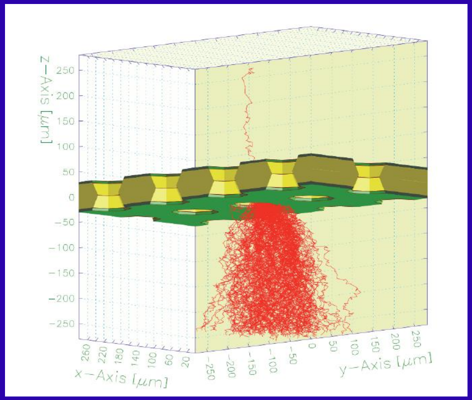
TPC Readout with GEMs & Pixels



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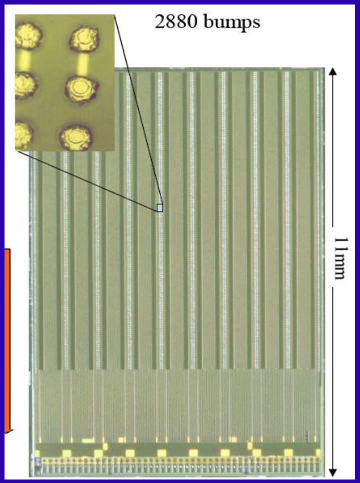

→ Linear Collider Tracking
Directional Dark Matter Detection
Directional Neutron Spectroscopy ?

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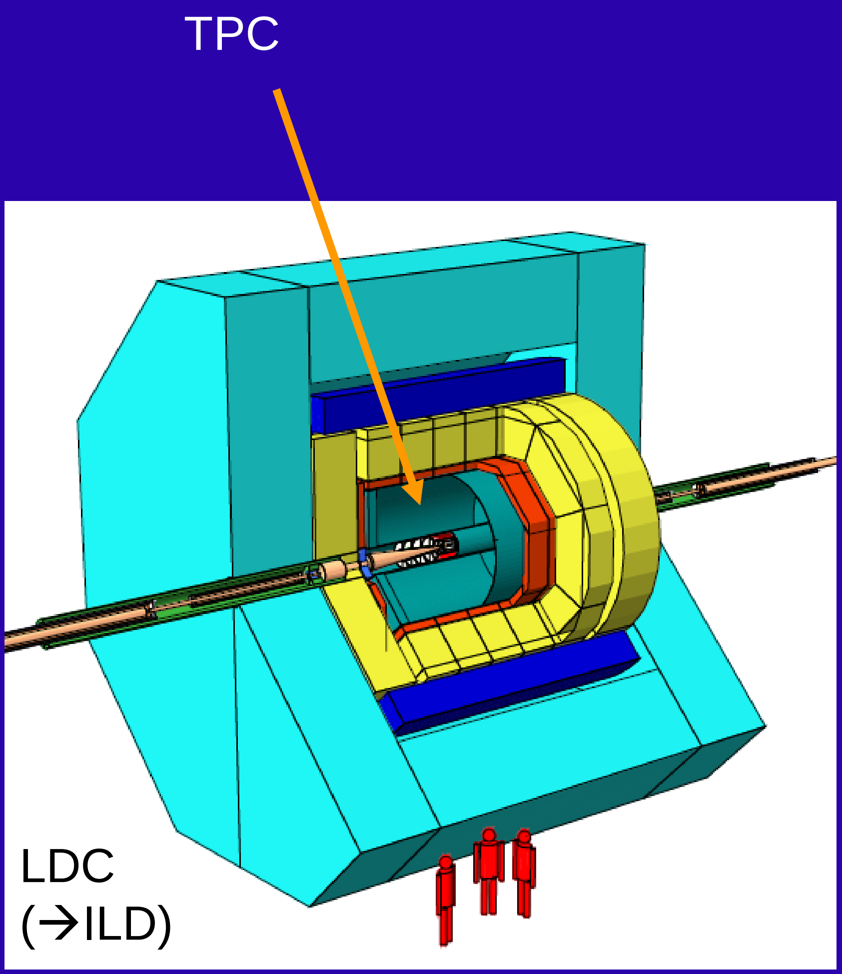
Cygnus 2009, Cambridge Massachusetts

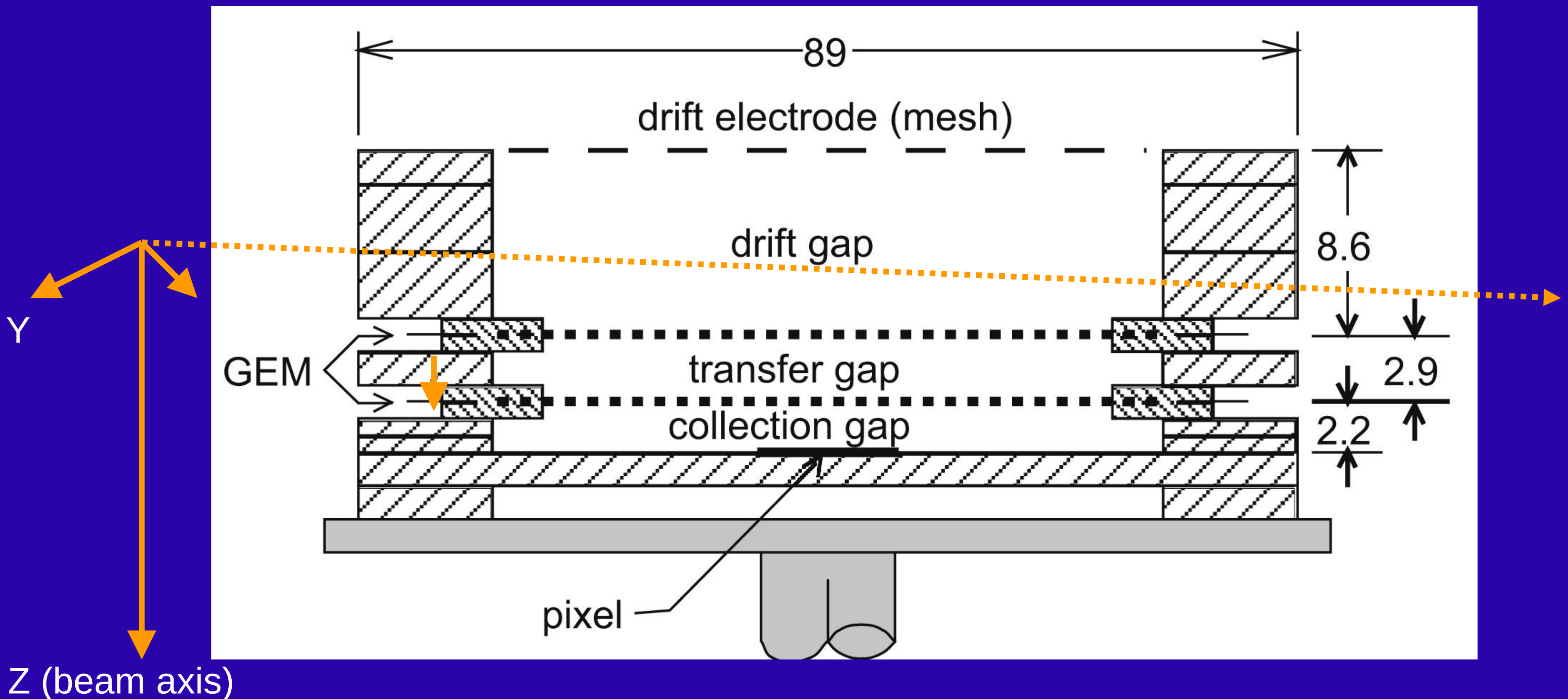
Our (Initial) Motivation

- Main tracking detector at future linear colliders will require exceptional momentum resolution
  - $\sigma_{1/P_T} \sim 5\mathrm{x}10^{-5}\ \mathrm{GeV}^{-1}$
- Possible with TPC, *if*
  - *>= 200 space points*
  - *Point resolution*
    - — σ_X, σ_Y ~100 μm
    - — σ_Z ~500 μm (z is beam axis)
- Need improved performance over previous TPCs
- Achievable with pixel-based charge readout?



Existing Prototype

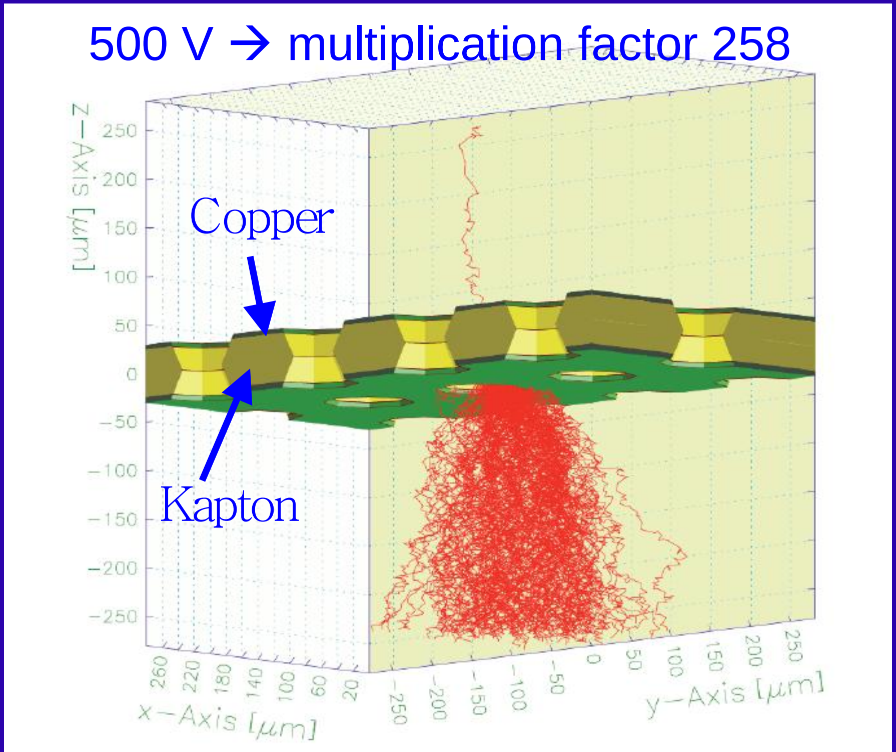
- Small - dimensions in *mm!*
- Read out drift charge with Gas Electron Multipliers (GEMs) + pixel chip

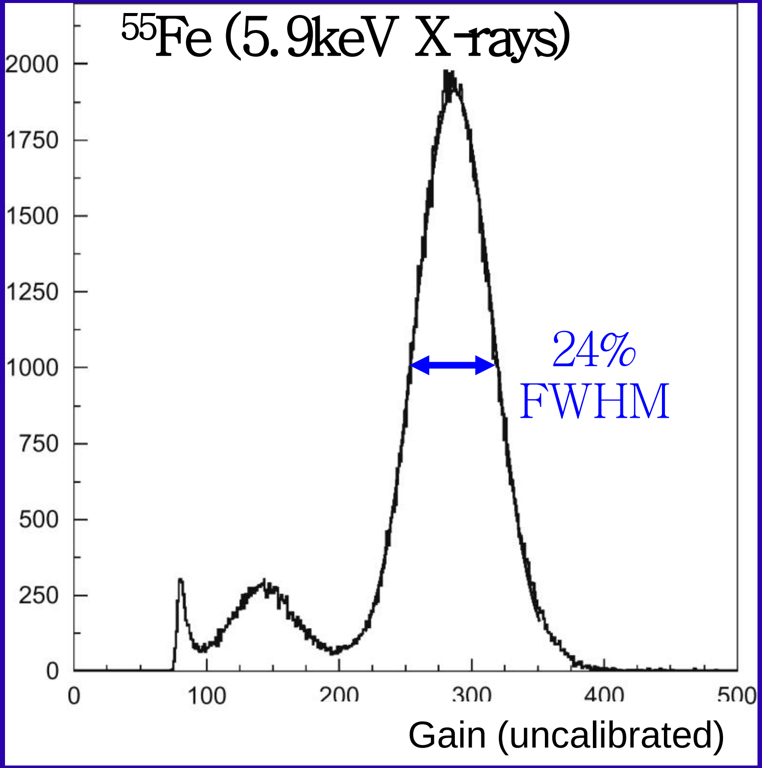


Readout of TPC tracking chambers with GEMs and pixel chip. T. Kim, M. Freytsis, J. Button-Shafer, J. Kadyk, S.E. Vahsen, W.A. Wenzel (LBL, Berkeley) . 2008. 12pp. NIM (2008)

Amplification: Gas Electron Multipliers (GEMs)

- Electrons multiplied by avalanching in GEMs
- Off-the shelf GEMs from CERN
  - 5cm x 5cm x 60 µm
  - Hole spacing: 140 µm
- Reliable without sparking with single-GEM gain up to 300 ($Ar/C0_2$)
- Two GEMS in series: higher gain with less risk of sparking: 500V + 400V → gain = 40000

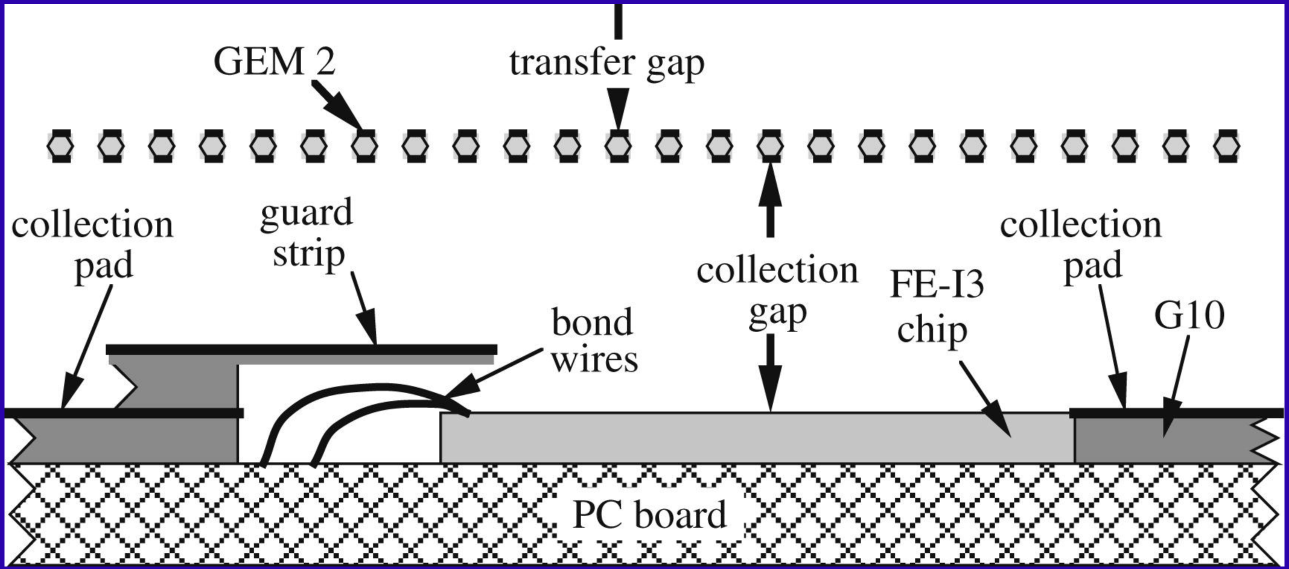




Simulated and measured gain consistent

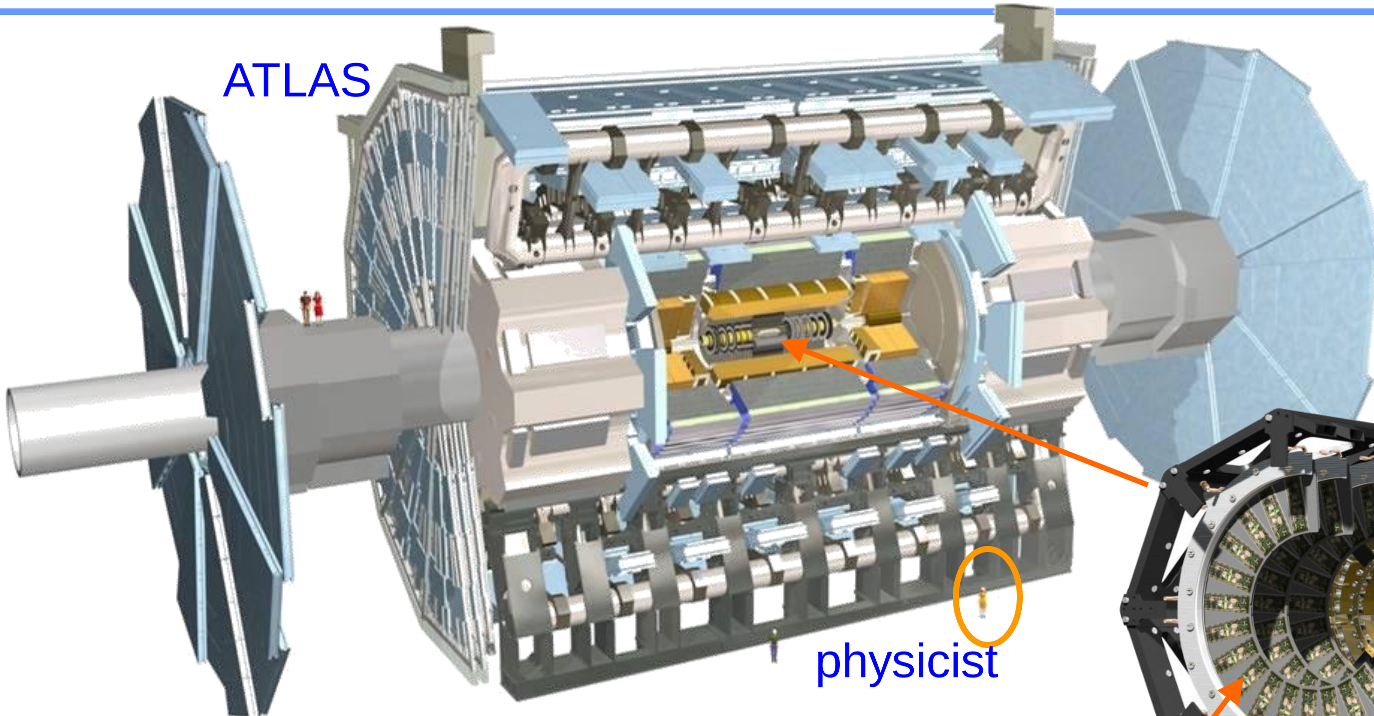
Charge Collection: FE-I3 Pixel Chip

- Same FE as in ATLAS pixel detector, Gold/Aluminum plated
- Same DAQ chain as during pixel production
- x/y from pixel coordinate (50x400μm)
- relative z from drift-time (25ns)
- fast-or LVL1 trigger from pixels
- Read out 16 "bunch crossings"
  - 16x 25ns*26 μm/ns = 10.4 mm (Ar/CO_2, 1kV/cm)
- Noise level ~120 electrons
- 2-3 pixels out of 2880 masked → no noise hits

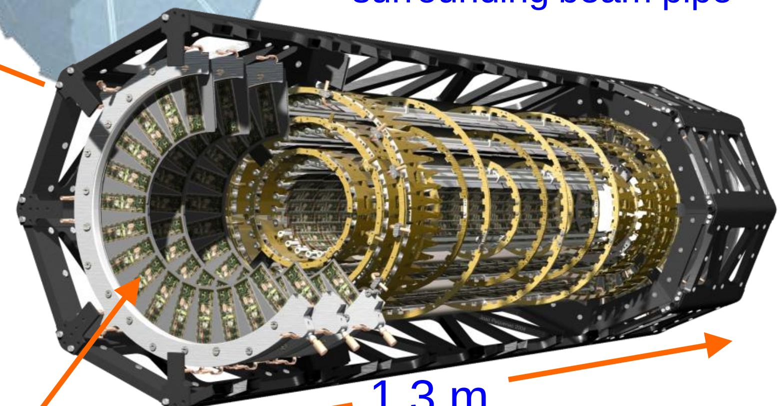


Expect good x,y resolution: gem hole spacing, pixel size
Expect good z resolution: fast electron signal & pixel FEs

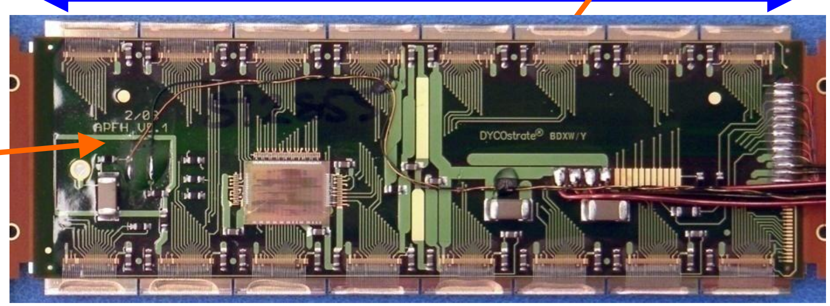
ATLAS at the LHC: 80 Million Pixels



ATLAS Pixel Detector
– Innermost tracking detector, surrounding beam pipe



6 cm



Pixel

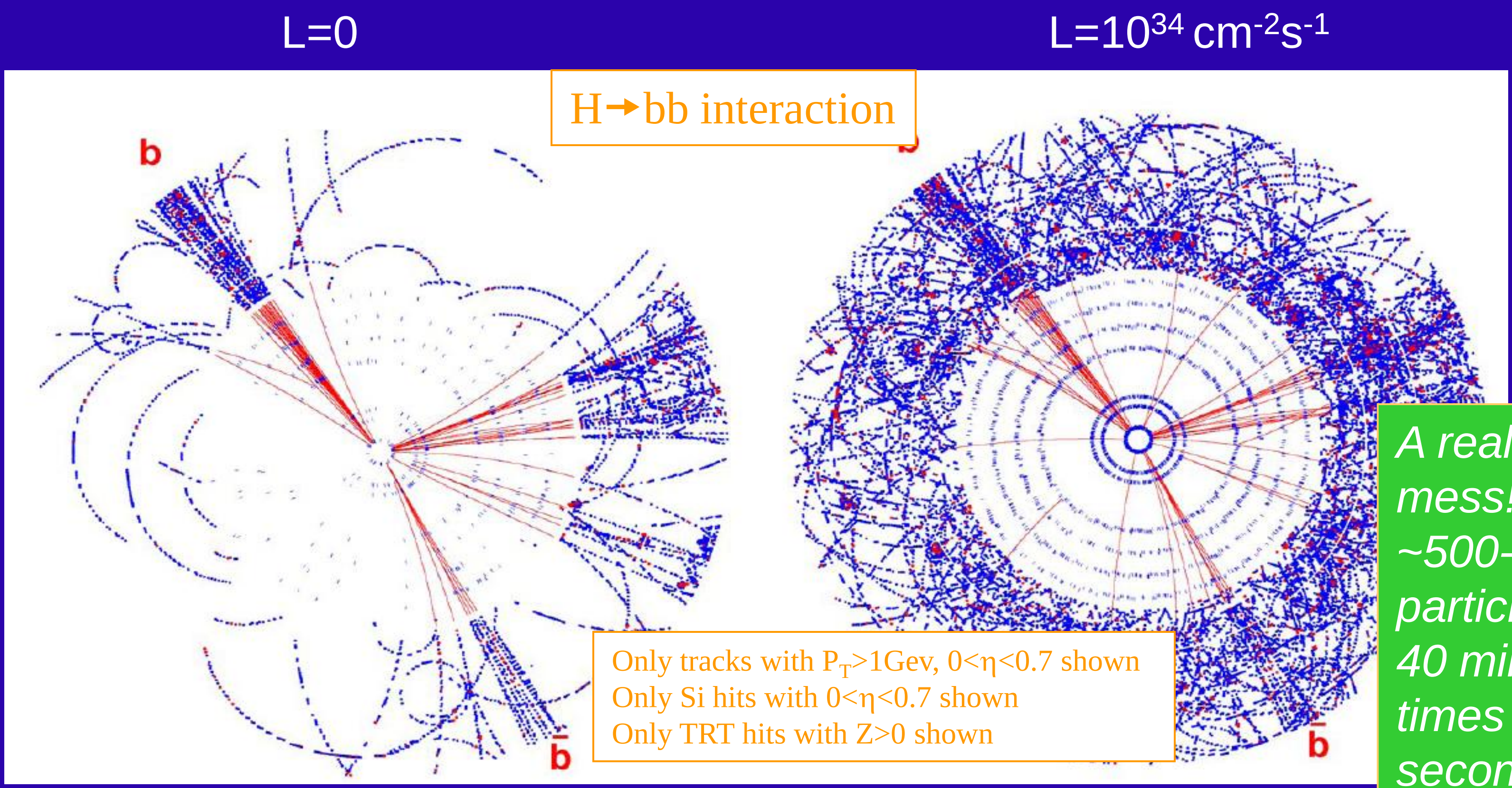
x46080

50 x 400 µm

Detection of charged particles takes place in 1744 identical *ATLAS Pixel Modules*

1744 modules x 46080 pixels = 80 million channels!

The Intended Use Case!

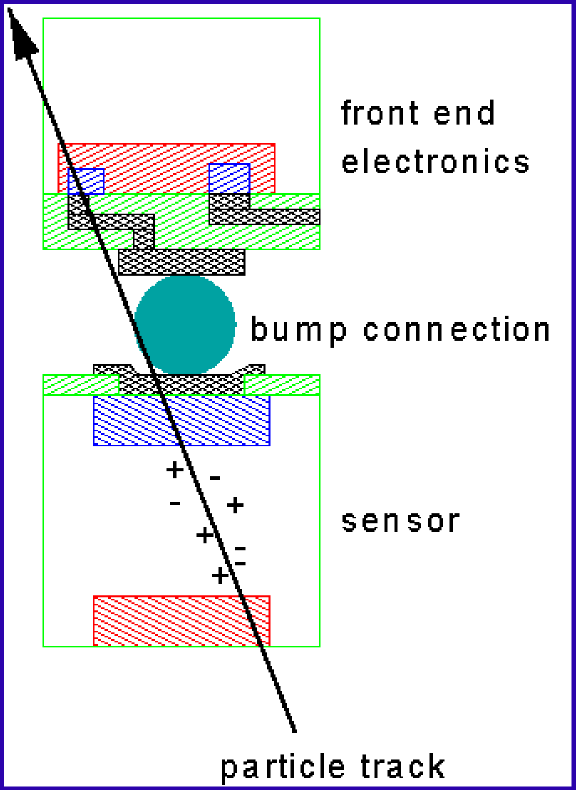


A real mess! ~500-1000 particles 40 million times per second!

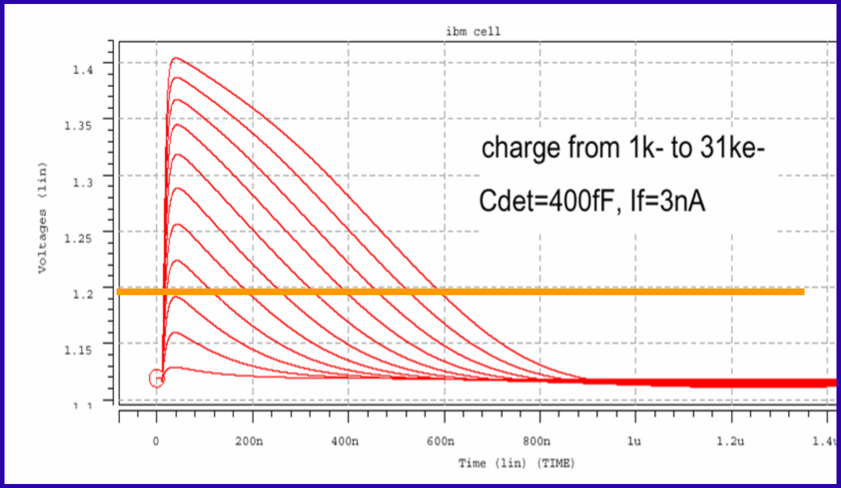
Pixel Detectors only way to do tracking close to beam pipe at LHC

- Perform pattern recognition in very high multiplicity environment
- Distinguishing hits 25ns apart
- Store hits up to 3.2 μs (LVL1 trigger latency)
- Withstand ~10^{15}n/cm^2 (20 years L2, 10 years L1, 3 years L0)
- Be highly reliable: No access for ~10 years

Single Pixel: Detection of a Charged Particle



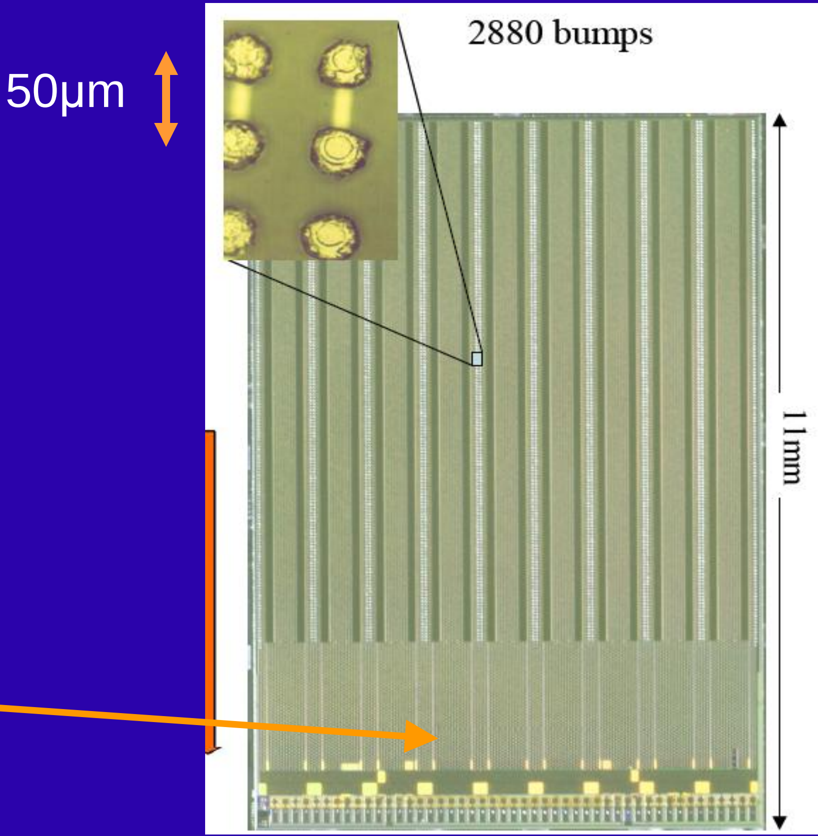
- With Silicon Sensor: MIP at normal incidence liberates ~20k electron-hole pairs
- In TPC case: Due to GEM; *20k electrons per ionized electron!*
- Charge swept into FE preamp, converted to voltage pulse

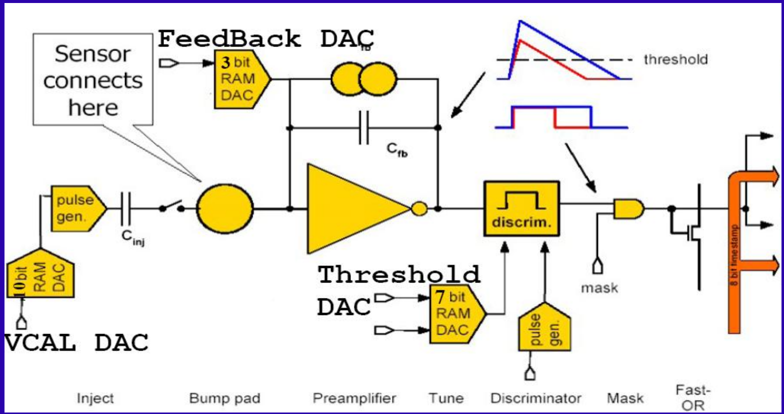


- If voltage pulse above discriminator *threshold*: digital hit
- Information stored
    - Location
    - Timestamp (25 ns units)
    - TOT (~charge)

FE-I3 Pixel Chip

- ~ 7 years, final version Dec ’03
- 2880 Channels, 3.5M transistors
- Each channel
  - — internal injection
  - — feedback current DAC
  - — threshold DAC
  - — enable, kill, hitbus
  - — LVL1 signal
- Hits stored in end-of-column buffers for up to 3.2 µs
- *Read out up to 16 BCs (x25ns)*



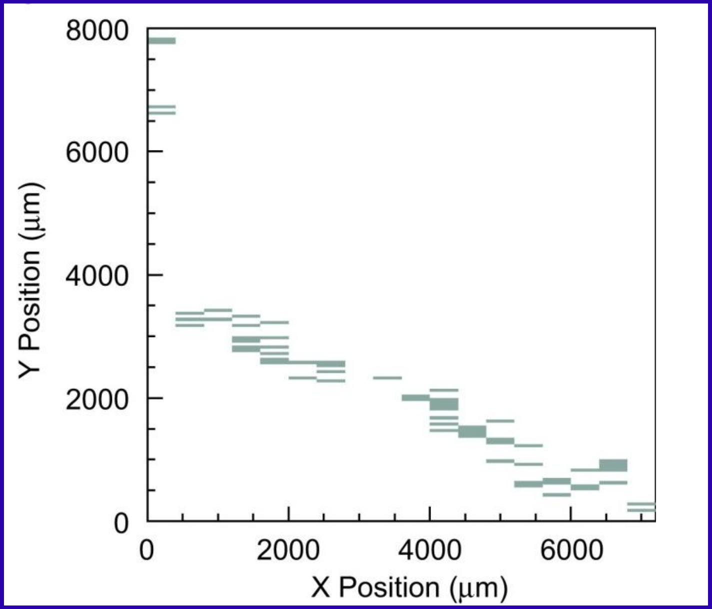


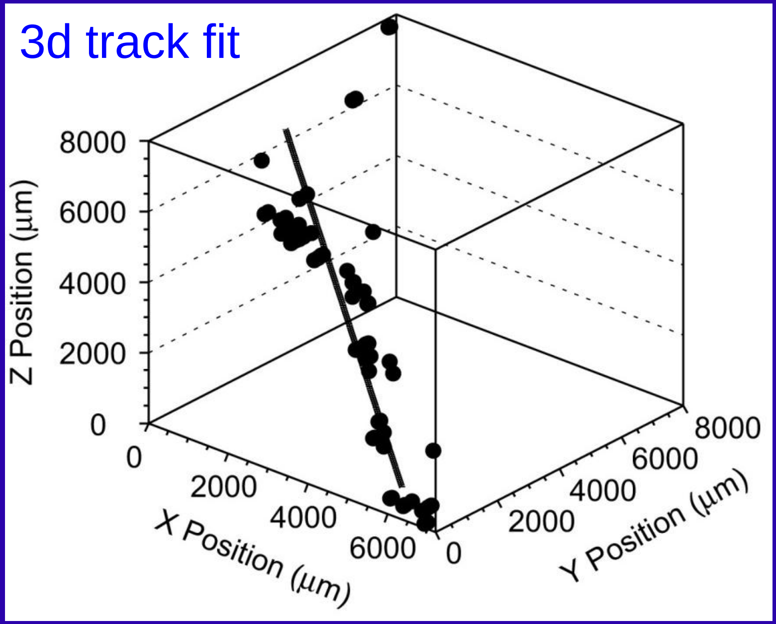
Position Resolution with Cosmics

σ_{Pixel}=14 μm

- Large sample of cosmic rays
- Require >10 pixel hits
- 3D track at least 4.5mm long
- Gain=9000, threshold=1800e-
- LC: diffusion < 100 μm w/ magnet

	track fit residual	Diffusion	$\sigma_{GEM+Pixel}$
σ_X (μm)	170	110	130
σ_Y (μm)	130	110	70
σ_Z (μm)	240	190	150

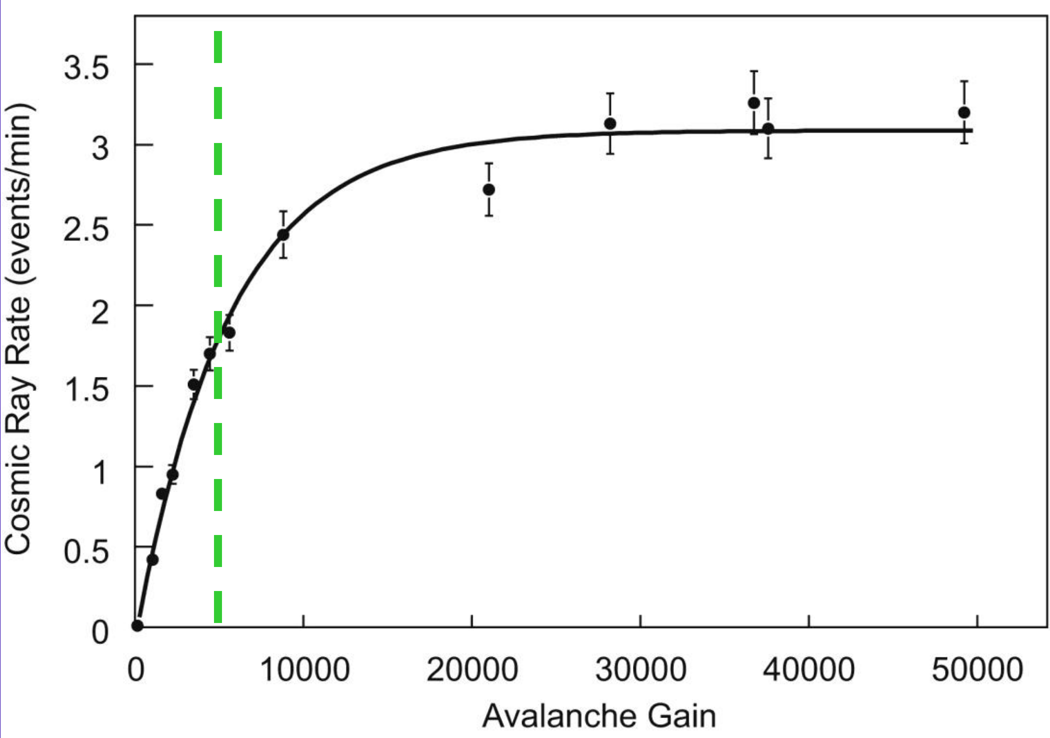




- Resolution requirements for LC were met even with *ATLAS* Pixel FE
- For LC / DM detection, need to reoptimize, FE geometry, gas mixture, GEM, etc…

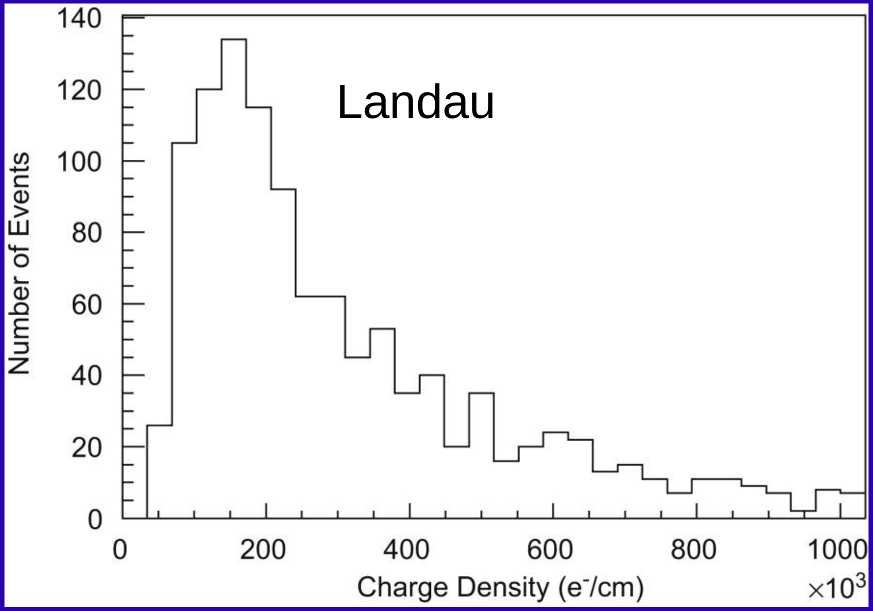
Cosmic Ray Rate

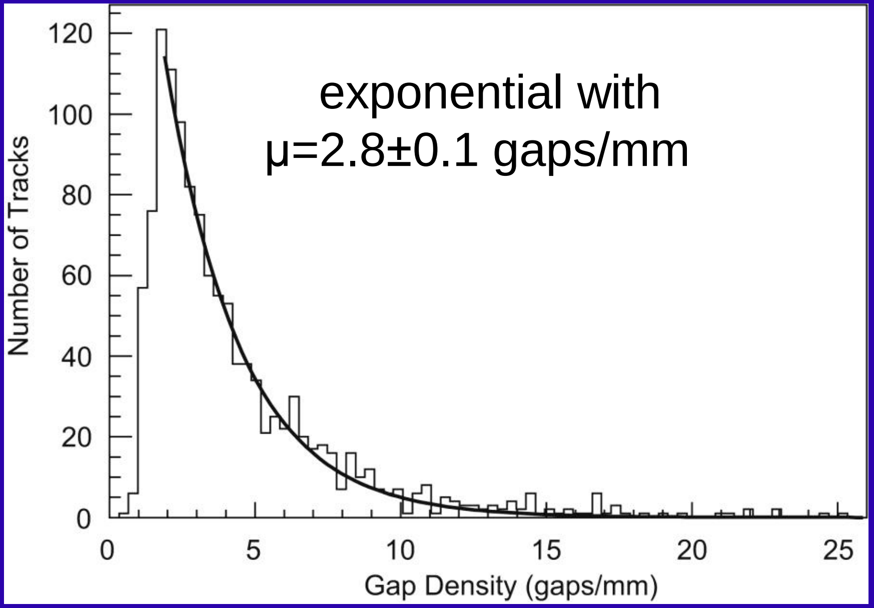
- Pixel threshold at 5k electrons
- Rate plateaus at gain ~20k
- 20k electrons per primary ionization electron (vs 20k electrons per MIP/layer in ATLAS)
- *Suggest system is capable of collecting all the ionization from primary track - even single electrons!*
- *Caveat: Did not study pixel noise versus GEM gain*



TPC Bonus: Track Ionization

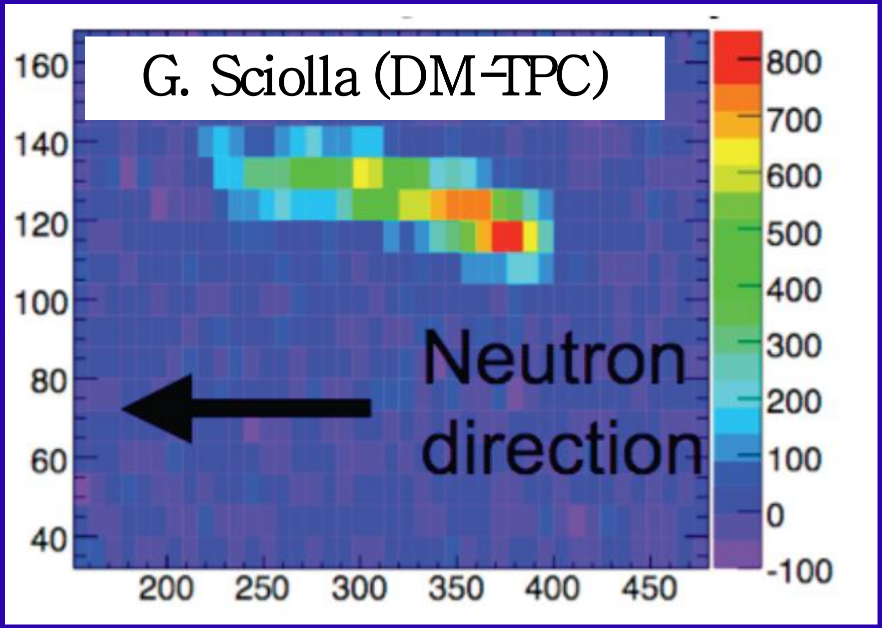
- Measurement of specific ionization for particle ID
- Demonstrated two methods
  1. Charge / unit track length from Pixel TOT
  2. Track gap density distribution





Applicable to Directional WIMP Detection?

- **Demonstrated good performance**
  - — simultaneous precise measurement of x,y,Δz/t,dE/dx
  - — very good signal/noise (75) and threshold/noise (15)
  - — read out all the primary ionization

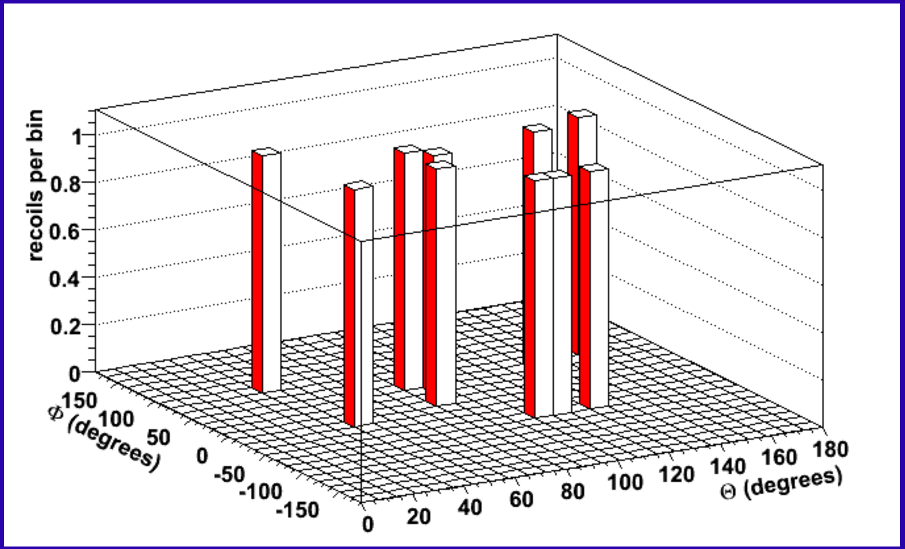


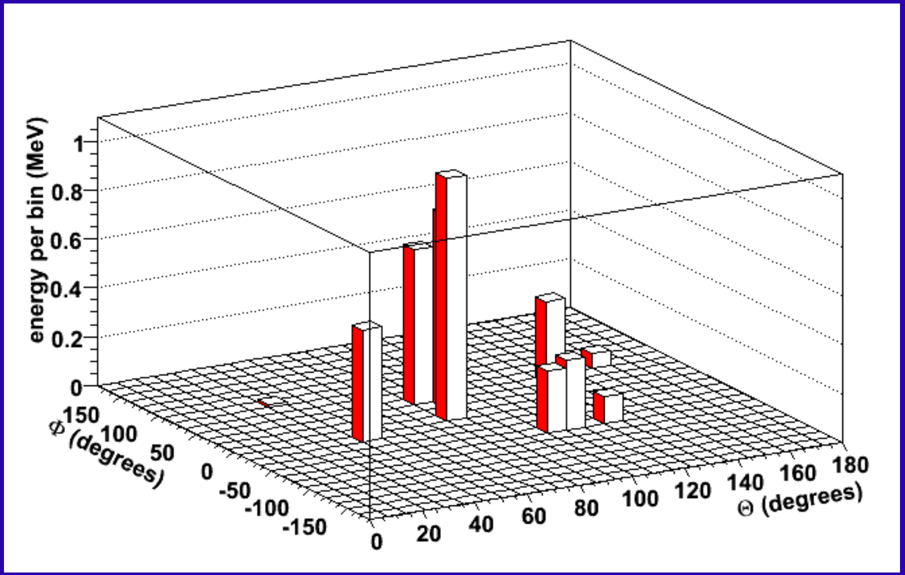
- Pixels increase costs, but should improve x,y,z,E,dE/dx resolutions
  → improved signal/background separation ?
  → better sensitivity / target volume ?
- High gain + low noise level → low threshold
- *Can we get absolute z from diffusion?*
- *Chip design limitation: Can only read out 16 time bins*

Neutron Detection

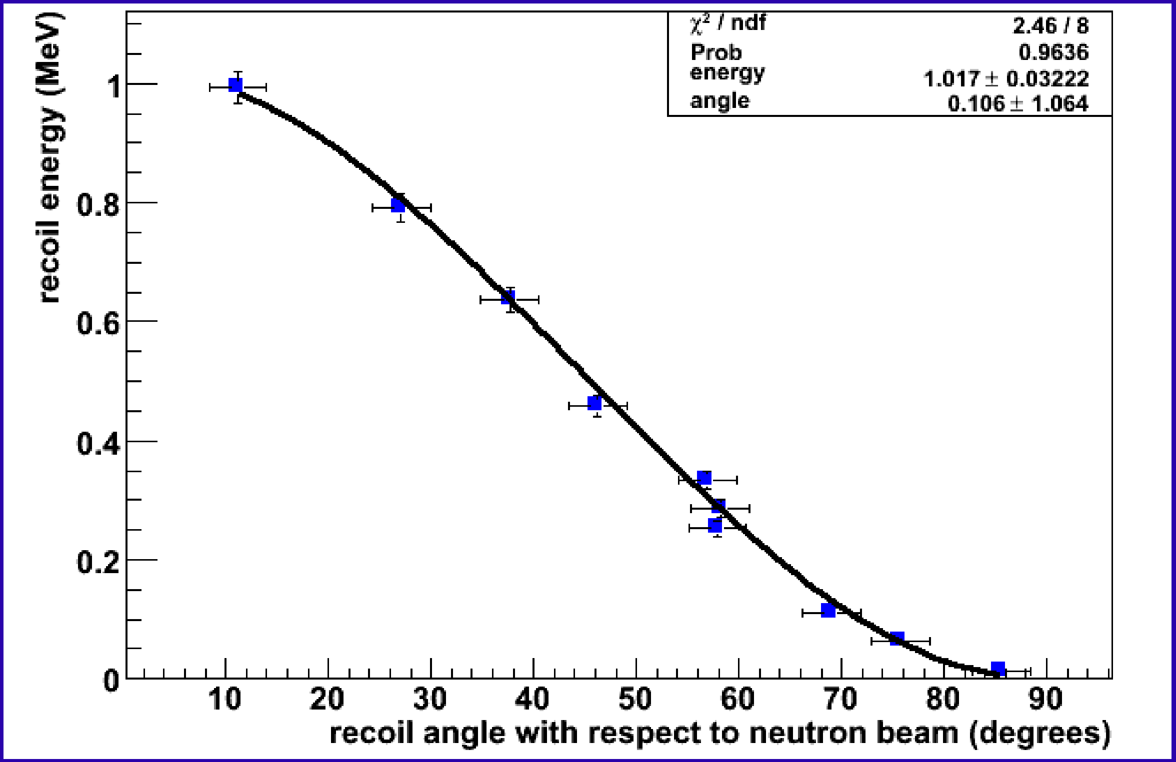
- Simplified scenario
  - — mono-energetic beam of 1 MeV neutrons
  - — incident at phi=0, theta=90 degrees
- Simulated detector performance based on measured performance with charged particles

- *Adding energy measurement also helps constrain neutron direction*





Neutron Detection II



- Assuming we can positively identify neutrons without background…
- Recoil energy depends uniquely on recoil angle
- Use angle and energy together in un-binned fit
- 10 nuclear recoils→ neutron energy to 3.2%, angle to ~1 degree
- Confirmed by pseudo-experiments, but are assumptions realistic?

1) Result needs checking 2) Realistic scenarios much more difficult to resolve!)

Future Plans

- Work targeted at WIMP / neutron detection
- Modify existing 1-chip setup to 10cm drift length
- Characterize performance with nuclear recoils (neutrons) and charged tracks (beta/alpha)
  - — x,y,Δz,E,dE/dx resolutions
  - — noise level, threshold
  - — head/tail sensitivity
  - — absolute z from x/y diffusion width
  - — optimal gas mixture and GEM/Pixel operating conditions
- Validate/tune simulation
- Design (10 cm)^3 prototype, optimized for WIMP / neutrons
  - — Pixel chip: ATLAS FEI3, FEI4, or Timepix/Medipix

Conclusion on GEM + Pixel Readout

- **Excellent performance in simple prototype**
  - — simultaneous precise measurement of x,y,Δz/t,dE/dx
  - — read out all the primary ionization
  - — very good signal/noise (75) and threshold/noise (15)
- Meets ILC requirements
- Suitable for Directional WIMP detection and neutron detection?
  - — Excellent performance
  - — But, expensive (~ \$18 / cm^2 = \$180k / m^2)
  - — Pixel chip needs design changes
  - — Can we get absolute z from diffusion width?
- Follow up with dedicated WIMP / neutron detection work
- Leading to design of (10cm)^3 detector year after