The Impact of Incorporating Shell corrections to Energy Loss in Silicon

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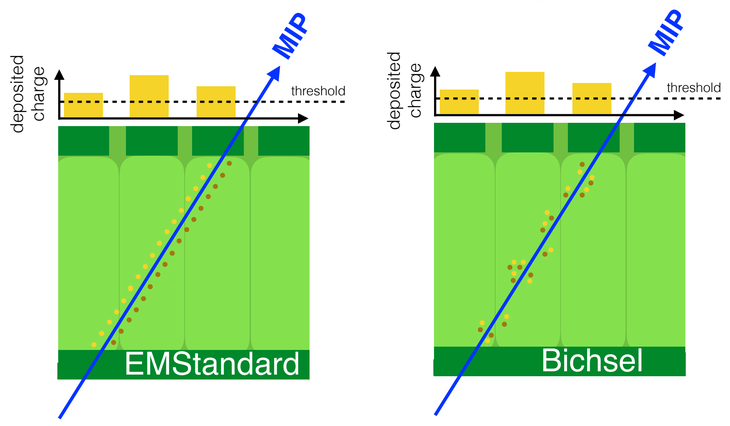
https://arxiv.org/abs/1711.05465, https://github.com/LBNLPixelProjects

Motivation

- Requirements on the material budget and radiation hardness are pushing sensors to become **thinner**.
- Landau-Vavilov distribution describes the energy fluctuations in thick sensors quite well, but not for thin sensors.
- For thin sensors, the Bichsel model is more complete and has been shown to reproduce measured energy losses.
- We implemented the Bichsel model into a standalone Geant4 package called Allpix and compare the result with other models.

What is Bichsel model?

- Bichsel straggling function accounts for shell-effects of silicon atom and has been shown to reproduce measured energy losses.



*We thank Hans Bichsel for his great work on this model.

- Fluctuations in the energy loss and mainly due to 2 sources:
  A. The number of collisions: Poisson distribution

$$\Pr(n) = \frac{(x/\lambda)^n}{n!} e^{-x/\lambda}$$

$$\lambda^{-1} = N \int dE \sigma(E)$$

λ: Mean free path, calculated from the collision cross section $\sigma(E)$

  B. Energy loss distribution after n collisions:

$$\sigma(\Delta)^{*n} = \int_0^{\Delta} \sigma(E) \sigma^{*(n-1)}(\Delta - E) dE$$

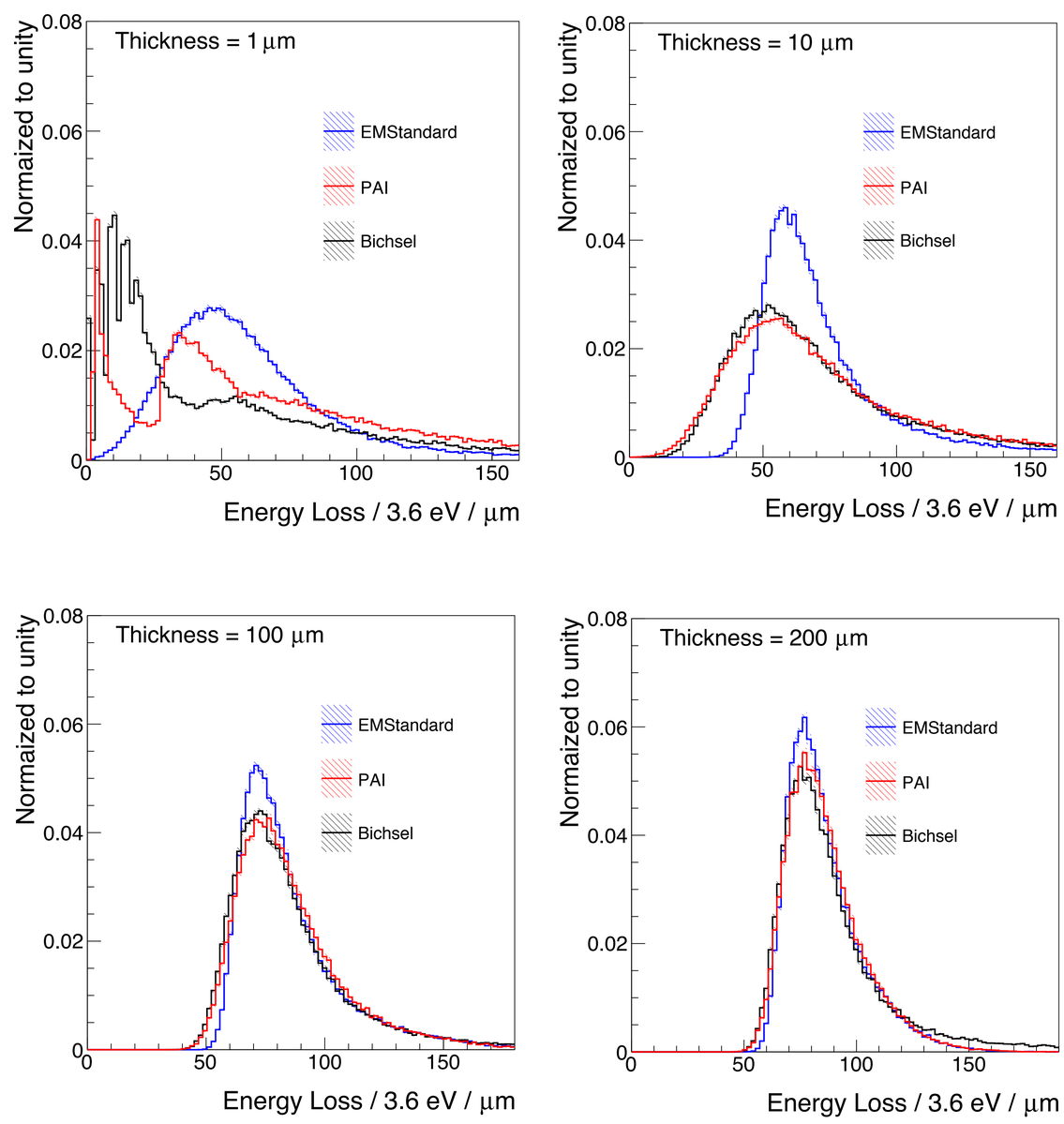
- The full straggling function of Bichsel model:

$$f(\Delta, x) = \sum_{n=0}^{\infty} \frac{(x/\lambda)^n e^{-x/\lambda}}{n!} \sigma(\Delta)^{*n}$$

- This equation does not admit a closed-form analytic solution, but numerical calculations are provided.

Model comparison metrics

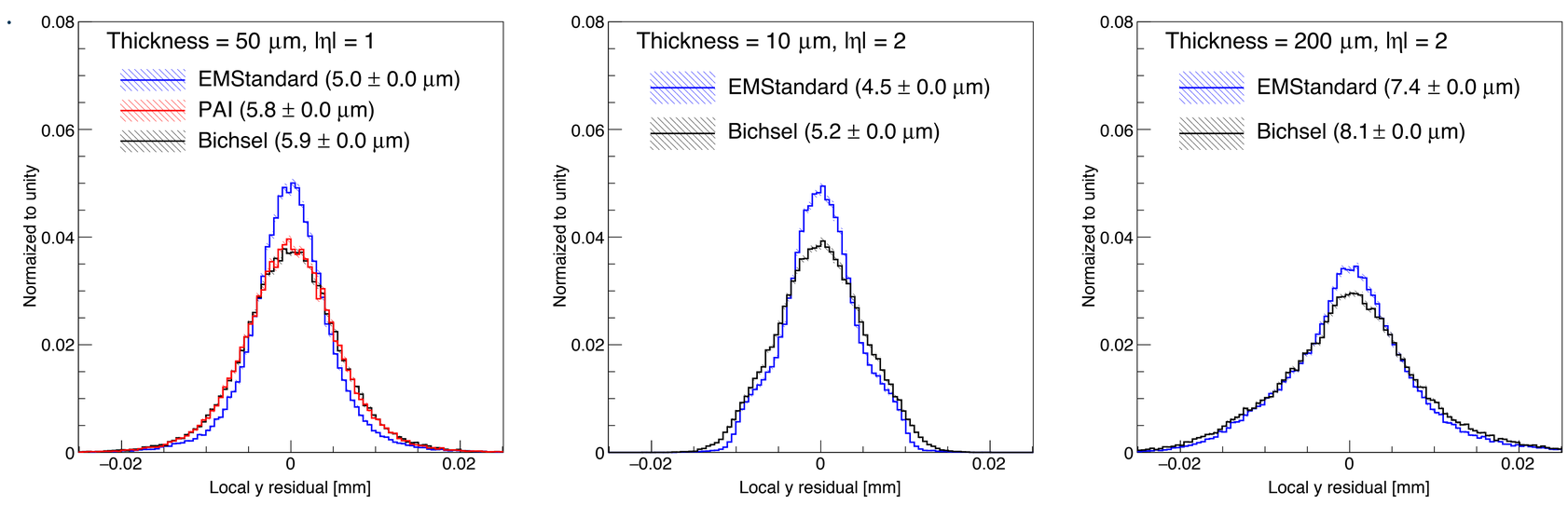
- EMstandard: most commonly used Geant4 physics model at the LHC. This model results in Landau-Vavilov-like distributions and does not include shell electron effects.
- The Photo Absorption Ionization (PAI) model: a more detailed energy loss model in Geant4. In good agreement with the experiment data on energy loss for moderately thin sensors.
- Energy deposition for a single layer of a silicon detector with various thickness.



- PAI and Bichsel models are similar because both of these two models include shell corrections
- Below 10 um, large differences between 3 models. The shell effects are very pronounced in the Bichsel model.

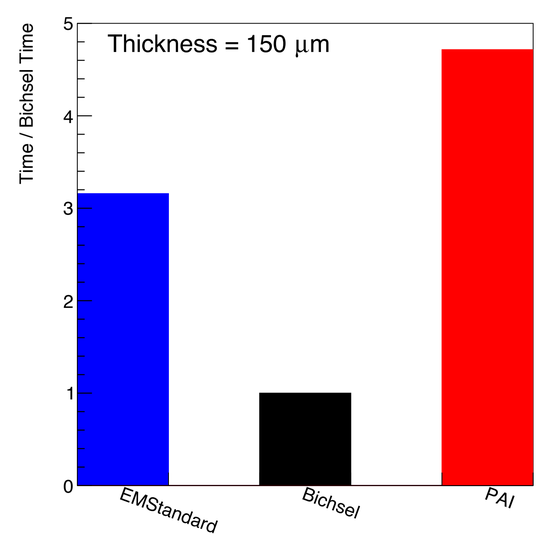
Position residual of 3 models

- Variations in the energy loss distributions lead to differences in the reconstructed hit position.
- Bichsel and PAI agree well with each other, but have a larger discrepancy with EMstandard.



Time comparison

- PAI is not used in practice due to its long simulation time.



- Our implementation of Bichsel: 5 times faster than PAI

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