Very Rare Decays in Beauty, Charm and Strange decays

LHCP
Bologna, 4-9 Giugno 2018

Nikhef

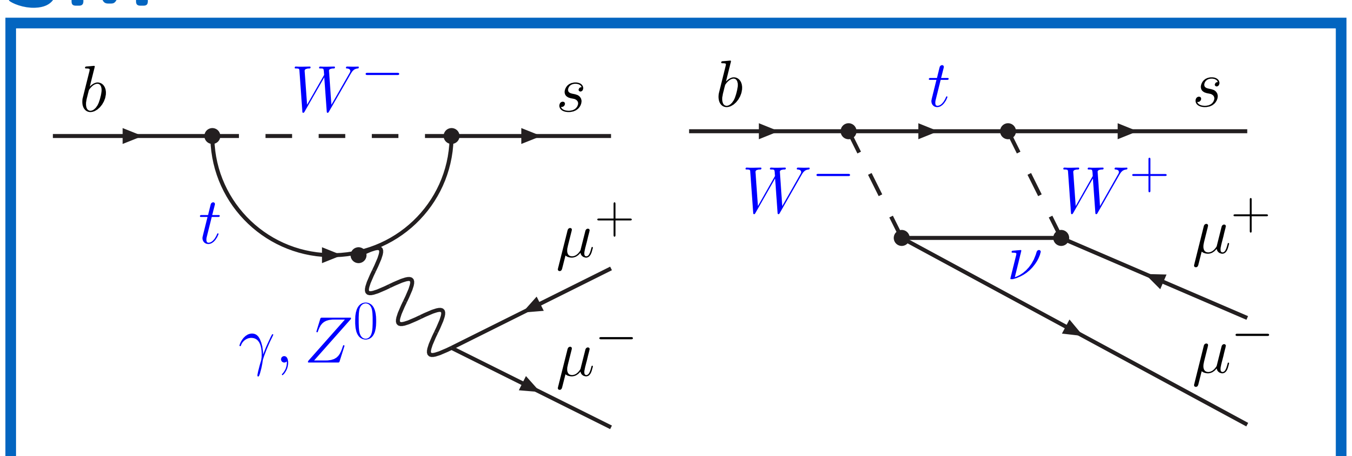
Flavio Archilli
on behalf of the ATLAS, CMS and LHCb collaborations

ATLAS EXPERIMENT
CMS
LHCb

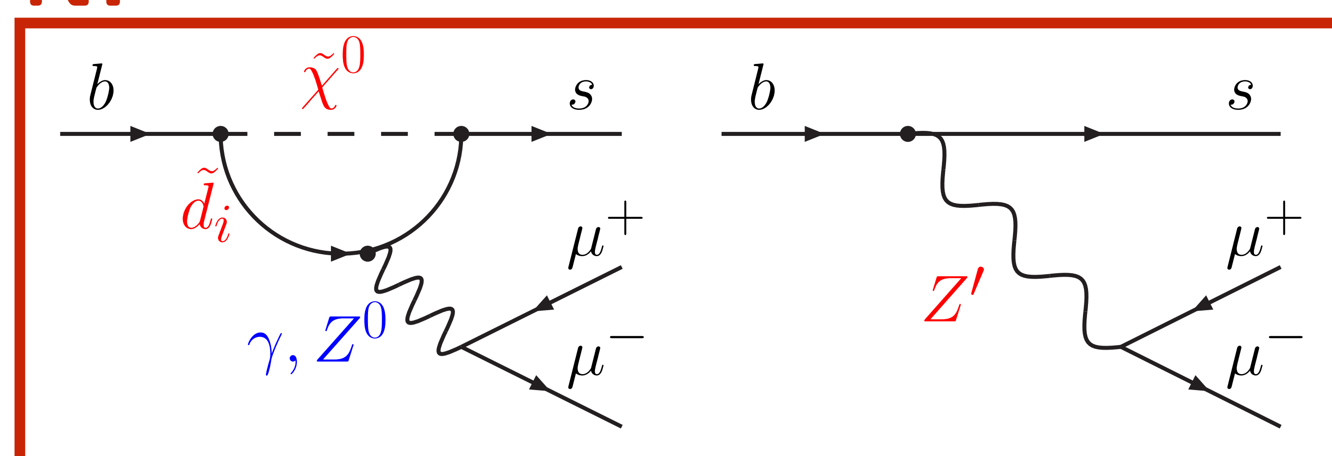
Rare decays

- Flavour changing neutral current (FCNC) process cannot proceed at tree level in the SM
- Sensitive to **new virtual particles** $\rightarrow$ possibility to probe higher energy scales w/ respect to direct searches
- NP effects can arise at the same level of or larger than **SM** one

SM



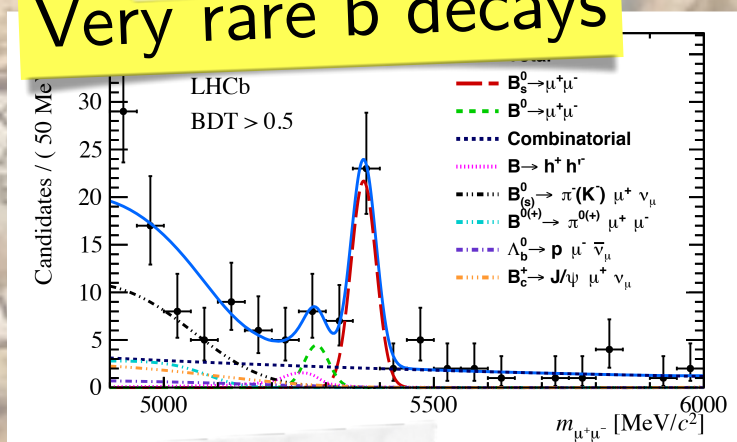
NP



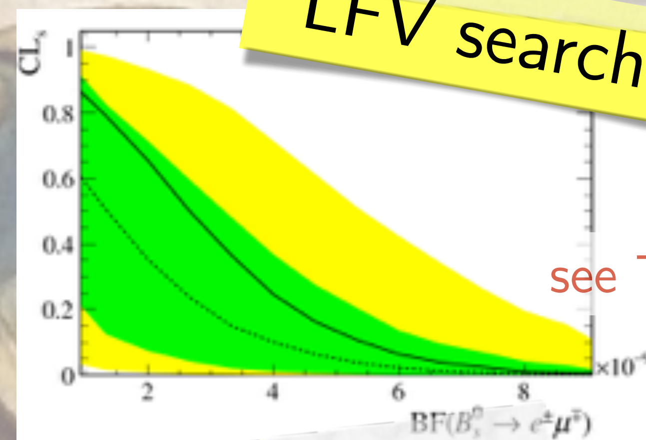
Rare decays overview

Diverse and rich research program on rare decays with b, c and s quarks

Very rare b decays

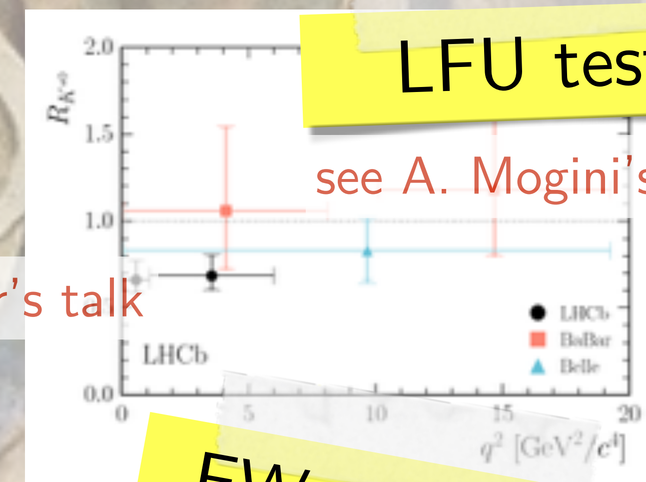


LFV searches



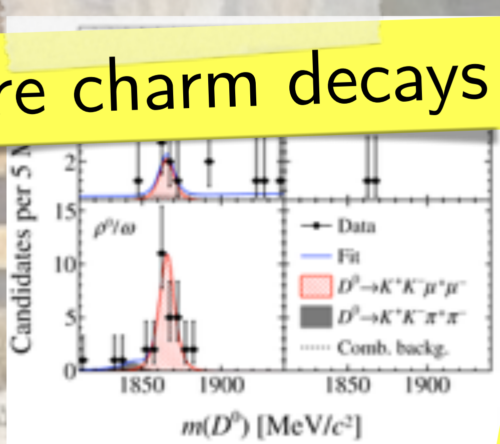
see T. Humair's talk

LFU tests

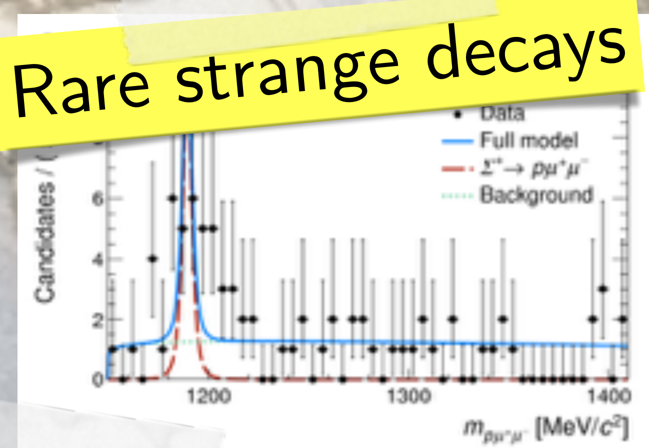


see A. Mogini's talk

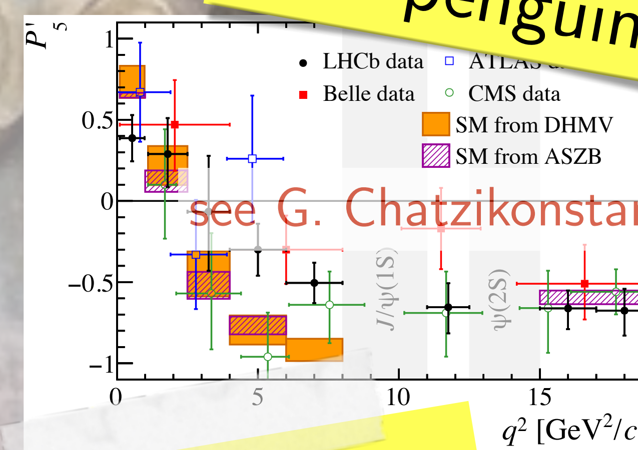
Rare charm decays



Rare strange decays

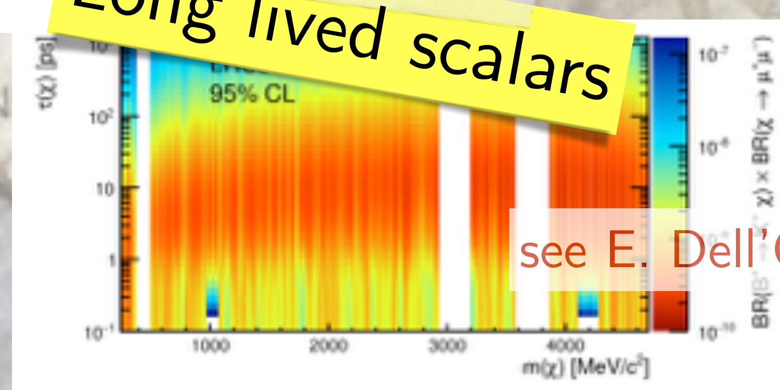


EW penguins



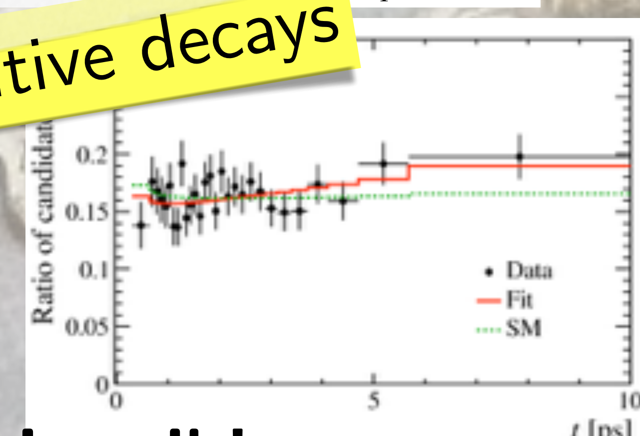
see G. Chatzikonstantinidis's talk

Long lived scalars



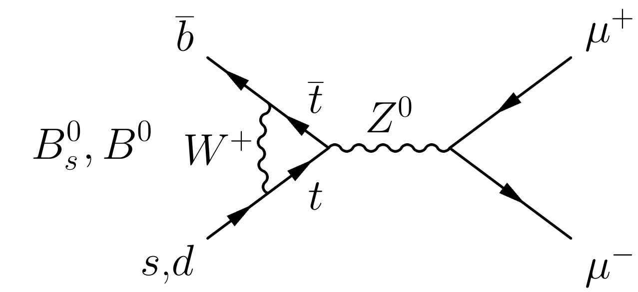
see E. Dell'Occo's talk

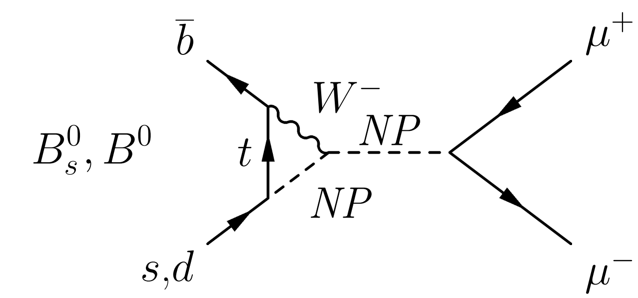
Radiative decays



Only a minor part will be covered in this talk!

$B^0_s \to \mu^+\mu^-$





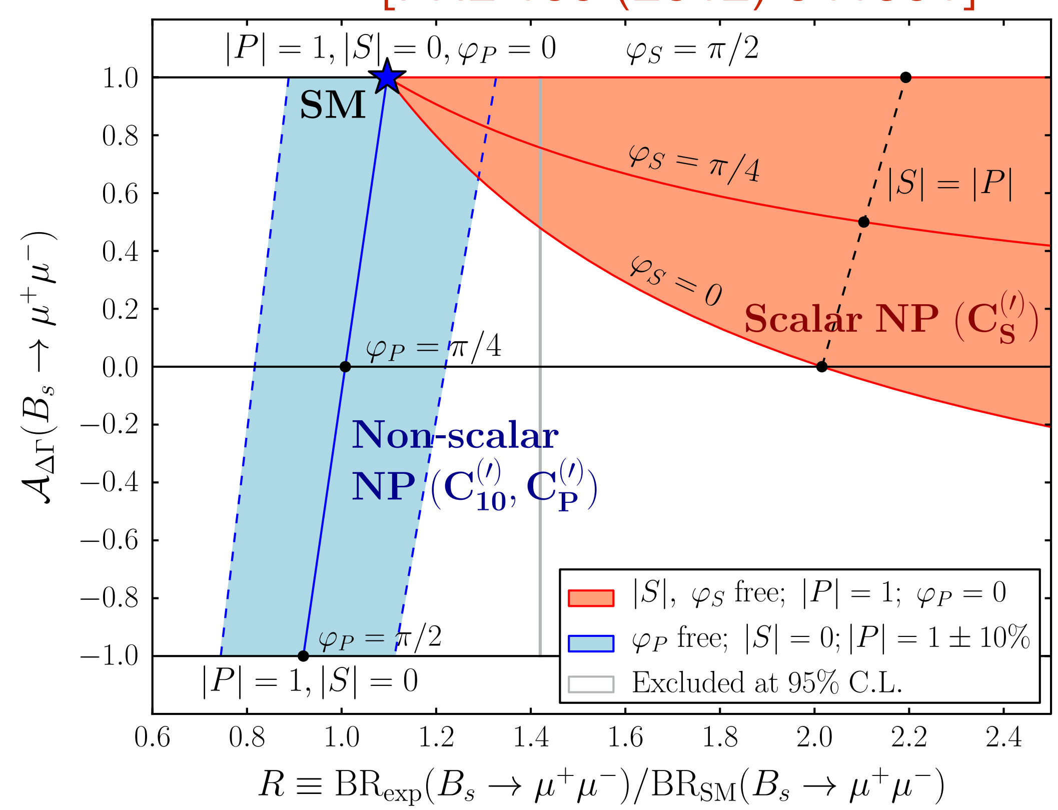
- Pure leptonic decays $B \to l^+l^-$ are even rarer in the SM due to helicity suppression
- SM expectation

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

[PRL 112 (2014) 101801]

- Theoretically clean
- Sensitive to (pseudo-)scalars mediators
- Observables such $A_{\Delta\Gamma}$ can provide additional separation between scalar and pseudo-scalar contributions

[PRL 109 (2012) 041801]



$$A^{\ell^+\ell^-}_{\Delta\Gamma} = \frac{\Gamma_{B_{s,H}\to\ell^+\ell^-} - \Gamma_{B_{s,L}\to\ell^+\ell^-}}{\Gamma_{B_{s,H}\to\ell^+\ell^-} + \Gamma_{B_{s,L}\to\ell^+\ell^-}} \stackrel{SM}{=} 1 \qquad \tau_{\ell^+\ell^-} = \frac{\tau_{B_s}}{1-y_s^2}\left[\frac{1 + 2A^{\ell^+\ell^-}_{\Delta\Gamma}\, y_s + y_s^2}{1 + A^{\ell^+\ell^-}_{\Delta\Gamma}\, y_s}\right]$$

$$y_s \equiv \tau_{B_s}\Delta\Gamma/2 = 0.062 \pm 0.006$$

$B^0_s \to \mu^+\mu^-$ previous results

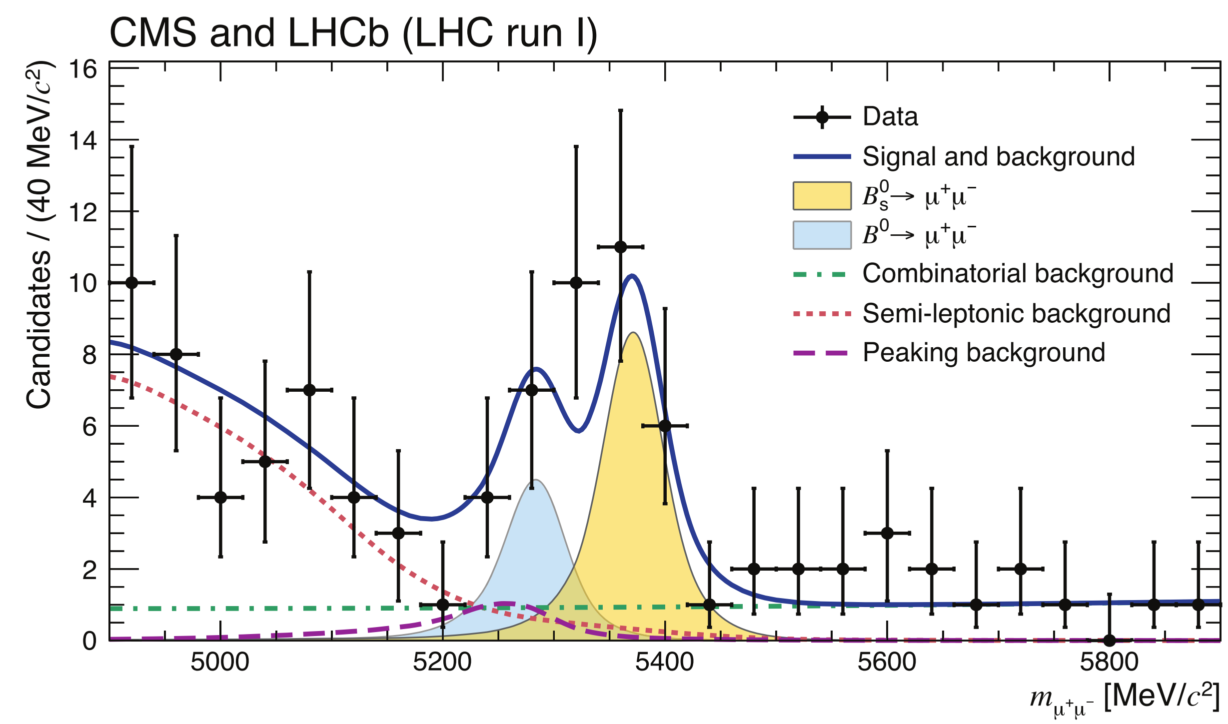
- First observation of Bs→μμ with CMS+LHCb combined analysis from full LHC Run1 dataset [Nature 522, 68-72]

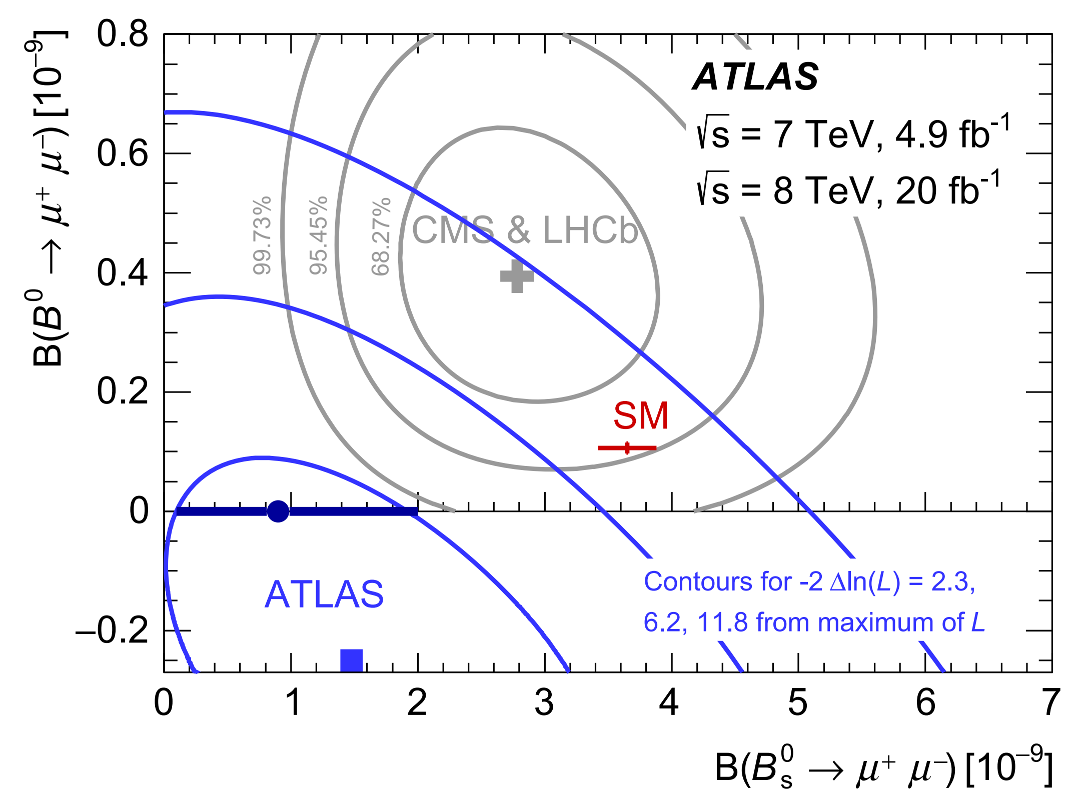
$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$$ **6.2σ**

- First evidence of B⁰→μμ

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$$ **3.0σ**

- ATLAS result based on full Run1 [EPJ C76 (2016) 9, 513]
- Low statistical significance on the Bs mode (1.4 σ), still consistent with the SM (2.0 σ)
- **Mild tension among experimental results. Excess on B⁰ intriguing, to be investigated**





$B^0_s \to \mu^+\mu^-$ update

[PRL 118, 191801 (2017)]

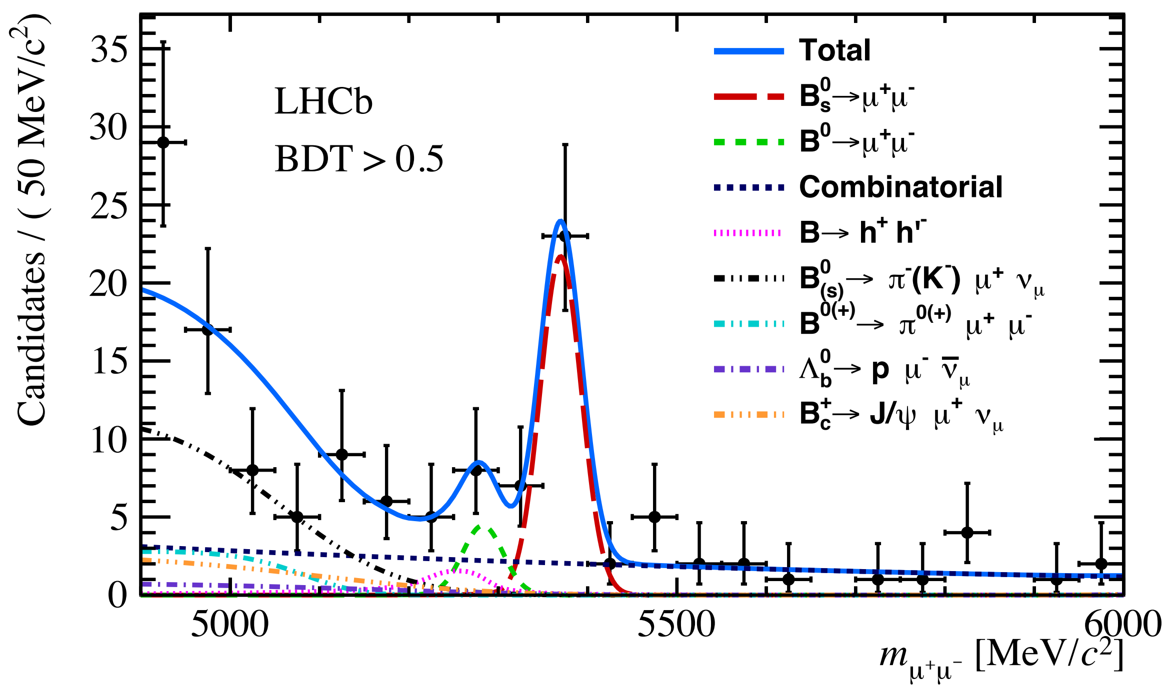
- Improved analysis using $3fb^{-1}$ of Run1 data + $1.4fb^{-1}$ of Run2
- Unbinned maximum likelihood fit of $m_{\mu\mu}$ simultaneously in 5 bins of BDT

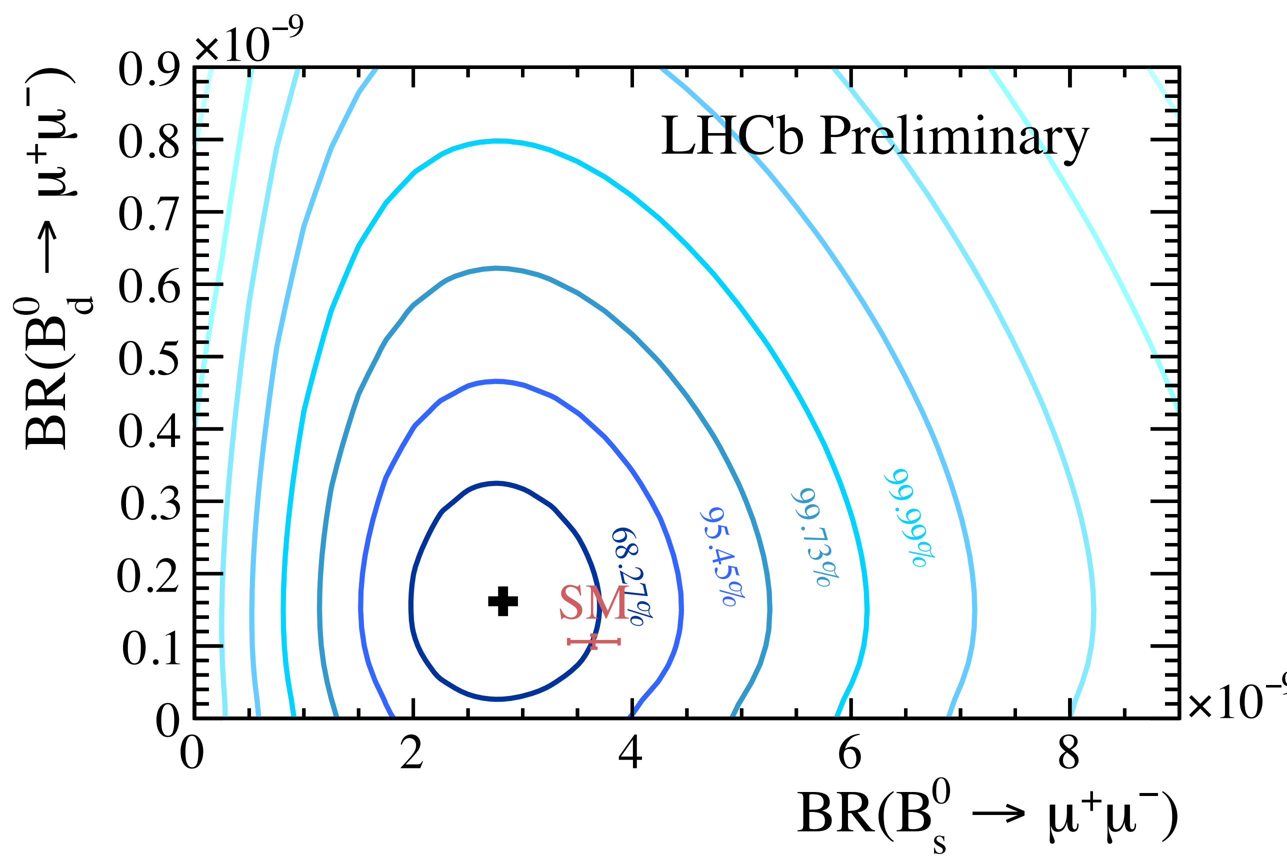
$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.0 + 0.6(\text{stat})^{+0.3}_{-0.2}(\text{syst})) \times 10^{-9} \quad \mathbf{7.8\sigma}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.5^{+1.2}_{-1.0}(\text{stat})^{+0.2}_{-0.1}(\text{syst})) \times 10^{-10} \quad \mathbf{1.6\sigma}$$

$$< 3.4 \cdot 10^{-10} \text{ @ } 95\% \text{ CL}$$

- The measurement of BF($Bs \to \mu\mu$) assumes $A_{\Delta\Gamma}$=1, it increases by 4.6% (10.9%) if $A_{\Delta\Gamma}$=0(-1)
- Main source of systematics:
  - $B^0_s \to \mu^+\mu^-$: knowledge of f_s/f_d
  - $B^0 \to \mu^+\mu^-$: exclusive backgrounds



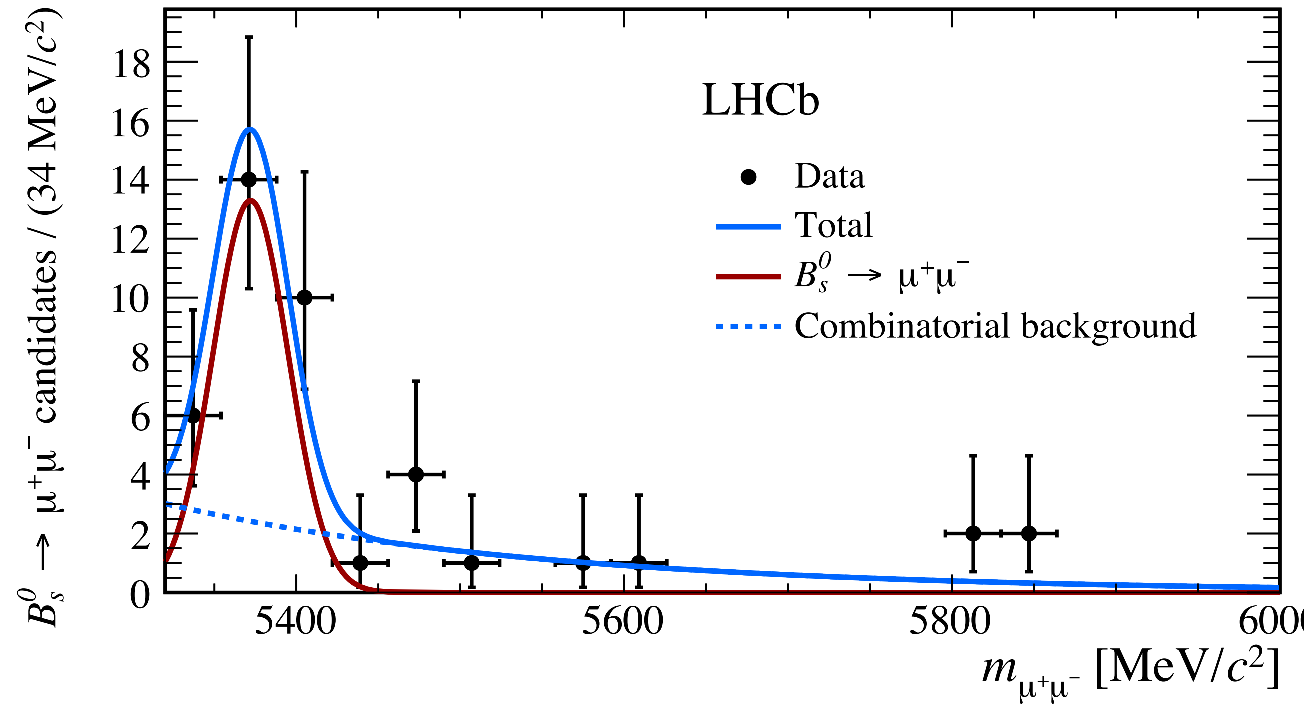


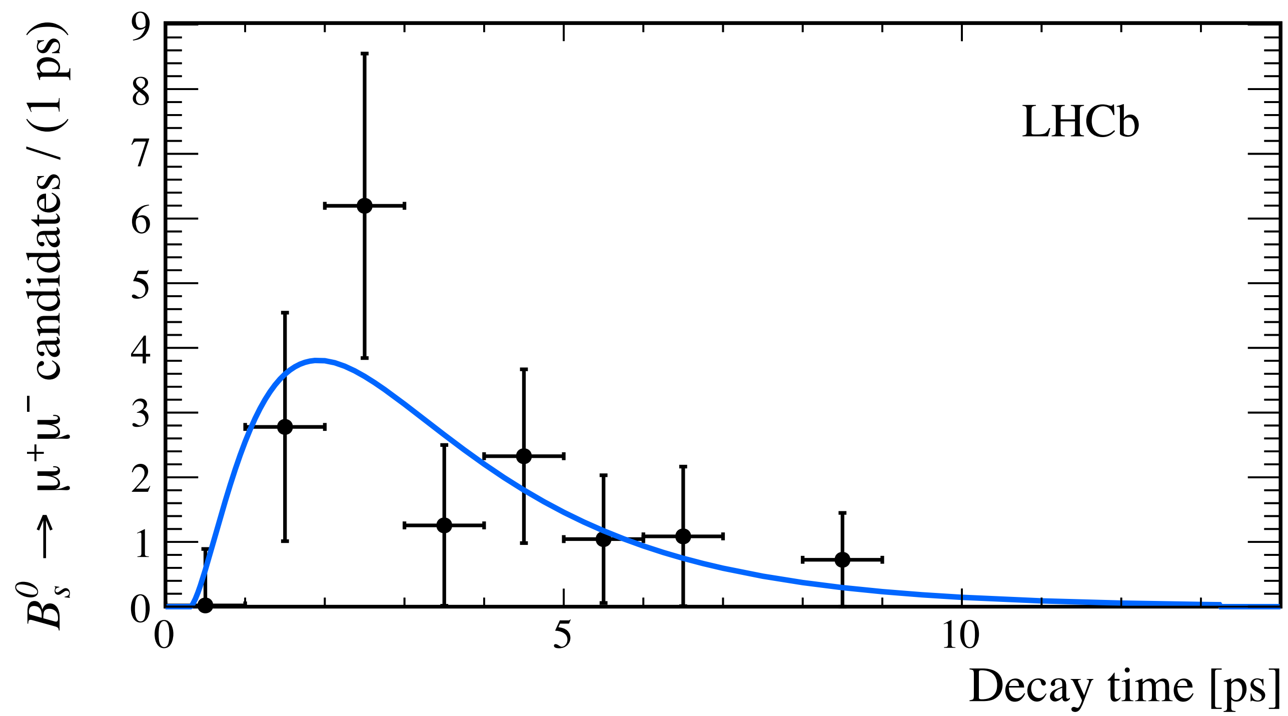
$B^0_s \to \mu^+\mu^-$ effective lifetime

[PRL 118, 191801 (2017)]

- Similar analysis strategy as for the BF, with a simplified BDT>0.55 requirement
- $\tau_{\mu\mu}$ extracted in 2 stages:
  - fit of $m_{\mu\mu}$ in [5320,6000]MeV/c^2 to evaluate the sWeights
  - fit the weighted decay-time distribution
- Acceptance function modelled on signal MC and validated with $B^0 \to K^+\pi^-$ decays

$$\tau(B^0 \to \mu^+\mu^-) = 2.04 \pm 0.44_{(\mathrm{stat})} \pm 0.05_{(\mathrm{syst})}\ \mathrm{ps}$$





$B^0_s \to \tau^+\tau^-$

- FCNC process analogous to $B_s \to \mu^+\mu^-$ but less helicity suppressed
- expected SM time-integrated BF:

$$\mathcal{B}(B^0_s \to \tau^+\tau^-)^{\langle t \rangle} = (7.73 \pm 0.49) \cdot 10^{-7}$$
$$\mathcal{B}(B^0 \to \tau^+\tau^-)^{\langle t \rangle} = (2.22 \pm 0.19) \cdot 10^{-8}$$

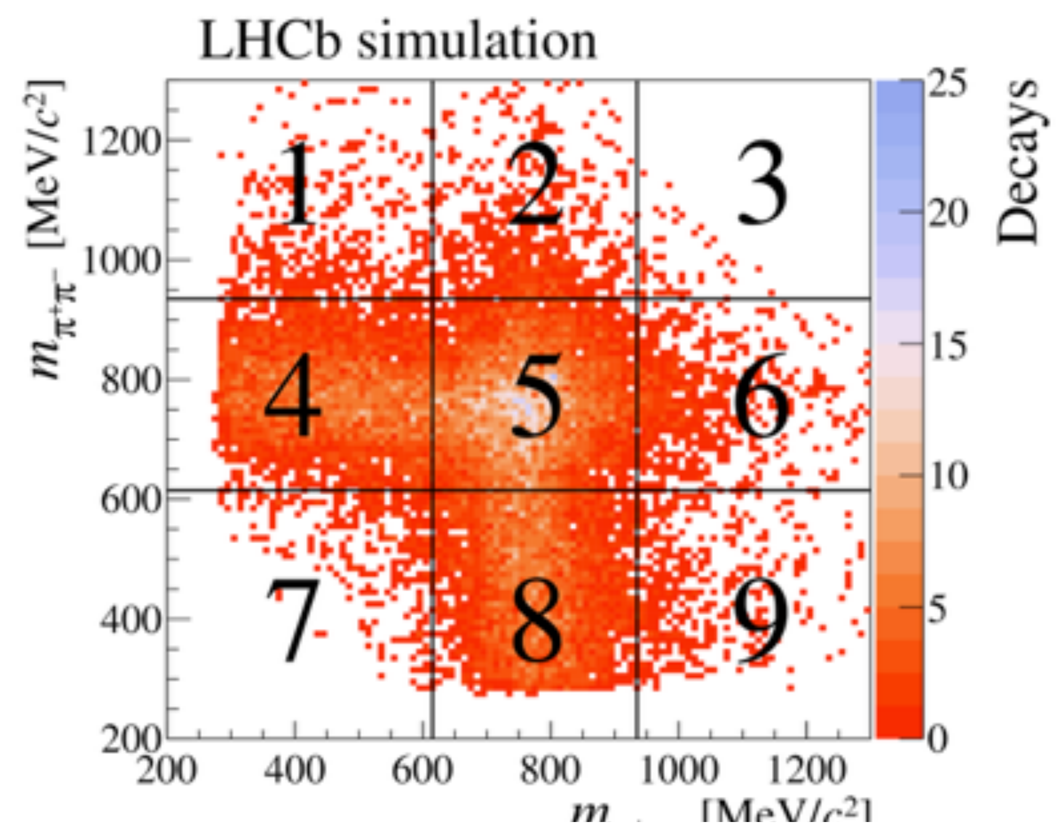
[Bobeth et al, PRL 112 (2014), 101801]

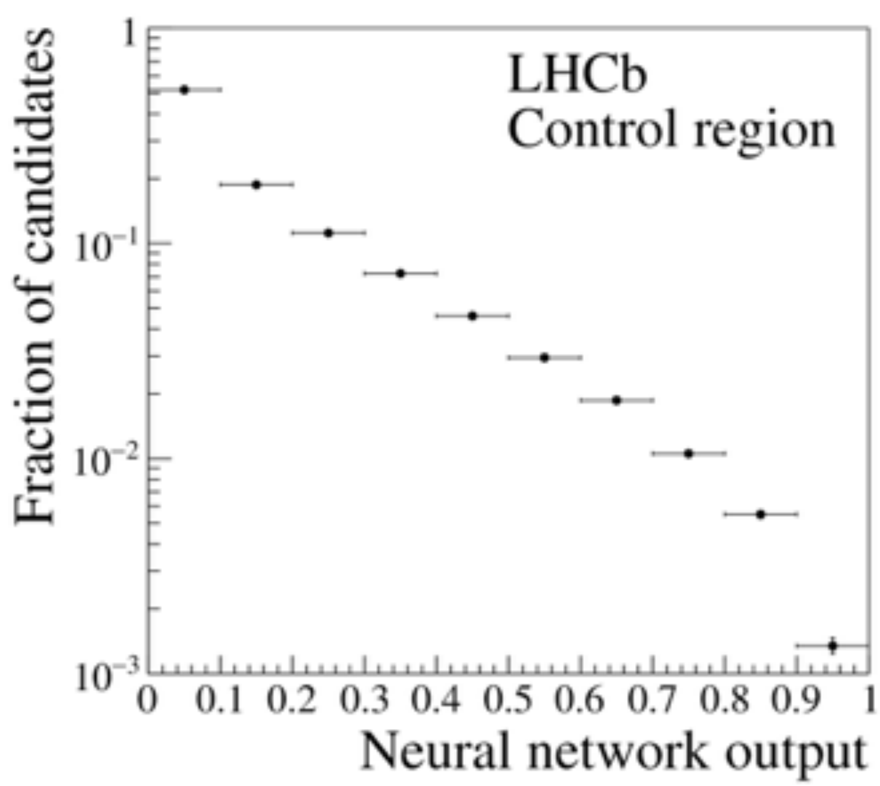
- tau leptons selected in $\tau \to \pi^+\pi^-\pi^+\bar{\nu}_\tau$.
- Simulated tau decay model tuned on BaBar
- 2 missing neutrinos, very challenging for LHCb $\to$ B_s and B^0 peaks cannot be resolved
- Previous result only on B^0 from BaBar: BF($B^0 \to \tau^+\tau^-$) < 4.1×10^{-3} at 90% CL

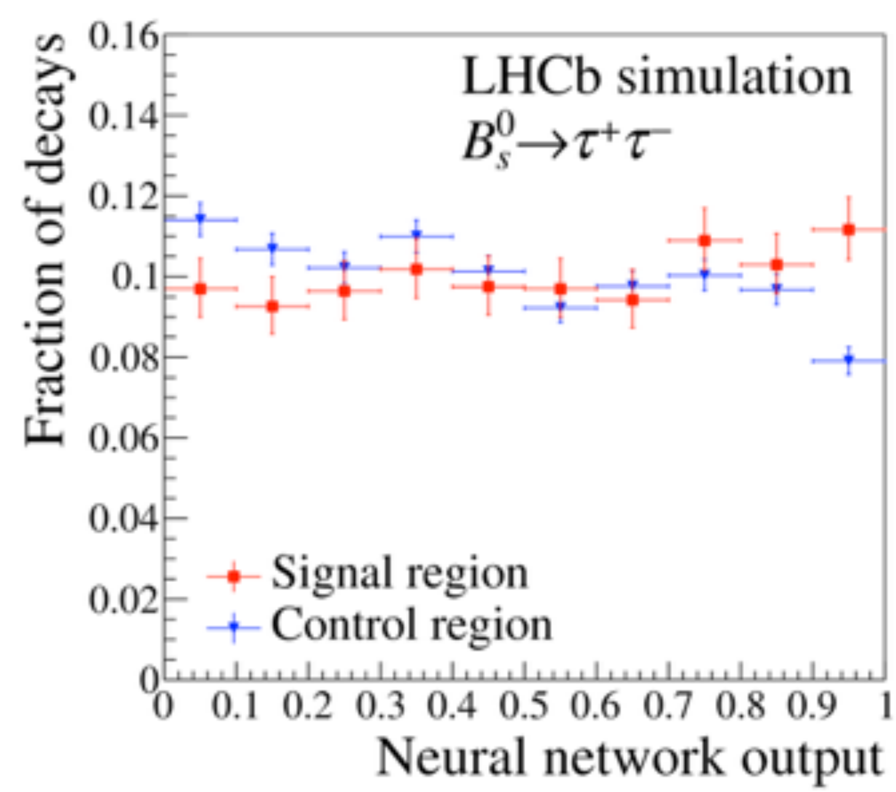
[PRL 96 (2006) 241802]

$B^0_s \to \tau^+\tau^-$ [PRL 118 (2017) 251802]

- Analysis performed on Run1 data
- Intermediate $\rho^0(770)$ resonance exploited to tag candidates
- After a loose preselection a NN built using kinematic, geometric and isolation variables used for signal/background separation







$B^0_s \to \tau^+\tau^-$ [PRL 118 (2017) 251802]

- $B^0 \to D^+(K^-\pi^+\pi^+)D^-_s(K^-K^+\pi^+)$ used as normalisation channel
- Result compatible with background only hypothesis.
- Observed upper limit:

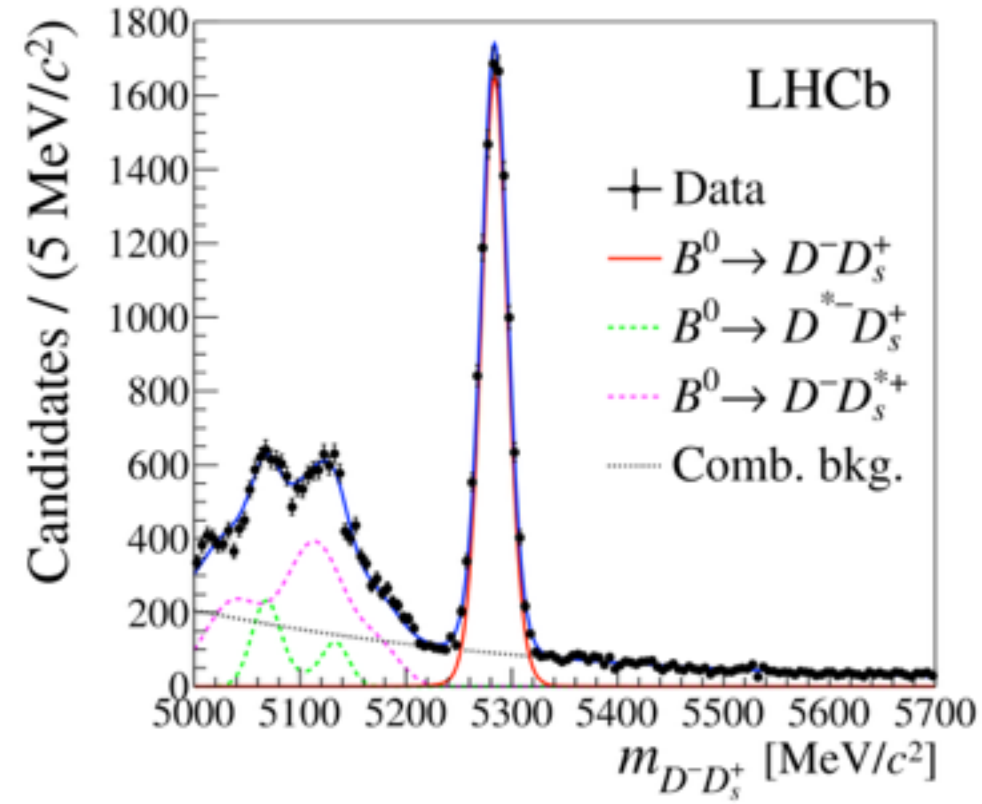
$$\mathcal{B}(B^0_s \to \tau^+\tau^-) < 5.2(6.8) \times 10^{-3} \text{ @90 (95)\% CL}$$

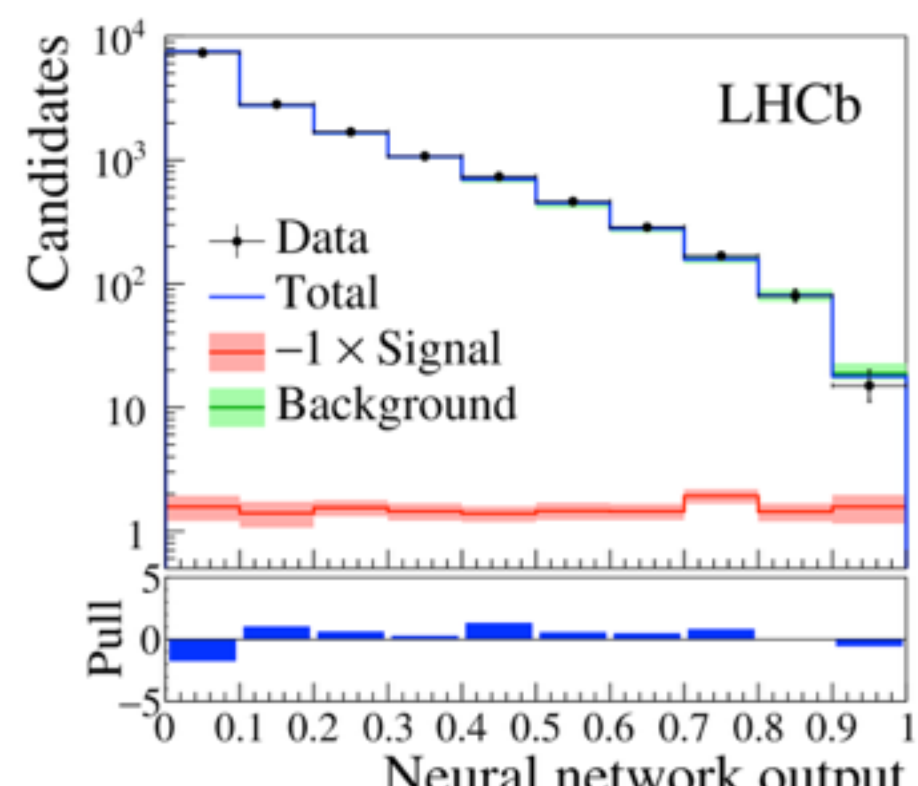
- Assuming signal fully dominated by B^0:

$$\mathcal{B}(B^0 \to \tau^+\tau^-) < 1.6(2.1) \times 10^{-3} \text{ @90 (95)\% CL}$$

- x4 improvements w.r.t. previous result from BaBar [PRL 96 (2006) 241802]

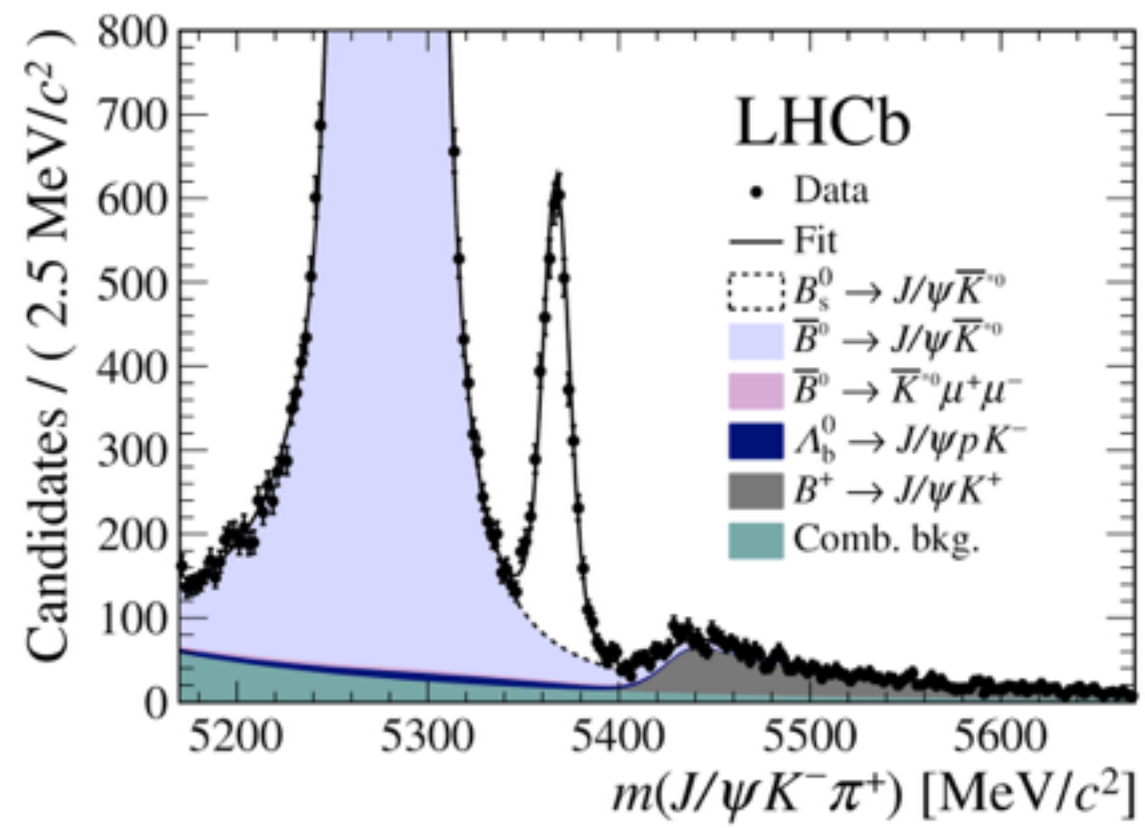
N^{obs}_{D-D+s}=10629±114





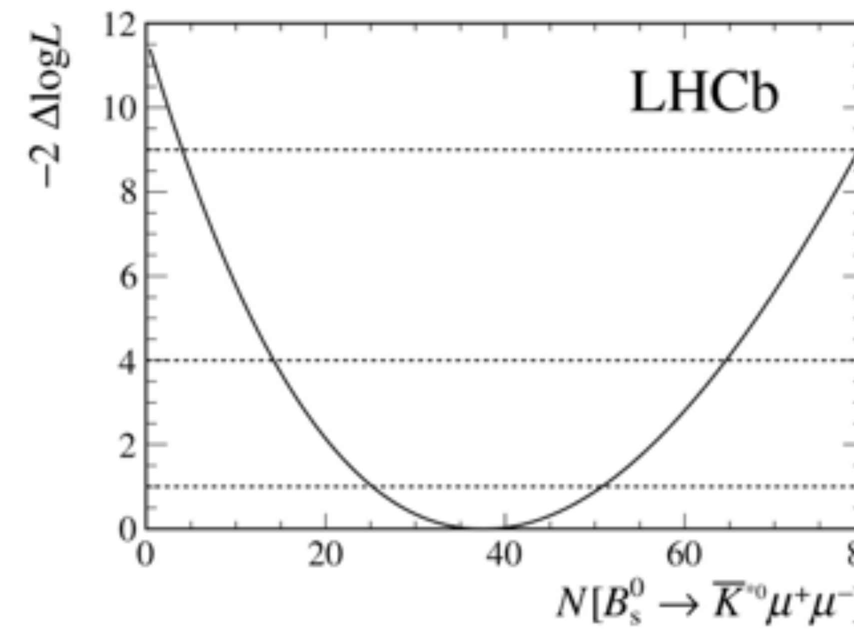
$B^0_s \to K^{*0}\mu^+\mu^-$ [arXiv:1804.07167]

- Several intriguing deviations observed in b→sll processes (see T. Humair's talk)
- b→dll transitions even more suppressed than b→sll transitions ($|V_{td}|/|V_{ts}| \sim 0.2$)
- LHCb already observed the $B^+\to\pi^+\mu^+\mu^-$ decay [JHEP 10 (2015) 034]
- Search performed using 3fb^{-1} Run1 and 1.6fb^{-1} Run2 data outside J/ψ and ψ(2S) region
- Normalise to the decay $B^0\to J/\psi(\to \mu\mu)K^{*0}$



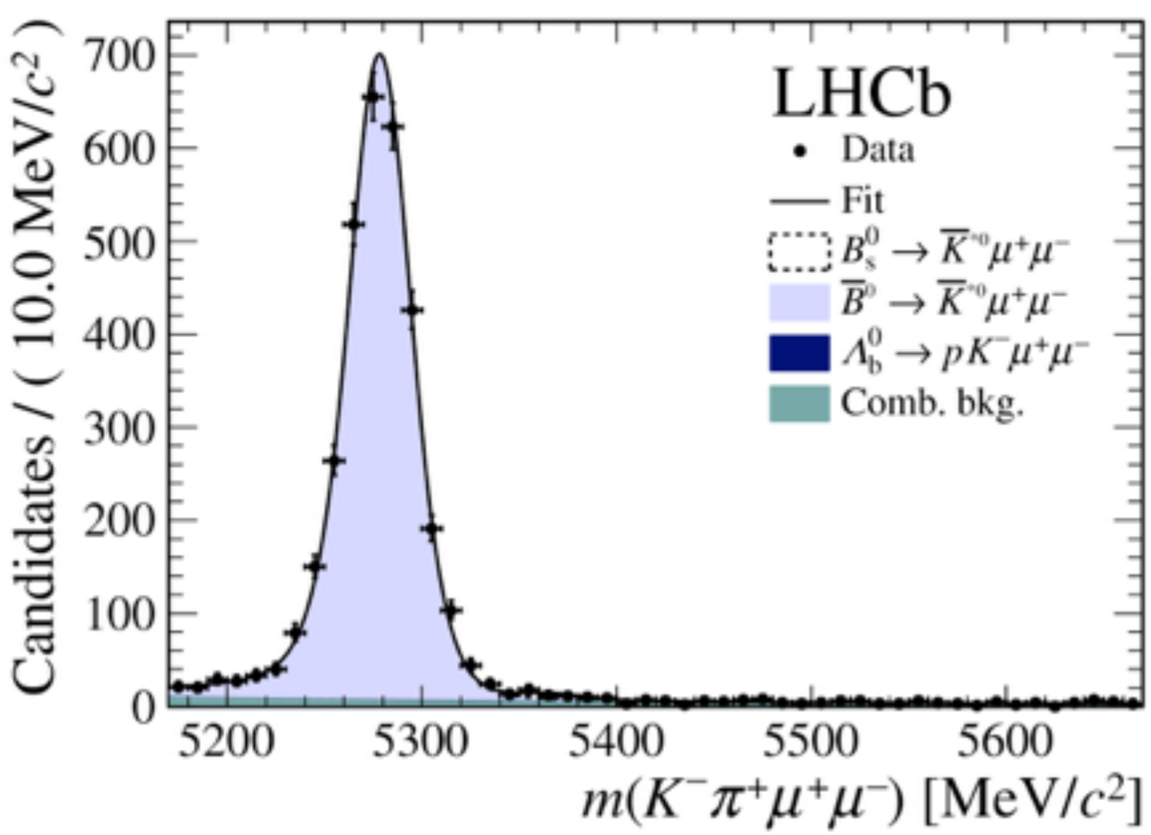
$B^0_s \to K^{*0}\mu^+\mu^-$

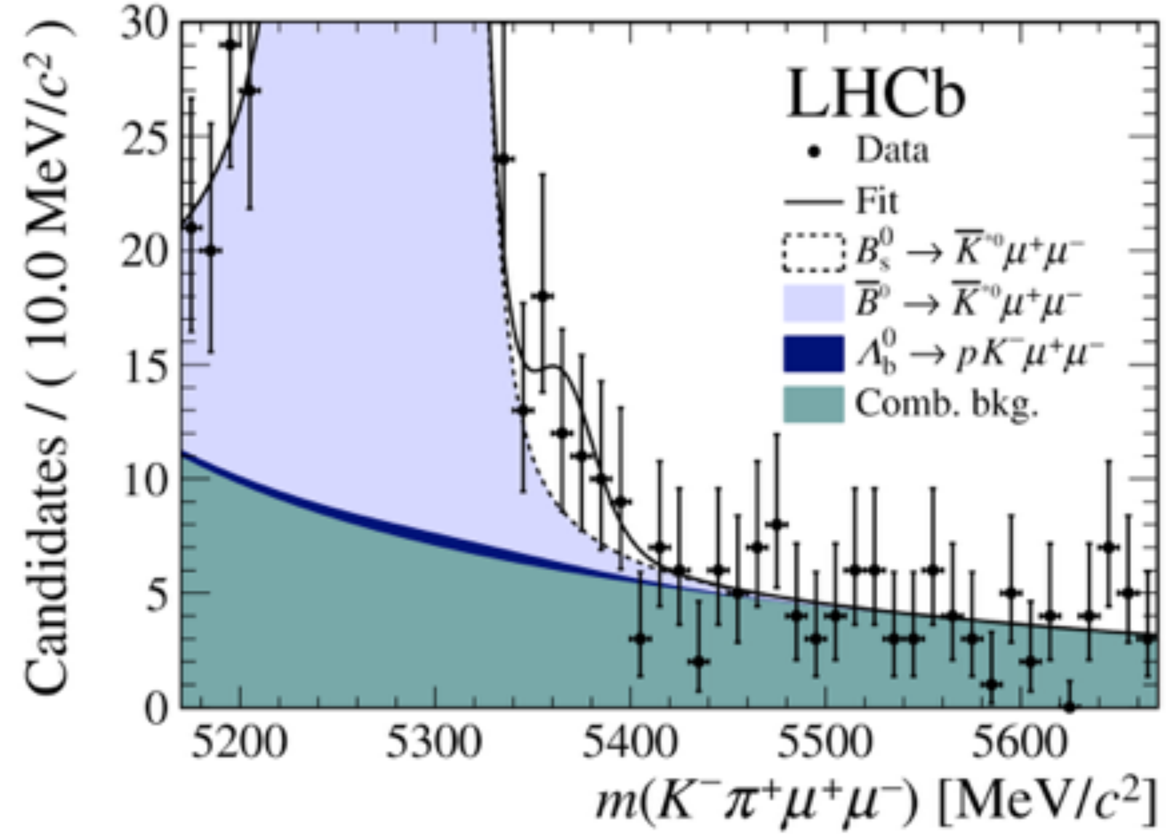
[arXiv:1804.07167]



- Observed 38±12 signal events
- First evidence at 3.4 σ for this decay

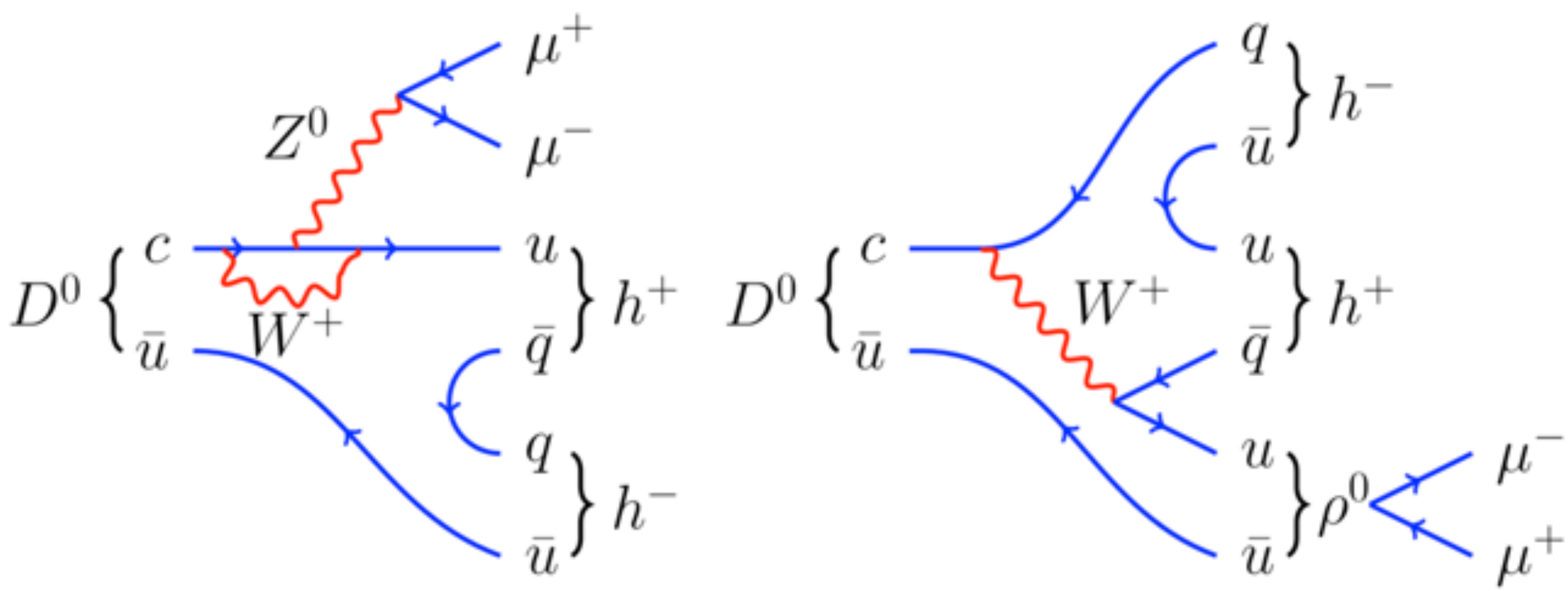
$$\mathcal{B}(B^0_s \to \overline{K}^{*0}\mu^+\mu^-) = [2.9 \pm 1.9(\text{stat}) \pm 0.2(\text{syst}) \pm 0.3(\text{norm})] \times 10^{-8}$$





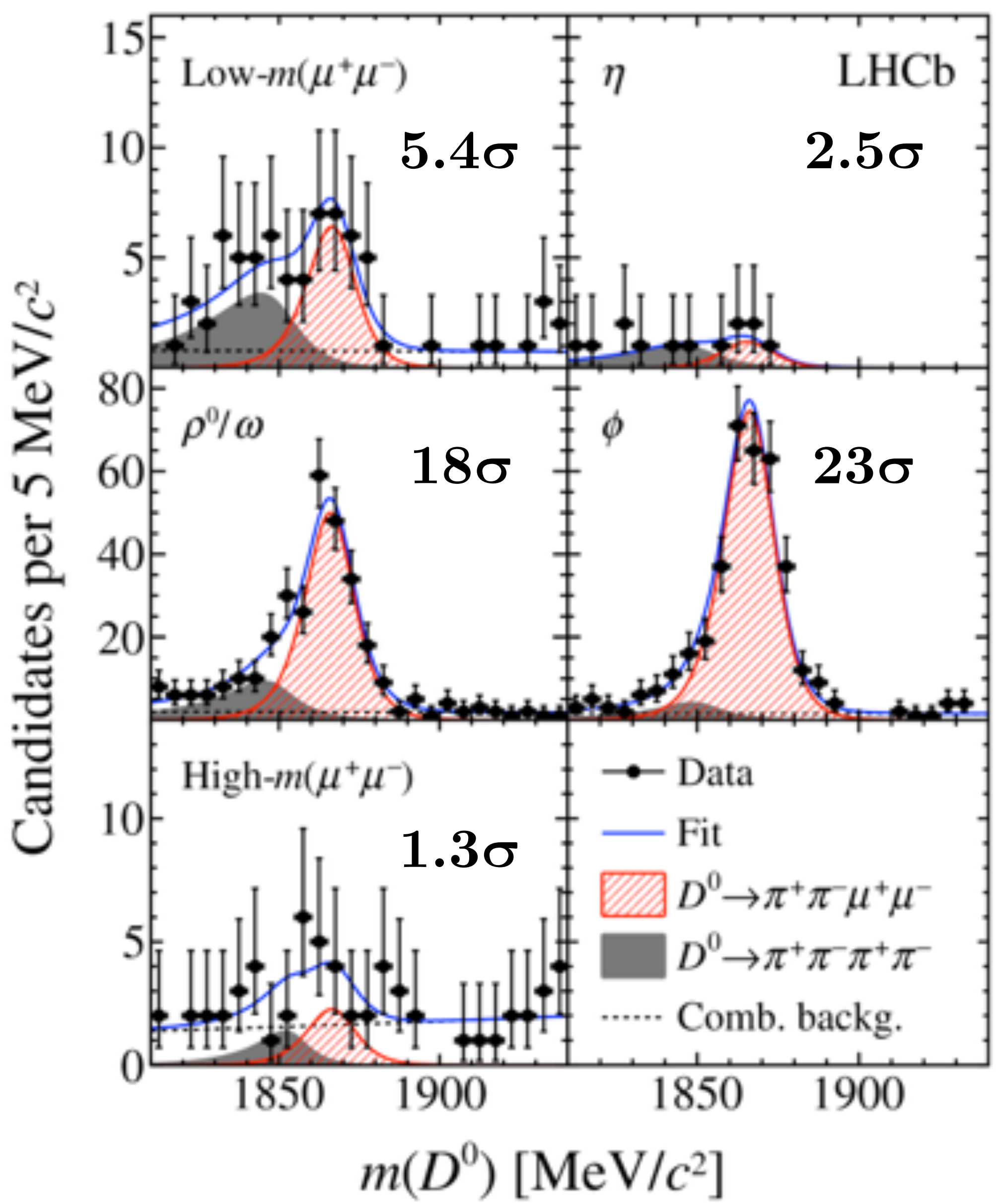
Rare charm

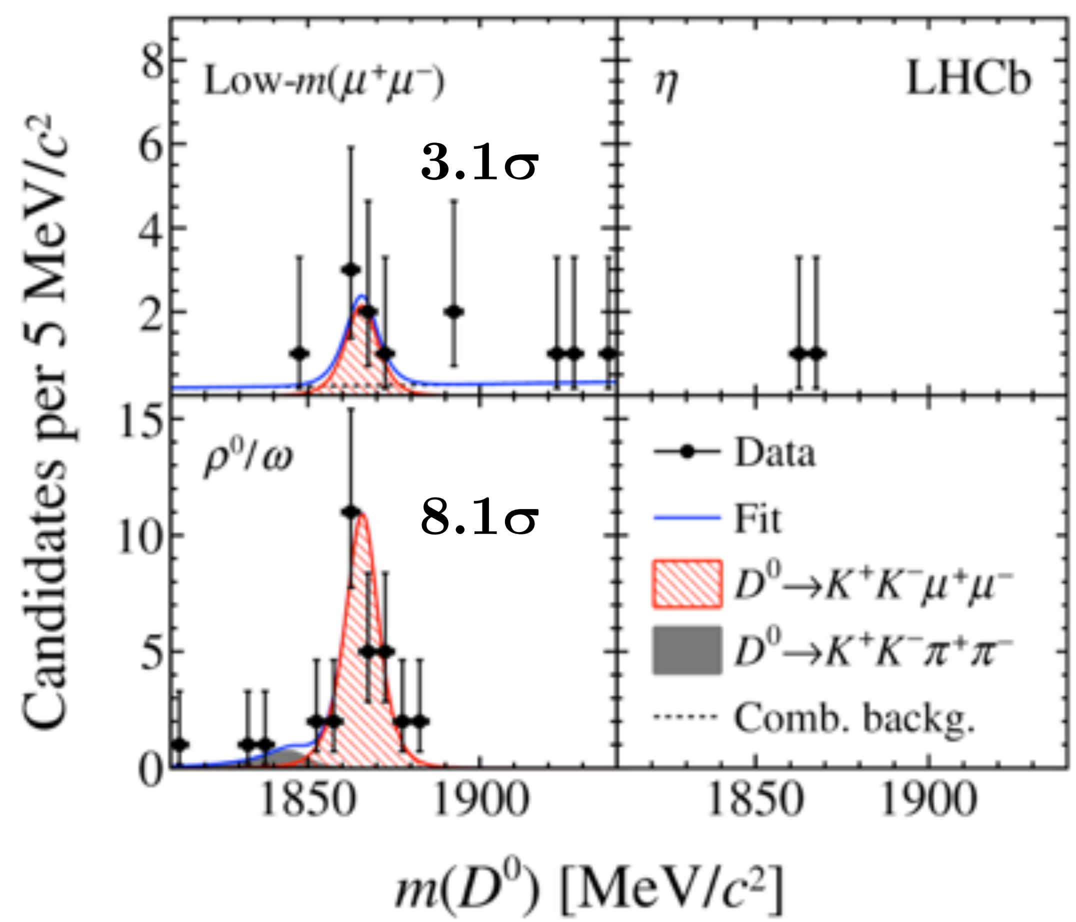
- FCNC process in the up-type quark sector $\rightarrow$ unique probe for BSM effects
- SM amplitude dominated by long-distance contribution proceeding through intermediate vector resonance in the dimuon spectrum
- non-resonant contribution expected at 10^{-9} in the SM



$D^0 \to h^+h^-\mu^+\mu^-$ [PRL 119 (2017) 181805]

- Search for $D^0 \to h^+h^-\mu^+\mu^-$ decays on 2fb^{-1} of Run1 data
- Exploited $D^{*+} \to D^0\pi^+$ decays to suppress combinatorial background
- $D^0 \to K^+\pi^-\mu^+\mu^-$ decay used as normalisation





$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97) \times 10^{-7}$$

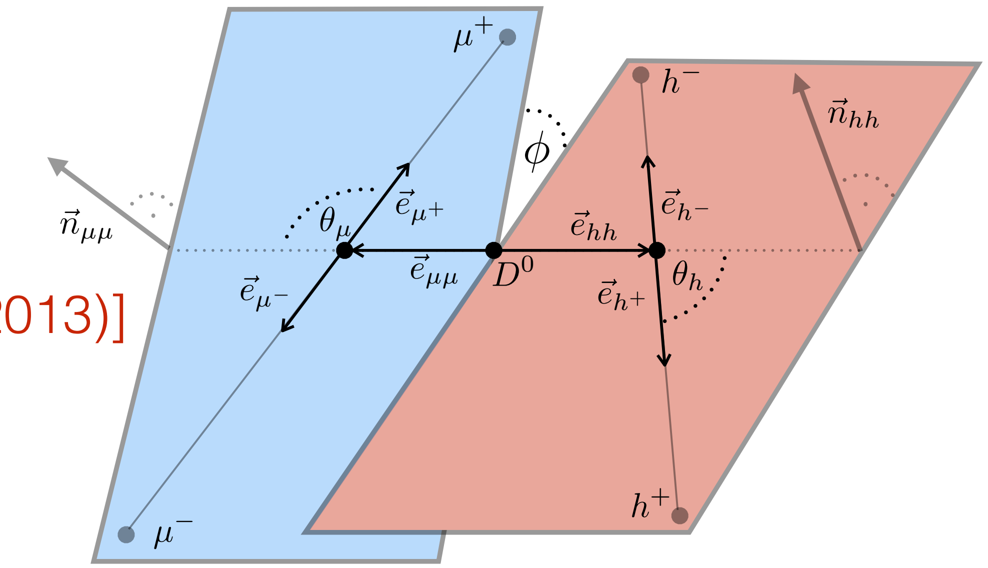
$$\mathcal{B}(D^0 \to K^+K^-\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16) \times 10^{-7}$$

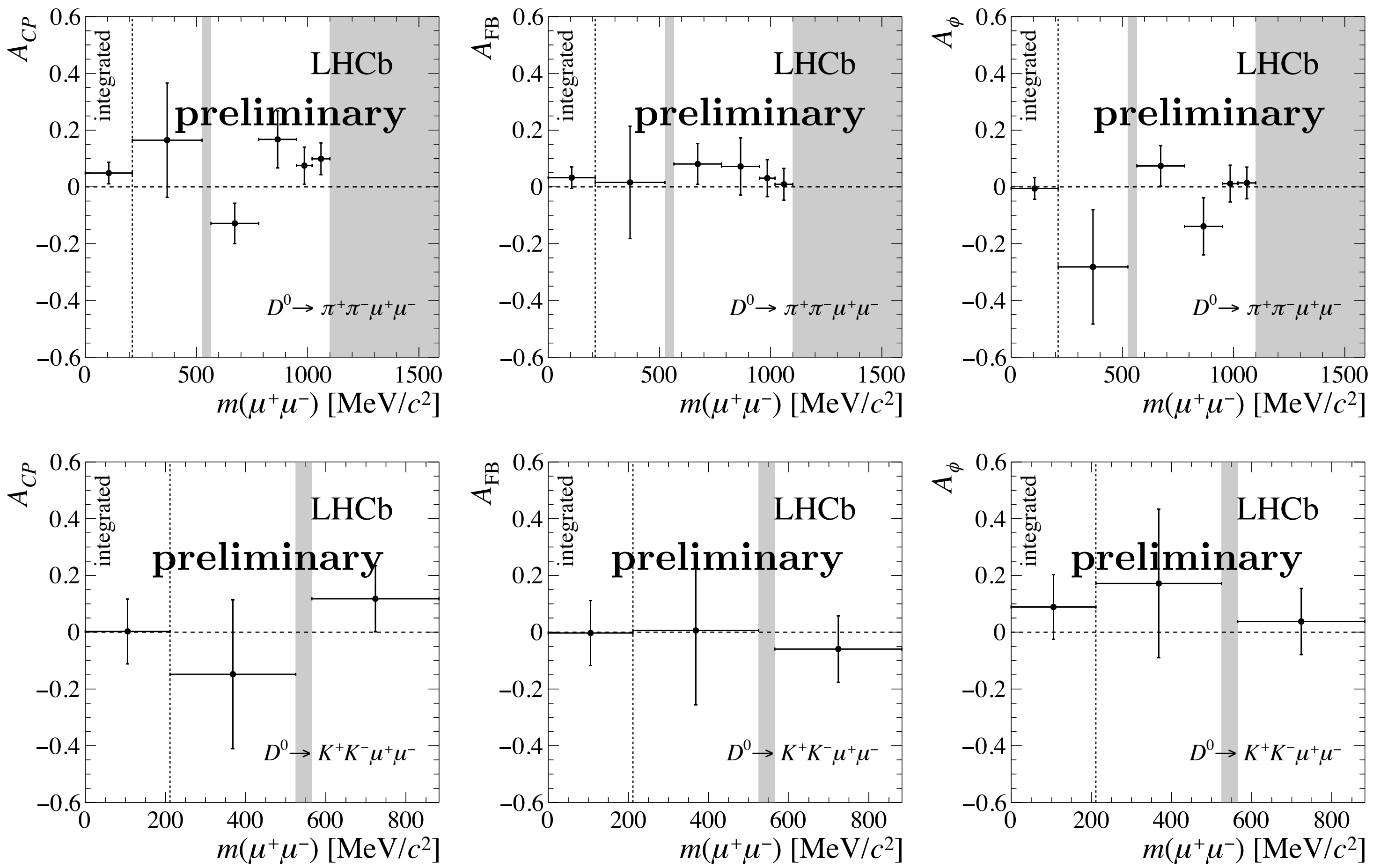
Rarest charm decay ever observed!

[LHCb-PAPER-2018-020]

$D^0 \to hh\mu\mu$ asymmetries

- Measurement of angular and CP asymmetries
- Deviation of O(few%) for some NP models [JHEP 1304 135 (2013), PRD 87 054026(2013)]
- Analysis on $5 fb^{-1}$ (2011-2016)





forward-backward asymmetry

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

triple product asymmetry

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

CP asymmetry

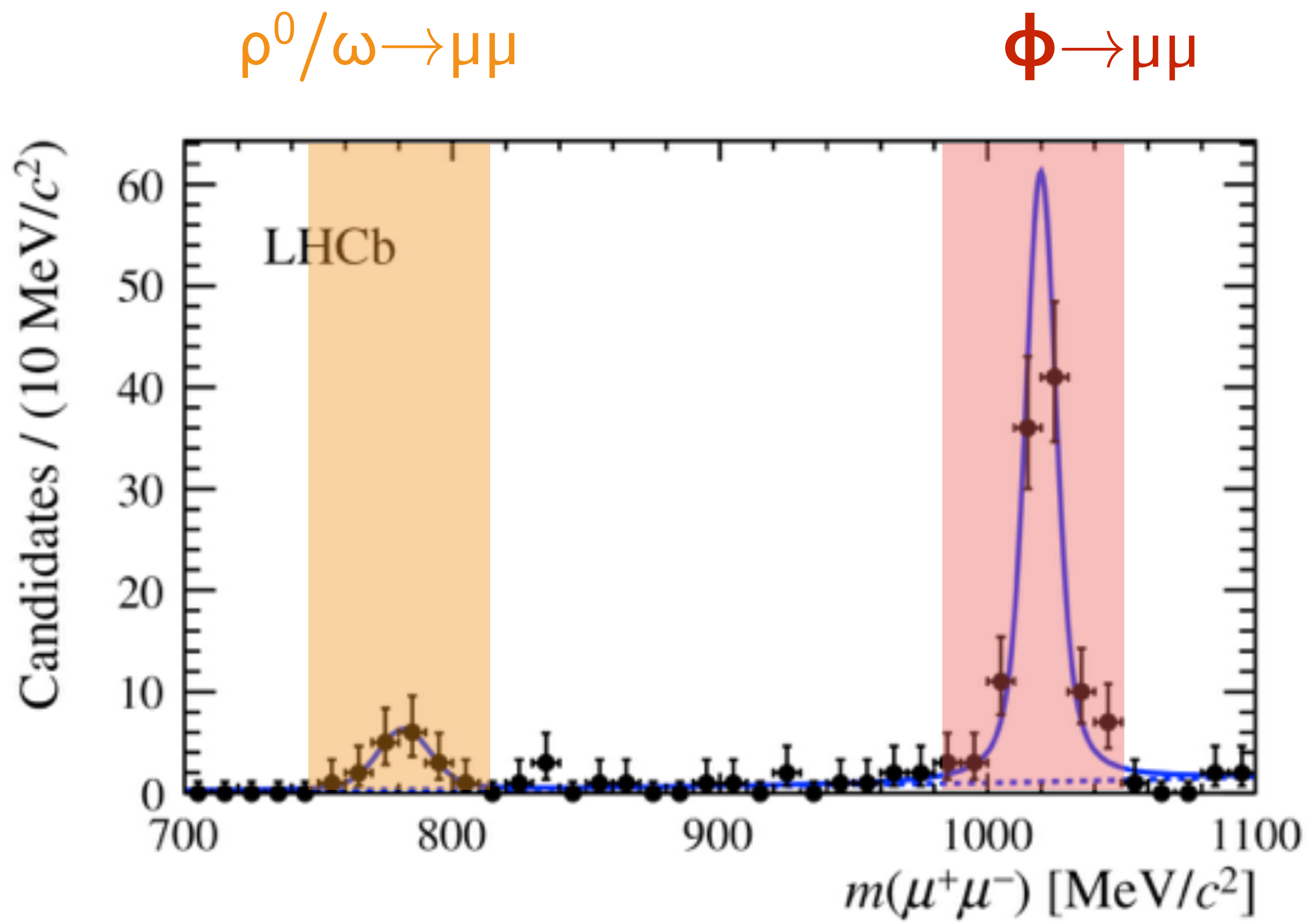
$$A_{CP} = \frac{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) - \Gamma(\overline{D}^0 \to h^+h^-\mu^+\mu^-)}{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) + \Gamma(\overline{D}^0 \to h^+h^-\mu^+\mu^-)}$$

All asymmetries consistent with zero

$\Lambda_c \to p\mu\mu$

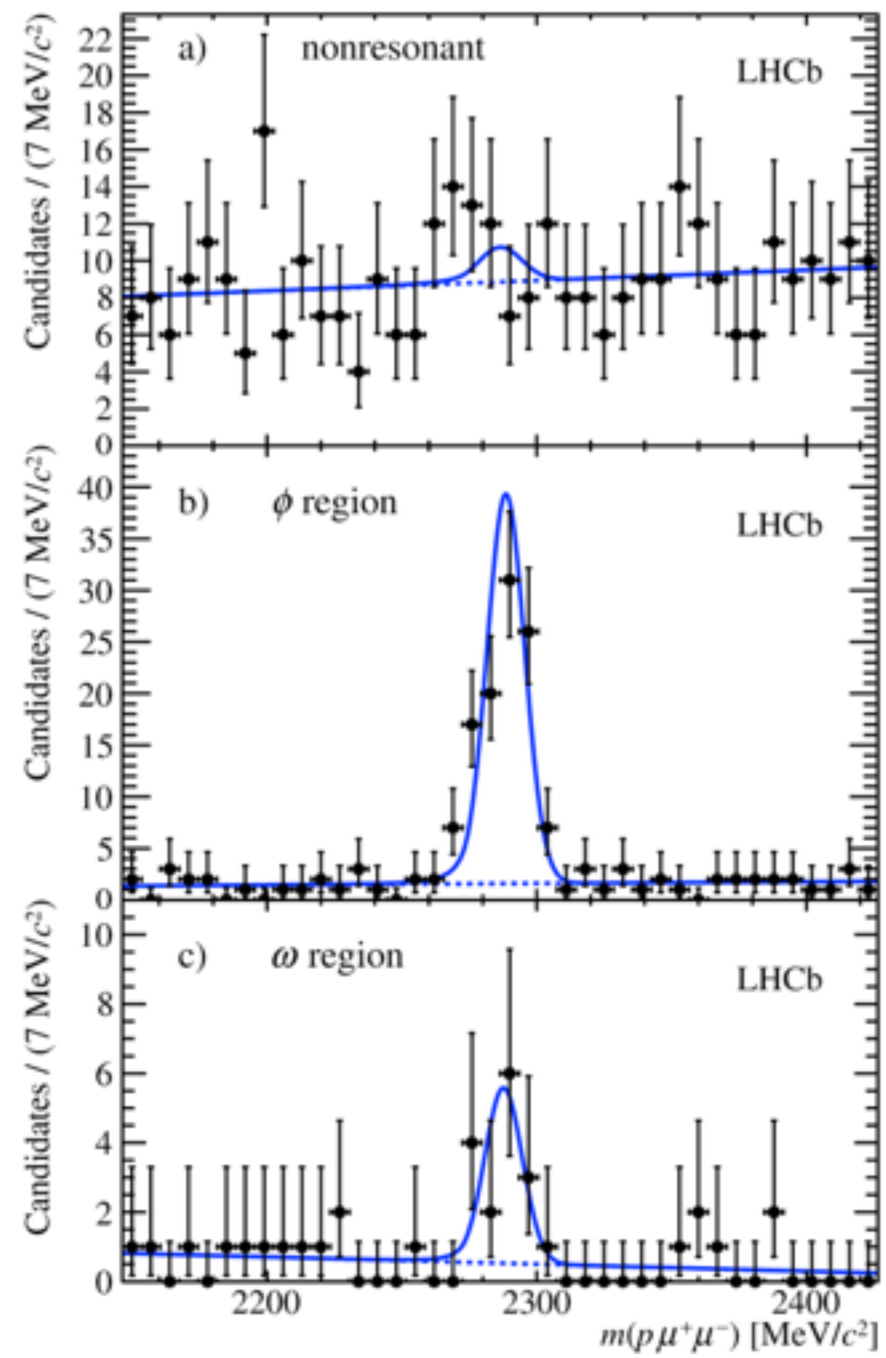
[PRD 97 (2018) 091101]

- Rare baryonic $c \to ull$ FCNC process
- SM short distance contribution expected to be $\sim 10^{-9}$
- Previous limit from BaBar at 4×10^{-5} @90% CL
- Search performed on $3 fb^{-1}$ of Run 1 data
- Performed in three region of $m_{\mu\mu}$:
  - Normalised to the resonant mode $\Lambda_c \to p\phi(\to\mu\mu)$
  - Searches performed in region around ρ^0/ω invariant mass region, and non-resonant region



$\Lambda_c \rightarrow p\mu\mu$

[PRD 97 (2018) 091101]



- No significant excess observed in the non-resonant region:

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

- factor ~1000x better than the previous limit from BaBar. [PRD 84 (2011) 072006]

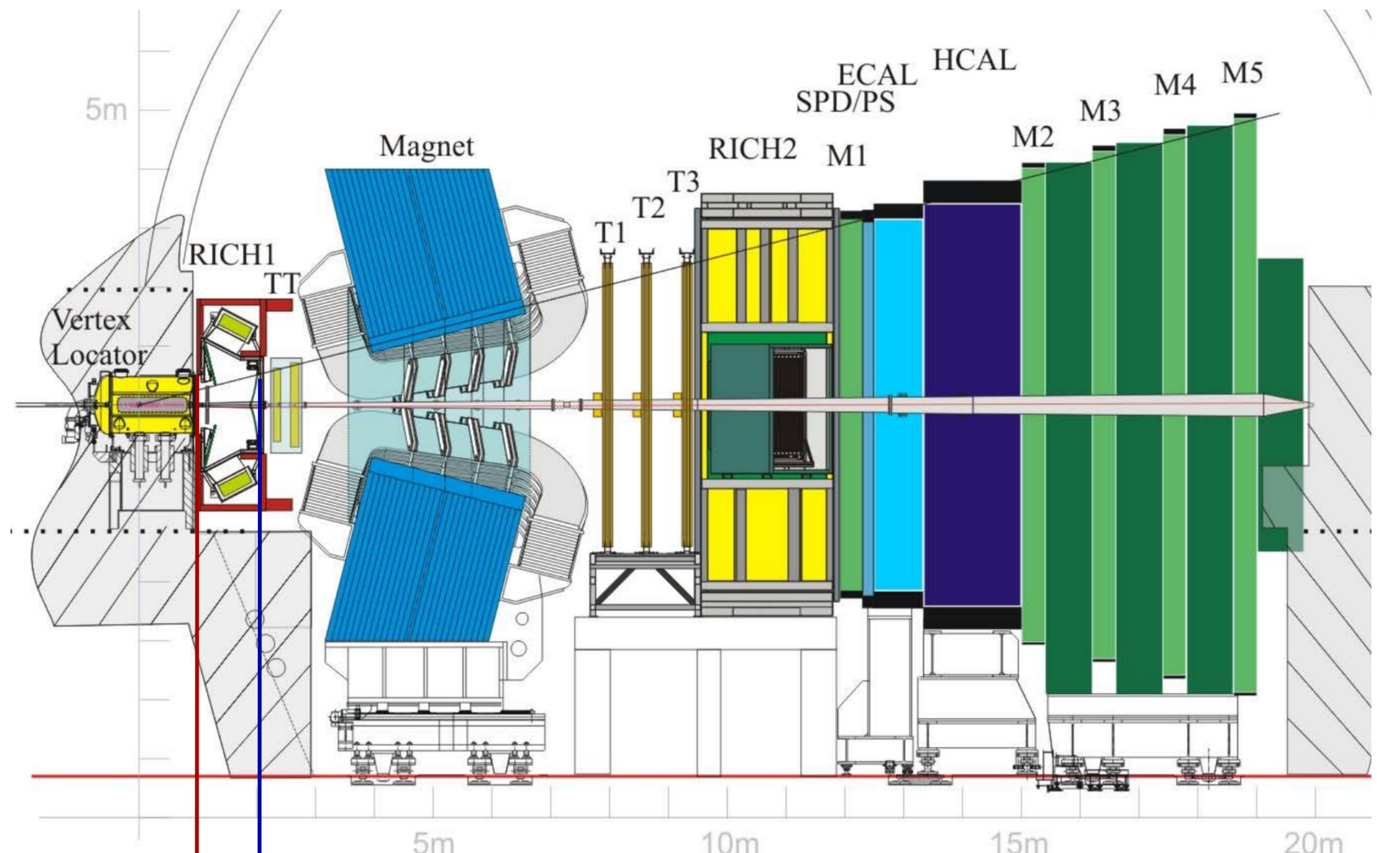
- First observation in the ρ/ω region

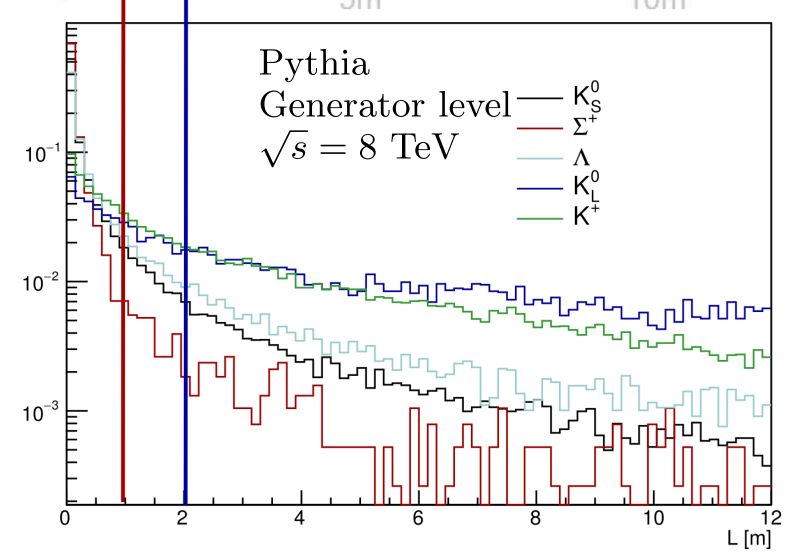
$$\mathcal{B}(\Lambda_c^+ \to p[\mu^+\mu^-]_{\rho/\omega}) = [9.4 \pm 3.2(\text{stat}) \pm 1.0(\text{syst}) \pm 2.0(\text{norm})] \times 10^{-4}$$

Strange @LHCb

- b/c hadrons $\tau \sim 10^{-12}$s
- Flight distance ~mm

- Strange hadrons $\tau \sim 10^{-10}$s
- Flight distance ~cm/m
- Low acceptance compensated by a huge production rate @LHCb: O(1) per collision



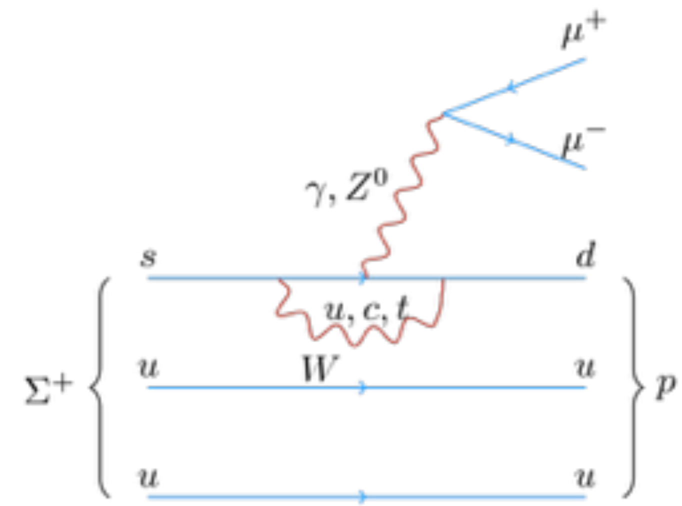


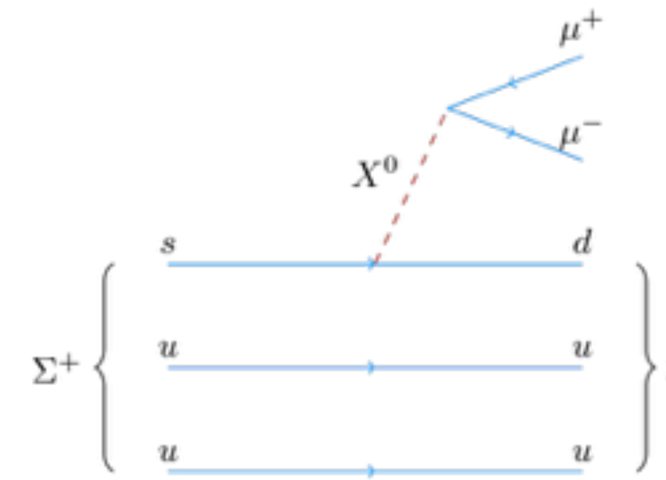
$\Sigma^+ \to p\mu^+\mu^-$

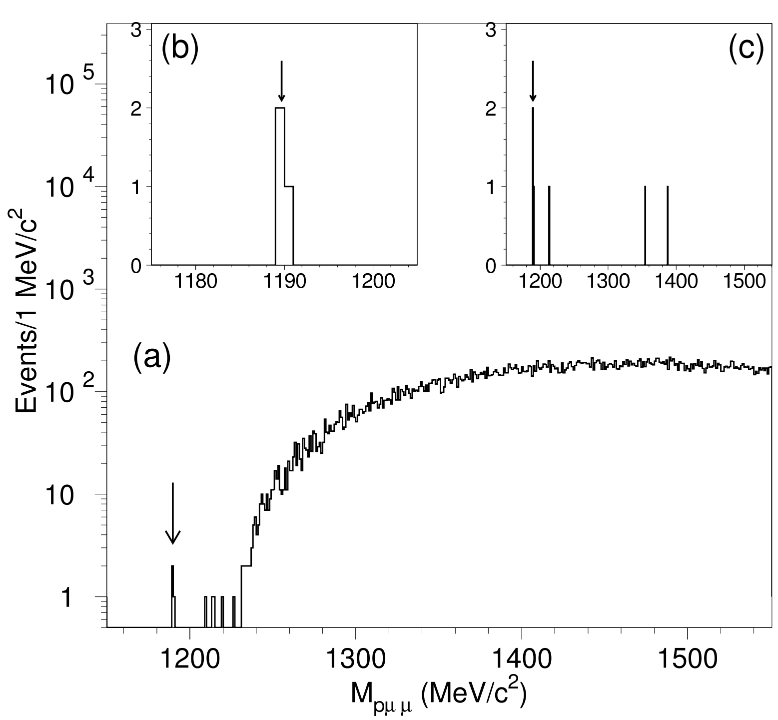
- $\Sigma^+ \to p\mu^+\mu^-$ decay is $s \to dll$ FCNC process
- dominated by long-distance contribution
- SM prediction $B(\Sigma^+ \to p\mu^+\mu^-)$ in $[1.6, 9.0] \times 10^{-8}$
- Evidence from HyperCP [Phys. Rev. Lett. 94, 021801 (2005)]

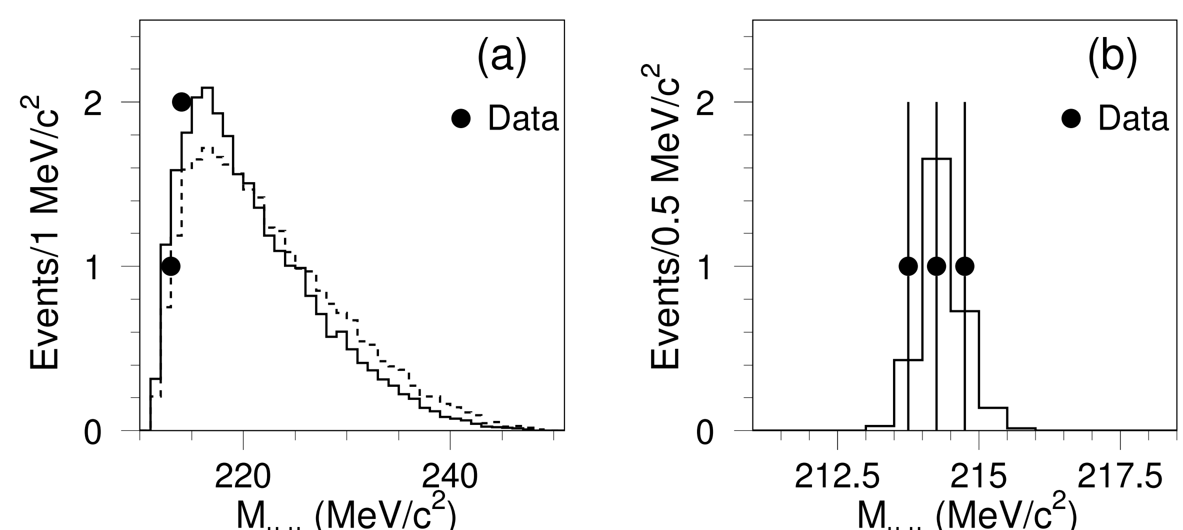
$$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (8.6^{+6.6}_{-5.4} \pm 5.5) \times 10^{-8}$$

  - 3 observed events in the same di-muon mass $\to$ possible existence of a new neutral particle







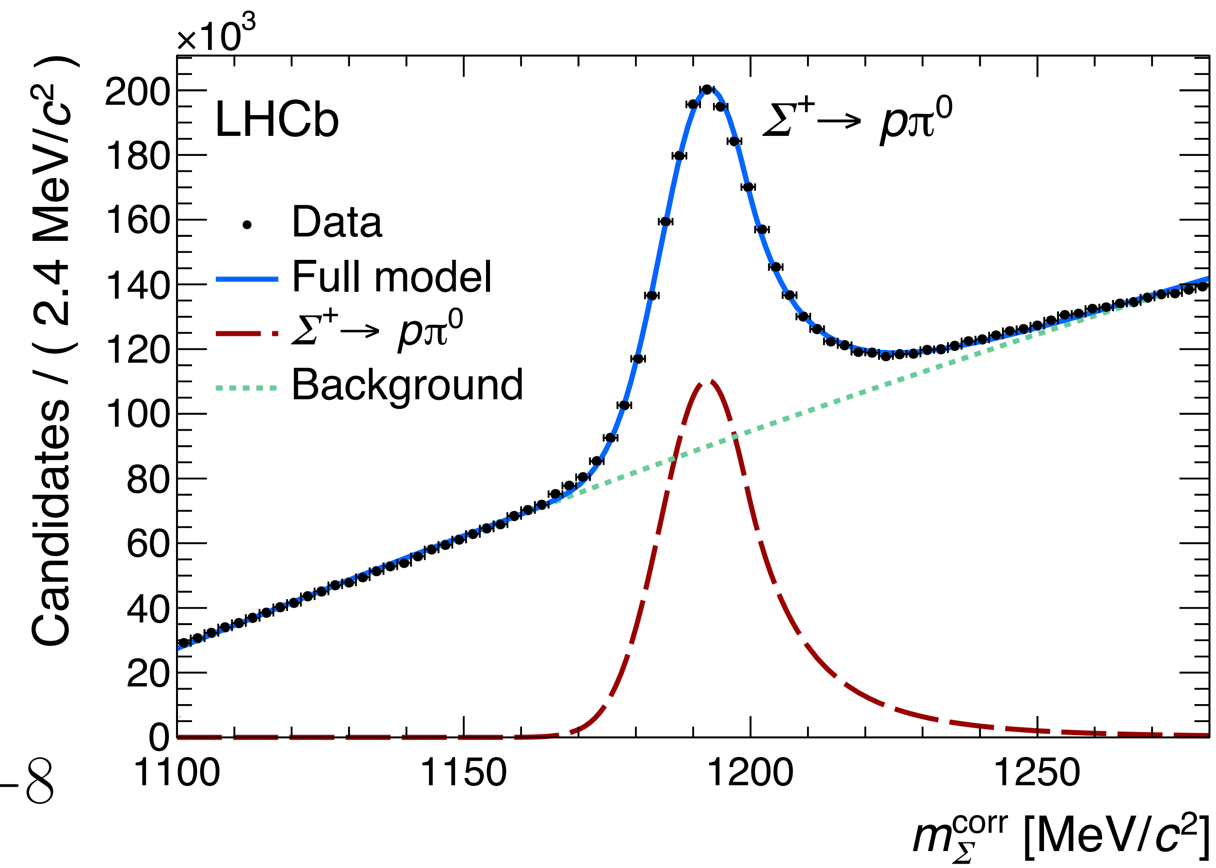


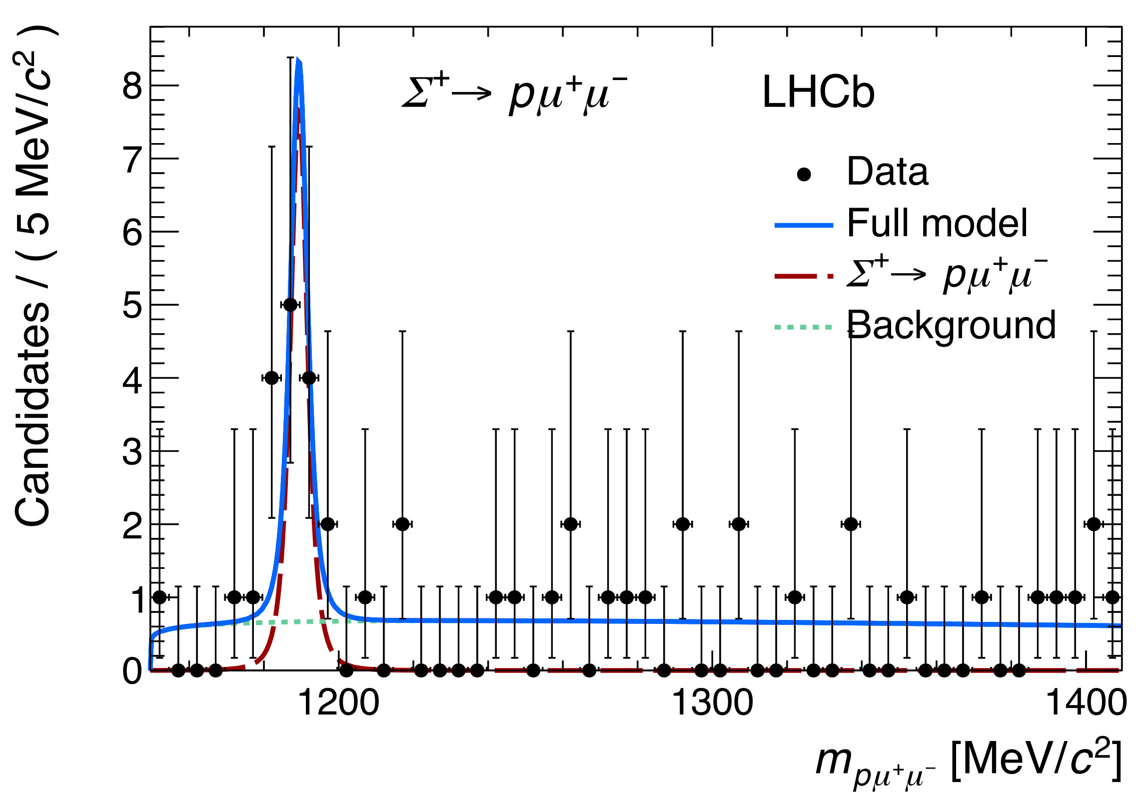
$\Sigma^+ \to p\mu^+\mu^-$

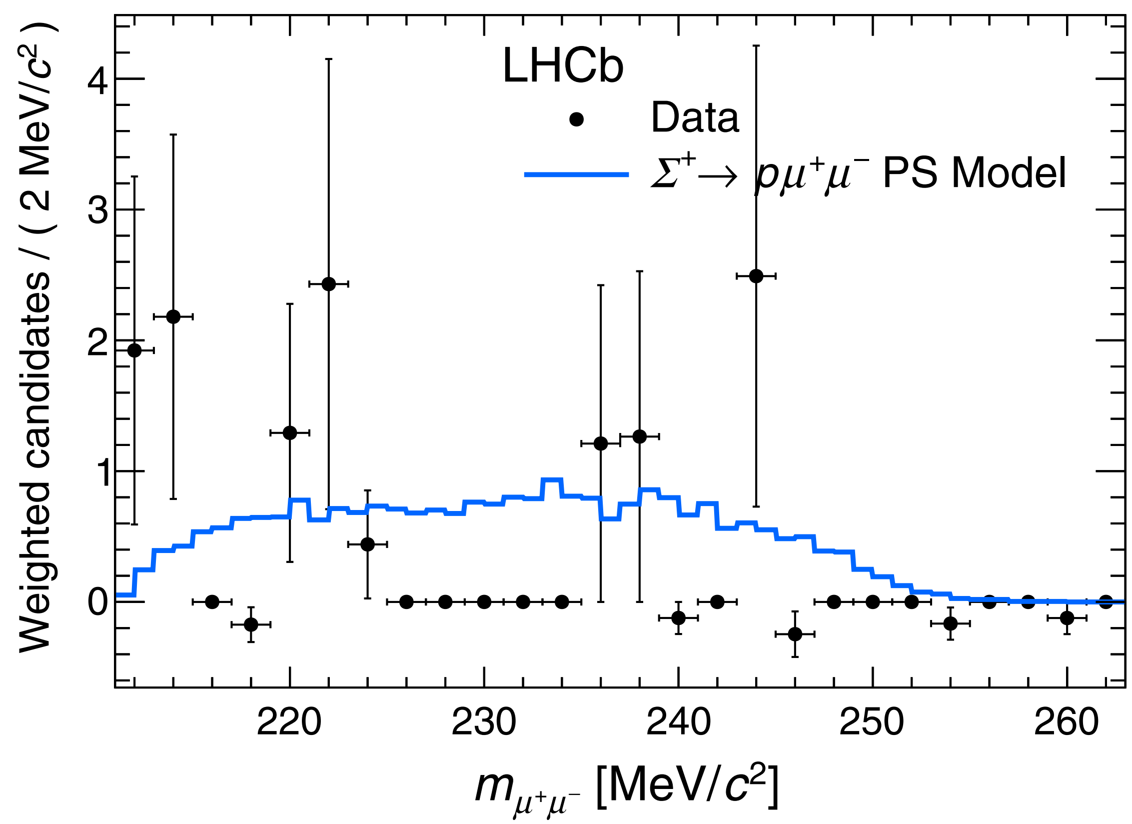
[PRL 120, 221803 (2018)]

- Search performed on 3fb^{-1} of Run 1 data
- Decay $\Sigma^+ \to p\pi^0$ used for normalisation
- Evidence at 4.1 σ but no structure observed in $m_{\mu\mu}$

$$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (2.2^{+0.9+1.5}_{-0.8-1.1}) \times 10^{-8}$$



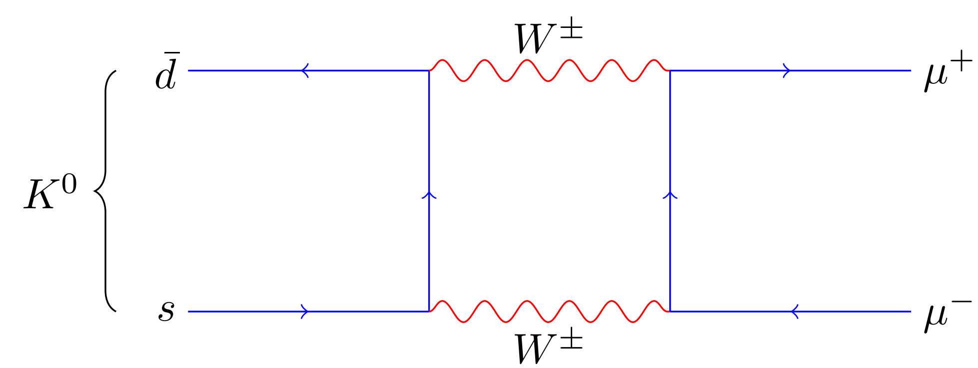


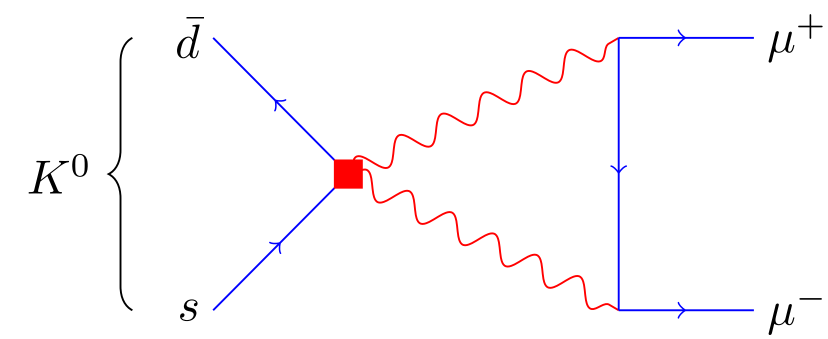


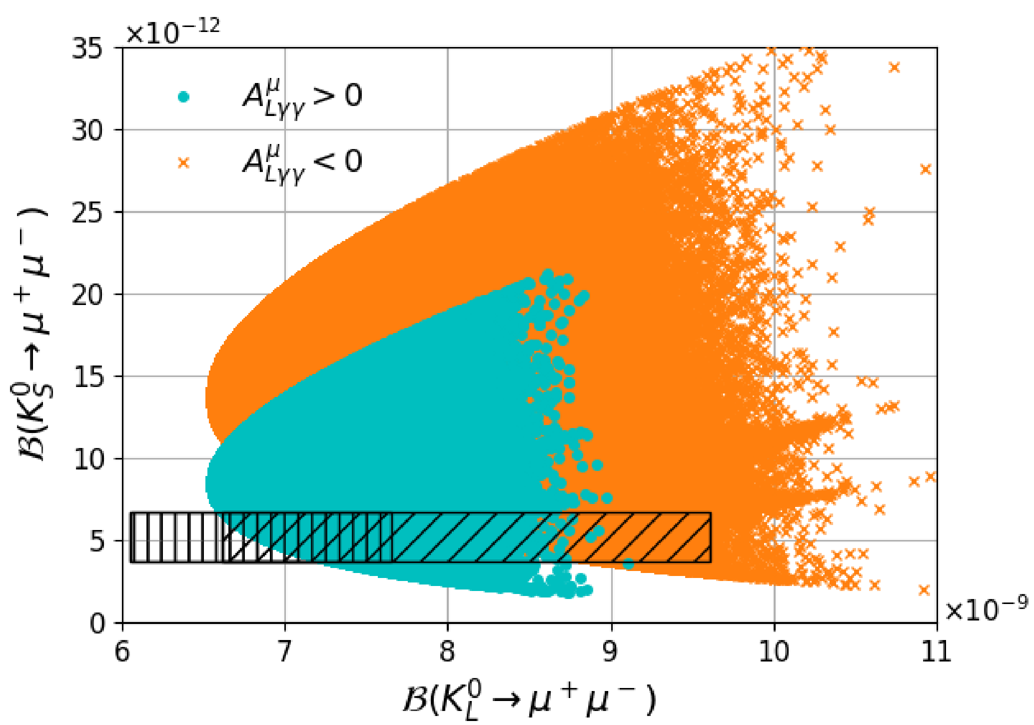
$K_S \to \mu^+\mu^-$

- Highly suppressed in the SM: FCNC s→ dll process. S-wave even more suppressed due to the small CPV.
- SM prediction at about 5.2×10^{-12} dominated by the long distance contribution
- Previous best limit from LHCb

$$\mathcal{B}(K_S \to \mu^+\mu^-) < 0.9 \times 10^{-8} \text{ @90\% CL}$$







example of a SUSY scenario

JHEP05(2018) 024

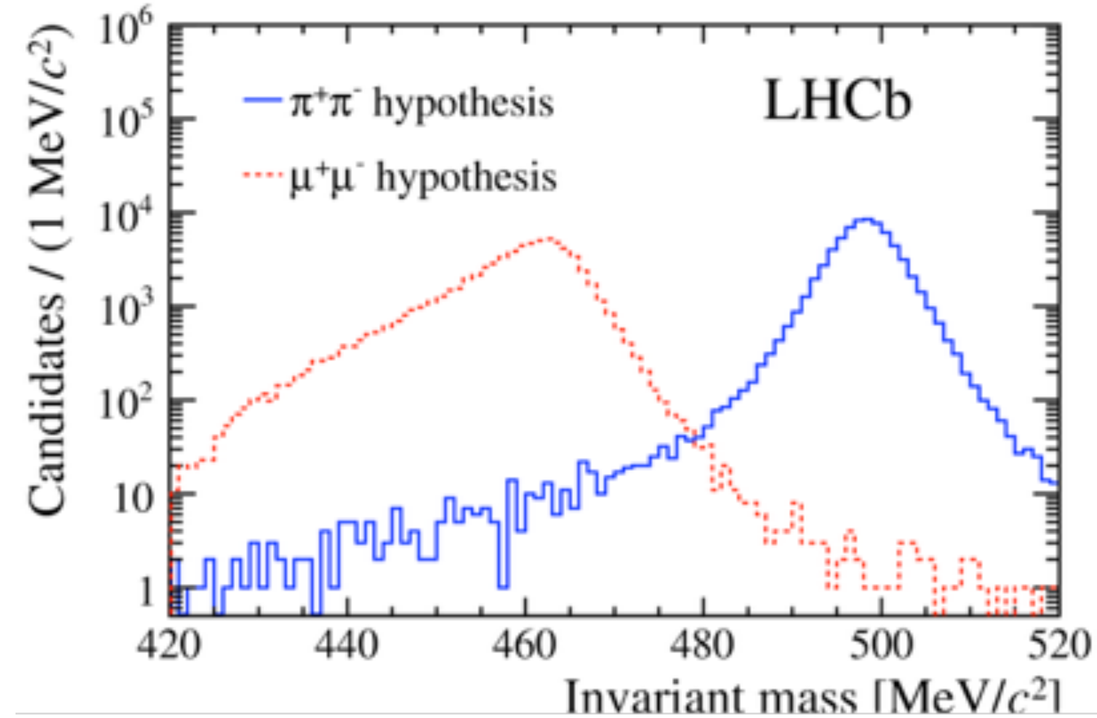
$K_S \to \mu^+\mu^-$

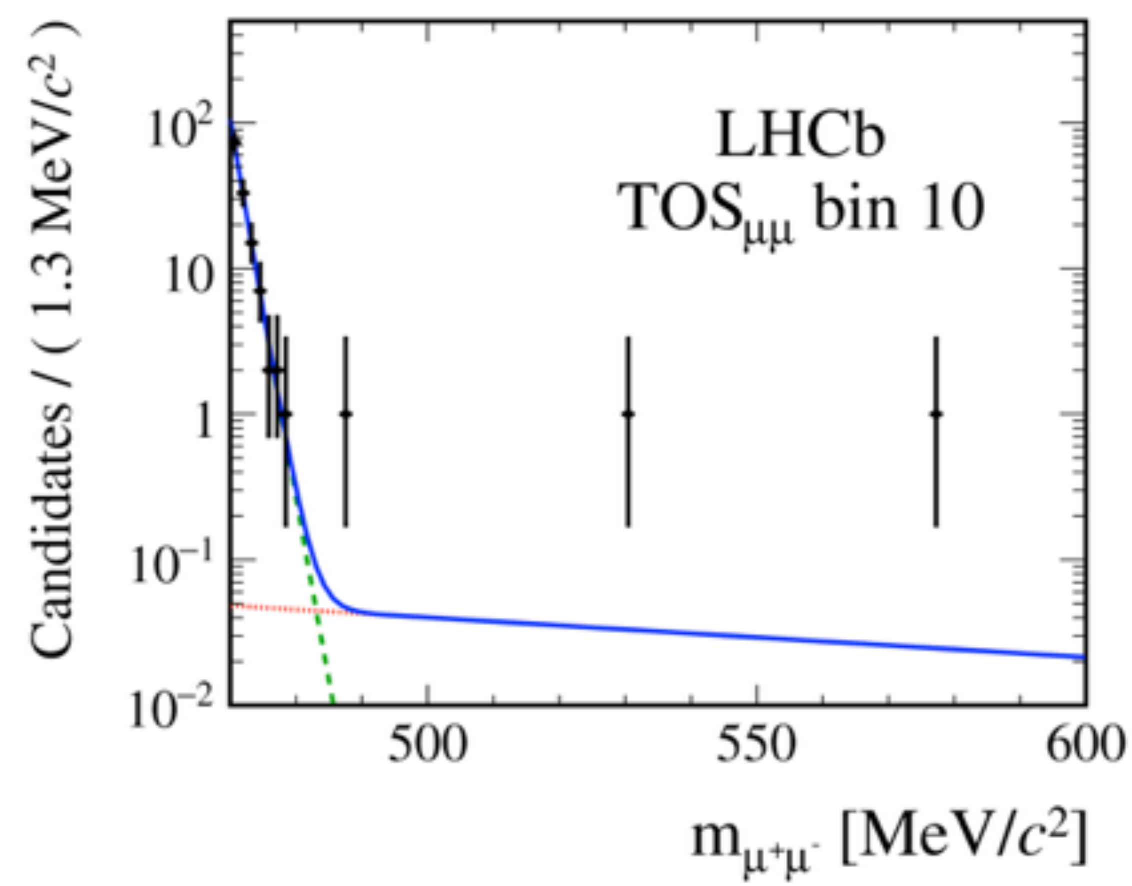
[EPJ C 77 (2017) 678]

- New result based on $3fb^{-1}$ of Run1 data
- Normalise w/ respect to $K_S \to \pi^+\pi^-$ which is also the main background
- Yield extracted from a fit in bins of MVA trained against $K_S \to \pi^+\pi^-$ background
- New limit on the BF:

$$\mathcal{B}(K_S \to \mu^+\mu^-) < 0.8 \times 10^{-9} \text{ @90\% CL}$$

- x11 better than previous result and x400 respect to pre-LHCb era
- SM value can be reached at the LHCb upgrade





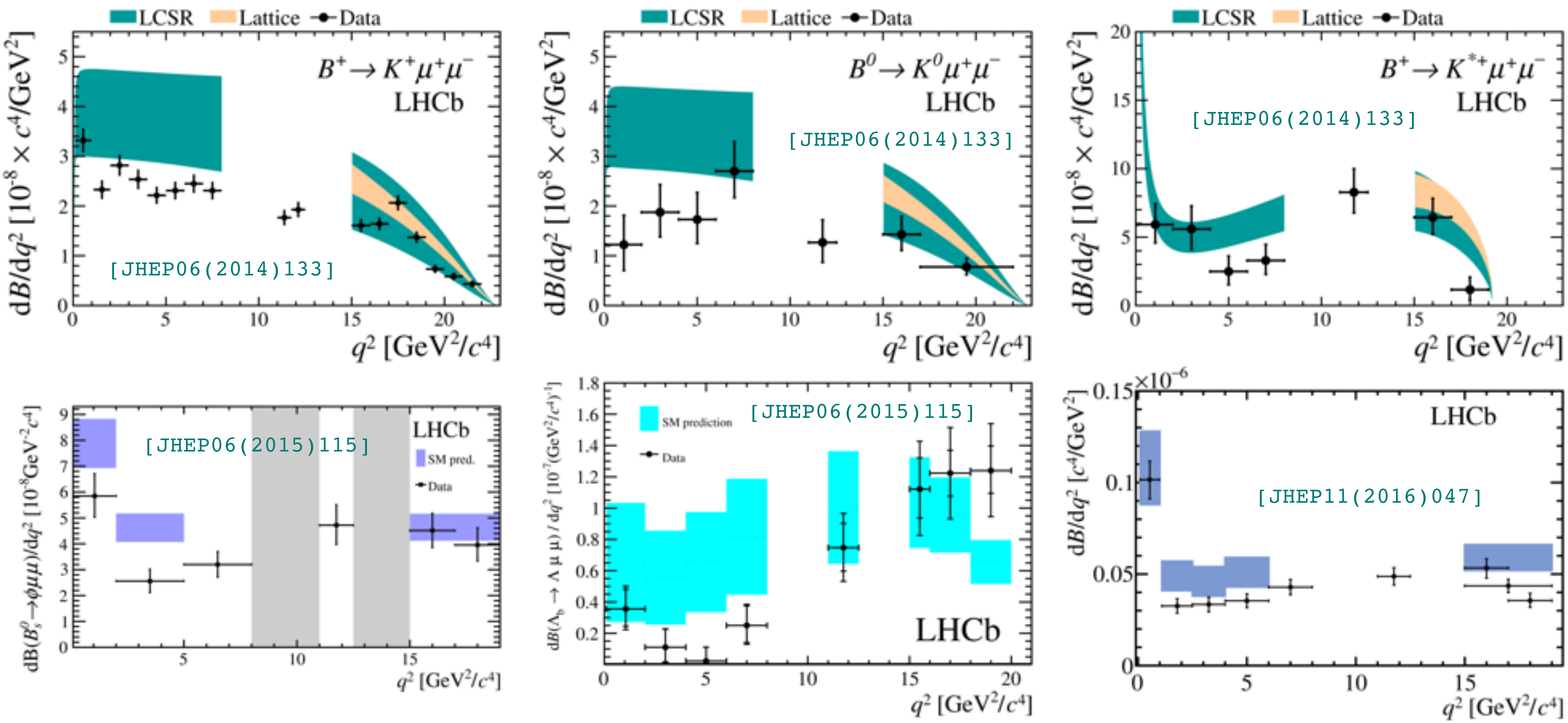
Conclusions

- FCNC processes provide powerful tools to probe the SM and NP scenarios
- LHCb is able to strongly impact on a variety of rare decays measurements
- Vary rare decays have provided stringent constraints on NP models
- Tantalising anomalies observed in LFU tests (see T. Humair's talk)
- Extremely interesting times ahead with new data from LHC and Belle II

backup

b→sll branching fractions

- Measurements of b→sll decay rates systematically below the SM predictions, 2-3 σ depending on the final state

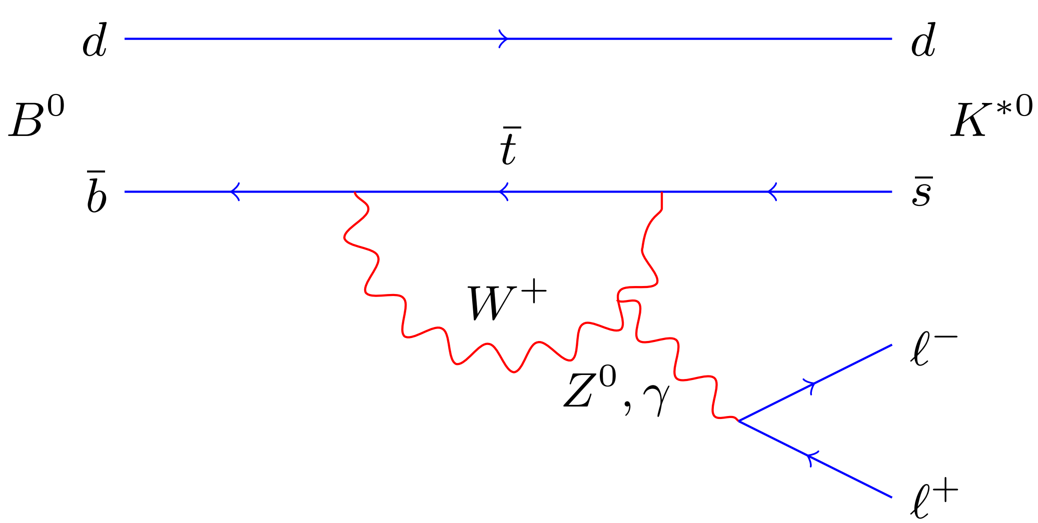


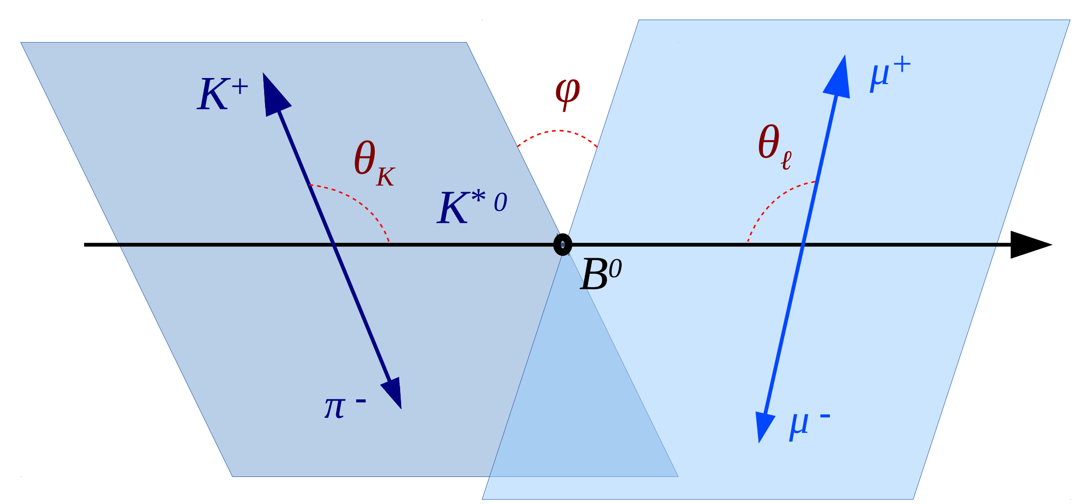
C_9 modification?

q^2 = four-momentum transferred to the di-leptons.

$B^0 \to K^{*0}\mu\mu$

- Differential decay rate of $B^0 \to K^{*0}\mu\mu$ as a function of the $q^2 = m_{\ell\ell}$ and three angles ($\theta_K, \theta_\ell, \varphi$)
- Angular coefficients depend on hadronic form factor $\rightarrow$ significant uncertainty at the leading order





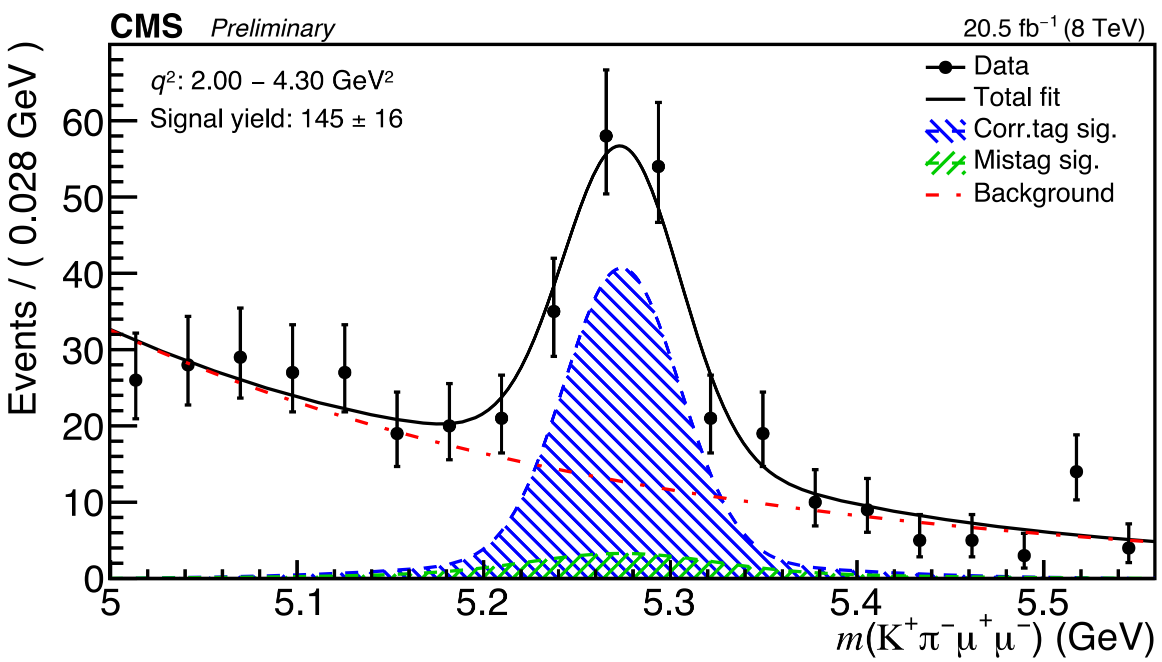
$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_\mathrm{L}\cos^2\theta_K\cos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

F_L = fraction of longitudinally polarised K*

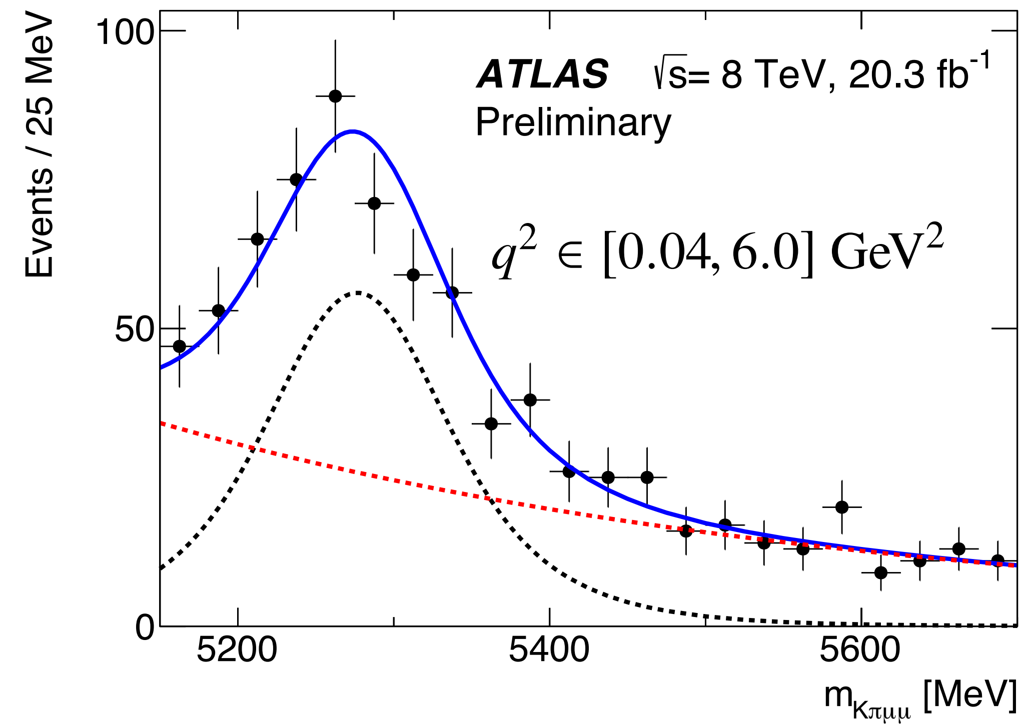
S_i = angular coefficients

Several recents measurements

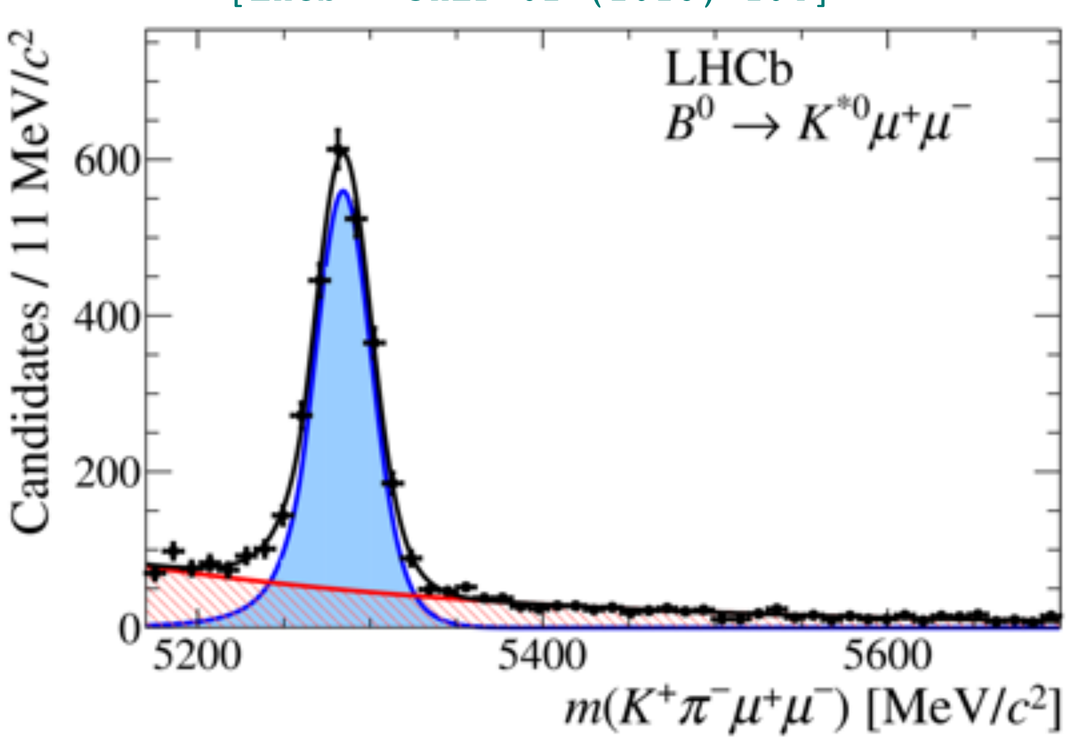
[CMS - CMS-PAS-BPH-15-008]



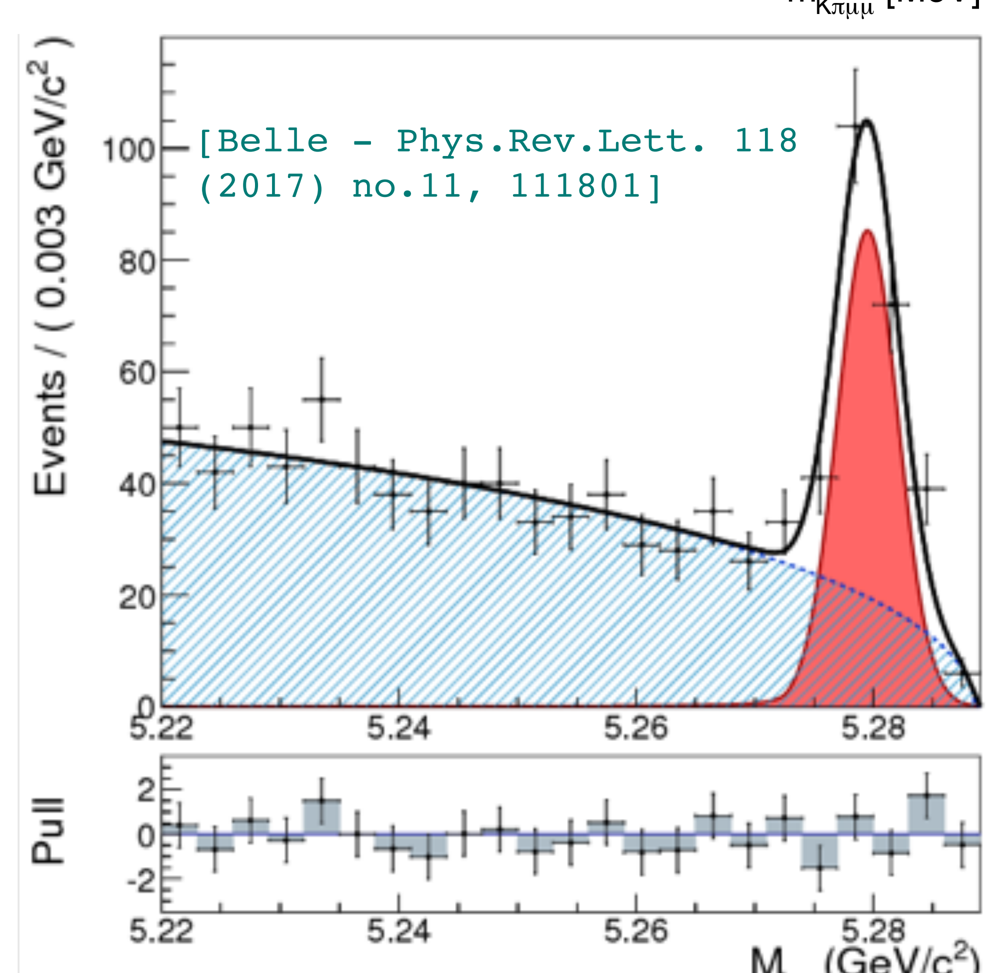
[ATLAS - ATLAS-CONF-2017-023]



[LHCb - JHEP 02 (2016) 104]

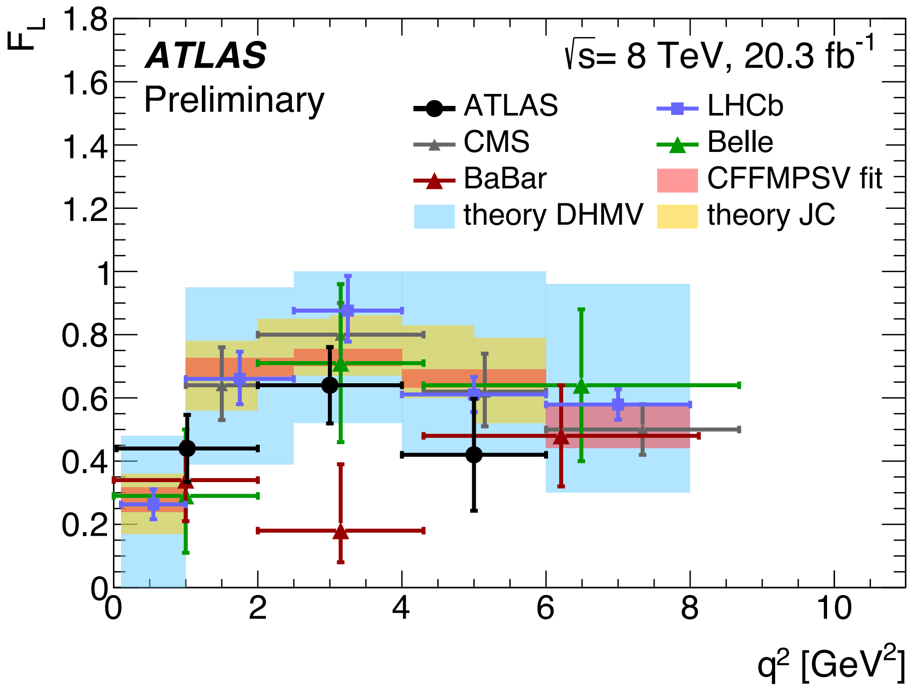


[Belle - Phys.Rev.Lett. 118 (2017) no.11, 111801]

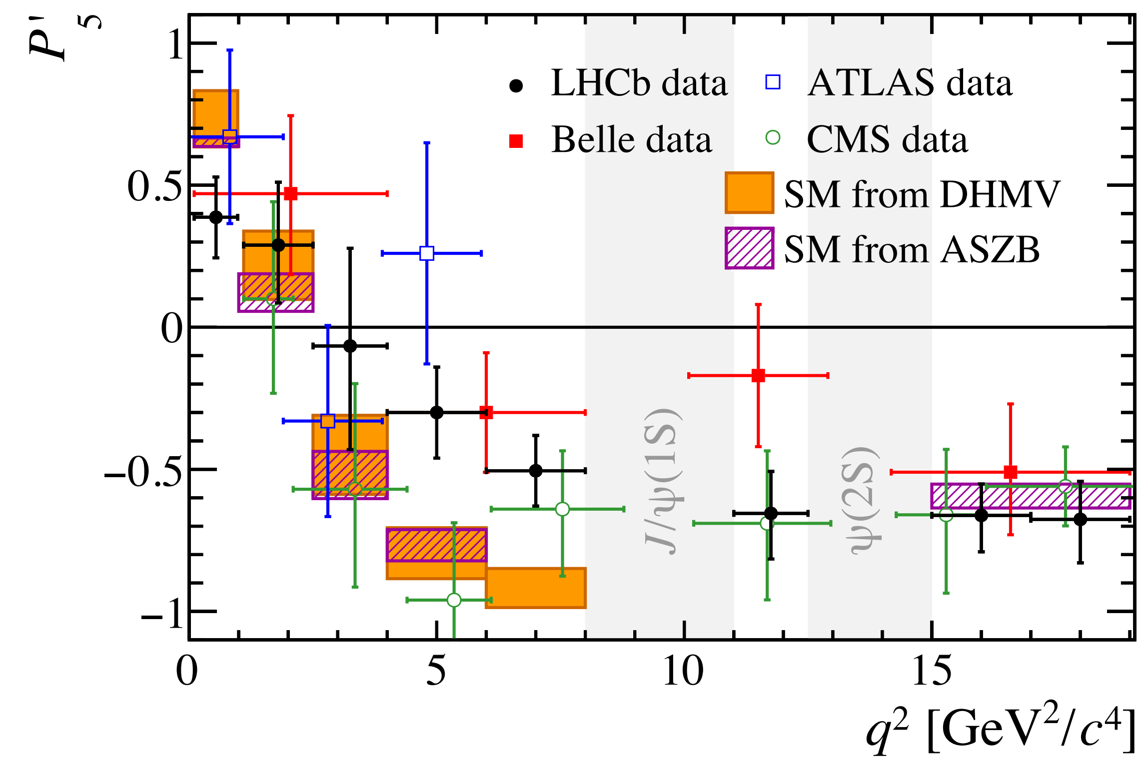


$B^0 \to K^{*0}\mu\mu$ results

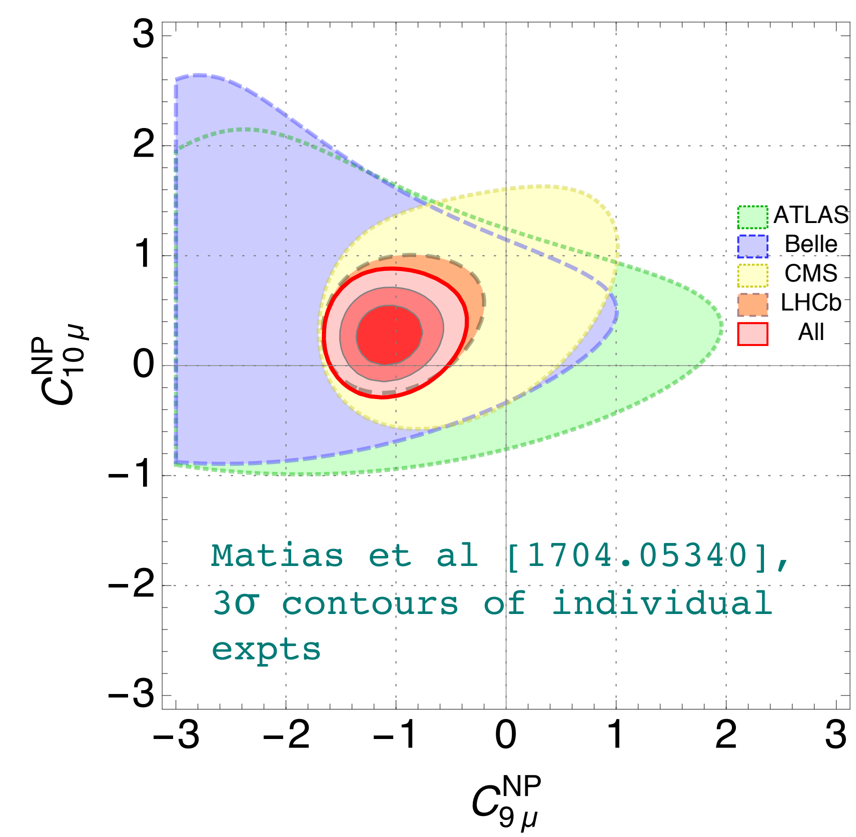
[ATLAS - ATLAS-CONF-2017-023]



ATLAS,CMS,Belle,LHCb at Moriond 2017



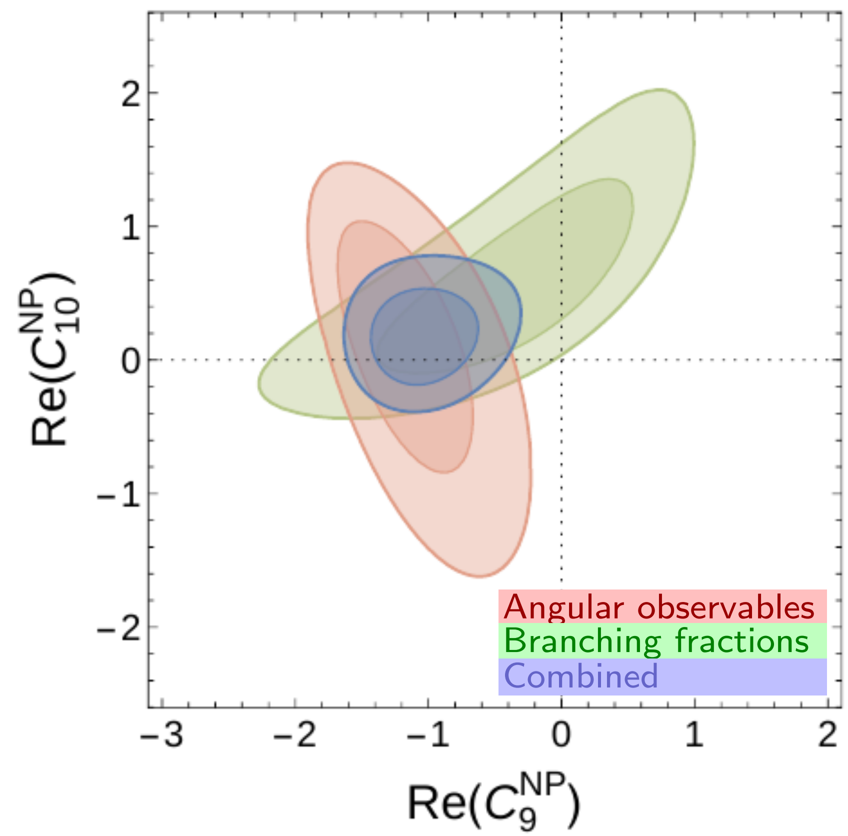
- Re-parametrisation of the angular coefficients in terms of observables with reduced dependency on FF
- P5' shows a significant discrepancy
- Global fits shows strong deviation in dilepton vector coupling $C_9 \to$ tension at the level of 4-5 σ



[Altmannshofer et al arXiv:1703.09189,
Matias et al arXiv:1704.05340]

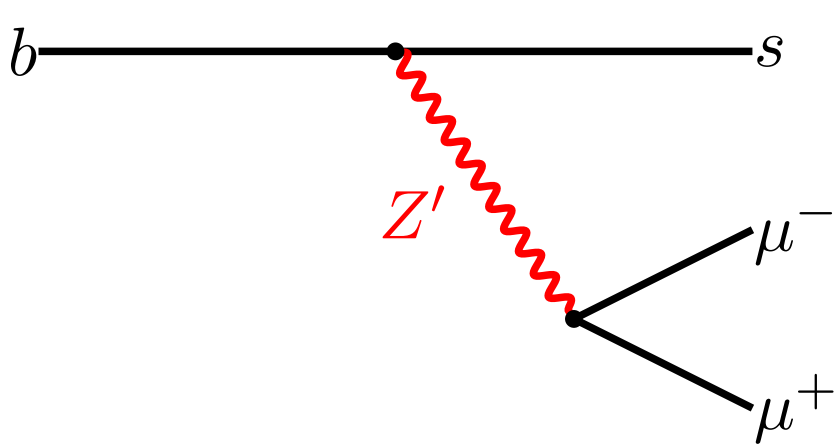
Interpretations

W. Altmannshofer et al., EPJC 75 (2015) 382



- Combine rare semileptonic decay observables in an independent global fit
- Several attempts to interpret the data

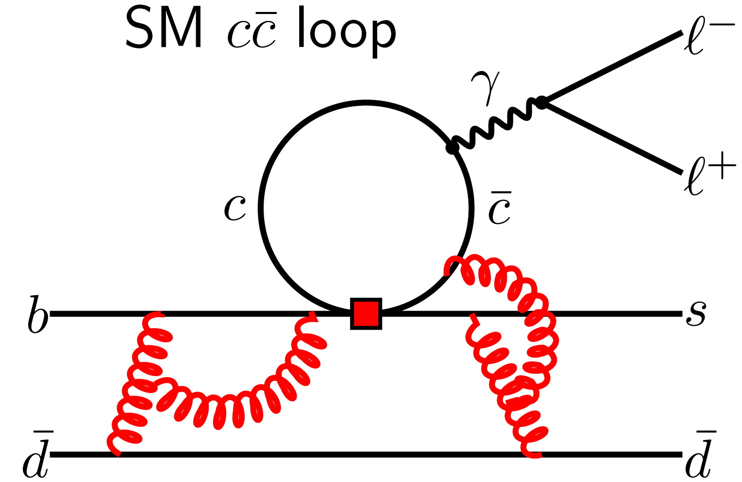
Possible NP



New vector Z', leptoquarks ...

Buttazzo et al [1604.03940]
Bauer et al [PRL116,141802(2016)]
Crivellin et al [PRL114,151801(2015)]
Altmannshofer et al[PRD89(2014)095033]

SM $c\bar{c}$ loop



$c\bar{c}$ contribution can mimic vector-like NP effect (corrections to C_9)

Lyon,Zwicky [1406.0566]
Altmannshofer Straub [1503.06199]
Ciuchini et al [1512.07157]

Prospects: $B_s \to \mu^+\mu^-$

LHC era			HL-LHC era	
Run1 (2010-12)	Run2 (2015-18)	Run3 (2021-23)	Run4 (2026-29)	Run5+ (2032+)
$3fb^{-1}$	$8fb^{-1}$	→	$50fb^{-1}$	*$300fb^{-1}$

* assumes Phase-II upgrade runs with L = $2x10^{34}$ $cm^{-2}s^{-1}$

$$\mathcal{R} = \frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)}$$

- By the end of Run 4 (50 fb-1):

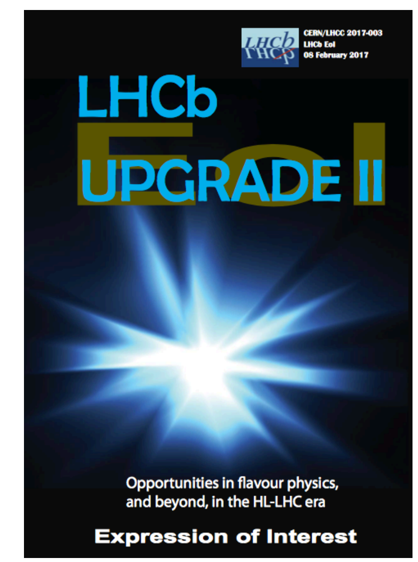
  $\sigma(R)$ ~22%

  $\sigma(\tau_{Bs\to\mu\mu})$ ~ 0.08 ps

- After hypothetical phase-II (300 fb-1):

  $\sigma(R)$ ~10%

  $\sigma(\tau_{Bs\to\mu\mu})$ ~ 0.03 ps



submitted to LHCC this year
https:/cds.cern.ch/record/2244311/

these estimates are based on the 2017 analysis performance assuming SM central values

$B_s \rightarrow \mu^+\mu^-$ LHCb update

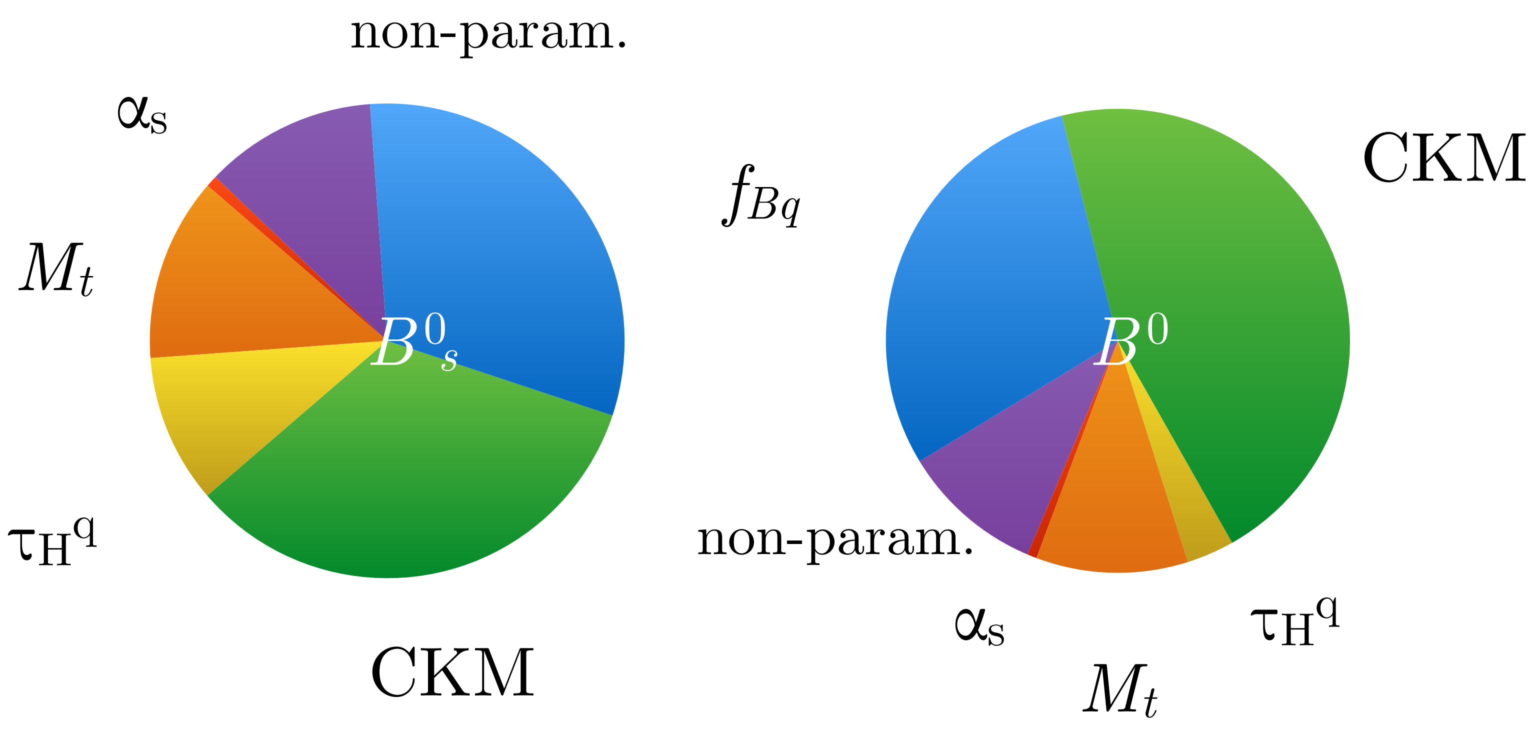
[PRL 118, 191801 (2017)]

- New measurement in 2017 using $3fb^{-1}$ of Run1 data + $1.4fb^{-1}$ of 2015+2016
- Improved analysis:
  - new BDT effective on combinatorial background
  - tighter PID selection $\rightarrow$ reduced physics background
  - more accurate estimate of background yields
- First measurement of $B_s \rightarrow \mu^+\mu^-$ effective lifetime

$B_s \to \mu^+\mu^-$

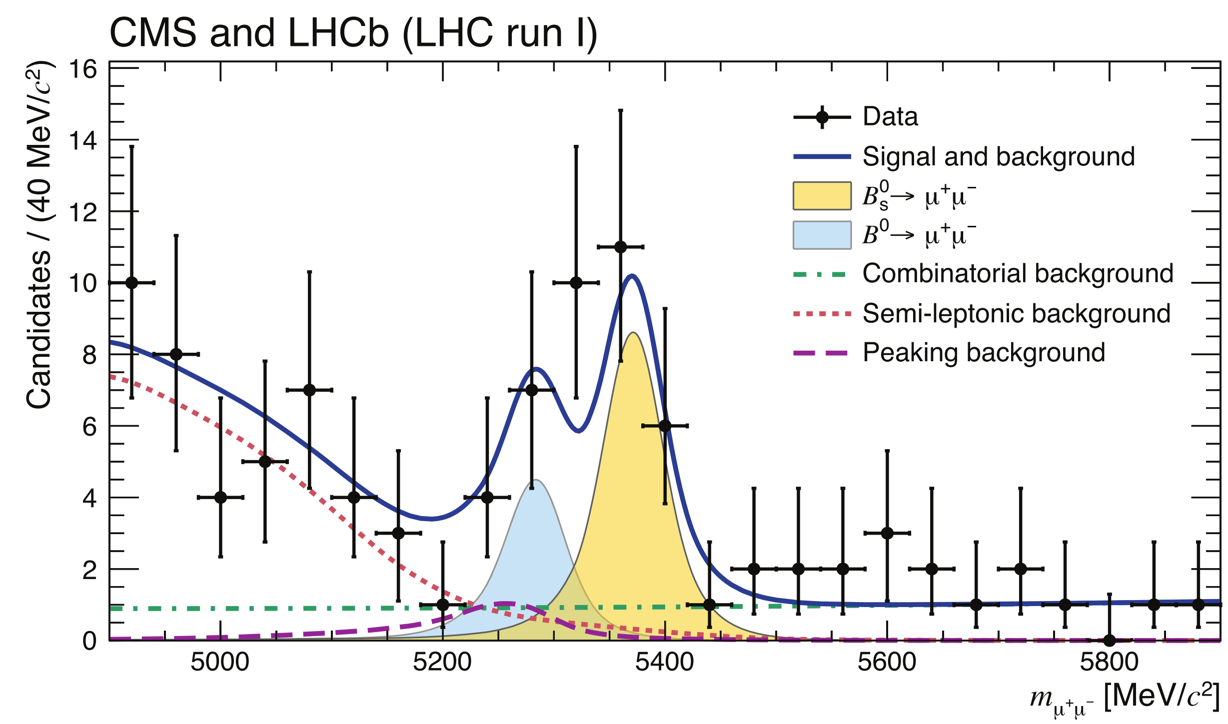
Bobeth et al.
[PRL 112 (2014) 101801]

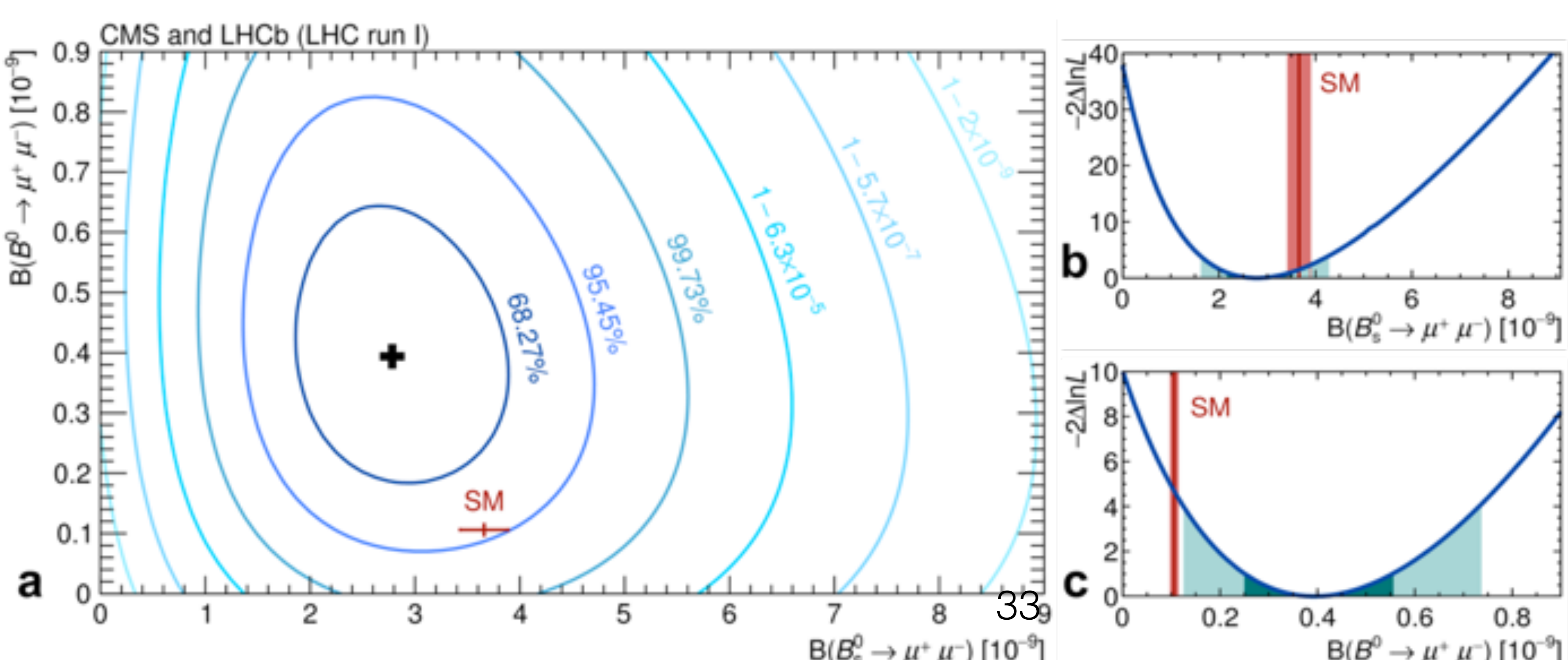
error budgets



$B_s \to \mu^+\mu^-$ (LHCb+CMS)

- First observation of Bs→μμ with CMS+LHCb combined analysis from full LHC Run1 dataset
- First evidence of B0→μμ





$B_s \to \mu^+\mu^-$ Atlas

- Data from full Run1 dataset
- Low statistical significance on the Bs mode (1.4 σ), still consistent with the SM (2.0 σ)
- Result still in agreement with CMS +LHCb result
- <result>