Investigating the Flavour Anomalies

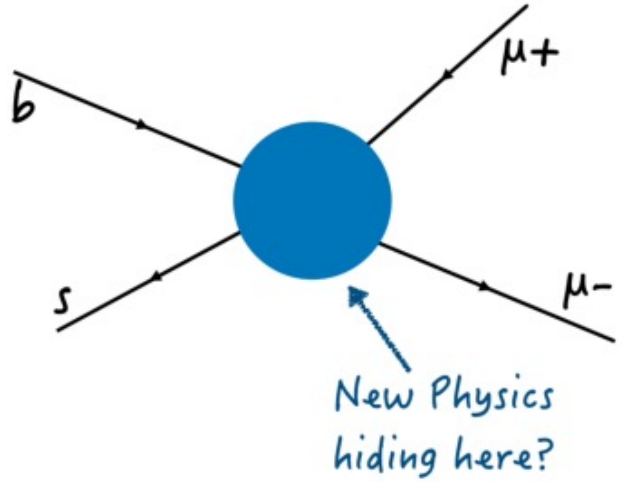
Manuel Abreu, Sónia D'Azevedo

Supervisors: Alessio Boletti, Nuno Leonardo

LABORATÓRIO DE INSTRUMENTAÇÃO E FÍSICA EXPERIMENTAL DE PARTÍCULAS

Flavour Anomalies

- The Standard Model (SM) has been very successful, but there are shortcomings: gravity, neutrino oscillations, matter-antimatter asymmetry, …
- Search for New Physics: directly or **indirectly**
- **Lepton flavour universality** (LFU) – In the SM, leptons have identical couplings from one generation to the next (electron, muon, tau)
- Beyond-SM scenarios may result in violations in the LFU principle
- In this work we are interested in b → sll decays, namely $B \to K\mu^+\mu^-$
- In the SM, the LFU observable $R = \frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to Ke^+e^-)} \approx 1$
- $\mathcal{B}(B \to K\mu^+\mu^-)$ is the Branching Fraction of $B \to K\mu^+\mu^-$ decay

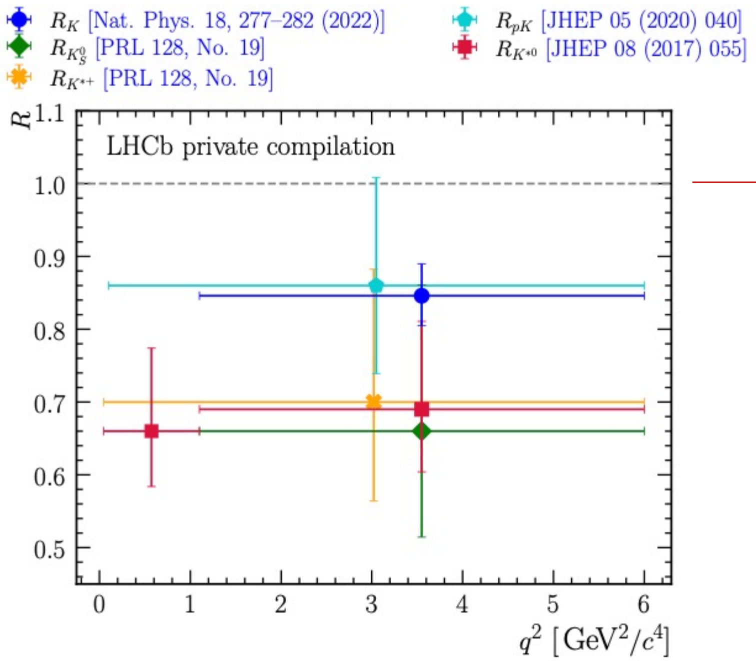


Flavour Anomalies

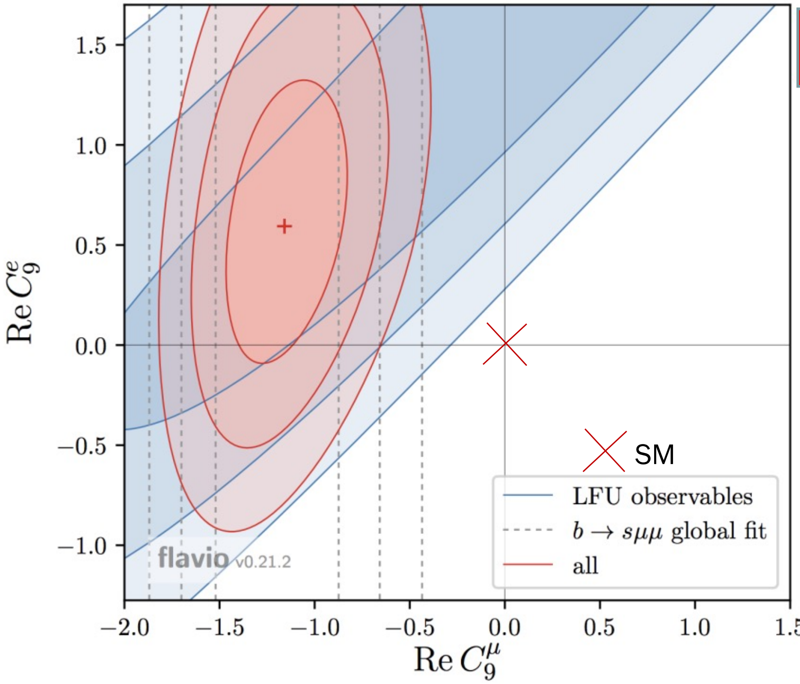
- Individual measurements of R are inconsistent with SM by a few σ

- When combined with angular analysis of $b \to sll$ decays, the significance in the deviation increases above 5σ

- Possible NP explanations: new bosons, lepto-quarks



SM



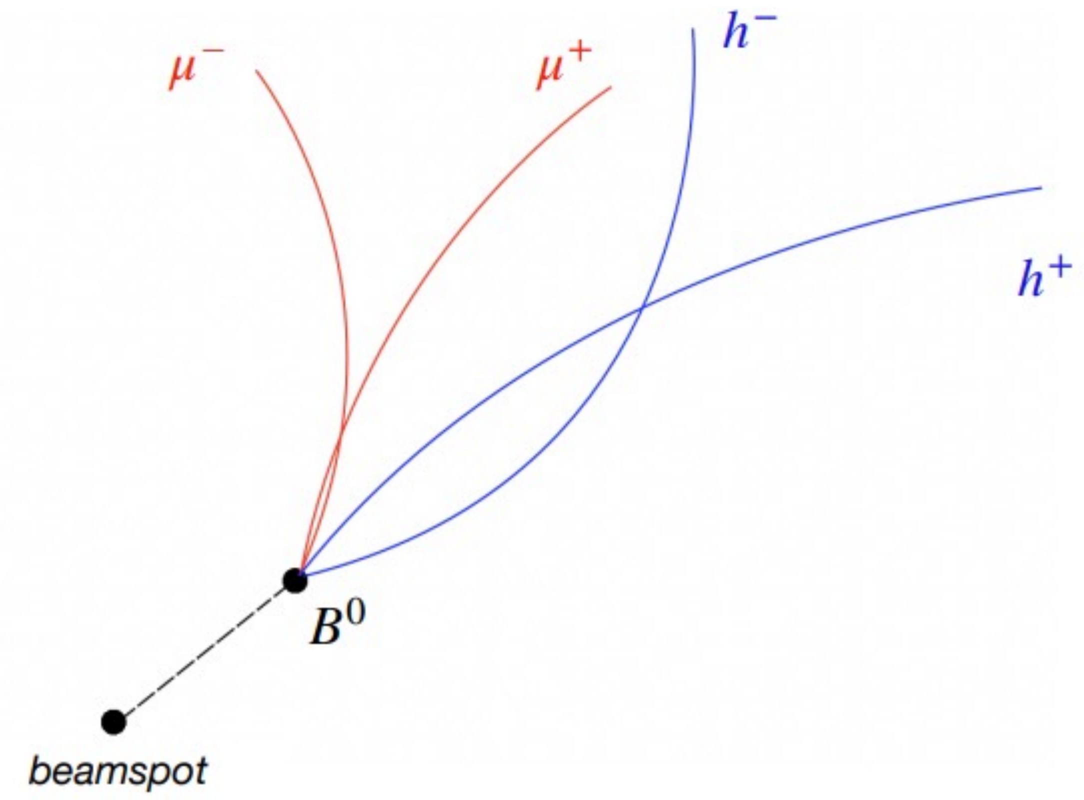
> 5σ

The Project

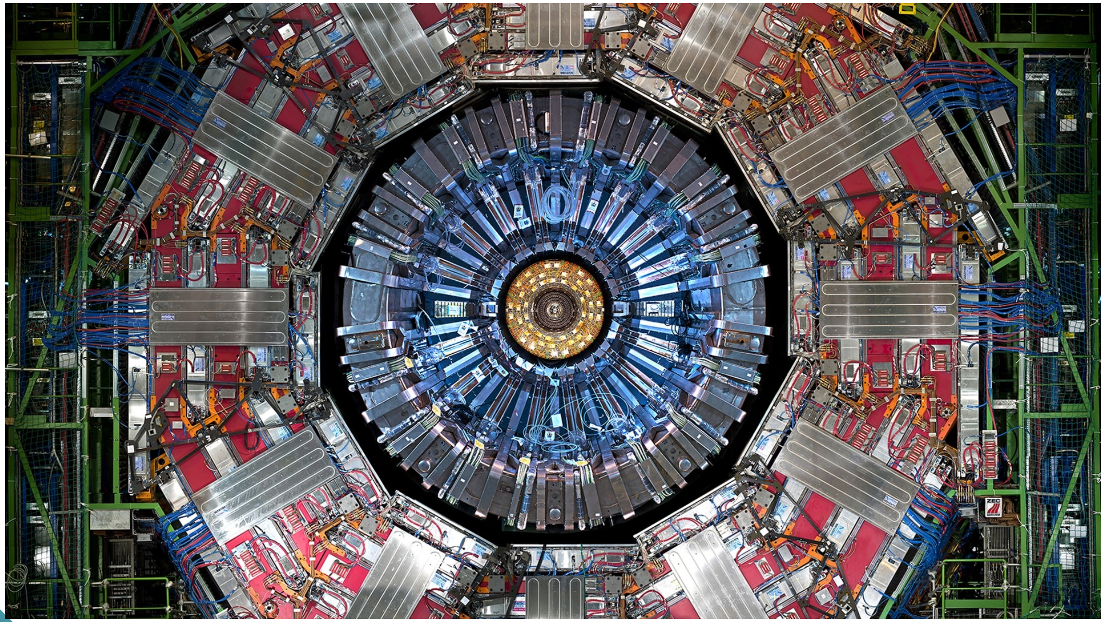
- Decay we're studying: $B^0 \rightarrow K^{*0}\mu^+\mu^- \rightarrow K^+\pi^-\mu^+\mu^-$
- Measure the differential branching fraction

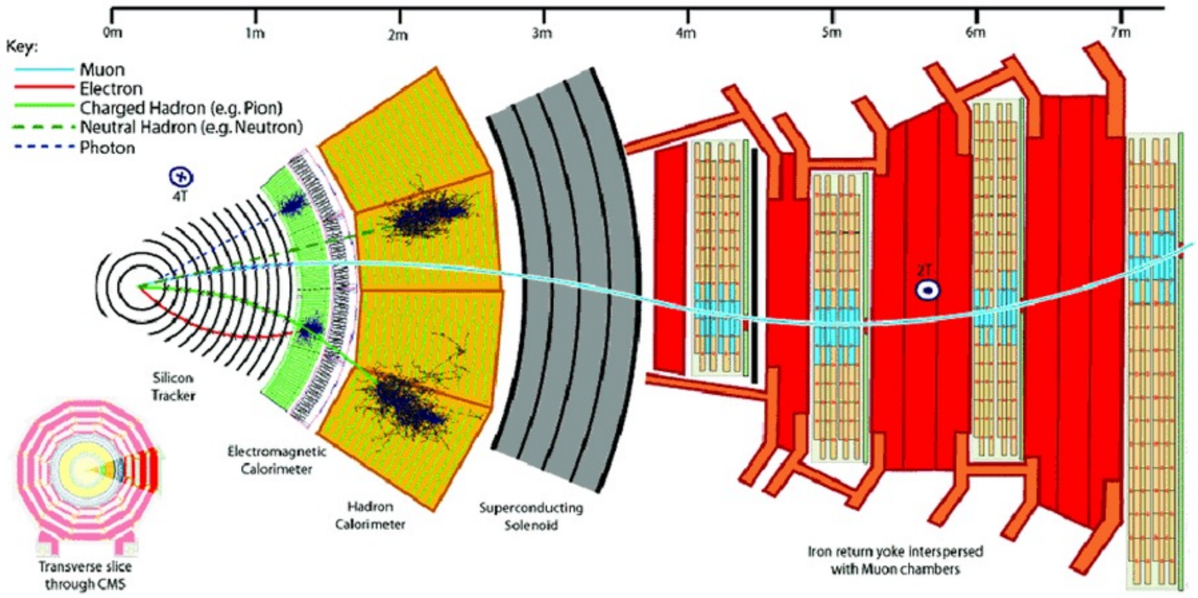
$$\frac{d\mathcal{B}(B^0 \rightarrow K^{*0}\mu^+\mu^-)}{dq^2} = \frac{Y_S}{Y_N}\frac{\epsilon_N}{\epsilon_S}\frac{\mathcal{B}(B^0 \rightarrow K^{*0}J/\psi)}{\Delta q_i^2}$$

- Y_S (signal Yield) and Y_N (normalization Yield) are both obtained from fits to the B^0 mass spectrum
- ϵ_S(signal efficiency) and ϵ_N(normalization efficiency) are both obtained from Monte Carlo simulations
- Normalization channel is known:
  - $\boldsymbol{\mathcal{B}}\,(B^0 \rightarrow K^{*0}\,J/\psi) = (7.5 \pm 0.3)\times 10^{-5}$



CMS (Compact Muon Solenoid)



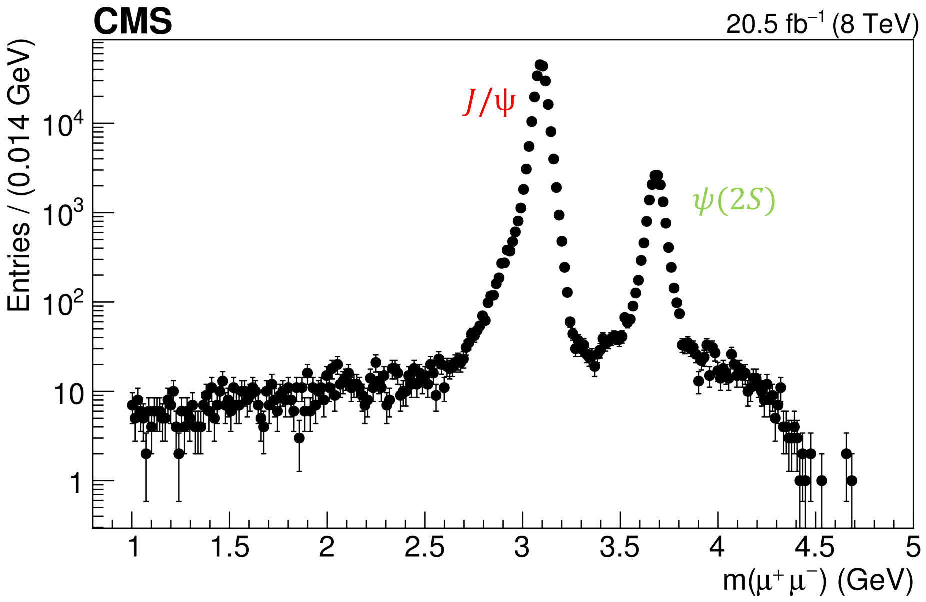


- Particle detector at LHC. It’s for multiple search purposes, that may include a lot of physics projects
- It’s composed by many different systems, being able to detect many different particles
- We are interested in muons and hadronic tracks
- Data from 2016 - 2018, collected by CMS experiment with a total integrated luminosity of $139.5\ fb^{-1}$, $\sqrt{s} = 13\ TeV$

The q^2 dependences

- Data divided in bins of the di-muon invariant mass squared (q^2)
- Different NP scenarios can affect different q^2 regions

- $B^0 \to J/\psi\, K^{*0}$ is used as the normalization channel
- $B^0 \to \psi(2S)\, K^{*0}$ is used as the control channel



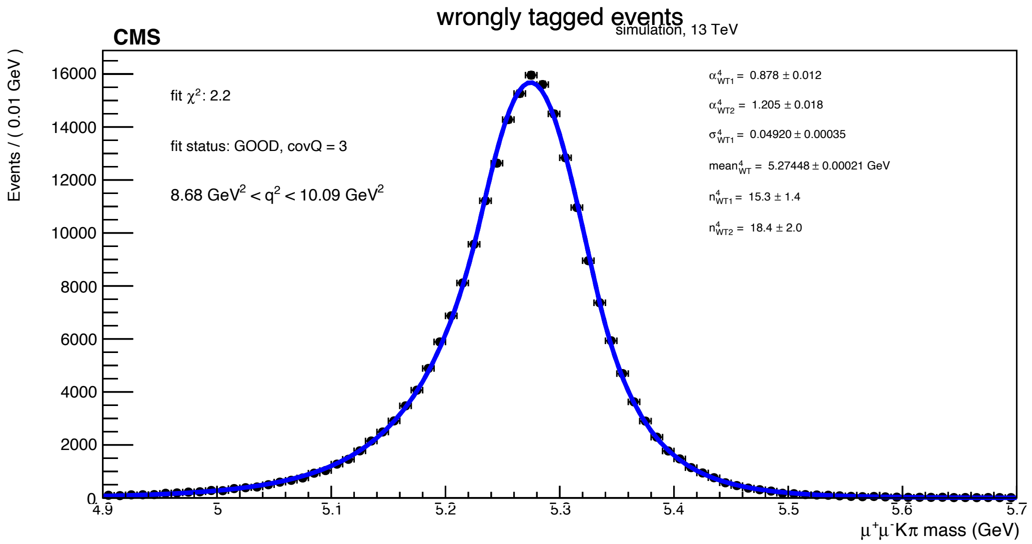
Bin index	q^2 range [GeV^2]
0	1-2
1	2-4.3
2	4.3-6
3	6-8.68
4 J/ψ	8.68-10.09
5	10.09-12.86
6 $\psi(2S)$	12.86-14.18
7	14.18-16

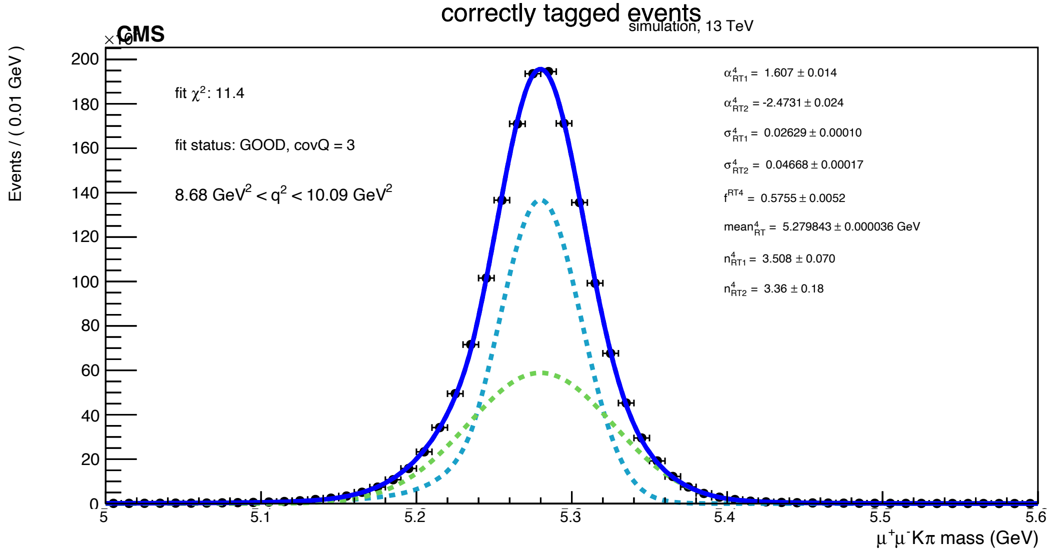
Flavour assignment

- $B^0 \rightarrow K^{*0}\mu^+\mu^- \rightarrow K^+\pi^-\mu^+\mu^-$
- Both $B^0 \rightarrow K^+\pi^-\mu^+\mu^-$ and $\bar{B}^0 \rightarrow K^-\pi^+\mu^+\mu^-$ decays occur
- Compute K^{*0} mass with $K^+\pi^-$ and with $K^-\pi^+$

- **Event tagging**: the combination closest to K^{*0} mass will be associated to the event

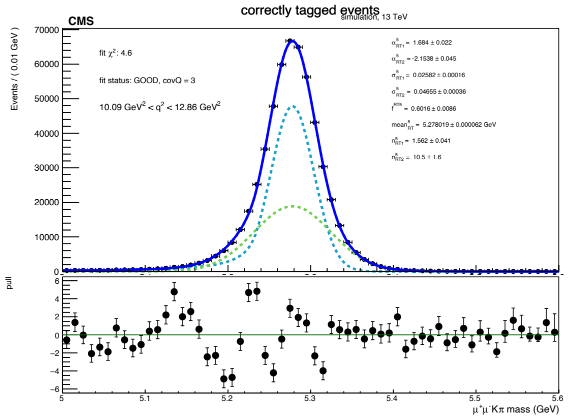
- A fraction of events can be wrongly tagged
- In Monte Carlo (MC) simulations we studied correctly tagged (RT) and wrongly tagged (WT) events separately



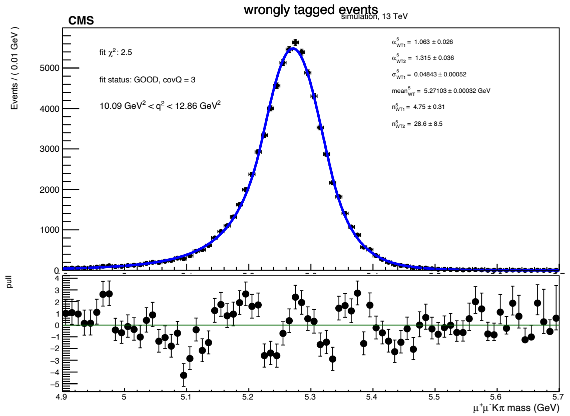


Fitting the mass distribution

- The signal yields are extracted performing a maximum likelihood fit
- Fits steps:
  - **Fit RT in MC**
  - **Fit WT in MC**
  - Fit the data, using signal MC-derived shapes
- Correctly tagged fit model:
  - q^2 bins 0-3: Double crystal ball
  - q^2 bins 4-6: Sum of two crystal ball functions
  - q^2 bin 7: Sum of one crystal ball with one gaussian



- Wrongly tagged fit model:
  - A double crystal ball function



- Wrongly tagged component has wider shape

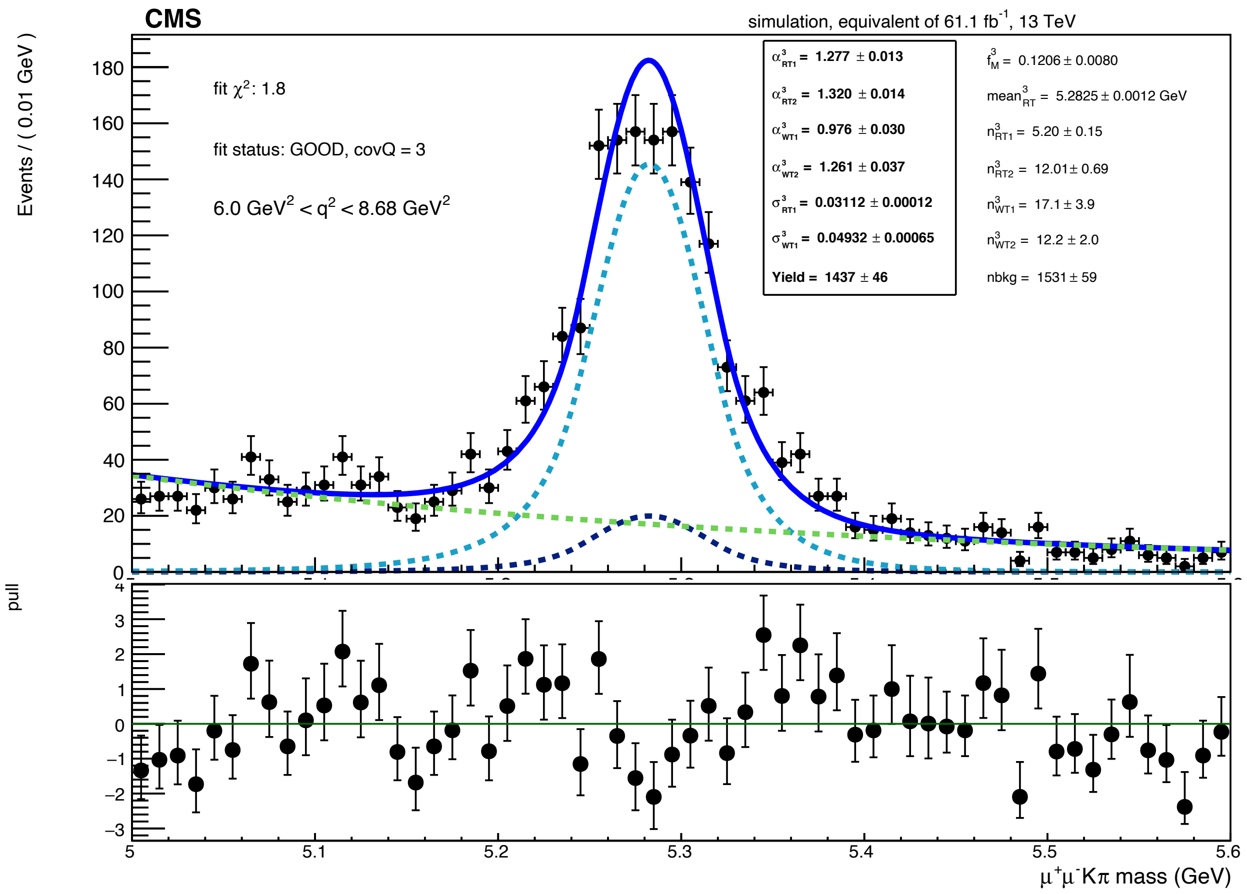
Yield =

Fitting the Data

- Finally, we fit the B^0 candidate invariant-mass distribution in data

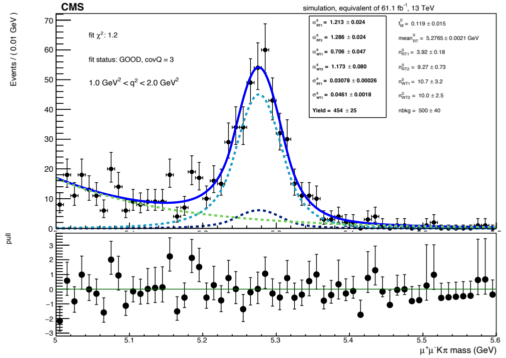
- The function used in the fit has three componentes:
  - Correctly tagged (from the RT Monte Carlo fits)
  - Wronlgy tagged (from the WT Monte Carlo fits)
  - Background function (exponential)

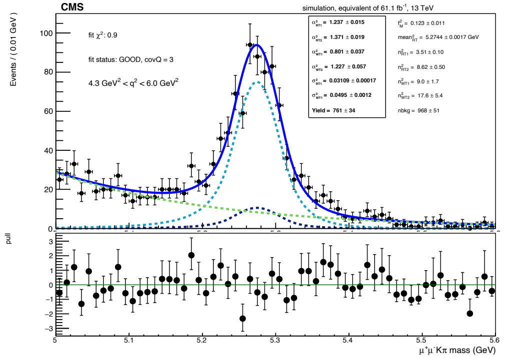
Yields are extrated from the fit

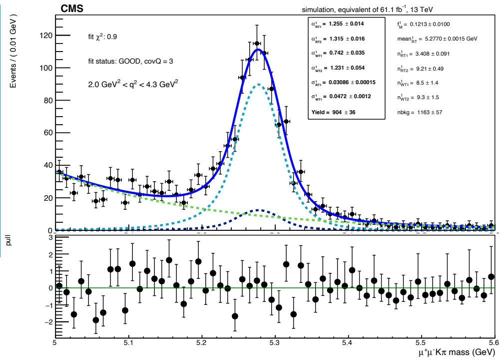


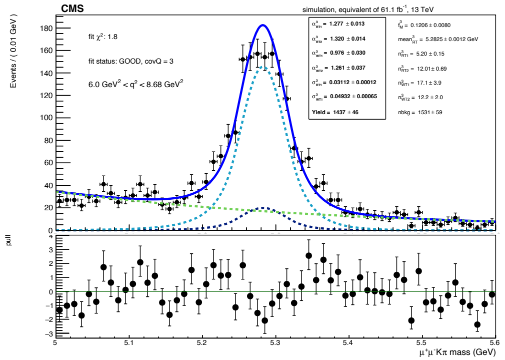
Fitting the data in each q2 bin

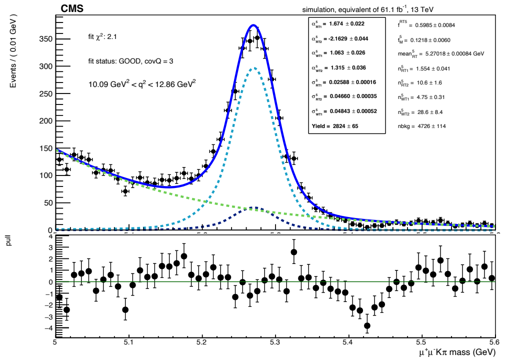
Signal



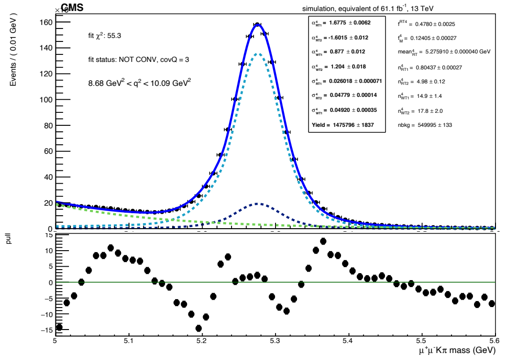




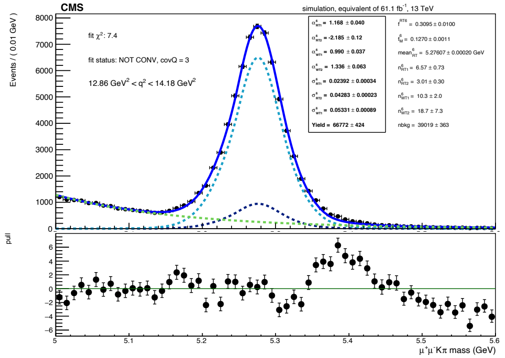




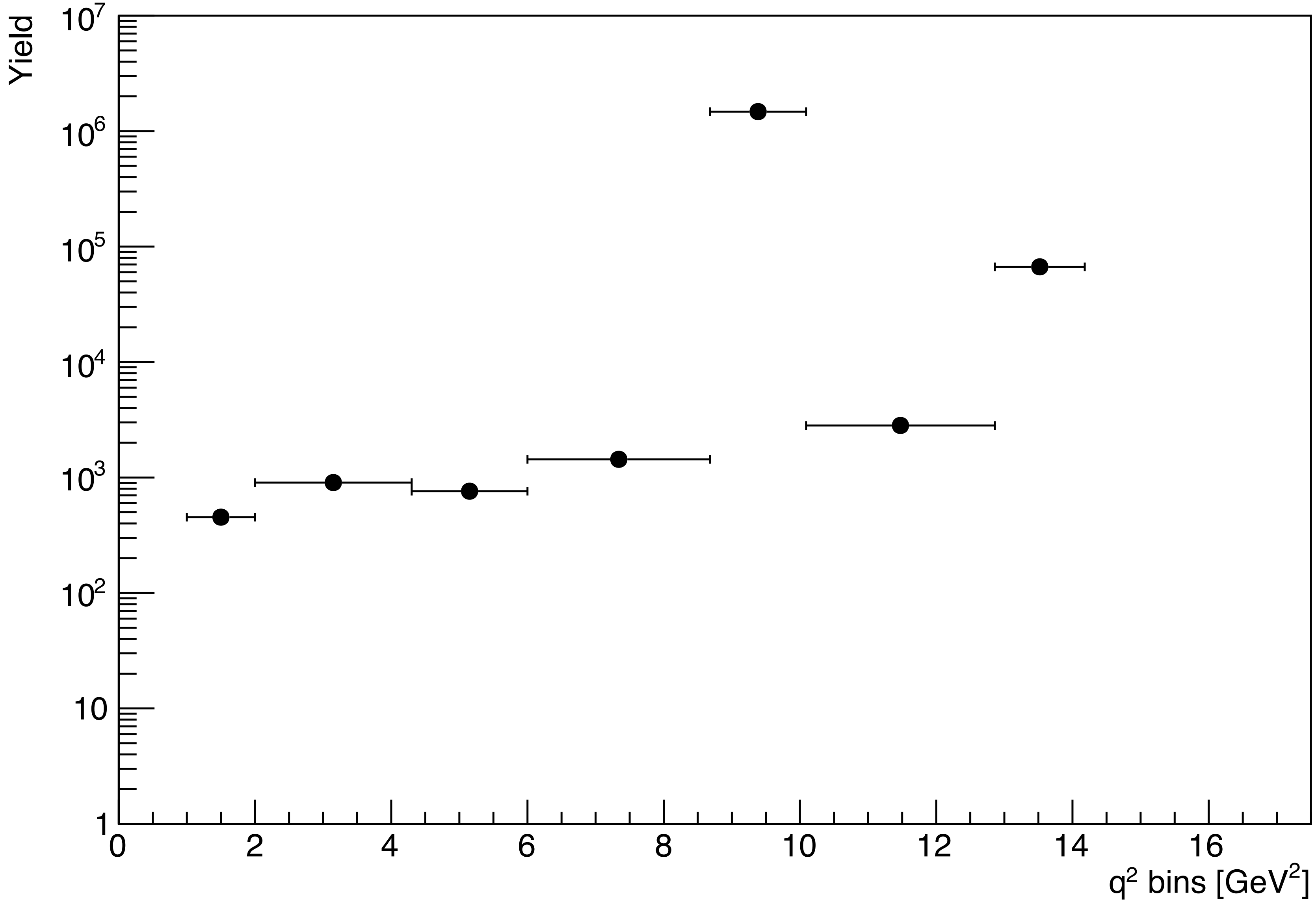
J/ψ



$\psi(2S)$

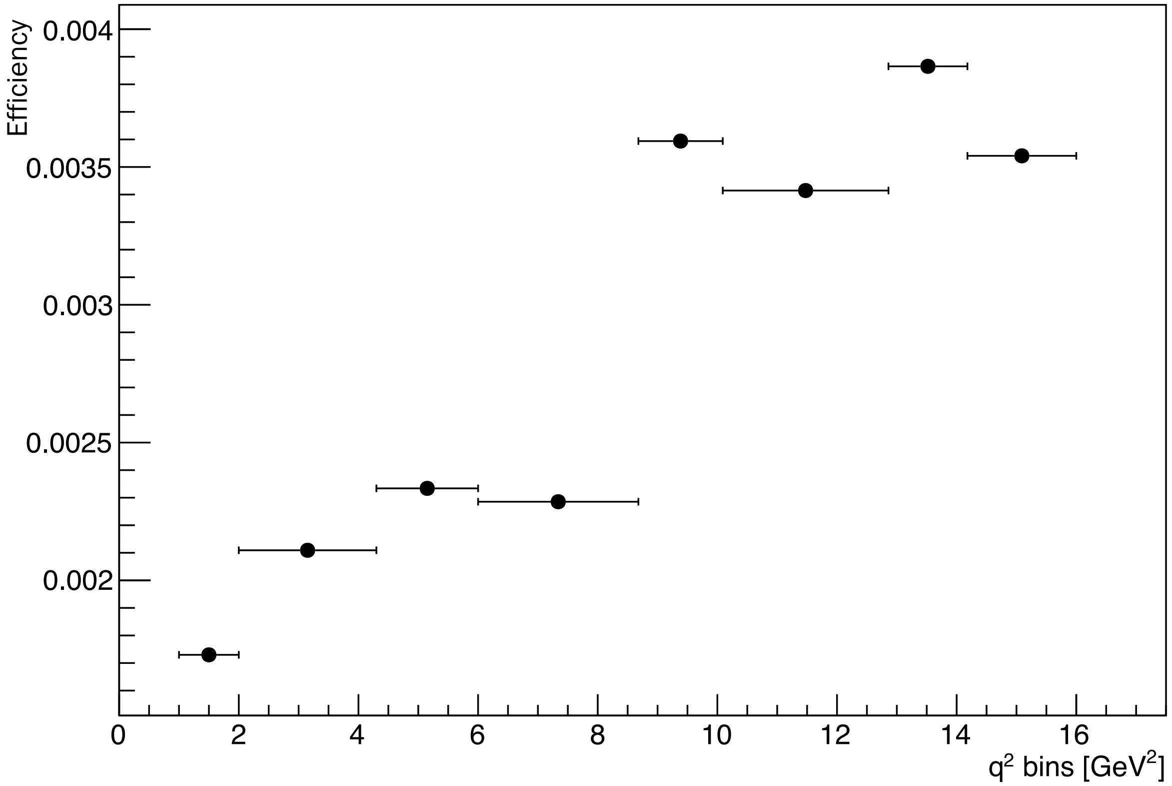


Yields



Efficiencies

- Efficiencies are determined from MC samples
- Fraction of events that pass the detector acceptance and analysis selection
- Efficiencies are determined for each q2 bin



Differential Branching Fraction

- Differential Branching Fraction for each q^2 region is finally computed puting together all ingredients
- Uncertanties:
    - Statistical from fit to data
    - Systematics from efficiencies, BF of the normalization channel

$$\frac{d\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{dq^2} = \frac{Y_S}{Y_N}\frac{\epsilon_N}{\epsilon_S}\frac{\mathcal{B}(B^0 \to K^{*0}J/\psi)}{\Delta q_i^2}$$

Signal Yield (Y_S)

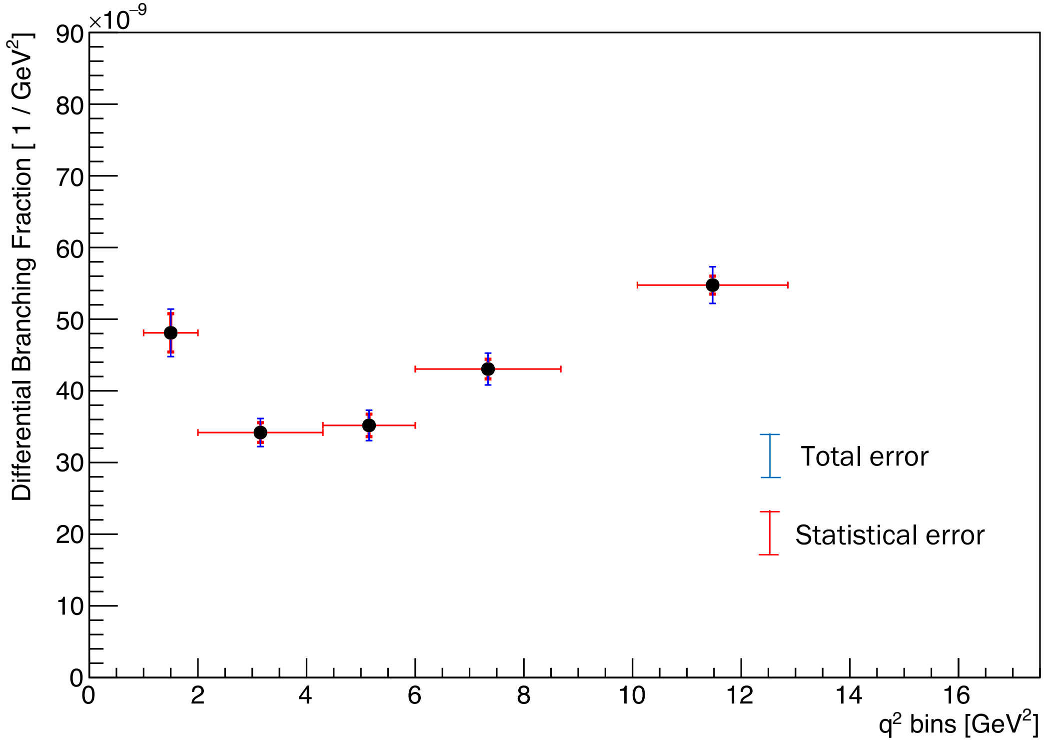
Normalized efficiency (ϵ_N)

Normalized Yield (Y_N)

Signal efficiency (ϵ_S)

Width of the q^2 bins (Δq_i^2)

BF of normalization channel ($\mathcal{B}(B^0 \to K^{*0}J/\psi)$)



Summary

- Flavour Anomalies are very strong candidate to search for New Physics

- We study the $B^0 \to K^{*0}\mu^+\mu^-$ decay:
  - Extract the yields from fits to the B^0 mass spectrum in data
  - Get the efficiencies from the Monte Carlo simulations

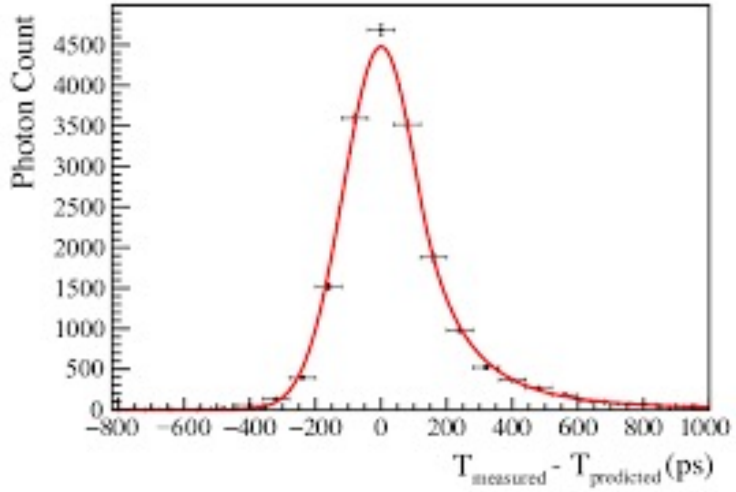
- We calculate the Differential Branching Fraction

- We now have $\boldsymbol{\mathcal{B}}\ (B\ \to K\mu^+\mu^-)$. This result is:
  - Sensitive to BSM and na input for the Flavour Anomalies global fits
  - The numerator of the LFU R ratio

Crystal Ball

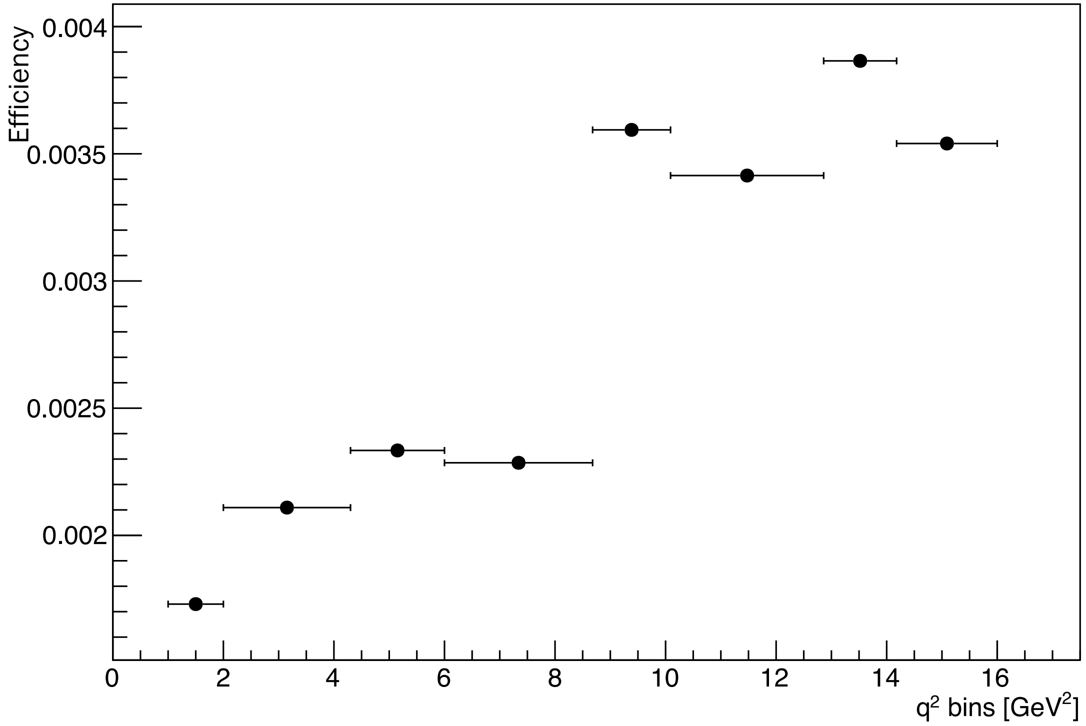
Simple Crystal Ball Function:

$$f(x;\alpha,n,\bar{x},\sigma) = N \cdot \begin{cases} \exp(-\frac{(x-\bar{x})^2}{2\sigma^2}), & \text{for } \frac{x-\bar{x}}{\sigma} > -\alpha \\ A \cdot (B - \frac{x-\bar{x}}{\sigma})^{-n}, & \text{for } \frac{x-\bar{x}}{\sigma} \leqslant -\alpha \end{cases}$$

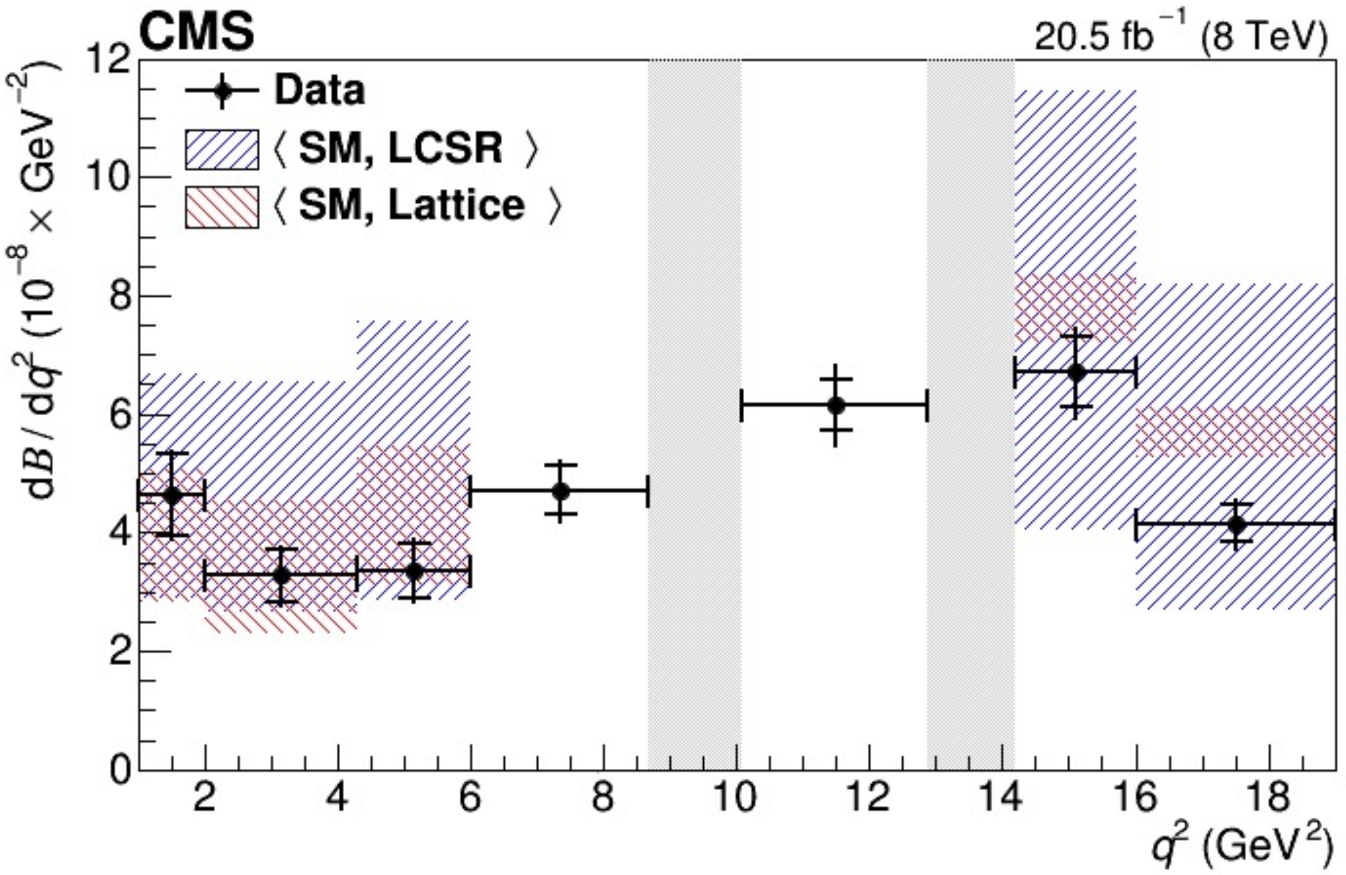


Why does efficiency change with the q^2bins?

- Higher q^2 increases the chances that all four particles are within the detector geometrical acceptance
- In the q^2 bins close to the resonances, we have to do some cleaning for the events that come from the resonant decays, and this reduce a little bit the signal efficiency.



Previous Results



Bibliography

- https://espace.cern.ch/CMS-LIP/INTERNSHIP/SUMMER2021/ANOMALIES/INTRO%20MATERIAL/BKMM_DIFF_BF_13TEV_ERD_MEETING.PDF
- https://espace.cern.ch/cms-lip/internship/summer2021/Presentations/anomalies_cms_20210806.pdf