Test of lepton flavour universality at LHCb

Quy Nhon, NuFact 2016

Federica Lionetto
on behalf of the LHCb collaboration

University of Zurich

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University of Zurich[UZH]

Outline

Motivation

LHCb

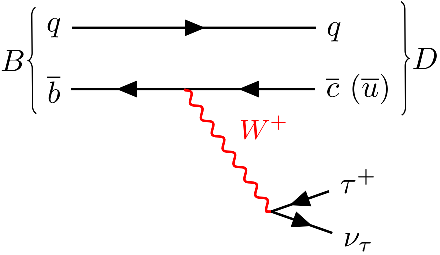
The R_{D^*} and R_K measurements

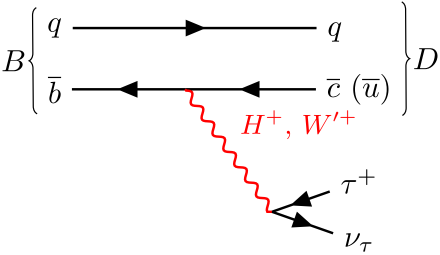
The $B^0 \to K^{*0}\mu^+\mu^-$ and $B^0 \to K^{*0}e^+e^-$ decays

Conclusions and future prospects

The $b \to c\tau^-\overline{\nu_\tau}$ transition

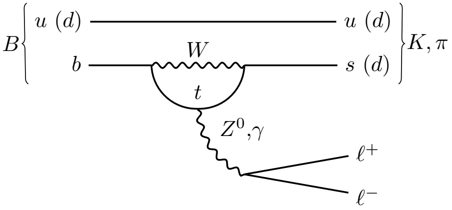
- At tree level in the Standard Model
- However, measured to a precision of $\mathcal{O}(20\%)$ in the τ final state
- Sensitive to NP preferentially coupling to 3rd generation fermions, *e.g.* Higgs-like charged scalars or W' bosons





The $b \to s\ell^+\ell^-$ transition

- Suppressed in the Standard Model
  - no FCNC at tree level
  - sensitive to New Physics contributions (including LFNU)



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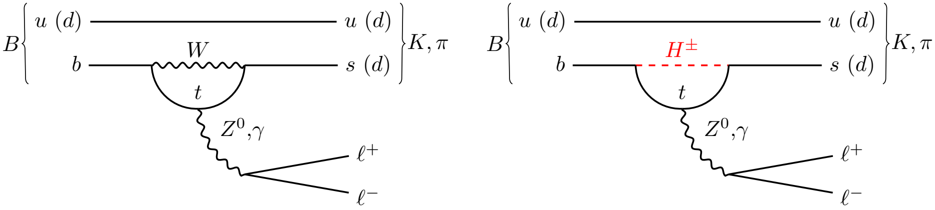

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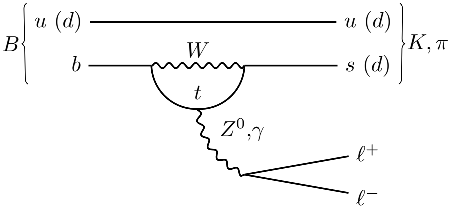
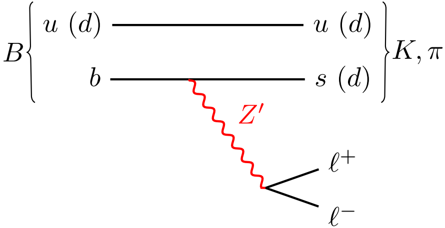




The $b \to s\ell^+\ell^-$ transition

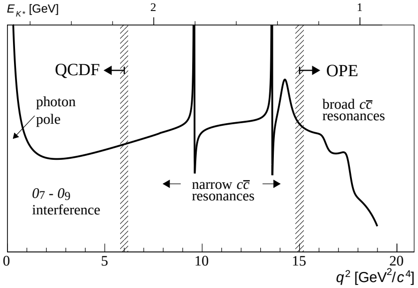
- Suppressed in the Standard Model
  - no FCNC at tree level
  - sensitive to New Physics contributions (including LFNU)
- Model-independent description

  $\Longrightarrow$ effective field theory
- Factorisation between
  - short-range contributions, Wilson coefficients $\mathcal{C}_i^{(\prime)}$
  - long-range contributions, local operators $\mathcal{O}_i^{(\prime)}$

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \left(\mathcal{C}_i \mathcal{O}_i + \mathcal{C}'_i \mathcal{O}'_i \right)$$

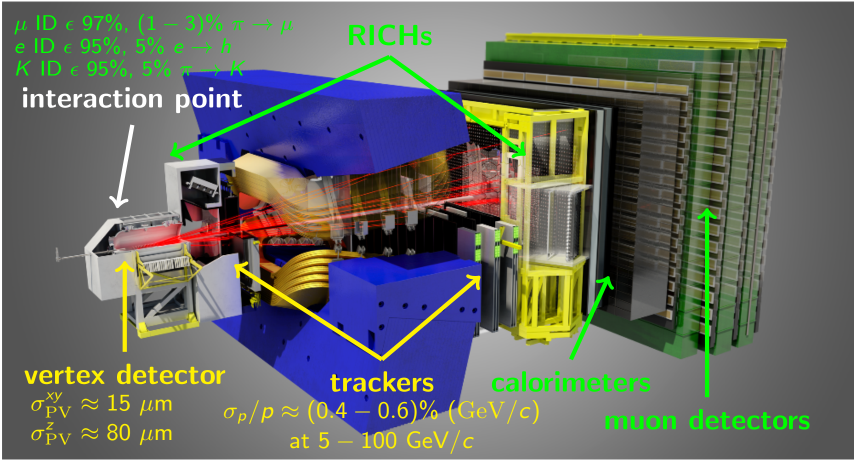
$B^0 \to K^{*0}\mu^+\mu^-$ differential decay width

Annu. Rev. Nucl. Part. Sci. 65 (2015) 113



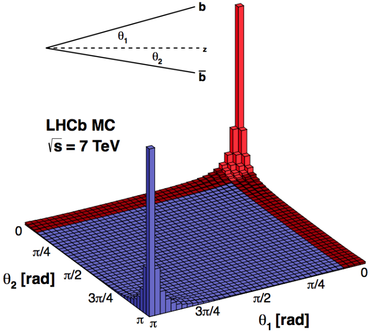
The LHCb detector

pp collisions at 7 – 13 TeV, pseudorapidity $2 < \eta < 5$



The LHCb experiment

- Tailored for heavy flavour physics at the LHC
- Ideal for studying rare *b*-hadron decays
  - excellent vertex and momentum resolution
  - good PID capabilities
- Run I
  - 3 fb^{-1} at $7-8$ TeV
  - large $b\bar{b}$ production cross section $\sigma_{b\bar{b}} = (75.3 \pm 14.1)\ \mu\text{b}$ in acceptance
- Run II
  - 1 fb^{-1} at 13 TeV already collected
  - increased $\sigma_{b\bar{b}}$



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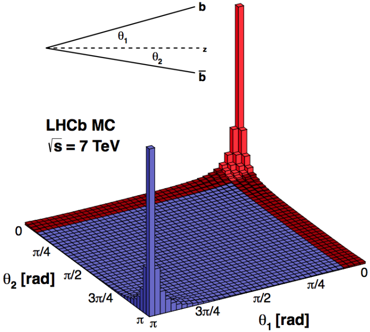


$$R_{D^*} = \frac{\overline{B^0} \to D^{*+}\tau^-\overline{\nu_\tau}}{\overline{B^0} \to D^{*+}\mu^-\overline{\nu_\mu}}$$

The R_{D^*} measurement

- Branching fraction ratio of $\overline{B^0} \to D^{*+}\tau^-\overline{\nu_\tau}$ to $\overline{B^0} \to D^{*+}\mu^-\overline{\nu_\mu}$
  - $R_{D^*} \stackrel{\text{SM}}{=} 0.252 \pm 0.003$
  - previously measured by BaBar and Belle

Experiment	R_{D^*}	SM discrepancy
BaBar*	$0.332 \pm 0.024 \pm 0.018$	$2.7\ \sigma$
Belle**	$0.293 \pm 0.038 \pm 0.015$	$1.8\ \sigma$
	$0.302 \pm 0.030 \pm 0.011$	$1.6\ \sigma$

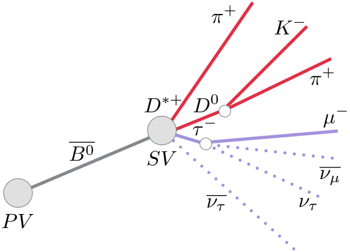
* Phys. Rev. Lett. 109, 101802 (2012), Phys. Rev. D 88, 072012 (2013)

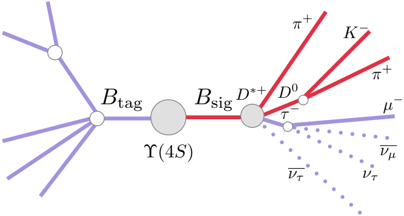
** Phys. Rev. D 92, 072014 (2015), arXiv:1607.07923, Belle-CONF-1602

Phys. Rev. Lett. 115 (2015) 111803

LHCb analysis strategy

- $D^{*+} \to D^0\pi^+$, with $D^0 \to K^-\pi^+$, and $\tau^- \to \mu^-\overline{\nu_\mu}\nu_\tau$
- 3ν final state
- Kinematic information on B_{tag} at B factories, but at LHCb?
  - B flight direction given by PV and SV
  - approximated B momentum along the beam $\Longrightarrow p_z = (m/m_{rec})p_{rec,z}$
- Signal and normalisation channels with identical visible final-state topologies





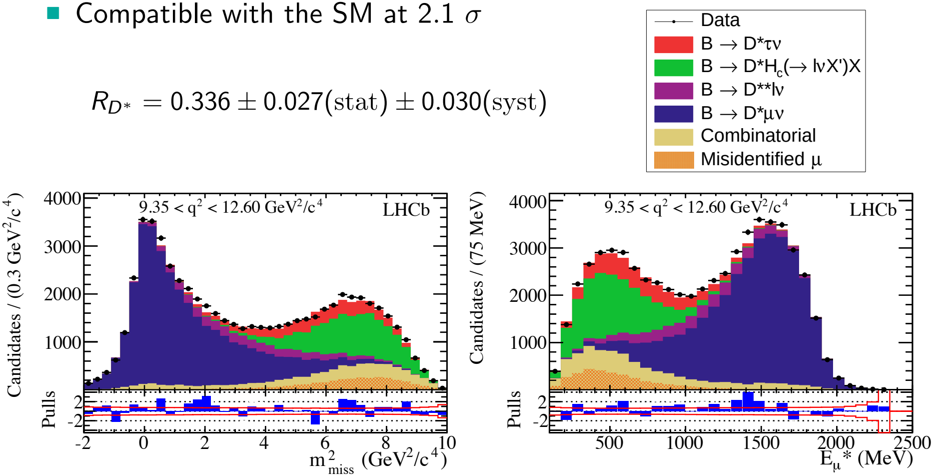
Yields determination

- Exploit
  - $\tau - \mu$ mass difference
  - presence of extras νs in the signal channel
- Evaluate E^*_μ, $m^2_{\rm miss} = (p^\mu_B - p^\mu_D - p^\mu_\mu)^2$, and $q^2 = (p^\mu_B - p^\mu_D)^2$ in the B rest frame
- Background from
  - partially reconstructed decays $B \to D^{*(*)} l\nu$, $B \to D^* DX$
  - combinatorial
- ML fit using template distributions from control samples and MC
- Simultaneous fit to several background-enriched samples (data-driven)

Results for R_{D^*}

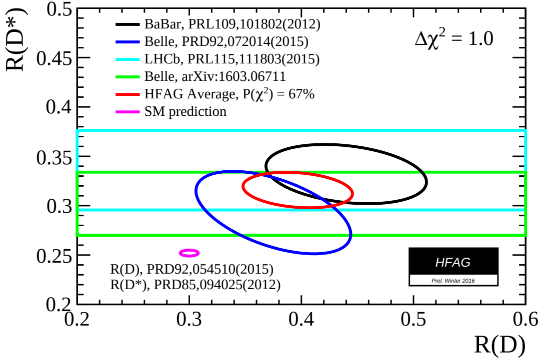
- First measurement of $b \to \tau$ decays at hadron colliders
- Compatible with the SM at 2.1 σ

$$R_{D^*} = 0.336 \pm 0.027(\mathrm{stat}) \pm 0.030(\mathrm{syst})$$



Combined results for R_D and R_{D^*}

- Excess w.r.t. SM prediction observed by several experiments
  - corresponding to 4 σ according to latest HFAG average



$$R_K = \frac{B^+ \to K^+ \mu^+ \mu^-}{B^+ \to K^+ e^+ e^-}$$

The R_K measurement

- Ratio of branching fractions of $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+e^+e^-$
  - $R_K \overset{\text{SM}}{=} 1 + \mathcal{O}(10^{-2})$
  - sensitive to new scalar and pseudoscalar interactions or Z' bosons
  - previously measured by BaBar and Belle

Experiment	q^2 (GeV^2)	R_K
BaBar*	$0.1 - 16.0$	$1.00^{+0.31}_{-0.25} \pm 0.07$
	$0.1 - 8.12$	$0.74^{+0.40}_{-0.31} \pm 0.06$
	> 10.11	$1.43^{+0.65}_{-0.44} \pm 0.12$
Belle**	$0.00 - 16.0$	$1.03 \pm 0.19 \pm 0.06$

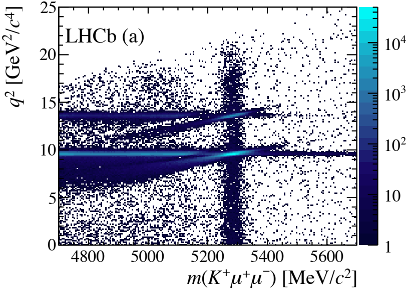
* Phys. Rev. D 86 (2012) 032012

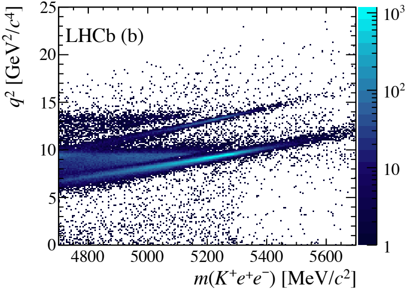
** Phys. Rev. Lett. 103 (2009) 171801

The R_K measurement at LHCb

- $q^2 \in [1, 6]$ GeV$^2/c^4$
- Double ratio with respect to the resonant decay mode $B^+ \to J/\psi K^+$

$$R_K = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\Gamma(B^+\to K^+\mu\mu)}{dq^2} dq^2}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\Gamma(B^+\to K^+ee)}{dq^2} dq^2} = \left(\frac{N_{K\mu\mu}}{N_{Kee}}\right)\left(\frac{N_{KJ/\psi(ee)}}{N_{KJ/\psi(\mu\mu)}}\right)\left(\frac{\epsilon_{Kee}}{\epsilon_{K\mu\mu}}\right)\left(\frac{\epsilon_{KJ/\psi(ee)}}{\epsilon_{KJ/\psi(\mu\mu)}}\right)$$





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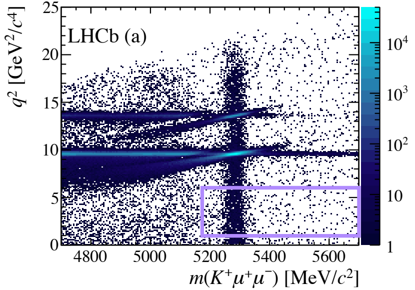
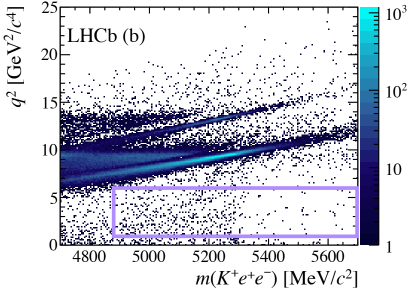
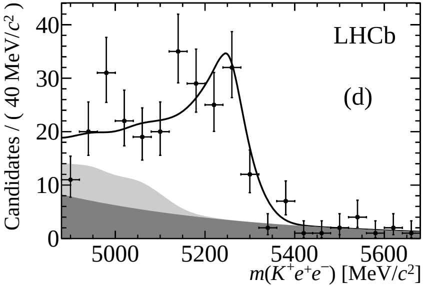




Results for R_K

- Distributions affected by
  - trigger
  - *bremsstrahlung* photons
- Most precise result to date
- Compatible with the SM at 2.6 σ

electron trigger, 172^{+20}_{-19} events



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

- Fundamental for future measurements of decays with electrons in the final state

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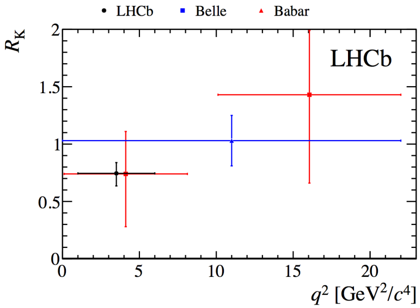

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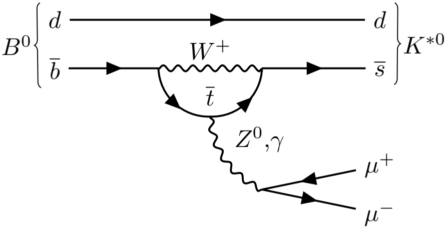
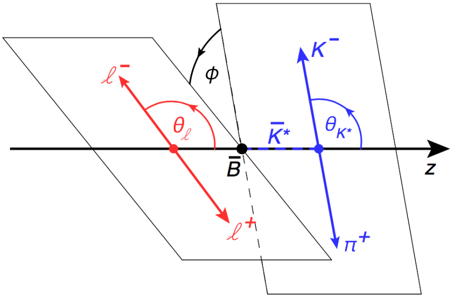
- Fundamental for future measurements of decays with electrons in the final state

Look at muons and electrons separately...

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

- Angular analysis in terms of $\vec{\Omega} = (\theta_l, \theta_k, \phi)$ and $q^2 = m^2_{\mu\mu}$





LHCb analysis strategy

- Determine

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

  with F_L, A_{FB}, $S_i = f(C_7^{(\prime)}, C_9^{(\prime)}, C_{10}^{(\prime)})$, combinations of K^{*0} decay amplitudes

- Theoretical uncertainty on hadronic form factors
  $\Longrightarrow$ reduced by moving to optimised observables, *e.g.* $P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$

  arXiv:1305.4808

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& + \tfrac{1}{4}(1-F_L)\sin^2\theta_k\cos 2\theta_\ell - F_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 \\
& + \sqrt{F_L(1-F_L)}P_5'\sin 2\theta_k\sin\theta_\ell\cos\phi + \tfrac{4}{3}A_{FB}\sin^2\theta_k\cos\theta_\ell \\
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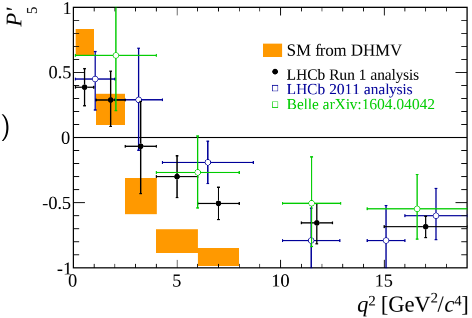
Results for $B^0 \to K^{*0}\mu^+\mu^-$

- Analysis in 8 bins of $q^2 \in [0.1, 19.0]$ GeV$^2/c^4$, $K^{*0} \to K^+\pi^-$
- Most angular observables compatible with SM predictions
- Tension observed in P'_5
  - global fit at 3.4 σ from the SM prediction
  - compatible with previous LHCb and recent Belle measurements
- Explainable in terms of
  - SM charm-loop effects (cannot explain tension in R_K) $\Longrightarrow$ JHEP 06 (2016) 116
  - NP involving $\mathcal{C}_9$ (and possibly $\mathcal{C}_{10}$), otherwise

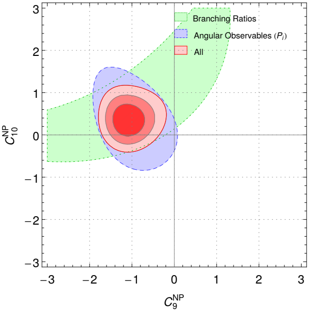


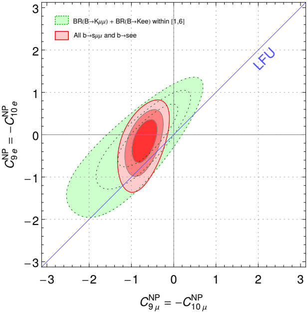
Theory interpretation in terms of NP

- Measurements in favour of a reduced $\mathcal{C}_9$
- Possible link to LFNU

  $\Longrightarrow$ arXiv:1605.03156, JHEP 12 (2014) 131, Phys. Rev. D 90, 054014 (2014)
- Can explain R_{D^*} anomaly, assuming W' and Z'

  $\Longrightarrow$ arXiv:1506.01705

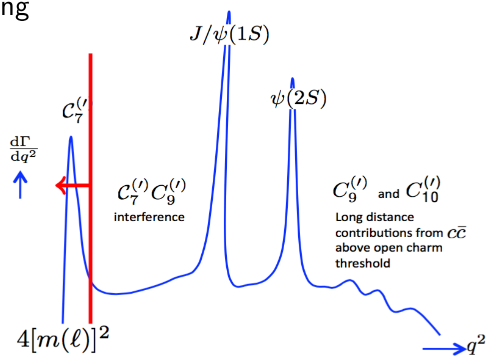




Compare to $B^0 \to K^{*0} e^+ e^-$...

The $B^0 \to K^{*0} e^+ e^-$ decay

- Simplified formalism, 4 angular observables
  - K^{*0} longitudinal polarisation fraction F_L
  - transverse asymmetries $A_T^{(2)}$, A_T^{Im} and A_T^{Re}
- Experimentally more challenging
  - statistics
  - resolution
  - trigger
  - *bremsstrahlung* photons
- $q^2 \in [0.002, 1.120]$ GeV$^2/c^4$
  - photon polarisation
- $K^{*0} \to K^+ \pi^-$
- ML fit of $\vec{\Omega}$ and $m_{K\pi ee}$



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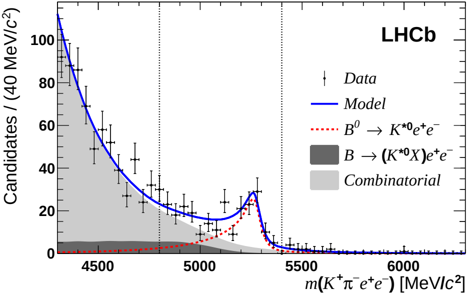
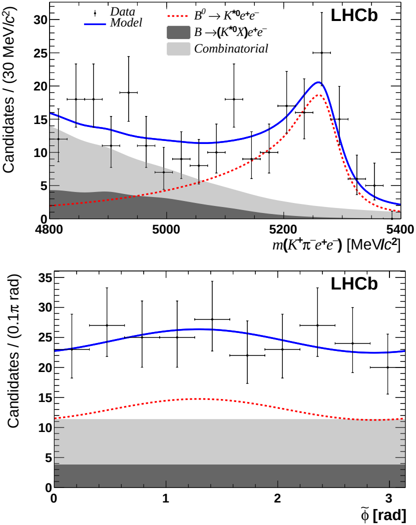
124 signal events



Results for $B^0 \to K^{*0} e^+ e^-$



$$F_L = +0.16 \pm 0.06 \pm 0.03$$
$$A_T^{(2)} = -0.23 \pm 0.23 \pm 0.05$$
$$A_T^{Im} = +0.14 \pm 0.22 \pm 0.05$$
$$A_T^{Re} = +0.10 \pm 0.18 \pm 0.05$$

$$F_L \stackrel{\text{SM}}{=} +0.10^{+0.11}_{-0.05}$$
$$A_T^{(2)} \stackrel{\text{SM}}{=} +0.03^{+0.05}_{-0.04}$$
$$A_T^{Im} \stackrel{\text{SM}}{=} (-0.2^{+1.2}_{-1.2}) \times 10^{-4}$$
$$A_T^{Re} \stackrel{\text{SM}}{=} -0.15^{+0.04}_{-0.03}$$

Phys. Rev. D 93, 014028 (2016)

In agreement with SM

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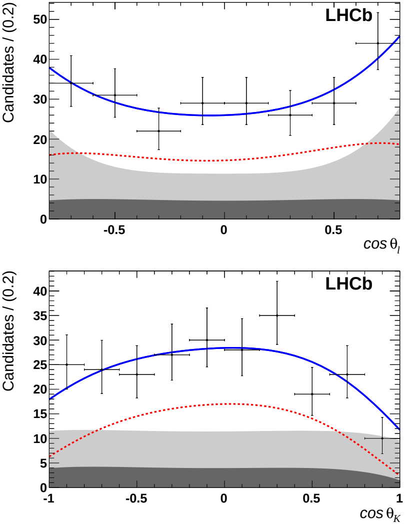

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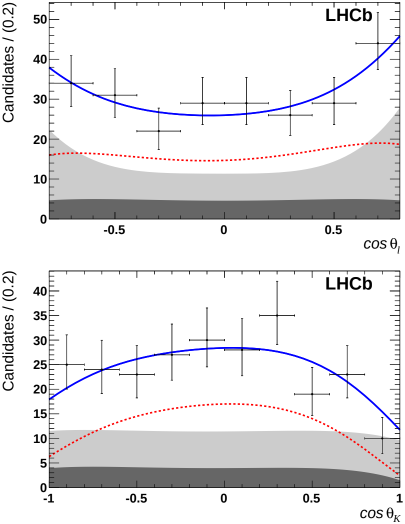

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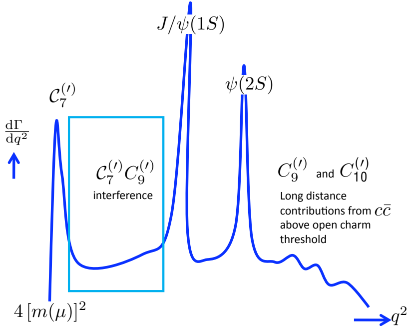
$$

Phys. Rev. D 93, 014028 (2016)

...and consistent with $B^0 \to K^{*0}\mu^+\mu^-$ anomaly, since contribution from $\mathcal{C}_7$ only

Future prospects

- R_{K^*}
  - analogous to R_K in the $B^0 \to K^{*0}\ell^+\ell^-$ decay mode
  - larger q^2 range
- R_ϕ, R_D, update for R_{D^*}
- S-wave scalar components $B^0 \to K^+\pi^-\mu^+\mu^-$ and $B^0 \to K^+\pi^-e^+e^-$
- Update for angular analyses of $B^0 \to K^{*0}\ell^+\ell^-$
- Asymmetry measurements in angular observables, *e.g.* $e-\mu$ asymmetry in P_5'



Conclusions

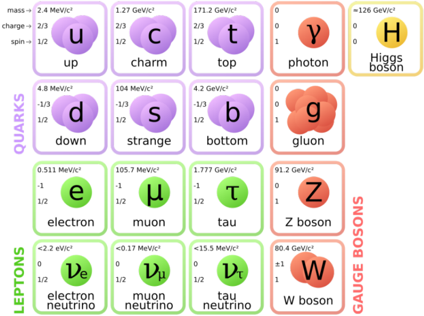
- Search for NP in the $b \to c\tau^- \overline{\nu_\tau}$ transition
  - excess of 4 σ w.r.t. SM prediction observed in R_{D^*}
  - might be a hint to LFU violation between μ and τ
- Search for NP in the $b \to s\ell^+\ell^-$ transition
  - hints of tension with SM predictions observed in R_K and $B^0 \to K^{*0}\mu^+\mu^-$
  - possible coherent pattern in terms of $\mathcal{C}_9$ (and possibly $\mathcal{C}_{10}$)
- Update with Run II statistics
- Further measurements foreseen at LHCb, stay tuned!

Thanks for the attention!

Spare slides

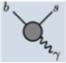
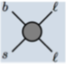
Motivation

- Lepton flavour conservation/universality due to SM accidental symmetry
- Any contrary evidence would be a clear hint of NP
  - neutrino oscillations
  - contribution from rare decays measurements at LHCb



Effective Hamiltonian approach

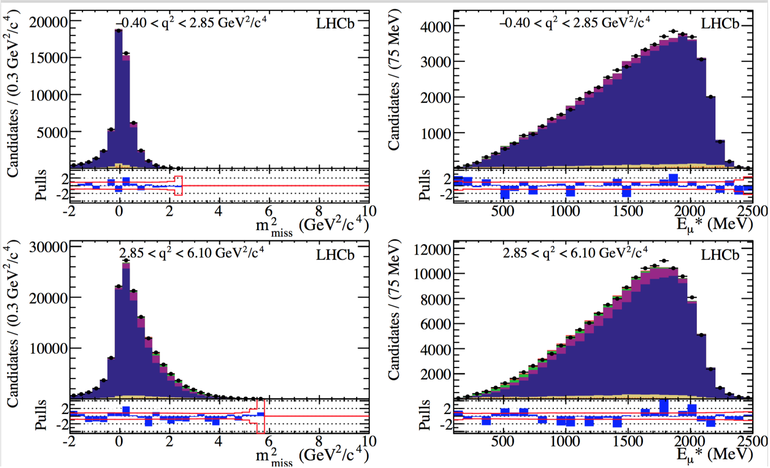
- Combine results from several decays in order to
  - classify NP contributions
  - perform consistency checks

	Operator $\mathcal{O}_i$	$B \to K^{*0}\gamma$	$B \to K^{*0}\mu^+\mu^-$	$B \to \mu^+\mu^-$
	$\mathcal{O}_7 \sim m_b(\bar{s}_L \sigma_{\mu\nu} b_R) F_{\mu\nu}$	✓	✓	
	$\mathcal{O}_9 \sim (\bar{s}b)_{V-A}(\bar{\ell}\ell)_V$		✓	
	$\mathcal{O}_{10} \sim (\bar{s}b)_{V-A}(\bar{\ell}\ell)_A$		✓	✓
	$\mathcal{O}_{S,P} \sim (\bar{s}b)_{S+P}(\bar{\ell}\ell)_{S,P}$			✓

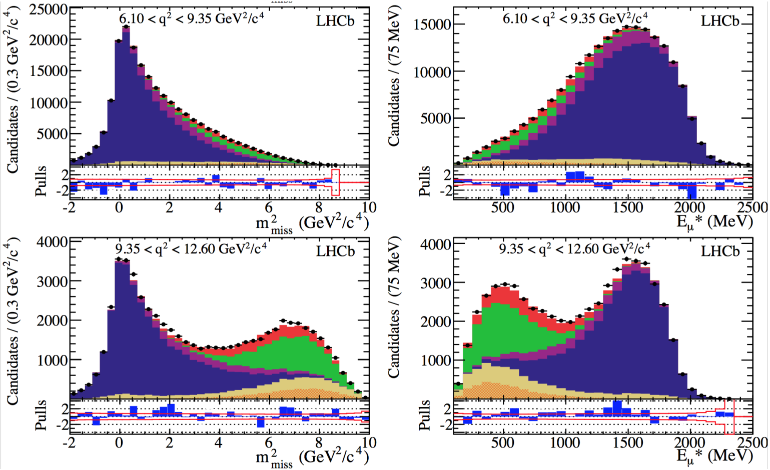
The R_{D^*} measurement at LHCb

- Background-enriched data samples by MVA applied on tracks (threshold on MVA output)
- Control samples for partially reconstructed decays
  - $D^{*+}\mu^-\pi^-$ (one track above threshold)
  - $D^{*+}\mu^-\pi^+\pi^-$ (two tracks above threshold)
  - $D^{*+}\mu^-K^\pm$ (one track above threshold identified as $K^\pm$)
- Efficiency from simulation validated against data
- Fit in
  - 4 bins of $q^2 \in [-0.4, 12.6]$ GeV^2
  - 30 bins of $E^*_\mu \in [100, 2500]$ MeV
  - 40 bins of $m^2_{\mathrm{miss}} \in [-2, 10]$ GeV^2

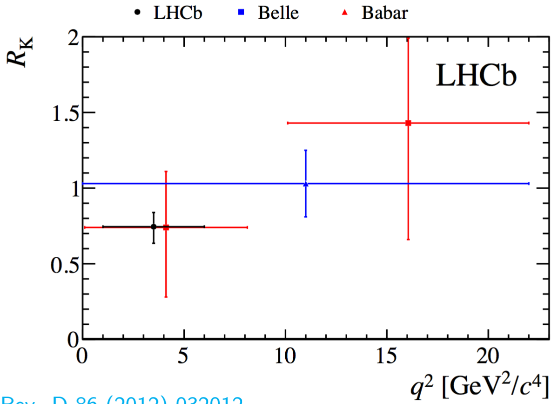
The R_{D^*} measurement at LHCb



The R_{D^*} measurement at LHCb



R_K



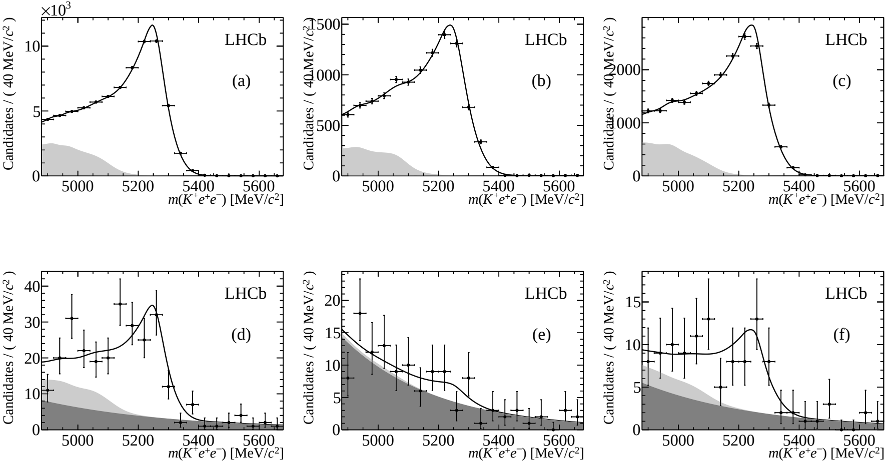
BaBar: Phys. Rev. D 86 (2012) 032012

Belle: Phys. Rev. Lett. 103 (2009) 171801

LHCb: Phys. Rev. Lett. 113 (2014) 151601

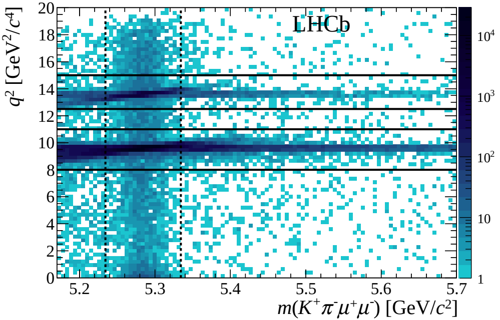
The R_K measurement at LHCb

L0 Electron | L0 Hadron | L0 TIS



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

- Contribution due to S-wave decay $B^0 \to K^+\pi^-\mu^+\mu^-$
- ML fit of $\vec{\Omega}$ and $m_{K\pi\mu\mu}$



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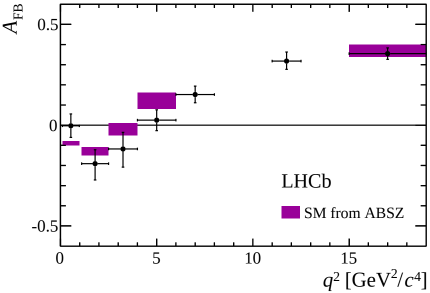
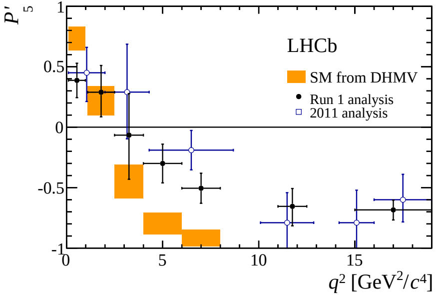
The $B^0 \to K^{*0}\mu^+\mu^-$ decay

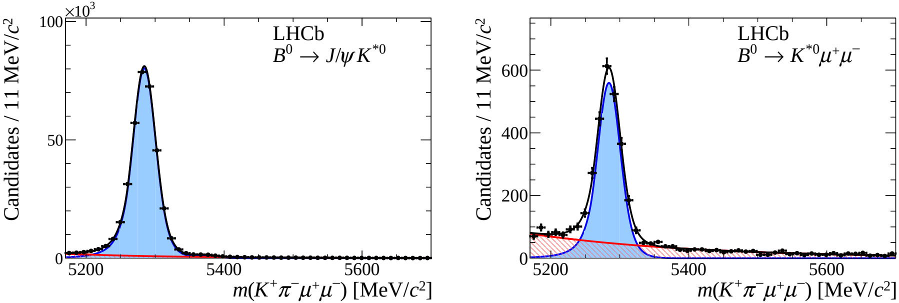
- Most angular observables compatible with SM predictions
- However, tension in P_5'
  - data fit at 3.4 σ from SM
  - compatible with the measurement based on 1 fb^{-1}





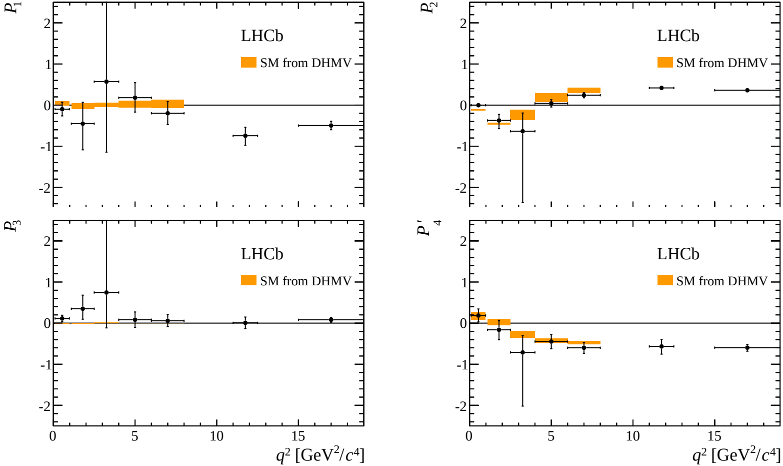
The $B^0 \to K^{*0}\mu^+\mu^-$ decay

- Invariant mass distributions for control and signal channels
- Integrated over the full q^2 range



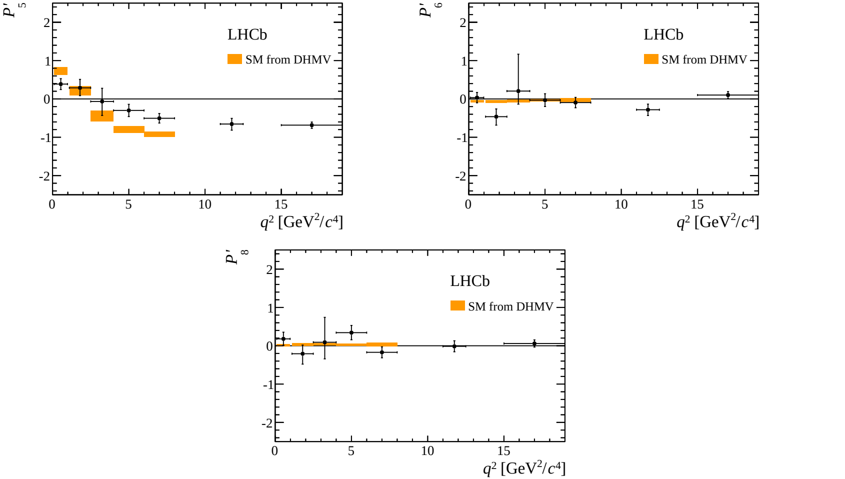
The $B^0 \to K^{*0}\mu^+\mu^-$ decay

- ML fit to the data



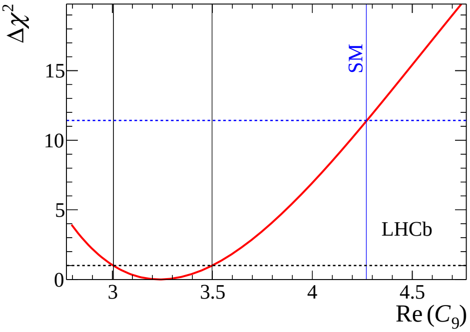
The $B^0 \to K^{*0}\mu^+\mu^-$ decay

- ML fit to the data



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

- χ^2 fit to F_L, A_{FB}, and $S_3 - S_9$ obtained from the ML fit to the data
- Best fit point at $\Delta\mathrm{Re}(\mathcal{C}_9) = -1.04 \pm 0.25$
- Significance of 3.4 σ



The $B^0 \to K^{*0} e^+ e^-$ decay

$$\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d^4(\Gamma+\bar{\Gamma})}{dq^2\, d\cos\theta_\ell\, d\cos\theta_k\, d\tilde{\phi}} = \frac{9}{16\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_k + F_L\cos^2\theta_k$$
$$+\left(\frac{1}{4}(1-F_L)\sin^2\theta_k - F_L\cos^2\theta_k\right)\cos 2\theta_\ell$$
$$+\frac{1}{2}(1-F_L)A_T^{(2)}\sin^2\theta_k\sin^2\theta_\ell\cos 2\tilde{\phi}$$
$$+(1-F_L)A_T^{Re}\sin^2\theta_k\cos\theta_\ell$$
$$+\frac{1}{2}(1-F_L)A_T^{Im}\sin^2\theta_k\sin^2\theta_\ell\sin 2\tilde{\phi}\Big]$$

$$F_L = \frac{|A_0|^2}{|A_0|^2+|A_\parallel|^2+|A_\perp|^2}$$
$$A_T^{(2)} = \frac{|A_\perp|^2-|A_\parallel|^2}{|A_\perp|^2+|A_\parallel|^2}$$
$$A_T^{Re} = \frac{2\Re(A_{\parallel L}A^*_{\perp L}+A_{\parallel R}A^*_{\perp R})}{|A_\parallel|^2+|A_\perp|^2}$$
$$A_T^{Im} = \frac{2\Im(A_{\parallel L}A^*_{\perp L}+A_{\parallel R}A^*_{\perp R})}{|A_\parallel|^2+|A_\perp|^2}$$

with

$$|A_0|^2 = |A_{0L}|^2+|A_{0R}|^2$$
$$|A_\parallel|^2 = |A_{\parallel L}|^2+|A_{\parallel R}|^2$$
$$|A_\perp|^2 = |A_{\perp L}|^2+|A_{\perp R}|^2$$

$$A_T^{(2)}(q^2\to 0) = \frac{2\mathcal{R}e(C_7C_7'^*)}{|C_7|^2+|C_7'|^2}$$
$$A_T^{Im}(q^2\to 0) = \frac{2\mathcal{I}m(C_7C_7'^*)}{|C_7|^2+|C_7'|^2}$$

Local operators

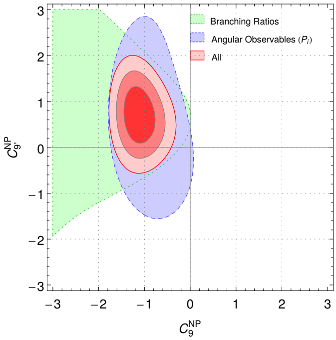
$$
\begin{aligned}
\mathcal{O}_7 &= \tfrac{m_b}{e}\bar{s}\sigma^{\mu\nu}P_R bF_{\mu\nu}\,, & \mathcal{O}_7' &= \tfrac{m_b}{e}\bar{s}\sigma^{\mu\nu}P_L bF_{\mu\nu} \\
\mathcal{O}_8 &= g_s\tfrac{m_b}{e^2}\bar{s}\sigma^{\mu\nu}P_R T^a bG^a_{\mu\nu}\,, & \mathcal{O}_8' &= g_s\tfrac{m_b}{e^2}\bar{s}\sigma^{\mu\nu}P_L T^a bG^a_{\mu\nu} \\
\mathcal{O}_9 &= \bar{s}\gamma_\mu P_L b\,\bar{\ell}\gamma^\mu\ell\,, & \mathcal{O}_9' &= \bar{s}\gamma_\mu P_R b\,\bar{\ell}\gamma^\mu\ell \\
\mathcal{O}_{10} &= \bar{s}\gamma_\mu P_L b\,\bar{\ell}\gamma^\mu\gamma_5\ell\,, & \mathcal{O}_{10}' &= \bar{s}\gamma_\mu P_R b\,\bar{\ell}\gamma^\mu\gamma_5\ell
\end{aligned} \tag{1}
$$

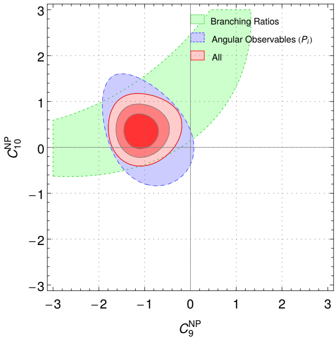
$$
\begin{aligned}
\mathcal{O}_{\mathrm{S}} &= \bar{s}P_R b\,\bar{\ell}\ell\,, & \mathcal{O}_{\mathrm{S}}' &= \bar{s}P_L b\,\bar{\ell}\ell \\
\mathcal{O}_{\mathrm{P}} &= \bar{s}P_R b\,\bar{\ell}\gamma_5\ell\,, & \mathcal{O}_{\mathrm{P}}' &= \bar{s}P_L b\,\bar{\ell}\gamma_5\ell
\end{aligned} \tag{2}
$$

$$
\mathcal{O}_{\mathrm{T}} = \bar{s}\sigma_{\mu\nu} b\,\bar{\ell}\sigma^{\mu\nu}\ell\,, \qquad \mathcal{O}_{\mathrm{T5}} = \bar{s}\sigma_{\mu\nu} b\,\bar{\ell}\sigma^{\mu\nu}\gamma_5\ell \tag{3}
$$

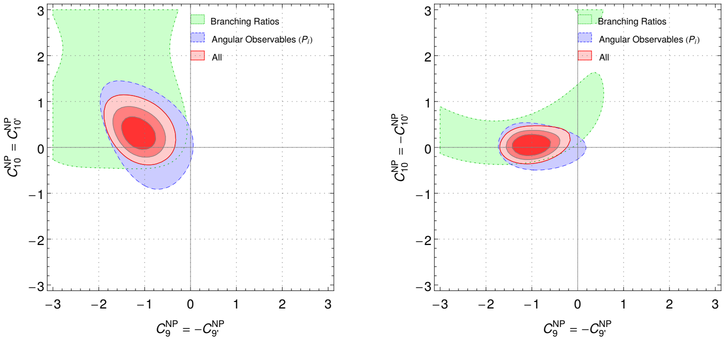
$$
\mathcal{O}_1 = \tfrac{4\pi}{\alpha_e}\bar{s}\gamma_\mu P_L b\,\bar{c}\gamma^\mu P_L c\,, \qquad \mathcal{O}_2 = \tfrac{4\pi}{\alpha_e}\bar{s}\gamma_\mu P_L c\,\bar{c}\gamma^\mu P_L b\,. \tag{4}
$$

Theory interpretation in terms of NP

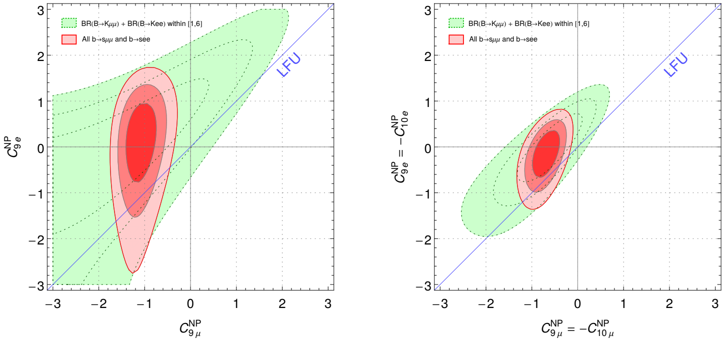




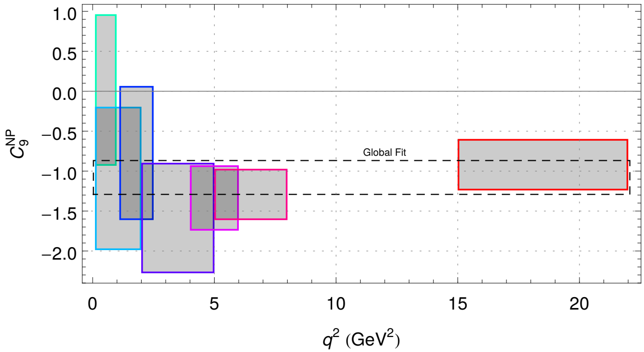
Theory interpretation in terms of NP



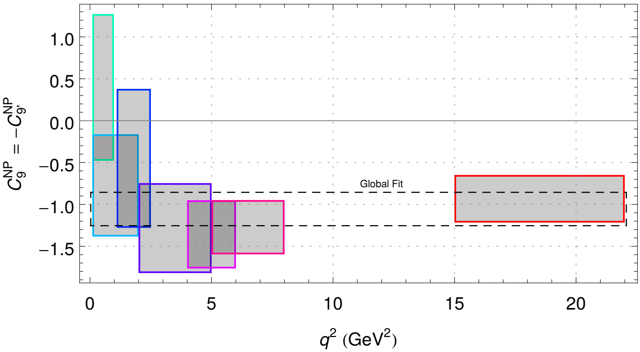
Theory interpretation in terms of NP



Theory interpretation in terms of NP



Theory interpretation in terms of NP



Theory interpretation in terms of NP