Study of rare and suppressed processes in B meson decays with ATLAS

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Outlook

- Limit on BR(B_s (5366)$\rightarrow \mu^+ \mu^-$) decay
- A measurement of the forward-backward asymmetry A_{FB} and the fraction of the K^{*0} longitudinal polarisation F_L in the decay $B^0_d(5280) \rightarrow K^{*0}\mu^+ \mu^-$) decay
- Summary

BR($B_s(5366)\rightarrow\mu^+\mu^-$)

- The SM predicts the BR($B_s(5366)\rightarrow\mu^+\mu^-$) =$(3.23\pm0.27)\cdot10^{-9}$;
- The branching fraction might be substantially enhanced by non-SM heavy particles in the loop diagrams
- Upper limits on this branching fraction have been presented by D0, CDF, CMS collaborations
- The LHCb collaboration recently reported first evidence for this decay with BR=$(3.23^{+1.4}_{-1.2}{}^{+0.5}_{-0.3})\cdot10^{-9}$
- The CMS collaboration limit is BR<$6.4\cdot10^{-9}$ at 90% C.L.
- Previous ATLAS result was based on half of the 2011 ATLAS dataset (2.4 fb^{-1})
- This note represents an update to the full 2011 ATLAS dataset (4.9 fb^{-1})

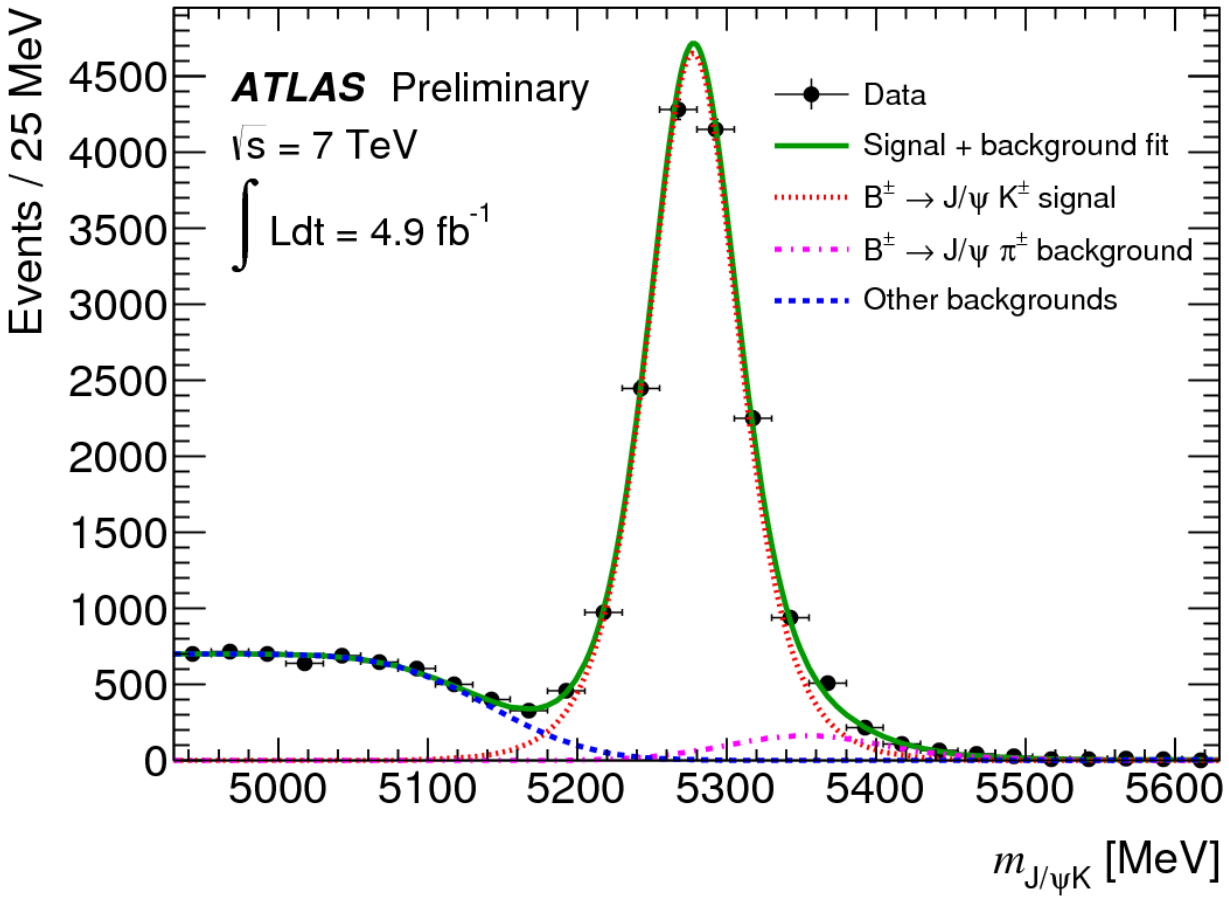
Data selection

- A muon trigger is used to select events, which requires a transverse momentum p_T >4 GeV/c for both muons
- B_s candidates loose selection: 4.0<m(μμ)<8.5 GeV;
- track selection: pseudorapidity |η|<2.5; combined muons us with p_T>4 GeV/c; requested at least 1 hit in Pixel, 6 in SCT and 9 in TRT detector
- Decay vertices were formed by $\mu^+ \mu^-$, requested χ^2/NDF<2.0
- selected B_s candidates at p_T >8 GeV and |η|<2.5;
- Signal mass band (5.066, 5.666) GeV and two side bands (4766, 5066]) or (4766, 5066) were defined
- after preselection approximately 390000 B_s candidates were selected

Normalization

- $B^{+-} \rightarrow J/\psi K^{+-}$ events used for normalization, with $J/\psi \rightarrow \mu^+ \mu^-$
- The same selection requirements on muon candidates were applied, selected J/ψ candidates with $2.5 < m(\mu^+ \mu^-) < 4.3$ GeV
- Extra charged tracks with $p_T > 2.5$ GeV were tested as kaon candidates, without kaon identification, with requirements on number of hits in Inner Detector parts
- Decay vertices were formed from $\mu^+ \mu^- K^{+-}$
- Signal mass band at (5.18, 5.38] GeV was chosen for B^{+-} candidates

Mass spectrum for B^{+-} candidates



MC optimization

- MC events were generated for both B_s and B^{+-} decays.
- Using the re-weighting method, MC simulated samples were adjusted by an iterative re-weighting procedure, a generator-level (GL) re-weighting based on simulation, followed by a data driven (DD) re-weighting. Events were generated in a wider range in the *b*-quark kinematics in (p_T, η) plane than the experimental cuts, which allow to do MC correction in 2 dimensions. Finally, a correction for the J/ψ polarization (missing in PYTHIA) was applied.
- This procedure uses the comparison of MC events to the sample of B_s and B^{+-} decays in collision data.
- only candidates with odd event numbers in the ATLAS dataset are used to determine the re-weighting procedure, while the remaining sample is used for the yield measurement.
- The ratio of the acceptance and selection efficiency in terms for the $B^0_s \rightarrow \mu^+\mu^-$ signal and the $B^{+-} \rightarrow J/\psi K^{+-}$ reference channel is evaluated using MC samples.

Backgrounds in $B_s \rightarrow \mu^+\mu^-$ study

- Two categories of background are considered: a continuum with a smooth dependence on the di-muon mass, MC show that the combinatorial background from b antib->($\mu^+\mu^-$X) provides reasonable description for the distributions of the discriminating variables.
- This MC sample used for the training of the MVA classifier (BDT).
- Resonant background due to B decay candidates containing either one or two hadrons erroneously identified as muons are expected to contribute inside the signal region.
- probability for a hadron to be misidentified as a muon was estimated from MC as well as efficiency, BR taken from PDG

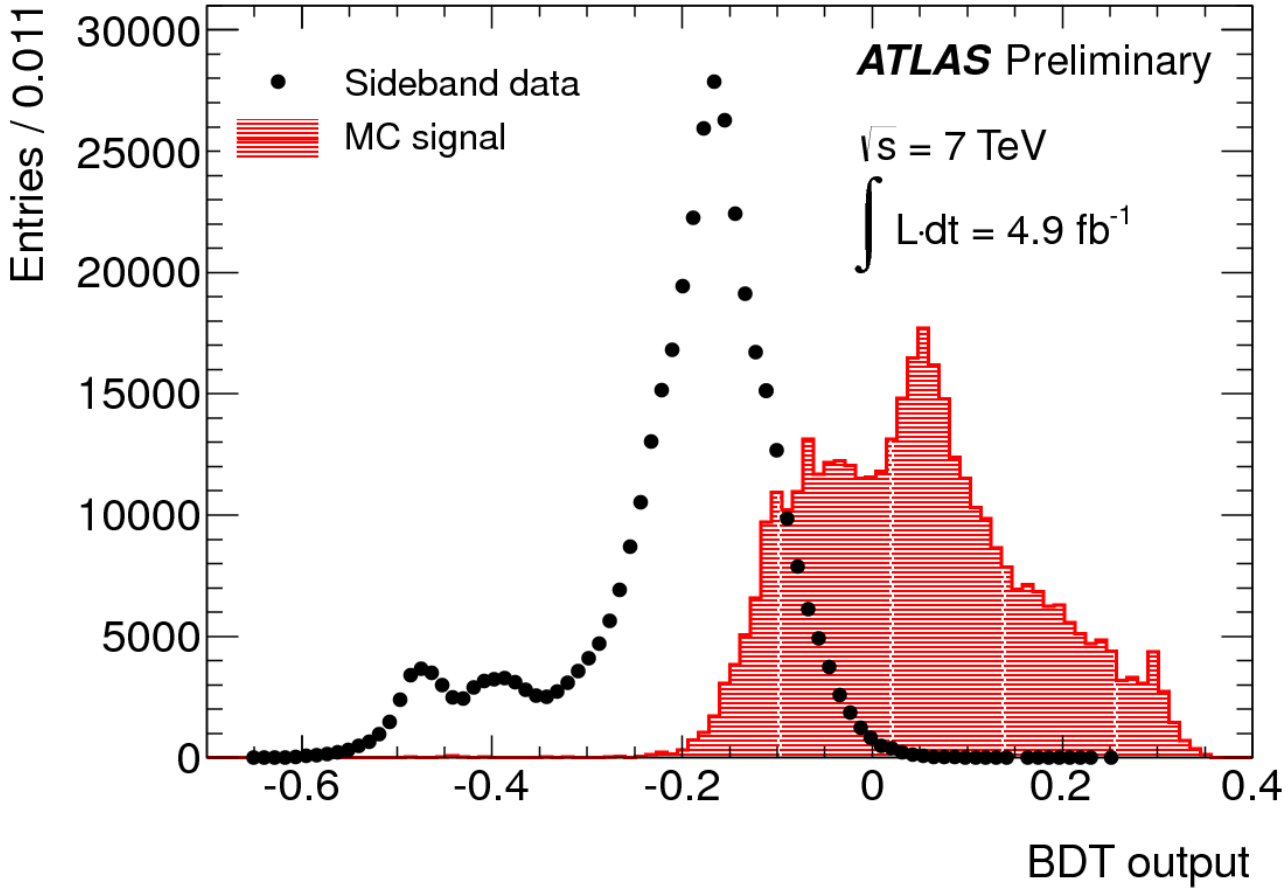
Optimization procedure

This constitutes a nearly irreducible background.

- The optimization procedure aims at selecting the best performing BDTs and obtaining the final selection cuts in the BDT output variable q and in the invariant mass window Δm to be applied to our data sample to obtain the best sensitivity to the signal.
- The optimization is performed by maximizing the following estimator of the separation power : $P=\varepsilon/(1+\sqrt{B})$, where ε is the signal efficiency and B is the number of BG events. Effectively, we are optimizing for two sigma background exclusion and two sigma signal discovery. The 2-dimensional optimization on the BDT output requirement and the signal region width, is performed on the signal MC sample and the odd-numbered sideband data events
- The odd-numbered event optimization gives a maximum P value at BDT output > 0.118 and $|\Delta m| < 121$MeV.

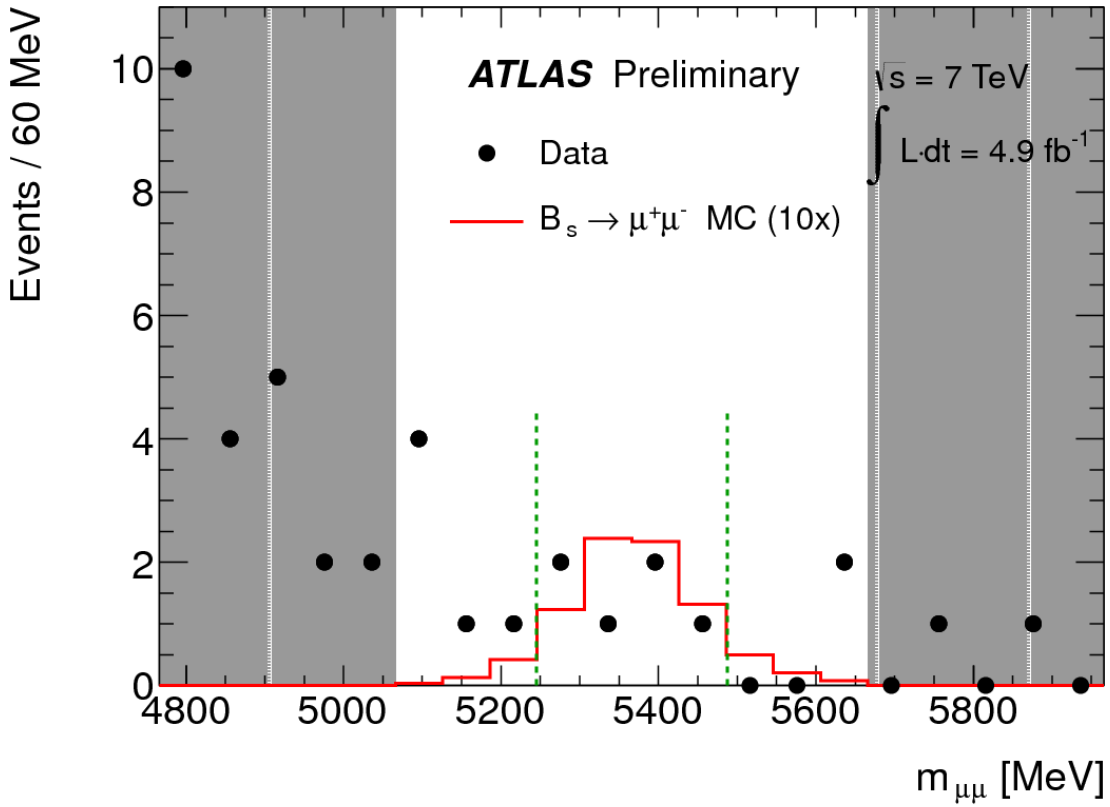
Discriminative variables

Variable	Description	Rank
L_{xy}	Scalar product in the transverse plane of vectors	1
$I_{0.7}$ isolation	Ratio of $\lvert\sim pB\mathrm{T}\rvert$ to the sum of $\lvert\sim pB\mathrm{T}\rvert$ and the transverse momenta of all tracks with isolation $p_T > 0.5$ GeV within a cone $R < 0.7$ from the B direction, excluding B decay prod.	2
$\lvert\alpha_{2d}\rvert$	Absolute value of the angle in the transverse plane between vectors $\sim x$ and $\sim pB$	3
$p_{L\,min}$	Minimum momentum of the two muon candidates along the B direction	4
pTB	B transverse momentum	5
ct significance	Proper decay length divided by its uncertainty	6
χ^2_z , χ^2_{xy}	Significance of the separation between production (PV) and decay vertex (SV)	7
$\lvert Dxy\rvert$min, $\lvert Dz\rvert$min	Absolute values of the minimum distance of closest approach in the xy plane or along z of tracks in the event to the B vertex	8
ΔR	R-parameter in two dimensions, $R=\sqrt{(\Delta\eta^2+\Delta\phi^2)}$	9
$\lvert d0\rvert$max, $\lvert d0\rvert$min	Absolute values of the maximum and minimum impact parameter of B-decay products in the transverse plane	10



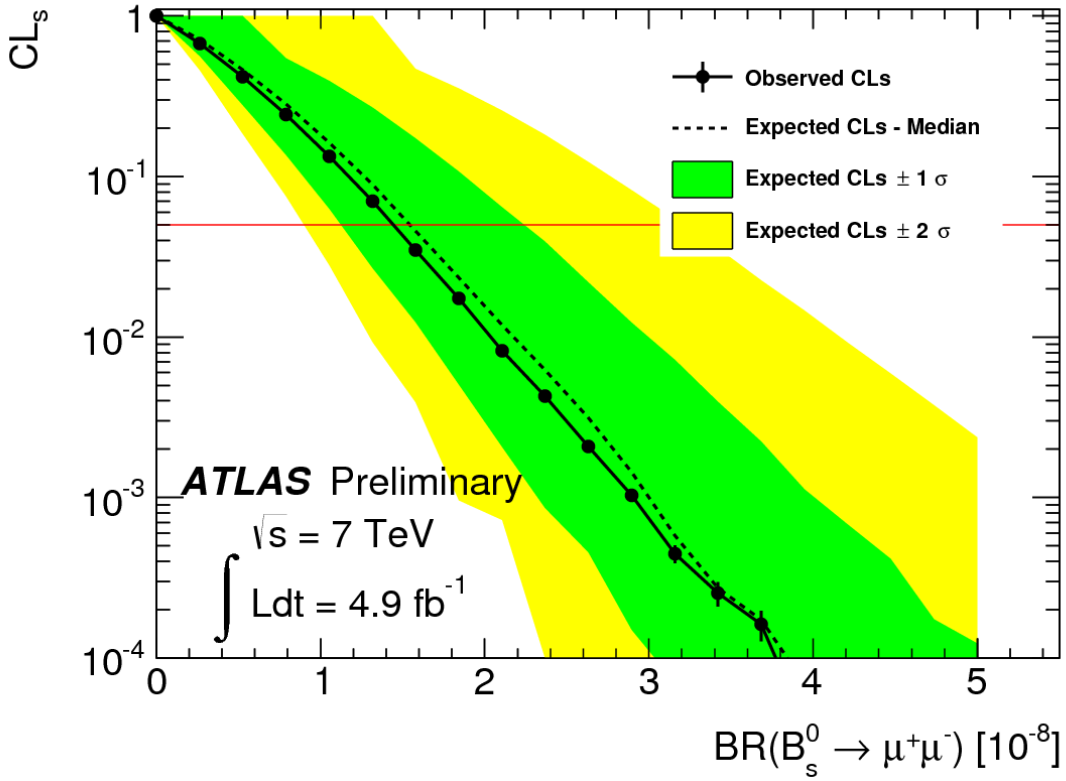
Distributions of the selected BDT for data-reweighted signal MC events and mass sideband data.
The areas are both normalized to the number of entries in the sideband data for shape comparison.

$BR(B_s \rightarrow \mu^+\mu^-)$ limit



After unblinding (taking even events), 6 events are counted in the signal region. Expected BG 6.8 events. The observed limit is $BR(B_s \rightarrow \mu^+\mu^-) < 1.5$ (1.2) $\times 10^{-8}$ at 95% (90%) CL. The plot also indicates the signal (continuous line) as predicted by Monte Carlo assuming $BR(B^0_s \rightarrow \mu^+\mu^-) = 3.5 \times 10^{-8}$ (scaled by a factor 10), the signal region (two dashed vertical lines) corresponding to the optimized Δm cut.

Observed Conf. Level as a function of $BR(B^0_s \rightarrow \mu^+\mu^-)$.



The 95% CL limit is indicated by the horizontal (red) line. The dark (green) and light (yellow) bands correspond to the ±1σ and ±2σ ranges of the background--only pseudo-experiments with the median of the expected CLs (dashed line)

$B_d \rightarrow \mu^+\mu^- K^{*0}(890)$ decay

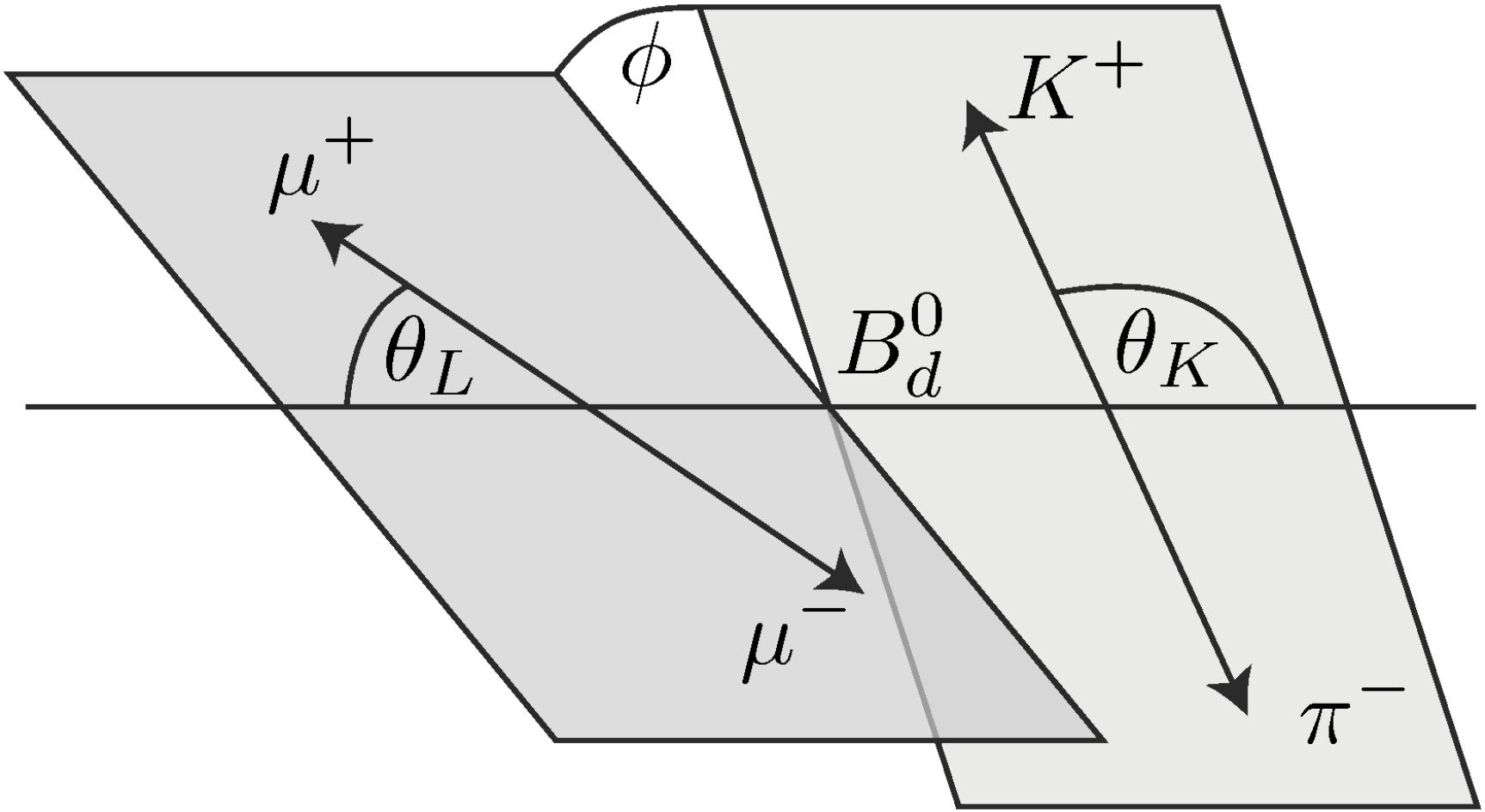
- Within the SM this decay occurs via loop diagrams that mediate the transition $b \rightarrow s\, l^+\, l^-$ and therefore has a small BR=$(1.06\pm0.1)\cdot10^{-6}$. Angular distributions and amplitudes are sensitive to possible new physics beyond the SM.
- The objective of this analysis are measurements of the forward-backward asymmetry A_{FB} and the fraction of the K^{*0} longitudinal polarization F_L in the $B_d \rightarrow \mu^+\mu^- K^{*0}(890)$ decay as a function of the di-muon invariant mass. This measurement was previously performed by BaBar, Belle, CDF and LHCb.
- This analysis uses 4.9 fb^{-1} of data from pp-collisions at $\sqrt{s}$=7 TeV collected in 2011. The dimuon trigger is described above.
- The muon candidates are required to have $|\eta| < 2.5$ and a common vertex satisfying $\chi^2/ndf<10$. The invariant mass of the di-muon pair is calculated from the ID tracks refitted accounting for the common B_d vertex.

$B_d \rightarrow \mu^+\mu^- K^*(890)$ selection

- Muons are described as being in barrel, if they have $|\eta| < 1.05$, or Endcap otherwise. Muon pairs are classified as BB if both muons are in the Barrel, BE if one of them is in Barrel and other in Endcap, EE if both muons are in Endcap(s). Regions in di-muon mass are excluded which cover 3σ around the J/ψ mass, the width of excluded region is ±116, ±159, ±226 MeV for BB,BE and EE cathegories, respectively. (Corresponding values for ψ(2s) exclusion are ±131, ±189, ±234 MeV).

- The $K^* \rightarrow K^+\pi^-$ candidates are reconstructed from all pairs of oppositely charged particles with $p_T > 0.5$ GeV and $|\eta| < 2.5$ which are not identified as muons. Pions and kaons are not identified. For each pair two different mass hypotheses are tested, and the track combination with the invariant mass closer to the value of the K^* mass is considered as the K^*candidate. The candidates are accepted if they fulfil $846 < m(K^+\pi^-) < 946$ MeV. Four tracks are fitted to a common vertex for each combination .
- Other selection requirements described in Backup slides.

Decay angles



Kinematic variables

- Kinematic variables:
- q^2 of the di-muon system;
- Θ_L is the angle between the μ^+ and the direction opposite to the B_d in the di-muon rest frame;
- Θ_K is the angle between the K^+ and the direction opposite to the B_d direction in the K^0 rest frame;
- ϕ is the angle between the plane defined by the two muons and the plane defined by the kaon-pion system in the B_d rest frame

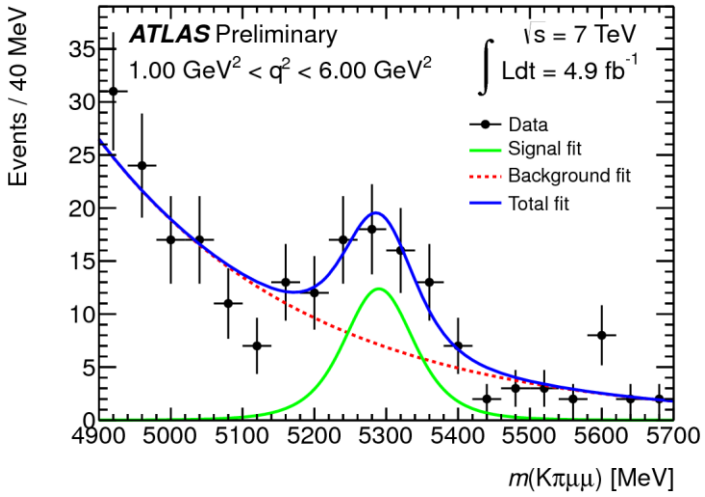
- The differential decay rate is projected from the four kinematic variables into the 2-dimensional distributions $d^2\Gamma/dq^2 d\cos\theta_L$ and $d^2\Gamma/dq^2 d\cos\theta_K$ by integrating over the two other variables. The values of the K^{*0} longitudinal polarization fraction F_L and of the lepton forward-backward asymmetry A_{FB} are extracted, averaged in the q^2 bins. q^2 bins corresponding to the excluded J/ψ and $\psi(2S)$ regions are not analyzed.

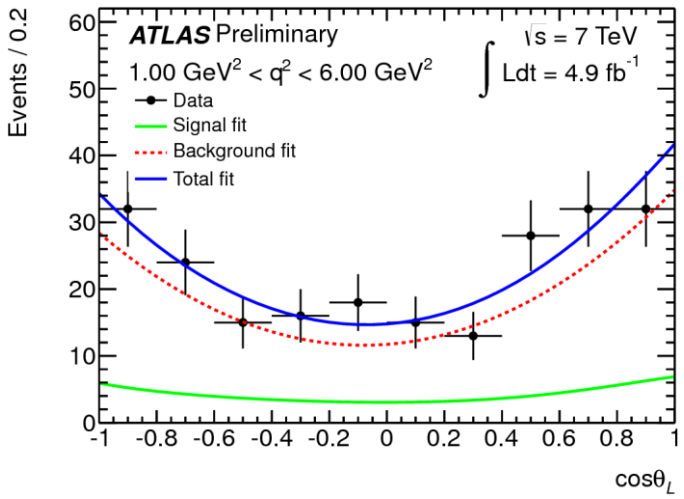
Mass and angular fits

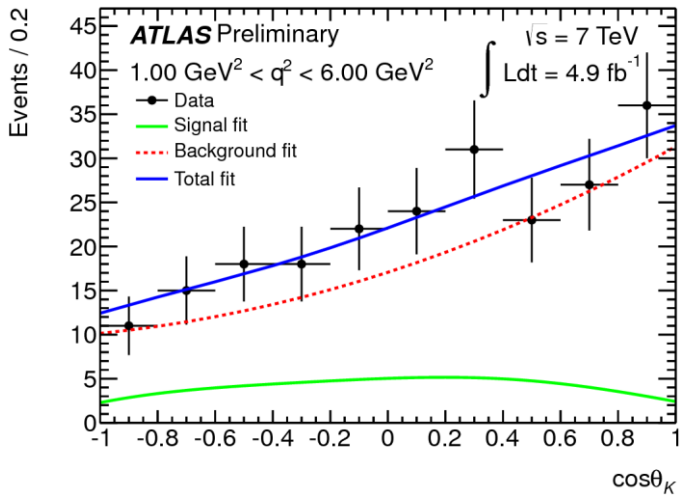
- Sequential unbinned maximum likelihood fit was performed. In the 1-st q^2 bin that had low statistics , at a first step the invariant Kπμμ mass distribution was fitted. Then the signal and background yields were fixed and the angular distributions are fitted. Ordinary mass-angular simultaneous fit was done in other bins.
- In the mass fit, the probability density function for the signal is modelled as a Gaussian function with mass m_i and per-candidate error δ_{mi} and the probability density function for the background as an exponential.
- An example of angular function: at a given q^2 the integration of the differential decay rate over θ_K and ϕ gives

$$\frac{1}{\Gamma}\frac{\mathrm{d}^2\Gamma}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_L} = \frac{3}{4}F_L(q^2)\left(1-\cos^2\theta_L\right) + \frac{3}{8}\left(1-F_L(q^2)\right)\left(1+\cos^2\theta_L\right) + A_{FB}(q^2)\cos\theta_L$$

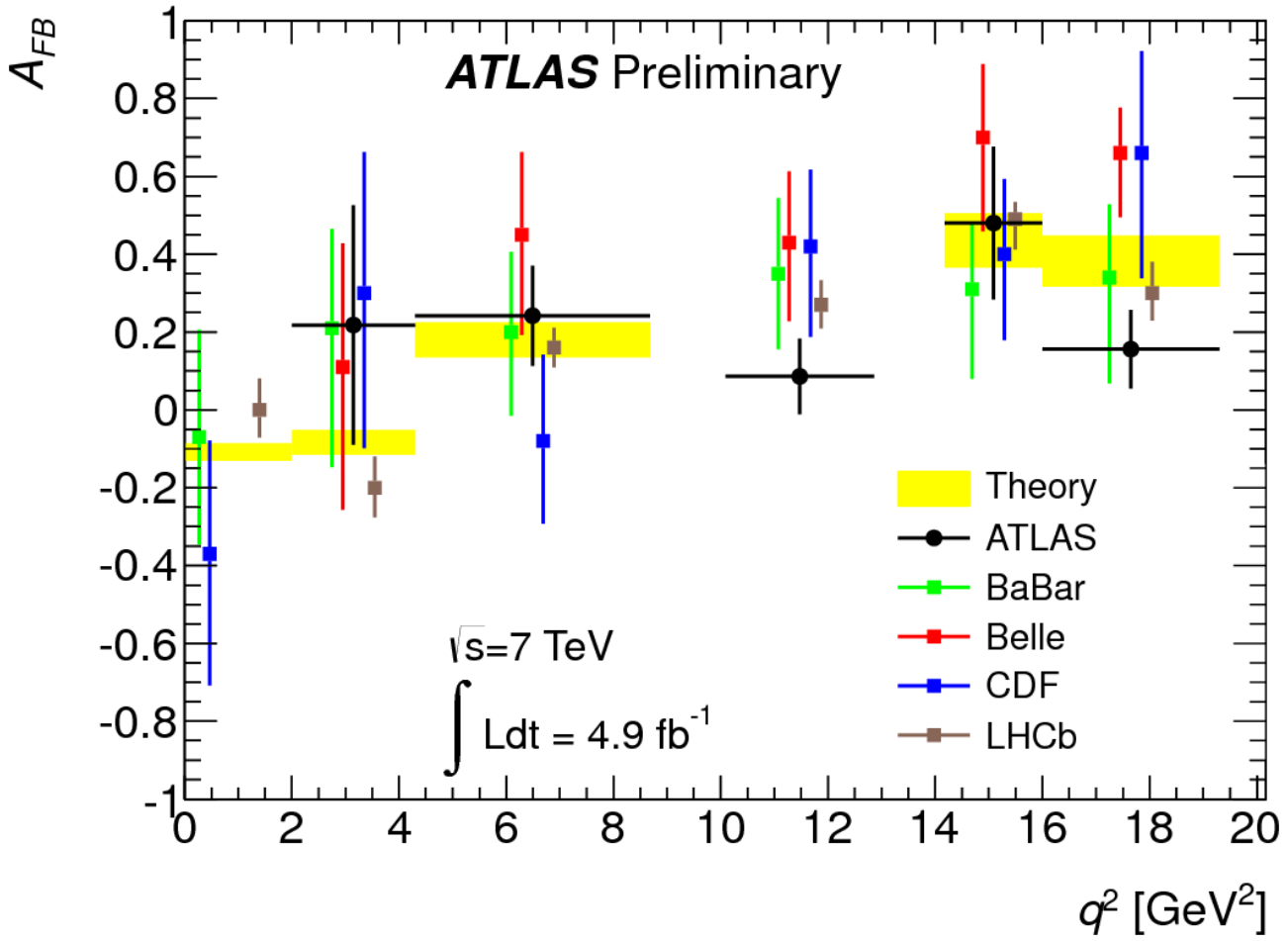
Mass and angular distributions for B_d candidates at $1.0<q^2<6.0$ GeV^2



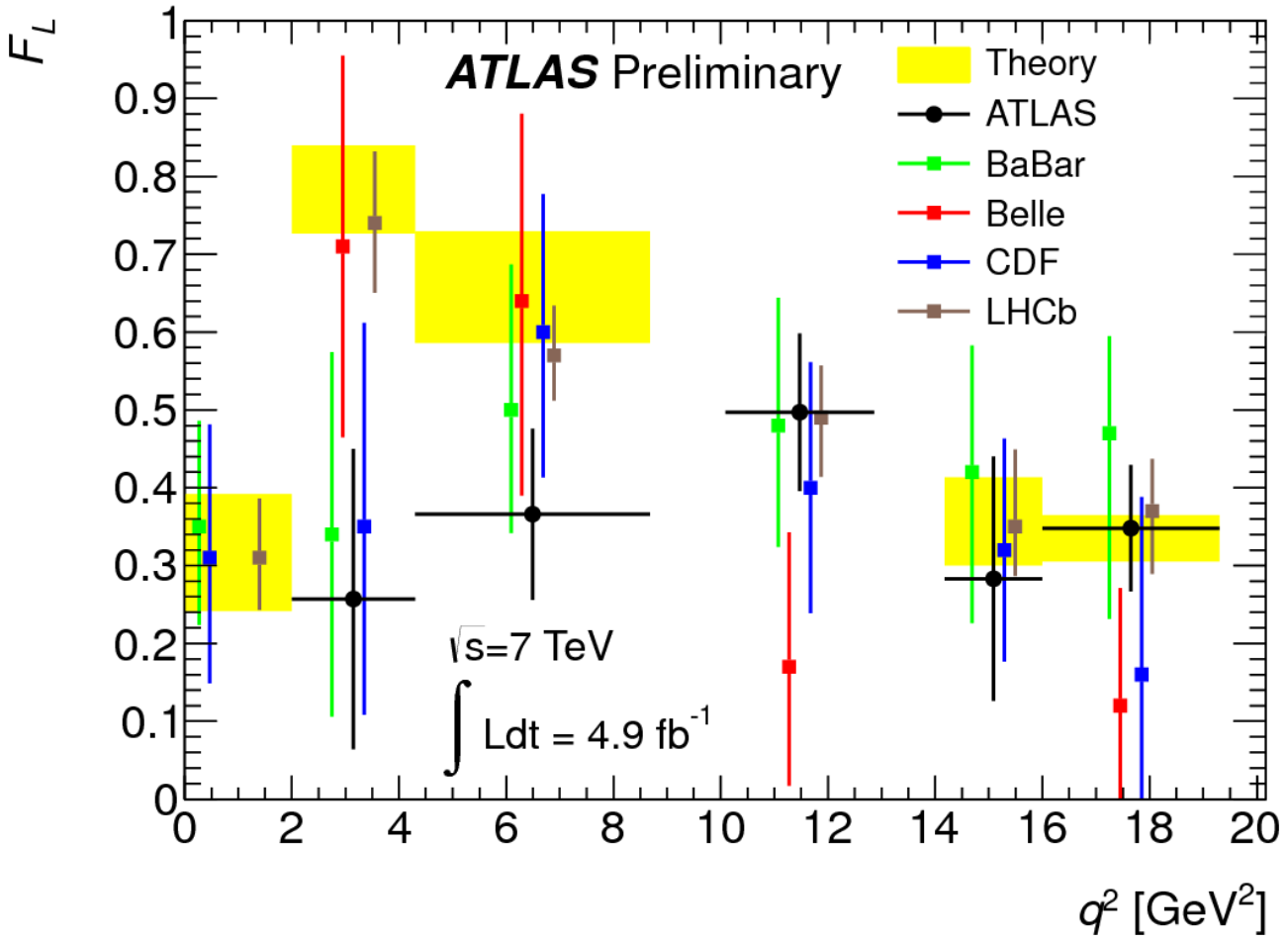




Compilation of forward-backward asymmetry A_{FB} measurements



Compilation of K^{*0} polarization measurements



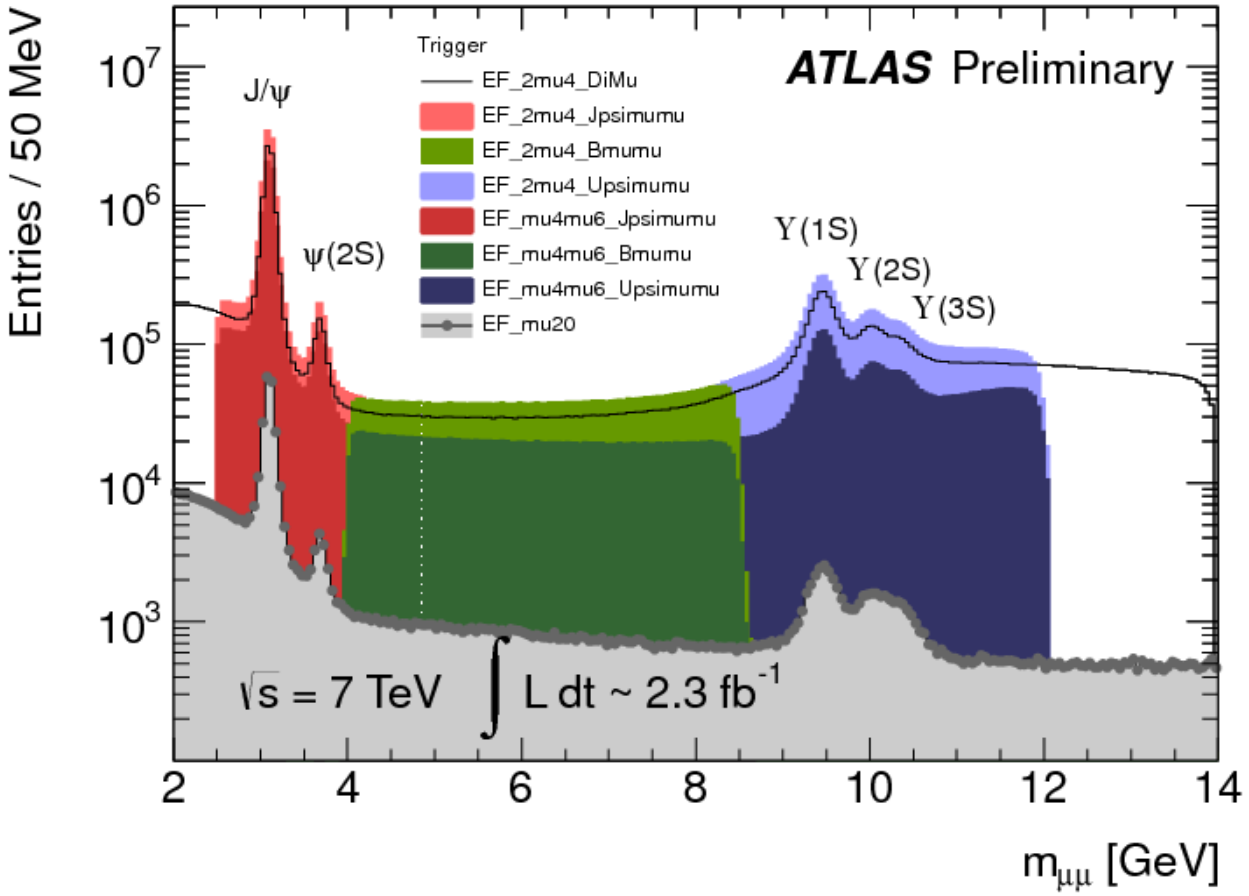
Summary

- Upper limit on BR($B_s \rightarrow \mu^+\mu^-$) measured using 4.9 fb^{-1} of integrated luminosity taken at $\sqrt{s}$ = 7 TeV at the ATLAS experiment. The measured limit is 15×10^{-8} at 95% confidence level, it is less strict in comparison with LHCb and CMS results. Analysis on the statistics acquired at $\sqrt{s}$ = 8 TeV is in preparation, at integrated luminosity close to 20 fb^{-1}.
- Using 4.9 fb^{-1} of integrated luminosity taken at $\sqrt{s}$ = 7 TeV, $B_d \rightarrow K^{*0}(890)\mu^+\mu^-$ events have been reconstructed and the angular distribution of their final state particles measured, excluded events with $m(\mu^+\mu^-)$ close to J/ψ and ψ(2s) masses. Forward backward asymmetry A_{FB} and the K^0 longitudinal polarization F_L have been measured as function of the di-muon mass squared q^2. The results obtained on A_{FB} and F_L are mostly consistent with theoretical predictions and measurements performed by other experiments. The results for F_L in the low q^2 bins slightly deviate from Standard Model expectations.

References

- ATLAS:
- Limit on $B0_s \rightarrow \mu^+\mu^-$ branching fraction based on 4.9 fb^{-1} of integrated luminosity, ATLAS-CONF-2013-076
- Study of the semi-rare decay $B_d \rightarrow K^*\mu^+\mu^-$. Analysis based on data collected in 2011, ATLAS-CONF-2013-038
- Search for the decay $B^o_s \rightarrow \mu\mu$, Phys. Lett. B713 (2012) 180, e-Print: arXiv:1204.0735 [hep-ex]
- Flavour tagged time dependent angular analysis of the $B_s \rightarrow J/\psi\ \varphi$ decay and extraction of $\Delta\Gamma_s$ and the weak phase ϕ_s in ATLAS, ATLAS-CONF-2013-039
- LHCb
- Measurement of the $B0_s \rightarrow \mu^+\mu^-$ branching fraction and search for $B0 \rightarrow \mu^+\mu^-$ decays at the LHCb experiment, R. Aaij et al., Phys.Rev.Lett. 111 (2013) 11, 112003, e-Print: arXiv:1307.5024 [hep-ex]
- CMS
- CMS Collaboration, S. Chatrchyan et al., JHEP 1204 (2012) 033, arXiv:1203.3976 [hep-ex].

Backup slides. Muon triggers pattern at √s=7 TeV



More details concerning $B_d \rightarrow \mu^+\mu^- K^{0*}(890)$ selection

- Each track is required to have at least one hit in the pixel detector and four hits in the SCT. Using these requirements, a total of approximately 64 million candidates are selected in the invariant mass region of 4600 < m(Kπμμ) < 5900 MeV.
- Several requirements were applied in order to reduce the

background. The optimization was performed using Monte Carlo. The Monte Carlo samples were re-weighted according to their corresponding cross-sections. The following requirements were applied:

- A cut on the lifetime significance of $\tau/\sigma(\tau) > 12.75$;
- A cut on the pointing angle $\cos\theta > 0.999$, where θ is angle between the B_d momentum vector and vector between Primary VX and B_d VX;
- A quality of B_d VX fit requirement, $X^2/ndf < 2.0$;
- p_T (K^*) > 3.0 GeV;

Final selection

- Finally, next requirement suppresses the radiative charmonium decays from corresponding B-decays with the subsequent decay of the charmonium into a photon and $\mu^+\mu^-$, events rejected if $|(m(B_d)_{rec-}m(B_d)_{PDG})-(m(\mu^+\mu^-)_{rec} - m(J/\psi)_{PDG})|<\Delta m$, where Δm=130 MeV.
- We select events in the mass region 4600 MeV < m(Kπμμ) < 5900 MeV and are left with 4 466 candidates in the full q^2 range, after the optimized selection. The full q^2 range is defined as the three continuous intervals obtained by removing the J/ψ and ψ(2S) regions as discussed earlier from the interval 0.04 GeV2 < q2 < 19.00 GeV^2 .