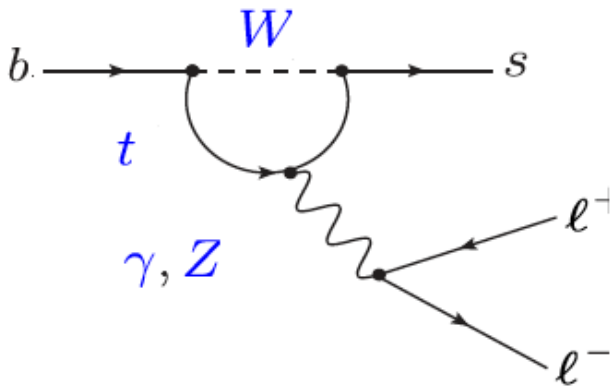
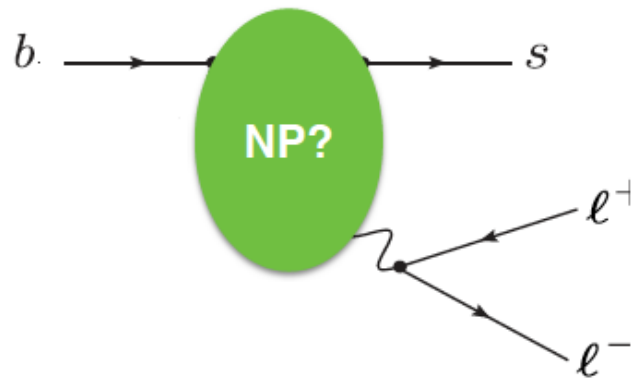
Rare decays at LHCb

Marina Artuso on behalf of the LHCb collaboration

Rare decays and generic searches for new physics





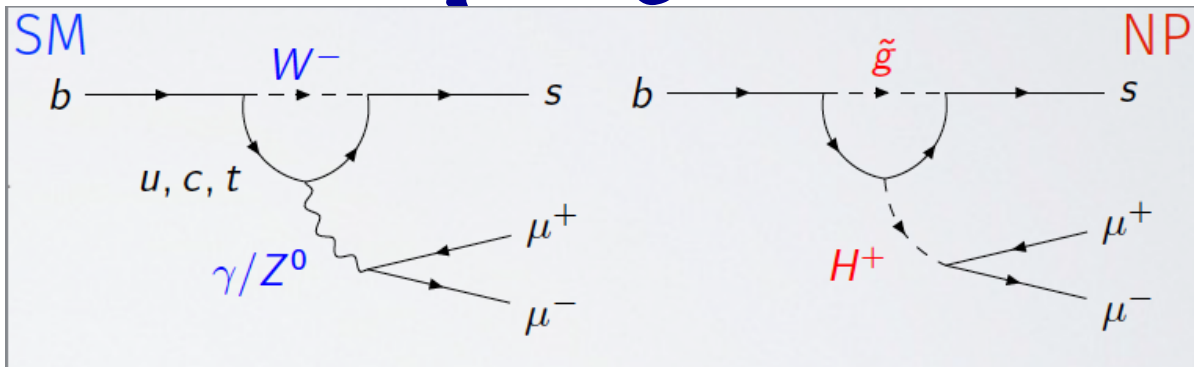
Rare decays are described by an effective Hamiltonian expressed in terms of an operator product expansion:

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i [\underbrace{\mathcal{C}_i(\mu)\mathcal{O}_i(\mu)}_{\text{left handed}} + \underbrace{\mathcal{C}'_i(\mu)\mathcal{O}'_i(\mu)}_{\text{right handed (suppressed in the SM)}}]$$

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

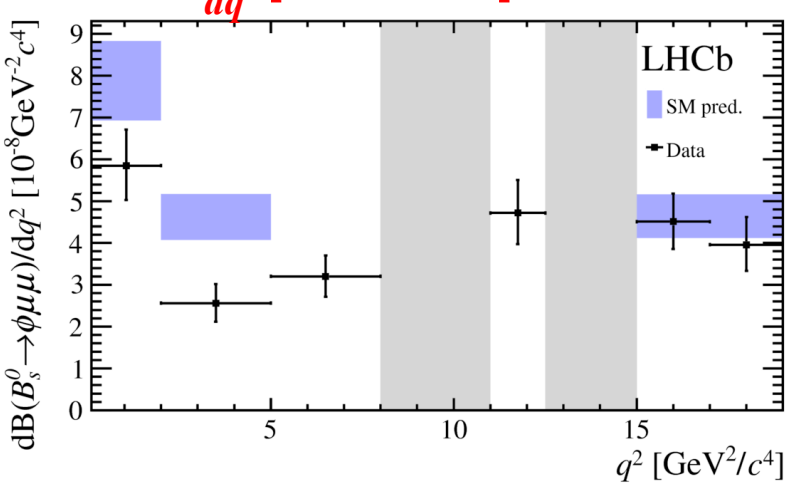
See S. Stone's contribution

EW penguins



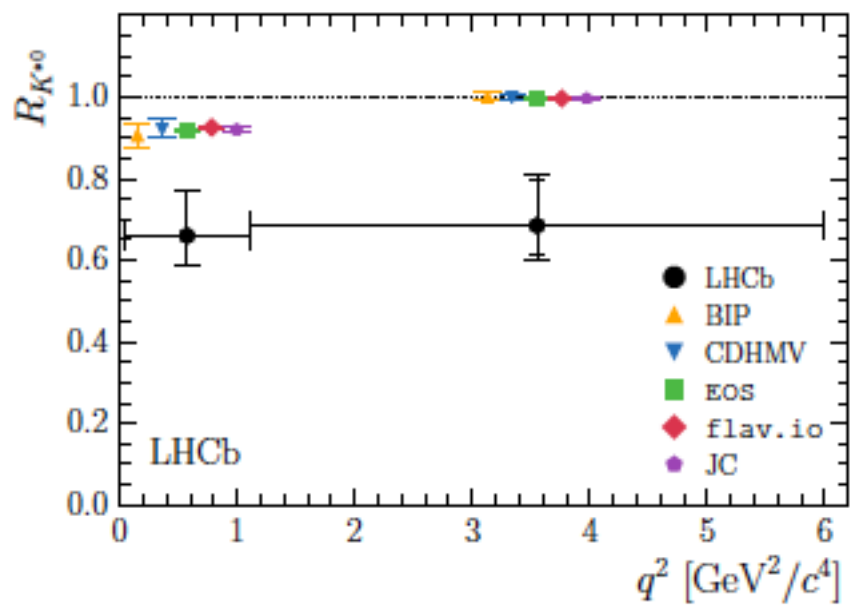
Tensions in angular distributions & branching fractions: Example: LHCb-PAPER-2015-023

$$\frac{dB}{dq^2}\left[B_s^0 \to \varphi\mu^+\mu^-\right]$$



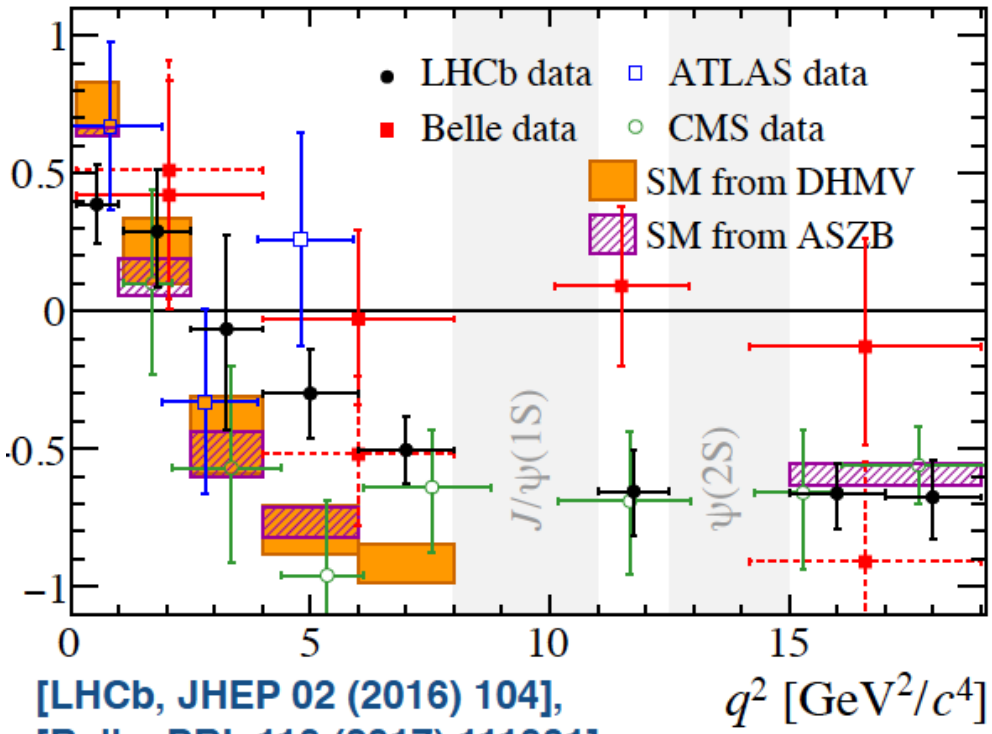
Lepton flavor violation:LHCb-PAPER-2017-013

$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))},$$



The P'_5 anomaly in the decay $B \to K^{(*)}\mu^+\mu^-$

T. BLAKE –EPS 2017



[LHCb, JHEP 02 (2016) 104],
[Belle, PRL 118 (2017) 111801],
[ATLAS-CONF-2017-023],
[CMS-PAS-BPH-15-008]

$$P'_5 = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

Less sensitive to hadronic uncertainties. However precise and well defined uncertainty assessment needed.

Critical step: lattice QCD input:

- ❑ Form factors from first principles

Challenges for the lattice:

- ❑ reliable evaluation of the form factors at large recoil
- ❑ treatment of an unstable particle (K*)

Other flavor-changing neutral current "tensions"

Interplay between precision measurements and state-of-the-art lattice QCD calculation will lead to more reliable assessment of current tensions

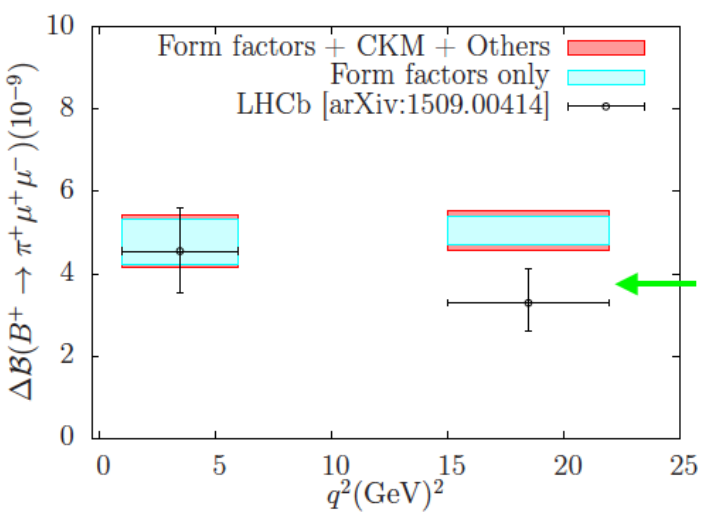
LHCb [arXiV:1509.00414]

FNAL/MILC:1510.02349

LHCb [arXiV:1503.07138]

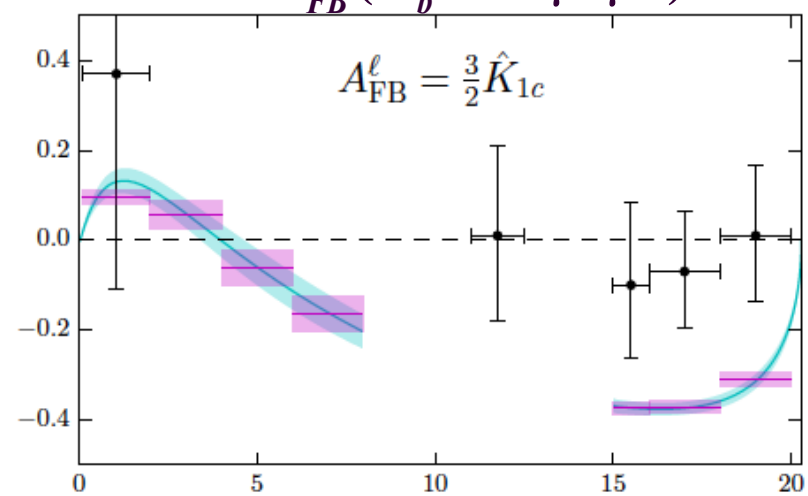
Detmold, Lehner, Meinel: 1602.01399

$\Delta\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)$



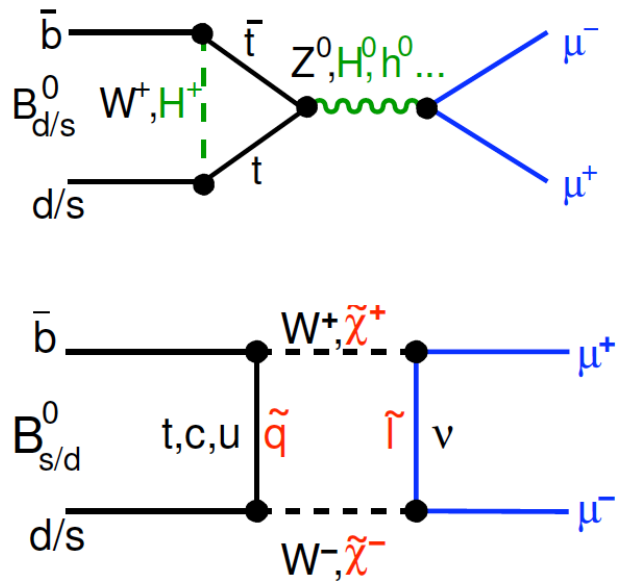
2σ tension

$A^{\ell}_{FB}(\Lambda_b^0 \to \Lambda\mu^+\mu^-)$



$B \to \ell^+\ell^-$

- Excellent probes of new physics:
  - CKM suppressed, loop suppressed, and helicity suppressed
  - Powerful probes of new scalar and pseudoscalar interactions

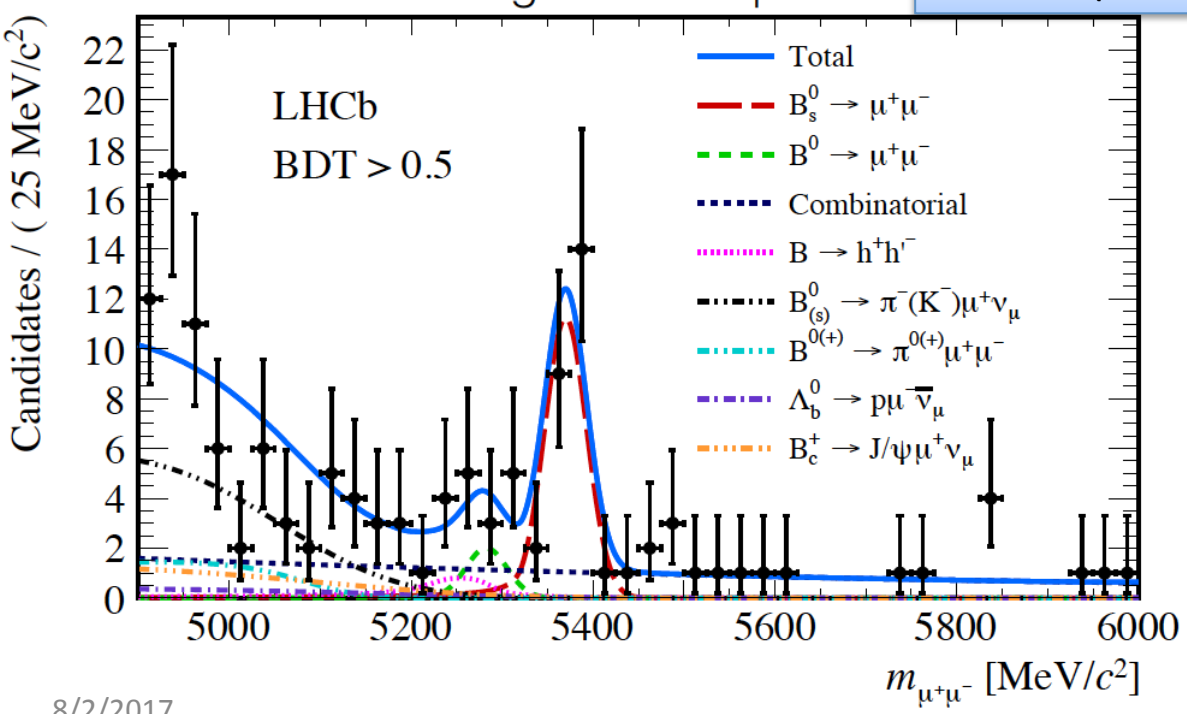


$B_s \to \mu^+\mu^-$

- Standard model expectations for $\mathcal{B}(B_s \to \mu^+\mu^-) \sim 3\times10^{-9}$
- LHCb found first evidence in Run I (PRL 110(2013)021801, combined LHCb-CMS yielded a 5σ observation [Nature 522(2015)68]

Candidates at large BDT response

PRL 118(2017)191801

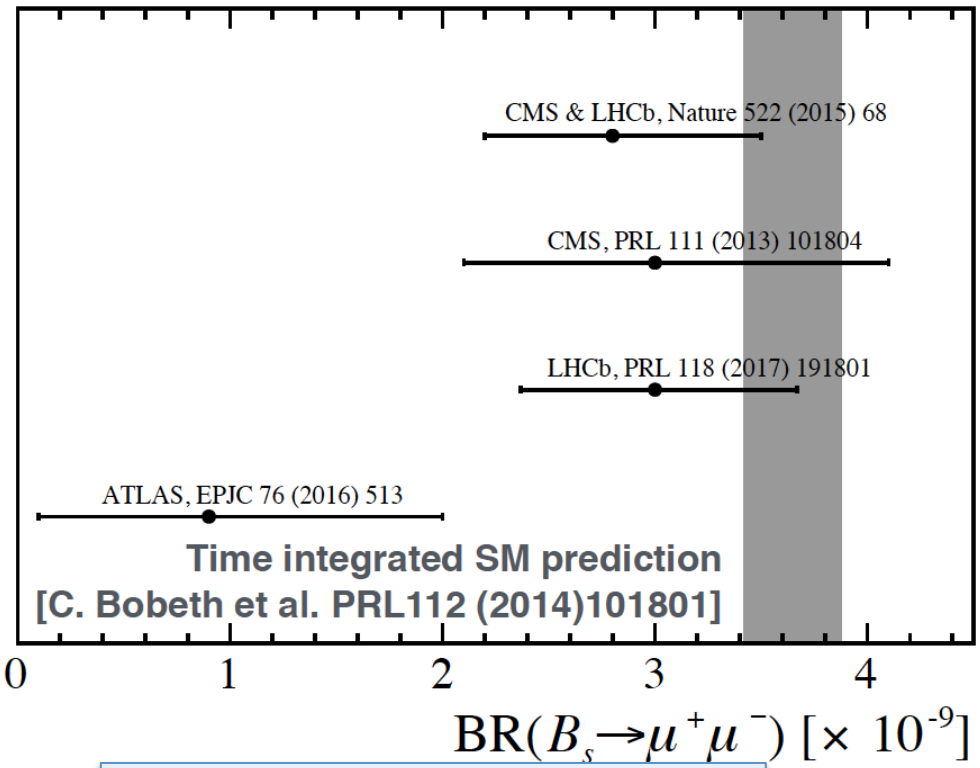


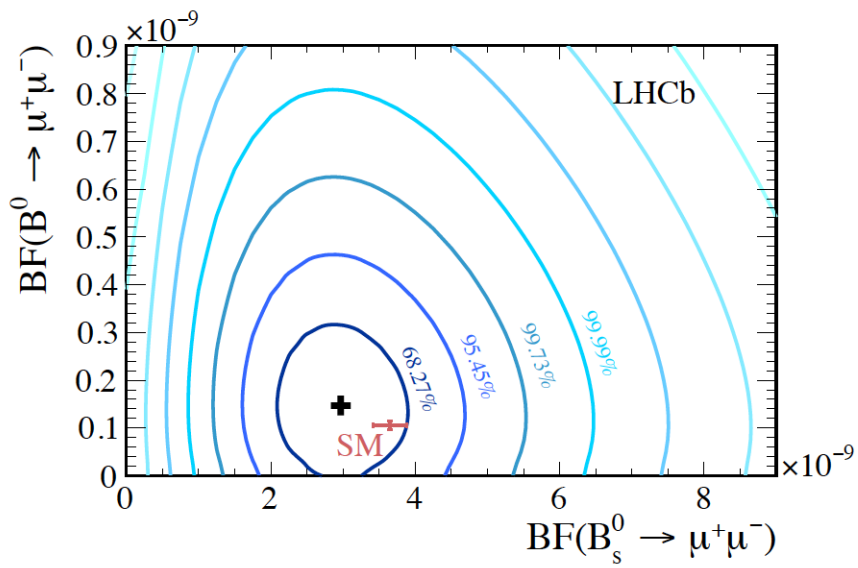
- Run 1 & 2 ($3\,fb^{-1}+1.4\,fb^{-1}$)
- Single experimental observation of $B_s \to \mu^+\mu^-$ at 7.8σ

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

- New LHCb result: $B(B_s \to \mu^+\mu^-) = \left(3.0 \pm 0.6^{+0.3}_{-0.2}\right) \times 10^{-9}$

  $B(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10}$ 95%CL





Theoretical uncertainty ~6%

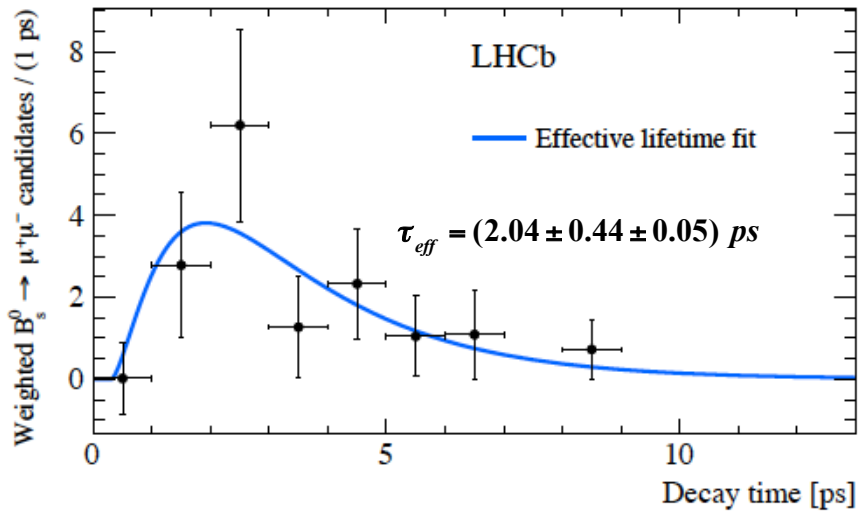
Effective lifetime

PRL 118(2017)191801

- The $\mathcal{A}_{\Delta\Gamma}$ parameter modifies the effective lifetime of the decay:

$$\tau_{eff} = \frac{\tau_{B_S}}{1-y_s^2}\left(\frac{1+2\mathcal{A}_{\Delta\Gamma}y_s+y_s^2}{1+\mathcal{A}_{\Delta\Gamma}y_s}\right)$$

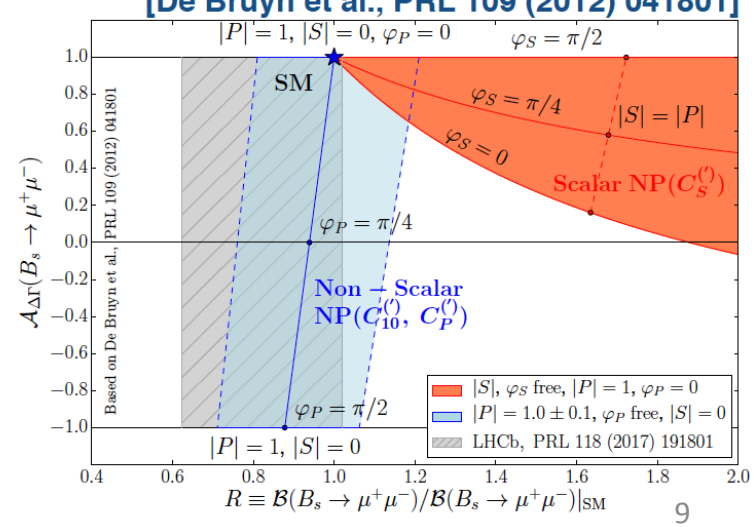
$$y_s = \tau_{B_S}\frac{\Delta\Gamma}{2}$$



- Not yet sensitive to $\mathcal{A}_{\Delta\Gamma}$ that provides separation between scalar and pseudoscalar NP contributions

- Good prospects for run 3&4

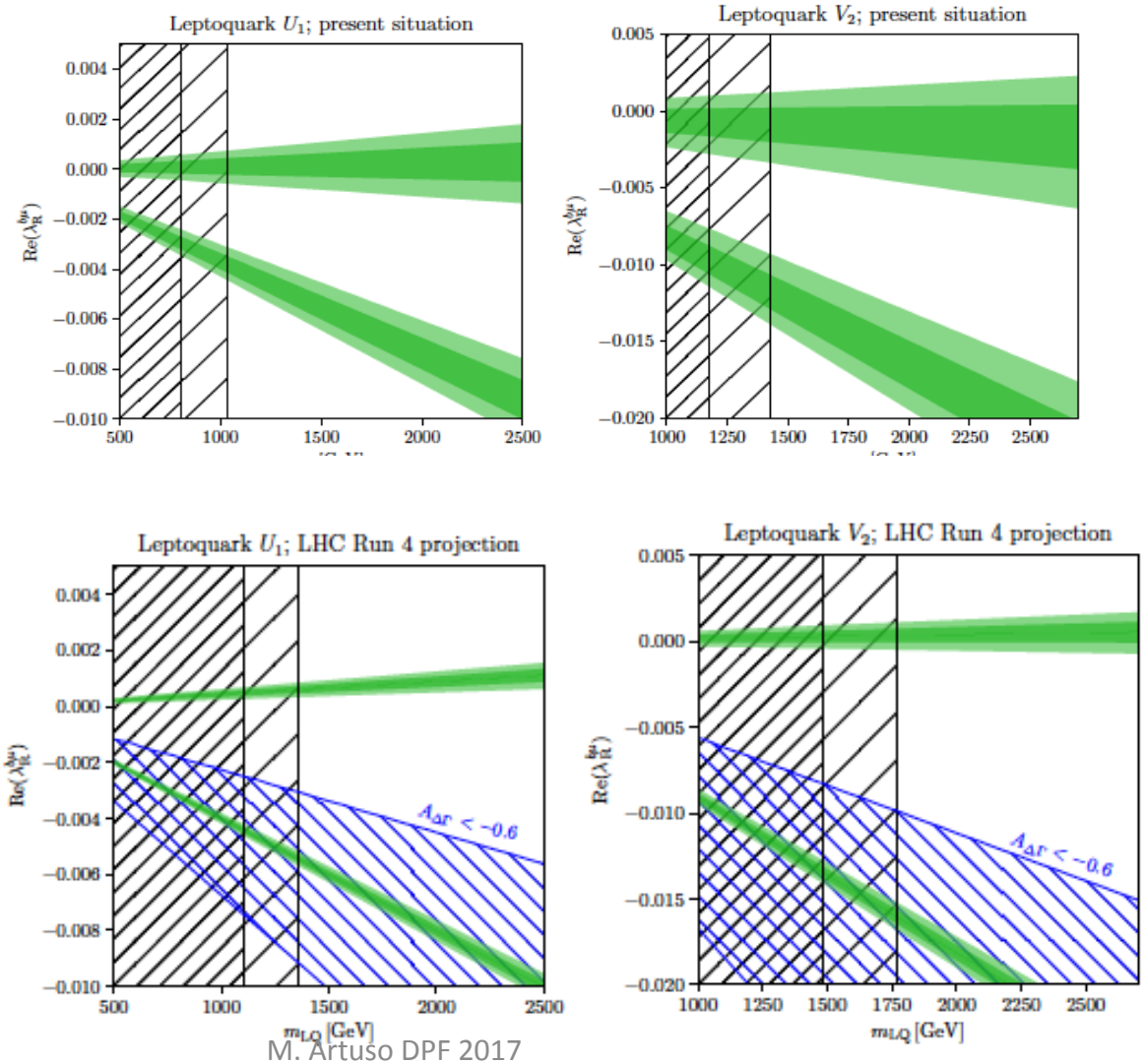
[De Bruyn et al., PRL 109 (2012) 041801]



Implications and prospects (leptoquark example)

Altmannshovfer, Niehoff and Straub, arXiV:1702.05598v2

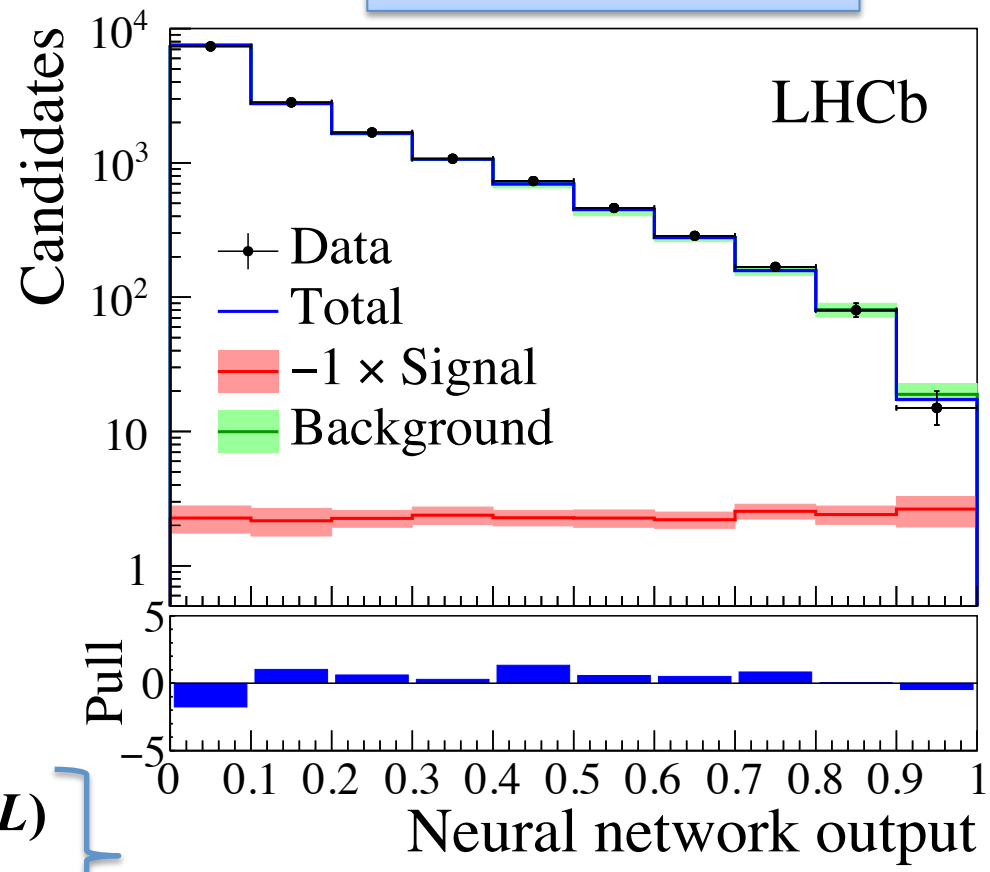
- Green: branching fraction constraint
- Black/hatched regions show extrapolated exclusions from direct searches



$B(s,d) \to \tau^+\tau^-$

- Based on $3fb^{-1}$ (run 1)
- Use $\tau^+ \to \pi^+\pi^-\pi^+\nu_\tau$ decay
- Presence of 2 undetected ν make this analysis challenging
- Use neural net to discriminate signal from background

PRL 118 (2017) 251802



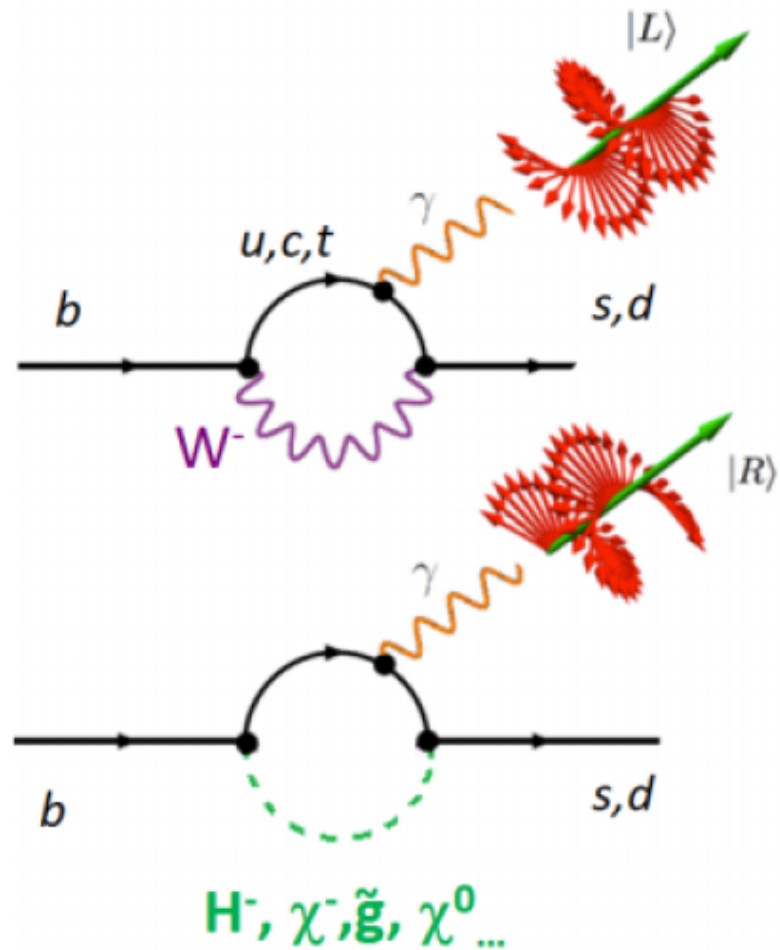
$$\mathcal{B}(B_s \to \tau^+\tau^-) < 6.8 \times 10^{-3} \quad (95\%CL)$$

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

Assuming no contribution from the other channel

Radiative B decays

- The branching fraction $B(b \to s\gamma)$ is consistent with the Standard Model & is a powerful constraint of new physics scenarios
- Sensitive to the O_7 operators
- CP violation and photon polarization add sensitivity to NP



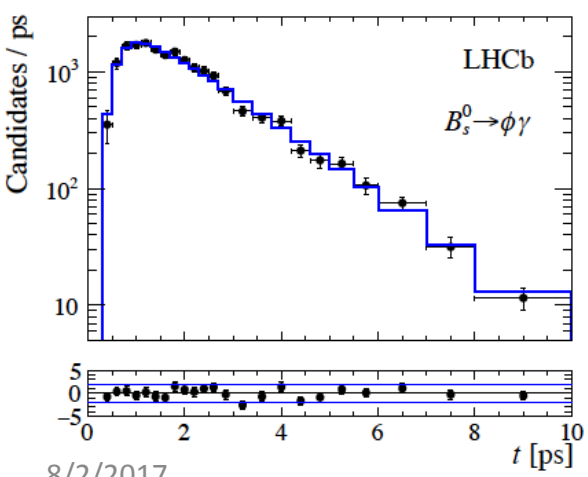
Photon polarization in $B_s \to \phi\gamma$

PHYS. REV. LETT. 118, 021801 (2017)

- First measurement of the photon polarisation in $B_s^0 \to \phi\gamma$.
  - Time-dependent decay rate is sensitive to photon polarisation:

$$\Gamma_{B_s^0 \to \phi\gamma}(t) \propto e^{-\Gamma_s t}\left[cosh(\Delta\Gamma_s t/2) - \mathcal{A}^{\Delta} sinh(\Delta\Gamma_s t/2)\right]$$

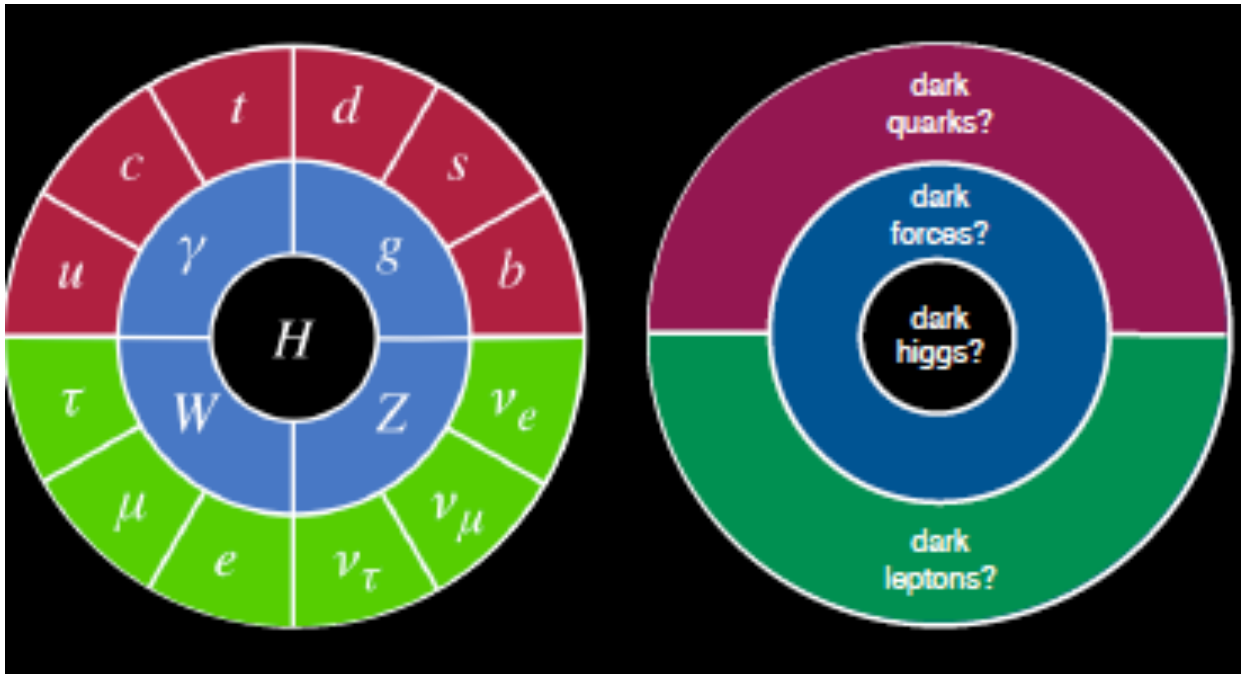
  - SM prediction: $\mathcal{A}^{\Delta} = 0.047^{+0.029}_{-0.025}$ [PRB 664 (2008) 174]



Compatible with the SM at 2.6σ

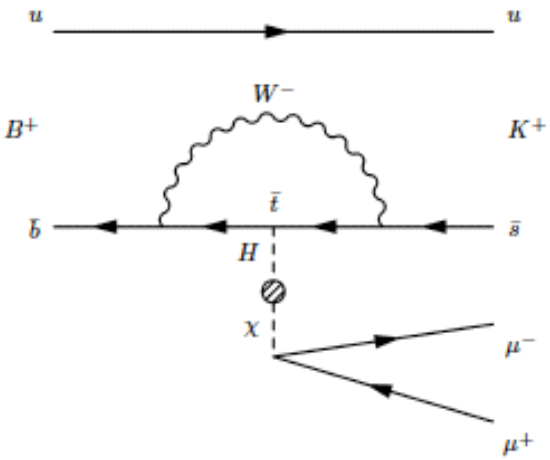
$$\mathcal{A}^{\Delta} = -0.98^{+0.46}_{-0.52}(stat.)^{+0.23}_{-0.20}(syst.)$$

The hidden sector

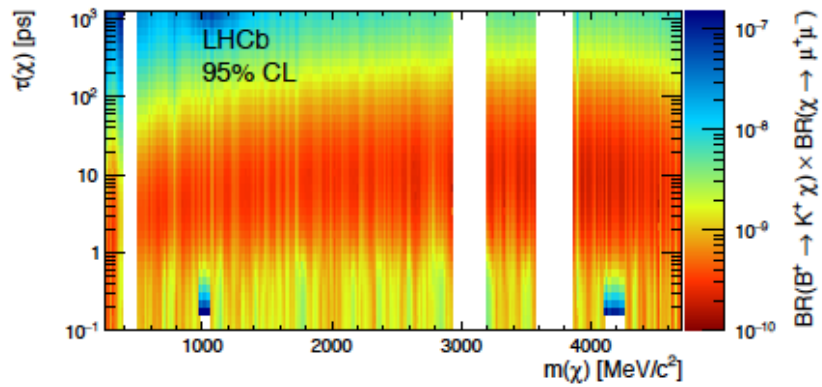


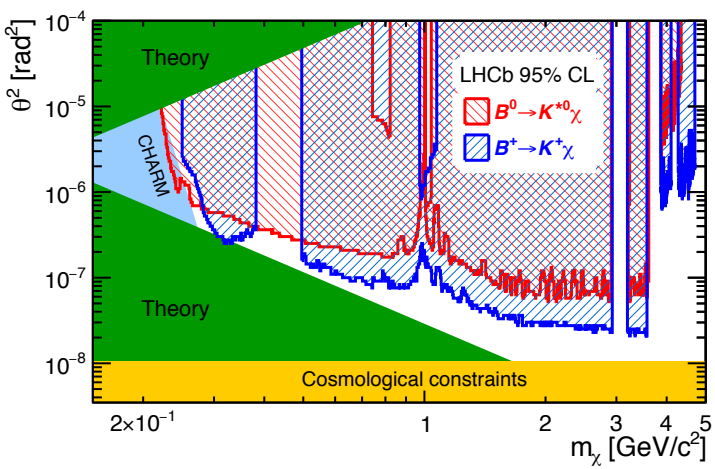
In this approach there is no Standard Model-dark matter connection but there could be portals (vector, axion, Higgs or neutrino portals)

Search for long lived scalar particles in $B \to K\chi(\mu^+\mu^-)$ at LHCb



PRD 95 (2017) 071101

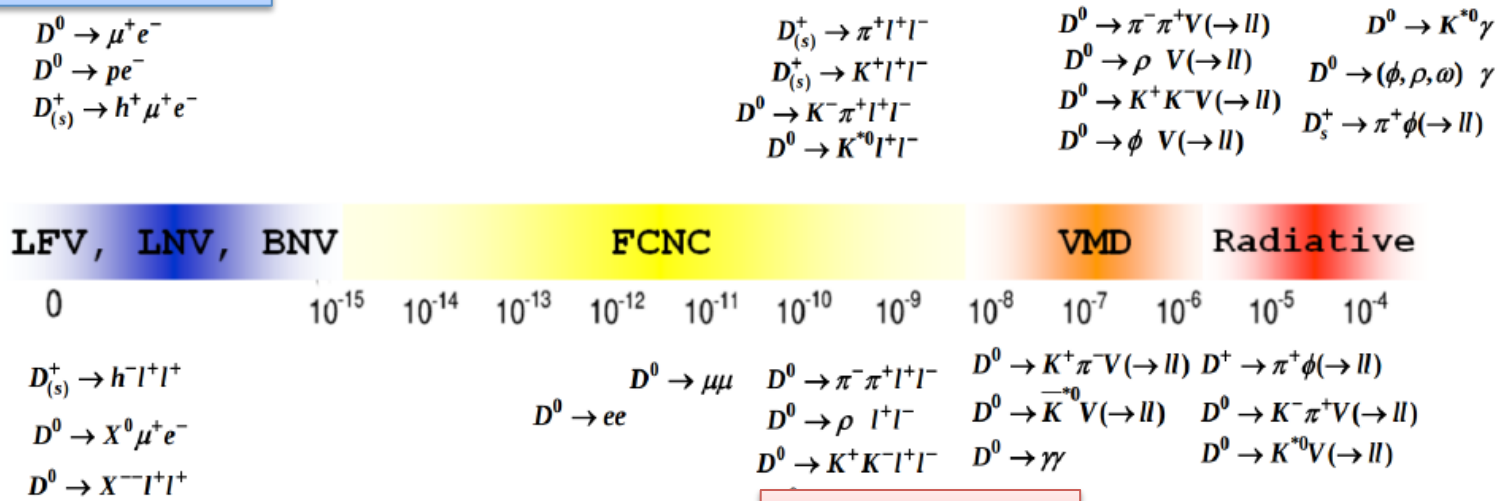


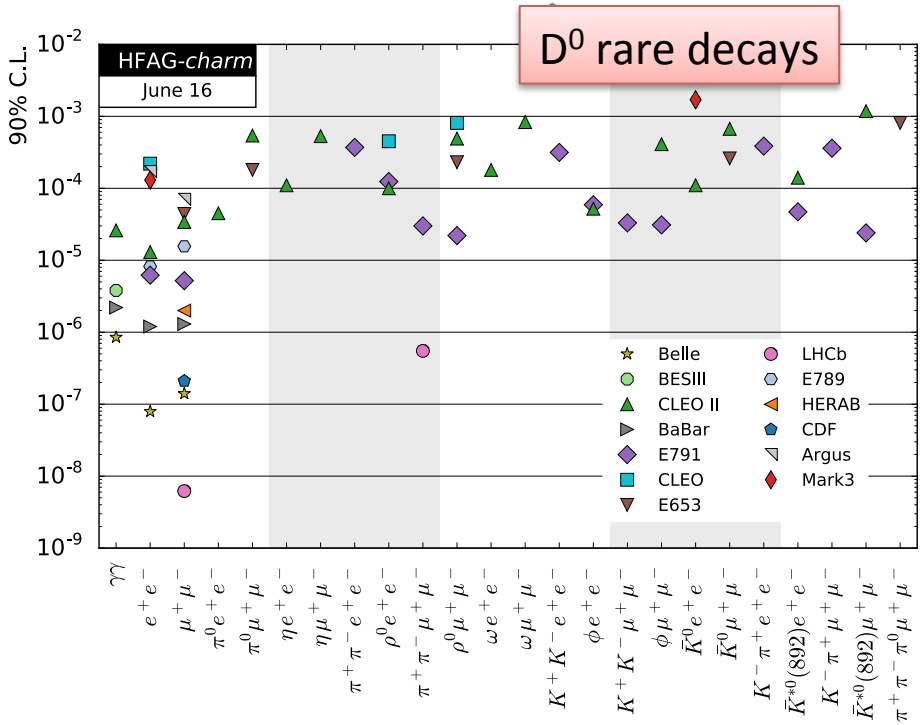


- Strongest constrain on a scalar with a mass $2m_\mu<m<2m_\tau$
- Parameter space of the inflaton model [Batell, Pospelov, Ritz (arXiv:09114939) Bezrukov, Gorbunov [arXiv: 0912.0390,1303.4395] highly constrained

Rare charm decays

J. Prisciandaro FPCP 2017

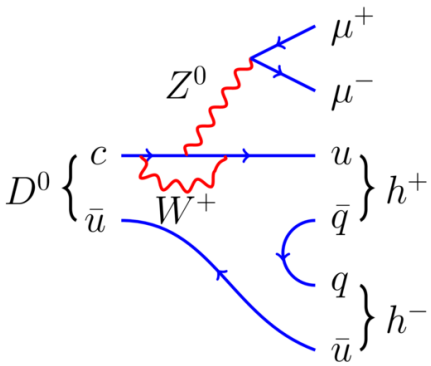




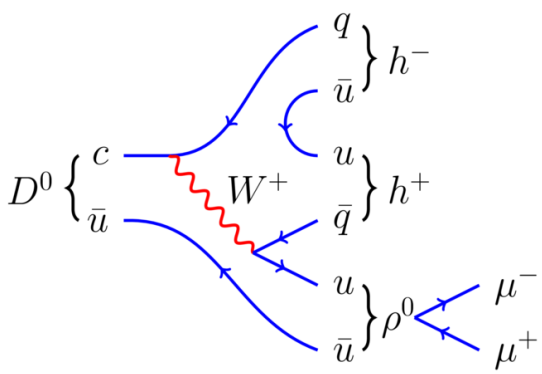
$D^0 \to K^+K^-(\pi^+\pi^-)\mu^+\mu^-$

New!

LHCb-PAPER-2017-019



Short distance

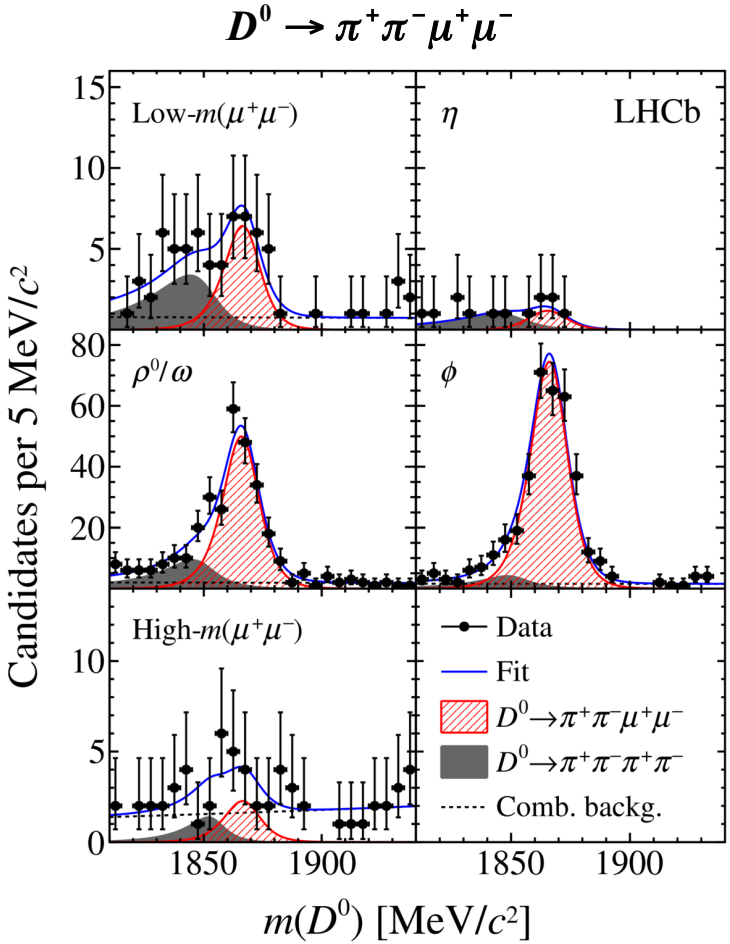


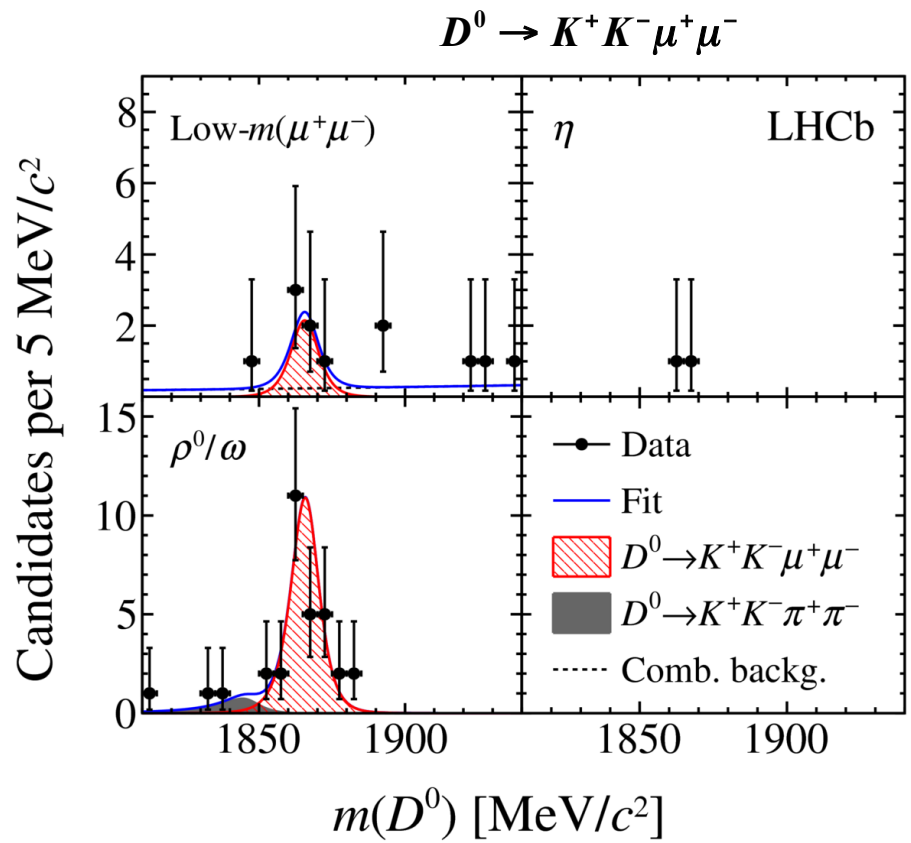
Long distance

- Short distance SM branching fraction expectations highly suppressed
  - [$\mathcal{O}(10^{-9})$- arXiV:1101.6053]
- Long distance contributions can increase BF to $\mathcal{O}(10^{-6})$ [arXiV: 0706.1133]
- Resonances affect all dimuon invariant mass spectrum but more prominent in low-mass resonance regions

Results

LHCb-PAPER-2017-019





$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97) \times 10^{-7},$$
$$\mathcal{B}(D^0 \to K^+K^-\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16) \times 10^{-7}.$$

Conclusions

- Tantalizing tensions in EW penguin decays have surfaced
- Study of $B \to \ell^+\ell^-$ is broadening its scope beyond branching fraction measurement
- New interesting observables in radiative $b \to s\gamma$ decays continue to be explored
- Rare B decays may open portals towards the hidden sector
- Study of rare and forbidden charm decay provides complementary information
- Much more to come with future upgrades

Back-up information will follow

THE END

Lepton universality in $B \to K^{(*)}\ell^+\ell^-$

- Study the double ratio

LHCb paper 2017-013

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

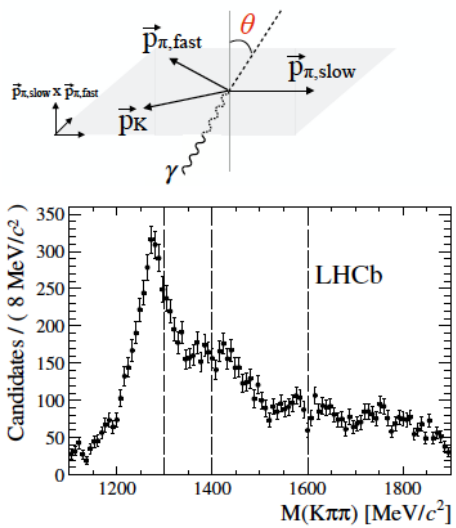
- Double ratio ensures that measurement is robust against systematic effects
- Measurement of control channels

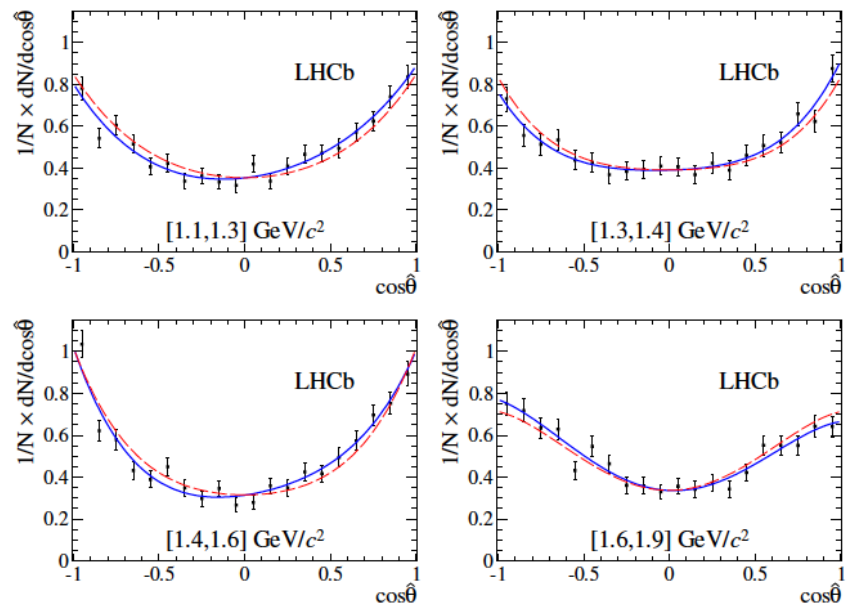
$$R_{J\psi} = \frac{B(B^0 \to J/\psi\mu^+\mu^-)}{B(B^0 \to J/\psi e^+e^-)} = 1.06 \pm 0.006[\text{stat}] \pm 0.045[\text{sys}]$$

Photon polarization in B→K*γ

PHYS. REV. LETT. 112, 161801 (2014)

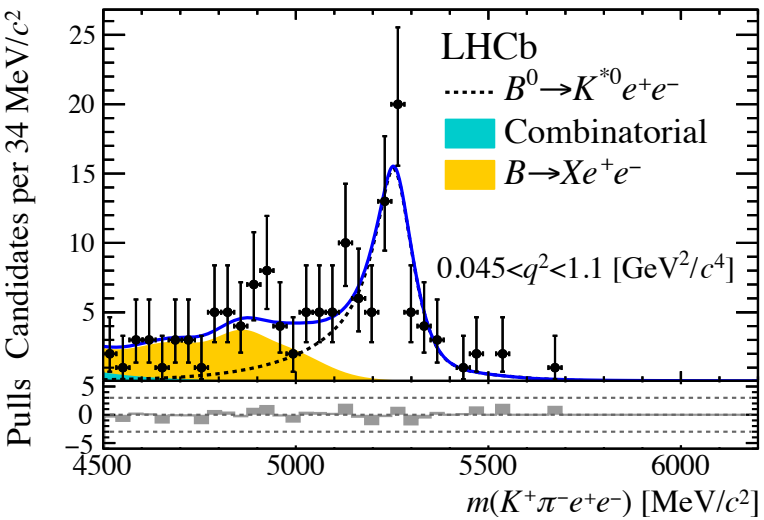
- First observation of photon polarisation in $B^+ \to K^+\pi^+\pi^-\gamma$:

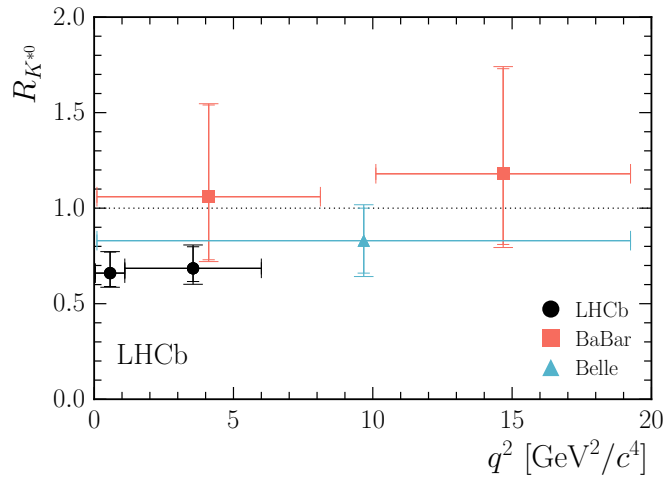


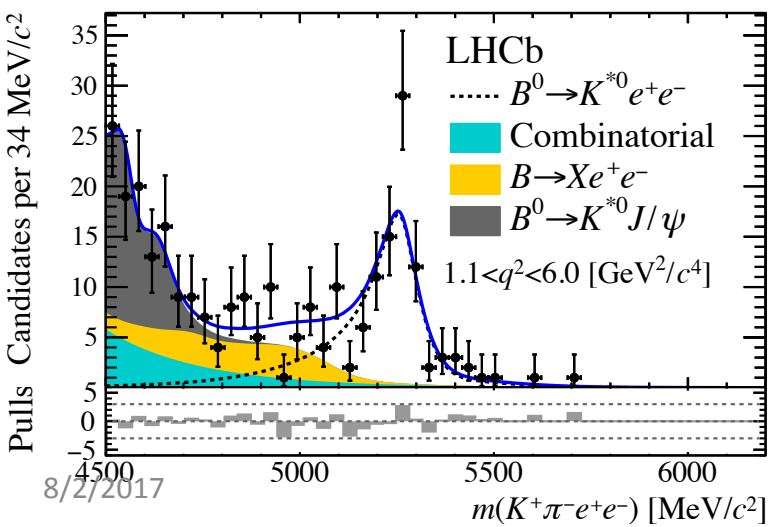


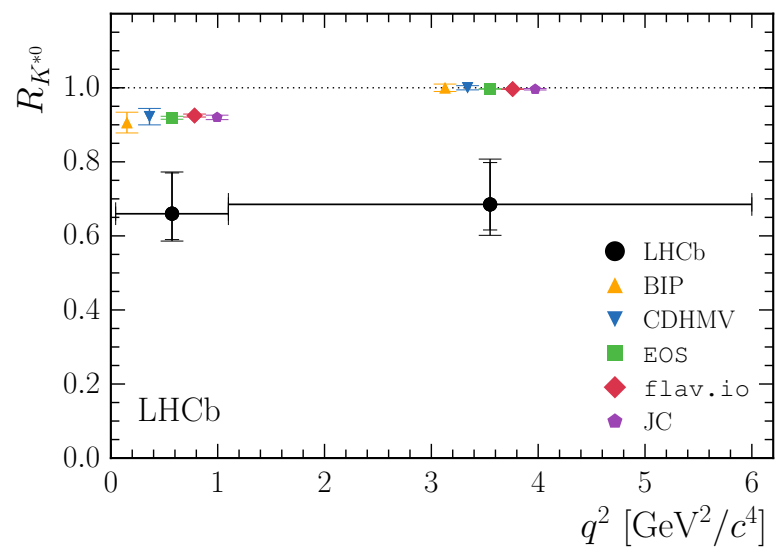
- Exact value of the polarisation depends on hadronic content
  → full amplitude analysis ongoing.

B→K*μ⁺μ⁻/B→K*e⁺e⁻


LHCb
$B^0 \to K^{*0} e^+e^-$
Combinatorial
$B \to X e^+e^-$
$0.045<q^2<1.1$ [GeV$^2/c^4$]
Candidates per 34 MeV/c^2
Pulls
$m(K^+\pi^-e^+e^-)$ [MeV/c^2]


$R_{K^{*0}}$
LHCb
BaBar
Belle
LHCb
q^2 [GeV$^2/c^4$]


LHCb
$B^0 \to K^{*0} e^+e^-$
Combinatorial
$B \to X e^+e^-$
$B^0 \to K^{*0} J/\psi$
$1.1<q^2<6.0$ [GeV$^2/c^4$]
Candidates per 34 MeV/c^2
Pulls
$m(K^+\pi^-e^+e^-)$ [MeV/c^2]


$R_{K^{*0}}$
LHCb
BIP
CDHMV
EOS
flav.io
JC
LHCb
q^2 [GeV$^2/c^4$]

Tensions in $b \to s\ell^+\ell^-$

Observable	Experiment	Standard Model	Pull (σ)
$\langle P_5' \rangle_{[4,6]}$	-0.30 ± 0.16	-0.82 ± 0.08	-2.9
$\langle P_5' \rangle_{[6,8]}$	-0.51 ± 0.12	-0.94 ± 0.08	-2.9
$R_K^{[1,6]}$	$0.745^{+0.097}_{-0.082}$	1.00 ± 0.01	$+2.6$
$R_{K^*}^{[0.045,1.1]}$	$0.66^{+0.113}_{-0.074}$	0.92 ± 0.02	$+2.3$
$R_{K^*}^{[1.1,6]}$	$0.685^{+0.122}_{-0.083}$	1.00 ± 0.01	$+2.6$
$\mathcal{B}^{[2,5]}_{B_s \to \phi\mu^+\mu^-}$	0.77 ± 0.14	1.55 ± 0.33	$+2.2$
$\mathcal{B}^{[5,8]}_{B_s \to \phi\mu^+\mu^-}$	0.96 ± 0.15	1.88 ± 0.39	$+2.2$