Search for physics beyond the standard model with rare decays at LHCb

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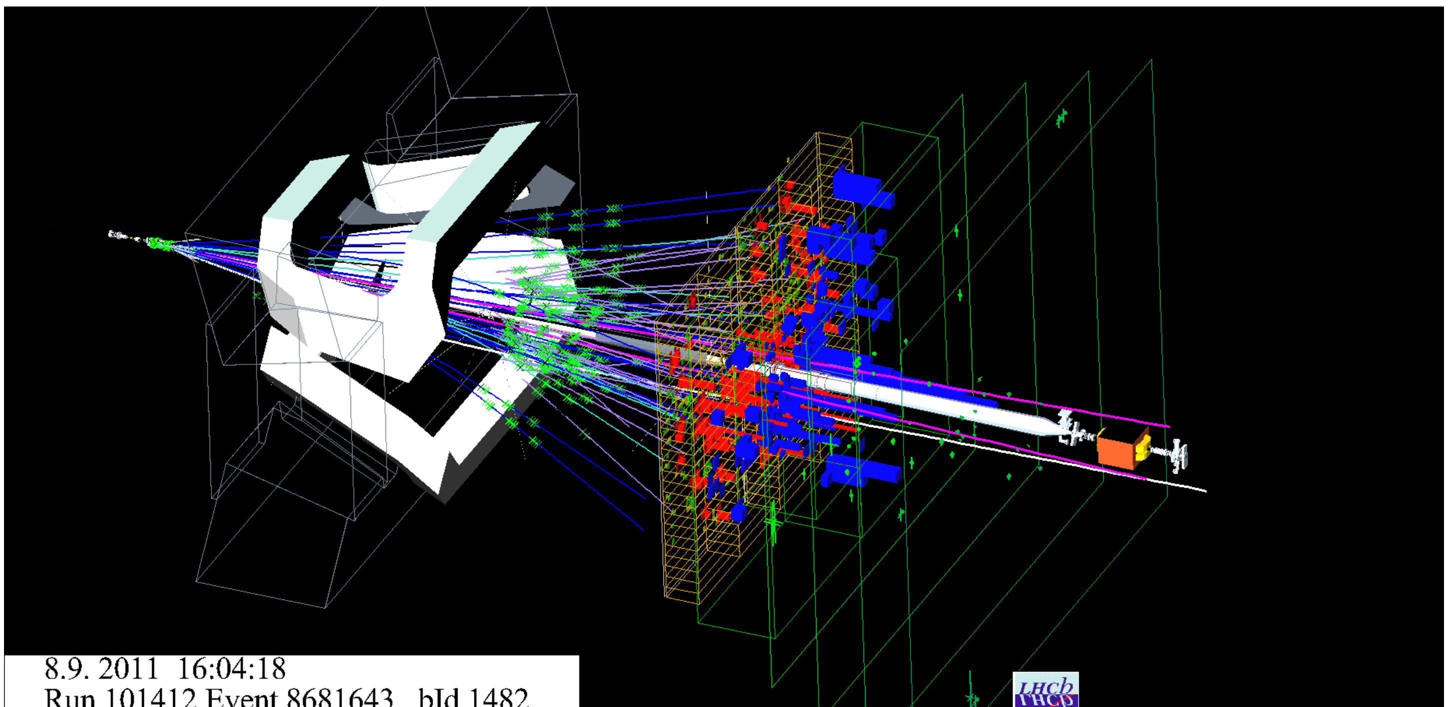


IPHC January 15th 2015

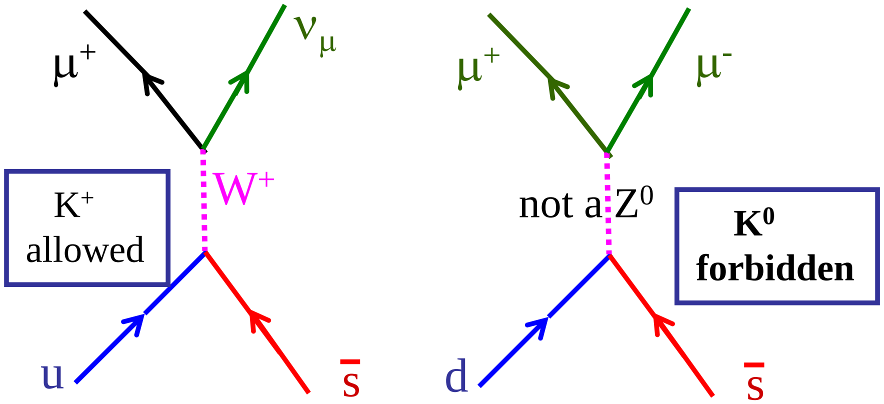
Outline

- Some historical facts about flavour physics
- LHCb
- How to look for new physics with rare decays
- Results
  - Test of lepton universality
  - Lepton flavor violation
  - Flavour changing neutral currents
- Prospects & summary

Some historical facts about flavour physics

In the past, flavour physics lead to several «indirect» discoveries:

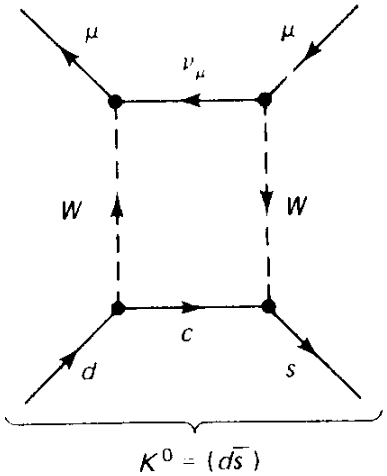
- 1970: Kaon semileptonic branching fractions



$$\frac{BR(K^0 \to \mu^+\mu^-)}{BR(K^+ \to \mu^+\nu_\mu)} = \frac{7\times10^{-9}}{0.64} \approx 10^{-8}$$

Glashow, Iliopoulos, Maiani (GIM) proposed a solution
$\Rightarrow$ No flavor changing neutral current (FCNC)
$\Rightarrow$ FCNC are suppressed by loop diagrams
$\Rightarrow$ charm quark prediction

Observed in 1973



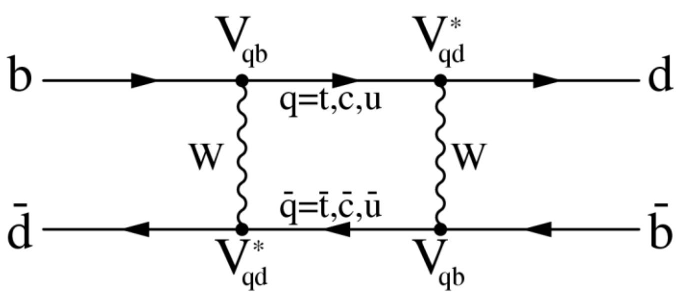
Some historical facts about flavour physics

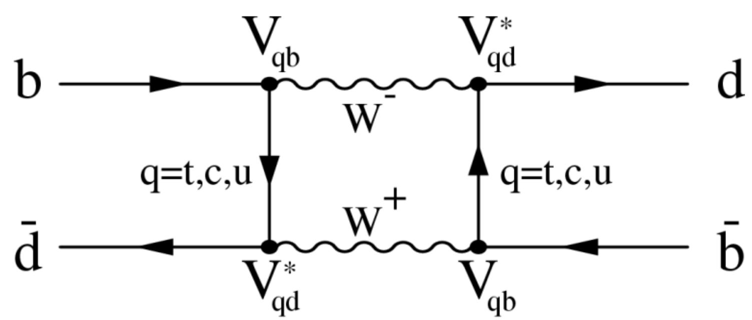
In the past, flavour physics lead to several «indirect» discoveries:

- 1964: observation of CP violation in kaons. In 1973 Kobayashi and Maskawa show that this can be explained if there are 3 generations

  $\Rightarrow$ prediction of the third family, directly observed in 1977

- 1987: B meson mixing





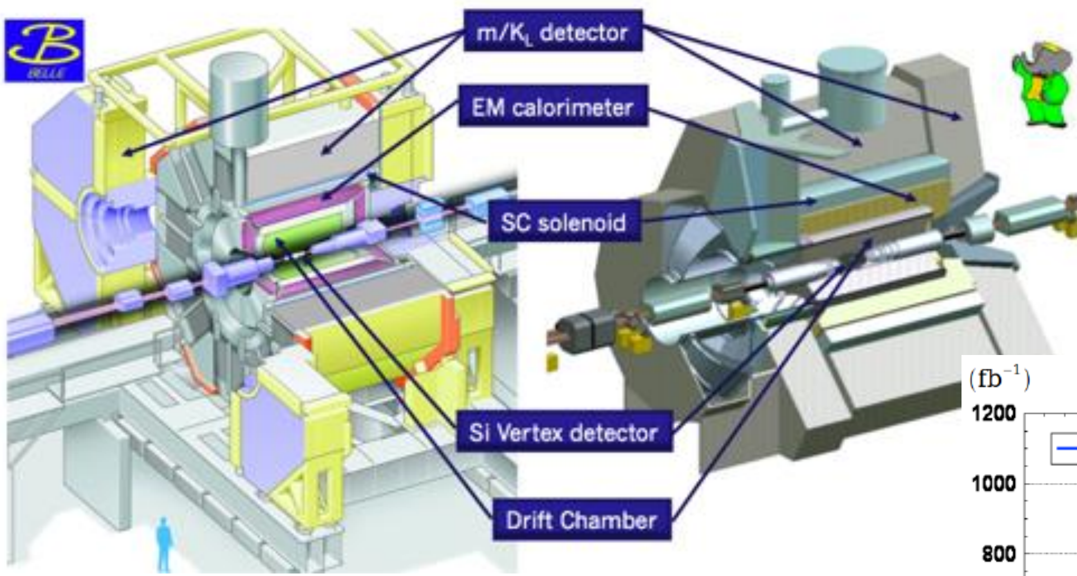
Argus measured

$$\Delta m_B \approx 0.00002 \cdot \left(\frac{m_t}{\mathrm{GeV}/c^2} \right)^2 \mathrm{ps}^{-1}$$
$$\approx 0.5\mathrm{ps}^{-1}$$

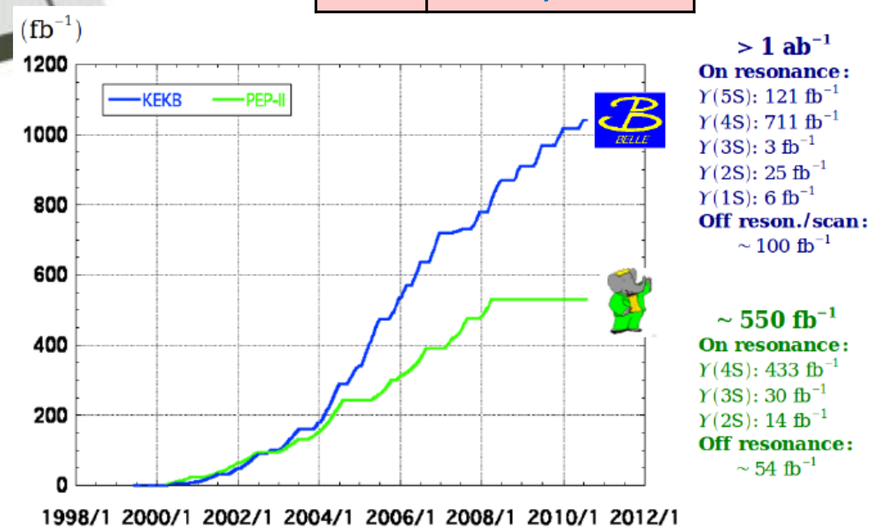
First hint of high quark top mass, discovered in 1995

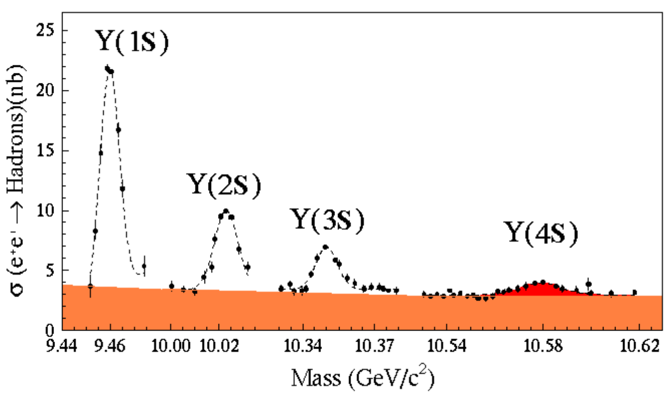
Some historical facts about flavour physics

- 2000-2010 : B mesons extensively studied by the B factories



$e^+e^- \to$	Cross section (nb)
uu	1,39
dd	0,35
ss	0,35
cc	**1,30**
bb	**1,10**

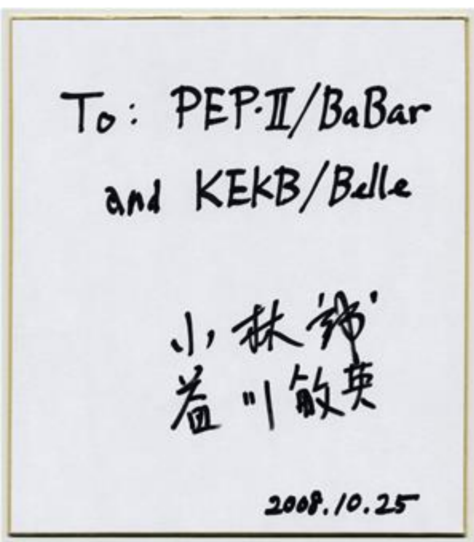




771M + 463M bb pairs accumulated

Only B_d and B_u produced, but very clean events

B factories produced a lot of results (~1000 publications), and a Nobel prize!



The Nobel Prize in Physics 2008

Photo: University of Chicago

Yoichiro Nambu

Prize share: 1/2

© The Nobel Foundation
Photo: U. Montan

Makoto Kobayashi

Prize share: 1/4

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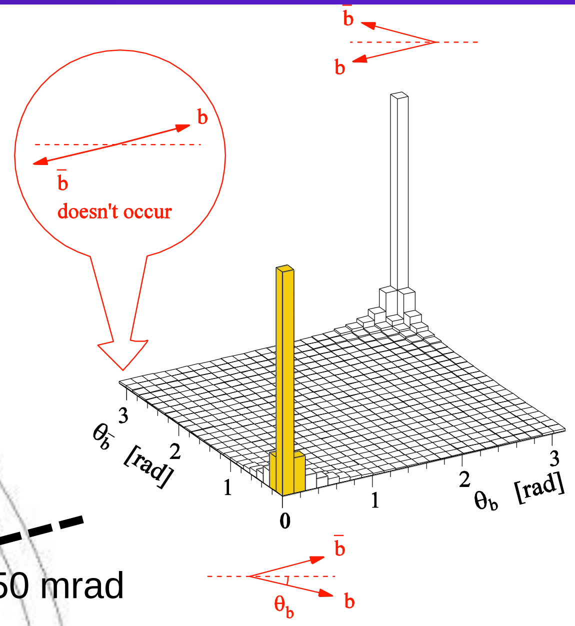
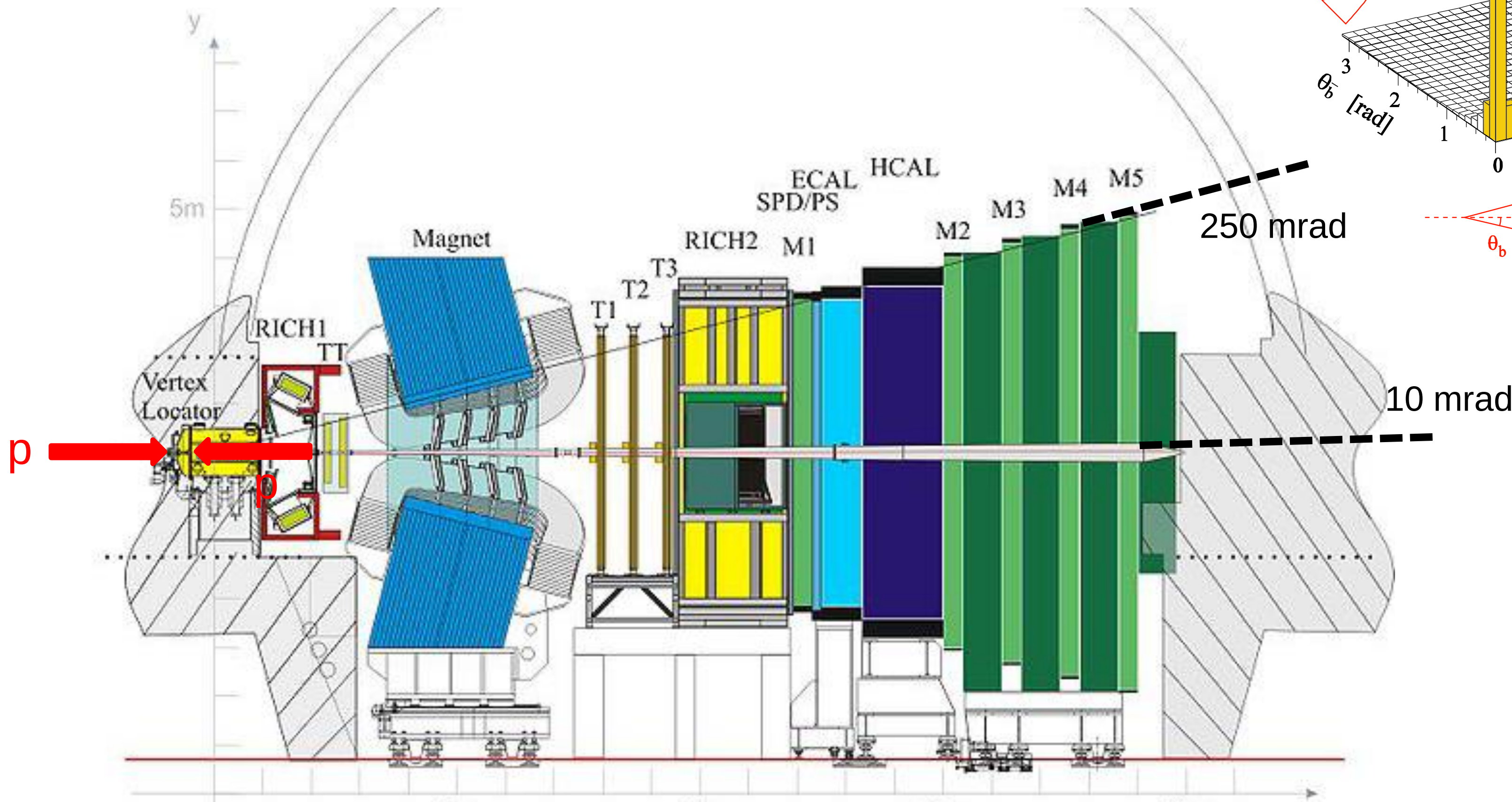
Toshihide Maskawa

Prize share: 1/4

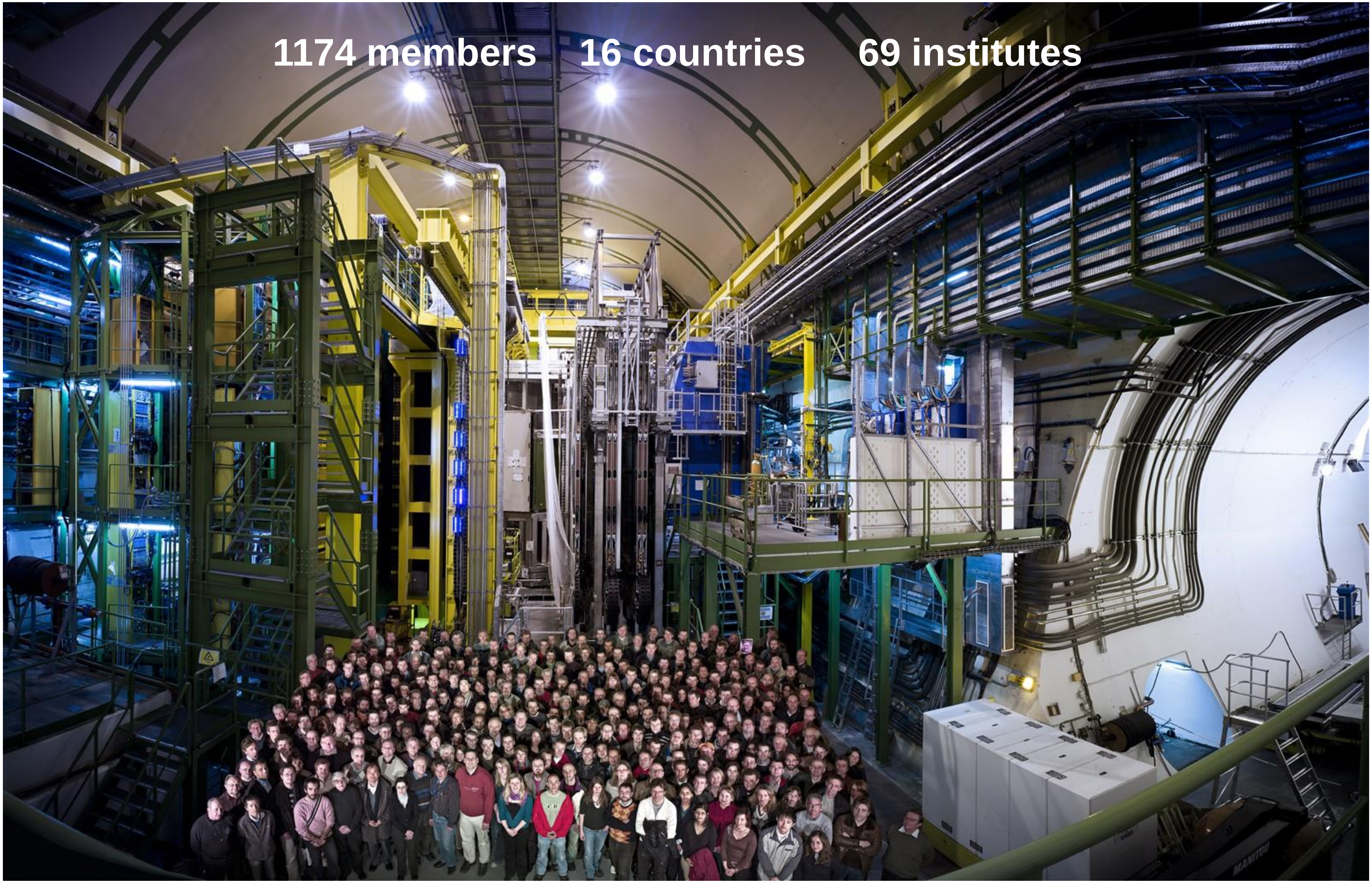
The Nobel Prize in Physics 2008 was divided, one half awarded to Yoichiro Nambu *"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"*, the other half jointly to Makoto Kobayashi and Toshihide Maskawa *"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"*.

- Forward spectrometer optimised for heavy flavour physics at the LHC
  - Large acceptance 2<η<5
  - Large boost : B mesons flight ~1cm





The LHCb Collaboration

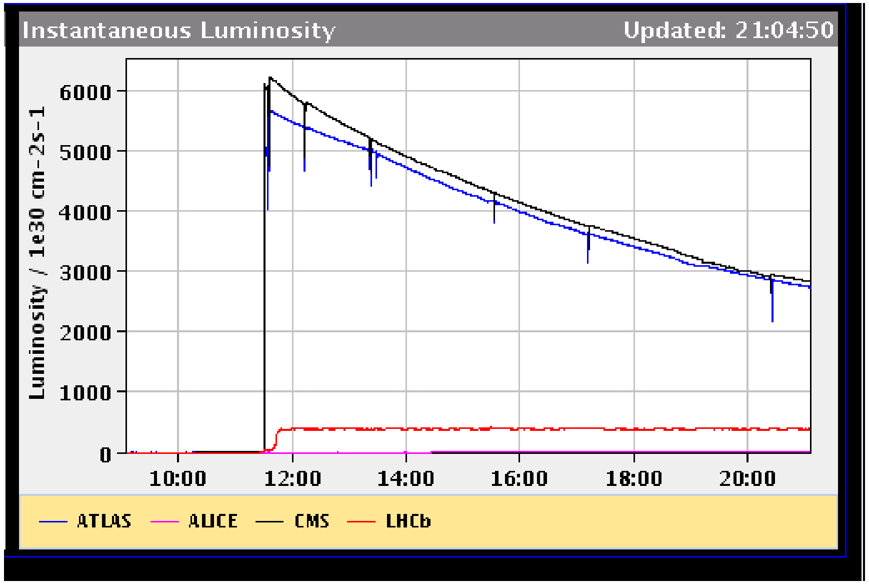


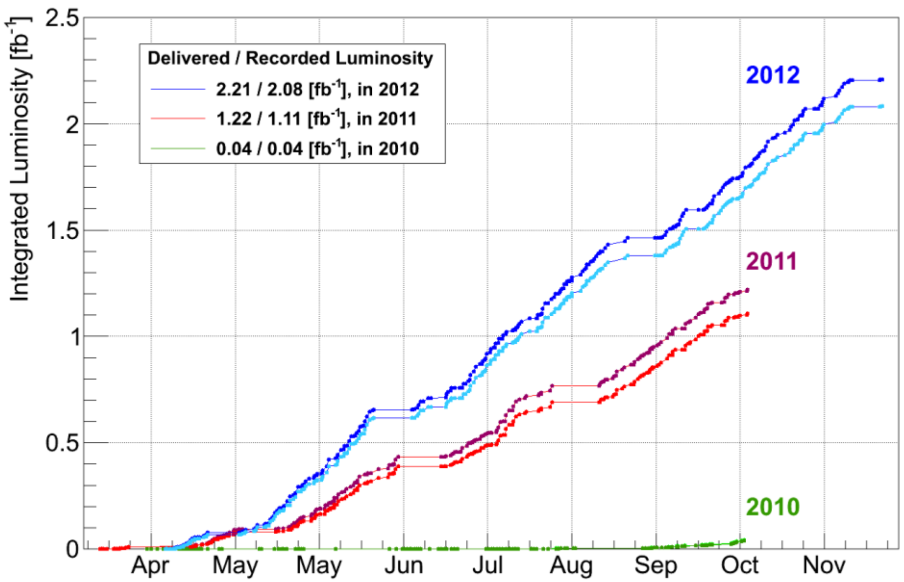
- Running at a constant luminosity of 4.10^{32} cm^{-2} s^{-1} thanks to the luminosity leveling

  This is twice the design luminosity!

- Number of interactions per bunch crossing: ~1.5

  This is four times more than design!



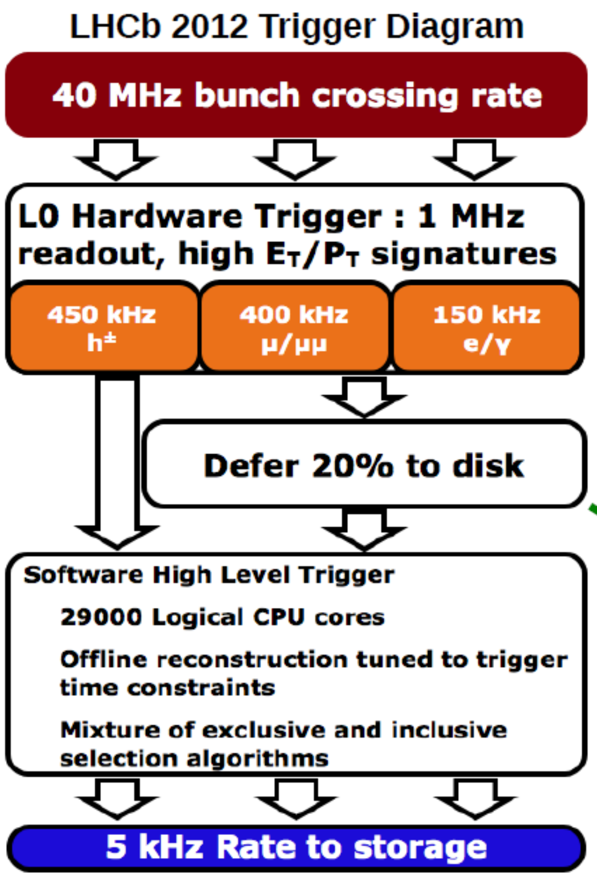


- Integrated luminosity of 3 fb^{-1} during Run 1, corresponds to ~300 billions of bb pairs produced in LHCb
- Recorded 0.32 fb^{-1} in 2015 (13TeV)
- The main consequence of the LHC higher energy is an increased bb cross section

LHCb trigger

pp→	Cross section at 14TeV (mb)
Inelastic	80
cc	3.5
bb	0.5

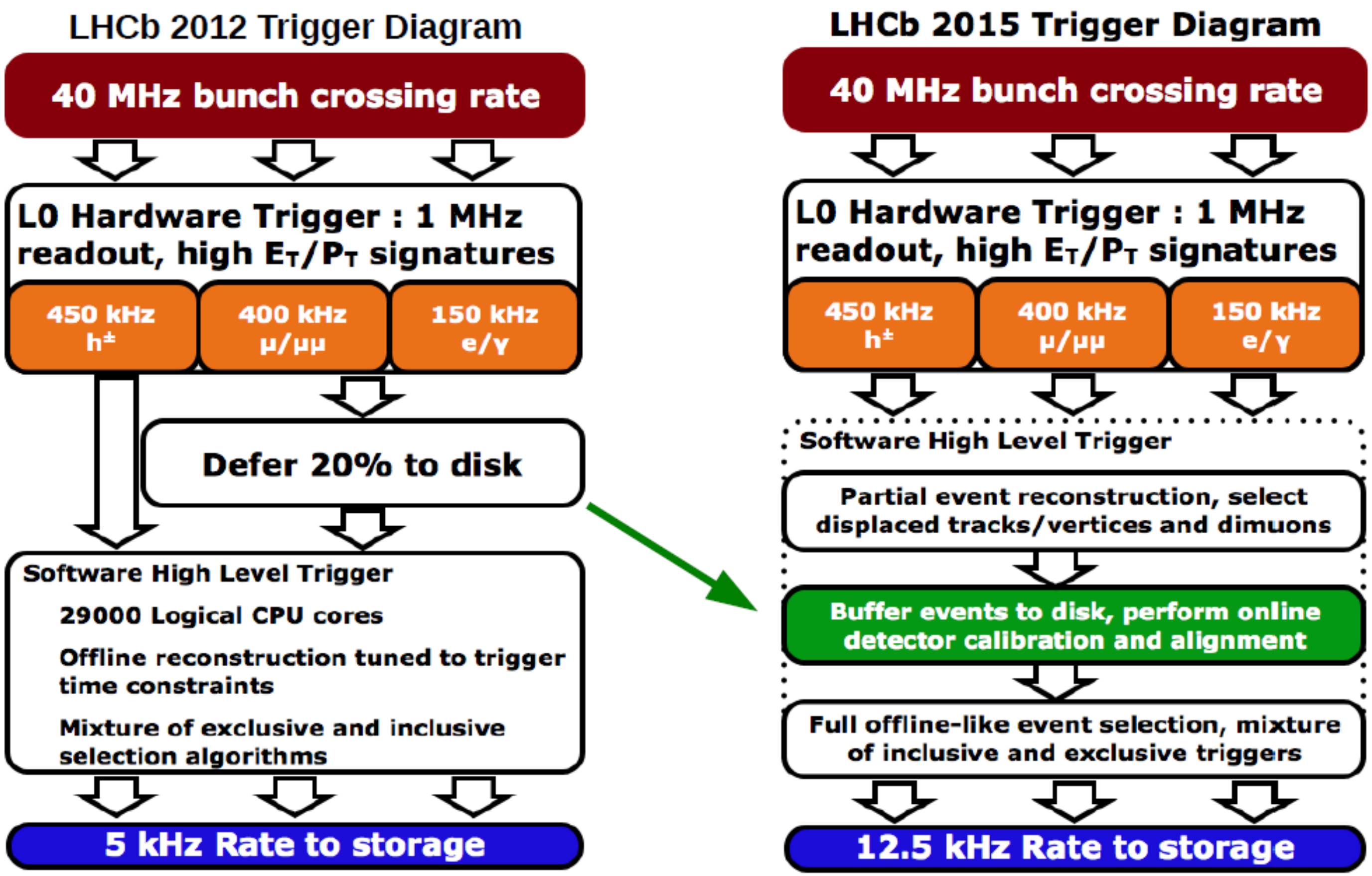
- A trigger is needed to select only interesting events and maintain manageable data rates
- Handles high p_T signals and displaced vertices



Due to technical stops and gaps between LHC fills, software trigger runs 20% of time
→ in 2012, introduced a deferral that temporarily store ~20% of the L0 triggered events and process them after the fill

LHCb trigger

- 2015 goal: have online trigger selection as close as possible to offline



- Allow to boost physics reach for channels that were limited at trigger level (prescaled) : efficiency of $B^+ \rightarrow D^0\pi$ passed from 75% to > 90%
- Enable lifetime unbiased trigger for hadronic final states

LHCb versus B factories

	B factories	LHCb
Statistics	☹	☺
Cleanness	☺	☹
heavy flavour hadrons produced	B^+, B^0, dedicated run for B_s, charm	B^+, B^0, B_s, B_c, baryons, and lot of charm
neutrino modes	☺	☹
Trigger bias	☺	☹

(This is a very simplistic table)

Some measurements can only be done by B factories OR LHCb
$\Rightarrow$ necessary to have both!
Cross-check and competition for common measurements

Search for new physics with flavour

- NP contribution can be expressed as a perturbation to the SM lagrangian

$$\boxed{\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{c_{NP}}{\Lambda^2}}$$

NP coupling

NP scale

- If NP particles are discovered at the LHC, we are able to study the flavour structure of the NP

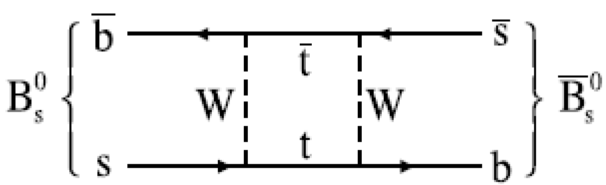
- Flavour physics can probe very high energy scale (even beyond the LHC reach)

- Considering the present experimental constraints in flavour physics:
  - if C=1, $\Lambda \sim O(100\text{TeV})$
  - If $\Lambda \sim 1\text{TeV}$ (quantum stabilization of electroweak scale), $C \sim O(10^{-7})$

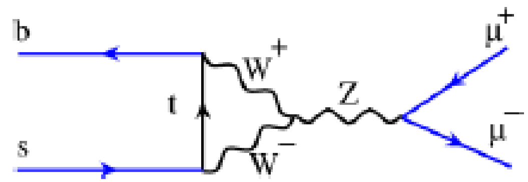
- Sensitivity to new physics through virtual particles that can appear in loop diagrams
- Method: measure observables precisely predicted in the SM

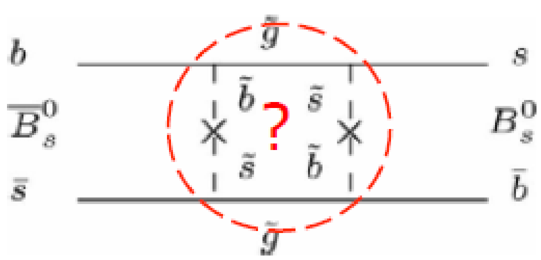
Mixing, CP violation

Rare decays

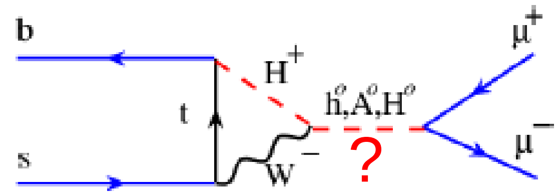


MS





NP



Which rare decays ?

- Different type of decays give access to different observables sensitive to different new physics contributions
- The correlations between the observables allows to identify the type of new physics involved $\Rightarrow$ important to measure all possible observables
- The usual suspects:

Lepton universality test

Lepton flavor violation

$B_{s/d} \to \mu^+\mu^-$

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

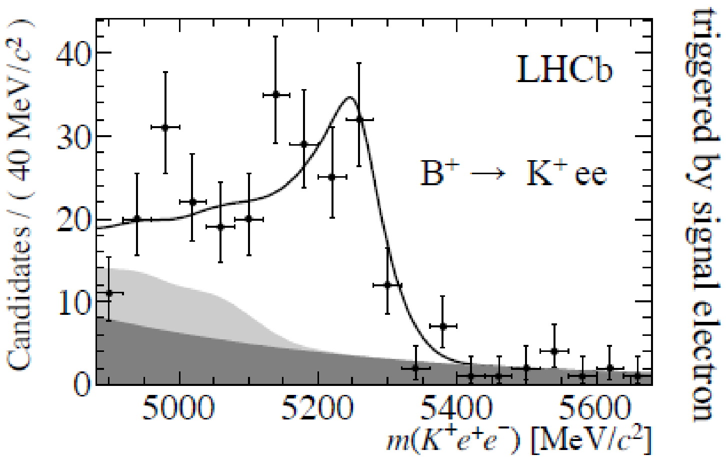
Other FCNCs

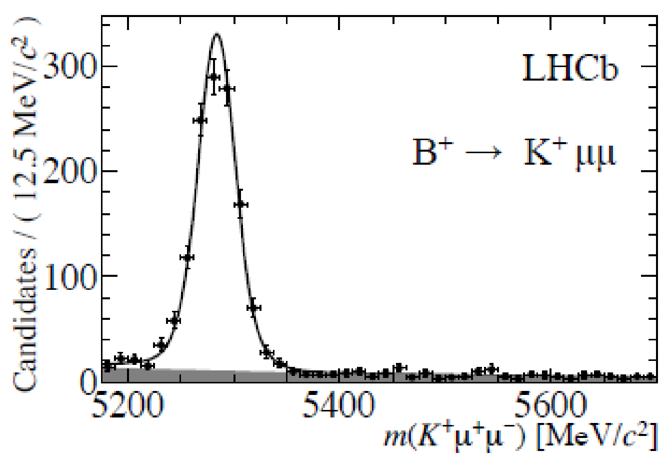
Test of lepton universality

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

- In the SM R_K is predicted to be 1, but this could change in presence of new scalar or pseudo scalar interaction (e.g. Z' with different coupling to e and μ)
- Measured using double ratio to minimize uncertainties

$$R_K = \left(\frac{N_{K^+\mu^+\mu^-}}{N_{K^+e^+e^-}}\right)\left(\frac{N_{J/\psi(e^+e^-)K^+}}{N_{J/\psi(\mu^+\mu^-)K^+}}\right)\left(\frac{\epsilon_{K^+e^+e^-}}{\epsilon_{K^+\mu^+\mu^-}}\right)\left(\frac{\epsilon_{J/\psi(\mu^+\mu^-)K^+}}{\epsilon_{J/\psi(e^+e^-)K^+}}\right)$$



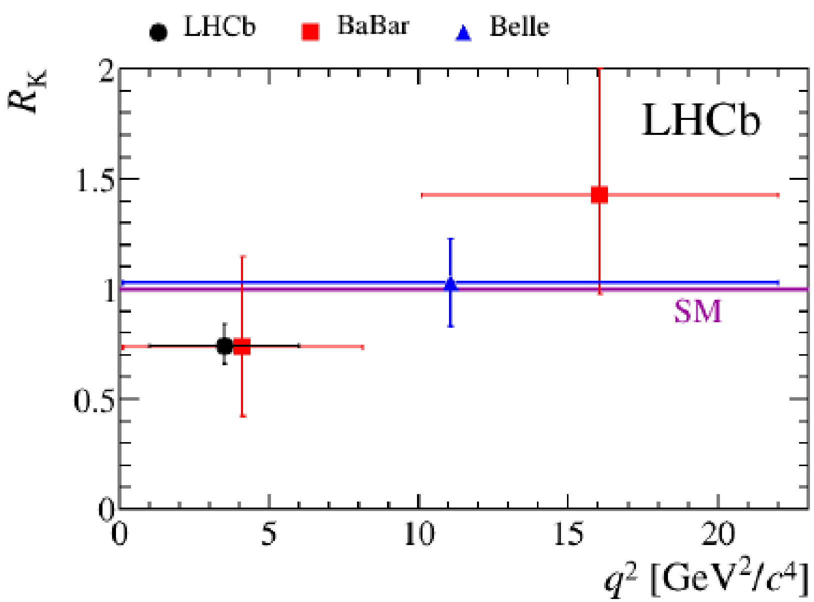


Test of lepton universality: R_K

PRL 113 (2014) 151601

LHCb measurement using 3fb^{-1} in region $1<q^2< 6$ GeV^2/c^4 (broad charmonium resonances may affect the high q^2 region)

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



$$q^2 = m(ll)^2$$

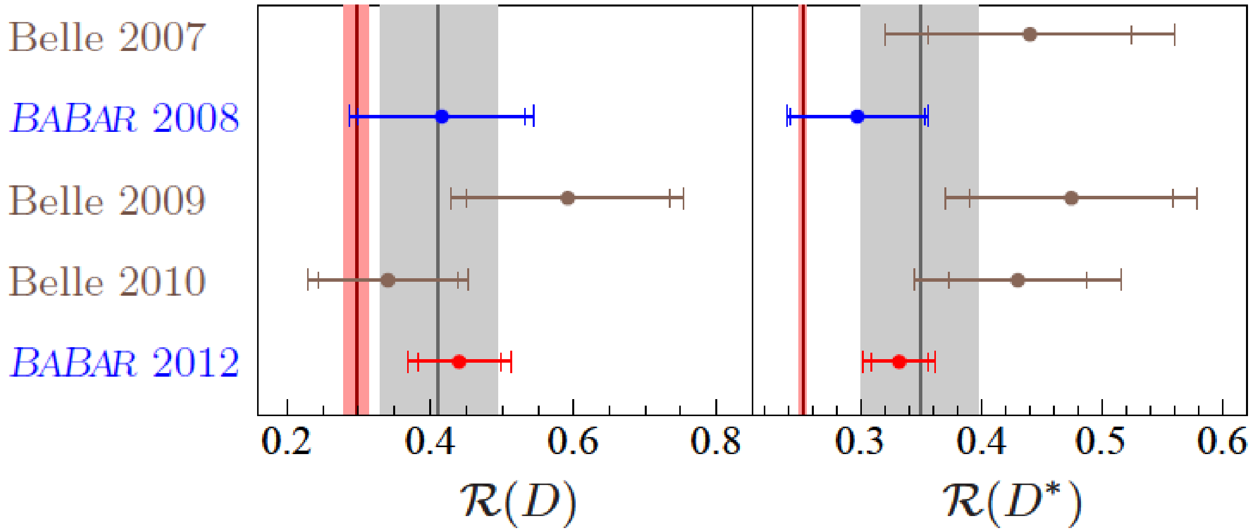
- 2.6 σ from SM
- electron mode is in agreement with SM ⇒ deficit of muon mode

Test of lepton universality: R(D*)

$$R(D^*) = \frac{B(B^0 \to D^{*+}\tau^-\upsilon)}{B(B^0 \to D^{*+}\mu^-\upsilon)}$$

- Lepton universality → expect similar branching ratio, except for phase space and helicity suppression
- Precise SM prediction : R(D*)=0.252 ± 0.003 (PRD 85 (2012) 094025)

- Some tension found in the past by Babar and Belle



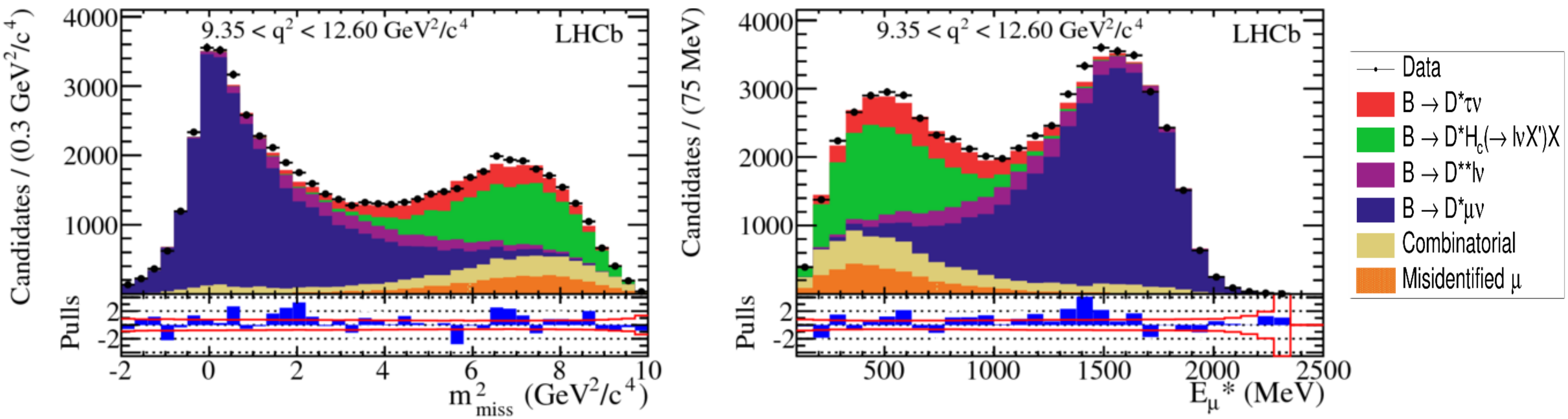
Test of lepton universality: R(D*)

- LHCb perform the first measurement of R(D*) at a hadronic collider, using $\tau \to \mu\nu\nu$: same final state for signal and normalization

- Exploit distinct kinematic in signal and normalization decay (3 neutrinos vs 1)

- Use isolation criteria to reject background ($B \to D^{**}\mu\nu$) with additional charged tracks

- Separate signal from background fitting $m_{miss}^2 = (p_B - p_{D^*} - p_\mu)^2$, $q^2=(p_B - p_{D^*})$ and E_μ. Fit result in the most sensitive q^2 bin:



Test of lepton universality: R(D*)

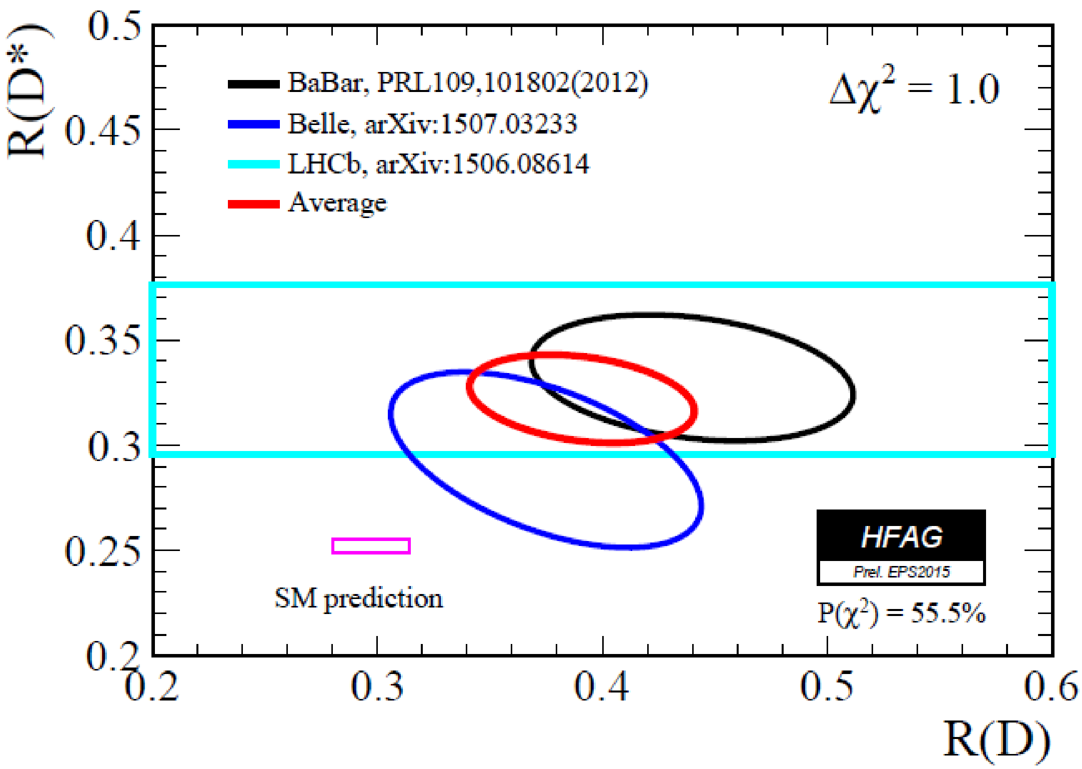
PRL 115, 111803 (2015)

- Result using 3 fb^{-1}: $R(D^*) = 0.336 \pm 0.027(stat) \pm 0.030(syst)$

2.1σ higher than SM prediction, confirming the tension

- Systematic dominated by the size of MC sample (so reducible)

Average of R(D) and R(D*) is 3.9σ away from SM



Prospects for test of lepton universality

- Expand physics program to more modes with electrons and taus
- Not only R_K = (B → Kee/B →Kμμ) but similar ratios with different hadronic systems (K*, φ, Λ,…)
- Not only D* $\tau\nu$ but also D$\tau\nu$, D_s $\tau\nu$, Λ_c $\tau\nu$, …
- Use tau hadronic decay: different background (B →D*DX..) but allow to reconstruct the tau decay vertex
- And also e/μ channel (as suggested by R_K) :

$$\mathcal{R}(\mathrm{D})^{\mathrm{Beauty}}_{\mu,e} = \frac{\mathcal{B}(\mathrm{B}^+ \to \overline{\mathrm{D}}{}^0 \mu^+ \nu_\mu)}{\mathcal{B}(\mathrm{B}^+ \to \overline{\mathrm{D}}{}^0 \mathrm{e}^+ \nu_\mathrm{e})}, \mathcal{R}(\mathrm{D})^{\mathrm{Charm}}_{\mu,e} = \frac{\mathcal{B}(\mathrm{D}^0 \to \mathrm{K}^- \mu^+ \nu_\mu)}{\mathcal{B}(\mathrm{D}^0 \to \mathrm{K}^- \mathrm{e}^+ \nu_e)}$$

(charged) Lepton Flavour Violation

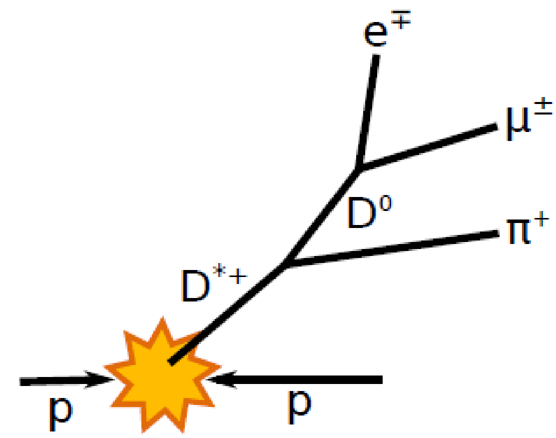
$D^0 \to e\mu$

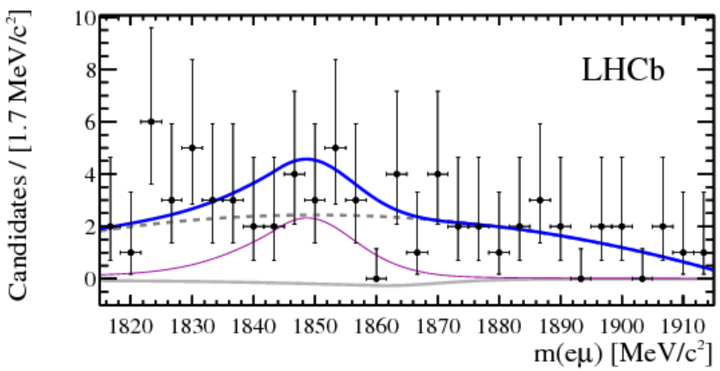
- Forbidden in the SM, contributions from neutrino oscillations well below experimental reach
- In presence of NP, predictions vary by 8 order of magnitude depending on the model
- Limits on $D^+ \to \pi e\mu$ and $D_s \to K e\mu$ suggest $B(D^0 \to e\mu) < 10^{-7} – 10^{-8}$ (Chin. Phys. C38 (2014) 123101, Int. J. Mod. Phys. A29 (2014) 1450169, arXiv:1510.00311)
- Previous world best limit by Belle $B(D^0 \to e\mu) < 2.6 \times 10^{-7}$ at 90%CL

$D^0 \to e\mu$

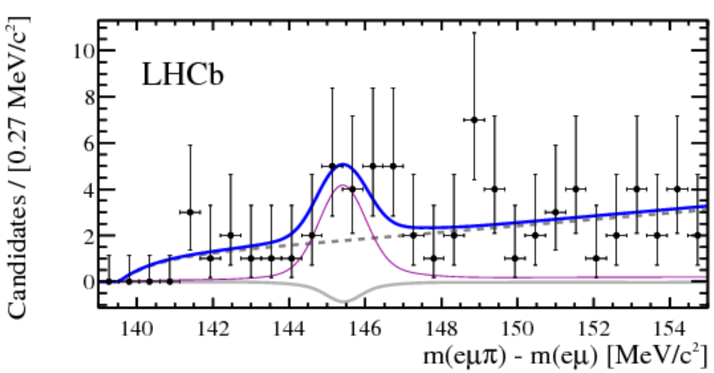
arXiv 1512.00322

- Select D^0 from $D^{*+} \to D^0 \pi^+$ decays
- Separate signal from background with a BDT based on geometric and isolation variables
- Fit simultaneously $m(D^0)$ and $\Delta m = m(D^{*+})-m(D^0)$ in 3 bins of BDT





Total
$D^0 \to \pi\pi$ bkg
signal



Upper limit set from the CLs method using $D^0 \to K\pi$ as normalization channel

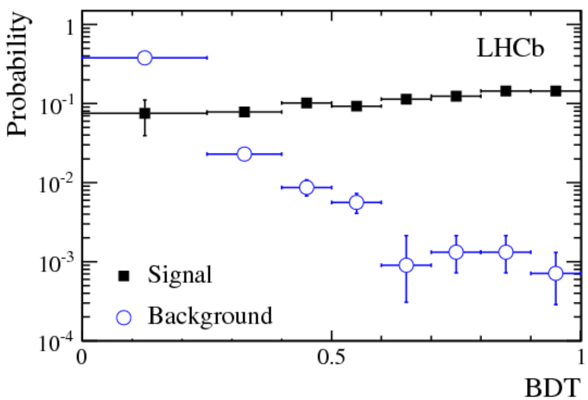
$$\mathcal{B}(D^0 \to e^{\pm}\mu^{\mp}) = \frac{N_{e\mu}/\epsilon_{e\mu}}{N_{K\pi}/\epsilon_{K\pi}} \times \mathcal{B}(D^0 \to K^-\pi^+)$$

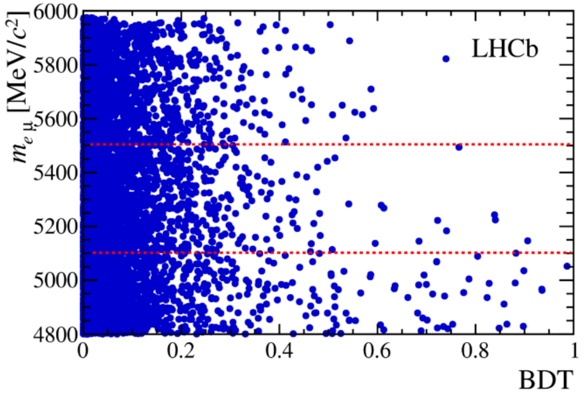
World's best limit obtained:
$B(D^0 \to e\mu) < 1.3 \times 10^{-8}$ at 90%CL

$B_{(s)} \rightarrow e\mu$

PRL 111 (2013) 141801

- Analysis performed on 1 fb^{-1} (update to 3 fb^{-1} ongoing)
  - Fit the eμ invariant mass in bins of a BDT





- New world best limits (95% CL): $B^0 \rightarrow e^{\pm}\mu^{\mp} < 3.7 \times 10^{-9}$ $B_s \rightarrow e^{\pm}\mu^{\mp} < 1.4 \times 10^{-8}$

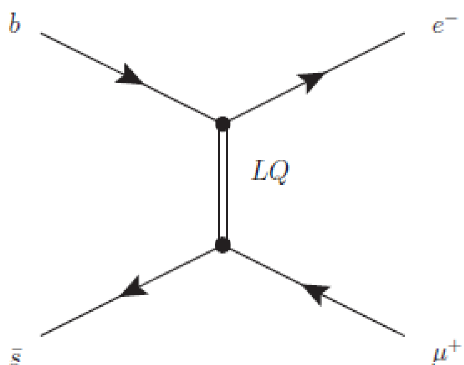
improvement by a factor ~20 with respect to previous CDF results

- Constraint on Pati-Salam leptoquark masses:

  (Improved by a factor ~2)

$m_{LQ}(B_s \rightarrow e^+\mu^-) > 107(101)\ TeV/c^2$ @ 90(95)%CL,

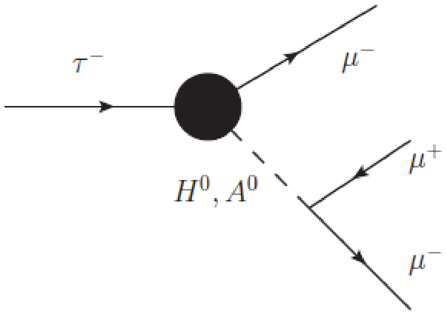
$m_{LQ}(B_d \rightarrow e^+\mu^-) > 135(126)\ TeV/c^2$ @ 90(95)%CL



τ lepton flavour and baryon number violation

- Use τ produced in decays of B and D mesons. Inclusive cross section ~85 μb at 7 TeV (mostly from the $D_s \rightarrow \tau\nu$)
- Normalization to the $D_s \rightarrow \varphi(\rightarrow \mu\mu)\pi$ channel

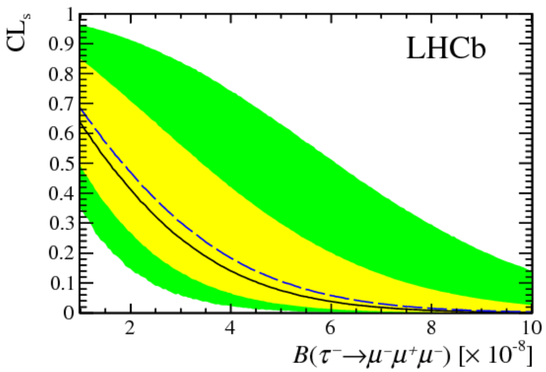
- $\tau^- \rightarrow \mu^+\mu^-\mu^-$ (3 fb^{-1})
- Current best limit from Belle at 2.1 x10^{-8}. BSM scenarios predicts BR up to 10^{-8}.
- Fit the invariant mass in bins of two classifiers (geometrical variables and PID)



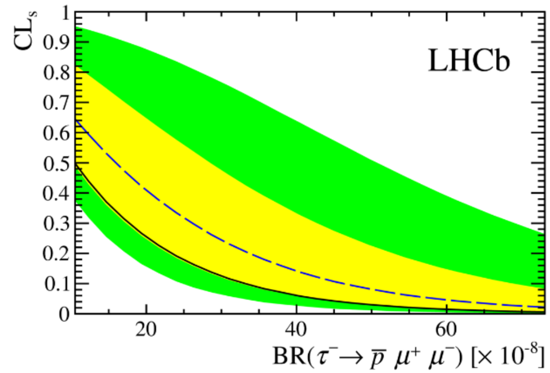
- $\tau^- \rightarrow \bar{p}\mu^-\mu^+$ and $\tau^- \rightarrow p\mu^-\mu^-$ (1 fb^{-1})
- both decays have Δ(B-L)=0, as required by SM and most of its extension
- No previous results. Limits on $\tau \rightarrow \Lambda h$ at ~10^{-7} set by Babar and Belle
- Fit the invariant mass in bins of classifiers based on geometrical variables

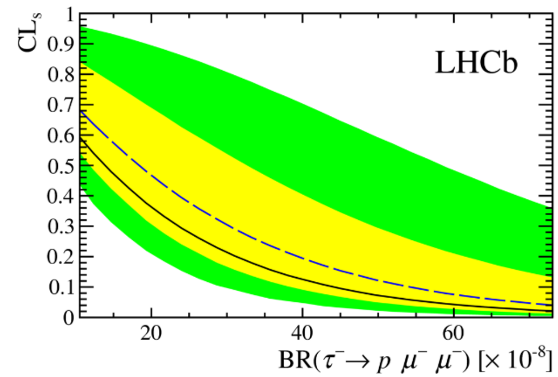
τ Lepton flavour and baryon number violation

JHEP 02 (2015) 121



PLB 724 (2013) 36

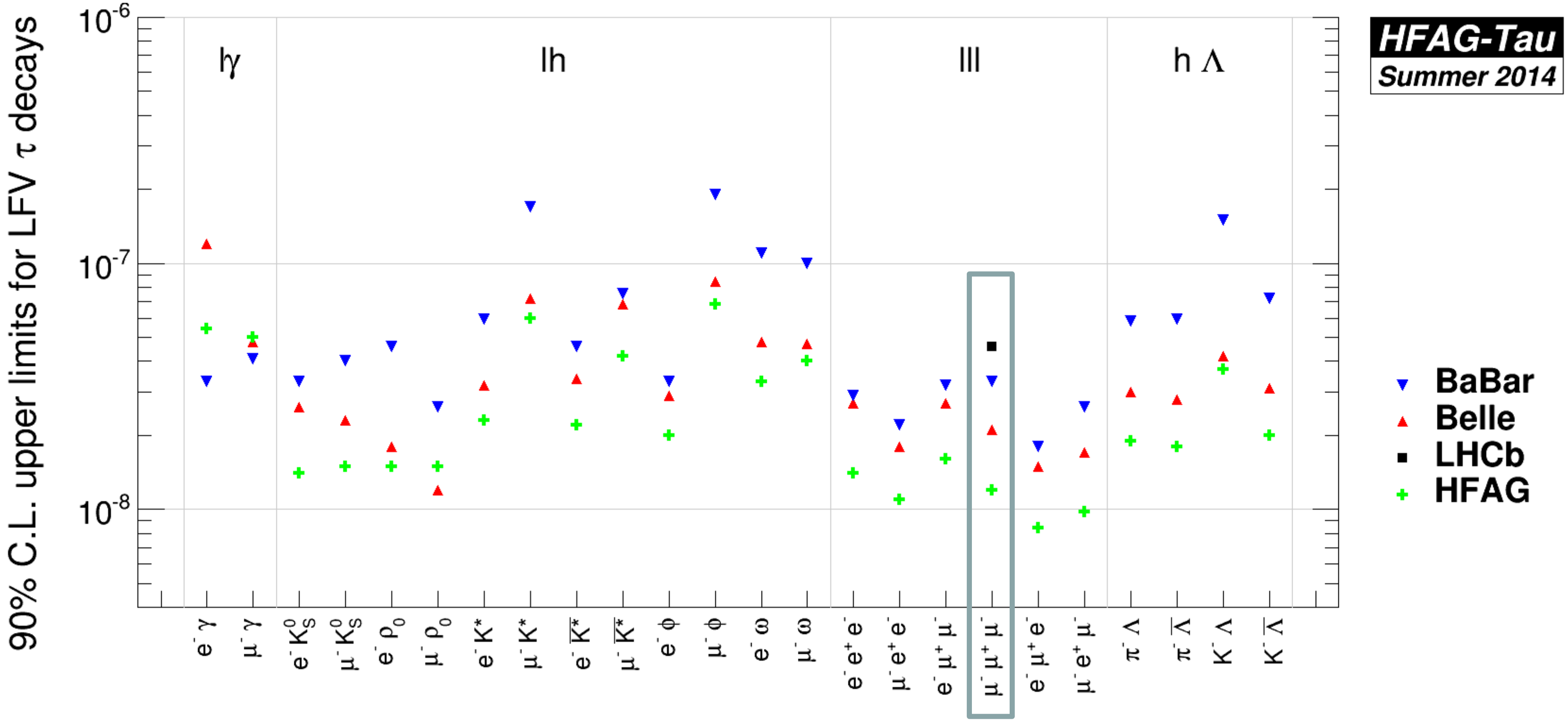




Channel	Expected (90% CL)	Observed (90% CL)
$\tau^- \to \mu^-\mu^+\mu^-$	5.0×10^{-8}	4.6×10^{-8}
$\tau^- \to \overline{p}\mu^+\mu^-$	4.6×10^{-7}	3.3×10^{-7}
$\tau^- \to p\mu^-\mu^-$	5.4×10^{-7}	4.4×10^{-7}

- First τ LFV results at a hadron collider
- $\tau^- \to \mu^+\mu^-\mu^-$ getting close to B factories sensitivity

Summary of τ LVF results

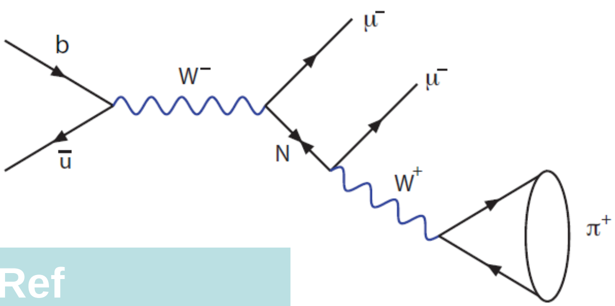


LHCb can also be competitive for channels with muons with Run 2 data

Other LFV channels studied at LHCb

- Ratio of cross section $\dfrac{\sigma(pp \to Z \to \tau\tau)}{\sigma(pp \to Z \to \mu\mu)} = 0.93 \pm 0.09$ *JHEP 01 (2013) 111*

- Searches for heavy Majorana neutrinos :
  (world best measurements)



Channel	Limit at 95%CL	Ref
$B^+ \to K^- \mu^+ \mu^+$	5.4×10^{-8}	*PRL 108 (2012) 101601*
$B^+ \to \pi^- \mu^+ \mu^+$	4.0×10^{-9}	*PRL 112 (2014) 131802*
$B^+ \to D^- \mu^+ \mu^+$	6.9×10^{-7}	*PRD 85 (2012) 112004*
$B^+ \to D^{*-} \mu^+ \mu^+$	2.4×10^{-6}	
$B^+ \to D_s^- \mu^+ \mu^+$	5.8×10^{-7}	
$B^+ \to D^0 \pi^- \mu^+ \mu^+$	1.5×10^{-6}	
$D_{(s)}^+ \to \pi^- \mu^+ \mu^+$	2.5×10^{-8} (1.4×10^{-7})	*PLB 724 (2013) 203-212*

Limits also set as function of neutrino mass and lifetime

- Other D LVF: $D_{(s)}^+ \to \pi^+ \mu^+ \mu^- < 8.3 \times 10^{-8}$ (4.8×10^{-7})

Prospect for LFV decays

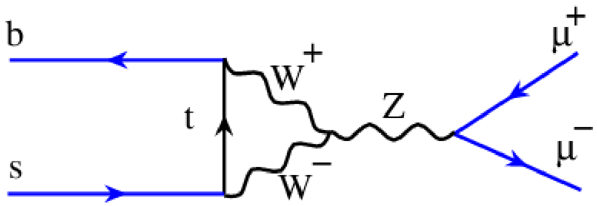
- Other B studies ongoing: $B\to \tau\mu$, $B\to he\mu$, $B\to h\tau\mu$, $B_s\to \phi e\mu$ … where $h = K,\pi$
- Search for decays of type $D_{(s)}^+\to h^+\ell\ell$ where $h = K,\pi$ and $\ell = e,\mu$ (28 channels in total)
  - $D_{(s)}^+\to h^+\ell^+\ell^-$ are suppressed in the SM
  - Others are lepton number/flavour violating

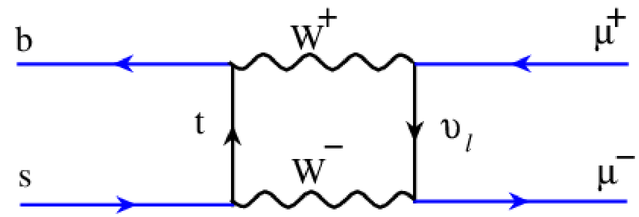
FCNC
(Flavour changing neutral current)

$B_{s/d} \rightarrow \mu^+\mu^-$

- Flavour changing neutral current and helicity suppressed decays

75%



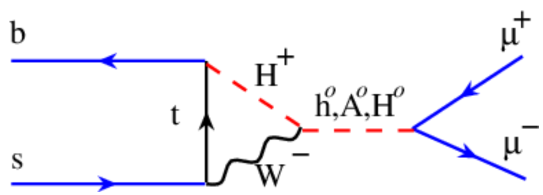


24%

- Precise SM prediction (PRL 112 (2014) 101801)
  - $BR(B_s \rightarrow \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$
  - $BR(B_d \rightarrow \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$

- Possible new particles in the loops

Ex:2HDM



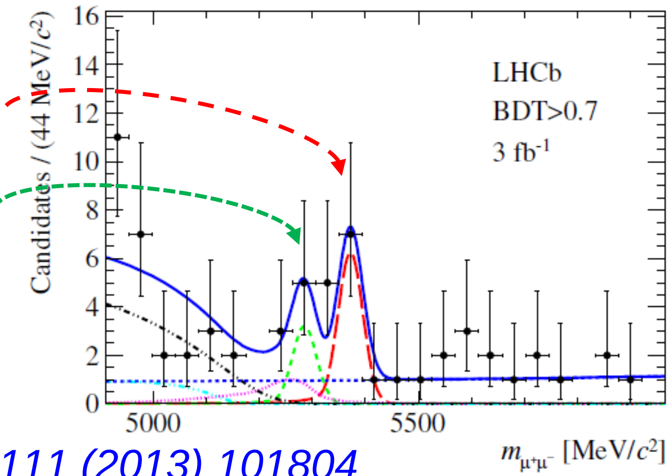
Very good place to look for physics beyond SM, intensively searched for over 30 years!

$B_{s/d} \rightarrow \mu^+\mu^-$

LHCb, 3fb^{-1} *PRL 111 (2013) 101805* :

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

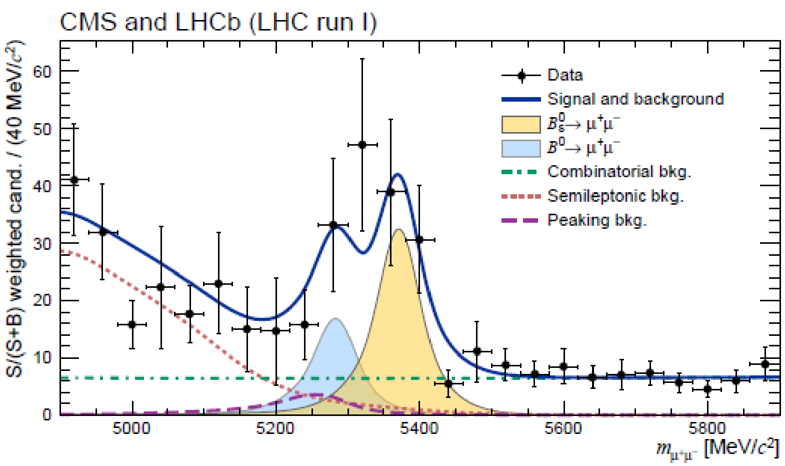
$$BR(B^0 \rightarrow \mu^+\mu^-) = (3.7^{+2.4}_{-2.1}(stat)^{+0.6}_{-0.4}(syst)) \times 10^{-10}$$

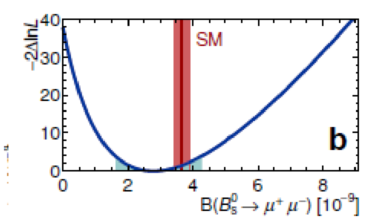


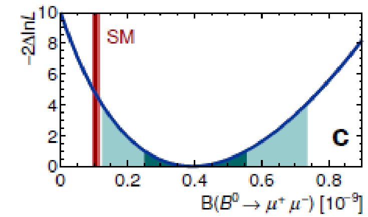
$B^0 \rightarrow \pi^-\mu^+\nu$
$B_s \rightarrow K^-\mu^+\nu$
$B^{0/+} \rightarrow \pi^{0/+}\mu\mu$
$B_{d/s} \rightarrow h^+h'^-$
$B_s \rightarrow \mu^+\mu^-$
$B^0 \rightarrow \mu^+\mu^-$
Total

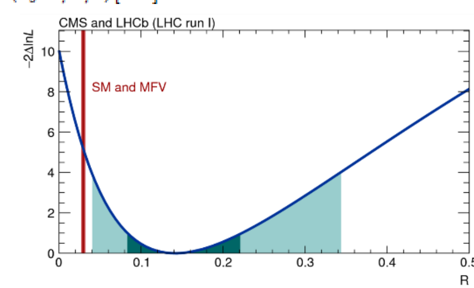
- CMS obtained similar results with 25 fb^{-1} *PRL 111 (2013) 101804*
- Combination *Nature 522 (2015) 68* :

First observation (at 6.2 σ) for B_s and first evidence (at 3.2 σ) for B^0





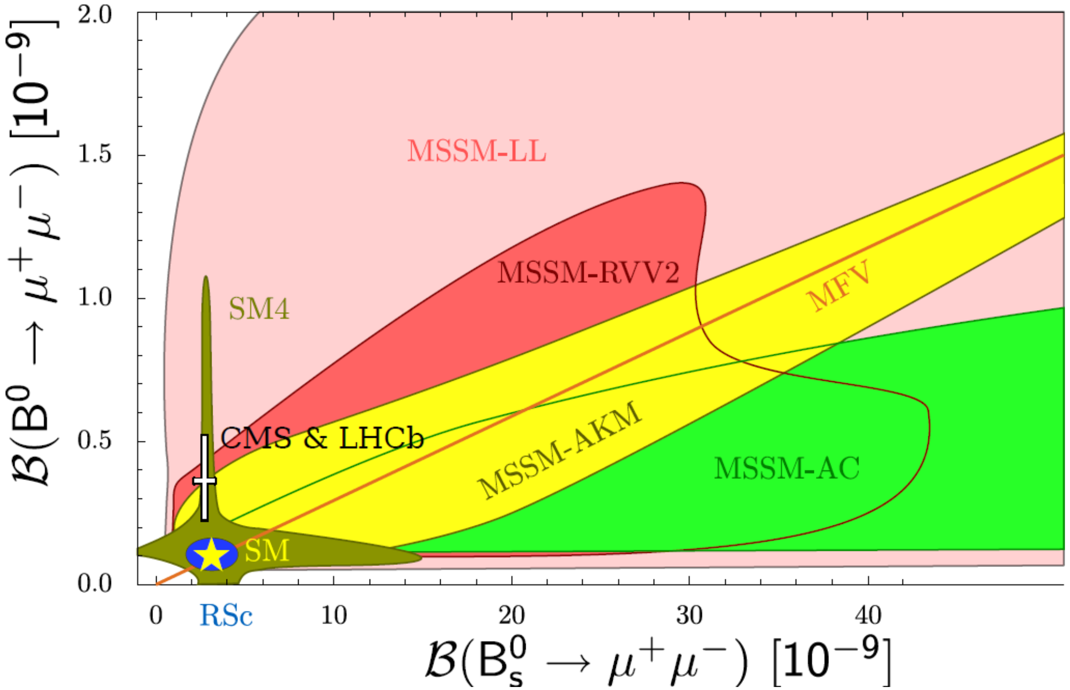




Results compatible with SM predictions at 1.2 σ for B_s , 2.2 σ for B_d and 2.3 σ for the ratio

$B_{s/d} \longrightarrow \mu^+\mu^-$

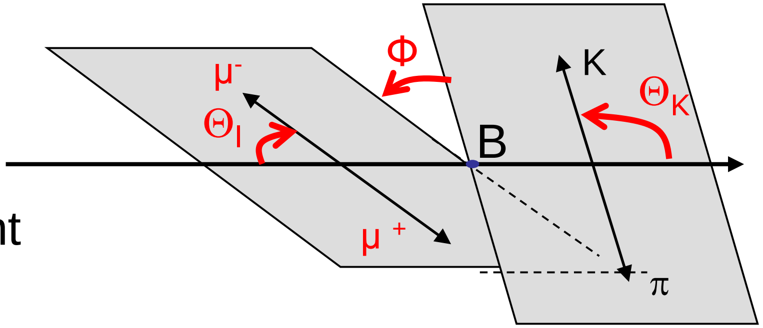
- Publicity plot adapted from Straub, arXiv:1205.6094



- Interest of measuring the ratio $BR(B^0 \to \mu^+\mu^-) / BR(B_s \to \mu^+\mu^-)$: test MFV hypothesis
- Long term prospect: effective lifetime measurement, also sensitive to NP

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

- $B_d \to K^{*0}\mu^+\mu^-$ provides excellent laboratory to search for new physics in FCNC processes
  - Rates, angular distributions and asymmetries sensitive to NP
  - Experimentally clean signature
  - Many kinematic variables with clean theoretical predictions



- Decay described by 3 angles and di-muon invariant mass squared q^2

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

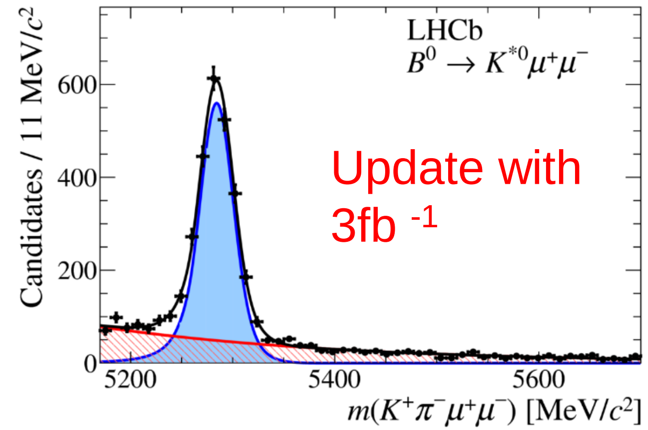
Angular observables of $B_d \to K^{*0}\mu^+\mu^-$

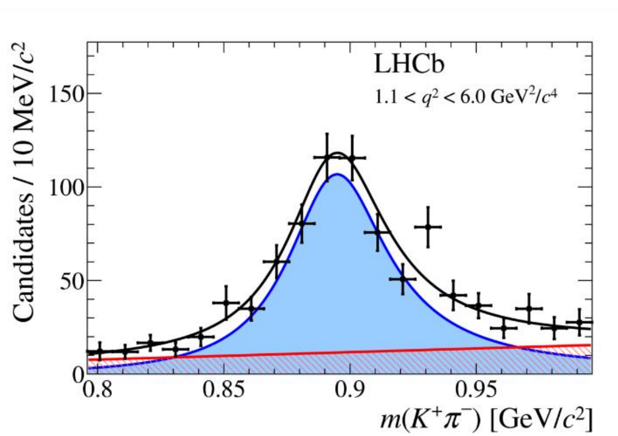
arXiv:1512.04442

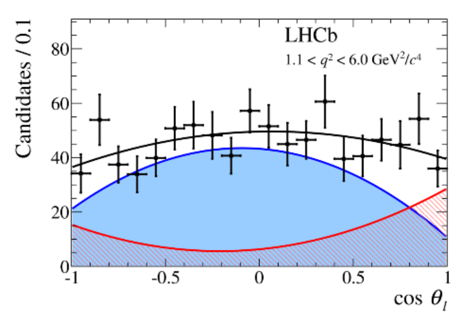
- Analysis updated with the $3fb^{-1}$ recorded during Run 1 : ~2400 signal events

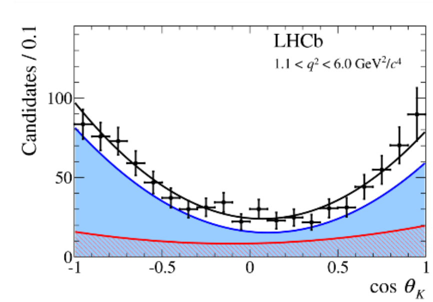
- Angular observables extracted from likelihood fit in decay angles and $m_{K\pi\mu\mu}$ in q^2 bins. Also performed with method of moments.
- $K\pi$ S-wave contribution taken into account by fitting simultaneously the $K\pi$ mass

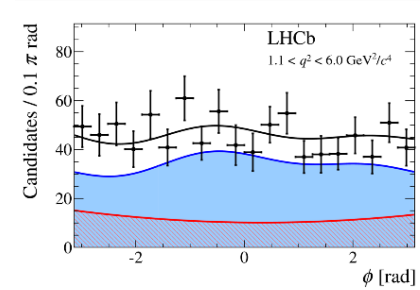
- Example in the bin $1.1<q^2< 6.0$ GeV^2:



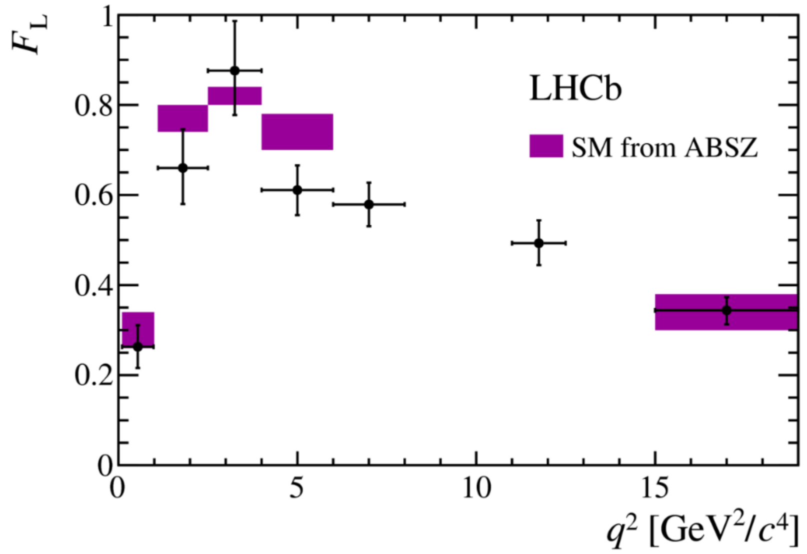


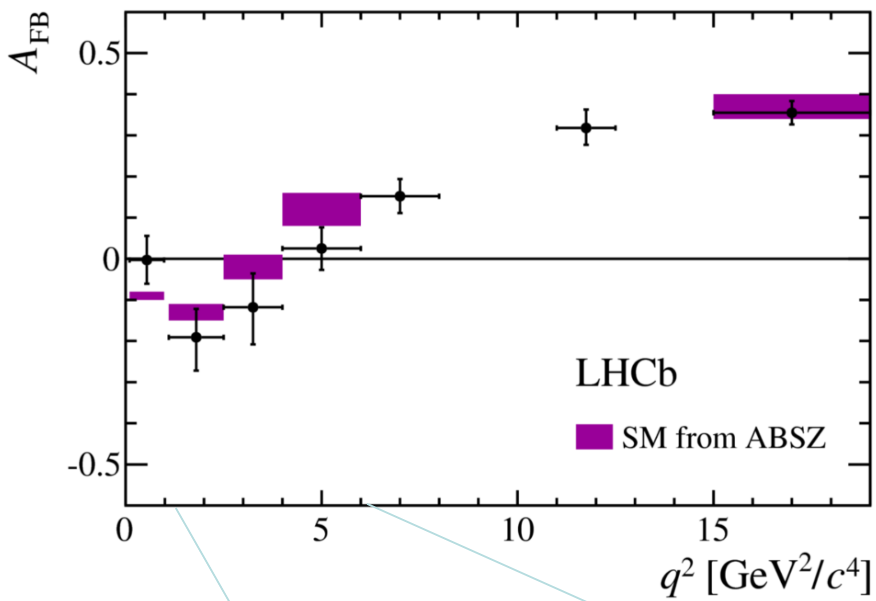






Angular observables of $B_d \to K^{*0}\mu^+\mu^-$

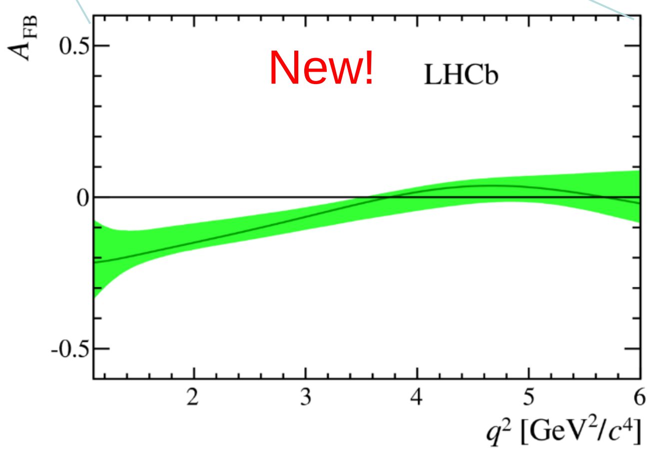




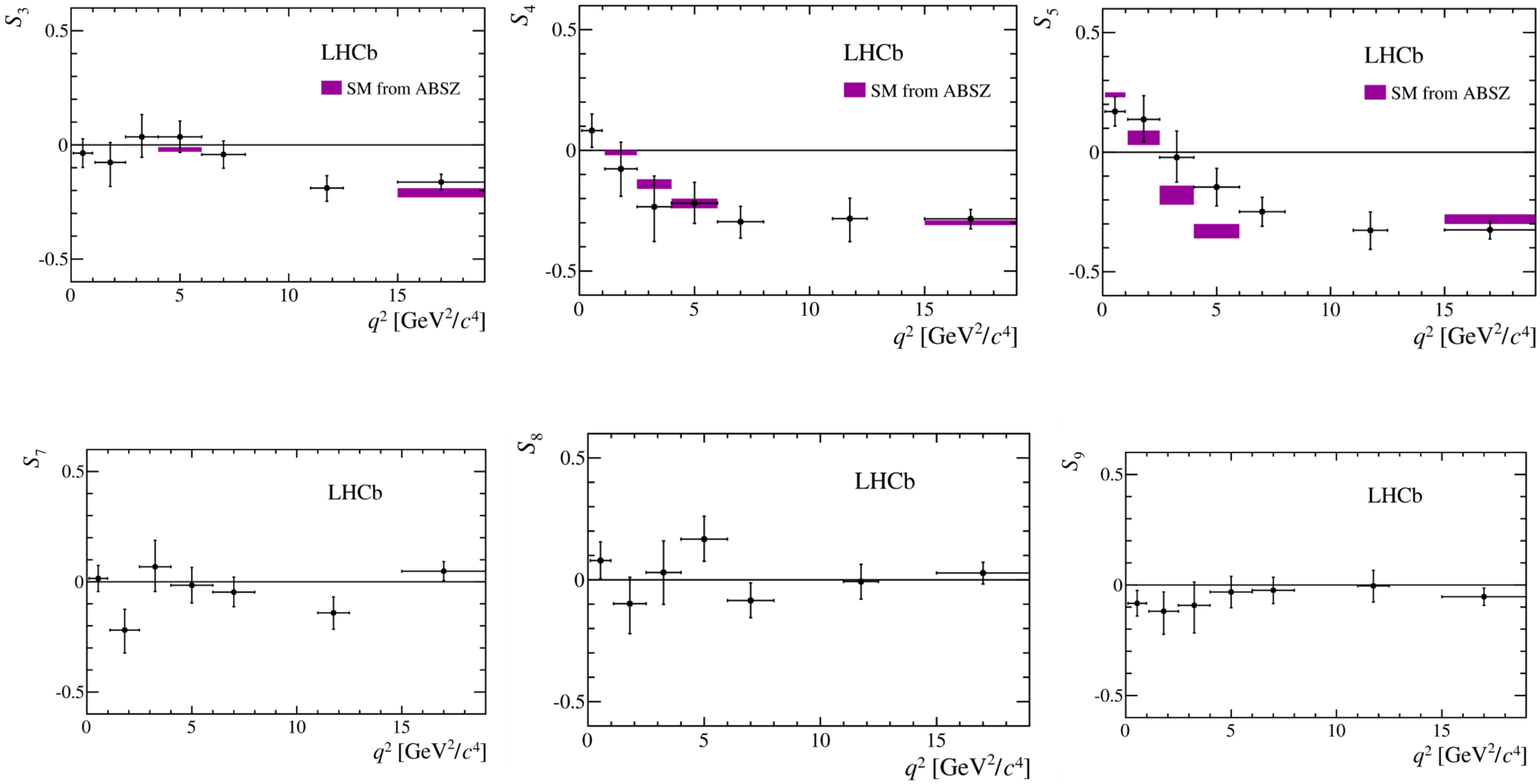
Theory prediction from arXiv:1503.6634, arXiv:1411.3161

- A_{FB} systematically below SM prediction
- Zero crossing point evaluated with a direct fit to the decay amplitudes, compatible with SM prediction (3.9-4.4 GeV^2)

$$q_0^2 \in [3.40, 4.87]\ \mathrm{GeV}^2$$

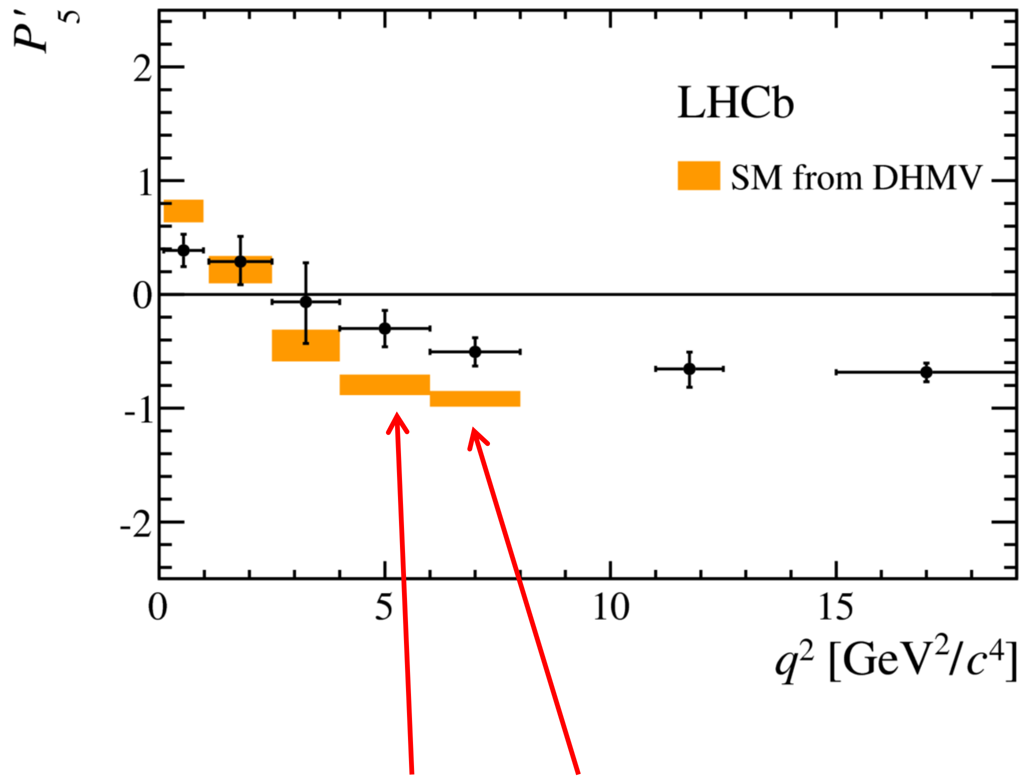


Angular observables of $B_d \rightarrow K^{*0}\mu^+\mu^-$



Angular observables of $B_d \to K^{*0}\mu^+\mu^-$

Theory from JHEP 1412 (2014) 125

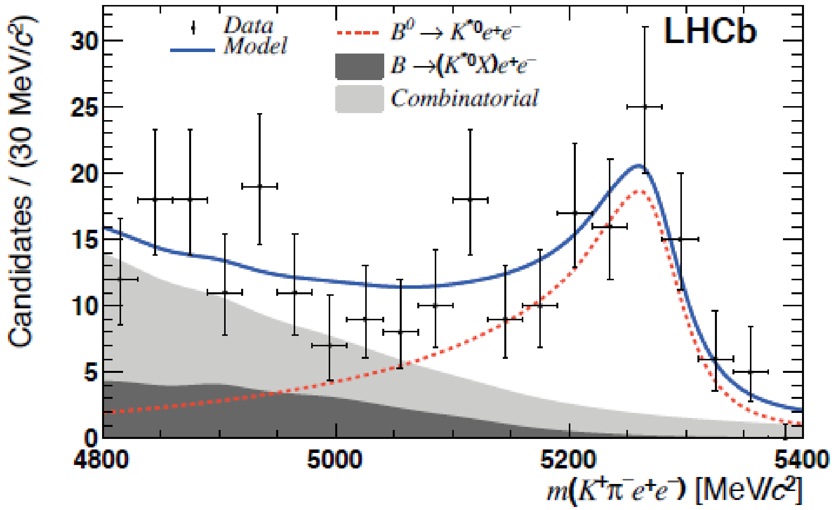


Discrepancy in P'_5 still there at 2.8 and 3 σ level in these two bins (compatible with 1 fb^{-1} measurement) . Lot of discussion with theory community on the interpretation of this discrepancy.

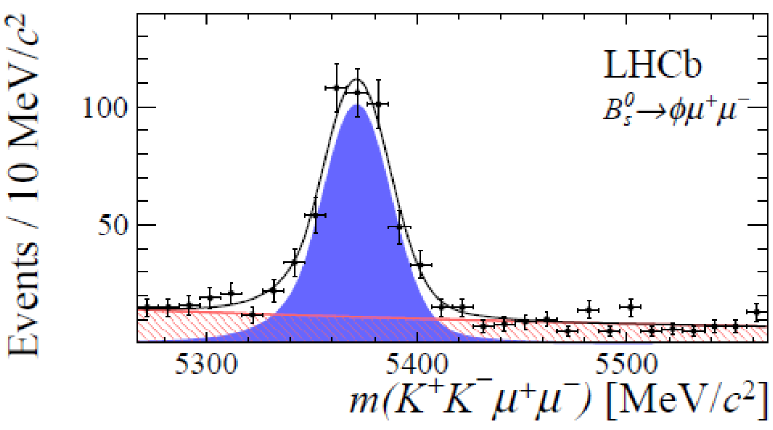
Other FCNCs

- Angular analysis of $B_d \to K^{*0} e^+ e^-$ at small q^2 values (sensitive to photon polarization)
- Full angular analysis of $B_s \to \phi \mu^+ \mu^-$
- $\Lambda_b \to \Lambda \mu^+ \mu^-$ too few events for a full angular analysis but we can measure foward-backward asymetries

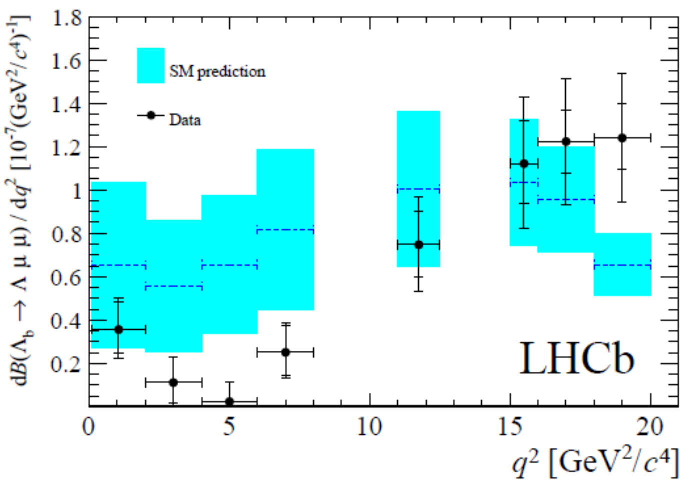
JHEP 04 (2015) 064



JHEP 09 (2015) 179

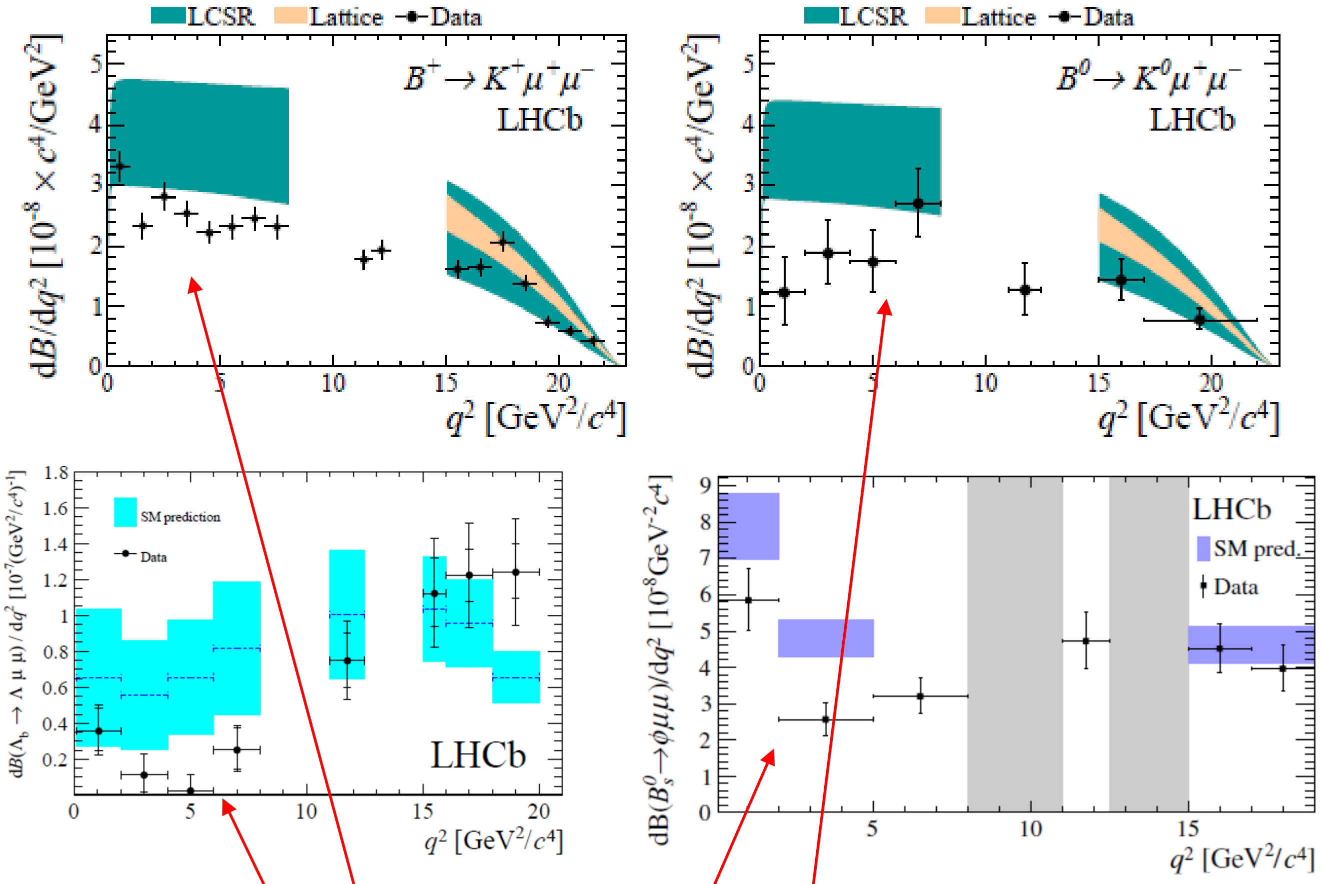


JHEP 06 (2015) 115



b → sμμ branching fractions vs q^2

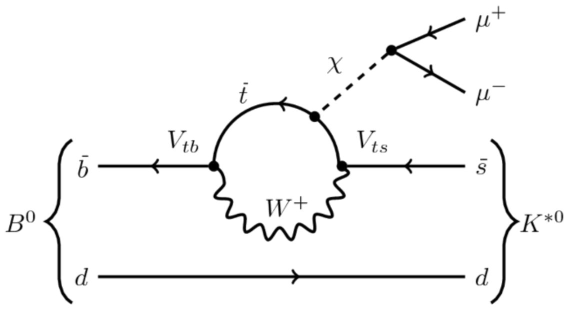
JHEP 06 (2014) 133



⇒ Branching fractions tend to lie below SM predictions..?

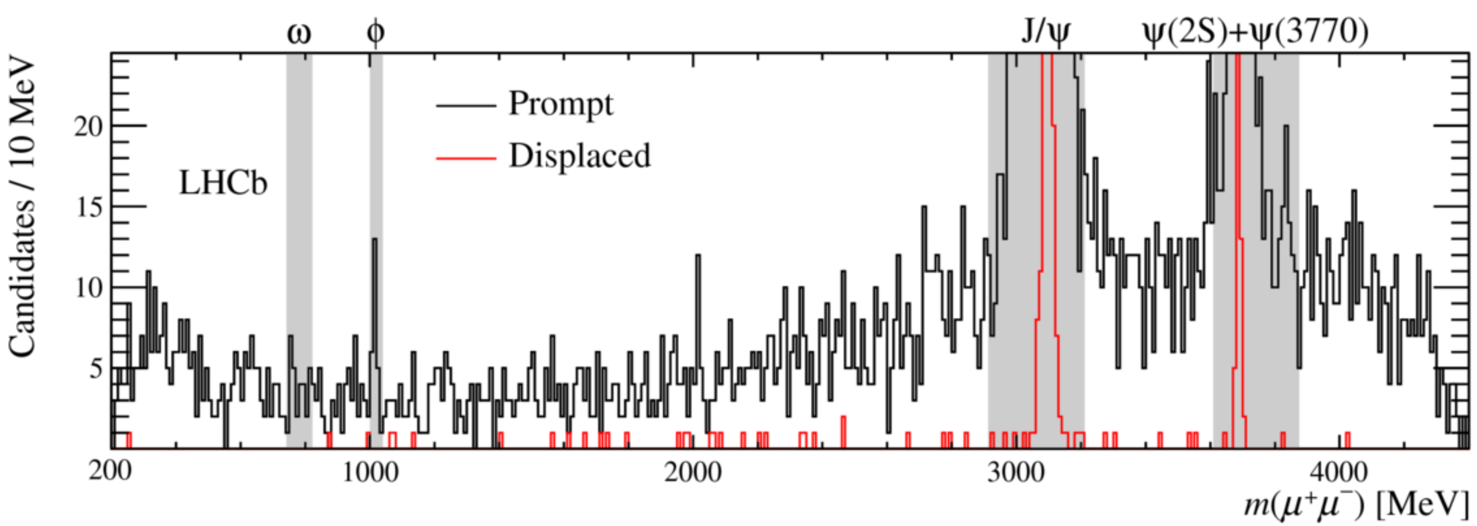
Search for hidden sector boson in $B_d \rightarrow K^{*0}\mu^+\mu^-$

- Lack of evidence for dark matter and various cosmic rays anomalies renewed interest in “hidden sector theories”



- Search for $B \rightarrow K^{*0}\chi$ with $\chi \rightarrow \mu^+\mu^-$
  - access to masses $2m(\mu) < m(\chi) < m(B)-m(K^*)$
  - Can search for long lived χ, giving displaced $\mu^+\mu^-$

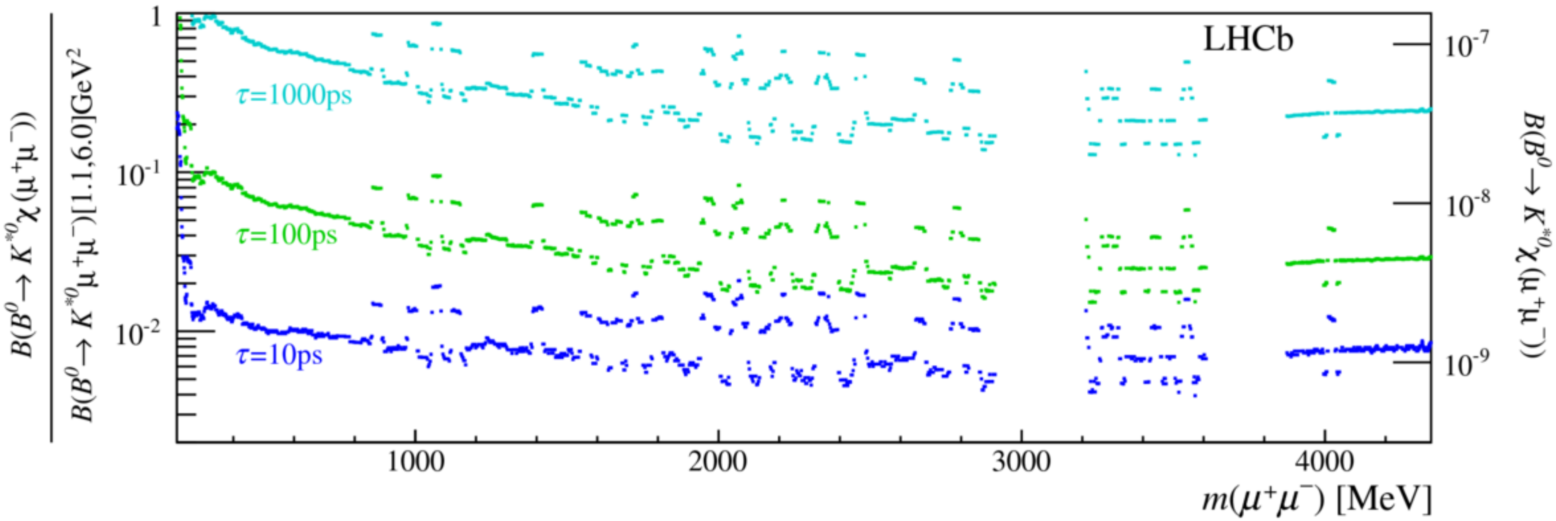
- Scan $m(\mu\mu)$ distribution for an excess of signal candidates (veto resonances)



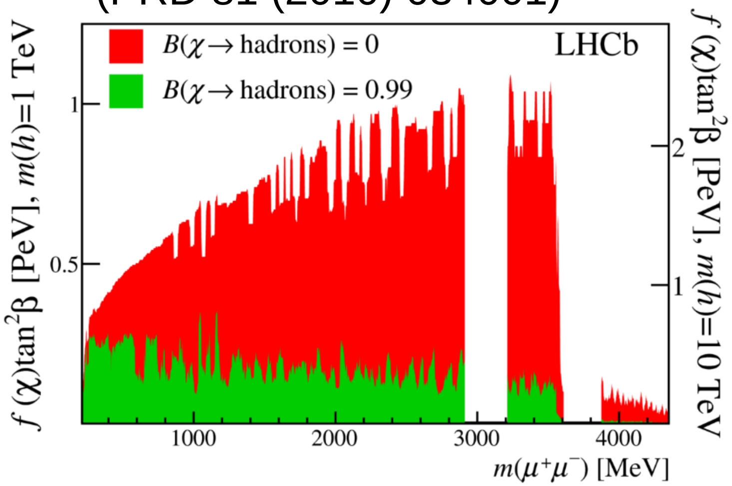
Search for hidden sector boson in $B_d \to K^{*0}\mu^+\mu^-$

- Upper limits on $B \to K^{*0}\chi(\to \mu^+\mu^-)$ at 95%CL:

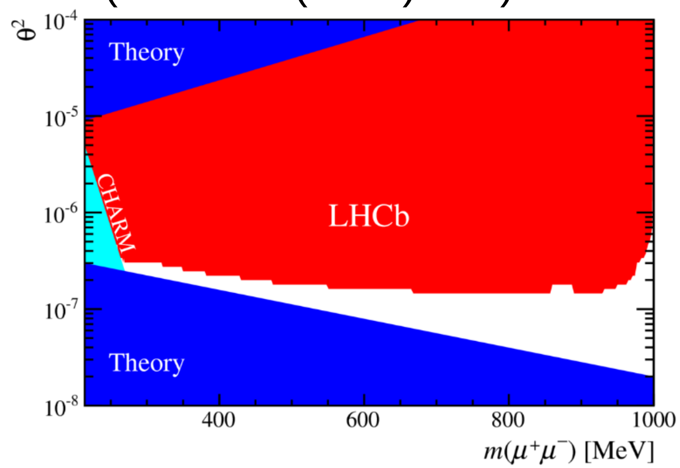
PRL 115 (2015) 161802

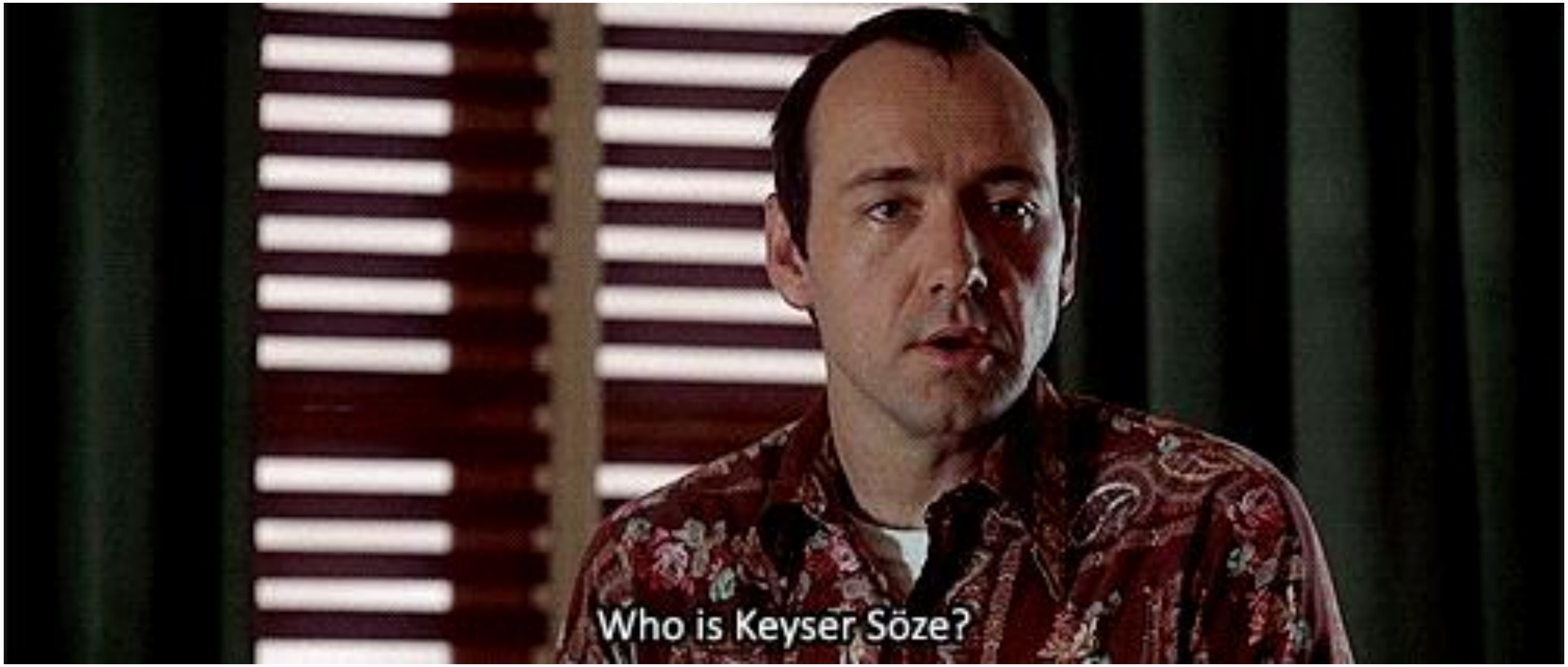


Constraint on axion model
(PRD 81 (2010) 034001)



Constraint on inflaton model
(PLB 736 (2014) 494)




Who is Keyser Söze?

How to interpret SM deviation ?

- b → s ℓℓ decays can theoretically be described by effective hamiltonian

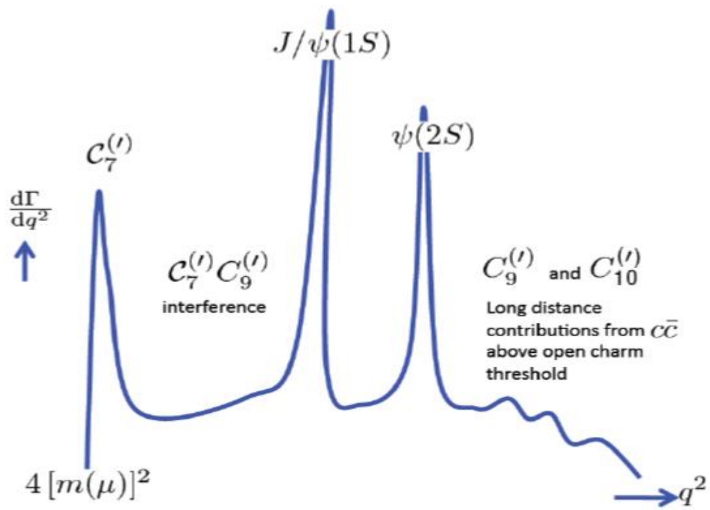
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i (C_i \mathcal{O}_i + C_i' \mathcal{O}_i')$$

left-handed part

right-handed part suppressed in SM

i=1,2 Tree
i=3-6,8 gluon penguin
i=7 photon penguin
i=9,10 electroweak penguin
i= S,P Scalar, Pseudo scalar penguin

- Operators O_i depends on hadronic form factors, which usually dominate theoretical uncertainties
- Wilson coefficient C_i describe short distance effects, they are sensitive to NP

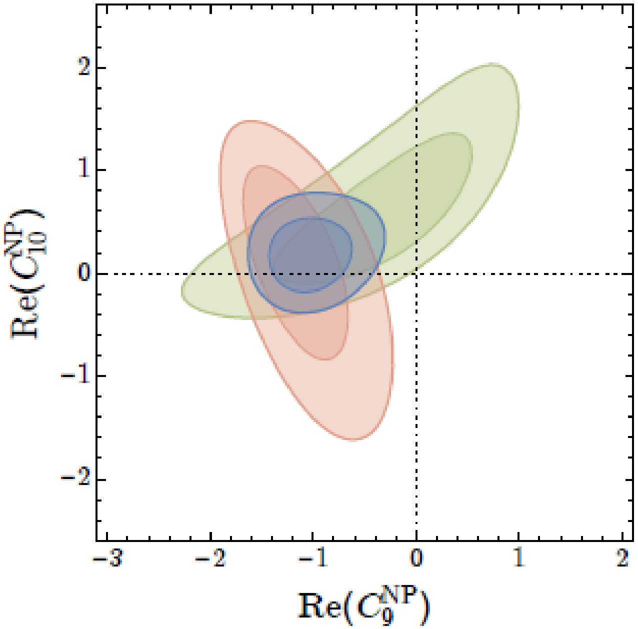


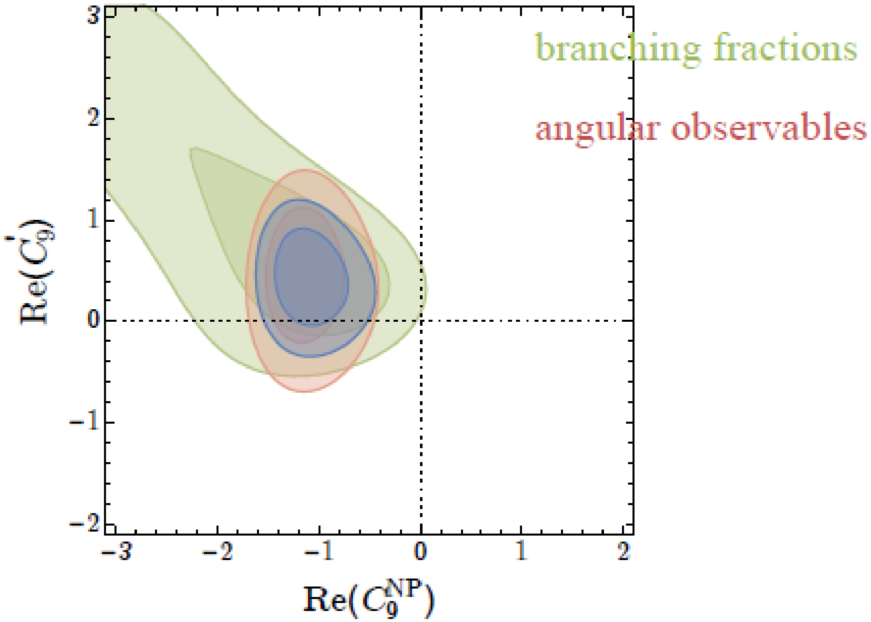
- $B \to K^* \ell\ell$: C_7 C_9 C_{10}
- $B \to \ell\ell$: C_{10} C_S C_P
- $B \to X_s \gamma$: C_7

Theoretical interpretation

Global model-independent fit of the Wilson coefficients using 88 measurements from ATLAS, CMS, LHCb (Altmannshofer et al, EPJC 75 (2015) 382)

($C_i = C_i^{SM} + C_i^{NP}$)





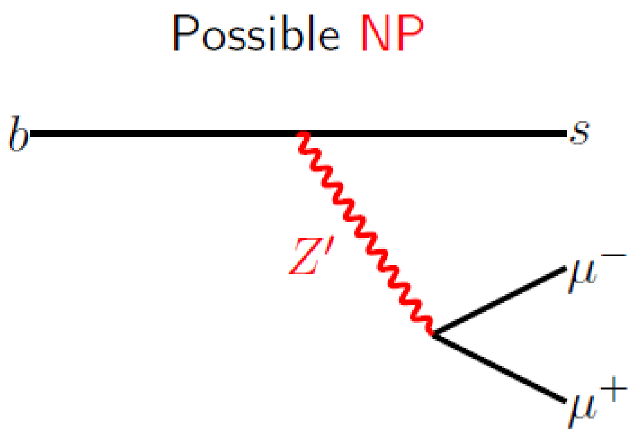
Consistency between angular observables and branching fractions

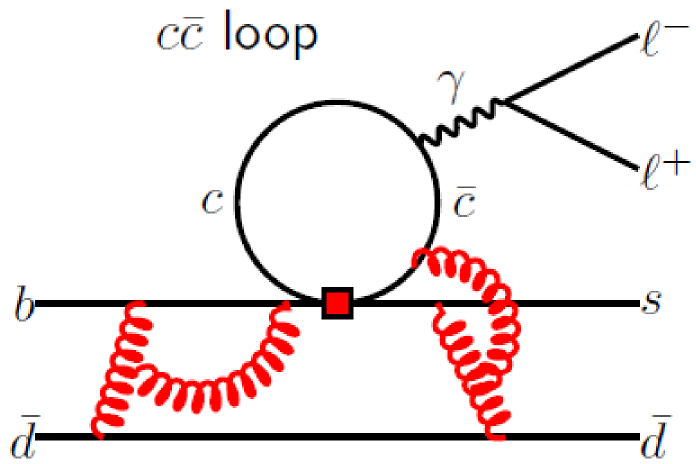
The fit prefers C_9^{NP}~-1, with significance of ~4σ

Same conclusion from S. Descotes-Genon et al (arXiv:1510.04239)

Theoretical interpretation

- Could be due to a Z' : Gauld et al., JHEP 1401 (2014) 069, Buras et al, JHEP 1402 (2014) 112, Altmannshofer et al. PRD 89 (2014) 095033
- Or leptoquark : Hiller et al, PRD 90 054014, Buras et al, arXiv: 1409.4557, Biswas et al, JHEP02 (2015)142
- Or not well understood hadronic effects..





What's next: LHCb upgrade

- Idea: read the entire detector at 40MHz (remove the hardware trigger)
- Installed during LS2 (2019-2020)
- Goal is to accumulated 50fb^{-1} in ~2028
- Expected sensitivity :

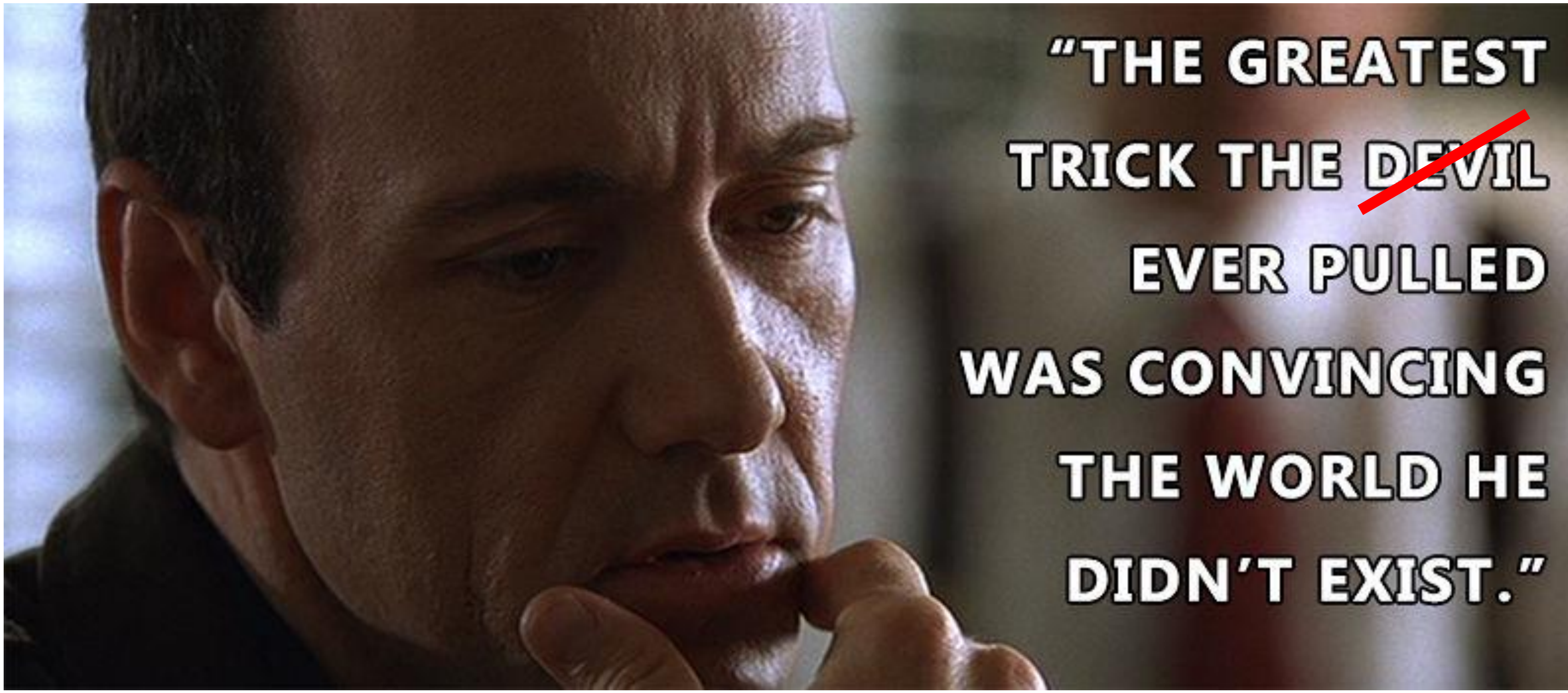
Type	Observable	LHC Run 1	LHCb 2018	LHCb upgrade	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.05	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\, f_0(980))$ (rad)	0.09	0.05	**0.016**	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.18	0.12	**0.026**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.029**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.04**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$	0.20	0.13	**0.030**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.8%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\, A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.14	0.07	**0.024**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\,\%$
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**1.1°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.4°**	negligible
	$\beta(B^0 \to J/\psi\, K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm *CP* violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.5**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.12**	–

Summary

- LHCb obtained a lot of interesting results from Run 1 data
  - Mainly using muonic decays but electrons and taus are coming!
  - Modes with neutrinos, previously thought to be impossible
  - (+ many not shown here..)

- Rare decays show several hints of beyond SM effects:
  - global analysis shows that a lower value of C_9 is prefered over SM at > 3 σ
  - P_5' in $B_d \to K^{*0}\mu^+\mu^-$
  - $B_s \to \phi\mu^+\mu^-$
  - $\Lambda_b \to \Lambda\, \mu^+\mu^-$
  - R_K, $R(D^*)$
  - …

Run 2 data will help understanding them!



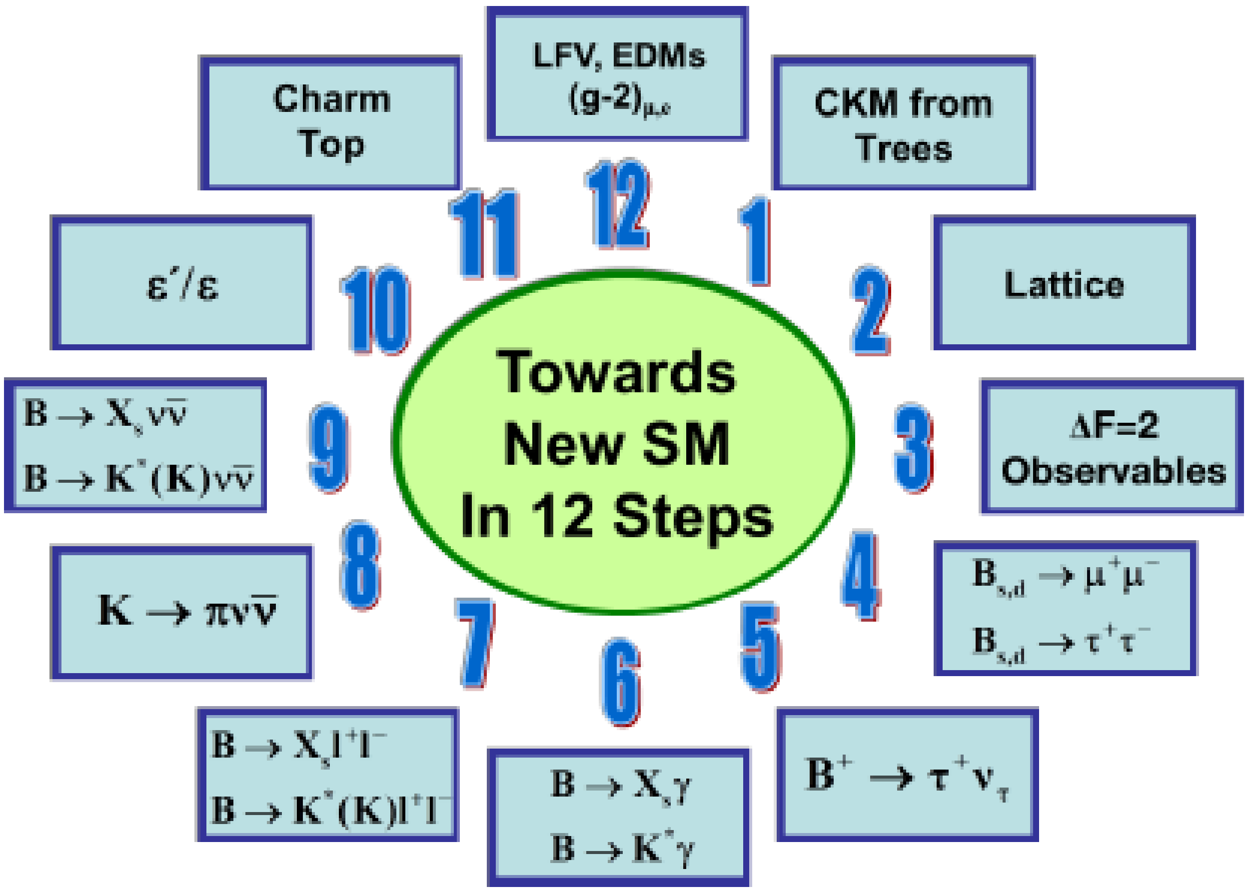
NP

We need to pursue the effort!

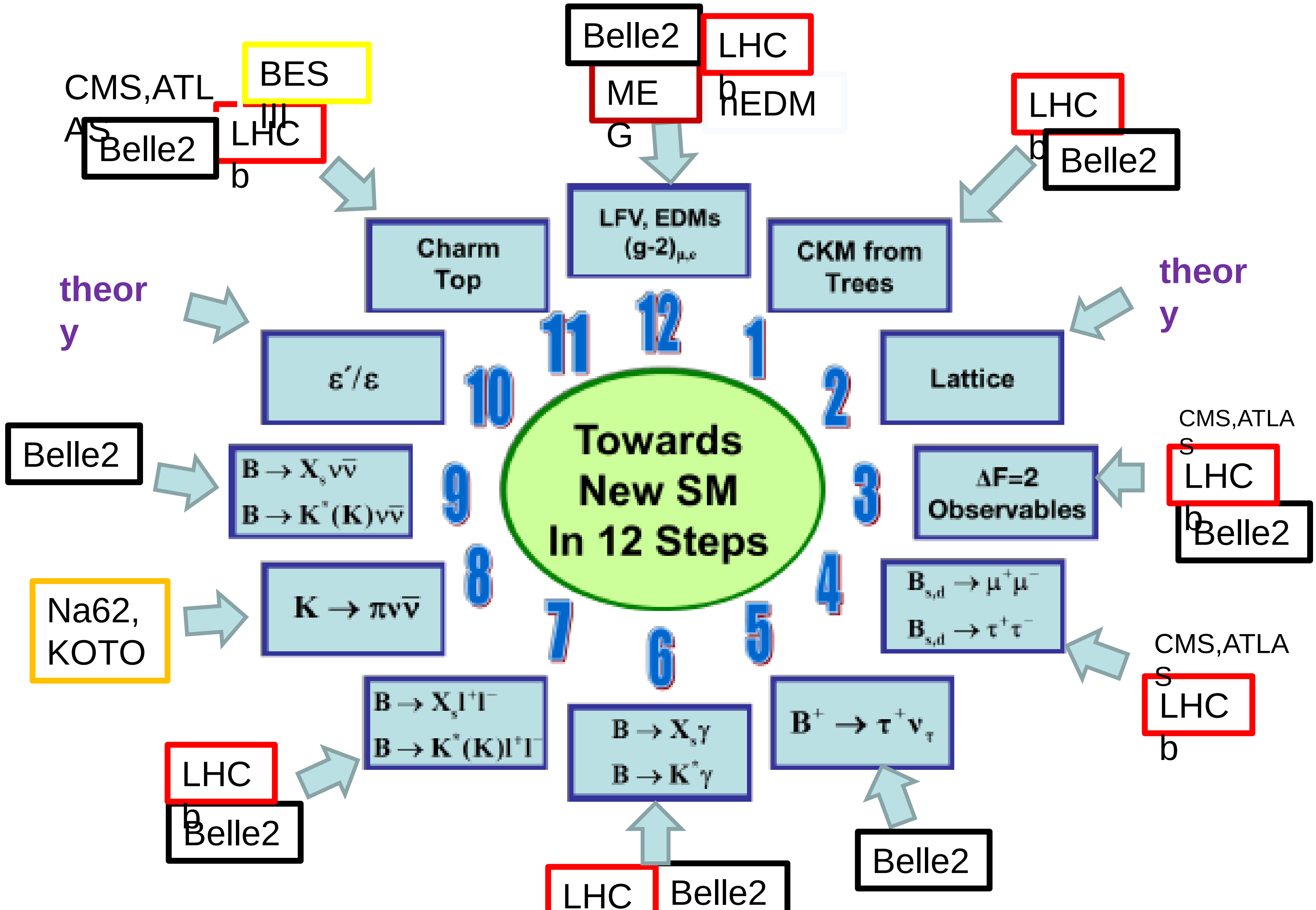
Want more ?

The main observables

From Buras arXiv:1306.3775



Correlations between observables can constrain NP models



Towards New SM In 12 Steps
1
CKM from Trees
2
Lattice
3
ΔF=2 Observables
4
$B_{s,d} \to \mu^+\mu^-$
$B_{s,d} \to \tau^+\tau^-$
5
$B^+ \to \tau^+\nu_\tau$
6
$B \to X_s\gamma$
$B \to K^*\gamma$
7
$B \to X_s l^+l^-$
$B \to K^*(K)l^+l^-$
8
$K \to \pi\nu\bar{\nu}$
9
$B \to X_s\nu\bar{\nu}$
$B \to K^*(K)\nu\bar{\nu}$
10
ε′/ε
11
Charm Top
12
LFV, EDMs $(g\text{-}2)_{\mu,e}$
Belle2
LHCb
MEG
nEDM
LHCb
Belle2
theory
CMS,ATLAS
LHCb
Belle2
CMS,ATLAS
LHCb
Belle2
LHCb
Belle2
LHCb
Belle2
Na62, KOTO
Belle2
theory
CMS,ATLAS
Belle2
BES III
LHCb

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

- Differential decay rate:

$$\frac{d^4\Gamma[\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-]}{dq^2\, d\vec{\Omega}} = \frac{9}{32\pi} \sum_{j(s,c)} I_{j(s,c)}(q^2) f_j(\vec{\Omega}) \quad \text{and}$$

$$\frac{d^4\bar{\Gamma}[B^0 \to K^{*0}\mu^+\mu^-]}{dq^2\, d\vec{\Omega}} = \frac{9}{32\pi} \sum_{j(s,c)} \bar{I}_{j(s,c)}(q^2) f_j(\vec{\Omega}) \quad ,$$

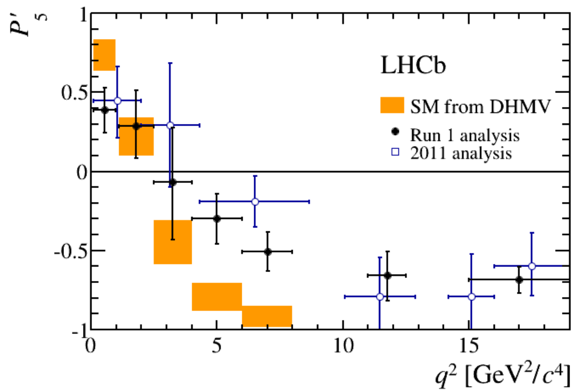
- CP average observables:

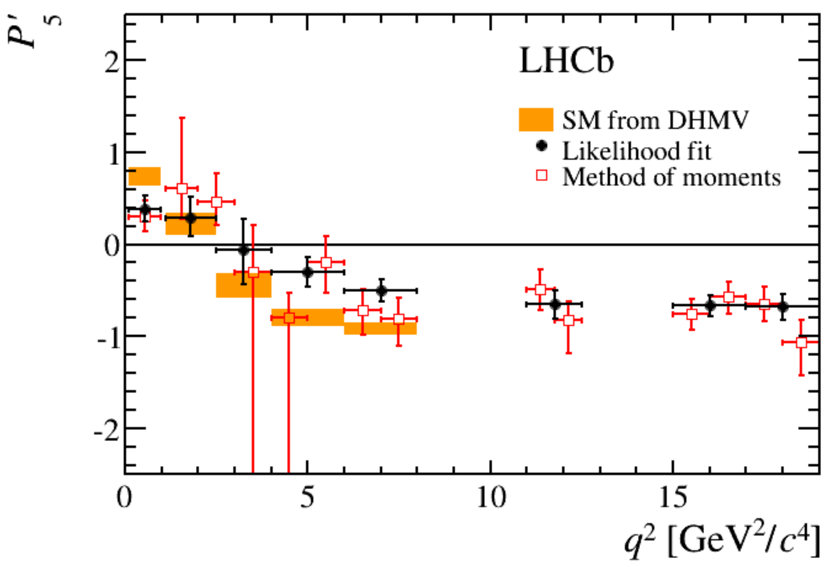
$$S_j = \left(I_{j(s,c)} + \bar{I}_{j(s,c)}\right) \Big/ \left(\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2}\right)$$

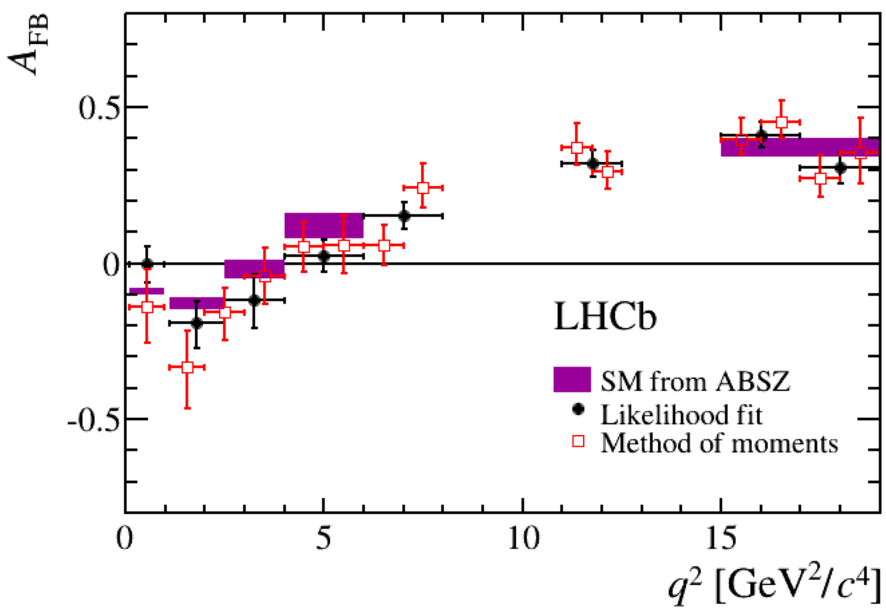
- S wave:

$$\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2} \frac{d^3(\Gamma+\bar{\Gamma})}{d\vec{\Omega}}\bigg|_{S+P} = (1-F_S)\, \frac{1}{d(\Gamma+\bar{\Gamma})/dq^2} \frac{d^3(\Gamma+\bar{\Gamma})}{d\vec{\Omega}}\bigg|_{P} + \frac{3}{16\pi} F_S \sin^2\theta_\ell \; + \; \text{S-P interference}$$

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

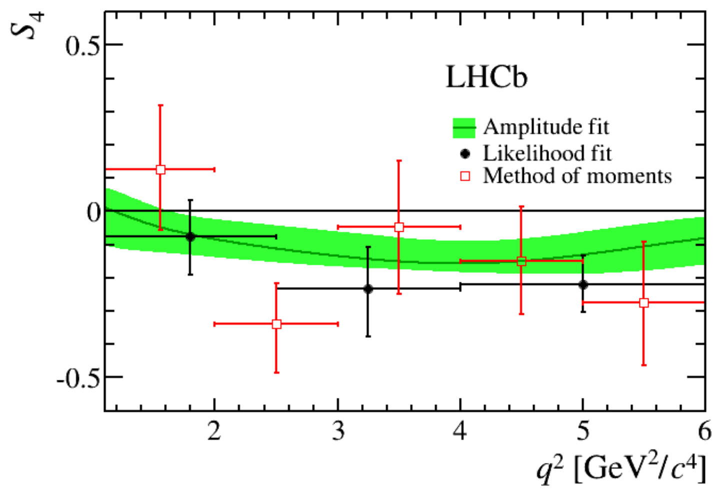




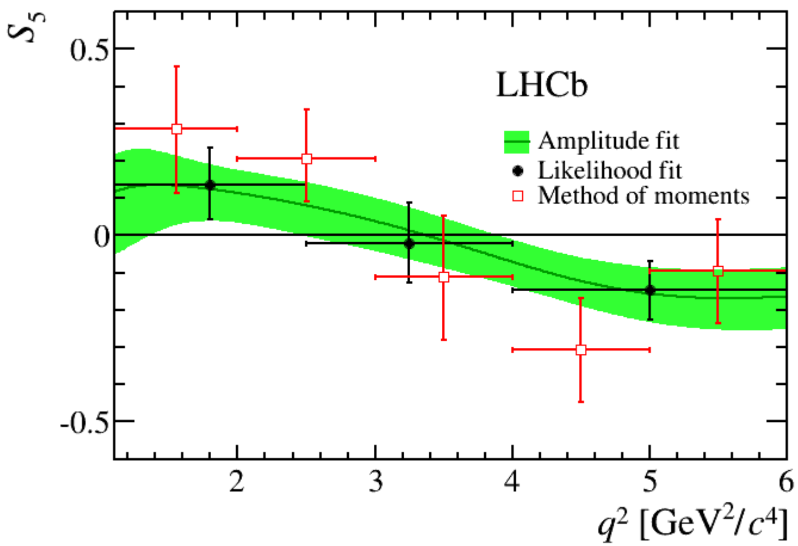


Method of moment less sensitive than likelihood fit
(10-30%) but allows narrower bin of 1GeV2

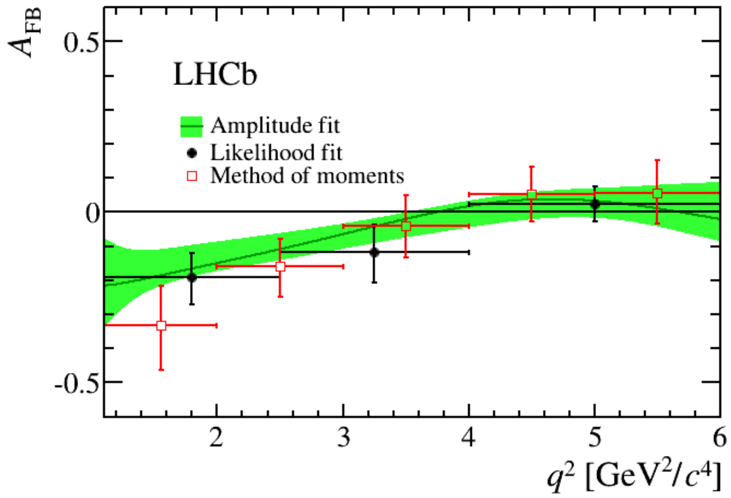
$B_d \to K^{*0}\mu^+\mu^-$



S_4
0.5
0
-0.5
LHCb
Amplitude fit
Likelihood fit
Method of moments
2
3
4
5
6
q^2 [GeV^2/c^4]



S_5
0.5
0
-0.5
LHCb
Amplitude fit
Likelihood fit
Method of moments
2
3
4
5
6
q^2 [GeV^2/c^4]

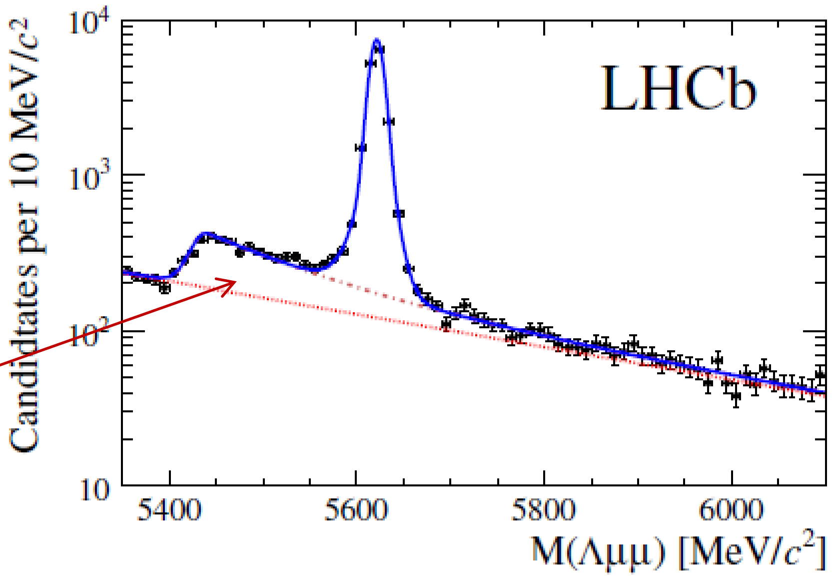


A_{FB}
0.5
0
-0.5
LHCb
Amplitude fit
Likelihood fit
Method of moments
2
3
4
5
6
q^2 [GeV^2/c^4]

$\Lambda_b \to \Lambda\, \mu^+\mu^-$

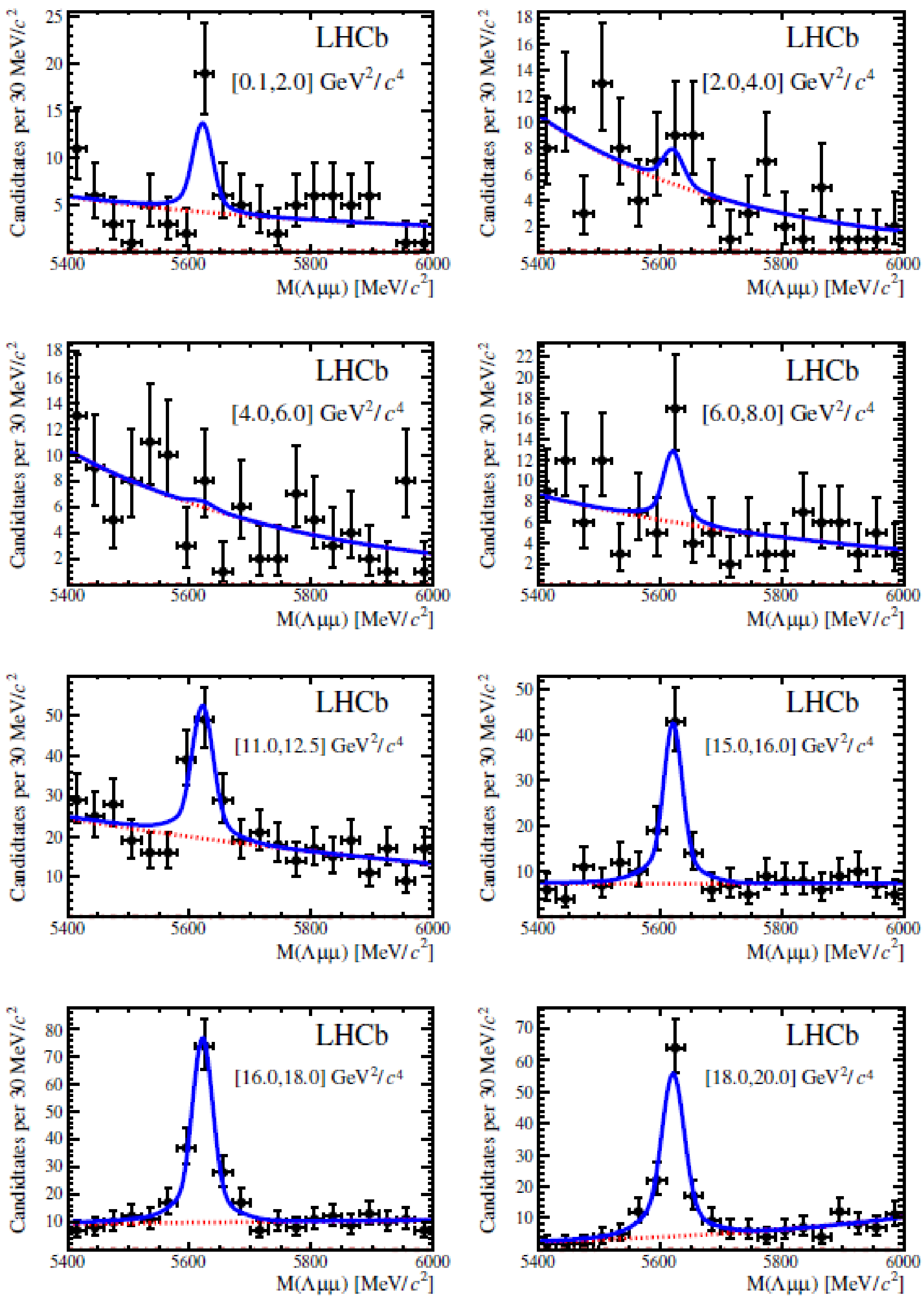
Normalization channel: $\Lambda_b \to J/\Psi\Lambda$

Peaking background $\Lambda_b \to J/\Psi Ks$



Signal yield $\Lambda_b \to \Lambda\, \mu^+\mu^-$

q^2 interval [GeV$^2/c^4$]	Total signal yield	Significance
0.1–2.0	16.0 ± 5.3	4.4
2.0–4.0	4.8 ± 4.7	1.2
4.0–6.0	0.9 ± 2.3	0.5
6.0–8.0	11.4 ± 5.3	2.7
11.0–12.5	60 ± 12	6.5
15.0–16.0	57 ± 9	8.7
16.0–18.0	118 ± 13	13
18.0–20.0	100 ± 11	14
1.1–6.0	9.4 ± 6.3	1.7
15.0–20.0	276 ± 20	21


LHCb
[0.1,2.0] GeV^2/c^4
LHCb
[2.0,4.0] GeV^2/c^4
LHCb
[4.0,6.0] GeV^2/c^4
LHCb
[6.0,8.0] GeV^2/c^4
LHCb
[11.0,12.5] GeV^2/c^4
LHCb
[15.0,16.0] GeV^2/c^4
LHCb
[16.0,18.0] GeV^2/c^4
LHCb
[18.0,20.0] GeV^2/c^4
Candidates per 30 MeV/c^2
M($\Lambda\mu\mu$) [MeV/c^2]

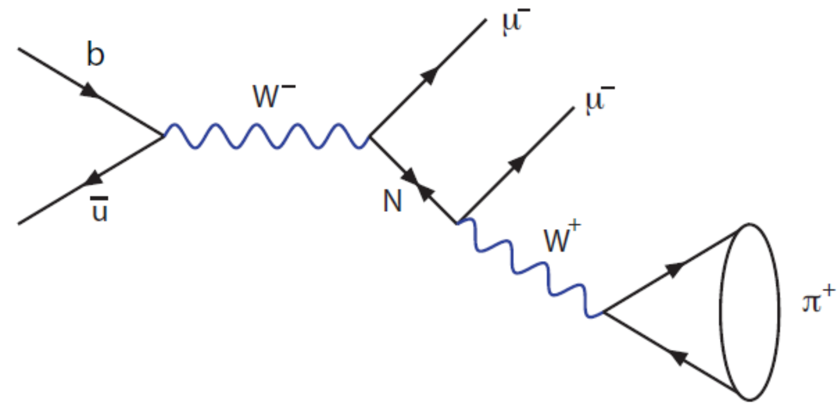
Search for Majorana neutrinos in $B^- \to \pi^+\mu^-\mu^-$

- Lepton number violating decay forbidden in the SM

- Can probe Majorana neutrino with any mass in $m(\pi)+m(\mu) < m(N) < 5$ GeV

- The lifetime of N is unknown, we search for N with a lifetime up to 1000 ps

- Experimental status:



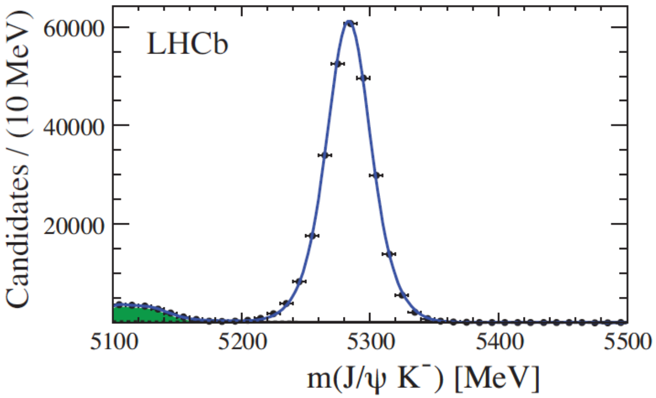
CLEO	$BR(B^- \to \pi^+\mu^-\mu^-) < 1.4\times10^{-6}$ at 90%, PRD65:111102 (2002)
Babar	$BR(B^- \to \pi^+\mu^-\mu^-) < 10.7\times10^{-8}$ at 90%, PRD85:071103 (2012)
LHCb ($0.41 fb^{-1}$)	$BR(B^- \to \pi^+\mu^-\mu^-) < 1.3\times10^{-8}$ at 95%, PRD 85:112004 (2012)

Here we present an update based on the $3 fb^{-1}$ recorded

Analysis strategy

arXiv:1401.5361

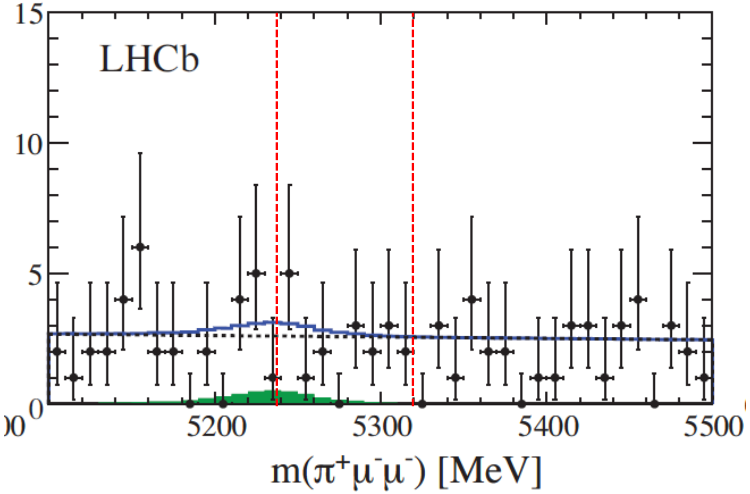
- 2 selections :
  - Assuming N has zero lifetime, B vertex formed by $\pi^+\mu^-\mu^-$
  - Detached neutrino: first vertex for $\pi^+\mu^-$, attached to the second μ^- to form the B candidate



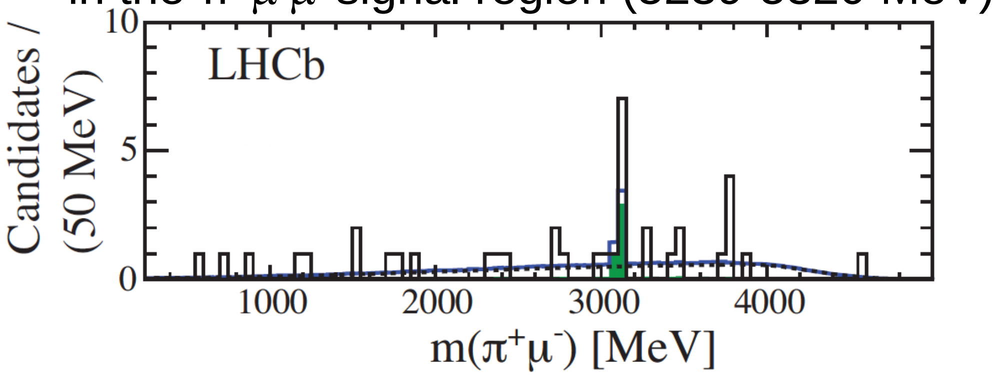
- Normalization to $B^+ \to J/\Psi K^+$
  - Find ~280 000 events
- Ratio of efficiencies taken from MC or data driven methods
- Extended maximum likelihood fit to the $\pi^+\mu^-\mu^-$ sidebands to determine the combinatorial background
- Peaking background shape taken from MC, yields constrained to $B^+ \to J/\Psi K^+$
- Limits obtained with the CLs method

$B^- \to \pi^+\mu^-\mu^-$, short neutrino lifetime

arXiv:1401.5361

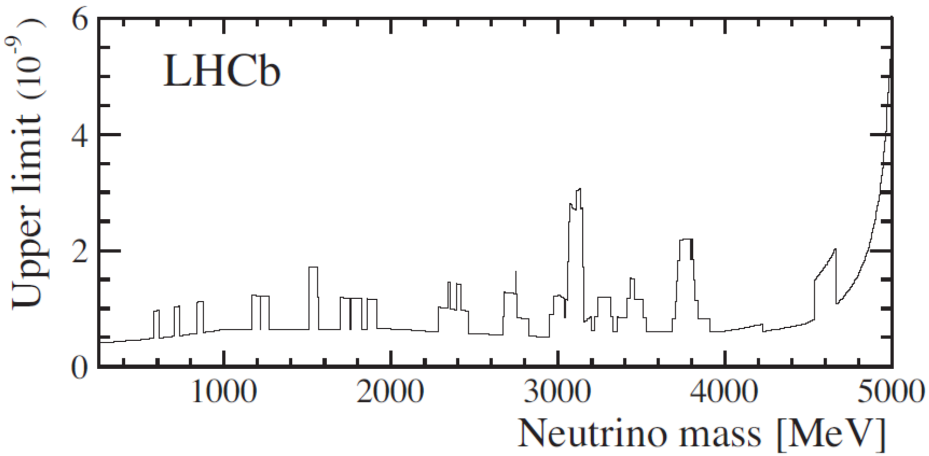


in the $\pi^+\mu^-\mu^-$ signal region (5239-5320 MeV)



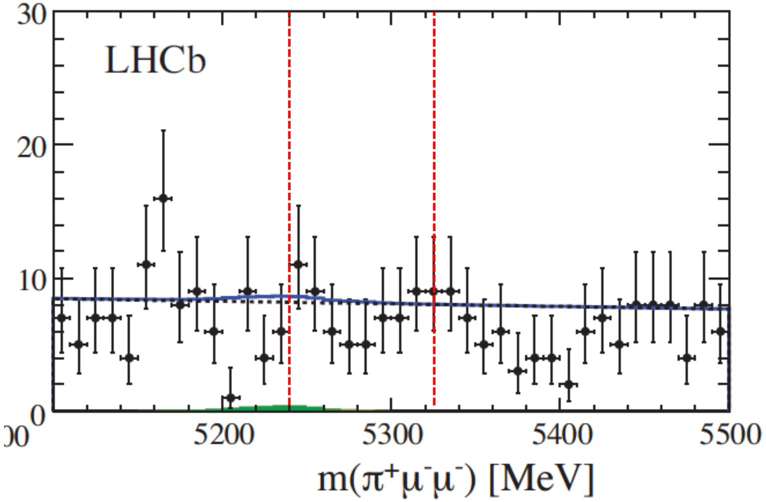
- Peaking background : $B^+ \to J/\Psi\ K^+(\pi^+)$, $B^+ \to \Psi(2S)\ K^+$
- No signal found, $BR(B^- \to \pi^+\mu^-\mu^-) < 4.0 \times 10^{-9}$ at 95% CL

- Limit as function of neutrino mass:
  - Scan over neutrino mass with 5 MeV step up to 5000 MeV
  - At each point, fit $m(\pi^+\mu^-)$ in a 3σ window, σ being the neutrino mass resolution evaluated from MC

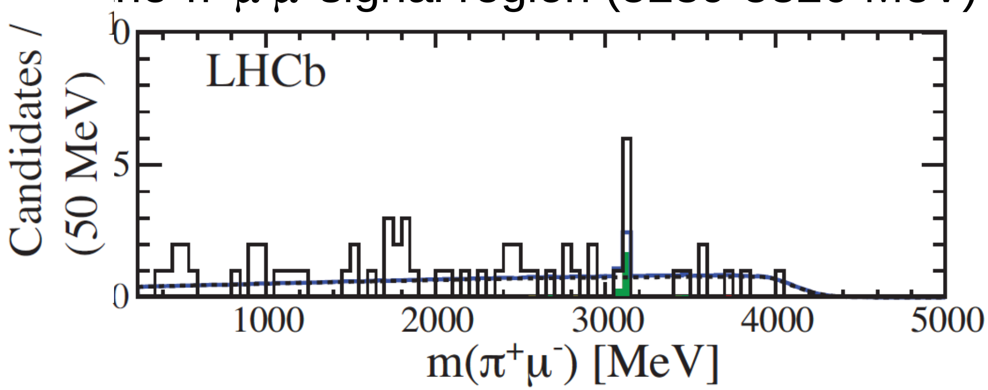


$B^- \to \pi^+\mu^-\mu^-$, long neutrino lifetime

arXiv:1401.5361

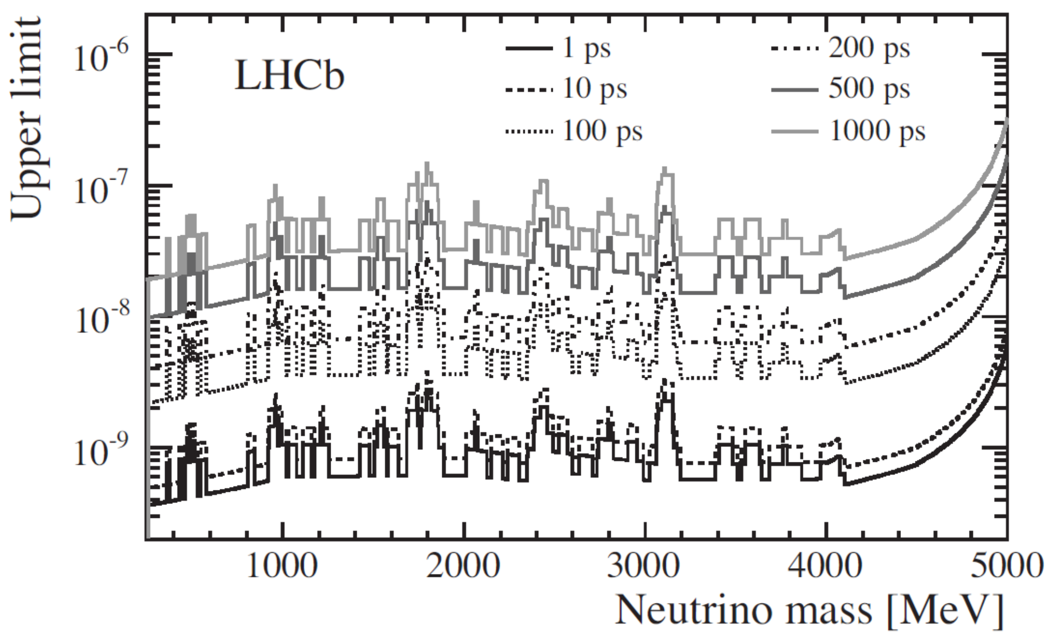


in the $\pi^+\mu^-\mu^-$ signal region (5239-5320 MeV)



- Peaking background : $B^+ \to J/\Psi K^+(\pi^+)$, $B^+ \to \Psi(2S) K^+$

- No signal found, limit as function of neutrino mass and lifetime



Bsmumu lifetime

- Experimental observable is the time integrated B:

$$B(B_s^0 \to f)_{\text{exp}} \equiv \frac{1}{2}\int_0^\infty \langle \Gamma(B_s^0(t) \to f)\rangle dt$$

- Theoretical definition for the prediction:

$$B(B_s^0 \to f)_{\text{theo}} \equiv \frac{\tau_{B_s^0}}{2}\langle \Gamma(B_s^0(t) \to f)\rangle \Big|_{t=0}$$

- Time integrated prediction:

$$BF(B_s^0 \to \mu^+\mu^-)_{exp} = BF(B_s^0(t) \to \mu^+\mu^-)_{t=0} \times \frac{1 + A_{\Delta\Gamma} y_s}{1 - y_s^2}$$

$$\mathcal{A}_{\Delta\Gamma}^f = \frac{\Gamma(B_{s,\mathrm{H}} \to f) - \Gamma(B_{s,\mathrm{L}} \to f)}{\Gamma(B_{s,\mathrm{H}} \to f) + \Gamma(B_{s,\mathrm{L}} \to f)} \qquad y_s = \frac{\Gamma_L - \Gamma_H}{\Gamma_L + \Gamma_H} = 0.0615 \pm 0.0085$$

$in\ the\ SM:\ A_{\Delta\Gamma} = 1 \quad B(B_s^0 \to \mu^+\mu^-)_{exp}^{SM} = (3.56 \pm 0.30) \times 10^{-9}$

De Bruyn et al., PRL 109, 041801(2012), uses ys from HFAG

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

- Angular analysis of $B_d \to K^{*0} e^+ e^-$ at small q^2 values is sensitive to photon polarization, which is predominantly left-handed in the SM
- Measurement of F_L , $A_T^{(2)}$ $A_T^{(Im)}$ $A_T^{(Re)}$ in the q^2 region [0.004,1.0] GeV^2, using 124 signal candidates

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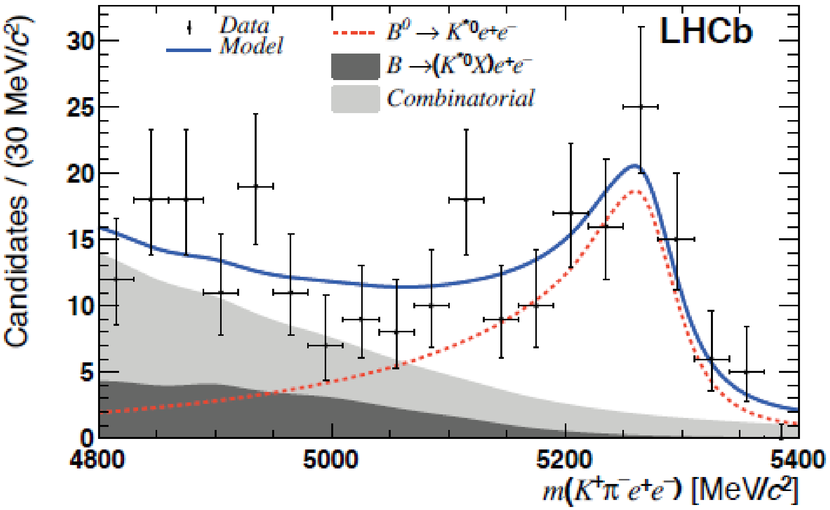

Result:

obs.	result
F_L	$+0.16 \pm 0.06 \pm 0.03$
$A_T^{(2)}$	$-0.23 \pm 0.23 \pm 0.05$
A_T^{Re}	$+0.10 \pm 0.18 \pm 0.05$
A_T^{Im}	$+0.14 \pm 0.22 \pm 0.05$

Jaeger et al. JHEP 05 (2013) 043

obs.	SM prediction
F_L	$+0.10^{+0.11}_{-0.05}$
$A_T^{(2)}$	$+0.03^{+0.05}_{-0.04}$
A_T^{Re}	$-0.15^{+0.04}_{-0.03}$
A_T^{Im}	$(-0.2^{+1.2}_{-1.2}) \times 10^{-4}$

Results consistent with SM, sensitivity to photon polarization comparable to time-dependent analysis of $B \to K_s \pi^0 \gamma$ by B factories (PRD 78 071102, PRD 74 111104)

$B_s \to \phi\mu^+\mu^-$

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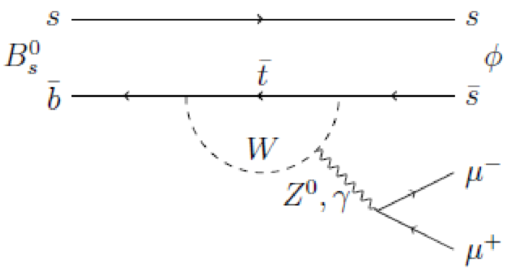
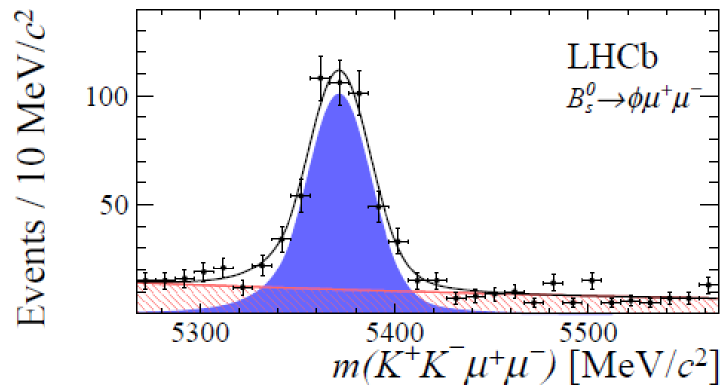
- Very similar to $B_d \to K^{*0}\mu^+\mu^-$, but not self-tagged

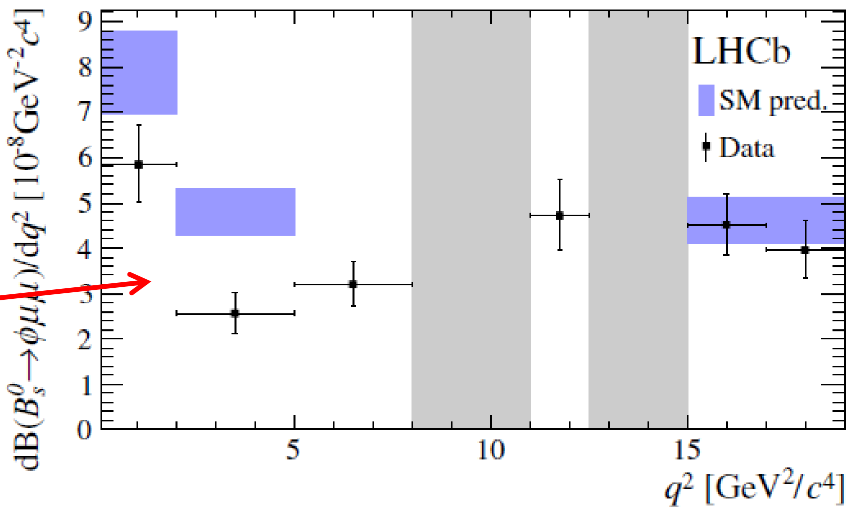




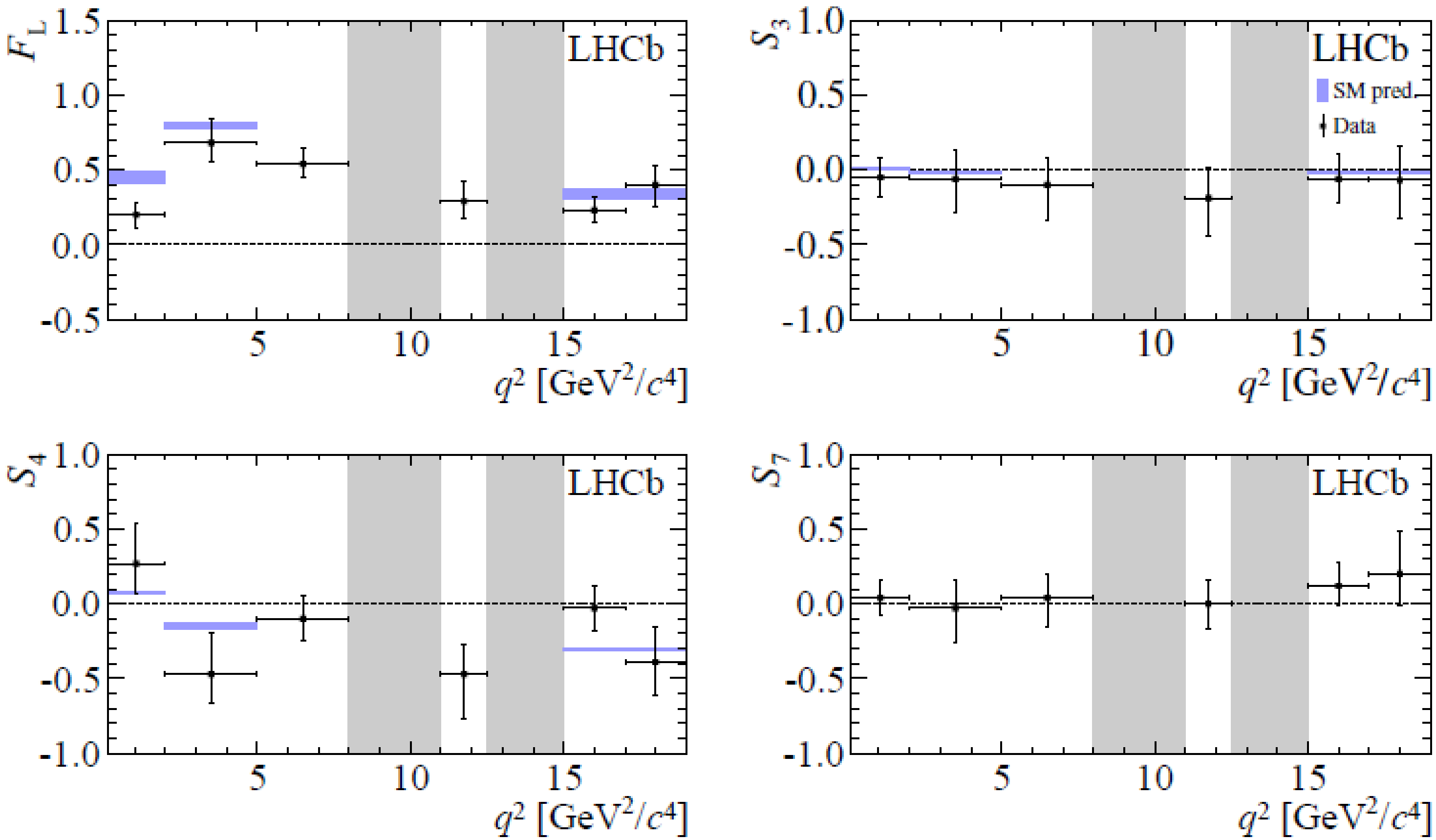
- Update with full Run1 data : 432 ± 24 signal events

- Full angular analysis performed

Branching fraction also shows tension with SM prediction at low q^2

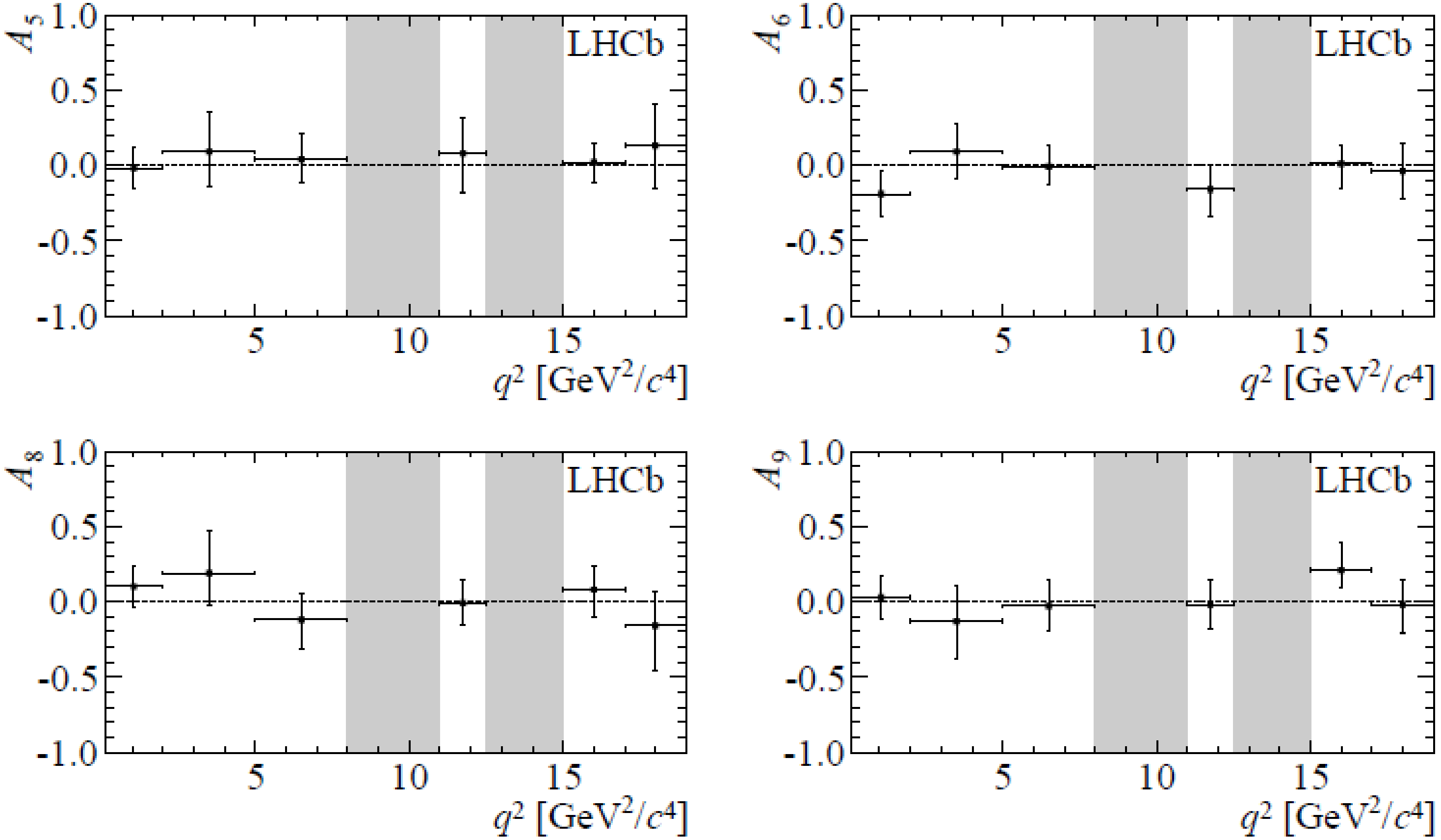


$B_s \to \phi\mu^+\mu^-$



All angular observables consistent with SM predictions

$B_s \to \phi\mu^+\mu^-$



All angular observables consistent with SM predictions

$\Lambda_b \rightarrow \Lambda\mu^+\mu^-$

- Baryonic system provides sensitivity to additional observables
- Measurement of the BR in 8 q^2 bins
- Rate still too low to perform a full angular analysis but forward-backward asymmetries are measured fitting one dimensional angular distributions

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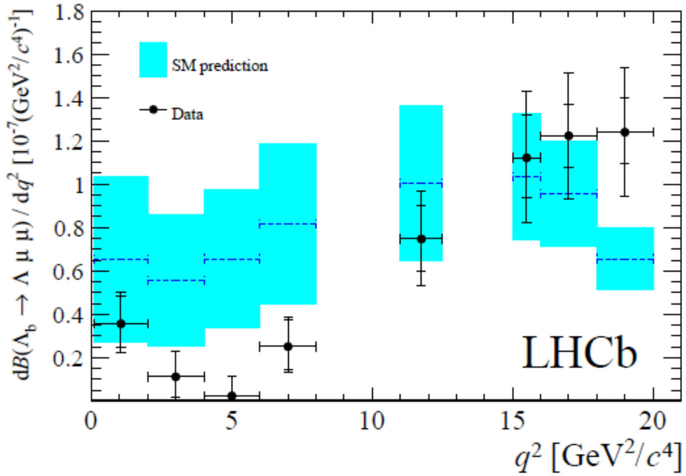

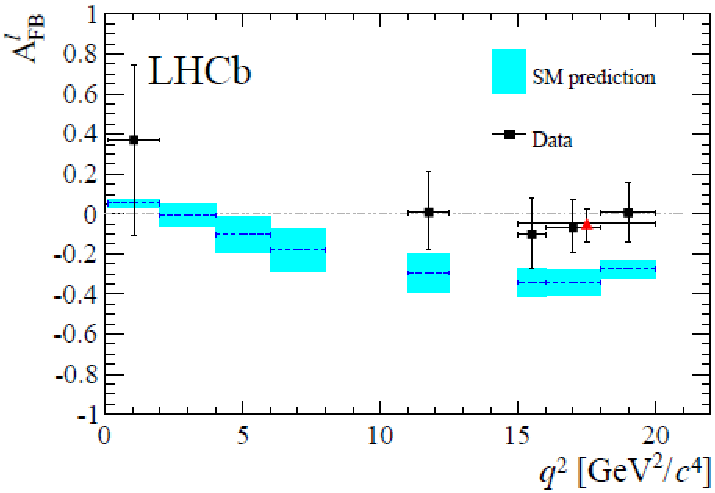

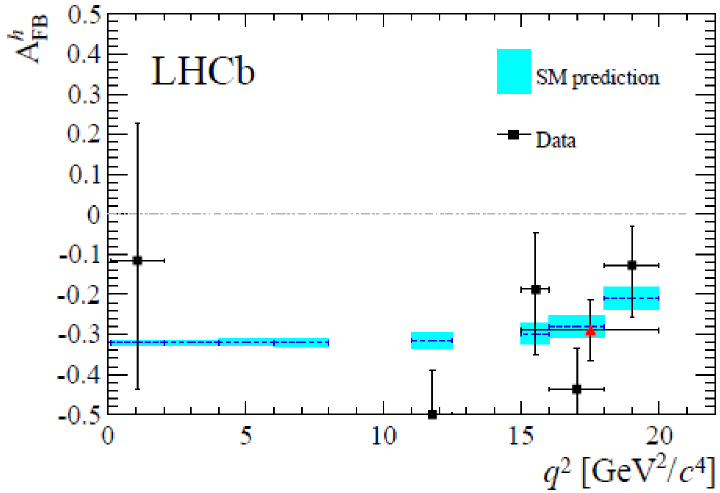

Similar tension with SM prediction for branching fraction at low q^2