Rare Decays and Angular Analyses of $B \to X\mu^+\mu^-$ at CMS

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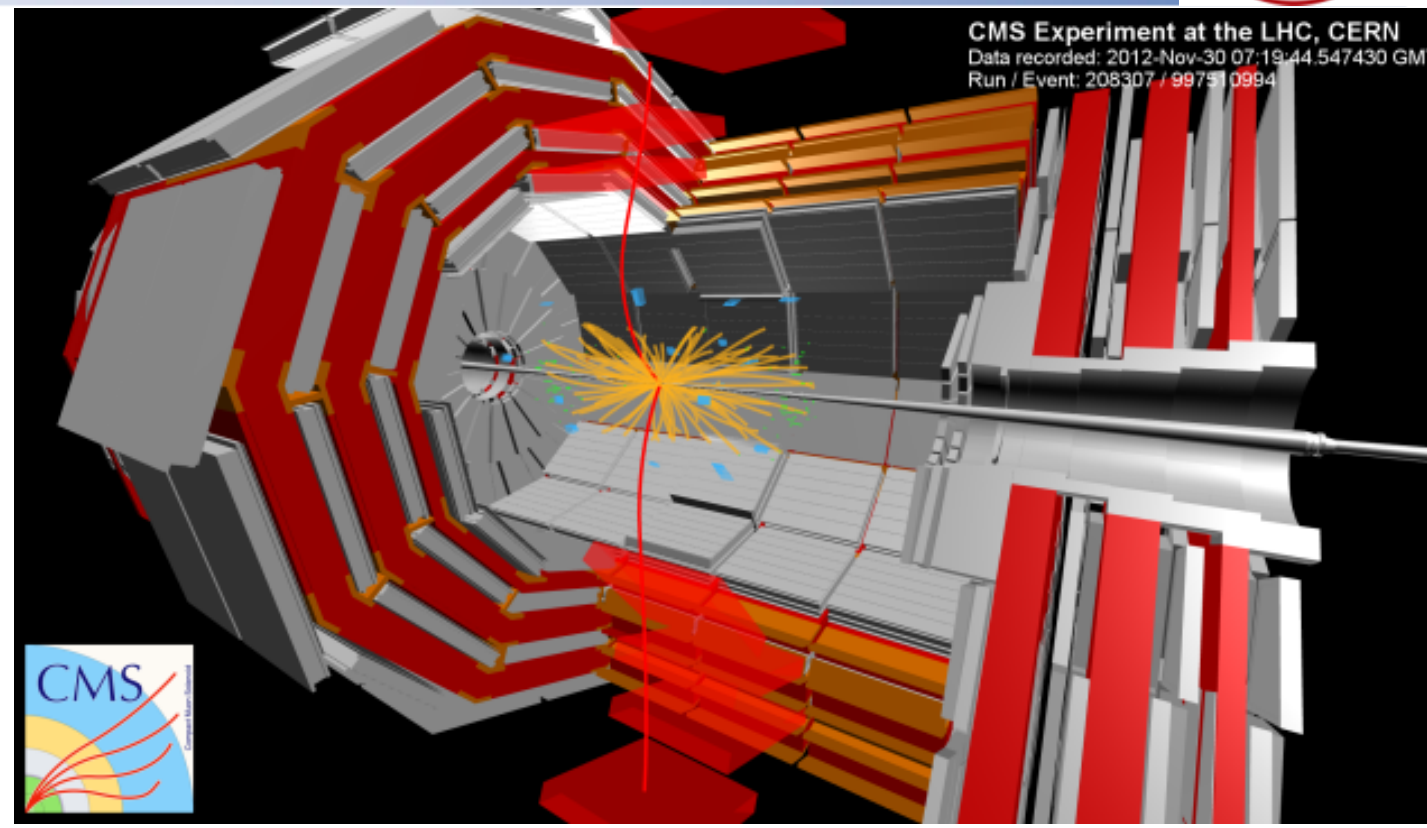
CMS is marvelous for HF studies



- 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 $|y|$).
  - Fake rate ≤0.1% for pi,K; ≤0.05% for proton.
  - MVA-based ID for $B\to \mu^+\mu^-$ analysis.

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

clean exp signature; robust theory calc; high sensitivity

Effective theory: model independent descriptions

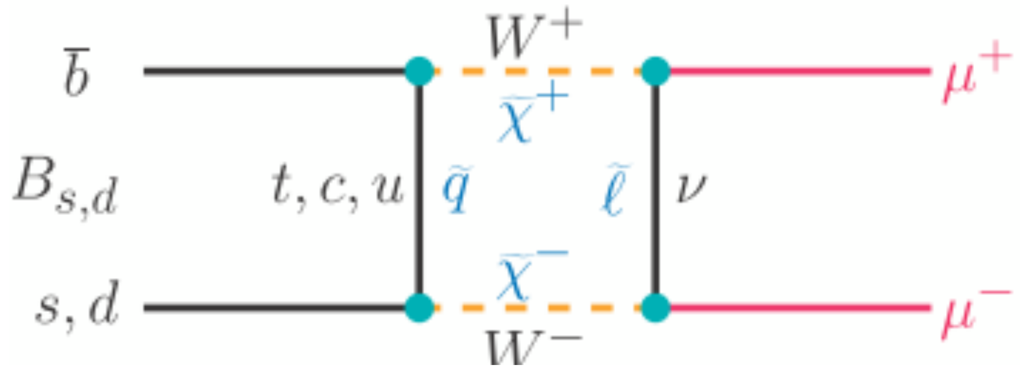
$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{\rm tb} V_{\rm tq}^* \sum_i \underbrace{\mathcal{C}_i \mathcal{O}_i}_{\text{Left handed}} + \underbrace{\mathcal{C}_i' \mathcal{O}_i'}_{\text{Right handed, } \frac{m_s}{m_b} \text{ suppressed}} + \sum \frac{c}{\Lambda_{\rm NP}^2} \mathcal{O}_{\rm NP}$$

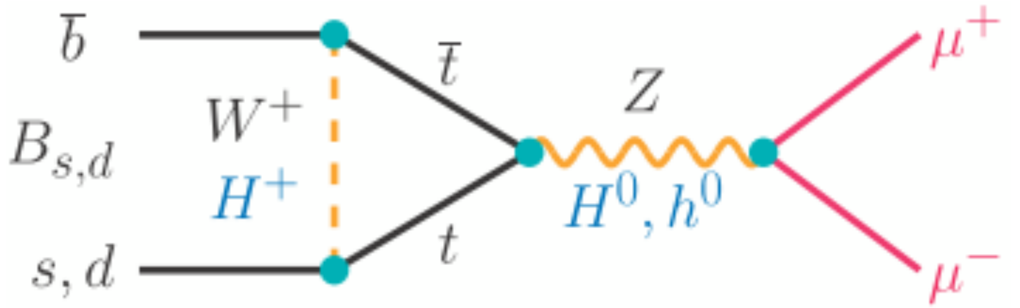
$i = 1, 2$	Tree
$i = 3-6, 8$	Gluon penguin
$i = 7$	Photon penguin
$i = 9, 10$	EW penguin
$i = S, P$	(Pseudo)scalar penguin

Differenct processes have sensitivities to different operators

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

Rare decay search: $B^0_{(s)} \to \mu^+\mu^-$





$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

Phys. Rev. Lett. 112 (2014) 101801

SM diagrams and prediction

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = 3.0\,^{+1.0}_{-0.9} \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = 3.5\,^{+2.1}_{-1.8} \times 10^{-10}$$

CMS: Phys. Rev. Lett. 111 (2013) 101804

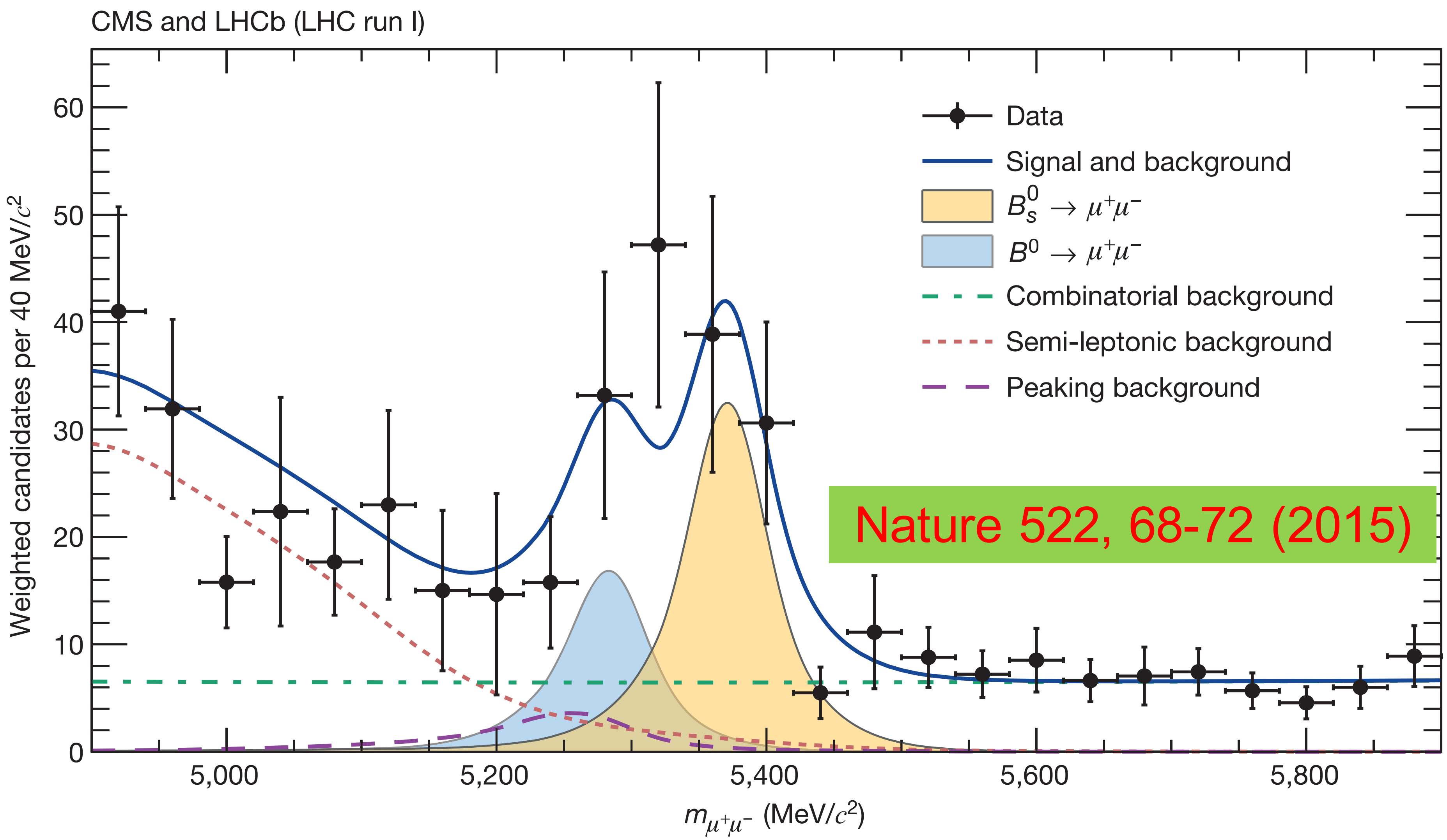
CMS made it with full Run-I data

Simultaneous publication with LHCb
Each with $> 4\sigma$ for $B_s \to \mu^+\mu^-$

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = 2.9\,^{+1.1}_{-1.0}\,^{+0.3}_{-0.1} \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = 3.7\,^{+2.4}_{-2.1}\,^{+0.6}_{-0.4} \times 10^{-10}$$

LHCb: Phys. Rev. Lett. 111 (2013) 101805

CMS&LHCb "deep" combination: First observation of $B_s \to \mu^+\mu^-$



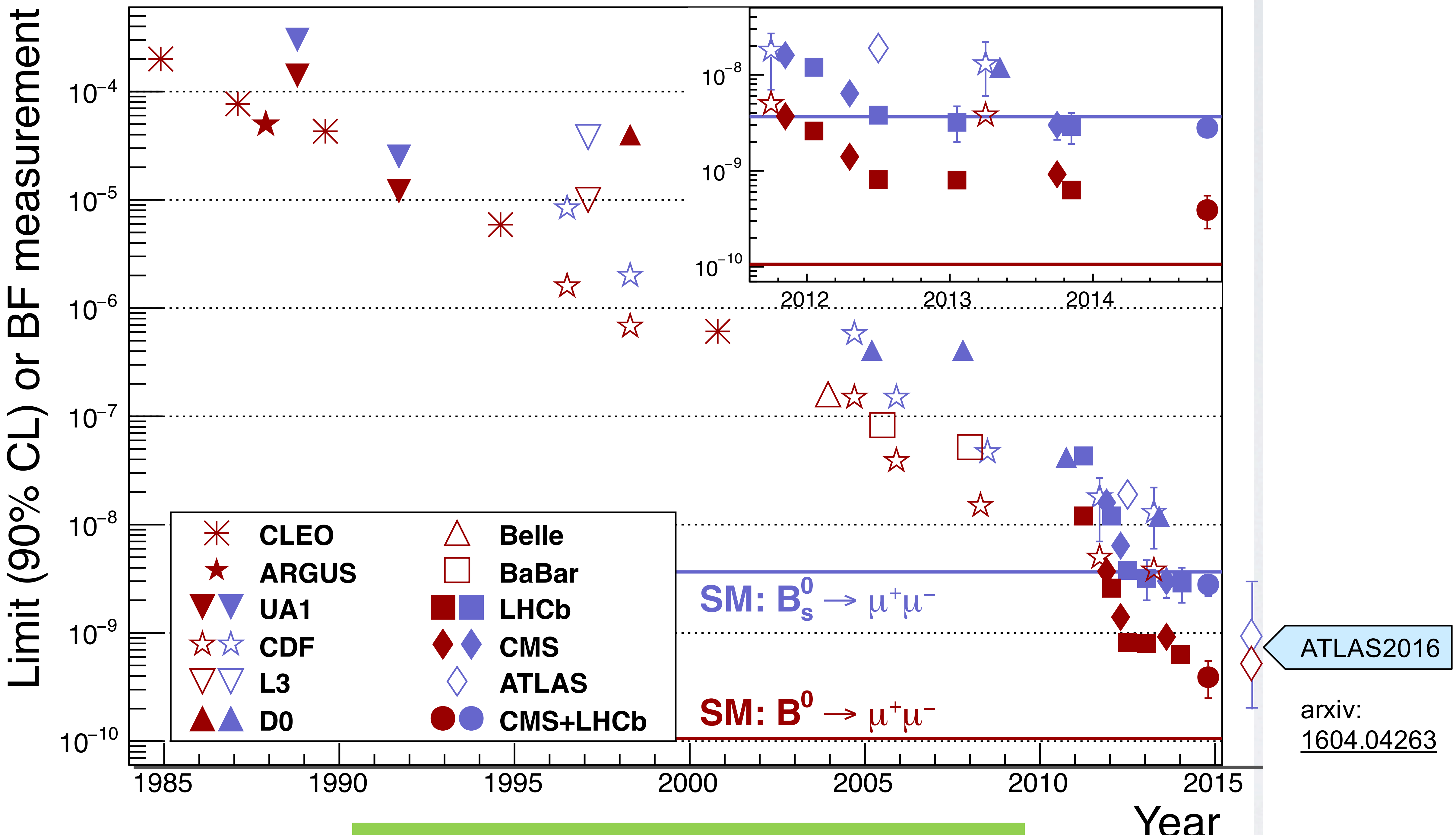
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.8\,^{+0.7}_{-0.6}\right) \times 10^{-9} \quad (6.2\sigma \text{ significance})$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(3.9\,^{+1.6}_{-1.4}\right) \times 10^{-10} \quad (3.0\sigma \text{ significance})$$

$\mathcal{R} = 0.14^{+0.08}_{-0.06}$, Also consistent with prediction

$$\mathcal{R} \equiv \mathcal{B}(B^0 \to \mu^+\mu^-)_{SM} / \mathcal{B}(B_s^0 \to \mu^+\mu^-)_{SM} = 0.0295^{+0.0028}_{-0.0025}.$$

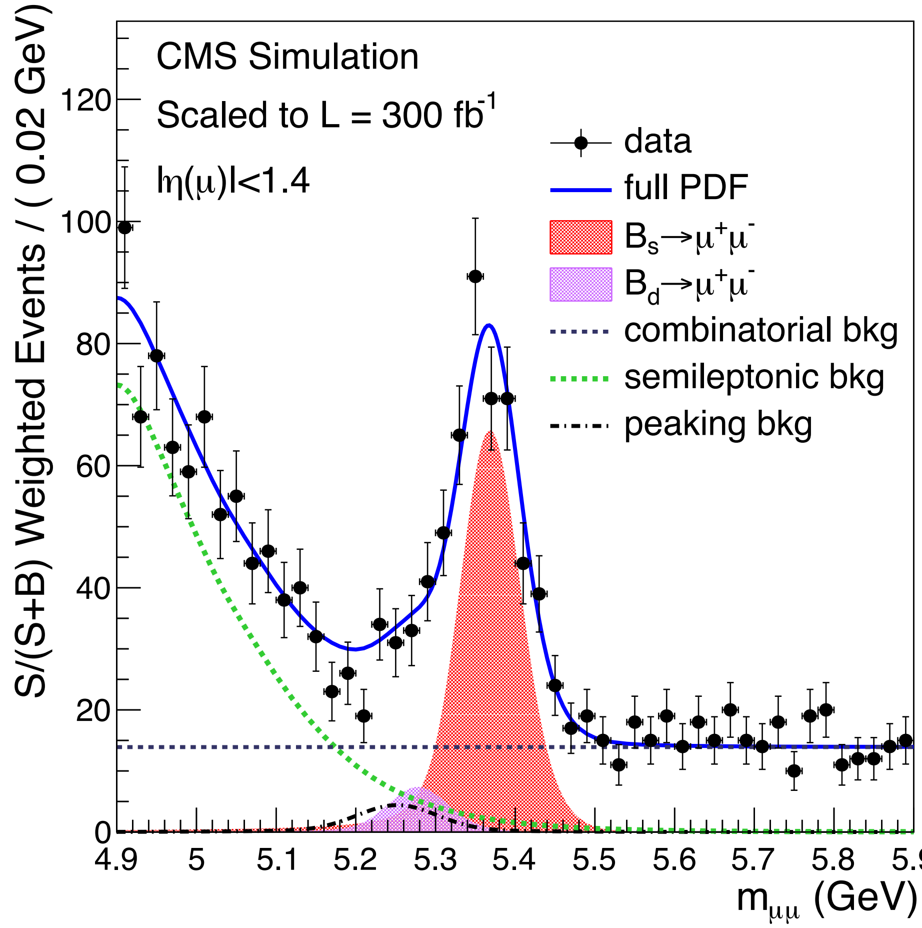
History: 30 years of search

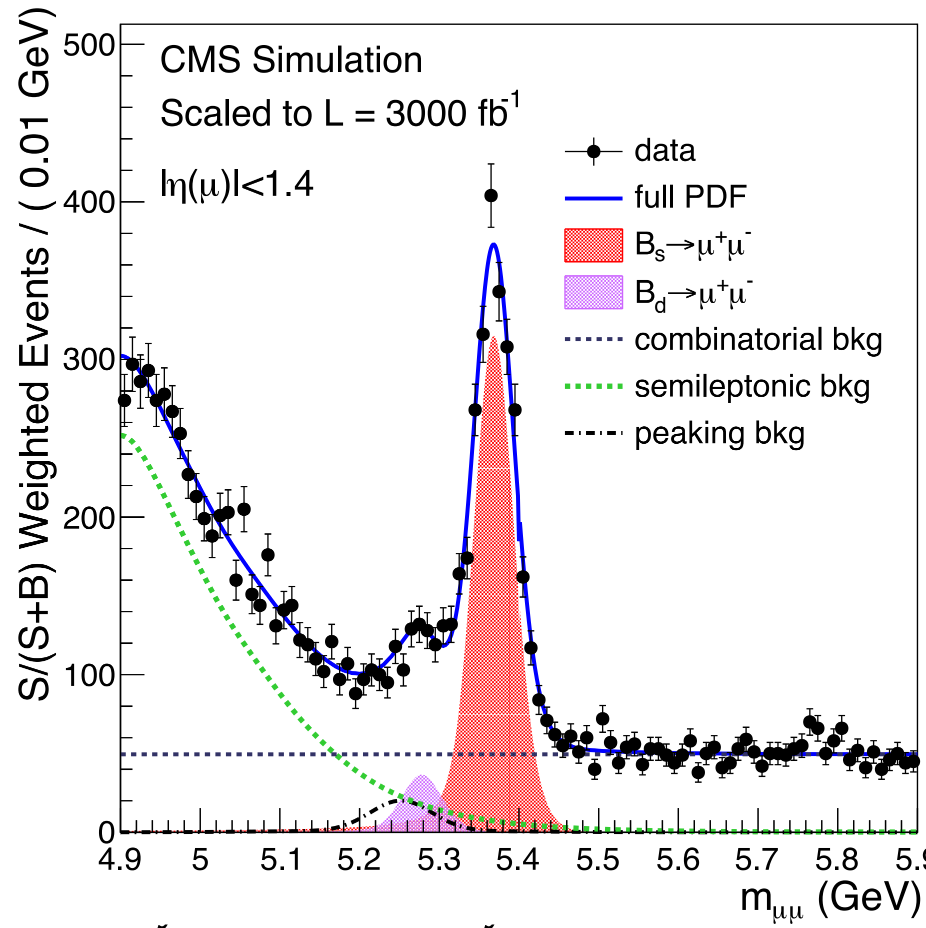


Nature 522, 68-72 (2015)

Future projection

- **Extrapolations using Phase I/II detector setups and L1 triggers**
- **Invariant mass resolution from full GEANT4 simulation**
- **Restrict analysis to barrel region**



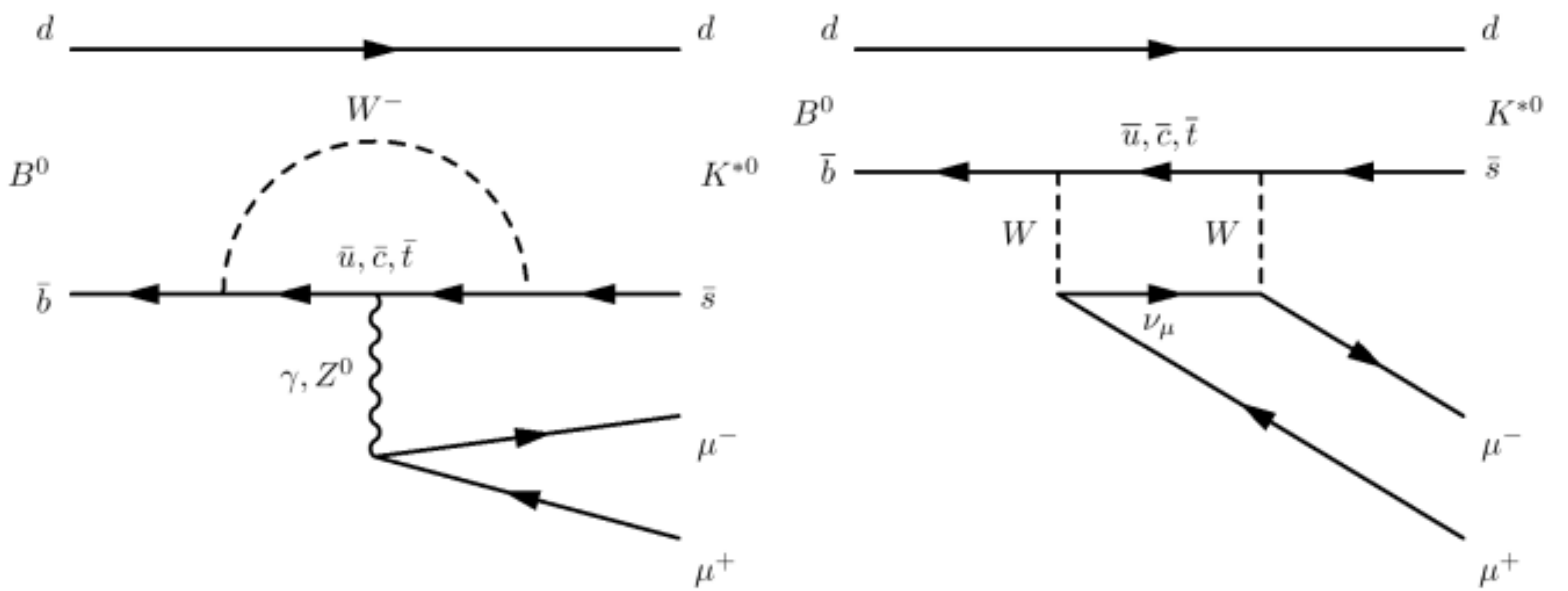


CMS-FTR-14-015

$\mathcal{L}$ (fb^{-1})	$N(B_s^0)$	$N(B^0)$	$\delta\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	$\delta\mathcal{B}(B^0 \to \mu^+\mu^-)$	B^0 sign.	$\delta\frac{\mathcal{B}(B^0\to\mu^+\mu^-)}{\mathcal{B}(B_s^0\to\mu^+\mu^-)}$
20	18.2	2.2	35%	$>100\%$	$0.0-1.5\,\sigma$	$>100\%$
100	159	19	14%	63%	$0.6-2.5\,\sigma$	66%
300	478	57	12%	41%	$1.5-3.5\,\sigma$	43%
300 (barrel)	346	42	13%	48%	$1.2-3.3\,\sigma$	50%
3000 (barrel)	2250	271	11%	18%	$5.6-8.0\,\sigma$	21%

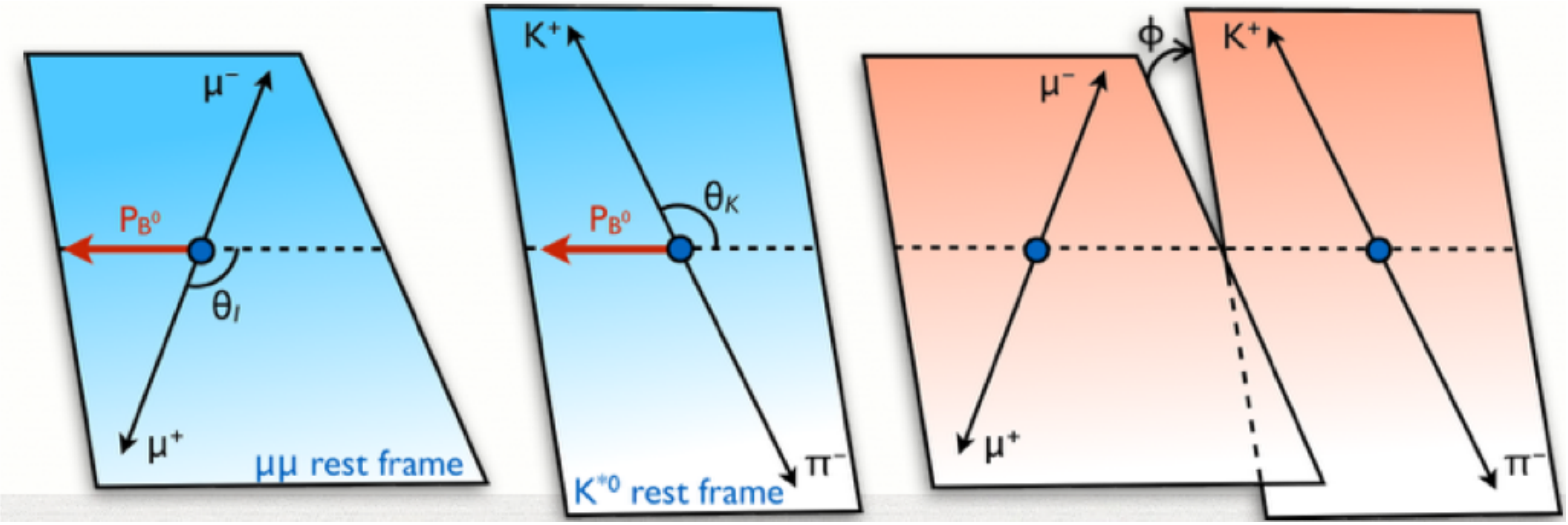
$B \to K^{(*)}\mu^+\mu^-$ anglular analyses

- $B \to K\mu^+\mu^-$ and $B \to K^*\mu^+\mu^-$ proceed dominantly through penguin and box diagrams.



- Integrating out the short distance dynamics $\to$ Wilson Coefficients:
  - $\mathcal{C}_7$ electromagnetic
  - $\mathcal{C}_9$ semi-leptonic vector
  - $\mathcal{C}_{10}$ semi-leptonic axial vector
- Observables depend on four-momentum transferred to dimuon, q^2.

Decay Parameters



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

Complete description of the decay rate: 11 variables!

Simplified decay rates and parameters

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

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

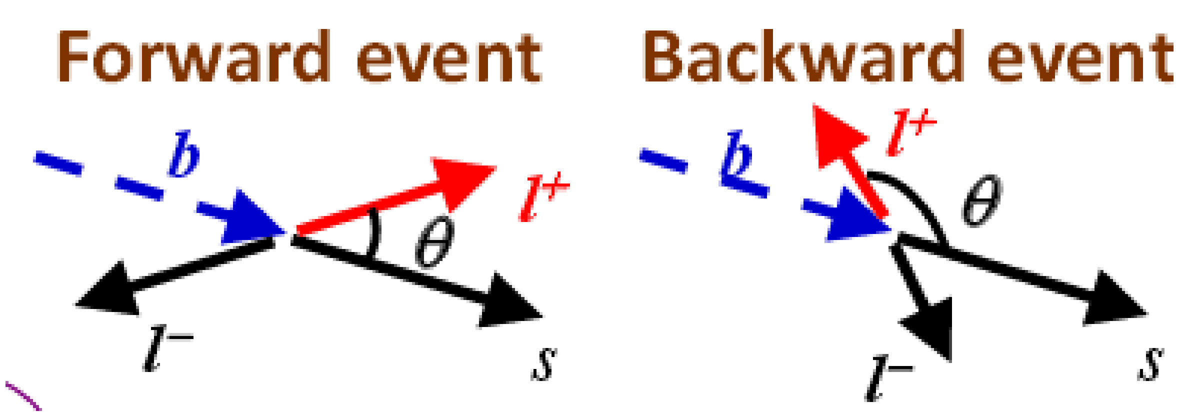
A_{FB} and F_L do not depend on ϕ, efficiency nearly constant.

F_L :Fraction of longitudinal polarization of the K*

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

dimuon invariant mass

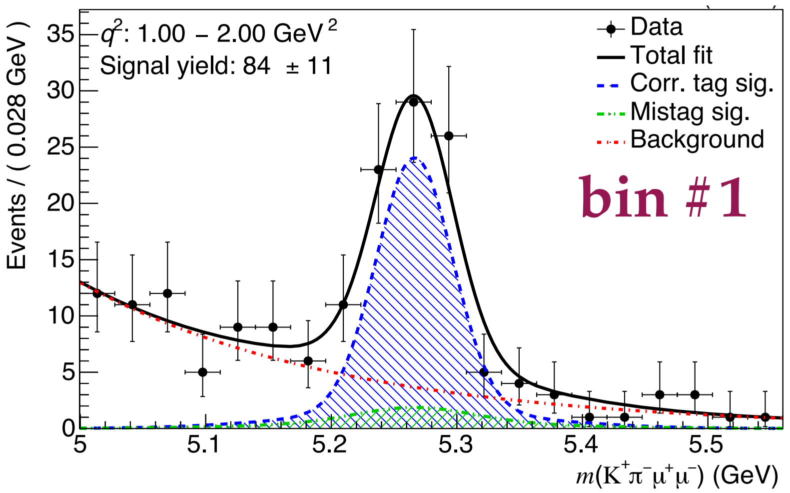
$$A_{FB} \propto -\mathrm{Re}\left[\left(2C_7^{eff} + \frac{q^2}{m_b^2}C_9^{eff}\right)C_{10}\right]$$

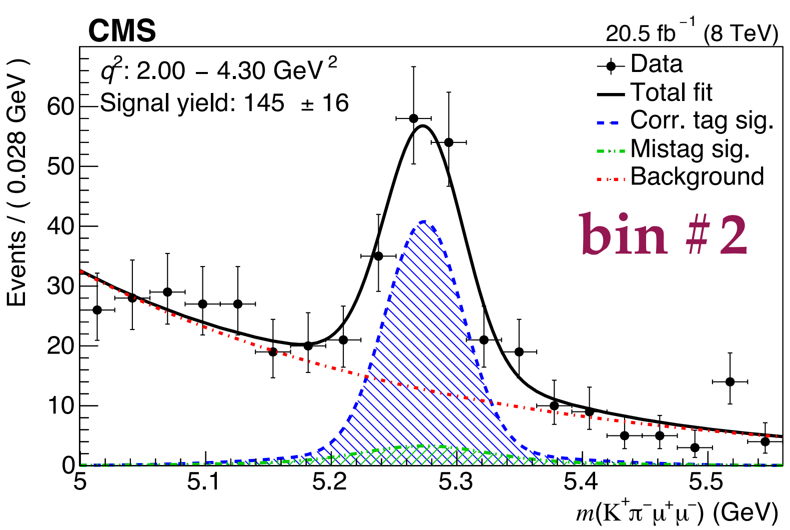


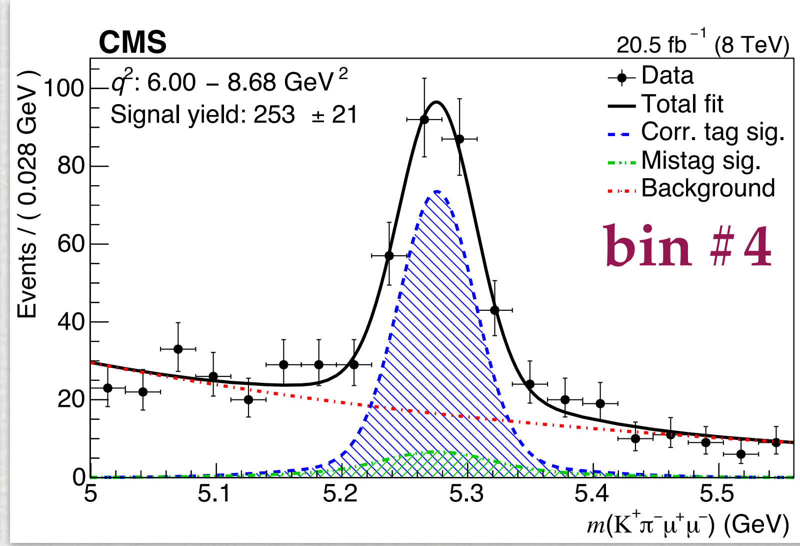
8TeV Signal Event Yields

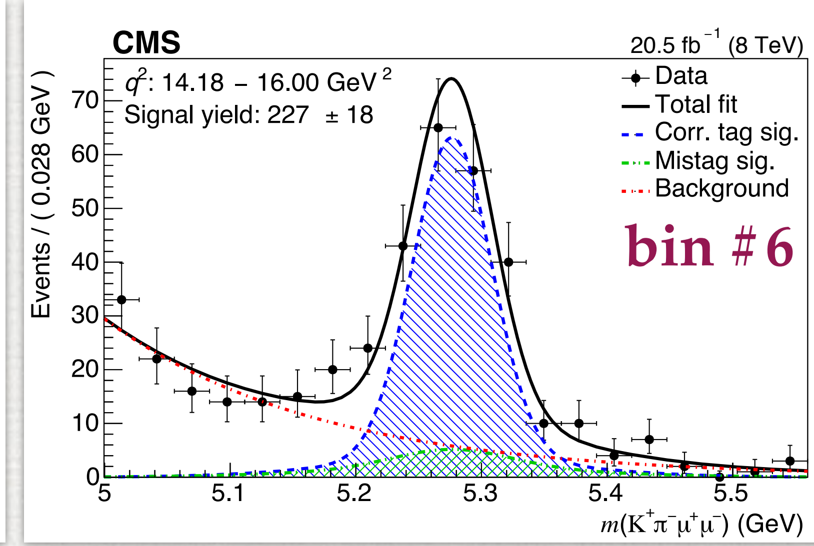
Phys. Lett. B 753, 424 (2016).

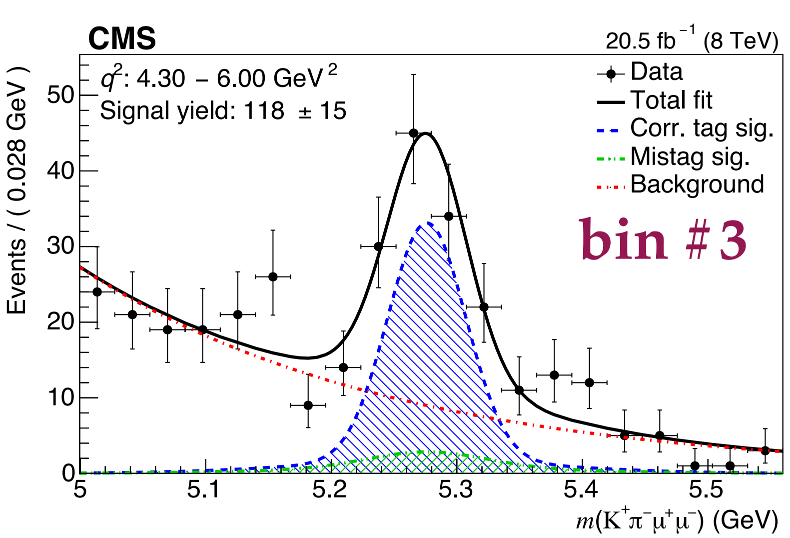
- Reconstruct the events in **7 q^2 bins**, excluding J/ψ & ψ' regions, total ~1426 signal events seen.
- Signal CP-tagged by the best $K\pi$ invariant mass.

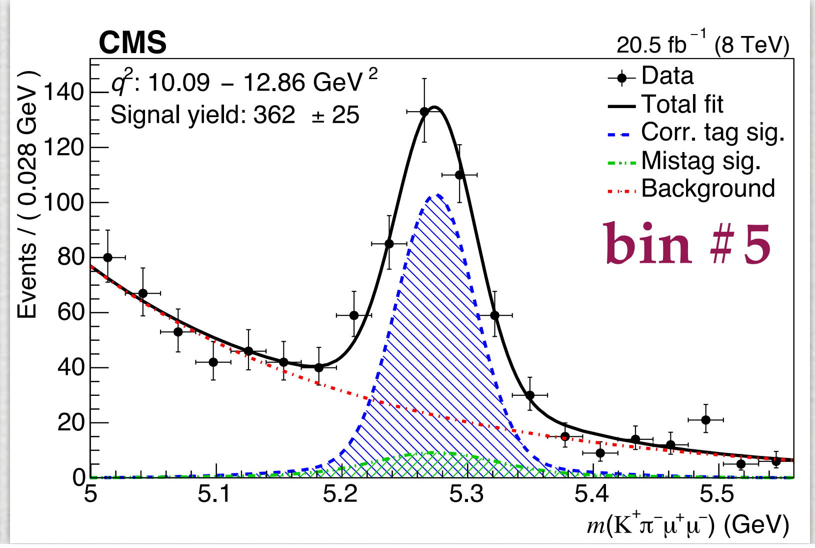


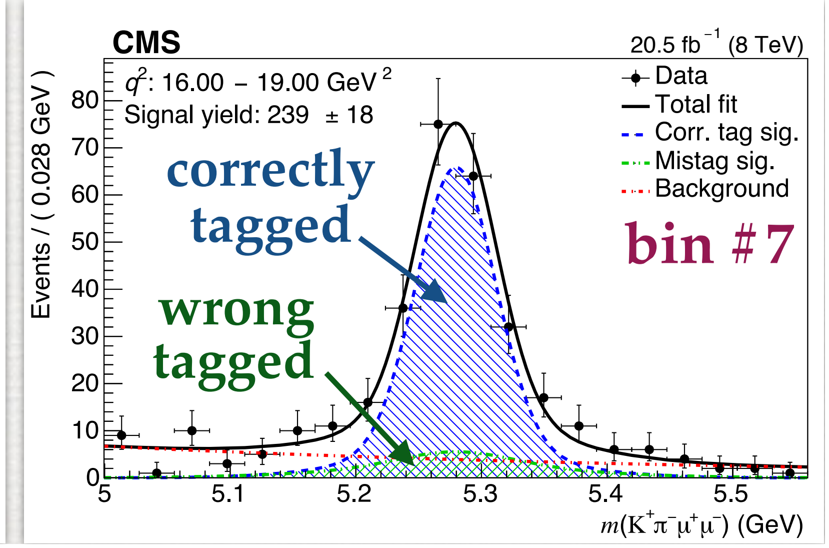




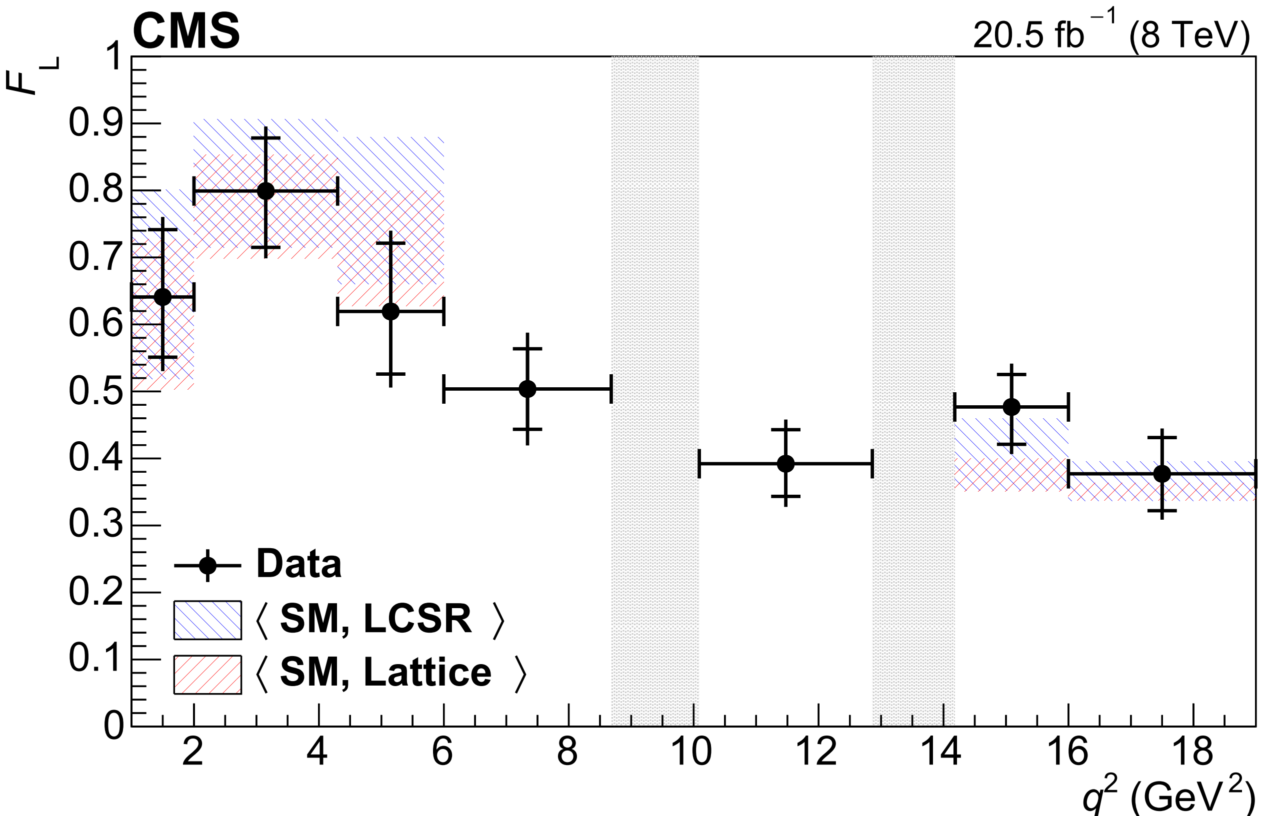


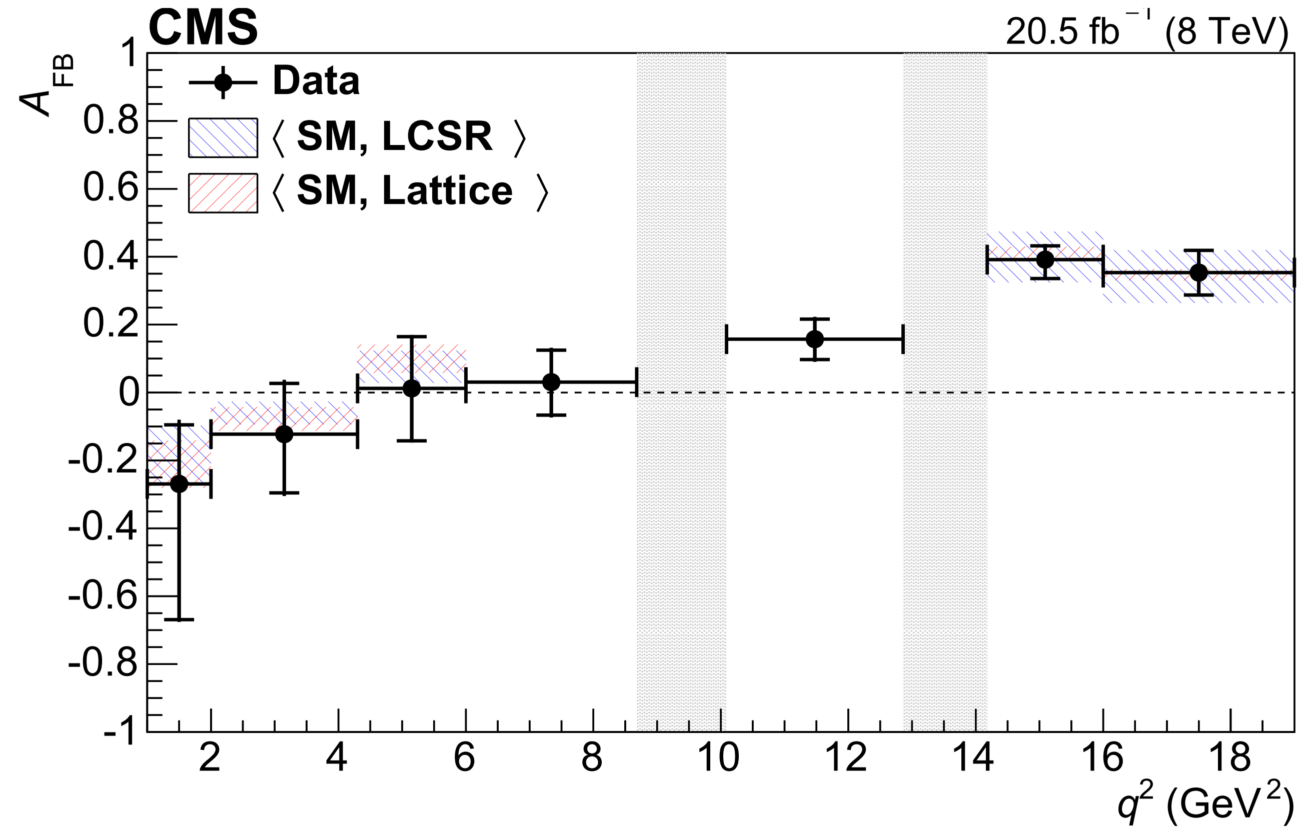


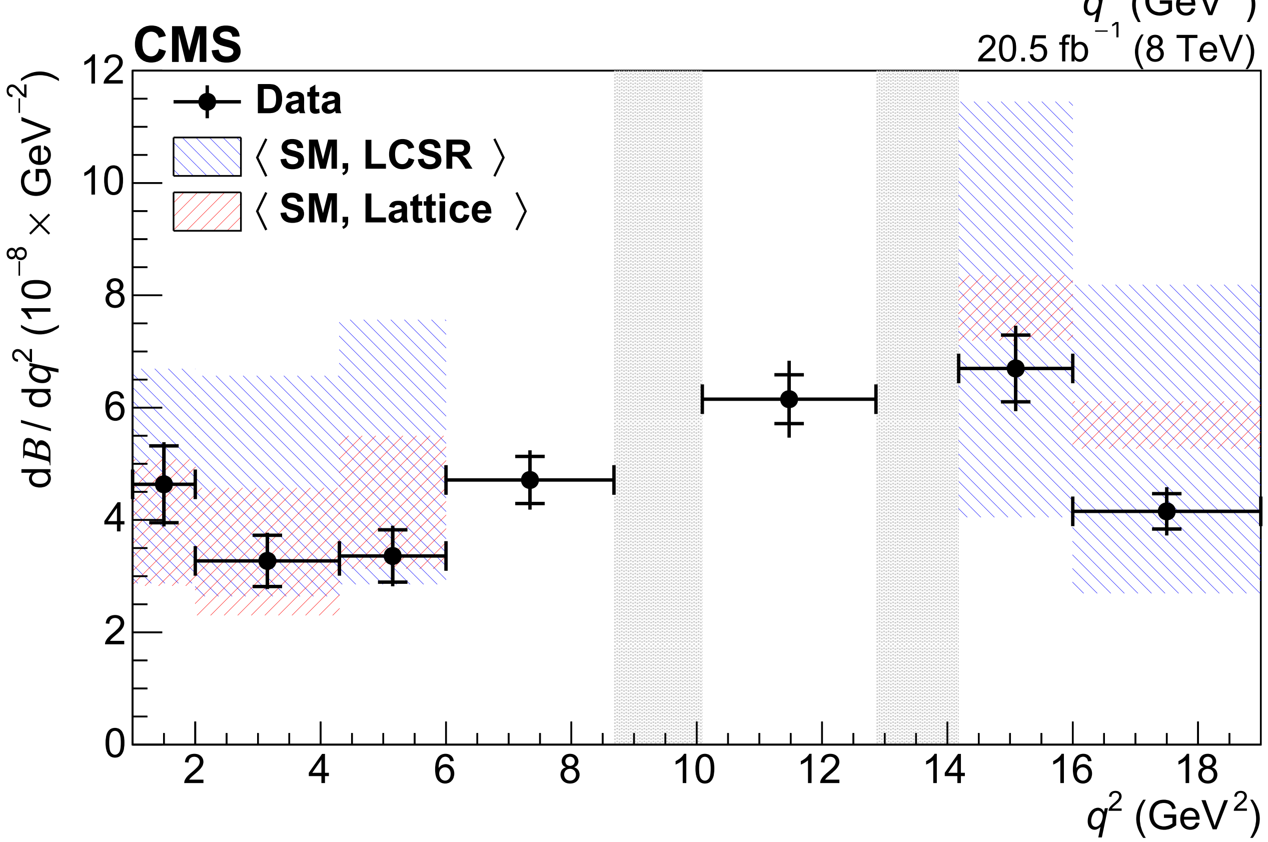




CMS 8TeV Results





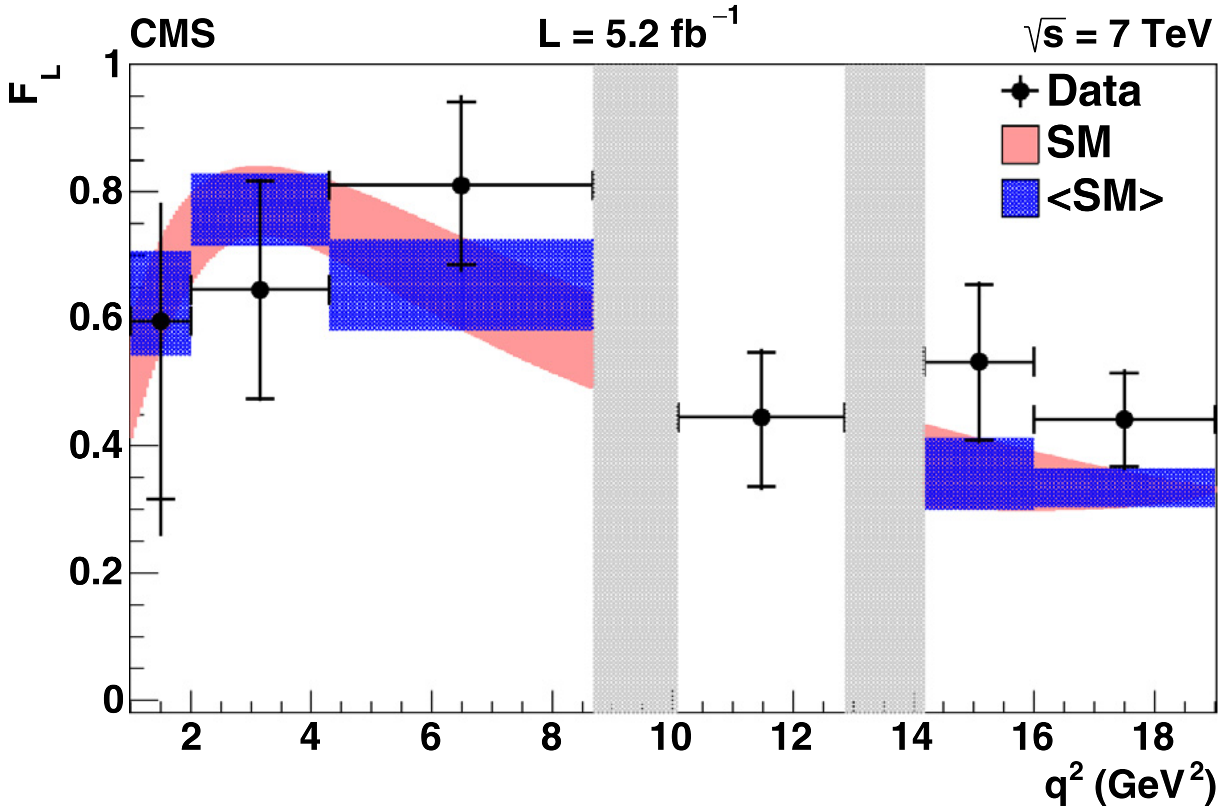


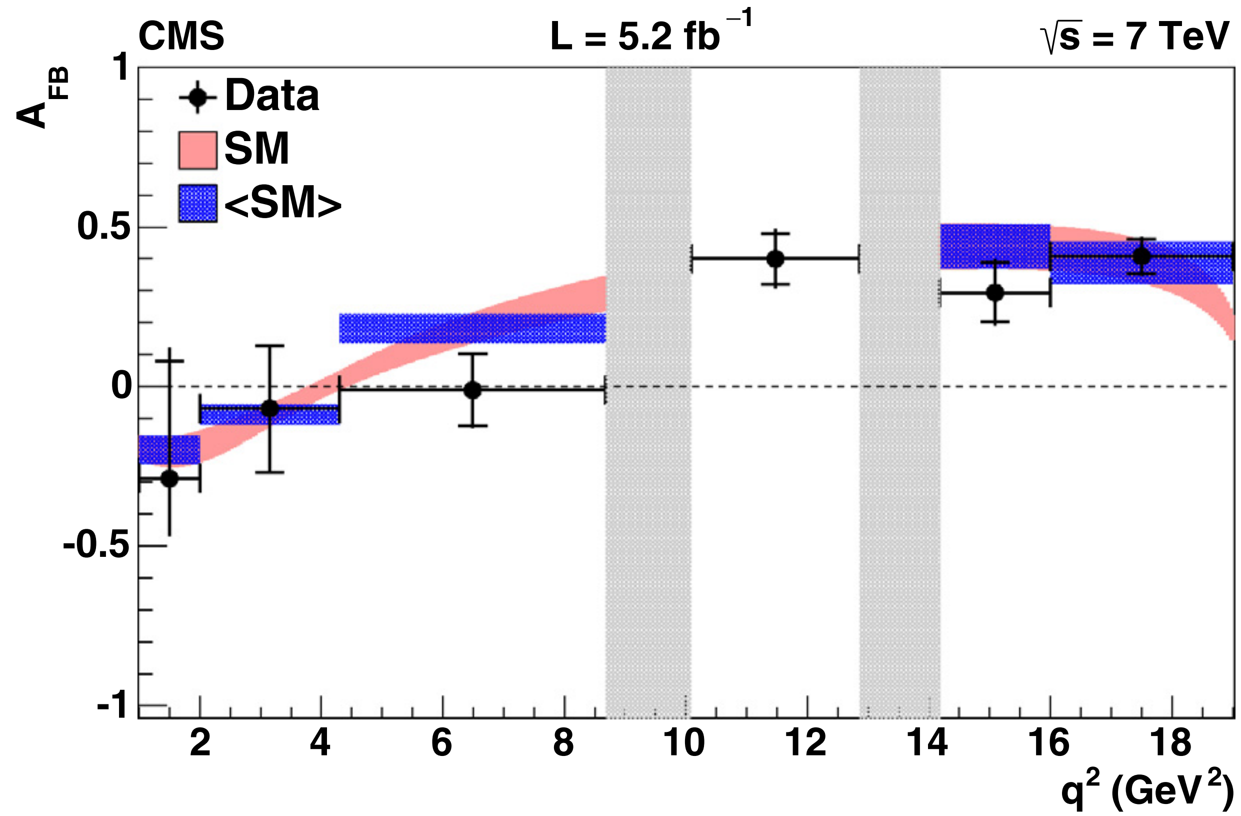
CMS-BPH-13- 010

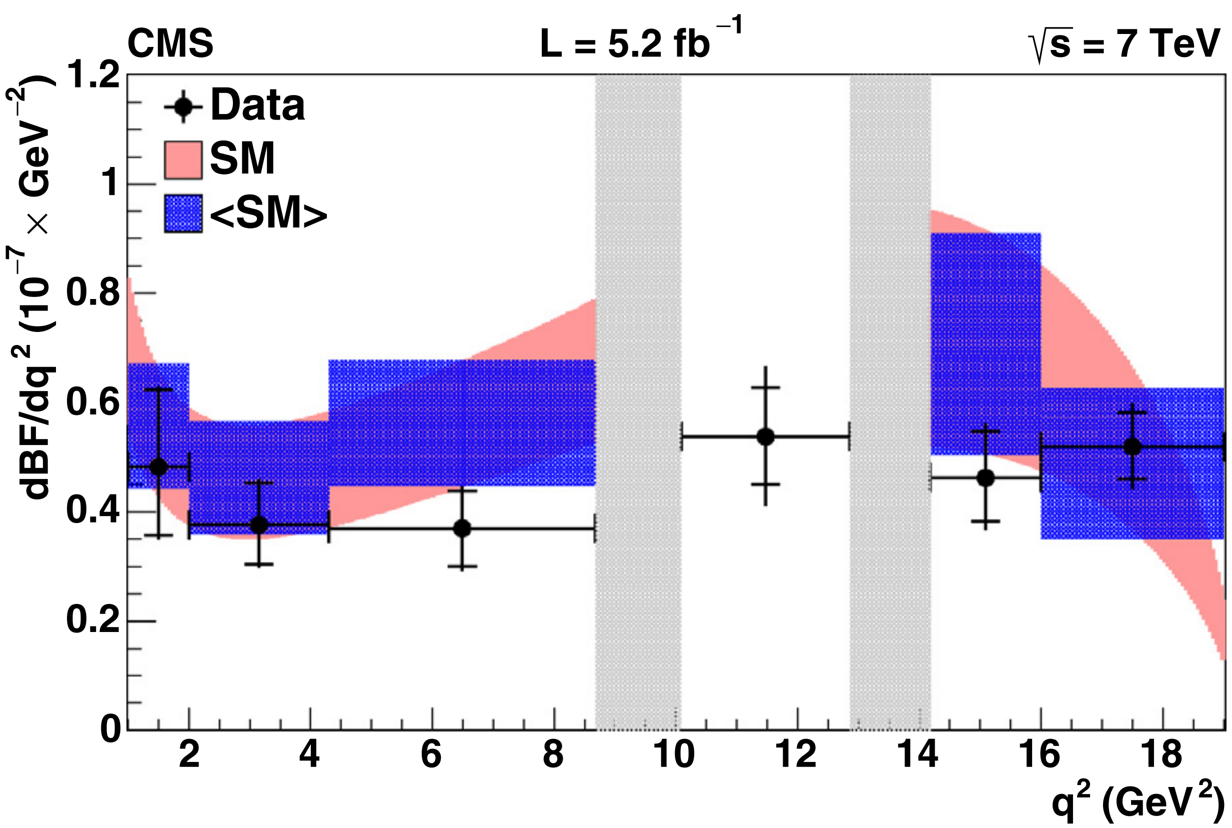
Phys. Lett. B 753, 424 (2016).

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

CMS 7TeV Results





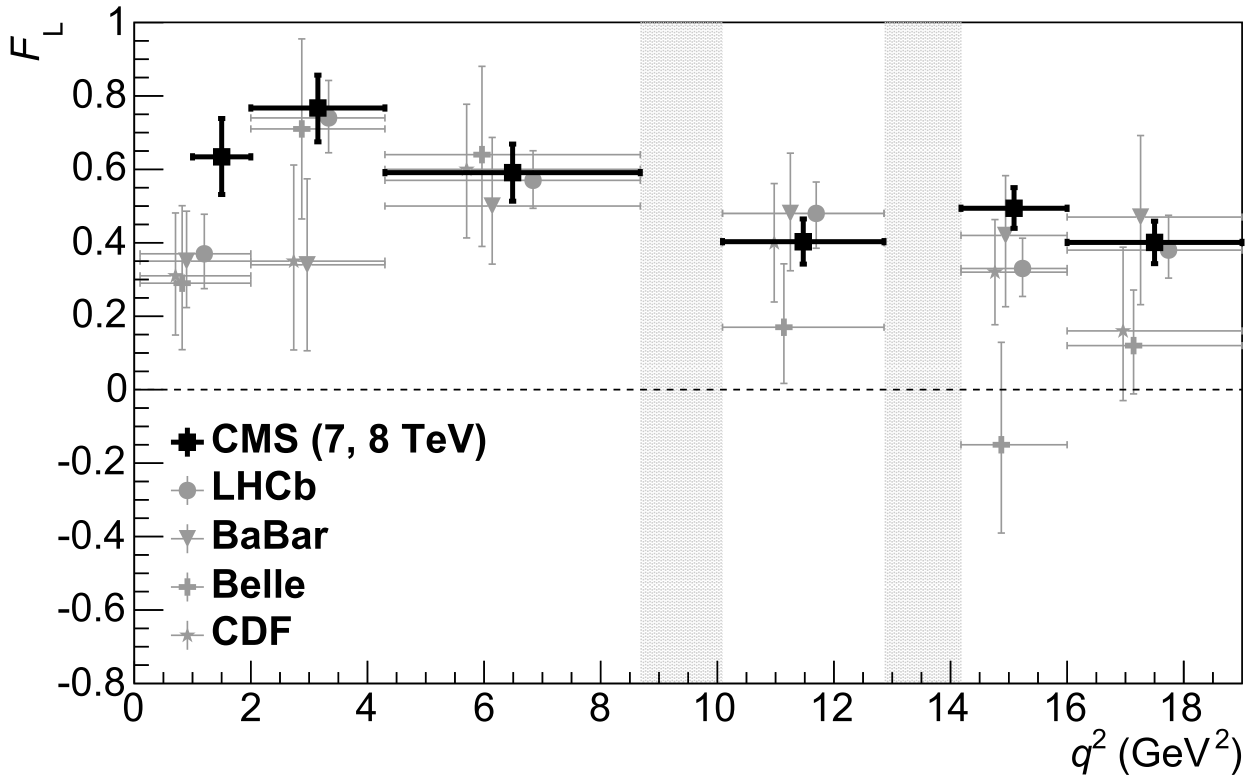


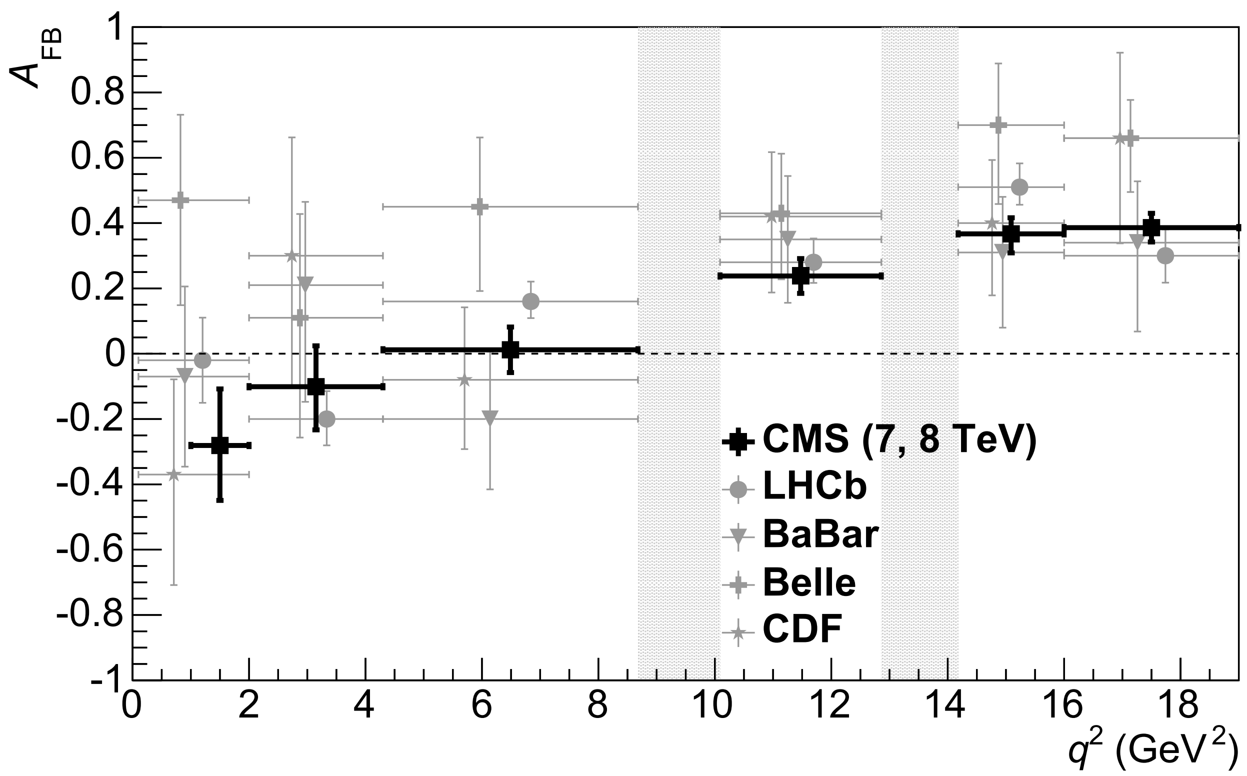
Phys. Lett. B 727 (2013) 77

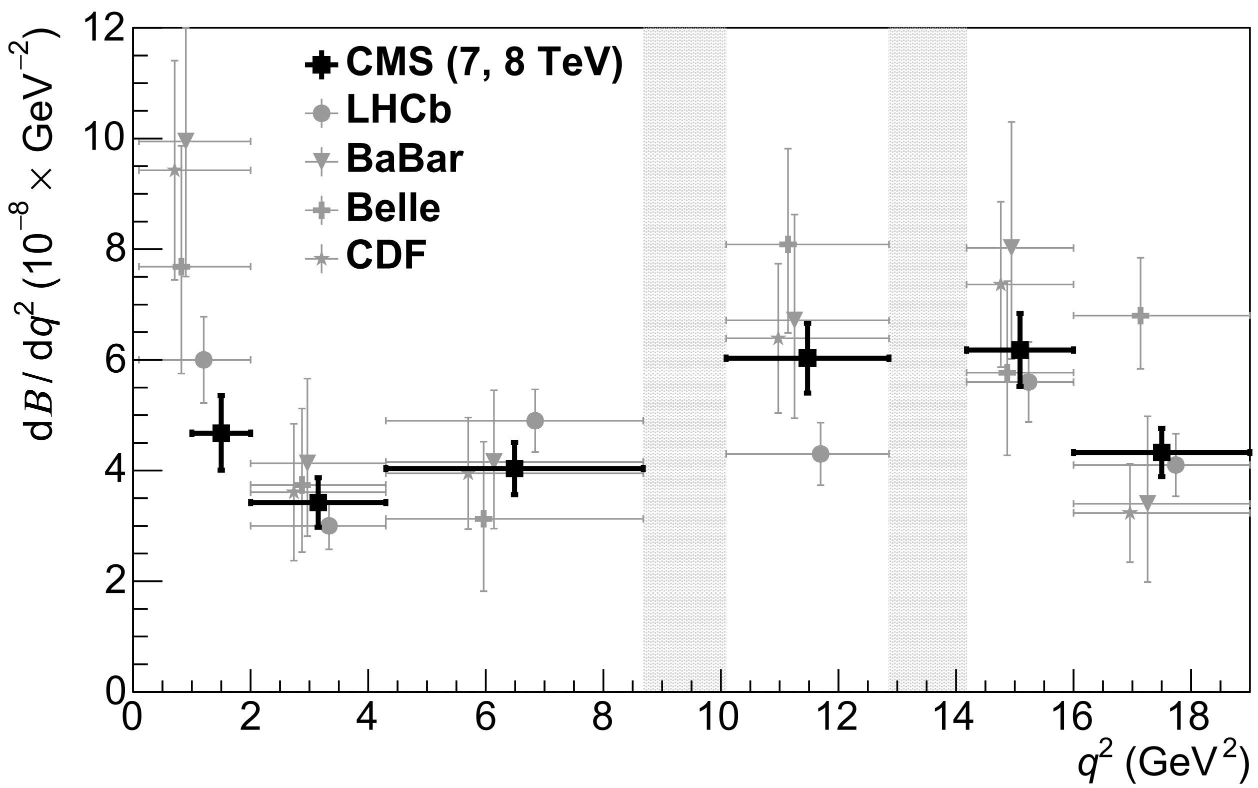
- CMS precisions are better than CDF, Belle, BaBar but not as good as LHCb (1 fb^{-1})
- More competitive in high q^2 region

- BaBar: *Phys. Rev. D* ***79*** *(2009) 031102*
- Belle: *Phys. Rev. Lett.* ***103*** *(2009) 171801*
- CDF: *Phys. Rev. Lett.* ***108*** *(2012) 081807*
- LHCb(1fb^{-1}): *Phys.Rev. Lett.* ***108*** *(2012) 181806*

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

Summary

- Rare FCNC decays are good probes of physics beyond standard model
- CMS has established $B_s \to \mu^+ \mu^-$ from Run-I data and big potential in Run-II with upgrade scenarios
- Angular analysis of $B^0 \to K^* \mu^+ \mu^-$ provides precise test of SM predictions and no deviation is seen
- More are coming ... Stay tuned!
  - P_5' of $B^0 \to K^* \mu^+ \mu^-$ based on Run-I data
  - Sister analyses of $B^+ \to K^{(*)} \mu^+ \mu^-$ with Run-I data
  - More results based on Run-II data

Thank You

extra slides...

Analysis Strategy

- Reject candidate events having the di-muon mass compatible with J/ψ or ψ' ➡ these events are used for the normalization and cross-check purpose
- Fit in bins of q^2 to the $K\pi\mu\mu$ mass and two angular variables (θ_ℓ, θ_K) to
  - estimate F_S and A_S in the $B^0 \to K^{*0}J/\psi$ channel
  - measure F_L and A_{FB} in the signal sample
- Determine the differential branching fraction, normalized w.r.t. $B^0 \to K^{*0}J/\psi$

$$\frac{\Delta\mathcal{B}(B^0 \to K^{*0}(K^+\pi^-)\mu^+\mu^-)}{\Delta q_i^2} = \left(\frac{Y_{Si}^R}{\varepsilon_{Si}^R} + \frac{Y_{Si}^M}{\varepsilon_{Si}^M}\right)\left(\frac{Y_N^R}{\varepsilon_N^R} + \frac{Y_N^M}{\varepsilon_N^M}\right)^{-1} \frac{\mathcal{B}(B^0 \to K^{*0}(K^+\pi^-)J/\psi(\mu^+\mu^-))}{\Delta q_i^2}$$

$$\begin{aligned}\mathrm{PDF}(m,\theta_K,\theta_l) = Y_S^C\Big[& S^C(m)\, S^a(\theta_K,\theta_l)\, \epsilon^C(\theta_K,\theta_l) \\ & + \frac{f^M}{1-f^M}\, S^M(m)\, S^a(-\theta_K,-\theta_l)\, \epsilon^M(\theta_K,\theta_l)\Big] \\ & + Y_B\, B^m(m)\, B^{\theta_K}(\theta_K)\, B^{\theta_l}(\theta_l),\end{aligned}$$

Unbinned likelihood fit performed in each q2 bin

- Fit m(K πμμ), cos θ_K , cos θ_l
- Background shapes from fit to m(B0) sidebands
- Signal m(B0) shapes and fraction of mistagged events from MC

Systematic uncertainties(8TeV)

Systematic uncertainty	$F_L (10^{-3})$	$A_{FB} (10^{-3})$	$d\mathcal{B}/dq^2$ (%)
Simulation mismodeling	1–17	0–37	1.0–5.5
Fit bias	0–34	2–42	–
MC statistical uncertainty	3–10	5–18	0.5–2.0
Efficiency	34	5	–
$K\pi$ mistagging	1–4	0–7	0.1–4.1
Background distribution	20–36	12–31	0.0–1.2
Mass distribution	3	1	3.2
Feed-through background	0–27	0–5	0.0–4.0
Angular resolution	6–24	0–5	0.2–2.1
Normalization to $B^0 \to J/\psi K^{*0}$	–	–	4.6
Total systematic uncertainty	41–65	18–74	6.4–8.6

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