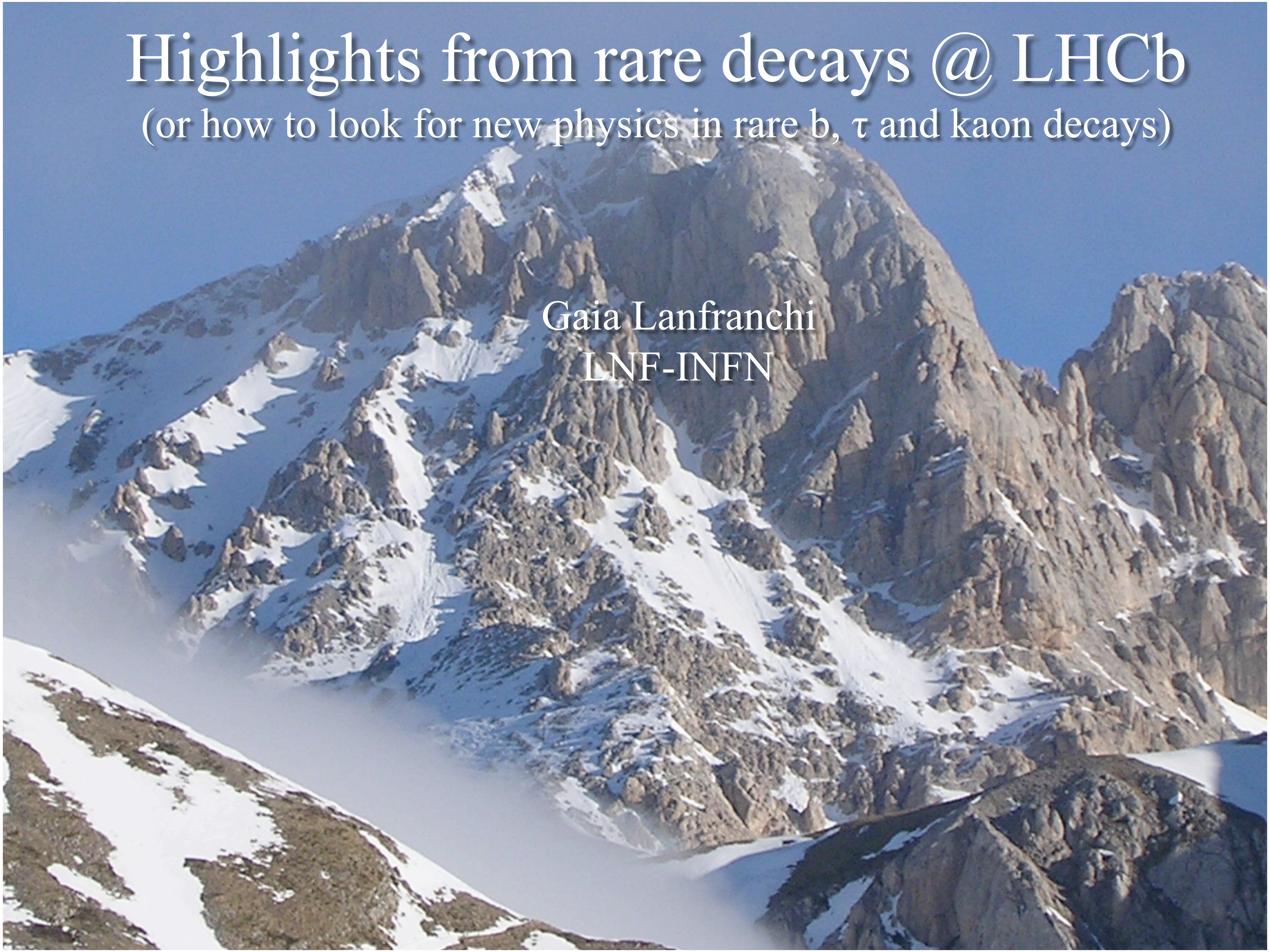
Highlights from rare decays @ LHCb

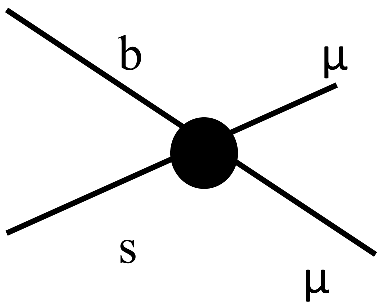
(or how to look for new physics in rare b, τ and kaon decays)

Gaia Lanfranchi
LNF-INFN

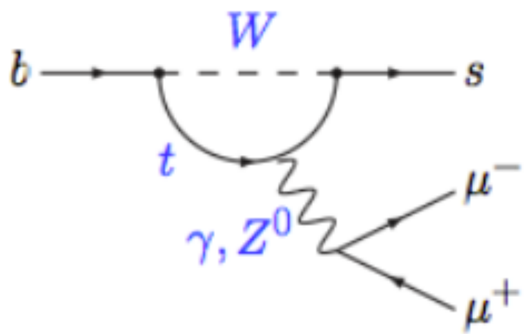


What we are doing

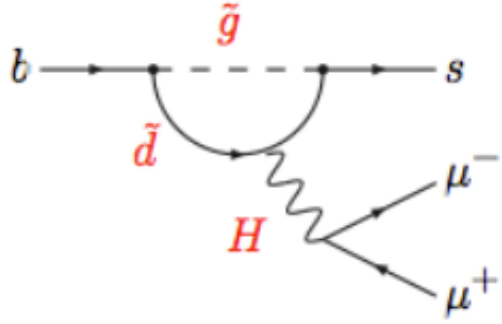
We are looking for New Physics in FCNC b-, K- decays and LFV τ decays that can be sensitive to quantum corrections from degrees of freedom **at** or **above** the electroweak scale.



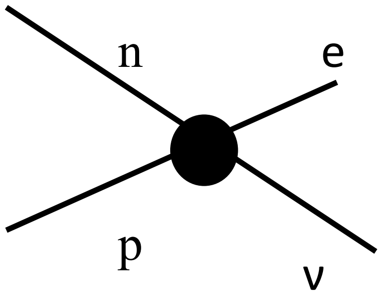
SM



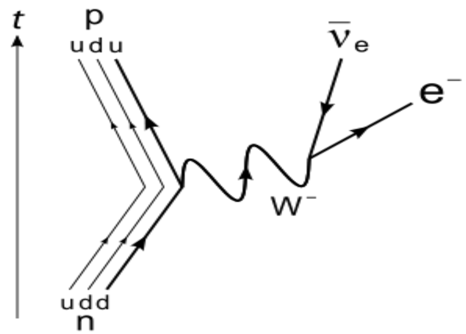
New Physics?



Nothing different from what was done in the past at the dawn of the electroweak theory:



1934: Fermi's theory of the nuclear beta decay (only S & V currents)
1936: Gamow-Teller transitions
→also T and A are possible
1957: Mme Wu experiment:
The parity is violated in weak interactions
1957: Feynman-Gellmann: V-A theory
….
1968: Glashow, Weinberg and Salam: Standard Model



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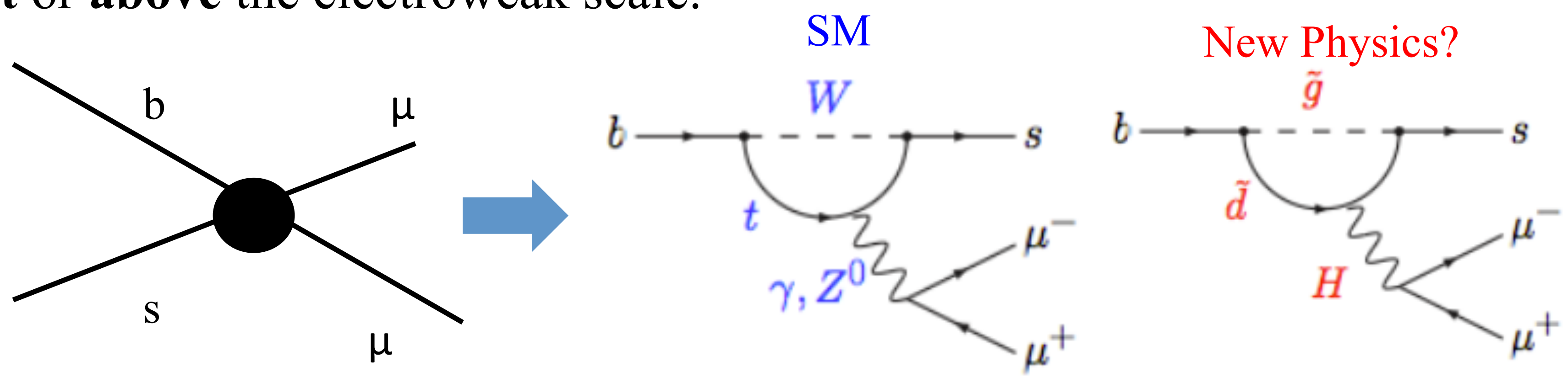

Today we describe FCNC processes by an effective Hamiltonian in the form of Operator Product Expansion to identify the types of operators that enter in the transitions:

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \Big[\underbrace{C_i(\mu) O_i(\mu)}_{\text{left-handed part}} + \underbrace{C_i'(\mu) O_i'(\mu)}_{\substack{\text{right-handed part} \\ \text{suppressed in SM}}} \Big] + \sum \frac{c}{\Lambda_{NP}^2} O_{NP}$$

i = 1,2	Tree
i = 3 − 6,8	Gluon penguin
i = 7	Photon penguin
i = 9,10	Electroweak penguin
i = S	Higgs (scalar) penguin
i = P	Pseudoscalar penguin

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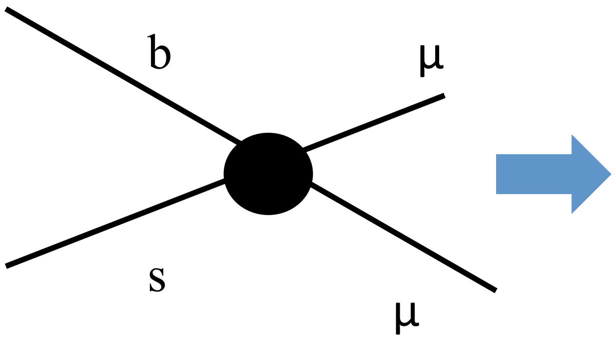

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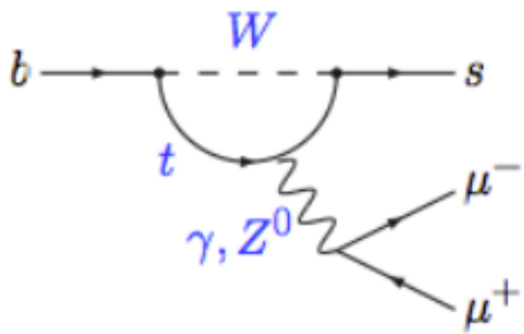
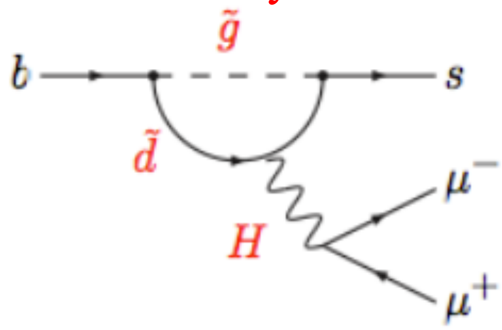


New Physics?



NP can modify the Wilson coefficients (C_i) affecting observable quantities as angular distributions in $B \rightarrow K^{(*)}\mu\mu$ decays (C_7,C_9,C_{10}), branching fractions in $B \rightarrow \mu\mu$ decays (C_s, C_p) and photon polarization (C'_7)

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Or add new operators (Majorana neutrinos, light mediators, etc) at an unknown scale Λ_{NP}

NP can modify angular distributions:

- Angular analysis of $B^+ \to K^+\mu^+\mu^-$ and $B_d \to K_s\,\mu^+\mu^-$ decays
- Full angular analysis of $B_d \to K^*\,\mu^+\mu^-$ decays
- Measurement of the differential BR and helicity structure of $\Lambda_b \to \Lambda\mu\mu$ decays

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..or modify the values of branching fractions…:

- Measurement of the isospin asymmetry in $B \to K^{(*)} \mu\mu$ decays
- Measurement of the ratio $R_k = BR(B^+ \to K^+ \mu^+ \mu^-)/BR(B^+ \to K^+ e^+ e^-)$
- First observation of the rare decays $B^+ \to K^+ \pi^+ \pi^- \mu^+ \mu^-$ and $B^+ \to \varphi K^+ \mu^+ \mu^-$
- Measurement of the $BR(B \to \pi^+ \pi^- \mu^+ \mu^-)$
- Measurement of differential BR and S-wave of $B_d \to K^* \mu^+ \mu^-$ decays
- Measurement of A_{CP} in $B \to K^{(*)} \mu^+ \mu^-$ decays
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- Measurement of the photon polarization in $B_s \rightarrow \varphi \gamma$ decays

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- Search for heavy Majorana neutrinos in $B^- \to \pi^+\mu^-\mu^-$ decays
- Search for $\tau \to 3\mu$ decays with 3 fb^{-1}
- Search for weakly interacting long-lived particles in B and Σ decays

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Some of the Rare Decays processes studied at LHCb in the last year

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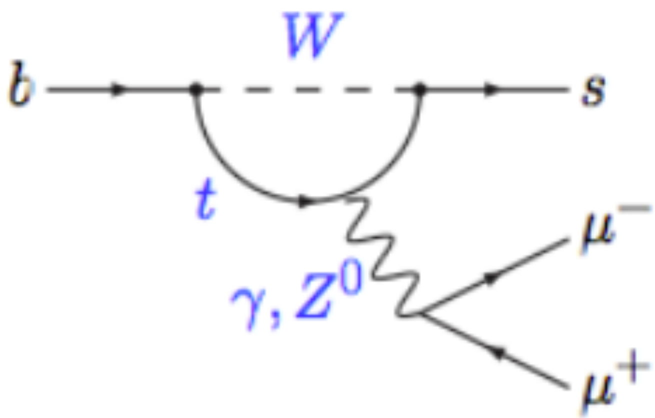
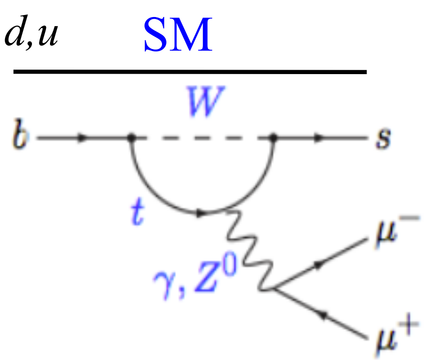
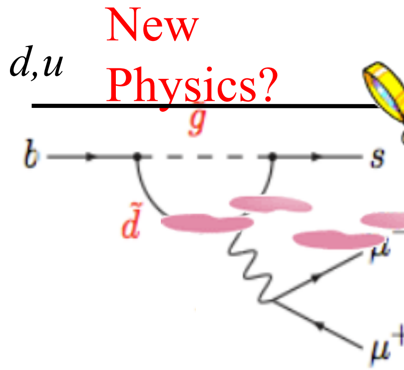
…You will see that, despite the variety of topics,
we will be talking almost always about the same diagram
(in different flavors)….



Angular analysis of B→ $K^{(*0)}\mu^+\mu^-$ decays

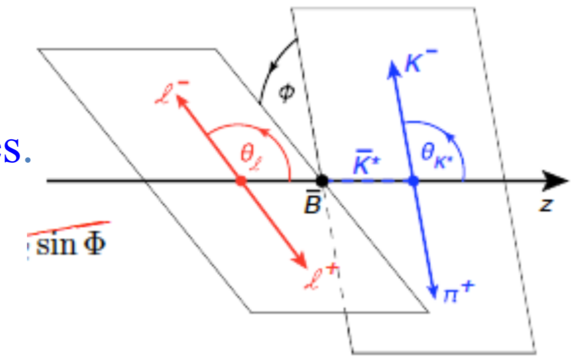
FCNC decays dominated by electro-weak penguins are extremely interesting as **New Physics amplitudes could enter at the same level of the standard model ones** and **modify angular distributions and branching fractions:**





However the angular analysis of the $B \rightarrow K^{*0}\mu^+\mu^-$ decay is complicated:

3 angles, 12 different J_i coefficients (which contain the information from Wilson coefficients) due to 6 complex numbers that define the K^{*0} spin amplitudes.



Angular analysis of $B^0 \rightarrow K^{*0}\,\mu^+\mu^-$ decays

Angular analysis of $B \rightarrow K^{*0}\,\mu^+\mu^-$ is complicated:

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_K\, d\cos\theta_l\, d\phi} = \frac{9}{32\pi}\Big[J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K + (J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_l$$

$$+J_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + J_4\sin 2\theta_K\sin 2\theta_l\cos\phi + J_5\sin 2\theta_K\sin\theta_l\cos\phi$$

$$+(J_{6s}\sin^2\theta_K + J_{6c}\cos^2\theta_K)\cos\theta_l + J_7\sin 2\theta_K\sin\theta_l\sin\phi + J_8\sin 2\theta_K\sin 2\theta_l\sin\phi$$

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$$+ J_9 \sin^2\theta_K \sin^2\theta_l \sin 2\phi\Big], \qquad (1)$$

J_i terms depend on the complex spin amplitudes $A_0^{L,R}, A_\parallel^{L,R}, A_\perp^{L,R}$

$$J_3 = \frac{1}{2}\beta_\ell^2\left[|A_\perp^L|^2 - |A_\parallel^L|^2 + |A_\perp^R|^2 - |A_\parallel^R|^2\right]$$

(an example)

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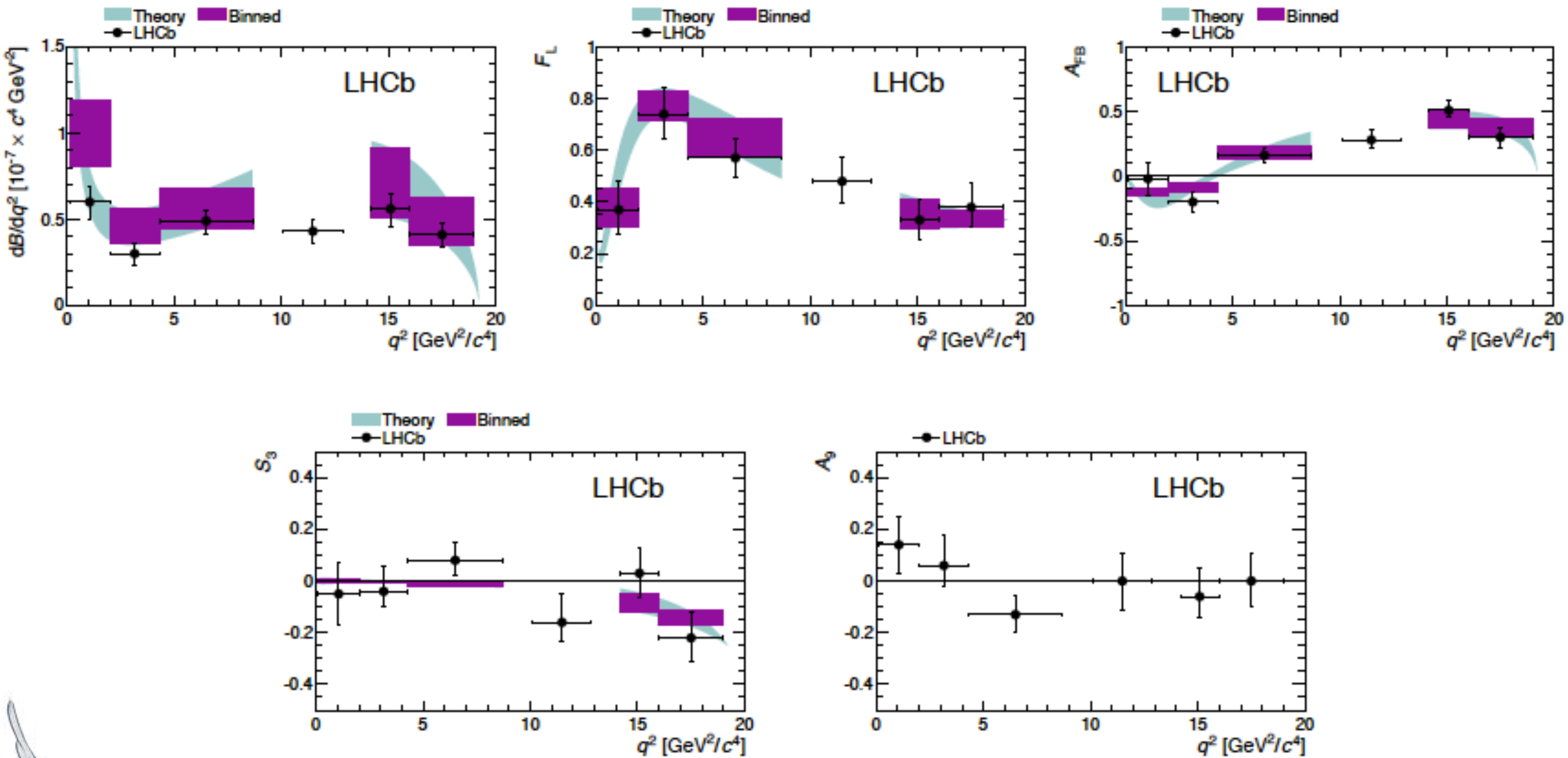
The spin amplitudes depend on the Wilson coefficients via form factors q^2 dependent;

$$A_\perp^{L(R)} = N\sqrt{2\lambda}\left\{\left[(C_9^{\rm eff} + C_9^{\prime\rm eff}) \mp (C_{10}^{\rm eff} + C_{10}^{\prime\rm eff})\right]\frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2}(C_7^{\rm eff} + C_7^{\prime\rm eff})T_1(q^2)\right\}$$

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

- Simultaneous fit was not possible with $1\,\mathrm{fb}^{-1}$
  $\to$ Angular foldings, *e.g.* $\Phi \to \Phi + \pi$ for $\Phi < 0$ cancels terms $\propto \sin\Phi, \cos\Phi$

LHCb , JHEP08 (2013) 131

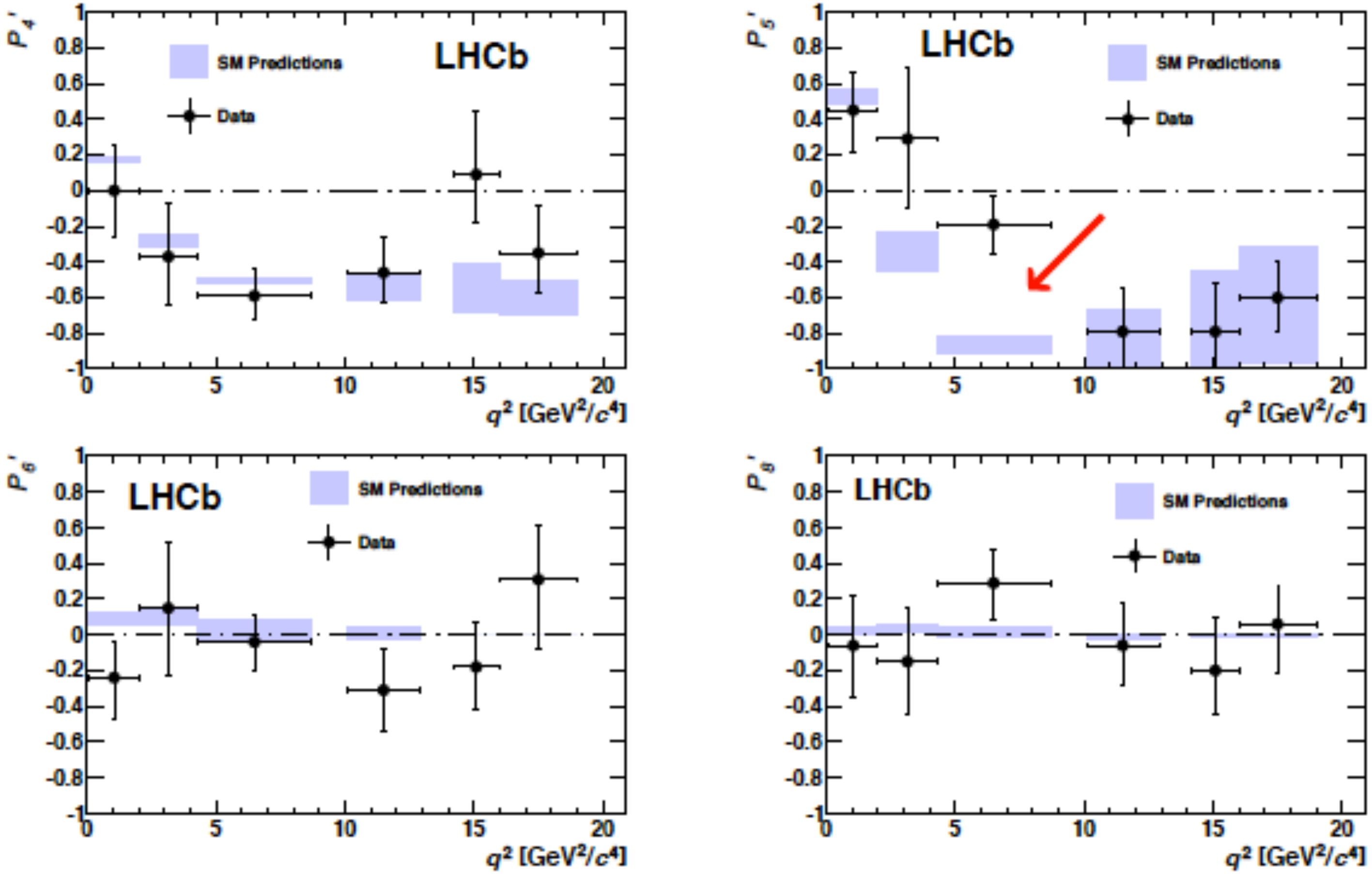


Results obtained with 1 fb^{-1} in good agreement with SM predictions
(C. Bobeth et al., JHEP07 (2011) 067)

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

- Remaining angular observables require different angular folding
- Determine $P'_{4,5,6,8} = S_{4,5,7,8}/\sqrt{F_L(1-F_L)}$

LHCb, PRL 111 (2013) 191801



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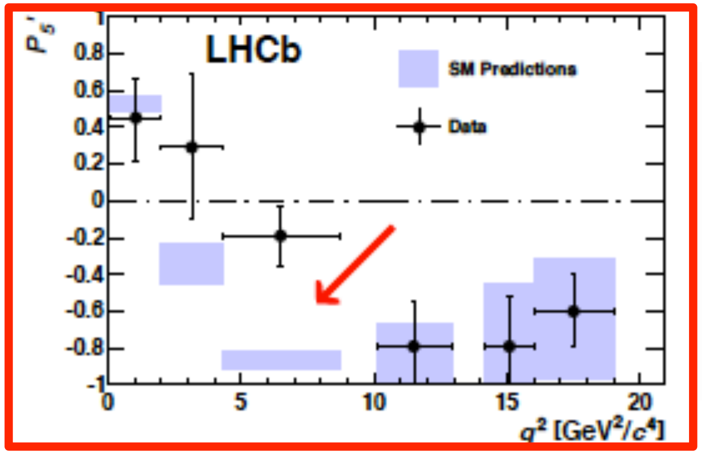
$4.3 < q^2 < 8.68$ GeV^2/c^4



Can be explained by a negative NP contribution to the Wilson coefficient C_9, namely C_9=C_9(SM)-1.5

Descotes-Genon, Virto, Matias PRD 88 (2013) 074002
D. Van Dyck, C. Bobeth, F. Beaujean arXiv 1310.2478
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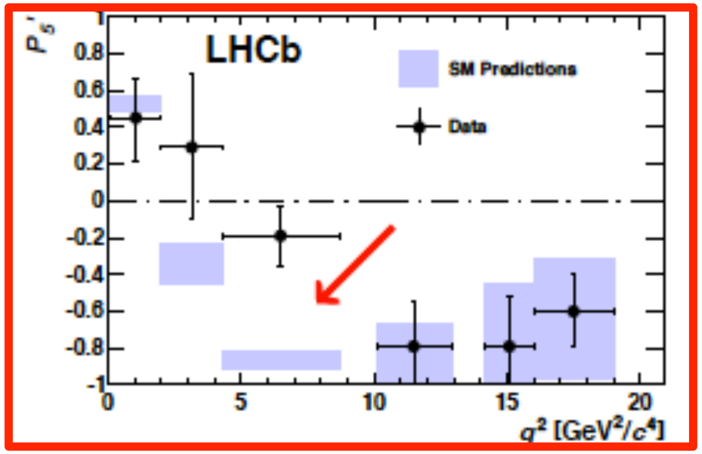

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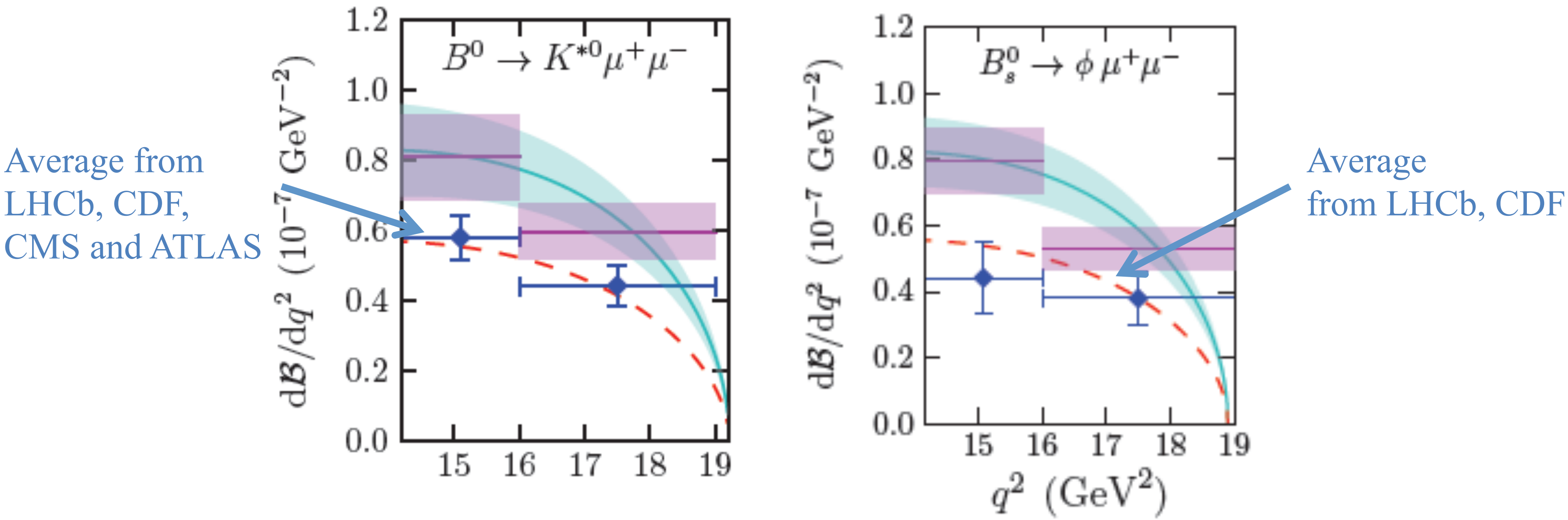
Z' contribution?
[Gauld et al., arXiv:1310.1082]
Exotic scalars?
[Datta et at., arXiv: 1310.1937]

Wait for analysis of the full 3 fb^{-1} dataset….

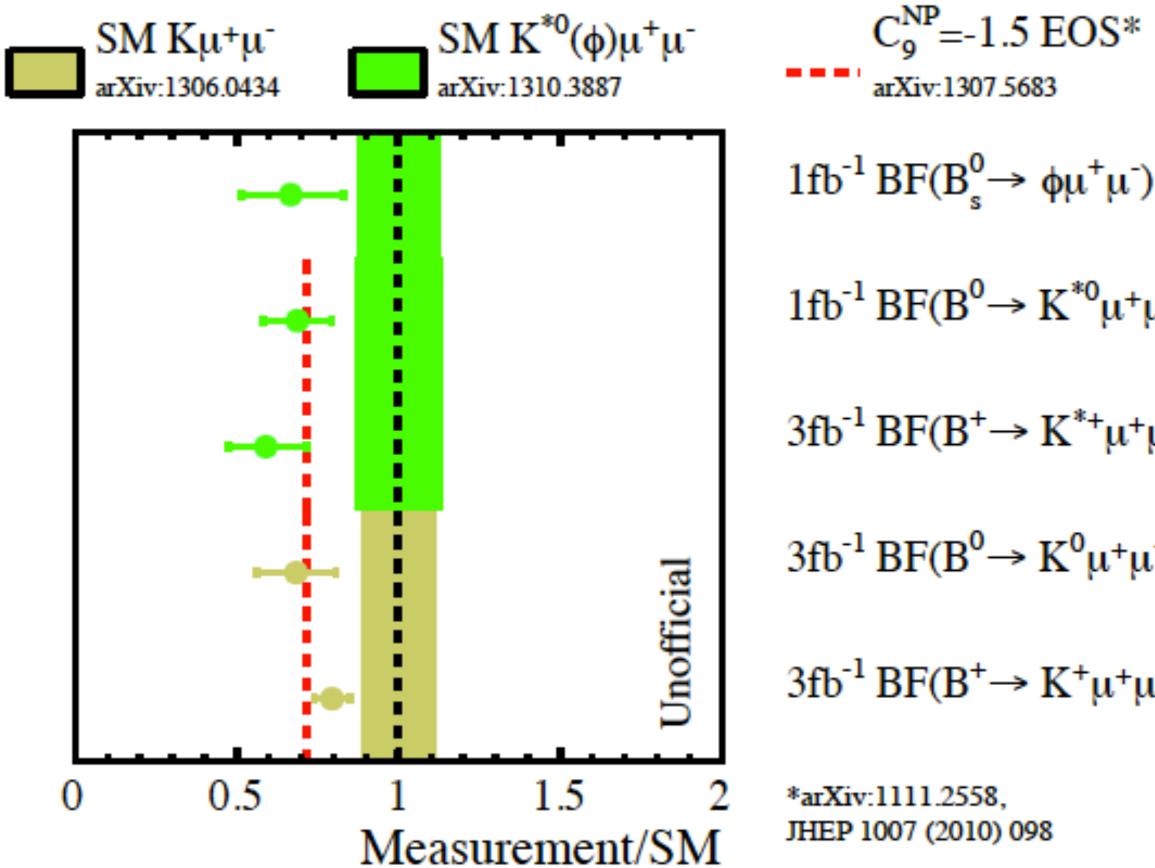
Differential BRs of $B^0 \rightarrow K^{*0}\mu^+\mu^-$ and $B_s \rightarrow \phi\mu^+\mu^-$ decays

Hints of deviation from SM predictions also in the differential BRs of $B \rightarrow K^{*0}\mu+\mu-$ and $B_s \rightarrow \varphi\mu+\mu-$ decays could be explained by the same value of C_9(NP) [Horgan et al., arXiv:1310.3887]



LHCb: arXiv 1308.1707, JHEP 1308 (2013)131, JHEP 1307 (2013) 084
CDF: Public note 10894
CMS: arXiv: 1308.3409
ATLAS: ATLAS-CONF-2013-038

High-q^2 differential branching fractions from $b \to s\mu\mu$ transitions @ LHCb



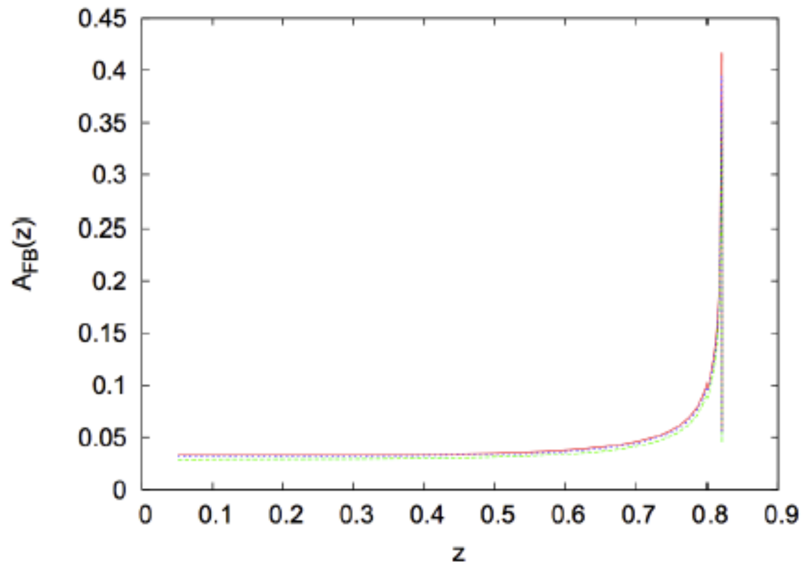
- **High q^2** branching fraction measurements are below the latest SM (lattice) predictions
- Better consistency with C_9^{NP}=-1.5 suggested by (**low q^2**) anomalous angular data

Angular analysis of $B^+ \to K^+ \mu^+ \mu^-$ decays

The angular distribution of $B^+ \to K^+ \mu^+ \mu^-$ decays is instead simple:
a single angle in the di-lepton system and two parameters, A_{FB} and F_H (the flat term)

$$\frac{1}{\Gamma_\ell}\frac{d\Gamma_\ell[B \to P\ell^+\ell^-]}{d\cos\theta_l} = \frac{3}{4}(1-F_{\rm H})(1-\cos^2\theta_l) + \frac{1}{2}F_{\rm H} + A_{\rm FB}\cos\theta_l$$

In the SM, the forward-backward asymmetry of the di-lepton system is expected to be zero. Any non-zero forward backward asymmetry would point to a contribution from NP

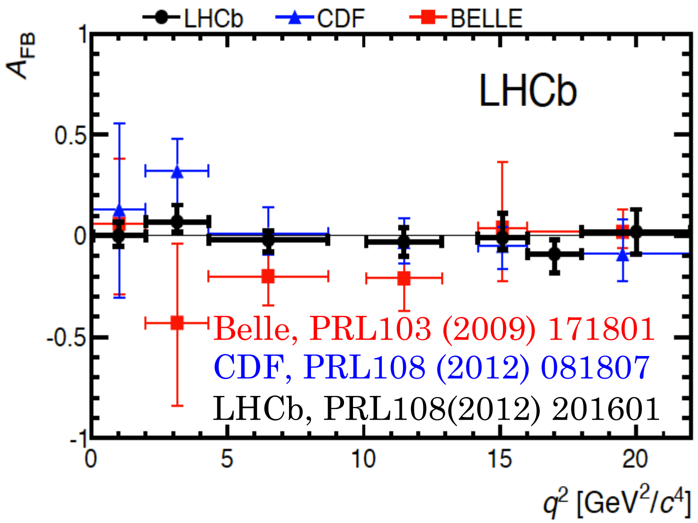


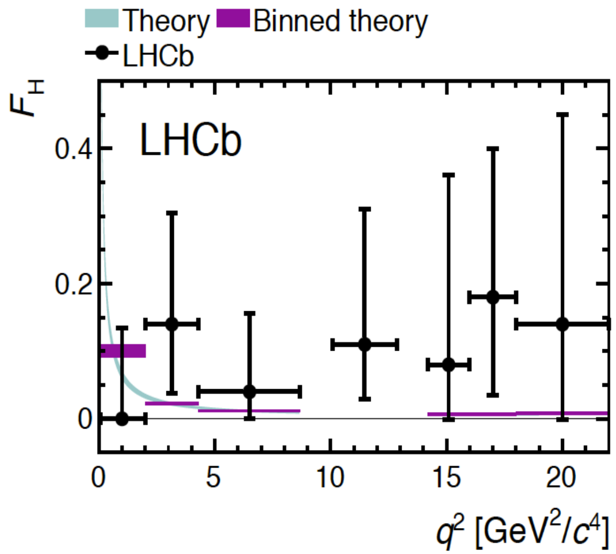
A_{FB} and F_H sensitive to (pseudo-)scalar and tensor couplings

Alok et al., PRD 78 (2008) 114025
C. Bobeth et al., JHEP 12 (2007) 040

Angular analysis of $B^+ \to K^+ \mu^+ \mu^-$ decays

Angular analysis performed with 1 fb^{-1} was already leading the world average and provided results compatible with SM





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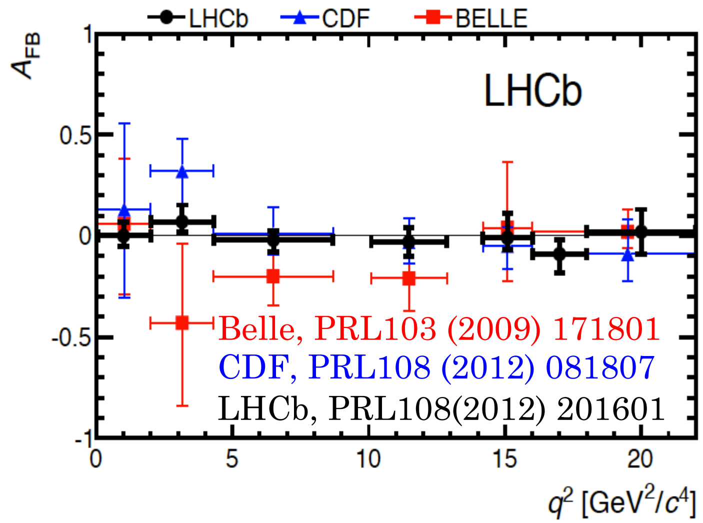
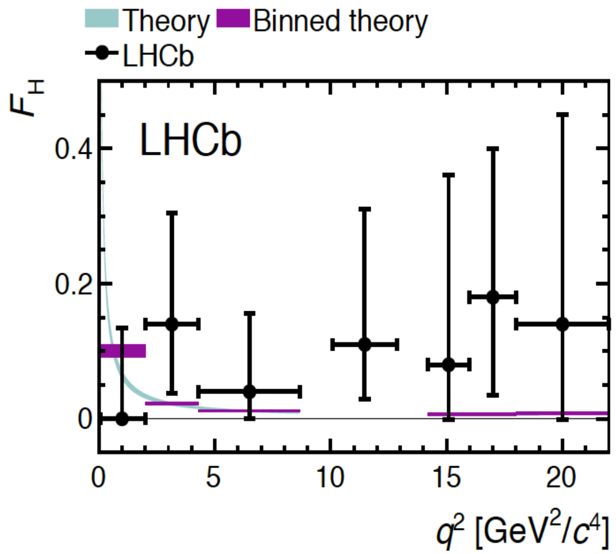
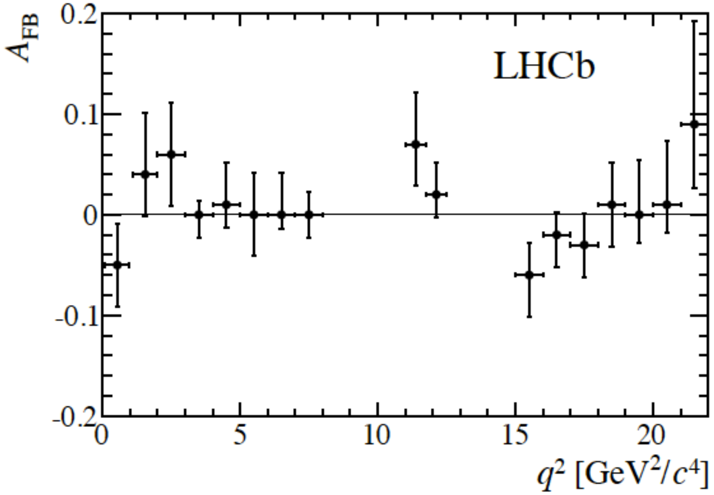
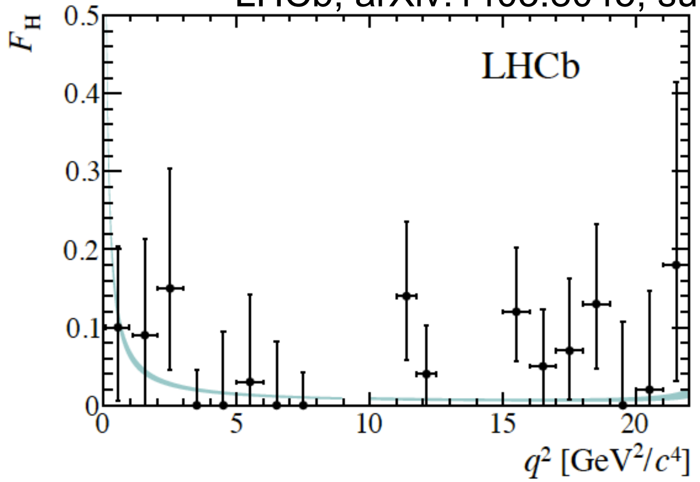




Angular analysis performed with 3 fb^{-1} confirms previous results.

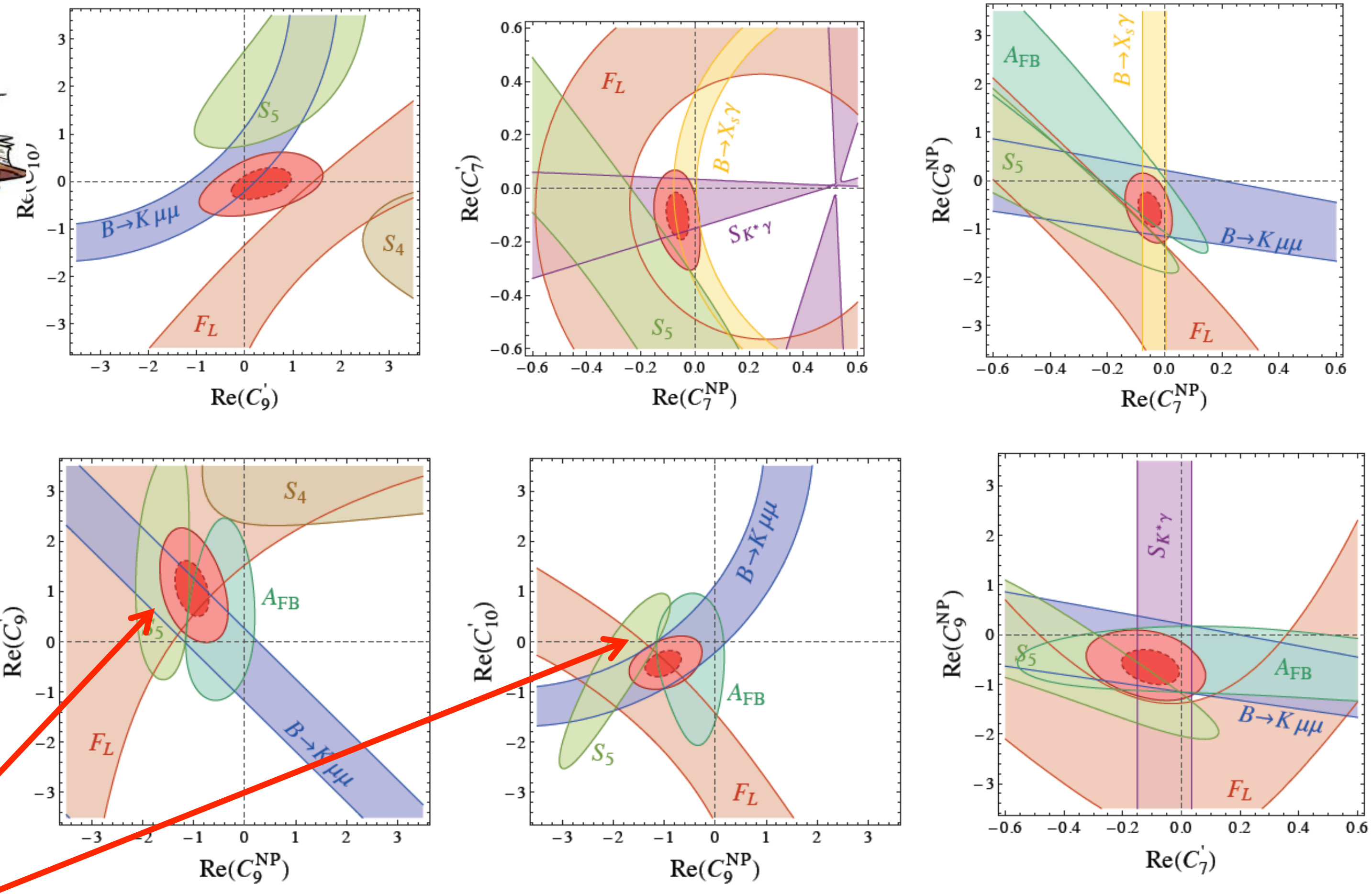
LHCb, arXiv:1403.8045, submitted to JHEP





The DNA of the Wilson coefficients

Global fit to the Wilson coefficients [Straub, Altmannshofer arXiv:1308.1501]



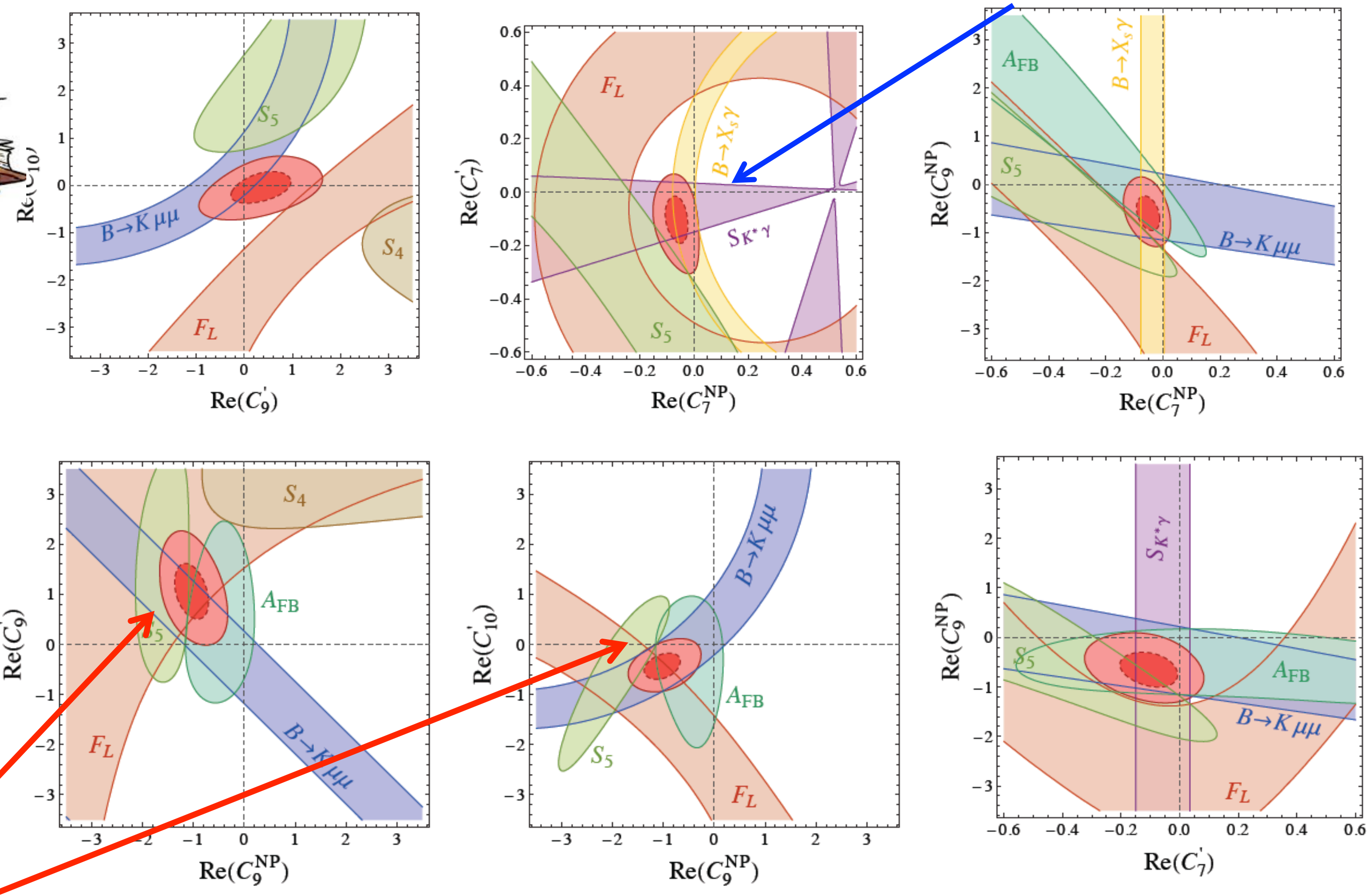
C_9(NP) is negative

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i \Big[\boxed{\underbrace{C_i(\mu)O_i(\mu)}_{\text{left-handed part}}} + \underbrace{C'_i(\mu)O'_i(\mu)}_{\substack{\text{right-handed part}\\ \text{suppressed in SM}}} \Big] + \sum \frac{c}{\Lambda^2_{NP}} O_{NP}$$

The DNA of the Wilson coefficients

Straub, Altmannshofer arXiv:1308.1501

C_7’ compatible with zero (so far)

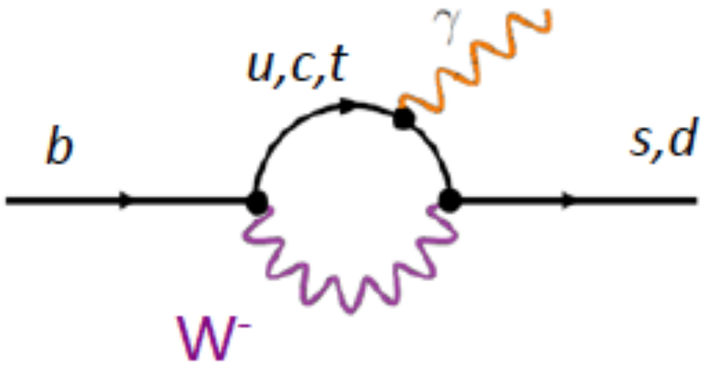


C_9(NP) is negative

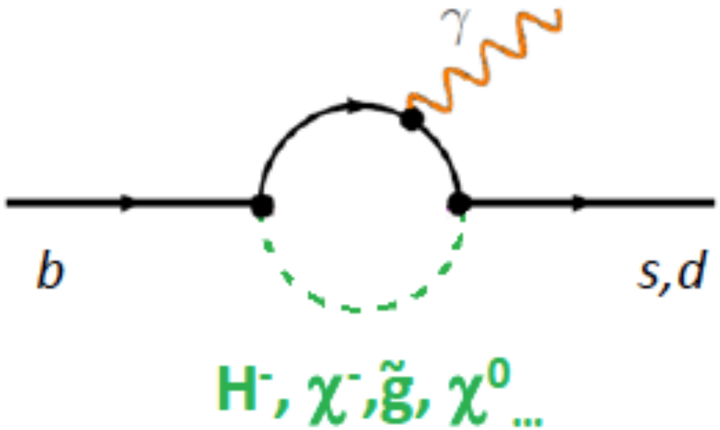
$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^{*} \sum_i \Big[\underbrace{C_i(\mu)O_i(\mu)}_{\text{left-handed part}} + \underbrace{C'_i(\mu)O'_i(\mu)}_{\substack{\text{right-handed part}\\ \text{suppressed in SM}}} \Big] + \sum \frac{c}{\Lambda_{NP}^2} O_{NP}$$

Measurement of the photon polarization in $B^+ \to K^+\pi^+\pi^- \gamma$ & $B_s \to \varphi \gamma$ decays

The SM predicts that the **photon emitted in $b \to s \gamma$ decays is predominantly left-handed**, since the recoil s-quark that couples to a W-boson is left-handed .



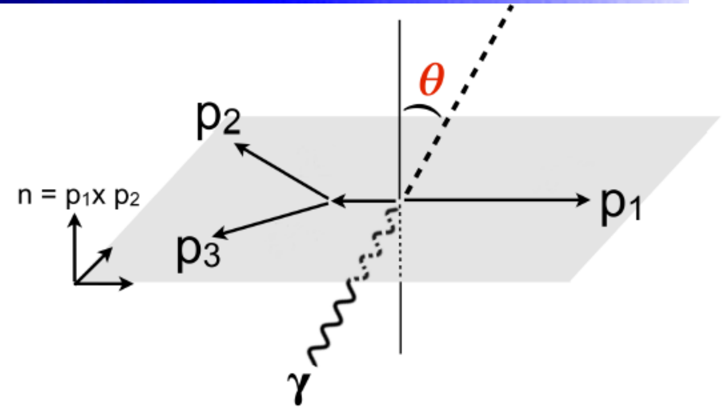
Several models beyond the SM predict the photon to **acquire a significant right-handed component due to the exchange of a heavy fermions** in the electroweak penguin loop.



D. Atwood, M. Gronau, A. Soni, PRL79(97) 185
M. Gronau, D. Pirjol, PRD66(02)054008
F.Yu, E. Kou,C.Lu, JHEP12(2013)102

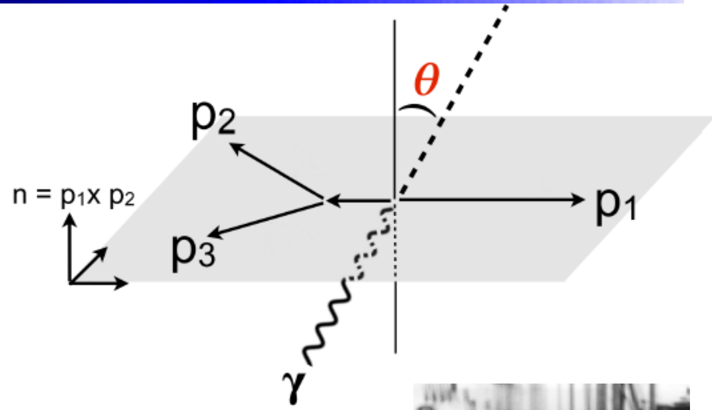
Measurement of the photon polarization in $B^+ \to K^+\pi^+\pi^- \gamma$ decays

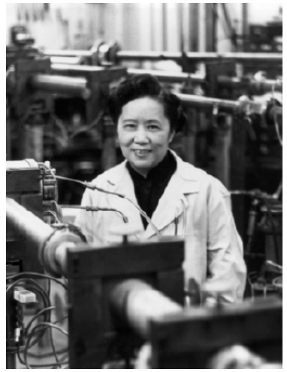
Information about the photon polarization is determined from the angular distribution of the photon with respect to the plane defined by the three final-state hadrons in their center-of-mass frame.



Measurement of the photon polarization in $B^+ \rightarrow K^+\pi^+\pi^- \gamma$ decays

Information about the photon polarization is determined from the angular distribution of the photon with respect to the plane defined by the three final-state hadrons in their center-of-mass frame.



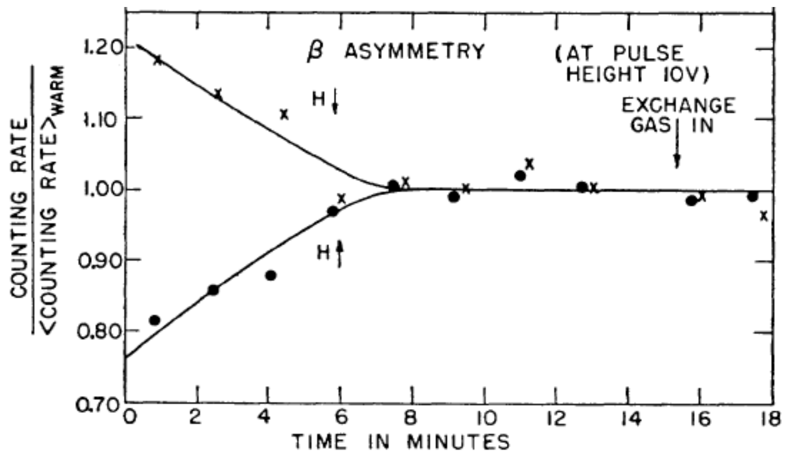


Conceptually is the same experiment performed by Mme Wu that led to the discovery of the parity violation in β decays…..

PRL 105 (1957) 1413

$^{60}\mathrm{Co} \rightarrow {}^{60}\mathrm{Ni} + e^- + \bar{\nu}_e$

… the emission of beta particles is more favored in the direction opposite to that of the nuclear spin. This naturally implies that the sign for C_T and $C'_{T'}$ (parity conserved and parity not conserved) must be opposite…

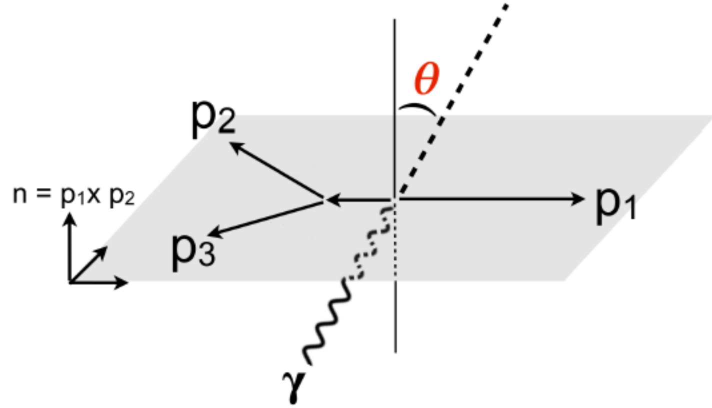


Measurement of the photon polarization in $B^+ \to K^+\pi^+\pi^- \gamma$ decays

LHCb, arXiv:1402.6852
Accepted by PRL

The up-down asymmetry is defined as:

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



where

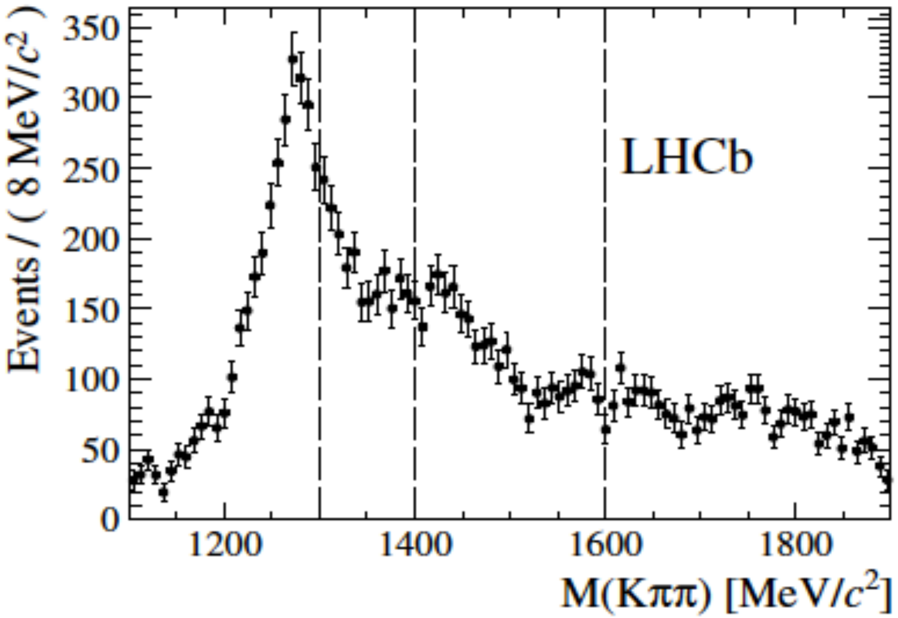
$$\frac{\mathrm{d}\Gamma}{\mathrm{d}s\,\mathrm{d}s_{13}\,\mathrm{d}s_{23}\,\mathrm{d}\cos\theta} \propto \sum_{i=0,2,4} a_i(s, s_{13}, s_{23}) \cos^i\theta + \lambda_\gamma \sum_{j=1,3} a_j(s, s_{13}, s_{23}) \cos^j\theta,$$

$$\lambda_\gamma \equiv \frac{|c_R|^2 - |c_L|^2}{|c_R|^2 + |c_L|^2},$$

Where $s_{ij} = (p_i+p_j)^2$ and the a_i contain the information about the resonances and their interference: the odd terms in $\cos\theta$ carry the photon polarization: If $\lambda\gamma \neq 0$ the photon is polarized. In SM $\lambda_\gamma \sim -1$ $(+1)$ for radiative $\overline{B}$ (B) decays up to $O(m_s^2/m_b^2)$ corrections.

Measurement of the photon polarization in $B^+ \to K^+\pi^+\pi^- \gamma$ decays

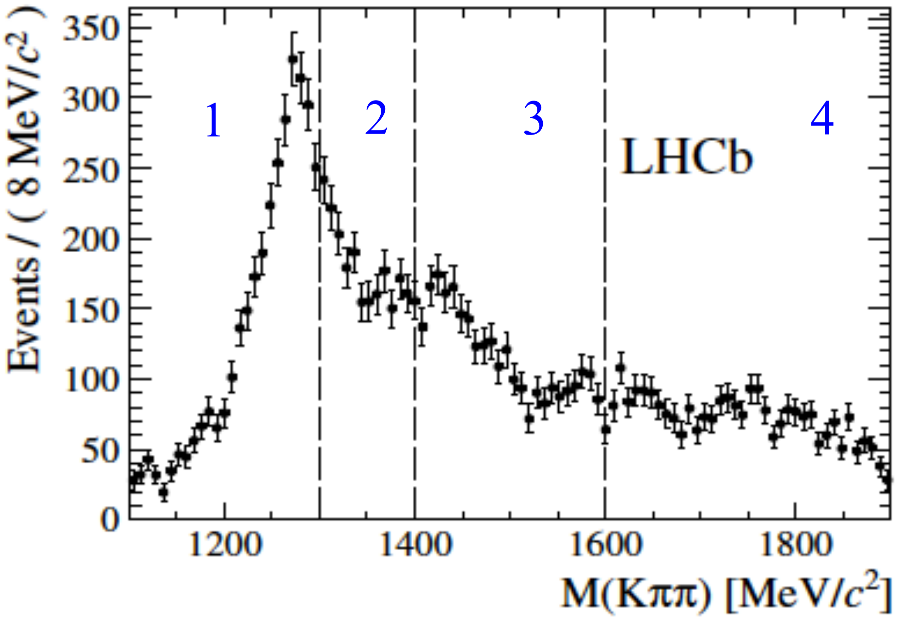
LHCb, arXiv:1402.6852
Accepted by PRL

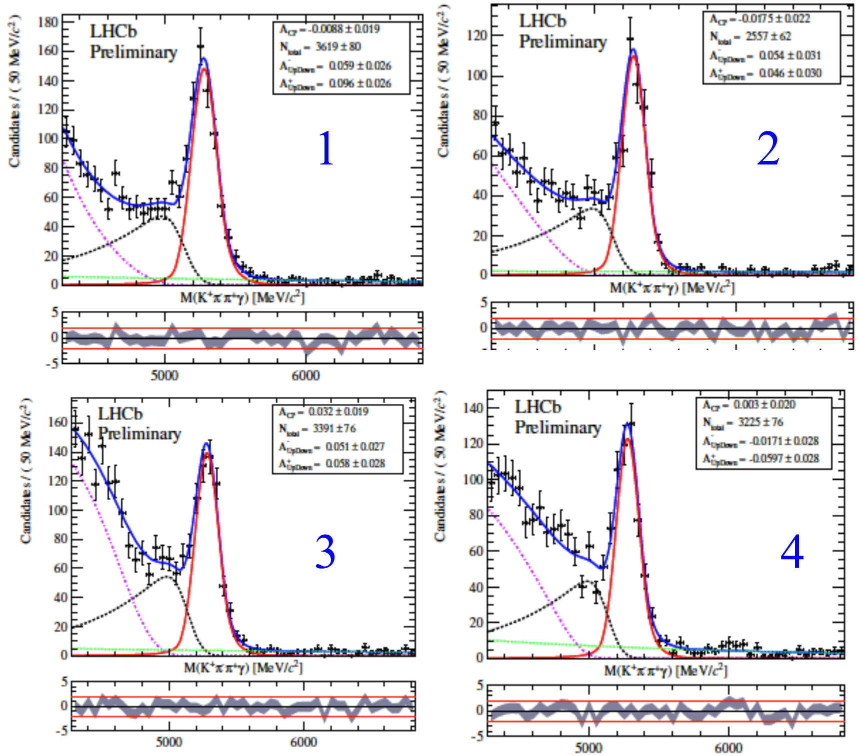


The problem is that the $K^+\pi^+\pi^-$ spectrum is given by a superposition of different resonances (main resonances are $K^+(1270)$ and $K^+(1400)$) and their interference: to translate a measurement of the up-down asymmetry into an actual value of λ_γ requires theory input !

Measurement of the photon polarization in $B^+ \to K^+\pi^+\pi^- \gamma$ decays

LHCb, arXiv:1402.6852
Accepted by PRL





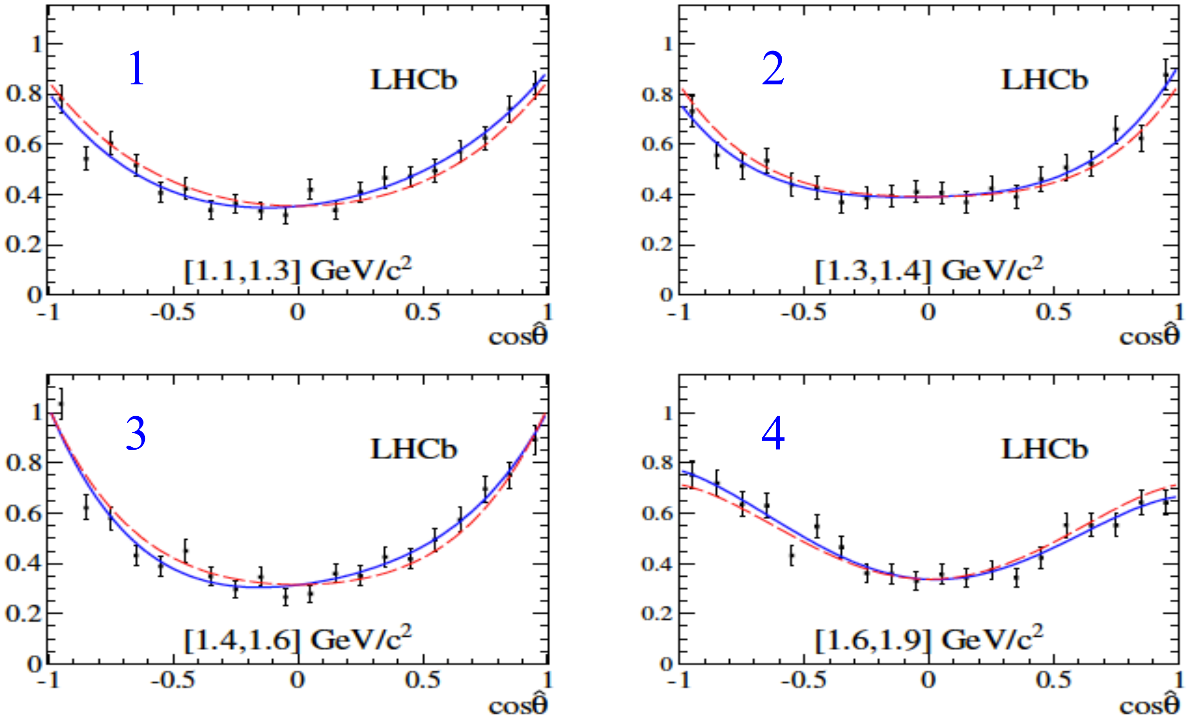
The analysis is performed in four region of interest: [1.1-1.3],[1.3-1.4],[1.4-1.6] and [1.6-1.9] GeV/c^2

In each region a simultaneous fit to the B-candidate mass spectra in bins of the photon direction angle is performed to determine the angular distributions.

Measurement of the photon polarization in $B^+ \to K^+\pi^+\pi^- \gamma$ decays

LHCb, arXiv:1402.6852
Accepted by PRL

Without odd terms
With odd terms



The resulting background-subtracted cosθ distributions, corrected for the selection acceptance and normalized to the inverse of the bin-width, are fit with a fourth-order polynomial function:

$$f(\cos\hat{\theta}; c_0 = 0.5, c_1, c_2, c_3, c_4) = \sum_{i=0}^{4} c_i L_i(\cos\hat{\theta}),$$

Where L_i is the Legendre polynomial of order i and c_i the coefficient.

The up-down asymmetry is: $A_{ud} = c_1 - c_3/4$

Measurement of the photon polarization in $B^+ \to K^+\pi^+\pi^- \gamma$ decays

LHCb, arXiv:1402.6852
Accepted by PRL

Four different significances for the A_{ud} to be different from zero are determined:

	[1.1, 1.3]	[1.3, 1.4]	[1.4, 1.6]	[1.6, 1.9]
c_1	6.3 ± 1.7	5.4 ± 2.0	4.3 ± 1.9	-4.6 ± 1.8
c_2	31.6 ± 2.2	27.0 ± 2.6	43.1 ± 2.3	28.0 ± 2.3
c_3	-2.1 ± 2.6	2.0 ± 3.1	-5.2 ± 2.8	-0.6 ± 2.7
c_4	3.0 ± 3.0	6.8 ± 3.6	8.1 ± 3.1	-6.2 ± 3.2
$\mathcal{A}_{\rm ud}$	6.9 ± 1.7	4.9 ± 2.0	5.6 ± 1.8	-4.5 ± 1.9

The sum of the squares of these values distribute as a χ^2 variable with four degrees of freedom for which a p-value=1.7×10^{-7} is obtained.

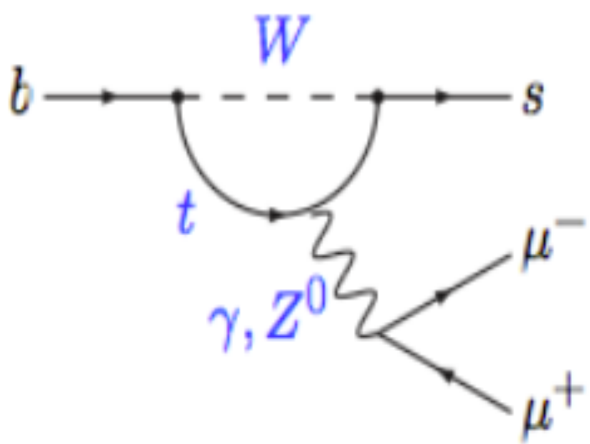
This translates into a 5.2 σ significance for A_{ud}

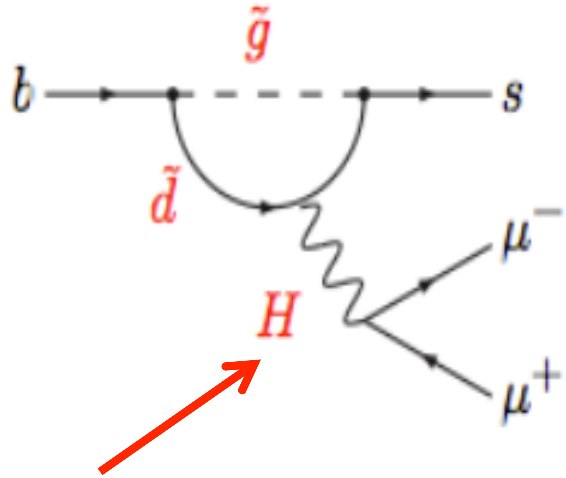
(to translate this value into a value for λ_γ requires theory input….)

Rare Decays and the Higgs
(or how rare processes can test non-SM Higgs couplings)

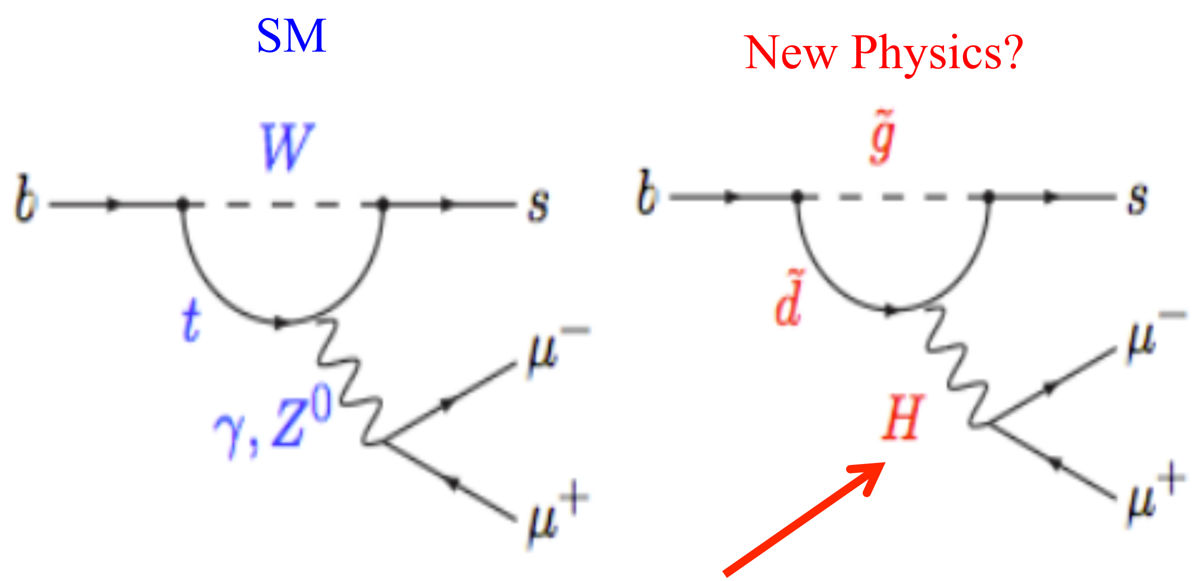
SM

New Physics?





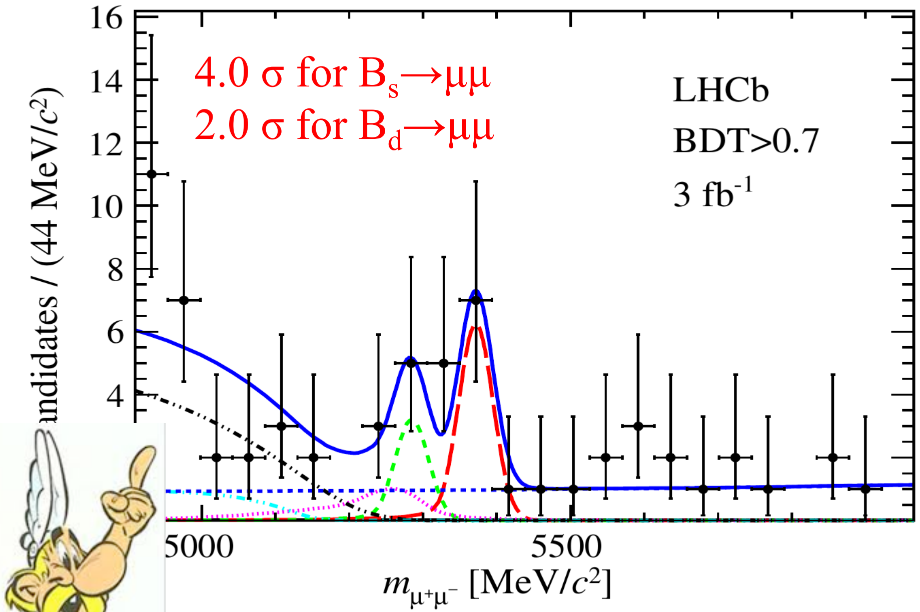
Rare Decays and the Higgs
(or how rare processes can test non-SM Higgs couplings)



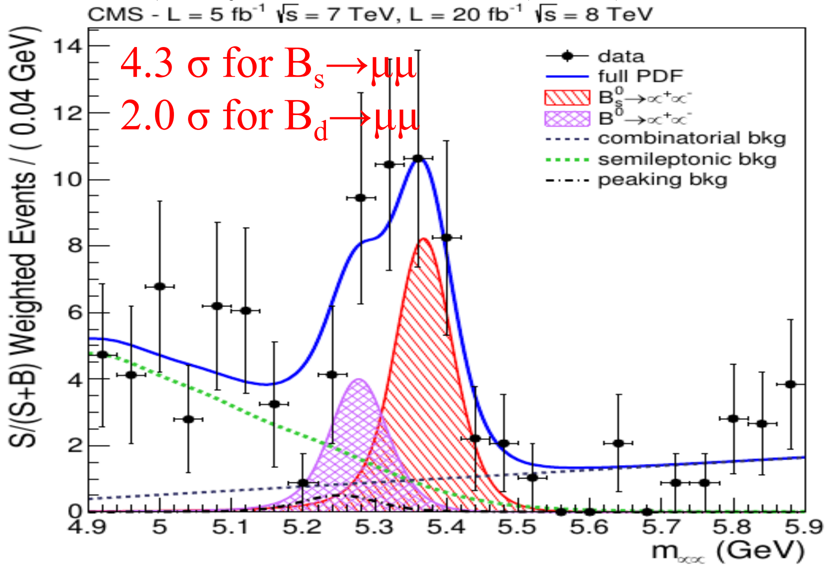
You can recognize here the main diagrams that drive the $B_{s,d} \rightarrow \mu^+\mu^-$ decays…

BR($B_{s,d}\to\mu^+\mu^-$): LHCb-CMS combination

LHCb, Phys.Rev.Lett. 111 (2013) 101805



CMS, Phys.Rev.Lett.111 (2013) 101804



See Mario Galanti's talk

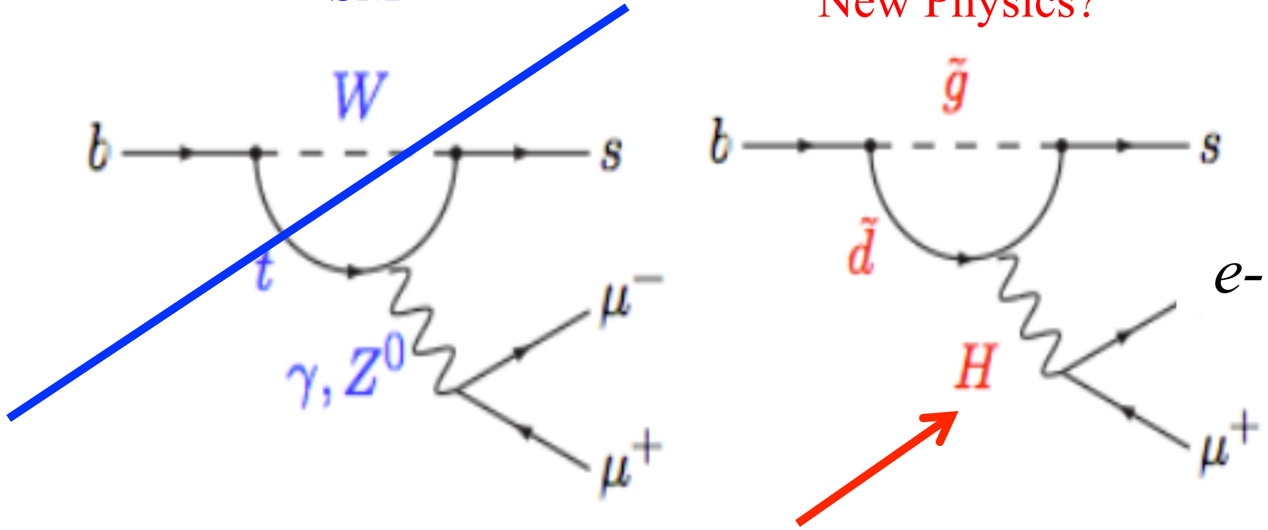
LHCb and CMS measurements of $B_{s,d}\to\mu\mu$ branching fractions are being combined:
- combined fit to the two datasets (sharing of all PDFs and correlated parameters as f_d/f_s, BR($B^+\to J/\psi\, K^+$), etc..). Results expected by summer.

Rare Decays and the Higgs: is the Higgs the SM one?

Let's now see whether the Higgs can have LFV decays….. B→ e μ

SM

New Physics?



$$-\mathcal{L}_{\text{Yukawa}} = \lambda_{ij}\bar{f}_L^i f_R^j H + \lambda'_{ij}\bar{f}_L^i f_R^j H \frac{H^\dagger H}{\Lambda^2} + \text{h.c.}$$

$$= m_i \bar{f}_L^i f_R^i + Y_{ij}\bar{f}_L^i f_R^j h^0 + \text{h.c.}$$

Flavor-violating Higgs(-like) coupling

(Harnik, Kopp, Zupan, hep-ph/1209.1397)

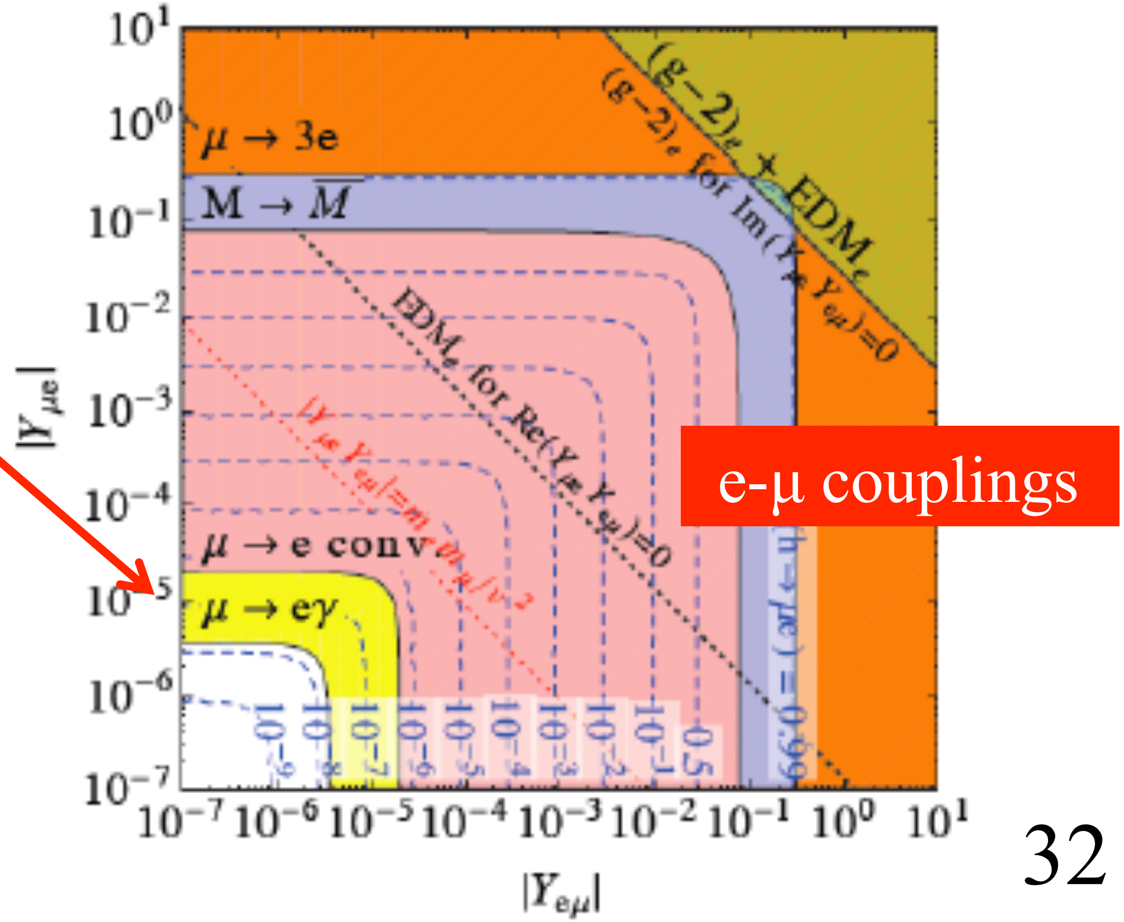
1) Search for B→e μ decays: can be mediated by the Higgs?

$$-\mathcal{L}_{\text{Yukawa}} = \lambda_{ij}\bar{f}^i_L f^j_R H + \lambda'_{ij}\bar{f}^i_L f^j_R H \frac{H^\dagger H}{\Lambda^2} + \text{h.c.}$$
$$= m_i \bar{f}^i_L f^i_R + Y_{ij}\bar{f}^i_L f^j_R h^0 + \text{h.c.}$$

Flavor-violating Higgs(-like) coupling

Bounds on flavor-violating Higgs(-like) coupling from experimental results:

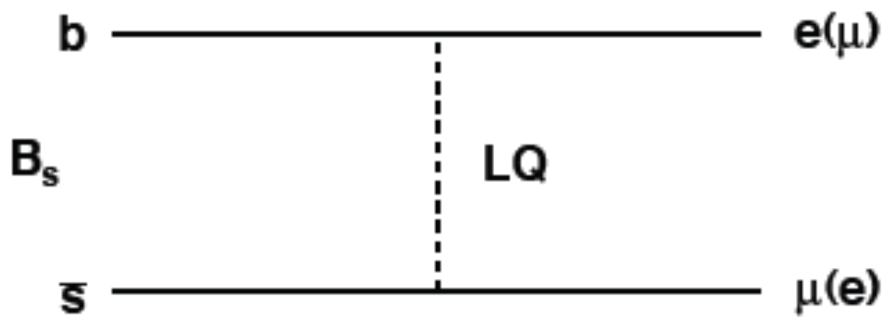
Current limits on the LFV Yukawa coupling eμ is dominated by MEG result: BR(μ→ e γ) < 5×10^{-13}



Search for B(s) → μ e decays: can be mediated by lepto-quarks?

Decays of the type B(s) → e μ are allowed in models with a local gauge symmetry between quarks and leptons.

[1]A. Ilakovic Phys. Rev. D 62 (2000) 036010.
[2]R. A. Diaz et al. Eur. Phys. J C 41 (2005) 305.
[3]J. C. Pati and A. Salam Phys. Rev. D 10 (1974) 275.

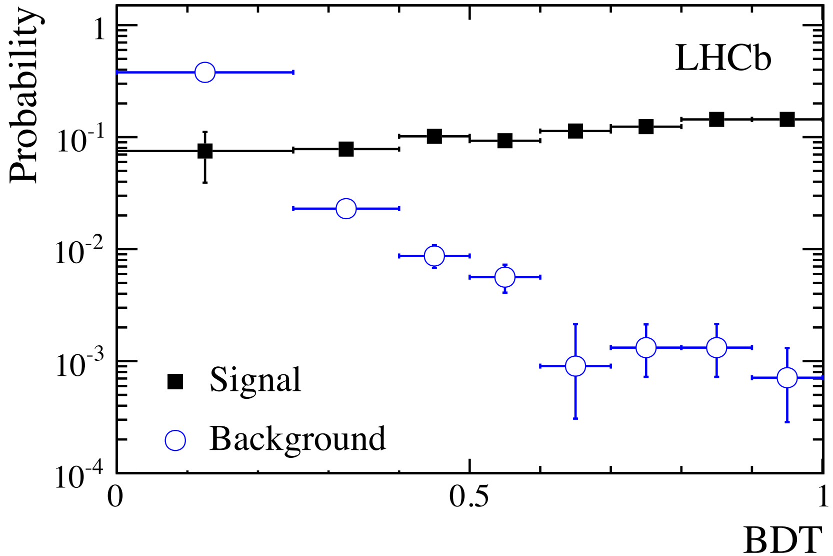


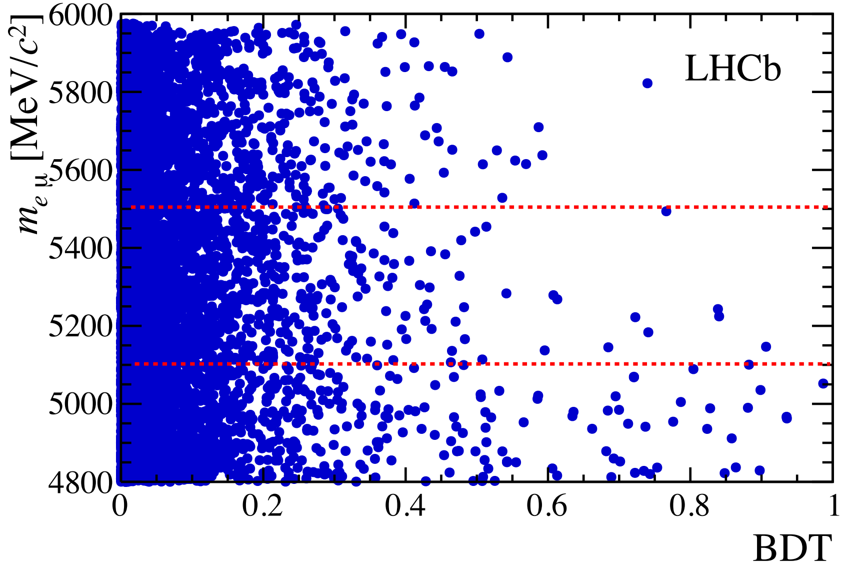
Direct searches by CMS and ATLAS put limits m_Q < [0.5-1] TeV depending on the final state
→They access lepto-quarks linking quark and leptons of the same generation;
→B→eμ decays can occur if lepto-quarks link different quark/lepton generations.

Valencia and Willenbrock, arXiv:hep-ph/9409201v1

Search for B(s) → μ e decays @ LHCb

Analysis strategy identical to that of the $B_{(s)} \to \mu\mu$
Events are classified in a 2D plane (mass vs BDT) and normalized to a control sample ($B_d \to K\pi$)





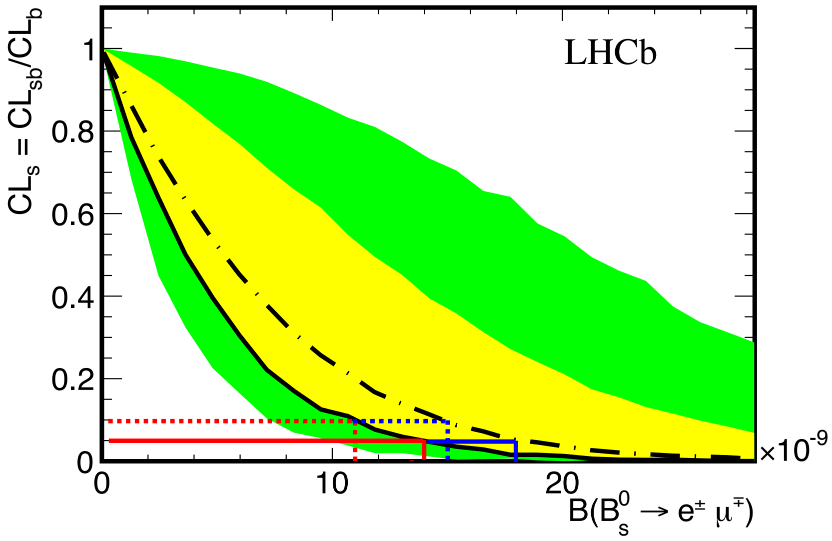
$$\mathrm{BR}_{B^0_{(s)}\to e^+\mu^-} = \mathrm{BR}_{\mathrm{cal}} \times \frac{f_d}{f_q} \times \frac{\epsilon_{cal}^{SEL|REC}\,\epsilon_{cal}^{TRIG|SEL}}{\epsilon_{sig}^{SEL|REC}\,\epsilon_{sig}^{TRIG|SEL}} \frac{1}{\epsilon_{SIG}^{PID}} \times \frac{N_{B^0_{(s)}\to e^+\mu^-}}{N_{\mathrm{cal}}}$$
$$= \alpha \times N_{B^0_{(s)}\to e^+\mu^-}$$

Search for $B_{(s)} \to \mu\, e$ decays @ LHCb

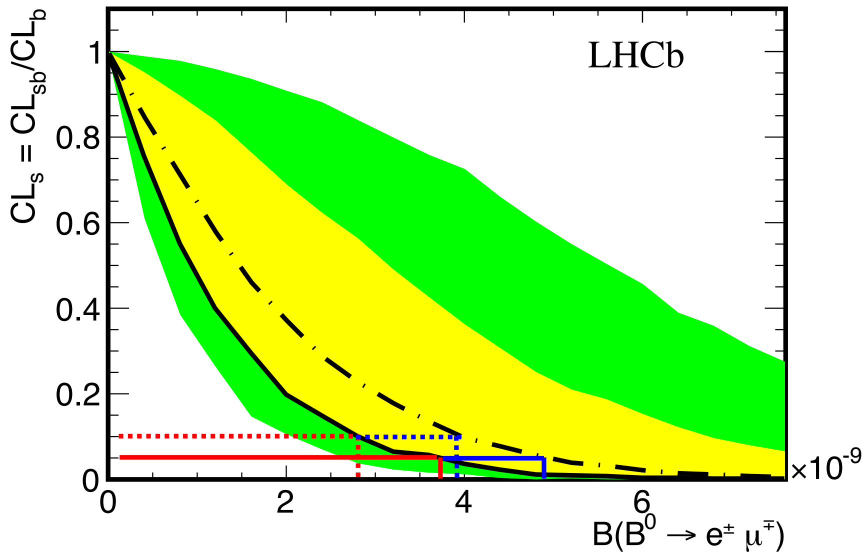
With 1 fb^{-1} LHCb has put limits 20x more stringent than the world best limits set by CDF.

LHCb, Phys.Rev.Lett. 111 (2013) 141801

$BR(B_s \to \mu\, e) < 1.36 \times 10^{-8}$ @ 95% CL



$BR(B \to \mu\, e) < 3.72 \times 10^{-8}$ @ 95% CL



	$BR(B_s^0 \to e^+\mu^-)\ \times 10^{-8}$ at 90% (95%) CL	$BR(B^0 \to e^+\mu^-)\ \times 10^{-9}$ at 90% (95%) CL
Expected LHC*b*, 1 fb^{-1}	1.53 (1.95)	3.97 (4.95)
Observed LHC*b*, 1 fb^{-1}	1.11 (1.36)	2.8 (3.72)
Current (CDF, 2 fb^{-1})	20.0(20.6)	64.0(79.0)

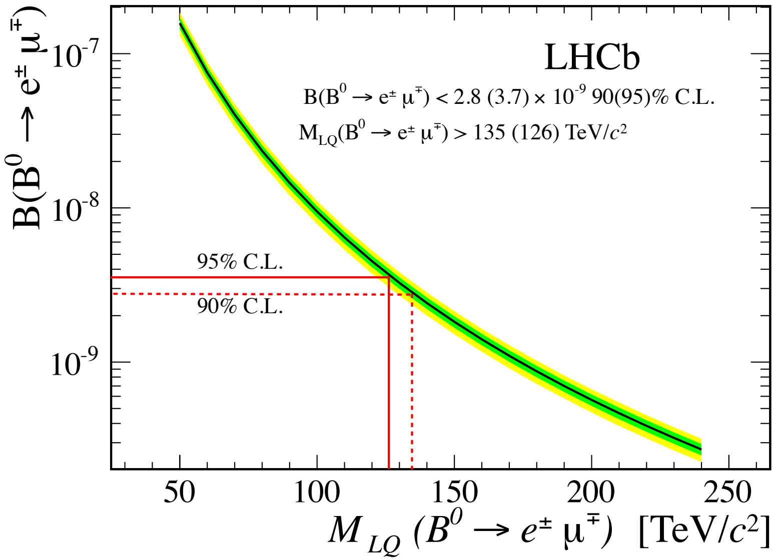
Search for $B_{(s)} \to \mu\, e$ decays @ LHCb

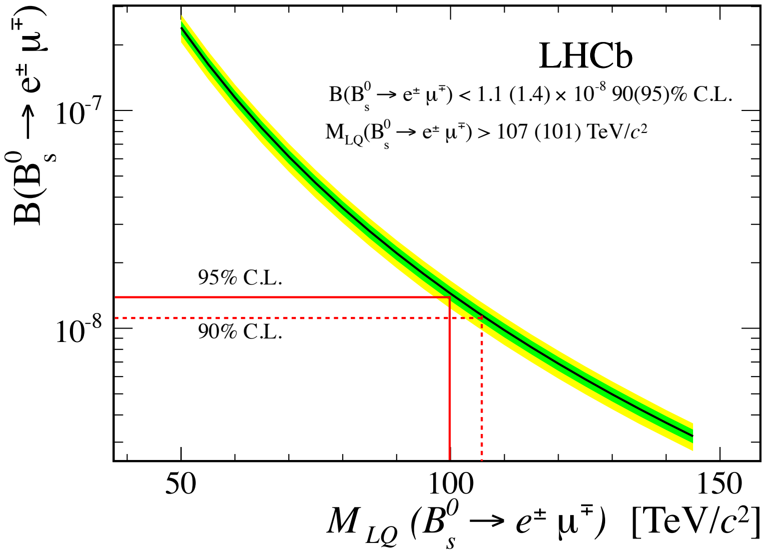
These limits can be translated into limits on the value of the mass of the leptoquarks

In the framework of the Pati-Salam model: LHCb, Phys.Rev.Lett. 111 (2013) 141801

$$\mathcal{B}(B^0_{(s)} \to e^\pm \mu^\mp) = \pi \frac{\alpha_S^2(M_{\rm LQ})}{M_{\rm LQ}^4} F^2_{B^0_{(s)}} m^3_{B^0_{(s)}} R^2 \frac{\tau_{B^0_{(s)}}}{\hbar},$$

Valencia and Willenbrock, PRD 50 (1994) 6843



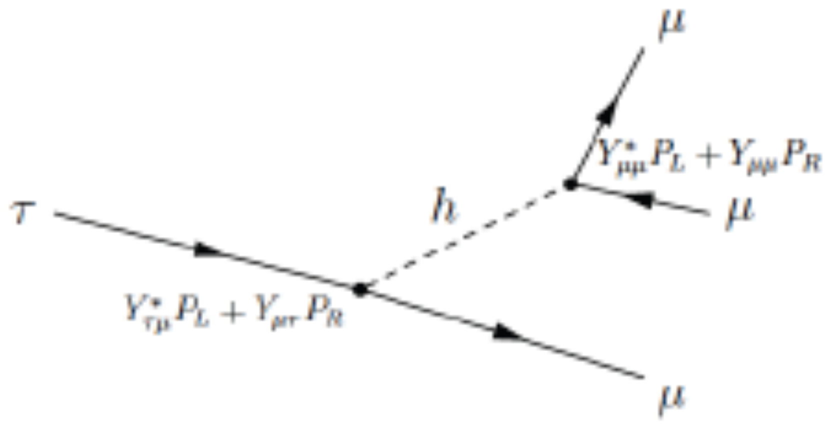


LHCb results: $m_{LQ}\ (B_s \to \mu\, e) > 101$ TeV/c^2 @ 95% CL

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

Rare Decays and the Higgs
(or how rare processes can test non SM Higgs couplings)

Non-SM Higgs (among other diagrams) can mediate the LFV decay τ→μμμ



Rare Decays and the Higgs: $\tau \to \mu\mu\mu$

First search at a hadron collider:

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

Huge cross section: $\sigma(pp \to \tau X) \sim 80$ μb 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):

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

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→ τ and c→τ branching fractions as measured by LEP experiments [3]

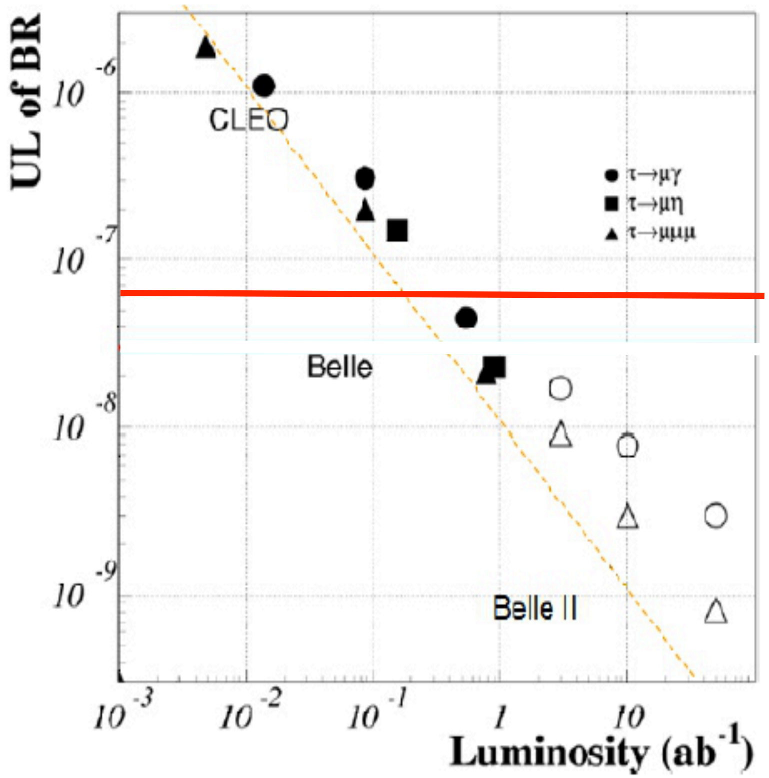
1] LHCb collaboration, Eur. Phys. J C71 (2011) 1645
2] LHCb collaboration, Nucl. Phys. B 271 (2013) 1
3] PDG, http://pdg.lbl.gov

Rare Decays and the Higgs: τ→μμμ

$\mathcal{B}(\tau^- \to \mu^+\mu^-\mu^-) \quad < \quad 8.0 \times 10^{-8}$ at 90% C.L. LHCb (using 2011 data)

$\mathcal{B}(\tau^- \to \mu^+\mu^-\mu^-) \quad < \quad 2.1 \times 10^{-8}$ at 90% C.L. Belle (World best)

$\mathcal{B}(\tau^- \to \mu^+\mu^-\mu^-) \quad < \quad 3.3 \times 10^{-8}$ at 90% C.L. BaBar limit



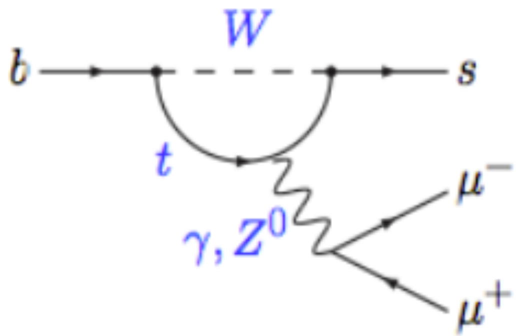
LHCb @ 1 fb^{-1}

..Result based on 3 fb^{-1} ready by summer.

Figure 3-10. *Extrapolation of the 90% upper limit sensitivity of Belle-II (open symbols) from existing limits (filled symbols). For $\tau \to \mu\gamma$, which has irreducible backgrounds, the limit scales as $1/\sqrt{\int \mathcal{L}dt}$. For $\tau \to \mu\mu\mu$, which is essentially background-free, the limit scales as $1/\int \mathcal{L}dt$.*

Back to the beginning: what are we doing?

We are looking for New Physics in FCNC b, Kaon decays and LFV τ decays that can be sensitive to quantum corrections from degrees of freedom **at** and **above** the electroweak scale.



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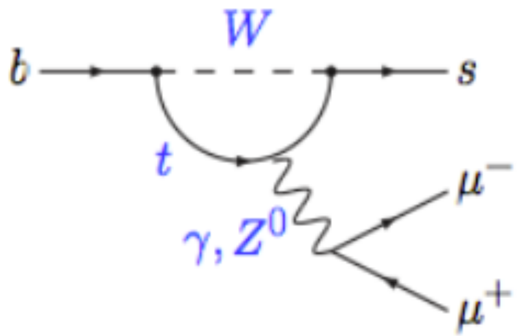
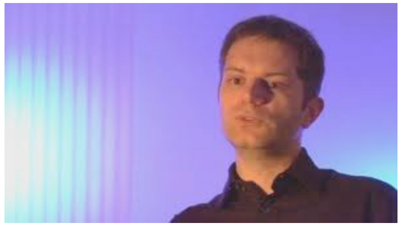


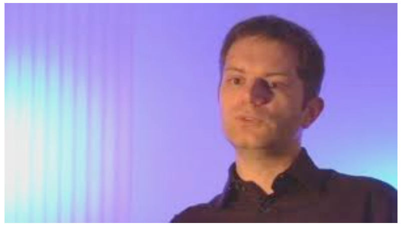
….. but if there was nothing up to Planck scale?



Higgs and naturalness

"Given the absence of unambiguous signal of new physics and the compatibility of the Higgs properties with the SM predictions some doubts arose about the relevance of the naturalness argument as an organizing principle at higher energies."

C. Grosjean, Future circular collider kick-off meeting, Geneva, February 12-14



Higgs and naturalness

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C. Grosjean, Future circular collider kick-off meeting, Geneva, February 12-14

"With a mass of the Higgs boson of ~126 GeV the Standard Model could be a self-consistent stable or meta-stable weakly coupled effective field theory up to very high scales (possibly up to the Planck scale) without adding new particles."

N. Arkani-Hamed, Future circular collider kick-off meeting, Geneva, February 12-14

But this cannot be the end of the story…

1. Neutrino oscillations require new degrees of freedom with respect to SM
2. Baryon asymmetry of the universe:

→ Measurements from BBN and CMB $\eta \sim 6 \times 10^{-10}$

→ Current measured CP violation in quark sector: $\eta \sim 10^{-20}$

3. Dark matter from indirect gravitation observations

→ Non baryon, neutral, stable or long lived

*….many extensions of the SM predict weakly interacting long-lived objects **below the ew-scale**…*

But this cannot be the end of the story…

1. Neutrino oscillations require new degrees of freedom with respect to SM
2. Baryon asymmetry of the universe:

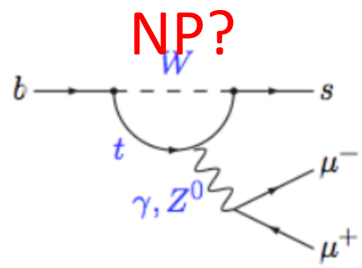
→ Measurements from BBN and CMB $\eta \sim 6\text{x}10^{-10}$

→ Current measured CP violation in quark sector: $\eta \sim 10^{-20}$

3. Dark matter from indirect gravitation observations

→ Non baryon, neutral, stable or long lived

*….many extensions of the SM predict weakly interacting long-lived objects **below the ew-scale**…*



… perhaps we are simply looking at the wrong place…?

A possible extension of the Standard Model: the νMSM

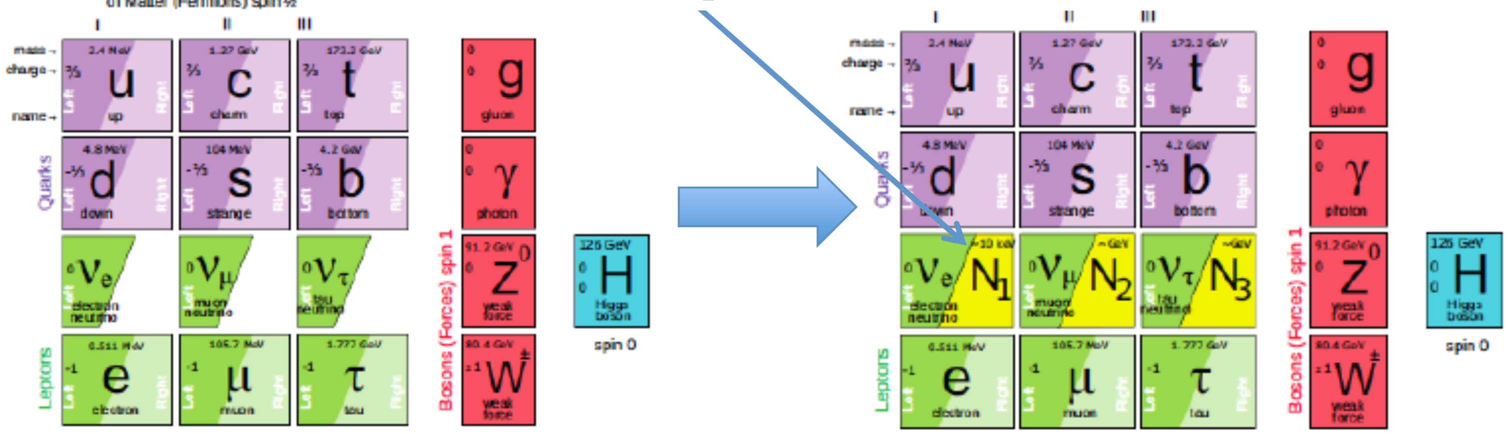
T. Asaka, M. Shaposhnikov PLB 620 (2005) 17

Ptolomy (~90-168 AD):
It is a good principle to explain phenomena by the simplest hypothesis possible!

A possible extension of the Standard Model: the νMSM

Introduction of three new fundamental fermions, right handed Majorana Heavy Neutral leptons, N_1, N_2 and N_3:

T. Asaka, M. Shaposhnikov PLB 620 (2005) 17



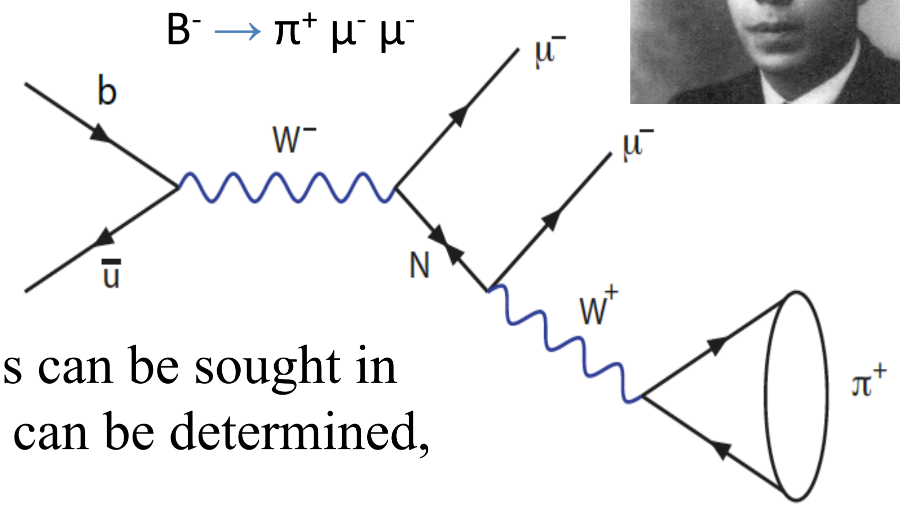
N = Heavy Neutral Lepton - HNL

Role of N_1 with mass in keV region: dark matter

Role of N_2, N_3 with mass in 100 MeV – GeV region: “give” masses to neutrinos and produce baryon asymmetry of the Universe

Role of the Higgs: give masses to quarks, leptons, Z and W and inflate the Universe.

Search for Majorana's Neutrinos in B decays



In LHCb heavy Majorana neutrinos can be sought in heavy flavor decays and couplings can be determined, or limits imposed.

The LNV decay $B^- \rightarrow \pi^+ \mu^- \mu^-$ is forbidden in SM but can proceed via the production of on-shell Majorana's neutrinos....

E. Majorana, Nuovo Cimento 14 (1937) 171
J.C.Pati and A. Salam, PRD 10 (1974) 275
Gribanov, Kovalenko Nucl.Phys. B 607 (2001) 355

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

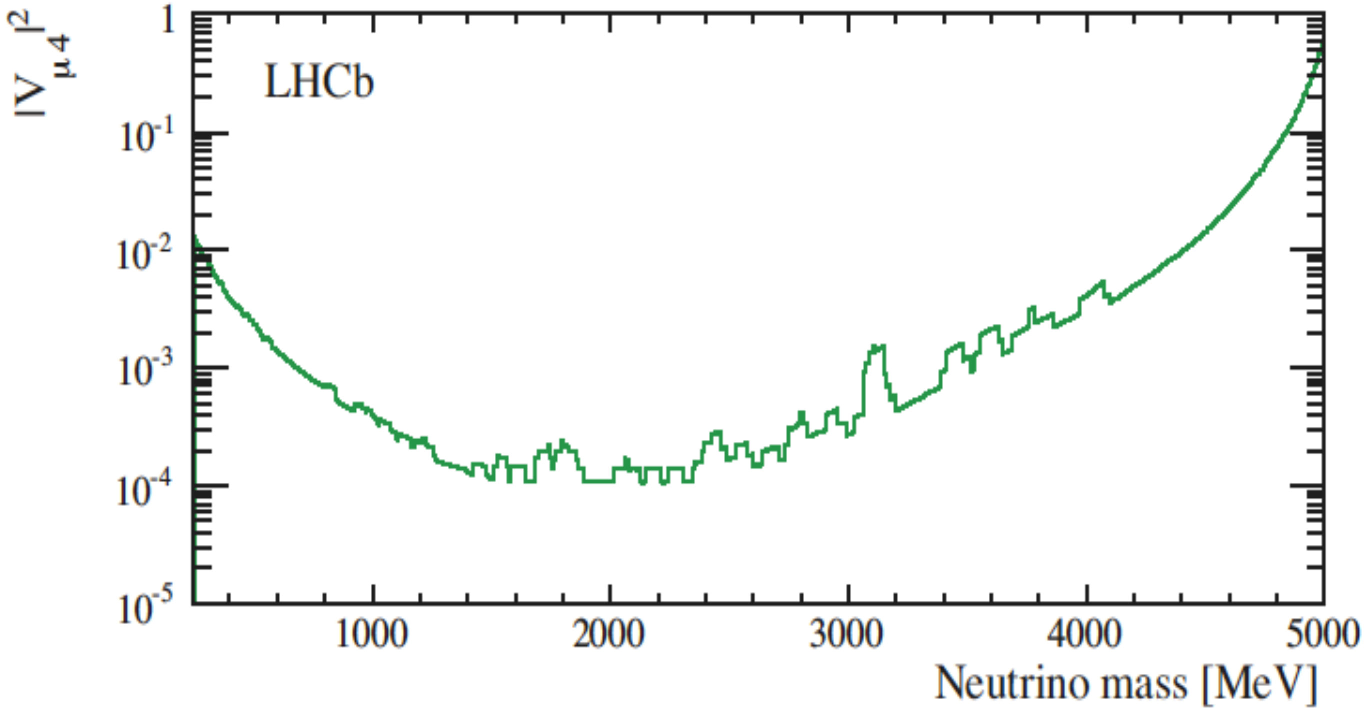
Limit on the branching fraction can be translated to a model-dependent upper limit on the coupling of a Majorana neutrino with muons, $|V_{\mu 4}|$

For each value of m_N are determined using the formula from Atre et al.[arXiv:0901.3589]

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

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

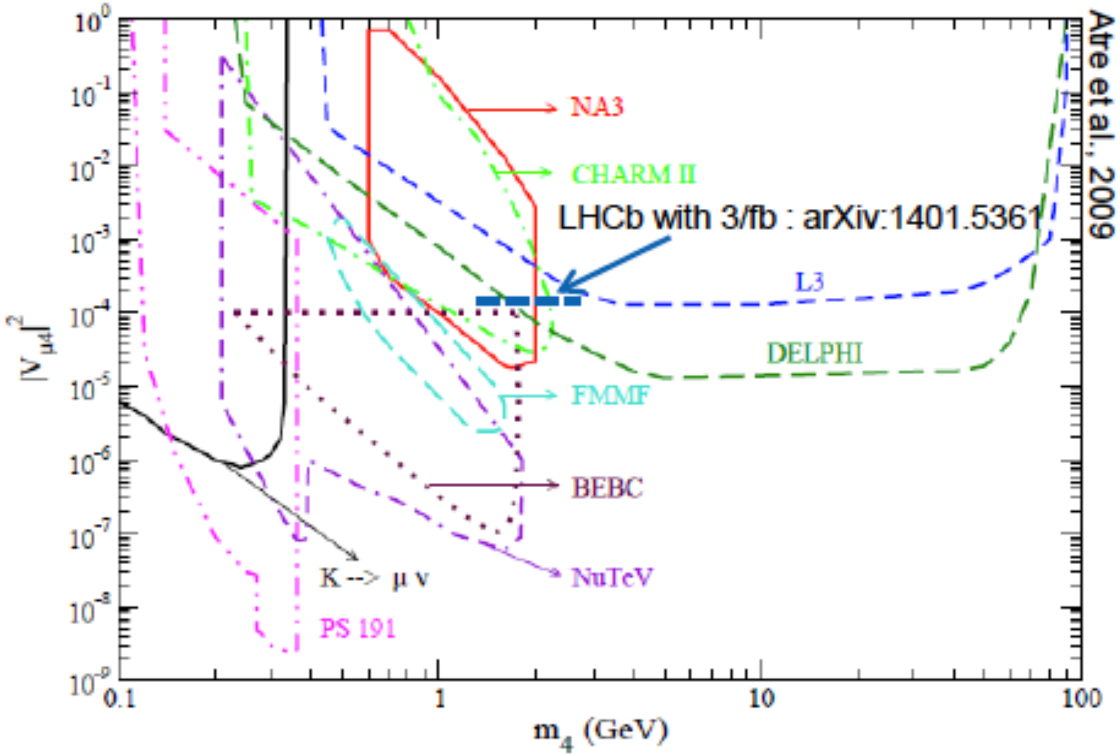
[model partially developed by Sheldon and Z. Xing]



LHCb with 3 fb^{-1}
arXiv:1401.5361
Accepted by PRL

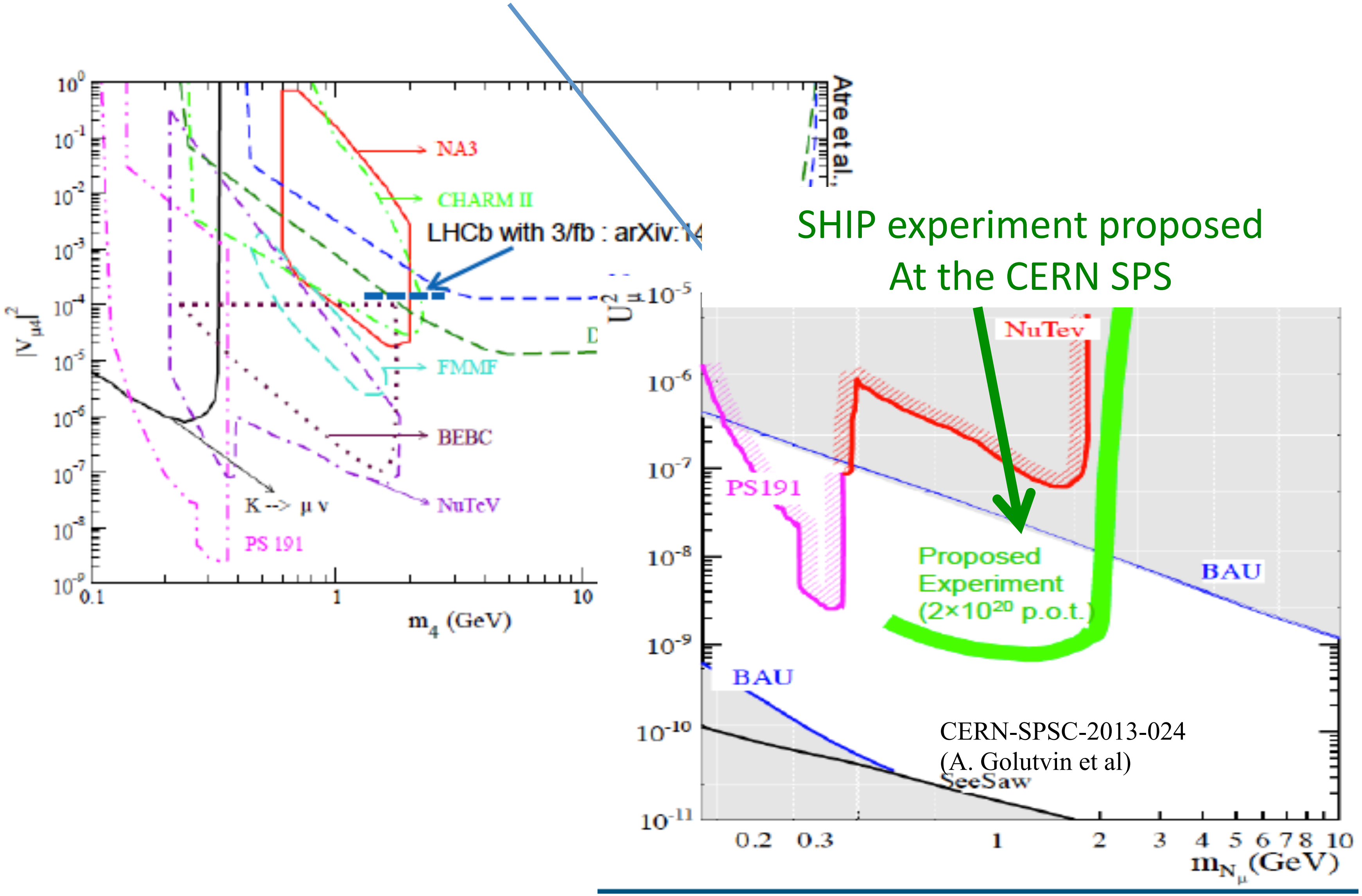
Search for Majorana Neutrinos in $B^- \to \pi^+ \mu^- \mu^-$ decays

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



Search for Majorana Neutrinos in $B^- \rightarrow \pi^+ \mu^- \mu^-$ decays

But – unfortunately! – well above the favored region by the baryon asymmetry of the universe….



Conclusions

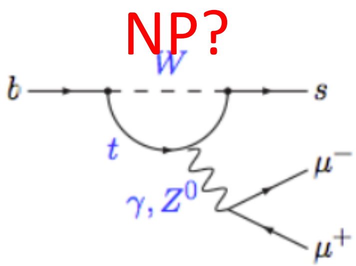
- We did not observe so far any deviation from SM predictions in the flavor sector:

$\longrightarrow$ either new physics is very heavy;

$\longrightarrow$ or it mimics the SM in its flavor-breaking pattern;

(Isidori @whatnext)

$\longrightarrow$ or it is simply **below the Fermi scale** and does not couple with quarks and charged leptons..and we are simply looking at the wrong place….



Spares

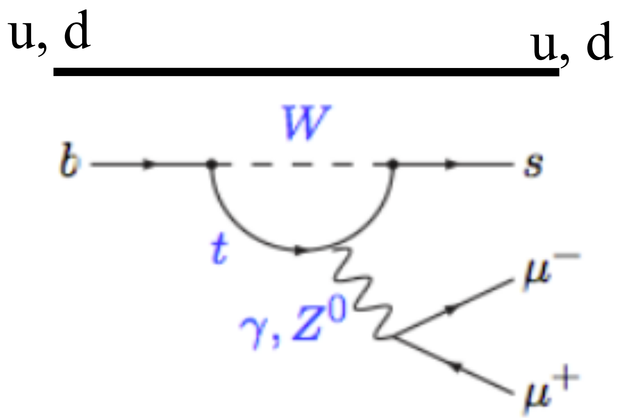
Differential BR and isospin asymmetry of B→ $K^{(*)}\mu^+\mu^-$ decays

LHCb-PAPER-2014-006
(almost) in circulation

The isospin asymmetry is defined as:

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

At leading order, isospin asymmetries (which involve the spectator quark) are expected to be zero in the SM



Differential BR and isospin asymmetry of $B \rightarrow K^{(*)}\mu^+\mu^-$ decays

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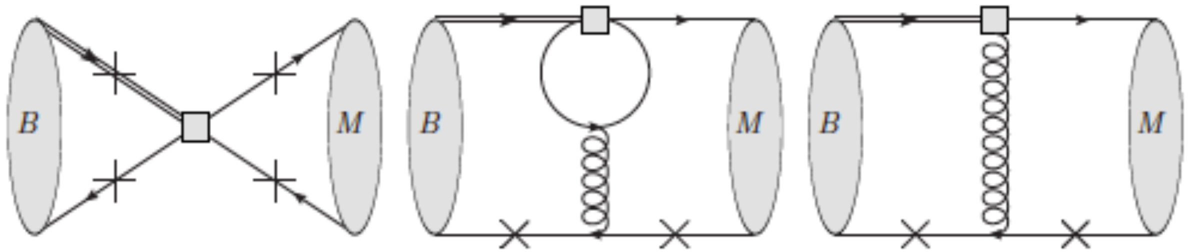
At leading order, isospin asymmetries (which involve the spectator quark) are expected to be zero in the SM. Isospin breaking effects are sub-leading m_q/m_b effects, which are difficult to estimate due to unknown power corrections.



The small isospin asymmetry predicted in the SM O(1%) is due to initial state radiation of the spectator quark, which is different between the neutral and charged decays (Lyon, Zwicky: PRD 88 (2013) 094004).

Differential BR and isospin asymmetry of $B \to K^{(*)}\mu^+\mu^-$ decays

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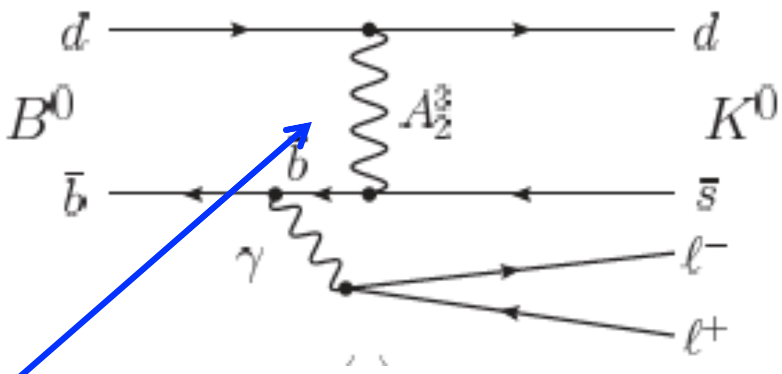
$$A_I = \frac{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) - \frac{\tau_0}{\tau_+}\mathcal{B}(B^\pm \to K^{(*)\pm}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) + \frac{\tau_0}{\tau_+}\mathcal{B}(B^\pm \to K^{(*)\pm}\mu^+\mu^-)}$$

NP can modify the isospin asymmetry at low dimuon invariant mass squared (q^2) :

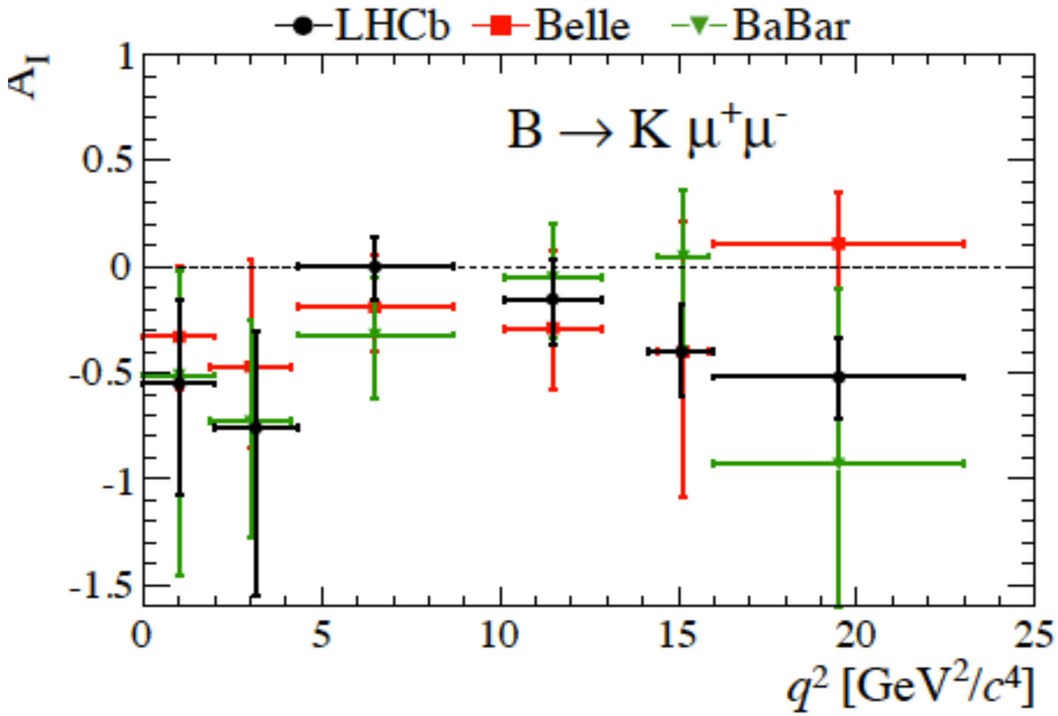


Example of a diagram from exotic gauge bosons
(Ishida, Koide arXiv: 1305.7342)

Differential BR and isospin asymmetry of $B \to K^{(*)}\mu^+\mu^-$ decays

Previous experimental evidence that A_I is not SM like:

- Babar had a deviation in both $B \to K^* \mu\mu$ and $B \to K\mu\mu$ at low q^2
- LHCb had a deviation only in $B \to K \mu\mu$ but at high and low q^2



Babar, PRL 102 (2008) 091803
Belle, PRL 103 (2009) 171801
LHCb, JHEP 07 (2012) 133

Differential BR and isospin asymmetry of $B \rightarrow K^{(*)}\mu^+\mu^-$ decays

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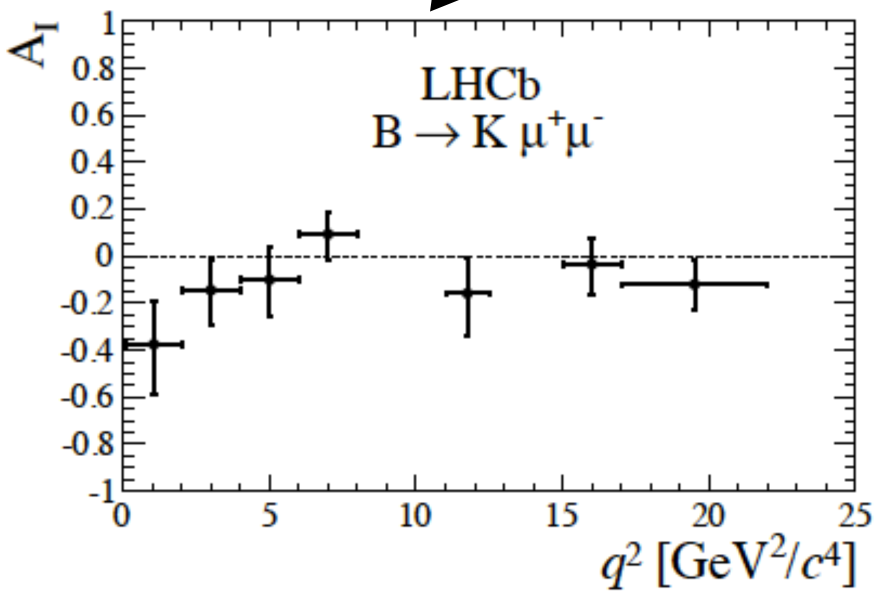
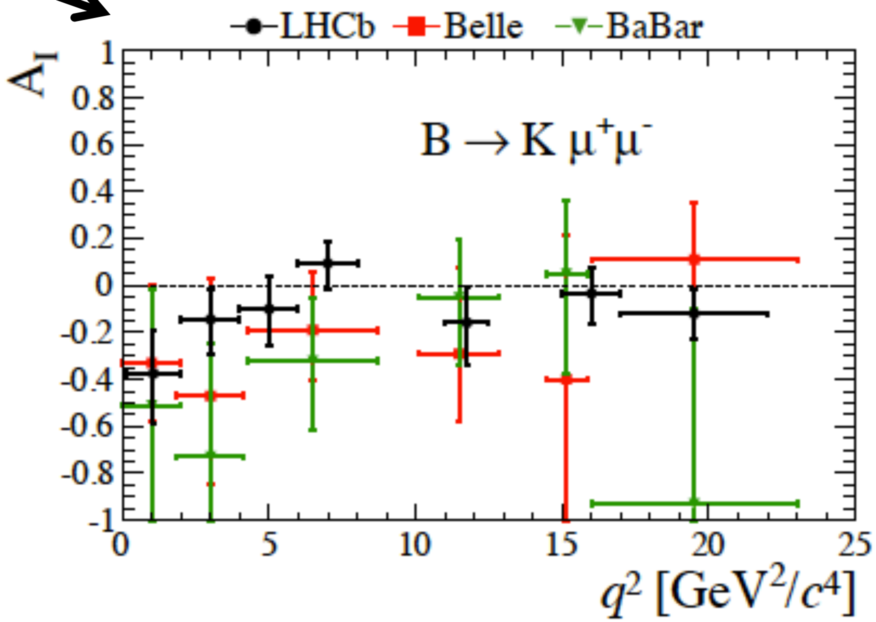
New results for $B \rightarrow K\mu\mu$ are now compatible with the SM and compatible with Belle and Babar (with hints of deviations at low q^2, though..)

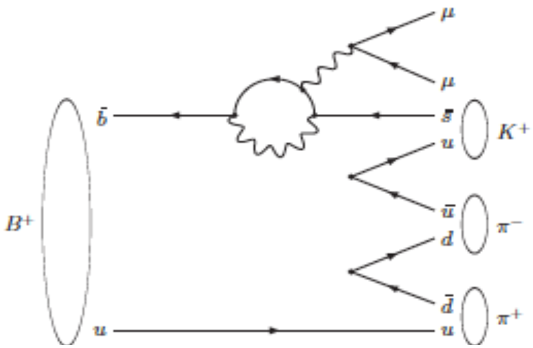


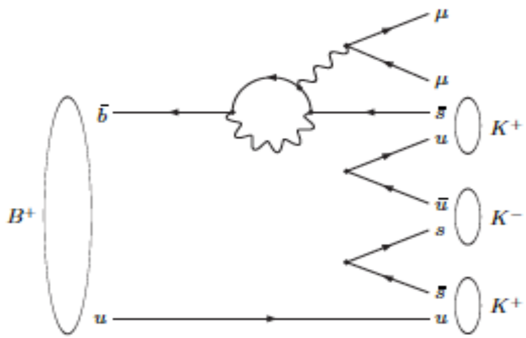


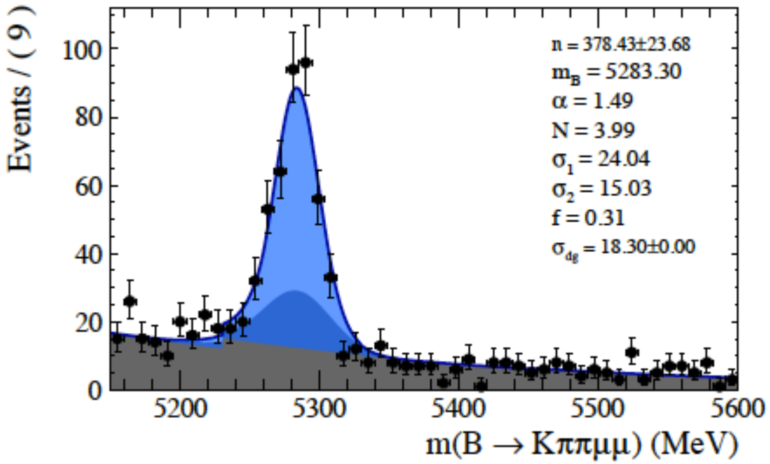
We assume A_I constant with q^2; the χ^2 of this hypothesis compared with the χ^2 wrt to zero is taken as a test statistics and compared with pseudo-experiments generated with A_I=0;

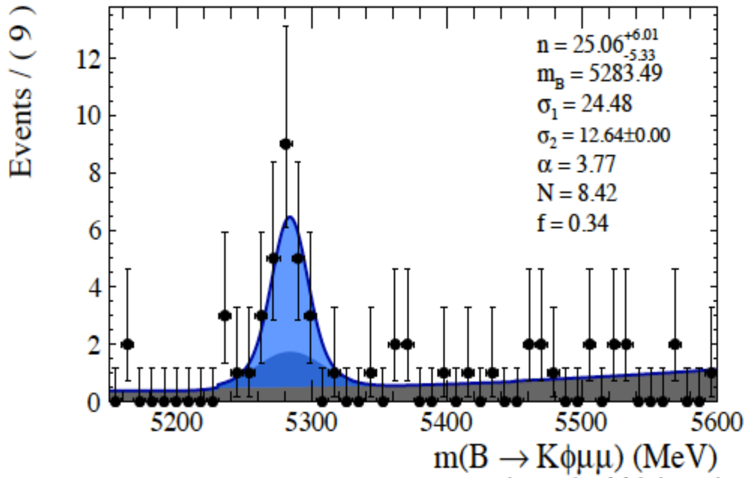
The global p-value is 11% assuming $A_I(B \rightarrow J/\psi\ h) = 0$ and corresponds to 1.5 σ significance

First observation of $B^+ \to K^+\pi^-\pi^+ \mu^+\mu^-$ and $B^+ \to \varphi K^+\mu^+\mu^-$ decays









$\mathcal{B} = (4.24\,^{+0.29}_{-0.27} \pm 0.19) \times 10^{-7}$

$\mathcal{B} = (8.03\,^{+1.93}_{-1.73} \pm 3.98) \times 10^{-8}$

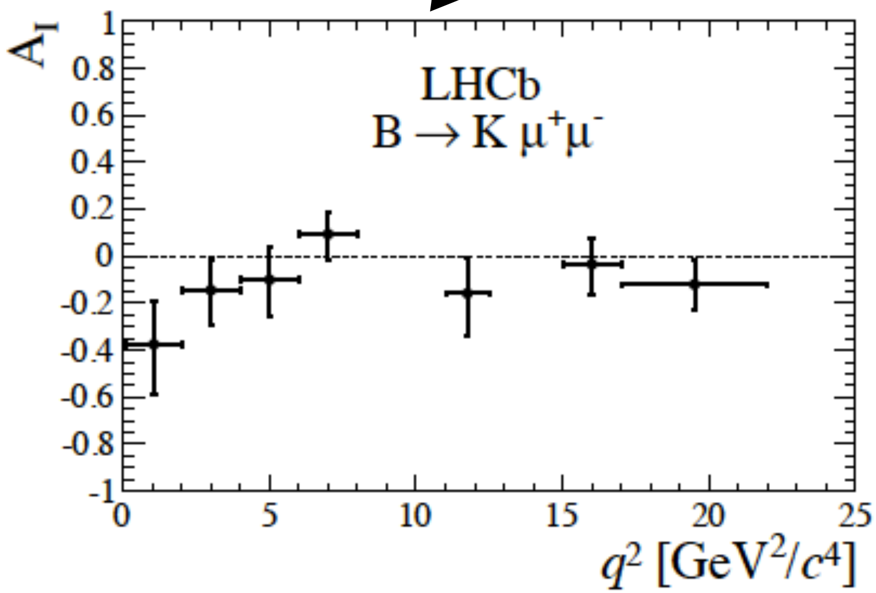
First observation with significances 22 σ and 6.6 σ, respectively.

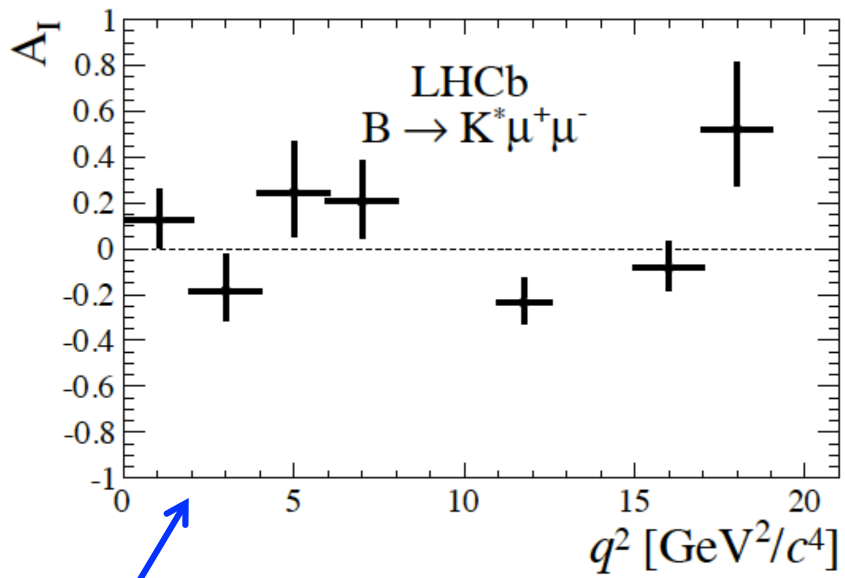
M(Kππ) spectrum similar to $B^+ \to K^+\pi^-\pi^+ \gamma$ but statistics too low to disentangle resonances

Differential BR and isospin asymmetry of $B \to K^{(*)}\mu^+\mu^-$ decays

LHCb-PAPER-2014-006
(almost) in circulation

New results for $B \to K\mu\mu$ are now compatible with the SM and compatible with Belle and Babar (with hints of deviations at low q^2, though..)





$B \to K^*\mu\mu$ isospin asymmetry is consistent with zero (like last time).

Rare Decays and the Higgs: τ→μμμ

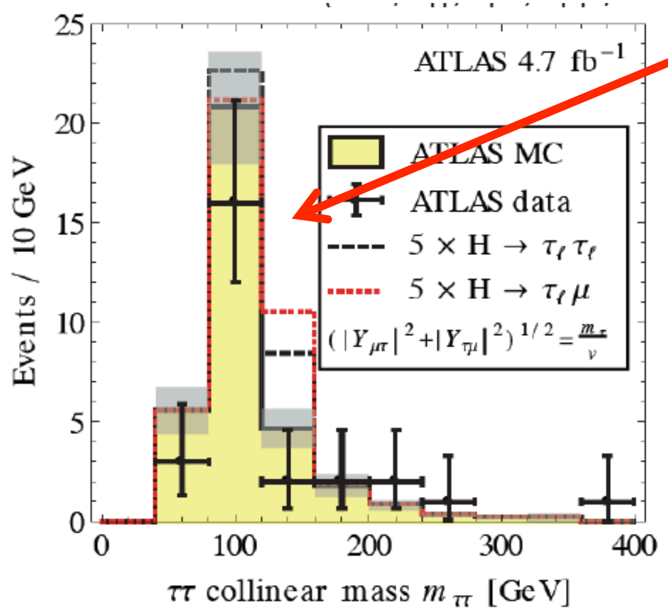
Harnik, Kopp, Zupan 1209.1397
Blankeburg, Ellis, Isidori 1202.5704
Brod, Haish,Zupan 1310.1385

$$-\mathcal{L}_{\text{Yukawa}} = \lambda_{ij} \bar{f}_L^i f_R^j H + \lambda'_{ij} \bar{f}_L^i f_R^j H \frac{H^\dagger H}{\Lambda^2} + \text{h.c.}$$
$$= m_i \bar{f}_L^i f_R^i + Y_{ij} \bar{f}_L^i f_R^j h^0 + \text{h.c.}$$

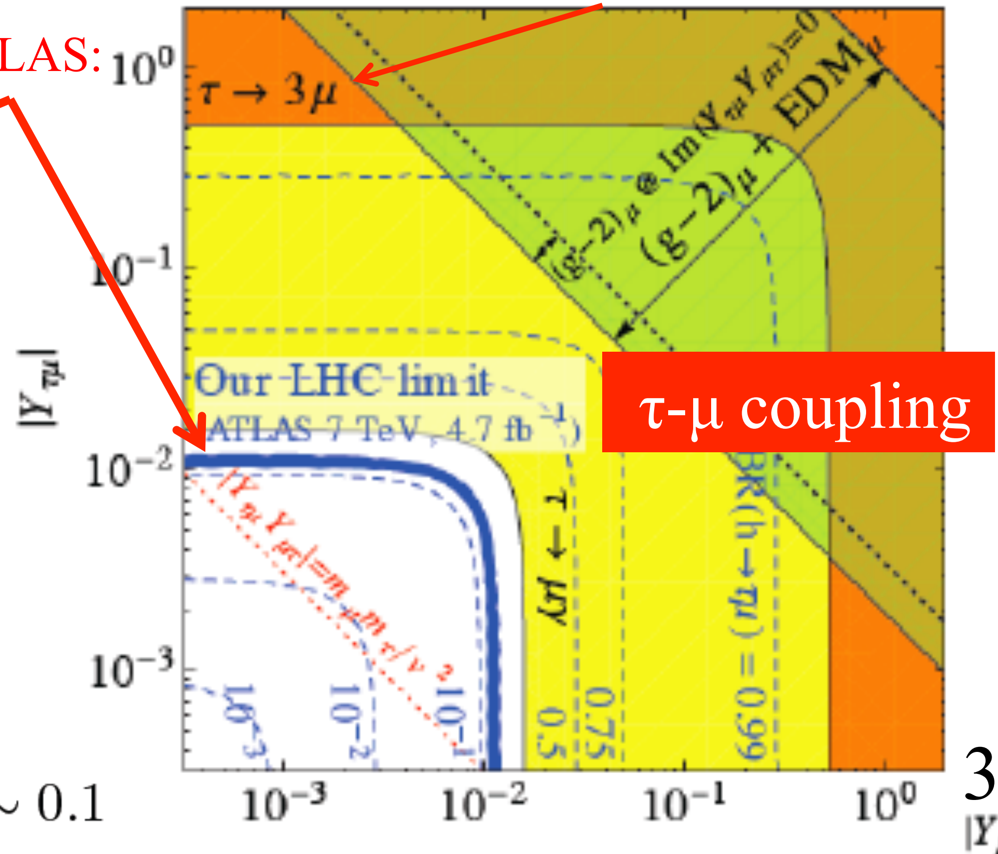
Flavor-violating Higgs(-like) coupling

Bounds on flavor-violating Higgs-coupling from experimental results:

Best limit from direct searches from ATLAS:



Limit from B -factories



The LFV Higgs decay is already constrained

$$\text{Br}(h \to \tau\mu(\tau e)) <\sim 0.1$$