ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Anomalies in B decays

University of Geneva,
April 25, 2018

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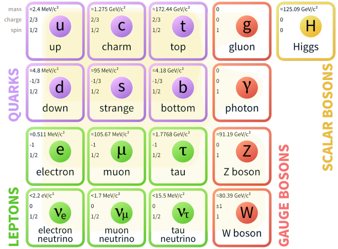
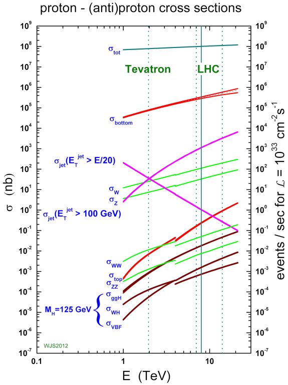
[www.hep.ph.ic.ac.uk]

B physics





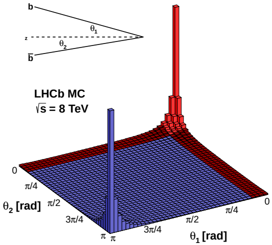
$$B^0 = |d\bar{b}\rangle, B^+ = |u\bar{b}\rangle, B_s^0 = |s\bar{b}\rangle, \Lambda_b^0 = |udb\rangle, B_c^+ = |c\bar{b}\rangle$$

- B physics is the study of bound states containing one b quark and their decays / dynamics.
- They decay in a multitude of final states, allowing the study of a wide range of physics.
- They are copiously produced at the LHC.

LHC physics (toy version)

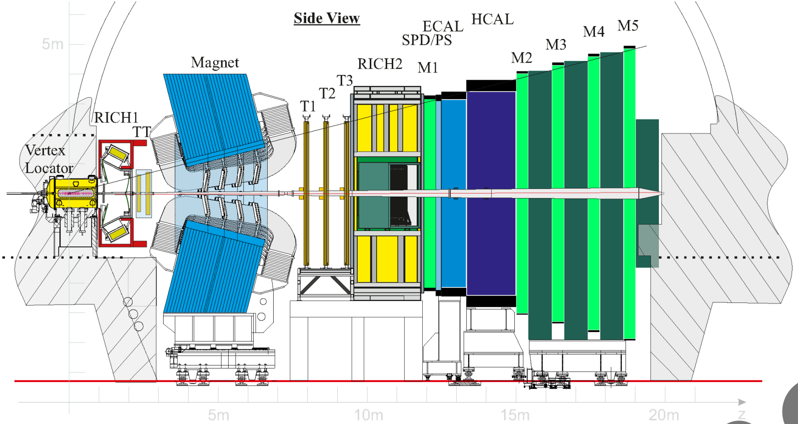
- Take a bunch of protons
- Smash them together and create a mess.
- Spend some millions to build a device to understand it.

B physics at the LHC

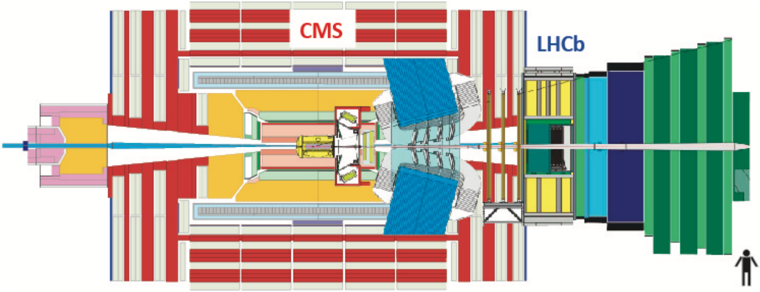


- b hadrons are moderately heavy ($\sim$ 5 GeV, $> \Lambda_{QCD}$) and are mainly produced in the forward or backward direction at the LHC
  $\longrightarrow$ build a forward detector.
- B hadrons have ”soft” decay products and travel $\sim$ 1 cm before decaying
  $\longrightarrow$ build a detector with low-p_T capability and good momentum / vertex resolution.
- B hadrons have a large variety of decay channels with different particle species in the final states
  $\longrightarrow$ need a particle ID.

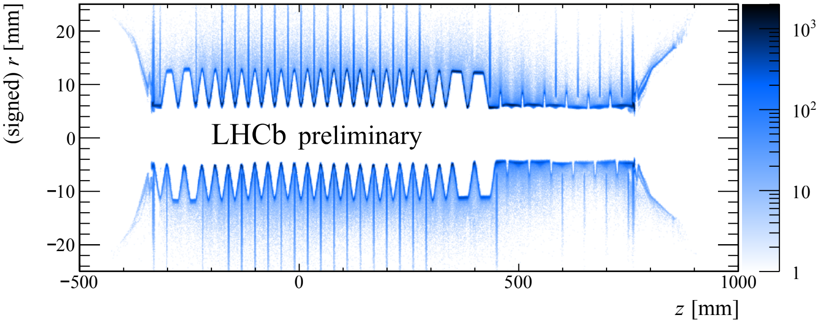
LHCb


Side View
5m
Magnet
RICH1
TT
Vertex
Locator
T1
T2
T3
RICH2
SPD/PS
ECAL
HCAL
M1
M2
M3
M4
M5
5m
10m
15m
20m
z

LHCb: Comparison with CMS



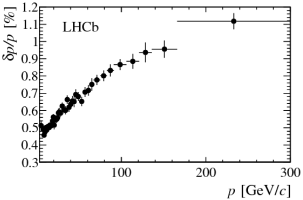
LHCb: Vertex Locator

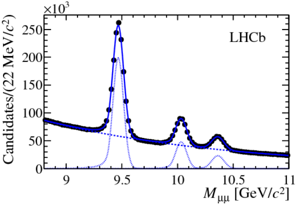


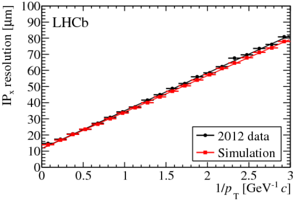
- Velo sensors 8mm from the beam position.
- Allows for very good Impact Parameter and Primary / Secondary Vertex resolution.

[Int. J. Mod. Phys. A 30, 1530022 (2015)]
[Eur. Phys. J. C 73 (2013) 2431]

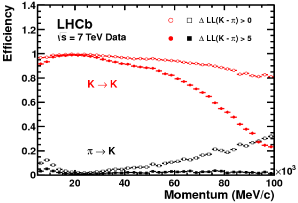
LHCb: Performance numbers



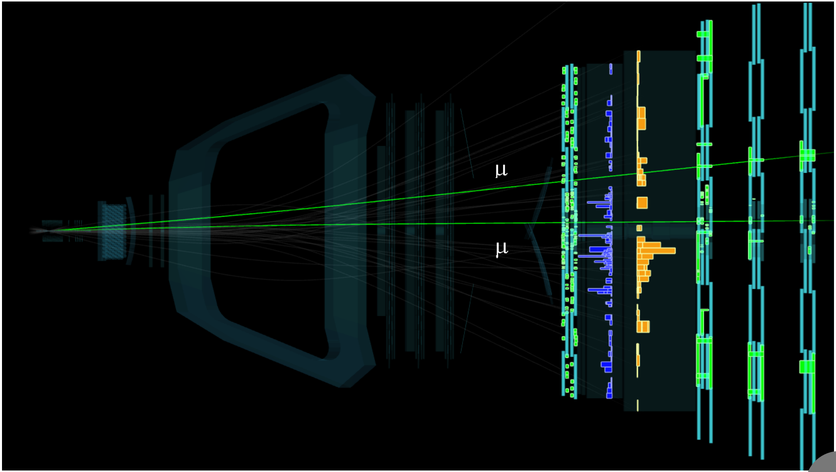




- Excellent momentum / mass resolution:
  - $\frac{\delta p}{p}$ = 0.5% (10 GeV/c) - 1.0% (200 GeV/c)
  - $\sigma_m(B_s^0 \to \mu^+\mu^-) \approx 20\,\mathrm{MeV}/c^2$
- Impact parameter resolution:
  - 15 +29/p_{T} [GeV/c]) μm
- High particle identification efficiency.
  - $\varepsilon_\mu \approx$ 97% with 1-3% $\pi \to \mu$ misidentification
  - $\varepsilon_K \approx$ 95% with $\approx$ 5% $\pi \to K$ misidentification

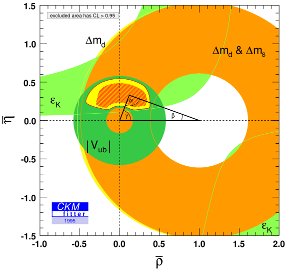


LHCb: Event display



Rare B Decays

B decays as a laboratory



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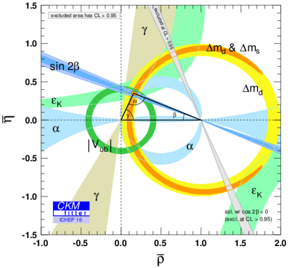
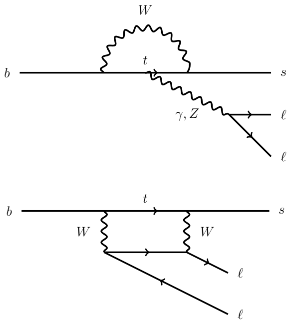
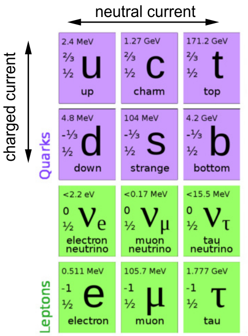


2016

- B hadrons are a perfect laboratory to perform measurements of many fundamental physics quantities.
- Decays governed by (electro)weak interaction, but hadronic state itself by strong interaction.
- B physics is by definition flavour physics and strongly linked to the CKM matrix.

Rare B decays



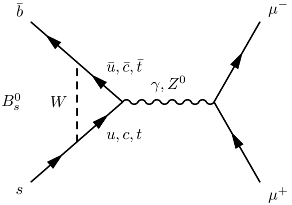


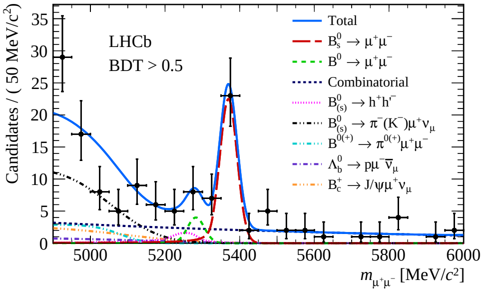
- Will (mostly) take about flavour-changing neutral current decays of b quarks today.
- And only consider electroweak interactions (no gluonic penguins).
- Decays are strongly suppressed, but heavy new particles (beyond the SM) can appear in the loop and alter the final state distributions.
- ”Rare B decays”: $\mathcal{B} \sim 10^{-6}$

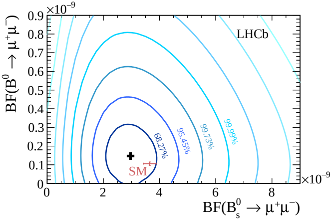
B

[PRL. 118, 191801 (2017)]

$B_s^0 \to \mu^+\mu^-$

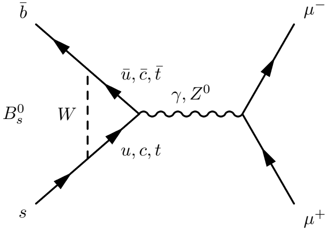


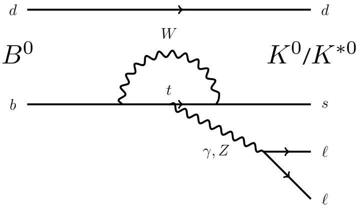




- Strongly helicity suppressed.
- Only leptons in the final state, very clean theoretically.
- $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \cdot 10^{-9}$
- $\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \cdot 10^{-10}$
- All compatible with standard model predictions.

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





$$m^2(\gamma, Z) = q^2 = m^2(B_s^0)$$

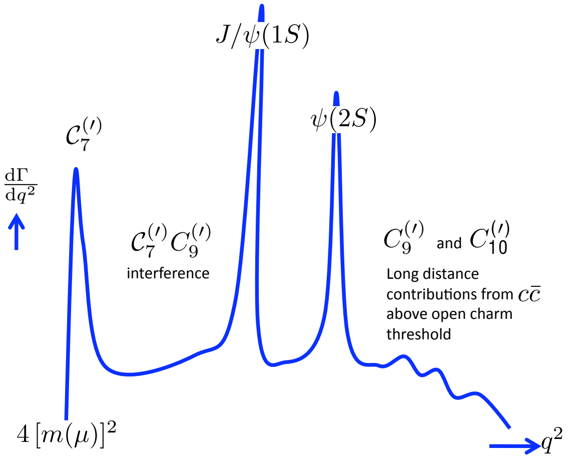
$$m^2(\gamma, Z) = q^2 > 4m_\ell^2$$

i.e. physics depends on q^2

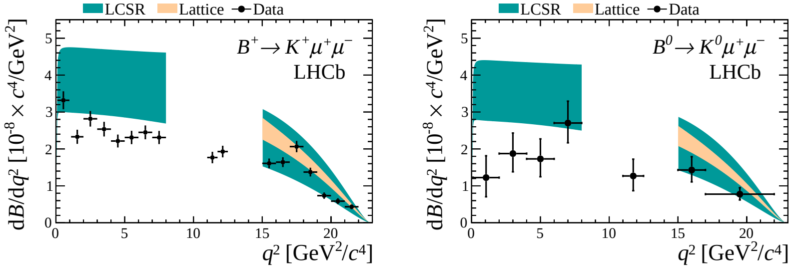
$$\frac{d\mathcal{B}}{dq^2}$$

All results with 3 fb^{-1} (Run I)

q^2 spectrum for $b \to s\ell^+\ell^-$



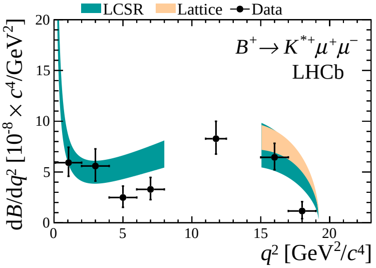
$b \to s\ell^+\ell^-$ differential branching fractions

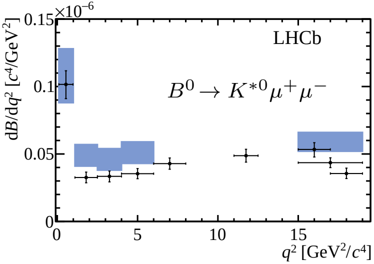


- Measure branching fractions as a function of q^2.
  - Normalize $B \to K\mu^+\mu^-$ to $B \to KJ/\psi$
- For $B^0 \to K^0\mu^+\mu^-$ use decay $K^0_{\rm S} \to \pi^+\pi^-$
- Measured values significantly below prediction for low q^2.

LCSR = Light-cone sum rules

$b \to s\ell^+\ell^-$ differential branching fractions

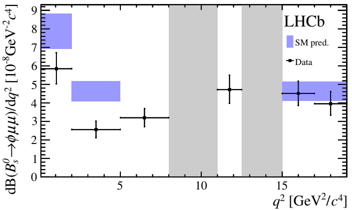




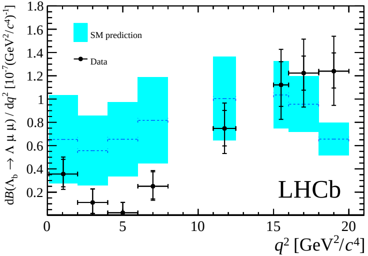
- Measure branching fractions as a function of q^2
  - Normalize $B \to K^*\mu^+\mu^-$ to $B \to K^* J/\psi$
- For $B^+ \to K^{*+}\mu^+\mu^-$ use decay $K^{*+} \to K^0_S\pi^+$
- Measured values below prediction for low q^2.

$b \to s\ell^+\ell^-$ differential branching fractions

$B_s^0 \to \phi\mu\mu$



$\Lambda_b^0 \to \Lambda\mu\mu$

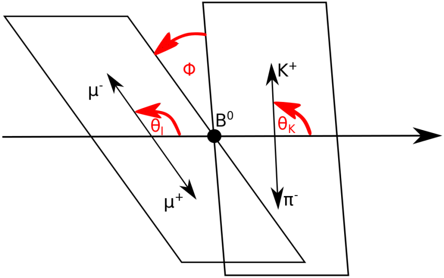


- Measure branching fractions as a function of q^2
  - Normalize $B_s^0 \to \phi\mu^+\mu^-$ to $B_s^0 \to \phi J/\psi$
  - Normalize $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ to $\Lambda_b^0 \to \Lambda J/\psi$
- Basically all differential branching fractions are lower than their prediction for low values of q^2.

$$\frac{d\mathcal{B}}{dq^2\,d\Omega}$$

All results with 3 fb^{-1} (Run I)

Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$



- Differential decay rate of P $\rightarrow$ VV decays depends on 3 decay angles and an observable, depending on q^2.
- $\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell d\cos\theta_K d\phi} = \frac{9}{32\pi}\sum_i J_i(q^2) f(\cos\theta_\ell, \cos\theta_K, \phi)$
- Best studied case in LHCb: $B^0 \to K^{*0}\mu^+\mu^-$

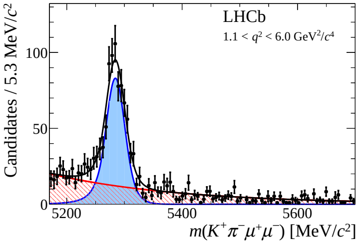
Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$

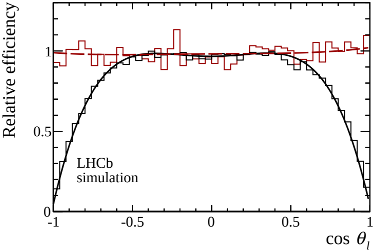
$$\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos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

- Call the coefficient in front of the angular expressions ”observable”.
- Angular terms are (almost all) orthogonal.
- $S_6 = \frac{4}{3}A_{FB} = \frac{4}{3}\frac{\#\cos\theta_\ell>0-\#\cos\theta_\ell<0}{\#\cos\theta_\ell>0+\#\cos\theta_\ell<0}$: Forward-backward asymmetry of the leptons.
- F_L: Longitudinal polarization of the K^{*0}

[JHEP 02 (2016) 104]

Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$

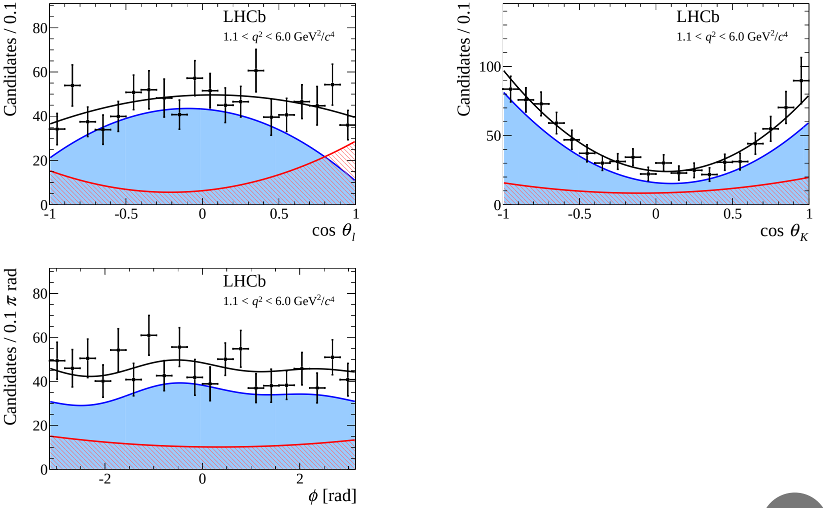




- Use a BDT to select the events, in total $\approx$ 2400 signal candidates.
- Use simulated sample of phase-space generated events to determine the effect of the acceptance and selection.

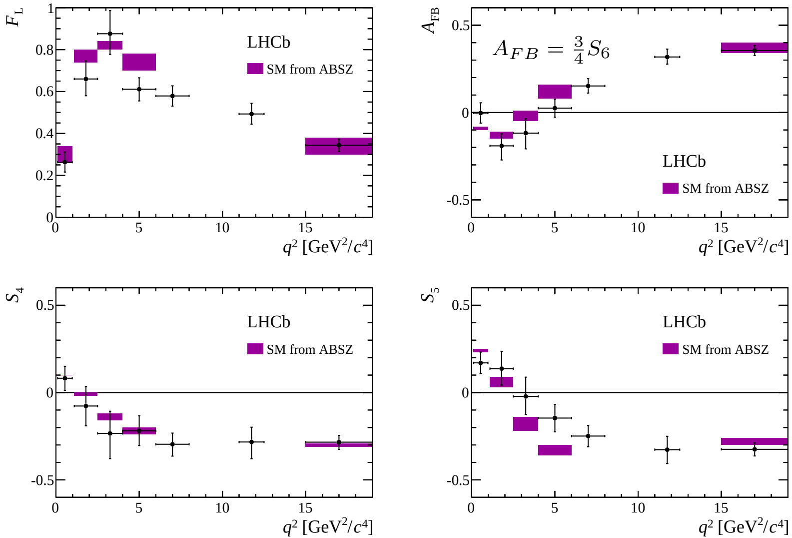
[JHEP 02 (2016) 104]

Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$

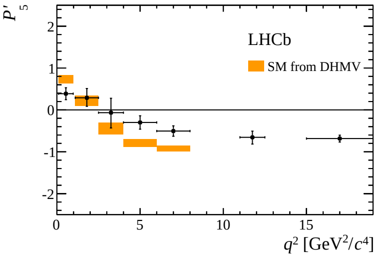


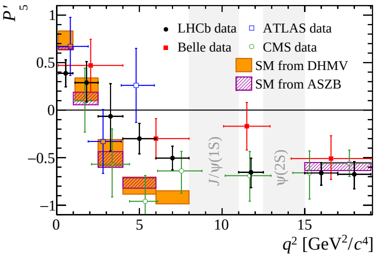
[JHEP 02 (2016) 104]

Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$



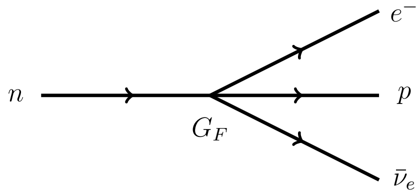
Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$





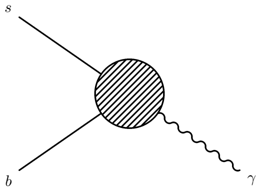
- $P'_5 = \frac{S_5}{\sqrt{1-F_L}}$
- The P'_i observables are less prone to hadronic form-factor uncertainties than the S_i ones (when using so-called ”soft form-factors”).
- Measurement also by Belle, CMS, ATLAS (but with less statistical power)
- Global significance is about 3.4σ from the SM (LHCb measurement alone).

Wilson coefficients (I)

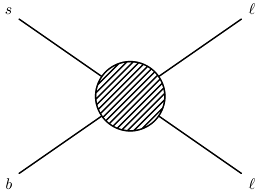


- Need a framework to describe all these different types of processes, with as little assumptions as possible.
- Fermi solved this problem already 85 years ago for the β decay by introducting a point interaction.
- G_F is a coupling constant that gives the strength of the interaction, as long as $E \ll m_W$.

Wilson coefficients (II)



$\mathcal{O}_7$

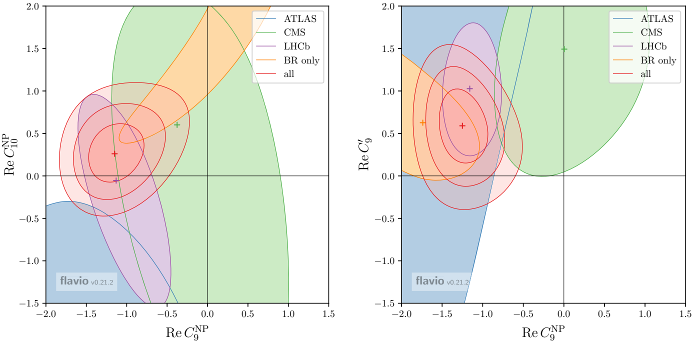


$\mathcal{O}_{9V}, \mathcal{O}_{10A}$

$$\mathcal{H}_{eff} = -4\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \mathcal{C}_i \mathcal{O}_i$$

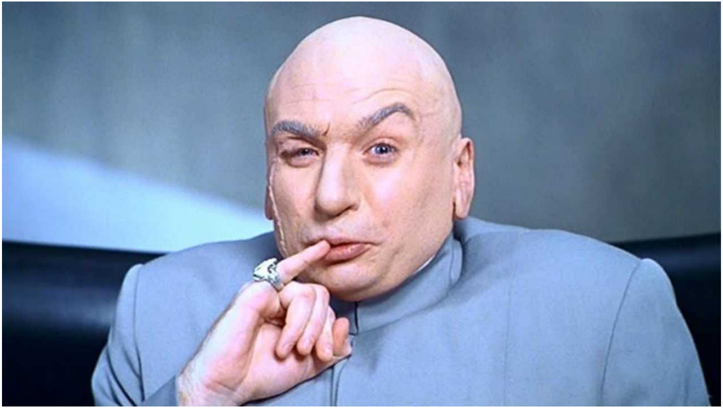
- Do the same thing for the 3 possible interactions in $b \to s\ell^+\ell^-$ processes.
- G_F is Fermi constant, V_{tb}, V_{ts}^* CKM elements.
- $\mathcal{C}_i$ are called Wilson coefficients, they are (complex) numbers.
- Derive $\mathcal{C}_i$ from all measurements and combine them in global fits.

Global fits (part I)

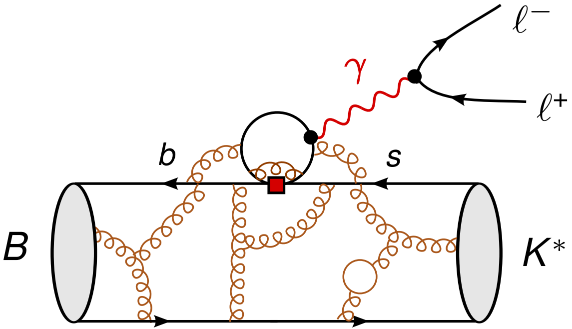


- Only consider C_9 and C_{10}.
- 0.0 / 0.0 is the Standard Model.
- Does not include lepton universality measurements (see later).
- $> 3\sigma$ away from Standard Model. Is it new physics?

The villain



The villain

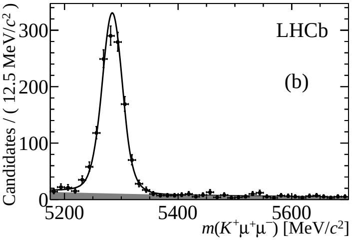


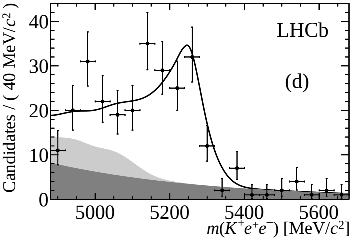
- This could mimic a new physics effect in C_9, and is not included in the uncertainties of the hadronic form-factors.
- One could measure effect of charm-loops by a precise analysis of the $\mu\mu$ invariant mass ($\longrightarrow$ backup).

LFU

All results with 3 fb^{-1} (Run I)

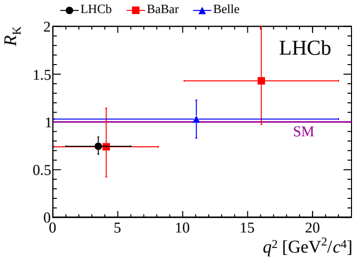
Lepton Flavour universality in loop decays

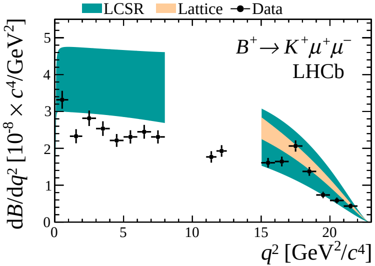




- Measure $R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$ in $q^2 \in [1,6]\ \mathrm{GeV}^2/c^4$
- Use $B^+ \to J/\psi\, K^+, J/\psi \to \ell\ell$ as normalization and control channel.
- Electrons are more challenging than muons, due to lower reconstruction efficiency and energy loss due to bremsstrahlung.
- Hadronic uncertainties cancel in the ratio.
- 2.6σ deviation from the SM, $\mathcal{B}(B^+ \to K^+e^+e^-)$ compatible with SM predictions.

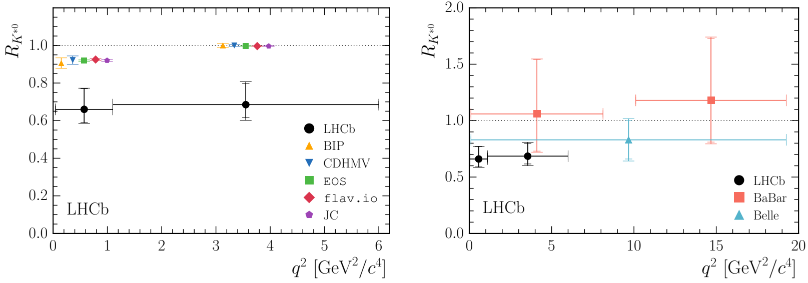
Lepton Flavour universality in loop decays





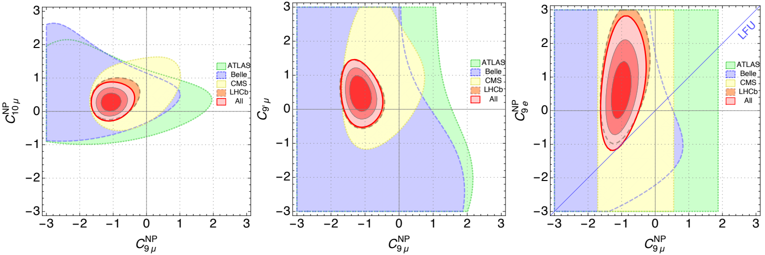
- 2.6σ from the standard model prediction in $1\,\mathrm{GeV}^2/c^4 < q^2 < 6\,\mathrm{GeV}^2/c^4$
- $\mathcal{B}(B^+ \to K^+e^+e^-)$ alone is measured to be compatible with the SM.
- Hm...

Lepton Flavour universality in loop decays



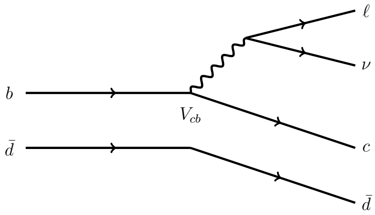
- Consider $R_{K^*} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}$
- Similar strategy as for R_K. Use $B^0 \to J/\psi\, K^*, J/\psi \to \ell\ell$ as normalization and control channel.
- Compatible at 2.2 and 2.4σ with SM prediction for low and intermediate q^2 region.

Global fits (part II)



- Can introduce a different Wilson coefficient C_9 for muons and electrons and redo global fits.
- Compatible with only deviations in the muon channels and not in the electron channels.

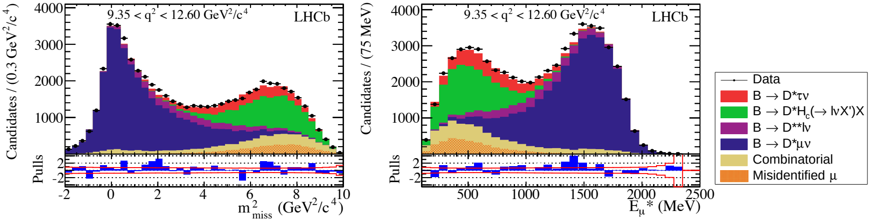
LFU in $\overline{B}^0 \to D^{*+}\ell\nu$



- Measure lepton flavour universality in charged-current (tree) decays.
- Measure $R_{D^*} = \frac{\mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\nu)}{\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\nu)}$

[PRL 115, 111803 (2015)]
[theo. prediction: Phys. Rev. D85 (2012) 094025]

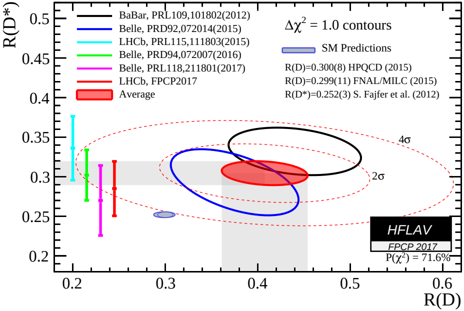
LFU in $\overline{B}^0 \to D^{*+}\ell\nu$, muonic mode

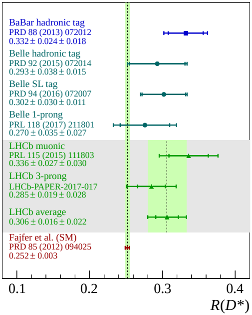


- Measure lepton flavour universality in charged-current (tree) decays.
- Measure $R_{D^*} = \frac{\mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\nu)}{\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\nu)}$
- Use $\tau^- \to \mu^-\nu\nu$, *i.e.* τ and μ modes have the same final state.
  - Distinguish with kinematical distributions
- $R_{D^*,\text{exp},\mu} = 0.336 \pm 0.027(\text{stat}) \pm 0.030(\text{syst})$
- $R_{D^*,\text{SM}} = 0.252 \pm 0.003$
- $\approx 2\sigma$ from the SM prediction.

[arxiv:1708.08856]

LFU in $\overline{B}^0 \to D^{*+}\ell\nu$, 3-prong mode

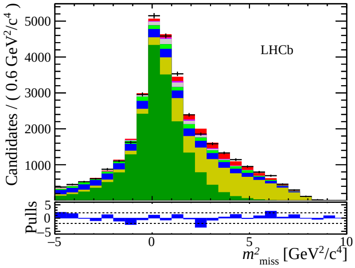


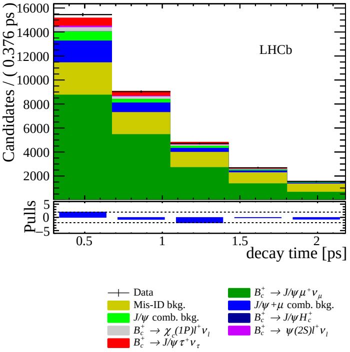


- Use $\tau^- \to \pi^-\pi^+\pi^-\nu$
- Use $\overline{B}^0 \to D^{*+}3\pi$ as normalisation channel, and known ratio $\mathcal{B}(\overline{B}^0 \to D^{*+}3\pi)/\mathcal{B}(\overline{B}^0 \to D^{*+}\mu\nu)$ to calculate R_{D^*}
- $R_{D^*,\text{exp},3\pi} = 0.286 \pm 0.019(\text{stat}) \pm 0.025(\text{sys}) \pm 0.021(\text{BR})$

[PRL 120, 121801 (2018)]
[theo. prediction: PRD73(2006)054024, PRD74(2006)074008]

LFU in $B_c^+ \to J/\psi\,\ell\nu$





- Measure $R_{J/\psi} = \dfrac{\mathcal{B}(B_c^+ \to J/\psi\,\tau^+\nu)}{\mathcal{B}(B_c^+ \to J/\psi\,\mu^+\nu)}$
- Including first measurement of $B_c^+ \to J/\psi\,\tau^+\nu\,(\tau^- \to \mu^-\nu\nu)$
- $R_{J/\psi,\text{theo}} = 0.25 - 0.28$
- $R_{J/\psi,\text{LHCb}} = 0.71 \pm 0.17(\text{stat}) \pm 0.18(\text{syst})$ (compatible within 2σ)
- Systematic uncertainties dominated by limited size of simulation and knowledge of $B_c^+ \to J/\psi$ form factors.

See *e.g.* [D. Straub, Model building overview]
See *e.g.* [Instant Workshop on B anomalies]

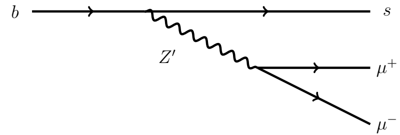
Models

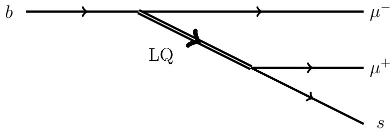
- There are a plethora of models that try to explain all anomalies simultaneously.
- Have to explain: Difference in branching fractions, angular distributions, lepton flavour on tree and loop level.
- Possible masses of BSM particles:

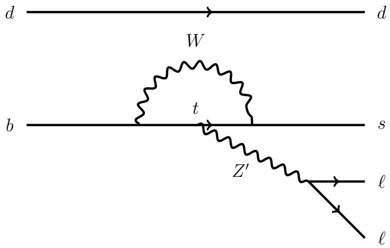
tree level, unsupressed $\sim 30\,\mathrm{TeV}$	loop level, unsupressed $\sim 2.5\,\mathrm{TeV}$
tree level, MFV $\sim 6\,\mathrm{TeV}$	loop level, MFV $\sim 0.5\,\mathrm{TeV}$

MFV = Minimal flavour violation, *i.e.* CKM structure holds BSM

Z' and Leptoquarks







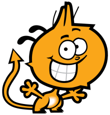
- Can introduce a Z' that causes a flavour-changing neutral current on tree level or loop level.
- Leptoquarks can simultaneously explain $R_{D^{*0}}$ (tree-level leptoquarks), R_K (loop-level leptoquarks) and muon $g-2$ (PRL116, 141802 (2016))

Optimist's point of view

- Many measurements show a deviation, and when combined, it is significant.
- The pattern is somewhat consistent, as shown by global fits.
- The effects are observed by several (independent) measurements and experiments.
- No large uncertainty in the theoretical prediction has been discovered.

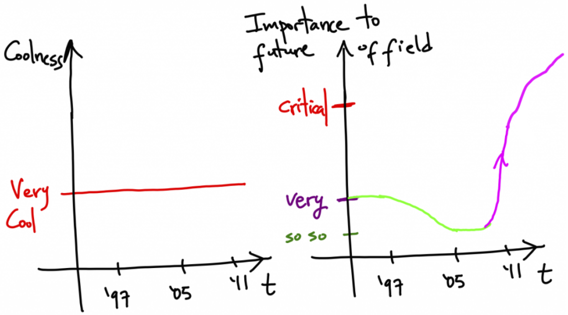
Pessimist's point of view

- ”The effect is of a magnitude that remains close to the limit of detectability, or many measurements are necessary because of the very low statistical significance of the results.”
  I. Langmuir on pathological science.



[Adapted from N. Arkani-Hamed]

Conclusion



- B decays are an exciting field of research.
- Several intriguing deviations from the SM have shown up in flavour-changing neutral and charged currents.
- The combination could hint to a deviation from the Standard Model.
- Nature of these anomalies will hopefully soon be resolved.

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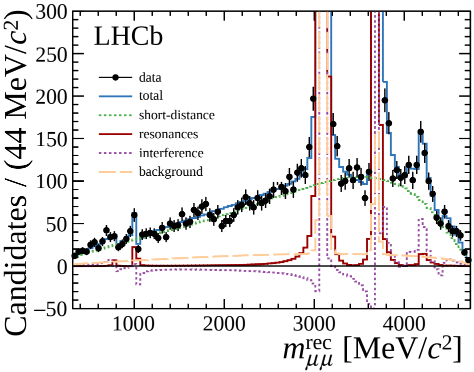
Backup

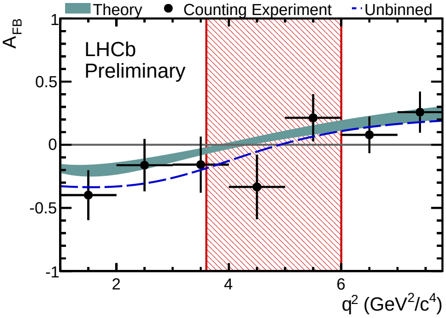
Short- and long-distance effects in $B \to K\mu^+\mu^-$



- Need to perform same analysis for $B^0 \to K^{*0}\mu^+\mu^-$ to understand effect of charm-loops.

[JHEP 02 (2016) 104]

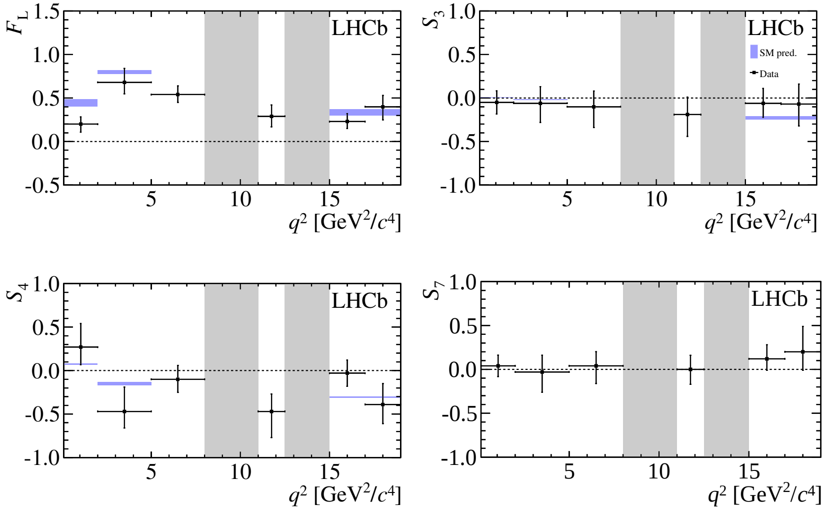
Zero-crossing point in $B^0 \to K^{*0}\mu^+\mu^-$



- Zero-crossing point of A_{FB} theoretically clean.
- For example: $S_6 = \frac{4}{3}A_{FB} = \frac{4}{3}\frac{\#\cos\theta_\ell>0-\#\cos\theta_\ell<0}{\#\cos\theta_\ell>0+\#\cos\theta_\ell<0}$:
  Forward-backward asymmetry of the leptons.

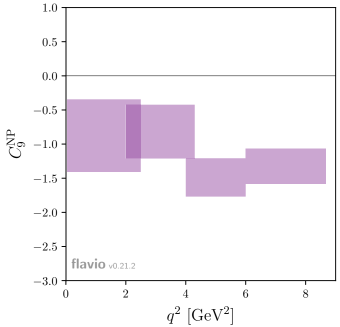
[JHEP09(2015)179]

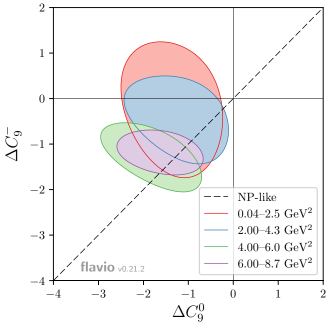
Angular analysis of $B_s^0 \to \phi\mu^+\mu^-$



[Eur. Phys. J. C (2017) 77:377]

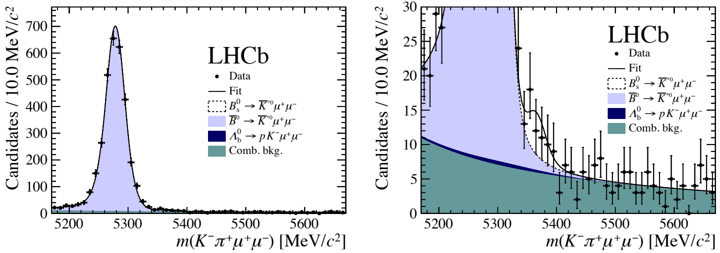
q^2 dependence of C_9





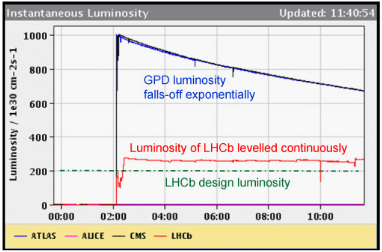
- Check shift of C_9 as a function of q^2. Should be constant (assuming the new physics is heavy enough).
- That's a hint, but not a confirmation for non-hadronic BSM effects.

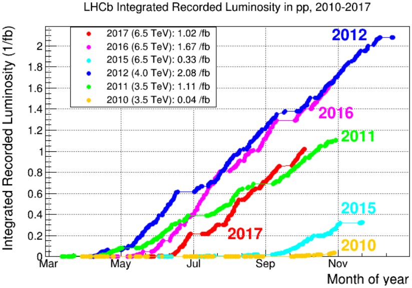
Analyses of $b \to d\ell\ell$ transitions



- First evidence of $B_s^0 \to K^*\mu^+\mu^-$ (3.4σ)
- Using 3 fb^{-1} of Run I and 1.6 fb^{-1} of Run II.
- $\mathcal{B}(B_s^0 \to K^*\mu^+\mu^-) = (3.0 \pm 1.0(\text{stat}) \pm 0.2(\text{syst}) \pm 0.3(\text{ext})) \cdot 10^{-8}$
- With the upgrade of LHCb from 2021, differential decay rates can be measured.

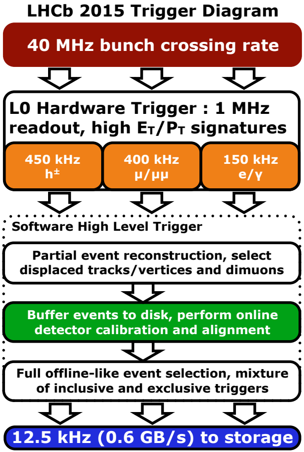
Luminosity levelling





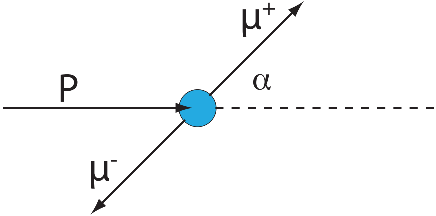
- LHCb does not run at the maximum instantaneous luminosity, as the occupancy in the forward region would be too high.
  - $\mu \approx 1.1$ for 25ns running.
- Luminosity for LHCb is leveled such that it is constant within a fill.
- Achieved by displacing the beams.

Trigger (Run II)



- Have the same reconstruction (charged and neutral particles) in the software trigger and offline.
- Perform a alignment & calibration after first stage of software trigger, *i.e.* automatically.

A toy angular analysis

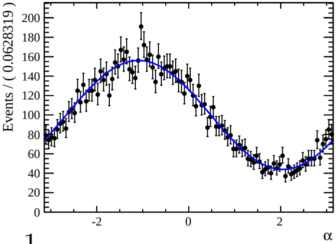


- A particle decays into two particles, with angle α.
- Suppose we can formulate the angular distribution as:

$$\frac{d\Gamma}{d\alpha} = \frac{1}{2\pi}\left[A\cos\alpha + B\sin\alpha + C\right] \quad \alpha \in [-\pi, \pi]$$

- The angular terms are given by kinematics / spin only.
- Remember: $\frac{d\sigma}{d\Omega}(e^+e^- \to \mu^+\mu^-) = \frac{\alpha^2}{4s}\left(1+\cos^2\theta\right)$

A toy angular analysis



$$\frac{d\Gamma}{d\alpha} = \frac{1}{2\pi}\left[A\cos\alpha + B\sin\alpha + C\right] \quad \alpha \in [-\pi, \pi]$$

- The coefficients contain the physics-information we are interested in.
- Do: Run an experiment, collect data, select your decay, plot number of events as a function of α.
- Fit the angular distribution in collision data with the pdf and extract the coefficients.