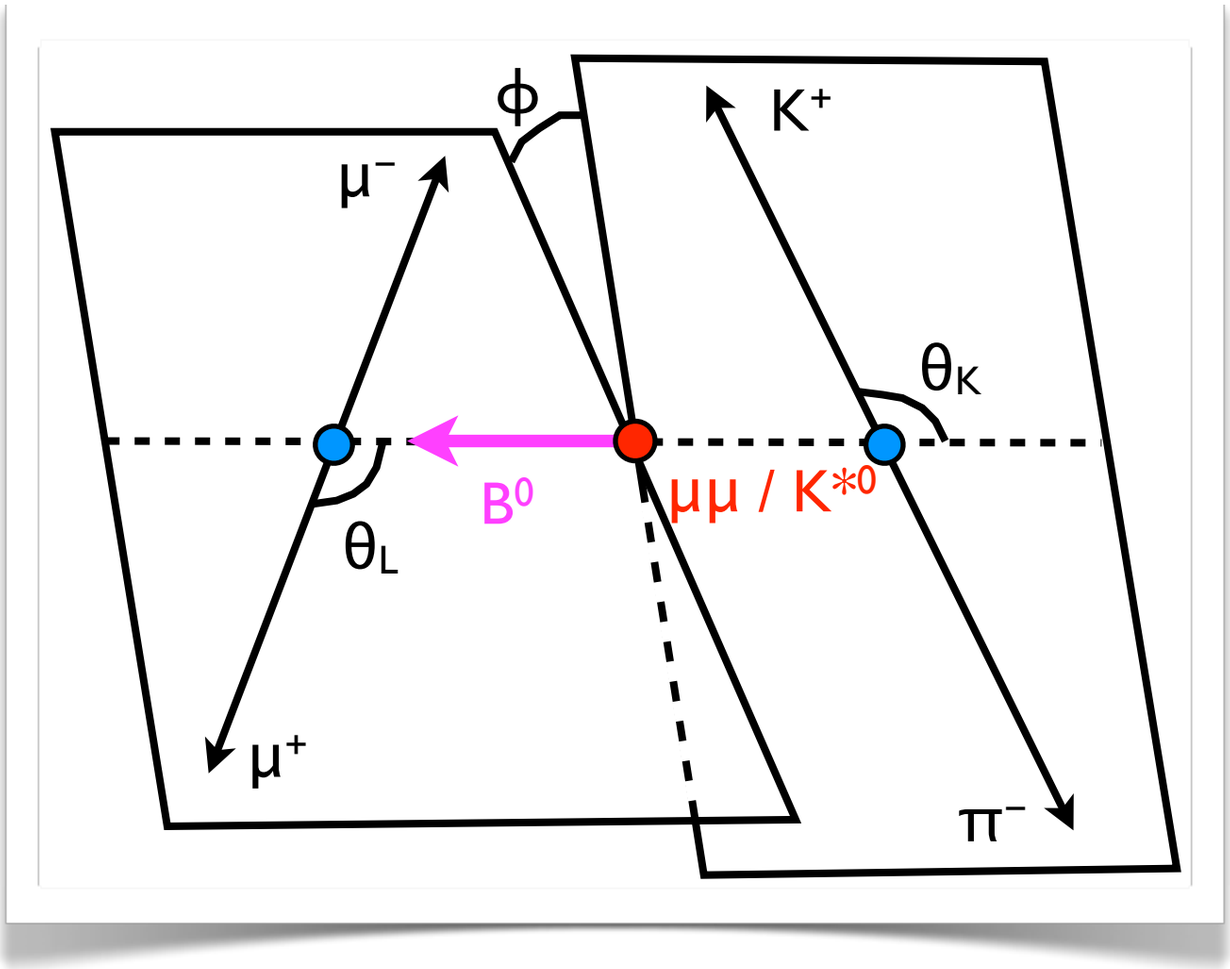
Beauty 2013

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



Mauro Dinardo

Universita` degli Studi di Milano Bicocca and INFN, Italy

on behalf of the CMS collaboration

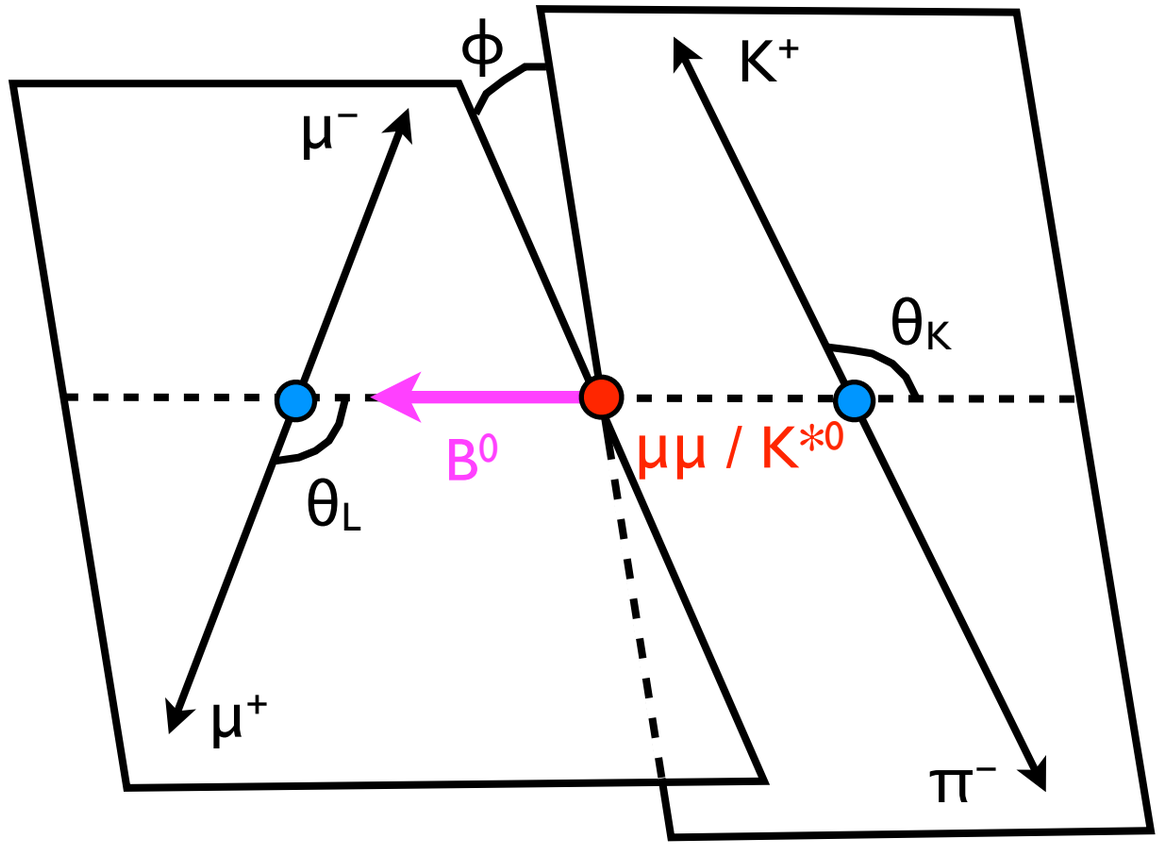
Outline

- Introduction
- Event Selection and Signal Evidence
- Fit Strategy
- Systematic Uncertainties
- Analysis Validation with Control Channels
- Measurements
- Comparison with other Experiments
- Conclusions

Introduction

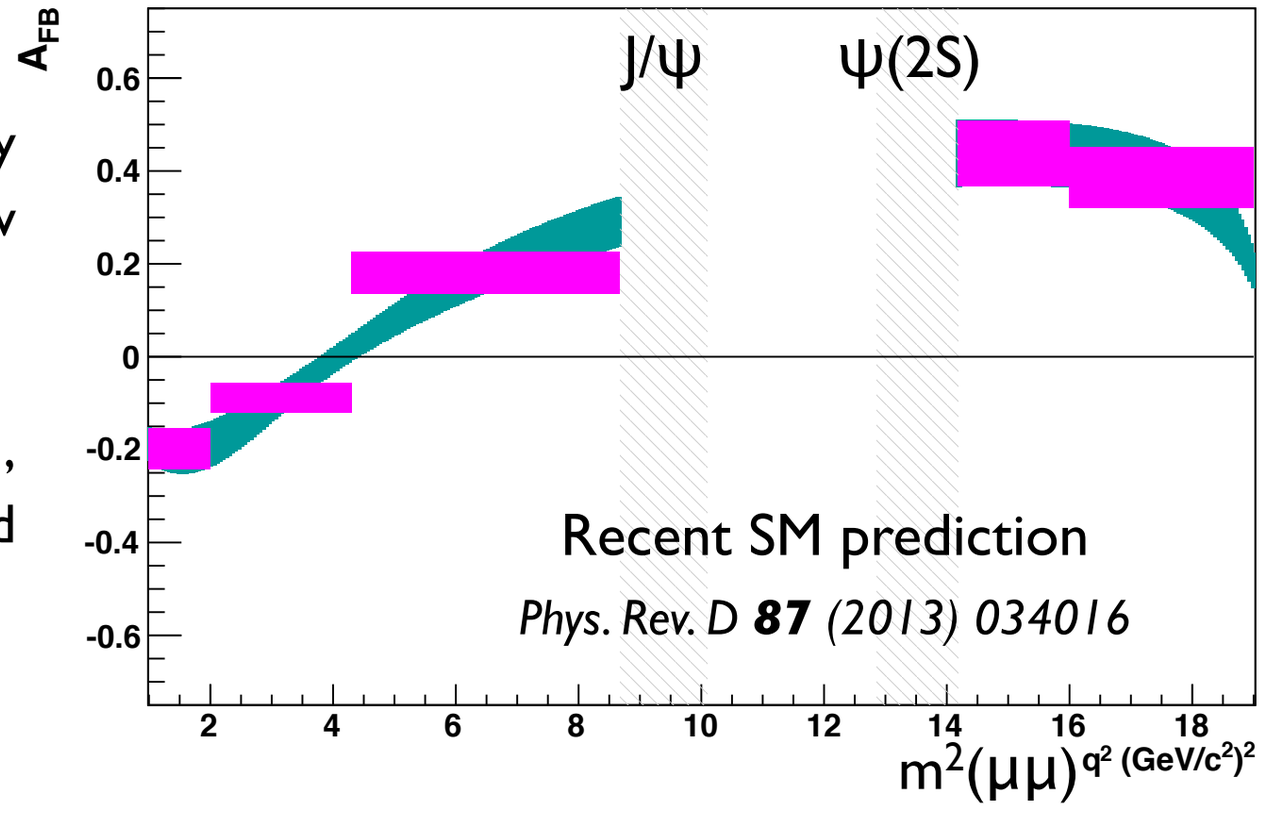
- **$B^0 \rightarrow K^{*0} \mu^+ \mu^-$** described within the SM as flavor changing neutral current process ➜ **(a)**small SM rates **(b)**small theoretical uncertainties **(c)**new physics predictions that differ from SM **(d)**experimental accessibility ➜ **good candidate for indirect searches for new phenomena**

- The decay is fully described with three angles (θ_L, θ_K , Φ) and $q^2 = m^2(\mu\mu)$



- Example of angular observables theoretically predicted with relatively small uncertainties at low q^2: μμ forward-backward asymmetry (**A_{FB}**)

- **Goal of the analysis:** measure **A_{FB}**, longitudinal polarization of K^{*0} (**F_L**), and differential branching fraction (**dBF/dq^2**) vs q^2



Event Selection

Remarks:

- Total collected data: ~5.2 fb^{-1} (full 2011 CMS statistics)
- Signal: $B^0 \rightarrow K^{*0} (K^+\pi^-) \mu^+ \mu^-$
- Two control channels: $B^0 \rightarrow K^{*0} (K^+\pi^-) J/\psi (\mu^+\mu^-)$ and $B^0 \rightarrow K^{*0} (K^+\pi^-) \psi(2S) (\mu^+\mu^-)$
- Analysis performed in bins of dimuon mass^2 (q^2) ➜ control channels are naturally included
- Signal and control channels are treated identically

Main muon selections:

- events recorded with dimuon low-mass, vertex displaced trigger
- μμ vertex L / 3σ (transverse) (in trigger)
- $1 < m(\mu\mu) < 4.8$ GeV/c^2 (in trigger)
- $p_T(\mu) > 3, 4, 4.5, 5$ GeV/c (depending on trigger)
- μμ vertex CL > 5%, 15% (depending on trigger)

B^0 selections:

- B^0 vertex CL > 9%
- B^0 vertex L / 12σ (transverse)
- cos(α) > 0.9994: α angle in transverse plane between B^0 momentum and line-of-flight

Hadron selections:

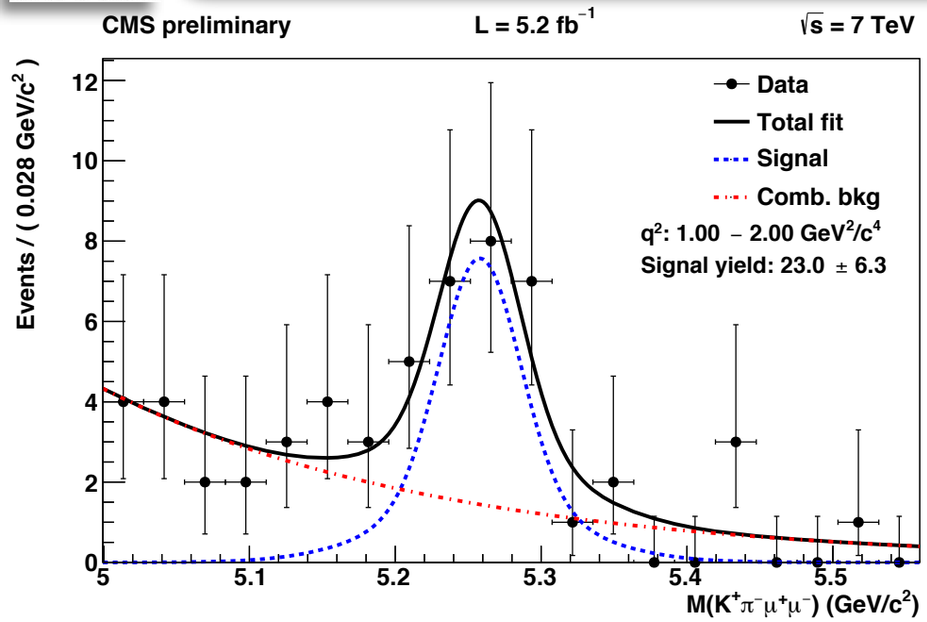
- hadron must fail muon ID
- $p_T(h) > 0.75$ GeV/c
- Distance Closest Approach(h) / 1.3σ (transverse)
- $|m(K\pi) - m_{PDG}K^{*0}| < 80$ MeV/c^2

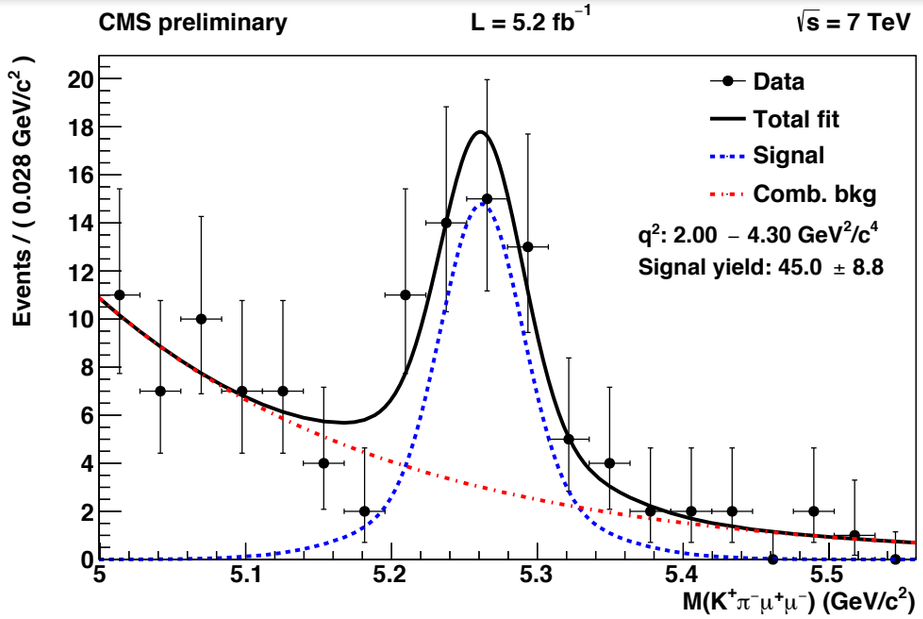
CP state assignment:

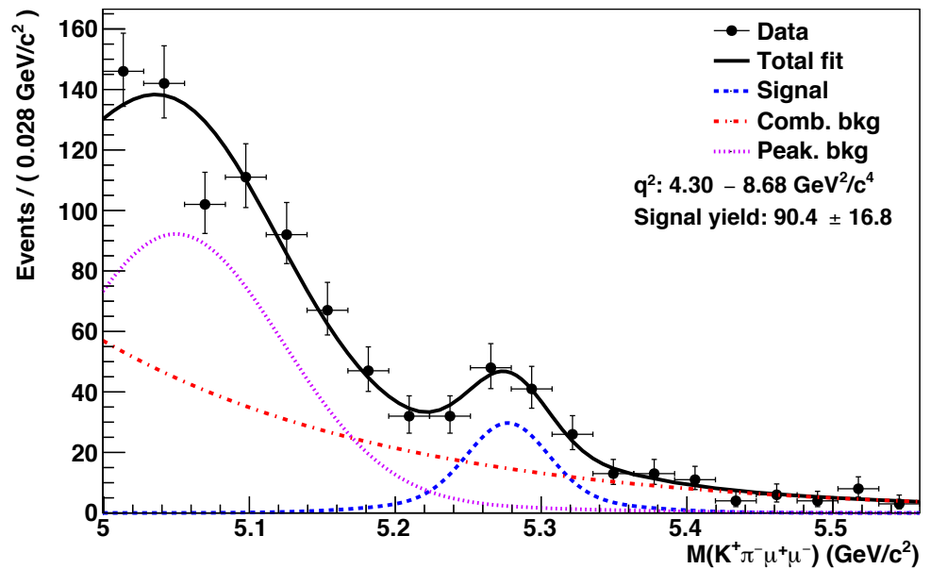
1. Reject event if both K^{*0} and $\overline{K}^{*0}$ masses are within 50 MeV/c^2 of PDG mass (~1Γ)
2. Tag the CP state based on closest distance from K^{*0} PDG mass

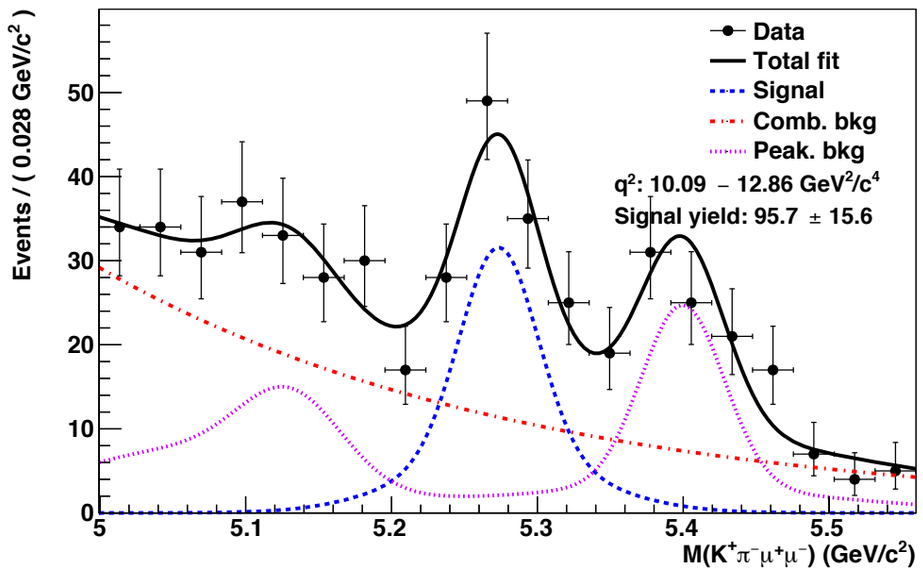
Mistag rate evaluated on MC ~8% and on data ~10%

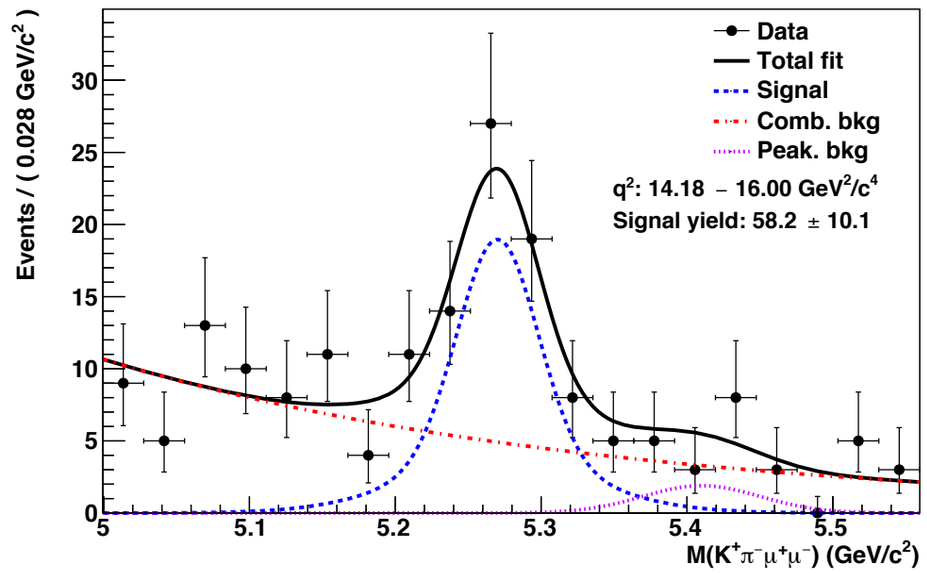
Signal Evidence

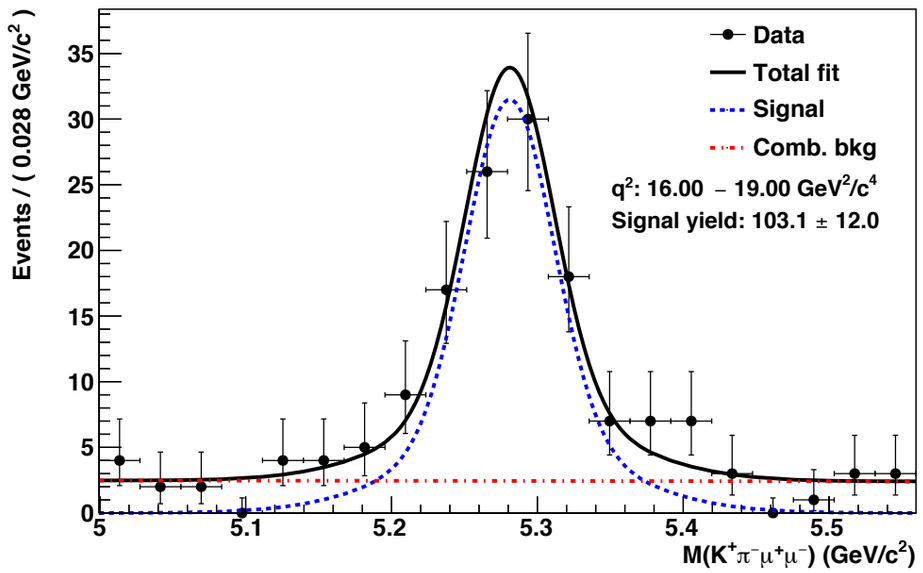










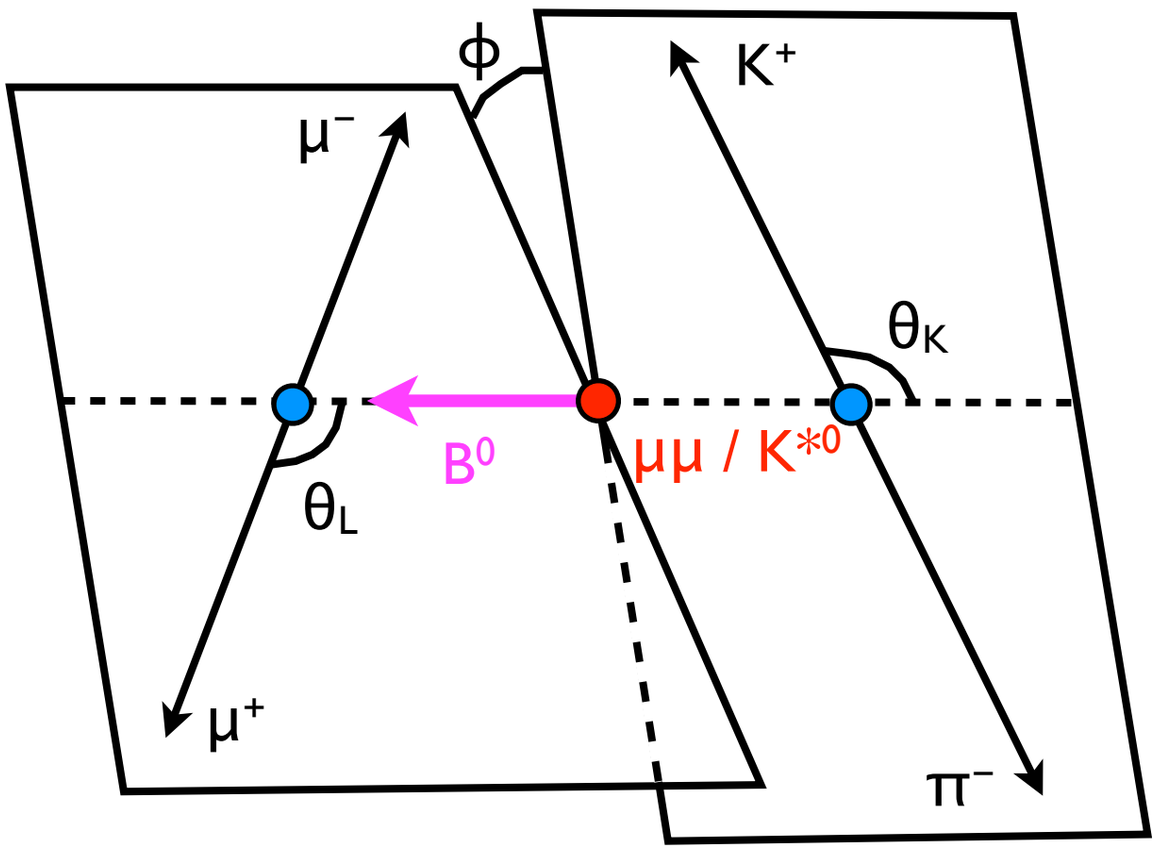


- **Signal**
- **Combinatorial background**: random association hadrons-muons
- **Peaking background**: feed-through from resonant channels

Fit Strategy

- We perform unbinned extended maximum likelihood fits to three variables: B^0 invariant mass and two angular variables θ_K and θ_l for each q^2 bin to extract **$F_L(q^2)$** and **$A_{FB}(q^2)$**

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



The full decay rate is weakly dependent on the Φ angle, therefore integrated in this analysis

- Using previous fit results, unbinnned extended maximum likelihood fits to B^0 invariant mass is used for each q^2 bin to extract **$dBF/q^2(q^2)$**

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

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

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

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

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

Fit Strategy: the p.d.f.

$$\text{p.d.f.}_i = \text{Kernel}_i \cdot \text{Penalty}_i =$$

$$\left(Y \cdot S^M(m) \cdot S^A(\theta_K,\theta_l) \cdot \varepsilon(\theta_K,\theta_l) + \right.$$

$$+ Y \cdot B^M(m) \cdot B^K(\theta_K) \cdot B^l(\theta_l) +$$

$$\left. + Y \cdot B^M(m) \cdot B^K(\theta_K) \cdot B^l(\theta_l)\right)_i \cdot$$

$$\cdot \text{Penalty}_i$$

Index i run on q^2 bins

Signal:

Y from data

$S^M(m)$:

- double Gaussian ➜ **from MC**

$S^A(\theta_K,\theta_l)$: decay rate

- polynomials ➜ from theory & data

$\varepsilon(\theta_K,\theta_l)$: efficiency

- polynomials ➜ fixed from MC

Peaking background:

Y from data

$B^M(m)$ from MC:

- 1 or 2 single/double Gaussians

$B^K(\theta_K) \cdot B^l(\theta_l)$ from MC:

- polynomials

Combinatorial background:

Y from data

$B^M(m)$ from data:

- single exponential

$B^K(\theta_K) \cdot B^l(\theta_l)$ from data:

- polynomials

- The kernel p.d.f. is multiplied by Gaussian **penalty terms** for the parameters determined **from MC**
- Final fit ALL parameters are free

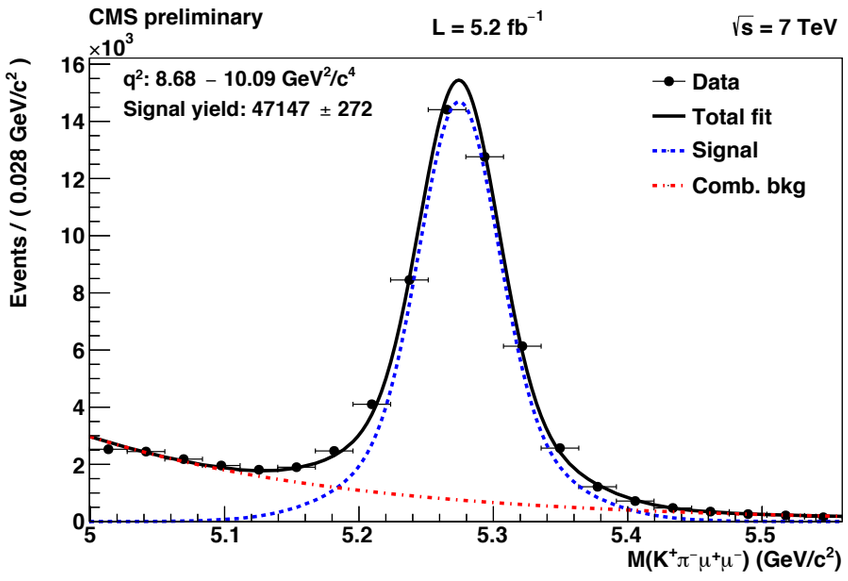
Systematic Uncertainties

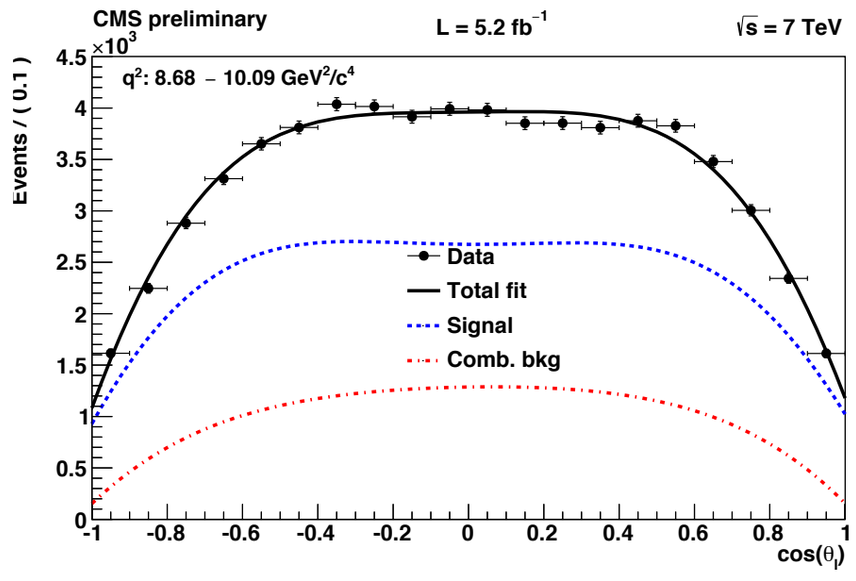
Sources of systematic uncertainty	F_L	A_{FB}	dBF/dq^2
Potential bias from fit ingredients	0	0−0.017	0−7.1%
Test of $\Gamma(B^0 \to K^{*0}J/\psi)$ / $\Gamma(B^0 \to K^{*0}\psi(2S))$	0	0	14.3%
Potential bias from fit algorithm (toy MC)	0.004−0.040	0.012−0.077	0−2.7%
Incorrect CP assignment of decay	0.002−0.006	0.002−0.006	0%
Effect of Kπ 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%**

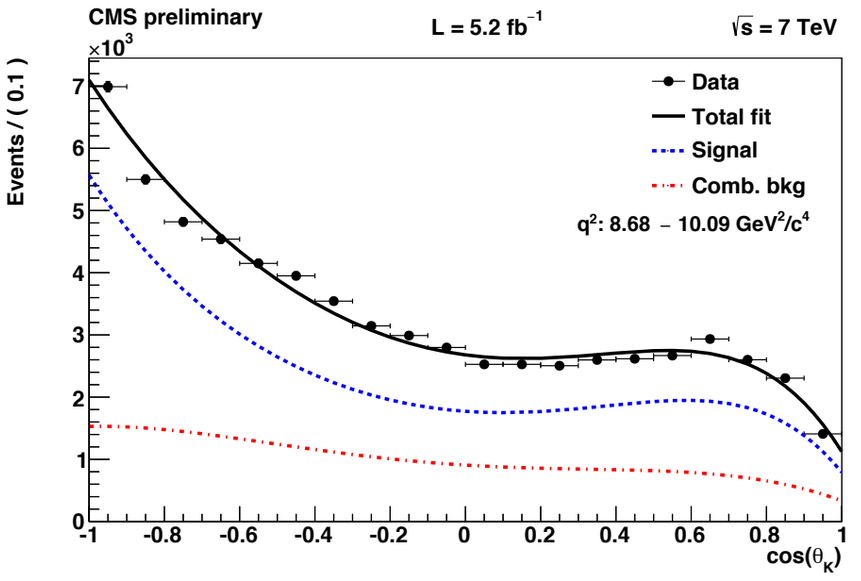
The uncertainty is dominated by the statistical error (see next slides)

Analysis Validation with Control Channels

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







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

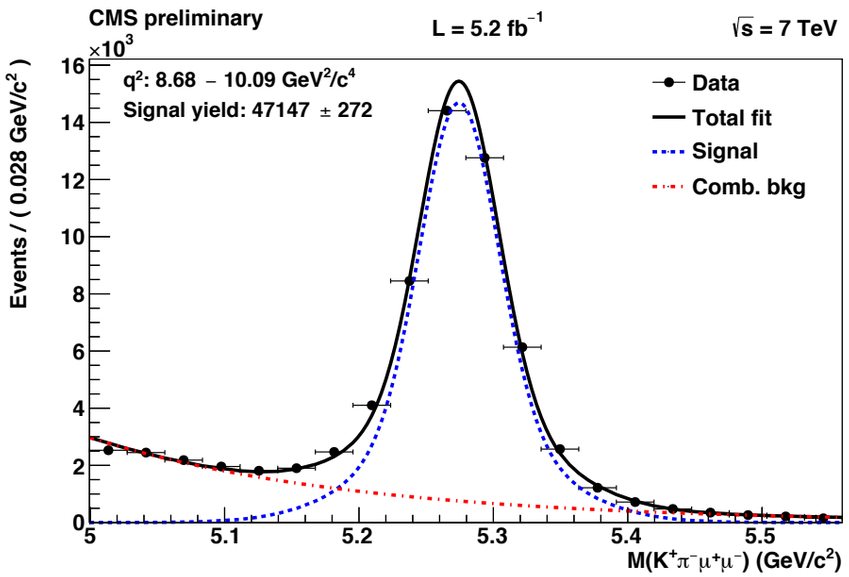
- **F_L:** 0.554 ± 0.004 (stat) ➜ PDG value 0.570 ± 0.008
- **A_{FB}:** −0.004 ± 0.004 (stat) ➜ compatible with zero

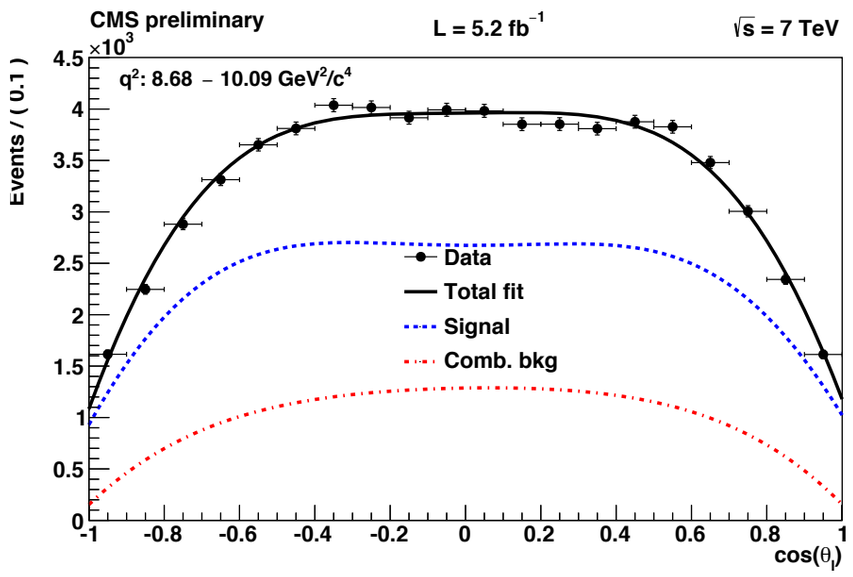
$B^0 \rightarrow K^{*0} (K^+\pi^-) \psi(2S) (\mu^+\mu^-)$

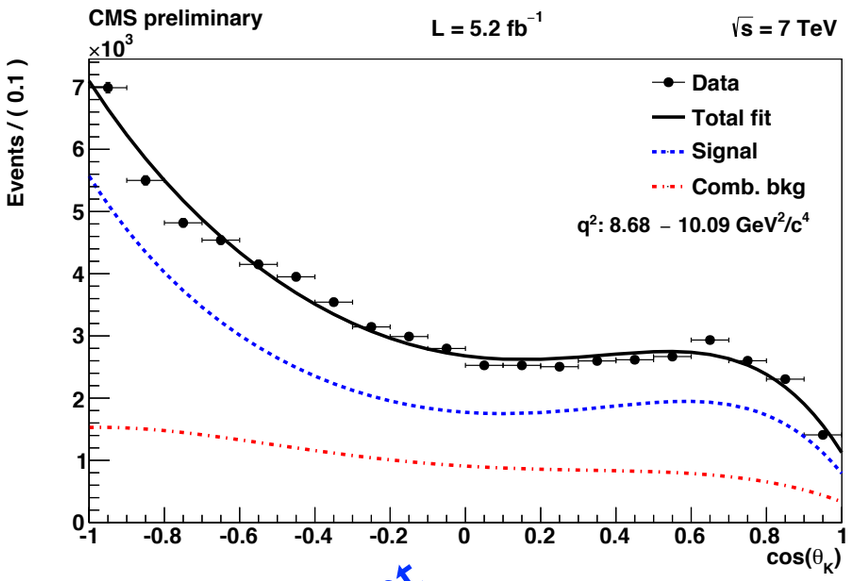
- **F_L:** 0.509 ± 0.016 (stat) ➜ PDG value 0.46 ± 0.04
- **A_{FB}:** 0.013 ± 0.014 (stat) ➜ compatible with zero

Analysis Validation with Control Channels

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

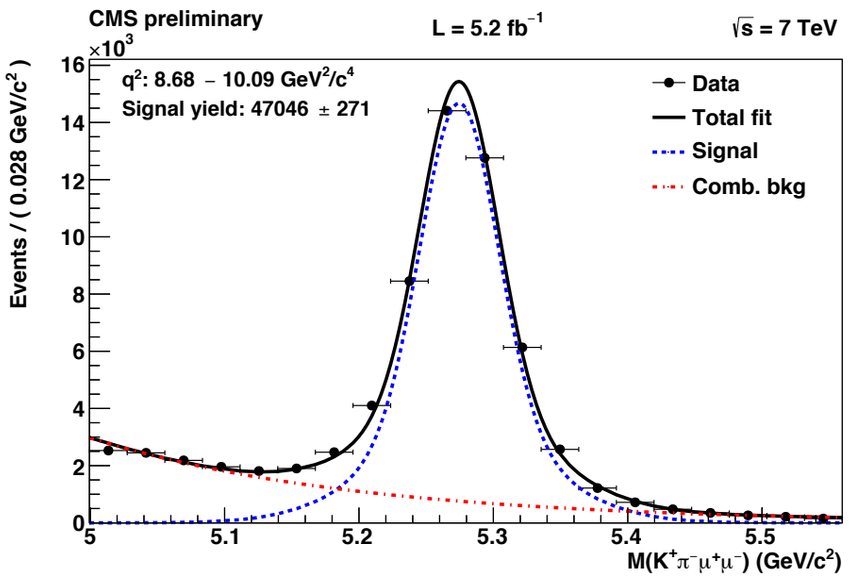


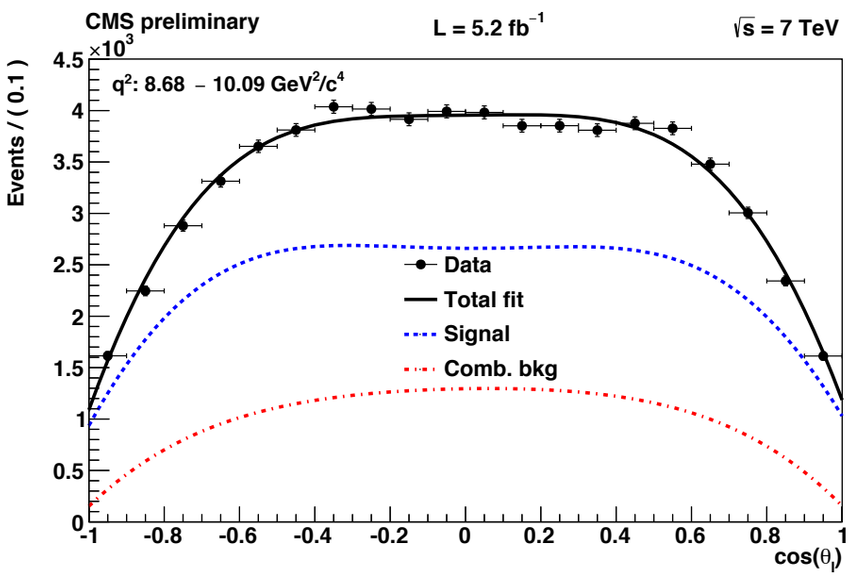


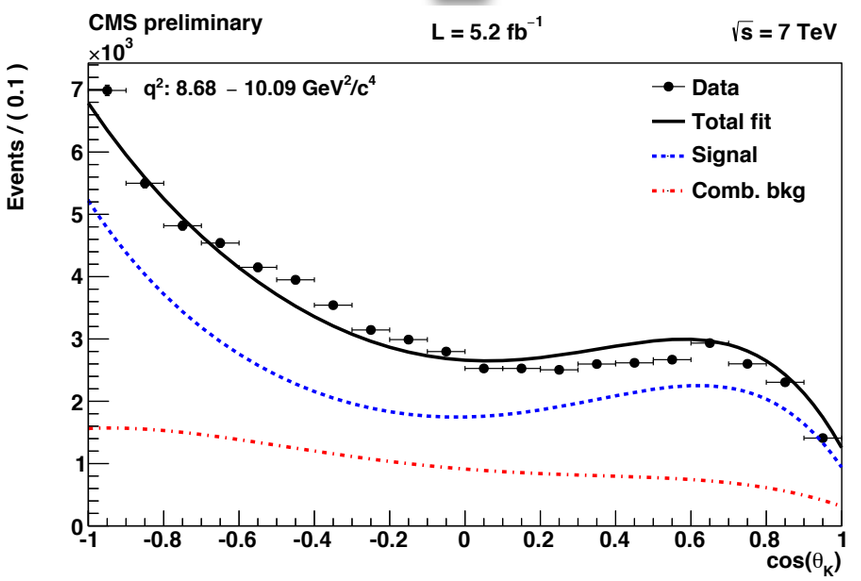


Fit performed considering both vector and scalar Kπ contributions

Clear improvement

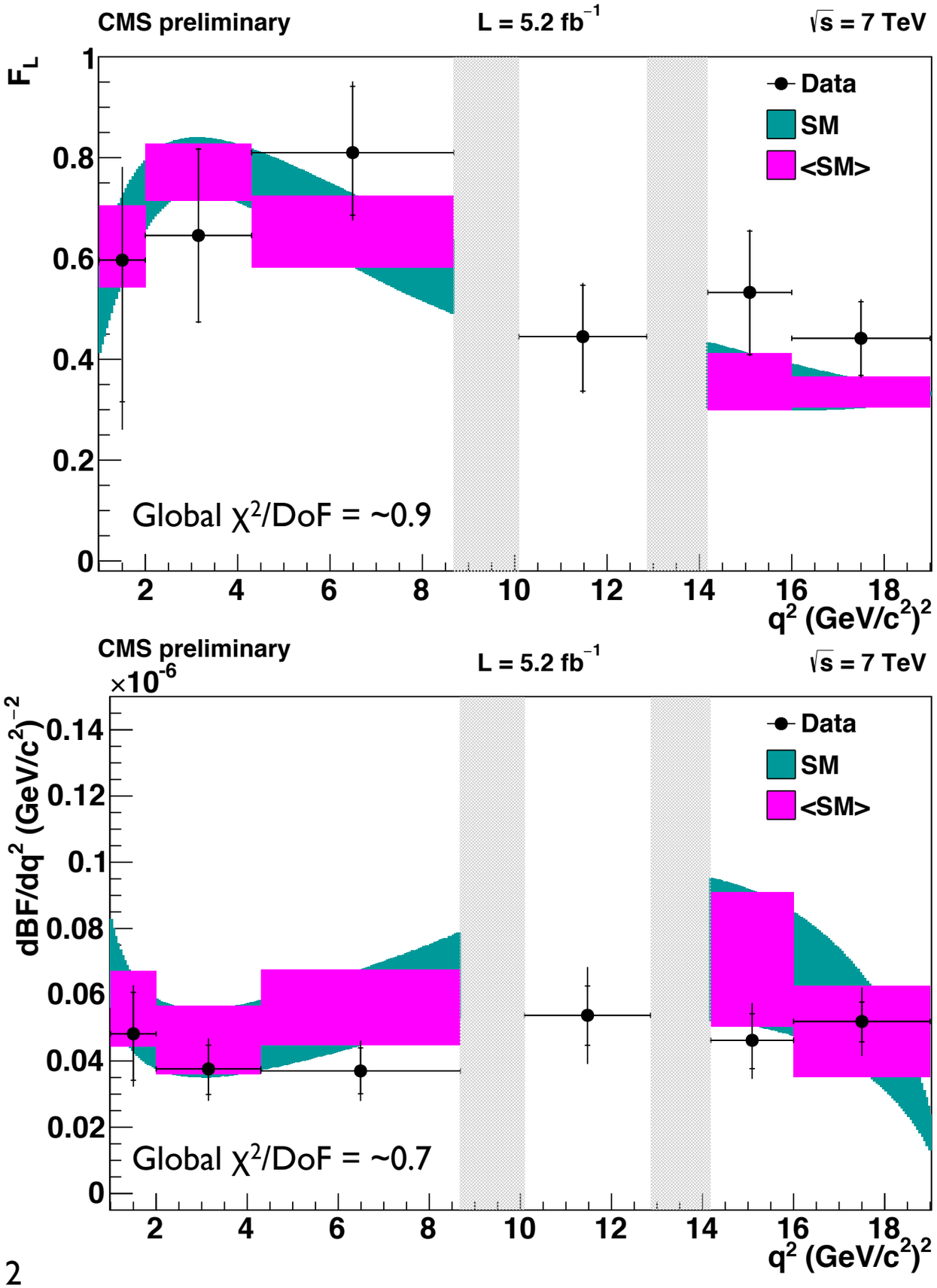


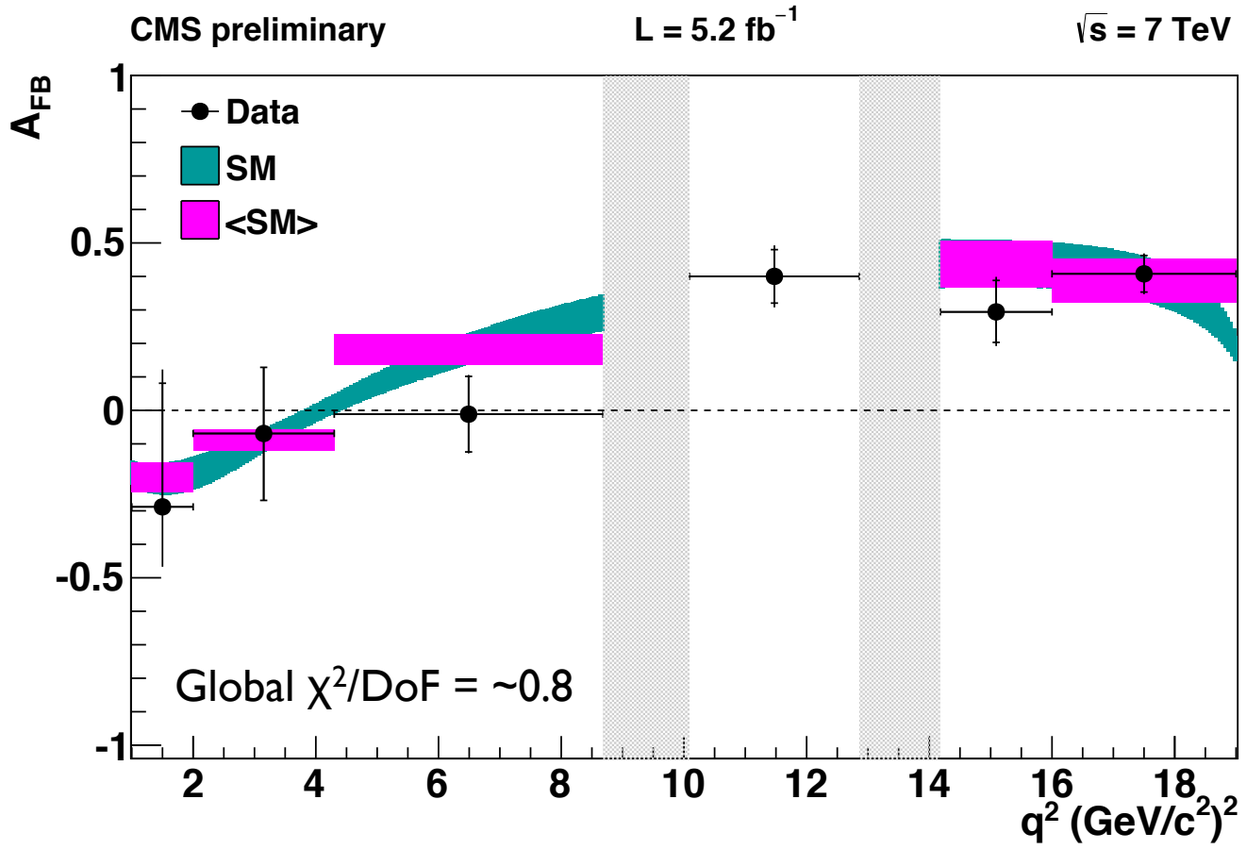




Fit performed ignoring the scalar Kπ contribution

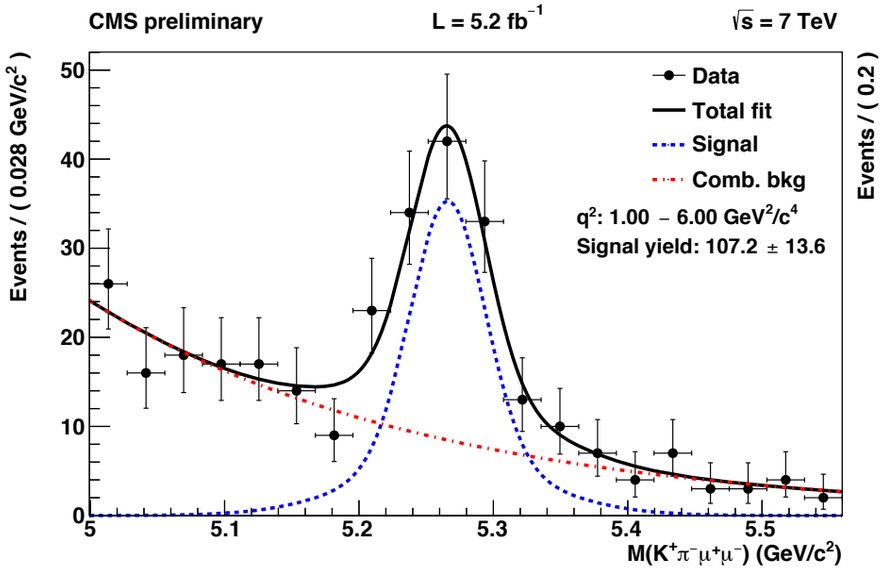
Measurements: First Results from CMS !

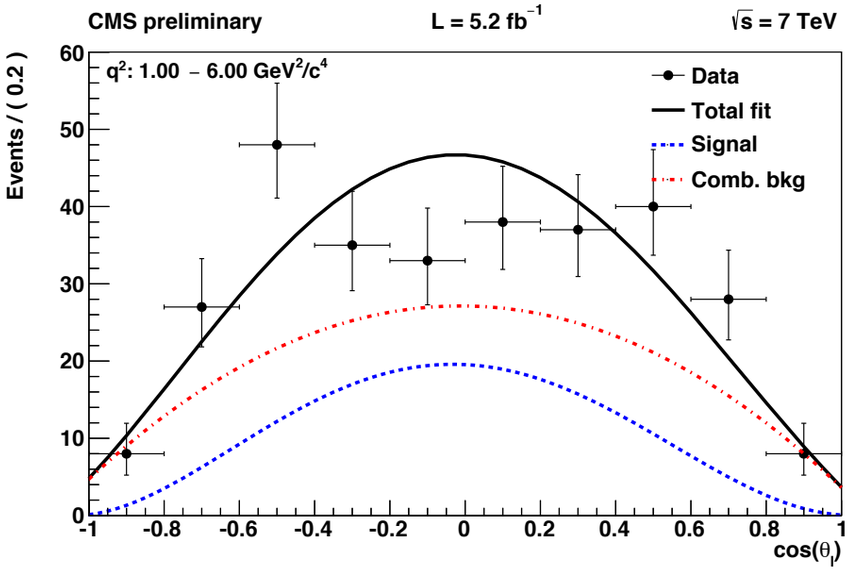


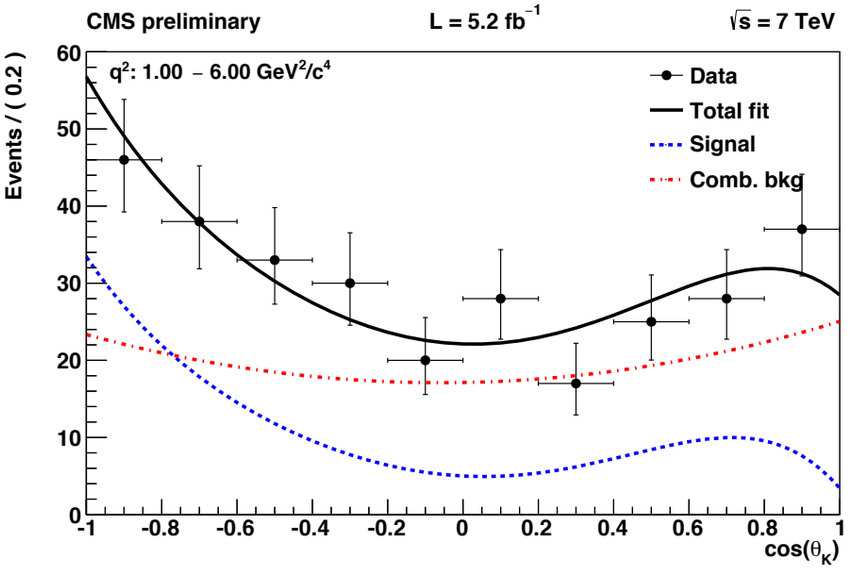


- Error bars with edges: statistical uncertainty
- Edgeless error bars: total uncertainty
- Purple region: standard model properly averaged over the bin (Phys. Rev. D **87** (2013) 034016)

Special q^2 bin: 1 – 6 $(GeV/c^2)^2$







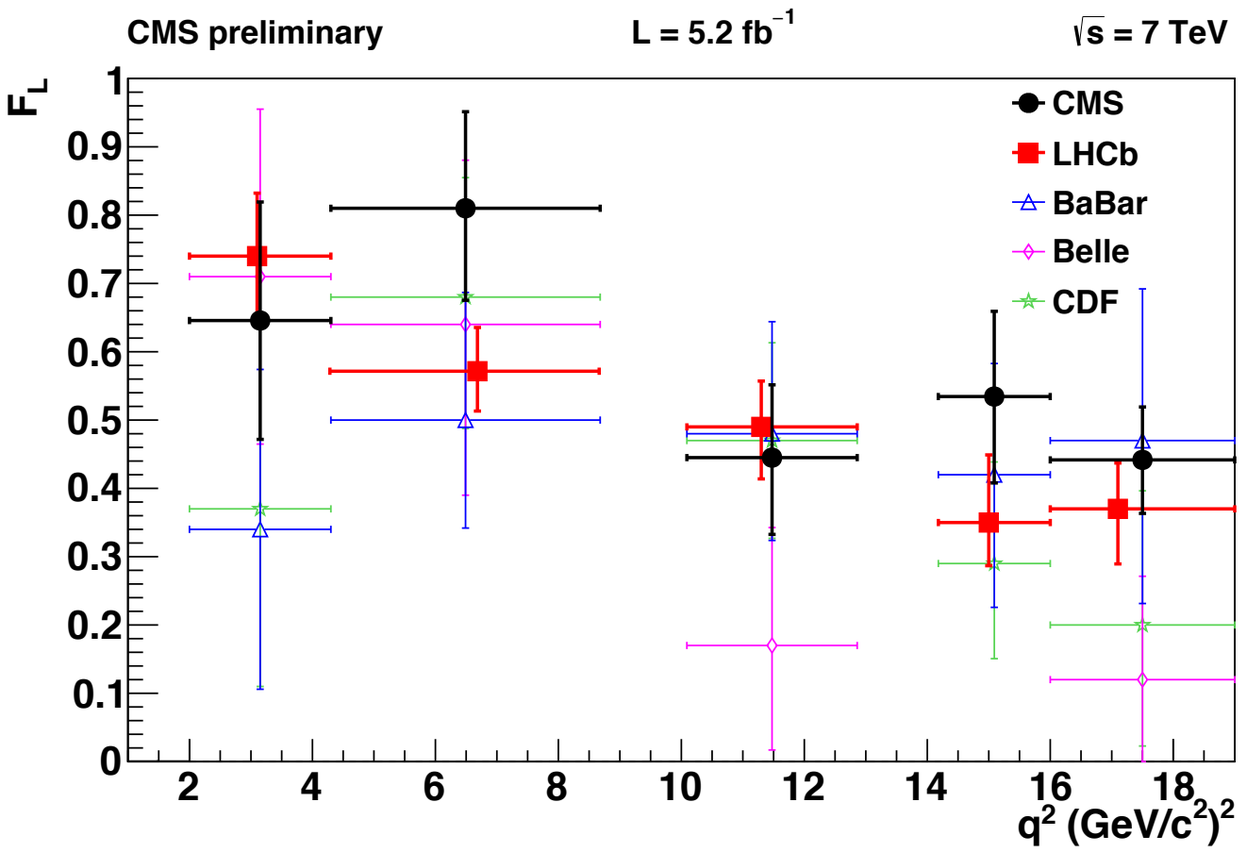
CMS measurements:

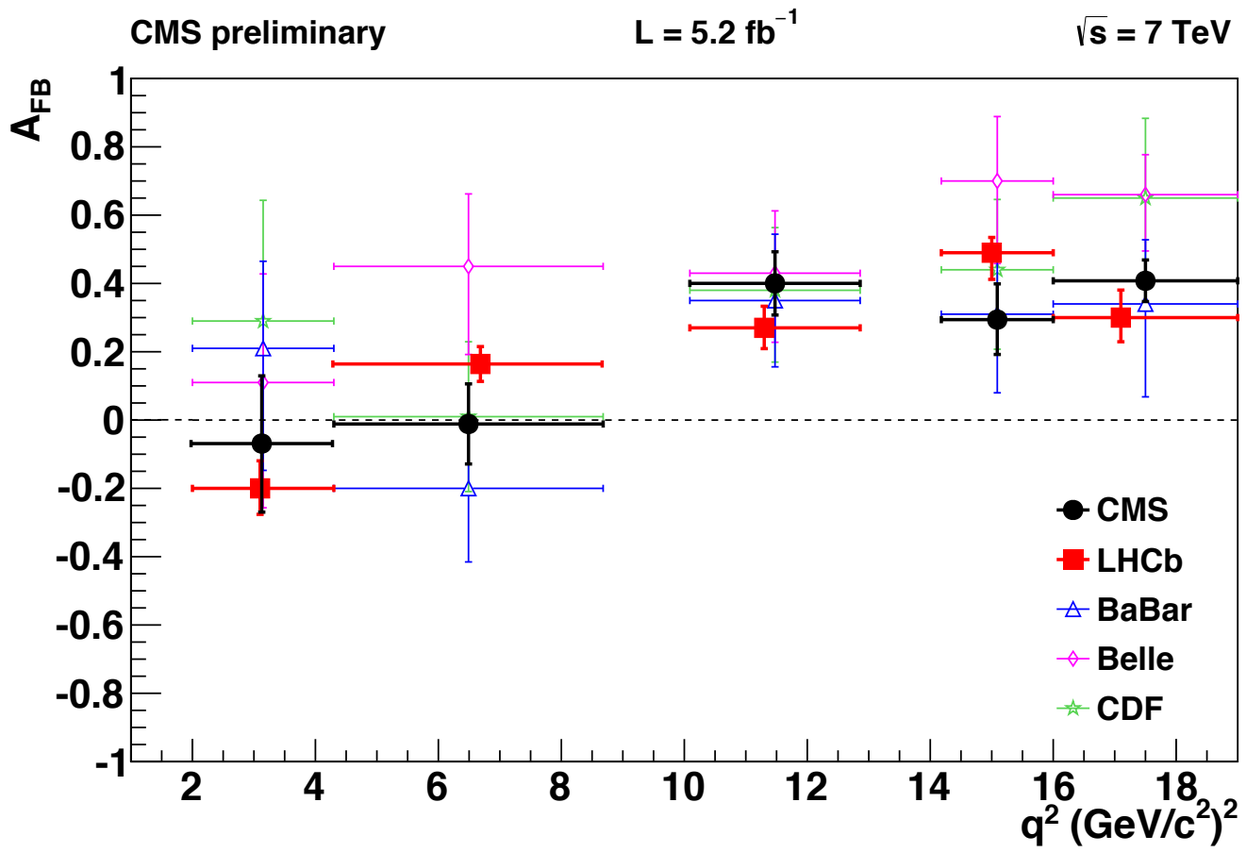
- **F_L:** 0.68 ± 0.10 (stat) ± 0.02 (syst)
- **A_{FB}:** −0.07 ± 0.12 (stat) ± 0.01 (syst)
- **dBF/dq^2:** (4.4 ± 0.6 (stat) ± 0.7 (syst)) x 10^{-8} c^4/GeV^2

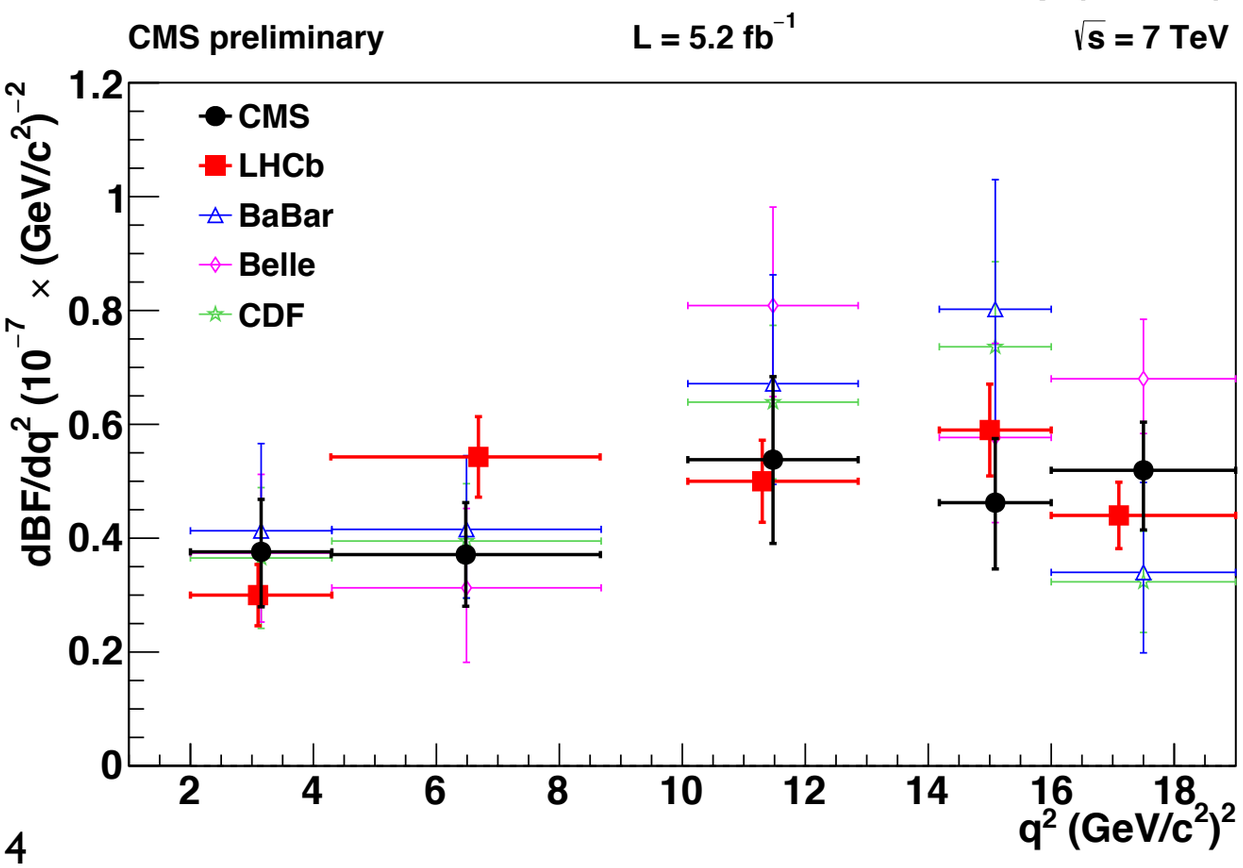
SM predictions (*Phys. Rev. D* ***87*** *(2013) 034016*)**:**

- **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







- CMS uncertainties are better than CDF, Belle, BaBar but not as good as LHCb (LHCb statistics: ~1 fb^{-1})
- CMS measurements are the second best

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

Conclusions

- We performed an angular analysis of **$B^0 \rightarrow K^{*0} \mu^+ \mu^-$**, using **~5.2 fb^{-1}** of data (2011)

- More than 400 signal (non-resonant) decays and nearly 50 000 normalization mode decays ($B^0 \rightarrow K^{*0} J/\psi$) are observed

- Unbinned maximum likelihood fits were performed in bins of dimuon invariant mass squared (q^2) with three independent variables: B^0 invariant mass, $\cos(\theta_K)$, and $\cos(\theta_l)$ to obtain values of forward-backward asymmetry of the muons, **A_{FB}**, and fraction of longitudinal polarization of the K^{*0}, **F_L**

- Using these results, unbinnned maximum likelihood fits to B^0 invariant mass in q^2 bins were used to extract differential branching fraction, **dBF/dq^2**

- **No deviations from the standard model predictions are found**

- Results with 2011 data are statistically limited ➜ analysis of the 2012 data is starting, with significantly more statistics **~20 fb^{-1}**

Documentation:

- Physics Analysis Summary: CMS-PAS-2011/009
- Public web page: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH11009

Other CMS Contributions to Beauty 2013

- Ilse Kraetschmer, "Quarkonium polarization from CMS and Tevatron" Mon. 16:40 - 17:00, Heavy Flavour Production (I)
- Torsten Dahms, "Upsilon melting in CMS / ALICE" Tue. 9:30 - 9:50, Heavy Flavour Production (II)
- Marco de Mattia, "$B_s \rightarrow \mu\,\mu$ in CMS" Tue. 14:30 - 14:50, Rare B Decays (I)
- Luigi Guiducci, "ATLAS, CMS and LHCb Trigger/DAQ systems for flavour physics" Wed. 14:40 - 15:10, Aspects of LHC Data Taking
- Sara Fiorendi, "Heavy flavour spectroscopy and production in CMS" Thu. 11:35 - 11:55, Spectroscopy

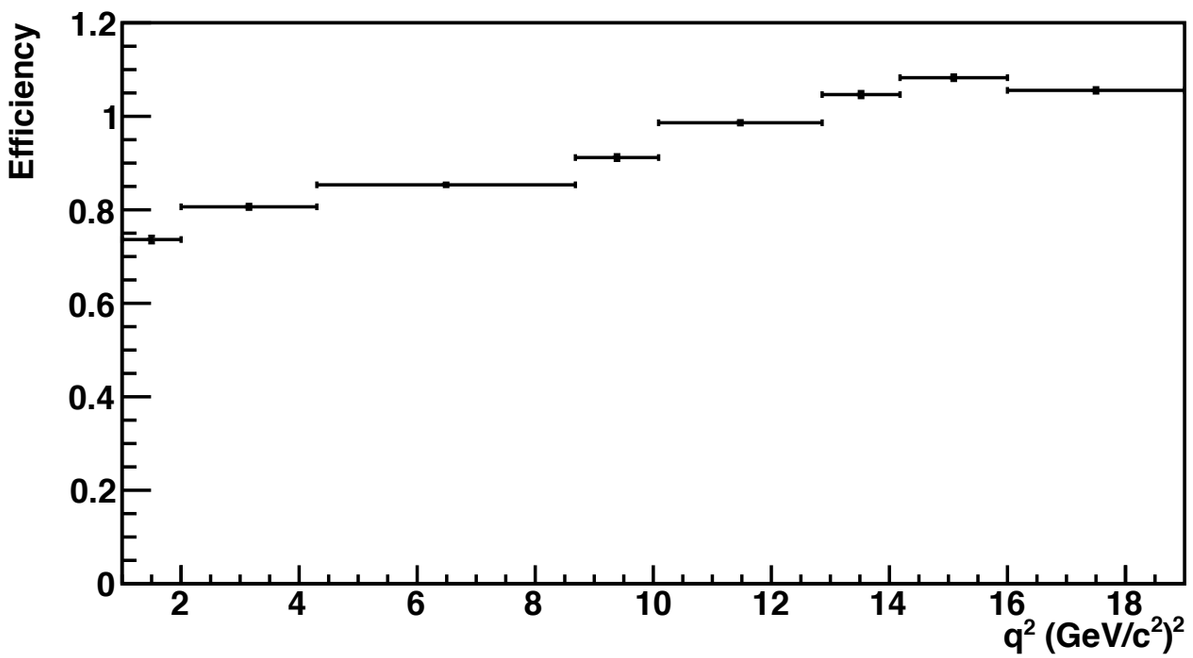
Poster session:

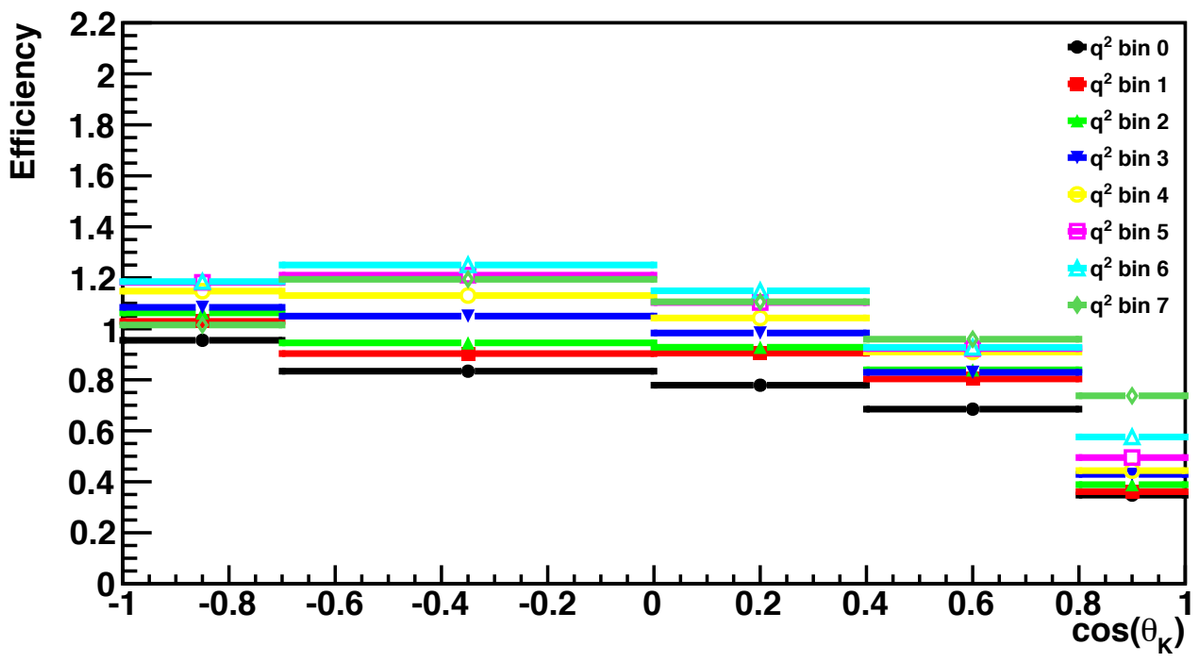
- Alexis Pompili, "Observation of two structures in the $J/\psi\ \Phi$ mass spectrum of exclusive $B^+ \rightarrow J/\psi\ \Phi\ K^+$ decays in CMS"
- Martino Dall'Osso, "Measurement of the X(3872) production cross section via decays to $J/\psi\ \pi\ \pi$"

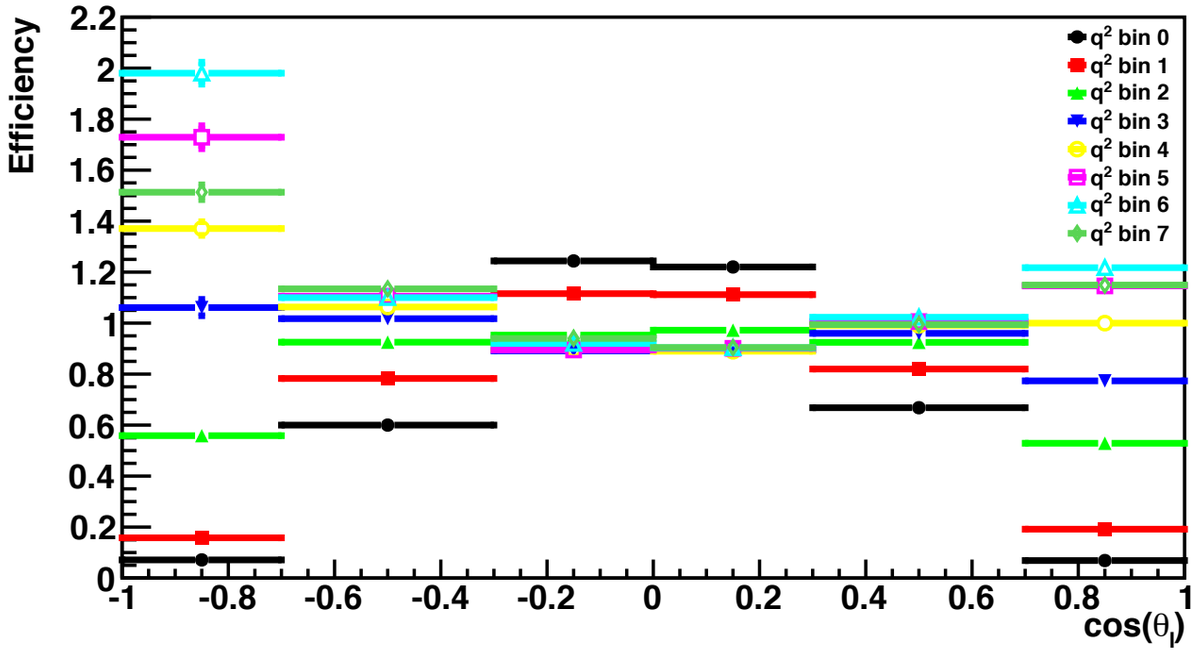
Backup

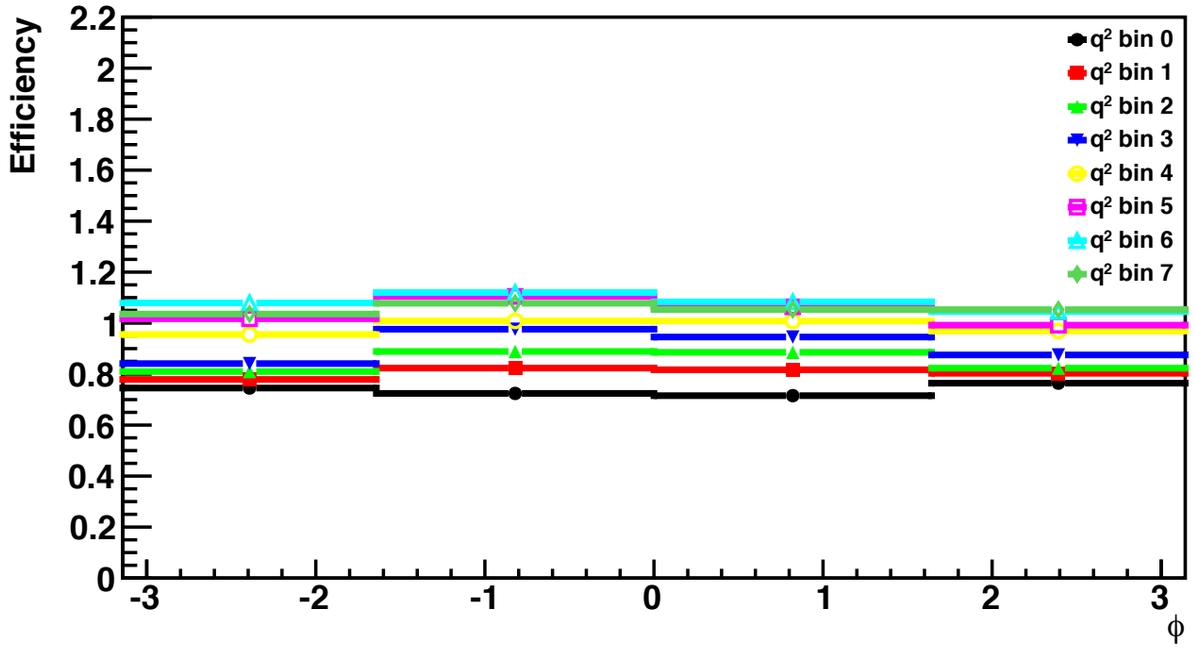
Efficiency Correction

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









Projections of the efficiency on angular variables and q^2

Analysis Strategy: Special Penalty Terms

$$\text{p.d.f.}_i = \text{Kernel}_i \cdot \text{Penalty}_i =$$

$$(Y \cdot S^M(m) \cdot S^A(\theta_k,\theta_l) \cdot \varepsilon(\theta_k,\theta_l) + Y \cdot B^M(m) \cdot B^k(\theta_k) \cdot B^l(\theta_l) +$$

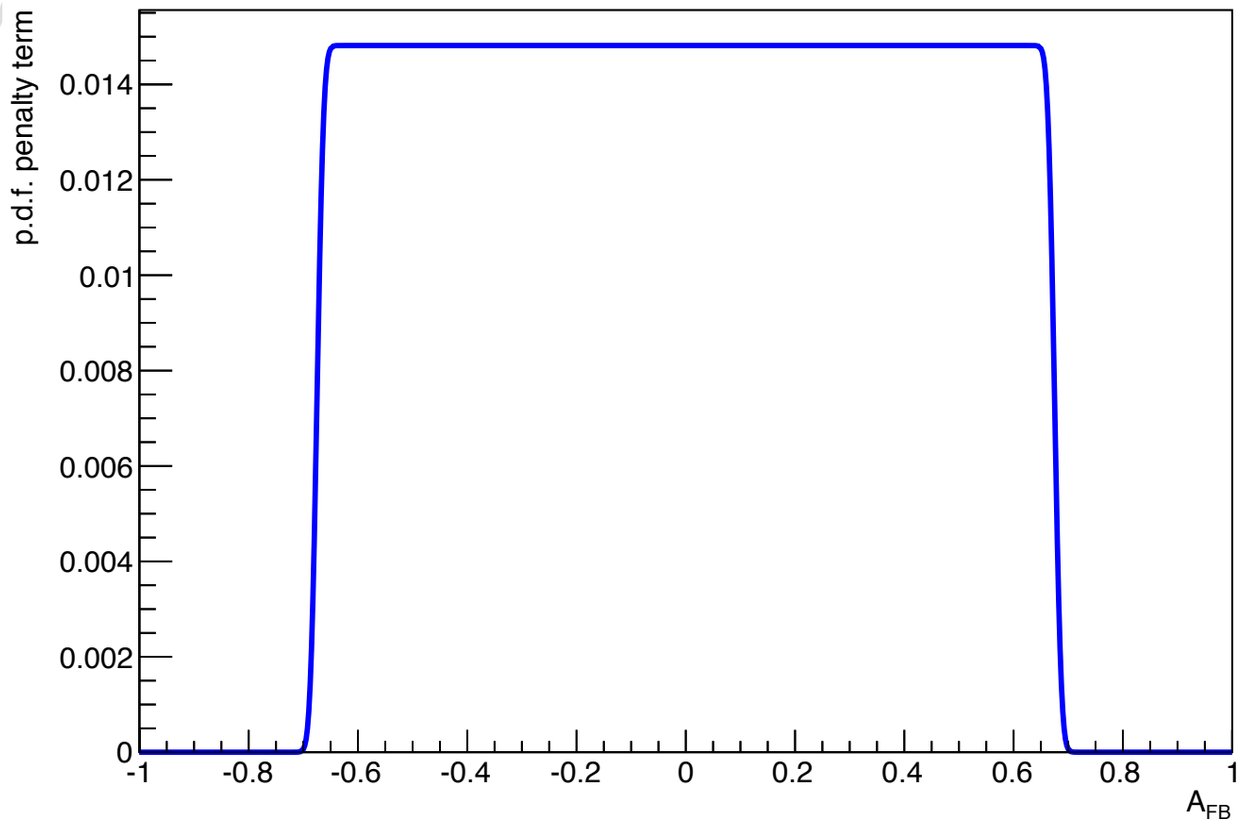
$$+ Y \cdot B^M(m) \cdot B^k(\theta_k) \cdot B^l(\theta_l))_i \cdot \text{Penalty}_i$$

Index i run on q^2 bins

In order to keep the decay rate always positive special penalty terms are added

The special penalty terms implement dynamic constraints on variable boundaries:

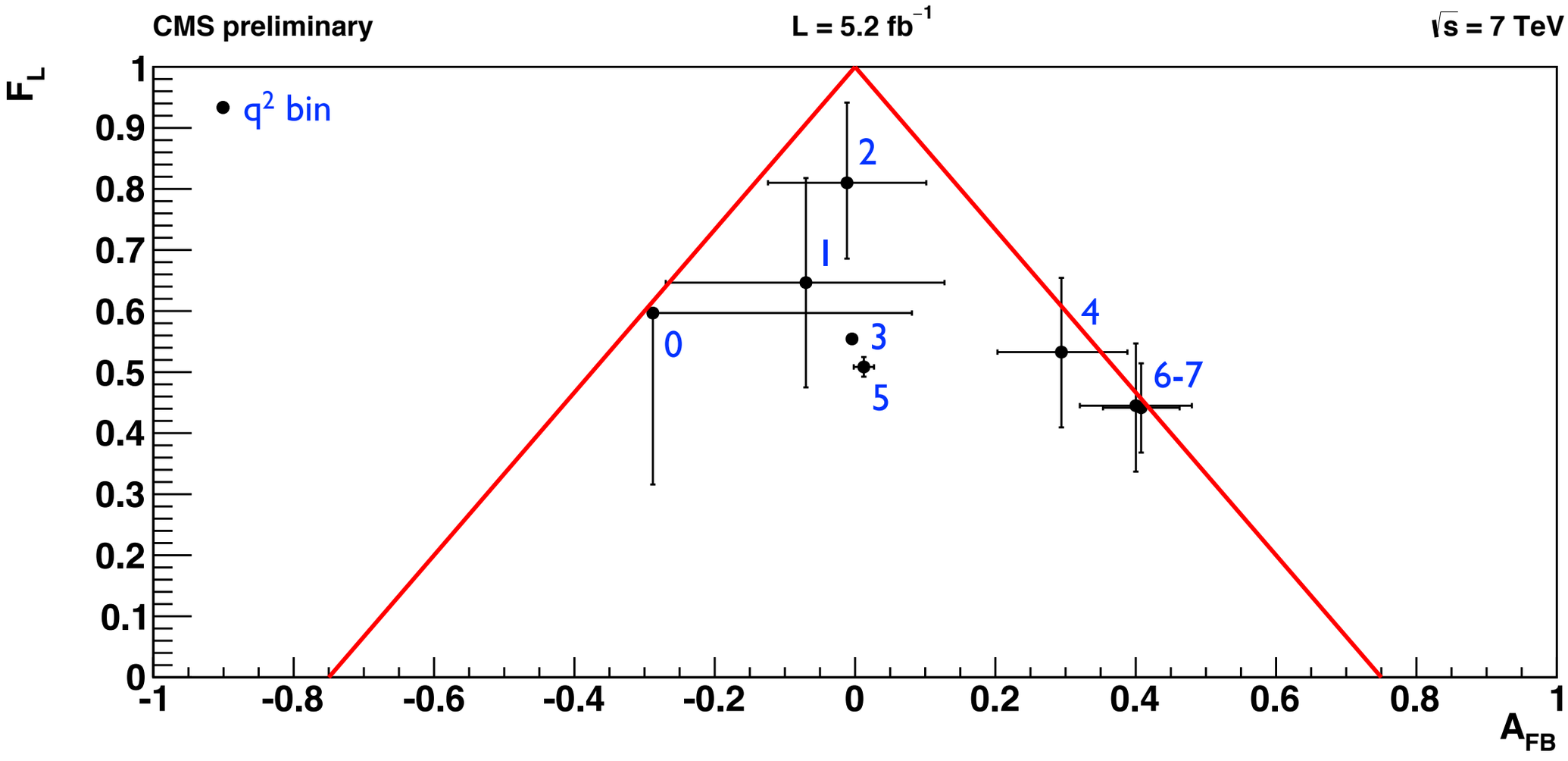
- $|A_{FB}| < 3/4\,(1-F_L)$
- $|A_S| < 1/2\,(F_S + 3F_L\,(1 - F_S))$



Physically-Allowed Region

From $B^0 \rightarrow K^{*0}\,(K^+\pi^-)\,J/\psi\,(\mu^+\mu^-)$ fit:

- $F_S = 0.013 \pm 0.010$ (stat.)
- $A_S = -0.098 \pm 0.005$ (stat.)
- $|A_S| < 1/2\,(F_S + 3F_L\,(1 - F_S))$ satisfied if $F_L > 0.16$ ☜ true for all measurements



All results lie in the physically-allowed region

Systematic Uncertainties

- Potential bias from fit ingredients
  - Run analysis on high statistics MC to check asymptotic behavior
- Test of $\Gamma(B^0 \to K^{*0}J/\psi)$ / $\Gamma(B^0 \to K^{*0}\psi(2S))$
  - Compare measured BF with PDG and assign higher error as systematic uncertainty
- Potential bias from fit algorithm (toy MC)
  - Generate 1000 toy-MC for each q^2 bin
  - Systematic errors are evaluated as the average deviation of fit parameters from p.d.f. values
- Incorrect CP assignment of decay
  - Estimated from B0 width from data control channel $B^0 \to K^{*0}$ ($K^+\pi^-$) J/ψ ($\mu^+\mu^-$):
  - Generate MC samples with artificially injected CP-mistag
  - Compare B0 width between data and MC samples
  - Run analysis on MC with 12% mistag rate (consistent with data + 1σ) and take difference to nominal as systematic uncertainty
- Effect of Kπ *S*-wave contribution
  - Re-fit data with *P*-wave only p.d.f. and compare with nominal p.d.f.
- Peaking background mass shape
  - Re-fit data with peaking background mass shape free to float and compare with nominal p.d.f.
- Combinatorial background shapes vs cos($\theta_{K/l}$)
  - Re-fit data with combinatorial background polynomial degree +1 and compare with nominal p.d.f.
- Angular resolution
  - Re-fit MC comparing results using reconstructed and generated angular values