Rare decays, radiative decays and $b \to sll$ transitions at LHCb

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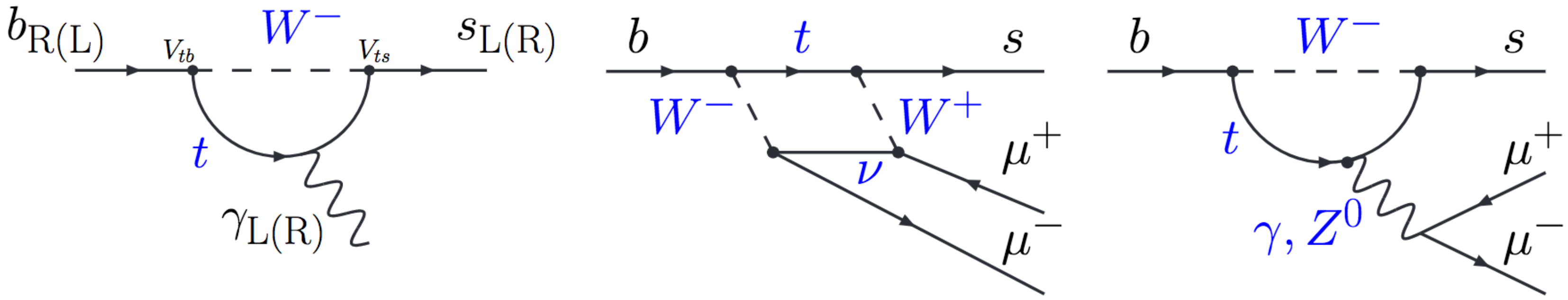
on behalf of the LHCb collaboration

30th Rencontres de Blois, 05.06.2018

Rare decays

- Rare decays: small/vanishing Standard Model (SM) predictions
  - Heavy suppression in Flavour Changing Neutral Current (FCNC) processes or even forbidden in the SM

    → Sensitive to New Physics (NP) processes at tree/loop-level
  - Searches complementary to direct NP searches → higher energy scales testable
- Look for NP effects in
  - (Differential) branching ratios
  - Angular distributions



Rare decays

- Rich field of different analyses, will only cover a few of the latest today
  - $B^0_{d,s} \to ll^{(\prime)}$: $B^0_{d,s} \to e\mu$
  - Anomalies in differential branching fractions of b→ sll transitions
  - b→dll transitions: $B^+ \to \pi^+\mu\mu$, $\Lambda_b \to p\pi\mu\mu$, $B^0_s \to K^{*0}\mu\mu$
  - c→ull transitions: $D^0 \to hh\mu\mu$, $\Lambda_c^+ \to p\mu\mu$
  - s→dll transitions: $K^0_S \to \mu\mu$, $\Sigma_c^+ \to p\mu\mu$
- Many more have been performed and are ongoing

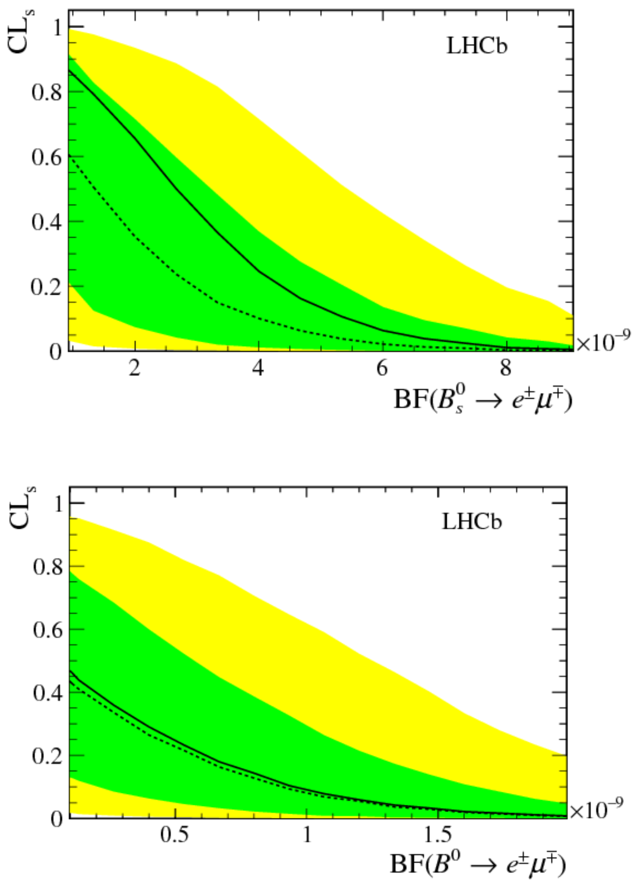
  → See also the talk on Lepton Flavour Universality measurements by Anna Lupato
- Results shown use $3\,\mathrm{fb}^{-1}$ data from Run 1 (few exceptions)

b→sll transitions: $B^0_{d,s} \to e\mu$

[PRL118 251802 (2017)]

- $B^0_{d,s} \to e\mu$ forbidden in the SM → sensitive to NP mediators
  - Large lepton flavour violation expected in many NP scenarios
  - (e.g. leptoquarks, SUSY) → enhancement of $B^0_{d,s} \to e\mu$
- Update of the measurement using the full $3\,\mathrm{fb}^{-1}$ of Run 1
  - Improvements: larger dataset, BDT based selection
  - Analysis based on $B^0_{d,s} \to \mu\mu$ analysis [PRL 118 (2017) 191801]
- Splitting the dataset in
  - 7 Bins of the (flattened) BDT response
  - With/without applied bremsstrahlung correction for the electron

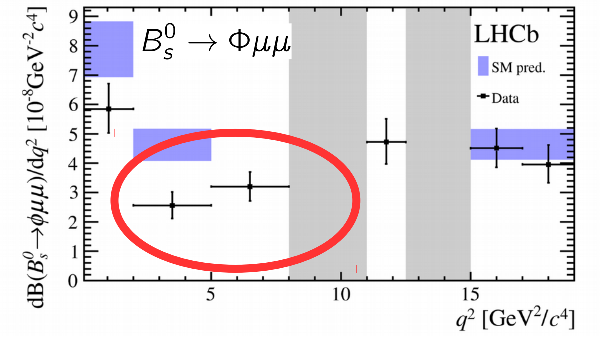
$$\mathcal{B}(B^0_s \to e^{\pm}\mu^{\mp}) < 6.3 \times 10^{-9} \text{ at } 95\% \text{ CL}$$
$$\mathcal{B}(B^0_d \to e^{\pm}\mu^{\mp}) < 1.3 \times 10^{-9} \text{ at } 95\% \text{ CL}$$



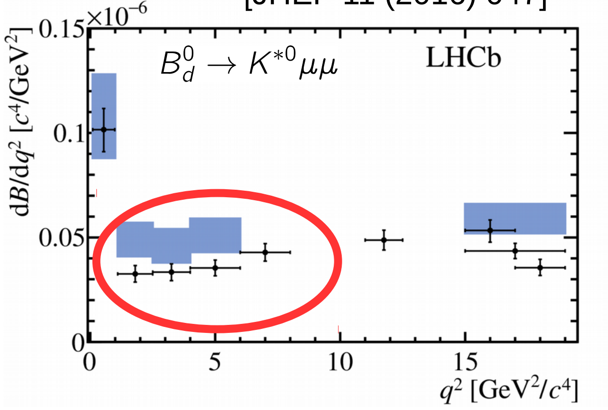
→ 2-3x improvement wrt to old analysis!

Diff. branching fractions in b→sll

[JHEP 09 (2015) 179]

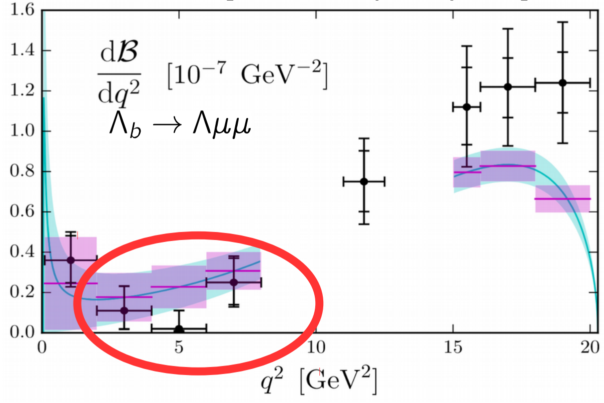


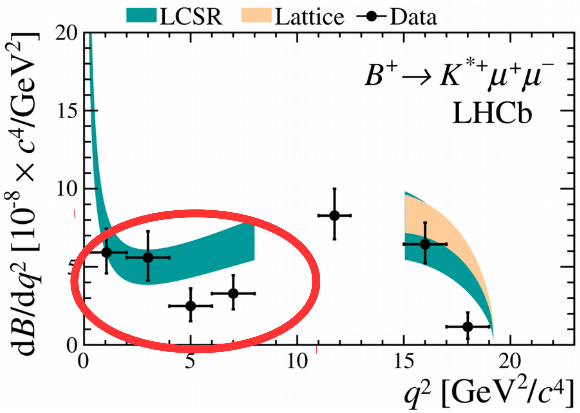
[JHEP 11 (2016) 047]

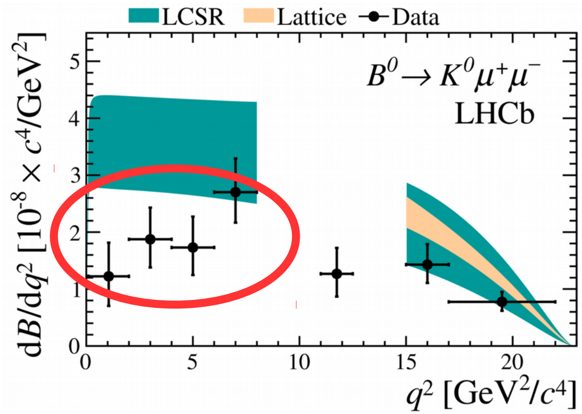


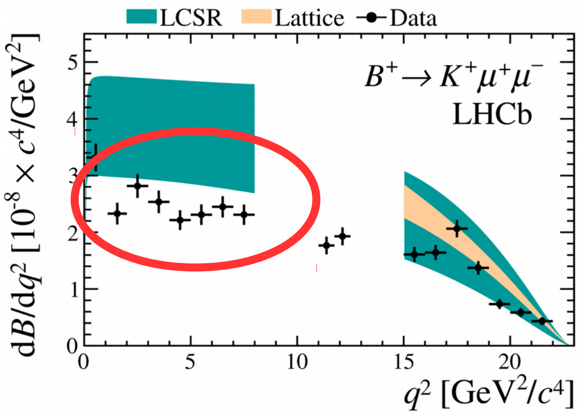
[Detmold and Meinel, PRD93 074501 (2016)]

[JHEP 06 (2015) 115]





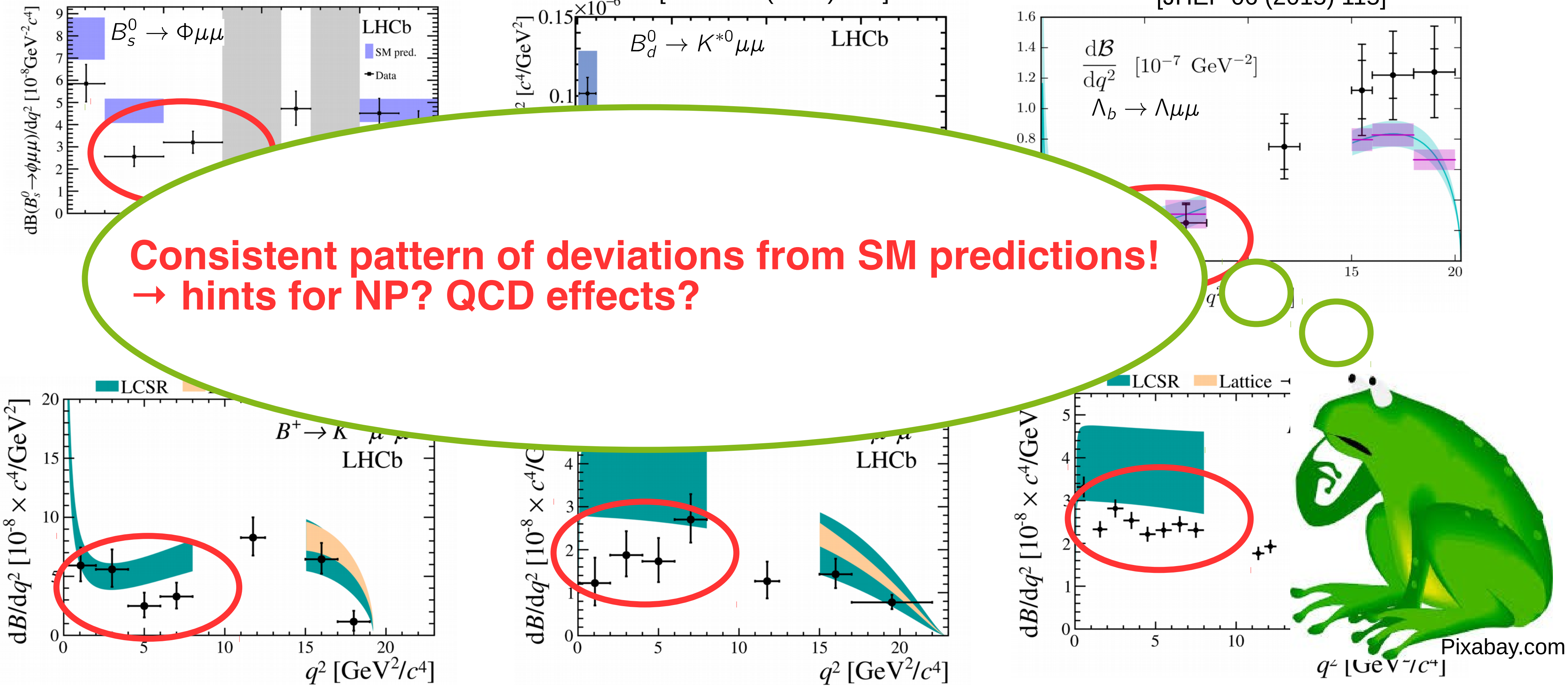




[JHEP 06 (2014) 133]

Diff. branching fractions in b→sll

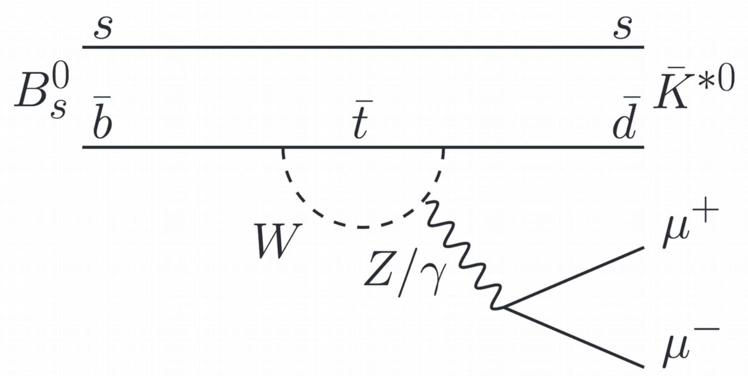
[JHEP 09 (2015) 179] [JHEP 11 (2016) 047] [Detmold and Meinel, PRD93 074501 (2016)] [JHEP 06 (2015) 115]



Consistent pattern of deviations from SM predictions!
→ hints for NP? QCD effects?

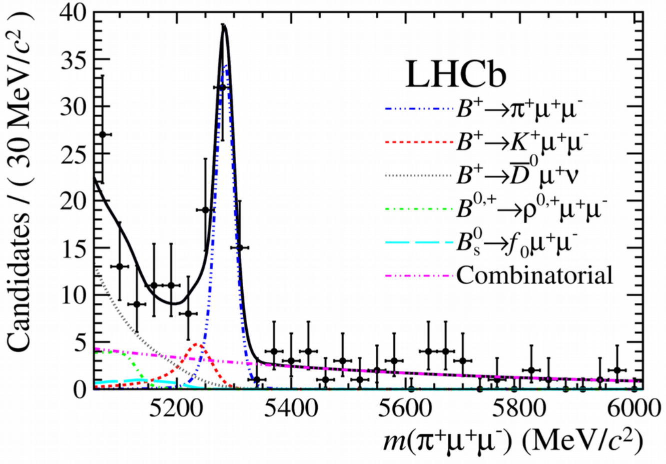
b→dll transitions

- Further CKM suppression in the SM by $|V_{td}/V_{ts}|^2$ compared to b→sll
- Similar but complementary information
- b→sll transitions show consistent pattern of deviations → same anomalies in b→dll?
- Combination with b→sll transitions and form factors to determine $|V_{td}/V_{ts}|$
  → Constraints on the Minimal Flavour Violation hypothesis
  [Feldmann and Mannel, JHEP 02 (2007) 067]
  [Buras et al., PLB 500 (2001) 161]
- Very rare processes, on the brink of observation
  → more data required for angular analyses



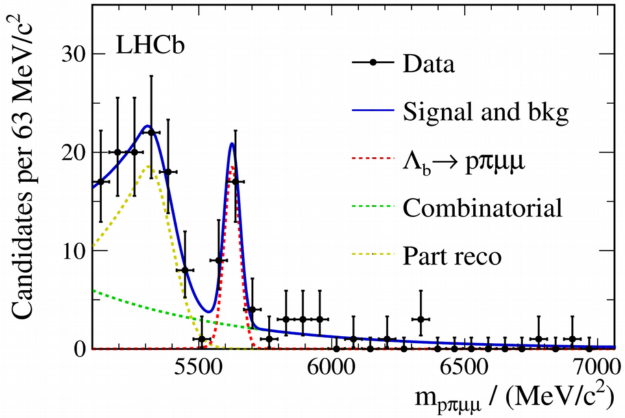
b→dll transitions

[JHEP 10 (2015) 034]



- Observed $B^+ \to \pi^+\mu\mu$ and used for determining $|V_{td}/V_{ts}|$
- Also observation of baryonic $\Lambda_b \to p\pi^-\mu\mu$

  → complicated hadronic system
  → form factors not available



[JHEP 04 (2017) 029]

$$\mathcal{B}(B^+\to\pi^+\mu\mu) = (1.83\pm0.24(\text{stat.})\pm0.05(\text{syst.}))\times10^{-8}$$
$$\mathcal{B}(\Lambda_b\to p\pi^-\mu\mu) = (6.9\pm1.9(\text{stat.})\pm1.1(\text{syst.})^{+1.3}_{-1.0}(\text{norm.}))\times10^{-8}$$

Combine with $B^+\to K^+\mu\mu$ and lattice to get

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.201\pm0.020$$

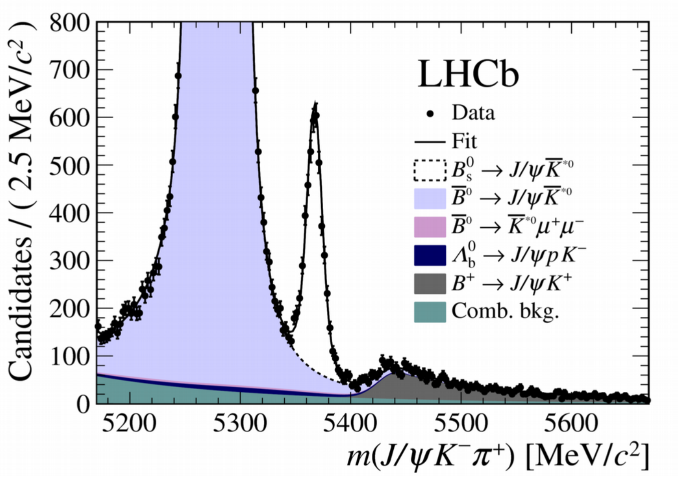
Du et al., [PRD 93 (2016) 034005]

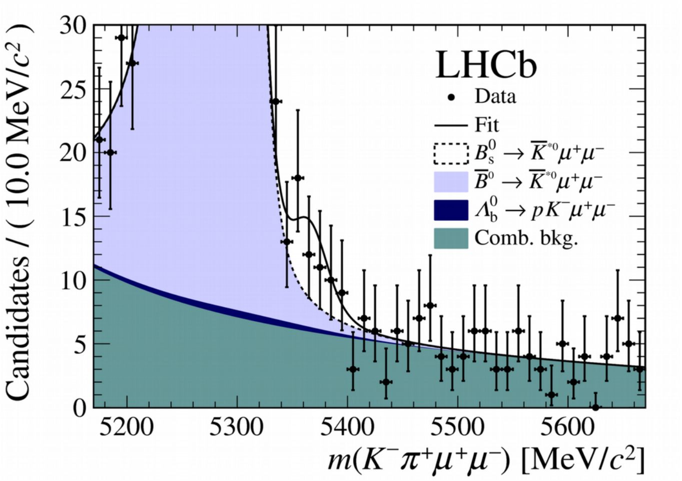
$B_s^0 \to \overline{K^{*0}}\mu\mu$

[arXiv:1804.07167]

- CKM suppressed version of $B_d^0 \to K^{*0}\mu\mu$
- Potential to measure $|V_{td}/V_{ts}|$(as in $B^+ \to \pi^+\mu\mu/B^+ \to K^+\mu\mu$)
- Use $q^2 \in [0.1, 19.0]\mathrm{GeV}^2/c^4$ and veto J/ψ and $\psi(2S)$ regions
- First evidence: 3.4σ at $3\,\mathrm{fb}^{-1}$ Run 1 and $1.6\,\mathrm{fb}^{-1}$ Run 2 data!

$$\mathcal{B}(B_s^0 \to \overline{K^{*0}}\mu\mu) = (2.9 \pm 1.0(\mathrm{stat.}) \pm 0.2(\mathrm{syst.}) \pm 0.3(\mathrm{norm.})) \times 10^{-8}$$



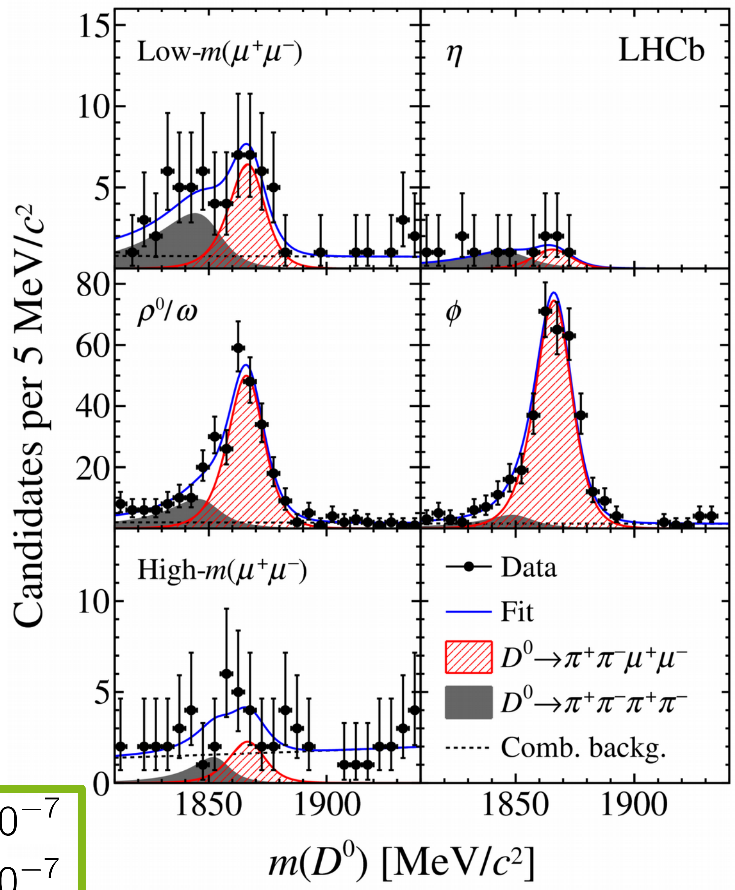


c→ull transitions: $D^0 \to hh\mu\mu$

[PRL 119 181805 (2017)]

- GIM suppression
- Long distance contributions are dominating
- 4 particles in the final state → angular observables will allow disentangling long and short distance
- First steps taken by observing $D^0 \to hh\mu\mu$ ($2\,\mathrm{fb}^{-1}$ Run 1 data)
- Detached D^0 from $D^{*+} \to D^0\pi^+$
- Normalising to $D^0 \to K\pi\mu\mu$
- Divide into 5 regions of dimuon mass

→ Rarest charm decays ever observed!



$$\mathcal{B}(D^0 \to \pi\pi\mu\mu) = (9.64 \pm 0.48(\text{stat.}) \pm 0.51(\text{syst.}) \pm 0.97(\text{norm.})) \times 10^{-7}$$
$$\mathcal{B}(D^0 \to KK\mu\mu) = (1.54 \pm 0.27(\text{stat.}) \pm 0.09(\text{syst.}) \pm 0.16(\text{norm.})) \times 10^{-7}$$

Angular and CP asymmetries in $D^0 \to hh\mu\mu$

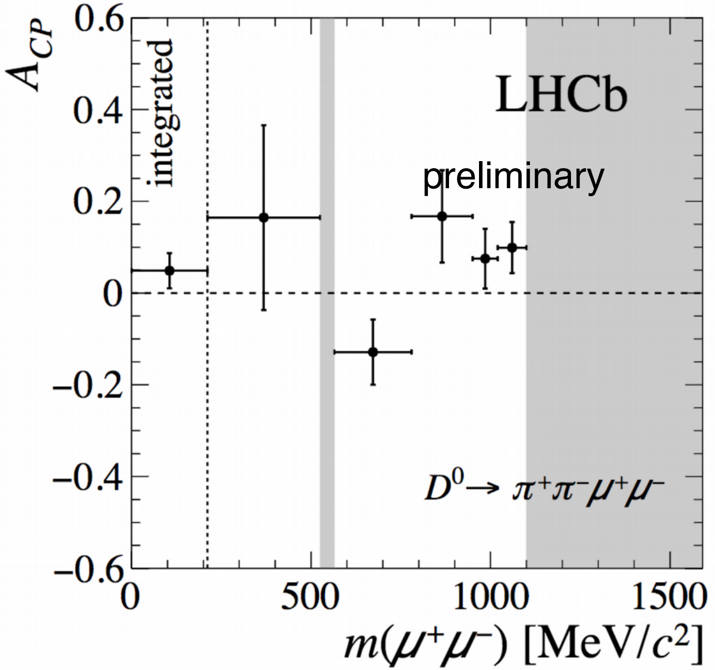
NEW!
LHCb-PAPER-2018-020

- First of such a measurement in a rare charm decay!
- Use $5\,\mathrm{fb}^{-1}$ data from years 2011-2016
- Measure asymmetries in low dimuon mass, ρ/ω-region and ϕ-region

$$A_{FB}(D^0 \to \pi\pi\mu\mu) = (3.7 \pm 3.3(stat.) \pm 0.6(syst.))\%$$
$$A_{\phi}(D^0 \to \pi\pi\mu\mu) = (-0.6 \pm 3.3(stat.) \pm 0.6(syst.))\%$$
$$A_{CP}(D^0 \to \pi\pi\mu\mu) = (4.9 \pm 3.8(stat.) \pm 0.7(syst.))\%$$

$$A_{FB}(D^0 \to KK\mu\mu) = (0 \pm 11(stat.) \pm 2(syst.))\%$$
$$A_{\phi}(D^0 \to KK\mu\mu) = (9 \pm 11(stat.) \pm 1(syst.))\%$$
$$A_{CP}(D^0 \to KK\mu\mu) = (0 \pm 11(stat.) \pm 2(syst.))\%$$

from years 2011-2016



Search for $\Lambda_c^+ \to p\mu\mu$

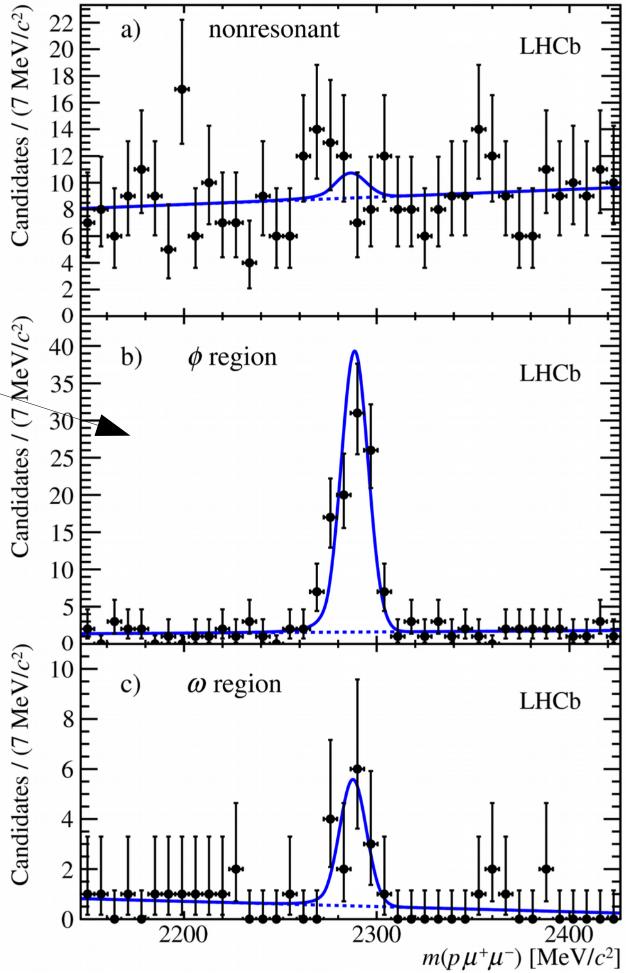
[PRD 97 (2018) 091101(R)]

- Rare baryonic c→ull FCNC process
- Long distance dominated
- Normalise to the resonant $\Lambda_c^+ \to p\phi$ mode
- Two-staged MVA selection
- Previous world-best limit (BaBar):
  $\Lambda_c^+ \to p\mu\mu < 4.4 \times 10^{-5}$ (90% CL) [PRD 84 (2011) 072006]
  → Improve world-best limit on $\Lambda_c^+ \to p\mu\mu$ by O(100):

$$\mathcal{B}(\Lambda_c^+ \to p\mu\mu) < 9.6 \times 10^{-8} \text{ (95\% CL)}$$

- First observation of $\Lambda_c^+ \to p\omega$!

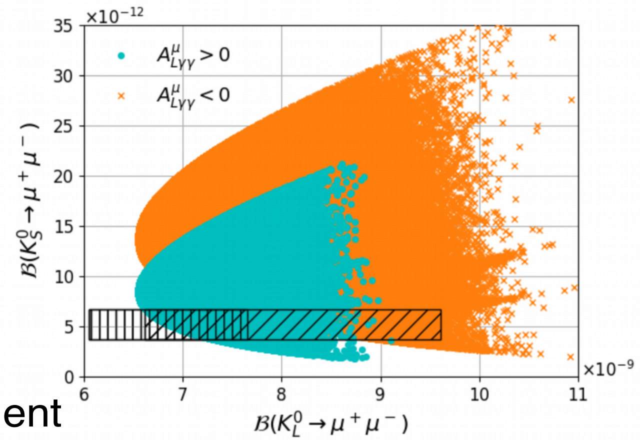
$$\mathcal{B}(\Lambda_c^+ \to p\omega) = (9.4 \pm 3.2(\text{stat.}) \pm 1.0(\text{syst.}) \pm 2.0(\text{norm.})) \times 10^{-4}$$



s→dll: $K^0_S \to \mu\mu$

[Eur. Phys. J. C, 77 10 (2017) 678]

[Chobanova et al., JHEP05 (2018) 024]

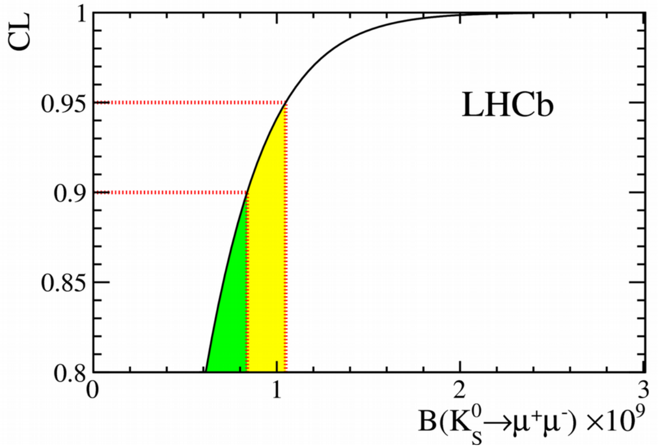


- Very sensitive to NP (e.g. light scalars)
- $3\,\mathrm{fb}^{-1}$ update wrt previous measurement using $1\,\mathrm{fb}^{-1}$ Run 1
- K^0_S abundant in LHCb ($\mathcal{O}(10^{13})$)
  - Low dimuon mass
    → Low trigger efficiency improved by removing mass requirement
  - Two MVA discriminants to remove combinatorial and $K^0_S \to \pi\pi$ backgrounds

→ $\mathcal{B}(K^0_S \to \mu\mu) < 1.0 \times 10^{-9}$ (95% CL)

→ Improve the limit by O(10)!

- SM prediction: $\mathcal{B}(K^0_S \to \mu\mu) = (5.0 \pm 1.5) \times 10^{-12}$
  [Isidori and Unterdorfer, JHEP 01 (2004) 009]



$\Sigma^+ \to p\mu\mu$

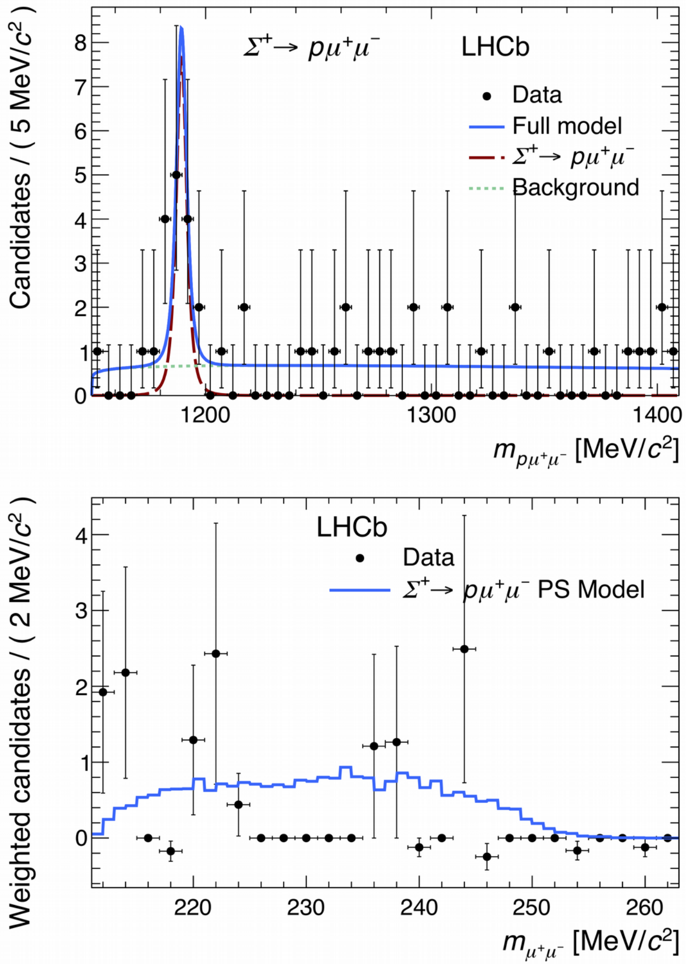
[PRL 120 (2018) 221803]

- Baryonic s→ dll process
- Dominated by long distance contributions
- Normalise to $\Sigma^+ \to p\pi^0$
- Excess of $\Sigma^+ \to p\mu\mu$ found at 4.1σ
  - Consistent with the SM
  - No significant dimuon resonance structure observed

→ $\mathcal{B}(\Sigma^+ \to p\mu\mu) = (2.2^{+1.8}_{-1.3}) \times 10^{-8}$

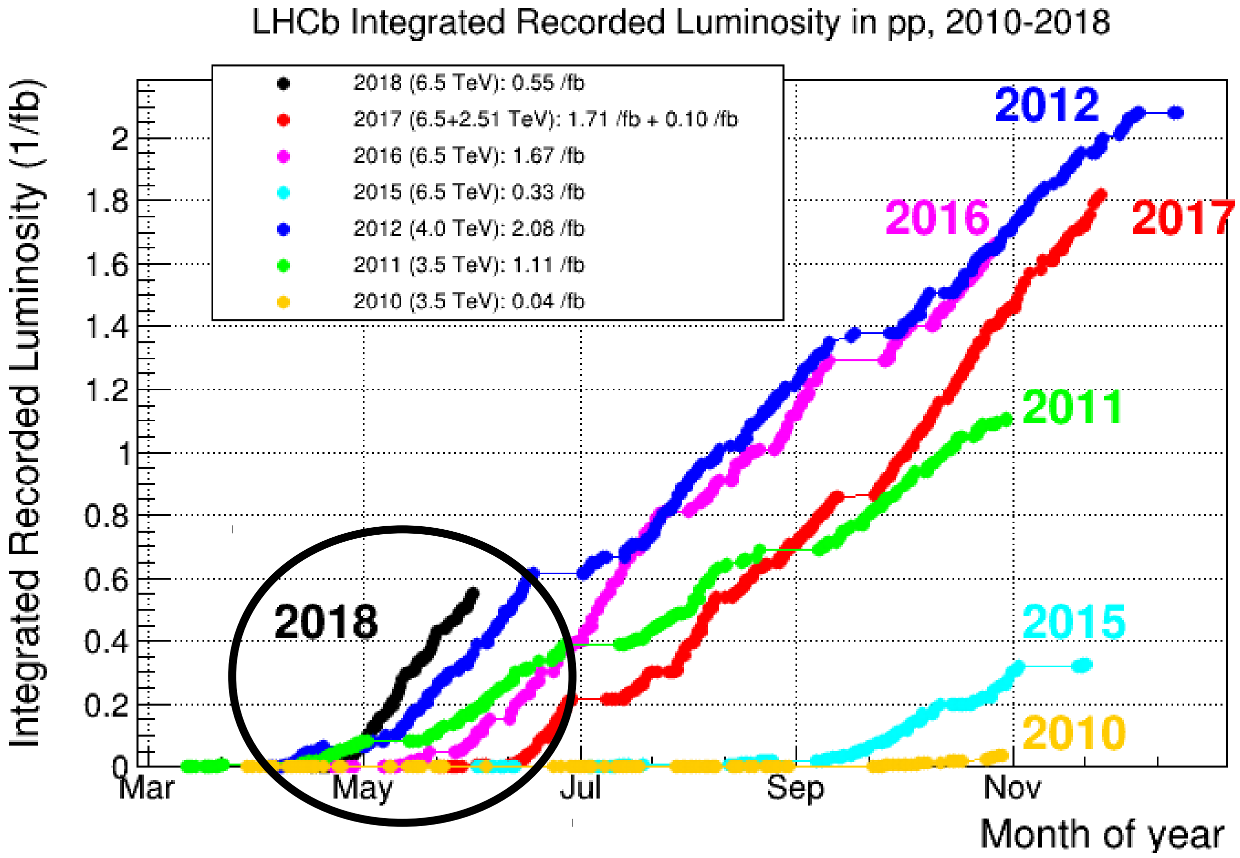
→ rules out dimuon resonance as indicated by HyperCP: excess of three candidates with close dimuon masses
[PRL 94 (2005) 021801]

→ $\mathcal{B}(\Sigma^+ \to pX^0(\to \mu\mu)) < 1.4 \times 10^{-8}$ (90% CL)



Conclusion

- Rare decays provide powerful tests of the SM and NP scenarios
- Many analyses are carried out at LHCb
  - Providing stringent constraints on NP models
  - Probing a variety of $q \rightarrow q'll$ transitions
  - Measurements in $b \rightarrow sll$ seem to favour a modification of the SM
  - Will we find similar anomalies in $b \rightarrow dll$ transitions?
- X3 more data on tape than yet analysed!



LHCb Integrated Recorded Luminosity in pp, 2010-2018
2018 (6.5 TeV): 0.55 /fb
2017 (6.5+2.51 TeV): 1.71 /fb + 0.10 /fb
2016 (6.5 TeV): 1.67 /fb
2015 (6.5 TeV): 0.33 /fb
2012 (4.0 TeV): 2.08 /fb
2011 (3.5 TeV): 1.11 /fb
2010 (3.5 TeV): 0.04 /fb
2012
2016
2017
2011
2018
2015
2010
Integrated Recorded Luminosity (1/fb)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Mar
May
Jul
Sep
Nov
Month of year

Backup

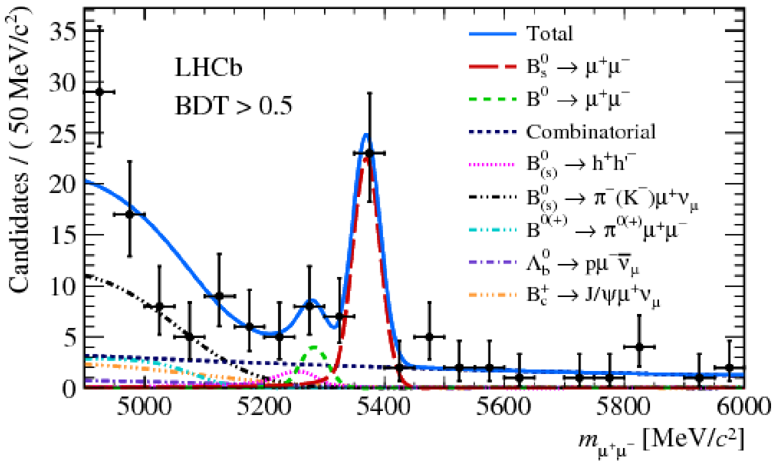
$B^0_{d,s} \to \mu\mu$

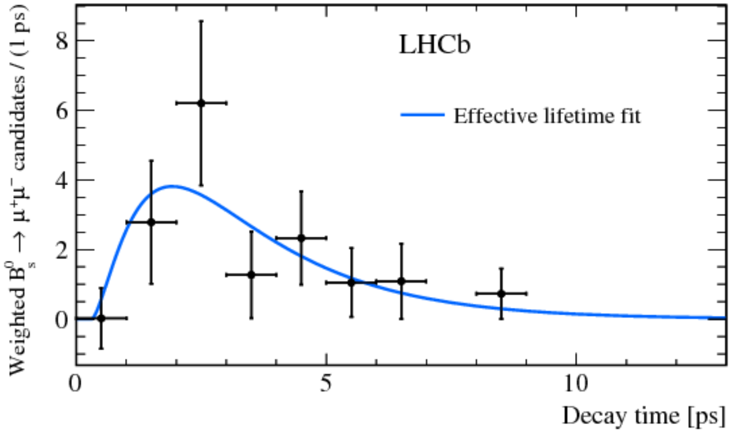
[PRL 118, 191801 (2017)]

- “Golden Channel”,
  loop and helicity suppressed in the SM
- Clean both experimentally and theoretically
- Search with $3\,\text{fb}^{-1}$ Run 1 and $1.4\,\text{fb}^{-1}$ Run 2 data
  - First single experiment observation of $B^0_s \to \mu\mu\,(7.8\sigma)$
  - Measurement of effective lifetime in $B^0_s \to \mu\mu$
  - Limit on $\mathcal{B}(B^0_d \to \mu\mu)$
- Results consistent with SM
  → stringent constraints on NP models

$$\mathcal{B}(B^0_s \to \mu\mu) = (3.0 \pm 0.6(\text{stat.})^{+0.3}_{-0.2}(\text{syst.})) \times 10^{-9}$$
$$\tau(B^0_s \to \mu\mu) = 2.04 \pm 0.44(\text{stat.}) \pm 0.05(\text{syst.})\ \text{ps}$$
$$\mathcal{B}(B^0_d \to \mu\mu) < 3.4 \times 10^{-10}\ (95\,\%\ \text{CL})$$

CKM suppressed





$B^0_{d,s} \to \tau\tau$

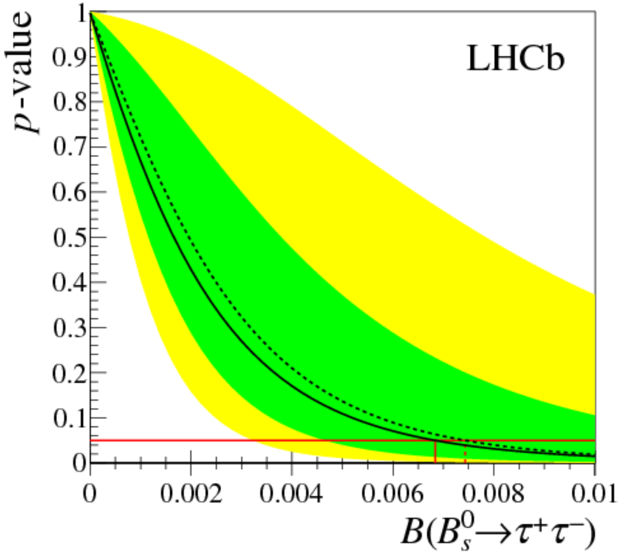
[PRL118, 251802 (2017)]

- Helicity suppression lifted due to the large m_τ , but experimentally challenging:
  - Complementary measurement to $B^0_{d,s} \to \mu\mu$
  - Very interesting in view of LFU results (talk by A. Lupato)

$$\mathcal{B}_{\mathrm{SM}}(B^0_s \to \tau\tau) = (7.73 \pm 0.49) \times 10^{-7}$$
$$\mathcal{B}_{\mathrm{SM}}(B^0_d \to \tau\tau) = (2.22 \pm 0.19) \times 10^{-8}$$

[PRL112 101801(2014)]
Bobeth et al.

$$\mathcal{B}(B^0_s \to \tau\tau) < 6.8 \times 10^{-3} \text{ at } 95\% \text{ CL}$$
$$\mathcal{B}(B^0_d \to \tau\tau) < 2.1 \times 10^{-3} \text{ at } 95\% \text{ CL}$$



Angular and CP asymmetries in $D^0 \to hh\mu\mu$

$$A_{\mathrm{CP}} = \frac{\Gamma(D^0 \to hh\mu\mu) - \Gamma(\overline{D^0} \to hh\mu\mu)}{\Gamma(D^0 \to hh\mu\mu) + \Gamma(\overline{D^0} \to hh\mu\mu)}$$

$$A_{\mathrm{FB}} = \frac{\Gamma(\cos\theta_\mu > 0) - \Gamma(\cos\theta_\mu < 0)}{\Gamma(\cos\theta_\mu > 0) + \Gamma(\cos\theta_\mu < 0)}$$

$$A_\phi = \frac{\Gamma(\sin 2\phi > 0) - \Gamma(\sin 2\phi < 0)}{\Gamma(\sin 2\phi > 0) + \Gamma(\sin 2\phi < 0)}$$