

# How to further exploit meson decays?



C. Langenbruch<sup>1</sup>

<sup>1</sup>RWTH Aachen, Germany

Emmy  
Noether-  
Programm

DFG Deutsche  
Forschungsgemeinschaft



$b \rightarrow s\ell\ell$  workshop Lyon  
September 4<sup>nd</sup> – 6<sup>th</sup>, 2019

# Outline

- Session: New observables/New ideas
- Try to present relatively unexplored ideas  
not yet discussed in too much detail at this WS
- Some more familiar ideas that will be possible with new data
- Many (maybe more interesting) new ideas in dedicated talks:
  - $q^2$  unbinned determination of Wilson coefficients (yesterday's session)
  - Long distance contributions: talks earlier this week
  - Tauonic final states: presentations by Justine and Matthias
  - Baryons: talks by Martin and Tom

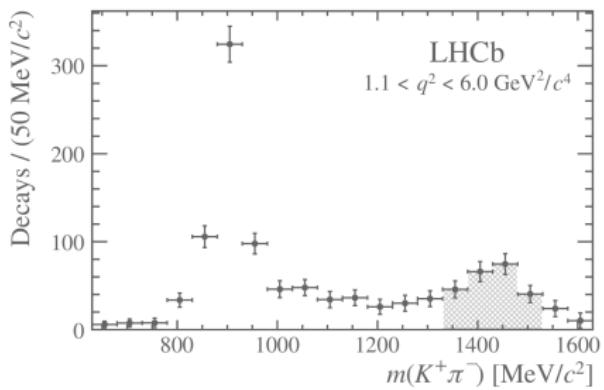
- Higher resonances
- Unexplored modes
- $B_c^+$  decays
- $b \rightarrow d\ell\ell$
- Inclusive analyses
- Normalisation modes

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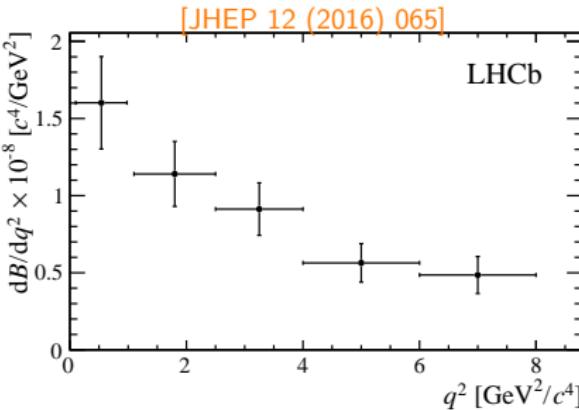
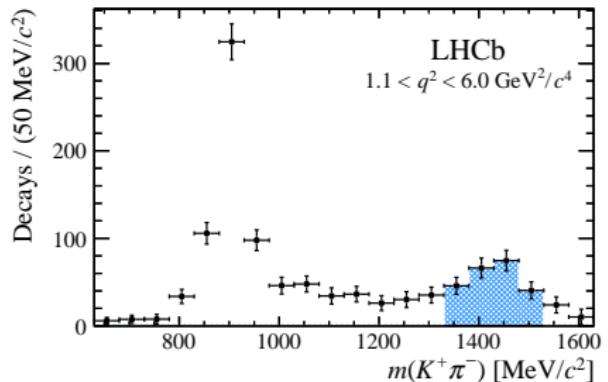
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- 1 Higher resonances
- 2 Unexplored modes
- 3  $B_c^+$  decays
- 4  $b \rightarrow d\ell\ell$
- 5 Inclusive analyses
- 6 Normalisation modes

## Higher $K\pi$ resonances

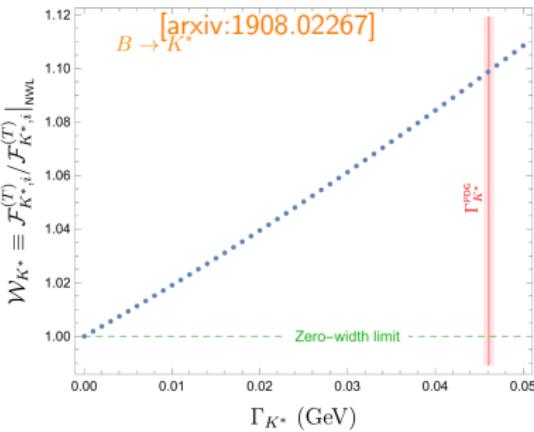
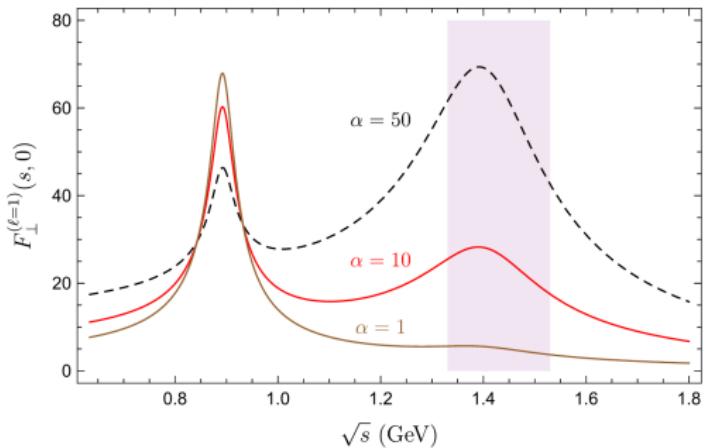


# Higher resonances in $B^0 \rightarrow K^+\pi^-\mu^+\mu^-$



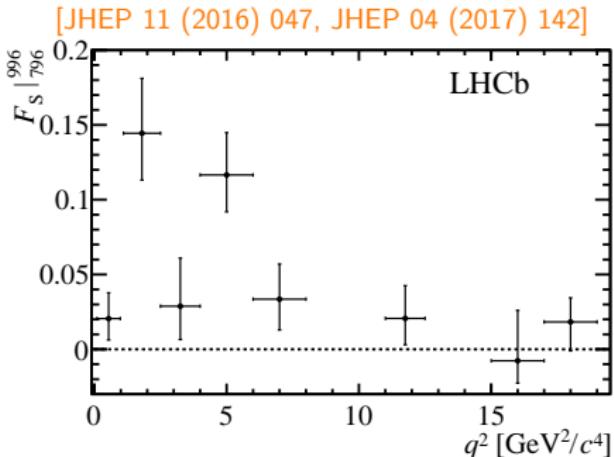
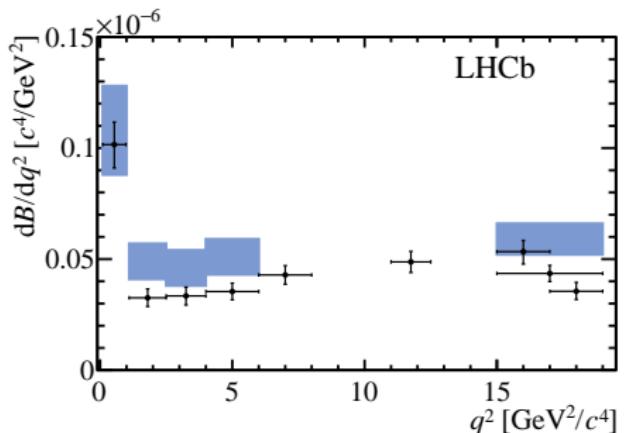
- Branching fraction and angular moments of  $B^0 \rightarrow K^+\pi^-\mu^+\mu^-$  determined in  $1330 < m_{K\pi} < 1530$  [JHEP 12 (2016) 065]
- Several contributions expected:  
S-wave  $K_0^*(1430)$ , P-wave  $K_1^*(1410)$ , D-wave  $K_2^*(1430)$
- Interpretation not straightforward, not many predictions available at the time [EPJC 67 (2010) 149-162] [PRD 85 (2012) 034014]
- Some very interesting recent work in theory!

# P-wave contributions to $B^0 \rightarrow K^+ \pi^- \mu^+ \mu^-$



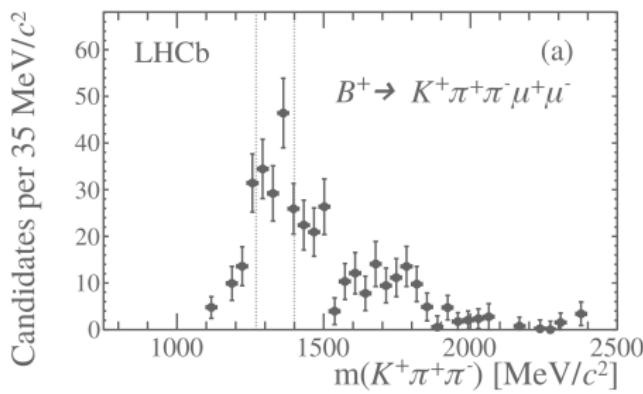
- P-wave including  $B^0 \rightarrow K_1^*(1410) \mu^+ \mu^-$  [arxiv:1908.02267]
- LCSR predict only weighed integral over  $m_{K\pi}$ , external information on factor  $\alpha$  required:  $\mathcal{F}_{K_1^*(1410)} = \alpha \mathcal{F}_{K_1^*(892)}$
- From  $\mathcal{B}$  measurement:  $\alpha \lesssim 3$  (at most 10%  $\mathcal{F}_{K_1^*(892)}$  reduction)
- Angular moments also give constraint:  $M_{||} : \alpha < 11$
- Interesting study of finite-width effect: Increases  $\mathcal{B}$  by 20% (!)
- Updates including more data needed,  
In case of specific wishes please let us know!

## S-wave

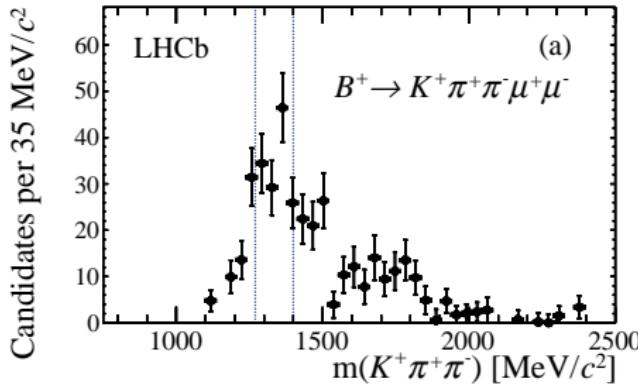
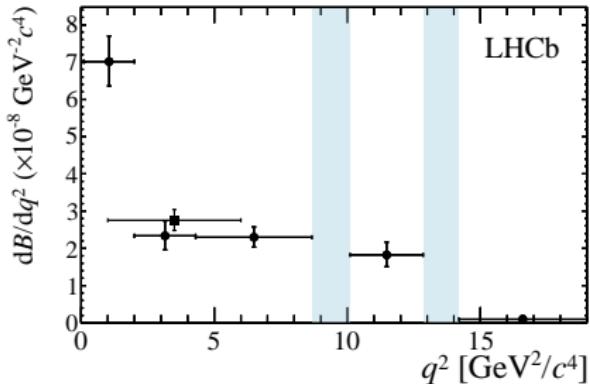


- $\mathcal{B}(P\text{-wave})$  and S-wave fraction measured in  
[JHEP 11 (2016) 047, JHEP 04 (2017) 142]
- Accounted for as nuisances in  $K^{*0}\mu^+\mu^-$  angular [JHEP 02 (2016) 104]
- $q^2$ -unbinned approaches [JHEP 11 (2017) 176] [EPJC 78 (2018) 453]  
model S-wave directly, input on form-factors very useful
- Improved S-wave predictions to appear soon? [arxiv:1908.02267]

## (Largely) Unexplored modes

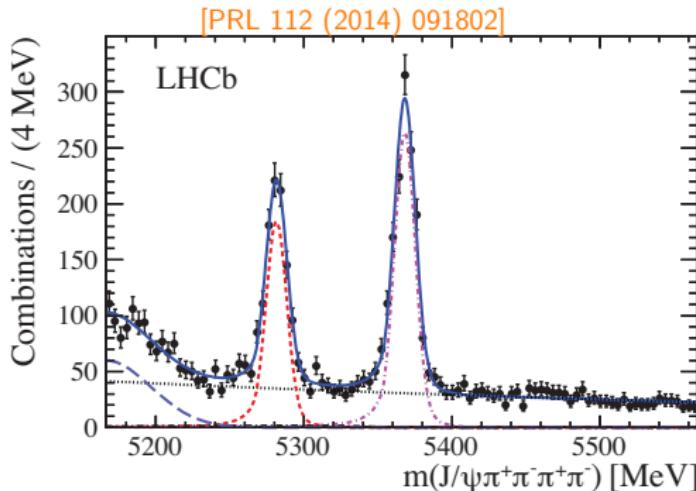


$$B^+ \rightarrow K^+ \pi^+ \pi^- \mu^+ \mu^-$$



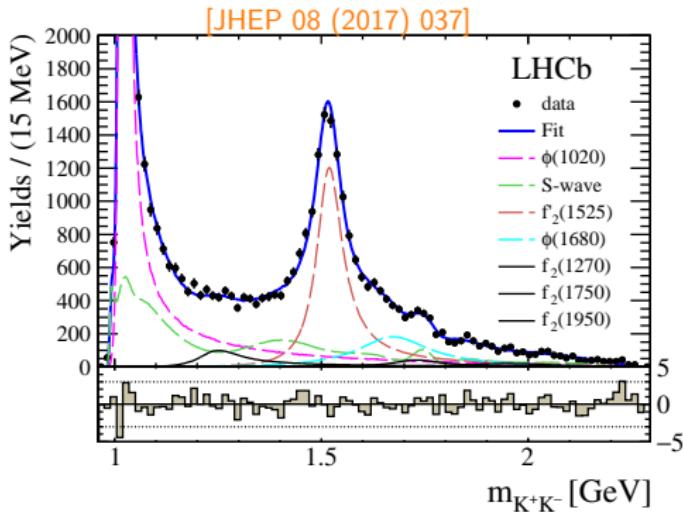
- First observed in [JHEP 10 (2014) 064]
- Inclusive branching fraction measured
- Contributions from  $K_1^+(1270)$  and  $K_1^+(1400)$  expected,  $m(K\pi\pi)$  spectrum as of yet inconclusive
- Additional data will allow a better resolution of different contributions, amplitude analysis?
- Related to  $B^+ \rightarrow K^+ \pi^+ \pi^- \gamma$  where amplitude analysis is underway
- $K_1(1270, 1400)$   $J^P = 1^+$  parity doublers for  $K^*(892)$  [JHEP 08 (2018) 178]

$$B_{(s)}^0 \rightarrow f_1(1285)(\rightarrow \pi^+ \pi^- \pi^+ \pi^-) \mu^+ \mu^-$$



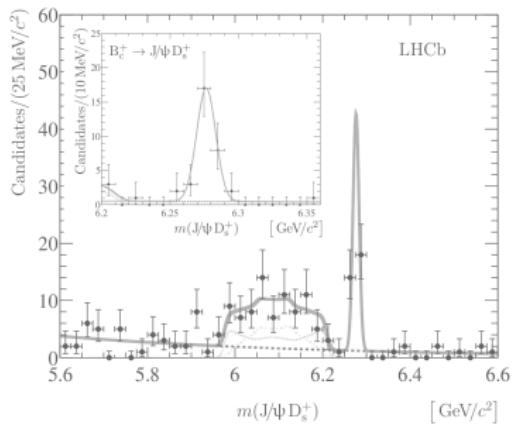
- Control mode  $B_{(s)}^0 \rightarrow J/\psi \pi^+ \pi^- \pi^+ \pi^-$  already observed [PRL 112 (2014) 091802]
- $f_1(1285)$  is the parity doubler to  $\omega(782)$ , i.e. the corresponding vector meson with opp. parity ( $J^P(\omega(782)) = 1^-$  and  $J^P(f_1(1285)) = 1^+$ )
- $B^0 \rightarrow \omega \mu^+ \mu^-$  should also be accessible (either  $\pi^+ \pi^-$  or  $\pi^+ \pi^- \pi^0$ )
- Significant interest in these new modes?

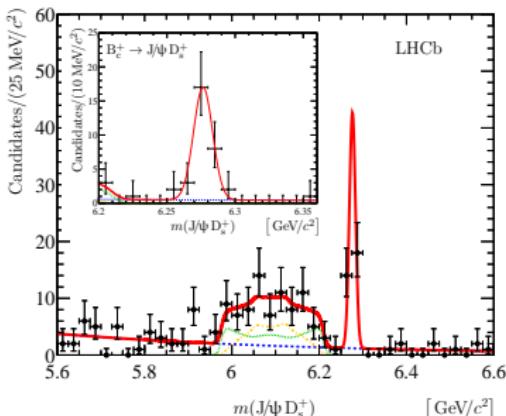
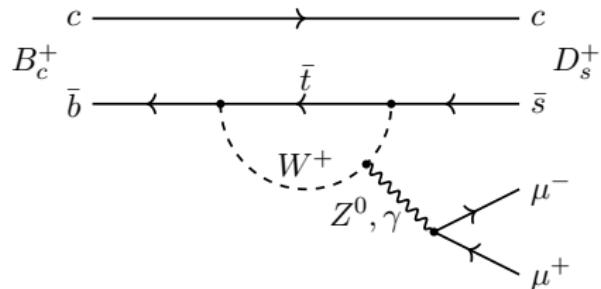
$$B_s^0 \rightarrow f'_2(1525)(\rightarrow K^+K^-)\mu^+\mu^-$$



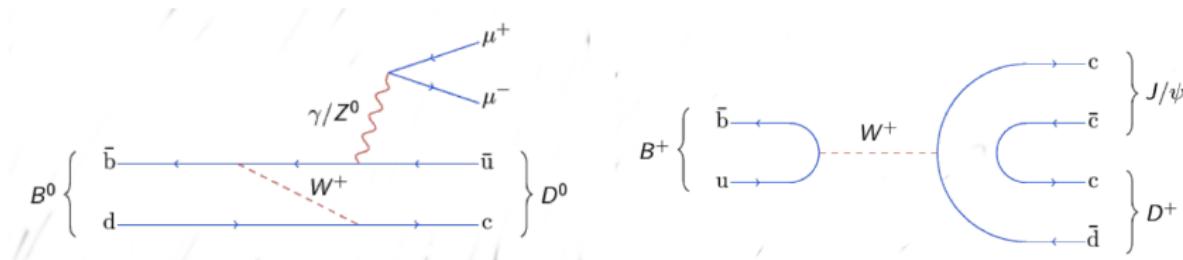
- Will be added to  $B_s^0 \rightarrow \phi\mu^+\mu^-$  update (same final state)
- Related normalisation mode  $B_s^0 \rightarrow J/\psi f'_2(1525)$  already observed [PRL 108 (2012) 151801] studied in the  $\phi_s$  context [JHEP 08 (2017) 037]
- Will perform moments analysis to confirm spin 2
- Not aware of predictions, interest in this quite narrow spin 2 state?

# $B_c^+$ decays



Electroweak penguin decay  $B_c^+ \rightarrow D_s^+ \mu^+ \mu^-$ 

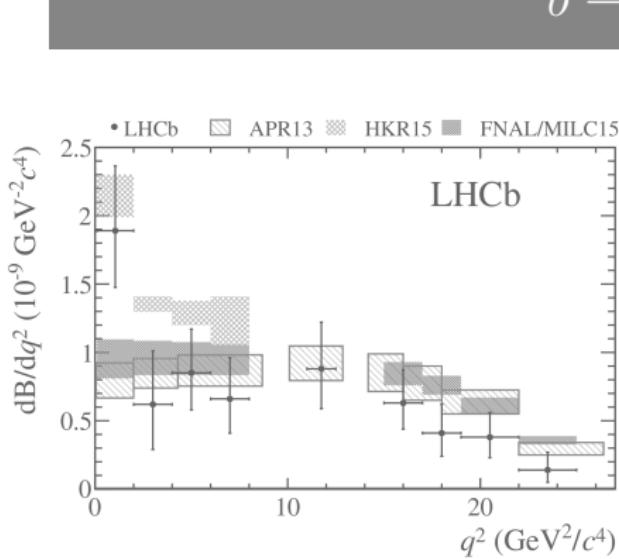
- Hadron machines allow access to  $B_c^+$ , production suppressed by  $f_c/f_u \sim 6.3 \times 10^{-3}$  [PRL 114 (2015) 132001][CPC 41 (2017) 013101]
- $B_c^+ \rightarrow D_s^{+(*)} \mu^+ \mu^-$  predictions [PRD 82 (2010) 034032] [arXiv:1906.02412] [EPJC 4 (2002) 18]
- Control mode  $B_c^+ \rightarrow J/\psi D_s^{+(*)}$  already observed [PRD 87 11 (2013) 112012]
- Reconstruction in  $\mathcal{B}(D_s^+ \rightarrow K^+ K^- \pi^+) \sim 5\%$ ,  $\mathcal{B}(D_s^{+*} \rightarrow D_s^+ \gamma) \sim 94\%$   
→ expect  $\mathcal{O}(1 - 10)$  events in LHCb Run 1+2

Other modes with  $D\mu^+\mu^-$  final states

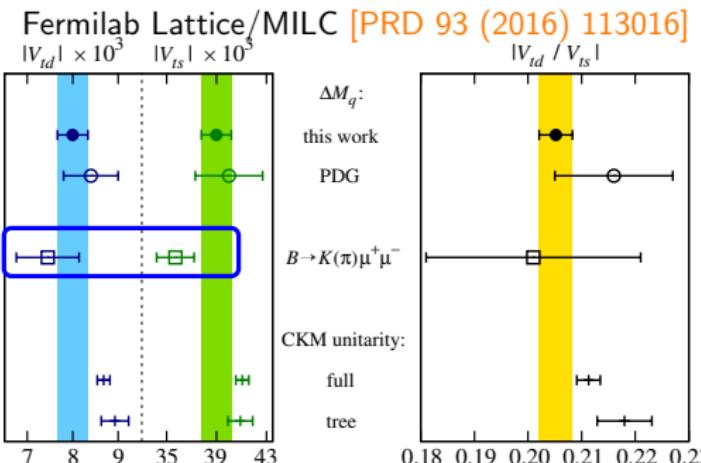
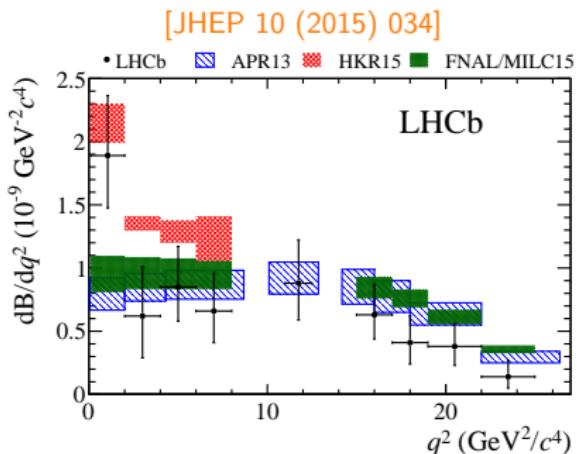
- $B \rightarrow D\mu^+\mu^-$  via  $W$ -exchange, annihilation diagrams
- Heavily suppressed, but large spread of predictions:
  - $\mathcal{B}(B^0 \rightarrow D^0\mu^+\mu^-, 1 < q^2 < 5 \text{ GeV}^2/c^4) = (9.7^{+4.2}_{-3.2}) \times 10^{-6}$  [JHEP 10 (2011) 152]
  - $\mathcal{B}(B^0 \rightarrow D^{*0}e^+e^-, q^2 > 1 \text{ GeV}^2/c^4) = 1.4 \times 10^{-8}$  [NPB 577 (2000) 240-260]
  - $\mathcal{B}(B^0 \rightarrow D^0e^+e^-, q^2 > 1 \text{ GeV}^2/c^4) = 2.6 \times 10^{-9}$  [NPB 577 (2000) 240-260]
  - $\mathcal{B}(B^+ \rightarrow D^{*+}e^+e^-, q^2 > 1 \text{ GeV}^2/c^4) = 9.1 \times 10^{-11}$  [PRL 83 (1999) 4947-4950]
  - $\mathcal{B}(B^+ \rightarrow D^+e^+e^-, q^2 > 1 \text{ GeV}^2/c^4) = 1.4 \times 10^{-11}$  [PRL 83 (1999) 4947-4950]
  - $\mathcal{B}(B^+ \rightarrow D_s^{*+}e^+e^-, q^2 > 1 \text{ GeV}^2/c^4) = 1.8 \times 10^{-9}$  [PRL 83 (1999) 4947-4950]
  - $\mathcal{B}(B^+ \rightarrow D_s^+e^+e^-, q^2 > 1 \text{ GeV}^2/c^4) = 2.7 \times 10^{-10}$  [PRL 83 (1999) 4947-4950]

- Interest in these modes?

$b \rightarrow d\ell\ell$



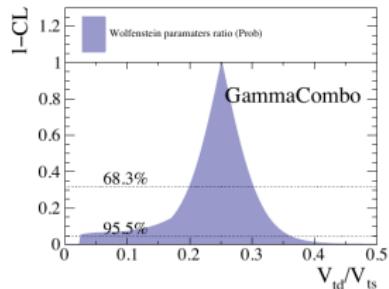
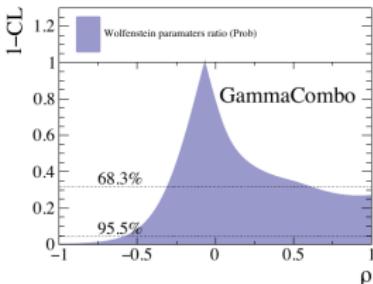
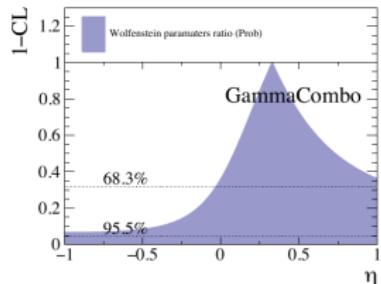
$b \rightarrow d\ell\ell$  status:  $B^+ \rightarrow \pi^+ \mu^+ \mu^-$



- Good agreement with but slightly lower than SM predictions  
APR13 [PRD 89 (2014) 094021] HKR15 [PRD 92 (2015) 074020] FNAL/MILC15 [PRL 115 (2015) 152002]
- $\mathcal{B} = (1.83 \pm 0.24 \pm 0.05) \times 10^{-8}$  and  $\mathcal{A}_{CP} = -0.11 \pm 0.12 \pm 0.01$   
 $|\frac{V_{td}}{V_{ts}}| = 0.24^{+0.05}_{-0.04}$ ,  $|V_{td}| = 7.2^{+0.9}_{-0.8} \times 10^{-3}$  and  $|V_{ts}| = 3.2^{+0.4}_{-0.4} \times 10^{-2}$
- Lattice predictions (Fermilab/MILC) [PRD 93 (2016) 034005] [PRD 93 (2016) 113016]  
Combined  $\sim 2\sigma$  tension of  $\mathcal{B}(B^+ \rightarrow K^+(\pi^+) \mu^+ \mu^-)$  with SM prediction
- Run 1  $N_{\text{sig}} \sim 90$ , ongoing Run 2 update will quadruple yield

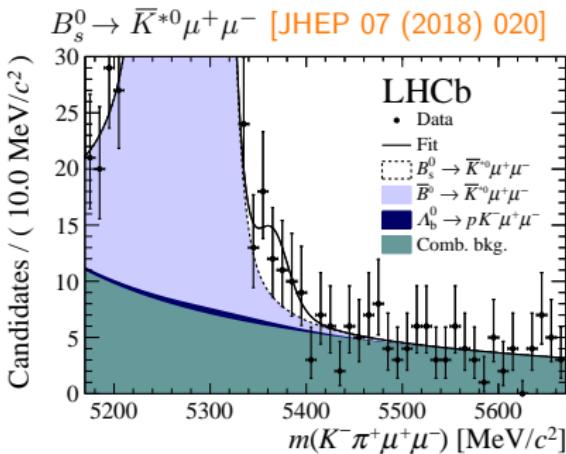
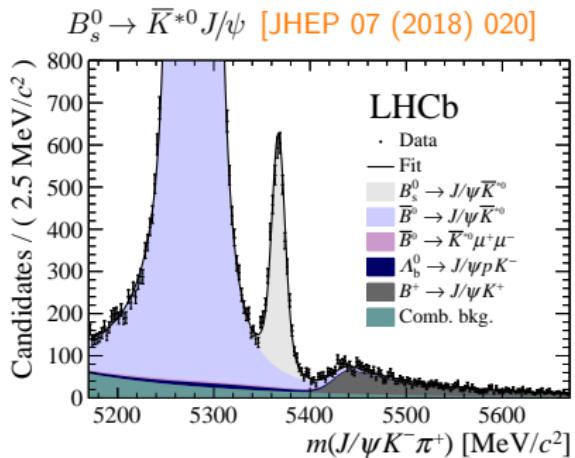
Improved  $V_{\text{td}}/V_{\text{ts}}$  determination from  $B^+ \rightarrow \pi^+\mu^+\mu^-$ 

plots by M. Whitehead



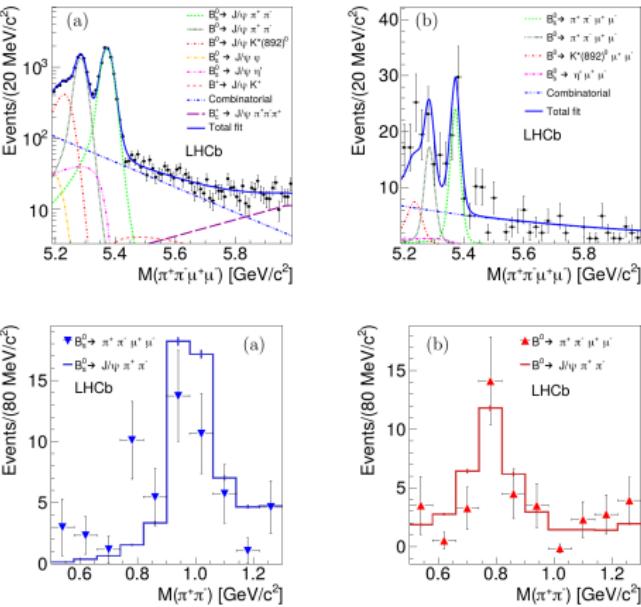
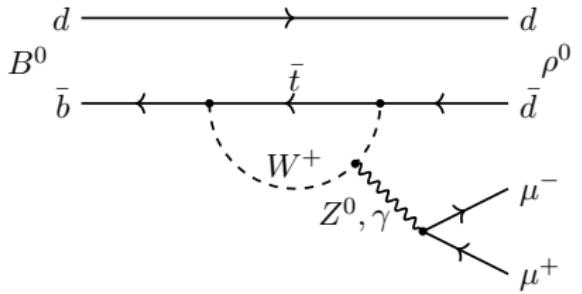
- Determination of  $V_{\text{td}}/V_{\text{ts}}$  not only given by FF ratio [JHEP 08 (2017) 112]  
$$\frac{\mathcal{B}(B^+ \rightarrow \pi^+\mu^+\mu^-)}{\mathcal{B}(B^+ \rightarrow K^+\mu^+\mu^-)} = \frac{|V_{\text{td}}/V_{\text{ts}}|^2}{\mathcal{F}_{B\pi}} \times (\mathcal{F}_{B\pi} + \text{corrections})$$
- Run 1 using [JHEP 08 (2017) 112] approach:  $V_{\text{td}}/V_{\text{ts}} = 0.24 \pm 0.05$   
good agreement with naive approach  $|V_{\text{td}}/V_{\text{ts}}| = 0.24^{+0.05}_{-0.04}$  [JHEP 10 (2015) 034]
- Run 2 expectation with improved determination  $\sigma(|V_{\text{td}}/V_{\text{ts}}|) \sim 0.03$   
Incl. corr. between theory inputs provided [JHEP 08 (2017) 112] authors

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



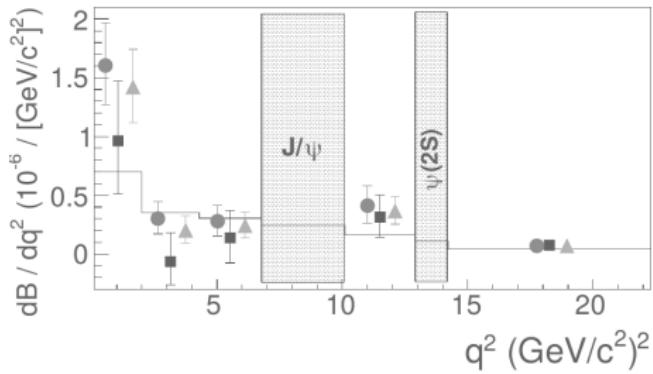
- $N_{\bar{K}^{*0} \mu\mu} \sim 40$  (Run 1+2016), first evidence at  $3.4\sigma$
- LHCb Run 1+2: expectation  $\sim 80$
- LHCb Upgrade II expects  $N_{\bar{K}^{*0} \mu\mu} \sim 4300$
- Allows for angular analysis of  $B_s^0 \rightarrow \bar{K}^{*0} \mu^+ \mu^-$  with better precision than Run 1  $B^0 \rightarrow K^{*0} \mu^+ \mu^-$  result

$$B^0 \rightarrow \rho^0 \mu^+ \mu^-$$



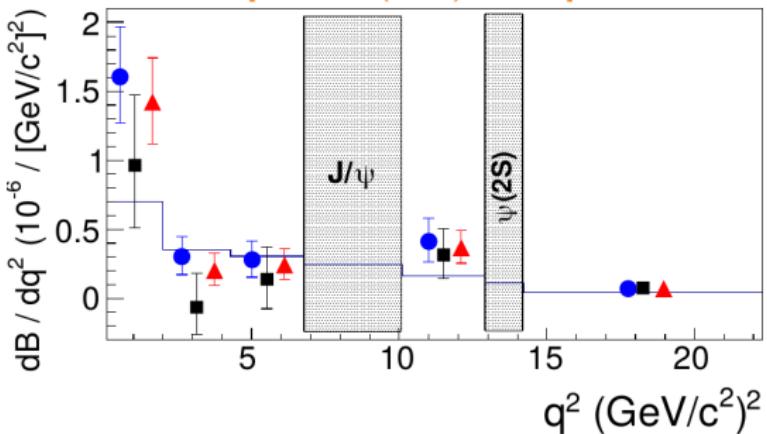
- First evidence for  $B^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$  in [PLB 743 (2015) 46]  
Compatible with  $\rho^0 \mu \mu$  but very limited stats
- Complex angular structure, similar to  $B_s^0 \rightarrow \phi \mu \mu$  as untagged  $B \rightarrow V$
- Untagged analysis allows access to angular CP-asymmetries

## Inclusive analyses

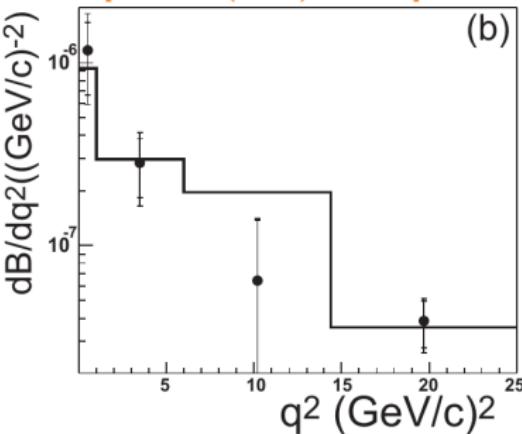


$B \rightarrow X_{s,d} \ell \ell$  inclusive status

[PRL 112 (2014) 211802]



[PRD 72 (2005) 092005]



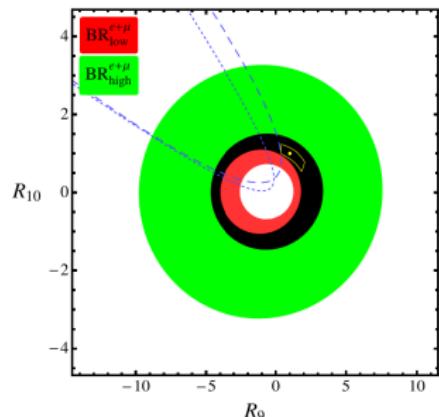
- Inclusive  $B \rightarrow X_{d,s} \ell \ell$  important complementary info. to excl. modes
- Two variables:  $q^2$  and  $z = \cos \theta_l$ :  

$$\frac{d^2\Gamma}{dq^2 dz} = \frac{3}{8} [(1+z^2)H_T(q^2) + 2zH_A(q^2) + 2(1-z^2)H_L(q^2)]$$

$$\frac{d\Gamma}{dq^2} = H_T(q^2) + H_L(q^2), \quad \frac{dA_{FB}}{dq^2} = \frac{3}{4}H_A(q^2)$$
- Experimental situation: BaBar  $\Gamma$  and  $A_{CP}$  [PRL 112 (2014) 211802]  
 Belle  $\Gamma$  [PRD 72 (2005) 092005] Belle  $A_{FB}$  [PRD 93 (2016) 032008]
- $\mathcal{B}(1 < q^2 < 6 \text{ GeV}^2/c^4) = (1.58 \pm 0.37) \times 10^{-6}$ ,  
 $\mathcal{B}(q^2 > 14.4 \text{ GeV}^2/c^4) = (4.8 \pm 1.0) \times 10^{-7}$  [JHEP 1506 (2015) 176]

# $B \rightarrow X_{s,d} \ell \ell$ interpretation and techniques

[JHEP 06 (2015) 176]



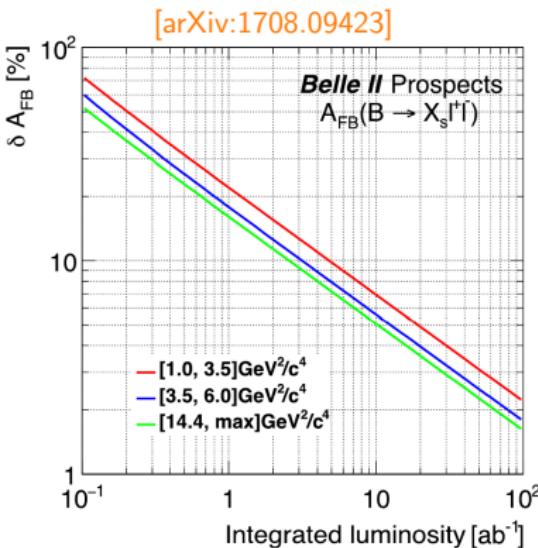
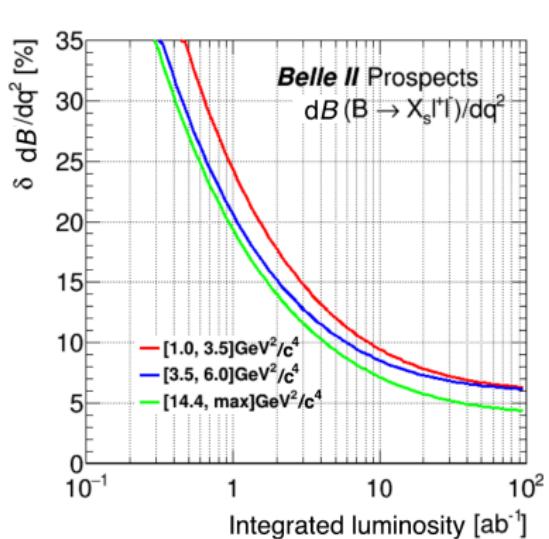
[PRD 93 (2016) 032008]

$\bar{B}^0$ decays		$B^-$ decays	
	$(K_S^0)$	$K^-$	
$K^- \pi^+$	$(K_S^0 \pi^0)$	$K^- \pi^0$	$K_S^0 \pi^-$
$K^- \pi^+ \pi^0$	$(K_S^0 \pi^- \pi^+)$	$K^- \pi^+ \pi^-$	$K_S^0 \pi^- \pi^0$
$K^- \pi^+ \pi^- \pi^+$	$(K_S^0 \pi^- \pi^+ \pi^0)$	$K^- \pi^+ \pi^- \pi^0$	$K_S^0 \pi^- \pi^+ \pi^-$
$(K^- \pi^+ \pi^- \pi^+ \pi^0)$	$(K_S^0 \pi^- \pi^+ \pi^- \pi^+)$	$(K^- \pi^+ \pi^- \pi^+ \pi^-)$	$(K_S^0 \pi^- \pi^+ \pi^- \pi^0)$

- Expected final sensitivity from current  $B$ -factories 15–20%
- All current measurements are sum of exclusives:
  - Approach allows to separate  $X_d$  from  $X_s$
  - Cut  $M_{X_s} \lesssim 1.8 \text{ GeV}/c^2$  introduces some theory uncertainty at low  $q^2$

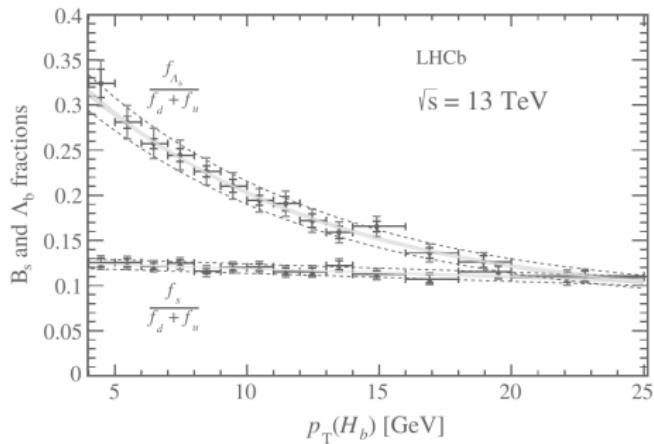
[PRD 74 (2006) 011501] [PRD 79 (2009) 114021] [NPB 09 (2010) 022]
- Can precise excl. measurements of all-track modes help reduce overall uncertainty?
- $B \rightarrow K^+ X \mu^+ \mu^-$  very challenging but maybe not impossible at LHCb

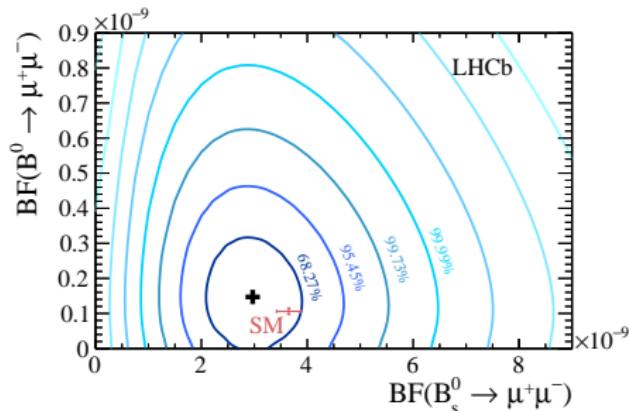
# $B \rightarrow X_s d\ell\ell$ Belle 2 expectation



- Exp. uncertainties 5–7% for  $\Gamma$  and 2–3% for  $A_{FB}$  with  $50 ab^{-1}$
- Start with sum over exclusive, then pursue fully inclusive [arXiv:1808.10567]
- Aims to measure  $R_{X_s} = \frac{\mathcal{B}(B \rightarrow X_s \mu^+ \mu^-)}{\mathcal{B}(B \rightarrow X_s e^+ e^-)}$  at 3–4% with  $50 ab^{-1}$
- Recent theory work to further reduce  $B \rightarrow X_d \ell\ell$  uncertainties [arXiv:1908.07507]

## Normalisation modes

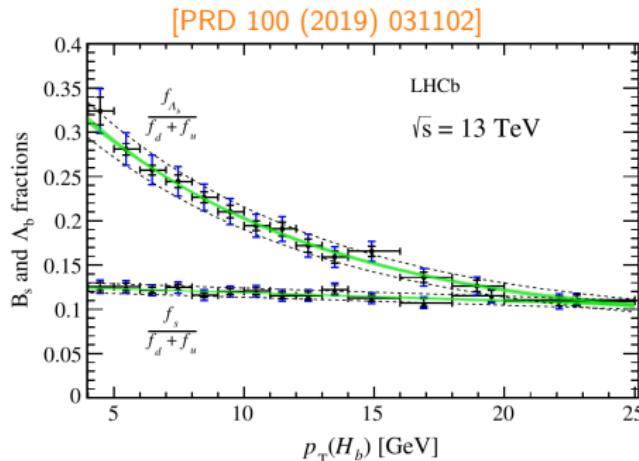


Normalisation for  $B_s^0 \rightarrow \mu^+ \mu^-$ 

[PRL 118 (2017) 191801]

Current Experimental Systematics (LHCb)	
Source	size
Hadronisation fraction $f_s/f_d$	5.8%
Normalisation modes	3%
Particle identification	2%
Track reconstruction	2%

- First observation by single experiment ( $7.8\sigma$ ):  
LHCb:  $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$  [PRL 118 (2017) 191801]
- Mode also well accessible by GPDs:  
CMS:  $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (2.9^{+0.7}_{-0.6} \pm 0.2) \times 10^{-9}$  [CMS-PAS-BPH-16-004]  
ATLAS:  $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (2.8^{+0.8}_{-0.7}) \times 10^{-9}$  [JHEP 04 (2019) 098]
- $\sigma_{\text{syst.}}$  limited by  $f_s/f_d = 0.259 \pm 0.015$  (5.8% rel.) [LHCb-CONF-2013-011]

Normalisation for  $B_s^0 \rightarrow \mu^+ \mu^-$  ||

- New  $f_s/(f_u + f_d) = 0.122 \pm 0.006$  (4.8% rel.) [PRD 100 (2019) 031102] using  $D^0 X \mu^- \bar{\nu}_\mu$ ,  $D^+ X \mu^- \bar{\nu}_\mu$ ,  $D_s^+ X \mu^- \bar{\nu}_\mu$  final states, for  $f_s/(f_u + f_d)$  dominant  $\sigma_{\text{syst.}}$  from  $\mathcal{B}(D_s^+ \rightarrow K^+ K^- \pi^+)$  (3.3%)
- Alternative: Normalise to  $B_s^0$  decay, but precision on  $\mathcal{B}$  limited
  - $\mathcal{B}(B_s^0 \rightarrow J/\psi \phi) = (1.08 \pm 0.08) \times 10^{-3}$
  - $\mathcal{B}(B_s^0 \rightarrow D_s^+ \pi^-) = (3.00 \pm 0.23) \times 10^{-3}$
- Belle 2 could improve both

# $B_s^0 \rightarrow \mu^+ \mu^-$ prospects

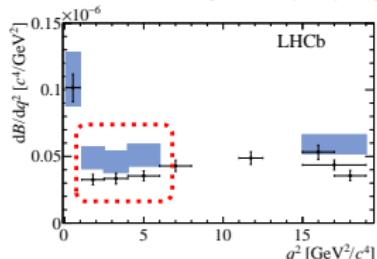
[arXiv:1812.07638]

Experiment	Scenario	$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$	$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)$
LHCb	$23 \text{ fb}^{-1}$	8.2	33
LHCb	$300 \text{ fb}^{-1}$	4.4	9.4
CMS	$300 \text{ fb}^{-1}$	12	46
CMS	$3 \text{ ab}^{-1}$	7	16
ATLAS	Run 2	22.7	135
ATLAS	$3 \text{ ab}^{-1}$ Conservative	15.1	51
ATLAS	$3 \text{ ab}^{-1}$ Intermediate	12.9	29
ATLAS	$3 \text{ ab}^{-1}$ High-yield	12.6	26

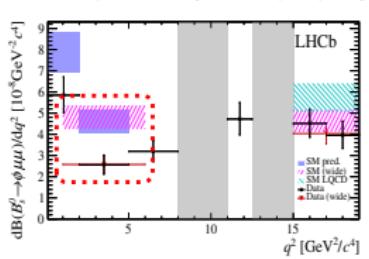
- LHCb expects 1.8% stat. uncertainty with  $300 \text{ fb}^{-1}$  (Upgrade 2)
- Above LHCb numbers assume reductions to  $\sigma_{\text{syst.}}^{f_s/f_d} \sim 3.5\%$ ,  $\sigma_{\text{syst.}}^{\mathcal{B} \text{ norm}} \sim 1.4\%$  after Upgrade 2 [arXiv:1812.07638]

# Connection to the Flavour anomalies: $b \rightarrow s\mu^+\mu^-$ rates

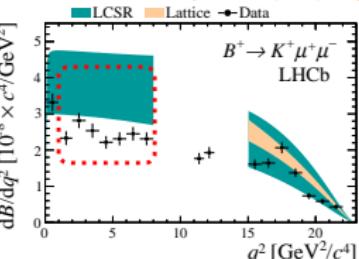
LHCb  $B^0 \rightarrow K^{*0}\mu^+\mu^-$  [JHEP 11 (2016) 047]



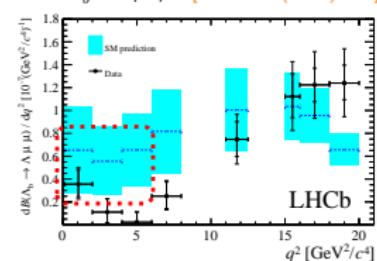
LHCb  $B_s^0 \rightarrow \phi\mu^+\mu^-$  [JHEP 09 (2015) 179]



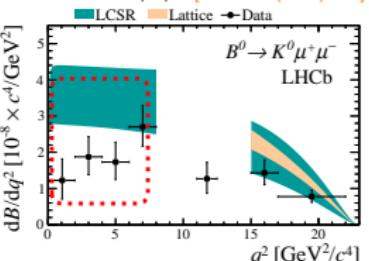
LHCb  $B^+ \rightarrow K^+\mu^+\mu^-$  [JHEP 06 (2014) 133]



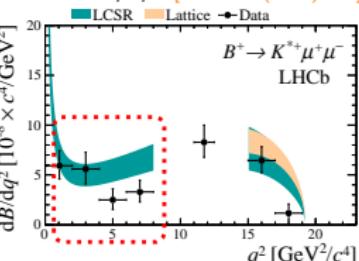
$\Lambda_b^0 \rightarrow \Lambda\mu^+\mu^-$  [JHEP 06 (2015) 115]



LHCb  $B^0 \rightarrow K^0\mu^+\mu^-$  [JHEP 06 (2014) 133]

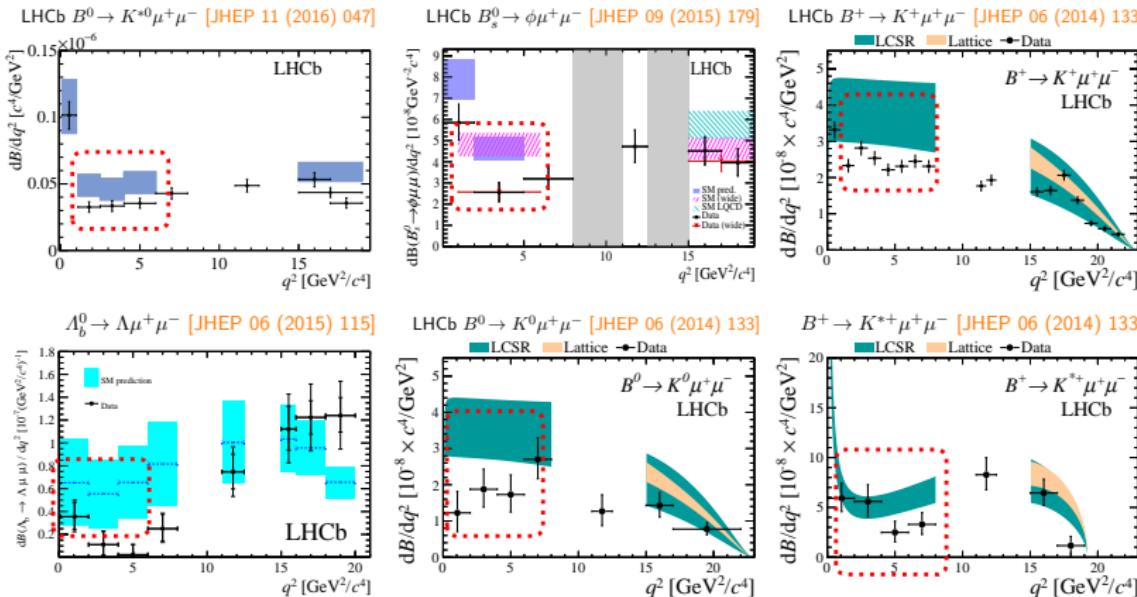


$B^+ \rightarrow K^{*+}\mu^+\mu^-$  [JHEP 06 (2014) 133]



- Pattern: Data generally below SM predictions (particularly at low  $q^2$ )
- Norm. modes (typically corr.  $J/\psi$  modes) close to (or already) limiting

# Connection to the Flavour anomalies: $b \rightarrow s\mu^+\mu^-$ rates



■ Numerically in  $1 < q^2 < 6 \text{ GeV}^2/c^4$ :

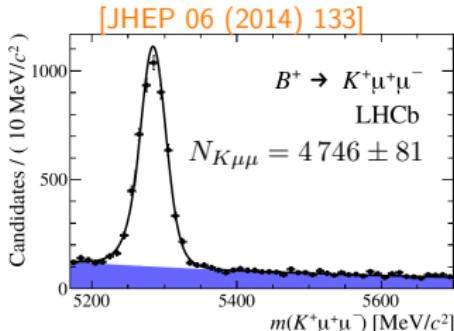
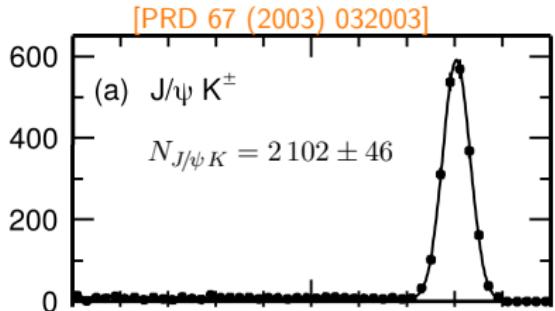
$$d\mathcal{B}(B^0 \rightarrow K^{*0}\mu^+\mu^-)/dq^2 = (3.42 \pm 0.17 \pm 0.09 \pm 0.23) \times 10^{-8}/\text{GeV}^2/c^4$$

$$d\mathcal{B}(B_s^0 \rightarrow \phi\mu^+\mu^-)/dq^2 = (2.58^{+0.33}_{-0.31} \pm 0.08 \pm 0.19) \times 10^{-8}/\text{GeV}^2/c^4$$

$$d\mathcal{B}(B^+ \rightarrow K^+\mu^+\mu^-)/dq^2 = (2.42 \pm 0.07 \pm 0.06 \pm 0.10) \times 10^{-8}/\text{GeV}^2/c^4$$

■ Note:  $\sigma(\mathcal{B}_{\text{norm}})$  correlated between all bins

# Connection to the Flavour anomalies: $b \rightarrow s\mu^+\mu^-$ rates



- Highest precision  $\mathcal{B}(B^+ \rightarrow J/\psi K^+) = (1.010 \pm 0.028) \times 10^{-3}$   
Some results assume equal  $B^+ B^- / B^0 \bar{B}^0$  production on  $\Upsilon(4S)$   
Current world average:  $f_+/f_0 = 1.058 \pm 0.024$  [EPJC 77 (2017) 895]
- Two of the most precise measurements included in average:  
BaBar  $\mathcal{B}(B^+ \rightarrow J/\psi K^+) = (1.061 \pm 0.015 \pm 0.048) \times 10^{-3}$  [PRL 94 (2005) 141801]  
124 M  $B\bar{B}$ , limiting systematics: efficiency determination (tracking, PID)  
Belle  $\mathcal{B}(B^+ \rightarrow J/\psi K^+) = (1.01 \pm 0.02 \pm 0.07) \times 10^{-3}$  [PRD 67 (2003) 032003]  
 $29.4 \text{ fb}^{-1}$ , limiting systematics: tracking, PID
- Sub-percent precision  $B$ -counting using off-res. samples [EPJC 74 (2014) 3026]
- Belle 2 (likely also BaBar/Belle) can easily improve these  
Would have significant impact in global fits

# Conclusions

- There is a lot of work to do,  
many interesting areas off the beaten track
- Interplay of experimental results on higher  $K\pi$  resonances  
and form factor predictions beyond the narrow width approximation
- Interest in new modes and observables?
- Larger samples will allow analyses of rare  $B_c^+$  decays  
and  $b \rightarrow d\ell\ell$  transitions
- A lot of improvement expected  
in inclusive analyses
- Branching fractions of  
normalisation modes have high impact

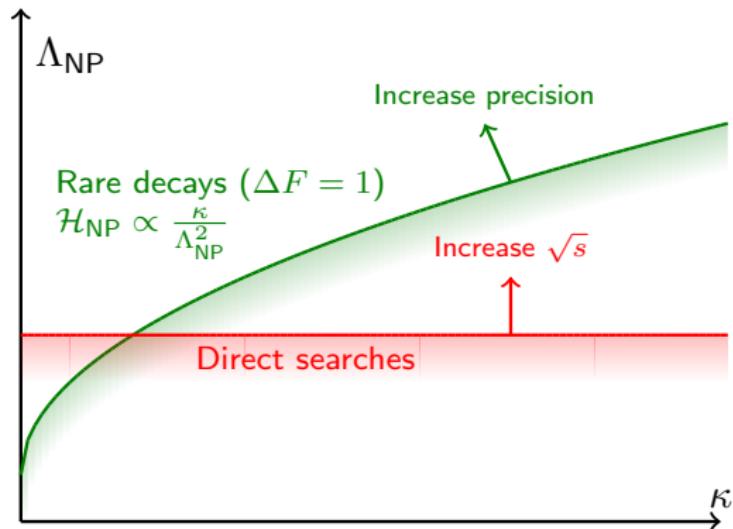




Backup

# The complementarity of NP searches with rare decays

## Exclusion limits for NP searches

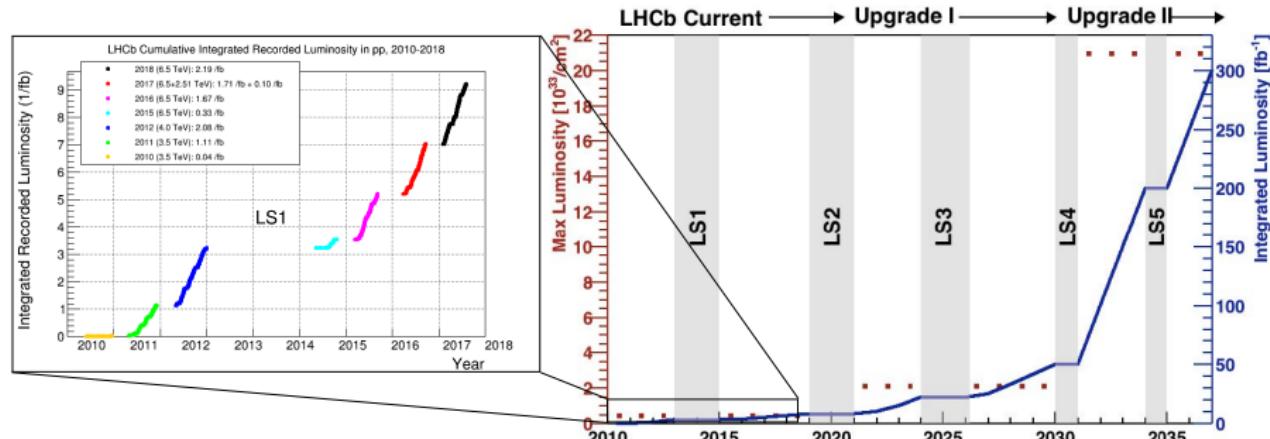


scenario	$\kappa$
Tree generic	1
Tree MFV	$V_{tb} V_{ts}$
Loop generic	$\frac{1}{16\pi^2}$
Loop MFV	$\frac{V_{tb} V_{ts}}{16\pi^2}$

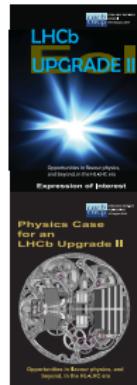
CKM-like flavour violation  $\longleftrightarrow$  generic flavour violation

- Direct searches limited by beam energy,  $\Lambda_{NP} < \sqrt{s}$
- Reach with rare decays scales with  $\sqrt{\kappa/\sigma(C_i)}$
- Typically  $\Lambda_{NP} \propto \sqrt{\kappa/\sigma(C_i)} \propto \sqrt{\kappa} \times \sqrt[4]{\int \mathcal{L} dt}$

# LHCb Upgrade schedule

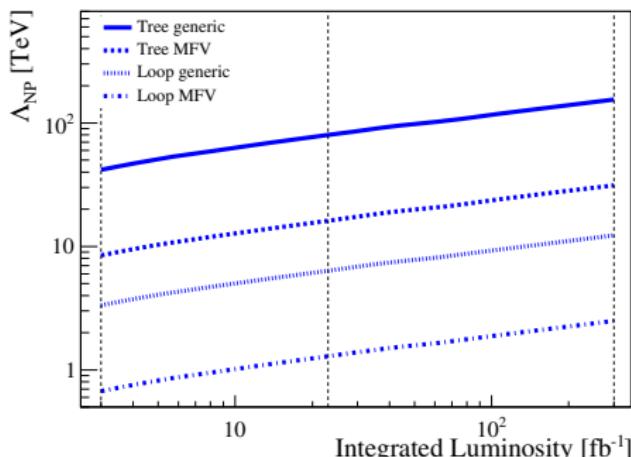


- Current status:  $9 \text{ fb}^{-1}$  in Run 1+2
- Upgrade I a+b:  $50 \text{ fb}^{-1}$  (Run 3+4 at  $\mathcal{L} = 2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ )
- Upgrade II:  $300 \text{ fb}^{-1}$  (Run 5 at  $\mathcal{L} = 2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ )
- LHCb Upgrade II summarised in EoI [CERN-LHCC-2017-003] and Physics case [CERN-LHCC-2018-027]
- Physics of the HL-LHC, WG 4 Flavour [arxiv:1812.07638]



# Typical NP reach of Rare Decays

$\Lambda_{\text{NP}}$  reach with LFU tests  $R_{K^{(*)}}$



$\int \mathcal{L} dt$	[Upgrade II Physics case]			[Physics of the HL-LHC WG 4]			
	3 fb⁻¹	23 fb⁻¹	300 fb⁻¹	3 fb⁻¹	23 fb⁻¹	300 fb⁻¹	
$R_K$ and $R_{K^*}$ measurements							
$\sigma(\mathcal{C}_9)$	0.44	0.12	0.03				
$\Lambda_{\text{NP}}^{\text{tree generic}} [\text{TeV}]$	40	80	155				
$\Lambda_{\text{NP}}^{\text{tree MFV}} [\text{TeV}]$	8	16	31				
$\Lambda_{\text{NP}}^{\text{loop generic}} [\text{TeV}]$	3	6	12				
$\Lambda_{\text{NP}}^{\text{loop MFV}} [\text{TeV}]$	0.7	1.3	2.5				
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ angular analysis							
$\sigma^{\text{stat}}(S_i)$	0.034–0.058	0.009–0.016	0.003–0.004				
$\sigma(\mathcal{C}'_{10})$	0.31	0.15	0.06				
$\Lambda_{\text{NP}}^{\text{tree generic}} [\text{TeV}]$	50	75	115				
$\Lambda_{\text{NP}}^{\text{tree MFV}} [\text{TeV}]$	10	15	23				
$\Lambda_{\text{NP}}^{\text{loop generic}} [\text{TeV}]$	4	6	9				
$\Lambda_{\text{NP}}^{\text{loop MFV}} [\text{TeV}]$	0.8	1.2	1.9				

- Reachable NP scales  $\Lambda_{\text{NP}} \propto \sqrt{1/\sigma(\mathcal{C}_{\text{NP}})} \propto \sqrt[4]{\int \mathcal{L} dt}^1$
- Precision flavour observables probe scales far beyond  $\sqrt{s} = 14 \text{ TeV}$
- Upgrade II can reach a factor 1.9 higher than Upgrade Ia

<sup>1</sup>Naive scaling: Assumes identical scaling of systematics

# Prospects summary

Table 10.1: Summary of prospects for future measurements of selected flavour observables for LHCb, Belle II and Phase-II ATLAS and CMS. The projected LHCb sensitivities take no account of potential detector improvements, apart from in the trigger. The Belle-II sensitivities are taken from Ref. [608].

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
<b>EW Penguins</b>					
$R_K$ ( $1 < q^2 < 6 \text{ GeV}^2 c^4$ )	0.1 [274]	0.025	0.036	0.007	—
$R_{K^*}$ ( $1 < q^2 < 6 \text{ GeV}^2 c^4$ )	0.1 [275]	0.031	0.032	0.008	—
$R_\phi, R_{pK}, R_\pi$	—	0.08, 0.06, 0.18	—	0.02, 0.02, 0.05	—
<b>CKM tests</b>					
$\gamma$ , with $B_s^0 \rightarrow D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	$4^\circ$	—	$1^\circ$	—
$\gamma$ , all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	$1.5^\circ$	$1.5^\circ$	$0.35^\circ$	—
$\sin 2\beta$ , with $B^0 \rightarrow J/\psi K_s^0$	0.04 [609]	0.011	0.005	0.003	—
$\phi_s$ , with $B_s^0 \rightarrow J/\psi \phi$	49 mrad [44]	14 mrad	—	4 mrad	22 mrad [610]
$\phi_s$ , with $B_s^0 \rightarrow D_s^+ D_s^-$	170 mrad [49]	35 mrad	—	9 mrad	—
$\phi_s^{\bar{s}s}$ , with $B_s^0 \rightarrow \phi \phi$	154 mrad [94]	39 mrad	—	11 mrad	Under study [611]
$a_{sl}^q$	$33 \times 10^{-4}$ [211]	$10 \times 10^{-4}$	—	$3 \times 10^{-4}$	—
$ V_{ub} / V_{cb} $	6% [201]	3%	1%	1%	—
<b><math>B_s^0, B^0 \rightarrow \mu^+ \mu^-</math></b>					
$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)/\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$	90% [264]	34%	—	10%	21% [612]
$\tau_{B_s^0 \rightarrow \mu^+ \mu^-}$	22% [264]	8%	—	2%	—
$S_{\mu\mu}$	—	—	—	0.2	—
<b><math>b \rightarrow c \ell^- \bar{\nu}_\ell</math> LUV studies</b>					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	—
$R(J/\psi)$	0.24 [220]	0.071	—	0.02	—
<b>Charm</b>					
$\Delta A_{CP}(KK - \pi\pi)$	$8.5 \times 10^{-4}$ [613]	$1.7 \times 10^{-4}$	$5.4 \times 10^{-4}$	$3.0 \times 10^{-5}$	—
$A_\Gamma (\approx x \sin \phi)$	$2.8 \times 10^{-4}$ [240]	$4.3 \times 10^{-5}$	$3.5 \times 10^{-4}$	$1.0 \times 10^{-5}$	—
$x \sin \phi$ from $D^0 \rightarrow K^+ \pi^-$	$13 \times 10^{-4}$ [228]	$3.2 \times 10^{-4}$	$4.6 \times 10^{-4}$	$8.0 \times 10^{-5}$	—
$x \sin \phi$ from multibody decays	—	$(K3\pi) 4.0 \times 10^{-5}$	$(K_S^0 \pi\pi) 1.2 \times 10^{-4}$	$(K3\pi) 8.0 \times 10^{-6}$	—