Rare B Decays at CMS and prospects with the CMS upgrade

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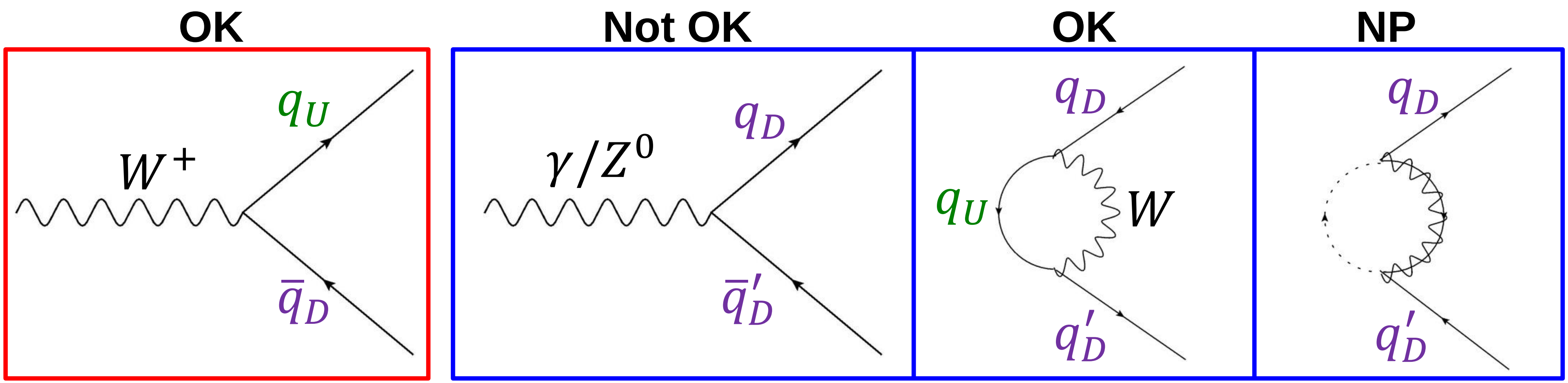
Prologue

- In the standard model (SM), only charged-current weak interactions take part in flavour changing transitions at tree level ⇨ heart of the CKM mechanism
  - Flavour changing neutral-current (FCNC) transitions are forbidden at tree level
  - Can occur via higher-order loop or penguin diagrams and strongly suppressed
  - Sensitive to potential new physics (NP) contributions appearing in the loops

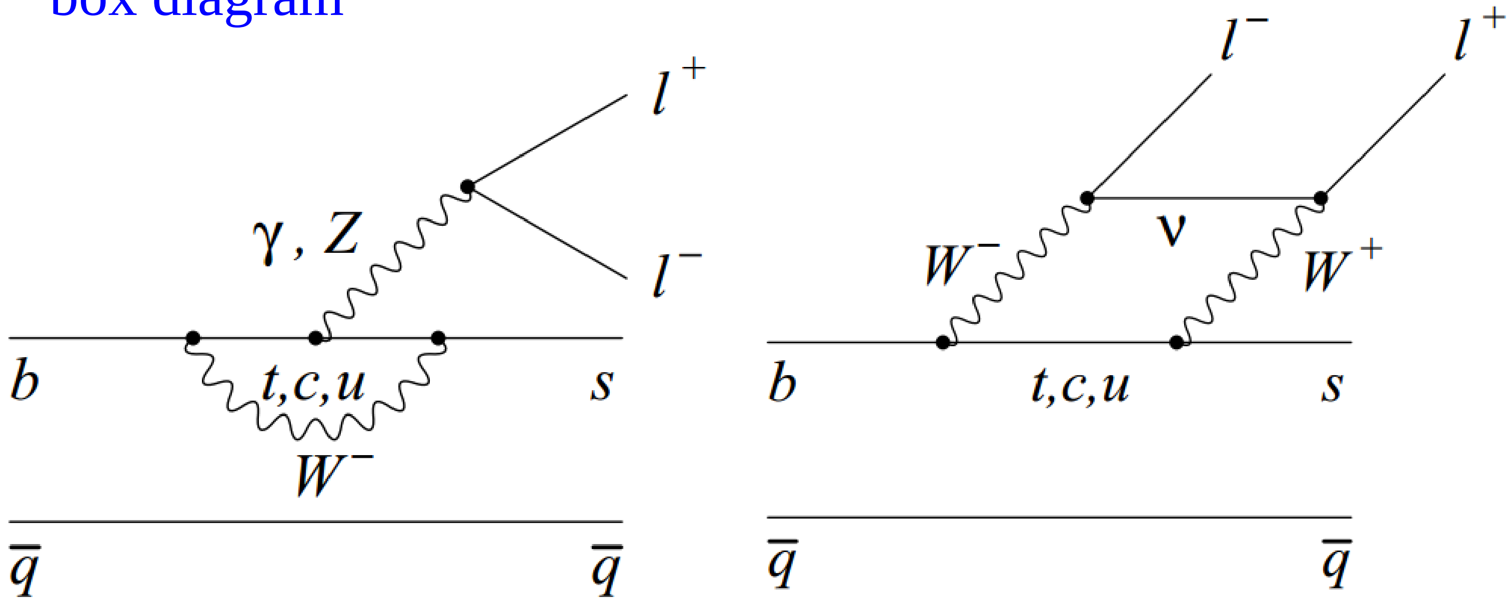


- Shall dwell on recent measurements of a FCNC decay $B^0 \to K^{\star 0}\mu^+\mu^-$ carried out by CMS [$K^\star$ here refers to the $K^\star(892)^0$] **PLB 727 (2013) 77**

- For $B_s^0 \to \mu^+\mu^-$ results please refer to the post-coffee break talk by F. Archilli

A bit on theory

- Lowest order contributions from the (left) electroweak penguin and (right) W^+W^- box diagram



- Effective Hamiltonian given in terms of operators and Wilson's coefficients

$$\boxed{H_{\mathrm{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \Big[\underbrace{C_i(\mu) O_i(\mu)}_{\text{left-handed part}} + \underbrace{C_i'(\mu) O_i'(\mu)}_{\substack{\text{right-handed part} \\ \text{suppressed in SM}}} \Big]}$$

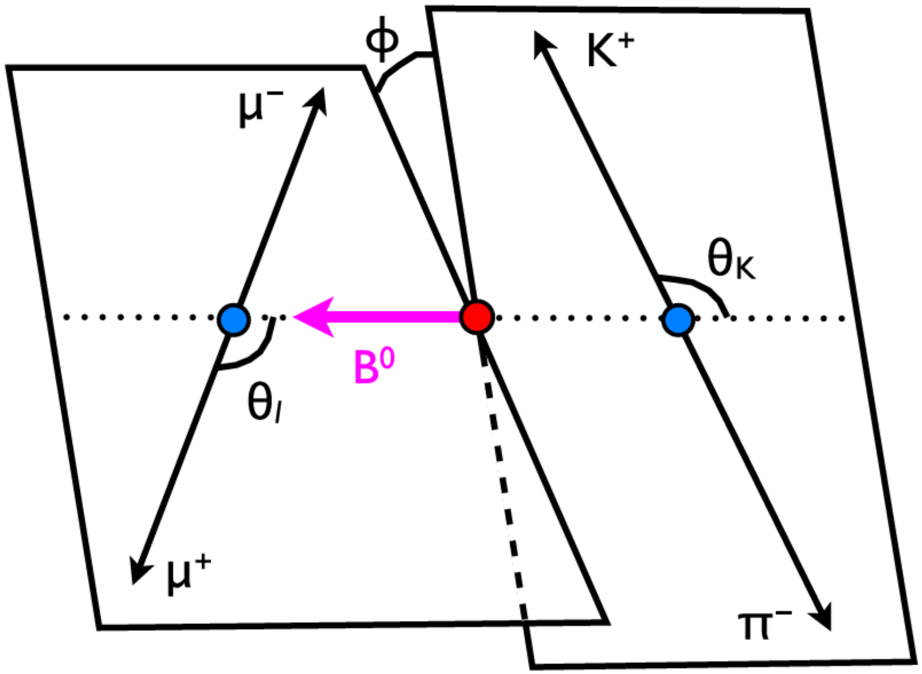
$B \to K^\star \ell^+ \ell^-$ decays are sensitive to $C_7^{(\prime)}$, $C_9^{(\prime)}$ and $C_{10}^{(\prime)}$

- Angular analysis involving differential distributions in $q^2 (m^2_{\ell^+\ell^-})$ allows a separation among various Wilson coefficients and can help reveal NP signal

Observables we are interested in

- Many (up to 24) observables can be constructed owing to different polarization states of $K^{\star 0}$ and $\mu\mu$ system as well as emission angles of charged particles
- After integrating out ϕ (does not affect acceptance $\times$ efficiency and observables of interest), the normalized angular distribution can be given as:

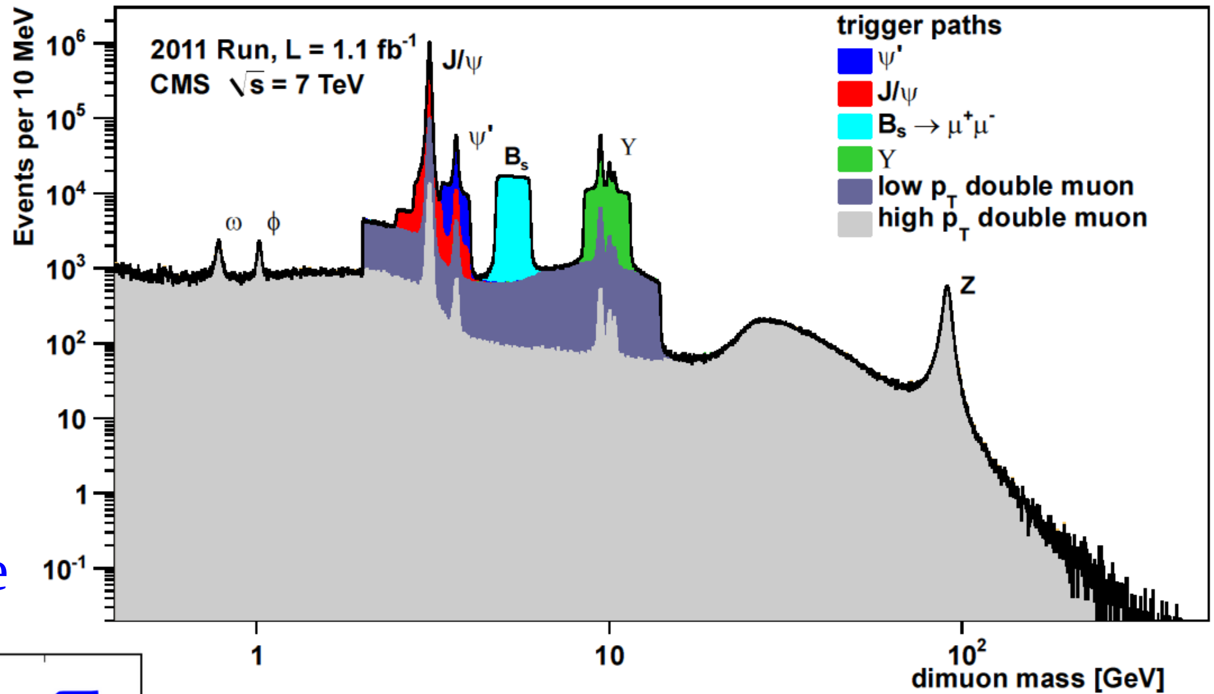
$$\frac{1}{\Gamma}\frac{\mathrm{d}^3\Gamma}{\mathrm{d}\cos\theta_K\,\mathrm{d}\cos\theta_l\,\mathrm{d}q^2} = \frac{9}{16}\left\{\left[\frac{2}{3}F_S + \frac{4}{3}A_S\cos\theta_K\right](1-\cos^2\theta_l) + (1-F_S)\left[2F_L\cos^2\theta_K(1-\cos^2\theta_l) + \frac{1}{2}(1-F_L)(1-\cos^2\theta_K)(1+\cos^2\theta_l)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

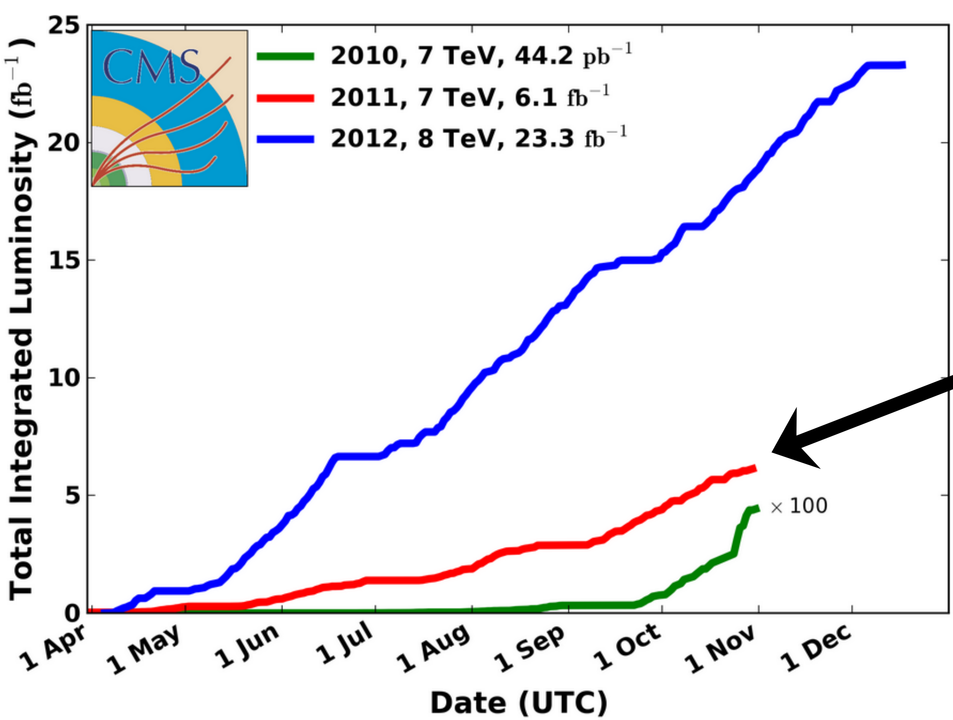


- Four parameters to be determined from the data
  - S-wave $K\pi$ contribution (F_S)
  - S- and P-wave interference (A_S)
  - $K^{\star 0}$ longitudinal polarization fraction (F_L)
  - Muon forward-backward asymmetry (A_{FB})

Compact di-Muon Solenoid?

- The $B^0 \to K^{\star 0}\mu^+\mu^-$ signal and control samples ($B^0 \to K^{\star 0}J/\psi$ and $B^0 \to K^{\star 0}\psi'$) are recorded using the same trigger with two identified muons of opposite charge
- Increasingly stringent trigger criteria with increase in L_{inst} to maintain an acceptable rate

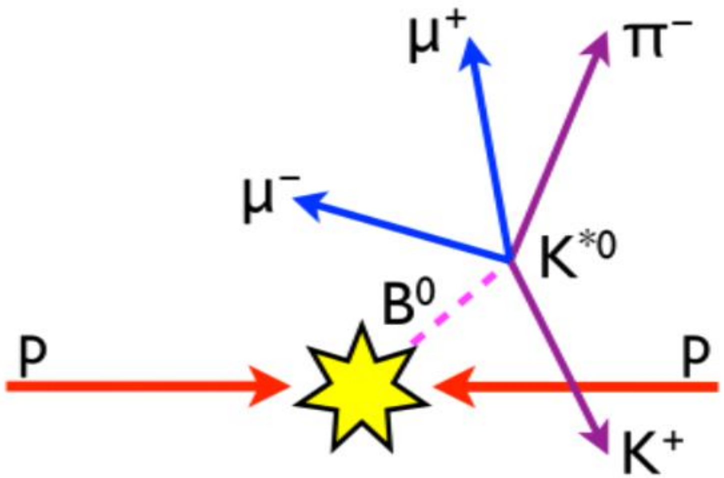




Data samples

- $\sqrt{s} = 7$ TeV , $\mathcal{L} = 5$ fb^{-1} (2011 run)

What are we looking for?



- ❑ A pair of oppositely charged muons originating from a vertex that is displaced from the nominal pp collision point
- ❑ $K^{\star 0} \to K^+\pi^-$ candidates are reconstructed using tracks that do not pass muon identification criteria ➡ invariant mass within 80 MeV of the nominal $K^\star$ mass
- ❑ The four-track vertex is identified as a B^0 ($\bar{B}^0$) candidate if the $K^+\pi^-$ ($K^-\pi^+$) invariant mass is closest to the $K^\star$ mass
  - ➢ Reject the event if both $K\pi$ combinations fall within a 50 MeV window of $K^\star$

Background

1) Peaking: feed through from $B^0 \to K^{\star 0}J/\psi$ and $K^{\star 0}\psi'$ events not removed by the dimuon mass (q^2) requirements
2) Combinatorial: misreconstruction due to randomly associated hadrons

A tour of the analysis

- Signal event yield as a function of the $K\pi\mu\mu$ invariant mass in different q^2 bins
- 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 $B^0 \to K^{\star 0} J/\psi$ channel
  - measure F_L and A_{FB} in the signal sample
- Determine the differential branching fraction, normalized w.r.t. $B^0 \to K^{\star 0} J/\psi$

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

Y: event yield
ϵ: efficiency

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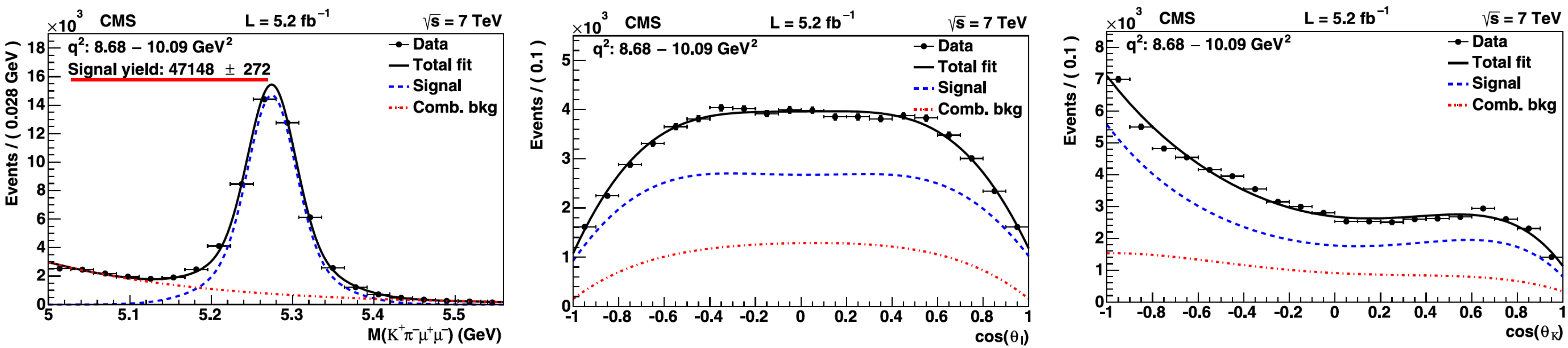

- Projections of fit in $M(K\pi\mu\mu)$, $\cos(\theta_\ell)$ and $\cos(\theta_K)$ distributions for the q^2 bin associated with the $B^0 \to K^{\star 0} J/\psi$ decay

$\boxed{F_S = 0.01 \pm 0.01,\ A_S = -0.10 \pm 0.01}$

$K^+\pi^-\mu^+\mu^-$ invariant-mass distributions

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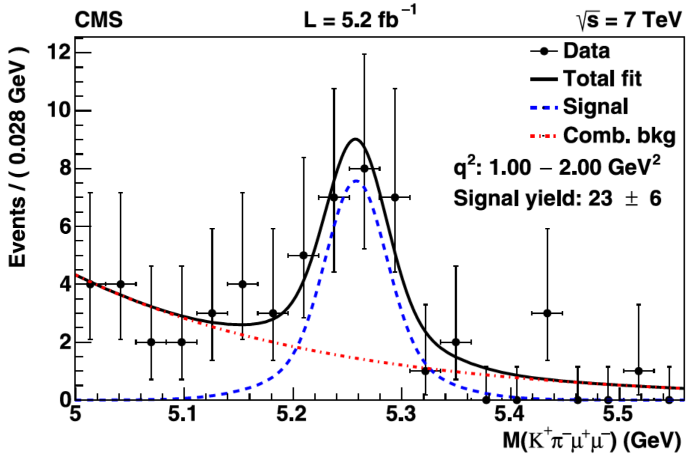
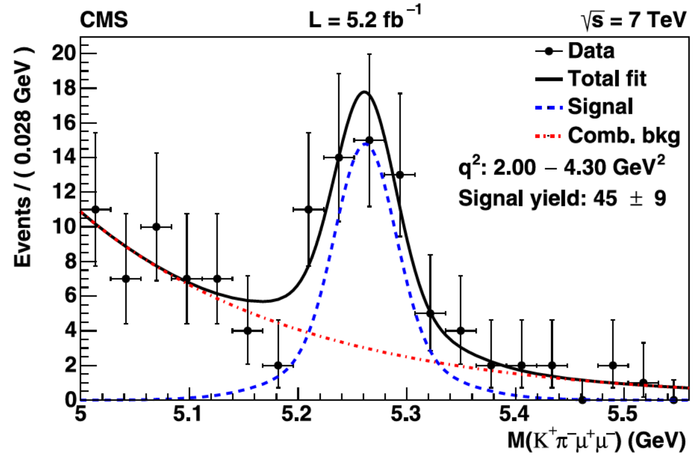
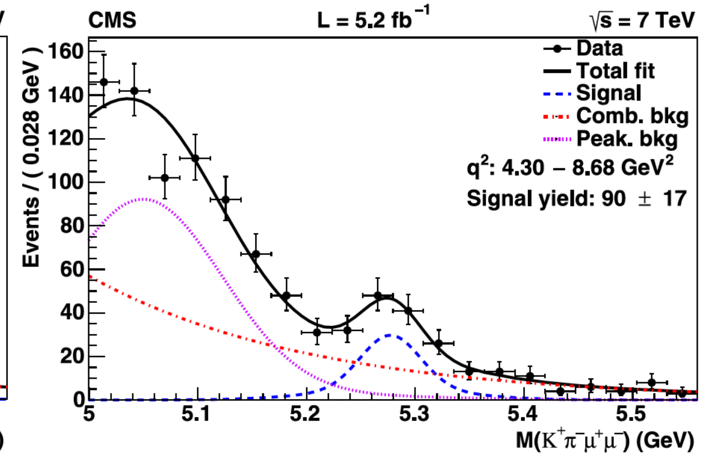


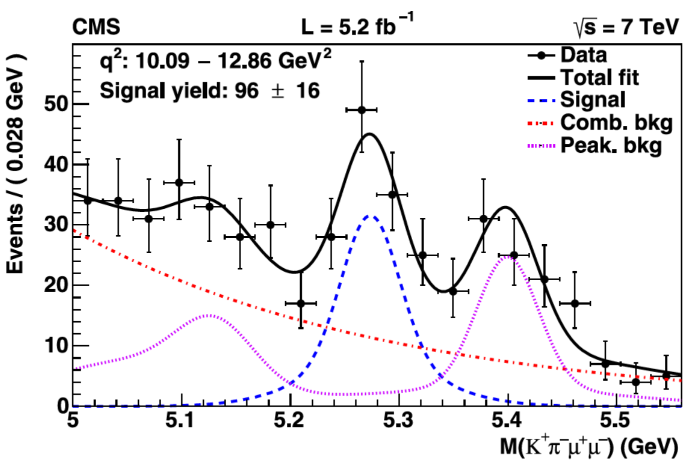
q^2: 1.00 – 2.00 GeV^2



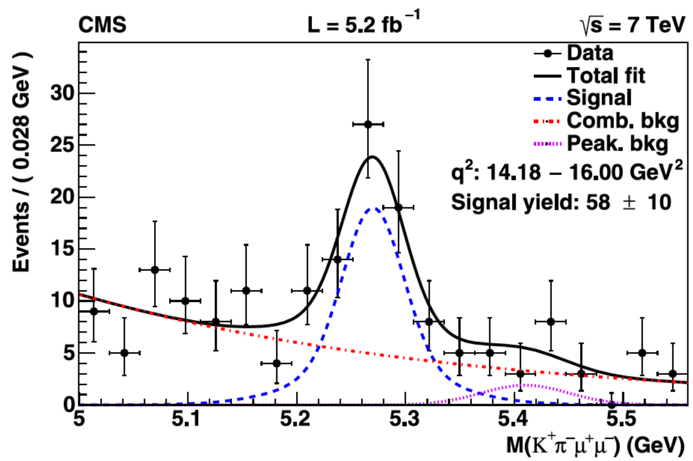
q^2: 2.00 – 4.30 GeV^2



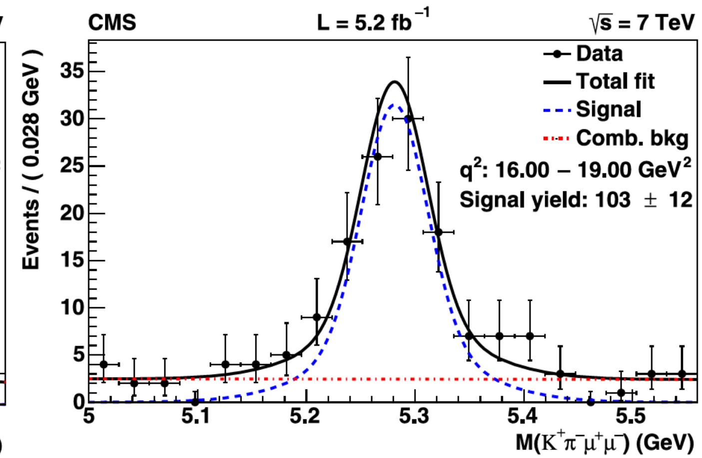
q^2: 4.30 – 8.68 GeV^2



q^2: 10.09 – 12.86 GeV^2



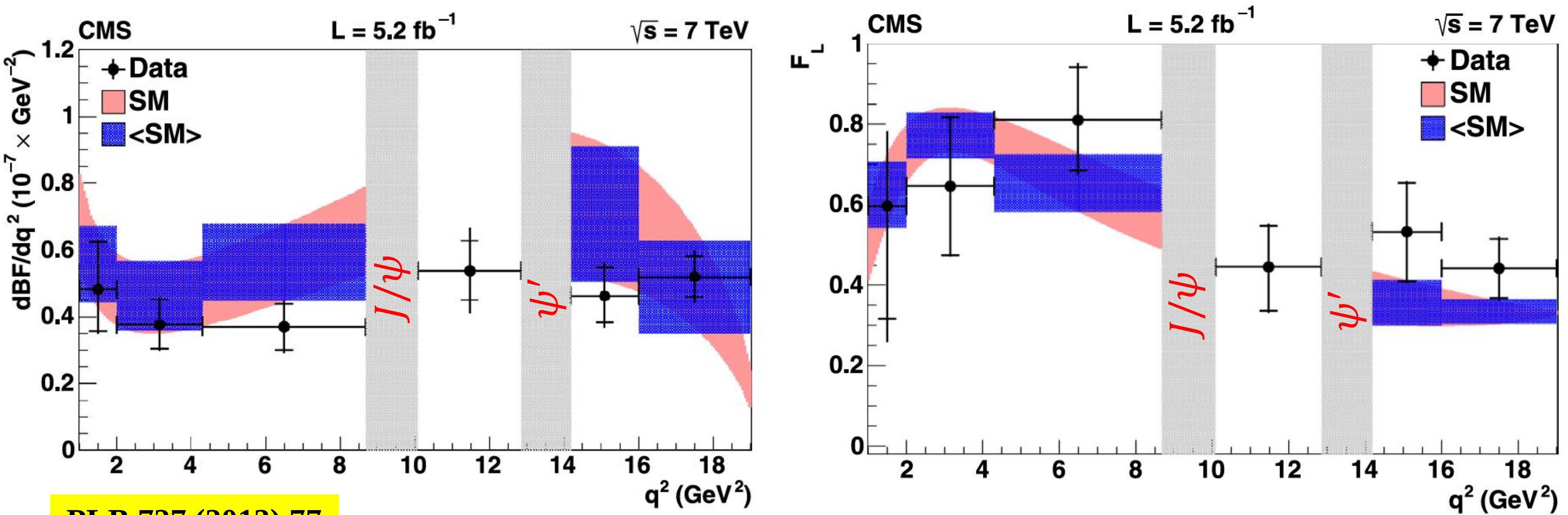
q^2: 14.18 – 16.00 GeV^2



q^2: 16.00 – 19.00 GeV^2

- Clear signals in each q^2 bin with yields ranging from 23 ± 6 to 103 ± 12 events
- ➡ about 400 events in total

Results on dBF/dq^2 and F_L



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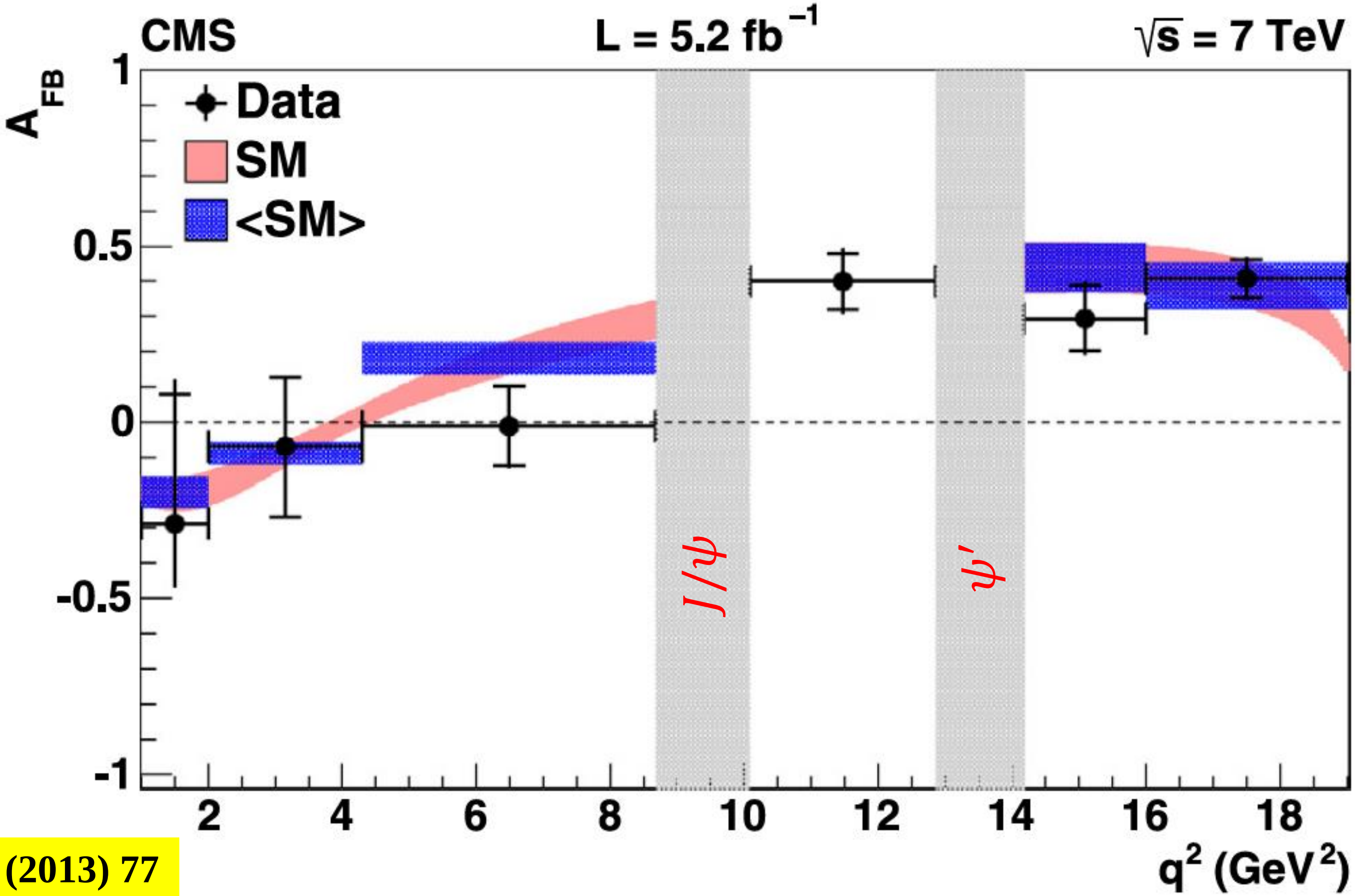
- Statistical uncertainties are shown by the inner error bars, while the outer ones give the total uncertainties including systematic
- SM predictions as a function of q^2
- the same after rate average over q^2 bins
- Reliable predictions do not exist for the intermediate region between the J/ψ and ψ' resonances ($10.09 < q^2 < 12.86$ GeV^2)
- No significant deviations with respect to the SM

Muon forward-backward asymmetry



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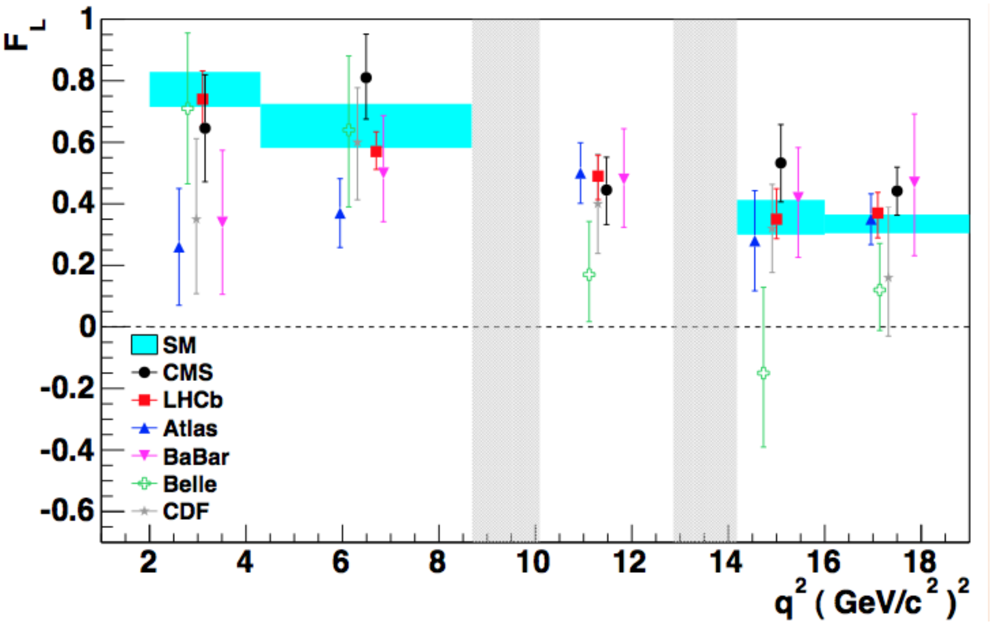
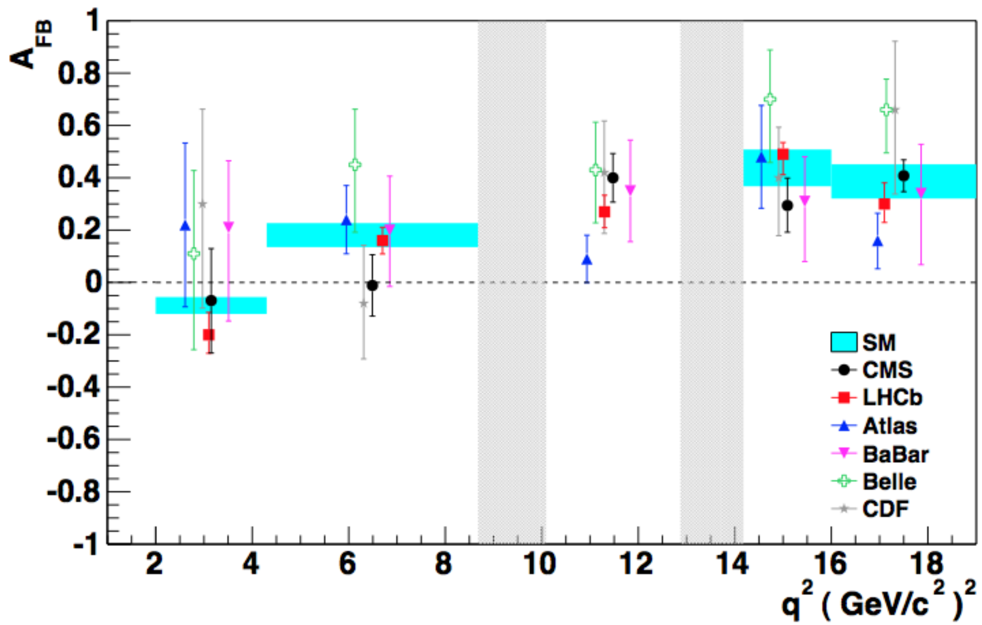
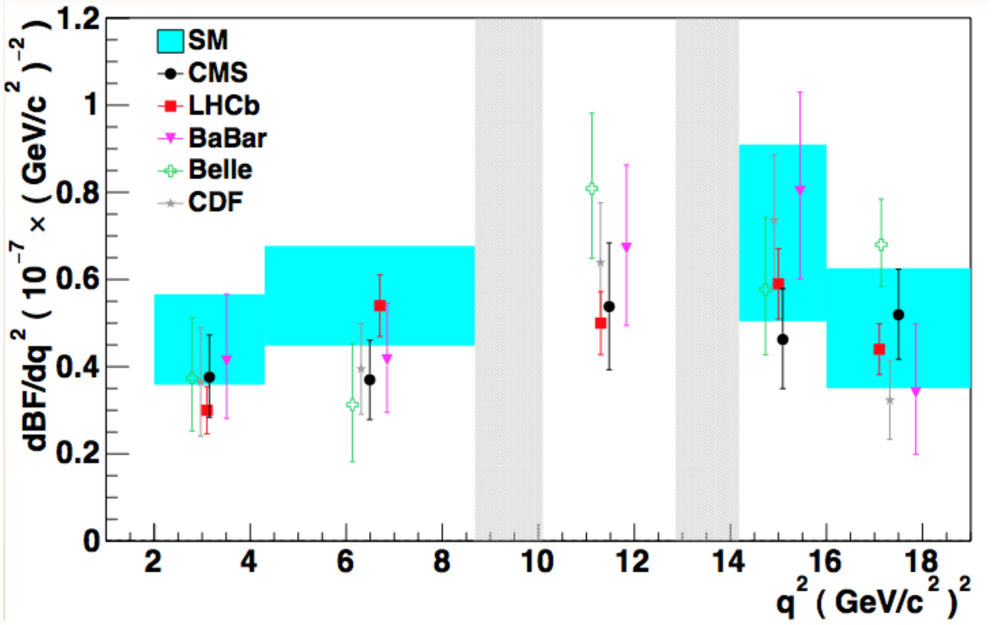
- Within uncertainties, consistent with the SM expectations
- Statistics dominated especially at the most interesting (low q^2) region

A comparison between experiments







- Results from LHC experiments are more precise than B-factory
- LHCb has the most sensitive results
- No striking evidence of tensions with SM, theory and experimental uncertainties are comparable

Summary and Outlook

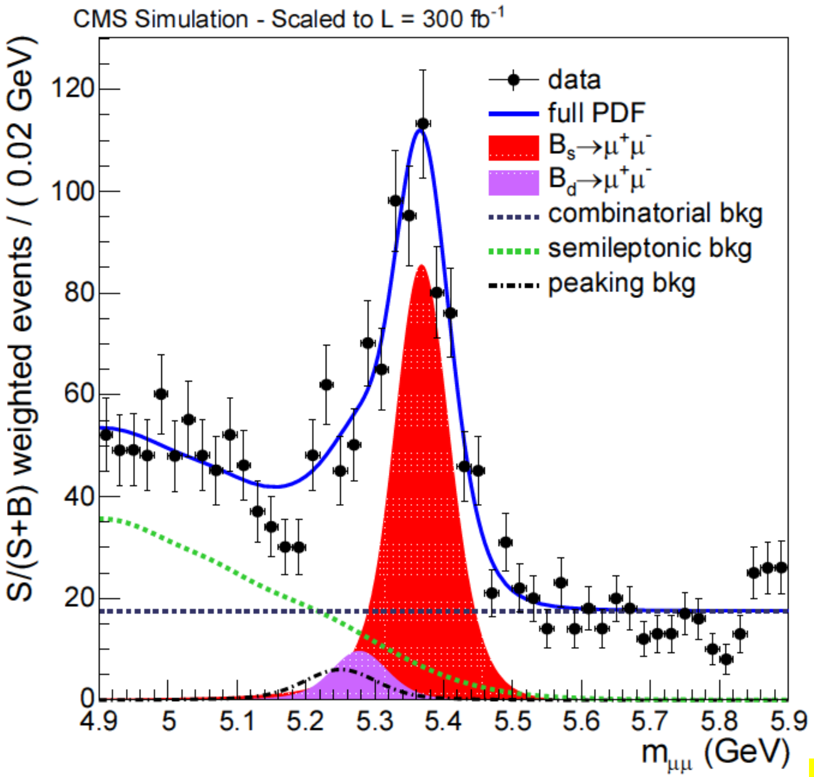
- Study of angular distributions in $B^0 \to K^{\star 0}(\to K^+\pi^-)\mu^+\mu^-$ performed in bins of q^2 by CMS using pp collision data recorded at $\sqrt{s} = 7$ TeV **PLB 727 (2013) 77**
  - Differential branching fraction
  - Muon forward-backward asymmetry
  - Longitudinal polarization fraction of $K^{\star 0}$

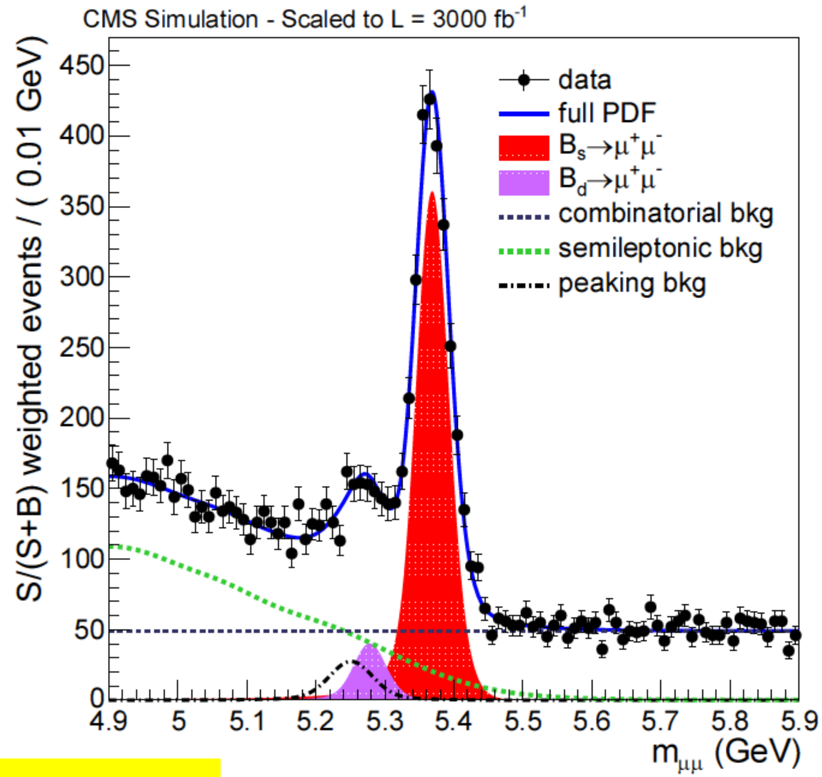
- Within errors (dominated by statistical ones) all results are consistent with SM predictions

- Results for the 8 TeV data (~20 fb^{-1}) are expected soon
  - Measure above three observables with higher statistics
  - Estimate zero crossing point of A_{FB} (related to the Wilson coefficient C_7) and new angular variables with small form-factor dependence

Looking even beyond…

➢ High-luminosity LHC: improved tracker with higher granularity and a muon system with coverage extended will significantly enhance *B*-physics capability





CMS PAS FTR-13-022

L (fb^{-1})	No. of B_s^0	No. of B^0	$\delta\mathcal{B}/\mathcal{B}(B_s{}^0 \to \mu^+\mu^-)$	$\delta\mathcal{B}/\mathcal{B}(B^0 \to \mu^+\mu^-)$	B^0 sign.	$\delta\frac{\mathcal{B}(B^0\to\mu^+\mu^-)}{\mathcal{B}(B_s^0\to\mu^+\mu^-)}$
20	16.5	2.0	35%	>100%	0.0–1.5 σ	>100%
100	144	18	15%	66%	0.5–2.4 σ	71%
300	433	54	12%	45%	1.3–3.3 σ	47%
3000	2096	256	12%	18%	5.4–7.6 σ	21%

Bonus Materials

Treatment of S-wave in the signal fit

- F_S and A_S values from the control sample $B^0 \to K^{\star 0} J/\psi$ are used in signal fit
- They are allowed to vary with Gaussian constraints equal to their uncertainties
- F_S (and F_L) are also constrained to lie in the physical region of 0 to 1; further penalty terms are added to ensure a positive decay rate
- Systematic uncertainty related to the S-wave treatment is estimated by taking the difference between the default results with that from a fit with no S-wave ($F_S = A_S = 0$)

Systematic uncertainty	$F_L\,(10^{-3})$	$A_{FB}\,(10^{-3})$	$d\mathcal{B}/dq^2\,(\%)$
Efficiency statistical uncertainty	5–7	3–5	1
Potential bias from fit algorithm	3–40	12–77	0–2.7
Potential bias from fit ingredients	0	0–17	0–7.1
Incorrect CP assignment of decay	2–6	2–6	0
Effect of Kπ S-wave contribution	5–23	6–14	5
Peaking background mass shape	0–26	0–8	0–15
Background shapes vs. $\cos\theta_{L,K}$	3–180	4–160	0–3.3
Signal mass shape	0	0	0.9
Angular resolution	0–19	0	0
Efficiency shape	16	4	4.3
Normalization to $B^0 \to K^{*0} J/\psi$	–	–	4.6
Total systematic uncertainty	31–190	18–180	8.6–17

Ranges provides here correspond to the variations over q^2 bins

Phase-II improvements leading to separation B_S^0 and B^0

- New phase-II tracker will have significantly less material budget that ranges between a factor of 2 to 3
- Combined with a smaller Si sensors pitch, this will improve track momentum resolution by about a factor of 1.5 in the barrel and 1.2 elsewhere
- Improved momentum resolution holds the key to a clear separation of the B^0 signal from the tail of the B_S^0 signal
- Extended muon detector coverage will provide a good support to the cause

For more details, refer to CMS PAS FTR-13-002