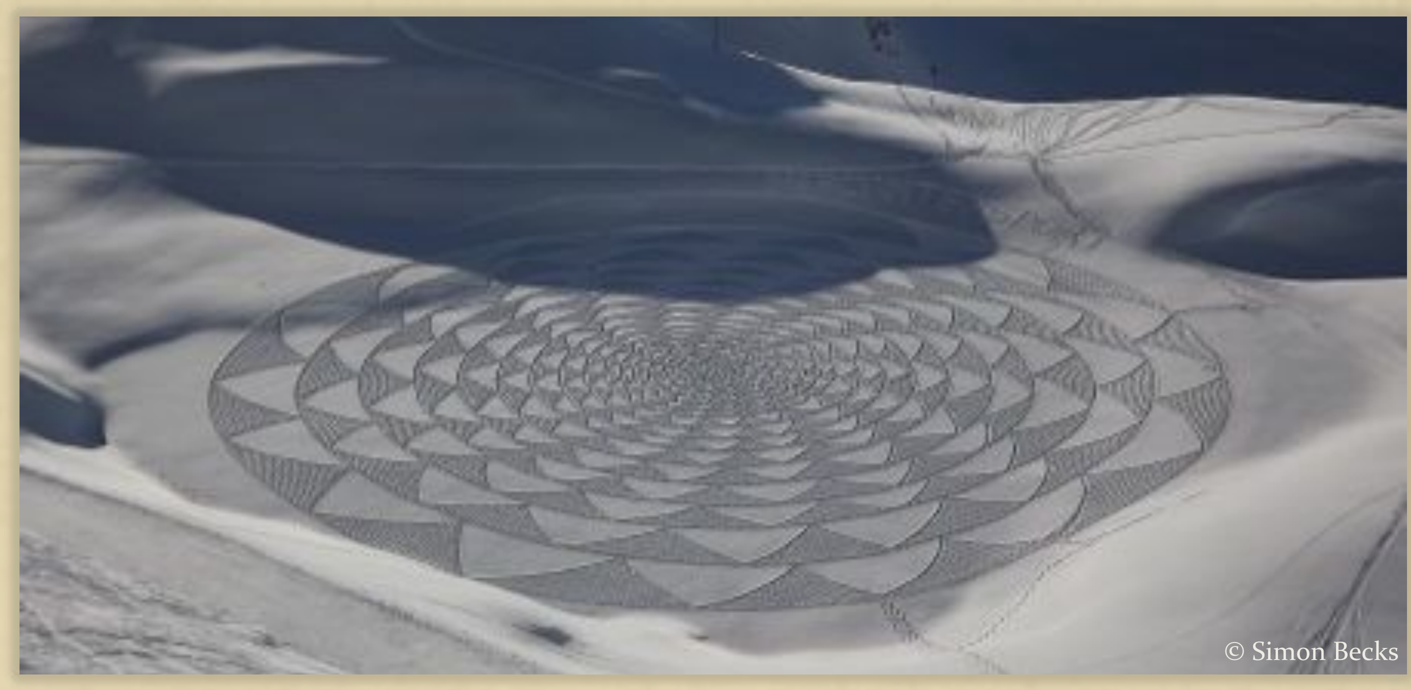
Testing the new physics scale in the B^0 system @ ATLAS



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XXVIII Rencontres de Physique de La Vallee d'Aoste

- Young Scientists Forum -

La Thuile, 28 of February 2014

Queen Mary
University of London

Outline

① Rare B decays for new physics

- ✧ $B_s \to \mu^+\mu^-$
  - Analysis strategy
  - Continuum background discrimination
  - Results on 4.9 fb^{-1}
- ✧ $B_d \to K^*\mu^+\mu^-$
  - Angular analysis
  - Measurements of A_{FB} and F_L
  - Results on 4.9 fb^{-1}

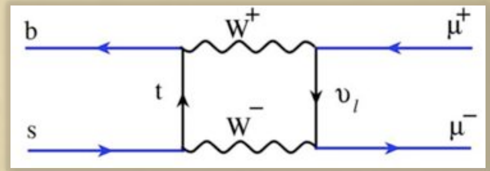
② Flavour-tagged time-dependent angular analysis in $B_s \to J/\psi\ \phi$

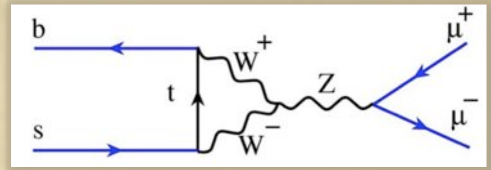
- ✧ Measurements of $\Delta\Gamma_s$ and ϕ_s
  - Angular analysis
  - Flavour tagging
  - Results on 4.9 fb^{-1}

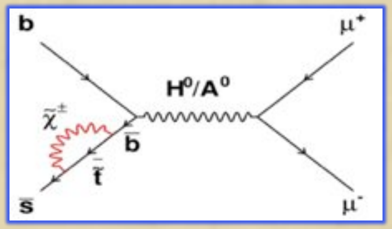
➢ Conclusions

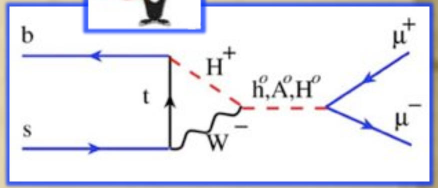
Rare B decays for new physics

- Flavour Changing Neutral Currents (FCNC) are highly suppressed in the SM
- **Rare decays $B_s \to \mu^+\mu^-$**
  - ✧ BR ratio expectation for: **$(3.27 \pm 0.27) \cdot 10^{-9}$**
    [*Buras et al., Eur.Phys.J. C72 (2012) 2172*]
  - ✧ Evidence from CMS and LHCb **$(2.9 \pm 0.7) \cdot 10^{-9}$**
    [LHCb: arXiv:1307.5024] and [CMS: arXiv:1307.5025]
  - ✧ Coupling to **non-SM particles** may **change the branching ratio**.
  - ✧ Powerful method for NP searches
  - ✧ Indirect research can reach higher scale w.r.t. direct search
    → orthogonal to direct search for BSM

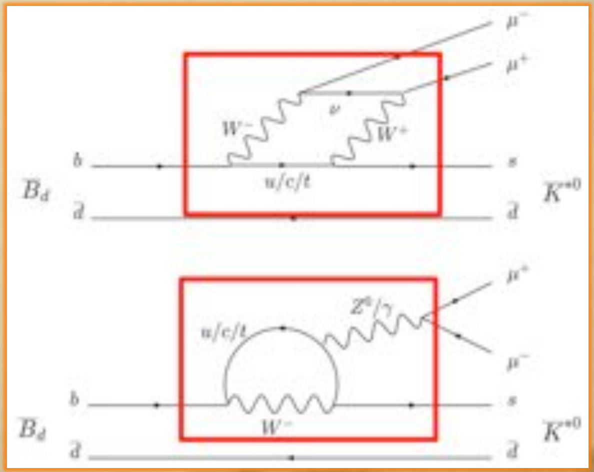








- **Semi-leptonic rare decays $B_d \to K^*\mu^+\mu^-$**
  - ✧ Studied through $b \to s$ transitions
    BR = $(1.06 \pm 0.10) \cdot 10^{-6}$
  - ✧ Angular distribution of the 4 final state particles and decay amplitude sensible to NP for interference with SM diagrams [*C. Bobeth et al. arXiv:1105.2659*]



Search for $B_s \rightarrow \mu^+\mu^-$

$B_s \to \mu^+\mu^-$ analysis strategy

ATLAS-CONF-2013-076

- Relative BR measurement

$$\mathrm{BR}(B_s \to \mu^+\mu^-) = \mathrm{BR}(B^+ \to J/\Psi K^+ \to \mu^+\mu^- K^+) \cdot \frac{f_u}{f_s} \cdot \frac{\epsilon_{J/\Psi K^+} \cdot A_{J/\Psi K^+}}{\epsilon_{\mu\mu} \cdot A_{\mu\mu}} \cdot \frac{N_{\mu\mu}}{N_{J/\Psi K^+}}$$

w.r.t. the reference channel $B^+ \to J/\psi\ (\to \mu^+\mu^-)\ K^+$

- B_S and B^+ selection synchronised in order to minimise the systematic
- Uncertainties on trigger and pre-selection efficiencies partially cancel out in the ratio
- **Blind analysis →** invariant mass region ± 300 MeV around B_S mass is blinded

- **Signal extraction**
  - counting events in the signal region
  - subtraction of the background using the interpolation of half of the sidebands (even-numbered events)
  - limit extracted using CL_S method

- **Background composition**
  - **Resonant:** $B \to hh$, hadrons misidentified as muons estimated from MC (negligible)
  - **Continuum:** non resonant $bb \to \mu\mu X$ (real muons, smooth shape in di-muon invariant mass)
  - **Semi-leptonic B decays** in the low mass sidebands ($B_d \to \pi\mu\nu$, $B_s \to K\mu\nu$, $\Lambda_b \to p\mu\nu$)

$B_s \to \mu^+\mu^-$ analysis strategy

ATLAS-CONF-2013-076

- Relative BR measurement

$$BR(B_s \to \mu^+\mu^-) = BR(B^+ \to J/\Psi K^+ \to \mu^+\mu^- K^+) \cdot \frac{f_u}{f_s} \cdot \frac{\epsilon_{J/\Psi K^+} \cdot A_{J/\Psi K^+}}{\epsilon_{\mu\mu} \cdot A_{\mu\mu}} \cdot \frac{N_{\mu\mu}}{N_{J/\Psi K^+}}$$

w.r.t. the reference channel $B^+ \to J/\psi\ K^+$

- B_S and B^+ selection synchronised in order to minimise the systematic
- Uncertainties on trigger and pre-selection efficiencies partially cancel out in the ratio
- **Blind analysis →** invariant mass region ± 300 MeV around B_S mass is blinded

- **Efficiencies and acceptances**
  - Derived from MC (calibrated on data)

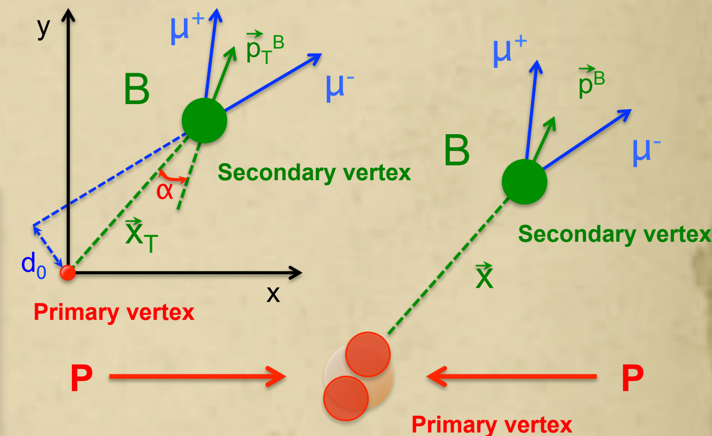
    $A \cdot \epsilon = N_{\text{reconstructed and selected}} / N_{\text{generated}}$
  - Reference channel selection: as close as possible to signal selection
  - Systematics evaluated on the reference channel using residual discrepancies between data and MC distributions of the discriminating variables and of some kinematic variables

- **Reference channel BR and f_u / f_s**
  - Taken from the PDG 2012 and the LHCb 2011 results [*JHEP* ***1304*** *(2013) 001, arXiv:1301.5286*]

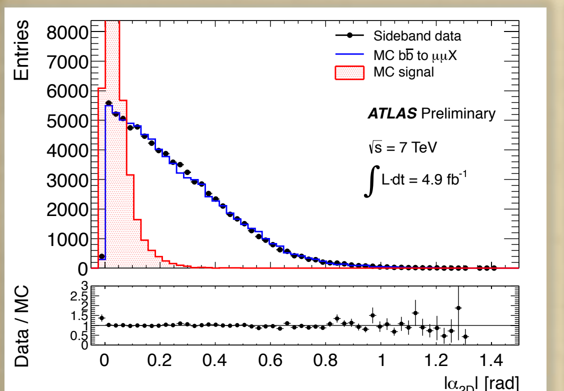
Continuum background discrimination

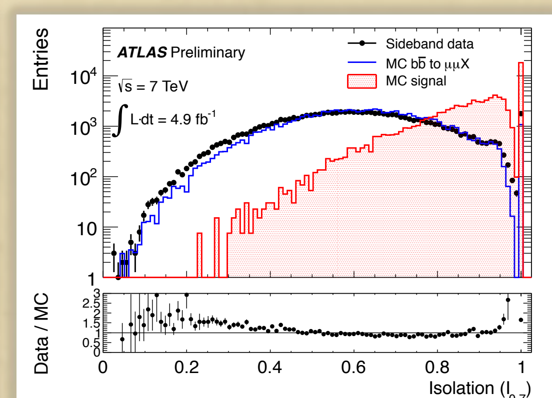
ATLAS-CONF-2013-076

- Dominated by bb $\rightarrow \mu\mu$ X
- Background distinguished from signal using **13 discriminating variables** used in a **Boosted Decision Tree** (BDT) trained on MC events



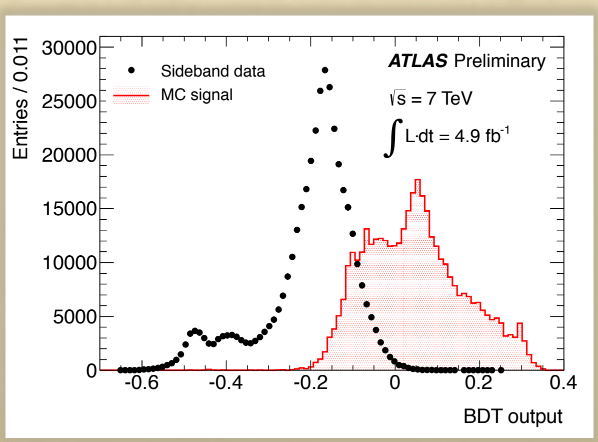
Two of the most powerful discriminating variables





$$I_{\Delta R} = \frac{p_T^B}{p_T^B + \sum_{\text{tracks}}^{\Delta R} p_T^{\text{tracks}}}$$

- BDT cut optimised on half of the sidebands (odd-numbered events)
- Subtraction of the background in the signal region by the interpolation of half of the sidebands (even-numbered events)



BDT output for data sidebands and MC signal

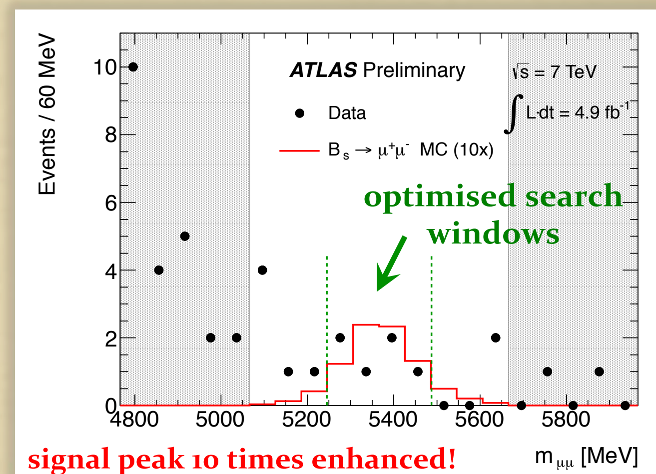
Results on 4.9 fb^{-1} @ 7 TeV

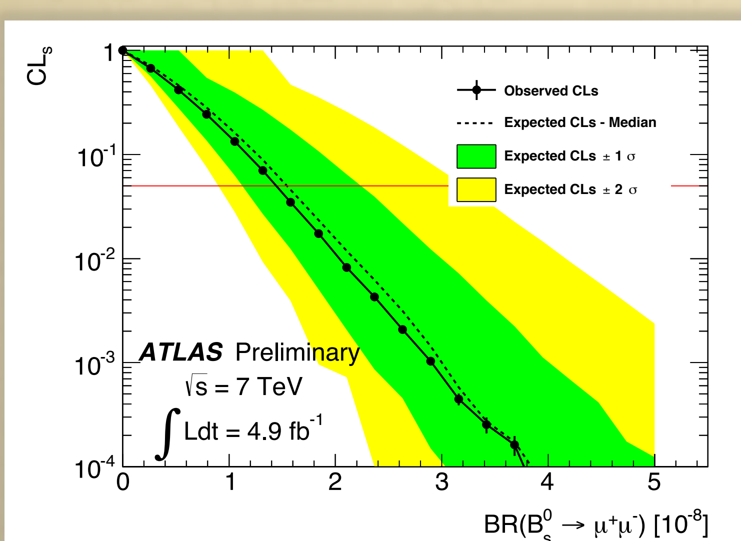
ATLAS-CONF-2013-076

- B^+ signal yield **= 15214 ± 1.1% (stat.) ± 2.4% (syst.)** (un-binned maximum likelihood fit with per-event mass resolution)
- Single event sensitivity

$$\mathrm{SES} = \mathrm{BR}(B^+ \to J/\Psi K^+) \cdot \frac{\epsilon_{J/\Psi K^+} \cdot A_{J/\Psi K^+}}{\epsilon_{\mu\mu} \cdot A_{\mu\mu}} \cdot \frac{f_u}{f_s} \cdot \frac{1}{N_{J/\Psi K^+}} = (2.07 \pm 0.26) \cdot 10^{-9}$$

- Single event sensitivity systematic = 12.5 % (dominated by reference channel BR and $A \cdot \epsilon$)
- In the optimised search windows
  - Expected number of background events **= 6.75**
  - Observed number of signal events **= 6**





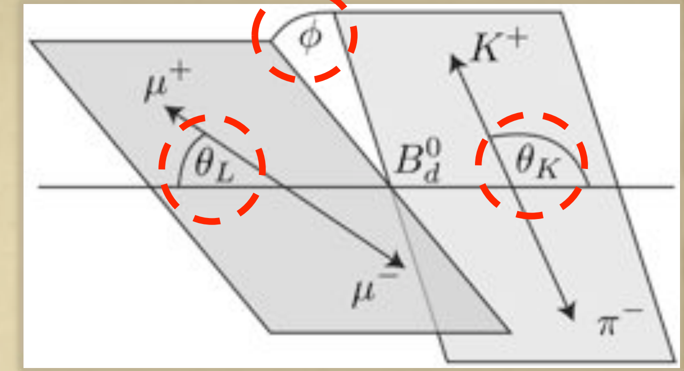
$$\mathrm{BR}(B_s \to \mu^+\mu^-) = \mathrm{SES} \cdot N_{\mu\mu}$$

- Expected upper limit: **< 1.6 · 10^{-8} @ 95 % CL**
- Measured upper limit: **< 1.5 · 10^{-8} @ 95 % CL**

$B_d \to K^* \mu^+ \mu^-$ angular analysis

$B_d \rightarrow K^* \mu^+ \mu^-$ angular analysis

ATLAS-CONF-2013-038



- Studying 4 kinematic variables:
  - di-lepton invariant mass squared $q^2 = m^2(\mu^+\mu^-)$ and 3 angles θ_L , θ_K and ϕ
- Two integrated 1D distributions to extract $\cos\theta_L$ and $\cos\theta_K$ (@ 7 TeV not enough statistic for 3D)

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

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

- ✓ F_L → fraction of longitudinal polarisation
- ✓ A_{FB} → muons forward-backward asymmetry

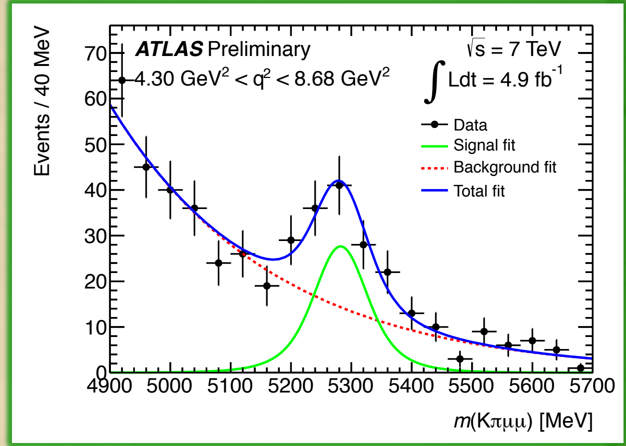
- Measurements performed using un-binned maximum likelihood fit in different q^2 bins
- Two different background contributions
  - Combinatorial background from bb $\rightarrow \mu\mu$X with small contributions from cc $\rightarrow \mu\mu$X and Drell-Yan
  - Resonant background from exclusive decay channels ($B_d \rightarrow K^*$ J/ψ and $B_d \rightarrow K^*$ ψ(2S))

Measurements of A_{FB} and F_L

ATLAS-CONF-2013-038

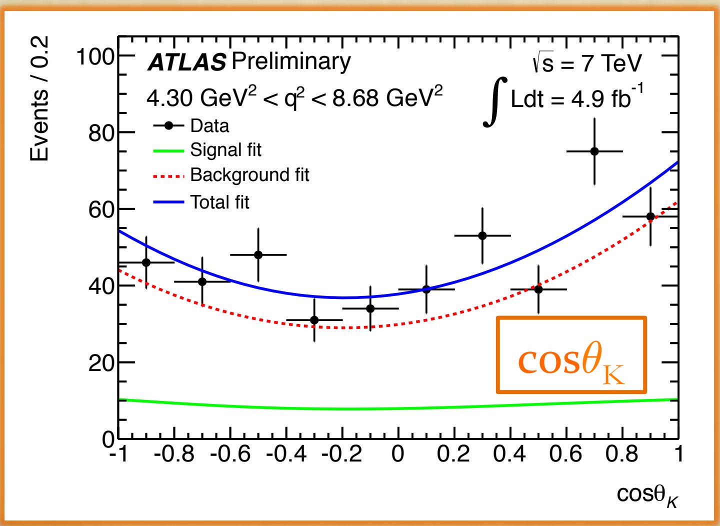
- A_{FB} and F_L measured in **8 q² bins** defined as for the Belle experiment.
- Un-binned maximum likelihood for **mass fit**
  - Gaussian with per-event error to model the signal
  - Exponential to model the background
  - J/ψ and $\psi(2S)$ regions excluded
  - Radiative charmonium decay and tails from J/ψ and ψ (2S) reconstruction removed by the cut

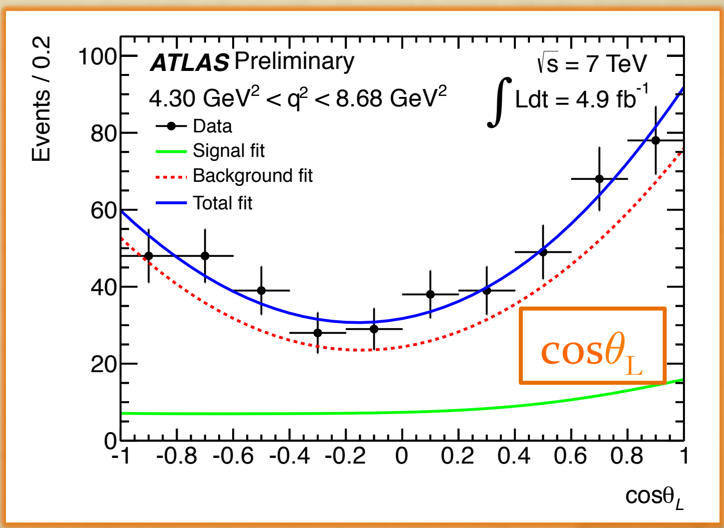
$$|(m(B^0{}_d)_{rec} - m(B^0{}_d)_{PDG}) - (m(\mu^+\mu^-)_{rec} - m(J/\psi)_{PDG})| < 130 \text{ MeV}$$



- Un-binned maximum likelihood for **angular fit**
  - Used the mass to separate signal and background

bin $4.30 < q^2 < 8.68$ GeV²

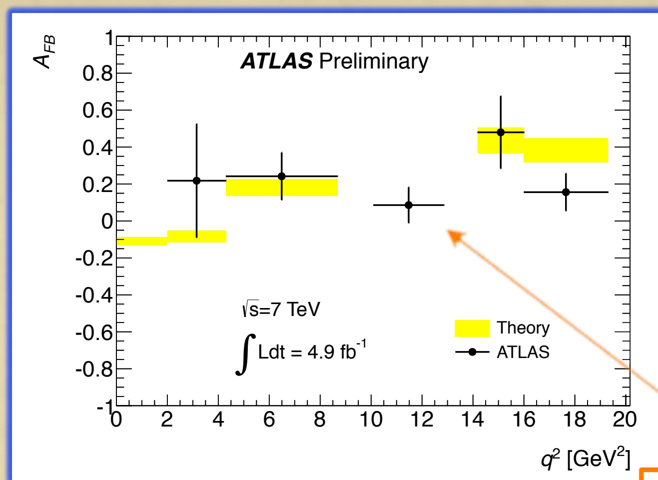


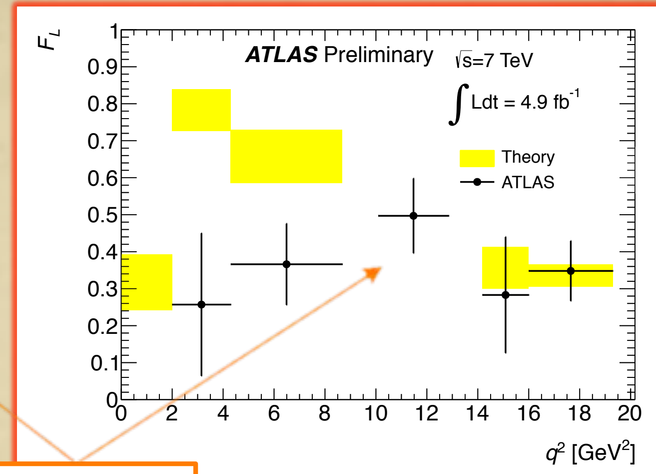


Results on 4.9 fb^{-1} @ 7 TeV

ATLAS-CONF-2013-038

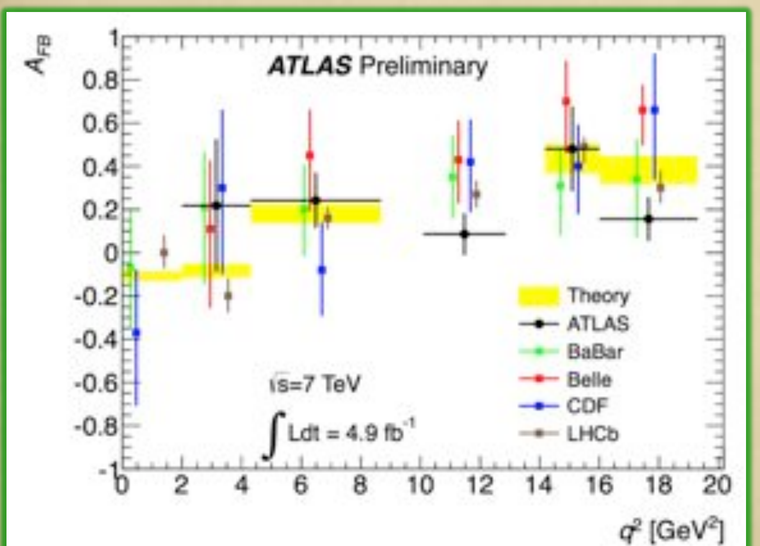
- Uncertainties limited by statistic
- **Results mostly consistent with SM predictions**





No theoretical calculation available

[Theoretical prediction: C. Bobeth et al. arXiv:1105.2659]



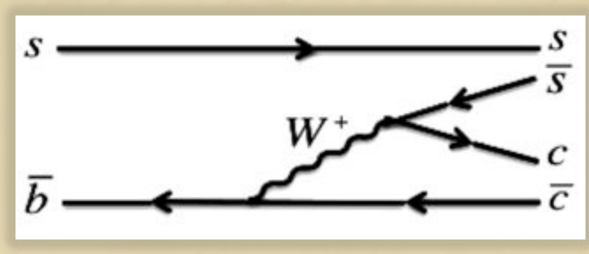
q^2 range (GeV^2)	N_{sig}	A_{FB}	F_L
$2.00 < q^2 < 4.30$	19 ± 8	$0.22 \pm 0.28 \pm 0.14$	$0.26 \pm 0.18 \pm 0.06$
$4.30 < q^2 < 8.68$	88 ± 17	$0.24 \pm 0.13 \pm 0.01$	$0.37 \pm 0.11 \pm 0.02$
$10.09 < q^2 < 12.86$	138 ± 31	$0.09 \pm 0.09 \pm 0.03$	$0.50 \pm 0.09 \pm 0.04$
$14.18 < q^2 < 16.00$	34 ± 10	$0.43 \pm 0.18 \pm 0.04$	$0.29 \pm 0.15 \pm 0.03$
$16.00 < q^2 < 19.00$	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	$0.07 \pm 0.20 \pm 0.07$	$0.18 \pm 0.15 \pm 0.03$

- ATLAS competitive with the other experiments in high q² bins

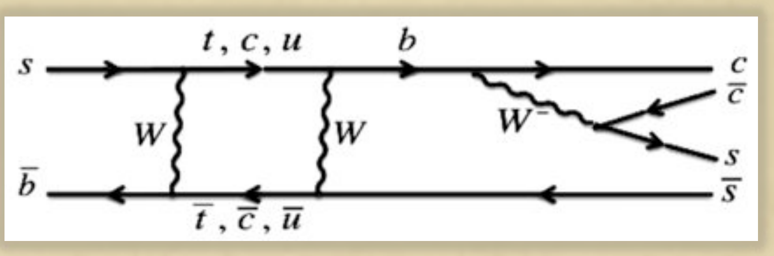
Flavour-tagged time-dependent angular analysis of $B_s \to J/\psi\ \phi$

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

- CP violation in B decays may be altered by new phenomena beyond the SM
- The time evolution of B_s meson mixing is characterized by
  - the mass difference Δm_s of the heavy (B_H) and light (B_L) mass eigenstates
  - the CP-violating mixing phase ϕ_s
  - the width difference $\Delta\Gamma_s = \Gamma_L - \Gamma_H$
- Interference between the B_s decays amplitudes to the CP eigenstate $J/\psi\ \phi$ or via mixing gives rise to a measurable CP violating phase ϕ_s



direct decay



decay with mixing

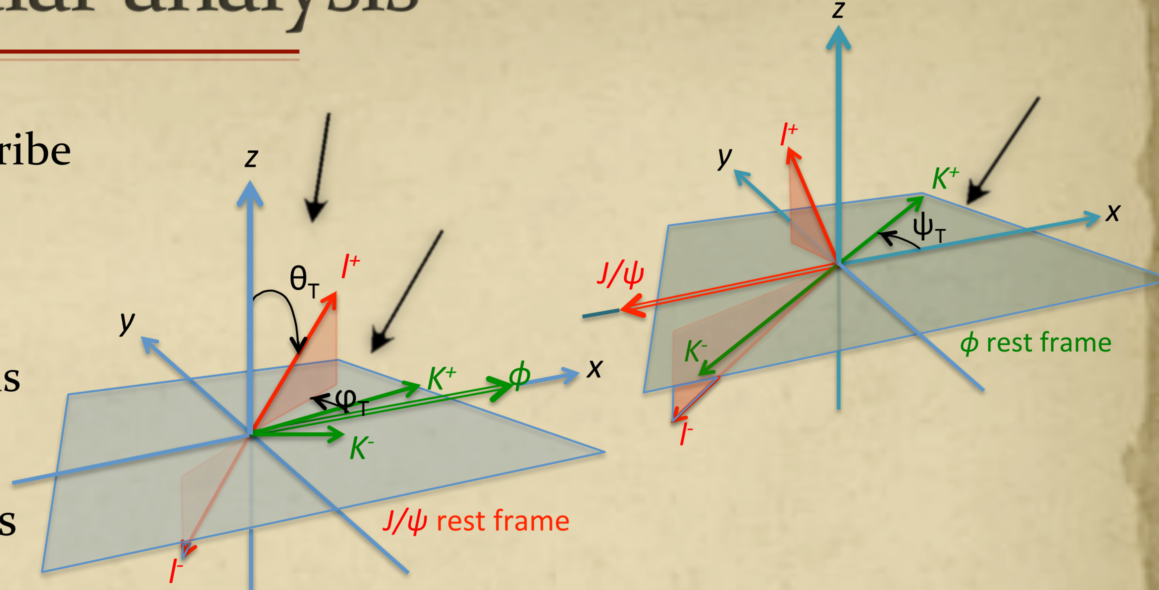
  - Indirect determination via global fits to experimental data → ϕ_s = -0.0364 ± 0.0016 rad
  - Small uncertainty makes direct measurement interesting since NP could modify ϕ_s and the ratio $\Delta\Gamma_s / \Delta m_s$ if new particles contributes to B_s/anti-B_s box diagrams.

$B_s \to J/\psi\, \phi$: angular analysis

ATLAS-CONF-2013-039

- Transversity angles used to describe the angular distributions
- Analysis on 4.9 fb^{-1} @ 7 TeV
- Each B candidate initial flavour is tagged (ATLAS-CONF-2013-039)

  → allows to improves fit results



❖ **Un-binned maximum likelihood fit to extract the signal**

trigger inefficiency (~ 1 %)

signal with amplitude f_s

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

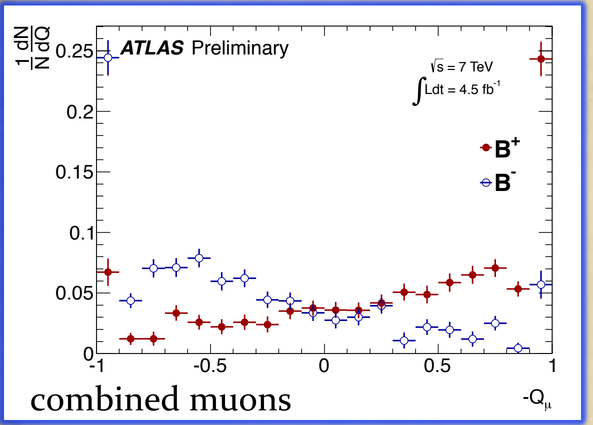
prompt and non-prompt combinatorial background described with empirical angular distribution (no K-π discrimination)

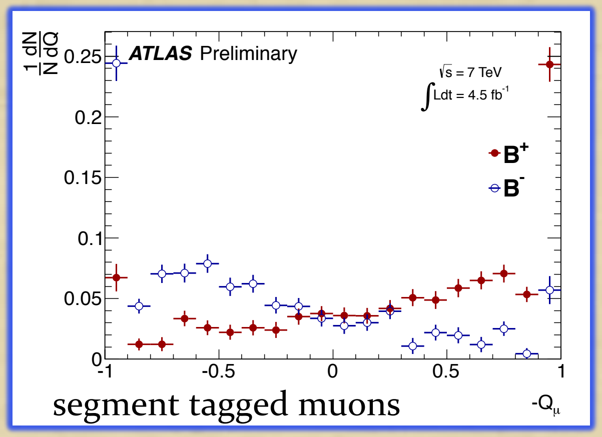
background from $B^0 \to J/\psi\, K^{*0}$ and $B^0 \to J/\psi\, K\, \pi$ with amplitude f_B

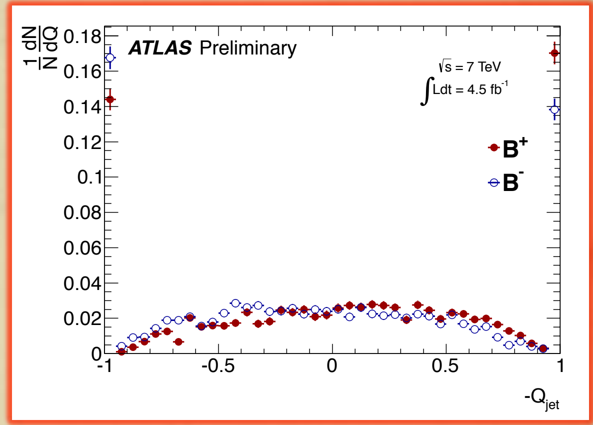
$B_s \to J/\psi\, \phi$: flavour tagging

ATLAS-CONF-2013-039

- Initial flavour of neutral B-mesons can be determined using information from the other B-meson that is typically produced from the other *b* quark in the event







Muon tagger

- Muon charge identified through semi-leptonic decay of B
- Evaluate muon cone charge Q_μ

Charge jet tagger

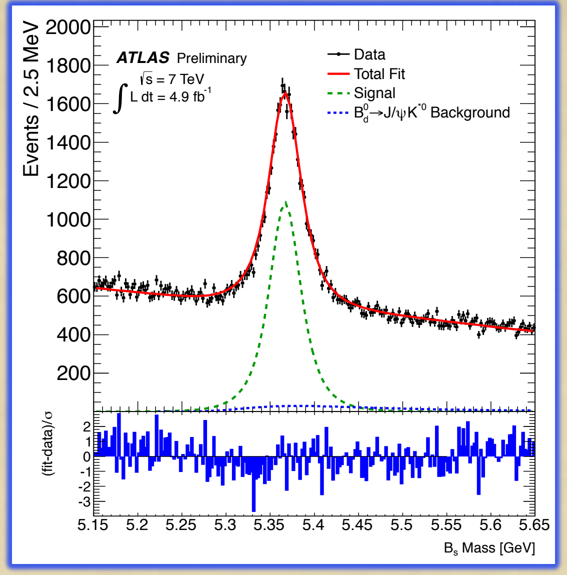
- Tracks associated to the jet from the same PV of signal decay
- Evaluate jet cone charge Q_{jet}

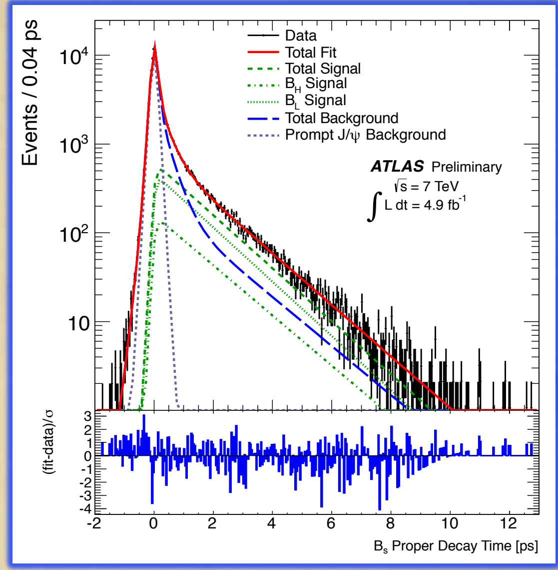
- **Two method combined according to the hierarchy of performance**
- Probability that signal decay contains b-bar as a function of Q_μ and Q_{jet} calibrated using $B^+ \to J/\psi\, K^+$ sample
- Un-binned maximum likelihood fit performed considering probability distribution and per-candidate probability (P=0.5 if no tagging information is available)

$B_s \to J/\psi\,\phi$: fit results

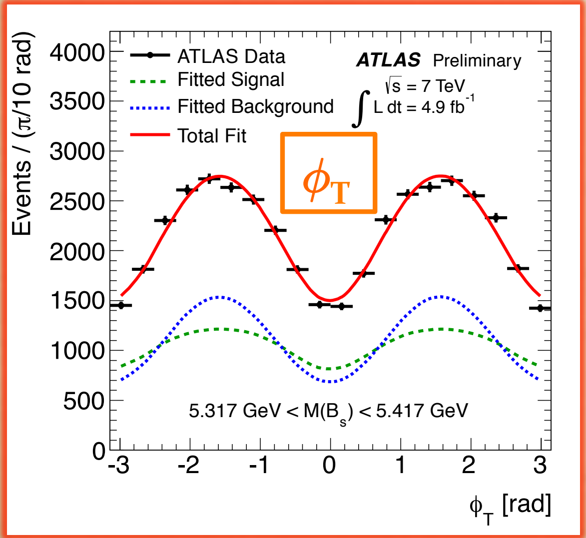
ATLAS-CONF-2013-039

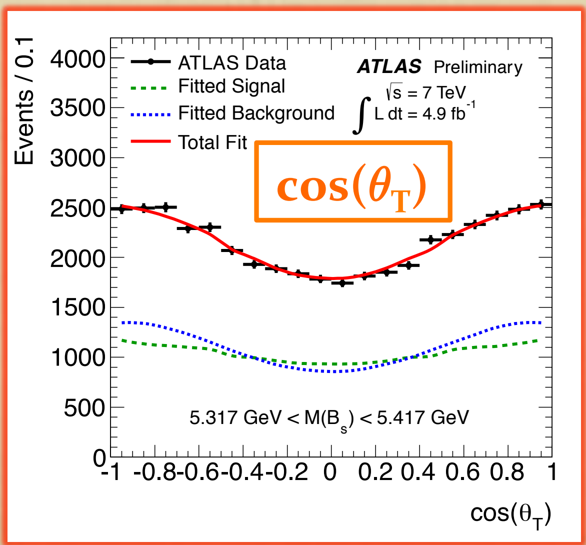
- **Projection on B_s mass and proper decay time**
  → 22670 ± 150 signal events from the fit

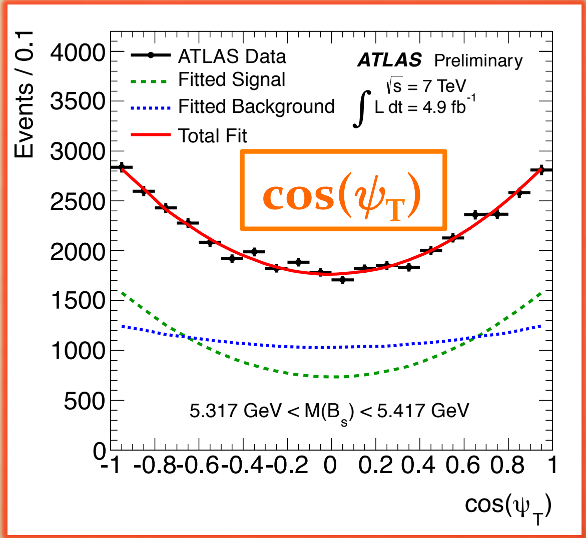




- **Projection on the three transversity angles**





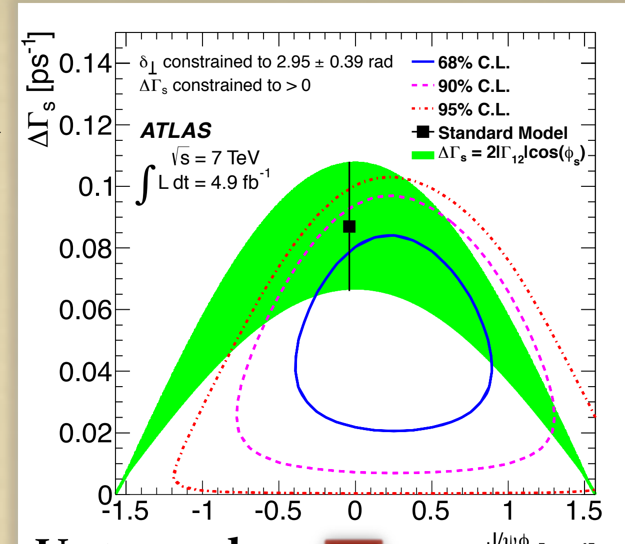


$B_s \to J/\psi\, \phi$: results

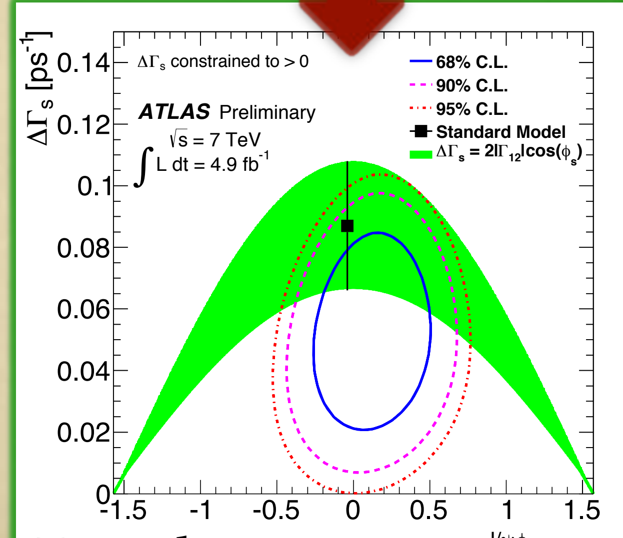
ATLAS-CONF-2013-039

- Tagging removes a constraint on the fit
  - **Statistical error on ϕ_s reduced by 40 %** compared to untagged analysis
  - $\Delta\Gamma_s$ central value and uncertainty unchanged
  - Measurement of the strong phase δ_T
- Main source of systematic → uncorrelated description of background angle distributions
- Results on 4.9 fb^{-1} @ 7 TeV
  - ϕ_s = 0.12 ± 0.25 (stat.) ± 0.11 (syst.) rad
  - $\Delta\Gamma_s$ = 0.053 ± 0.021 (stat.) 0± 0.009 (syst.) ps^{-1}
  - Γ_s = 0.677 ± 0.007 (stat.) ± 0.003 (syst.) ps^{-1}
  - $|A_0(0)|^2$ = 0.529 ± 0.006(stat.) ± 0.011 (syst.)
  - $|A_{||}(0)|^2$ = 0.220 ± 0.008(stat.) ± 0.009 (syst.)
  - δ_T = 3.89 ± 0.46 (stat.) ± 0.13 (syst.) rad

Likelihood profile in the ϕ_s - $\Delta\Gamma_s$



Untagged



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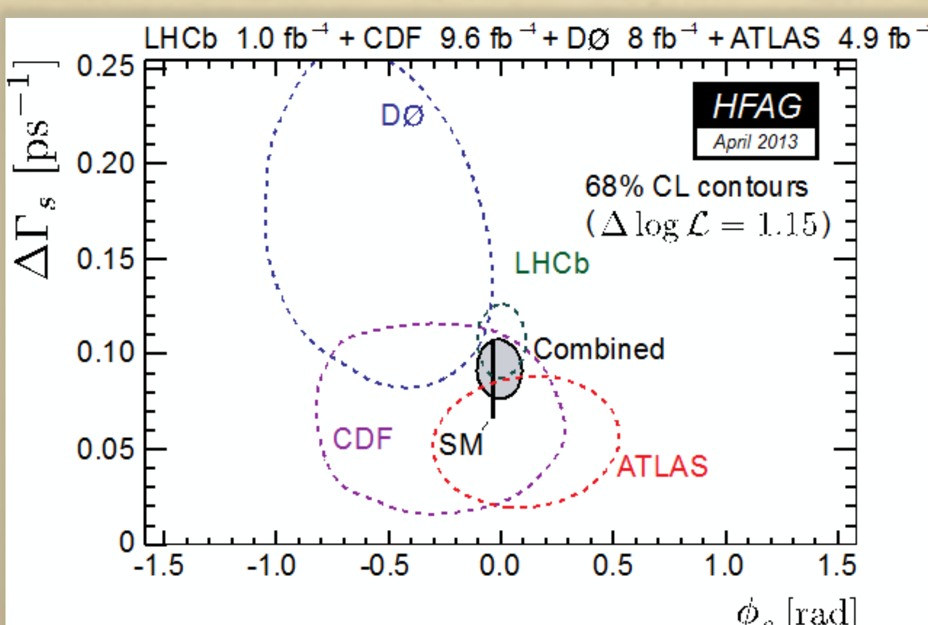
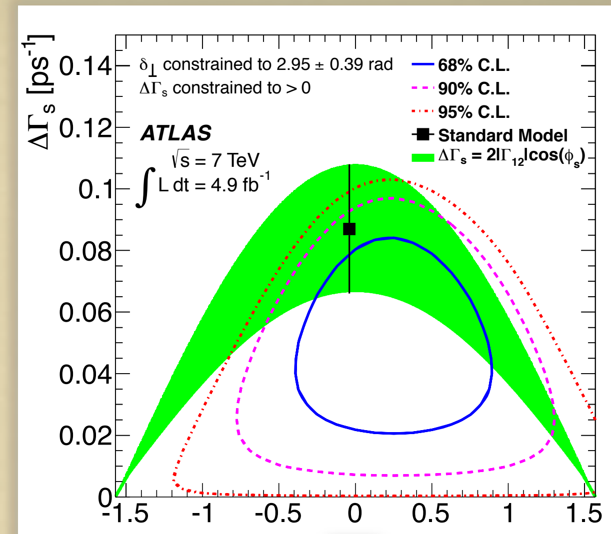
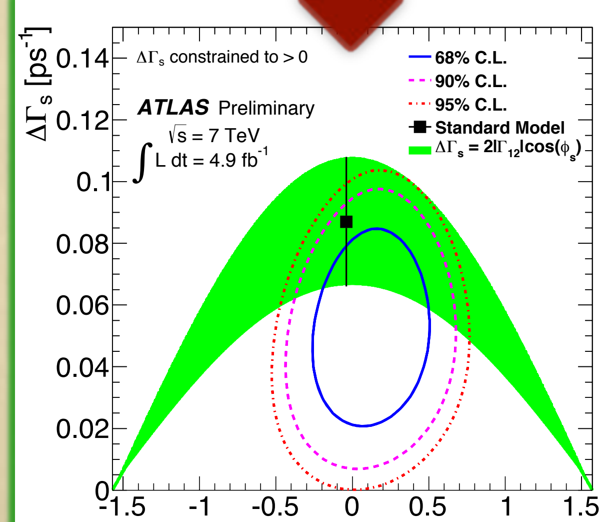
- Main source of systematic → uncorrelated description of background angle distributions
- Comparison with the other experiments



Likelihood profile in the ϕ_s - $\Delta\Gamma_s$



Untagged



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ATLAS-CONF-2013-039

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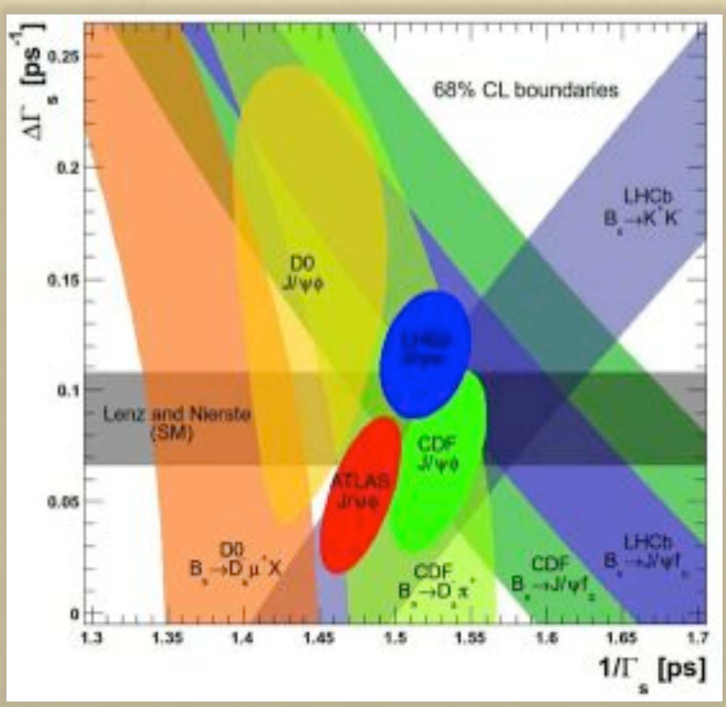
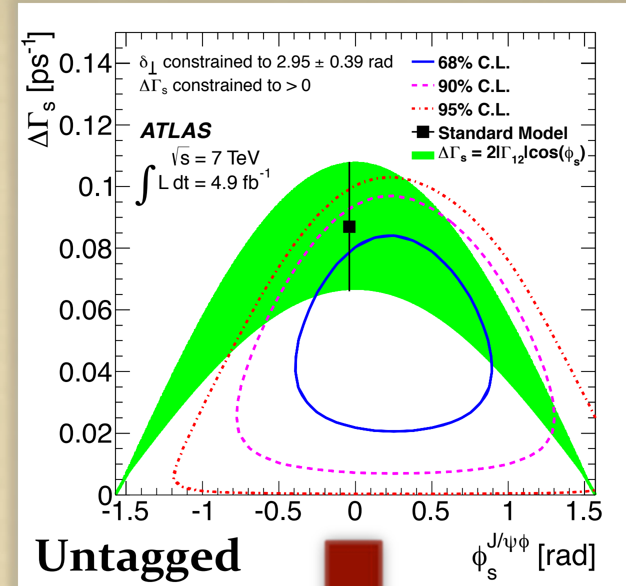
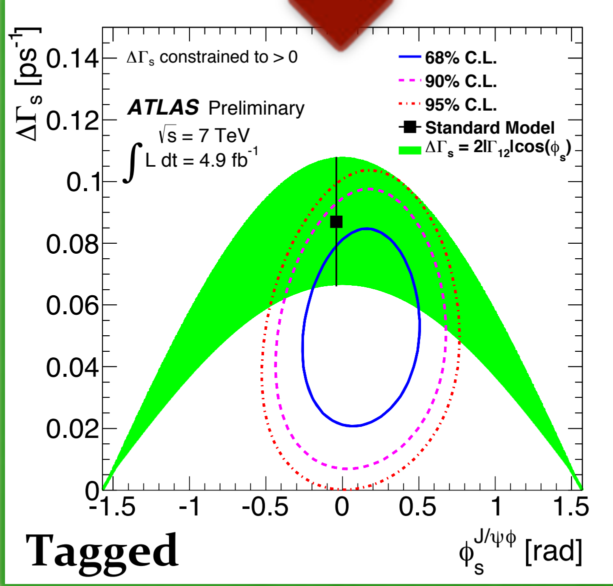
- Main source of systematic → uncorrelated description of background angle distributions
- $\Delta\Gamma_s$ vs $1/\Gamma_s$



Likelihood profile in the ϕ_s - $\Delta\Gamma_s$



Untagged



Tagged

Conclusions

- ATLAS can provide high quality measurements in the B^0 system
  - $B_d \rightarrow K^* \mu^+ \mu^-$ angular analysis

    ATLAS-CONF-2013-038
  - $B_s \rightarrow \mu^+ \mu^-$ search

    ATLAS-CONF-2013-076
  - $B_s \rightarrow J/\psi\ \phi$ measurements of CP violating phase ϕ_s and decay width difference $\Delta\Gamma_s$ **(to be published very soon)**

    ATLAS-CONF-2013-039

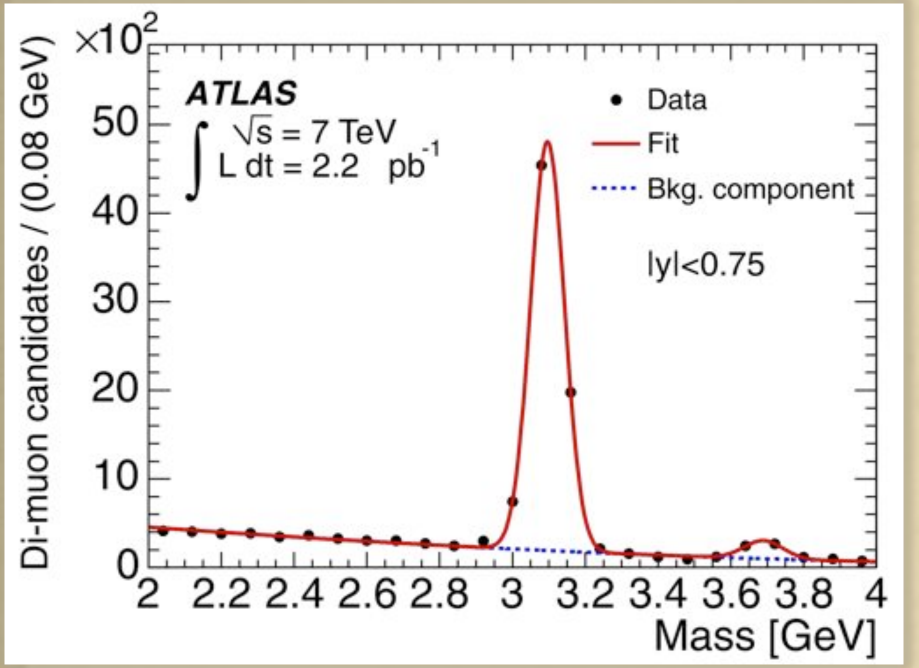
- Results consistent with SM predictions
- Measurements performed on 4.9 fb^{-1} of data (2011) are statistically limited
- Analyses on ~ 20 fb^{-1} of data collected in the 2012 ongoing → **plenty of possibilities for improvements**

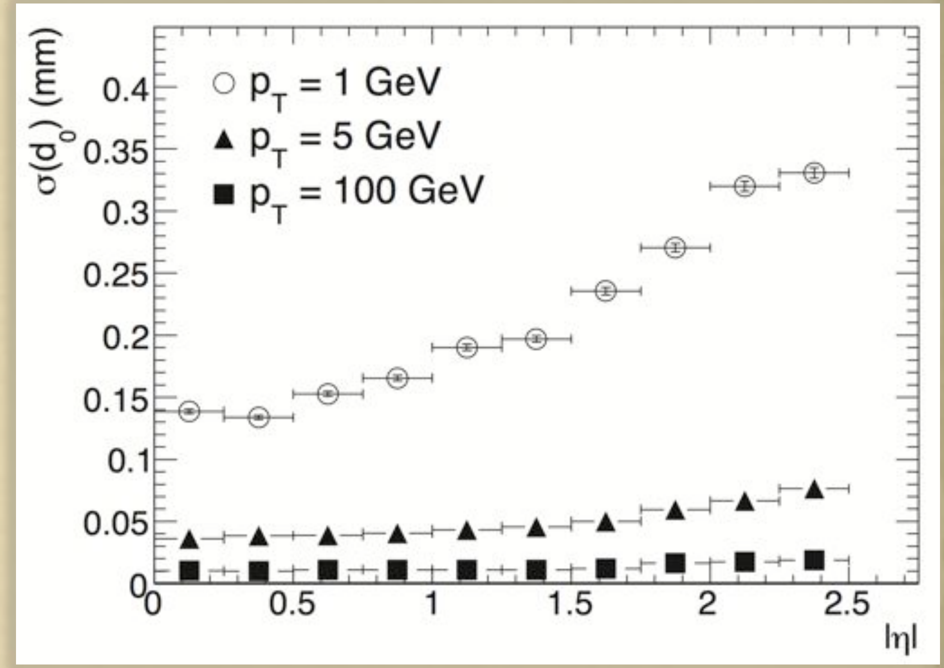
Backup

ATLAS performance

- For good S/B separation
  → need good mass resolution

- For lifetime measurements
  → need good impact parameter resolution

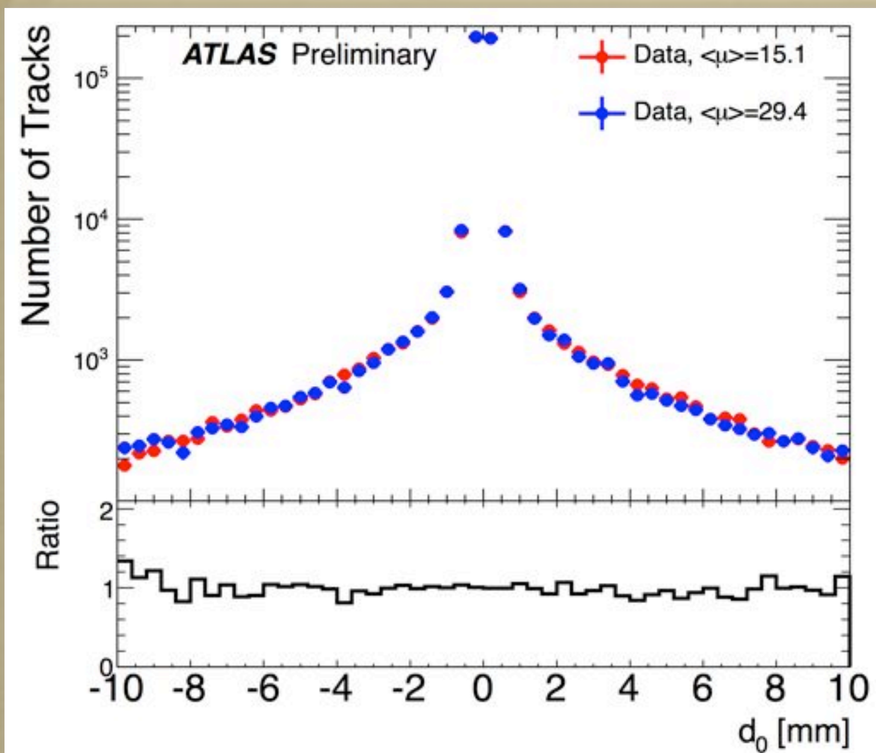


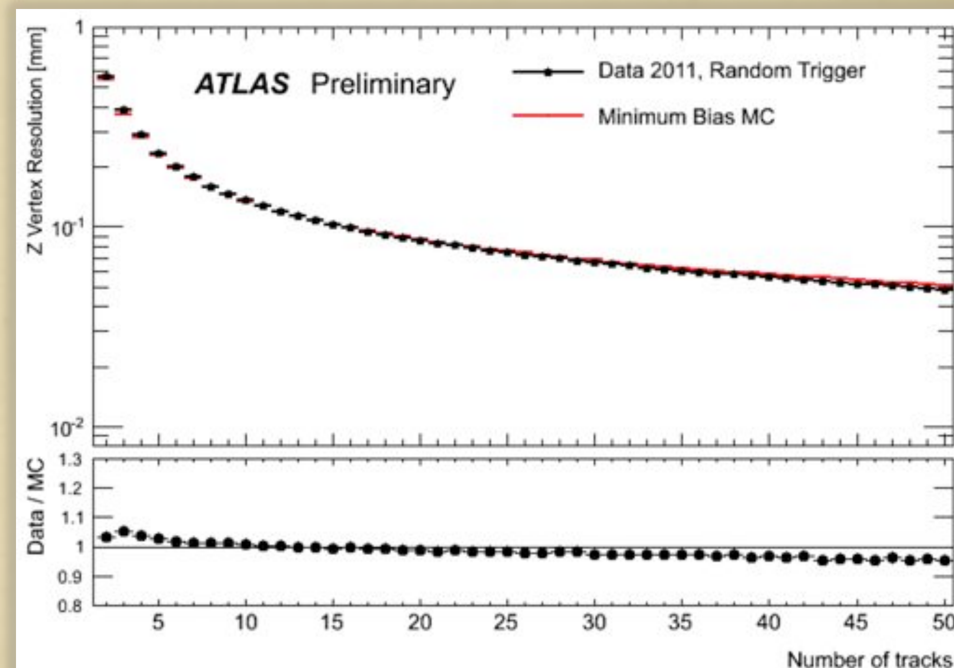


- K/π separation possible, but limited to $p_T < 1$ GeV/c

ATLAS performance

- Vertex resolution important to have very precise measurements
  → rare decays, CP violation, lifetime





$B_d \to K^*\mu^+\mu^-$: q^2 binning

- Used the same binning adopted by Belle experiment:
  - $0.04 < q^2 < 2.00$ GeV² (low statistic, **no angular analysis**)
  - $2.00 < q^2 < 4.30$ GeV²
  - $4.30 < q^2 < 8.68$ GeV²
  - $8.68 < q^2 < 10.09$ GeV² (J/ψ mass region, **not considered**)
  - $10.09 < q^2 < 12.86$ GeV²
  - $12.86 < q^2 < 14.18$ GeV² ($\psi(2S)$ mass region, **not considered**)
  - $14.18 < q^2 < 16.00$ GeV²
  - $16.00 < q^2 < 19.00$ GeV²

  - $1.00 < q^2 < 6.00$ GeV² (wider bin)

$B_d \to K^*\mu^+\mu^-$: mass fit

- Extended maximum likelihood fit in each q^2 bin
- Sequential fit:
  1) fit $m(K\pi\mu\mu)$ distribution
  2) fit the angular distributions with mass term parameters fixed
  - Checked that sequential fit gives same results as single-step fit → OK apart from lowest q^2 bin (included in the systematic)
- Mass fit:

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

- Gaussian with per-candidate error for the signal:

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

- Exponential for the background: $\mathcal{M}_{\text{bckg}}(m_i) = e^{-\lambda \cdot m_i}$

$B_d \to K^*\mu^+\mu^-$: angular analysis

- Angular fit likelihood:

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

- PDFs for the signal:

$$\mathcal{M}_{L,\rm sig}(\cos\theta_{L,i}) = \left(\frac{3}{4}F_L\left(1-(\cos\theta_{L,i})^2\right) + \frac{3}{8}(1-F_L)\left(1+(\cos\theta_{L,i})^2\right) + \tilde{A}_{FB}\cos\theta_{L,i}\right) \cdot f(\cos\theta_{L,i})$$

$$\mathcal{M}_{K,\rm sig}(\cos\theta_{K,i}) = \frac{3}{2}F_L(\cos\theta_{K,i})^2 + \frac{3}{4}(1-F_L)\left(1-(\cos\theta_{K,i})^2\right) \cdot f(\cos\theta_{K,i})$$

- PDF for the background:

$$\mathcal{M}_{L(K),\rm bkg} = 1 + p_{1\,L(K)} \cos\theta_{L(K),i} + p_{2\,L(K)}(2\cos^2\theta_{L(K),i} - 1)$$

linear combination of Chebyshev polynomials up to 2nd order

- Acceptance functions (detector and selection effect on the angular shape)

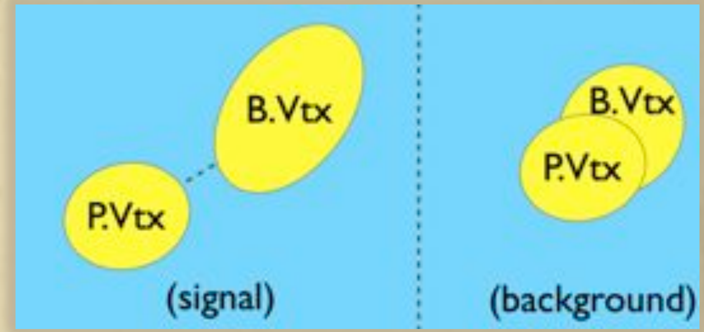
$$\alpha_L(\cos\theta_{L,i}) \quad , \quad \alpha_K(\cos\theta_{K,i})$$

$B_d \to K^*\mu^+\mu^-$ systematic uncertainties

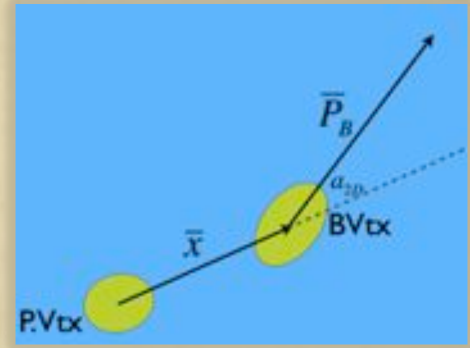
- Mass fit region ranges
  - Differ in q^2 bins due to ΔM cut effect
- Angular background shapes
  - 2^{nd} and 3^{rd} Chebyshev polynomials
- Contribution of $B^\pm \to \mu^+\mu^- K^\pm$ events
  - Estimated by removing potential $B^\pm \to \mu^+\mu^- K^\pm$ candidates
- Angular acceptance effects
  - 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
- Other negligible sources
  - 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)

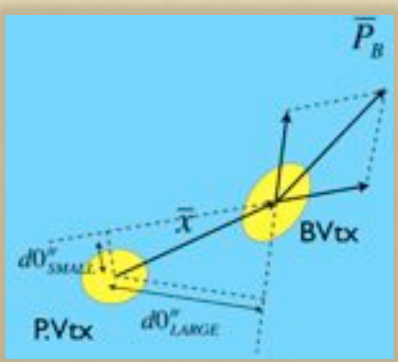
$B_s \to \mu^+\mu^-$: background discrimination

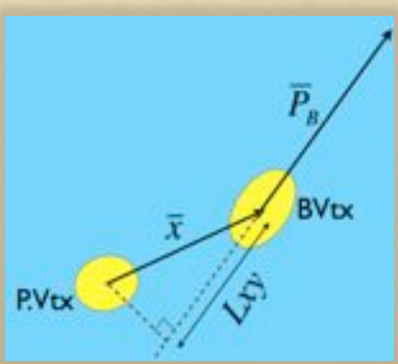
- Discriminating variables to separate signal from background events
  - 13 discriminating variables used in a Boosted Decision Tree (BDT)
    - ✓ **not correlated with invariant mass**
    - ✓ highest discriminating power
    - ✓ excluded variables with high correlation



  - Exploit
    - ✓ PV-SV separation → L_{xy} , proper time significance.
    - ✓ Symmetry of the final state → $|\alpha_{2D}|$, d_0 …
    - ✓ Full reconstruction → $|\alpha_{2D}|$, d_0 , DCA, ZCA …
    - ✓ B hadronisation features → p_T , Isolation …







$B_s \to \mu^+\mu^-$: background discrimination

Variable	Description
α_{2D}	(pointing angle) 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 $\Delta\vec{x} \cdot \vec{p}^B / \lvert\vec{p_T}^B\rvert$
ct significance	Proper decay length $ct = L_{xy} \times m_B / p_T^B$
χ^2_{xy}, χ^2_z	vertex separation significance between PV and SV in x-y plane and z respectively
$I_{0.7}$ (isolation)	ratio of $\lvert p_T^B\rvert$ to the sum of $\lvert p_T^{\vec{B}}\rvert$ 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 the B decay products
$\lvert d_0^{min}\rvert$, $\lvert d_0^{max}\rvert$	Absolute values of the minimum and maximum impact parameter in the transverse plane of the B decay products relative to the primary vertex
DCA, ZCA	Values of the minimum distance of closest approach in the $x - y$ plane (or along z) of tracks in the event to the B vertex
p_L^{min}	Minimum momentum of the two muon candidates along the B direction
p_T^B	B transverse momentum

$B_s \to J/\psi\ \phi$: flavour tagging

- Identifying the charge of a muon through the semi-leptonic decay of the *B* meson provides strong power of separation
- The $b \to \mu$ transitions are diluted through neutral *B* meson oscillations, as well as by cascade decays $b \to c \to \mu$ which can alter the sign of the muon relative to the one coming from direct semi-leptonic decays $b \to \mu$.
- The separation power of tag muons can be enhanced by
  - considering a weighted sum of the charge of the tracks in a cone around the muon

$$Q_\mu = \frac{\sum_i^{N\ \text{tracks}} q^i \cdot (p_T^i)^k}{\sum_i^{N\ \text{tracks}} (p_T^i)^k}$$

  - considering a weighted sum of charged tracks associated to the opposite side B meson

$$Q_{\text{jet}} = \frac{\sum_i^{N\ \text{tracks}} q^i \cdot (p_T^i)^k}{\sum_i^{N\ \text{tracks}} (p_T^i)^k}$$

- Probability to tag a signal event as b-bar

$$P(B|Q) = \frac{P(Q|B^+)}{P(Q|B^+) + P(Q|B^-)}$$

$$P(\bar{B}|Q) = 1 - P(Q|B)$$

$B_s \to J/\psi\ \phi$: systematic uncertainties

- **Inner Detector alignment →** residual misalignment affect the impact parameter w.r.t. PV (estimated using simulated events)
- **Angular acceptance method →** estimated the size of the systematic uncertainty introduced from the choice of the binning
- **Trigger efficiencies**
- **Defaults fit method**
- **Signal and background mass model, resolution model, background lifetime and background angles model →** variations of the model tested in pseudo-experiments to estimate the size of the systematic uncertainties caused by the assumption of the fit model.
- **B_d contribution**
- **Tagging →** systematic errors of the fit parameters due to uncertainty in tagging are estimated by comparing the default fit with the fits using alternate tag probabilities

Systematic	ϕ_s(rad)	$\Delta\Gamma_s$(ps^{-1})	Γ_s(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