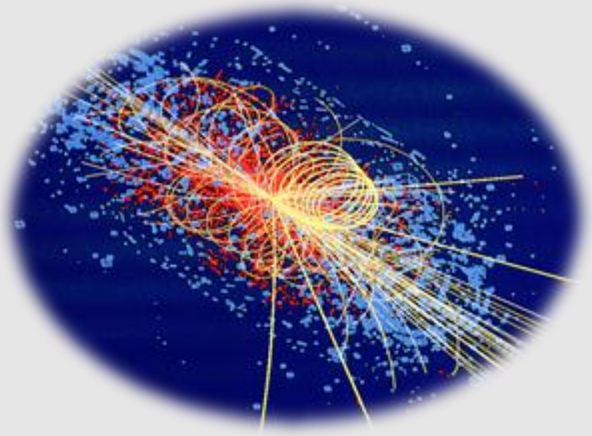


A Precise Measurement of the Lifetime of B_{d}^{0}-mesons, Measurement of the CP-violating Parameters of B_{s}^{0}-mesons, the ATLAS Experiment at the LHC, and Development of Silicon Detectors for Future Particle Physics Experiments

Easwar Anand Narayanan

September 5th, 2024

University of Washington Seminar

My Ph.D. Research Projects

My Ph.D. research projects can be divided into four topics:

- Precision measurements using ATLAS data
- Preparation of ATLAS Run 3 High Level Triggers for B-Physics
- Simulation of radiation induced damage effects in silicon sensors
- Development/Construction of ATLAS Inner Tracker Pixel

Analysis

Simulation

Detectors

Roughly 80% of my PhD work involved data analysis and simulation

My main analysis topic is measurement of the lifetime of B_{d}^{0}-mesons. The analysis is currently undergoing internal ATLAS review and is expected to be published by the end of this year. My main contributions are related to the triggers and their efficiencies (Aug 2020 to Dec 2023)

Heavy Quark Expansion and Lifetimes of *B*-Mesons

- *B*-mesons have long lifetimes compared to other heavy particles due to the heavy *b*-quark
- Lifetimes follow this hierarchy[1]: $\tau_{B^{\pm}} > \tau_{B_s^0} \sim \tau_{B_d^0} > \tau_{B_c^{\pm}}$
- Long lifetime and hierarchy can be explained by using QCD inspired Heavy Quark Expansion (HQE) model[2]

$$\Gamma = \Gamma_0 \left[a_0 + a_2 \left(\frac{\Lambda_{\mathrm{QCD}}}{m_{\mathrm{b}}} \right)^2 + a_3 \left(\frac{\Lambda_{\mathrm{QCD}}}{m_{\mathrm{b}}} \right)^3 + .. \right],\ \text{where}$$

Λ_{QCD} - QCD energy scale
m_{b} - mass of *b*-quark
a_{i} - calculable coefficients

- Decay width solely due to *b*-quark (spectator model where all *B*-meson species have same lifetime)
- Responsible for heavy and light quark spin interactions
- Explains the lifetime differences between baryons and mesons
- Responsible for spectator quark effects – weak annihilation and Pauli interference. Explains the lifetime differences between all *B*-meson species

Precise *B*-meson lifetime measurements

- Test and constrain the HQE model
- Extraction of CKM parameters

---

1. A. Lenz, Lifetimes and HQE, Int. J. Mod. Phys. A 30 (2015) 1543005, arxiv: 1405.3601 [hep-ph]
2. M. Kirk et al., Dimension-six matrix elements for meson mixing and lifetimes with sum rules, JHEP 12 (2017) 068, arxiv: 1711.02100 [hep-ph]

Decay Channel for B_{d}^0 and Current Measurements

- Measurements of lifetimes of *b*-hadrons have been reported by a variety of experiments[1-5]

- The decay channel - $B_{\mathrm{d}}^0 \to J/\psi(\to \mu^+\mu^-)K^{*0}(\to K^+\pi^-)$ is selected
  - due to their high branching ratio => large statistical samples
  - Further, these are useful in *CPV* studies in $B_{\mathrm{s}}^0 \to J/\psi(\to \mu^+\mu^-)\phi(\to K^+K^-)$:
    - $B_{\mathrm{d}}^0 \to J/\psi K^{*0}$ decays occur as a prominent background in $B_s^0 \to J/\psi\phi$ decays. Fundamental properties like mass and lifetime of B_{d}^0 meson are needed to separate B_s^0 signal from B_{d}^0 background;
    - Large statistical samples => calibration of dimuon triggers used in all *B*-Physics

- Statistical precision of B_{d}^0 lifetime over the previous ATLAS result[6] using Run 1 (4.9 fb^{-1}) will be improved by a factor of about 5.3

- Ratio of decay widths ${}^{\Gamma_{\mathrm{d}}}/_{\Gamma_{\mathrm{s}}}$ will be also measured using the Γ_{s} that was measured[7] using the ATLAS data collected from 2015 to 2017. This value has been predicted by the HQE[8] and Lattice QCD[9]

---

1. LHCb Collaboration, Measurements of the B^+, B^0, B_s^0 meson and Λ_b^0 baryon lifetimes, JHEP 04 (2014) 114, arxiv: 1402.2554 [hep-ex]
2. LHCb Collaboration, Effective lifetime measurements in the $B_s^0 \to K^+K^-$, $B^0 \to K^+\pi^-$ and $B_s^0 \to \pi^+K^-$ decays, Phys.Lett.B736 (2014) 446-454, arxiv: 1406.7204 [hep-ex]
3. ATLAS Collaboration, Measurement of the B_d^0 and B_s^0 lifetimes in the decay modes $B_{\mathrm{d}}^0 \to J/\psi K^*$ and $B_s^0 \to J/\psi\phi$ in ATLAS, ATLAS-CONF-2011-092
4. ATLAS Collaboration, Measurement of the Λ_b^0 lifetime and mass in the ATLAS experiment, Phys. Rev. D 87, 032002 (2013), arxiv: 1207.2284 [hep-ex]
5. CMS Collaboration, Measurement of b hadron lifetimes in pp collisions at $\sqrt{S} = 8$ TeV, Eur. Phys. J. C 78 (2018) 457, arxiv: 1710.08949 [hep-ex]
6. ATLAS Collaboration, Measurement of the relative width difference of the $B^0 - \bar{B}^0$ system with the ATLAS detector, JHEP 06 (2016) 081, arxiv: 1605.07485 [hep-ex]
7. ATLAS Collaboration, Measurement of the CP-violating phase ϕ_s in $B_s^0 \to J/\psi\phi$ decays in ATLAS 13 TeV, Eur. Phys. J. C 81 (2021) 342, arxiv: 2001.07115 [hep-ex]
8. A. Lenz, M. L. Piscopo and A. V. Rusov, Disintegration of beauty: a precision study, (2022), arxiv: 2208.02643 [hep-ph]
9. D. Becirevic, Theoretical progress in describing the B meson lifetimes, PoS HEP2001 (2001) 098, ed. by D. Horváth, P. Lévai and A. Patkós, arxiv: hep-ph/0110124

Time Efficiency Correction

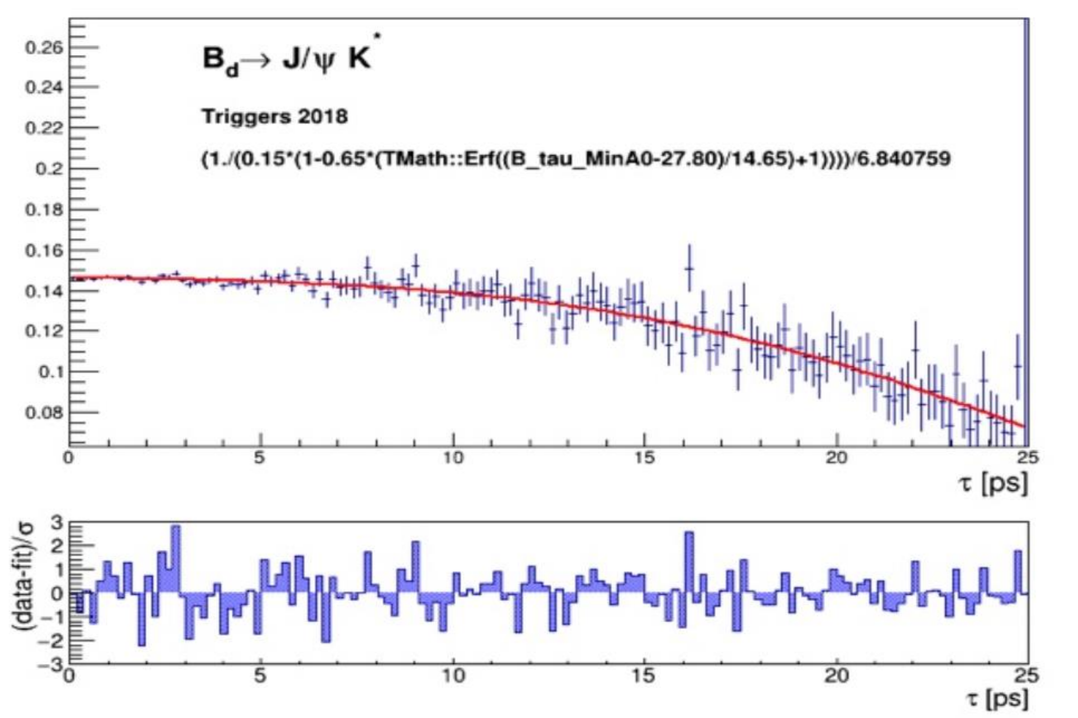
Dimuon triggers are crucial for the reconstruction of $B_\mathrm{d}^0 \to J/\psi K^{*0}$ decays
However, these triggers are inefficient in accepting low p_T dimuon events. This can cause lifetime bias towards the large value

Solution - introduce a weighting factor to lifetime distributions obtained by comparing signal MC events before and after applying triggers and selection cuts

In this analysis, since trigger lists are different for each year, I obtained corrections for all triggers in each year

An example of a trigger efficiency plot, which is the ratio of events passing the selection cuts and triggers to the events before selection and trigger cuts

Efficiency starts to drop after about 4 ps. Fit is nicely described by a single error function



Summary of My Contributions

Identification and selection of the most dominant triggers in Run 2 dataset

Obtained time efficiency corrections of triggers and selection cuts

Performed simultaneous mass and lifetime maximum likelihood fit to extract B_d^0-meson lifetime

Obtained systematic uncertainty due to the application of time-efficiency corrections

Extracted decay width Γ_{d} from effective lifetimes of B_{d}^0

Used ROOT + RooFit used in this study
Main Code used in this study
https://gitlab.cern.ch/ranovotn/MassLifetimeFits

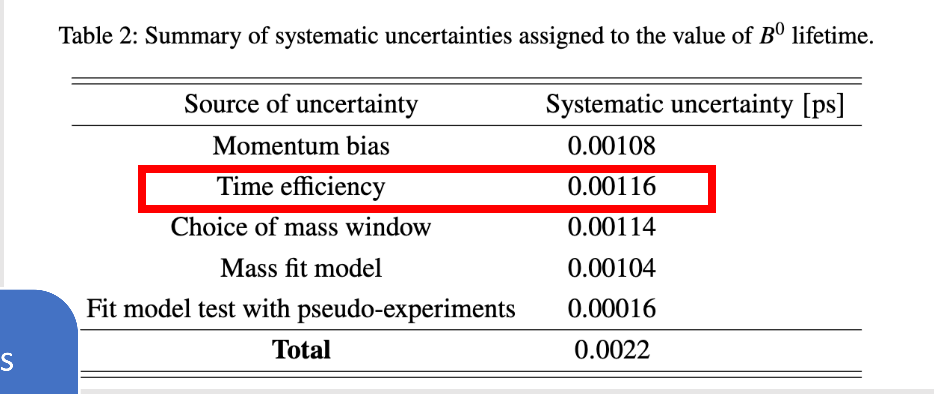


Table 2: Summary of systematic uncertainties assigned to the value of B^0 lifetime.

Source of uncertainty	Systematic uncertainty [ps]
Momentum bias	0.00108
Time efficiency	0.00116
Choice of mass window	0.00114
Mass fit model	0.00104
Fit model test with pseudo-experiments	0.00016
Total	0.0022

Time-efficiency corrections are the significant contributors of systematic uncertainty in our measurements

I also studied the efficiency of best χ^2selection on rejecting the self- background events

Contributed to the ATLAS Papers, prepared extensive internal documents and defended during review process within ATLAS

B-Meson Lifetime Studies - Status

$B_\mathrm{d}^0 \to J/\psi K^{*0}$ analysis is complete, and results are about to be published by the end of this year

The results* using 140 fb^{-1} of data collected by the ATLAS detector during the period 2015-18 are:

$$\tau_{B^0} = 1.5194 \pm 0.0013\ (\text{stat.}) \pm 0.0022\ (\text{syst.})\ \text{ps}$$

$$\Gamma_d = 0.6578 \pm 0.0006(\text{stat.}) \pm 0.011(\text{syst.}) \pm 0.0038(\text{ext.})\ \text{ps}^{-1}$$

These measurements are consistent with the SM predictions and results from other experiments

The ratio* of decay widths:

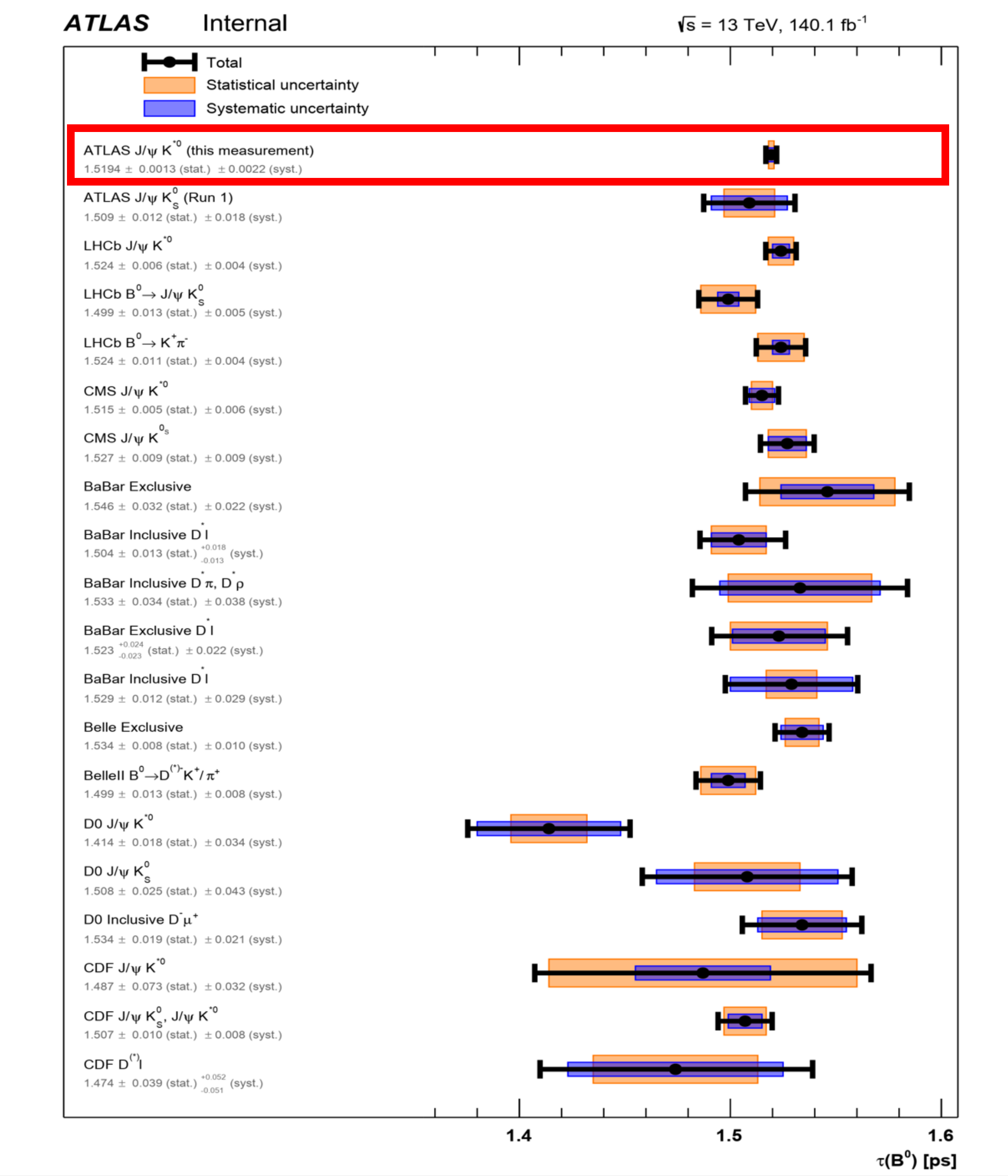
$$\Gamma_d / \Gamma_s = 0.9814 \pm 0.0022(\text{stat.}) \pm 0.031(\text{sys.}) \pm 0.0057(\text{ext.})$$

..shows a tension at 3σ with model predictions and experimental average

https://cds.cern.ch/record/2845218

*these numbers are still under internal review within ATLAS and thus are not public

Comparison With Other Experimental Results



ATLAS result using Run 2 data achieves 2.5 times better statistical precision over PDG!

The precision measurement shown in previous slides rely heavily on triggers. To improve precisions of the measurements using Run 3 data, I implemented and studied the performance of B-Physics dimuon triggers that are crucial for the analyses using $B_\mathrm{s}^0 \to J/\psi\phi$ and $B_\mathrm{d}^0 \to J/\psi K^{*0}$ decays in the newly implemented multithreaded software framework, AthenaMT, using Monte Carlo samples

(May 2020 – May 2021)

HLT *B*-Physics Triggers – My Tasks

My Focus

Level 1 Trigger (L1)
40 MHz →100 KHz

High Level Trigger (HLT)
100 KHz → 1 KHz

Offline Reconstruction

The HLT further analyzes the events selected by the L1 trigger using more sophisticated algorithms and finer granularity information from all the sub-detectors

- ATLAS software framework has been optimized for reduced CPU and memory usage. The new version, AthenaMT, is now default in Run 3

my tasks

- Migrated and implemented triggers for *B*-Physics (dimuon + 1 or 2 tracks) from Run-2 framework to AthenaMT and contributed to further development of these triggers - https://its.cern.ch/jira/browse/ATR-22240
- Validated the working of migrated *B*-Physics dimuon triggers by performing a preliminary reconstruction of a *B*-meson (like offline reconstruction, selecting events from a large pool of events in MC samples)

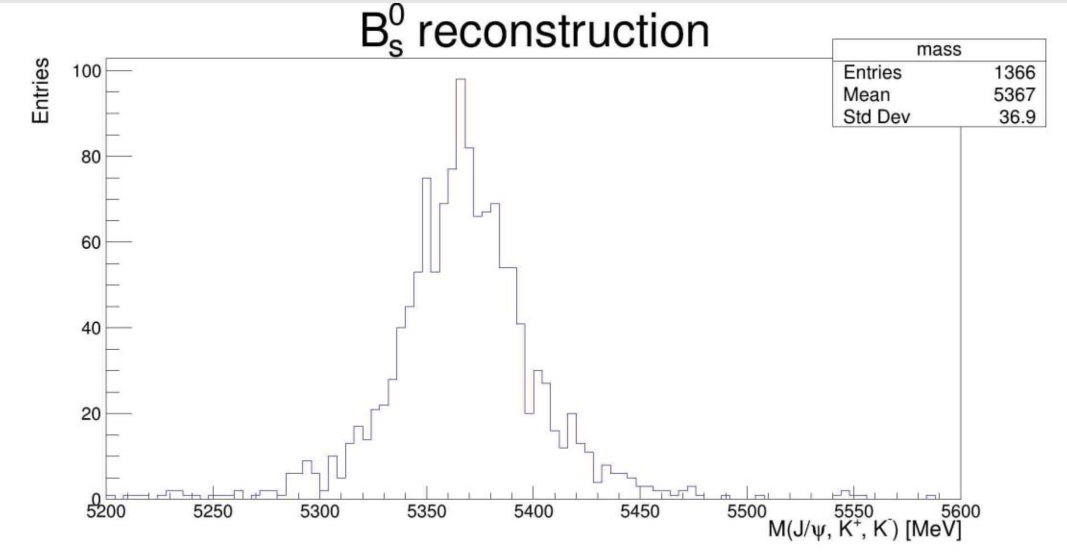
Implementing Triggers via TrigHypo Package

- Added various BmumuX trigger chains to AthenaMT via TrigBPhysHypo package:
  - Hypothesis Testing: The TrigHypo package evaluates if an event meets specific criteria for further analysis by applying selection cuts and algorithms
  - Trigger Decision: Based on this evaluation, the TrigHypo package decides whether to flag the event for further processing and storage or discard it
- This was done mostly by implementing hypothesis algorithms through selection cuts
- Performed test transformation (Raw Object Data (ROD) to Analysis Object Data (AOD))
- The AOD was used to study the efficiency of implemented triggers
- Used tools and programming languages – ROOT, git, C/C++, Python
- The ROD to AOD transformation was done using CONDOR batch system

Trigger Validation

This plot represents the distribution of events in a MC containing $B_s^0 \rightarrow J/\psi\phi$ events on a mass scale. The peak of the distribution is about 5367 MeV (the PDG value of B_s^0 is 5366.79 MeV)

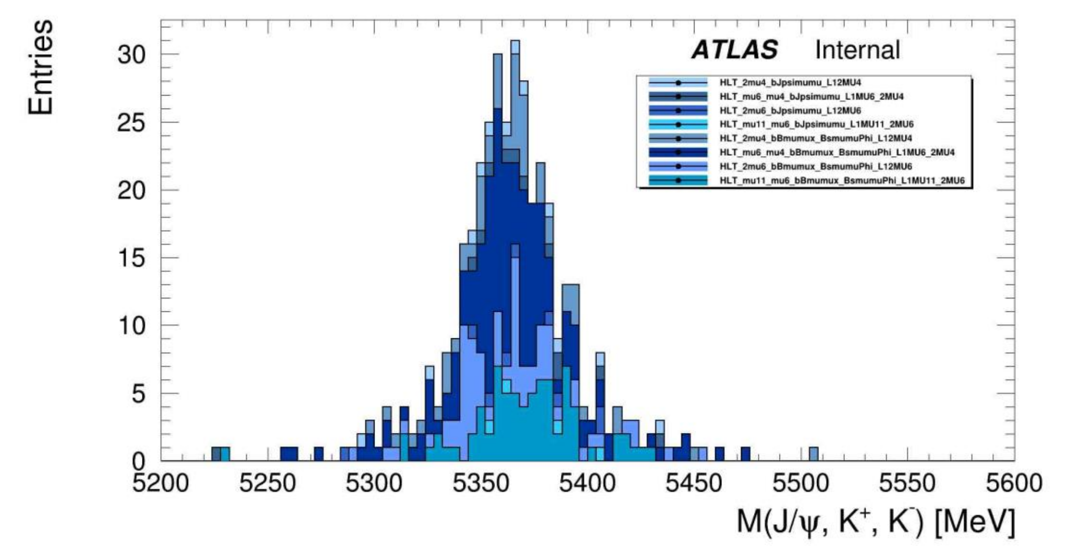
Thus, we have observed signal for B_s^0 events from the given pool of events after selecting relevant triggers and performing reconstruction steps



This plot shows how events in each trigger are distributed on a mass scale

- Triggers with $p_T > 4$ GeV have highest number of events
- No bias to low or high values of mass
- Efficiency of triggers is about 80%

Triggers are validated



Tracking detectors in current and future experiments at hadron colliders are exposed to intense radiation that damages them, causing their operating and readout characteristics to evolve during the lifetime of the experiment. I diagnosed and predicted these effects for my experiment and the next ones

(June 2020 – Mar 2024)

Introduction to Radiation Damage Studies

Higher Luminosity → Increased Particle Radiation → Damaged sensors

Searching for New Physics using rare processes requires large amounts of data. For this, luminosity (collision rate) is increased as much as possible

More collisions means increased particle radiation which is measured in fluence (number of 1 MeV neutrons applied to a sensor of surface area of $1 cm^2$ that cause damage equivalent to that of all particles that went through the sensor)

Irradiation causes nonstop damage to the silicon, effectively producing artificial donor- and acceptor-like sites in the lattice

Bulk damage:

- Caused by dislocations in the crystal lattice that disrupt the band structure
- Grows over time, hence needs to be monitored regularly

Types of Radiation Damage

Surface Damage:

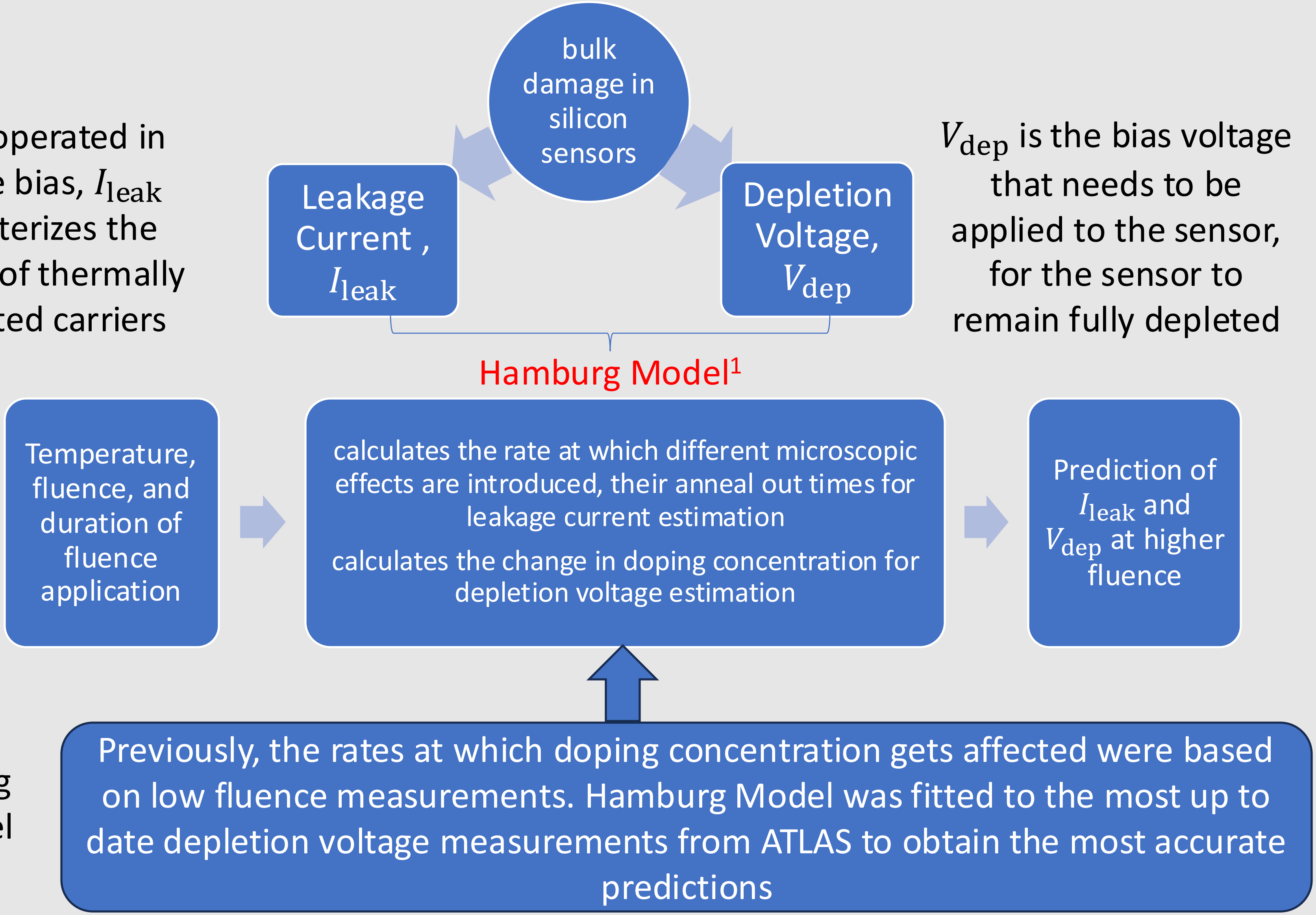
- Caused by developing bound charges at the interfaces of silicon
- Significant effect on the electronics, but less problematic than the bulk damage, for the sensors
- Saturates after initial radiation

Tracking detectors are placed close to the interaction point, so they undergo radiation damage → ATLAS Pixel detector has received an unprecedented amount of radiation at the end of Run 2

- Monitor radiation damage in Run 3
- Project to future years, to support development of HL-LHC detectors

Leakage Current and Depletion Voltage

When operated in reverse bias, I_{leak} characterizes the amount of thermally generated carriers



bulk damage in silicon sensors

Leakage Current , I_{leak}

Depletion Voltage, V_{dep}

V_{dep} is the bias voltage that needs to be applied to the sensor, for the sensor to remain fully depleted

Hamburg Model[1]

Temperature, fluence, and duration of fluence application

calculates the rate at which different microscopic effects are introduced, their anneal out times for leakage current estimation

calculates the change in doping concentration for depletion voltage estimation

Prediction of I_{leak} and V_{dep} at higher fluence

Improving the model

Previously, the rates at which doping concentration gets affected were based on low fluence measurements. Hamburg Model was fitted to the most up to date depletion voltage measurements from ATLAS to obtain the most accurate predictions

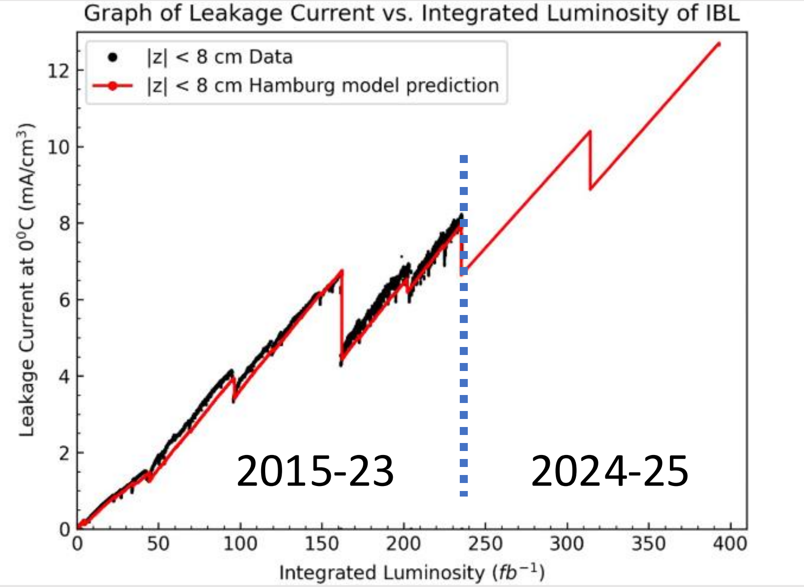
Hamburg Model code - [Link]

---

[1] M. Moll, 'Radiation damage in silicon particle detectors: Microscopic defects and macroscopic properties', Ph.D thesis: Hamburg U., 1999

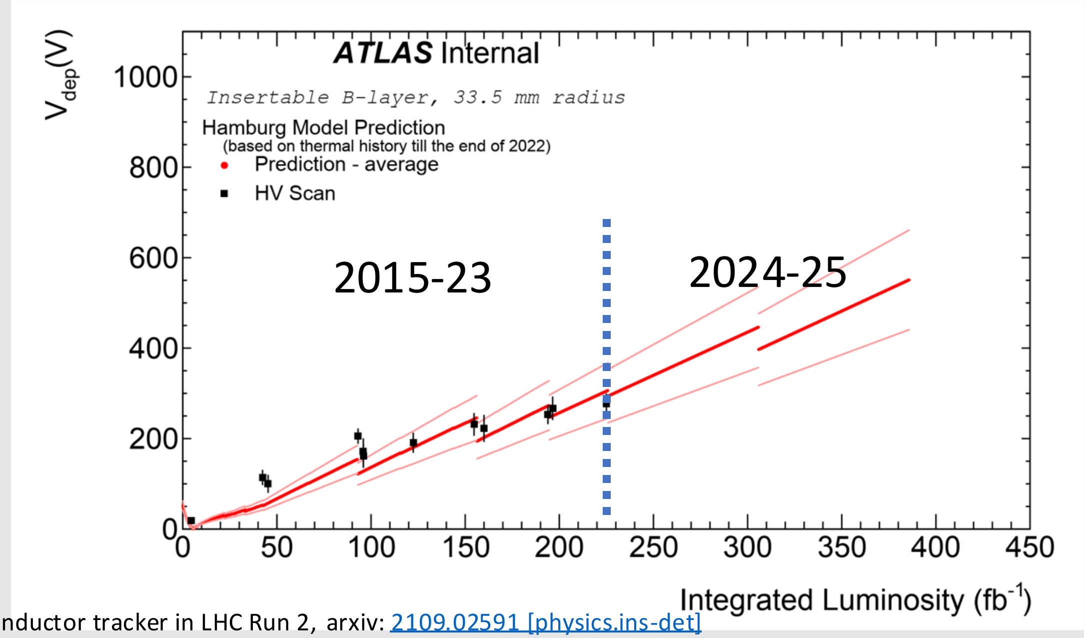
Hamburg Model – Prediction Vs Data

A comparison of the Hamburg model prediction and data (collected with the help of another group member) for the leakage current in the modules of the Insertable B-Layer (IBL) closest to the IP. The IBL is operated at -12°C (normalized to 0°C)



Depletion voltage – prediction vs data. Hamburg model was fitted to the data collected till 2023.

Performed $\Delta\chi^2$ minimization using TMinuit package in ROOT toolkit



Uncertainty in depletion voltage is due to the uncertainty in Hamburg Model parameters[1] which is approximately 20%

---

1. ATLAS Collaboration, Operation and performance of the ATLAS semiconductor tracker in LHC Run 2, arxiv: 2109.02591 [physics.ins-det]

Additional Projects

- Contributed to the measurement of the CP-violating parameters in $B_s^0 \rightarrow J/\psi\phi$. I studied the efficiency of dimuon triggers in the same manner as I did in the lifetime measurement of the B_d^0-meson. However, the analysis is not complete and was beyond the scope of my dissertation

- Extrapolated the depletion voltage in the Inner Tracker (ITk Pixel) for HL-LHC using the Hamburg Model and trends in radiation damage in the current Pixel detector for several operating scenarios spanning from 2029 to 2041 - https://cds.cern.ch/record/2777941

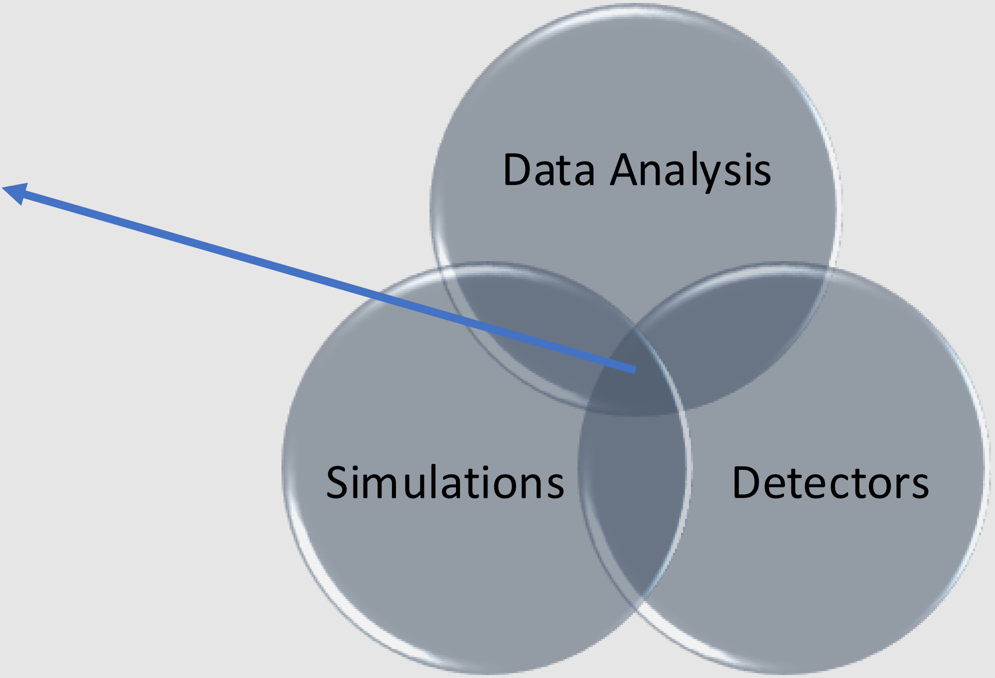
- Contributed to the development of the ITk Pixel, focusing on quality assurance and quality control (QA/QC). Additionally, I wrote Python scripts to upload QA/QC data, including measurements like pixel dimensions and IV curves, to the ITk production database

Miscellaneous

- All projects were challenging considering the size of the datasets
- The most challenging task was studying the radiation damage in the detectors using the Hamburg Model
- Firstly, it takes a considerable amount of time to perform simulations since the code is poorly optimized (it uses a single core on a multicore CPU for all calculations). I discussed the issue in the Snowmass 2021 paper - http://arxiv.org/pdf/2203.06216
- The Hamburg Model (HM) takes temperature, fluence, and the duration of fluence application as inputs to extrapolate radiation damage. However, fitting the Hamburg Model to data such as depletion voltage was exceptionally challenging due to the large input range (spanning from 2015 to 2023) and the limited number of data points
- Often, the minimization algorithms found the HM parameters that resulted in a straight-line fit, disregarding the physics (annealing)

My Research - Conclusions

My Ph.D. equipped me with a wide range of skills that allow me to work on different topics in experimental particle physics. I have a strong interest in learning new and emerging fields such as machine learning and other fascinating aspects of data science

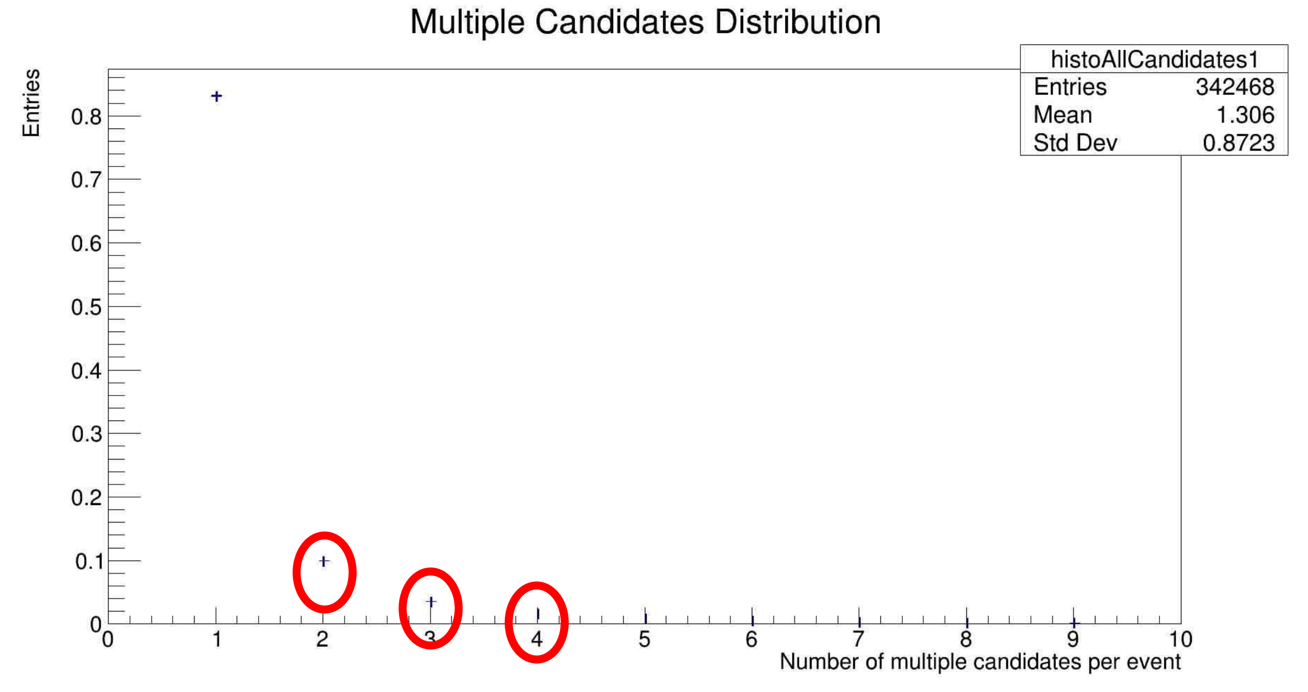


I received my PhD on May 11, and I am working as a postdoctoral scholar at Southern Methodist University in Dallas since June

BACKUP

Multiple Candidates in the Data and MC

- A vertex fit of the four tracks (μ^+, μ^-, K and π) is performed to get an event
- It is possible to get multiple candidates for one event by performing this vertex fitting and only one candidate is a true event. This is because two oppositely charged particles that are not muons are assigned kaon and pion mass – invariant mass hypothesis (ATLAS detector does not have a particle ID)
- Events reconstructed from J/ψ directly produced in pp collisions (called self background events) and incorrect combinations for hadronic track push the lifetime towards a lower value
- True event is selected by imposing selection cuts on mass of the parent particle, transverse momentum (p_{T}), χ^2, etc. However, some events with multiple candidates can still pass the selection cuts



About 82% of the events are single candidate events while about 18% of the events have multiple candidates in MC. In Run 2 data, about 10% of the events have multiple candidates

Is Our Low χ^2 selection the Best Selection Method?

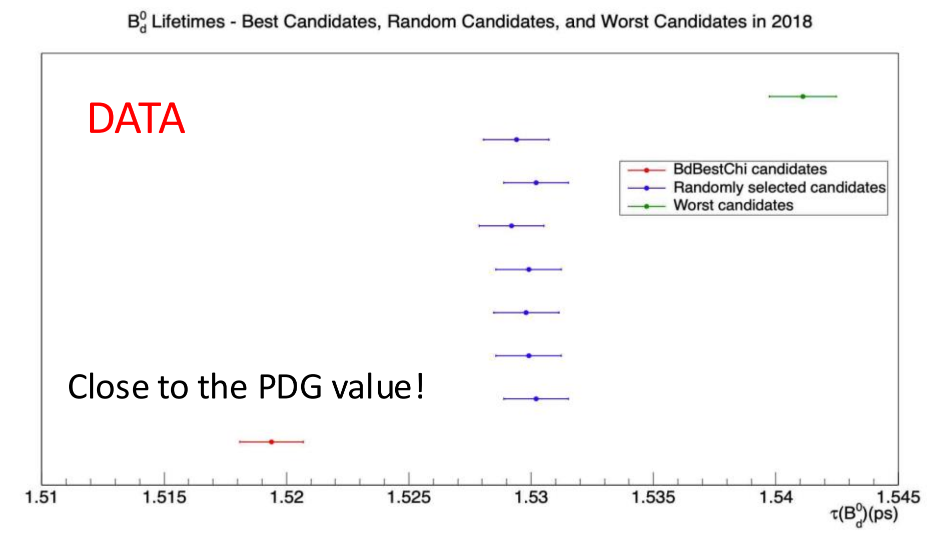
$\mu^+\mu^-$ and $K^+\pi^-$ tracks are fitted to a common vertex. Candidates with lowest χ^2/ndof for the vertex fit are selected. This selection is referred to as best χ^2 selection

A preliminary test to understand whether best χ^2 selection selects the best events from multiple candidates was performed using Run 2 data set and MC

Result using best χ^2 selection was compared to results using:

- seven ntuples of randomly selected events
- one ntuple of events satisfying worst χ^2 selection

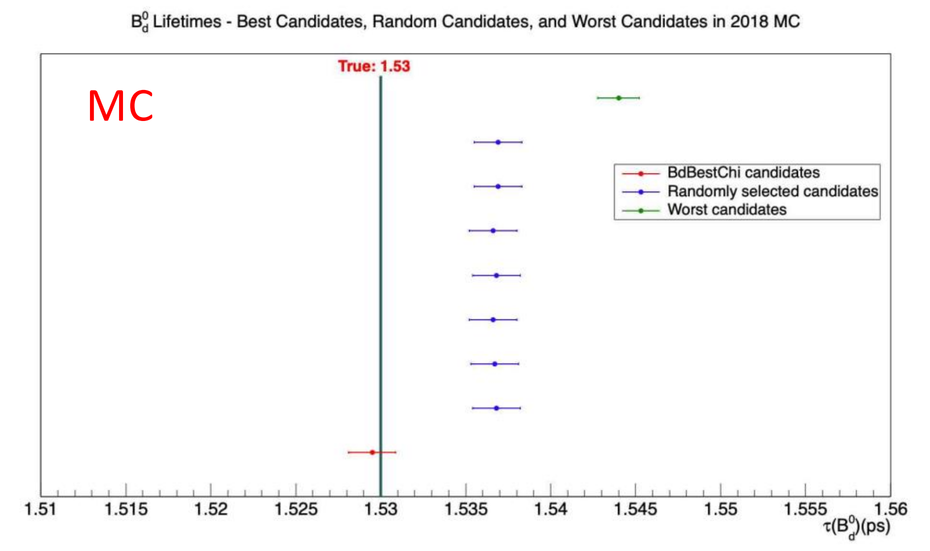
On both data and MC, we can see that the best χ^2 criterion selects the best events


B_d^0 Lifetimes - Best Candidates, Random Candidates, and Worst Candidates in 2018

DATA

Close to the PDG value!

SAME PATTERN


B_d^0 Lifetimes - Best Candidates, Random Candidates, and Worst Candidates in 2018 MC

MC

Systematic Uncertainty due to Time Efficiency Correction

- Estimated systematic uncertainties that get introduced in the lifetimes due to time efficiency corrections

- This was done by performing a default fit and a fit for systematic uncertainties

- Default fit (used in all the fits shown in the previous slides):
  - ratio of reconstructed candidates passing triggers and selection cuts to the true candidates in MC
  - Fitted by an error function

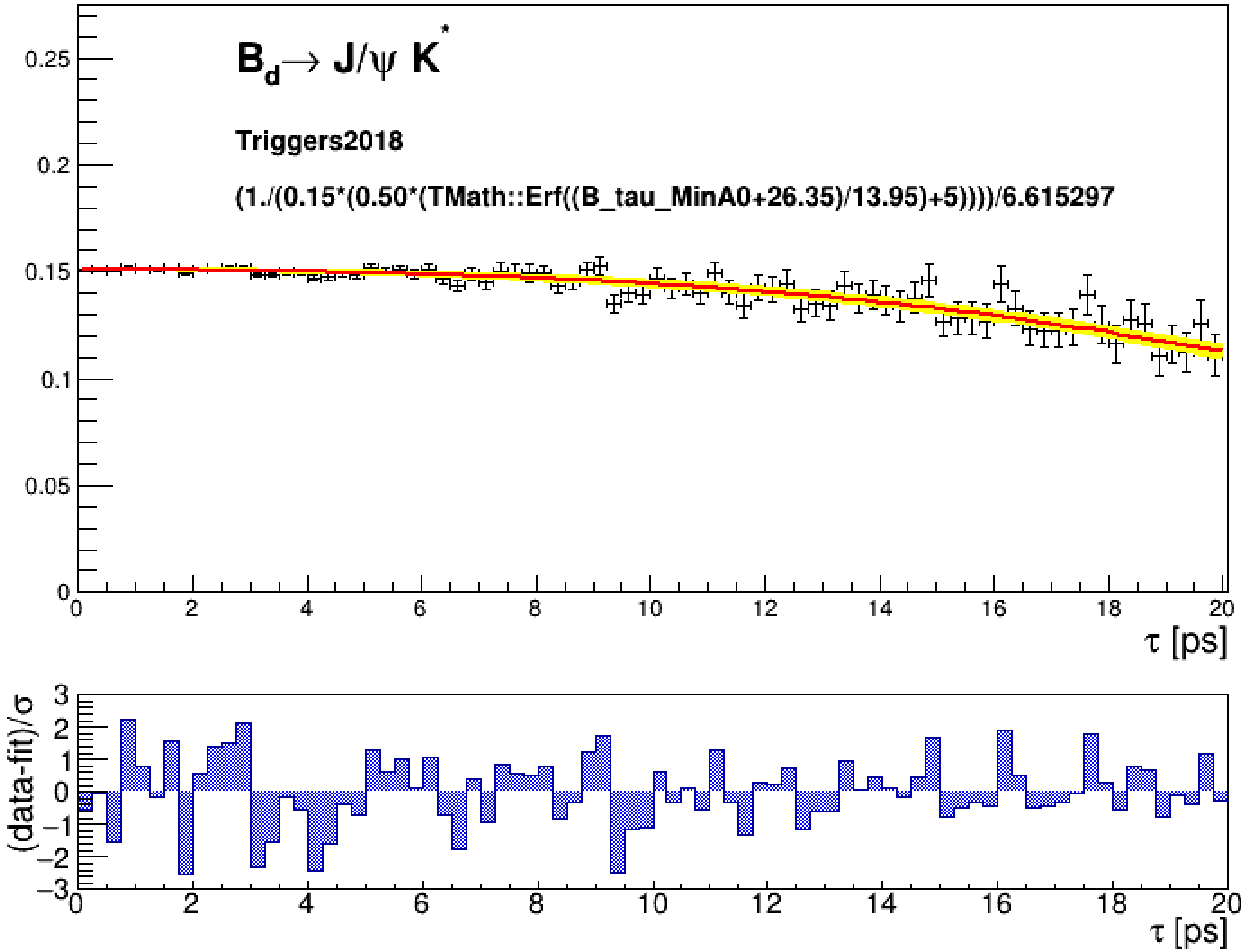
- Fit for systematics: In each bin, for true candidates, we use Poisson randomization and for reconstructed candidates, we use binomial randomization (this is to smear input data to account for the limited MC statistics)

- We then study the variations of the lifetimes. A plot illustrating differences of lifetimes of default fit and fit for systematics are made

- I obtained time efficiency corrections using default fit and fit for systematics (50 fits). Then I used these corrections in mass lifetime fits to extract lifetimes

Time Efficiency Correction – 2018 – Default Fit

Time efficiency correction for triggers and selections

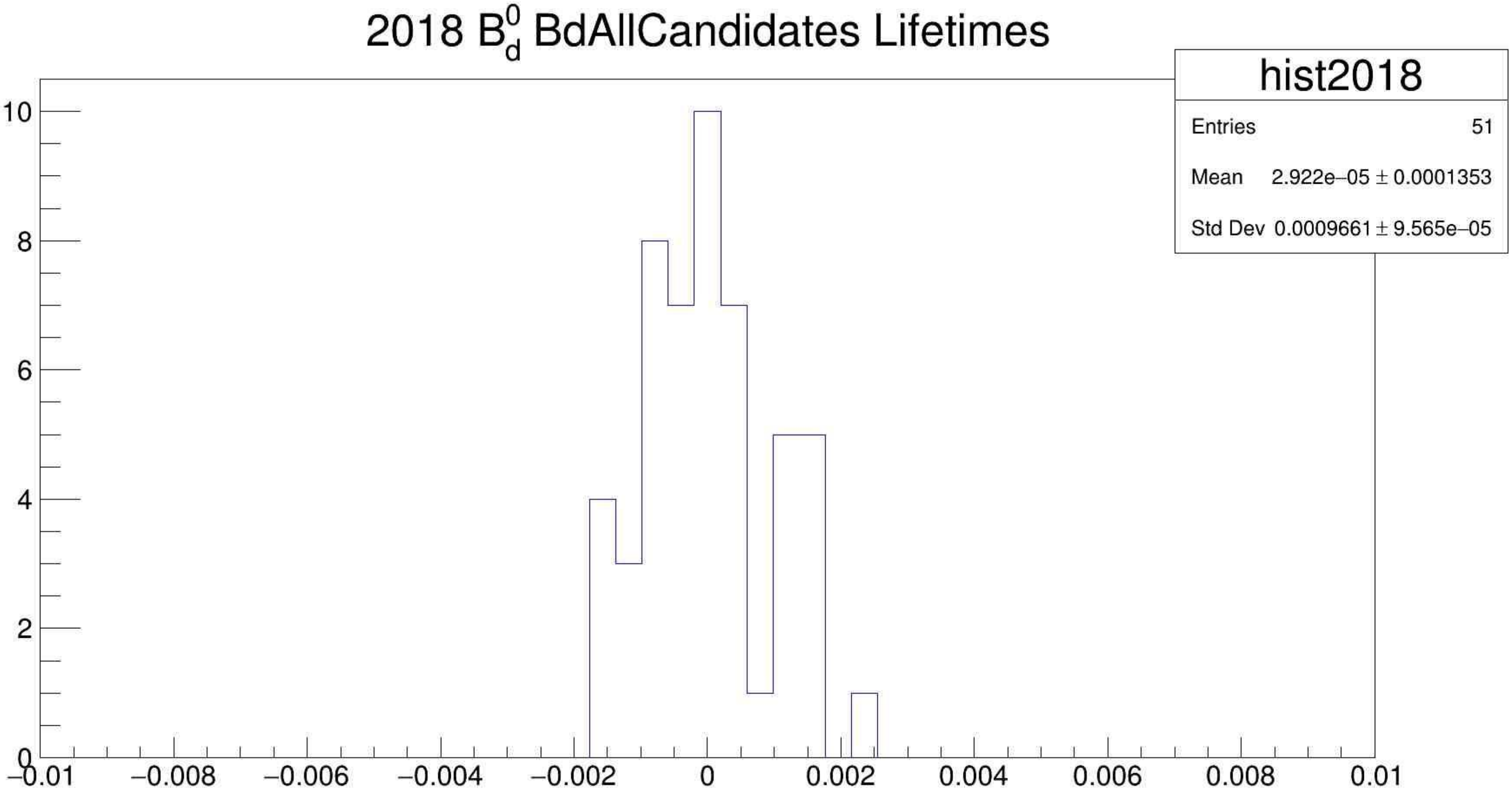


The fitted error function describes the ratio nicely

Time Efficiency Correction – 2018 – Systematics

These are 50 alternative time efficiency fits for 2018 MC events. The corrections from these 50 fits are then used to study the variations in the lifetime measurement

Lifetimes – 2018 – Systematic Uncertainty



Systematic uncertainty is 0.001 using 50 time efficiency fits for systematic uncertainties

CP violation parameters in $B_s^0 \to J/\psi\phi$ decays

SM parameters in $B_s^0 \to J/\psi\phi$ decay

ϕ_s

- A *CP*-violating weak phase difference between mixing amplitude and decay amplitude
- Related to the CKM matrix via $\phi_s \approx -2\beta_{s,}$ with $\beta_s = \arg[-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*]$.
- Assuming no New Physics is involved, a value of $-2\beta_s = -0.03696^{+0.00072}_{-0.00082}$ rad was predicted by the CKMFitter group[1] and $-2\beta_s = 0.03700 \pm 0.00104$ rad by the UTfit Collaboration[2]
- Highly sensitive to New Physics

Γ_s

- The average of the decay widths of light and heavy mass eigenstates
- Not sensitive to New Physics
- Can be used to constrain models through ${}^{\Gamma_d}/_{\Gamma_s}$

$\Delta\Gamma_s$

- Difference between the decay widths of light and heavy mass eigenstates
- In the Standard Model, the value[3] for $\Delta\Gamma_s$ is predicted to be (0.085 ± 0.015) ps^{-1}
- Moderately sensitive to New Physics

+ 6 parameters arising from angular analysis

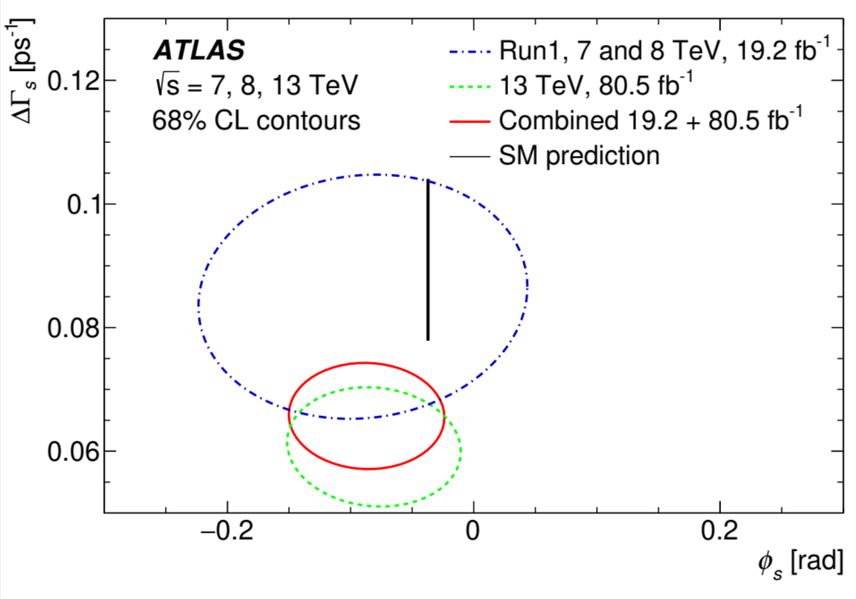
If New Physics is involved, we expect different values of ϕ_s and $\Delta\Gamma_s$ compared to Standard Model predictions

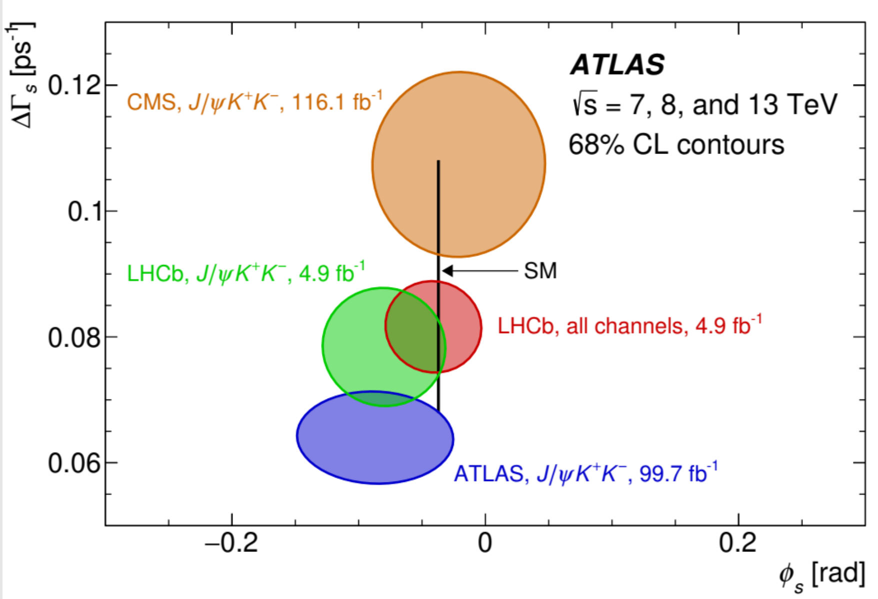
---

1. CKMfitter group, Charles, J. et al., *Current status of the Standard Model CKM fit and constraints on $\Delta F = 2$ New Physics*, Phys. Rev. D 91 (2015) 073007, Numbers updated using the results from the 2019 values in https://ckmfitter.in2p3.fr/www/results/plots_summer19/ckm_res_summer19.html, arxiv: 1501.05013 [hep-ph]
2. UTfit Collaboration, M. Bona et al., *The unitarity triangle fit in the standard model and hadronic parameters from lattice QCD: A reappraisal after the measurements of Δm_s and $BR(B \to \tau\vartheta_\tau)$*, JHEP 10 (2006) 081, Numbers updated to the 2018 results from https://www.utfit.org/UTfit/ResultsSummer2018SM, arxiv: hep-ph/0606167 [hep-ph]
3. M. Artuso, G. Borissov and A. Lenz, CP violation in the B_s^0 system, Rev. Mod. Phys. 88 (2016) 045002, [Addendum: Rev. Mod. Phys. 91, no. 4, 049901 (2019)], arxiv: 1511.09466 [hep-ph]

Current Measurements of *SM* parameters at ATLAS

Combined results[1] using Run 1 (7, 8 TeV) and Run 2 till 2017 (13 TeV) data





The measurement of the *CP*-violating phase ϕ_s is consistent with the Standard Model prediction, and it improves on the precision of previous ATLAS measurements.

Additional data set of 58.5 fb^{-1} collected in 2018 is being included to improve statistical precision of 1.32 over the above results

1. ATLAS Collaboration, Measurement of the CP-violating phase ϕ_s in $B_s^0 \to J/\psi\phi$ decays in ATLAS 13 TeV, Eur. Phys. J. C 81 (2021) 342, arxiv: 2001.07115 [hep-ex]

Leakage Current in Hamburg Model

The difference in leakage current at a fluence Φ_{eq} relative to the value before irradiation

$$\Delta \boldsymbol{I} = \boldsymbol{\alpha} \cdot \boldsymbol{\Phi}_{\mathbf{eq}} \cdot \boldsymbol{V}$$

current-related damage coefficient,
strongly dependent on temperature

volume of the sensor

Implementation of the equation, $\Delta \boldsymbol{I} = \boldsymbol{\alpha} \cdot \boldsymbol{\Phi}_{\mathbf{eq}} \cdot \boldsymbol{V}$, in the Hamburg Model[1]

- The current-related damage coefficient in the leakage current equation can be written as a combination of exponential functions
- Different types of microscopic defects in the sensor cause leakage current and anneal out at different rates in a process that follows a first order reaction
- Hamburg Model Simulation of leakage current requires inputs of fluence rate, sensor temperature and time span of the fluence application

1. M. Moll, ‘Radiation damage in silicon particle detectors: Microscopic defects and macroscopic properties’, Ph.D thesis: Hamburg U., 1999.

Leakage Current in Hamburg Model

- Hamburg Model Simulation of leakage current requires inputs of fluence rate, sensor temperature and time span of the fluence application
- Hamburg Model equation[1] : For n time intervals of fluence application,

$$\Delta I = (\Phi_{\mathrm{eq}}/L_{\mathrm{int}}) \times V \cdot \sum_{i=1}^{n} L_{\mathrm{int},i} \cdot \left[\alpha_{\mathrm{I}} \exp\left(-\sum_{j=i}^{n} \frac{t_j}{\tau(T_j)}\right) + \alpha_0^* - \beta \log\left(\sum_{j=i}^{n} \frac{\Theta(T_j) \cdot t_j}{t_0}\right)\right]$$

where the variables are

  - L_{int} is the integrated luminosity, t_i is the time, T_i is the temperature in period i and $t_0 = 1\mathrm{min}$
  - $\alpha_{\mathrm{I}} = (1.23 \pm 0.06) \times 10^{-17}$ A/cm
  - $\tau^{-1} = \left(1.2^{+5.3}_{-1.0}\right) \times 10^{13}\,\mathrm{s}^{-1} \times e^{(-1.11 \pm 0.05)/k_B T}$ where units of $k_B T$ are eV
  - $\alpha_0^* = 7.07 \times 10^{-17}$ A/cm
  - $\beta = (3.29 + 0.18) \times 10^{-18}$ A/cm
  - $\Theta(T) = \exp\left[-\frac{E_{\mathrm{eff}}}{k_{\mathrm{B}}}\left(\frac{1}{T} - \frac{1}{T_{\mathrm{R}}}\right)\right]$, where E_{eff} is the effective silicon band gap energy after irradiation which is

set to 1.26 eV for IBL[2] and 1.21 eV for B-Layer[2] and T_R is the reference temperature which is set to 21°C throughout the study

- Leakage current depends on the sensor temperature T and can be converted to that at reference temperature T_{R} by the following equation

$$I_{\mathrm{leak}}(T_{\mathrm{R}}) = I_{\mathrm{leak}}(T) \left(\frac{T_{\mathrm{R}}}{T}\right)^2 \exp\left[-\frac{E_{\mathrm{eff}}}{2k_{\mathrm{B}}}\left(\frac{1}{T_{\mathrm{R}}} - \frac{1}{T}\right)\right]$$

---

1. M. Moll, 'Radiation damage in silicon particle detectors: Microscopic defects and macroscopic properties', Ph.D thesis: Hamburg U., 1999
2. ATLAS Collaboration, Measurements of sensor radiation damage in the ATLAS inner detector using leakage currents , CERN-EP-2021-055

Depletion Voltage in Hamburg Model

- Depletion voltage V_{dep} of a sensor depends linearly on the effective doping concentration N_{eff} and the full depletion depth d

q – unit of charge
ε – permittivity
ε_0 – relative permittivity

$$V_{\text{dep}} = \frac{|N_{\text{eff}}| d^2 q}{2\varepsilon\varepsilon_0}$$

affected by irradiation.

- Change in doping concentration N_{eff} after irradiation is given by the following equation[1]

$$\Delta N_{\text{eff}} = N_{\text{A}} + N_{\text{C}} + N_{\text{Y}}$$

$N_{\text{A}} = g_{\text{A}}\Phi_{\text{eq}} e^{-t/\tau_{\text{a}}}$	Short term beneficial annealing
$N_{\text{Y}} = g_{\text{Y}}\Phi_{\text{eq}}(1 - e^{-t/\tau_{\text{Y}}})$	Reverse annealing, grows over time but can be effectively frozen out under -5^0C
$N_{\text{C}} = N_{\text{C,0}}\left(1 - c\Phi_{\text{eq}}\right) + g_{\text{C}}\Phi_{\text{eq}}$	Stable damage and initial dopant removal $N_{\text{C,0}}$ with removal constant c

here, τ_{a} and τ_{Y} are defined by Arrhenius equations and have a temperature dependence.

g_{C}, g_{A} and g_{Y} are called the introduction rates

---

1. M. Moll, 'Radiation damage in silicon particle detectors: Microscopic defects and macroscopic properties', Ph.D thesis: Hamburg U., 1999.

Hamburg Model Introduction Rates for IBL and B-Layer

- Used $\Delta\chi^2$ minimization where $\Delta\chi^2 = \frac{(V_{\mathrm{dep}}(g_{\mathrm{A}}, g_{\mathrm{Y}}, g_{\mathrm{C}}) - V_{\mathrm{dep}}(\mathrm{HV\ Scan}))^2}{\delta V_{dep}(\mathrm{HV\ Scan})^2}$

This present work

IBL

Introduction Rate	**HM default[1] ($\times 10^{-2}$ cm^{-1})**	**Fitted-2018[2] (by J. Beyer) ($\times 10^{-2}$ cm^{-1})**	**Fitted-2023§ ($\times 10^{-2}$ cm^{-1})**
g_{A} (beneficial)	1.0	0.7 ± 0.3	0.59 ± 0.23
g_{Y} (reverse)	1.6	$6.0^{+1.6}_{-2.3}$	3.7 ± 2.9
g_{C} (constant)	1.0	0.7 ± 0.3	0.617 ± 0.064

$\chi^2/ndf = 1.48$

B-Layer

Introduction Rate	**HM default[1] ($\times 10^{-2}$ cm^{-1})**	**Fitted-2018[2] (by J. Beyer) ($\times 10^{-2}$ cm^{-1})**	**Fitted-2023§ ($\times 10^{-2}$ cm^{-1})**
g_{A} (beneficial)	1.0	0.6 ± 0.2	0.19 ± 0.4
g_{Y} (reverse)	1.6	$6.0^{+1.6}_{-2.3}$	2.5 ± 2.6
g_{C} (constant)	1.0	0.43 ± 0.3	0.67 ± 0.16

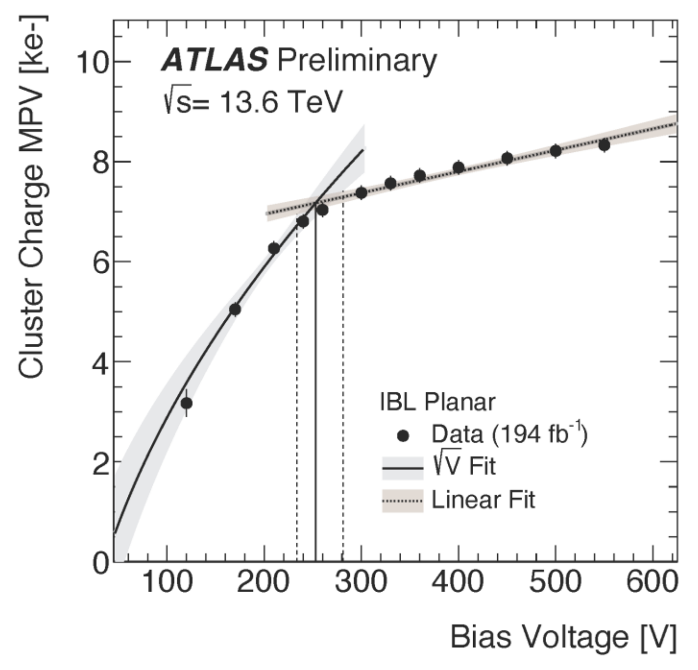
$\chi^2/ndf = 0.48$

§ Used the HV scans for IBL and B-Layer measured by Marco Battaglia

1. ROSE collaboration, 3rd RD48 status report: the ROSE collaboration (R&D on silicon for future experiments), CERN-LHCC-2000-009, CERN, Geneva,Switzerland (2010)
2. https://indico.cern.ch/event/695271/contributions/2958674/attachments/1637640/2613544/beyer_depl_volt_ATLAS.pdf

Further Studies on the Hamburg Model

The Hamburg Model does not fit all the data well. The voltage increase is not linear according to the HV scans. The space charge density in the sensor reaches a maximum at higher fluences, but the Hamburg Model does not account for this. There is an important "term" missing in the Hamburg Model equation. This is beyond the scope of this PhD



Nonlinearity[1] in the space-charge distribution

---

1. M. Battaglia, M. Bomben, M. Bindi and E. Narayanan, Measurement of the Planar IBL Sensor Depletion Voltage as a function of Particle Fluence with Run 2 and 3 Collision Data, ATL-INDET-INT-2023-009