Proceeding to the LHC seminar talk *Update of the $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ angular analysis at LHCb experiment* held by Eluned Smith on behalf of the LHC collaboration on 13th of March 2020.

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I assume this is the abstract? Why is B2K*mumu not mentioned earlier? Can you make this a real abstract by separating it from the rest of the proceeding?

The LHCb collaboration has published new results regarding flavor changing neutral currents based on recent studies for physics beyond standard model. FCNC are very promising decay types since they only occur at loop level and are therefore very sensitive for new physics. The data from the previous analysis in 2011 and 2012 were expanded by the 2016 data which results in twice the amount of statistics. With this and a deeper understanding of theoretical uncertainties an angular analysis was performed. The hints on a local tension in $P_5{}'$ were confirmed with this analysis. One of the explanations points to a shift in the wilson coefficient C_9. The most sensitive observables to C_9 are the q^2 dependence of the forward-backward asymmetry and $P_5{}'$. The significance of the tension results in 2.7 - 3.3σ. The complete set of measurements into the $b \rightarrow s\mu^-\mu^+$ transition performed by various experiments includes the observables R_K and R_K^*, describing ratios corresponding to $B \rightarrow K^*ll$ decays involving muons and electrons. This analysis focusses on observables in the P_i and S_i basis and does not include R_K and R_K^*.

The stated process is of such importance because the $b \rightarrow s\mu\mu$ transition is forbidden at tree level due to FCNC and can only occur at loop order. Because of that, these processes are much more sensitive to new physics(NP).

To gather information about short distance NP above the SM energy scale μ, wilson coefficients $C_i(\mu)$ and low-energy QCD Operators O_i are used to describe that.

The wilson coefficients C_7, C_9 and C_{10} are of great importance since observables like the

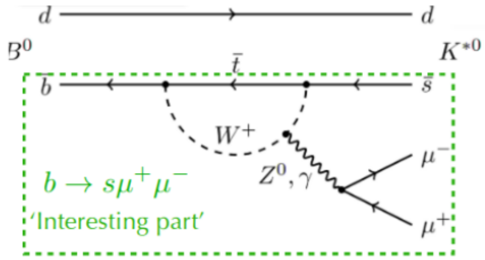

Figure 1: The SM process of $b \rightarrow s\mu^-\mu^+$. The green box can be described with NP models.

forward-backward asymmetry and $P_5{}'$ are sensitive for C_9 especially.

In an effective theory, C_9 and C_{10} are used to describe the contribution from loops, in which electroweak gauge bosons are produced. wilson coefficient C_7 describes the contribution from loopdiagramms which produce photons from the loops.

This can be summarized by an effective hamiltonian

What would h.c. imply here? What does the h.c. part mean for the physics of the SM and the NP contributions?

$$H_{eff} = -\frac{4G_f}{\sqrt{2}} \mathrm{V}_{tb}\mathrm{V}_{ts}^* \sum_i C_i \cdot O_i + \text{h.c.}$$

There is no mu in the formula

G_F is Fermi's constant, μ ist the renormalization scale, $\mathrm{V}_{tb}\mathrm{V}_{ts}^*$ contains leading flavor factors of the SM which lie in the CKM matrix elements V_{ij}.

To measure the decay rate as a function of angles of the decay products, an angular analysis is performed. This is motivated by the fact, that the K^{0*} is a meson with spin 1 therefore has three polarisation states. This results in a rich angular structure. The definition of the angular observables θ_k, θ_l and ϕ is schematically shown in figure 2

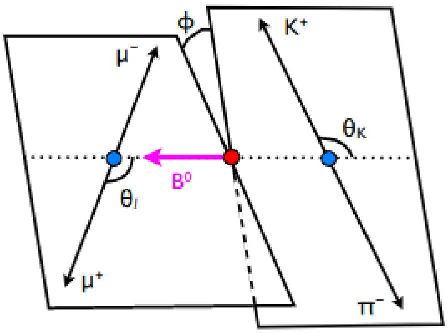

Figure 2: image of the angular observables.[4]

In this analysis, the forward-backard asymmetry A_{FB}, F_L the fraction of the longitudinal polarisation of the K^{*0} and the decay rate of the process $B^0 \to K^{*0}\mu\mu$ was measured. The definition of the angular observables are the following. θ_l is the angle between the negatively charged lepton and $\bar{B}$ in the dimuon center of mass system (c.m.s). θ_k is the angle between the Kaon and the $\bar{B}$ in the K^{*0} c.m.s.. The angle between the K^{*0}-plane and the dimuon-plane is defined by the angle ϕ[3]. in the rest frame of the B

Considering that S-wave contribution, spinless $K^+\pi^-$ constellations, can pollute the measurement, therefore a parametrization such as $(1-F_S)$ for this was taken into account where $(1-F_S)$ is the S-wave fraction which describes the amount of S-wave contribution. The interference Amplitude between P-wave and S-wave decays are parametrized by A_S. The angular distribution[4] for the $B^0 \to K^{*0}\mu\mu$ decay reads

Why do cite an CMS analysis when writing the procceeding about an LHCb analysis that does the measurements differently?

$$\frac{1}{\Gamma}\frac{\mathrm{d}^3\Gamma}{\mathrm{d}\theta_k \mathrm{d}\theta_l \mathrm{d}q^2} = \frac{9}{16} f(F_S, A_S, \theta_k, \theta_l, A_{FB}, F_L) \ . \tag{1}$$

This is wrong!

The efficiency is not flat in any of the angles in this measurement! Maybe it is in the C M S measurement. Also the phi dependency is not integrted out. See slides 35 and 42 for example in the semianr talk

Since A_{FB}, F_L and the acceptance $\mathcal{A}\times\epsilon$ do not depend on the angle ϕ, it is already integrated out. The angular description for The B and $\bar{B}$ are combined afterwards and expanded into a sum of the angular variables() multiplied with a fitparameter, which are the A_{FB}, F_L and S_i, as seen in figure 3, which are called CP-averaged observables. The angular distribution in the S_i then reads

If you compare this formula with figure 3 there is still a difference in dimensions

$$\frac{1}{\Gamma}\frac{\mathrm{d}^3\Gamma[\bar{B}^0 \to \bar{K}^{0*}\mu^+\mu^-]}{\mathrm{d}\cos\theta_l \mathrm{d}\cos\theta_k \mathrm{d}q^2} = \frac{9}{16}\sum_i S_i(q^2_{min}, q^2_{max}) f_i(\vec{\Omega})$$

The CP asymmetries need to be analyzed further because NP could contribute differently to CP-conjugated processes. Good!

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

F_L :fraction of longitudinal polarisation of the K^{*0}

A_{FB} :forward-backward asymmetry of dimuon system

Make this an equation please!

Figure 3: Angular description for B and $\bar{B}$ combined.

Afterwards the S_i basis was reparametrised to the P_i basis. This was done to eliminate first order uncertainties in the form factors primarily since form factors carry theoretical uncertainties which cancel when ratios of them are calculated. The fit to the angular distribution yields seven CP violating observables including F_L.

"This was done to cancel theoretical uncertainties on the form factors to first order"

CP violating -> CP-averaged

$$P_1 = \frac{2S_3}{1-F_L} \qquad P_{4,5,8}{}' = \frac{S_{4,5,8}}{\sqrt{F_L\,(1-F_L)}}$$

$$P_2 = \frac{2}{3}\frac{A_{FB}}{1-F_L} \qquad P_6{}' = \frac{S_7}{\sqrt{F_L\,(1-F_L)}}$$

$$P_3 = \frac{-S_9}{1-F_L}$$

Here the angles used for the angular function $f_i(\Omega)$ are $\vec{\Omega} = (\cos\theta_l, \cos\theta_k)$. The S_i basis contains the six angular coefficients which are the combinations of the K^{0*} amplitudes. These amplitudes describe the polarisation states of the Kaon and depend on the wilson coefficients and form factors. An example for the K^{0*} amplitudes is

+phi

Why are there six and not 3 when having a spin 1 particle? There are more coefficients in the Si basis! See figure 3.

$$A_\perp^{L(R)} = \mathcal{N}\sqrt{2\lambda}\{[(C_9^{\mathrm{eff}} + C_9^{\mathrm{eff}\prime}) \mp (C_{10}^{\mathrm{eff}} + C_{10}^{\mathrm{eff}\prime})\frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_B}{q^2}(C_7^{\mathrm{eff}} + C_7^{\mathrm{eff}\prime})\,T_1(q^2)]\} \, ,$$

where $T_1(q^2)$ and $V(q^2)$ are form factors and C_i are wilson coefficients.

For this analysis the data sets used are from the years 2011, 2012 and 2016. The data sets from 2011 and 2012 are from run 1. The 2011 data was taken at a centre-of-mass energy of $\sqrt{s} = 7\,\mathrm{TeV}$, the 2012 data at $\sqrt{s} = 8\,\mathrm{TeV}$ and the added data set from 2016 was taken at $\sqrt{s} = 13\,\mathrm{TeV}$. Adding the 2016 data also doubled the statistic to around 4,7/fb. 4.7fb^{-1}

For the selection of candidates it is required, that the impact paramters for the daughter particles are quite significant since they do not originate from the primary vertex. Daughter particles that come from the primary vertex need

This doesn't make sense?! Either the particle is coming from the PV. Then it is not a child particle. Or it is coming from a secondary vertex from a decaying parent particle

Track fit and vertex fit are different things! A vertex of good quality is achieved if the particles' tracks fit well to common point. Track fit is good if the hits in the detector components fit together well so that one can be sure that they come from the same particle

to have a very small impact parameter and also a quality vertex is necessary. That means the track fit $\frac{\chi^2}{dof}$ must be small, where dof are the degrees of freedom. Also two muon candidates, a kaon and a pion are required. To suppress peaking background as seen in figure 4 the particle identification is used. The FCNC process here is described by $B^0 \rightarrow K^{0*}\mu\mu$, but the subprocesses such as $B^0 \rightarrow K^{0*}(\bar{c}c \rightarrow \gamma^* \rightarrow \mu\mu)$ are statistical relevant since they proceed at tree level. Therefore charmonium resonances pollute the q^2 spectrum, especially at the J/$\Psi(1S)$ and the $\Psi(2S)$ mass. Around these peaks a mass-veto region is defined where signal decays are neglected if they fall into the veto region. Left, in between and on the right of the peaks the signal regions are defined. A multivariate analysis(MVA)[6] is performed to suppress combinatorial background, incorrectly vertexed tracks, even further. ~~MVA is a machine learning technique in which a classifier or regressor takes several features to learn from and to make a prediction on what is background and what belongs to the signal.~~ To suppress $J/\Psi \rightarrow ll$ contributions, the invariant mass spectrum is looked at. The most common features are: small momentum particles and small opening angles and a large dE/dx. Other input variables are the B^0 decay time, vertex-fit quality, momentum and transverse momentum of B^0 candidate, θ_{DIRA} as well as particle identification from the RICH detector. θ_{DIRA} describes the opening angle between the reconstructed B^0 momentum and the vector connecting the reconstructed B^0 decay vertex to the primary vertex. The classifier is trained on $B \rightarrow J/\Psi K^{0*}$ candidates as signal. The background consists of candidates from the mass region $m(B \rightarrow K^+\pi^-\mu^+\mu^-) \in [5350\mathrm{MeV}, 7000\mathrm{MeV}]$. ~~Since the detector cannot know which lepton pairs belong together, all possible combinations are tested. Combinations with same signed leptons (N^{++} or N^{--}) are always uncorrelated so the signal S results in $S = N^{+-} - (N^{++} + N^{--})$. This is called the like-sign method[5]. N^{+-} are the opposite sign lepton pairs.~~

The background from charmonia has nothing to do with misID. They just decay to the same final state! There are other important backgrounds (see slide 18 or paper)

Redundant. Jpsi background is not combinatorial Jpsi are even used to train the classifier!

not in LHCb

data sidebands

Not imprtant

For the full fit model the shape of the invariant mass plots are used to determine the amount of

This spectrum is for Kmumu, which is different compared to the one of K*mumu as K is a spin0 particle. For example there is no photon pole at low q^2

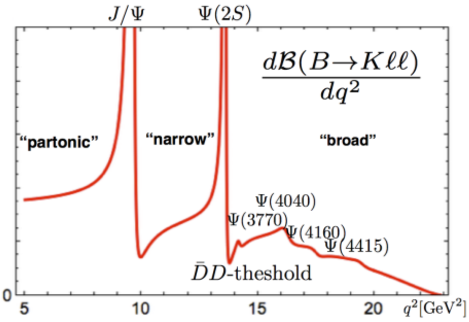

Figure 4: spectrum in q^2 for the lepton pair in Kll branching fraction[2].

signal and background in the data.

$$\mathrm{PDF}_{total} = f_{sig}\mathrm{PDF}_{sig}(\vec{\Omega}, m) + (1 - f_{sig})\mathrm{PDF}_{bkg}(\vec{\Omega}, m)$$

The PDF function can be separated into an angular part and a massive part. After that a maximum likelihood fit is performed. The massive part of the signal PDF is a gaussian function with a radiative tail and the background PDF results in an exponential function.

q^2

Because of the factorization of the signal and background PDF

angular and q^2 dependence factorizes, bkg and sig is independent anyway as you take the sum

$$\mathrm{PDF}_{sig}(\vec{\Omega}, m) = \mathrm{PDF}_{sig}(\vec{\Omega}) \times \mathrm{PDF}_{sig}(m)$$
$$\mathrm{PDF}_{bkg}(\vec{\Omega}, m) = \mathrm{PDF}_{bkg}(\vec{\Omega}) \times \mathrm{PDF}_{bkg}(m)$$

the angular part of the signal PDF of the Run 1 data and the data from 2016 are shared in the analysis to perform a simultaneous fit $\sum_i S_{i,q^2_{bin}} f_i(\Omega)$. This is possible since they do not share the same mass and angular background because the conditions in the 2016 data sample differs from Run 1 data. This is the reason why only the mass shape is shared! The rest is different!!!
The efficiency needs correction since it's behavior is not flat. Legendre polynomials are used for the dimuon mass and the three angles which results in a 4D formular. The correlation between the observables negates the factorization of the 4D function to 1D functions.

forbids/prohibits

The dominant systematic uncertainties are acceptance variations with q^2, peaking backgrounds and bias corrections as seen in figure 4. The uncertainty related to the contribution from the S-wave or P+S interference is evaluated by taking the difference between the default results, obtained by fitting with a function accounting for the S-wave (1), with the results from a fit performed with no S-wave or interference terms

This is not done by LHCb!

where $F_S = 0$ and $A_S = 0$.[4] Bias relates to the S-wave contribution F_S. If it is small, the angular spectrum is biased towards the P-wave. If $F_S \approx 1$, it is biased towards the S-wave.
With the datasets from Run 1 and 2016 combined a significance of 2,5 in the $q^2 \in [4.0, 6.0]\frac{\mathrm{GeV}^2}{c^4}$ bin was yielded. For the $q^2 \in [6.0, 8.0]\frac{\mathrm{GeV}^2}{c^4}$ bin a significance of 2,9 was yielded. A local tension in figure 6 was reduced in comparison to figure 5 for both data sets combined. The global significance is obtained by fitting all observables of the S_i basis to the complete set of CP-averaged observables. The wilson coefficients and all bins in q^2 need to be extracted. The theory uncertainty regarding form factors and parametrisation of sub-leading corrections have decreased from previous publications.

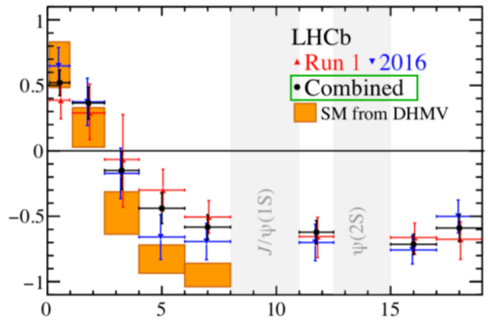

Figure 5: local tension in $P_5{}'$ with combined data.

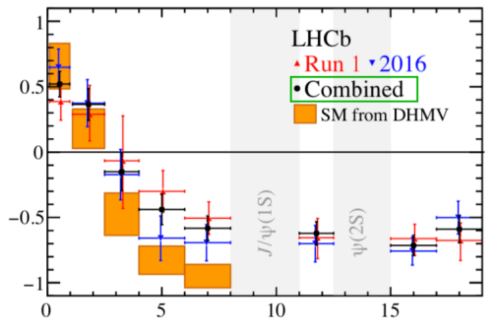

Figure 6: local tension in $P_5{}'$ with combined data.

also in C10 there is a shift

A variation in the real part of C_9 and C_{10} lead to a measureable shift in wilson coefficient C_9, also in agreement to Run 1 as seen in figure 7. When only varying C_9 the preferred shift can be seen in figure 8. It occurs that the 2016 analysis and Run 1 show similar results. The combination of Run 1 and 2016 yielded, when including the bin $q^2 \in [6.0, 8.0]\mathrm{GeV}/c^4$, a significance of 3,3 and 2,4 when excluded.

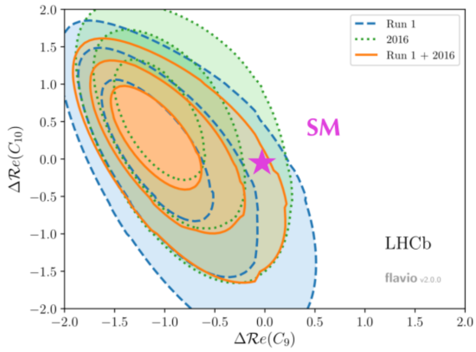

Figure 7: Shift in C_9 and C_{10} compared to SM.

In figure 9 the angular observable $P_5{}'$ as a function of q^2 for the SM prediction and the theory prediction with preferred wilson coefficents is shown. It can be seen, that a shift closes the gap between both predictions.

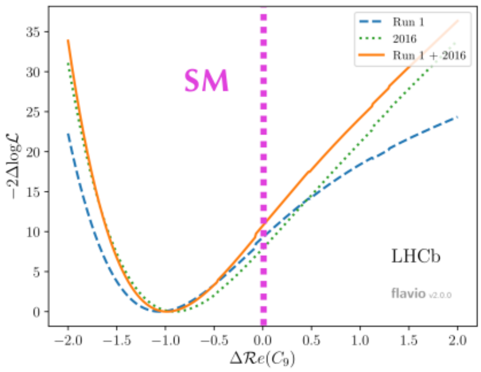

Figure 8: shift in the real part of C_9 yielded from the analysis.

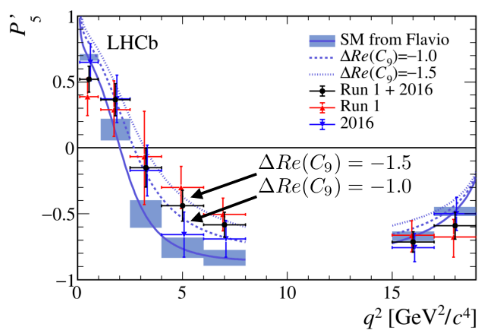

Figure 9: angular observable $P_5{}'$.

With that being said, the results presented in the seminar emphasize the overall tension proposed in Run 1 data from previous measurements. The higher overall tension does not confirm new physics but only hint at it. Different measurements at different scales could yield a deeper understanding an a more precise measurement which might confirm the hints. Futher studies in $b \to s$ transitions such as $b \to s\gamma$ could contribute to the analysis[1]. In order to study new physics at higher scales, an angular analysis is important since the optimised basis reduce the theoretical uncertainties from form factors.

Not necessarily to this analysis but to the global picture of the Wilson coeffcients C7, C9 and C10

References

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[5] Bjørn Bäuchle Stefan Kniege. *How to subtract combinatorial Background*. URL: https://fias.frankfurtium.de/downloads/04_hqm_cb.pdf (visited on 08/09/2020).

[6] R. E. Schapire Y. Freund. *A Decision-Theoretic Generalization of On-Line Learning and an Application to Boosting*. URL: https://doi.org/10.1006/jcss.1997.1504 (visited on 08/14/2020).

None of these references is important for the proceeding. Please cite the seminar talk and LHCb paper. Other measurements from b->sll transitions could be cited as well (but not so important)