

# Type Inversion in Irradiated Silicon Detectors: a half truth?

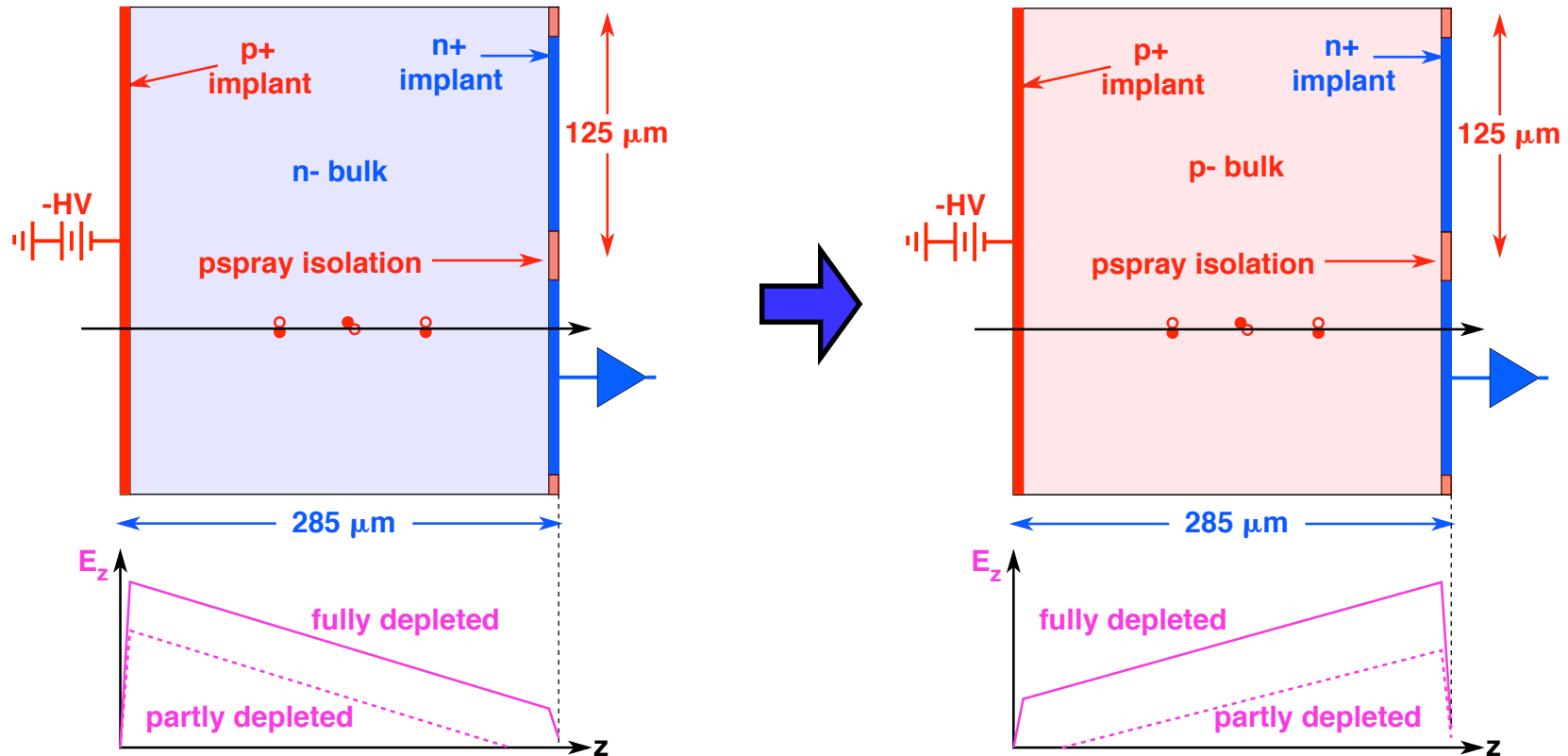
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# Introduction

n/n detectors are widely believed to "type invert" after irradiation:

- pn junction moves from p+ side to n+ side
- fields vary linearly in z before and after irradiation



Why do we believe this?

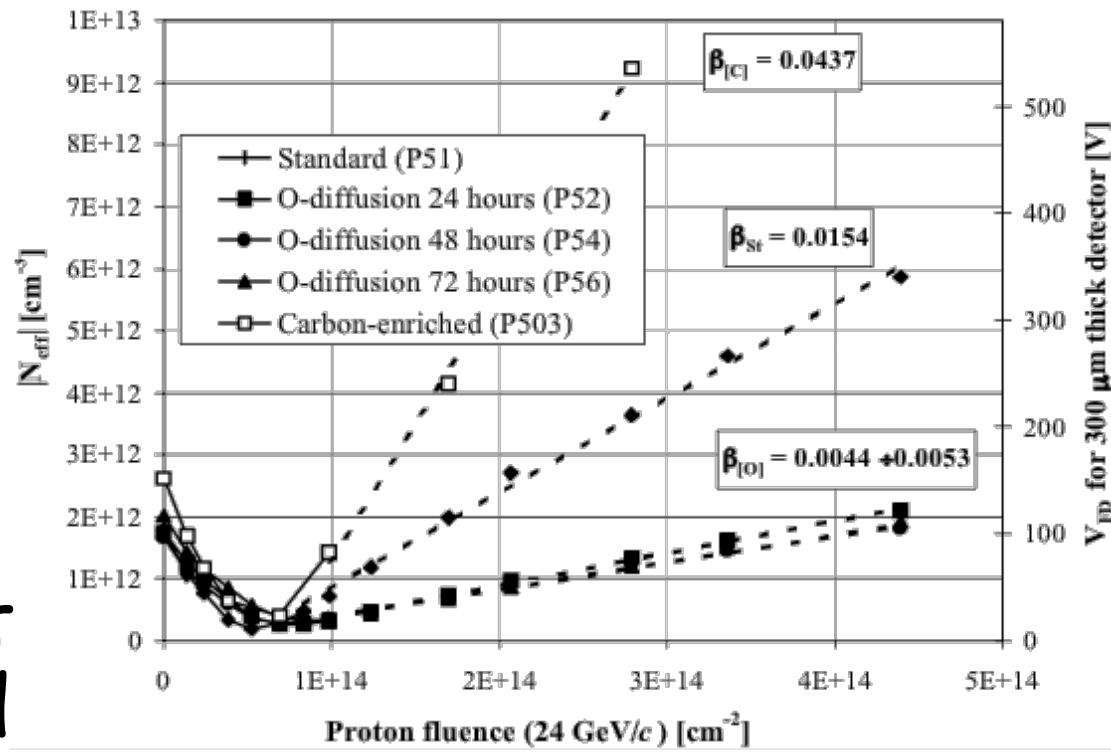
The depletion voltage and resistivity are related to the net (constant) density of ionized impurities  $N_{\text{eff}}$

$$V_{\text{FD}} \simeq \frac{e}{2\epsilon_s} N_{\text{eff}} \ell^2 \quad \rho = \frac{6 \times 10^{15} \Omega/\text{cm}^2}{N_{\text{eff}}}$$

→ description works well for unirradiated detectors

Standard picture suggests that irradiation induces acceptor defects which "invert" the n-substrate,

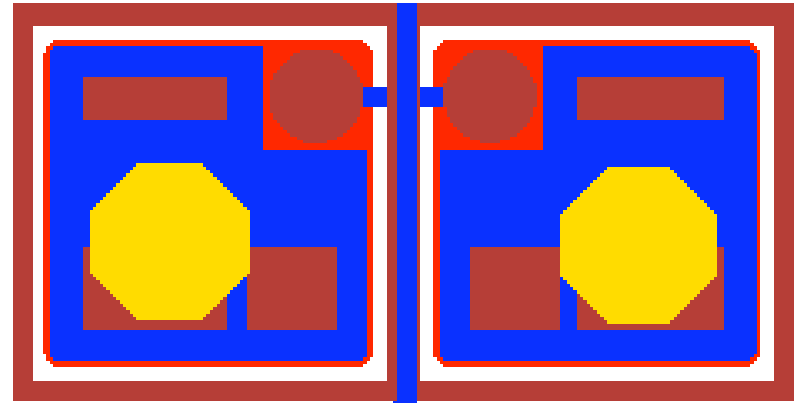
- $V_{\text{max-Q}} \sim V_{\text{FD}}$  has a minimum at a modest fluence
- interpreted to mean that substrate is now p-doped



Nice, simple picture ... is this really what happens?

# CMS Pixel Beam Test

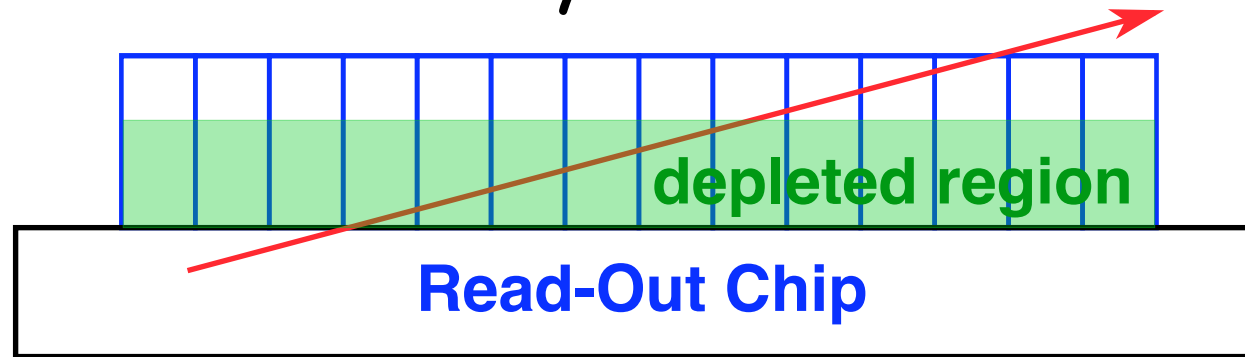
All results are based upon  $125\mu\text{m}\times 125\mu\text{m}$  CiS pspray test sensors:



- 22x32 cells on each chip
- 285 $\mu\text{m}$  thick doFz substrate from Wacker
  - n- doped with  $\rho=2-5\text{ k}\Omega\text{-cm}$ ,  $\langle 111 \rangle$  orientation
- irradiated with 21 GeV protons at PS to fluences:
  - $6\times 10^{14}\text{ n}_{\text{eq}}/\text{cm}^2$  nominal:  $(8.1\pm 0.7)\times 10^{14}\text{ n}_{\text{eq}}/\text{cm}^2$  actual
  - $9\times 10^{14}\text{ n}_{\text{eq}}/\text{cm}^2$  nominal:  $(1.0\pm 0.1)\times 10^{15}\text{ n}_{\text{eq}}/\text{cm}^2$  actual
- irradiated/bump-bonded at  $\sim 30^\circ\text{C}$ , stored at  $-20^\circ\text{C}$

# Charge Collection Studies

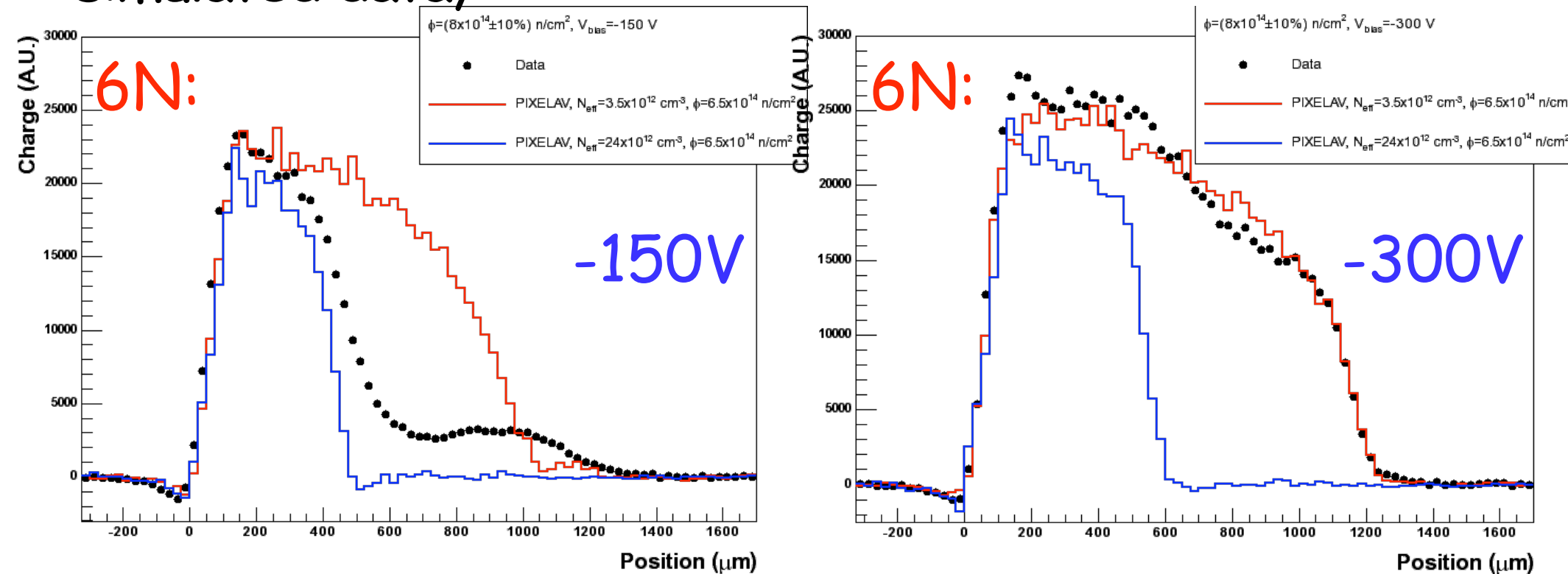
Charge collection was studied from the signal profiles in a row of pixels illuminated by a  $15^\circ$  beam and  $B=0$ ,



- each pixel samples charge deposited at a different depth
- precise beam telescope info is used to refine profile
- collected charge profiles are sensitive to trapping
  - trap rates measured by Ljubljana + Dortmund groups
  - need a simulation to interpret the data

# Irradiated Data vs Sim.

Comparing the charge collection profiles of real and simulated data,



- -300V data are well described by  $N_{\text{eff}} = 3.5 \times 10^{12} \text{ cm}^{-3} \text{ p-}$
- width of -150V peak requires  $N_{\text{eff}} = 24 \times 10^{12} \text{ cm}^{-3} \text{ p-}$ 
  - tail not described

# Double Junctions

There has been experimental evidence of a double peaked electric field in heavily irradiated silicon detectors since 1992 [Li+Kramer]. Eremin, Verbitskaya, and Li have recently modeled this effect using a pair of midgap traps: 1 e-trap and 1 h-trap [see 3rd RD50 workshop, NIM A476, 556 (2002), etc]. The EVL model is based on SRH statistics and generates the effective charge density from the trapping of leakage current,

$$\rho_{\text{eff}} = e [N_D f_D - N_A f_A] + \rho_{\text{dopants}}$$

where  $N_D$  and  $N_A$  are the densities of h- and e-traps and  $f_D$  and  $f_A$  are the trap occupation probabilities. Note that trap energies are far enough from the quasi-Fermi levels that they are not thermodynamically ionized.

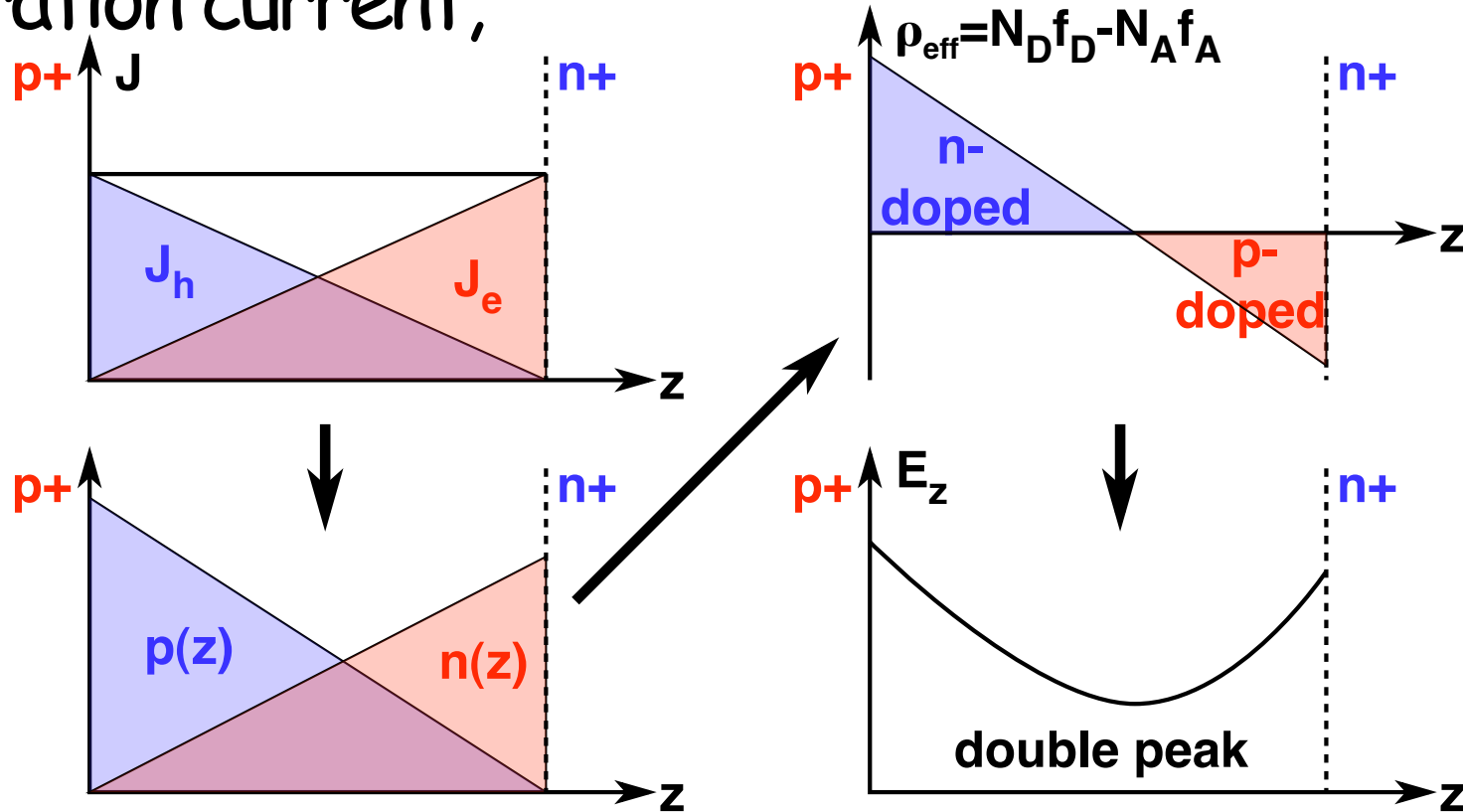
The trap occupation probabilities are given in terms of the usual SRH quantities:

$$f_D = \frac{v_h \sigma_h^D p + v_e \sigma_e^D n_i e^{E_D/kT}}{v_e \sigma_e^D (n + n_i e^{E_D/kT}) + v_h \sigma_h^D (p + n_i e^{-E_D/kT})}$$

$$f_A = \frac{v_e \sigma_e^A n + v_h \sigma_h^A n_i e^{-E_A/kT}}{v_e \sigma_e^A (n + n_i e^{E_A/kT}) + v_h \sigma_h^A (p + n_i e^{-E_A/kT})}$$

- $E_D, E_A$  are defined relative to the mid-bandgap energy
- $\sigma_e$  and  $\sigma_h$  are not well-known in general
- rescaling  $\sigma_{e/h} \Rightarrow r \sigma_{e/h}$  leaves  $f_D$  and  $f_A$  invariant. They depend upon  $\sigma_h/\sigma_e$  only! [key point]

EVL creates double junctions from the trapping of the generation current,



- the trap parameters (3rd RD50 Workshop) are:

trap	$E$ (eV)	$g_{\text{int}}$ ( $\text{cm}^{-1}$ )	$\sigma_e$ ( $\text{cm}^2$ )	$\sigma_h$ ( $\text{cm}^2$ )
donor	$E_V + 0.48$	6	$1 \times 10^{-15}$	$1 \times 10^{-15}$
acceptor	$E_C - 0.525$	3.7	$1 \times 10^{-15}$	$1 \times 10^{-15}$

# DJs in Simulation

Use ISE TCAD to solve for E-field map for sensor simulation. The implementation of the EVL model in TCAD DESSIS device simulator is complicated by the fact that EVL separates the trap dynamics from the leakage current. In Dessis, any attempt to add current-generating defects also traps charge. Solution is to:

- rescale  $\sigma_{e/h} \Rightarrow r\sigma_{e/h}$  (leaves  $f_D, f_A$  invariant) but increases SRH generation current by a factor of  $r$ ,

$$U = \frac{rv_h v_e \sigma_h^D \sigma_e^D N_D (np - n_i^2)}{v_e \sigma_e^D (n + n_i e^{E_D/kT}) + v_h \sigma_h^D (p + n_i e^{-E_D/kT})} + \frac{rv_h v_e \sigma_h^A \sigma_e^A N_A (np - n_i^2)}{v_e \sigma_e^A (n + n_i e^{E_A/kT}) + v_h \sigma_h^A (p + n_i e^{-E_A/kT})} = rU_0$$

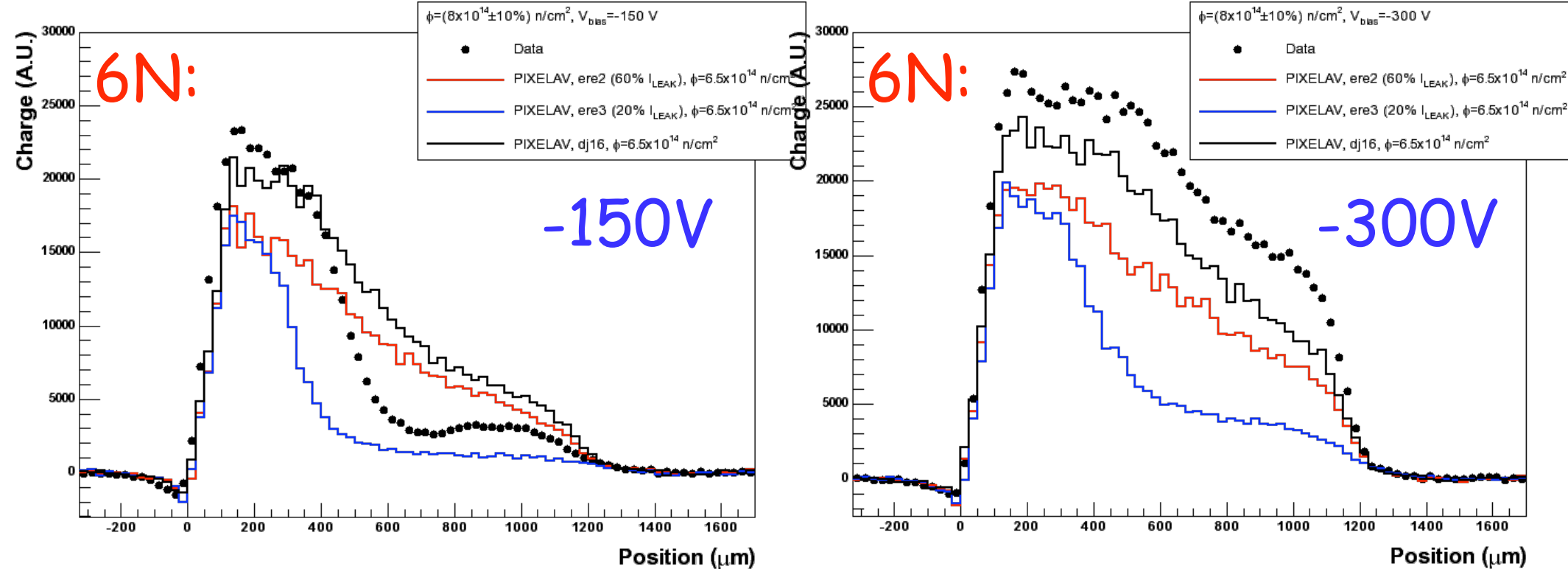
- can adjust leakage current without appealing to external sources
- EVL fix  $\sigma_e = \sigma_h = 10^{-15} \text{ cm}^{-2}$ , keeping  $\sigma_e = \sigma_h$  is mathematically equivalent
- adjusting  $r$  does affect  $n$  and  $p$  which have 1st-order effects on  $f_D, f_A, \rho_{\text{eff}}$  (which we want)
- should reproduce EVL model

What current should we use? After bump-bonding,  $I$  increases by factor 2

$$\Phi = 8 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2:$$

bias	$\alpha = I(20\text{C}) / (V\Phi) \text{ [A/cm]}$
-150V	$15 \times 10^{-17}$
-300V	$19 \times 10^{-17}$
-450V	$25 \times 10^{-17}$

Expect  $\alpha_0 \sim 4 \times 10^{-17} \text{ A/cm}$ : adjust  $r$ , try several values of  $I$



- Model ere2 is normalized to produce 60% of  $I_{\text{obs}}$
- Model ere3 is normalized to produce 20% of  $I_{\text{obs}}$  (saturates  $\alpha = \alpha_0$ )
- Model dj16 scales the introduction rates to 12.5% of the nominal ones and sets current to 55% of  $I_{\text{obs}}$

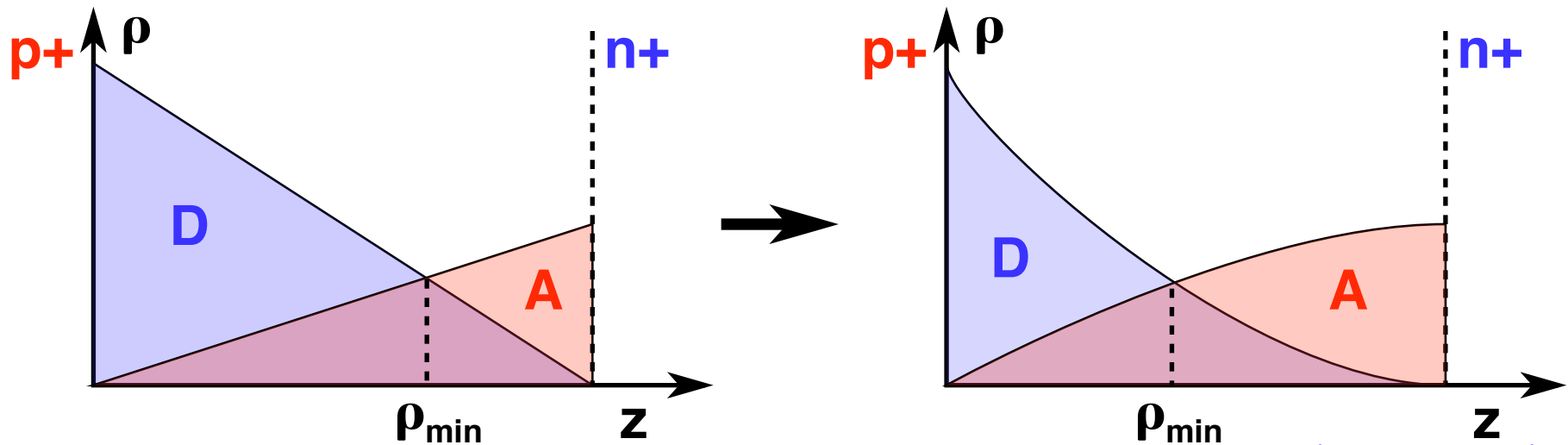
None of these can describe -150V AND -300V data!

# "Fitting" the Data

The EVL model may have the correct qualitative features to describe the charge collection data. In order to adjust it quantitatively, the parameters  $N_A, N_D, \sigma_e^A, \sigma_h^A, \sigma_e^D, \sigma_h^D$  were varied keeping the same  $E_A, E_D$  as EVL. Additionally, the signal trapping rates  $\Gamma_e, \Gamma_h$  are uncertain ( $\pm 10\%$  level due to  $\Phi$  uncertainties and  $\pm 30\%$  level due to possible annealing) and were also varied in the procedure:

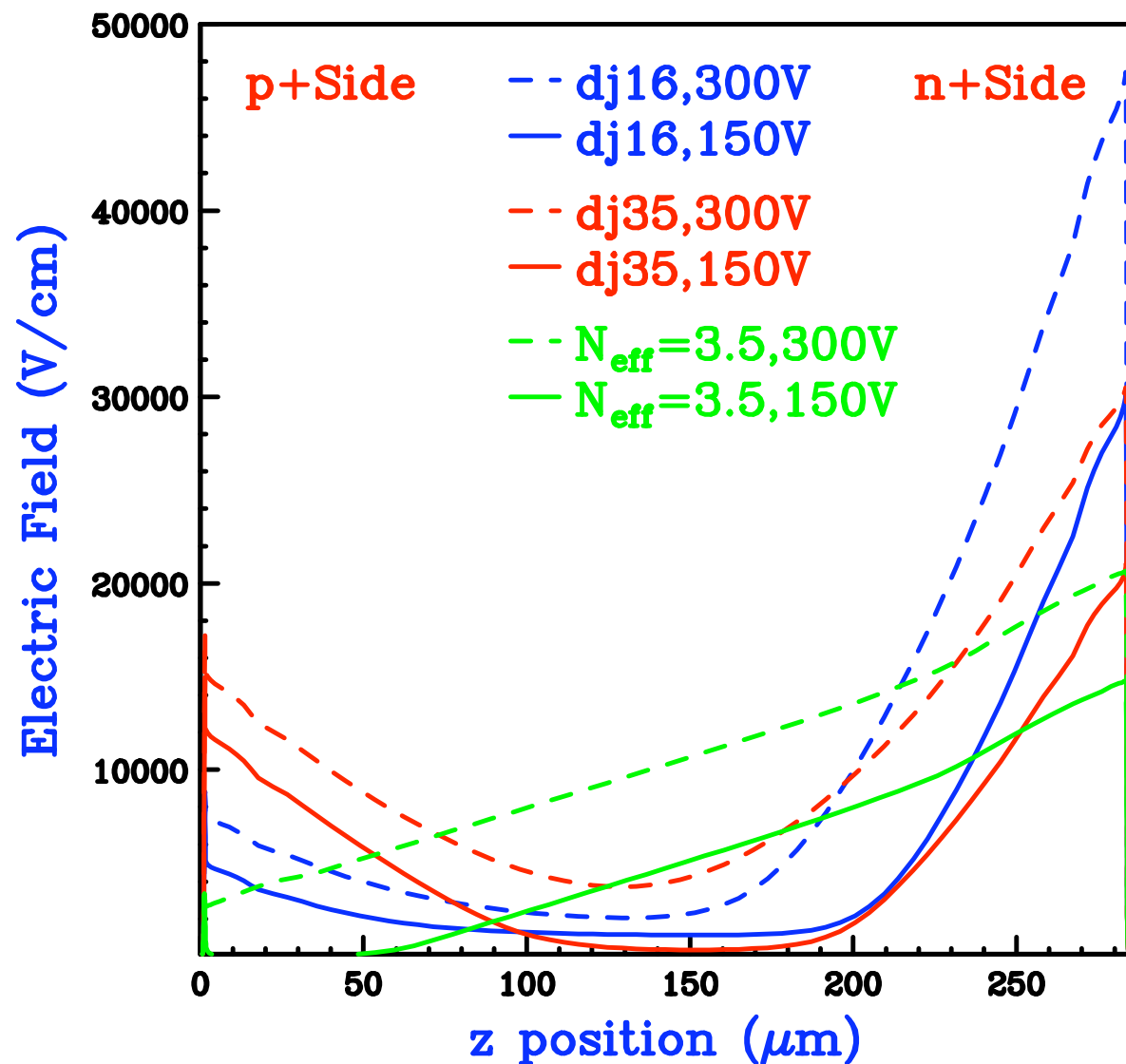
- very slow and tedious: 8hr TCAD run + 2x16hr Pixelav runs + test beam analysis
  - 5 months to produce 36 iterations: dj01 to dj36
- "eyeball" fitting only - no  $\chi^2$  or error matrix
- strong correlations between parameters

None of the EVL models has enough electric field on the **p+** side of the detector to describe the data. The **p+** side field can be increased by increasing  $N_D$  (h-trap density) relative to  $N_A$  (e-trap density). Unfortunately, this makes the high-field region on the **n+** side too narrow at -150V:



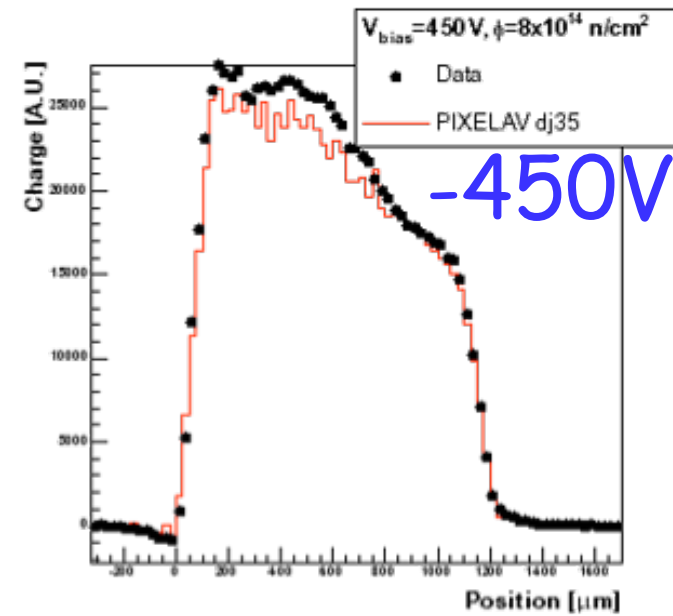
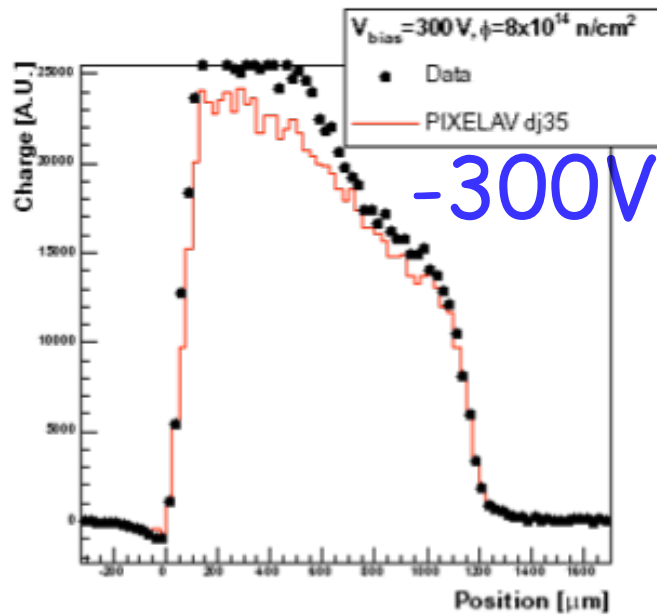
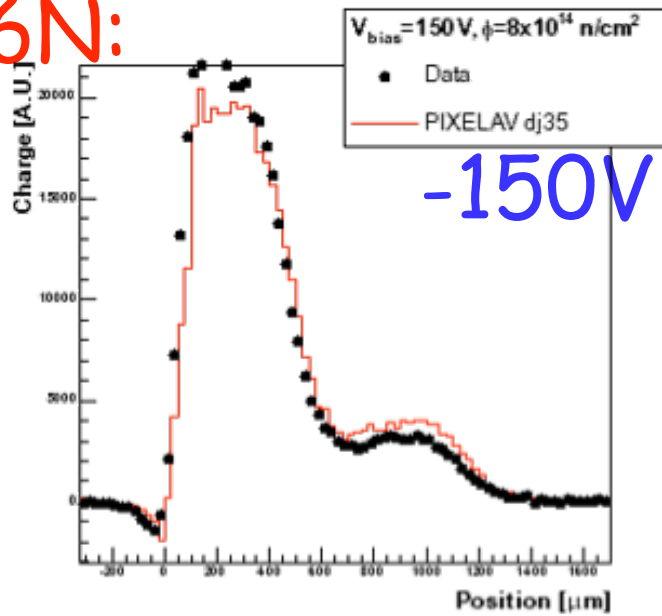
- solution is to adjust the ratios  $\sigma_h^A = 0.3\sigma_e^A$ ;  $\sigma_h^D = 0.3\sigma_e^D$
- adjusting both  $\sigma_h^A$  and  $\sigma_h^D$  minimizes  $E$  at  $\rho_{\min}$
- best current fit to data has  $N_A = 0.4N_D$

- **dj16** is a rescaled EVL model
- **dj35** is the current "best fit" to the lower fluence data
  - low field "gate" is essential to explain large increase in signal with  $V$
- $N_{\text{eff}} = 3.5 \times 10^{12} \text{ cm}^{-3}$  shown for reference

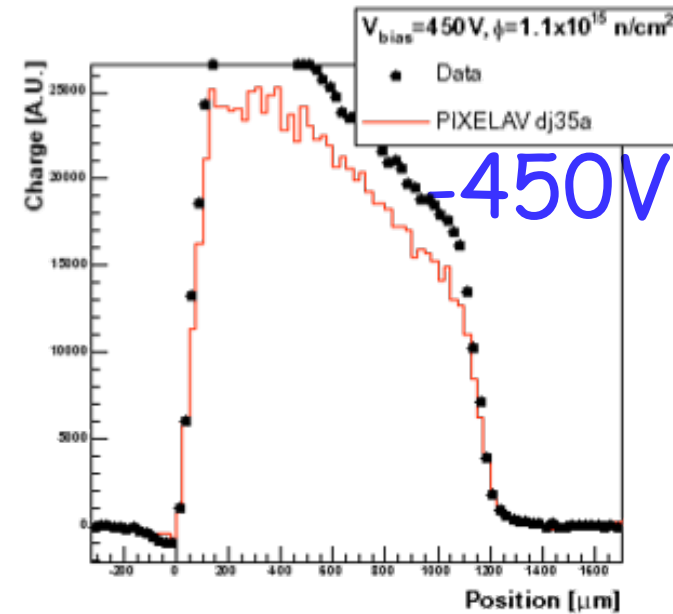
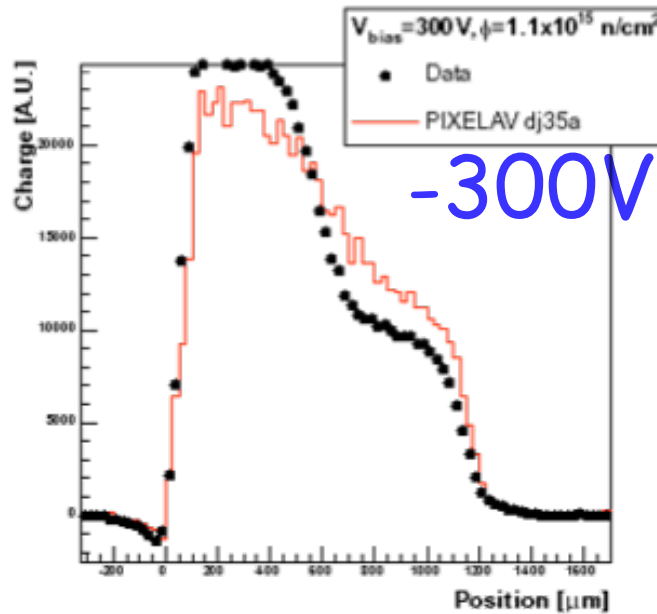
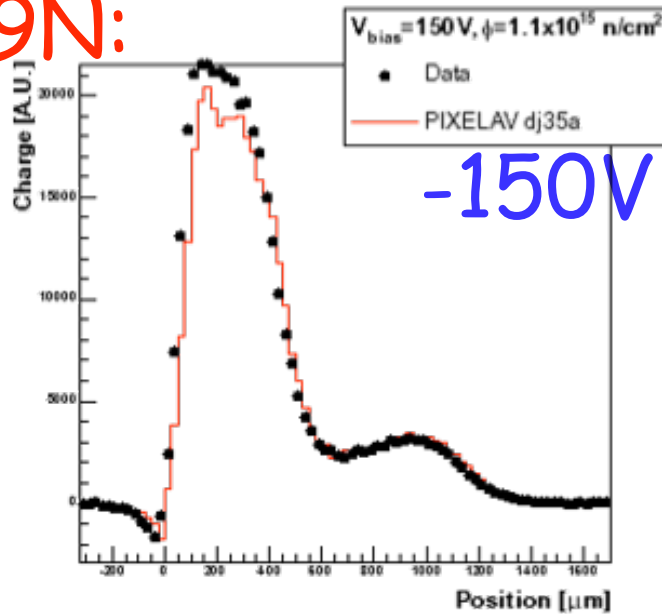


To fit the charge collection data, it was also necessary to scale  $\Gamma_e$  by **0.8** (data aren't very sensitive to  $\Gamma_h$ ),

6N:



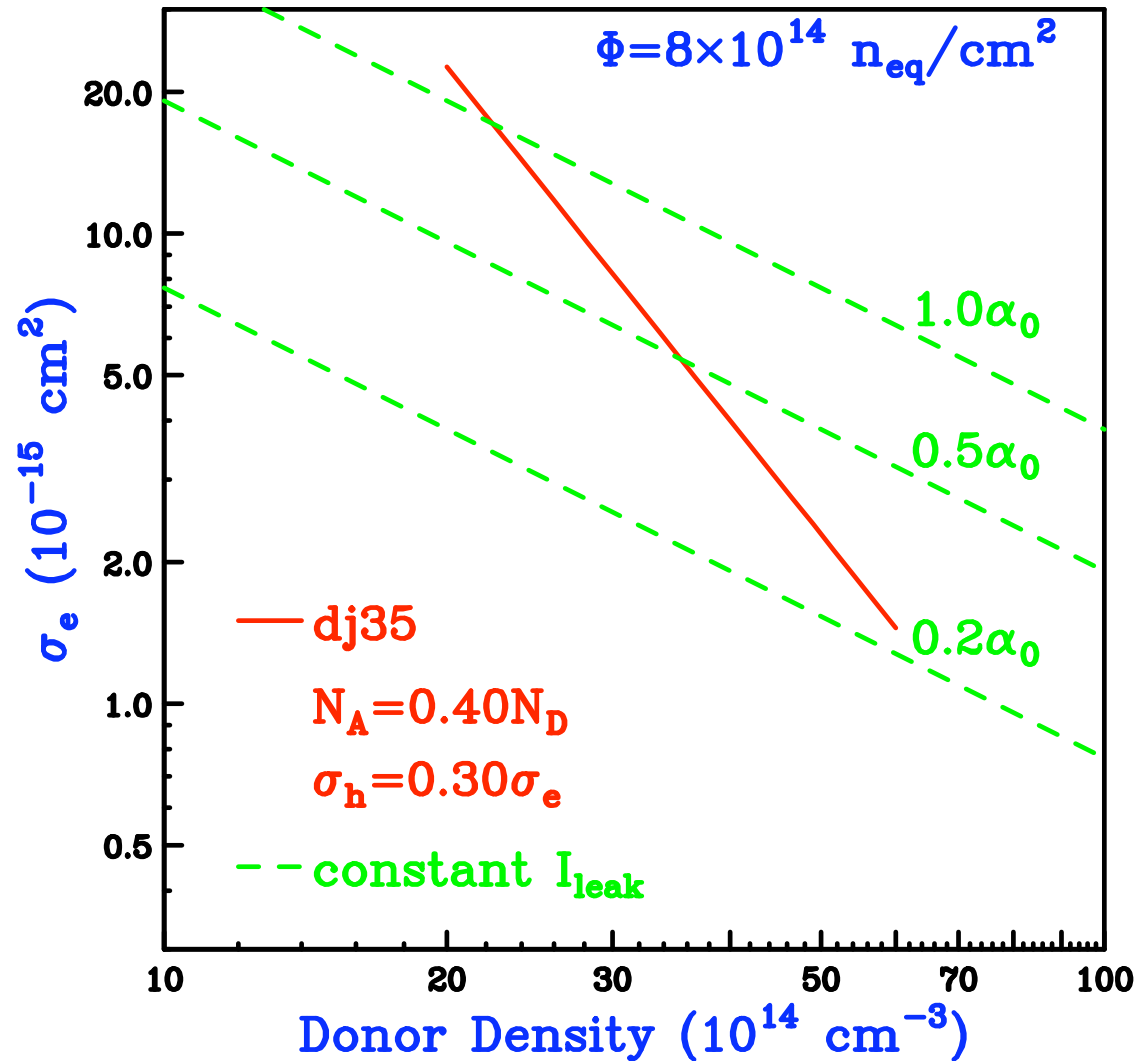
9N:



- high  $\Phi$  model is a scaling of  $N_A, N_D, \Gamma_e, \Gamma_h$  by  $\Phi_{9N}/\Phi_{6N}$
- 150V "wiggle" caused by hole collection on p+ side

There is a contour in  $N_D$  vs  $\sigma_e$  space ( $\sigma_e \propto N_D^{-2.5}$ ) that produces (more or less) the same efield in the detector:

- large  $z$ , -150V tail becomes too large at small  $N_D$  ( $N_D < 20 \times 10^{14}$ )
- large  $z$ , -300V signal becomes too small at large  $N_D$  ( $N_D > 50 \times 10^{14}$ )
- $I \propto N_D \sigma_e$  so virtually any  $I$  up to  $\alpha_0$  fits data ( $\alpha = \alpha_0$  is still too small to account for meas  $I$ )

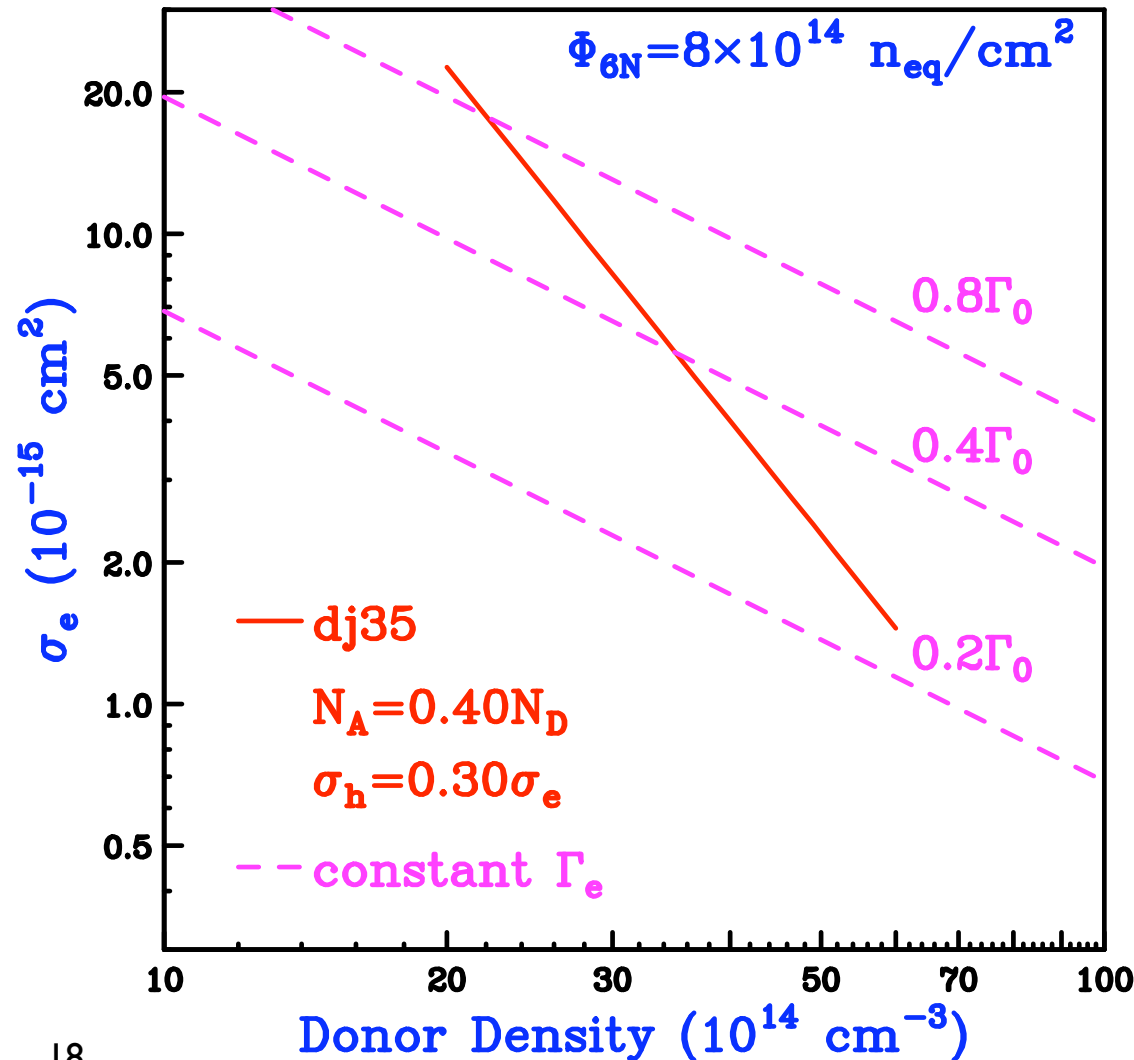


The defects could also contribute to the effective signal trapping rates. Assuming that  $f_D$  and  $f_A$  are small,

$$\Gamma_e = v_e \left[ \sigma_e^A N_A (1 - f_A) + \sigma_e^D N_D f_D \right] \simeq v_e \sigma_e^A N_A$$

$$\Gamma_h = v_h \left[ \sigma_h^D N_D (1 - f_D) + \sigma_h^A N_A f_A \right] \simeq v_h \sigma_h^D N_D$$

- since  $v_e \sim v_h$ , dj35 predicts  $\Gamma_e \sim \Gamma_h$
- $\Gamma_e = v_e N_A \sigma_e \propto N_D \sigma_e$  so virtually any  $\Gamma_e$  up to  $0.8\Gamma_0$  fits data ( $\Gamma_0$  is rate expected for  $\Phi_{6N}$ )
- can account for all signal trapping that we see!

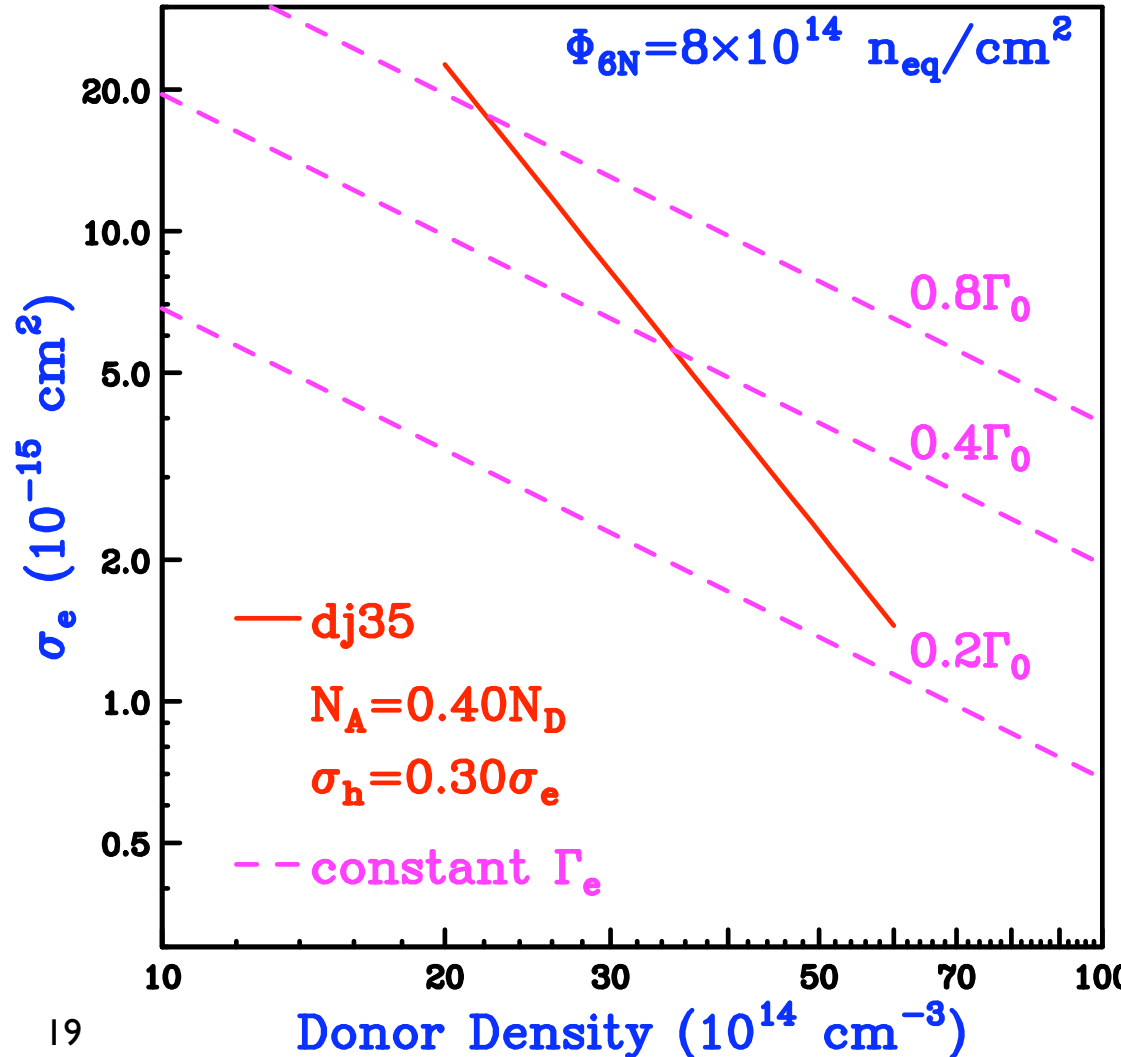


The same plot also suggests a solution to the apparent puzzle that  $\rho_{\text{eff}}$  is sensitive to  $O_2$  whereas  $\Gamma_{e/h}$  are not.

We can add another donor/acceptor pair (suppressed by added  $O_2$ ) which have large  $N_{D/A}$  but small  $\sigma_{e/h}$ :

➔ could have large effect on  $\rho_{\text{eff}}$  and small effect on  $\Gamma_{e/h}$

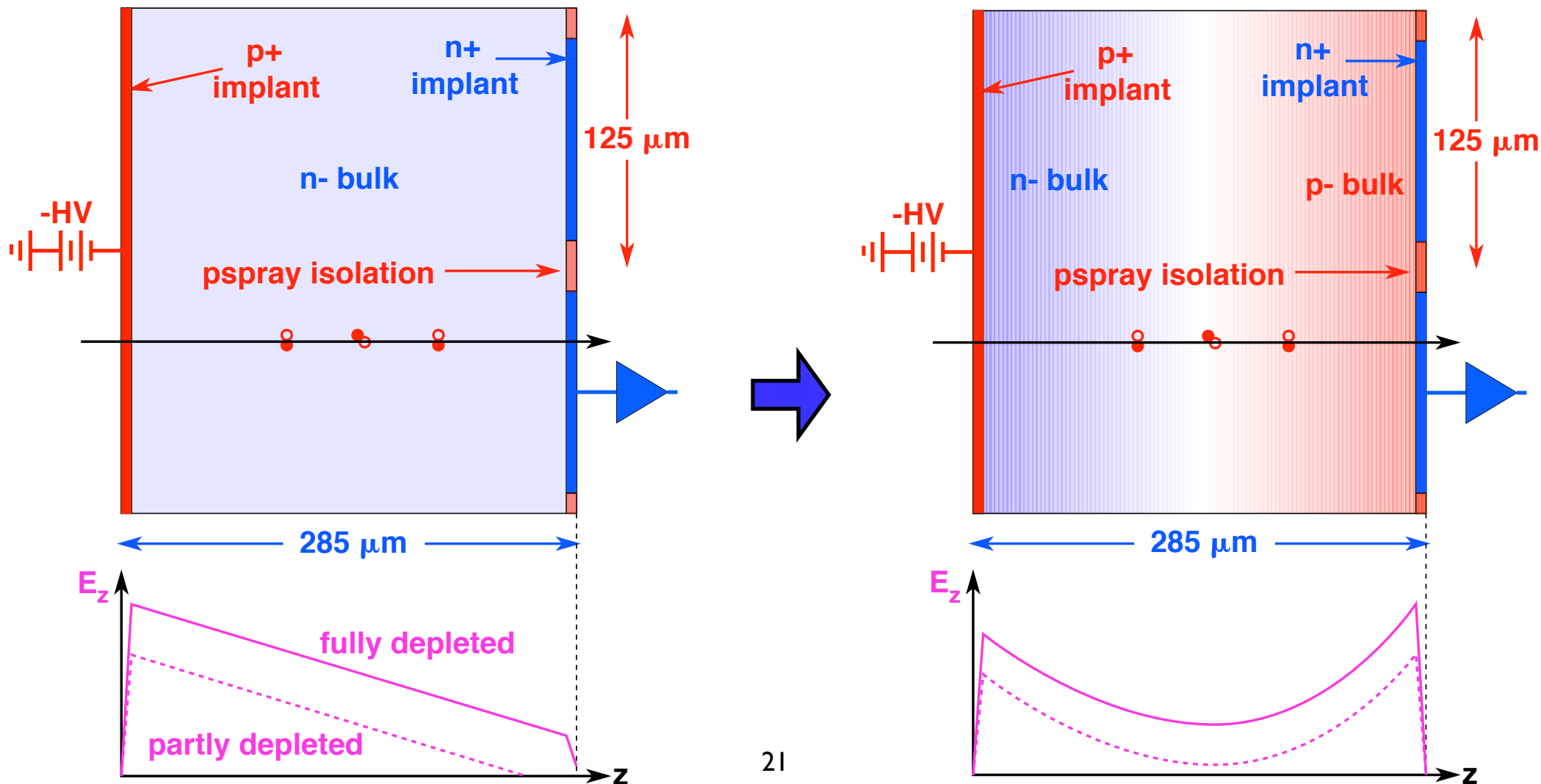
- $\rho_{\text{eff}}$  is affected equally by large- $\sigma$  "fast" traps and small- $\sigma$  "slow" traps
- $\Gamma_{e/h}$  are affected only by large- $\sigma$  "fast" traps



# Conclusions

- It is clear that a two-peak electric field is necessary to describe our charge collection data
- A two-trap double junction model can be tuned to provide reasonable agreement with the data
  - can describe any  $I$  up to theoretical value (smaller than observed value)
  - can account for trapping rate up to observed value
  - suggests mechanism for  $O_2$  dependence of  $\rho_{\text{eff}} + \Gamma_{e/h}$
- Two-trap model is an "effective" theory:
  - there are many trapping states, ionized defects are still possible: model parameters probably not physical
- Model will be very useful in charge-sharing calibration

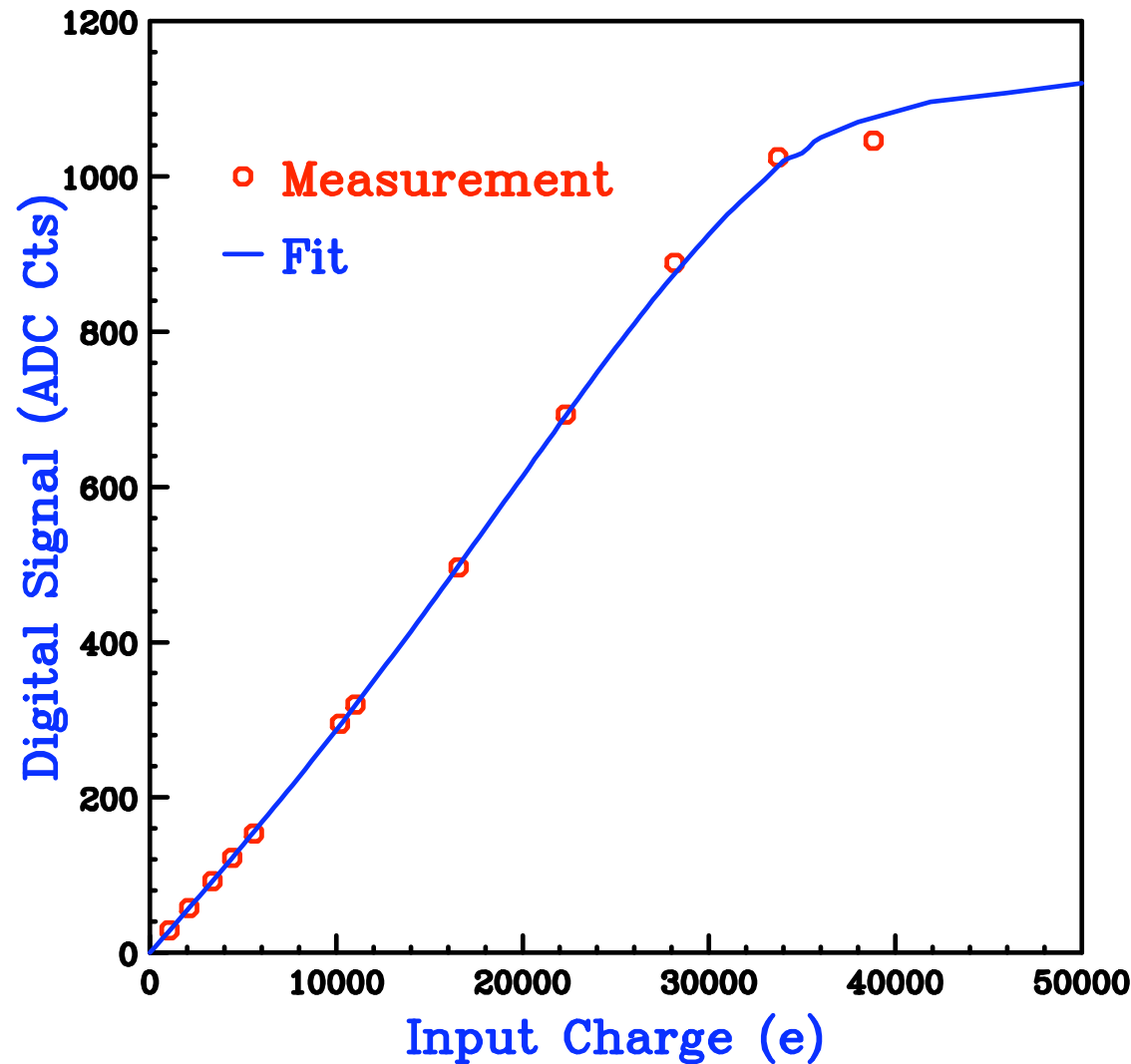
- Usual model of type inversion after irradiation is wrong:
  - only  $\sim 1/2$  of the junction inverts,  $\rho_{\text{eff}}$  is not constant
  - “full depletion” is an ill-defined concept:  $V_{\text{max-Q}}$  is related to  $N_{\text{eff}}$  by a physically meaningless relation



# Extra Slides

# Readout Chip

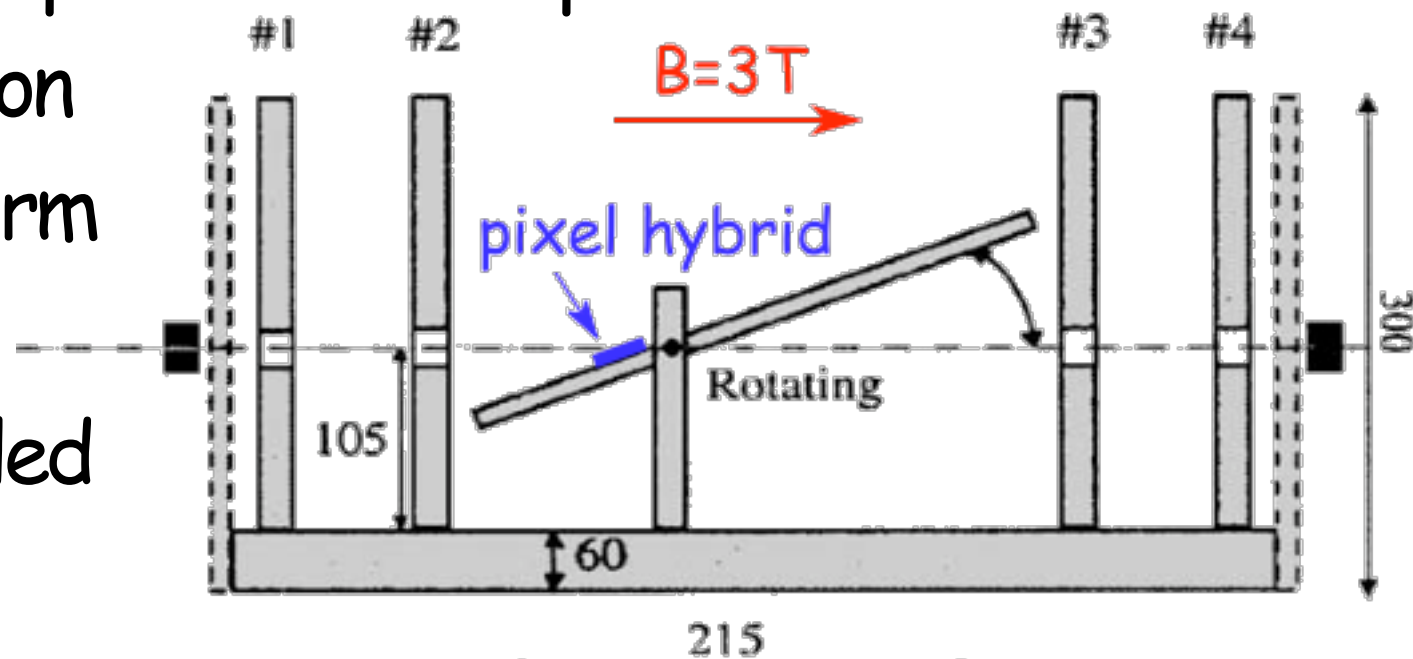
- sensors bump-bonded to PSI30 ROC from Honeywell
  - doesn't sparsify data, permits readout of small signals
  - good linearity to 30k e (at 15°, mp charge deposit is ~10k e)
  - not very rad-hard
- irradiated sensors bump-bonded "cold" to unirradiated ROCs



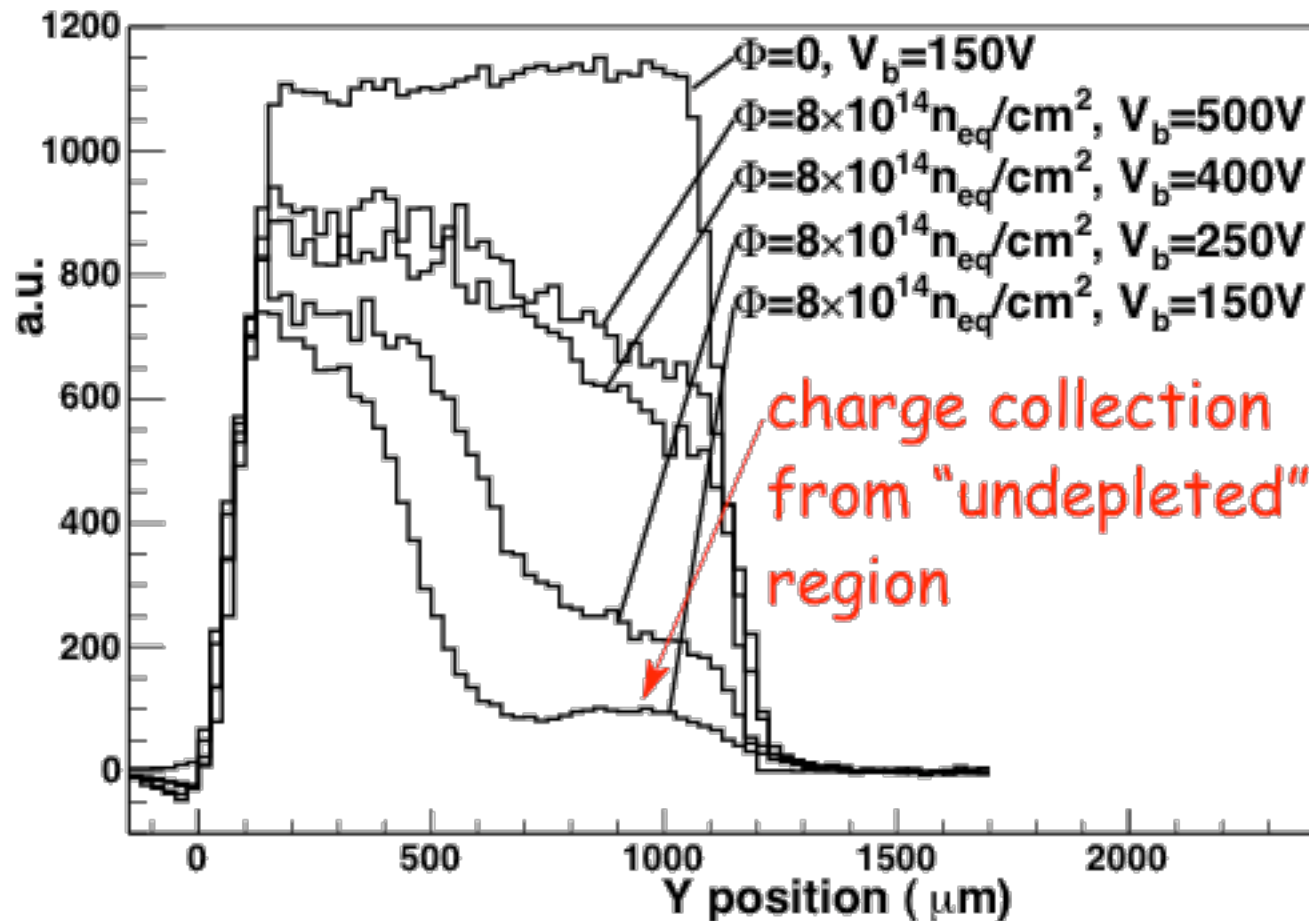
# Test Beam Layout

Beam tests performed in SPS H2 beam:

- 150-225 GeV  $\pi^+$ /p
- 3T open geometry magnet with field along beam axis
- 4xy plane Si strip beam telescope
  - 1  $\mu\text{m}$  resolution
  - hybrid platform rotates
  - platform cooled to  $-20^\circ\text{C}$
  - heat load from ROC increases sensor temp to  $\sim -10^\circ\text{C}$



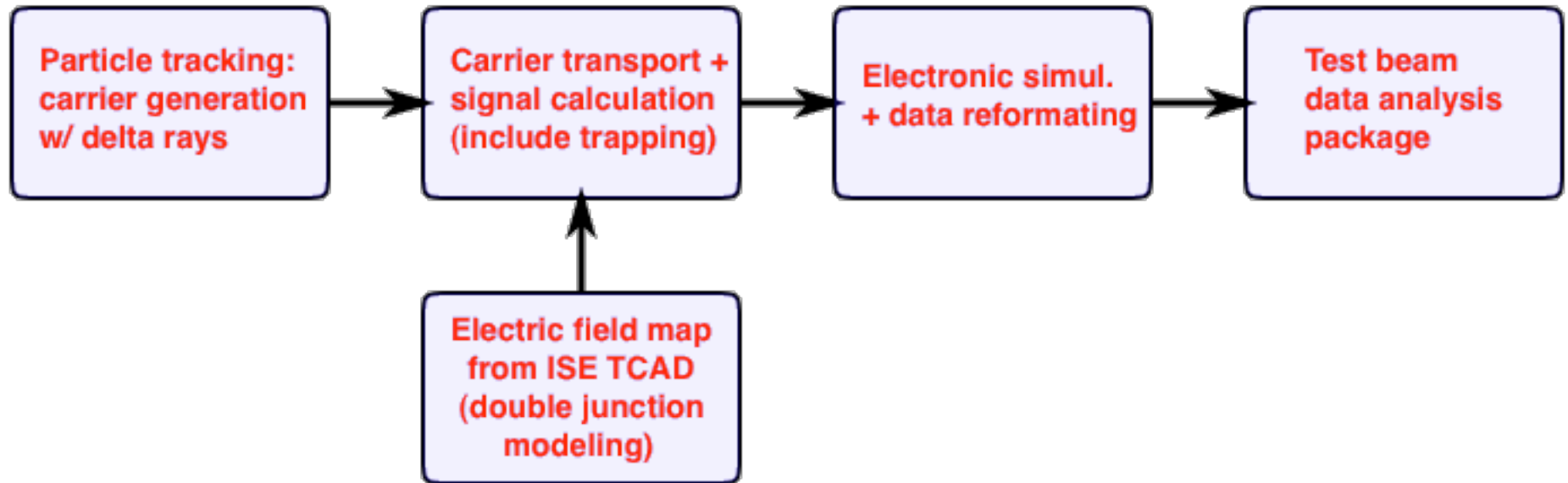
The charge collection profiles for a fully depleted unirradiated sensor and for a heavily irradiated sensor at several bias voltages show interesting features:



- field across the entire junction at low bias
- $Q(300V)/Q(150V) = 2.1$ , faster than  $(2)^{1/2}$

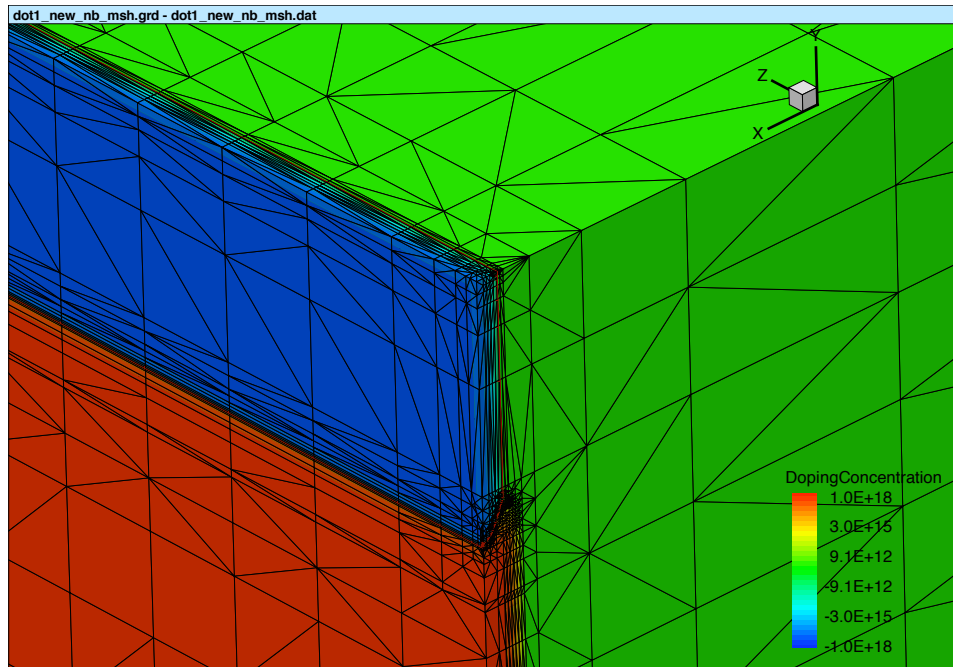
# Simulation

Over the last several years, we have constructed a detailed sensor simulation, Pixelav [NIM A511, 88 (2003)]

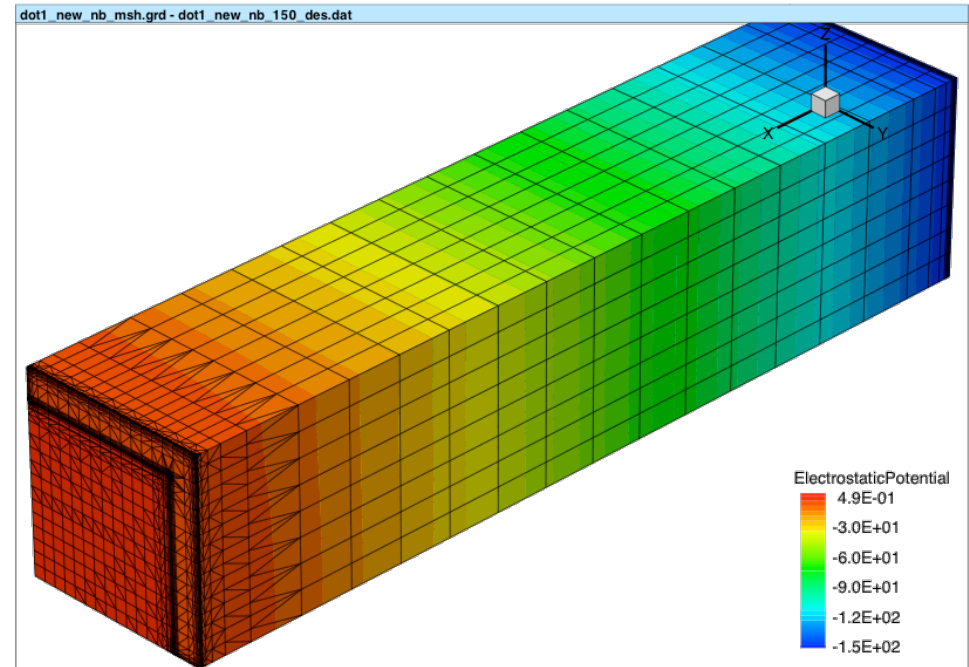


- Particle tracking: e-h pairs are generated according to x-sections of Bichsel [RMP 60, 663 (1988)]
  - $E < 1$  MeV delta rays propagated according to range/energy relation (density of e-h pairs from  $dE/dx$ )

- Electric field calculation: uses ISE TCAD software
  - simulate 1/4 pixel cell to keep mesh size ~25,000 nodes. This requires 4-fold symmetry (no bias dot)
  - no process simulation, use MESH w/ analytic doping profiles to generate grid and doping files



doping profiles



potential distribution

- Transport calculations are done by integrating the fully saturated equation of motion for the carriers

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

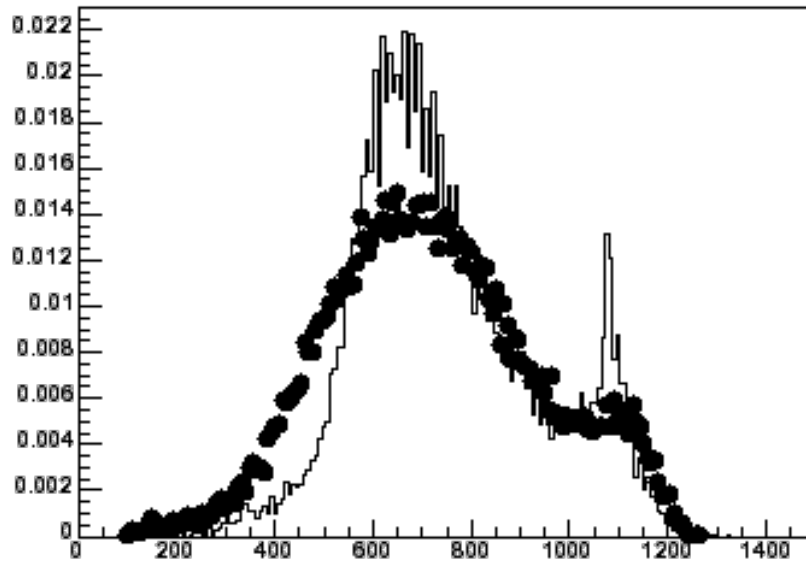
- 4th-order R-K calc is vectorized for G4 processor
- incorporates diffusion and trapping
- signal induced from displaced, trapped charge is calculated from segmented parallel plate cap. model
- Electronics Simulation:
  - includes leakage current and electronic noise
  - readout chip analog response from measurements
  - ADC digitization
  - reformat data to look like test beam data

# Unirradiated Data

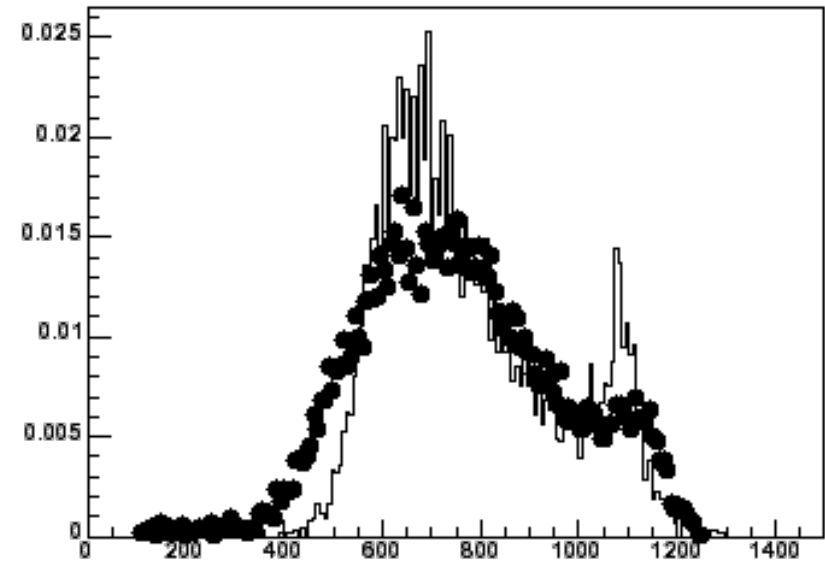
Simulation is checked by comparing w/ unirradiated data:

- Pulse height distributions:

Highest Pixel Signal



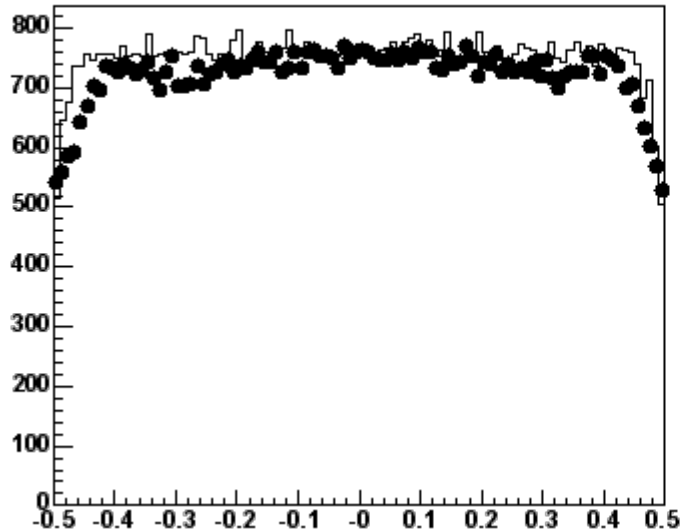
Highest Pixel w/ cut



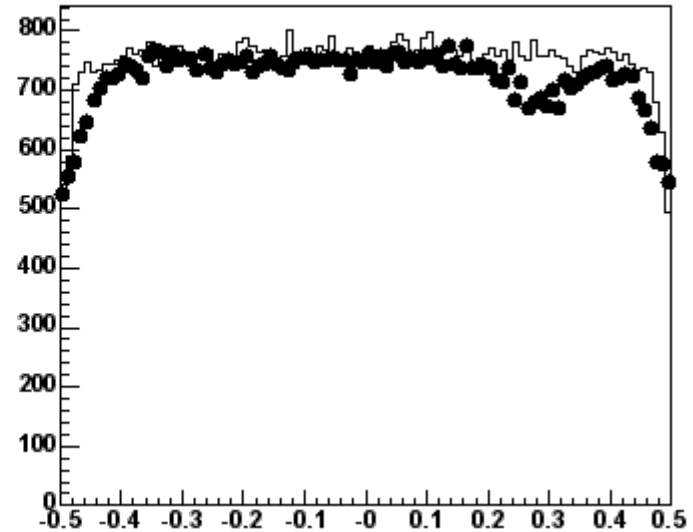
- mean agrees well with data
  - too few low charges in simulation
  - too many simulated large charge events
- ➡ bias dot doesn't collect charge and is not simulated!

- Diffusive charge sharing for normally incident tracks:

Charge profile vs x: Hit pixel



Charge profile vs y: Hit pixel



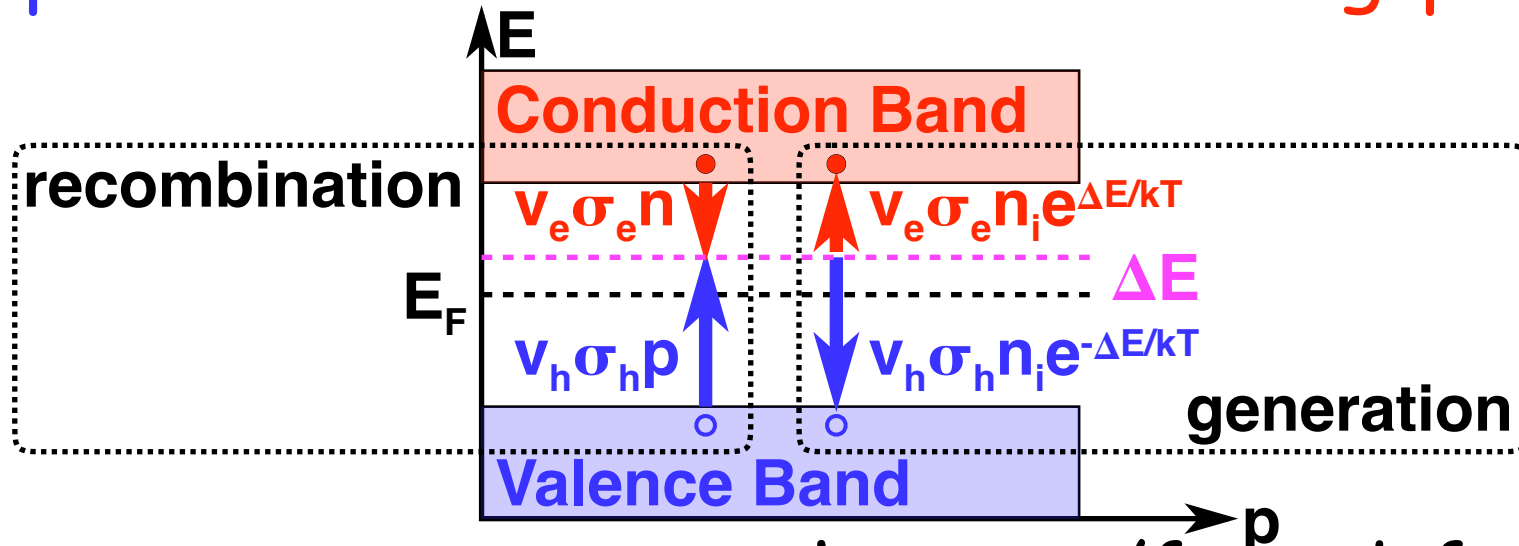
- charge loss due to bias dot is visible in data

- Lorentz angle:

Bias (V)	Data (deg)	Simulation (deg)
150	22.8±0.7	24.7±0.9
300	14.7±0.5	17.4±0.9
450	11.2±0.5	12.0±0.9

➔ Simulation does a reasonable job describing the data

Shockley-Read-Hall statistics is a description of the generation and recombination of  $e-h$  pairs in indirect semiconductors (like Si). Since  $m_e^* \neq m_h^*$ , cannot conserve  $E$  and  $p$  without lattice momentum: **need midgap defects**



- four processes transport charge to/from defect state
- $v_e$  and  $v_h$  are thermal velocities
- $\sigma_e$  and  $\sigma_h$  are capture cross sections
- $n, p$  are carrier densities;  $n_i$  is intrinsic carrier density