Measurement of the CP-violating phase ϕ_s in $B_s^0 \to J/\psi(\mu^+\mu^-) + \phi(K^+K^-)$ decays

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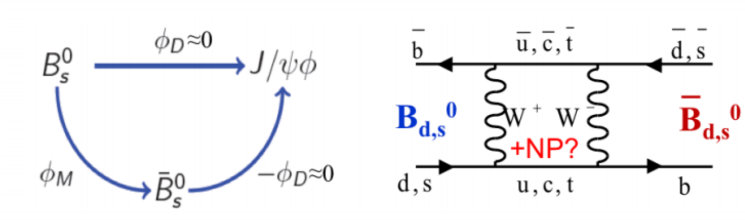
CP violating phase

- Weak phase difference between the $B_s^0 - \bar{B}_s^0$ mixing amplitude and the $b \to c\bar{c}s$ decay amplitude
    - Very sensitive to the New Physics



- Can be related to the CKM matrix: $\phi_s = -2\beta_s$, $\beta_s = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$
- Theoretical prediction assuming no NP contribution:

$$\phi_s = -0.0363^{+0.0016}_{-0.0015}$$

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High precision SM test

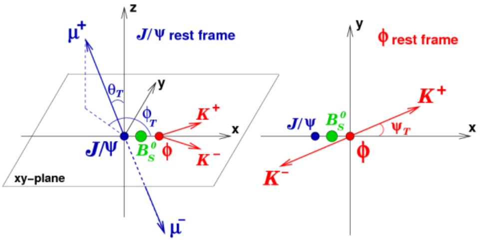
$B_s^0 \to J/\psi(\mu^+\mu^-) + \phi(K^+K^-)$ physics parameters:

- $\Gamma_s = \frac{1}{2}(\Gamma_s^L + \Gamma_s^H)$, $\Delta\Gamma = \Gamma_s^L - \Gamma_s^H$
  - Not sensitive to New Physics, however measurement is interesting to test a theory
  - Γ_s^L, Γ_s^H are decay widths of the different mass eigenstates
- $|A_0|^2$, $|A_\parallel|^2$, $|A_\perp|^2$, $\delta_\parallel$, $\delta_\perp$, $\delta_0 = 0$
  - CP odd ($\parallel$, 0) and even ($\perp$) amplitudes and strong phases
- $|A_S|^2$, δ_S
  - S-wave contribution, $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi f_0$
  - can significantly bias measurement of ϕ_s
- Differential decay rate with combination of time-dependent and angular terms

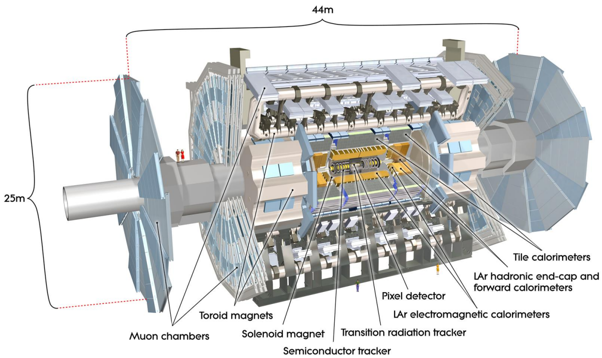
$$\frac{\mathrm{d}^4\Gamma}{\mathrm{d}t\mathrm{d}\Omega} = \sum_{k=1}^{10} \mathcal{O}^k(t) g^k(\theta_T, \psi_T, \phi_T)$$

High precision SM test

k	$\mathcal{O}^{(k)}(t)$ $\pm \to B_s/\bar{B}_s$	$g^{(k)}(\theta_T, \psi_T, \phi_T)$
1	$\frac{1}{2}\lvert A_0(0)\rvert^2 \left[(1+\cos\phi_s)\, e^{-\Gamma_{\mathrm{L}}^{(s)}t} + (1-\cos\phi_s)\, e^{-\Gamma_{\mathrm{H}}^{(s)}t} \pm 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$2\cos^2\psi_T(1-\sin^2\theta_T\cos^2\phi_T)$
2	$\frac{1}{2}\lvert A_\parallel(0)\rvert^2 \left[(1+\cos\phi_s)\, e^{-\Gamma_{\mathrm{L}}^{(s)}t} + (1-\cos\phi_s)\, e^{-\Gamma_{\mathrm{H}}^{(s)}t} \pm 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\sin^2\psi_T(1-\sin^2\theta_T\sin^2\phi_T)$
3	$\frac{1}{2}\lvert A_\perp(0)\rvert^2 \left[(1-\cos\phi_s)\, e^{-\Gamma_{\mathrm{L}}^{(s)}t} + (1+\cos\phi_s)\, e^{-\Gamma_{\mathrm{H}}^{(s)}t} \mp 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\sin^2\psi_T\sin^2\theta_T$
4	$\frac{1}{2}\lvert A_0(0)\rvert\lvert A_\parallel(0)\rvert\cos\delta_{\parallel}$ $\left[(1+\cos\phi_s)\, e^{-\Gamma_{\mathrm{L}}^{(s)}t} + (1-\cos\phi_s)\, e^{-\Gamma_{\mathrm{H}}^{(s)}t} \pm 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$-\frac{1}{\sqrt{2}}\sin 2\psi_T\sin^2\theta_T\sin 2\phi_T$
5	$\lvert A_\parallel(0)\rvert\lvert A_\perp(0)\rvert[\frac{1}{2}(e^{-\Gamma_{\mathrm{L}}^{(s)}t} - e^{-\Gamma_{\mathrm{H}}^{(s)}t})\cos(\delta_\perp-\delta_{\parallel})\sin\phi_s$ $\pm e^{-\Gamma_s t}(\sin(\delta_\perp-\delta_\parallel)\cos(\Delta m_s t) - \cos(\delta_\perp-\delta_\parallel)\cos\phi_s\sin(\Delta m_s t))]$	$\sin^2\psi_T\sin 2\theta_T\sin\phi_T$
6	$\lvert A_0(0)\rvert\lvert A_\perp(0)\rvert[\frac{1}{2}(e^{-\Gamma_{\mathrm{L}}^{(s)}t} - e^{-\Gamma_{\mathrm{H}}^{(s)}t})\cos\delta_\perp\sin\phi_s$ $\pm e^{-\Gamma_s t}(\sin\delta_\perp\cos(\Delta m_s t) - \cos\delta_\perp\cos\phi_s\sin(\Delta m_s t))]$	$\frac{1}{\sqrt{2}}\sin 2\psi_T\sin 2\theta_T\cos\phi_T$
7	$\frac{1}{2}\lvert A_S(0)\rvert^2 \left[(1-\cos\phi_s)\, e^{-\Gamma_{\mathrm{L}}^{(s)}t} + (1+\cos\phi_s)\, e^{-\Gamma_{\mathrm{H}}^{(s)}t} \mp 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\frac{2}{3}\left(1-\sin^2\theta_T\cos^2\phi_T\right)$
8	$\lvert A_S(0)\rvert\lvert A_\parallel(0)\rvert[\frac{1}{2}(e^{-\Gamma_{\mathrm{L}}^{(s)}t} - e^{-\Gamma_{\mathrm{H}}^{(s)}t})\sin(\delta_\parallel-\delta_S)\sin\phi_s$ $\pm e^{-\Gamma_s t}(\cos(\delta_\parallel-\delta_S)\cos(\Delta m_s t) - \sin(\delta_\parallel-\delta_S)\cos\phi_s\sin(\Delta m_s t))]$	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin^2\theta_T\sin 2\phi_T$
9	$\frac{1}{2}\lvert A_S(0)\rvert\lvert A_\perp(0)\rvert\sin(\delta_\perp-\delta_S)$ $\left[(1-\cos\phi_s)\, e^{-\Gamma_{\mathrm{L}}^{(s)}t} + (1+\cos\phi_s)\, e^{-\Gamma_{\mathrm{H}}^{(s)}t} \mp 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin 2\theta_T\cos\phi_T$
10	$\lvert A_0(0)\rvert\lvert A_S(0)\rvert[\frac{1}{2}(e^{-\Gamma_{\mathrm{H}}^{(s)}t} - e^{-\Gamma_{\mathrm{L}}^{(s)}t})\sin\delta_S\sin\phi_s$ $\pm e^{-\Gamma_s t}(\cos\delta_S\cos(\Delta m_s t) + \sin\delta_S\cos\phi_s\sin(\Delta m_s t))]$	$\frac{4}{3}\sqrt{3}\cos\psi_T\left(1-\sin^2\theta_T\cos^2\phi_T\right)$



ATLAS Detector



- Inner Detector: PIX, SCT and TRT, $p_{\mathrm{T}} > 0.4$ GeV, $|\eta| < 2.5$
  - In Run2: IBL
  - Run1 resolution in b-hadron proper decay time was $\sim$100 fs (30% improvement with IBL)
- Muon Spectrometer: triggering ($|\eta| < 2.4$), precision tracking ($|\eta| < 2.7$)

Data Analysis

Data:

- Using **80.5 fb**$^{-1}$ of *pp* 2015-17 data, 13 TeV
- Statistically combined with Run1 ATLAS results:
  - 4.9 fb^{-1} (7 TeV, *pp* 2011)
  - 14.3 fb^{-1} (8 TeV, *pp* 2012) - statistically combined with 7 TeV
- Collected by trigger based on identification of J/ψ with $p_{\mathrm{T}}(\mu)$ threshold (mainly 4 and 6 GeV)
- Including MC samples for $B_s^0 \to J/\psi\phi$ and dedicated backgrounds $B_d^0 \to J/\psi K^*$, $B_d^0 \to K^*\pi$ and $\Lambda_b \to J/\psi pK$
- No lifetime cut - signal-background separation done by the fit

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Final state

- Admixture of *CP*-odd (L = 1) and *CP*-even (L = 0, 2) states distinguishable through time-dependent angular analysis

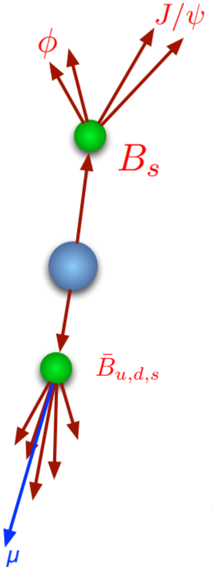
Initial state

- Flavour tagging

Flavour Tagging Overview

- Punzi terms (conditional probability):

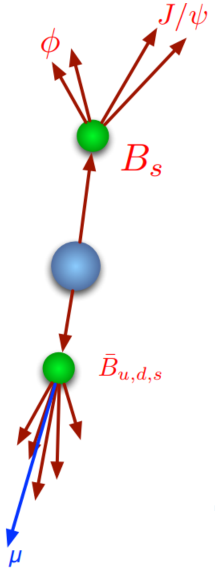
$$\mathcal{F}_{\mathrm{s}}(m_i, t_i, \sigma_{t_i}, \Omega_i, \boxed{P(B|Q)}, p_{\mathrm{T}_i}) =$$
$$P_{\mathrm{s}}(m_i) \cdot P_{\mathrm{s}}(\Omega_i, t_i, \boxed{P(B|Q)}, \sigma_{t_i}) \cdot P_{\mathrm{s}}(\sigma_{t_i})$$
$$\cdot P_{\mathrm{s}}(\boxed{P(B|Q)}) \cdot A(\Omega_i, p_{\mathrm{T}_i}) \cdot P_{\mathrm{s}}(p_{\mathrm{T}_i}).$$



Flavour Tagging Overview

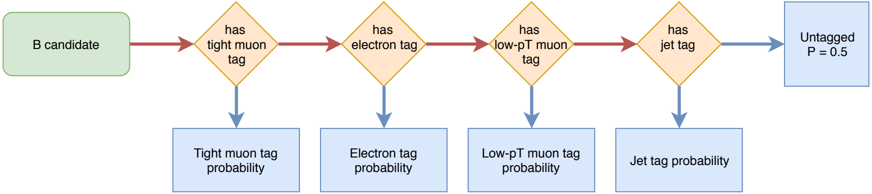
- Opposite side tagging
  - Use $b - \bar{b}$ pair correlation to infer initial signal flavour from the other B meson
  - Provide the probability of signal candidate to be B_s^0 or $\overline{B}_s^0$
- Punzi terms (conditional probability):

$$\mathcal{F}_{\mathrm{s}}(m_i, t_i, \sigma_{t_i}, \Omega_i, \boxed{P(B|Q)}, p_{\mathrm{T}_i}) =$$
$$P_{\mathrm{s}}(m_i) \cdot P_{\mathrm{s}}(\Omega_i, t_i, \boxed{P(B|Q)}, \sigma_{t_i}) \cdot P_{\mathrm{s}}(\sigma_{t_i})$$
$$\cdot P_{\mathrm{s}}(\boxed{P(B|Q)}) \cdot A(\Omega_i, p_{\mathrm{T}_i}) \cdot P_{\mathrm{s}}(p_{\mathrm{T}_i}).$$



Flavour Tagging Overview

- Opposite side tagging (Tight muons, Electrons, Low-p_{T} muons and Jets),
  - Events tagged by the method with the highest statistical power



- Muon and Electron Tagging
  - $b \to l$ transitions are clean tagging method
  - $b \to c \to l$ and neutral B-meson oscillations dilute the tagging
- Jet-Charge
  - information from tracks in b-tagged Jet, when no lepton is found
- Calibration using $B^{\pm} \to J/\psi K^{\pm}$

$B^{\pm}$ Calibration Channel

- Opposite side lepton or jet, with tracks in cone $\Delta R < 0.5$

$$Q = \frac{\sum_i^{Ntracks} q^i (p_{\mathrm{T}}^i)^\kappa}{\sum_i^{Ntracks} (p_{\mathrm{T}}^i)^\kappa} \quad \rightarrow \quad P(Q|B^{\pm}) \qquad Q \in < -1; 1 >$$

- Events separated - discrete contribution (cone charge +1 or -1) and continuous contribution

Tag method	Efficiency [%]	Effective Dilution [%]	Tagging Power [%]
Tight muon	4.50 ± 0.01	43.8 ± 0.2	0.862 ± 0.009
Electron	1.57 ± 0.01	41.8 ± 0.2	0.274 ± 0.004
Low-p_{T} muon	3.12 ± 0.01	29.9 ± 0.2	0.278 ± 0.006
Jet	5.54 ± 0.01	20.4 ± 0.1	0.231 ± 0.005
Total	14.74 ± 0.02	33.4 ± 0.1	1.65 ± 0.01

$$\varepsilon = \frac{\mathrm{N_{tagged}}}{\mathrm{N_{total}}} \qquad D = 1 - 2\frac{\mathrm{N_{wrong}}}{\mathrm{N_{tagged}}} \qquad TP = \varepsilon D^2$$

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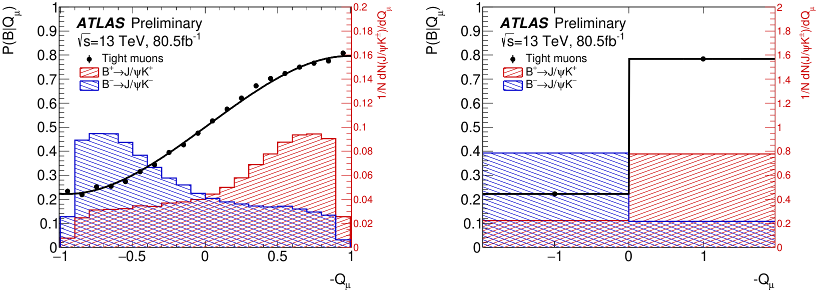


- The probability to tag a B_s^0 meson as containing a $\bar{b}$-quark:

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

- By using calibration curves: we get the B_s^0 tag probability

B_s^0 Decay Rate Fit Model

Unbinned maximum likelihood fit performed:

- Determine 9 physics variables to describe $B_s \to J/\psi\phi$ and S-wave: $\Delta\Gamma_s, \phi_s, \Gamma_s, |A_0(0)|^2, |A_{||}(0)|^2, |A_S(0)|^2, \delta_{||}, \delta_\perp, \delta_S$

$$\ln\ \mathcal{L} = \sum_{i=1}^{N}\{w_i \cdot \ln(f_\mathrm{s} \cdot \mathcal{F}_\mathrm{s}(m_i, t_i, \sigma_t, \Omega_i, P(B|Q))+ \\ + f_\mathrm{s} \cdot f_{B^0} \cdot \mathcal{F}_{B^0}(m_i, t_i, \sigma_t, \Omega_i)+ \\ + (1 - f_\mathrm{s} \cdot (1 + f_{B^0})) \cdot \mathcal{F}_\mathrm{bkg}(m_i, t_i, \Omega_i))\}$$

Signal PDF:

$$\mathcal{F}_\mathrm{s}(m_i, t_i, \sigma_{t_i}, \Omega_i, P(B|Q), p_{\mathrm{T}_i}) = P_\mathrm{s}(m_i) \cdot P_\mathrm{s}(\Omega_i, t_i, P(B|Q), \sigma_{t_i}) \\ \cdot P_\mathrm{s}(\sigma_{t_i}) \cdot P_\mathrm{s}(P(B|Q)) \cdot A(\Omega_i, p_{\mathrm{T}_i}) \cdot P_\mathrm{s}(p_{\mathrm{T}_i}).$$

- Differential decay rate with combination of time-dependent and angular terms

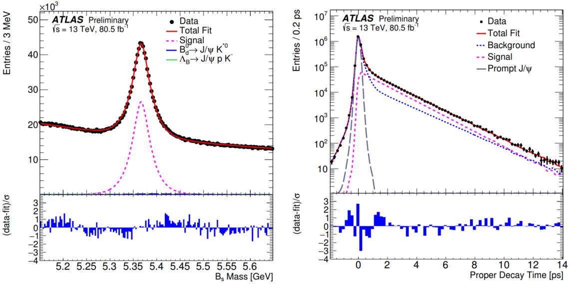
$$P_\mathrm{s}(\Omega_i, t_i, P(B|Q), \sigma_{t_i}) = \frac{\mathrm{d}^4\Gamma}{\mathrm{d}t\mathrm{d}\Omega} = \sum_{k=1}^{10} \mathcal{O}^k(t) g^k(\theta_T, \psi_T, \phi_T)$$

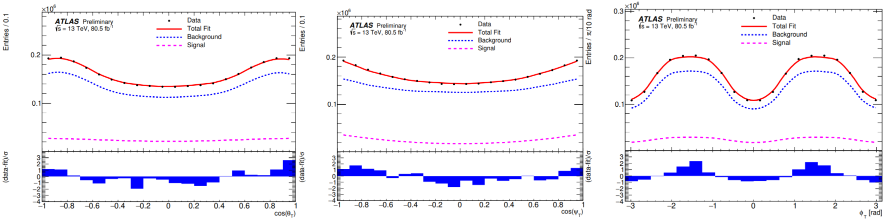
B_s^0 Decay Rate Fit Model

- Signal PDF consists of:
  - **Mass PDF**: gaussian with per-candidate error and scale factor
  - **Time-angular PDF** convolved with time resolution function $G(t, \sigma(t_i))$
  - **Angular acceptance** (from MC, in bins of p_T)
  - **Punzi terms**: empirical distributions of σ_{m_i}, σ_{t_i}, p_T, and $P(B|Q)$
- Background PDF:
  - **Mass PDF**: exponential + const.
  - **Time PDF**: delta-function + 3 exponentials convolved with time resolution function $G(t, \sigma(t_i))$
  - **Angular PDF**: Legendre polynomial functions

ATLAS 2015-2017 Results

- Fit projection to all data passing selection: 3 210 429 B_s^0 candidates (477240 ± 760 signal events)





ATLAS 2015-2017 Results

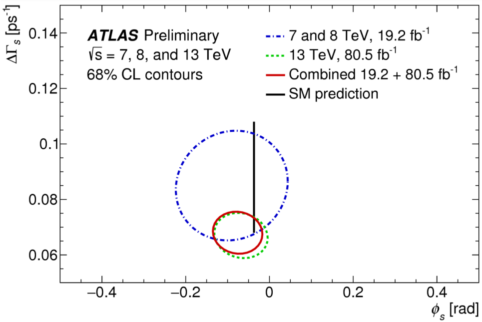
Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s[rad]	−0.068	0.038	0.018
$\Delta\Gamma_s$[ps^{-1}]	0.067	0.005	0.002
Γ_s[ps^{-1}]	0.669	0.001	0.001
$\lvert A_\parallel(0)\rvert^2$	0.219	0.002	0.002
$\lvert A_0(0)\rvert^2$	0.517	0.001	0.004
$\lvert A_S(0)\rvert^2$	0.046	0.003	0.004
$\delta_\perp$ [rad]	2.946	0.101	0.097
$\delta_\parallel$ [rad]	3.267	0.082	0.201
$\delta_\perp - \delta_S$ [rad]	−0.220	0.037	0.010

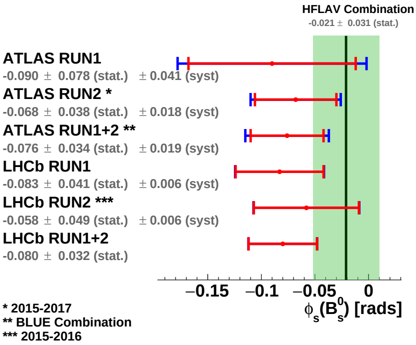
2015-2017 results

Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s[rad]	−0.076	0.034	0.019
$\Delta\Gamma_s$[ps^{-1}]	0.068	0.004	0.003
Γ_s[ps^{-1}]	0.669	0.001	0.001
$\lvert A_\parallel(0)\rvert^2$	0.220	0.002	0.002
$\lvert A_0(0)\rvert^2$	0.517	0.001	0.004
$\lvert A_S\rvert^2$	0.043	0.004	0.004
$\delta_\perp$ [rad]	3.075	0.096	0.091
$\delta_\parallel$ [rad]	3.295	0.079	0.202
$\delta_\perp - \delta_S$ [rad]	−0.216	0.037	0.010

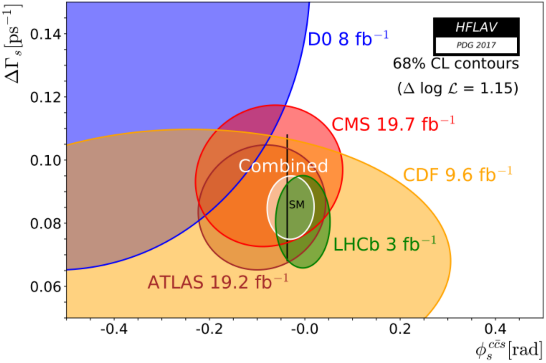
combined with Run1

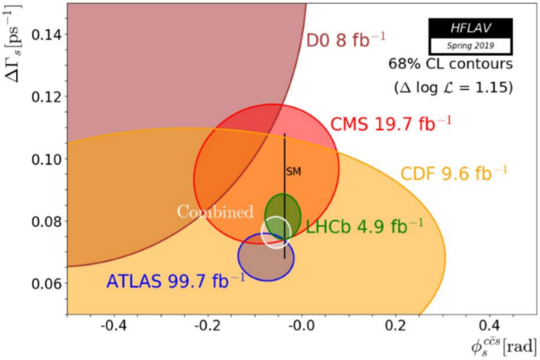
- The combination makes use of a Best Linear Unbiased Estimate (BLUE)





Comparison of Results



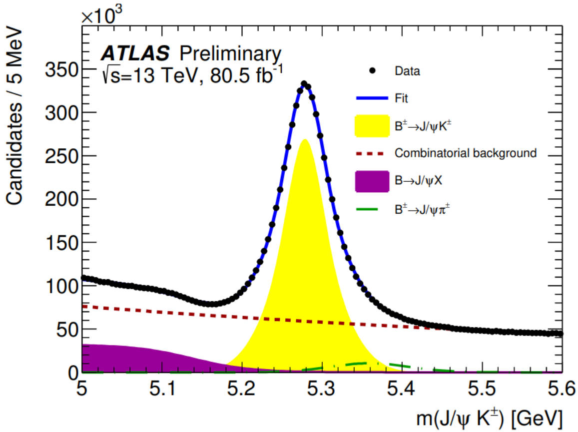


Summary

- Analysis of the 2015+2016+2017 ATLAS data performed
- Results combined with Run1 results
- Very impressive and competitive results
- Compatible with LHCb and CMS and the SM prediction
- Complete Run2 analysis ongoing (60 fb^{-1} more data)

Back-up Slides

$B^{\pm}$ Mass



×10^3
Candidates / 5 MeV
ATLAS Preliminary
√s=13 TeV, 80.5 fb^-1
Data
Fit
B±→J/ψK±
Combinatorial background
B→J/ψX
B±→J/ψπ±
0
50
100
150
200
250
300
350
5
5.1
5.2
5.3
5.4
5.5
5.6
m(J/ψ K±) [GeV]

Using Tag Information in B_s^0 Fit - Discrete Part

- Fractions of events f_{+1} and f_{-1} with charges $+1$ and -1, respectively, are determined separately for signal and background
- Remaining fraction of events, $1 - f_{+1} - f_{-1}$, constitute the continuous part

Tag method	Signal		Background	
	f_{+1} [%]	f_{-1} [%]	f_{+1} [%]	f_{-1} [%]
Tight muon	6.9 ± 0.3	7.5 ± 0.3	4.7 ± 0.1	4.9 ± 0.1
Electron	20 ± 1	19 ± 1	16.8 ± 0.2	17.3 ± 0.2
Low-p_T muon	10.9 ± 0.5	11.7 ± 0.5	7.0 ± 0.1	7.6 ± 0.1
Jet	4.51 ± 0.15	4.58 ± 0.16	3.76 ± 0.03	3.86 ± 0.03

Fraction of Tagged Events

Tag method	Signal efficiency [%]	Background efficiency [%]
Tight muon	4.00 ± 0.06	3.16 ± 0.01
Electron	1.87 ± 0.04	1.48 ± 0.01
Low-p_T muon	2.91 ± 0.05	2.64 ± 0.01
Jet	14.4 ± 0.1	11.96 ± 0.02
Untagged	76.7 ± 0.3	80.77 ± 0.05

Correlation Table

	$\Delta\Gamma$	Γ_s	$\lvert A_{\lvert\lvert}(0)\rvert^2$	$\lvert A_0(0)\rvert^2$	$\lvert A_S(0)\rvert^2$	$\delta_{\lvert\lvert}$	$\delta_\perp$	$\delta_\perp - \delta_S$
ϕ_s	−0.111	0.038	0.000	−0.008	−0.015	0.019	−0.001	−0.011
$\Delta\Gamma$	1	−0.563	0.092	0.097	0.042	0.036	0.011	0.009
Γ_s		1	−0.139	−0.040	0.103	−0.105	−0.041	0.016
$\lvert A_{\lvert\lvert}(0)\rvert^2$			1	−0.349	−0.216	0.571	0.223	−0.035
$\lvert A_0(0)\rvert^2$				1	0.299	−0.129	−0.056	0.051
$\lvert A_S(0)\rvert^2$					1	−0.408	−0.175	0.164
$\delta_{\lvert\lvert}$						1	0.392	−0.041
$\delta_\perp$							1	0.052

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Systematic Table

	ϕ_s [rad]	$\Delta\Gamma_s$ [ps^{-1}]	Γ_s [ps^{-1}]	$\lvert A_\parallel(0)\rvert^2$	$\lvert A_0(0)\rvert^2$	$\lvert A_S(0)\rvert^2$	$\delta_\perp$ [rad]	$\delta_\parallel$ [rad]	$\delta_\perp - \delta_S$ [rad]
Tagging	1.7×10^{-2}	0.4×10^{-3}	0.3×10^{-3}	0.2×10^{-3}	0.2×10^{-3}	2.3×10^{-3}	1.9×10^{-2}	2.2×10^{-2}	2.2×10^{-3}
Acceptance	0.7×10^{-3}	$<10^{-4}$	$<10^{-4}$	0.8×10^{-3}	0.7×10^{-3}	2.4×10^{-3}	3.3×10^{-2}	1.4×10^{-2}	2.6×10^{-3}
ID alignment	0.7×10^{-3}	0.1×10^{-3}	0.5×10^{-3}	$<10^{-4}$	$<10^{-4}$	$<10^{-4}$	1.0×10^{-2}	7.2×10^{-3}	$<10^{-4}$
S–wave phase	0.2×10^{-3}	$<10^{-4}$	$<10^{-4}$	0.3×10^{-3}	$<10^{-4}$	0.3×10^{-3}	1.1×10^{-2}	2.1×10^{-2}	8.3×10^{-3}
Background angles model:									
Choice of fit function	1.8×10^{-3}	0.8×10^{-3}	$<10^{-4}$	1.4×10^{-3}	0.7×10^{-3}	0.2×10^{-3}	8.5×10^{-2}	1.9×10^{-1}	1.8×10^{-3}
Choice of p_T bins	1.3×10^{-3}	0.5×10^{-3}	$<10^{-4}$	0.4×10^{-3}	0.5×10^{-3}	1.2×10^{-3}	1.5×10^{-3}	7.2×10^{-3}	1.0×10^{-3}
Choice of mass interval	0.4×10^{-3}	0.1×10^{-3}	0.1×10^{-3}	0.3×10^{-3}	0.3×10^{-3}	1.3×10^{-3}	4.4×10^{-3}	7.4×10^{-3}	2.3×10^{-3}
Dedicated backgrounds:									
B_d^0	2.3×10^{-3}	1.1×10^{-3}	$<10^{-4}$	0.2×10^{-3}	3.1×10^{-3}	1.4×10^{-3}	1.0×10^{-2}	2.3×10^{-2}	2.1×10^{-3}
Λ_b	1.6×10^{-3}	0.4×10^{-3}	0.2×10^{-3}	0.5×10^{-3}	1.2×10^{-3}	1.8×10^{-3}	1.4×10^{-2}	2.9×10^{-2}	0.8×10^{-3}
Fit model:									
Time res. sig frac	1.4×10^{-3}	1.1×10^{-3}	$<10^{-4}$	0.5×10^{-3}	0.6×10^{-3}	0.6×10^{-3}	1.2×10^{-2}	3.0×10^{-2}	0.4×10^{-3}
Time res. p_T bins	3.3×10^{-3}	1.4×10^{-3}	0.1×10^{-2}	$<10^{-4}$	$<10^{-4}$	0.5×10^{-3}	6.2×10^{-3}	5.2×10^{-3}	1.1×10^{-3}
Total	1.8×10^{-2}	0.2×10^{-2}	0.1×10^{-2}	0.2×10^{-2}	0.4×10^{-2}	0.4×10^{-2}	9.7×10^{-2}	2.0×10^{-1}	0.1×10^{-1}