A CP violation measurement of B_s mesons at ATLAS and the LHC

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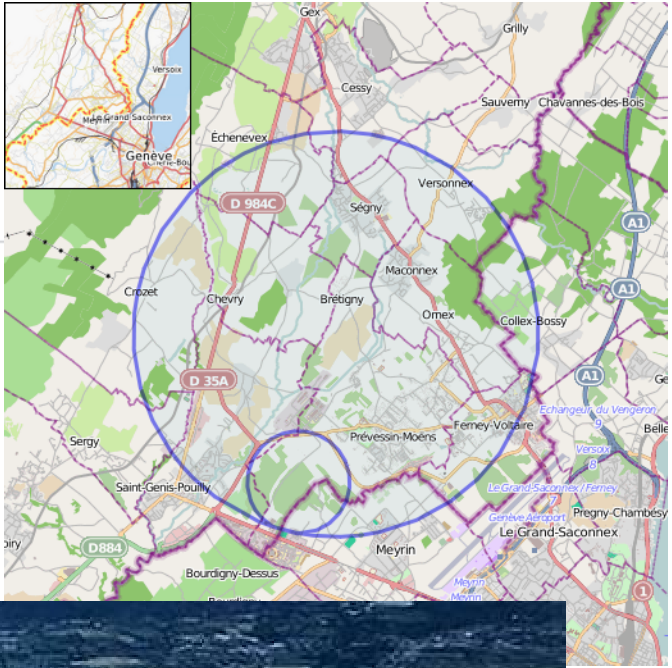
ATLAS Collaboration

The LHC



The large hadron collider is the world's largest and highest energy synchrotron collider in the world.

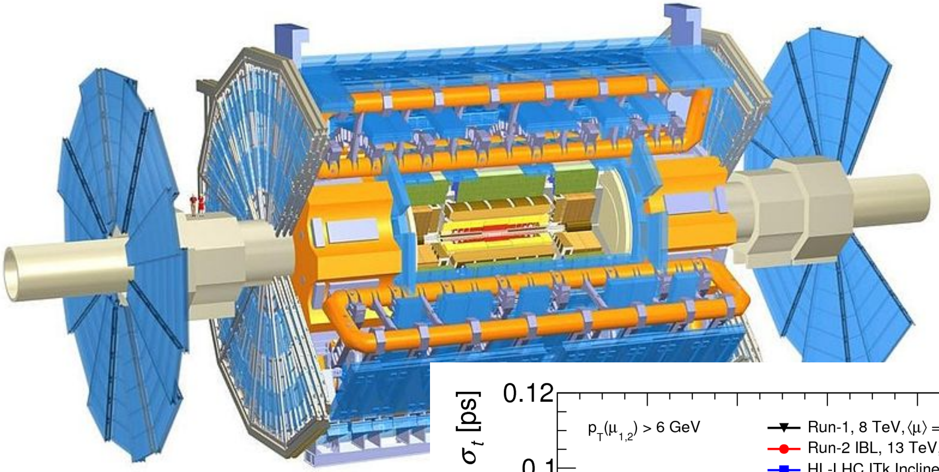
It is built and run by CERN (the European/Everyone Organization for Nuclear Research)

It can collide protons at energies of 14 TeV, (currently running at 13TeV

It is located in a 27 kilometer tunnel under Geneva near the Jura mountains.

The ATLAS (A Toroidal LHC ApparatuS) detector

ATLAS is a 45 by 50 metres in size

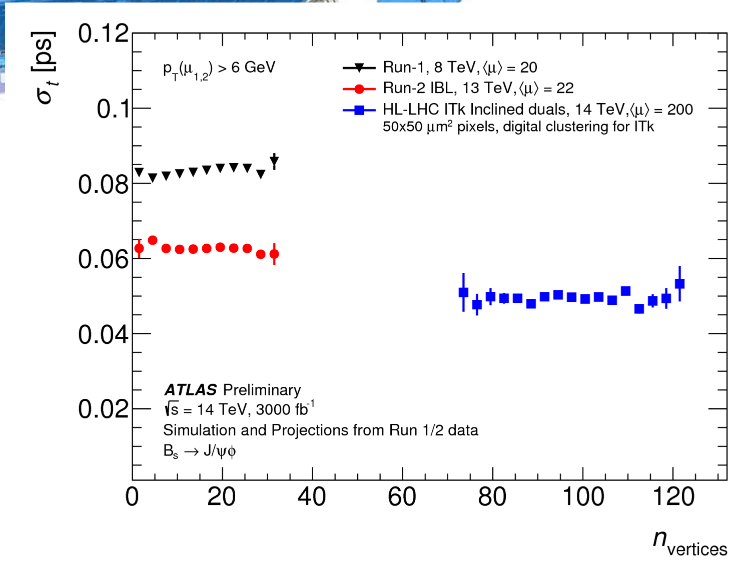


Muon Spectrometer:
- (1) Monitored Drift Tube
- (2) Thin Gap Chamber

Magnet system:
- (3) End-Cap Toroid Magnet
- (4) Barrel Toroid Magnet

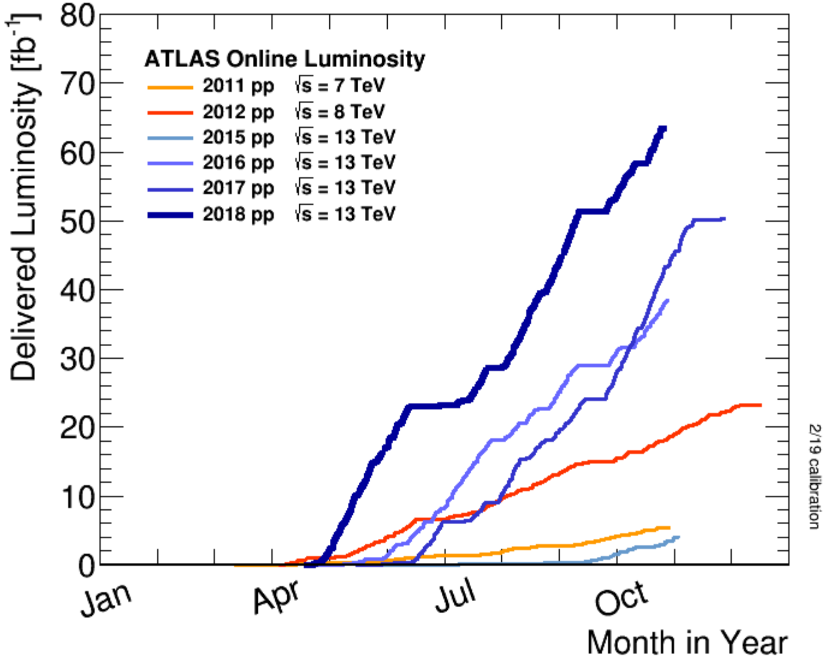
Inner Detector:
- (5) Transition Radiation Tracker
- (6) Semi-Conductor Tracker
- (7) Pixel Detector

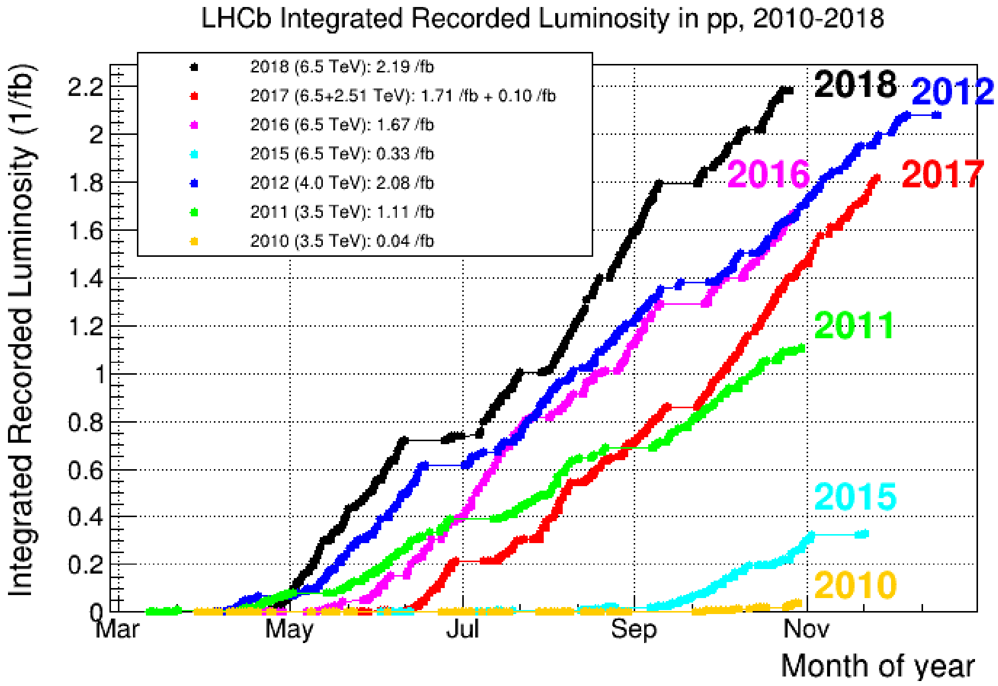
Calorimeters:
- (8) Electromagnetic Calorimeter
- (9) Hadronic Calorimeter



At the start of run 2 (2015) an insertable B-layer was installed to give better vertex and lifetime resolution

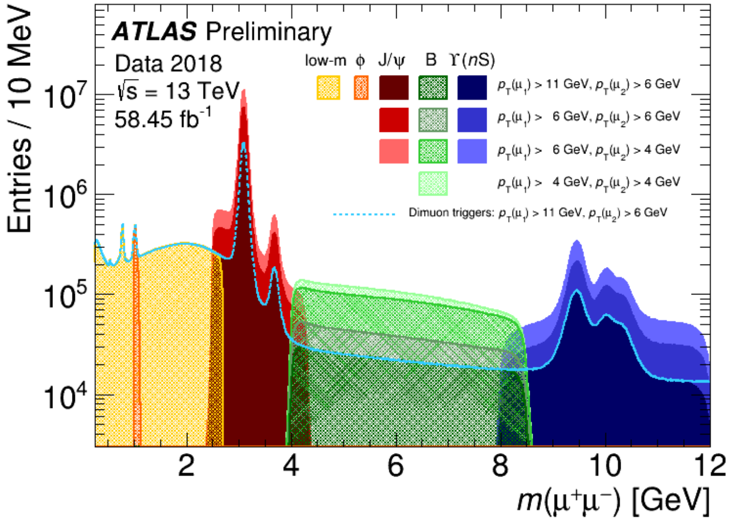
Data Collection



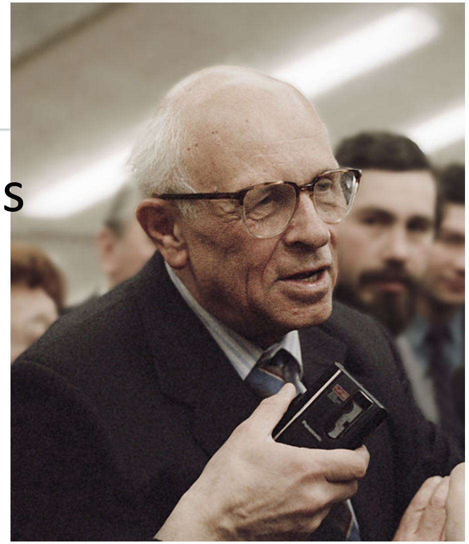


B-physics and Light-States

- ATLAS B-physics and Light-States programme:
  - Comprehensive measurements across a variety of decay modes:
    - Precise property measurements including CPV (Bs->J/ψ ϕ)
    - Cross-section measurements including Quarkonium
    - Rare decay processes; e.g FCNC $B_{(s,d)} \rightarrow \mu\mu$
    - Spectroscopy, exotic states (e.g pentaquarks)
    - Charged lepton flavour violation (τ -> 3μ)
- Typically rely on low-pT di-muon signatures.

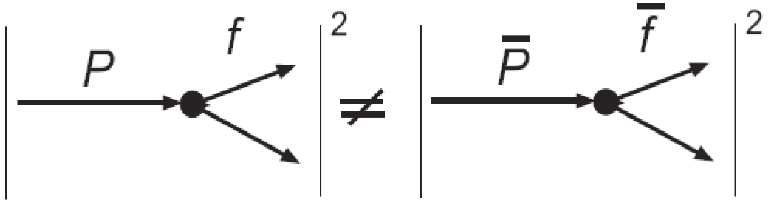


Introduction to the CP violation

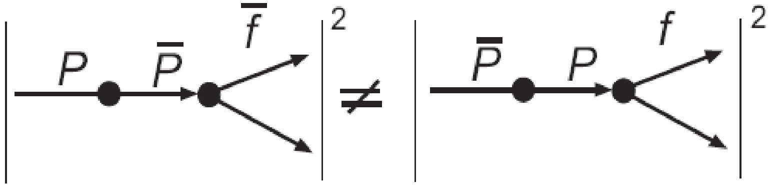


- Charge Parity (CP) symmetries mean that particle interactions should produce matter and antimatter in equal quantities
- In 1967 Soviet Nuclear Physicist Andrei Sakharov proposed CP violation:
  - Since the observed universe seems devoid of stable antimatter there must be baryon number violating transitions in particle physics.
  - CP has to be violated otherwise there would be equal amounts of anti matter
  - CP violations must occur during interactions and not in thermal equilibrium

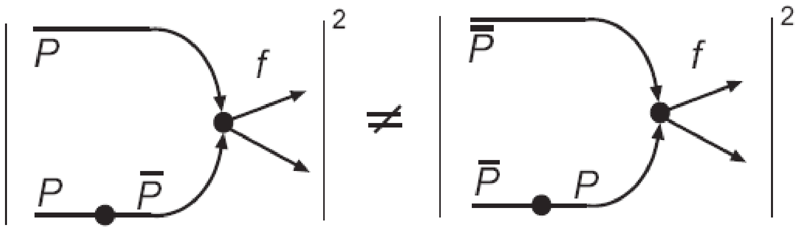
3 Types of CP violation



(a) Direct CP violation.



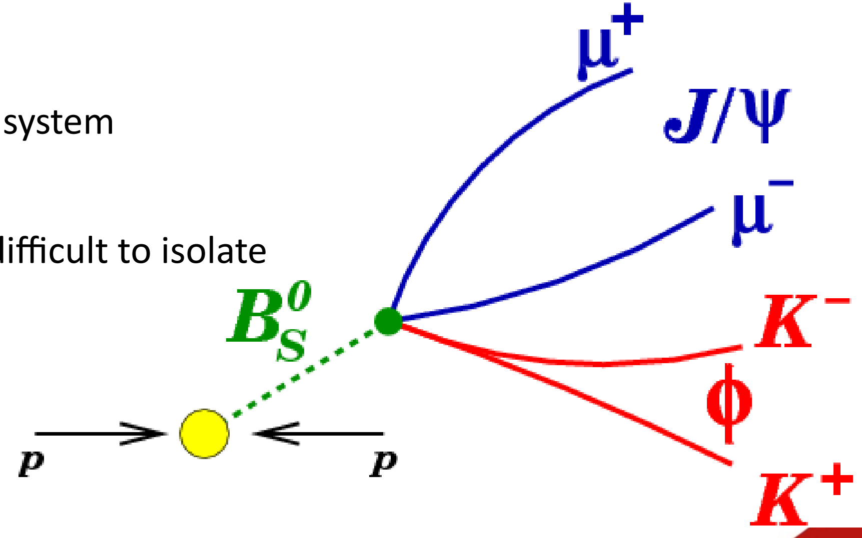
(b) CP violation in mixing.



(c) CP violation in interference.

Exclusive decay chain

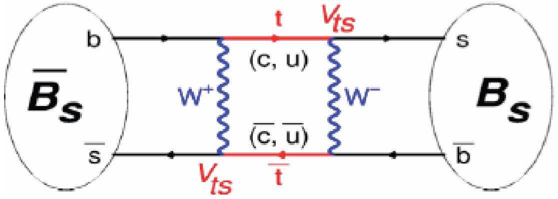
- While φ_s can be accessed a number of ways the easiest way at ATLAS is through the exclusive decay $B_s \rightarrow J/\psi\ \varphi$ where
  - $J/\psi \rightarrow \mu^+\mu^-$ selected nicely from the muon system
  - $\varphi \rightarrow K^+ K^-$ ATLAS has no particle ID so this is difficult to isolate

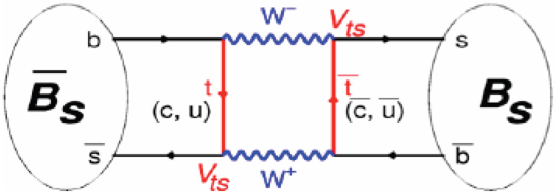


CP Violation in neutral B_s system

Mixing of flavour eigenstates are governed by:

$$i\frac{d}{dt}\begin{pmatrix} B_s^0(t) \\ \overline{B}_s^0(t) \end{pmatrix} = H \begin{pmatrix} B_s^0(t) \\ \overline{B}_s^0(t) \end{pmatrix} \equiv \Bigg[\underbrace{\begin{pmatrix} M_0 & M_{12} \\ M_{12}^* & M_0 \end{pmatrix}}_{\text{mass matrix}} - \frac{i}{2}\underbrace{\begin{pmatrix} \Gamma_0 & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_0 \end{pmatrix}}_{\text{decay matrix}}\Bigg] \begin{pmatrix} B_s^0(t) \\ \overline{B}_s^0(t) \end{pmatrix}$$





- The mass eigenstates

$$|B_s^H\rangle = p\,|B_s^0\rangle - q\,|\bar{B}_s^0\rangle$$

$$|B_s^L\rangle = p\,|B_s^0\rangle + q\,|\bar{B}_s^0\rangle$$

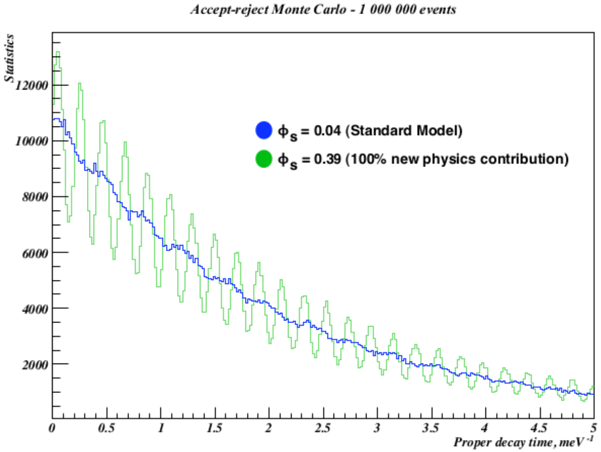
- $\Delta m_S = m_H - m_L \approx 2|M_{12}|$

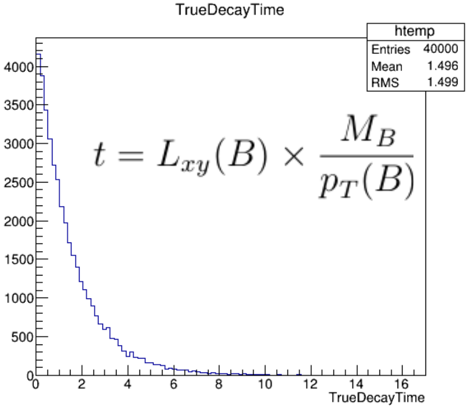
- $\boldsymbol{\varphi_S^{SM}}=\arg(-M_{12}/\Gamma_{12}) \approx -0.04$ - CP violating phase

- $\boldsymbol{\Gamma}$ is the average lifetime of the two states $(\Gamma_L+\Gamma_H)/2$

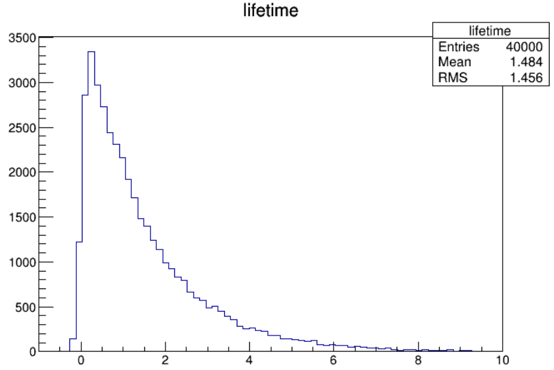
- $\boldsymbol{\Delta\Gamma}=\Gamma_L-\Gamma_H \approx 2\,|\Gamma_{12}|\cos(2\,\varphi_S^{SM})$ – Can be considered the difference of the two lifetime states

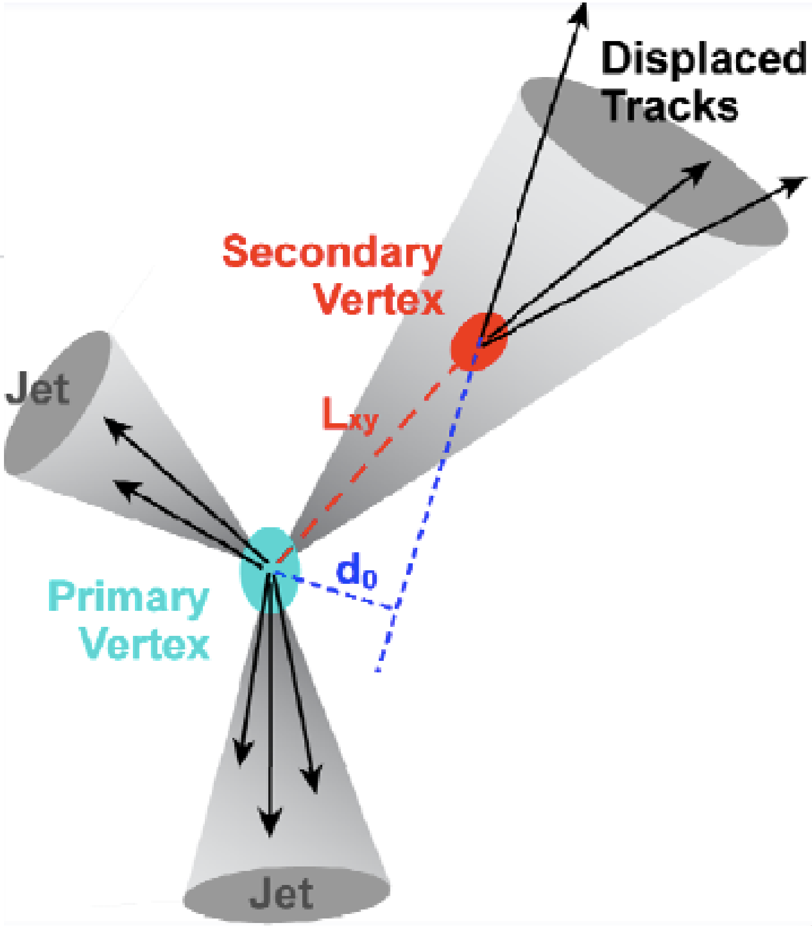
Measuring a particle lifetime





$$t = L_{xy}(B) \times \frac{M_B}{p_T(B)}$$

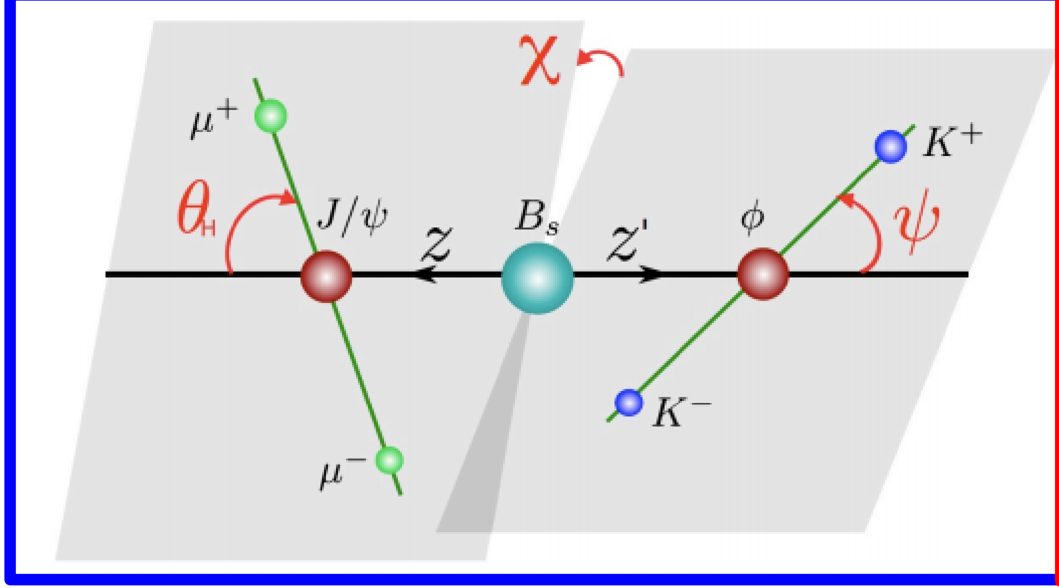




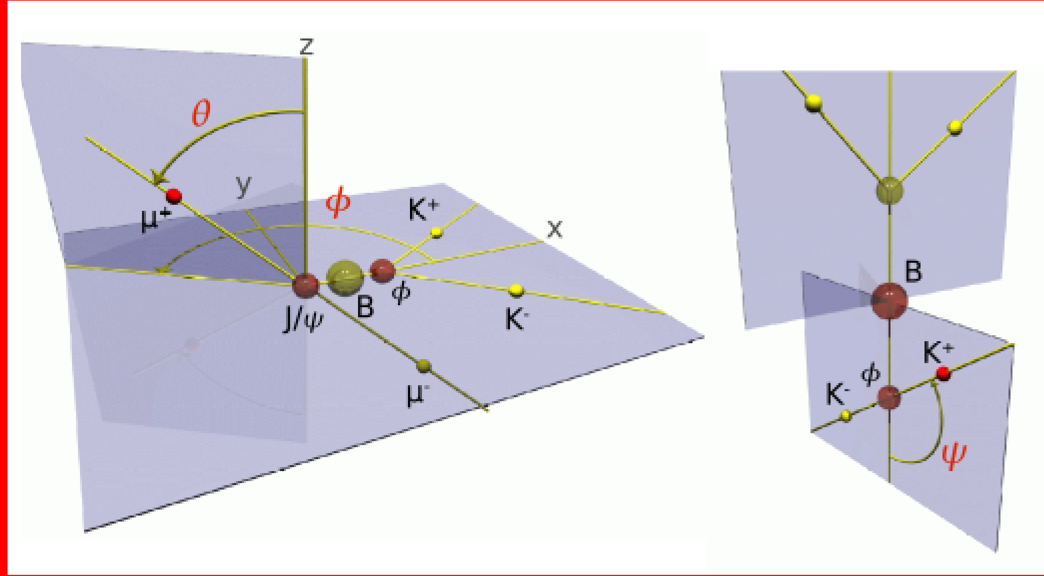
Angular Systems for Bs→ J/ψ φ

- You can access the key physical variables for this decay using one of 2 angular definitions

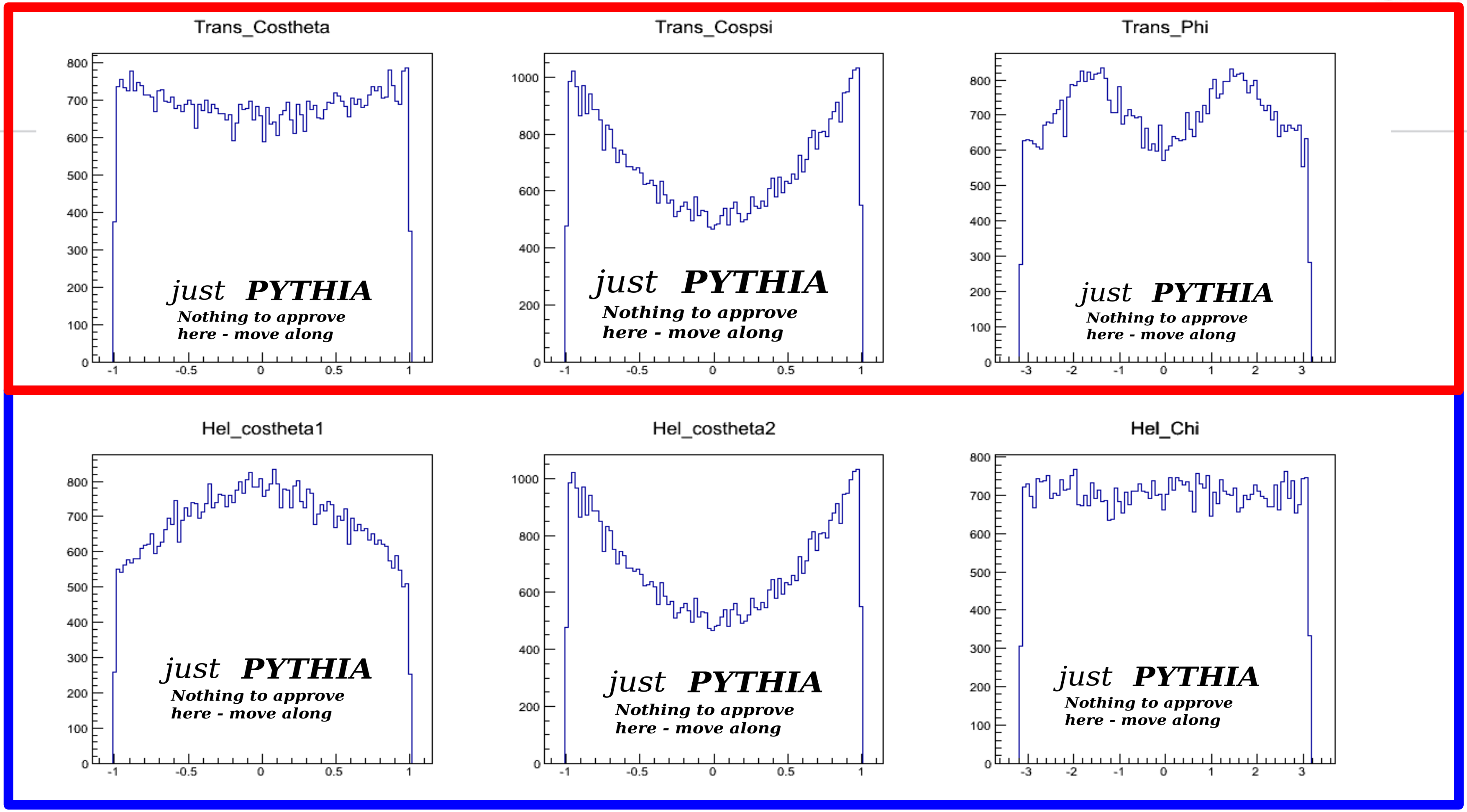
Helicity Basis



Transversity Basis



What the signal looks like

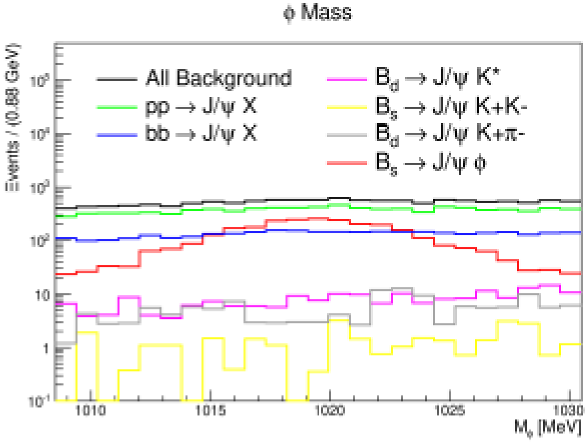


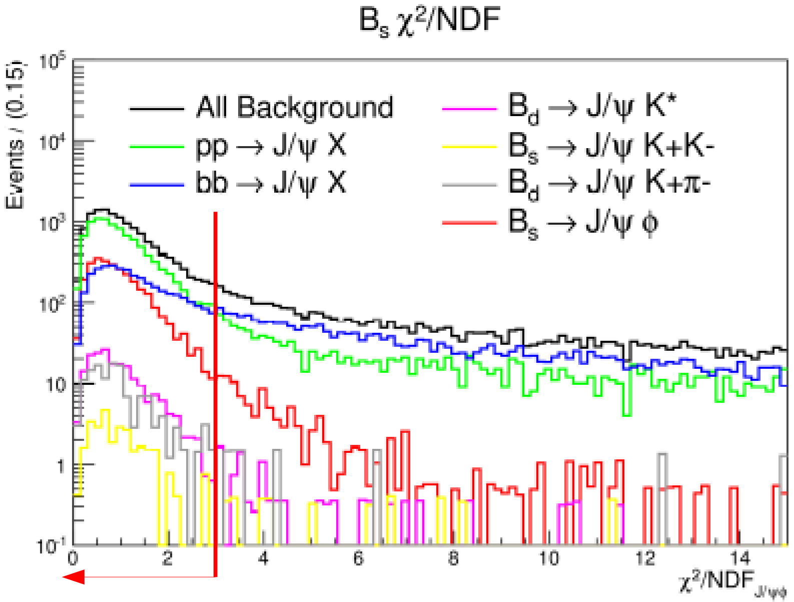
Provisional MC Generation – no cuts applied so no acceptance effects

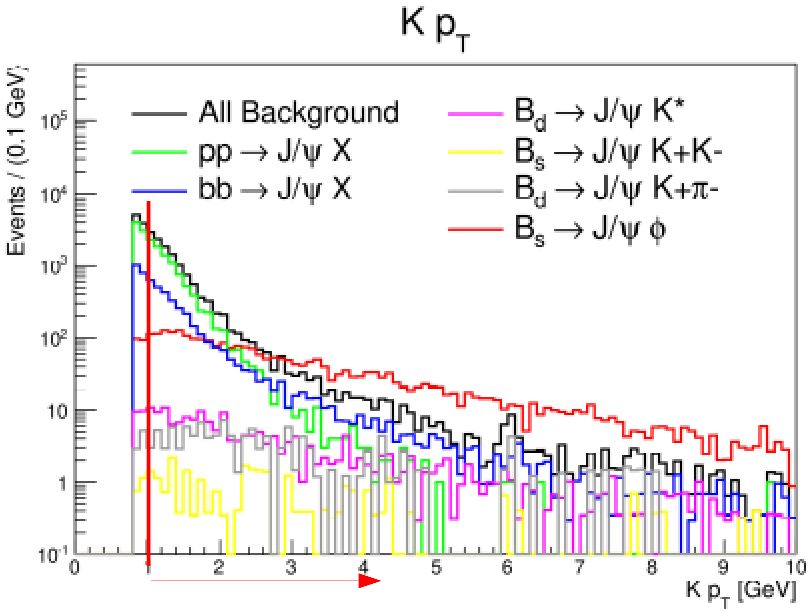
ATLAS Publications

- Time dependent untagged φ_s and $\Delta\Gamma_s$ from $B_s \rightarrow J/\psi\varphi$ JHEP 1212 (2012) 072 – 02-AUG-12
- Time dependent flavour-tagged φs and ΔΓs from $B_s \rightarrow J/\psi\varphi$ at 7 TeV Phys. Rev. D. 90, 052007 (2014) 05-JUL-14
- Time dependent flavour-tagged φ_s and $\Delta\Gamma_s$ from $B_s \rightarrow J/\psi\varphi$ in Run 1 JHEP 08 (2016) 147 13-JAN-16
- Measurement of the CP violation phase φ_s in $B_s \rightarrow J/\psi\varphi$ decays in ATLAS at 13 TeV 23 Mar 2019 (Conf-Note going to publication)
- Next paper will include all Run-2 data.

Deciding cuts







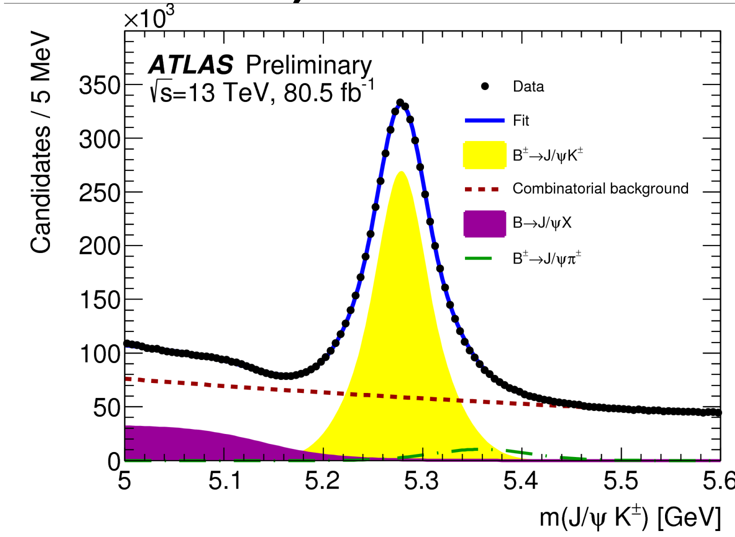
ATLAS-CONF-2019-009

Deciding Cuts

- This analysis follows are previous measurement using 19.2 fb^{-1} of √s=7 TeV and 8 TeV ("run 1")
- The new analysis uses datasets from 2015 to 2017 with √s=13 TeV totalling 80.5 fb^{-1}.
- Full decay reconstruction using inner detector and muon detectors, no K/pi separation:
  - J/ψ selection – di-muon vertex $\chi2/_{NDF}<10$, J/ψ invariant mass windows width 0.27 ... 0.48 GeV (barrel → endcap)
  - ϕ selection – $p_T(K^{\pm}) > 1$ GeV, Invariant mass window 22 MeV
  - B candidates – 4-track vertex $\chi2/_{NDF}<3$, (5.15 – 5.65) GeV, no proper decay time cut.

Flavour Tagging

- The analysis gains precision with tagging information. We use opposite-side tagging (OST).
- We use 4 tagging methods: "Tight" muons, electrons, Low-p_T muons, Jet
- Charge of p_T-weighted tracks in a cone around the opposite primary object, used to build per-candidate B_s tag probability.
- Calibrated from $B^+ \rightarrow J/\psi K^+$ sample

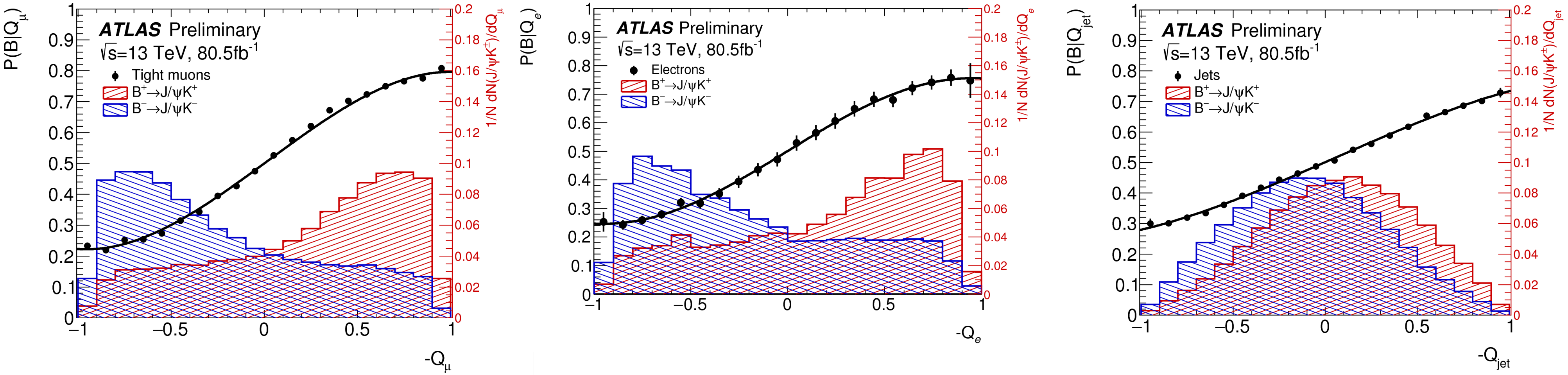


Tagging: weighted sum of charge in a cone

$$Q_x = \frac{\sum_i^{N \text{ tracks}} q_i \cdot (p_{\mathrm{T}i})^\kappa}{\sum_i^{N \text{ tracks}} (p_{\mathrm{T}i})^\kappa},$$

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

In events where multiple methods are available the highest dilution is selected.



Symmetries: $\{\phi_s, \Delta\Gamma_s, \delta_\perp, \delta_\parallel\} \rightarrow \{\pi - \phi_s, -\Delta\Gamma_s, \pi - \delta_\perp, 2\pi - \delta_\parallel\}$

~~$\{\phi_s, \Delta\Gamma_s, \delta_\perp, \delta_\parallel, \delta_S\} \rightarrow \{-\phi_s, \Delta\Gamma_s, \pi - \delta_\perp, -\delta_\parallel, -\delta_S\}$~~ (untagged fit only)

Signal Likelihood

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

CP +1
CP +1
CP -1

Interference terms

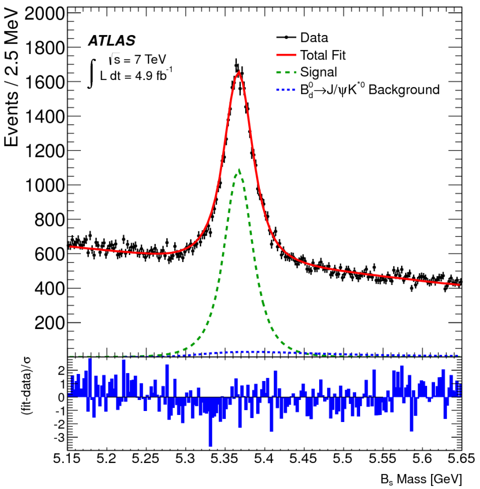
S-wave terms

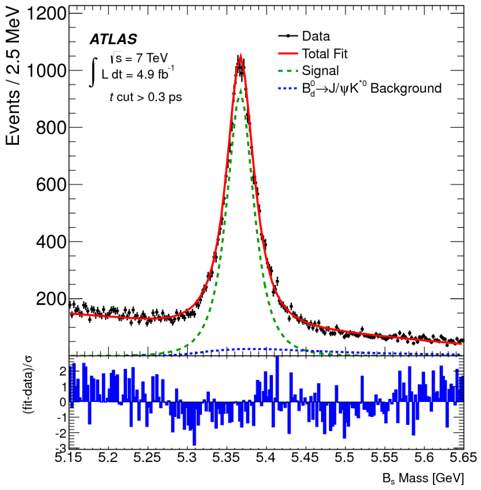
The solution with a negative $\Delta\Gamma_s$ is excluded using another LHCb measurement which determines the $\Delta\Gamma_s$ to be positive

Background description

- To make a precision measurement it is necessary to either exclude or accurately describe the background
- The different backgrounds present are:
- Direct pp → J/ψ background
- Misreconstructed complete decays such as B_d → J/ψK* and Λ_b→J/ψ Λ*(Kp)
- Miscellaneous combinatorics from bb→ J/ψX

Mass spectrum including Direct background





Mass spectrum excluding direct background by lifetime cut

Unbinned Maximum Likelihood Fit

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

$B_d \to J/\psi K^*(K\pi)$ and $\Lambda_b \to J/\psi \Lambda^*(Kp)$ decay reflections, derived from MC, PDG and the LHCb $\Lambda_b \to J/\Lambda Kp$ measurement; fixed shape and relative contribution in the fit

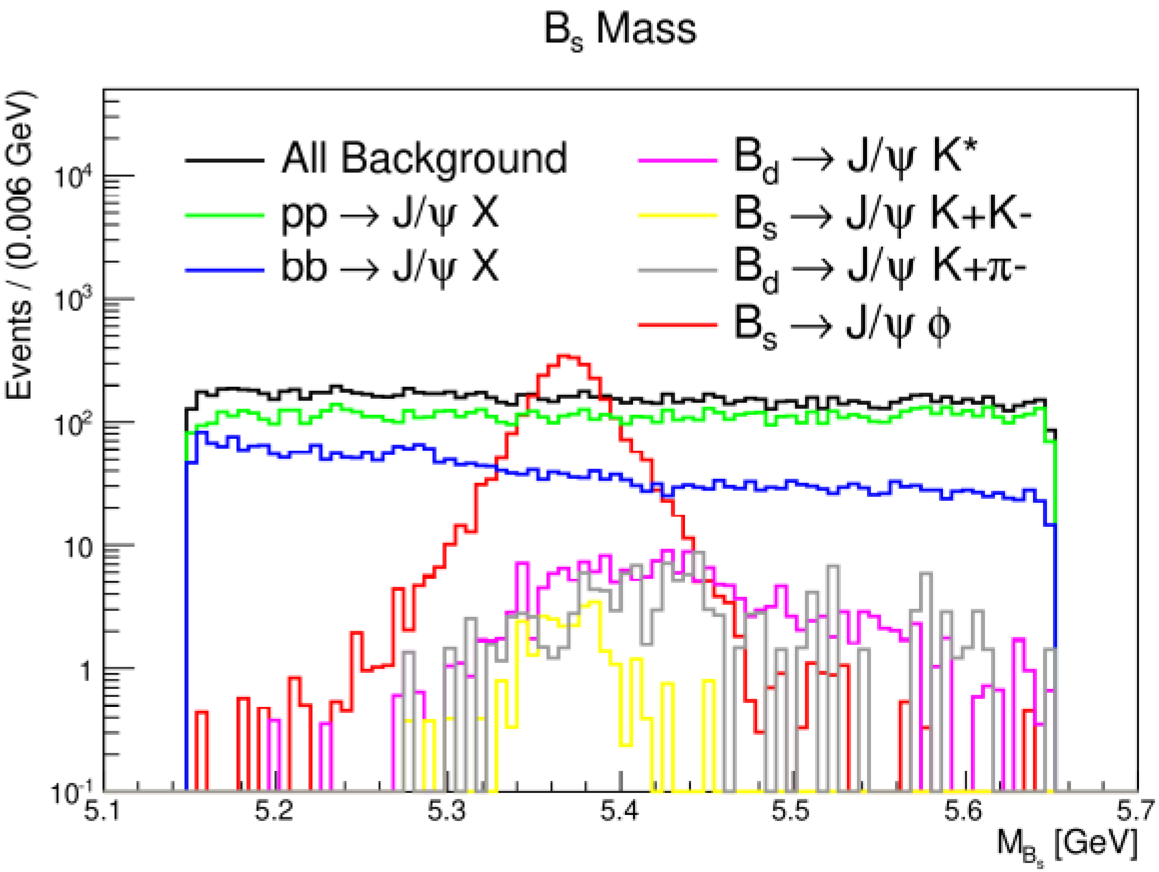
Measured variables:

- B_s mass m_i
- B_s proper decay time t_i and its uncertainty σ_{ti}
- 3 angles $\Omega_i(\theta_T, \psi_T, \varphi_T)$
- B_s momentum p_T
- B_s tag probability $p_{B|Qi}$
- tagging method M_i

Combinatorial background description, derived from data sidebands; angular distribution described by spherical harmonics and fixed in the fit

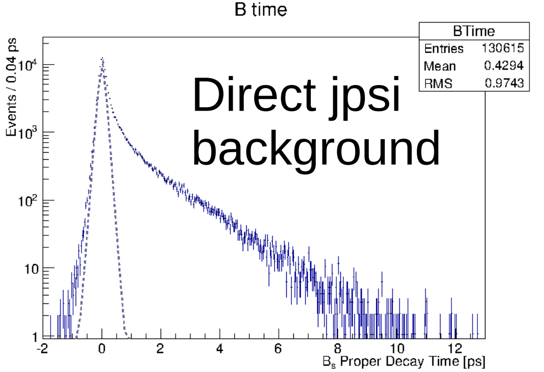
Weights accounting for **proper decay time trigger efficiency** (muons track d_0 reconstruction efficiency bias); estimated from MC

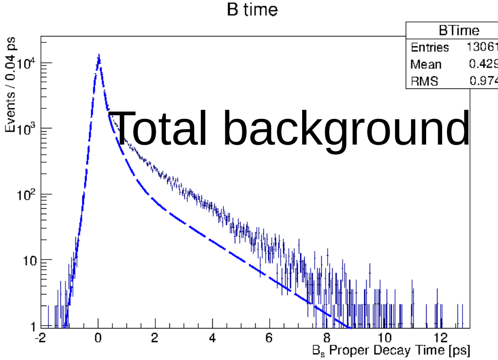
Background with Monte Carlo

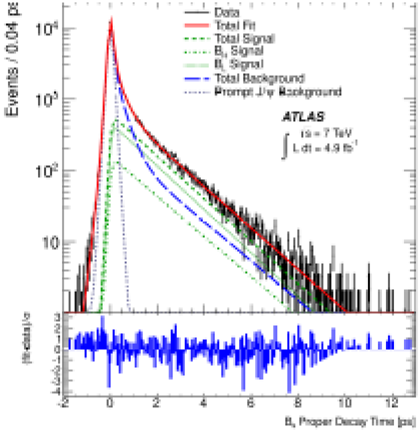


Background representation in the fit

- Time component of background:
  - Prompt background: delta function at 0, convoluted by Gauss **per-candidate resolution** σ_{ti}
  - Two exponentials representing longer-lived backgrounds
  - Small negative exponential component for events with poor vertex resolution
- Background angular shapes
  - Arise from detector and kinematic sculpting
  - Described by empirical functions with parameters determined in the fit
- Background mass model – linear function
- $B^0 \rightarrow J/\psi K^{*0}$ and $\Lambda b \rightarrow J/\psi\ \Lambda^*(Kp)$ contamination treated separately
  - fractions are determined from MC
  - mass, angular shapes - from MC
  - used in PDF but no free parameters of fit







Angular Background

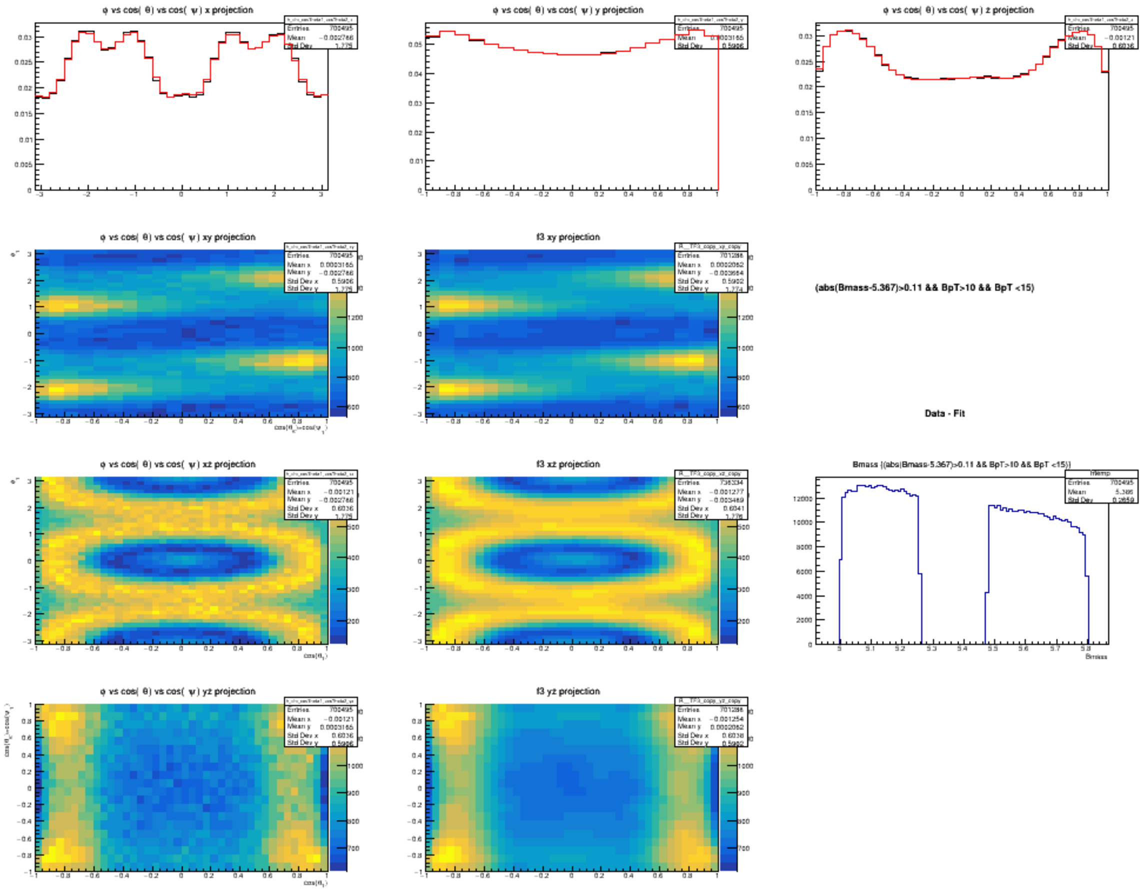
- The angular component of the background is shaped by detector and acceptance effects producing a non-trivial 3D shape that is also p_T dependent
- The mass side bands are taken and a Legendre polynomial function is used to fit the shape. The resulting parameters are fixed and used in the main fit.
- The dedicated backgrounds are simulated with monte carlo, their shaping applied and also fit by spherical harmonics

$$Y_l^m(\theta_T) = \sqrt{(2l+1)/(4\pi)}\sqrt{(l-m)!/(l+m)!}P_l^{|m|}(\cos\theta_T)$$

$$P_k(x) = \frac{1}{2^k k!}\frac{\mathrm{d}^k}{\mathrm{d}x^k}(x^2-1)^k$$

$$\mathscr{P}_\mathrm{b}(\theta_T,\psi_T,\phi_T) = \sum_{k=0}^{14}\sum_{l=0}^{14}\sum_{m=-l}^{l}\begin{cases} a_{k,l,m}\sqrt{2}Y_l^m(\theta_T)\cos(m\phi_T)P_k(\cos\psi_T) & \text{where } m>0 \\ a_{k,l,m}\sqrt{2}Y_l^{-m}(\theta_T)\sin(m\phi_T)P_k(\cos\psi_T) & \text{where } m<0 \\ a_{k,l,m}\sqrt{2}Y_l^0(\theta_T)P_k(\cos\psi_T) & \text{where } m=0 \end{cases}$$

Angular Background



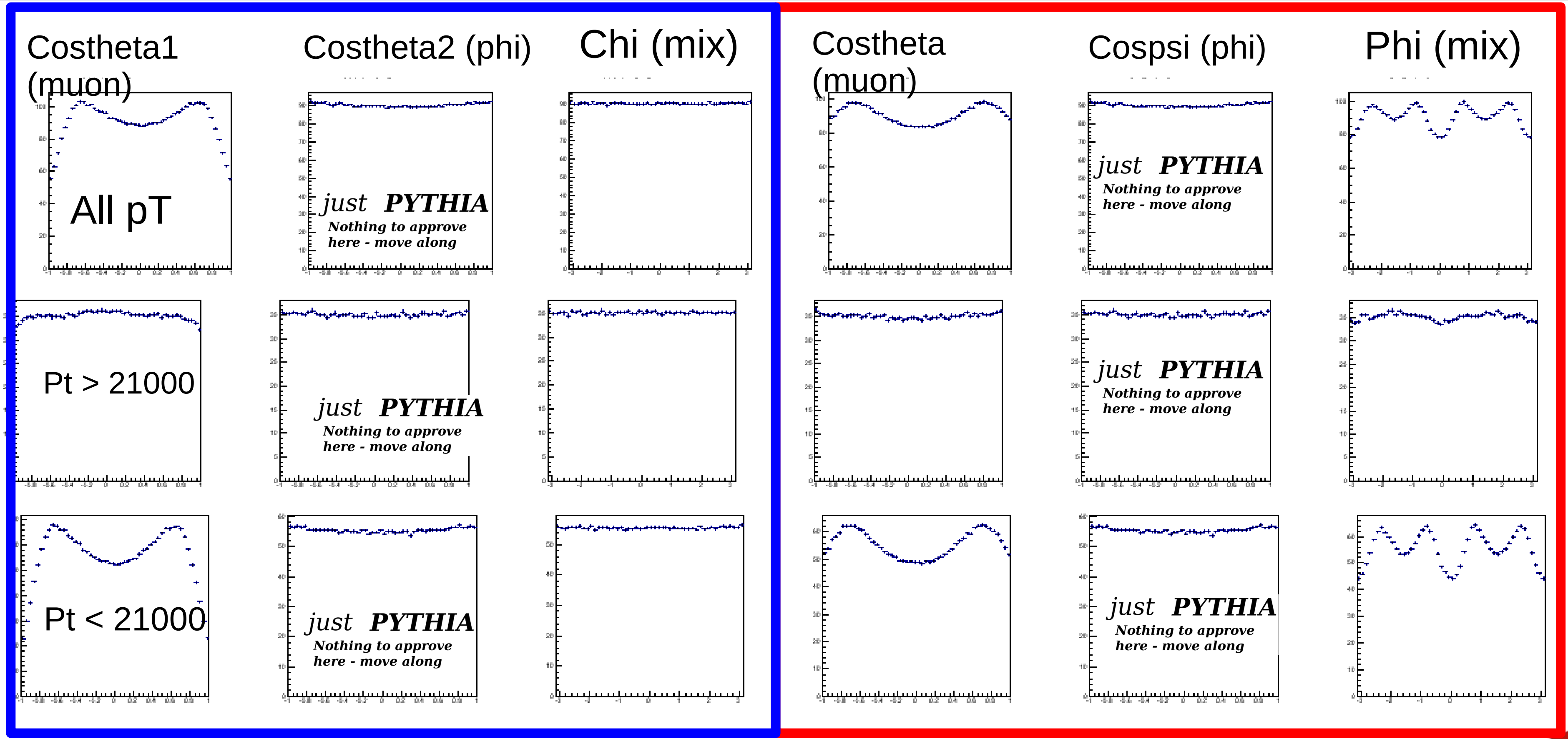
Kinematic Acceptance

- It is necessary to exclude (cut) low energy tracks to exclude large quantities of background.
  - The muon trigger applies at least a 4GeV cut on the muons (triggers vary according to the luminosity)
  - Kaon cuts are applied after reconstruction to reduce the background.
- This biases the angular distributions distorting the “true” distribution.
- This is attained by simulating a naïve level of physics so the angular distributions are flat, and then feeding these events through the detector simulator and applying the standard cuts.

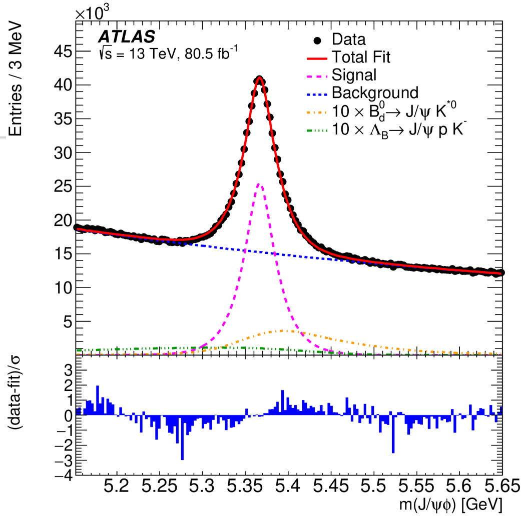
What Acceptances look like (mu4mu4)

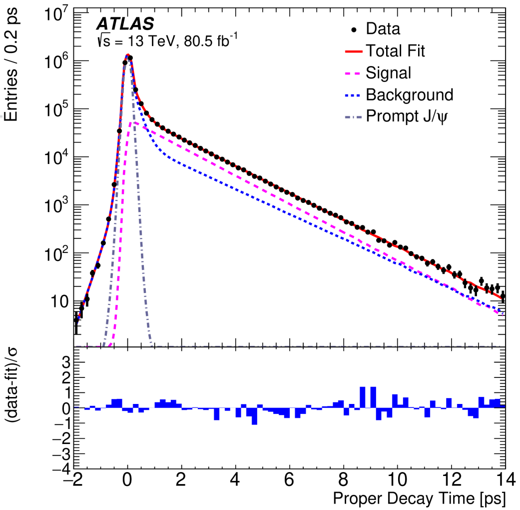
Helicity

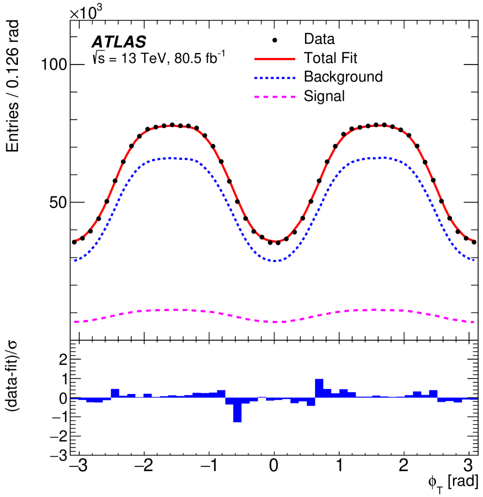
Transversity

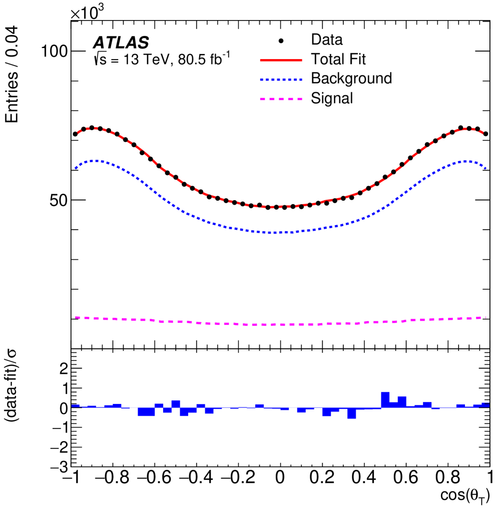


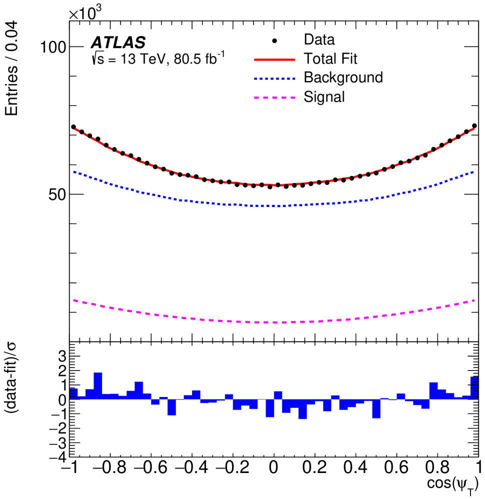
Fit Projections











Systematic Uncertainties

	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
Acceptance	0.5	< 0.1	< 0.1	1.0	0.8	2.6	30	50	11
ID alignment	0.8	0.2	0.5	< 0.1	< 0.1	< 0.1	11	7.2	< 0.1
Best candidate selection	0.5	0.4	0.7	0.5	0.2	0.2	12	17	7.5
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 interval	0.4	0.1	0.1	0.3	0.3	1.3	4.4	7.4	2.3
Dedicated backgrounds:									
B_d^0	2.3	1.1	< 0.1	0.2	3.0	1.5	10	23	2.1
Λ_b	1.6	0.3	0.2	0.5	1.2	1.8	14	30	0.8
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	0.2	< 0.1	< 0.1	0.3	< 0.1	0.3	11	21	8.4
Fit bias	4.1	1.7	0.9	1.4	< 0.1	1.5	19	0.9	7.0
Total	20	2.5	1.6	2.3	3.5	4.5	50	79	18

Uncertainty in the calibration of the B_s-tag probability; MC statistical uncertainty included in fit stat. error

Alternative detector acceptance fit-functions and binning determined from MC

Radial expansion uncertainties determined from their effect on tracks d_0 in the data

Background angles model (fixed in UML fit) extracted from data with varying sidebands size and binning

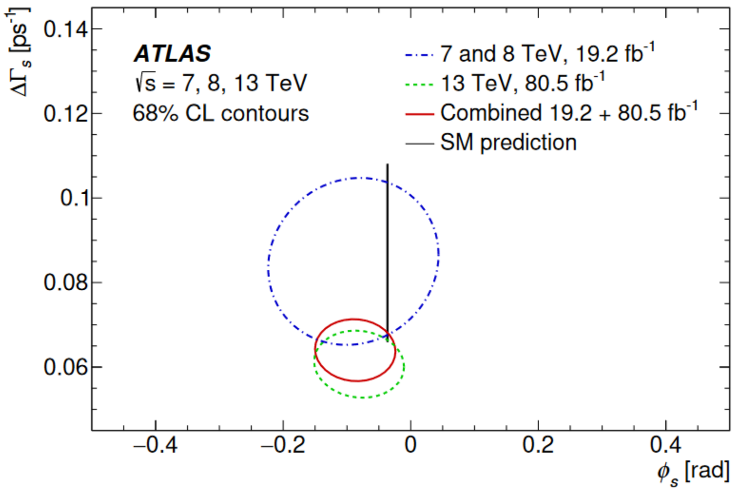
Uncertainties of relative fraction; fit-model and P-wave contribution

Uncertainties of relative fraction; fit-model and contributions from $\Lambda_b \to J/\psi \Lambda^*$ decays

Toy-MC studies; pulls of the default fit model, default fit on toy-data generated with modified PDFs

Result of the CPV Bs→ J/ψ ϕ Study

Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s [rad]	−0.081	0.041	0.020
$\Delta\Gamma_s$ [ps^{-1}]	0.0607	0.0046	0.0025
Γ_s [ps^{-1}]	0.6687	0.0015	0.0017
$\|A_{\|\|}(0)\|^2$	0.2213	0.0020	0.0022
$\|A_0(0)\|^2$	0.5131	0.0013	0.0034
$\|A_S(0)\|^2$	0.0321	0.0034	0.0044
$\delta_\perp$ [rad]	3.12	0.11	0.05
$\delta_{\|\|}$ [rad]	3.35	0.05	0.06
$\delta_\perp - \delta_S$ [rad]	−0.25	0.05	0.01



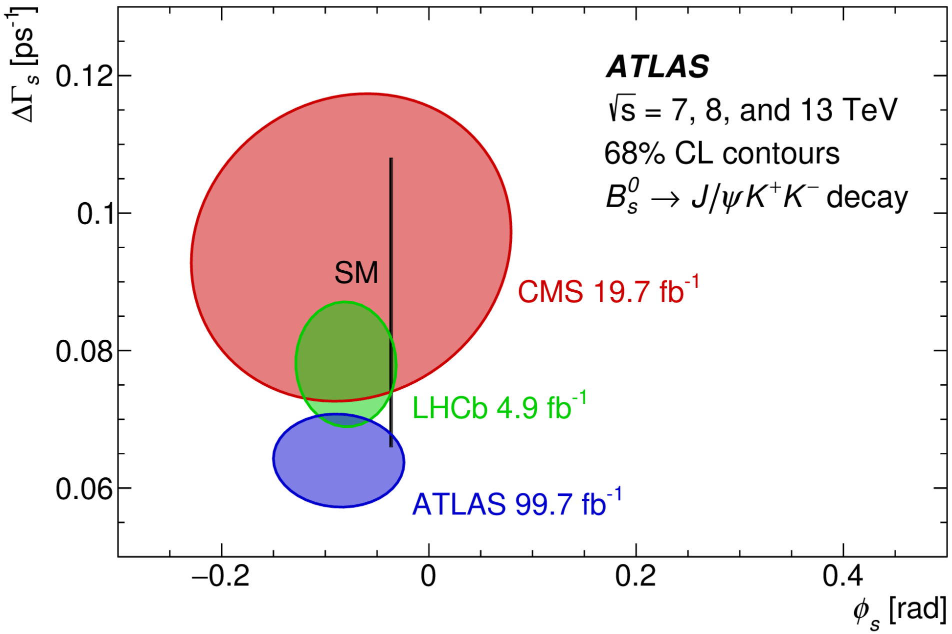
Fit correlation matrix:

	$\Delta\Gamma$	Γ_s	$\|A_{\|\|}(0)\|^2$	$\|A_0(0)\|^2$	$\|A_S(0)\|^2$	$\delta_{\|\|}$	$\delta_\perp$	$\delta_\perp - \delta_S$
ϕ_s	−0.080	0.016	−0.003	−0.004	−0.008	0.007	0.004	−0.007
$\Delta\Gamma$	1	−0.580	0.089	0.094	0.051	0.032	0.005	0.020
Γ_s		1	−0.127	−0.043	0.083	−0.089	−0.024	0.016
$\|A_{\|\|}(0)\|^2$			1	−0.341	−0.187	0.541	0.144	−0.056
$\|A_0(0)\|^2$				1	0.278	−0.108	−0.037	0.071
$\|A_S(0)\|^2$					1	−0.378	−0.126	0.245
$\delta_{\|\|}$						1	0.265	−0.089
$\delta_\perp$							1	−0.001

Combination with 7 TeV and 8 TeV results

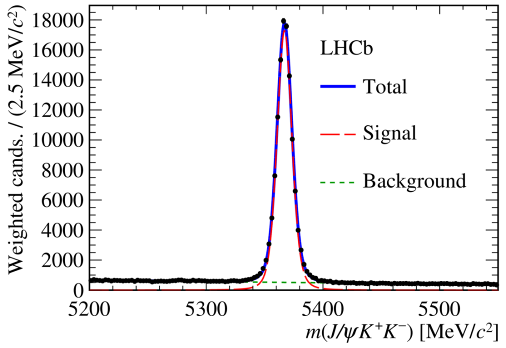
- We present a combined result (BLUE) of this result with our previous “run-1” result.

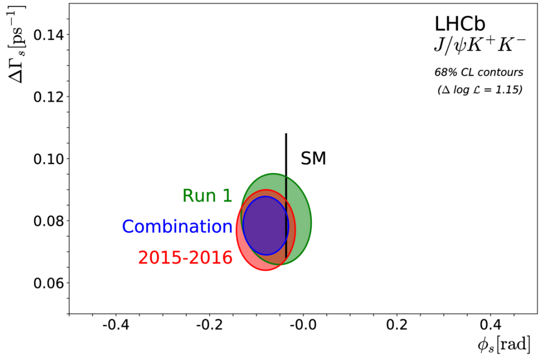
Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s [rad]	−0.087	0.037	0.019
$\Delta\Gamma_s$ [ps^{-1}]	0.0640	0.0042	0.0024
Γ_s [ps^{-1}]	0.6698	0.0014	0.0015
$\lvert A_{\parallel}(0)\rvert^2$	0.2221	0.0018	0.0022
$\lvert A_0(0)\rvert^2$	0.5149	0.0012	0.0031
$\lvert A_S\rvert^2$	0.0343	0.0032	0.0044
$\delta_\perp$ [rad]	3.21	0.10	0.05
$\delta_\parallel$ [rad]	3.36	0.05	0.08
$\delta_\perp - \delta_S$ [rad]	−0.24	0.05	0.02



LHCb - 2019

- LHCb have recently released an updated result.
- LHCb has particle ID hardware allowing them to significantly reduce background, but cannot record as much luminosity reducing statistics
- Resulting in a worse statistical error but better systematic error.





$\Phi_s = -0.083 \pm 0.041 \pm 0.006$ rad

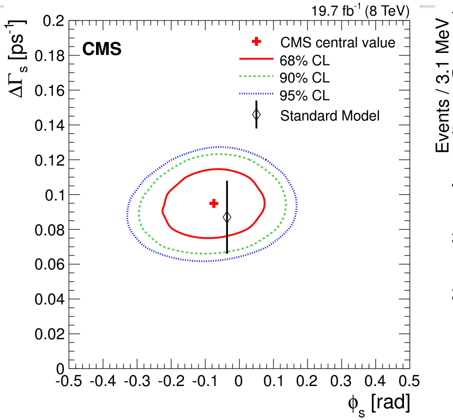
$\Delta\Gamma_s = 0.077 \pm 0.008 \pm 0.003$ ps−1

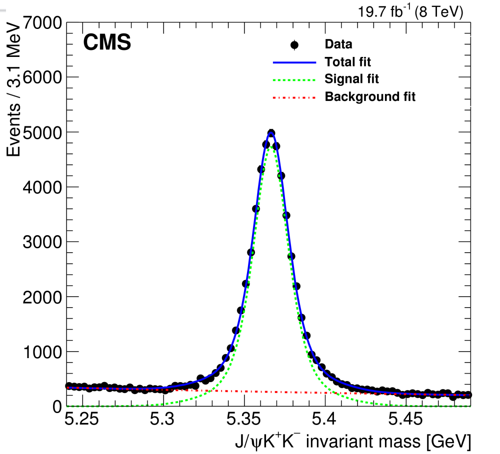
ATLAS

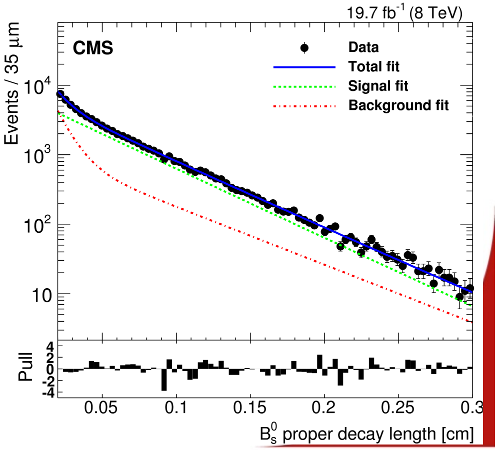
$$\phi_s = -0.076 \pm 0.034\ (\text{stat.}) \pm 0.019\ (\text{syst.})\ \text{rad}$$
$$\Delta\Gamma_s = 0.068 \pm 0.004\ (\text{stat.}) \pm 0.003\ (\text{syst.})\ \text{ps}^{-1}$$

CMS - 2015

- CMS have a measurement from 2015 using run-1 data.
- CMS has a similar strategy to ATLAS but cut out the direct pp background.







CMS

φ_s = -0.075 ± 0.097 (stat) ± 0.031 (syst) rad

$\Delta\Gamma_s$ = 0.095 ± 0.013 (stat) ± 0.007 (syst) ps^{-1}

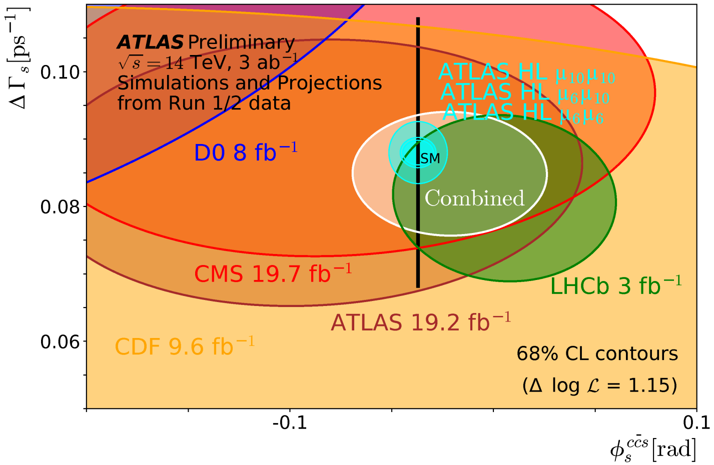
ATLAS

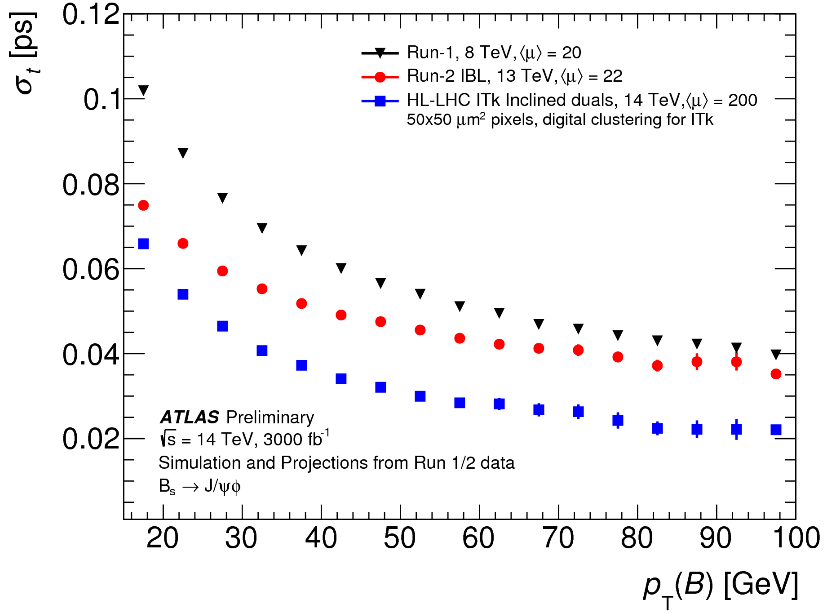
$$\phi_s = -0.076 \pm 0.034\ (\text{stat.}) \pm 0.019\ (\text{syst.})\ \text{rad}$$
$$\Delta\Gamma_s = 0.068 \pm 0.004\ (\text{stat.}) \pm 0.003\ (\text{syst.})\ \text{ps}^{-1}$$

Detector Improvements

ATL-PHYS-PUB-2018-041

- In run-2 IBL improves time resolution → improved φ_s
- We estimate φ_s for future analyses give various muon threshold scenarios.

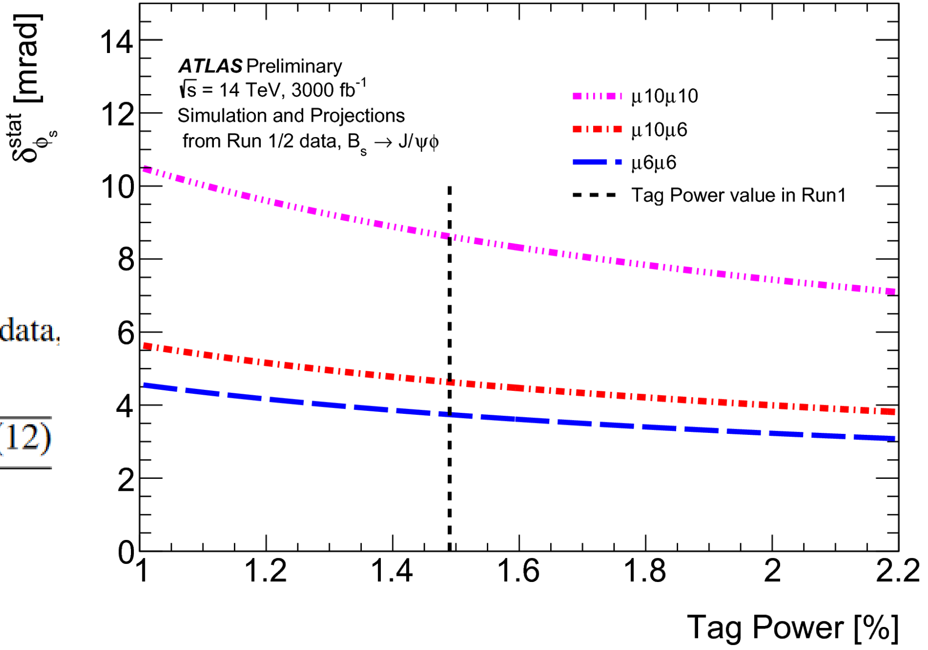


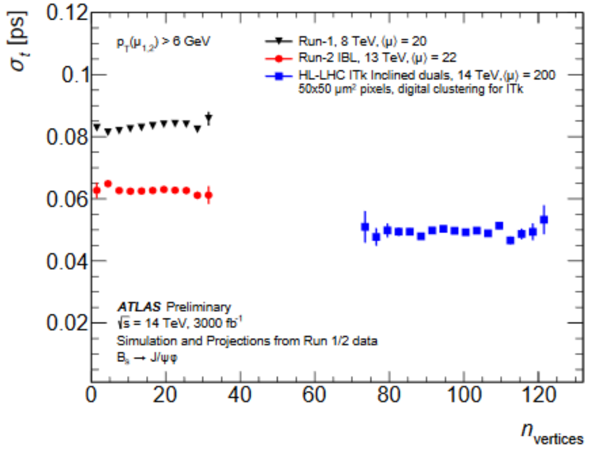


Tagging Projections

The predicted $\delta^{\rm stat}_{\phi_s}$ values are calculated relative to the value measured using 2012 data,

$$\delta^{\rm stat}_{\phi_s} = \delta^{\rm stat}_{\phi_s}(12) \cdot \frac{\sqrt{TP(12)} \cdot f_{\rm sig}(12) \cdot \exp\left[-\frac{1}{2}(\sigma_t(12)\Delta m_s)^2\right] \cdot \sqrt{N_{\rm sig}(12)}}{\sqrt{TP} \cdot f_{\rm sig} \cdot \exp\left[-\frac{1}{2}(\sigma_t \Delta m_s)^2\right] \cdot \sqrt{N_{\rm sig}}}$$





Period	$L_{\rm int}$ [fb^{-1}]	$N_{\rm sig}$	$f_{\rm sig}$	Tag Power [%]	$\sigma(\tau)$ [ps]	$\delta^{\rm stat}_{\phi_s}$ [rad] measured (extrapolated)	$\delta^{\rm stat}_{\Delta\Gamma_s}$ [ps^{-1}] measured (extrapolated)
2012	14.3	73693	0.20	1.49	0.091	0.082	0.013
2011	4.9	22690	0.17	1.45	0.100	0.25 (0.22)	0.021 (0.023)
						$\delta^{\rm stat}_{\phi_s}$ [rad] extrapolated	
HL-LHC	3000						
Trigger μ6μ6		$9.72 \cdot 10^6$	0.17	1.49	0.048	0.004	0.0011
Trigger μ10μ6		$5.93 \cdot 10^6$	0.17	1.49	0.044	0.005	0.0014
Trigger μ10μ10		$1.75 \cdot 10^6$	0.15	1.49	0.038	0.009	0.003

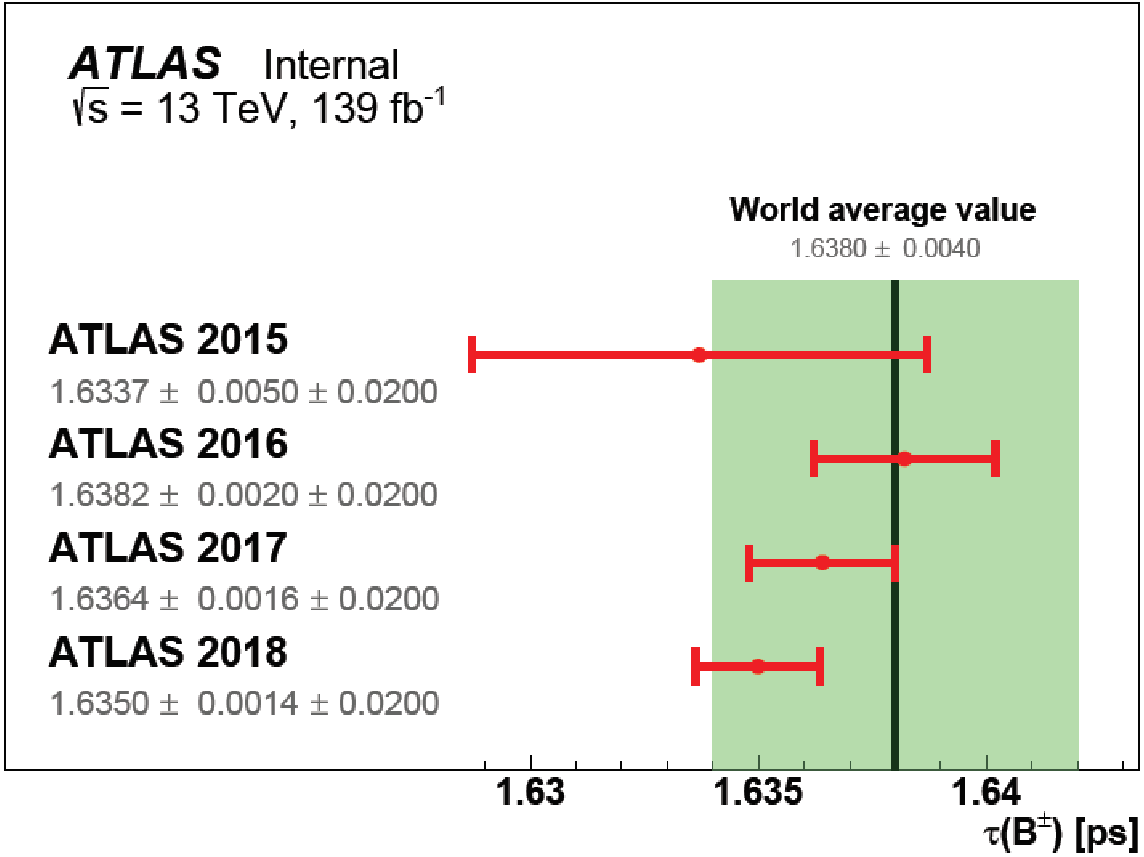
Summary

- ATLAS' measurement is compatible with the standard model and other experiments.
- ATLAS remains competitive with other experiments

$$
\begin{aligned}
\phi_s &= -0.087 \pm 0.037 \text{ (stat.)} \pm 0.019 \text{ (syst.) rad} \\
\Delta\Gamma_s &= 0.0640 \pm 0.0042 \text{ (stat.)} \pm 0.0024 \text{ (syst.) ps}^{-1} \\
\Gamma_s &= 0.6698 \pm 0.0014 \text{ (stat.)} \pm 0.0015 \text{ (syst.) ps}^{-1} \\
|A_{\parallel}(0)|^2 &= 0.2221 \pm 0.0018 \text{ (stat.)} \pm 0.0022 \text{ (syst.)} \\
|A_0(0)|^2 &= 0.5149 \pm 0.0012 \text{ (stat.)} \pm 0.0031 \text{ (syst.)} \\
|A_S(0)|^2 &= 0.0343 \pm 0.0032 \text{ (stat.)} \pm 0.0044 \text{ (syst.)} \\
\delta_{\perp} &= 3.21 \pm 0.10 \text{ (stat.)} \pm 0.05 \text{ (syst.) rad} \\
\delta_{\parallel} &= 3.36 \pm 0.05 \text{ (stat.)} \pm 0.08 \text{ (syst.) rad} \\
\delta_{\perp} - \delta_S &= -0.24 \pm 0.05 \text{ (stat.)} \pm 0.02 \text{ (syst.) rad}
\end{aligned}
$$

Backup slides

Lifetime confirmation



$$\ln \mathcal{L} = \sum_{i=1}^{N} \{ \underbrace{w_i}_{\text{Tau weight}} \cdot \ln(\underbrace{f_s \cdot \mathcal{F}_s}_{\text{Signal}} + \underbrace{f_s \cdot f_{B_d^0} \cdot \mathcal{F}_{B_d^0} + f_s \cdot f_{\Lambda_b} \cdot \mathcal{F}_{\Lambda_b}}_{\text{Peaking background}} + \underbrace{(1 - f_s \cdot (1 + f_{B_d^0} + f_{\Lambda_b})) \cdot \mathcal{F}_{\text{bkg}}}_{\text{Combinatorial background}})\}$$

- Data are corrected by the decay time correction
- Mass as well as lifetime use per-candidate width and scale factor, with flavour-dependent terms weighted by tagging probability $P(B|Q)$
- Contributions from $B_d^0 \to J/\psi K^{*0}$, $B_d^0 \to J/\psi K\pi$ and $\Lambda_b^0 \to J/\psi Kp$ due to wrong mass assignment (KK)
  - Efficiencies and acceptance from MC
  - BR from PDG
  - Fragmentation fractions from other measurements
- Combinatorial background for angular distribution use Legendre polynomials from sidebands; fixed in the main fit