Heavy Flavor Physics with ATLAS

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Introduction

- The ATLAS experiment has been designed to discover new particles
  → first success: the Higgs discovery in July 2012

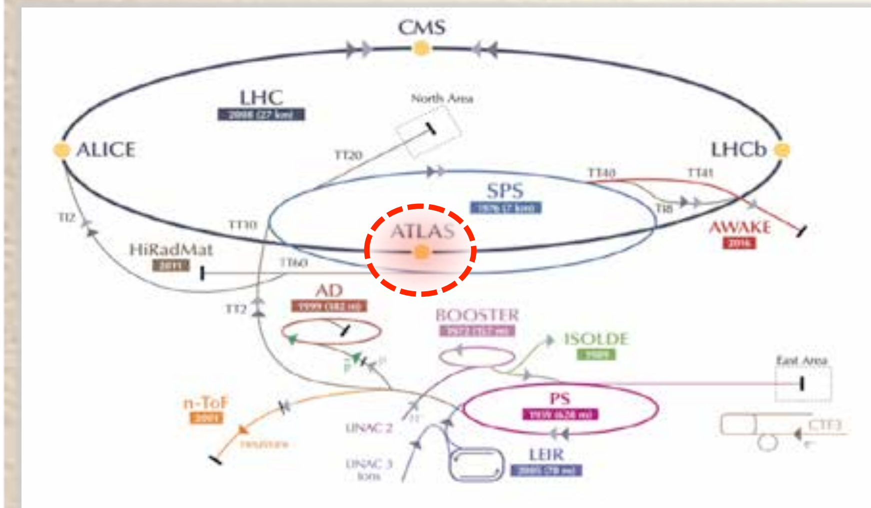
- However, the excellent vertex finding, tracking and muon identification capabilities of the ATLAS detector provide good conditions for studies of B mesons and B baryons

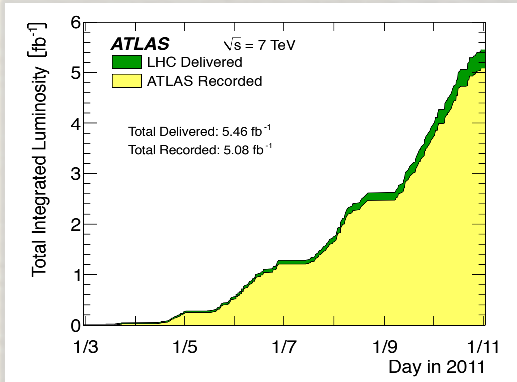
- ATLAS has performed several measurements, e.g. B^+ and b hadron production cross sections, B^0_d, B^0_s and Λ_b lifetimes, *CP* violation in the B^0_s system, studies of the B^+_c decay, search for $B^0_s \to \mu^+\mu^-$,

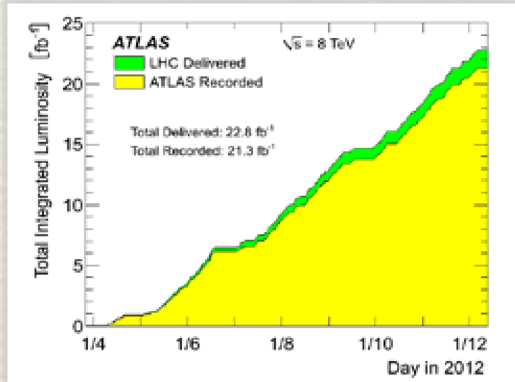
- Present here:
  - Flavor-tagged time-dependent angular analysis in $B_s^0 \to J/\psi\phi$ and prospects for run II and the high luminosity upgrades
  - Status of $B_s^0 \to \mu^+\mu^-$ and the measurement of f_s/f_d
  - Expectations for run II

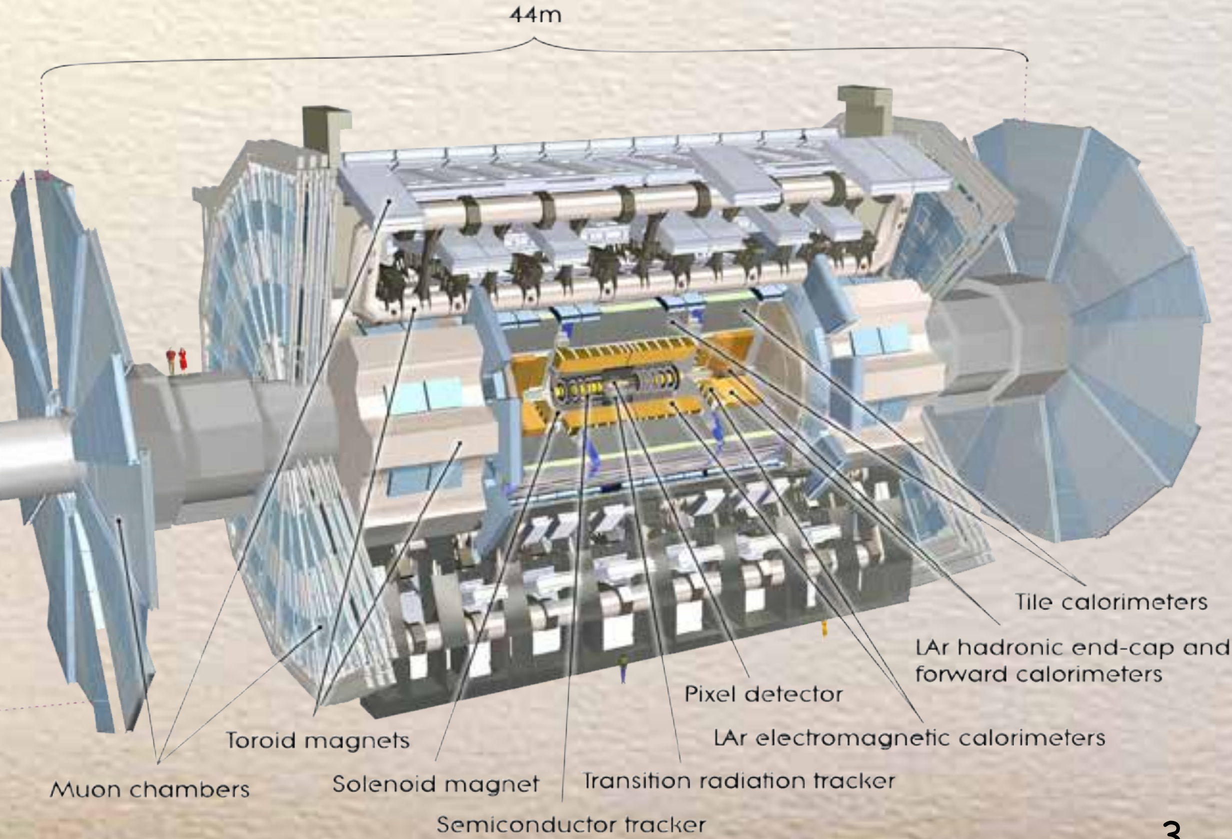
The ATLAS Detector and Run I Data

- ATLAS is a multi-purpose detector providing excellent tracking, calorimetry and μ identification









25m

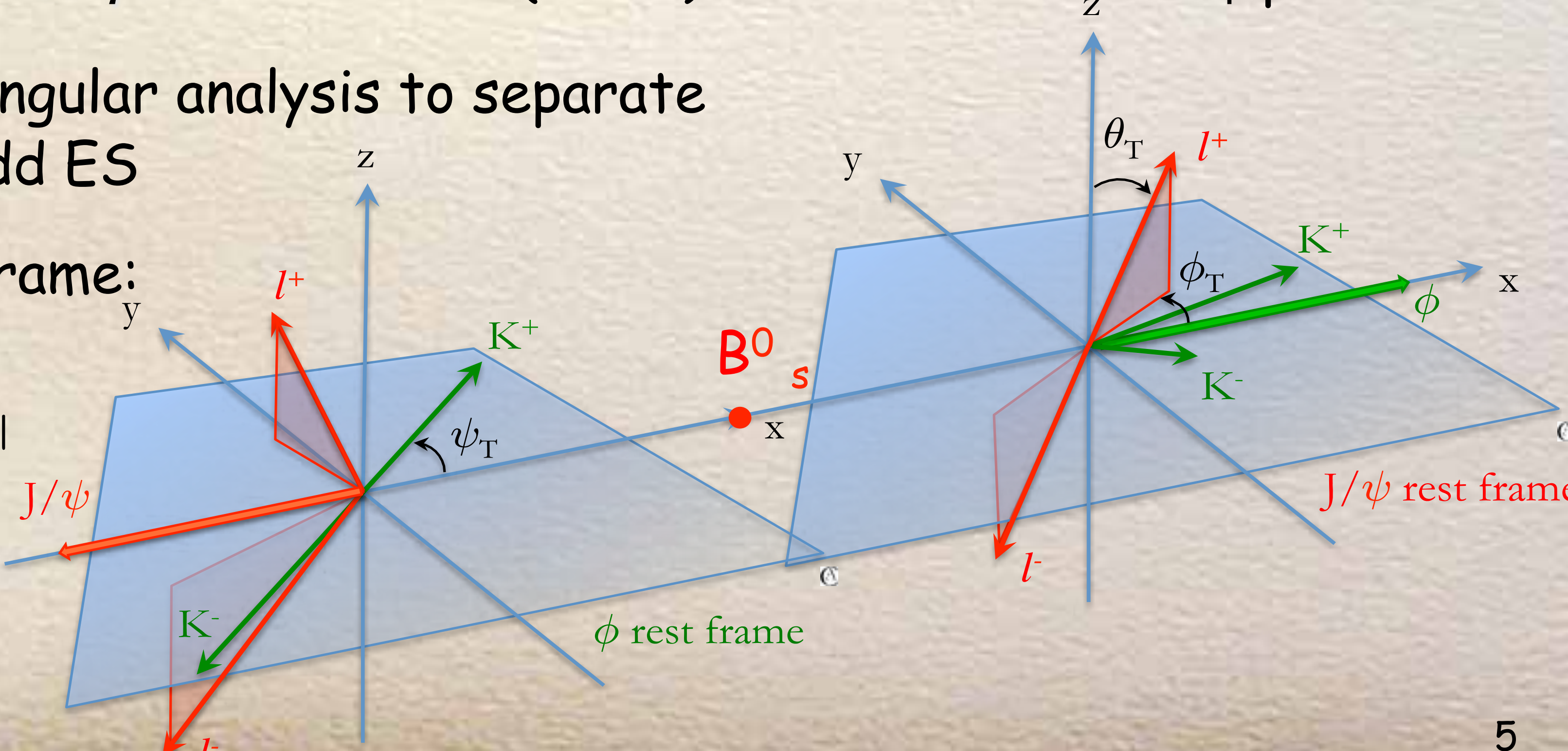
- μ identification from combined μ spectrometer (MS) & inner detector (ID) tracking

- ID tracks provide precision momemtum and lifetime measurements for momentum range being of interest for B physics

Flavor-tagged time-dependent angular analysis in $B_s^0 \rightarrow J/\psi\phi$

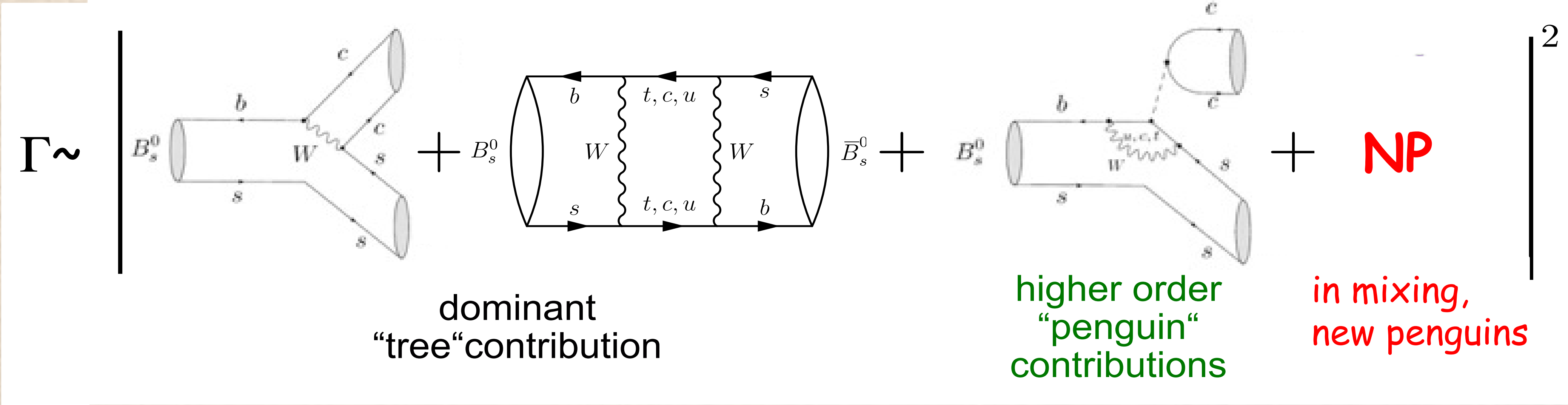
Study of $B^0_s \to J/\psi\phi$

- B^0_s mesons form a light *CP*-even (B_L) and a heavy *CP*-odd (B_H) eigenstate
- Mass difference of the 2 *CP* ES is $\Delta M = m(B_H) - m(B_L) = 17.757 \pm 0.021\ ps^{-1}$ (data)
- Lifetime difference of the 2 *CP* ES is $\Delta\Gamma = \Gamma(B_H) - \Gamma(B_L) = 0.087 + 0.021\ ps^{-1}$ (SM)
- $B^0_s \to J/\psi\phi$ is a vector vector decay ➔ not a pure *CP* ES, since S, P, & D waves contribute (*CP*=+1 for S & D wave; *CP*=-1 for P wave)
  ➔ in addition, $B^0_s \to J/\psi K^+K^-$ in S wave (CP=-1) contributes under ϕ peak
- Need to perform angular analysis to separate *CP*-even from *CP*-odd ES
- Use transversity frame: $\Omega_T = (\psi_T, \theta_T, \phi_T)$ ➔ amplitudes A_0, A_T, $A_{||}$ project S, P & D wave contributions and A_S for S-wave background



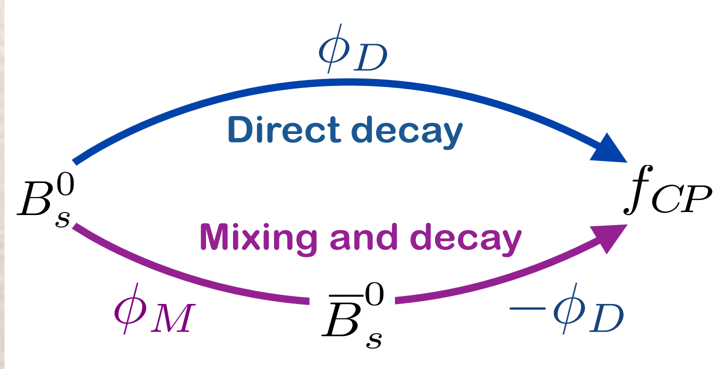
CP Violation in $B^0_s \to J/\psi\phi$

- In $B^0_s \to J/\psi\phi$, CP violation is caused by interference between mixing and decay



- Weak phase

$$\phi_s = \phi_M - 2\phi_D$$
$$= -2\beta_s + \Delta\phi_s^{penguin} + \delta^{NP}$$



- In the SM w/o penguins

$$\phi_s^{SM} = -0.0363^{+0.0012}_{-0.0014}\ rad$$

$$\beta_s = arg\left(-\frac{V_{ts}V^*_{tb}}{V_{cs}V^*_{cb}}\right)$$

Candidate Selection

- 2 oppositely charged muons from di-muon trigger ($p_T^{\mu 1}$ =4 GeV & $p_T^{\mu 2}$ =6 GeV) from a common vertex (χ^2/dof <10) having $m_{\mu\mu}$ consistent with J/ψ mass

BB: (both muons in barrel)	2989 < $m(J/\psi)$ < 3199 MeV
EB: (1 μ in endcap, 1 μ in barrel)	2944 < $m(J/\psi)$ < 3242 MeV
EE: (both muons in endcap)	2827 < $m(J/\psi)$ < 3357 MeV

- 2 oppositely charged hadrons from common $h^+h^-\mu^+\mu^-$ vertex (χ^2/dof <3) having m_{KK} consistent with ϕ mass with $p_T(K^\pm)$ > 1 GeV

- Determine proper decay time $t = \frac{L_{xy} m_B}{p_{T_B}}$ (L_{xy}: transverse decay length)

- The average pile up is 20.7 pp interaction per bunch crossing ➔ determine 3-d impact parameter d_0 and select smallest

  d_0: distance between the line extrapolated from the reconstructed B^0_s vertex in the direction of the B^0_s momentum for each primary vertex

- Select mass range 5.15 < $m_{J/\psi\phi}$ < 5.65 GeV

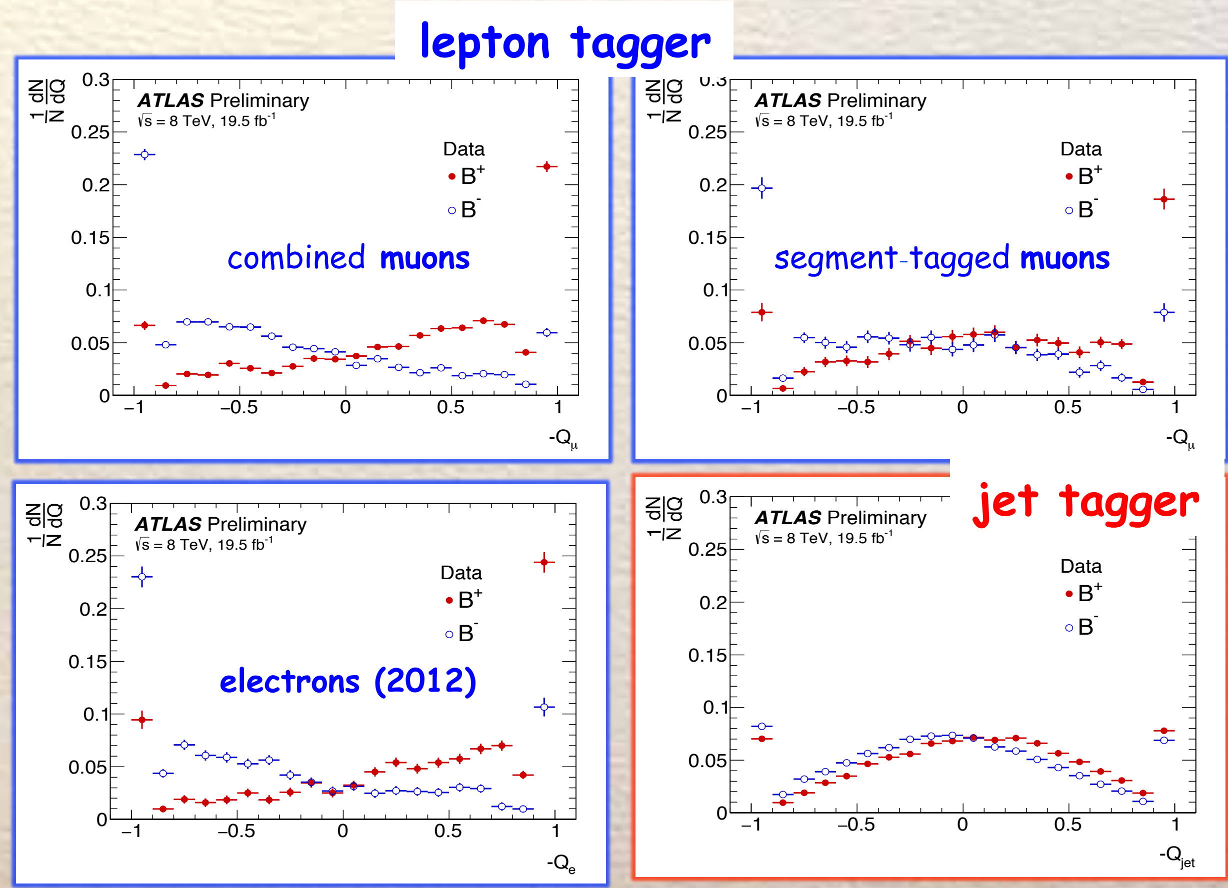
B^0_s Flavor Tagging

- Identify B^0_s flavor at production point by tagging the flavor of the other b quark in the event (in semileptonic decays, Q_e/Q_μ tags b flavor)
- Define cone charge for tagging categories μ, e , jet: ($\kappa_{\mu,jet}$ =1.1; κ_e =1.0) q_i: charge, p^i_T: transverse momentum

$$Q_i = \frac{\sum_i^{N_{tracks}} q_i \cdot \left(p_T^i\right)^\kappa}{\sum_i^{N_{tracks}} \left(p_T^i\right)^\kappa}$$

- Tagging power: $T = \varepsilon\left(1-2\omega\right)^2$
  ε: efficiency
  ω: probability to tag b flavor correctly (ω=0.5 for untagged)
- Use $B^\pm \to J/\psi K^\pm$ to determine B charge

Tagger	Tagging Power [%]
Combined μ	0.92 ± 0.02
Electrons	0.29 ± 0.01
Segment Tagged μ	0.10 ± 0.01
Jet charge	0.19 ± 0.01
Total	**1.49 ± 0.02**



Maximum-Likelihood Fit

- Perform unbinned maximum-likelihood fit to reconstructed mass m_i, measured proper decay time t_i plus its uncertainty σ_{ti} ,tagging probability ω_i and the transversity angles Ω_{Ti} for tagging category i to extract Γ_s, $\Delta\Gamma_s$, ϕ_s

PDF for B^0_d misidentified as B^0_s

$$\ln\mathcal{L} = \sum_{i=1}^{N}\Big\{w_i \cdot \ln\Big(f_s \cdot \mathcal{F}_s(m_i, t_i, \sigma_{t_i}, \Omega_i, \omega_i) + f_s \cdot f_{B^0_d} \cdot \mathcal{F}_{B^0_d}(m_i, t_i, \sigma_{t_i}, \Omega_i, \omega_i) + \big(1 - f_s \cdot (1 + f_{B^0_d})\big) \cdot \mathcal{F}_{bkg}(m_i, t_i, \sigma_{t_i}, \Omega_i, \omega_i)\Big)\Big\}$$

Signal PDF

PDF for combinatorial Background

f_s: signal fraction
N: number of selected candidates
w_i: weighting factor for trigger efficiencies
$f_{B^0_d}$: fraction of B^0_d events misidentified as B^0_s events

- Use only 2012 data for the fit ($\mathcal{L}_{tot}$ =14.3 fb^{-1}); add 2011 data (4.9 fb^{-1}) later

- Both the acceptance and the time and angular-dependent PDFs depend on the transversity angles ➔ must normalize them together

$B^0_s \to J/\psi\phi$ Systematic Uncertainty

- Background angular model ➔ vary sideband mass regions
  ➔ account for mis-reconstructed $B^0_d \to J/\psi K^{*0}$ correct angular shapes
  ➔ include $B^0_d \to J/\psi K\pi$ contamination and interference with $B^0_d \to J/\psi K^{*0}$
- Tagging ➔ uncertainty due to finite size of $B^0_d \to J/\psi K^{*0}$ calibration sample
  ➔ Precision of the tagging calibration (use alternate parameterizations)
- Assumption about fit model ➔ variation of the model tested in toy studies
- Angular acceptance method and trigger efficiency

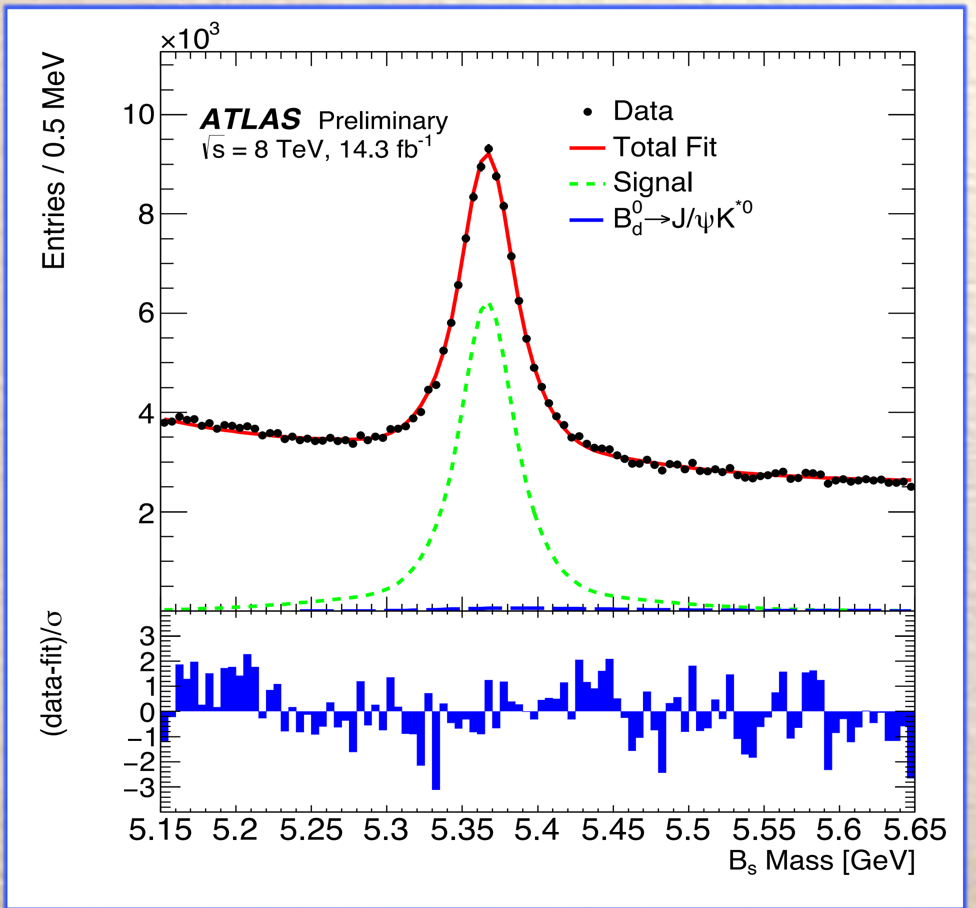
	ϕ_s [rad]	$\Delta\Gamma_s$ [ps^{-1}]	Γ_s [ps^{-1}]	$\lvert A_\parallel(0)\rvert^2$	$\lvert A_0(0)\rvert^2$	$\lvert A_S(0)\rvert^2$	$\delta_\perp$ [rad]	$\delta_\parallel$ [rad]	$\delta_\perp - \delta_S$ [rad]
Tagging	0.026	0.003	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	0.001	0.238	0.014	0.004
Acceptance	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	0.003	$<10^{-3}$	0.001	0.004	0.008	$<10^{-3}$
Background angles model:									
Choice of p_T bins	0.02	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^0_d background model	0.008	$<10^{-3}$	$<10^{-3}$	0.001	$<10^{-3}$	0.008	0.007	$<10^{-3}$	0.005
Fit model:									
Default fit	0.001	0.002	$<10^{-3}$	0.002	$<10^{-3}$	0.002	0.025	0.015	0.002
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
Total	0.036	0.007	0.003	0.006	0.001	0.013	0.25	0.05	0.01

ATLAS Preliminary

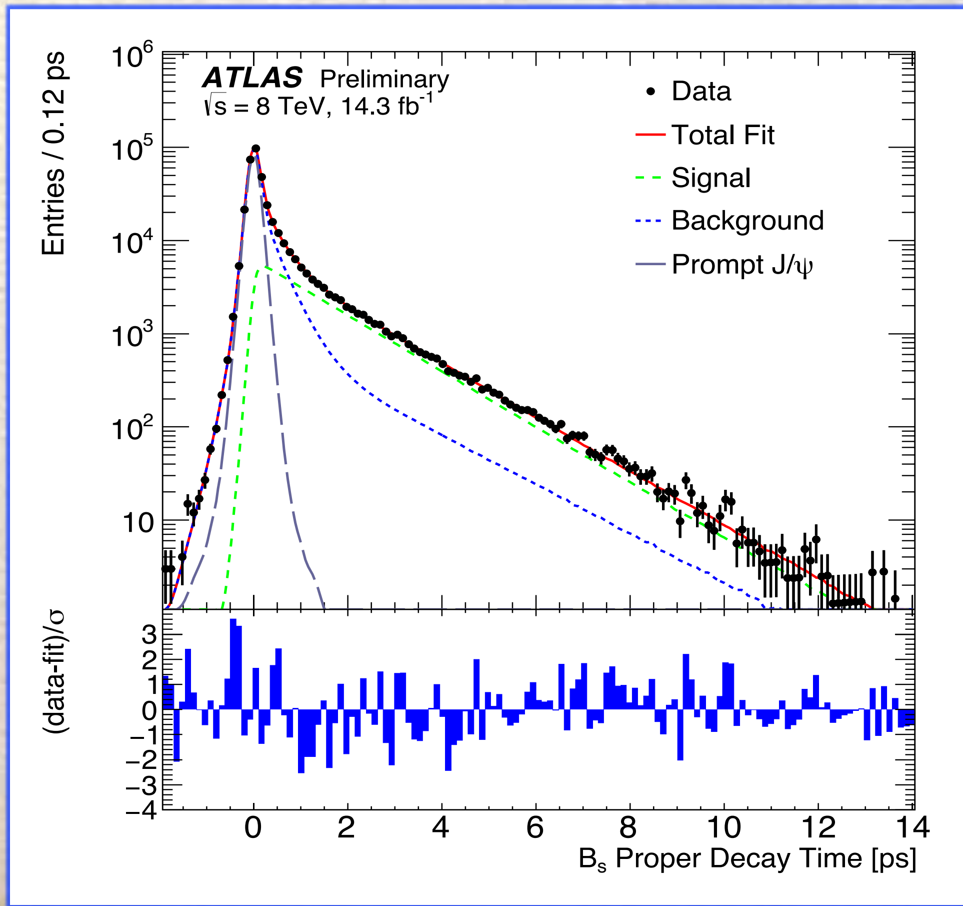
$B^0_s \to J/\psi\phi$ Fit Results for 8 TeV Data

- Projections of the maximum-likelihood fit on the B^0_s mass and the proper decay time
- No requirements on the B^0_s lifetime

B^0_s mass



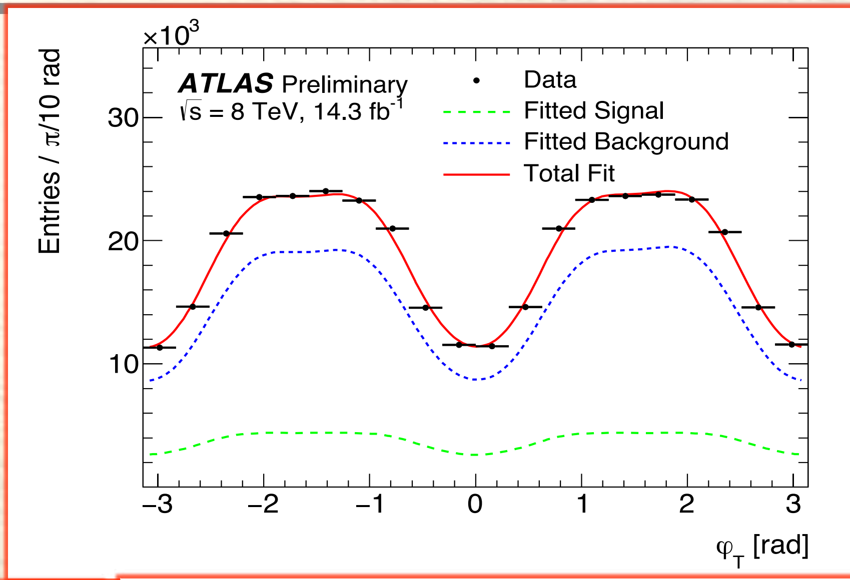
B^0_s proper decay time



$B^0_s \to J/\psi\phi$ Fit Results for 8 TeV Data

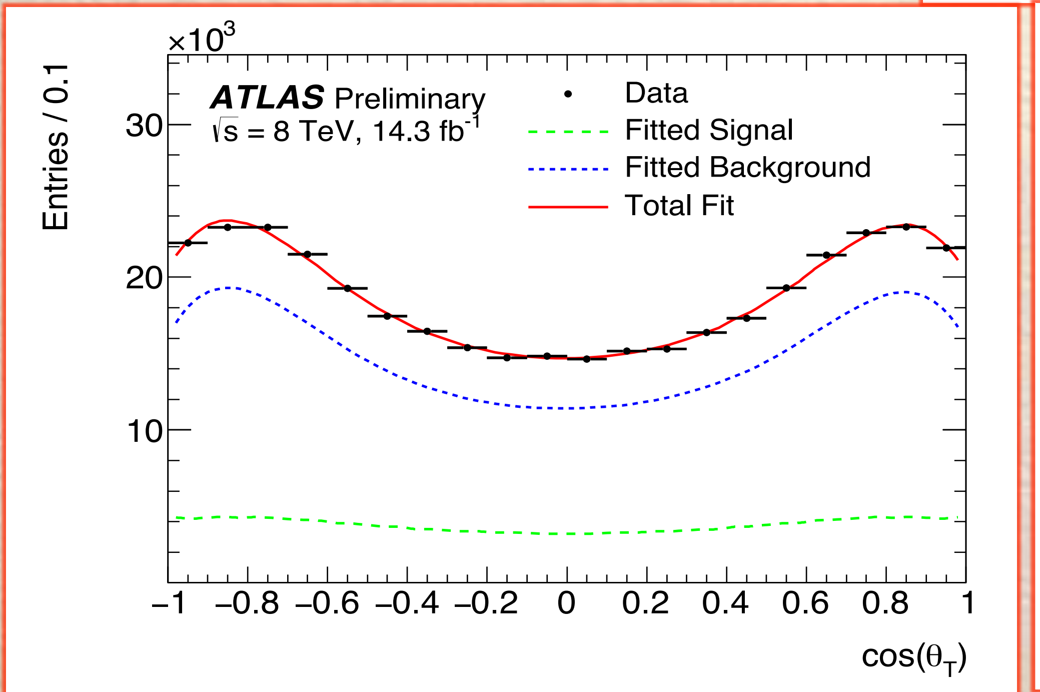
- Projections of the maximum-likelihood fit on the three transversity angles

ϕ_T



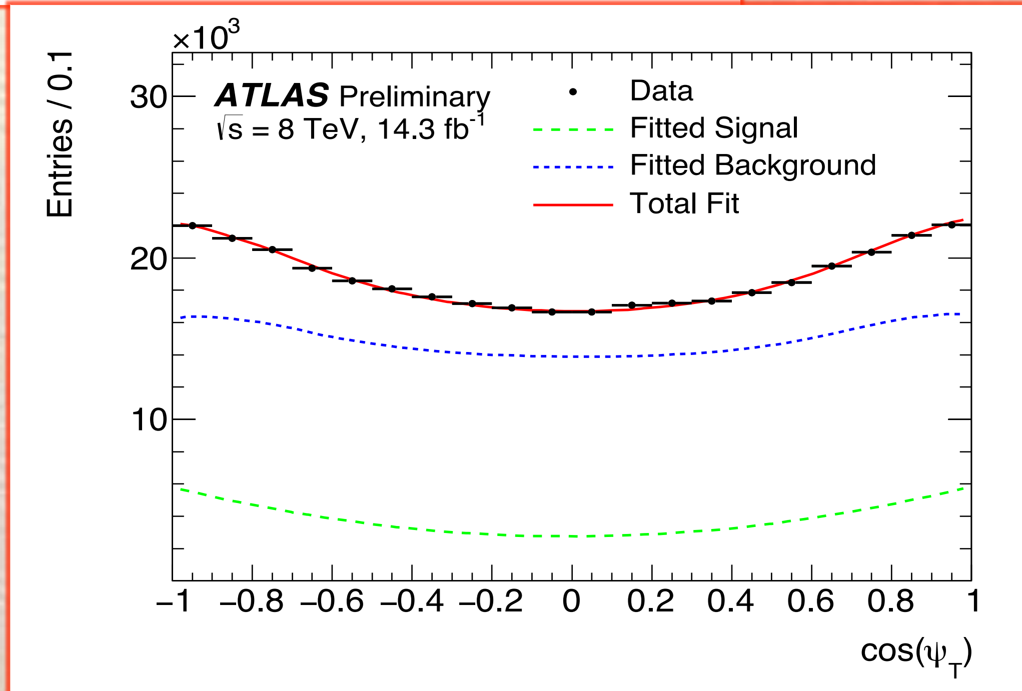
Angle between x-axis and $p_{xy}(\mu^+)$, μ^+ momentum projection in the x-y plane, in the J/ψ rest frame

$\cos(\theta_T)$



Angle between the x-y plane in the J/ψ rest frame and $p_{xy}(\mu^+)$

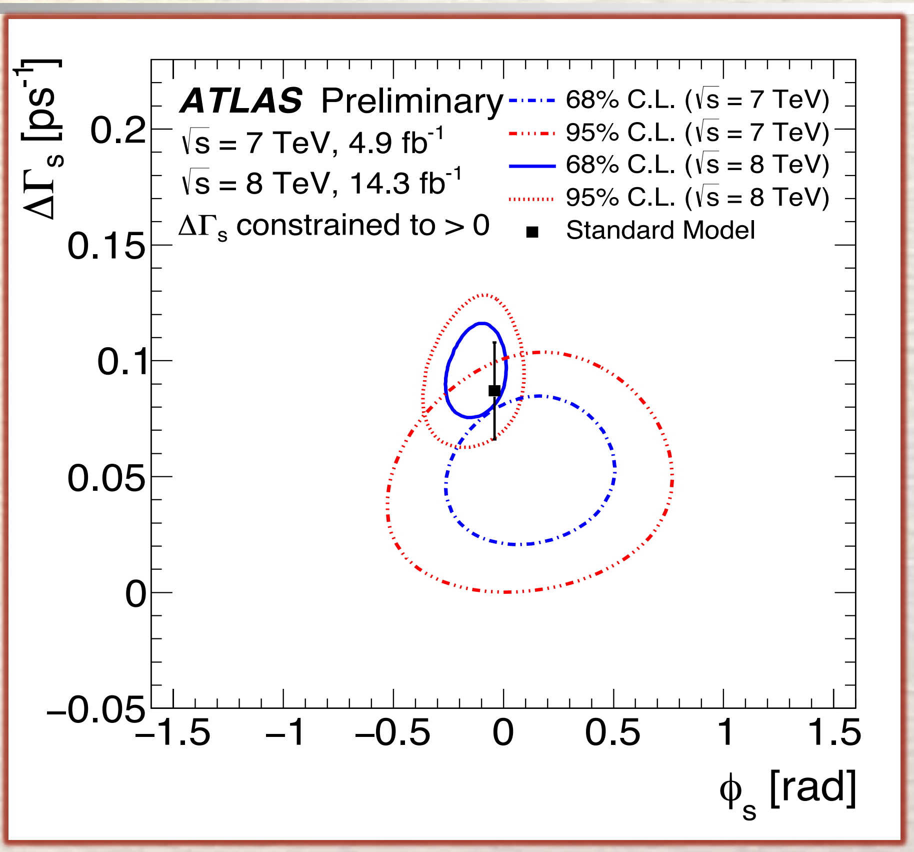
$\cos(\psi_T)$



Angle between $p(K^+)$ and $-p(J/\psi)$ in the ϕ rest frame

Fit Results for $B^0_s \to J/\psi\phi$

- Results for 8 TeV (14.3 fb^{-1}):
  - $\phi_s = -0.119 \pm 0.088_{stat} \pm 0.036_{sys}$ rad
  - $\Delta\Gamma_s = 0.096 \pm 0.013_{stat} \pm 0.007_{sys}$ ps^{-1}
  - Correlation: $(\phi_s, \Delta\Gamma_s) = 0.110$
- Results for 7 TeV (4.9 fb^{-1}):
  - $\phi_s = 0.12 \pm 0.25_{stat} \pm 0.05_{sys}$ rad
  - $\Delta\Gamma_s = 0.053 \pm 0.021_{stat} \pm 0.010_{sys}$ ps^{-1}
  - Correlation: $(\phi_s, \Delta\Gamma_s) = 0.107$



- Combination of 2011 & 2012 results

$\phi_s = -0.094 \pm 0.082_{stat} \pm 0.033_{sys}$ rad

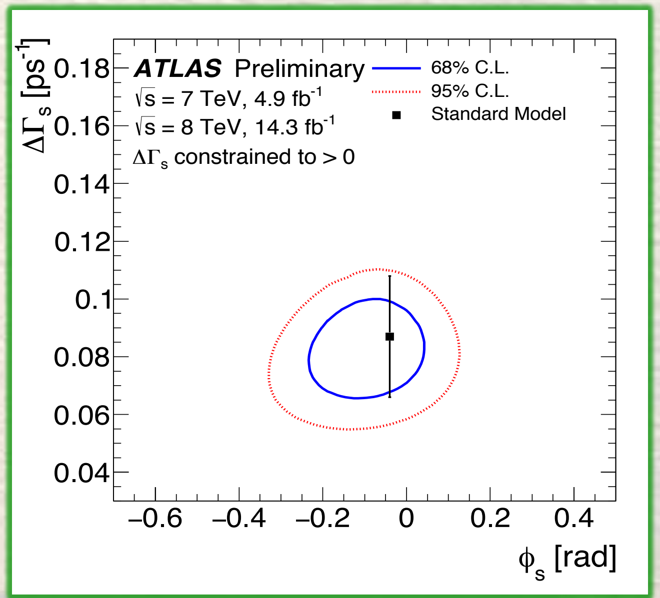
$\Delta\Gamma_s = 0.082 \pm 0.011 \pm 0.007$ ps^{-1}

  - Statistical combination
  - Best Linear Unbiased Estimate (BLUE) of 7 TeV and 8 TeV results

➔ Minimize the variance in the estimator

Comparison of ϕ_s and $\Delta\Gamma_s$ Results

- 2012 & 2011 combined results agree well with the SM prediction and with results of other experiments



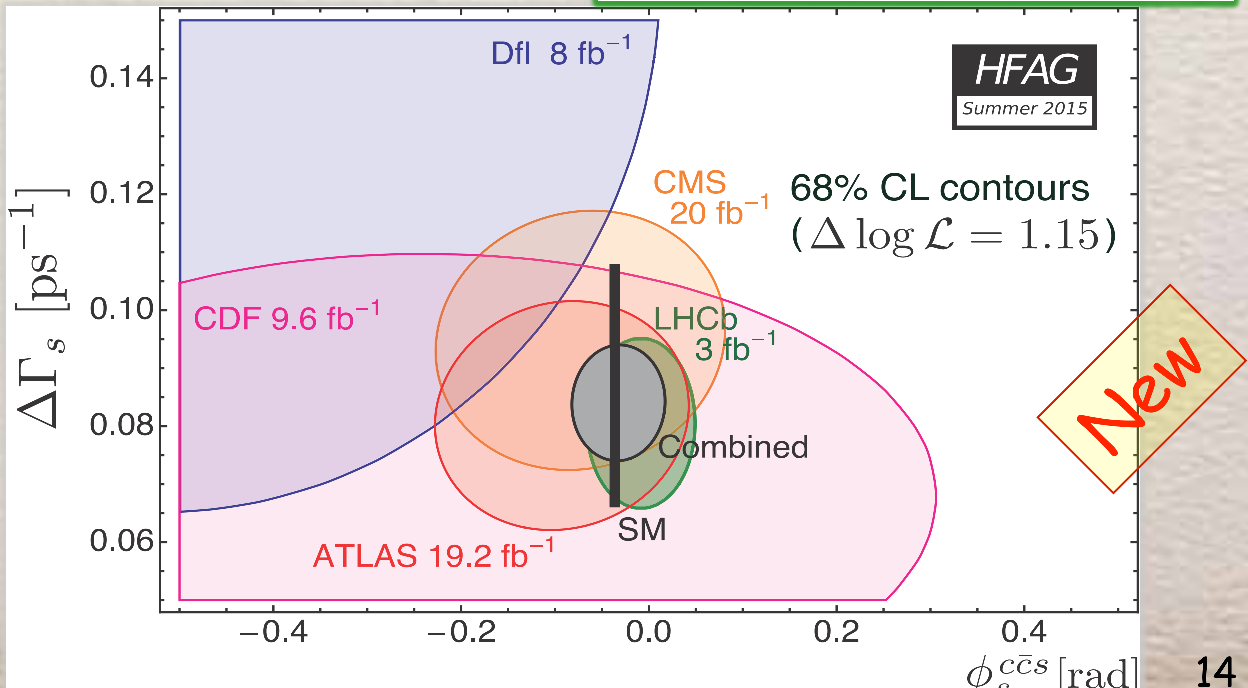
- SM results:

$$\phi_s^{SM} = -0.0363^{+0.0012}_{-0.0014}\ rad$$
$$\Delta\Gamma_s^{SM} = 0.087 \pm 0.021\ ps^{-1}$$

- Combination of ATLAS, CMS, LHCb, CDF & D0 yields (HFAG 2015)

$$\phi_s^{c\bar{c}s} = -0.034 \pm 0.033\ rad$$
$$\Delta\Gamma_s = 0.082 \pm 0.006\ ps^{-1}$$

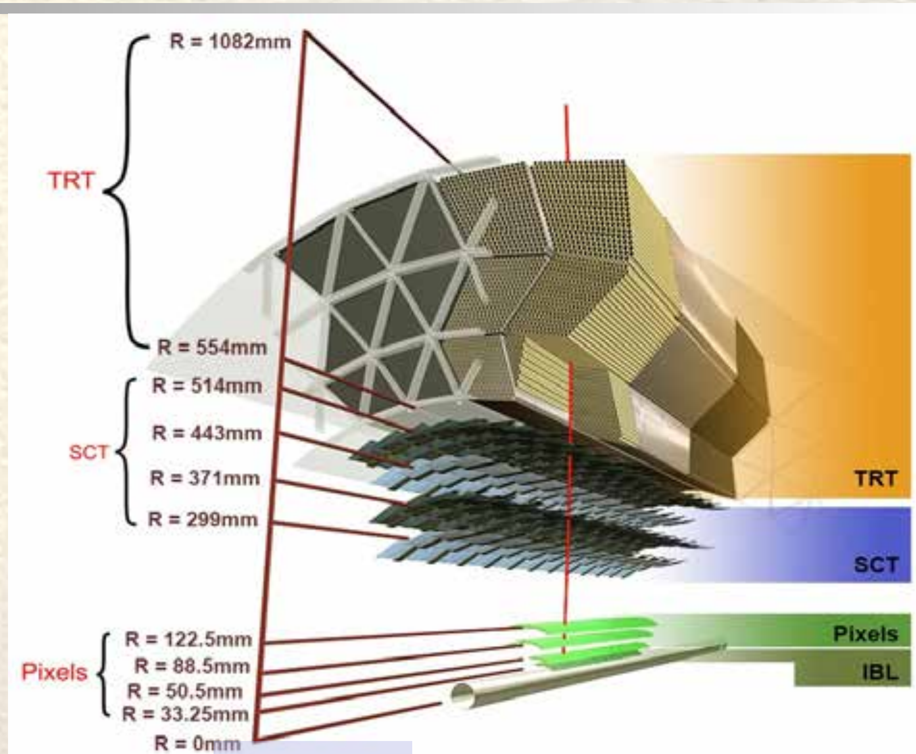
- Precision is at the level of the central value



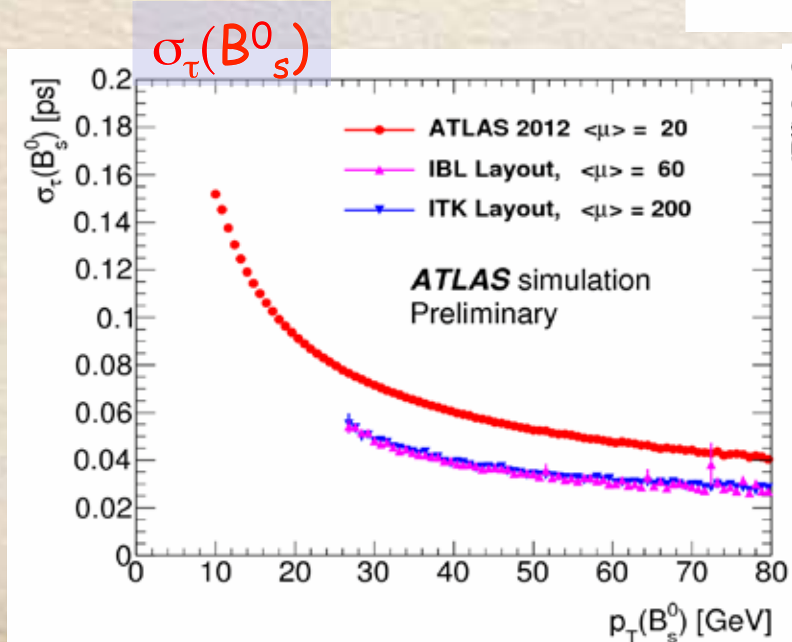
CDF: PRL 109, 171802 (2012)
D0: PRD 85, 032006 (2012)
ATLAS: PRD 90, 052007 (2014),
CMS: update for EPS 2015
LHCb: PRL 114, 041801 (2015)

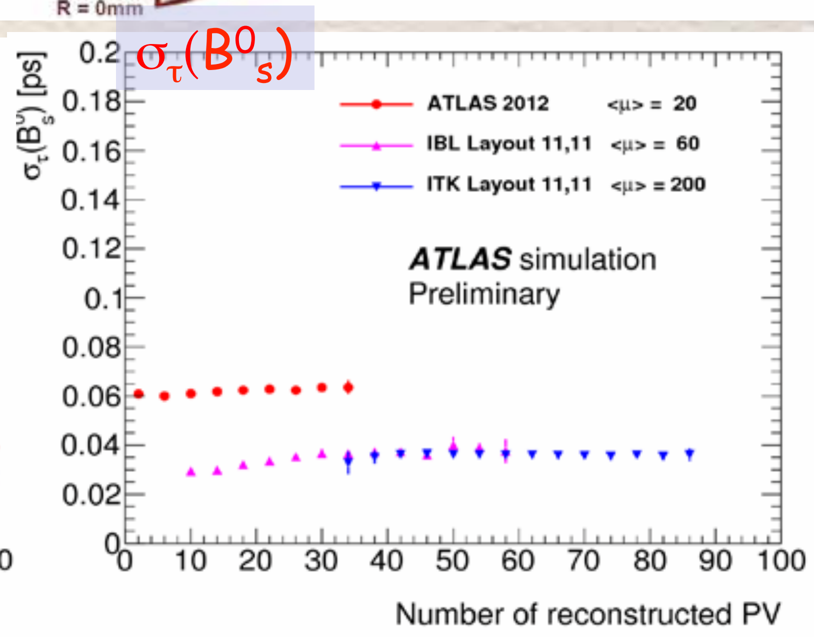
Future Expectations for ϕ_s Measurements

- Simulate performance for run II and after the high-luminosity upgrade
  - A new pixel layer (IBL) was installed near the beam pipe ➔ expect 30% improvement in resolution wrt 2012 performance
  - Pile-up will increase to 60 in run II and to 200 after the HL upgrade
  - b cross section will be twice as large as for 7 TeV



- Extract proper decay time resolution vs p_T & $\#_{\text{reconstructed PV}}$
- Resolution improves by ~30%





B^0_s Tag Probability Distributions

- Assume di-muon thresholds of $p_T^{\mu 1}=6$, $p_T^{\mu 2}=6$ GeV for run II and $p_T^{\mu 1}=11$, $p_T^{\mu 2}=11$ GeV for HL run
- Validate model with 2011 data and check 2012 data

	2011	2012	2015-17		2019-21	2023-30+
Detector	current	current	IBL		IBL	ITK
Average interactions per BX $<\mu>$	6-12	21	60		60	200
Luminosity, fb^{-1}	4.9	20	100		250	3 000
Di-μ trigger p_T thresholds, GeV	4 - 4(6)	4 - 6	6 - 6	11 - 11	11 - 11	11 - 11
Signal events per fb^{-1}	4 400	4 320	3 280	460	460	330
Signal events	22 000	86 400	327 900	45 500	114 000	810 000
Total events in analysis	130 000	550 000	1 874 000	284 000	758 000	6 461 000
MC $\sigma(\phi_s)$ (stat.), rad	0.25	0.12	0.054	0.10	0.064	0.022

- Despite higher pile-up and higher muon p_T thresholds, the statistical uncertainty on ϕ_s will improve to 0.054 rad in run II and 0.022 rad for HL running in 2030s

Status of $B_s^0 \to \mu^+\mu^-$

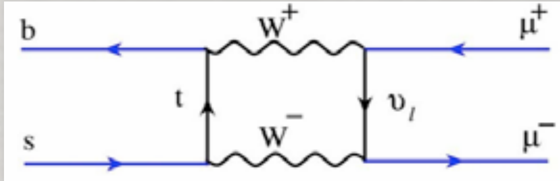
and

measurement of f_s/f_d

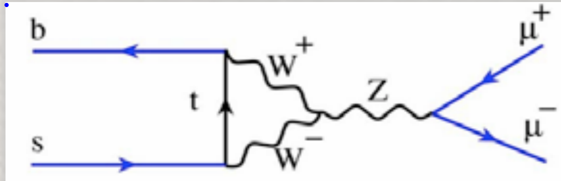
ATLAS: ArXiv:hep-ex/1507.08925

$B^0_{s,d} \to \mu^+\mu^-$

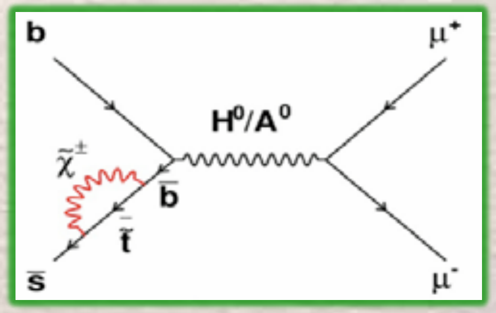
- Flavor-changing neutral currents (FCNC) are forbidden in the SM at tree level but are allowed at higher orders



- The decays $B^0_{s,d} \to \mu^+\mu^-$ are highly suppressed:
  - $\mathcal{B}_{SM}(B^0_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$ C. Bobeth et al., Phys. Rev. Lett. 112, 101801 (2014)
  - $\mathcal{B}_{SM}(B^0_d \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$



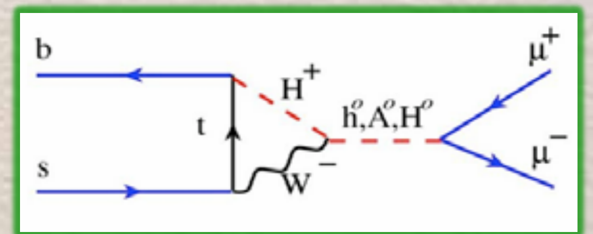
- New physics contributions may modify branching fraction



- Evidence from LHCb and CMS (combined result)
  - $\mathcal{B}(B^0_s \to \mu^+\mu^-) = (2.8 \pm 0.7) \times 10^{-9}$
  - $\mathcal{B}(B^0_d \to \mu^+\mu^-) = (3.9 \pm 1.6) \times 10^{-9}$

  Nature, 522, 7554, 68 (2015) [arXiv:1411.4413]

  ➔consistent with SM prediction (some room for NP)



- ATLAS analysis with full data set is ongoing results for 2011 presented ATLAS-CONF-2013-076

- New result on ratio of fragmentation fraction f_s/f_d

Motivation for f_s/f_d Measurement

- The ratio f_s/f_d needs to be known to calculate the number of B^0_s mesons produced in ATLAS: $N_{Bs}=\mathcal{L}\bullet\sigma_b\bullet f_s$

- Extract f_s/f_d from ratio of yields in $B^0_s \to J/\psi\phi$ and $B^0_d \to J/\psi K^{*0}$

measure

PDG

efficiency ratio (~0.8) from simulation

$$\frac{f_s}{f_d} = \frac{N_{B^0_s}}{N_{B^0_d}} \frac{\mathcal{B}(B^0_d \to J/\psi K^{*0})}{\mathcal{B}(B^0_s \to J/\psi\phi)} \frac{\mathcal{B}(K^{*0} \to K^+\pi^-)}{\mathcal{B}(\phi \to K^+K^-)} \mathcal{R}_{eff}$$

$$0.83^{+0.03}_{-0.02}(\omega_B)^{+0.01}_{-0.00}(f_M)^{+0.01}_{-0.02}(a^\sigma_k)^{+0.01}_{-0.02}(m_c)$$

PDG

from theory

X. Liu *et al.*, PRD 89, 094010 (2014)
ArXiv:hep-ph/1309.0313

- Both decays are vector vector decays that have similar topologies and similar angular distribution ➔ many common uncertainties cancel

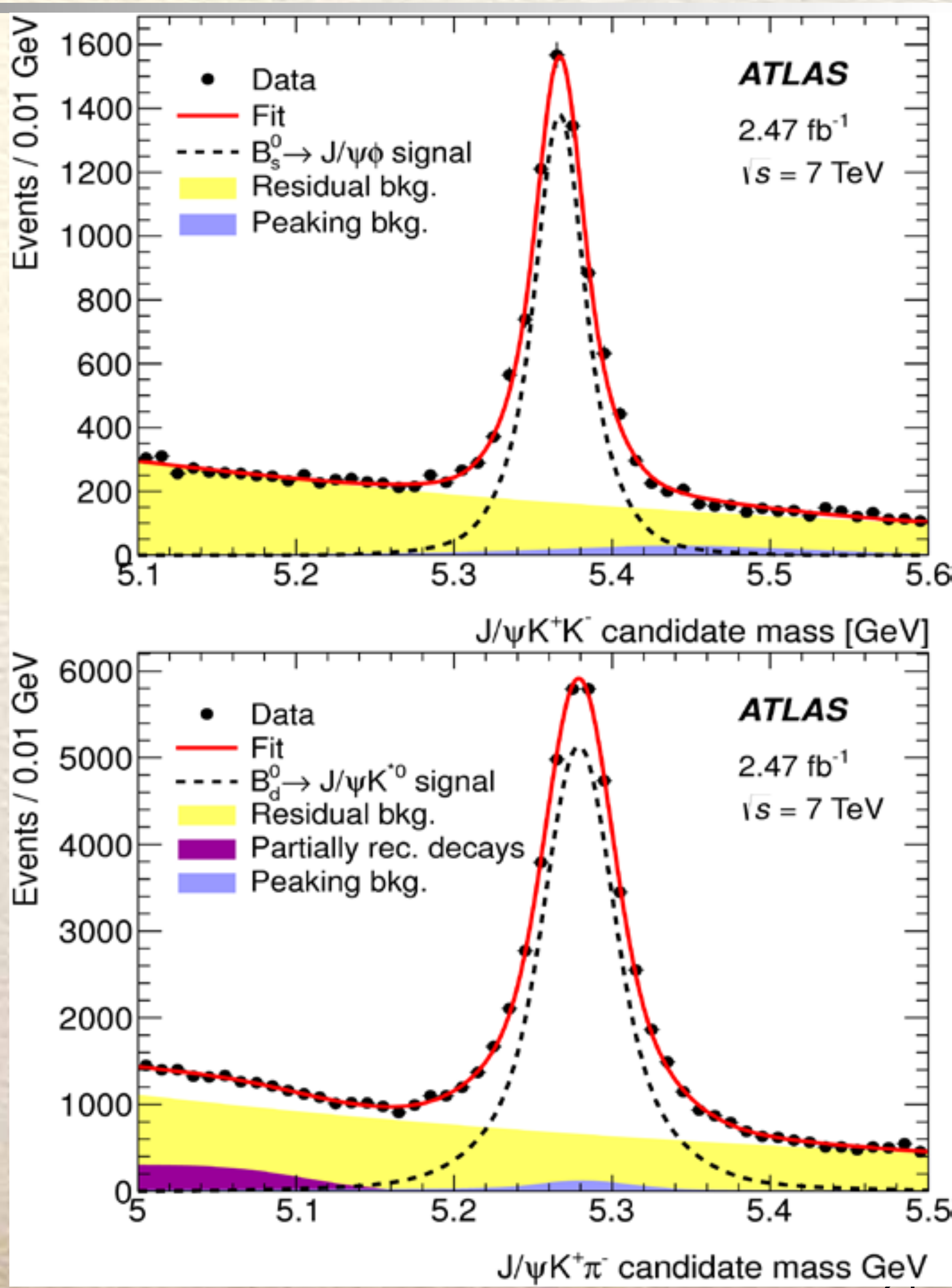
- Use 2.47 fb^{-1} of 2011 data that is sufficient as measurement is systematics dominated

Analysis Strategy

- Select 2 oppositely-charged muons with p_T > 4 GeV from a common vertex with χ^2/dof < 10
- Select J/ψ events in similar 3 detector regions (BB, EB EE) as in the time-dependent $B^0_s \to J/\psi\phi$ analysis
- Select ϕ candidates within ± 2 widths and K^{*0} candidates within ±1 width p_T (K, π) > 0.8 GeV
- Final selection for B^0_s (B^0_d) signal candidates
  - $p_T(B^0_s, B^0_d)$ > 8 GeV
  - χ^2/dof <2.4 (2.6) for 4 track vertex
  - Transverse decay length L_{xy}> 0.26 (0.30) mm
  - Pointing angle a < 0.14 (0.12) rad
- Backgrounds: direct J/ψ decays
  inclusive $b\bar{b} \to J/\psi X$
  combinatorial $b\bar{b} \to J/\psi X$
  peaking ($J/\psi hh'$) (h,h': charged hadrons)

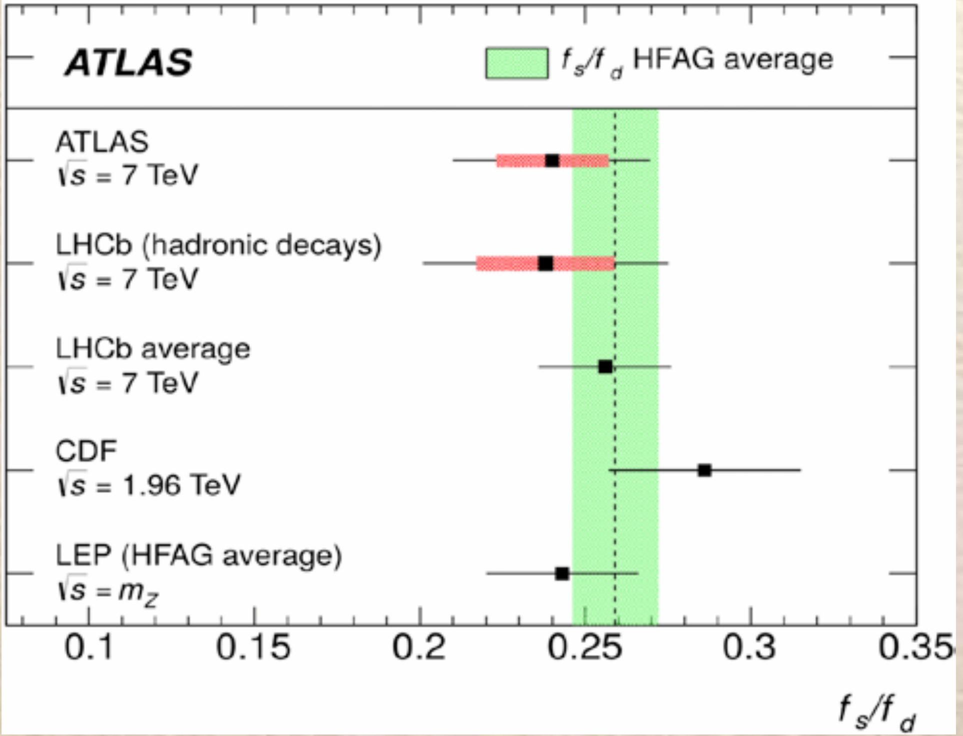
Signal f_s/f_d Measurement

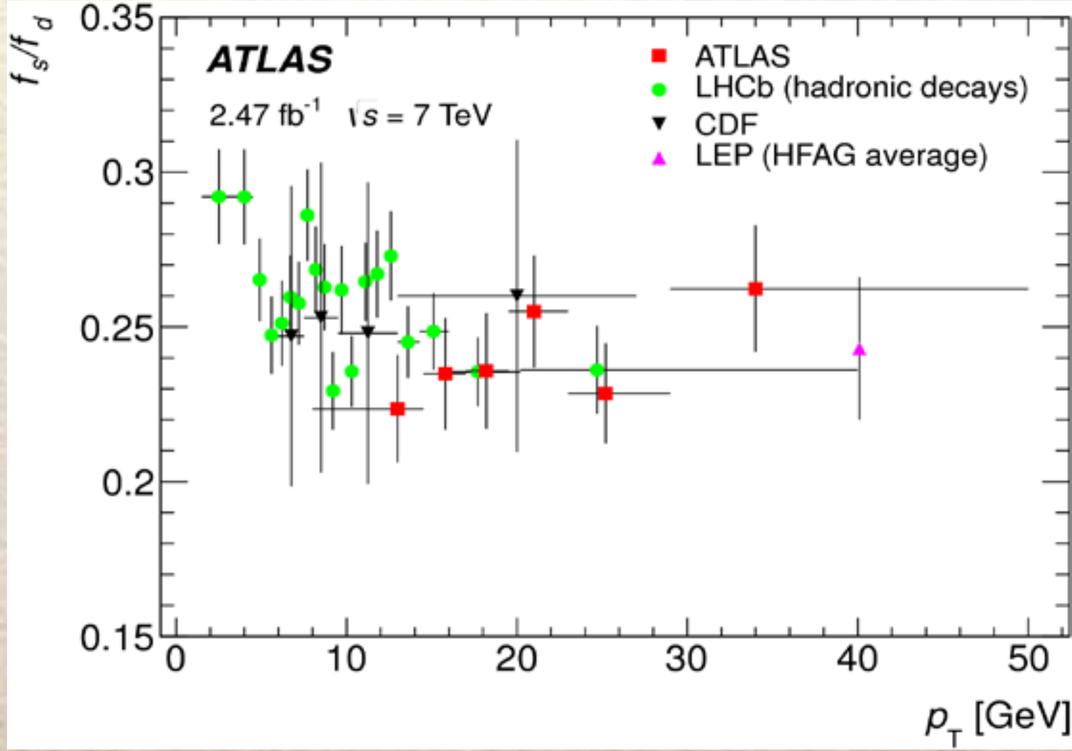
- Perform extended unbinned maximum likelihood fit to $m_{J/\psi\phi}$ & $m_{J/\psi K^*}$ spectra to extract $B^0_s \rightarrow J/\psi\phi$ & $B^0_d \rightarrow J/\psi K^{*0}$ signal yields
- Model:
  - $B^0_s \rightarrow J/\psi\phi$ & $B^0_d \rightarrow J/\psi K^{*0}$ signal with 3 Gaussians
  - $B^0_s \rightarrow J/\psi\phi$ background with exponential & Crystal Ball function
  - $B^0_d \rightarrow J/\psi K^{*0}$ background with exponential & complementary error function & CB function & Gaussian
- Observe $6644 \pm 102_{stat} \pm 219_{sys}$ $J/\psi\phi$ signal candidates
- Observe $36287 \pm 324_{stat} \pm 653_{sys}$ $J/\psi K^{*0}$ signal candidates



Results for f_s/f_d

- From the yields, measure $$\frac{f_s}{f_d}\frac{\mathcal{B}\left(B_s^0 \to J/\psi\phi\right)}{\mathcal{B}\left(B_d^0 \to J/\psi K^{*0}\right)} = 0.199 \pm 0.004_{stat} \pm 0.010_{sys}$$
- yielding $$\frac{f_s}{f_d} = 0.240 \pm 0.004_{stat} \pm 0.013_{sys} \pm 0.017_{th}$$ Total systematic error is 5.2%
- ATLAS measurement is in good agreement with the LHCb results
- Above 8 GeV, p_T distribution is consistent with being uniform





 LHCb: HEP 1304, 01 (2013) LEP: ArXiv:hep-ex/1412.7515 CDF: note 10795 (2012)

Performance

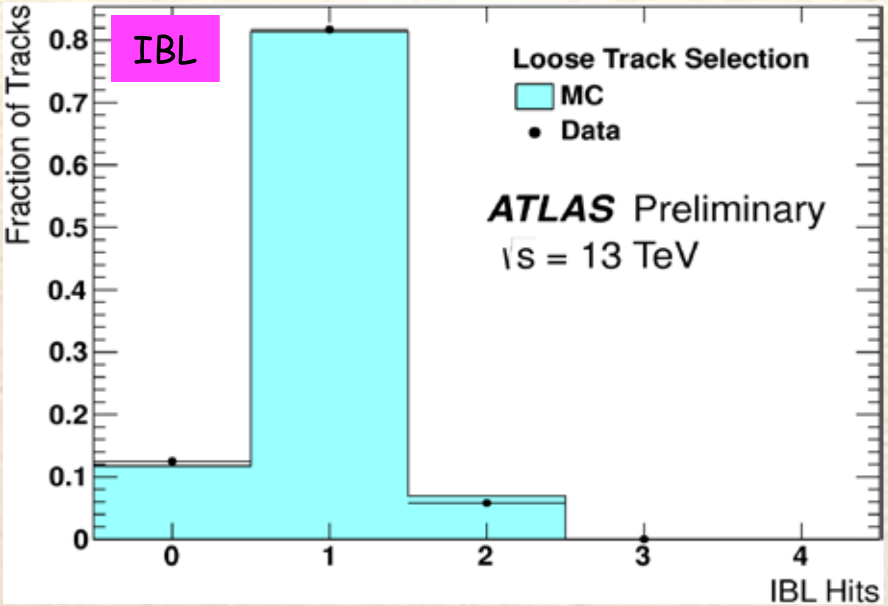
in run II

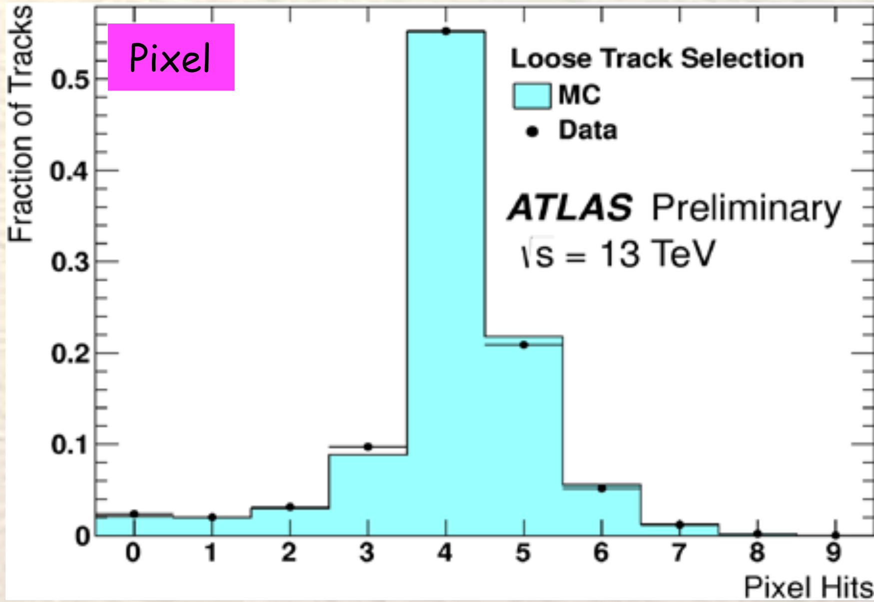
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/Summer2015-13TeV

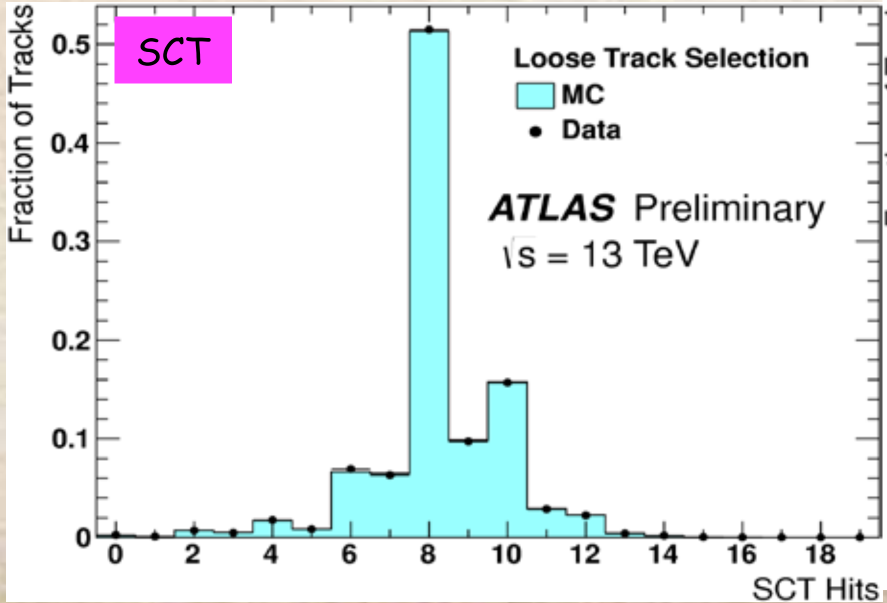
Tracking Performance

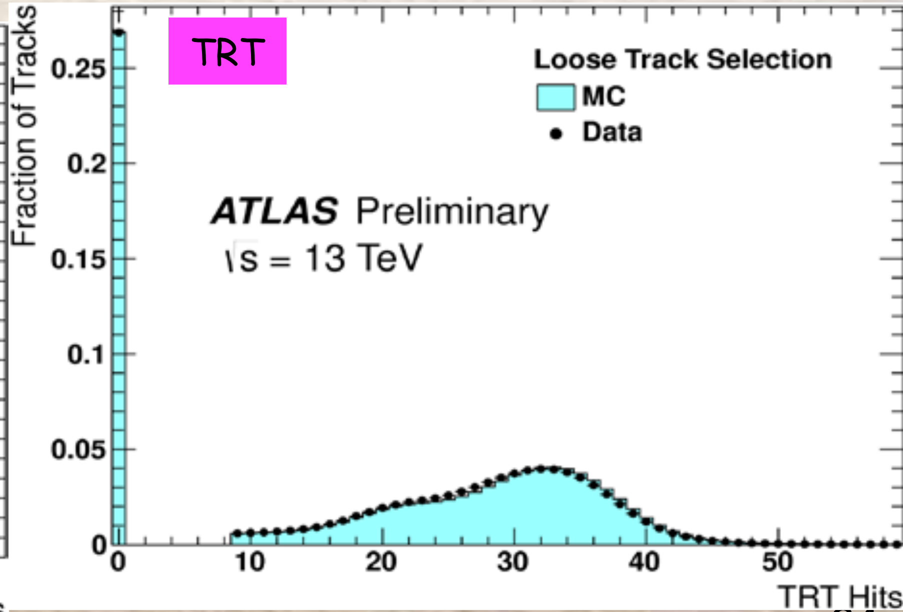
- Hit distributions in IBL, pixel, SCT and TRT

- IBL: <H>≈1
- Pixel: <H>≈4
- SCT: <H>≈8
- TRT: <H>≈32







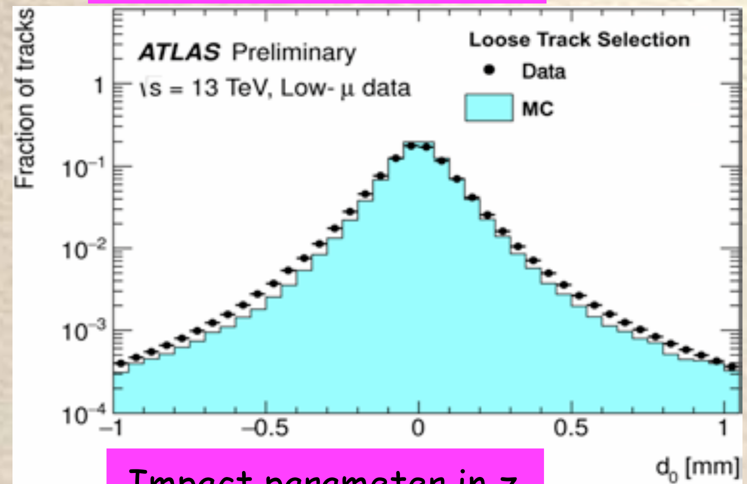


Tracking Performance

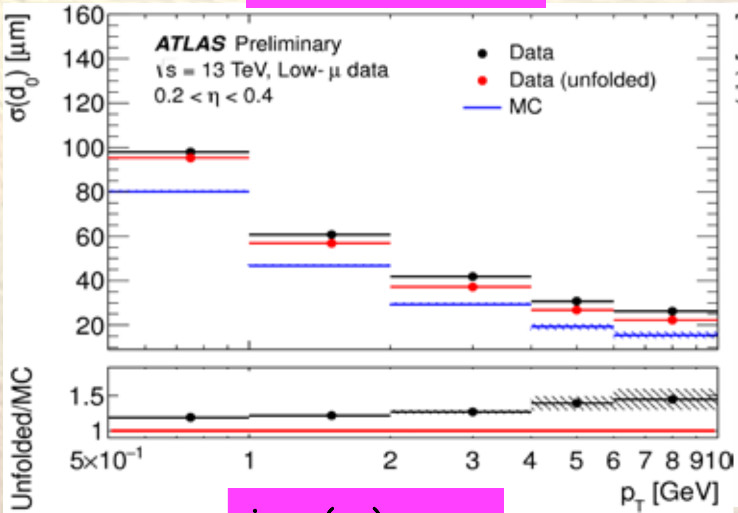
- Observed difference in impact parameter resolution is due material in the IBL not-accounted for in the simulation (mainly at low p_T)
- Additional misalignment effects

Impact parameter resolution

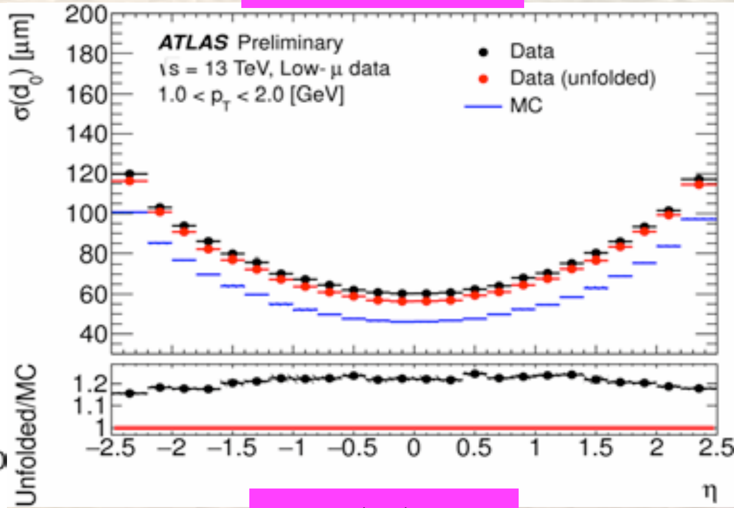
Impact parameter in xy



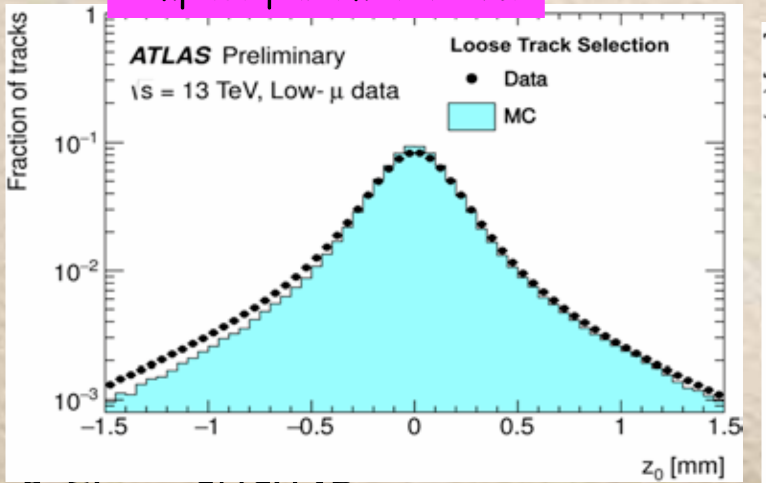
in xy (d_0) vs p_T



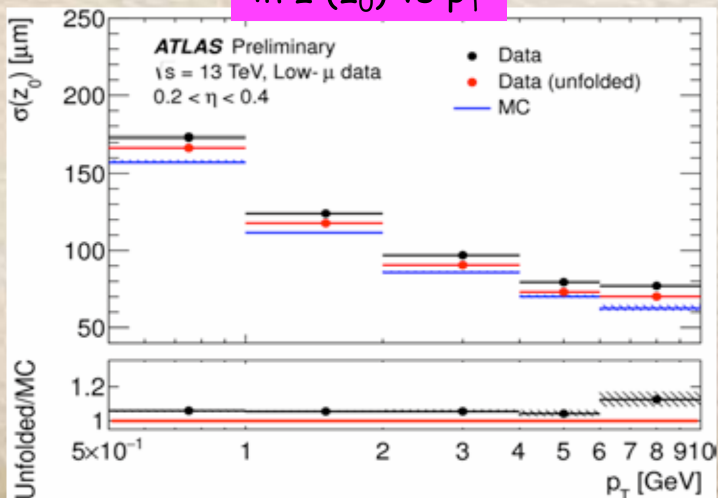
in xy (d_0) vs η



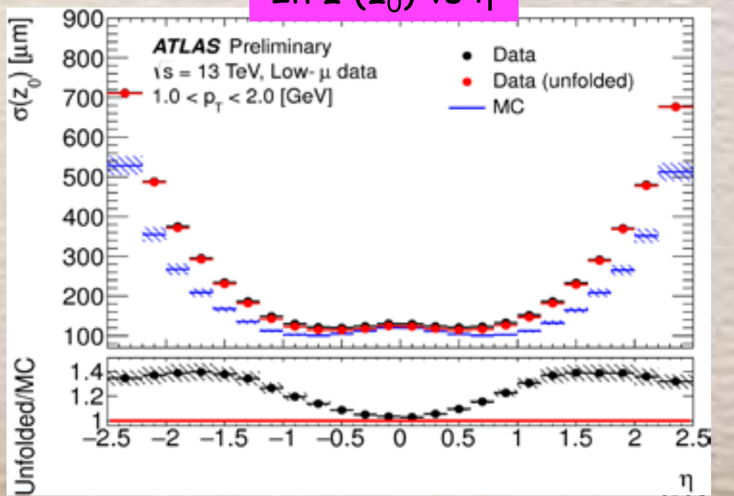
Impact parameter in z



in z (z_0) vs p_T



In z (z_0) vs η

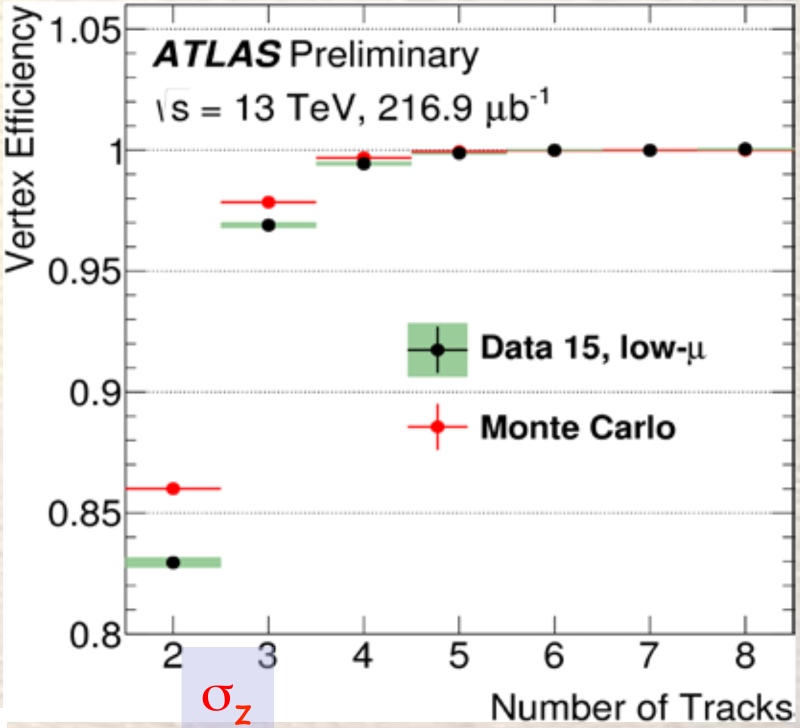


Vertexing Performance

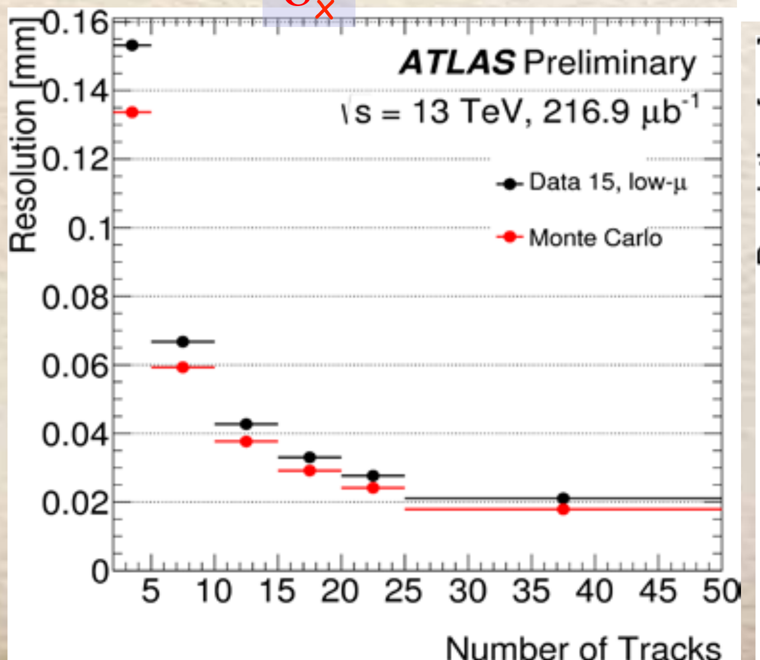
- Vertex reconstruction requires ≥2 tracks
- Apply scale factors to fitted vertex resolution in data that are derived using the split vertex method
- Assume that tracks originate from single interaction (no beam spot constraint)
- Determine scale factor from

$$pull_x = \frac{x_{1,PV} - x_{2,PV}}{\sqrt{\sigma^2_{x1,fit} + \sigma^2_{x2,fit}}}$$

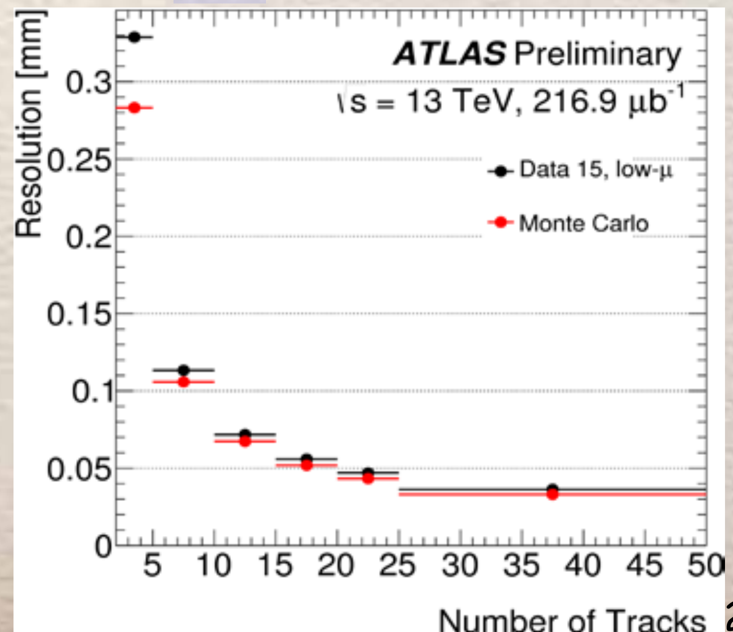
- Scaled resolutions are close to values in simulation



σ_x



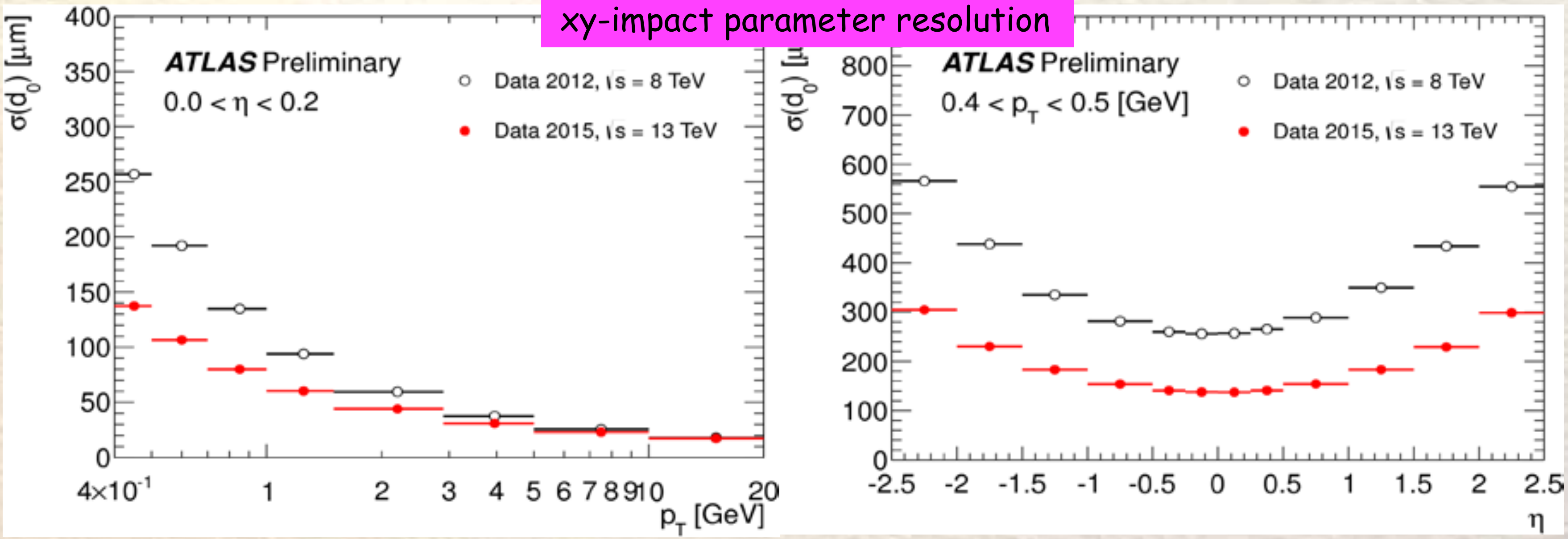
σ_z



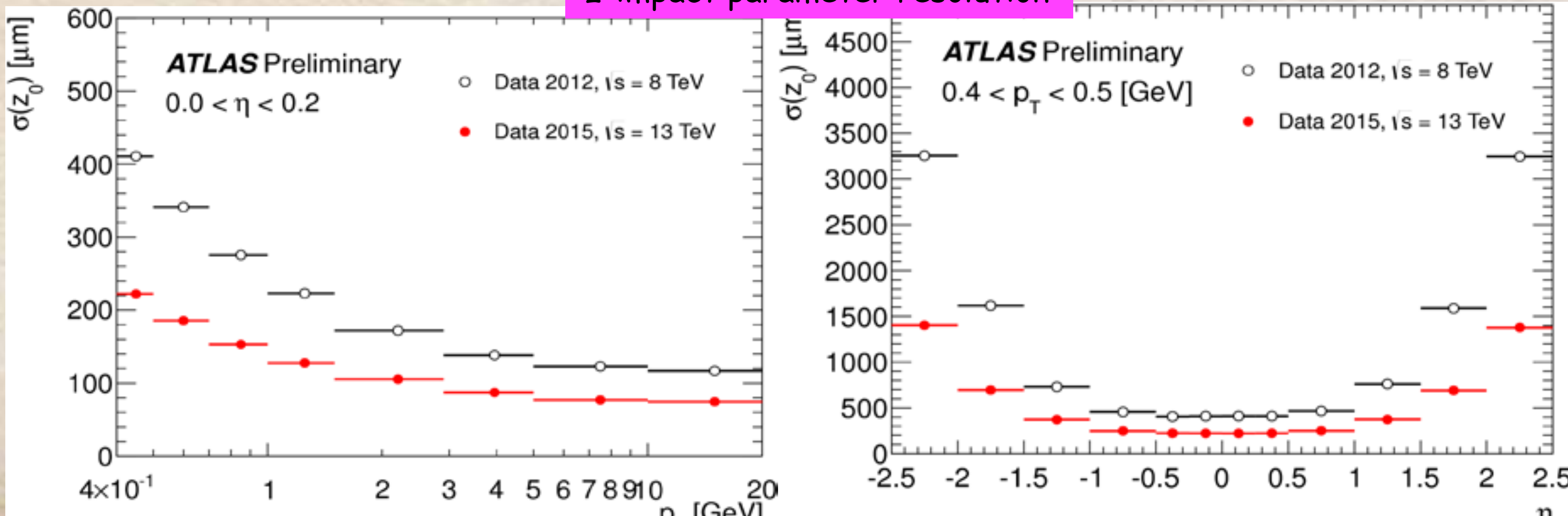
Impact Parameter Resolution

- With the IBL in place, the impact parameter resolution is improved considerably

xy-impact parameter resolution



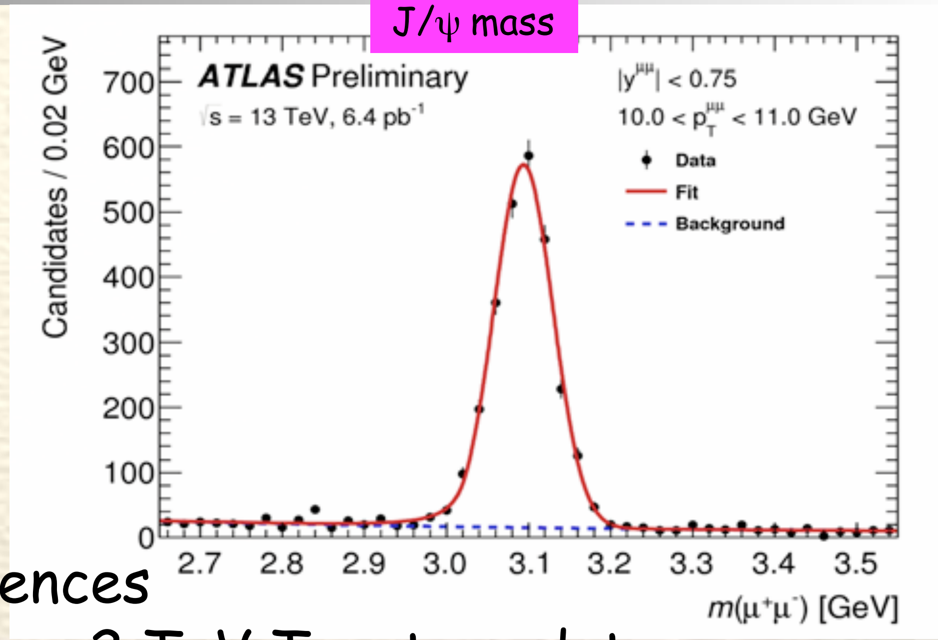
z-impact parameter resolution



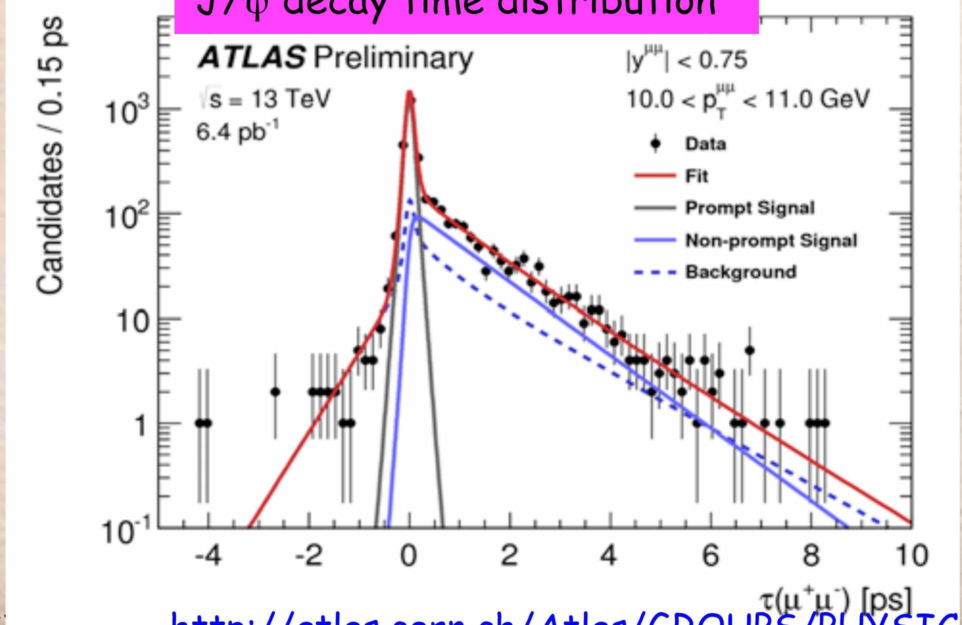
J/ψ Performance at 13 TeV

- Use 6.4 pb^{-1} pp collisions at 13 TeV
- Perform unbinned maximum-likelihood fit to $m_{\mu\mu}$ and lifetime spectra
- See no change in non-prompt J/ψ fraction between 7 and 13 TeV data
- Precision is high enough to observe differences between 13 TeV data & 7/8 TeV LHC data or 2 TeV Tevatron data

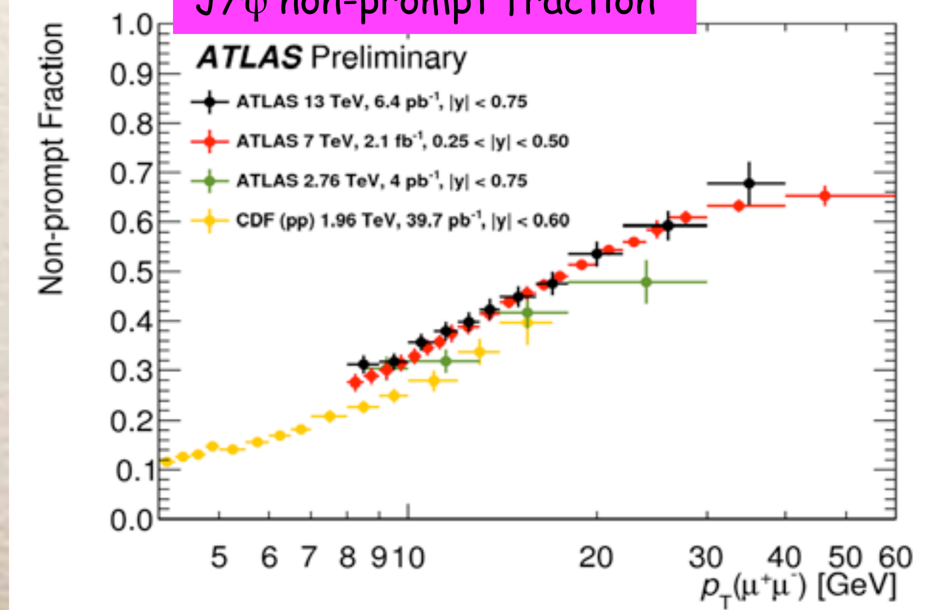
J/ψ mass



J/ψ decay time distribution



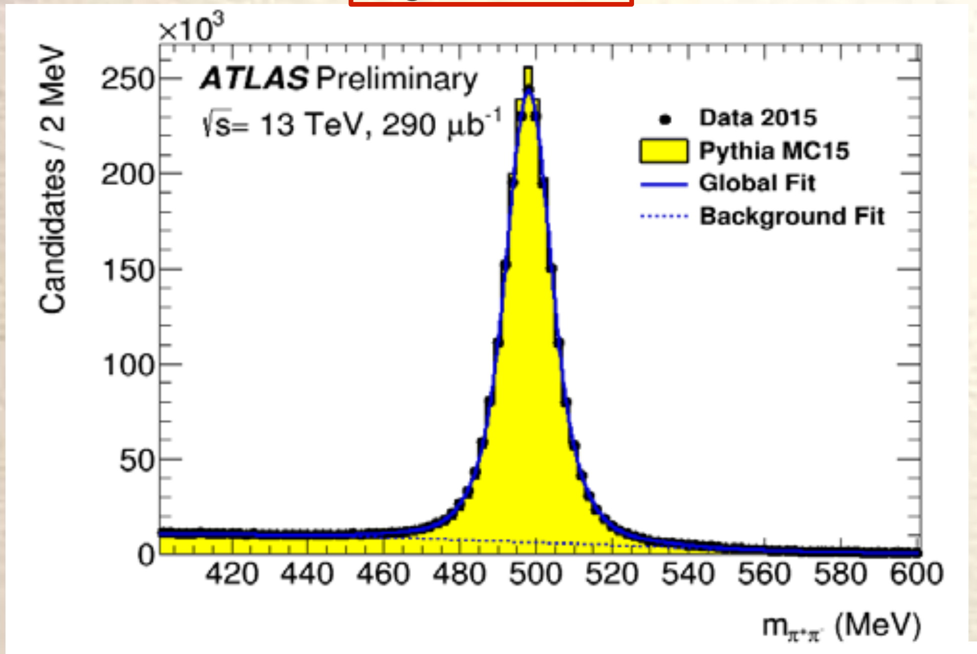
J/ψ non-prompt fraction



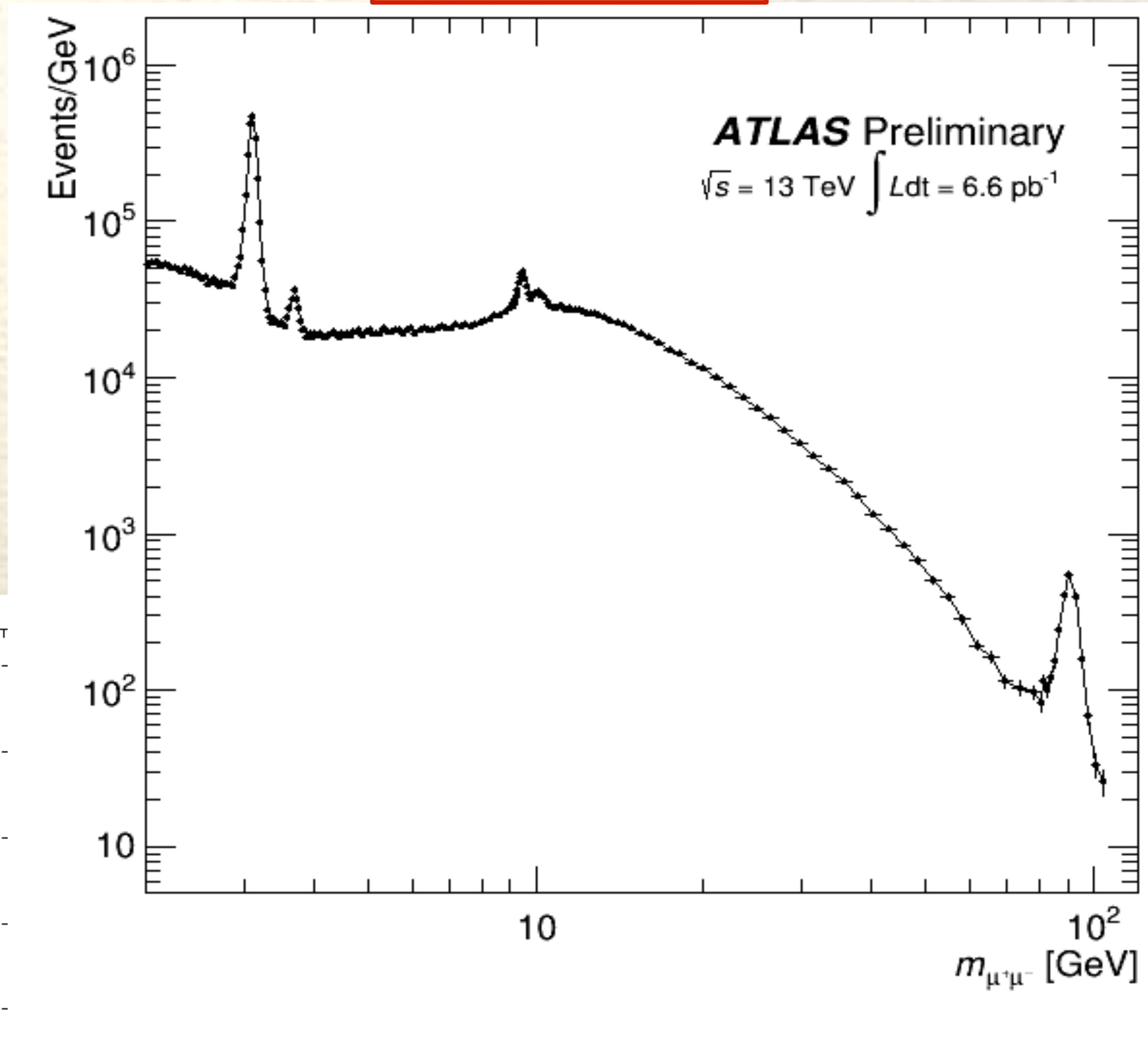
http://atlas.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2015-30/

Invariant-Mass Distributions

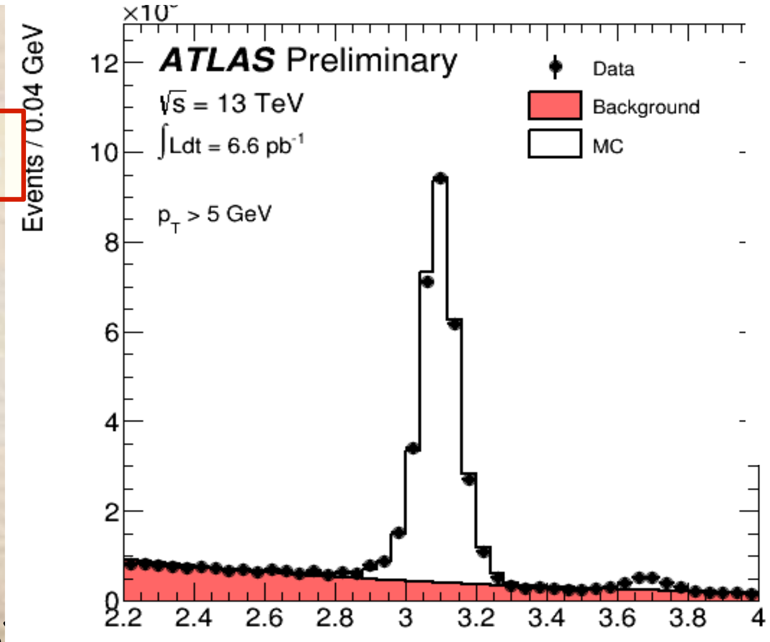
K^0_s mass



dimuon mass



J/ψ mass



Conclusions

- New ATLAS measurement of ϕ_s=-0.094±0.082$_{stat}$±0.033$_{sys}$ rad agrees with the SM prediction and with the results of CMS, LHCb, CDF and D0
- In run II, the uncertainty on ϕ_s will be reduced to ~0.054 rad and in the HL run it will improve to ~0.022 rad
- The ATLAS $B^0_{s,d}\to\mu^+\mu^-$ analysis is almost finalized
- ATLAS has measured f_s/f_d=0.240±0.004$_{stat}$± 0.013$_{sys}$±0.017$_{th}$
- The ATLAS detector is performing well in run II and is ready for new CP violation (ϕ_s, ..) and rare B decay measurements

Backup Slides

Signal PDF for $B^0_s \to J/\psi\phi$

- Factorize the signal and background PDFs

$$\mathcal{F}_s(m_i, t_i, \sigma_{t_i}, \Omega_i, \omega_i) = P_s(m_i) \cdot P_s(\Omega_i, t_i, \omega_i, \sigma_{t_i}) \cdot P_s(\sigma_{t_i}) \cdot P_s(\omega_i) \cdot A(\Omega_i, p_{T_i}) \cdot P_s(p_{T_i})$$

$$\mathcal{F}_{bkg}(m_i, t_i, \sigma_{t_i}, \Omega_i, \omega_i) = P_b(m_i) \cdot P_b(t_i | \sigma_{t_i}) \cdot P_b(\omega_i) \cdot P_b(\Omega_i) \cdot P_b(\sigma_{t_i}) \cdot P_b(p_{T_i})$$

- $P_s(m_i)$: 3 Gaussians
  $P_{s,b}(\sigma_{ti})$: Gamma function
  $P_{s,b}(p_{Ti})$: Gamma function
  $P_s(\omega_i)$: measured distributions for each of the 4 tagging categories
  $A(\Omega_i, p_{Ti})$: 4-d binned acceptance model
  $P_s(\Omega_i, t_i, \omega_i, \sigma_{ti})$: combined decay time and full angular distribution
  $P_b(t_i|s_{ti})$: Gaussian for prompt peak +2 positive & 1 negative exponentials
  $P_b(\Omega_i)$: parameterize by Legendre polynomials
  $P_b(m_i)$: exponential plus constant

- $\mathcal{F}_{B^0_d}$ accounts for (2.4±0.2)% misidentified B^0_d; PDF shapes from MC

PDF for Decay Distribution of $B^0_s \to J/\psi\phi$

- $P_s(\Omega_i, t_i, \sigma_{ti}, \omega_i)$ is a joint PDF of decay time and transversity angles

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

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

$B^0_s \to J/\psi\phi$ Fit Results for Run I

- Combine 2011 and 2012 results
- Correlation of Fit Parameters

	Value	Stat.	Syst.	Unit
ϕ_s	-0.094	0.083	0.033	rad
$\Delta\Gamma_s$	0.082	0.011	0.007	ps^{-1}
Γ_s	0.677	0.003	0.003	ps^{-1}
$\lvert A_{\parallel}(0)\rvert^2$	0.227	0.004	0.006	
$\lvert A_0(0)\rvert^2$	0.515	0.004	0.002	
$\lvert A_S(0)\rvert^2$	0.086	0.007	0.012	
$\delta_{\parallel}$	4.13	0.34	0.15	rad
$\delta_{\perp}$	3.16	0.13	0.05	rad
$\delta_{\perp} - \delta_S$	-0.08	0.03	0.01	rad

	ϕ_s	Γ	Γ_s	$\lvert\ _{\parallel}(0)\rvert^2$	$\lvert\ _0(0)\rvert^2$	$\lvert\ _S(0)\rvert^2$	$\delta_{\parallel}$	$\delta_{\perp}$	$\delta_{\perp} - \delta_S$
ϕ_s	1.000	0.110	-0.097	0.043	0.030	0.046	0.093	0.034	-0.001
Γ		1.000	-0.421	0.104	0.139	0.051	0.021	0.012	-0.011
Γ_s			1.000	-0.124	-0.047	0.156	-0.051	-0.017	0.019
$\lvert\ _{\parallel}(0)\rvert^2$				1.000	-0.33	0.056	0.201	0.058	-0.019
$\lvert\ _0(0)\rvert^2$					1.000	0.216	-0.019	0.004	0.014
$\lvert\ _S(0)\rvert^2$						1.000	-0.094	-0.012	0.055
$\delta_{\parallel}$							1.000	0.235	-0.014
$\delta_{\perp}$								1.000	0.010
$\delta_{\perp} - \delta_S$									1.000