smartpixels demonstrator testbeam proposal

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and the smartpixels team

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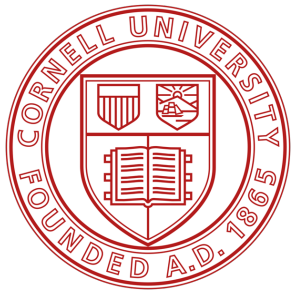


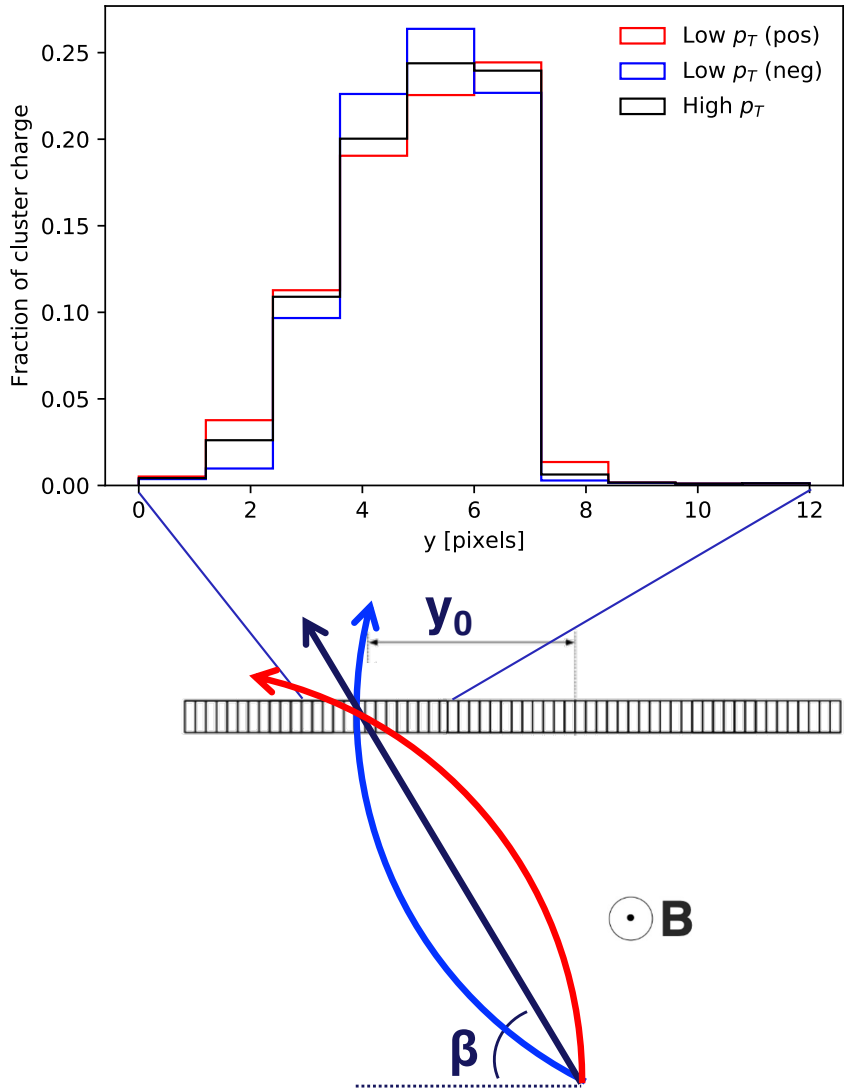
What are smartpixels?

- **Cluster shape contains information about the particle trajectory**
- Can be used to infer transverse momentum or regress track angles, given sufficiently granular pixels
- Read out cluster information → data reduction
- Two strategies

→ *Filter: reject tracks with low (< 200 MeV) pT*

→ *Regression: infer track position and angles*

$$\cos\left(\beta + \arctan\left(\frac{y_0}{R}\right)\right) = \frac{qRB}{2p_T}$$



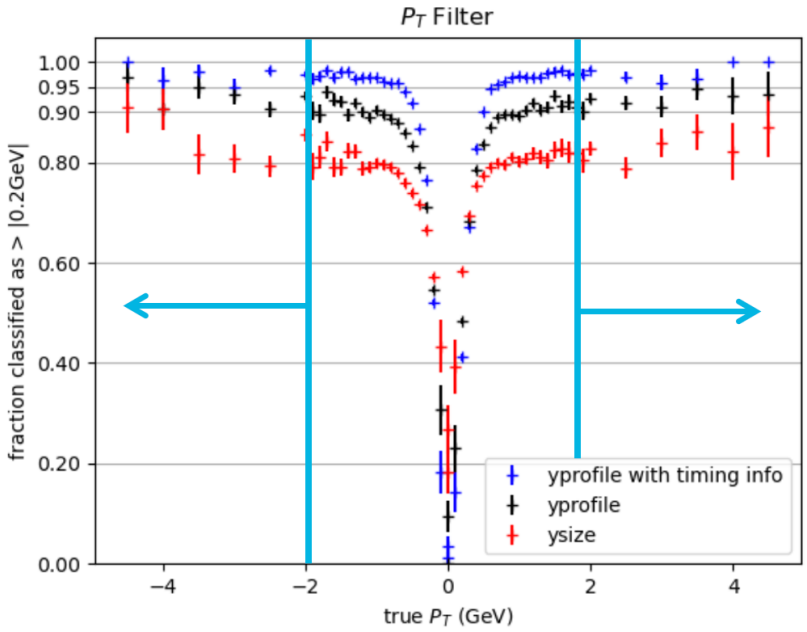
Snapshot: p_T filter

p_T filter with full precision inputs

- Full precision network:
  1. Projected cluster size only.
     Minimal information
  2. Projected cluster shape, integrated over 4ns.
     Selected for implementation
  3. Projected cluster shape at 8 200ps time points.
     5-10% gain in signal efficiency
- Signal efficiency

  How much of the $p_T > 2$ GeV sample do we keep?
- Background rejection

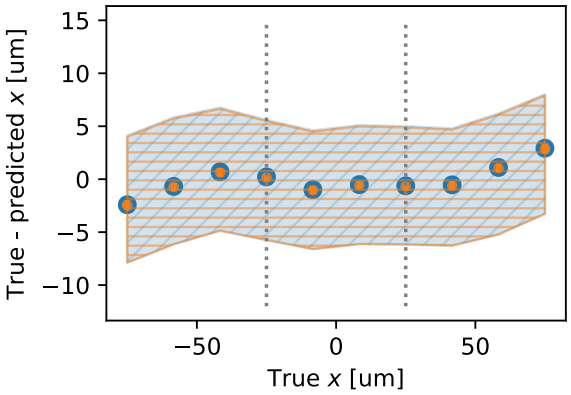
  How much of the $p_T < 2$ GeV sample do we discard?

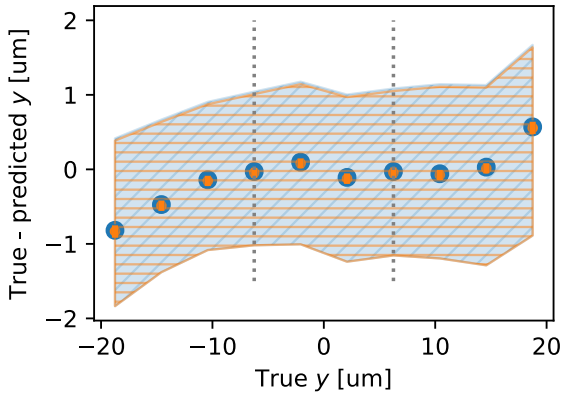


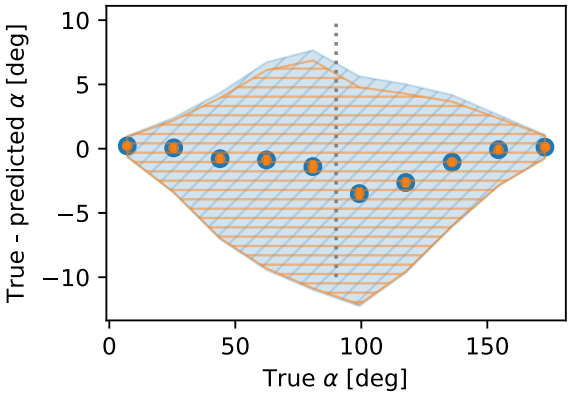
Model	Sig. efficiency	Bkg. rejection
Model 1	84.8 %	26.6 %
Model 2	93.3 %	25.1 %
Model 3	97.6 %	21.7 %

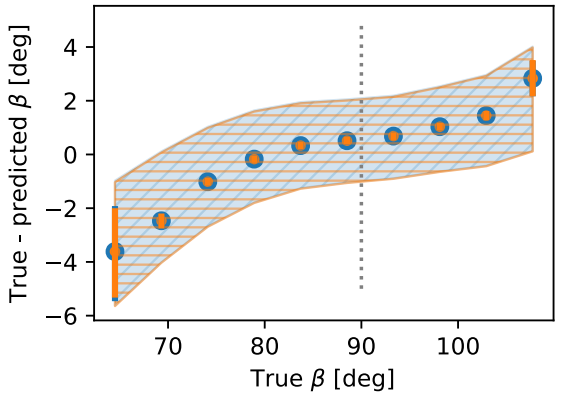
https://arxiv.org/abs/2310.02474

Snapshot: parameter regression









Use ”mixed-density” network with convolutional layers to predict **not just local position and angles but their uncertainties as well.**

β = angle in the bending plane
Colors represent hls4ml synthesized (orange cross-hatched) vs. QKeras (blue)

Hit position x, y

Pattern of bias repeats across each pixel

Mean predicted uncertainties:

$\langle \sigma_x \rangle = 5.7\ \mu m$

$\langle \sigma_y \rangle = 1.1\ \mu m$

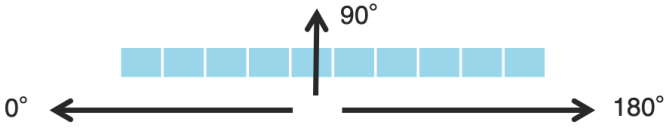
Angles α, β

Largest uncertainty near α=90° due to single pixel hits

Dataset covers limited range in β

$\langle \sigma_\alpha \rangle = 3.8°$

$\langle \sigma_\beta \rangle = 1.7°$



https://arxiv.org/abs/2312.11676

Requirements and deliverables

- We will need to:
  - → *Integrate DAQ with the telescope DAQ including ability to take triggers*
    - "Traditional" pixel readout in addition to cluster-based readout
  - → *Build support structures for devices, eventually with cooling*
  - → *Set up analysis for measurements below*

- **Deliverables**
  - → *Bump bond sensors to smartpixels ASICs*
  - → *Measure standard efficiency, cluster shape and charge, position resolution*
  - → *Measure track rejection vs angle for filter algorithm*
    - Different angles correspond to different momenta at different positions on the device
  - → *Measure parameter resolution for regression algorithm*
  - → *Stretch goal: irradiate at FNAL or LANL and characterize impact on performance*

Context and current work

- ASIC development
  - → *5x5 mm^2 chip under development, will tentatively include several algorithm options in separate areas, RD53A-style*
- Test beam options depend on the timing of the chip
  - → *FTBF (120 GeV protons) currently scheduled to shut down end 2026*
  - → *CERN North area (200-400 GeV protons) also shutdown 2026 – late 2028*
  - → *DESY* (electron beam) *operation foreseen until at least 2030* (electron beam)
    - Need to understand access options for US groups for DESY or CERN
- Algorithm development so far assuming 100 μm thick planar silicon devices, 12.5 x 50 μm^2 pixels, assume n-in-p
  - → *Work ongoing using simulation to estimate how the performance depends on pixel pitch & sensor depth*
- In the coming months:
  - → *Use TCAD and pixelAV simulations to determine sensor geometry*
  - → *Discussion with external partners (BNL, SLAC) about sensors*

Connection to RDC3/4

- RDC3: evolution of pixels towards thinner wafers and finer pitch

  → *Pixel detector finer-pitch than Phase 2 standard, close to limit of what can be bump bonded*

- RDC4: testing a new ASIC

  → *Validation of algorithm performance by simulating different momenta and impact positions using beam angle and using trained weights for different impact point (y_0)*

Schedule

- Year 1
  - → *Sensor fabrication and bump-bonding*
  - → *Request 2 separate 2-week blocks of beam*
    - Block 1: establish basic operations, commission DAQ, take data for first analysis
    - Block 2: systematic characterization of filter and regression algorithms
  - → *Feed back performance information and concerns to ASIC and algorithm teams*
- Year 2
  - → *Complete analysis and publication of Year 1 data*
  - → *Hybridization of updated ASIC*
  - → *Measurement program (similar to year 1) with updated ASIC (new algorithms, analog options, etc)*
- Year 3
  - → *Irradiation (stretch goal)*
  - → *Complete analysis and publications*

Funding and teams

- Subset of broader *smartpixels* effort
- Each participating group has specific areas of expertise and interest and cross-cutting interests. These areas are, by topic:
  - → *Smart pixels algorithm – U. Chicago, Cornell, UIC, Fermilab*
  - → *Silicon sensor simulation and characterization – UIC*
  - → *Test beam operations and analysis – UIC, Cornell, U. Chicago*
  - → *Electronics/DAQ - U. Chicago, Fermilab*
- Most smartpixels funding coming from AI/ML and ASIC development
  - → *"handshake" between that funding to provide an ASIC compatible with being bump-bonded, and for us to design a sensor that works with the ASIC*
- Outside collaborators: discussions with BNL and SLAC on sensor fabrication and bump-bonding

backup

Fermilab testbeam and telescope

- 120 GeV proton beam at Fermilab (FTBF), well-established “telescope” of silicon strip and pixel planes with 4-5 mm pointing precision to Device Under Test (DUT) in the center
- Testbeam shuts off for accelerator complex upgrades in 2027

→ *Nominally 1 January, may be delayed*