Angular analysis: status and perspective

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on behalf of CMS collaboration

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INFN Padova

BPH Workshop,
CERN, 10 March 2018

Angular analysis: status and perspectives

- Currently, there are four angular analysis being performed at CMS
  - $B_0 \to K^* \mu\mu$
  - $B^+ \to K^{+*} \mu\mu$
  - $B^+ \to K^+ \mu\mu$
  - $B_s \to \phi\mu\mu$

This presentation

I will focus on the current status and on the following items:

- plan for the analysis, and which data you will consider (2016/2017/2018 all together?)
- are there improvements foreseen in the analysis procedure itself?
- expected results
- timescale and manpower commitment

$B_0 \to K^* \mu\mu$: Status

- ✓ paper in publication (PLB second round of reply) with 2012 data.
  - other two paper previously published:
    - 7 TeV, $\sim 400ev$, A_{FB}, F_L, $d\mathcal{B}/dq^2$ [PLB 727 (2013) 77]
    - 8 TeV, $\sim 1400ev$, A_{FB}, F_L, $d\mathcal{B}/dq^2$ [PLB 753 (2016) 424]
- ✗ major complains during conferences are about having some of the parameter fixed
- ✗ second is the complexity of the fit (this is of course correlated)
- ✗ third are the results, too close to SM (especially from Matias . . .)

$B_0 \to K^*\mu\mu$: Perspective

Improvements for 13 TeV data

- people: Padova (S., Alessio), PKU (Dayong, Linwei), MiB (Sara, Paolo, Mauro)

✓ better selection: cut based→MVA

✓ better tagging

🕒 Fully free fit!
  - single fit with all parameters (8 from p-wave)
  - full correlation among parameters from the fit
  - try GPU based fit to improve timing

🕒 efficiency modelling
  - good description of all feature, fit-friendly (fast fit!)

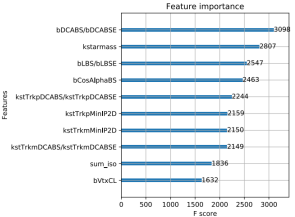
✗ s-wave treatment
  - expected to be $< 10\%$, but cannot be treated as a systematics uncertainties
  - for a precision measurement, neither the s/p-wave interference can.
  - this is the origin of all our fit stability problems.

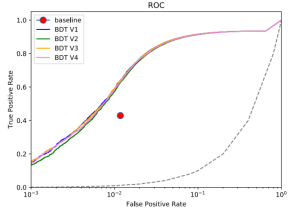
✗ more, finer bins?

✗ momenta method (by LHCb) still not explored.
  - Less statistical power, but with larger stat we might be syst limited, so maybe worth.

Selection and expected yield

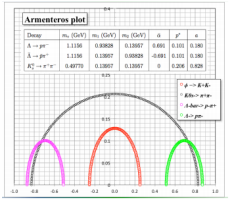
- ✓ 8 TeV was cut based, moving to MVA.
  - Large improvement of signal eff. $\sim 60\%$ wrt 2012-optimized cut;
  - ✓ optimization on number of variables used
- background is at the same level as 2012
- we did see some yield fluctuation on 2016 data (as seen in BMM4). Better in 2017.
- ✓ Roughly $100\text{ev}/\text{fb}^{-1}$, namely do have now $\sim 6 - 8000$ signal events, can can hope to have $\sim 12 - 15000$.
- same statistics expected by LHCb! (but they have lower background and lower mis-tag rate)

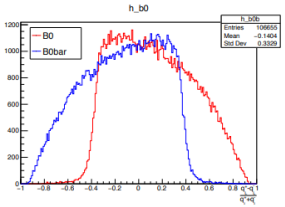


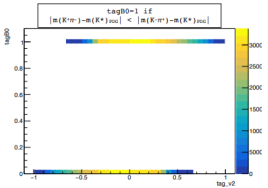


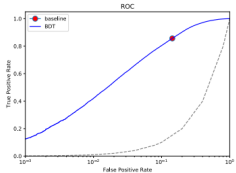
Flavour tagging B_0 vs $\overline{B_0}$

- In 8 TeV data we used $M_{K\pi}$ distribution
- tried some improvement (Armenteros-Podolanski plot)
  - look at $\alpha = \dfrac{p_l^+ - p_l^-}{p_l^+ + p_l^-}$
  - Preliminary results not showing significant improvements, will investigate further
- given the large stat, we can possibly consider to cut away a subset where the mistag is particularly high, in order to improve the correct over mistag ratio. To be studied.









Efficiency

What we need: 3D eff, no factorization, and no folding

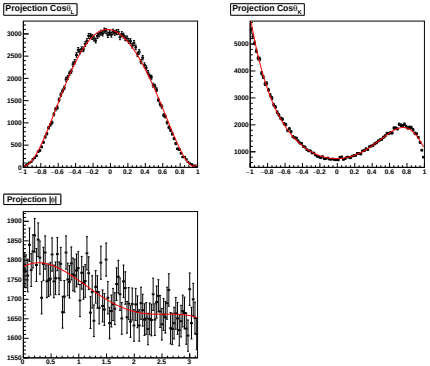
✓ we have 3x MC as in 2012,

✗ but no folding means 4x phase space

- **we are considering several different choices**
  - binned vs unbinned eff
  - KDE (as for 8 TeV)
  - projection on orthonormal basis of 3D function (LHCb)
  - fit
  - MVA (also from LHCb idea)

need to ensure a fast fit!

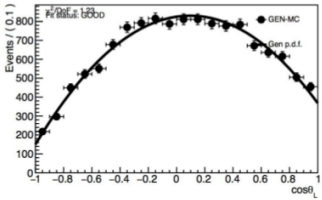
An example of closure test (GEN$\times\varepsilon$ vs RECO) with ε modelled with polynomial fit (up to pol5).

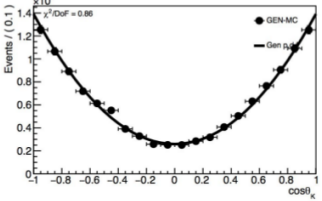


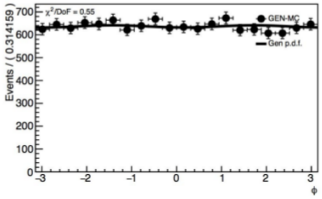
fit done using via GooFit (RooFit plus `CUDA` on `nVidia` GPUs)

First test of free fit on 2-16 MC

MC, GEN level. 8 free parameters: (p-wave only). $F_L, P_{1,2,3}, P'_{4,5,6,8}$



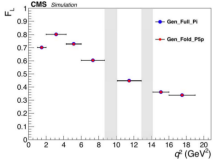


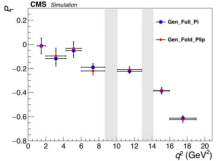


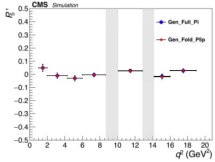
Bin 2

GEN-level fully free fit

Comparison of parameter from free fit and fit after folding





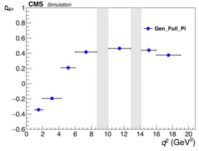


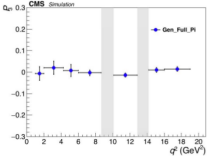
- Full angular fitting from gen MC
- Folding at $\cos\theta_L = 0$ and $\phi = 0$ (same with BPH-15-008)

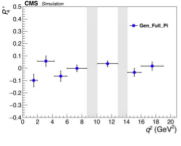
J/ψ and ψ(2S) region

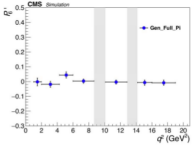
in good agreement

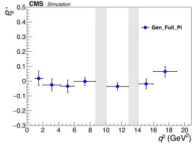
new parameters output











- Full angular fitting from gen MC

J/ψ and ψ(2S) region

S-wave

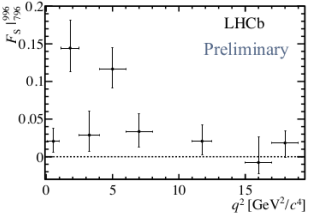
Determination of FS is performed through a fit to the kaon helicity angle θ_K and $m^2_{K\pi}$:

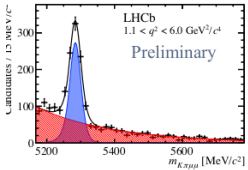
$m^2_{K\pi} \in [644, 1200]$ and $[796, 996]$ MeV^2

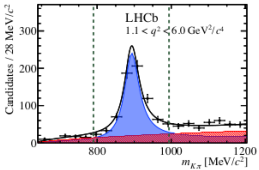
Explicitly modelling of the $m^2_{K\pi}$ spectrum:

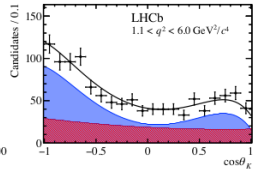
- P-wave [K*(892)]: Relativist BW
- S-wave [*i.e.* K*(1430) + NonRes]: LASS

LHCb, JHEP 11 (2016) 047, JHEP 04 (2017) 142





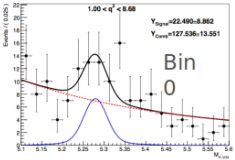


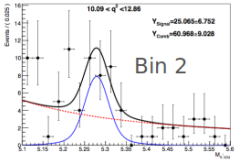


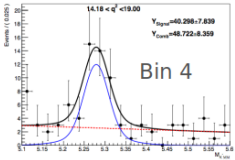
- We know that s-wave is small $\sim 10\%$
- LHCb measured it via amplitude fit ($\cos\theta_K$ and $M_{K\pi}$)
- but we are using $M_{K\pi}$ for flavour tagging, biased distribution: can we fit?
- furthermore we do not have an s-wave MC to play with
- very difficult to have MC with interference

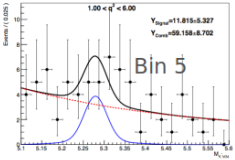
- Team: Po-Hsun/Sanjay
- **AN-12-066, BPH-15-009**
- still on 8 TeV dataset latest update: 6 march 2018.
  - reduced number of bins of q^2
    - $[1-8.68], J/\psi, [10.09-12.86], \psi', [14.18, 19]$ GeV^2 plus $[1-6]$ GeV^2
  - better treatment of background: low/high SB added separately to the final fit
  - FC for stat uncert
  - full syst uncert determination
- ARC not yet responded
- Personal (Stefano): pre-approval was 24/11/2015, need to check if ARC are still available
- Po-Hsun and Niladri are leaving (after graduating), so manpower will be an issue

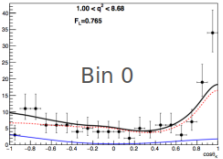
$B^+ \to K^{+*}\mu\mu$ (II)

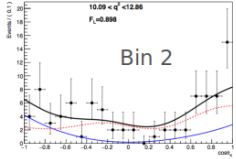

1.00 < q² < 8.68
Y_Signal=22.490±8.862
Y_Comb=127.536±13.551
Bin 0

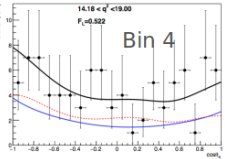

10.09 < q² <12.86
Y_Signal=25.065±6.752
Y_Comb=60.968±9.028
Bin 2

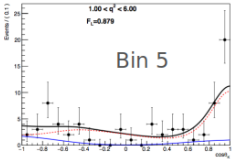

14.18 < q² <19.00
Y_Signal=40.298±7.839
Y_Comb=48.722±8.359
Bin 4


1.00 < q² < 6.00
Y_Signal=11.815±5.327
Y_Comb=59.158±8.702
Bin 5

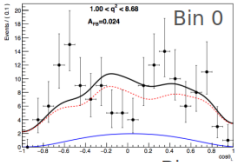

1.00 < q² < 8.68
F_L=0.765
Bin 0

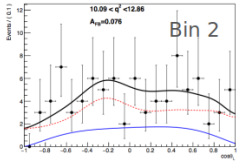

10.09 < q² <12.86
F_L=0.898
Bin 2

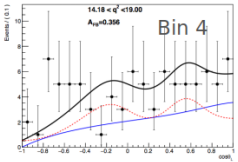

14.18 < q² <19.00
F_L=0.522
Bin 4

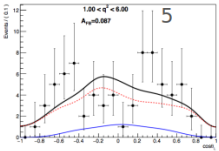

1.00 < q² < 6.00
F_L=0.879
Bin 5

$B^+ \to K^{+*}\mu\mu$ (III)









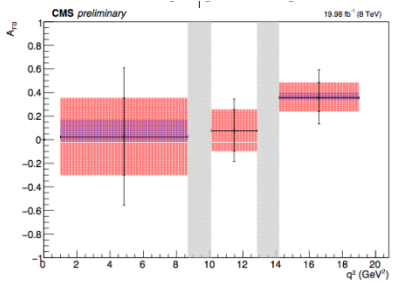
Syst. err. \ q^2 bin	0	2	4	5	6
Uncorrelated systematic uncertainties					
Limited MC size	0.0512	0.0324	0.0428	0.0546	0.0141
simu. mismodel	0.0008	0.0031	0.0051	0.0020	0.0114
eff. mapping	0.0020	0.0011	0.0007	0.0001	0.0025
comb. bkg. shape	0.140	0.097	0.052	0.142	0.109
angular resolution	0.0457	0.0378	0.0164	0.0527	0.0128
S-P wave interf.	0.0558	0.0149	0.0020	0.0742	0.0049
B^+ mass range	0.0008	0.0006	0.0004	0.0003	0.0004
Total	0.1656	0.1101	0.0695	0.1773	0.1114

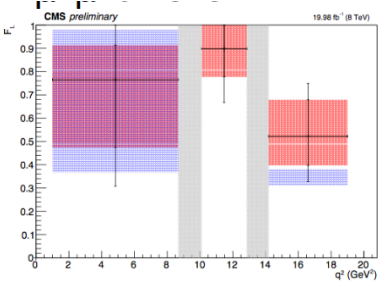
Systematic uncertainty for AFB

Syst. err. \ q^2 bin	0	2	4	5	6
Uncorrelated systematic uncertainties					
Limited MC size	0.0432	0.0289	0.0412	0.0441	0.0129
simu. mismodel	0.0702	0.0302	0.0888	0.0117	0.0433
eff. mapping	0.0032	0.0006	0.0006	0.0142	0.0246
comb. bkg. shape	0.232	0.073	0.039	0.285	0.080
angular resolution	0.0371	0.0248	0.0142	0.0423	0.0168
S-P wave interf.	0.0569	0.0112	0.0016	0.0689	0.0022
B^+ mass range	0.0001	0.0001	0.0001	0.0001	0.0002
Total	0.2554	0.0884	0.1063	0.3001	0.0547

Systematic uncertainty for FL

$B^+ \to K^{+*}\mu\mu$ (IV)





K*0 $F_L = 0.716 \pm 0.062\,(\text{stat}) \pm 0.044\,(\text{syst})$
$A_{FB} = -0.115^{+0.083}_{-0.080}\,(\text{stat}) \pm 0.047\,(\text{syst})$ $(1 < q^2 < 6\ \text{GeV}^2)$

K*+ $F_L = 0.878^{+0.122}_{-0.388}\,(\text{stat}) \pm 0.177\,(\text{syst})$
$A_{FB} = 0.089^{+0.394}_{-0.480}\,(\text{stat}) \pm 0.300\,(\text{syst})$ $(1 < q^2 < 6\ \text{GeV}^2)$

Good agreement with the SM predictions within uncertainties.

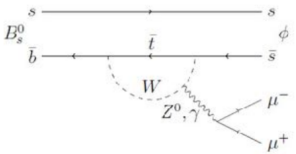
- **Team** Dayong, Geng (PKU)
- **Status** BPH-15-002 approved in time Moriond
- Currently in CWR (ended): target journal PRD-RC
- Perspective for RunII
  - Geng is gradating and will not continue Run-II analysis, PKU are identifying a new student to follow it.
  - reuse most of Run-1 tools
  - try to measure some asymmetries in addition to A_{FB} and $F_{L(H)}$
  - manpower is an issue: Geng is leaving, need to attract more people
- PKU is also interested in $R(K)$, $R(K*)$
- Possibly a new Ph.D student could work on this topic.

$B_s \to \phi\mu\mu$: Motivation

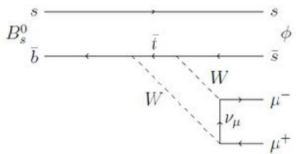
Goal: angular analysis at CMS wth 36 fb^{-1} at 13 TeV for $B_s \to \phi\mu\mu$ FCNC

Team: Deepak Kumar Sahoo, Niladribihari Sahoo, Martha Cecilia Duran Osuna, Seema Bahinipati

- FCNC process in SM mediated by EW loop and box diagrams [JHEP 07 (2008) 106]
- final state not self tagging, reduced set of observable
- Indirect search to NP: sensitive to $C_{7,9,10}$ (γ and EW penguin)
- done by LHCb[LHCb, JHEP 09 (2015) 179] 3.0 fb^{-1}
  - full set of observable $F_L, S_{3,4,7}, A_{5,6,8,9}$. No significant deviation from SM

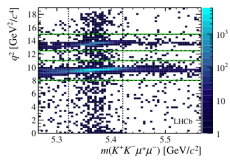


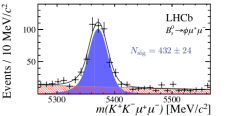
EW Penguin Diagram

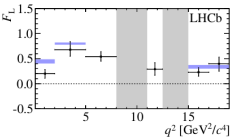


EW Box Diagram

[LHCb, JHEP 09 (2015) 179]



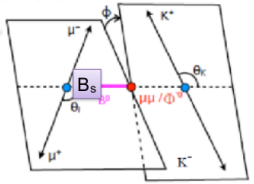




Observable

- Differential decay rate of $B_s \to \Phi\mu^+\mu^-$ decay as a function of cos θ_k, cos θ_l, Φ and q^2 [JHEP 07 (2008) 106]

$$\frac{1}{d\Gamma/dq^2}\frac{d^3\Gamma}{d\cos\theta_\ell d\cos\theta_k d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_k + F_L\cos^2\theta_k + \frac{1}{4}(1-F_L)\sin^2\theta_k\cos 2\theta_\ell - F_L\cos^2\theta_k\cos 2\theta_\ell + S_3\sin^2\theta_k\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_k\sin 2\theta_\ell\cos\phi + A_5\sin 2\theta_k\sin\theta_\ell\cos\phi + A_6\sin^2\theta_k\cos\theta_\ell + S_7\sin 2\theta_k\sin\theta_\ell\sin\phi + A_8\sin 2\theta_k\sin 2\theta_\ell\sin\phi + A_9\sin^2\theta_k\sin^2\theta_\ell\sin 2\phi\Big]$$



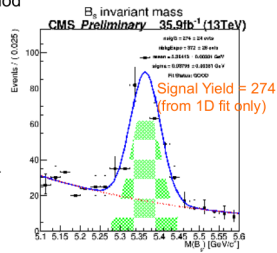
- Using Full decay rate equation, one can access
  F_L, S_3, S_4, S_7: CP Averaged Observables
  A_5, A_6, A_8, A_9: CP Asymmetric Observables

- Integrating out from Φ, one can access F_L and A_6 observables (due to low statistics)

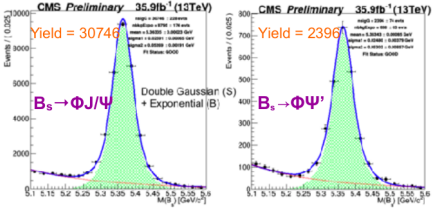
$$\frac{1}{d\Gamma/dq^2}\frac{d^2\Gamma}{d\cos\theta_\ell d\cos\theta_k} = \frac{9}{16}\Big[\frac{1}{2}(1-F_L)(1-\cos^2\theta_k)(1+\cos^2\theta_\ell) + 2F_l\cos^2\theta_k(1-\cos^2\theta_\ell) + A_6(1-\cos^2\theta_k)\cos\theta_\ell\Big]$$

Selection and yield

- Optimized selection cuts using cut and count method
  - $K^{+/-}$ p_T > 1.3 GeV
  - $K^{+/-}$ D.C.A/σ > 0.8
  - B_S L_{xy}/σ > 8.5
  - B_S cos α_{xy} > 0.9992
  - B_S vertex CL > 0.04
  - M_Φ : [1.01,1.03] GeV
  - M_{Bs}: [5.1, 5.6] GeV
- Select single candidate having best B_s-vertex CL
- Anti-radiation cuts applied



Control Channels



Binning:

- **Bin 0**: $1 - 4.30\ \text{GeV}^2$
- **Bin 1**: $4.30 - 8.68\ \text{GeV}^2$
- **Bin 2**: J/ψ
- **Bin 3**: $10.09 - 12.86\ \text{GeV}^2$
- **Bin 4**: ψ'
- **Bin 5**: $14.18 - 16\ \text{GeV}^2$
- **Bin 6**: $16 - 19\ \text{GeV}^2$
- **Bin 7 (summary)**: $1 - 6\ \text{GeV}^2$
- **Bin 8 (summary)**: all

observed low stat in bin 3,5, investigating

4

Status and plan

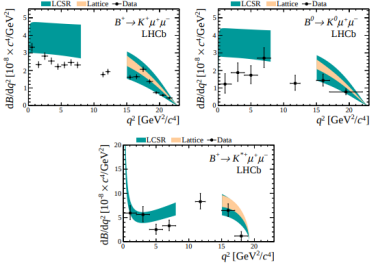
- ✓ Selection optimization: cut and count
- ✓ B_s mass in control channel
- ✓ Gen level fitting
- ✓ eff mapping
- Reco level fitting
- ✗ 3D fitting ($\cos\theta_\ell, \cos\theta_k, \phi$)
  - validation with signal MC and
- AN-18-068 (ongoing)
- MVA (ongoing)

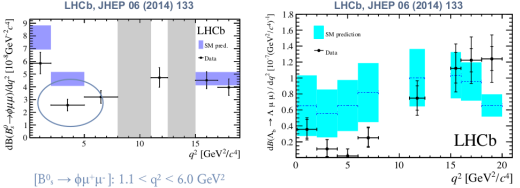
Plan:

data	only 2016, full run II later (is it allowed?)
timescale	pre-approval late summer
manpower	looks ok
other	few similar decay modes $B_s \to f_2'(1525)\mu\mu$ with $f_2'(1525) \to KK$

- Niladri to report some preliminary study in one of BPH meeting

- Rumors: new $B_0 \to K^* \mu\mu$ will be out this summer, with partial statistics. Full dataset will follow
- **Angular analysis:**
  - $B_s \to \phi\mu\mu$ (signal events: 432 ± 24 [LHCb, JHEP 09 (2015) 179])
  - $B^+ \to K^+\mu\mu$ phase difference [LHCb, EPJC (2017) 77: 161]
  - $\Lambda_b \to \Lambda\mu\mu$ [JHEP 06 (2015) 115]
- Many analysis on $\mathbf{d\mathcal{B}/dq^2}$, almost all showing lower than SM results
  - ✓ $B_0 \to K^* \mu\mu$ [LHCb, JHEP 06 (2014) 133]
  - ✗ $B^+ \to K^{*+}\mu\mu$ [LHCb, JHEP 06 (2014) 133]
  - ✗ $B^+ \to K^+\mu\mu$ [LHCb, JHEP 06 (2014) 133]
  - ✗ $\Lambda_b \to \Lambda\mu\mu$ [JHEP 06 (2015) 115]
  - 🕒 $B_s \to \phi\mu\mu$ [LHCb, JHEP 09 (2015) 179].





$[B^0_s \to \phi\mu^+\mu^-]$: $1.1 < q^2 < 6.0$ GeV^2 is 3.3σ from SM

- $B_0 \to K^* \mu\mu$
  - 8 TeV in publication, hopefully soon.
  - 13 TeV Good overall status, gaining momentum, enough manpower
- $B^+ \to K^{+*} \mu\mu$
  - Lately good progress, still some work before approval
  - manpower very limited
  - Run-II critical
- $B^+ \to K^+ \mu\mu$
  - 8 TeV CWR ended
  - 13 TeV not yet started
  - manpower limited, need more people
- $B_s \to \phi \mu\mu$
  - 13 TeV status good
  - would suggest more regular status report, even if only to report the issues found
  - manpower seems ok
- $\Lambda_b \to \Lambda \mu\mu$
  - Anyone?

Additional stuff

Additional or backup slides

Effective operator expansion

Rare b decays are a multi-scale problem: $\Lambda^2_{\rm NP} \gg m_W \gg m_b > \Lambda_{QCD}$

FCNC effective hamiltonian described as operator product expansion

Wilson coefficients ("effective coupling")

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \mathcal{C}_i \mathcal{O}_i$$

Local operator

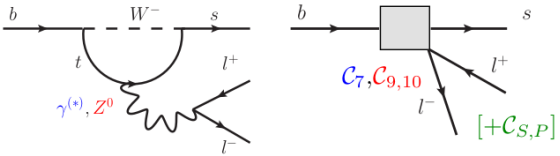
i = 1,2	Tree
i = 3 – 6,8	Gluon penguin
i = 7	Photon penguin
i = 9,10	Electroweak penguin
i = S	Higgs (scalar) penguin
i = P	Pseudoscalar penguin

Flavour-violating coupling

$$\Delta\mathcal{H}_{\rm NP} = \frac{\kappa}{\Lambda^2_{\rm NP}} \mathcal{O}_i$$

NP scale

Sensitivity to Wilson coefficients



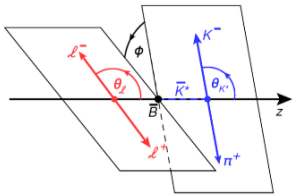
- $B^0_{(s)} \to l^+l^-$ $[\mathcal{C}_{10}, \mathcal{C}_S, \mathcal{C}_P]$
- $b \to s l^+ l^-$ $[\mathcal{C}_7, \mathcal{C}_9, \mathcal{C}_{10}]$

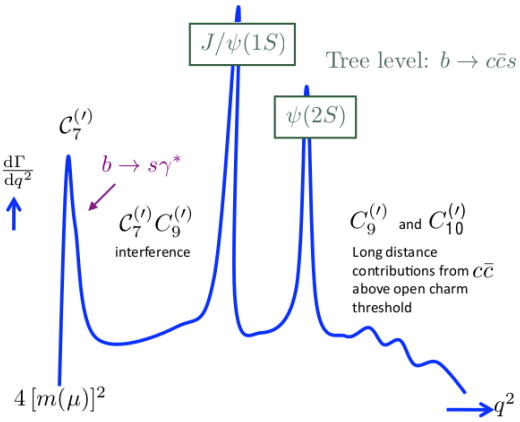
Sensitivity to Wilson coefficient vs q^2

Large number of observables: BF fractions, CP asymmetries and angular observables (5-dimension)

Sensitive to several q^2 regimes: *e.g.* new vector or axial-vector currents and virtual photon polarisation

Reconstructed as a four track final state, *i.e.* kaon, pion and di-muon





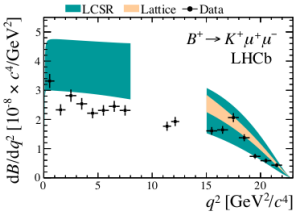
Differential BR vs q^2 at LHCb (I)

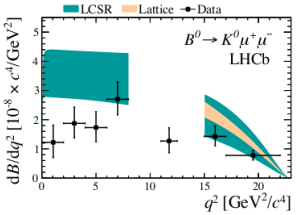
Large LHCb datasets allows for precise measurements of the differential BF

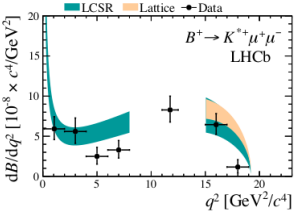
- Results hint towards lower rates than predicted by theory

[Theory uncertainty are correlated across the squared di-muon mass (q^2)]

[LHCb, JHEP 06 (2014) 133]



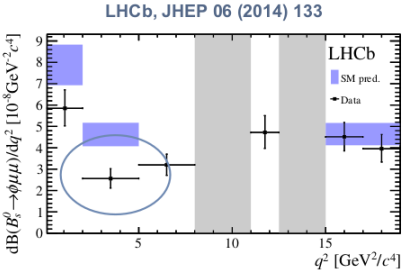


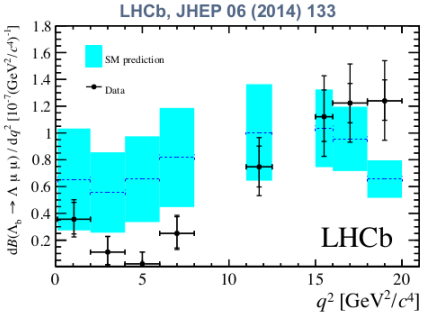


LCSR Bobeth et al [JHEP07(2011)067]

Lattice Bouchard et al [1310.3207] and Horgan et al [PRL112,212003(2014)]

Differential BR vs q^2 at LHCb (II)





$[B^0_s \to \phi\mu^+\mu^-]$: $1.1 < q^2 < 6.0$ GeV^2 is 3.3σ from SM

All branching fraction measurements could potentially point to new physics in C_9/C_{10}

SM pred. Bharucha et al [1503.05534]

SM pred. Detmold et al [PRD87(2013)074502]

$d\mathcal{B}/dq^2$ and S-wave in $B_0 \to K^*\mu\mu$

LHCb, JHEP 11 (2016) 047, JHEP 04 (2017) 142

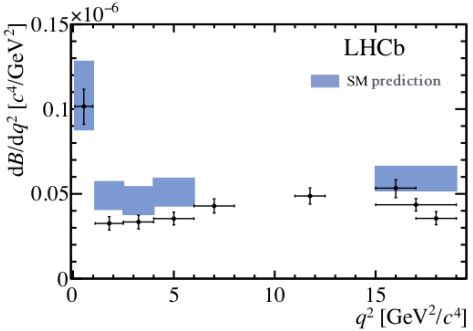
First exclusive measurement of the differential BF of $B^0 \to K^*(892)^0\mu^+\mu^-$

$$\frac{d\mathcal{B}[B^0 \to K^*(892)^0\mu^+\mu^-]}{dq^2} = \frac{R_\epsilon}{q^2_{\max} - q^2_{\min}} \frac{(1 - F_S|^{1200}_{644})}{(1 - F_S^{J/\psi K^{*0}})} \frac{N^{K^{*0}\mu\mu}}{N_{J/\psi K^{*0}}} \mathcal{B}(B^0 \to J/\psi K^{*0})\mathcal{B}(J/\psi \to \mu^+\mu^-)$$

Results compatible both with SM predictions and new physics scenarios hinted by R_K and other $b \to sll$ branching fractions

Measurements of the S-wave fraction are compatible with theory predictions and previous estimations

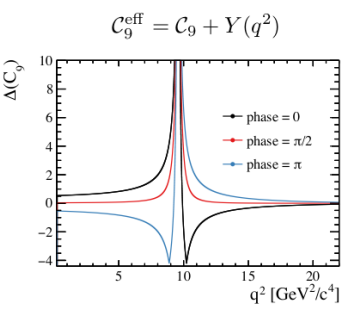
SM Bharucha et al [1503.05534]

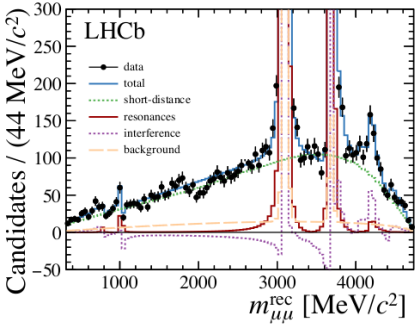


Phase difference short/long-distance amplitudes in $B^+ \to K^+\mu\mu$

Amplitude fit using "Isobar Model" baseline, *i.e.* charmonium states parametrised by the sum of Breit-Wigners

[LHCb, Eur. Phys. J. C (2017) 77: 161]





- Effect depends strongly on the relative phase with penguin
- Interference between short and long distance components found to be small
- See further discussion for $B^0 \to K^{*0}\mu^+\mu^-$ in [arXiv:1709.03921]