Simulation of “Heavily” Irradiated Si Pixel Detectors

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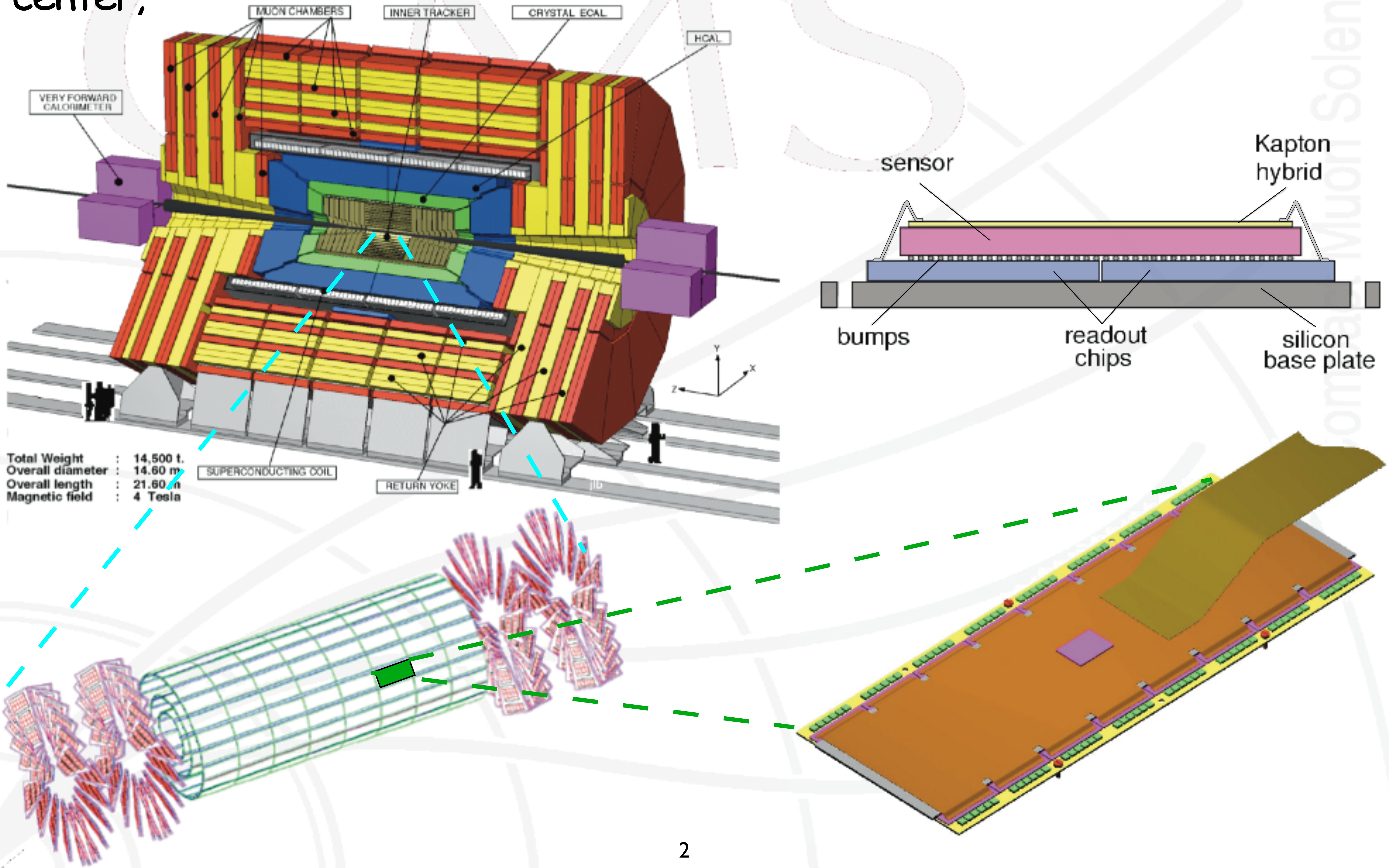
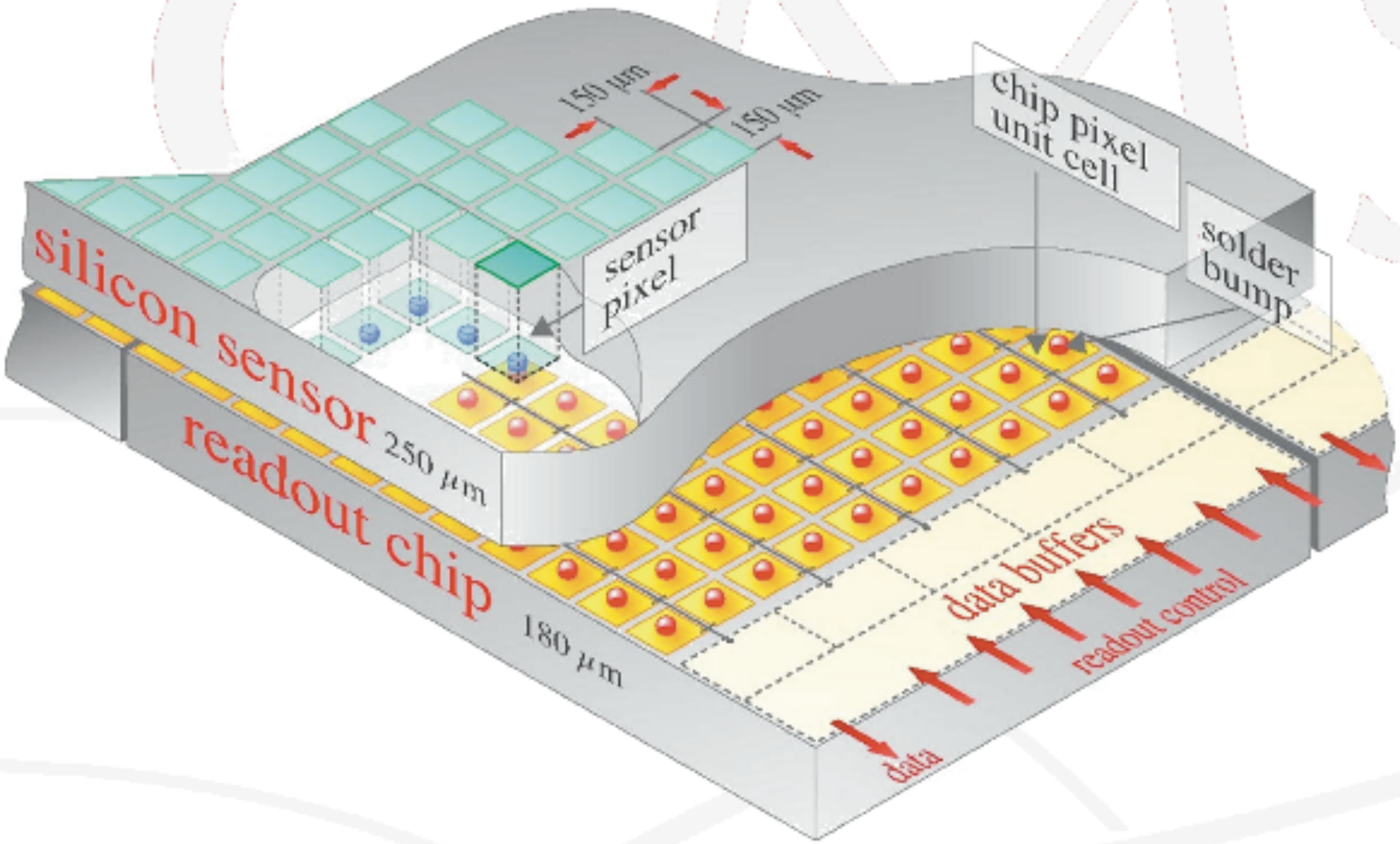
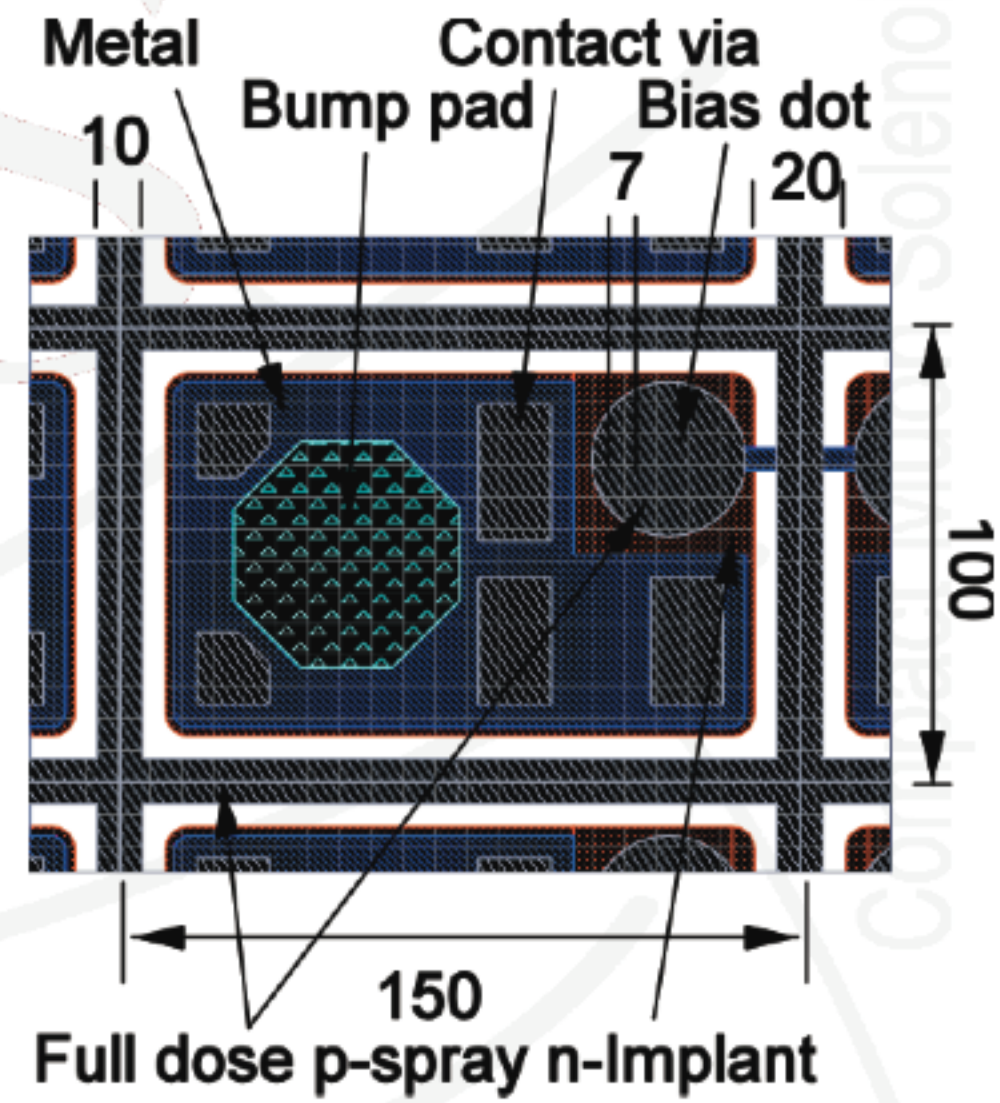
CMS Pixel Tracking System

CMS contains 66 million element hybrid-pixel based tracking system at its center,



The pixels are composed of 150x100μm cells fabricated on 285μm thick n-doped diffusively oxygenated float zone (dofz) silicon substrate. Each cell is bump-bonded to it's own preamp-readout circuit



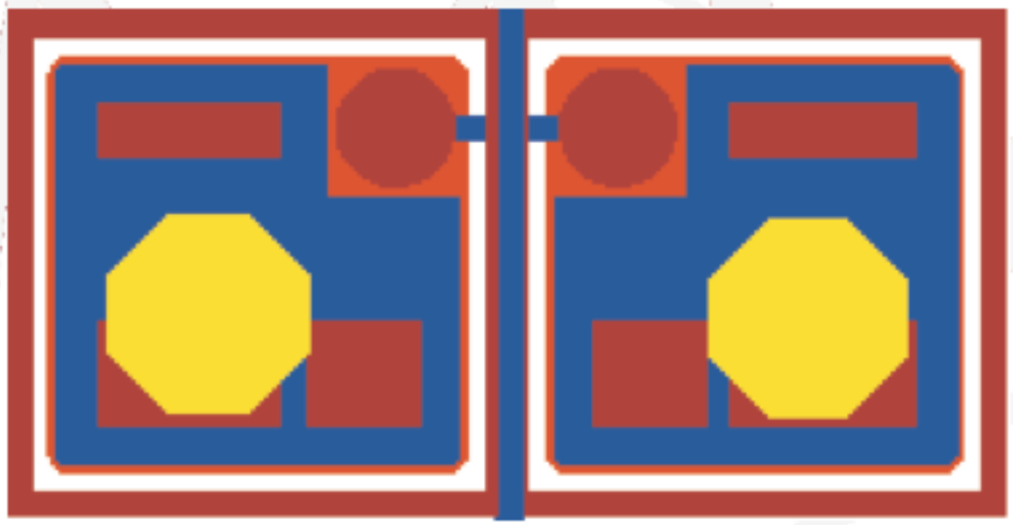


Designed to collect e- from n+ implants:

- Electrons have high mobility μ and collect more quickly than holes
- Lorentz angle is proportional to μ: 2-3 times larger than holes
- After "type-inversion" can be operated in partial depletion

2004 CMS Beam Test Sensors

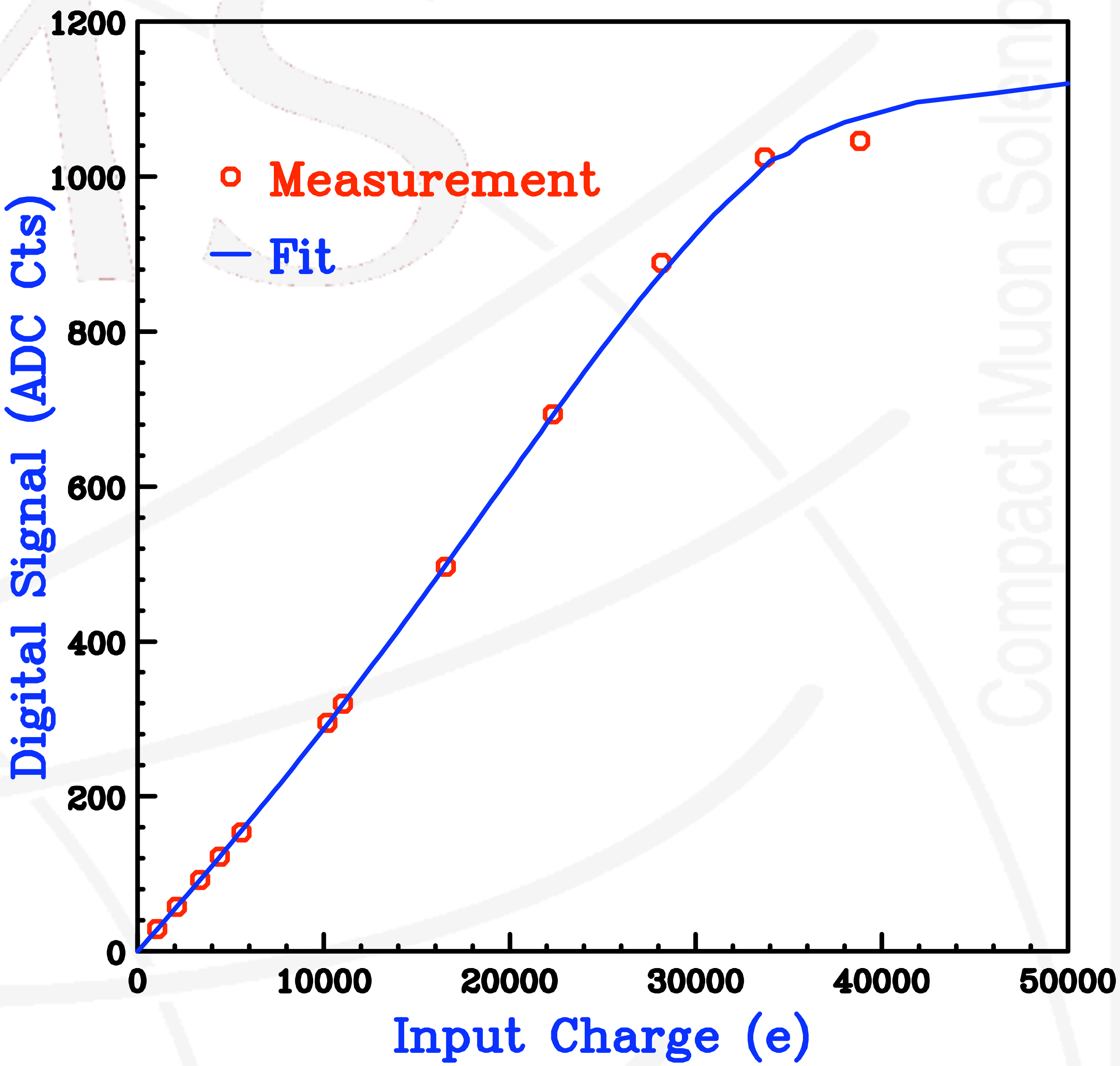
125μmx125μm CiS pspray test sensors:



- 22x32 cells on each chip
- 285μm thick dofz substrate from Wacker
  - n- doped with ρ=2-5 kΩ-cm, <111> orientation
  - oxygenated at 1150°C for 24 hours
- irradiated with 24 GeV protons at PS to fluences: $(5.9, 2.0, 0.47) \times 10^{14}\ n_{eq}/cm^2$
- annealed for 3 days at 30°C
  - all sensors are "Standard Annealed"
- bump-bonded at 20°C, stored at -20°C

Readout Chip

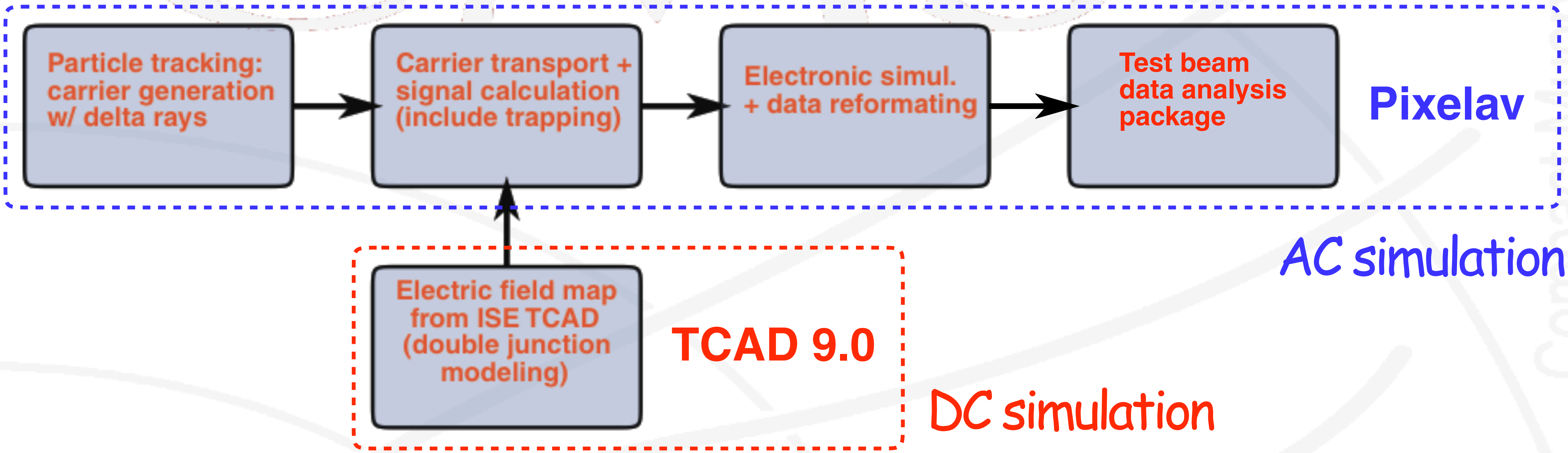
- sensors bump-bonded to PSI30 ROC from Honeywell
  - doesn't sparsify data, permits readout of small signals (crucial for this work)
  - good linearity to 30k e (at 15°, mp charge deposit is ~10k e)
  - not very rad-hard
- irradiated sensors bump-bonded "cold" to unirradiated ROCs



supply of PSI30 now exhausted!

Simulation

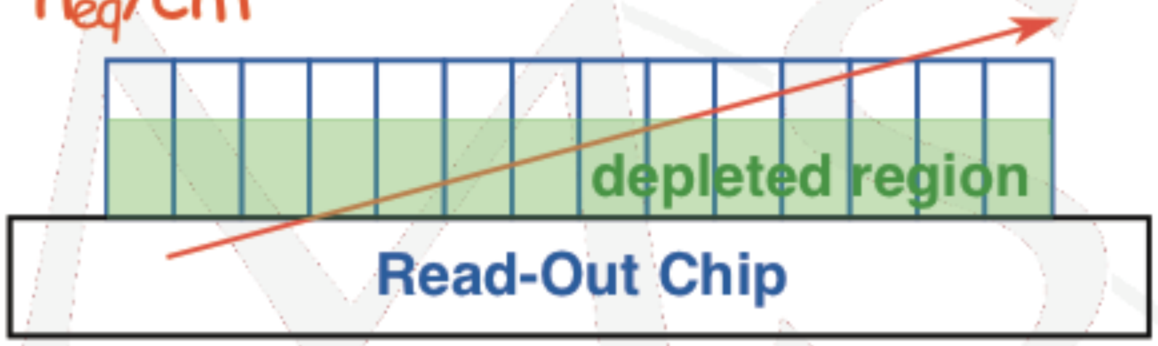
Needed to interpret the charge collection profiles. Over the last several years, we have constructed a detailed sensor simulation, Pixelav [NIM A511, 88 (2003)]

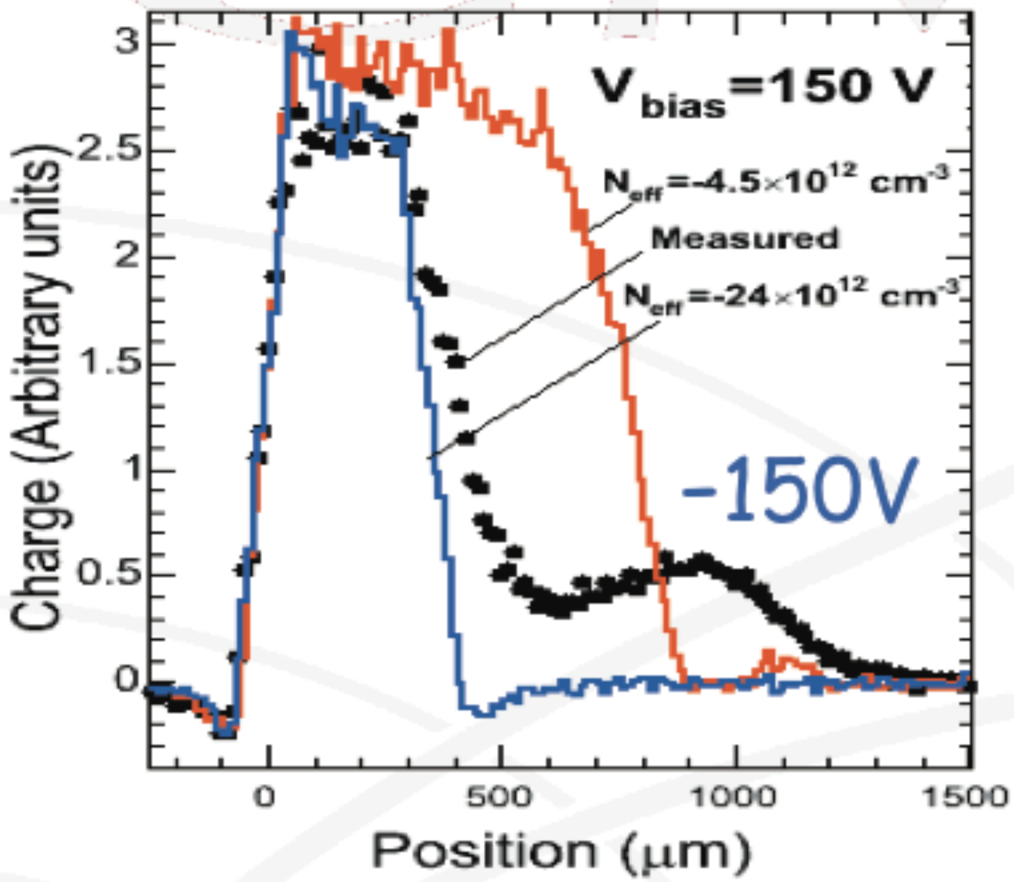


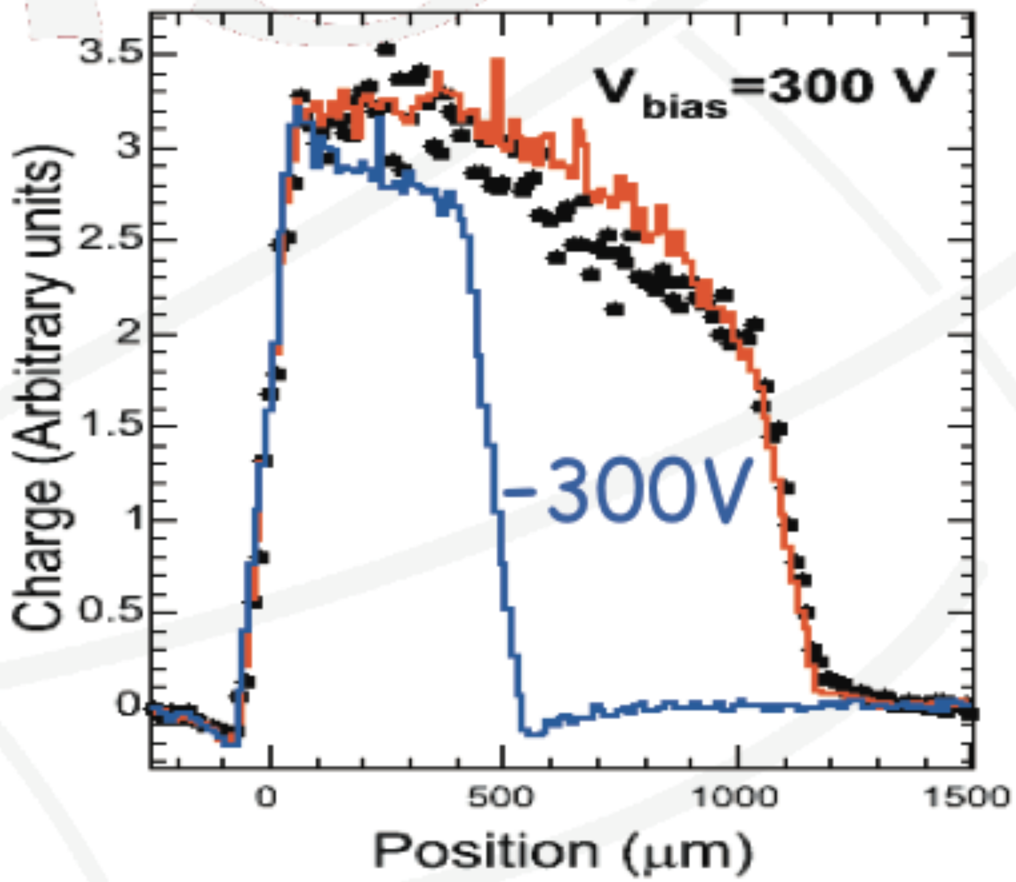
- Electric field calculation: uses TCAD 9.0 software
  - simultaneously solves Poisson and carrier continuity eqs
  - includes lots of semiconductor physics (including SRH)

Irradiated Data vs Simulation

Comparing grazing-angle charge collection profiles of real and simulated data at Φ_1=5.9x10^{14} n_{eq}/cm^2





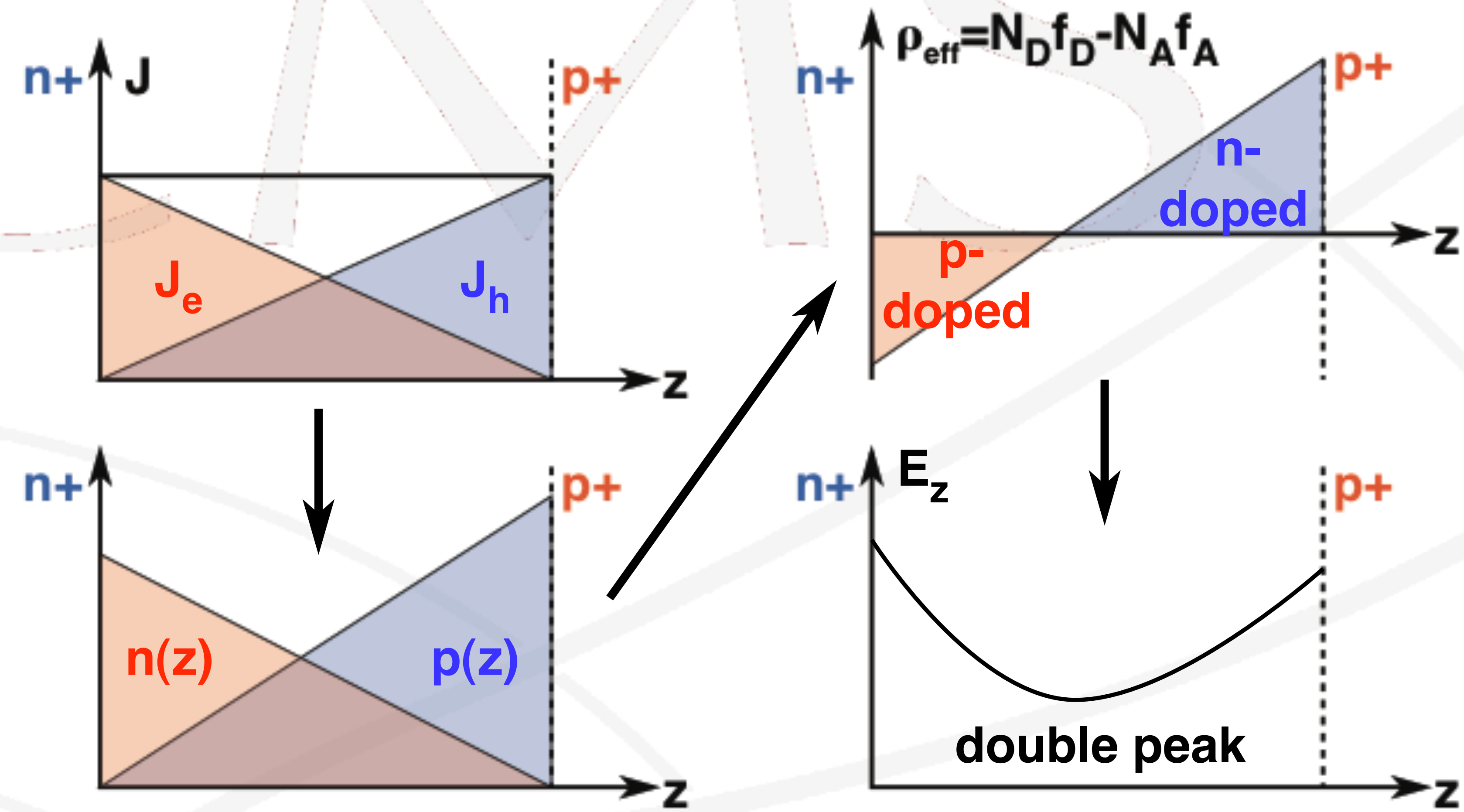


T=-10C

- -300V data are well described by N_{eff}=4.5x10^{12}cm^{-3} p-
- width of -150V peak requires N_{eff}=24x10^{12}cm^{-3} p-
  - tail not described
- Constant N_{eff} and linear E-fields are ruled out!

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	1×10^{-15}	1×10^{-15}
acceptor	E_C-0.525	3.7	1×10^{-15}	1×10^{-15}

Modeling of Sensors

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

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

- 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
  - 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:

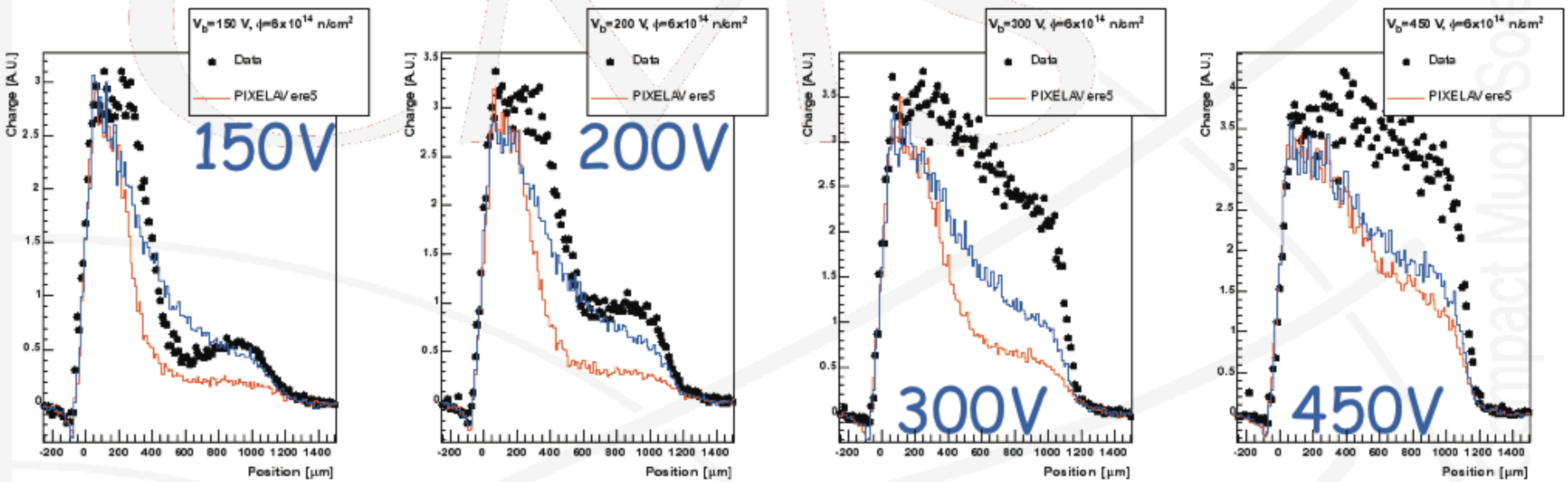
$$f_D = \frac{v_h \sigma_h^D p + v_e \sigma_e^D n_i e^{E_D/kT}}{v_e \sigma_e^D (n + n_i e^{E_D/kT}) + v_h \sigma_h^D (p + n_i e^{-E_D/kT})}$$

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

- 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!
- rescaling $\sigma_{e/h} \Rightarrow r\sigma_{e/h}$ rescales SRH gen current $I \Rightarrow rI$.
- 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)

Simulate EVL model in TCAD by rescaling the trapping x-sections to get correct leakage current:

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}

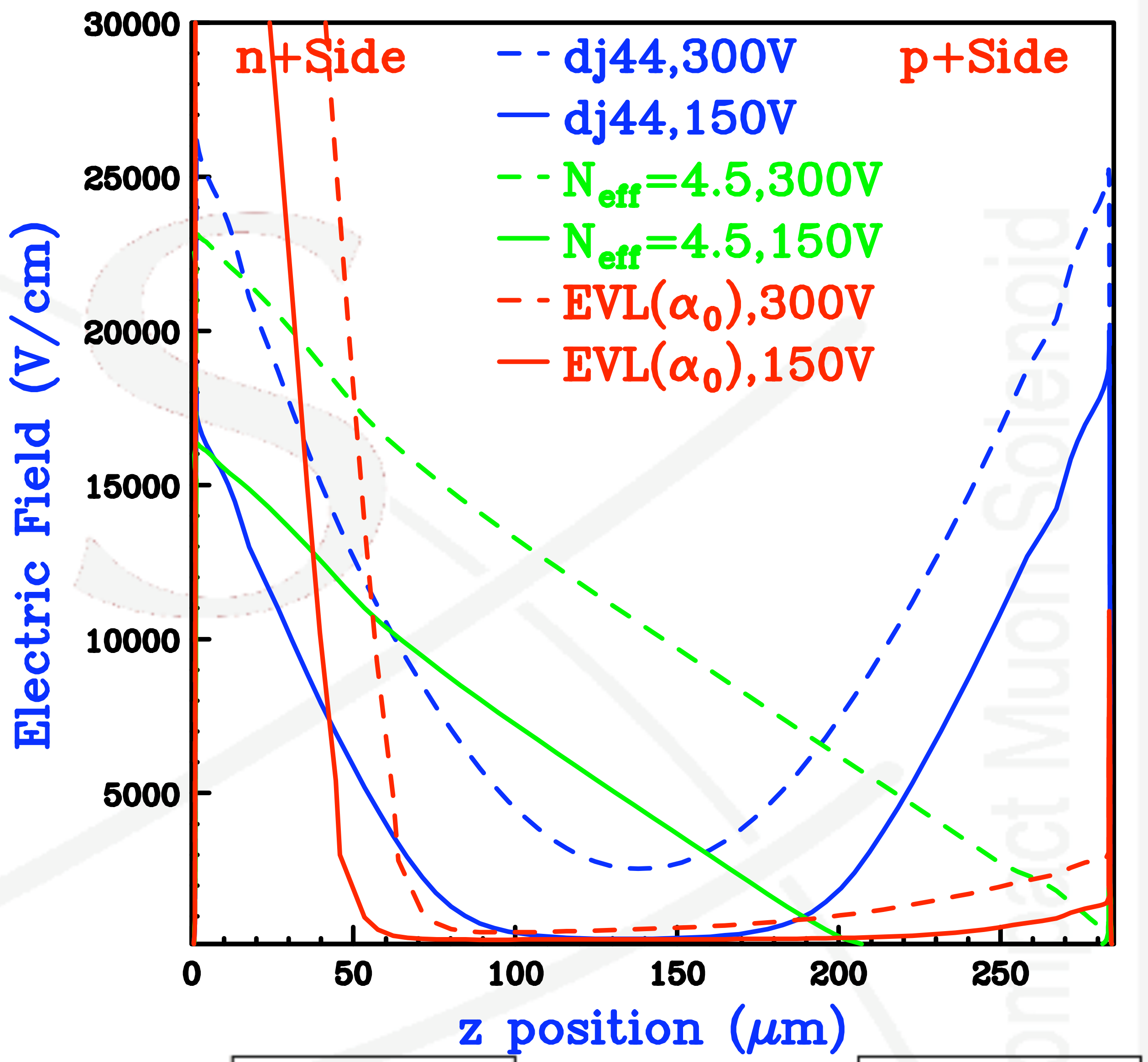
Neither of these can describe the data!

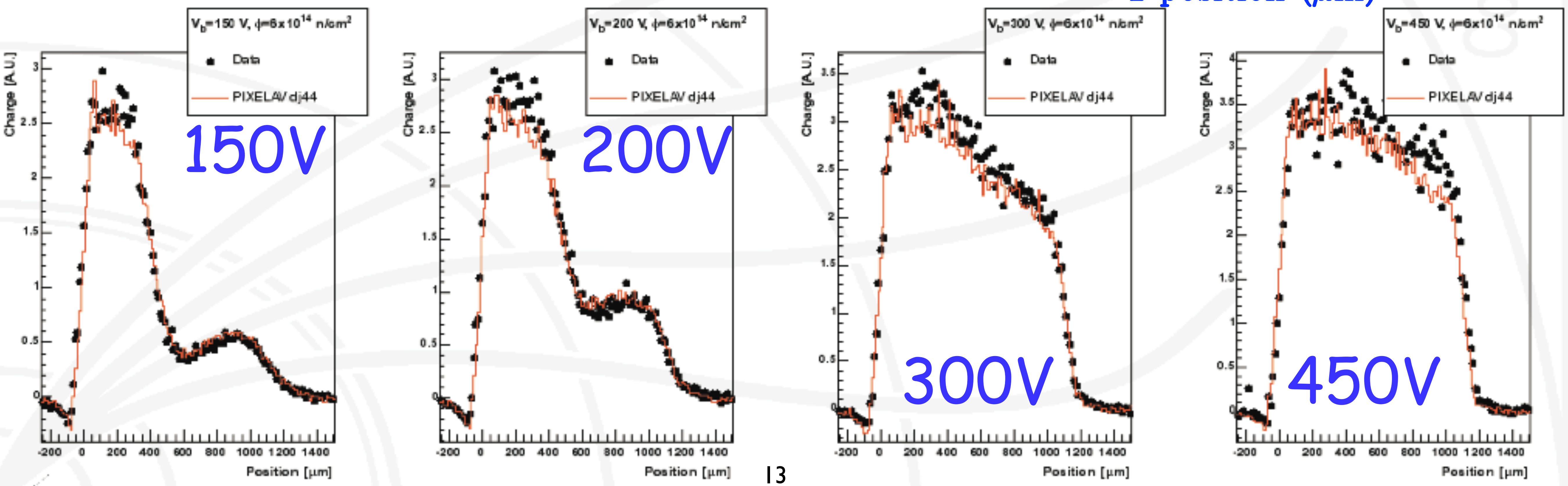
"Fitting" the Data

- parameters N_D, N_A, $\sigma^A{}_e$, $\sigma^A{}_h$, $\sigma^D{}_e$, $\sigma^D{}_h$, varied keeping the same E_D, E_A 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

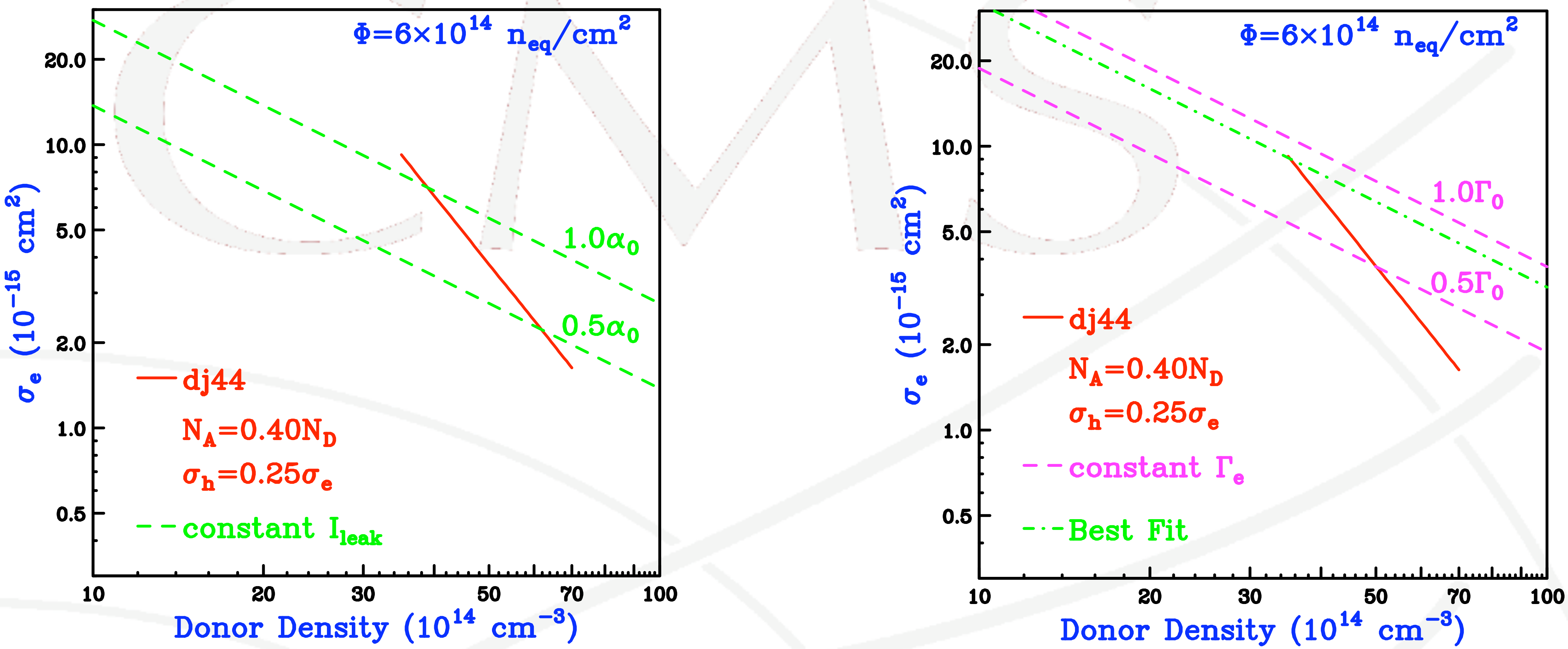
Best fit to 5.9×10^{14} neq/cm^2: labelled dj44

- σ_h/σ_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 E-field in the detector:

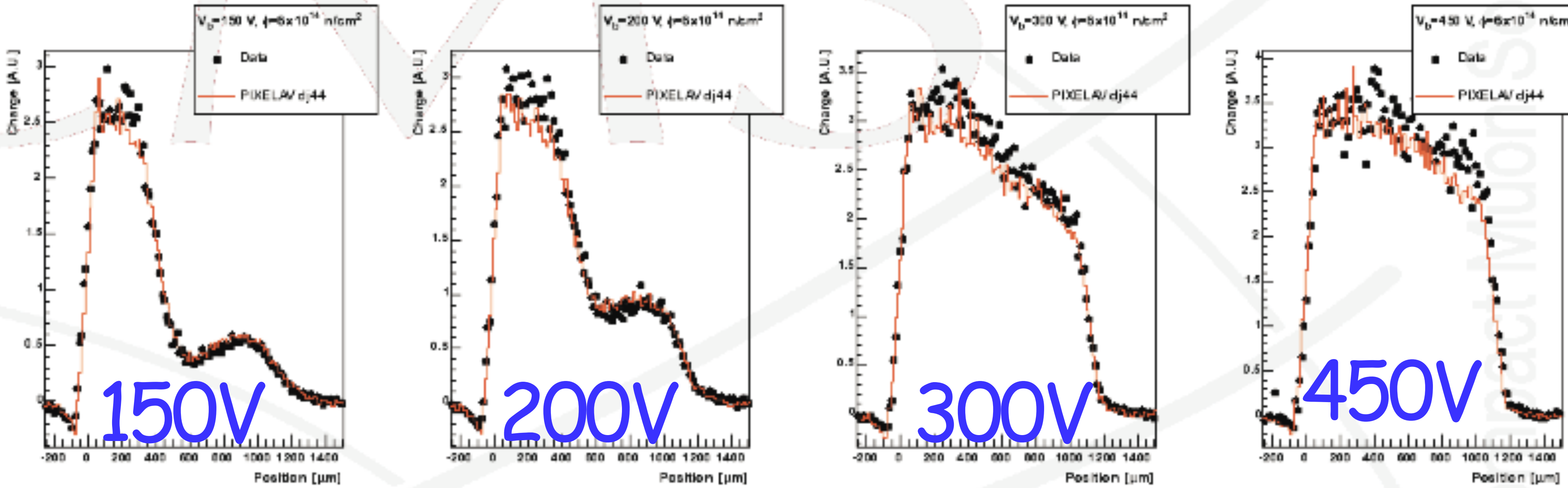


- large z, -150V tail becomes too large for N_D<35×10^{14}
- large z, -300V signal becomes too small for N_D>70×10^{14}
- $I \propto N_D\sigma_e$ so any I from $\alpha_0/2$ to α_0 fits data
- $\Gamma_e \sim v_e N_A \sigma_e \propto N_D\sigma_e$ so observed Γ_e is just OK

Temperature Dependence

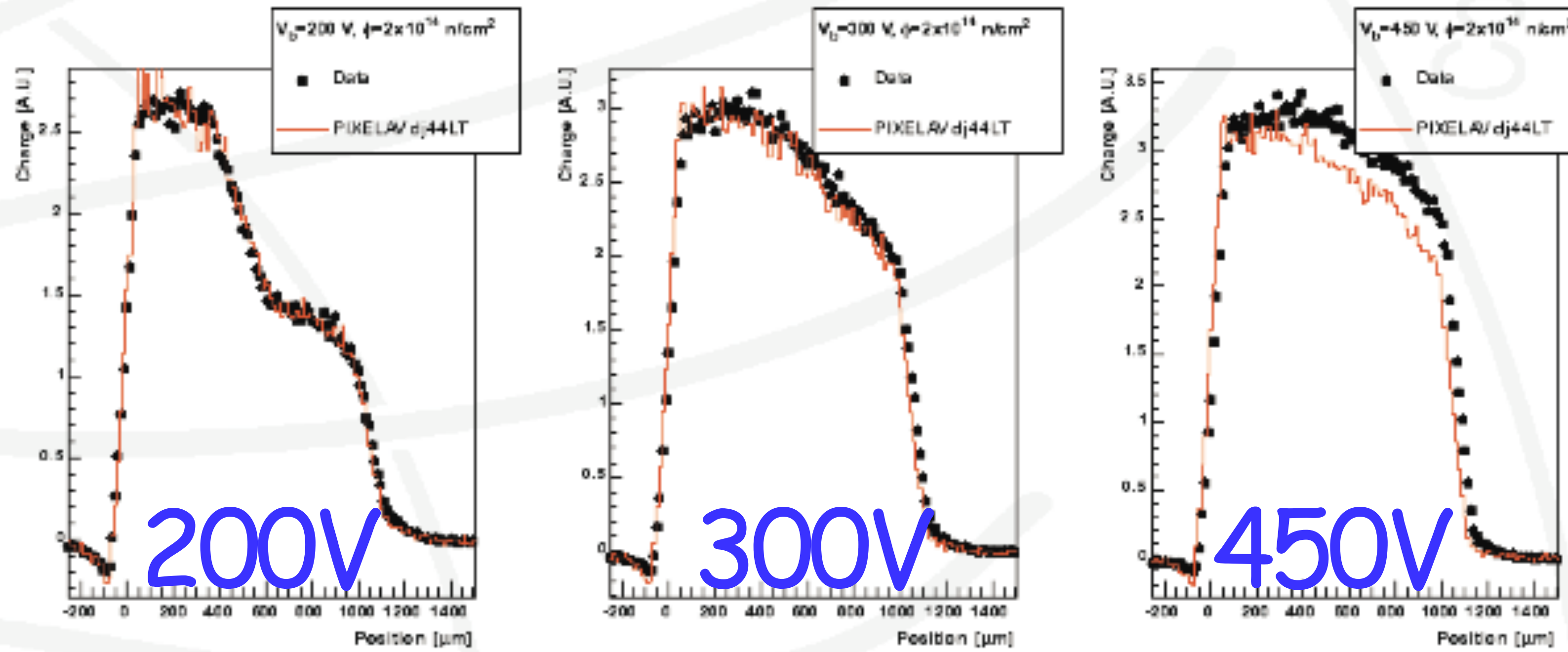
Use T-dependent recombination in TCAD and T-dependent quantities in Pixelav ($\mu_{e/h}$, $D_{e/h}$, and $\Gamma_{e/h}$):

T=-10C



Φ_1=6x10^{14} n_{eq}/cm^2:

T=-25C

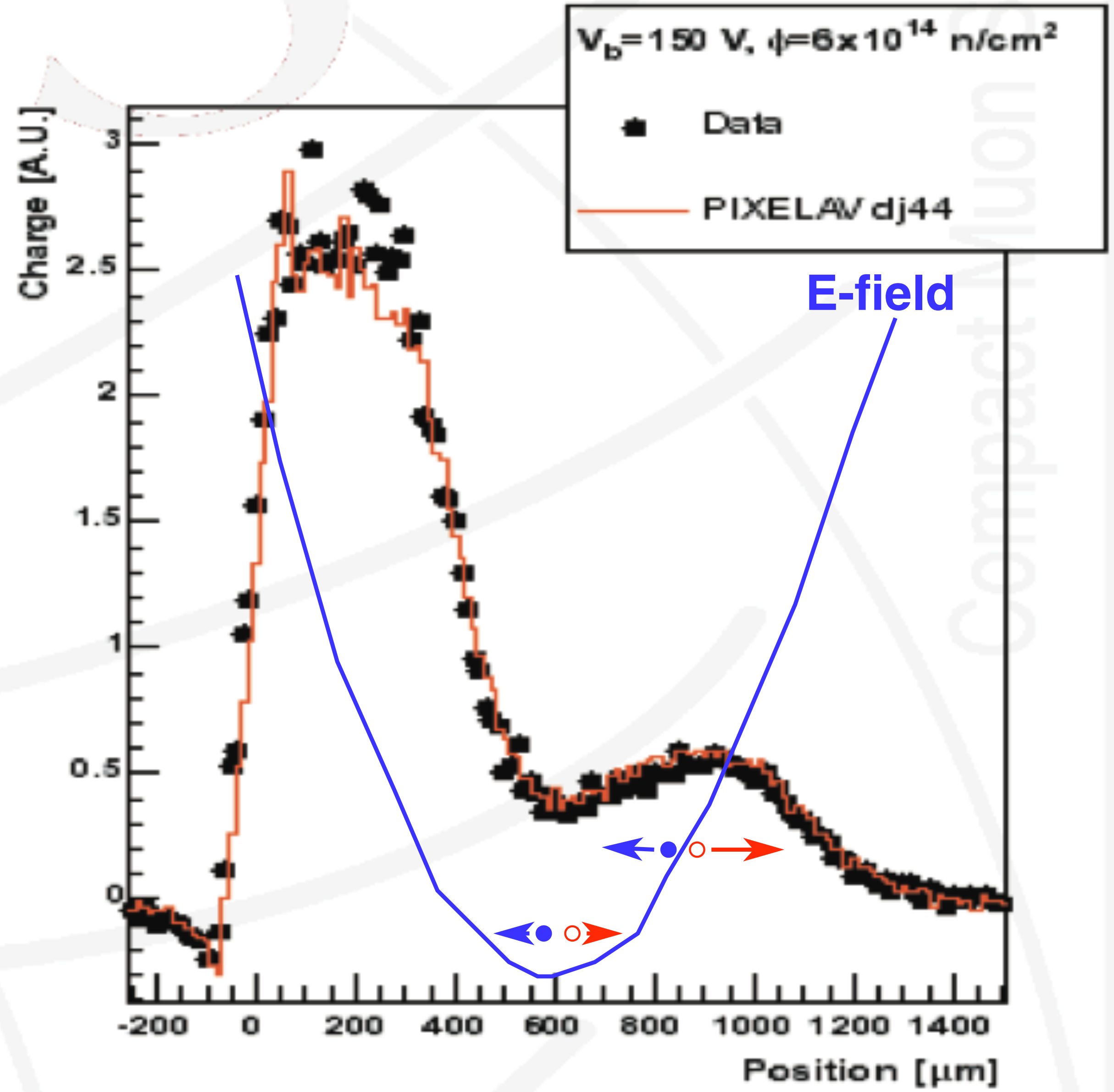


- dj-model is predictive!

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)



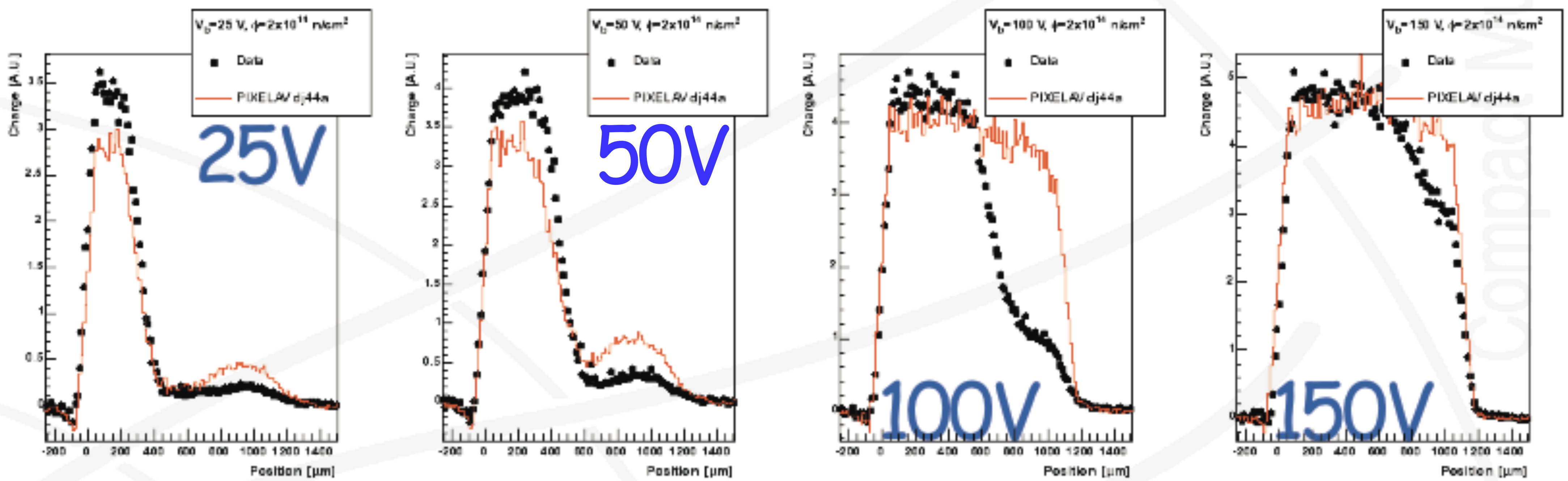
Scaling to Lower Fluences

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

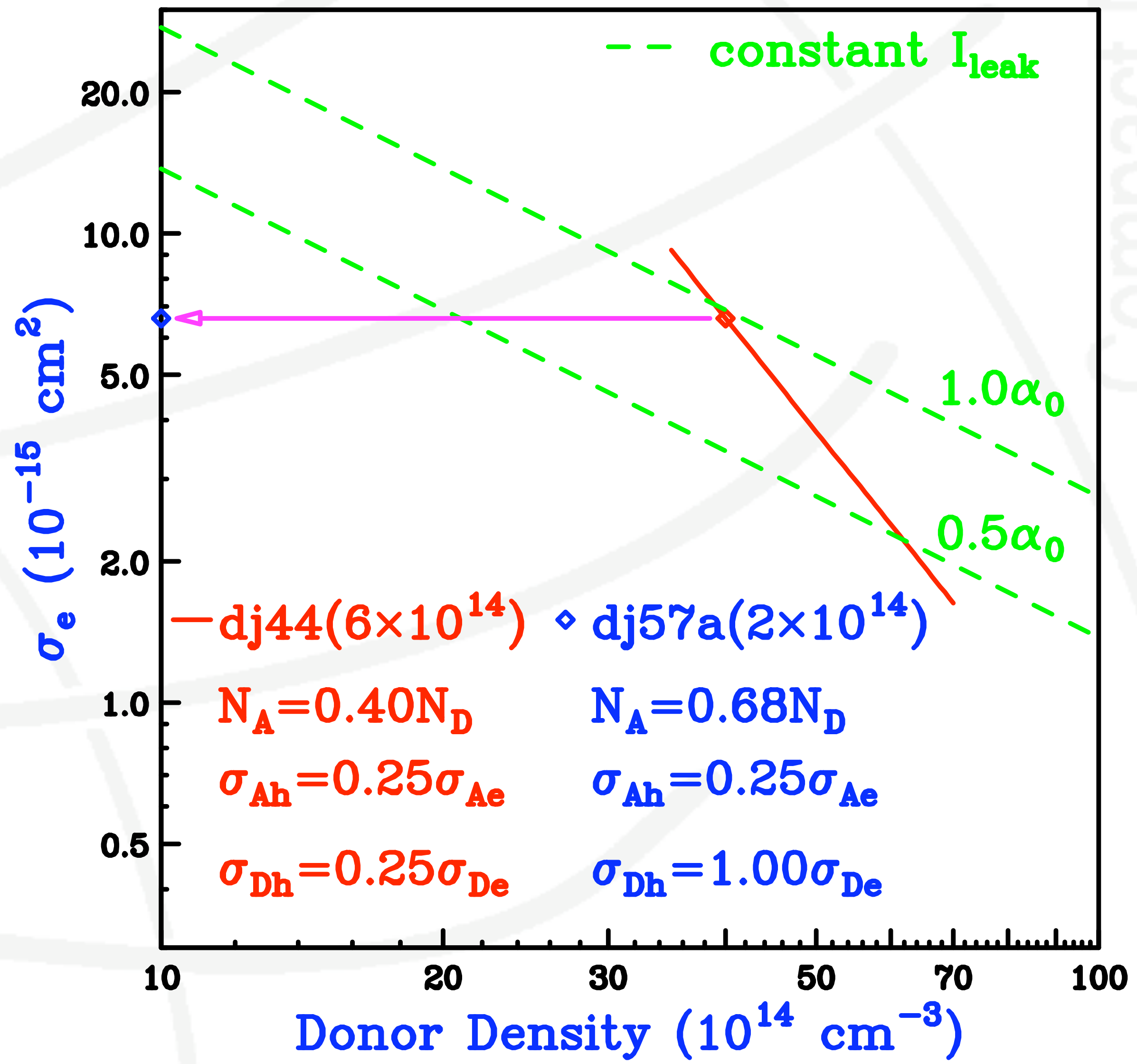
Why doesn't linear Φ scaling work?

- 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

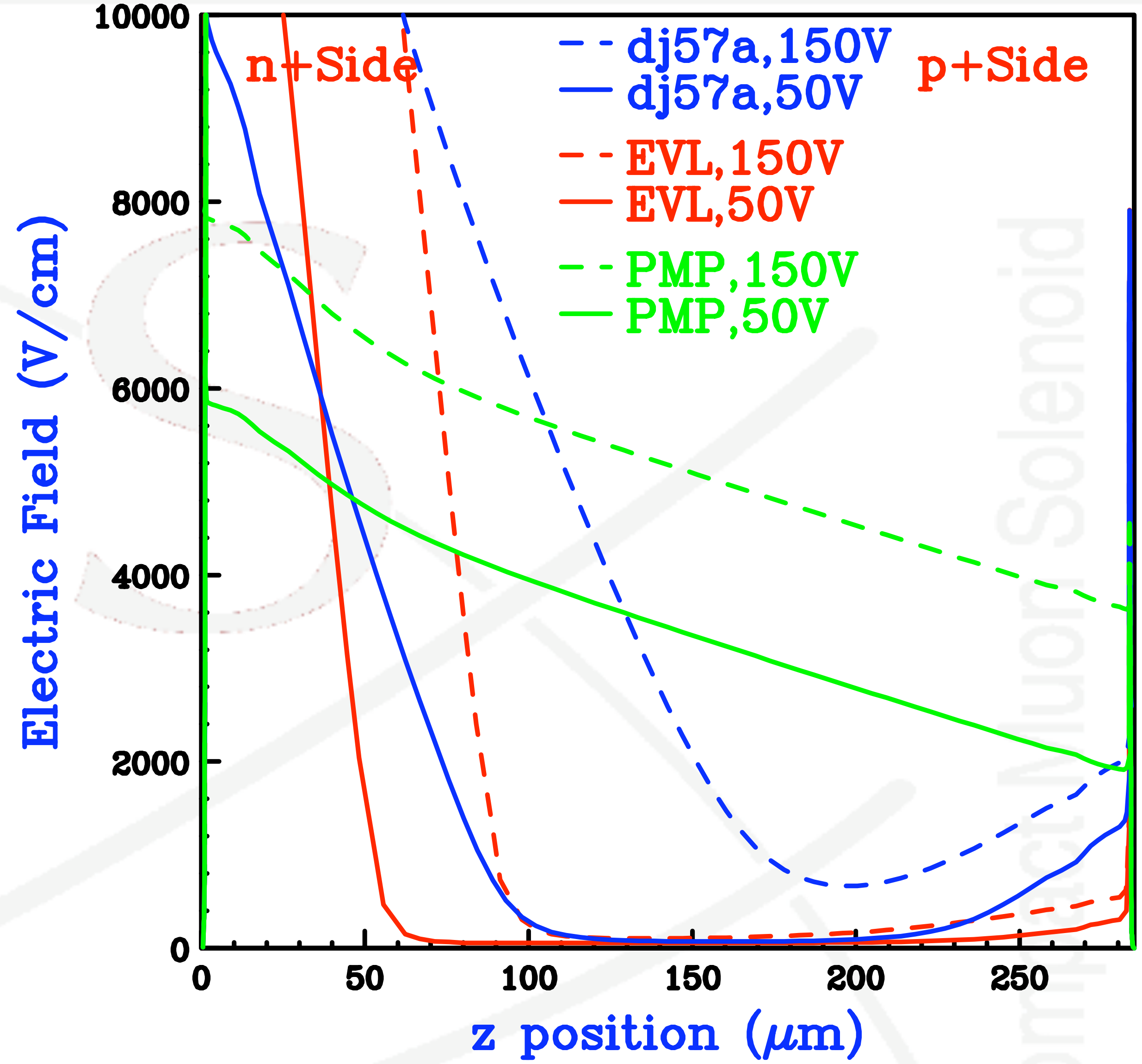
$$R_\Gamma = \frac{\Phi_2}{\Phi_1}, \quad R_A = R_\Gamma(1+\delta), \quad R_D = R_\Gamma(1-\delta)$$

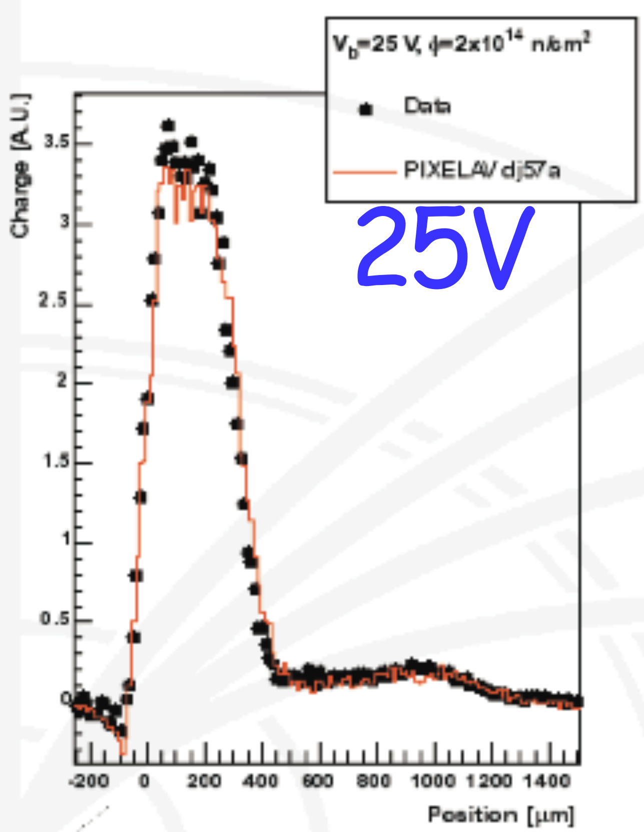
- $R_\Gamma=(R_A+R_D)/2$, keeps I linear
- increase N_A/N_D from 0.4 to 0.68 (closer to EVL value of 0.62)
- must scale the "full" I_{leak} point (range is ~ ±10% in N_D)
- net donor σ_h/σ_e also prefers to increase (not very sensitive)
- took 3 months of tuning!

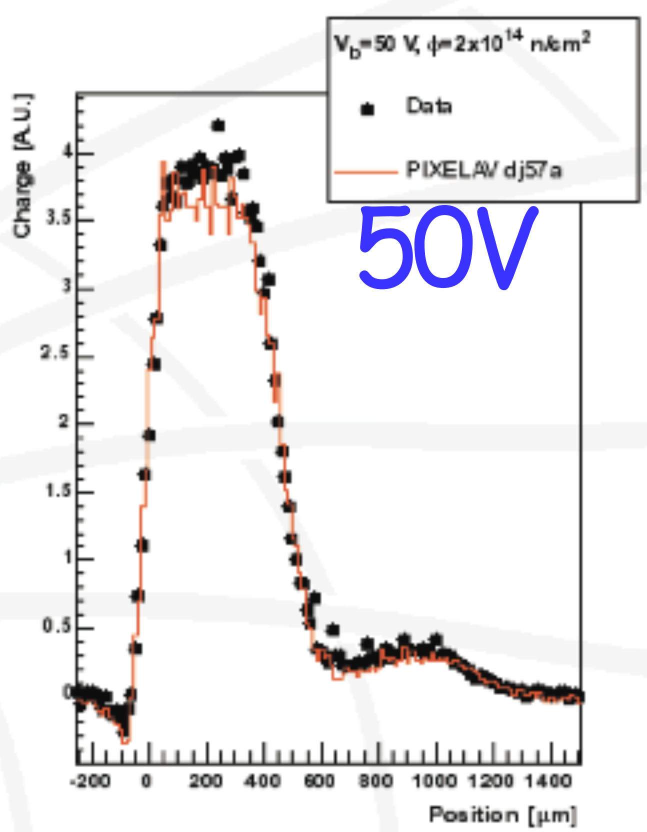


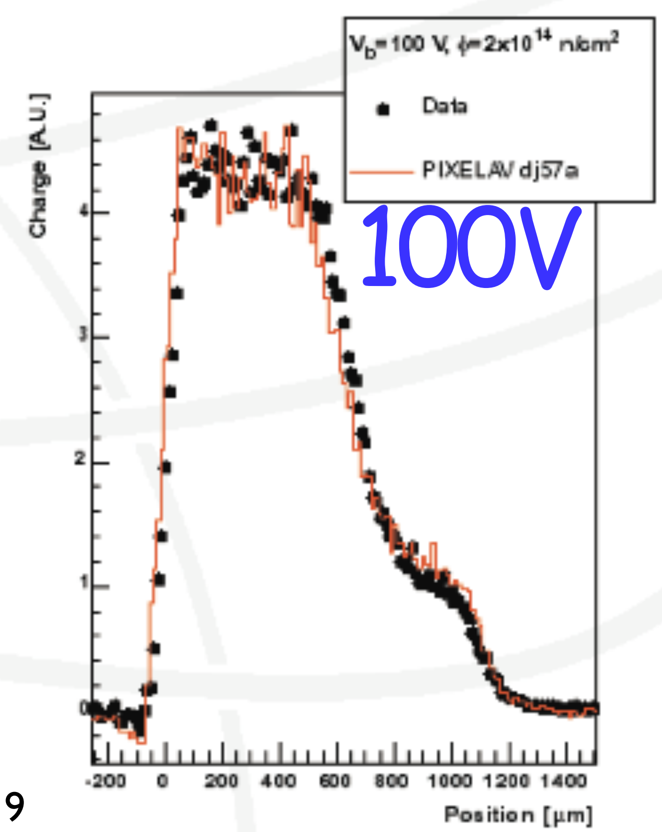
Best fit to $2.0\times10^{14}\ n_{eq}/cm^2$ is labelled dj57a

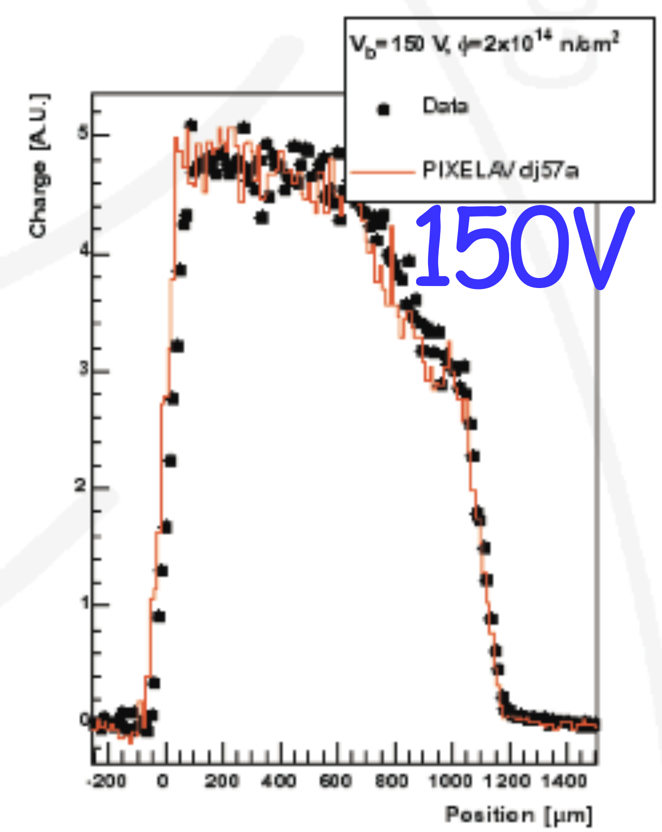
- $N_A/N_D=0.68$
- $\sigma_{Ah}/\sigma_{Ae}=0.25$, $\sigma_{Dh}/\sigma_{De}=1.00$,
- E-field still doubly-peaked (more than EVL prediction)
- Also compare with PMP model







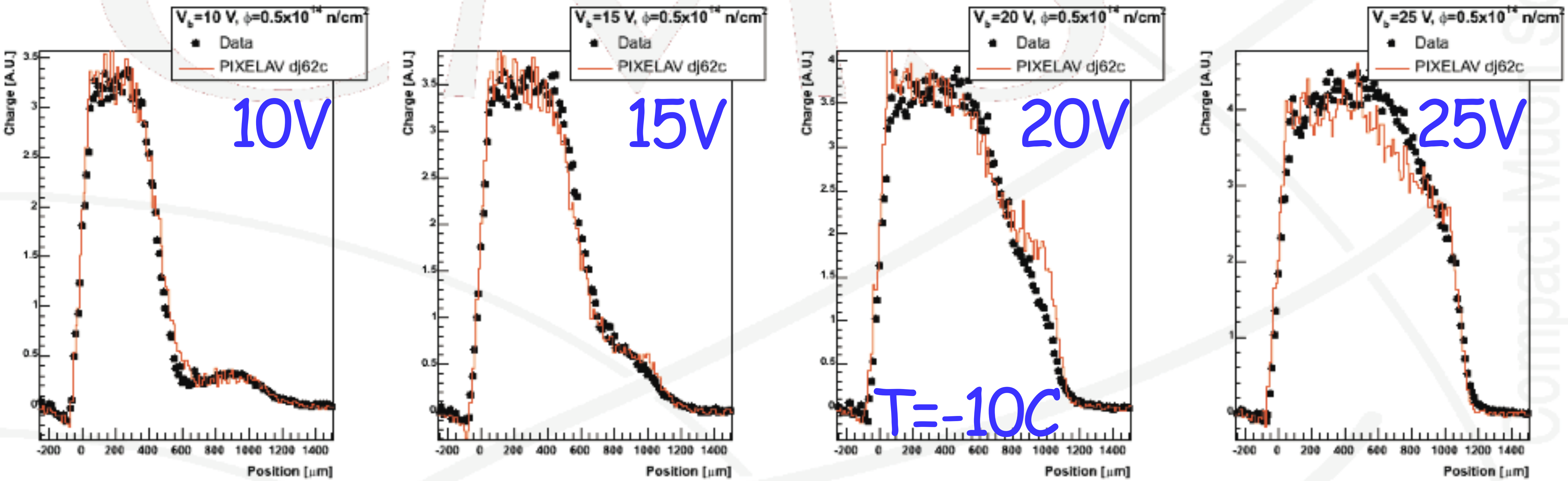




Scaling to Even Lower Fluences

Scale dj57a to increase N_A/N_D at Φ_3=0.47x10^{14} n_{eq}/cm^2

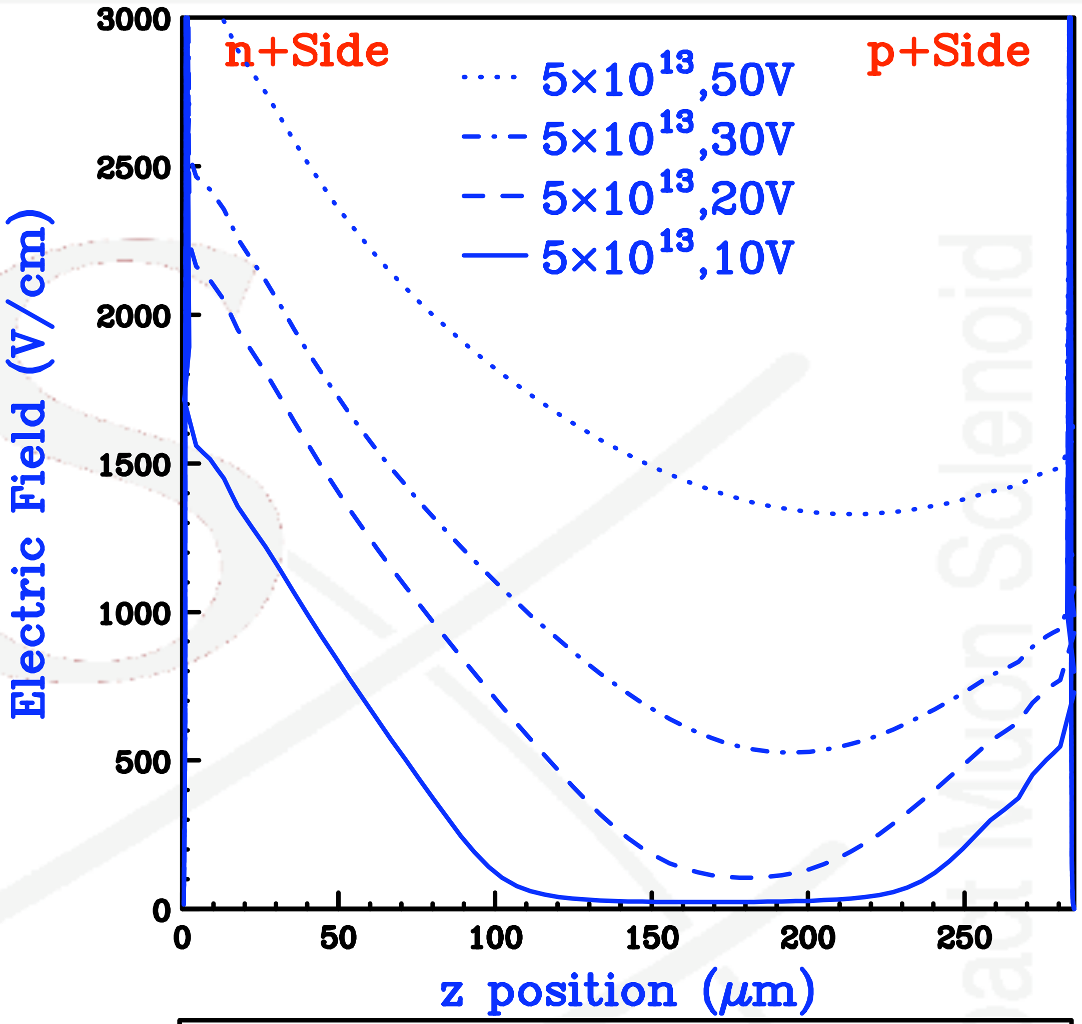
$$R_\Gamma = \frac{\Phi_3}{\Phi_2}, \quad R_A = R_\Gamma(1+\delta'), \quad R_D = R_\Gamma(1-\delta')$$



- dj62b: N_A/N_D =0.75, σ_{Ah}/σ_{Ae}=0.25, σ_{Dh}/σ_{De}=1.00
  - charge drift times now comparable to preamp shaping (simulation may not be reliable)
- the data "wiggle" is still present at Φ_3=0.47x10^{14} n_{eq}/cm^2
  - a doubly-peaked field persists at lowest fluence!!!

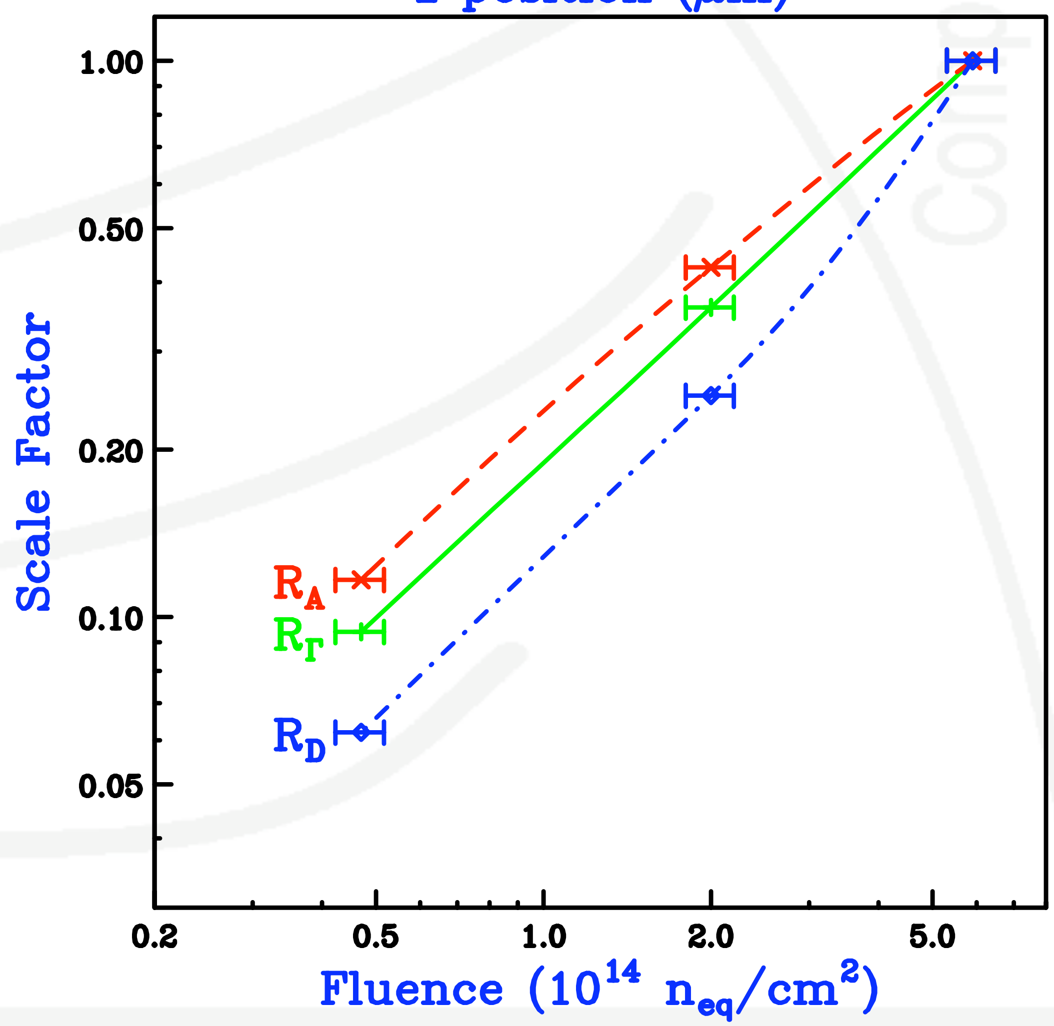
We can still see evidence of a doubly-peaked electric field near the "type-inversion" fluence:

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



Scale factor summary:

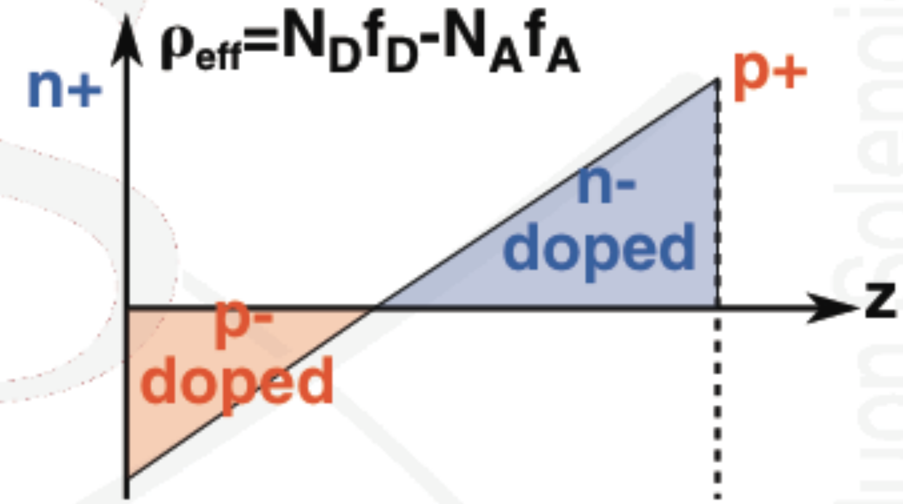
- trapping rates are linear in Φ
- N_A/N_D increases from 0.40 at Φ_1=5.9x10^{14} n_{eq}/cm^2 to 0.75 at Φ_3=0.47x10^{14} n_{eq}/cm^2

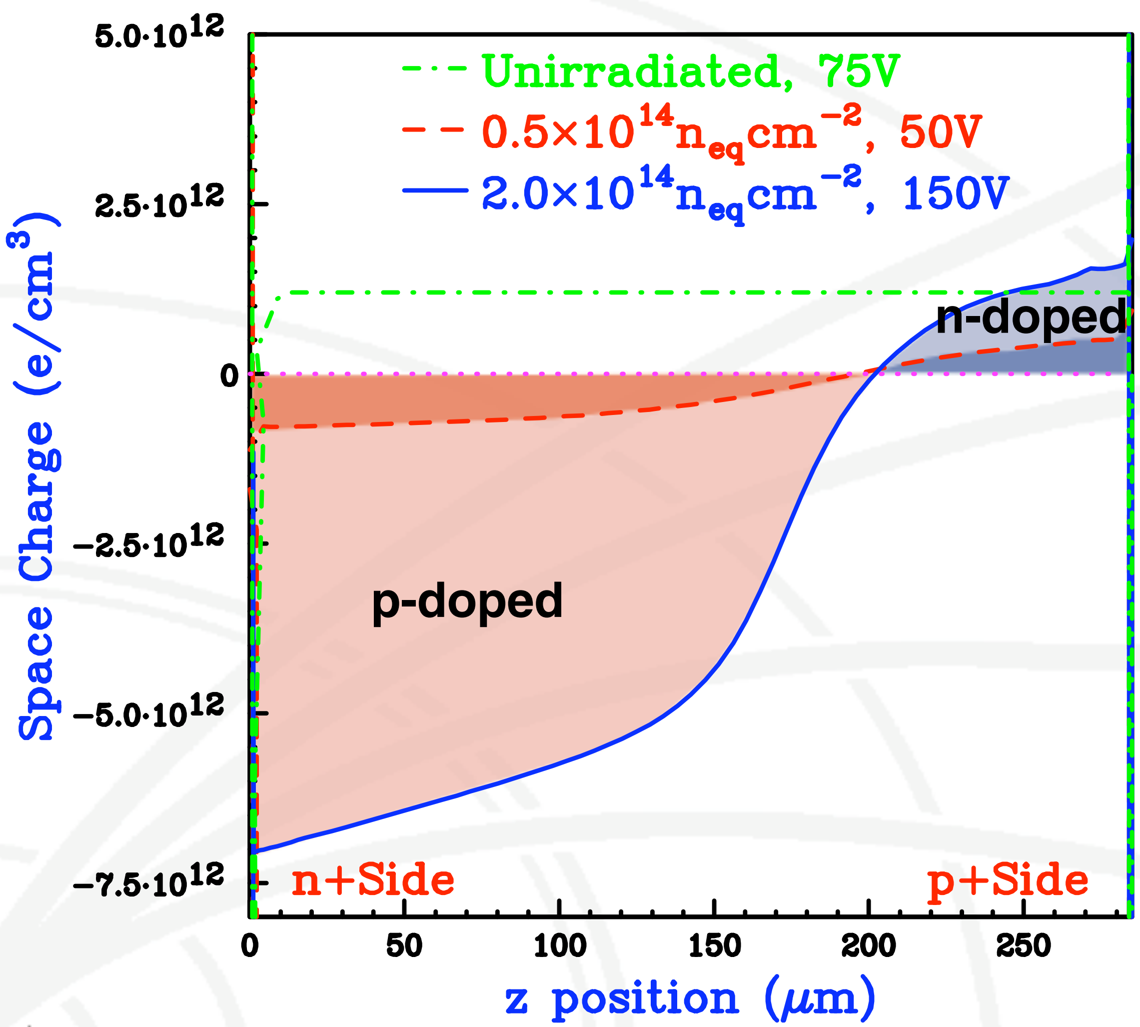


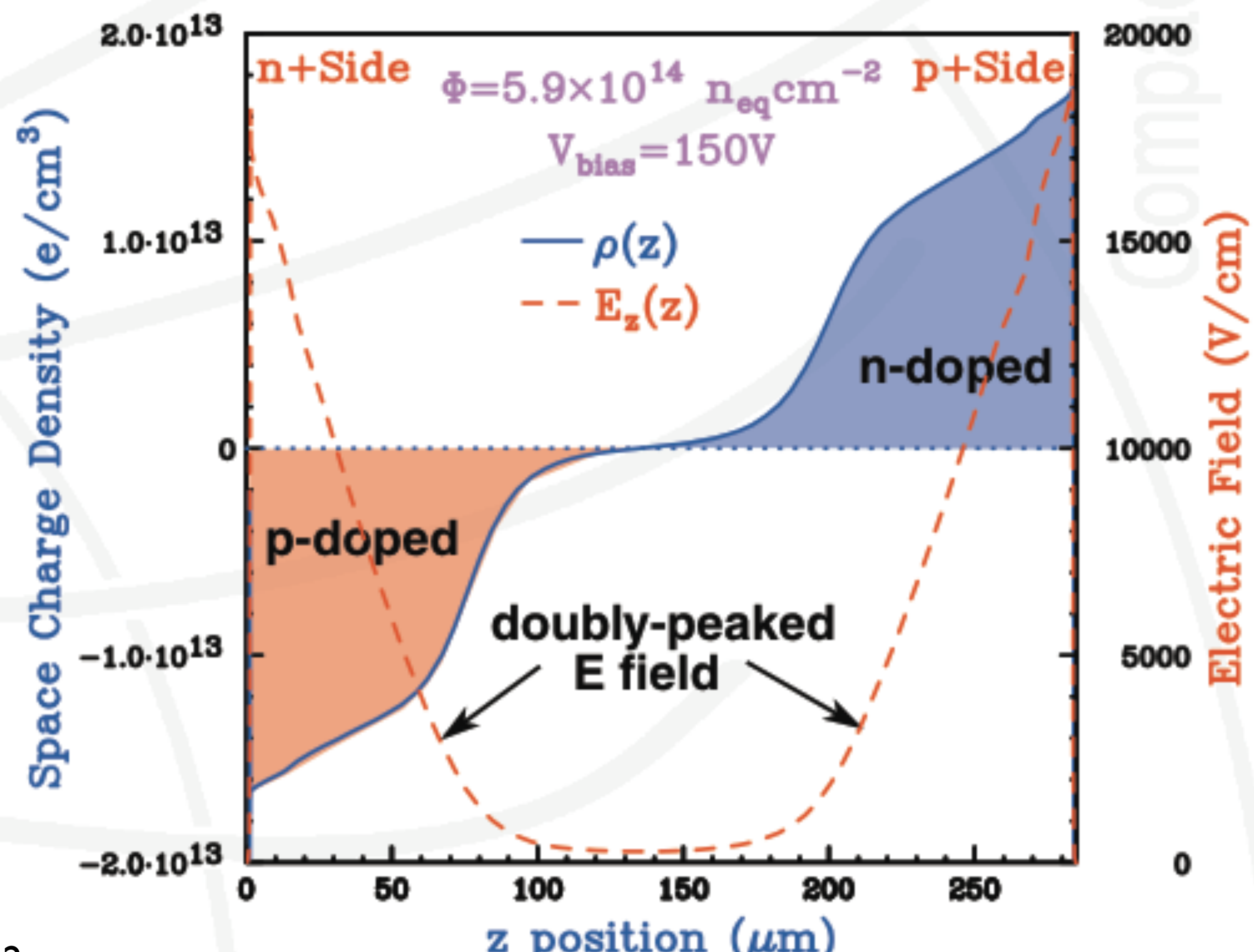
Space Charge Distributions

The tuned models do not have the idealized linear space charge distributions predicted by the EVL model:

- carrier velocities are not uniform
- current conservation ➔ non-linear ρ_{eff}

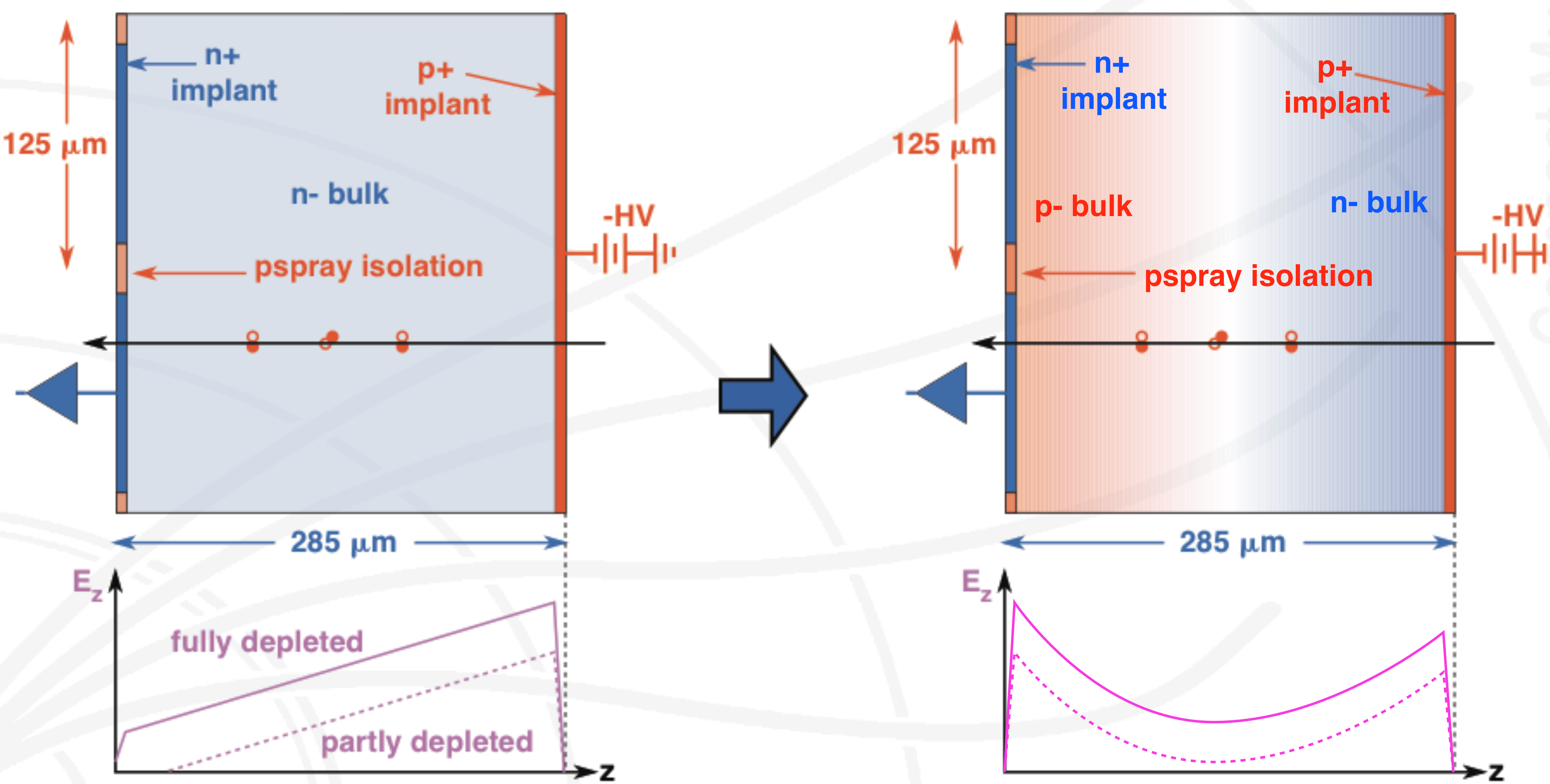






Conclusions

- It is clear that a two-peak electric field is necessary to describe our charge collection data even at low fluence
  - Usual model of type inversion after irradiation is wrong:
    - only ~1/2 of the junction inverts, ρ_{eff} is not constant



- Usual terminology that describes unirradiated sensors: V_{dep}, ℓ_{dep}, N_{eff} doesn't really describe the physics of irradiated sensors:
  - what does this curve really mean?

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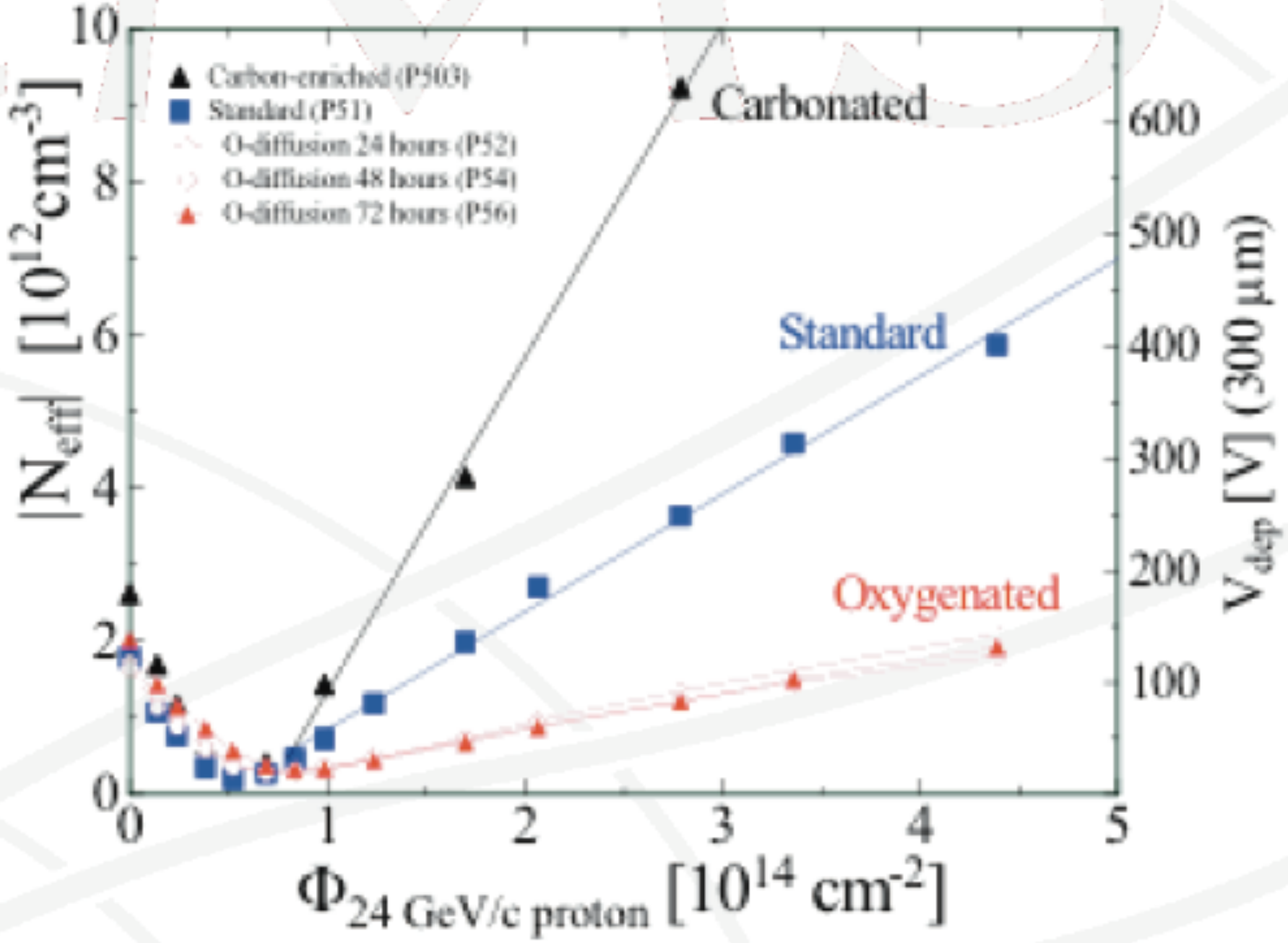
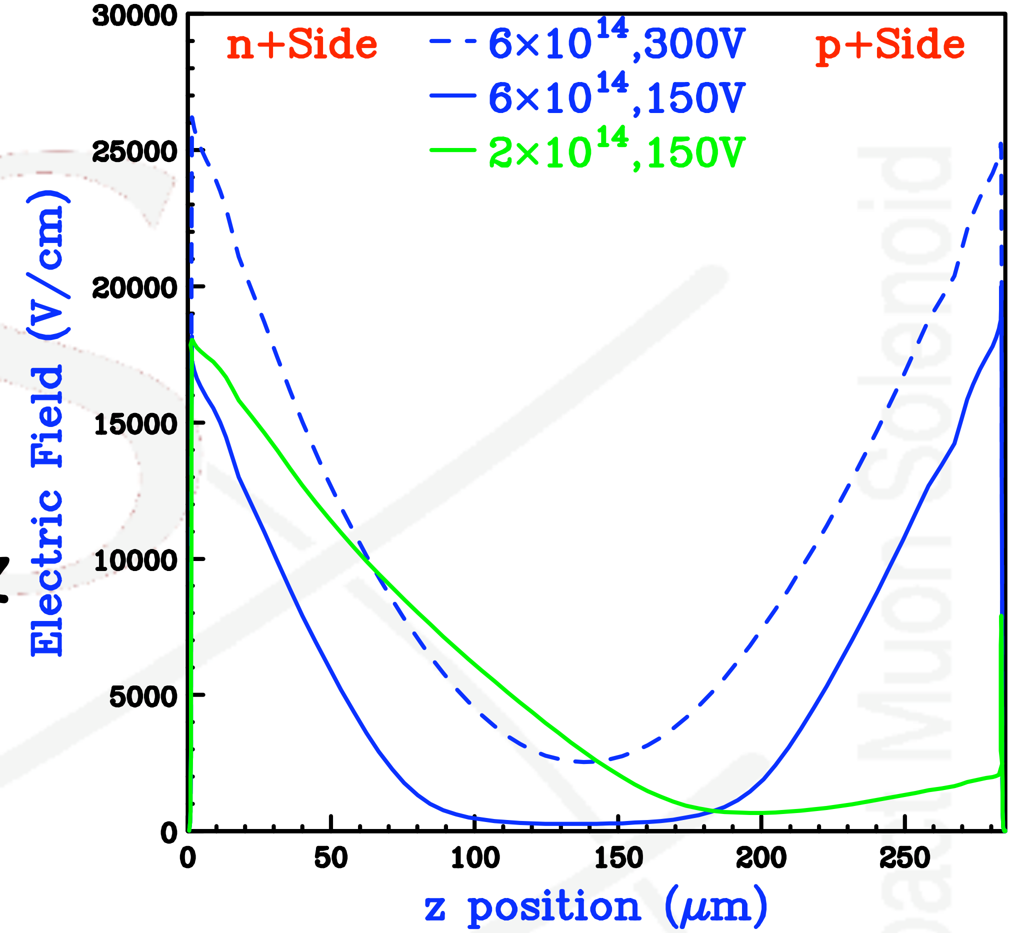
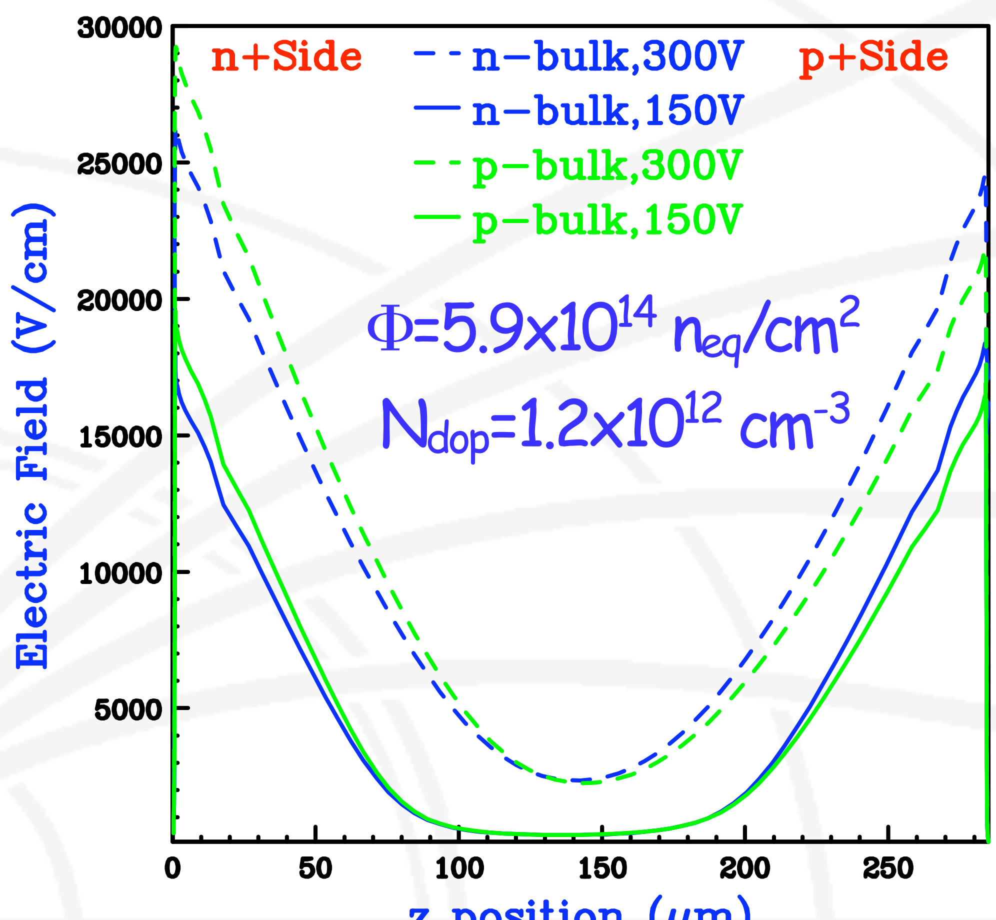
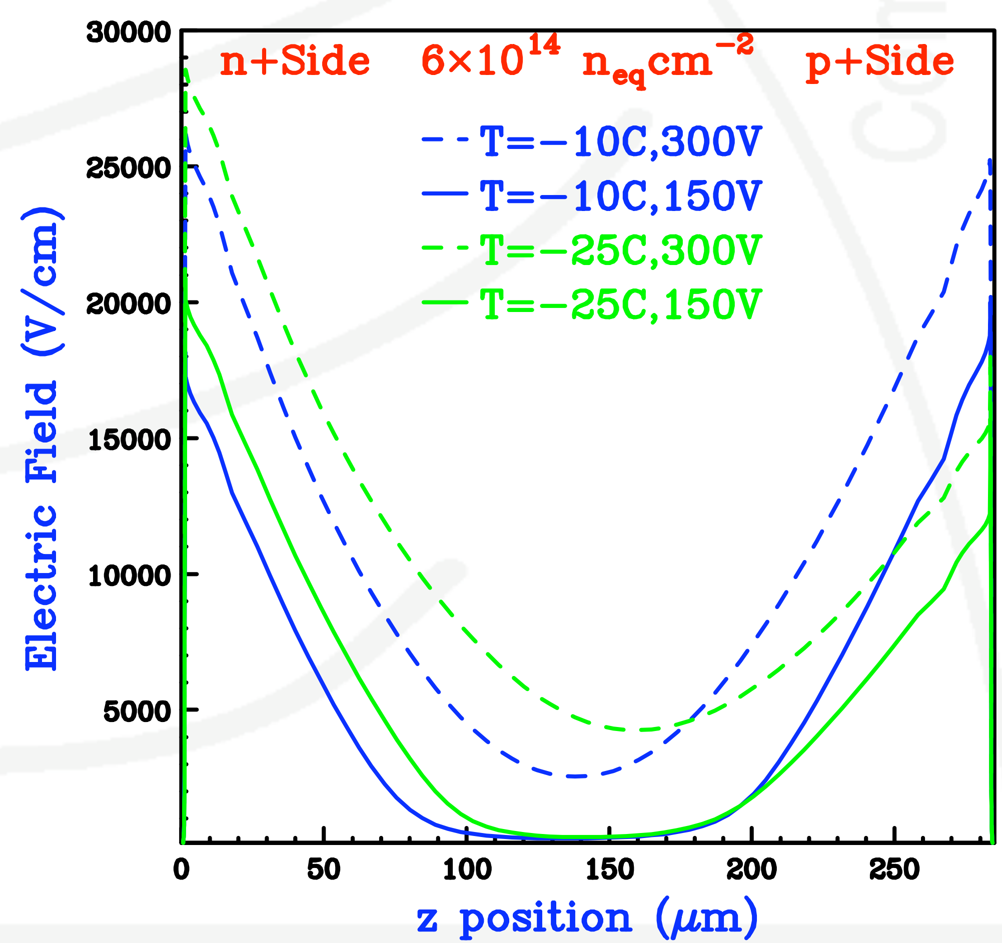


  - need an analytic or semi-analytic dj description to characterize irradiated sensors

- 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 V, T and Φ dependence of E-field
- Assume 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)



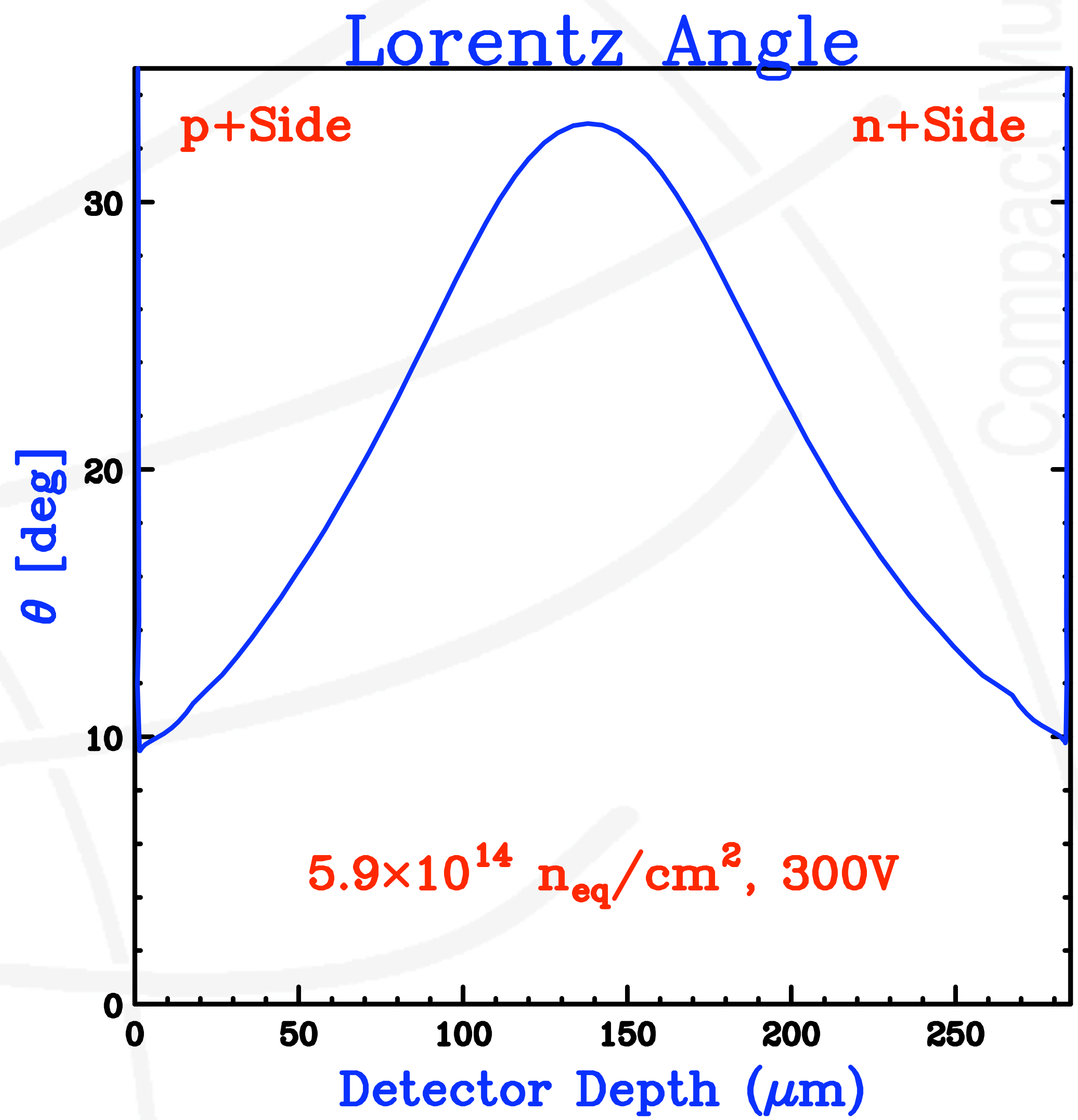




- Model will be important to calibrate the hit reconstruction after irradiation in LHC
  - Charge Sharing in 4T CMS: dominated by Lorentz drift. The Lorentz angle is linear in the mobility $\mu(E)$

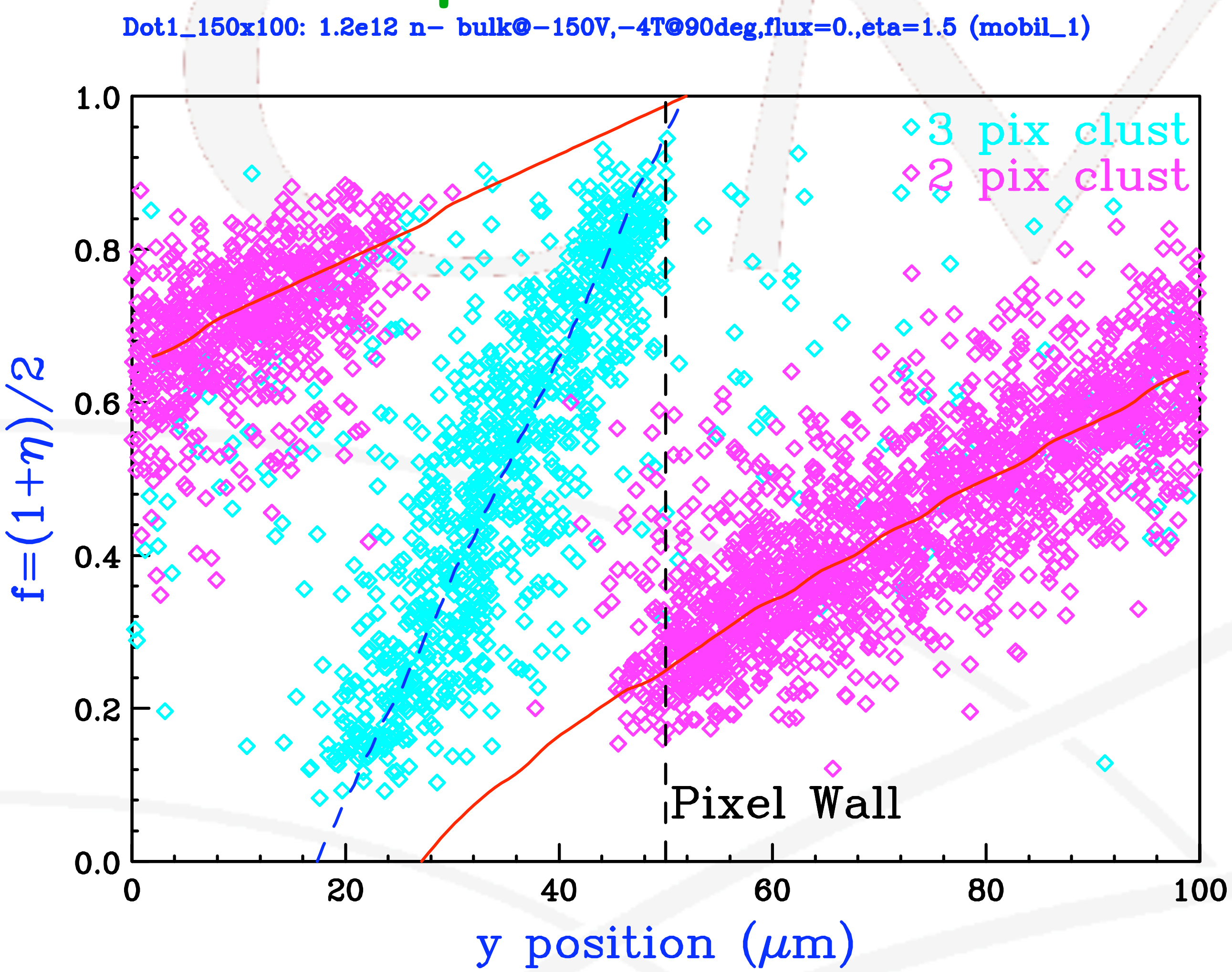
$$\tan\theta_L \simeq \frac{e r_H v B \sin\theta_{vB}}{eE} = r_H \mu(E) B \sin\theta_{vB}$$

- ✦ $\mu(E)$ 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

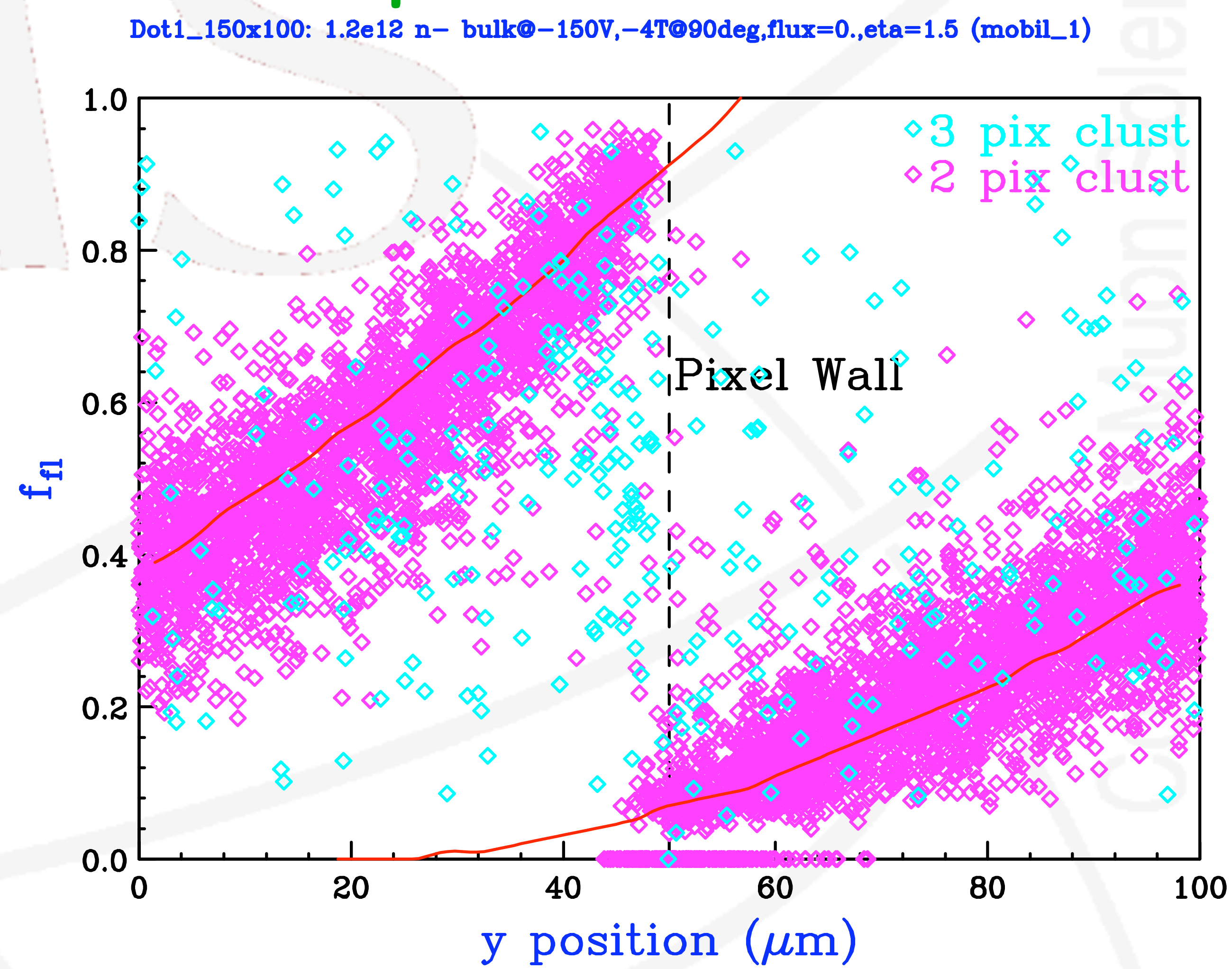


Plotting the fraction of charge $f=Q_L/(Q_F+Q_L)$ shared in the last and first pixels of an azimuthal cluster vs the hit position

η=1.5 new



η=1.5 irr



- Before irradiation: linear sharing w/ large offset from Lorentz drift
- After irradiation: 3-pixel clusters vanish
  - 2-pixel clusters have non-linear hit position dependence on f
- need model to understand and correct for this