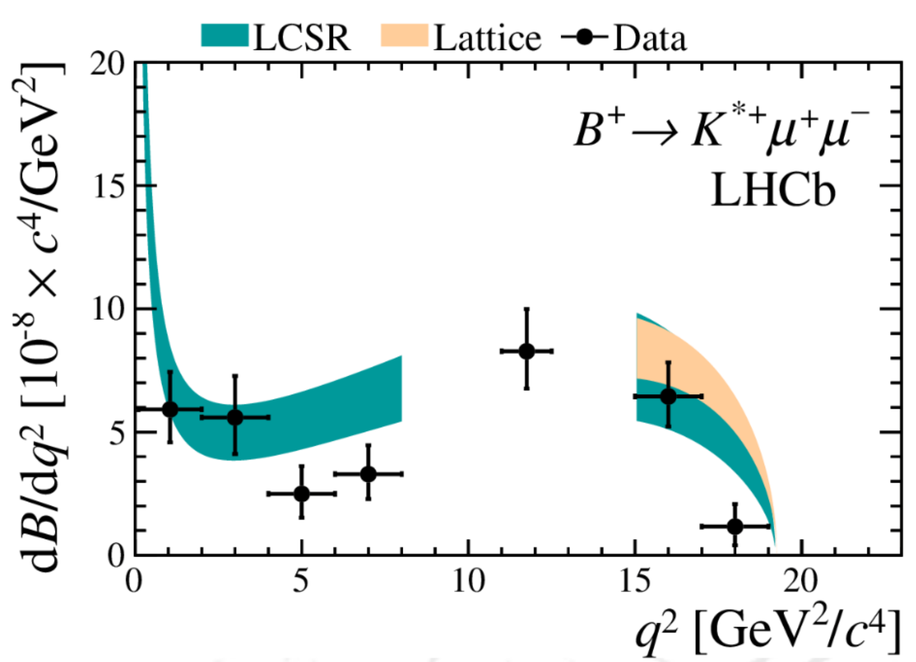
Altmannshofer, Paradisi, Straub 1111.1257

Branching fraction measurements

JHEP 06 (2014) 133







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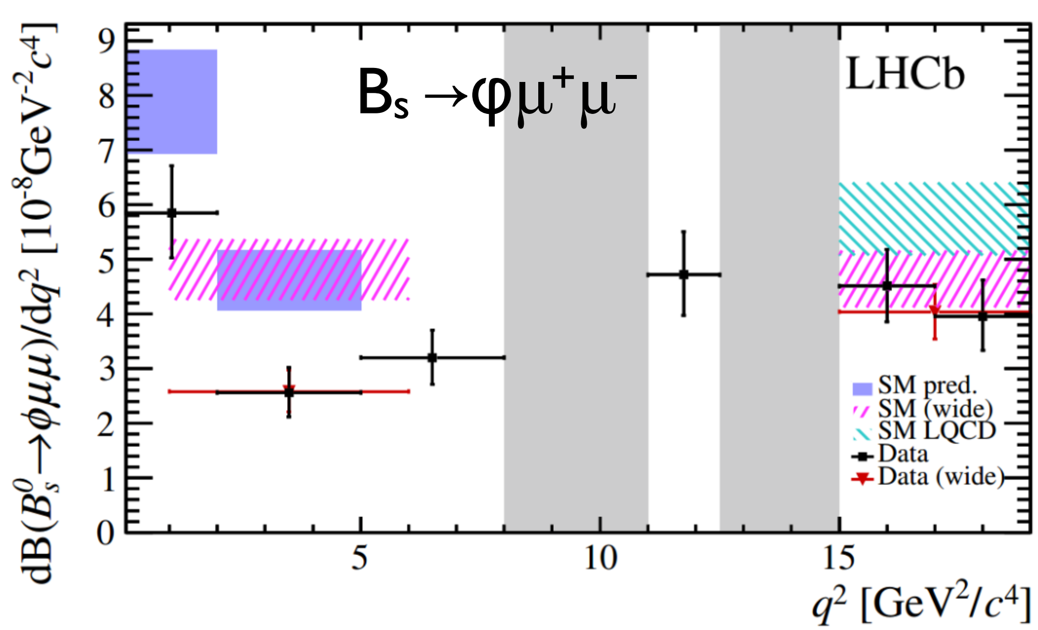
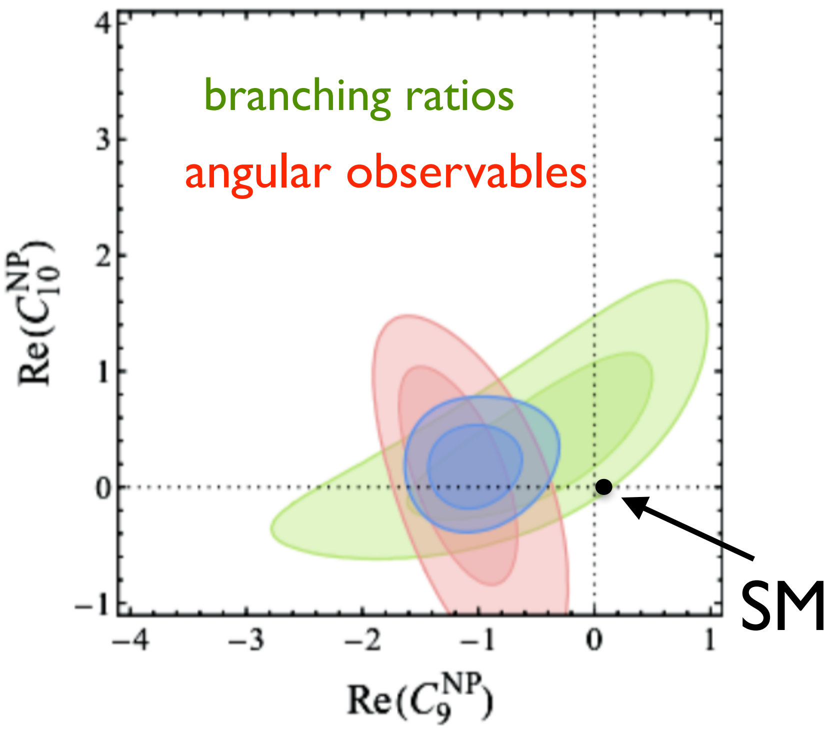
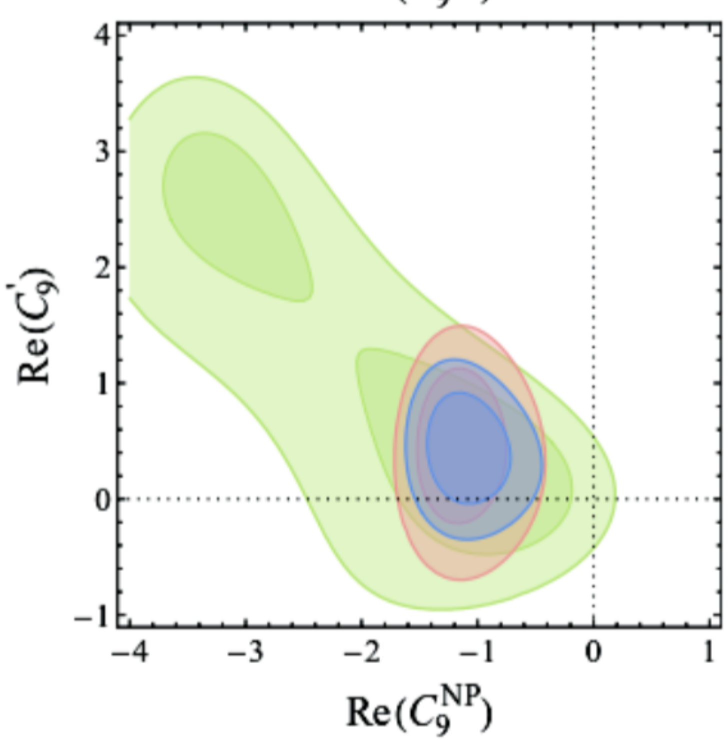


Despite the large theoretical errors, the results are consistently smaller than SM predictions

Theory implications: global fits to Wilson coefficients

Altmannshofer, Straub
1503.06199





The SM is disfavoured at ~ 4σ in all different fits

Several options for NP fit that are hard to distinguish:

$C_9^{NP} = -1 \quad C_{10}^{NP} = 0$

Leads towards Z' type models

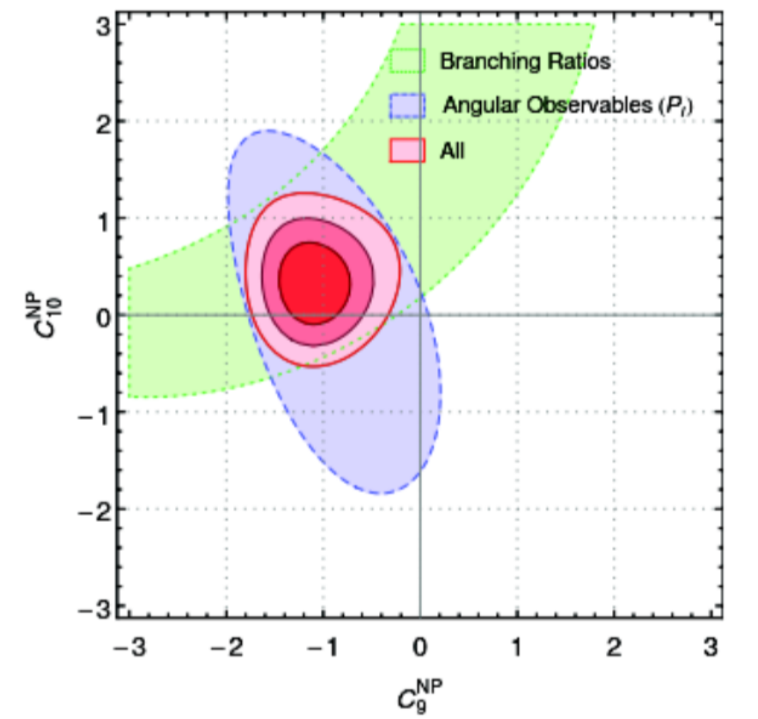
$C_9^{NP} = -C_{10}^{NP} = -1$

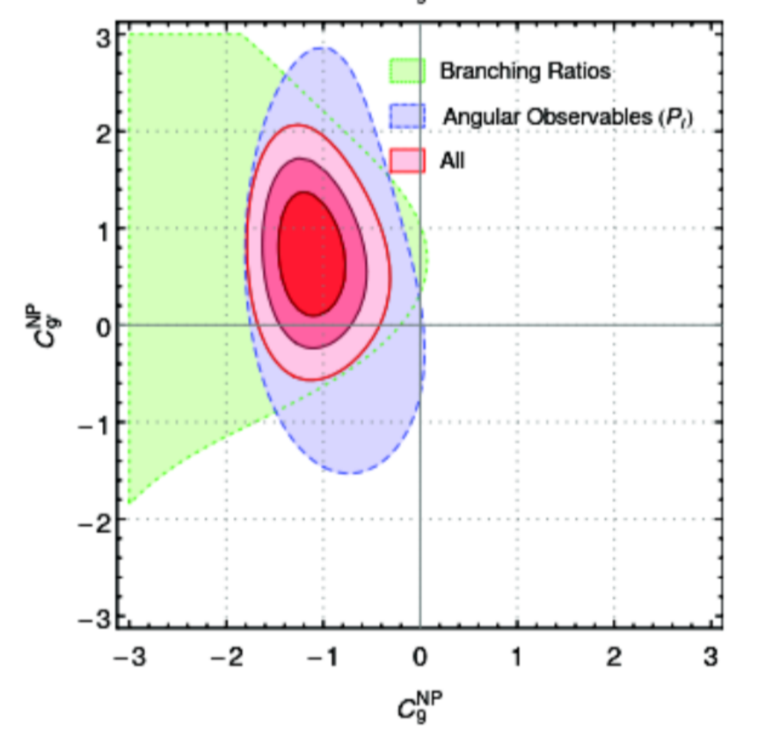
Leptoquark models

$C_9^{NP} = -C_9'^{NP} = -1$

Leads to L-R symmetric models

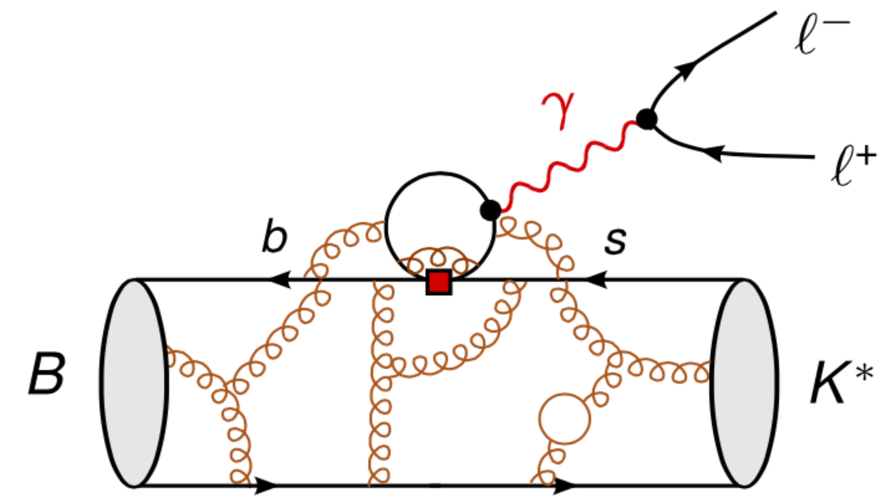
Descotes-Genon/Hofer/
Matias/Virto 1510.04239





NP or unexpected hadronic effect?

Hadronic effects like charm loop are photon mediated → vector-like coupling to leptons just like C9

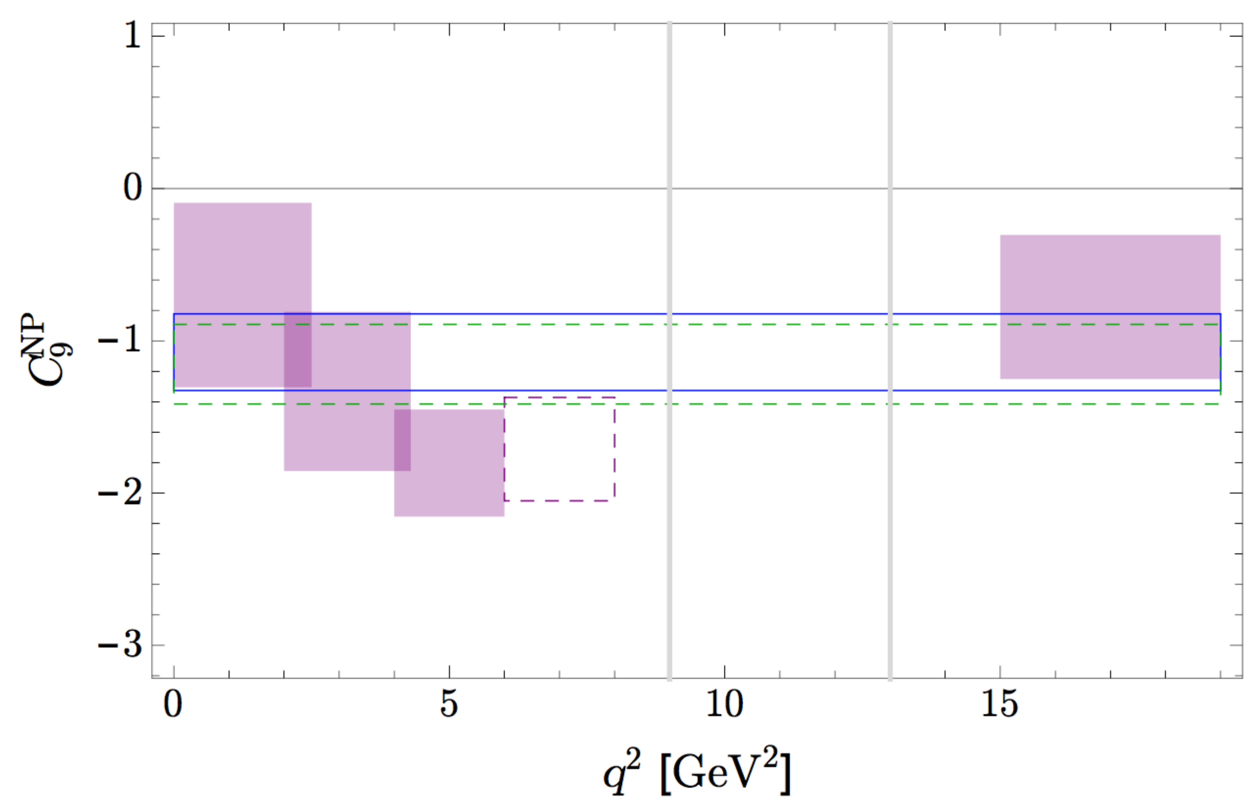


Khodjamirian et al. 1006.4945,
Jager et al. 1212.2263

Discussion among theoreticians just started:
e.g. Ciuchini et al. 1512.07157 reassess the charm loop uncertainty obtaining full compatibility btw SM and LHCb results

How to disentangle NP from QCD?

The NP hypothesis, as opposed to charm loop, requires a q^2 independent shift in C_9



Hadronic effect is lepton flavour universal, not necessarily NP → compare muon with electron decays!

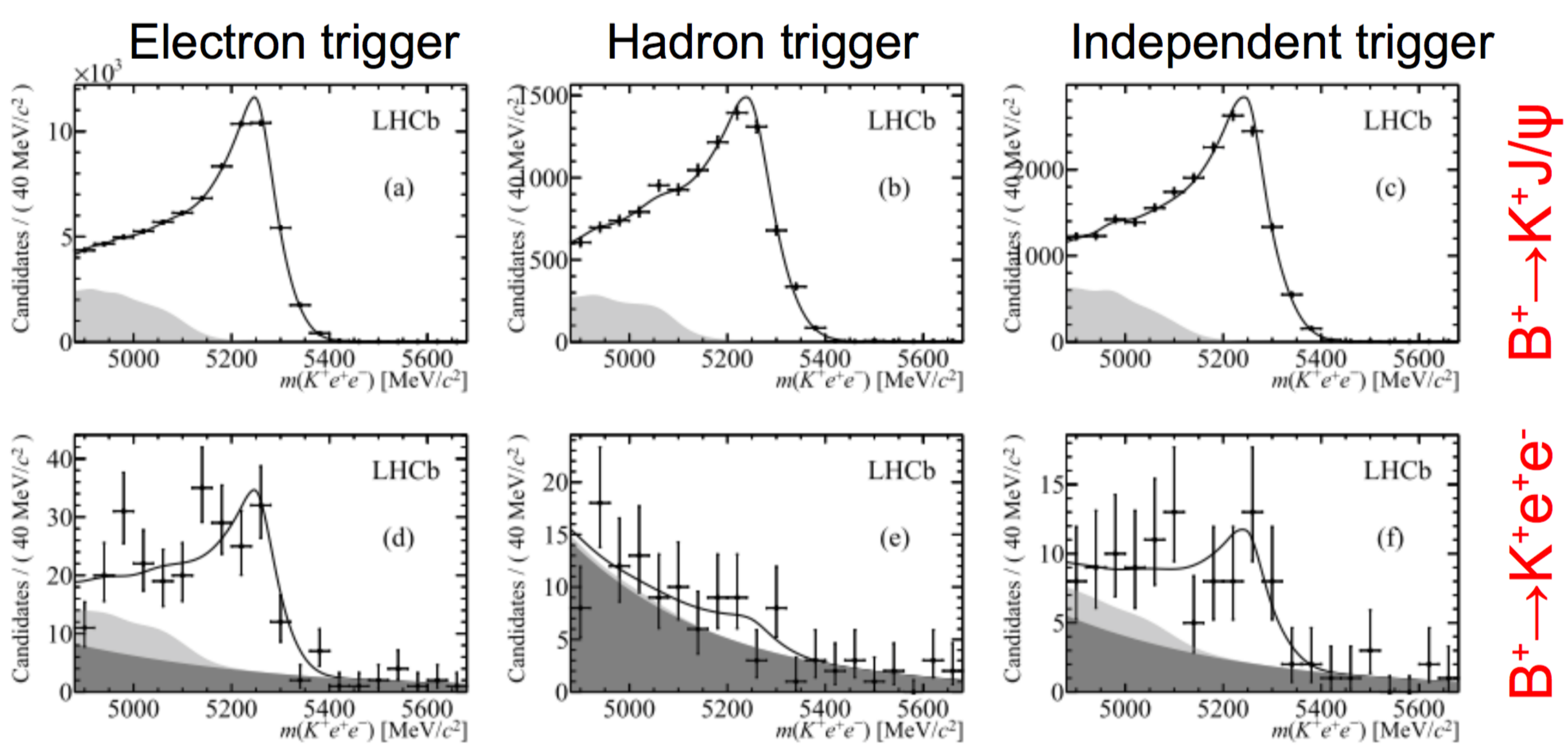
Lepton universality

Lepton universality in $B^+ \to K^+\ell^+\ell^-$

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

The electron channel is challenging due to bremsstrahlung: use $B^\pm \to J/\psi K^\pm$ control sample, with $J/\psi \to e^+e^-$

RUN I data, 3fb^{-1}



Compatible results among different categories

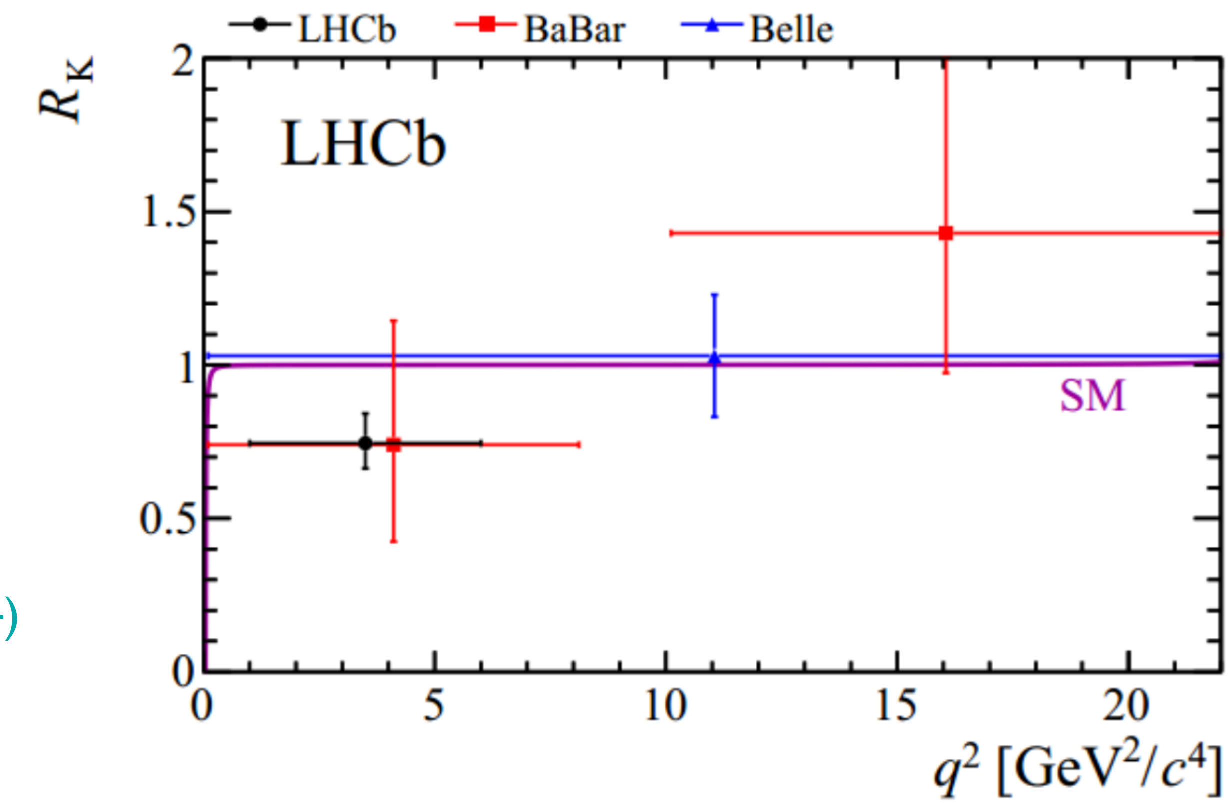
Lepton universality in $B^+ \to K^+\ell^+\ell^-$

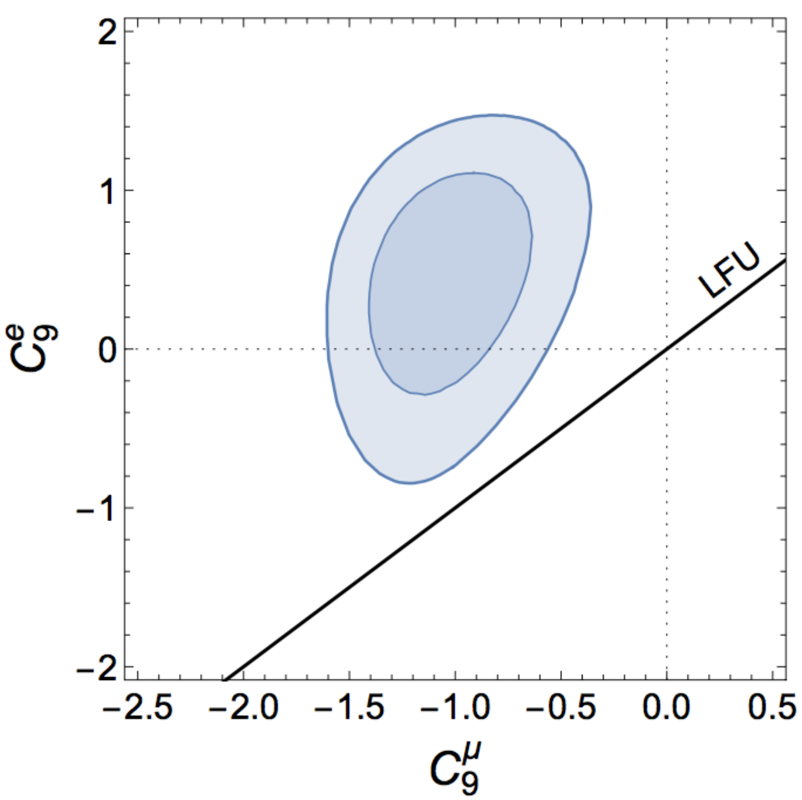
In 3fb[-1], LHCb measures

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

2.6σ from SM

PRL 113, 151601 (2014)





Global fit to $b \to s\, \mu^+\mu^-$ and $b \to s\, e^+e^-$ data

Ghosh et al. 1408.4097,
Hurth et al. 1410.4545

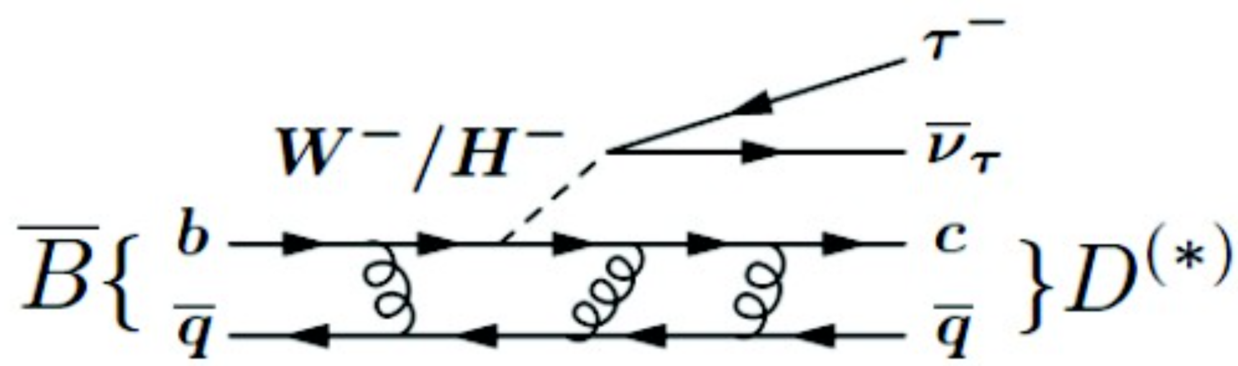
If confirmed, this is impossible to explain by hadronic effect!

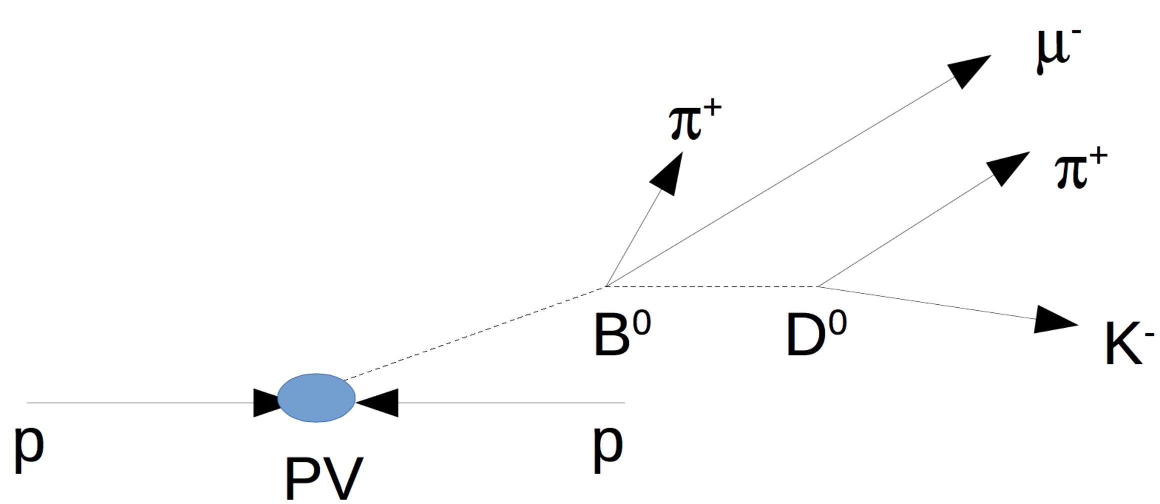
Waiting for LHCb result on R_{K^*} with 3fb[-1] …

There's more: lepton universality in $B \rightarrow D^*\tau\nu / B \rightarrow D^*\mu\nu$

In the SM, lepton universality assures that decays to e, μ and τ should differ only in phase space and helicity suppression

Many extensions of the SM predict however a difference between flavours, for instance a charged Higgs would enhance decays to τ





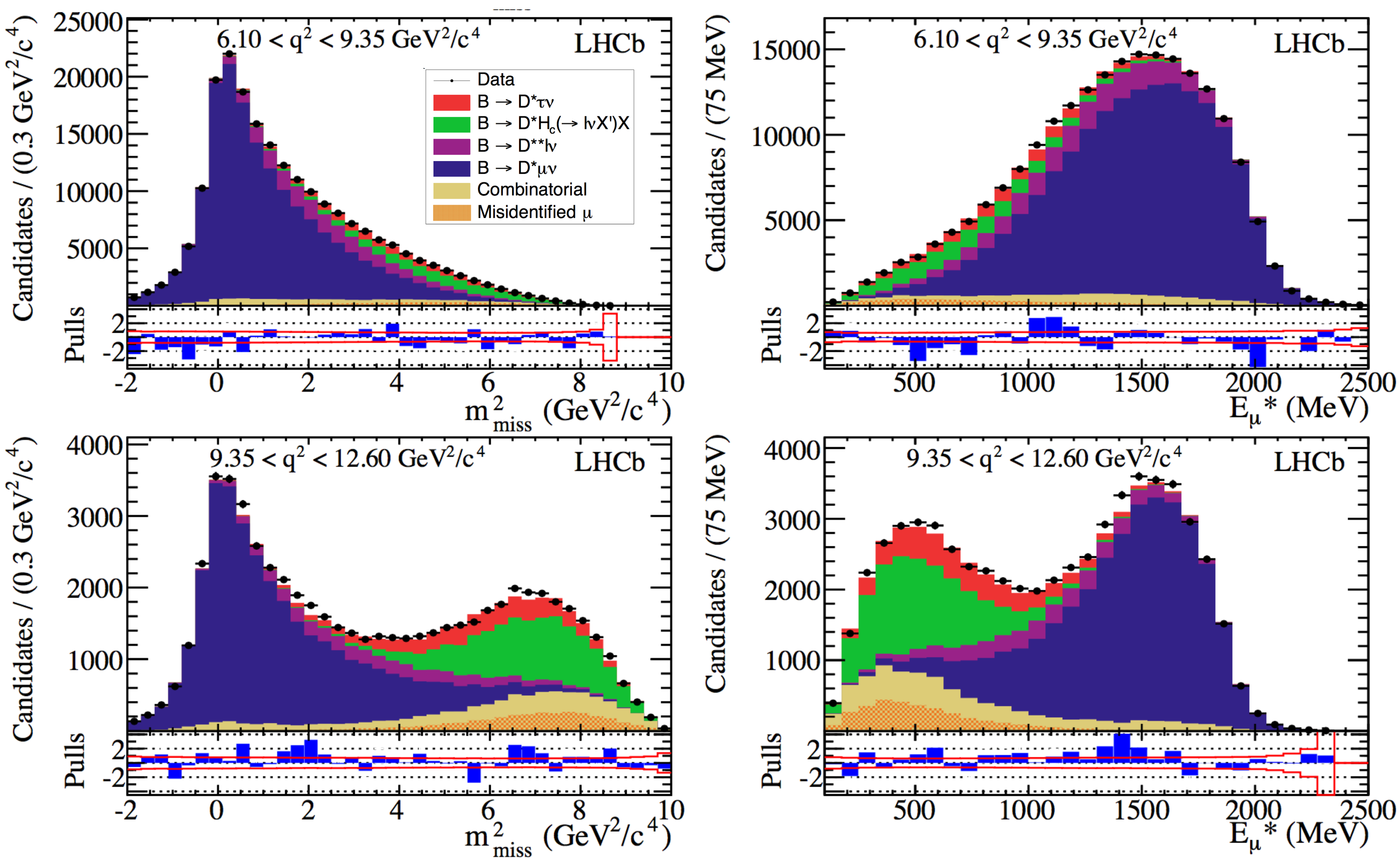
LHCb analysis:

- $\tau \rightarrow \mu\nu\nu$ decay selected
- exploit secondary vertex recontruction and muon identification
- B meson rest frame is not known: determine B direction from PV and B vertex; approximate B boost along the beam direction with boost of the visible system

$$p_z(B^0) = \frac{m_{B^0}}{m(D^*\mu)} p_z(D^*\mu)$$

$B \to D^*\tau\nu$ and $B \to D^*\mu\nu$ signal extraction

Simultaneous fit to m^2_{miss}, E_μ^* and q^2 distributions, with 3D templates representing signals and background sources



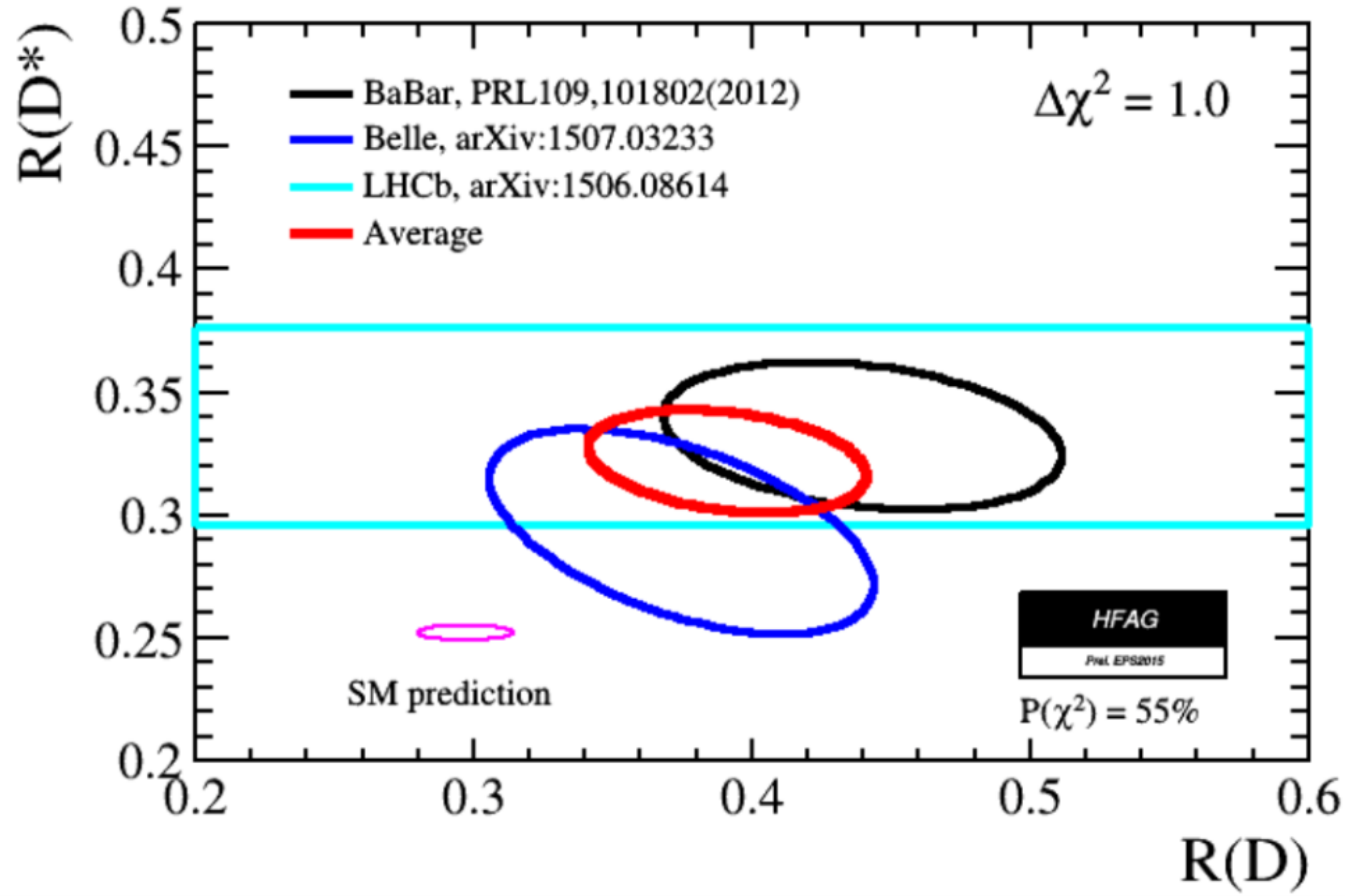
$R(D^*) = BF(B \to D^*\tau\nu)/BF(B \to D^*\mu\nu)$

In $3fb^{-1}$, LHCb measures

$R(D^*)=0.336\pm0.027\pm0.030$

PRL 115 (2015) 112001

2.1σ from SM



SM prediction: $R(D^*)=0.252\pm0.003$ PRD 85, 094025 (2012)

HFAG average: $R(D^*)=0.322\pm0.022$

3.9σ discrepancy with SM

Ongoing analyses at LHCb: R(D*) hadronic, R(D), R(D_s), R(Lambda_c)

The path to clarify the picture

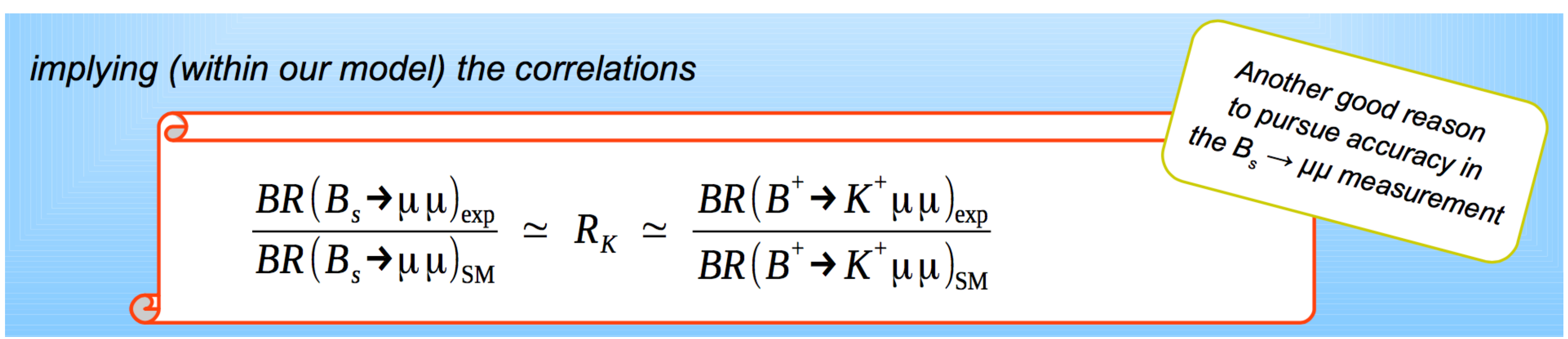
Theory: better estimates for the electroweak penguins

Experiments: better measurements on lepton universality

Going more in detail, what experiments should do (see e.g. Altmannshofer, Straub 1503.06199):

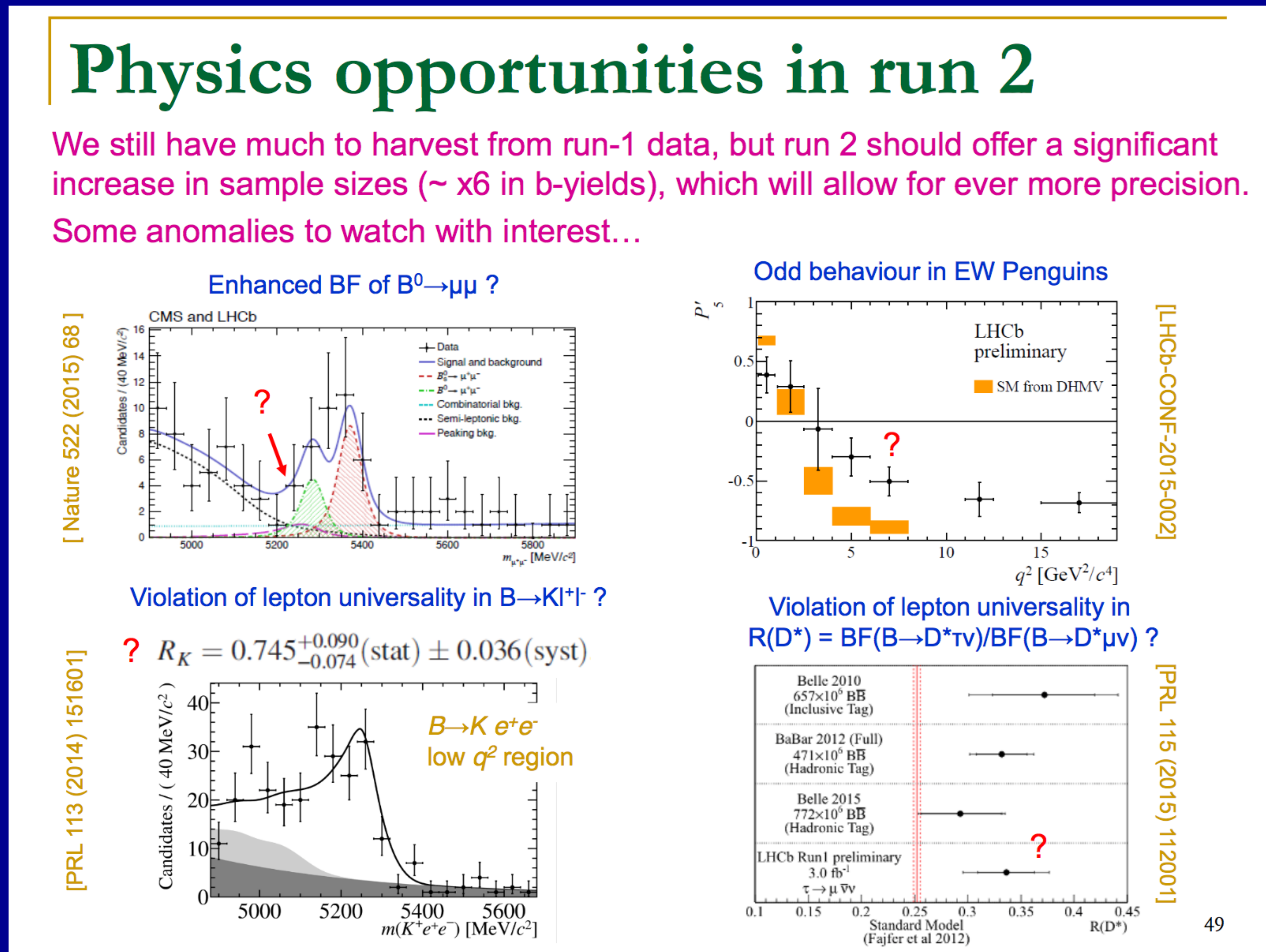
- Test LFU in the $B \to K^* \mu^+ \mu^-$ vs. $B \to K^* e^+ e^-$ branching fractions and angular observables, where spectacular deviations from the SM universality prediction would occur if the R_K anomaly is due to NP, which can be accomodated in various NP models with a Z' boson or leptoquarks
- Search for lepton flavour violating B decays like $B \to K^{(*)} e\mu$, $B \to K^{(*)} \mu\tau$, because LFV is quite natural in leptoquark and Z' models, which are candidates in explaining the observed anomalies
- Measure $BR(B_s \to \mu^+\mu^-)$ more precisely as a clean(er) probe of C_{10}. Also, some models predict a correlation between R_K e the value of $BR(B_s \to \mu^+\mu^-)$

Glashow et al. 1411.0565



This is our program for RUN II !

LHCb spokesman (Guy Wilkinson) at LHCb@20 fest (nov. 2015)



+ LFV analyses on RUN I data: update of B →eμ with 3fb^{-1} , B →K$^{(*)}$eμ, B → ϕeμ, more challenging B →hμτ and B →hh'μτ also being developed

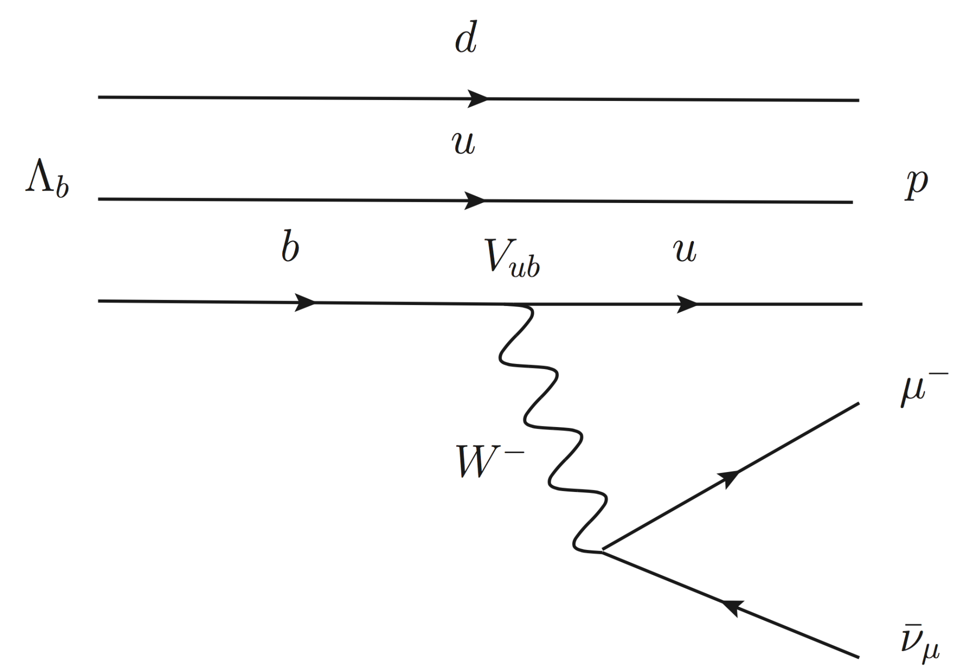
CKM and CP violation

V_{ub} and V_{cb} from BF($\Lambda_b \to p\mu\nu$)/BF($\Lambda_b \to \Lambda_c\mu\nu$)

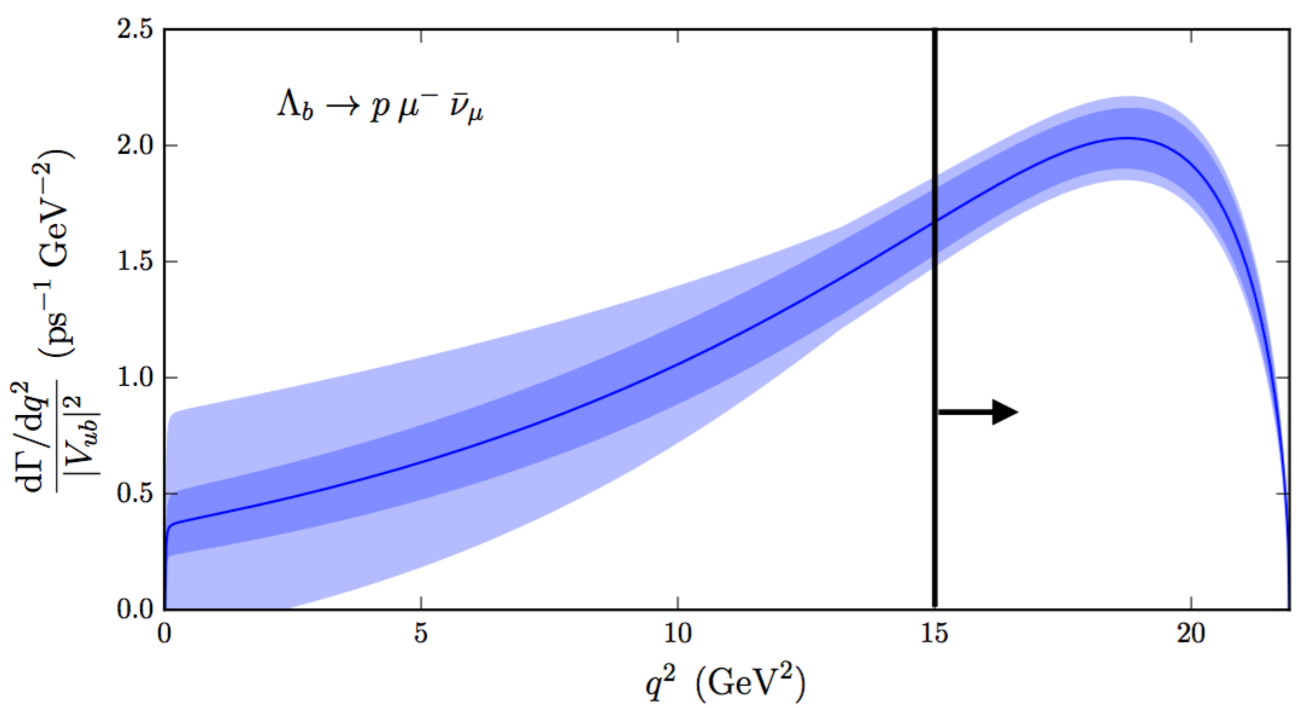
$\Lambda_b \to p\mu\nu$ is the baryonic version of $B \to \pi\ell\nu$ (used for V_{ub} at B factories)

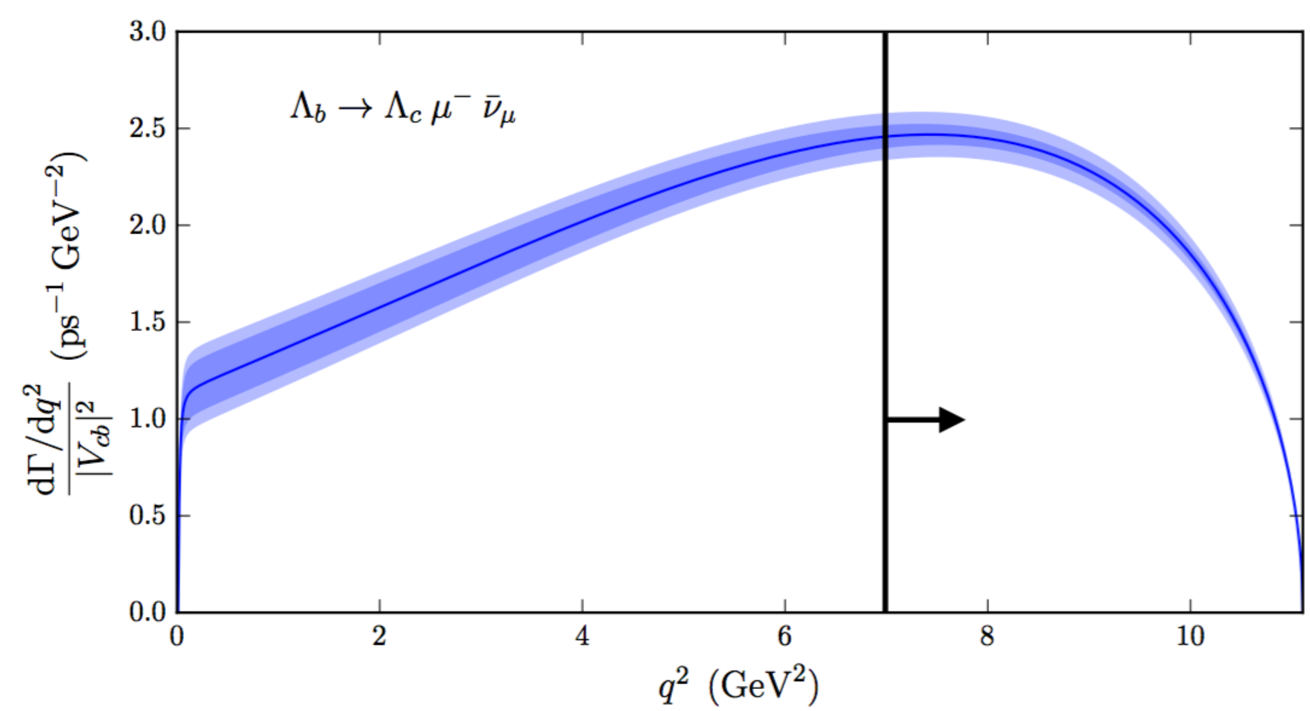
$\Lambda_b \to$ baryons produced at the LHC half as often as B mesons

Cleaner at LHCb as protons are rarer than kaons/pions



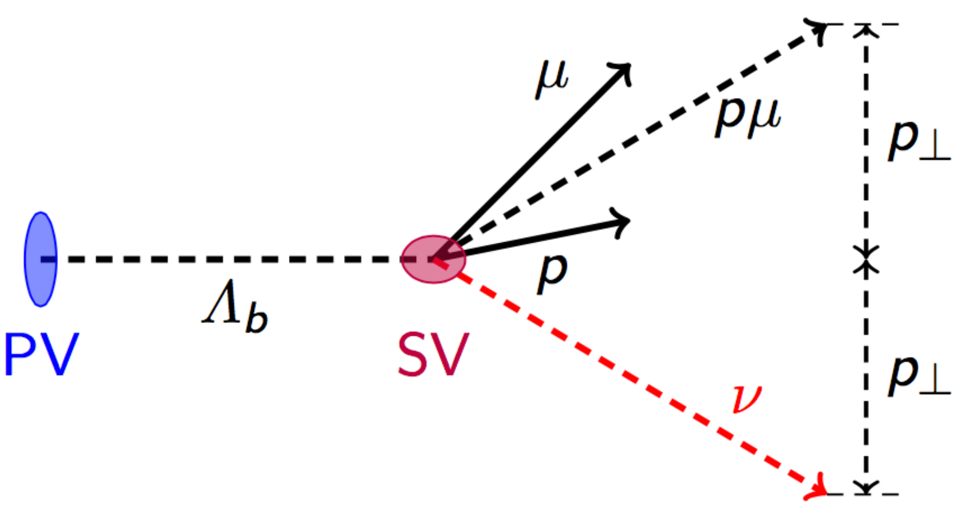
Measure the BF in high q^2 region only, where lattice calculation is more accurate → 5% uncertainty on V_{ub}





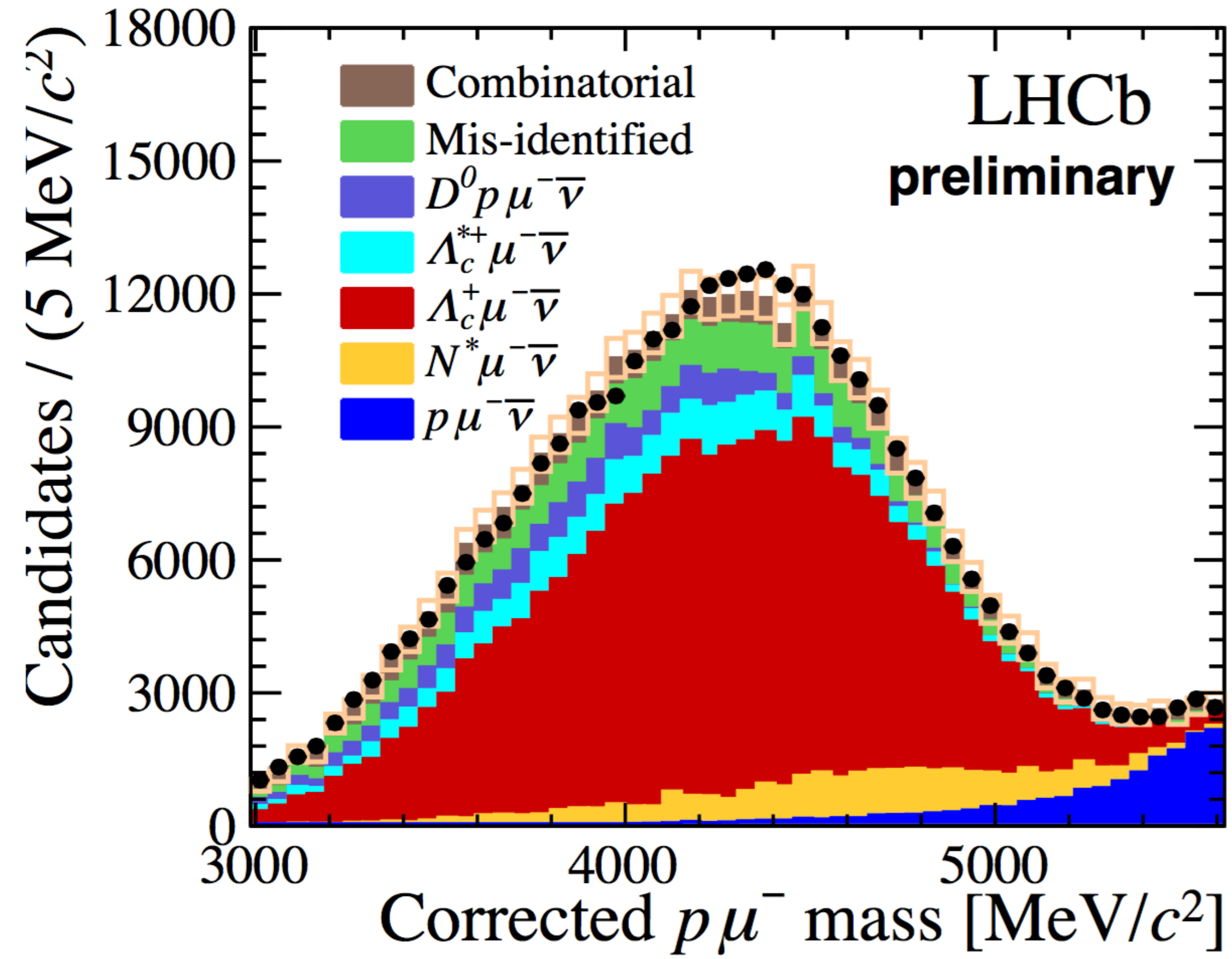
W. Detmold, C. Lehner and S. Meinel 1503.01421

$\Lambda_b \to p\mu\nu$ signal extraction and result



$$M_{corr} = \sqrt{p_\perp^2 + M_{p\mu}^2} + p_\perp$$

Nature Physics 11 (2015) 743



First observation of $\Lambda_b \to p\mu\nu$ decay:

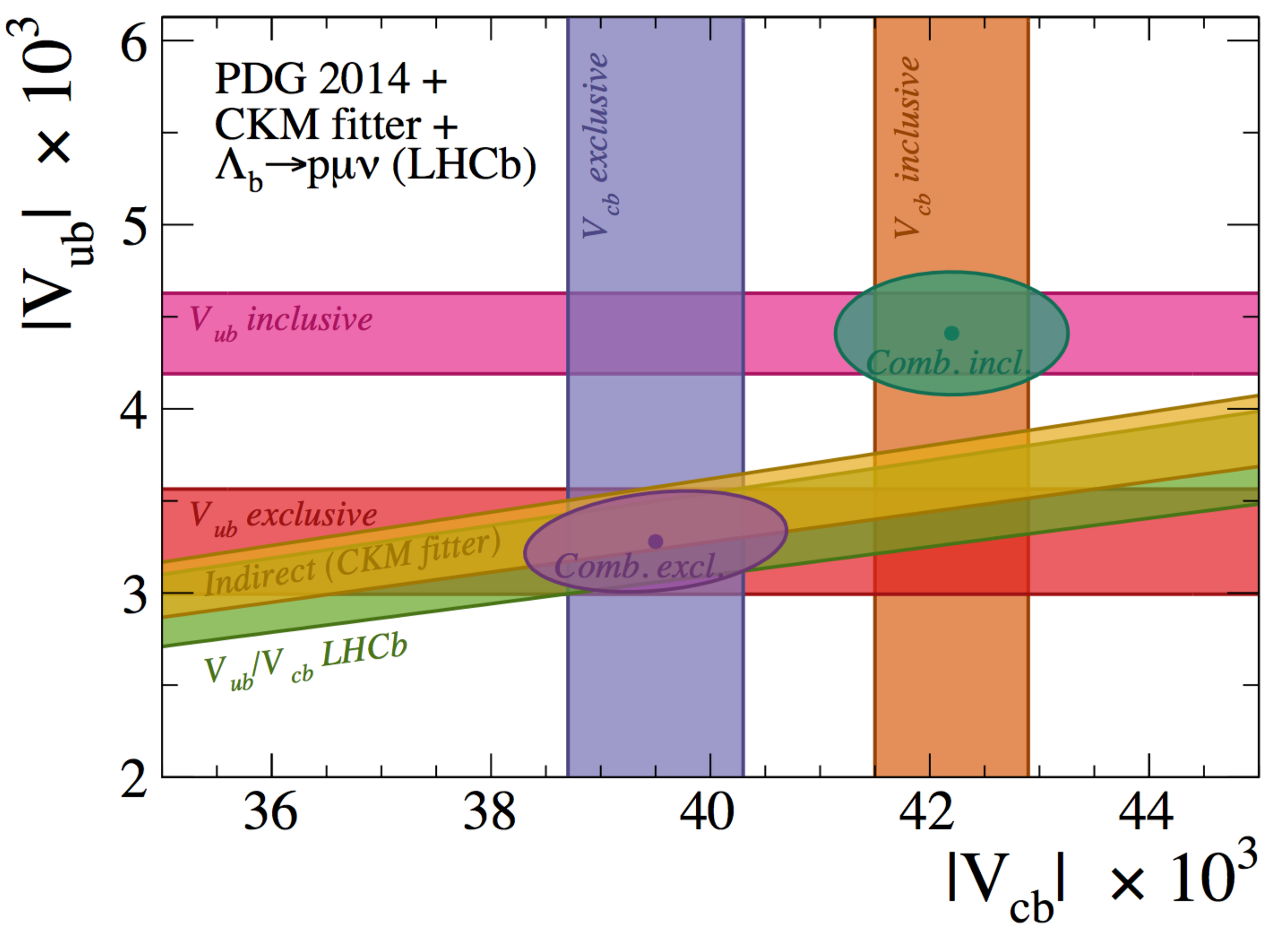
$$N(\Lambda_b^0 \to p\mu\nu) = 17,687 \pm 733$$

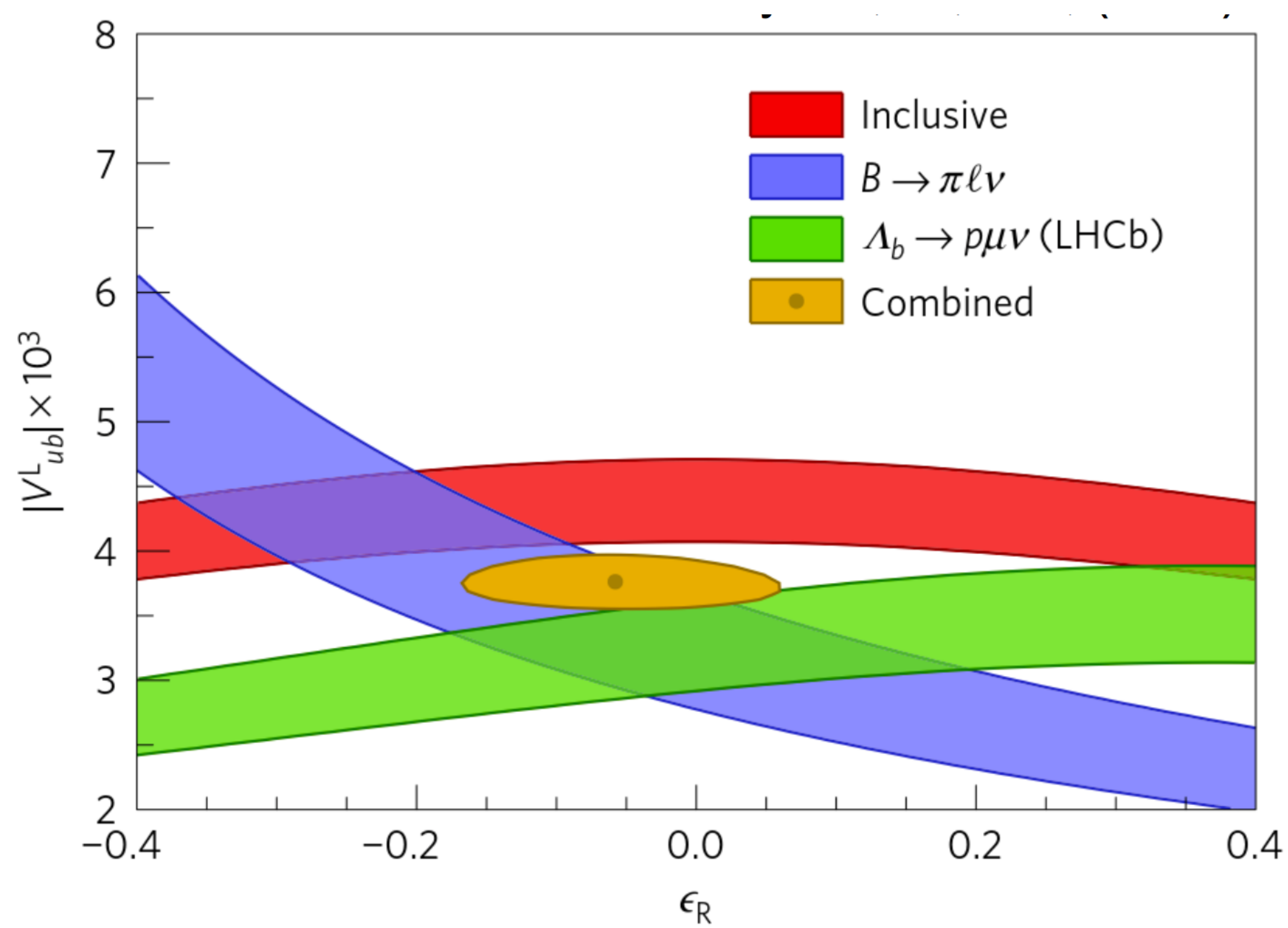
$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004(\text{expt}) \pm 0.004(\text{lattice})$$

From experimental side need to improve BF($\Lambda_c \to pK\pi$) Belle, PRL 113 (2014) 042002

V_{ub} and V_{cb} inclusive vs exclusive

LHCb result confirms the discrepancy between exclusive and inclusive results…





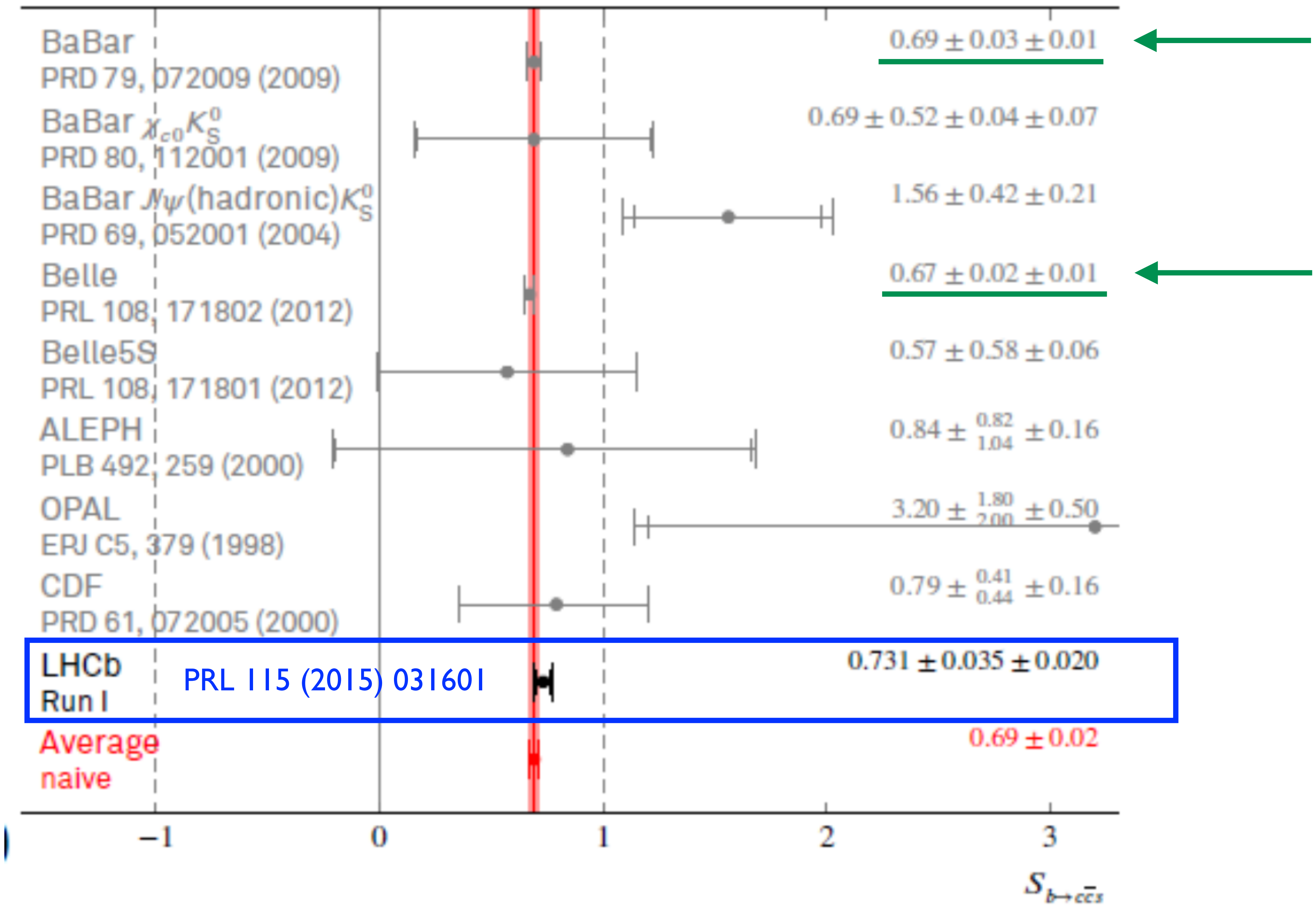
… and does not support the evidence for a right handed current affecting the V_{ub} measurements

Next steps:

- $B_s \to K\mu\nu$ has the potential of producing the best exclusive meas., better FF than $B \to \pi\ell\nu$, but the signature is more difficult than $\Lambda_b \to p\mu\nu$ … big effort on this!
- $B \to \mu\mu\mu\nu$, $B \to pp\mu\nu$
- $B \to KK\pi\mu\nu$, $B \to KK\mu\nu$ help in understanding incl. meas., (I.Bigi 1507.01842)

Matteo Palutan, INFN-LNF

sin(2β) at LHCb



Using full RUN I dataset and improved flavour tagging, LHCb is competitive with B-factories, but syst still a factor of two larger…

Tree-level determination of γ

Combining several independent decay modes is the key to achieve the ultimate precision

Time independent: $B^+ \to DK^+$, $B \to D\pi^+$ and $B^+ \to DK^{*0}$ decays

- $B^+ \to Dh^+$, $D \to hh$, GLW/ADS Phys. Lett. **B712** (2012) 203 — 1 fb^{-1}
- $B^+ \to Dh^+$, $D \to K\pi\pi\pi$, ADS Phys. Lett. **B723** (2013) 44 — 1 fb^{-1}
- $B^+ \to DK^+$, $D \to K^0_S hh$, GGSZ JHEP **10** (2014) 097 — 3 fb^{-1}
- $B^+ \to DK^+$, $D \to K^0_S K\pi$, GLS Phys. Lett. **B733** (2014) 36 — 3 fb^{-1}
- $B^0 \to DK^{*0}$, $D \to hh$, GLW/ADS Phys. Rev. **D90** (2014) 112002 — 3 fb^{-1}

RUN I potential not fully exploited still

Time dependent: $B_s \to D_s K$ JHEP **11** (2014) 060 — 1 fb^{-1}

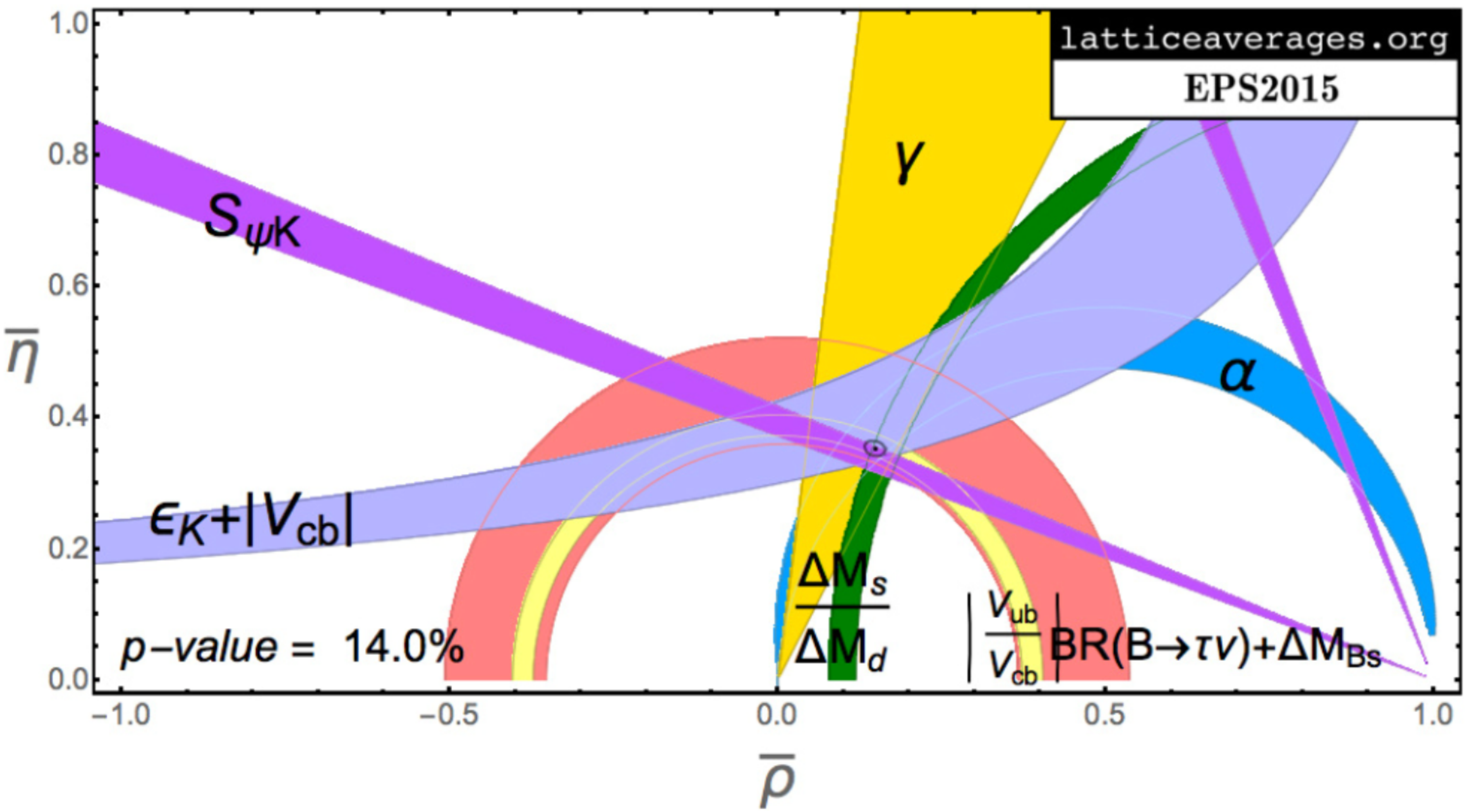
LHCb: $\gamma = 73^{+9}_{-10}$ LHCb-CONF-2014-004

Belle: $\gamma = 68^{+15}_{-14}$ arXiv:1301.2033

Babar: $\gamma = 69^{+17}_{-16}$ PRD 87 (2013) 052015

LHCb is starting now to dominate the world average, 4 deg precision is expected at the end of RUN II

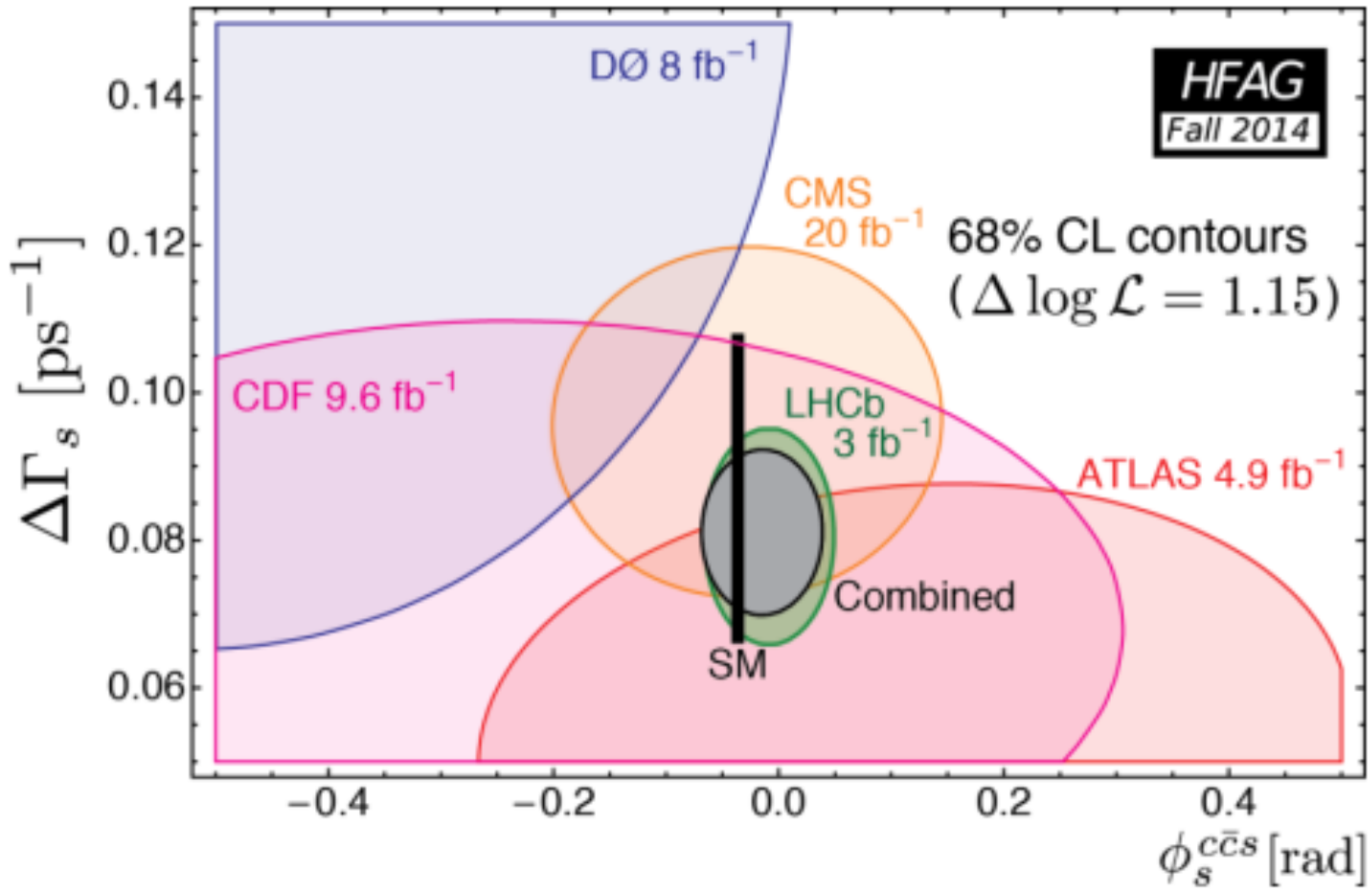
Global CKM fits



At the moment, there's no evidence for heavy flavour CP violation anomalies…

ϕ_s from $b \to c\bar{c}s$

But there's still plenty of scope for NP to show up in Bs oscillations



$B_s \to J/\psi K^+K^-$ (3 fb^{-1}): ϕ_s = -58±49±6 mrad PRL 114 (2015) 041801

Still fully dominated by stat

…and no CPV in charm decays

$$\Delta A_{CP} \equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$$

~ cancel production and detection asymmetries

arXiv:1602.03160

- The ΔA_{CP} saga:

Prompt, 0.6 fb^{-1}

$$\Delta A_{CP} = (-0.82 \pm 0.21 \pm 0.11)\%$$

PRL 108 (2012) 111602

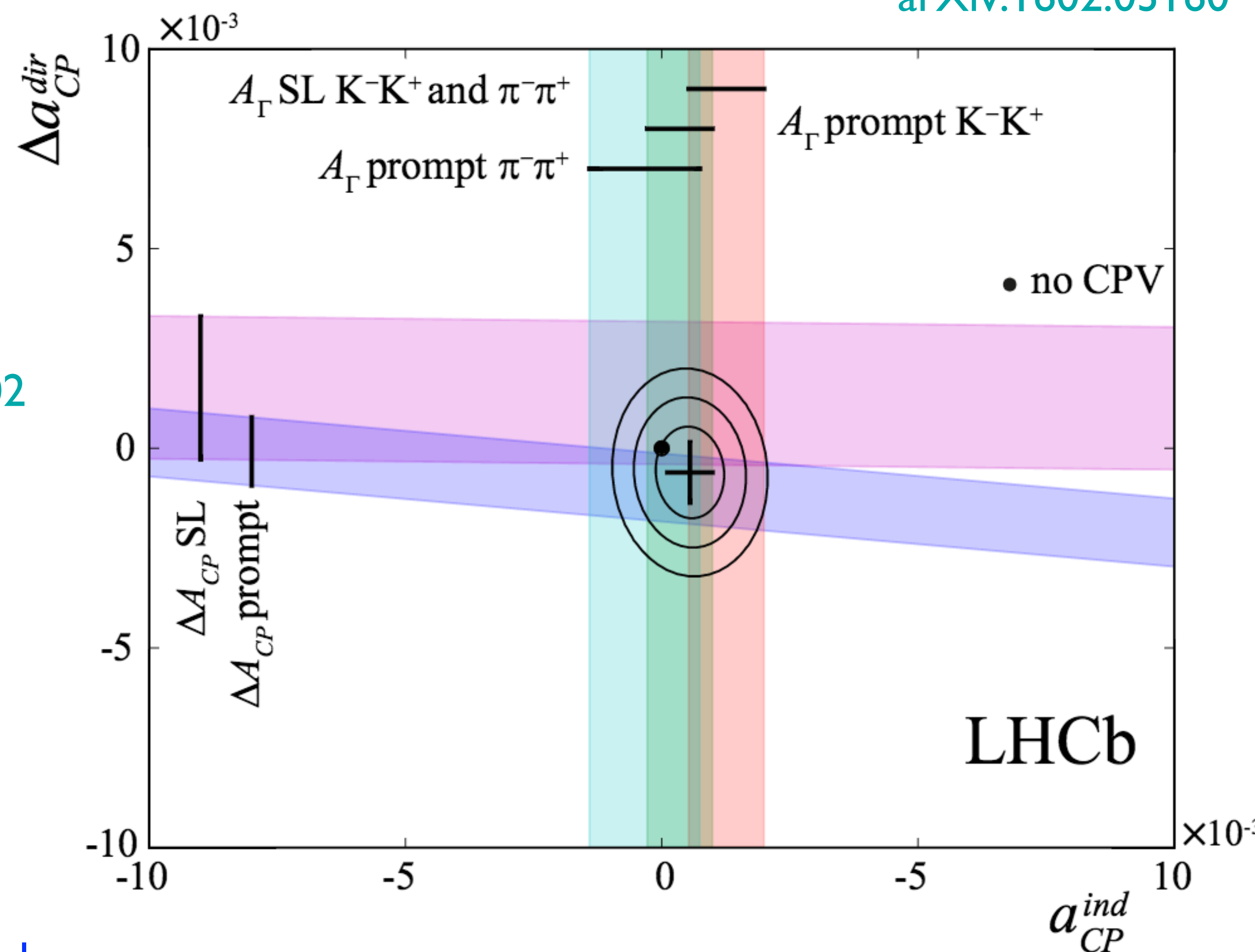
CPV in charm?

Semileptonic, 3 fb^{-1}

$$\Delta A_{CP} = (+0.14 \pm 0.16 \pm 0.08)\%$$

JHEP 07 (2014) 041

no CPV in charm…



And finally, prompt updated to 3 fb^{-1}

$$\Delta A_{CP} = (-0.10 \pm 0.08\ (\text{stat}) \pm 0.03\ (\text{syst}))\,\%$$

arXiv:1602.03160

Conclusions

- Flavor-changing transitions represent a unique window on physics beyond the SM: there is still a lot to learn and explore

LHC (and LHCb) is acting as a fantastic flavour-factory

- In general the agreement with the SM is excellent: large NP contributions, *O*(SM), ruled out in many cases. **Fortunately, there are few interesting anomalies, which are under investigation**

Need combined th+exp precision at the few % level

- We're at the beginning of RUN II, which should offer significant increase in sample sizes (x6 in b-yields) and, hopefully, good opportunities for clarifying the present experimental picture

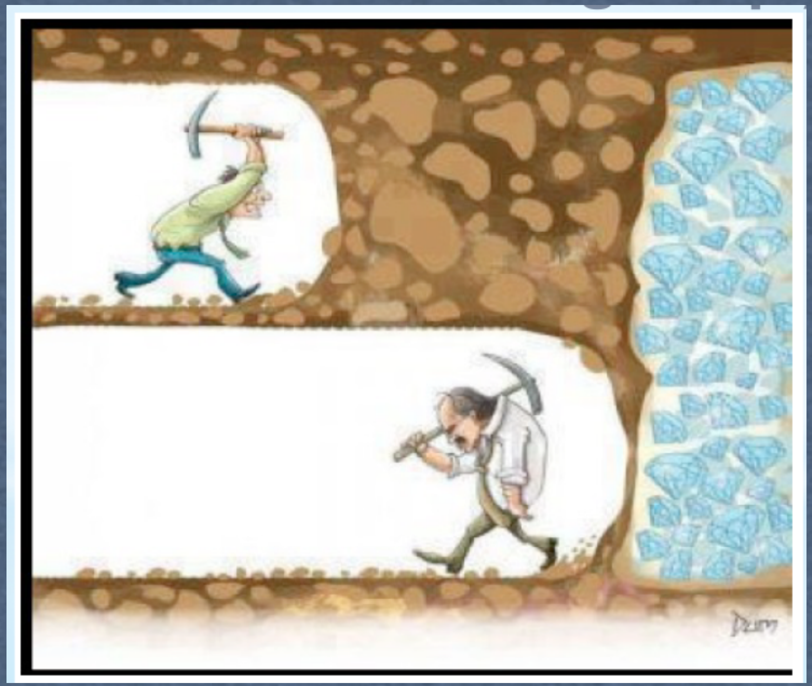
- **Interplay between low energy precision measurements and direct searches as strong as ever**

Conclusions

- Flavor-changing transitions represent a unique window on physics beyond the SM: there is still a lot to learn and explore

LHC (and LHCb) is acting as a fantastic flavour-factory

We don't know yet what is the scale of NP: cast a wide net!



- **Interplay between low energy precision measurements and direct searches as strong as ever**

SPARES

FCNC processes in effective field theory

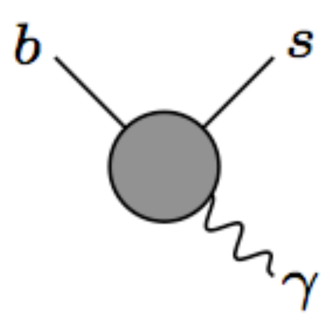
- Effective Hamiltonian for b→s FCNC transistions

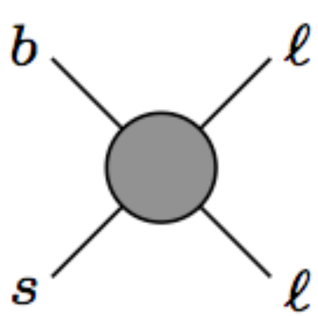
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i (C_i \mathcal{O}_i + C_i' \mathcal{O}_i')$$

- Wilson coefficients C_i encode short-distance physics from SM and **from possible NP effects**, computed perturbatively

- Local operators O_i with different Lorentz structure absorbe long distance effects

- O'_i helicity flipped operators, m_s/m_b suppressed in SM





Operator		
$\mathcal{O}_7^{(\prime)}$	$\frac{e}{g^2} m_b (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu})$	photon penguin
$\mathcal{O}_9^{(\prime)}$	$\frac{e^2}{g^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \mu)$	ew. penguin
$\mathcal{O}_{10}^{(\prime)}$	$\frac{e^2}{g^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$	
$\mathcal{O}_S^{(\prime)}$	$\frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b)(\bar{\mu}\mu)$	scalar penguin
$\mathcal{O}_P^{(\prime)}$	$\frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b)(\bar{\mu}\gamma_5 \mu)$	pseudoscalar penguin

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

Time-integrated BR vs CP-averaged BR

$$\mathcal{B}(B^0_s \to \mu^+\mu^-)^{\mathrm{TH},\,\langle t\rangle} = \frac{1+y_s A_{\Delta\Gamma}}{1-y_s^2} \times \mathcal{B}(B^0_s \to \mu^+\mu^-)^{CP}$$

$$=_{SM} \frac{1}{1-y_s} \times \mathcal{B}(B^0_s \to \mu^+\mu^-)^{CP}$$

$$y_s = \frac{\Delta\Gamma_s}{2\Gamma_s} = 0.0615 \pm 0.0085$$

$$\mathcal{A}_{\Delta\Gamma} = \frac{\Gamma_{B^0_{s,H}\to\mu\mu} - \Gamma_{B^0_{s,L}\to\mu\mu}}{\Gamma_{B^0_{s,H}\to\mu\mu} + \Gamma_{B^0_{s,L}\to\mu\mu}} \overset{SM}{=} 1$$

Lifetime bias in the analysis efficiency

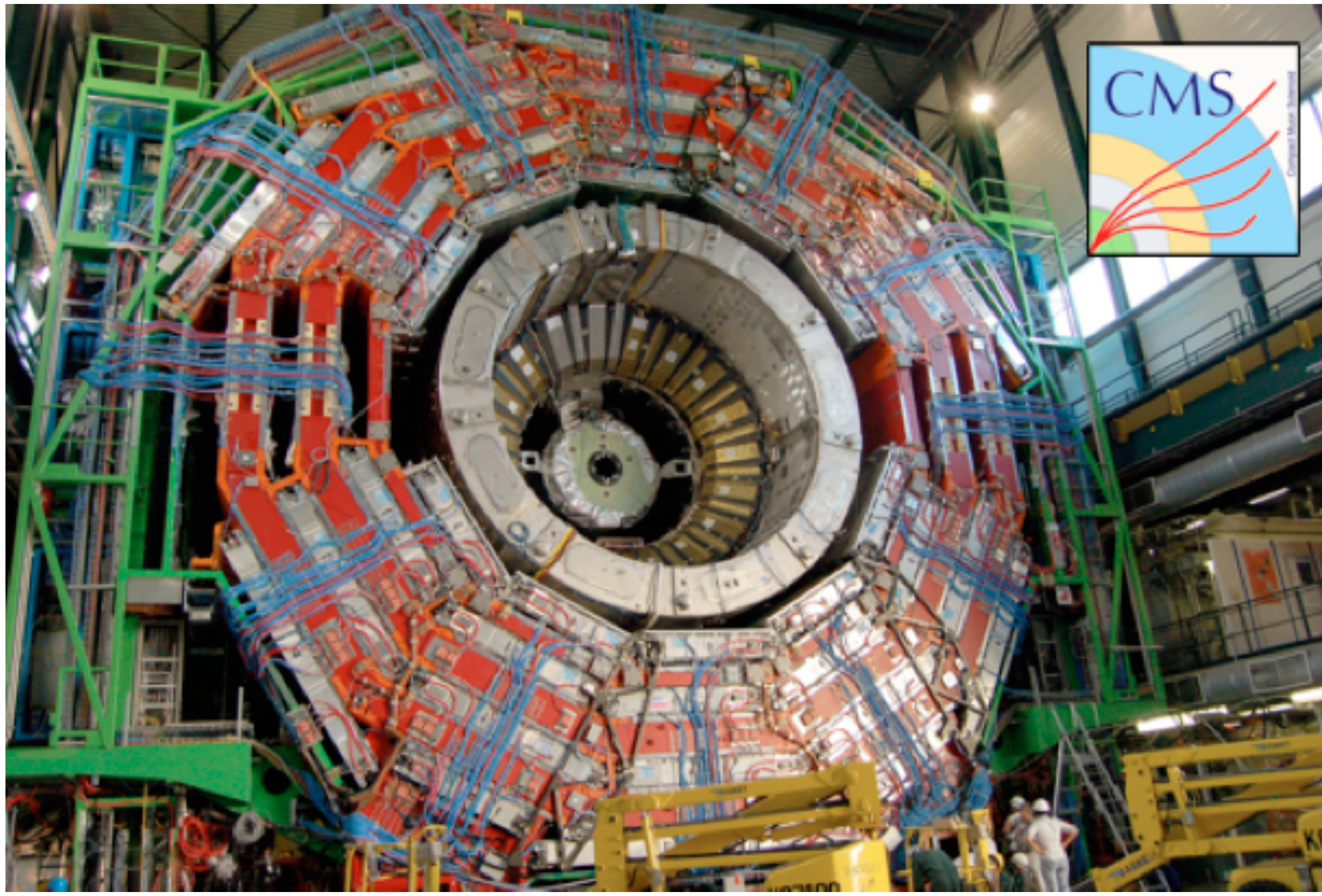
$$\epsilon = \frac{\int_0^\infty \Gamma(B^0_s(t) \to \mu^+\mu^-, \mathcal{A}_{\Delta\Gamma}, y_s)\epsilon(t)\mathrm{d}t}{\int_0^\infty \Gamma(B^0_s(t) \to \mu^+\mu^-, \mathcal{A}_{\Delta\Gamma}, y_s)\mathrm{d}t},$$

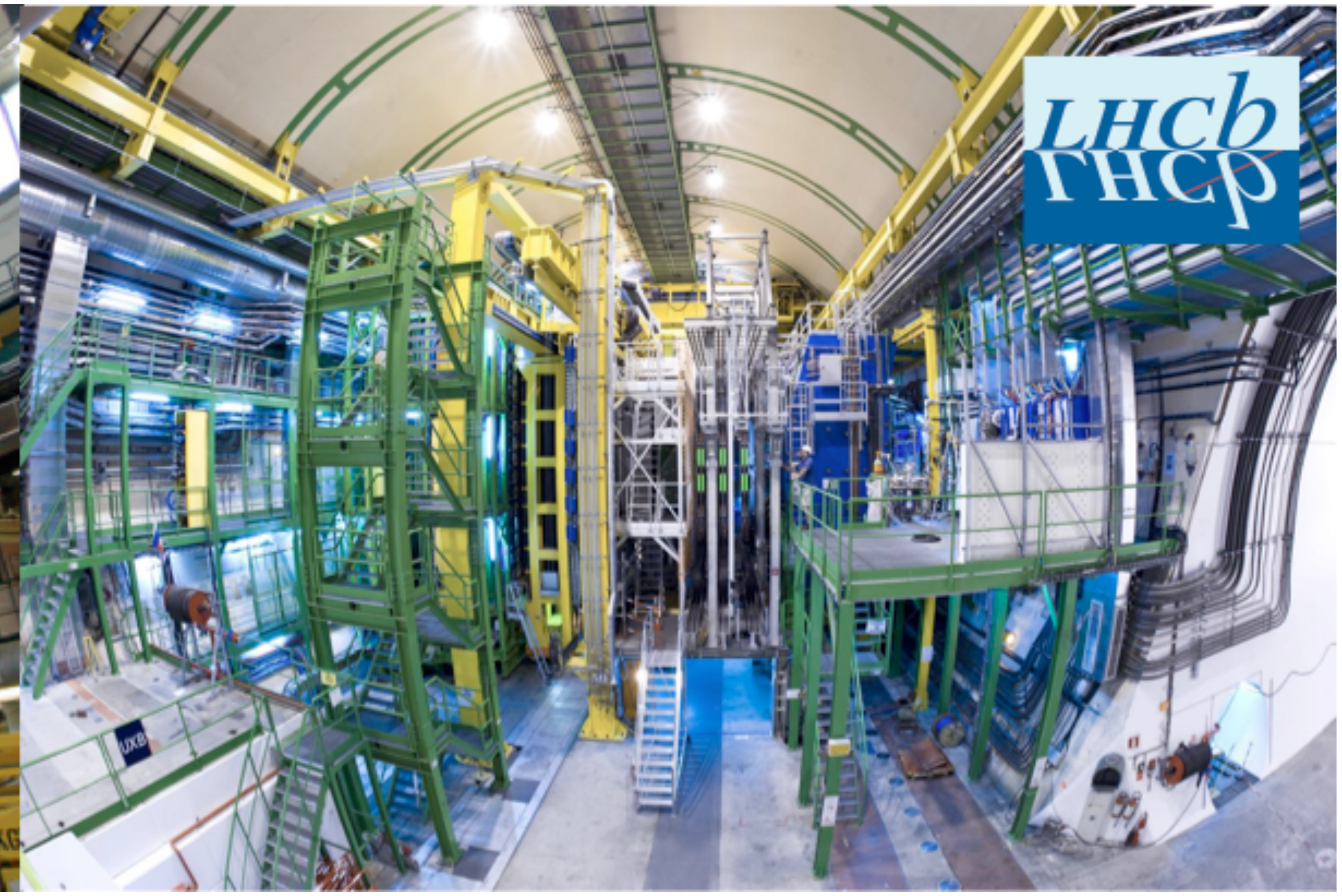
$$\delta_\epsilon = \frac{\epsilon^{\mathcal{A}_{\Delta\Gamma}, y_s}}{\epsilon^{MC}} = \frac{\int_0^\infty \Gamma(B^0_s(t) \to \mu^+\mu^-, \mathcal{A}_{\Delta\Gamma}, y_s)\epsilon(t)\mathrm{d}t}{\int_0^\infty \Gamma(B^0_s(t) \to \mu^+\mu^-, \mathcal{A}_{\Delta\Gamma}, y_s)\mathrm{d}t} \cdot \frac{\int_0^\infty e^{-\Gamma_{MC} t}\mathrm{d}t}{\int_0^\infty e^{-\Gamma_{MC} t}\epsilon(t)\mathrm{d}t}$$

Correction for B_s = 4.50±0.03%
Correction for B^0 = 1.48±0.01%

a residual dependence vs analysis lifetime-dependent cuts is also corrected

A comparison between LHCb and CMS





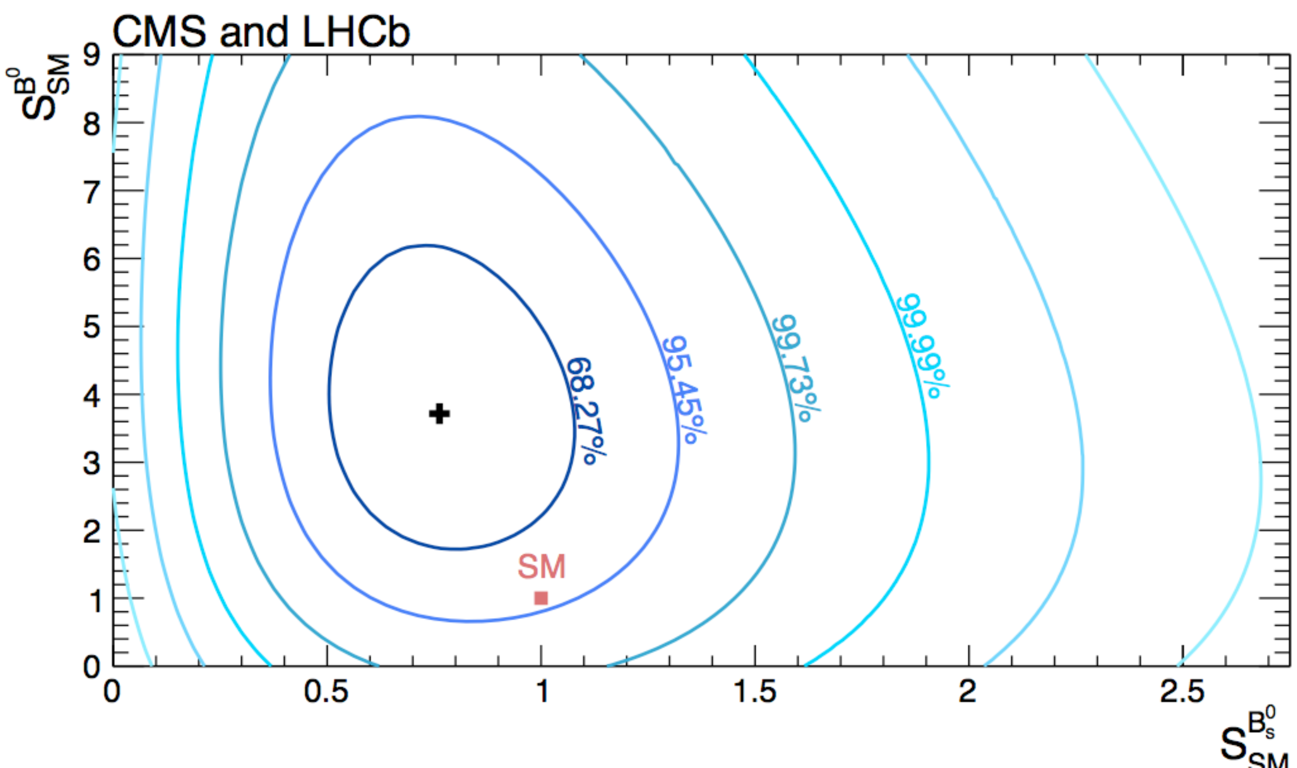
- Good trigger and muon ID
- **No hadron PID**
- Excellent silicon tracking to resolve signal decays in the high pile-up environment
- **Di-muon mass resolution 32-75 MeV/c^2**
- **CMS: 5+20 fb^{-1} at 7 and 8 TeV**

- Efficient muon trigger
- **Good muon and hadron PID**
- Track impact parameter resolution ≤20μm
- Luminosity levelling at 4x10^{32} cm^{-2}s^{-1}
- **Di-muon mass resolution 25 MeV/c^2**
- **LHCb: 1+2 fb^{-1} at 7 and 8 TeV**

~1 fb^{-1} at LHCb is equivalent to ~10 fb^{-1} at CMS

Comparison with SM

Signal strength



- 2D LL scan performed for the signal strength BR/BR$_{SM}$:

$\mathcal{S}_{\rm SM}^{B^0_s} = 0.76^{+0.20}_{-0.18}$

$\mathcal{S}_{\rm SM}^{B^0} = 3.7^{+1.6}_{-1.4}$

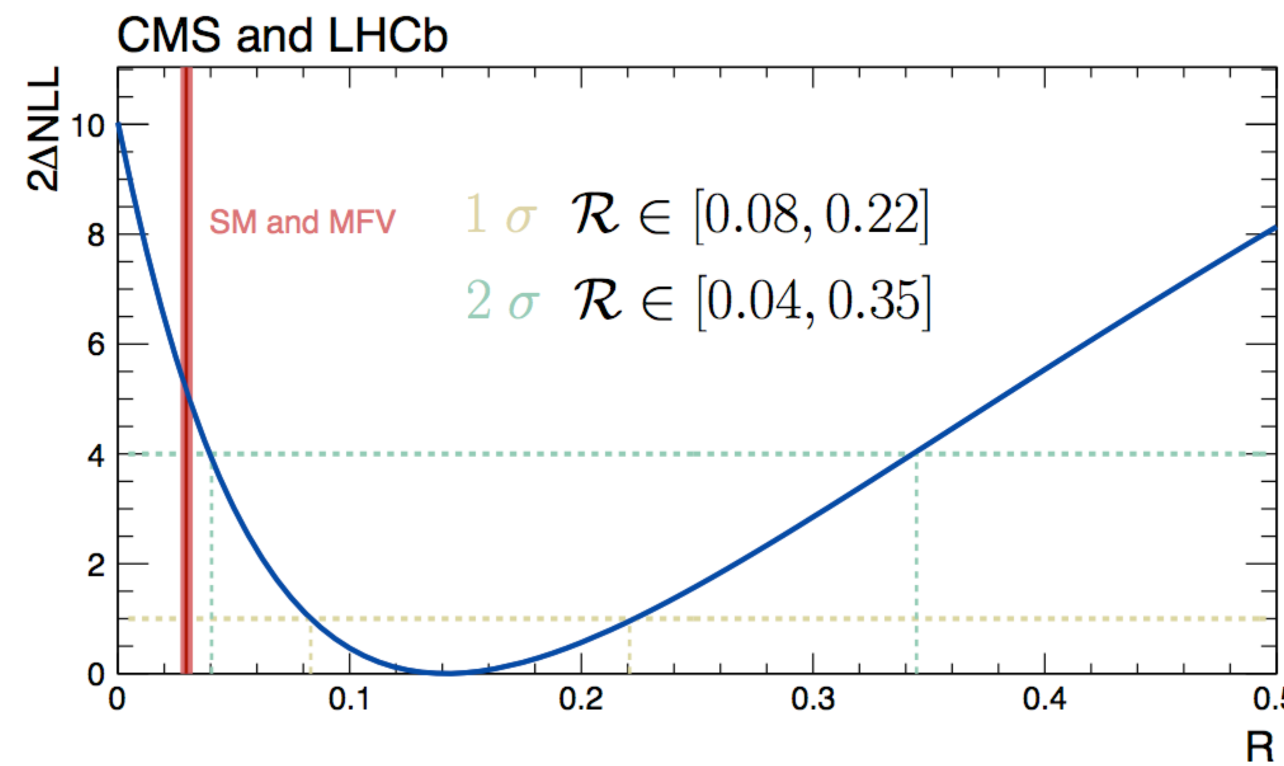
- Compatibility with SM:

1.2σ for B^0_s

2.2σ for B^0

theoretical errors included in the fits

B^0/B^0_s ratio



- 1D LL scan of the B^0/B^0_s ratio:

$\mathcal{R} = 0.14^{+0.08}_{-0.06}$

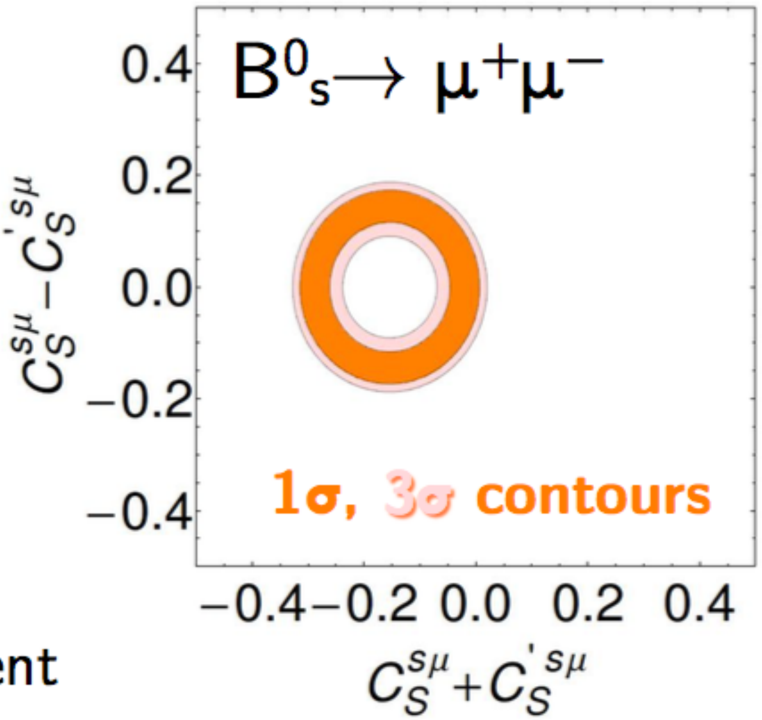
- Compatibility with SM (and MFV):

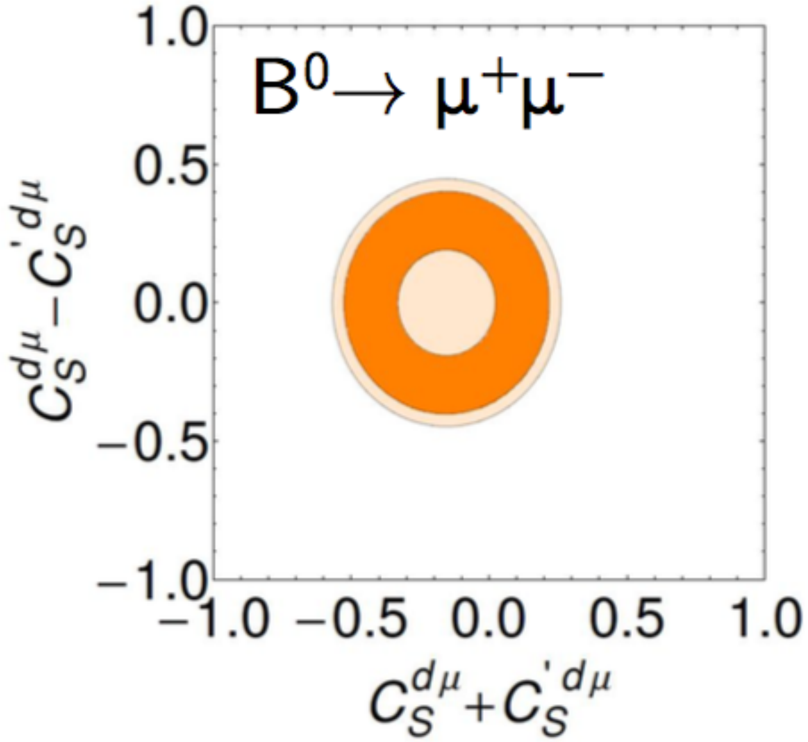
2.3σ for B^0/B^0_s ratio

future of $B_s \to \mu\mu$

- **radius** proportional to the branching fraction while the **width of the rings** the experimental accuracy

- **Breaking the degeneracy will require other observables!**



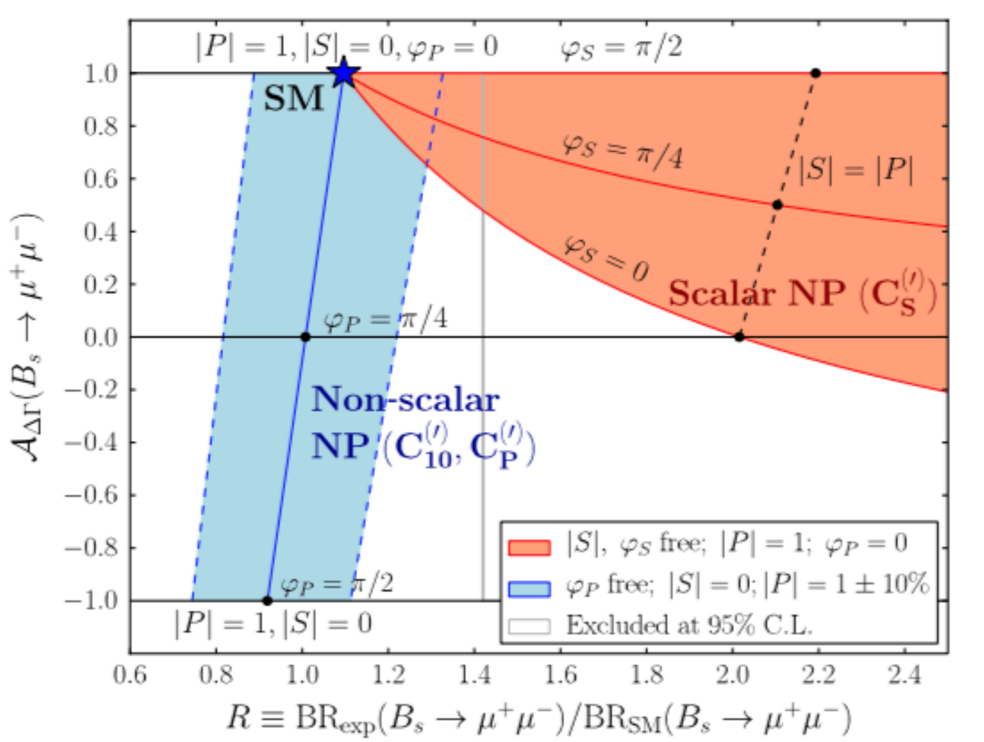


[Phys. Rev. Lett. 113, 241802 (2014)]

- Ratio with SM expectation not sufficient

$$\overline{R}_{ql} = \frac{\overline{\mathcal{B}}_{ql}}{(\overline{\mathcal{B}}_{ql})_{\rm SM}} = \frac{1 + \mathcal{A}^{ll}_{\Delta\Gamma}\, y_q}{1 + y_q}\left(|S|^2 + |P|^2\right)$$

[K. De Bruyn et al. Phys.Rev.Lett. 109 (2012) 041801]



- $A_{\Delta\Gamma}$ proportional to the effective lifetime

$$\tau_{\mu\mu} = \frac{\tau_{B_s}}{(1 - y_s^2)}\,\frac{1 + 2\mathcal{A}_{\Delta\Gamma} y_s + y_s^2}{1 + \mathcal{A}_{\Delta\Gamma} y_s}$$

- Effective lifetime offers theoretically clean probe of NP complementary to branching fraction.

- LHCb could reach a 5% uncertainty on the effective lifetime with $46\,\mathrm{fb}^{-1}$.

Implications (model dependent): CMSSM

• Latest results on $B^0_{(s)} \to \mu^+\mu^-$ strongly constrain the parameter space for many NP models, complementing direct searches from ATLAS/CMS: in particular, large tanβ with light pseudo-scalar Higgs in CMSSM is strongly disfavored

[Mamhoudi arXiv:1310.2556]

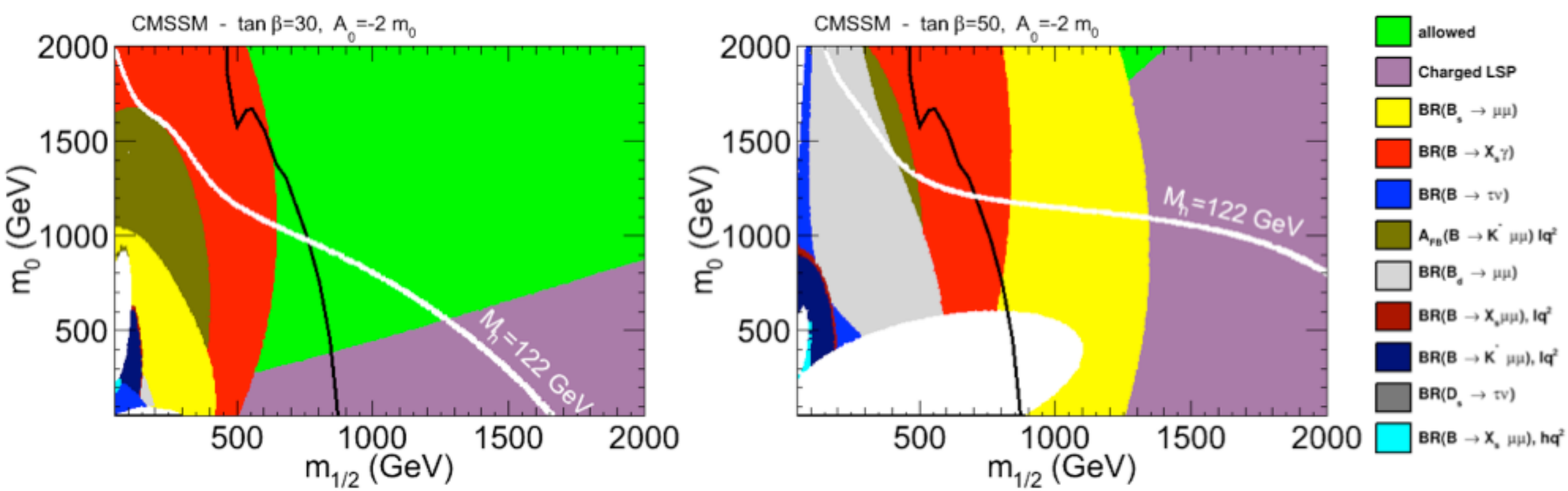


Figure 1: Flavour constraints in the CMSSM, in the $(m_{1/2}, m_0)$ parameter plane with $A_0 = -2m_0$, for $\tan\beta = 30$ in the left and $\tan\beta = 50$ in the right. The black lines delimit the ATLAS SUSY direct search limits with 20.3 fb^{-1} of data and the white lines show where the Higgs mass can reach a value of 122 GeV.

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

$$\frac{\mathrm{d}^4\Gamma[\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-]}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\sum_i I_i(q^2) f_i(\vec{\Omega}) \quad \text{and}$$

$$\frac{\mathrm{d}^4\bar{\Gamma}[B^0 \to K^{*0}\mu^+\mu^-]}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\sum_i \bar{I}_i(q^2) f_i(\vec{\Omega}) \,,$$

$$S_i = \left(I_i + \bar{I}_i\right) \Bigg/ \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} + \frac{\mathrm{d}\bar{\Gamma}}{\mathrm{d}q^2}\right) \quad \text{and}$$

$$A_i = \left(I_i - \bar{I}_i\right) \Bigg/ \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} + \frac{\mathrm{d}\bar{\Gamma}}{\mathrm{d}q^2}\right).$$

Table 1: Angular observables I_j and their corresponding angular terms for dimuon masses that are much larger than twice the muon mass. The terms in the lower part of the table arise from the $K^+\pi^-$ S-wave contribution to the $K^+\pi^-\mu^+\mu^-$ final state. The $\bar{I}_i$ coefficients are obtained by making the substitution $\mathcal{A} \to \bar{\mathcal{A}}$, *i.e.* by complex conjugation of the weak phases in the amplitudes.

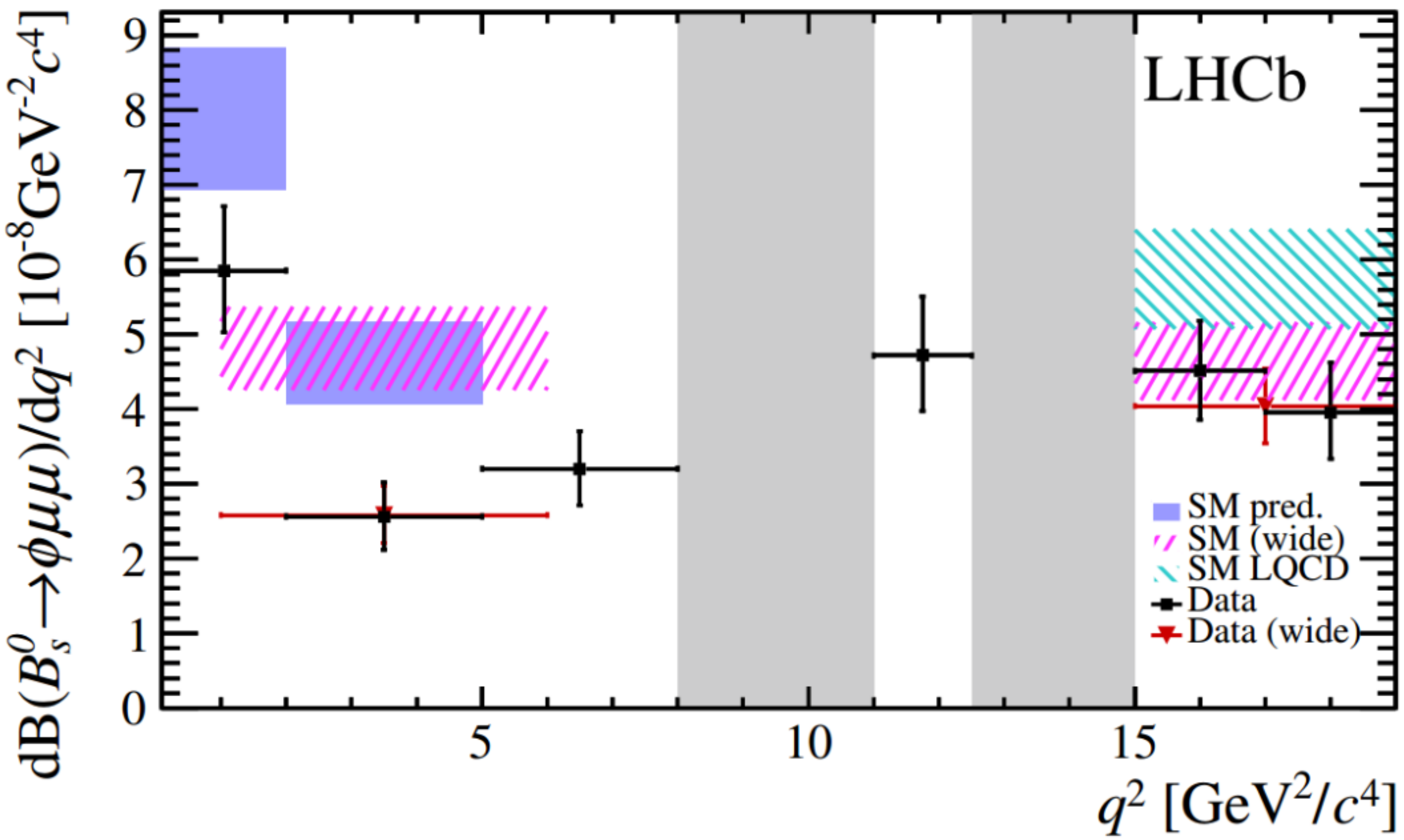
i	I_i	f_i
1s	$\frac{3}{4}\left[\lvert\mathcal{A}_\parallel^{\mathrm{L}}\rvert^2 + \lvert\mathcal{A}_\perp^{\mathrm{L}}\rvert^2 + \lvert\mathcal{A}_\parallel^{\mathrm{R}}\rvert^2 + \lvert\mathcal{A}_\perp^{\mathrm{R}}\rvert^2\right]$	$\sin^2\theta_K$
1c	$\lvert\mathcal{A}_0^{\mathrm{L}}\rvert^2 + \lvert\mathcal{A}_0^{\mathrm{R}}\rvert^2$	$\cos^2\theta_K$
2s	$\frac{1}{4}\left[\lvert\mathcal{A}_\parallel^{\mathrm{L}}\rvert^2 + \lvert\mathcal{A}_\perp^{\mathrm{L}}\rvert^2 + \lvert\mathcal{A}_\parallel^{\mathrm{R}}\rvert^2 + \lvert\mathcal{A}_\perp^{\mathrm{R}}\rvert^2\right]$	$\sin^2\theta_K \cos 2\theta_l$
2c	$-\lvert\mathcal{A}_0^{\mathrm{L}}\rvert^2 - \lvert\mathcal{A}_0^{\mathrm{R}}\rvert^2$	$\cos^2\theta_K \cos 2\theta_l$
3	$\frac{1}{2}\left[\lvert\mathcal{A}_\perp^{\mathrm{L}}\rvert^2 - \lvert\mathcal{A}_\parallel^{\mathrm{L}}\rvert^2 + \lvert\mathcal{A}_\perp^{\mathrm{R}}\rvert^2 - \lvert\mathcal{A}_\parallel^{\mathrm{R}}\rvert^2\right]$	$\sin^2\theta_K \sin^2\theta_l \cos 2\phi$
4	$\sqrt{\frac{1}{2}}\mathrm{Re}(\mathcal{A}_0^{\mathrm{L}}\mathcal{A}_\parallel^{\mathrm{L}*} + \mathcal{A}_0^{\mathrm{R}}\mathcal{A}_\parallel^{\mathrm{R}*})$	$\sin 2\theta_K \sin 2\theta_l \cos\phi$
5	$\sqrt{2}\mathrm{Re}(\mathcal{A}_0^{\mathrm{L}}\mathcal{A}_\perp^{\mathrm{L}*} - \mathcal{A}_0^{\mathrm{R}}\mathcal{A}_\perp^{\mathrm{R}*})$	$\sin 2\theta_K \sin\theta_l \cos\phi$
6s	$2\mathrm{Re}(\mathcal{A}_\parallel^{\mathrm{L}}\mathcal{A}_\perp^{\mathrm{L}*} - \mathcal{A}_\parallel^{\mathrm{R}}\mathcal{A}_\perp^{\mathrm{R}*})$	$\sin^2\theta_K \cos\theta_l$
7	$\sqrt{2}\mathrm{Im}(\mathcal{A}_0^{\mathrm{L}}\mathcal{A}_\parallel^{\mathrm{L}*} - \mathcal{A}_0^{\mathrm{R}}\mathcal{A}_\parallel^{\mathrm{R}*})$	$\sin 2\theta_K \sin\theta_l \sin\phi$
8	$\sqrt{\frac{1}{2}}\mathrm{Im}(\mathcal{A}_0^{\mathrm{L}}\mathcal{A}_\perp^{\mathrm{L}*} + \mathcal{A}_0^{\mathrm{R}}\mathcal{A}_\perp^{\mathrm{R}*})$	$\sin 2\theta_K \sin 2\theta_l \sin\phi$
9	$\mathrm{Im}(\mathcal{A}_\parallel^{\mathrm{L}*}\mathcal{A}_\perp^{\mathrm{L}} + \mathcal{A}_\parallel^{\mathrm{R}*}\mathcal{A}_\perp^{\mathrm{R}})$	$\sin^2\theta_K \sin^2\theta_l \sin 2\phi$
10	$\frac{1}{3}\left[\lvert\mathcal{A}_{\mathrm{S}}^{\mathrm{L}}\rvert^2 + \lvert\mathcal{A}_{\mathrm{S}}^{\mathrm{R}}\rvert^2\right]$	1
11	$\sqrt{\frac{4}{3}}\mathrm{Re}(\mathcal{A}_{\mathrm{S}}^{\mathrm{L}}\mathcal{A}_0^{\mathrm{L}*} + \mathcal{A}_{\mathrm{S}}^{\mathrm{R}}\mathcal{A}_0^{\mathrm{R}*})$	$\cos\theta_K$
12	$-\frac{1}{3}\left[\lvert\mathcal{A}_{\mathrm{S}}^{\mathrm{L}}\rvert^2 + \lvert\mathcal{A}_{\mathrm{S}}^{\mathrm{R}}\rvert^2\right]$	$\cos 2\theta_l$
13	$-\sqrt{\frac{4}{3}}\mathrm{Re}(\mathcal{A}_{\mathrm{S}}^{\mathrm{L}}\mathcal{A}_0^{\mathrm{L}*} + \mathcal{A}_{\mathrm{S}}^{\mathrm{R}}\mathcal{A}_0^{\mathrm{R}*})$	$\cos\theta_K \cos 2\theta_l$
14	$\sqrt{\frac{2}{3}}\mathrm{Re}(\mathcal{A}_{\mathrm{S}}^{\mathrm{L}}\mathcal{A}_\parallel^{\mathrm{L}*} + \mathcal{A}_{\mathrm{S}}^{\mathrm{R}}\mathcal{A}_\parallel^{\mathrm{R}*})$	$\sin\theta_K \sin 2\theta_l \cos\phi$
15	$\sqrt{\frac{8}{3}}\mathrm{Re}(\mathcal{A}_{\mathrm{S}}^{\mathrm{L}}\mathcal{A}_\perp^{\mathrm{L}*} - \mathcal{A}_{\mathrm{S}}^{\mathrm{R}}\mathcal{A}_\perp^{\mathrm{R}*})$	$\sin\theta_K \sin\theta_l \cos\phi$
16	$\sqrt{\frac{8}{3}}\mathrm{Im}(\mathcal{A}_{\mathrm{S}}^{\mathrm{L}}\mathcal{A}_\parallel^{\mathrm{L}*} - \mathcal{A}_{\mathrm{S}}^{\mathrm{R}}\mathcal{A}_\perp^{\mathrm{R}*})$	$\sin\theta_K \sin\theta_l \sin\phi$
17	$\sqrt{\frac{2}{3}}\mathrm{Im}(\mathcal{A}_{\mathrm{S}}^{\mathrm{L}}\mathcal{A}_\perp^{\mathrm{L}*} + \mathcal{A}_{\mathrm{S}}^{\mathrm{R}}\mathcal{A}_\perp^{\mathrm{R}*})$	$\sin\theta_K \sin 2\theta_l \sin\phi$

$$F_{\mathrm{L}} = S_{1c} = \frac{|\mathcal{A}_0^{\mathrm{L}}|^2 + |\mathcal{A}_0^{\mathrm{R}}|^2}{|\mathcal{A}_0^{\mathrm{L}}|^2 + |\mathcal{A}_0^{\mathrm{R}}|^2 + |\mathcal{A}_\parallel^{\mathrm{L}}|^2 + |\mathcal{A}_\parallel^{\mathrm{R}}|^2 + |\mathcal{A}_\perp^{\mathrm{L}}|^2 + |\mathcal{A}_\perp^{\mathrm{R}}|^2}\,.$$

$$F_{\mathrm{S}} = \frac{|\mathcal{A}_{\mathrm{S}}^{\mathrm{L}}|^2 + |\mathcal{A}_{\mathrm{S}}^{\mathrm{R}}|^2}{|\mathcal{A}_{\mathrm{S}}^{\mathrm{L}}|^2 + |\mathcal{A}_{\mathrm{S}}^{\mathrm{R}}|^2 + |\mathcal{A}_0^{\mathrm{L}}|^2 + |\mathcal{A}_0^{\mathrm{R}}|^2 + |\mathcal{A}_\parallel^{\mathrm{L}}|^2 + |\mathcal{A}_\parallel^{\mathrm{R}}|^2 + |\mathcal{A}_\perp^{\mathrm{L}}|^2 + |\mathcal{A}_\perp^{\mathrm{R}}|^2}\,,$$

$$\begin{aligned}
\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}}\bigg|_{\mathrm{S+P}} = {}& (1-F_{\mathrm{S}})\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}}\bigg|_{\mathrm{P}} \\
&+ \frac{3}{16\pi}F_{\mathrm{S}}\sin^2\theta_l \\
&+ \frac{9}{32\pi}(S_{11} + S_{13}\cos 2\theta_l)\cos\theta_K \\
&+ \frac{9}{32\pi}(S_{14}\sin 2\theta_l + S_{15}\sin\theta_l)\sin\theta_K\cos\phi \\
&+ \frac{9}{32\pi}(S_{16}\sin\theta_l + S_{17}\sin 2\theta_l)\sin\theta_K\sin\phi\,,
\end{aligned}$$

Branching fraction measurement: $B_s \to \phi\mu^+\mu^-$



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Suppressed by fs/fd, cleaner because of narrow ϕ resonance

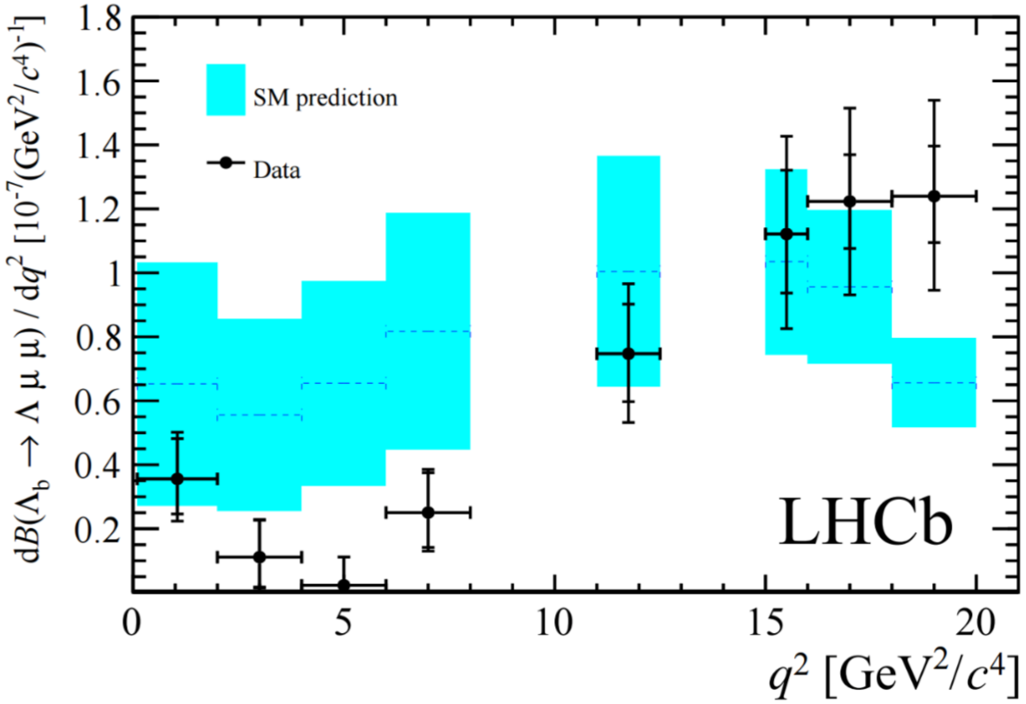
3.3 σ from deviation from SM for $1<q^2<6$ GeV$^2/c^4$

angular spectrum in agreement with SM (S5 not accessible)

Branching fraction measurement: $\Lambda_b \to \Lambda \mu^+ \mu^-$

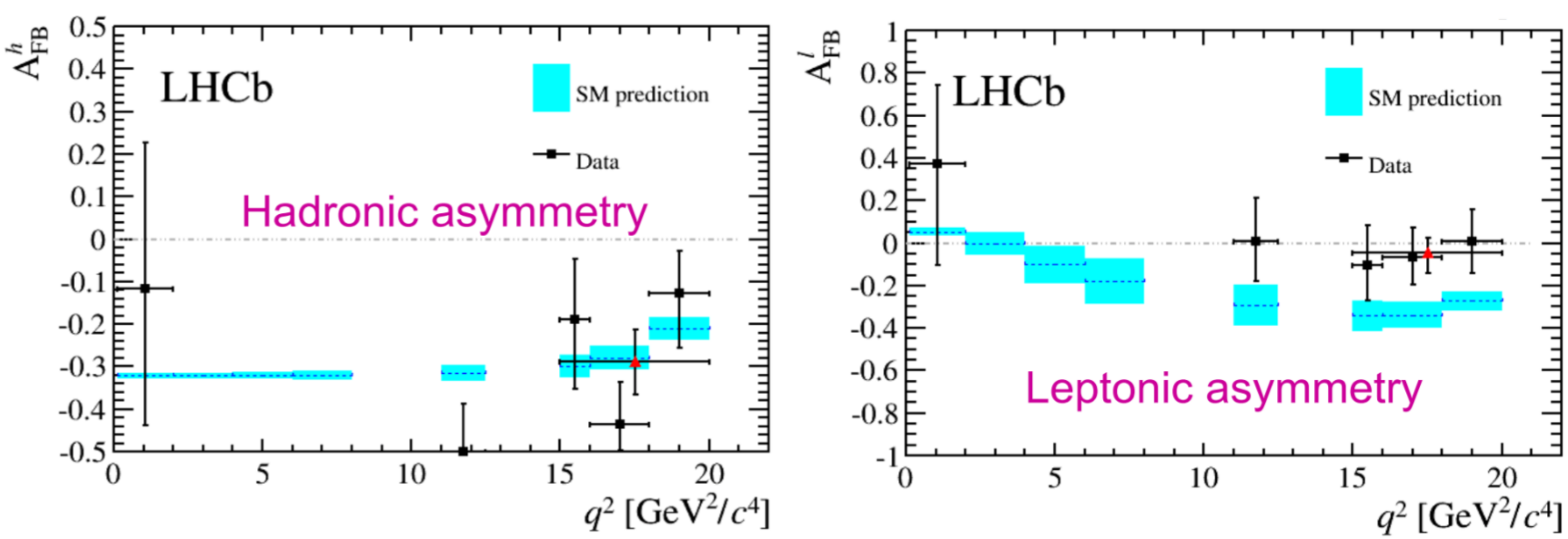
JHEP 06 (2015) 115

dBF/dq^2



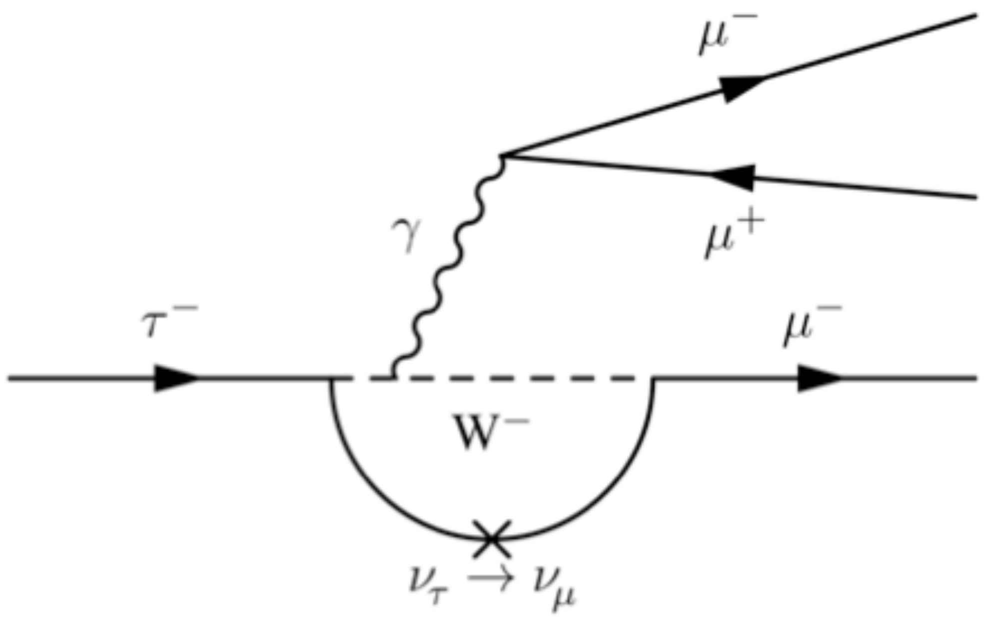
In total ~300 candidates in data set, decay not visible at low q2

Angular asymmetries



Forward-backward angular asymmetries computed for q^2 bins with >3σ significance

Search for lepton flavour violation in $\tau \to \mu\mu\mu$



- Possible as penguin with neutrino oscillation; SM prediction $\sim 10^{-40}$, beyond experimental reach

- (some) NP predictions: SUSY $\sim 10^{-10}$, mSUGRA+seesaw $\sim 10^{-9}$, non universal $Z' \sim 10^{-8}$

- With $\sim 1.4 \times 10^9$ τ at the B-factories the current limits are:

Belle:	$BR(\tau \to \mu\mu\mu) < 2.1 \times 10^{-8}$ at 90%CL
BaBar:	$BR(\tau \to \mu\mu\mu) < 3.3 \times 10^{-8}$ at 90%CL

arXiv:1001.3221

arXiv:1002.4550

- At the LHC τ are copiously produced (mainly from charm decays, $Ds \to \tau\nu$): $\sim 10^{11}$ τ/fb^{-1} ($\sim 5 \times 10^{14}$ at HL-LHC!).

LHCb presented at TAU2014 the search based on 3 fb^{-1}

$BR(\tau \to \mu\mu\mu) < 4.6 \times 10^{-8}$ at 90% CL

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$\tau \to \mu\mu\mu$ analysis at LHCb

First search at a hadron collider:

→Possible thanks to the very low pT thresholds of the LHCb muon triggers

Huge cross section: $\sigma(pp \to \tau X) \sim 80\ \mu b$ at $\sqrt{s} = 7$ TeV

→8×10^9 τ produced in 1 fb^{-1} almost exclusively from B and D_s

But also huge background:

→Cut based analysis followed by multivariate one in the PID and kinematical plane

Normalization using $D_s \to \varphi(\mu\mu)\, \pi$ (very similar topology):

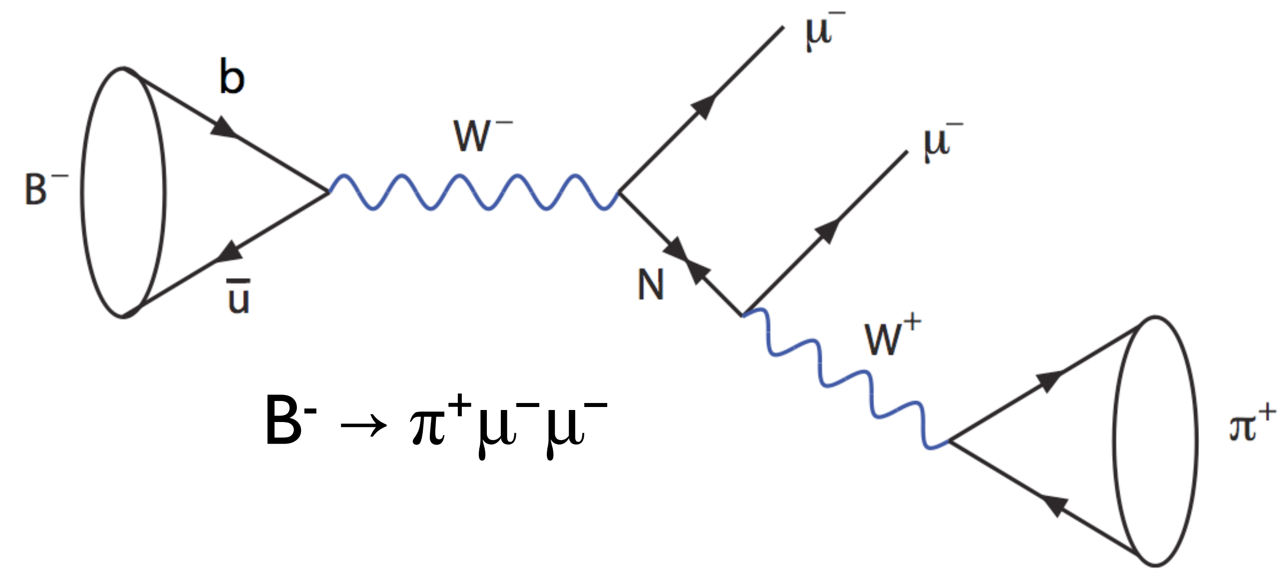
$$BR(\tau^- \to \mu^-\mu^+\mu^-) = BR(D_S^- \to \phi(\mu^+\mu^-)\pi^-) \times \frac{f^{\tau}_{D_s}}{BR(D_S \to \tau^-\overline{\nu}_\tau)} \times \frac{\epsilon_{\text{cal}}}{\epsilon_{\text{sig}}} \times \frac{N_{\text{sig}}}{N_{\text{cal}}}$$
$$= \alpha \times N_{\text{sig}}$$

Fraction of τ leptons which originate from Ds decays, calculated using bb and cc cross section as measured by LHCb [1,2] and the inclusive $b \to \tau$ and $c \to \tau$ branching fractions as measured by LEP experiments [3]

1] LHCb collaboration, Eur. Phys. J C71 (2011) 1645
2] LHCb collaboration, Nucl. Phys. B 271 (2013) 1
3] PDG, http://pdg.lbl.gov

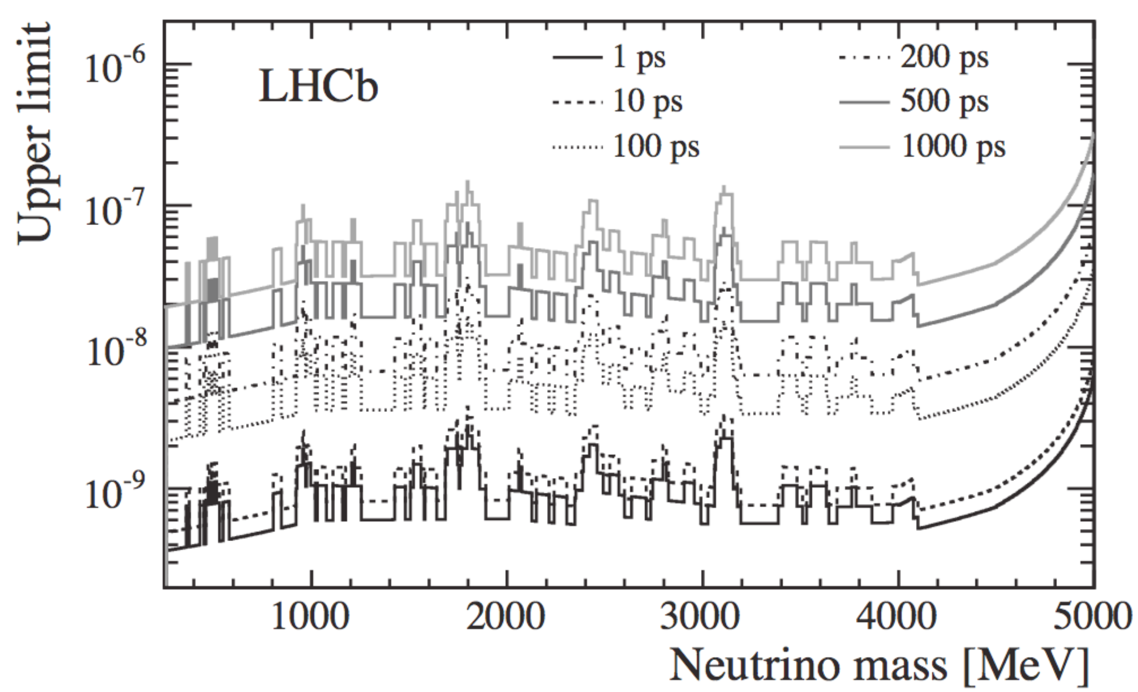
Search for Majorana neutrinos

- Observation of neutrino oscillations is a strong theoretical motivation for Majorana neutrinos to exist
- In LHCb, heavy Majorana neutrinos can be sought in $B^- \to \pi^+\mu^-\mu^-$ decay, which is forbidden in SM but can proceed via production of on-shell massive neutrinos



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

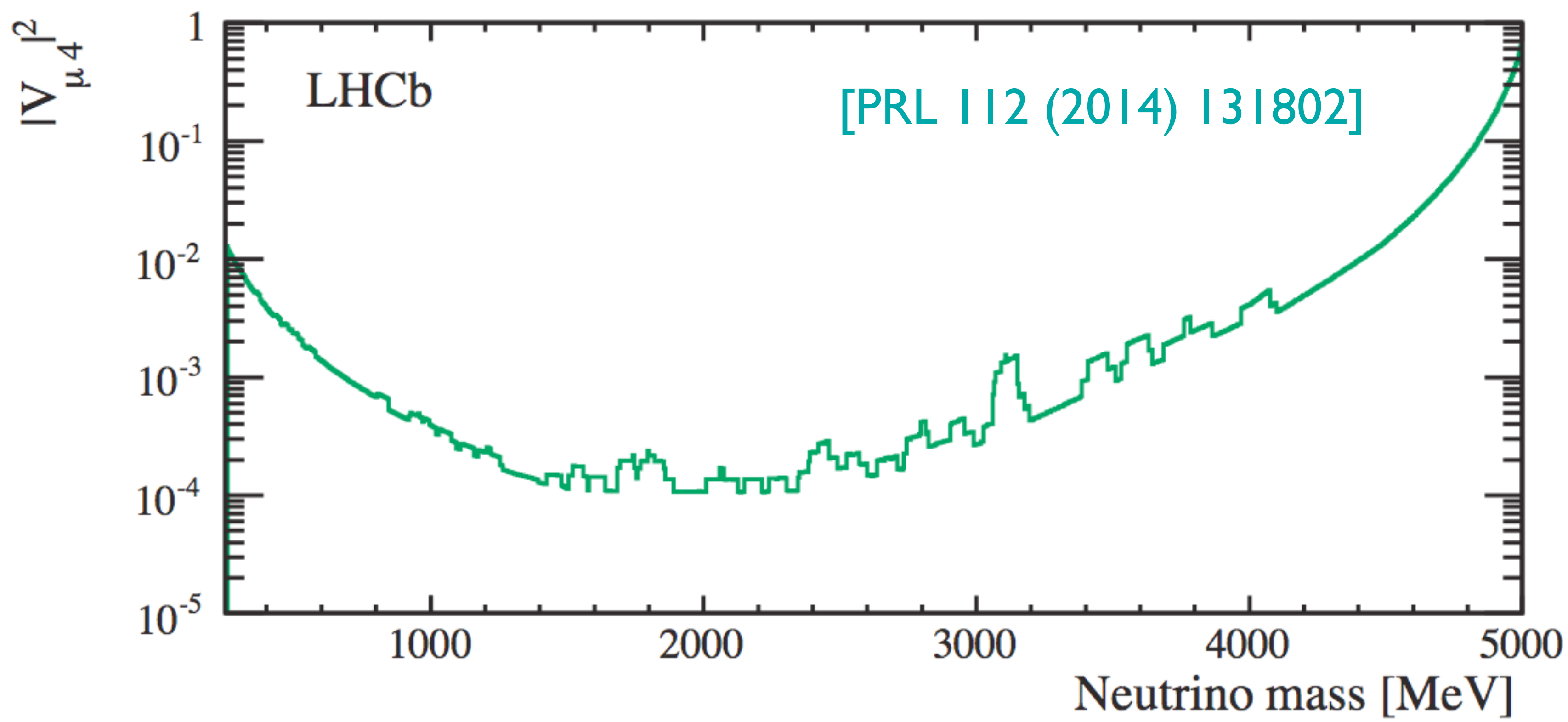
- BR upper limits as a function of mass and lifetime in [1-1000]ps



[PRL 112 (2014) 131802]

Search for Majorana neutrinos

- Limit on BR($B^- \to \pi^+\mu^-\mu^-$) from $3fb^{-1}$ can be translated (with a model-dependent assumption on the decay width) to an upper limit on the coupling between muon and fourth generation neutrino



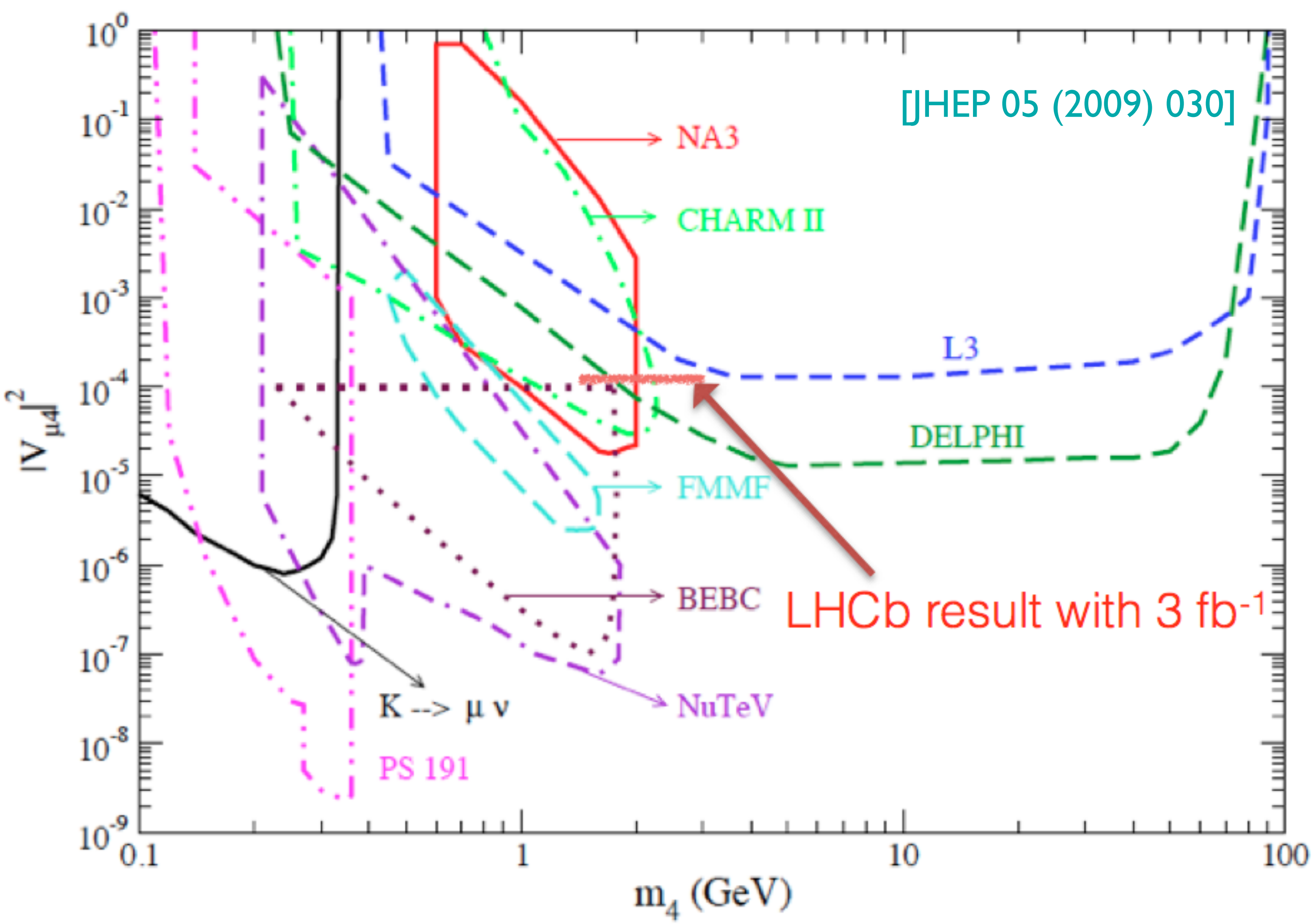
$$\mathcal{B}(B^- \to \pi^+\mu^-\mu^-) = \frac{G_F^4 f_B^2 f_\pi^2 m_B^5}{128\pi^2\hbar}|V_{ub}V_{ud}|^2\tau_B \left(1 - \frac{m_N^2}{m_B^2}\right)\frac{m_N}{\Gamma_N}|V_{\mu 4}|^4,$$

where: $\Gamma_N = [3.95 m_N^3 + 2.00 m_N^5 (1.44 m_N^3 + 1.14)]\, 10^{-13}|V_{\mu 4}|^2,$

decay width from
Atre et al. JHEP 05 (2009) 030
+ S. Stone, Z. Xing '13

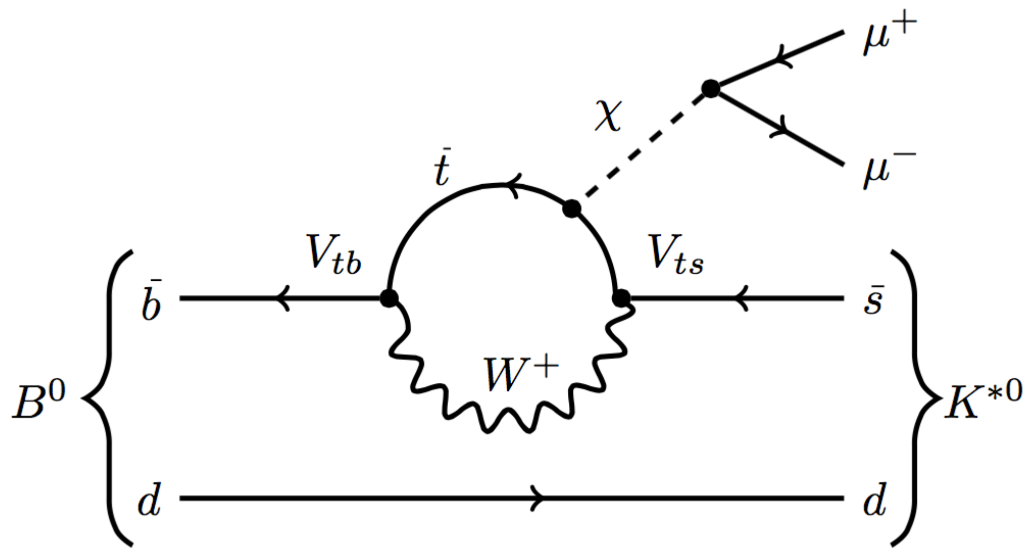
Search for Majorana neutrinos - implications

- With this result LHC join the search for Heavy Neutral Leptons performed all around the world, both at colliders and fixed target experiments.

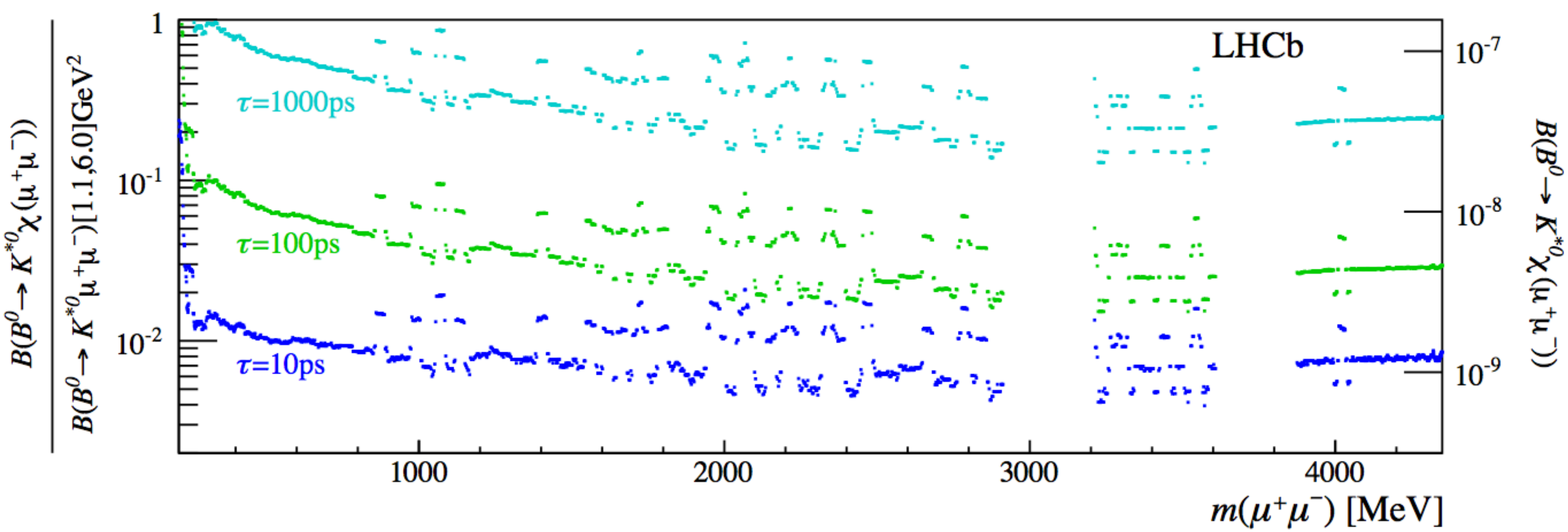


Given have to mix-in and mix-out,and are affected by lifetime also, limit on coupling improves very slowly with branching fraction probed

Search for hidden-sector bosons in $B^0 \to K^{*0}\mu^+\mu^-$



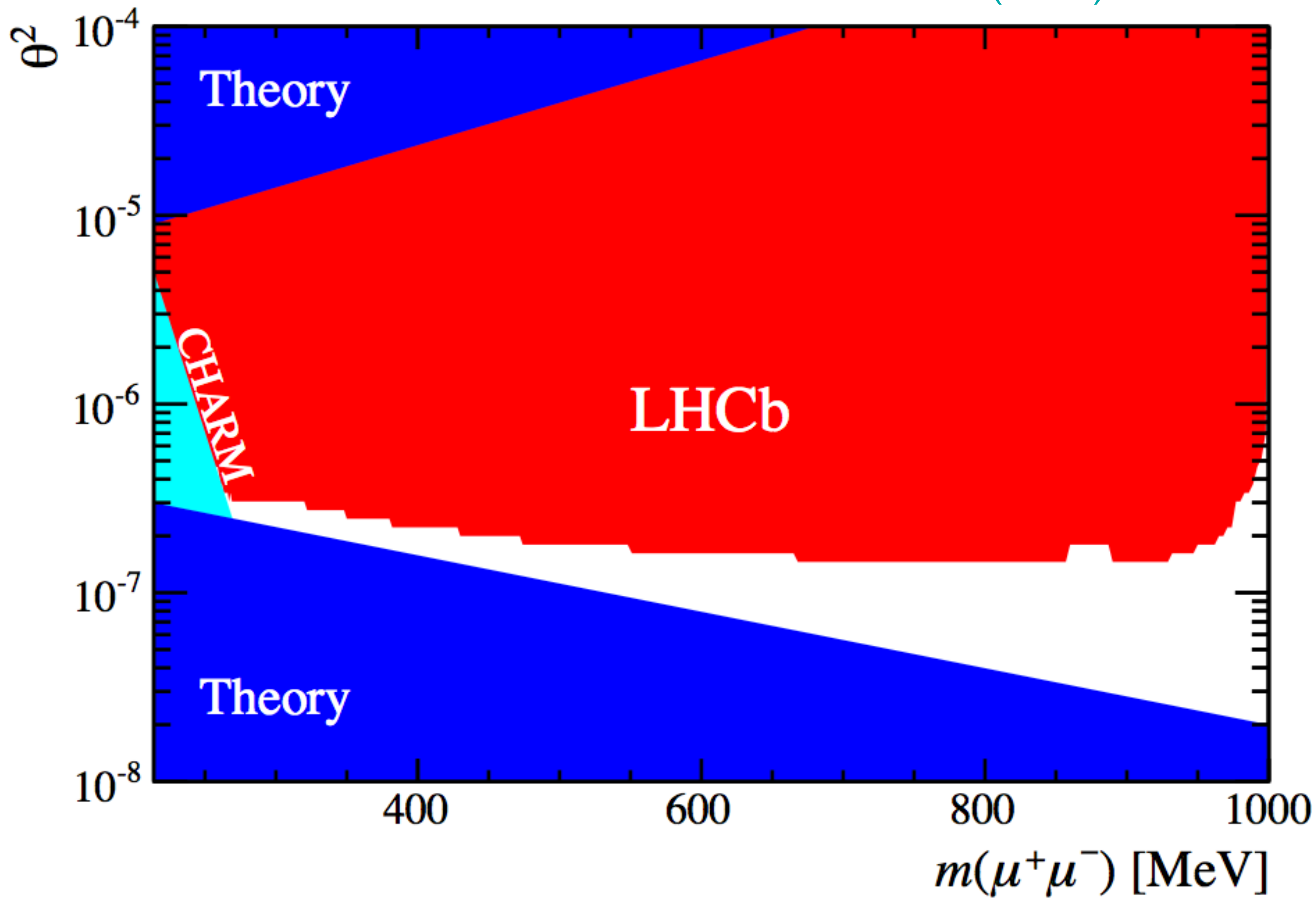
PRL 115 (2015) 161802



Search for hidden-sector bosons in $B^0 \to K^{*0}\mu^+\mu^-$

PRL 115 (2015) 161802

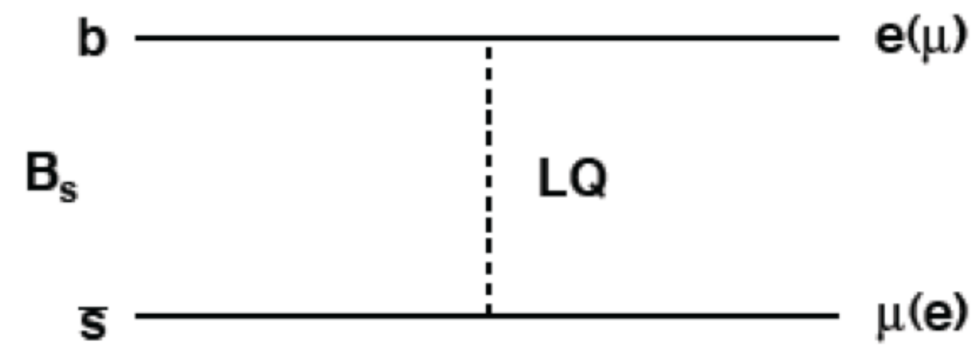
θ is the mixing angle between the Higgs and the inflation fields



Exclusion regions at 95% CL on the inflaton model of PLB 736 (2014) 494 (Bezrukov and Gorbunov): the regions excluded by the theory and by the CHARM experiment [PLB 157 (1985) 458] are also shown.

Search for lepton flavour violation in $B_{(s)} \to \mu e$

• Decays of the type $B_{(s)} \to \mu e$ are allowed in models with a local gauge symmetry between quarks and leptons, with lepto-quark linking different quark/lepton generations



[Pati, Salam PRD 10 (1974) 275]

[Valencia, Willenbrock arXiv:hep-ph/9409201v1]

• With **1 fb^{-1}** LHCb has put limits x20 more stingent than the previous best limits set by CDF

$BR(B^0_s \to \mu e) < 1.1 \times 10^{-8}$ at 90% CL

$BR(B^0 \to \mu e) < 2.8 \times 10^{-9}$ at 90% CL

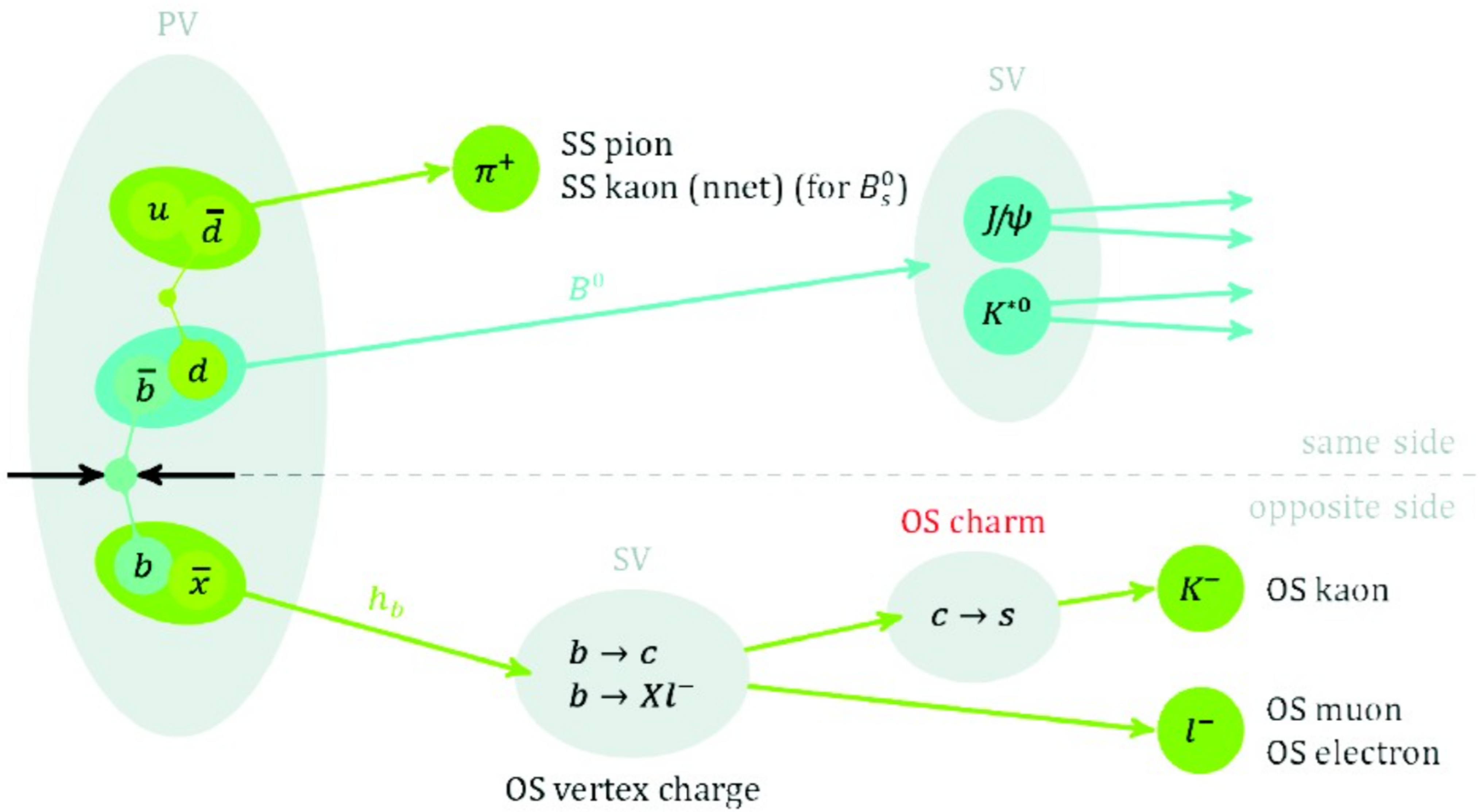
[PRL 111 (2013) 141801]

• These limits can be translated into limits on the value of the lepto-quark mass in the framework of the Pati-Salam model:

$m_{LQ}(B_s \to \mu e) > 101$ TeV/c^2 at 95% CL

$m_{LQ}(B \to \mu e) > 126$ TeV/c^2 at 95% CL

Tagging



- OS tagging obtained similarly to B Factories, however
- no correlation between the evolution of the two B hadrons => intrinsic dilution => intrinsically small effective tagging efficiency

Projections

Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\mathrm{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s$ ($B_s^0 \to J/\psi\ \phi$)	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s$ ($B_s^0 \to J/\psi\ f_0(980)$)	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\rm fs}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\rm eff}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\rm eff}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\, A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %	~ 10 %
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	γ ($B \to D^{(*)}K^{(*)}$)	~ 10–12° [19, 20]	4°	0.9°	negligible
	γ ($B_s^0 \to D_s K$)	–	11°	2.0°	negligible
	β ($B^0 \to J/\psi\, K_S^0$)	0.8° [18]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–

2012: LHCb Upgrade Framework TDR
http://cdsweb.cern.ch/record/1443882/files/LHCB-TDR-012.pdf