Full angular analysis of the $B^0 \to K^{*0}\mu^+\mu^-$ decay in proton-proton collisions at CMS

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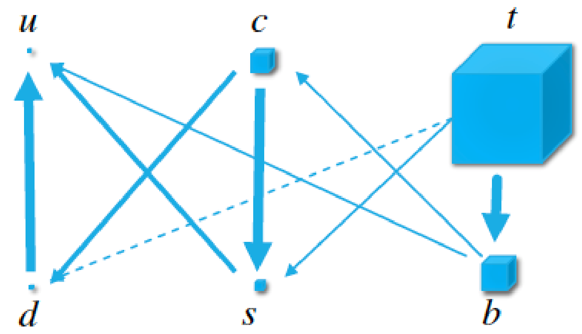
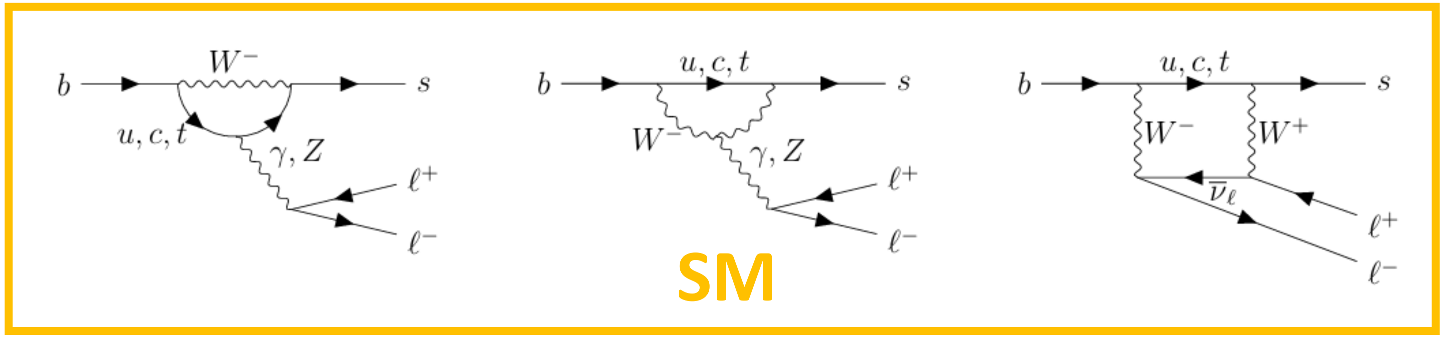
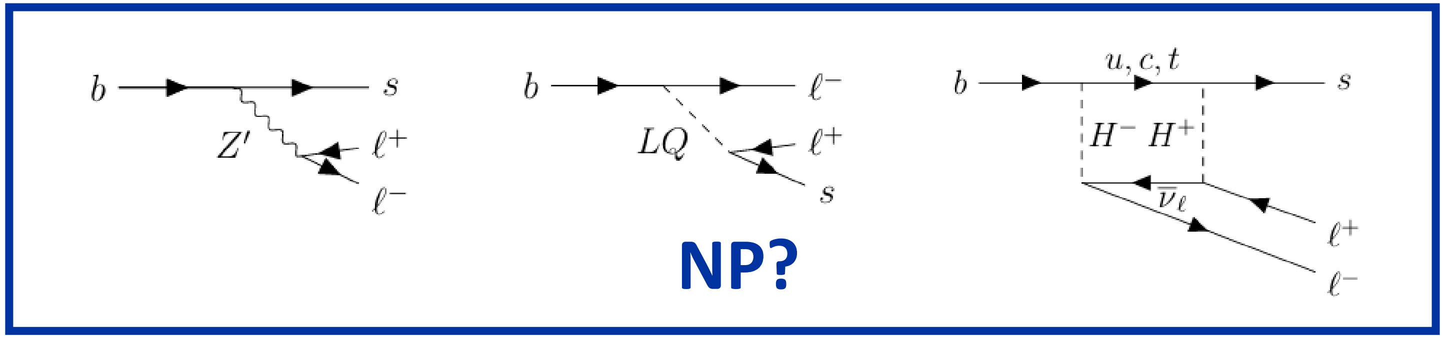
$b \to sll$ process

- $b \to sll$ is a Flavour-changing-neutral-current (FCNC) transition: transitions between quarks of the same electric charge
- SM: forbidden at tree level, need more complex diagrams to achieve
- Enhanced in many BSM theories: new particles can contribute at the loop or tree level
- NP can modify angular parameters, decay rates …

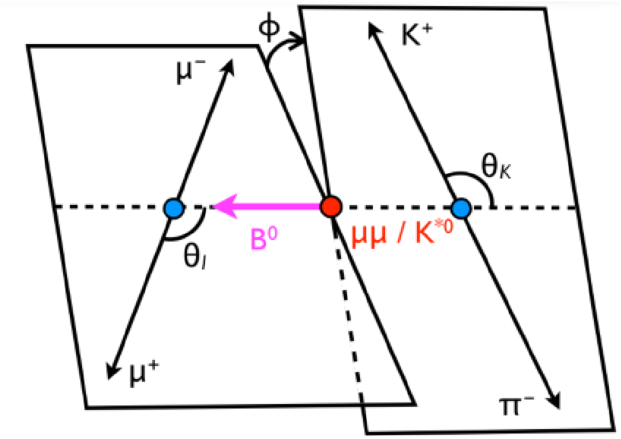






$B^0 \to K^{*0}\mu\mu$ process

- **Experimentally good channel:** Easy to identified muons; fully charged final states; Many B0 produced at LHC
- Can be fully described by **the three angles (θ_l, θ_k, ϕ)** and **the dimuon invariant mass squared q^2**
- **Angular analysis compared to measuring the branching fractions:** give access to large range of observables with reduced theory uncertainties



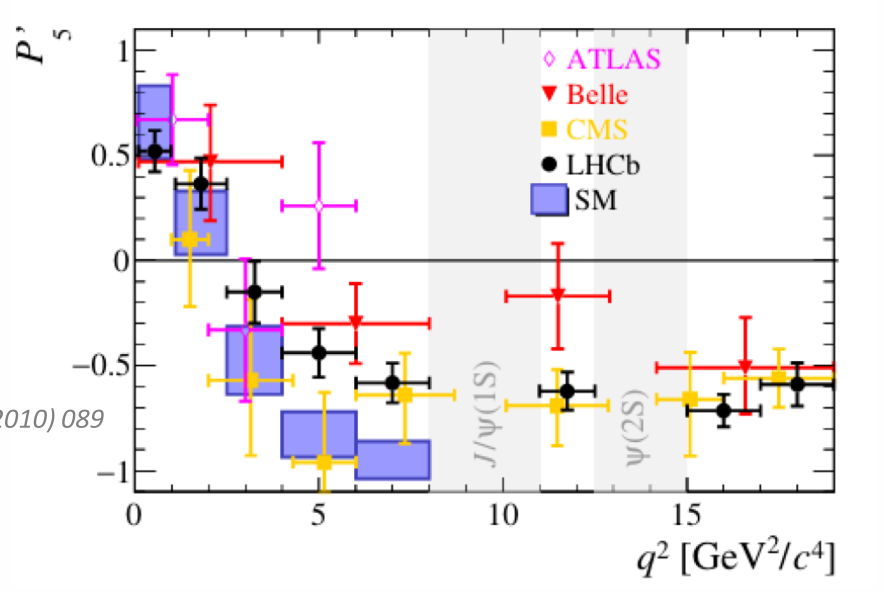
bin index	q^2 range [GeV ^{2}]
0	1.1 - 2
1	2 - 4.3
2	4.3 - 6
3	6 - 8.68
4	8.68 - 10.09 (J/ψ control region)
5	10.09 - 12.86
6	12.86 - 14.18 ($\psi(2S)$ control region)
7	14.18 - 16
8	16 - 19

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\theta_l\mathrm{d}\cos\theta_K\mathrm{d}\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}F_T\sin^2\theta_K + F_L\cos^2\theta_K + \big(\frac{1}{4}F_T\sin^2\theta_K - F_L\cos^2\theta_K\big)\cos 2\theta_l + \frac{1}{2}P_1F_T\sin^2\theta_K\sin^2\theta_l\cos 2\phi + \sqrt{F_TF_L}\big(\frac{1}{2}P'_4\sin 2\theta_K\sin 2\theta_l\cos\phi + P'_5\sin 2\theta_K\sin\theta_l\cos\phi\big) - \sqrt{F_TF_L}\big(P'_6\sin 2\theta_K\sin\theta_l\sin\phi - \frac{1}{2}P'_8\sin 2\theta_K\sin 2\theta_l\sin\phi\big) + 2P_2F_T\sin^2\theta_K\cos\theta_l - P_3F_T\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

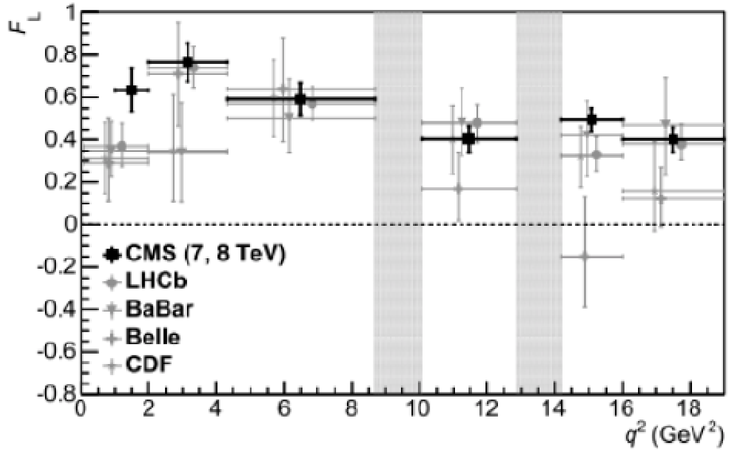
- $F_T = 1 - F_L$
- 8 angular parameters
- P'_i basis: form factor uncertainties cancel at first order

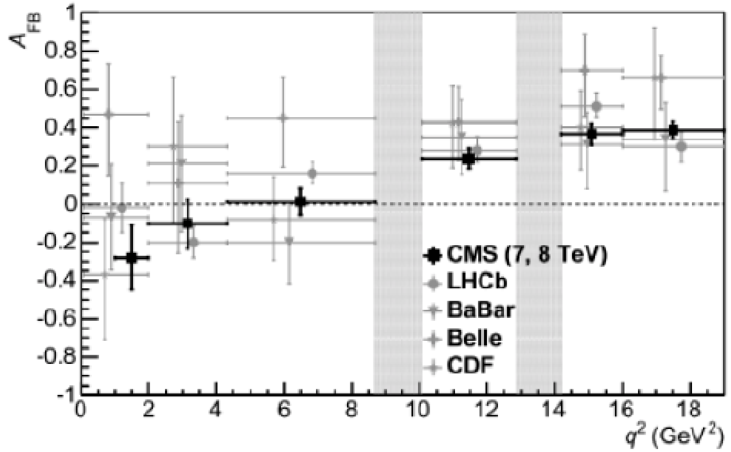
Previous analyses

- Long history of measurement at B-factories and hadron colliders
- No deviation from SM for F_L and A_{FB}
- **Long standing discrepancy in P_5' (since first measurement in 2013 at LHCb)**
- CMS Run-1 partial angular analyses results consistent with SM
- **CMS Run-2 collected 140 fb^{-1} of 13 TeV p-p data -> make it possible to perform a full angular analysis!**



CMS: PLB 781 (2018) 517541
LHCb: PRL 125 (2020) 011802
ATLAS: JHEP 10 (2018) 047
Belle: PRL 118 (2017)
SM: JHEP 12 (2014) 125, JHEP 09 (2010) 089





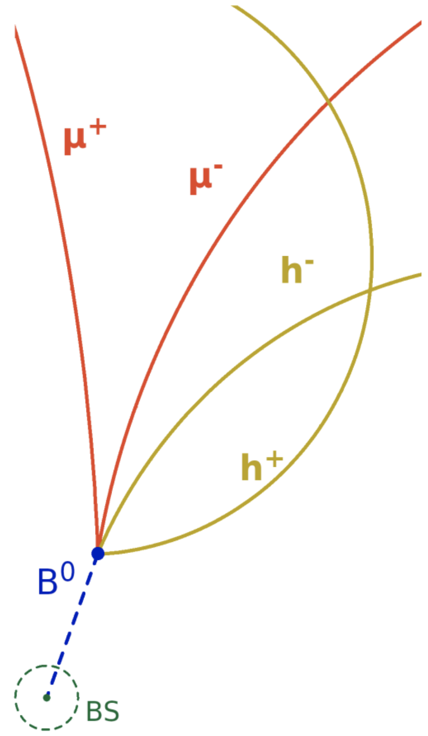
BaBar: PRD 86 (2012) 032012
Belle: PRL 88 (2001) 021801
PRL 103 (2009) 171801
CDF: PRD 79 (2009) 031102
PRL 108 (2012) 081807
CMS: PLB 727 (2013) 77
PLB 753 (2016) 424
LHCb: JHEP 08 (2013) 131

Reconstruction and Preselection

- **Trigger:** low mass displaced dimuon trigger: two muons and one track forming a displaced vertex

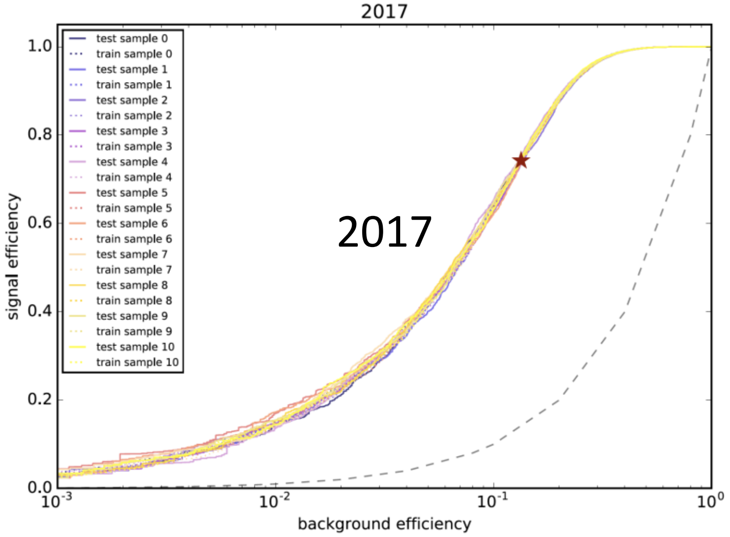
HLT path	Dimuon invariant mass window [GeV]
HLT_DoubleMu4_JpsiTrk_Displaced	2.9 - 3.3
HLT_DoubleMu4_PsiPrimeTrk_Displaced	3.3 - 4.05
HLT_DoubleMu4_LowMassNonResonantTrk_Displaced	1-2.9, 4.0 - 4.8

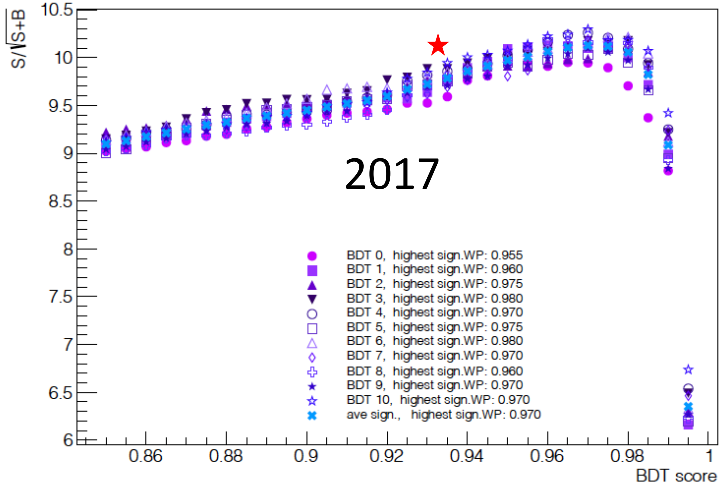
- **B^0 candidate reconstructed combining**
  - 2 opposite-sign muons with SoftMuonID
  - 2 opposite-sign tracks with muon veto
- **No PID to distinguish K from π → ID of kaon and pion assigned based on mass hypothesis closer to K^{*0} PDG mass (cause correctly-tagged and wrongly-tagged events in the signal)**
- **Offline selection:**
  - μ: single muon $p_T > 3.5$ GeV, $|\eta| < 2.5$, dimuon $p_T > 6.9$ GeV, $1 < m(\mu\mu) < 4.8$ GeV
  - Hadron Track: $p_T > 2.8$ GeV, $|\eta| < 2.4$, $|m(K\pi) - m(K^{*0}\ PDG)| < 150$ MeV, $m(KK) > 1.035$ GeV (ϕ rejection)



BDT selection

- **Training sample:**
  - ➢ Signal MC sample
  - ➢ Background from data mass sidebands
- **Input variables:** include decay-vertex quality and displacement, isolation, mass of $K\pi$ system
- **Samples are split into 11 subsamples**
  - ➢ 7 for training, 3 for testing, applied to the last
  - ➢ repeated 11 times, each of the 11 subsamples used once as the analysis data to avoid correlations
- **Working point optimization**
  - ➢ Measure $\mathbf{S/\sqrt{(S+B)}}$ **vs BDT score** in each subsample
  - ➢ Choose the working point that maximizes the average of $\mathrm{S}/\sqrt{(\mathrm{S}+\mathrm{B})}$ value





Analysis strategy

For each q^2 bin: **4D simultaneous fit** on three years' data samples

Angular decay rate — KDE efficiency functions

$$
\begin{aligned}
\mathrm{pdf}(m, \cos\theta_K, \cos\theta_l, \phi) = Y_S \Big[& S^C(m)\, S^a(\cos\theta_K, \cos\theta_l, \phi)\, \epsilon^C(\cos\theta_K, \cos\theta_l, \phi) \\
& + R \cdot S^M(m)\, S^a(-\cos\theta_K, -\cos\theta_l, -\phi)\, \epsilon^M(\cos\theta_K, \cos\theta_l, \phi) \Big] \\
& + Y_B B^m(m)\, B^a(\cos\theta_K, \cos\theta_l, \phi)
\end{aligned}
$$

Correctly-tagged(CT) events

Wrongly-tagged(WT) events

Background events

Signal and background mass shapes — Background angular shape

- **R parameter:** mistag correction value, the ratio between the mistag fraction in data and the one computed on MC, account for possible data/MC difference in mistag fraction
- **Y_S, Y_B**: yield of signal and background

KDE Efficiency functions

- **Evaluated from MC for CT and WT separately**

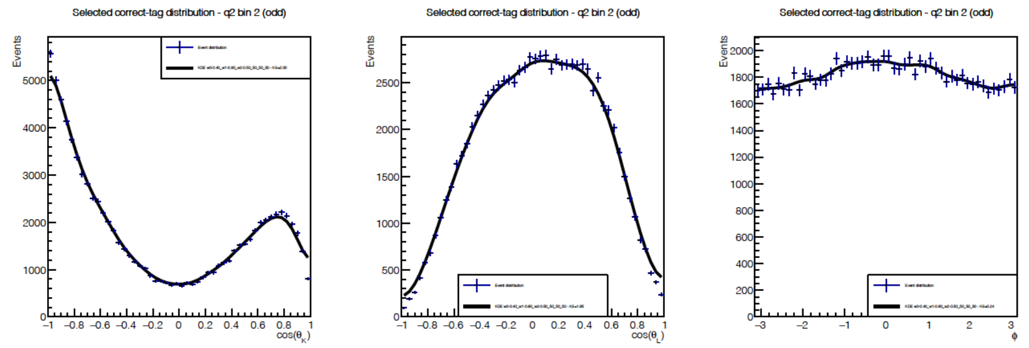
$$\epsilon^C(\cos\theta_K,\cos\theta_l,\phi) = \frac{N_{\rm acc}(\cos\theta_K,\cos\theta_l,\phi)_{\rm GEN}}{D_{\rm acc}(\cos\theta_K,\cos\theta_l,\phi)_{\rm GEN}} \cdot \frac{N^{\rm corr}_{\rm sel}(\cos\theta_K,\cos\theta_l,\phi)_{\rm RECO}}{D_{\rm sel}(\cos\theta_K,\cos\theta_l,\phi)_{\rm GEN}} \,.$$

$$\epsilon^M(\cos\theta_K,\cos\theta_l,\phi) = \frac{N_{\rm acc}(-\cos\theta_K,-\cos\theta_l,-\phi)_{\rm GEN}}{D_{\rm acc}(-\cos\theta_K,-\cos\theta_l,-\phi)_{\rm GEN}} \cdot \frac{N^{\rm mis}_{\rm sel}(\cos\theta_K,\cos\theta_l,\phi)_{\rm RECO}}{D_{\rm sel}(-\cos\theta_K,-\cos\theta_l,-\phi)_{\rm GEN}} \,.$$

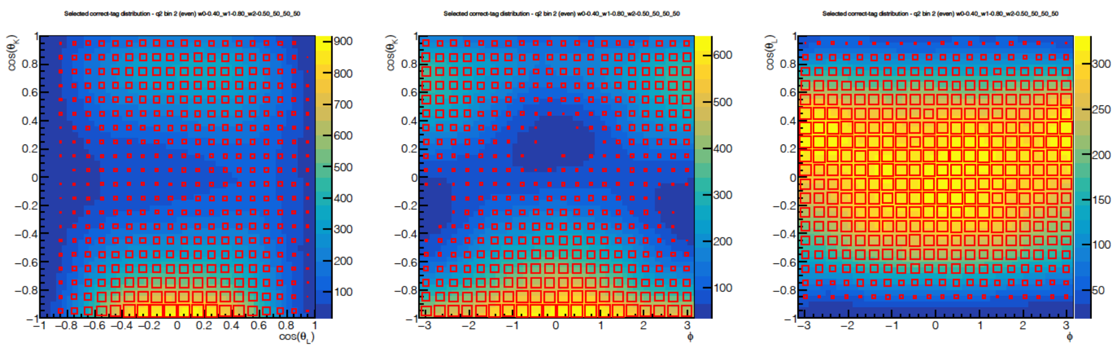
- **Using Kernel Density Estimators**
  - ➢ Method to describe distributions as sum of multi-variate Gaussians
  - ➢ Applied on numerators and denominators, then ratio is performed on the functions

q^2 bin 2 2016

1D and 2D projections of KDE function for correct tag numerator



$\cos\theta_K$ $\cos\theta_l$ ϕ

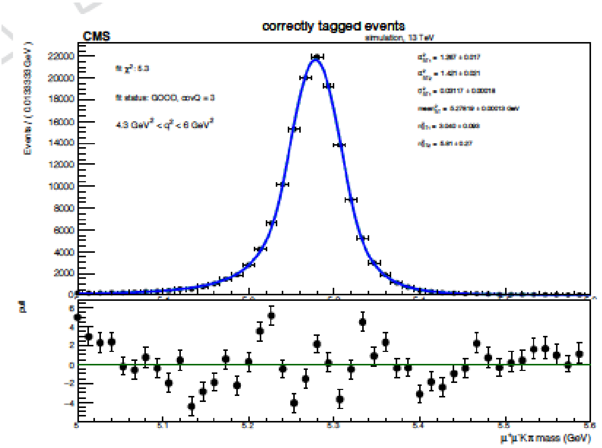


$\cos\theta_K$ vs $\cos\theta_l$ $\cos\theta_K$ vs ϕ $\cos\theta_l$ vs ϕ

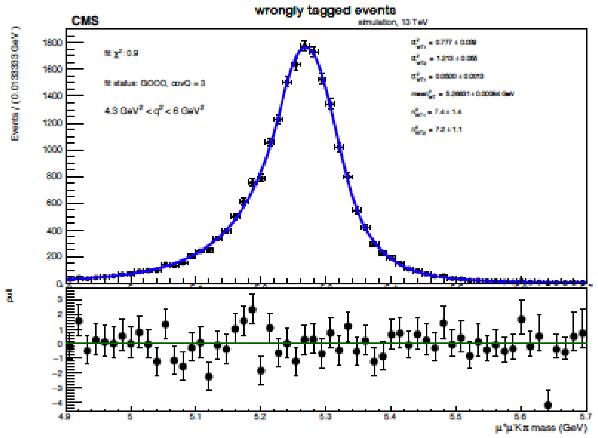
Mass shape

- **Mass model for each signal component (CT and WT) are modeled on MC**
  - parametrized by a **Double Crystal-ball** function or combination of **Gaussian and Crystal-ball functions** used (according to q^2bin)

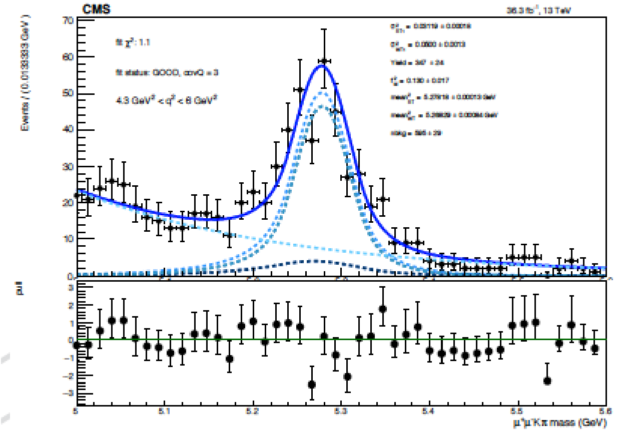
- **The data mass distribution is then fit with the model defined on the MC**
  - means, widths, mistag fraction have **gaussian constraints** to values fitted on signal MC
  - The background is parametrized using an **exponential function**



MC CT



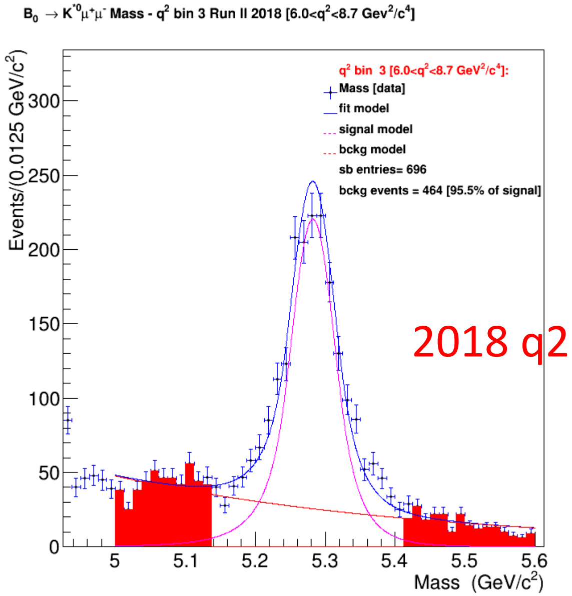
MC WT



Data

2016 q2Bin2 1D mass fit

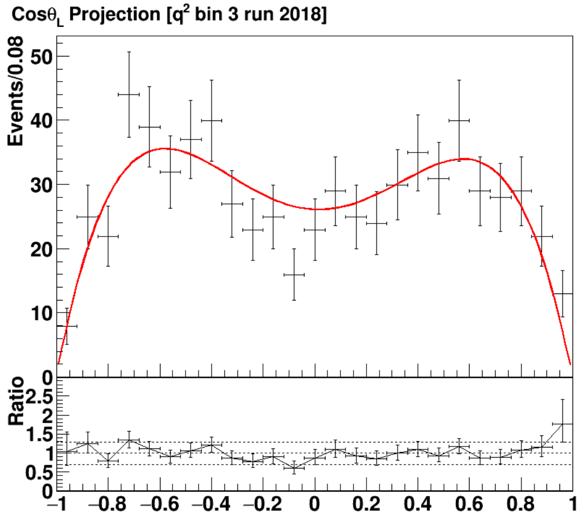
Background angular shape

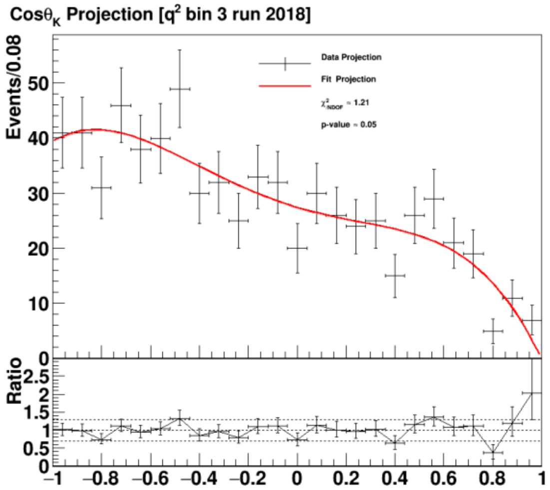


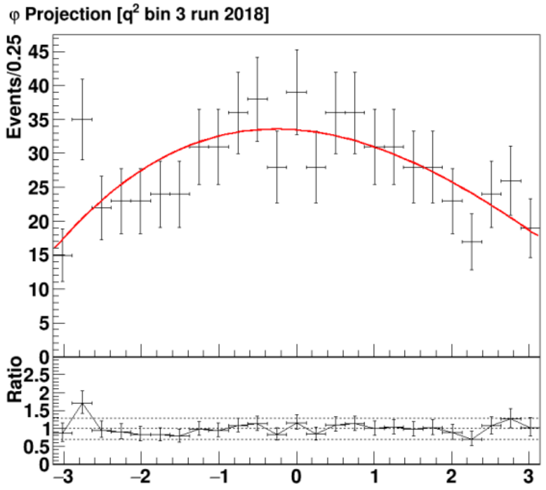
2018 q2Bin3

Bkg angular shape extracted from sidebands

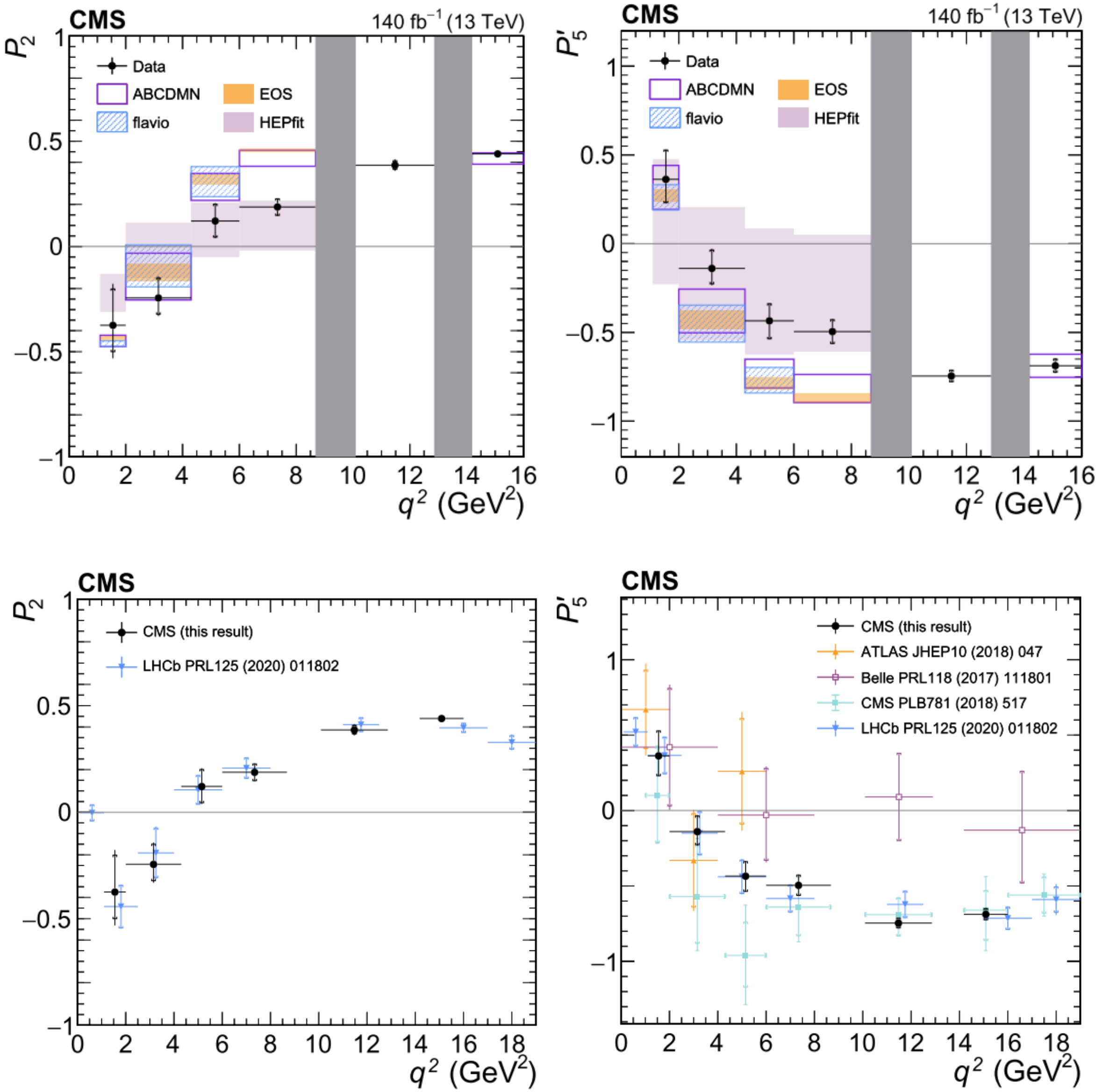
- Defined to have **<6% of signal pollution**
- Fit with **multivariate Bernstein polynomials**







Results



- **First full angular analysis of $B^0 \to K^{*0}\mu\mu$ at CMS, published on PLB (PLB 864 (2025) 139406)**
- **Among the most precise experimental measurements**
- **Deviation for P_5' with EOS predictions**

  $4.3 < q^2 < 6.0\ \mathrm{GeV/c^2}$: **3.2σ**

  $6.0 < q^2 < 8.0\ \mathrm{GeV/c^2}$: **4.9σ**
- **Deviation for P_2 with EOS predictions**

  $4.3 < q^2 < 6.0\ \mathrm{GeV/c^2}$: **2.2σ**

  $6.0 < q^2 < 8.0\ \mathrm{GeV/c^2}$: **6.4σ**
- **Measurements are compatible with previous results from CMS Run-1 and other experiments**