Calibration of Radiation Damage: Effects on Pixel Reconstruction

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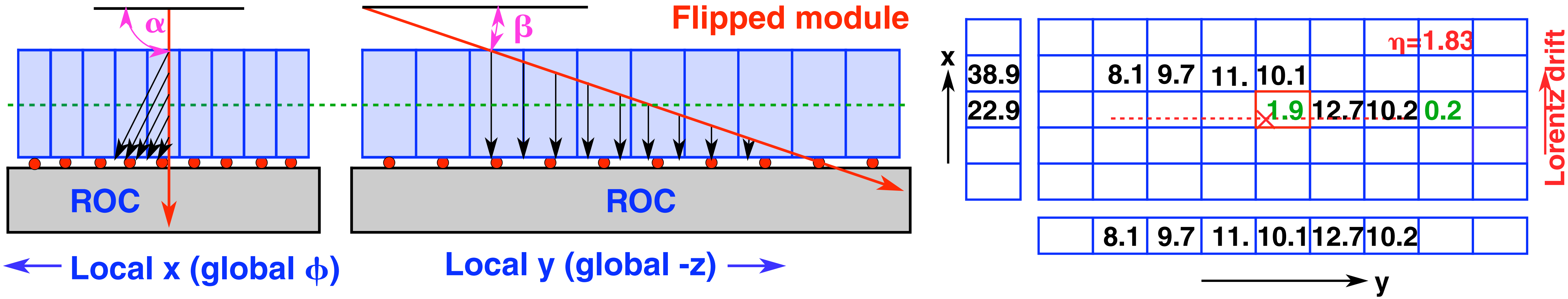
Hit Reconstruction

Tracks deposit distinct patterns of charge on the pixel sensors



- Hit position estimation is based on 1D projections of the 2D cluster
  - factorizes due to field configurations and cell periodicity
  - projected shapes depend upon the projected angles α and β
    - reconstruction algorithms use angle information iteratively
- Two techniques used in track reconstruction
  - "Generic" technique is η-like, uses end pixel charges of projection
    - faster, less precise algorithm used for all but last tracking pass
    - needs external Lorentz drift calibration
  - "Template" technique fits projections to simulated profiles
    - slower, more precise algorithm used for final fitting pass
    - needs full cluster shape calibration
    - generates probabilities that test the consistency of the shapes

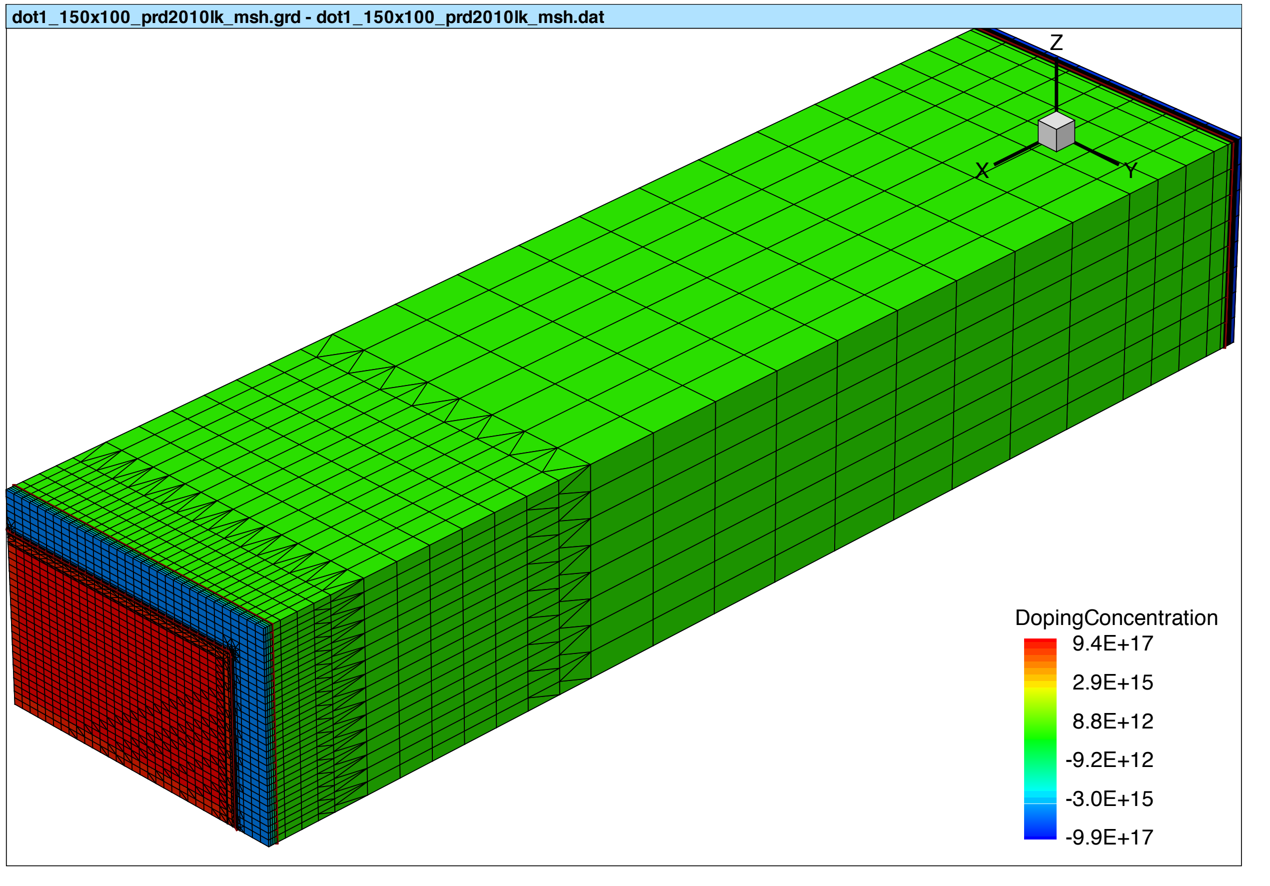
Pixelav Detailed Simulation

Created to interpret beam tests of irradiated sensors, now used to perform Lorentz calibrations and generate template profile shapes:

- Charge deposition model based on Bichsel π-Si x-sections
  - delta ray range: Continuous Slowing Down Approx + Nist Estar dedx
  - plural scattering and magnetic curvature of delta ray tracks
- Carrier transport from Runge-Kutta integration of saturated drift

$$\frac{d\vec{x}}{dt} = \vec{v} = \frac{\mu\left[q\vec{E} + \mu r_H \vec{E}\times\vec{B} + q\mu^2 r_H^2(\vec{E}\cdot\vec{B})\vec{B}\right]}{1+\mu^2 r_H^2|\vec{B}|^2}$$

  - electric field map from ISE TCAD simulation of pixel cell
  - includes diffusion, trapping, and charge induction on implants
- Electronic Simulation: noise, linearity, thresholds, mis-calibration



Calibration of Reconstruction Algs

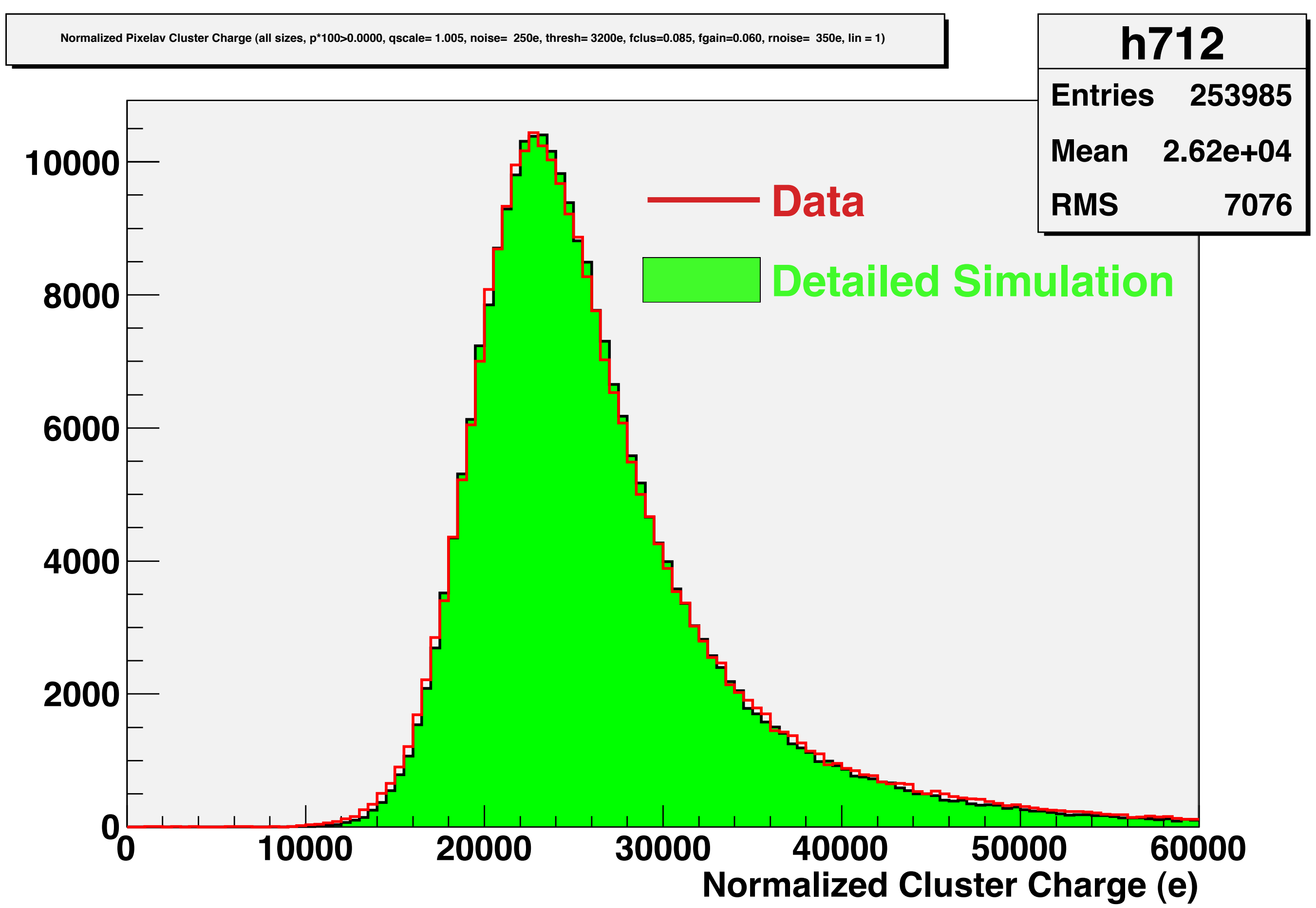
Sensor Structure, V_{bias}, T, r_H, Φ, electronic response (6 params)

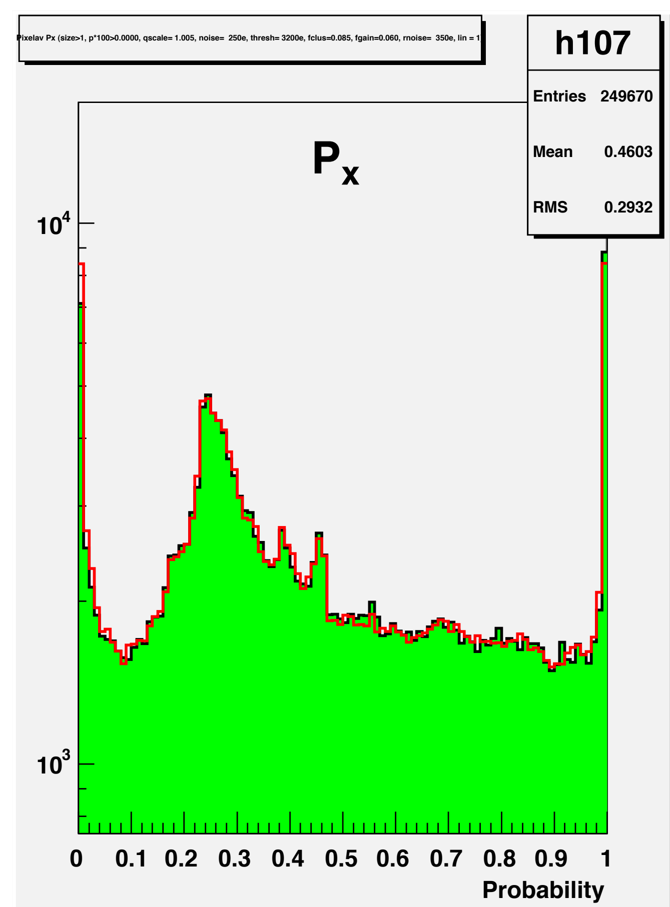
→ **Pixelav** (detailed simulation)

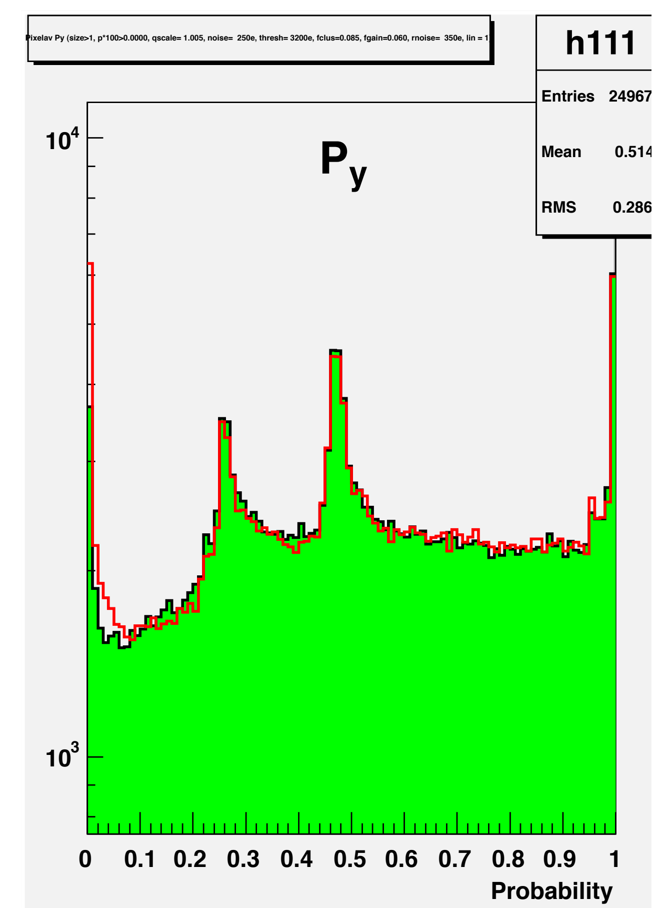
→ **Simulated Data:**
- charge distribution
- size distributions
- shape probabilities
- Lorentz angle cals
  - *clust size vs cot(α)
  - *grazing angle
- charge coll profiles (after rad damage)

→ **Calibrations:**
- Standard Reco
  - * Lorentz corrs
  - * error estimates
- Template Reco
  - *cluster shapes
  - *error estimates
  - *probability info
  - *cluster split info

Adjust these to match these to data







Modeling of Irradiated Sensors

Space charge in irradiated sensors can be produced by ionized traps. The Shockley-Read-Hall (SRH) description is based on ALL trapping states:

$$\rho_{\mathrm{eff}} = e\sum_D N_D f_D - e\sum_A N_A f_A + \rho_{\mathrm{dopants}}$$
$$\simeq e\left[N_D f_D - N_A f_A\right] + \rho_{\mathrm{dopants}}$$

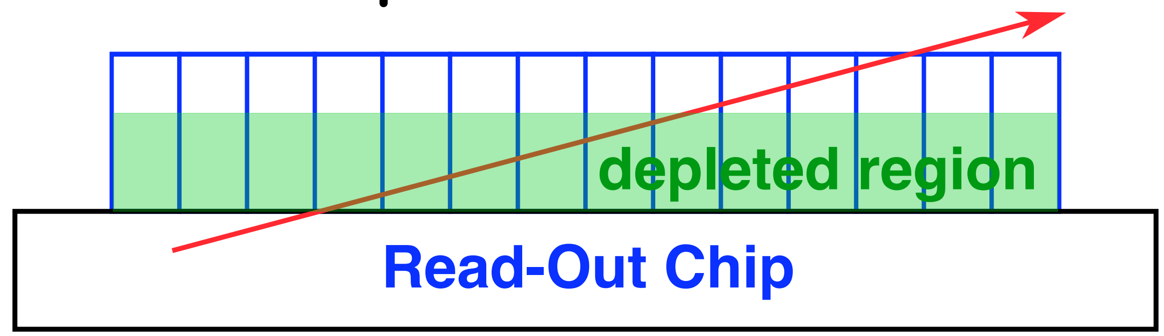
N_D and N_A are the densities of h- and e-traps

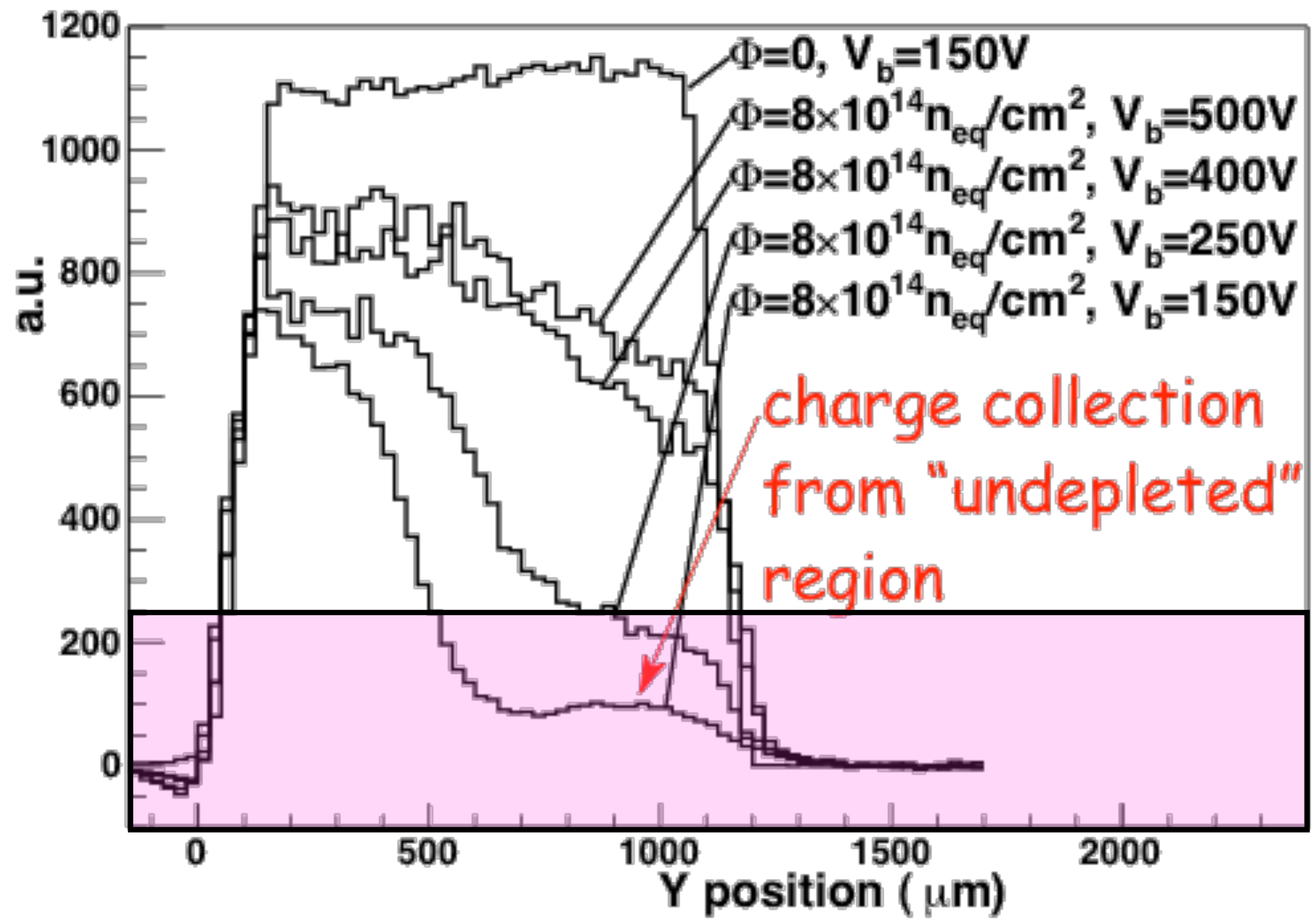
f_D and f_A are the trap occupation probabilities

- follow Eremin, Verbitskaya, Li (EVL): use single h/e-traps to model E-field
  - D and A states don't have to be physical states: they represent average quantities!
  - model parameters are not physical
- e/h trapping is modeled independently in Pixelav using measured trapping rates to relate them the fluence Φ

Tuning the Simulation

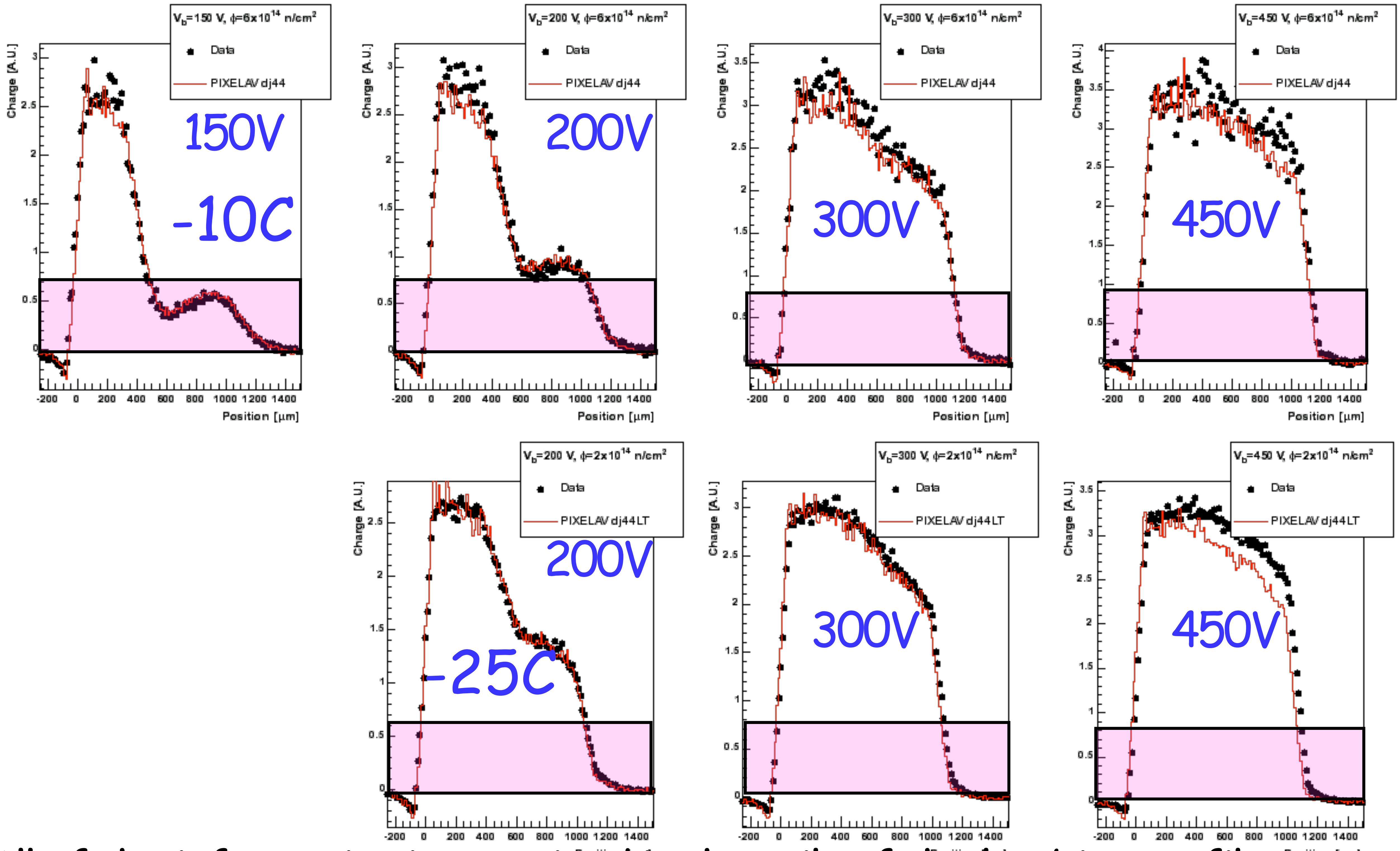
Compare the charge collection profiles of real and simulated data





- Our test beam experience was based upon reading all pixels (no threshold)
  - in CMS, we will not see the smallest ~25% of the signals

Successful tuning of sensor at Φ_1=5.9x10^{14} n_{eq}/cm^2



- All of the information is contained in the tails of the low bias profiles
  - the "feature" corresponding to the field minimum is observable at some V and T!

Scale to lower fluences using an empirical set of relationships

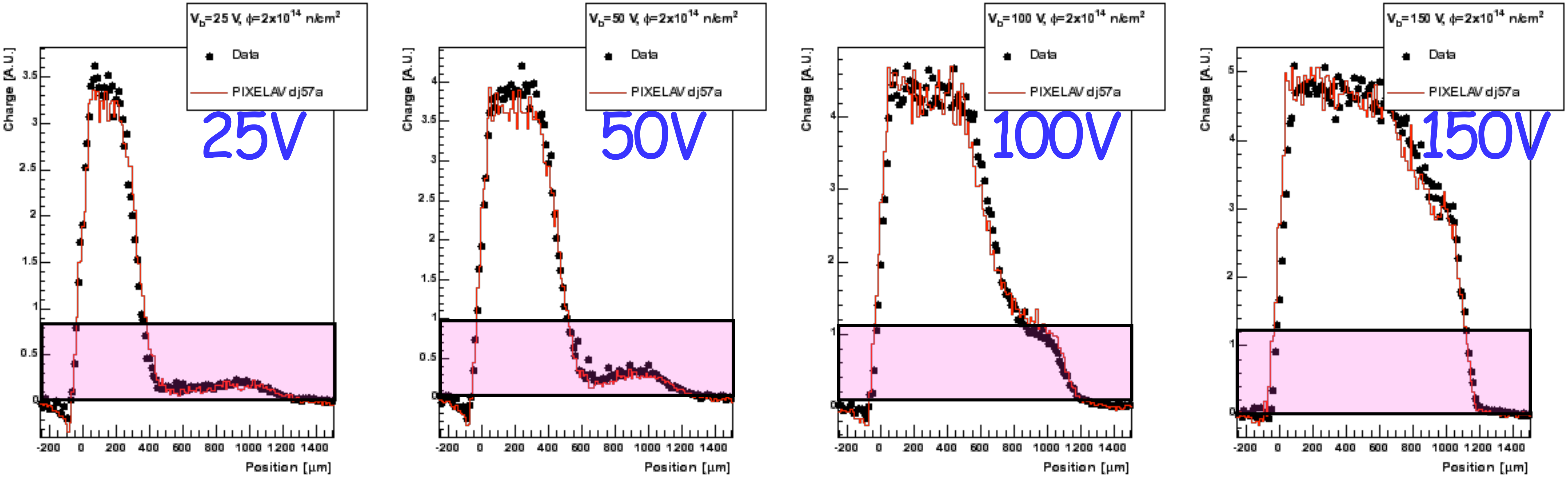
$$\Gamma_{e/h}(\Phi_2) = R_\Gamma \cdot \Gamma_{e/h}(\Phi_1) \qquad R_\Gamma = \Phi_2/\Phi_1$$

$$N_A(\Phi_2) = R_A \cdot N_A(\Phi_1) \qquad R_A = R_\Gamma(1+\delta)$$

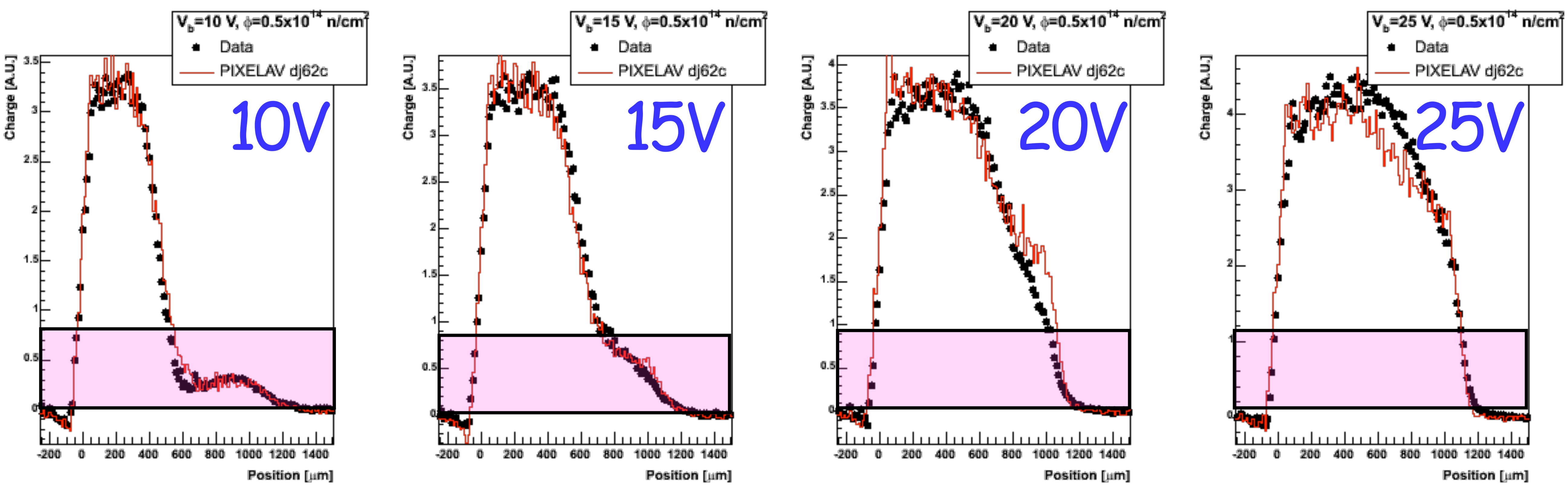
$$N_D(\Phi_2) = R_D \cdot N_D(\Phi_1) \qquad R_D = R_\Gamma(1-\delta)$$

- Trapping rates are linear in the fluence (observed from direct measurements)
- Scale donor and acceptor densities to keep the average factor equal to the ratio of fluences
  - keeps leakage current approximately linear in fluence (also well established)
  - allows the ratio N_A/N_D to vary with fluence

$\Phi_2 = 2.0 \times 10^{14}\ n_{eq}/cm^2$

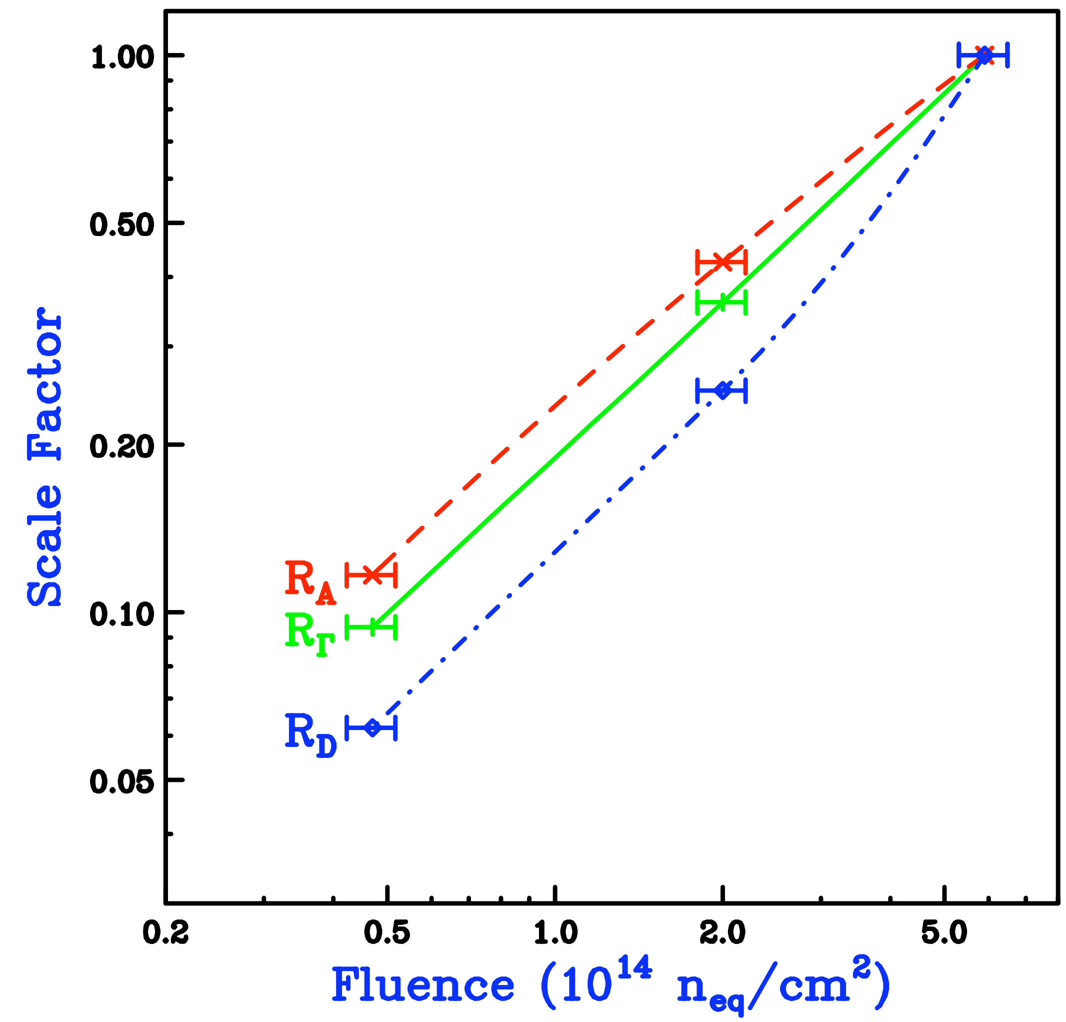


$\Phi_3 = 0.5 \times 10^{14}\ n_{eq}/cm^2$



Scale factor summary:

- trapping rates are linear in Φ
- N_A/N_D increases from 0.40 at $\Phi_1=5.9\times10^{14}\ n_{eq}/cm^2$ to 0.75 at $\Phi_3=0.47\times10^{14}\ n_{eq}/cm^2$



The good news:

- We have a good understanding of the Φ dependence of the sensor response
  - depends upon only 1 parameter (Φ) modulo annealing effects

The bad news:

- ROC readout thresholds will limit ability to see the profile tails
  - need voltage points near transition to backside charge collection
- Poorer resolution of track entry point into sensor than test beam

Expected Effect of Fluence Calibrations

Use tuned simulation to predict performance after damage: with and without calibration

Generic Algorithm (Barrel)

Fluence Φ	Bias	x Bias	x Res (rms)	x Pull (rms)	y Bias	y Res (rms)	y Pull (rms)
0	150V	-0.6μm	16.3μm	1.00	0.1μm	25.1μm	1.02
2×10^{14} n_{eq}/cm^2(no cal)	200V	-12.4μm	17.0μm	1.80	-0.1μm	34.0μm	1.51
2×10^{14} n_{eq}/cm^2(w/ cal)	200V	0.8μm	17.1μm	0.94	0.0μm	29.2μm	0.98
6×10^{14} n_{eq}/cm^2(no cal)	400V	-22.0μm	17.4μm	1.91	0.1μm	35.1μm	1.64
6×10^{14} n_{eq}/cm^2(w/ cal)	400V	1.0μm	17.1μm	0.93	0.1μm	30.6μm	1.00

Template Algorithm (Barrel)

Fluence Φ	Bias	x Bias	x Res (rms)	x Pull (rms)	y Bias	y Res (rms)	y Pull (rms)
0	150V	-0.3μm	12.0μm	1.06	0.1μm	23.0μm	1.06
2×10^{14} n_{eq}/cm^2(no cal)	200V	-13.5μm	15.1μm	2.13	-0.1μm	34.0μm	1.66
2×10^{14} n_{eq}/cm^2(w/ cal)	200V	0.3μm	13.2μm	1.00	0.0μm	27.2μm	1.01
6×10^{14} n_{eq}/cm^2(no cal)	400V	-22.3μm	15.6μm	2.30	0.1μm	34.4μm	1.79
6×10^{14} n_{eq}/cm^2(w/ cal)	400V	0.3μm	14.7μm	0.98	0.1μm	29.0μm	1.01

Summary

- Bias scans are essential to tune the radiation damage parameters
  - measure charge profiles at a sequence of voltages
  - readout thresholds will hide interesting features
    - may need fairly fine scan in voltage to see them
    - can guess voltages from information already available
- Tuned radiation damage simulation is needed even to interpret Lorentz calibrations
  - already have a ~10% correction to account for implant focusing
  - trapping and charge induction change everything even more: can get large offsets
- Tuned simulation is essential to keep the template reco working
  - resolution is improved, biases eliminated
- Tuned simulation is essential to keep error estimates accurate
  - existing error calibration would produce large pulls in both techniques
    - tracking and b-tagging would be significantly impacted