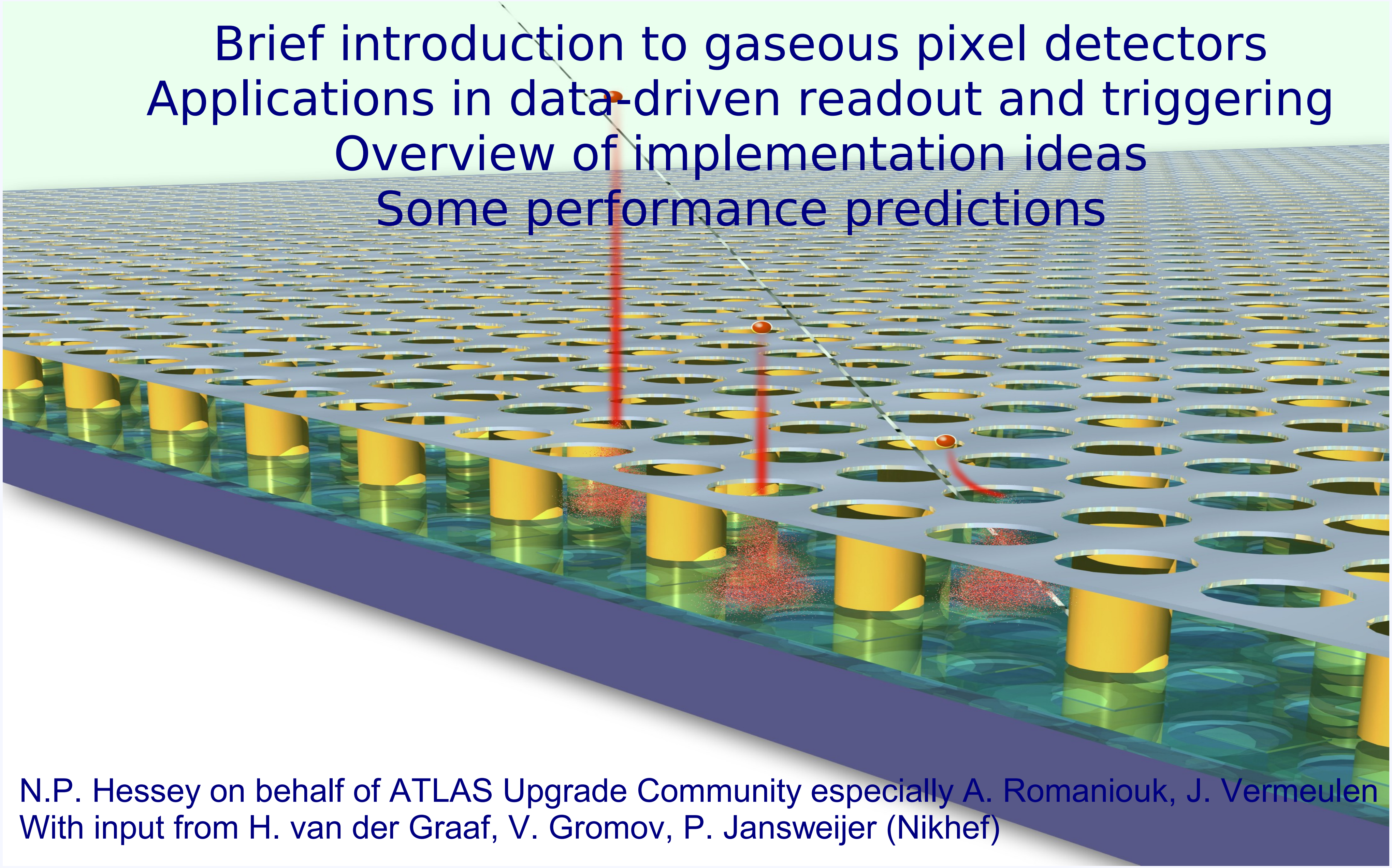
Front-end Intelligence for triggering and local track recognition in Gas Pixel Detectors



Brief introduction to gaseous pixel detectors
Applications in data-driven readout and triggering
Overview of implementation ideas
Some performance predictions

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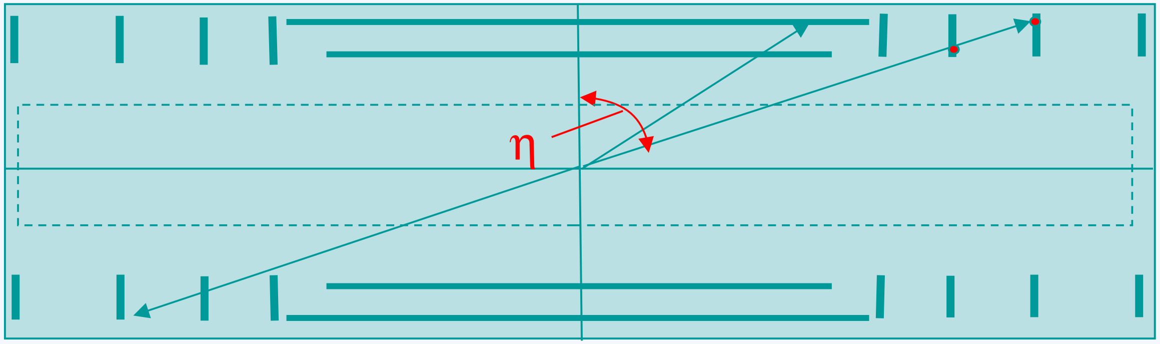
With input from H. van der Graaf, V. Gromov, P. Jansweijer (Nikhef)

Applications introduction: Drift Chamber Triggering

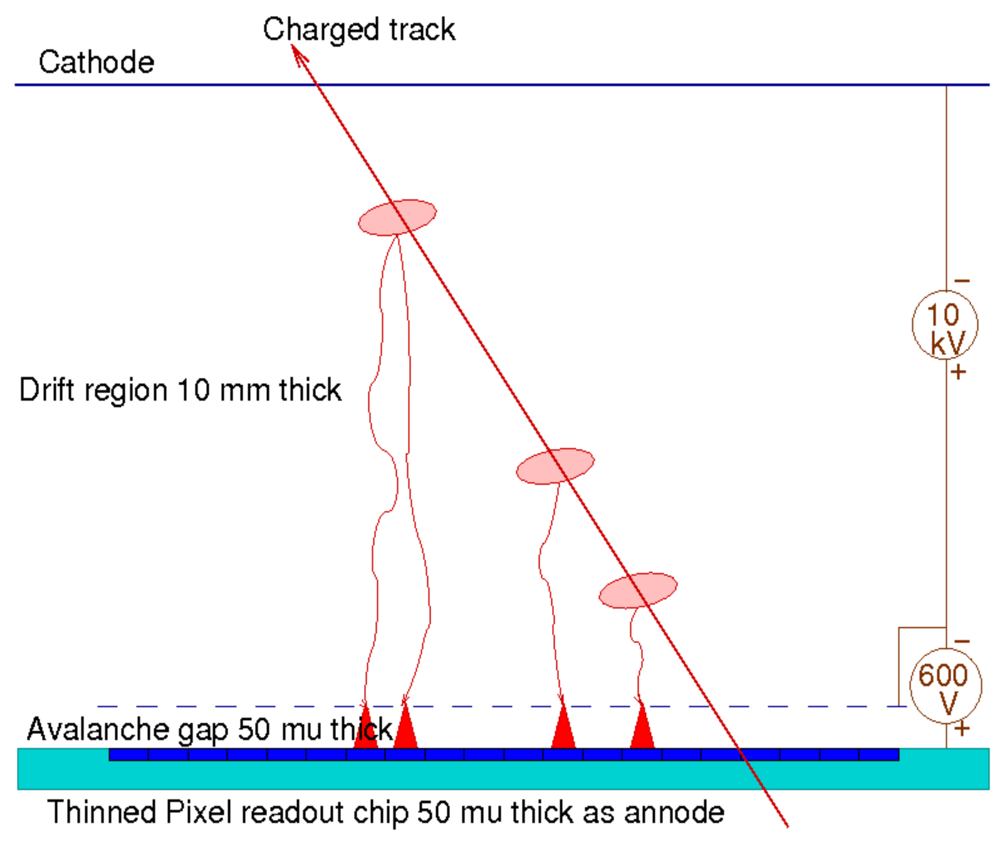
- Traditionally drift chambers rely on external detectors to trigger their readout and to determine the "t0" - the time-of-passage of a track
- The ability of a drift chamber to recognise internally when a track has passed could be a very generally useful addition
  - Triggerless/data-driven readout
  - Data reduction for reduced bandwidth in data links
  - E.g. medical applications for proton beam monitoring
- As a further step, determining the track angle can be used especially at the HL-LHC for track-triggers
  - Track triggers at HL-LHC for ATLAS and CMS are needed
  - Most work based on silicon detectors, but a gaseous pixel detector has some advantages, which is the main point of this talk



Two layers of GasPix detectors in a solenoid field for triggering on high pT (transverse momentum) tracks

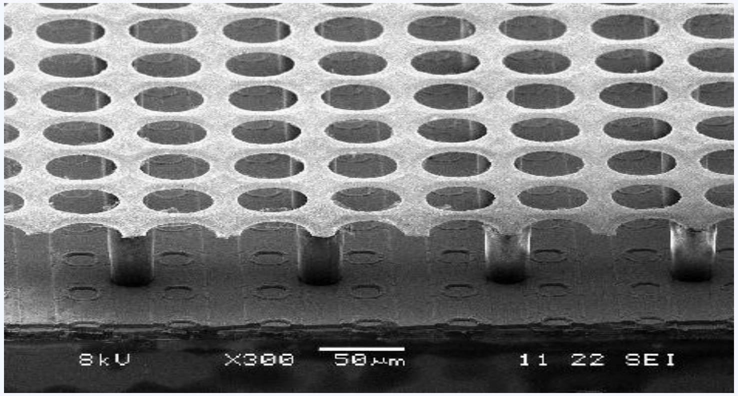
GasPix Detectors

Primary ionisation electrons drifted to a grid
  - max. drift time ~250 ns for 10 mm
After the grid, high field gives gas multiplication
Pixel readout chip detects the signal
Drift gap chosen to suit application:
: ~1 mm (Gossip, B-layer region)
 ~10 mm outer layers e.g. track triggers
 ~1 m (TPC at ILC)

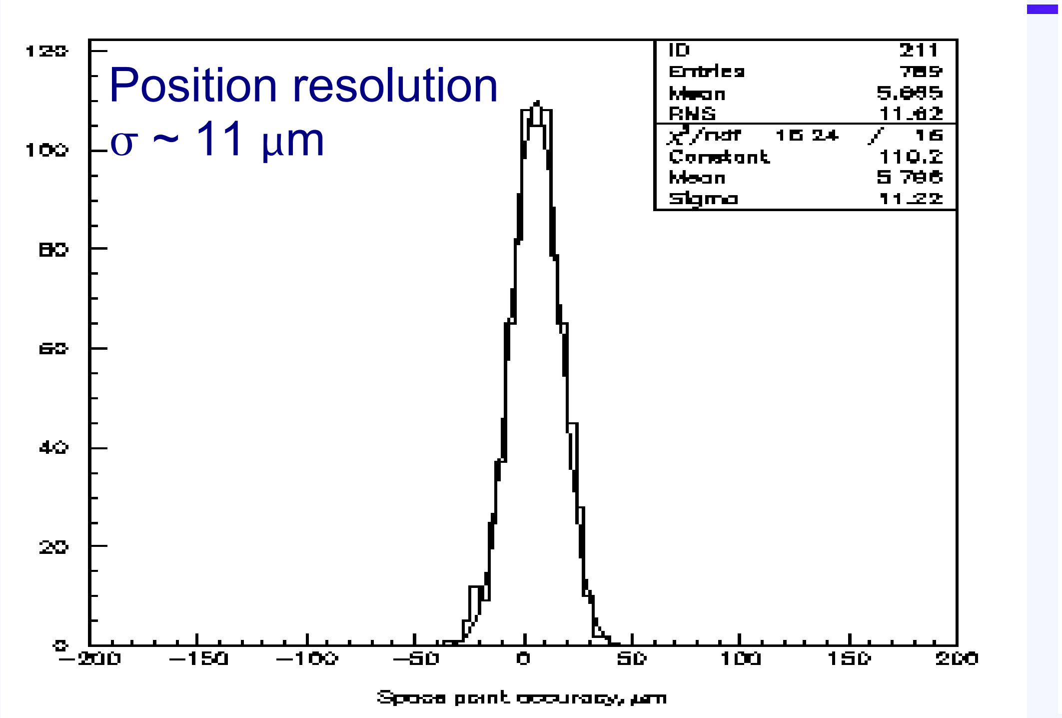


3D detection: x, y from pixel; z from drift time.
  ~ 20 µm each e-, each direction
Correct time-slewing with ToT
Gives a **track vector** (5D: x, y, z, θ, ϕ) cf 2D (strip)
3D (stereo strips and pixels).

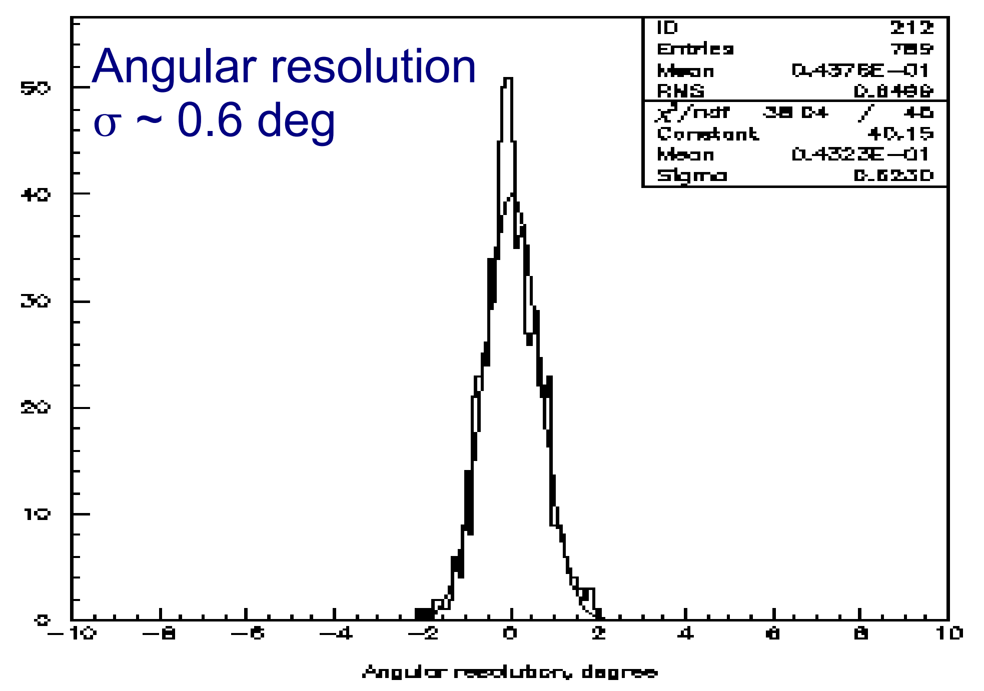
InGrid built with MEMS techniques on readout chip
Spark protection layer for electronics (Si-rich N)
Support pillars between readout pads
  - no dead areas



GasPix Performance



Position resolution
σ ~ 11 µm



Angular resolution
σ ~ 0.6 deg

Each primary e- detected --> much higher precision than previous gaseous detectors

Achievable Offline Performance:

- Position ~10 micron
- Angles ~10 mrad

Small ion-drift region (50 um)

- high rate capability

Current results based on Timepix chip

Far from ideal - slow front end (150 ns time slewing), 10 ns tdc, and no ToT with hit arrival time

2009 Testbeam result plots from Anatoli Romaniouk, 4th Workshop on Advanced Transition Radiation Detectors for Accelerator and Space Applications

Currently prototyping efforts going beyond proof of principle to reliable production and robustness

Comparison with Silicon

- Some main advantages:
  - Track angles in addition to position (3D hit measurement)
  - No silicon detector and bump-bonding
    - Potential for lower radiation length and cost compared to silicon pixel detectors
  - Continuously-replaced detection medium
    - Possibility for rad-hardness
  - Possibility of pT trigger in inner trackers with all data collected on one chip
    - Higher pT resolution
    - Both angles welll measured cf double strip layers
- Some challenges relevant to intelligence in front-end:
  - Measurement of all electrons --> much higher data rate (~50 hits for 10 mm gap)
    - Reduction of amount of data read out is desirable
  - Usually drift chambers need external reference/trigger to start readout and give track passage time
    - Stand-alone trigger for "data-driven" readout desirable

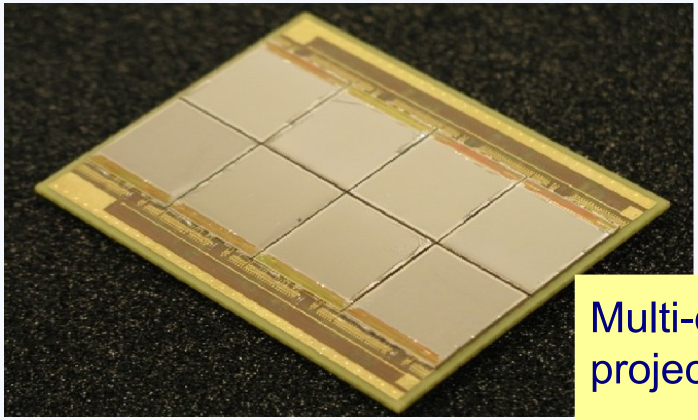
Goals of current work

- Fast recognition of passage of a track and identify track arrival time without external input
  - Use for data-driven readout
- Fast determination of track angle
  - Correlated to particle momentum when used in a solenoidal magnetic field
  - L1Track trigger at LHC experiments
  - Advantages over silicon pixel or strip correlated pairs...
    - No 40 MHz correlator-chip and high speed local bus
    - No large CAM off-detector pattern recognition
- Dream even further: Local determination of track parameters
  - Can we switch from hits readout (pixel x and y, hit arrival time, ToT) for every hit to track readout: track x, y, theta and phi and track arrival time?
  - Much reduced data rate; higher precision and better information for L1Track Trigger

Detector dimensions considered here

B-field	2 T	CMS is 4 T giving better resolution at equal radius
Radius	1 m	CMS may need less to reduce photon conversions
Chip size	14 x 14 mm	Like Timepix3; prefer bigger, e.g. FE-I4 ~graticule limited
Pixel size	110 x 220 μm^2	8 times bigger than Timepix: 110 μm is in phi/pT direction Electron diffusion limits advantages of going smaller than 110 μm. Other direction is less important.
Drift gap	10 mm	Larger gives longer max. drift time and needs higher voltage, but gives better pT resolution
TDC per pixel	25/16 ns bins	"tic" on plots
Peaking time	25 ns	
Gas	CO2-DME 50-50	Very low diffusion but needs a high field for fast drift

Read-out chip would be combination of
TimePix-3 pixels
FE-I4 LHC-type readout
+ additional triggering circuitry



Multi-chip modules ("Octopuce" project) ~ 8cm x 4 cm or bigger

Monte Carlo Simulations

Garfield to get basic parameters -
  Full simulation for:
    - Ionisation features: clusters/mm, cluster-size distribution
    - Drift parameters: velocity, diffusion

Fast (smearing) MC using Garfield parameters as input:
- Primary ionisation (including cluster size distribution)
-Drift (including diffusion)
- Avalanche (Polya distribution controlled by Byrne parameter)
- Signal development
    e^- and ion induced signals
    parallel plate capacitor geometry for now
- Electronics signal processing:
    Noise, shaping (25 ns peaking time)

Process fast MC output
  Simulate digital signal processing (Stage 1, 2, 3)
  Get efficiencies, resolutions, histograms

Track passage recognition and T0 determination

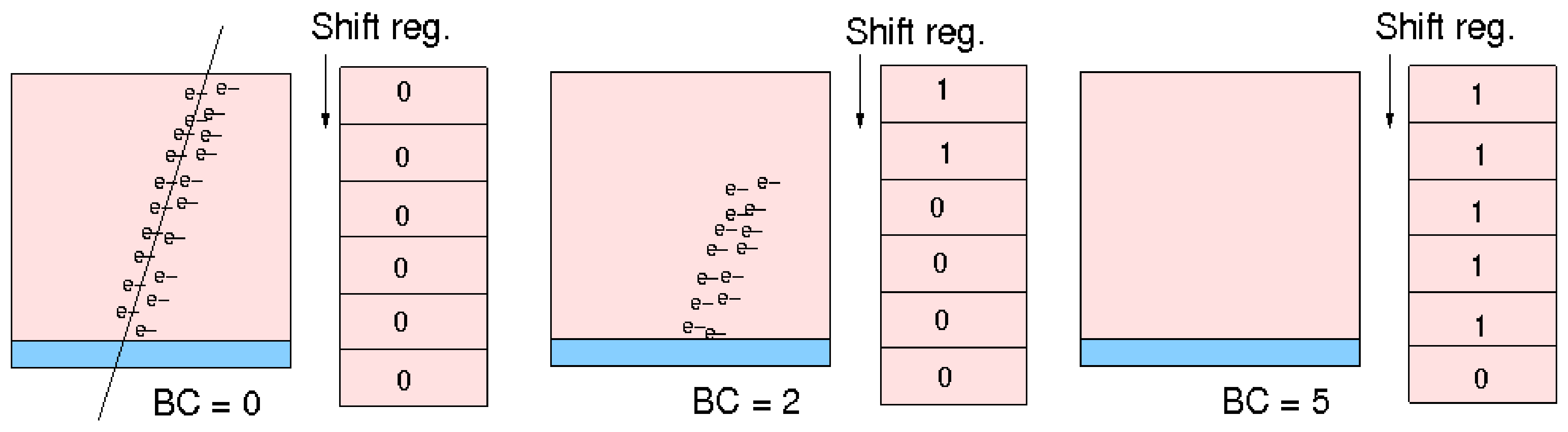
- Drift detectors usually employ other detectors to determine the passage time of a track
  - Hit arrival time minus track passage time --> drift-time
  - Drift-time times drift-velocity gives 3rd coordinate
- For GasPix detectors, there is the possibility to determine the track passage time internally (with useful time resolution, ~8 ns)
  - In many cases, one can use external information to convert this low resolution to a high precision T0
  - e.g. at LHC, once the BC is identified the 40 MHz clock determines the track passage time very precisely
- Generally useful in many scenarios, not just LHC

See Vladimir Gromov's talk on Friday for details of how this can be implemented
Including power, space and latency estimates
Here I give a slightly different schematic, looking ahead to the pT measurement

Concept of T0 recognition

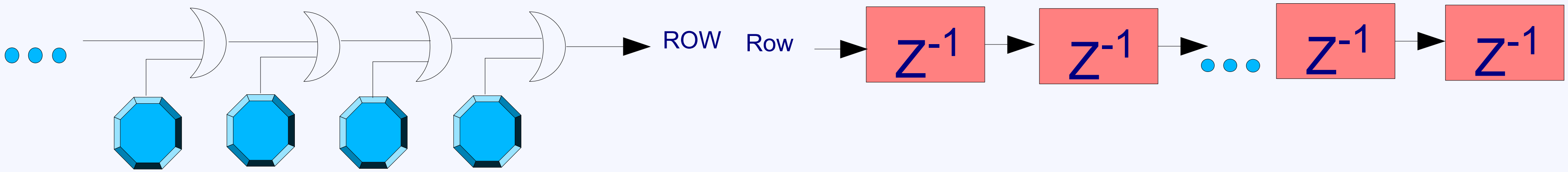
Conceptually:
Look at a projection of hits onto drift direction
When hits stretch from chip to cathode, a track passed in the corresponding BC

Realisation:
Feed hits into a shift register (SR) clocked at 40 MHz
Typically 5 e- per mm = 25 ns
 - SR gets filled with continuous row of hits
Picture below assumes max drift time = 5 BC
0 - 1 transition plus 5 registers with hits determines track arrival time



Implementation: OR into SR

OR all pixels in a row together
Feed each row-output into a shift register (SR) clocked with the LHC 40 MHz clock
1-bit per row; (max. drift time + 1) cells long
Keeps a history of an entire row for duration of max. drift time

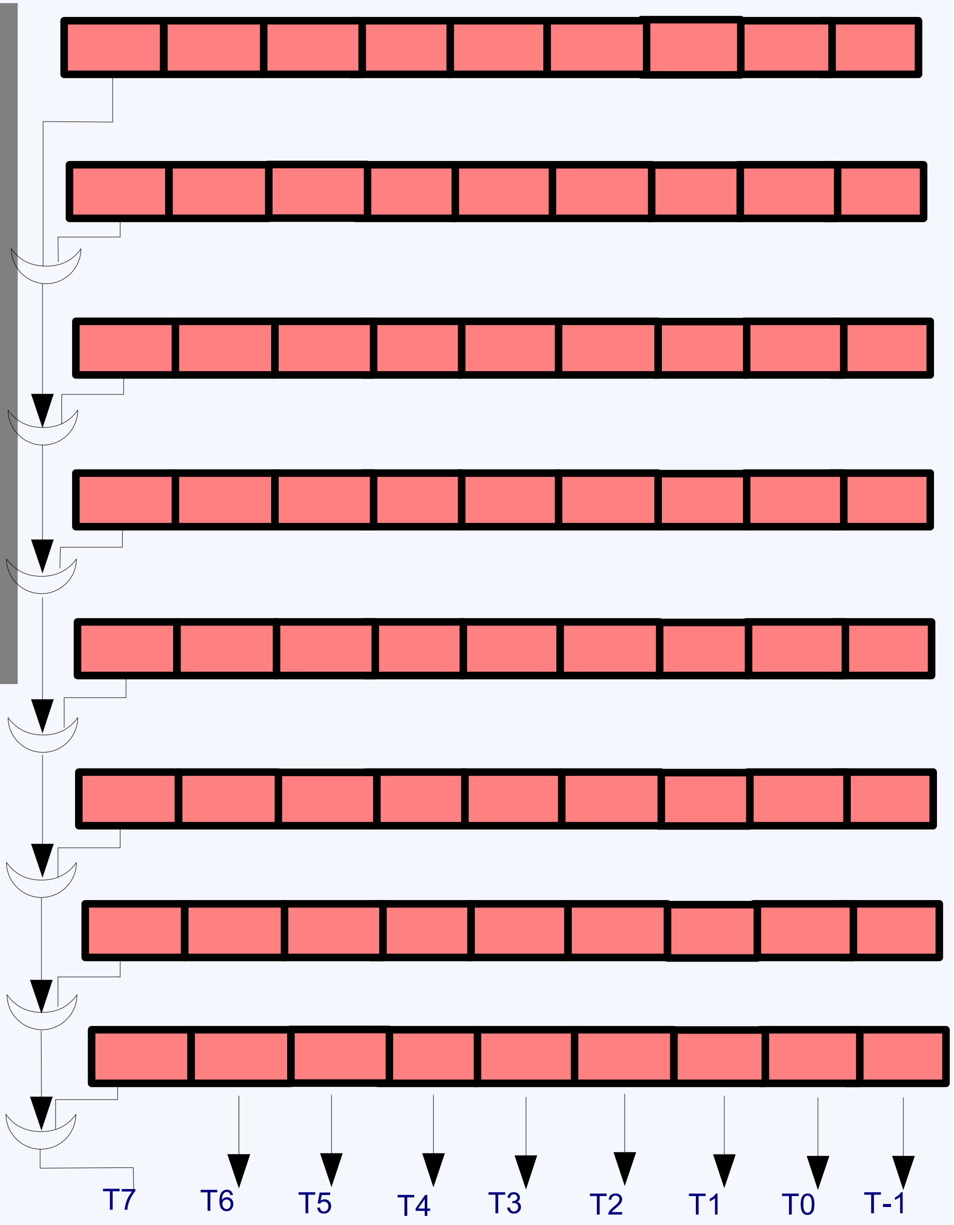


Groups of Shift Registers

Split chip into several phi-regions: here 8 rows wide
Number of rows depends on the track angles you are interested in; 16 might be more interesting at LHC

Within each region, OR the SR-cells in all rows (vertically)

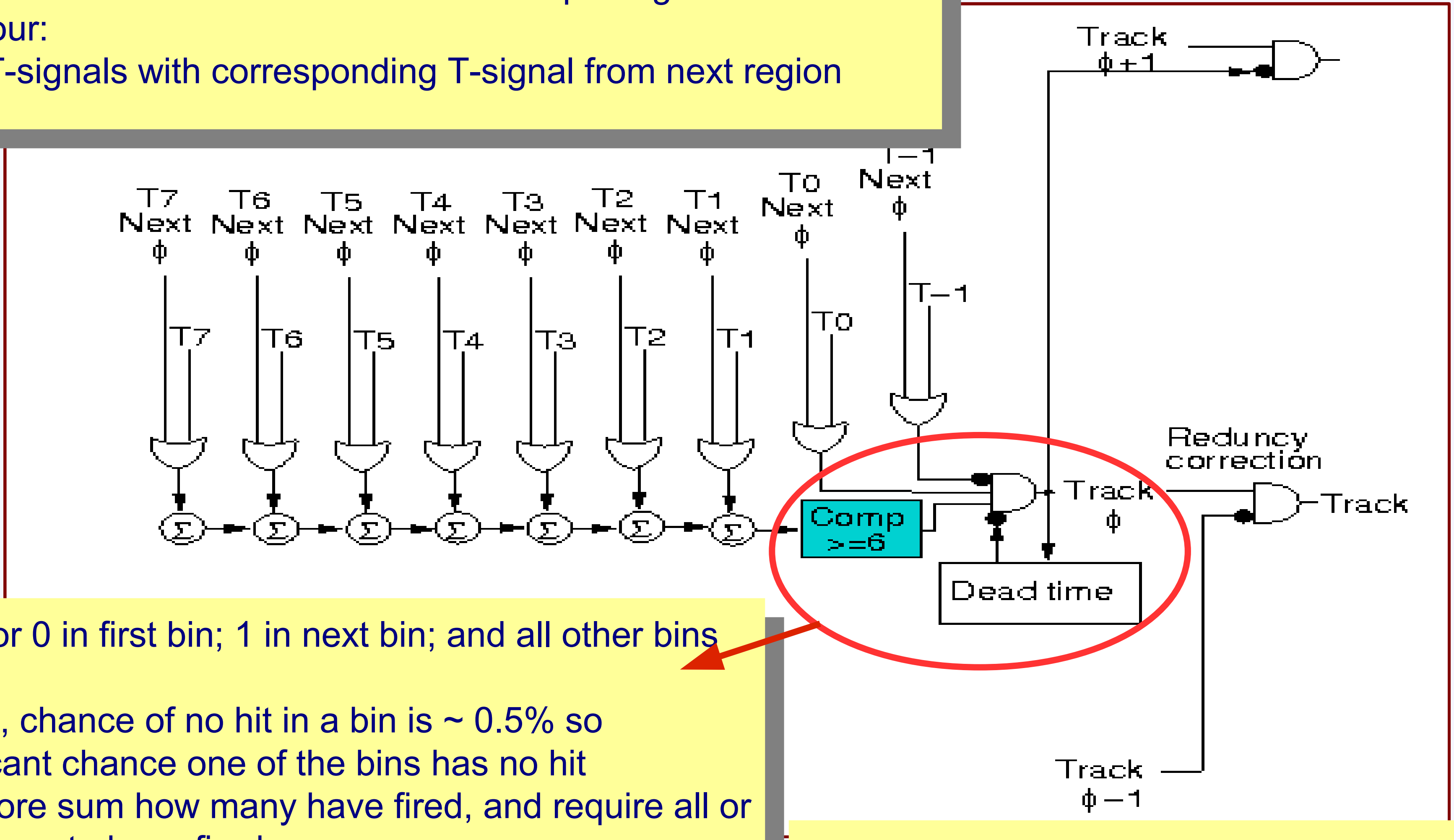
T-1 is the time bin before the track passed
T7 is the time bin in which the last electrons should arrive at the pixel readout chip



Track and T0 recognition

Must allow for tracks which cross from one phi region to the neighbour:

OR T-signals with corresponding T-signal from next region



Look for 0 in first bin; 1 in next bin; and all other bins to fire.

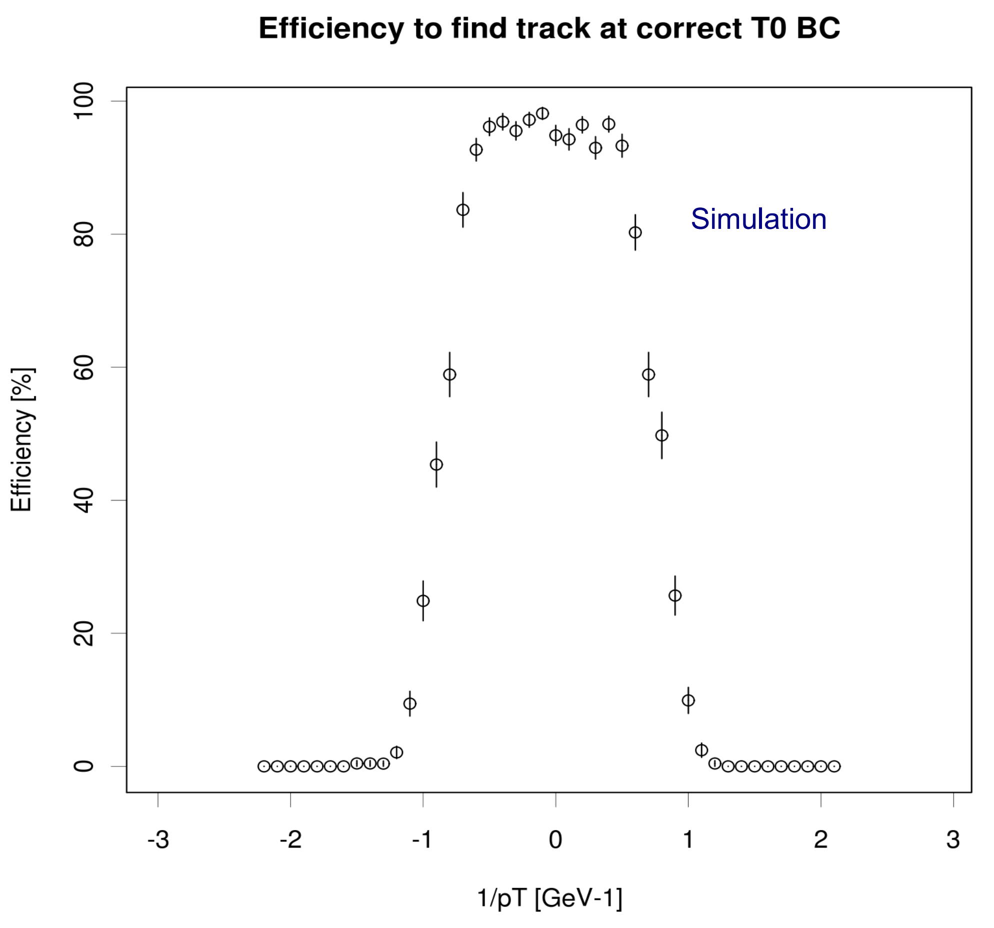
In fact, chance of no hit in a bin is ~ 0.5% so significant chance one of the bins has no hit

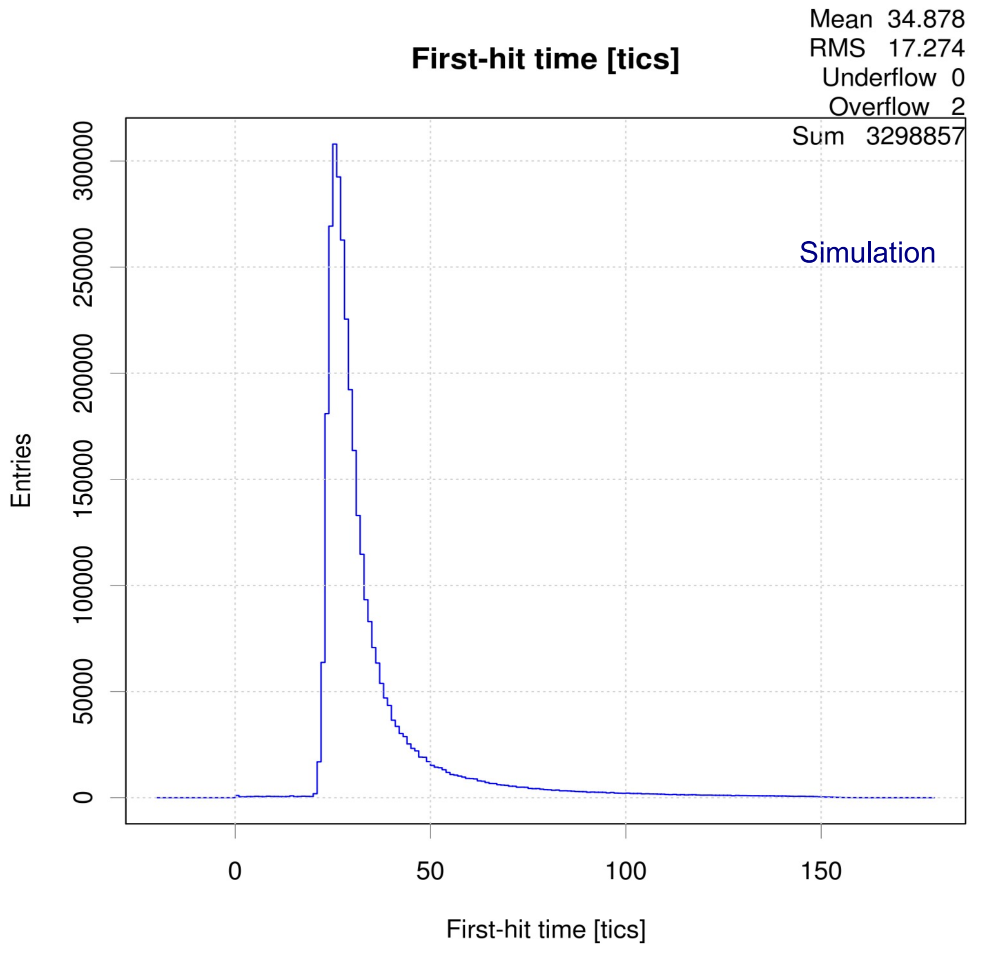
Therefore sum how many have fired, and require all or all but one to have fired.

Reduncy correction:

Veto triggers in neighbour phi-region to avoid 2 triggers from the same track

Performance of track arrival recognition and T0 determination



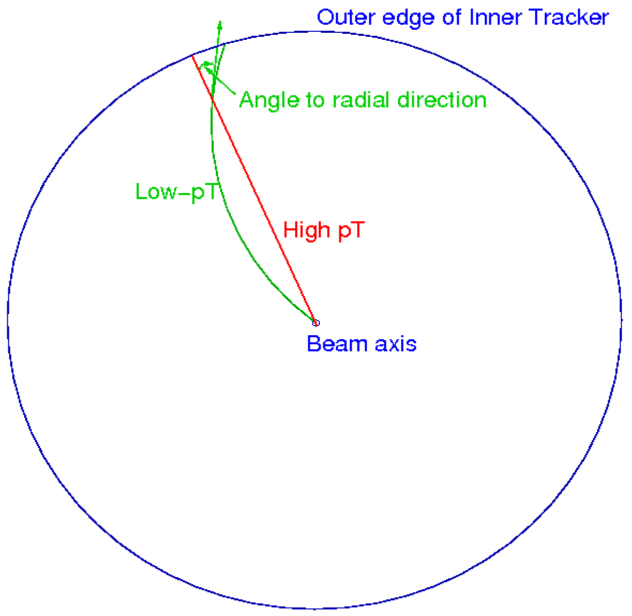


Approx. 96 % efficient at identifying track in correct BC for pT > 2 GeV/c
Use two layers for high efficiency

Time resolution:
FWHM = 8 bins x25/16 = 13 ns
sigma ~ 5 ns (ignoring tail)
(or: 25/sqrt(12) ~ 8ns)

Momentum measurement using cluster width

- Bring inner trackers into the L1 trigger with high-momentum track selection
- L1GasPix sends out BC, track position, and pT information for off-detector trigger processors to analyse and make L1 trigger decision
- Similar to proposals with silicon detectors, but:
  - In place of correlator-chips and data-buses transfering hit information from one silicon detector to another, use drift of electrons to transfer the information
  - Large drift gap gives good resolution up to higher pT
  - If silicon strip detectors are used for the trigger, the strips must be parallel and you lose 2nd coordinate precision - no track angle to magnetic field axis
    - Gas pixel detector can give good angular and second coordinate precision
    - Angle to magnetic field can be used to select tracks from primary vertex
  - No need for large off-detector array of contents-addressable memory for track pattern recognition from all silicon layers



Rates

Track rates at outer radius are not so high even at HL-LHC:
~0.25 MHz/cm^2 (200 pile-up)

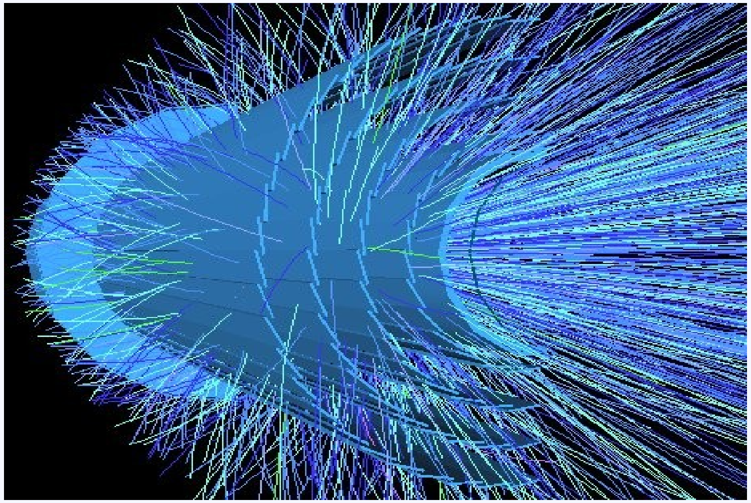
Drops very rapidly with p_T

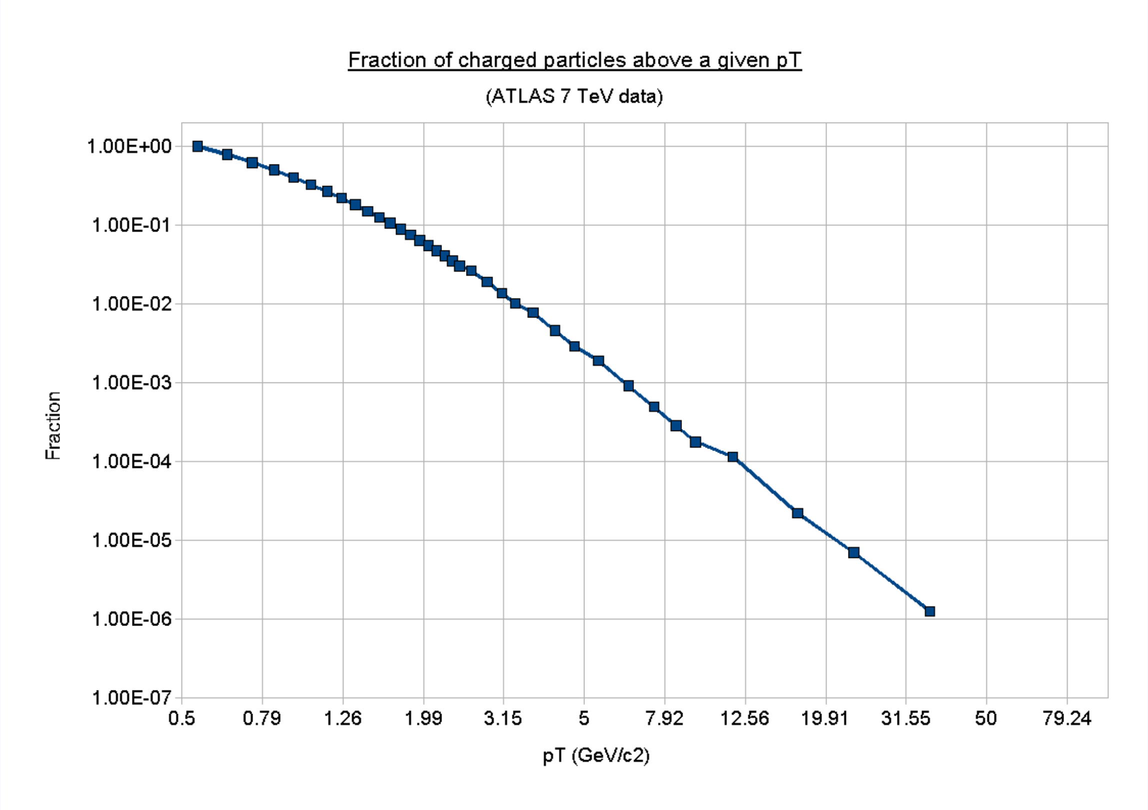
Factor 100 at 3 GeV/c: 2.5 kHz/cm^2

Factor 10^5 at 20 GeV/c --> 1 MHz total tracker rate

Jets: Several cm between tracks

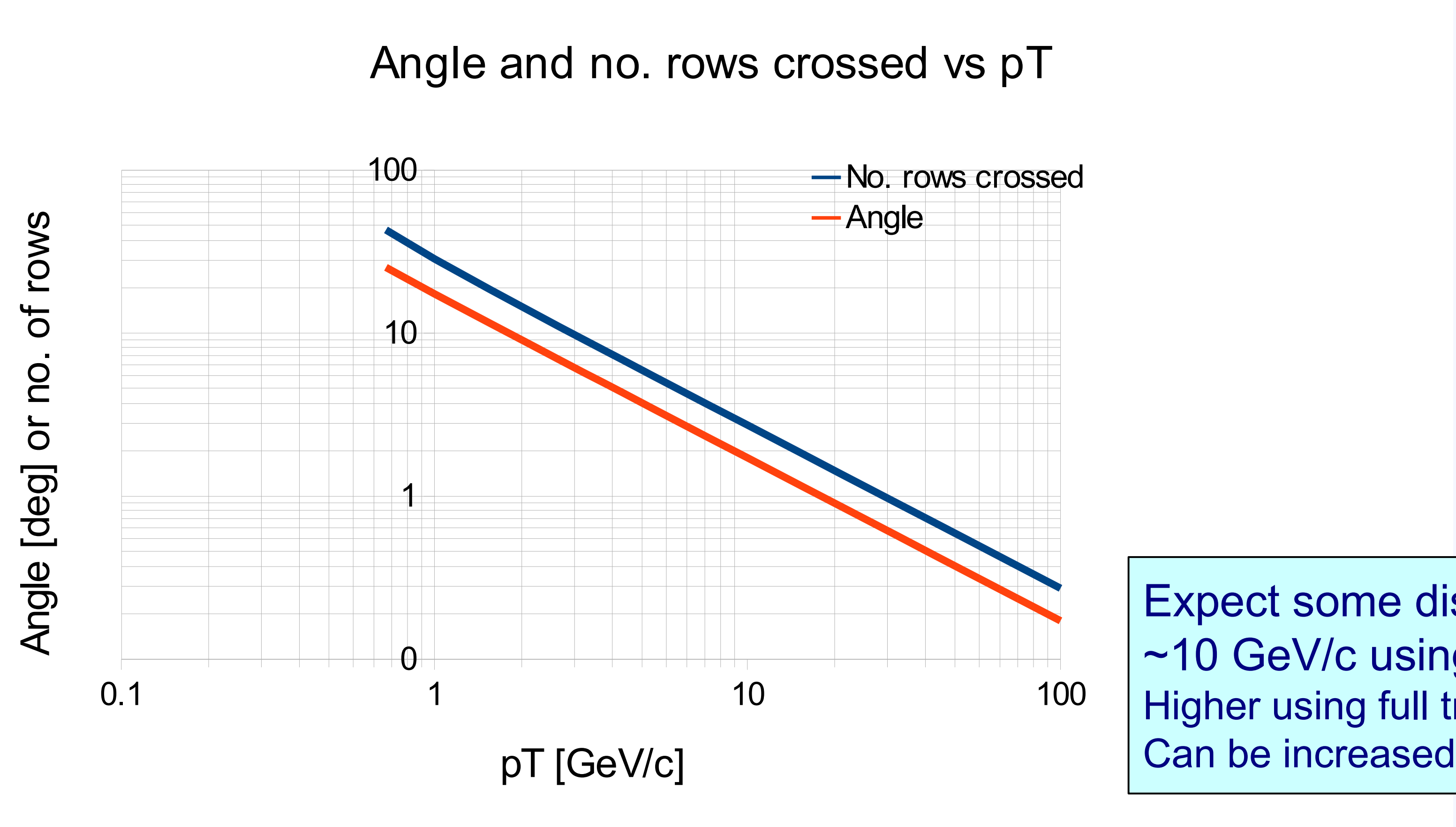
p_T < 300 MeV/c curl up and don't reach the outer layers





Fast momentum measurement from cluster width

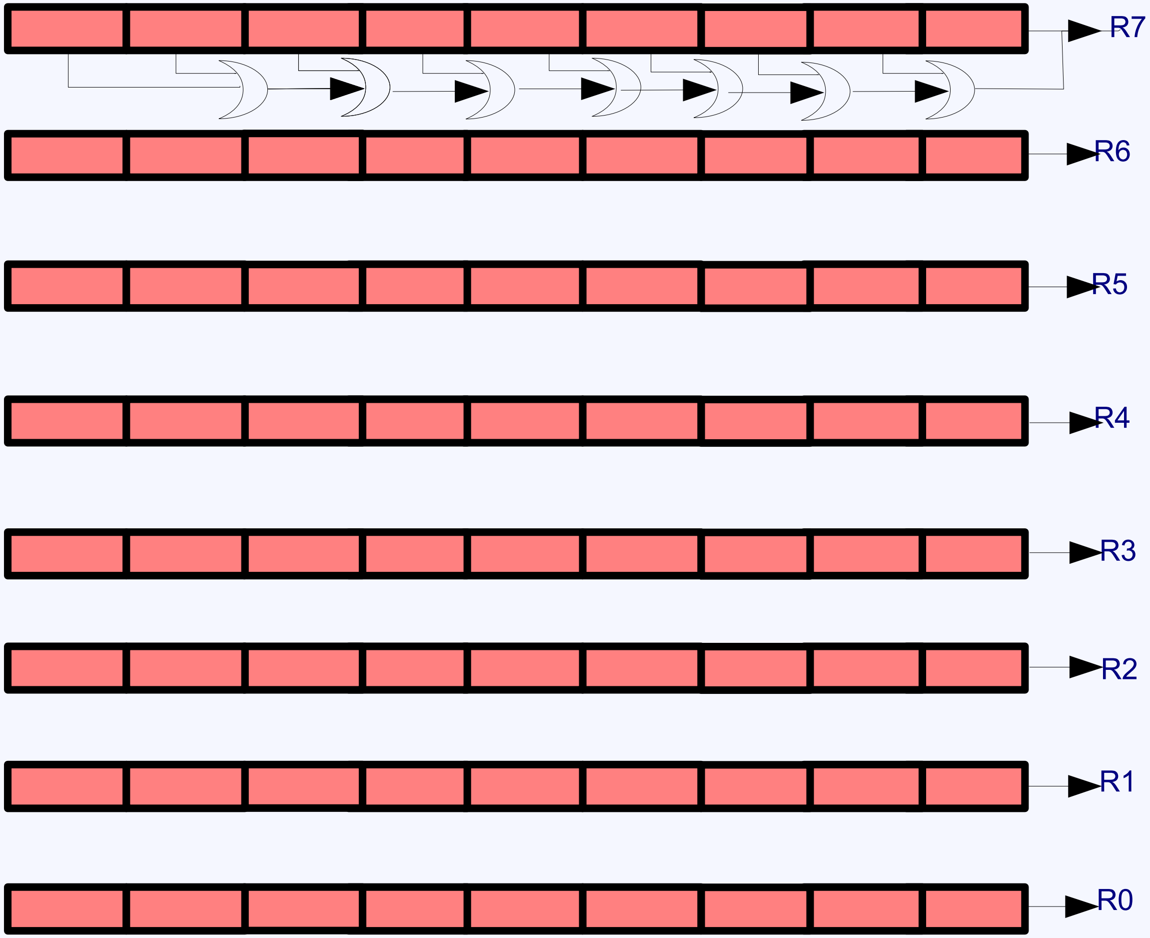
Conceptually:
Project hits onto momentum-analysing direction (rows)
Gives a cluster of hits with width correlated with 1/pT



Expect some discrimination up to ~10 GeV/c using cluster width
Higher using full track-angle information
Can be increased with larger drift gap

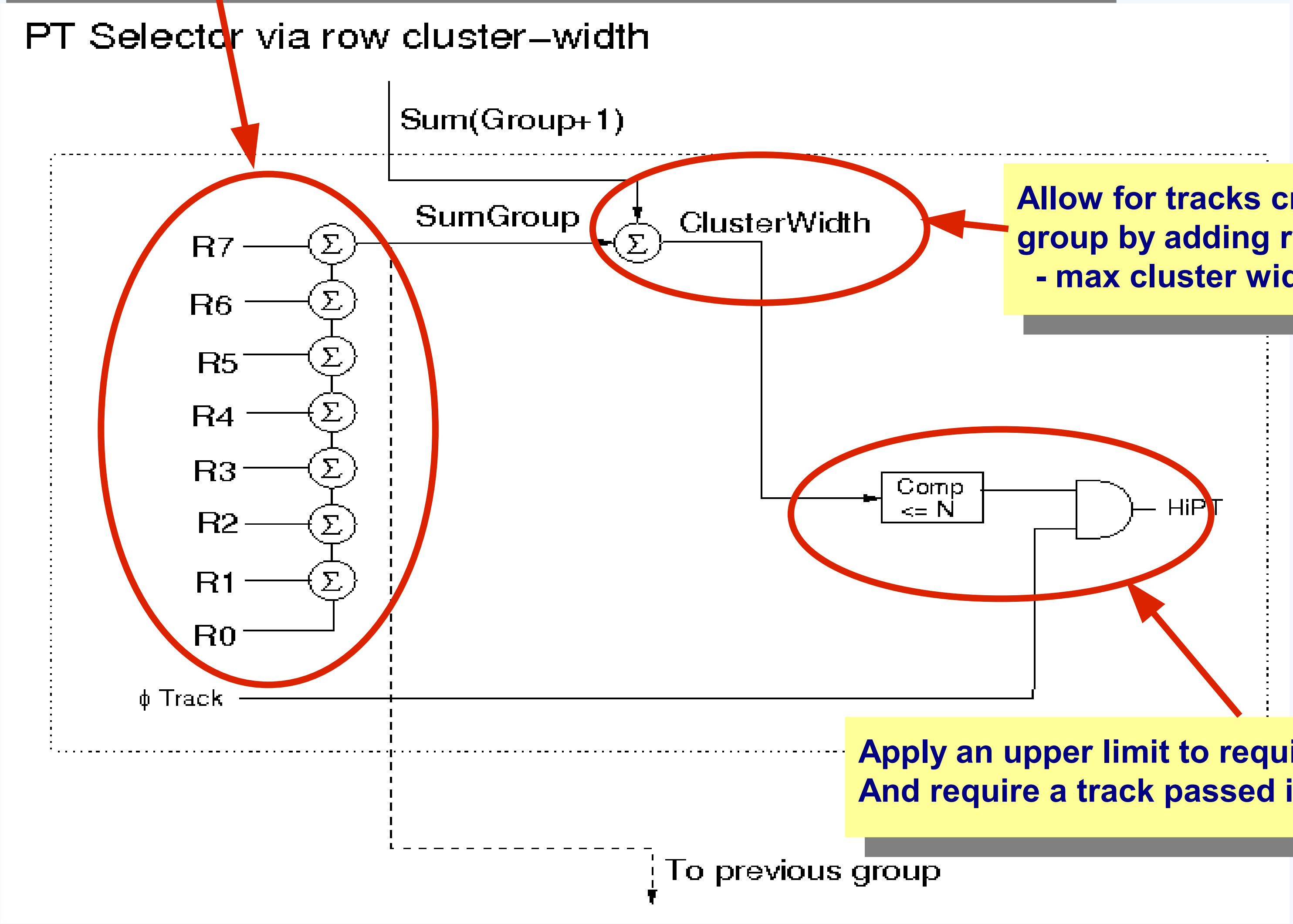
Re-use of shift registers row-wise

Use same SR as for T0, but now OR all times together within a row
Produce Rn signals indicating which rows had a hit during the last maximum drift time period



Cluster-width selection

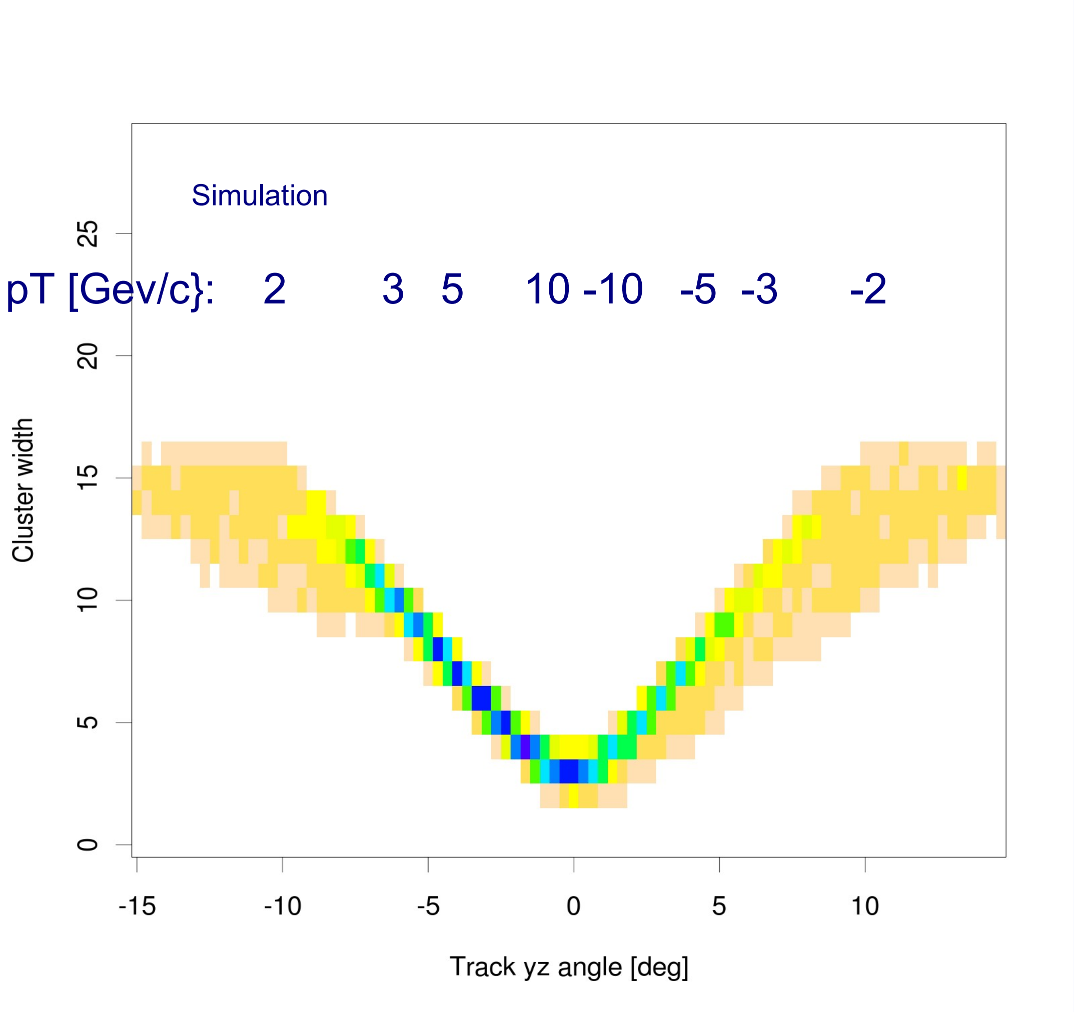
Count number of rows within a group with a hit in relevant time range



Allow for tracks crossing to neighbour group by adding rows in neighbour group
- max cluster width 16

Apply an upper limit to require high-pT tracks
And require a track passed in this BC

Cluster-width performance



Max measured is 16, i.e. twice the group width
Increasing the groupwidth to say 16 would halve the pT-threshold for track recognition

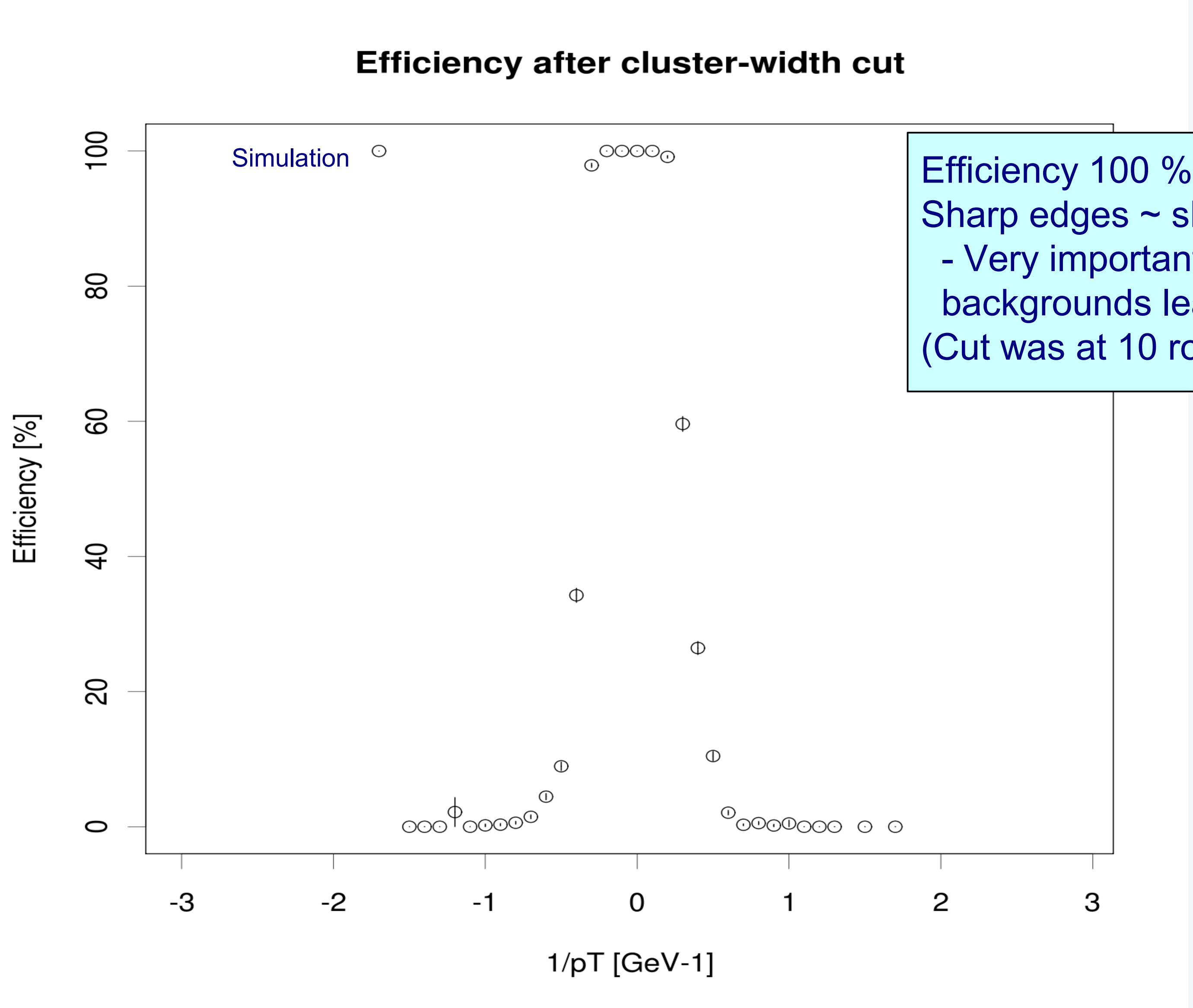
A higher threshold can then be recovered with a cluster width cut

This is more easily programmable on the chip than trying to alter the group width

Asymmetry for +ve and -ve charged tracks is due to ordering of groups
- needs further study

Some discrimination up to 3 deg = 7 GeV/c

Cluster-width efficiency



Efficiency 100 % in central region
Sharp edges ~ sharp threshold
- Very important for avoiding low-pT backgrounds leaking through

(Cut was at 10 rows hit)

Fast fits to track parameters

- Having reduced the trigger rate very substantially, you can now read out all hits in the relevant row and time region
- Can imagine a local FPGA serving several pixel chips processing these hits
- Fit straight line using integer arithmetic
- Calculate track x, y, theta, phi and quality of fit ("chi-sq")
- Send this data off-detector for high precision trigger data
  - For some applications e.g. beam monitoring this may be precise enough
  - For LHC triggers, combine this much-reduced data with other detector elements to form an L1 trigger
  - Then read-out all hits from tracks in this BC, for maximum off-line performance

Fitting tracks

When a high-pT track has been found with its T0, read-out all hit tdc's in the relevant phi-region

Do an unweighted linear regression in η and ϕ separately

- all integer arithmetic
- make various sums of tdc's, their row numbers, and columns
- combine these to get chi-sq and the coefficients in:

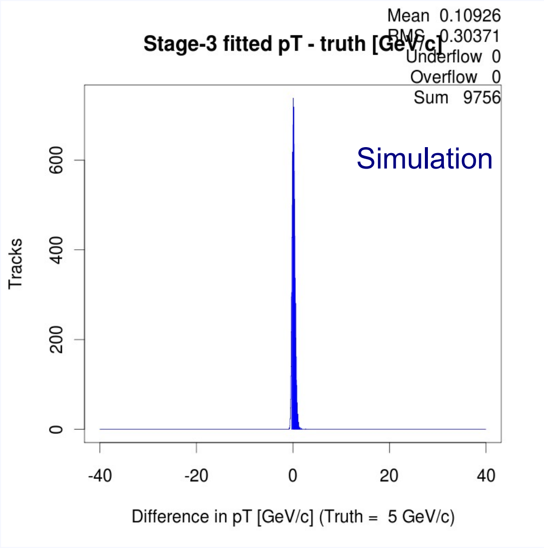
$x = a_x + b_x z$ (η direction; z-vertex pointing)

$y = a_y + b_y z$ (ϕ direction; momentum analysing)

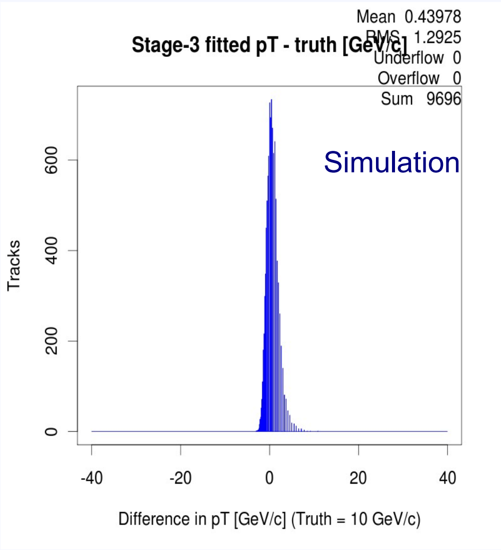
Choose units to avoid scaling:
Length units: pixel sizes
z-coordinate: in units of drift velocity

Apply cuts on chi-sq, b_y (for p_T), b_x (vertex region in z)
==> Well-measured high-pT track
Send track position (ax, ay), track direction (bx, by), and chi-sq values off-detector.

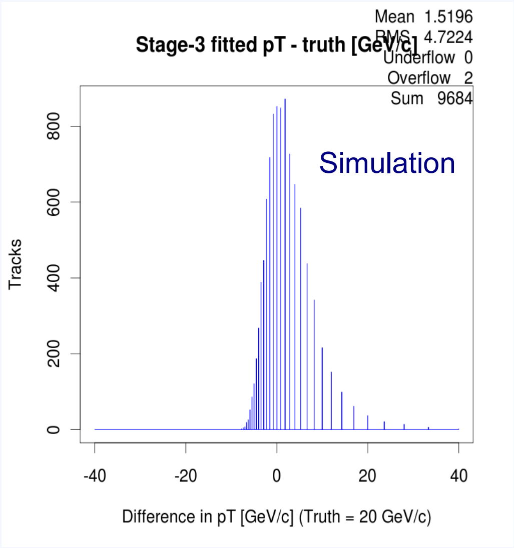
Track fitting performance



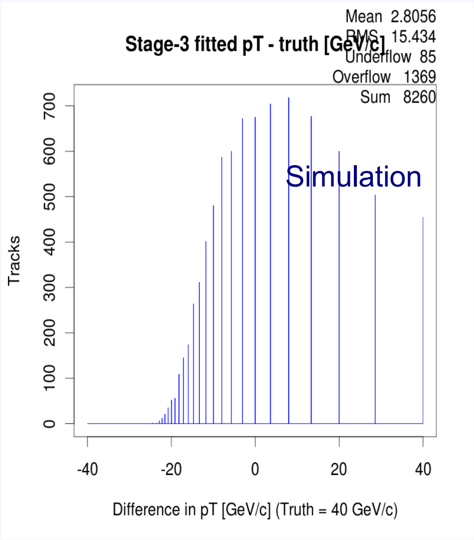
5 GeV/c
rms resolution 6 %



10 GeV/c
rms resolution 13 %



20 GeV/c
rms resolution 23 %



40 GeV/c
rms resolution 40 %

Resolution evolution with pT:

- For 10 mm drift gap at 1 m
- For 40 GeV, you need thicker drift gap or combine two layers off-detector

These results are from earlier studies with slightly different arrangment and geometry; however, do not expect much change

Angular resolution in eta direction depends on pixel size, but extrapolation could give ~1 mm precision on z-vertex
Could be important in a high-pile-up environment

Summary

- Intelligence in the front-end of a gaseous pixel detector can have major benefits:
  - Data-driven readout
  - Data reduction
  - Data-driven L1 Track Triggers at LHC
- Simulation shows FE chip can recognise particle passage with 8 ns precision without external input
- Simulation shows a FE chip can very quickly (~max. drift time of 200 ns) apply a momentum threshold and have an approximate momentum estimate ready for readout
- A further stage can be imagined with trigger selection up to 20 GeV/c in an ATLAS-like inner tracker using track fits