Rare B-decays

Lars Eklund on behalf of the LHCb Collaboration

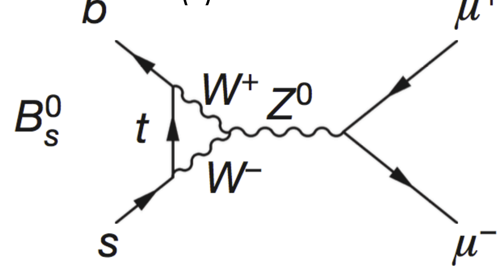
Experimental overview

Results from Babar, Belle, LHCb, ATLAS and CMS

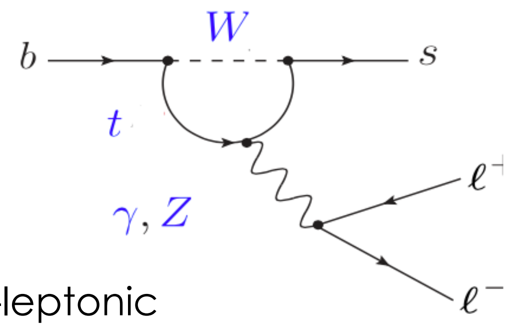
Why study rare processes?

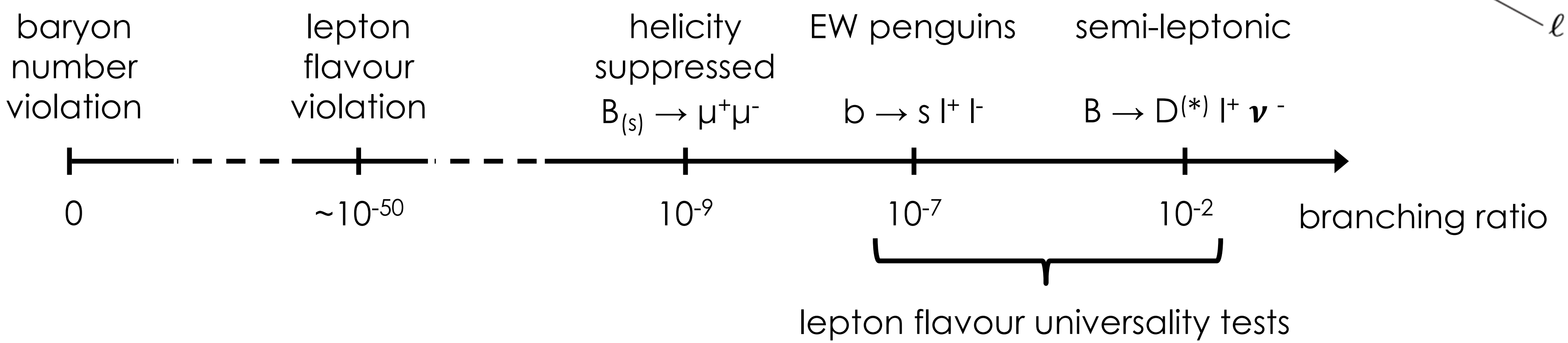
- Rare decays: SM is suppressed
  - Sensitive to BSM contributions
- Flavour Changing Neutral Currents (FCNC)
  - Forbidden at tree-level in the SM
  - Further suppression, e.g. helicity
- Probes mass scales beyond direct searches
  - Up to ~ 100 TeV

$B_{(s)} \rightarrow \mu^+\mu^-$



$b \rightarrow s\, l^+ l^-$





FCNC: theoretical description

- Processes at many different energy scales

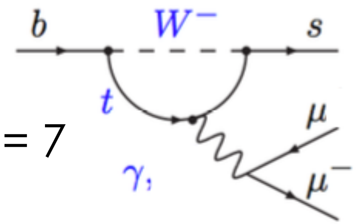
0.2 GeV	...	4 GeV	...	80 GeV	...	10-100 TeV
Λ_{QCD} (non-perturbative)		Λ_b b mass		Λ_{EW} W mass		Λ_{BSM} BSM scale

- Described by an effective Hamiltonian
  - O_i (Operators): long-distance, non-perturbative physics
  - C_i (Wilson coefficients): short distance, high energy physics
    - BSM processes may modify these coefficients

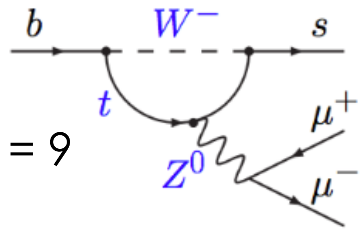
$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i [\underbrace{\mathcal{C}_i(\mu)\mathcal{O}_i(\mu)}_{\text{left handed}} + \underbrace{\mathcal{C}'_i(\mu)\mathcal{O}'_i(\mu)}_{\text{right handed (suppressed in the SM)}}]$$

Example of SM terms

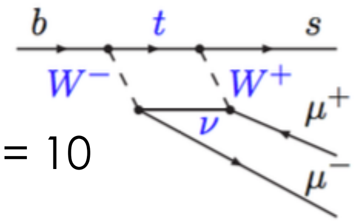
i = 7



i = 9



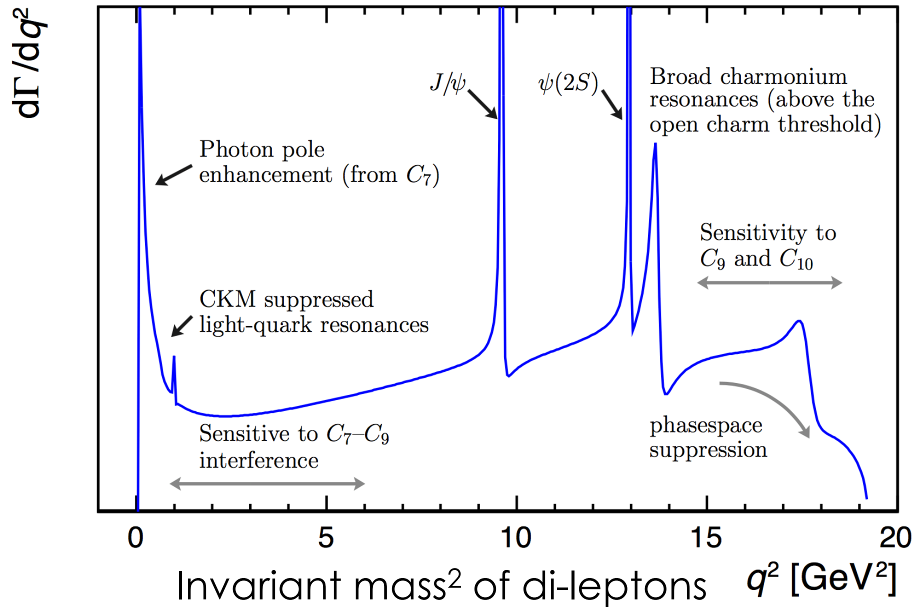
i = 10



Rare decay observables

- (Differential) branching ratios
  - q^2 dependence for $b \rightarrow s\, l^+ l^-$
    - E.g. $B^0 \rightarrow K^* \mu^+ \mu^-$
- Angular distributions
  - $b \rightarrow s\, l^+ l^-$ decays
- Effective lifetime
  - B_s decays where $\Delta\Gamma_s \neq 0$
    - Measure of CP violation

Reproduced from arXiv:1606.00916v2



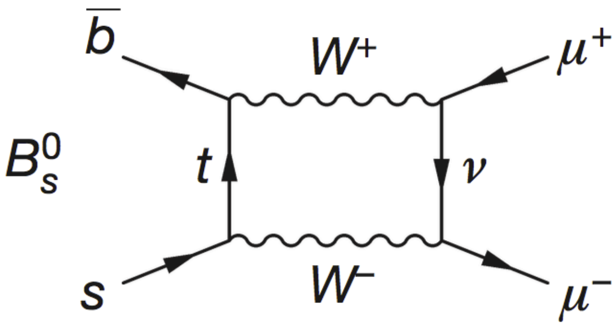
- BSM processes can modify the effective Hamiltonian by
  - Modifying Wilson coefficients of operators present in SM
  - Making Wilson coefficients dependent on lepton flavour
  - Introducing new operators

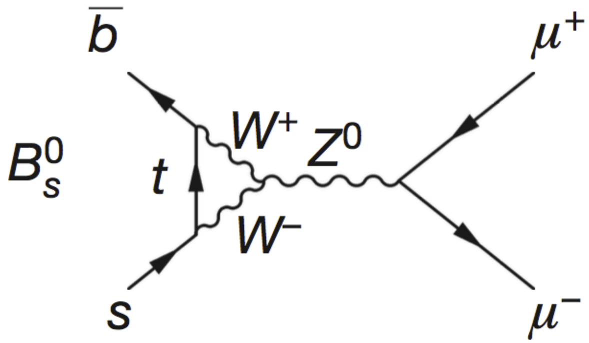
Overview of results

- Fully leptonic decays
  - $B_{(s)} \to \mu^+\mu^-$ & $B_{(s)} \to \tau^+\tau^-$
- Electroweak $b \to s\, l^+ l^-$ transitions
  - $B^0 \to K^*\mu^+\mu^-$ and friends
  - Differential branching ratios & angular analysis
  - Global fits to Wilson coefficients
- Lepton flavour universality test ($l^+ = e^+, \mu^+$ or τ^+)
  - $B \to K^{(*)} l^+ l^-$ decay rates
  - $B \to D^{(*)} l^+ \nu$ decay rates
- Outlook

Fully leptonic final states

$B_{(s)} \rightarrow \mu^+\mu^-$ and friends





$B_{(s)} \to \mu^+\mu^-$ branching ratio

- Very precise predictions available
  - Only C_{10} contribute in the SM: $BR(B_q \to l^+ l^-) \propto m_l^2 \sqrt{1 - \frac{4m_l^2}{m_{B_q}^2}} |C_{10}|^2$

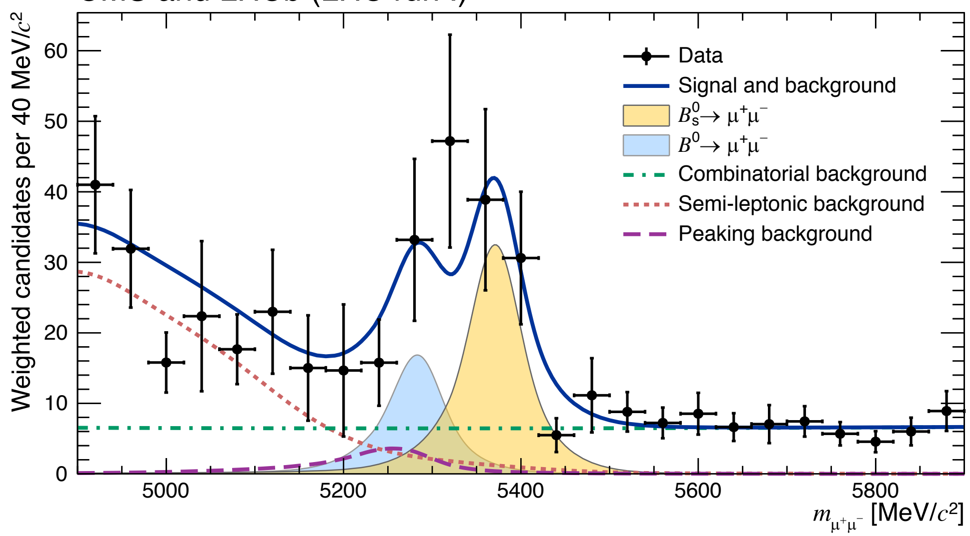
$$\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = (3.52 \pm 0.15) \times 10^{-9}, \qquad \mathrm{BR}(B^0 \to \mu^+\mu^-)_{\mathrm{SM}} = (1.12 \pm 0.12) \times 10^{-10}$$

  - BSM scalar & pseudo-scalar operators may contribute
    - Change in decay rate
    - Mixing induced CP violation

- LHCb & CMS: Run 1 dataset
  - Observation of $B_s \to \mu^+\mu^-$ (6.2 σ)
  - Evidence for $B^0 \to \mu^+\mu^-$ (3.0 σ)

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.0^{+1.6}_{-1.4}) \times 10^{-10}$$

Nature 522, 68–72



$B_{(s)} \to \mu^+\mu^-$ branching ratio

- ATLAS: 25 fb^{-1} run I
  - First ATLAS result on $B_{(s)} \to \mu^+\mu^-$

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(0.9^{+1.1}_{-0.8}\right) \times 10^{-9}$$

Significance: 1.4σ (3.0 expected from SM)

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 4.2 \times 10^{-10} \text{ (95 \% CL)}$$

- LHCb 3+1.4 fb^{-1} run I+II
  - First single experiment observation
    - 7.9σ significance $B_s \to \mu^+\mu^-$

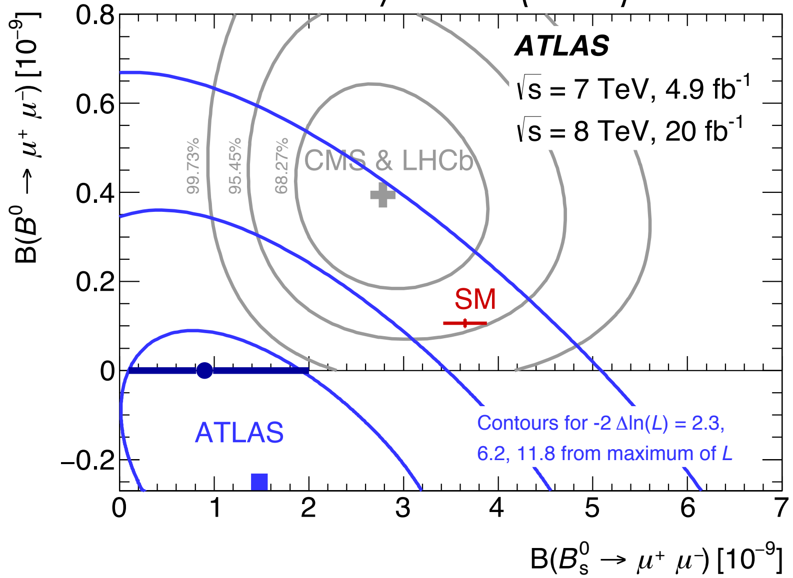
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$

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

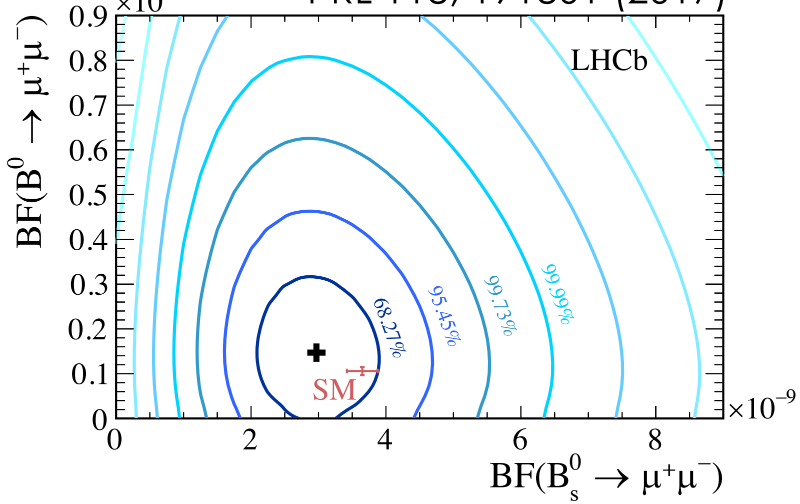
  - Effective lifetime of $B_s \to \mu^+\mu^-$

$$\tau(B_s^0 \to \mu^+\mu^-) = 2.04 \pm 0.44 \pm 0.05 \text{ ps}$$

Eur. Phys. J. C (2016) 76:513



PRL 118, 191801 (2017)



The heavier cousin: $B_{(s)} \to \tau^+\tau^-$

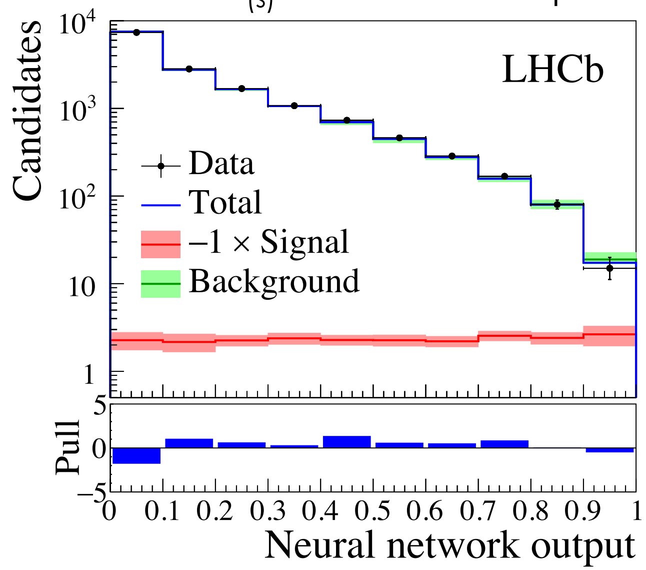
- LHCb 3 fb^{-1} run 1 PRL 118, 251802 (2017)
  - Larger branching ratio due to the larger mass
    - Additional enhancement possible in BSM scenarios that violate LFU

$$\overline{\mathrm{BR}}(B_s \to \tau^+\tau^-)_{\mathrm{SM}} = (7.46 \pm 0.30) \times 10^{-7}, \qquad \mathrm{BR}(B^0 \to \tau^+\tau^-)_{\mathrm{SM}} = (2.35 \pm 0.24) \times 10^{-8}$$

  - Experimentally challenging: multiple neutrinos in the final state
    - Reconstructed in the mode $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$
    - Normalisation $B_s \to D^-(\to K^+\pi^-\pi^-)D_s(\to K^-K^+\pi^+)$

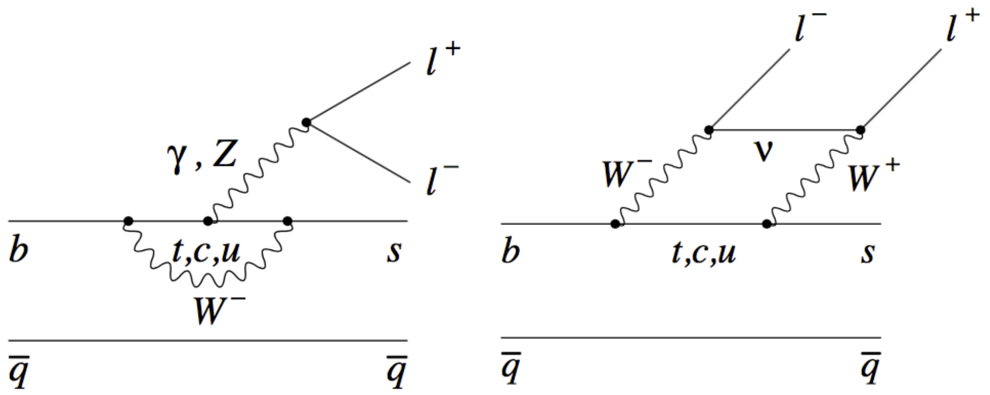
$$\mathcal{B}(B_s^0 \to \tau^+\tau^-) < 6.8 \times 10^{-3} \text{ at } 95\% \text{ CL}$$
$$\mathcal{B}(B^0 \to \tau^+\tau^-) < 2.1 \times 10^{-3} \text{ at } 95\% \text{ CL}$$

Fit to $B_{(s)} \to \tau^+\tau^-$ NN output



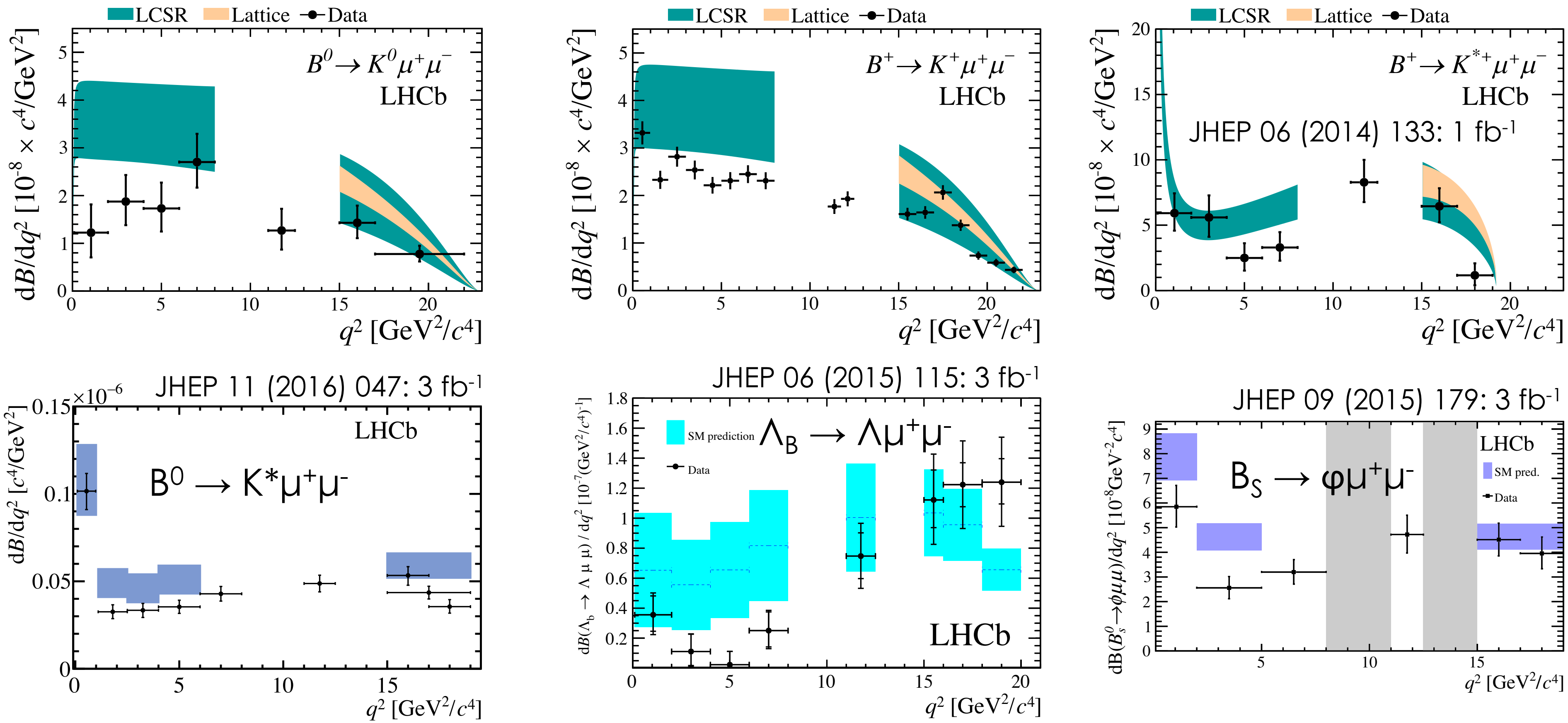
Electroweak b → s l^+ l^- transitions

$B^0 \to K^*\mu^+\mu^-$ and friends



$b \rightarrow s\, l^+ l^-$ differential branching ratios

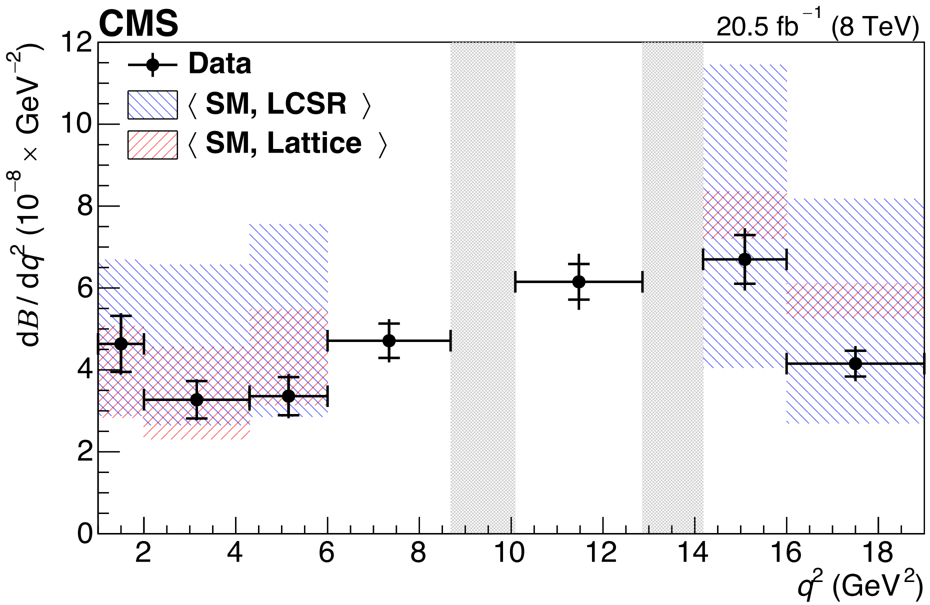
- LHCb: differential branching fractions in several $b \rightarrow s\, l^+ l^-$ modes
  - Versus di-muon invariant mass squared: q^2



- Discrepancy in the low di-muon invariant mass region

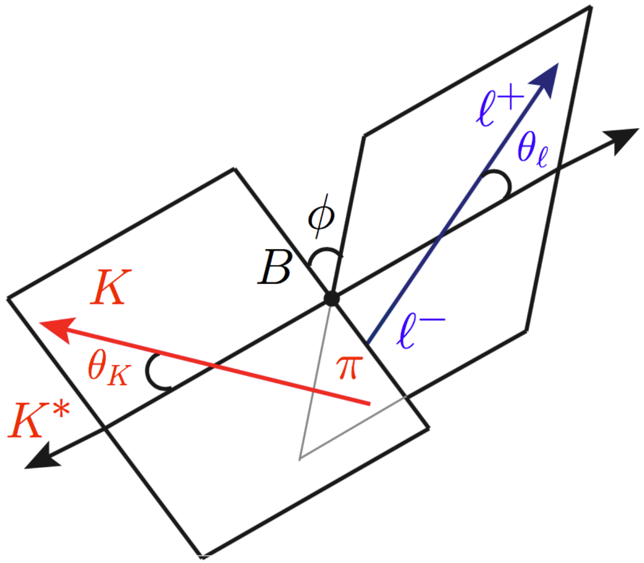
$b \rightarrow s\, l^+ l^-$ differential branching ratios

- CMS: 20.5 fb^{-1} run I   Phys. Lett. B 753 (2016) 424
  - $B^0 \rightarrow K^*\mu^+\mu^-$ differential branching ratio
  - Compatible with SM & LHCb results



b → s l⁺ l⁻ angular observables

- Angles defined in B meson rest frame
  - Angular variables: θ_l, θ_K & Φ
  - Di-lepton invariant mass²: q^2
  - Fit PDF for $B^0 \to K^*\mu^+\mu^-$



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

- Form-factor uncertainties in the predictions of observables
  - Alternative set of 7 observables with reduced uncertainties: $P_i^{(\prime)}$

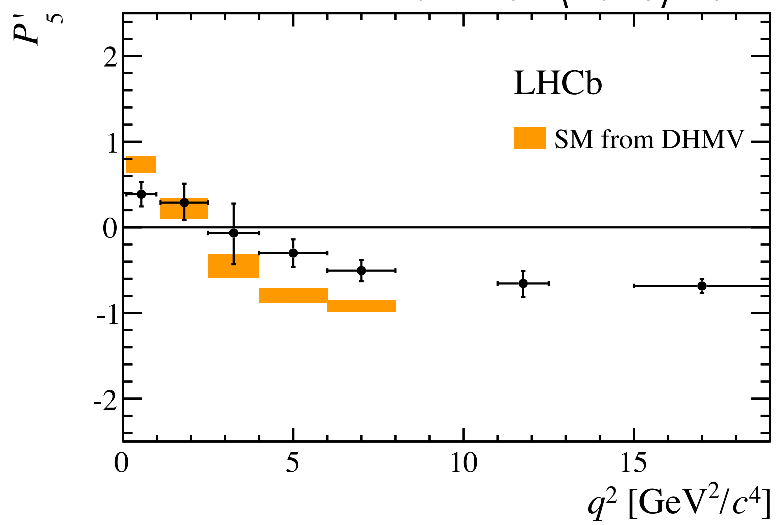
For instance:

$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

$B \to K^* \mu^+ \mu^-$ angular analysis

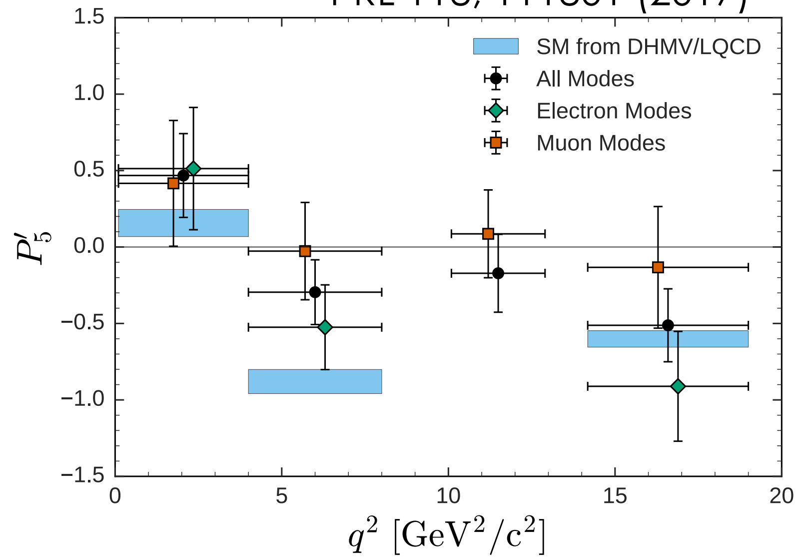
- LHCb: 3 fb^{-1} run I data set
  - Full angular analysis $B \to K^* \mu^+ \mu^-$
  - Local SM deviation P_5'
    - 2.8σ in $4 < q^2 < 6$ GeV^2/c^4
    - 3.0σ in $6 < q^2 < 8$ GeV^2/c^4
  - Fit to C_9 3.4σ from SM

JHEP02 (2016) 104



- Belle: 711 fb^{-1} full data set
  - Both $e^\pm$ and $\mu^\pm$ modes
  - Local SM deviation P_5'
    - 2.6σ in $4 < q^2 < 8$ GeV^2/c^4 in the muon mode
    - $e^\pm$ mode consistent with SM

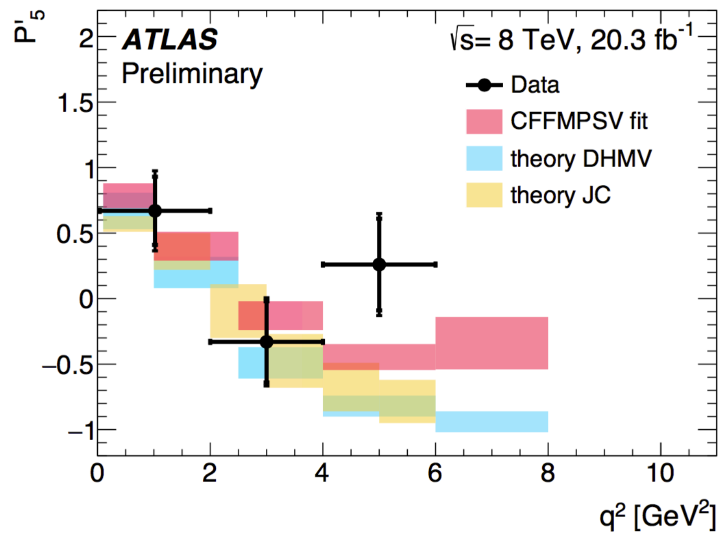
PRL 118, 111801 (2017)



$B \rightarrow K^* \mu^+ \mu^-$ angular analysis

- ATLAS: 20.3 fb^{-1} run I data

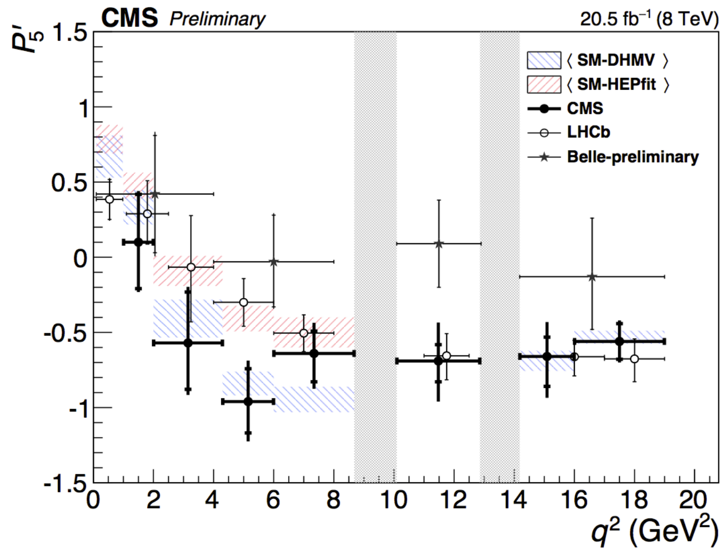
  ATLAS-CONF-2017-023



- CMS: 20.5 fb^{-1} run 1 data

  CMS PAS BPH-15-008

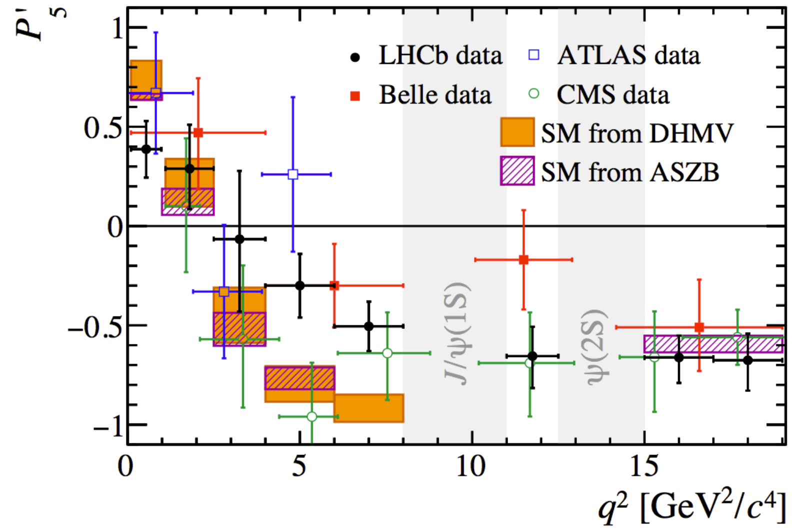
  - Recent, preliminary result
  - Compatible with SM
  - Compatible with LHCb & Belle



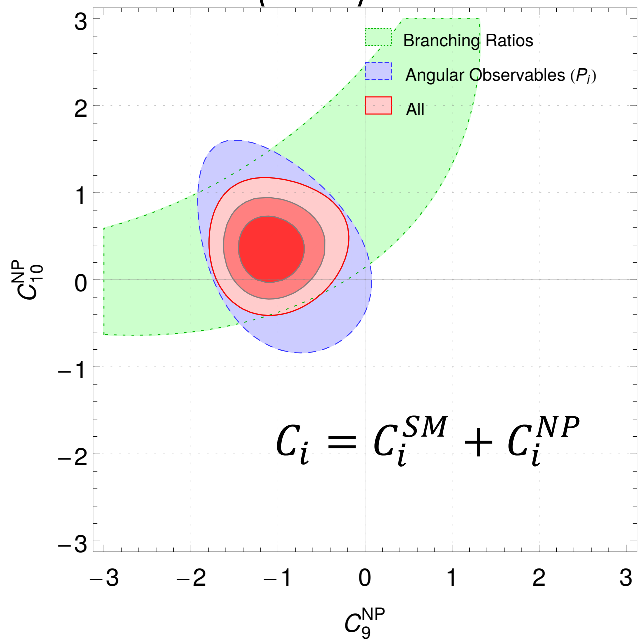
Global fits to Wilson coefficients

- Is there a pattern in these deviations?
- Global fits of Wilson coefficients
  - Approximately 100 observables
    - $B_{(s)} \to \mu^+\mu^-$ and $b \to s \gamma$ BR
    - $b \to s\, l^+ l^-$ BR & angular observables
  - Several global fits in literature
    - Fits prefer BSM contribution to C9
    - 3-5σ from SM depending on constraints
- Possible interpretations
  - BSM physics contributions
    - e.g. Z' of a few TeV
  - Limits in our understanding of QCD
    - E.g. contributions from charm loops

$B \to K^* \tau^+ \tau^-$ not yet observed
Babar limit BR < 2.3×10^{-3}
PRL 118, 031802 (2017)



JHEP 06 (2016) 092



Lepton flavour universality

Ratios of branching ratios – comparing lepton flavour

$$\mathcal{R}_{K^{(*)}} \equiv \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \qquad \mathcal{R}_{D^*}^{\mathrm{SM}} = \frac{\mathcal{B}(\bar{B} \to D^*\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^*e^-\bar{\nu}_e)}$$

See talk by **Anna Lupato:**
"Lepton flavour universality tests at LHCb"
Sunday 15:40 in 'Test of symmetries and conservation laws'

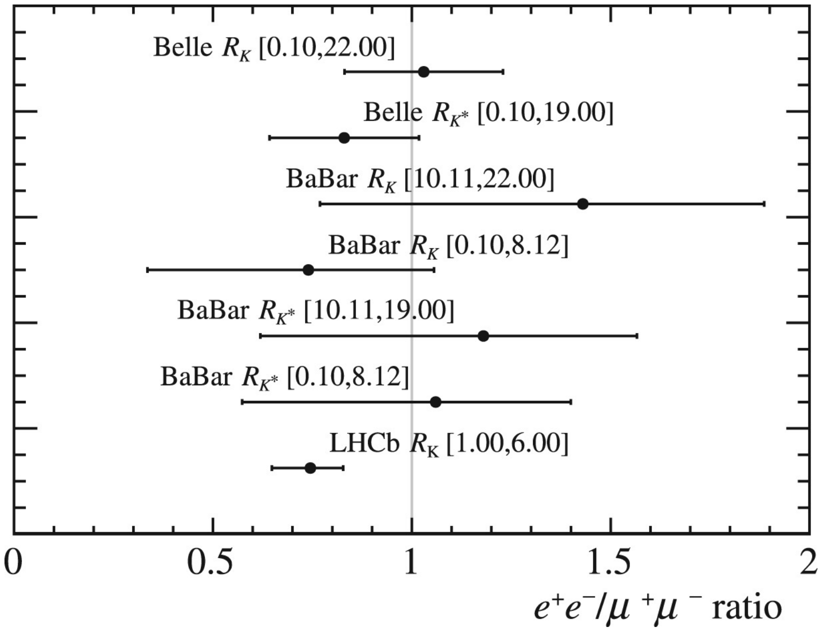
LFU: $B \rightarrow K^{(*)} \mu^+ \mu^-$ vs. $B \rightarrow K^{(*)} e^+ e^-$

- Lepton flavour universality test
  - Close to unity in SM

$$R_{K^{(*)}} = \frac{\mathcal{B}(B^{0/+} \rightarrow K^{0/+(*)}\mu^+\mu^-)}{\mathcal{B}(B^{0/+} \rightarrow K^{0/+(*)}e^+e^-)}$$

- Measurements by Belle & Babar
  - Combines B^0 & B^+ ratios
  - R(K) and R(K*) for different q^2 ranges
    - Consistent with SM prediction

Summary plot from arXiv:1606.00916v2



Babar: PRD 86 (2012) 032012
Belle: PRL 103 (2009) 171801

- LHCb 3 fb^{-1} run I: R_K PRL 113 (2014)151601
  - Measured as a double ratio

$$R_K = \frac{\mathcal{B}(B^+ \rightarrow K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \rightarrow K^+ J/\psi\ (\rightarrow \mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^+ \rightarrow K^+ J/\psi\ (\rightarrow e^+e^-))}{\mathcal{B}(B^+ \rightarrow K^+e^+e^-)}$$

$$R_K = 0.745^{+0.090}_{-0.074}\,(\text{stat}) \pm 0.036\,(\text{syst})$$

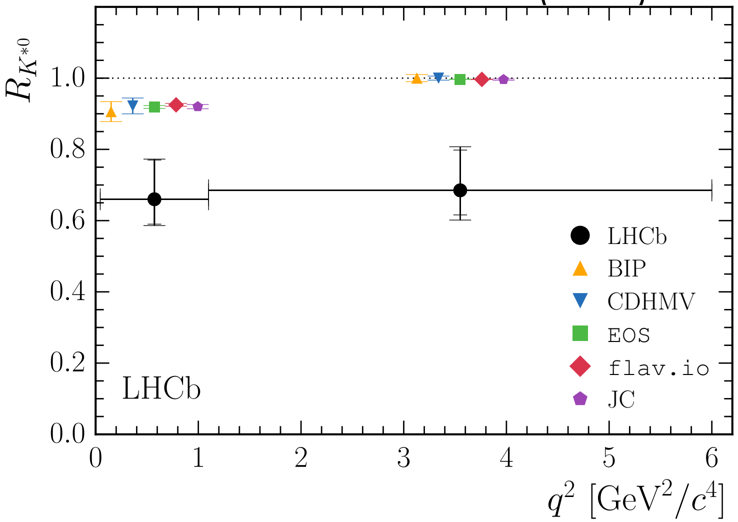
- 2.6σ deviation from SM

LFU: $B \to K^{(*)} \mu^+ \mu^-$ vs. $B \to K^{(*)} e^+ e^-$

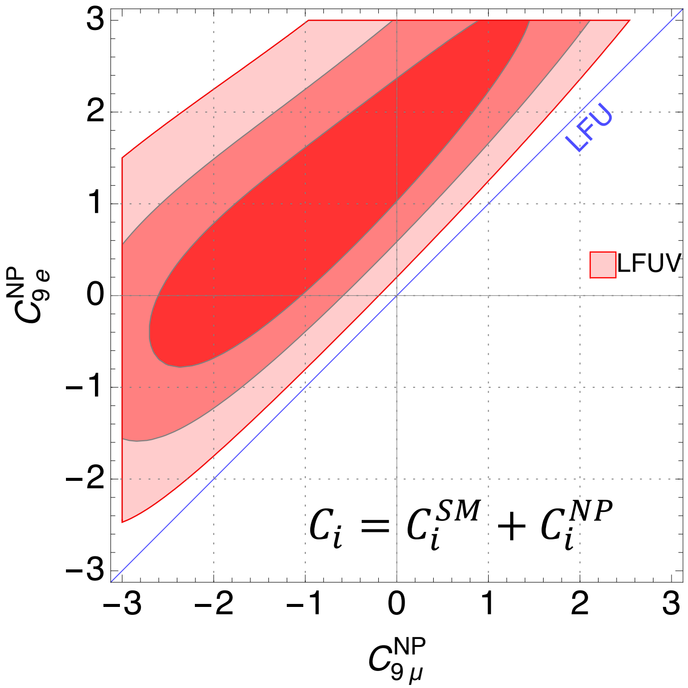
- LHCb: 3 fb^{-1} run I: R_{K*}
  - Tension with SM
    - 2.1-2.3σ in $0.045 < q^2 < 1.1$ GeV^2/c^4
    - 2.2-2.4σ in $1.1 < q^2 < 6.0$ GeV^2/c^4

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

JHEP01 (2017) 055



- Fit to Wilson coefficients
  - Allowing for $C_{ie}^{NP} \neq C_{i\mu}^{NP}$
    - 3.5σ from SM
    - Preference for $C_{9\mu}^{NP} \neq 0$

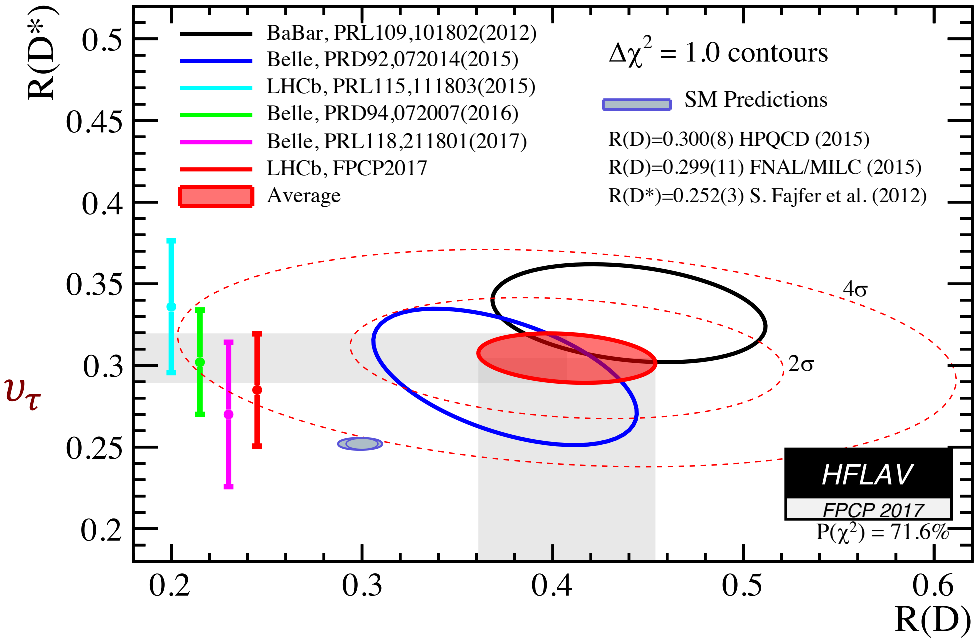


PSI-PR-17-05 arXiv:1704.05340

LFU: B → $D^{(*)}$ $\tau^+\nu$ vs. B → $D^{(*)}$ l^+ ν^- (l = e or μ)

- LFU ratios for semi-leptonic $D^{(*)}$ decays
- R_D measurements
  - Belle & Babar
    - Hadronic tag, $\tau^- \to l^-\bar{\nu}_l\nu_\tau$
- R_{D^*} measurements
  - Belle & Babar
    - Hadronic tag, $\tau^- \to l^-\bar{\nu}_l\nu_\tau$
  - Belle
    - Hadronic tag, $\tau^- \to \pi^-\nu_\tau$, $\tau^- \to \rho^-\nu_\tau$
    - Semi-leptonic tag, $\tau^- \to l^-\bar{\nu}_l\nu_\tau$
  - LHCb 3 fb^{-1} (run I)
    - $\tau^- \to l^-\bar{\nu}_l\nu_\tau$
    - $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$

$$R_{D^{(*)}} = \frac{\mathcal{B}(B^{0/-} \to D^{0/-(*)}\tau^+\nu_\tau)}{\mathcal{B}(B^{0/-} \to D^{0/-(*)}l^+\nu_l)}$$



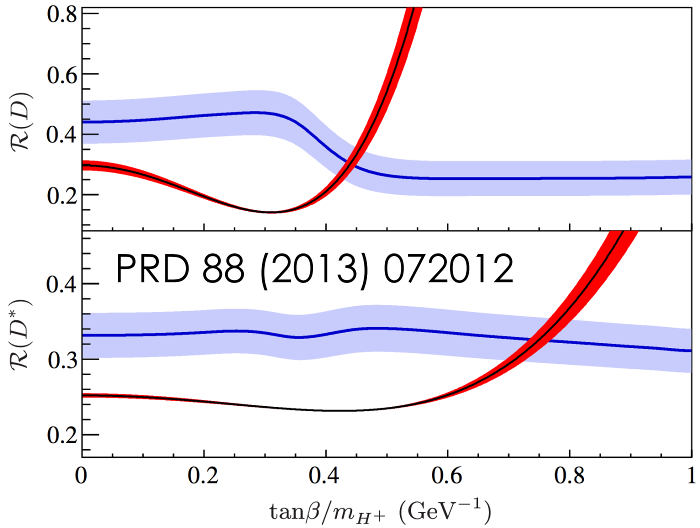
Tension with SM prediction

- 2.3σ in R_D
- 3.4σ in R_{D^*}
- 4.1σ combined

Interpretations of the $R_{D^{(*)}}$ results

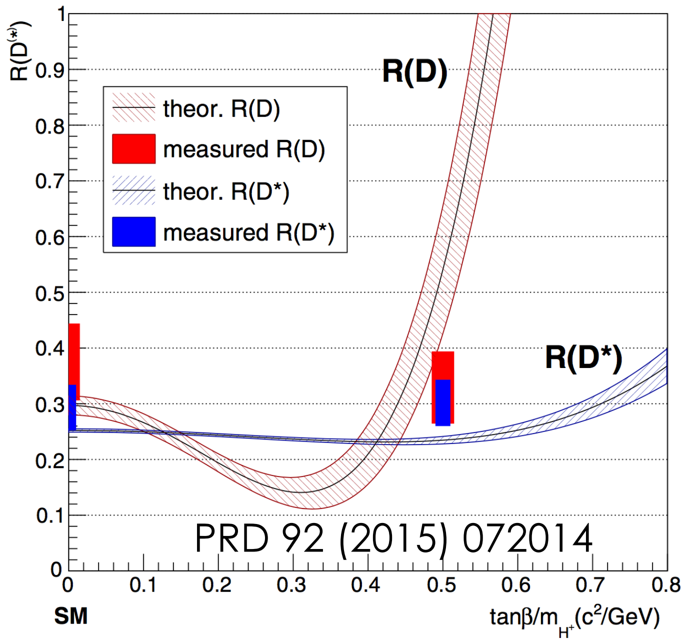
- Example of BSM model that would influence $R_{D^{(*)}}$
  - 2-Higgs-dublet model Type II
    - Parametrised by $\tan(\beta)/m_{H^+}$
  - Affects both measured and predicted $R_{D^{(*)}}$

Comparison with Babar hadronic result



Not consistent with 2HDM type II

Comparison with Belle hadronic result



Consistent with 2HDM type II with $\tan(\beta)/m_{H^+} \sim 0.45$

Outlook

Many exciting results in the years to come

LHCb datasets

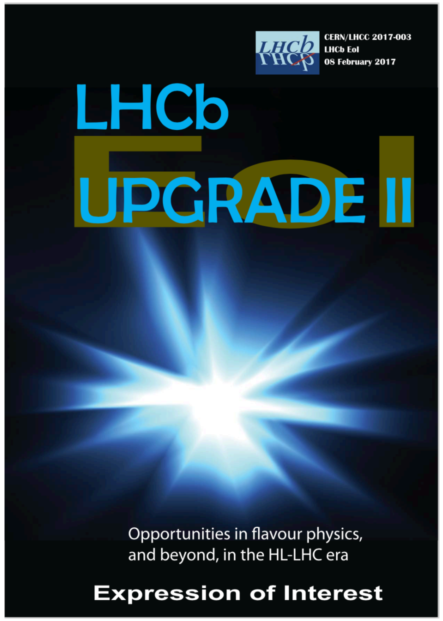
- LHCb results almost exclusively from 3 fb^{-1} Run I data
  - Run II doubles signal yield/fb^{-1}
    - Increased $b\bar{b}$ cross section

CERN-LHCC-2017-003

	LHC Run	Period of data taking	Maximum $\mathcal{L}$ $[\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	Cumulative $\int \mathcal{L}\, dt$ $[\mathrm{fb}^{-1}]$
Current detector	1 & 2	2010–2012, 2015–2018	4×10^{32}	8
Phase-I Upgrade	3 & 4	2021–2023, 2026–2029	2×10^{33}	50
Phase-II Upgrade	5 $\rightarrow$	2031–2033, 2035 $\rightarrow$	2×10^{34}	300

- LHCb Phase-I upgrade
  - Remove H/W trigger – 40 Mhz readout
    - Doubles signal yield/fb^{-1} for hadronic channels
    - Construction progressing at full speed

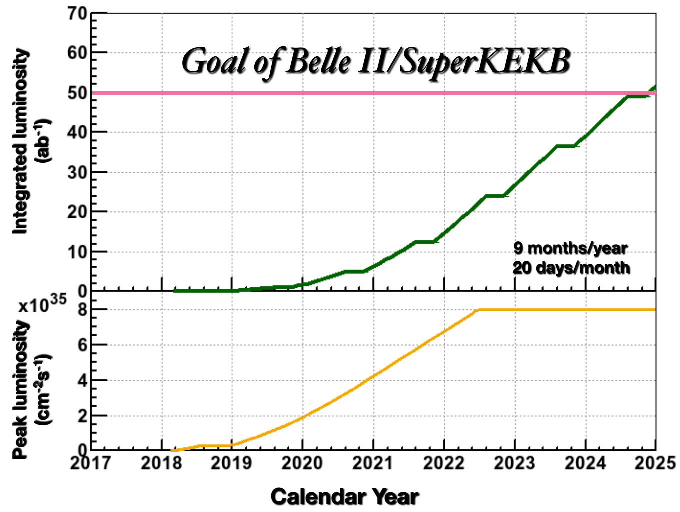
- LHCb Phase-II upgrade
  - Preliminary studies ongoing
    - Major detector upgrade
    - EoI submitted



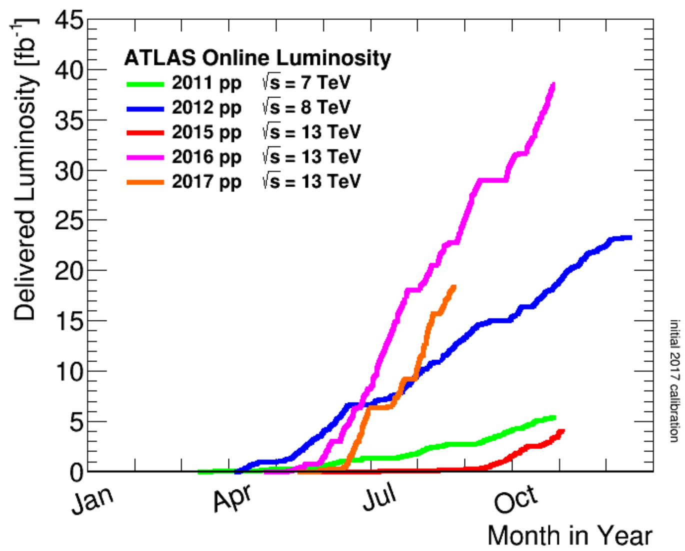
Belle II, ATLAS & CMS

- Babar & Belle datasets
  - 550 + 1000 fb^{-1}
- Belle II: 50 ab^{-1}
  - Physics data taking from 2018
    - See previous speaker (Mikihiko Nakao)
  - Dedicated talk by Jake Bennet
    - Sunday, 14:50 (accelerators & detectors)

SuperKEKB luminosity projection



- ATLAS & CMS: results from 20-25 fb^{-1}
  - ~ 80 fb^{-1} on tape
    - Expect ~300 fb^{-1} by 2023
  - 3 ab^{-1} for sLHC upgrade era
  - Many important results are expected



Physics prospects

- Belle II: R_D & R_{D^*}

$$\sigma_{BelleII} = \sqrt{(\sigma_{stat}^2 + \sigma_{sys}^2)\frac{\mathcal{L}_{Belle}}{50\ \mathrm{ab}^{-1}} + \sigma_{\mathrm{irred}}^2}$$

arXiv:1002.5012 and
EPS-HEP 2017 talk by S. Falke

	Current precision	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
R_D	12%	5.6%	3.2%
R_{D^*}	5.4%	3.9%	2.2%
R_K	12%	7%	2%

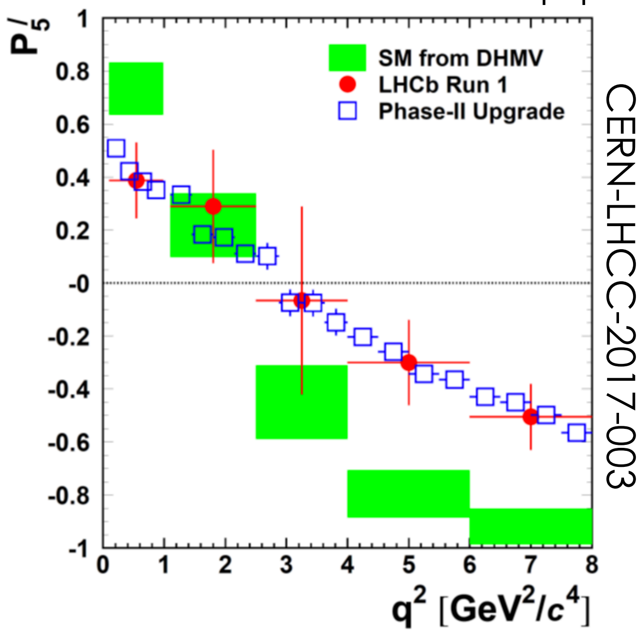
- LHCb Phase I & II

CERN-LHCC-2017-003
CERN-LHCC-2012-007

$B_{(s)} \to \mu^+\mu^-$	Current precision	Phase-I 50 fb^{-1}	Phase-II 300 fb^{-1}
σ_{BR} x10^{-9}	0.7	0.15	0.07
Effective lifetime σ_τ	25%	5%	2%

ATLAS & CMS are competitive in $B_{(s)} \to \mu^+\mu^-$

Prediction for $B^0 \to K^*\mu^+\mu^-$



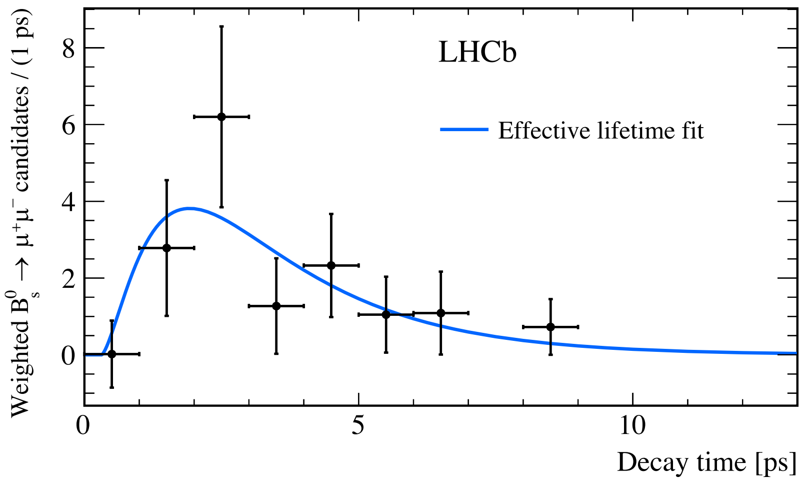
Summary

- Rare B-decays are an excellent probe for BSM physics
- $B_{(s)} \rightarrow \mu^+\mu^-$ branching ratios consistent with SM
  - Within experimental precision
- Intriguing deviations from SM predictions
  - $b \rightarrow s\, l^+ l^-$ branching ratios & angular observables
  - Lepton flavour universality test: $R_{K^{(*)}}$ and $R_{D^{(*)}}$
- Exciting results expected from
  - Data already recorded
  - Upgraded detectors

Backup slides

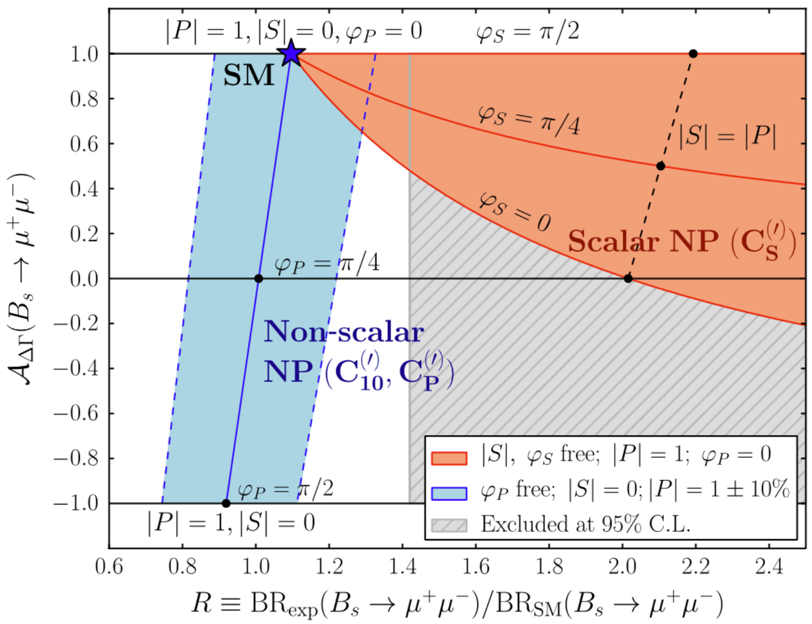
$B_s \rightarrow \mu^+\mu^-$ effective lifetime

- LHCb update: 3 fb^{-1} (run I) + 1.4 fb^{-1} (run 2)
- New observable sensitive to CP violation
  - $A_{\Delta\Gamma}$ = 1 in SM (i.e. no CPV) $\tau_{eff} = \tau_{B_H} = 1.619 \pm 0.009$



$$\tau(B_s^0 \rightarrow \mu^+\mu^-) = 2.04 \pm 0.44 \pm 0.05 \text{ ps}$$

Measurement for the sLHC era

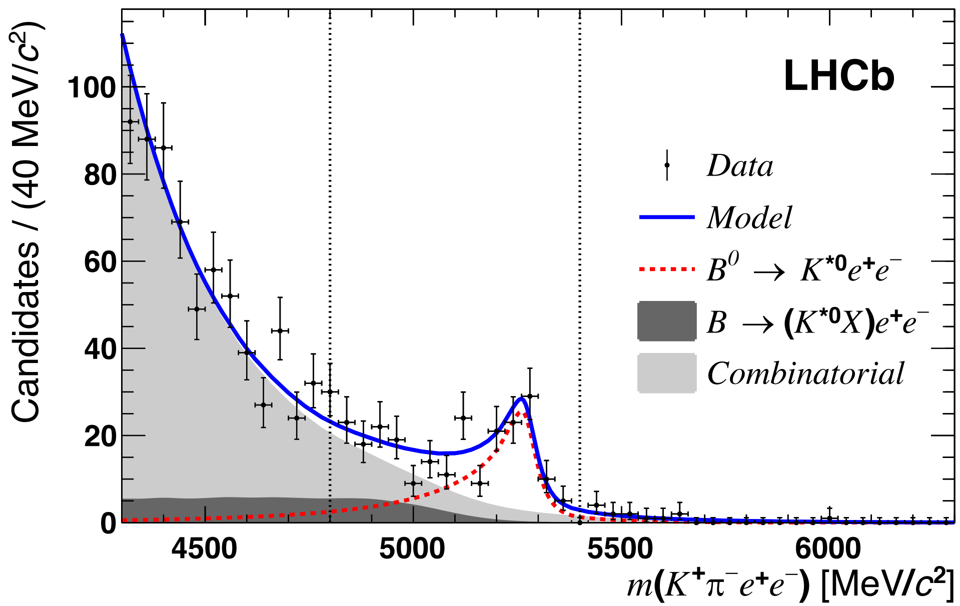


De Bruyn et al., PRL 109, 041801 (2012)

$B^0 \to K^* e^+ e^-$ angular analysis

- LHCb: 3 fb-1 run I
  - Particular interest in the low q^2 region
    - Sensitivity to photon polarisation
    - Wilson coefficients C_7 & C_7'
  - Folded angular distributions
    - Increase sensitivity for low yields
    - 4 observables

JHEP04 (2015) 064



$0.002 < q^2 < 1.12$ GeV^2/c^4

$$\begin{aligned} F_{\rm L} &= 0.16 \pm 0.06 \pm 0.03 \\ A_{\rm T}^{(2)} &= -0.23 \pm 0.23 \pm 0.05 \\ A_{\rm T}^{\rm Im} &= +0.14 \pm 0.22 \pm 0.05 \\ A_{\rm T}^{\rm Re} &= +0.10 \pm 0.18 \pm 0.05 \end{aligned}$$

Belle: τ polarisation in B → D* $\tau^+ \nu$

- Belle full dataset
  - Complementary observable
  - Hadronic tag, $\tau^- \to \pi^- \upsilon_\tau$, $\tau^- \to \rho^- \upsilon_\tau$
- Polarisation of τ^-

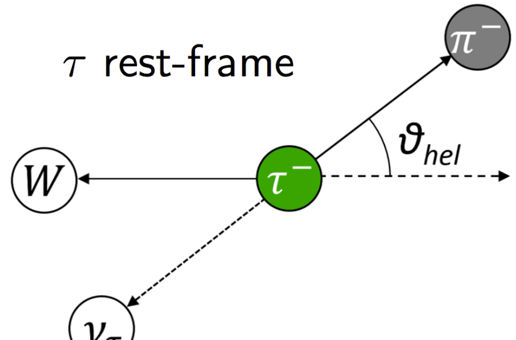
$$P_\tau(D^*) = \frac{\Gamma^+(D^*) - \Gamma^-(D^*)}{\Gamma^+(D^*) + \Gamma^-(D^*)}$$

  - $\Gamma^\pm(D^*)$: decay rate with τ helicity ±½
  - Differential BR

$$\frac{d\Gamma(D^*)}{d\cos\vartheta_{hel}} = \frac{\Gamma(D^*)}{2}\left[1 + \alpha P_\tau(D^*)\cos\vartheta_{hel}\right]$$

$$\tau \to \pi\nu_\tau \ (\alpha = 1)$$

$$\tau \to \rho\nu_\tau \ (\alpha = 0.45)$$



Result:

$P_\tau^{SM} = -0.497 \pm 0.013$

$P_\tau = -0.38 \pm 0.51^{+0.21}_{-0.16}$

Compatible with SM