Angular Analyses of $b \to s\mu^+\mu^-$ transitions at CMS

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(for CMS Collaboration)

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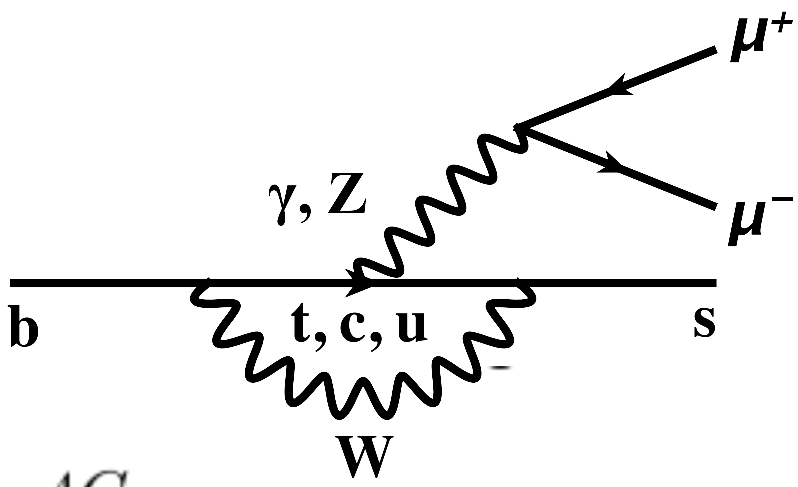
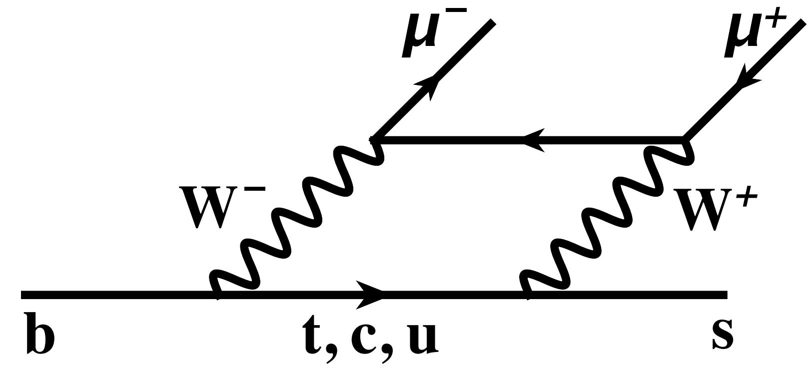
FCNC processes $b \to s\mu^+\mu^-$: golden indirect probes of NP





$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{\rm tb} V_{\rm tq}^* \sum_i \underbrace{\mathcal{C}_i \mathcal{O}_i}_{\text{Left handed}} + \underbrace{\mathcal{C}_i' \mathcal{O}_i'}_{\text{Right handed, } \frac{m_s}{m_b} \text{ suppressed}} + \sum \frac{c}{\Lambda_{\rm NP}^2} \mathcal{O}_{\rm NP}$$

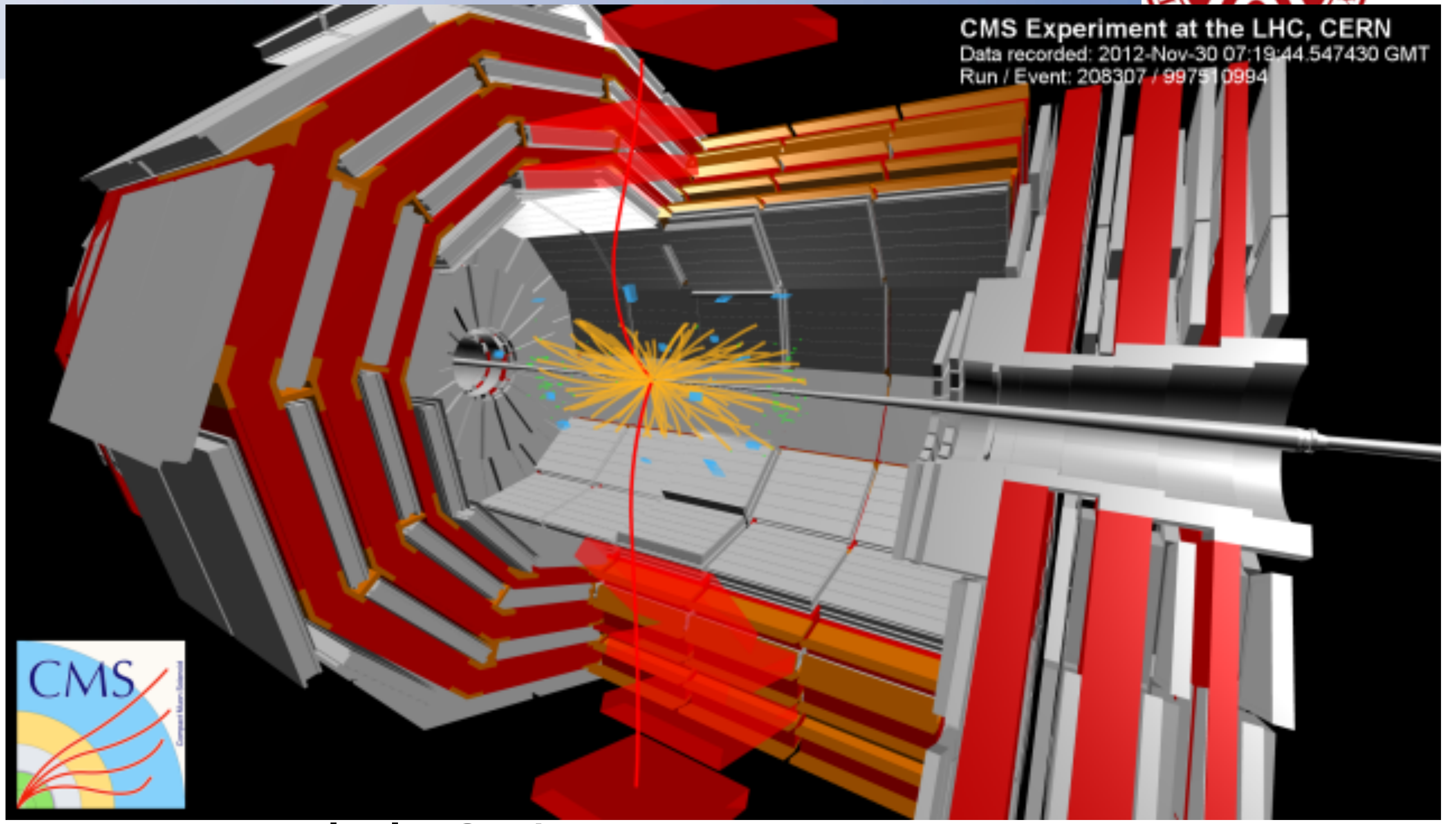
$i = 1, 2$	Tree
$i = 3-6, 8$	Gluon penguin
$i = 7$	Photon penguin
$i = 9, 10$	EW penguin
$i = S, P$	(Pseudo)scalar penguin

Effective theory: Different processes are sensitive to different operators

Operator $\mathcal{O}_i$	$B_{s,d} \to X_{s,d}\mu^+\mu^-$	$B_{s,d} \to \mu^+\mu^-$	$B_{s,d} \to X_{s,d}\gamma$
$\mathcal{O}_7 \sim m_b(\bar{s}_L \sigma^{\mu\nu} b_R) F_{\mu\nu}$	✓		✓
$\mathcal{O}_9 \sim (\bar{s}_L \gamma^\mu b_L)(\bar{\ell}\gamma_\mu \ell)$	✓		
$\mathcal{O}_{10} \sim (\bar{s}_L \gamma^\mu b_L)(\bar{\ell}\gamma_5\gamma_\mu \ell)$	✓	✓	
$\mathcal{O}_{S,P} \sim (\bar{s}b)_{S,P}(\bar{\ell}\ell)_{S,P}$	(✓)	✓	

clean exp signature;
robust theory calc;
high sensitivity

CMS is marvelous for HF studies



- Flexible triggers
- Large silicon tracker
- Strong magnetic field
- Broad acceptance
- Superb muon systems
  - Three different devices, coverage up to $|\eta|<2.4$
  - Dimuon mass resolution ~0.6-1.5% (depending on $|y|$).
  - General fake rate ≤1%
    - ≤0.1% for pi,K; ≤0.05% for proton with a tight muon ID

In this talk: results based on ~$20fb^{-1}$ data from 2012(8TeV)

$B^0 \rightarrow K^{*0}\mu^+\mu^-$: A_{FB}, F_L and BF — Phys. Lett. B 753, 424 (2016).

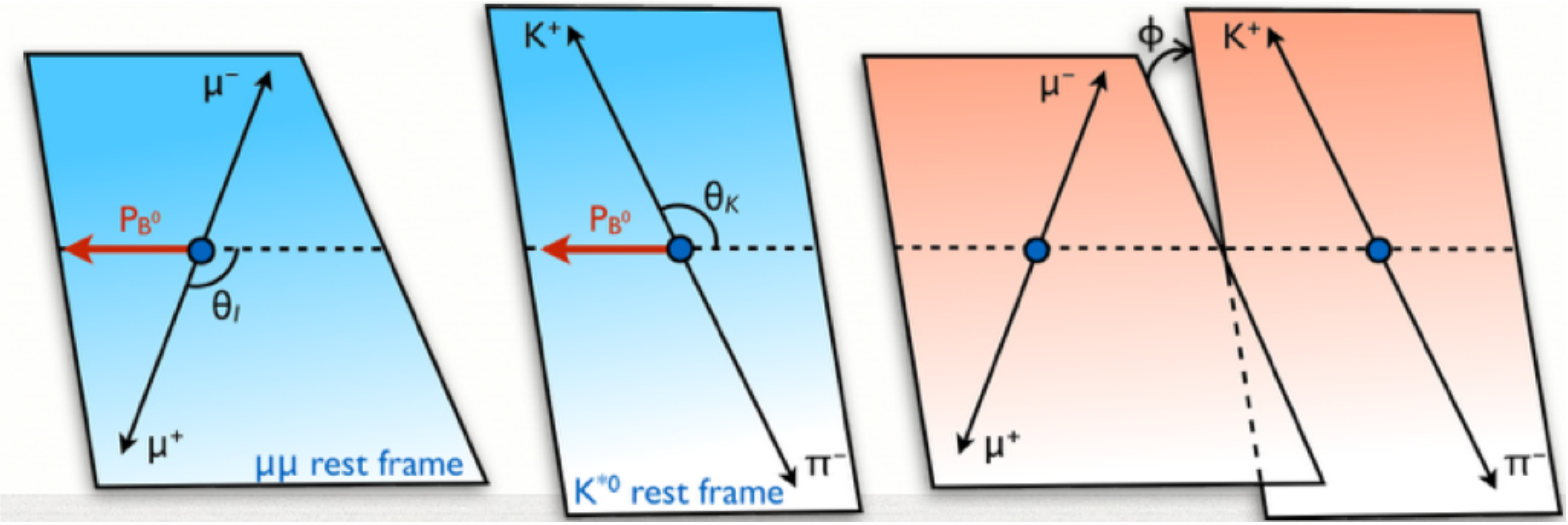
$B^0 \rightarrow K^{*0}\mu^+\mu^-$: P1, P5' — arxiv: 1710.02846, Phys. Lett. B (2018)

$B^+ \rightarrow K^+\mu^+\mu^-$: A_{FB}, F_H — CMS-BPH-15-001

See also talks:

- Manzoni, Fedi, Ronchese, Guisao, Ozcelik, Boletti
- S. Fiorendi talk for HL-LHC aspects

$B^0 \to K^{*0} \mu^+\mu^-$ Decay Parameters



$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi} = \frac{9}{32\pi}\Big[\boxed{S_1^s}\sin^2\theta_K + \boxed{S_1^c}\cos^2\theta_K + \boxed{S_2^s}\sin^2\theta_K\cos 2\theta_\ell + \boxed{S_2^c}\cos^2\theta_K\cos 2\theta_\ell + \boxed{S_3}\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + \boxed{S_4}\sin 2\theta_K\sin 2\theta_\ell\cos\phi + \boxed{S_5}\sin 2\theta_K\sin\theta_\ell\cos\phi + \boxed{S_6}\sin^2\theta_K\cos\theta_\ell + \boxed{S_7}\sin 2\theta_K\sin\theta_\ell\sin\phi + \boxed{S_8}\sin 2\theta_K\sin 2\theta_\ell\sin\phi + \boxed{S_9}\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big],$$

Complete description of the decay rate: 11 variables!

Simplified decay rates and parameters

$$\frac{1}{\Gamma}\frac{d^3\Gamma}{d\cos\theta_K d\cos\theta_l dq^2} = \frac{9}{16}\Bigg\{\frac{2}{3}\left[F_S + A_S\cos\theta_K\right](1-\cos^2\theta_l) + (1-F_S)\Big[2F_L\cos^2\theta_K(1-cos^2\theta_l) + \frac{1}{2}(1-F_L)(1-\cos^2\theta_K)(1+\cos^2\theta_l) + \frac{4}{3}A_{FB}(1-\cos^2\theta_K)\cos\theta_l\Big]\Bigg\}$$

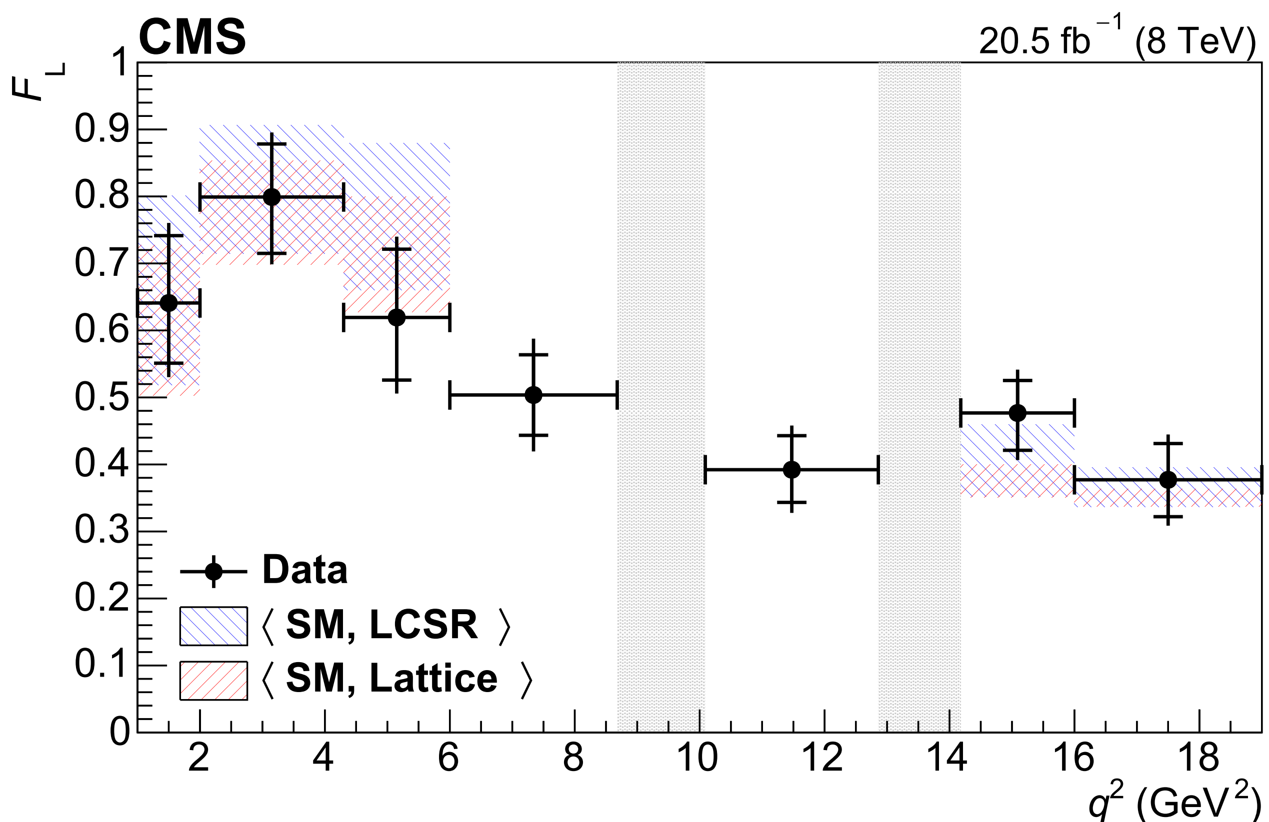
F_S: fraction of S-wave (~few %)
A_S: interference amplitude

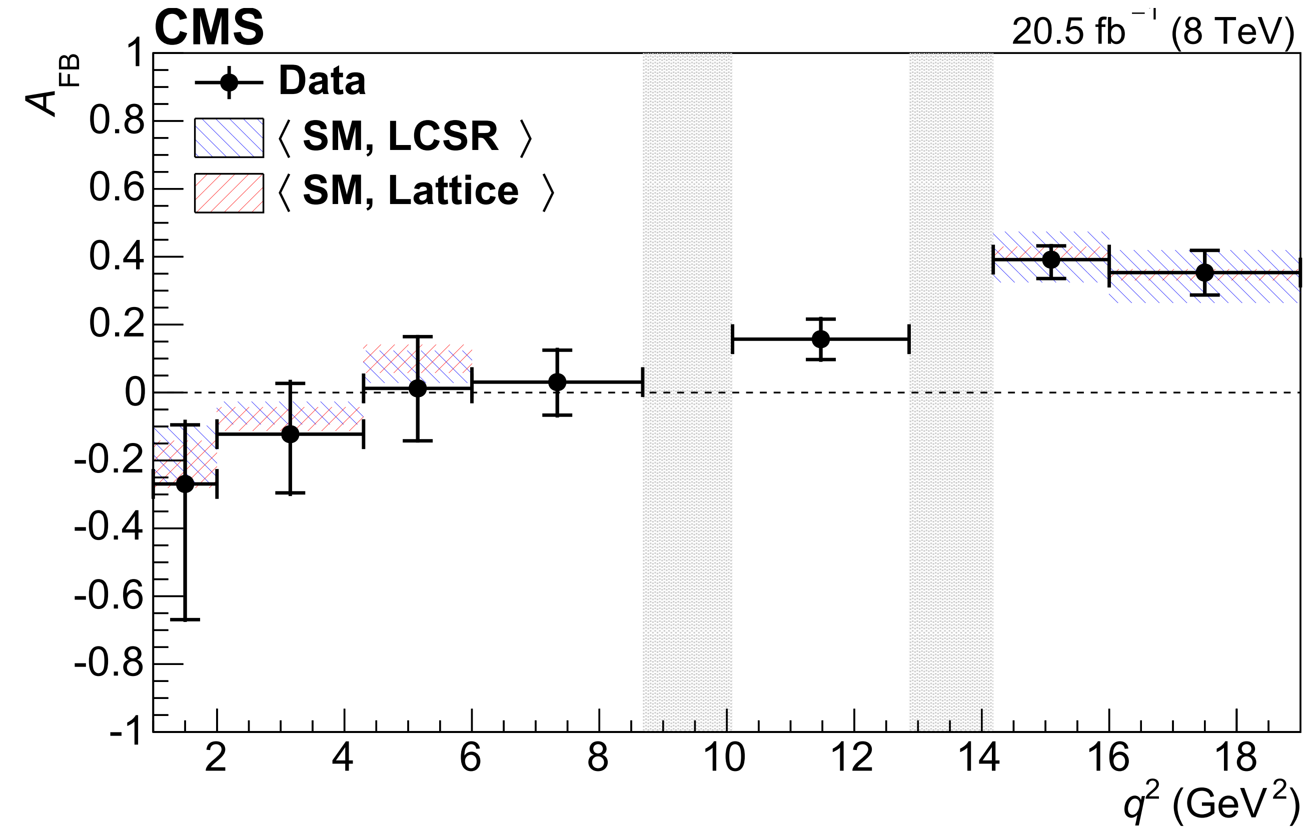
A_{FB} and F_L do not depend on ϕ, efficiency nearly constant.

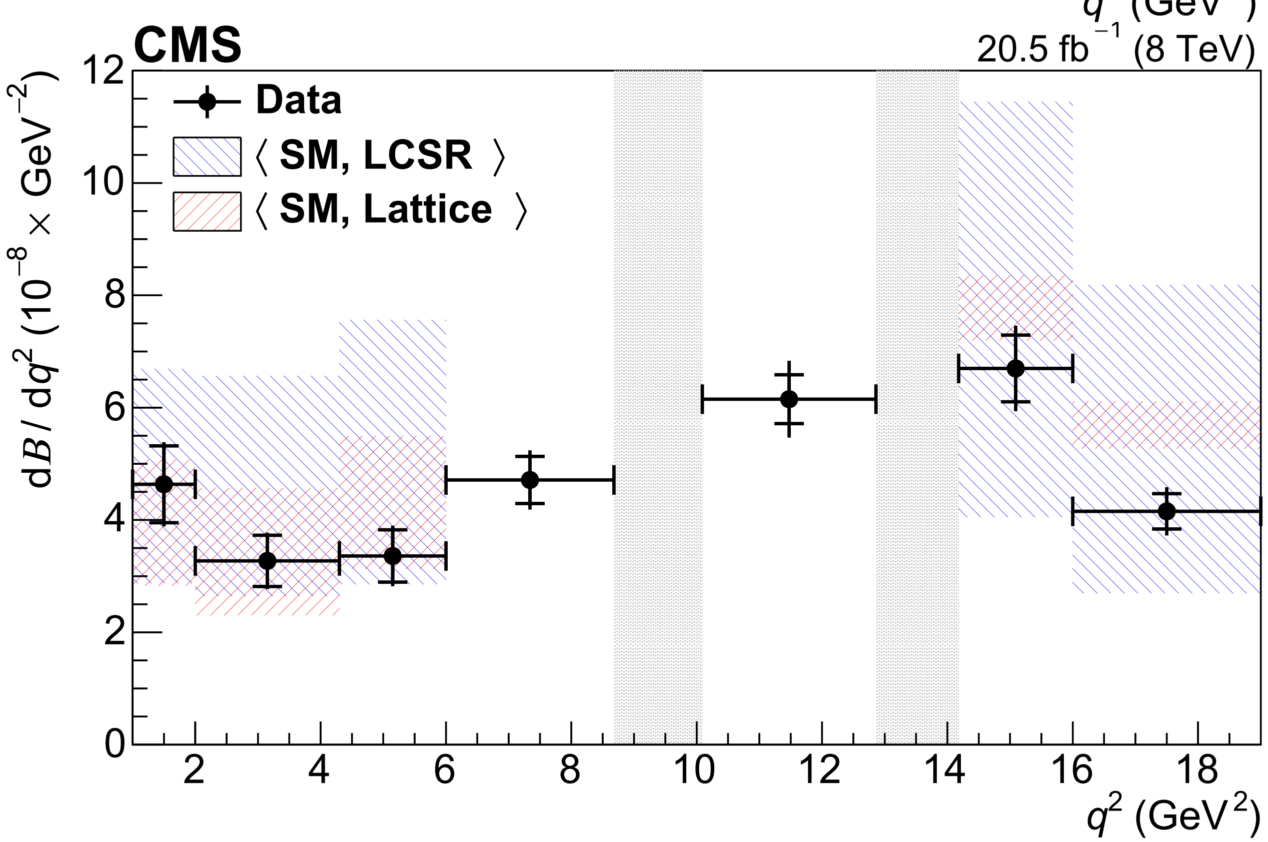
F_L :Fraction of longitudinal polarization of the K*

A_{FB}:Forward-backward asymmetry of the dilepton system

CMS 8TeV Results





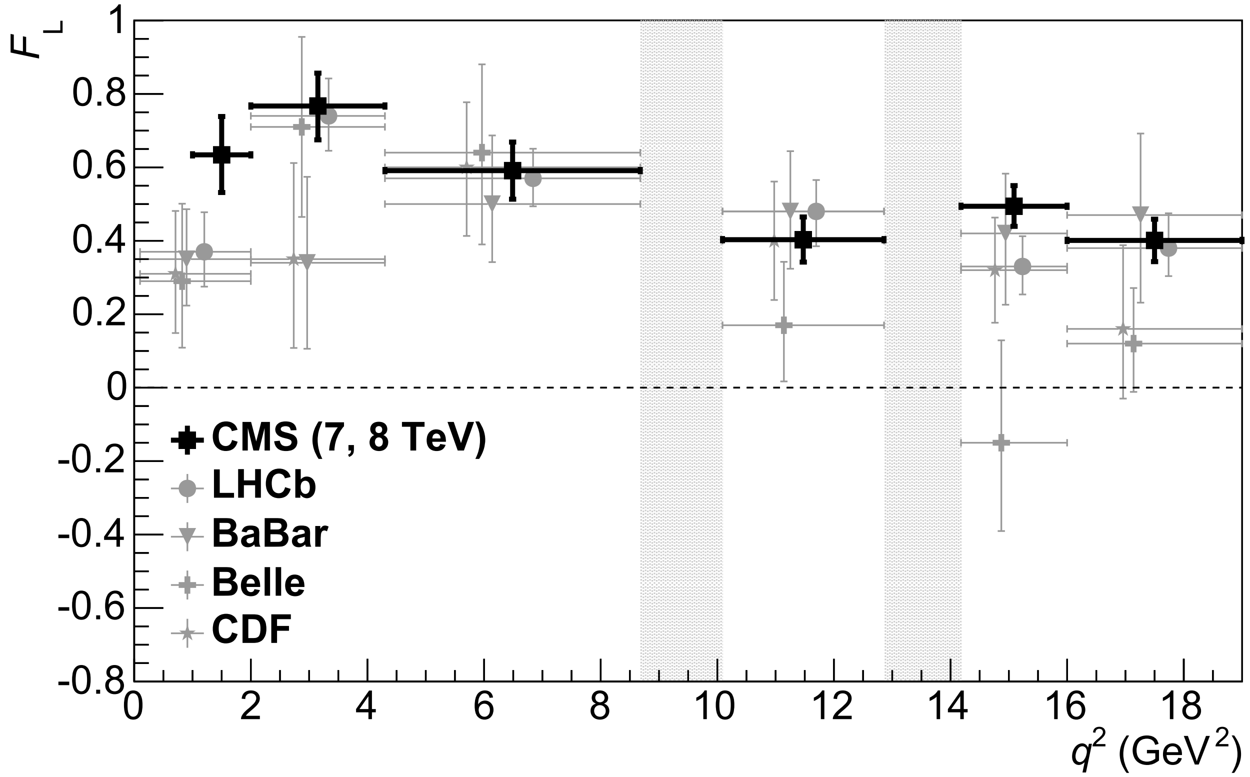


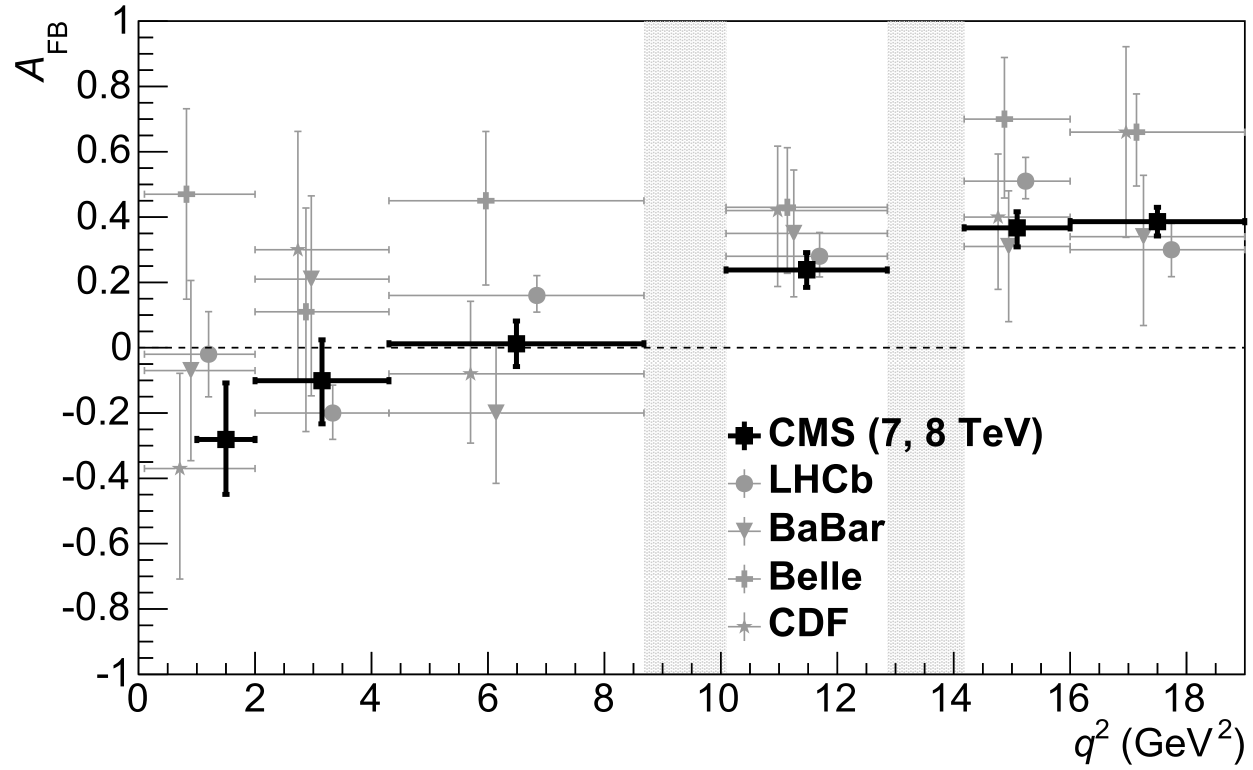
CMS-BPH-13- 010

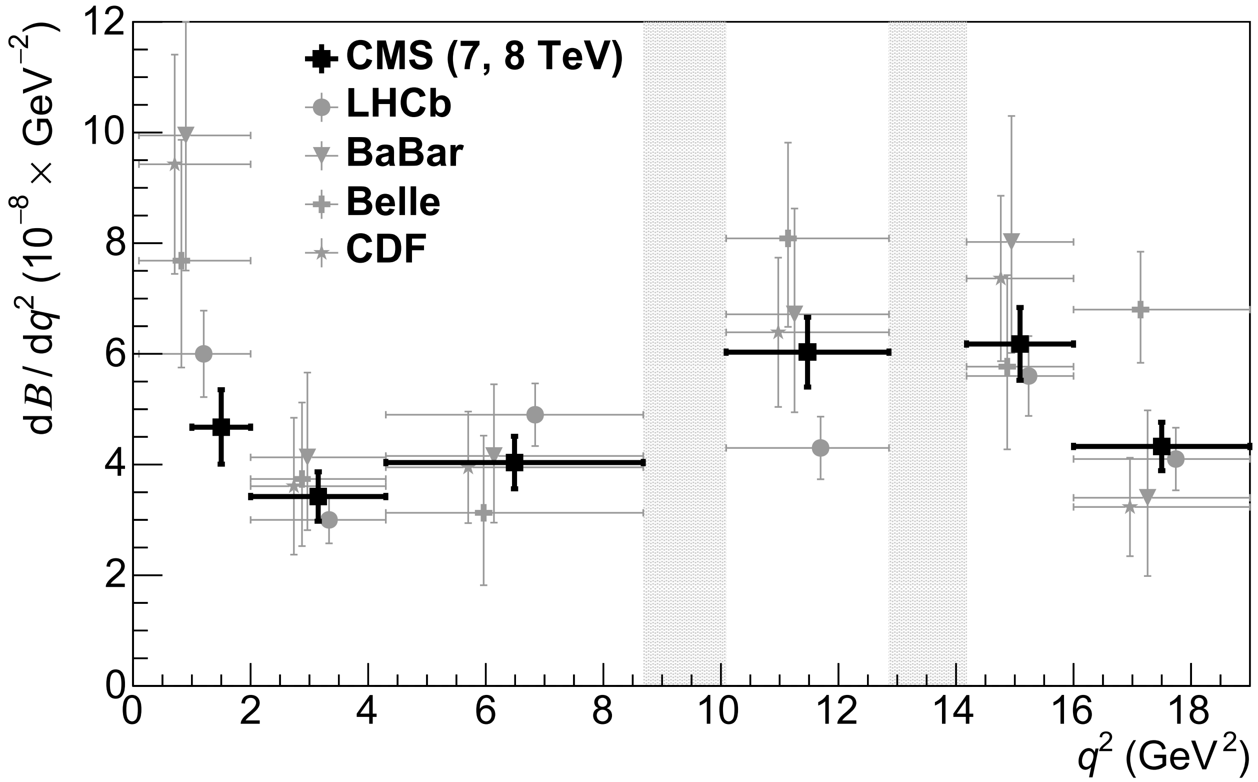
Phys. Lett. B 753, 424 (2016).

The CMS results are in good agreement with the SM predictions, indicating no strong contribution from physics beyond the standard model.

Combined results 7/8TeV







Phys. Lett. B 753, 424 (2016).

The CMS measurements are consistent with the other results, with comparable or higher precision.

- BaBar: Phys. Rev. D 86 (2012) 032012,
- Belle: *Phys. Rev. Lett.* ***103*** *(2009) 171801*
- CDF: *Phys. Rev. Lett.* ***108*** *(2012) 081807*
  Phys. Rev. Lett. 106 (2011) 161801
- LHCb (3 fb^{-1}): JHEP 08 (2013) 131

$B^0 \to K^{*0}\,\mu^+\mu^-$: angular observables of $\mathbf{P1, P5'}$

- Several B anomalies point to discrepancy with SM at ~3sigma
- Form-factor independent observables P5’, P1 could be checked by CMS
- Folding the pdf around $\boldsymbol{\Phi}$=0 and $\boldsymbol{\theta_l}=\pi/2$

S-wave and S&P-wave interference

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

P-wave

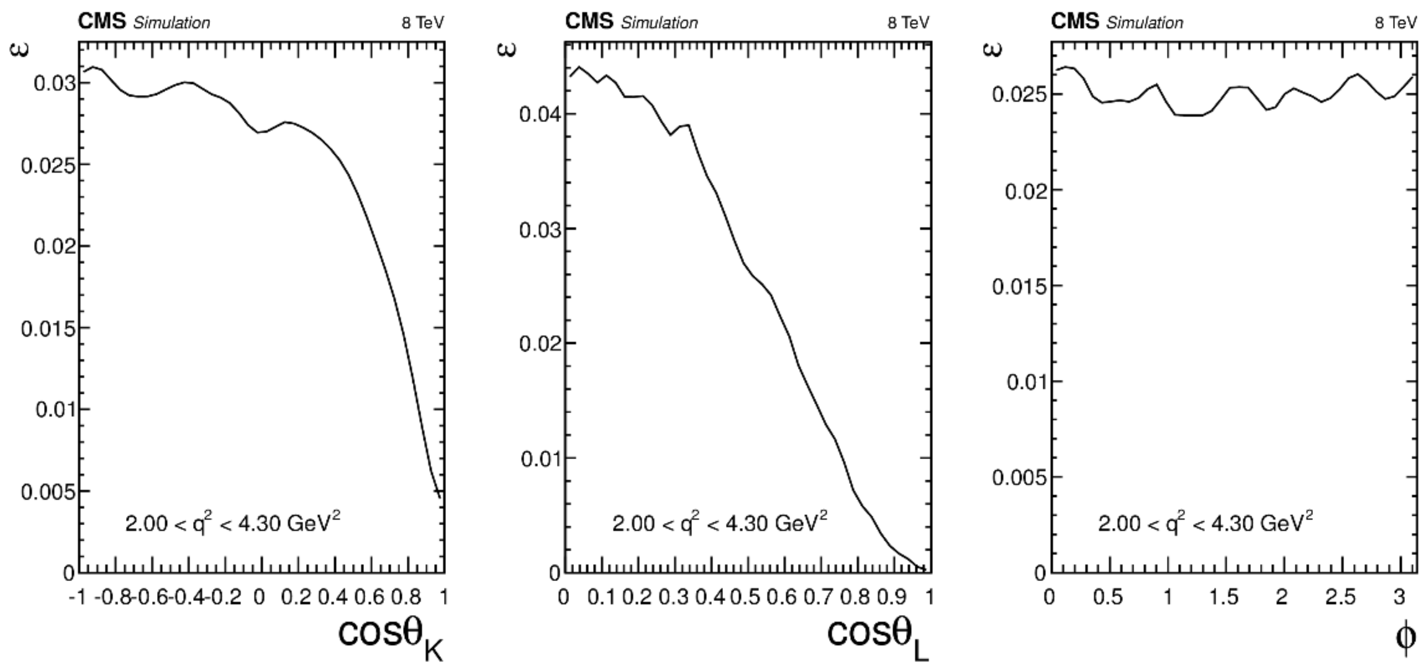
CMS-BPH-15-008

Efficiency & p. d. f $\quad B^0 \rightarrow K^{*0}\mu^+\mu^-$

Efficiency

- signal , control channels;
- correctly tagged , mistagged ever

$2^{nd}\ q^2$ bin, Correctly tagged events



The probability density function

$$\text{p.d.f.}(m,\theta_K,\theta_l,\Phi) = \boxed{Y_S^C}\Big[\boxed{S^C(m)}\boxed{S^a(\theta_K,\theta_l,\phi)}\boxed{\epsilon^C(\theta_K,\theta_l,\phi)}$$

Correctly tagged events

Mistag fraction

$$+\frac{\boxed{f^M}}{1-f^M}\boxed{S^M(m)}\boxed{S^a(-\theta_K,-\theta_l,\phi)}\boxed{\epsilon^M(\theta_K,\theta_l,\phi)}\Big]$$

Mistagged events

$$+\boxed{Y_B\, B^m(m)\, B^{\theta_K}(\theta_K)\, B^{\theta_l}(\theta_l)\, B^{\phi}(\phi)},$$

Background

Signal contribution: mass shape (double gaussian), decay rate, and 3D efficiency function.

Background contribution: mass shape (exponential) and different degrees polynomial functions for each angular variable

Fitting & Validation

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

Strategy

- Extracted from unbinned extended maximum likelihood fit in each bin:

  $\boldsymbol{m(K^+\pi^-\mu^+\mu^-)}$, **cos($\boldsymbol{\theta_l}$), cos($\boldsymbol{\theta_k}$), $\boldsymbol{\Phi}$**

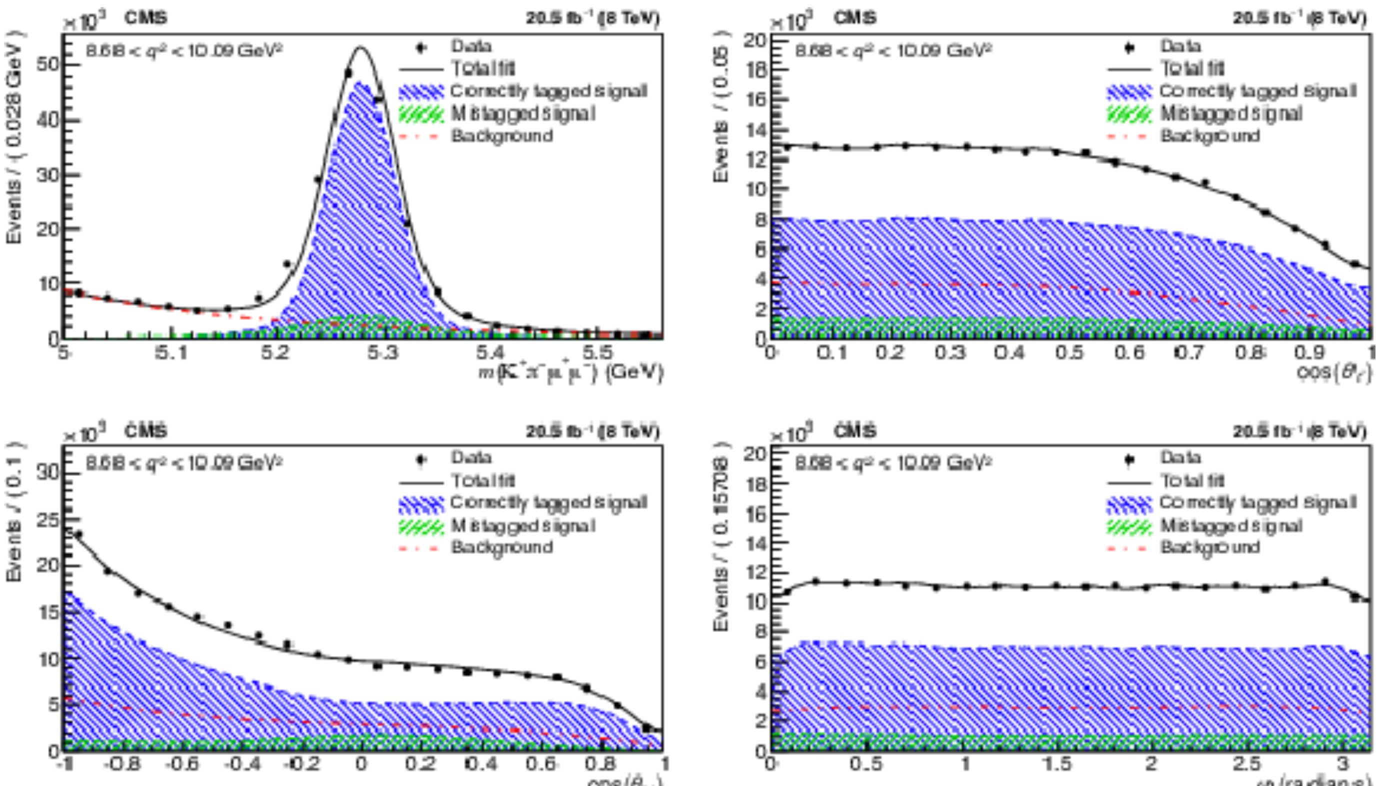
- Fit performed in two steps:

  1. fit sidebands to determine background shape, fixed in the next step
  2. fit whole mass spectrum, 5 free parameters

- **Feldman-Cousins** method with profiling nuisance parameters

Validation with **data control channels**

- Fit performed with F_L free to float
- Measured F_L agrees with PDG value



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

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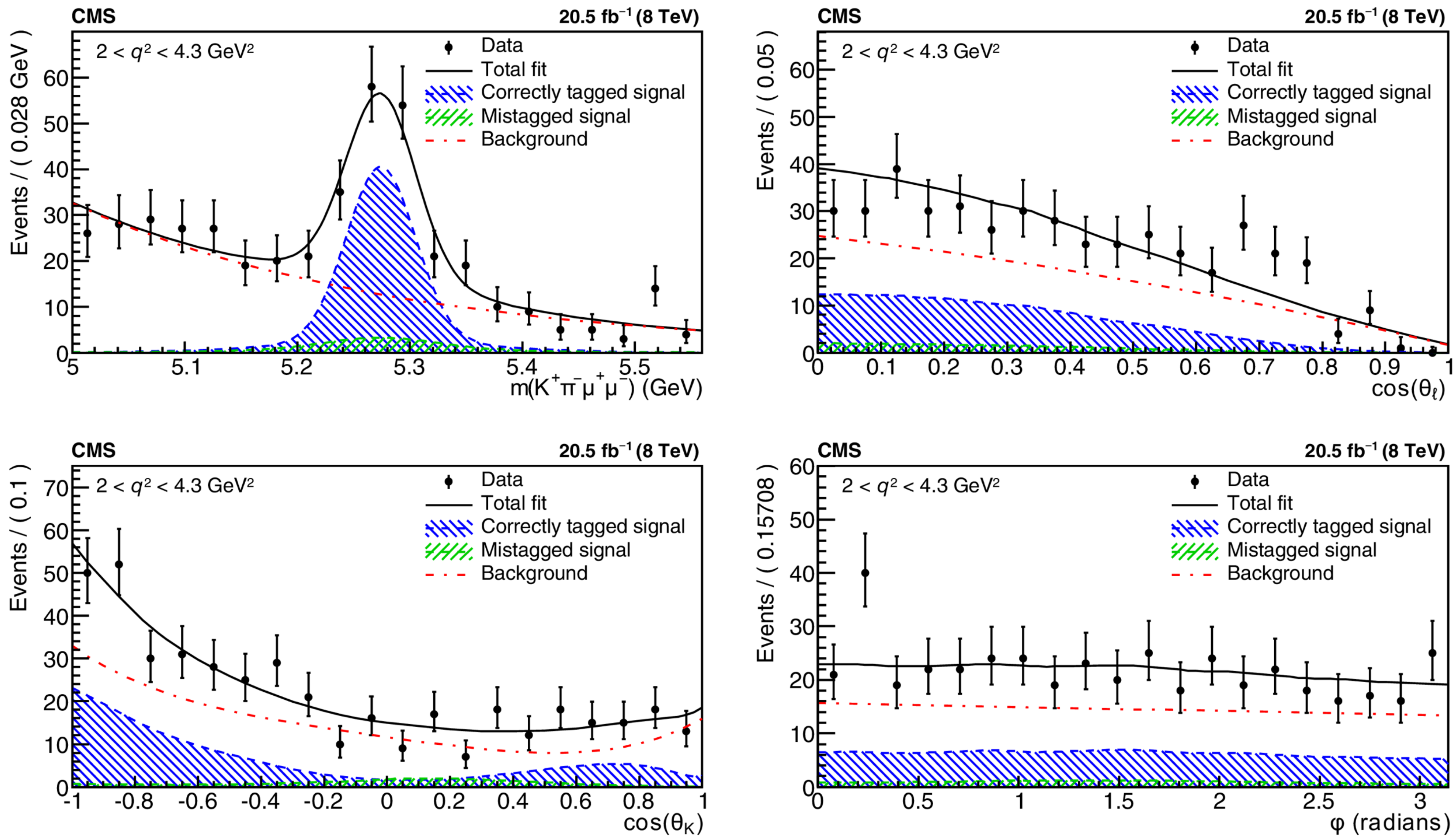
Fitting Results

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

$2^{nd}\ q^2$ bin

A total of ~1400 signal events in all q^2 bins



Total fit

Signal (correctly tagged)

Signal (mistagged)

Background

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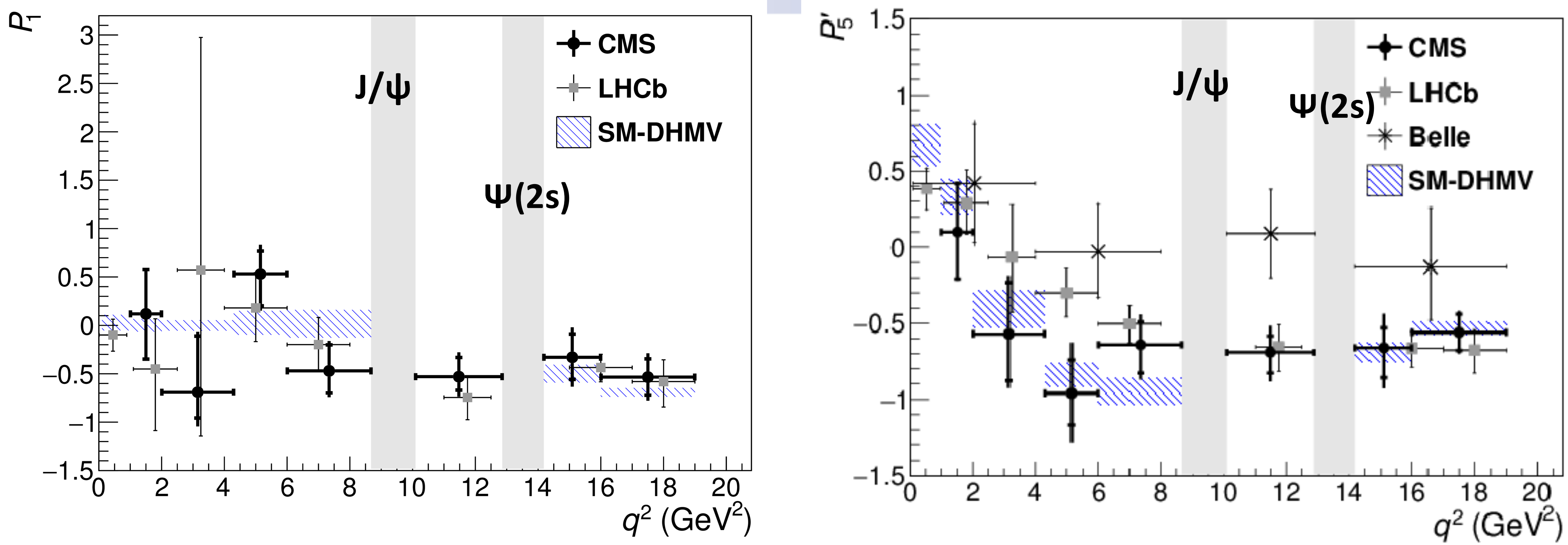
P_1 and P_5' results

$B^0 \rightarrow K^{*0}\, \mu^+ \mu^-$

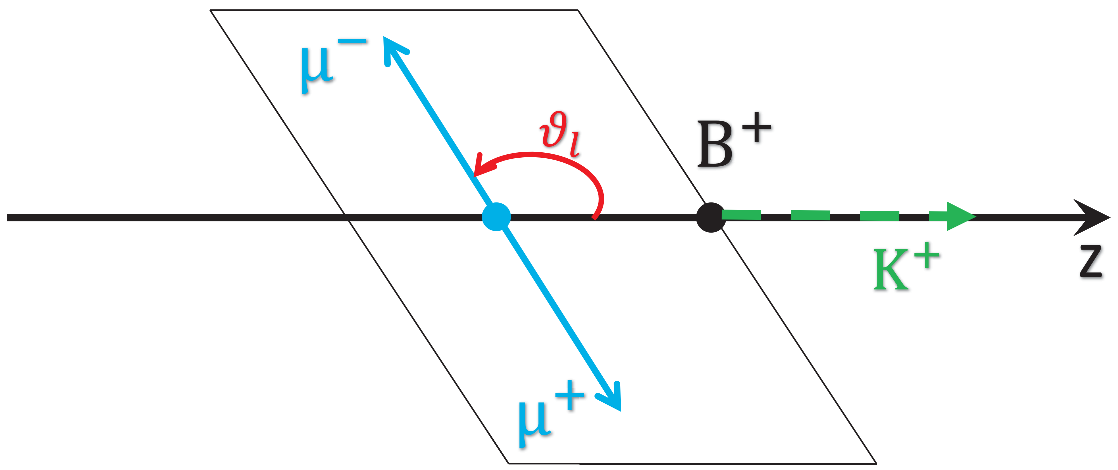


- The events are fit in seven q^2 bins from 1 to 19 GeV^2, yielding 1397 signal and 1794 background events in total.
- CMS results are consistent with SM and previous measurements.

LHCb: *JHEP 02 (2016) 104*
Belle: *Phys. Rev. Lett. 118, 111801 (2017)*
SM-DHMV: *JHEP 01 (2013) 048, JHEP 05 (2013) 137*

arxiv: 1710.02846
Phys. Lett. B (2018) in press.

Public result page:
https://cms-results.web.cern.ch/cms-results/public-results/publications/BPH-15-008/index.html



- The differential decay rate of the $B^+(B^-)$ decay, as a function of $\cos\theta_l$, can be written as:

$$\frac{1}{\Gamma}\frac{d\Gamma[B^+\to K^+\mu^+\mu^-]}{d\cos\theta_l} = \frac{3}{4}(1-F_H)(1-\cos^2\theta_l) + \frac{1}{2}F_H + \mathcal{A}_{FB}\cos\theta_l$$

$$0 \le F_H \le 3, \quad |\mathcal{A}_{FB}| \le \min(1, F_H/2)$$

θ_l : angle between the $\mu^+(\mu^-)$ and the $K^-(K^+)$ in the rest frame of the dimuon system.
$\mathcal{A}_{FB}$: $\mu^+\mu^-$ forward-backward asymmetry.
F_H: the contribution from (pseudo)scalar and tensor amplitudes to the decay width.

CMS-BPH-15-001

$B^+ \to K^+\mu^+\mu^-$: pdf and efficiency

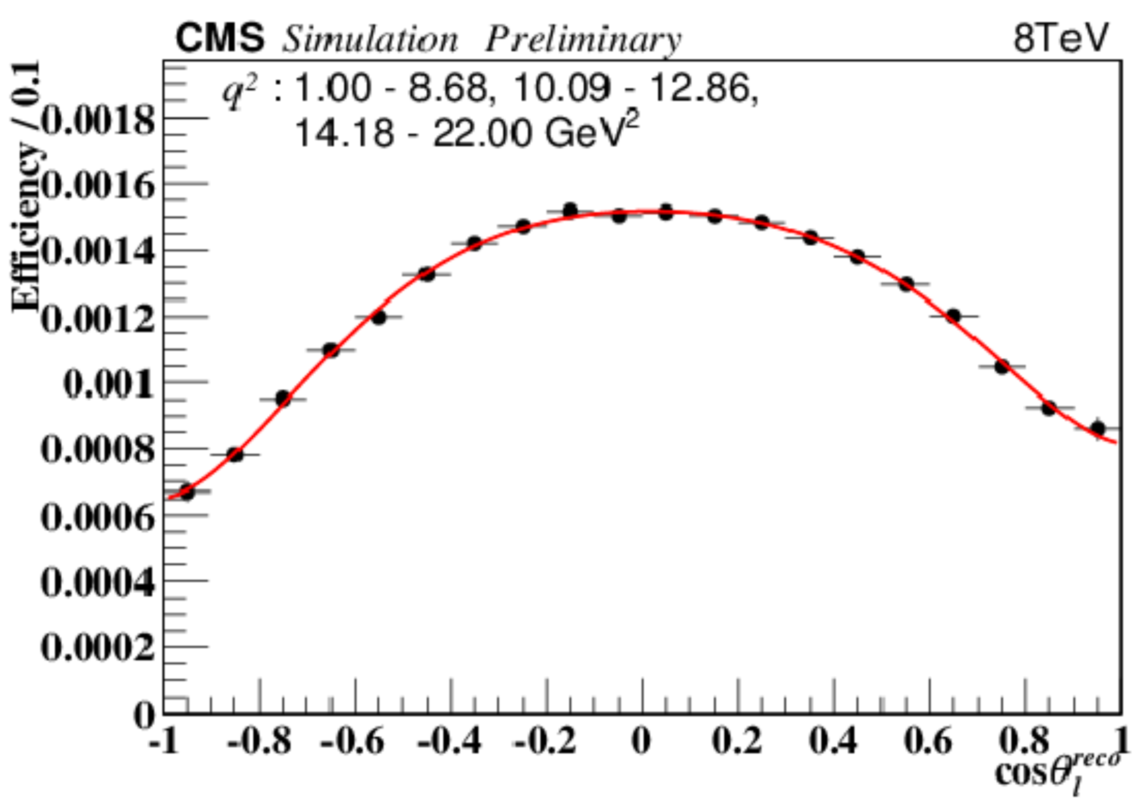
➢ $pdf(m, \vartheta_l) = Y_S \cdot \boxed{S(m)} \cdot \boxed{S(\theta_l)} \cdot \boxed{\varepsilon(\theta_l)} + Y_B \cdot B(m) \cdot B(\theta_l)$

✓Signal: mass shape (double Gaussian), angular shape, and efficiency function.

✓Background contribution: mass shape (exponential) and different degrees polynomial plus a Gaussian function for each angular variable.

➢ Efficiency:

- Factorized into an acceptance and a reco efficiency, for each q^2 bin
- the signal efficiency $\varepsilon(\cos\theta_l)$ is parametrized with a sixth-order polynomial.



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Fitting and validation

➢Fitting strategy:

✓extracted from un-binned extended maximum likelihood fit in each bin:

$m(K^+\mu^+\mu^-)$, $cos\theta_l$

✓Fit performed in two steps:

1) fit sidebands to determined background shape, fixed in the next step;

2) fit whole mass spectrum, 5 free parameters, A_{FB}, F_{H}, yields and background mass shape parameters.

➢Validation with data control channels:

✓Cross section $\sigma_{\mathrm{J/\psi K^+}}$ measured, comparable with 7TeV(CMS-BPH-10-004) and 13TeV(CMS-BPH-15-004) results, extrapolated by FONLL;

✓Ratio of branching fractions measured agrees with PDG value.

➢Several validation steps are performed with simulation:

- with large size of MC signal sample
- with signal MC subsamples
- with 200 pseudo experiments

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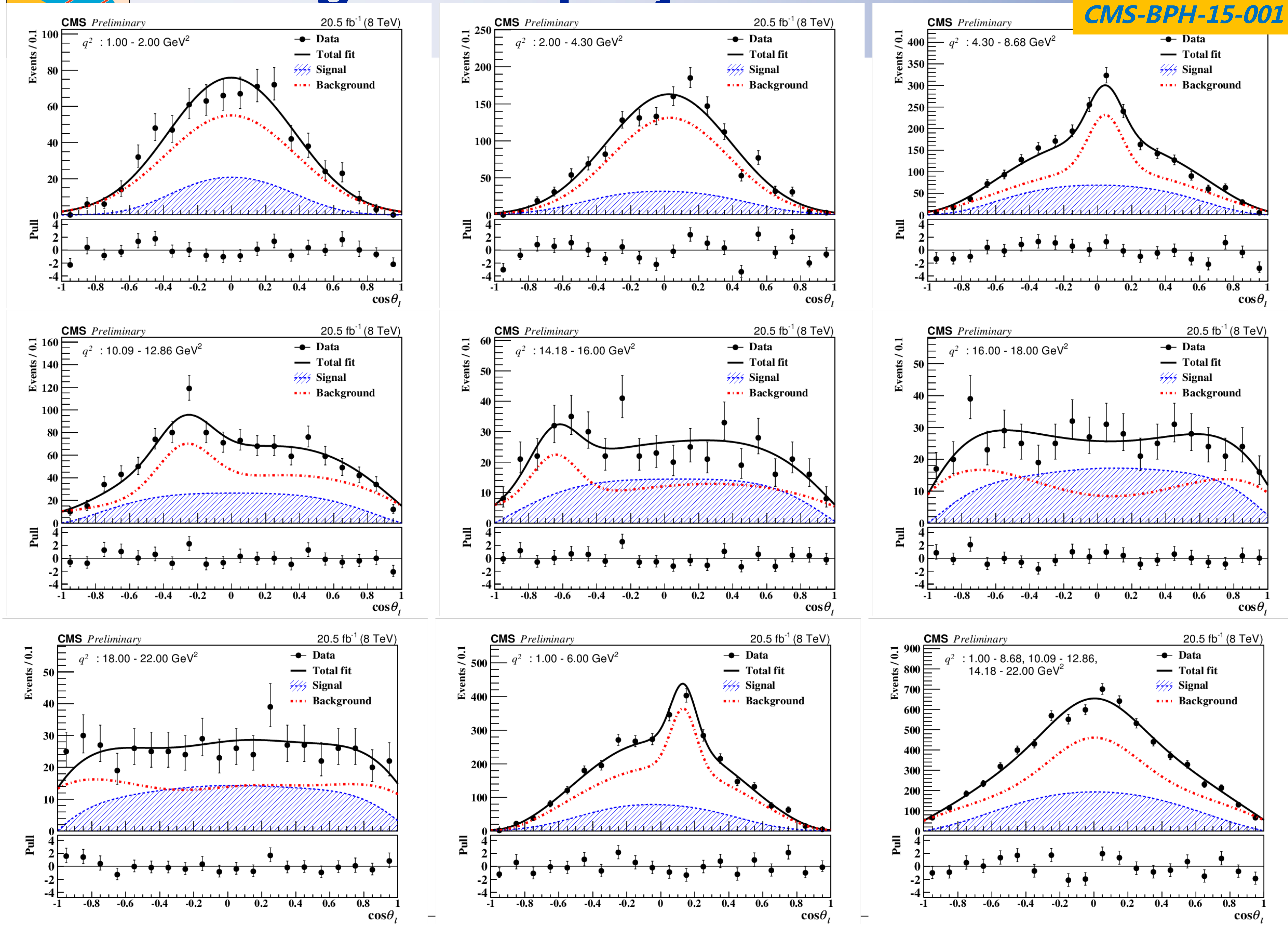
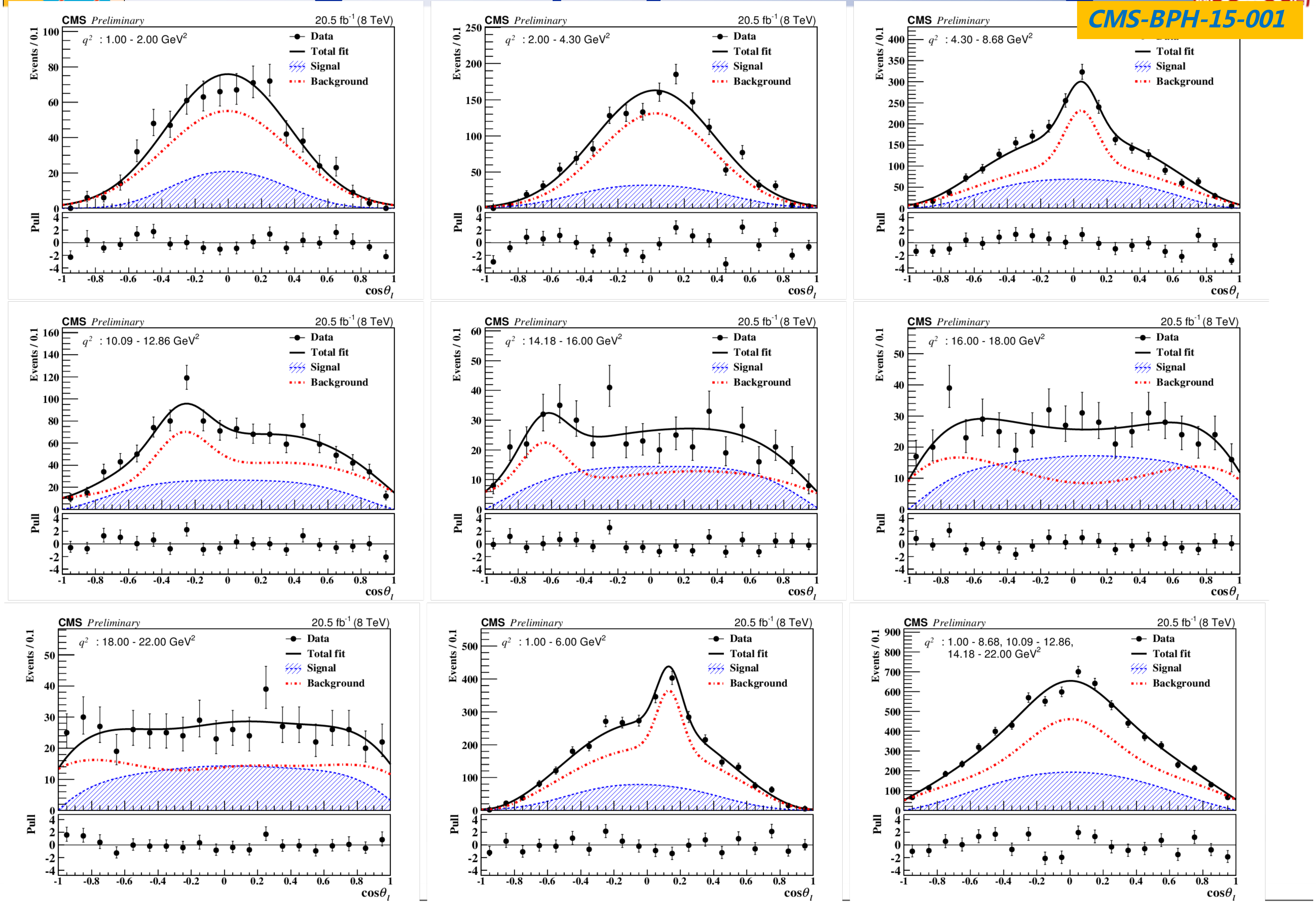
Fitting result projections on mass

CMS-BPH-15-001

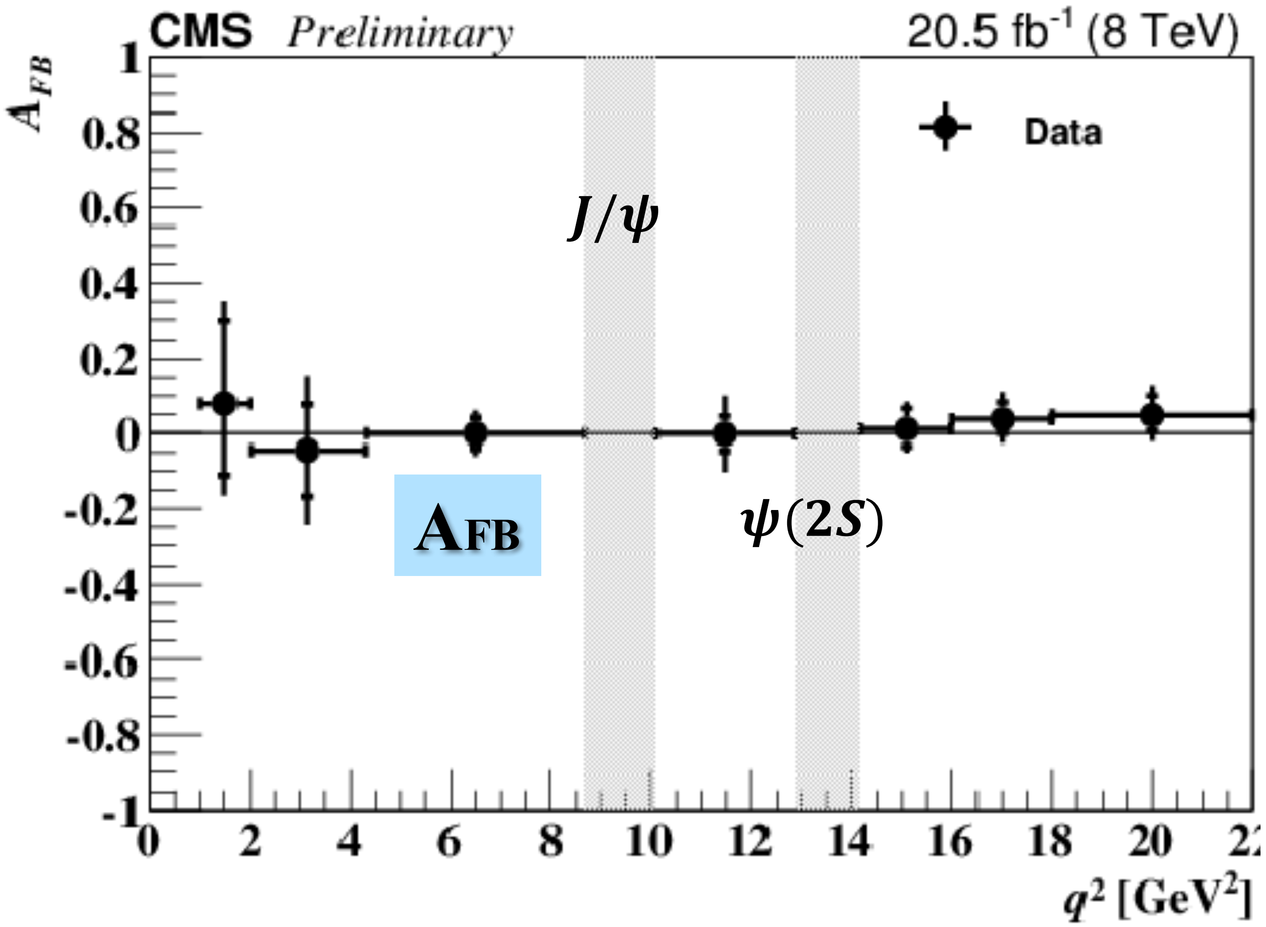


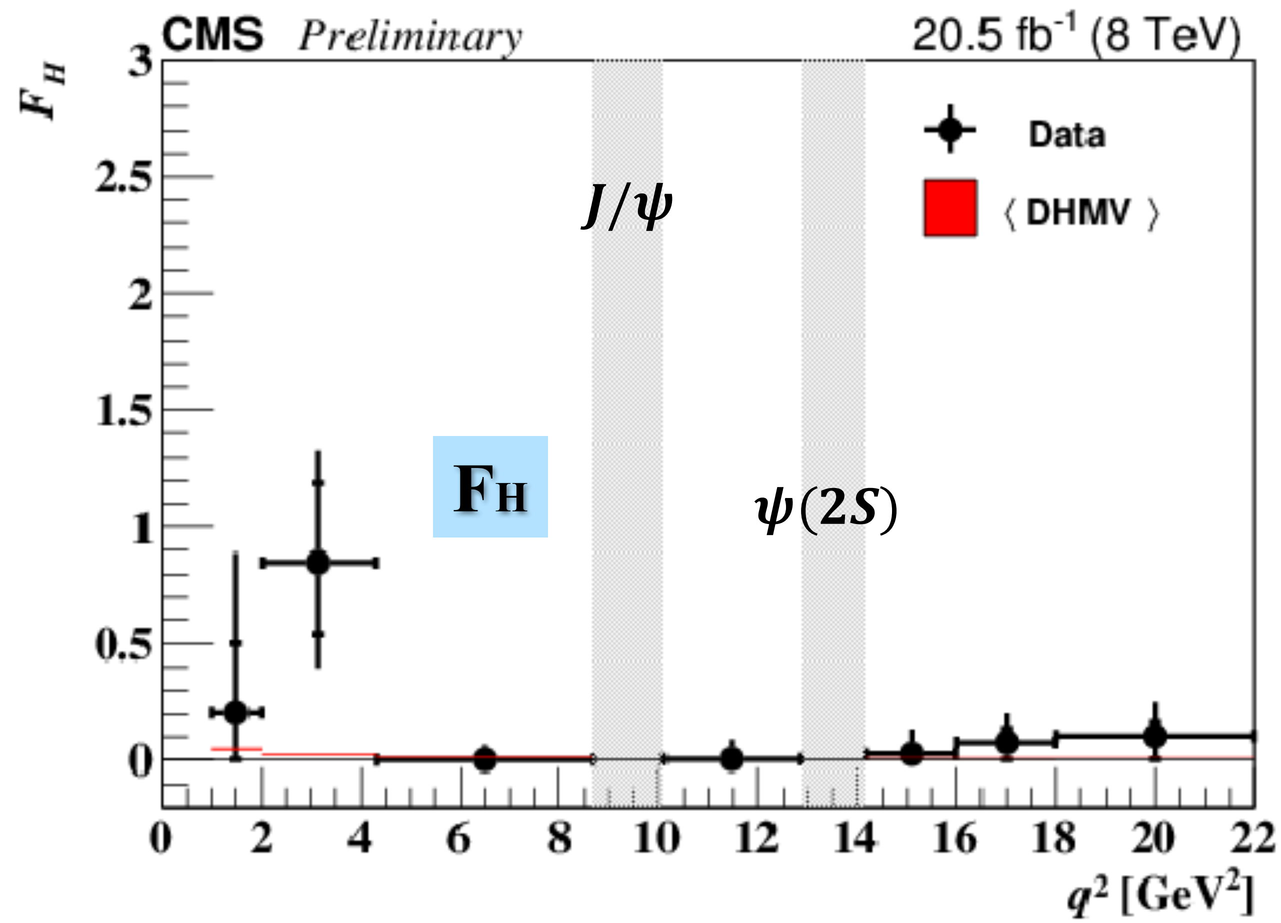
Fitting result projections on angle

CMS-BPH-15-001



$B^+ \to K^+\mu^+\mu^-$ A_{FB} and F_H results





The measured A_{FB} and F_H show good agreement with the SM predictions within the uncertainty.

No clear indication of new physics beyond the SM could be drawn from present results.

CMS-BPH-15-001

Public result page:
https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/BPH-15-001/index.html

Summary

- **Rare FCNC transitions $b \to s\mu^+\mu^-$ are good probes of physics beyond standard model**
- **CMS has performed several angular analyses**
  - **$B^0 \to K^{*0}\mu^+\mu^-$: A_{FB}, F_L and BF** — Phys. Lett. B 753, 424 (2016).
  - **$B^0 \to K^{*0}\mu^+\mu^-$: P1, P5'** — arxiv: 1710.02846, Phys. Lett. B (2018)
  - **$B^+ \to K^+\mu^+\mu^-$: A_{FB}, F_H** — CMS-BPH-15-001
- **They provide precise tests of SM predictions. No deviations from theory are seen**
- **More are coming ... Stay tuned!**
  - **Sister analyses with Run-I data**
  - **More results based on Run-II data**

Thank You

Systematic uncertainty

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

Source	$P_1 (\times 10^{-3})$	$P_5' (\times 10^{-3})$
Simulation mismodeling	1–33	10–23
Fit bias	5–78	10–120
Finite size of simulated samples	29–73	31–110
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	0–210	0–210
Angular resolution	2–68	0.1–12
Total	100–230	70–250

F_L, F_S, A_s uncertainty propagation:

- Generate a **large** data, $\mathcal{O}(100\times\text{data})$, pseudo experiments (one per q^2)
- Fit with all 6 angular parameters **free to float**
- Fit with $\boldsymbol{F_L, F_S, A_s}$ **fixed**
- Ratio of uncertainties between free and partially-fixed fit is used to compute the systematic uncertainty

CMS-BPH-15-008

$B^+ \to K^+\mu^+\mu^-$ Systematic uncertainty

- **Limited size of MC samples:**
- **Efficiency description:**
- **Kinematic mis-modeling:**
- **Background parametrization model:**
- **Angular resolution:**
- **Dimuon mass resolution:**
- **Fitting bias:**
- **Background distribution:** .

Systematic uncertainty	$A_{FB}(\times 10^{-2})$	$F_H(\times 10^{-2})$
Limited size of MC samples	0.4–1.8	0.9–5.0
Efficiency description	0.1–1.5	0.1–7.8
Kinematic mismodeling	0.1–2.8	0.1–1.4
Background parametrization model	0.1–1.0	0.1–5.1
Angular resolution	0.1–1.7	0.1–3.3
Dimuon mass resolution	0.1–1.0	0.1–1.5
Fitting biases	0.1–3.2	0.4–25
Background distribution	0.1–7.2	0.1–29
Total systematic uncertainty	1.6–7.5	4.4–39

$B^+ \to K^+\mu^+\mu^-$ numerical results

- Results of the fit for each q^2 bin, together with several SM predictions.
  - ✓the inclusive q^2 bin 1.00–22.00 GeV^2 does not include events from the J/ψ and ψ′ resonance regions.
  - ✓the first uncertainties are statistical, calculated by profiled Feldman-Cousins method.
  - ✓the values from fifth to seventh columns are SM prediction.

q^2 [GeV^2]	Y_S	A_{FB}	F_H	$F_{H(EOS)}$	$F_{H(DHMV)}$	$F_{H(FLAVIO)}$
1.00–2.00	169 ± 22	$0.08^{+0.22}_{-0.19} \pm 0.05$	$0.21^{+0.29}_{-0.21} \pm 0.39$	0.047	0.046	0.045
2.00–4.30	331 ± 32	$-0.04^{+0.12}_{-0.12} \pm 0.07$	$0.85^{+0.34}_{-0.31} \pm 0.14$	0.024	0.023	0.022
4.30–8.68	785 ± 42	$0.00^{+0.04}_{-0.04} \pm 0.02$	$0.01^{+0.02}_{-0.01} \pm 0.04$	–	0.012	0.011
10.09–12.86	365 ± 29	$0.00^{+0.05}_{-0.05} \pm 0.05$	$0.01^{+0.02}_{-0.01} \pm 0.06$	–	–	–
14.18–16.00	215 ± 19	$0.01^{+0.06}_{-0.05} \pm 0.02$	$0.03^{+0.03}_{-0.03} \pm 0.07$	0.007	0.007	0.006
16.00–18.00	262 ± 21	$0.04^{+0.05}_{-0.04} \pm 0.03$	$0.07^{+0.06}_{-0.07} \pm 0.07$	0.007	0.007	0.006
18.00–22.00	226 ± 20	$0.05^{+0.05}_{-0.04} \pm 0.02$	$0.10^{+0.06}_{-0.10} \pm 0.09$	0.008	0.009	0.008
1.00–6.00	778 ± 47	$-0.14^{+0.07}_{-0.06} \pm 0.03$	$0.38^{+0.17}_{-0.21} \pm 0.09$	0.025	0.025	0.020
1.00–22.00	2286 ± 73	$0.00^{+0.02}_{-0.02} \pm 0.03$	$0.01^{+0.01}_{-0.01} \pm 0.06$	–	–	–

CMS-BPH-15-001

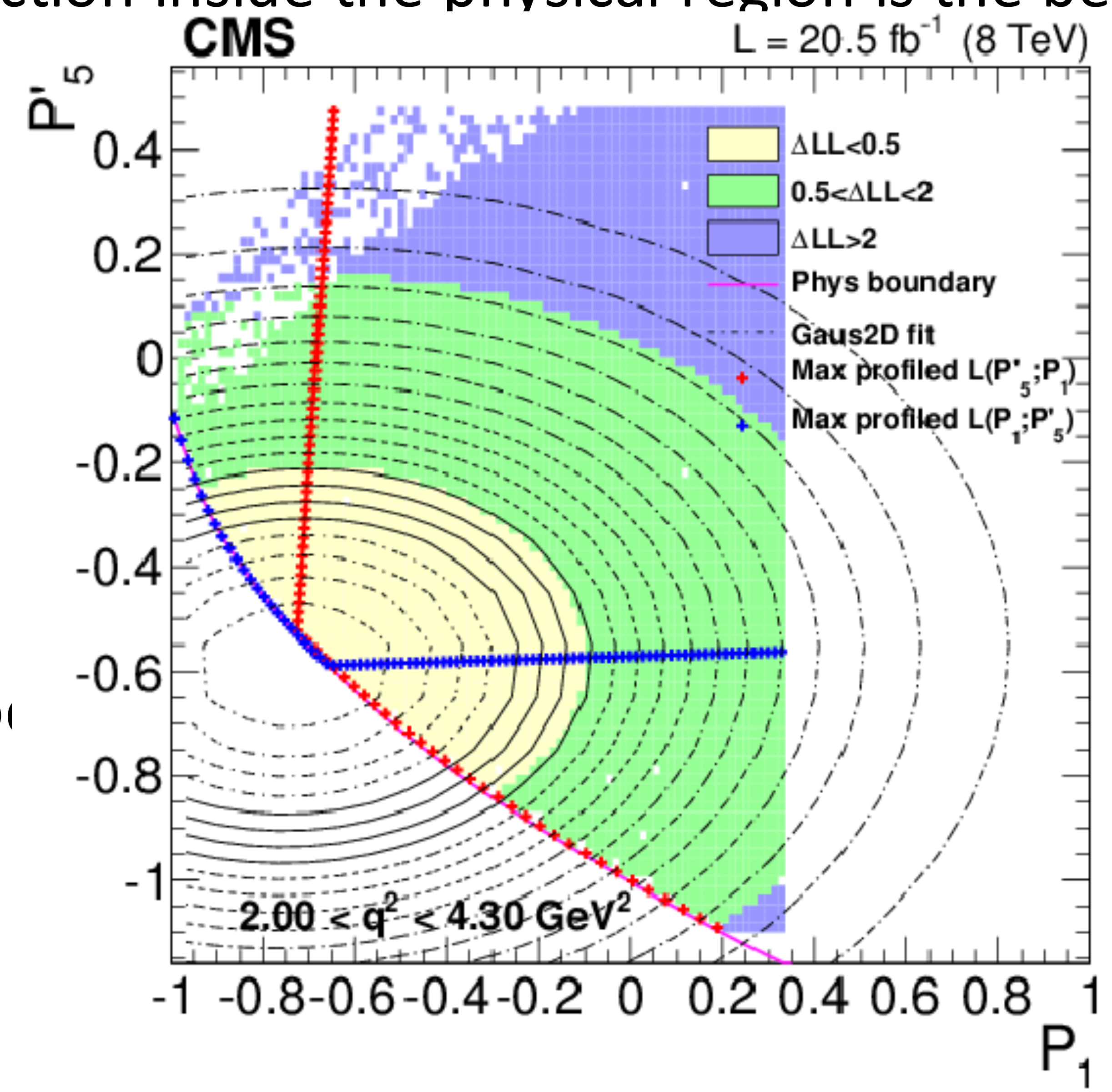
Profiled Feldman-Cousins

$B^0 \to K^{*0}\,\mu^+\mu^-$

The **best estimate** of $\boldsymbol{P_1}$ and $\boldsymbol{P'_5}$ is computed by:

- Discretize the bi-dimensional space $\boldsymbol{P_1}$-$\boldsymbol{P'_5}$
- Maximize the likelihood as a function of $\boldsymbol{Y_S}, \boldsymbol{Y_B}$, and $\boldsymbol{A_5^S}$ at fixed values of $\boldsymbol{P_1}, \boldsymbol{P'_5}$
- Fit the likelihood distribution with a 2D-gaussian function
- The maximum of this function inside the physical region is the best estimate

Coverage: the confidence interval's construction is performed only along two 1D paths determined by profiling the 2D-gaussian description of the likelihood inside the physical region



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

Paths:
- Profile likelihood for P1
- Profile likelihood for P5'

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