# Recent experimental results in flavour physics

Marco Gersabeck (The University of Manchester)
on behalf of the LHCb collaboration
including results from other flavour experiments

Portorož 2017, Portorož, 18 April 2017

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# Introduction

Neubert

## Introduction

| | | |
|---|---|---|
| $\sim 3.5\sigma$ | $(g-2)_\mu$ anomaly | |
| $\sim 3.5\sigma$ | non-standard like-sign dimuon charge asymmetry | |
| $\sim 3.5\sigma$ | enhanced $B \to D^{(*)}\tau\nu$ rates | $R_{D^{(*)}}$ |
| $\sim 3.5\sigma$ | suppressed branching ratio of $B_s \to \phi\mu^+\mu^-$ | |
| $\sim 3\sigma$ | tension between inclusive and exclusive determination of $\lvert V_{ub}\rvert$ | |
| $\sim 3\sigma$ | tension between inclusive and exclusive determination of $\lvert V_{cb}\rvert$ | |
| $2-3\sigma$ | anomaly in $B \to K^*\mu^+\mu^-$ angular distributions | $P_5'$ |
| $2-3\sigma$ | SM prediction for $\epsilon'/\epsilon$ below experimental result | |
| $\sim 2.5\sigma$ | lepton flavor non-universality in $B \to K\mu^+\mu^-$ vs. $B \to Ke^+e^-$ | $R_K$ |
| $\sim 2.5\sigma$ | non-zero $h \to \tau\mu$ | |

Wolfgang Altmannshofer (UC) | Theoretical Advances in Flavor Physics | January 14, 2016 | 18 / 34

(Wolfgang Altmannshofer, Aspen Winter Conference on Particle Physics 2016)

M. Neubert: Heavy Flavour Physics (Introductory Talk) 2

Pippa Wells Moriond QCD Experimental Summary 30

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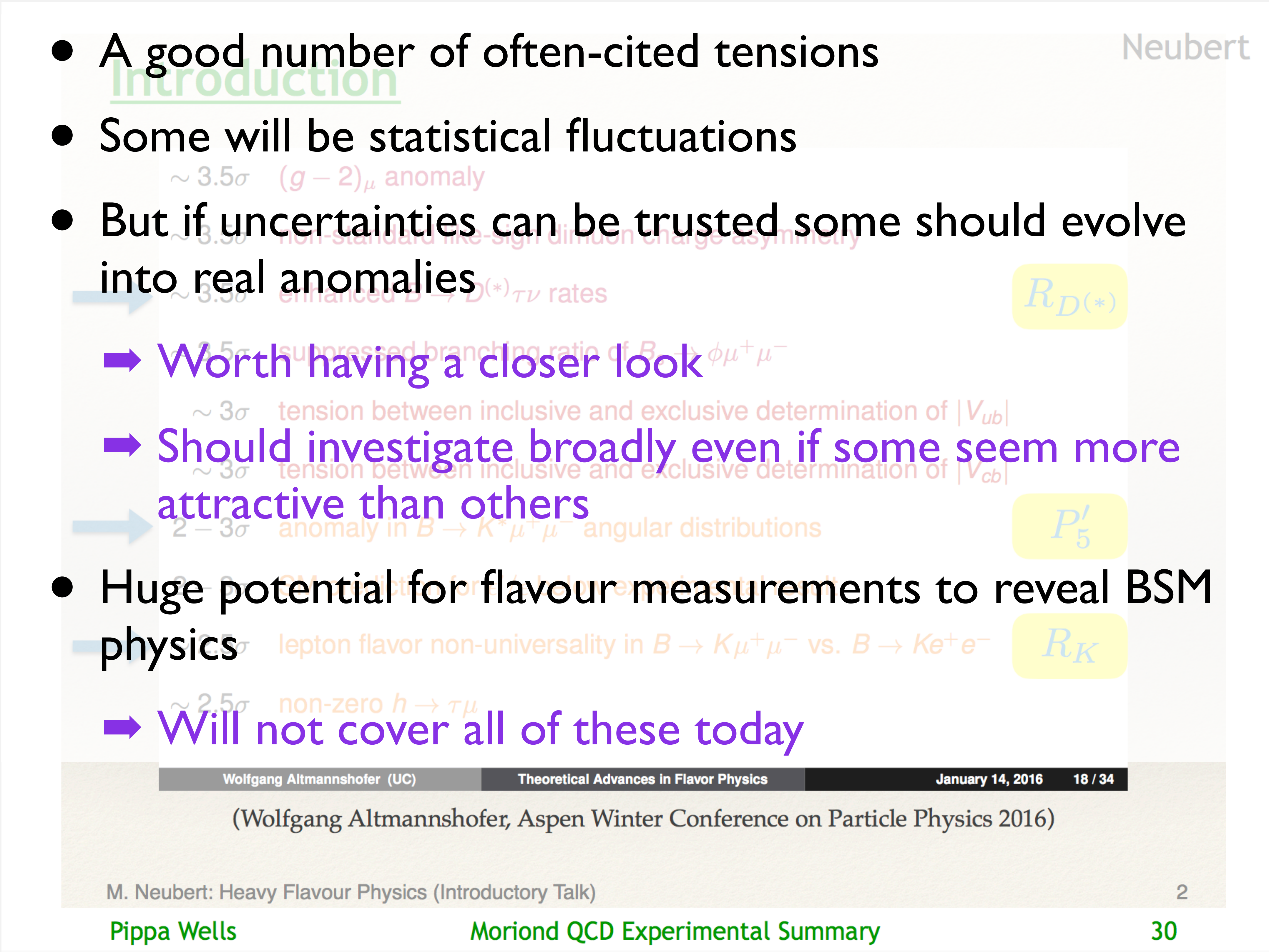
# Introduction

- A good number of often-cited tensions
- Some will be statistical fluctuations
- But if uncertainties can be trusted some should evolve into real anomalies
  - ➡ Worth having a closer look
  - ➡ Should investigate broadly even if some seem more attractive than others
- Huge potential for flavour measurements to reveal BSM physics
  - ➡ Will not cover all of these today

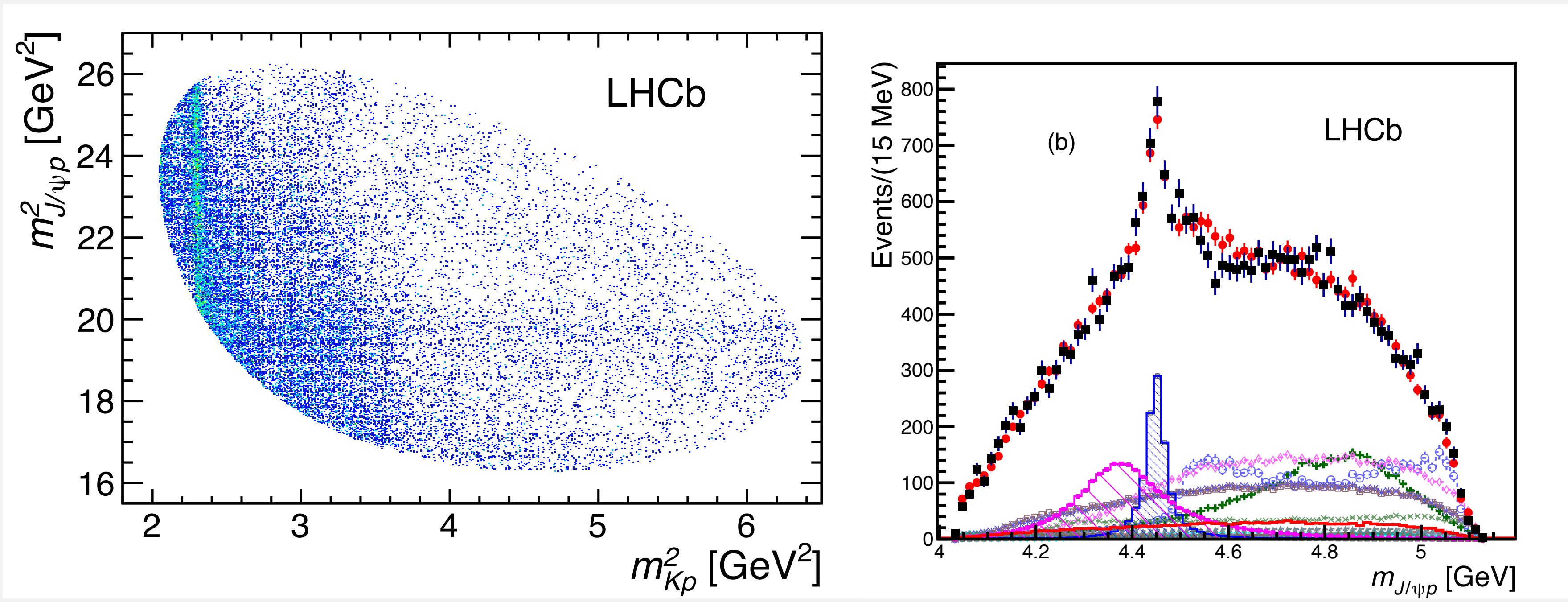


# Spectroscopy

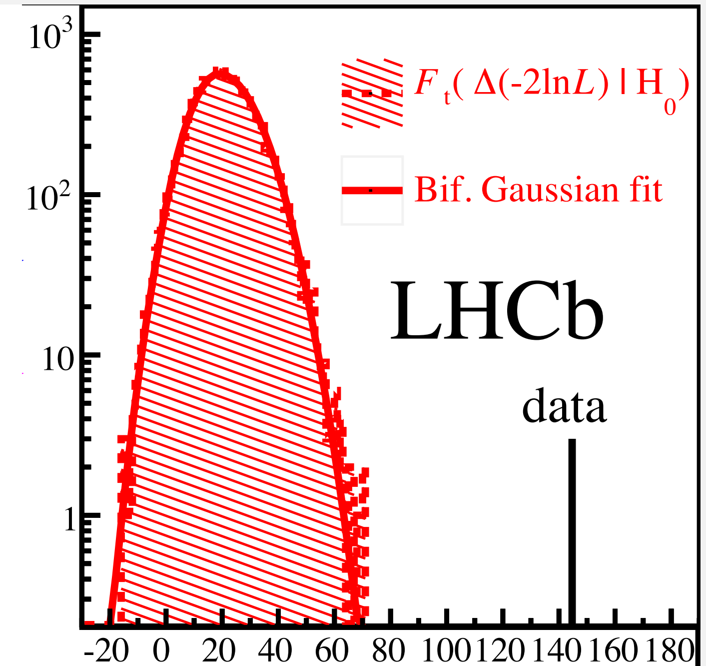
## A brief visit to the world of many states

# Tetraquarks and Pentaquarks

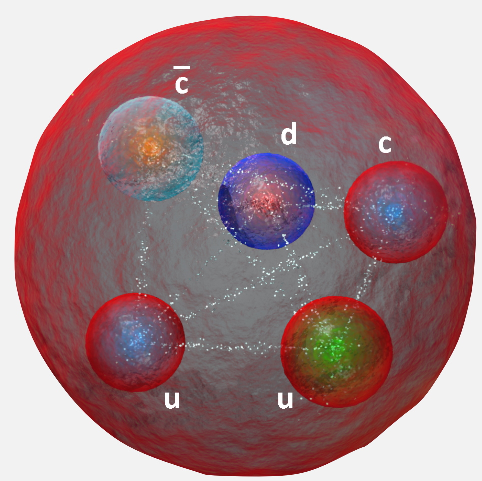
PRL 115 (2015) 072001



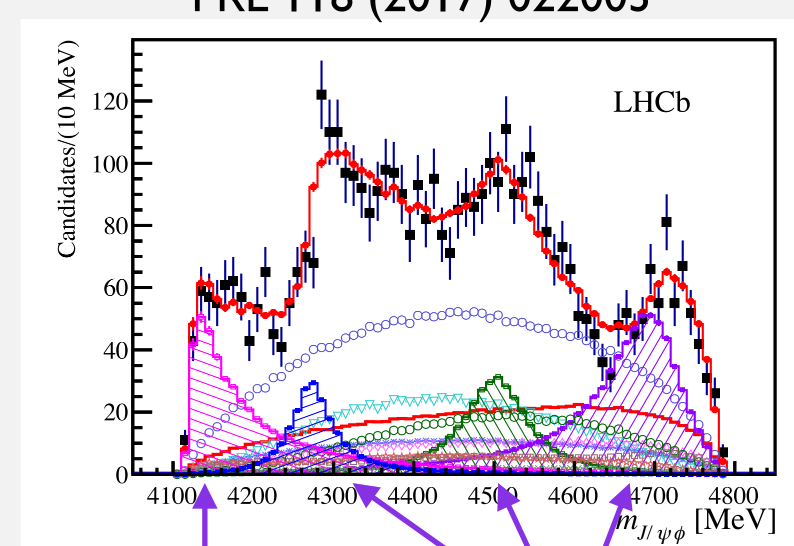

PRL 117 (2016) 082002




- Two pentaquark candidates discovered in 2015 decaying to J/ψp
  - ➡ $P_c(4380)$, $P_c(4450)$
  - ➡ Model-independent confirmation in 2016
- Four tetraquark candidates observed decaying to J/ψϕ
  - ➡ First full amplitude analysis
  - ➡ Three new states plus one known suspect
  - ➡ X(4140), X(4274), X(4500), X(4700)




PRL 118 (2017) 022003

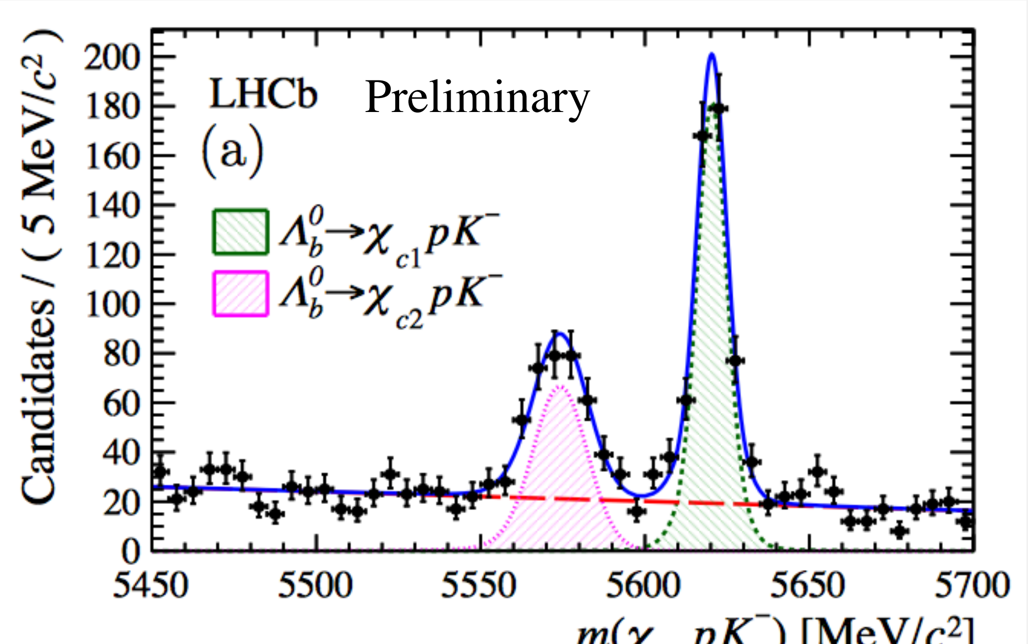



$D_sD_s^*$ rescattering?

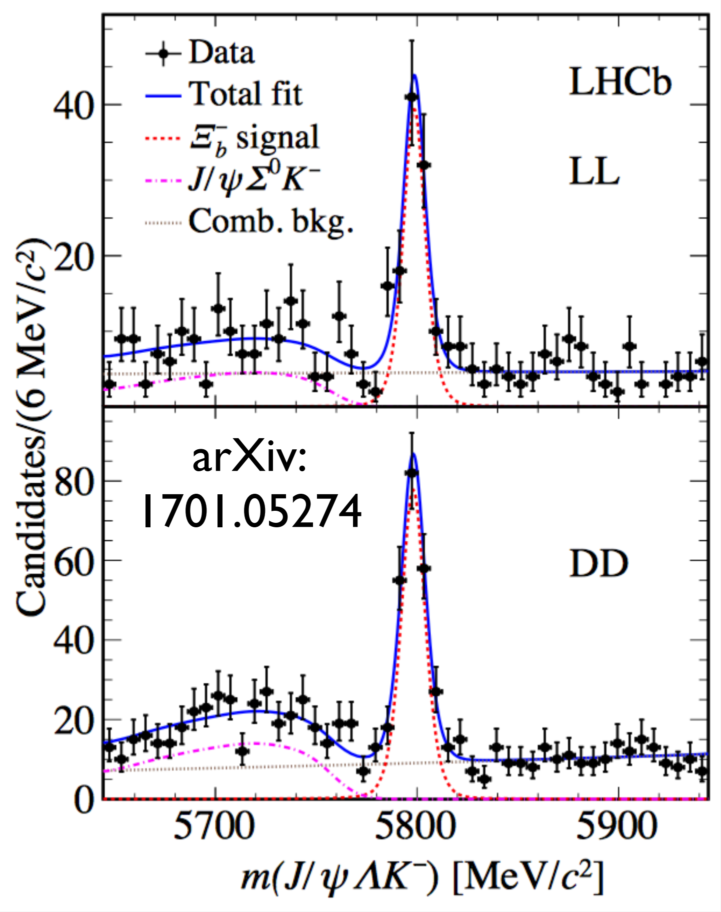
NEW

# Towards further confirmation

- $P_c(4450)$ just above $\chi_{c1}p$ threshold
- First observation of $\Lambda_b \to \chi_{c1}p$ and $\chi_{c2}p$
  ➡ Can be used to test exotic nature of $P_c$
- Strangeness hidden charm pentaquark state predicted to decay into $J/\psi\Lambda$
  ➡ Observed $\Xi_b^- \to J/\psi\Lambda K$ decays
- Phase-space analyses to follow

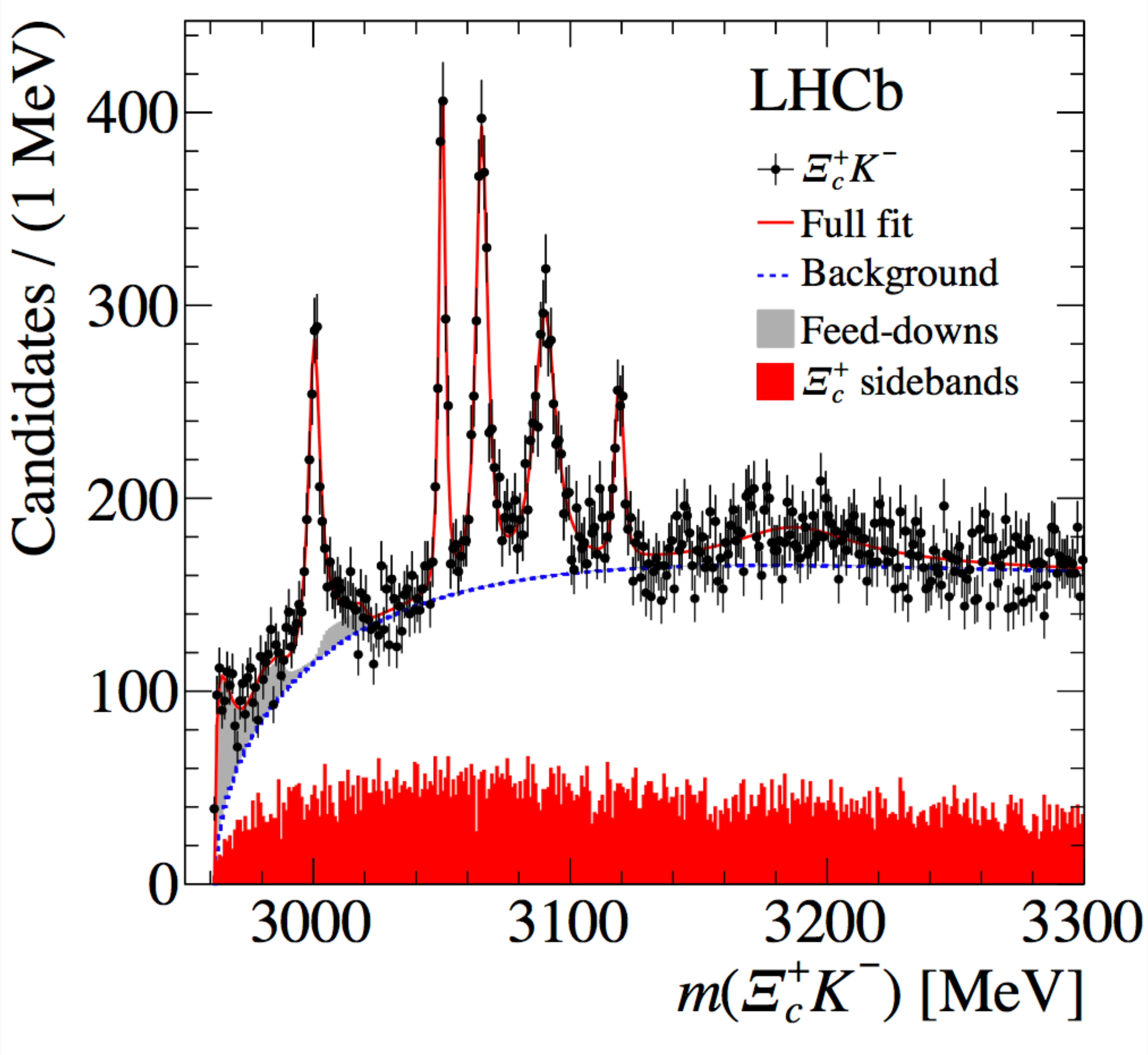


LHCb-PAPER-2017-011



# $\Omega_c$ gets excited

- 5 new narrow states observed in $\Xi_c K$ spectrum
  - ➡ m = 3-3.12 GeV
  - ➡ Γ = 1-10 MeV
  - ➡ New excited $\Omega_c$ states
- Expected feed-down seen and taken into account
- Sidebands and same-sign combinations show no structures



# CP violation

## 3 quark generations or more?

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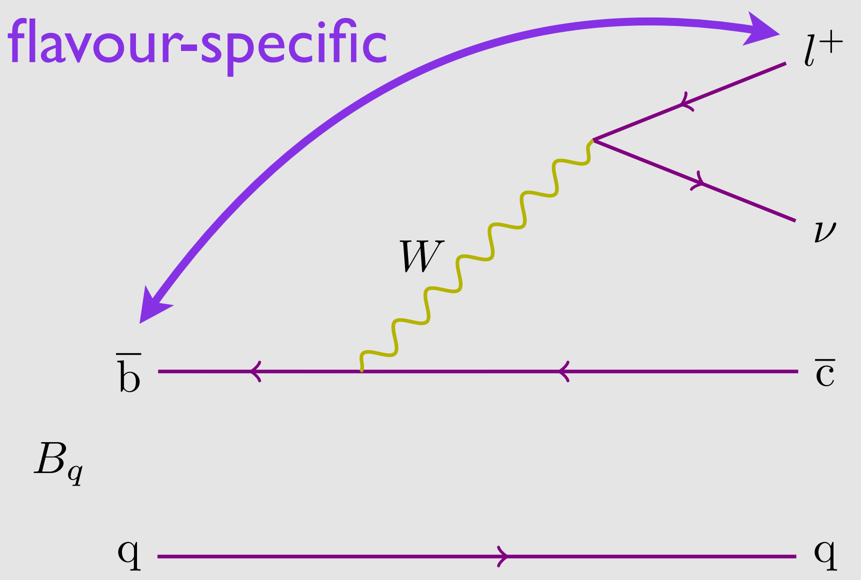
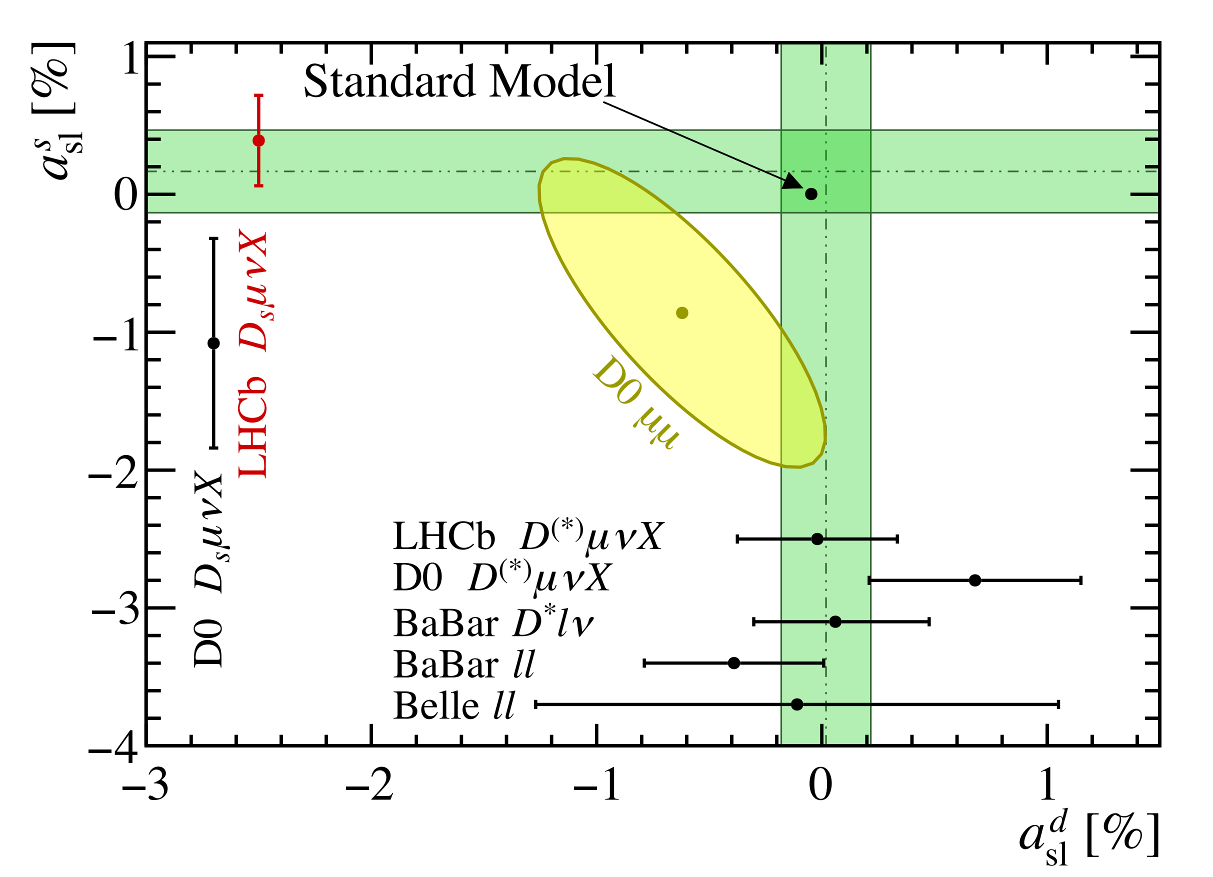
# CP violation in mixing




- Look for $\bar{B} \to l^+$ decays
  - ➡ Forbidden directly, requires $\bar{B} \to B$ oscillation
- Measure asymmetry of $\bar{B} \to l^+$ and $B \to l^-$ rates
  - ➡ CP violation in mixing
- SM expectation far below current sensitivity
- Can measure this separately for $B_d$ and $B_s$ mesons
  - ➡ Separate access to $A_{sl}(B_d)$ & $A_{sl}(B_S)$
- Alternatively look for same-sign lepton pairs and compare $l^+l^+$ with $l^-l^-$
  - ➡ Measures combination of $A_{sl}(B_d)$ & $A_{sl}(B_S)$

# Latest results

- D0 dimuon measurement differs from SM by about 3σ
  - ➡ Difficult to motivate by non-SM physics
- Direct measurements of $a_{sl}(B_d)$ & $a_{sl}(B_S)$ show agreement with SM
- Possible differences in SM contribution to observables?
- LHCb has best single measurement of $a_{sl}(B_d)$ and $a_{sl}(B_s)$
  - ➡ Latest: $a_{sl}(B_s)=(0.39\pm0.26\pm0.20)\%$
    PRL 117 (2016) 061803



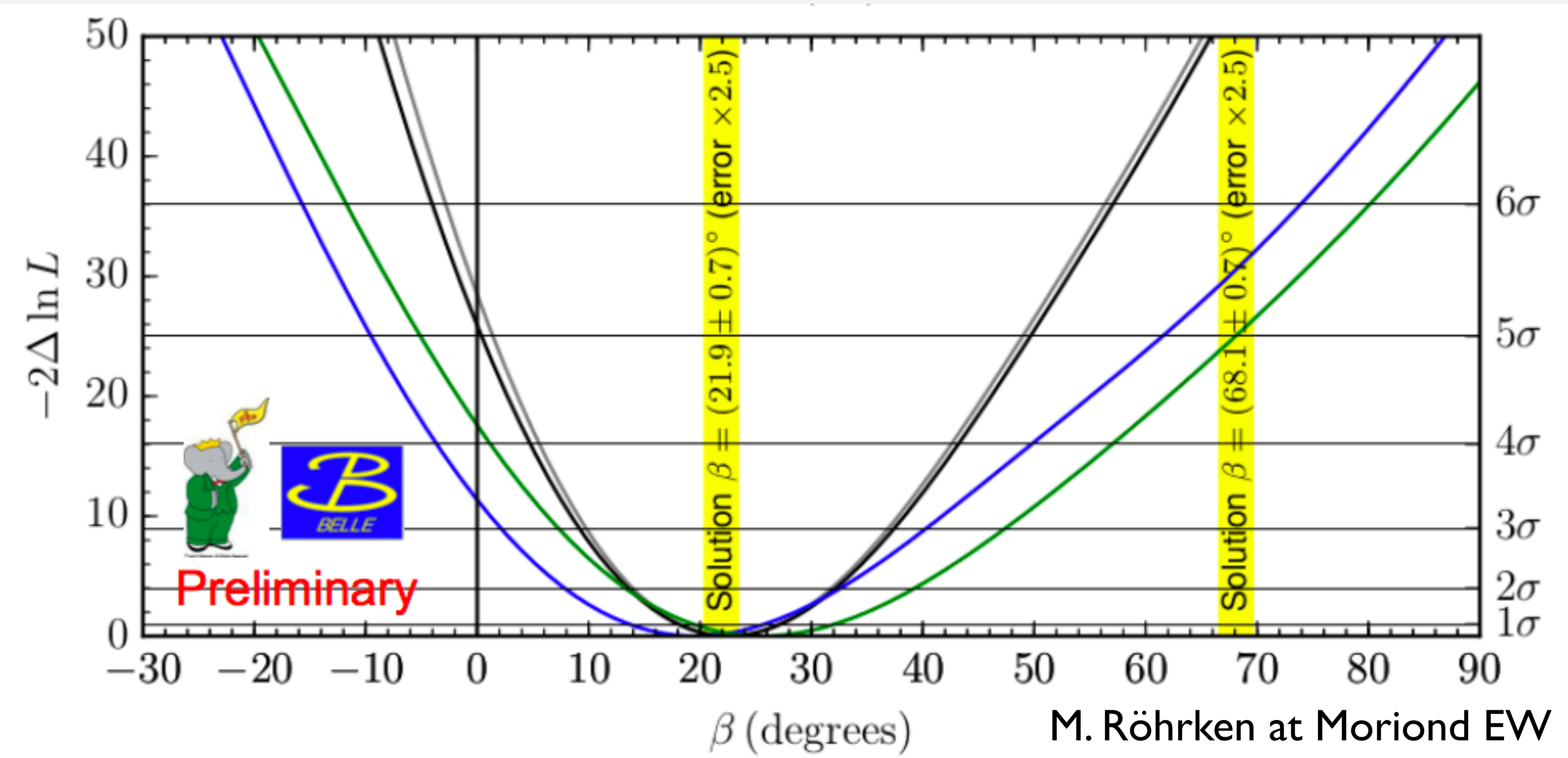

- ATLAS now contributing constraints on potential direct CP violation contributions
  - ➡ Using top decays
  - ➡ No firm conclusion on D0 anomaly yet

| | Data $(10^{-2})$ | | MC $(10^{-2})$ | | Existing limits $(2\sigma)$ $(10^{-2})$ | | SM prediction $(10^{-2})$ | |
|---|---|---|---|---|---|---|---|---|
| $A^{ss}$ | −0.7 | ± 0.8 | 0.05 | ± 0.23 | - | | $< 10^{-2}$ | [19] |
| $A^{os}$ | 0.4 | ± 0.5 | −0.03 | ± 0.13 | - | | $< 10^{-2}$ | [19] |
| $A^{b}_{mix}$ | −2.5 | ± 2.8 | 0.2 | ± 0.7 | < 0.1 | [95] | $< 10^{-3}$ | [96] [95] |
| $A^{b\ell}_{dir}$ | 0.5 | ± 0.5 | −0.03 | ± 0.14 | < 1.2 | [94] | $< 10^{-5}$ | [19] [94] |
| $A^{c\ell}_{dir}$ | 1.0 | ± 1.0 | −0.06 | ± 0.25 | < 6.0 | [94] | $< 10^{-9}$ | [19] [94] |
| $A^{bc}_{dir}$ | −1.0 | ± 1.1 | 0.07 | ± 0.29 | - | | $< 10^{-7}$ | [97] |

JHEP 02 (2017) 071

# News on β

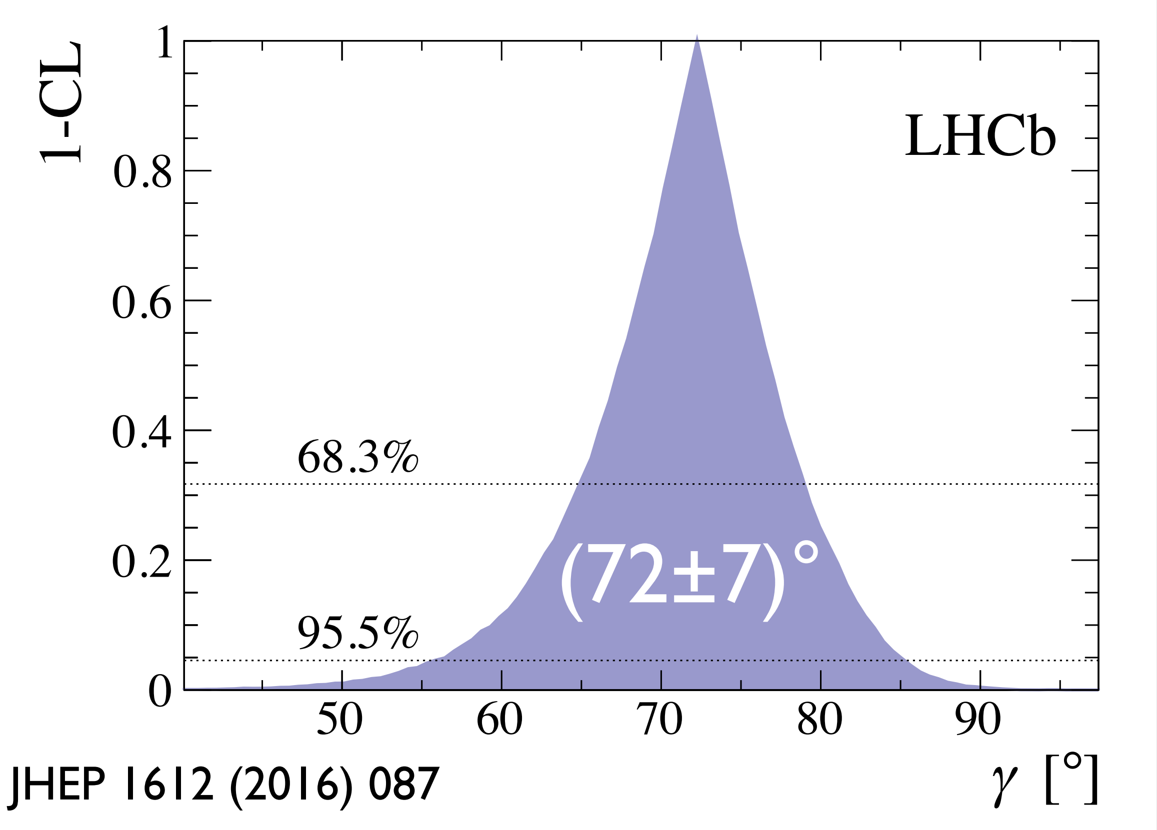
- Combined BaBar and Belle analysis (1.1ab$^{-1}$)
- Time-dependent analysis of
  - ➡ $B^0 \to D^{(*)0} h^0$ with $D^0 \to K_S \pi\pi$ decays
- First evidence for cos(2β)>0
- Excludes second solution of unitarity triangle fit




M. Röhrken at Moriond EW

# Improving γ precision

- Combining LHCb measurements of $B_{(s)} \to DK^{(*)}$ decays
- BaBar average*:
  ➡ (70±18)°
- Belle average*:
  ➡ (73±14)°
- LHCb improves by factor 2
- All based on tree decays
  ➡ SM measurements
  ➡ Access to beyond SM particles through loops in γ measurements using B→hh(h) decays

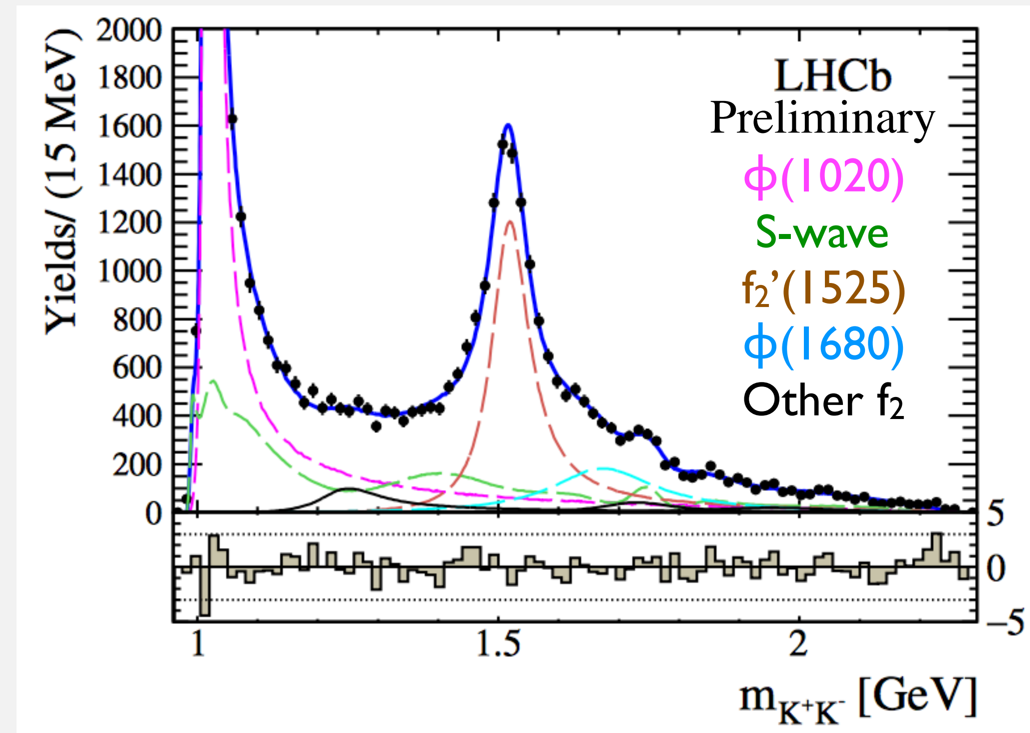


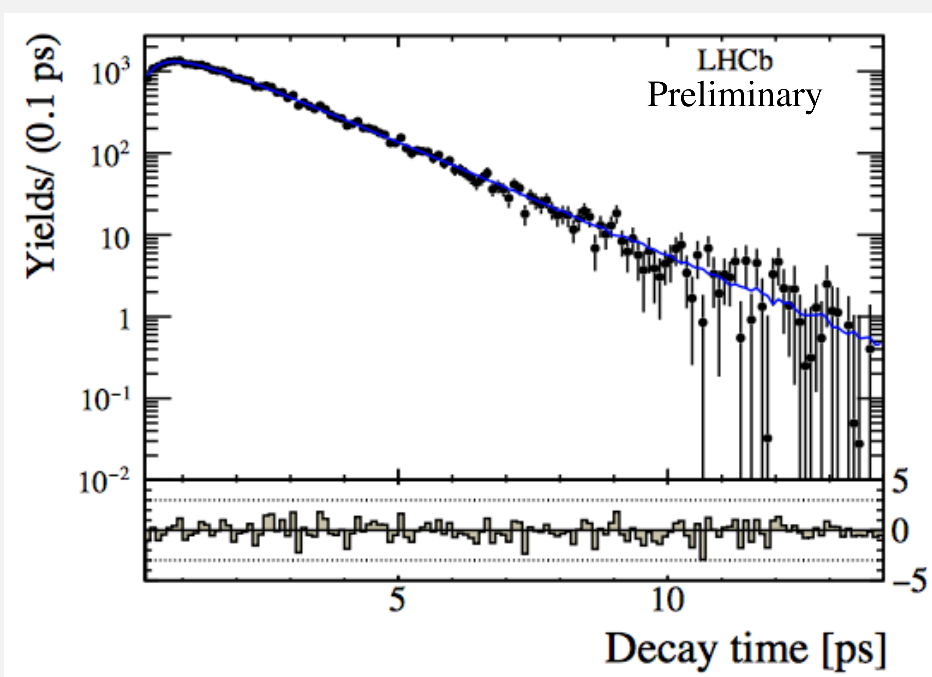

*CKMFitter Summer 2014

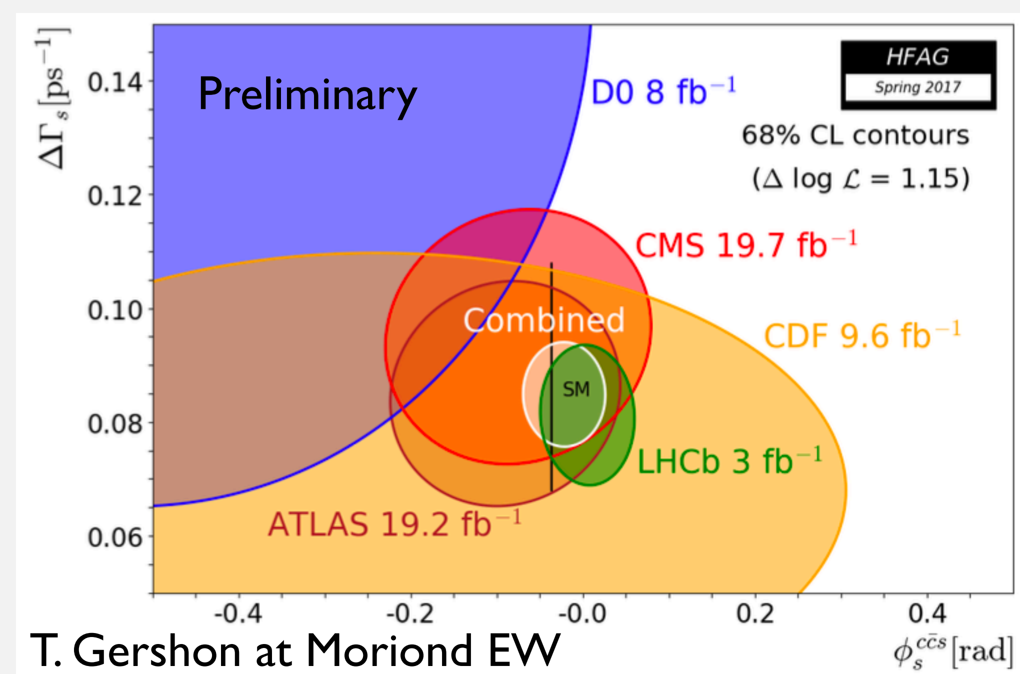
# CP violating phase $\phi_s$

- First measurement in $B_s \to J/\psi KK$ with $m_{KK}$ above $\phi$ resonance
- Preliminary results:

$$\phi_s = 119 \pm 107 \pm 34\,\mathrm{mrad}$$



Nature Physics 13 (2017) 391

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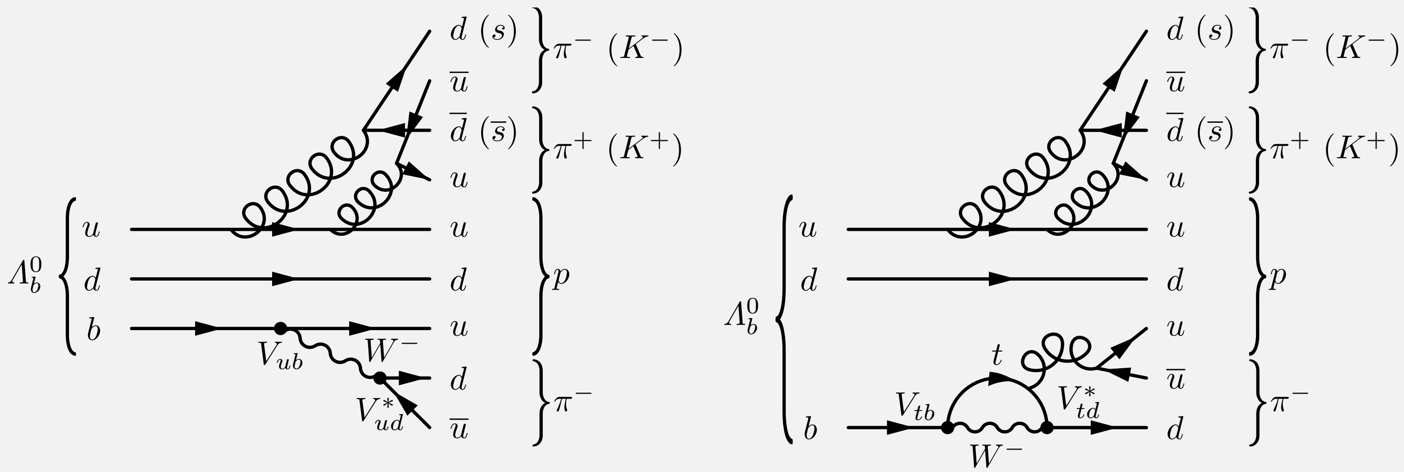
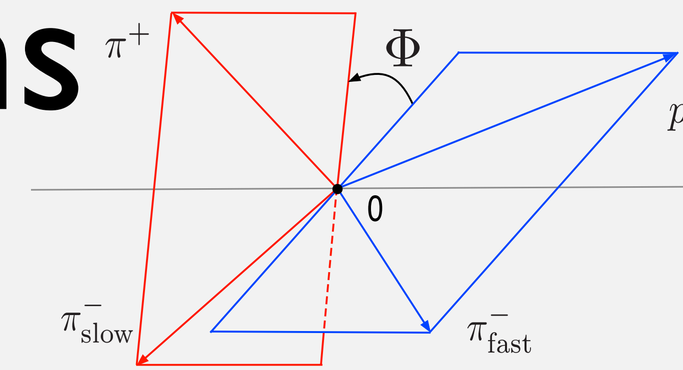
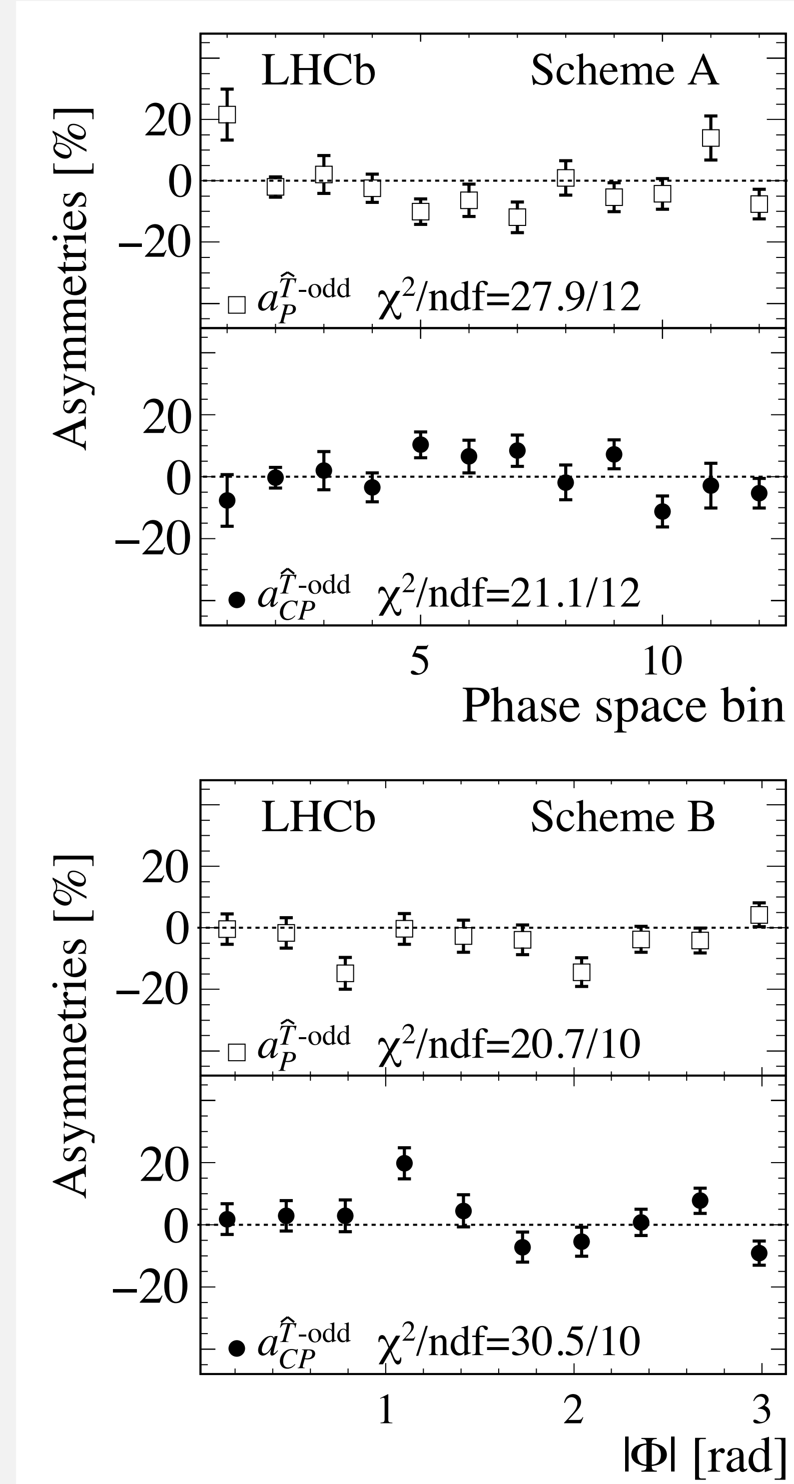
# CP violation in Baryons




- CP violation has never been measured in baryons
- Study local triple-product asymmetries
  - ➡ in bins of phase space
  - ➡ in bins of decay-plane angle
- Triple-products are robust against systematic uncertainties
- Angular bins for $\Lambda_b \rightarrow p\pi^-\pi^+\pi^-$ show 3.3σ deviation from no-CPV hypothesis
- Weaker signals in phase-space binning and smaller $\Lambda_b \rightarrow p\pi^-K^+K^-$ sample



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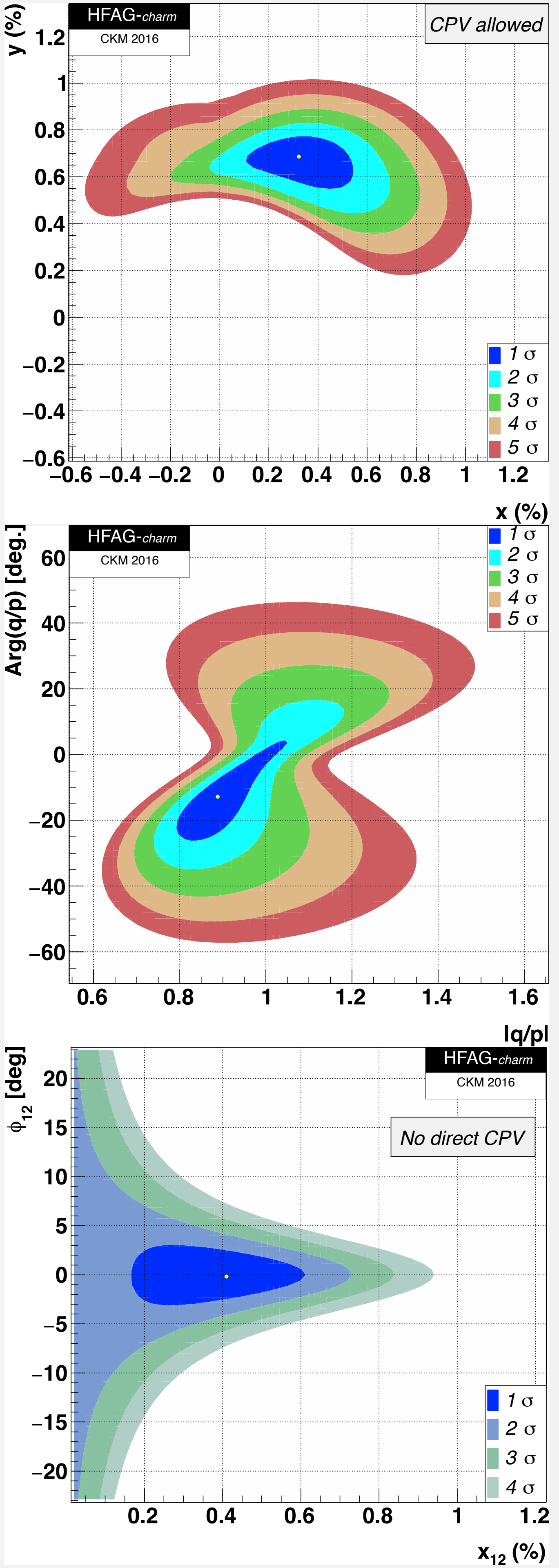
# CPV in charm

- Mass difference of eigenstates still unknown
- No sign of indirect CPV
  - ➡ How long will super-weak constraint remain valid?
  - ➡ $A_\Gamma$ now constraint to $3\times10^{-4}$ arXiv:1702.06490
- Some low p-values in tests for CPV in multi-body ($D^0\rightarrow4\pi$) decays arXiv:1612.03207
  - ➡ Too early to make a claim



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# Rare decays

Plenty to learn from the not so plentiful

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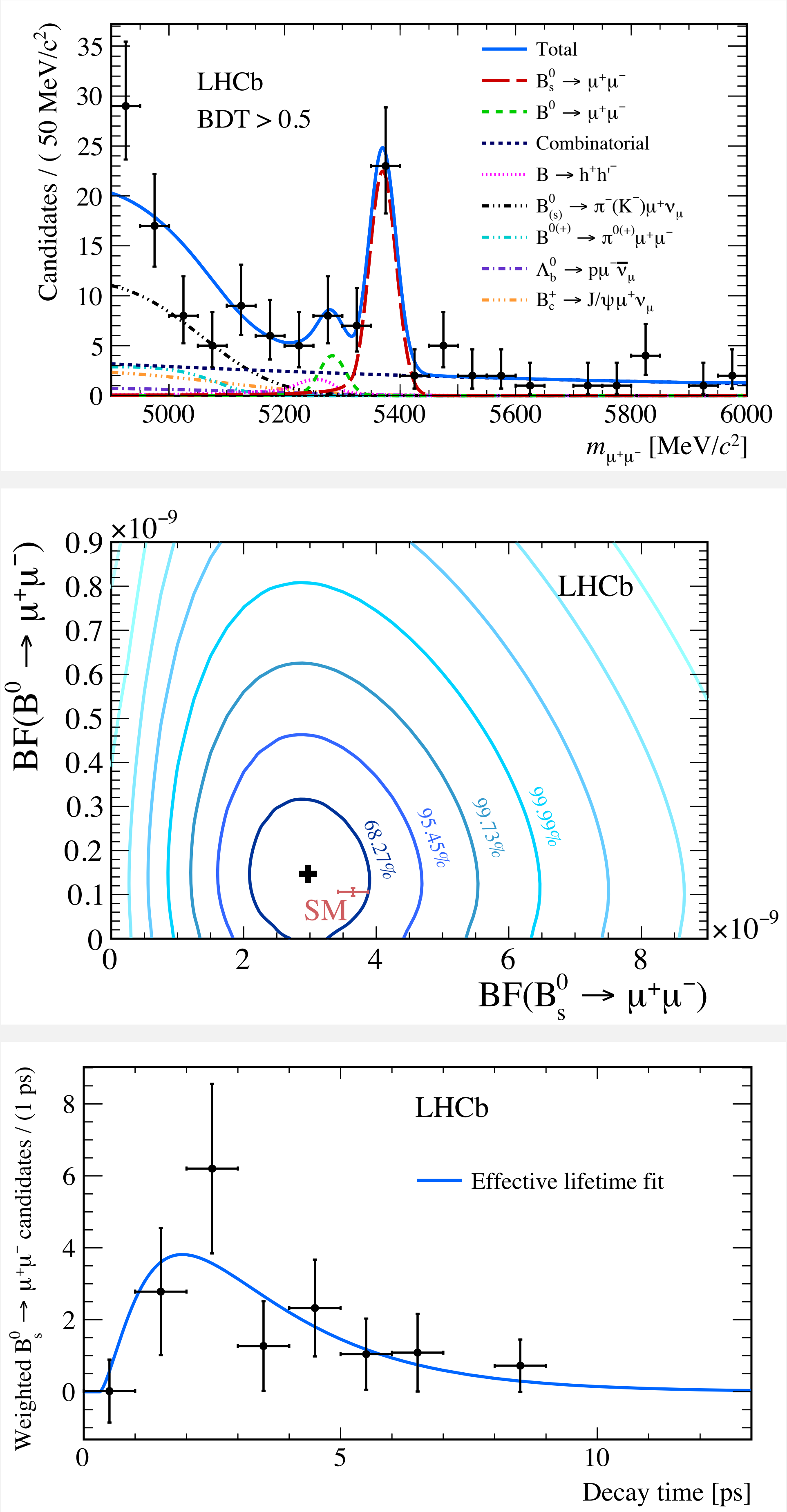
# $B^0 \rightarrow \mu\mu$

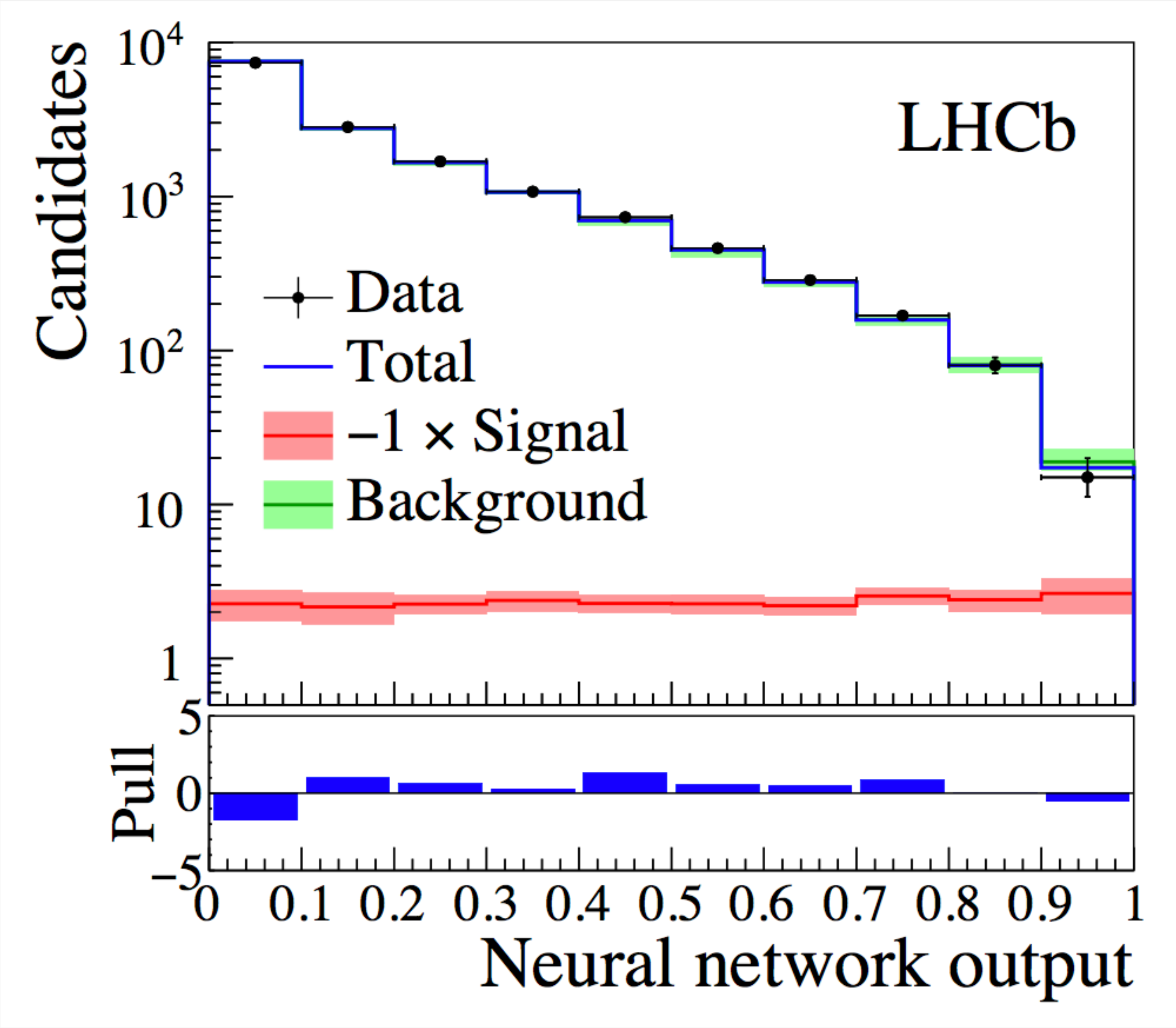
- LHCb update with Run 2 data
- First single-experiment observation of $B_s \rightarrow \mu\mu$ (7.8σ)
- No significant signal for $B_d \rightarrow \mu\mu$ (1.6σ)
- SM looks very healthy here
- First measurement of effective lifetime

➡ $\tau(B_s \rightarrow \mu^+\mu^-) = 2.04 \pm 0.44 \pm 0.05$ps



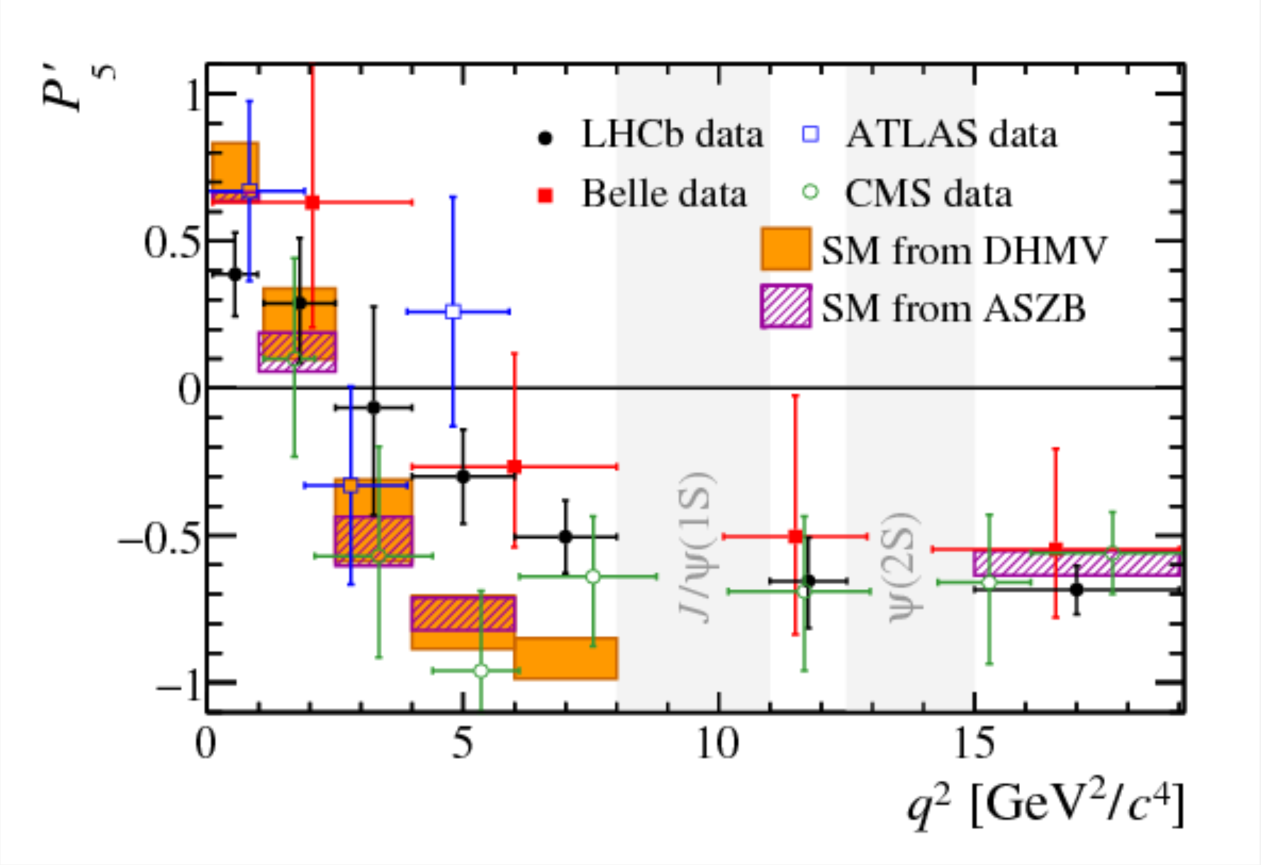
# $B_s \to \tau\tau$

- First direct limit on $B_s$ decay
  - ➡ $\mathcal{B}(B_s \to \tau^+\tau^-) < 6.8\times10^{-3}$
- World best limit on $B_d$ decay
  - ➡ $\mathcal{B}(B_d \to \tau^+\tau^-) < 2.1\times10^{-3}$
- Both at 95% CL



# K*μμ and friends

- LHC analyses based on full Run 1 data
  - ➡ Awaiting Run 2 updates
- LHCb performs full angular analysis
- Belle, ATLAS and CMS use angular folding, differences in observables, background treatment and control modes




LHCb: JHEP 02 (2016) 104
Belle: BELLE-CONF-1603
ATLAS: ATLAS-CONF-2017-023
CMS: CMS-PAS-BPH-15-008

DHMV: JHEP 12(2014)125
ASZB: EPJC 75 (2015) 382

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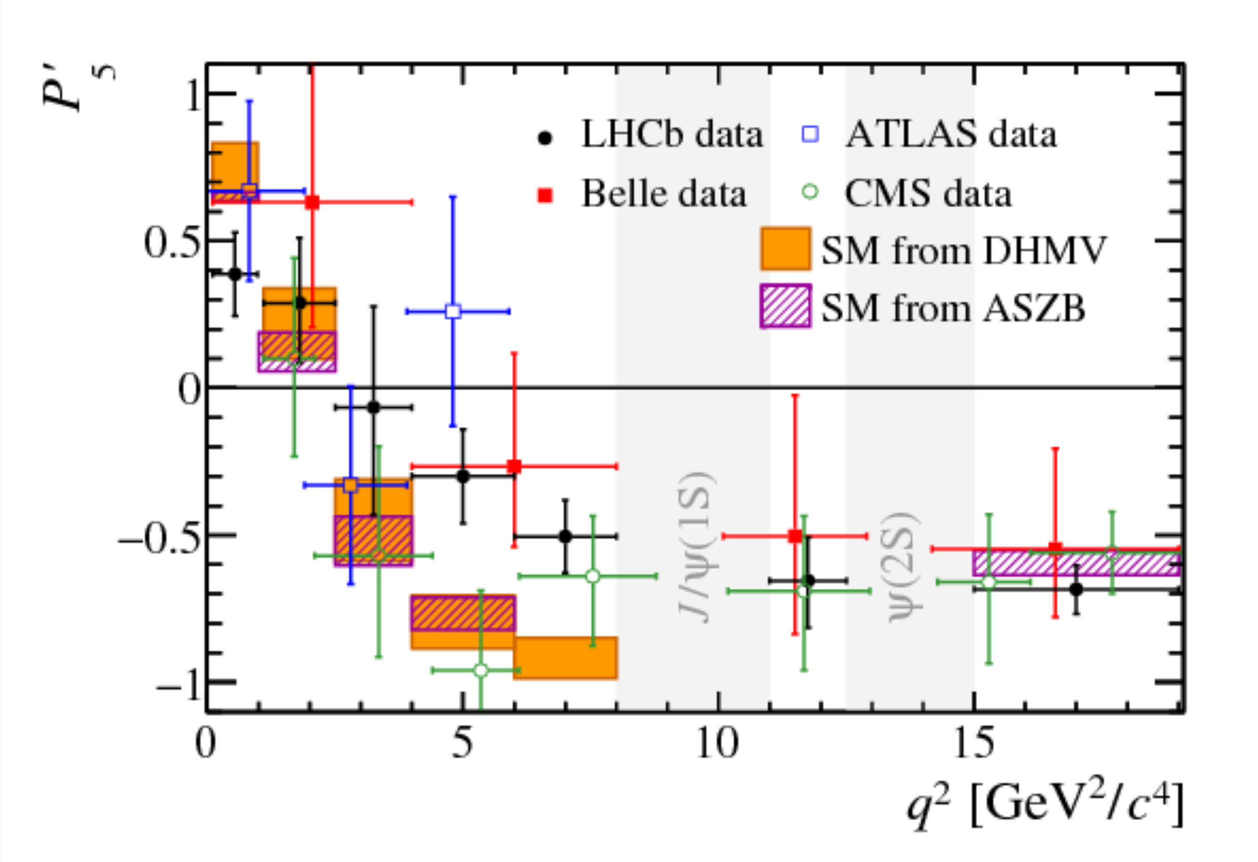


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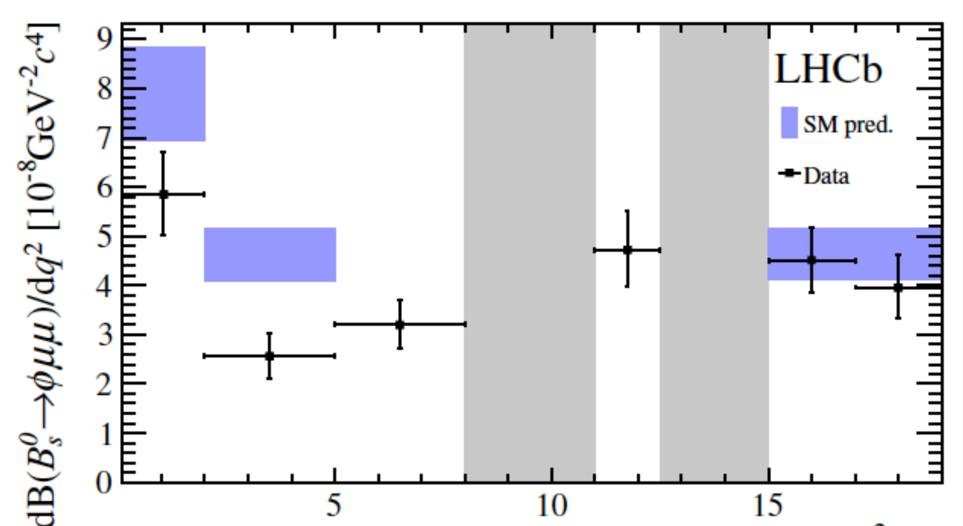
DHMV: JHEP 12(2014)125
ASZB: EPJC 75 (2015) 382

Also investigating related $b\to sll$ channels

e.g. slight tension in $BF(B_s\to\phi\mu\mu)$




JHEP 09 (2015) 179

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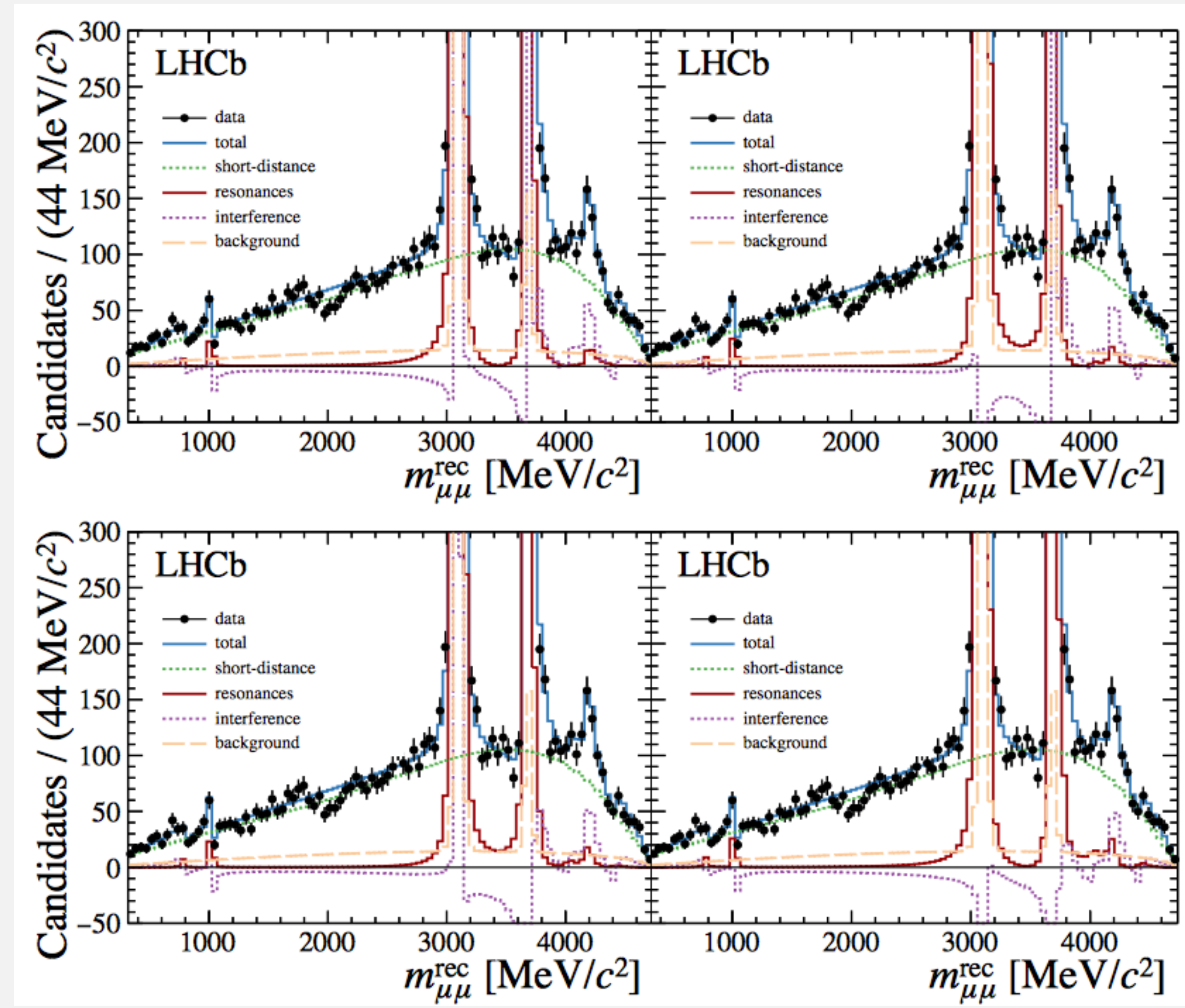
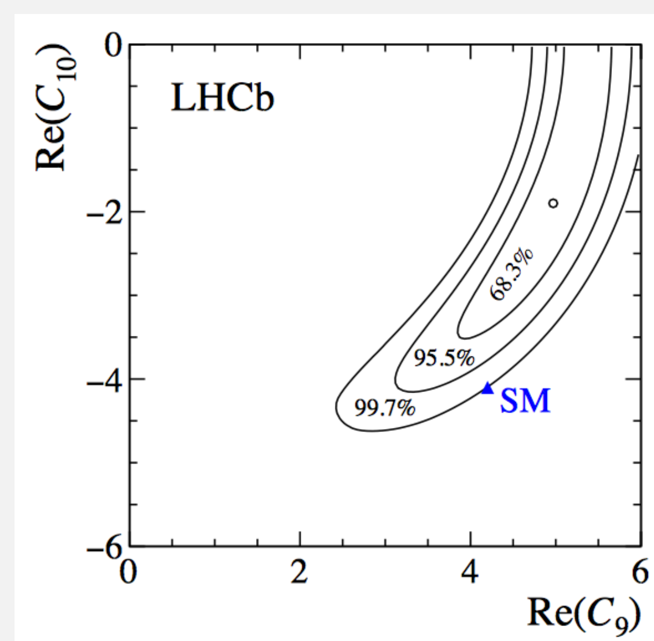
# more K*μμ friends

- Fits with different phase hypotheses for long-distance contributions
- Minimal influence on short-distance branching fraction
  - ➡ Found to be below SM
  - ➡ Improved modelling shows no significant change w.r.t. previous analysis of these data
- Scan of Wilson coefficients disfavours SM solution
- Analyses of other channels underway
  - ➡ More complex if hadron not pseudo-scalar




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

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# Lepton flavour universality

## A basic principle under attack

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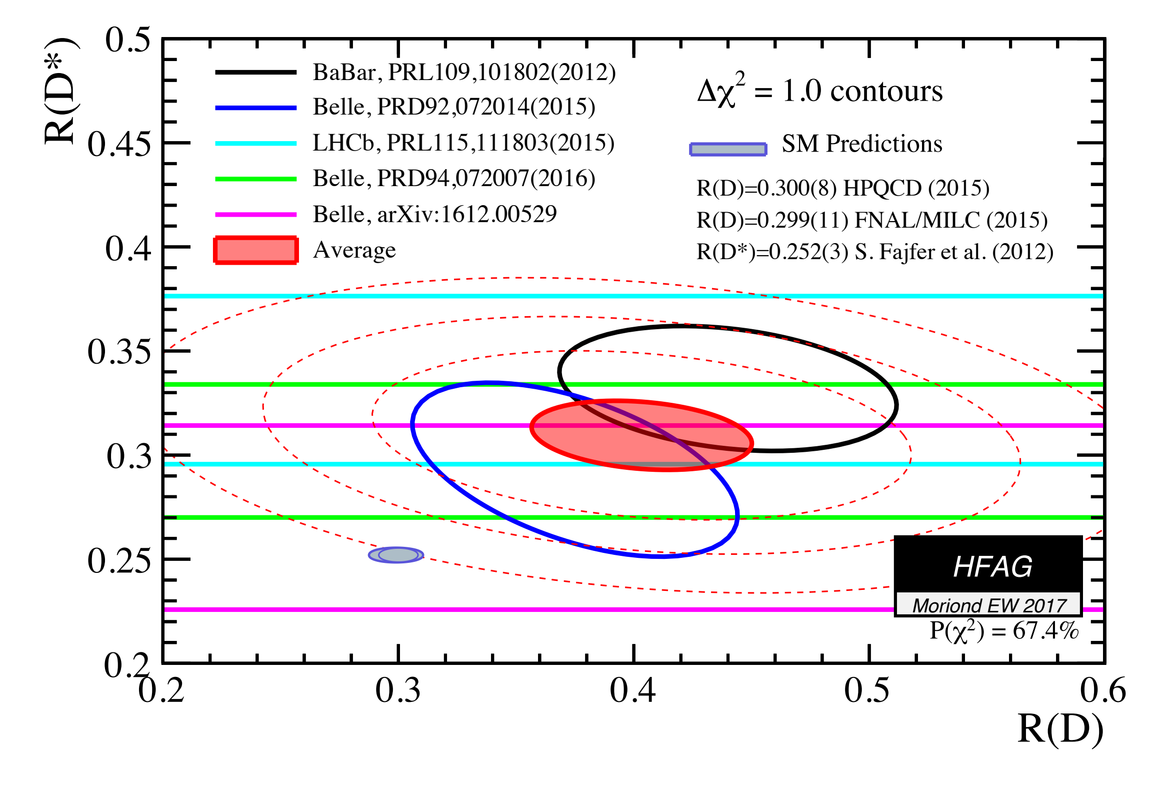
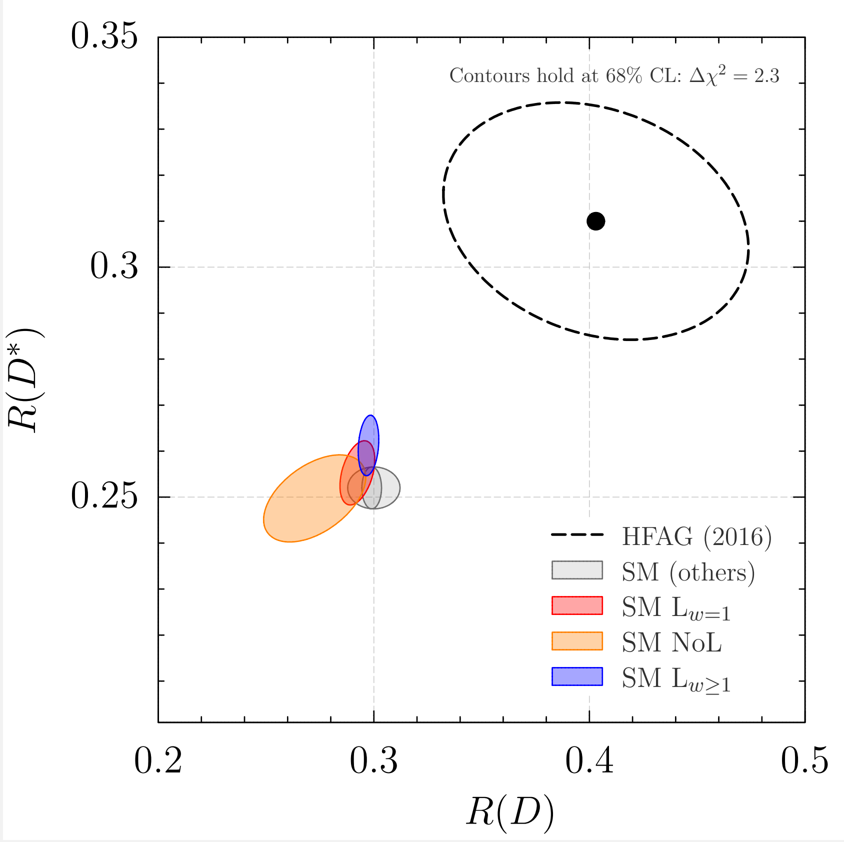
# Lines of attack

- Tree-level processes
  - ➡ $b \to cl\nu$: R(D), R(D$^*$), … in beauty
  - ➡ $c \to dl\nu$: R(K), R(K$^*$), … in charm
- Penguin/FCNC processes
  - ➡ $b \to d/sll$: R(K), R(K$^*$), … in beauty
  - ➡ Charm FCNC remain to be observed

# R(D), R(D*), …

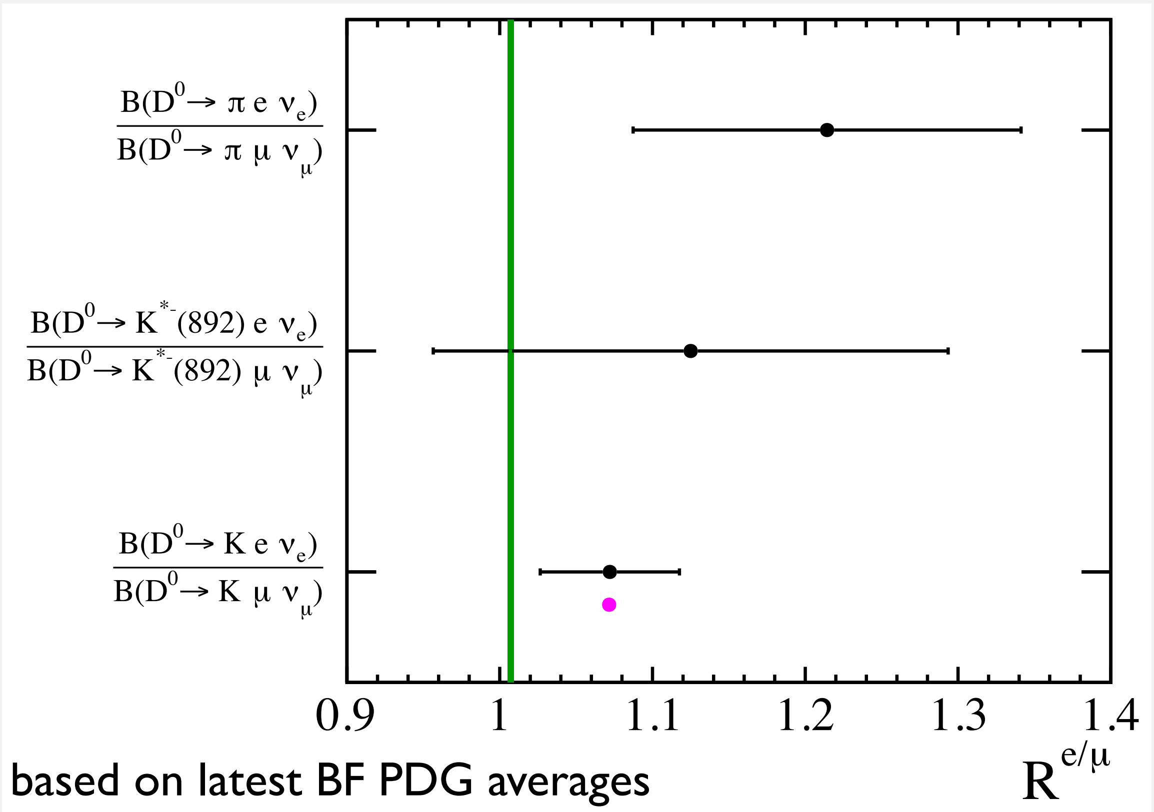
- SM disfavoured by 3.9σ
- New Belle measurement on R(D*)
- Many related measurements in the making
  - ➡ R(J/psi), R(D**), baryonic
- Form factors show no strong impact on discrepancy with SM
  - ➡ Bernlochner, Ligeti, Papucci, Robinson, 1703.05330
- Plenty of room for BSM

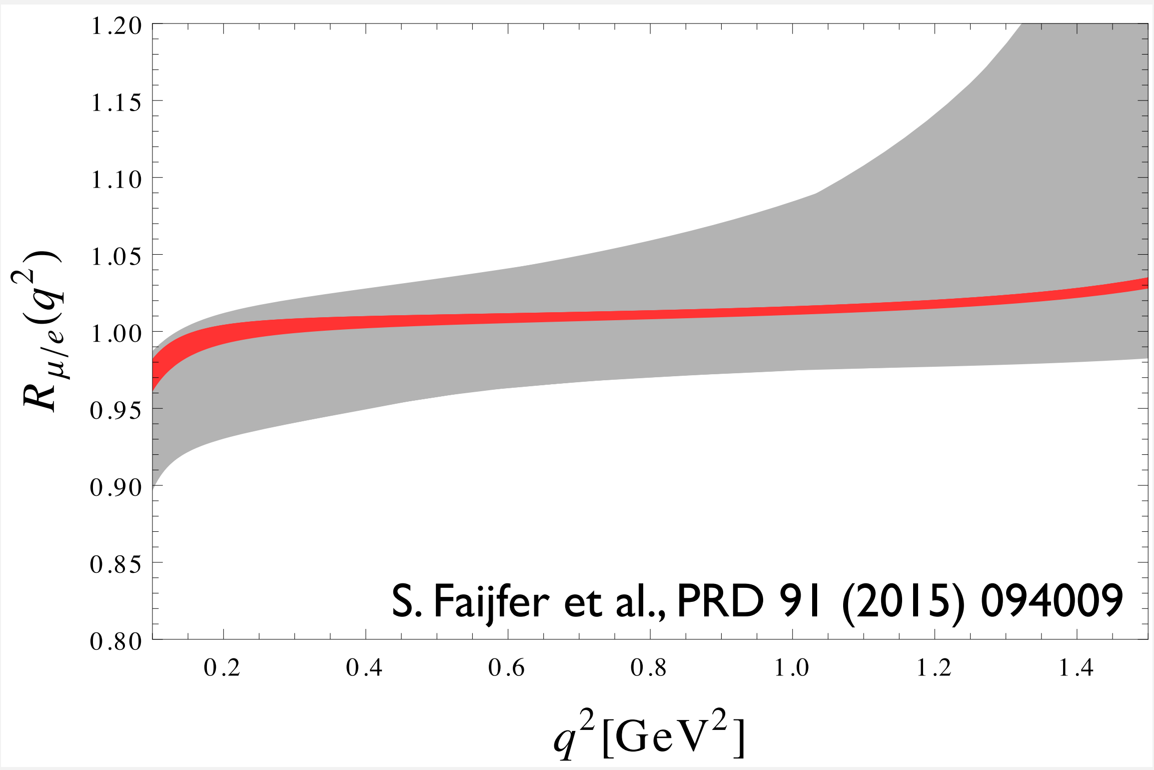


# LU tests in charm

- So far only measurements of branching fractions
  - ➡ All ratios above unity
- Direct measurement of ratio can exploit cancellation of uncertainties
- Further insight through $q^2$-dependent measurement
- To what degree will this be limited by knowledge of form factors?



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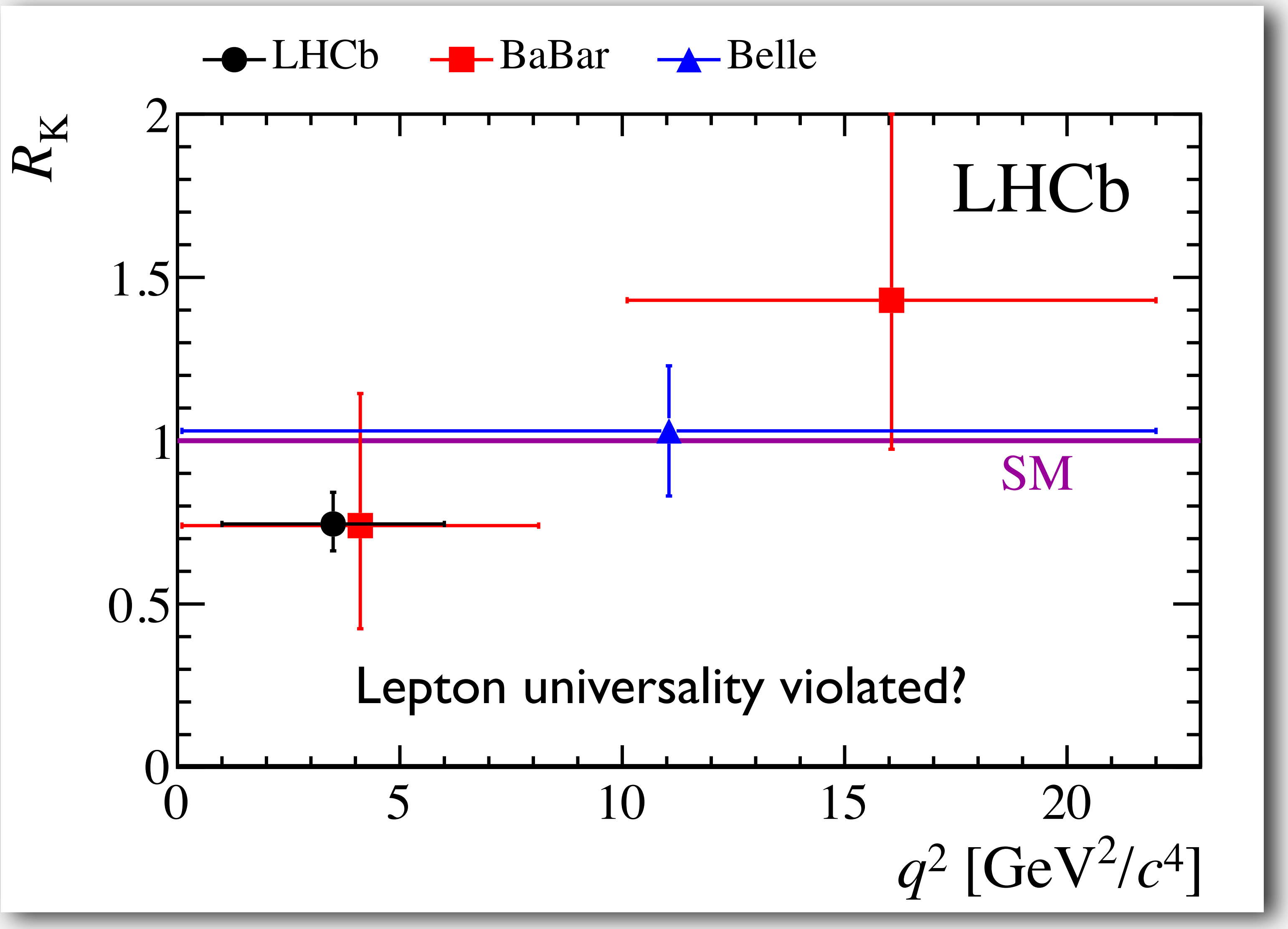
# R(K)

- Moderate tension with SM
  - ➡ LHCb Run I result
- Would be clear theoretical signature
- Updates eagerly awaited…



LHCb-PAPER-2017-013

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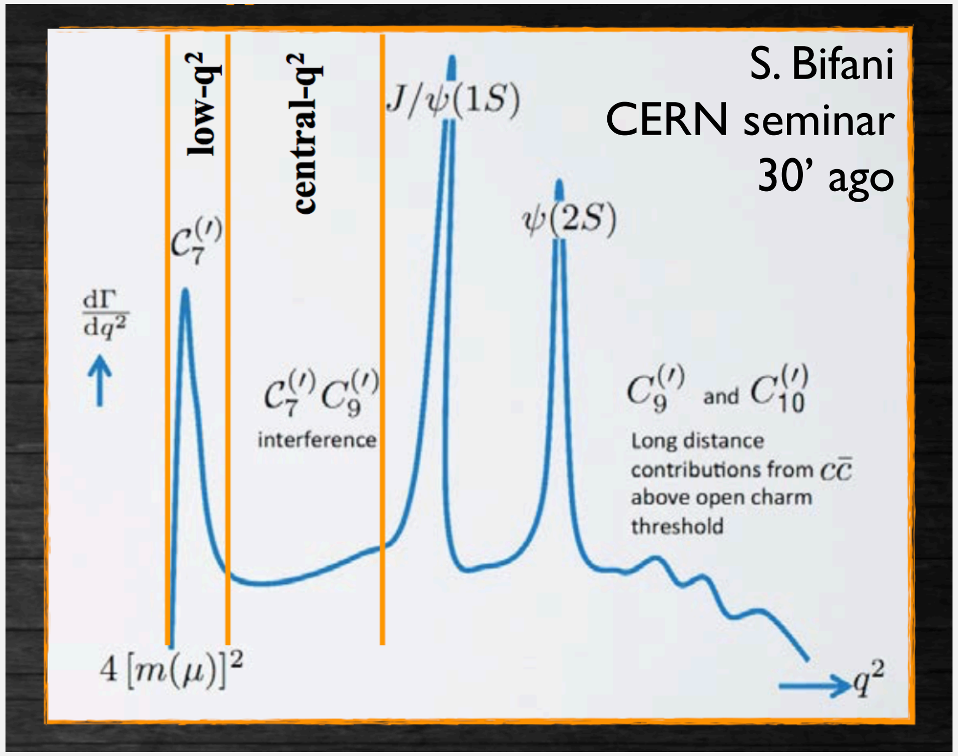
# R(K*)

NEW

- Measuring double ratio

$$\mathcal{R}_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}.$$

- Measuring in two bins of $q^2$
  - ➡ Low: 0.045-1.1, central: 1.1-6 GeV/$c^2$
- Using full Run I data
- Veto mis-ID and partially reconstructed background
- Fits separated by trigger three categories for electron mode
  - ➡ Results in good agreement
- Main systematics due to simulation corrections and residual backgrounds (for central $q^2$ bin)
- Cross-checks with various control channels



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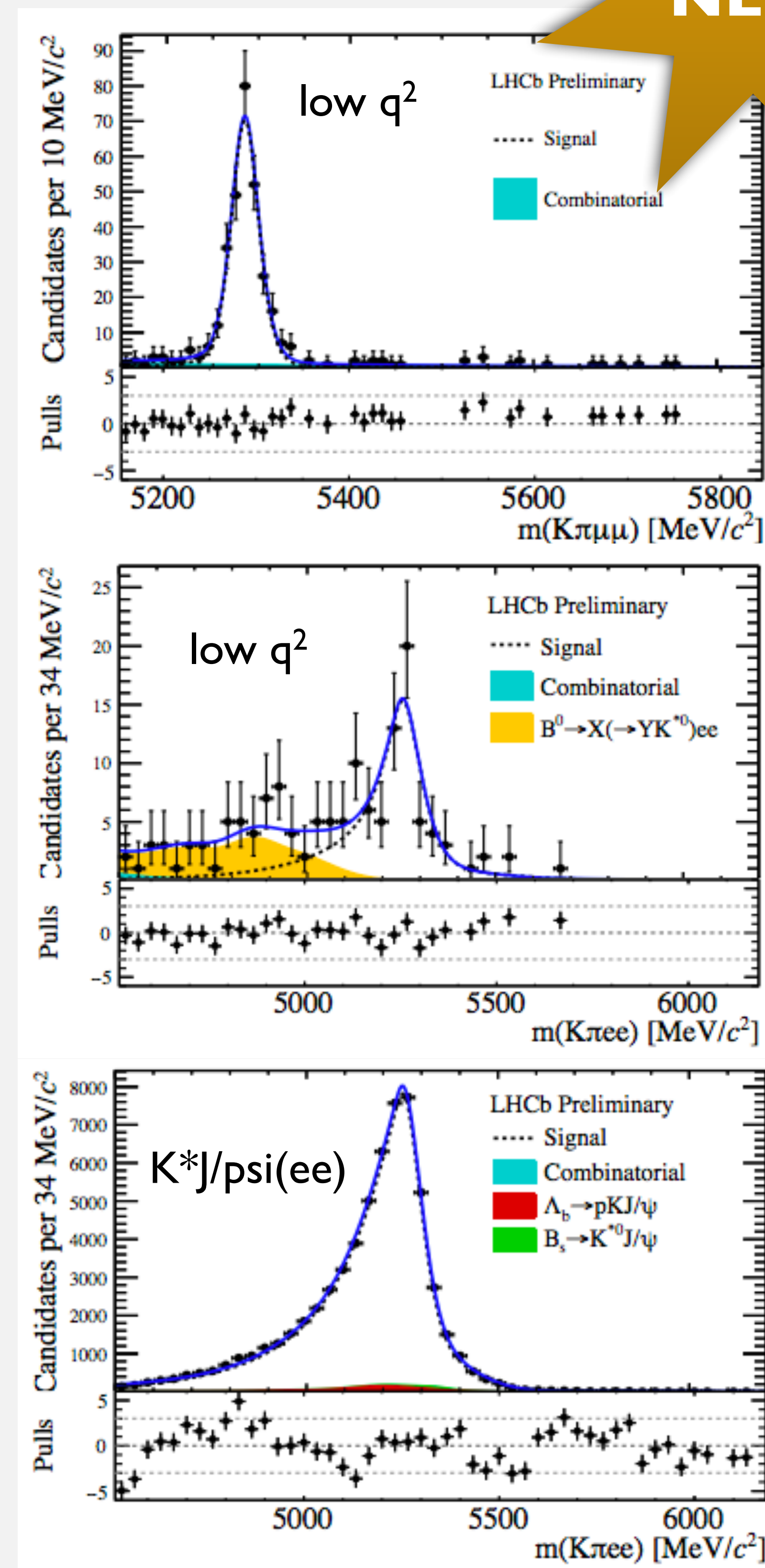

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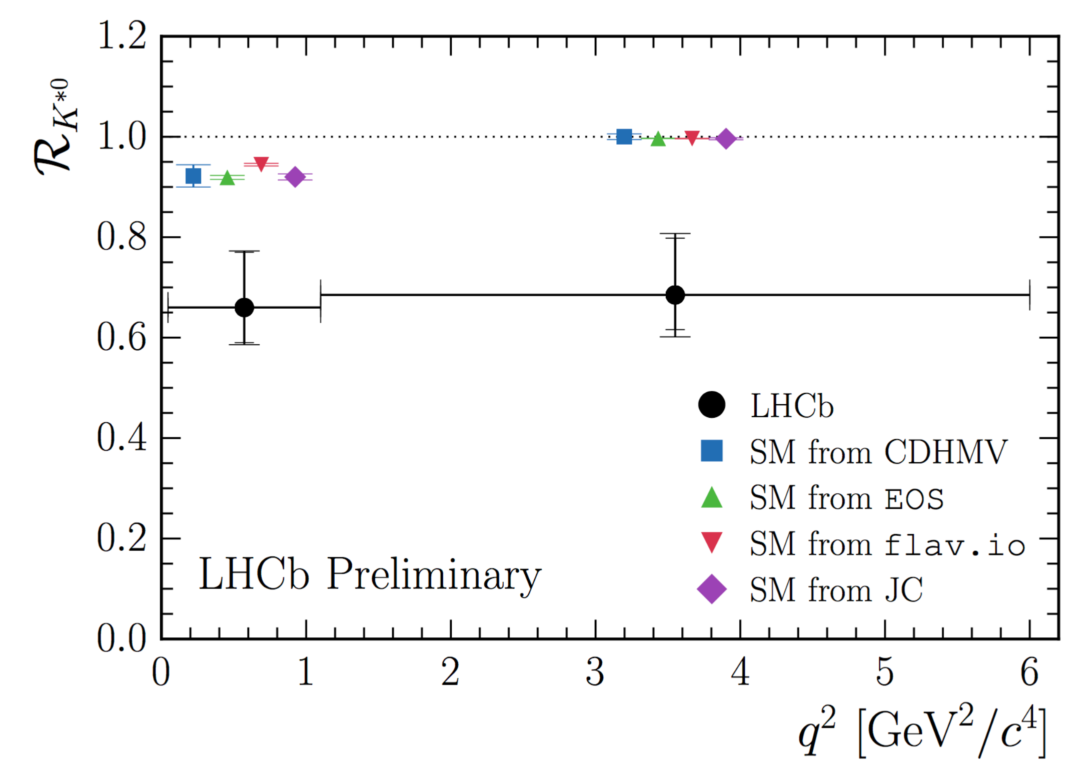
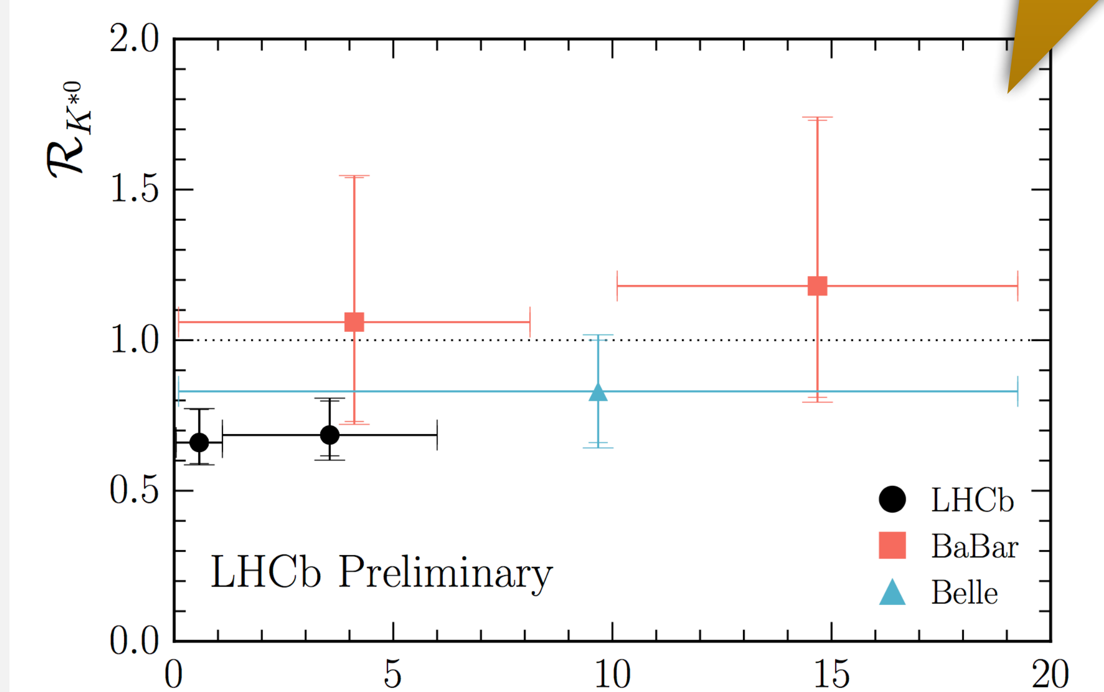
# R(K*)

NEW




- PRD 86 (2012) 032012
- PRL 103 (2009) 171801

- Preliminary results for R(K*)

| | low-$q^2$ | central-$q^2$ |
|---|---|---|
| $\mathcal{R}_{K^{*0}}$ | $0.660\ ^{+\ 0.110}_{-\ 0.070} \pm 0.024$ | $0.685\ ^{+\ 0.113}_{-\ 0.069} \pm 0.047$ |
| 95% CL | 0.517–0.891 | 0.530–0.935 |
| 99.7% CL | 0.454–1.042 | 0.462–1.100 |

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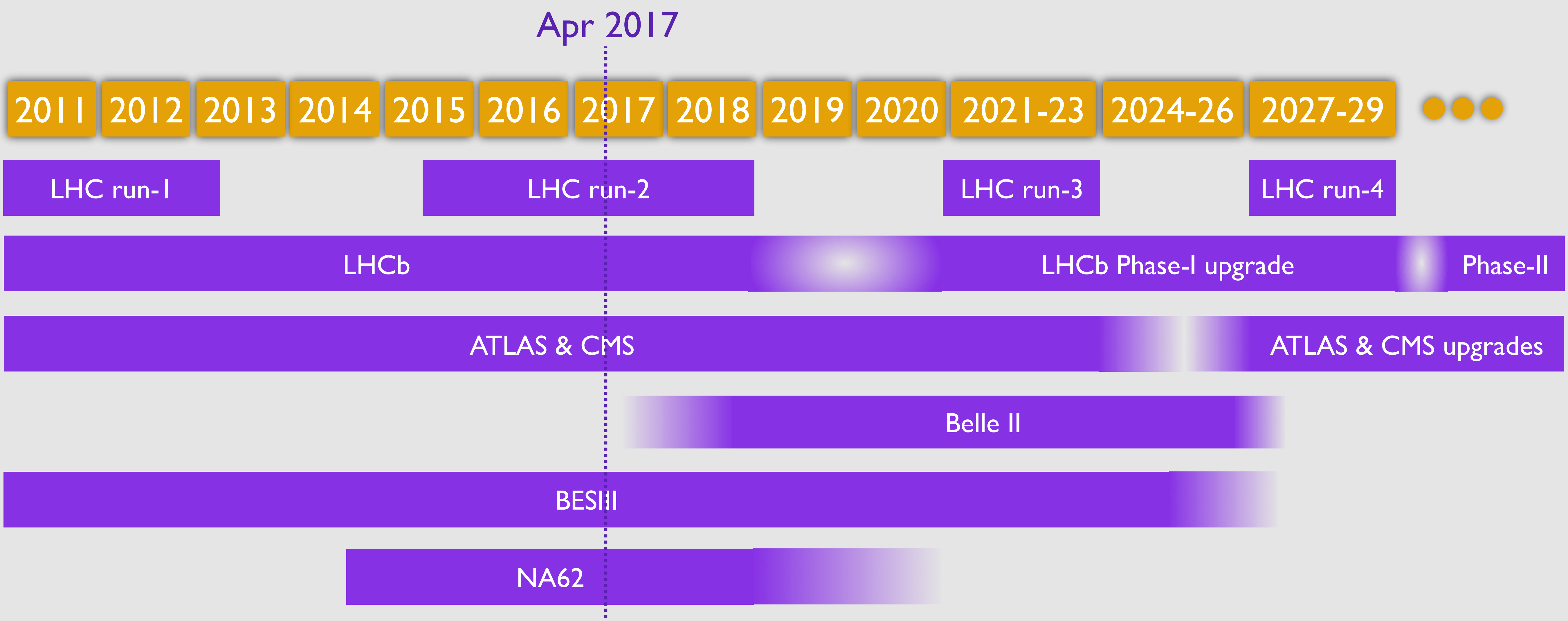
# Outlook

## Towards a flavourful future

# A flavourful decade




- Plus lots of activity on charged lepton flavour

➡ MEG, mu3e, mu2e, COMET, g-2, …

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# LHCb upgrade

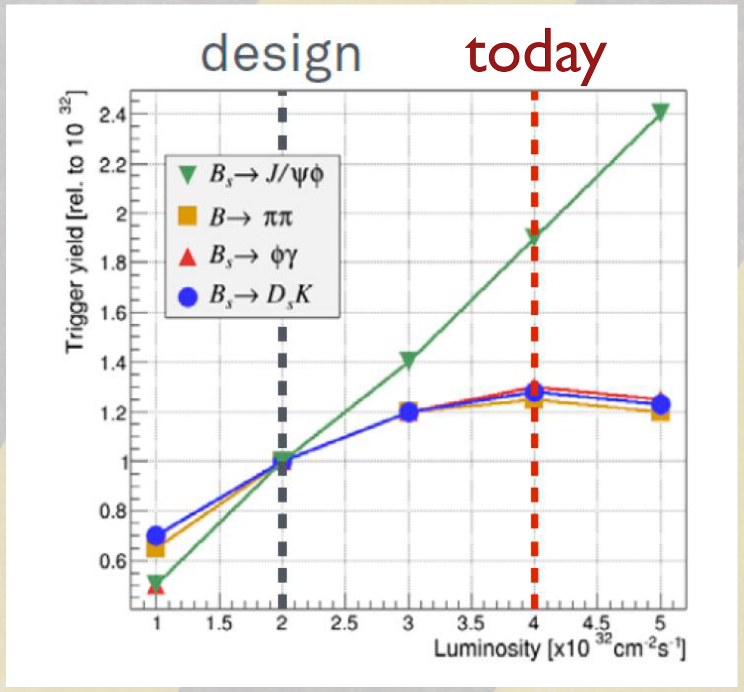
Apr 2017

| 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021-23 | 2024-26 | 2027-29 | ... |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

LHC run-1 · LHC run-2 · LHC run-3 · LHC run-4

LHCb · LHCb Phase-I upgrade · Phase-II

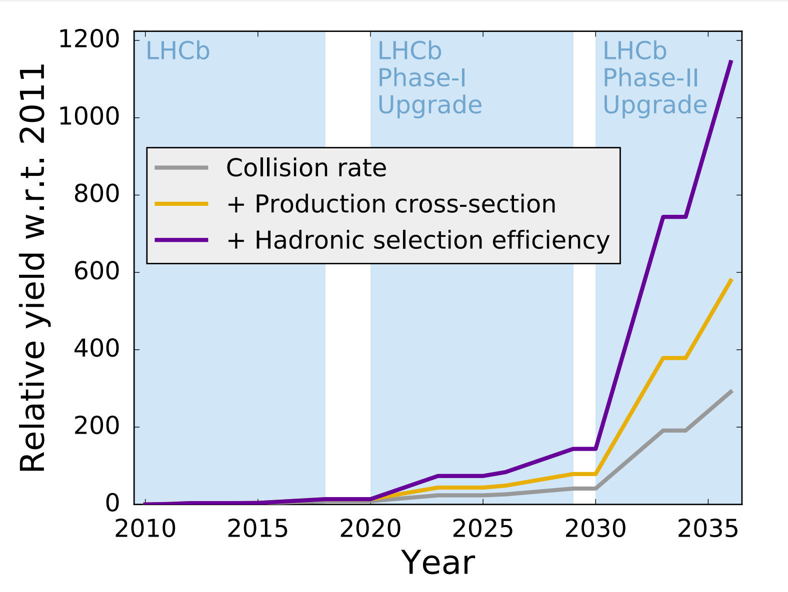
- With increased luminosity hadron channels would saturate
  - ➡ Limited by hardware trigger
- Upgrade to allow full detector readout at 40 MHz and increased luminosity: collect ~8fb$^{-1}$ / year
  - ➡ Requires several new detectors (all tracking plus RICH) and new readout electronics otherwise
- Full software trigger
  - ➡ Massively improved trigger efficiencies
  - ➡ Offline quality reconstruction in trigger
- Maintain/improve current level of detector performance
- Phase-1b consolidation and Phase-II upgrade planned in LS3 and LS4



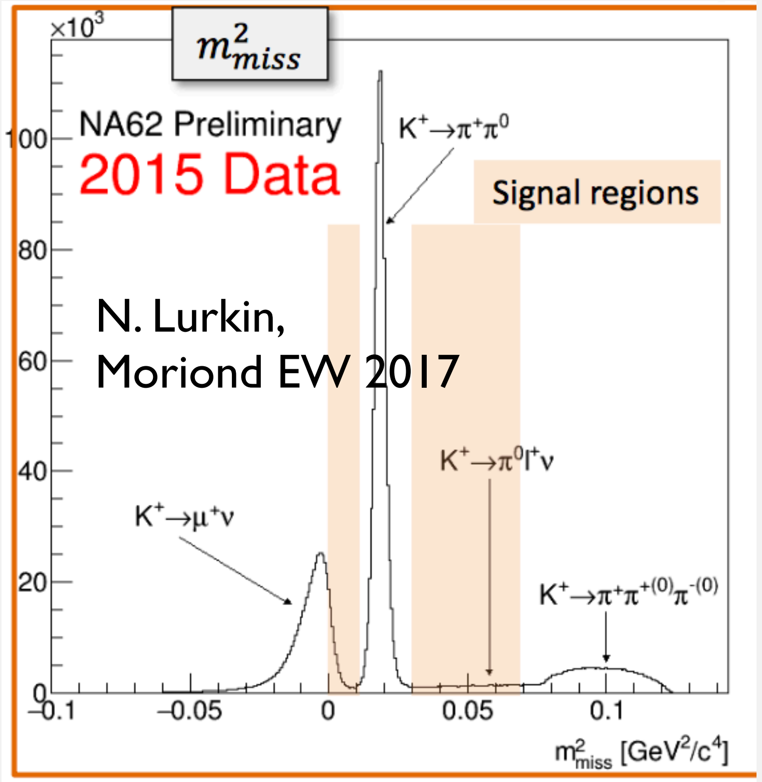

UNDER CONSTRUCTION

# Future potential

- Pure software trigger will significantly improve efficiencies,
  - ➡ Particularly for soft final states
    - Charm, tau, strange, multi-body
  - ➡ Benefits exceeding increase in luminosity




- Healthy competition with Belle II during LHCb Phase-I upgrade
- LHCb Phase-II upgrade will boost yields by another order of magnitude
  - ➡ The ultimate precision frontier
- Don't forget the kaons…



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# Conclusion

- LHCb has taken over the leading role in flavour physics
- No smoking gun signal for physics beyond the SM
- Several hints demand more precise and complementary measurements as well as advances on the theoretical side
  - ➡ New result shown on $R(K^*)$
- Good chance that strong signals will emerge with Run 2
  - ➡ First results shown today
- Need LHCb upgrades to probe to Standard Model level precision
- Next decade will be flavourful
  - ➡ Belle II, BESIII, COMET, g-2, LHCb Run 2, LHCb upgrade(s), MEG, mu2e, mu3e, NA62, …