CKM 2016
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Tata Institute of Fundamental Research, Mumbai

Latest ATLAS Results on ϕ_s

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The ATLAS Experiment

General purpose detector

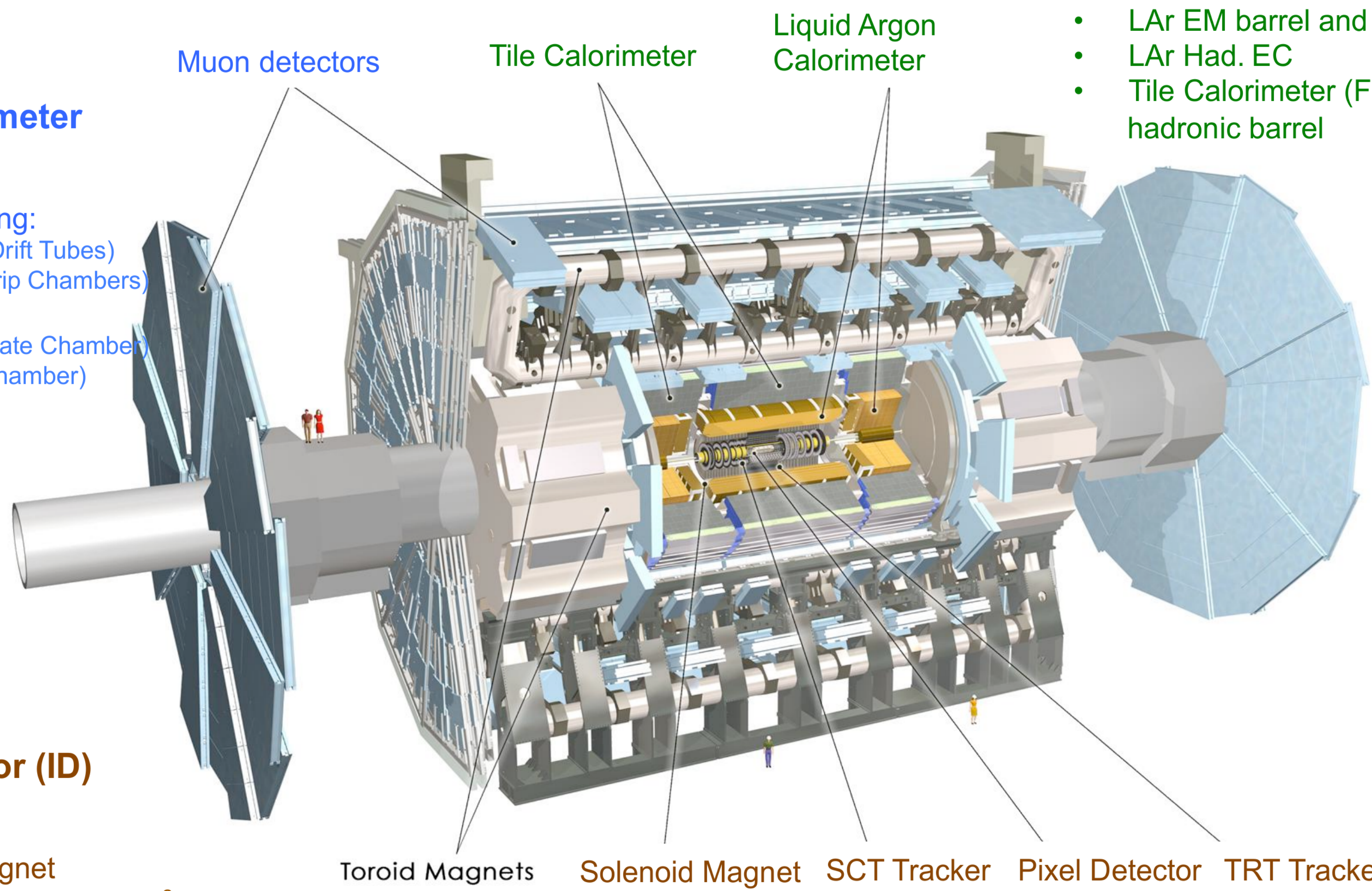
Calorimeter System

EM and Hadronic energy
- LAr EM barrel and EC
- LAr Had. EC
- Tile Calorimeter (Fe-Scin.) hadronic barrel

Muon Specrometer

Toroid Magnets
Precision μ tracking:
- MDT (Monitored Drift Tubes)
- CSC (Cathode Strip Chambers)

Trigger:
- RPC (Resistive Plate Chamber)
- TGC (Thin Gas Chamber)



Inner Detector (ID)

Tracking
2T Solenoid Magnet
- Silicon Pixels, 50x400 μm^2
- Silicon Strips (SCT), 80 μm stereo
- Transition Ratiation Tracker (TRT) 36 points/track

The ATLAS Experiment

- Triggering $|\eta| < 2.4$
- Precision Tracking $|\eta| < 2.7$

B-Physics

Calorimeter System

EM and Hadronic energy
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- LAr Had. EC
- Tile Calorimeter (Fe-Scin.) hadronic barrel

Muon Specrometer

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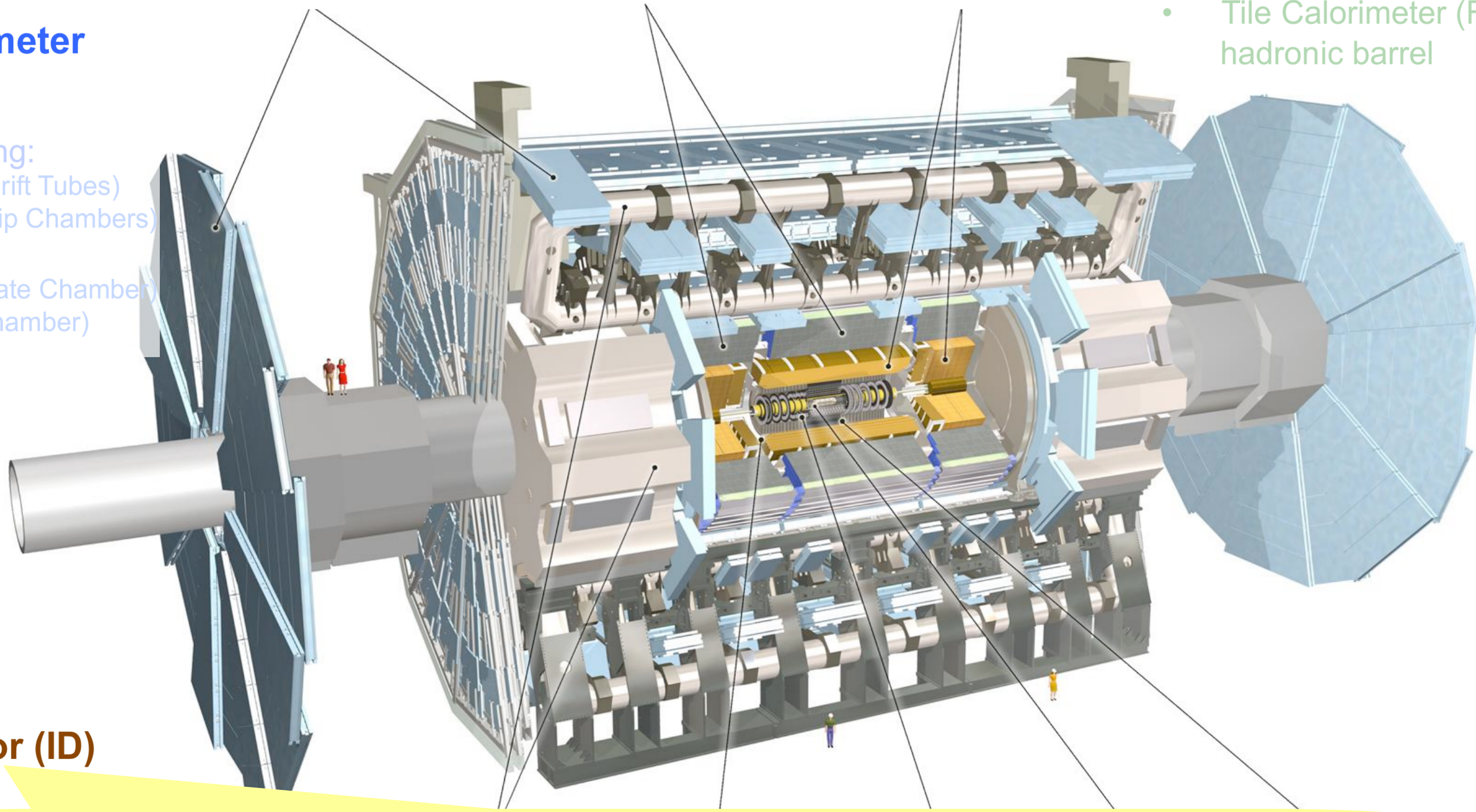


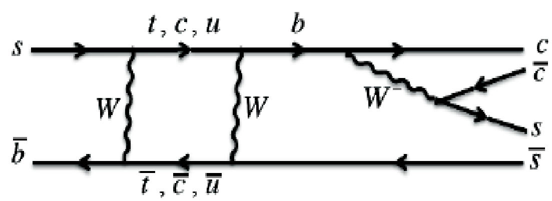
Inner Detector (ID)

- $p_T > 0.4$ GeV, $|\eta| < 2.5$
- New for Run2: Insertable B-Layer (IBL) an additional inner-most pixel layer ($r = 33$mm) and lower x/X_0 beam pipe
- Resolution in $m_{\mu+\mu-}$: around 50 MeV for J/ψ and 150 MeV for $\Upsilon(nS)$
- Resolution in b-hadron proper decay time in Run-1 data around 100 fs (~30% improvement with IBL in Run-2)

Measurement of $\Delta\Gamma_s$ and ϕ_s in $B_s \to J/\psi(\mu\mu)\phi(KK)$

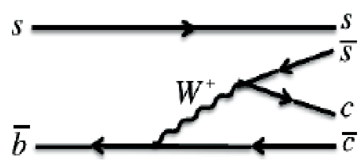
- CP violation in $B_s \to J/\psi\phi$ occurs through the interference in mixing and decay

Decay rate ~ $\Big|$



Decay amplitude with mixing

+



Direct decay amplitude $\Big|^2$

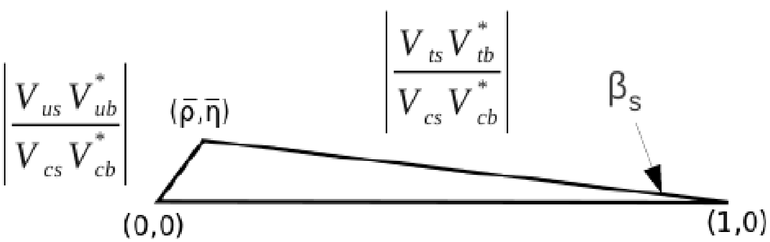
B_s mixing:

- Mass difference $\Delta m = m_H - m_L$
- Mixing phase ϕ_s
- Decay width difference $\Delta\Gamma_s = \Gamma_L - \Gamma_H$

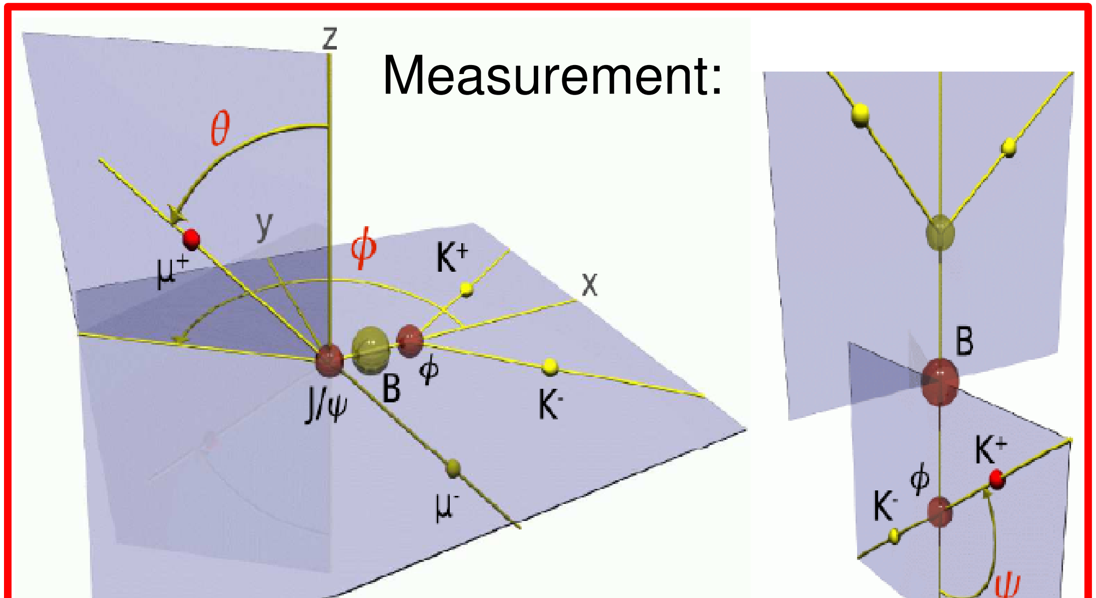
$$|B_s^H\rangle = p|B_s^0\rangle - q|\bar{B}_s^0\rangle$$
$$|B_s^L\rangle = p|B_s^0\rangle + q|\bar{B}_s^0\rangle$$

- Time evolution of flavour tagged $B_s \to J/\psi\phi$ very sensitive to New Physics
- 9 physics parameters to describe $B_s \to J/\psi\phi$ decay

Γ_s, $\Delta\Gamma_s$	decay with and decay width difference
ϕ_s ($\approx 2\beta_s$)	CP violating phase
$\lvert A_0\rvert^2$, $\lvert A_{\parallel}\rvert^2$	CP state amplitudes
$\delta_{\parallel}$, $\delta_{\perp}$	Strong phases
$\lvert A_S\rvert^2$, δ_S	S-wave parameters



ϕ_s small in SM, clear to see potential excess from NP



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

Datasets and Selection

- Latest result using Run-1 pp collision data at 8 TeV, combined with previous 7 TeV analysis

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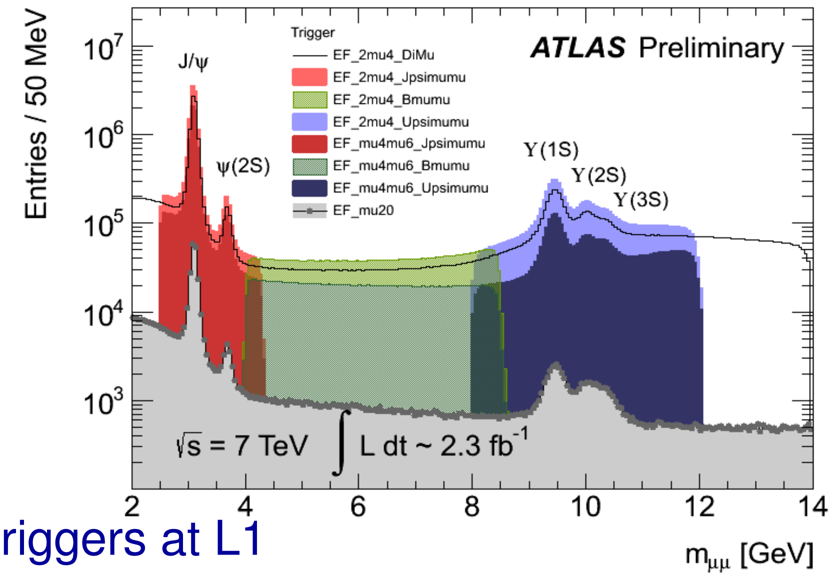
- **Datasets (pp):** 7 TeV data, 5.08 fb^{-1} (used 4.9 fb^{-1}), $L_{max} = 3.7\times10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

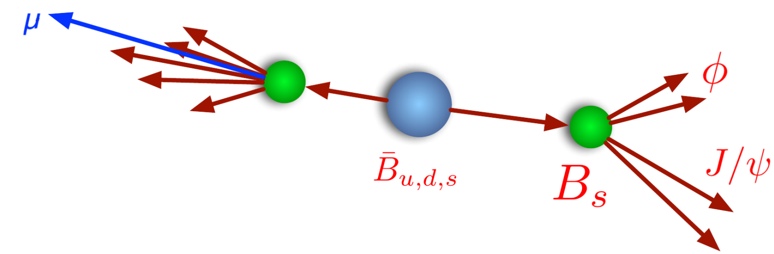
  8 TeV data, 21.3 fb^{-1} (used 14.3 fb^{-1}), $L_{max} = 7.7\times10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

- **Trigger:** 20 MHz collision rate → ~400 Hz recording
  - B-physics concentrates on low-p_T di-muon signatures, in this case $J/\psi \to \mu\mu$
  - Trigger on low-p_T (4,6 GeV) di-muon
    - 2 muons at L1 (HW-based)
    - Confirmed at HLT
    - Track vertex fit and J/ψ mass cuts at HLT
  - 8 TeV data: low-p_T maintained introducing barrel triggers at L1



- **Selection:** full $B_s \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ decay chain reconstruction with Inner Detector, no K/π separation
  - J/ψ selection – di-muon vertex $\chi^2/_{NDF}<10$, J/ψ invariant mass windows width 0.27 ... 0.48 GeV (barrel → endcap)
  - ϕ selection – $p_T(K^\pm) > 1$ GeV, ϕ invariant mass window 22 MeV
  - B_s candidates – 4-track vertex $\chi^2/_{NDF}<3$, $J/\psi\phi$ invariant mass range for analysis (5.15 – 5.65) GeV, no proper decay time cut

B-Flavour Tagging in $B_s \to J/\psi\phi$



- Knowledge of $B_s/\overline{B}_s$ flavour at production significantly increases signal PDF sensitivity to ϕ_s
- Three taggers: muon, electron, b-tagged jet
- Key variable: charge of p_T-weighted tracks in a cone (ΔR) around the opposite side primary object (μ, e, b-jet), used to build per-candidates B_s tag probability

Muon tagger:
- muon $p_T > 2.5$ GeV
- $\Delta z(\mu)$ w.r.t. PV < 5 mm
- ΔR (cone) = 0.5
- $\kappa = 1.1$
- tracks $p_{Ti} > 0.5$ GeV

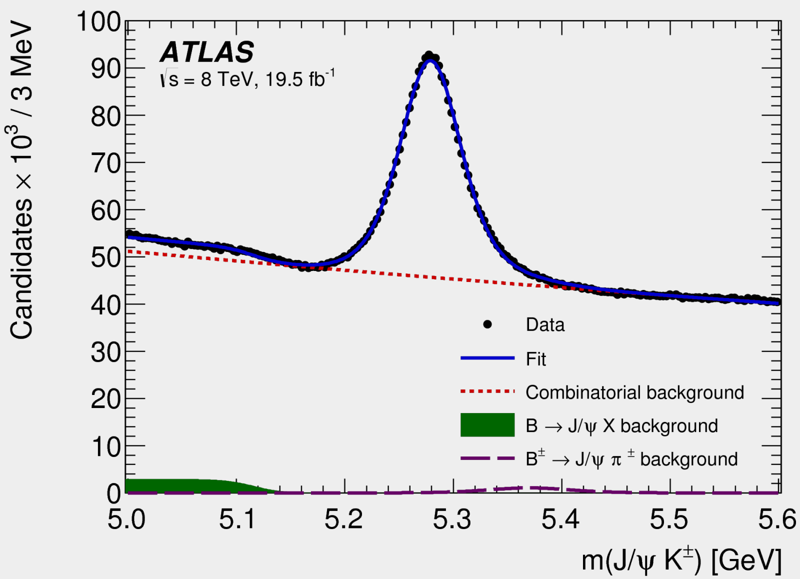
Electron tagger:
- electron $p_T > 0.5$ GeV
- $\Delta z(e)$ w.r.t. PV < 5 mm
- $\Delta R(e^{\pm}, B_s) > 0.4$
- ΔR (cone) = 0.5
- $\kappa = 1.0$
- tracks $p_{Ti} > 0.5$ GeV

b-jet tagger:
- b-tag weight 0.7 maximizing the tagging power on $B^{\pm}$ sample
- anti-k_T (R = 0.8)
- $\kappa = 1.1$
- using all tracks associated to the jet

$$Q_{\rm jet} = \frac{\sum_i^{N\ \rm tracks} q_i \cdot (p_{\rm T}i)^\kappa}{\sum_i^{N\ \rm tracks} (p_{\rm T}i)^\kappa}$$

$$Q_\mu = \frac{\sum_i^{N\ \rm tracks} q_i \cdot (p_{\rm T}i)^\kappa}{\sum_i^{N\ \rm tracks} (p_{\rm T}i)^\kappa}$$

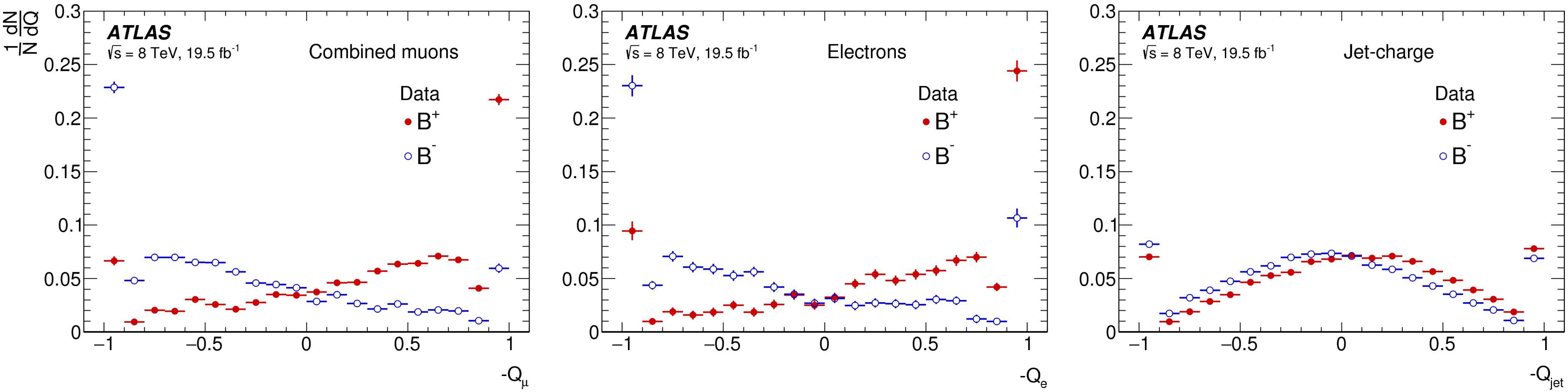
- Calibration on self-tagged $B^{\pm} \to J/\psi K^{\pm}$ channel:
  3-track vertex, $p_T(K) > 1$ GeV, Lxy > 0.1 mm



B-Flavour Tagging Results

Tagger	Efficiency [%]	Dilution [%]	Tagging Power [%]
Combined μ	4.12 ± 0.02	47.4 ± 0.2	0.92 ± 0.02
Electron	1.19 ± 0.01	49.2 ± 0.3	0.29 ± 0.01
Segment-tagged μ	1.20 ± 0.01	28.6 ± 0.2	0.10 ± 0.01
Jet-charge	13.15 ± 0.03	11.85 ± 0.03	0.19 ± 0.01
Total	19.66 ± 0.04	27.56 ± 0.06	1.49 ± 0.02

- Per each B_s-candidate, only one out of the available taggers is selected – the one with the highest Dilution



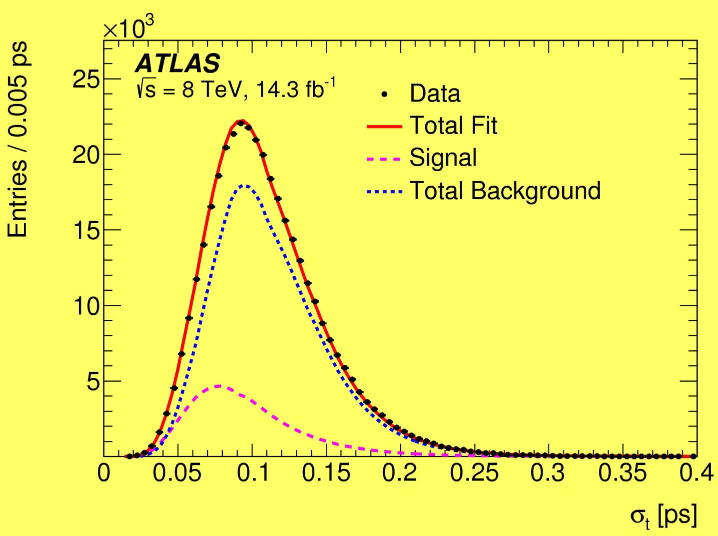
Unbinned Maximum Likelihood Fit

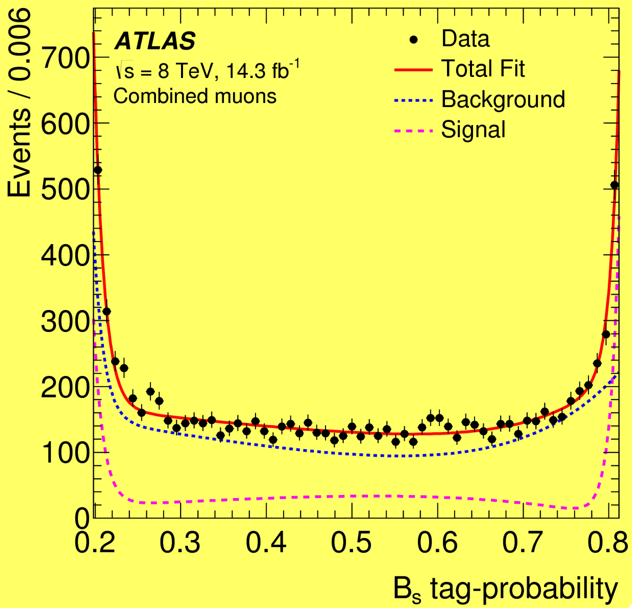
$$\ln\mathcal{L} = \sum_{i=1}^{N}\{w_i\cdot\ln(f_{\mathrm{s}}\cdot\mathcal{F}_{\mathrm{s}}(m_i,t_i,\sigma_{t_i},\Omega_i,P(B|Q),p_{\mathrm{T}_i}) + f_{\mathrm{s}}\cdot f_{B^0}\cdot\mathcal{F}_{B^0}(m_i,t_i,\sigma_{t_i},\Omega_i,P(B|Q),p_{\mathrm{T}_i}) + f_{\mathrm{s}}\cdot f_{\Lambda_b}\cdot\mathcal{F}_{\Lambda_b}(m_i,t_i,\sigma_{t_i},\Omega_i,P(B|Q),p_{\mathrm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

Measured variables:

- B_s mass m_i
- B_s proper decay time t_i and its uncertainty σ_{ti}
- 3 angles Ω_i $(\theta_{Ti}, \varphi_{Ti}, \psi_{Ti})$
- B_s momentum p_{Ti}
- B_s tag probability $p_{B|Qi}$
- tagging method M_i

Signal and background PDFs for conditional observables determined from data using sidebands subtraction; PDFs fixed in the fit





Unbinned Maximum Likelihood Fit

$$\begin{aligned}\ln\mathcal{L} = \sum_{i=1}^{N}\{\boxed{w_i}\cdot\ln(f_\mathrm{s}\cdot&\boxed{\mathcal{F}_\mathrm{s}(m_i,t_i,\sigma_{t_i},\Omega_i,P(B|Q),p_{\mathrm{T}_i})}\\
+f_\mathrm{s}\cdot f_{B^0}\cdot&\boxed{\mathcal{F}_{B^0}(m_i,t_i,\sigma_{t_i},\Omega_i,P(B|Q),p_{\mathrm{T}_i})}\\
+f_\mathrm{s}\cdot f_{\Lambda_b}\cdot&\boxed{\mathcal{F}_{\Lambda_b}(m_i,t_i,\sigma_{t_i},\Omega_i,P(B|Q),p_{\mathrm{T}_i})}\\
+(1-f_\mathrm{s}\cdot(1+f_{B^0}+f_{\Lambda_b}))&\boxed{\mathcal{F}_\mathrm{bkg}(m_i,t_i,\sigma_{t_i},\Omega_i,P(B|Q),p_{\mathrm{T}_i}))}\}\end{aligned}$$

Signal decay main parameters:

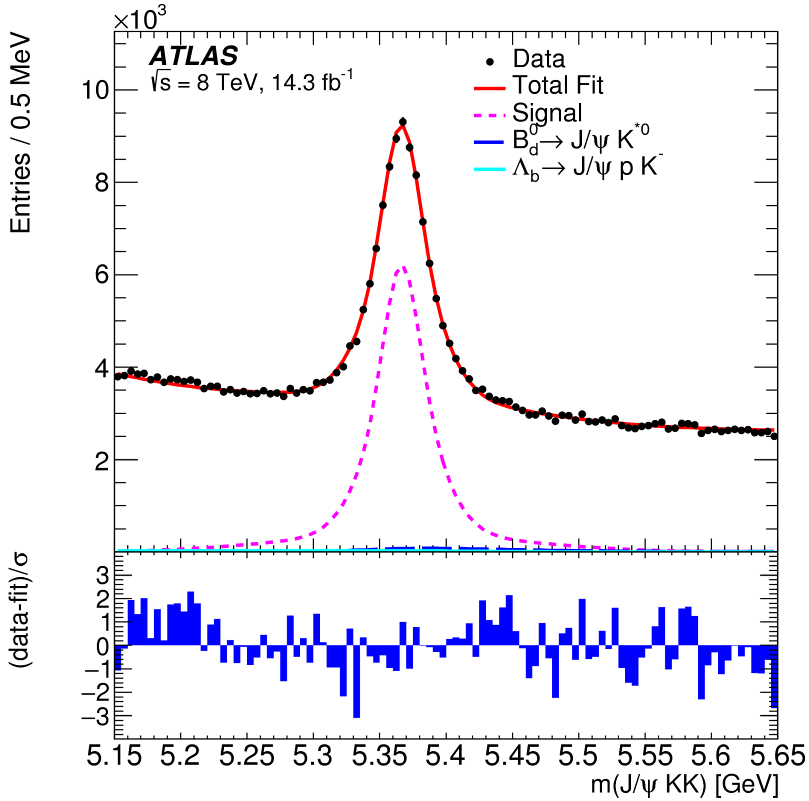
- CP violating phase ϕ_s
- Decay width $\Gamma_s = (\Gamma_H + \Gamma_L)/2$
- Decay width difference $\Delta\Gamma = \Gamma_H - \Gamma_L$
- CP state amplitudes $|A_0(0)|^2$ and $|A_{||}(0)|^2$
- Strong phases $\delta_{||}$ and $\delta_\perp$
- S-wave amplitude $|A_S(0)|^2$ and phase δ_S (fitting $\delta_S - \delta_\perp$ to avoid high correlations)
- B_s mean mass
- (Δm_s fixed to 17.77 ps^{-1})

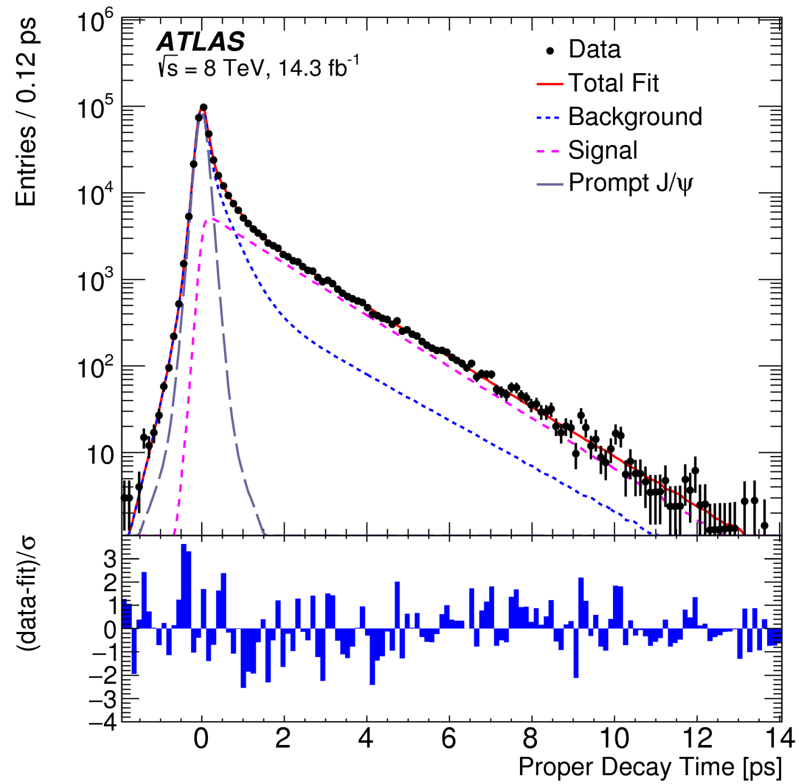
$B_d \to J/\psi K^*(K\pi)$ and $\Lambda_b \to J/\psi \Lambda^*(Kp)$ decay reflections, derived from MC, PDG and the LHCb $\Lambda_b \to J/\psi Kp$ measurement; fixed shape and relative contribution in the fit

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

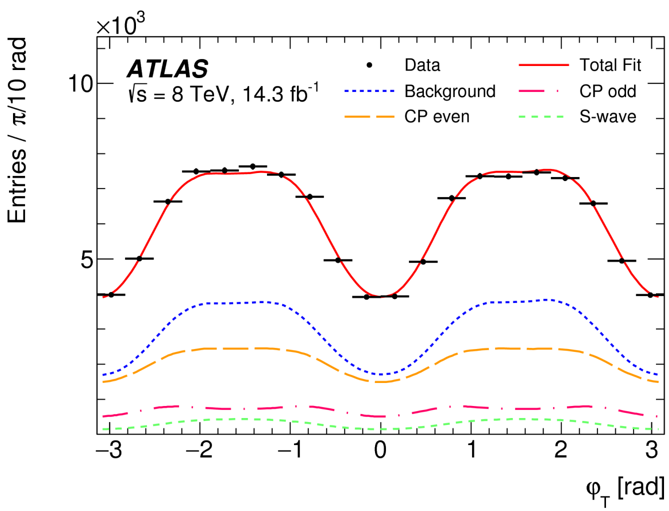
Weights accounting for **proper decay time trigger efficiency** (muons track d_0 reconstruction efficiency bias); estimated from MC

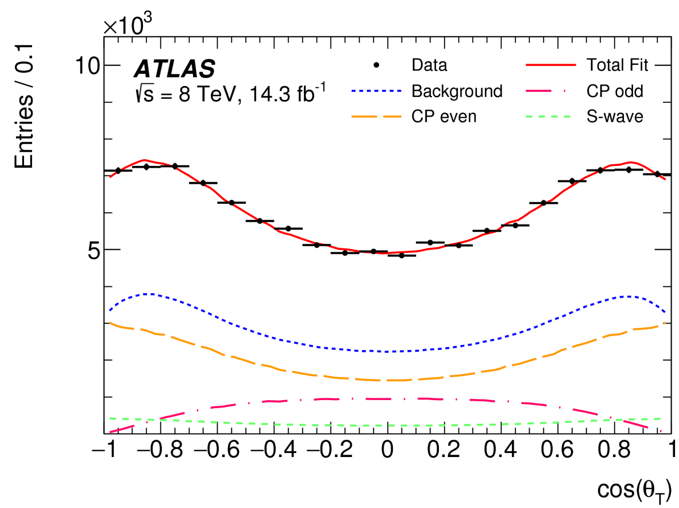
Fit Projections

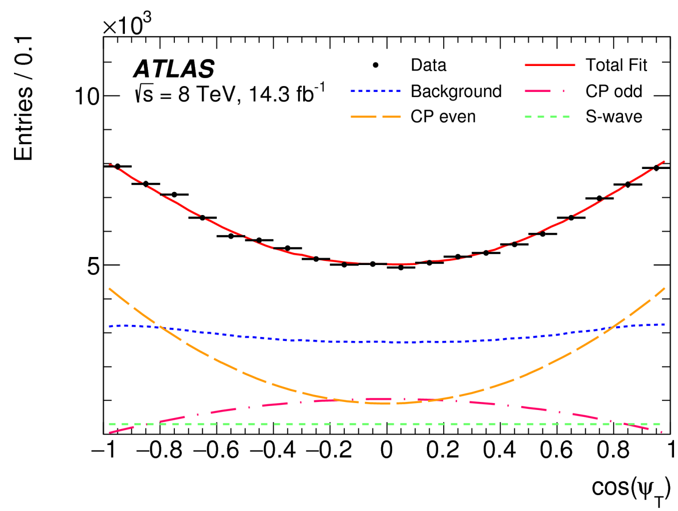




$$\ln\mathcal{L} = \sum_{i=1}^{N}\{w_i\cdot\ln(f_{\mathrm{s}}\cdot\mathcal{F}_{\mathrm{s}} + f_{\mathrm{s}}\cdot f_{B^0}\cdot\mathcal{F}_{B^0} + f_{\mathrm{s}}\cdot f_{\Lambda_b}\cdot\mathcal{F}_{\Lambda_b} + (1-f_{\mathrm{s},B^0,\Lambda_b})\mathcal{F}_{\mathrm{bkg}})\}$$







Systematic Uncertainties

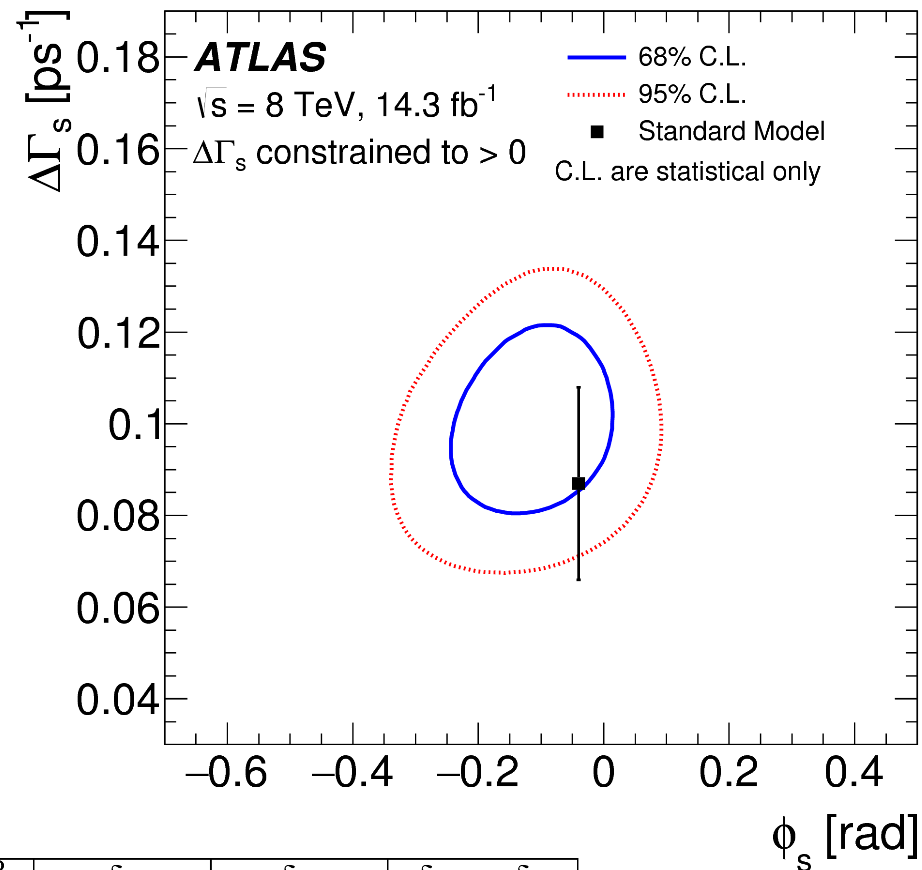
	ϕ_s [rad]	$\Delta\Gamma_s$ [ps^{-1}]	Γ_s [ps^{-1}]	$\lvert A_{\parallel}(0)\rvert^2$	$\lvert A_0(0)\rvert^2$	$\lvert A_S(0)\rvert^2$	$\delta_\perp$ [rad]	$\delta_\parallel$ [rad]	$\delta_\perp - \delta_S$ [rad]
Tagging	0.025	0.003	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	0.001	0.236	0.014	0.004
Acceptance	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	0.003	$<10^{-3}$	0.001	0.004	0.008	$<10^{-3}$
Inner detector alignment	0.005	$<10^{-3}$	0.002	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	0.134	0.007	$<10^{-3}$
Background angles model:									
Choice of p_T bins	0.020	0.006	0.003	0.003	$<10^{-3}$	0.008	0.004	0.006	0.008
Choice of mass interval	0.008	0.001	0.001	$<10^{-3}$	$<10^{-3}$	0.002	0.021	0.005	0.003
B_d^0 background model	0.023	0.001	$<10^{-3}$	0.002	0.002	0.017	0.090	0.011	0.009
Λ_b background model	0.011	0.002	0.001	0.001	0.007	0.009	0.045	0.006	0.007
Fit model:									
Mass signal model	0.004	$<10^{-3}$	$<10^{-3}$	0.002	$<10^{-3}$	0.001	0.015	0.017	$<10^{-3}$
Mass background model	$<10^{-3}$	0.002	$<10^{-3}$	0.002	$<10^{-3}$	0.002	0.027	0.038	$<10^{-3}$
Time resolution model	0.003	$<10^{-3}$	0.001	0.002	$<10^{-3}$	0.002	0.057	0.011	0.001
Default fit model	0.001	0.002	$<10^{-3}$	0.002	$<10^{-3}$	0.002	0.025	0.015	0.002
Total	0.042	0.007	0.004	0.006	0.007	0.022	0.30	0.05	0.01

- 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 $\Lambda_b \rightarrow \Lambda^* J/\psi$ decays
- Toy-MC studies; pulls of the default fit model, default fit on toy-data generated with modified PDFs
- (Trigger efficiency modeling in MC found negligible)

Result of the CPV $B_s \to J/\psi\phi$ Study

- Result with 8 TeV data

Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s[rad]	-0.110	0.082	0.042
$\Delta\Gamma_s[\mathrm{ps}^{-1}]$	0.101	0.013	0.007
$\Gamma_s[\mathrm{ps}^{-1}]$	0.676	0.004	0.004
$\|A_{\|\|}(0)\|^2$	0.230	0.005	0.006
$\|A_0(0)\|^2$	0.520	0.004	0.007
$\|A_S(0)\|^2$	0.097	0.008	0.022
$\delta_\perp$ [rad]	4.50	0.45	0.30
$\delta_{\|\|}$ [rad]	3.15	0.10	0.05
$\delta_\perp - \delta_S$ [rad]	-0.08	0.03	0.01



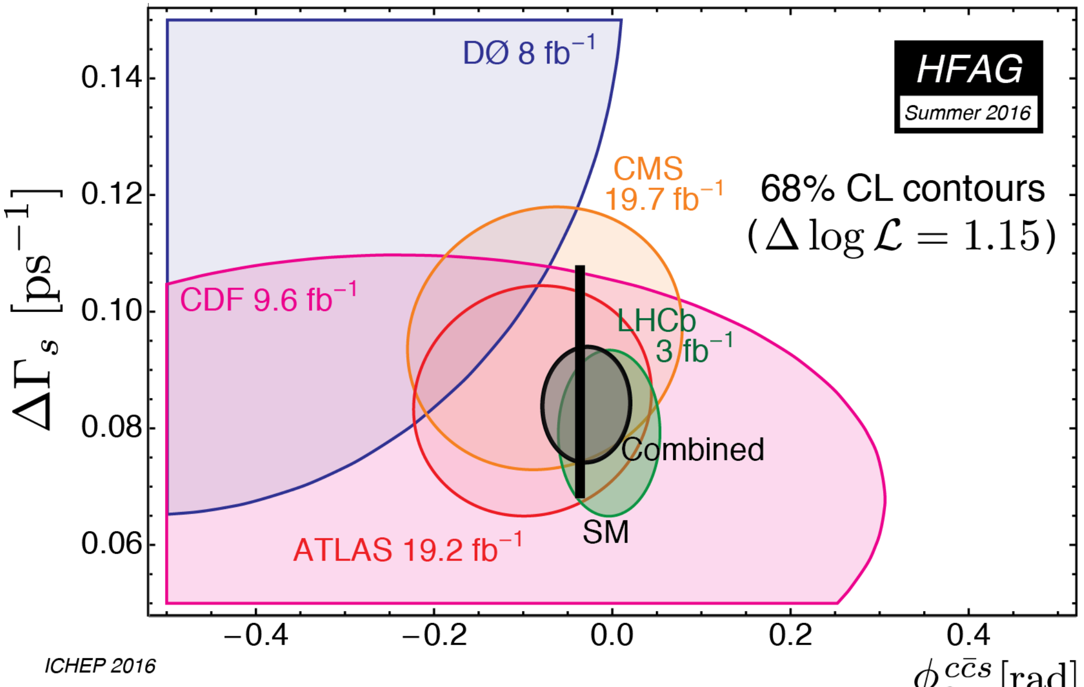
- Fit correlation matrix:

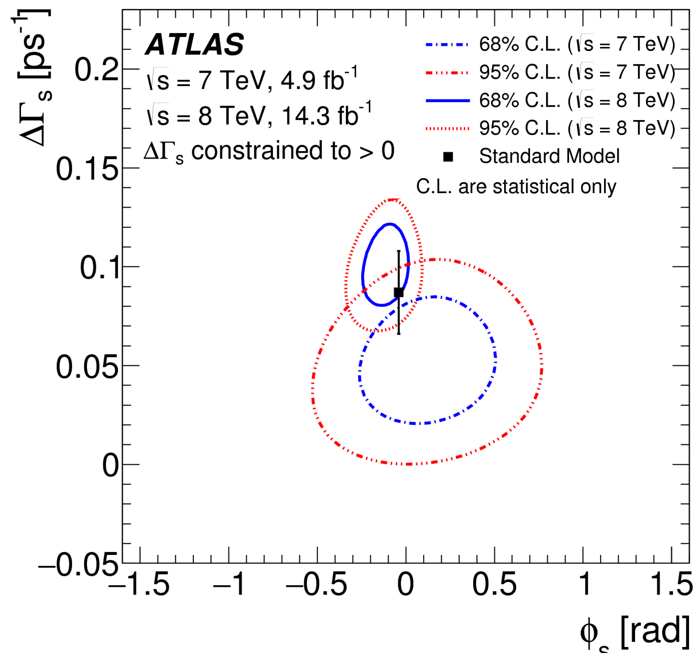
	$\Delta\Gamma$	Γ_s	$\|A_{\|\|}(0)\|^2$	$\|A_0(0)\|^2$	$\|A_S(0)\|^2$	$\delta_{\|\|}$	$\delta_\perp$	$\delta_\perp - \delta_S$
ϕ_s	0.097	-0.085	0.030	0.029	0.048	0.067	0.035	-0.008
$\Delta\Gamma$	1	-0.414	0.098	0.136	0.045	0.009	0.008	-0.011
Γ_s		1	-0.119	-0.042	0.167	-0.027	-0.009	0.018
$\|A_{\|\|}(0)\|^2$			1	-0.330	0.072	0.105	0.025	-0.018
$\|A_0(0)\|^2$				1	0.234	-0.011	0.007	0.014
$\|A_S(0)\|^2$					1	-0.046	0.004	0.052
$\delta_{\|\|}$						1	0.158	-0.006
$\delta_\perp$							1	0.018

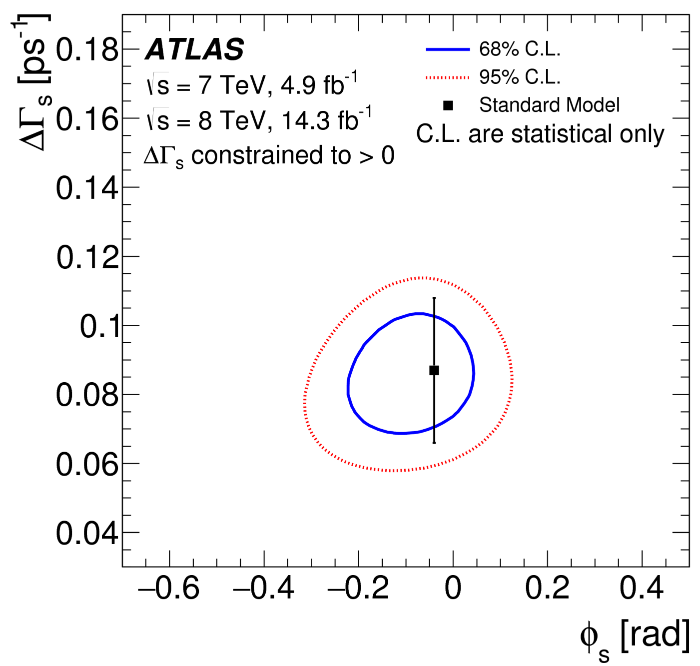
Result of the CPV $B_s \to J/\psi\phi$ Study

- Combination of 7 & 8 TeV results (BLUE comb.)

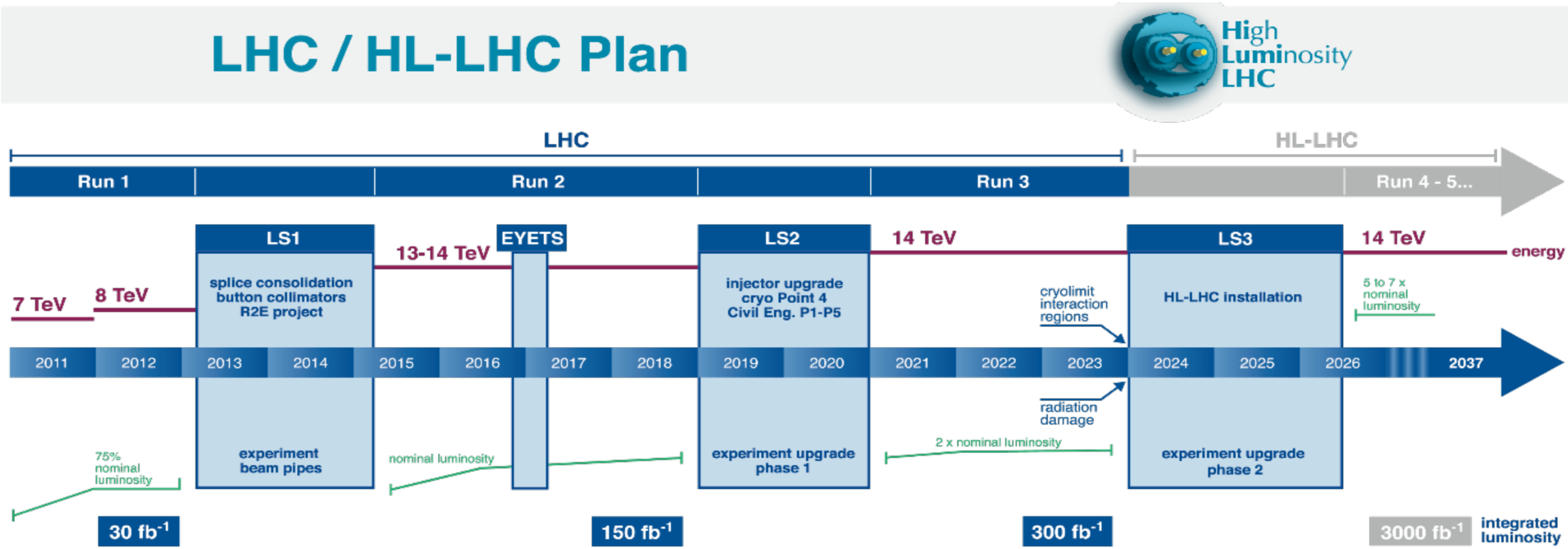
Par	Run1 combined Value	Stat	Syst
ϕ_s[rad]	-0.090	0.078	0.041
$\Delta\Gamma_s[\mathrm{ps}^{-1}]$	0.085	0.011	0.007
$\Gamma_s[\mathrm{ps}^{-1}]$	0.675	0.003	0.003
$\lvert A_\parallel(0)\rvert^2$	0.227	0.004	0.006
$\lvert A_0(0)\rvert^2$	0.522	0.003	0.007
$\lvert A_S\rvert^2$	0.072	0.007	0.018
$\delta_\perp$ [rad]	4.15	0.32	0.16
$\delta_\parallel$ [rad]	3.15	0.10	0.05
$\delta_\perp - \delta_S$ [rad]	-0.08	0.03	0.01



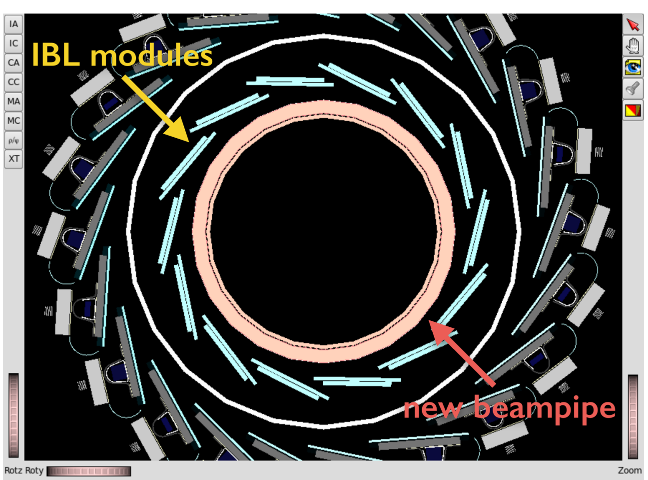




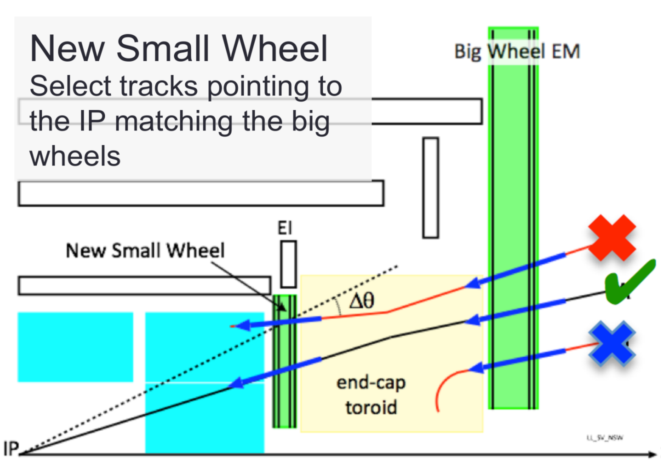
Measurements in Run-2 and Beyond



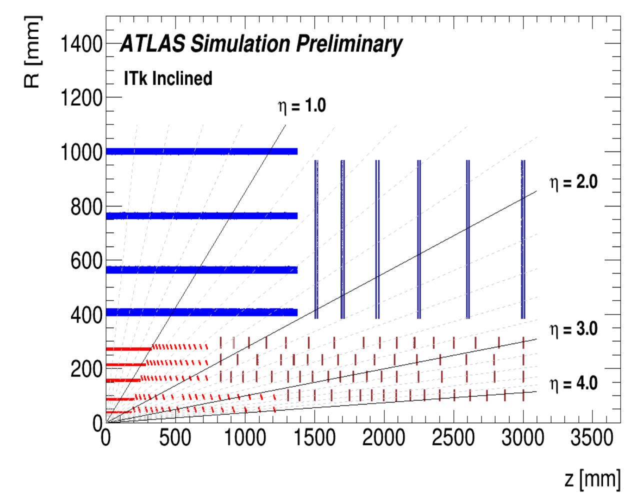
- New pixel layer (IBL, 32-38 mm) + small radius Be beam pipe
- Topological L1 trigger



- New small muon wheel
- Fast tracking trigger (FTK) at LVL 1.5; available in Run-2



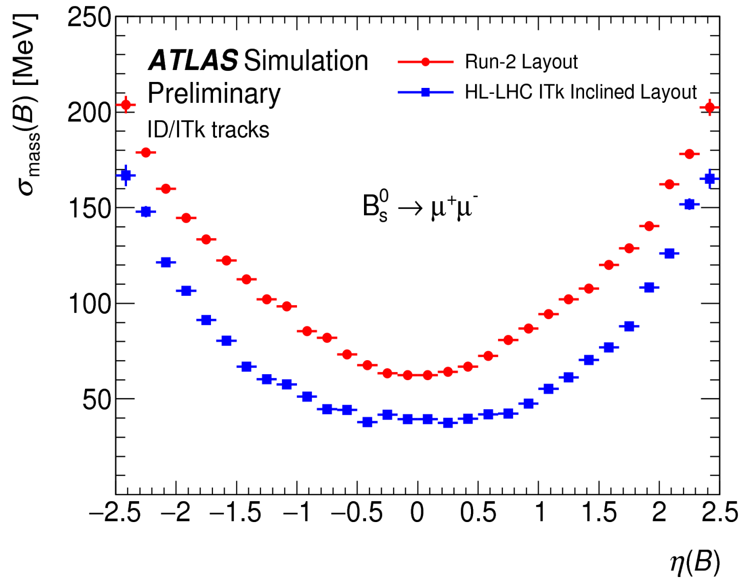
- Completely new Si based tracker (ITK)

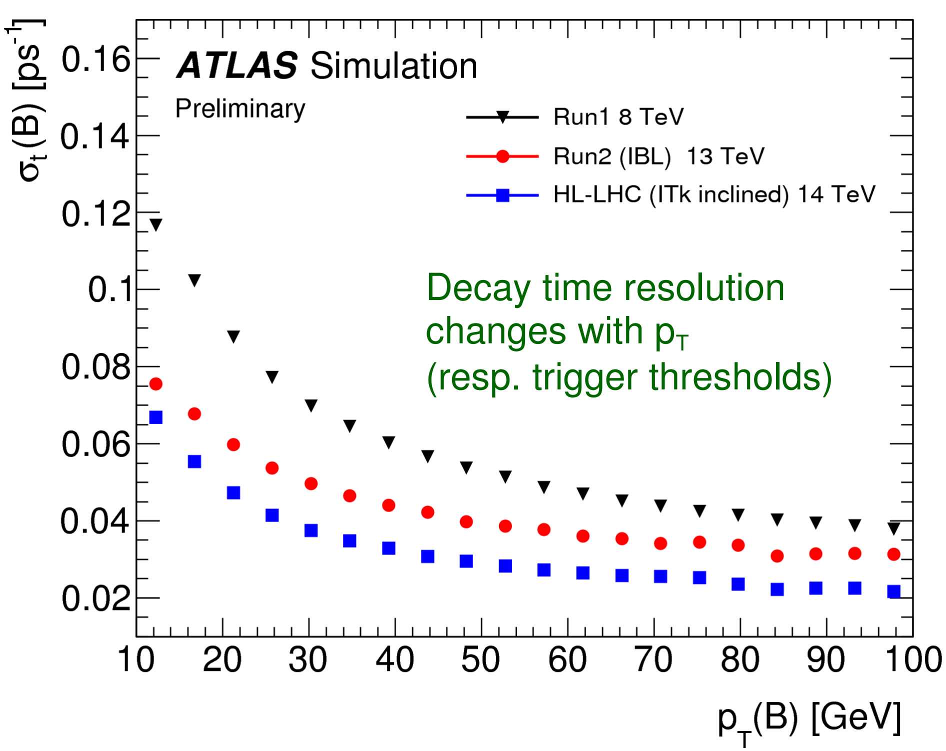


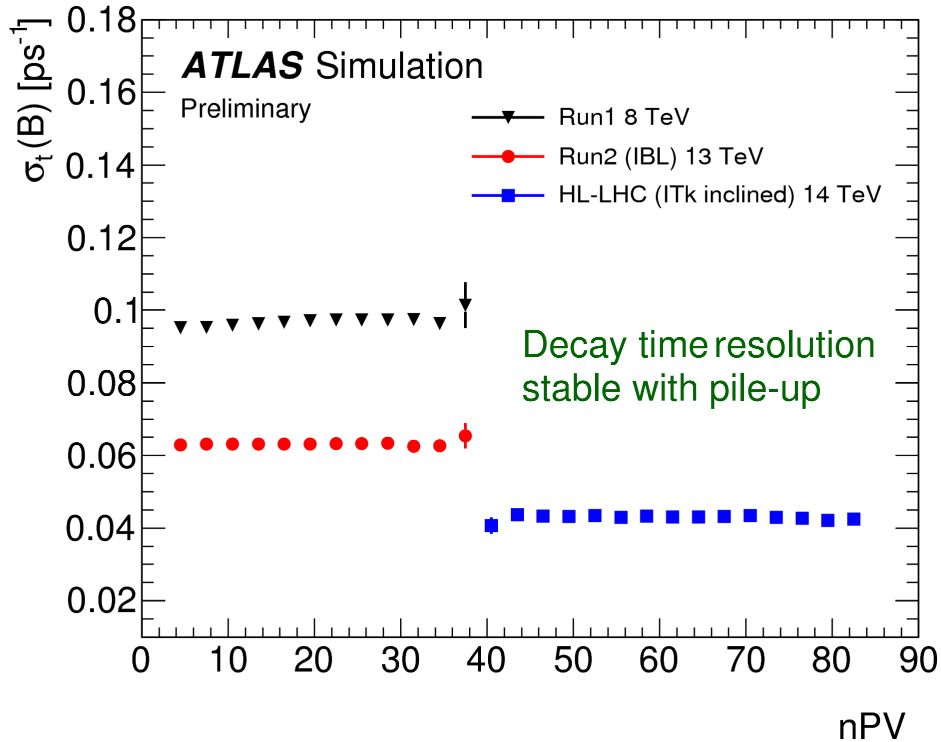
Detector Performance in Run-2 and Beyond

ATL-PHYS-PUB-2016-025

- **Resolution:** invariant mass in decay $B_s \to \mu^+\mu^-$, proper decay time in $B_s \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ decay
- Comparison of Run-1, Run-2 (IBL) and HL-LHC (ITk) performances
- **Trigger:** use L1-topo (keep low thresholds at L1) and complicated HLT with full $B_s \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ decay topology reconstruction at trigger level







Summary

- ATLAS has measured ϕ_s with full Run-1 dataset, combining 7 & 8 TeV pp collision data, in the decay channel $B_s \rightarrow J/\psi(\mu^+\mu^-)\,\phi(K^+K^-)$
  - Results are consistent with Standard Model prediction as well as with other measurements:

$$\phi_s = -0.090 \pm 0.078\ (\text{stat.}) \pm 0.041\ (\text{syst.})\ \text{rad}$$
$$\Delta\Gamma_s = 0.085 \pm 0.011\ (\text{stat.}) \pm 0.007\ (\text{syst.})\ \text{ps}^{-1}$$
$$\Gamma_s = 0.675 \pm 0.003\ (\text{stat.}) \pm 0.003\ (\text{syst.})\ \text{ps}^{-1}$$

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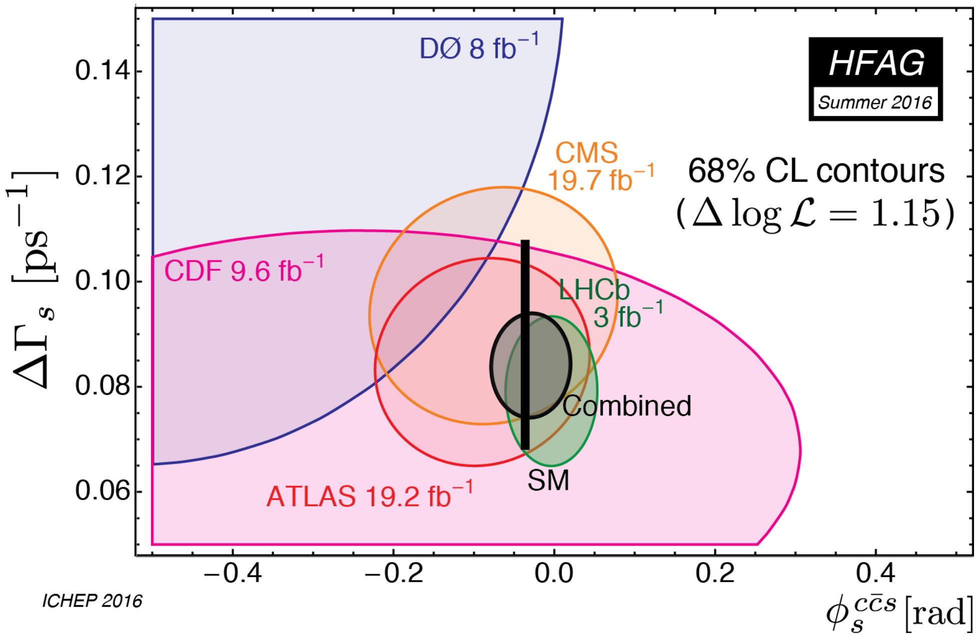
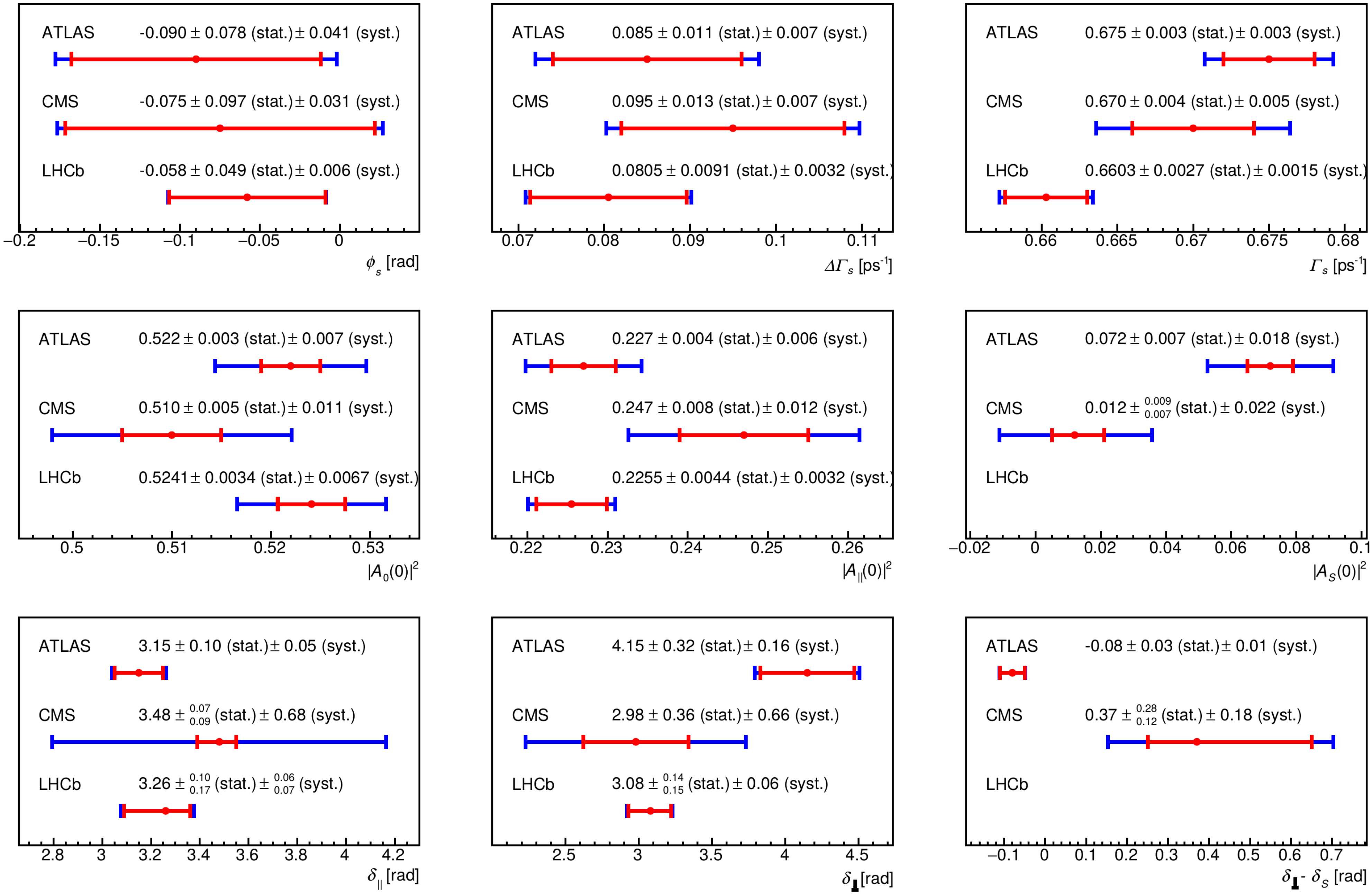


- The analysis is continuing in Run-2 and will continue also in the future stages of the LHC
  - Detector upgrades (namely in **tracking** and **muon system**) and new **trigger strategies** and tools will help to cope with the high-luminosity environment and achieve precision needed to examine possible beyond-SM effects

Backup

Comparison with Other Experiments

- $B_s \to J/\psi\phi(KK)$ channel: ATLAS **JHEP 1608 (2016) 147**, CMS **PLB 757 (2016) 97**, LHCb **PRL 114 (2015) 041801**



Signal PDF

- Signal time-angular PDF:
  (convolved with detector resolution)

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

2 PDFs for B_s and $\overline{B}_s$ (alternative ± signs): PDF(B_s), PDF($\overline{B}_s$)
Tagged fit: Prob(B_s-tag)*PDF(B_s) + (1-Prob(B_s-tag))*PDF($\overline{B}_s$)
Untagged fit: Prob(B_s-tag) = 0.5

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

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

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

Unbinned Maximum Likelihood Fit

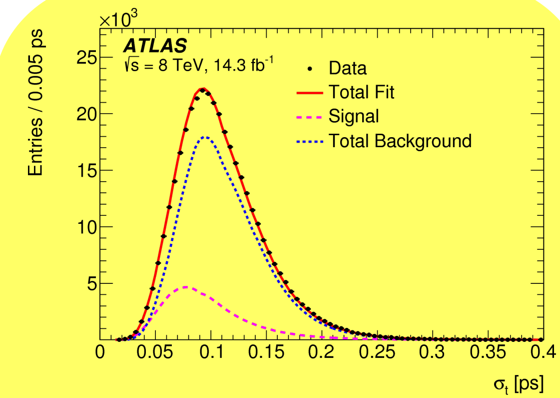
$$\ln \mathcal{L} = \sum_{i=1}^{N} \{ \boxed{w_i} \cdot \ln(f_s \cdot \boxed{\mathcal{F}_s (m_i, t_i, \sigma_{t_i}, \Omega_i, P(B|Q), p_{T_i})}$$
$$+ f_s \cdot f_{B^0} \cdot \boxed{\mathcal{F}_{B^0} (m_i, t_i, \sigma_{t_i}, \Omega_i, P(B|Q), p_{T_i})}$$
$$+ f_s \cdot f_{\Lambda_b} \cdot \boxed{\mathcal{F}_{\Lambda_b}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

Measured variables:
- B_s mass m_i
- B_s proper decay time t_i and its uncertainty σ_{ti}
- 3 angles Ω_i $(\theta_{Ti}, \varphi_{Ti}, \psi_{Ti})$
- B_s momentum p_{Ti}
- B_s tag probability $p_{B|Qi}$
- tagging method M_i

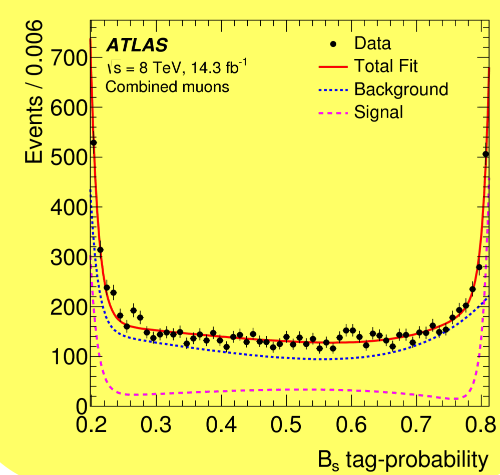
Signal decay main parameters:
- CP violating phase ϕ_s
- Decay width $\Gamma_s = (\Gamma_H + \Gamma_L)/2$
- Decay width difference $\Delta\Gamma = \Gamma_H - \Gamma_L$
- CP state amplitudes $|A_0(0)|^2$ and $|A_{||}(0)|^2$
- Strong phases $\delta_{||}$ and $\delta_\perp$
- S-wave amplitude $|A_S(0)|^2$ and phase δ_S (fitting $\delta_S - \delta_\perp$ to avoid high correlations)
- B_s mean mass
- (Δm_s fixed to 17.77 ps^{-1})

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

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



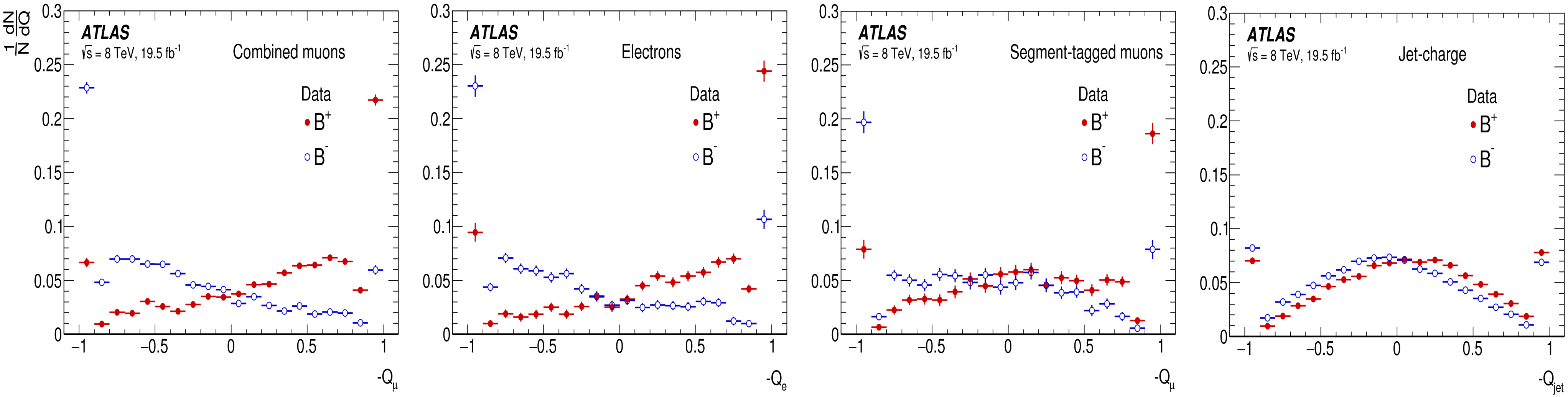
Signal and background PDFs for conditional observables determined from data using sidebands subtraction; PDFs fixed in the fit



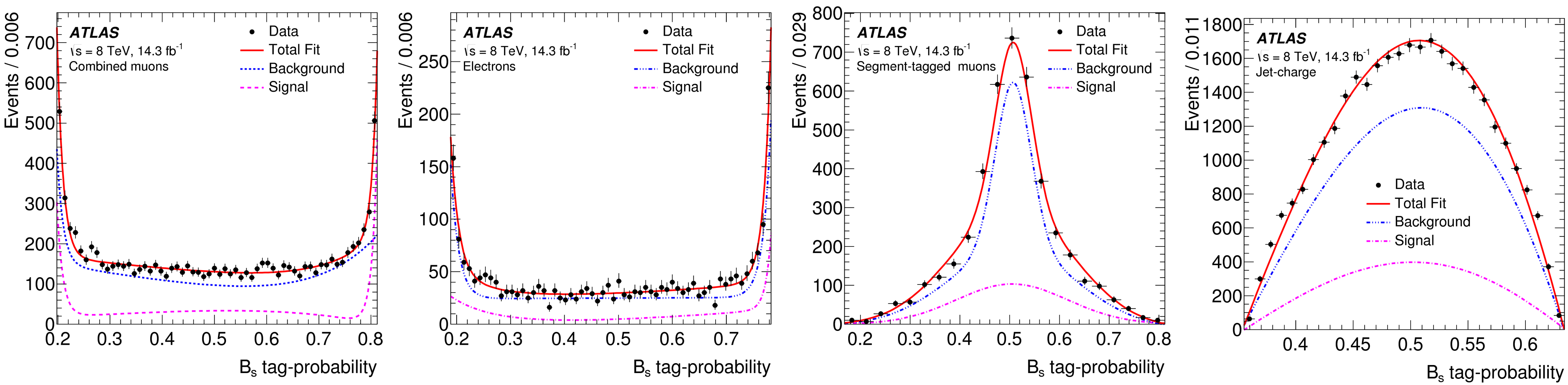
Combinatorial background description, derived from data sidebands; angular distribution described by spherical harmonics and fixed in the fit

B-Flavour Tagging Distributions

- Cone charge for the calibration B^+ and B^- data samples

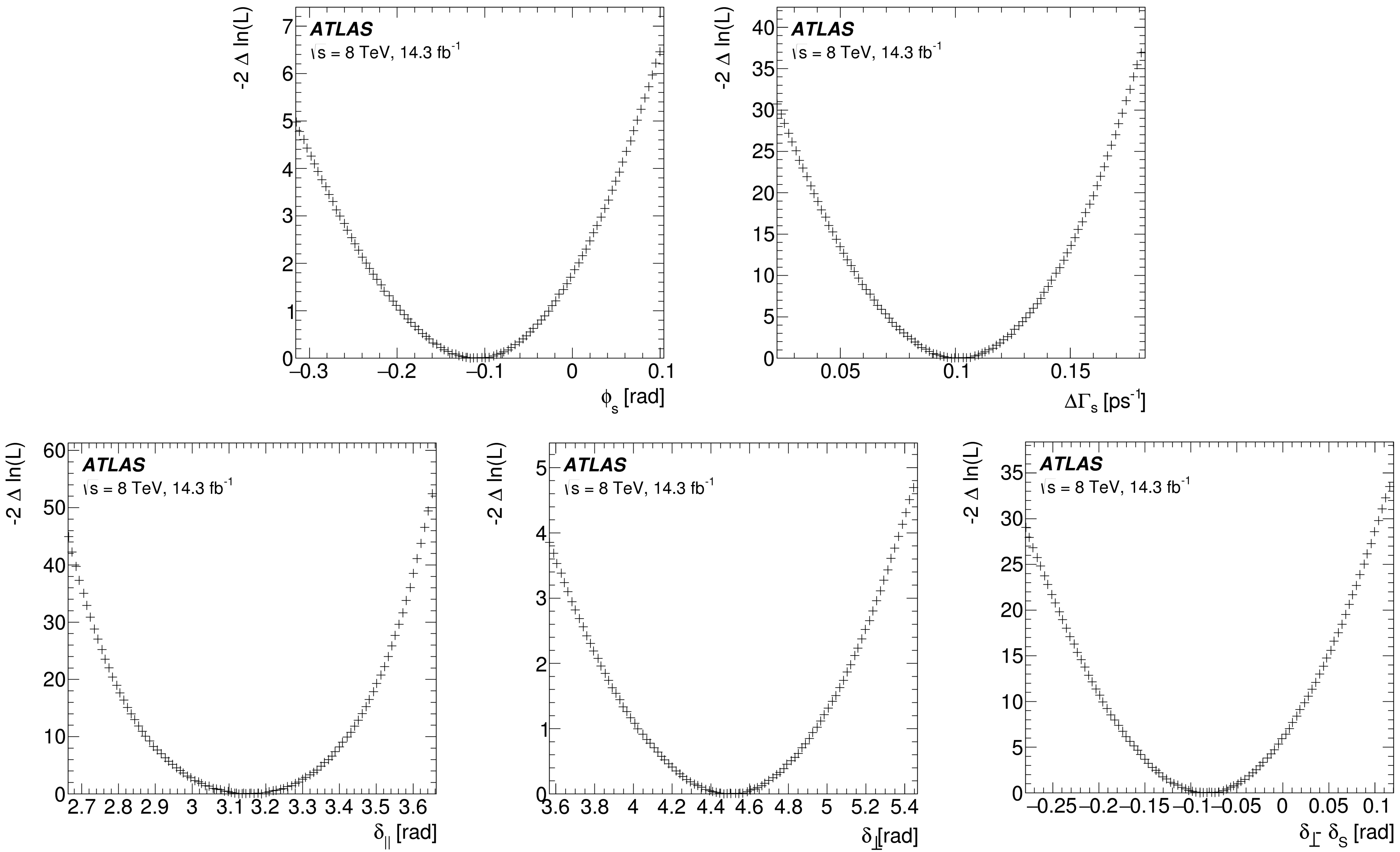


- B_s-tag probablity distribution in the fit, signal & background obtained using sidebands-subtraction method on the real data



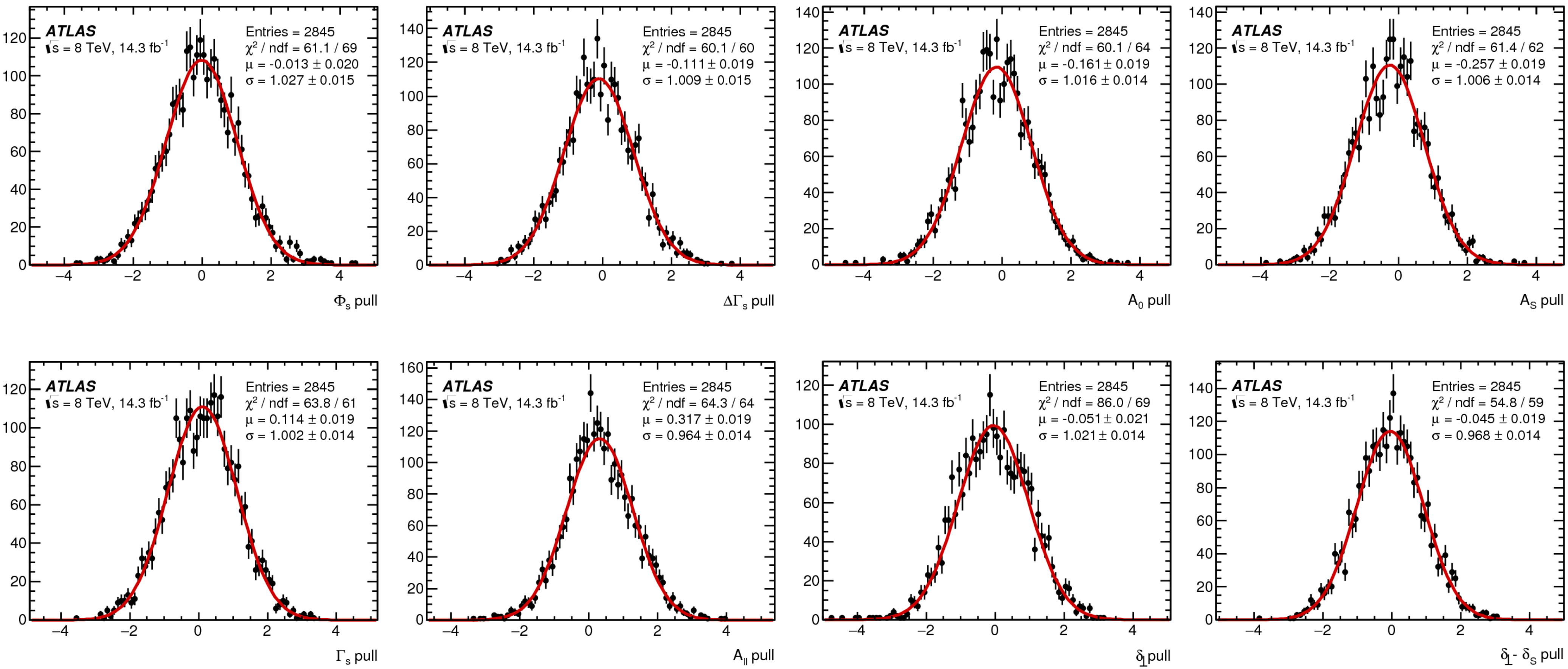
1D Likelihood Scans

- Cross-check of the Gaussian behavior of the likelihood, resp. asymmetry of the errors



UML Fit Pulls

- Cross-check of the self-consistency of the Unbinned Maximum Likelihood fit

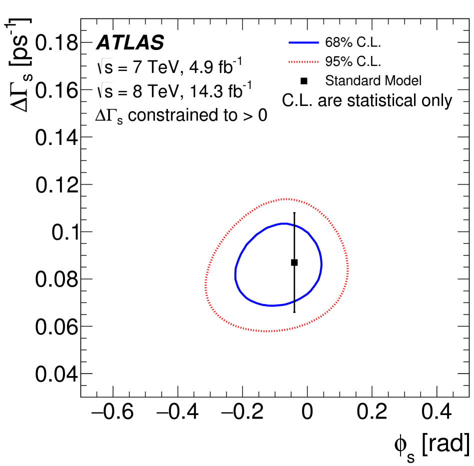


ATLAS ϕ_s Measurements in Run-1

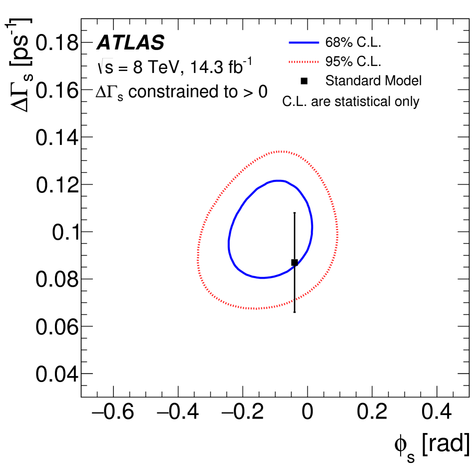
- Comparison of the 7 and 8 TeV tagged analyses with the combination

Par	8 TeV data			7 TeV data			Run1 combined		
	Value	Stat	Syst	Value	Stat	Syst	Value	Stat	Syst
ϕ_s[rad]	-0.110	0.082	0.042	0.12	0.25	0.05	-0.090	0.078	0.041
$\Delta\Gamma_s$[ps^{-1}]	0.101	0.013	0.007	0.053	0.021	0.010	0.085	0.011	0.007
Γ_s[ps^{-1}]	0.676	0.004	0.004	0.677	0.007	0.004	0.675	0.003	0.003
$\lvert A_{\parallel}(0)\rvert^2$	0.230	0.005	0.006	0.220	0.008	0.009	0.227	0.004	0.006
$\lvert A_0(0)\rvert^2$	0.520	0.004	0.007	0.529	0.006	0.012	0.522	0.003	0.007
$\lvert A_S\rvert^2$	0.097	0.008	0.022	0.024	0.014	0.028	0.072	0.007	0.018
$\delta_\perp$ [rad]	4.50	0.45	0.30	3.89	0.47	0.11	4.15	0.32	0.16
$\delta_{\parallel}$ [rad]	3.15	0.10	0.05	[3.04, 3.23]		0.09	3.15	0.10	0.05
$\delta_\perp - \delta_S$ [rad]	-0.08	0.03	0.01	[3.02, 3.25]		0.04	-0.08	0.03	0.01

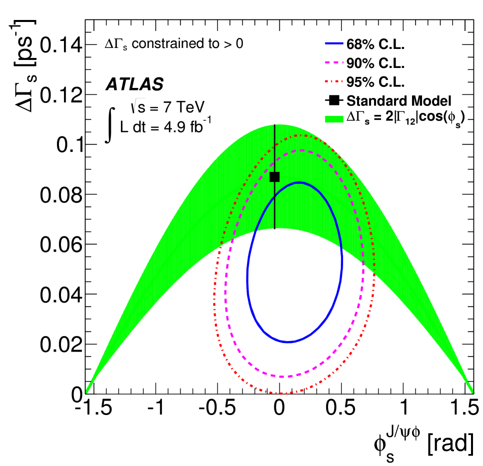
7 & 8 TeV
JHEP 1608 (2016) 147



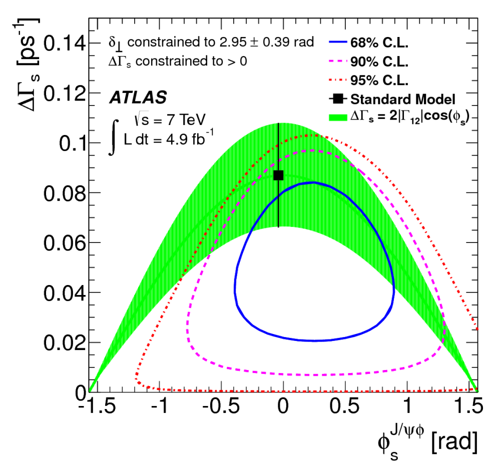
8 TeV
JHEP 1608 (2016) 147



7 TeV
PRD 90 (2014) 052007

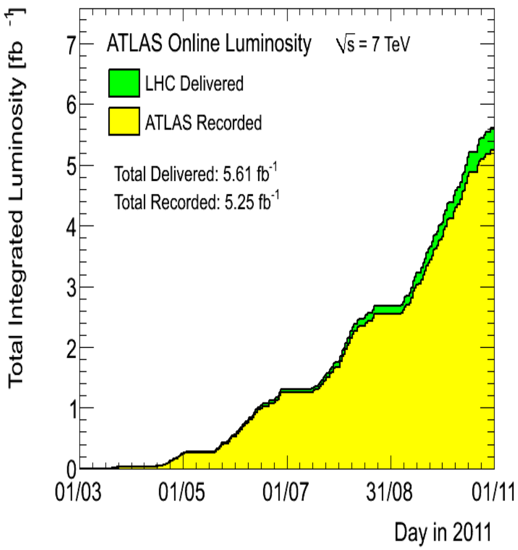


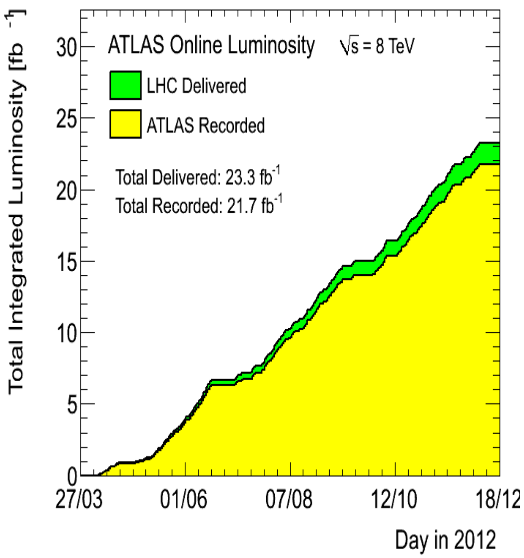
7 TeV (untagged)
JHEP 12 (2012) 072

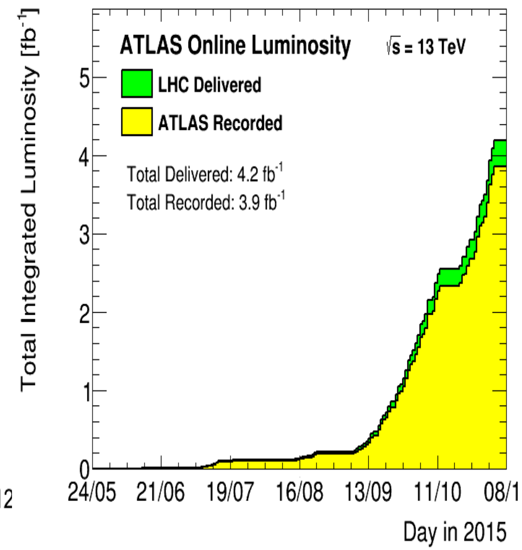


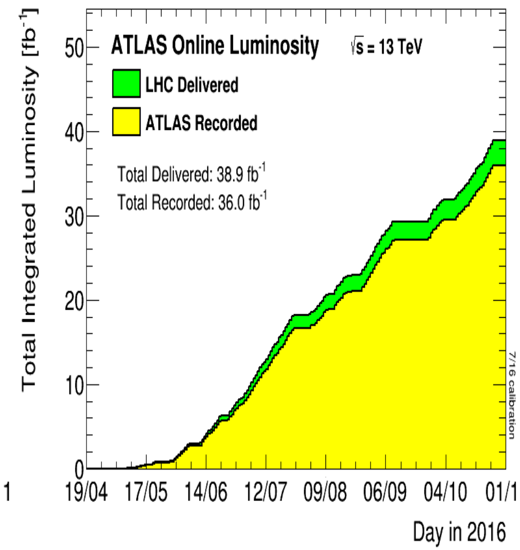
Data Taking (pp): Run-1 and Run-2

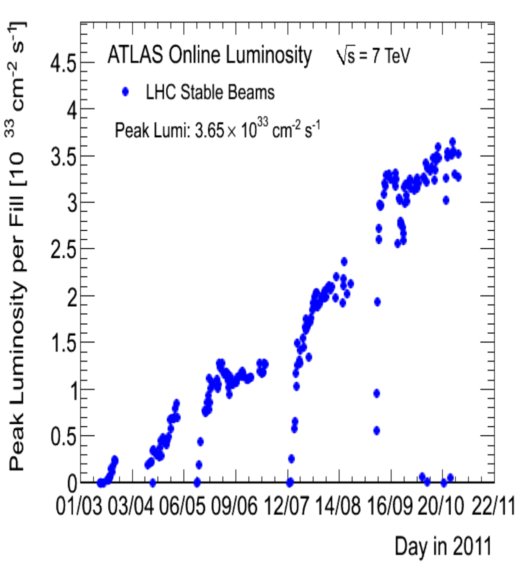
- 7 TeV data, 5.08 fb^{-1}, 50ns, $3.7\times10^{33}\ cm^{-2}s^{-1}$
- 8 TeV, 21.3 fb^{-1}, 50ns, $7.7\times10^{33}\ cm^{-2}s^{-1}$
- 13 TeV (2015), 3.9 fb^{-1}, 50/25ns, $5.0\times10^{33}\ cm^{-2}s^{-1}$
- 13 TeV (2016), 36.0 fb^{-1}, 25ns, $13.7\times10^{33}\ cm^{-2}s^{-1}$

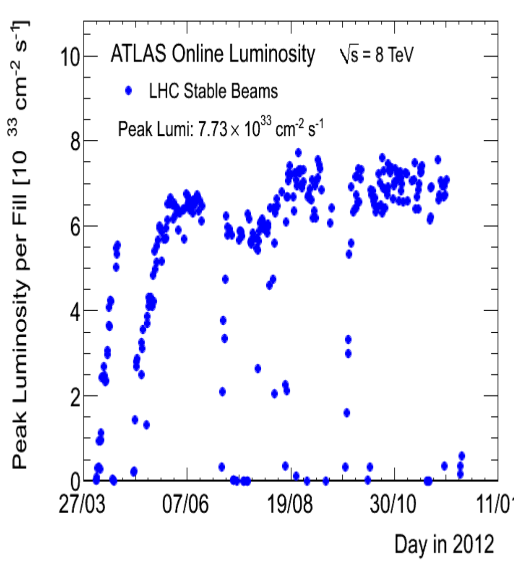


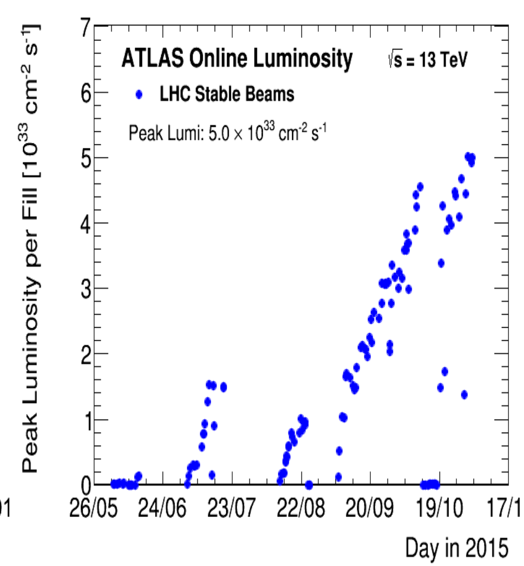


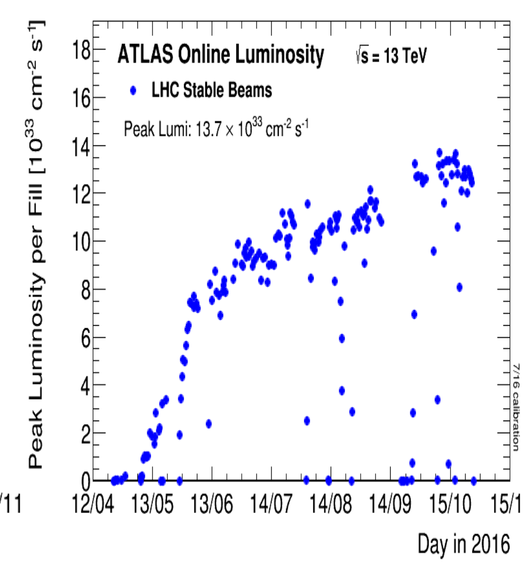






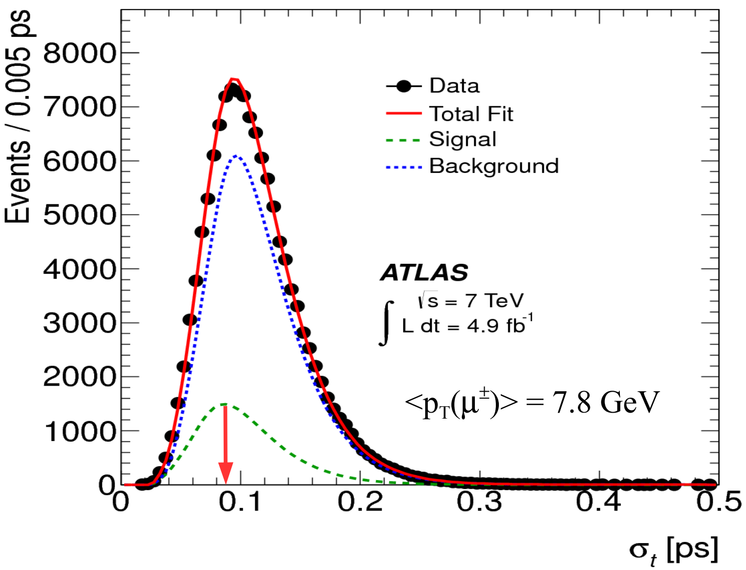


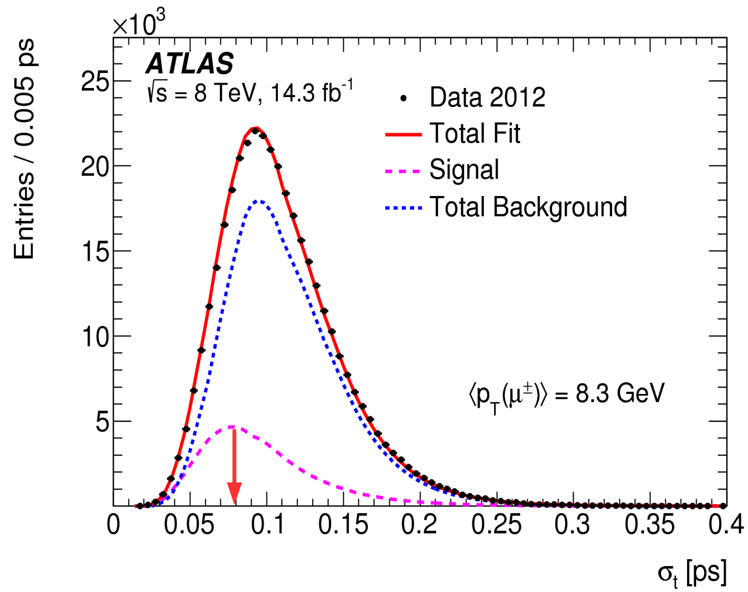


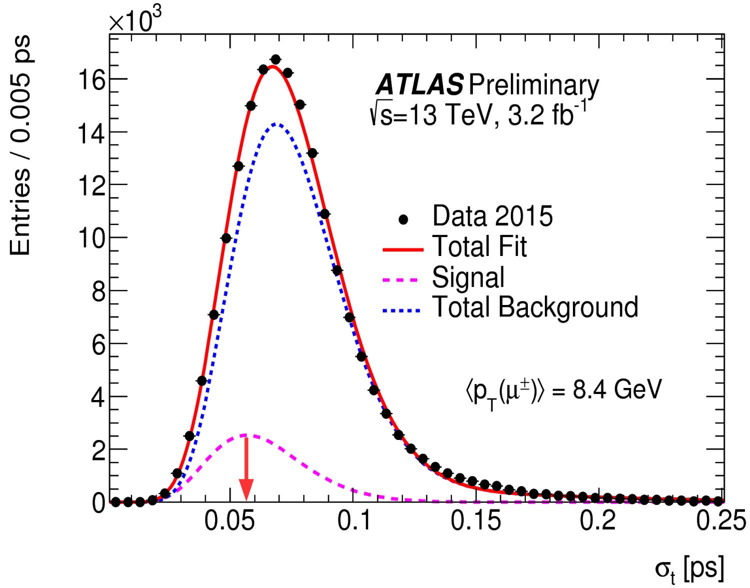


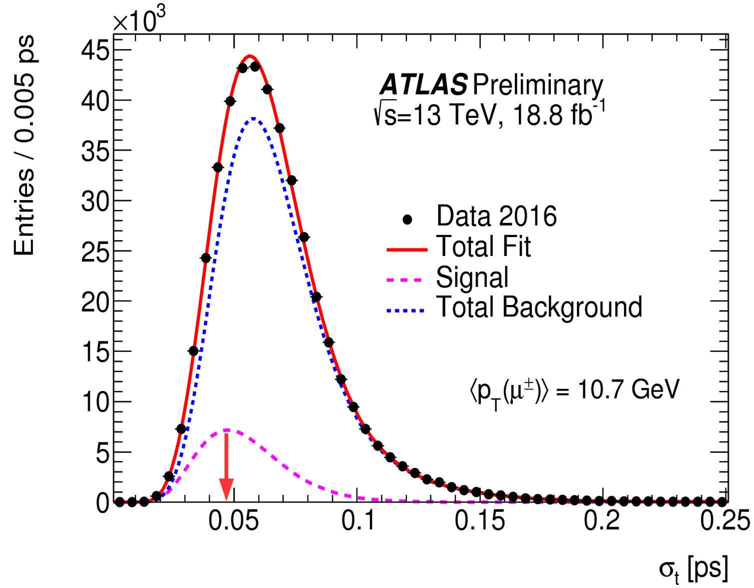
Proper Decay Time Resolution in Real Data

- Comparison of the proper decay time resolution distributions in Run-1 and Run-2 data:



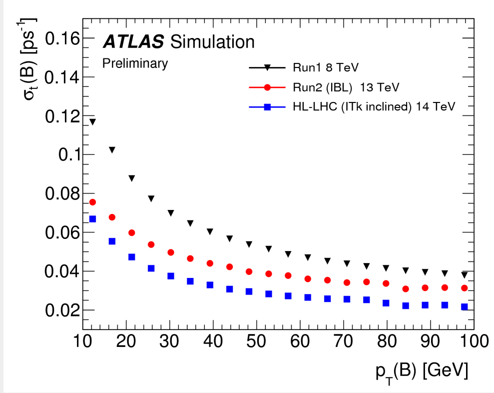






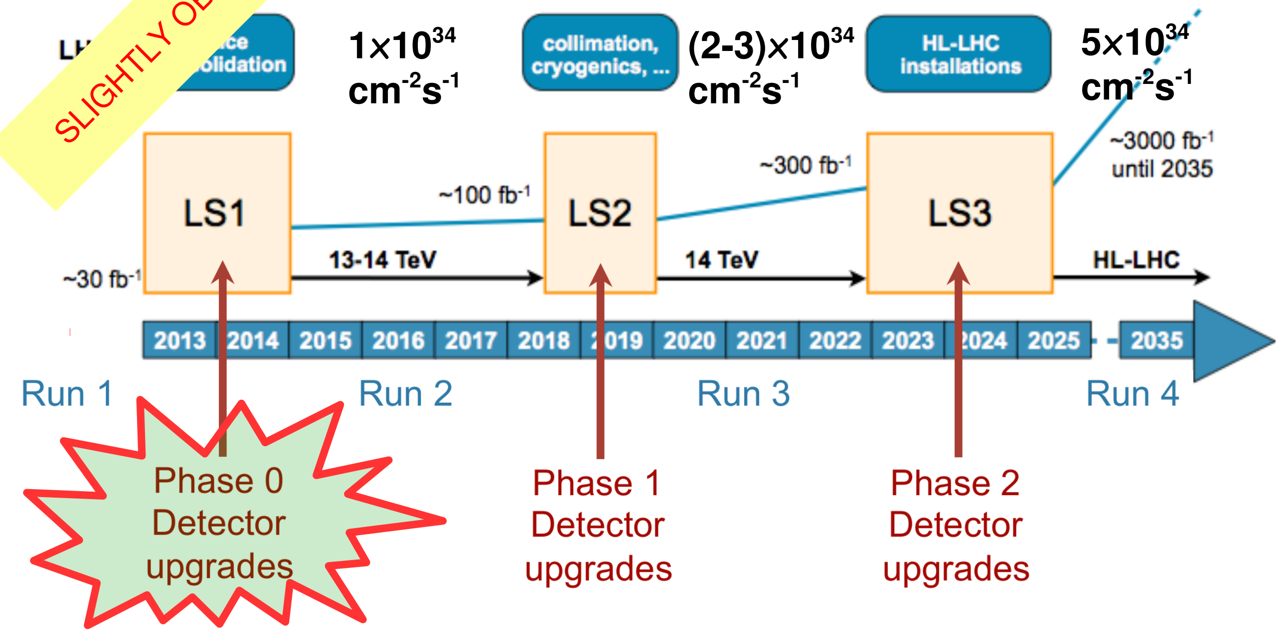
Average proper decay time distribution driven by:

- Tracking performance (with or without IBL)
- Trigger muon p_T thresholds $\rightarrow$ average B_s-meson momentum

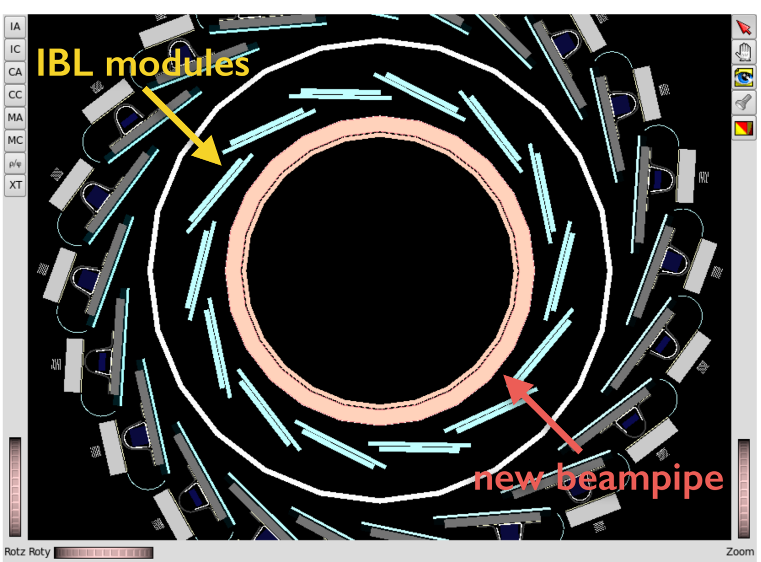


etector & Trigger Upgrades – Phase 0

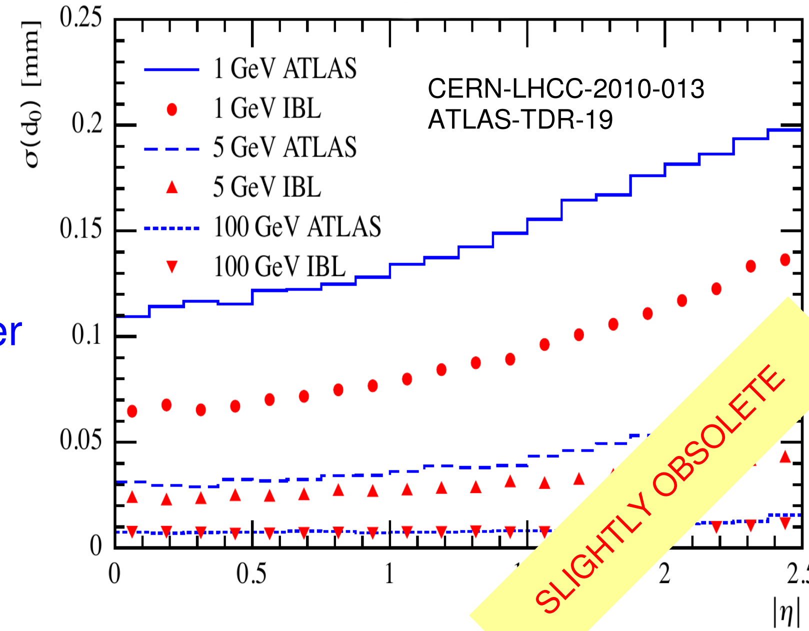
SLIGHTLY OBSOLETE



- Long Shutdown (LS) 1 almost over, LHC starts providing physics data in Spring 2015
- **Additional Pixel Layer (IBL)** and Be small radius beam pipe
- **Topological L1 trigger**
- Improved coverage of Muon spectrometer ($1.0 < |\eta| < 1.3$)
- Diamond Beam Monitor, consolidation of some parts of the detector (cooling etc.)



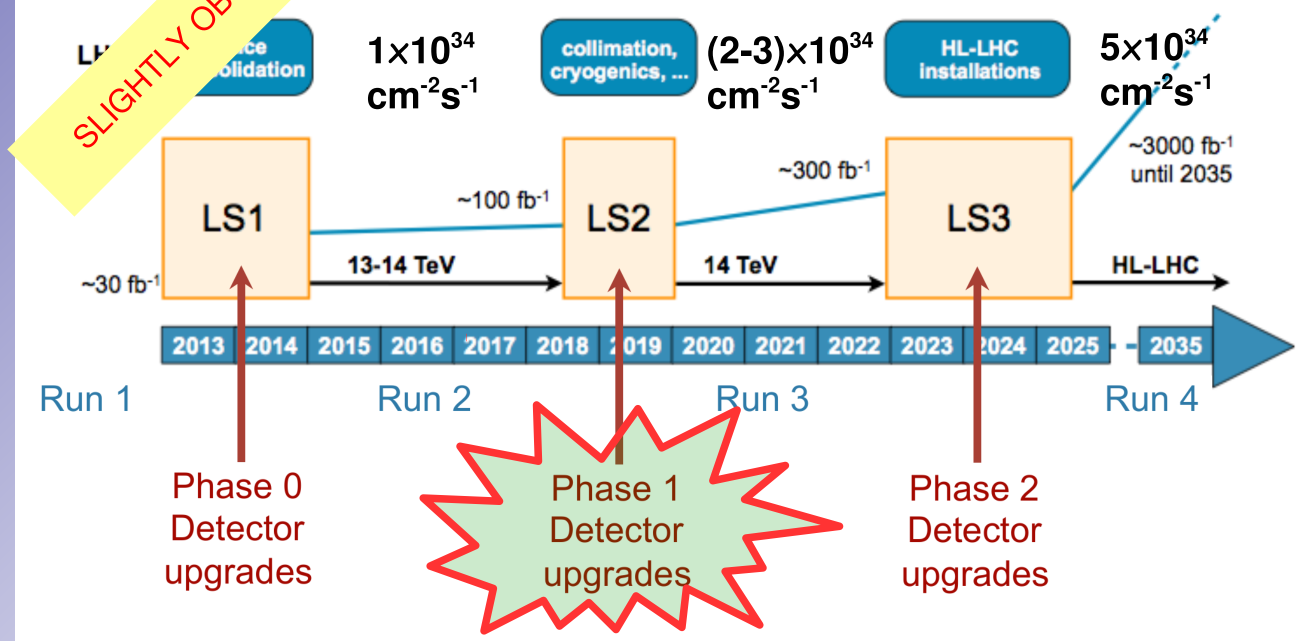
- Small radius (32-38 mm; current B-layer at 50.5 mm), small material budget
- 4th pixel layer => more robust track reconstruction, better impact parameter d_0 and z_0 resolution
- Better θ and ϕ resolution at low p_T ~ 1 GeV



SLIGHTLY OBSOLETE

SLIGHTLY OBSOLETE

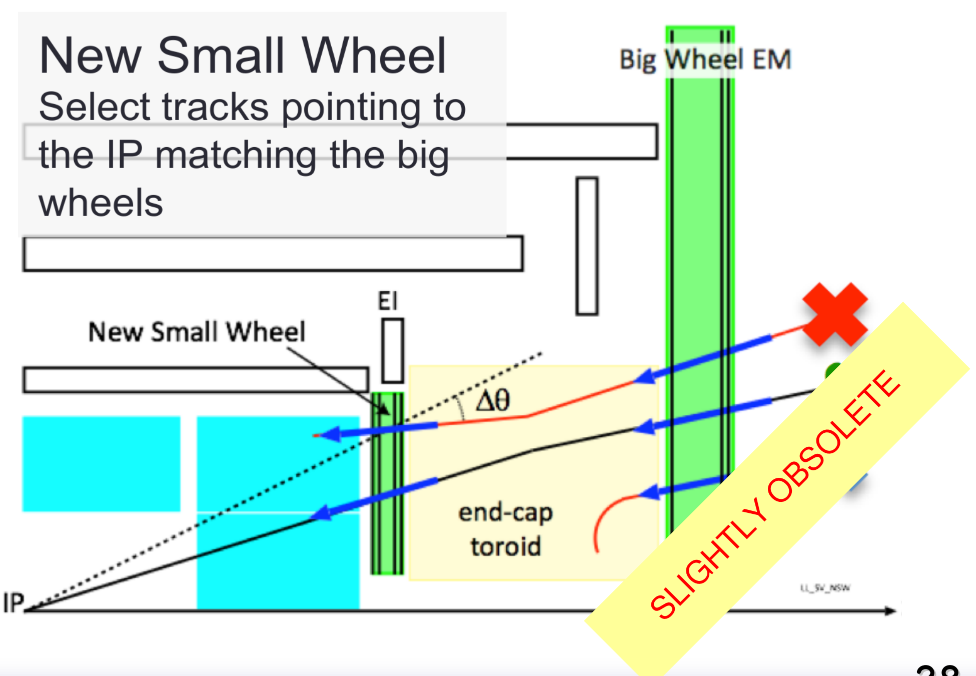
etector & Trigger Upgrades – Phase 1



- Goal: no loss of performance when going above LHC nominal luminosity
- **New small muon wheel**
- **New fast-tracking (FTK) at trigger level 1.5. Gradually implemented already during Run 2**
- Higher granularity and precision L1 trigger for calorimeter
- TDAQ improved performance

Fast tracking trigger:

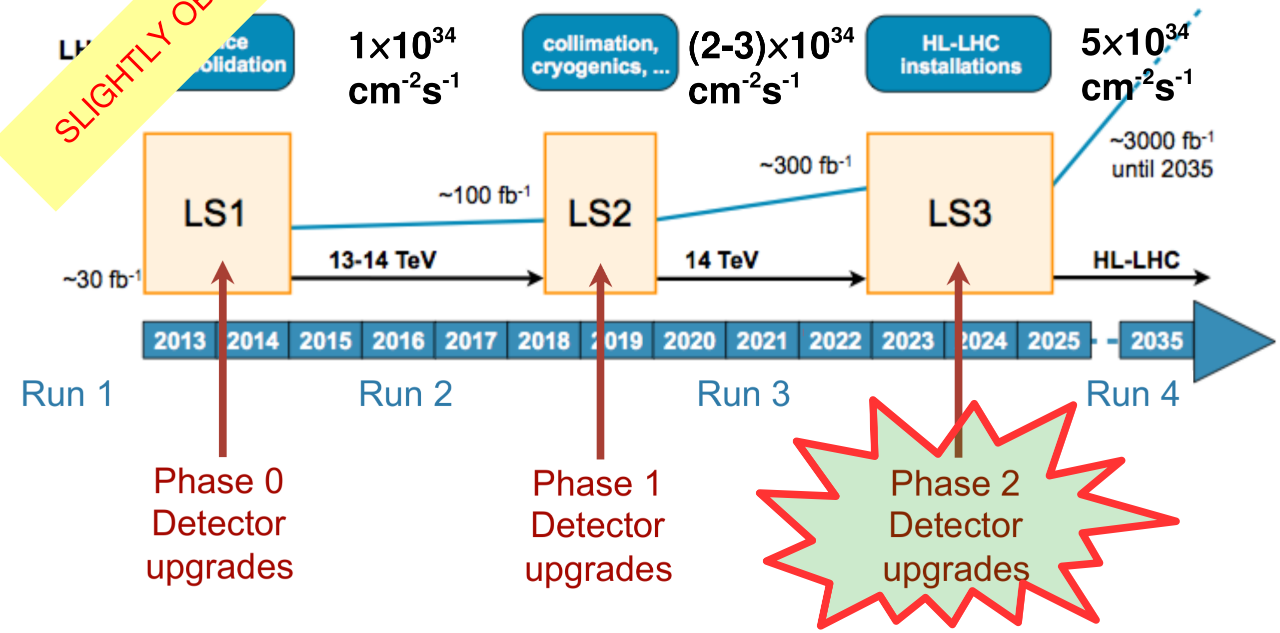
- HW based track finder in the Inner Detector silicon layers at "offline precision"
- Provides tracks already before the L2 trigger (first SW based trigger layer)
- Two-step processing: hit pattern matching & subsequent linear fitting in FPGAs



SLIGHTLY OBSOLETE

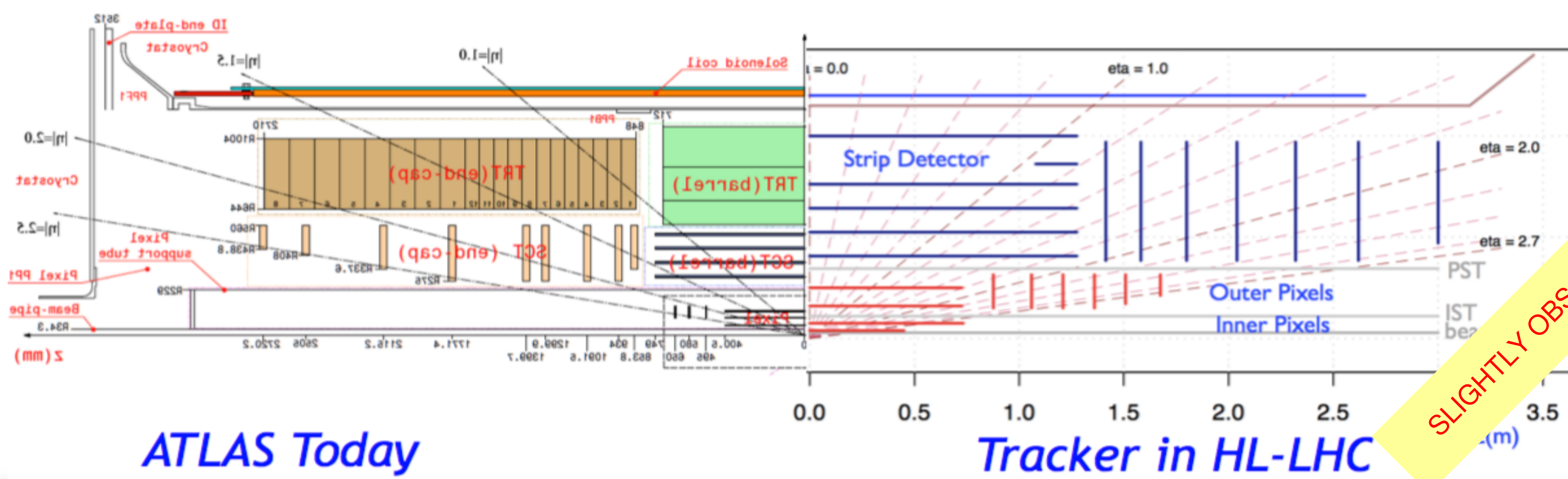
Detector & Trigger Upgrades – Phase 2

SLIGHTLY OBSOLETE



- Goal: maintain/improve performance despite high lumi.
- **Completely new Si based tracking (ITK)**
- New trigger system – possibly will include HW-based L1 track trigger
- Full granularity calorimetry information
- Upgrade part of the muon systems, fast trigger

Phase 2 Inner Tracker: current ID will become inefficient due to radiation damage; too high occupancy in TRT; high granularity (~4x better) required to cope with high pileup (~up to 200)



SLIGHTLY OBSOLETE