New physics searches with flavour in ATLAS

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on behalf of the ATLAS Collaboration

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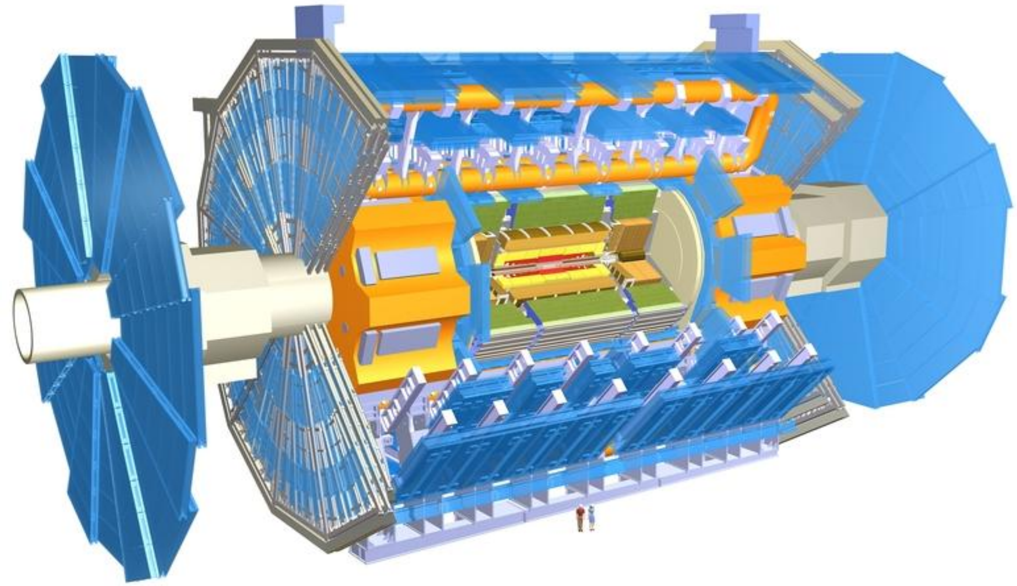
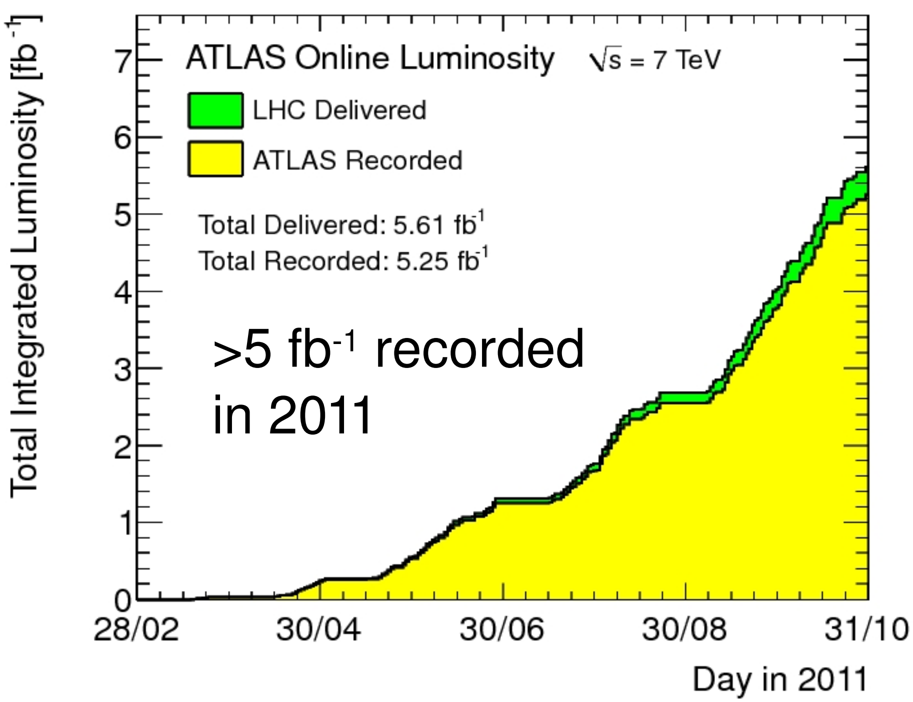
outline

- ATLAS data, detector and triggers
- search for rare decays B_s to $\mu\mu$
- angular analysis of semirare decays B_d to $K^*\mu\mu$
- CP violation measurement in $B_s \rightarrow J/\psi\phi$
- conclusions

ATLAS

- *Tracking*
  - Silicon (Pixel+Semiconductor tracker) and Transition Radiation Tracker
  - 2T solenoidal field
- *Muon identification:*
  - Dedicated tracking chambers
  - 0.5-2 T toroidal field





- bb-production mostly at large η
  ATLAS sensitive to $|\eta| < 2.5$ region
  - expect about ~150G B^0–pairs
  - ~30M $B_S \rightarrow J/\psi\phi$ events for 5 fb^{-1}

di-muon triggers are our main tool

- we ran with constant trigger thresholds for di-muons all across 2011

> 20 fb^{-1} of data collected in 2012
- specific di-muon selections with Barrel/Endcap logic
- new dedicated $\mu\mu X$ trigger

search for rare decays: $B_s \rightarrow \mu\mu$

search for rare decays: $B_s \to \mu\mu$

- flavour changing neutral currents (FCNC) are highly suppressed in the Standard Model
  - expected $B_s \to \mu\mu$ SM branching ratio:

    $(3.23 \pm 0.27)\ 10^{-9}$ *Buras et al., Eur.Phys.J. C72 (2012) 2172*

    time-integrated expected value:

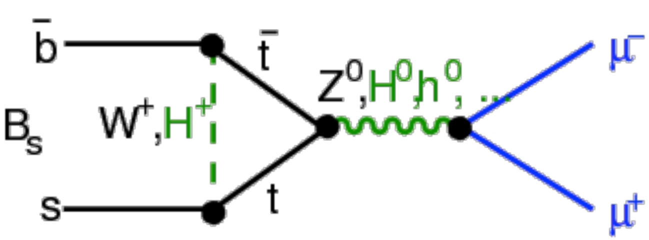
    $(3.54 \pm 0.30)\ 10^{-9}$ *K.De Bruyn et al., Phys.Rev.Lett. 109 (2012) 041801*

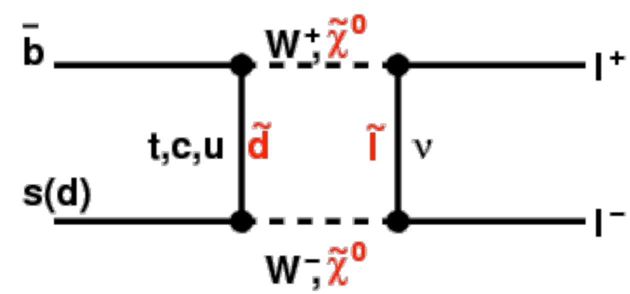
    evidences from CMS and LHCb:

    $(2.9 \pm 0.7)\ 10^{-9}$ *CMS and LHCb Collaborations*

    LHCb: arXiv:1307.5024
    CMS: arXiv:1307.5025

- B to $\mu\mu$ branching ratio might be substantially enhanced by coupling to non-SM particles
  - being the SM well under control this channel provides a powerful method to peek into NP.. .. or further constraining it.
  - orthogonal search for physics beyond the standard model: can reach higher scales wrt the direct search





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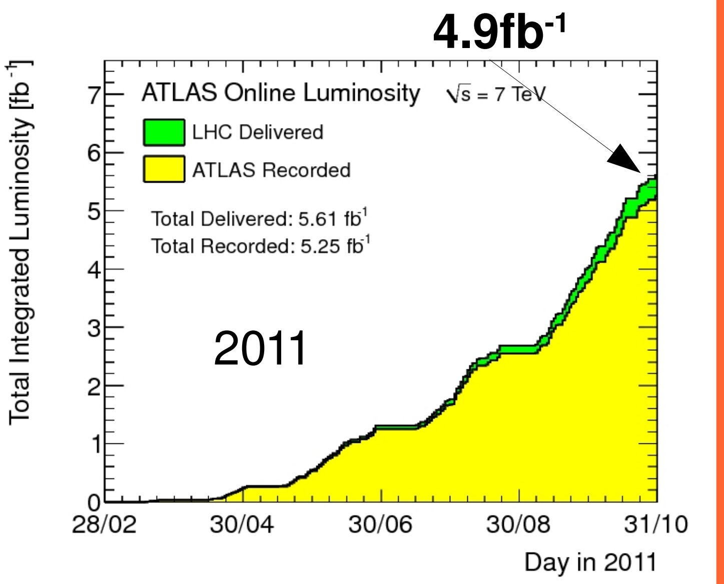
analysis strategy @ ATLAS:



- **Integrated luminosity 4.9 fb^{-1} used**
- **Relative BR measurement:**
  - partial cancellation of uncertainties: on luminosity, cross-section, ..
  - reference channel ($B^\pm \to J/\psi K^\pm$, $J/\psi \to \mu^+\mu^-$)
  - blind analysis: signal region ± 300 MeV around B_s
  - limit placed using CLs method

$$BR(B_s \to \mu\mu) = \boxed{N_{B_s\to\mu\mu}\frac{1}{N_{B^\pm\to J/\psi K^\pm}}} BR(B^\pm \to J/\psi K^\pm)\frac{f_u}{f_s}\,\frac{\varepsilon_{B^\pm\to J/\psi K^\pm}}{\varepsilon_{B_s\to\mu\mu}}\frac{A_{B^\pm\to J/\psi K^\pm}}{A_{B_s\to\mu\mu}}$$

- **Signal extraction:**
  - event count in “signal region”
  - “subtraction” of sidebands: interpolation from 50% of sidebands (even events)
- **Background composition:**
  - resonant: B → hh, with hadrons misidentified as muons estimated from MC. Currently still negligible but included in the analysis
  - continuum: dominated by non-resonant $b\bar{b}$ production with $\mu\mu X$ final states. Contains real muons. Has a smooth shape in the di-muon mass.

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analysis strategy @ ATLAS:

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    on luminosity, cross-section, ..
  - reference channel ($B^\pm \to J/\psi K^\pm$, $J/\psi \to \mu^+\mu^-$)
  - blind analysis: signal region ± 300 MeV around B_s mass blinded
  - limit placed using CLs method

$$BR(B_s \to \mu\mu) = N_{B_s\to\mu\mu} \frac{1}{N_{B^\pm\to J/\psi K^\pm}} \boxed{BR(B^\pm \to J/\psi K^\pm)\frac{f_u}{f_s}} \boxed{\frac{\varepsilon_{B^\pm\to J/\psi K^\pm}}{\varepsilon_{B_s\to\mu\mu}} \frac{A_{B^\pm\to J/\psi K^\pm}}{A_{B_s\to\mu\mu}}}$$

- **Efficiencies & acceptances**
  - derived from simulation ("calibrated" on data)
    $\varepsilon \cdot A = (N_{\text{reconstructed and selected}}/N_{\text{generated}})$
  - reference channel ($B^\pm \to J/K^\pm$) selected with as-close-as-possible selection
  - systematics taken from the data-MC discrepancies in signal distributions
- **BR of the reference channel and relative production rate f_u/f_s**
  - taken from PDG and the latest LHCb results

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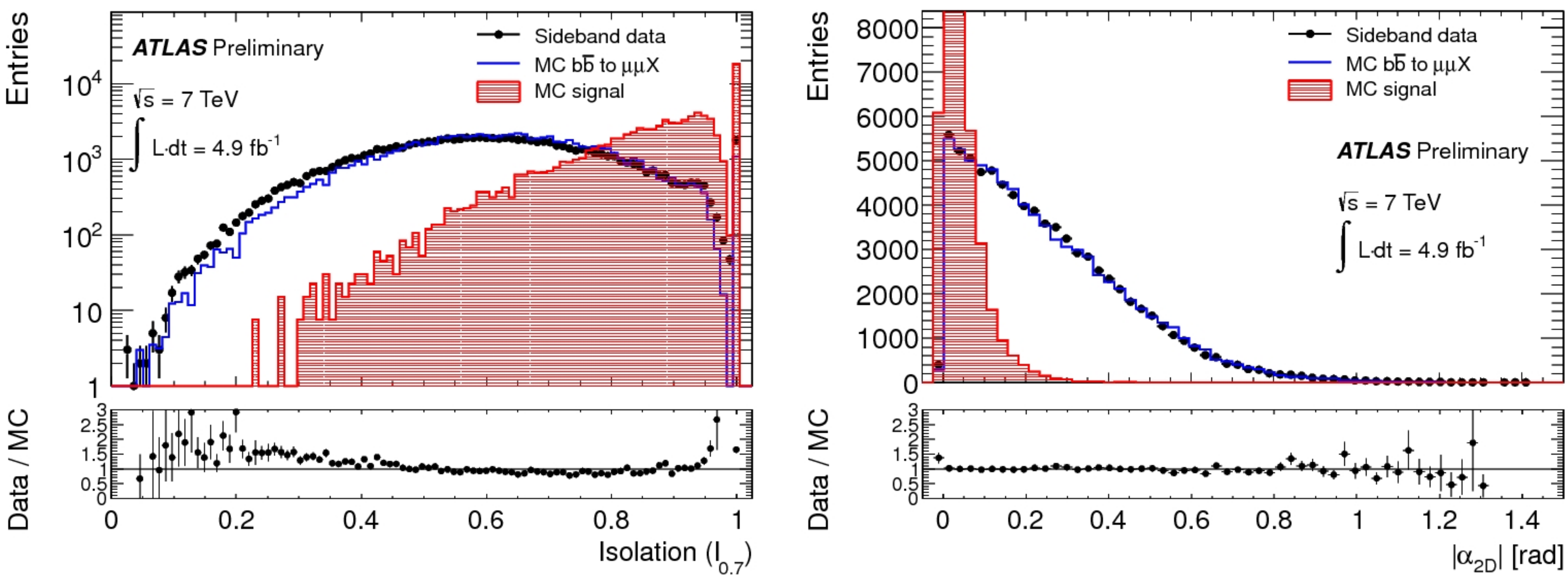
background discrimination

- **continuum:**
  - dominated by non-resonant $b\bar{b}$ production with $\mu\mu X$ final states → real muons
  - to discriminate against this background 13 discriminating variables used in a boosted decision tree (BDT) trained on simulated events
  - best BDT configuration and selection criteria optimised on half of the sideband data (odd events) and signal MC.
  - contamination to the signal region measured by interpolation from sideband data into the signal region



data-MC agreement for the continuum background in two of the most powerful variables

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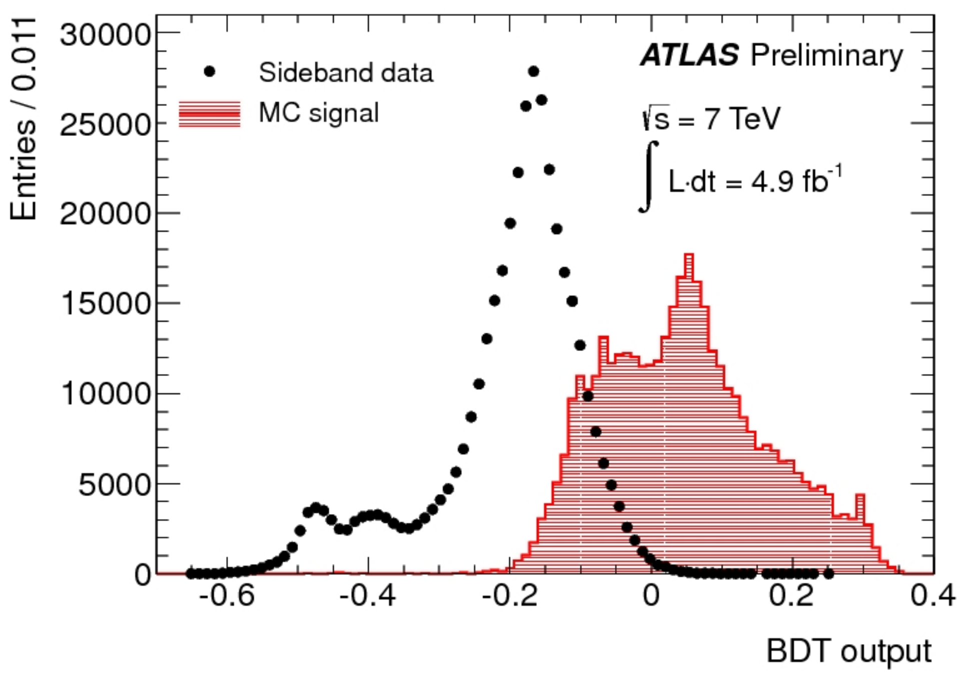

background (sidebands) vs **B_s signal (MC)**

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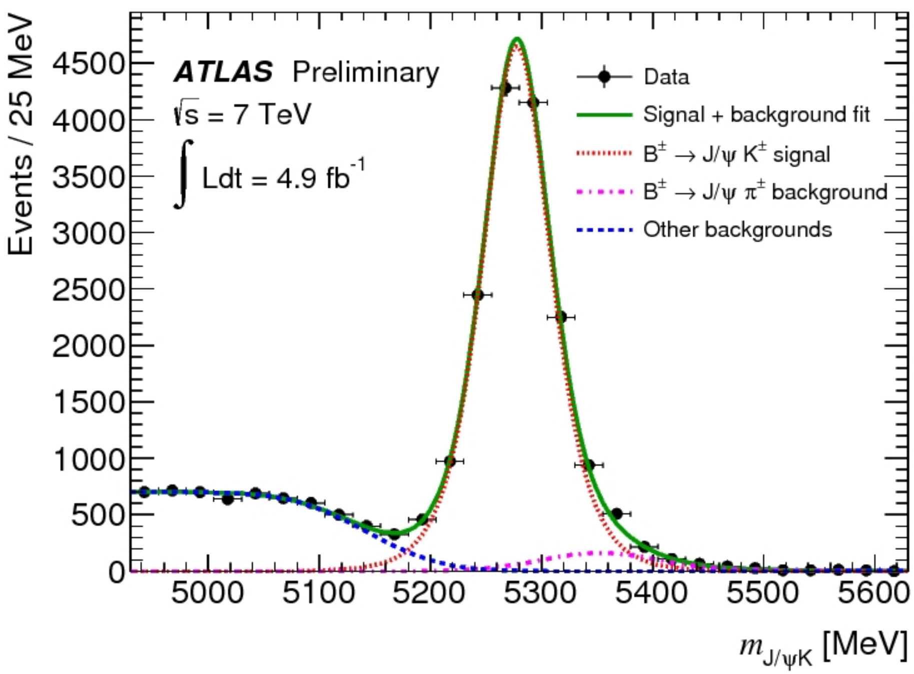
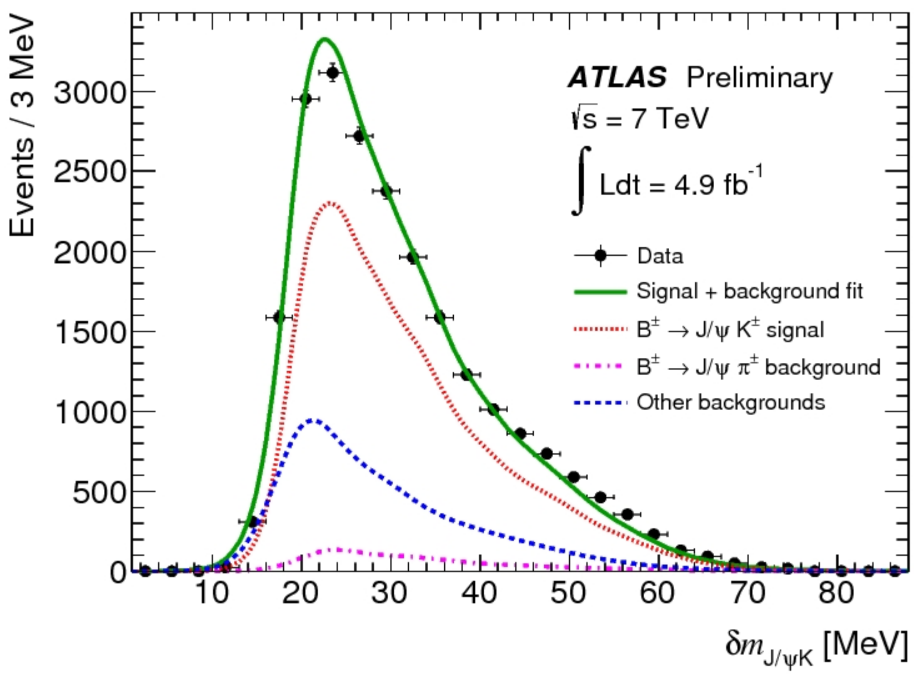
reference channel

- selections synchronised and same signal BDT used to minimise systematics
- yield extraction via unbinned maximum likelihood fit
- inclusion of per-event mass resolution δm in the fit
- main systematics estimated by varying continuum background models





$N_{J/\psi K+}$ = 15214 ± 1.1%(stat) ± 2.4%(syst)

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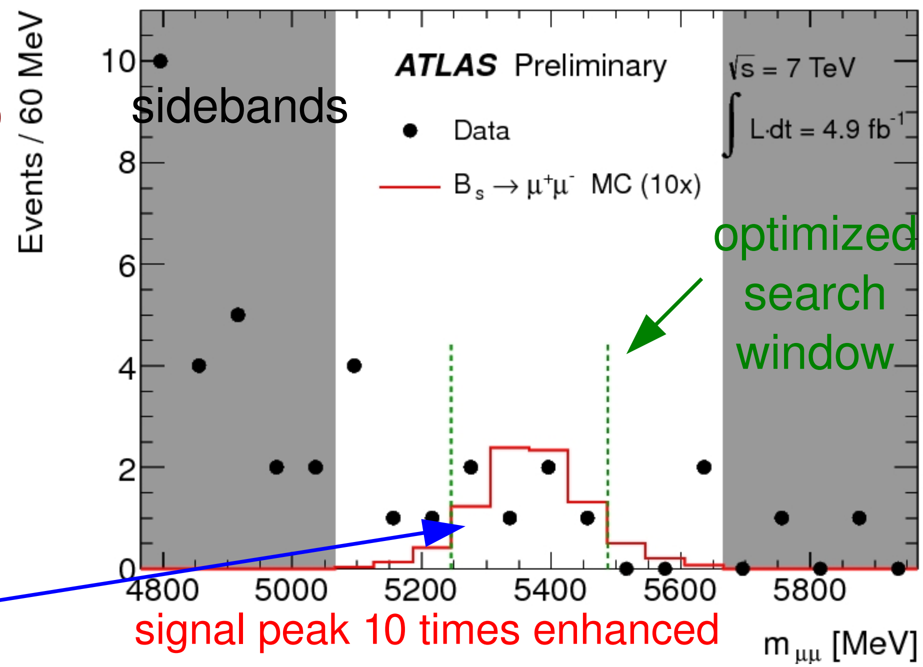
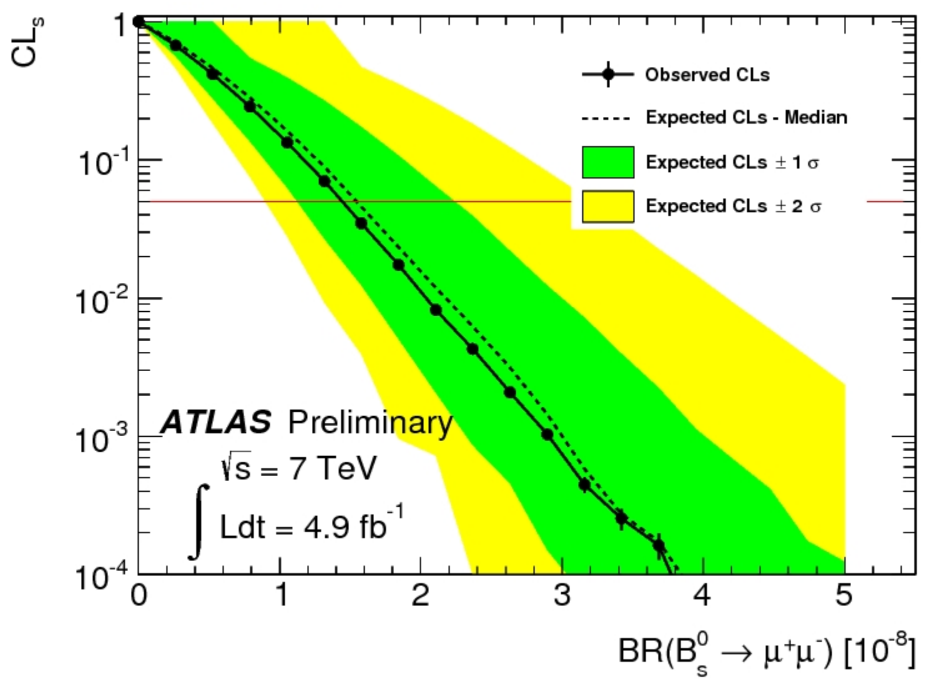
signal and CLs extraction

- single event sensitivity: $(2.07 \pm 0.26)\ 10^{-9}$
- systematics on the SES: 12.5%
  dominated by contribution from reference channel BR and acceptance and efficiency ratio
- number of expected background events in the signal window: 6.75
- number of events observed in the signal window: 6



signal peak 10 times enhanced

- expected upper limit obtained using the number of expected background events (6.75)
  $< 1.6\ 10^{-9}$ @ 95%
- measured upper limit from the number of observed events
  $< 1.5\ 10^{-9}$ @ 95%



angular analysis of decays: $B_d \rightarrow K^*\mu\mu$

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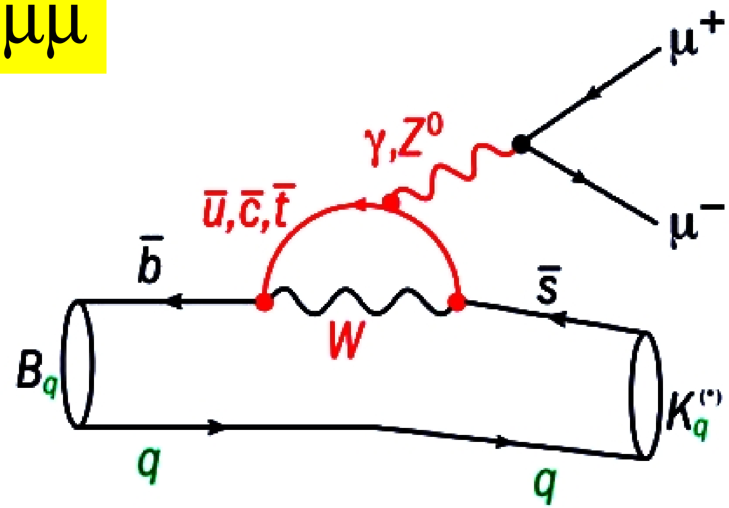
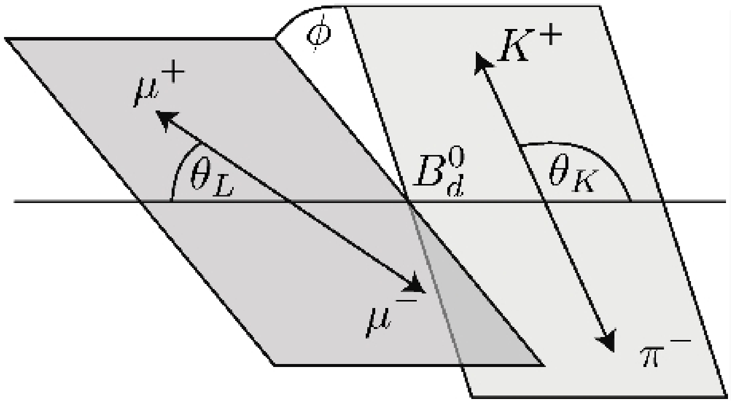


- another way to look at FCNC
  - occurs through a $b \rightarrow s$ transition
  - BR ~ $1.1\ 10^{-6}$
- angular distribution of the 4 particles in the final state sensitive to new physics for the interference of NP and SM diagrams
- decay described by three angles (θ_L, θ_K, ϕ) and the di-muon mass q^2 study the 2D distributions:



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

$$\frac{1}{\Gamma}\frac{\mathrm{d}^2\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\theta_K} = \frac{3}{2}F_L(q^2)\cos^2\theta_K + \frac{3}{4}\left(1-F_L(q^2)\right)\left(1-\cos^2\theta_K\right).$$

- Measure forward-backward asymmetry (A_{FB}) and longitudinal polarization fraction (F_L) with unbinned maximum likelihood fit in q^2 bins

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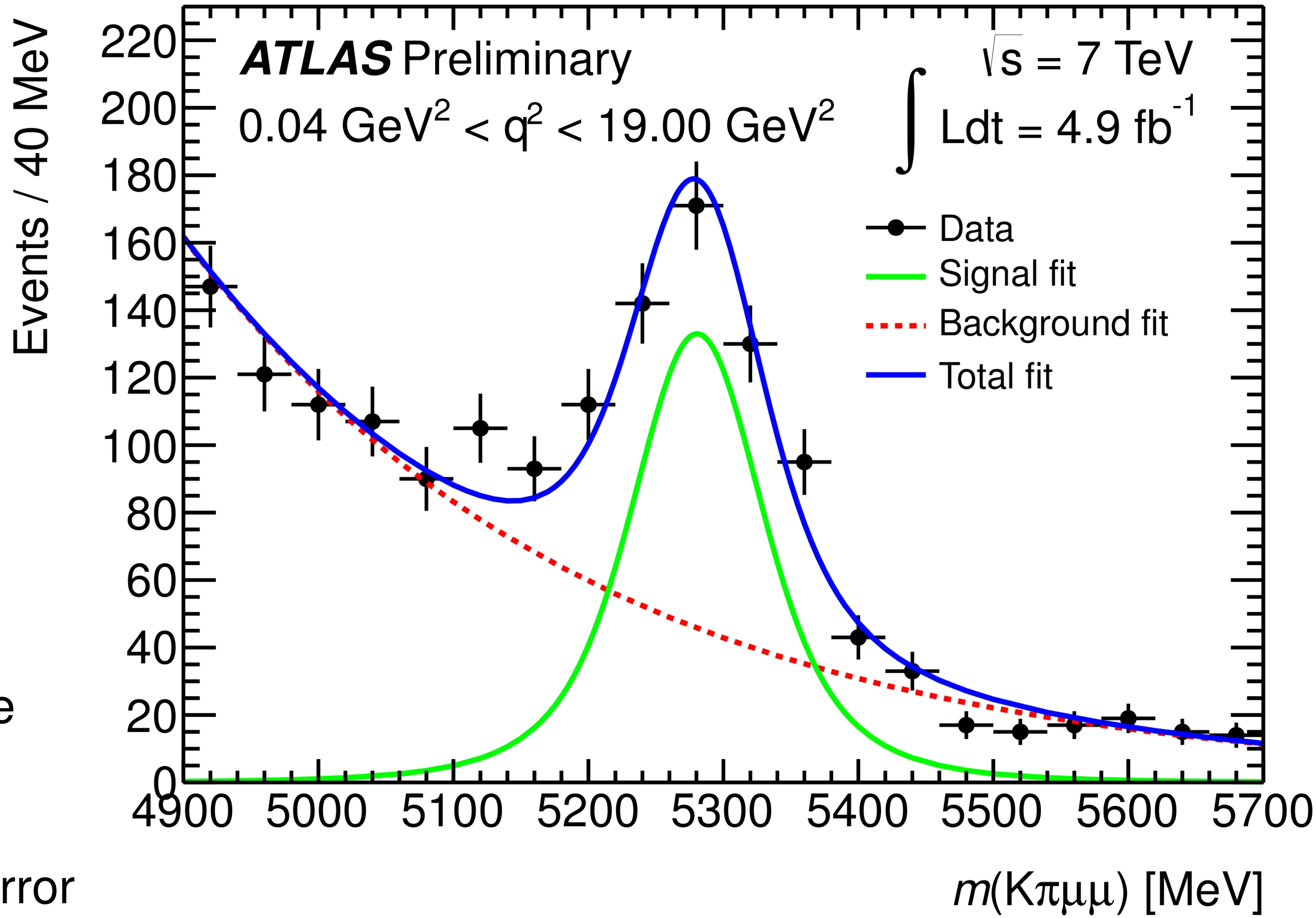
signal observation



- mass fit with Gaussian shape for the signal including the per-candidate error and exponential shape for the background
- full di-muon mass range with J/ψ and $\psi(2S)$ regions excluded
- signal yield: $N_{sig} = 466 \pm 34$

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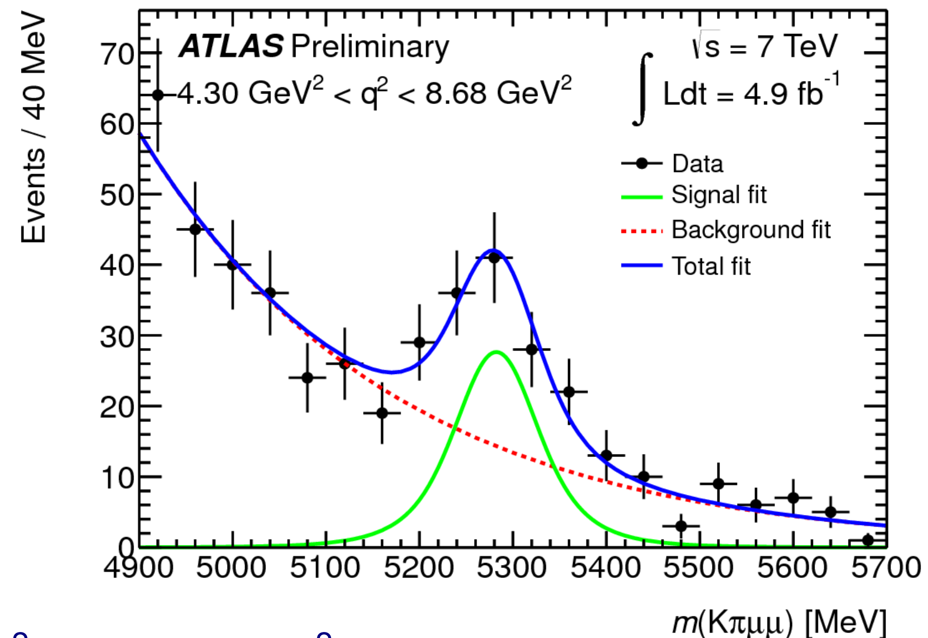
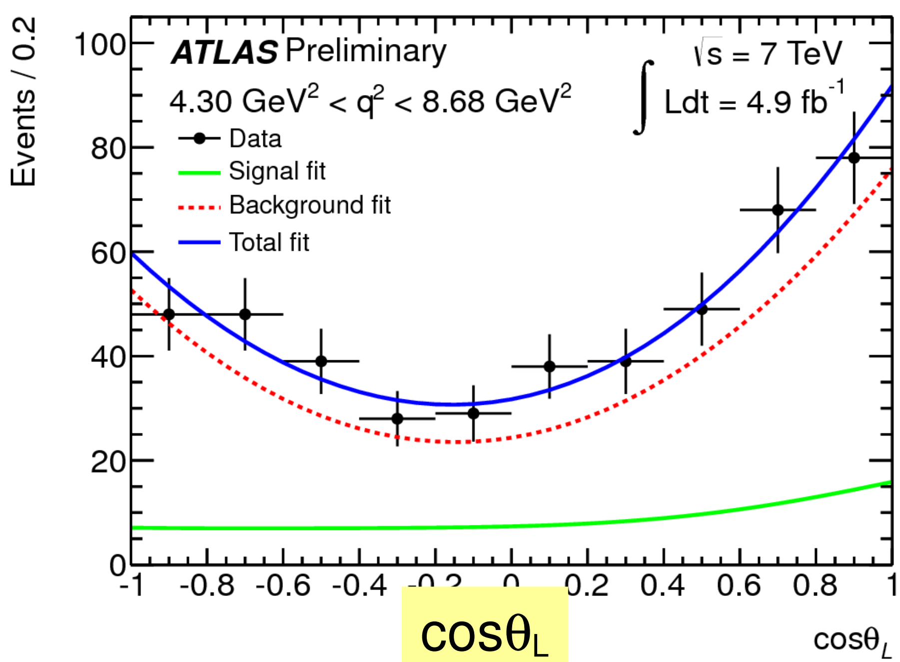
measurements of A_{FB} and F_L

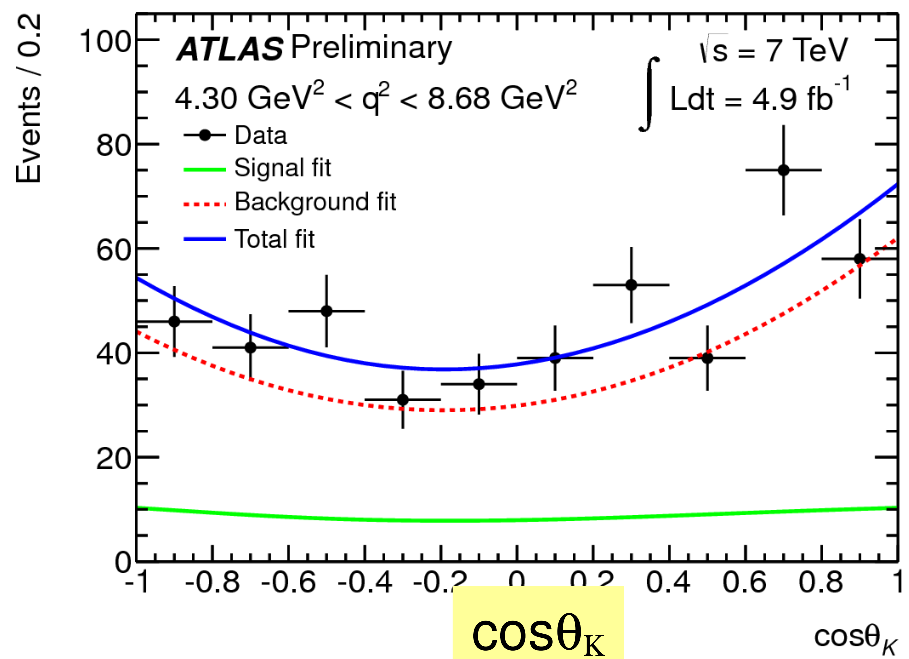
- A_{FB} and F_L in different regions of q^2:
  8 bins used defined *à la Belle*
- use unbinned maximum likelihood fit
  sequential fit approach applied
  use mass to separate signal and background contributions
  angular fit with yields fixed to the results from the mass fit



$4.30 < q^2 < 8.68$ GeV^2



$\cos\theta_L$



$\cos\theta_K$

results

Theoretical prediction from C. Bobeth et al. arXiv:1105.2659

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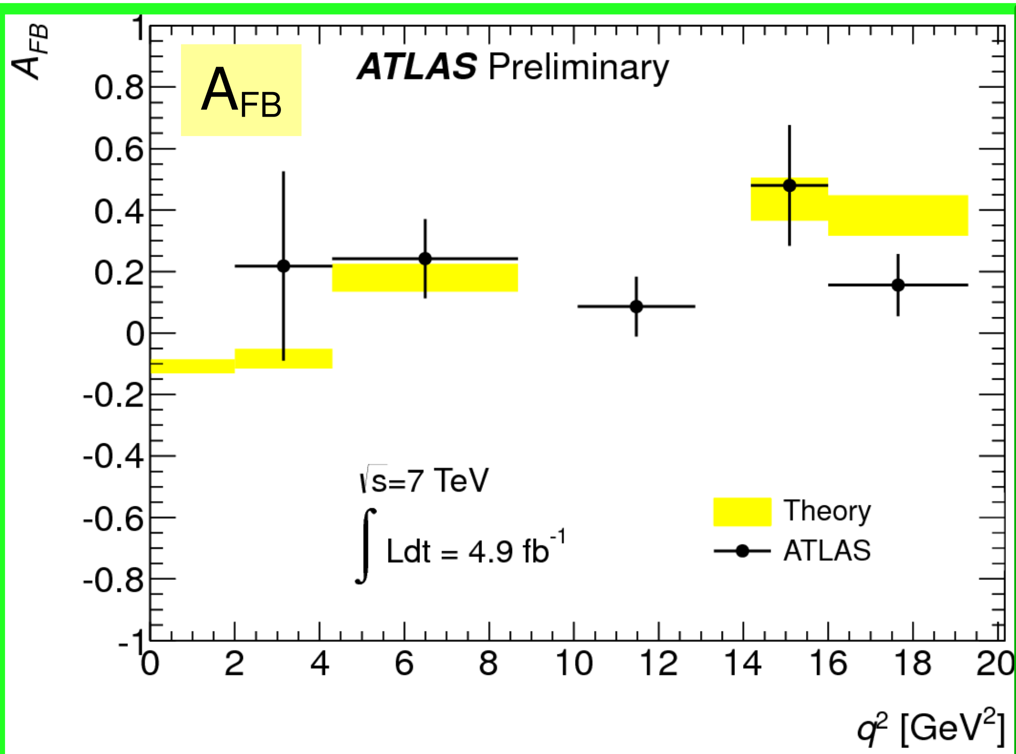
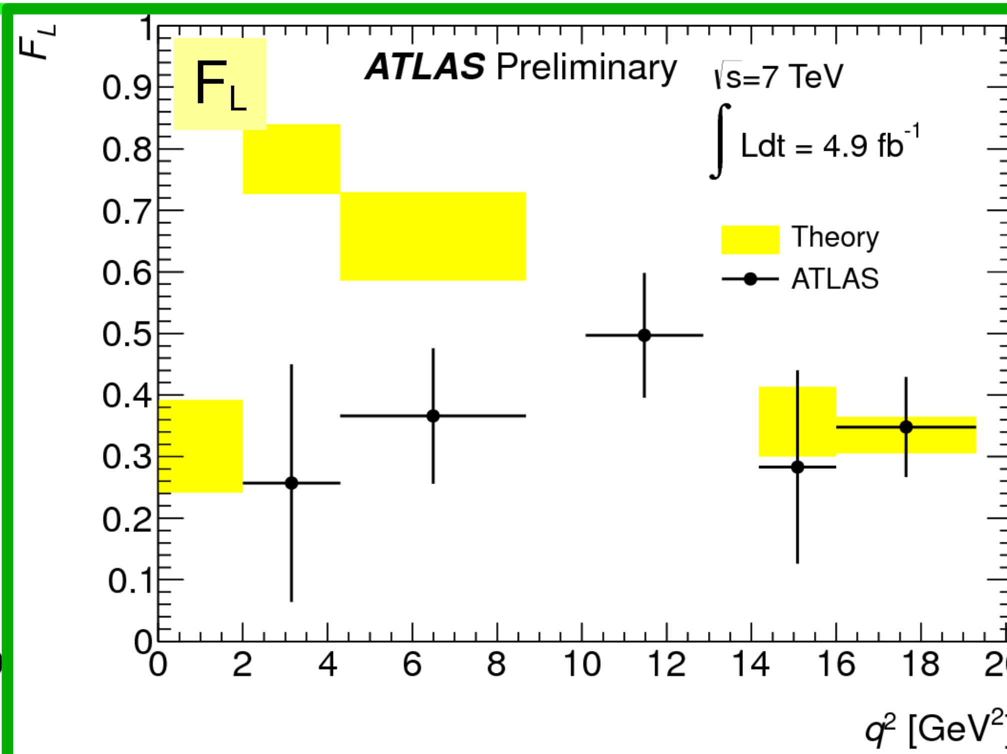




- statistically limited uncertainty
- measurement consistent with the SM prediction

q^2 range (GeV^2)	N_{sig}	A_{FB}	F_L
$2.00 < q^2 < 4.30$	19 ± 8	$0.22 \pm 0.28 \pm 0.14$	$0.26 \pm 0.18 \pm 0.06$
$4.30 < q^2 < 8.68$	88 ± 17	$0.24 \pm 0.13 \pm 0.01$	$0.37 \pm 0.11 \pm 0.02$
$10.09 < q^2 < 12.86$	138 ± 31	$0.09 \pm 0.09 \pm 0.03$	$0.50 \pm 0.09 \pm 0.04$
$14.18 < q^2 < 16.00$	32 ± 14	$0.48 \pm 0.19 \pm 0.05$	$0.28 \pm 0.16 \pm 0.03$
$16.00 < q^2 < 19.00$	149 ± 24	$0.16 \pm 0.10 \pm 0.03$	$0.35 \pm 0.08 \pm 0.02$
$1.00 < q^2 < 6.00$	42 ± 11	$0.07 \pm 0.20 \pm 0.07$	$0.18 \pm 0.15 \pm 0.03$

$\Delta\Gamma_s$ and ϕ_s measurement from $B_s \to J/\psi\phi$

$\Delta\Gamma_s$ and ϕ_s measurement from $B_s \to J/\psi\phi$

- The time evolution of the meson B_S and $\overline{B}_S$ is described by the superposition of B_H and B_L states, with masses $m_S \pm \Delta m_S/2$ and lifetimes $\Gamma_S \pm \Delta\Gamma_S/2$.

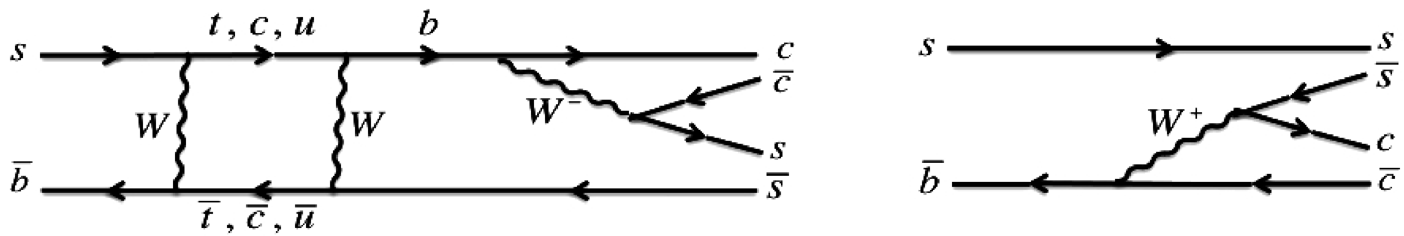
  These states deviate from defined values CP = ± 1, as described in the SM by the mixing phase ϕ_S ($\phi_S = -2\beta_S$),

  SM prediction (fit): $\phi_S = -0.0368 \pm 0.0018$ *rad*

  $\Delta\Gamma_S = 0.082 \pm 0.021\ ps^{-1}$

  New Physics can contribute to ϕ_S, and change the ratio $\Delta\Gamma_S/\Delta m_S$.

- In general, the decay to a final state that is coupled to B_S and/or $\overline{B}_S$, exhibits fast oscillations driven by Δm_S. Interference between amplitudes for both states generates CP violation, and conveys information on ϕ_S .



Decay amplitude with mixing (φ_s) Amplitude with direct decay

the $\overline{B}$/B flavour at production is now determined.

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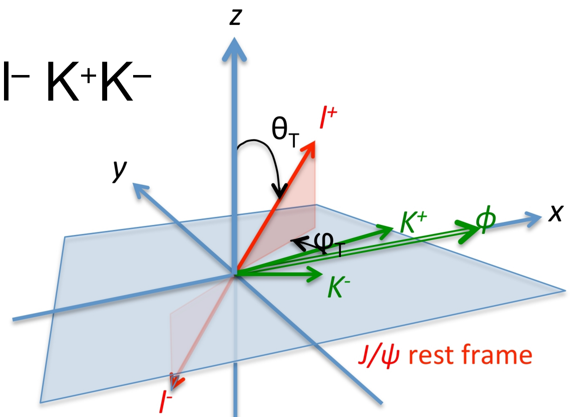
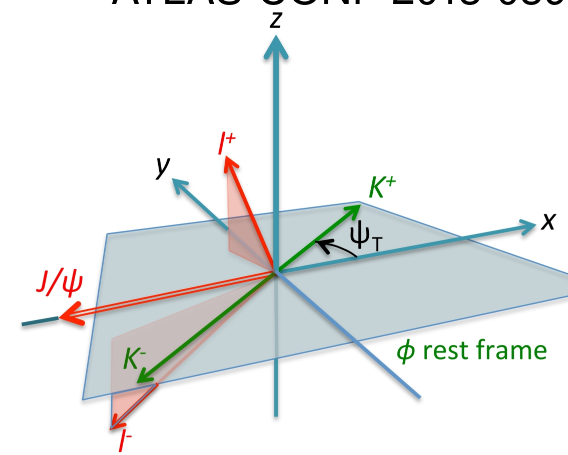
angular analysis in $B_s \to J/\psi\phi$

- in the decay $\overline{B}_S(B_S) \to J/\psi\phi \to l^+l^- K^+K^-$ different components in the angular-distributions amplitudes correspond to CP = +1 or –1





- the "transversity angles" are used to describe the angular distributions

- analysis using data collected in 2011, corresponding to 4.9 fb^{-1}
- updated using flavour tagging: update of JHEP 12 (2012) 072
- signal extracted from a maximum likelihood fit:

the signal with amplitude f_s

$$\ln \mathcal{L} = \sum_{i=1}^{N} \{ w_i \cdot \ln(f_s \cdot \boxed{\mathcal{F}_s(m_i, t_i, \Omega_i)} + f_s \cdot f_{B^0} \cdot \boxed{\mathcal{F}_{B^0}(m_i, t_i, \Omega_i)} + (1 - f_s \cdot (1 + f_{B^0})) \boxed{\mathcal{F}_{\mathrm{bkg}}(m_i, t_i, \Omega_i)}) \} + \ln P(\delta_\perp)$$

the prompt and non-prompt combinatorial background described with empirical angular distribution. (No K-π discrimination.)

the background due to $B^0 \to J/\psi\, K^{*0}$ and $B^0 \to J/\psi\, K\pi$ with amplitude f_{B0}

w_i describes a small trigger inefficiency (~1%)..

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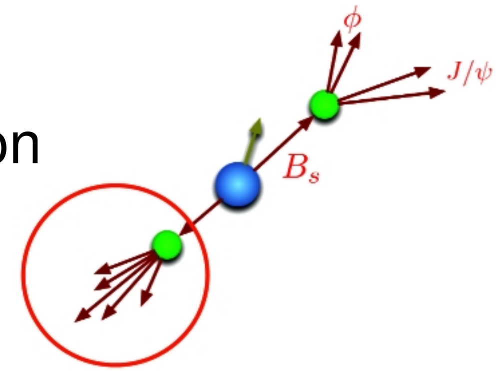
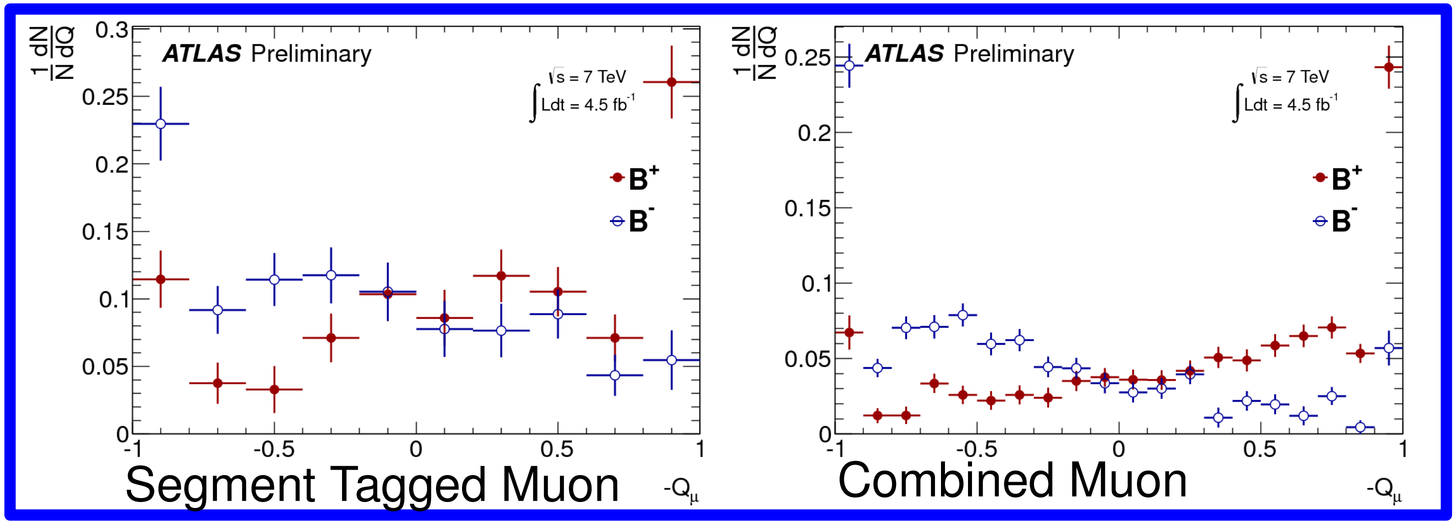
flavour tagging

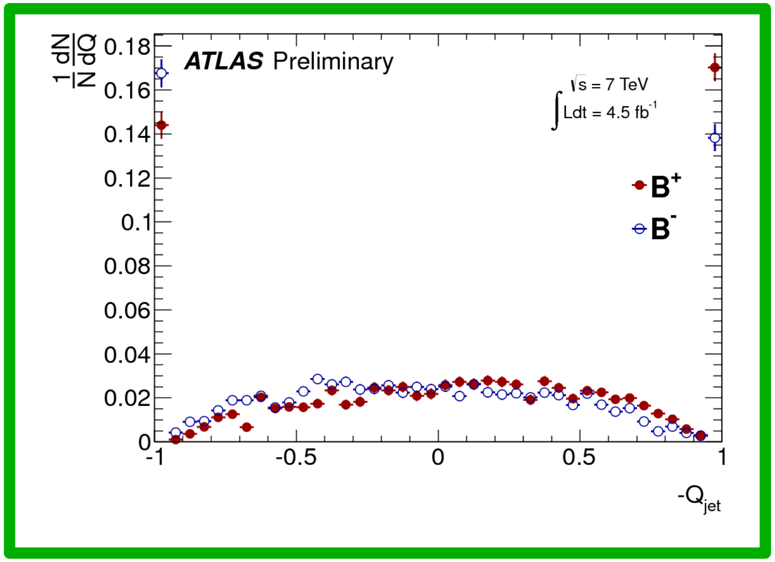
- determine flavour eigenstate of B_s meson at production
- opposite side flavour tagging used





Muon Tagger

- Identify the muon from semileptonic decay
- Calculate muon cone charge Q_μ



Jet Charge Tagger

- Identify jet originating from same primary vertex
- Calculate jet charge Q_{jet}

- Two different methods applied in hierarchy of performance

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flavour tagging

- determine probability that signal decay contains $\bar{b}$ as function of Q_μ and Q_{jet} using calibration sample $B^+ \to J/\psi K^+$

Tagger	Efficiency [%]	Dilution [%]	Tagging Power [%]
Segment Tagged muon	1.08 ± 0.02	36.7 ± 0.7	0.15 ± 0.02
Combined muon	3.37 ± 0.04	50.6 ± 0.5	0.86 ± 0.04
Jet charge	27.7 ± 0.1	12.68 ± 0.06	0.45 ± 0.03
Total	32.1 ± 0.1	21.3 ± 0.08	1.45 ± 0.05

Efficiency ε: fraction of successfully tagged candidates

Dilution D: 1-2w (where w is the wrong-tag fraction)

Tagging power: $\varepsilon D^2 = \sum_i \varepsilon_i D_i^2$

Combined Muon: a muon with inner detector and muon spectrometer track information

Segment Tagged Muon: muons with only muon spectrometer track information

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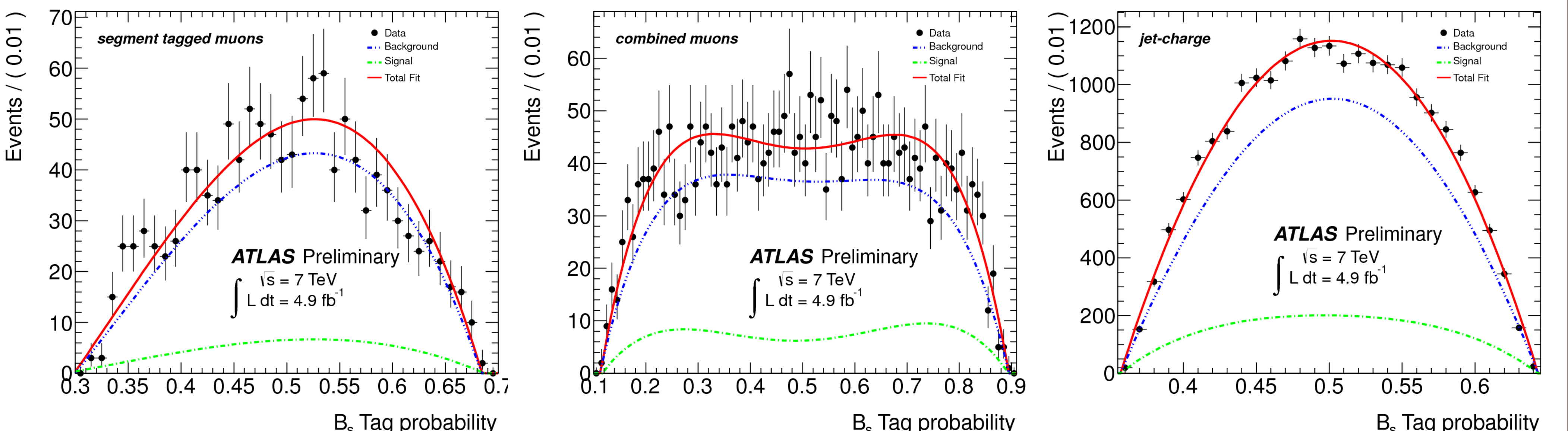
Total	32.1 ± 0.1	21.3 ± 0.08	1.45 ± 0.05

- In the likelihood fit to B_s data, the per-candidate probability and probability distributions are considered. P=0.5 in absence of tagging information.



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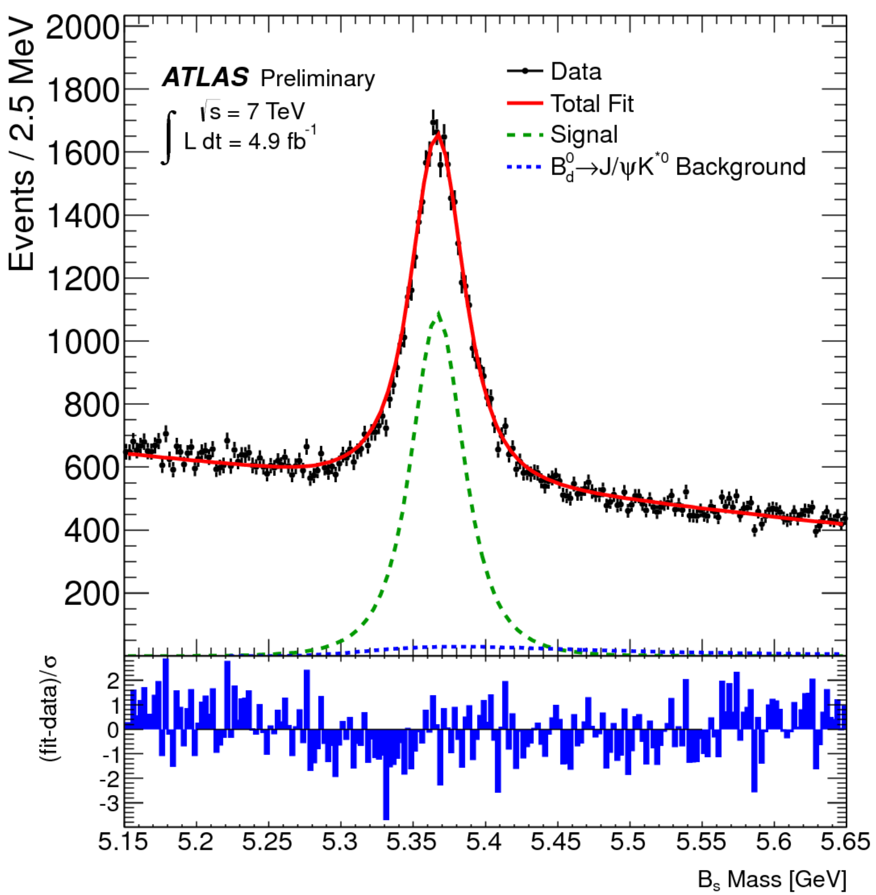
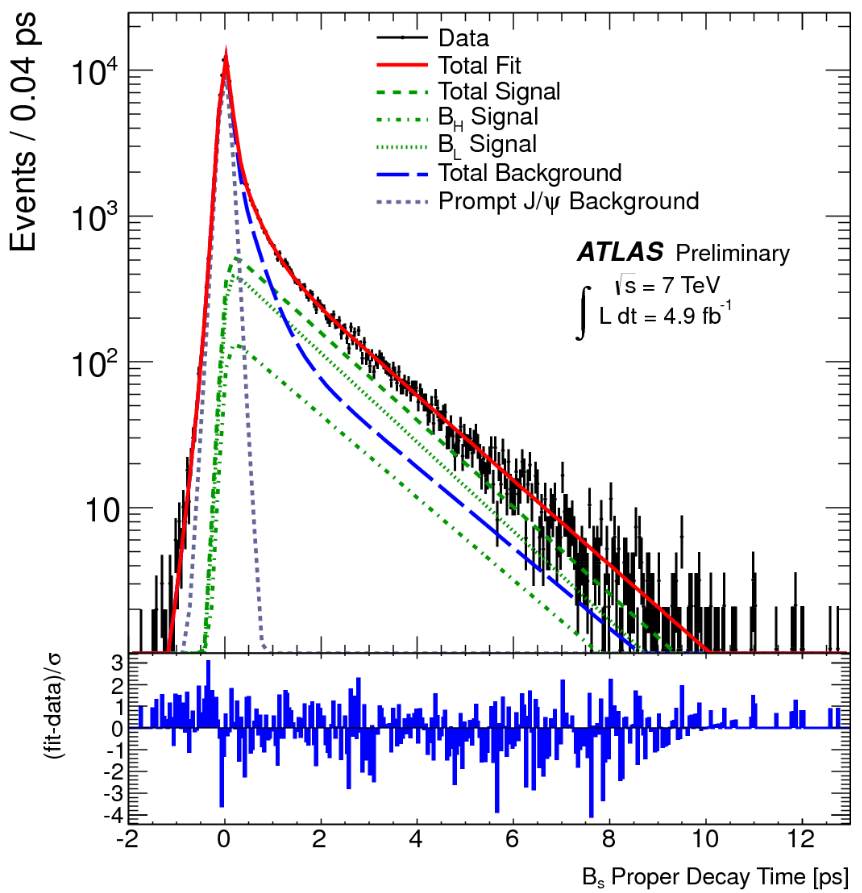
results of the fit

observables: mass, proper decay time and their errors,
three transversity angles and the tagging probability





projection on B_s mass and proper decay time: 22,670 ± 150 signal events from fit.

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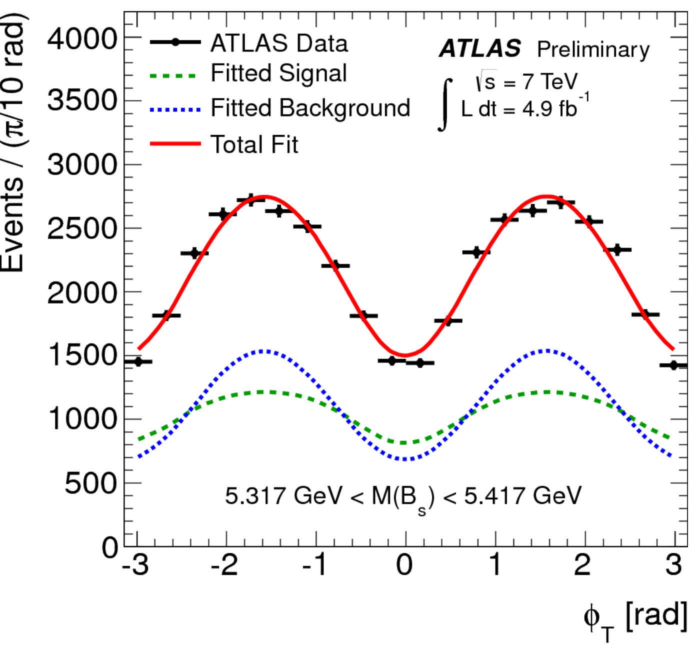
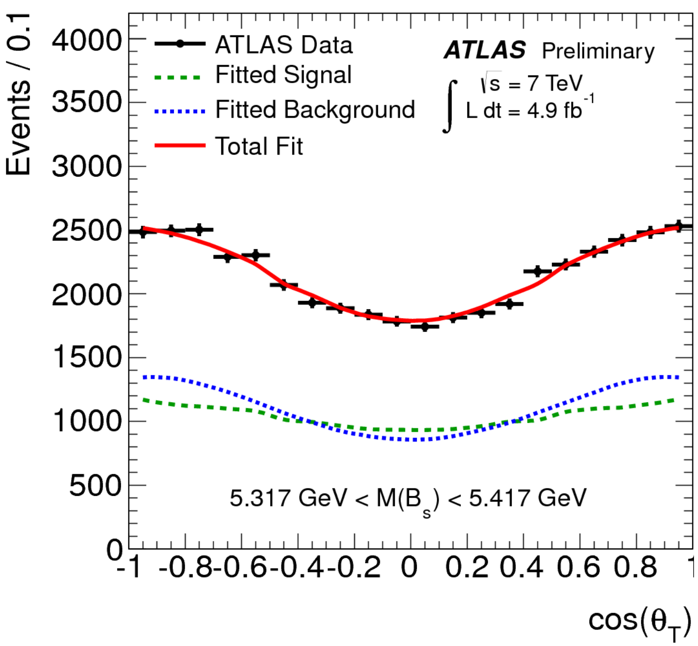
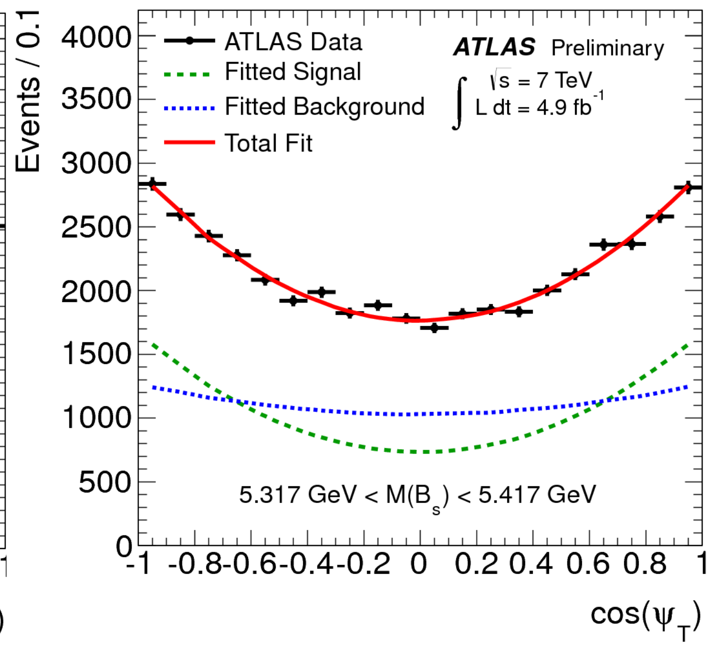
ϕ_T



$\cos(\theta_T)$



$\cos(\psi_T)$



projections on the three transversity angles: ϕ_T, $\cos(\theta_T)$ and $\cos(\psi_T)$

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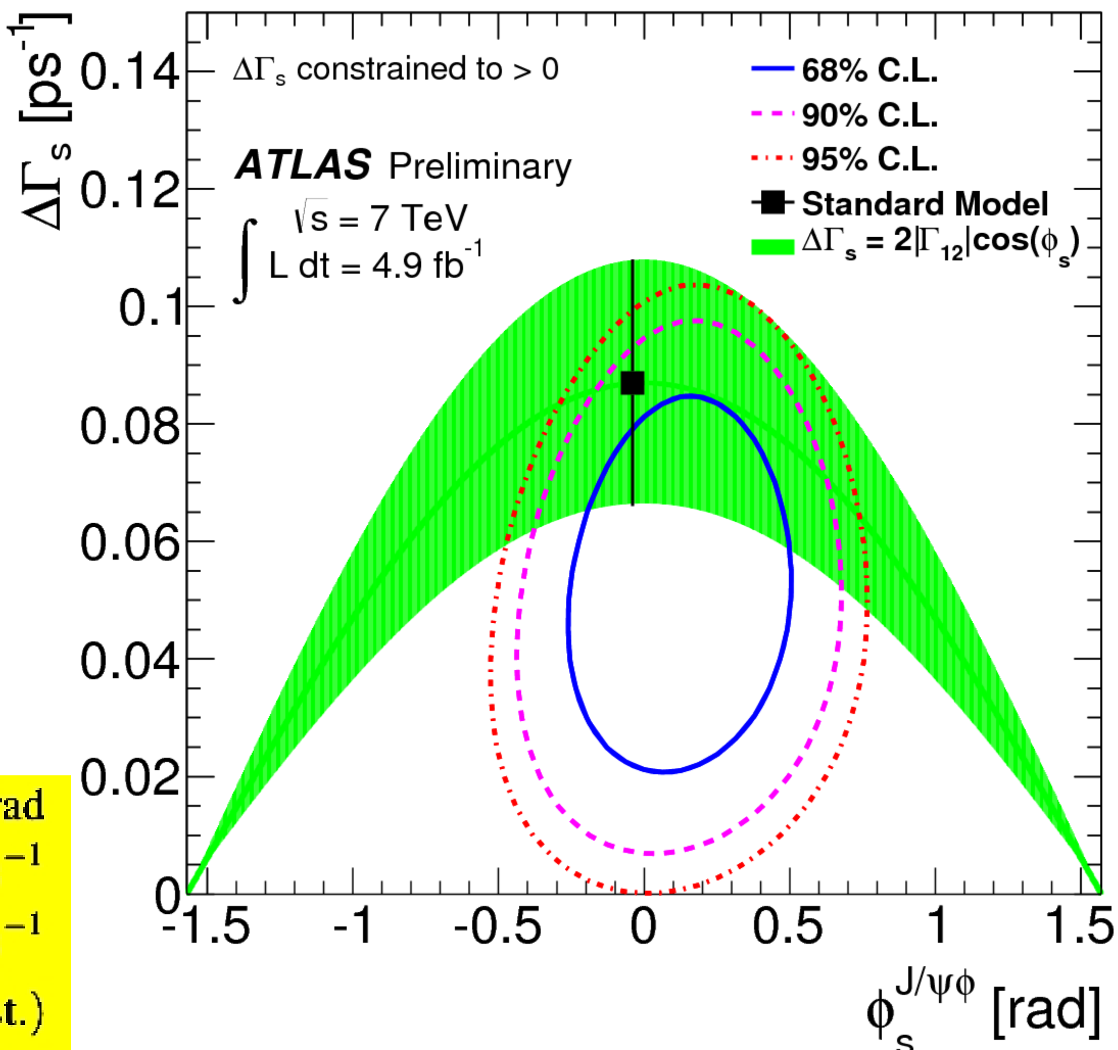
results for ϕ_S and $\Delta\Gamma_S$ in $B_s \rightarrow J/\psi\phi$

- uncertainty of ϕ_s improved by 40% compared to untagged analysis
- $\Delta\Gamma_s$ central value and uncertainty unchanged
- also the strong phase $\delta_\perp$ can now be determined
- dominant systematic uncertainty: uncorrelated description of background angle distributions

$$\phi_s = 0.12 \pm 0.25\ (\text{stat.}) \pm 0.11\ (\text{syst.})\ \text{rad}$$
$$\Delta\Gamma_s = 0.053 \pm 0.021\ (\text{stat.}) \pm 0.009\ (\text{syst.})\ \text{ps}^{-1}$$
$$\Gamma_s = 0.677 \pm 0.007\ (\text{stat.}) \pm 0.003\ (\text{syst.})\ \text{ps}^{-1}$$
$$|A_0(0)|^2 = 0.529 \pm 0.006 (\text{stat.}) \pm 0.011\ (\text{syst.})$$
$$|A_\parallel(0)|^2 = 0.220 \pm 0.008 (\text{stat.}) \pm 0.009\ (\text{syst.})$$
$$\delta_\perp = 3.89 \pm 0.46\ (\text{stat.}) \pm\ 0.13\ (\text{syst.})\ \text{rad}$$

Likelihood profiles in the $\phi_S - \Delta\Gamma_S$ plane



(Statistical errors only)
Agreement with the SM prediction

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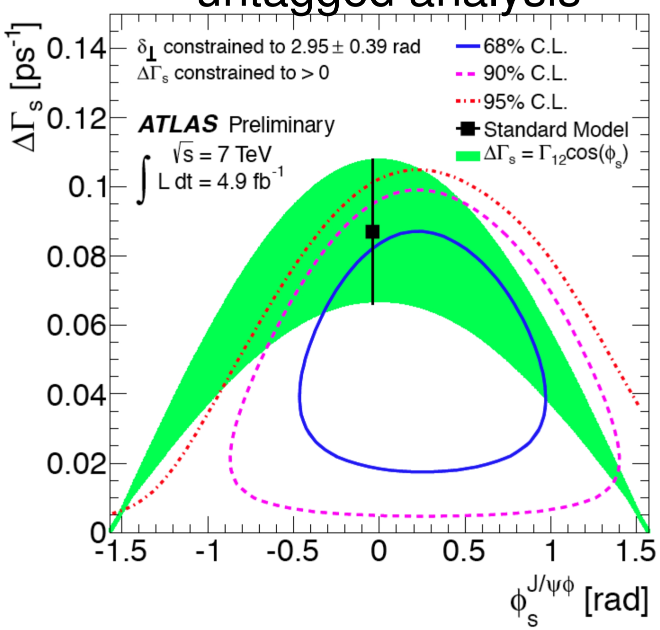
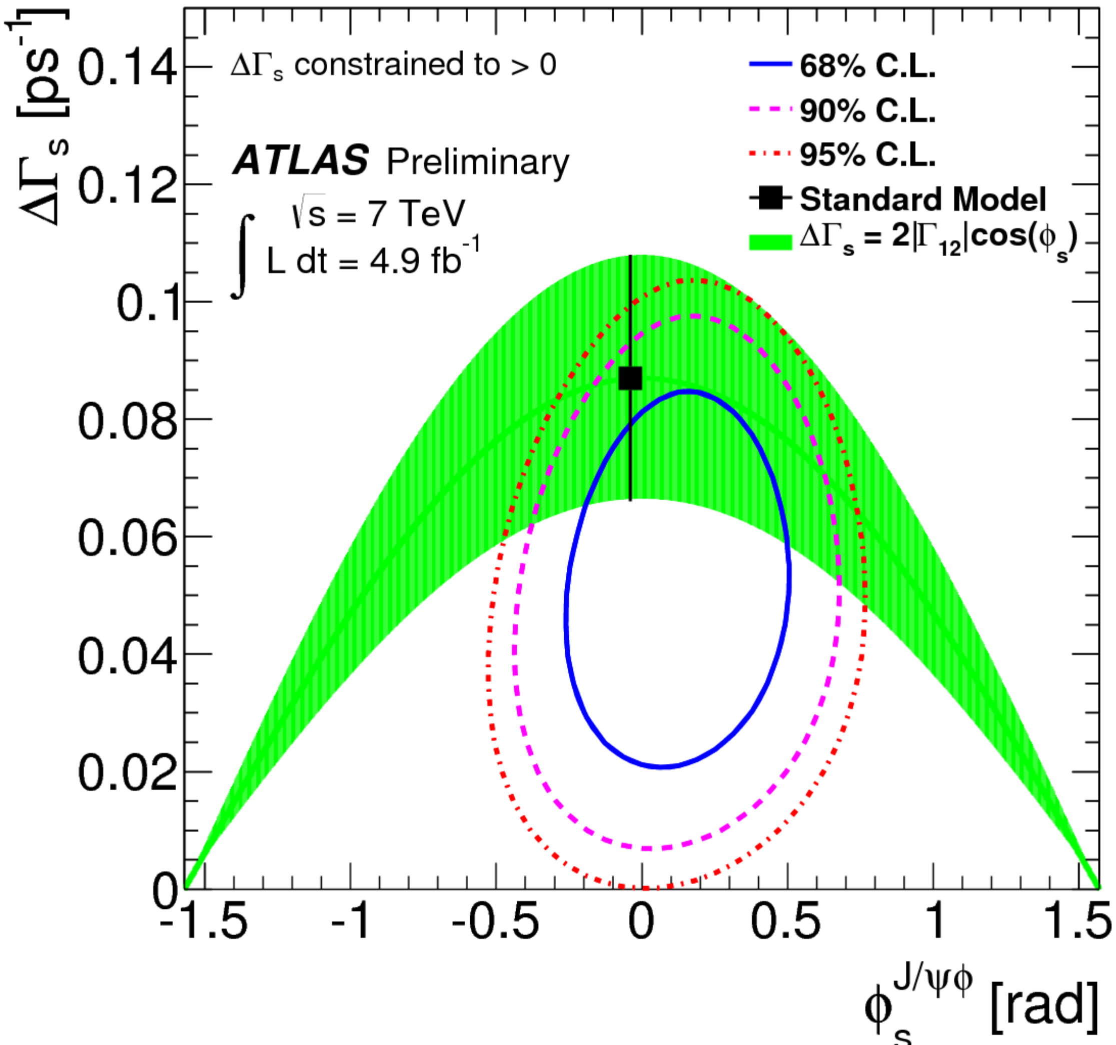
results for ϕ_s and $\Delta\Gamma_s$ in $B_s \to J/\psi\phi$

- uncertainty of ϕ_s improved by 40% compared to untagged analysis
- $\Delta\Gamma_s$ central value and uncertainty unchanged

untagged analysis



Likelihood profiles in the $\phi_s - \Delta\Gamma_s$ plane

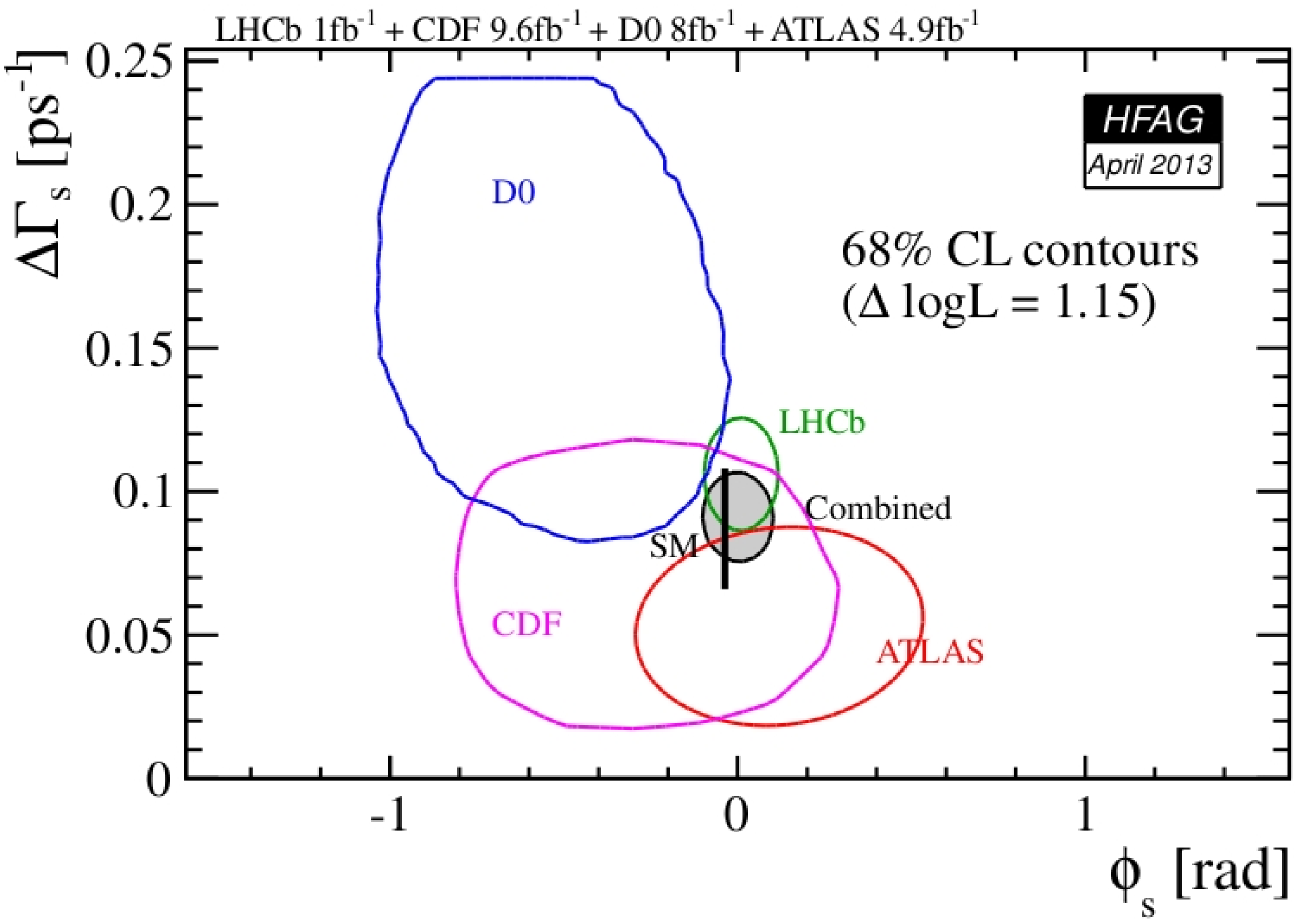


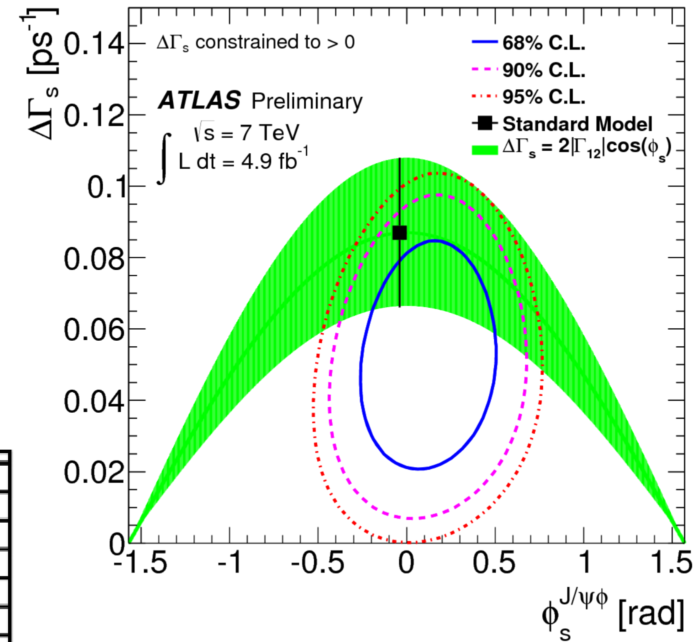
(Statistical errors only)
Agreement with the SM prediction

comparison with other experiments

on the $\phi_S - \Delta\Gamma_S$ plane

ATLAS-CONF-2013-039





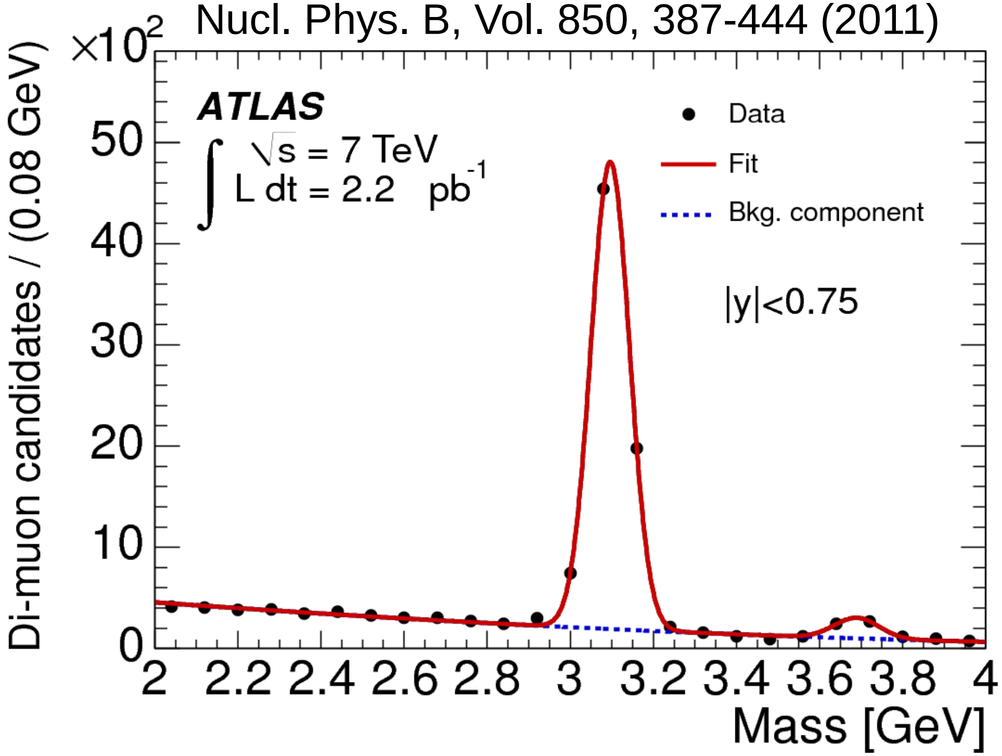
conclusions

- ATLAS able to provide high quality B-physics measurements:
  - search for the rare decay $B_s \to \mu\mu$ ATLAS-CONF-2013-076
  - angular analysis of the decay $B^0 \to K^{0*}\mu\mu$ ATLAS-CONF-2013-038
  - measurement of CP violating phase ϕ_s and the decay width difference $\Delta\Gamma_s$ in the decay $B_s \to J/\psi\phi$ ATLAS-CONF-2013-039 (to be published soon)
- all measurements are consistent with predictions from the Standard Model
  - no sign for physics beyond the Standard Model
- all measurements are statistically limited
- analyses including 2012 data (~20/fb) ongoing
  - plenty of possibilities for improvements

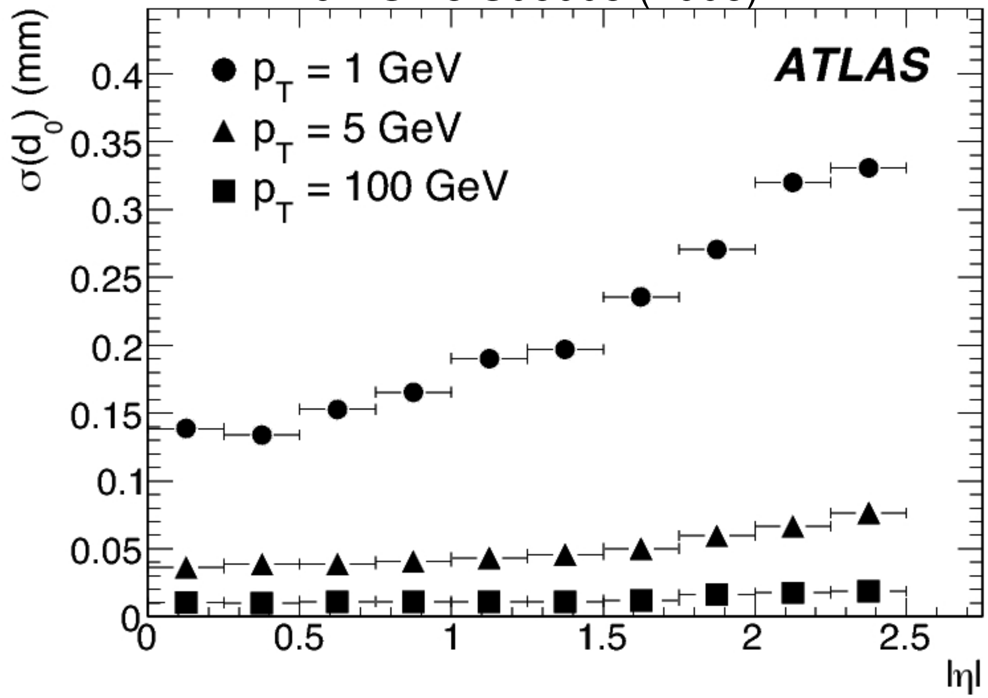
backup

performances

Nucl. Phys. B, Vol. 850, 387-444 (2011)



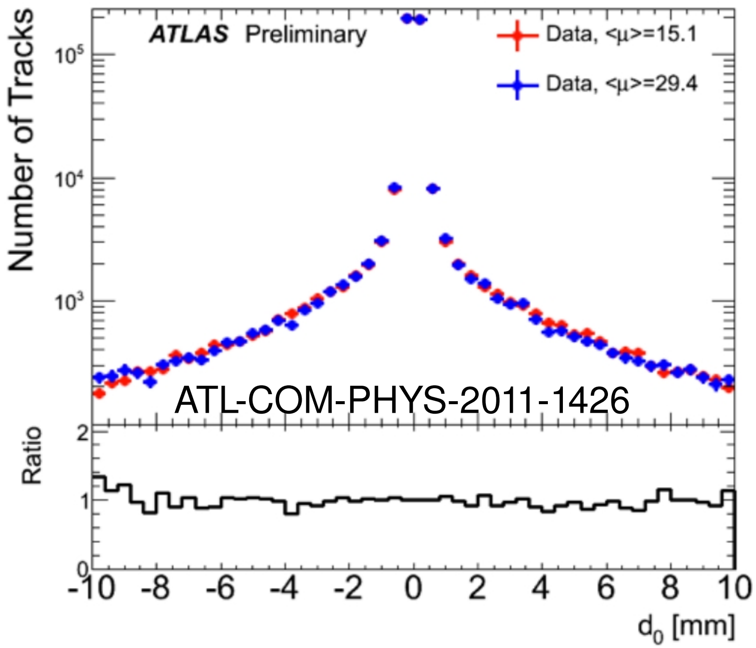
JINST 3 S08003 (2008)

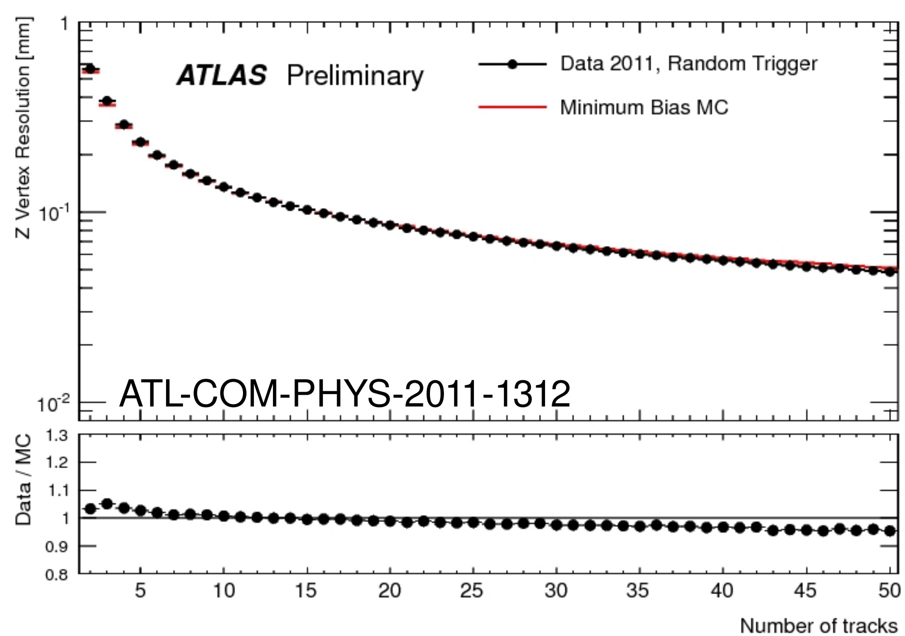


- good mass resolution required for good S/B performance
- limited particle ID: only for $p_T < 1$GeV/c K/π separation possible
- good impact parameter resolution required for lifetime measurements

tracking-vertexing performance in pile-up

- Vertex resolution important for precision B-physics measurements: lifetime, CPV, rare decays.
- Quality of vertexing monitored over 2011 as pileup increased
- d_0 (top plot) of the reconstructed tracks with respect to the PV for 2 different number of pileups:
    - The tails are sensitive to the rate of secondaries and fakes. No significant increase in the fake rate observed.
- Good z-resolution of primary vertex (bottom plot) important at high luminosities





background composition and discrimination

$B_s \rightarrow \mu\mu$

- Continuum background:
  - discriminating variables to separate between B signals and continuum;
  - 14 variables explored to build a unique discriminating variable: Boosted Decision Tree (BDT) gives the best performances;
  - best BDT configuration and selection criteria optimised on half of the sideband data (odd-numbered events) and signal MC.
- Peaking background:
  - fake rates for $\pi^{\pm}$/ K^{+}/K^{-} obtained on MC: 2.1/4.1/3.3 ‰
  - latest BR from HFAG used;
  - 0.3 ev contribution to the signal region;
  - included in the optimisation procedure and in the upper limit calculation.

Variable	Description
$\lvert\alpha_{2D}\rvert$ pointing angle	Absolute value of the angle in the transverse plane between $\Delta\vec{x}$ and $\vec{p}^{B}$
ΔR	Angle $\sqrt{(\Delta\phi)^2+(\Delta\eta)^2}$ between $\Delta\vec{x}$ and $\vec{p}^{B}$
L_{xy}	Scalar product in the transverse plane of $(\Delta\vec{x}\cdot\vec{p}^{B})/\lvert\vec{p}^{B}_{T}\rvert$
ct significance	Proper decay length $ct = L_{xy} \times m_B/p^{B}_{T}$ divided by its uncertainty
χ^2_{xy}, χ^2_{z}	Vertex separation significance $\Delta\vec{x}^{T}\cdot\left(\sigma^2_{\Delta\vec{x}}\right)^{-1}\cdot\Delta\vec{x}$ in (x, y) and z, respectively
$I_{0.7}$ isolation	Ratio of $\lvert\vec{p}^{B}_{T}\rvert$ to the sum of $\lvert\vec{p}^{B}_{T}\rvert$ and the transverse momenta of all tracks with $p_T > 0.5$ GeV within a cone $\Delta R < 0.7$ from the B direction, excluding B decay products
$\lvert d_0\rvert^{max}, \lvert d_0\rvert^{min}$	Absolute values of the maximum and minimum impact parameter in the transverse plane of the B decay products relative to the primary vertex
$\lvert D_{xy}\rvert^{min}, \lvert D_z\rvert^{min}$	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
p^{min}_{L}	Minimum momentum of the two muon candidates along the B direction
p^{B}_{T}	B transverse momentum

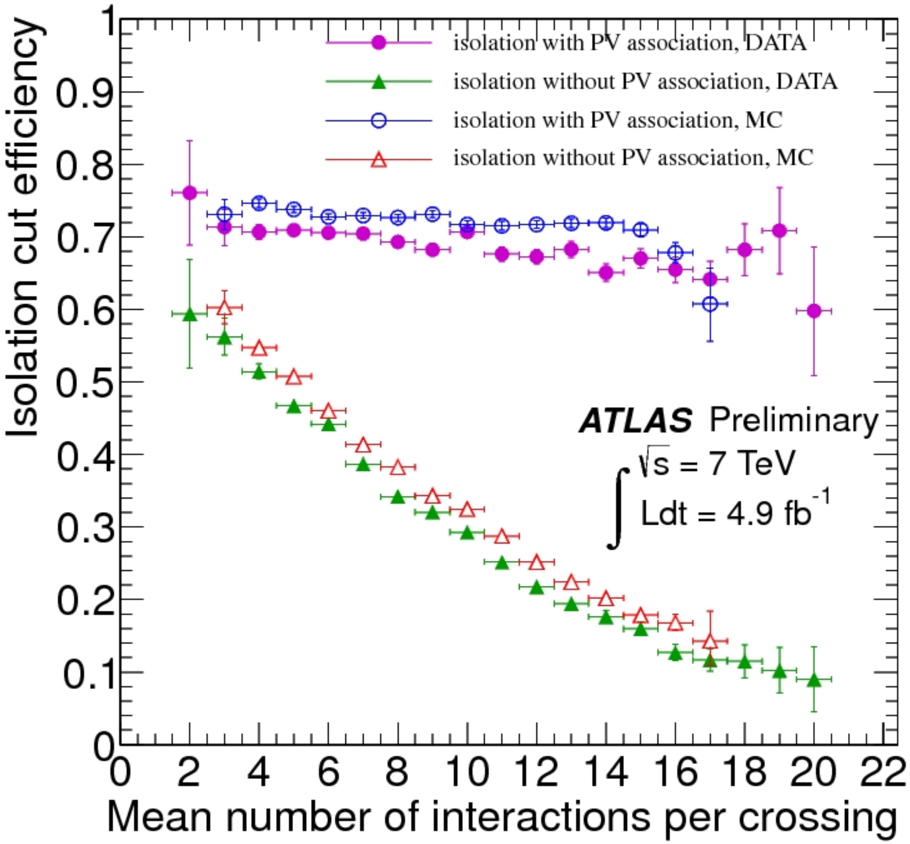
background discrimination: isolation variable

$B_s \to \mu\mu$

- Isolation variable:

$$I^{\Delta R} = \frac{P_T^B}{P_T^B + \sum_i^{\Delta R} p_T^i}$$

tracks with $p_T > 0.5$ GeV excluding B daughters in the cone $\Delta R < 0.7$, where $\Delta R = \mathrm{sqrt}((\Delta\eta)^2+(\Delta\phi)^2)$



- PV association of tracks:
  - gets rid of the interference from the other interactions
  - isolation cut efficiency is pile-up independent

final selection optimisation

$B_s \to \mu\mu$

- optimisation on half sideband data (odd-numbered events) and reweighted signal MC;
- optimisation for a selection on the BDT classifier and the signal region width;
- maximisation of the Punzi estimator: $\mathcal{P} = \frac{\epsilon}{1 + \sqrt{B}}$
  - signal efficiency calculated directly
  - background from sidebands

- The odd-numbered event optimisation gives a maximum $\mathcal{P}$ value of 0.0145.
- The corresponding final selection cuts on the mass window and the BDT variable are:

BDT classifier > 0.118 and $|\Delta m|$ < 121 MeV

acceptance x efficiency ratio

$B_s \rightarrow \mu\mu$

$$BR(B_s \rightarrow \mu\mu) = N_{B_s\rightarrow\mu\mu} \frac{1}{N_{B^\pm\rightarrow J/\psi K^\pm}} \; BR(B^\pm \rightarrow J/\psi K^\pm) \frac{f_u}{f_s} \boxed{\frac{\varepsilon_{B^\pm\rightarrow J/\psi K^\pm}}{\varepsilon_{B_s\rightarrow\mu\mu}} \frac{A_{B^\pm\rightarrow J/\psi K^\pm}}{A_{B_s\rightarrow\mu\mu}}}$$

⇒ determined on reweighted B_s and B^+ MC samples wrt the fiducial volume:

$N^B_{generated}$: $p_T^B > 8$ GeV and $|\eta_B| < 2.5$

$\varepsilon \times A = N^B_{\text{reconstructed and selected}} / N^B_{generated}$

⇒ systematic uncertainties:

- ⇒ main contribution from data-MC discrepancies of separation variables
  - two main discrepancies on isolation and L_{xy}
    - isolation depends on the flavour of the B
    - L_{xy} is correlated with the vertex reconstruction so with some other discriminant variables but it does not depend on the flavour of the B

acceptance x efficiency ratio

$B_s \to \mu\mu$

$$BR(B_s \to \mu\mu) = N_{B_s\to\mu\mu}\frac{1}{N_{B^\pm\to J/\psi K^\pm}}\; BR(B^\pm \to J/\psi K^\pm)\frac{f_u}{f_s}\boxed{\frac{\varepsilon_{B^\pm\to J/\psi K^\pm}}{\varepsilon_{B_s\to\mu\mu}}\frac{A_{B^\pm\to J/\psi K^\pm}}{A_{B_s\to\mu\mu}}}$$

⇒ determined on reweighted B_s and B^+ MC samples wrt the fiducial volume:

$N^B_{generated}$: $p_T^B > 8$ GeV and $|\eta_B| < 2.5$

$\varepsilon \times A = N^B_{\text{reconstructed and selected}} / N^B_{generated}$

⇒ systematic uncertainties:

⇒ main contribution from data-MC discrepancies of separation variables

two main discrepancies on isolation and L_{xy}

Channel	$A \times \epsilon$	$R_{A\epsilon}$
B^+	$1.317 \pm 0.008\%$ (stat)	$0.267 \pm 1.8\%$ (stat) $\pm 6.9\%$ (syst)
B_s^0	$4.929 \pm 0.084\%$ (stat)	

single event sensitivity

$B_s \rightarrow \mu\mu$

from the interpolation of 50% of the sideband events (8 even events)
we expect: 6.75 background events in the optimised search window

$$BR(B_s \to \mu\mu) = N_{B_s\to\mu\mu} \boxed{\frac{1}{N_{B^\pm\to J/\psi K^\pm}} \boxed{BR(B^\pm \to J/\psi K^\pm)\frac{f_u}{f_s}} \frac{\varepsilon_{B^\pm\to J/\psi K^\pm}}{\varepsilon_{B_s\to\mu\mu}} \frac{A_{B^\pm\to J/\psi K^\pm}}{A_{B_s\to\mu\mu}}}$$

reference channel branching ratio is taken from the PDG and the relative hadronisation f_u/f_s is taken from LHCb.

quantity	value
$N_{J/\psi K^\pm}$	$15\,214 \pm 1.10\% \pm 2.39\%$
$R_{A\epsilon}$	$0.267 \pm 1.8\% \pm 6.9\%$
SES	$(2.07 \pm 0.26) \cdot 10^{-9}$
R^{obs}_{bkg}	1.240 ± 0.050
N^{exp}_{SR}	6.75
$N^{obs}_{bkg,SB}$	8
$N_{B\to hh}$	0.30

Single Event Sensitivity (SES)

corresponds to the $B_s \to \mu^+\mu^-$ branching fraction which would yield one observed signal event in the data sample.

systematics summary on the SES

$B_s \rightarrow \mu\mu$

description	contribution
PDG branching fractions and f_s/f_d	8.5%
$K^{\pm}$ tracking efficiency	5%
vertexing efficiency	2%
$K^{\pm}$ charge asymmetry. in $B^{\pm} \rightarrow J/\psi K^{\pm}$	1%
$B^{\pm} \rightarrow J/\psi K^{\pm}$ yield	2.4%
$R_{A\epsilon}$	6.9%
total (comb. in quadrature)	12.5%

statistical uncertainty on SES: 2.1%

contributions from backgrounds:

- background interpolation from sidebands $\rightarrow$ 4% on R_{bkg}
- B $\rightarrow$ hh' negligible

dominant contributions from BR and f_u/f_s
from the acc-vs-eff ratio (data-MC discrepancies)
and then from the K tracking efficiency

upper limit extraction

$B_s \to \mu\mu$

CLs method with profile likelihood ratio:
likelihood for CLs:

signal region

sidebands

$$\mathcal{L} = \text{Poisson}(N^{obs}_{SR} | \epsilon \mathcal{B} + N_{bkg} + N_{B\to hh})\, \text{Poisson}(N^{obs}_{bkg,SB} | R_{bkg} N_{bkg}) \times \text{Gauss}(\epsilon^{obs} | \epsilon, \sigma_\epsilon)\, \text{Gauss}(R^{obs}_{bkg} | R_{bkg}, \sigma_{R_{bkg}})$$

1/SES constraint

$R=\Delta_{sb}/\Delta_{sr}$ constraint

with $\varepsilon = ses^{-1}$

the expected UL is calculated assuming as number of events in the signal region as the number of expected events obtained from the sideband interpolation (6.75 events):

$\rightarrow$ we obtain $BR(B_s \to \mu^+\mu^-) < 1.6\ 10^{-8}$ [expected UL]

analysis strategy @ ATLAS:

$B_s \rightarrow \mu\mu$

- **Relative BR measurement:**
  - partial cancellation of uncertainties:
    on luminosity, cross-section, ..
  - reference channel ($B^{\pm} \rightarrow J/\psi K^{\pm}$, $J/\psi \rightarrow \mu^+\mu^-$)
  - blind analysis: signal region ± 300 GeV around B_s mass blinded
  - limit placed using CLs method

$$BR(B_s \to \mu\mu) = N_{B_s\to\mu\mu} \boxed{\frac{1}{N_{B^\pm\to J/\psi K^\pm}} \, BR(B^\pm \to J/\psi K^\pm) \frac{f_u}{f_s} \, \frac{\varepsilon_{B^\pm\to J/\psi K^\pm}}{\varepsilon_{B_s\to\mu\mu}} \frac{A_{B^\pm\to J/\psi K^\pm}}{A_{B_s\to\mu\mu}}}$$

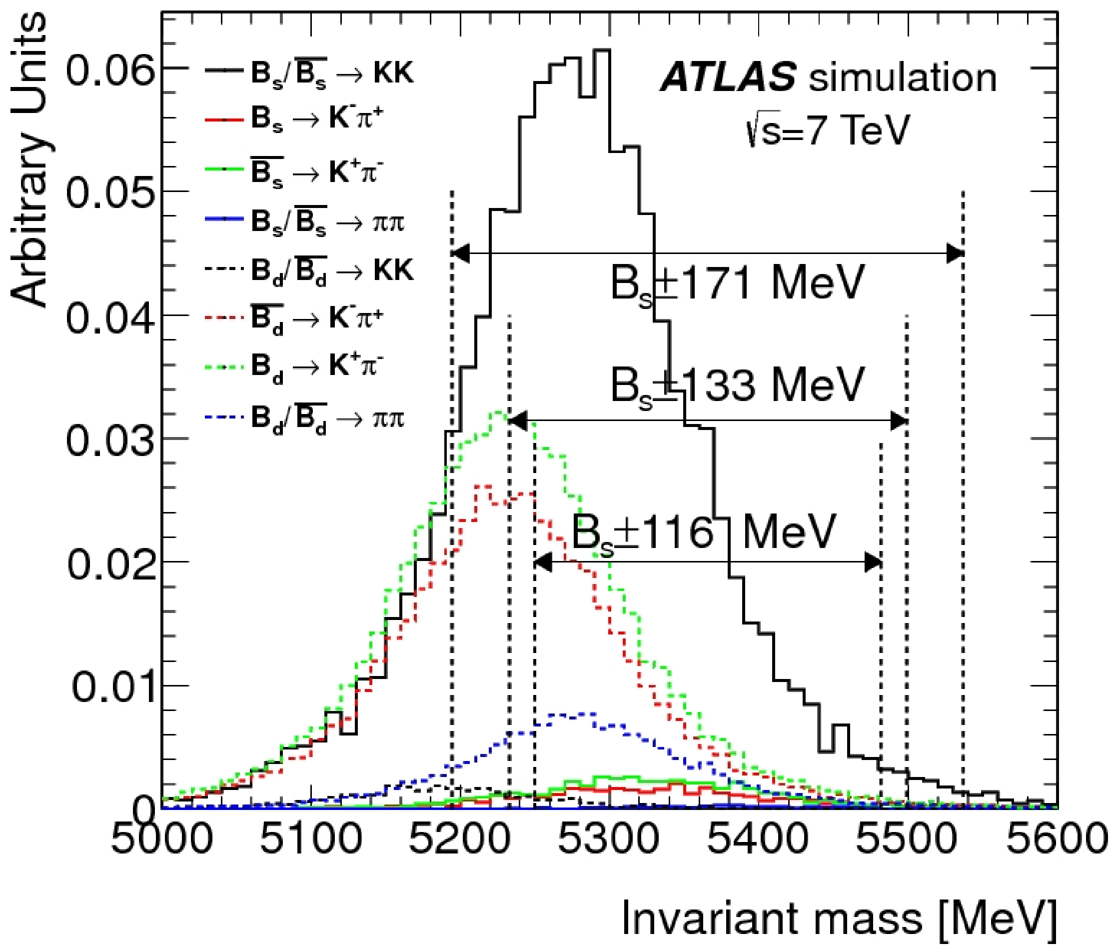
Single Event Sensitivity (SES)

corresponds to the $B_s \rightarrow \mu^+\mu^-$ branching fraction which would yield one observed signal event in the data sample.

background composition

$B_s \to \mu\mu$

- **continuum:**
  - dominated by non-resonant bb production with μμX final states
  - real muons
  - smooth shape in the di-muon mass
  - limited MC statistics available in ATLAS
  - measured by interpolation from sideband data into the signal region

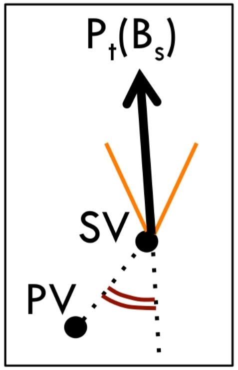


- **resonant**:
  - B → hh, with hadrons misidentified as muons
  - mainly B → $K^+\pi^-/\pi^+\pi^-$ decays
  - BR x (fake rate) ≈ 10^{-9} close to the SM B_s to μμ BR
  - similar decay topology → hard to suppress
  - contribution estimated from MC currently still quite small

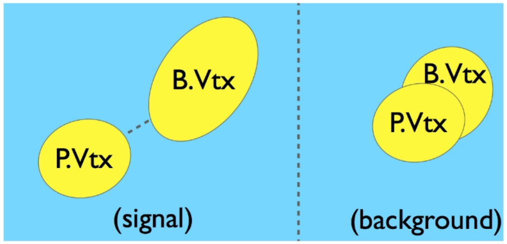
reconstruction and event selection

$B_s \to \mu\mu$

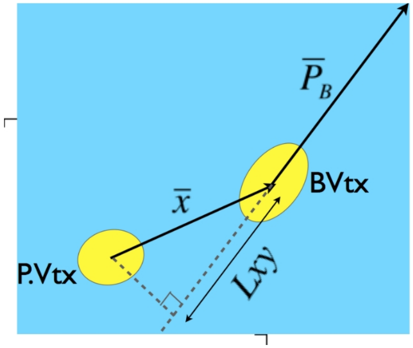
- 2, 3 or 4 prong vertex constraint depending on decay topology
- Primary Vertex selection:
  - the closest in z to the B candidate
  - Re-fit excluding B daughters
- Tracks:
  - At least 1 pixel, 6 SCT and 9 TRT hits (*good tracks*)
  - $|\eta| < 2.5$ and $p_T > 4$ (2.5) GeV for muons (kaons)
  - tracks from the tracking systems matched to muon spectrometer tracks
- B candidates: $p_T > 8$ GeV and $|\eta|<2.5$

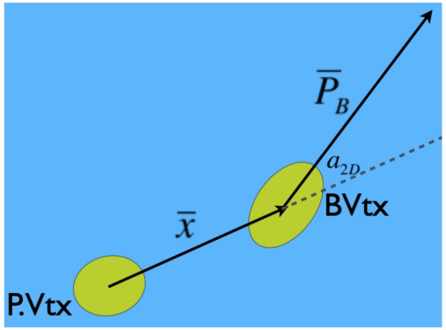


- select events based on their decay topology
- discriminating variables to distinguish between B and continuum events
- 14 variables identified and used in a boosted decision tree (BDT):
  - not correlated with invariant mass
  - highest discriminating power
  - highly correlated variables excluded



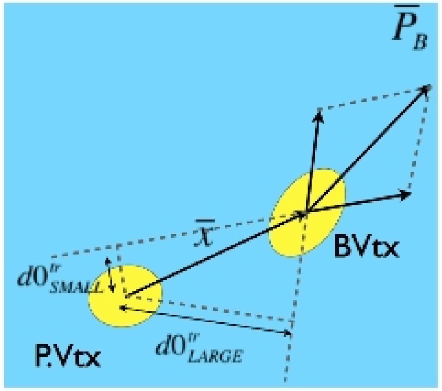
discriminating variables

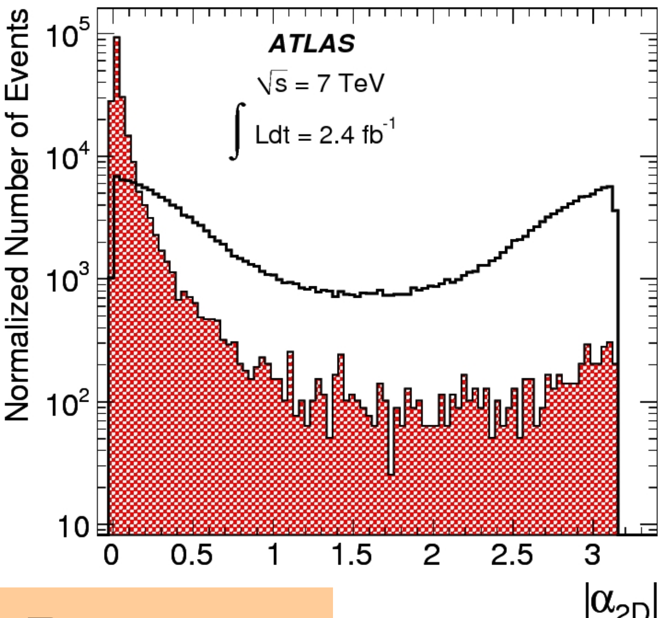


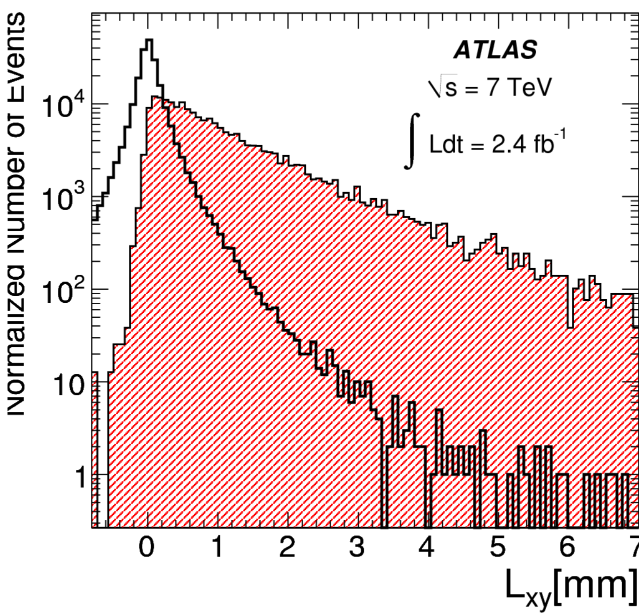


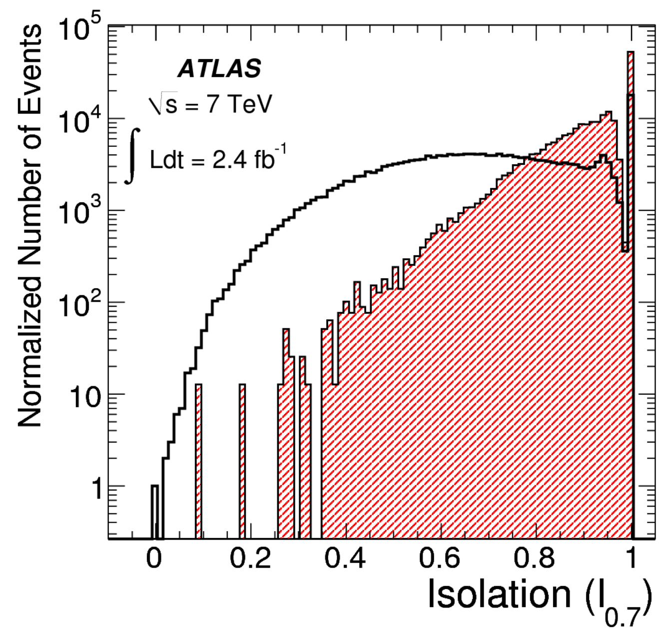
Exploit:

- Primary Vertex-Secondary Vertex separation: L_{xy}, cτ significance
- Symmetry of final state: pointing angle, d_0…
- Full reconstruction: pointing angle, D_{min}…
- B hadronization features: Isolation, p_T of the B…









$B_s \rightarrow \mu\mu$

Binning in q^2

$B_d \rightarrow K^*\mu\mu$

Bins are identical to those used by Belle

- $0.04 < q^2 < 2.00$ GeV^2 (no angular analysis performed due to low statistics)
- $2.00 < q^2 < 4.30$ GeV^2
- $4.30 < q^2 < 8.68$ GeV^2
- $8.68 < q^2 < 10.09$ GeV^2 (J/ψ mass region, excluded)
- $10.09 < q^2 < 12.86$ GeV^2
- $12.86 < q^2 < 14.18$ GeV^2 ($\psi(2S)$ mass region, excluded)
- $14.18 < q^2 < 16.00$ GeV^2
- $16.00 < q^2 < 19.00$ GeV^2

$1.00 < q^2 < 6.00$ GeV^2

Fit strategy

$B_d \to K^*\mu\mu$

Extended unbinned maximum likelihood fit in each q^2 bin

Sequential fit: first fit m(Kπμμ) distribution, then the angular distributions with mass term parameters fixed.

The procedure checked to give same results as single-step fit except the lowest q^2 bin (included in systematics there).

- Mass fit (*in each q^2 bin*):

$$\mathcal{L} = \prod_{i=1}^{N} \left[N_{\rm sig} \cdot \mathcal{M}_{\rm sig}(m_i, \delta_{m_i}) + N_{\rm bckg} \cdot \mathcal{M}_{\rm bckg}(m_i) \right]$$

- Signal mass PDF – gaussian with per-candidate errors:

$$\mathcal{M}_{\rm sig}(m_i, \delta_{m_i}) = \frac{1}{\sqrt{2\pi} s_m \delta_{m_i}} \exp\left(\frac{-(m_i - m_{B_d^0})^2}{2(s_m \delta_{m_i})^2} \right)$$

- Background mass PDF – exponential

$$\mathcal{M}_{\rm bckg}(m_i) = e^{-\lambda \cdot m_i}$$

Fit strategy (2)

$B_d \rightarrow K^*\mu\mu$

- Angular fit (*in each* q^2 *bin*):

$$\mathcal{L} = \prod_{i=1}^{N} [N_{\mathrm{sig}}^{\mathrm{fix}} \cdot \mathcal{M}_{\mathrm{sig}}(m_i, \delta_{m_i}|\mathrm{fixed}) \cdot \mathcal{A}_{L,\mathrm{sig}}(\cos\theta_{L,i}) \cdot \alpha_L(\cos\theta_{L,i}) \cdot \mathcal{A}_{K,\mathrm{sig}}(\cos\theta_{K,i}) \cdot \alpha_K(\cos\theta_{K,i}) + N_{\mathrm{bckg}}^{\mathrm{fix}} \cdot \mathcal{M}_{\mathrm{bckg}}(m_i|\mathrm{fixed}) \cdot \mathcal{A}_{L,\mathrm{bckg}}(\cos\theta_{L,i}) \cdot \mathcal{A}_{K,\mathrm{bckg}}(\cos\theta_{K,i})]$$

- Signal PDFs:

$$\mathcal{A}_{L,\mathrm{sig}}(\cos\theta_{L,i}) = \frac{3}{4} F_L(q^2)\left(1-\cos^2\theta_{L,i}\right) + \frac{3}{8}\left(1-F_L(q^2)\right)\left(1+\cos^2\theta_{L,i}\right) + A_{FB}(q^2)\cos\theta_{L,i}$$

$$\mathcal{A}_{K,\mathrm{sig}}(\cos\theta_{K,i}) = \frac{3}{2} F_L(q^2)\cos^2\theta_{K,i} + \frac{3}{4}\left(1-F_L(q^2)\right)\left(1-\cos^2\theta_{K,i}\right)$$

- Background PDF – linear combination of Chebyshev polynomials up to 2nd order:

$$\mathcal{A}_{L(K),\mathrm{bkg}} = 1 + p_{1L(K)}\cos\theta_{L(K),i} + p_{2L(K)}\left(2\cos^2\theta_{L(K),i} - 1\right)$$

- $\alpha_L(\cos\theta_{L,i})$, $\alpha_K(\cos\theta_{K,i})$ – acceptance functions taking into account detector and selection effect on the angular shapes

Systematic uncertainties

$B_d \to K^*\mu\mu$

Ranges of the mass fit region
- Differ in q^2 bins due to ΔM cut effect

Angular background shapes
- Varied between 2nd and 3rd Chebyshev polynomials

Contribution of $B^\pm \to \mu^+\mu^-K^\pm$ events
- Estimated by removing potential $B^\pm \to \mu^+\mu^-K^\pm$ candidates

Angular acceptance effects
- Mainly from limited MC statistics
- Various signal angular shapes tested

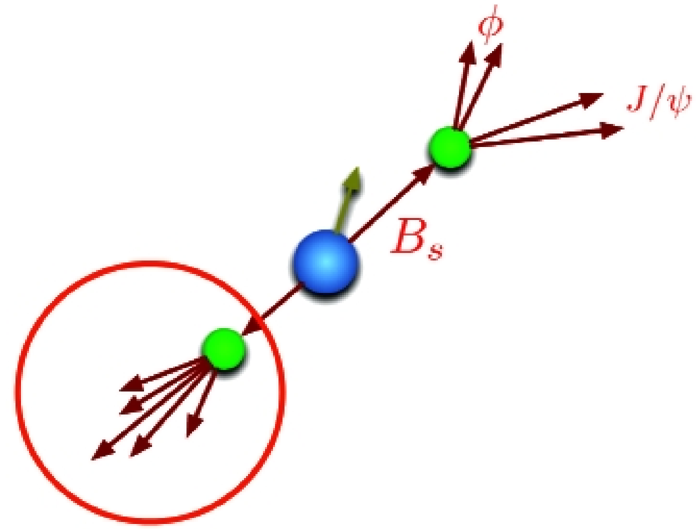
Sequential fitting approach
- Non-negligible effect only in $2.00 < q^2 < 4.30$ GeV^2 bin due to low statistics

Following sources found to be negligible
- Contribution from S-wave ($B^0_d \to \mu^+\mu^-K^+\pi^-$ decays)
- Contribution from $B_s \to \phi\,(\to K^+K^-)\,\mu^+\mu^-$ events
- Background mass shape
- Possible bias due to angular fit approach (neglecting correlation)

flavour tagging

$B_s \to J/\psi\phi$

Analysis updated including flavour tagging:
previous analysis: JHEP 12 (2012) 072



determine flavour eigenstate of Bs meson at production time

Opposite side flavour tagging used
Two different methods applied in hierarchy of performance

Muon Tagger
Identify the muon from semileptonic decay
Calculate muon cone charge Q_μ

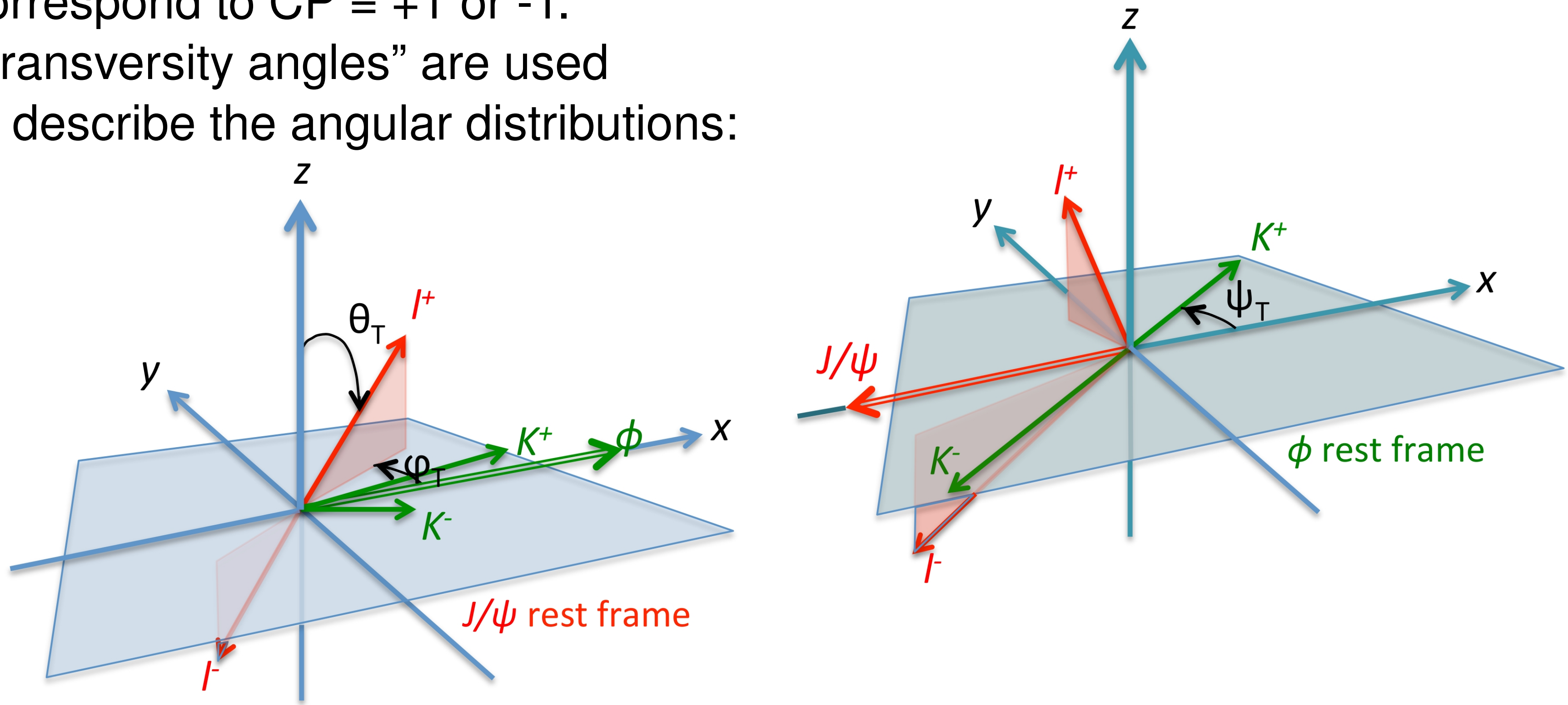
Jet Charge Tagger
Identify jet originating from same primary vertex
Calculate jet charge Q_{jet}

Determine probability that signal decay contains b as function of Qμ and Qjet using calibration sample B+g J/ψK+

angular analysis in $B_s \to J/\psi\phi$

$B_s \to J/\psi\phi$

In the decay $\overline{B}_S(B_S) \to J/\psi\phi \to l^+l^- K^+K^-$
different components in the angular-distributions amplitudes
correspond to CP = +1 or -1.
The "transversity angles" are used
to describe the angular distributions:



In the J/ψ (or ϕ) rest frames, the direction of ϕ (opposite to J/ψ) defines the x axis, and the xy-plane is defined by the K^+K^- decay plane, with K^+ oriented towards positive y; θ_T and φ_T are the polar angles of l^+, ψ_T is the angle between K^+ and x-axis

the measurement of ATLAS in $B_s \to J/\psi\phi$

$B_s \to J/\psi\phi$

Analysis using data collected in 2011 (4.7 fb^{-1}).
Trigger selection based in di-muon and single-muon triggers
    (p_T threshold 4 GeV or higher)
Offline selection based on J/ψ and ϕ invariant masses, χ^2/NDF< 3
    in fit to decay vertex, $|\eta|<2.5$ for all tracks,
    p_T > 0.5 GeV for kaon candidates.
Decay time computed in the plane normal to collision axis.
Average number of primary interactions 5.6:
    wrong association to primary vertex is < 1% and
    effects are negligible.
Acceptance computed on large samples of signal and
background channels
    (e.g.: $B^0 \to J/\psi K^{*0}$, $bb \to J/\psi X$, $pp \to J/\psi X$).
Efficiency via data-driven procedures.

systematic uncertainties

$B_s \to J/\psi\phi$

Systematic	ϕ_s(rad)	$\Delta\Gamma_s(\mathrm{ps}^{-1})$	$\Gamma_s(\mathrm{ps}^{-1})$	$\lvert A_{\parallel}(0)\rvert^2$	$\lvert A_0(0)\rvert^2$	$\lvert A_S(0)\rvert^2$
Inner Detector alignment	0.04	< 0.001	0.001	< 0.001	< 0.001	< 0.01
Trigger efficiency	< 0.01	< 0.001	0.002	< 0.001	< 0.001	< 0.01
Signal mass model	0.02	0.002	< 0.001	< 0.001	< 0.001	< 0.01
Background mass model	0.03	0.001	< 0.001	0.001	< 0.001	< 0.01
Resolution model	0.05	< 0.001	0.001	< 0.001	< 0.001	< 0.01
Background lifetime model	0.02	0.002	< 0.001	< 0.001	< 0.001	< 0.01
Background angles model	0.05	0.007	0.003	0.007	0.008	0.02
B^0 contribution	0.05	< 0.001	< 0.001	< 0.001	0.005	< 0.01
Totals	0.10	0.008	0.004	0.007	0.009	0.02

These are calculated with different techniques, including:

changes in detector simulation (alignment),
data based studies (efficiency),
pseudo-experiments Montecarlo (mass models, background angles)
and variations in analysis methods and assumptions.

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symmetries in the likelihood

$B_s \to J/\psi\phi$

The term describing $B_S \to J/\psi\ \phi$ in the likelihood is invariant under the transformations:

$$\{\phi_s, \Delta\Gamma_s, \delta_\perp, \delta_\parallel\} \to \{\pi - \phi_s, -\Delta\Gamma_s, \pi - \delta_\perp, 2\pi - \delta_\parallel\}$$

$$\{\phi_s, \Delta\Gamma_s, \delta_\perp, \delta_\parallel\} \to \{-\phi_s, \Delta\Gamma_s, \pi - \delta_\perp, 2\pi - \delta_\parallel\}$$

with the latter characteristic of untagged analyses.

The ATLAS analysis favours values of ϕ_S close to 0 (π), for which an untagged analysis is scarcely sensitive to the phase $\delta_\perp$.

We therefore proceed as follows:

- we constrain the value of $\delta_\perp$ to 2.95 ± 0.39 rad as recently measured (LHCb) [or its complement to π].
- the four minima of the likelihood do not overlap, only one of them is compatible with previous measurements, and we show the result for that minimum.

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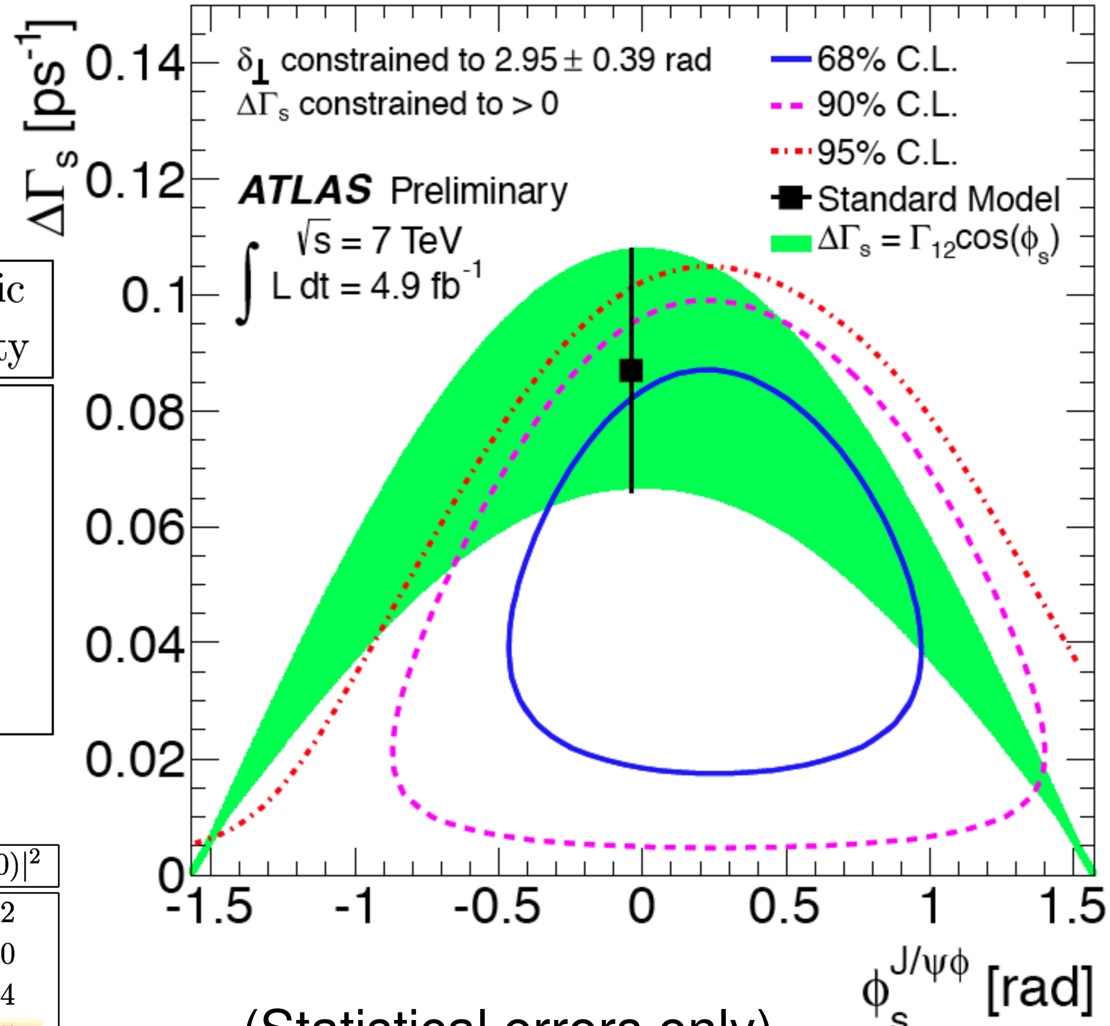
result for ϕ_s and $\Delta\Gamma_s$ in $B_s \to J/\psi\phi$

$B_s \to J/\psi\phi$

Likelihood profiles in the $\phi_s - \Delta\Gamma_s$ plane



Result of likelihood fit

Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s(rad)	0.22	0.41	0.10
$\Delta\Gamma_s$(ps^{-1})	0.053	0.021	0.008
Γ_s(ps^{-1})	0.677	0.007	0.004
$\|A_0(0)\|^2$	0.528	0.006	0.009
$\|A_\parallel(0)\|^2$	0.220	0.008	0.007
$\|A_S(0)\|^2$	0.02	0.02	0.02

Correla1on coefficients

	ϕ_s	$\Delta\Gamma_s$	Γ_s	$\|A_0(0)\|^2$	$\|A_\parallel(0)\|^2$	$\|A_S(0)\|^2$
ϕ_s	1.00	−0.13	0.38	−0.03	−0.04	0.02
$\Delta\Gamma_s$		1.00	−0.60	0.12	0.11	0.10
Γ_s			1.00	−0.06	−0.10	0.04
$\|A_0(0)\|^2$				1.00	−0.30	0.35
$\|A_\parallel(0)\|^2$					1.00	0.09
$\|A_S(0)\|^2$						1.00

(Statistical errors only)
Agreement with the SM prediction

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