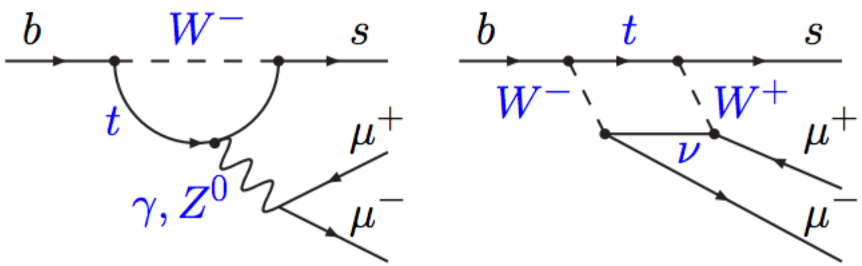
b -> sll AND RADIATIVE DECAYS AT LHCb



Francesco Polci
(LPNHE-CNRS/IN2P3)
on behalf of the LHCb collaboration

CKM 2016, Mumbai, Nov 28th – Dec 2nd 2016

OUTLINE

- **Introduction**
- **Overview of *b->sll* BF and angular analysis measurements**
- **First *b->dll* measurements**
- **Results on the photon polarization from *b->sγ* decays**

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All results based on Run1 (3fb^{-1})

This talk will not cover:

- B_s->$\mu\mu$ discussed in M. Rama's talk (https://indico.tifr.res.in/indico/contributionDisplay.py?contribId=33&confId=5095)
- LFU/LFV tests discussed in P. Alvarez Cartelle's talk (https://indico.tifr.res.in/indico/contributionDisplay.py?contribId=16&confId=5095)

OUTLINE

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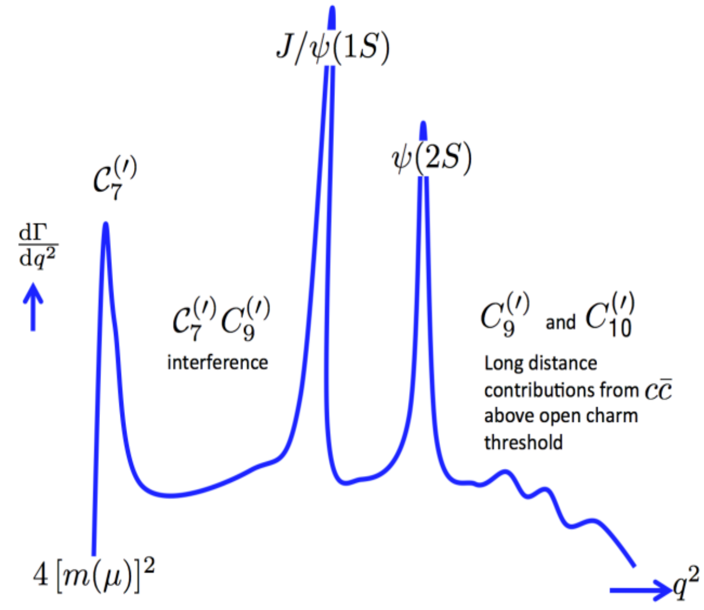
$b \to s\ell\ell$ AND $b \to s\gamma$ AS PROBES FOR NP

- *b->s(d)ll* and *b->sγ* transitions are powerful probe of New Physics:
  - FCNC proceeding via loop diagrams only;
  - suppressed in the SM, so more sensitive to NP;
  - rich phenomenology and many precise SM predictions available;
  - explore higher mass scales than the current collider energies.

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

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

Operators Oi: non-perturbative long-distance effects
Wilson coefficients Ci: perturbative short-distance effects

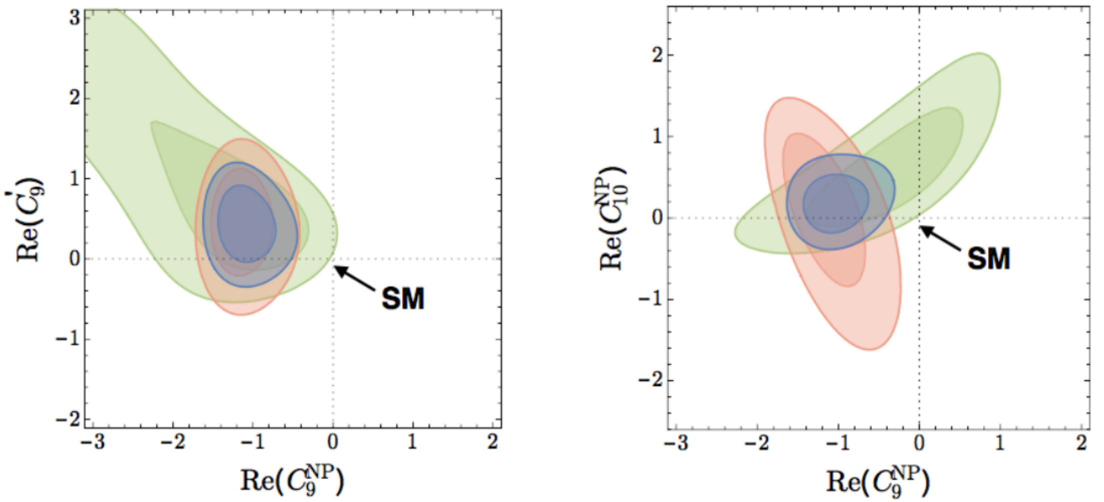


- *New particles in the loop could enhance/suppress decay rates, introduce new sources of CP violation, modify angular distributions.*

Several global fits of *b->s* data have been performed
(e.g. arXiv:1503.06199, JHEP06 (2016) 092 , JHEP06 (2016) 116)

Use 80 observables from 6 experiments, including *b->μμ*, *b->sll* and *b->sγ*

All fits require an additional contribution to the SM predictions, preferring $C_9^{NP} \neq 0$ at ~4σ



arXiv:1503.06199

branching fractions, angular observables and combination

- NP scenarios (ex: new *Z'* vector with mass of few TeV)? This will be also coherent with LFU tests (R_K=1 at 2.6 σ)
- QCD effects (charm loops, as for ex. JHEP06 (2016) 116)?

More data are needed!

Notes: B_s->μμ has important implications for C_{10}
LFU tests are not sensitive to charm loops

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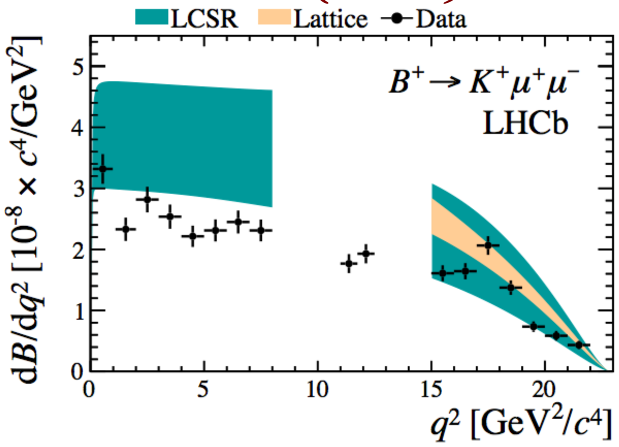
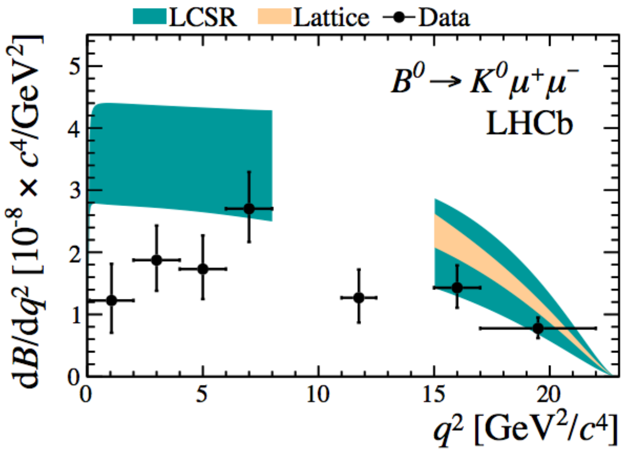
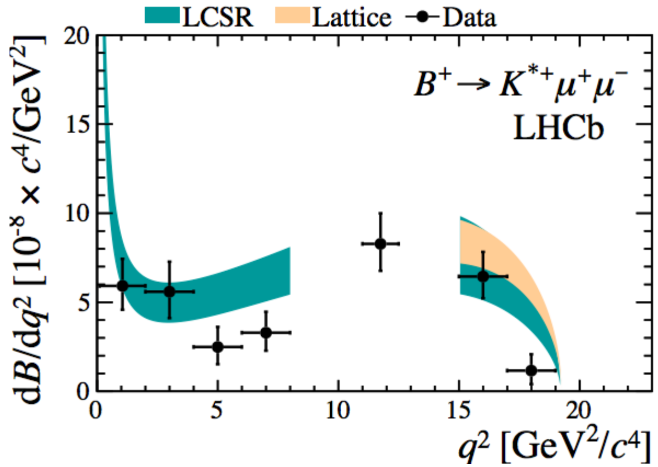
$b \to s\mu\mu$ BRANCHING RATIOS

- Measured *BR* are consistently lower than predicted in SM, despite large error from the form factors
- Beware: theory uncertainties are correlated across the q^2

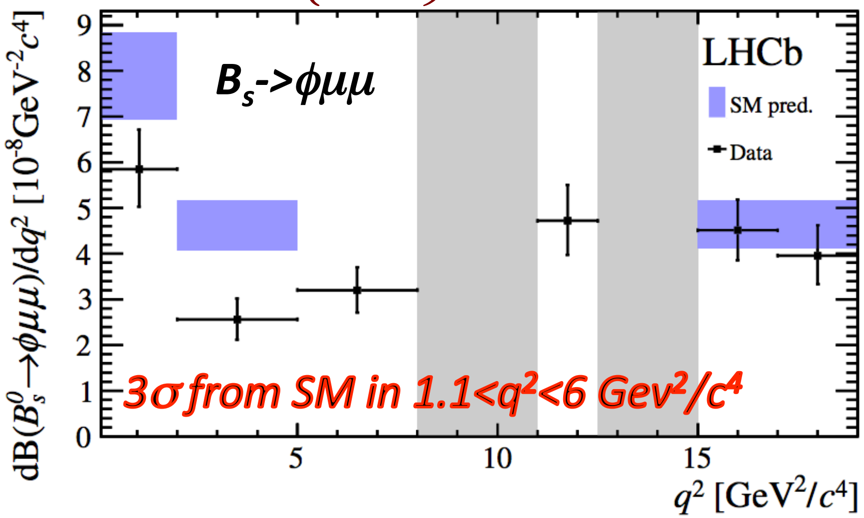
JHEP 06 (2014) 133



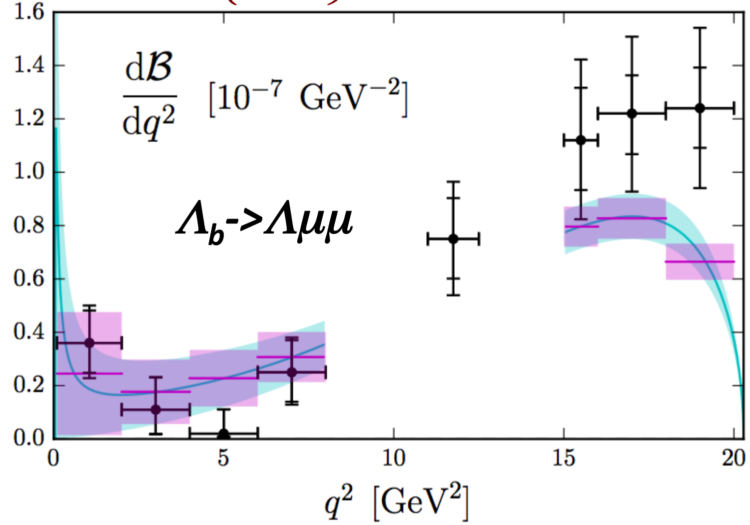




JHEP 09 (2015) 179



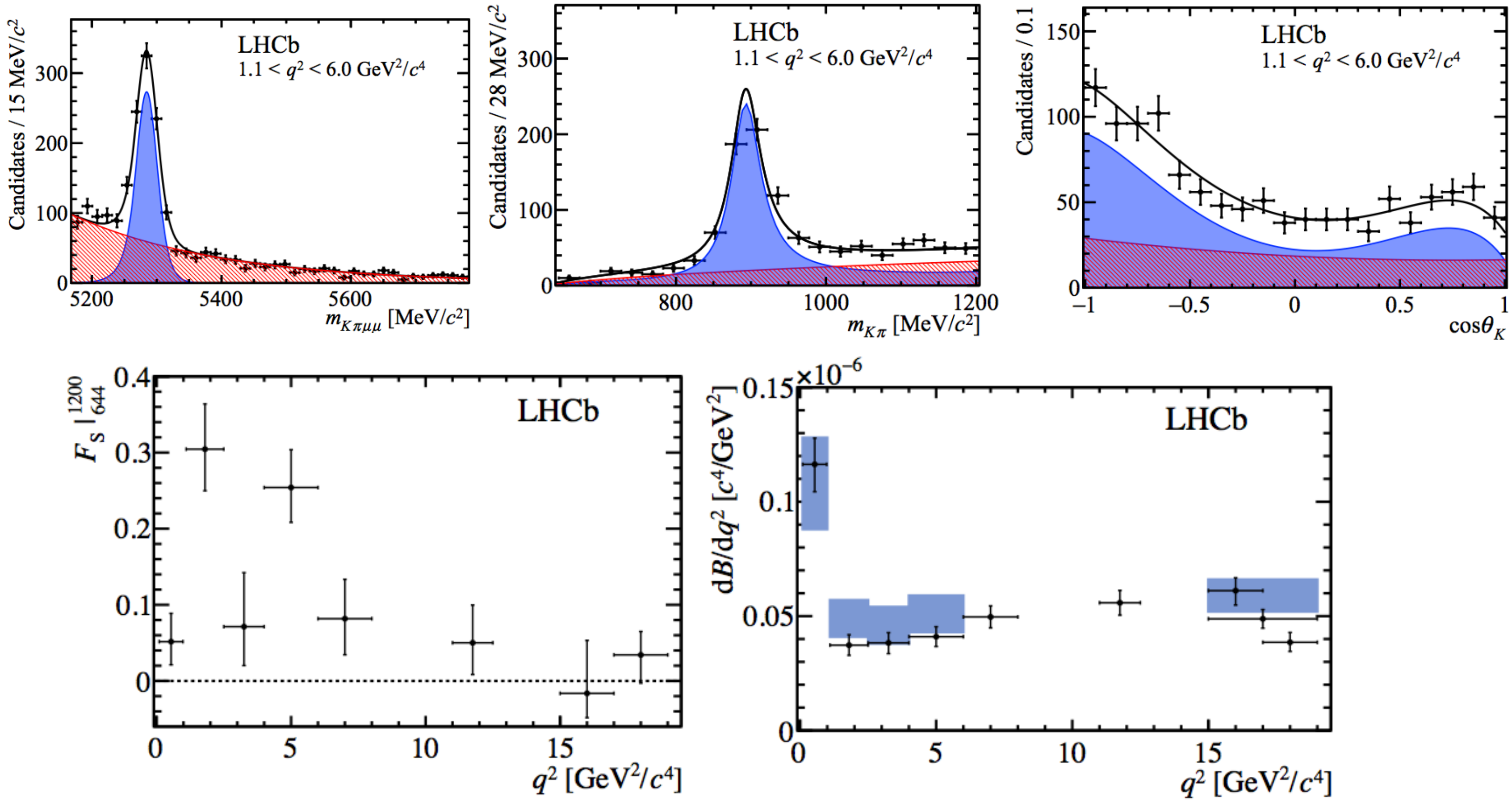
JHEP 06 (2015) 115 and arXiv:1602.01399



NEW B->K*μμ *BR MEASUREMENT*

JHEP11 (2016) 047

- First determination of the P-wave only BR of B->K*(892)μμ
- Measuring S-wave fraction in 644 <m($K\pi$) <1200 MeV/c²
- Fitting m($K\pi\mu\mu$), m($K\pi$) and angular distribution cos(θ_K)

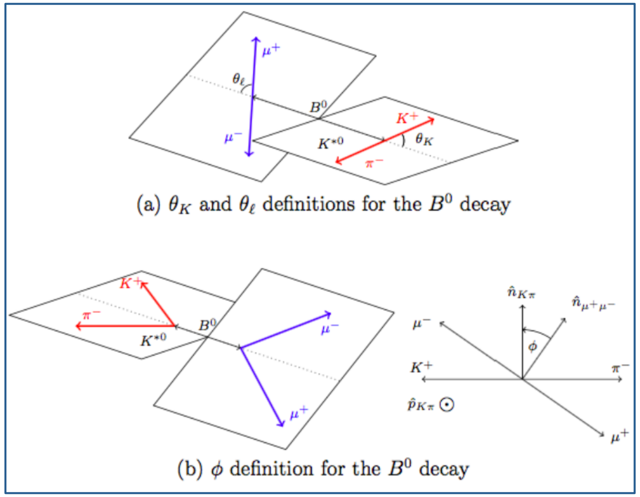


*B -> K*μμ* ANGULAR ANALYSIS

Study the full angular distribution (θ_l, θ_K, ϕ) of the 4 final state particles.

Described by eight independent observables:

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



(a) θ_K and θ_ℓ definitions for the B^0 decay

(b) ϕ definition for the B^0 decay

Observables (A_{FB}, F_L and S_j) are function of the Wilson coefficients.

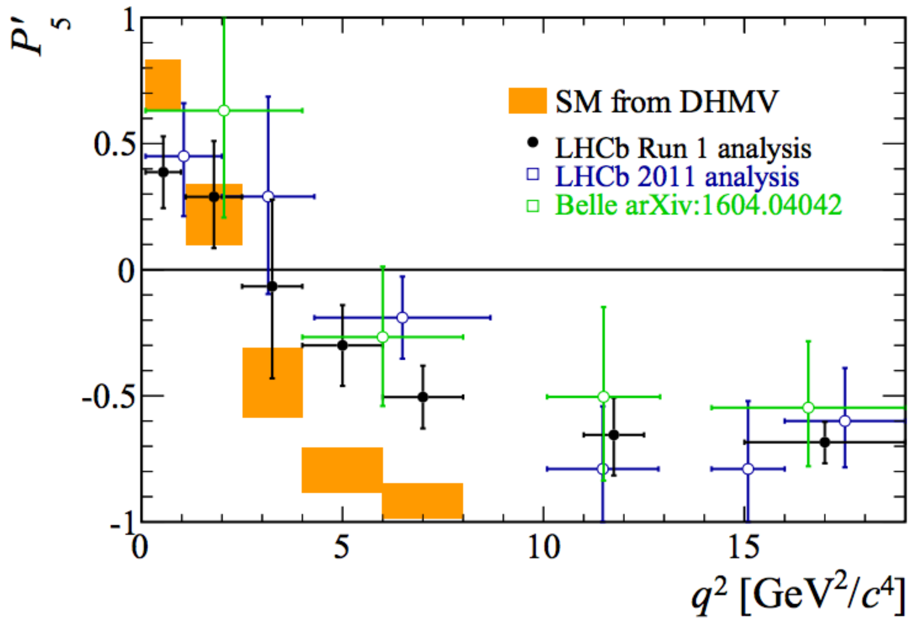
A cleaner set of observables, where hadronic form factor uncertainties cancels at the leading order, can be defined (*JHEP 1305(2013)137*), ex:

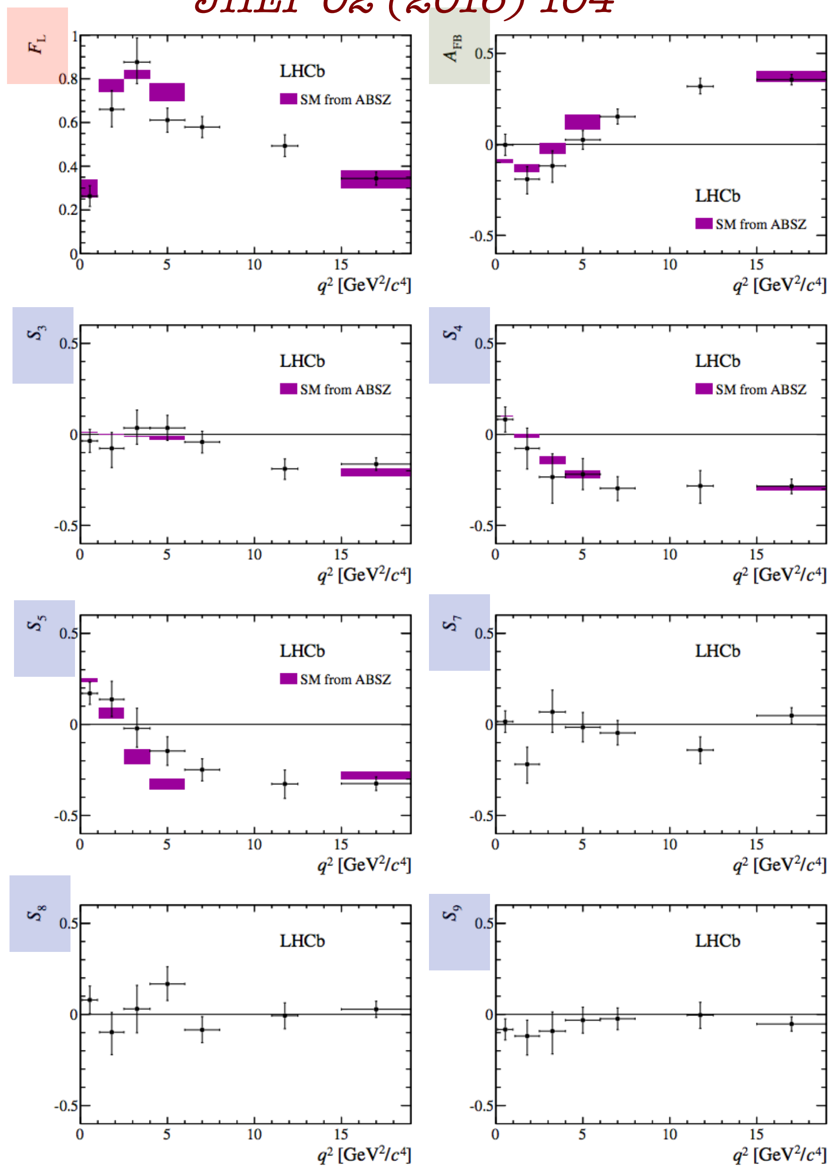
$$P_5' \equiv \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

JHEP 02 (2016) 104

LHCb performed the first full angular analysis of $B \to K^*\mu\mu$, using Run1 (3 fb^{-1})

- full set of CP-averaged angular terms
- full set of CP-asymmetries
- correlation matrix published
- form-factor independent ratios of observables measured (P')

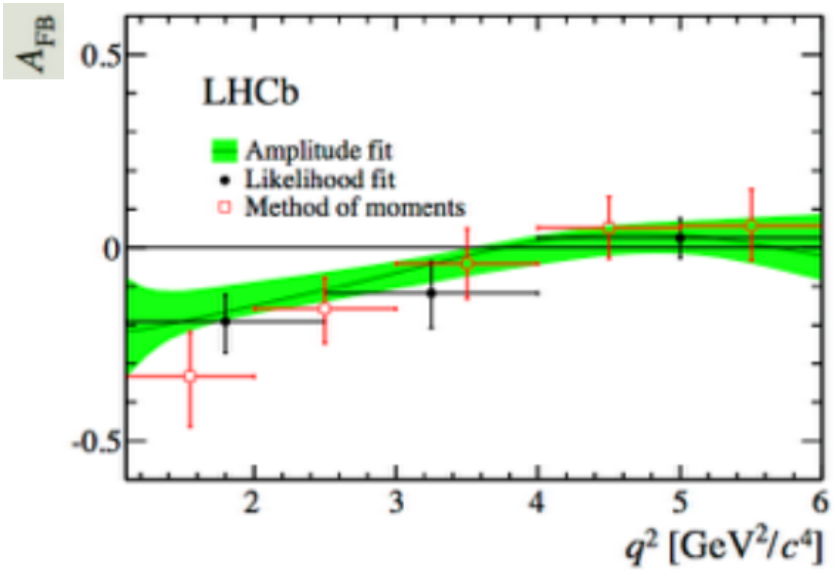




Global fit to $B \to K^*\mu\mu$ is 3.4σ from SM.

Additional measurement of the zero-crossing point, parameterizing the angular distribution with q^2 dependent decay amplitudes

JHEP 02 (2016) 104



$$q_0^2(S_5) \in [2.49, 3.95]\,\mathrm{GeV}^2/c^4 \text{ at } 68\%\text{ CL}$$

$$q_0^2(A_{\mathrm{FB}}) \in [3.40, 4.87]\,\mathrm{GeV}^2/c^4 \text{ at } 68\%\text{ CL}$$

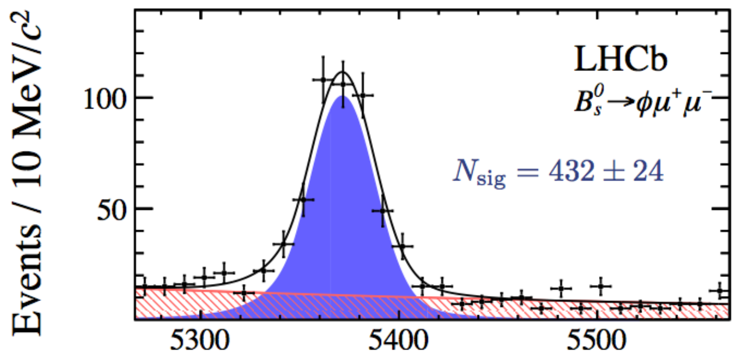
$$\text{SM: } q_0^2(A_{\mathrm{FB}}) \sim [3.9, 4.4]\,\mathrm{GeV}^2/c^4$$

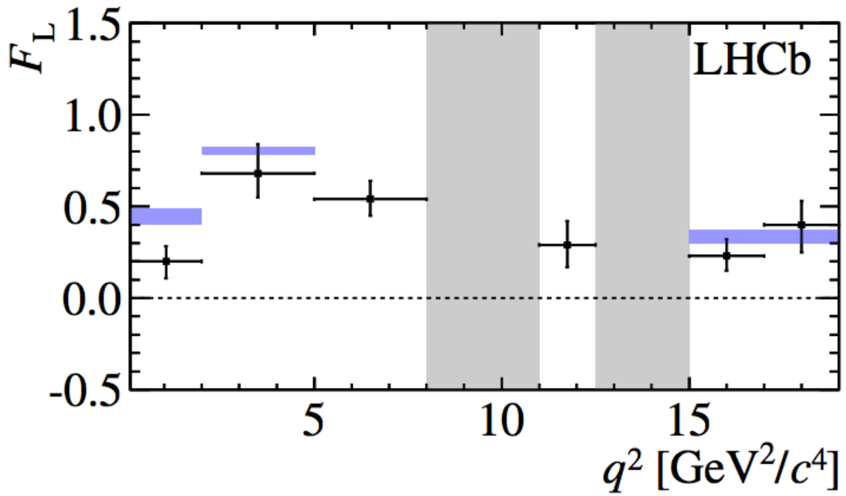
[JHEP 01 (2012) 107, EPJ C41 (2005) 173, EPJ C47 (2006) 625]

ANGULAR ANALYSES OF $B_s \to \phi\mu\mu$ AND $\Lambda_b \to \Lambda\mu\mu$

- $B_s \to \phi\mu\mu$ is very clean experimentally!
- Final state not self-tagging: less observables

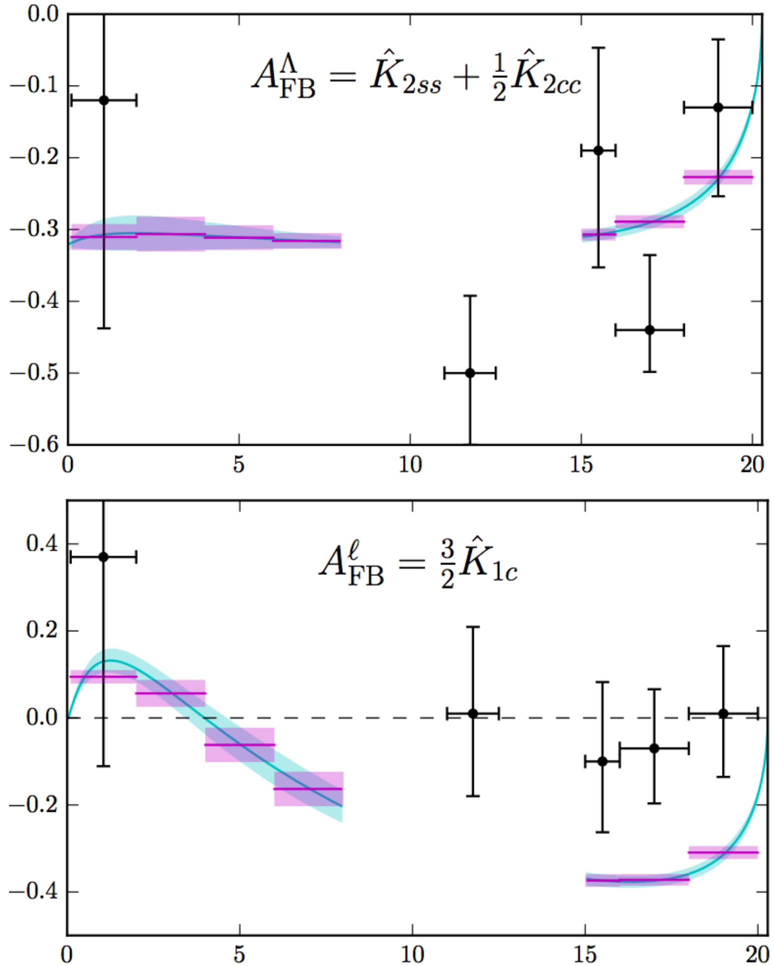
JHEP 09 (2015) 179



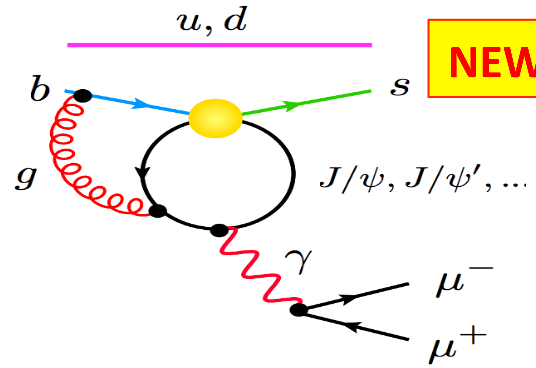


- $\Lambda_b \to \Lambda\mu\mu$ gives access to different combinations of Wilson coefficients
- More statistics needed

JHEP 06 (2015) 115 and arXiv:1602.01399



EVALUATING CHARM CONTRIBUTIONS IN $B^+ \to K^+\mu\mu$



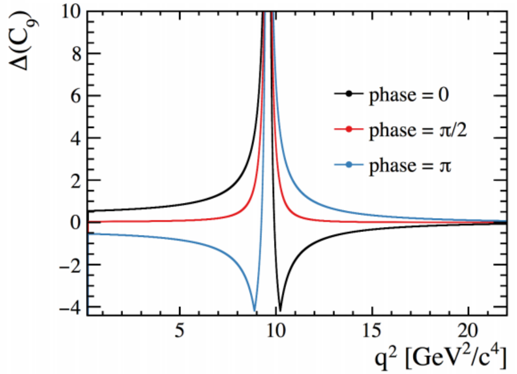
NEW

Purpose: measure the phase difference between short- (FCNC) and long-distance amplitudes

- Sizeble effect of the long-distance contributions far from the resonances could explain the observed tensions

Method: analize the dimuon mass spectrum

- long-distance modeled as sum of BW
- magnitudes, phases, C_9, C_{10} floated
- C_7 fixed to SM
- hadronic form factors f_+ constrained
- crucial control of the **resolution function**



$$\frac{d\Gamma}{dq^2} = \frac{G_F^2\alpha^2|V_{tb}V_{ts}^*|^2}{2^7\pi^5}|\boldsymbol{k}|\beta\left\{\frac{2}{3}|\boldsymbol{k}|^2\beta^2\left|C_{10}f_+(q^2)\right|^2 + \frac{4m_l^2(m_B^2-m_K^2)^2}{q^2}\left|C_{10}f_0(q^2)\right|^2 + |\boldsymbol{k}|^2\left[1-\frac{1}{3}\beta^2\right]\left|C_9^{\mathrm{eff}}f_+(q^2)+2C_7\frac{m_b+m_s}{m_B+m_K}f_T(q^2)\right|^2\right\},$$

$$C_9^{\mathrm{eff}} = C_9 + \sum_j |\eta_j| e^{i\delta_j} A_j^{\mathrm{res}}(q^2)$$

$$P_{\mathrm{sig}}(m_{\mu\mu}^{\mathrm{rec}}) \propto R(m_{\mu\mu}^{\mathrm{rec}}, m_{\mu\mu}) \otimes \left(\varepsilon(m_{\mu\mu})\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2}\frac{\mathrm{d}q^2}{\mathrm{d}m_{\mu\mu}}\right)$$

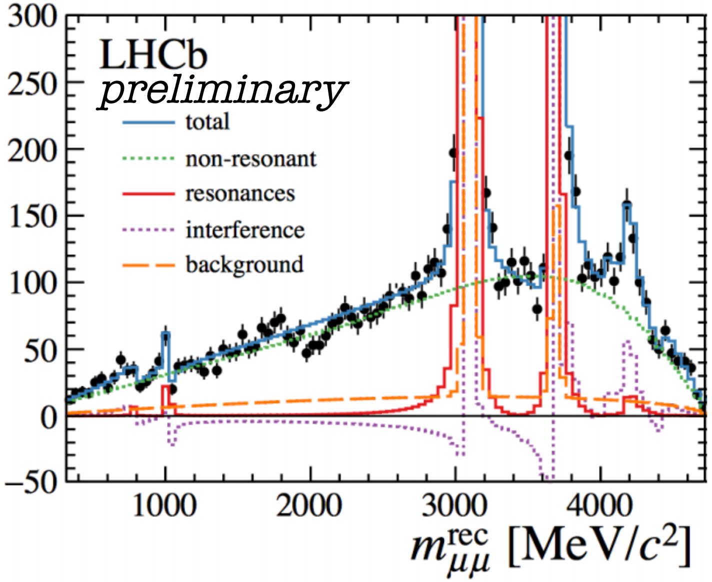
EVALUATING CHARM CONTRIBUTIONS IN $B^+ \to K^+\mu\mu$

- Four degenerate solutions, corresponding to the ambiguities of J/Psi and Psi(2s) phases being negative or positive
- J/Psi phase is compatible with +/-π/2 => is small away from the pole
- Preferred values: $|C_{10}|<|C_{10}^{SM}|$ and $|C_9|>|C_9^{SM}|$

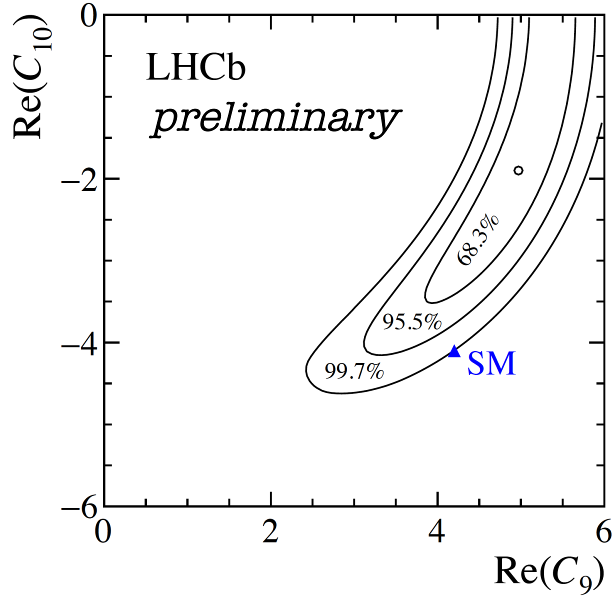
  If $C_{10} = C_{10}^{SM}$, $|C_9|<|C_9^{SM}|$

NEW

LHCb-PAPER-2016-045
COMING SOON



Resonance
$\rho(770)$
$\omega(780)$
$\phi(1020)$
J/ψ
$\psi(2S)$
$\psi(3770)$
$\psi(4040)$
$\psi(4160)$
$\psi(4415)$



- BF compatible with previous measurement and smaller than the SM:

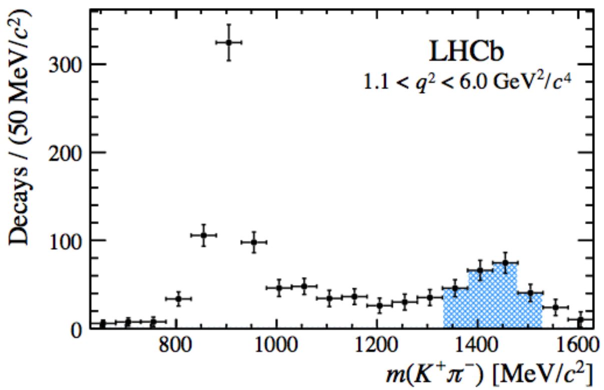
$$\mathcal{B}(B^+ \to K^+\mu^+\mu^-) = (4.37 \pm 0.15\,(\text{stat}) \pm 0.23\,(\text{syst})) \times 10^{-7}$$

For the future: improved *B->K* form factors and more data needed.
More difficult for the *K**: helicity states can have different relative phases

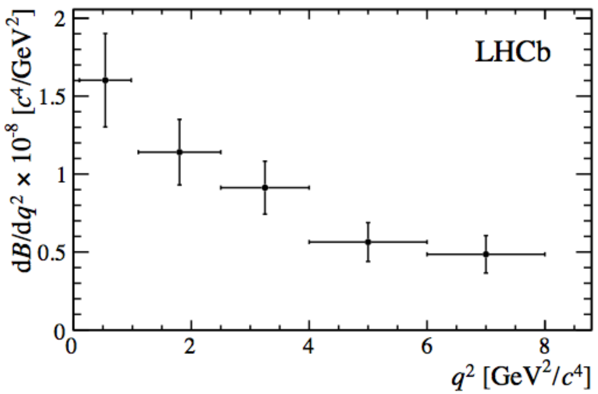
$B^0 \to K\pi\mu\mu$ IN THE $K_{0,2}^*(1430)^0$ REGION

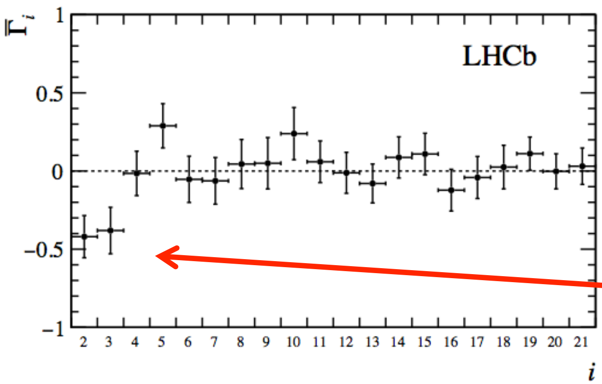
$B \to K\pi\mu\mu$ BR and angular analysis in the range 1330<$m(K\pi)$<1530 MeV/c2

- 40 normalised angular moments sensitive to interference between S, P and D wave
- No significant D wave observed (F_D <0.29 @95% CL)
- More theory constraints are needed for constraining the Wilson coefficients



arXiv:1609.04736





Large interference between S, P, D

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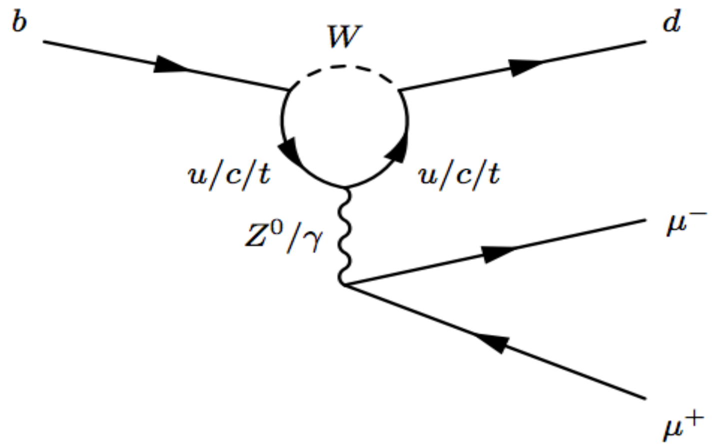
- Results on the photon polarization from *b->sγ* decays

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

- First $b \to d$ transition observed!
- Additional CKM suppression
- Allows to measure $|V_{td}/V_{ts}|$

$$|V_{td}/V_{ts}|^2 = \frac{\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)} \times \frac{\int F_K \mathrm{d}q^2}{\int F_\pi \mathrm{d}q^2}$$

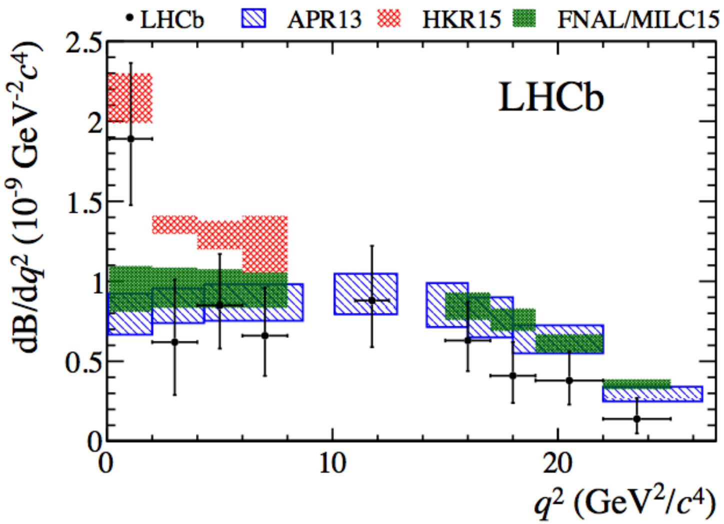


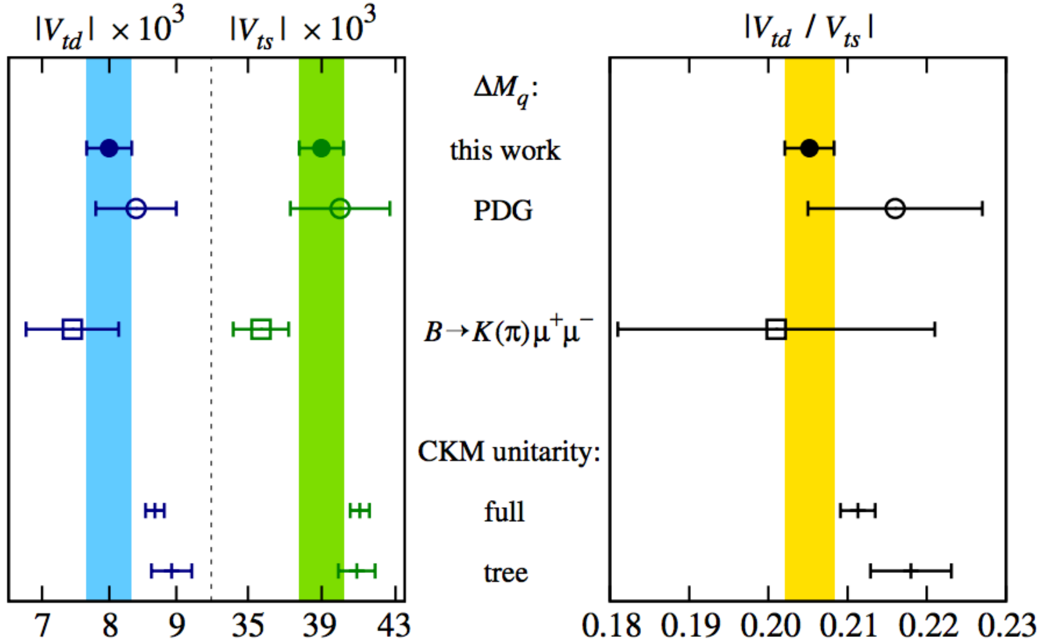
- The CP asymmetry is also measured:

$$\mathcal{A}_{CP}(B^\pm \to \pi^\pm\mu^+\mu^-) = -0.11 \pm 0.12\,(\text{stat}) \pm 0.01\,(\text{syst})\,,$$

- Test MFV nature of possible NP when comparing with mixing

JHEP 10 (2015) 034



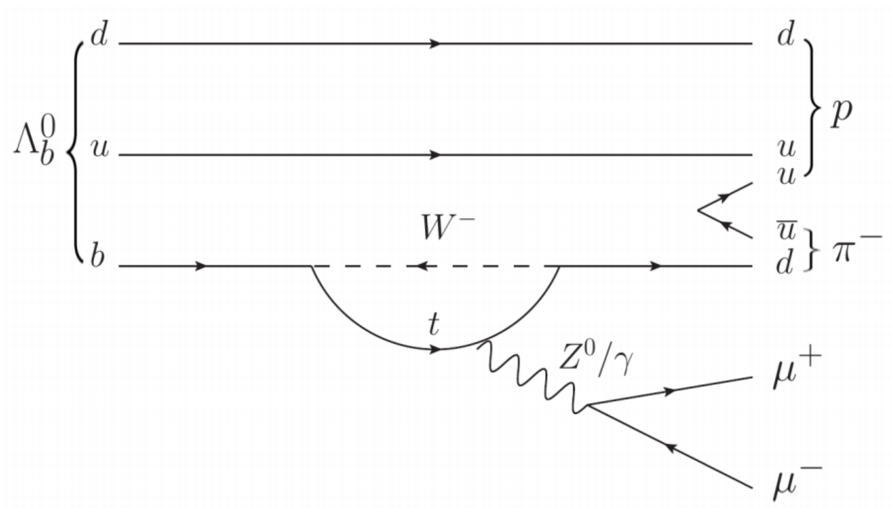


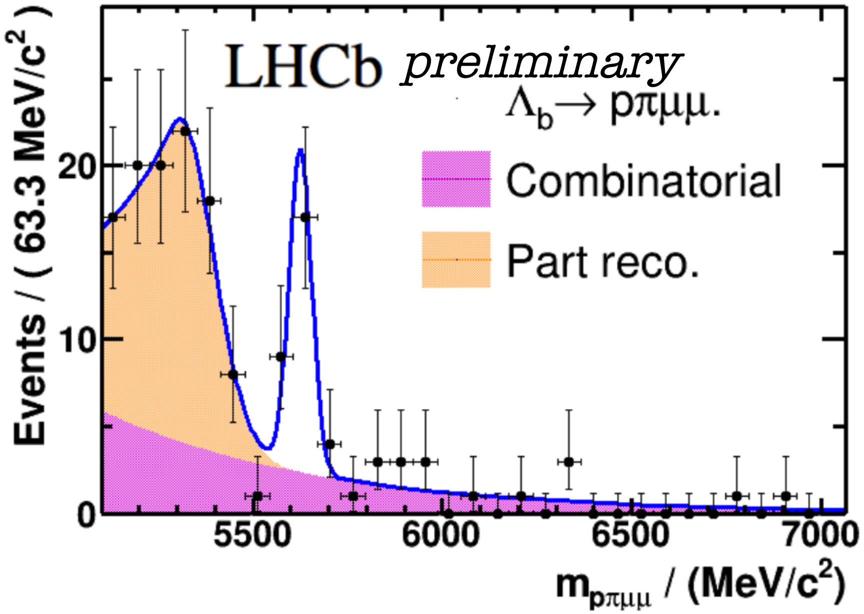
FNAL/MILC PRD93,113016 (2016)

Λ_b -> $p\pi\mu\mu$

- First observation (5.5σ) of a baryonic *b->d* transition!

NEW





$$\frac{\mathcal{B}(\Lambda_b^0 \to p\pi^-\mu^+\mu^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi\, p\pi^-)} = 0.044 \pm 0.012 \pm 0.007,$$

$$\mathcal{B}(\Lambda_b^0 \to p\pi^-\mu^+\mu^-) = (6.9 \pm 1.9 \pm 1.1^{+1.3}_{-1.0}) \times 10^{-8}$$

LHCb-PAPER-2016-049
COMING SOON

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PHOTON POLARIZATION

- In the SM, since the W boson couples only to left-handed fermions, the emitted photon is dominantly left-handed:
  maximal parity violation
  (right-handed at level of m_s/m_b)

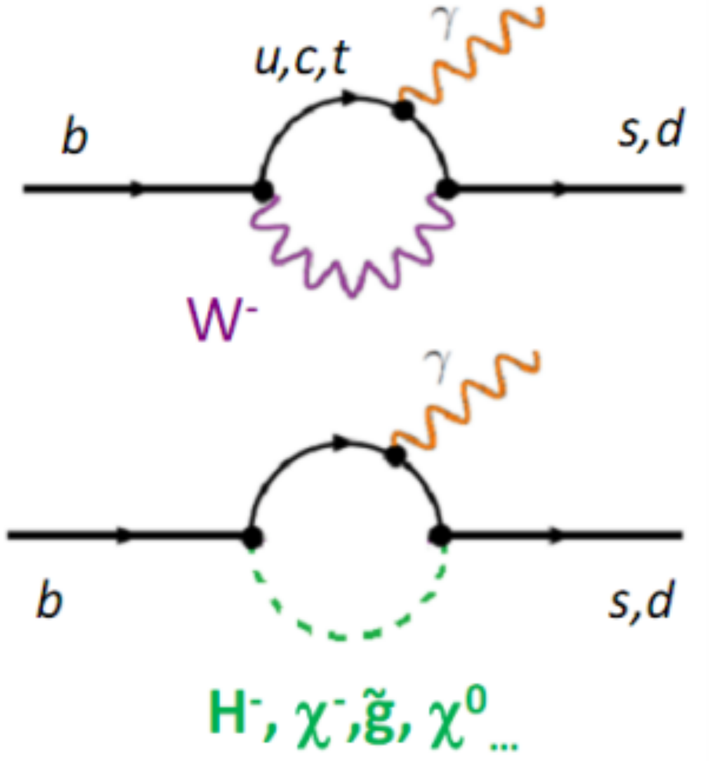
- Extensions of the SM predict right-handed polarization [PRL79(1997)185]

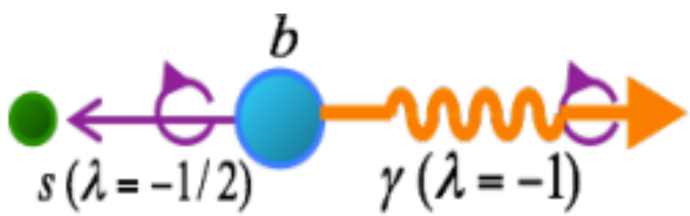
- The measured rates of $b\text{->}s\gamma$ transitions are in agreement with the SM

- What about the photon polarization?

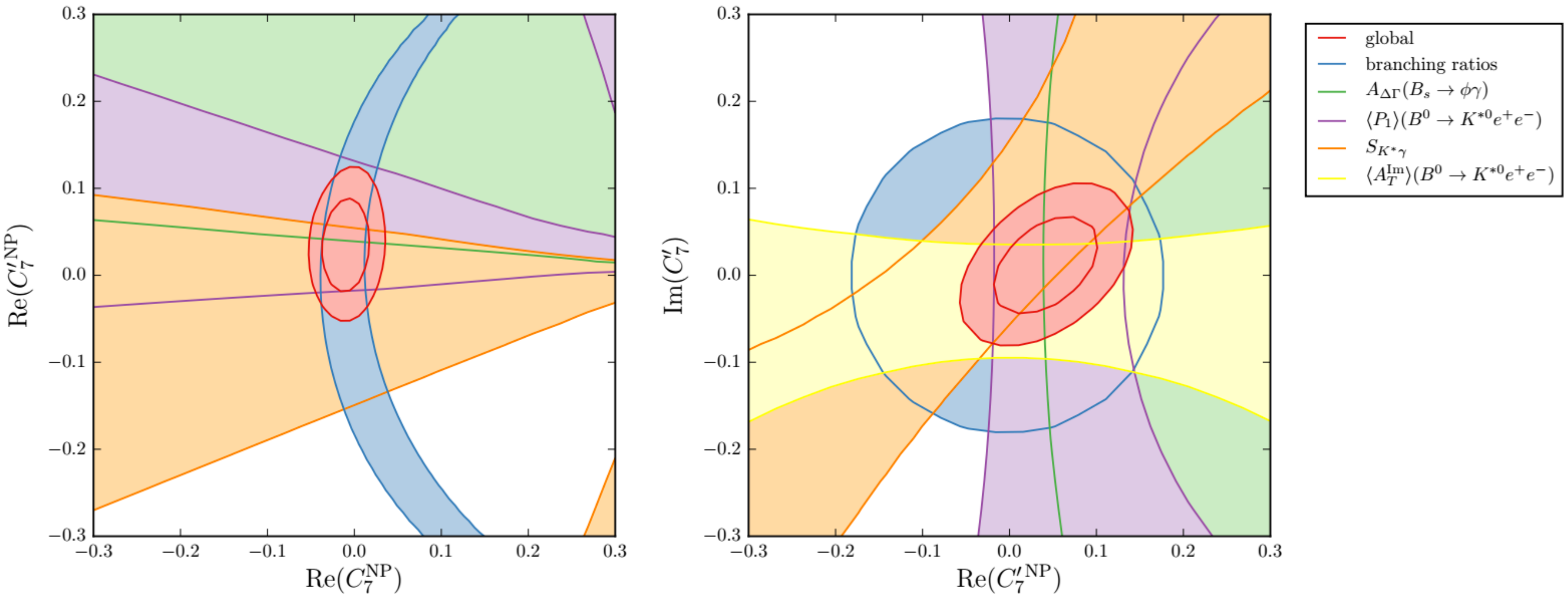
$$\lambda_\gamma^{(i)} = \frac{\left|C_{7R}\right|^2 - \left|C_{7L}\right|^2}{\left|C_{7R}\right|^2 + \left|C_{7L}\right|^2} \equiv \lambda_\gamma$$

λ_γ is 1 for $\bar{b}$ and -1 for b





CONSTRAINING C_7

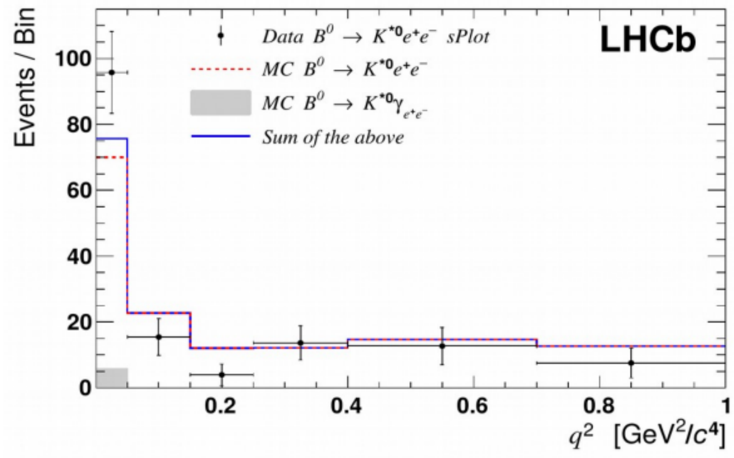


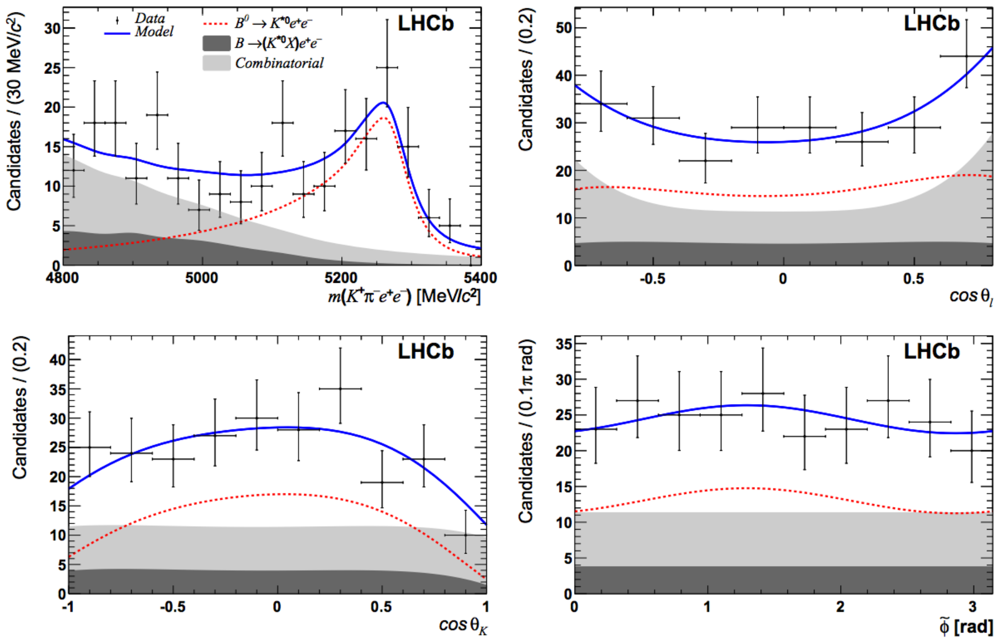
Paul, Straub: arXiv:1608.02556

Currently best constraint is provided by *B->K*ee* angular analysis (JHEP 04 (2015)064)

ANGULAR ANALYSIS OF *B->K*ee*

- Experimentally challenging for trigger and bremsstrahlung effects.
- Explores low q^2 region: high sensitivity to C_7 (photon polarization).
- Lower yields than muon channel.
- Results in agreement with SM.





$$F_L = 0.16 \pm 0.06 \pm 0.03$$

$$A_T^{Re} = 0.10 \pm 0.18 \pm 0.05$$

$$A_T^{(2)} = -0.23 \pm 0.23 \pm 0.05$$

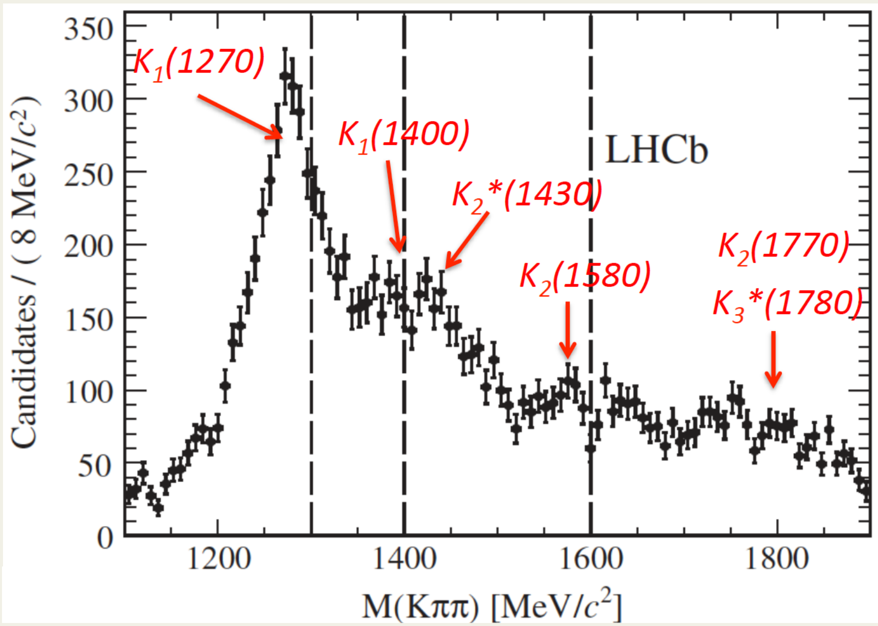
$$A_T^{Im} = 0.14 \pm 0.22 \pm 0.05$$

JHEP 04 (2015)064

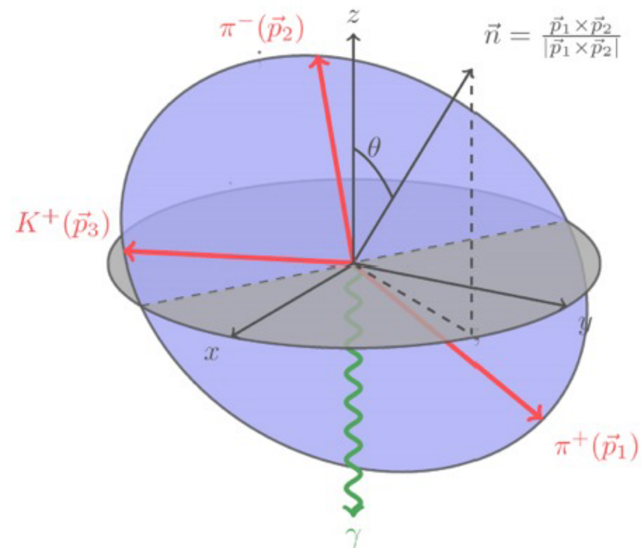
$B \to K\pi\pi\gamma$

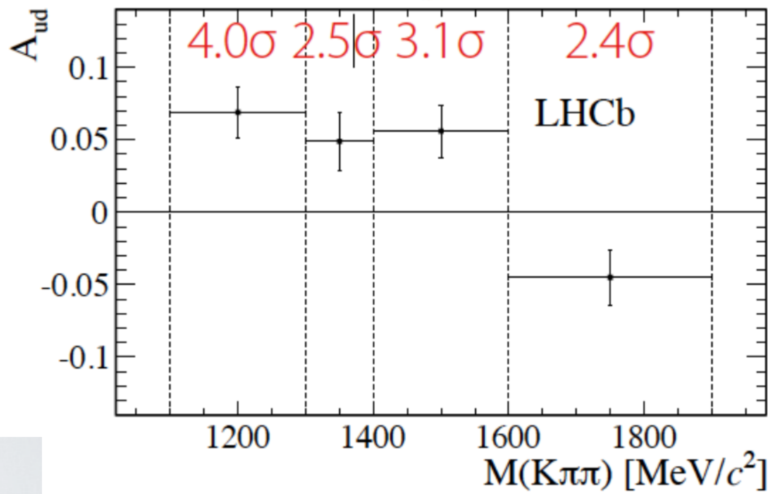
PRL 112, 161801 (2014)

- ***First observation of γ polarization in b->sγ***
- Inclusive analysis in four bins
- More data needed to separate the resonances



Background-subtracted Kππ spectrum





$$\mathcal{A}_{\rm UD} \equiv \frac{\int_0^1 d\cos\theta \frac{d\Gamma}{d\cos\theta} - \int_{-1}^0 d\cos\theta \frac{d\Gamma}{d\cos\theta}}{\int_{-1}^1 d\cos\theta \frac{d\Gamma}{d\cos\theta}} = C\lambda_\gamma$$

different from 0 at 5.2 σ

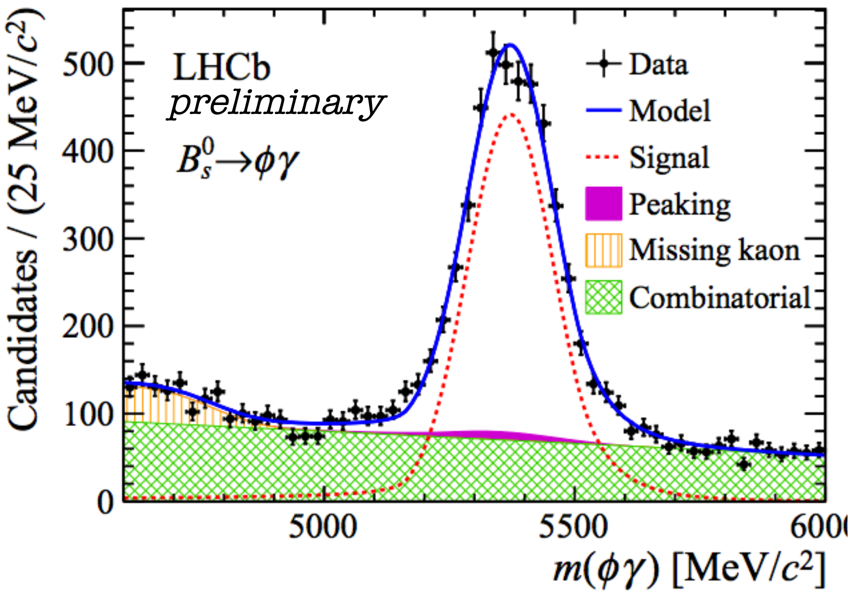
$B_s \to \phi\gamma$

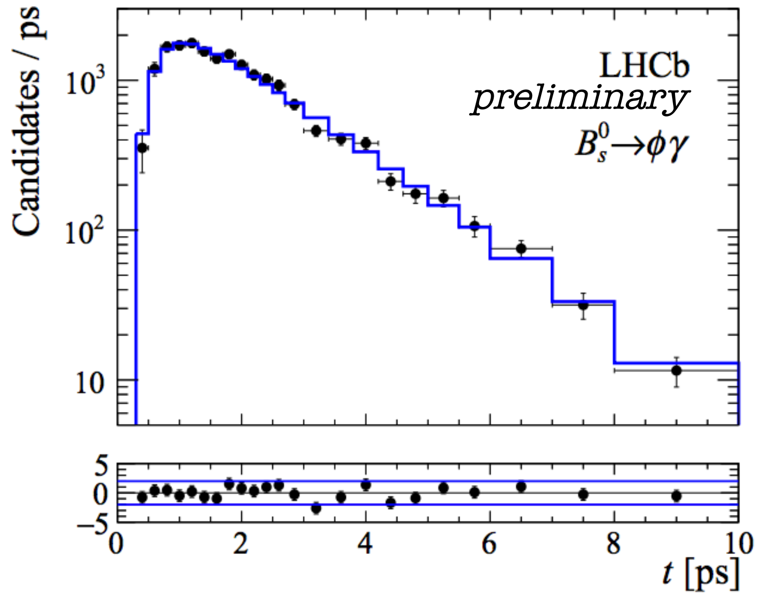
arXiv:1609.02032

- First measurement of photon polarization in radiative B_s decays
- Untagged measurement of the time dependent decay rate of $B_s \to \phi\gamma$

$$\Gamma(B_s + \overline{B}_s)(t) \propto e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) - A^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_s}{2}t\right)\right]$$

$$A^{\Delta\Gamma} \sim \frac{|\mathcal{A}(B_s \to \phi\gamma_L)|}{|\mathcal{A}(B_s \to \phi\gamma_R)|}\cos\phi_s$$





NEW

- $B^0 \to K^{*0}\gamma$ used to constrain efficiency as function of decay time
- Consistent with SM within 2σ: $\mathcal{A}^{\Delta} = -0.98\,^{+0.46}_{-0.52}\,^{+0.23}_{-0.20}$

$$A^{\Delta\Gamma}(SM) = 0.047^{+0.029}_{-0.025}$$ Muheim et al. [PLB664(08)174]

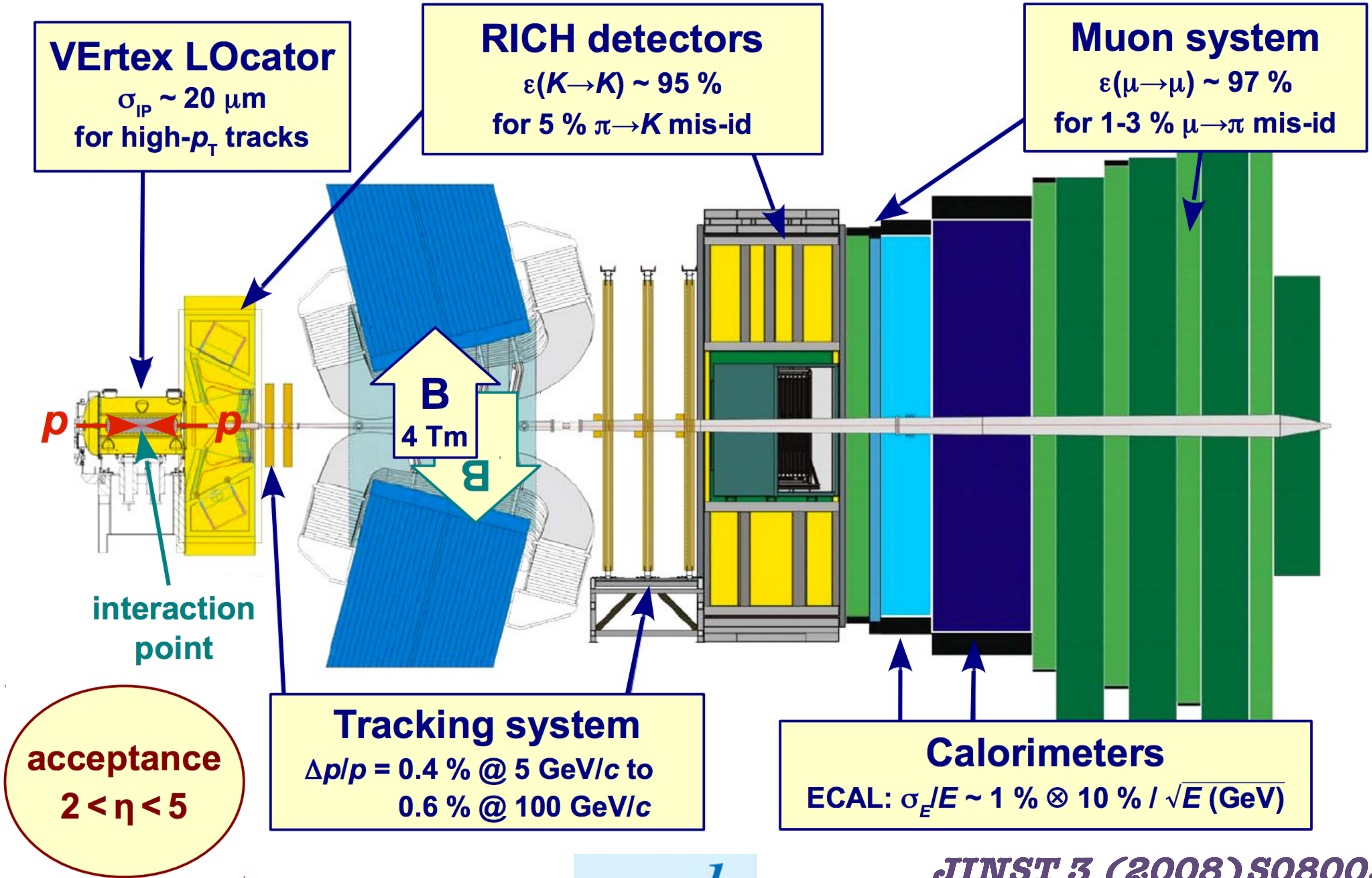
See also talk from A. Oyanguren
(https://indico.tifr.res.in/indico/contributionDisplay.py?contribId=134&sessionId=16&confId=5095)

CONCLUSIONS

- LHCb has a rich and outstanding research program in the *b->sll*, *b->dll* and *b->sγ* transitions
- Unique potential for baryonic decays!
- Some tensions are appearing in different channels and analyses, giving all combined a 4σ deviation from the SM, potentially interpretable in a coherent way as NP and/or induced by QCD effects.
- This effect is coherent with the lepton flavour universality R_K measurement (Phys. Rev. Lett. 113 (2014) 151601), insensitive to QCD effects.
- Repeating all measurements with the enlarged dataset ($5fb^{-1}$ now!), improving our analysis techniques, analyzing new channels (ex: final states with electrons), will help to shed lights on these results.

BACKUP

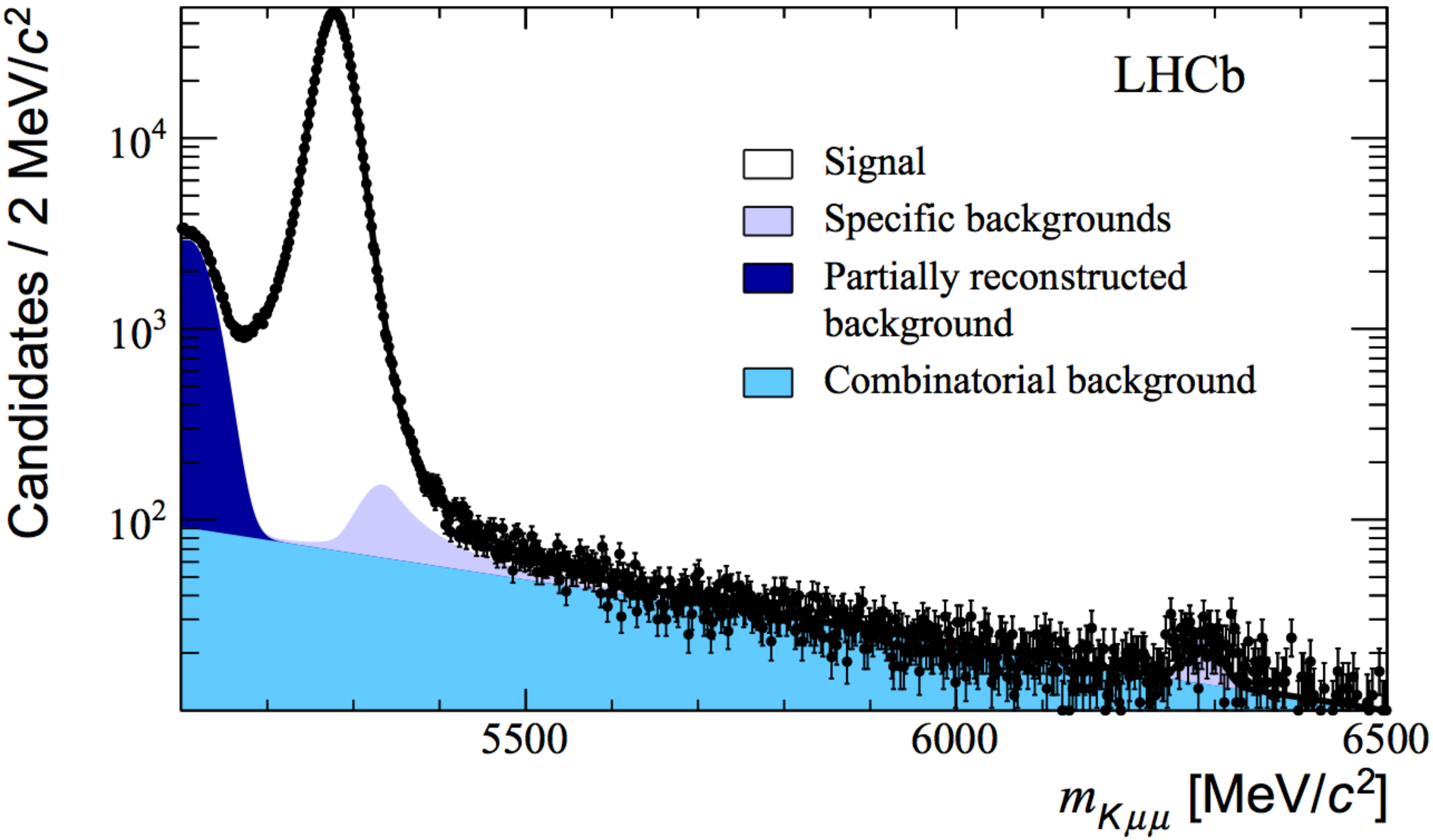
A FLAVOUR PHYSICS DETECTOR: LHCb



JINST 3 (2008) S08005

EVALUATING CHARM CONTRIBUTIONS IN $B^+ \to K^+ \mu\mu$

LHCb-PAPER-2016-045
COMING SOON



EVALUATING CHARM CONTRIBUTIONS IN $B^+ \to K^+\mu\mu$

LHCb-PAPER-2016-045
COMING SOON

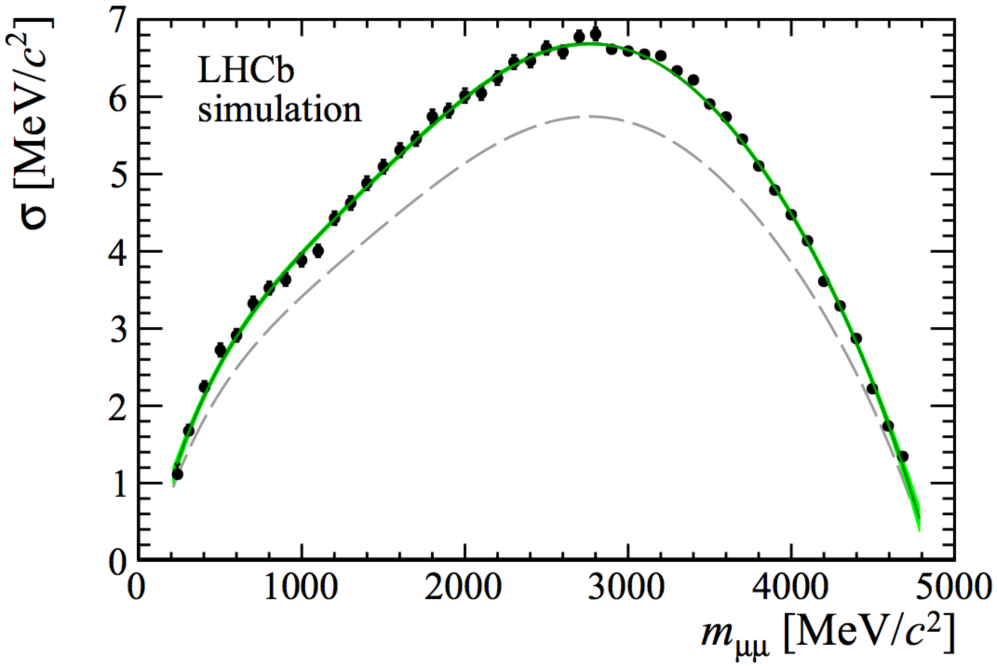


Figure 2: Parameterisation of the dependence of the resolution model on $m_{\mu\mu}$ in simulated events. The width of the Gaussian component, σ_G, is illustrated by the green-solid-line and the width of the component with power law tails, σ_G, by the grey-dashed-line. The ratio of the two widths is fixed from a large sample of simulated $B^+ \to J/\psi K^+$ decays. The data points corresponds to the measured value of σ_G for the simulated $B^+ \to K^+\mu^+\mu^-$ decays. Note, the width of the resolution is expected to tend to zero as $m_{\mu\mu}$ tends to $2m_\mu$ or $m_B - m_K$.

EVALUATING CHARM CONTRIBUTIONS IN $B^+ \to K^+\mu\mu$

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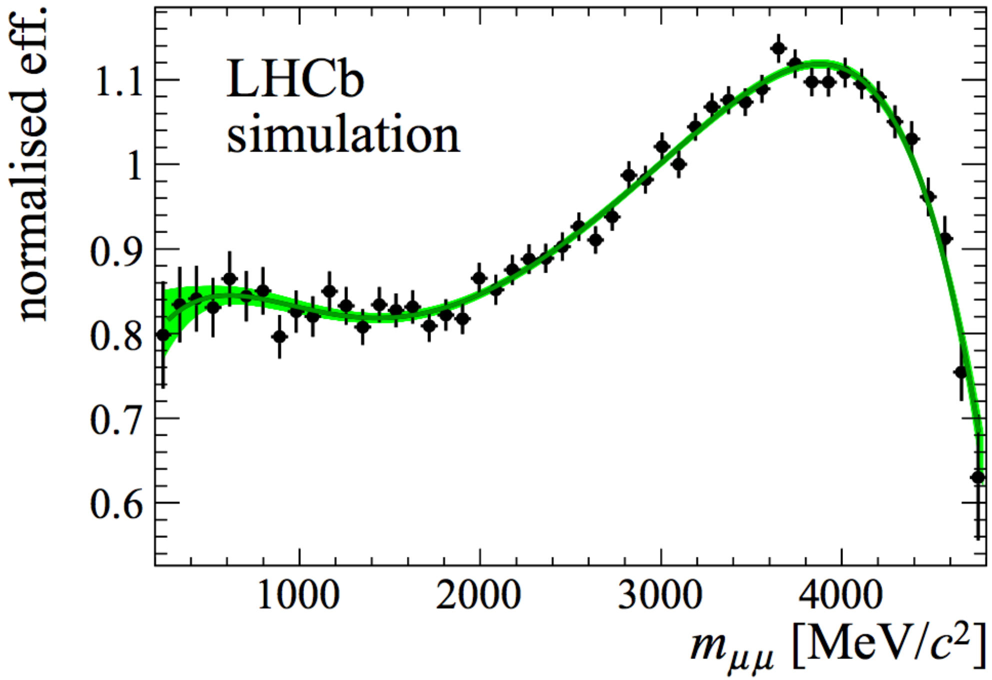


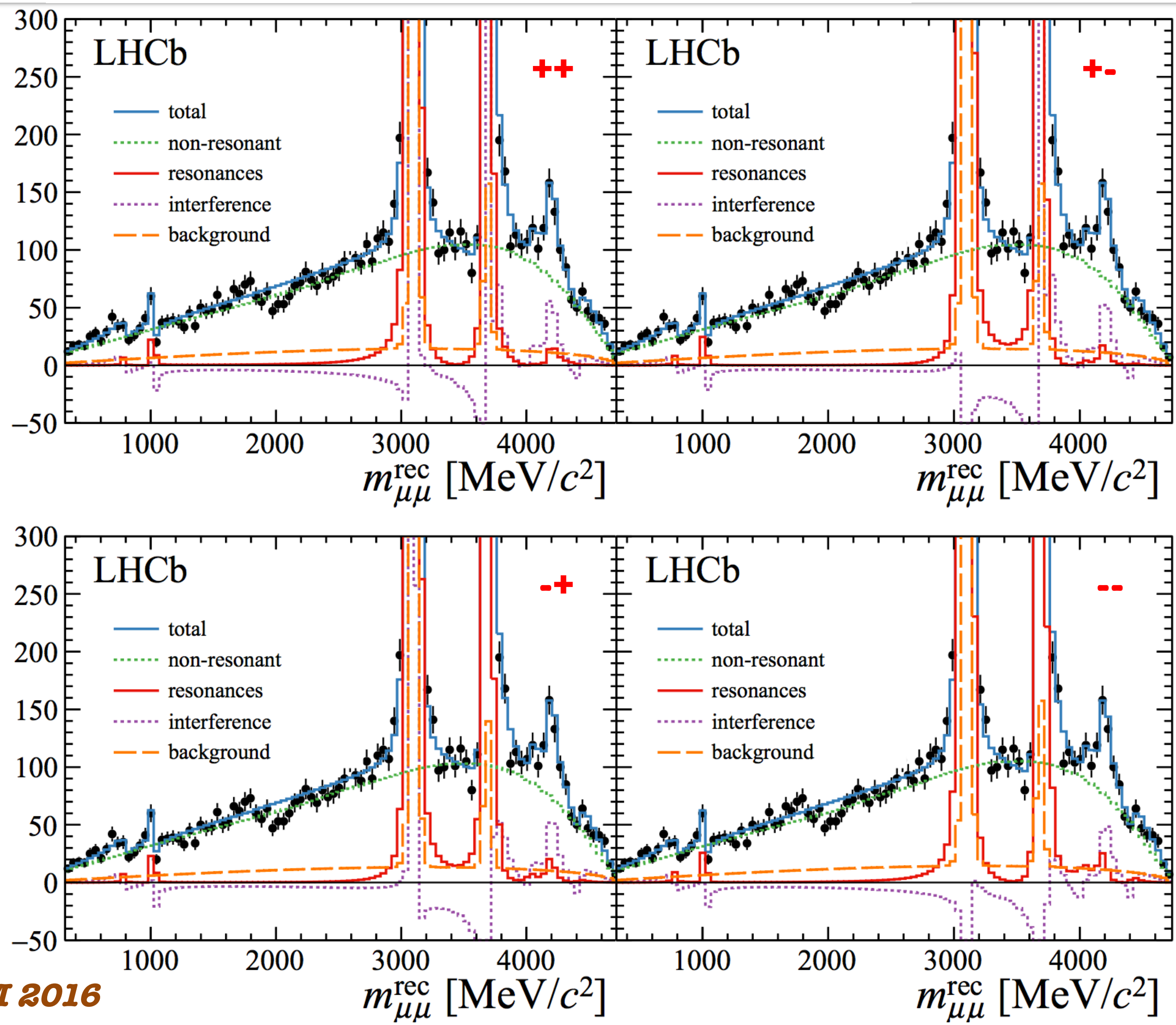
Figure 3: Efficiency to reconstruct, trigger and select simulated $B^+ \to K^+\mu^+\mu^-$ decays as a function of the true dimuon mass. The efficiency is normalised to the efficiency at the J/ψ meson mass. The band indicates a polynomial fit to the simulated data.

EVALUATING CHARM CONTRIBUTIONS IN $B^+ \to K^+\mu\mu$

$$P_{\rm sig}(m_{\mu\mu}^{\rm rec}) \propto R(m_{\mu\mu}^{\rm rec}, m_{\mu\mu}) \otimes \left(\varepsilon(m_{\mu\mu}) \frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} \frac{\mathrm{d}q^2}{\mathrm{d}m_{\mu\mu}}\right)$$

LHCb-PAPER-2016-045
COMING SOON

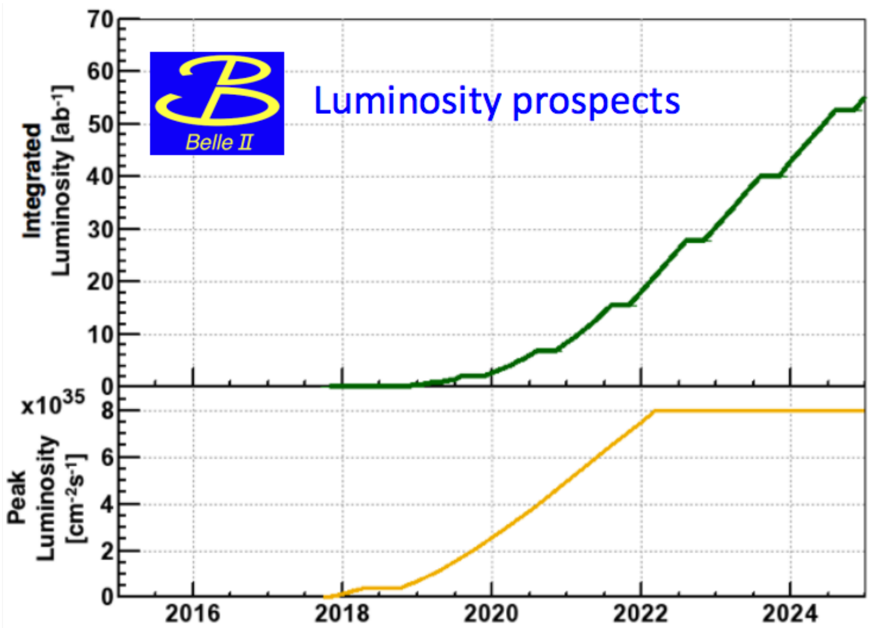
Resonance
$\rho(770)$
$\omega(780)$
$\phi(1020)$
J/ψ
$\psi(2S)$
$\psi(3770)$
$\psi(4040)$
$\psi(4160)$
$\psi(4415)$



...AND MORE LUMINOSITY TO COME!

	LHC era			HL-LHC era	
	Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2021-24)	Run 4 (2027-30)	Run 5+ (2031+)
ATLAS, CMS	25 fb^{-1}	100 fb^{-1}	300 fb^{-1}	⟶	3000 fb^{-1}
LHCb	3 fb^{-1}	8 fb^{-1}	25 fb^{-1}	50 fb^{-1}	*300 fb^{-1}

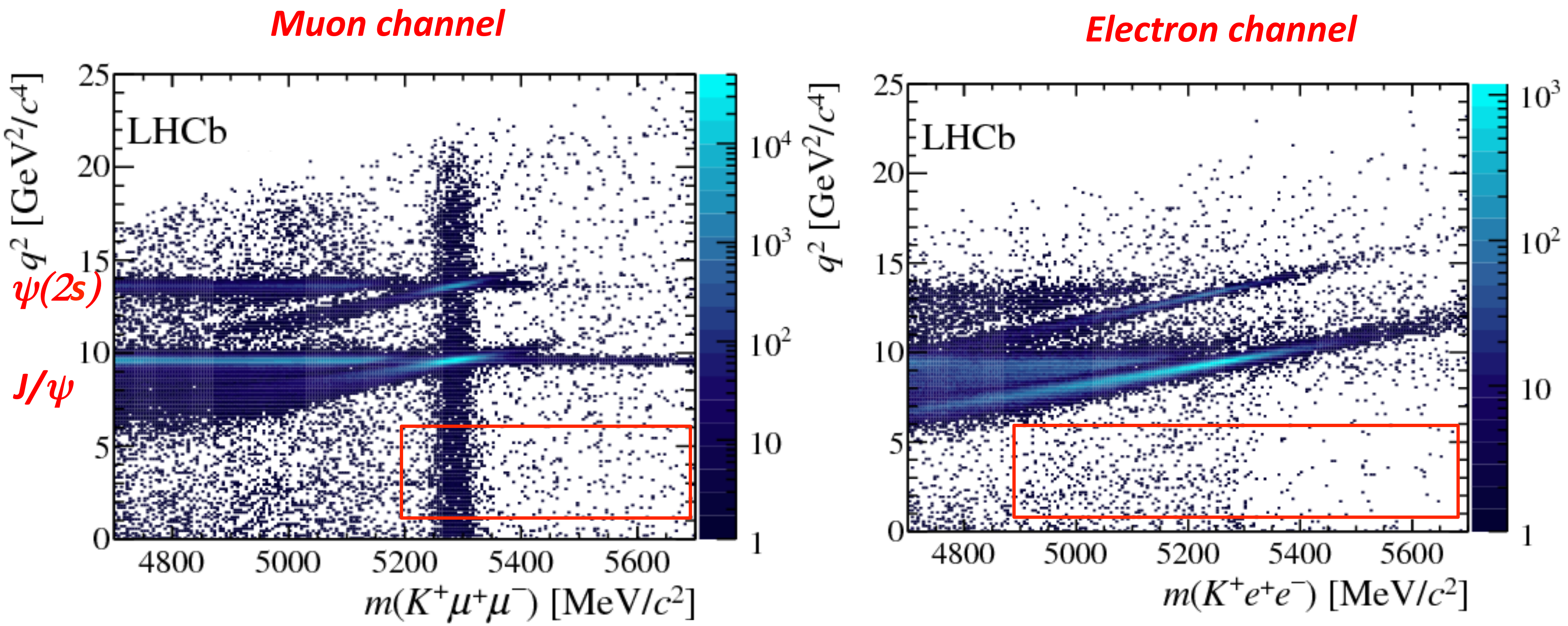
* assumes a future LHCb upgrade to raise the instantaneous luminosity to 2×10^{34} $cm^{-2}s^{-1}$



R_K : THE DATASET

- Experimentally challenging for trigger/ tracking reconstruction differences between muons and electrons, bremsstrahlung effects...
- Use the double ratio of the rare to the J/ψ channel to reduce systematics:

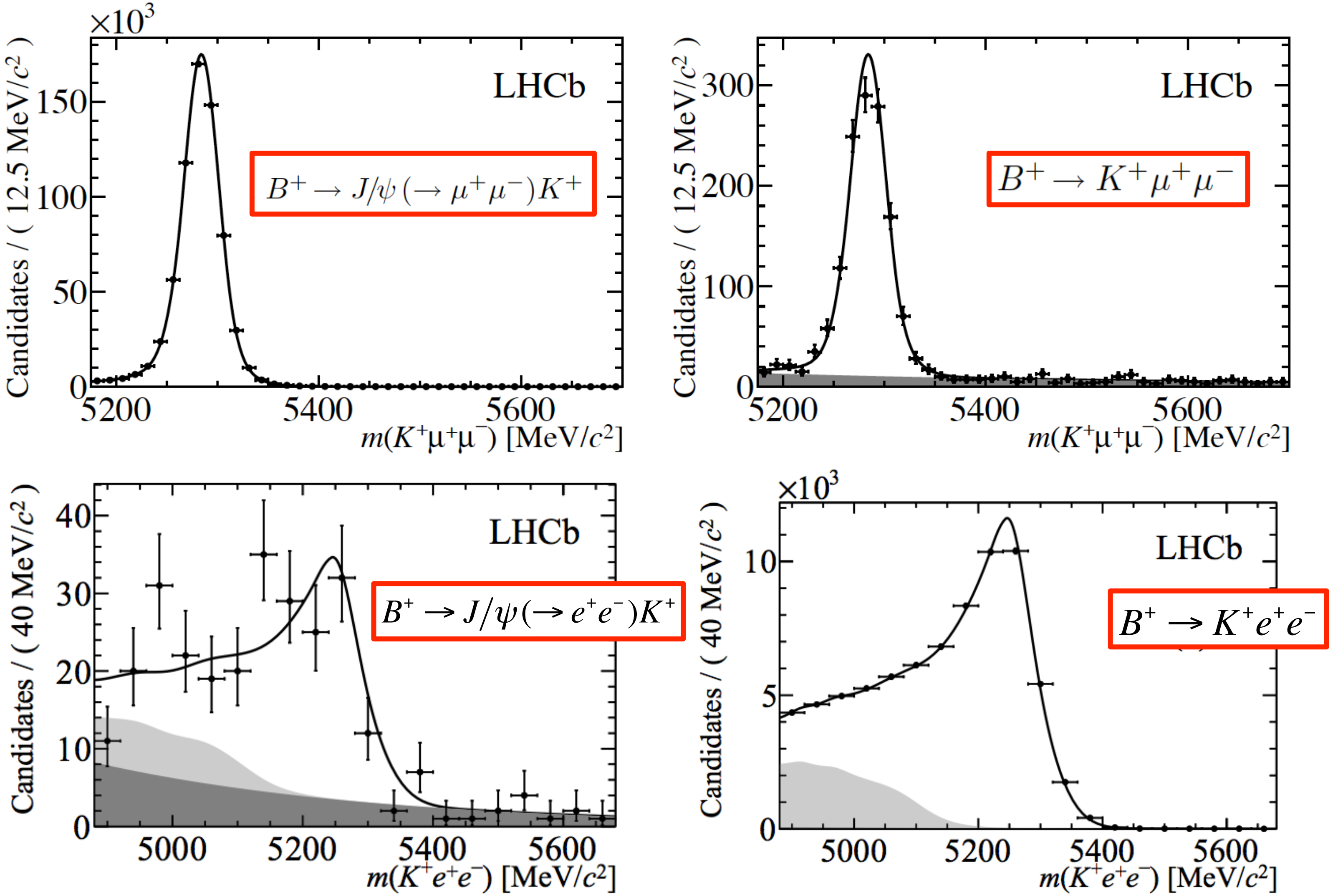
$$R_K = \left(\frac{\mathcal{N}_{K^+\mu^+\mu^-}}{\mathcal{N}_{K^+e^+e^-}}\right)\left(\frac{\mathcal{N}_{J/\psi(e^+e^-)K^+}}{\mathcal{N}_{J/\psi(\mu^+\mu^-)K^+}}\right)\left(\frac{\epsilon_{K^+e^+e^-}}{\epsilon_{K^+\mu^+\mu^-}}\right)\left(\frac{\epsilon_{J/\psi(\mu^+\mu^-)K^+}}{\epsilon_{J/\psi(e^+e^-)K^+}}\right)$$



PRL 113, 151601 (2014)

R_K

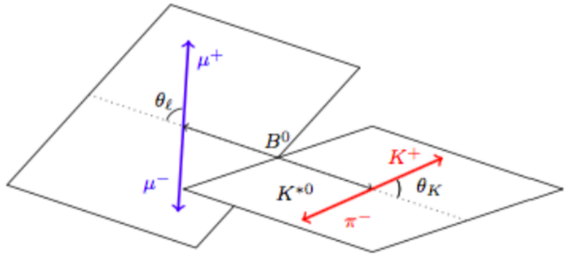
- Muon final states has excellent resolution and is very clean
- Electron final states suffers from bremsstrahlung effects



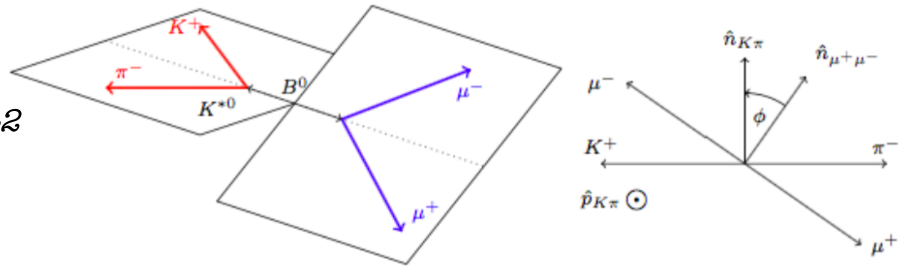
PRL 113, 151601 (2014)

THE PRINCIPLE OF ANGULAR ANALYSES

- Angular analyses are complex, but a rich framework to measure a variety of observables, sensitive to different sources of new physics depending on q^2
- Decays with four particles in the final state are described by:
  - three angles in the helicity basis;
  - the di-lepton invariant mass squared q^2
- Observables depend on Wilson coefficients (underlying short-distance physics) and form-factors (hadronic matrix elements)



(a) θ_K and θ_ℓ definitions for the B^0 decay



(b) ϕ definition for the B^0 decay

Example: ***B->K*μμ***

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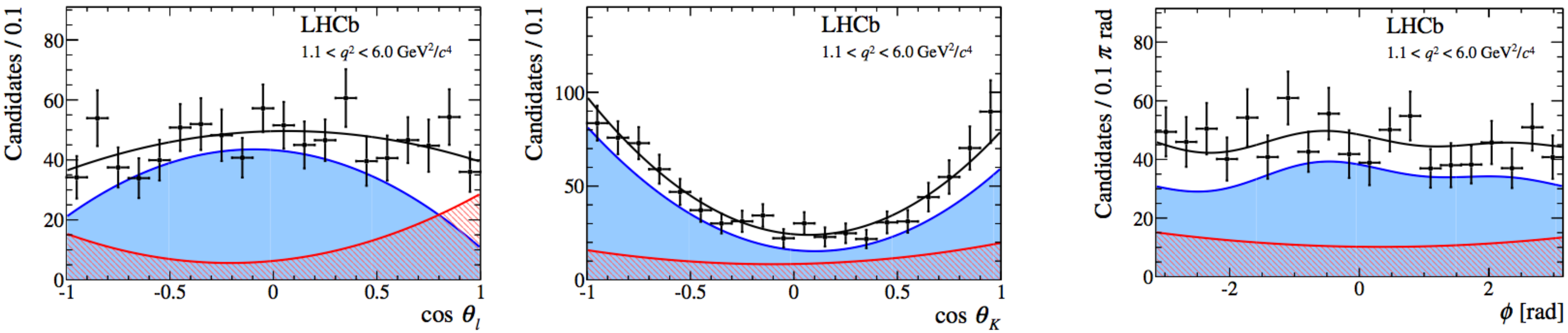

PHOTON POLARIZATION

Complementary approaches are provided by:

[Becirevic et al, JHEP08 (2012) 090]

- Time-dependent analysis:
  $B_{(s)} \to f^{CP}\gamma \quad (ex: f^{CP} = \phi,\ K_s\pi^0)$
- Transverse asymmetry:
  $B^0 \to K^* l^+ l^-$
- Angular distributions of radiative decays with 3 charged tracks:
  $B \to K\pi\pi\gamma$
- b-baryons radiative decays:
  $\Lambda_b \to \Lambda^*\gamma$
  $\Xi_b \to \Xi^*\gamma$