ATLAS Measurements of CP-Violation and Rare Decay Processes with B-Mesons

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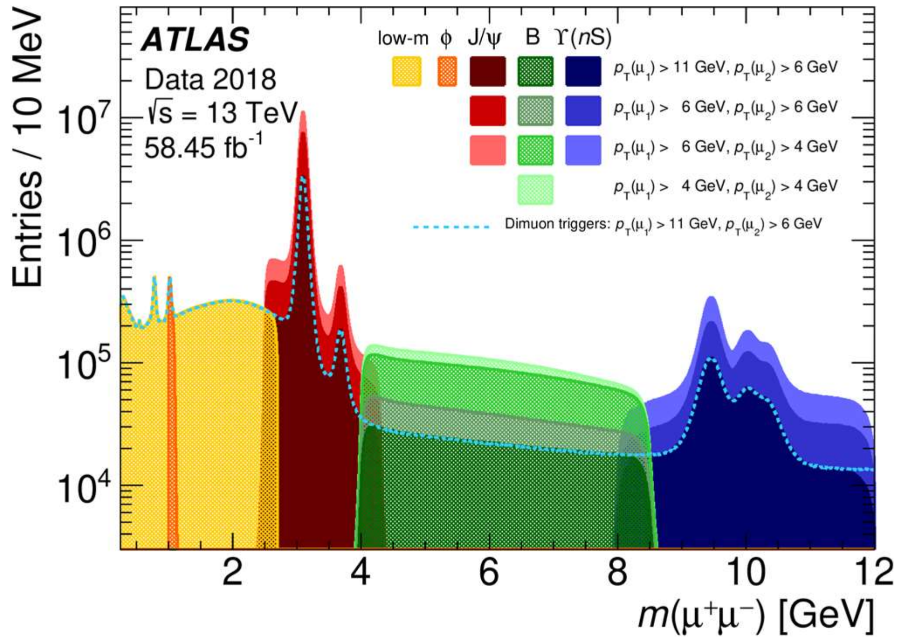
Introduction

- ATLAS has a rich and diverse physics program.
- Focus today on two b-physics results + future prospects:
  - CP-Violation in $B_s \rightarrow J/\psi\ \phi$ decays, *Eur. Phys. J. C* **81**, 342 (2021).
    - Run1 + 2015-2017
  - The rare decay $B_s \rightarrow \mu^+\mu^-$, *J. High Energ. Phys.* **2019**, 98 (2019).
    - Run1 + 2015-2016
    - Also ATLAS-CONF-2020-049 for LHC combinations.
- Other public results can be found here.
- And talks here at CIPANP22, HE, HP, and CKM tracks…

b-Physics in ATLAS

- 139 fb^{-1} of pp collisions collected during the LHC's Run2.
  - + 26.9 fb^{-1} during Run1.
  - > 2 Million $b\bar{b}$ pairs a second
- b-Physics studies focus mainly on:
  - Muonic states + full-reconstruction.
- Low-p_T (di-)muon triggers.
  - Vertex/Mass cuts for J/ψ-like triggers.
  - Tracks + cuts for 3/4/5 track signals.



CP-Violation in $B_s \rightarrow J/\psi\ \phi$ Decays

CP-Violation in $B_s \to J/\psi\ \phi$ Decays

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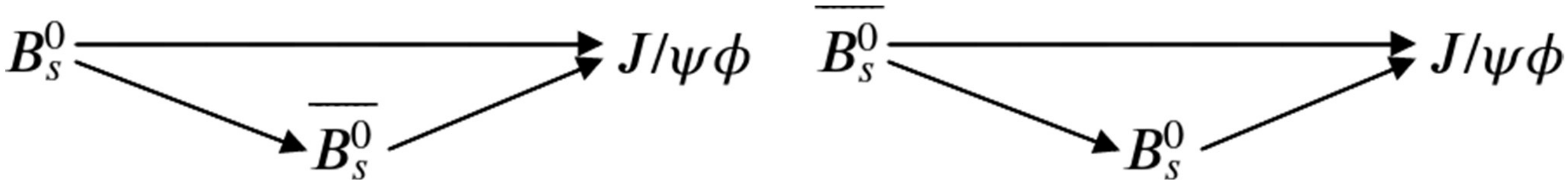
- Neutral meson oscillation + Decay → Interference + CP-Violation.
- Was (one of many) “Golden Channels” in b-physics for a long time…
  - NP in b → ccs, colour singlets, colour octets, and many, many others!
- Focus now comparison of direct measurements vs global fits.
  - $\Phi_s \approx -2\beta_s = -0.03696^{+0.00072}_{-0.00082}$ rads [CKMFitter], if no NP in mixing.



The Fit and Physics Parameters - 1

- Signal decay is pseudo-scalar → vector + vector…
  - Untangle CP-even/odd states with a time-dependent angular analysis.
- The end-state is $B_s \rightarrow J/\psi(\mu^+\mu^-)\ \phi(K^+K^-)$
  - Additional non-resonant KK contribution also fitted.
- Four decay amplitudes + interference → 10 term PDF:
  - Each with an amplitude, kinematic, flavour, and angular component.
  - Measure signal candidate lifetime + angles (+ errors).
  - Production flavour of the signal candidate.
  - Fit for:
    - Γ_s, $\Delta\Gamma_s$, Φ_s, 3 amplitudes + 3 phases for CP-even/odd states.
  - Fit other PDF parameters from public results.
    - ΔM_s from the PDG, λ_s (direct CP-violation) is fixed to 1.

The Fit and Physics Parameters - 2

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

The Fit and Physics Parameters - 2

Kinematics.

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

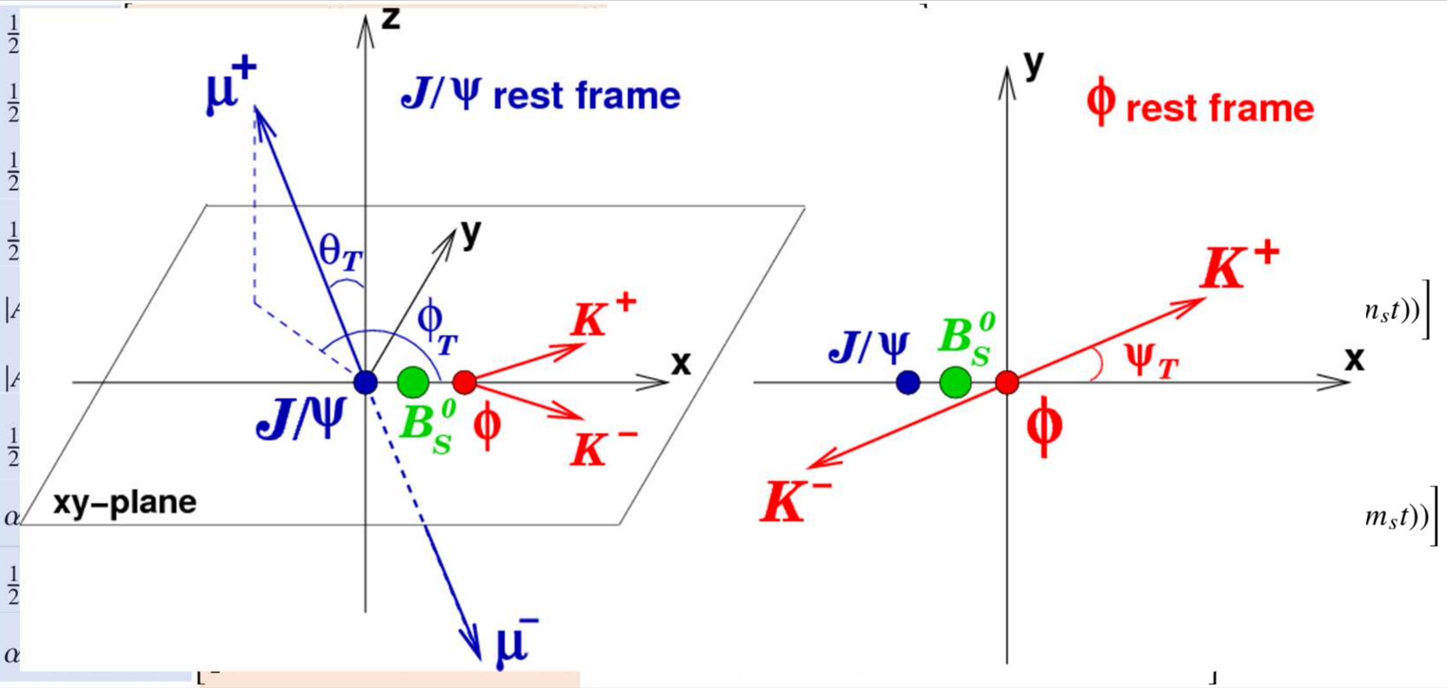
Amplitudes.

The Fit and Physics Parameters - 2

Kinematics.

Angles.

k	$\mathcal{O}^{(k)}(t)$	$g^{(k)}(\theta_T, \psi_T, \phi_T)$
1	$\frac{1}{2}$	$2\cos^2\psi_T(1-\sin^2\theta_T\cos^2\phi_T)$
2	$\frac{1}{2}$	$\sin^2\psi_T(1-\sin^2\theta_T\sin^2\phi_T)$
3	$\frac{1}{2}$	$\sin^2\psi_T\sin^2\theta_T$
4	$\frac{1}{2}$	$\frac{1}{\sqrt{2}}\sin 2\psi_T\sin^2\theta_T\sin 2\phi_T$
5	$\lvert A$ … $n_s t))\rvert$	$-\sin^2\psi_T\sin 2\theta_T\sin\phi_T$
6	$\lvert A$	$\frac{1}{\sqrt{2}}\sin 2\psi_T\sin 2\theta_T\cos\phi_T$
7	$\frac{1}{2}$	$\frac{2}{3}\left(1-\sin^2\theta_T\cos^2\phi_T\right)$
8	α … $m_s t))\rvert$	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin^2\theta_T\sin 2\phi_T$
9	$\frac{1}{2}$	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin 2\theta_T\cos\phi_T$
10	α	$\frac{4}{3}\sqrt{3}\cos\psi_T\left(1-\sin^2\theta_T\cos^2\phi_T\right)$



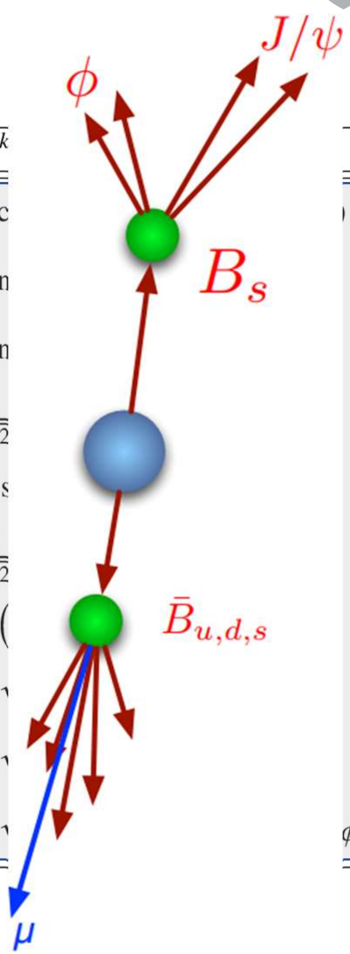
Amplitudes.

The Fit and Physics Parameters - 2

Lancaster University

Kinematics.

k	$O^{(k)}(t)$	$g^{(k}$
1	$\frac{1}{2}\lvert A_0(0)\rvert^2 \left[(1+\cos\phi_s)\, e^{-\Gamma_L^{(s)} t} + (1-\cos\phi_s)\, e^{-\Gamma_H^{(s)} t} \pm 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	2 c …)
2	$\frac{1}{2}\lvert A_\parallel(0)\rvert^2 \left[(1+\cos\phi_s)\, e^{-\Gamma_L^{(s)} t} + (1-\cos\phi_s)\, e^{-\Gamma_H^{(s)} t} \pm 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	sin
3	$\frac{1}{2}\lvert A_\perp(0)\rvert^2 \left[(1-\cos\phi_s)\, e^{-\Gamma_L^{(s)} t} + (1+\cos\phi_s)\, e^{-\Gamma_H^{(s)} t} \mp 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	sin
4	$\frac{1}{2}\lvert A_0(0)\rvert\lvert A_\parallel(0)\rvert\cos\delta_\parallel \left[(1+\cos\phi_s)\, e^{-\Gamma_L^{(s)} t} + (1-\cos\phi_s)\, e^{-\Gamma_H^{(s)} t} \pm 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\frac{1}{\sqrt{2}}$
5	$\lvert A_\parallel(0)\rvert\lvert A_\perp(0)\rvert \left[\frac{1}{2}(e^{-\Gamma_L^{(s)} t} - e^{-\Gamma_H^{(s)} t})\cos(\delta_\perp-\delta_\parallel)\sin\phi_s \pm e^{-\Gamma_s t}(\sin(\delta_\perp-\delta_\parallel)\cos(\Delta m_s t) - \cos(\delta_\perp-\delta_\parallel)\cos\phi_s\sin(\Delta m_s t))\right]$	− s
6	$\lvert A_0(0)\rvert\lvert A_\perp(0)\rvert \left[\frac{1}{2}(e^{-\Gamma_L^{(s)} t} - e^{-\Gamma_H^{(s)} t})\cos\delta_\perp\sin\phi_s \pm e^{-\Gamma_s t}(\sin\delta_\perp\cos(\Delta m_s t) - \cos\delta_\perp\cos\phi_s\sin(\Delta m_s t))\right]$	$\frac{1}{\sqrt{2}}$
7	$\frac{1}{2}\lvert A_S(0)\rvert^2 \left[(1-\cos\phi_s)\, e^{-\Gamma_L^{(s)} t} + (1+\cos\phi_s)\, e^{-\Gamma_H^{(s)} t} \mp 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\frac{2}{3}$ (
8	$\alpha\lvert A_S(0)\rvert\lvert A_\parallel(0)\rvert \left[\frac{1}{2}(e^{-\Gamma_L^{(s)} t} - e^{-\Gamma_H^{(s)} t})\sin(\delta_\parallel-\delta_S)\sin\phi_s \pm e^{-\Gamma_s t}(\cos(\delta_\parallel-\delta_S)\cos(\Delta m_s t) - \sin(\delta_\parallel-\delta_S)\cos\phi_s\sin(\Delta m_s t))\right]$	$\frac{1}{3}$
9	$\frac{1}{2}\alpha\lvert A_S(0)\rvert\lvert A_\perp(0)\rvert\sin(\delta_\perp-\delta_S) \left[(1-\cos\phi_s)\, e^{-\Gamma_L^{(s)} t} + (1+\cos\phi_s)\, e^{-\Gamma_H^{(s)} t} \mp 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\frac{1}{3}$
10	$\alpha\lvert A_0(0)\rvert\lvert A_S(0)\rvert \left[\frac{1}{2}(e^{-\Gamma_H^{(s)} t} - e^{-\Gamma_L^{(s)} t})\sin\delta_S\sin\phi_s \pm e^{-\Gamma_s t}(\cos\delta_S\cos(\Delta m_s t) + \sin\delta_S\cos\phi_s\sin(\Delta m_s t))\right]$	$\frac{4}{3}$ … $\phi_T)$



Amplitudes.

Flavour.

The Fit and Physics Parameters - 2

Kinematics.

Angles.

k	$O^{(k)}(t)$	$g^{(k)}(\theta_T, \psi_T, \phi_T)$
1	$\frac{1}{2}\|A_0(0)\|^2 \left[(1+\cos\phi_s)\,e^{-\Gamma_L^{(s)}t} + (1-\cos\phi_s)\,e^{-\Gamma_H^{(s)}t} \pm 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$2\cos^2\psi_T(1-\sin^2\theta_T\cos^2\phi_T)$
2	$\frac{1}{2}\|A_\parallel(0)\|^2 \left[(1+\cos\phi_s)\,e^{-\Gamma_L^{(s)}t} + (1-\cos\phi_s)\,e^{-\Gamma_H^{(s)}t} \pm 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\sin^2\psi_T(1-\sin^2\theta_T\sin^2\phi_T)$
3	$\frac{1}{2}\|A_\perp(0)\|^2 \left[(1-\cos\phi_s)\,e^{-\Gamma_L^{(s)}t} + (1+\cos\phi_s)\,e^{-\Gamma_H^{(s)}t} \mp 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\sin^2\psi_T\sin^2\theta_T$
4	$\frac{1}{2}\|A_0(0)\|\|A_\parallel(0)\|\cos\delta_\parallel \left[(1+\cos\phi_s)\,e^{-\Gamma_L^{(s)}t} + (1-\cos\phi_s)\,e^{-\Gamma_H^{(s)}t} \pm 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\frac{1}{\sqrt{2}}\sin 2\psi_T\sin^2\theta_T\sin 2\phi_T$
5	$\|A_\parallel(0)\|\|A_\perp(0)\| \left[\frac{1}{2}(e^{-\Gamma_L^{(s)}t} - e^{-\Gamma_H^{(s)}t})\cos(\delta_\perp-\delta_\parallel)\sin\phi_s \pm e^{-\Gamma_s t}(\sin(\delta_\perp-\delta_\parallel)\cos(\Delta m_s t) - \cos(\delta_\perp-\delta_\parallel)\cos\phi_s\sin(\Delta m_s t))\right]$	$-\sin^2\psi_T\sin 2\theta_T\sin\phi_T$
6	$\|A_0(0)\|\|A_\perp(0)\| \left[\frac{1}{2}(e^{-\Gamma_L^{(s)}t} - e^{-\Gamma_H^{(s)}t})\cos\delta_\perp\sin\phi_s \pm e^{-\Gamma_s t}(\sin\delta_\perp\cos(\Delta m_s t) - \cos\delta_\perp\cos\phi_s\sin(\Delta m_s t))\right]$	$\frac{1}{\sqrt{2}}\sin 2\psi_T\sin 2\theta_T\cos\phi_T$
7	$\frac{1}{2}\|A_S(0)\|^2 \left[(1-\cos\phi_s)\,e^{-\Gamma_L^{(s)}t} + (1+\cos\phi_s)\,e^{-\Gamma_H^{(s)}t} \mp 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\frac{2}{3}\left(1-\sin^2\theta_T\cos^2\phi_T\right)$
8	$\alpha\|A_S(0)\|\|A_\parallel(0)\| \left[\frac{1}{2}(e^{-\Gamma_L^{(s)}t} - e^{-\Gamma_H^{(s)}t})\sin(\delta_\parallel-\delta_S)\sin\phi_s \pm e^{-\Gamma_s t}(\cos(\delta_\parallel-\delta_S)\cos(\Delta m_s t) - \sin(\delta_\parallel-\delta_S)\cos\phi_s\sin(\Delta m_s t))\right]$	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin^2\theta_T\sin 2\phi_T$
9	$\frac{1}{2}\alpha\|A_S(0)\|\|A_\perp(0)\|\sin(\delta_\perp-\delta_S) \left[(1-\cos\phi_s)\,e^{-\Gamma_L^{(s)}t} + (1+\cos\phi_s)\,e^{-\Gamma_H^{(s)}t} \mp 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin 2\theta_T\cos\phi_T$
10	$\alpha\|A_0(0)\|\|A_S(0)\| \left[\frac{1}{2}(e^{-\Gamma_H^{(s)}t} - e^{-\Gamma_L^{(s)}t})\sin\delta_S\sin\phi_s \pm e^{-\Gamma_s t}(\cos\delta_S\cos(\Delta m_s t) + \sin\delta_S\cos\phi_s\sin(\Delta m_s t))\right]$	$\frac{4}{3}\sqrt{3}\cos\psi_T\left(1-\sin^2\theta_T\cos^2\phi_T\right)$

Amplitudes.

Flavour.

Flavour Tagging - 1

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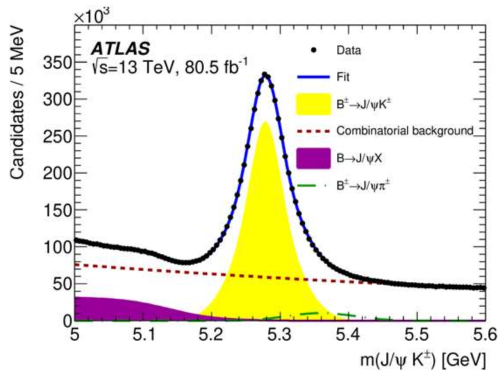
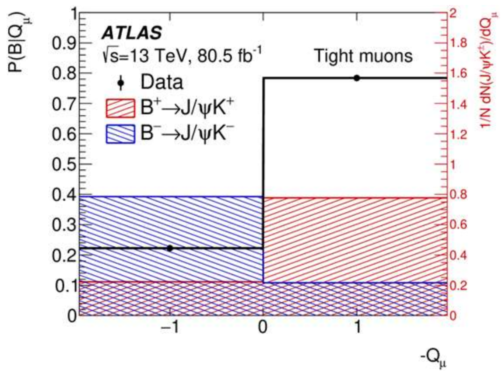
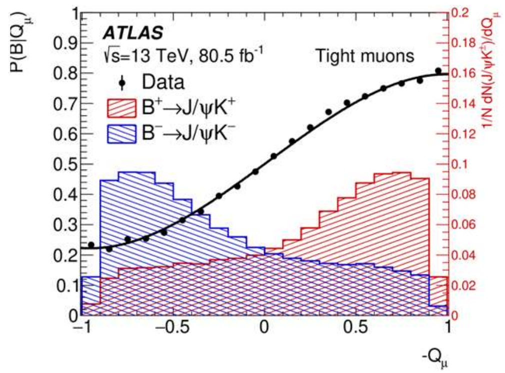
- Tag the signal candidates flavour from the pair-produced b-quark.
  - Looking for muons, electrons, or b-tagged jets.
  - Build a `cone charge`, Q_X, as sum of p_T weighted charges.
    - $Q_x = \frac{\sum_i q_i \cdot p_{Ti}^{\kappa}}{p_{Ti}^{\kappa}}$
- Calibrated/optimised on the self-tagging $B^{\pm} \rightarrow J/\psi\, K^{\pm}$ channel.







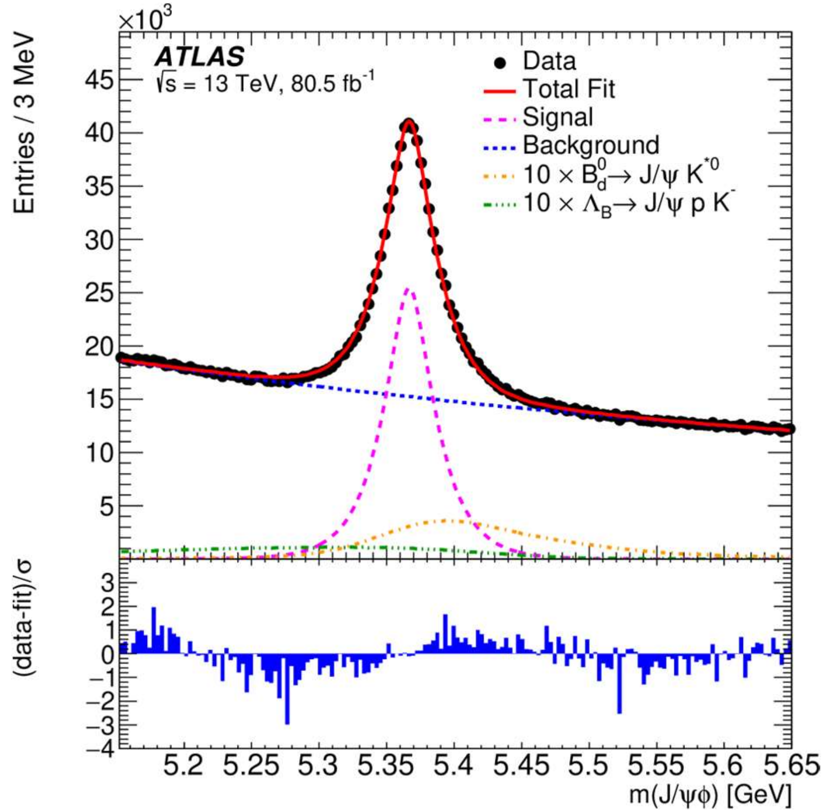
Flavour Tagging - 2

- From the cone charge, build per-candidate tag probability.
  - $P(B|Q) = \frac{P(Q|B^+)}{P(Q|B^+)+P(Q|B^-)}$
- Classify taggers by efficiency, dilution, and tagging power.
  - How often, how often right, how good over all…

Tag method	ϵ_x [%]	D_x [%]	T_x [%]
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	12.04 ± 0.02	16.6 ± 0.1	0.334 ± 0.006
Total	21.23 ± 0.03	28.7 ± 0.1	1.75 ± 0.01

Fits to Data

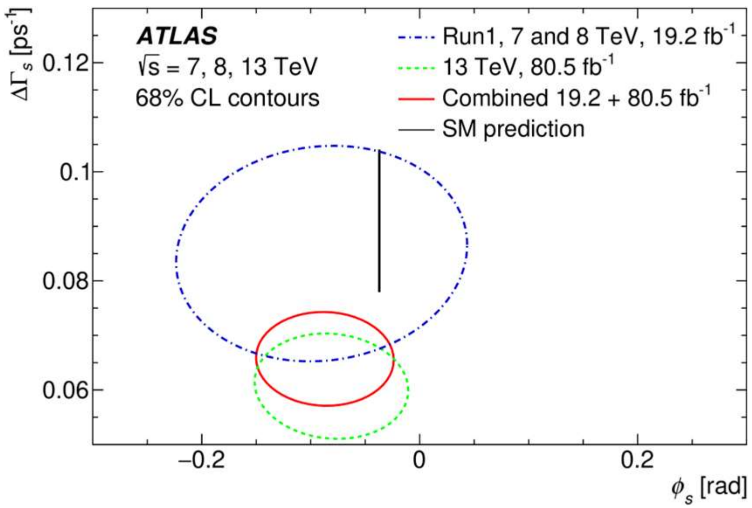
- Fit is performed using a 10D UML:
  - Observables:
    - Mass, lifetime, angles.
  - Conditional observables:
    - Trigger weight, measurement errors, Q_X
- Fit PDFs for:
  - Signal
  - Combinatorial background
  - Peaking backgrounds (B_d and Λ_b)
  - Punzi terms.
    - Model differences for signal/background.



Fit Results

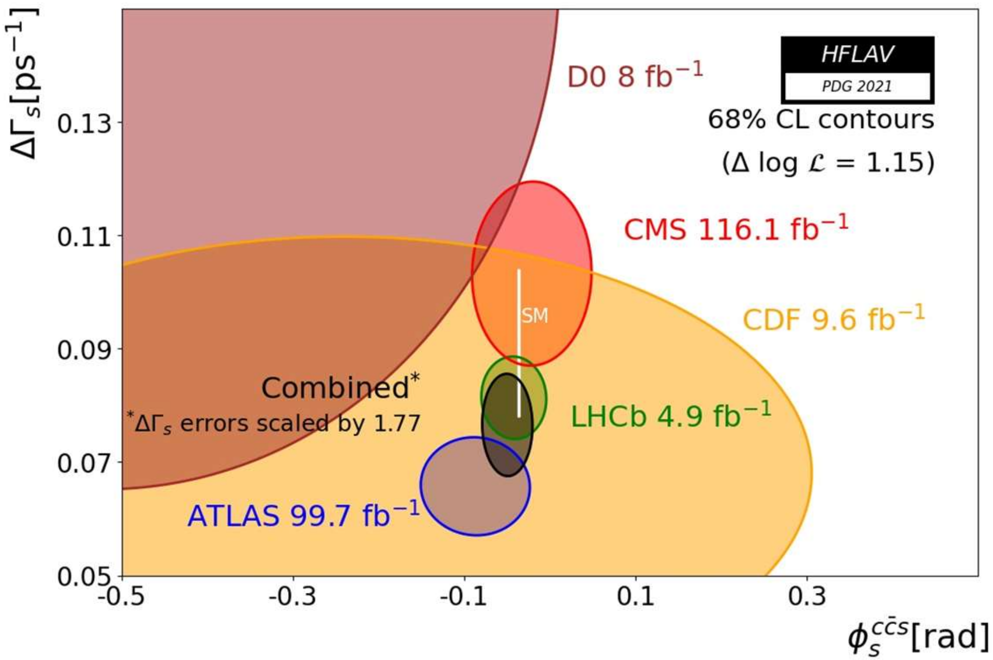
- Compatible with SM predictions.
  - Some tension in $\Delta\Gamma_s$, second solution in $\delta_{\parallel}$- $\delta_{\perp}$ plane.
- Dominant systematics from flavour tagging.

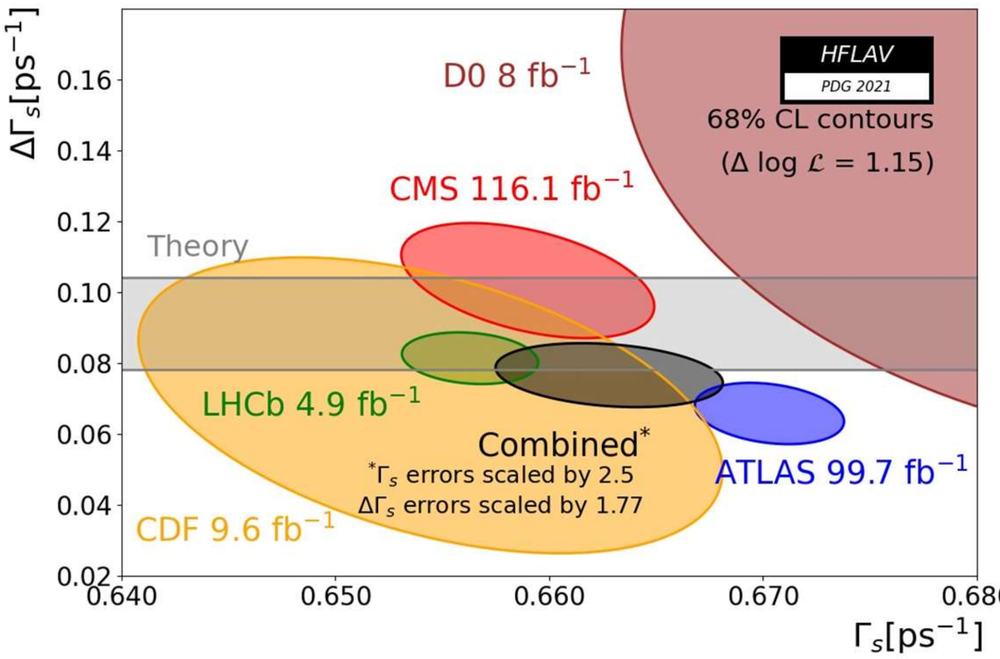
Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s [rad]	−0.081	0.041	0.022
$\Delta\Gamma_s$ [ps^{-1}]	0.0607	0.0047	0.0043
Γ_s [ps^{-1}]	0.6687	0.0015	0.0022
$\lvert A_{\parallel}(0)\rvert^2$	0.2213	0.0019	0.0023
$\lvert A_0(0)\rvert^2$	0.5131	0.0013	0.0038
$\lvert A_S(0)\rvert^2$	0.0321	0.0033	0.0046
$\delta_{\perp} - \delta_S$ [rad]	−0.25	0.05	0.04
Solution (a)			
$\delta_{\perp}$ [rad]	3.12	0.11	0.06
$\delta_{\parallel}$ [rad]	3.35	0.05	0.09
Solution (b)			
$\delta_{\perp}$ [rad]	2.91	0.11	0.06
$\delta_{\parallel}$ [rad]	2.94	0.05	0.09



Comparisons With Other Experiments

Lancaster University



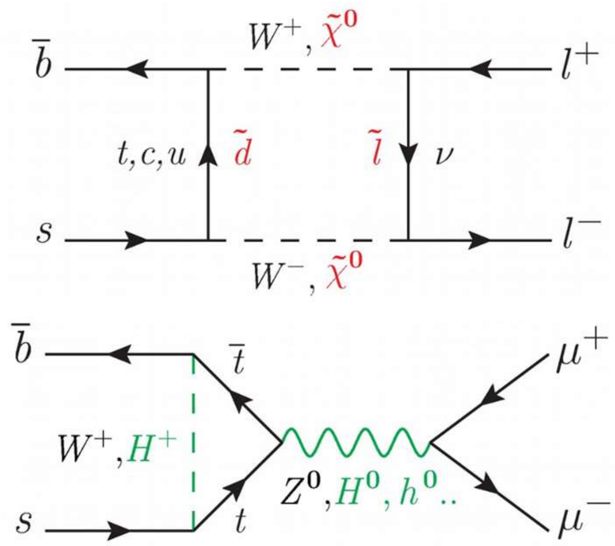


[HFLAV/PDG 2021]

The Rare Decay $B_s \rightarrow \mu^+\mu^-$

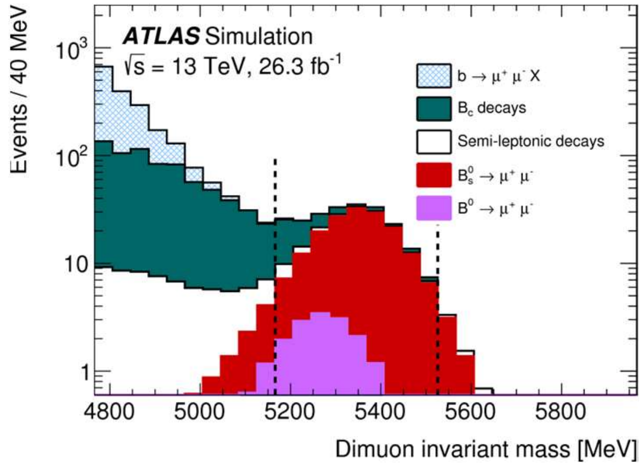
The Rare Decay $B_s \to \mu^+\mu^-$

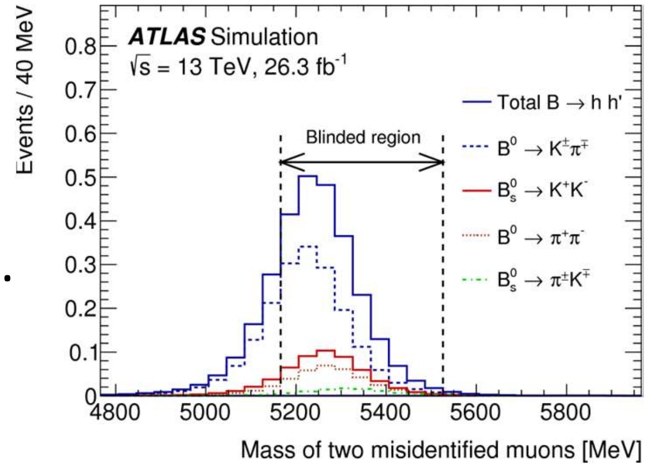
- FCNC decays are heavily suppressed in the SM.
  - Loop and/or box diagrams, and helicity suppression.
- Typical SM branching ratios, $Br \sim 10^{-9}$
  - Significant enhancements possible with NP.
- Aim to measure $Br(B_s \to \mu^+\mu^-)$ and $Br(B_d \to \mu^+\mu^-)$
  - Measure branching ratios relative to $B^\pm \to J/\psi\, K^\pm$
  - Use $B_s \to J/\psi\, \phi$ as a control channel.
  - Extract yields from UML mass spectra.
- Significant overlap between B_d and B_s signals due to mass resolution.
  - Many interesting backgrounds...



Background Modelling

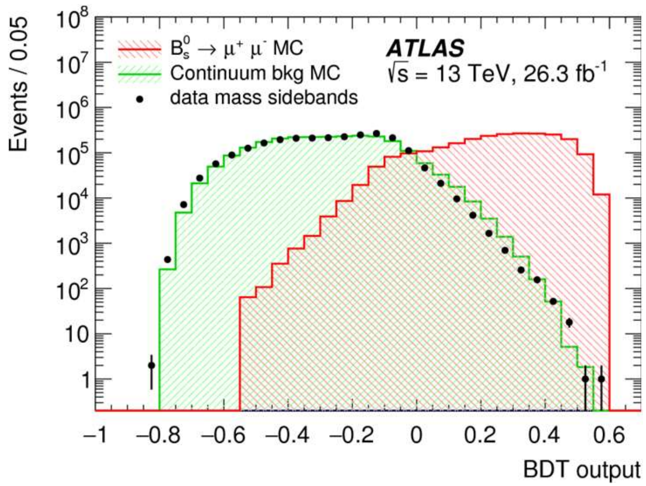
- Misreconstructed Backgrounds:
  - Same Side – b → cμX → s(d)μX’
  - Same Vertex – B → $\mu^+\mu^-$X
  - Incorrect muon ID – B → μhX
- Peaking backgrounds:
  - Mostly B → hh with two incorrect muon IDs.
- Continuum background:
  - Combinatorics of random μμ, μh, and hh pairs.
  - Suppressed through a BDT.

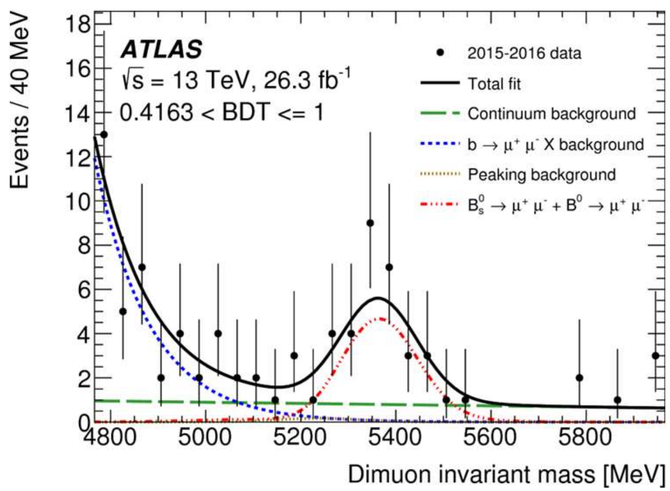




BDTs and Signal Extraction

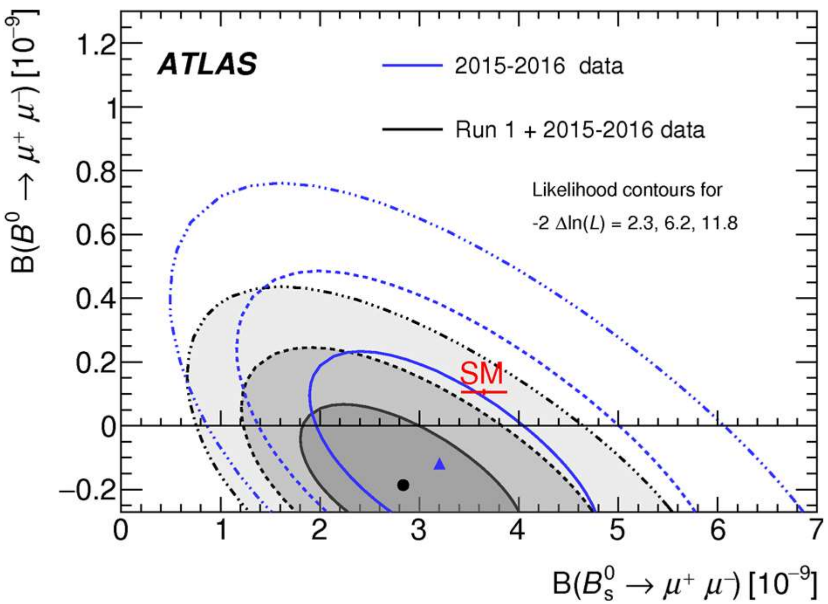
- BDTs trained to reject continuum background.
  - 15 BDT inputs - Vertex, Muon, and Event.
  - Signal region is divided into 4 bins of constant signal efficiency.
  - Validated in reference and control channels.





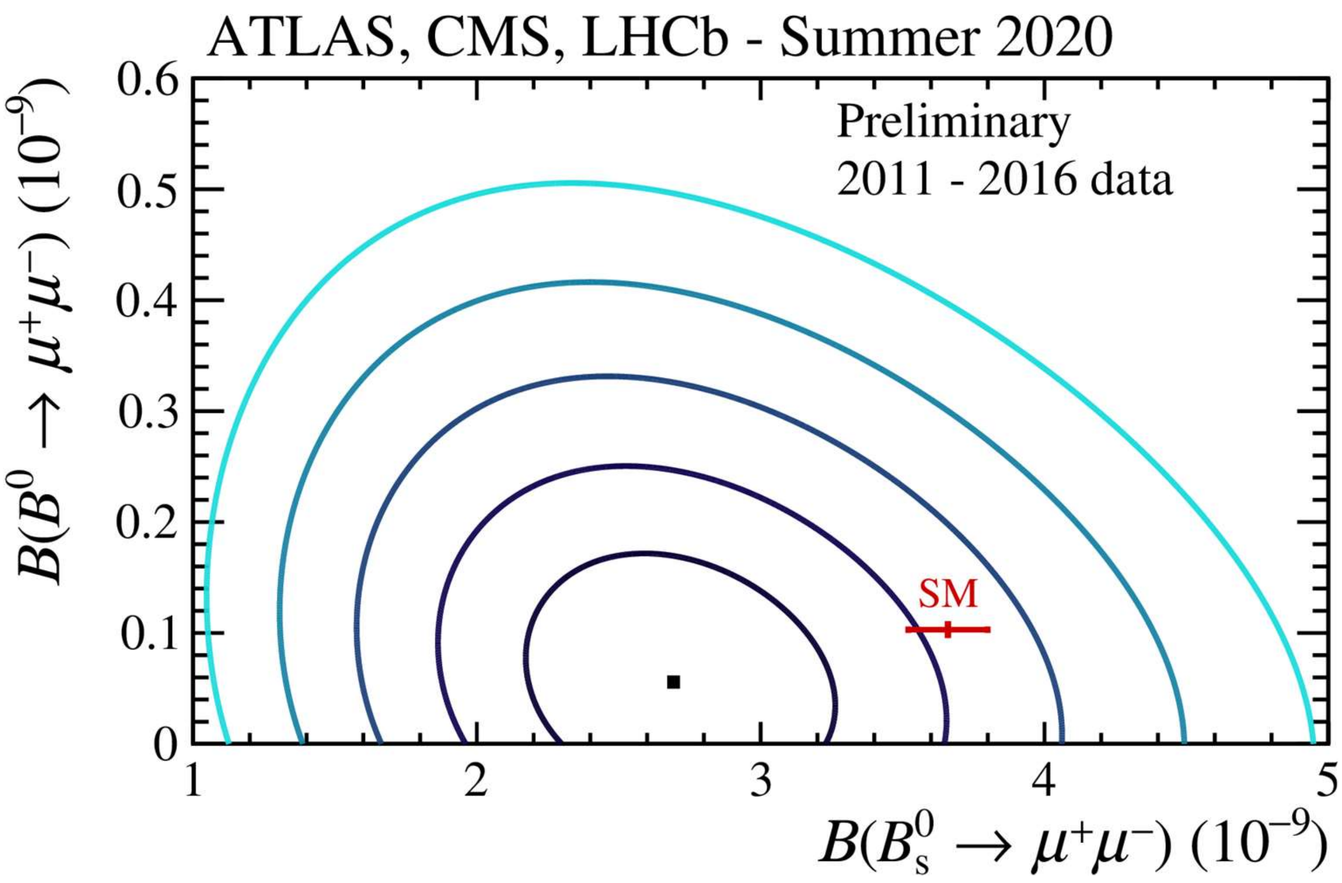
ATLAS Results

Channel	SM	ATLAS 2015 + 2016	ATLAS Run1 + 2015 + 2016
$Br(B_s \to \mu^+\mu^-)$	$(3.66 \pm 0.14) \times 10^{-9}$	$(3.2^{+1.1}_{-1.0}) \times 10^{-9}$	$(2.8^{+0.8}_{-0.7}) \times 10^{-9}$
$Br(B_d \to \mu^+\mu^-)$	$(1.03 \pm 0.15) \times 10^{-10}$	$< 4.3 \times 10^{-10}$ @ 95% CL	$< 2.1 \times 10^{-10}$ @ 95% CL



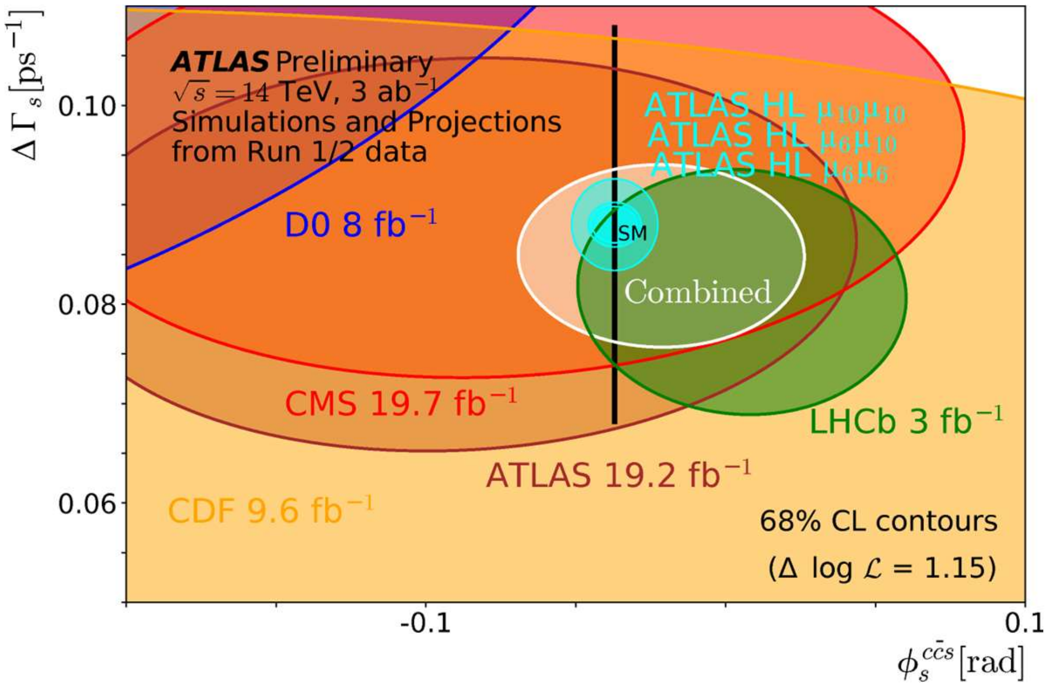
- Event Count:
  - $N_s = 80 \pm 22$
  - $N_d = -12 \pm 20$
- Compatible with SM at 2.4σ
- Statistically limited.
  - Though significant systematic effects from the di-muon mass fitting methodology.

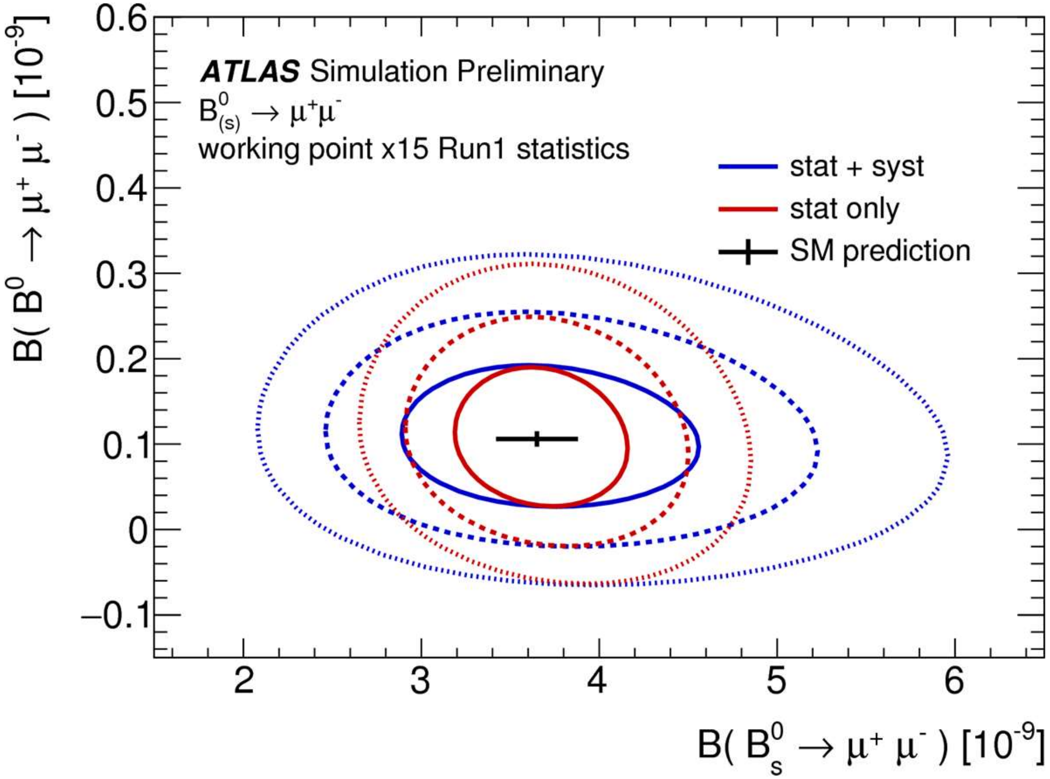
LHC Combinations



Future Prospects

HL-LHC Prospects for $B_s \rightarrow J/\psi\ \phi$ and $B_s \rightarrow \mu^+\mu^-$





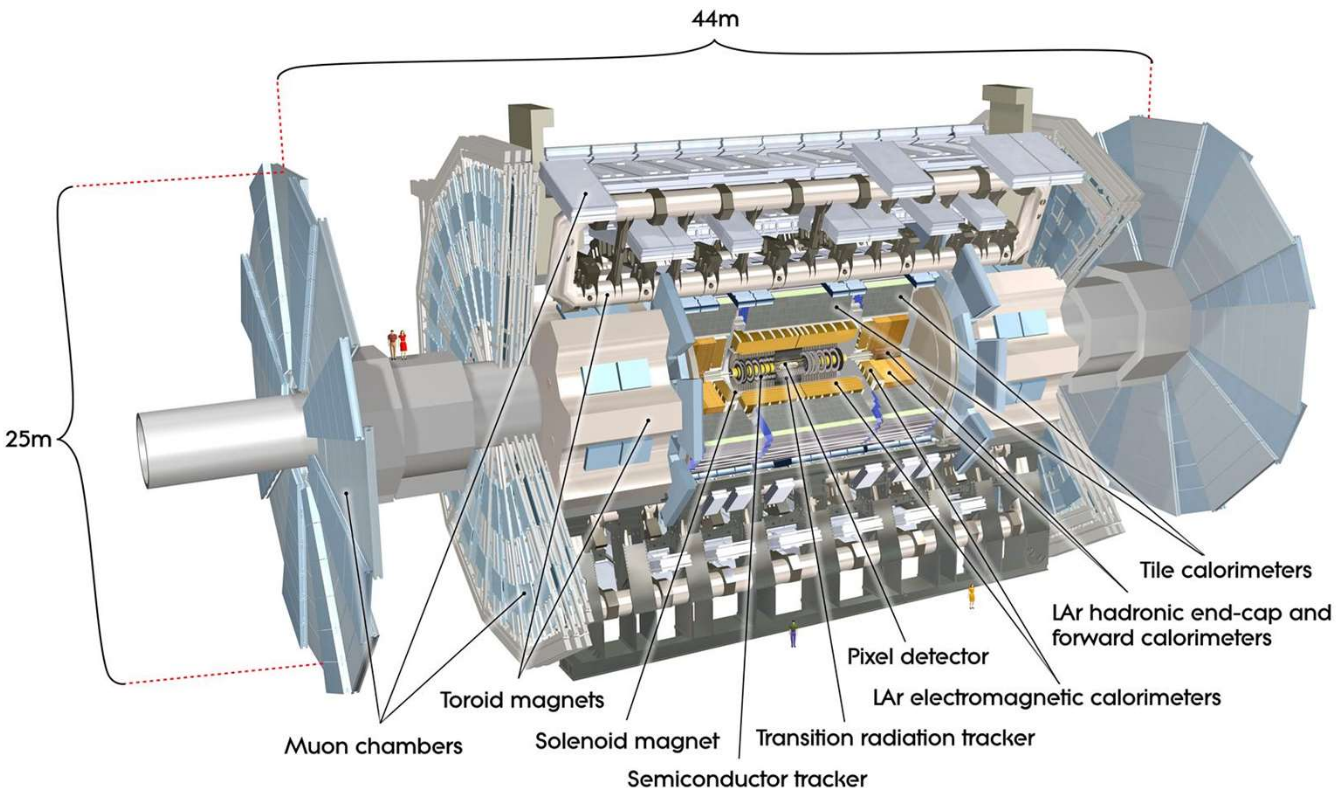
[Report on the Physics at the HL-LHC, and Perspectives for the HE-LHC, Addendum]

Summary

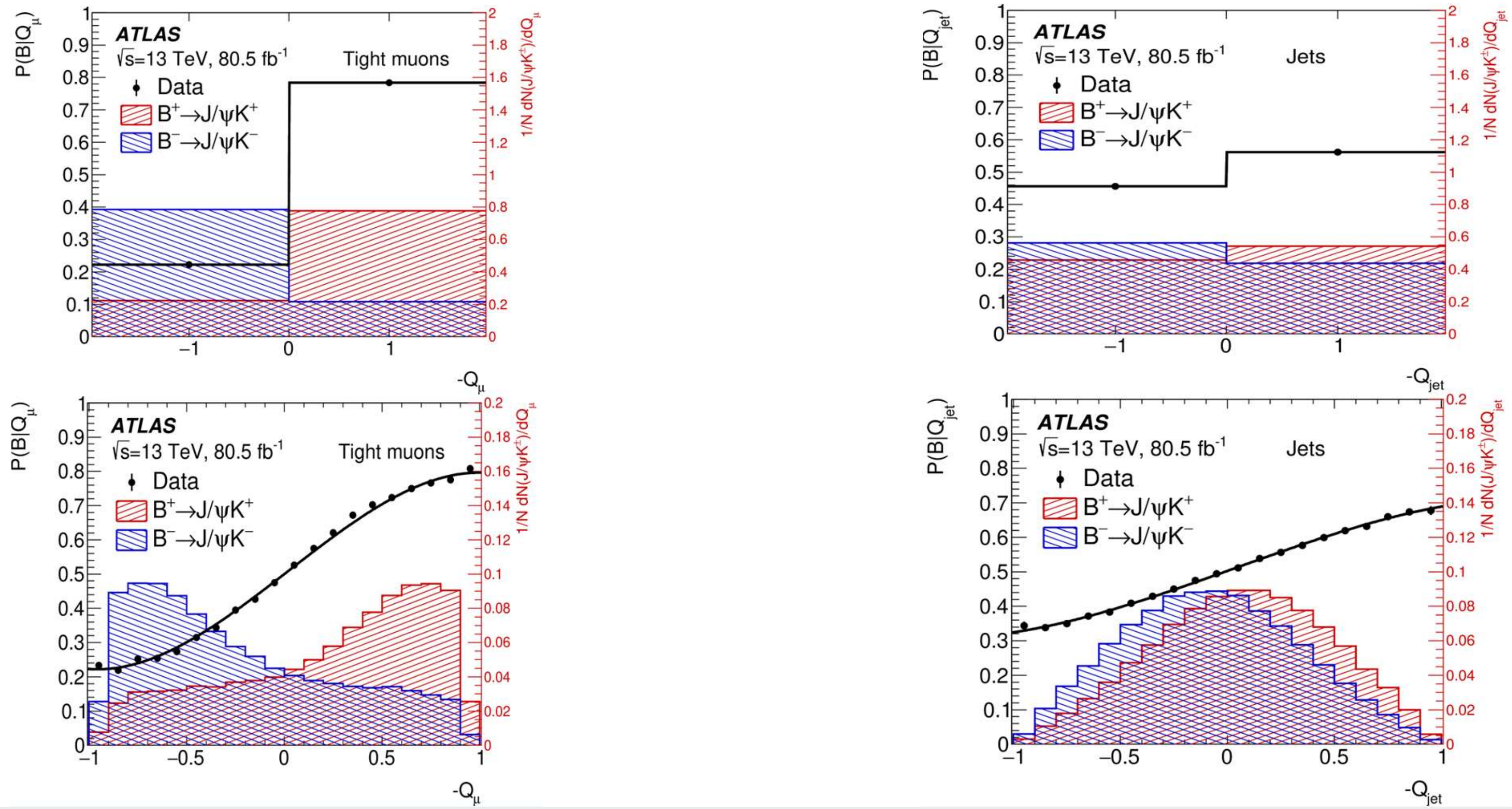
- ATLAS is producing competitive results.
  - And actively collaborating with our LHC partners!
- $B_s \rightarrow J/\psi\ \phi$ remains a solid channel for NP searches.
  - But nothing interesting yet!
- ATLAS's $B_s \rightarrow \mu^+\mu^-$ result is broadly consistent with SM predictions.
- All of these analyses are currently working toward full Run2 results.
- We are well prepared for Run3 data.

Backup

The ATLAS Detector



Flavour Tagging

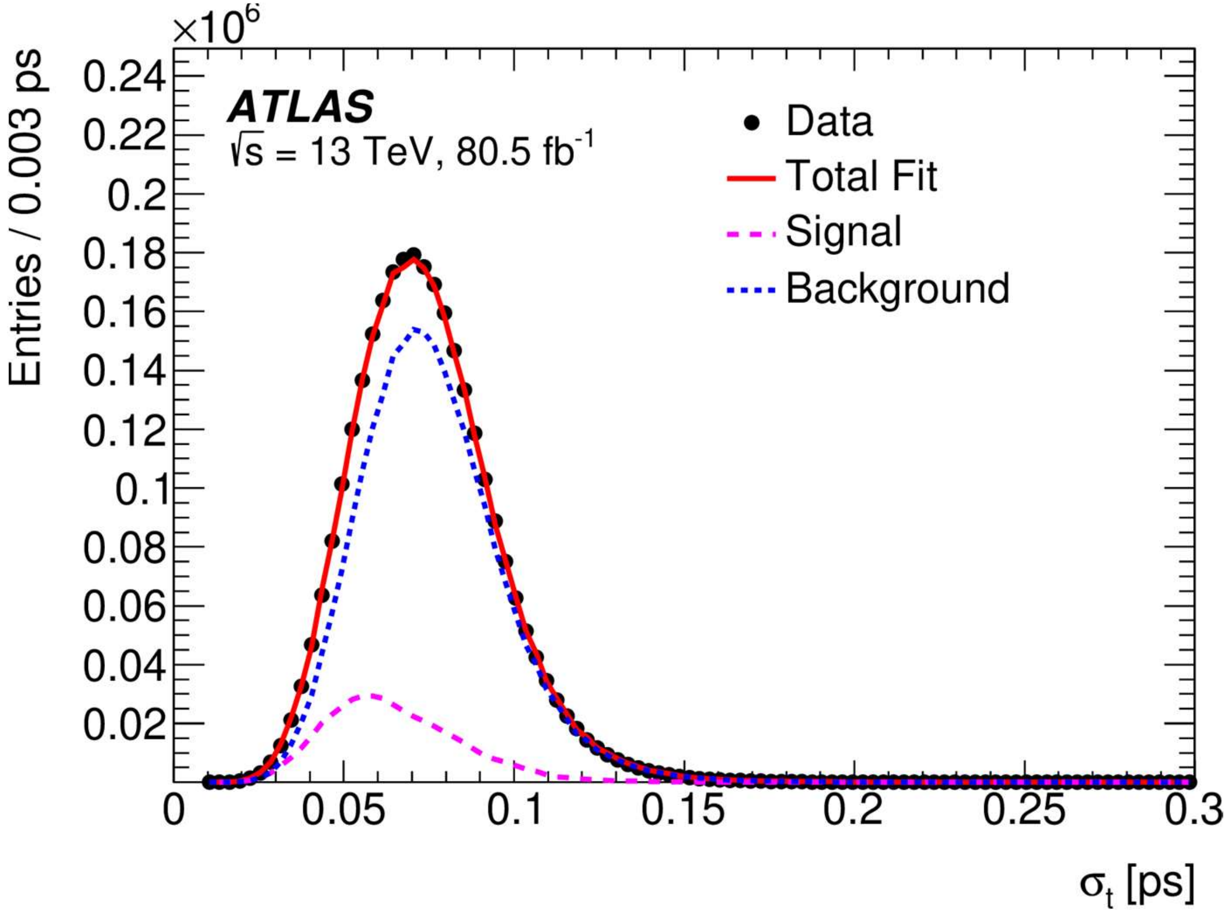


Fit Models - $B_s \rightarrow J/\psi\ \phi$

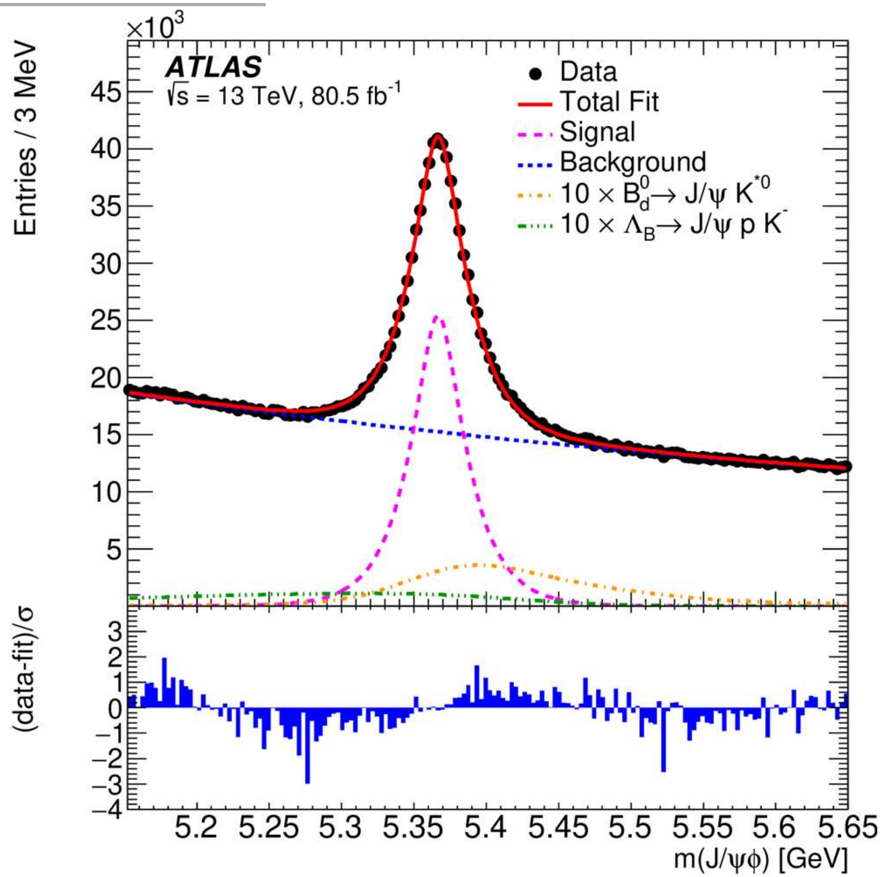
$$\ln \mathcal{L} = \sum_{i=1}^{N} w_i \cdot \ln[f_s \cdot \mathcal{F}_s(m_i, t_i, \sigma_{m_i}, \sigma_{t_i}, \Omega_i, P_i(B|Q_x), p_{T_i})$$
$$+ f_s \cdot f_{B^0} \cdot \mathcal{F}_{B^0}(m_i, t_i, \sigma_{m_i}, \sigma_{t_i}, \Omega_i, P_i(B|Q_x), p_{T_i})$$
$$+ f_s \cdot f_{\Lambda_b} \cdot \mathcal{F}_{\Lambda_b}(m_i, t_i, \sigma_{m_i}, \sigma_{t_i}, \Omega_i, P_i(B|Q_x), p_{T_i})$$
$$+ (1 - f_s \cdot (1 + f_{B^0} + f_{\Lambda_b}))\mathcal{F}_{\text{bkg}}(m_i, t_i, \sigma_{m_i}, \sigma_{t_i},$$
$$\Omega_i, P_i(B|Q_x), p_{T_i})],$$

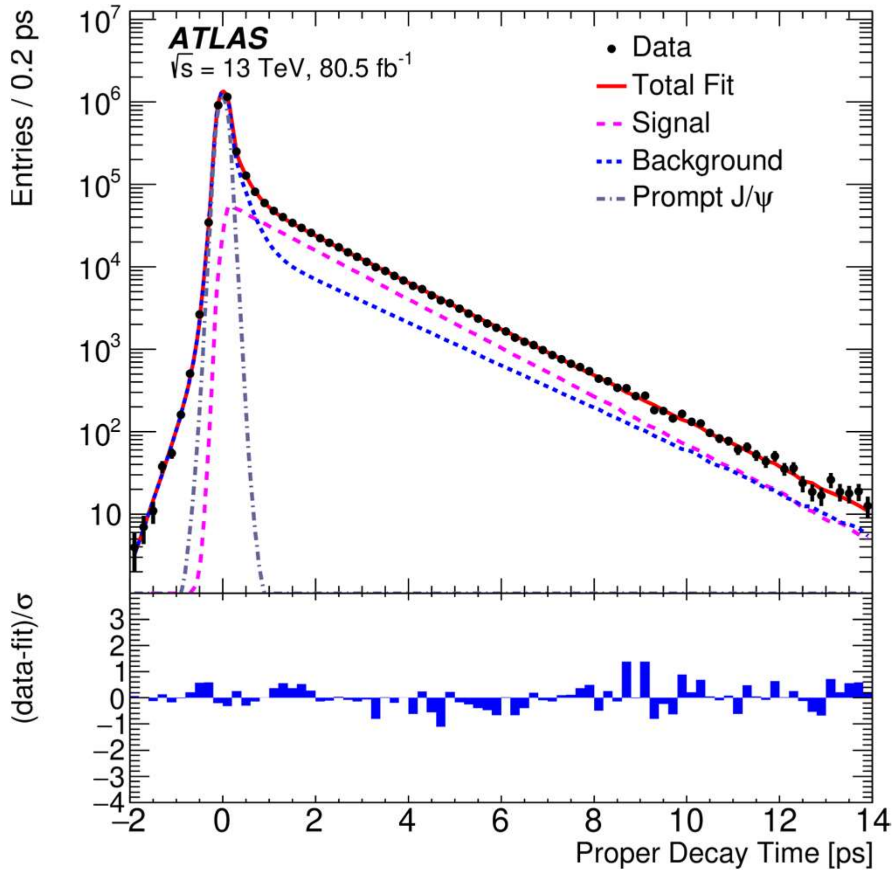
$$\mathcal{F}_s(m_i, t_i, \sigma_{m_i}, \sigma_{t_i}, \Omega_i, P_i(B|Q_x), p_{T_i})$$
$$= P_s(m_i|\sigma_{m_i}) \cdot P_s(\sigma_{m_i}|p_{T_i}) \cdot P_s(t_i, \Omega_i|\sigma_{t_i}, P_i(B|Q_x))$$
$$\cdot P_s(\sigma_{t_i}|p_{T_i}) \cdot P_s(P_i(B|Q_x)) \cdot A(\Omega_i, p_{T_i}) \cdot P_s(p_{T_i}).$$

Fit Projections - $B_s \rightarrow J/\psi\ \phi$



Fit Projections - $B_s \rightarrow J/\psi\ \phi$





Results - $B_s \rightarrow J/\psi\ \phi$

Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s [rad]	−0.081	0.041	0.022
$\Delta\Gamma_s$ [ps^{-1}]	0.0607	0.0047	0.0043
Γ_s [ps^{-1}]	0.6687	0.0015	0.0022
$\lvert A_{\parallel}(0)\rvert^2$	0.2213	0.0019	0.0023
$\lvert A_0(0)\rvert^2$	0.5131	0.0013	0.0038
$\lvert A_S(0)\rvert^2$	0.0321	0.0033	0.0046
$\delta_\perp - \delta_S$ [rad]	−0.25	0.05	0.04
Solution (a)			
$\delta_\perp$ [rad]	3.12	0.11	0.06
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Solution (b)			
$\delta_\perp$ [rad]	2.91	0.11	0.06
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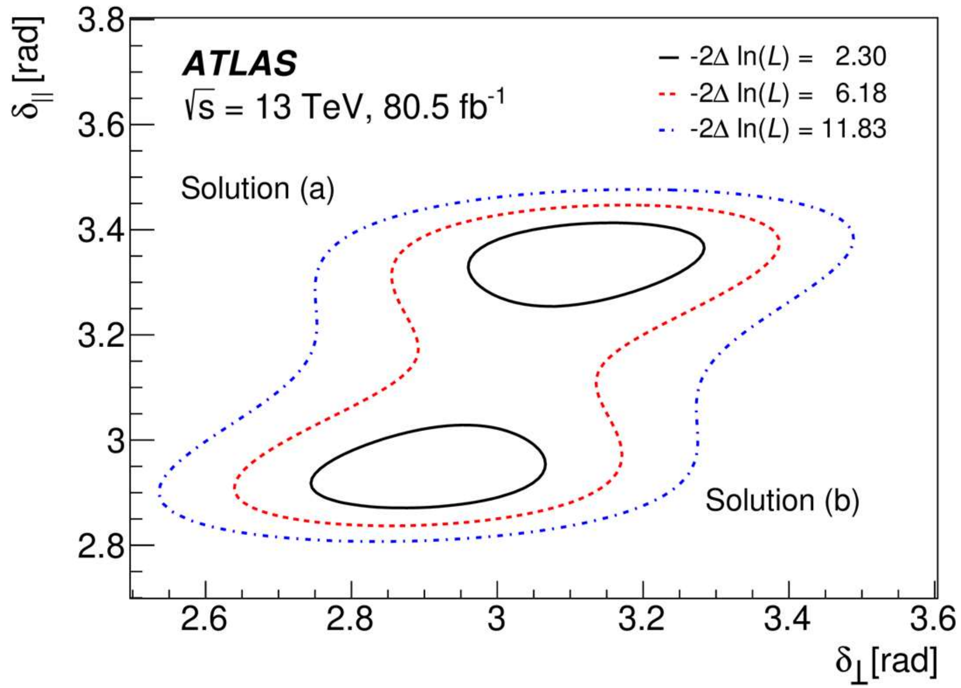


Results - $B_s \rightarrow J/\psi\ \phi$

	$\Delta\Gamma$	Γ_s	$\|A_{\|\|}(0)\|^2$	$\|A_0(0)\|^2$	$\|A_S(0)\|^2$	$\delta_{\|\|}$	$\delta_\perp$	$\delta_\perp - \delta_S$
ϕ_s	−0.080	0.017	−0.003	−0.004	−0.007	0.007	0.004	−0.007
$\Delta\Gamma$	1	−0.586	0.090	0.095	0.051	0.032	0.005	0.020
Γ_s		1	−0.125	−0.045	0.080	−0.086	−0.023	0.015
$\|A_{\|\|}(0)\|^2$			1	−0.341	−0.172	0.522	0.133	−0.052
$\|A_0(0)\|^2$				1	0.276	−0.103	−0.034	0.070
$\|A_S(0)\|^2$					1	−0.362	−0.118	0.244
$\delta_{\|\|}$						1	0.254	−0.085
$\delta_\perp$							1	0.001

Systematics - $B_s \rightarrow J/\psi\ \phi$

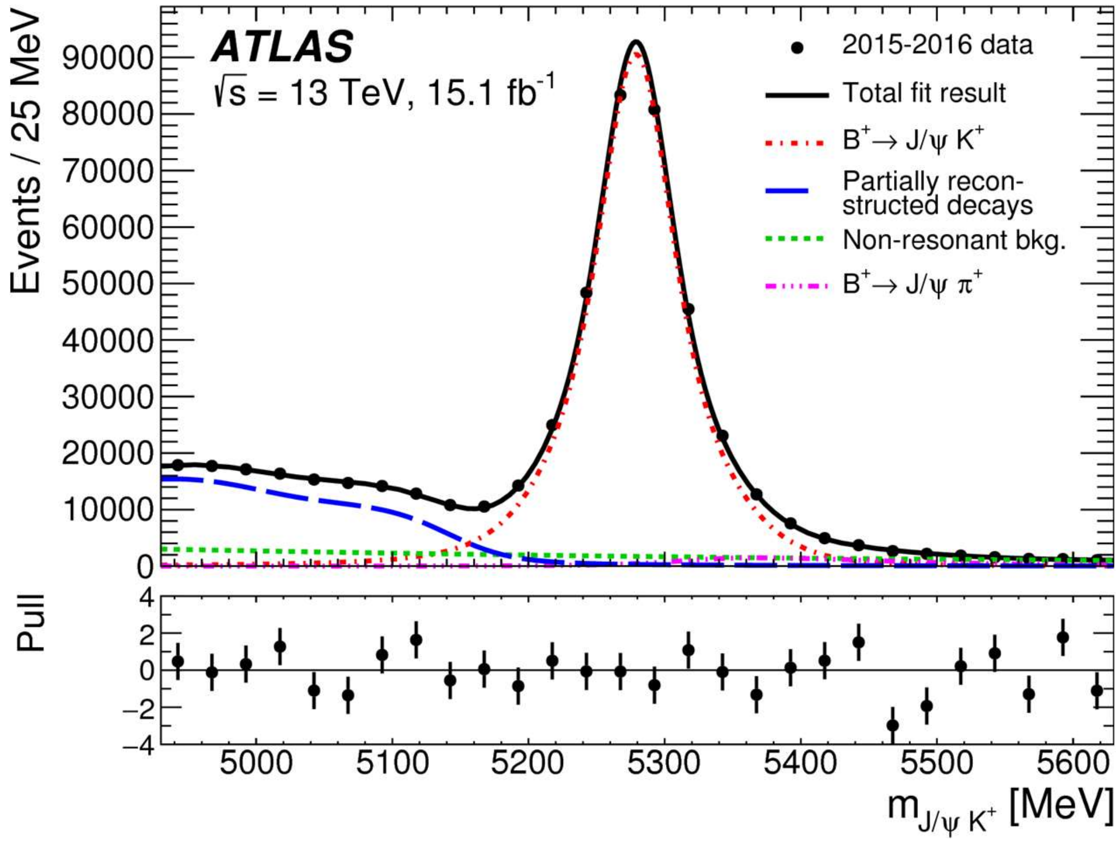
	ϕ_s [10^{-3} rad]	$\Delta\Gamma_s$ [10^{-3} ps^{-1}]	Γ_s [10^{-3} ps^{-1}]	$\lvert A_{\parallel}(0)\rvert^2$ [10^{-3}]	$\lvert A_0(0)\rvert^2$ [10^{-3}]	$\lvert A_S(0)\rvert^2$ [10^{-3}]	$\delta_{\perp}$ [10^{-3} rad]	$\delta_{\parallel}$ [10^{-3} rad]	$\delta_{\perp} - \delta_S$ [10^{-3} rad]
Tagging	19	0.4	0.3	0.2	0.2	1.1	17	19	2.3
ID alignment	0.8	0.2	0.5	< 0.1	< 0.1	< 0.1	11	7.2	< 0.1
Acceptance	0.5	0.3	< 0.1	1.0	0.9	2.9	37	64	8.6
Time efficiency	0.2	0.2	0.5	< 0.1	< 0.1	0.1	3.0	5.7	0.5
Best candidate selection	0.4	1.6	1.3	0.1	1.0	0.5	2.3	7.0	7.4
Background angles model:									
Choice of fit function	2.5	< 0.1	0.3	1.1	< 0.1	0.6	12	0.9	1.1
Choice of p_T bins	1.3	0.5	< 0.1	0.4	0.5	1.2	1.5	7.2	1.0
Choice of mass window	9.3	3.3	0.2	0.4	0.8	0.9	17	8.6	6.0
Choice of sidebands intervals	0.4	0.1	0.1	0.3	0.3	1.3	4.4	7.4	2.3
Dedicated backgrounds:									
B_d^0	2.6	1.1	< 0.1	0.2	3.1	1.5	10	23	2.1
Λ_b	1.6	0.3	0.2	0.5	1.2	1.8	14	30	0.8
Alternate Δm_s	1.0	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	15	4.0	< 0.1
Fit model:									
Time res. sig frac	1.4	1.1	0.5	0.5	0.6	0.8	12	30	0.4
Time res. p_T bins	0.7	0.5	0.8	0.1	0.1	0.1	2.2	14	0.7
S-wave phase	0.3	< 0.1	< 0.1	< 0.1	< 0.1	0.2	8.0	15	37
Fit bias	5.7	1.3	1.2	1.3	0.4	1.1	3.3	19	0.3
Total	22	4.3	2.2	2.3	3.8	4.6	55	88	39

Branching Ratios - $B_s \rightarrow \mu^+\mu^-$

$$\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-) = \frac{N_{d(s)}}{\varepsilon_{\mu^+\mu^-}} \times \left[\mathcal{B}(B^+ \to J/\psi\, K^+) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)\right] \frac{\varepsilon_{J/\psi K^+}}{N_{J/\psi K^+}} \times \frac{f_u}{f_{d(s)}}$$

$$= N_{d(s)} \frac{\mathcal{B}(B^+ \to J/\psi\, K^+) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)}{\mathcal{D}_{\rm ref}} \times \frac{f_u}{f_{d(s)}}\,,$$

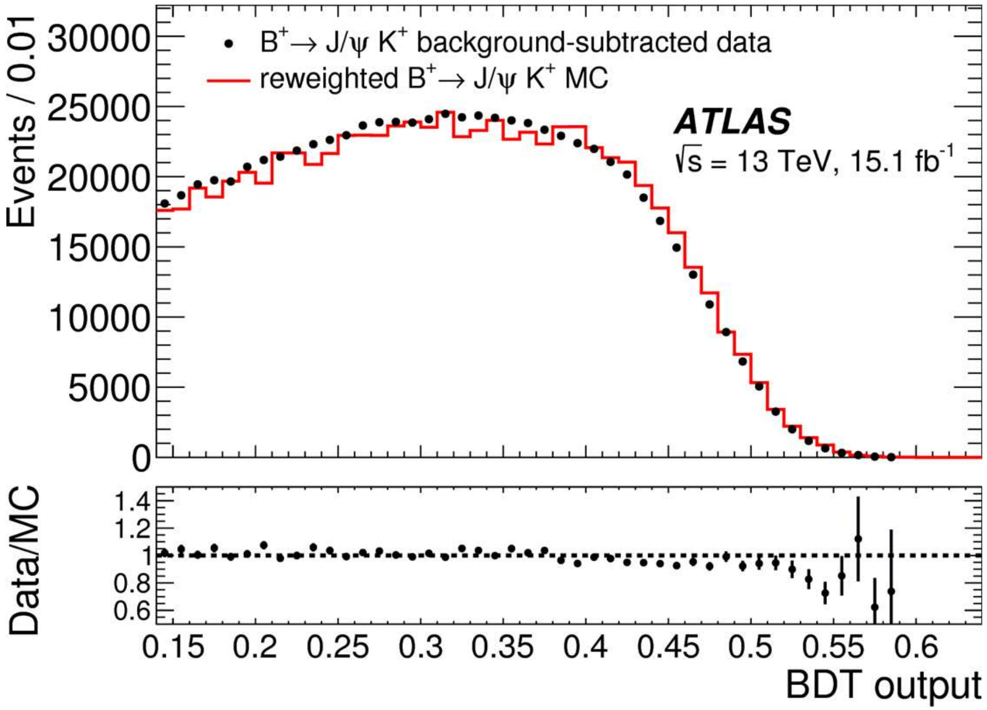
$B^{\pm} \rightarrow J/\psi K^{\pm}$ - $B_s \rightarrow \mu^+\mu^-$

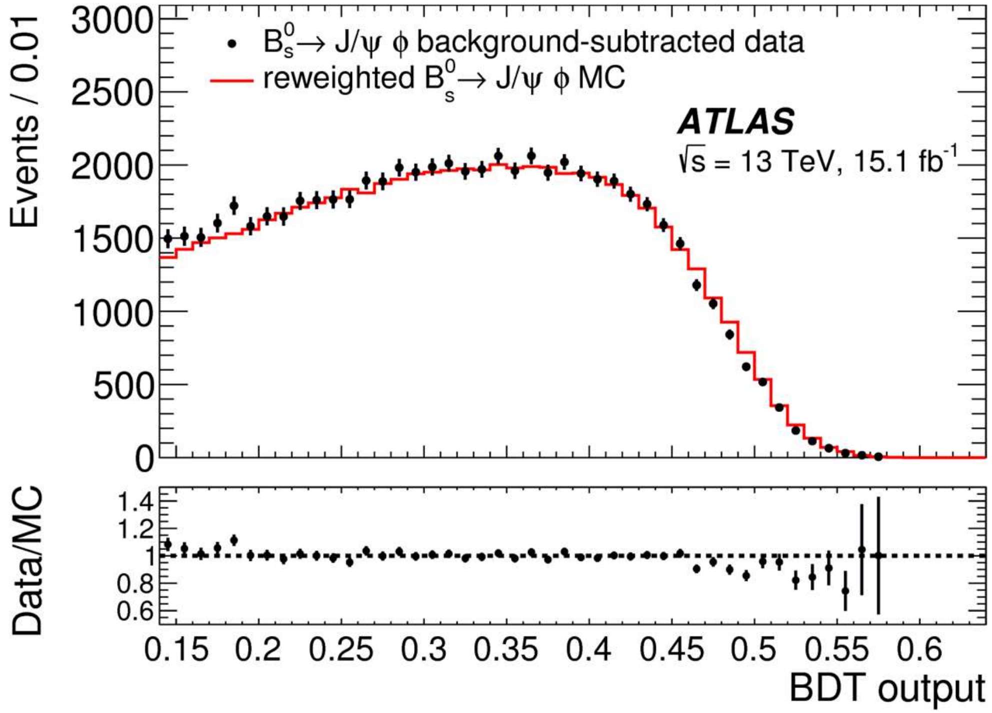


BDT - $B_s \rightarrow \mu^+\mu^-$

Variable	Description
p_{T}^{B}	Magnitude of the B candidate transverse momentum $\overrightarrow{p_{\mathrm{T}}}^{B}$.
$\chi^2_{\mathrm{PV,DV}\,xy}$	Compatibility of the separation $\overrightarrow{\Delta x}$ between production (i.e. associated PV) and decay (DV) vertices in the transverse projection: $\overrightarrow{\Delta x}_{\mathrm{T}} \cdot \Sigma^{-1}_{\overrightarrow{\Delta x}_{\mathrm{T}}} \cdot \overrightarrow{\Delta x}_{\mathrm{T}}$, where $\Sigma_{\overrightarrow{\Delta x}_{\mathrm{T}}}$ is the covariance matrix.
$\Delta R_{\mathrm{flight}}$	Three-dimensional angular distance between $\vec{p}^{B}$ and $\overrightarrow{\Delta x}$: $\sqrt{\alpha_{2\mathrm{D}}{}^2 + (\Delta\eta)^2}$
$\lvert\alpha_{2\mathrm{D}}\rvert$	Absolute value of the angle in the transverse plane between $\overrightarrow{p_{\mathrm{T}}}^{B}$ and $\overrightarrow{\Delta x}_{\mathrm{T}}$.
L_{xy}	Projection of $\overrightarrow{\Delta x}_{\mathrm{T}}$ along the direction of $\vec{p}_{\mathrm{T}}^{B}$: $(\overrightarrow{\Delta x}_{\mathrm{T}} \cdot \overrightarrow{p_{\mathrm{T}}}^{B})/\lvert\overrightarrow{p_{\mathrm{T}}}^{B}\rvert$.
$\mathrm{IP}_{B}^{3\mathrm{D}}$	Three-dimensional impact parameter of the B candidate to the associated PV.
$\mathrm{DOCA}_{\mu\mu}$	Distance of closest approach (DOCA) of the two tracks forming the B candidate (three-dimensional).
$\Delta\phi_{\mu\mu}$	Azimuthal angle between the momenta of the two tracks forming the B candidate.
$\lvert d_0\rvert^{\mathrm{max}}$-sig.	Significance of the larger absolute value of the impact parameters to the PV of the tracks forming the B candidate, in the transverse plane.
$\lvert d_0\rvert^{\mathrm{min}}$-sig.	Significance of the smaller absolute value of the impact parameters to the PV of the tracks forming the B candidate, in the transverse plane.
$P_{\mathrm{L}}^{\mathrm{min}}$	The smaller of the projected values of the muon momenta along $\overrightarrow{p_{\mathrm{T}}}^{B}$.
$I_{0.7}$	Isolation variable defined as ratio of $\lvert\overrightarrow{p_{\mathrm{T}}}^{B}\rvert$ to the sum of $\lvert\overrightarrow{p_{\mathrm{T}}}^{B}\rvert$ and the transverse momenta of all additional tracks contained within a cone of size $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.7$ around the B direction. Only tracks matched to the same PV as the B candidate are included in the sum.
$\mathrm{DOCA}_{\mathrm{xtrk}}$	DOCA of the closest additional track to the decay vertex of the B candidate. Only tracks matched to the same PV as the B candidate are considered.
$N_{\mathrm{xtrk}}^{\mathrm{close}}$	Number of additional tracks compatible with the decay vertex (DV) of the B candidate with $\ln(\chi^2_{\mathrm{xtrk,DV}}) < 1$. Only tracks matched to the same PV as the B candidate are considered.
$\chi^2_{\mu,\mathrm{xPV}}$	Minimum χ^2 for the compatibility of a muon in the B candidate with any PV reconstructed in the event.

BDT - $B_s \rightarrow \mu^+\mu^-$





Systematics - $B_s \rightarrow \mu^+\mu^-$

Source	Contribution [%]
Statistical	0.8
BDT input variables	3.2
Kaon tracking efficiency	1.5
Muon trigger and reconstruction	1.0
Kinematic reweighting (DDW)	0.8
Pile-up reweighting	0.6

Source	B_s^0 [%]	B^0 [%]
f_s/f_d	5.1	-
B^+ yield	4.8	4.8
R_ε	4.1	4.1
$\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)$	2.9	2.9
Fit systematic uncertainties	8.7	65
Stat. uncertainty (from likelihood est.)	27	150

P_n' in $B_d \rightarrow K^* \mu^+ \mu^-$

- Tension with theory predictions in the angular observables:
  - See *J. High Energ. Phys.* **2016**, 104 (2016).