Radiative penguins at hadron machines

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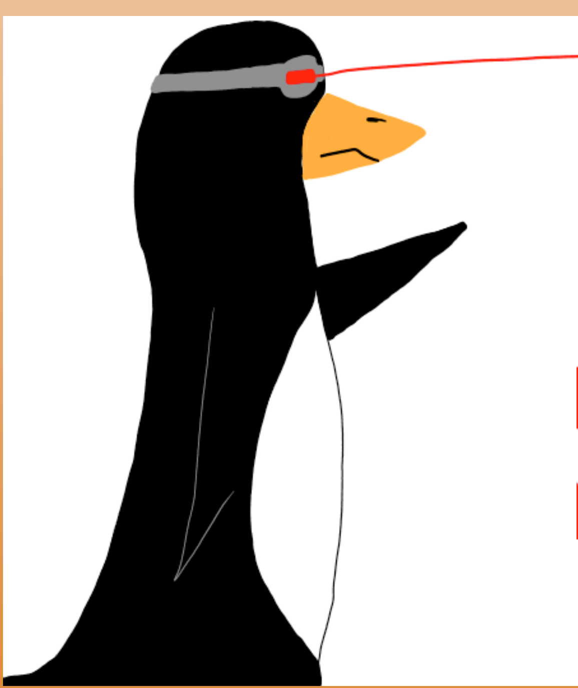
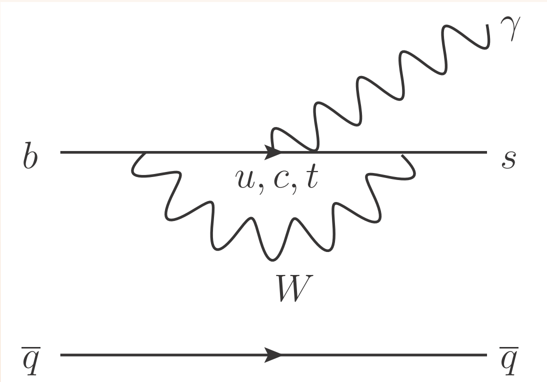
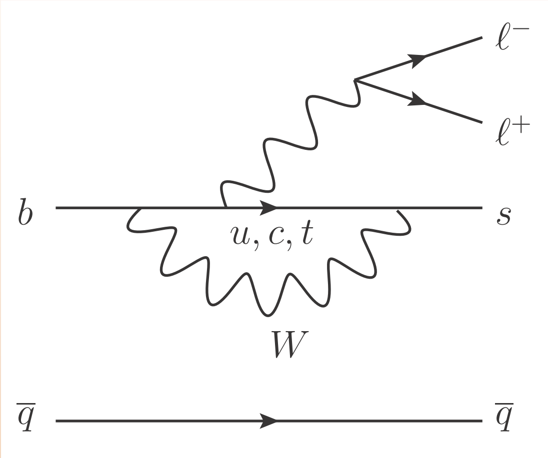
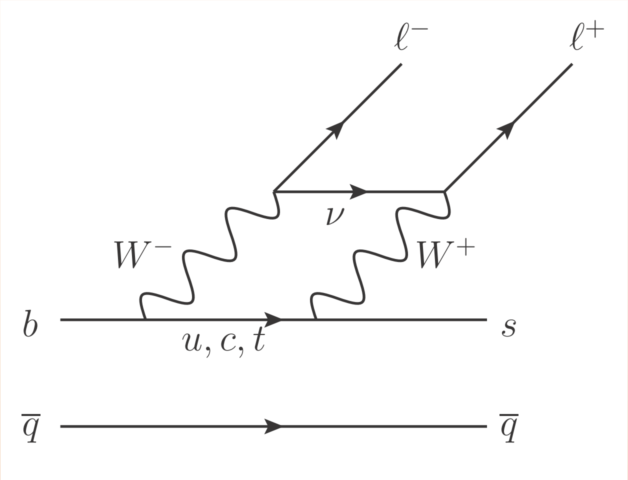


Introduction

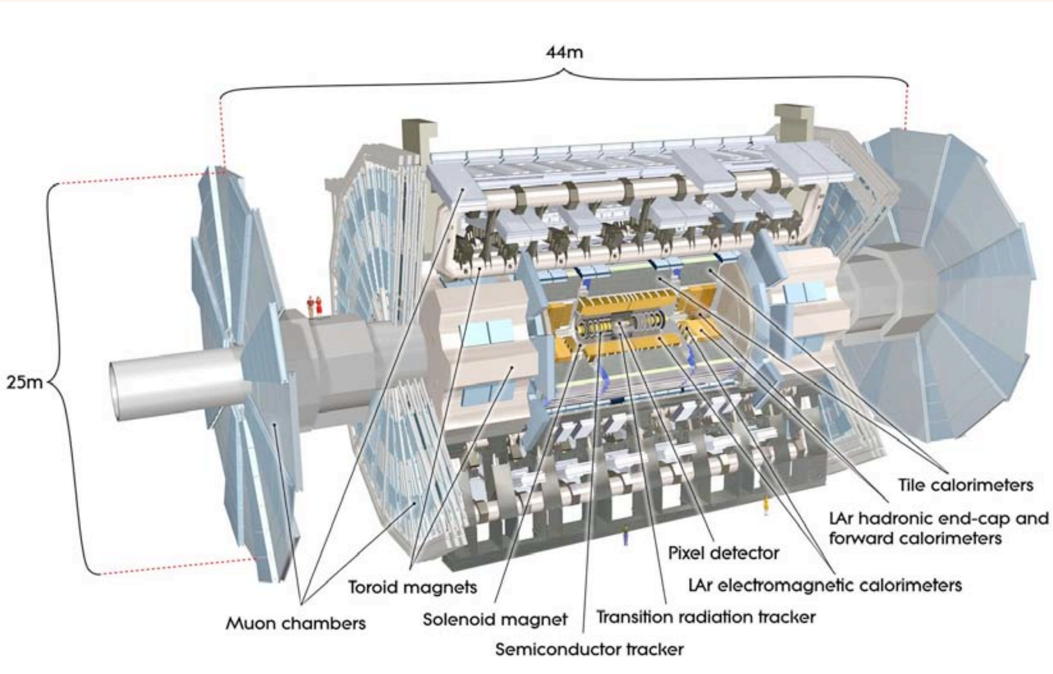


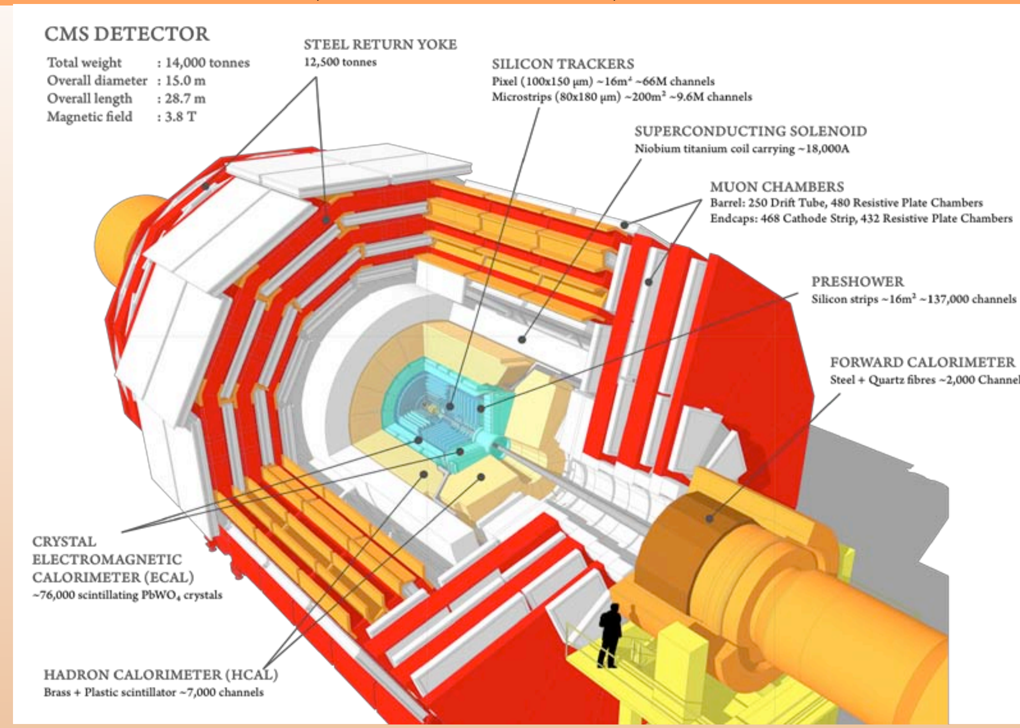


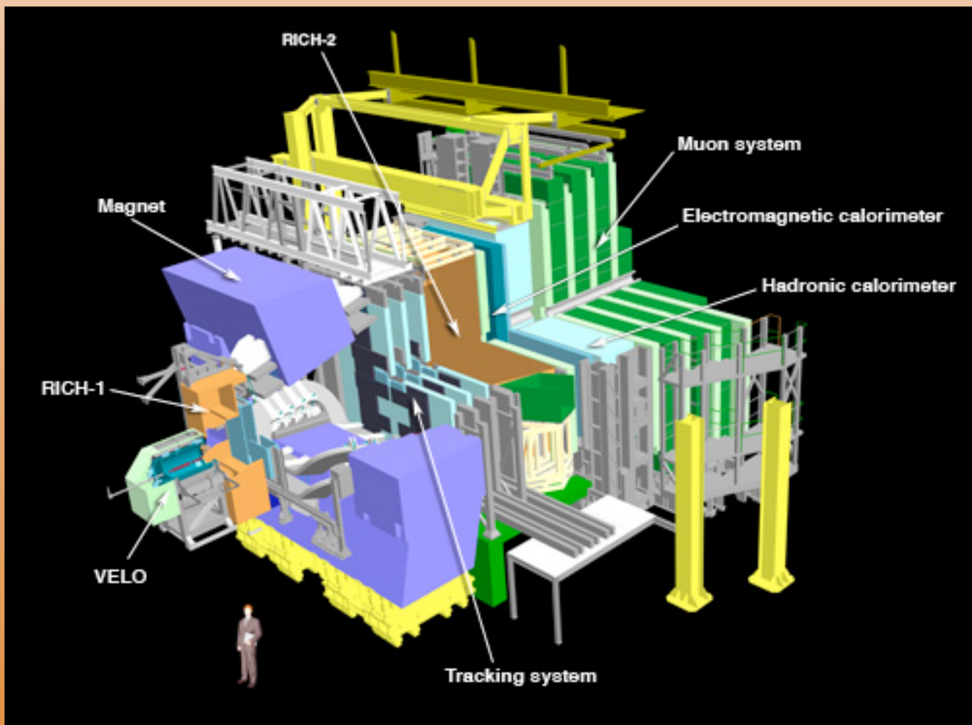


- Radiative penguins involve b to s,d transitions with a radiated photon (b→sγ).
- b→sll also contain an electroweak box diagram.
- Highly suppressed in standard model but new physics can add particle to loop, changing the decay rate or details of the decay.

Results from LHC: ATLAS, CMS, LHCb







- ATLAS and CMS are general purpose experiments covering the central region (designed for high-p_T physics)
- LHCb is a dedicated b-physics experiment covering the forward region.

$B^0 \rightarrow K^{*0}\gamma$ and $B_s \rightarrow \phi\gamma$ from LHCb

- Trigger requires EM energy cluster of E_T>2.5, followed by requiring a displaced tracks and then requiring two tracks to match $K^{*0} \rightarrow K^+\pi^-$ or $\varphi \rightarrow K^+K^-$, with a B mass within 1 GeV of nominal.
- Offline requirements similar to trigger plus particle ID from RICH and a helicity cut to reduce π^0 contribution.
- Fit to B mass includes contributions from subdominant partially reconstructed $b \rightarrow s\gamma$ and charmless decays with π^0.

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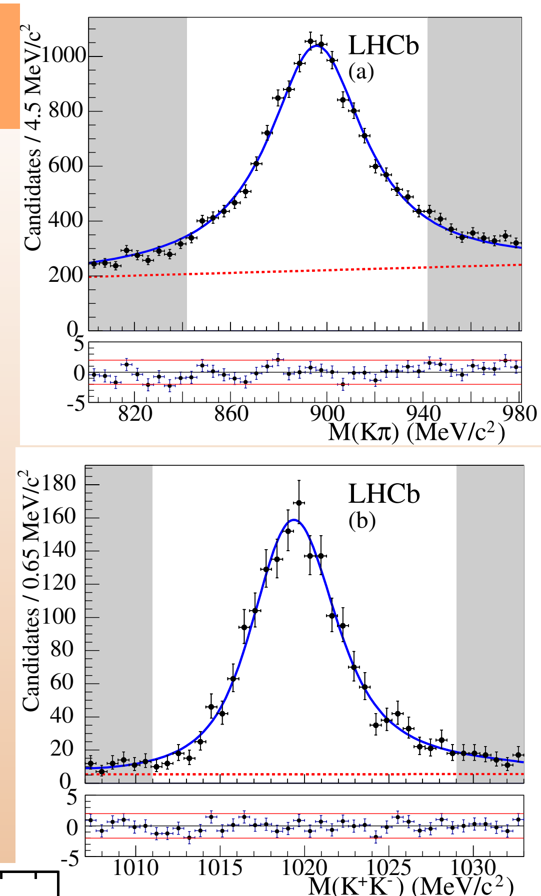
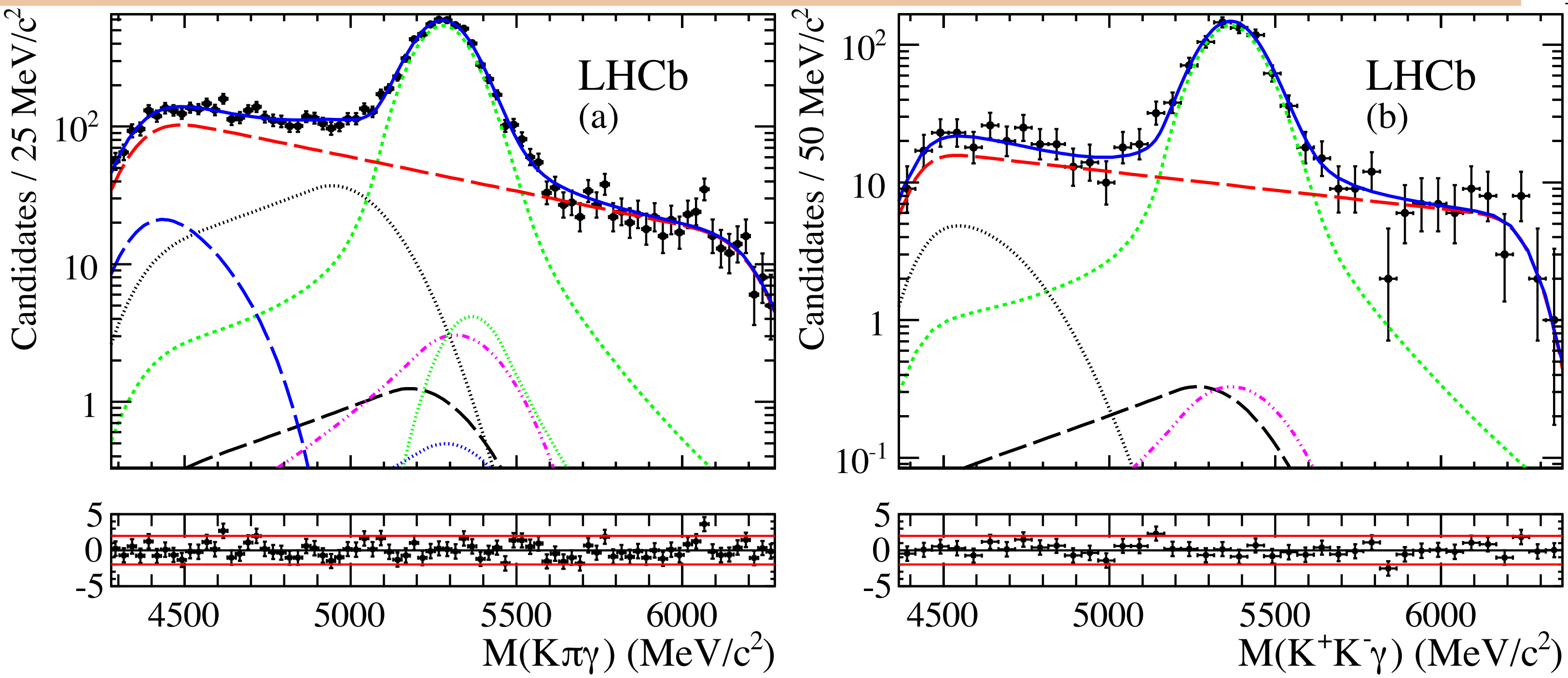




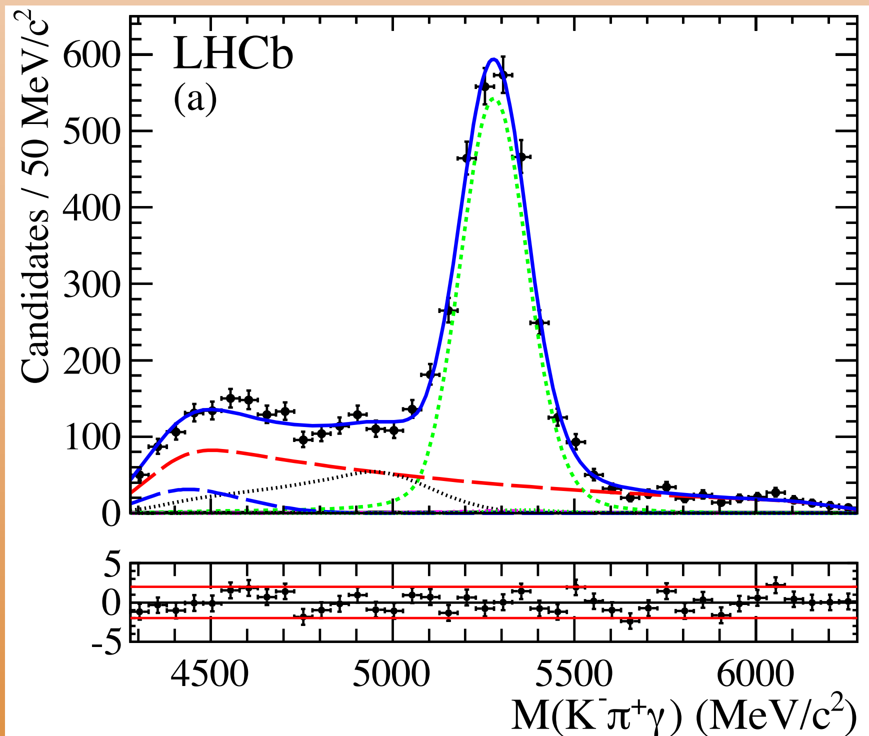
$b \to s\gamma$ decays at a hadron machine!

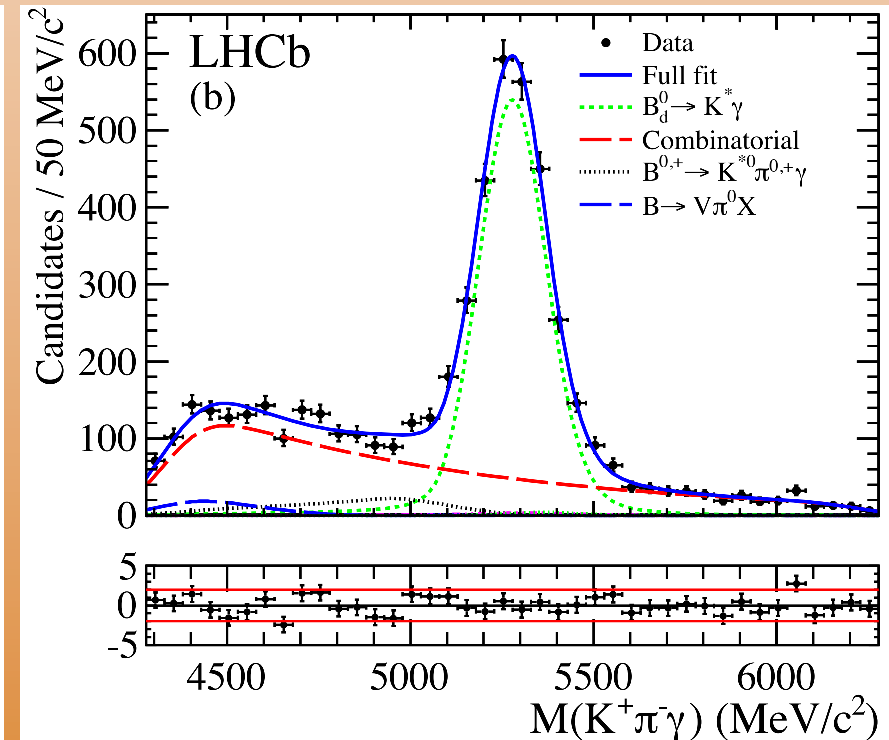
- From the yields, efficiencies, and the LHCb measurement of f_s/f_d (the production ratio of B_s to B_d), the following ratio is measured:

$$\frac{\mathcal{B}(B^0 \to K^{*0}\gamma)}{\mathcal{B}(B_s^0 \to \phi\gamma)} = 1.23 \pm 0.06\,(\text{stat.}) \pm 0.04\,(\text{syst.}) \pm 0.10\,(f_s/f_d)$$

- The $B^0 \to K^{*0}\gamma$ sample is split into particle and antiparticle to search for direct CP violation.
- After correcting for production related effects, material related effects, and detector related effects, no asymmetry is found:

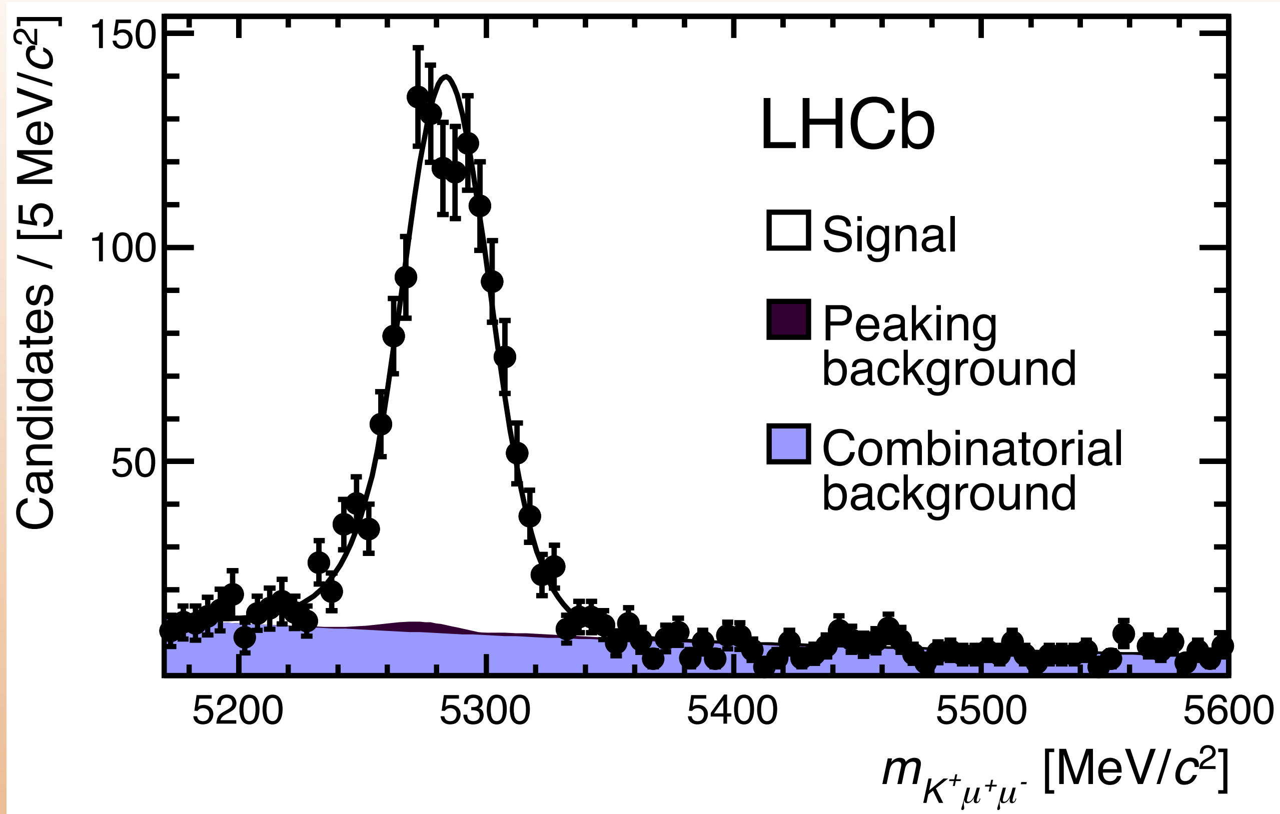
$$\mathcal{A}_{CP}(B^0 \to K^{*0}\gamma) = (0.8 \pm 1.7\,(\text{stat.}) \pm 0.9\,(\text{syst.}))\%$$





Reconstructing $B^+ \to K^+\mu^+\mu^-$ at LHCb

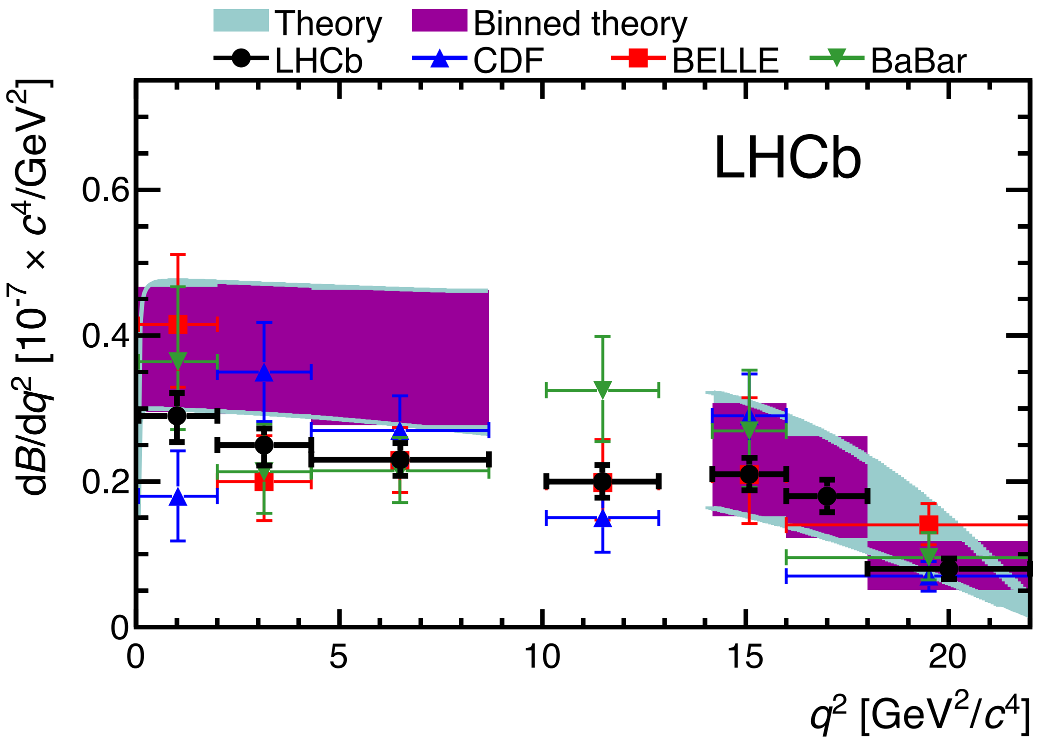
- Triggered by muon with p_T>1.5 GeV, a displaced track, and requirements based on partial or full reconstruction of B^+.
- Offline: cuts and BDT based on standard criteria (vertex fit quality, vertex displacement, momentum point-back, impact parameters, etc.) and neural network for particle ID.

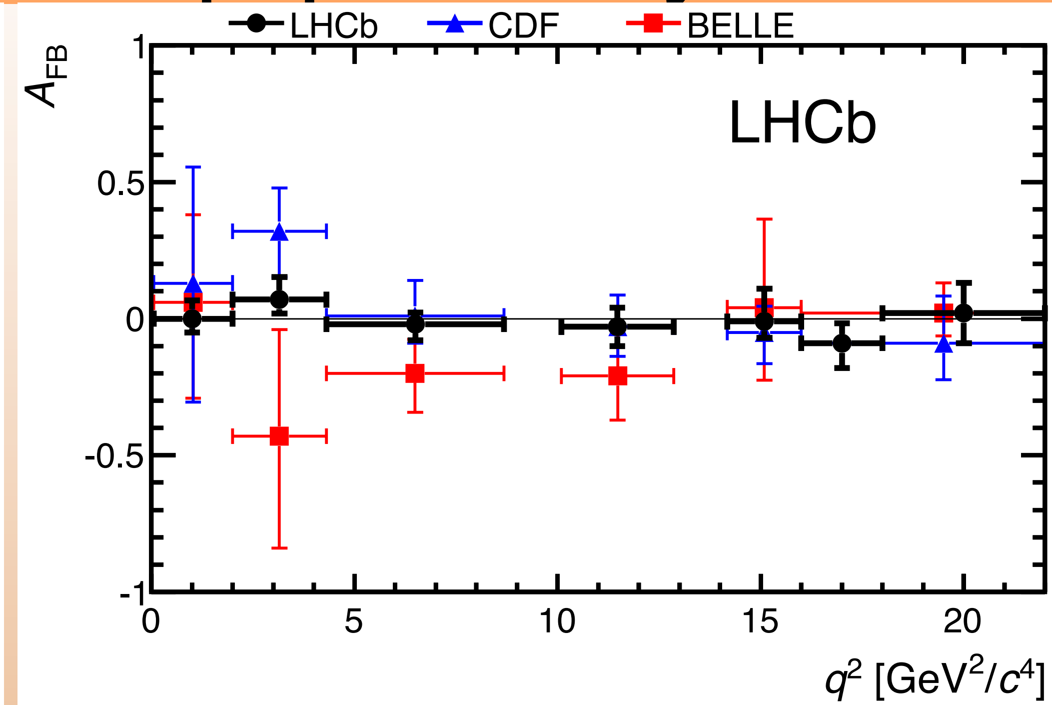


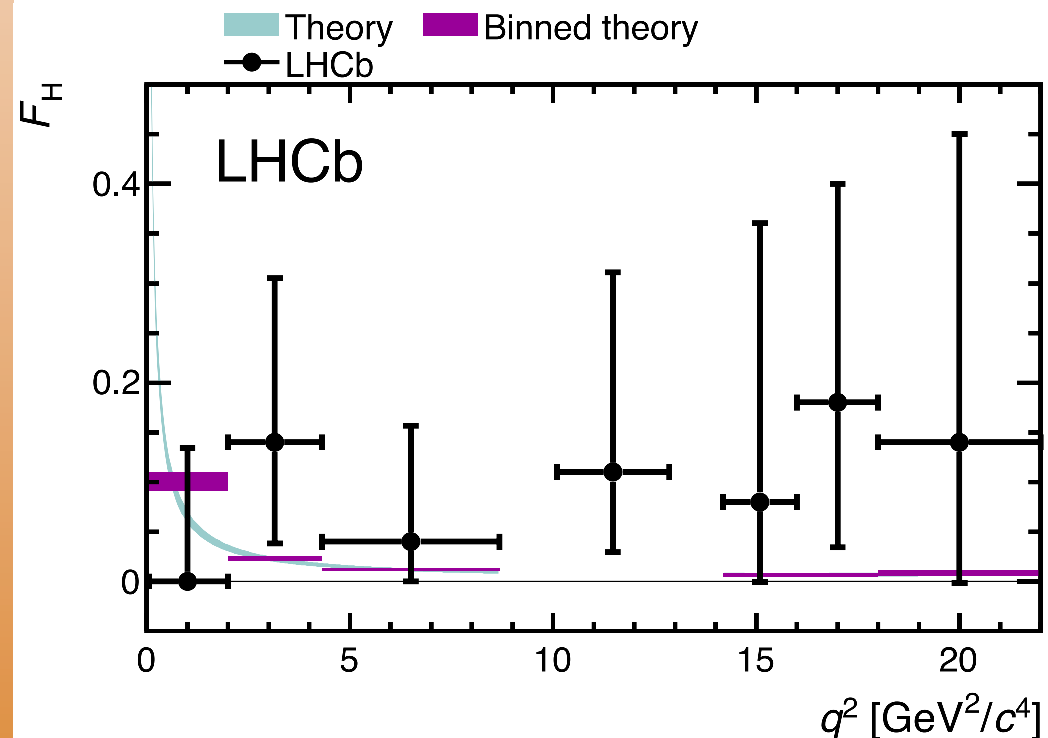
- Decay described by one angle, θ_l, plus $q^2=m^2(\mu\mu)$. Analysis fits $\cos\theta_l$ and B^+ mass in bins of q^2 to obtain the yield and two parameters related to the decay: F_H and A_{FB}.

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma[B^+ \to K^+\mu^+\mu^-]}{\mathrm{d}\cos\theta_l} = \frac{3}{4}(1-F_{\mathrm{H}})(1-\cos^2\theta_l) + \frac{1}{2}F_{\mathrm{H}} + A_{\mathrm{FB}}\cos\theta_l$$

Results for $B^+ \to K^+\mu^+\mu^-$ decay







LHCb results are by far the most precise. Small deviation in branching fraction at low q^2. The forward-backward asymmetry is consistent with 0 as expected. The F_H parameter, measured for the first time, is also consistent with the SM.

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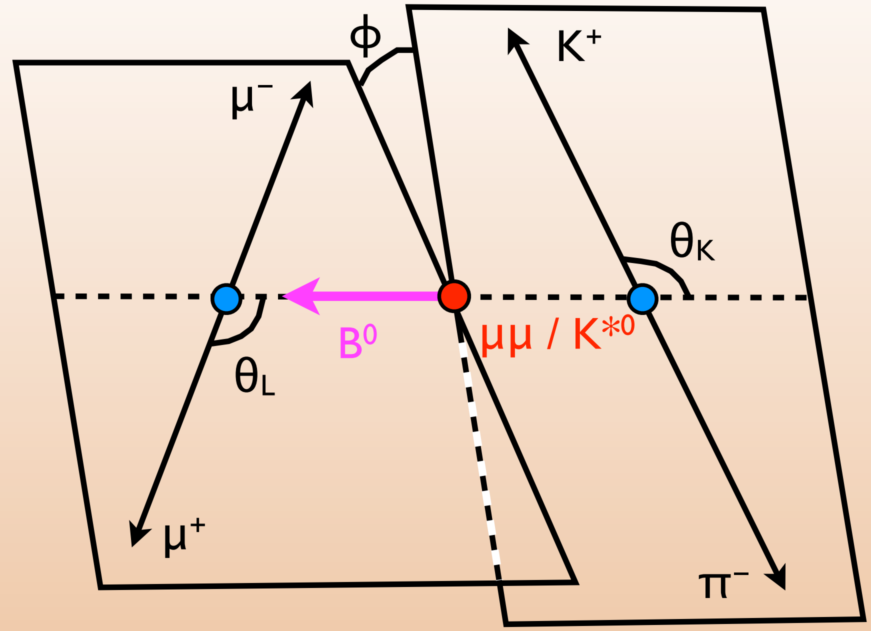
$B^0 \to K^{*0}\mu^+\mu^-$ decay

- The kinematics of the $B^0 \to K^{*0}\mu^+\mu^-$ decay are described by three angles (θ_K, θ_L, φ) plus the q^2 of the decay = $m^2(\mu\mu)$.
- Data is usually binned in q^2 and fitted to the angular variables.
- Full theoretical description of decay is below:



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

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

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

For $q^2 \gg 4m^2_\mu$:
$F_L = S^c_1 = -S^c_2$
$1-F_L = \frac{3}{4}S^s_1 = 4S^s_2$

Terms cancel when ϕ is folded

$A_{FB} = -\frac{3}{4}S_6$

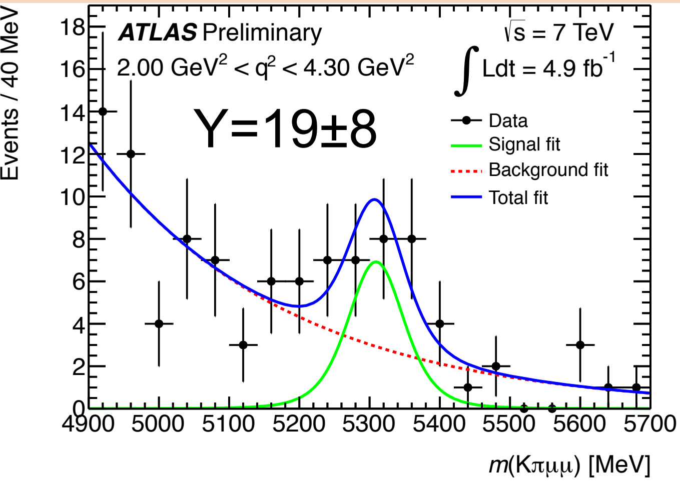
$S_9 \to A_9$ when $\phi \to -\phi$ for anti-B^0; A_9 is better for CP-asymmetries.

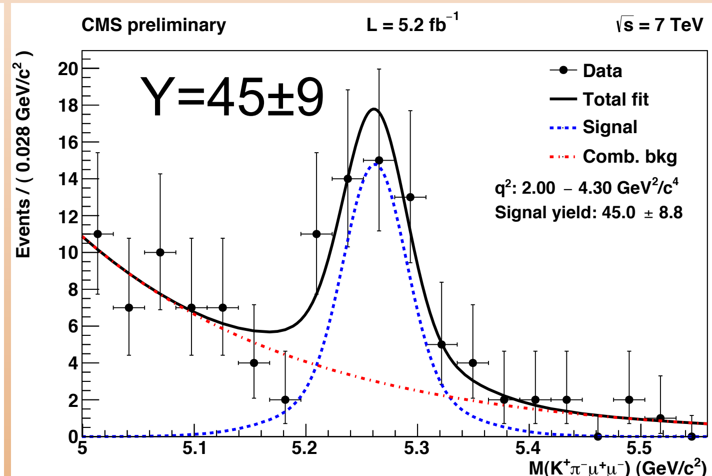
$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_K\, d\cos\theta_\ell\, d\phi} = \frac{9}{16\pi}\Big[F_L \cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K) - F_L \cos^2\theta_K (2\cos^2\theta_\ell - 1) + \frac{1}{4}(1-F_L)(1-\cos^2\theta_K)(2\cos^2\theta_\ell - 1) + S_3 (1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\cos 2\phi + \frac{4}{3}A_{FB}(1-\cos^2\theta_K)\cos\theta_\ell + A_9 (1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\sin 2\phi \Big]$$

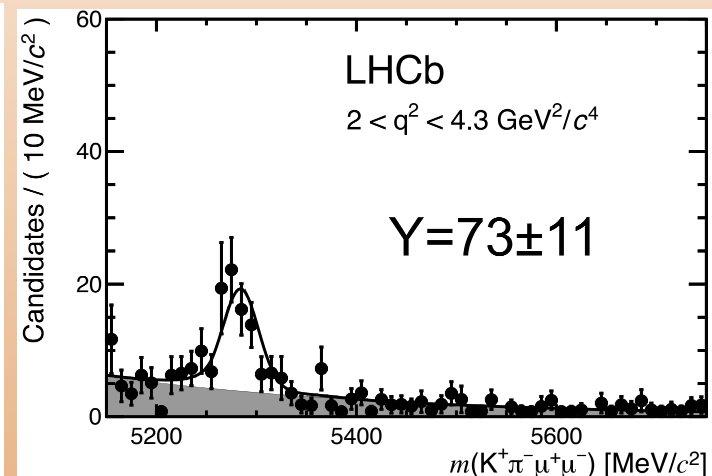
With the assumptions of large q^2 and folding the ϕ distribution, expression simplifies to 4 free parameters. LHCb fits this equation while other experiments integrate over ϕ to simplify further.

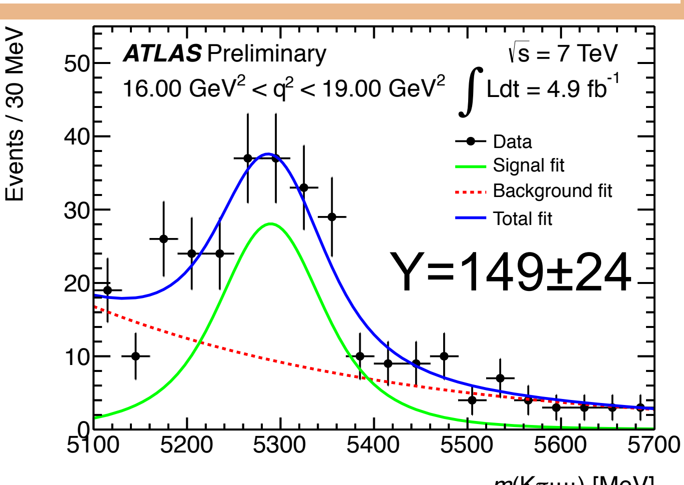
Reconstructing $B^0 \to K^{*0}\mu^+\mu^-$

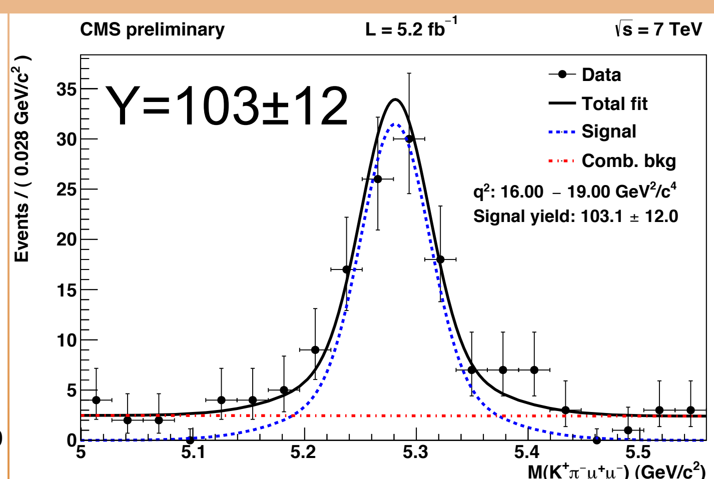
The B^0 candidate is composed of four charged tracks: K^+, π^-, μ^+, μ^-. Backgrounds are reduced by requiring a good vertex, displaced from the production points and with a momentum vector consistent with the production point. Also, explicit cuts on backgrounds (like $B_s \to \phi\mu^+\mu^-$). Below are $B^0 \to K^{*0}\mu\mu$ invariant mass plots from the 3 experiments for the smallest common q^2 bin (top) and largest q^2 bin (bottom).

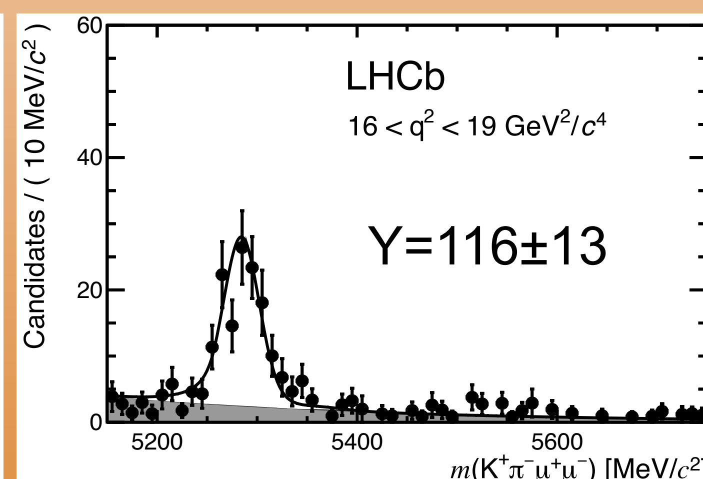












Fitting the $B^0 \to K^{*0}\mu^+\mu^-$ decay

LHCb:

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_K\, d\cos\theta_\ell\, d\phi} = \frac{9}{16\pi}\Big[\mathbf{F_L}\cos^2\theta_K + \frac{3}{4}(1-\mathbf{F_L})(1-\cos^2\theta_K) - \mathbf{F_L}\cos^2\theta_K(2\cos^2\theta_\ell - 1) + \frac{1}{4}(1-\mathbf{F_L})(1-\cos^2\theta_K)(2\cos^2\theta_\ell - 1) + \mathbf{S_3}(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\cos 2\phi + \frac{4}{3}\mathbf{A_{FB}}(1-\cos^2\theta_K)\cos\theta_\ell + \mathbf{A_9}(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\sin 2\phi \Big]$$

4D fit to $\cos\theta_K$, $\cos\theta_l$, ϕ, and invariant mass in q^2 bins to get $\mathbf{F_L}$, $\mathbf{A_{FB}}$, $\mathbf{S_3}$, $\mathbf{A_9}$. 1D mass fit for yield used in branching fraction.

arXiv:1304.6325

CMS:

CMS-PAS-BPH-11-009

$$\frac{d^3\Gamma}{dq^2\, d\cos\theta_K\, d\cos\theta_\ell} = \frac{9}{16}\Big\{ \Big[\frac{2}{3}\mathbf{F_S} + \frac{4}{3}\mathbf{A_S}\cos\theta_K\Big](1-\cos^2\theta_\ell) + (1-\mathbf{F_S})\Big[2\mathbf{F_L}\cos^2\theta_K(1-\cos^2\theta_\ell) + \frac{1}{2}(1-\mathbf{F_L})(1-\cos^2\theta_K)(1+\cos^2\theta_\ell) + \frac{4}{3}\mathbf{A_{FB}}(1-\cos^2\theta_K)\cos\theta_\ell\Big]\Big\}$$

3D fit to $\cos\theta_K$, $\cos\theta_l$, and invariant mass in q^2 bins to get $\mathbf{F_L}$ and $\mathbf{A_{FB}}$. plus 1D mass fit for yield used in branching fraction. S-wave contribution included in fit (with values for $\mathbf{F_S}$ and $\mathbf{A_S}$ taken from $B^0 \to J/\psi K^{*0}$).

ATLAS:

$$\frac{d^2\Gamma}{dq^2\, d\cos\theta_\ell} = \frac{3}{4}\mathbf{F_L}(1-\cos^2\theta_\ell) + \frac{3}{8}(1-\mathbf{F_L})(1+\cos^2\theta_\ell) + \mathbf{A_{FB}}\cos\theta_\ell$$

1D fit to invariant mass to get signal and background yields and shapes.

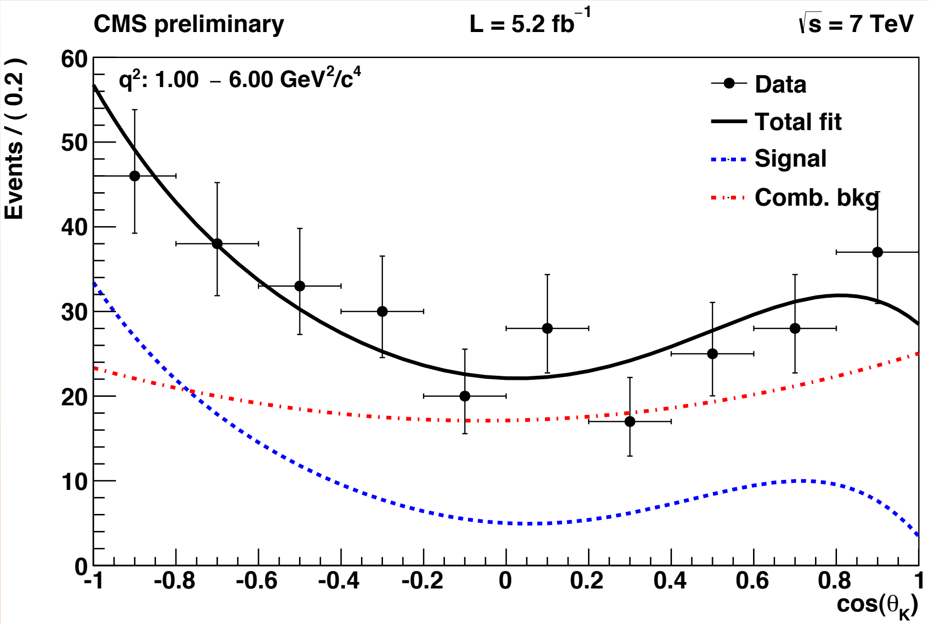
$$\frac{d^2\Gamma}{dq^2\, d\cos\theta_K} = \frac{3}{2}\mathbf{F_L}\cos^2\theta_K + \frac{3}{4}(1-\mathbf{F_L})(1-\cos^2\theta_K)$$

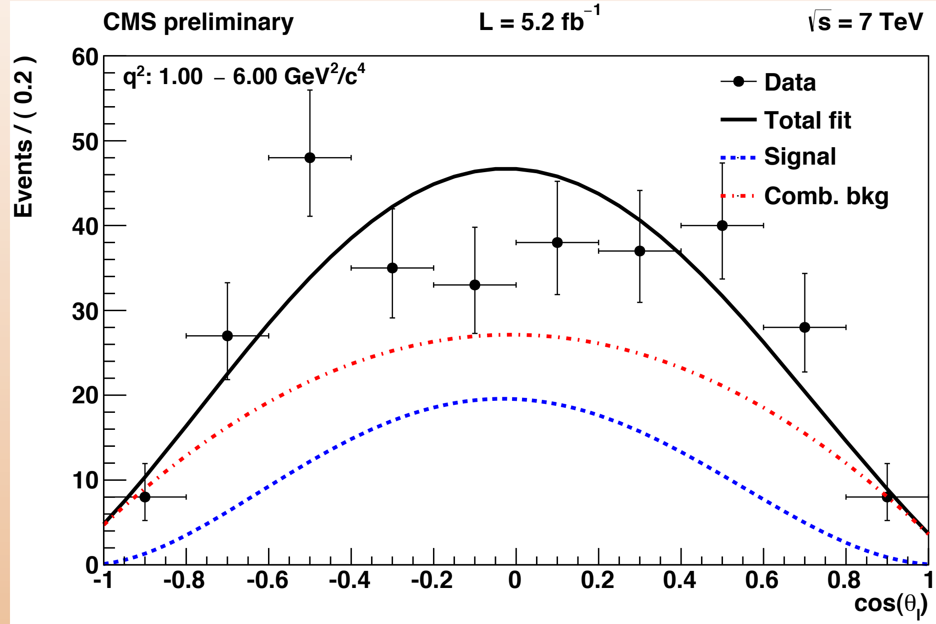
3D fit to $\cos\theta_K$, $\cos\theta_l$, and invariant mass done using independent description of two angles. Obtain results for $\mathbf{F_L}$ and $\mathbf{A_{FB}}$.

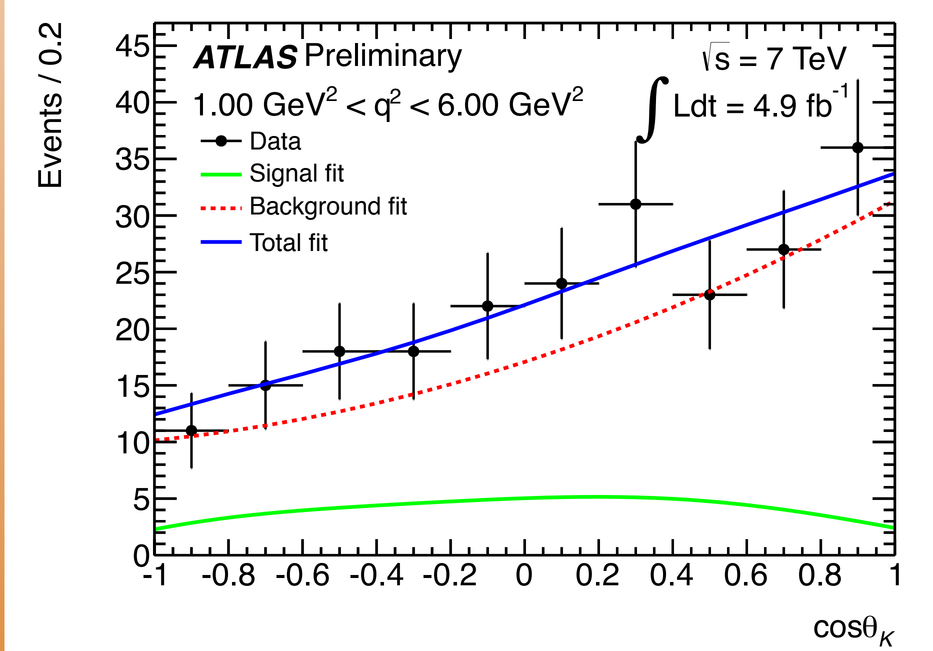
ATLAS-CONF-2013-038

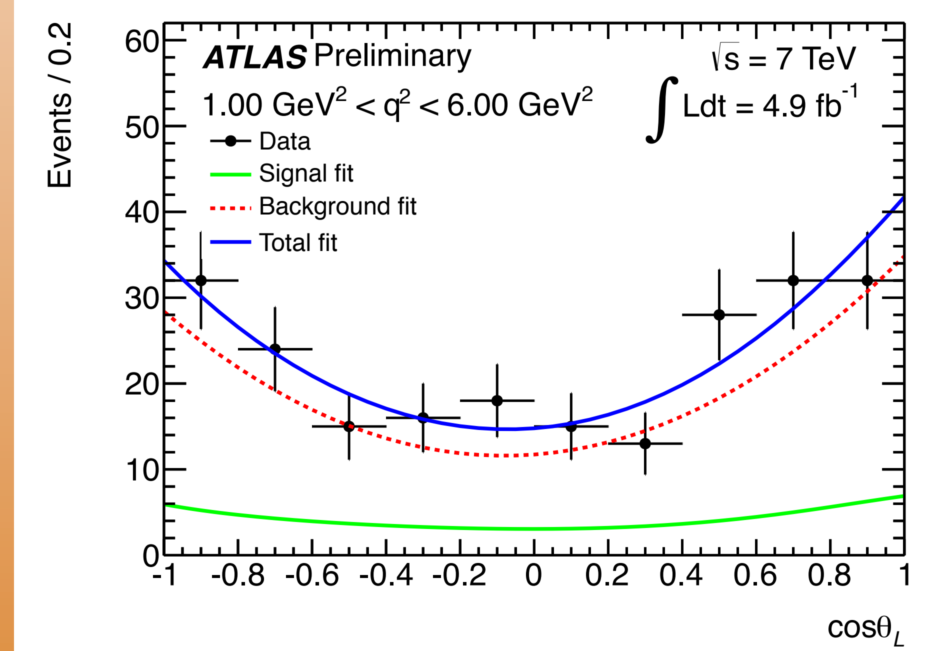
Fitting the $B^0 \to K^{*0}\mu^+\mu^-$ decay

Projections of fits to angular variables look reasonable. Differences between ATLAS and CMS may be from cuts or angle definitions.



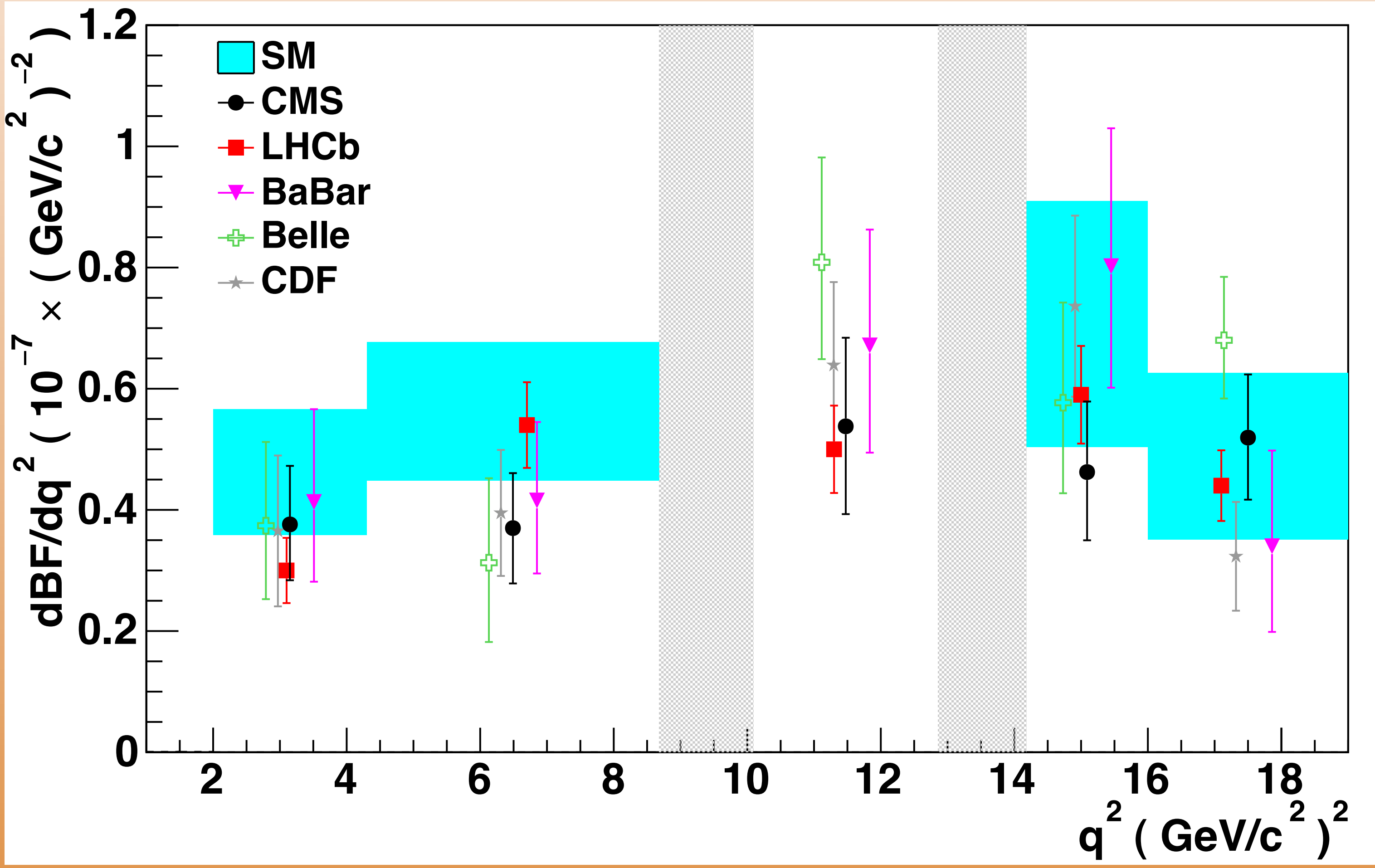






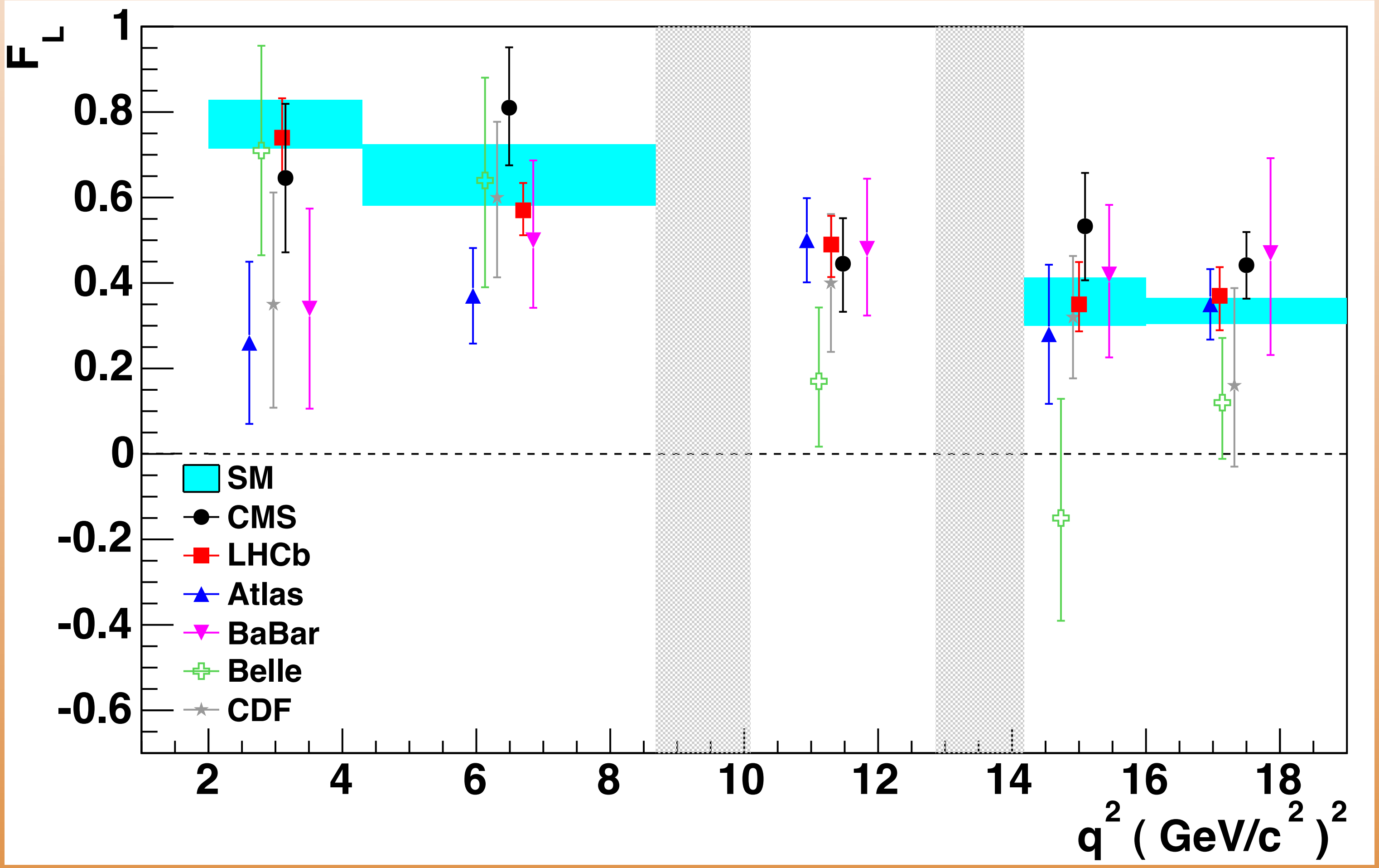
$B^0 \to K^{*0}\mu^+\mu^-$ branching fraction

- The branching fraction measurement for $B^0 \to K^{*0}\mu^+\mu^-$ utilizes the normalization mode $B^0 \to J/\psi\, K^{*0}$. The ratios of yields are corrected by ratios of efficiencies and the PDG value of the $B^0 \to J/\psi\, K^{*0}$ branching fraction is used to obtain an absolute rate.
- Results are consistent with standard model.



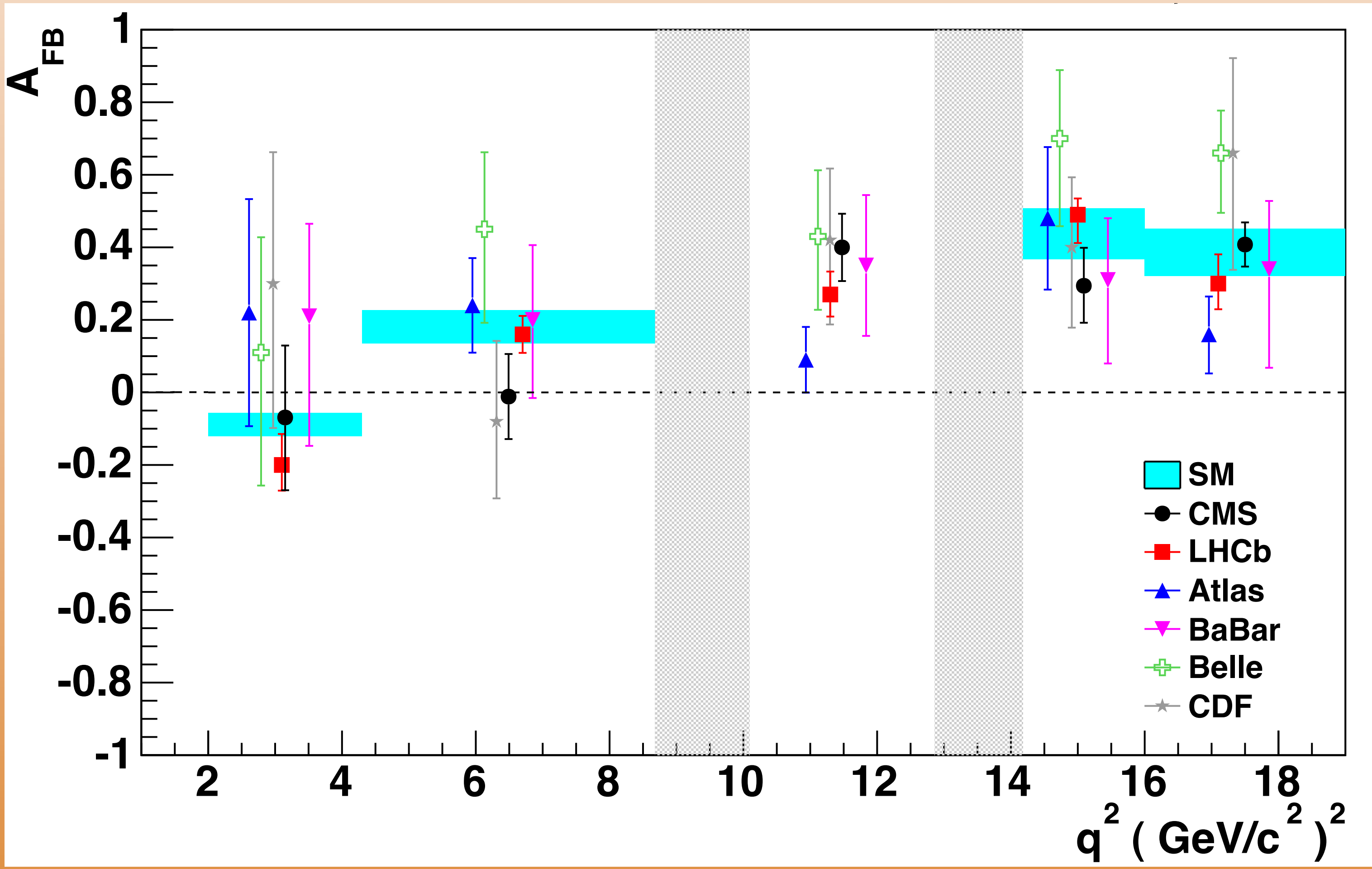
F_L from $B^0 \rightarrow K^{*0}\mu^+\mu^-$

- The fraction of longitudinally polarized K^{*0} mesons in the decay is extracted from the fit.
- The 3 LHC based results are more precise than the b-factory results.
- Taken as a whole, no indication of deviation from the standard model. Note the theory and experimental uncertainties are comparable.



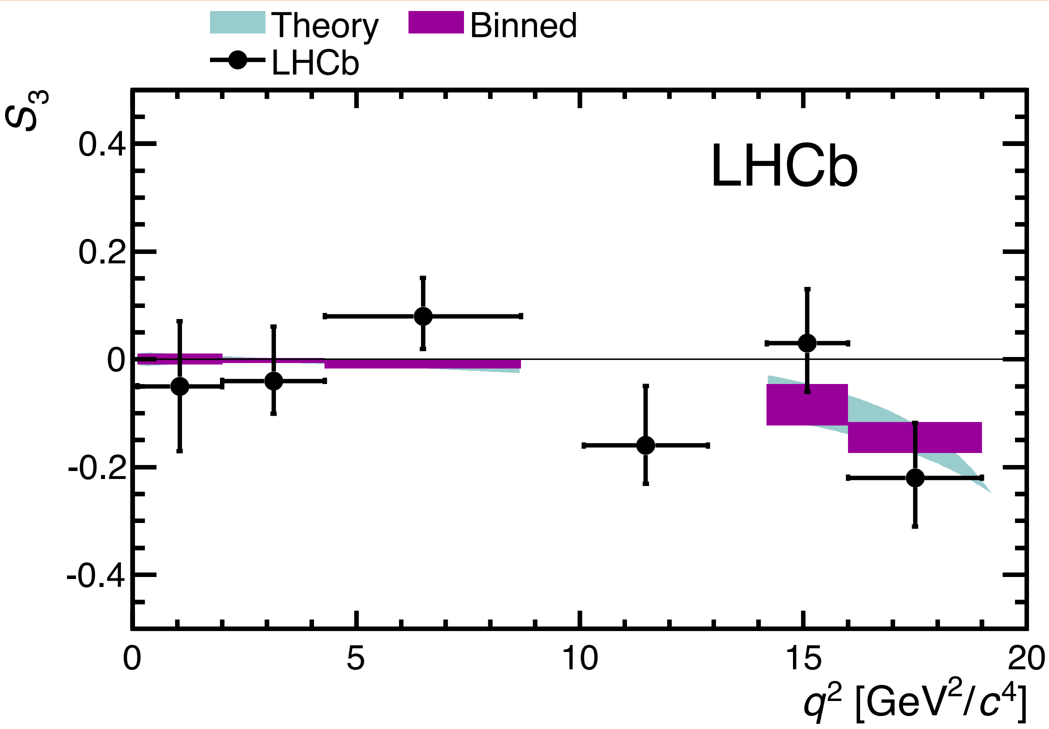
A_{FB} from $B^0 \rightarrow K^{*0}\mu^+\mu^-$

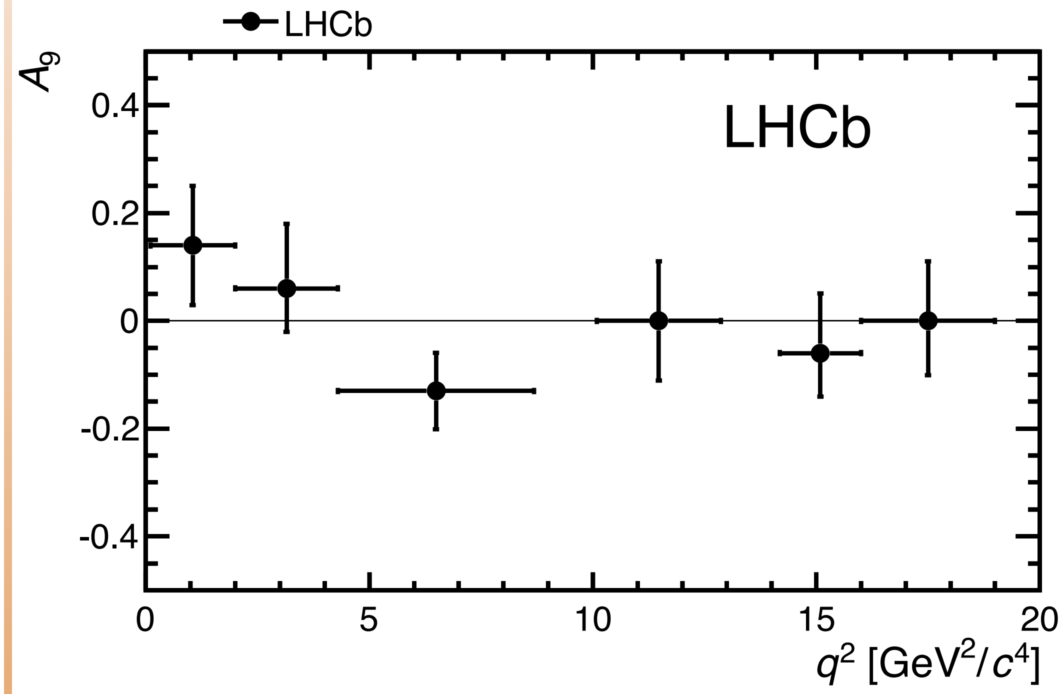
- The forward-backward asymmetry of the two muons in the decay is extracted from the fit.
- The 3 LHC based results are more precise than the b-factory results.
- No indication of deviation from the standard model.
- In addition, LHCb measures the location of the 0 crossing point to be 4.9±0.9 GeV^4, consistent with the standard model.



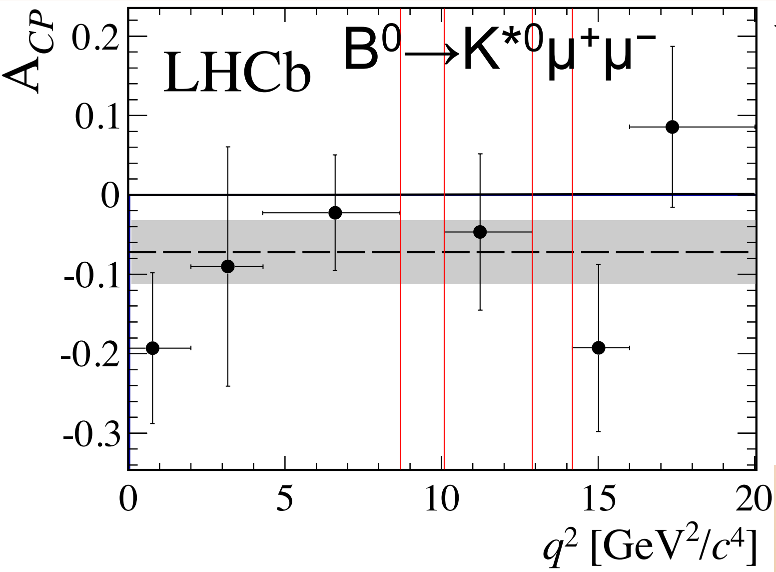
Other angular analysis results from $B^0 \to K^{*0}\mu^+\mu^-$

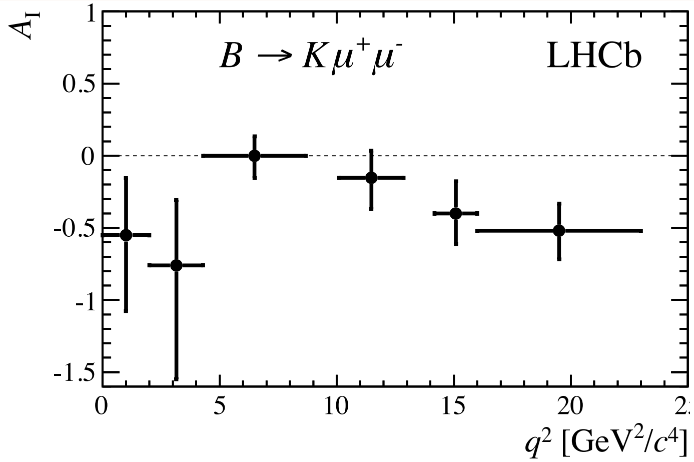
- From the fit to all three angles, LHCb extracts two other parameters related to the decay, S_3 and A_9.
- These also don't show indications of new physics (yet).

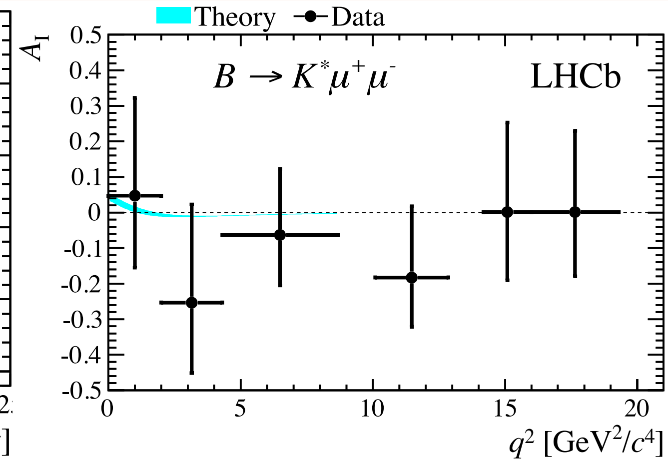




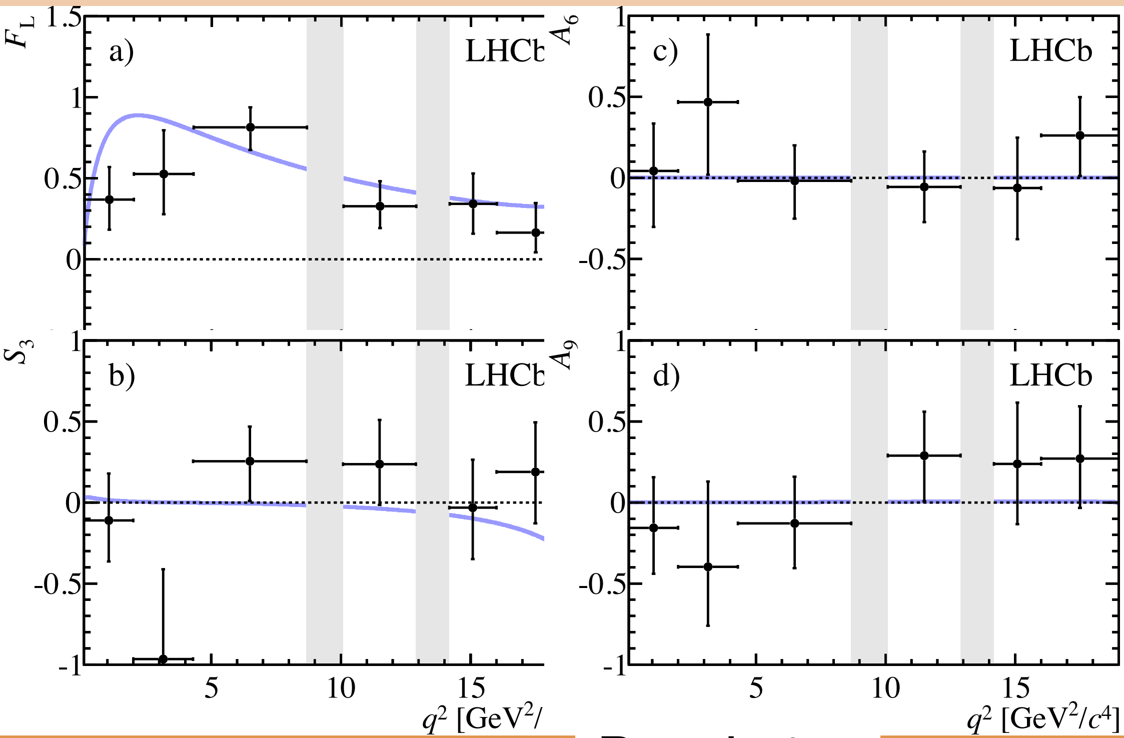
Uncovered results (all from LHCb)





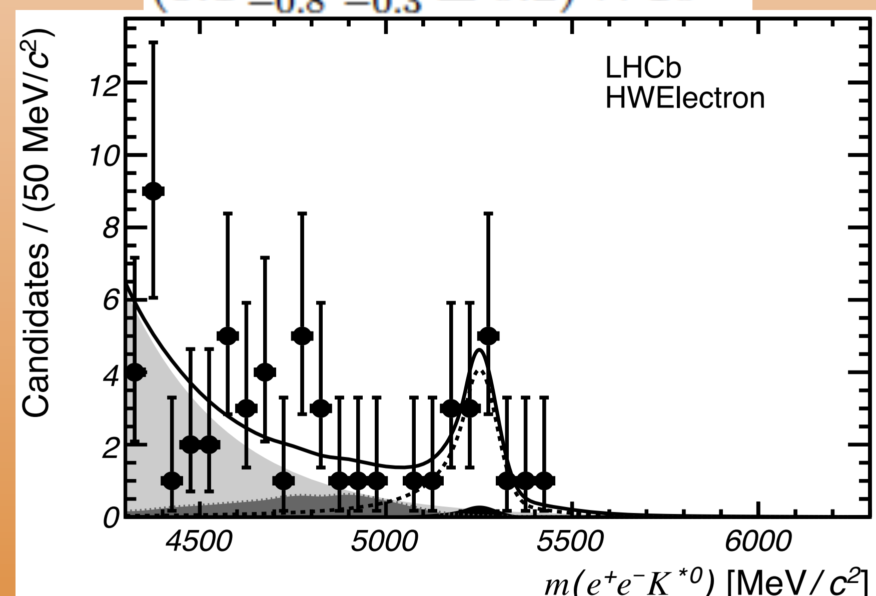


Covered by Marc-Olivier Bettler on Monday



$B_s \to \phi\mu^+\mu^-$

$$\mathcal{B}(B^0 \to K^{*0}e^+e^-)^{30-1000\,\mathrm{MeV}/c^2} = (3.1\,^{+0.9}_{-0.8}\,^{+0.2}_{-0.3} \pm 0.2) \times 10^{-7}$$



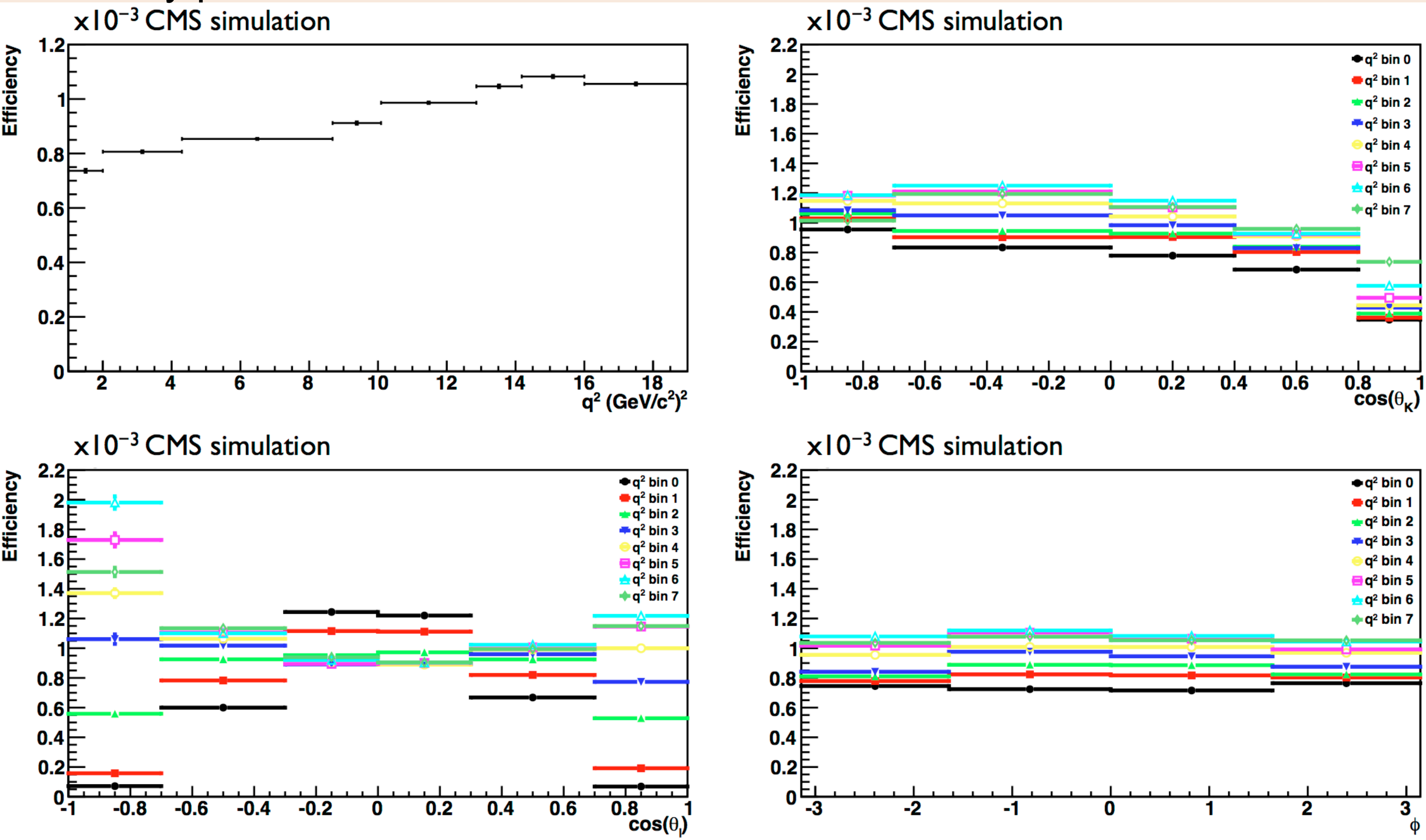
Summary and outlook

- Results from the LHC experiments, especially LHCb, have eclipsed the b-factories in some very important areas of radiative penguin decays, most notably in $B^0 \rightarrow K^{*0}\mu^+\mu^-$.
- Unfortunately, new physics has not yet been found.
- Results shown here are from 2011 data taking (about 1 fb^{-1} for LHCb and about 5 fb^{-1} from ATLAS/CMS).
- The 2012 data provide an additional 2 fb^{-1} for LHCb and 20 fb^{-1} for ATLAS/CMS. Should allow for more decay modes (such as $\Lambda_b \rightarrow \Lambda\mu^+\mu^-$), better precision on existing decay modes, and checking more variables in existing decay modes.
- The hunt for new physics continues…

Backup

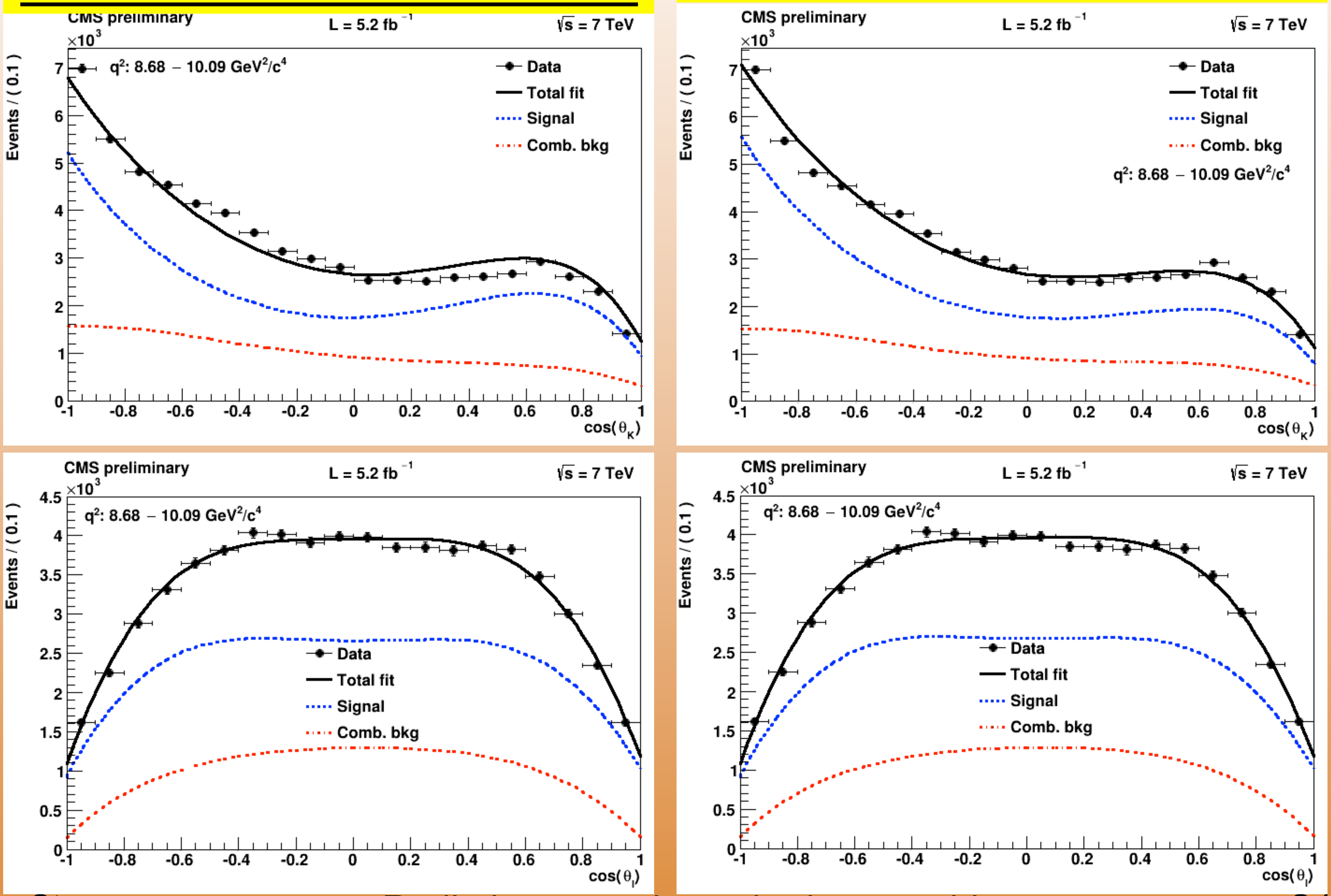
$B^0 \to K^{*0}\mu^+\mu^-$ efficiencies from CMS

Efficiencies versus q^2 (integrated over angles) and versus $\cos\theta_K$, $\cos\theta_L$, and ϕ (in bins of q^2). Representative only; 2D functions in $(\cos\theta_K, \cos\theta_L)$ used for efficiency parameterization in likelihood fit.

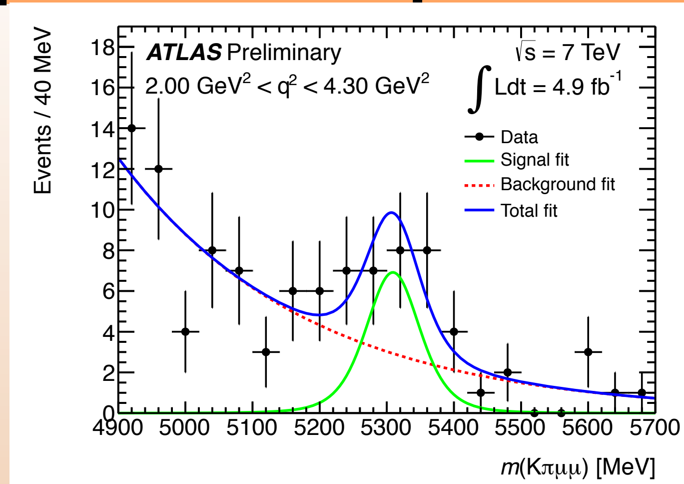


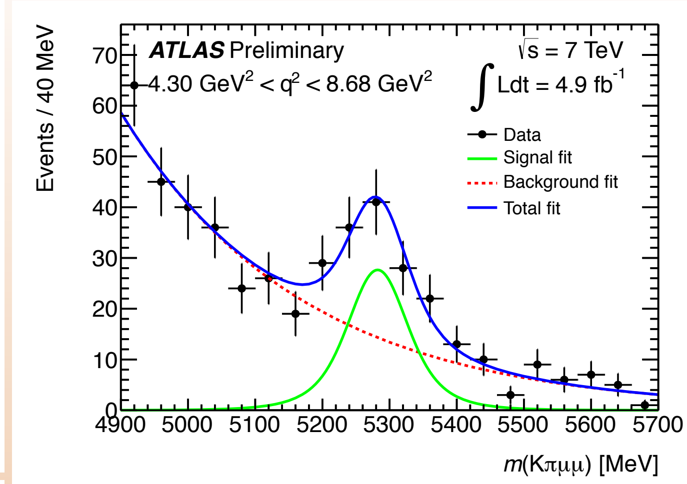
Effect of S-wave on $B^0 \to J/\psi K^{*0}$ distributions

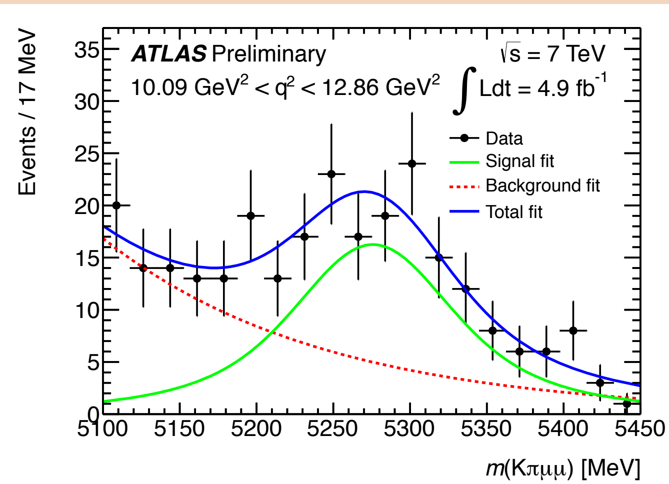
No allowance for S-wave in fit | **S-wave allowed in fit**

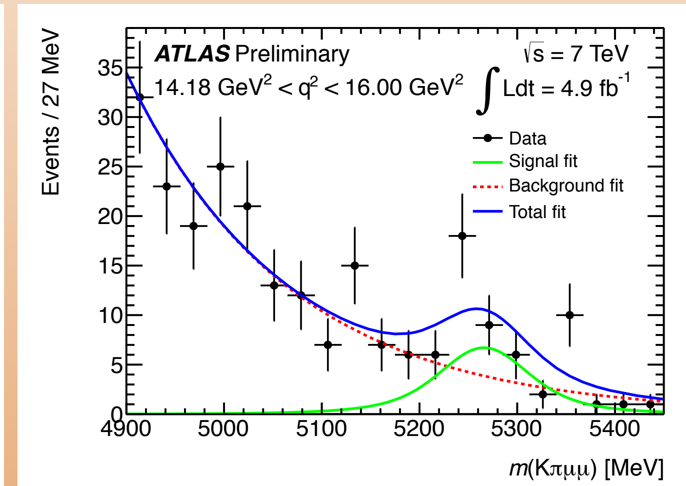


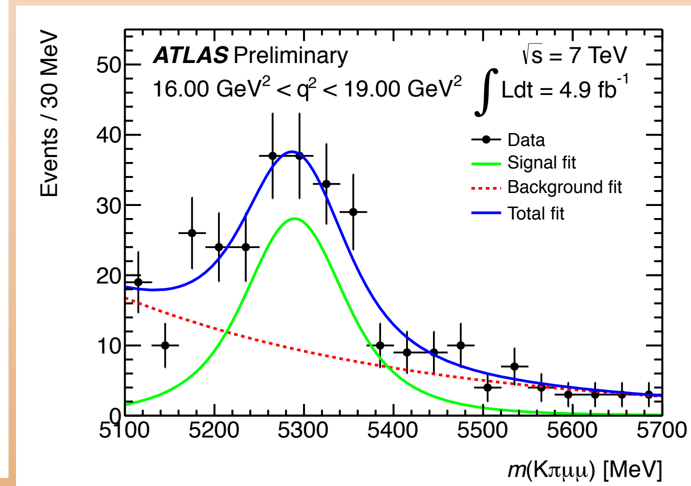
$B^0 \to K^{*0}\mu^+\mu^-$ mass plots from ATLAS

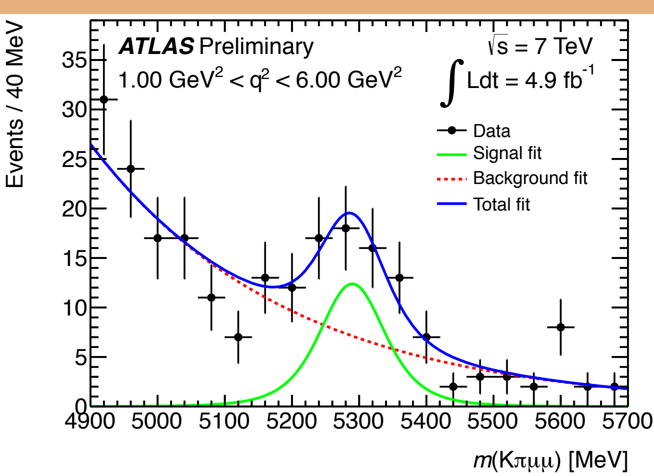










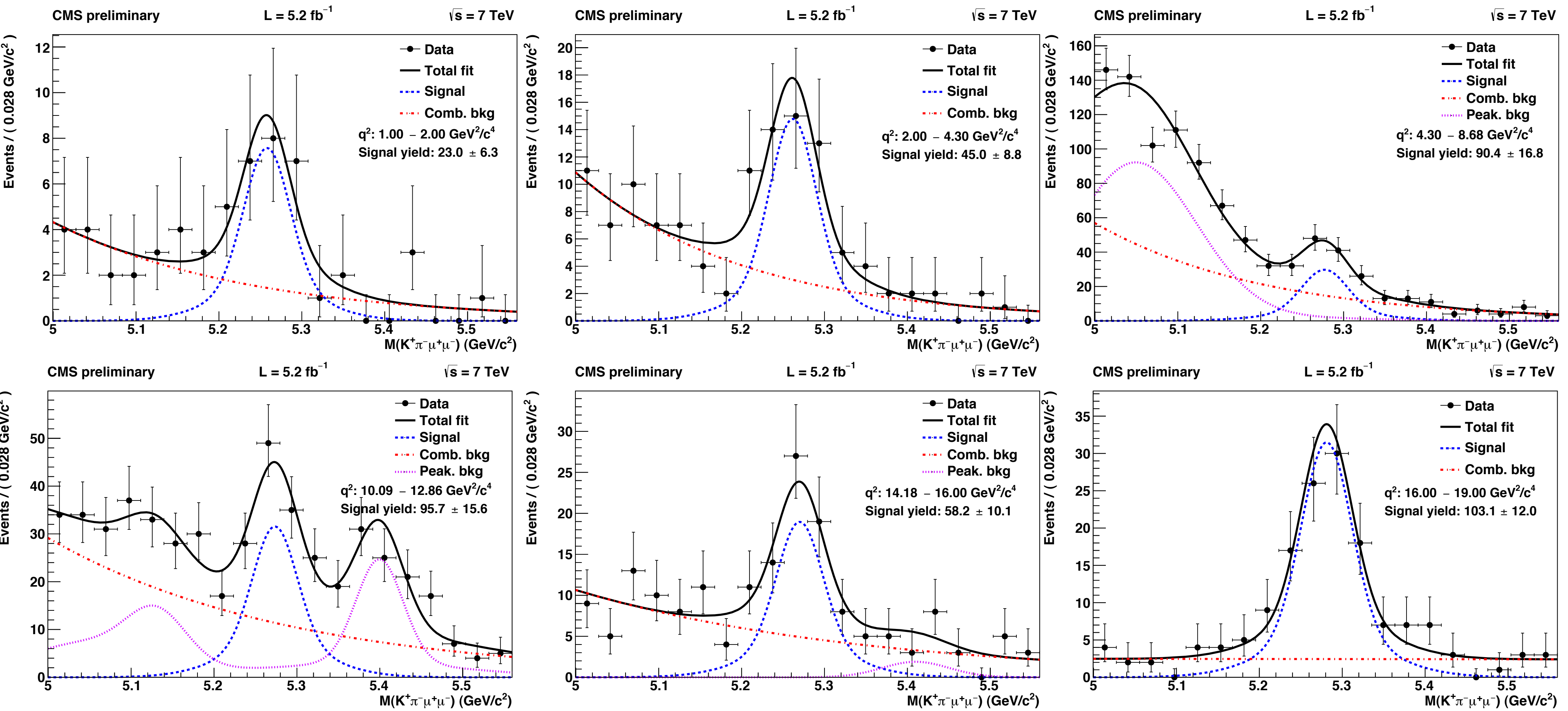


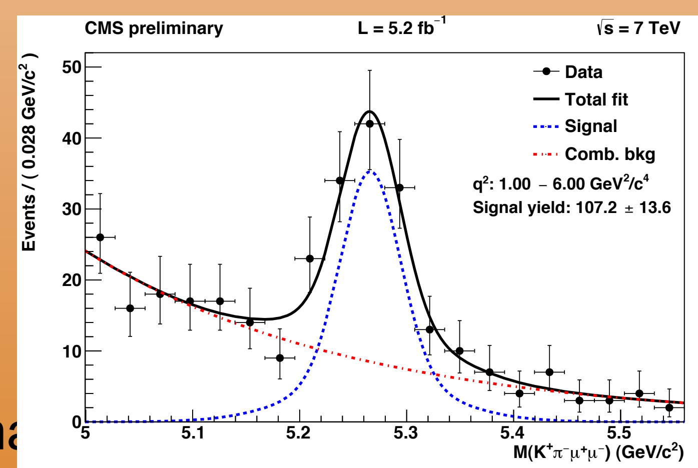
Contributions from radiative tail of charmonium modes removed using cut of:

$$\left|\left[m\left(B^0\right)_{\rm rec} - m\left(B^0\right)_{\rm PDG}\right] - \left[m\left(\mu^+\mu^-\right)_{\rm rec} - m\left(J/\psi\right)_{\rm PDG}\right]\right| < 130\,{\rm MeV}$$

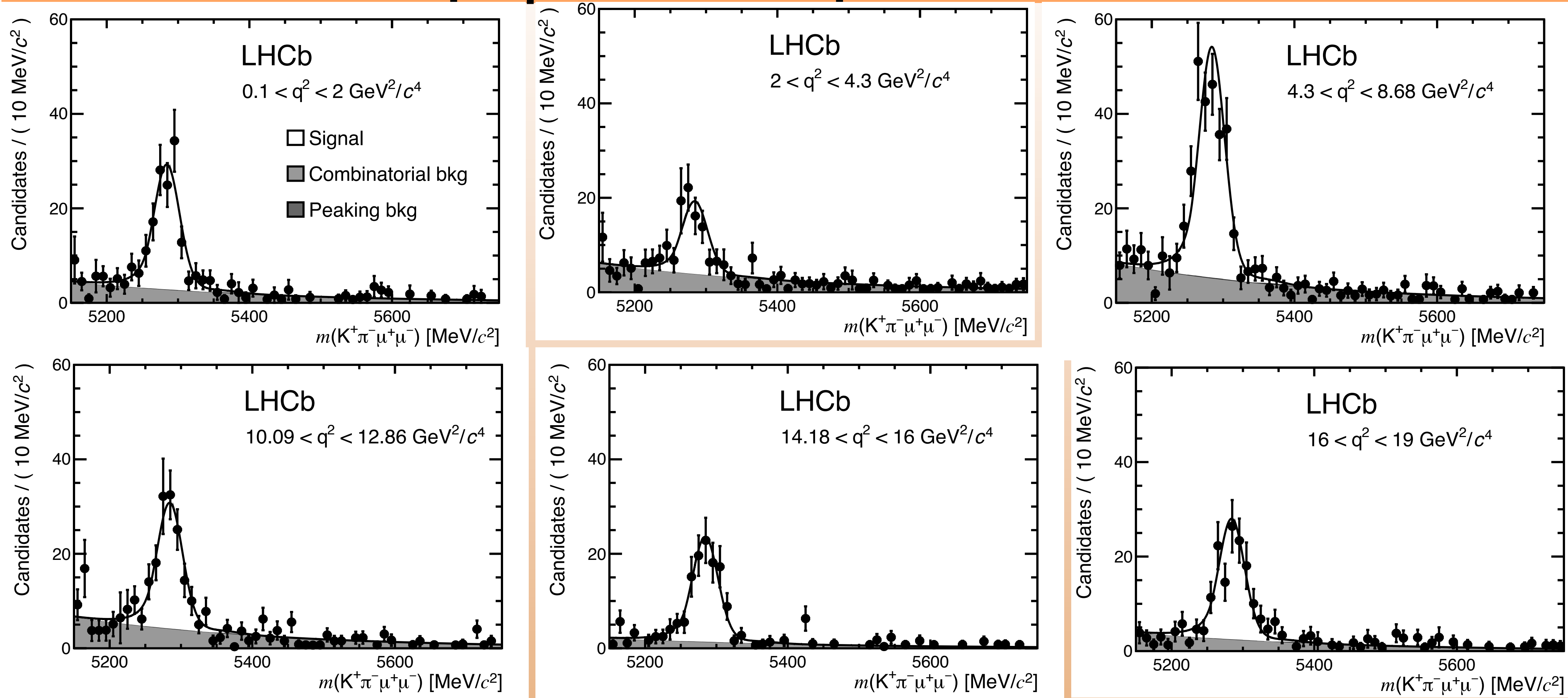
and similar cut for ψ(2S).

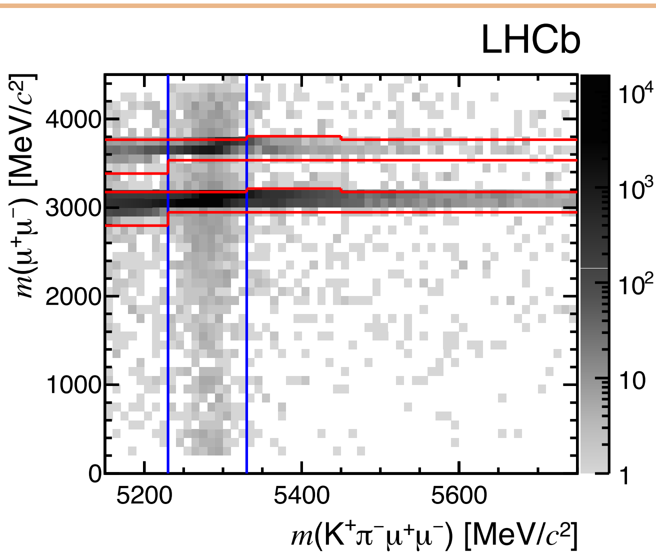
$B^0 \to K^{*0} \mu^+ \mu^-$ mass plots from CMS





$B^0 \to K^{*0}\mu^+\mu^-$ mass plots from LHCb





Charmonium decays (including misreconstructed and with soft photons) are removed by applying cut including information on Kπμμ mass.