Studies of rare B meson decays with the CMS detector

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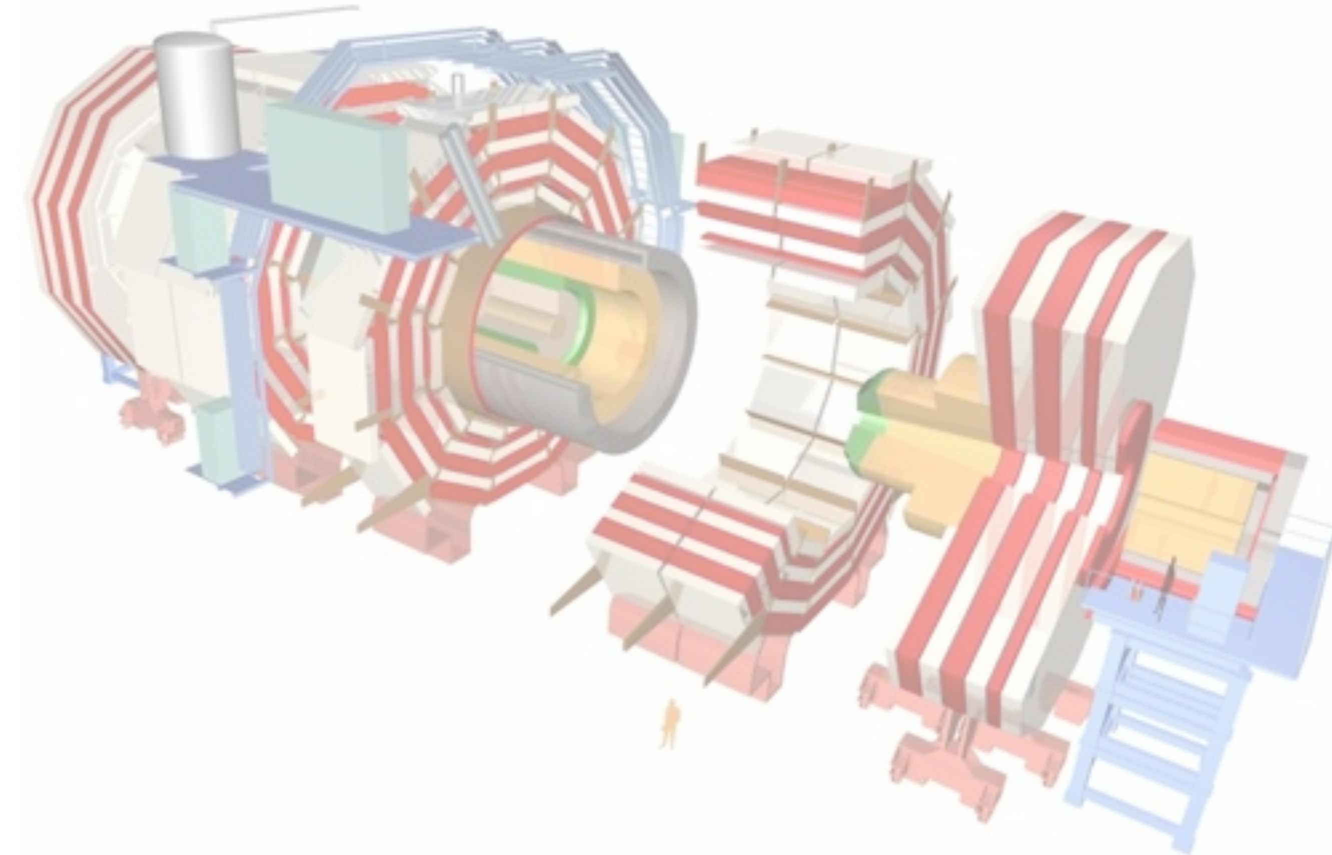
On behalf of CMS collaboration

DIS 2013

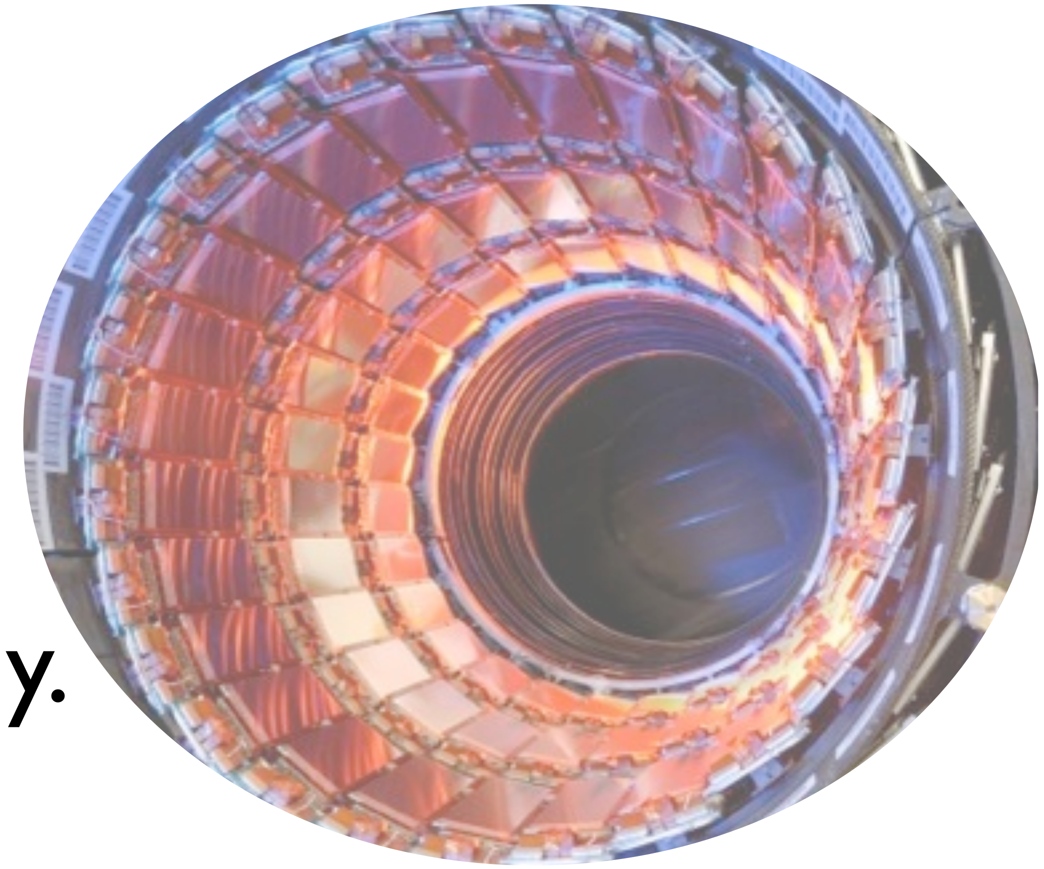
Outline



- Introduction
- Angular analysis and differential branching fraction of the decay $B^0 \to K^{*0} \mu^+ \mu^-$
- Search for B_s and B^0 decay to dimuons
- Summary

Introduction

- CMS is a general purpose detector at the LHC.
- Inner tracker consists of silicon pixel and silicon strip layers.
- Muons are measured by drift tubes (DT), cathode strip chambers (CSC) and resistive plate chambers (RPC).

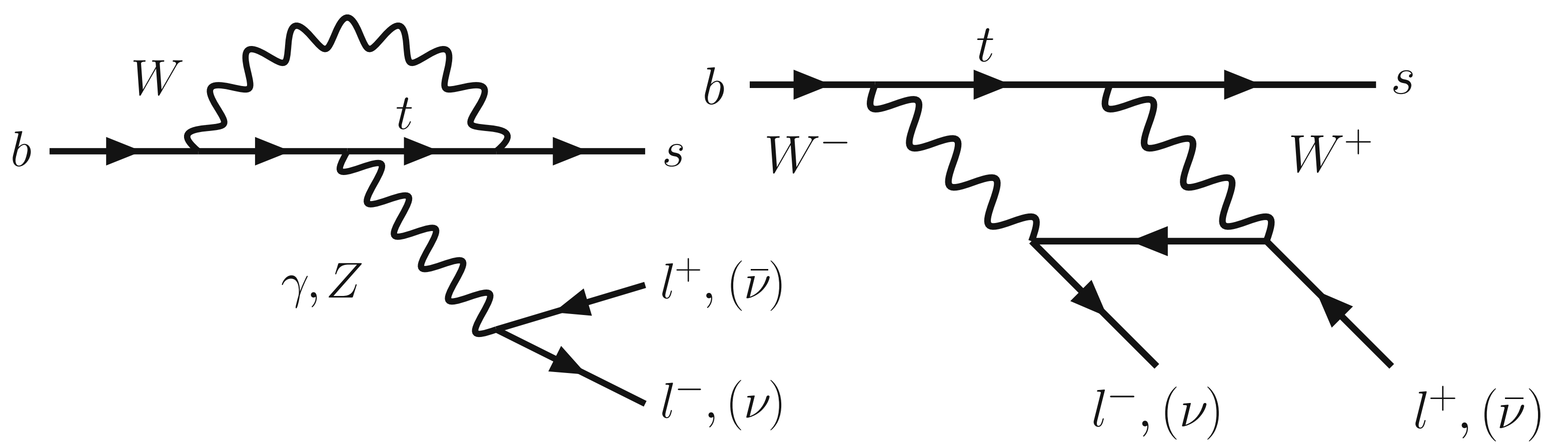


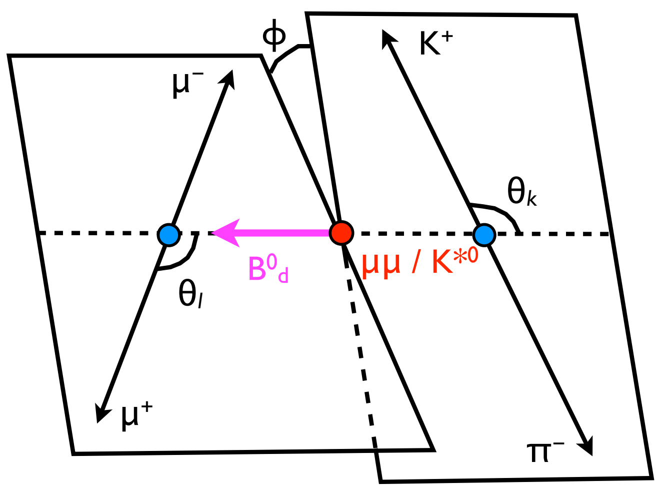
- The dimuon mass resolution is less than 1%.
- Powerful tool for B-physics study.

Angular analysis and differential branching fraction of the decay $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

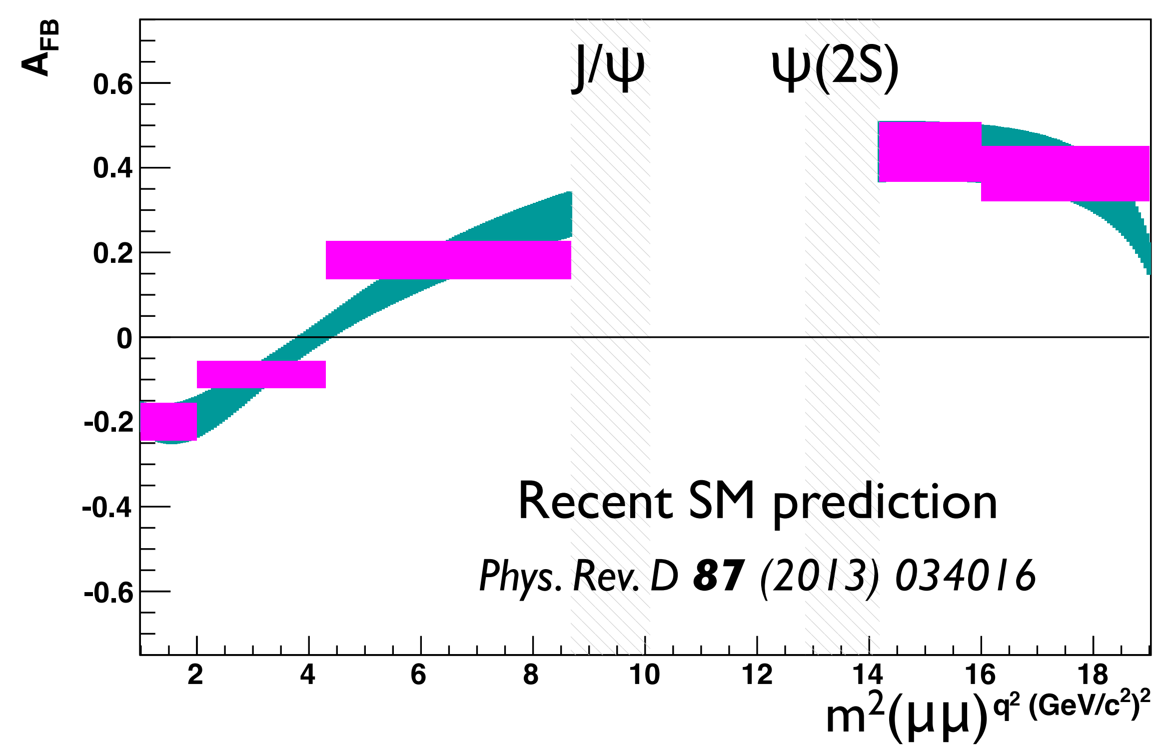
Motivation

- The $b \rightarrow s\ell^+\ell^-$ transition is a FCNC process:
  - The amplitudes may interfere with non-SM particle contributions.
  - The decay is fully described with three angles (**θ_L**, **θ_K** , **Φ**) and **q^2** = $m^2(\mu\mu)$



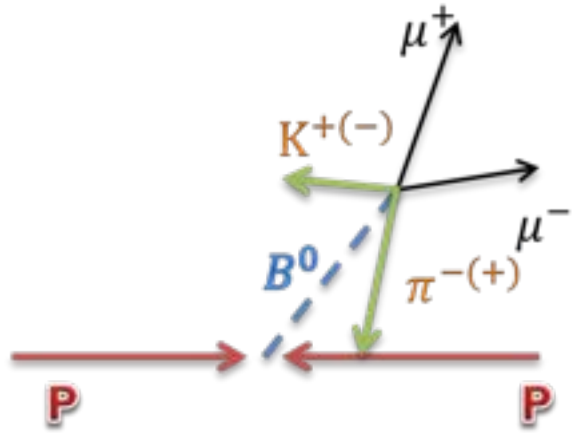


- $B^0 \rightarrow K^{*0}\ \mu^+\ \mu^-$ decay is well described with theory
  - Example of angular observables theoretically predicted with relatively small uncertainties at low q^2: μμ forward-backward asymmetry (**A_{FB}**)



Event Selection

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

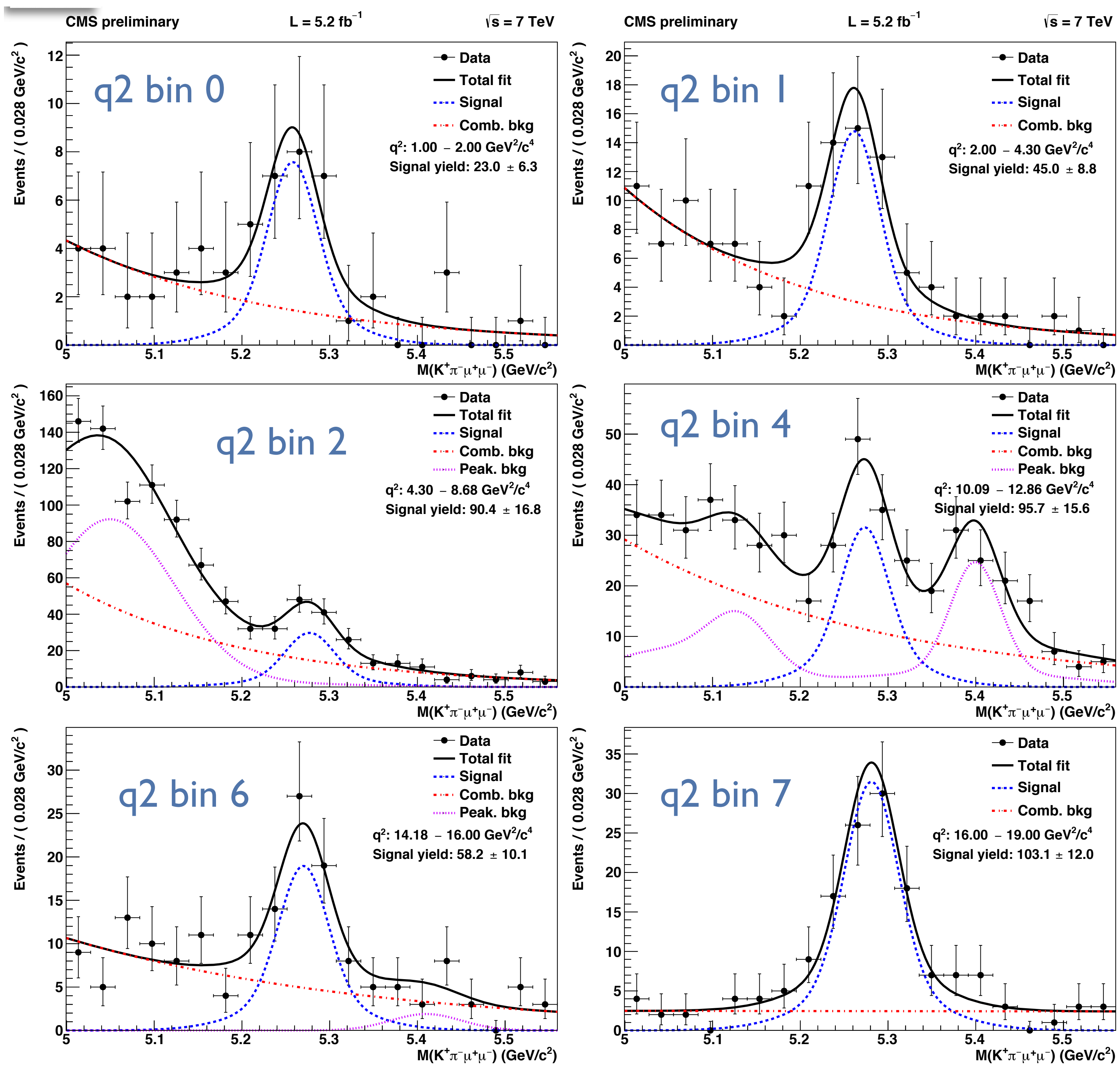


- 2011 dataset ~5.2 fb^{-1}
- Dimuon trigger selection
  - μμ vertex L/σ > 3(transverse)
  - $1 < m(\mu\mu) < 4.8$ GeV/c^2
  - dimuon P_T from 6.5 GeV/c (up to 6.9 GeV/c)
  - $P_T(\mu) > 3$ GeV/c (~5 GeV/c with different trigger)
  - μμ vertex CL > 5%, 15% (with different trigger)
- B^0 selection:
  - B^0 vertex CL > 9%
  - B^0 vertex L/σ > 12 (transverse)
  - cos(α) > 0.9994: α angle in transverse plane between B^0 momentum and line-of-flight
- Two oppositely charged hadrons
  - No overlap with muons
  - PT(h) > 0.75 GeV/c
  - Distance Closest Approach / σ > 1.3
  - $|m(K\pi) - m_{PDG}K^{*0}| < 80$ MeV/c^2
- CP state assignment
  - Tag the CP state of K^{*0} and $\overline{K^{*0}}$ masses based based on closest distance from PDG
  - Reject event if both K^{*0} and $\overline{K^{*0}}$ masses are within 50 MeV/c^2 of PDG mass (~1Γ)

Signal Yields in q^2 bins

- Signal + Combinatorial background + Peaking background

(feed-through from resonant channels)



q^2 bin index	mass range $(GeV/c^2)^2$
0	1 - 2
1	2 - 4.3
2	4.3 - 8.68
4	10.09 - 12.86
6	14.18 - 16
7	16 - 19

Fit Strategy

- Unbinned maximum likelihood fits: B0 mass, θ_K and θ_l for each q^2 bin to extract $F_L(q^2)$ and $A_{FB}(q^2)$

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

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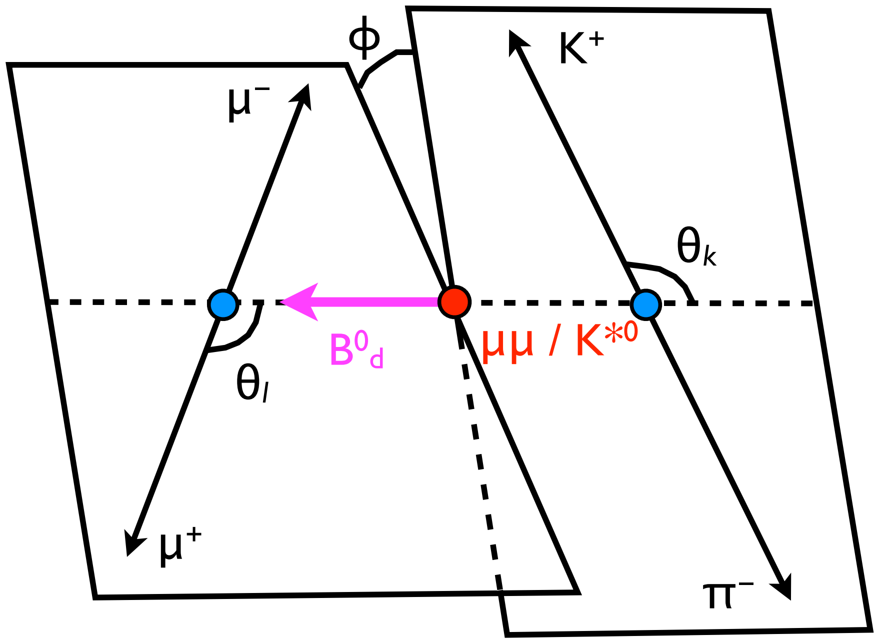


- P and S wave of Kπ and their interference are also considered in the PDF, and fit from $B^0 \to K^{*0} J/\psi$
  - F_S: fraction of S-wave
  - A_S: interference between S and P-waves

- Using previous fit results, then fit the B0 invariant mass to extract the branching fraction: $dBF/q^2(q^2)$

$$\frac{dBF}{dq^2} = \frac{Y_S\, \varepsilon_N\, BF[B^0 \to K^{*0}(K^+\pi^-)\, J/\psi\, (\mu^+\mu^-)]}{Y_N\, \varepsilon_S\, dq^2}$$

- Y_S, Y_N: yields of the signal and normalization channel.
- ε_S, ε_N: efficiency of the signal and normalization channel.

Maximum Likelihood fit: p.d.f.

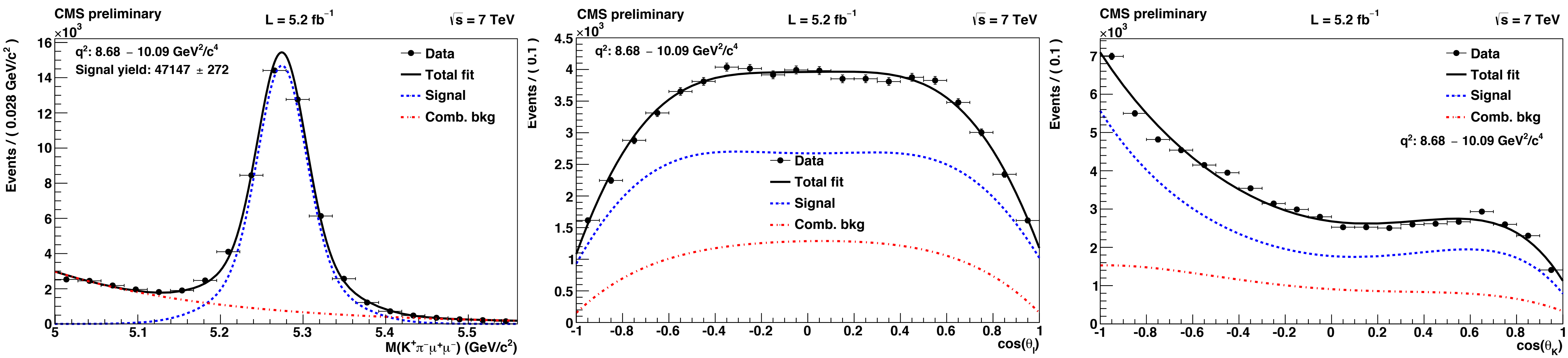
$$\text{p.d.f.}(m,\theta_k,\theta_l) = Y_{Si}\, S_i^{M}(m)\cdot S_i^{A}(\theta_k,\theta_l)\cdot \mathcal{E}_i(\theta_k,\theta_l) +$$
$$+\, Y_{Bi}^{c}\, B_i^{Mc}(m)\cdot B_i^{\theta_k c}(\theta_k)\cdot B_i^{\theta_l c}(\theta_l) +$$
$$+\, Y_{Bi}^{p}\, B_i^{Mp}(m)\cdot B_i^{\theta_k p}(\theta_k)\cdot B_i^{\theta_l p}(\theta_l),$$

Index i runs over q^2 bins

- Signal: data yield, lineshape of mass (double Gaussian from MC) and decay rate (physics).
- Combinatorial background: data yield, lineshape of mass (exponential) and angles (polynomials).
- Peaking background: data yield, lineshape of mass (1 or 2 single/double Gaussians from MC) and angles (polynomials from MC).

Validation with Control Channels

$B^0 \to K^{*0}\,(K^+\pi^-)\,J/\psi\,(\mu^+\mu^-)$



$B^0 \to K^{*0}\,(K^+\pi^-)\,J/\psi\,(\mu^+\mu^-)$

- **F_L:** 0.554 ± 0.004 (stat) ➜ PDG value 0.570 ± 0.008
- **A_{FB}:** −0.004 ± 0.004 (stat) ➜ compatible with zero

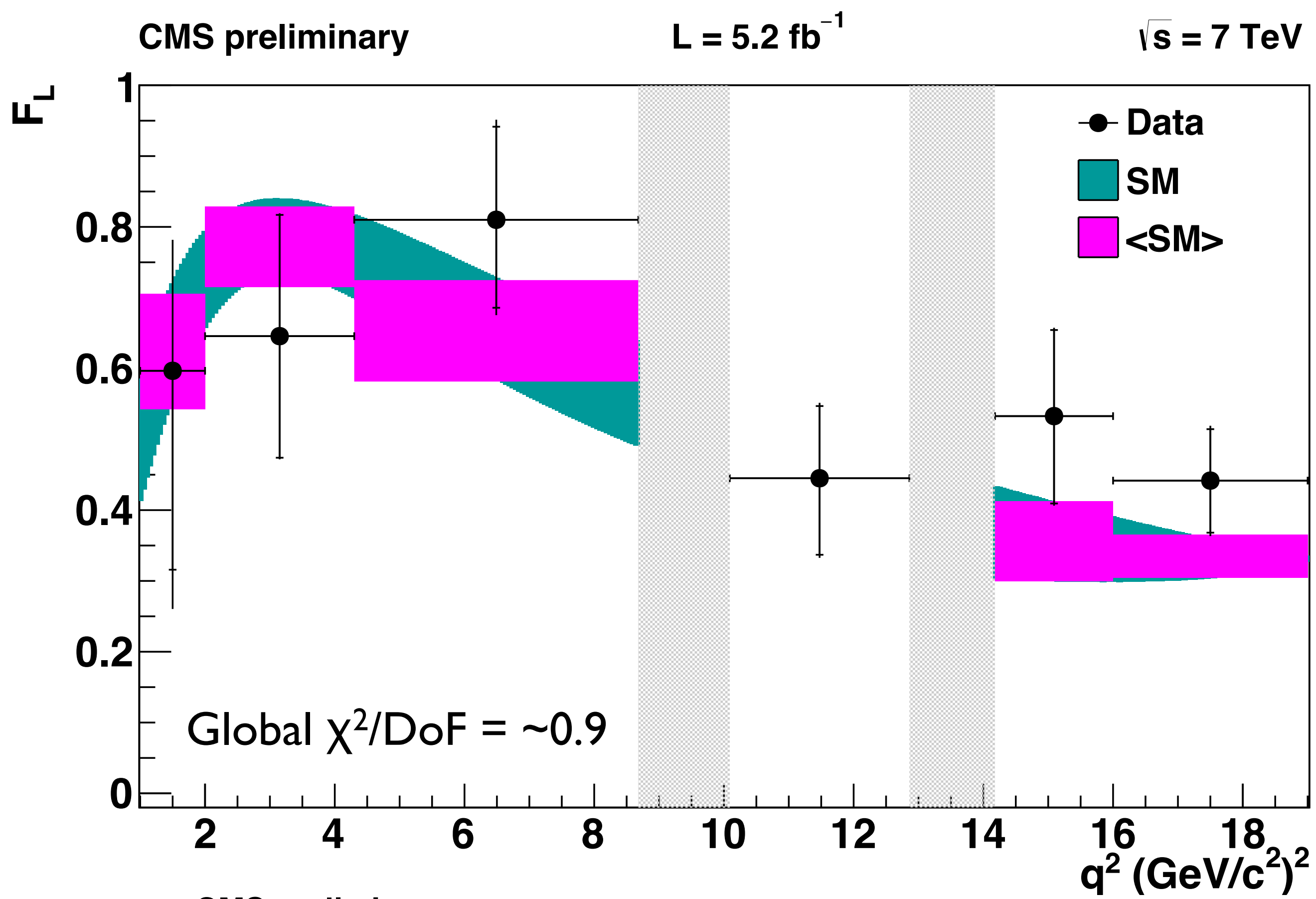
$B^0 \to K^{*0}\,(K^+\pi^-)\,\psi(2S)\,(\mu^+\mu^-)$

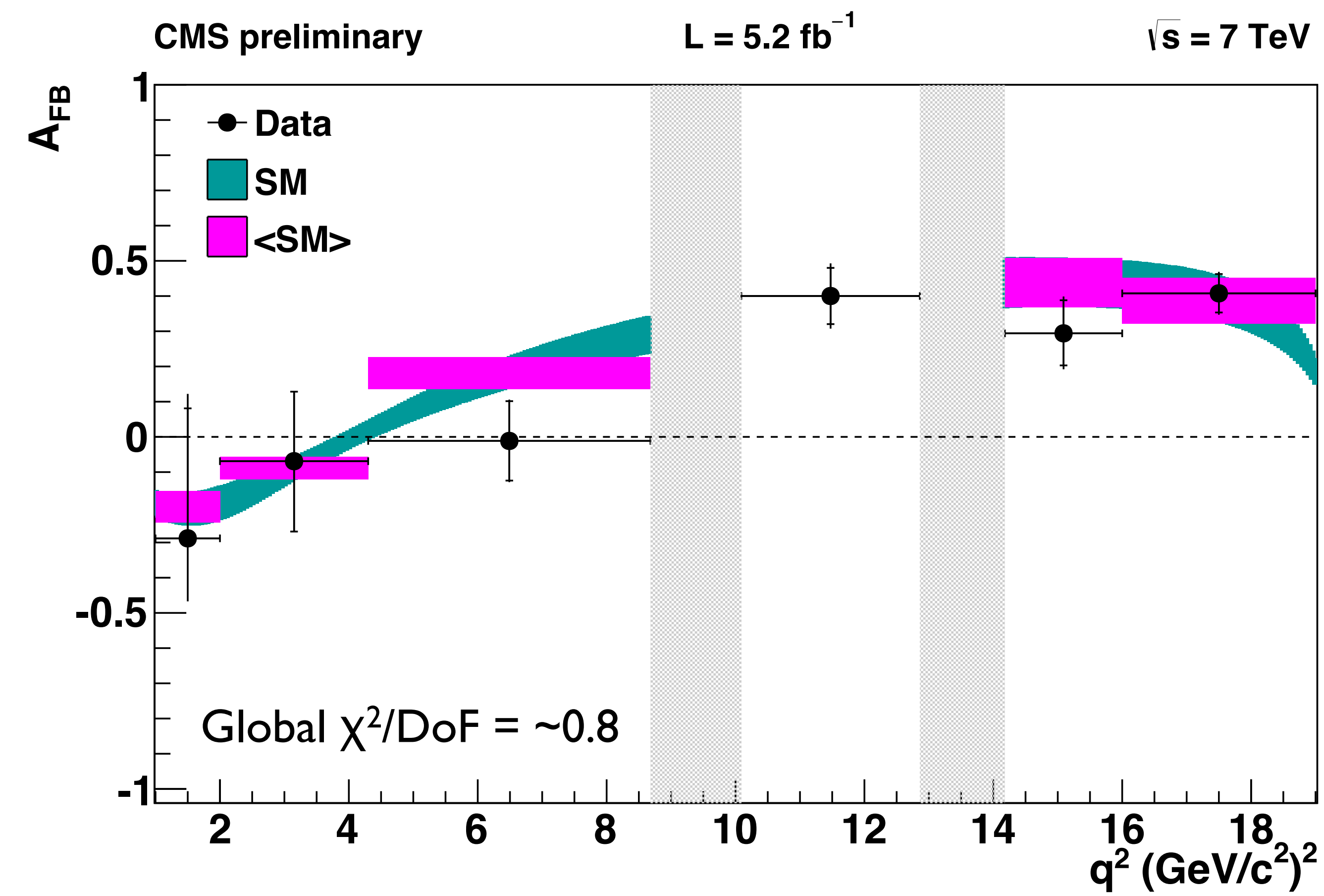
- **F_L:** 0.509 ± 0.016 (stat) ➜ PDG value 0.46 ± 0.04
- **A_{FB}:** 0.013 ± 0.014 (stat) ➜ compatible with zero

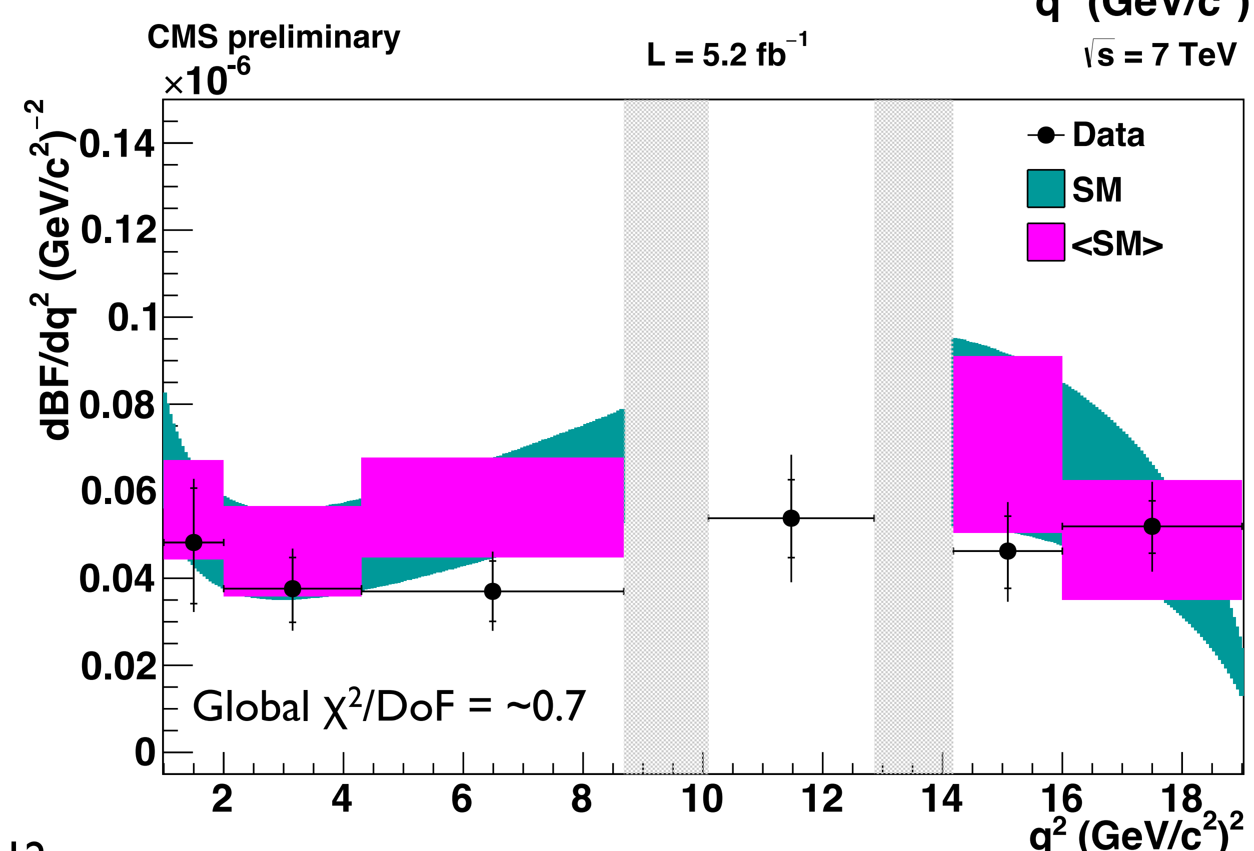
Systematic Uncertainties

Sources of systematic uncertainty	F_L	A_{FB}	dBF/dq^2
Potential bias from fit ingredients	0	0−0.017	0−7.1%
Test of $\Gamma(B^0 \to K^{*0}J/\psi)$ / $\Gamma(B^0 \to K^{*0}\psi(2S))$	0	0	14.3%
Potential bias from fit algorithm (toy MC)	0.004−0.040	0.012−0.077	0−2.7%
Incorrect CP assignment of decay	0.002−0.006	0.002−0.006	0%
Effect of $K\pi$ *S*-wave contribution	0.005−0.023	0.006−0.014	5%
Peaking background mass shape	0−0.026	0−0.008	0−15.2%
Combinatorial background shape vs $\cos(\theta_{K/l})$	0.003−0.179	0.004−0.161	0−3.3%
Angular resolution	0−0.019	0	0
Signal mass shape	0	0	0.9%
Statistical uncertainty of simulated events	0.005−0.007	0.003−0.005	1%
Total systematic uncertainty	**0.027−0.185**	**0.018−0.179**	**15.5−21.5%**

Fitting results







- Error bars with edges: statistical uncertainty
- Edgeless error bars: total uncertainty
- Purple region: standard model properly averaged over the bin (Phys. Rev. D **87** (2013) 034016)

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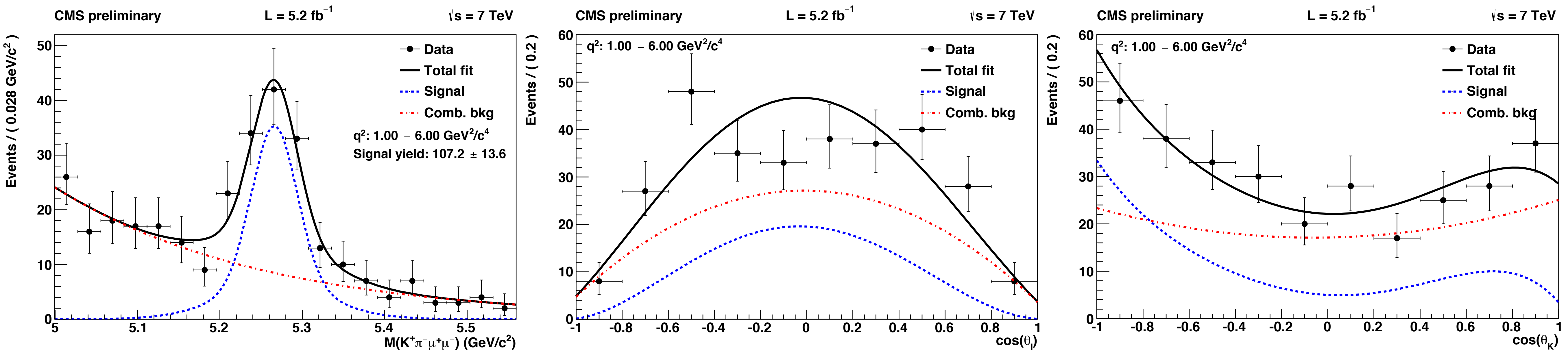
Special q^2 bin: 1 - 6 $(GeV/c^2)^2$



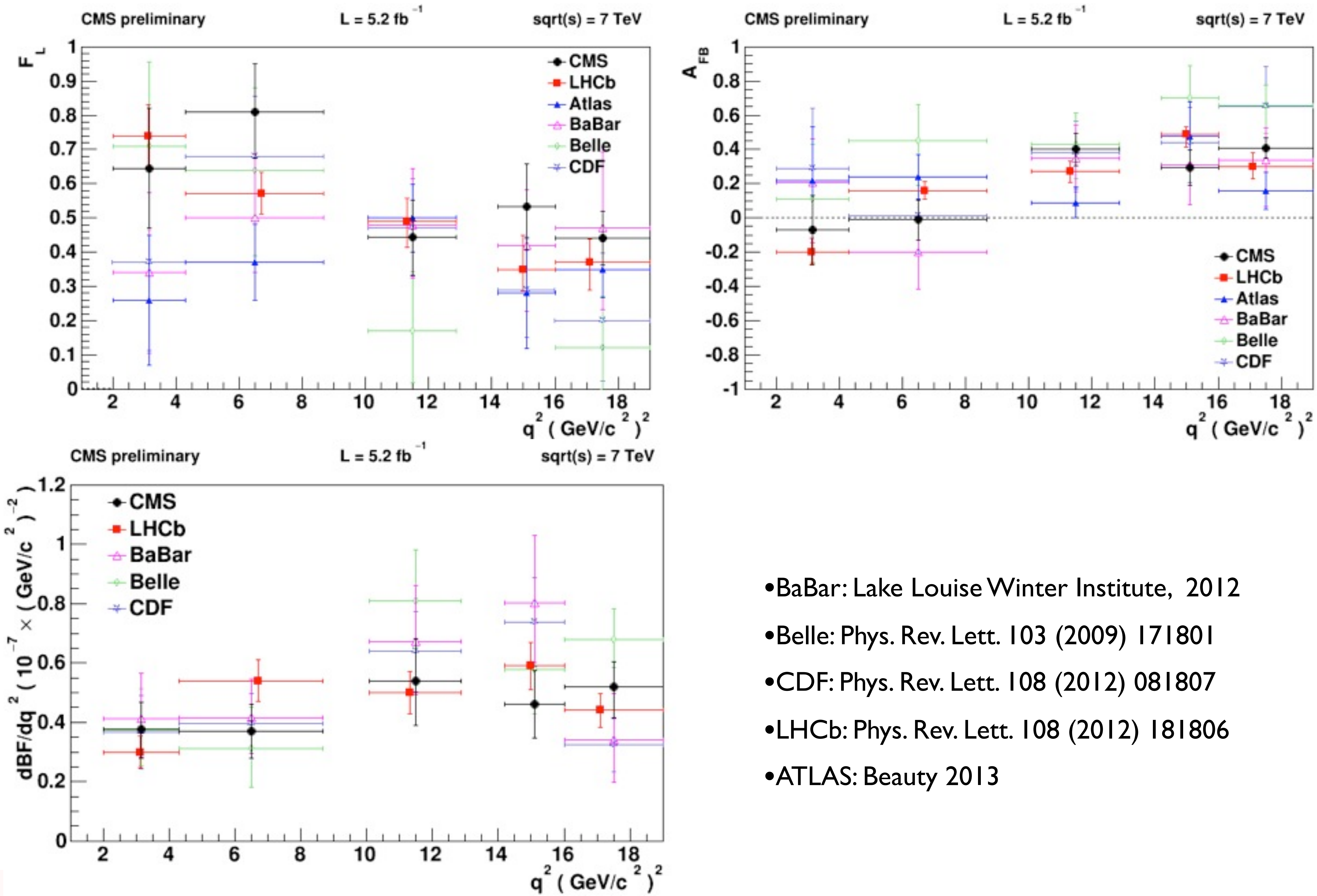
CMS measurements:

- F_L: 0.68 ± 0.10 (stat) ± 0.02 (syst)
- A_{FB}: −0.07 ± 0.12 (stat) ± 0.01 (syst)
- dBF/dq^2: (4.4 ± 0.6 (stat) ± 0.7 (syst)) x 10^{-8} c^4/GeV^2

SM predictions (*Phys. Rev. D* ***87*** *(2013) 034016*)**:**

- F_L: 0.74 + 0.06 −0.07
- A_{FB}: −0.04 ± 0.03
- dBF/dq^2: (4.9 + 1.0 −1.1) x 10^{-8} c^4/GeV^2

Comparison with other experiments

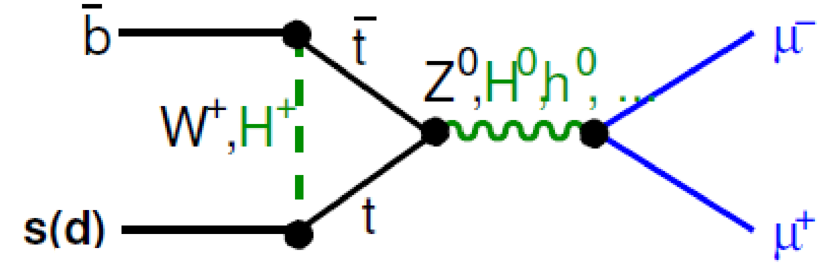


- BaBar: Lake Louise Winter Institute, 2012
- Belle: Phys. Rev. Lett. 103 (2009) 171801
- CDF: Phys. Rev. Lett. 108 (2012) 081807
- LHCb: Phys. Rev. Lett. 108 (2012) 181806
- ATLAS: Beauty 2013

Search for B_s and B^0 decay to dimuons

B_s and B^0 decay to dimuons

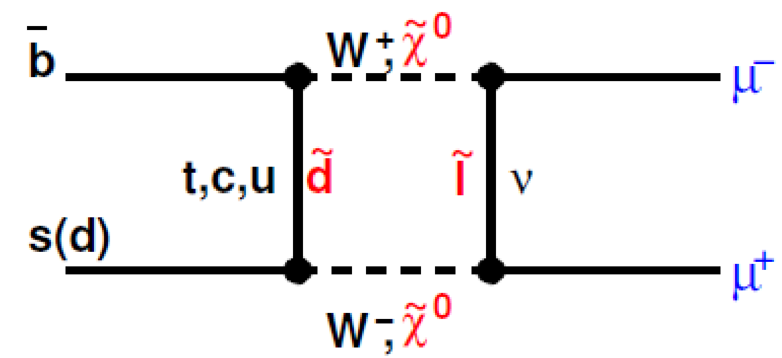
- Doubly suppressed in the SM (FCNC, helicity and Cabibbo suppression)



- Well predicted in theory:

Phys. Lett. B694, 402 (2010)

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\mathrm{SM}} = (3.2 \pm 0.2) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-)_{\mathrm{SM}} = (1.0 \pm 0.1) \times 10^{-10}$$



- Sensitive to New Physics:

Phys. Lett. B639, 499 (2006)

$$\frac{\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\mathrm{CMSSM}}}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\mathrm{SM}}} \approx 1.2^{+0.8}_{-0.2}$$
$$\frac{\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\mathrm{NUHM1}}}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\mathrm{SM}}} \approx 1.9^{+1.0}_{-0.9}.$$

- CMSSW: Constrained Minimal Supersymmetric extension of the Standard Model, Phys. Rev. D 47 (1993) 376
- NUHM1: Non-Universal Higgs Mass 1 model, Phys. Rev. D 71 (2005) 095008

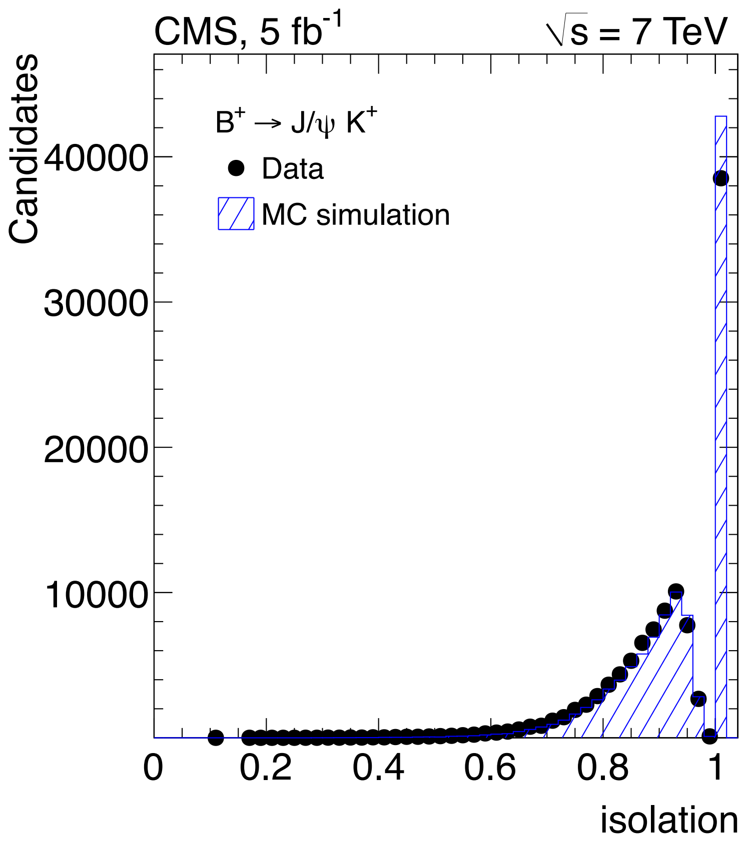
Analysis Technique

- Blind analysis with $B^+ \rightarrow J/\psi K^+$ as normalization channel.
  - Remove uncertainties on lumi and σ_{bb}
  - Reduce syst. uncertainty in BR ratio. $\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = \frac{N_S}{N_{obs}^{B^+}} \frac{f_u}{f_s} \frac{\varepsilon_{tot}^{B^+}}{\varepsilon_{tot}} \mathcal{B}(B^+),$

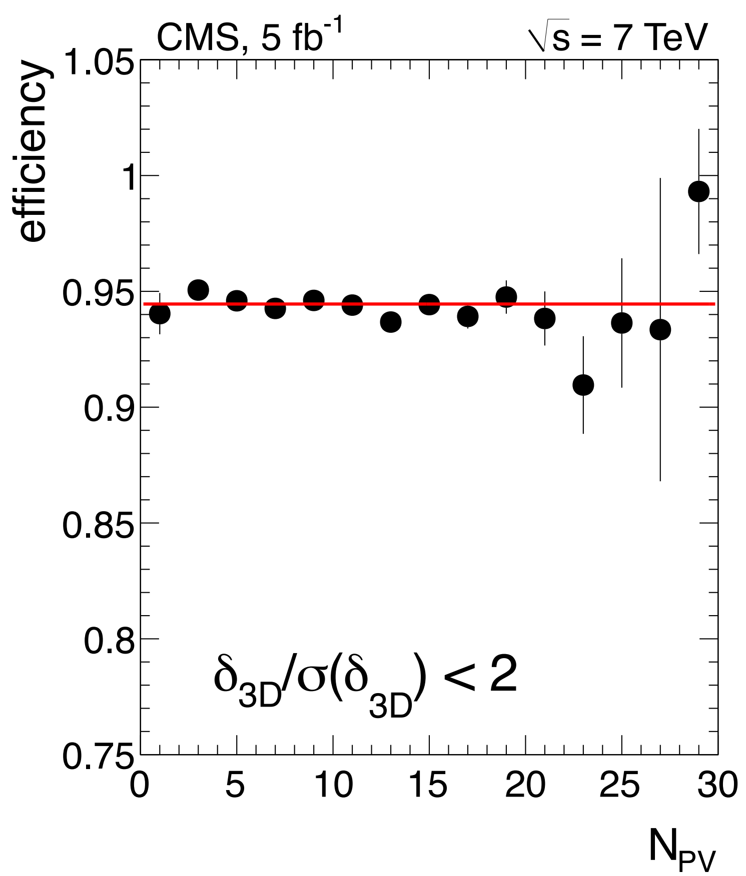
- Main backgrounds:
  - Collimated muons from two semileptonic B decays (gluon splitting)
  - One muon from semileptonic B decay and one mis-identified hadron
  - Rare decays: Peaking (e.g. $B_s \rightarrow K^+K^-$) Non-peaking (e.g. $B_s \rightarrow K^+ \mu^-\nu$)

Signal Selection

- Variables in selection:
  - Muon and dimuon p_T
  - Vertex χ^2 probability
  - Pointing angle
  - Impact parameter and flight length significance
  - Dimuon isolation in a cone around the B direction

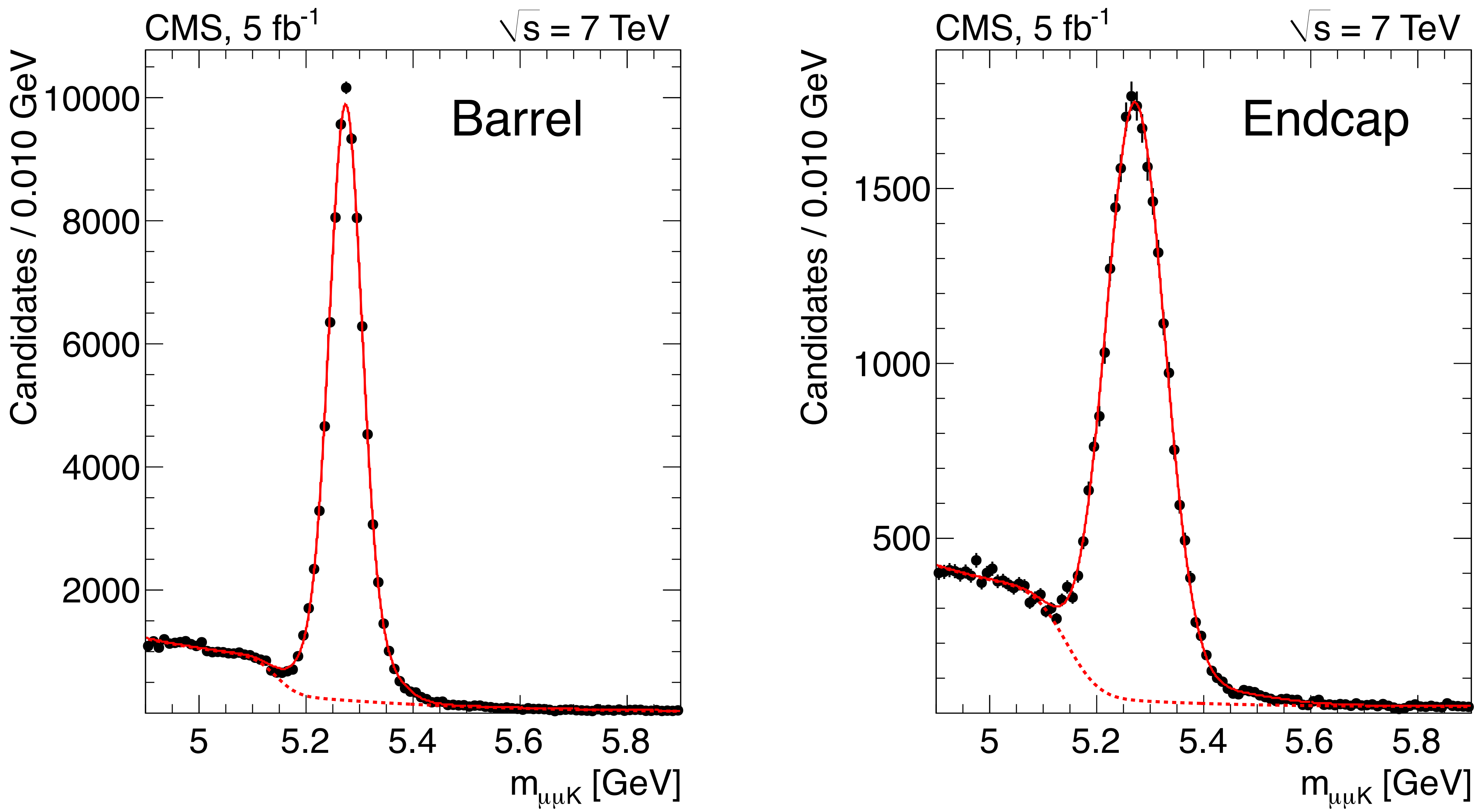


- Cut optimization and count in B^0 and B_s mass windows.
  - Check robustness against pile-up variations.
  - Mass sidebands for expected background estimation
- Efficiency ratios from MC and checked in data
  - "tag-and-probe" method and Bs J/ψ Φ control sample.



Normalization and background

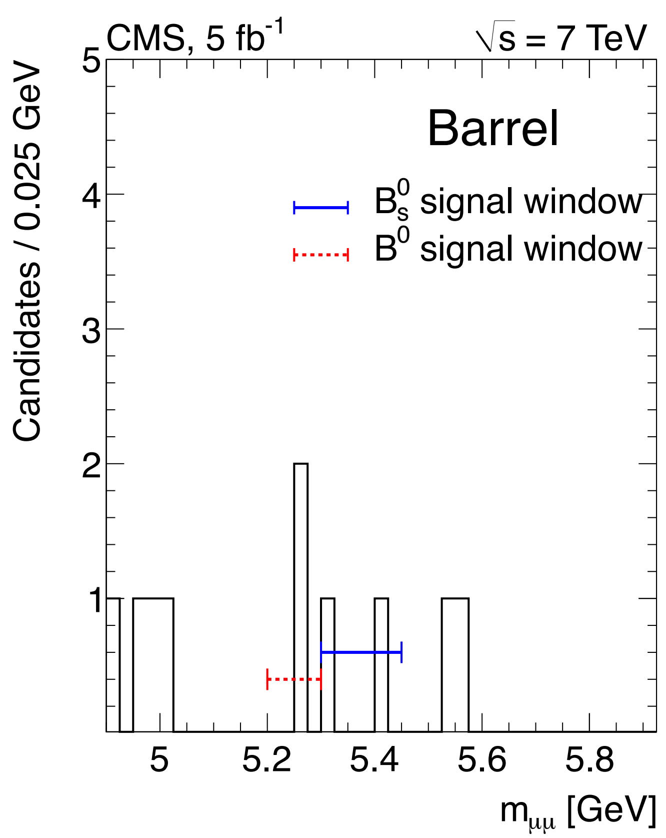
- N_{norm} from invariant mass fit to $B^+ \to J/\psi K^+$ sample

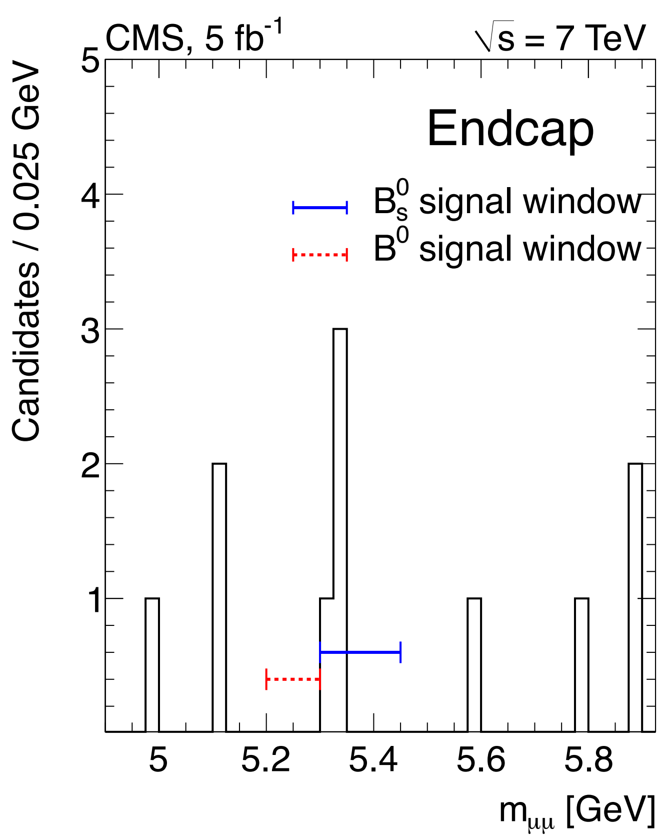


- Combinatorial background from dimuon mass sideband interpolation assuming flat distribution
- Peaking background shapes from MC

Results

Variable	$B^0 \to \mu^+\mu^-$ Barrel	$B_s^0 \to \mu^+\mu^-$ Barrel	$B^0 \to \mu^+\mu^-$ Endcap	$B_s^0 \to \mu^+\mu^-$ Endcap
ε_{tot}	0.0029 ± 0.0002	0.0029 ± 0.0002	0.0016 ± 0.0002	0.0016 ± 0.0002
N_{signal}^{exp}	0.24 ± 0.02	2.70 ± 0.41	0.10 ± 0.01	1.23 ± 0.18
N_{peak}^{exp}	0.33 ± 0.07	0.18 ± 0.06	0.15 ± 0.03	0.08 ± 0.02
N_{comb}^{exp}	0.40 ± 0.34	0.59 ± 0.50	0.76 ± 0.35	1.14 ± 0.53
N_{total}^{exp}	0.97 ± 0.35	3.47 ± 0.65	1.01 ± 0.35	2.45 ± 0.56
N_{obs}	2	2	0	4





Expected ULs:

BR ($B_s \to \mu\mu$) < 8.4×10^{-9} @ 95% CL

BR ($B_d \to \mu\mu$) < 1.6×10^{-9} @ 95% CL

Observed ULs:

BR ($B_s \to \mu\mu$) < 7.7×10^{-9} @ 95% CL

BR ($B_d \to \mu\mu$) < 1.8×10^{-9} @ 95% CL

Summary

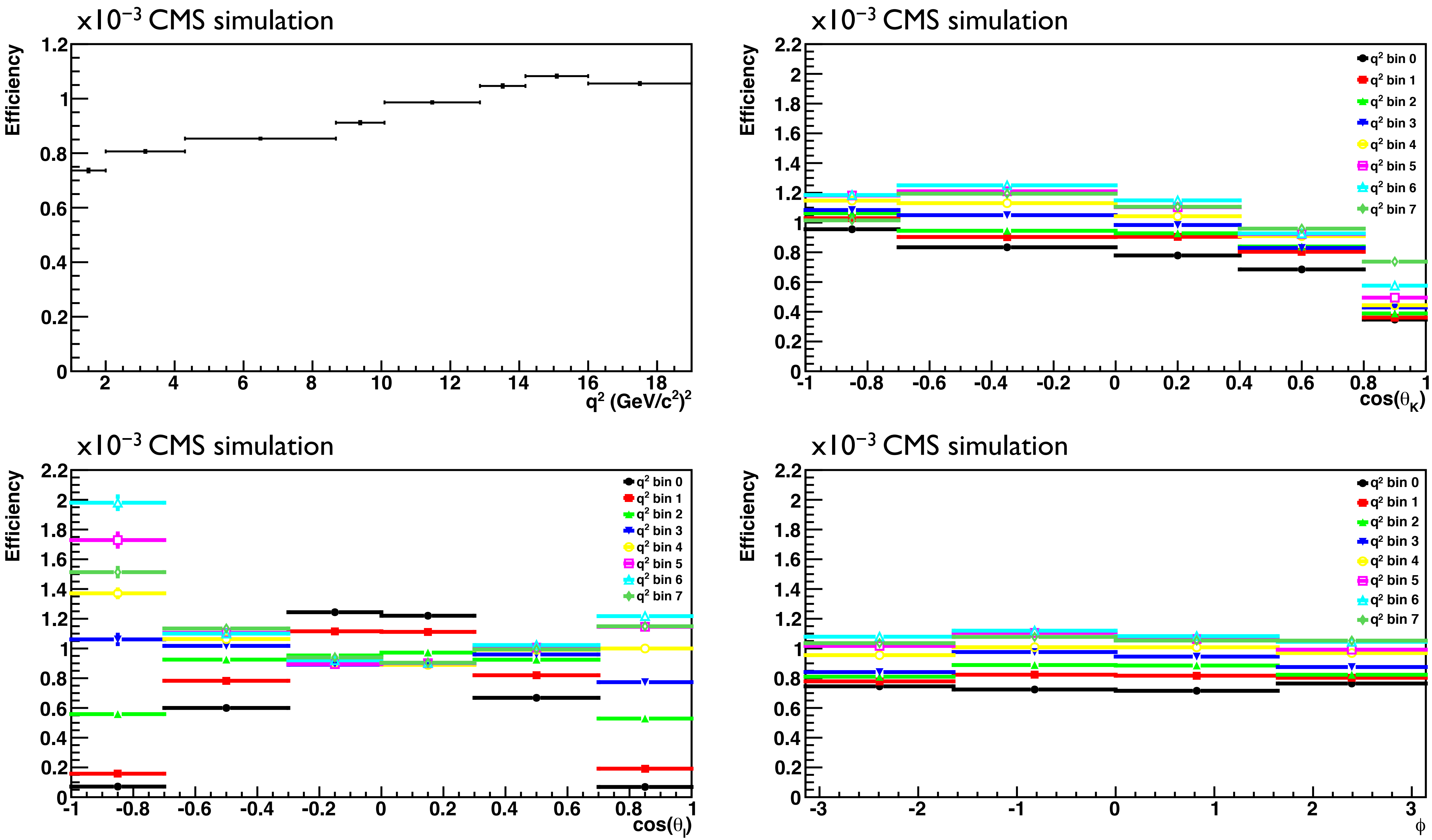
- CMS is a powerful detector for studying rare B decays because of its excellent tracking and lepton identification.
- First result from the angular analysis and differential branching fraction of the decay $B^0 \rightarrow K^{*0} \mu^+ \mu^-$
- Stringent constraints on new physics with the search for B_s and B^0 decay to dimuons
- Stay tuned for the updates with the full 2012 data!

All public results can be found at:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH

Backup

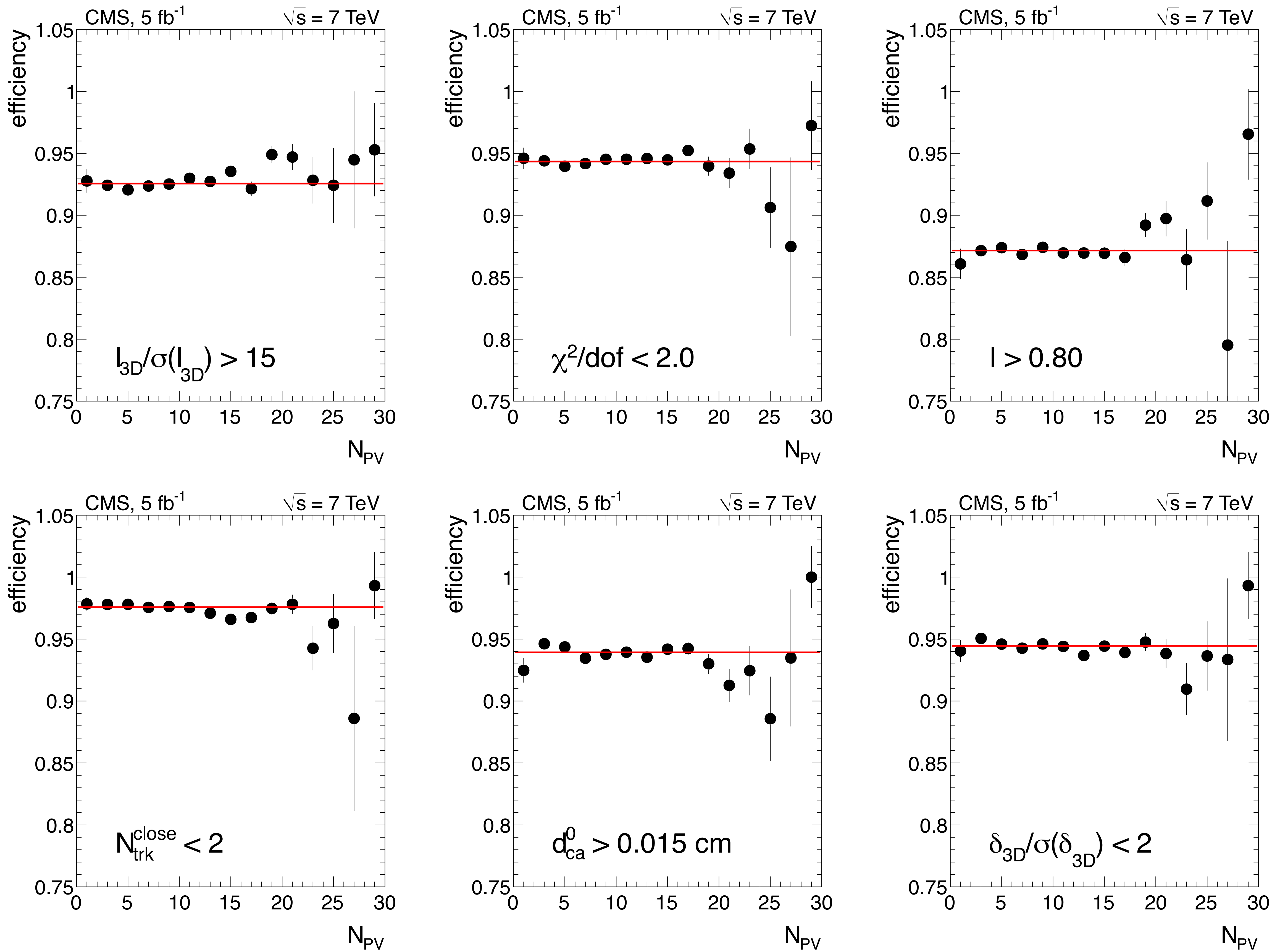
Efficiency Correction

The efficiency is entirely computed from MC versus angles and q^2 bins



Projections of the efficiency on angular variables and q^2

Efficiency vs # primary vertices



Fit Strategy

- In small fraction (few %) of decays Kπ are in *S*-wave state (*BaBar: Phys. Rev. D* ***76*** *(2007) 031102*)
- We are interested in decays where Kπ are in *P*-wave
- In our p.d.f. the decay rate describes both *P* and *S* wave, together with their interference

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

- **F_S:** fraction of *S*-wave
- **A_S:** forward-backward asymmetry of kaons

F_S *and* ***A_S*** *are determined from $B^0 \to K^{*0}$ ($K^+\pi^-$) J/ψ ($\mu^+\mu^-$) channel and fixed, with Gaussian constraints, for non-resonant q^2 bins*