Rare decays at LHCb

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Rare Decays at LHCb

Muonic B decays

- $\Rightarrow$ Br $B_s^0 / B_d^0 \to \mu\mu/\tau\tau$.
- $\Rightarrow$ Br + Ang. $B \to K^* \mu\mu$.
- $\Rightarrow$ Br + Ang. $B_s^0 \to \phi\mu\mu$.
- $\Rightarrow$ Isospin $B \to K\mu\mu$.
- $\Rightarrow$ CP asymmetry $B \to \pi\mu\mu$.

Charm decays

- $\Rightarrow$ $D \to \pi\pi\mu\mu$
- $\Rightarrow$ $D \to K\pi\mu\mu$
- $\Rightarrow$ $D \to e\mu$.

$\Rightarrow$ Enormous Physics program which is constantly expanding.
$\Rightarrow$ Will cover only part of the results.

LFU test

- $\Rightarrow$ $B^+ \to K^+ \ell\ell$
- $\Rightarrow$ $B_d^0 \to K^* \ell\ell$

$\Rightarrow$ See G.Andreassi talk for LUV!!!

Strange decays

- $\Rightarrow$ $K_S^0 \to \mu\mu$.

Radiative decays

- $\Rightarrow$ $B \to K^* \gamma$
- $\Rightarrow$ $B_s^0 \to \phi\gamma$
- $\Rightarrow$ $B_s^0 / B_d^0 \to J/\psi\gamma$

$\Rightarrow$ See H.Evans talk.

$B_{s/d} \to \mu\mu$

⇛ Golden channel for LHCb.

⇛ Normalized to the $B \to K\pi$ and $B \to KJ/\psi$.

⇛ The selection is achived by BDT trained on MC and calibrated on data.

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

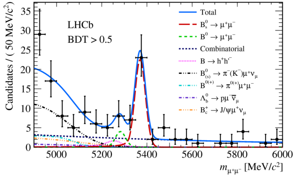
7.8 σ significant!

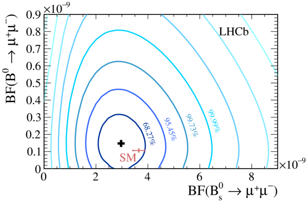
⇛ $\mathcal{B}(B_d^0 \to \mu\mu) < 3.4 \times 10^{-10}$, 90%CL

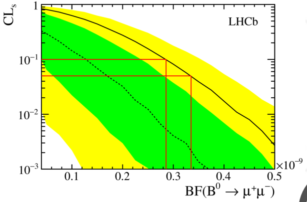
Effective lifetime

⇛ Sensitivity to non-scalar NP.

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







$B_{s/d} \to \mu\mu$

arXiv:1703.05747

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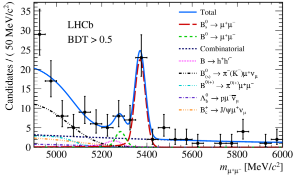
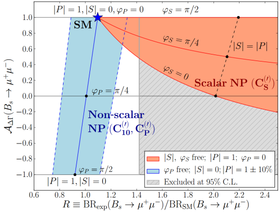
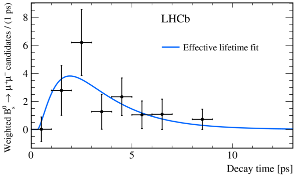






$B_{s/d} \to \tau\tau$

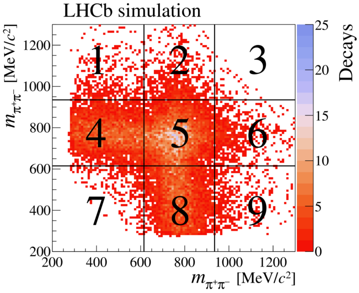
$\Rrightarrow$ NP sensitivity enhanced due to the high τ mass.

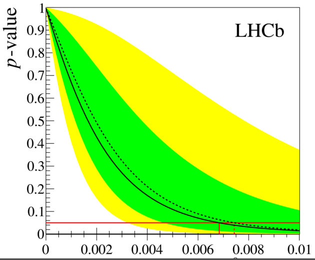
$\Rrightarrow$ More challenging: at least 2ν are escaping.

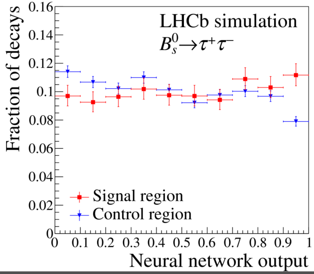
$\Rrightarrow$ Selecting $\tau \to 3\pi\nu$, $\to$ $9.31\ \%$

$\Rrightarrow$ Normalization channel: $B \to D(K\pi\pi)D_s(KK\pi)$.

$\Rrightarrow$ No peak in the B mass window $\to$ fit the NN output.





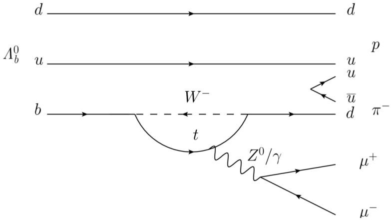


$\Rrightarrow$ First observation of $b \to d$ in baryon system!

$\Rrightarrow$ BDT selection trained on MC

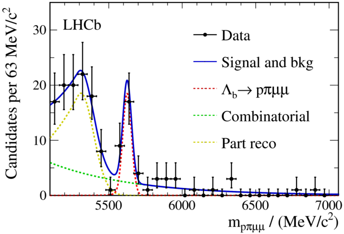
$\Rrightarrow$ Normalized to $\Lambda_b \to p\pi J/\psi$

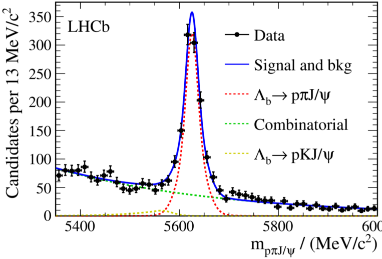
$\Rrightarrow$ With futher QCD improvements we will be able to to measure $\frac{|V_{ts}|}{|V_{td}|}$.



$\Rrightarrow$ $\frac{\mathcal{B}(\Lambda_b \to p\pi\mu\mu)}{\mathcal{B}(\Lambda_b \to p\pi J/\psi)} = 0.044 \pm 0.012 \pm 0.007$

$\Rrightarrow$ 5.5 σ significance! $\Rrightarrow$ First observation.





$\mathcal{B}(\Lambda_b \to p\pi\mu\mu) =$
$(6.9 \pm 1.9 \pm 1.1^{+1.3}_{-1.0}) \times 10^{-8}$

Search for light scalars

⇛ Hidden sector models are gathering more and more attention.

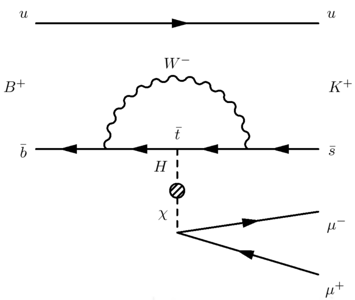
⇛ Inflaton model: new scalar then mixes with the Higgs.

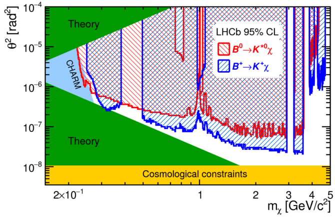
⇛ B decays are sensitive as the inflaton might be light.

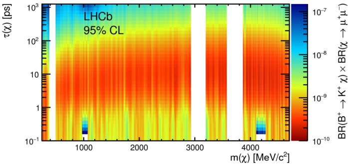
⇛ Searched for long living particle χ produced in: $B \to \chi(\mu\mu)K$.

⇛ Analysis performed blindly as a peak search.

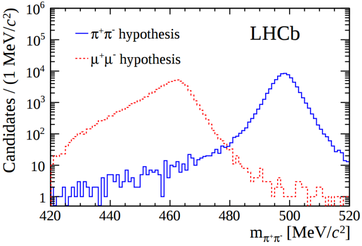
⇛ Light inflaton essentially ruled out:

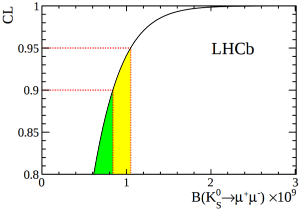






$\Rightarrow$ pp collisions create enormous amount of strange mesons.
$\Rightarrow$ Can be used to search for $K_S^0 \to \mu\mu$.
$\Rightarrow$ SM prediction:
$\mathcal{B}(K_S^0 \to \mu\mu) = (5.0 \pm 1.5) \times 10^{-12}$
$\Rightarrow$ Dominated by the long distance effects.
$\Rightarrow$ Bkg dominated by $K_S^0 \to \pi\pi$.





$\Rightarrow$ No significant enhanced of signal has been observed and UL was set:

$\mathcal{B}(K_S^0 \to \mu\mu) < 0.8(1.0) \times 10^{-9}$ at $90(95)\%$ CL

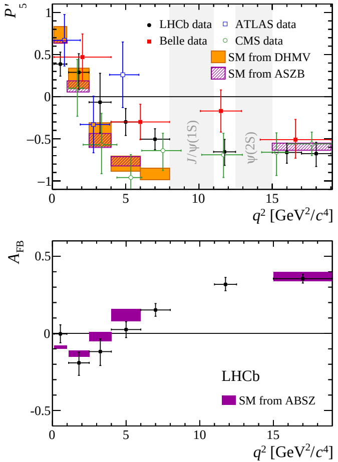
⇛ $B^0 \to K^* \mu^- \mu^+$ is a smoking gun for NP hunting!

⇛ Reach angular observables makes is sensitive to different NP models

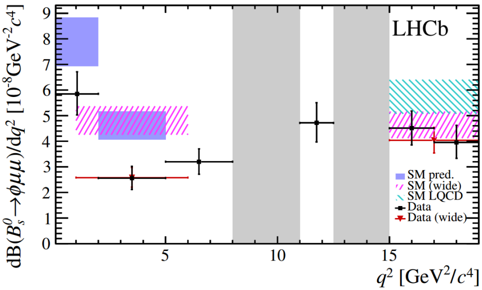
⇛ In addition one can construct less form factor dependent observables:

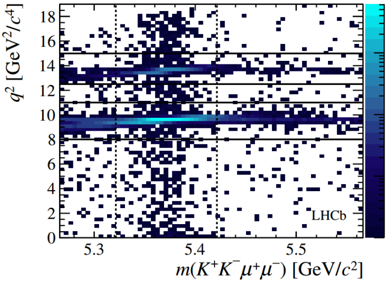
$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

⇛ In single analysis observed $3.4\ \sigma$ discrepancy in the C_9 WC.



Branching fraction measurements of $B_s^0 \to \phi\mu\mu$



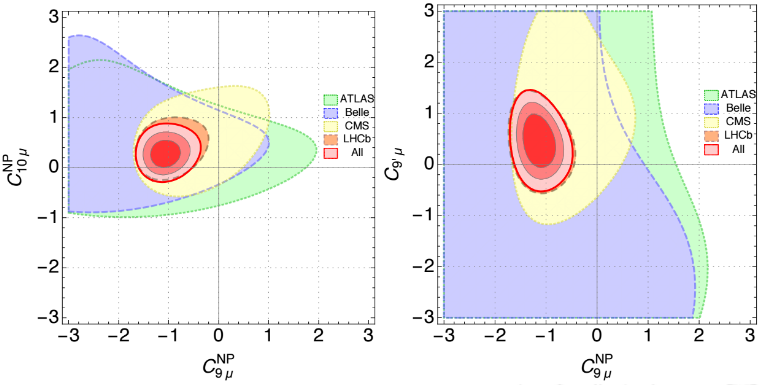


- Recent LHCb measurement, JHEP09 (2015) 179.
- Suppressed by $\frac{f_s}{f_d}$.
- Cleaner because of narrow ϕ resonance.
- $3.3\ \sigma$ deviation in SM in the $1-6\mathrm{GeV}^2$ bin.
- Angular part in agreement with SM (S_5 is not accessible).

Theory implications of $b \to s\ell\ell$

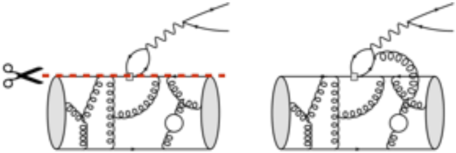
JHEP 06 (2016) 092

- A fit prepared by `S. Descotes-Genon, L. Hofer, J. Matias, J. Virto`.
- The data can be explained by modifying the C_9 Wilson coefficient.
- Overall there is $> 4\ \sigma$ discrepancy wrt. the SM prediction.



If not NP?

- We are not there yet!
- There might be something not taken into account in the theory.
- Resonances (J/ψ, $\psi(2S)$) tails can mimic NP effects.
- There might be some non factorizable QCD corrections.
  " However, the central value of this effect would have to be significantly larger than expected on the basis of existing estimates" D.Straub, arXiv:1503.06199.



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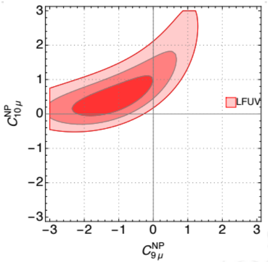
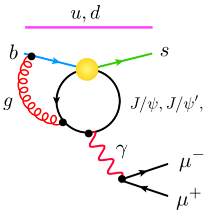


$\Rightarrow$ See F.Polci talk.

Measurement of phase difference

Phys. Rev. D 95, 071101 (2017)



⇛ One could try to measure the phase difference between the resonances and the nonresonant amplitudes to see if the interference is large enough to explain the effects.

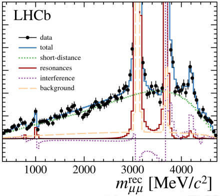
⇛ Measured firstly done for the decay $B \to K\mu\mu$.

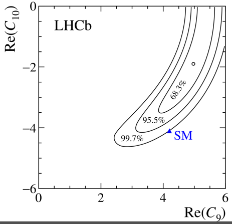
⇛ The analysis based:

$$C_9^{\text{eff}} = C_9 + Y(q^2) = C_9 + \sum_j \eta_j e^{i\delta_i} A_j^{\text{res}}(q^2)$$

⇛ The amplitudes are modelled Briet-Wigner and Flatte functions.

⇛ Interference cannot explain the observed anomalies.





Conclusions

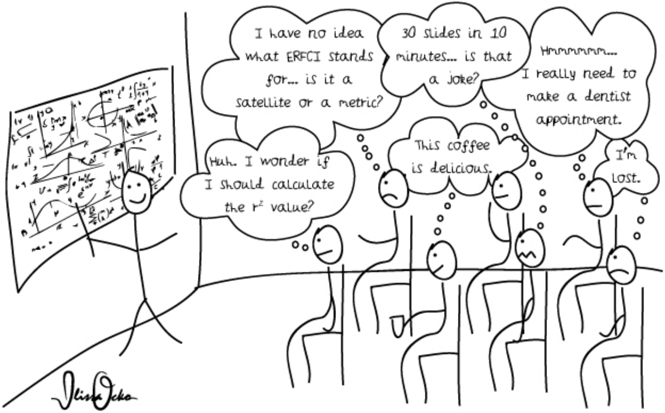
- Clear tensions wrt. SM predictions!
- Measurements cluster in the same direction.
- We are not opening the champagne yet!
- Still need improvement both on theory and experimental side.
- Time will tell if this is QCD+fluctuations or new Physics:

Conclusions

- Clear tensions wrt. SM predictions!
- Measurements cluster in the same direction.
- We are not opening the champagne yet!
- Still need improvement both on theory and experimental side.
- Time will tell if this is QCD+fluctuations or new Physics:

"... when you have eliminated all the
Standard Model explanations, whatever remains,
however improbable, must be New Physics."
Prof. Joaquim Matias

Thank you for the attention!



Backup

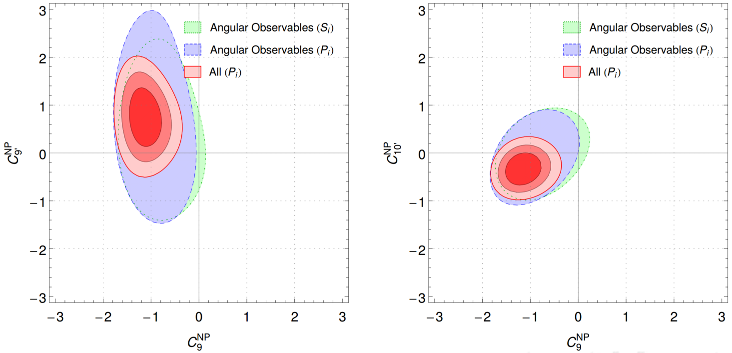
Theory implications

Coefficient	Best fit	1σ	3σ	Pull_{SM}	p-value (%)
$\mathcal{C}_7^{\text{NP}}$	-0.02	$[-0.04, -0.00]$	$[-0.07, 0.04]$	1.1	16.0
$\mathcal{C}_9^{\text{NP}}$	-1.11	$[-1.32, -0.89]$	$[-1.71, -0.40]$	**4.5**	62.0
$\mathcal{C}_{10}^{\text{NP}}$	0.58	$[0.34, 0.84]$	$[-0.11, 1.41]$	2.5	25.0
$\mathcal{C}_{7'}^{\text{NP}}$	0.02	$[-0.01, 0.04]$	$[-0.05, 0.09]$	0.7	15.0
$\mathcal{C}_{9'}^{\text{NP}}$	0.49	$[0.21, 0.77]$	$[-0.33, 1.35]$	1.8	19.0
$\mathcal{C}_{10'}^{\text{NP}}$	-0.27	$[-0.46, -0.08]$	$[-0.84, 0.28]$	1.4	17.0
$\mathcal{C}_9^{\text{NP}} = \mathcal{C}_{10}^{\text{NP}}$	-0.21	$[-0.40, 0.00]$	$[-0.74, 0.55]$	1.0	16.0
$\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{10}^{\text{NP}}$	-0.69	$[-0.88, -0.51]$	$[-1.27, -0.18]$	**4.1**	55.0
$\mathcal{C}_{9'}^{\text{NP}} = \mathcal{C}_{10'}^{\text{NP}}$	-0.09	$[-0.35, 0.17]$	$[-0.88, 0.66]$	0.3	14.0
$\mathcal{C}_{9'}^{\text{NP}} = -\mathcal{C}_{10'}^{\text{NP}}$	0.20	$[0.08, 0.32]$	$[-0.15, 0.56]$	1.7	19.0
$\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{9'}^{\text{NP}}$	-1.09	$[-1.28, -0.88]$	$[-1.62, -0.42]$	**4.8**	72.0
$\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{10}^{\text{NP}} = -\mathcal{C}_{9'}^{\text{NP}} = -\mathcal{C}_{10'}^{\text{NP}}$	-0.68	$[-0.49, -0.49]$	$[-1.36, -0.15]$	3.9	50.0
$\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{10}^{\text{NP}} = \mathcal{C}_{9'}^{\text{NP}} = -\mathcal{C}_{10'}^{\text{NP}}$	-0.17	$[-0.29, -0.06]$	$[-0.54, 0.18]$	1.5	18.0

Table 2: *Best-fit points, confidence intervals, pulls for the SM hypothesis and p-values for different one-dimensional NP scenarios.*

If not NP?

- How about our clean P_i observables?
- The QCD cancel as mentioned only at leading order.
- Comparison to normal observables with the optimised ones.



Transversity amplitudes

⇛ One can link the angular observables to transversity amplitudes

$$J_{1s} = \frac{(2+\beta_\ell^2)}{4}\left[|A_\perp^L|^2 + |A_\parallel^L|^2 + |A_\perp^R|^2 + |A_\parallel^R|^2\right] + \frac{4m_\ell^2}{q^2}\mathrm{Re}\left(A_\perp^L A_\perp^{R*} + A_\parallel^L A_\parallel^{R*}\right),$$

$$J_{1c} = |A_0^L|^2 + |A_0^R|^2 + \frac{4m_\ell^2}{q^2}\left[|A_t|^2 + 2\mathrm{Re}(A_0^L A_0^{R*})\right] + \beta_\ell^2 |A_S|^2,$$

$$J_{2s} = \frac{\beta_\ell^2}{4}\left[|A_\perp^L|^2 + |A_\parallel^L|^2 + |A_\perp^R|^2 + |A_\parallel^R|^2\right], \qquad J_{2c} = -\beta_\ell^2\left[|A_0^L|^2 + |A_0^R|^2\right],$$

$$J_3 = \frac{1}{2}\beta_\ell^2\left[|A_\perp^L|^2 - |A_\parallel^L|^2 + |A_\perp^R|^2 - |A_\parallel^R|^2\right], \qquad J_4 = \frac{1}{\sqrt{2}}\beta_\ell^2\left[\mathrm{Re}(A_0^L A_\parallel^{L*} + A_0^R A_\parallel^{R*})\right],$$

$$J_5 = \sqrt{2}\beta_\ell\left[\mathrm{Re}(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*}) - \frac{m_\ell}{\sqrt{q^2}}\mathrm{Re}(A_\parallel^L A_S^* + A_\parallel^{R*} A_S)\right],$$

$$J_{6s} = 2\beta_\ell\left[\mathrm{Re}(A_\parallel^L A_\perp^{L*} - A_\parallel^R A_\perp^{R*})\right], \qquad J_{6c} = 4\beta_\ell\frac{m_\ell}{\sqrt{q^2}}\mathrm{Re}(A_0^L A_S^* + A_0^{R*} A_S),$$

$$J_7 = \sqrt{2}\beta_\ell\left[\mathrm{Im}(\mathrm{A}_0^\mathrm{L}\mathrm{A}_\parallel^{\mathrm{L}*} - \mathrm{A}_0^\mathrm{R}\mathrm{A}_\parallel^{\mathrm{R}*}) + \frac{\mathrm{m}_\ell}{\sqrt{\mathrm{q}^2}}\mathrm{Im}(\mathrm{A}_\perp^\mathrm{L}\mathrm{A}_\mathrm{S}^* - \mathrm{A}_\perp^{\mathrm{R}*}\mathrm{A}_\mathrm{S}))\right],$$

$$J_8 = \frac{1}{\sqrt{2}}\beta_\ell^2\left[\mathrm{Im}(\mathrm{A}_0^\mathrm{L}\mathrm{A}_\perp^{\mathrm{L}*} + \mathrm{A}_0^\mathrm{R}\mathrm{A}_\perp^{\mathrm{R}*})\right], \qquad J_9 = \beta_\ell^2\left[\mathrm{Im}(\mathrm{A}_\parallel^{\mathrm{L}*}\mathrm{A}_\perp^\mathrm{L} + \mathrm{A}_\parallel^{\mathrm{R}*}\mathrm{A}_\perp^\mathrm{R})\right],$$

Link to effective operators

$\Rrightarrow$ So here is where the magic happens. At leading order the amplitudes can be written as (soft form factors):

$$A_{\perp}^{L,R} = \sqrt{2} N m_B (1-\hat{s}) \left[(\mathcal{C}_9^{\text{eff}} + \mathcal{C}_9^{\text{eff}\prime}) \mp (\mathcal{C}_{10} + \mathcal{C}_{10}^{\prime}) + \frac{2\hat{m}_b}{\hat{s}} (\mathcal{C}_7^{\text{eff}} + \mathcal{C}_7^{\text{eff}\prime}) \right] \xi_{\perp}(E_{K^*})$$

$$A_{\parallel}^{L,R} = -\sqrt{2} N m_B (1-\hat{s}) \left[(\mathcal{C}_9^{\text{eff}} - \mathcal{C}_9^{\text{eff}\prime}) \mp (\mathcal{C}_{10} - \mathcal{C}_{10}^{\prime}) + \frac{2\hat{m}_b}{\hat{s}} (\mathcal{C}_7^{\text{eff}} - \mathcal{C}_7^{\text{eff}\prime}) \right] \xi_{\perp}(E_{K^*})$$

$$A_0^{L,R} = -\frac{N m_B (1-\hat{s})^2}{2\hat{m}_{K^*}\sqrt{\hat{s}}} \left[(\mathcal{C}_9^{\text{eff}} - \mathcal{C}_9^{\text{eff}\prime}) \mp (\mathcal{C}_{10} - \mathcal{C}_{10}^{\prime}) + 2\hat{m}_b (\mathcal{C}_7^{\text{eff}} - \mathcal{C}_7^{\text{eff}\prime}) \right] \xi_{\parallel}(E_{K^*}),$$

where $\hat{s} = q^2/m_B^2$, $\hat{m}_i = m_i/m_B$. The $\xi_{\parallel,\perp}$ are the form factors.

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$$A_{0}^{L,R} = -\frac{N m_B (1-\hat{s})^2}{2\hat{m}_{K^*}\sqrt{\hat{s}}} \left[(\mathcal{C}_9^{\rm eff} - \mathcal{C}_9^{\rm eff\prime}) \mp (\mathcal{C}_{10} - \mathcal{C}_{10}^{\prime}) + 2\hat{m}_b (\mathcal{C}_7^{\rm eff} - \mathcal{C}_7^{\rm eff\prime}) \right] \xi_{\parallel}(E_{K^*}),$$

where $\hat{s} = q^2/m_B^2$, $\hat{m}_i = m_i/m_B$. The $\xi_{\parallel,\perp}$ are the form factors.

$\Rrightarrow$ Now we can construct observables that cancel the ξ form factors at leading order:

$$P_5' = \frac{J_5 + \bar{J}_5}{2\sqrt{-(J_2^c + \bar{J}_2^c)(J_2^s + \bar{J}_2^s)}}$$

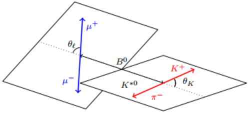
$B^0 \to K^* \mu^- \mu^+$ kinematics

$\Rrightarrow$ The kinematics of $B^0 \to K^* \mu^- \mu^+$ decay is described by three angles θ_l, θ_k, ϕ and invariant mass of the dimuon system (q^2).

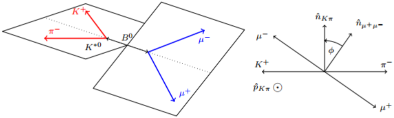
$\Rrightarrow$ $\cos\theta_k$: the angle between the direction of the kaon in the K^* ($\overline{K}^*$) rest frame and the direction of the K^* ($\overline{K}^*$) in the B^0 ($\bar{B}^0$) rest frame.

$\Rrightarrow$ $\cos\theta_l$: the angle between the direction of the μ^- (μ^+) in the dimuon rest frame and the direction of the dimuon in the B^0 ($\bar{B}^0$) rest frame.

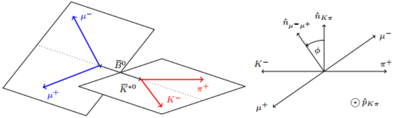
$\Rrightarrow$ ϕ: the angle between the plane containing the μ^- and μ^+ and the plane containing the kaon and pion from the K^*.



(a) θ_K and θ_ℓ definitions for the B^0 decay



(b) ϕ definition for the B^0 decay



(c) ϕ definition for the $\overline{B}^0$ decay

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

⇛ The kinematics of $B^0 \to K^{*}\mu^{-}\mu^{+}$ decay is described by three angles θ_l, θ_k, ϕ and invariant mass of the dimuon system (q^2).

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_K\, d\cos\theta_l\, d\phi} = \frac{9}{32\pi}\Big[J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K + (J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_l$$
$$+ J_3 \sin^2\theta_K \sin^2\theta_l \cos 2\phi + J_4 \sin 2\theta_K \sin 2\theta_l \cos\phi + J_5 \sin 2\theta_K \sin\theta_l \cos\phi$$
$$+ (J_{6s}\sin^2\theta_K + J_{6c}\cos^2\theta_K)\cos\theta_l + J_7 \sin 2\theta_K \sin\theta_l \sin\phi + J_8 \sin 2\theta_K \sin 2\theta_l \sin\phi$$
$$+ J_9 \sin^2\theta_K \sin^2\theta_l \sin 2\phi \Big],$$

⇛ This is the most general expression of this kind of decay.

⇛ The CP averaged angular observables are defined:

$$S_i = \frac{J_i + \bar{J}_i}{(d\Gamma + d\bar{\Gamma})/dq^2}$$

Link to effective operators

$\Rrightarrow$ The observables J_i are bilinear combinations of transversity amplitudes: $A_\perp^{L,R}$, $A_\parallel^{L,R}$, $A_0^{L,R}$.

$\Rrightarrow$ So here is where the magic happens. At leading order the amplitudes can be written as:

$$A_\perp^{L,R} = \sqrt{2} N m_B (1-\hat{s}) \left[(\mathcal{C}_9^{\rm eff} + \mathcal{C}_9^{\rm eff\prime}) \mp (\mathcal{C}_{10} + \mathcal{C}_{10}') + \frac{2\hat{m}_b}{\hat{s}} (\mathcal{C}_7^{\rm eff} + \mathcal{C}_7^{\rm eff\prime}) \right] \xi_\perp(E_{K^*})$$

$$A_\parallel^{L,R} = -\sqrt{2} N m_B (1-\hat{s}) \left[(\mathcal{C}_9^{\rm eff} - \mathcal{C}_9^{\rm eff\prime}) \mp (\mathcal{C}_{10} - \mathcal{C}_{10}') + \frac{2\hat{m}_b}{\hat{s}} (\mathcal{C}_7^{\rm eff} - \mathcal{C}_7^{\rm eff\prime}) \right] \xi_\perp(E_{K^*})$$

$$A_0^{L,R} = -\frac{N m_B (1-\hat{s})^2}{2\hat{m}_{K^*} \sqrt{\hat{s}}} \left[(\mathcal{C}_9^{\rm eff} - \mathcal{C}_9^{\rm eff\prime}) \mp (\mathcal{C}_{10} - \mathcal{C}_{10}') + 2\hat{m}_b (\mathcal{C}_7^{\rm eff} - \mathcal{C}_7^{\rm eff\prime}) \right] \xi_\parallel(E_{K^*}),$$

where $\hat{s} = q^2/m_B^2$, $\hat{m}_i = m_i/m_B$. The $\xi_{\parallel,\perp}$ are the soft form factors.

Link to effective operators

$\Rightarrow$ The observables J_i are bilinear combinations of transversity amplitudes: $A_{\perp}^{L,R}$, $A_{\parallel}^{L,R}$, $A_0^{L,R}$.

$\Rightarrow$ So here is where the magic happens. At leading order the amplitudes can be written as:

$$A_{\perp}^{L,R} = \sqrt{2} N m_B (1-\hat{s}) \left[(\mathcal{C}_9^{\text{eff}} + \mathcal{C}_9^{\text{eff}\prime}) \mp (\mathcal{C}_{10} + \mathcal{C}_{10}^{\prime}) + \frac{2\hat{m}_b}{\hat{s}} (\mathcal{C}_7^{\text{eff}} + \mathcal{C}_7^{\text{eff}\prime}) \right] \xi_{\perp}(E_{K^*})$$

$$A_{\parallel}^{L,R} = -\sqrt{2} N m_B (1-\hat{s}) \left[(\mathcal{C}_9^{\text{eff}} - \mathcal{C}_9^{\text{eff}\prime}) \mp (\mathcal{C}_{10} - \mathcal{C}_{10}^{\prime}) + \frac{2\hat{m}_b}{\hat{s}} (\mathcal{C}_7^{\text{eff}} - \mathcal{C}_7^{\text{eff}\prime}) \right] \xi_{\perp}(E_{K^*})$$

$$A_0^{L,R} = -\frac{N m_B (1-\hat{s})^2}{2\hat{m}_{K^*}\sqrt{\hat{s}}} \left[(\mathcal{C}_9^{\text{eff}} - \mathcal{C}_9^{\text{eff}\prime}) \mp (\mathcal{C}_{10} - \mathcal{C}_{10}^{\prime}) + 2\hat{m}_b (\mathcal{C}_7^{\text{eff}} - \mathcal{C}_7^{\text{eff}\prime}) \right] \xi_{\parallel}(E_{K^*}),$$

where $\hat{s} = q^2/m_B^2$, $\hat{m}_i = m_i/m_B$. The $\xi_{\parallel,\perp}$ are the soft form factors.

$\Rightarrow$ Now we can construct observables that cancel the ξ soft form factors at leading order:

$$P_5^{\prime} = \frac{J_5 + \bar{J}_5}{2\sqrt{-(J_2^c + \bar{J}_2^c)(J_2^s + \bar{J}_2^s)}}$$

Symmetries in $B \to K^* \mu\mu$

$\Rightarrow$ We have 12 angular coefficients (S_i).
$\Rightarrow$ There exist 4 symmetry transformations that leave the angular distributions unchanged:

$$n_\parallel = \begin{pmatrix} A_\parallel^L \\ A_\parallel^{R*} \end{pmatrix}, \quad n_\perp = \begin{pmatrix} A_\perp^L \\ -A_\perp^{R*} \end{pmatrix}, \quad n_0 = \begin{pmatrix} A_0^L \\ A_0^{R*} \end{pmatrix}.$$

$$n_i^{'} = U n_i = \begin{bmatrix} e^{i\phi_L} & 0 \\ 0 & e^{-i\phi_R} \end{bmatrix} \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \cosh i\tilde{\theta} & -\sinh i\tilde{\theta} \\ -\sinh i\tilde{\theta} & \cosh i\tilde{\theta} \end{bmatrix} n_i .$$

$\Rightarrow$ Using this symmetries one can show that there are 8 independent observables. The pdf can be written as:

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