Modeling MOSFET Process Variation using PSP

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What this talk is about:

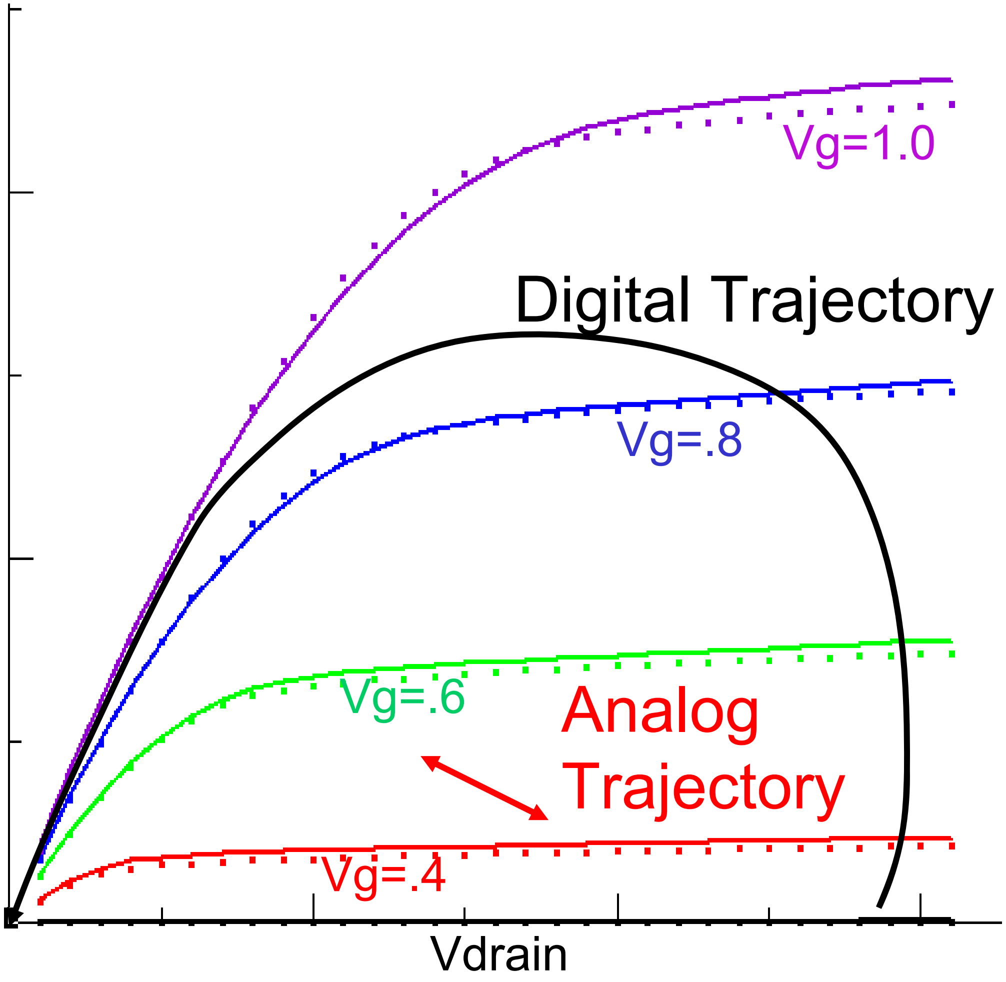
- **How to setup a production methodology to model chip mean variation of MOSFET channel current**
  - For designers of any style circuit for any application
  - For high volume production modeling
  - Using the PSP Global Parameter Set
    - PSP is the next generation MOSFET model select by the CMC

Approaches to model variation

- **Fixed corners**
  - Different parameter sets for Fast, Slow, High leakage, NFET fast – PFET Slow, etc.
- **Skewing parameter aka user defined corners**
- **Monte Carlo**
- **We believe you a good Monte Carlo model to develop the others**

Circuit Designer Requirement for the Process Model

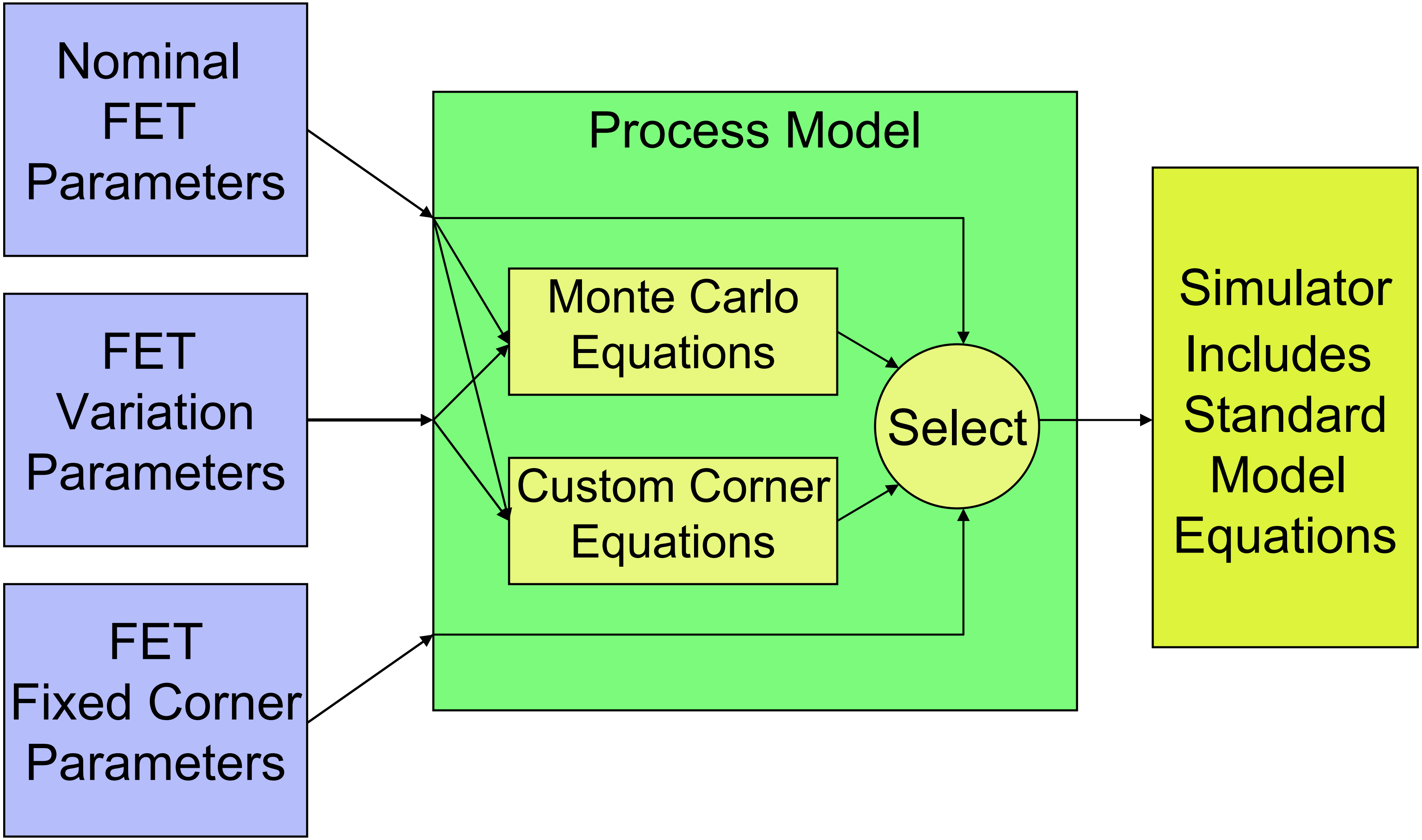
- **Predict range of circuit performance by**
- **covering the full range of device performance**
  - Vt
  - Id
  - Gm
  - etc.
- **Capture the relationships between characteristics**



Modelers Requirement for the Process Model

- **Standard form for**
  - Rapid Development Testing & Deployment
  - Model build using limited data
- **Model parameters to varied which capture physical correlations (even when you don’t have data)**
- **Model parameters are robust i.e. effective for various device types and model fits**

Standard Form: Anatomy of an FET compact model



Nominal FET Parameters

FET Variation Parameters

FET Fixed Corner Parameters

Process Model

Monte Carlo Equations

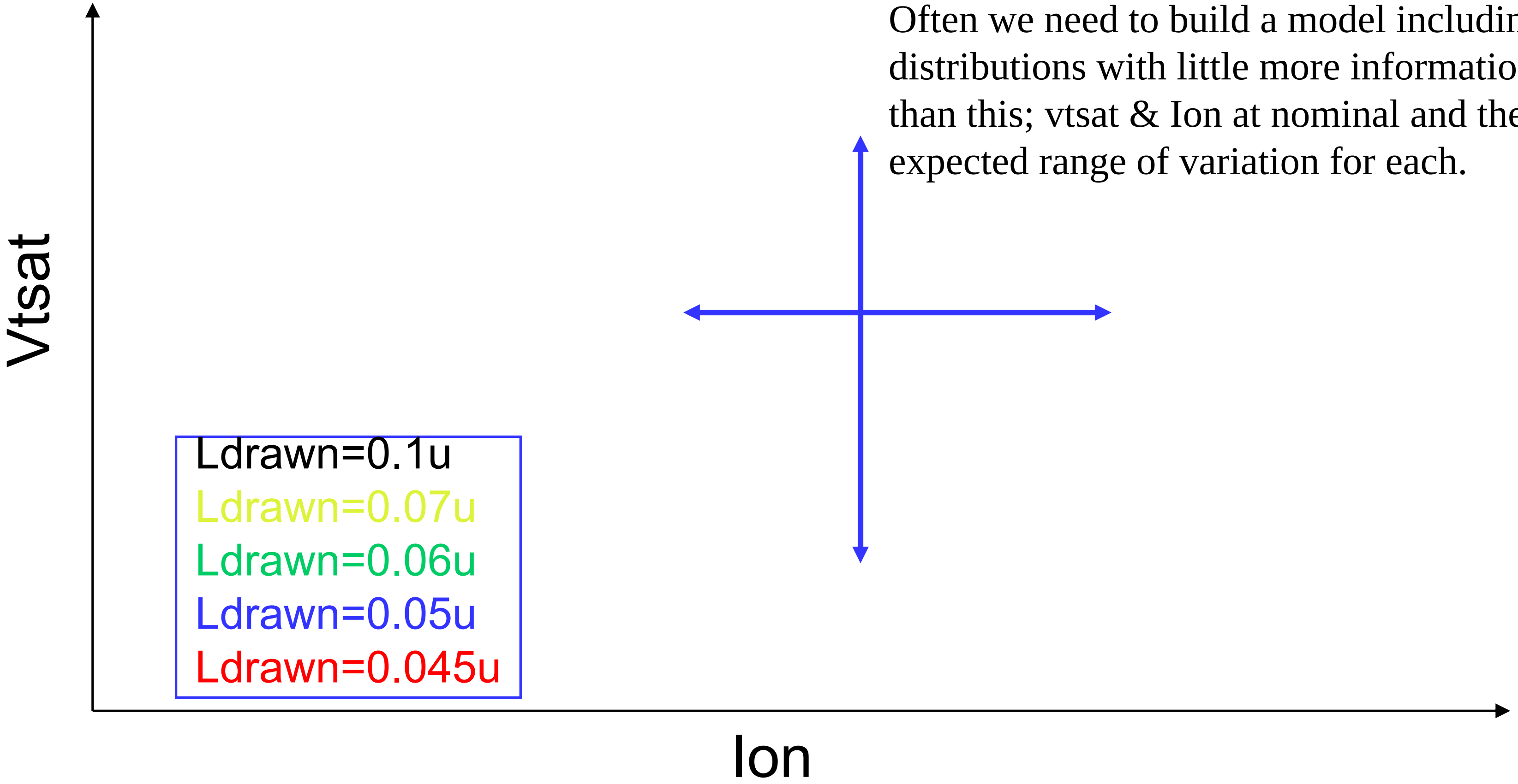
Custom Corner Equations

Select

Simulator Includes Standard Model Equations

Modelers Requirement for the Process Model

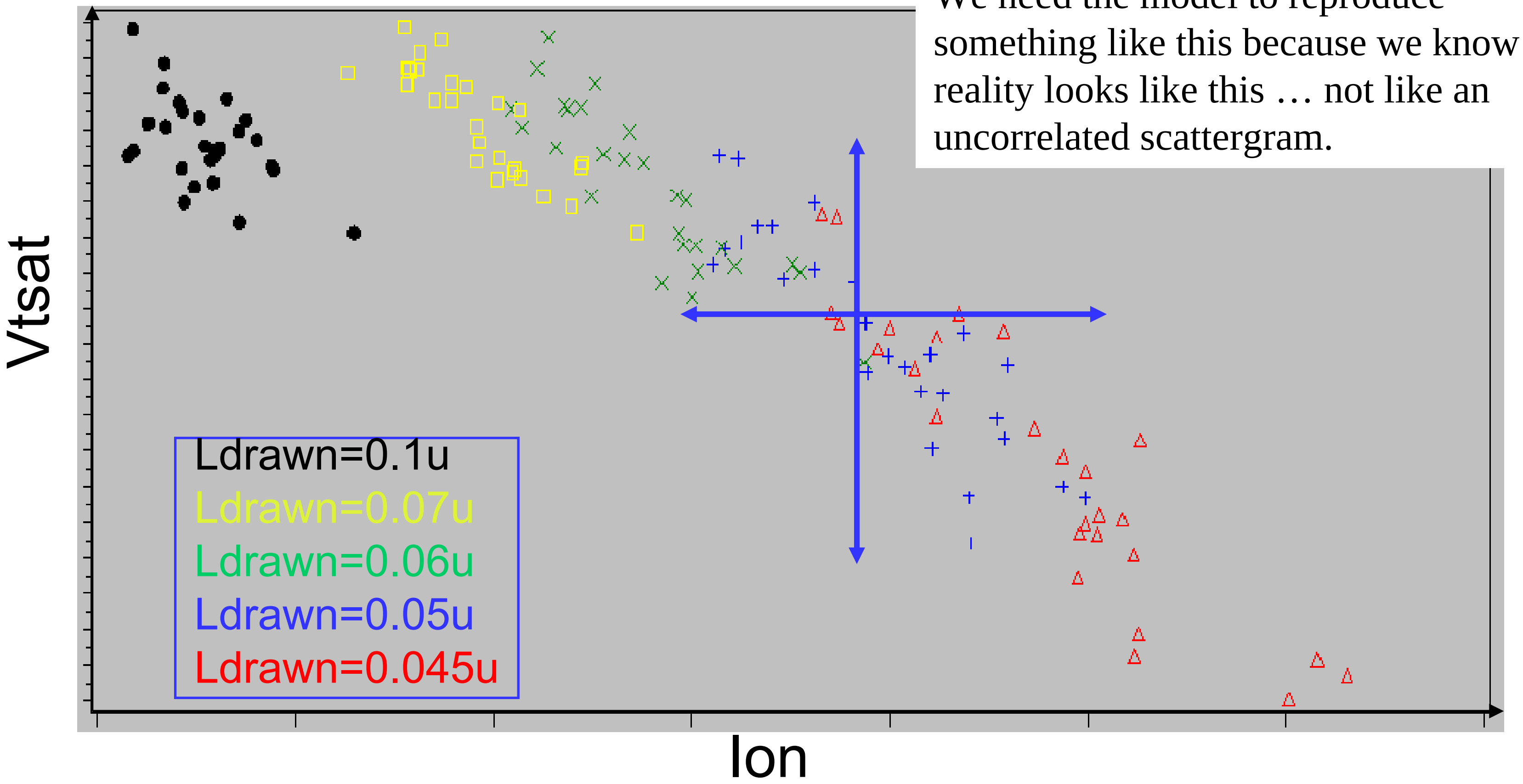
- **Build the process model from limited or imaginary data**
- **Capture the relationships between characteristics**



Often we need to build a model including distributions with little more information than this; vtsat & Ion at nominal and the expected range of variation for each.

Modelers Requirement for the Process Model

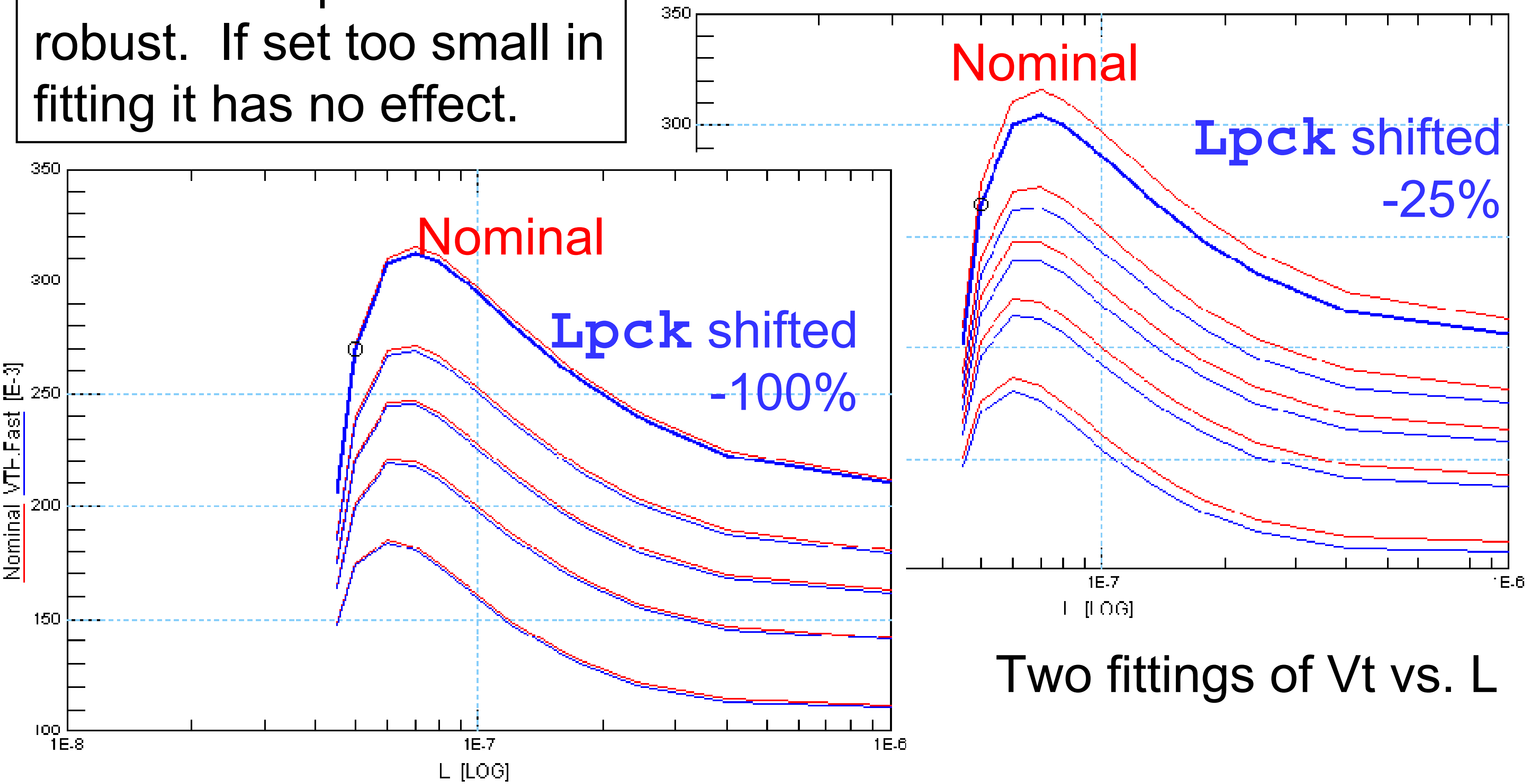
- **Build the process model from limited or imaginary data**
- **Capture the relationships between characteristics**



We need the model to reproduce something like this because we know reality looks like this … not like an uncorrelated scattergram.

Model Parameters used are robust

Parameter Lpck is not robust. If set too small in fitting it has no effect.



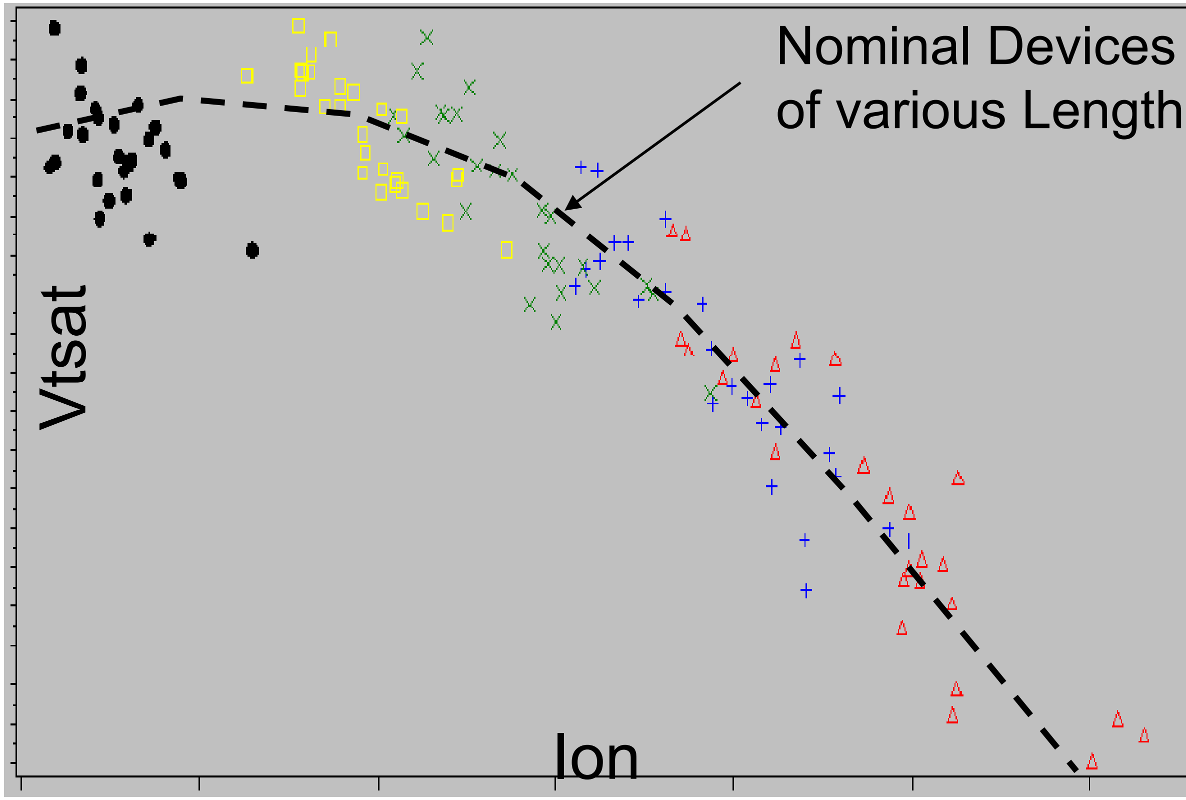
Two fittings of Vt vs. L

How to start?

- **Choose a technology where you have real variation data from running the line over time.**
  - I have a 65nm NFET/PFET pair
  - A dozen wafers from a dozen lots over a year's production
- **Measure detailed data from multiple chips**
  - Full IdVg and IdVd sweeps at multiple Vbody steps
- **Examine the data for independent modes of variation**
- **Look for Robust parameters to model the modes**
  - Ideal parameters are measurable independently

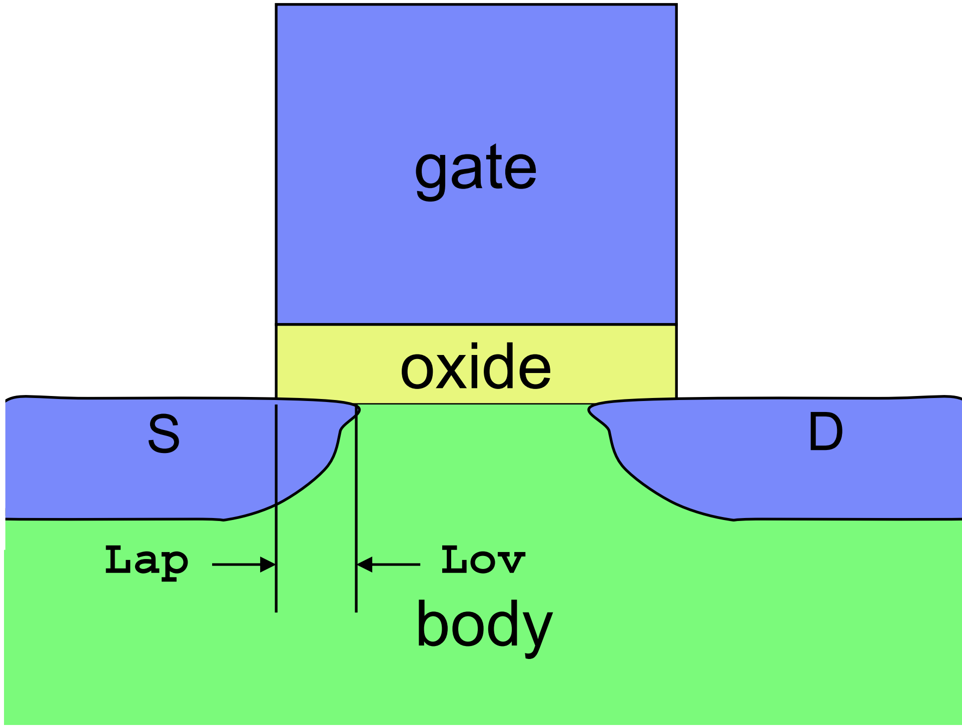
Length and Width

- `LVARO, WVARO`
- **Good measurements taken inline, can set independent of electrical data**
- **Strong effect regardless of fit**
- **Physically capture Id, Vt, etc.**



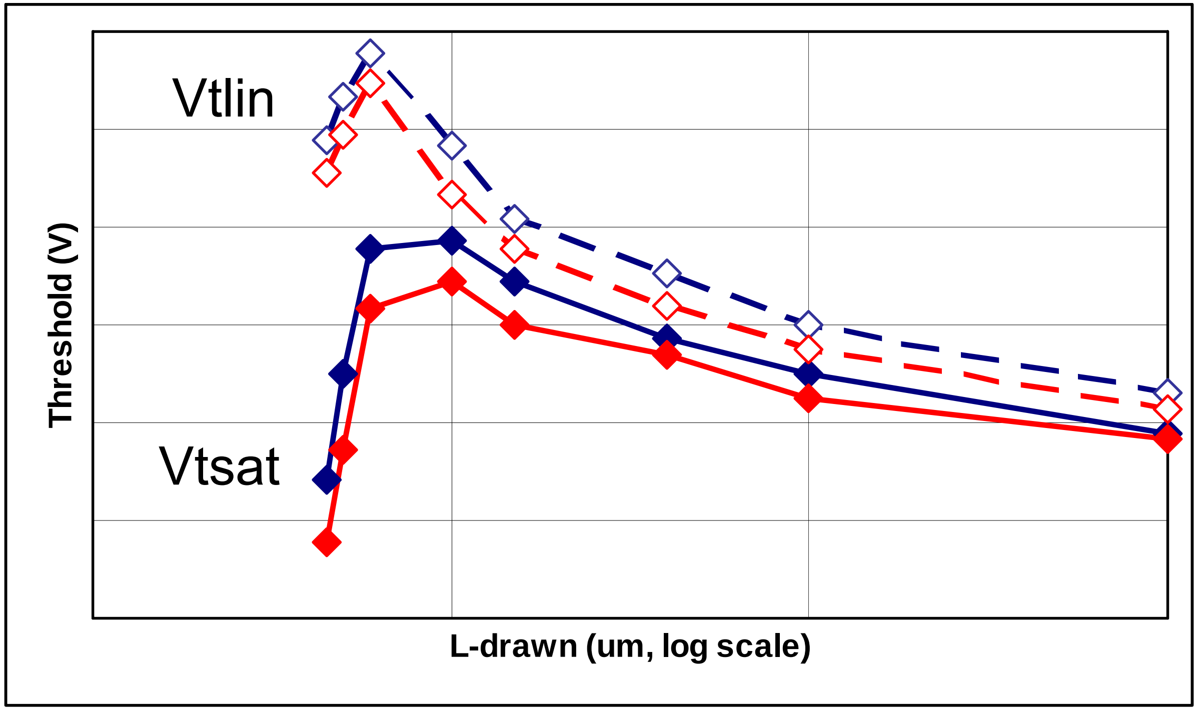
`Lap` and `Lov`

- **`Lap` and `Lov` represent the same physical distance for IV and CV respectively**
- **Cov and L-dependent quantities like Ion are correlated even if your data doesn't show it**
- **`ΔLap = ΔLov * mcov`**



Variation in the Vt vs. L curve

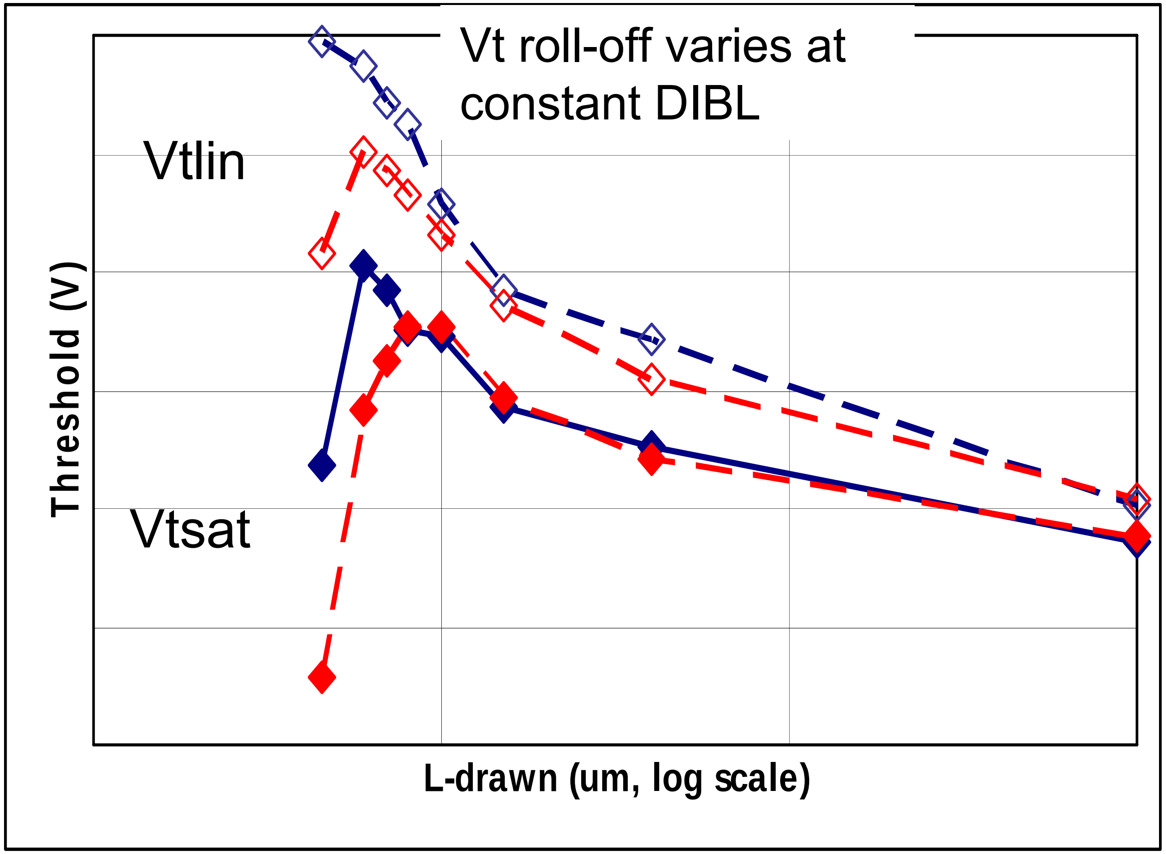
- **Overall shift**
  - **`Nsub`**
  - Moves overall Vt
  - Moves body effect
  - Very robust



Blue and Red represent measured data from different chips

Variation in the Vt vs. L curve

- **Short channel variation**
  - Constant long channel VT
  - Constant DIBL
  - Variation in Roll-off
  - Also see variation in DIBL but ΔL variation model this



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Possible PSP parameters for Vt variation of short FETs

$$\mathrm{NSUB} = f(N_{\mathrm{subO,eff}}, N_{\mathrm{pck,eff}}, L_{\mathrm{pck,eff}})$$

where f is an increasing function of all arguements and

$$N_{\mathrm{pck,eff}} = \mathrm{NPCK} \cdot \mathrm{MAX}\left(\left[1 +\right.\right.$$

$$L_{\mathrm{pck,eff}} = \mathrm{LPCK} \cdot \mathrm{MAX}\left(\left[1 +\right.\right.$$

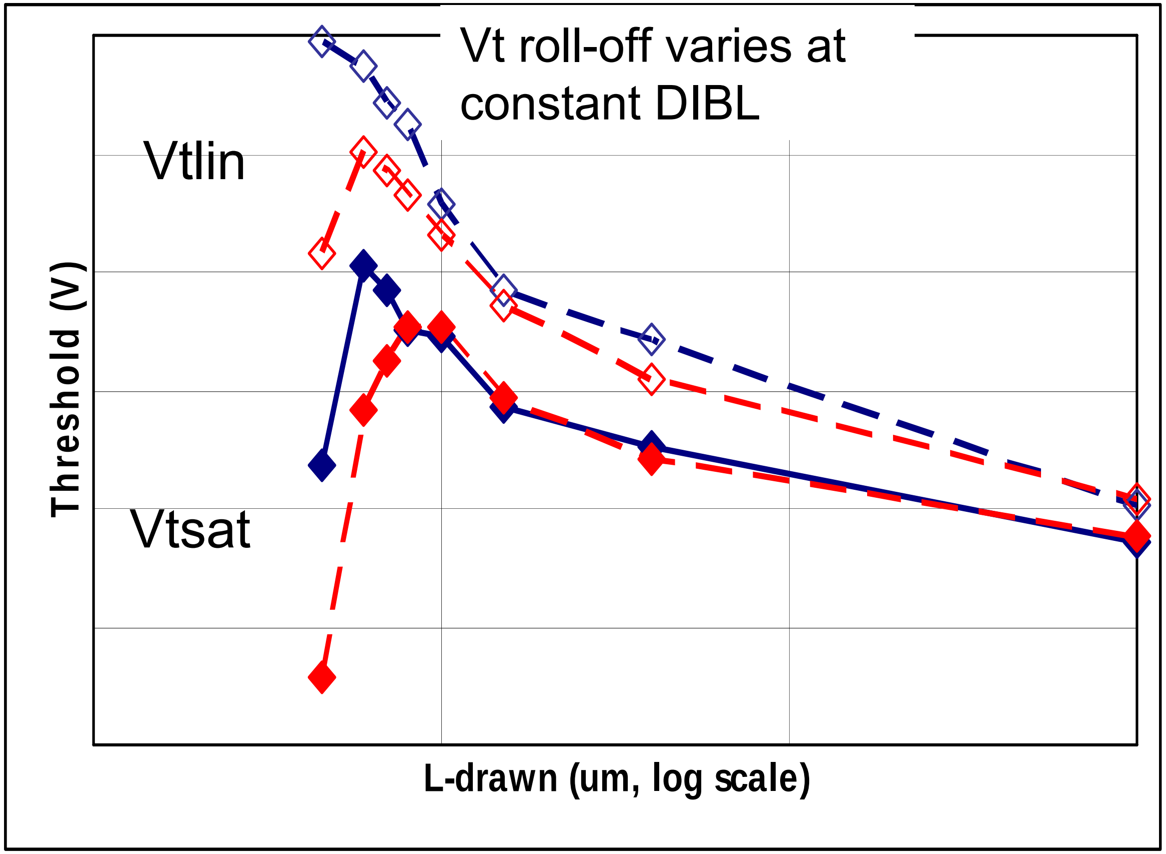
Narrow W terms

$$\mathrm{NEFF} = N_{\mathrm{sub}} \cdot \left(1 - \mathrm{FOL1} \cdot \frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}} - \mathrm{FOL2} \cdot \left[\frac{L_{\mathrm{EN}}}{L_{\mathrm{E}}}\right]^2\right)$$

- `NSUBO` effects all lengths
- `NPCK, LPCK` model halo doping
- `FOL1, FOL2` are short channel fitting terms
- `VFBL` is a short channel adjustment to flatband

Variation in the Vt vs. L curve

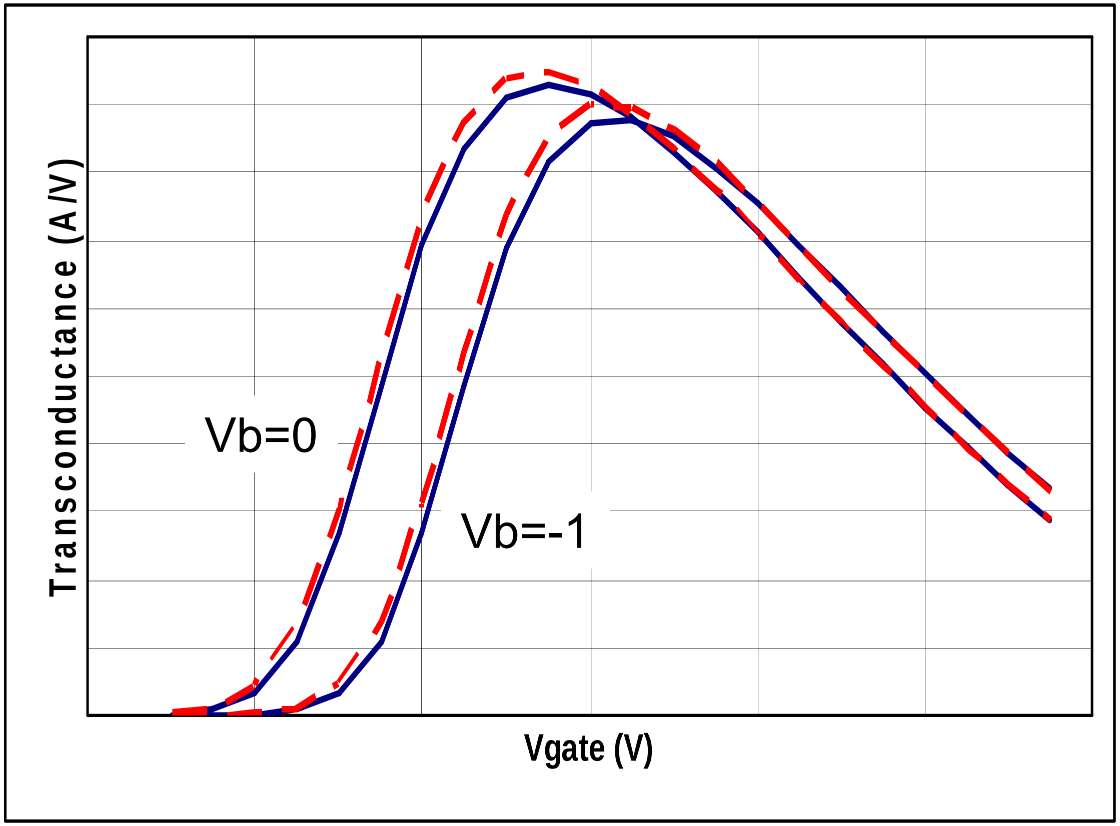
- **Short channel variation**
  - x **`Npck`**(pocket doping parameter) too strong for long devices + not appropriate for no-halo FETs
  - x **`Fol1`** or **`Fol2`**(Short Channel Effect parameters) not robust to fitting.
  - x **`VFBL`** not as strongly short channel, does not change body effect
  - √ **`Fol1`** and **`Fol2`** by the same fraction



Blue and Red represent measured data from different chips

Transconductance, long L

- **Variation in peak gm of long devices with similar Vt**
  - Small effect
  - Model with ʊo(base mobility)
  - Other features of gm curves are quite constant



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Transconductance: Short L

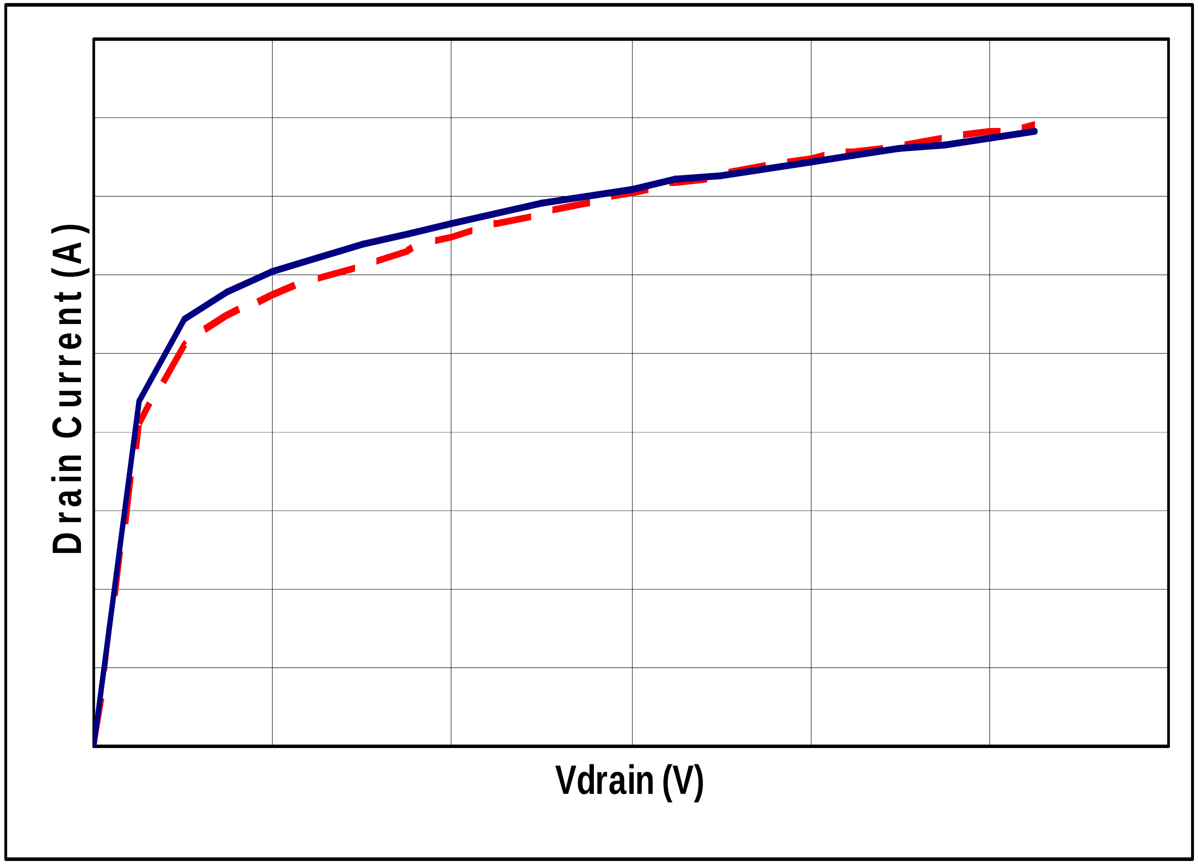
- **Variation in peak gm of short devices**
  - Short channel mobility?
  - Series resistance?
  - Constant fraction at all Vg suggests R
  - `Rsw1` is more robust than the available mobility scaling parameters

gm variation (1 sigma)		
Ldrawn	**Peak gm**	**Gm at Vg=1.1*Vdd**
1.0um	**1.0%**	**0.6%**
0.05um	**3.6%**	**3.7%**

Output Conductance

- gds varies with Vt and u0 but IdVd curves will not cross
- `Alpl` is robust and has the proper behavior over length

Long channel IdVd



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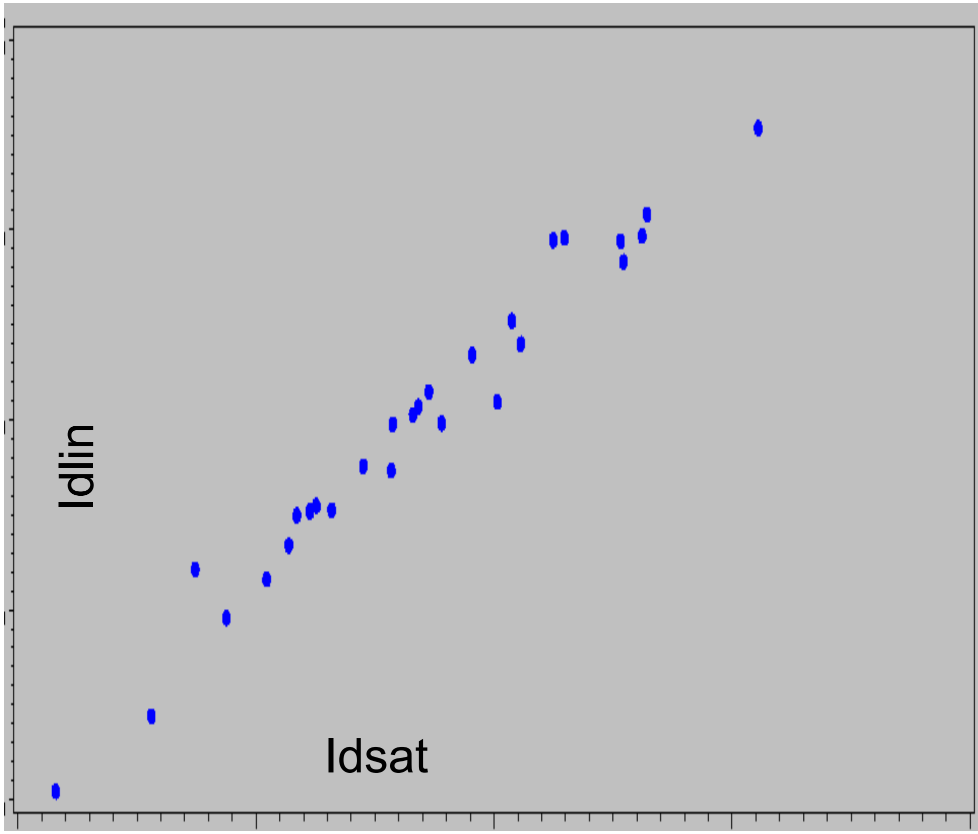
Things that we didn’t need

- **Short channel linear vs. saturated current**
  - I(Vd=.05) vs. I(Vd=1.0)
  - R^2 = .98 NFET; .92 PFET
- **Addition Narrow Effects**
  - Have variation of delta W
  - Have random dopant flucuations



Summary

- **Modeling Process Variation in a Production Environment requires**
  - A predefined process model
  - Parameters which describe independent physical sources of variation
  - Parameters which are robust in the sense that they are effective for various device design and various examples of poor fitting.