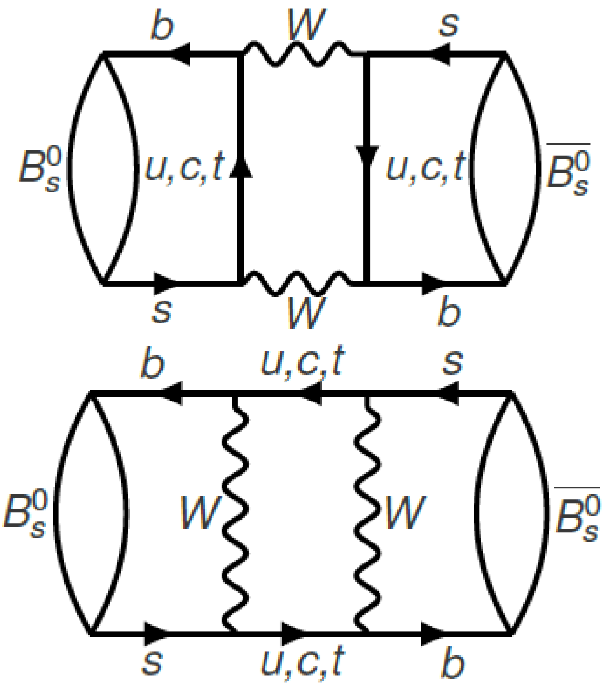
CP violation with the ATLAS and CMS experiments

LHCP 2021

Adam Barton on behalf of the ATLAS collaboration

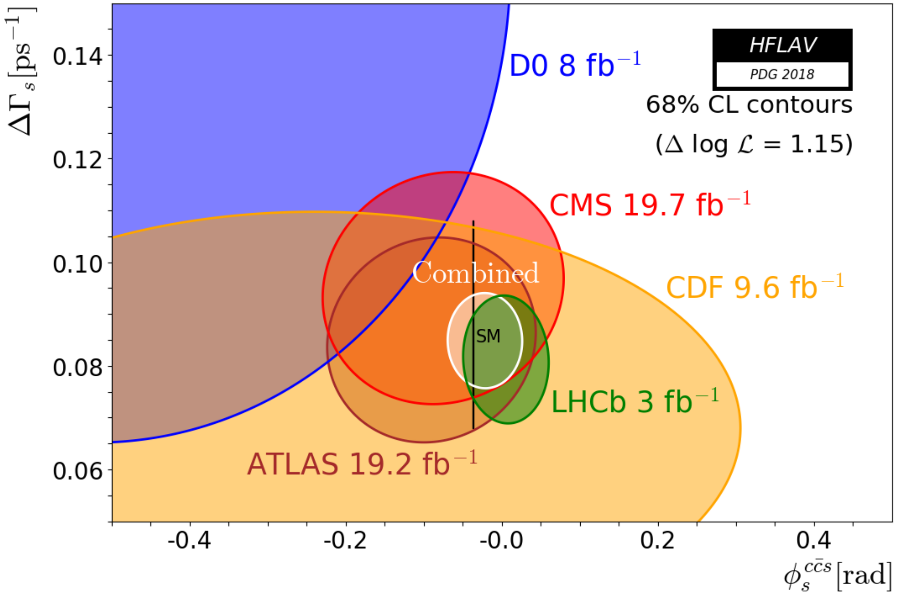
Motivations

- φ_s is a CP-violating phase arising from the interference between Bs decays proceeding directly and through Bs-Bs-bar mixing to the CP-final state.
- SM prediction: $\varphi_s \approx -2\ \beta_s = -36.96 \pm\sim 0.80$ mrad.
- Theorists suggest new Physics can change the value of φ_s up to ~10mrad.
- $B_s \rightarrow J/\psi\ \varphi$ is considered the golden channel to measure φ_s
  - No direct CPV
  - Only one CPV phase
  - Fairly easy to reconstruct
- Also involves Γ_s, $\Delta\Gamma_{s}$, $|\lambda|$, Δm_s
- The theory prediction is $\Delta\Gamma_s = (0.091 \pm 0.013)\ \mathrm{ps}^{-1}$



Measurements before LHC Run2

- This measurement was previously done at the Tevatron with both the CDF and D0 experiments.
- The results were consistent with the SM prediction within the large measured uncertainties.
- Although large deviations from the SM prediction have been excluded there is still potential room for discoveries.



ATLAS and CMS measurements in LHC Run2

ATLAS
Eur. Phys. J. C 81 (2021) 342

- √s = 13 TeV collected between years 2015 and 2017 corresponding to 80.5 $fb^{-}1$.
- Events collected with mixture of triggers based on J/ψ identification, with muon pT thresholds of either 4 GeV or 6 GeV (vary over run periods)
- No lifetime or impact parameter cut at trigger level

CMS
Phys. Lett. B 816 (2021) 136188

- √s = 13 TeV collected between years 2017 and 2018 corresponding to 96.4 $fb^{-}1$.
- The trigger requires three muons, with the minimum pT requirement on the highest pT and second-highest pT muons of pT > 5 and 3 GeV, respectively, and the dimuon invariant mass < 9 GeV.
- Proper decay length cut ct > 70μm

Offline Selection

ATLAS		CMS	
		$p_T(\mu)$	> 3.5 GeV
$p_T(K)$	> 1 GeV	$p_T(K)$	> 1.2 GeV
J/ψ window varies by muon η		J/ψ window	150 MeV
φ(1020) window 11 MeV			
pT(Bs)	> 11 GeV	pT(Bs)	> 10 GeV
no tau cut		ct(Bs)	> 70 μm
Vtx chi/NDF	< 3	4 trk Vtx prob	> 0.1%
M(Bs) Window	[5.15, 5.65] GeV	M(Bs) Window	[5.24, 5.49] GeV

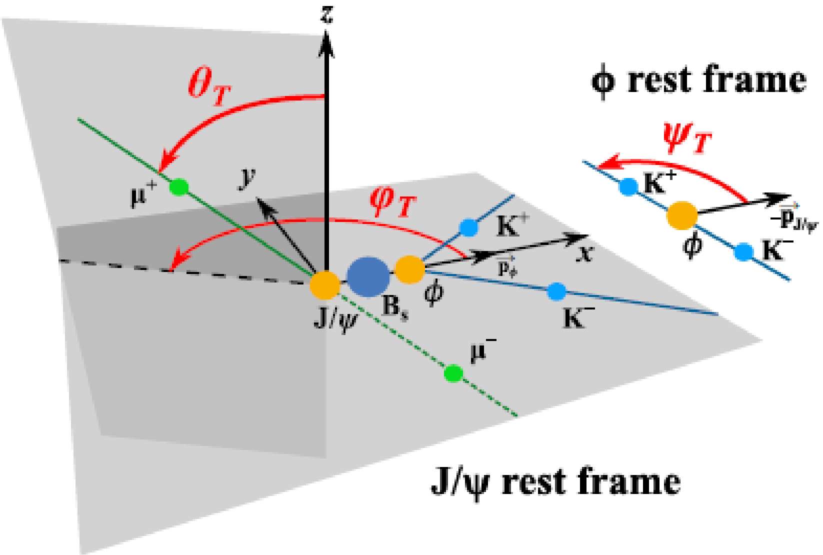
L_{int}=80.5fb^{-1} collected in 2015 to 2017
N of extracted signal B_s = ~ 446,600

L_{int}=96.4fb^{-1} collected in 2017 and 2018
N of extracted signal B_s =~ 48,500

Vertex fit performed with J/ψ mass constraint

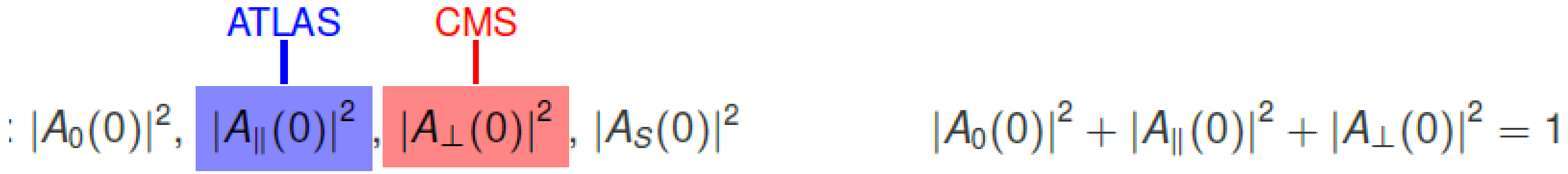
Angular Analysis

- Bs → J/ψ φ = pseudoscalar to vector-vector
- Final state: admixture of CP-odd (L = 1) and CP-even (L = 0; 2) states
- Distinguishable through time-dependent angular analysis
- Non-resonant S-wave decay Bs → J/ψ $K^+ K^-$ contributes to the final state
- This has to be included in the differential decay rate due to interference with the resonant decay.
- Decay can be described in Transversity or Helicity basis. Both experiments use the Transversity basis (pictured)



Mass-lifetime-angular fit

- An unbinned maximum-likelihood fit is performed on the combined data samples extracting parameters of interest:
  - CPV phase $\varphi_{s,}$ decay widths: $\Delta\Gamma_s$, $\Gamma_s = \frac{\Gamma_L+\Gamma_H}{2}$
  - The amplitudes at t=0



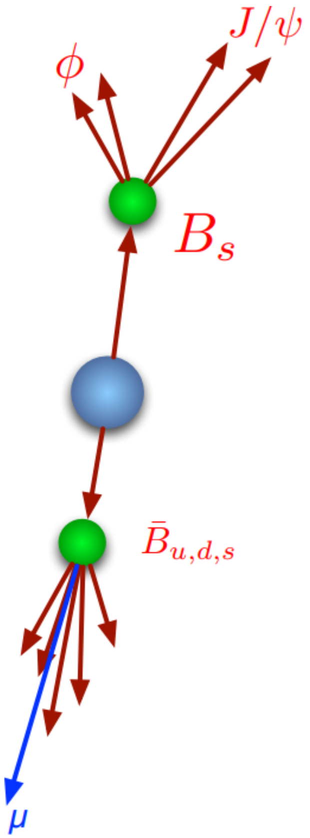
: $|A_0(0)|^2$, $|A_\parallel(0)|^2$, $|A_\perp(0)|^2$, $|A_S(0)|^2$

$$|A_0(0)|^2 + |A_\parallel(0)|^2 + |A_\perp(0)|^2 = 1$$

- The strong phases $\delta_\parallel$, $\delta_\perp$, δ_S, $\delta_0 = 0$ (CMS $\delta_{S\perp} = \delta_S - \delta_\perp$)
- $\Delta m_s = |m_L - m_H|$ (ATLAS uses value fixed to PDG $\Delta m_s = 17.77\,\mathrm{ps}^{-1}$)
- $|\lambda|$ (ATLAS uses value fixed to 1.0)

Flavour tagging

- Opposite side tagging
  - Use bb pair correlation to infer initial signal flavour from the other B meson, the probability it is a particle or anti-particle
- Semi-leptonic Tagging method
  - b→l transitions are clean tagging method
  - b→c→ l and neutral B-meson oscillations dilute the tagging
- Jet-Charge – information from tracks in b-tagged jets
- Calibration using B → J/ψ $K^{\pm}$ (self tagging, non-oscillating channel)
- ATLAS uses “tight” muons, electrons, “low-pT” muons, jets
- CMS uses muons in the last publication



Tagging performance

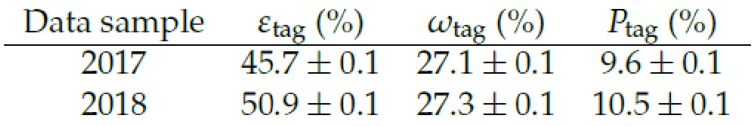
- The probability to tag a B_s meson as containing a b-quark:

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

- Efficiency: Fraction of signals with specific tagger
- Dilution: D = (1-2ω), where ω is the mistag probability that is defined as ratio between the number of wrongly tagged events and the total number of tagged events
- Tagging Power: metric of tagger performance

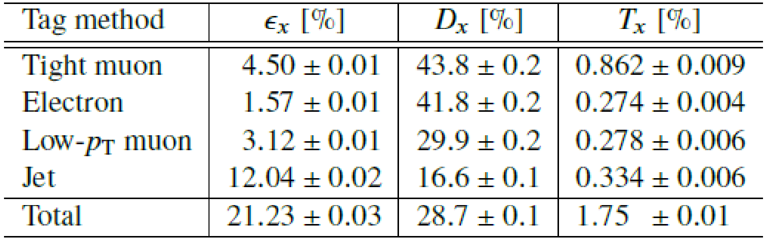
$$P = T = \varepsilon D^2 = \varepsilon(1 - 2\omega)^2$$

CMS



Data sample	ε_{tag} (%)	ω_{tag} (%)	P_{tag} (%)
2017	45.7 ± 0.1	27.1 ± 0.1	9.6 ± 0.1
2018	50.9 ± 0.1	27.3 ± 0.1	10.5 ± 0.1

ATLAS



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

Efficiencies

- Both experiments use efficiency corrections for the lifetime
- Detector acceptance and event selection lead to non uniform angular efficiency
- 3D angular efficiency is evaluated in bins of $\cos\theta_T$, $\cos\psi_T$ and ϕ_T, using simulated samples
  - CMS Binning: 70 bins for $\cos\theta_T$ and $\cos\psi_T$, and 30 for ϕ_T
  - ATLAS Binning: 8 pt bins x 10 $\cos\theta_T$ x 4 $\cos\psi_{T,}$ and 28 for ϕ_T
- CMS uses a spherical harmonic function with Legendre polynomials up to order six while ATLAS uses a histogram

Systematic uncertainties

ATLAS

Flavour tagging: calibration,MC difference and dependencies on the pile-up distribution

Fit bias: fit stability is validated by the pseudo-experiments with default fit results

Background angles model: varying the bin boundaries, invariant mass window and sideband definition

Best candidate selection: statistically equivalent sample is created where all candidates in the event are retained

Angular acceptance method: different acceptance functions are calculated using different numbers of p_T bins as well as different widths and central values of the bins

CMS

Model bias: pseudo experiments, each statistically equivalent to the data samples, from the fitted model in data

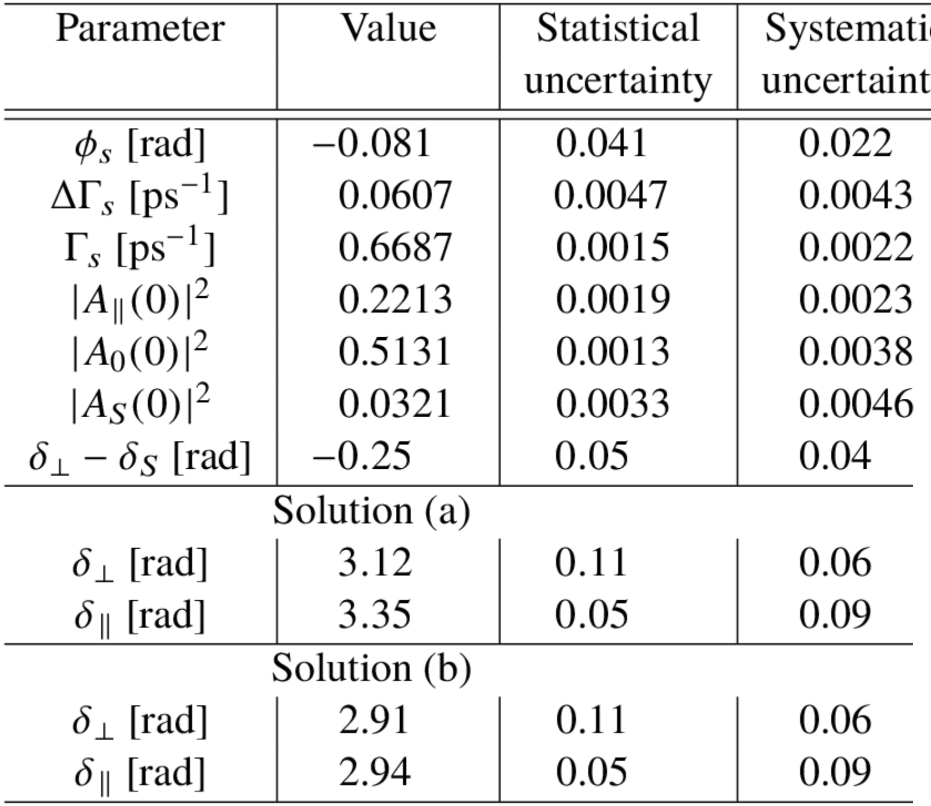
Angular efficiency: systematic uncertainty related to the limited MC event count used to estimate the angular efficiency function is evaluated by regenerating the efficiency histograms

Proper decay length resolution: varying the correction factor κ by 10%, as estimated from a data-to-simulation comparison

Sig./bkg. ω difference: differences in the mistag probabilities between signal and background studied on the sideband and signal range

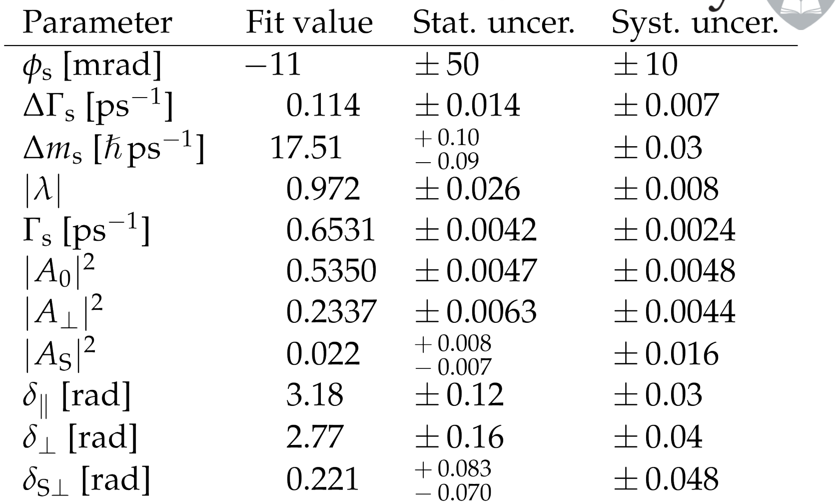
Results

ATLAS

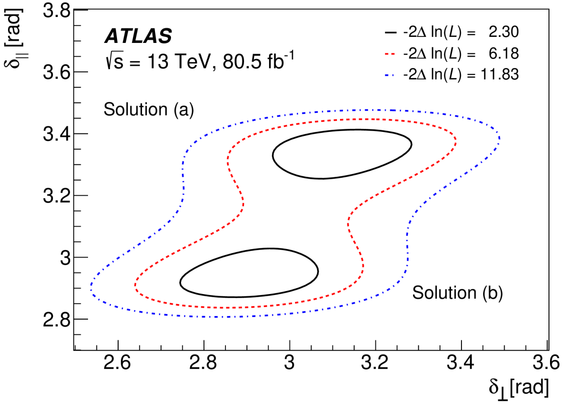


Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s [rad]	-0.081	0.041	0.022
$\Delta\Gamma_s$ [ps^{-1}]	0.0607	0.0047	0.0043
Γ_s [ps^{-1}]	0.6687	0.0015	0.0022
$\lvert A_\parallel(0)\rvert^2$	0.2213	0.0019	0.0023
$\lvert A_0(0)\rvert^2$	0.5131	0.0013	0.0038
$\lvert A_S(0)\rvert^2$	0.0321	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

CMS



Parameter	Fit value	Stat. uncer.	Syst. uncer.
ϕ_s [mrad]	-11	± 50	± 10
$\Delta\Gamma_s$ [ps^{-1}]	0.114	± 0.014	± 0.007
Δm_s [$\hbar$ ps^{-1}]	17.51	$^{+0.10}_{-0.09}$	± 0.03
$\lvert\lambda\rvert$	0.972	± 0.026	± 0.008
Γ_s [ps^{-1}]	0.6531	± 0.0042	± 0.0024
$\lvert A_0\rvert^2$	0.5350	± 0.0047	± 0.0048
$\lvert A_\perp\rvert^2$	0.2337	± 0.0063	± 0.0044
$\lvert A_S\rvert^2$	0.022	$^{+0.008}_{-0.007}$	± 0.016
$\delta_\parallel$ [rad]	3.18	± 0.12	± 0.03
$\delta_\perp$ [rad]	2.77	± 0.16	± 0.04
$\delta_{S\perp}$ [rad]	0.221	$^{+0.083}_{-0.070}$	± 0.048

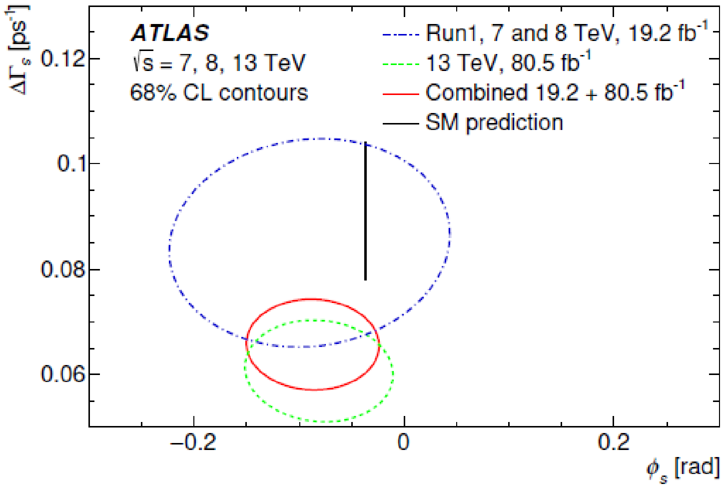


Combination with Run1 results

- Both experiments performed a statistical combination of their new results with those obtained in Run1 using the BLUE method. This method uses the measured values and uncertainties of the parameters as well as the correlations between them

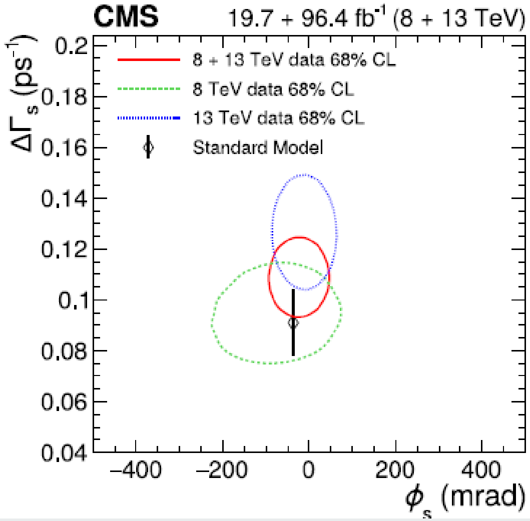
$$\phi_s = -87 \pm 36(\text{stat.}) \pm 21(\text{syst.})\,\text{mrad},$$

$$\Delta\Gamma_s = 0.0657 \pm 0.0043(\text{stat.}) \pm 0.0037(\text{syst.})\,\text{ps}^{-1}$$



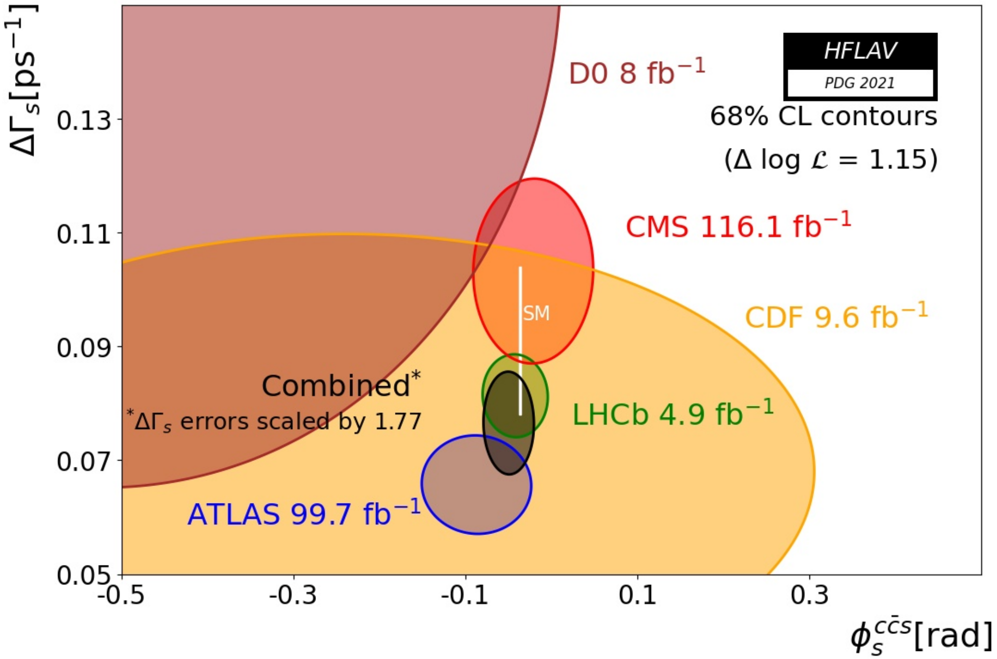
$$\phi_s = -21 \pm 44(\text{stat.}) \pm 10(\text{syst.})\,\text{mrad},$$

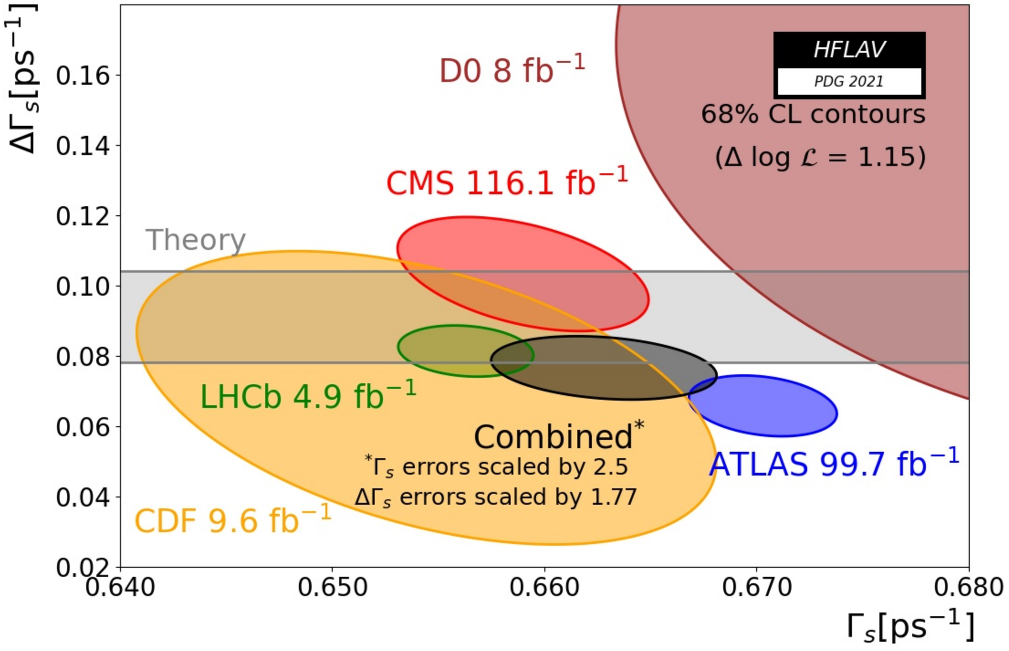
$$\Delta\Gamma_s = 0.1032 \pm 0.0095(\text{stat.}) \pm 0.0048(\text{syst.})\,\text{ps}^{-1}$$



HFLAV Plots

- Experiments are consistent with the SM and to an extent each other (tension especially Γ_s which correlates with $\Delta\Gamma_s$)





Conclusion

- ATLAS and CMS performed analysis on a subset of LHC Run2 data
- Both experiments are consistent with Run 1 results and with SM predictions

- ATLAS is working on the full Run2 measurement (additional 60 fb^{-1} from 2018) with updated fit model that include the extraction of Δm_s and $|\lambda|$ parameters
- CMS is working on the measurement with full Run2 statistics with more general triggers that do not require 3rd muon in the event, and they plan also to use more tagging methods (electron, jet)

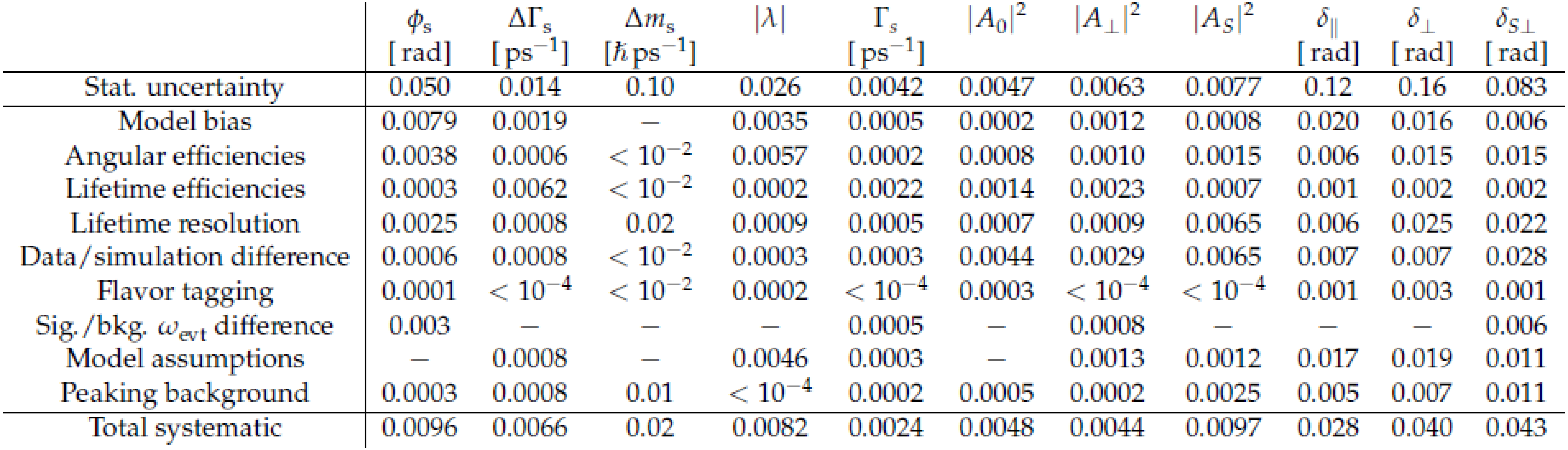
- Preparations for Run3 are very active, especially on the trigger side, to ensure a large amount of high quality data

Backup

After session meeting

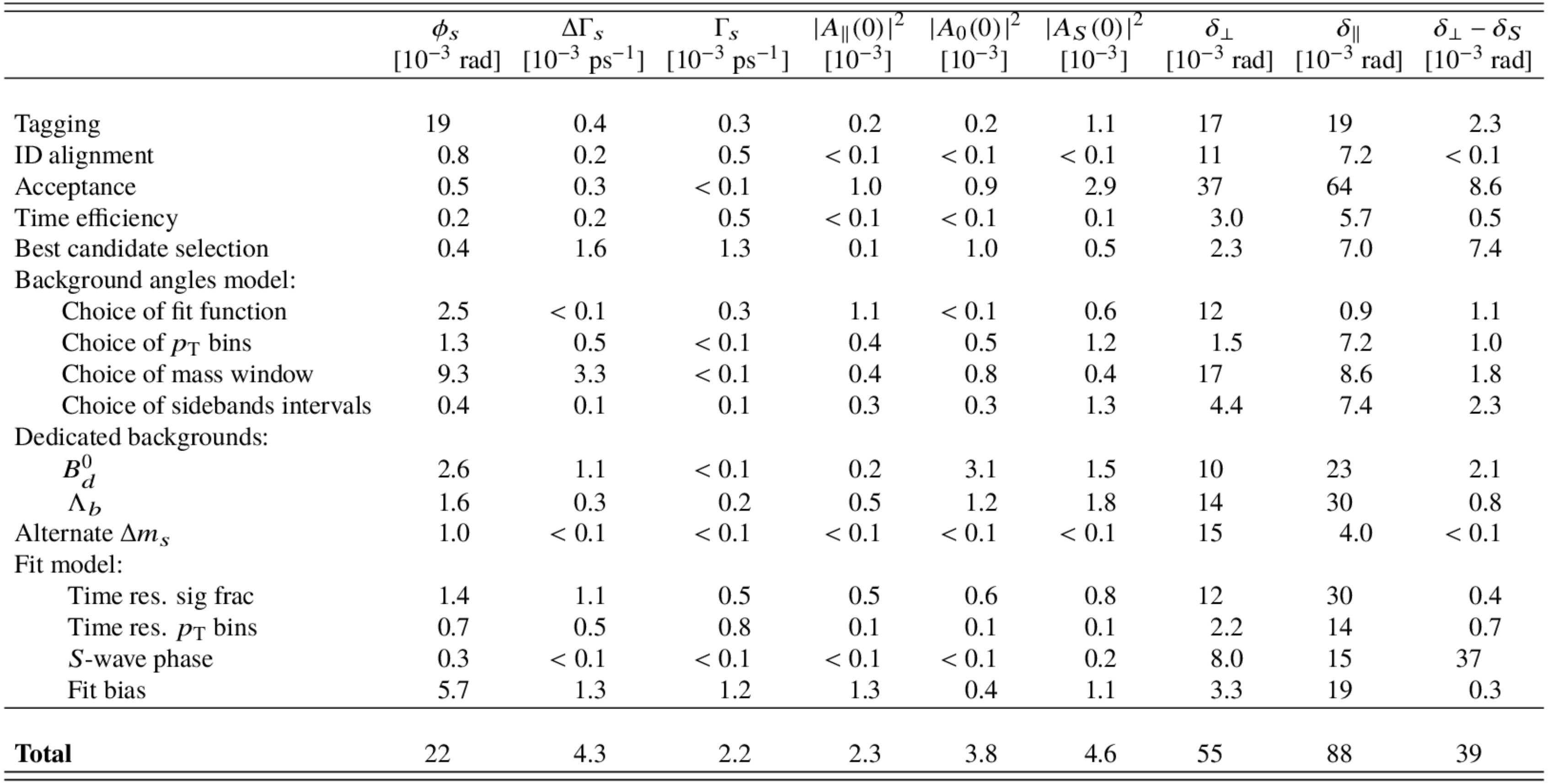
Join Zoom Meeting
https://cern.zoom.us/j/4423962481

CMS Systematics



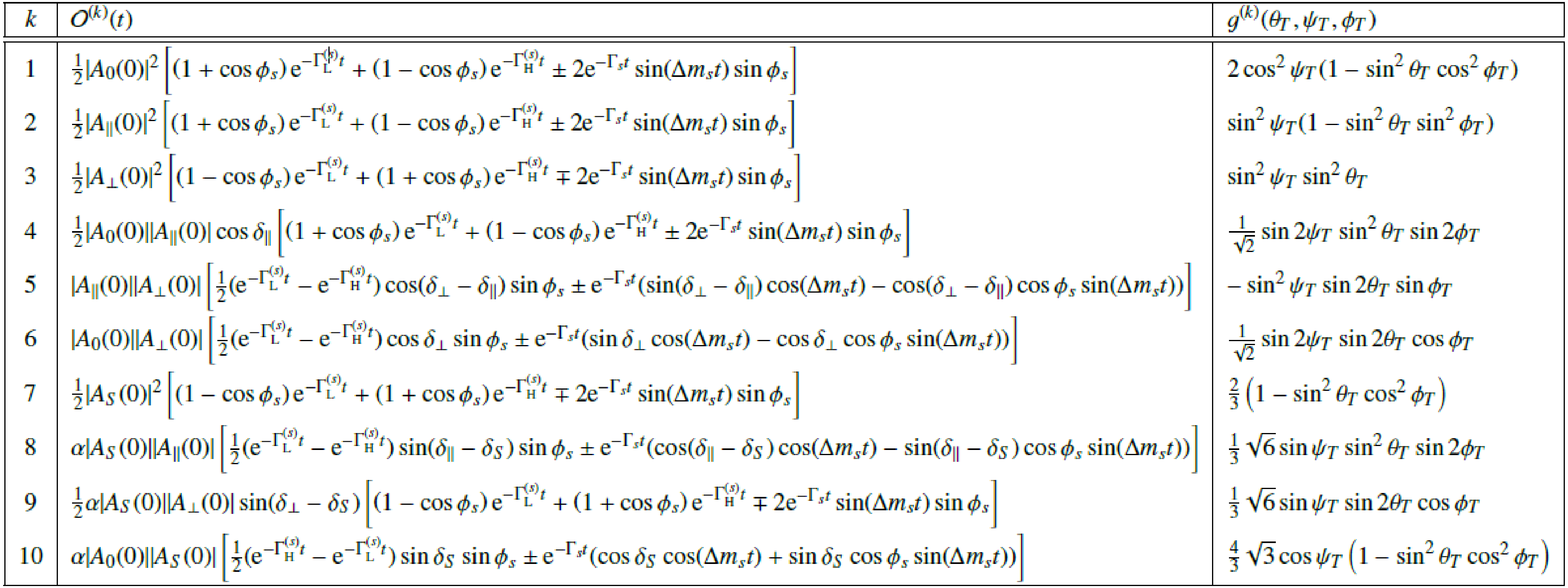
	ϕ_s [rad]	$\Delta\Gamma_s$ [ps^{-1}]	Δm_s [$\hbar$ ps^{-1}]	$\lvert\lambda\rvert$	Γ_s [ps^{-1}]	$\lvert A_0\rvert^2$	$\lvert A_\perp\rvert^2$	$\lvert A_S\rvert^2$	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	$\delta_{S\perp}$ [rad]
Stat. uncertainty	0.050	0.014	0.10	0.026	0.0042	0.0047	0.0063	0.0077	0.12	0.16	0.083
Model bias	0.0079	0.0019	–	0.0035	0.0005	0.0002	0.0012	0.0008	0.020	0.016	0.006
Angular efficiencies	0.0038	0.0006	$< 10^{-2}$	0.0057	0.0002	0.0008	0.0010	0.0015	0.006	0.015	0.015
Lifetime efficiencies	0.0003	0.0062	$< 10^{-2}$	0.0002	0.0022	0.0014	0.0023	0.0007	0.001	0.002	0.002
Lifetime resolution	0.0025	0.0008	0.02	0.0009	0.0005	0.0007	0.0009	0.0065	0.006	0.025	0.022
Data/simulation difference	0.0006	0.0008	$< 10^{-2}$	0.0003	0.0003	0.0044	0.0029	0.0065	0.007	0.007	0.028
Flavor tagging	0.0001	$< 10^{-4}$	$< 10^{-2}$	0.0002	$< 10^{-4}$	0.0003	$< 10^{-4}$	$< 10^{-4}$	0.001	0.003	0.001
Sig./bkg. ω_{evt} difference	0.003	–	–	–	0.0005	–	0.0008	–	–	–	0.006
Model assumptions	–	0.0008	–	0.0046	0.0003	–	0.0013	0.0012	0.017	0.019	0.011
Peaking background	0.0003	0.0008	0.01	$< 10^{-4}$	0.0002	0.0005	0.0002	0.0025	0.005	0.007	0.011
Total systematic	0.0096	0.0066	0.02	0.0082	0.0024	0.0048	0.0044	0.0097	0.028	0.040	0.043

ATLAS Systematics



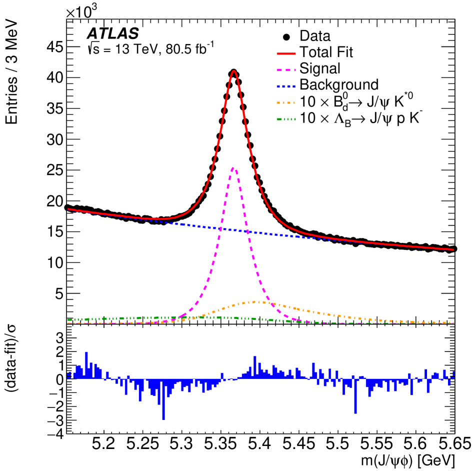
	ϕ_s [10^{-3} rad]	$\Delta\Gamma_s$ [10^{-3} ps^{-1}]	Γ_s [10^{-3} ps^{-1}]	$\lvert A_{\parallel}(0)\rvert^2$ [10^{-3}]	$\lvert A_0(0)\rvert^2$ [10^{-3}]	$\lvert A_S(0)\rvert^2$ [10^{-3}]	$\delta_\perp$ [10^{-3} rad]	$\delta_\parallel$ [10^{-3} rad]	$\delta_\perp - \delta_S$ [10^{-3} rad]
Tagging	19	0.4	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	< 0.1	0.4	0.8	0.4	17	8.6	1.8
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

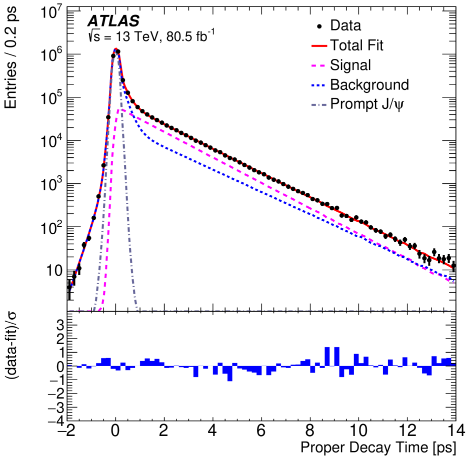
Time-Angular signal PDF (by ATLAS)

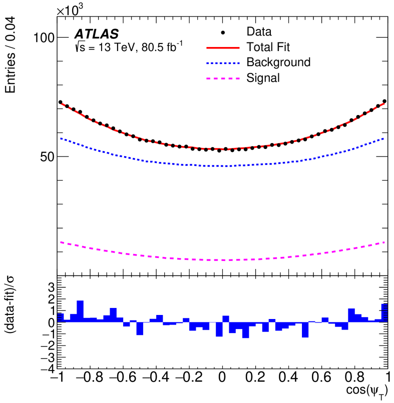


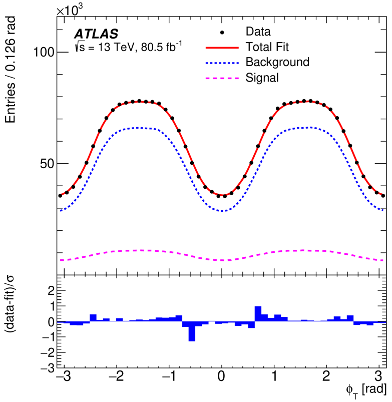
k	$\mathcal{O}^{(k)}(t)$	$g^{(k)}(\theta_T, \psi_T, \phi_T)$
1	$\frac{1}{2}\lvert A_0(0)\rvert^2\left[(1+\cos\phi_s)\,e^{-\Gamma_L^{(s)}t}+(1-\cos\phi_s)\,e^{-\Gamma_H^{(s)}t}\pm 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$2\cos^2\psi_T(1-\sin^2\theta_T\cos^2\phi_T)$
2	$\frac{1}{2}\lvert A_\parallel(0)\rvert^2\left[(1+\cos\phi_s)\,e^{-\Gamma_L^{(s)}t}+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

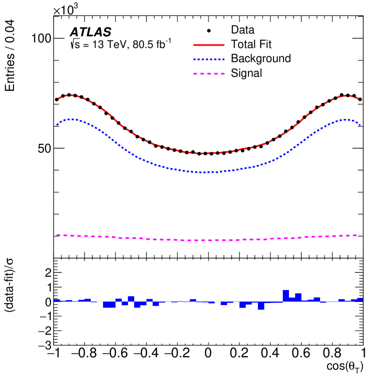
ATLAS Fit projections



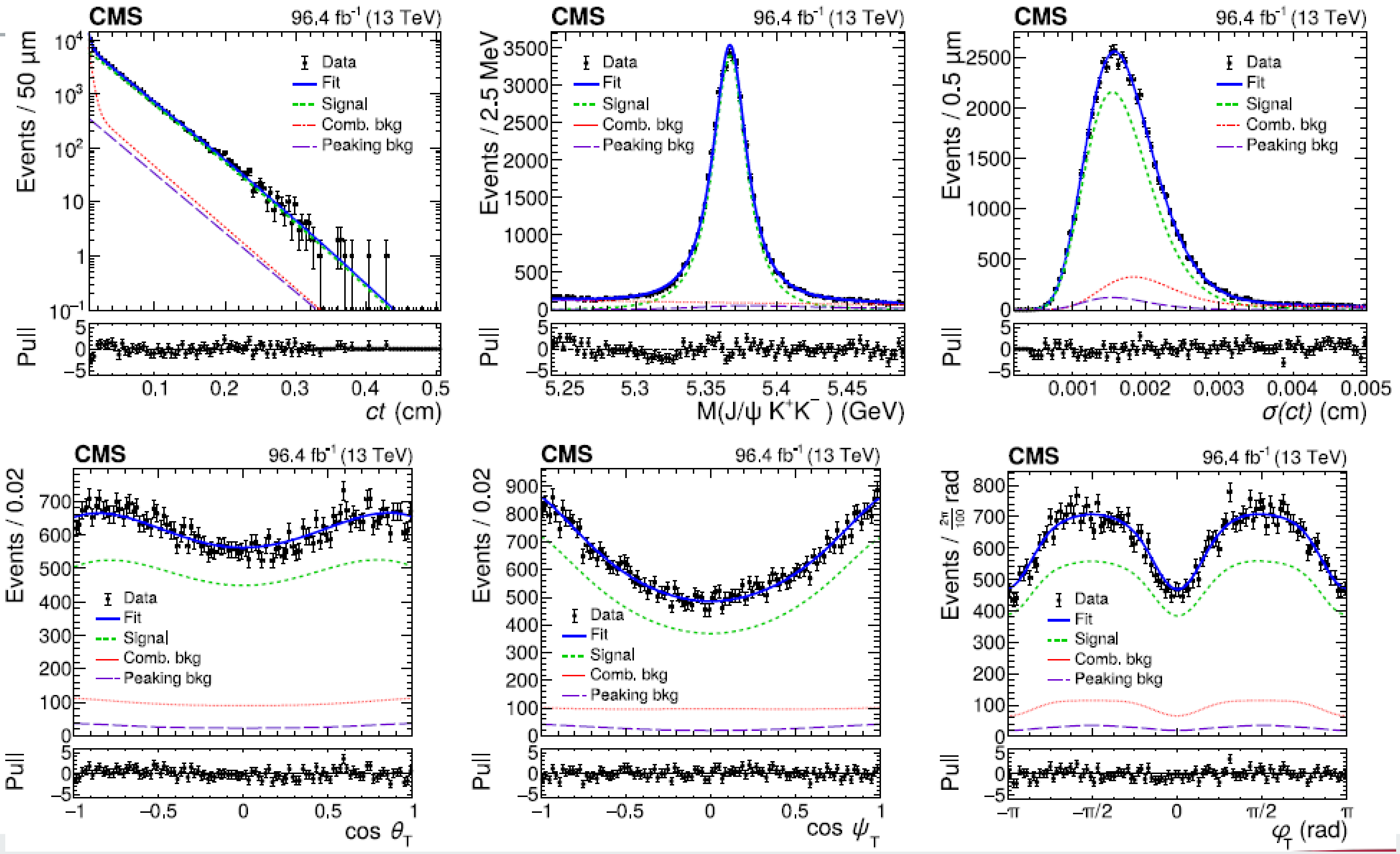








CMS Fit projections



ATLAS Likelihood function

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