$b \to s\ell\ell$ decays and $B \to K^{*}\ell\ell$ angular distributions

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Outline

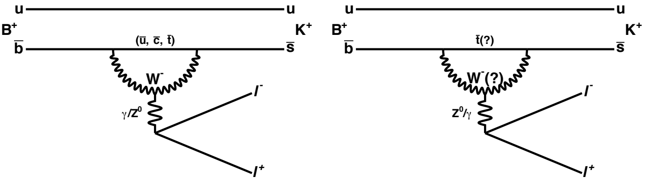
Angular Analysis of $B \to K^* \ell\ell$ [Belle, PRL 118, 111801 (2017)]

Test of LFU in $B \to K^* \ell\ell$ decays [Belle, arXiv: 1904.02440]
Test of LFU in $B \to K \ell\ell$ decays [LHCb, arXiv: 1903.09252]

Search for LFV $B^0 \to K^{*0} \mu e$ decays [Belle, PRD 98, 071101 (2018)]

Introduction

- $B \to K\ell\ell$ and $B \to K^*\ell\ell$ involve quark transition from $b \to s$ which are FCNCs. These processes occur through penguin loop and box diagrams in SM.



- Global analysis of B decays hint at lepton flavor non universality.
- These decays are highly suppressed and very small BR ($\mathcal{O}$ (10^{-6})).
- These decays are very sensitive to NP.
- Rare b-hadron decays place strong constraints on many BSM models by probing energy scales higher than direct searches.

New physics can contribute by:

- enhancing or suppressing decay rates.
- modifying the angular distribution of the final state particles.

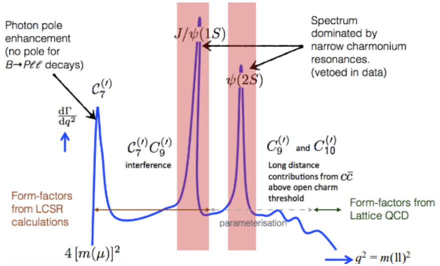
Introduction

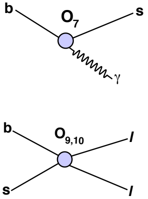
- The amplitude of a hadron decay process is described as:

$$A(M \to F) = \langle F|\mathcal{H}_{eff}|M\rangle = \frac{G_F}{\sqrt{2}} \sum_i V^i_{CKM} C_i(\mu) \langle F|O_i(\mu)|M\rangle$$

Wilson coefficients C_i = Perturbative short distance effects
Operators O_i = non-perturbative long distance effects.
$i = 7$: Photon penguin
$i = 9, 10$: Electoweak penguin

- NP can affect SM operator contributions (Wilson coefficients) and/or enter through new operators.

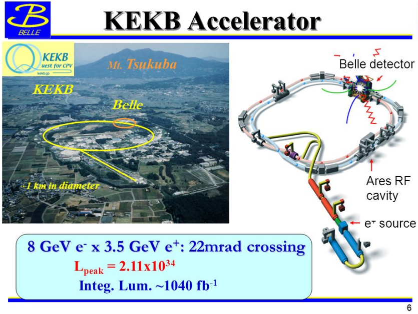




- Contribution of C_7, C_9 and C_{10} depends on q^2 (invariant mass square of two leptons).

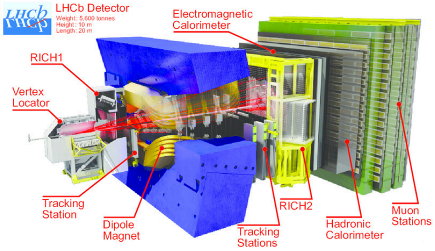
- The angular analysis for $B \to K^* \ell\ell$ has complex angular distribution that provides many observables sensitive to different types of BSM physics.
- Each observable depends on different Wilson coefficiencts and form-factors. [S. Descotes-Genon et al. JHEP 01(2013) 048]
- In the SM, couplings of the gauge bosons to leptons are independent of lepton flavour. [G. Hiller and M. Schmaltz JHEP02(2015) 055]
- Branching fractions of e, μ and τ differ only by phase space and helicity-suppressed contributions.
- Any sign of lepton non-universal interation would be a direct sign of new physics.
- NP models accomodating LFU violation, will also show LFV [S.L Glashow et.al PRL 114, 091801 (2015)].

Experimental facilities



$$e^+e^- \to \Upsilon(4S) \to B\bar{B}$$

- The Belle experiment is located at the KEKB accelerator in Tsukuba, Japan.
- Data taking from 1999 to 2010.
- It is designed as a B-factory.
- Data collected: 772 million $B\bar{B}$ pairs.



- Located at the CERN LHC proton-proton collider
- Forward spectrometer with Vertex, Tracking, PID and Calorimetry
- Run 1, Collision energies 7,8 TeV (2011,2012) 3 fb^{-1}
- Run 2, Collision energy 13 TeV (2015,2016) 3 fb^{-1}

$B \to K^* \ell\ell$ angular analysis

The differential decay rate is given by:

$$\frac{1}{d\Gamma/dq^2}\,\frac{d^4\Gamma}{d\cos\theta_\ell\;d\cos\theta_K\;d\phi\;dq^2} =$$
$$\frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell +$$
$$S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell +$$
$$S_7\sin 2\theta_K\sin\theta_\ell\sin\phi + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

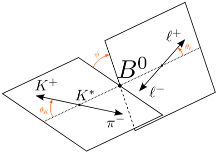
- In the lepton massless limit there are eight independent observables:

F_L: Fraction of the longitudinal polarization of the K^*
S_6: The forward-backward asymmetry of the dimuon system
$S_{3,4,5,7,8,9}$: The remaining CP-averaged observables

- F_L and S_i are function of q^2.
- Observable P_i' and Q_i

$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$ JHEP 05(2013) 137

$$Q_i = P_i^\mu - P_i^e,\; i = 4, 5$$ JHEP 10(2016) 075



- P_i' are free of form-factor uncertainties.
- Any deviation from zero for Q_i, would be a hint for NP.

Belle: $B \to K^* \ell\ell$ Angular analysis

- The channels reconstructed for analysis are

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

- K^* is reconstructed from:

$$K^{*0} \to K^+\pi^-$$
$$K^{*+} \to K^+\pi^0$$
$$K^{*+} \to K^0_S\pi^+$$

- Multivariate analysis technique (NN) is used to identify each particle type in the decay chain.
- Kinematic variables which distinguish signal from background are

$$M_{bc} = \sqrt{E^2_{beam}/c^4 - |p_B|^2/c^4}$$
$$\Delta E = E_B - E_{beam}$$

- Requirment on kinematic variables:

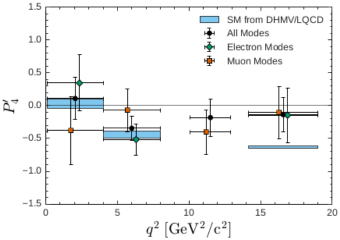
$$5.22 < M_{bc} < 5.20 \text{ GeV}/c^2 \text{ and } -0.10\ (-0.05) < \Delta E < 0.05 \text{ GeV for ee}(\mu\mu)$$

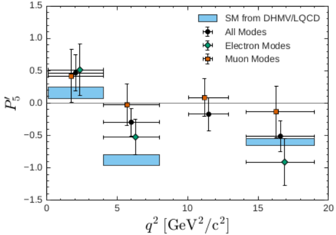
- Final selection requirment on the top-level NN is optimized by maximizing a figure of merit

$$\text{FOM} = \frac{n_s}{\sqrt{n_s + n_b}}$$

- Extended maximum likelihood fit to extract signal.

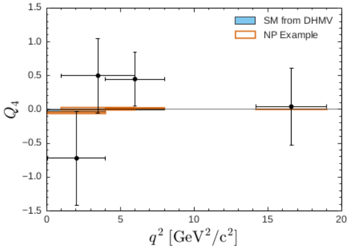
Belle results for P'_4 and P'_5 [PRL 118 (2017) 111801]

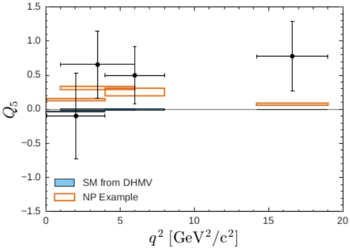




- All measurements are compatible with SM predictions.
- The strongest tension of 2.6σ is observed in P'_5 of the muon modes for the region $4 < q^2 < 8$ GeV$^2/c^4$.
- For $4 < q^2 < 8$ GeV$^2/c^4$ bin, 1.3σ deviation is found in electron mode.
- Combining muon and electron modes, deviation is $\mathbf{2.5}\sigma$.

Belle results for Q_4 and Q_5 [PRL 118 (2017) 111801]



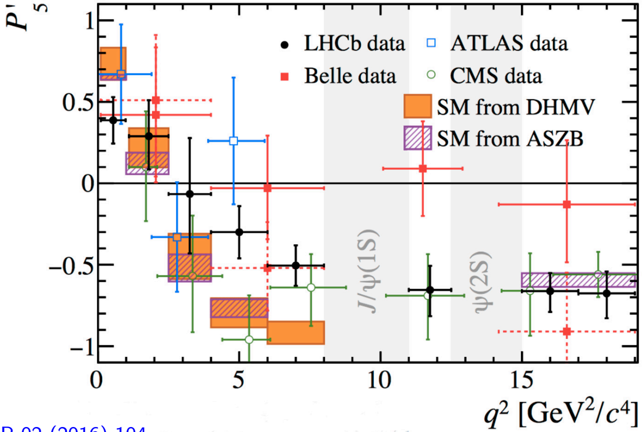


- $Q_{4,5}$ observables show no significant deviation from zero.

q^2 GeV$^2/c^4$	Q_4	Q_5
$[1.00, 6.00]$	$0.498 \pm 0.527 \pm 0.166$	$0.656 \pm 0.485 \pm 0.103$
$[0.10, 4.00]$	$-0.723 \pm 0.676 \pm 0.163$	$-0.097 \pm 0.601 \pm 0.164$
$[4.00, 8.00]$	$0.448 \pm 0.392 \pm 0.076$	$0.498 \pm 0.410 \pm 0.095$
$[14.18, 19.00]$	$0.041 \pm 0.565 \pm 0.082$	$0.778 \pm 0.502 \pm 0.065$

P. Cartelle, Dark Matter @ LHC Heidelberg, April 2018

https://cds.cern.ch/record/2311960/files/FlavourAnomaliesLHCbAlvarez.pdf



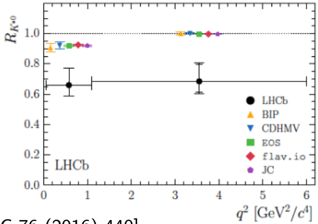
- LHCb JHEP 02 (2016) 104
- Belle: PRL 118 (2017) 111801
- ATLAS: JHEP 10 (2018) 517
- CMS: Phys. Lett. B 781(2018) 517

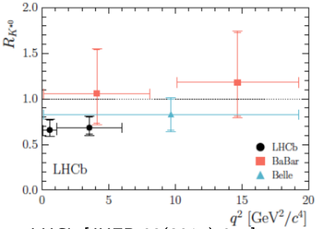
3.4σ deviation for LHCb $4 < q^2 < 6$ GeV$^2/c^4$

Test of LFU (R_{K^*}) for $B \to K^*\ell\ell$ Prior to Moriond, 2019

- LHCb measurement of
  $R_{K^*} = \dfrac{BR(B^0 \to K^{*^0}\mu^+\mu^-)}{BR(B^0 \to K^{*^0}e^+e^-)}$ shows deviations from SM expectation.
  $R_{K^*}(0.045 < q^2 < 1.1\ \mathrm{GeV}^2/c^4) = 0.66^{+0.11}_{-0.07} \pm 0.03$
  $R_{K^*}(1.1 < q^2 < 6\ \mathrm{GeV}^2/c^4) = 0.69^{+0.11}_{-0.07} \pm 0.05$
- Compatibility with the SM estimated to be at the level of $2.1 - 2.3\sigma$ for low q^2 and $2.4 - 2.5\sigma$ at central q^2 for a data sample of $3\mathrm{fb}^{-1}$.
- Belle measurement for whole q^2 region, $R_{K^*} = 0.83 \pm 0.17 \pm 0.08$, is consistent with SM prediction.
- BaBar measured for low and high q^2 bins and are consistent with SM with high uncertainty.

P. Cartelle, Dark Matter @ LHC Heidelberg, April 2018
https://cds.cern.ch/record/2311960/files/FlavourAnomaliesLHCbAlvarez.pdf





▲ BIP [EPJC 76 (2016) 440]
▼ CDHMV [JHEP 04 (2017) 016]
■ EOS [PRD 95 (2017) 035029]
◆ flav. io [EPJC 77 (2017) 377]
● JC [PRD 93 (2016) 014028]

● LHCb [JHEP 08(2017) 055]
■ BaBar [PRD 86 (2012) 032012]
▲ Belle [PRL 103 (2009) 171801]

New Belle results for R_{K^*} arXiv: 1904.02440

- Similar particle selection and fitting procedure as that of $B \to K^* \ell\ell$ angular analysis.

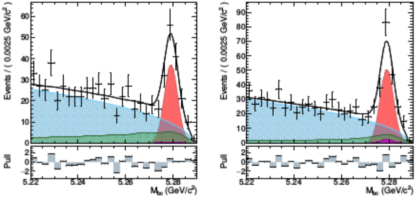
- The $B \to K^* \ell\ell$ mode is reconstructed by hierachical NN.
- Background is suppressed by multivariate analysis technique which uses event topology and NN outputs.
- $B \to KJ/\psi$ is used as a control sample.
- Signal is extracted using extended maximum likelihood fit.
- R_{K^*} is calculated.

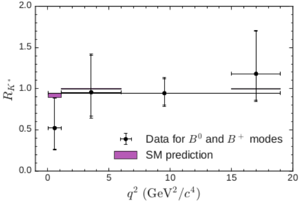
$$R_{K^*} = \frac{B \to K^* \mu\mu}{B \to K^* ee}$$

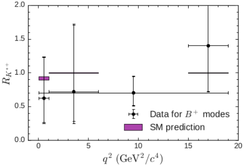
Belle: R_{K^*} Data fit

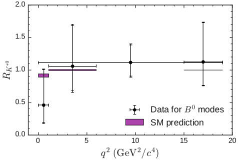
- Perfomed extended maximum likelihood fit.
- PDF parameterization:
  - Signal : CB with the shape parameters determined from $B \to K^* J/\psi(\to \ell\ell)$ candidates in J/ψ region.
  - Combinatorial background: Argus shape.
  - Events from charmonium decay: The events which pass the charmonium veto because of misreconstruction are modeled with kernel density function.
  - Peaking background: Peaking from double flavor misidentification fitted with KDF.
- The normalization from peaking and charmonium are derived from MC and fixed in the fit for the signal yield.
- Example fit for $q^2 > 0.045$ GeV$^2/c^4$.
- $103.0^{+13.4}_{-12.7}$ and $139.9^{+16.0}_{-15.4}$ events for electon and muon modes, respectively.

Belle [arXiv:1904.02440]









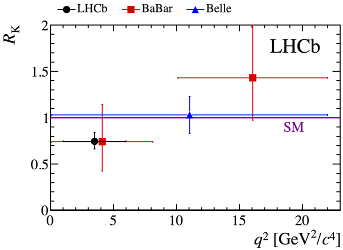
First measurement of $R_{K^{*+}}$

q^2 GeV$^2/c^4$	All modes	B^0 modes	B^+ modes
$[0.045, 1.1]$	$0.52^{+0.36}_{-0.26} \pm 0.05$	$0.46^{+0.55}_{-0.27} \pm 0.07$	$0.62^{+0.60}_{-0.36} \pm 0.10$
$[1.1, 6]$	$0.96^{+0.45}_{-0.29} \pm 0.11$	$1.06^{+0.63}_{-0.38} \pm 0.13$	$0.72^{+0.99}_{-0.44} \pm 0.18$
$[0.1.8]$	$0.90^{+0.27}_{-0.21} \pm 0.10$	$0.86^{+0.33}_{-0.24} \pm 0.08$	$0.96^{+0.56}_{-0.35} \pm 0.14$
$[15 - 19]$	$1.18^{+0.52}_{-0.32} \pm 0.10$	$1.12^{+0.61}_{-0.36} \pm 0.10$	$1.40^{+1.99}_{-0.68} \pm 0.11$
$[0.045,]$	$0.94^{+0.17}_{-0.14} \pm 0.08$	$1.12^{+0.27}_{-0.21} \pm 0.09$	$0.70^{+0.24}_{-0.19} \pm 0.07$

- All results are found to compatible with SM prediction.

Test of LFU (R_K) for $B \to K\ell\ell$ Prior to Moriond 2019

- SM prediction is very accurate. $R_K^{(SM)} = 1 \pm \mathcal{O}\,(10^{-2})$
- LHCb (PRL 113, 151601(2014)) shows deviation from SM
  $R_K = \dfrac{BR(B^+ \to K^+\mu^+\mu^-)}{BR(B^+ \to K^+e^+e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036$
  in $q^2 = [1-6]$ GeV$^2/c^4$: 2.6σ tension for 3fb^{-1} data sample (2011-12 data).
- This observable is theoretically very clean, as most of the hadronic uncertainties cancel out in the ratio.
- The value of R_K for Belle was consistent with unity within the uncertainty limit measured for a data sample of 605fb^{-1}.



Bin	R_K	Collaboration
$1 < q^2 < 6$	$0.745^{+0.090}_{-0.074} \pm 0.036$	LHCb (2014)
$1.1 < q^2 < 6$	$0.846^{+0.060+0.016}_{-0.054-0.014}$	LHCb (2019)
whole q^2	$1.03 \pm 0.19 \pm 0.06$	Belle
$0.10 < q^2 < 8.12$	$0.74^{+0.40}_{-0.31} \pm 0.06$	BaBar
$q^2 > 10.11$	$1.43^{+0.65}_{-0.44} \pm 0.12$	BaBar

Updated R_K measurement with LHCb data [arXiv: 1903.09252]

- The analsysis of 2011 and 2012 data is re-optimized and analysis strategy is re-designed.
- 2015 and 2016 LHCb data are added.
- This analysis uses twice as many B's as the previous analysis.

R_K measurement at LHCb

- Electron and muon tracks are very different in LHCb.
  - Because of bremsstrahlung, electron has worse q^2 resolution and low reconstruction efficiency.
  - Better PID and trigger performances for muons.
- Use double ratio to cancel out most of the systematic uncertainties.

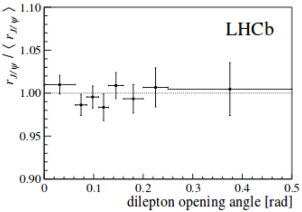
$$R_K = \frac{BR(B^+ \to K^+\mu^+\mu^-)}{BR(B^+ \to K^+e^+e^-)} \Big/ \frac{BR(B^+ \to K^+J/\psi(\to \mu^+\mu^-))}{BR(B^+ \to K^+J/\psi(\to e^+e^-))}$$

$$\Rightarrow R_K = \frac{N(K^+\mu\mu)}{N(K^+J/\psi(\mu\mu)}\cdot\frac{N(K^+J/\psi(ee))}{N(K^+ee)}\cdot\frac{\varepsilon(K^+J/\psi(\mu\mu))}{\varepsilon(K^+\mu\mu)}\cdot\frac{\varepsilon(K^+ee)}{\varepsilon(K^+J/\psi(ee))}$$

- To check efficiencies are correct,

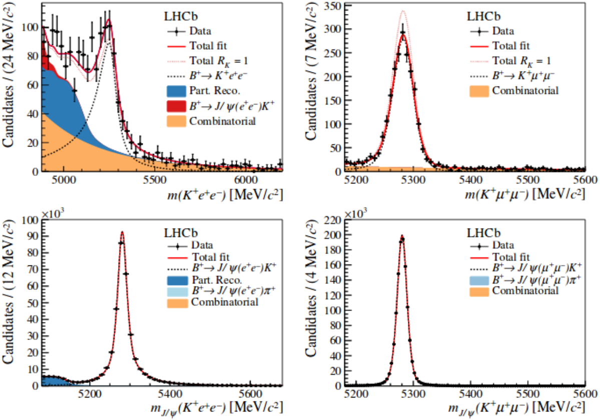
$$r_{J/\psi} = \frac{BR(B^+ \to K^+J/\psi(\to \mu\mu))}{BR(B^+ \to K^+J/\psi(\to ee))} = 1.0$$

  $r_{J/\psi}$ is found to be 1.014 ± 0.035 (stat. + syst.)
- Efficiencies should be understandable as a function of any variable.
  - $r_{J/\psi}$ should be flat for all variables examined.



Fit for $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+e^+e^-$

- A single fit to the $m(K^+\ell^+\ell^-)$ distributions is performed to determine R_K from the entire 2011-2016 dataset.



- The red-dotted line shows the distribution that would be expected from the observed number of $B^+ \to K^+\mu^+\mu^-$ or $B^+ \to K^+e^+e^-$ decays and $R_K = 1$.

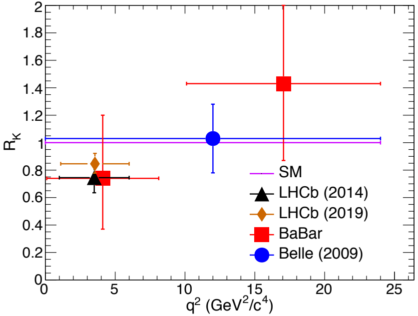
R_K result with 2011 to 2016 data [arXiv: 1903.09252]

- Using 2011 and 2012 LHCb data, R_K was:

$$R_K[1.0-6.0] = 0.745^{+0.090}_{-0.074} \pm 0.036$$
2.6σ from SM prediction.

- Adding 2015 and 2016 data, R_K become:

$$\mathbf{R_K([1.1-6.0]) = 0.846^{+0.016+0.060}_{-0.054-0.014}}$$
$\sim$ **2.5**σ from SM.



Lepton Flavor Violation

- The deviation from SM expectation in R_K and R_{K^*} from LHCb result possibly show LFU violation.
- LFV can come together with LFU violation [S. L. Glashow et.al PRL 114, 091801 (2015)].
- Belle has published LFV decays $B^0 \to K^{*^0}\ell\ell'$, where $\ell = \mu, e$ [PRD 98.071101(2018)].

Analysis procedure for LFV $B^0 \to K^{*^0} \ell\ell'$

Particle selection and Background suppression

- Charged particles are selected which satisfy PID criteria and originate from a region near the e^+e^- interaction point.
- Kaon and pion candidates are combined to form K^{*0}.
- B candidate is reconstructed by combining K^{*0}, $\mu^\pm$ and $e^\pm$ candidates.
- Constraint on kinematic variables are

$$M_{bc} > 5.2 \text{ GeV}/c^2$$
$$-0.05 < \Delta E < 0.04 \text{ GeV}$$

- Strong contribution from continuum ($q\bar{q}$) and generic B ($B\bar{B}$) backgrounds.
- Two stage NN is used to suppress the backgrounds. $i.e.$, Optimization of generic B background from the optimal cut of continuum background.

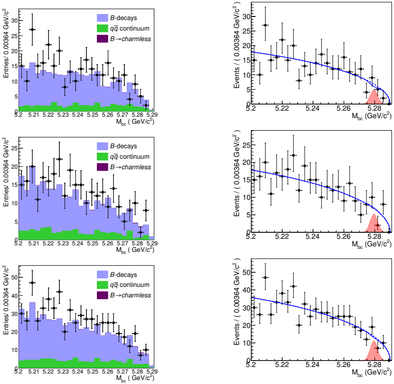
Peaking Background

Peaking background due $B^0 \to K^{*0}(\to K^+\pi^-)J/\psi(\to \ell\ell)$, and PID misidentification
We veto:

- For $B^0 \to K^{*0}\mu^+e^-$
  $M(\ell^+\ell^-) \notin [3.04, 3.12]$ GeV/c^2
  $M(K^+e^-) \notin [2.90, 3.12]$ GeV/c^2
  $M(\pi^-\mu^+) \notin [3.06, 3.12]$ GeV/c^2
- For $B^0 \to K^{*0}\mu^-e^+$
  $M(\ell^+\ell^-) \notin [3.02, 3.12]$ GeV/c^2
  $M(\pi^-e^+) \notin [3.02, 3.12]$ GeV/c^2

Results for $B^0 \to K^{*0} \ell \ell'$

- Good agreement between data and MC.
- No evidence of signal observed $\to$ upper limit is estimated.



Mode	ε (%)	N_{sig}	$N_{sig}^{(UL)}$	$\mathcal{B}^{(\mathcal{UL})}$ (10^{-7})
$B^0 \to K^{*0} \mu^+ e^-$	8.8	$-1.5^{+4.7}_{-4.1}$	5.2	1.2
$B^0 \to K^{*0} \mu^- e^+$	9.3	$0.4^{+4.8}_{-4.5}$	7.4	1.6
$B^0 \to K^{*0} \mu^\pm e^\mp$	9.0	$-1.2^{+6.8}_{-6.2}$	8.0	1.8

Conclusion

- The angular analysis variable P_5' of $B \to K^* \ell\ell$ show a deviation of 2.5σ from SM prediction for the bin of $4 < q^2 < 8\ \mathrm{GeV}^2/c^4$. This deviation is maximum for $\mu\mu$ mode.
- R_{K^*} measurements are compatible with SM prediction for Belle data.
- Updated R_K analysis from LHCb has a significantly improved precision. There is $\sim 2.5\sigma$ tension with SM.
- Most stringent upper limit is found for $B^0 \to K^{*0}\mu e$ mode.
- More data from LHCb collected in 2017 and 2018 is being analyzed.
- Upgraded LHCb detector will collect many times more data in the early 2020's.
- The Belle II experiment (50 times more data than Belle) will also provide stringent limits on any deviation from SM predictions.
- Lots more data to come!