Rare B decays at CMS

Results on $B_s^0, B_d^0 \to \mu\mu$ decays and measurement of P_5' and P_1 parameters in $B_0 \to K^*\mu\mu$ decay

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on behalf of CMS collaboration

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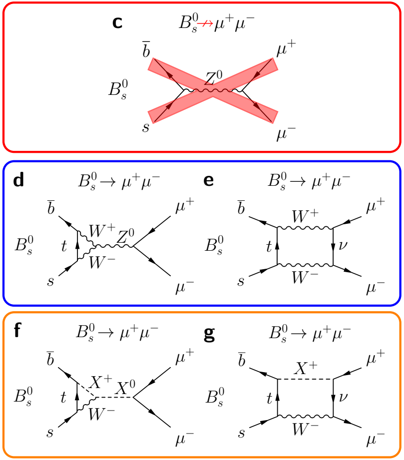
B^0 Rare Decays:

- FCNC are ideal playground for NP searches:
  - forbidden at tree level in SM, possible via penguin and box diagrams
  - NP can change rates or angular distribution
- $B^0 \to \mu\mu$ decay
- $B^0 \to K^*\mu\mu$ decay
- Accessible to CMS

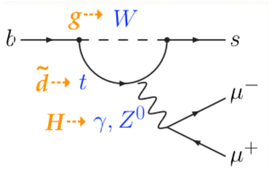
B^0 Rare Decays:

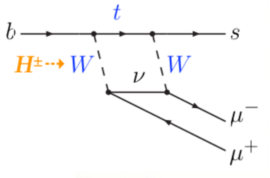
- FCNC are ideal playground for NP searches:
- $B^0 \to \mu\mu$ decay: [PRL 111 (2013) 101804, Nature 522 (2015) 68]
  - Highly suppressed in SM
    - ★ only via Z-penguin and box diagrams: $([m_W/m_t]^2)$
    - ★ Cabibbo suppressed: $|V_{tq}|^2$
    - ★ Helicity suppressed: $[m_\mu/m_B]^2$
  - NP can change decay rate [arXiv:1012.3893]
- $B^0 \to K^*\mu\mu$ decay
- Accessible to CMS



B^0 Rare Decays:

- FCNC are ideal playground for NP searches:
- $B^0 \to \mu\mu$ decay
- $B^0 \to K^*\mu\mu$ decay [CMS-PAS-BPH-15-008]
  - FCNC via penguin or box diagram;
  - angular analysis of the fully reconstructed decay;
  - many observables, as a function of $q^2 = M^2(\mu\mu)$
    - ★ BR, A_{FB}, F_L, angular parameters P_1, P_5', ...
  - robust SM prediction
  - NP can change the angular distribution
- Accessible to CMS





Introduction

B^0 Rare Decays:

- FCNC are ideal playground for NP searches:
- $B^0 \to \mu\mu$ decay
- $B^0 \to K^*\mu\mu$ decay
- Accessible to CMS
  - both channels are accessible to CMS, thanks to:
  - two μ for trigger purpose;
  - fully charged final state: full reconstruction.

In this talk will show results based on 7+8 TeV data (2011, 2012), with 5+20 fb^{-1}

$B^0_s \to \mu\mu$ Analysis in a nutshell

PRL 111 (2013) 101804

Signal (BDT selection)

- a good, isolated $\mu^{\pm}$ pair from displaced vertex
- momentum aligned along flight direction;
- invariant mass peaking at $M(B^0_s, B^0_d)$

$$\mathcal{B}(B^0_s \to \mu\mu) = N_s \cdot \frac{\mathcal{B}(B^{\pm} \to J/\psi K^{\pm})}{N(B^{\pm} \to J/\psi K^{\pm})} \cdot \frac{\varepsilon(B^{\pm})}{\varepsilon(B^0_s)} \frac{f_u}{f_s}$$

- ε include acceptance, trigger, and selection
- f_s/f_u B-factorization

Background

- combinatorial (semileptonic decay): side bands
- rare decays
  - non peaking $B^0_s \to K^-\mu\nu$, $\Lambda_b \to p\mu\nu$ (MC)
  - peaking $B^0 \to KK, K\pi, \pi\pi$: absolute yield evaluated on independent single-μ trigger
- μ quality, good sec. vertex, isolation, pointing angle, and $M_{\mu\mu}$ resolution: $\to$ powerful background suppression

- Normalization channel $B^{\pm} \to J/\psi K^{\pm} \to \mu\mu K^{\pm}$, calibration $B^0_s \to J/\psi\phi \to \mu\mu KK$
- UML symultaneous fit to Bs and Bd
- several categories based on event classification (BDT) and region (Barrel-Endcap)

CMS results for $\mathcal{B}(B_{s,d} \to \mu\mu)$

$(B^0_s) = 3.0^{+0.9}_{-0.8}(\text{stat.})^{+0.6}_{-0.4}(\text{syst.}) \times 10^{-9}$

$(B^0_d) = 3.5^{+2.1}_{-1.8}(\text{stat.}+\text{syst.}) \times 10^{-10}$

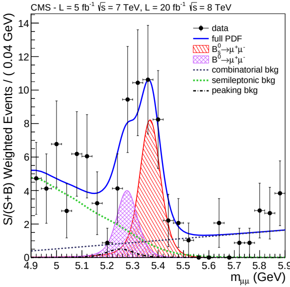
Significance

$(B^0_s \to \mu\mu) = 4.3\sigma$

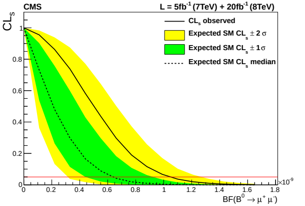
$(B^0_d \to \mu\mu) = 2.0\sigma$

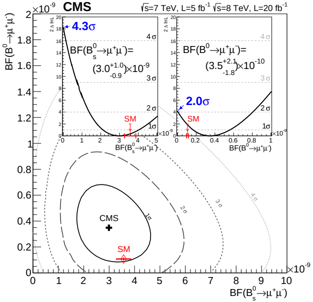
$\mathcal{B}(B^0_d \to \mu\mu) < 1.1 \cdot 10^{-9}$ 95% CL

		$\varepsilon_{tot}[10^{-2}]$	N^{exp}_{signal}	N^{exp}_{total}	N_{obs}
7 TeV	B^0 Barrel	(0.33 ± 0.03)	0.27 ± 0.03	1.3 ± 0.8	3
	B^0_s Barrel	(0.30 ± 0.04)	2.97 ± 0.44	3.6 ± 0.6	4
	B^0 Endcap	(0.20 ± 0.02)	0.11 ± 0.01	1.5 ± 0.6	1
	B^0_s Endcap	(0.20 ± 0.02)	1.28 ± 0.19	2.6 ± 0.5	4
8 TeV	B^0 Barrel	(0.24 ± 0.02)	1.00 ± 0.10	7.9 ± 3.0	11
	B^0_s Barrel	(0.23 ± 0.03)	11.46 ± 1.72	17.9 ± 2.8	16
	B^0 Endcap	(0.10 ± 0.01)	0.30 ± 0.03	2.2 ± 0.8	3
	B^0_s Endcap	(0.09 ± 0.01)	3.56 ± 0.53	5.1 ± 0.7	4



$S/(S+B)$ weighted mass





No deviation from SM

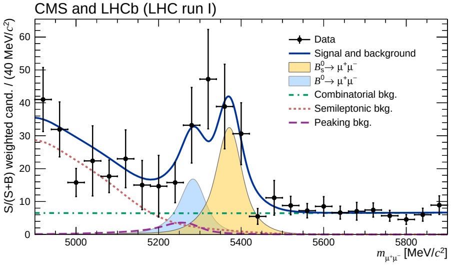
$\mathbf{B(B^0_s \to \mu\mu) = (3.65 \pm 0.23) \cdot 10^{-9}}$

$\mathbf{B(B^0_d \to \mu\mu) = (1.06 \pm 0.09) \cdot 10^{-10}}$

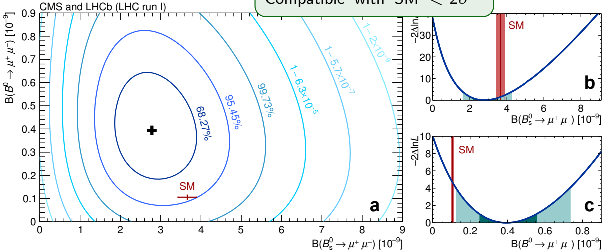
[PRL 112 (2014) 101801]

LHC Run-I: CMS+LHCb

$S/(S+B)$ weighted mass



Compatible with SM $< 2\sigma$

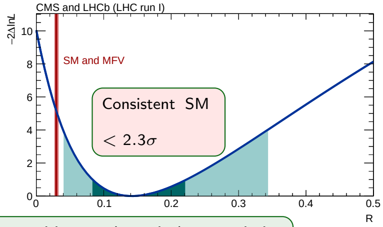


Combined fit to CMS ($25\,\text{fb}^{-1}$) + LHCb ($3\,\text{fb}^{-1}$) dataset, at 7 and 8 TeV

$$BR(\mathrm{B_s^0} \to \mu\mu) = (2.8^{+0.7}_{-0.6}) \cdot 10^{-9} \quad 6.2\sigma \ (7.4 \ \text{exp.})$$

$$BR(\mathrm{B_d^0} \to \mu\mu) = (3.9^{+1.6}_{-1.4}) \cdot 10^{-10} \quad 3.2\sigma \ (0.8 \ \text{exp.})$$

$$\mathcal{R} = \frac{\mathcal{B}(\mathrm{B_d^0} \to \mu\mu)}{\mathcal{B}(\mathrm{B_s^0} \to \mu\mu)} = 0.14^{+0.08}_{-0.06}$$

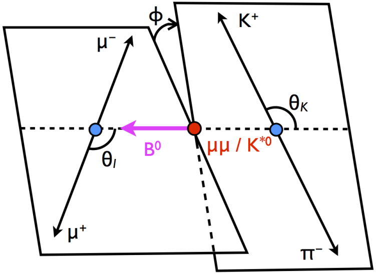


Consistent SM $< 2.3\sigma$

less sensitive to theoretical uncertainties

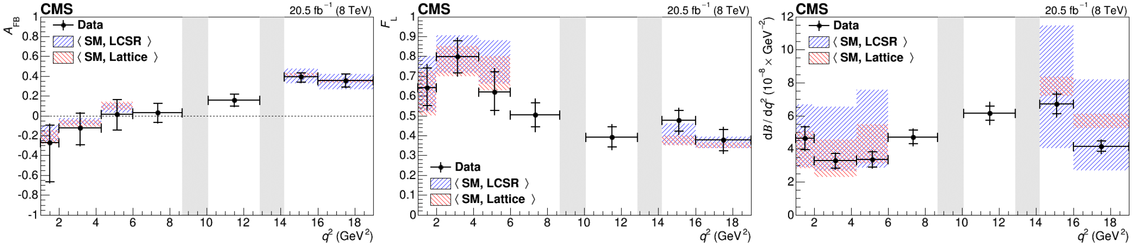
$B^0 \to K^*(892)\mu\mu \to K^+\pi^-\mu^+\mu^-$ angular analysis

- $B^0 \to K^*\mu\mu$ FCNC process
- Fully described by three angles: $\theta_\ell, \theta_K, \varphi$ and $q^2 = M^2_{\mu\mu}$;
- B^0 ($\overline{B}^0$) identified by K and π charges;
- Robust SM calculations of several angular parameters in most of the phase space
  - forward-backward asymmetry of the muons, A_{FB},
  - longitudinal polarization fraction of the K^*, F_L
  - combination of Wilson coefficient P_i and P'_i
- Discrepancy of the angular parameters vs q^2 with respect to SM might be hint of NP



Analysis history

- First iteration of the analysis [PLB 753 (2016) 424] 8 TeV, 20 fb^{-1}: measured A_{FB}, F_L, and dB/dq^2 vs q^2. Signal Yield $\sim$ 1400 events
  - No deviation from SM prediction
- Then $> 3\sigma$ from SM seen by LHCb [JHEP 02 (2016) 104] on P_5' observable at $q^2 < 6\,\mathrm{GeV}^2$
- Second iteration **with same dataset** dedicated to measure P_5' and P_1 with CMS data



Dataset selection

Trig Dedicated HLT trigger path:
Low pt dimuon, displaced, low invariant mass

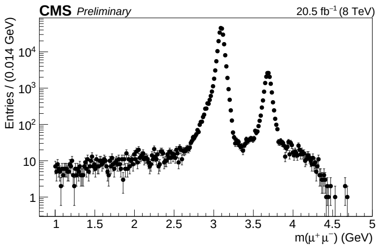
h $p_T^h > 0.8\,\mathrm{GeV}$, $|M(\mathrm{K}\pi) - M_{\mathrm{K}^*}| < 90$ MeV, $M_{\mathrm{KK}} > 1.035$ (ϕ veto), displaced $DCA/\sigma > 2$

μ $p_T^\mu > 3.5\,\mathrm{GeV}$, $p_T^{\mu\mu} > 6.9$ GeV, $1 < M_{\mu\mu} < 4.8\,\mathrm{GeV}$, displaced $L/\sigma > 3$

B^0 $p_t > 8\,\mathrm{GeV}$, $|\eta| < 2.2$, displaced ($L/\sigma > 12$), $\cos\alpha > 0.9994$, $|M - M_{\mathrm{B}^0}| < 280$ MeV

- Both B^0 and $\overline{\mathrm{B}}^0$ considered, if more than one candidate, take the one with best B^0 vtx CL
- anti radiation cut against feed-down of $J/\psi/\psi'$

CR signal and control sample J/ψ and ψ' treated same way.



CMS has no PID capability to distinguish K from π
CP state assignment based on which hypothesis $M(\mathrm{K}^+\pi^-/\mathrm{K}^-\pi^+)$ is closer to $M_{\mathrm{K}^*}(PDG)$:
mistag rate 14% (MC)

Signal Pdf

- Final state $K^+\pi^-\mu^+\mu^-$ has contribution from P-wave (K^*) and S-wave
- in total, PDF has 14 parameters: fold around $\varphi = 0$ and $\theta_\ell = \pi/2$ to reduce them

$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{dq^2 d\cos\theta_l d\cos\theta_K d\phi} = \frac{9}{8\pi}\left\{\frac{2}{3}\left[(F_S + A_S\cos\theta_K)\left(1-\cos^2\theta_l\right) + A_S^5\sqrt{1-\cos^2\theta_K}\sqrt{1-\cos^2\theta_l}\cos\phi\right]\right.$$
$$+(1-F_S)\left[2F_L\cos^2\theta_K\left(1-\cos^2\theta_l\right)+\frac{1}{2}(1-F_L)\left(1-\cos^2\theta_K\right)\left(1+\cos^2\theta_l\right)\right.$$
$$+\frac{1}{2}P_1(1-F_L)(1-\cos^2\theta_K)(1-\cos^2\theta_l)\cos 2\phi$$
$$\left.\left.+2P_5'\cos\theta_K\sqrt{F_L(1-F_L)}\sqrt{1-\cos^2\theta_K}\sqrt{1-\cos^2\theta_l}\cos\phi\right]\right\}$$

- 6 parameters left: statistics not enough to perform a fully floating fit
- F_L, F_S, and A_s fixed from previous CMS measurement
- P_1 and P_5' measured, A_s^5 nuisance parameter

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$$+(1-F_S)\left[2F_L\cos^2\theta_K\left(1-\cos^2\theta_l\right) + \frac{1}{2}(1-F_L)\left(1-\cos^2\theta_K\right)\left(1+\cos^2\theta_l\right)\right.$$
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$$+(1-F_\mathrm{S})\left[2F_\mathrm{L}\cos^2\theta_\mathrm{K}\left(1-\cos^2\theta_l\right)+\frac{1}{2}(1-F_\mathrm{L})\left(1-\cos^2\theta_\mathrm{K}\right)\left(1+\cos^2\theta_l\right)\right.$$
$$+\frac{1}{2}P_1(1-F_\mathrm{L})(1-\cos^2\theta_\mathrm{K})(1-\cos^2\theta_l)\cos 2\phi$$
$$\left.\left.+2P_5'\cos\theta_\mathrm{K}\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}\sqrt{1-\cos^2\theta_\mathrm{K}}\sqrt{1-\cos^2\theta_l}\cos\phi\right]\right\}$$

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$$+ (1-F_S)\left[2F_L\cos^2\theta_K\left(1-\cos^2\theta_l\right) + \frac{1}{2}(1-F_L)\left(1-\cos^2\theta_K\right)\left(1+\cos^2\theta_l\right)\right.$$
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$$\left.\left. + 2P_5'\cos\theta_K\sqrt{F_L(1-F_L)}\sqrt{1-\cos^2\theta_K}\sqrt{1-\cos^2\theta_l}\cos\phi\right]\right\}$$

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Full PDF, including mis-tagged events and background

$$
\begin{aligned}
\text{p.d.f.}(m, \cos\theta_{\mathrm{K}}, \cos\theta_l, \phi) = Y_S^C \cdot \Big(& S_i^R(m) \cdot S_i^a(\cos\theta_{\mathrm{K}}, \cos\theta_l, \phi) \cdot \epsilon_i^R(\cos\theta_{\mathrm{K}}, \cos\theta_l, \phi) \\
& + \frac{f_i^M}{1 - f_i^M} \cdot S_i^M(m) \cdot S_i^a(-\cos\theta_{\mathrm{K}}, -\cos\theta_l, -\phi) \cdot \epsilon_i^M(-\cos\theta_l, -\cos\theta_{\mathrm{K}}, -\phi) \Big) \\
& + Y_B \cdot B_i^m(m) \cdot B_i^{\cos\theta_{\mathrm{K}}}(\cos\theta_{\mathrm{K}}) \cdot B_i^{\cos\theta_l}(\cos\theta_l) \cdot B_i^{\phi}(\phi).
\end{aligned}
$$

Full PDF, including mis-tagged events and background

$$\text{p.d.f.}(m, \cos\theta_K, \cos\theta_l, \phi) = Y_S^C \cdot \Big(S_i^R(m) \cdot S_i^a(\cos\theta_K, \cos\theta_l, \phi) \cdot \epsilon_i^R(\cos\theta_K, \cos\theta_l, \phi)$$

$$+ \frac{f_i^M}{1 - f_i^M} \cdot S_i^M(m) \cdot S_i^a(-\cos\theta_K, -\cos\theta_l, -\phi) \cdot \epsilon_i^M(-\cos\theta_l, -\cos\theta_K, -\phi) \Big)$$

$$+ Y_B \cdot B_i^m(m) \cdot B_i^{\cos\theta_K}(\cos\theta_K) \cdot B_i^{\cos\theta_l}(\cos\theta_l) \cdot B_i^{\phi}(\phi).$$

Correct-Tag

Wrong-Tag

Background

Full PDF, including mis-tagged events and background

$$\text{p.d.f.}(m, \cos\theta_K, \cos\theta_l, \phi) = Y_S^C \cdot \Big(S_i^R(m) \cdot S_i^a(\cos\theta_K, \cos\theta_l, \phi) \cdot \epsilon_i^R(\cos\theta_K, \cos\theta_l, \phi)$$

$$+ \frac{f_i^M}{1 - f_i^M} \cdot S_i^M(m) \cdot S_i^a(-\cos\theta_K, -\cos\theta_l, -\phi) \cdot \epsilon_i^M($$

$$+ Y_B \cdot B_i^m(m) \cdot B_i^{\cos\theta_K}(\cos\theta_K) \cdot B_i^{\cos\theta_l}(\cos\theta_l) \cdot B_i^{\phi}(\phi).$$

Mass Shape (double gauss)

Full PDF, including mis-tagged events and background

$$
\begin{aligned}
\text{p.d.f.}(m, \cos\theta_{\mathrm{K}}, \cos\theta_l, \phi) = {} & Y_S^C \cdot \Big(S_i^R(m) \cdot S_i^a(\cos\theta_{\mathrm{K}}, \cos\theta_l, \phi) \cdot \epsilon_i^R(\cos\theta_{\mathrm{K}}, \cos\theta_l, \phi) \\
& + \frac{f_i^M}{1 - f_i^M} \cdot S_i^M(m) \cdot S_i^a(-\cos\theta_{\mathrm{K}}, -\cos\theta_l, -\phi) \cdot \epsilon_i^M(-\cos\theta_l, -\cos\theta_{\mathrm{K}}, -\phi) \Big) \\
& + Y_B \cdot B_i^m(m) \cdot B_i^{\cos\theta_{\mathrm{K}}}(\cos\theta_{\mathrm{K}}) \cdot B_i^{\cos\theta_l}(\cos\theta_l) \cdot B_i^{\phi}(\phi).
\end{aligned}
$$

Signal pdf

Full PDF, including mis-tagged events and background

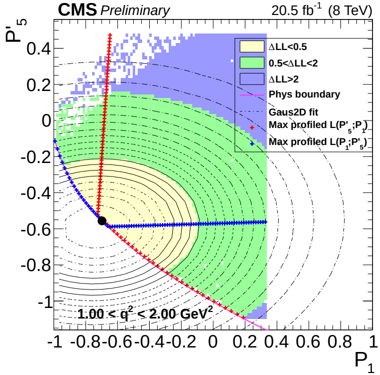
$$\text{p.d.f.}(m, \cos\theta_K, \cos\theta_l, \phi) = Y_S^C \cdot \Big(S_i^R(m) \cdot S_i^a(\cos\theta_K, \cos\theta_l, \phi) \cdot \epsilon_i^R(\cos\theta_K, \cos\theta_l, \phi)$$
$$+ \frac{f_i^M}{1-f_i^M} \cdot S_i^M(m) \cdot S_i^a(-\cos\theta_K, -\cos\theta_l, -\phi) \cdot \epsilon_i^M(-\cos\theta_l, -\cos\theta_K, -\phi) \Big)$$
$$+ Y_B \cdot B_i^m(m) \cdot B_i^{\cos\theta_K}(\cos\theta_K) \cdot B_i^{\cos\theta_l}(\cos\theta_l) \cdot B_i^{\phi}(\phi).$$

3D Efficiency

Full PDF, including mis-tagged events and background

$$\text{p.d.f.}(m, \cos\theta_K, \cos\theta_l, \phi) = Y_S^C \cdot \Big(S_i^R(m) \cdot S_i^a(\cos\theta_K, \cos\theta_l, \phi) \cdot \epsilon_i^R(\cos\theta_K, \cos\theta_l, \phi)$$
$$+ \frac{f_i^M}{1 - f_i^M} \cdot S_i^M(m) \cdot S_i^a(-\cos\theta_K, -\cos\theta_l, -\phi) \cdot \epsilon_i^M(-\cos\theta_l, -\cos\theta_K, -\phi) \Big)$$
$$+ Y_B \cdot B_i^m(m) \cdot B_i^{\cos\theta_K}(\cos\theta_K) \cdot B_i^{\cos\theta_l}(\cos\theta_l) \cdot B_i^{\phi}(\phi).$$

- Fit performed for 7 (+2 CR) different q^2 bins
- Fit m side bands to determine the background shape;
- Fit whole mass spectrum with 5 floating parameters;
- used unbinned extended maximum likelihood estimator
  - discretize P_1, P_5' space
  - maximize $\mathcal{L}(Y_S, Y_B, A_s^5)$
  - fit $\mathcal{L}$ with 2D-gaussian
  - find abs max of $\mathcal{L}$ inside the physically allowed region
- stat uncert using FC construction along the 1D profiled $\mathcal{L}$



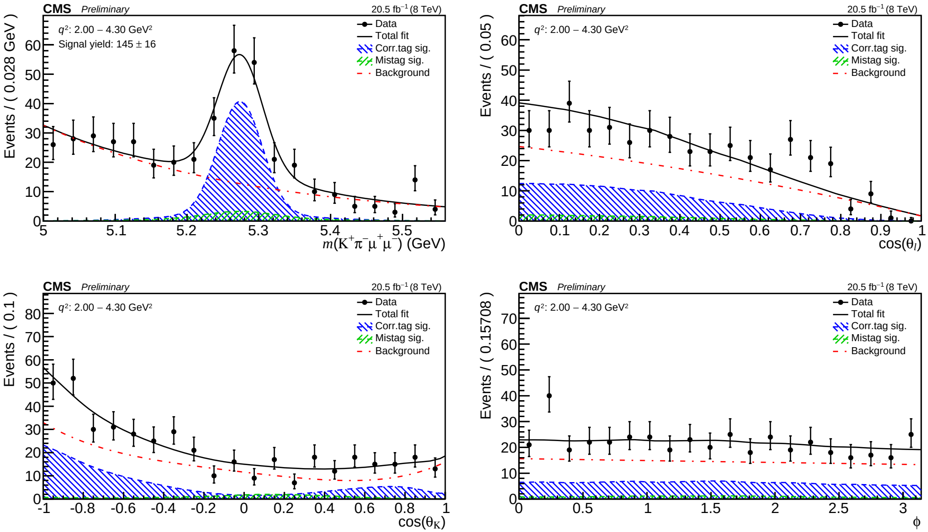
Systematics

Systematic uncertainty	$P_1 (10^{-3})$	$P'_5 (10^{-3})$
Simulation mismodeling	1–33	10–23
Fit bias	5–78	10–119
MC statistical uncertainty	29–73	31–112
Efficiency	17–100	5–65
$K\pi$ mistagging	8–110	6–66
Background distribution	12–70	10–51
Mass distribution	12	19
Feed-through background	4–12	3–24
F_L, F_S, A_S uncertainty propagation	0–126	0–200
Angular resolution	2–68	0.1–12
Total systematic uncertainty	60–220	70–230

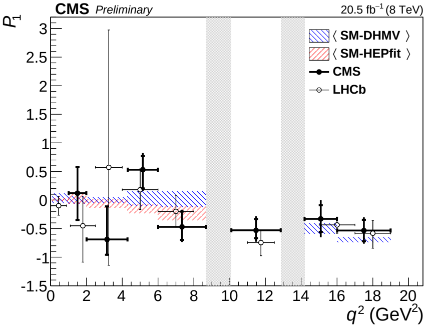
- Comparing fit results on MC (high stat) with input (**sim mismod**)
- **Fit bias** with cocktail signal MC + toy background from data side-bands;
- **MC stat** due to limited statistics in efficiency shape evaluation
- Comparing F_L on CR wrt PDG (**efficiency**)
- **$K\pi$ mistag** evaluated in J/ψ control region and propagated to all bins;

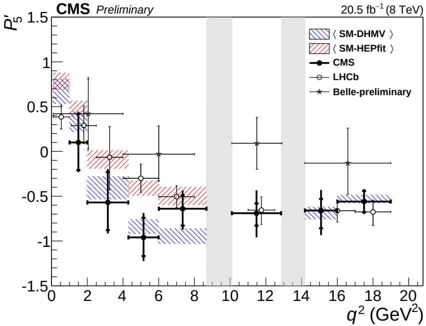
Propagation of F_L, F_S, and A_s uncertainties:

- generate pseudo experiments, with x100 events, for each q^2 bin;
- Fit with F_L, F_S, A_s free to float and with F_L, F_S, A_s fixed;
- ratio of stat. uncert. on P_1 and P'_5 with free and fixed fit used to estimate syst uncertainties.


CMS Preliminary
20.5 fb^{-1} (8 TeV)
q^2: 2.00 – 4.30 GeV²
Signal yield: 145 ± 16
Data
Total fit
Corr.tag sig.
Mistag sig.
Background
Events / (0.028 GeV)
$m(K^+\pi^-\mu^+\mu^-)$ (GeV)
Events / (0.05)
$\cos(\theta_l)$
Events / (0.1)
$\cos(\theta_K)$
Events / (0.15708)
ϕ

Results vs SM prediction and LHCb/Belle measurements





LHCb [JHEP 02 (2016) 104],
Belle [PRL 118 (2017) 111801],
ATLAS results not shown [ATLAS-CONF-2017-023]

SM-DHMV is computed using soft form factors in addition with parametrised power corrections and with the hadronic charm-loop contribution derived from calculations [JHEP 01 (2013) 048, JHEP 05 (2013) 137]

SM-HEPfit uses full QCD computation of the form factors and derives the hadronic contribution from LHCb data [JHEP 06 (2016) 116, arXiv:1611.04338]

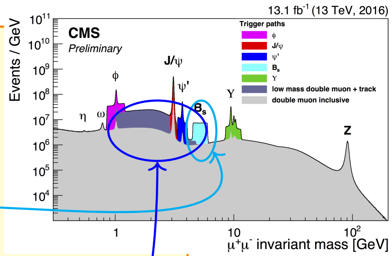
No significant deviation wrt SM prediction, more compatible with SM-DHMV

Summary

FCNC rare decays are being extensively studied in CMS

- $B_s^0 \to \mu\mu$ clearly seen. B_d^0 at $> 3\sigma$ with LHCb
- BR compatible with SM.
  - analysis on $35\,\mathrm{fb}^{-1}$ at 13 TeV is beeing actively carried on;
  - dedicated trigger in place also for the 2017 data-taking:
  - more statistics will be available
  - improve B_s^0 and further study B_d^0 decay.
- $B^0 \to K^* \mu\mu$ angular analysis has been extended to measure P_1 and P_5' parameters:
  - no significant deviation to SM prediction seen within the uncertainties
  - trigger available: have and will collect more events at 13 TeV
- *Credi, [...], no la xe finia* [V.Monti, Aristodemo, 3^{rd} act]

It's not over, yet! stay tuned



Additional stuff

Additional or backup slides

Introduction

Motivation

The search for new physics can be performed via different paths:

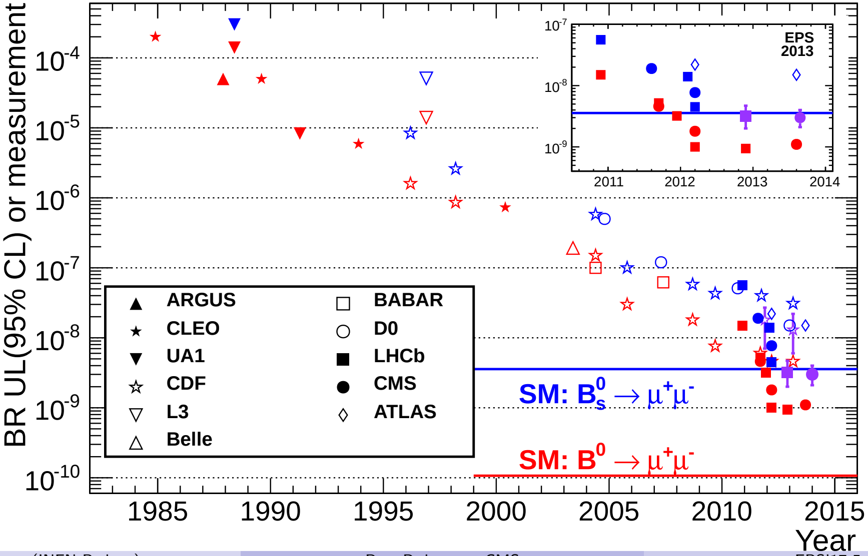
- direct searches
  - try to produce any new particle and detect it via its decay or interaction with the detector
- indirect searches
  - perform precise measurement of processes and compare with Standard Model prediction
  - New Phisics present in the loops can be seen if a significan discrepancy wrt to SM prediction is present.

This talk:

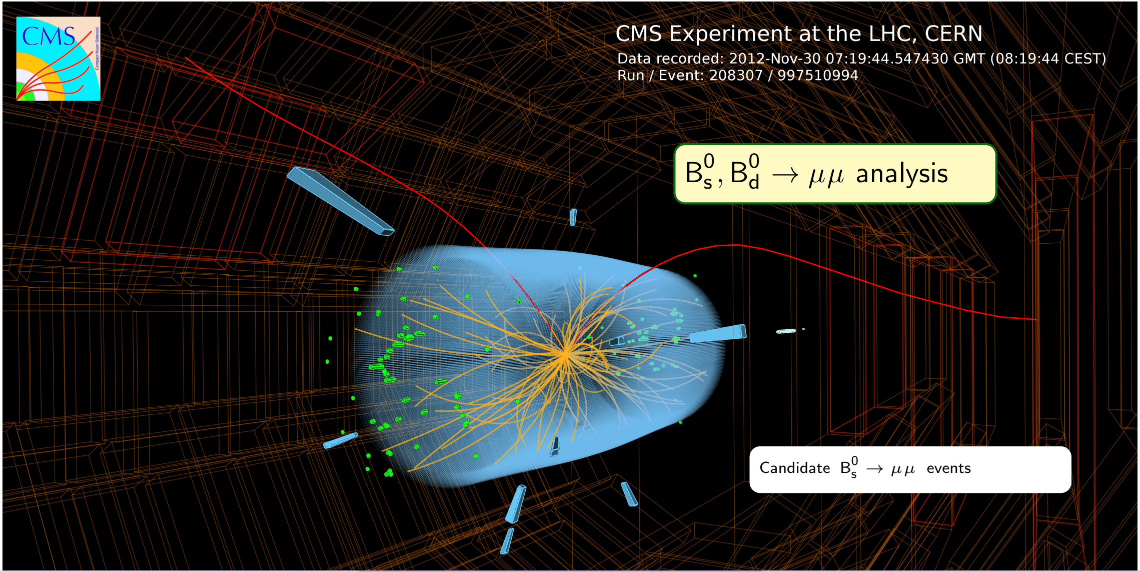
- $B_s^0, B_d^0 \to \mu\mu$
- $B^0 \to K^*\mu\mu$

Flavour Changing Neutral Current

- FCNC are ideal playground for NP searches:
  - forbidden at tree level in SM, possible via penguin and box diagrams
  - NP can change rates or angular distribution

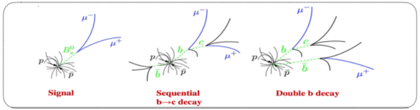

BR UL(95% CL) or measurement
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
1985
1990
1995
2000
2005
2010
2015
Year
ARGUS
CLEO
UA1
CDF
L3
Belle
BABAR
D0
LHCb
CMS
ATLAS
SM: $B_s^0 \to \mu^+\mu^-$
SM: $B^0 \to \mu^+\mu^-$
EPS
2013
2011
2012
2013
2014

$B_s^0, B_d^0 \to \mu\mu$



Signal

- two muons from the same, displaced vertex;
- momentum aligned along flight direction;
- invariant mass peaking at $M(B_s^0, B_d^0)$
- blind analysis



Background

- combinatorial: control sample from side bands
  - double semileptonic B decay
  - single semileptonic plus μ mis-id
- background from rare decays (MC)
  - yield normalized to same $B^{\pm}$ yield as data
  - peaking $B^0 \to KK, K\pi, \pi\pi$
    - ★ absolute yield evaluated on independent single-μ trigger
  - non peaking $B_s^0 \to K^-\mu\nu$, $\Lambda_b \to p\mu\nu$
- powerful background suppression:
  - μ quality, good sec. vertex, isolation, pointing angle, and $M_{\mu\mu}$ resolution

Analysis strategy

$$\mathcal{B}(B_s^0 \to \mu\mu) = \frac{N_s}{N(B^\pm \to J/\psi K^\pm)} \times \mathcal{B}(B^\pm \to J/\psi K^\pm) \times \frac{A(B^\pm)}{A(B_s^0)} \frac{\varepsilon(B^\pm)}{\varepsilon(B_s^0)} \frac{f_u}{f_s}$$

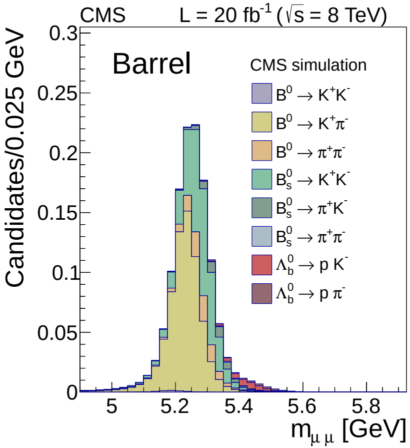
- Normalization channel $B^\pm \to J/\psi K^\pm \to \mu\mu K^\pm$
- Calibration/validation channels $B_s^0 \to J/\psi\phi \to \mu\mu KK$
- UML symultaneous fit to Bs and Bd
- several categories based on event classification and region
  - Boosted Decision Tree (BDT) method by including several topological and kinematical variables for background suppression
  - barrel and endcap (different M_B resolution)

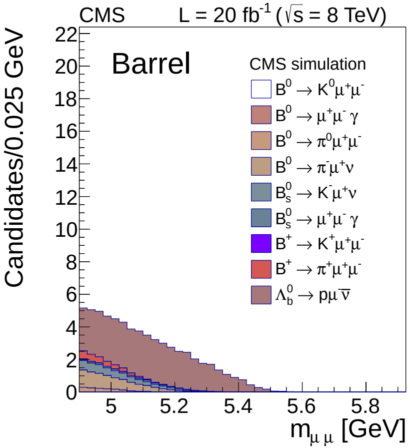
ε include acceptance, trigger, and selection

- trigger and selection similar between signal and normalization channel to reduce systematics

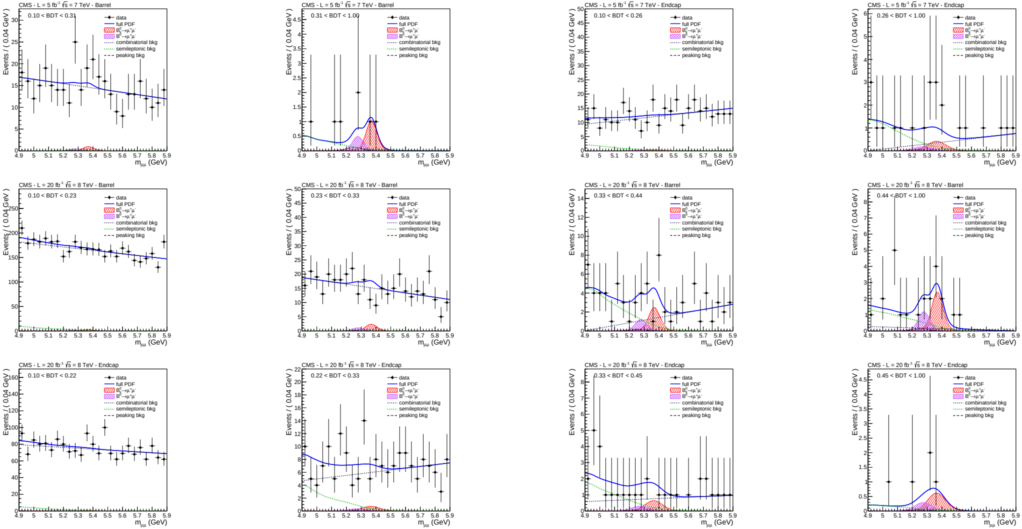
f_s/f_u B-factorization composition (from LHCb measurement 0.259 ± 0.015 [JHEP 04 (2013) 001])

Illustration of the rare peaking and rare semileptonic (and other non-peaking) backgrounds in barrel categories





Invariant mass for different BDT region/categories

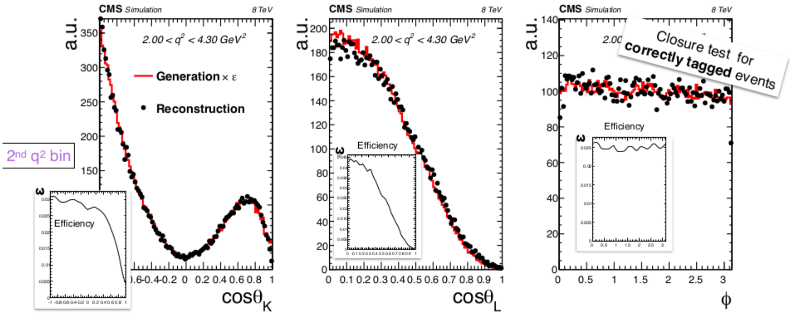


Efficiency and closure test (right tag)

- Numerator and denominator of efficiency are separately described with nonparametric technique implemented with a kernel density estimator on unbinned distributions
- Final efficiency distributions in the p.d.f. obtained from the ratio of 3D histograms derived from the sampling of the kernel density estimators

Closure test:

- compute efficiency with half of the MC simulation and use it to correct the other half
- same test performed both for correctly and mistagged events independently



- Numerator and denominator of efficiency are separately described with nonparametric technique implemented with a kernel density estimator on unbinned distributions
- Final efficiency distributions in the p.d.f. obtained from the ratio of 3D histograms derived from the sampling of the kernel density estimators

Closure test:

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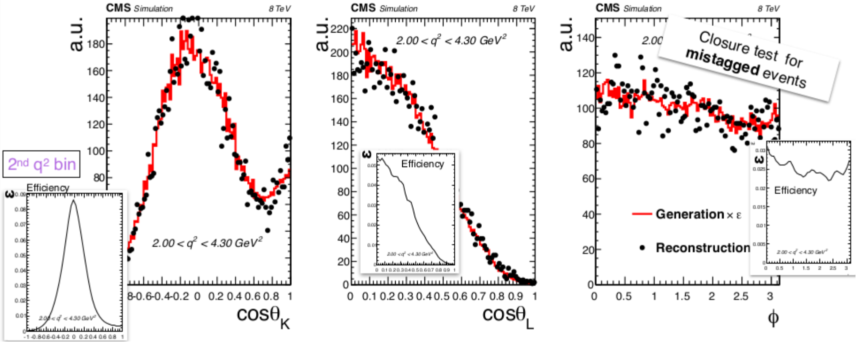


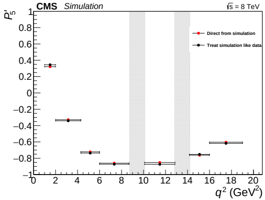
Background considered included:

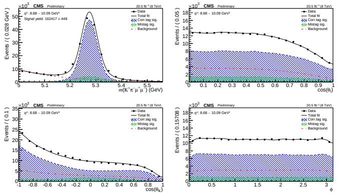
- Partially reconstructed B^0 decay might pollute left M_{B^0} side bands
  - restrict left s.b. $(5.1 < M < 5.6\,\mathrm{GeV}$, default $5 < M < 5.6\,\mathrm{GeV})$
  - redo fit: change in P_1 and P_5' within the systmatics uncertainties.
- $\mathrm{B}^\pm \to \mathrm{K}^\pm\mu\mu$ plus and additional random $\pi^\mp$:
  - distribution ends at $M > 5.4\,\mathrm{GeV}$, further reduced by $\cos\alpha$ cut, and BR similar to $\mathrm{B}^0 \to \mathrm{K}^*\mu\mu$
- $\Lambda_\mathrm{b} \to \mathrm{pK J}/\psi(\mu^+\mu^-)$
  - look at event in the $M_{\mathrm{K}\pi\mu\mu} \approx M_{\mathrm{B}^0}$ peak, reconstruct them using p, K mass hypothesis: no peak seen.
- $\mathrm{B}^0 \to DX$, with $D \to hh$ and h mis-id as μ
  - requires two mis-id: $P_{misId} \sim 1 \cdot 10^{-3}$: given $BR \sim 1 \cdot 10^{-3}$ negligible.
- $\mathrm{B}^0 \to \mathrm{J}/\psi(\mu\mu)\mathrm{K}^*(\mathrm{K}\pi)$, with one h and one μ switched
  - $P_{misId\ \mu} \cdot (1 - \varepsilon_\mu) \sim 1 \cdot 10^{-4}$, $Y_{\mathrm{B}^0 \to \mathrm{J}/\psi\mu\mu} \sim 1.6 \cdot 10^5$: few events in bin close to J/ψ
  - J/ψ feed contamination in close bin included in the fit model

Fit validation

extensive fit validation with MC: used as **systematics**

- compare fit results with MC input values (**sim mismodeling**)
- compare with data-like MC (**fit bias**)
  - signal only correct tag
  - signal correct+wrong tag
  - signal + background
- Data control channel (J/ψ and ψ'), comparing fit results with PDG (F_L) (**efficiency**)
- compare P_1 and P'_5 on J/ψ and ψ' w/ and w/o F_L fixed: no bias





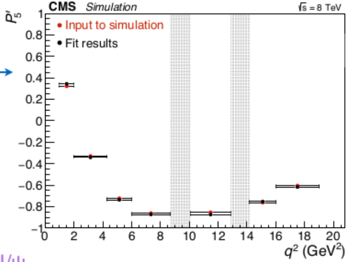
$$\frac{\mathcal{B}(B^0 \to K^* \psi')}{\mathcal{B}(B^0 \to K^* J/\psi)} == \frac{Y_{\psi'}}{\epsilon_{\psi'}} \frac{\epsilon_{J/\psi}}{Y_{J/\psi}} \frac{\mathcal{B}(J/\psi \to \mu^+\mu^-)}{\mathcal{B}(\psi' \to \mu^+\mu^-)} = 0.480 \pm 0.008(\mathrm{stat}) \pm 0.055(\mathrm{R}_{\psi}^{\mu\mu})$$

vs PDG $0.484 \pm 0.018(\mathrm{stat}) \pm 0.011(\mathrm{syst}) \pm 0.012(\mathrm{R}_{\psi}^{ee})$

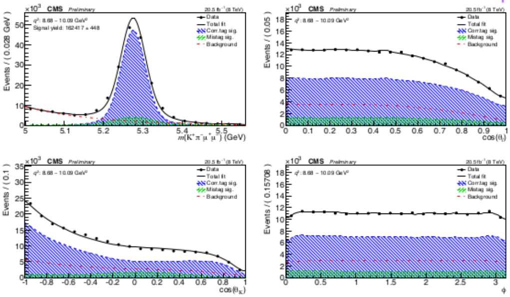
Fit Validation (2)

Several validation steps are performed with simulation:

- with statistically precise MC signal sample: compare fit results with input values to the simulation (**simulation mismodeling**)
- with 200 data-like MC signal+background samples: compare average fit results with fit to the statistically precise MC signal sample (**fit bias**)
- with pseudo-experiments



$B^0 \to K^{*0} J/\psi$

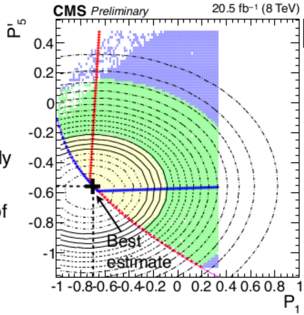


Validation with data control channels:

- Fit performed with F_L free to vary
- The difference of F_L with respect to PDG value is propagated to the signal q^2 bins as systematic uncertainty (**efficiency**)

Fit procedure

- The decay rate can become negative for certain values of the angular parameters (**P_1**, **P_5'**, **A^5_s**)
- The presence of such a physically allowed region greatly complicates the numerical maximisation process of the likelihood by `MINUIT` and especially the error determination by `MINOS`, in particular next to the boundary between physical and unphysical regions
- The **best estimate** of **P_1** and **P_5'** is computed by:
  - discretise the bi-dimensional space **P_1-P_5'**
  - maximise the likelihood as a function of **Y_S**, **Y_B**, and **A^5_s** at fixed values of **P_1**, **P_5'**
  - fit the likelihood distribution with a 2D-gaussian function
  - the maximum of this function inside the physically allowed region is the best estimate
- To ensure correct coverage for the **uncertainties** of **P_1** and **P_5'**, the Feldman-Cousins method is used in a simplified form: the confidence interval's construction is performed only along two 1D paths determined by profiling the 2D-gaussian description of the likelihood inside the physically allowed region



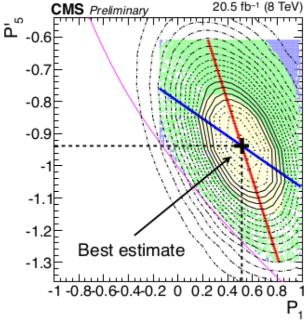
2nd q^2 bin

Color code Log Likelihood (LL):
- yellow = 0 to 0.5 LL
- green = 0.5 to 2 LL

Coloured paths:
- Profile likelihood for P_1
- Profile likelihood for P_5'

FC stat uncertainties determination

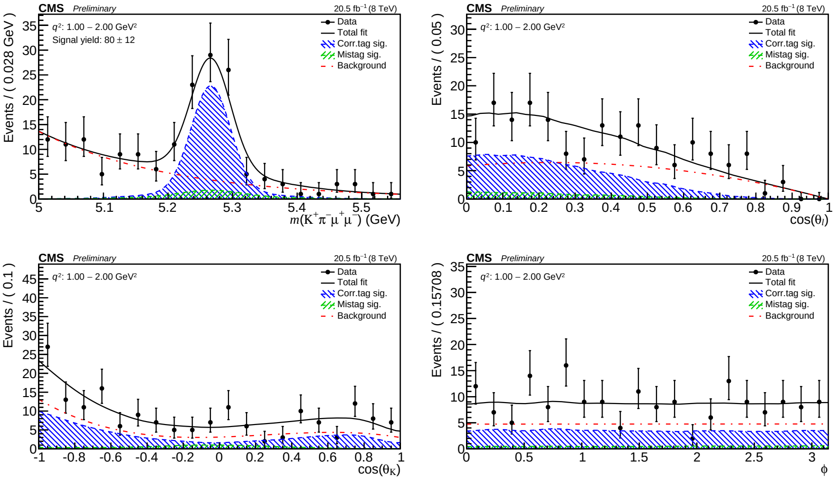
- To ensure correct coverage for the **uncertainties** of P_1 and P_5', the Feldman-Cousins method is used in a simplified form: the confidence interval's construction is performed only along the two 1D paths determined by profiling the 2D-gaussian description of likelihood inside the physically allowed region:
  - generate 100 pseudo-experiments for each point of the path
  - fit and rank according to the likelihood-ratio
  - confidence interval bound is found when data likelihood-ratio exceeds the 68.3% of the pseudo-experiments



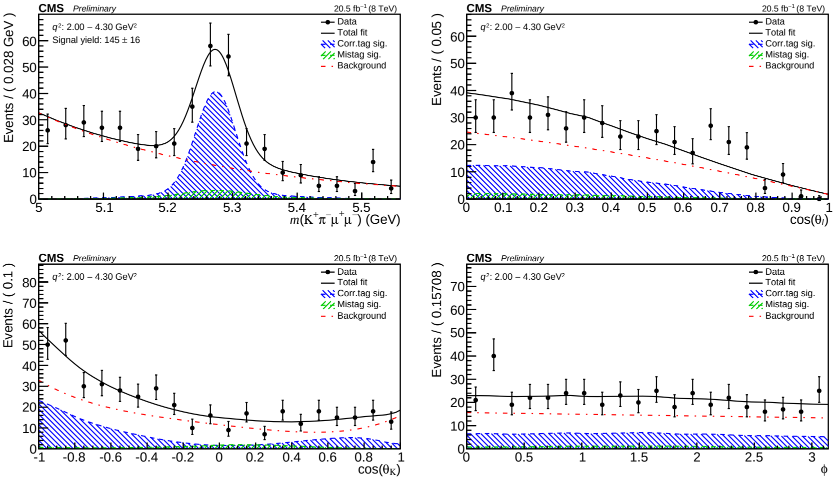
- Due to the limited number of pseudo-experiments statistical fluctuations are present
- To produce a robust result, the ranking of the data likelihood-ratio is plotted for several scan points
- The intersection is then computed using a linear fit

CMS results (table)

q^2 (GeV^2)	Signal yield	P_1	P'_5
1.00–2.00	80 ± 12	$+0.12^{+0.46}_{-0.47} \pm 0.06$	$+0.10^{+0.32}_{-0.31} \pm 0.12$
2.00–4.30	145 ± 16	$-0.69^{+0.58}_{-0.27} \pm 0.09$	$-0.57^{+0.34}_{-0.31} \pm 0.15$
4.30–6.00	119 ± 14	$+0.53^{+0.24}_{-0.33} \pm 0.18$	$-0.96^{+0.22}_{-0.21} \pm 0.16$
6.00–8.68	247 ± 21	$-0.47^{+0.27}_{-0.23} \pm 0.13$	$-0.64^{+0.15}_{-0.19} \pm 0.14$
10.09–12.86	354 ± 23	$-0.53^{+0.20}_{-0.14} \pm 0.14$	$-0.69^{+0.11}_{-0.14} \pm 0.23$
14.18–16.00	213 ± 17	$-0.33^{+0.24}_{-0.23} \pm 0.22$	$-0.66^{+0.13}_{-0.20} \pm 0.19$
16.00–19.00	239 ± 19	$-0.53^{+0.19}_{-0.19} \pm 0.13$	$-0.56^{+0.12}_{-0.12} \pm 0.07$

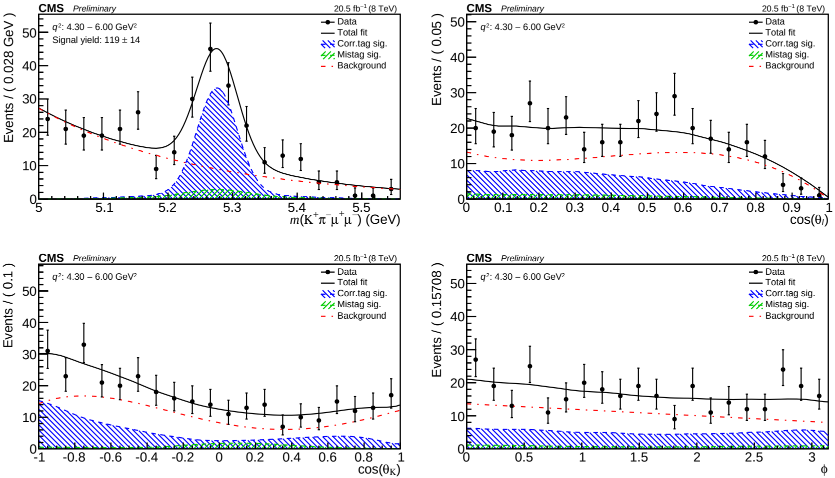

CMS Preliminary
20.5 fb⁻¹ (8 TeV)
q²: 1.00 – 2.00 GeV²
Signal yield: 80 ± 12
Data
Total fit
Corr.tag sig.
Mistag sig.
Background
Events / (0.028 GeV)
m(K⁺π⁻μ⁺μ⁻) (GeV)
Events / (0.05)
cos(θ_l)
Events / (0.1)
cos(θ_K)
Events / (0.15708)
ϕ

Fit Bin 2

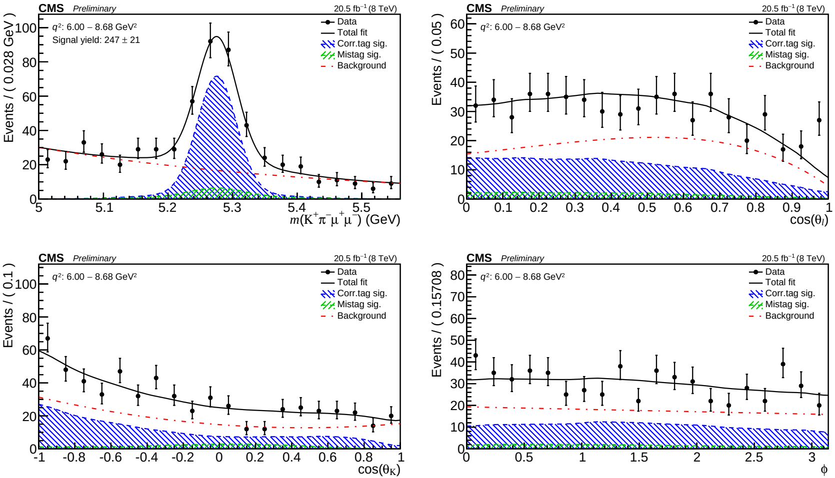


CMS Preliminary
20.5 fb^{-1} (8 TeV)
q^2: 2.00 – 4.30 GeV²
Signal yield: 145 ± 16
Data
Total fit
Corr.tag sig.
Mistag sig.
Background
Events / (0.028 GeV)
$m(K^+\pi^-\mu^+\mu^-)$ (GeV)
Events / (0.05)
$\cos(\theta_l)$
Events / (0.1)
$\cos(\theta_K)$
Events / (0.15708)
ϕ

Fit Bin 3

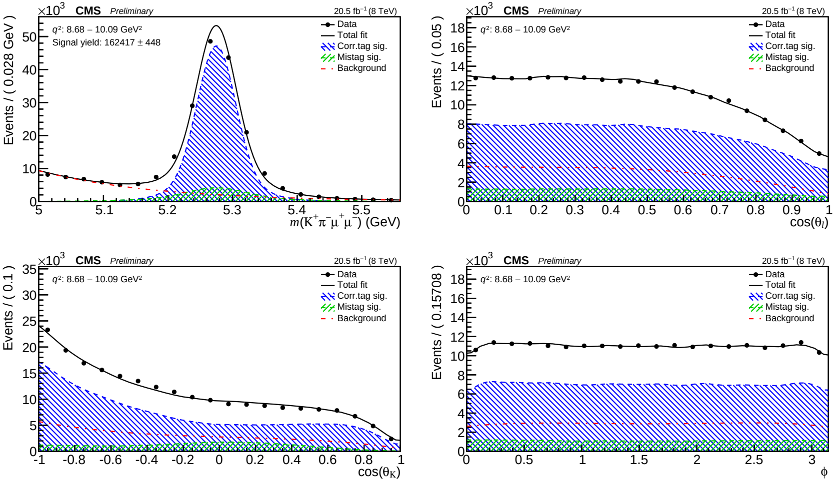


CMS Preliminary
20.5 fb^{-1} (8 TeV)
q^2: 4.30 – 6.00 GeV^2
Signal yield: 119 ± 14
Data
Total fit
Corr.tag sig.
Mistag sig.
Background
Events / (0.028 GeV)
$m(K^+\pi^-\mu^+\mu^-)$ (GeV)
Events / (0.05)
$\cos(\theta_l)$
Events / (0.1)
$\cos(\theta_K)$
Events / (0.15708)
ϕ

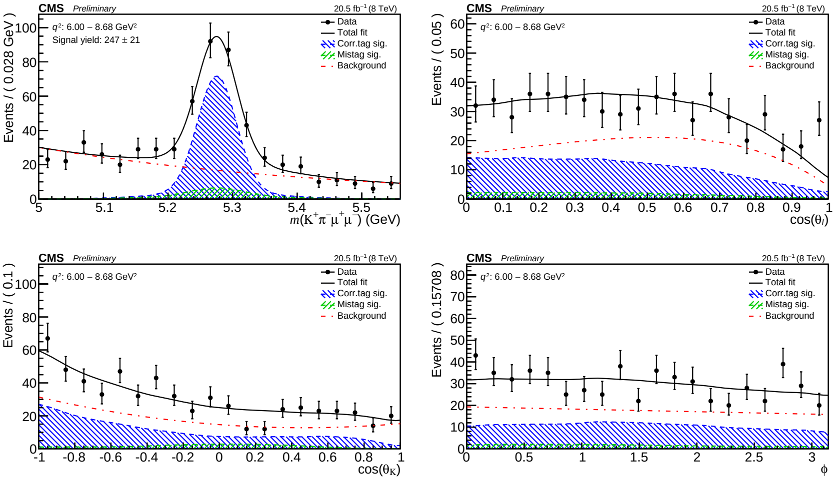


CMS Preliminary
20.5 fb^{-1} (8 TeV)
q^2: 6.00 – 8.68 GeV^2
Signal yield: 247 ± 21
Data
Total fit
Corr.tag sig.
Mistag sig.
Background
Events / (0.028 GeV)
$m(K^+\pi^-\mu^+\mu^-)$ (GeV)
Events / (0.05)
$\cos(\theta_l)$
Events / (0.1)
$\cos(\theta_K)$
Events / (0.15708)
ϕ

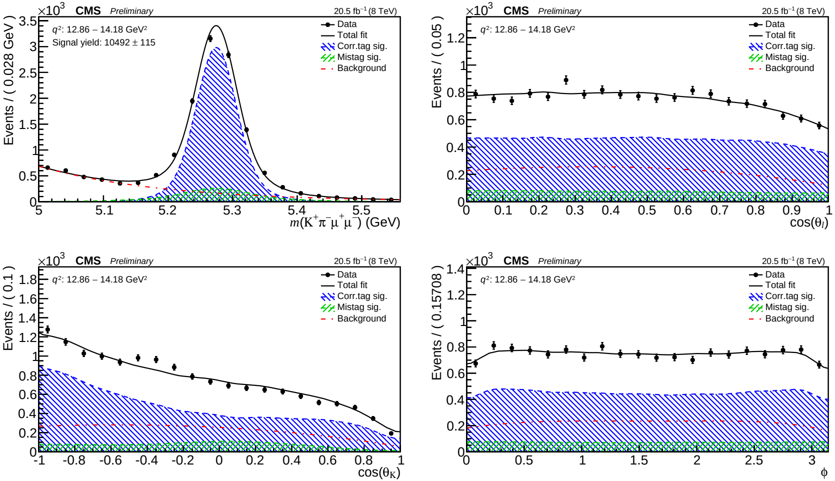
Fit Bin 5 (J/ψ)



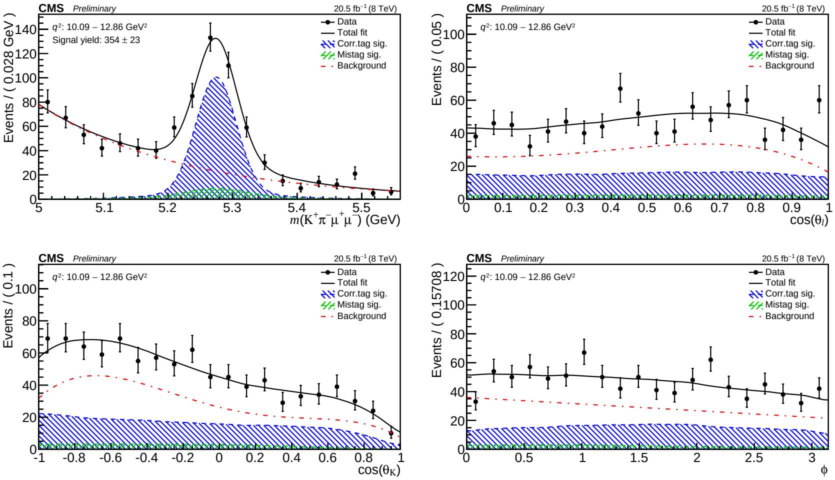
Fit Bin 6


CMS Preliminary
20.5 fb⁻¹ (8 TeV)
q²: 6.00 – 8.68 GeV²
Signal yield: 247 ± 21
Data
Total fit
Corr.tag sig.
Mistag sig.
Background
Events / (0.028 GeV)
m(K⁺π⁻μ⁺μ⁻) (GeV)
Events / (0.05)
cos(θ_l)
Events / (0.1)
cos(θ_K)
Events / (0.15708)
ϕ

Fit Bin 7 (ψ')

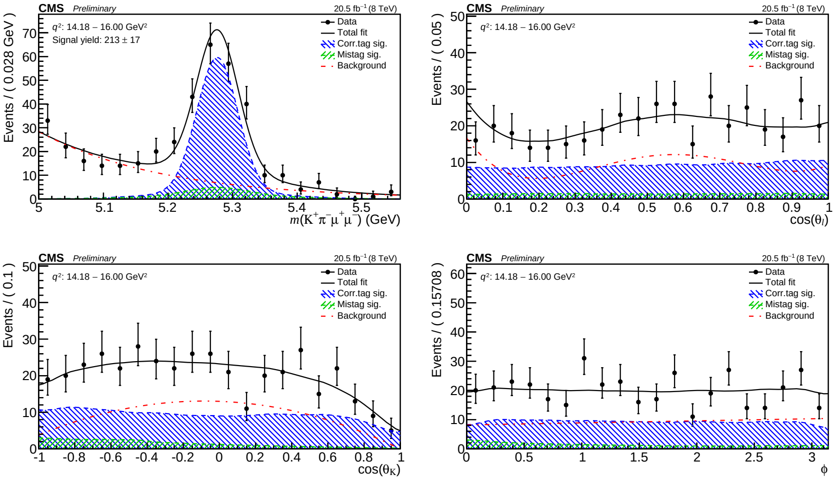


CMS Preliminary
20.5 fb⁻¹ (8 TeV)
q²: 12.86 – 14.18 GeV²
Signal yield: 10492 ± 115
Data
Total fit
Corr.tag sig.
Mistag sig.
Background
Events / (0.028 GeV)
m(K⁺π⁻μ⁺μ⁻) (GeV)
Events / (0.05)
cos(θ_l)
Events / (0.1)
cos(θ_K)
Events / (0.15708)
ϕ



CMS Preliminary
20.5 fb^{-1} (8 TeV)
q^2: 10.09 – 12.86 GeV^2
Signal yield: 354 ± 23
Data
Total fit
Corr.tag sig.
Mistag sig.
Background
Events / (0.028 GeV)
$m(K^+\pi^-\mu^+\mu^-)$ (GeV)
Events / (0.05)
$\cos(\theta_l)$
Events / (0.1)
$\cos(\theta_K)$
Events / (0.15708)
ϕ

Fit Bin 9



CMS Preliminary
20.5 fb⁻¹ (8 TeV)
q²: 14.18 – 16.00 GeV²
Signal yield: 213 ± 17
Data
Total fit
Corr.tag sig.
Mistag sig.
Background
Events / (0.028 GeV)
m(K⁺π⁻μ⁺μ⁻) (GeV)
Events / (0.05)
cos(θ_l)
Events / (0.1)
cos(θ_K)
Events / (0.15708)
φ

Anti-radiation cut

The signal sample is required to pass the selection:

- $m(\mu\mu) < m_{J/\psi PDG} - 3\sigma_{m(\mu\mu)}$ or
- $m_{J/\psi PDG} + 3\sigma_{m(\mu\mu)} < m(\mu\mu) < m_{\psi' PDG} - 3\sigma_{m(\mu\mu)}$ or
- $m(\mu\mu) > m_{\psi' PDG} + 3\sigma_{m(\mu\mu)}$;

for the control channel $B^0 \to K^{*0}(K^+\pi^-)J/\psi(\mu^+\mu^-)$ the requirement is:

- $|m(\mu\mu) - m_{J/\psi PDG}| < 3\sigma_{m(\mu\mu)}$.

while for the $B^0 \to K^{*0}(K^+\pi^-)\psi'(\mu^+\mu^-)$ channel is:

- $|m(\mu\mu) - m_{\psi' PDG}| < 3\sigma_{m(\mu\mu)}$.

To further reject feed-through from control channels ➜

Events are **rejected** if $m(\mu\mu) < m_{J/\psi PDG}$, then:

- $|(m(K\pi\mu\mu) - m_{B^0 PDG}) - (m(\mu\mu) - m_{J/\psi PDG})| < 160\ \mathrm{MeV}/c^2$;
- $|(m(K\pi\mu\mu) - m_{B^0 PDG}) - (m(\mu\mu) - m_{\psi' PDG})| < 60\ \mathrm{MeV}/c^2$;

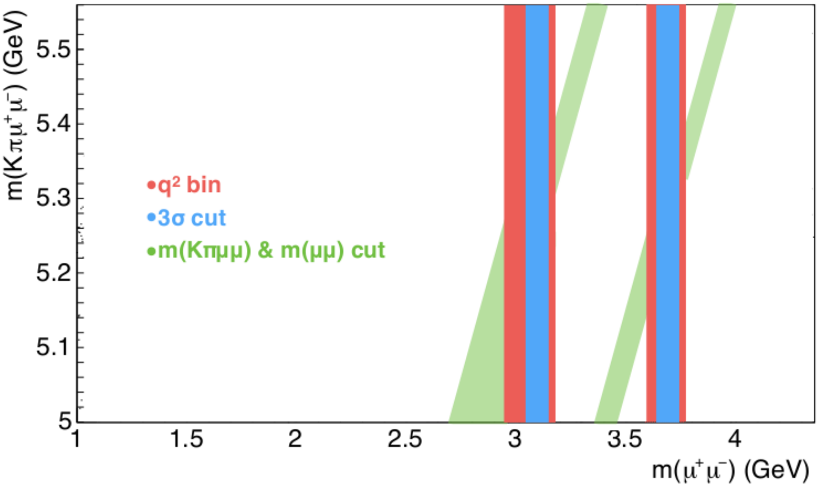
while if $m_{J/\psi PDG} < m(\mu\mu) < m_{\psi' PDG}$, then:

- $|(m(K\pi\mu\mu) - m_{B^0 PDG}) - (m(\mu\mu) - m_{J/\psi PDG})| < 60\ \mathrm{MeV}/c^2$;
- $|(m(K\pi\mu\mu) - m_{B^0 PDG}) - (m(\mu\mu) - m_{\psi' PDG})| < 60\ \mathrm{MeV}/c^2$;

and if $m(\mu\mu) > m_{\psi' PDG}$, then:

- $|(m(K\pi\mu\mu) - m_{B^0 PDG}) - (m(\mu\mu) - m_{J/\psi PDG})| < 60\ \mathrm{MeV}/c^2$;
- $|(m(K\pi\mu\mu) - m_{B^0 PDG}) - (m(\mu\mu) - m_{\psi' PDG})| < 30\ \mathrm{MeV}/c^2$.

Anti-radiation cut 2



Decay rate

$$\frac{\mathrm{d}^4\Gamma[\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-]}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\sum_i I_i(q^2) f_i(\vec{\Omega})$$

→ Decay rate involving b quark, *i.e.* B^0_{bar} meson

$$\frac{\mathrm{d}^4\bar{\Gamma}[B^0 \to K^{*0}\mu^+\mu^-]}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\sum_i \bar{I}_i(q^2) f_i(\vec{\Omega})$$

→ Decay rate involving b_{bar} quark, *i.e.* B^0 meson

- Γ and Γ_{bar}: expression of the decay
- *$f(\vec{\Omega})$*: combinations of spherical harmonics
- *I* and *I_{bar}*: q^2-dependent angular parameters (combinations of six complex decay amplitudes)

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

Assumptions / simplifications:

- CP-averaged measurement
- Massless limit, *i.e.* $q^2 \gg 4m^2_\mu$

⬇

8 independent angular parameters

Decay rate parameterisation
(*JHEP 01 (2013) 048*)

For example $P_5' = \dfrac{S_5}{\sqrt{F_L(1-F_L)}}$

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_K\, d\cos\theta_l\, d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}F_L \sin^2\theta_K + F_L\cos^2\theta_K + (\frac{1}{4}F_L\sin^2\theta_K - F_L\cos^2\theta_K)\cos 2\theta_l + \frac{1}{2}P_1 F_L \sin^2\theta_K \sin^2\theta_l \cos 2\phi + \sqrt{F_L F_L}\left(\frac{1}{2}P_4'\sin 2\theta_K \sin 2\theta_l \cos\phi + P_5' \sin 2\theta_K \sin\theta_l \cos\phi\right) - \sqrt{F_L F_L}\left(P_6'\sin 2\theta_K\sin\theta_l\sin\phi - \frac{1}{2}P_8'\sin 2\theta_K \sin 2\theta_l \sin\phi\right) + 2P_2 F_L \sin^2\theta_K\cos\theta_l - P_3 F_L \sin^2\theta_K \sin^2\theta_l \sin 2\phi\Big] = \frac{d\Gamma^4_{\text{P-wave}}}{dq^2\, d\Omega}$$

Two channels can contribute to the final state $K^+\pi^-\mu^+\mu^-$:

- **P-wave** channel, $K^+\pi^-$ from the meson vector resonance K^{*0} decay
- **S-wave** channel, $K^+\pi^-$ not coming from any resonance

We have to parametrise both decay rates !

$$\frac{d\Gamma^4_{\text{Total}}}{dq^2\, d\Omega} = (1 - F_S)\frac{d\Gamma^4_{\text{P-wave}}}{dq^2\, d\Omega} + \frac{d\Gamma^4_{\text{S/SP-wave}}}{dq^2\, d\Omega}$$

Both S-wave and S&P wave interference

$$\frac{d\Gamma^4_{\text{S/SP-wave}}}{dq^2\, d\Omega} = \frac{3}{16\pi}\left[F_S \sin^2\theta_\ell + A_S \sin^2\theta_\ell\cos\theta_K + A_S^4 \sin\theta_K \sin 2\theta_\ell \cos\phi + A_S^5 \sin\theta_K\sin\theta_\ell\cos\phi + A_S^7\sin\theta_K\sin\theta_\ell\sin\phi + A_S^8 \sin\theta_K \sin 2\theta_\ell \sin\phi\right]$$

6 independent parameters