Measurement of the B^0 width difference with the ATLAS detector

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Motivation

- The relative value of $\Delta\Gamma_d/\Gamma_d$ is reliably predicted in the Standard Model (arXiv: 1102.4274 [hep-ph]):

$$\Delta\Gamma_d/\Gamma_d = (0.42 \pm 0.08) \times 10^{-2}$$

- It has been shown (arXiv: 1404.2531 [hep-ph]) that a relatively large variation of $\Delta\Gamma_d$ due to a possible new physics contribution would not contradict other existing SM results.

- A precise measurement of $\Delta\Gamma_d$ would therefore provide a stringent test of the underlying theory, complementary to other searches.

- The current experimental uncertainty on $\Delta\Gamma_d$ is much larger than the SM central value, preventing a meaningful test of the SM prediction.

- Furthermore, the measurements of $\Delta\Gamma_d$ made by Belle (arXiv: 1203.0930 [hep-ex]) and LHCb (arXiv: 1402.2554 [hep-ex]) differ by more than 1.5σ, which introduces a controversy in the experimental result.

- Therefore, more precise measurements of $\Delta\Gamma_d$ are needed to establish its value and perform an important test of the SM.

Measurement method

- The decay rate of the light and heavy mass eigenstates (B_d^L and B_d^H) to a given final f state can be different. Therefore the time dependence of the decay rate of $B^0 \to f$ is sensitive to f.

- The untagged time-dependant decay rate of a B^0 meson into final state f is given by:

$$\Gamma(f,t) \propto e^{-\Gamma_d t}\left[\cosh\frac{\Delta\Gamma_d t}{2} + A_p A_{CP}^{dir}\cos(\Delta m_d t) + A_{\Delta\Gamma}\sinh\frac{\Delta\Gamma_d t}{2} + A_p A_{CP}^{mix}\sin(\Delta m_d t)\right]$$

- The final states we consider are J/ψ K_S and J/ψ K^{*0}. The J/ψ is reconstructed using the decay J/ψ $\to \mu^+\mu^-$. The K_S and K^{*0} are reconstructed using the $K_S \to \pi^+\pi^-$ and $K^{*0} \to K^+\pi^-$ decay modes.

- For the J/ψ K^{*0} channel, $A_{CP}^{dir} = \pm 1, A_{\Delta\Gamma} = 0, A_{CP}^{mix} = 0$.

- For the J/ψ K_S channel, $A_{CP}^{dir} = 0, A_{\Delta\Gamma} = \cos 2\beta,\ A_{CP}^{mix} = -\sin 2\beta$, where β is the Unitarity Triangle angle measured as $\sin 2\beta = 0.679 \pm 0.020$.

- A_p is the production asymmetry of B^0 and $\overline{B^0}$: $A_p = \frac{\sigma(B^0)-\sigma(\overline{B^0})}{\sigma(B^0)+\sigma(\overline{B^0})}$

Measurement method

- The value of $\Delta\Gamma_d$ can be determined by measuring the experimental ratio of proper decay lengths L^B_{prop} of the two channels:

$$R\left(L^B_{prop}\right) = \frac{N(B^0 \rightarrow \mathrm{J}/\psi\ K_S, L^B_{prop})}{N(B^0 \rightarrow \mathrm{J}/\psi\ K^{*0}, L^B_{prop})}$$

where $N(B^0 \rightarrow \mathrm{J}/\psi\ K_S, L^B_{prop})$ and $N(B^0 \rightarrow \mathrm{J}/\psi\ K^{*0}, L^B_{prop})$ are the number of reconstructed B^0 decays to the specified final state as a function of L^B_{prop}.

- The predicted decay rate as a function of L^B_{prop} for the decay $B^0 \rightarrow f$ is:

$$\Gamma\left(f, L^B_{prop}\right) = \int_0^{\infty} G(\,L^B_{prop} - ct, f)\Gamma(f, t)\, dt$$

- $G(L^B_{prop} - ct, f)$ is the function describing the resolution of L^B_{prop} for a given channel f.

- $R\left(L^B_{prop}\right)$ is dependent on $\Delta\Gamma_d$ which can therefore be measured by fitting $R\left(L^B_{prop}\right)$ using the predicted decay rates of the $\mathrm{J}/\psi\ K_S$ and $\mathrm{J}/\psi\ K^{*0}$ channels.

Measurement of B^0 proper decay length

- The technique used to measure the proper decay length (L^B_{prop}) is designed to use the same input information for both the $B^0 \to J/\psi\, K_S$ and $B^0 \to J/\psi\, K^{*0}$ channels. This reduces the experimental bias in $R\left(L^B_{prop}\right)$.

- The origin of the B^0 (x^{PV}, y^{PV}) is measured using a PV fit in which the decay products of the B^0 are removed. The primary vertex which has the smallest $|\delta z|$ relative to the B^0 trajectory is selected as the PV of B^0 production.

- The position of the B^0 decay is defined by the J/ψ decay vertex $(x^{J/\psi}, y^{J/\psi})$, which is constructed from the vertex fit of the two muons.

- For each reconstructed $B^0 \to J/\psi\, K_S$ and $B^0 \to J/\psi\, K^{*0}$ candidate, we construct the proper decay length L^B_{prop}, defined as:

$$L^B_{prop} = \frac{\left(x^{J/\psi} - x^{PV}\right)p^B_{T,x} + \left(y^{J/\psi} - y^{PV}\right)p^B_{T,y}}{(p^B_T)^2} m_{B^0}$$

Measurement of B^0 proper decay length

- The proper decay length distribution is obtained by first dividing the range of L^B_{prop} between -0.3 and 6.0 mm into ten bins defined below:

Bin number	1	2	3	4	5	6	7	8	9	10
Lower edge [mm]	-0.3	0.0	0.3	0.6	0.9	1.2	1.5	1.8	2.1	3.0
Upper edge [mm]	0.0	0.3	0.6	0.9	1.2	1.5	1.8	2.1	3.0	6.0

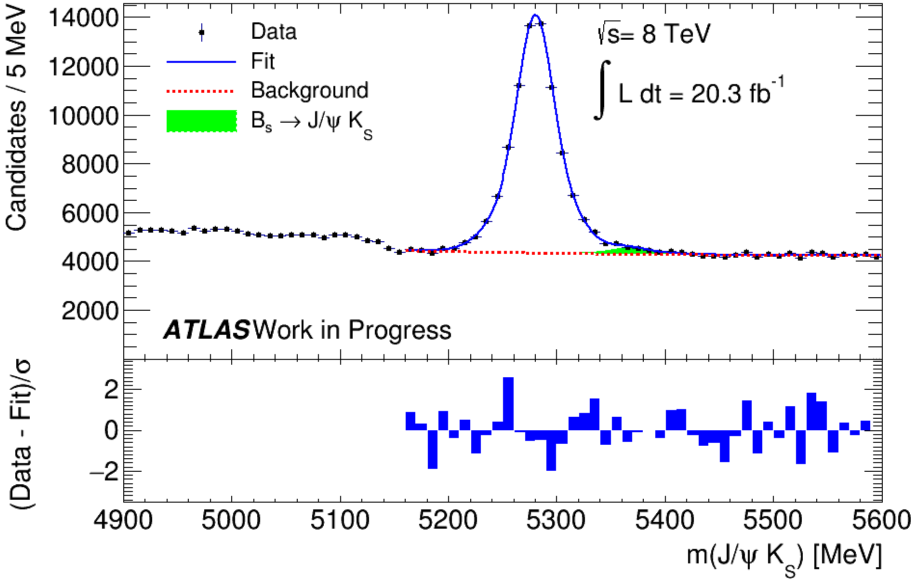
- In each bin, distributions of the invariant mass of J/ψ K_S and J/ψ K^{*0} are produced and the number of signal $B^0 \rightarrow$ J/ψ K_S and $B^0 \rightarrow$ J/ψ K^{*0} in each bin is determined by a fit to these distributions.

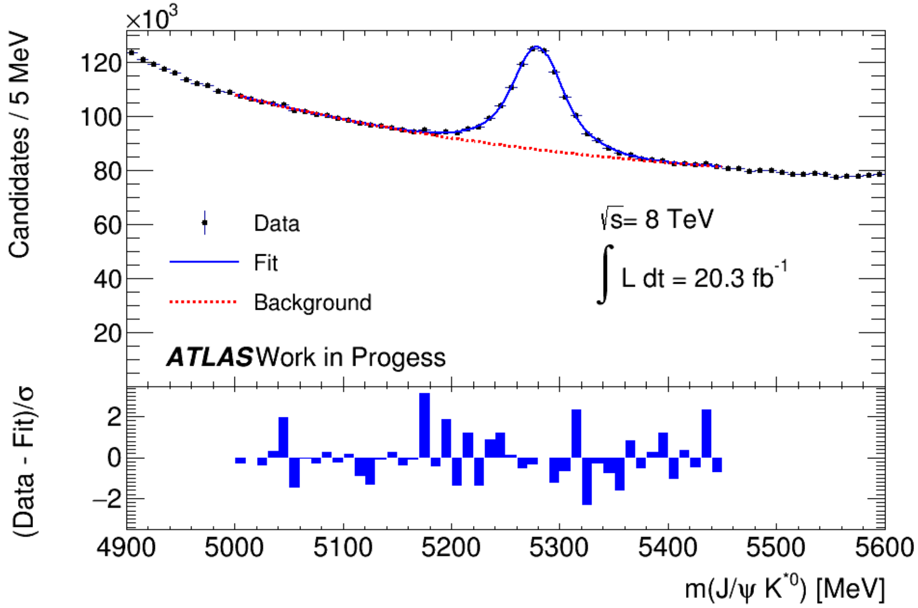
- For the $B^0 \rightarrow$ J/ψ K^{*0}, the signal is modelled as the sum of two Gaussian functions. The background is modelled using an exponential of the form $e^{-a-bx-cx^2}$.

- For the $B^0 \rightarrow$ J/ψ K_S, the signal is modelled as the sum of two Gaussian functions. The background is modelled in two parts. First, the contribution from $B_s \rightarrow$ J/ψ K_S decays is modelled by two Gaussian functions. Second, the combinatorial background is modelled by an exponential of the form $e^{-a-bx-cx^2}$.

Measurement of B^0 proper decay length

- E.g. in the bin $0.0 < L_{prop}^{B} < 0.3$ mm:





- In each bin of L_{prop}^{B}, the number of signal events and its statistical uncertainty are extracted from the fit.

- The ratio of the number of B^0 candidates in the two channels in each L_{prop}^{B} bin gives the experimental ratio $R_{i,uncor}\left(L_{prop}^{B}\right)$:

$$R_{i,uncor}\left(L_{prop}^{B}\right) = \frac{N_i(J/\psi\ K_S)}{N_i(J/\psi\ K^{*0})}$$

Ratio of reconstruction efficiencies

- The experimental ratio $R_{uncor}\left(L^B_{prop}\right)$ must be corrected to account for the difference in the reconstruction efficiencies of the $B^0 \rightarrow$ J/ψ K_S and $B^0 \rightarrow$ J/ψ K^{*0} channels.

- The difference in reconstruction efficiencies exists because the hadronic tracks in the $B^0 \rightarrow$ J/ψ K_S decay come from a displaced $K_s \rightarrow \pi\pi$ vertex, while all 4 tracks from the $B^0 \rightarrow$ J/ψ K^{*0} decay come from a single vertex.

- This difference is the largest source of experimental bias in $R_{uncor}\left(L^B_{prop}\right)$ and it can be assessed only with MC.

- We therefore measure the ratio of reconstruction efficiencies in MC defined as:

$$R_{i,eff}\left(L^B_{prop}\right) = \frac{\varepsilon_i(B^0 \rightarrow J/\psi\, K_s, L^B_{prop})}{\varepsilon_i(B^0 \rightarrow J/\psi\, K^{0*}, L^B_{prop})}$$

- $R_{i,uncor}\left(L^B_{prop}\right)$ is then divided by $R_{i,eff}\left(L^B_{prop}\right)$ to obtain the corrected ratio $R_{i,cor}\left(L^B_{prop}\right)$.

Fit to obtain $\Delta\Gamma_d/\Gamma_d$

- For each bin *i* of L^B_{prop}, the expected number of events in each channel is given by:

$$N_i(B^0 \to J/\psi\, K_S, \Delta\Gamma_d/\Gamma_d) = C_1 \int_{L_i^{min}}^{L_i^{max}} \Gamma\left(J/\psi\, K_S, L^B_{prop}\right)\, dL^B_{prop}$$

$$N_i(B^0 \to J/\psi\, K^{*0}, \Delta\Gamma_d/\Gamma_d) = C_2 \int_{L_i^{min}}^{L_i^{max}} \Gamma\left(J/\psi\, K^{*0}, L^B_{prop}\right)\, dL^B_{prop}$$

where L_i^{min} and L_i^{max} are the lower and upper bin edges of the given bin *i*.

- The sensitivity to $\Delta\Gamma_d$ comes from $\Gamma\left(J/\psi\, K_S, L^B_{prop}\right)$ while $\Gamma\left(J/\psi\, K^{*0}, L^B_{prop}\right)$ provides the normalization.

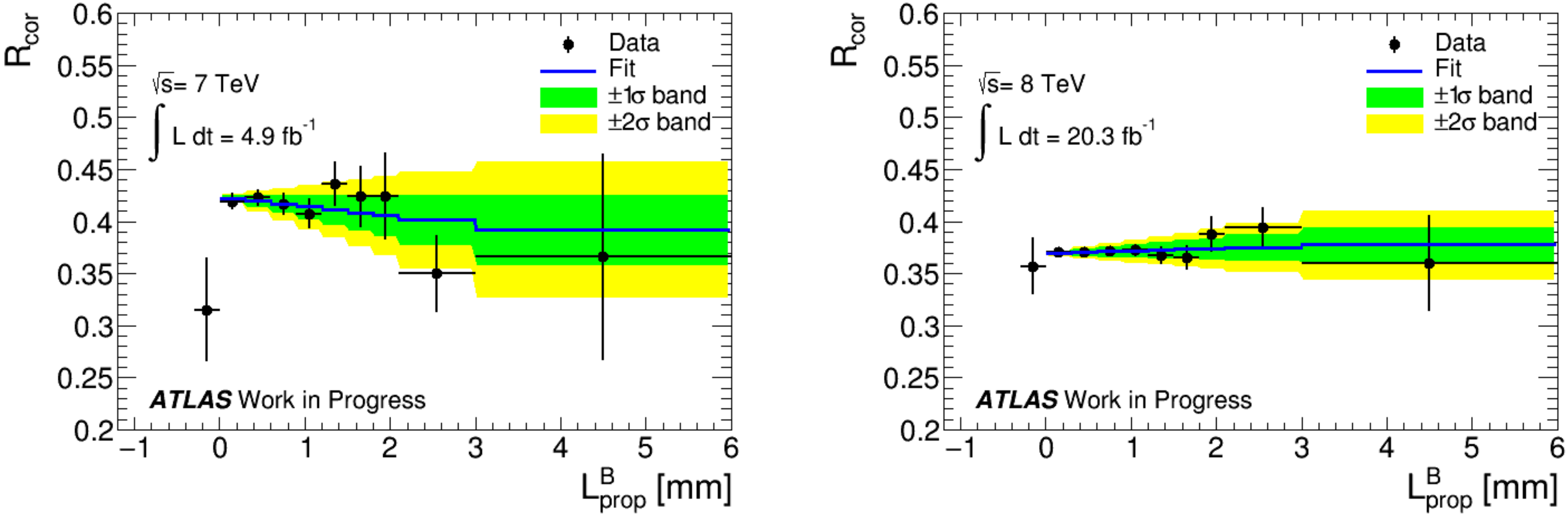
- The expected ratio of decay rates in bin *i* is then:

$$R_{i,exp}(\Delta\Gamma_d/\Gamma_d) = \frac{N_i(B^0 \to J/\psi\, K_S, \Delta\Gamma_d/\Gamma_d)}{N_i(B^0 \to J/\psi\, K^{*0}, \Delta\Gamma_d/\Gamma_d)}$$

- The corrected ratio $R_{i,cor}(L^B_{prop})$ is fitted using $R_{i,exp}(\Delta\Gamma_d/\Gamma_d)$ and the value of $\Delta\Gamma_d/\Gamma_d$ is obtained from the χ^2 minimization of:

$$\chi^2(\Delta\Gamma_d/\Gamma_d) = \sum_{i=2}^{10} \frac{\left(R_{i,cor} - R_{i,exp}(\Delta\Gamma_d/\Gamma_d)\right)^2}{\sigma_i^2}$$

Fit to obtain $\Delta\Gamma_d/\Gamma_d$



- The fit has $\chi^2/ndf = 4.34/7$ in 2011 and $\chi^2/ndf = 2.81/7$, which demonstrates that the fit describes the data very well.

- Two separate results for the 2011 and 2012 datasets:

$$\Delta\Gamma_d/\Gamma_d = (-2.8 \pm 2.2(stat.) \pm 1.5(MC\ stat.)) \times 10^{-2}\ [2011]$$ ***ATLAS*** Work in Progress

$$\Delta\Gamma_d/\Gamma_d = (+0.8 \pm 1.3(stat.) \pm 0.5(MC\ stat.)) \times 10^{-2}\ [2012]$$ ***ATLAS*** Work in Progress

Systematic uncertainties

- The procedure used to extract the L^{B}_{prop} distribution is designed explicitly to be similar for both the $B^0 \rightarrow J/\psi\ K_S$ and $B^0 \rightarrow J/\psi\ K^{*0}$ channels. Therefore, many systematics such as trigger selection, decay-time resolution or B^0 production properties cancel when the ratio $R\left(L^{B}_{prop}\right)$ is made.

- However, some differences between the two channels cannot be eliminated and their systematic impact must be estimated.

- The following table shows the considered sources of systematic uncertainty and their values.

Source	$\delta(\Delta\Gamma_d/\Gamma_d)$, 2011	$\delta(\Delta\Gamma_d/\Gamma_d)$, 2012
K_S decay length	0.21×10^{-2}	0.16×10^{-2}
K_S pseudorapidity	0.14×10^{-2}	0.01×10^{-2}
$B^0 \rightarrow J/\psi K_S$ mass range	0.47×10^{-2}	0.59×10^{-2}
$B^0 \rightarrow J/\psi K^{*0}$ mass range	0.30×10^{-2}	0.15×10^{-2}
Background description	0.16×10^{-2}	0.09×10^{-2}
$B_s^0 \rightarrow J/\psi K_S$ contribution	0.11×10^{-2}	0.08×10^{-2}
L^{B}_{prop} resolution	0.29×10^{-2}	0.29×10^{-2}
Fit bias (Toy MC)	0.07×10^{-2}	0.07×10^{-2}
B^0 production asymmetry	0.01×10^{-2}	0.01×10^{-2}
MC statistics	1.54×10^{-2}	0.45×10^{-2}
Total uncertainty	1.69×10^{-2}	0.84×10^{-2}

ATLAS Work in Progress

Results and conclusion

- The measurements of $\Delta\Gamma_d/\Gamma_d$ with statistical and systematic uncertainties are:

$$\Delta\Gamma_d/\Gamma_d = \left(-2.8 \pm 2.2(stat.) \pm 1.7(syst.)\right) \times 10^{-2} \quad [2011]$$ **ATLAS** Work in Progress

$$\Delta\Gamma_d/\Gamma_d = \left(+0.8 \pm 1.3(stat.) \pm 0.8(syst.)\right) \times 10^{-2} \quad [2012]$$ **ATLAS** Work in Progress

- The results from the two years are consistent. We therefore combine the two measurements, taking into account any correlation of sources of systematics between the two years.

- The combined result for the statistics collected by the ATLAS detector in Run I is then:

$$\Delta\Gamma_d/\Gamma_d = (-0.1 \pm 1.4) \times 10^{-2}$$

- It is in agreement with the standard model standard model prediction of:

$$\Delta\Gamma_d/\Gamma_d = (0.42 \pm 0.08) \times 10^{-2}$$

- It is also consistent with other measurements at other experiments performed by BaBar, Belle and LHCb.

- An important by-product of this analysis is the measurement of the B^0 production asymmetry in the region $|\eta(B^0)| < 2.5$:

$$A_p = (+0.25 \pm 0.48 \ \pm 0.05) \times 10^{-2}$$ **ATLAS** Work in Progress

- This is the first measurement of the quantity in ATLAS and it is consistent with the LHCb measurement in the region $2.5 < |\eta(B^0)| < 4.0$.

Backup Slides

Production asymmetry

- The B^0 production asymmetry A_P can be measured from the charge asymmetry of the $B^0 \to \mathrm{J}/\psi\, K^{*0}$ decay which is measured in each bin of L^B_{prop}:

$$A_{i,obs} = \frac{N(\mathrm{J}/\psi\, K^{*0}, i) - N\left(\mathrm{J}/\psi\, \overline{K^{*0}}, i\right)}{N(\mathrm{J}/\psi\, K^{*0}, i) + N\left(\mathrm{J}/\psi\, \overline{K^{*0}}, i\right)}$$

- $N\left(\mathrm{J}/\psi\, \overline{K^{*0}}, i\right)$ is the observed number of $\mathrm{J}/\psi\, \overline{K^{*0}}$ decays. It includes genuine $\overline{B^0} \to \mathrm{J}/\psi\, \overline{K^{*0}}$ and $B^0 \to \mathrm{J}/\psi\, K^{*0}$ decays. The contribution of $B^0 \to \mathrm{J}/\psi\, K^{*0}$ decays is due to a mis-assignment of the kaon and pion masses to the charged tracks.

- Likewise, $N(\mathrm{J}/\psi\, K^{*0}, i)$ consists of both $B^0 \to \mathrm{J}/\psi\, K^{*0}$ and $\overline{B^0} \to \mathrm{J}/\psi\, \overline{K^{*0}}$ decays.

- The mistag fraction W quantifies the fraction of true $B^0 \to \mathrm{J}/\psi\, K^{*0}$ in $N\left(\mathrm{J}/\psi\, \overline{K^{*0}}, i\right)$. W does not depend on B^0 lifetime. Using MC, we obtain a value of $W = 0.12 \pm 0.02$.

- The mistag fraction is found to be the same for $\overline{B^0} \to \mathrm{J}/\psi\, \overline{K^{*0}}$ and $B^0 \to \mathrm{J}/\psi\, K^{*0}$ decays.

Production asymmetry

- The expected asymmetry in bin i of L^B_{prop} is given by:

$$A_{i,exp} = (A_{det} + A_{i,osc})(1 - 2W)$$

- A_{det} is the detector asymmetry, which is mainly due to the difference in the interaction cross-sections of K^+ and K^-, and does not depend on the B^0 lifetime.

- $A_{i,osc}$ is the asymmetry due to B^0 oscillations and the factor $(1 - 2W)$ accounts for incorrectly identified B^0 decays.

- The time dependent decay rates of the decays $B^0 \to J/\psi\, K^{*0}$ and $\overline{B^0} \to J/\psi\, \overline{K^{*0}}$ are given by, respectively:

$$\Gamma(J/\psi\, K^{*0}, t) \propto e^{-\Gamma_d t}\left[\cosh\frac{\Delta\Gamma_d t}{2} - A_p \sin(\Delta m_d t)\right]$$

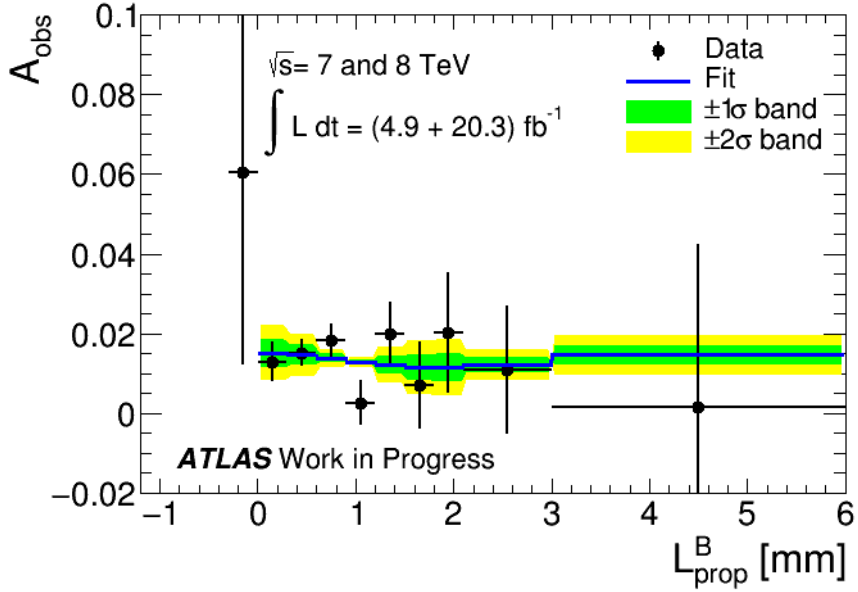
$$\Gamma\left(J/\psi\, \overline{K^{*0}}, t\right) \propto e^{-\Gamma_d t}\left[\cosh\frac{\Delta\Gamma_d t}{2} + A_p \sin(\Delta m_d t)\right]$$

- $A_{i,osc}$ is obtained by convoluting the decay rates with the detector resolution $G(L^B_{prop} - ct, J/\psi\, K^{*0})$ and then integrating over the range of bin i.

- The measured charge asymmetry $A_{i,obs}$ is fitted using $A_{i,exp}$ and the production asymmetry A_P is obtained from the χ^2 minimization of:

$$\chi^2(A_{det}, A_P) = \sum_{i=2}^{10} \frac{\left(A_{i,obs} - A_{i,exp}\right)^2}{\sigma_i^2}$$

Production asymmetry



- From the fit we obtain:

$$A_{det} = (+1.33 \pm 0.24 \ \pm 0.22) \times 10^{-2}$$ **ATLAS** Work in Progress

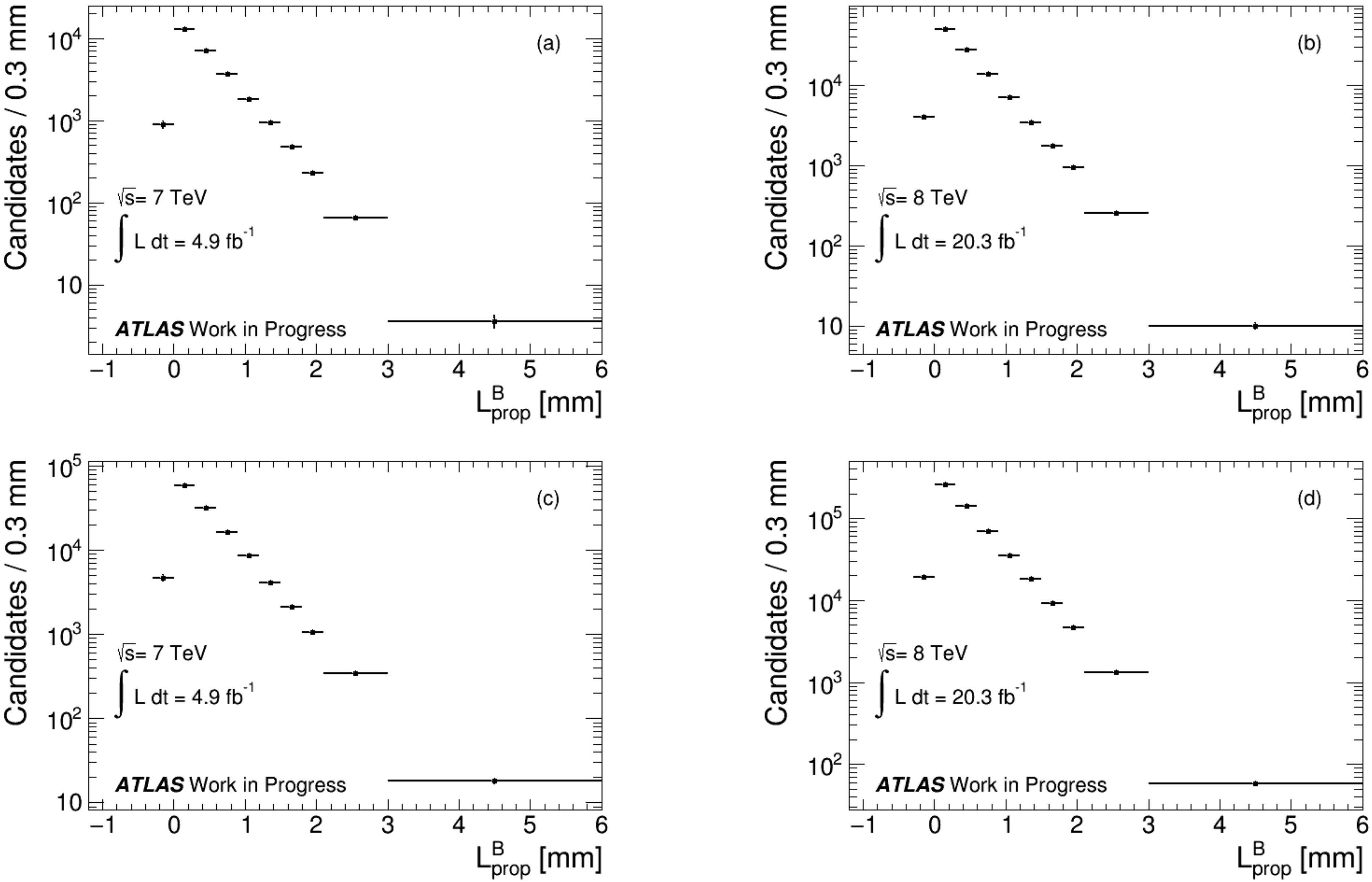
$$A_p = (+0.25 \pm 0.48 \ \pm 0.05) \times 10^{-2}$$ **ATLAS** Work in Progress

- The uncertainties are due to statistical limitations and the uncertainty in the mistag fraction.

- This is the first measurement of the B^0 production asymmetry by ATLAS in the central η region ($|\eta(B^0)| < 2.5$). The result is consistent with and more precise than the current LHCb measurement for the region $2.5 < |\eta(B^0)| < 4.0$:

$$A_p = (-0.36 \pm 0.76 \ \pm 0.28) \times 10^{-2}$$

L_{prop}^{B} distributions



Ratio of efficiencies