A new technique for the reconstruction, validation and simulation of hybrid pixel hits

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Hybrid Pixel Hit Reconstruction

Pixel hit reconstruction differs in some substantial ways from the strip detector problem:

- pixels are not electromagnetically coupled
  - all signal sharing is due to charge collection (no capacitive coupling matrix to understand)
  - 2D clusters contain hit position and track angle information
    - fine sampling of cluster provides new capabilities
- very large Lorentz drift effects
  - the η distributions are highly asymmetric (usual η technique doesn't self-calibrate)
- radiation damage causes significant changes to signal sharing functions
  - need a calibrate-able algorithm that can be modified with parameters
  - need to monitor the charge sharing fcns vs detector region and time

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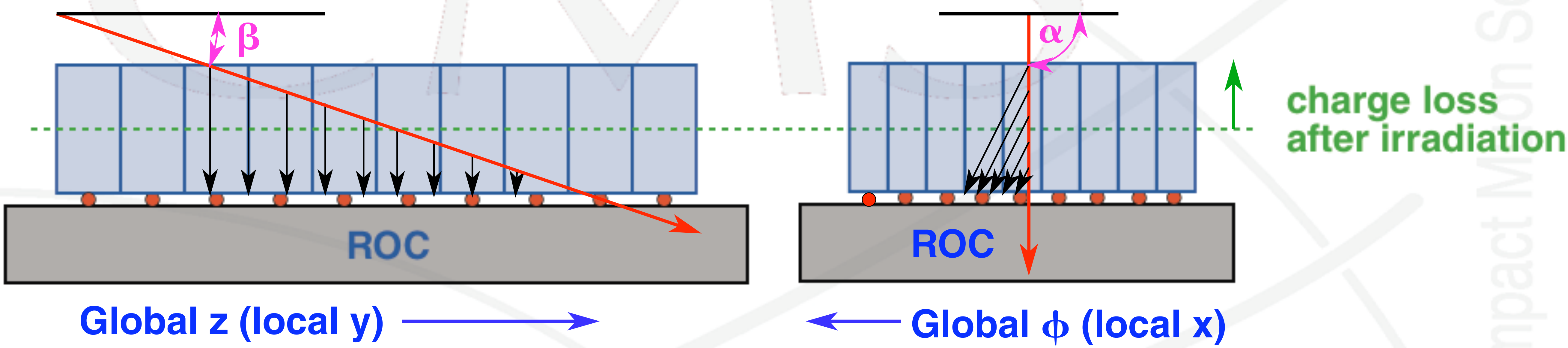
Charge Sharing

Before irradiation, the charge sharing is uniform along z and approximately uniform in ϕ

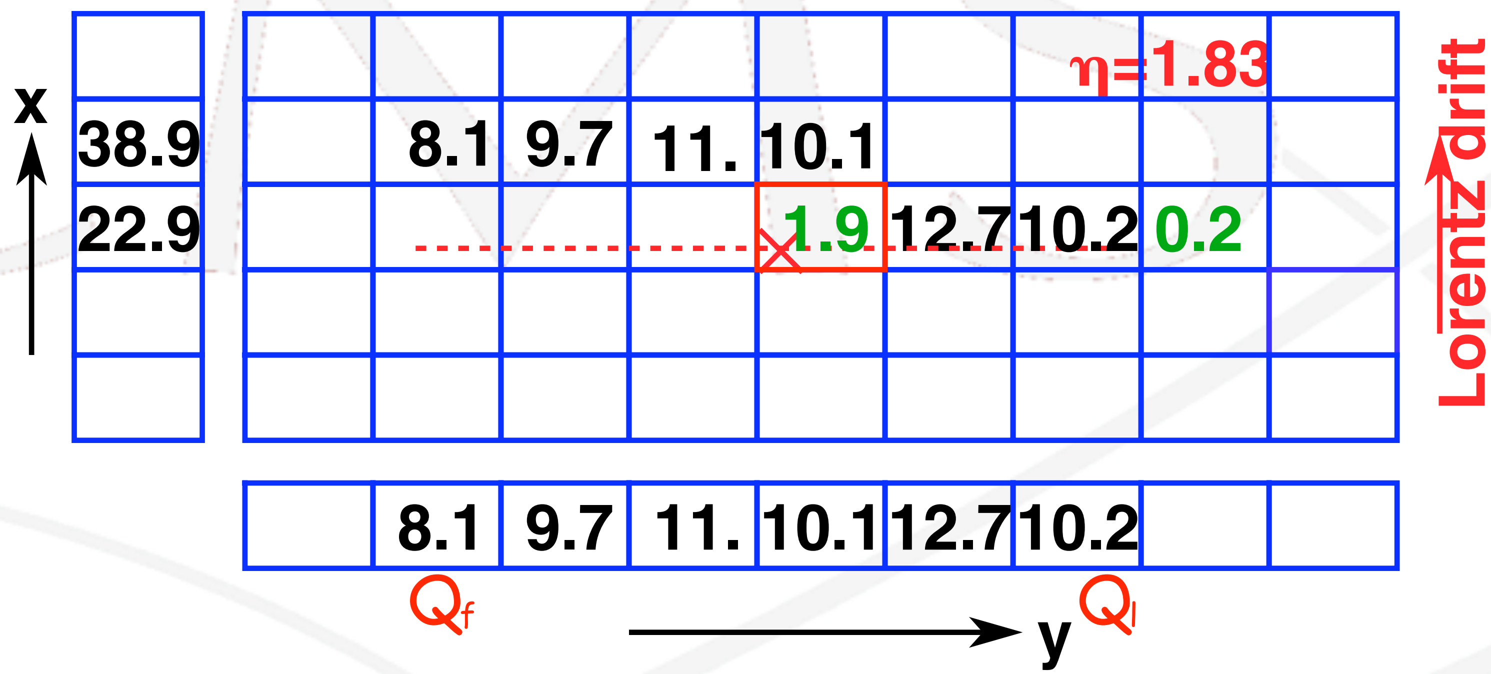


After irradiation:

- trapping removes charge from one side of clusters
  - clusters become smaller, asymetrically
- Lorentz drift varies non-monotonically across the sensor thickness
  - non-linearity appears in charge sharing

Clustering

A typical high η barrel cluster looks something like this



- clustering algorithm needs to include corner adjacency
  - thresholds create apparently unlikely cluster shapes
- sum cluster into z and ϕ projections
  - problem factorizes due to field configuration and periodicity of cells
  - define charges of first and last pixels: Q_f and Q_l
- large pixel-to-to pixel charge fluctuations

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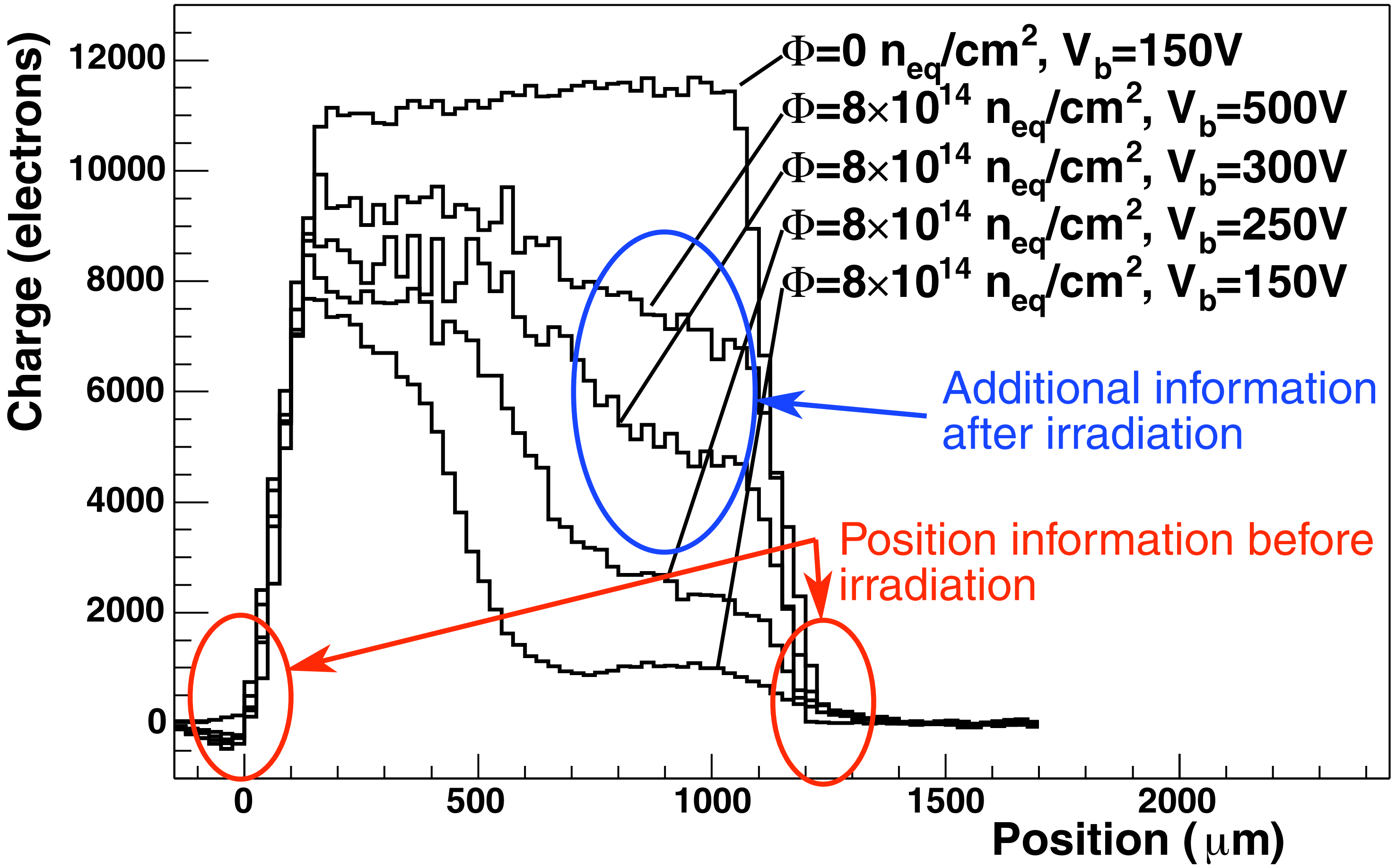
Cluster Projections

y (global z) projections are sensitive to Φ, T, and V_{bias}



$$\delta y \simeq C \frac{\sqrt{s(y)}}{ds/dy}$$

position information is best where s(y) is small and ds/dy is large

- before irradiation, all y-position information is in edge pixels
  - charges in interior pixels are correlated with uncertainties
- after irradiation, interior pixels acquire position information
- there is no position information in signals larger than "plateau"

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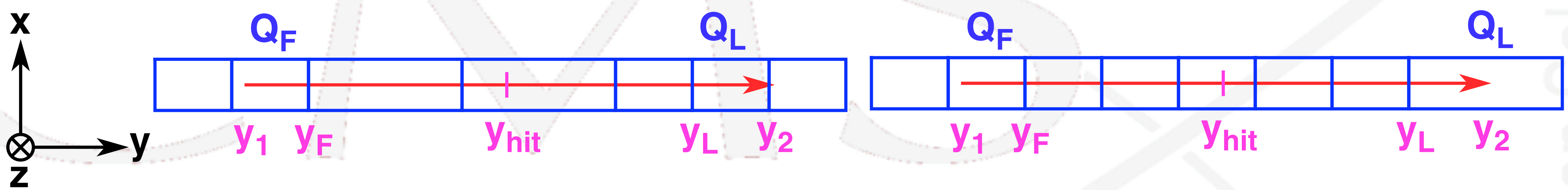
Standard Technique

The basic hit position estimator uses an η-like technique based upon the edge pixels,



$$y = \frac{y_F + y_L}{2} + \frac{Q_L^y - Q_F^y}{Q_L^y + Q_F^y} \cdot W_{\text{eff}}^y(\cot\beta), \quad x = \frac{x_F + x_L}{2} + \frac{Q_L^x - Q_F^x}{Q_L^x + Q_F^x} \cdot W_{\text{eff}}^x(\cot\alpha) - \Delta_x$$

- simple, robust algorithm
- take W^y_{eff} = $(pitch_F+pitch_L)/2$ => angle independent
- works well for un-irradiated sensors
  - relatively insensitive to large delta rays
- works for clusters containing double-size pixels
- for irradiated sensors at $\Phi=6\times10^{14}\ n_{eq}/cm^2$:
  - develops large (~ 50 μm in y and ~ 30 μm in x) offsets
  - resolution worsens due to trapping and non-linearities in x

➡ Try to use the entire cluster projection in a fitting procedure

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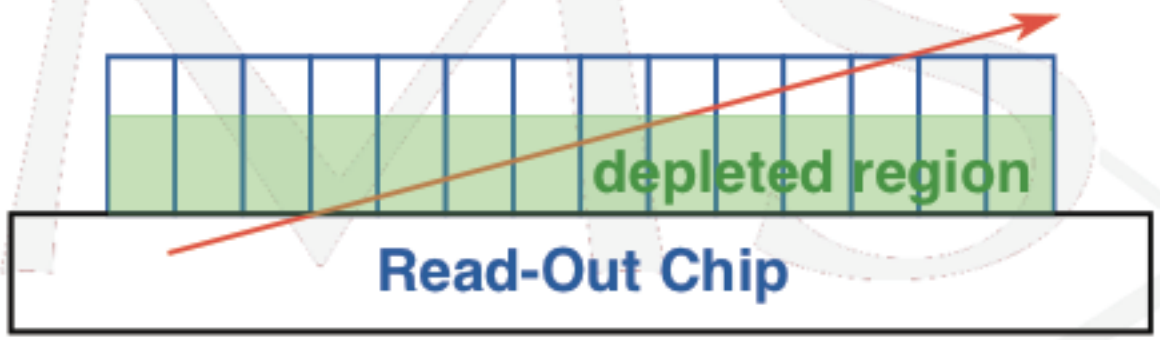
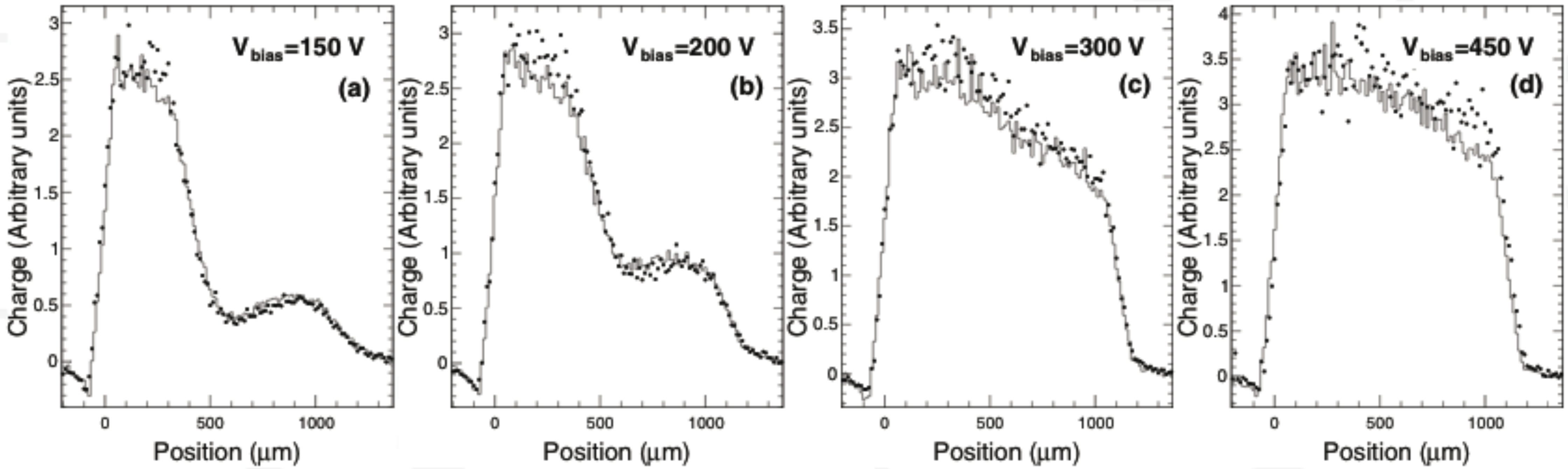
Sensor Modeling

Over the last 4 years, we (VC + MS) have successfully modeled irradiated pixel sensors fabricated on DOFZ substrates at several Φ and T,

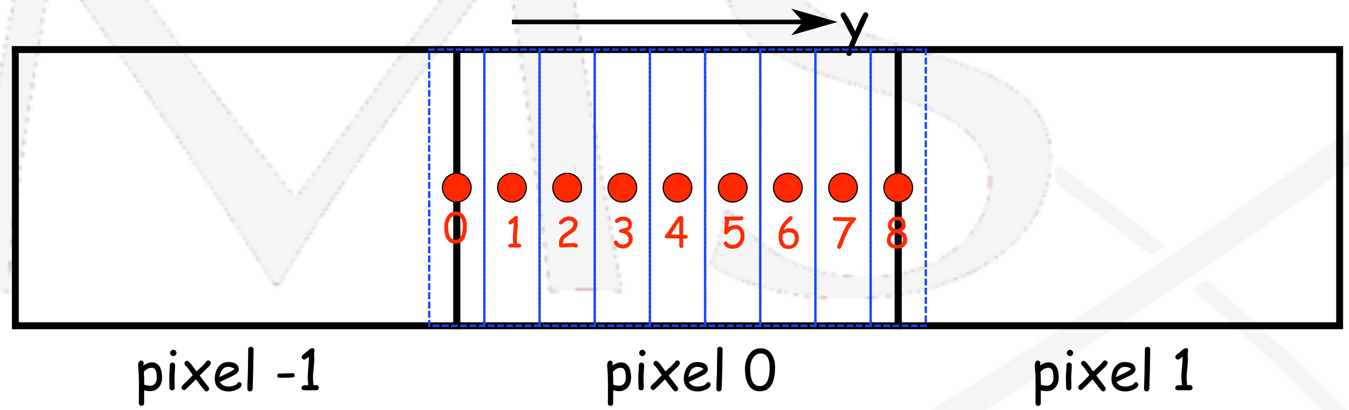




- Pixelav transport simulation + E-field modeling w/ TCAD 9.0
  - data well described by tunable double-junction model from $\Phi = (0.5\text{-}6)\times10^{14}\ n_{eq}/cm^2$
- Use to calculate a priori cluster shapes for improved analysis technique

Template-based Reconstruction Algorithm

Generate average cluster profiles as function of track angles using low delta-ray activity events



$\cot\beta = 1.97$

Unirradiated Template

Bin	Px-6	Px-5	Px-4	Px-3	Px-2	Px-1	Px 0	Px+1	Px+2	Px+3	Px+4	Px+5	Px+6
0	.0	.0	.0	.0	11884.5	13587.8	13549.2	11913.7	.0	.0	.0	.0	.0
1	.0	.0	.0	.0	10198.0	13727.3	13592.2	13404.4	252.2	.0	.0	.0	.0
2	.0	.0	.0	.0	8512.6	13597.7	13559.3	13577.9	1688.0	.0	.0	.0	.0
3	.0	.0	.0	.0	6762.7	13607.2	13677.0	13601.3	3428.0	.0	.0	.0	.0
4	.0	.0	.0	.0	5165.2	13569.4	13603.1	13644.9	5039.3	.0	.0	.0	.0
5	.0	.0	.0	.0	3412.1	13718.7	13604.0	13630.6	6812.7	.0	.0	.0	.0
6	.0	.0	.0	.0	1703.1	13589.0	13566.5	13567.4	8556.2	.0	.0	.0	.0
7	.0	.0	.0	.0	216.7	13396.4	13685.1	13544.1	10208.5	.0	.0	.0	.0
8	.0	.0	.0	.0	.0	11884.5	13587.8	13549.2	11913.7	.0	.0	.0	.0

$\Phi = 6\times10^{14}\ n_{eq}/cm^2$ Template

Bin	Px-6	Px-5	Px-4	Px-3	Px-2	Px-1	Px 0	Px+1	Px+2	Px+3	Px+4	Px+5	Px+6
0	.0	.0	.0	.0	8741.4	8925.9	7156.1	5599.7	661.8	117.3	.0	.0	.0
1	.0	.0	.0	.0	7476.2	9160.4	7301.2	6194.2	872.6	148.9	.9	.0	.0
2	.0	.0	.0	.0	6160.6	9403.8	7423.7	6417.5	1429.4	187.5	9.6	.0	.0
3	.0	.0	.0	.0	4736.1	9578.0	7614.0	6610.0	2081.9	233.6	20.6	.0	.0
4	.0	.0	.0	.0	3432.4	9790.6	7814.7	6764.0	2789.8	291.1	34.0	.0	.0
5	.0	.0	.0	.0	2112.5	9944.1	8087.9	6894.2	3490.9	357.9	49.4	.0	.0
6	.0	.0	.0	.0	750.7	10174.1	8382.4	7018.6	4199.1	440.9	67.9	.0	.0
7	.0	.0	.0	.0	33.3	10014.0	8695.2	7053.7	4882.2	538.5	90.1	.0	.0
8	.0	.0	.0	.0	.0	8741.4	8925.9	7156.1	5599.7	661.8	117.3	.0	.0

- Bin the charge in the struck pixel and neighbors vs hit position in 1/8 bins

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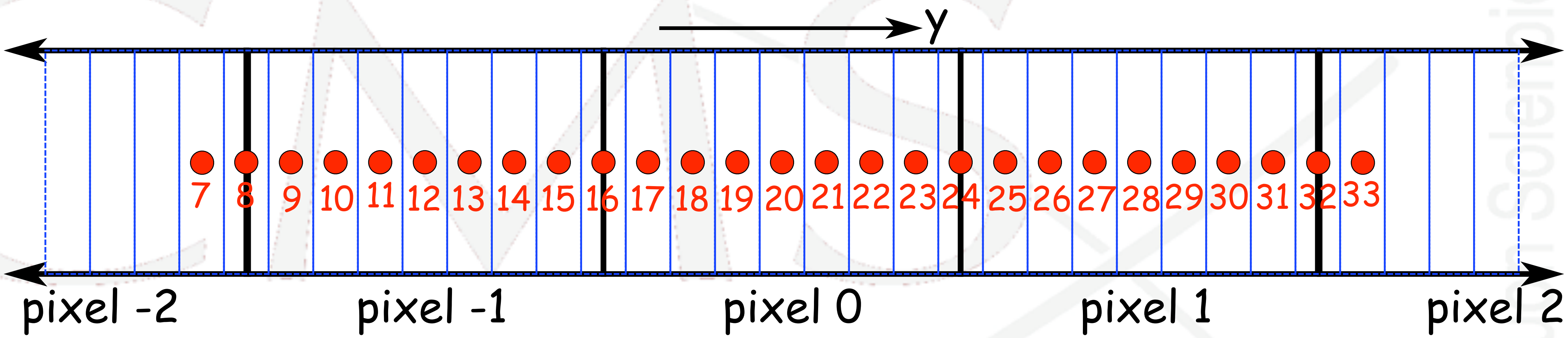
- Span 3 (5) central pixels with 25 (41) bins by shifting the basic template
  - expected signal in pixel i, bin j is $S^{y/x}_{i,j}$

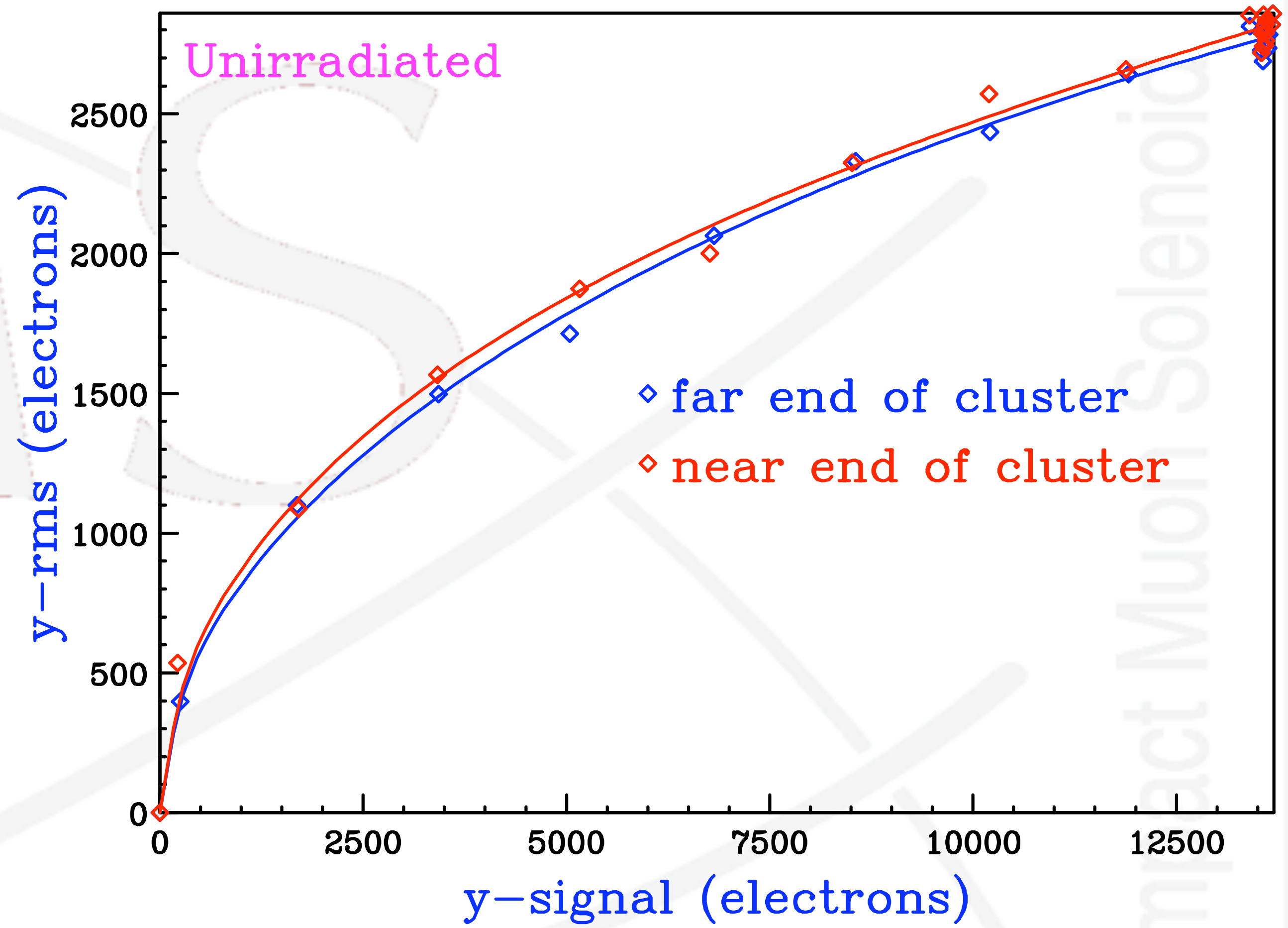


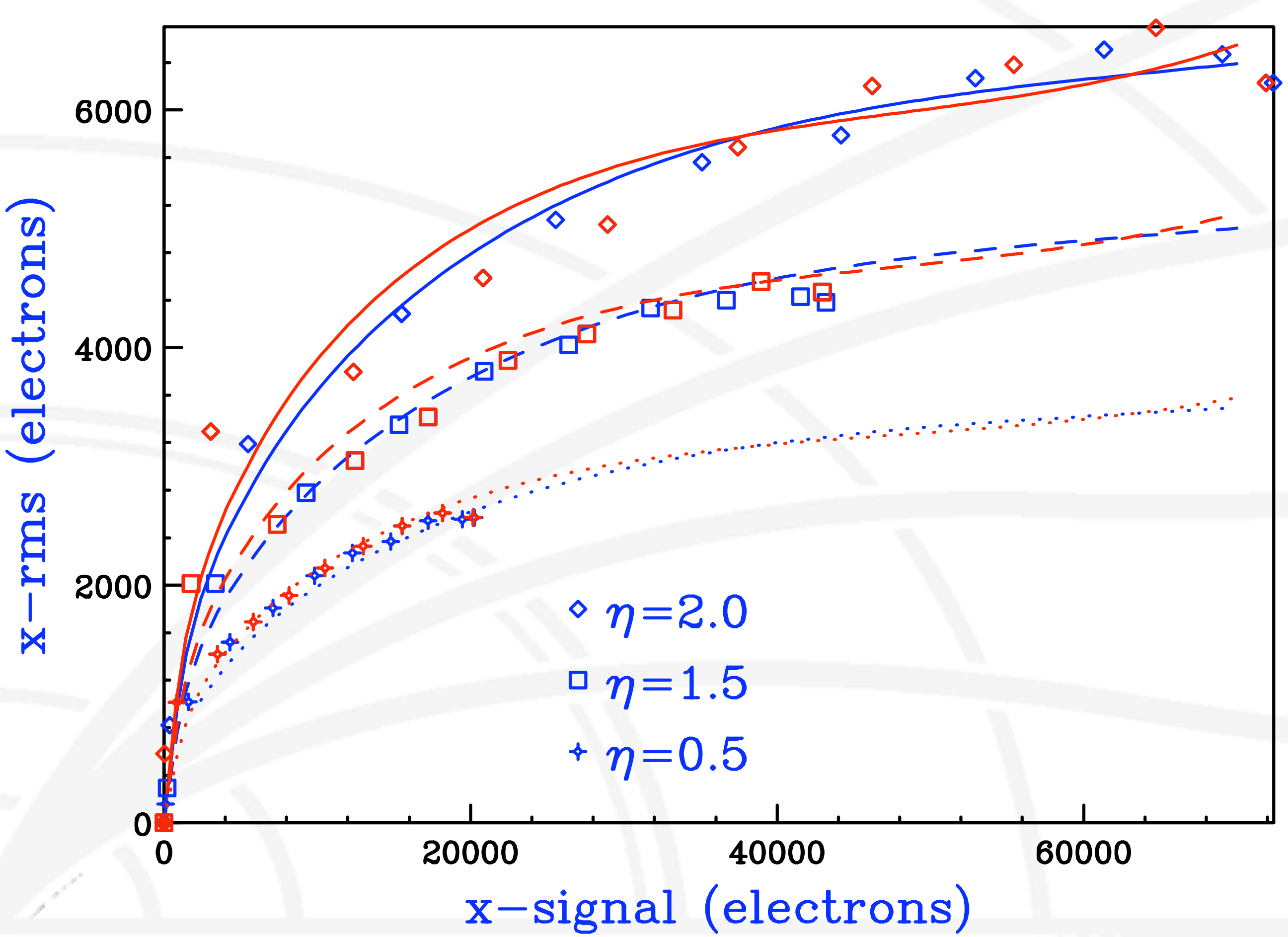
$\cot\beta = 1.97$

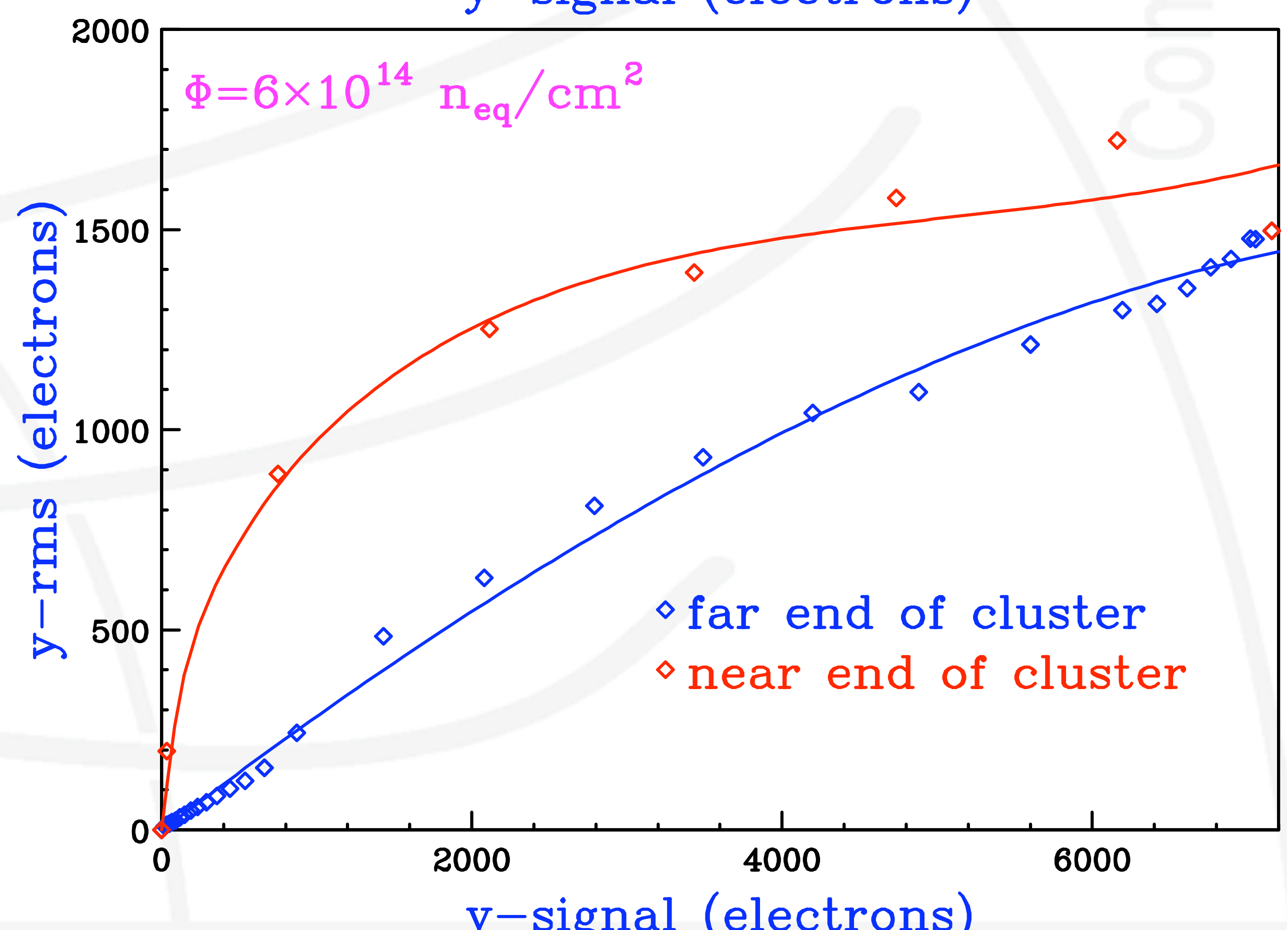
Bin	Px-6	Px-5	Px-4	Px-3	Px-2	Px-1	Px 0	Px+1	Px+2	Px+3	Px+4	Px+5	Px+6
7	.0	.0	216.7	13396.4	13685.1	13544.1	10208.5	.0	.0	.0	.0	.0	.0
8	.0	.0	.0	11884.5	13587.8	13549.2	11913.7	.0	.0	.0	.0	.0	.0
9	.0	.0	.0	10198.0	13727.3	13592.2	13404.4	252.2	.0	.0	.0	.0	.0
10	.0	.0	.0	8512.6	13597.7	13559.3	13577.9	1688.0	.0	.0	.0	.0	.0
11	.0	.0	.0	6762.7	13607.2	13677.0	13601.3	3428.0	.0	.0	.0	.0	.0
12	.0	.0	.0	5165.2	13569.4	13603.1	13644.9	5039.3	.0	.0	.0	.0	.0
13	.0	.0	.0	3412.1	13718.7	13604.0	13630.6	6812.7	.0	.0	.0	.0	.0
14	.0	.0	.0	1703.1	13589.0	13566.5	13567.4	8556.2	.0	.0	.0	.0	.0
15	.0	.0	.0	216.7	13396.4	13685.1	13544.1	10208.5	.0	.0	.0	.0	.0
16	.0	.0	.0	.0	11884.5	13587.8	13549.2	11913.7	.0	.0	.0	.0	.0
17	.0	.0	.0	.0	10198.0	13727.3	13592.2	13404.4	252.2	.0	.0	.0	.0
18	.0	.0	.0	.0	8512.6	13597.7	13559.3	13577.9	1688.0	.0	.0	.0	.0
19	.0	.0	.0	.0	6762.7	13607.2	13677.0	13601.3	3428.0	.0	.0	.0	.0
20	.0	.0	.0	.0	5165.2	13569.4	13603.1	13644.9	5039.3	.0	.0	.0	.0
21	.0	.0	.0	.0	3412.1	13718.7	13604.0	13630.6	6812.7	.0	.0	.0	.0
22	.0	.0	.0	.0	1703.1	13589.0	13566.5	13567.4	8556.2	.0	.0	.0	.0
23	.0	.0	.0	.0	216.7	13396.4	13685.1	13544.1	10208.5	.0	.0	.0	.0
24	.0	.0	.0	.0	.0	11884.5	13587.8	13549.2	11913.7	.0	.0	.0	.0
25	.0	.0	.0	.0	.0	10198.0	13727.3	13592.2	13404.4	252.2	.0	.0	.0
26	.0	.0	.0	.0	.0	8512.6	13597.7	13559.3	13577.9	1688.0	.0	.0	.0
27	.0	.0	.0	.0	.0	6762.7	13607.2	13677.0	13601.3	3428.0	.0	.0	.0
28	.0	.0	.0	.0	.0	5165.2	13569.4	13603.1	13644.9	5039.3	.0	.0	.0
29	.0	.0	.0	.0	.0	3412.1	13718.7	13604.0	13630.6	6812.7	.0	.0	.0
30	.0	.0	.0	.0	.0	1703.1	13589.0	13566.5	13567.4	8556.2	.0	.0	.0
31	.0	.0	.0	.0	.0	216.7	13396.4	13685.1	13544.1	10208.5	.0	.0	.0
32	.0	.0	.0	.0	.0	.0	11884.5	13587.8	13549.2	11913.7	.0	.0	.0
33	.0	.0	.0	.0	.0	.0	10198.0	13727.3	13592.2	13404.4	252.2	.0	.0

Use the same simulated events to to estimate the pixel rms as functions of simulated signal

- RMS's scale mostly as $(S)^{1/2}$
  - ΔS^2 well fit by polynomial
- After irradiation, near and far ends are quite different
- X-RMS scale in β as $Q^{1/2}(\beta)$

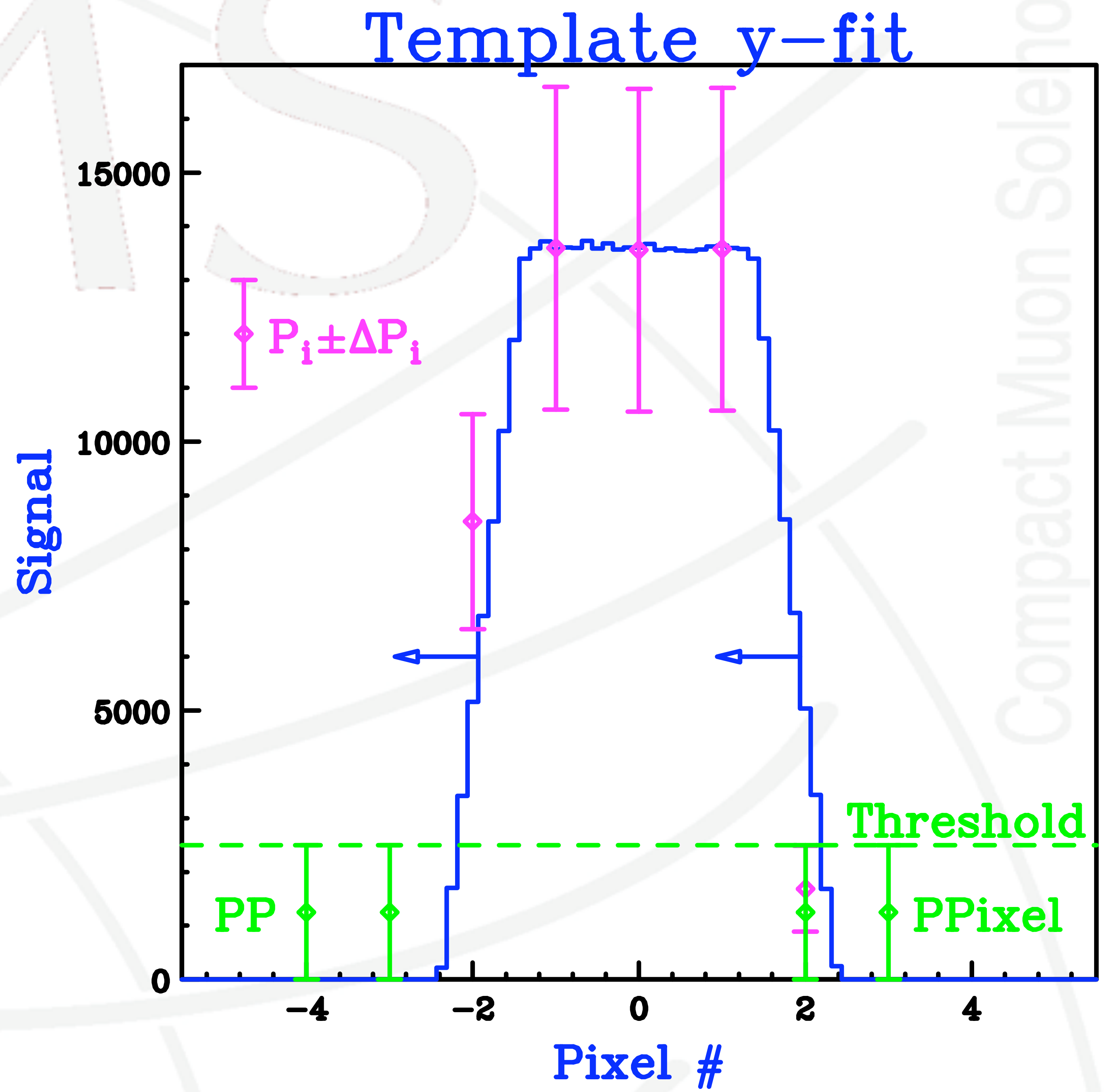






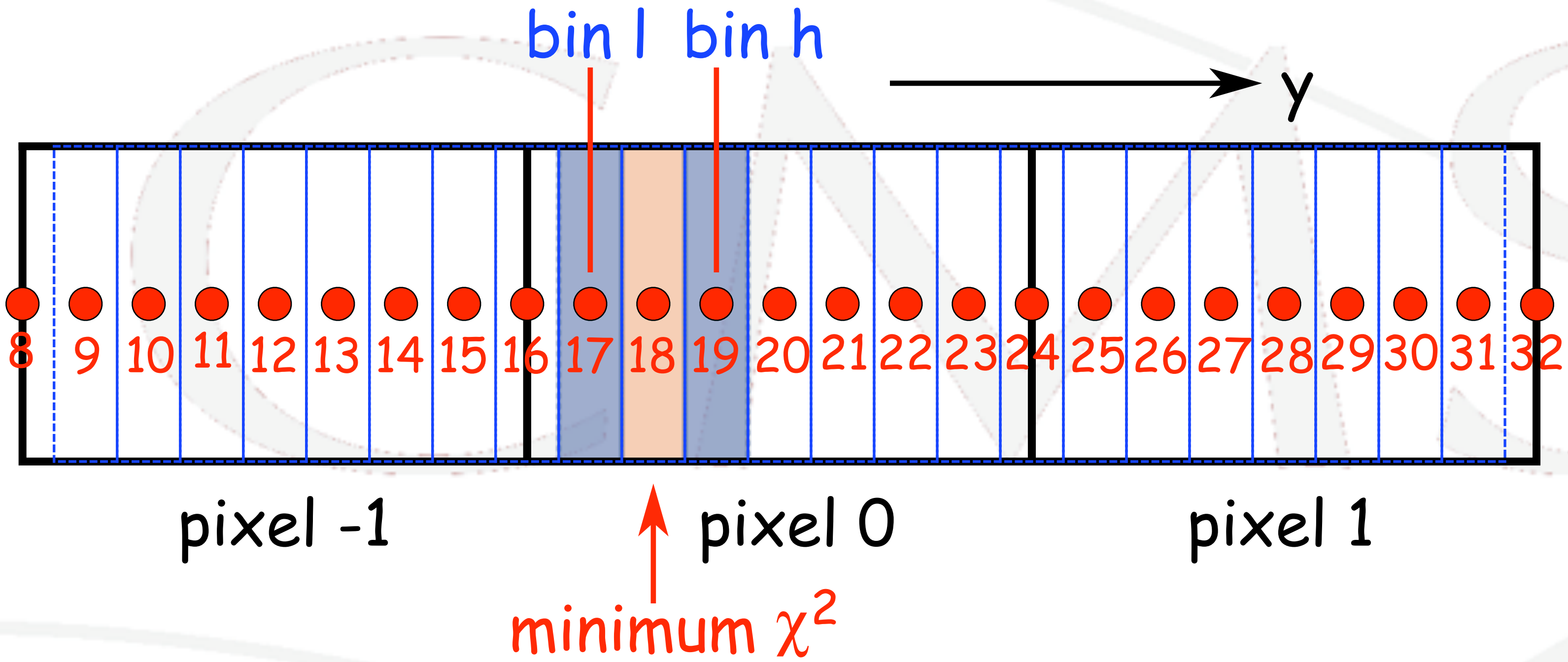
Before the a priori information can be used to fit the measured cluster projections, the measured data are "conditioned":

- Sum charges on all pixels: Q_{clus}
- Truncate individual pixel signals to $\cot\beta$-dependent maximum
  - sum projections: $P^{y/x}_i$
- Account for thresholds:
  - add information back by creating Pseudo-Pixels at the ends of the cluster
  - have 50% of threshold height and 100% uncertainties
  - pulls fit near cluster edges and improves resolution



Apply fitting procedure to projections P^y_i and P^x_i

Take central pixel of cluster center to define pixel 0:



$$\chi^2(j) = \sum_i \frac{(P_i^{y/x} - N_j S_{i,j}^{y/x})^2}{(\Delta P_i^{y/x})^2}$$

- find bin j with minimum χ^2, take ±1/8 pixel bins which bracket it (P.M.)
- do interpolation with ±1 bin templates $S_{i,l}$ (at bin l) and $S_{i,h}$ (at bin h)
  - sum χ^2 over all non-zero signal bins

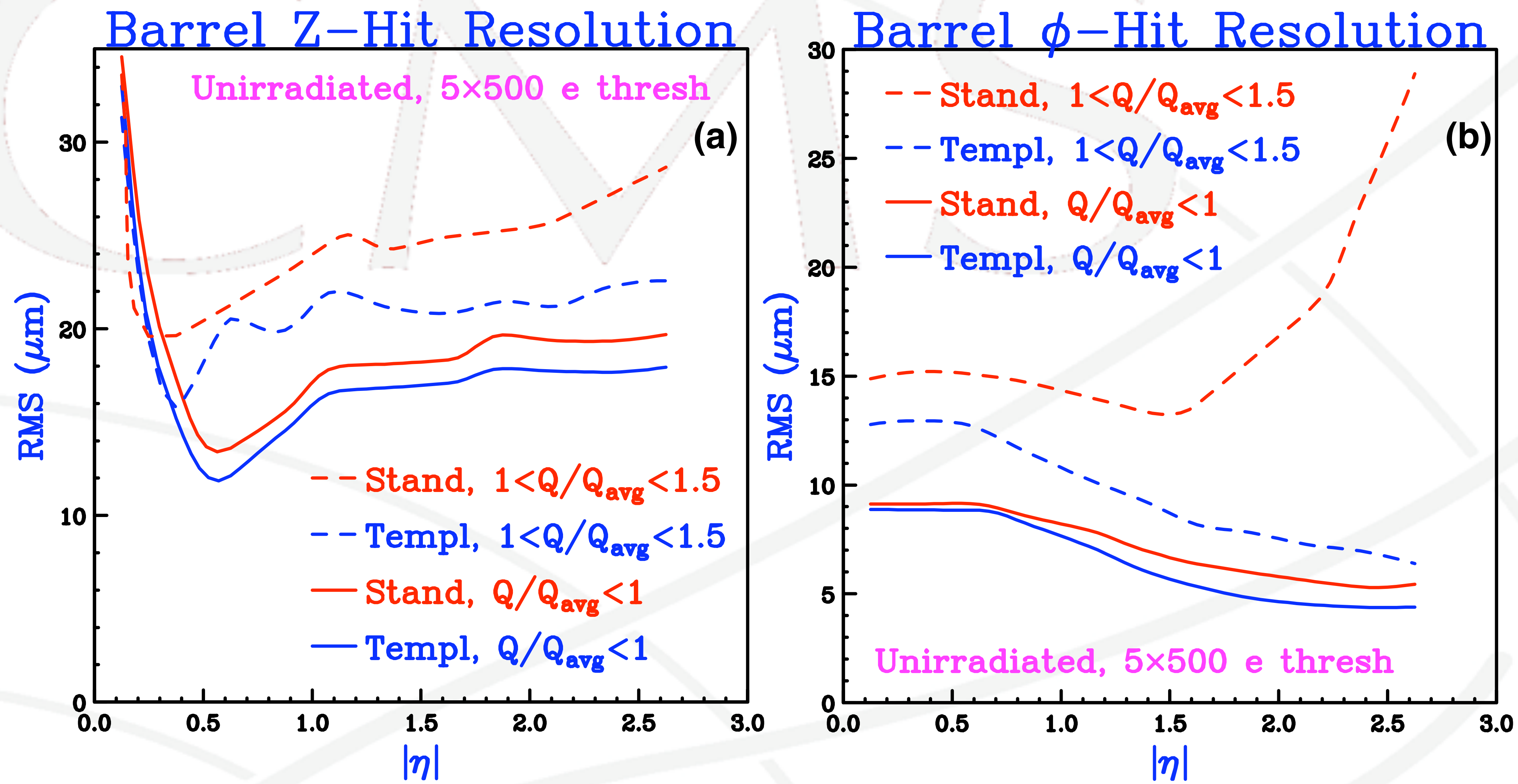
$$\chi^2 = \sum_i \frac{\{P_i - N[(1-r)S_{i,l} + rS_{i,h}]\}^2}{\Delta P_i^2}$$

$$r = \frac{\sum_i P_i(S_{i,h} - S_{i,l})/\Delta P_i^2 \sum_i P_i S_{i,l}/\Delta P_i^2 - \sum_i P_i^2/\Delta P_i^2 \sum_i S_{i,l}(S_{i,h} - S_{i,l})/\Delta P_i^2}{\sum_i P_i^2/\Delta P_i^2 \sum_i (S_{i,h} - S_{i,l})^2/\Delta P_i^2 - [\sum_i P_i(S_{i,h} - S_{i,l})/\Delta P_i^2]^2}$$

- new position x = x(lbin)+r[x(hbin)-x(lbin)]

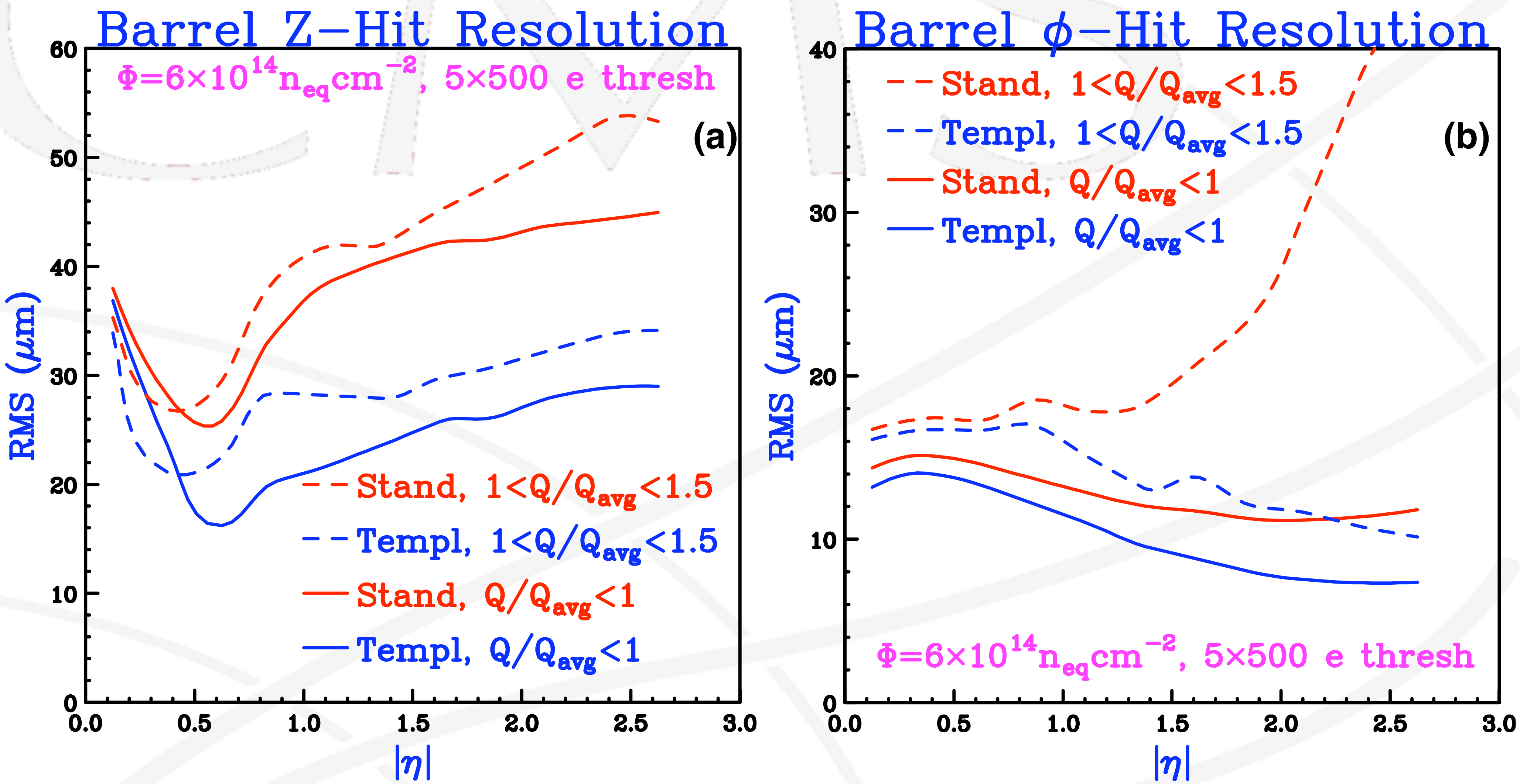
Comparison with Standard Algorithm

After small corrections for residual effects



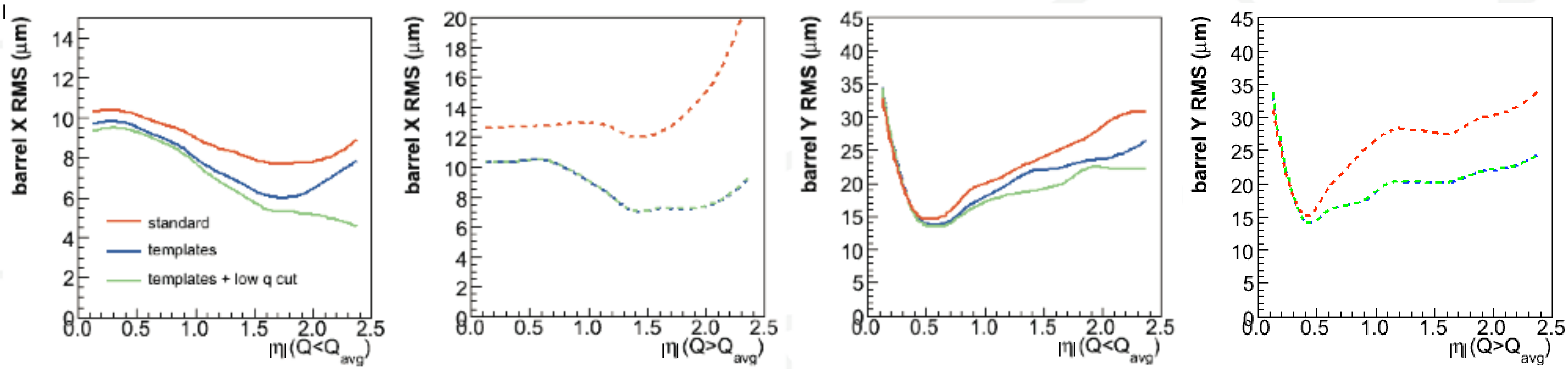
- RMS residuals not Gaussian fit sigma (tails included)
- Before irradiation, template algorithm improves the resolution at all η
  - for $Q/Q_{avg}<1$ (60% of all hits), 10-20% improvement
  - for $1<Q/Q_{avg}<1.5$ (30% of all hits), 20-100% improvement

- After irradiation, Standard technique is more affected than templates
  - z-resolution in both charge bands, 100% improvement
  - ϕ-resolution at large η, 30-200% improvement



Implementation in CMS Tracking

- Template reconstruction has moderate sensitivity to track angles
  - use Standard technique for first pass track finding/fitting
  - use Template technique in second pass track fit (angles from 1st pass)
- Study with sample of simulated muon tracks

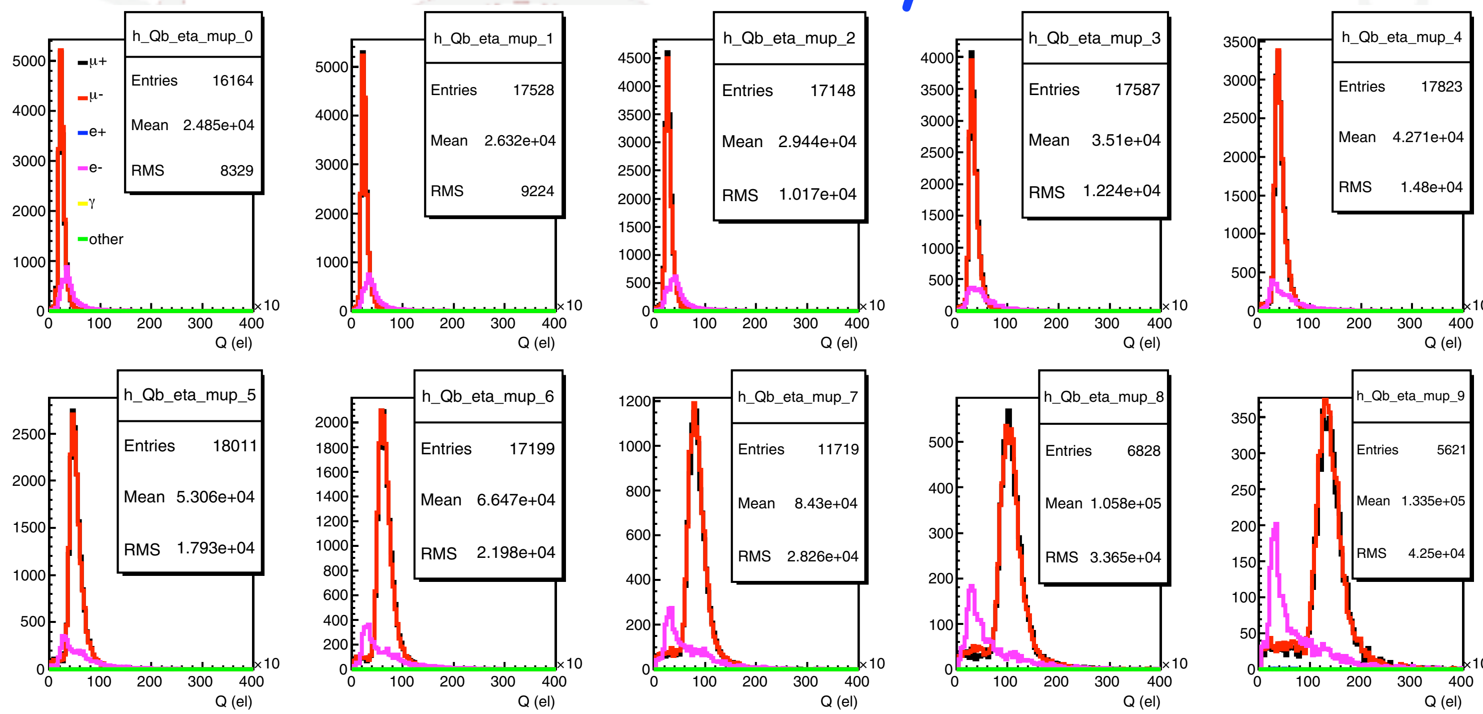


- Template technique exceeds the Standard technique at all η and Q_{clus}
- $x(\phi)$ resolution worsens at large η ?
  - caused by low Q_{clus} "junk" from showering in our not-so-thin detector
  - ~ 7% of high-η tracks have low-Q_{clus} hits on them

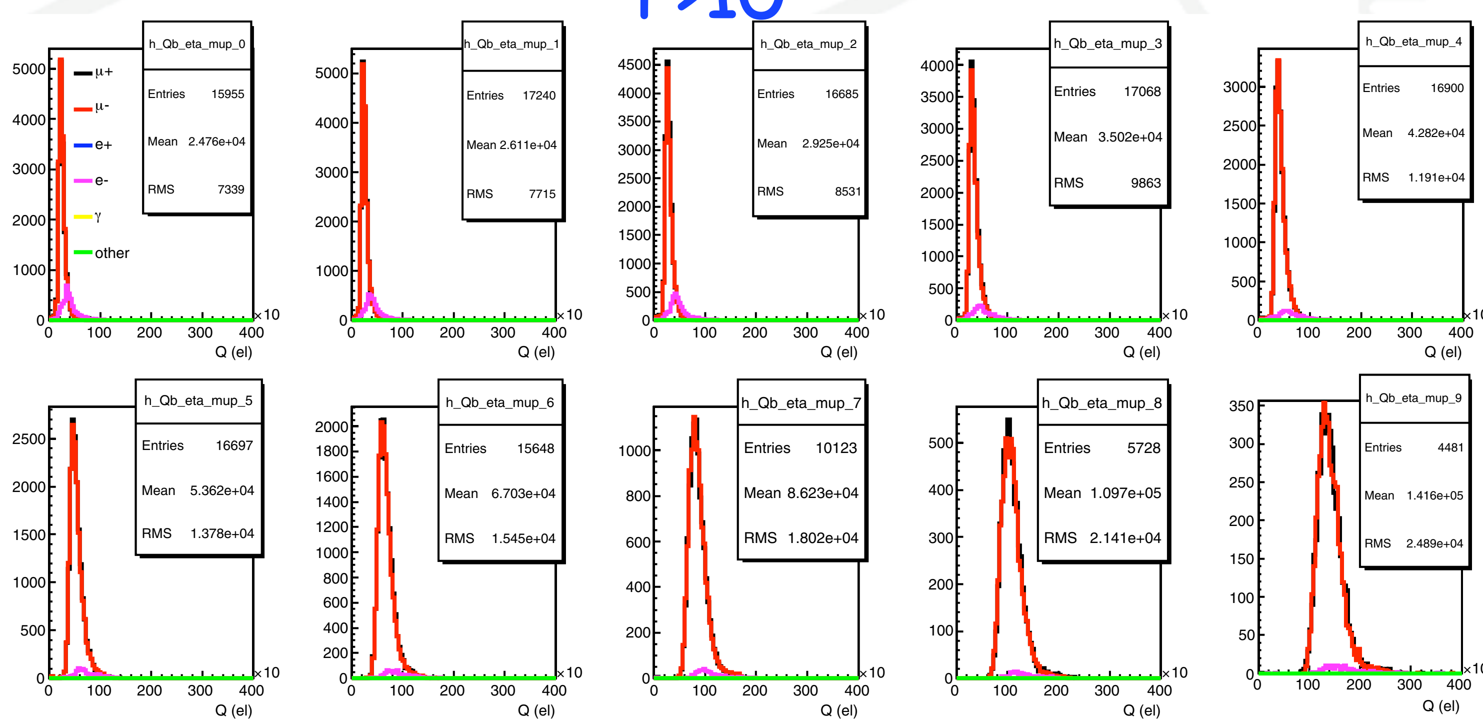
Goodness-of-fit

- A by-product of the template fitting procedure is a χ^2 that reflects the consistency between the shapes of the cluster projection and the interpolated template
  - template object stores the expected χ^2 distribution in a simple parameterization that depends upon Q_{clus}
  - convert these into x- and y-probabilities
- Suppresses low-Q junk clusters that arise from secondary interactions with 1-2 % inefficiencies
- Can remove low-Q with no inefficiency

No Probability Cut



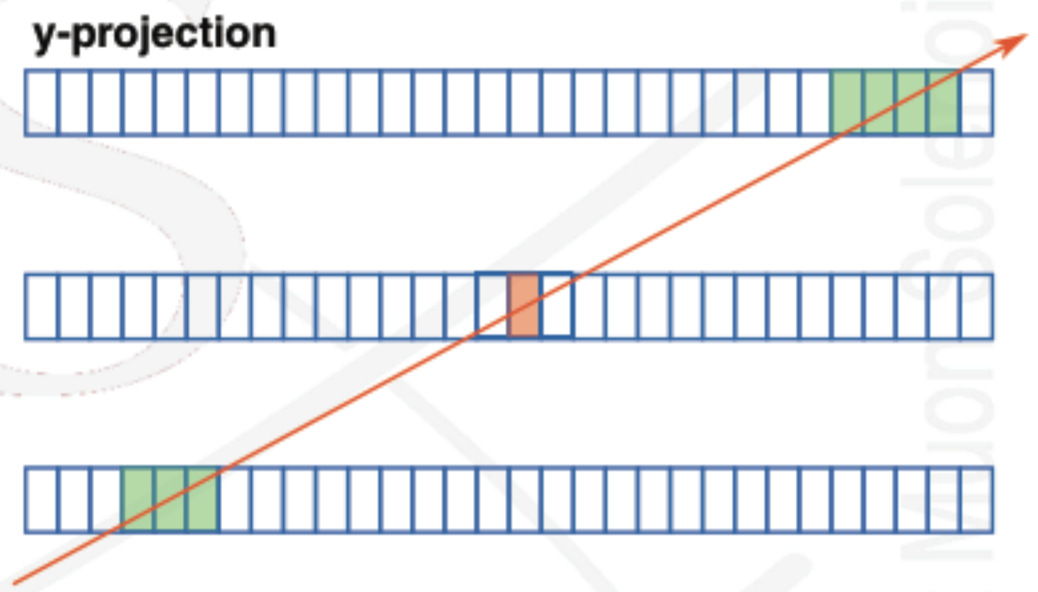
$P>10^{-3}$



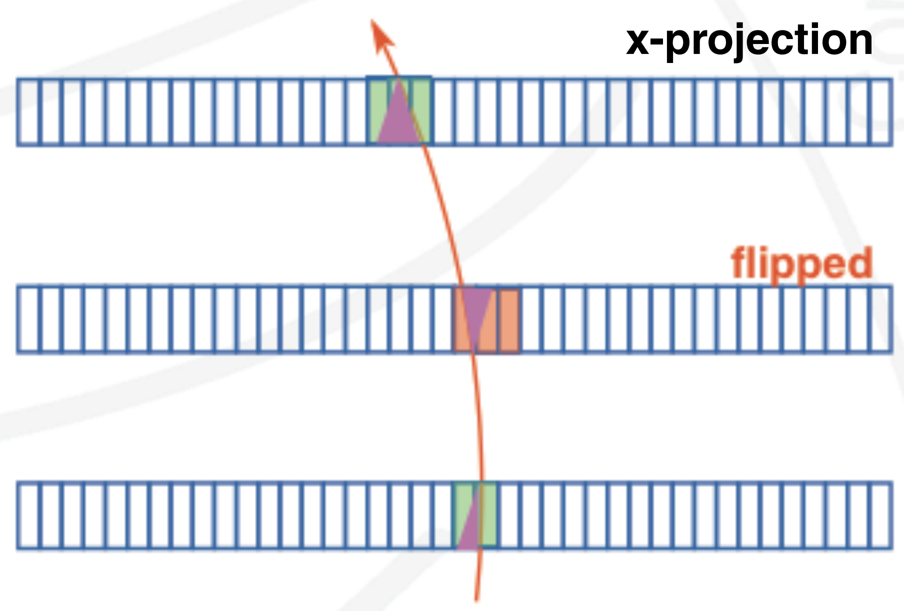
Track Seeding

- A. Dominguez has been developing an improved pixel track seeder that compares the lengths of y-clusters (global z) in the pixel barrels
  - can significantly reduce the number of trial seeds and therefore the track finding time (dominates reco time)
- Intrinsic y-length resolution of the templates is about twice that of the simple cluster length method
  - seeds have local angles, can use templates in 2nd pass
  - template probabilities determine consistency with angle hypotheses and are normalized to resolution
  - can do both x- and y-projections
  - can do barrel/FPix seeds
- Avoids "junk" hits on tracks (may be more junk in real LHC environment)

y (global z)

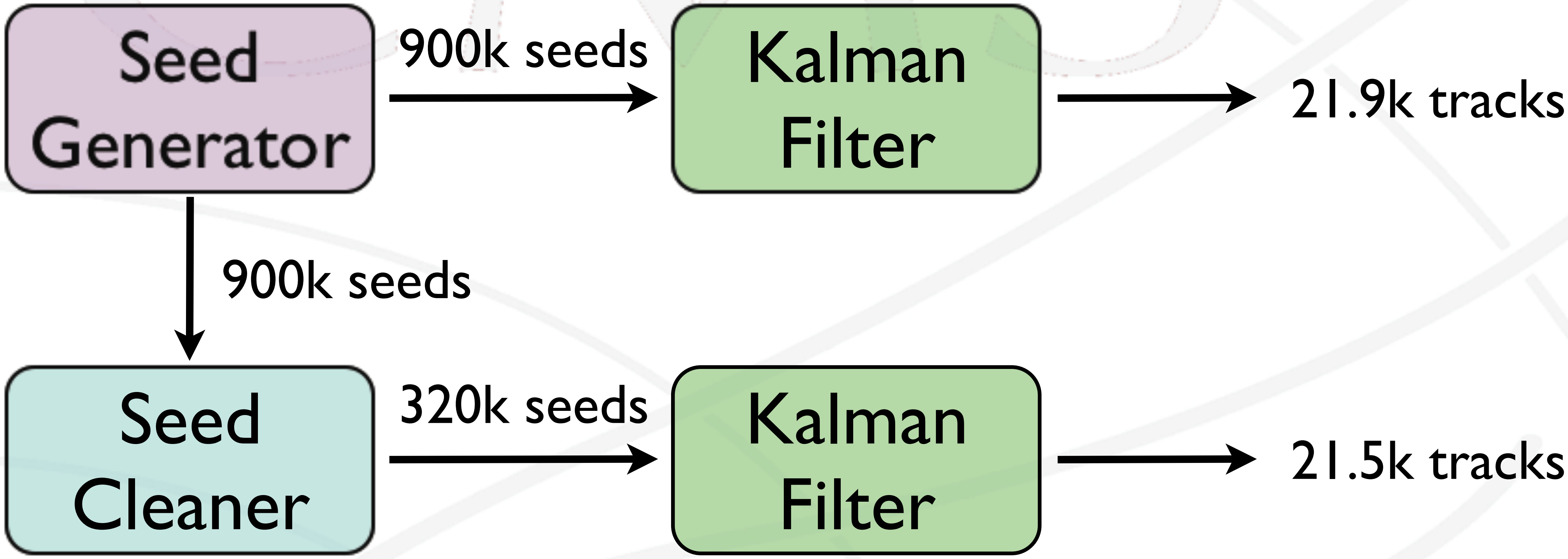


x (global ϕ)



First Seeding Results (hyper-preliminary)

D. Fehling, P. Maksimovic (JHU) have created a template-based seed cleaner that works with pixel-doublet seeds. The first test was done with a sample of simulated 475 t-tbar events:



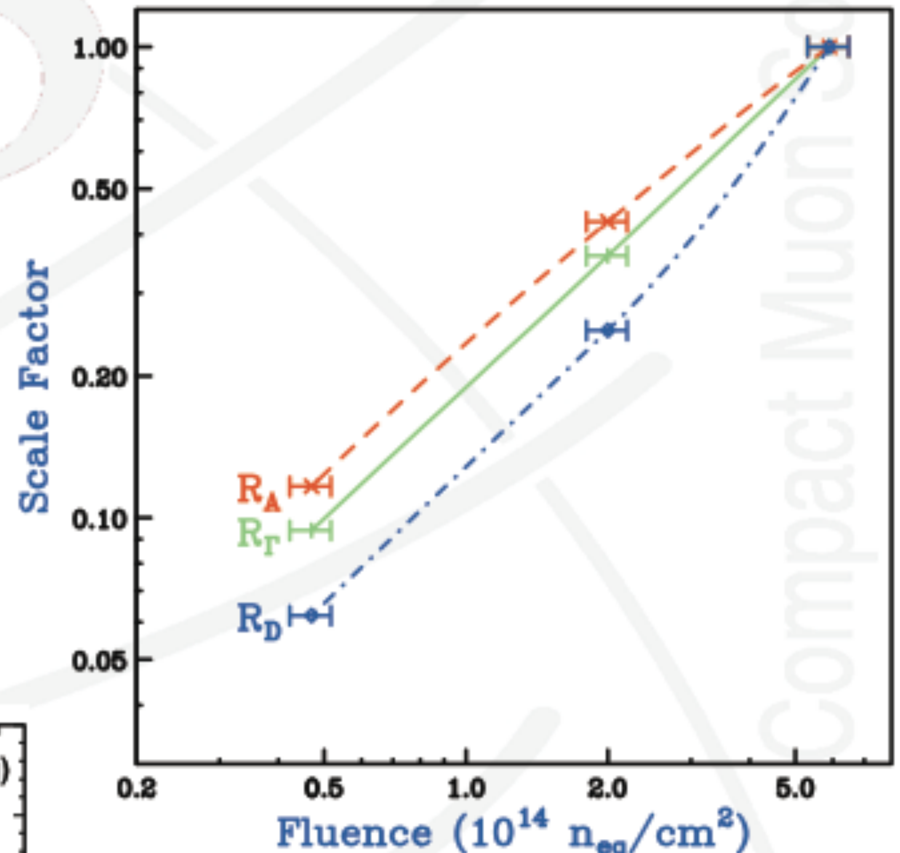
- Reduces number of seeds (tracking time?) by factor of 3!
- Loses 1.8% of tracks
  - quality of lost tracks is unknown as yet
- No attempt to optimize cuts or use low-Q cut yet

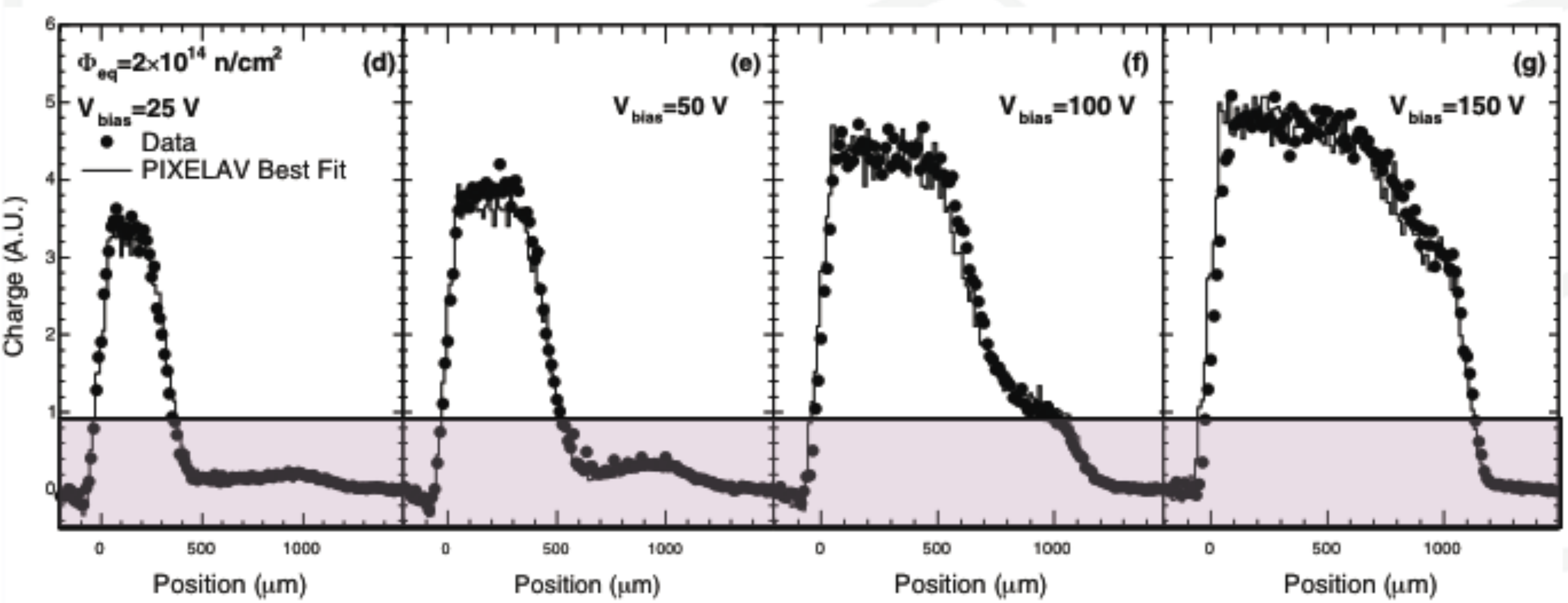
Calibration of Sensor Model

We know how to scale our detector model with n-equiv fluence:

$$N_A(\Phi) = R_A(\Phi)N_A(\Phi_0),\ N_D(\Phi) = R_D(\Phi)N_D(\Phi_0),\ \Gamma_{e/h}(\Phi) = R_\Gamma(\Phi)\Gamma_{e/h}(\Phi_0)$$

- Need to vary ~1 parameter to tune model
- Repeat beam test charge collection profile measurements in-situ in CMS
  - lots of inclined tracks even near barrel center
  - must live with zero-suppressed readout
  - need fine voltage scan to compensate



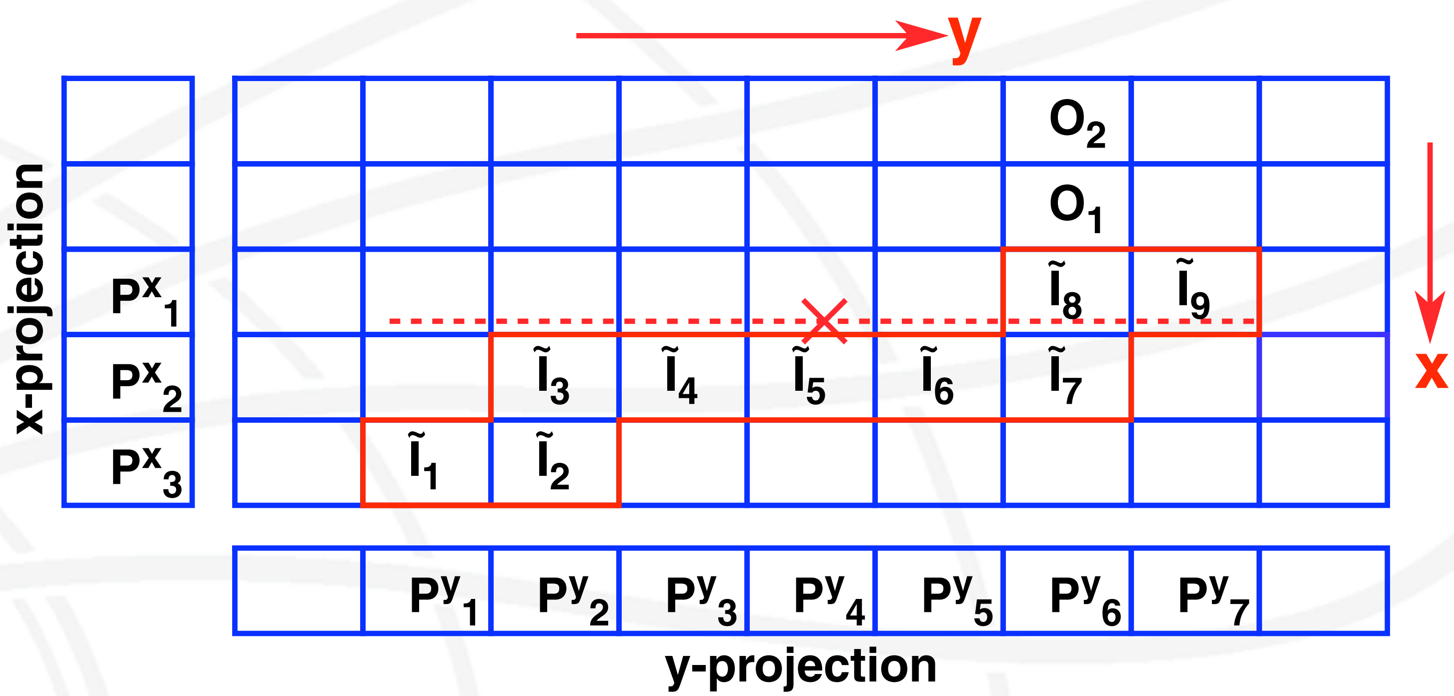


Templates in Simulation

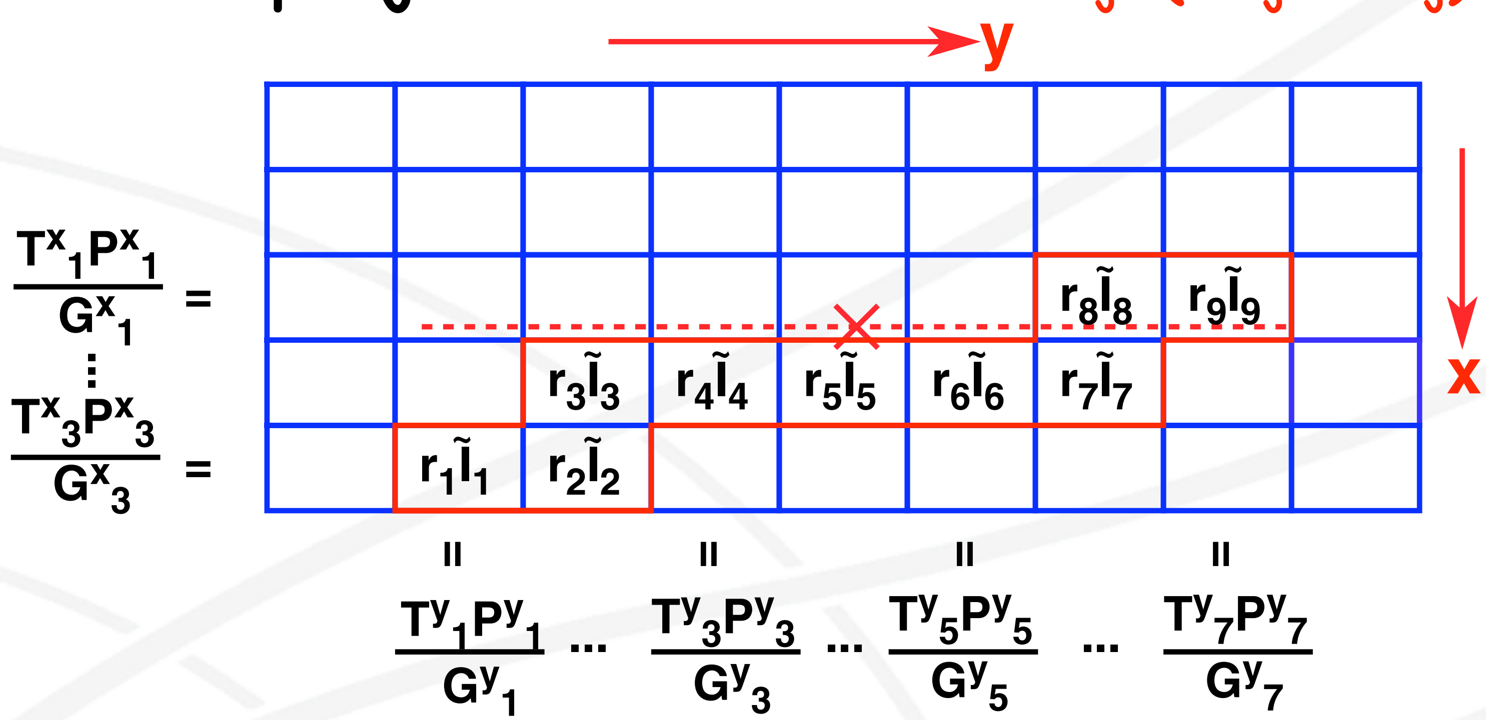
- Templates provide an unbiased "optimal" reconstruction of hits in an irradiated pixel detector
  - CMSSW does not now simulate radiation-damaged sensors
    - simplified charge transport model requires 12 ms/cluster
  - Pixelav is too slow to be incorporated into CMSSW
    - Powerpc version: ~ 1.5s/cluster (2.5 GHz G5)
    - Intel port: ~ 3s/cluster (2.8 GHz Xeon) due to vector architecture
- Need a faster simulation of a radiation damaged pixel detector
  - try using the template information to do this
    - advantage: same template object used for reconstruction and simulation - they stay "synched"
    - difficulty: templates are 1-D cluster projections and we need 2-D clusters in CMSSW

Compact Muon Solenoid

- Step 1:
  - call template interpolation for CMSSW simhit position/angles
    - produces "generated" templates G^x_j, G^y_k
    - consider only rows/columns with template projections $G_i > 0.5 *$ (readout threshold) - defines "inside" region
  - examine input 2-D CMSSW simhit cluster
    - index pixels in the "inside" I_i and "outside" O_i regions
    - use only inside pixels with signals $I_i > 0.5 *$ (readout threshold)
  - truncate signals to $\tilde{I}_i = MIN(I_i, I_{MAX})$ [decapitation cut]
    - suppresses effects of large fluctuations
  - form x-, y-projections of the truncated cluster: P^x_j, P^y_k

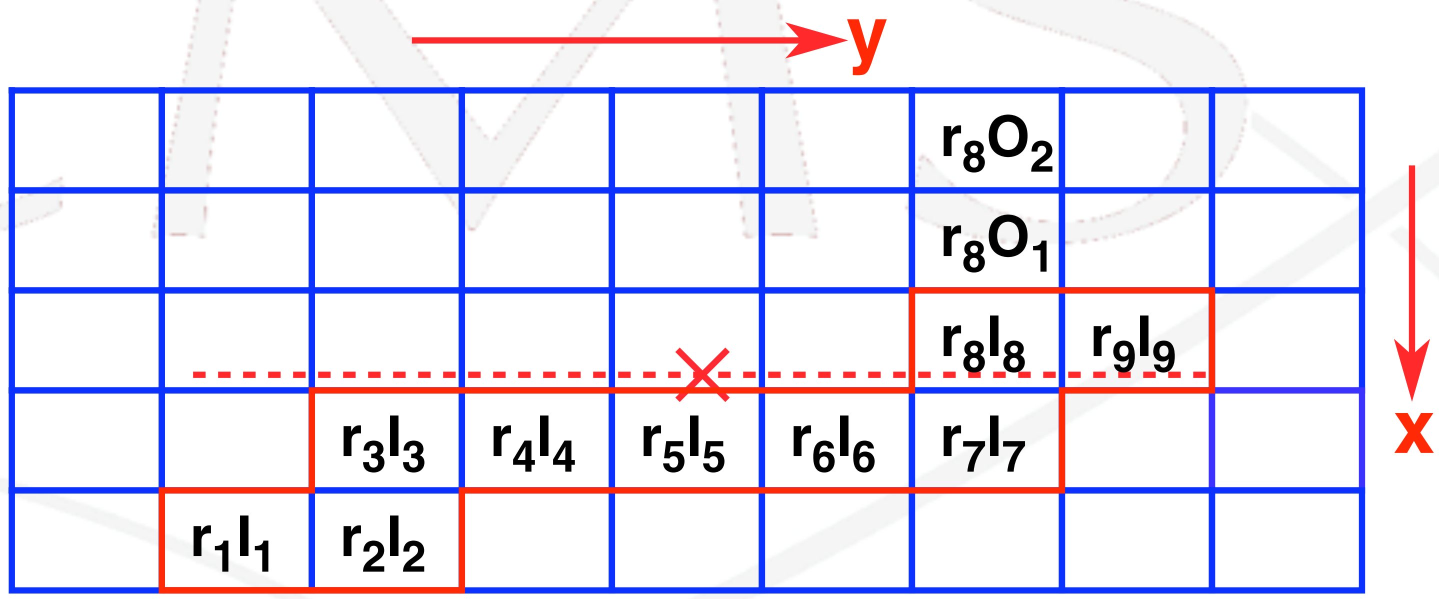


- Step 2:
  - call physical template interpolation for simhit position/angles
    - produces "output" templates T^x_j, T^y_k
  - formulate linear problem:
    - re-weight each of N pixels $\tilde{I}_i$ by factor r_i where $0 < r_i < 1$
    - require the y-projections to sum to $P^y_k*(T^y_k/G^y_k)$
    - require the x-projections to sum to $P^x_j*(T^x_j/G^x_j)$



  - In matrix form: $A*R=b$
    - $M \times N$ matrix A has M = #rows + #cols ($M>=N$ in 97% of cases)
    - solution for $R=(r_i)$ via SVD often yields $r_i<0$!
    - require $0 < r_i < 1$: Quadratic Programming Problem

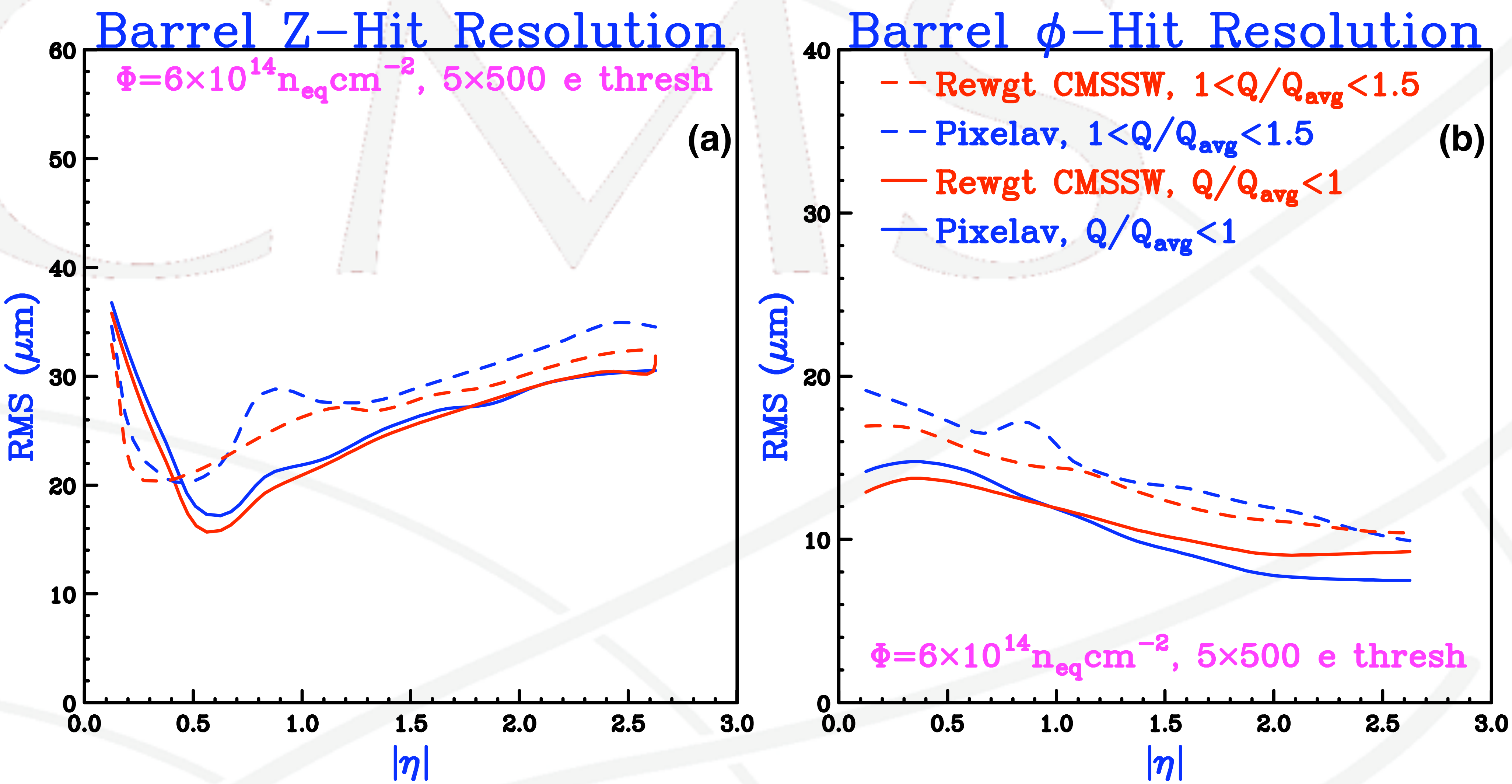
- Step 3 (Solve using Object Oriented Quadratic Programming):
  - apply OOQP solution for R to the original (un-truncated) cluster
    - ✳ use closest weight for "outside" pixels that may be present



- Comments:
  - reweighting 150V CMSSW clusters to 300V irradiated operation produces "correct" resolutions but biased residuals (~10μm)
  - reweighting 300V CMSSW clusters (Lorentz angle reduced from 23 to 16 degrees) to 300V irradiated operation produces unbiased residuals [starting cluster topology is closer to final topology]
  - despite "slow" OOQP, procedure is fast: ~ 0.3 ms/cluster

Compact Muon Solenoid

- Comparison to full-blown pixelav simulation
  - reconstruct Pixelav and re-weighted CMSSW-like hits w/ templates



- very good agreement in z-resolution, ϕ-resolution has slightly wrong η-dependence
- only alternative for simulation of more realistic detector currently available to us

Summary/Conclusions

Templates are a new pixel hit reconstruction technique:

- based upon the fitting of a priori cluster shapes
- calibrate-able for optimal reconstruction after radiation damage
- improved resolution before and after irradiation
- Goodness-of-fit can be used to validate hits
  - suppresses "junk" hits
  - can "measure" the track direction, very useful in track seeding
  - useful in High Level Trigger?
- Templates can be used to re-weight simulated clusters for a fast simulation of radiation damaged detectors

Current Status

- second pass in normal track reconstruction implemented (needs infrastructural improvements)
- need to write "in-situ" calibration tools
- seed cleaner is in development and testing
- "portable" cluster re-weighter exists but needs to be interfaced to CMSSW simulation

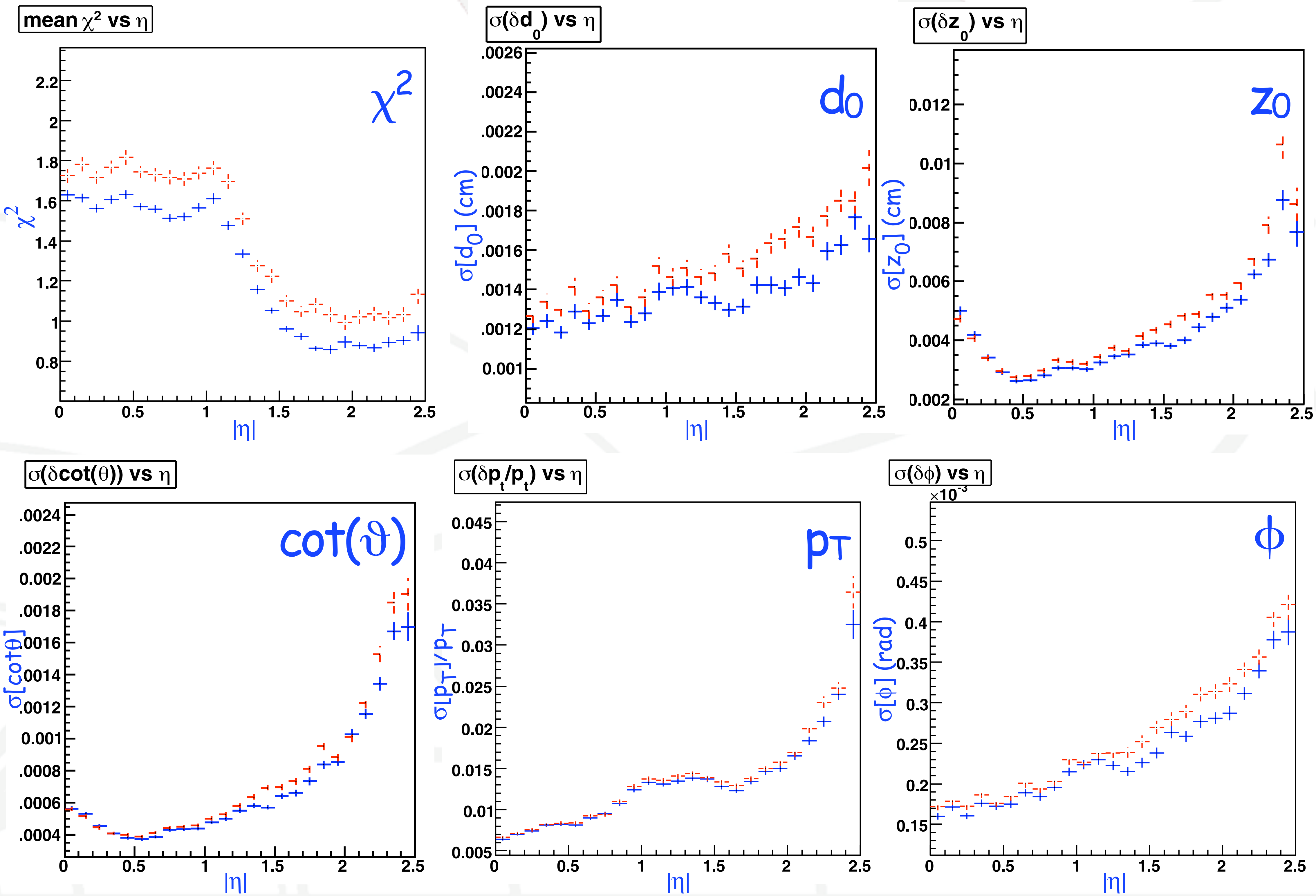
Compact Muon Solenoid

Extra Slides

CMS
Compact Muon Solenoid

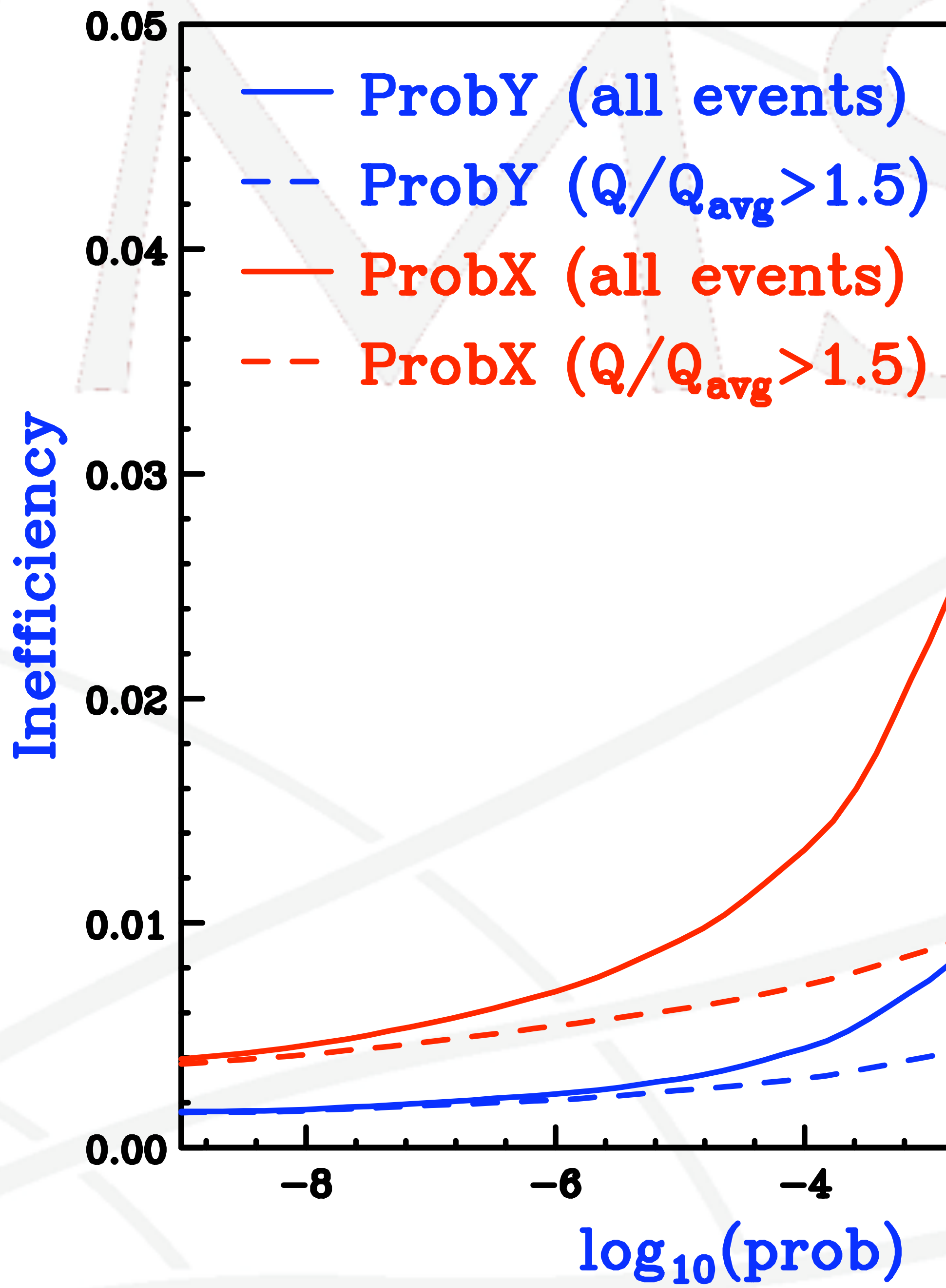
Effect on Track Parameters

- Show Gaussian fit sigmas (RMS's are probably better)
- biggest improvements in impact parameter at large η



Compact Muon Solenoid

Inefficiency of Template Probability Cuts



- For $P_{x,y} < 10^{-4}$, losses are dominated by events with large delta ray activity