Rare decays at LHCb

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on behalf on the LHCb Collaboration

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outline

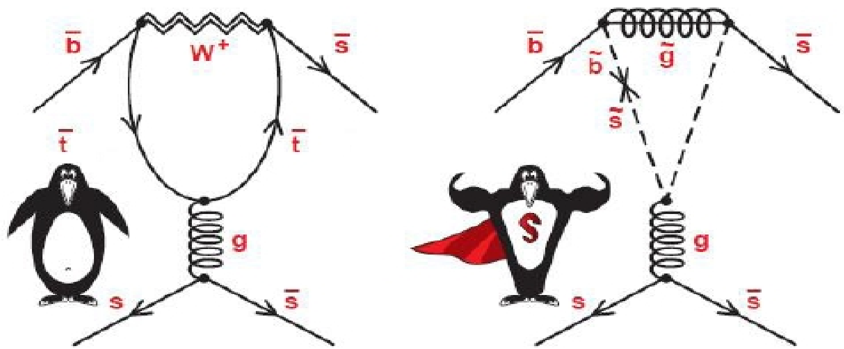
- $B_{(s)} \rightarrow \mu^+\mu^-$
- Semileptonic $B^0 \rightarrow K^{(*)0}\mu^+\mu^-$ decay
- Observation of a resonance in the $B^+ \rightarrow K^+\mu^+\mu^-$ decay
- Radiative $B^+ \rightarrow K^+\pi^-\pi^+\gamma$ decay

(selected results of many LHCb measurement concerning rare decays)

Utility of rare decays

- Rare B decays to the $K^{(*)}\mu\mu$ or $K\pi\pi\gamma$ are Flavour Changing Neutral Curents (FCNC) processes

  → proceed via penguin and box diagram



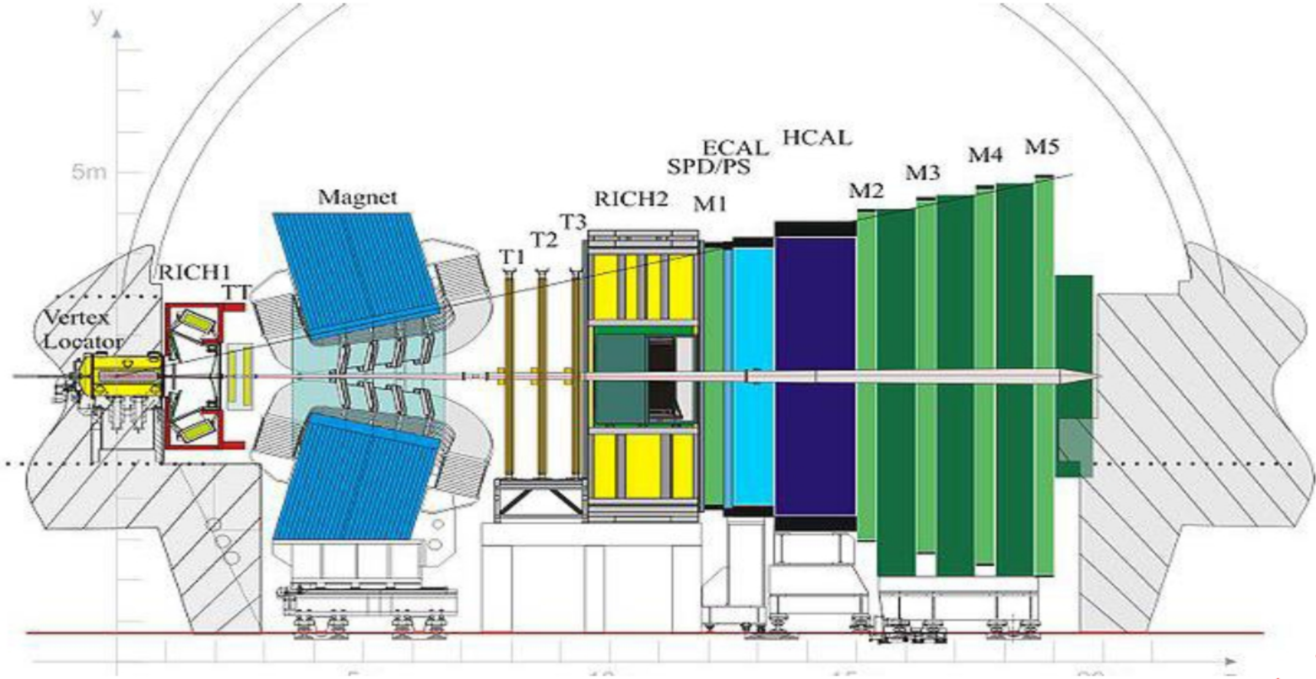
- Indirect searches of New Physics (NP) - new virtual particles may occur in the diagrams loops

  → probing high energy scale (much higher than for direct searches)

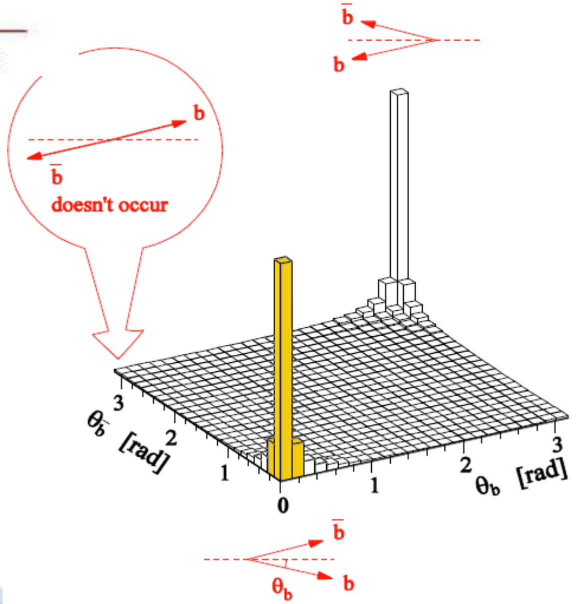
  → possible modification of several observables like differential branching fractions, angular variables, CP asymmetries etc...

LHCb

LHCb detector – single-arm forward spectrometer optimized for B physics



- Unique acceptance range ($2 < \eta < 5$)
- Excellent particle identification and vertexing
- Very efficient trigger:
  ~ 90% for dimuon channels
- 3 fb^{-1} accumulated during 2011 and 2012

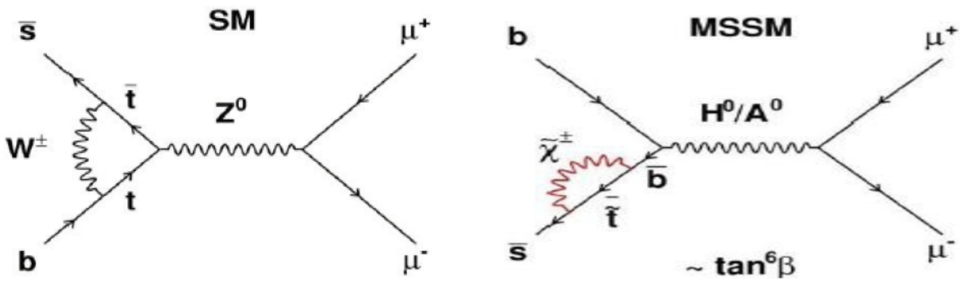


Phys.Rev. Lett.111(2013) 101805

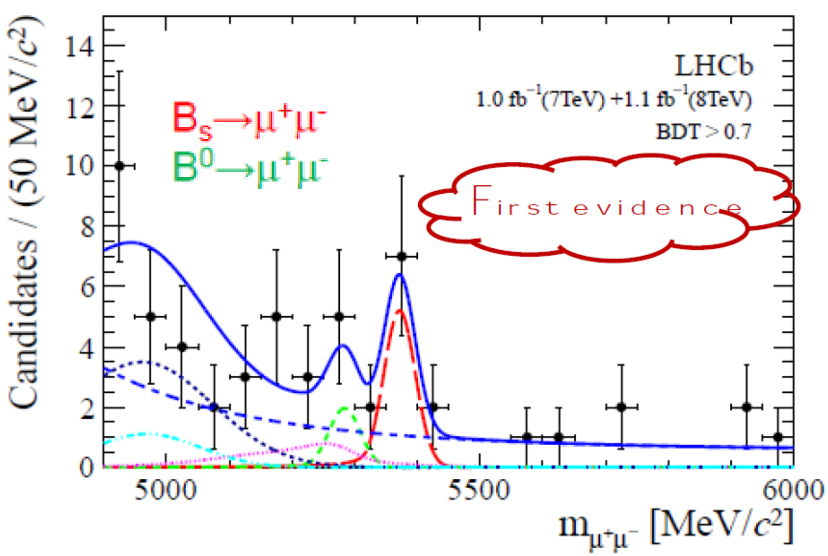
$B_{(s)} \rightarrow \mu^+\mu^-$

3 fb^{-1}
data

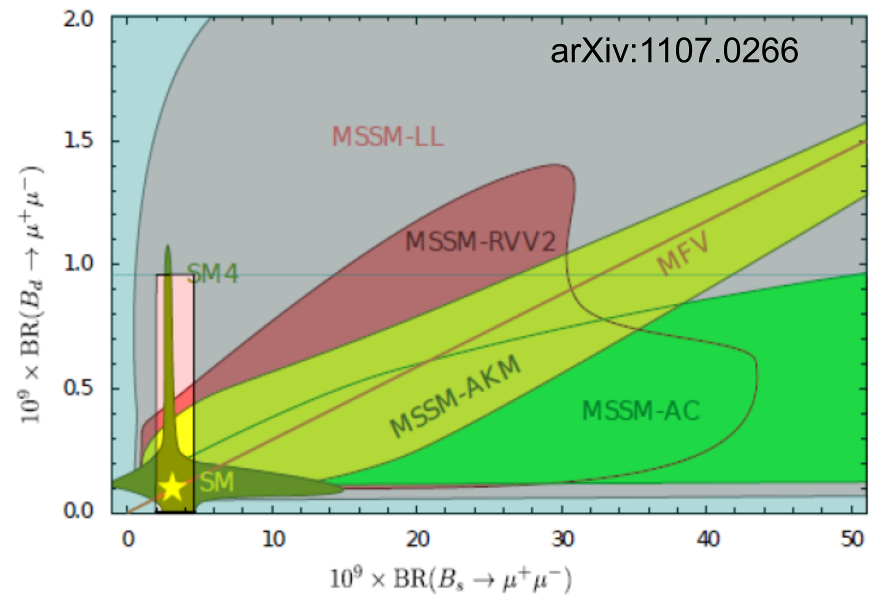
Very rare decays (FCNC and helicity supressed)



Good probe for *extended Higgs sectors models* (incl. MSSM)



Significant NP constraint



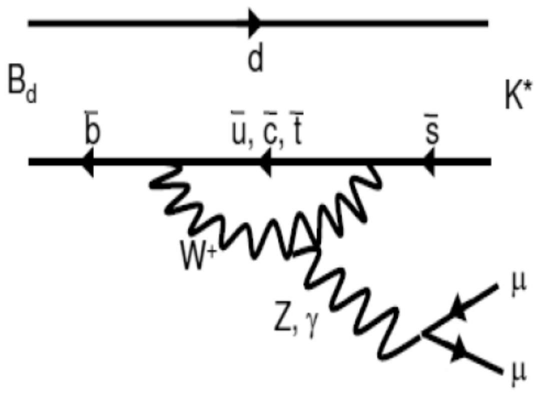
$$BR(B_S^0 \rightarrow \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}(stat)^{+0.3}_{-0.1}(syst)) \times 10^{-9}$$ **4.0 σ**

$$BR(B^0 \rightarrow \mu^+\mu^-) < 7.4 \times 10^{-10}$$

Consistent with SM

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

- FCNC $b \to s\, l^+l^-$ transition



- $B \to K^{*0}$ amplitudes depends on:

  Wilson Coefficients – short distance effects – **sensitive for New Physics!**

  Form-factors – long distance effects - **significant source of theoretical uncertainty**

- Construction of special observables that minimize long distance effects

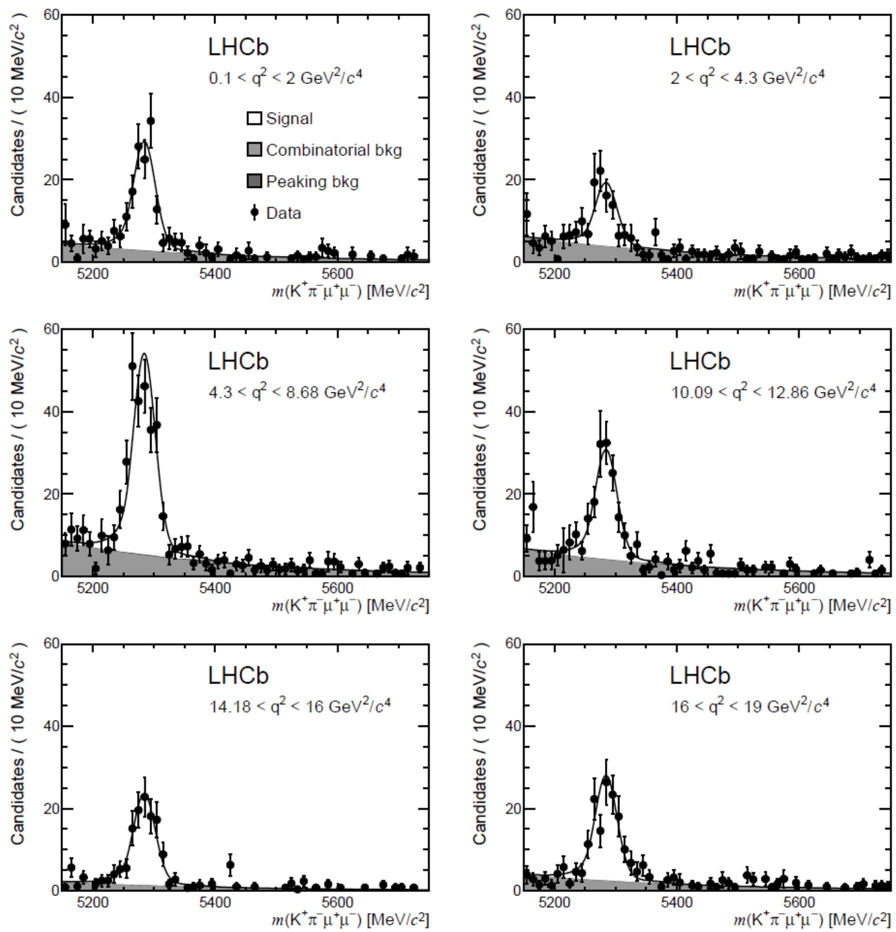
  → angular observables, asymmetries...

JHEP 08 (2013) 131

$B^0 \rightarrow K^{*0} \mu^+\mu^-$

1 fb^{-1} data

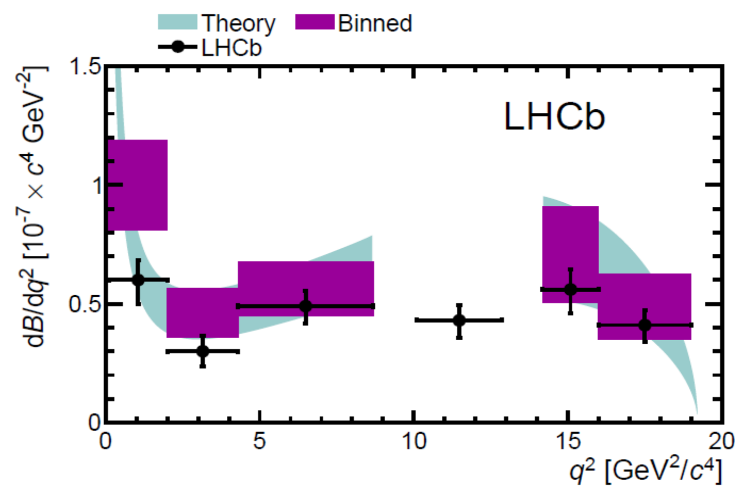
6 intervals of $\mathbf{q^2}$ (invariant mass sqared of the dimuon system)



Differential BF

normalized to the reference $B^0 \rightarrow J/\Psi K^{*0}$ yield:

$$\frac{d\mathcal{B}}{dq^2} = \frac{1}{q^2_{\max} - q^2_{\min}} \frac{N_{\rm sig}}{N_{K^{*0}J/\psi}} \frac{\varepsilon_{K^{*0}J/\psi}}{\varepsilon_{K^{*0}\mu^+\mu^-}} \times \mathcal{B}(B^0 \to K^{*0}J/\psi) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)$$

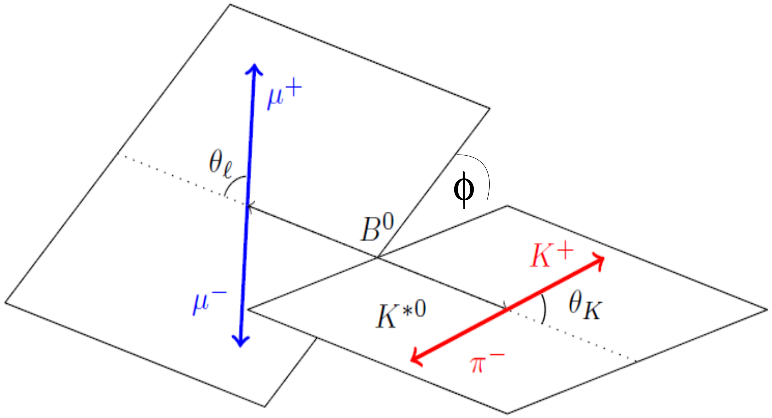


In good agreement with SM

Angular observables in $B^0 \to K^{*0} \mu^+\mu^-$

Differential decay rate: → depends on θ_l, θ_K, ϕ (angles) and q^2

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\hat{\phi}} = \frac{9}{16\pi}\Big[F_L\cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K) - F_L\cos^2\theta_K(2\cos^2\theta_\ell - 1) + \frac{1}{4}(1-F_L)(1-\cos^2\theta_K)(2\cos^2\theta_\ell-1) + S_3(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\cos 2\hat{\phi} + \frac{4}{3}A_{FB}(1-\cos^2\theta_K)\cos\theta_\ell + A_9(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\sin 2\hat{\phi}\Big].$$



for B^0 and $\bar{B}^0$ decays combined

ϕ transformations („folding techniques")

F_L A_{FB} S_3 A_9 (q^2) - depend on K* decay amplitudes

fraction of the longitudinal polarization of K^{*0}

forward-backward asymmetry of the dimuon system

Wilson Coeff. dependence

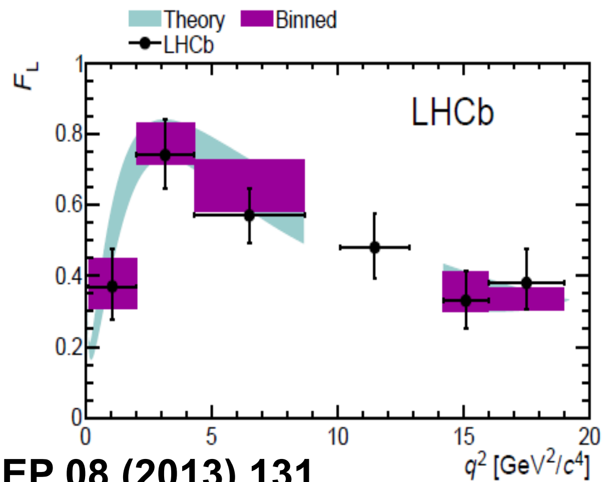
probe New Physics

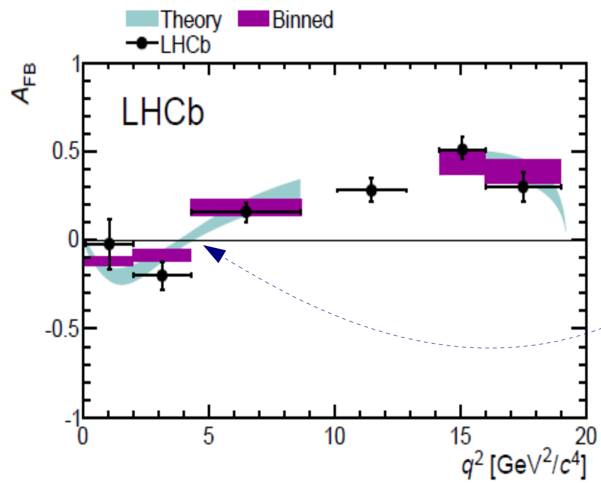
F_L A_T^{Re} A_T^2 A_9 (q^2) Alternative „transverse observables" (reduced form-factor uncertainties)

Angular observables - results

Simultaneous fit to (cos**θ**$_l$, cos**θ**$_\mathbf{K}$, ϕ) and invariant B mass – in six $\mathbf{q}^2$ bins

→ extracted $A_{\rm FB}\ (A_{\rm T}^{\rm Re})$, F_L, $S_3\ (A_{\rm T}^2)$ and A_9





JHEP 08 (2013) 131

The zero-crossing point of $A_{\rm FB}$

Phys.Rev. D87 (2013) 034016

$q_0^2 = 4.9 \pm 0.9\,{\rm GeV}^2/c^4$

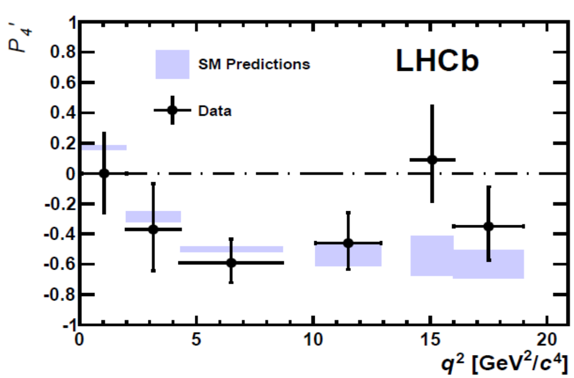
Results consistent with SM

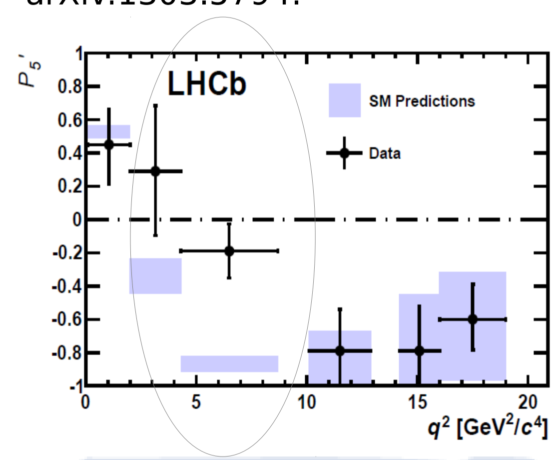
1 fb^{-1} data

$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_{\rm L}(1-F_{\rm L})}}$$

new angular obsevables with reduced form-factor uncertainties

arXiv:1303.5794.





Phys. Rev. Lett. 111 (2013) 191801

local deviation from the SM:

$4.30 < q^2 < 8.68\,{\rm GeV}^2/c^4$ - **3.7 σ**

NP may affect Wilson Coefficient C_9

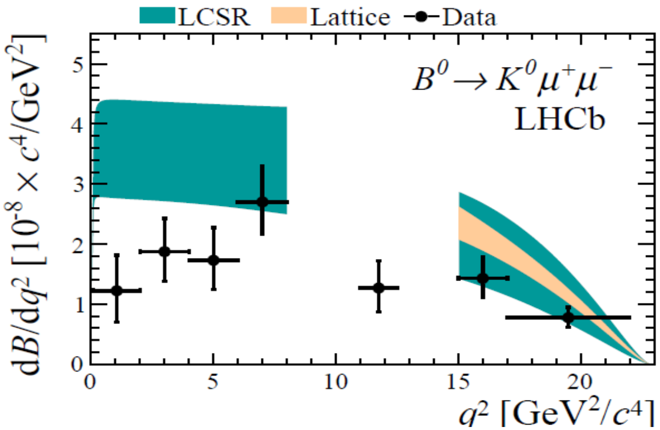
Possible explanations include presence of flavour changing Z'
arXiv:1311.6729

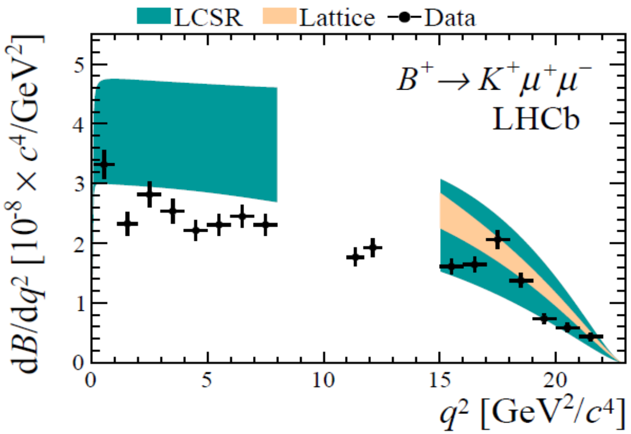
arXiv:1403.8044v2

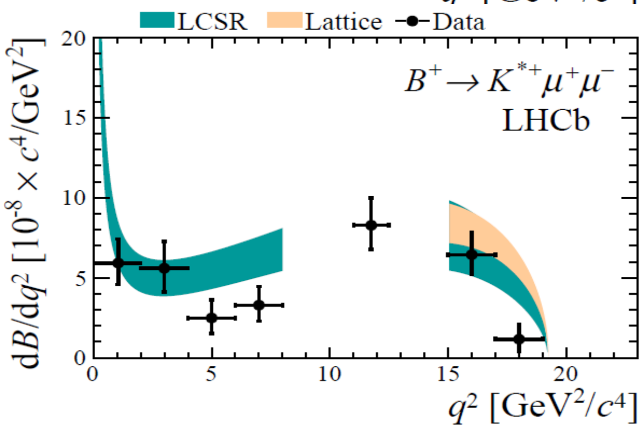
Differential BF for B → $K^{(*)}$ $\mu^+\mu^-$

Theory: Phys.Rev. D88 (2013) 054509, Phys. Rev. D71 (2005) 014029, arXiv:1006.4945.

3 fb^{-1} data







Decay mode	Measurement	Prediction
$B^+ \to K^+\mu^+\mu^-$	$8.5 \pm 0.3 \pm 0.4$	10.7 ± 1.2
$B^0 \to K^0\mu^+\mu^-$	$6.7 \pm 1.1 \pm 0.4$	9.8 ± 1.0
$B^+ \to K^{*+}\mu^+\mu^-$	$15.8\ ^{+3.2}_{-2.9} \pm 1.1$	26.8 ± 3.6

Integrated over high q^2 region

Each value consistent with SM, but all below the SM prediction!

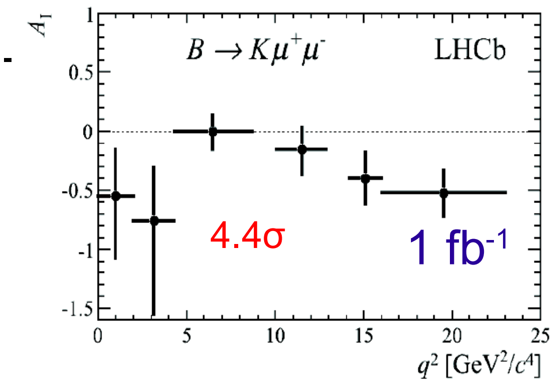
arXiv:1403.8044v2

Isospin asymmetry A_I

Puzzling results for A_I measurement on 1 fb^{-1} for $\mathbf{B^+ \to K^+\mu^+\mu^-}$

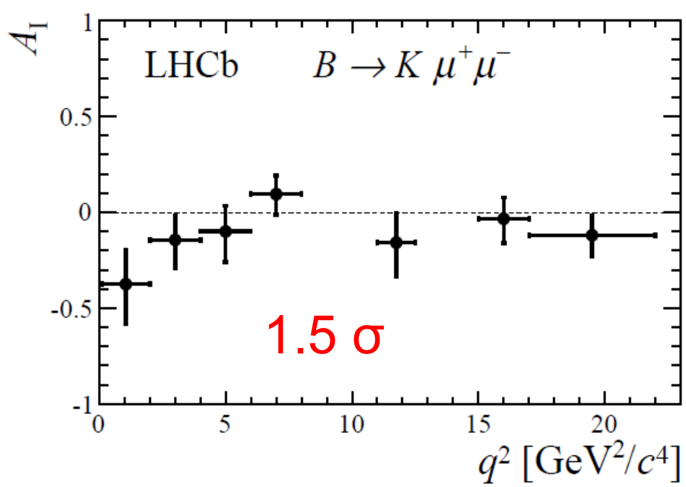
→ 4.4σ discrepancy from zero

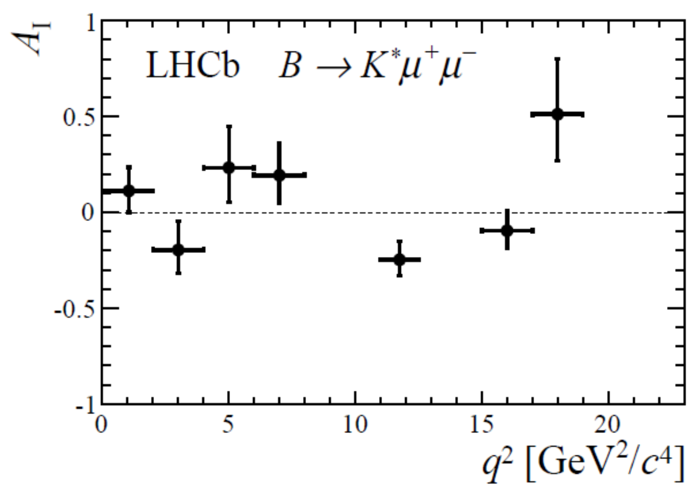
$$A_I = \frac{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) - (\tau_0/\tau_+)\cdot\mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) + (\tau_0/\tau_+)\cdot\mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)}$$



New, updated analysis performed on the full LHCb dataset

updated reconstruction and event selection





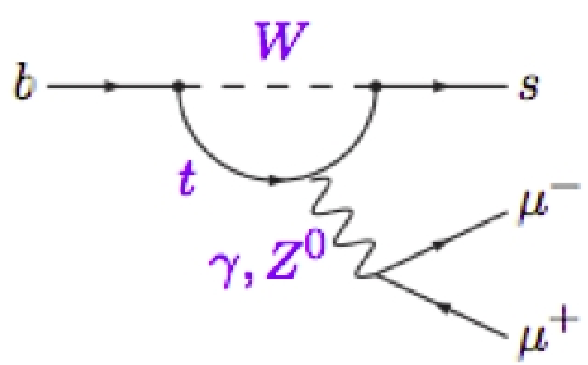
3 fb^{-1}
data

Consistent with SM expectations

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

- Dedicated analysis of $B^+ \rightarrow K^+\mu^+\mu^-$ at low recoil (high q^2 region) , above the open-charm threshold
- Observation of higher charmonium resonances (tree level diagrams in addition to the nonresonant FCNC loops)

  → essential to understand these broad and overlaping states to probe NP contribution to the FCNC decays



Phys. Rev. Lett. 111 (2013) 112003

3 fb^{-1} data

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

Kinematic fit with $K^+\mu\mu$ mass constrained to the nominal B mass

→ ***Improvement in $\mu^+\mu^-$ invariant mass resolution!***

We consider:

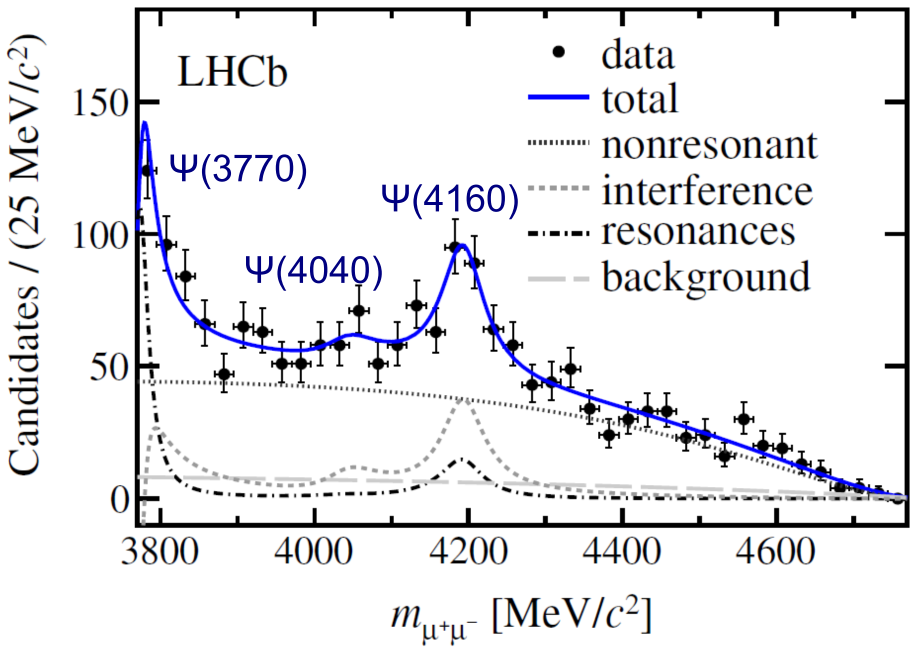
1 Non-resonant $B \rightarrow K^+\mu\mu$ signal

2 Resonant component

axial-vector   vector

interference

3



resonances observed due to constructive interference

- **First observation of $B \rightarrow \Psi(4160)K^+$, $\Psi(4160) \rightarrow \mu\mu$**

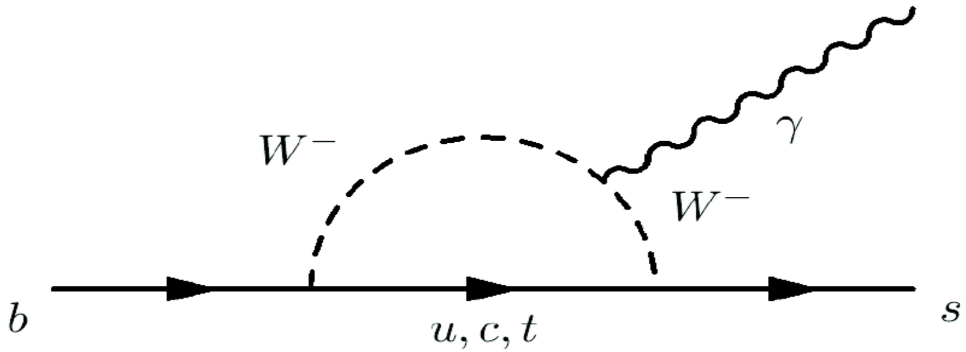
Bf ($B \rightarrow \Psi(4160)K^+$) = $(5.1^{+1.3}_{-1.2} \pm 3.0) \times 10^{-4}$ (assuming lepton universality)

- Ψ(4040) not significant
- 20% of the Ψ(4160) contribution in the total signal

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

- $b \rightarrow s\gamma$ transition: elektroweak penguin loop → photon predominantly left-handed in the SM

  (small right-handed γ contribution of the order of m_s/m_b)
- Maximal parity violation



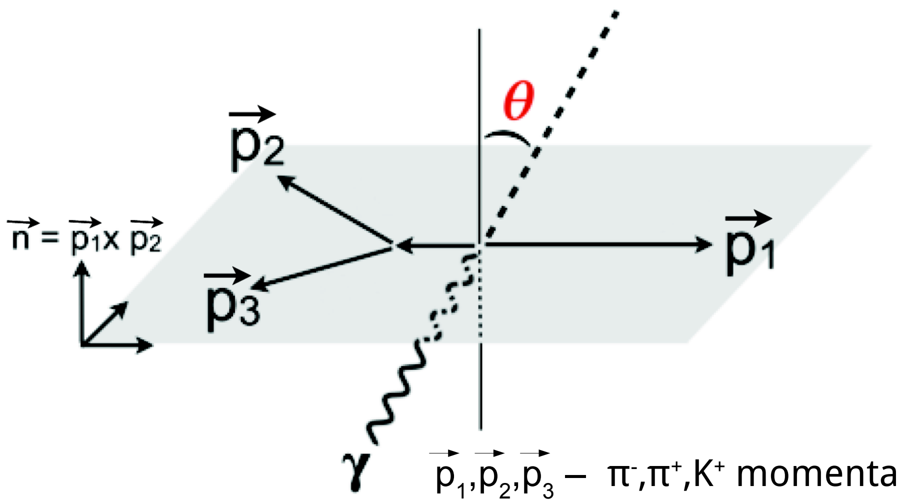
- In several extensions of SM – significant right-handed contribution (heavy fermion in penguin loop)

Phys. Rev. Lett. 112, 161801 (2014)

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

We measure:

- Angle (θ) of the γ with respect to the plane of three hadrons (K π π)
  → in different intervals of Kππ mass
- Asymmetry between number of events On each side of the plane



Differential decay rate:

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

γ polarisation

Asymmetry (up-down)

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

depends only on odd powers of cosθ

→ **Up-down asymmetry proportional to the γ polarisation**

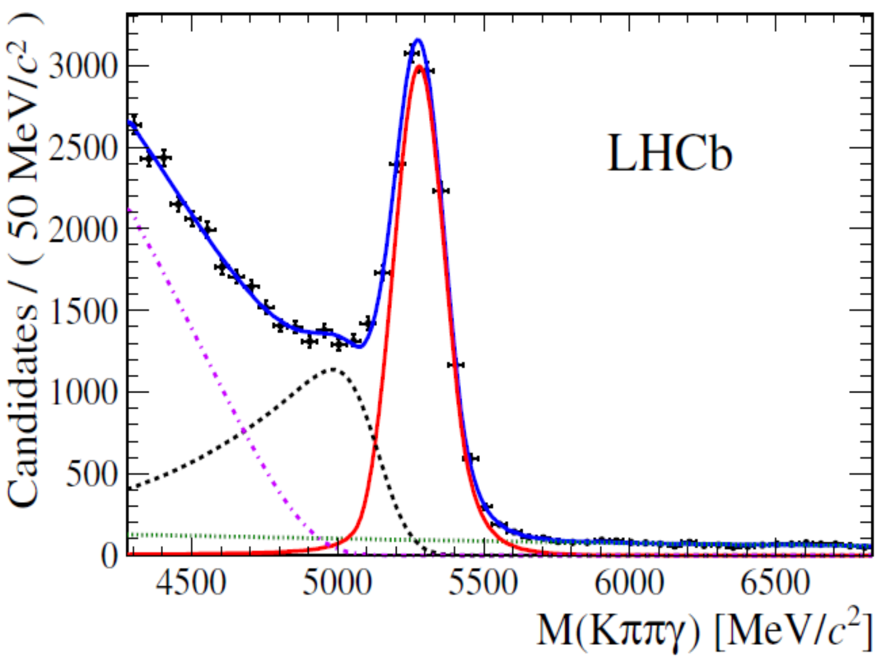
$$\mathcal{A}_{ud} \sim \lambda_\gamma$$

Phys. Rev. Lett. 112, 161801 (2014)

3 fb^{-1} data

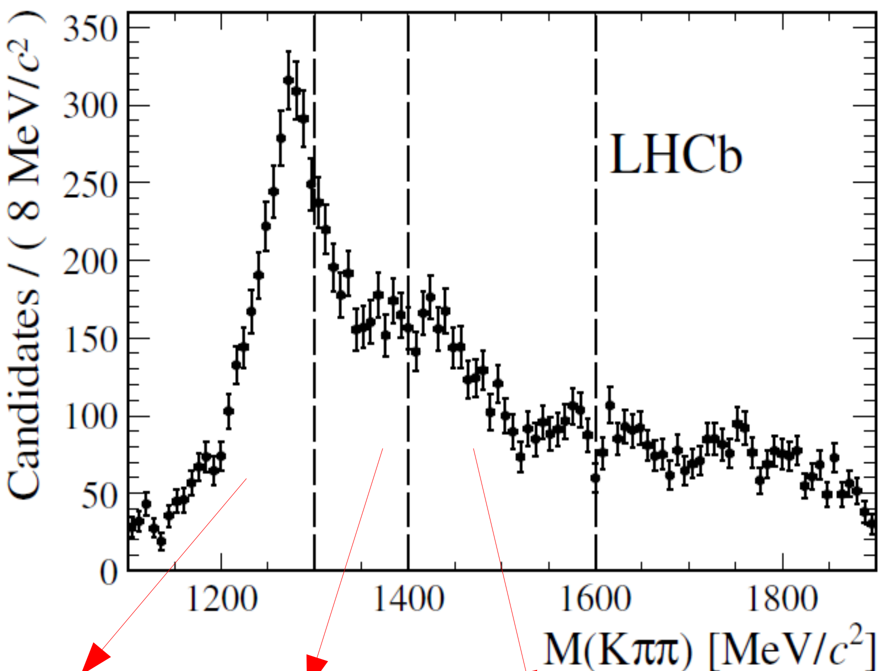
$B^+ \to K^+ \pi^- \pi^+ \gamma$

Maximum likelihood fit to the B mass candidate:



→ ~ 14 000 signal events

background subtracted Kππ invariant mass



$K_1(1270)$ $K_1(1400)$ $K^*(1410)$ $K_2^*(1430)$ $K_2(1580)$ $K_2(1770)$

interference of several resonances

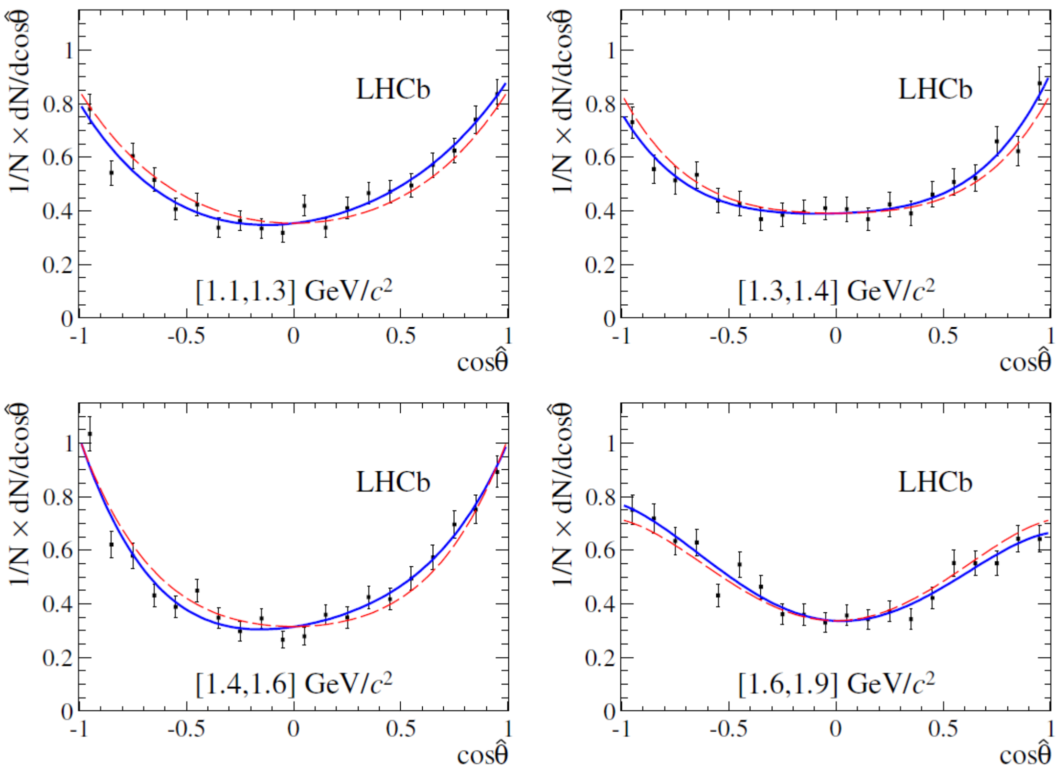
- inclusive measurement in 4 bins
- theoretical limitations for extracting λ_γ

Phys. Rev. Lett. 112, 161801 (2014)

3 fb^{-1}
data

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

Background subtracted angular distribution from the fit to the B mass candidate in each bin of θ angle



Fitted with:

$$f(\cos\hat{\theta}; c_i) = \sum_{i=0}^{4} c_i L_i(\cos\hat{\theta})$$

Legendre pol.

$$\mathcal{A}_{\rm ud} = c_1 - \frac{c_3}{4}$$

First observation of the parity-violating γ polarization ≠ 0 at 5.2σ

Determination of the λ_γ value from $\mathcal{A}_{\rm ud}$ and cosθ shape may **constrain the effects of NP in the b→sγ sector!**

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

Summary

- Measurement of differential branching fractions and form-factor independent angular observables in $B^0 \to K^{*0} \mu^+\mu^-$

  results consistent with SM except for local tension for P_5' variable

- Updated measurement of the isospin asymmetry for $B \to K^{(*)} \mu^+\mu^-$

  consistent with SM!

- First observation of the decay $B^+ \to \Psi(4160) K^+$, $\Psi(4160) \to \mu^+\mu^-$

  observed through constructive interference!

- First observation of the γ polarisation in $B^+ \to K^+ \pi^- \pi^+ \gamma$ decay

  theory input required for SM test

- Many other interesting analyses

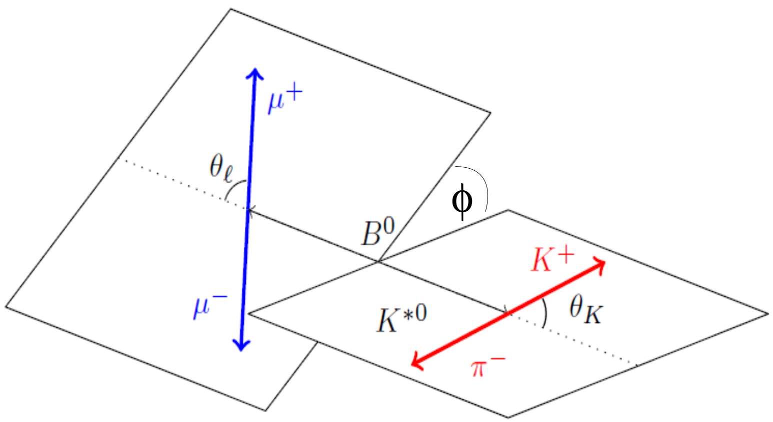
  $B_{(s)} \to \mu^+\mu^-$
  majorana neutrinos in $B^- \to \pi^+\mu^-\mu^-$
  $D^0 \to \pi^+\pi^-\mu^+\mu^-$
  ....

BACKUP

Angular observables in B → K* μμ

Differential decay rate:

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[I_1^s \sin^2\theta_K + I_1^c \cos^2\theta_K + I_2^s \sin^2\theta_K \cos 2\theta_\ell + I_2^c \cos^2\theta_K \cos 2\theta_\ell + I_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + I_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi + I_5 \sin 2\theta_K \sin\theta_\ell \cos\phi + I_6 \sin^2\theta_K \cos\theta_\ell + I_7 \sin 2\theta_K \sin\theta_\ell \sin\phi + I_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi + I_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi \Big],$$



→ Depends on θ_l, θ_K, ϕ (angles) and q^2

q^2 - invariant mass sqared of the dimuon system

I_j coefficients are combinations of K* decay amplitudes, that are functions of:

1. Wilson Coefficients – short distance effects – **sensitive for New Physics!**
2. form factors – long distance effects - **significant source of theoretical uncertainty**

JHEP 08 (2013) 131

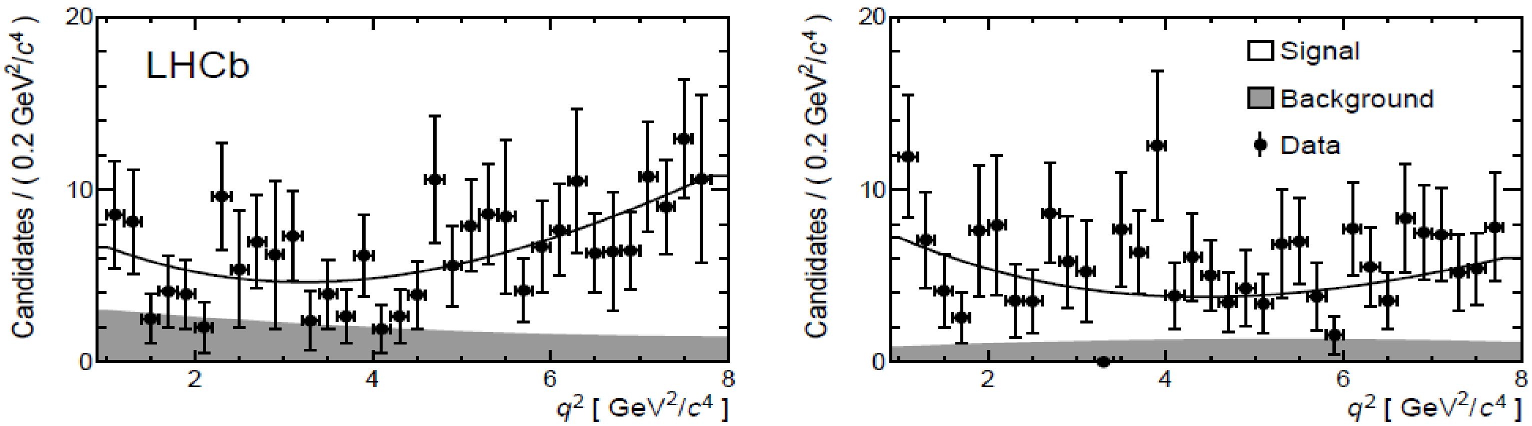
Zero-crossing point of A_{FB}

In the Standard Model: A_{FB} (q^2) changes sign at certain predicted value q_0^2

Two separate subsamples:

forward-going candidates ($\cos\theta_l > 0$)

backward-going candidates ($\cos\theta_l < 0$)



- $\mathbf{q^2}$ distributions fitted with polynomials P_F , P_B
- Asymmetry: $$A_{\rm FB}(q^2) = \frac{P_{\rm F}(q^2) - P_{\rm B}(q^2)}{P_{\rm F}(q^2) + P_{\rm B}(q^2)}$$

1 fb^{-1} data

The zero-crossing point of $A_{\rm FB}$ $\quad q_0^2 = 4.9 \pm 0.9\,{\rm GeV}^2/c^4$ → **consistent with SM**

PRL 111 (2013) 191801

New angular observables (improved „folding”)

JHEP 05 (2013) 137, arXiv:1303.5794.

with reduced form-factor uncertainty:

1 fb^{-1} data

local deviation from the SM:

$4.30 < q^2 < 8.68\,\mathrm{GeV}^2/c^4$ - 3.7 σ deviation

$1.0 < q^2 < 6.0\,\mathrm{GeV}^2/c^4$ - 2.5 σ deviation

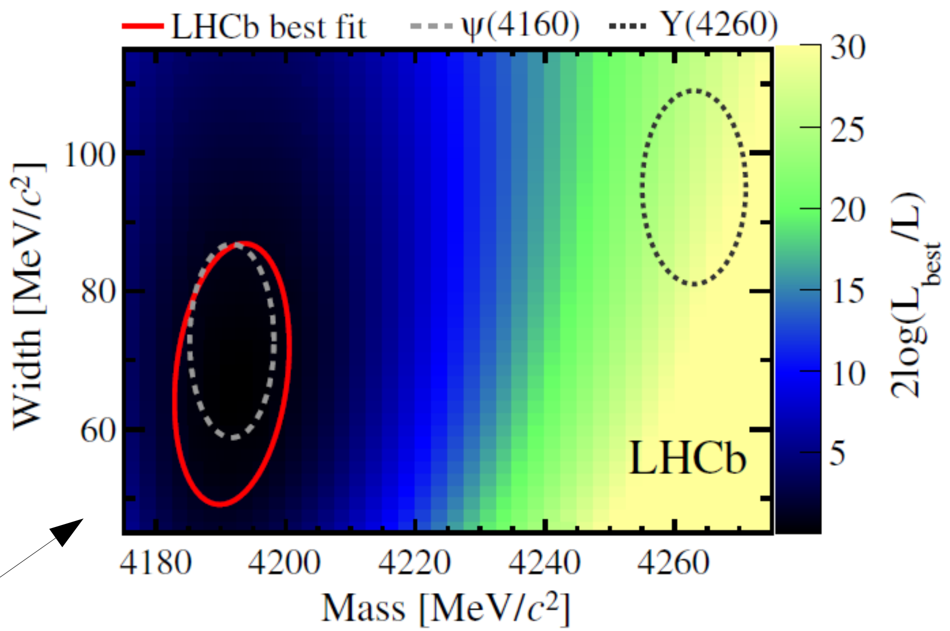
→

NP may affect Wilson Coefficient C_9 ...

- updating to the full LHCb statistics
- more modes need to be studied! →

Phys. Rev. Lett. 111 (2013) 112003

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



Ψ(4160) state observed with the significance greater then 6σ!

FIRST OBSERVATION OF
B → Ψ(4160)K⁺, Ψ(4160)→μμ

Mass and width consistent with previous LHCb measurement

Bf (B → Ψ(4160)K^+) = $(5.1^{+1.3}_{-1.2} \pm 3.0) \times 10^{-4}$ (assuming lepton universality)

Ψ(4040) not significant
→ upper limit set BF < $1.3\,(1.5) \times 10^{-9}$ at 90 (95)% CL

20% of the Ψ(4160) contribution in the total signal

3 fb^{-1}
data

Angular observables K* mu mu

$$S_j = \left(I_j + \bar{I}_j\right) \Big/ \frac{d\Gamma}{dq^2} \qquad A_j = \left(I_j - \bar{I}_j\right) \Big/ \frac{d\Gamma}{dq^2}$$

$$A_{FB} = \tfrac{3}{4}\left(1 - F_L\right) A_T^{Re}$$

$$F_L = S_1^c = -S_2^c$$

$$A_{FB} = \tfrac{3}{4} S_6 \qquad S_3 = \tfrac{1}{2}\left(1 - F_L\right) A_T^2$$

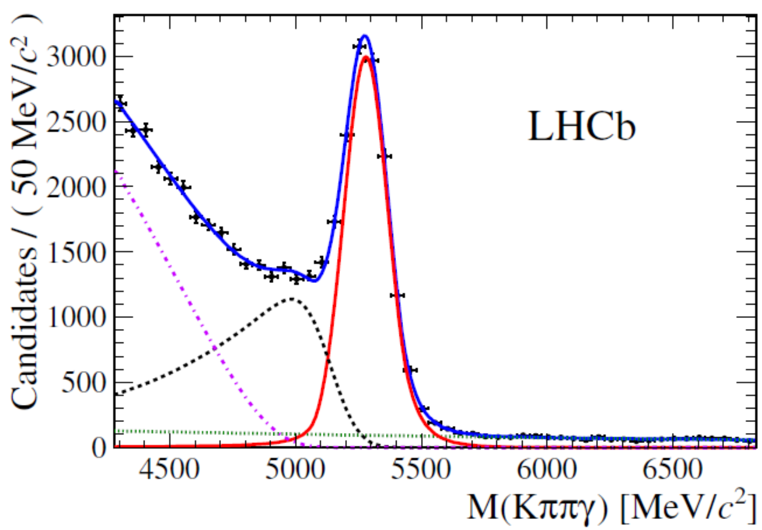
$$\begin{aligned}\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\hat{\phi}} = \frac{9}{16\pi}\Big[& F_L\cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K) \; - \\ & F_L\cos^2\theta_K(2\cos^2\theta_\ell - 1) \; + \\ & \frac{1}{4}(1-F_L)(1-\cos^2\theta_K)(2\cos^2\theta_\ell - 1) \; + \\ & S_3(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\cos 2\hat{\phi} \; + \\ & \frac{4}{3}A_{FB}(1-\cos^2\theta_K)\cos\theta_\ell \; + \\ & A_9(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\sin 2\hat{\phi} \; \Big] .\end{aligned}$$

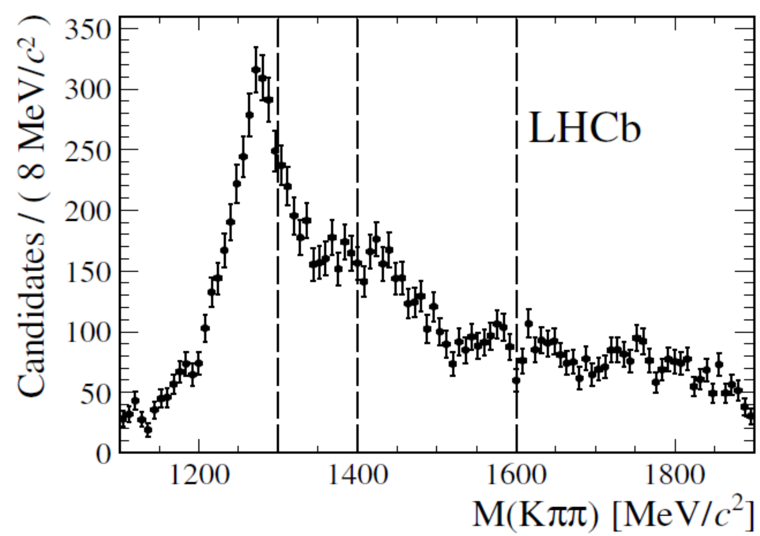
$$\hat{\phi} = \begin{cases} \phi + \pi & \text{if } \phi < 0 \\ \phi & \text{otherwise} \end{cases}$$

$$A_T^{Re} = \frac{S_6}{1 - F_L}$$

$$A_T^2 = \frac{2S_3}{1 - F}$$

$B \to K \pi \pi \gamma$





$$\cos\hat{\theta} \equiv \mathrm{charge}(B)\cos\theta$$

to account for the opposite
γ polarization for B^+ and B^-