Updated double junction simulation of CMS pixel test beam data

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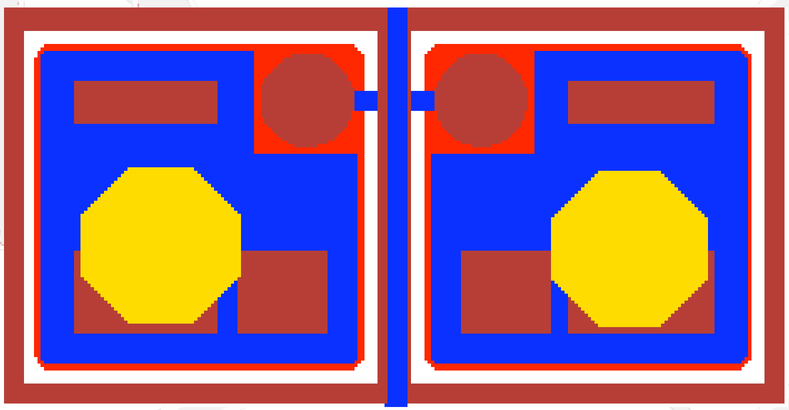
2004 CMS Pixel Beam Test

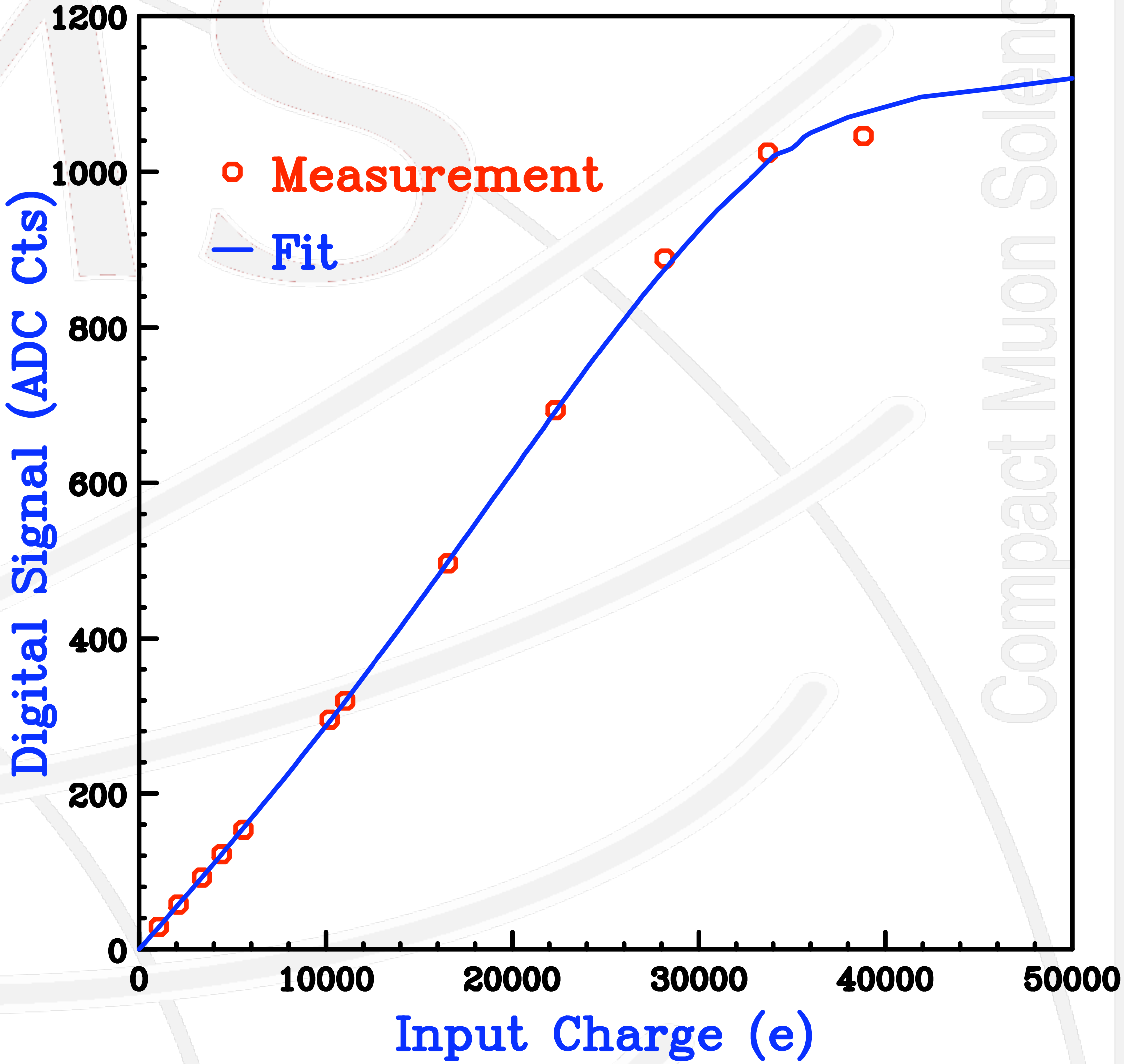
All results are based upon 125μmx125μm CiS pspray test sensors:



- 22x32 cells on each chip
- 285μm thick dofz substrate from Wacker
  - n- doped with ρ=2-5 kΩ-cm, <111> orientation
  - oxygenated at 1150C for 24 hours
- irradiated with 24 GeV protons at PS to fluences: $(5.9, 2.0, 0.47)\times10^{14}\ n_{eq}/cm^2$
- annealed for 3 days at 30°C
  - all sensors are "Standard Annealed"
- bump-bonded at 20°C, stored at -20°C

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

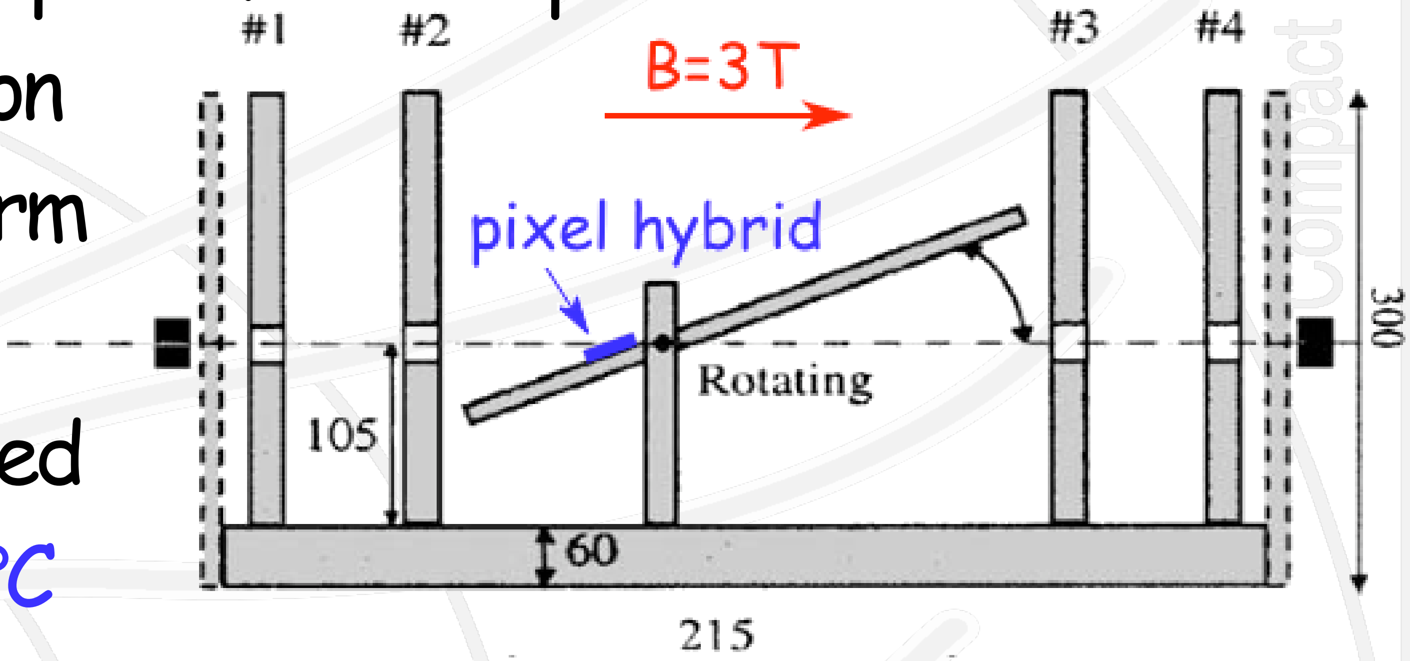


supply of PSI30 now exhausted!

Test Beam Layout

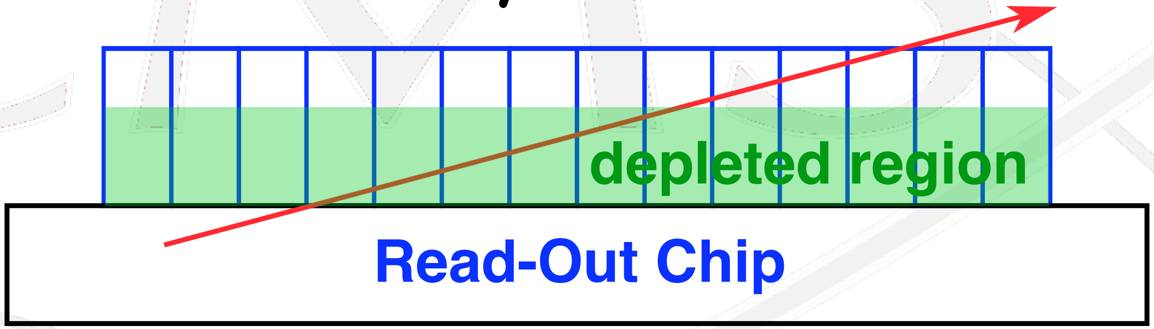
Beam tests performed in SPS H2 beam:

- 150-225 GeV π^+/p
- 3T open geometry magnet with field along beam axis
- 4xy plane Si strip beam telescope
  - 1 μm resolution
  - hybrid platform rotates
  - platform cooled to: -15°C, -30°C
  - ROC heat load increases sensor T to: -10°C, -25°C



Charge Collection (V. Chiochia+M.S.)

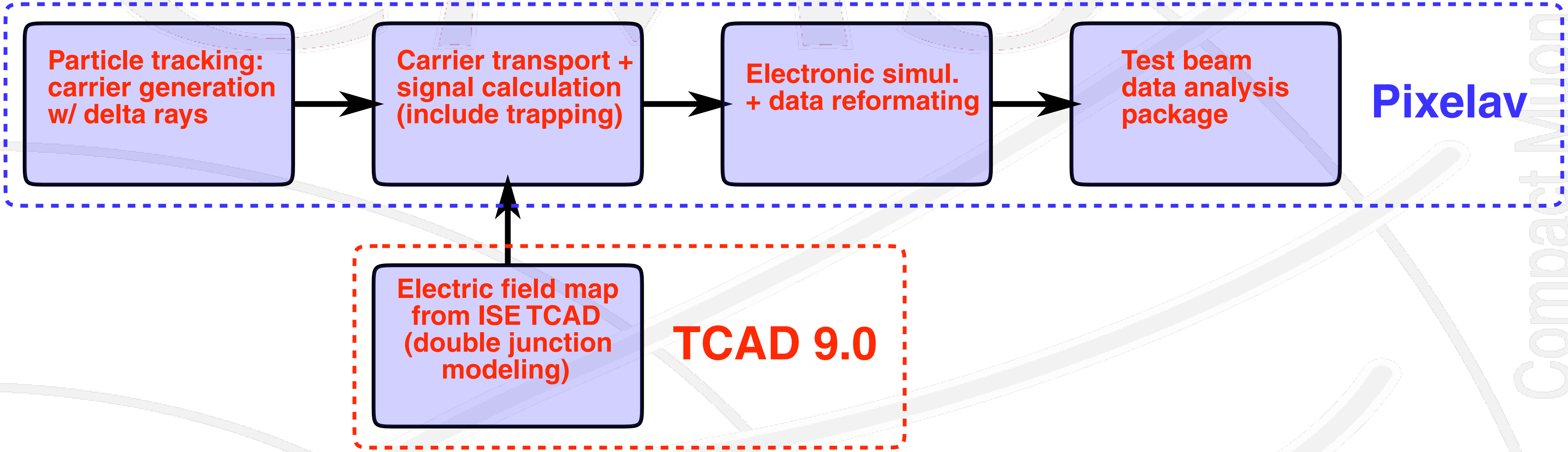
Charge collection was studied from the signal profiles in a row of pixels illuminated by a 15° beam and B=0,



- each pixel samples Q 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
- profiles at several V provide enormous information/ contraints on E-field profiles

Simulation

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



Particle tracking: carrier generation w/ delta rays

Carrier transport + signal calculation (include trapping)

Electronic simul. + data reformatting

Test beam data analysis package

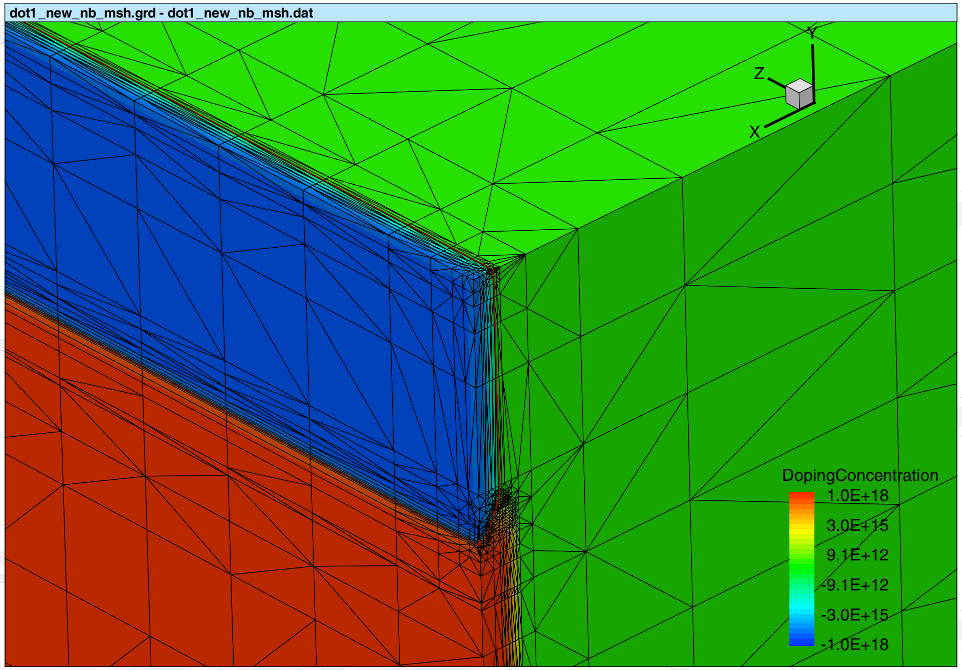
Pixelav

Electric field map from ISE TCAD (double junction modeling)

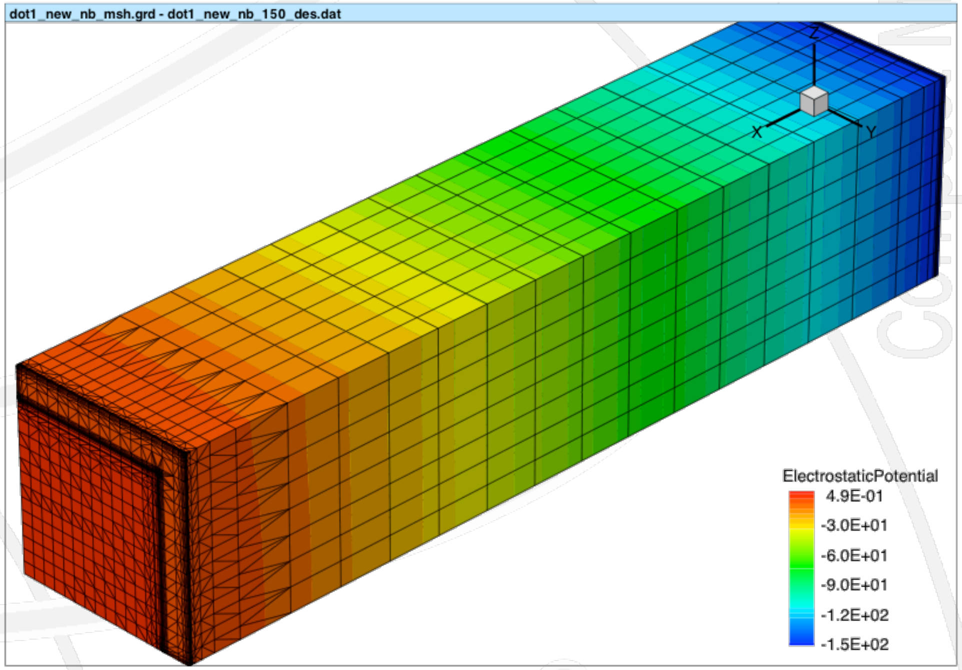
TCAD 9.0

- 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 TCAD 9.0 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

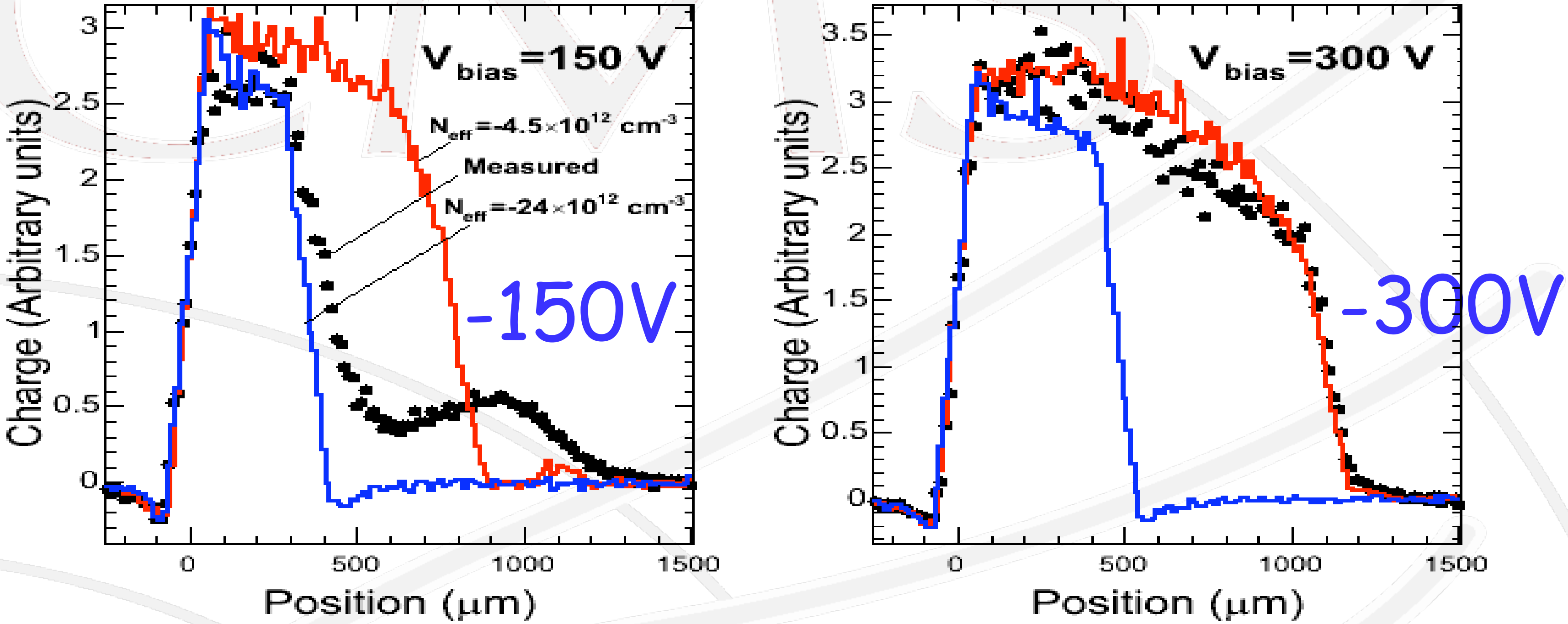
- Transport calculations are done by integrating the fully saturated equation of motion for the carriers

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

  - 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

Irradiated Data vs Simulation

Comparing the charge collection profiles of real and simulated data at $\Phi_1 = 5.9\times10^{14}\ n_{eq}/cm^2$



- -300V data are well described by $N_{eff}=4.5\times10^{12}cm^{-3}$ p-
- width of -150V peak requires $N_{eff}=24\times10^{12}cm^{-3}$ p-
  - tail not described
- Constant N_{eff}/linear E-fields ruled out!

Modeling of Sensors

Space charge in irradiated sensors can be produced by ionized traps. The 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 and use single h/e-traps
  - D and A states don't have to be physical states: they represent average quantities!
  - model parameters are not physical

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

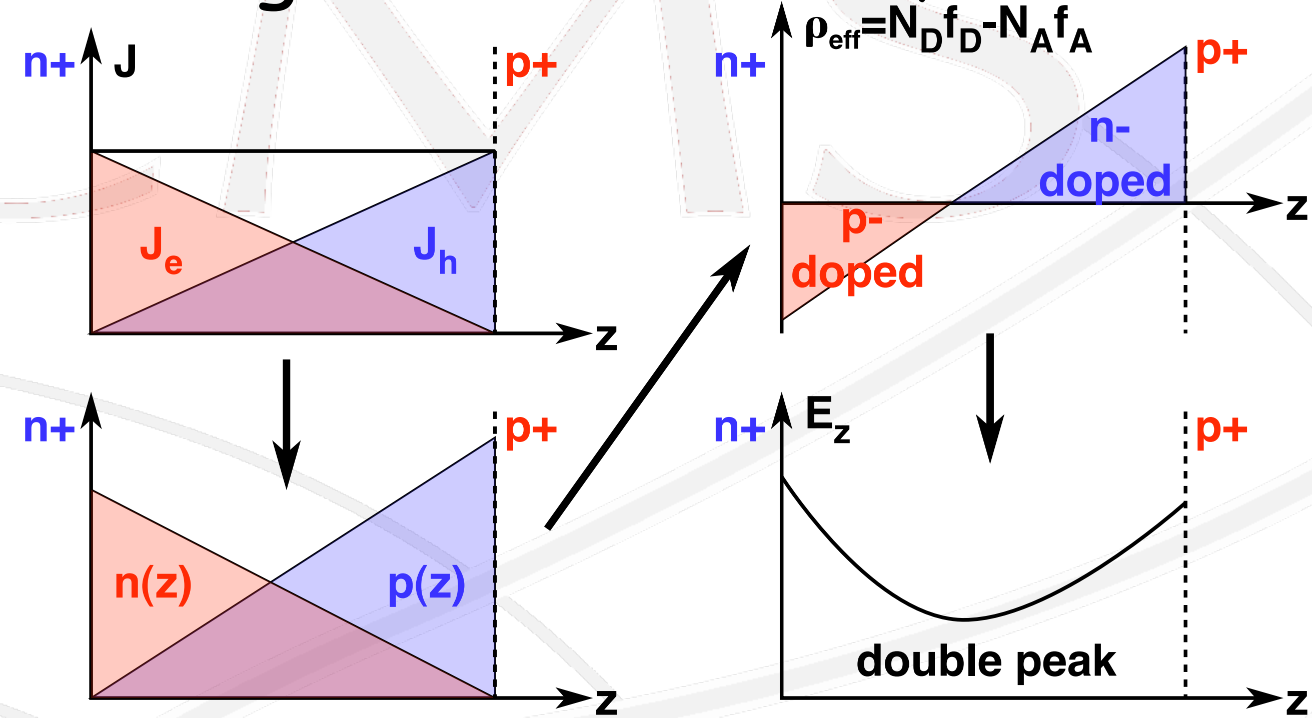
$$f_D = \frac{v_h \sigma_h^D p + v_e \sigma_e^D n_i e^{E_D/kT}}{v_e \sigma_e^D (n + n_i e^{E_D/kT}) + v_h \sigma_h^D (p + n_i e^{-E_D/kT})}$$

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

- E_D, E_A are defined relative to the mid-bandgap energy
- σ_e and σ_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 σ_h/σ_e only! [key point]
- rescaling $n/p \Rightarrow r(n/p)$ does not leave f_D and f_A invariant (f_D and f_A depend on I and E_D, E_A)

EVL Model

Eremin, Verbitskaya, Li create double junctions from the trapping of the generation current,



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

trap	E (eV)	g_{int} (cm^{-1})	σ_e (cm^2)	σ_h (cm^2)
donor	E_V+0.48	6	$1x10^{-15}$	$1x10^{-15}$
acceptor	E_C-0.525	3.7	$1x10^{-15}$	$1x10^{-15}$

DJs in ISE DESSIS

EVL separates the trap dynamics from the leakage current. In Dessis, any attempt to add current-generating defects also traps charge. Solution:

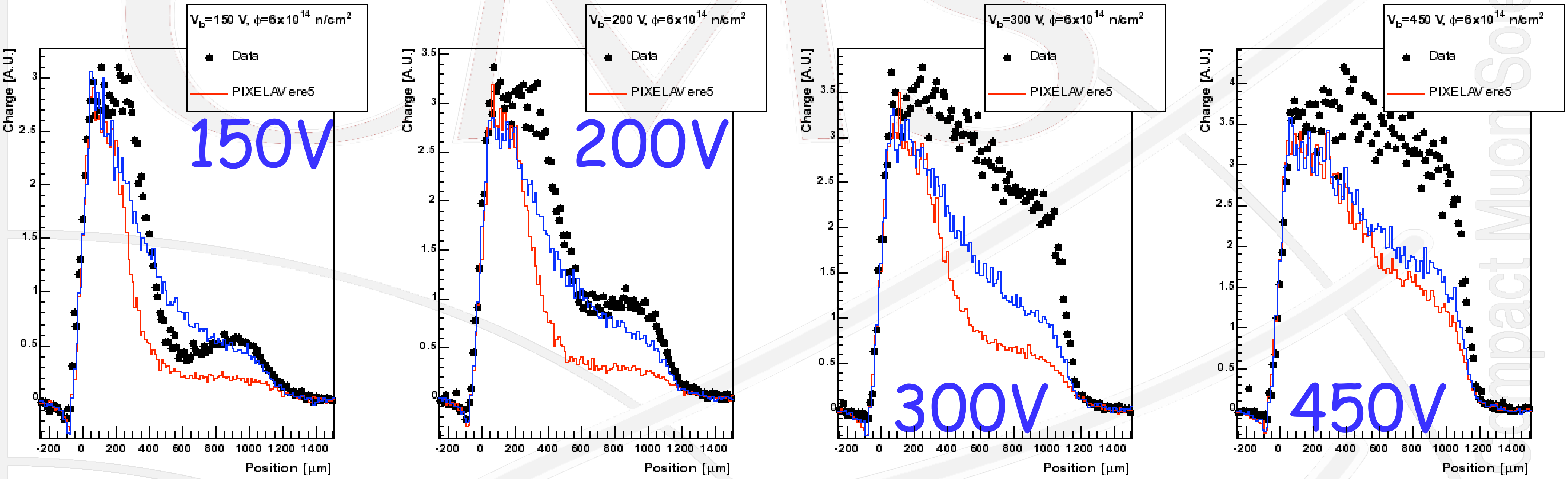
- rescale $\sigma_{e/h} \Rightarrow r\sigma_{e/h}$ (leaves f_D,f_A invariant) but increases SRH generation current by a factor of r,

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

  - can adjust leakage current without appealing to external sources
  - EVL fix $\sigma_e = \sigma_h = 10^{-15}$ cm^{-2}, keeping $\sigma_e = \sigma_h$ is mathematically equivalent

What current should we use? I is larger than one would expect for a 2.75x4x0.285 mm^3 volume: try 2 values

Φ_1=5.9x10^{14} n$_{eq}$/cm^2



- Model ere5 is normalized to produce 30% of I$_{obs}$ [saturates α=I(20C)/(VΦ)=α_0=4x10^{-17} A/cm @300V]
- Model ere6 is normalized to produce 100% of I$_{obs}$

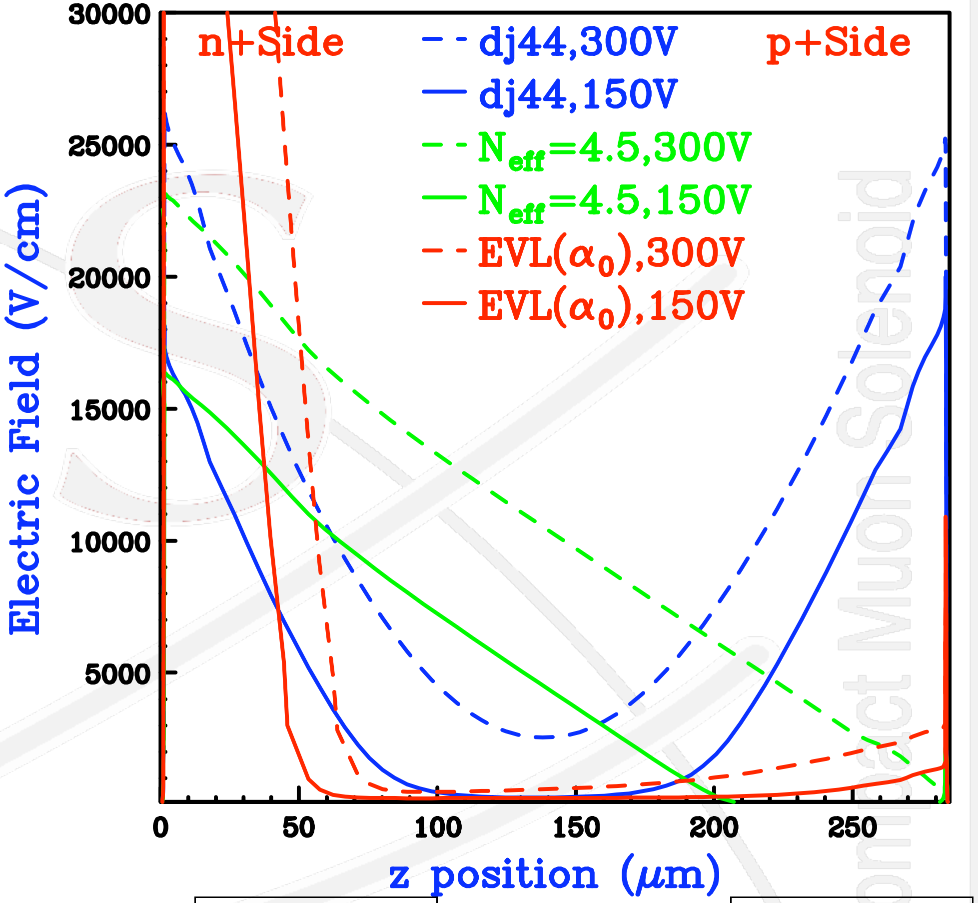
Neither of these can describe the data!

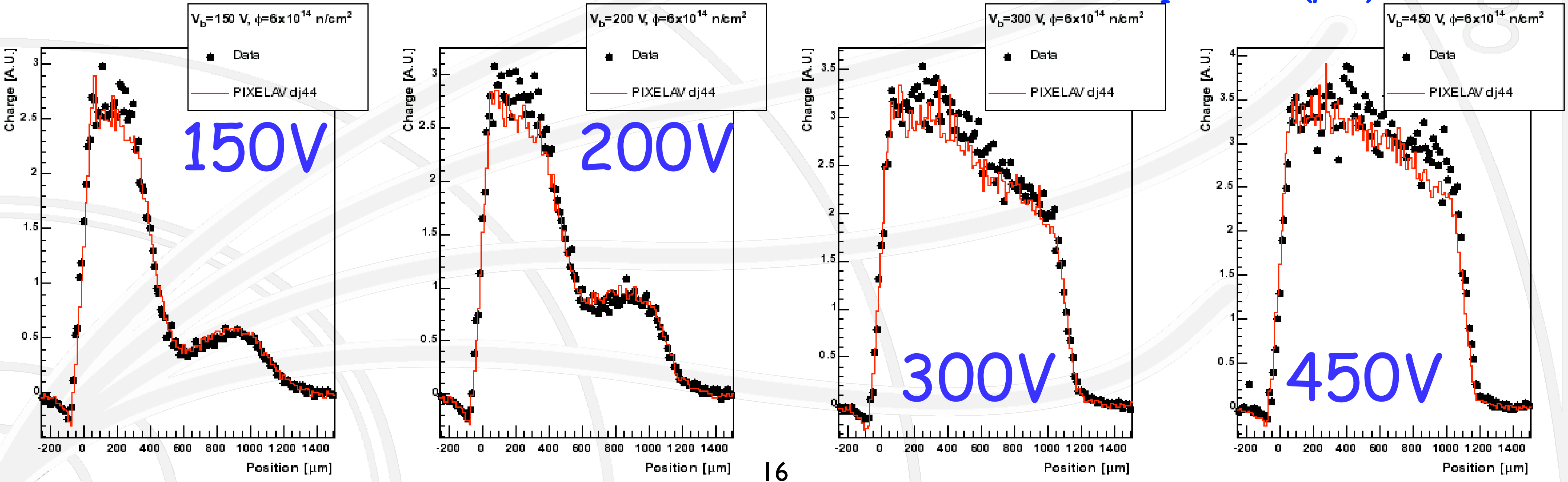
"Fitting" the Data

- parameters N_A, N_D, σ_e^A, σ_h^A, σ_e^D, σ_h^D are varied keeping the same E_A, E_D as EVL
- signal trapping rates Γ_e, Γ_h are uncertain (±10% level due to Φ uncertainties and ±30% level due to possible annealing) and were also varied in the procedure
- very slow and tedious: 8-12hr TCAD run + 4x(8-16)hr Pixelav runs + test beam analysis
- "eyeball" fitting only - no χ^2 or error matrix
  - parameters varied by hand (no Minuit)
- strong correlations between parameters

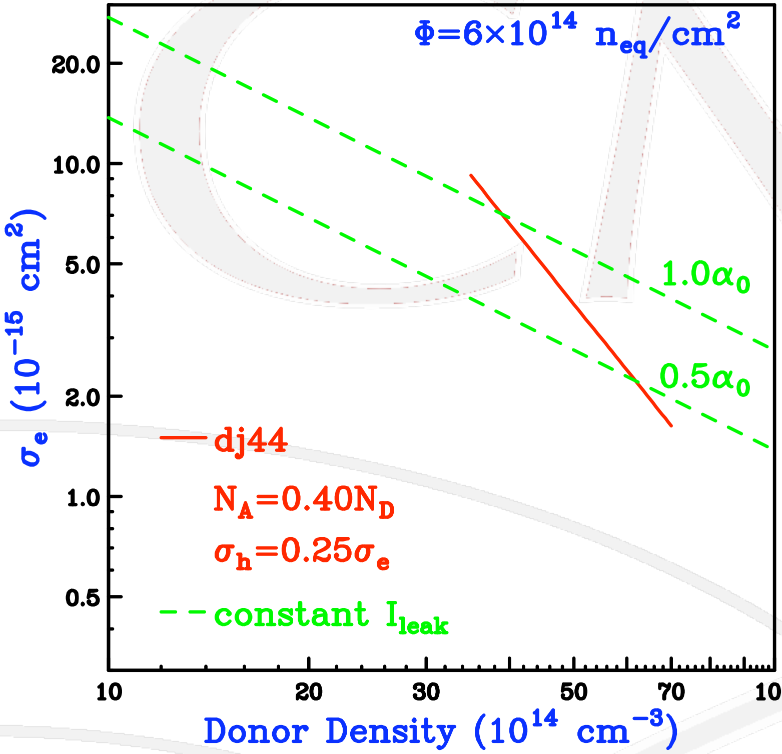
Best fit to $5.9\times10^{14}\ n_{eq}/cm^2$: labelled dj44

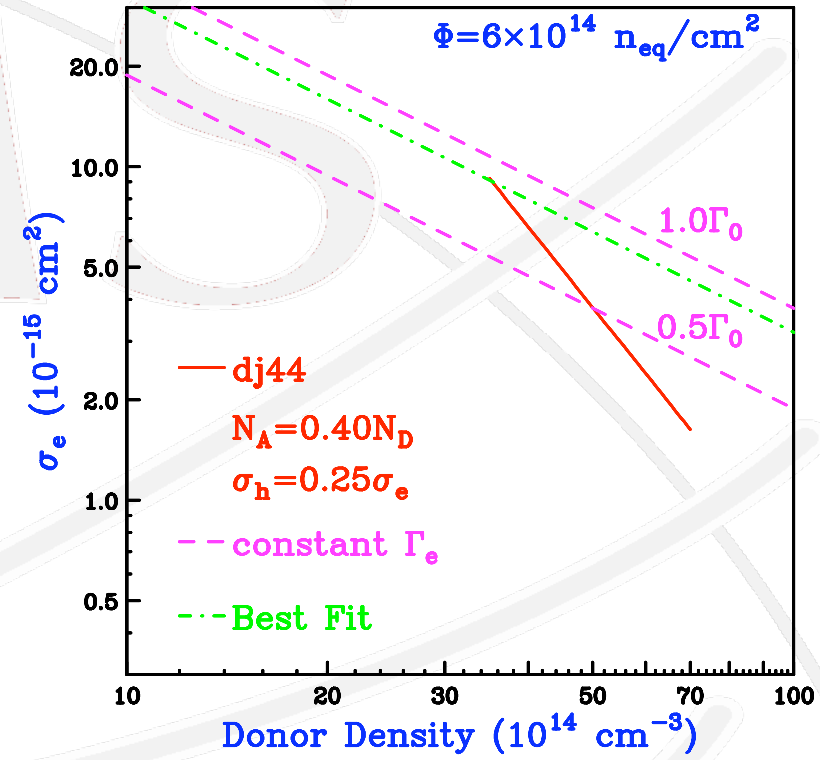
- $\sigma_h/\sigma_e=0.25, N_A/N_D=0.40$
- scale $\Gamma_{e/h}$ by 0.8 as compared with rate Γ_0 expected for Φ
- E-field is quite symmetric across sensor





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



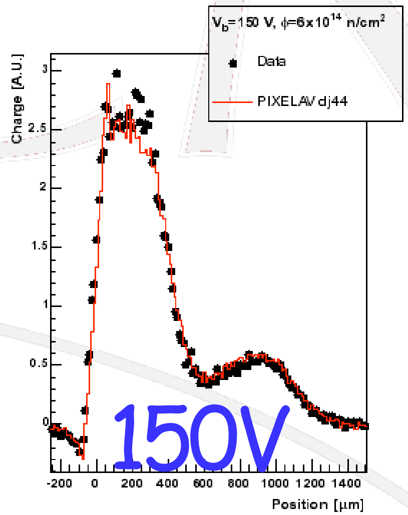


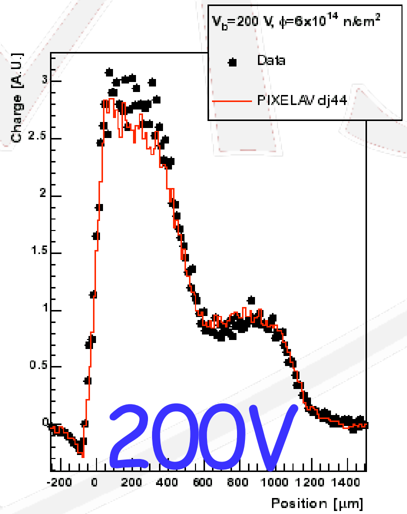
- large z, -150V tail becomes too large for $N_D < 35\times10^{14}$
- large z, -300V signal becomes too small for $N_D > 70\times10^{14}$
- $I \propto N_D \sigma_e$ so any I from $\alpha_0/2$ to α_0 fits data
- $\Gamma_e \sim v_e N_A \sigma_e \propto N_D \sigma_e$ so observed Γ_e is just OK

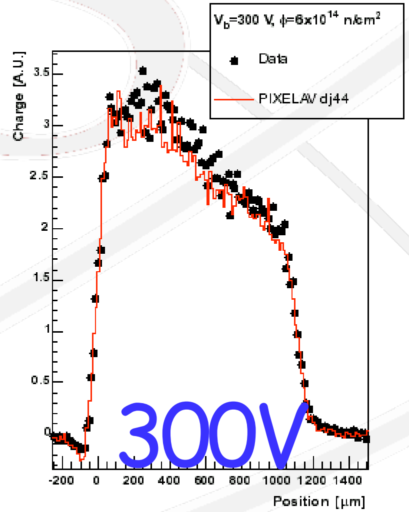
Temperature Dependence

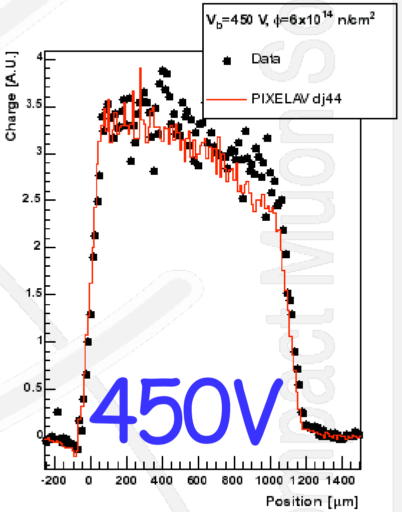
Use T-dependent recombination in TCAD and T-dependent quantities in Pixelav ($\mu_{e/h}$, $D_{e/h}$, and $\Gamma_{e/h}$):

T=-10C



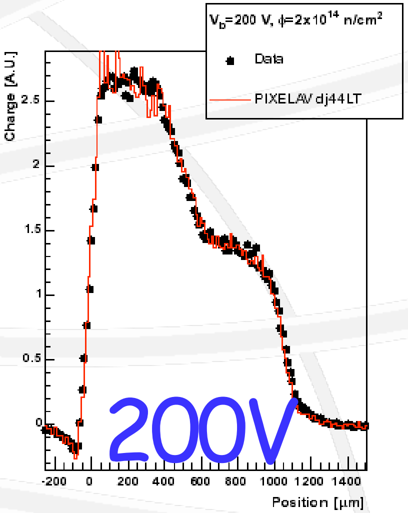


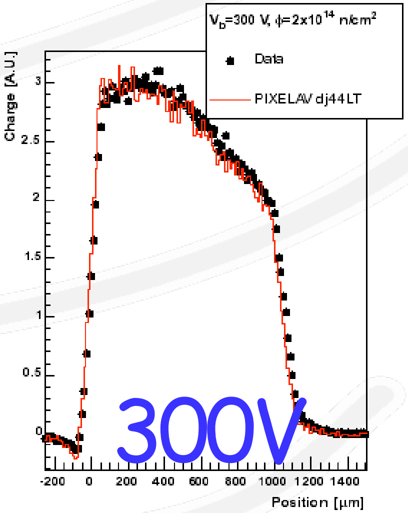


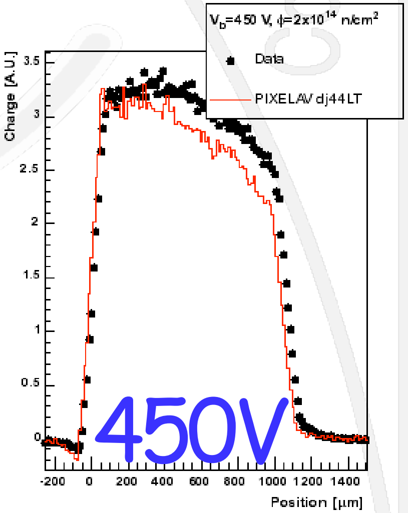


Φ_1=6x10^{14} n_{eq}/cm^2:

T=-25C





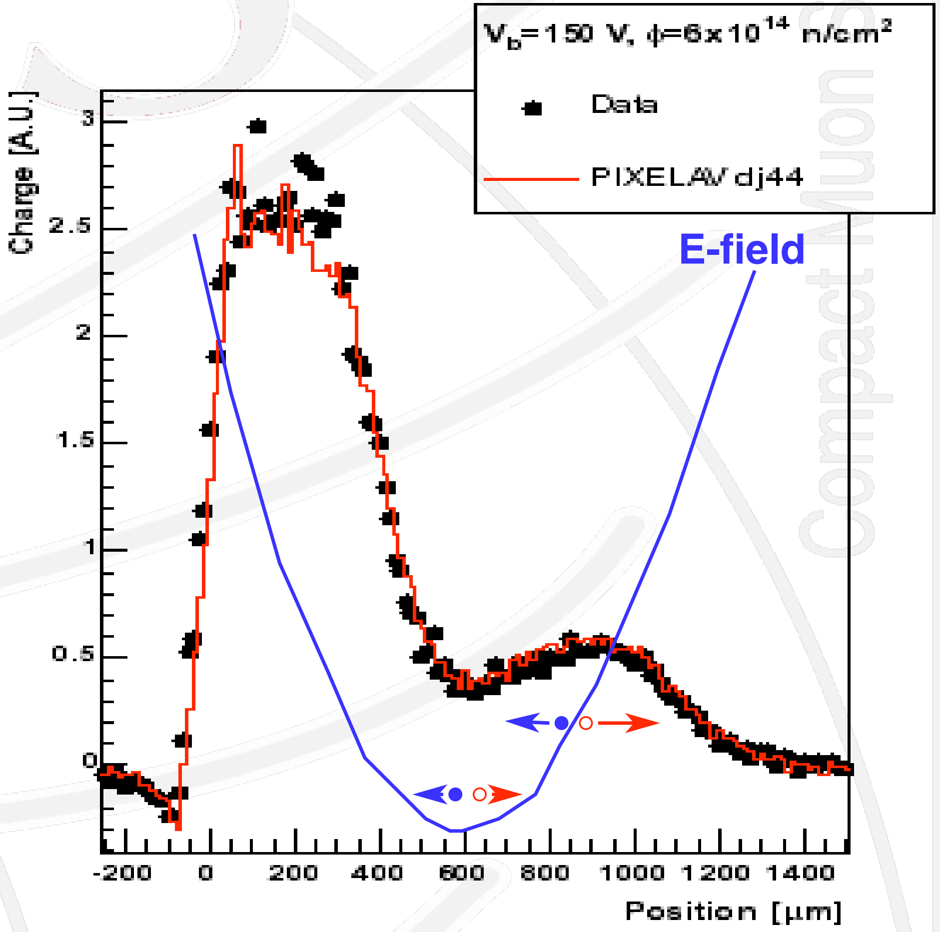


- dj-model is predictive!

The "Wiggle"

The charge collection profiles show a "wiggle" at low bias:

- signature of a doubly-peaked electric field:
  - e-h pairs deposited near field minimum separate only a little before trapping, produces local minimum
  - the apparently "unphysical" bump is caused by collection of holes in the higher field region near the p+ implant (e's drift into low field region and trap)



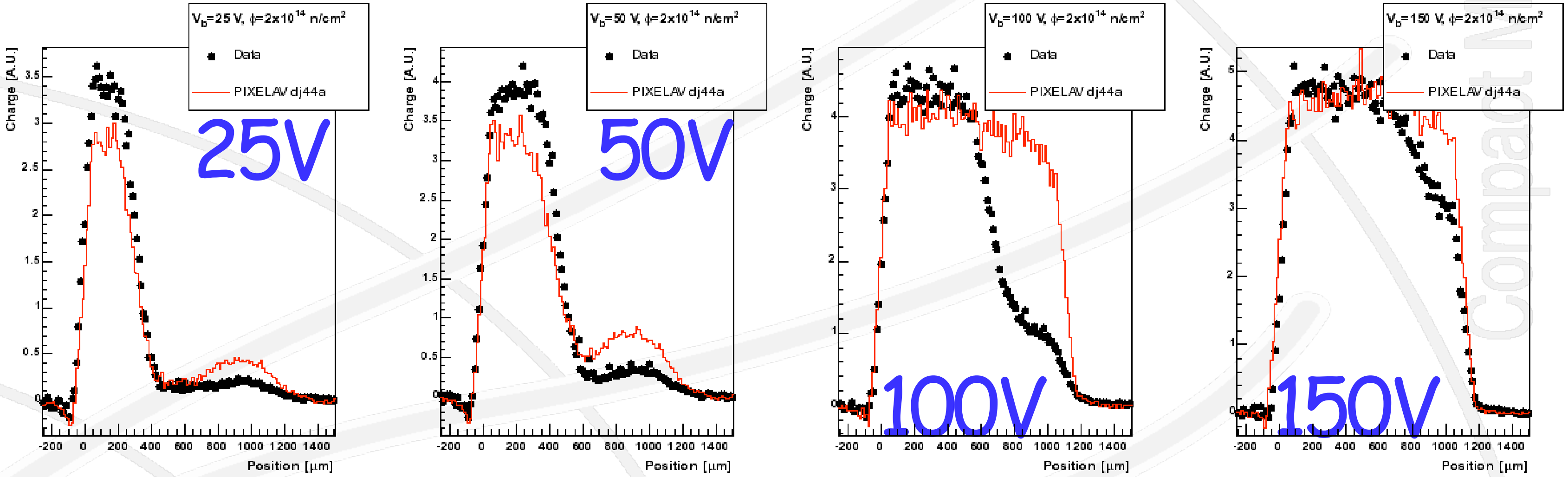
Scaling to Lower Fluences

Scale densities + trapping rates of dj44 linearly by fluence:

$$\left.\begin{aligned} N_A(\Phi_2) &= R_A \cdot N_A(\Phi_1) \\ N_D(\Phi_2) &= R_D \cdot N_D(\Phi_1) \\ \Gamma_{e/h}(\Phi_2) &= R_\Gamma \cdot \Gamma_{e/h}(\Phi_1) \end{aligned}\right\} R_A = R_D = R_\Gamma = \frac{\Phi_2}{\Phi_1}$$

T=-10C

Φ_2=2x10^{14}



- ✦ linear scaling of the trap densities doesn't work!
  - ✶ too much field on the p+ side
- ✦ the "wiggle" is still present at Φ_2=2x10^{14} n$_{eq}$/cm^2
  - ✶ a doubly-peaked field persists at lower fluences

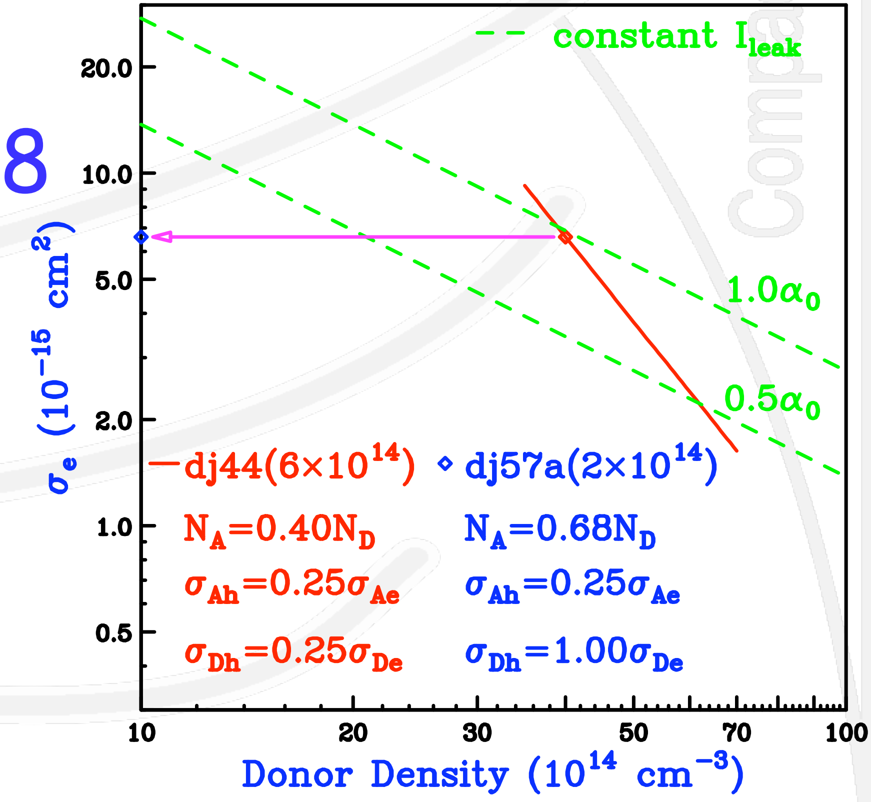
Why doesn't linear Φ scaling work?

- scaling of $f_{A/D}$ with n,p is wrong (wrong $E_{A/D}$)?
- quadratic Φ scaling of V_2X states?

Can increase n+ side field and decrease p+ side by increasing N_A/N_D but keeping $\Gamma_{e/h}$ and I linear in Φ

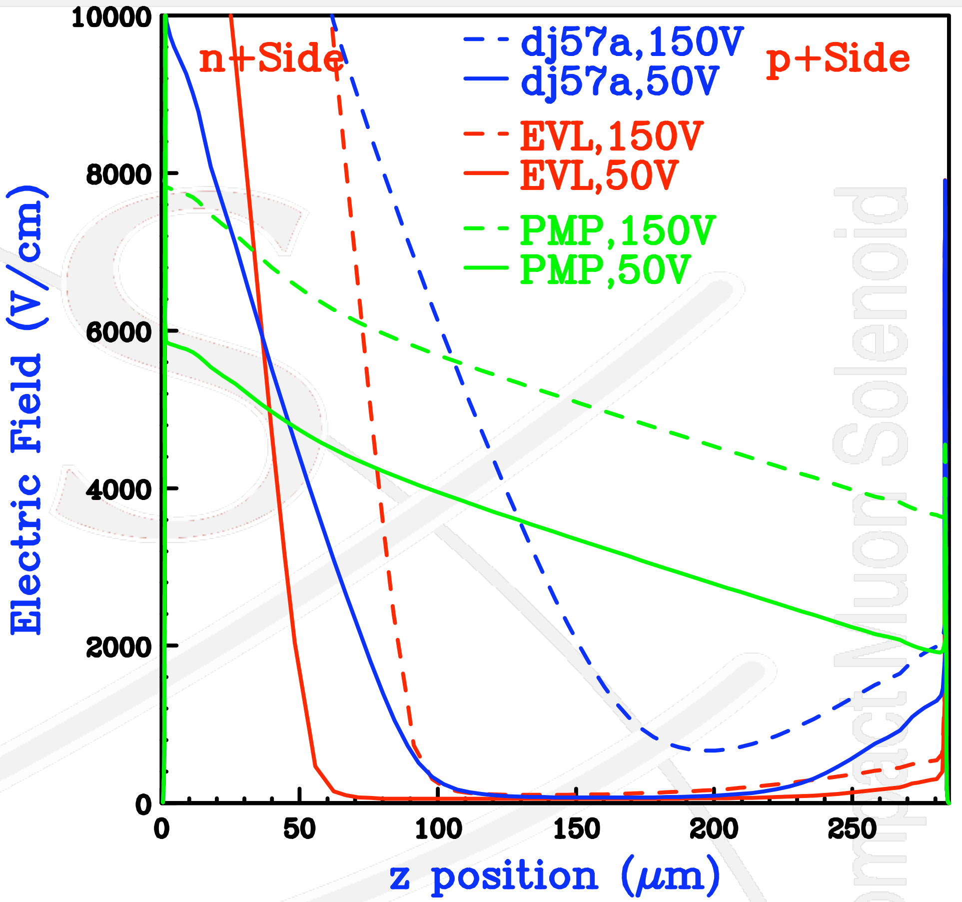
$$R_\Gamma = \frac{\Phi_2}{\Phi_1}, \quad R_A = R_\Gamma(1+\delta), \quad R_D = R_\Gamma(1-\delta)$$

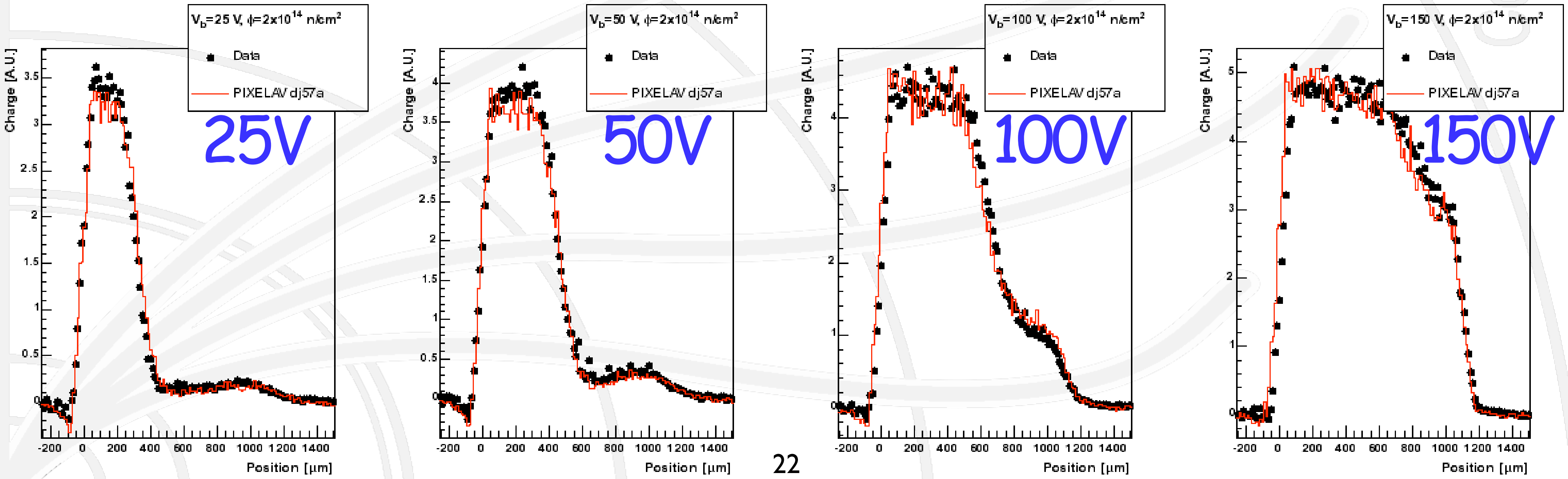
- $R_\Gamma=(R_A+R_D)/2$, keeps I linear
- increase N_A/N_D from 0.4 to 0.68 (closer to EVL value of 0.62)
- must scale the "full" I_{leak} point (range is ~ ±10% in N_D)
- net donor σ_h/σ_e also prefers to increase (not very sensitive)
- took 3 months of tuning!



Best fit to 2.0×10^{14} n_{eq}/cm^2: labelled dj57a

- $N_A/N_D = 0.68$
- $\sigma_{Ah}/\sigma_{Ae} = 0.25$, $\sigma_{Dh}/\sigma_{De} = 1.00$,
- E-field still doubly-peaked (more than EVL prediction)
- Also compare with PMP model



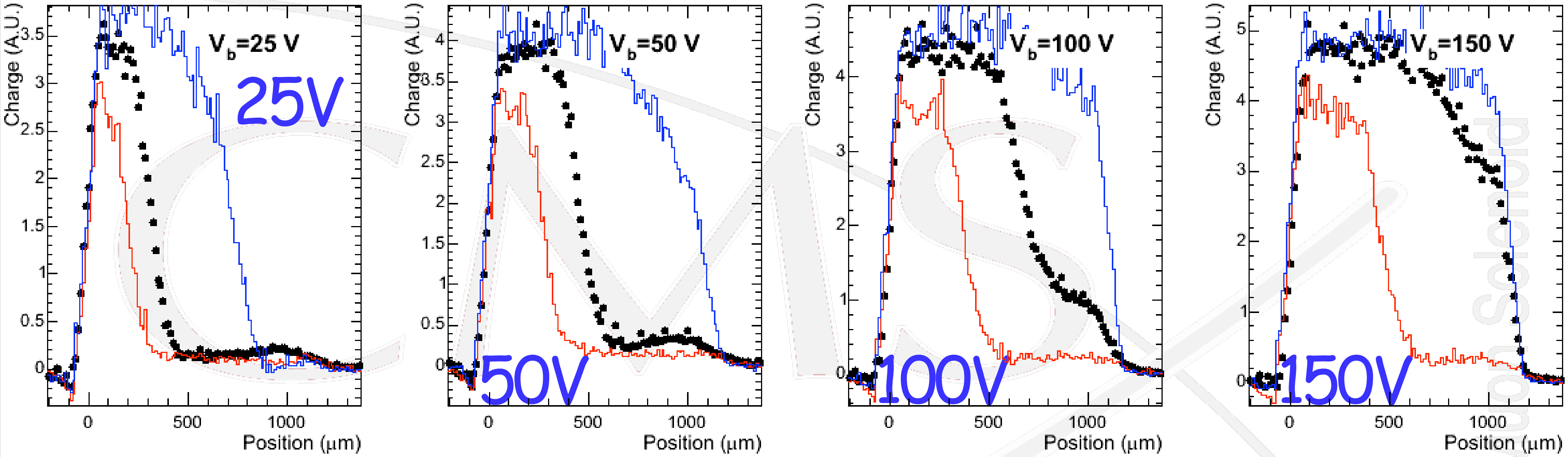


PMP Model

Petasecca, Moscatelli, and Pignatel showed a 3-state model of irradiated n-type silicon at the 5th RD50 workshop:

trap	E (eV)	g_{int} (cm^{-1})	σ_e (cm^2)	σ_h (cm^2)
donor	E_V+0.36	1	1×10^{-15}	1×10^{-16}
acceptor	E_C-0.42	26	1×10^{-16}	8×10^{-15}
acceptor	E_C-0.50	0.1	1×10^{-16}	1×10^{-15}

- dominant acceptor traps e- creating net negative space charge (effective p-type doping)
  - model of linear charge inversion
  - no double junctions or doubly-peaked E-fields



$2.0x10^{14}\ n_{eq}/cm^2$ compared with EVL and PMP

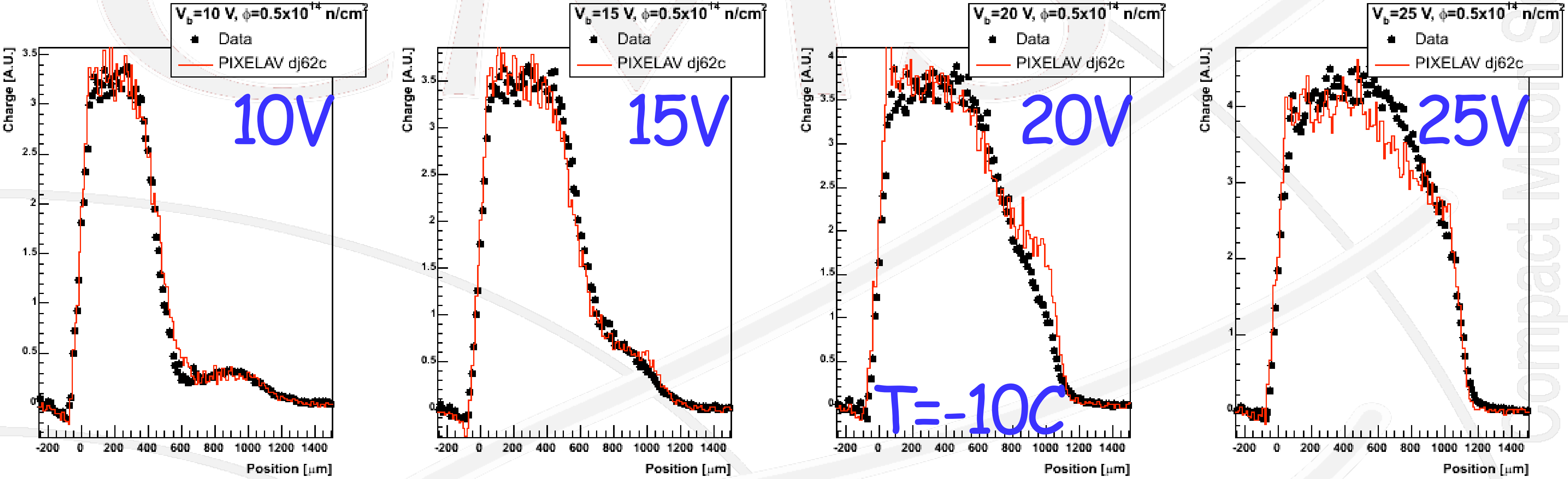
- EVL is adjusted to produce expected leakage current
- PMP produces more or less correct leakage current (a bit low)

What about the $0.47x10^{14}\ n_{eq}/cm^2$ point?

Scaling to Even Lower Fluences

Scale dj57a to increase N_A/N_D at $\Phi_3=0.47\times10^{14}\ n_{eq}/cm^2$

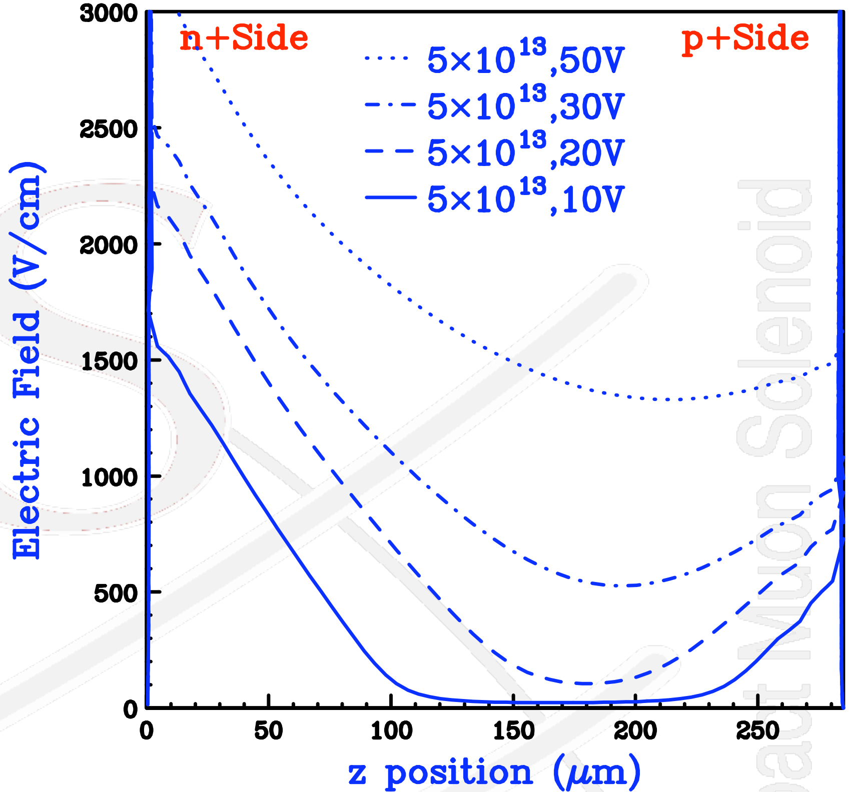
$$R_\Gamma = \frac{\Phi_3}{\Phi_2}, \quad R_A = R_\Gamma(1+\delta'), \quad R_D = R_\Gamma(1-\delta')$$



- ✦ dj62b: $N_A/N_D=0.75$, $\sigma_{Ah}/\sigma_{Ae}=0.25$, $\sigma_{Dh}/\sigma_{De}=1.00$
  - ✶ charge drift times now comparable to preamp shaping (simulation may not be reliable)
- ✦ the data "wiggle" is still present at $\Phi_3=0.47\times10^{14}\ n_{eq}/cm^2$
  - ✶ a doubly-peaked field persists at lowest fluence!!!

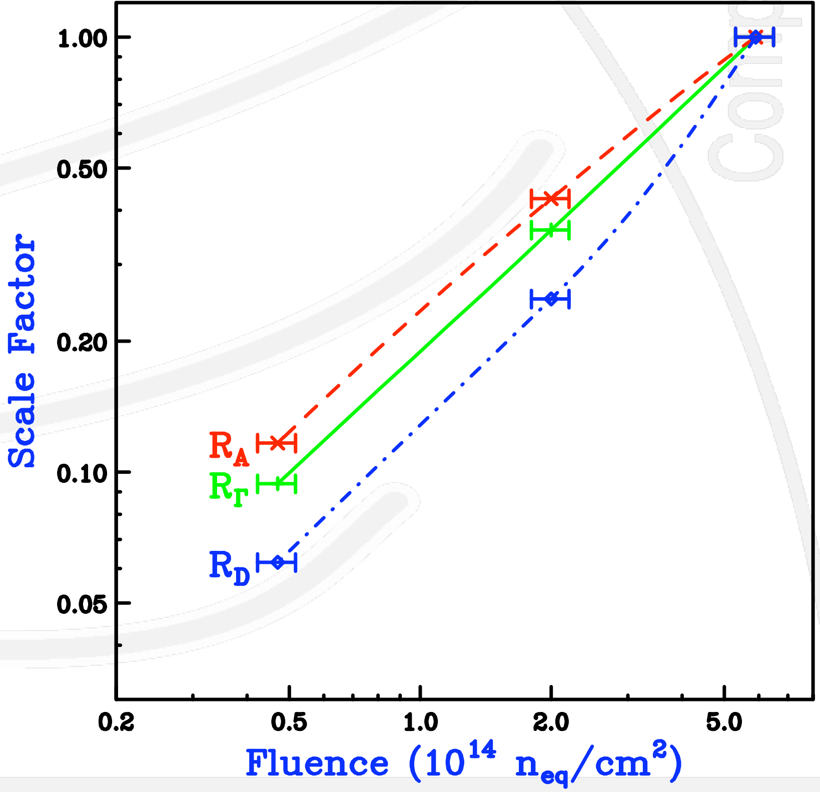
We can still see evidence of a doubly-peaked electric field near the "type-inversion" fluence:

- profiles are not described by thermodynamically ionized acceptors alone
- trapped leakage current can describe everything



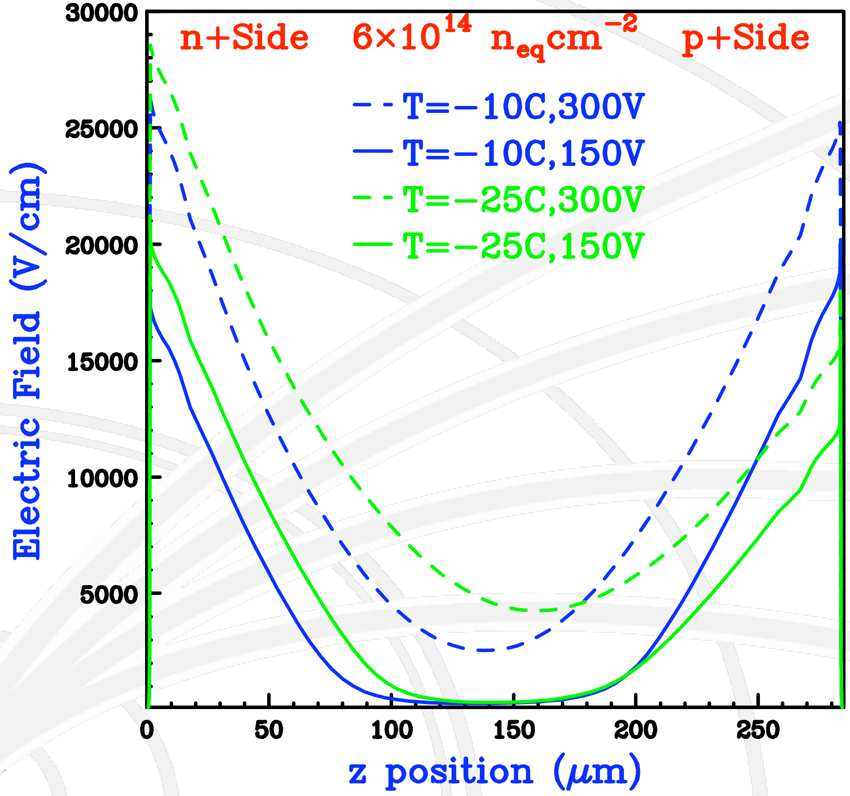
Scale factor summary:

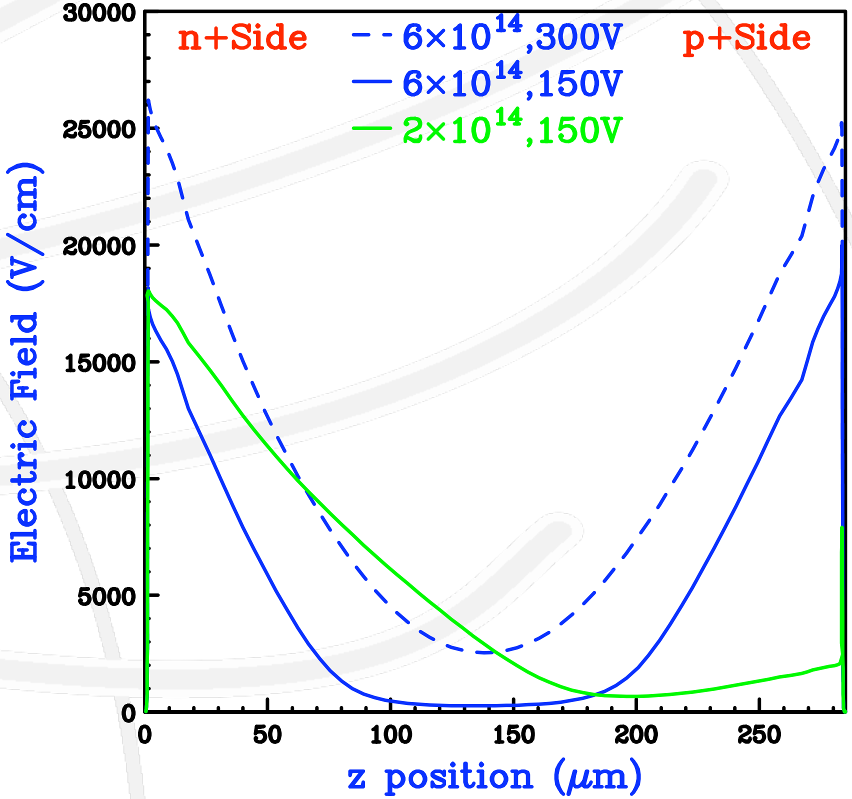
- trapping rates are linear in Φ
- N_A/N_D increases from 0.40 at $\Phi_1=5.9\times10^{14}$ n_{eq}/cm^2 to 0.75 at $\Phi_3=0.47\times10^{14}$ n_{eq}/cm^2



Conclusions

- It is clear that a two-peak electric field is necessary to describe our charge collection data even at low fluence
- A two-trap double junction model can be tuned to provide reasonable agreement with the data
  - N_A/N_D must vary with fluence
  - describes non-trivial T and Φ dependence of E-field

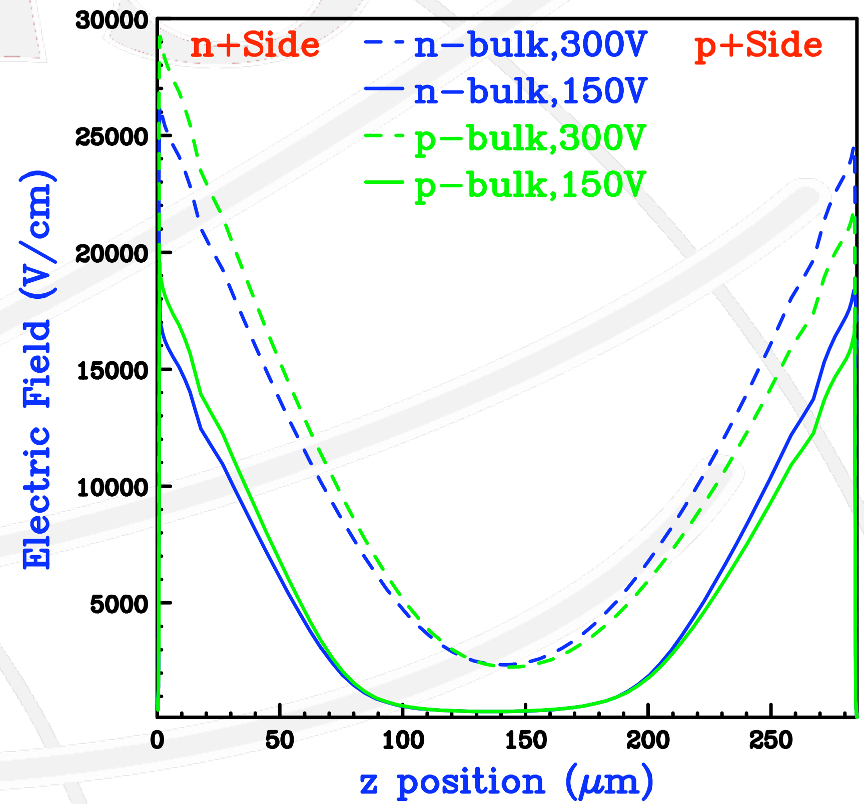




- Assuming that the “chemistry” of irradiated dofz silicon is independent of initial dopant
  - suggests that there is no advantage of n/n over n/p at high Φ (n/p is much cheaper to build)

Φ=5.9x10^{14} n$_{eq}$/cm^2

N$_{dop}$=1.2x10^{12} cm^{-3}



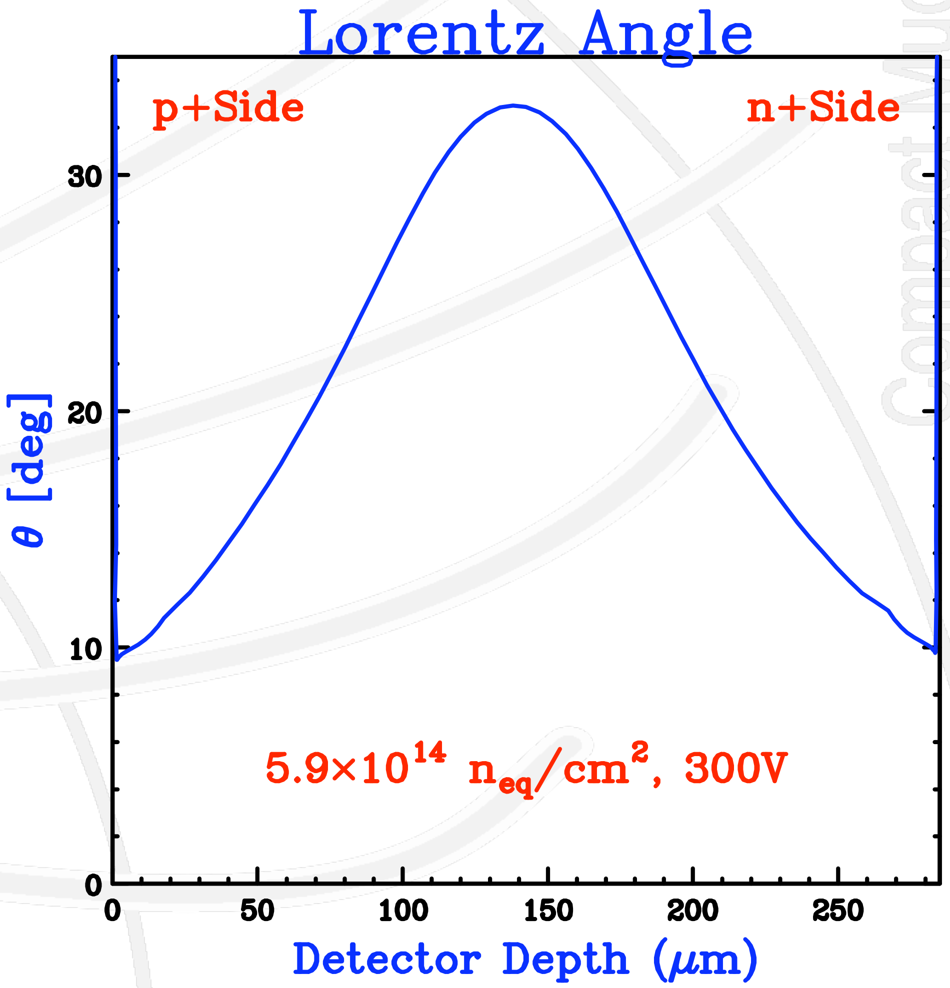
- Model will be important to calibrate the hit reconstruction after irradiation in LHC

- Charge Sharing in 4T CMS After Irradiation

The Lorentz angle is linear in the mobility μ(E)

$$\tan\theta_L \simeq \frac{e r_H v B \sin\theta_{vB}}{eE} = r_H \mu(E) B \sin\theta_{vB}$$

- μ(E) varies by ~3 across the detector thickness in irradiated sensors
  - creates very non-linear charge sharing
  - largest in middle and smallest near implants
- trapping also causes non-linear response in irradiated sensors


Lorentz Angle