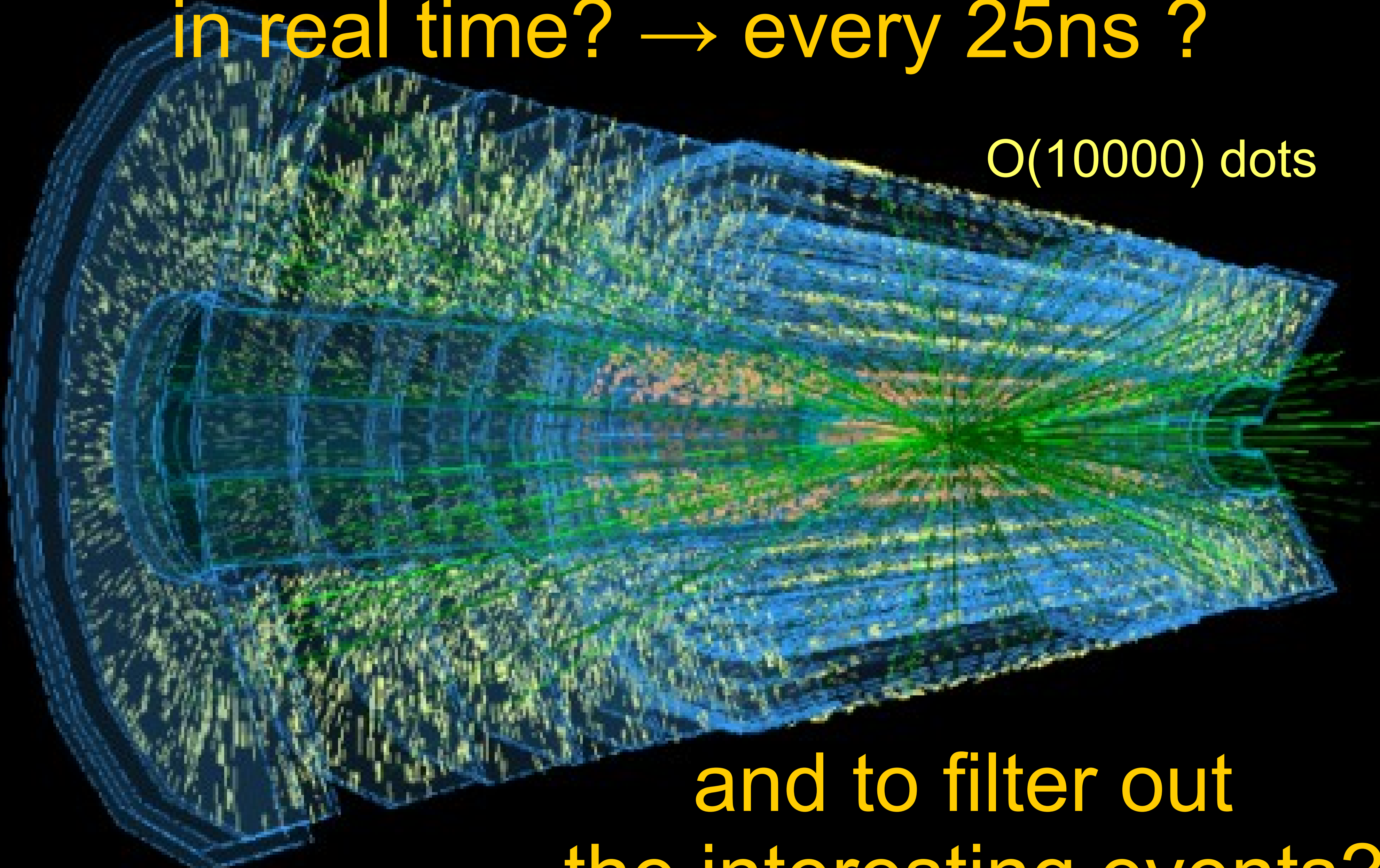
Potential of Monolithic CMOS Pixel Detectors for Future Track Triggers

André Schöning
Heidelberg University
Physics Institute

Connecting the Dots 2017
Orsay, Paris
6. March 2017

Is it possible to reconstruct all tracks in real time? → every 25ns ?



and to filter out the interesting events?

Overview

Part I

- motivation for track triggers
- track trigger methodologies
- requirements for future track triggers (upgraded LHC and beyond (FCC))

Part II

- monolithic CMOS pixel detector technologies

Part III

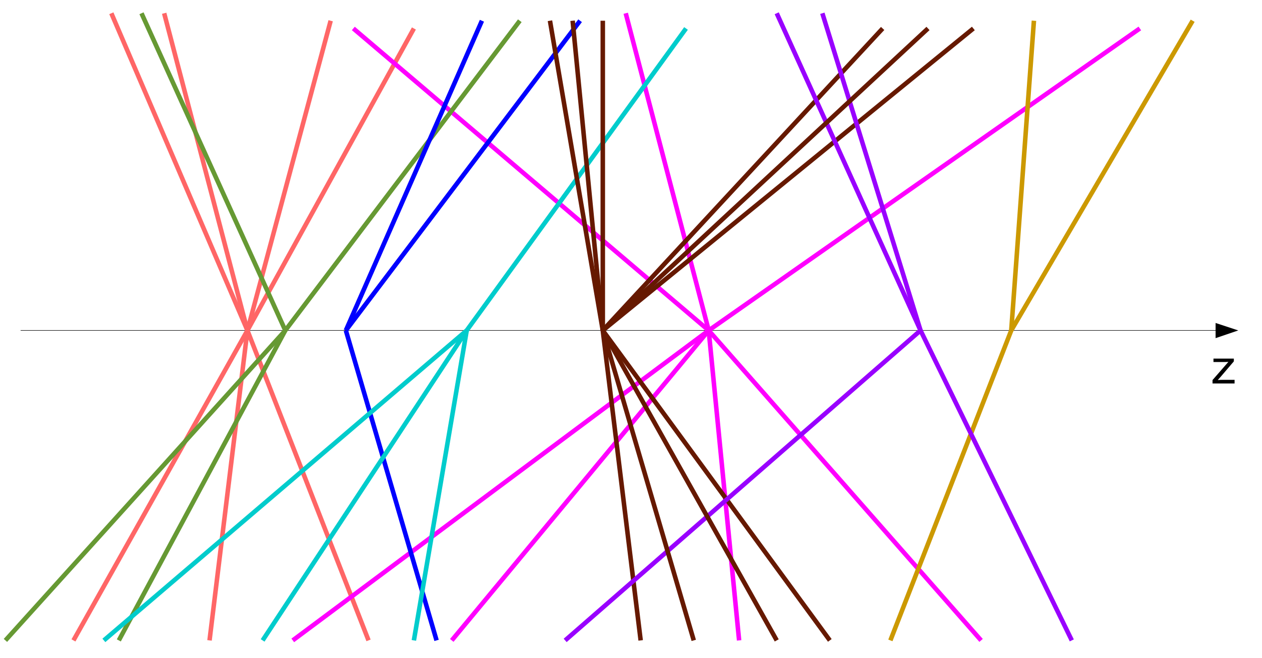
- track trigger designs based on monolithic pixel detectors
- simulation results

Conclusion

Motivation for Track Triggers @ hadron colliders with high pileup

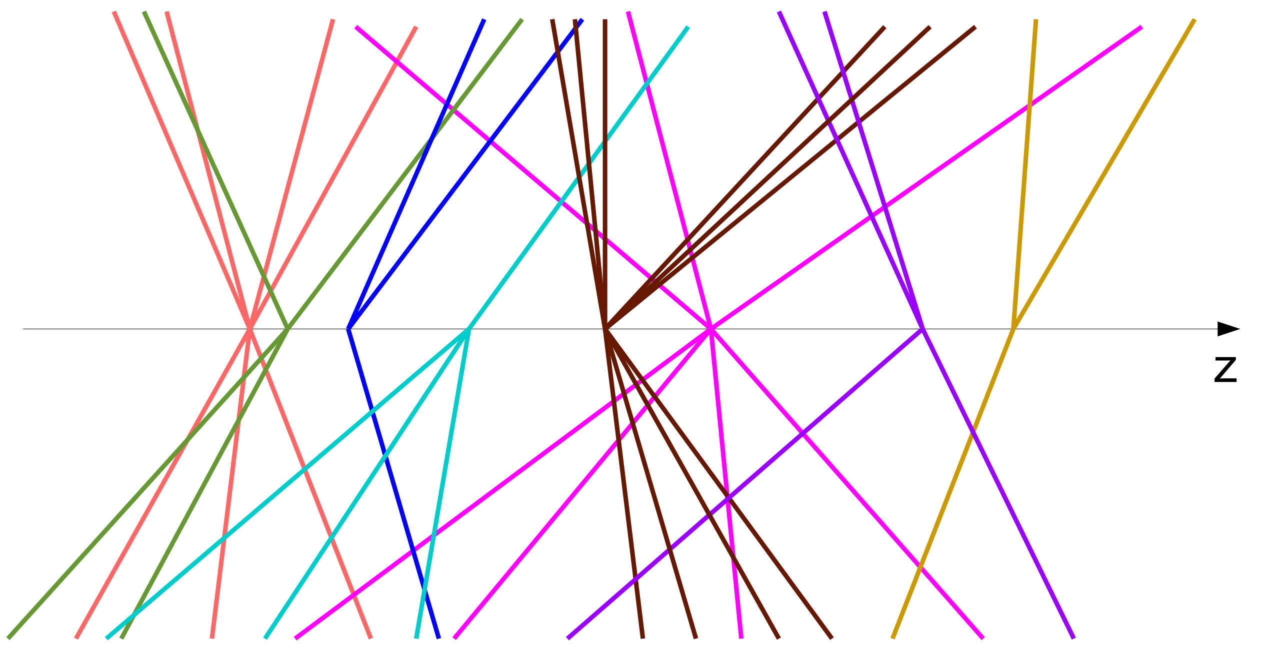
- Calorimeter triggers: → **energy** distribution and rough particle ID
- Muon triggers: → **muon** identification and momentum
- Track triggers: → **momentum, origin** and **separation** of charged particles

event pileup:



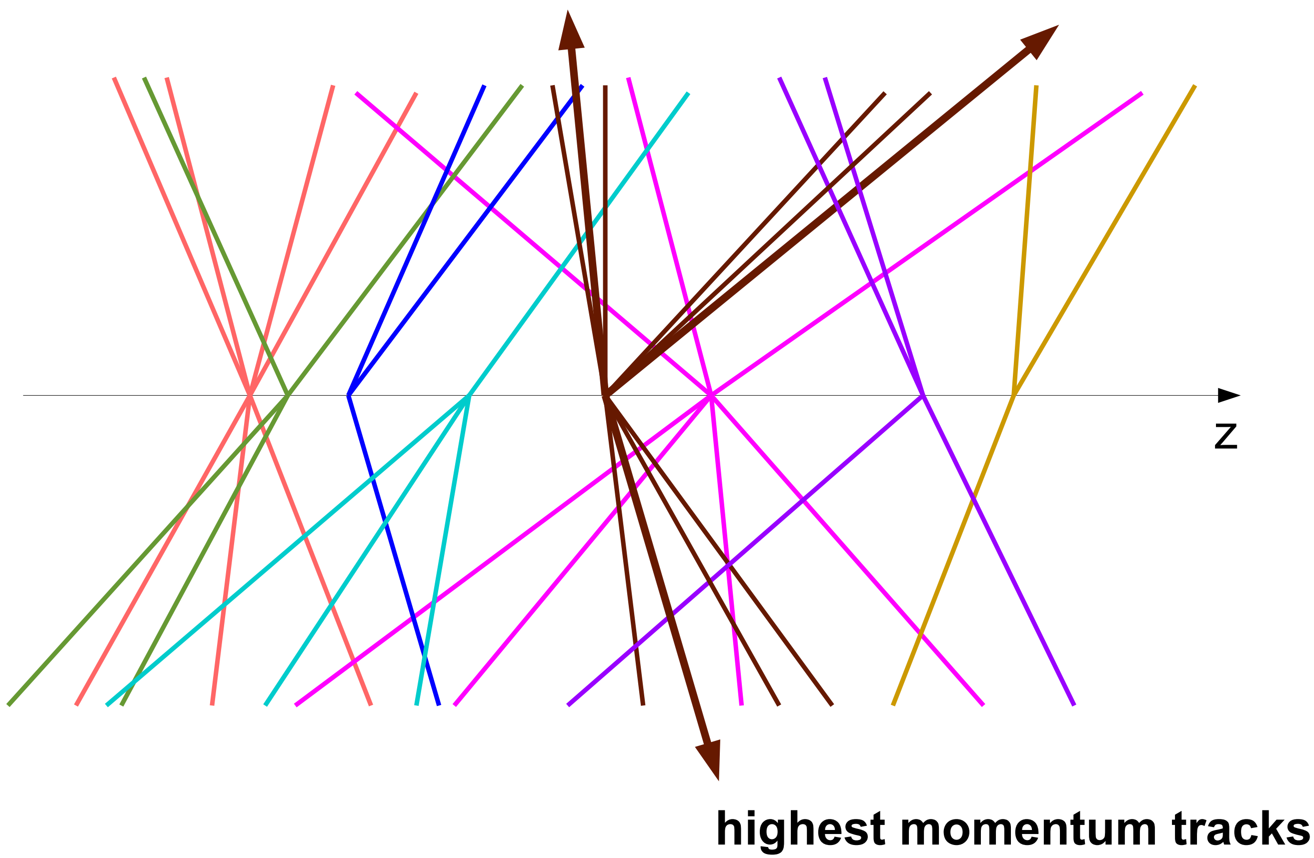
Motivation for Track Triggers
@ hadron colliders with high pileup

- Mutijet-Track Trigger:



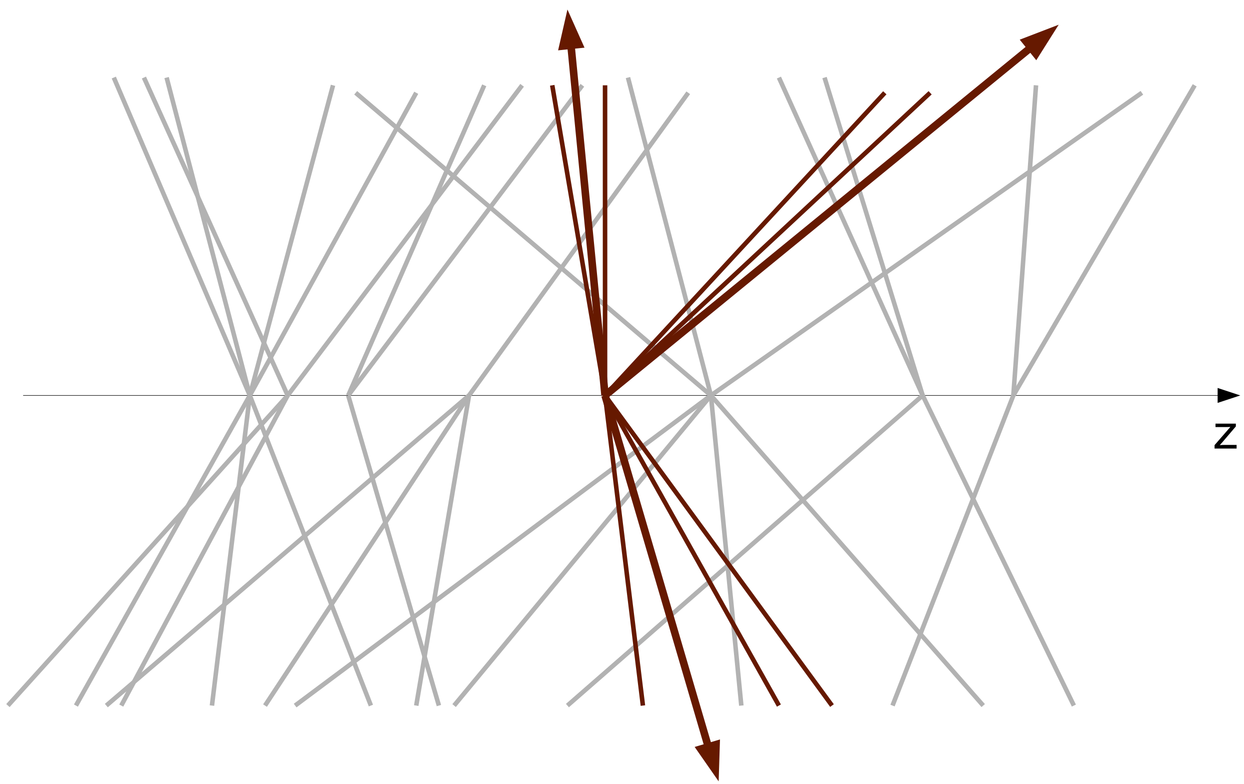
Motivation for Track Triggers
@ hadron colliders with high pileup

- Mutijet-Track Trigger:



Motivation for Track Triggers
@ hadron colliders with high pileup

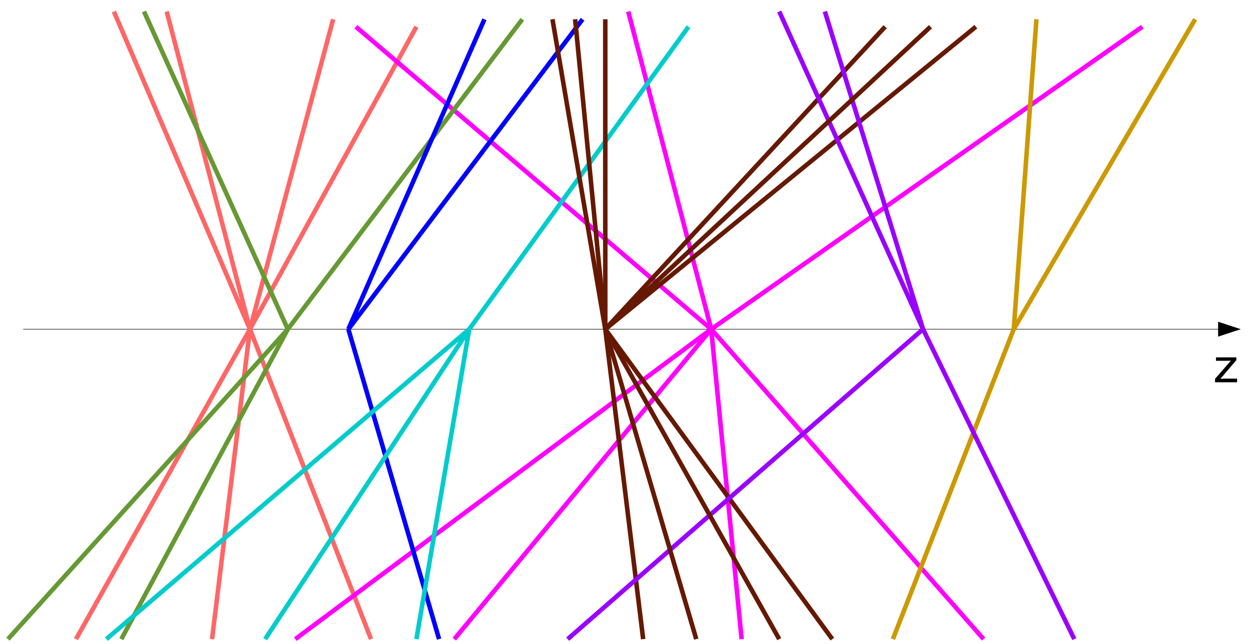
- Mutijet-Track Trigger:



→ Identification of multi-jet topologies

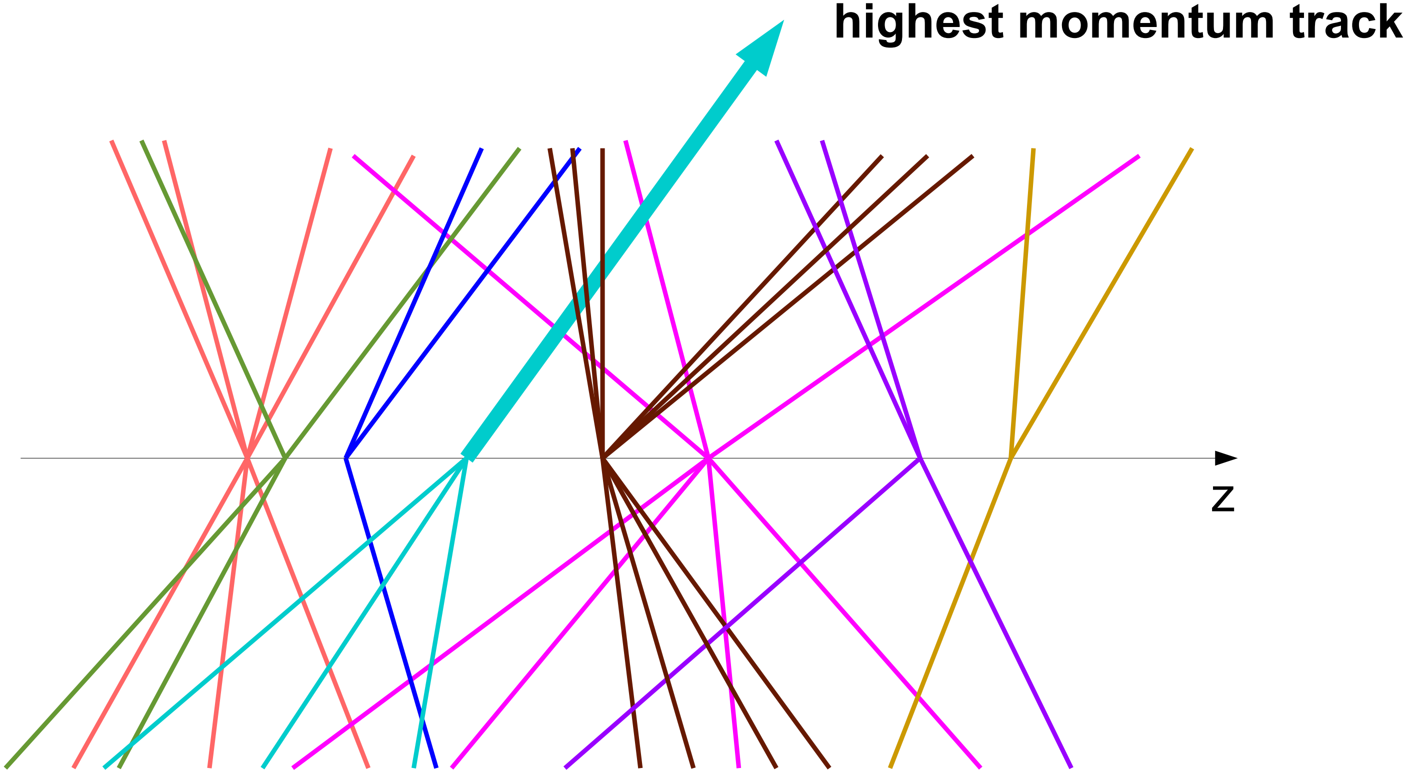
Motivation for Track Triggers
@ hadron colliders with high pileup

- Isolated high-momentum track trigger:



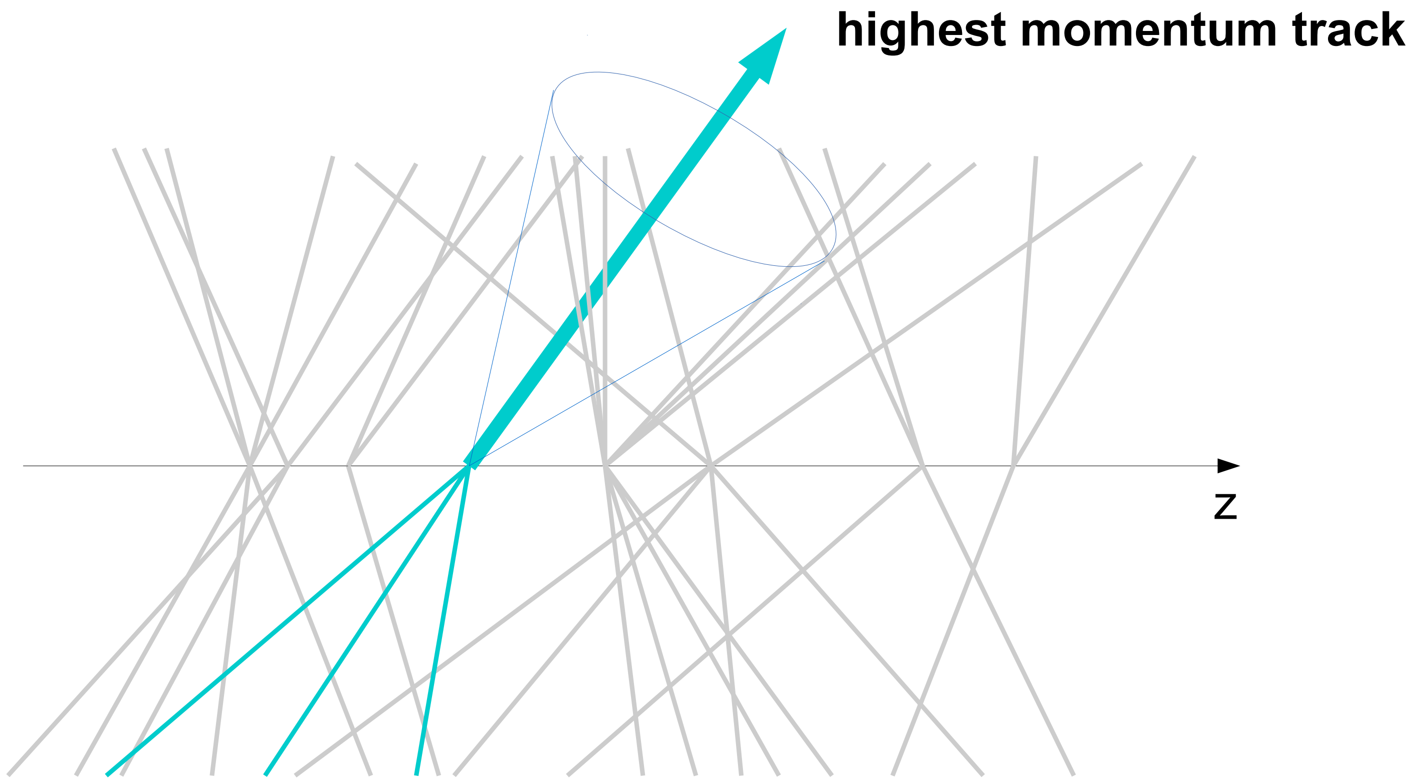
Motivation for Track Triggers
@ hadron colliders with high pileup

- Isolated high-momentum track trigger:



Motivation for Track Triggers
@ hadron colliders with high pileup

- Isolated high-momentum track trigger:



→ signature for high momentum e, μ, τ leptons
(electroweak processes)

Motivation for Track Triggers
@ hadron colliders with high pileup

track triggers can provide useful information about:

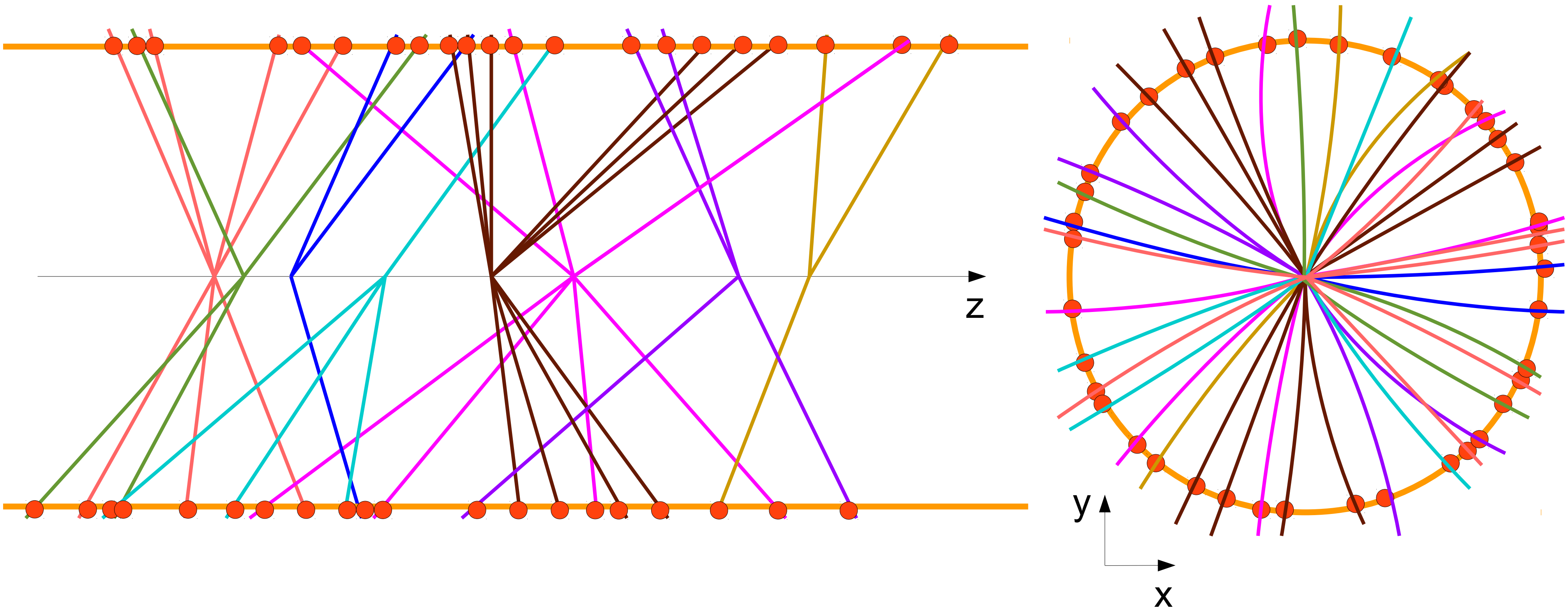
- particle momentum
- particle direction
- origin (primary vertex, secondary vertex)
- particle counting
- particle isolation (→ lepton identification)
- particle identification (in combination with other triggers)

→ **complementary to calo/muon triggers**
→ **improve selectivity of trigger in general**

Track Trigger Methodologies I

- Track counting:

  requires one tracking layer

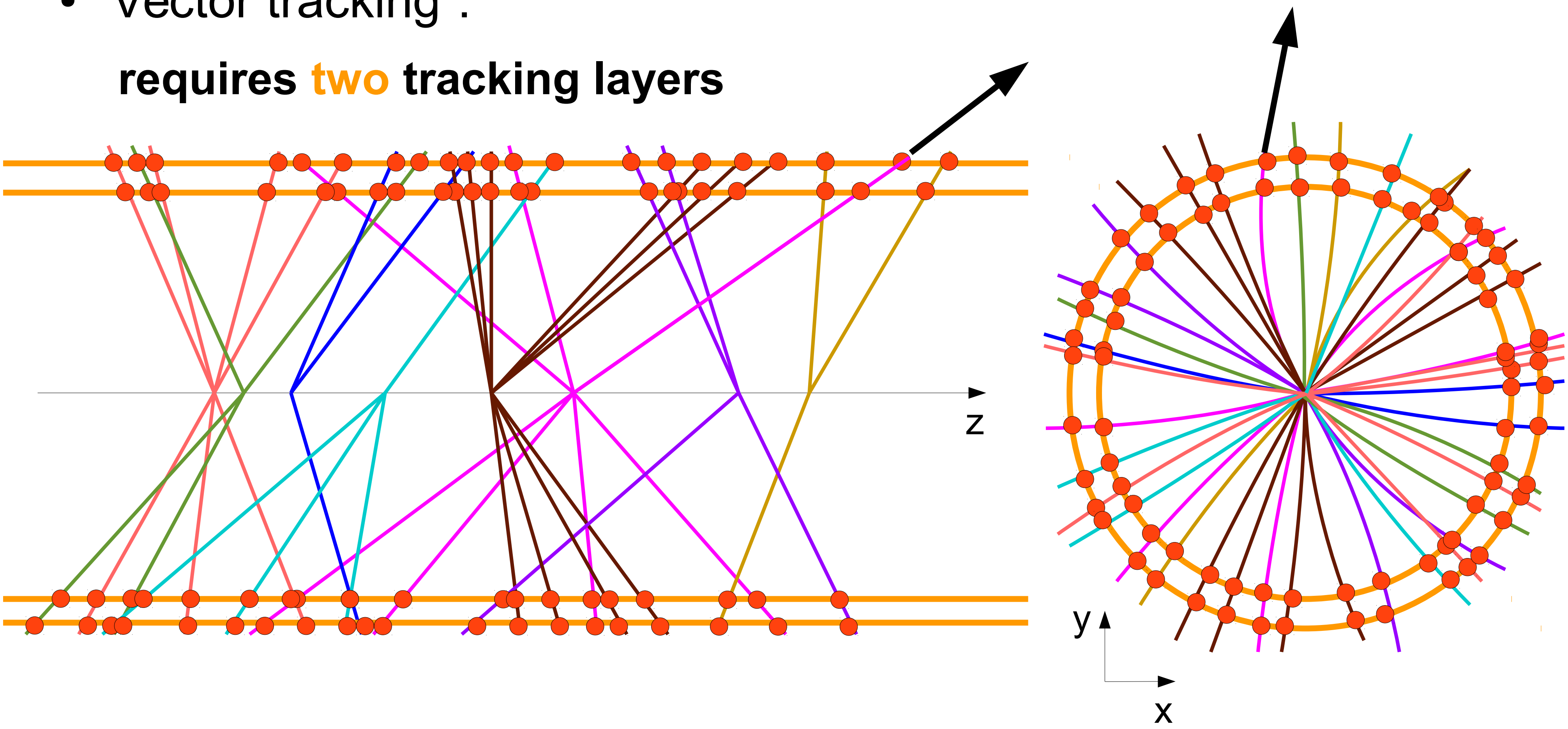


→ useless information for high pileup events (colliders)

Track Trigger Methodologies II

- “Vector tracking”:

  requires two tracking layers



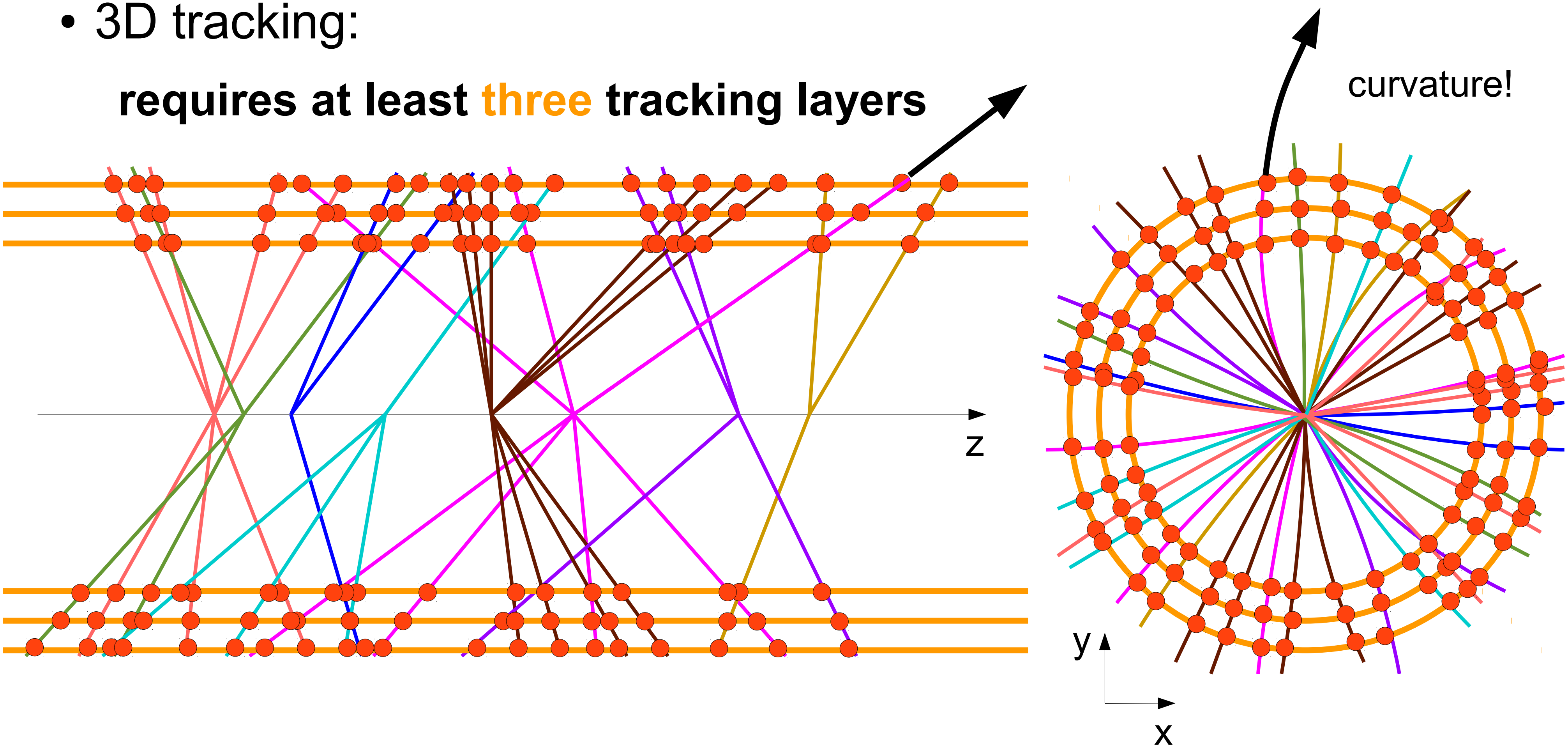
→ z-vertex reconstruction only possible with <u>two pixel layers</u>

→ momentum reconstruction only by applying <u>beam-line constraint</u>

Track Trigger Methodologies III

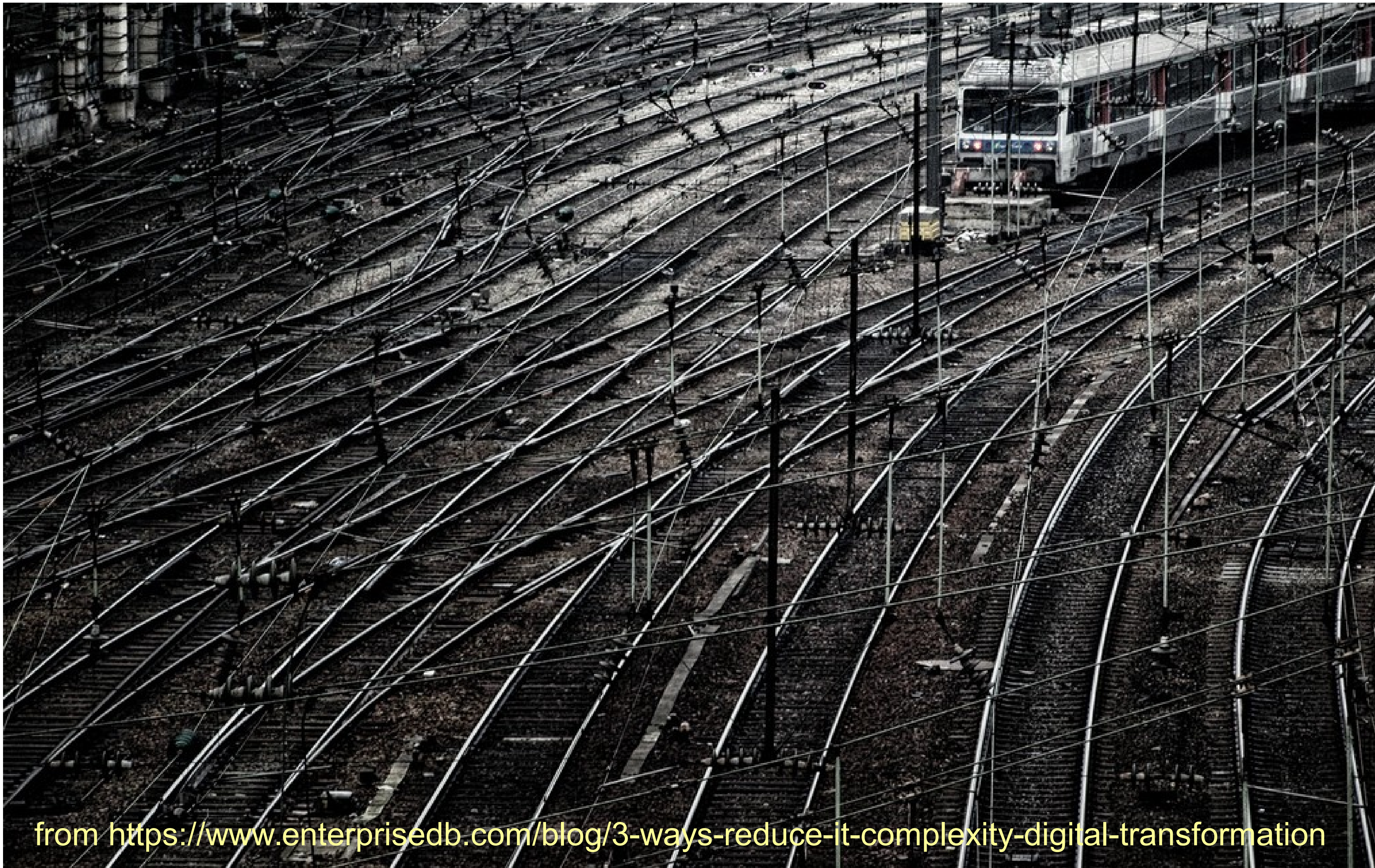
- 3D tracking:

requires at least three tracking layers

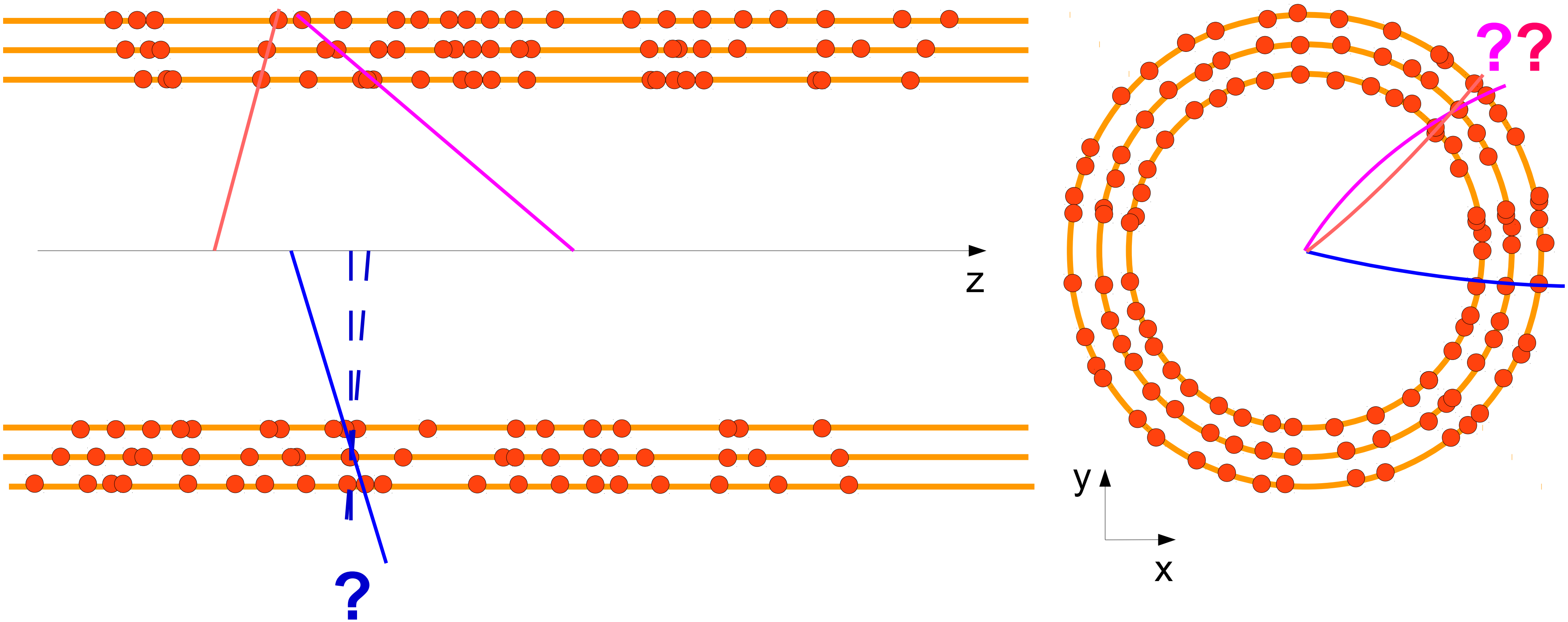


→ full track parameter determination with three pixel layers
(if multiple scattering is negligible)

The Track Trigger Enemies



Enemy I: Track Linking and Hit Confusion Problem



→ **hit ambiguities are best resolved in 3D (pixel)**

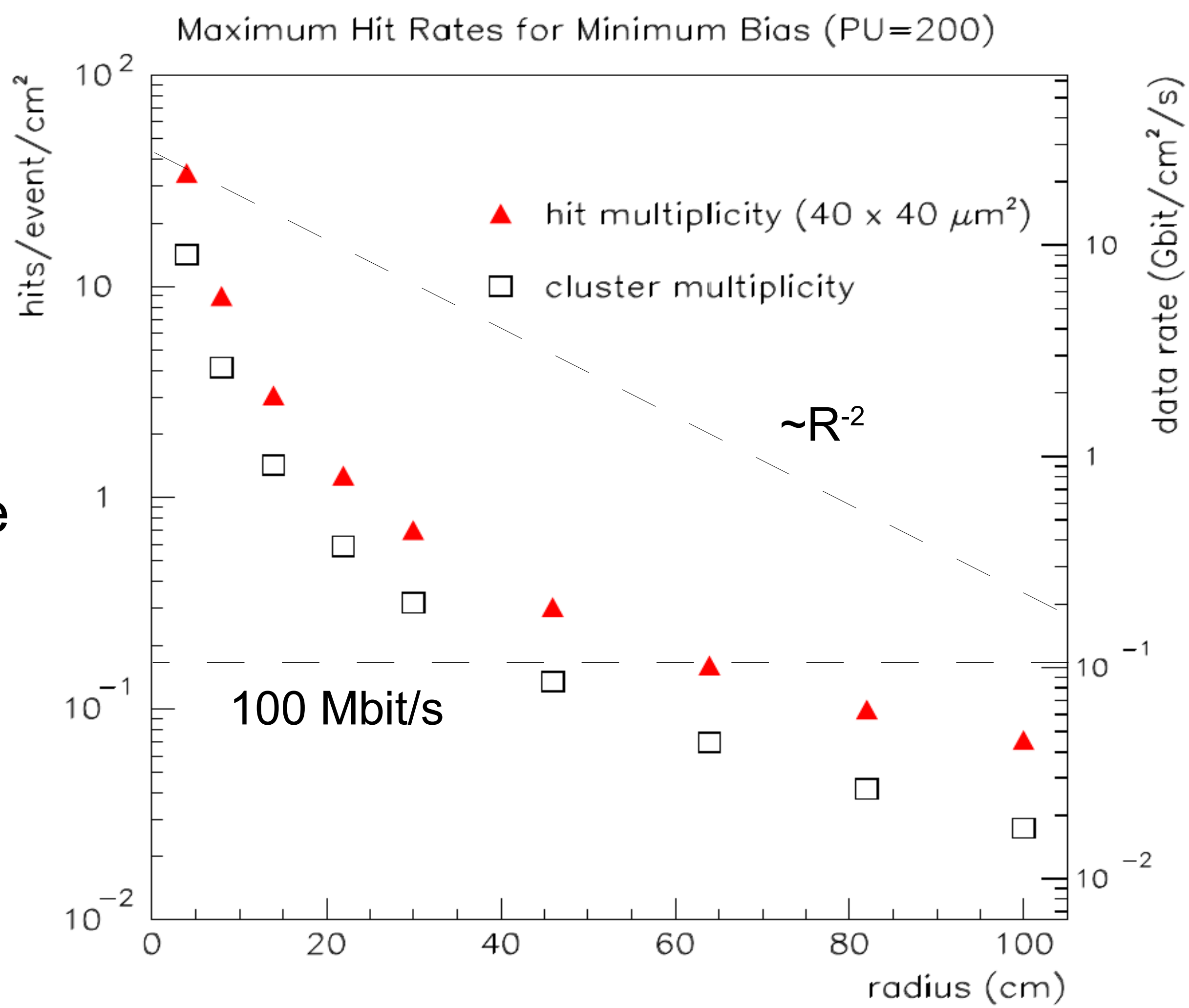
→ **pixel information simplifies track linking and improves purity!**

Enemy II: Hit Rates and Limited Readout Bandwidth

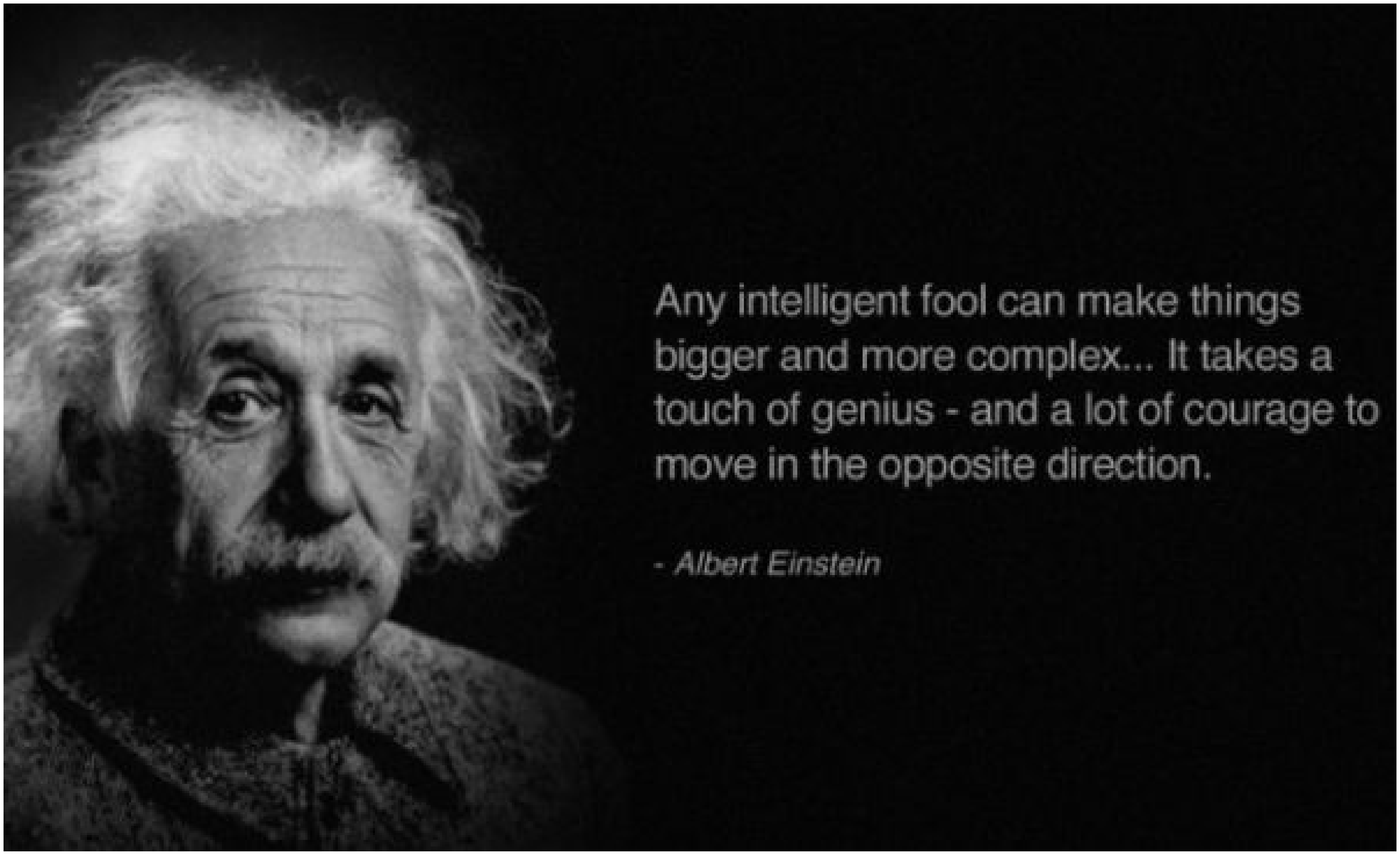
- rates in ATLAS detector for HL-LHC
- readout of **all hits** for every bunch crossing only feasible for large radii

➔ full tracking requires track trigger layers at large radii

→ **large sensitive areas**



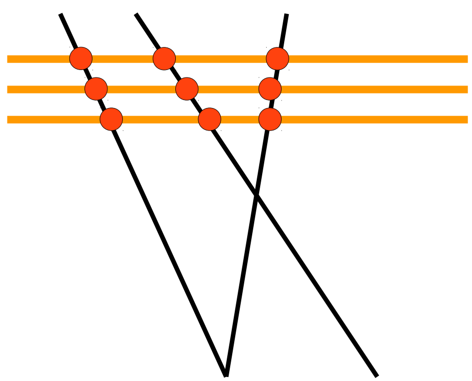
Enemy III: Complexity



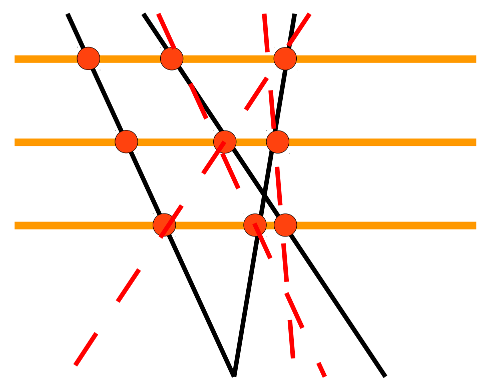
Enemy III: Complexity

For fast track triggers there is just no time performing complex operations:

- **local processing** preferred over global processing
- linearisations instead of non-linear problem solving
- use simple (stacked) geometries which reduce the hit confusion problem



no ambiguities



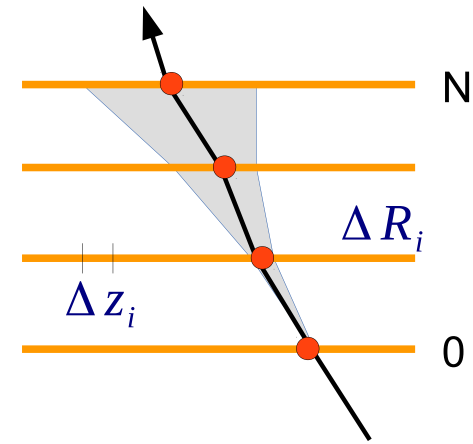
ambiguities

→ tracking detector design issue!

Enemy IV: Tracking Material

Tracks with momenta of p< O(10 GeV) are dominated by multiple scattering (MS) at LHC

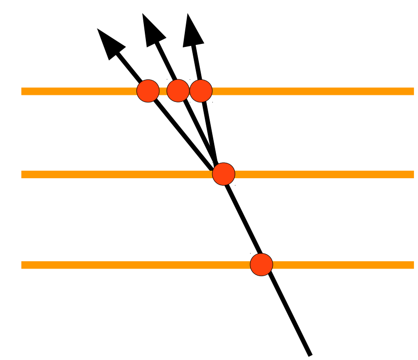
- adds additional complexity for track reconstruction
- increases significantly **phase space** of allowed patterns
- relevant for all methods of track reconstruction:
  - Kalman fitler
  - lookup techniques
  - associated memories (AM)
  - Hough trafo, conformal mapping



$$PS \propto \frac{1}{p^{(N-1)}} \left(\prod_{i=1}^{N-1} \frac{x_i}{X_{0,i}} \right)^{\frac{1}{2}} \prod_{i=0}^{N} \frac{\Delta R_i}{\Delta z_i}$$

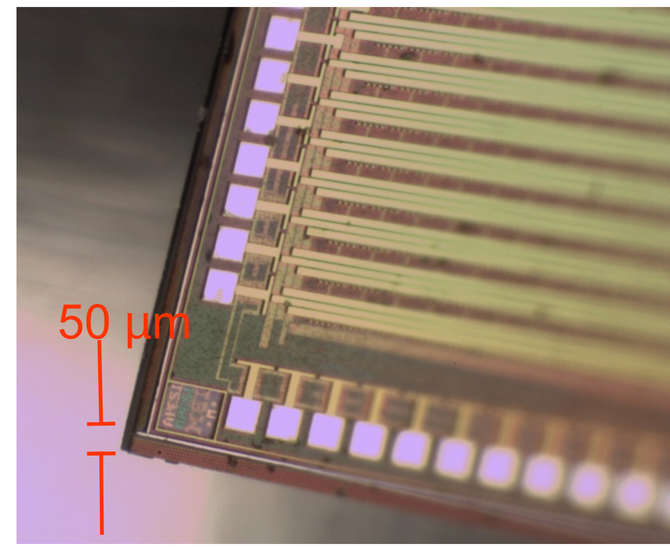
Material also increases the probability for

- electromagnetic interactions
- nuclear interactions
  - → secondary & tertiary particles



The Seven Requirements for Future Track Triggers

- highly granular pixel
  - → 3D tracking and vertexing
  - → reducing ambiguities
- little material
  - → reduces MS, secondary interactions and thus confusion problem
- good timing
  - → resolve bunch crossing
- high efficiency @ low noise
  - → fewer tracking layers
  - → reducing ambiguities
- fast readout capabilities
  - → high track rates
- radiation hardness
  - → high track rates
- affordable
  - → large sensitive areas



Mupix7
HV-CMOS AMS 180 nm

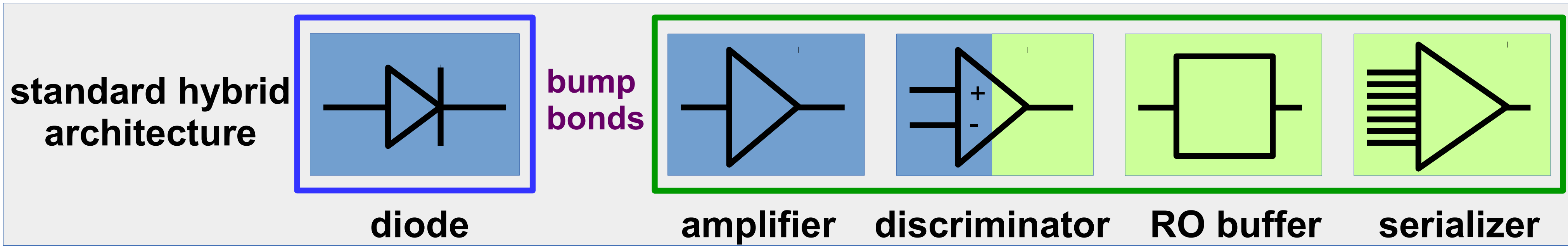
Part II

→ monolithic CMOS pixel detector technologies

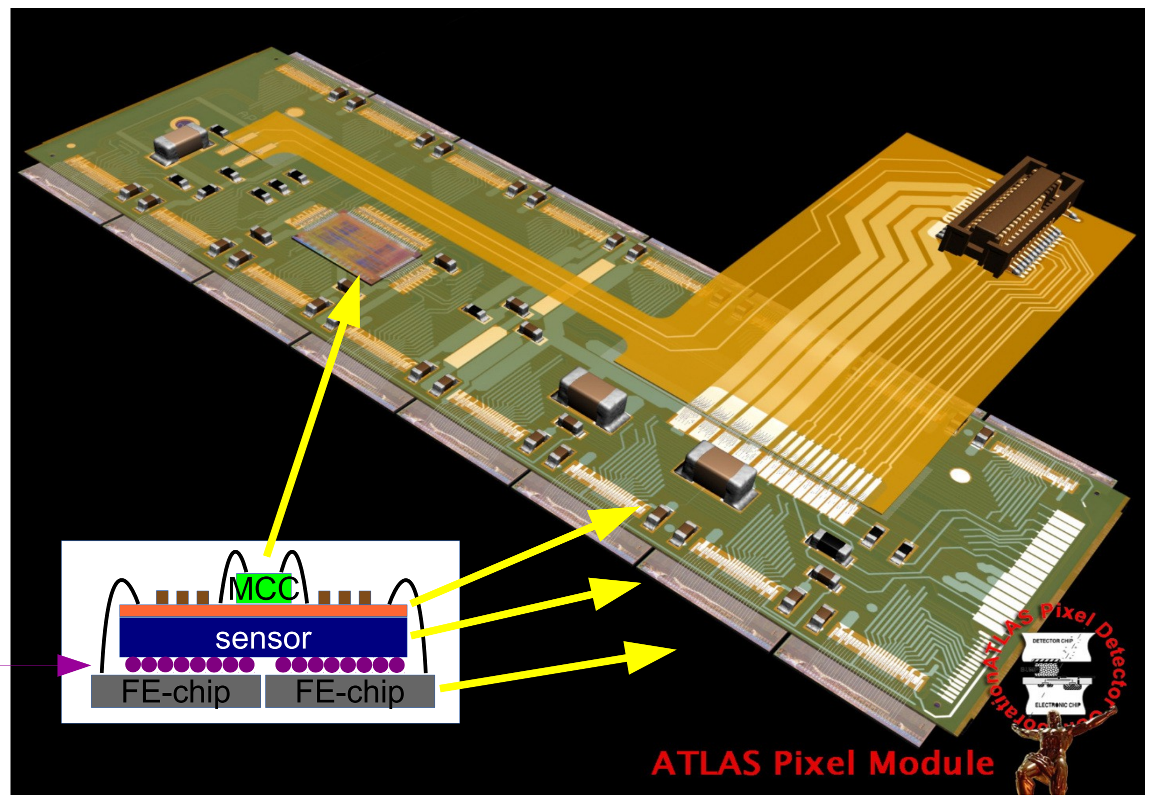
Pixel Readout Concepts

sensor

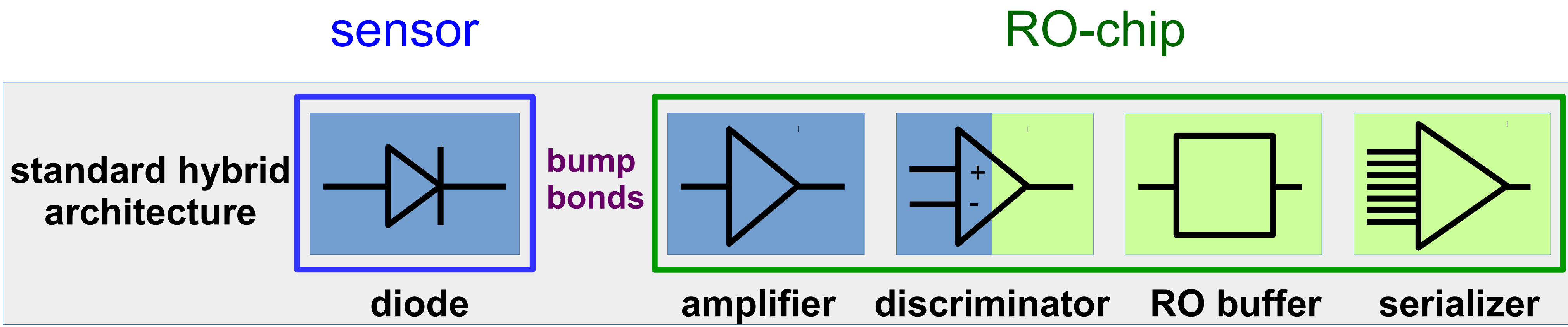
RO-chip

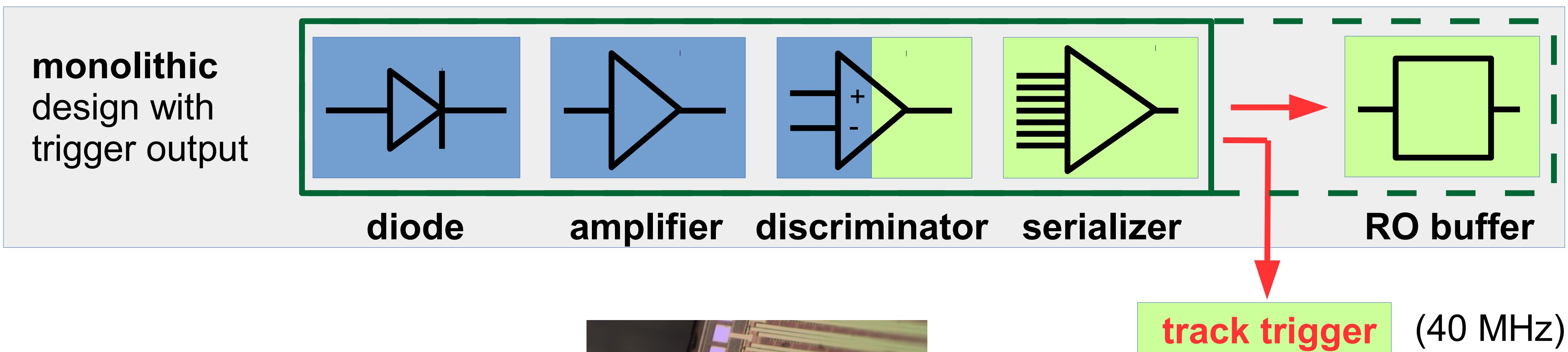


bump bonds

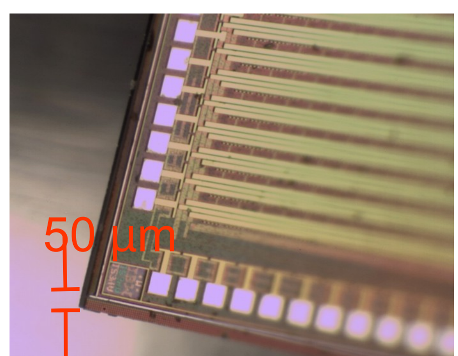


Pixel Readout Concepts II





Mupix7
HV-CMOS AMS 180 nm

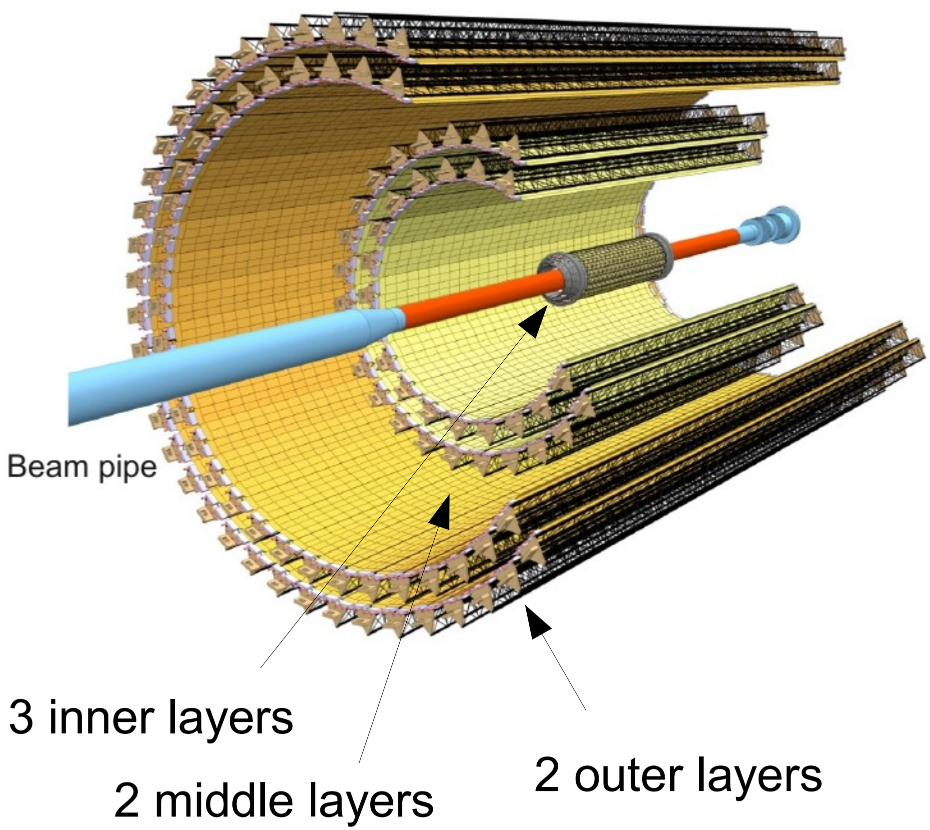


Pixel Detector Comparison

pixel detector	pixel size (μm^2)	thickness/X_0	monolithic
ATLAS IBL	50 x 250	1.9%	no
CMS (current)	100 x 150	~2.0%	no
CMS (upgrade)	25 x 100 or 50 x 50	~1.1%	no
ALICE (current)	50 x 425	~1.1%	no
ALICE (upgrade)	29 x 27	~0.3%	yes
STAR	21 x 21	~0.4%	yes
Belle II	50 x 75	~0.2%	no
Mu3e	80 x 80	~0.1%	yes

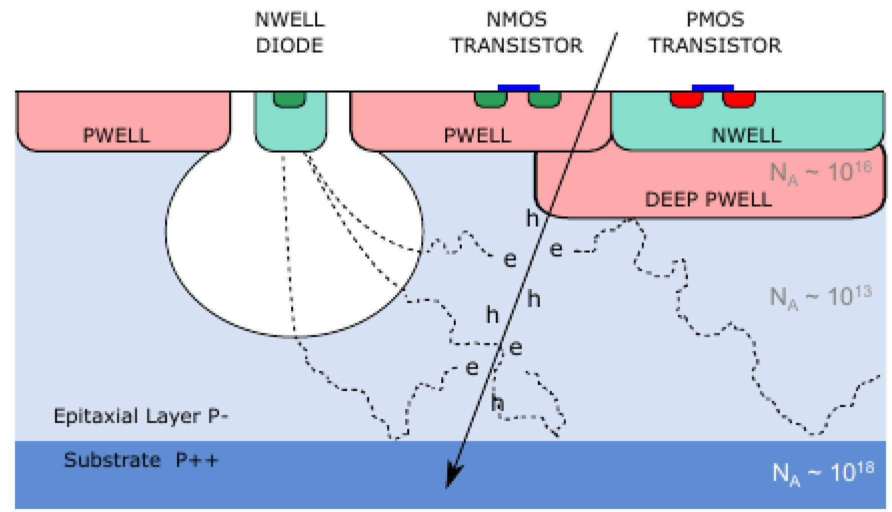
monolithic concept → thin tracking layers with high pixel granularity

ALICE Upgrade: ALPIDE Project



~ 10 m^2 active surface

Pixel:



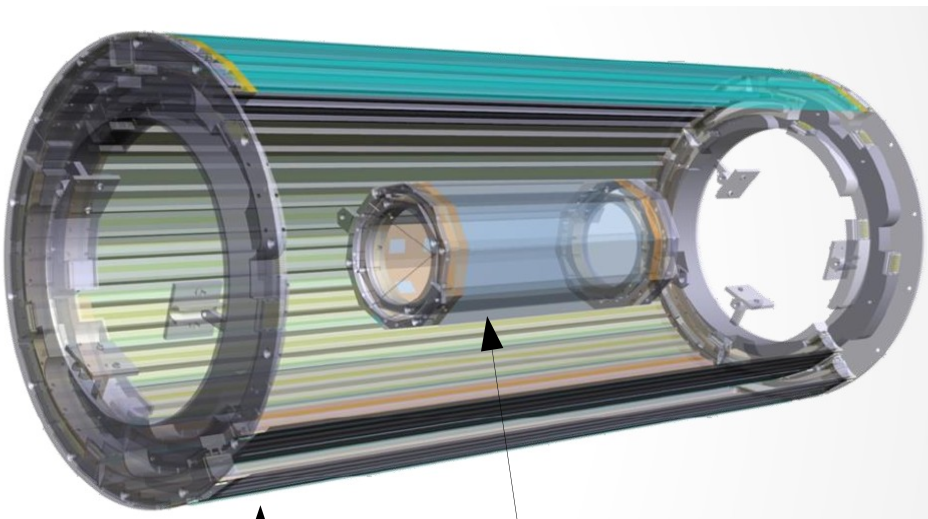
- TowerJazz 180nm with high resistivity epitaxial layer
- small N-well diode
- deep p-weel shields NWELL of PMOS transistors
- pixel size 27 x 29 mum
- charge collection mainly by <u>diffusion</u>

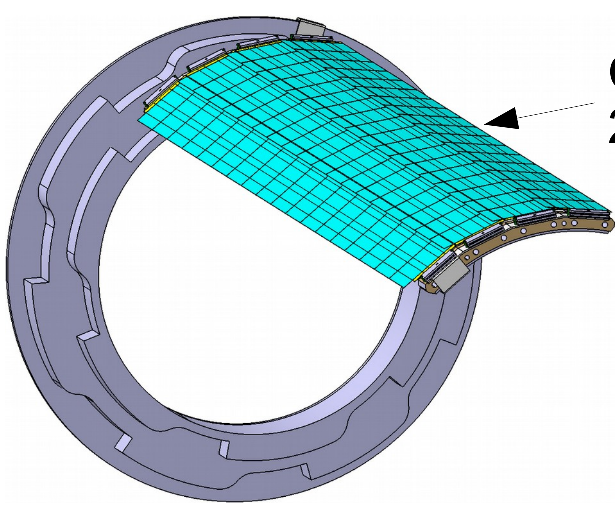
→ **slow timing;** not very radiation hard

Mupix for Mu3e (Search for μ → eee)

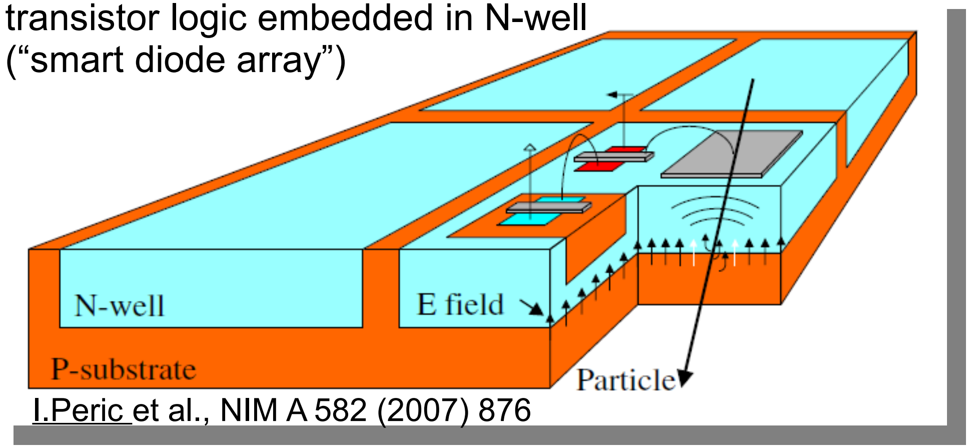
→ talks by Dorothea and Alex

Central Mupix pixel tracker



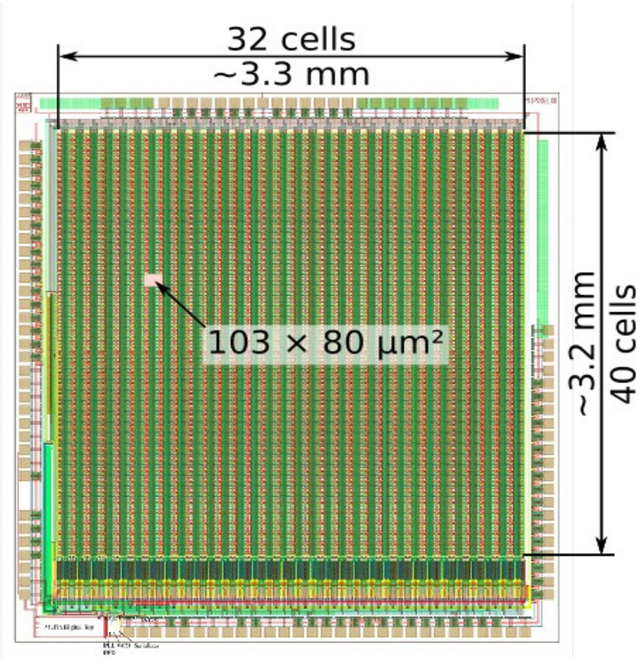


High Voltage-Monolithic Active Pixel Sensor (HV-MAPS)

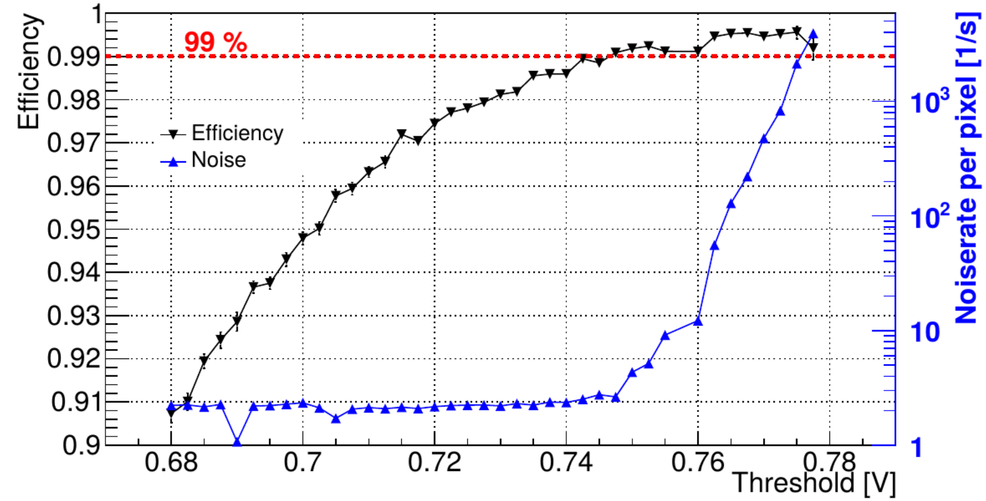


- **active sensor**
  → hit finding + digitisation + readout
- HV-CMOS: 60-85 V (Austria Micro Systems)
- charge collection by drift → **fast timing**
- "low cost" process
- sensor thickness 50 μm
- zero suppressed **continuous readout** of all hits
- fast serial links (1.5 Gbit/s) integrated

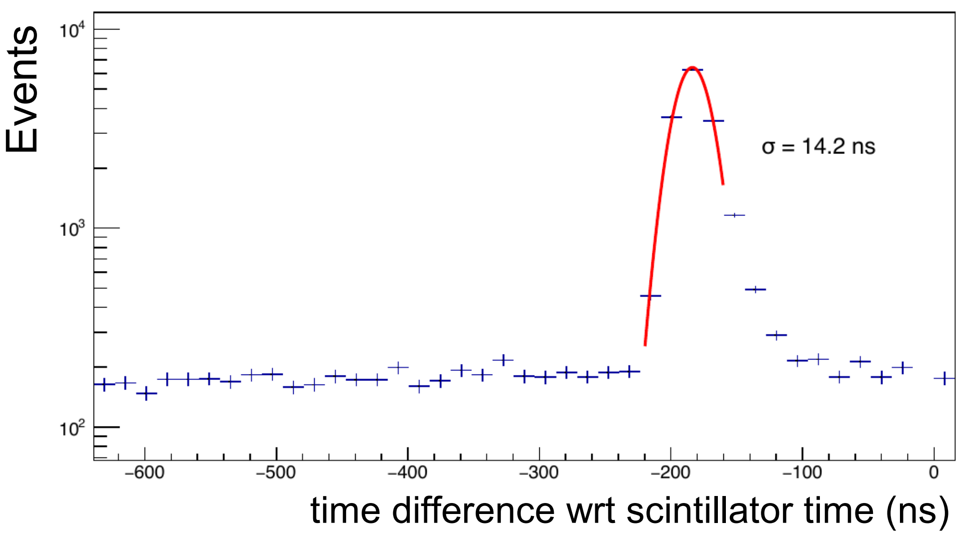
Mupix7 Prototype Test Results



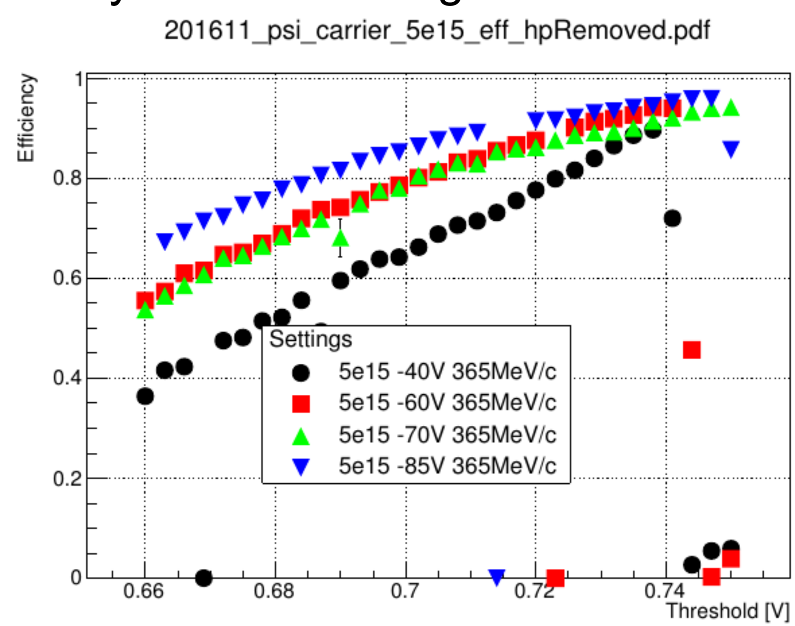
efficiency and noise:



time resolution of hits:



efficiency after irradiating 5e15 neutrons/cm^2:



ATLAS CMOS Demonstrator Project

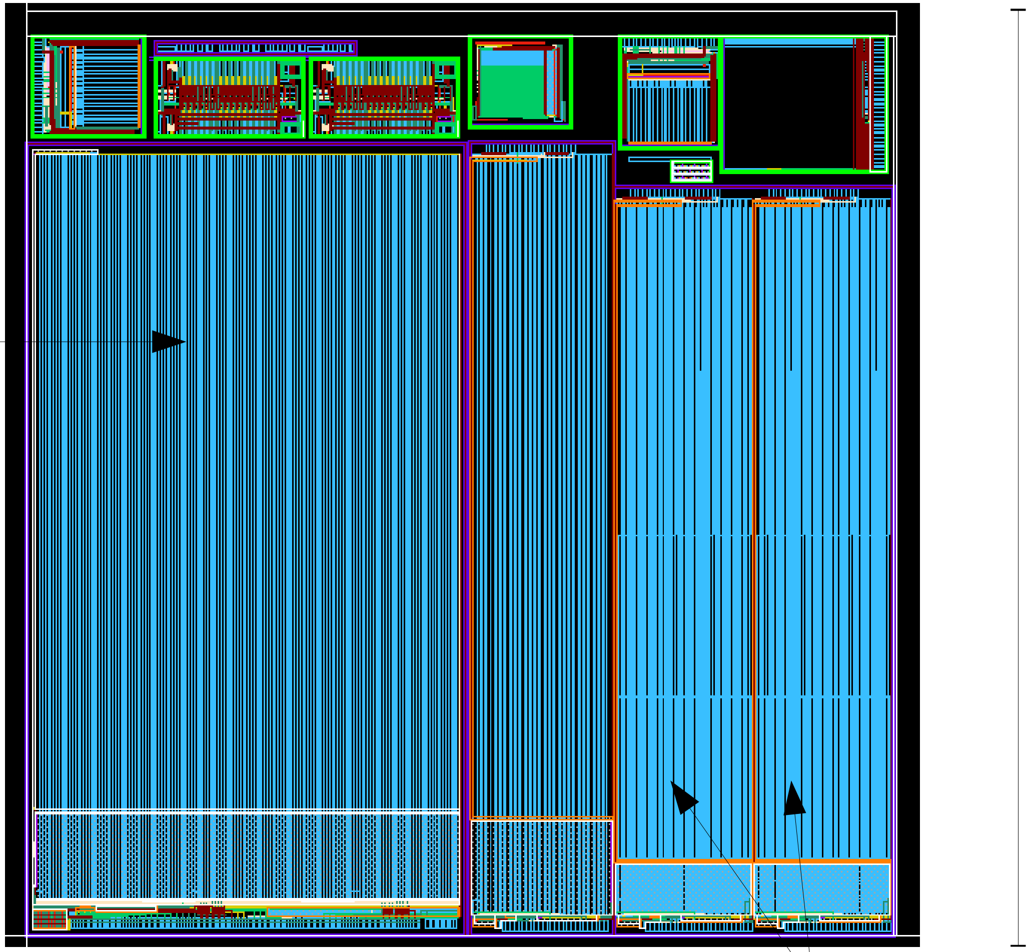
CMOS technologies considered for (non-)monolithic CMOS designs:

- AMS (Austria Microsystems) 180 nm HV-CMOS (Depleted MAPS)
  - ➔ charge collection mainly by **drift**
- Lfoundry 150nm with high resistivity substrate (Depleted MAPS)
  - ➔ charge collection mainly by **drift**
- TowerJazz 150nm with epitaxial layer (low fill factor)
  - ➔ charge collection mainly by **diffusion**
- TSMC 90 nm with epitaxial layer (low fill factor)
  - ➔ charge collection mainly by **diffusion**

Recent Monolithic Pixel Chip Submission

AMS aH18 process
- HV-CMOS 180 nm
- being diced right now

Mupix8 for Mu3e (+LHC)
- 80 x 80 μm^2 pixel
- comparator in periphery
- ➢ **track trigger outputs**

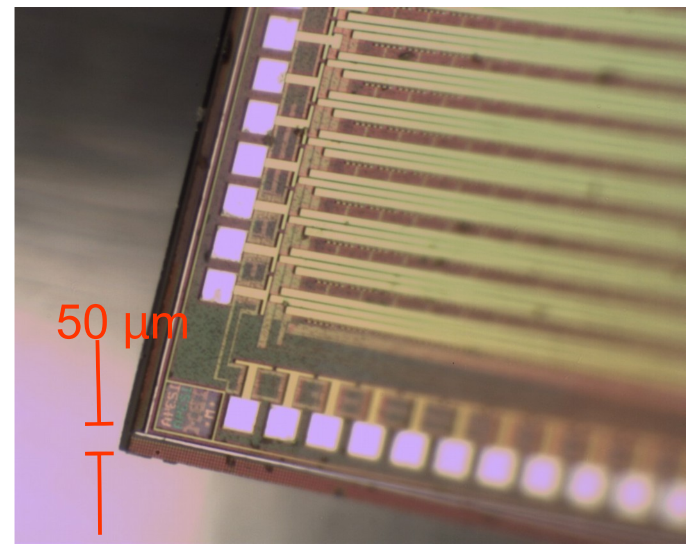


main designer I.Peric (KIT)

dedicated test structures
- 40 x 130 μm^2 pixel
- comparator in pixel
- ➢ **track trigger outputs**

The Seven Requirements for Future Track Triggers

- highly granular pixel ✔
  - → 3D tracking and vertexing
  - → reducing ambiguities
- little material ✔
  - → reduces MS and confusion problem
- good timing ✔
  - → resolve bunch crossing
- high efficiency @ low noise ✔
  - → fewer tracking layers
  - → reducing ambiguities
- fast readout capabilities ✔
  - → high track rates
- radiation hardness ✔
  - → high track rates
- affordable ✔
  - → large sensitive areas

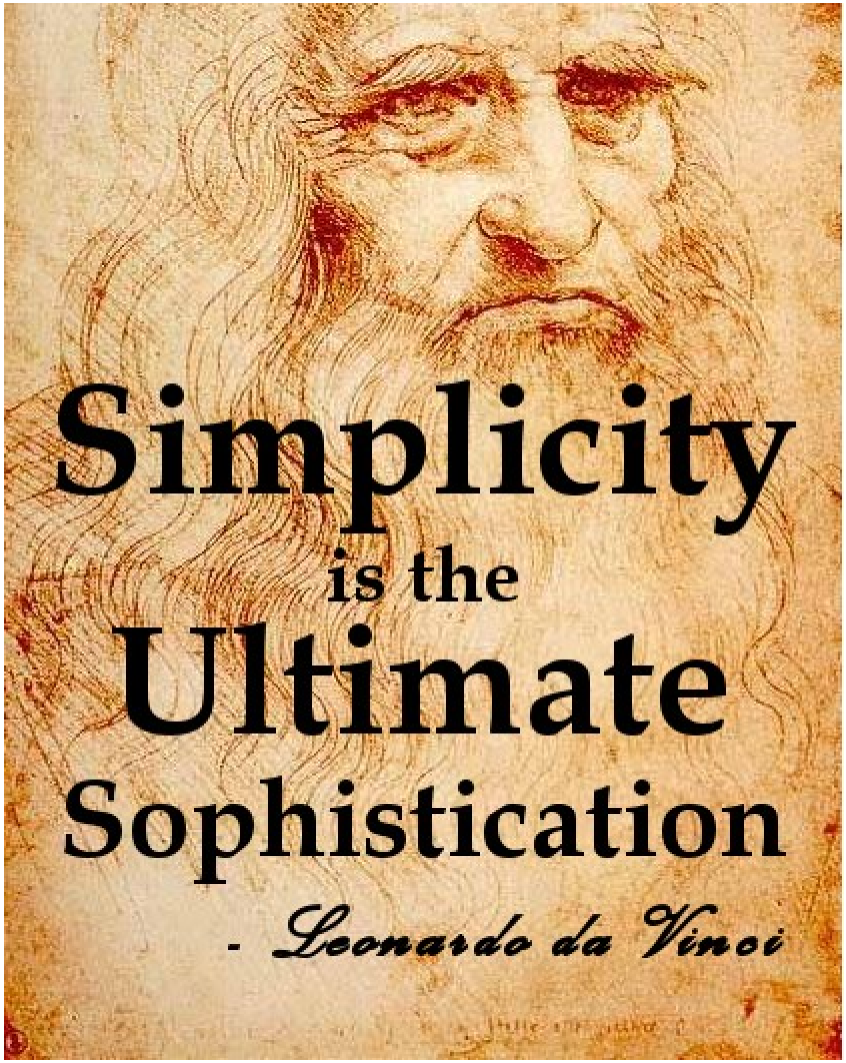


Mupix7
HV-CMOS AMS 180 nm

Part III

- ➔ track trigger designs based on monolithic pixel detectors
- ➔ simulation results

Simple Track Trigger Design

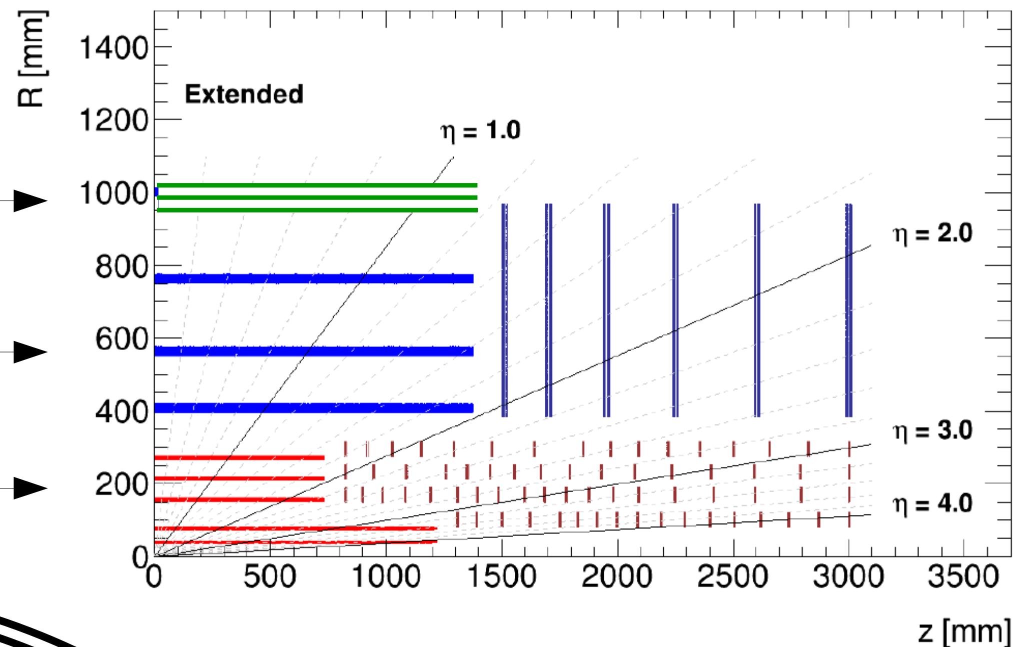


Studied Track Trigger Design (ATLAS-"inspired")

3 monolithic pixel trigger layers

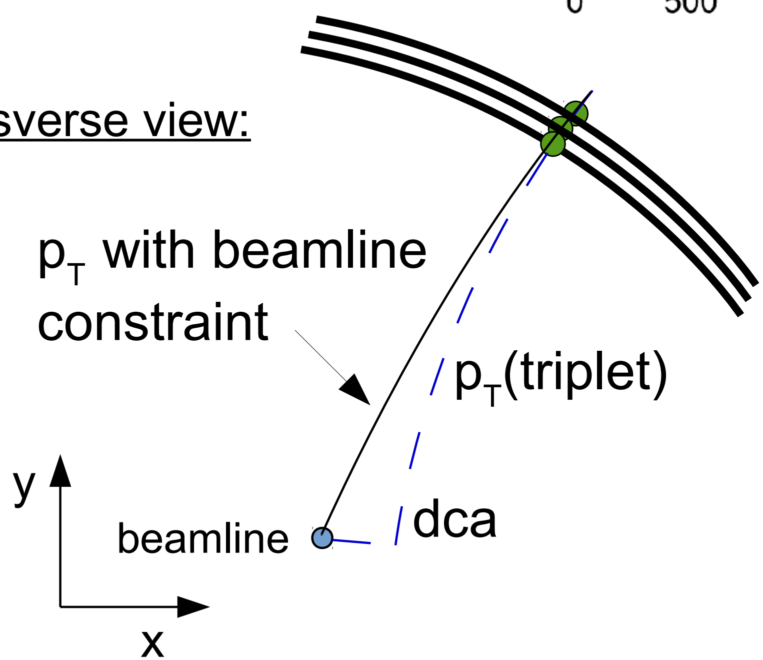
strip layers

pixel layers

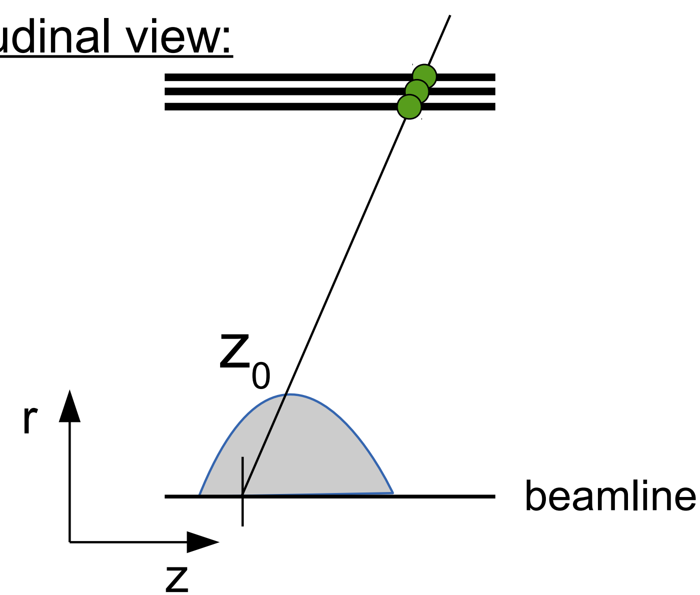


only **local** hit processing is required!

transverse view:



longitudinal view:



Optimal Distance between Trigger Layers?

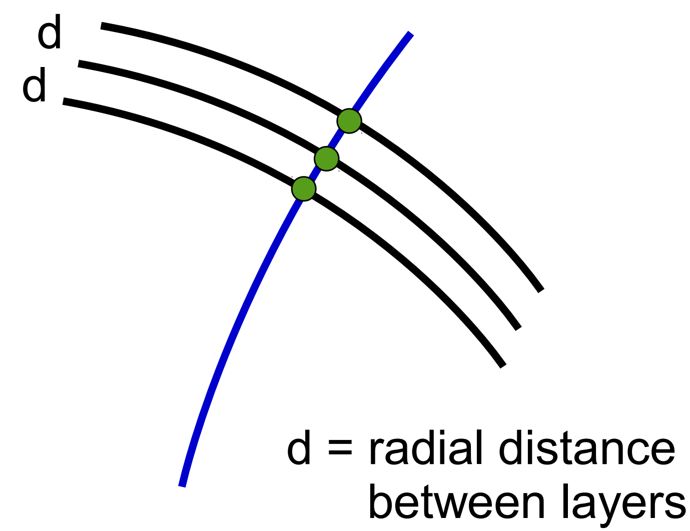
Momentum measurement only possible if:

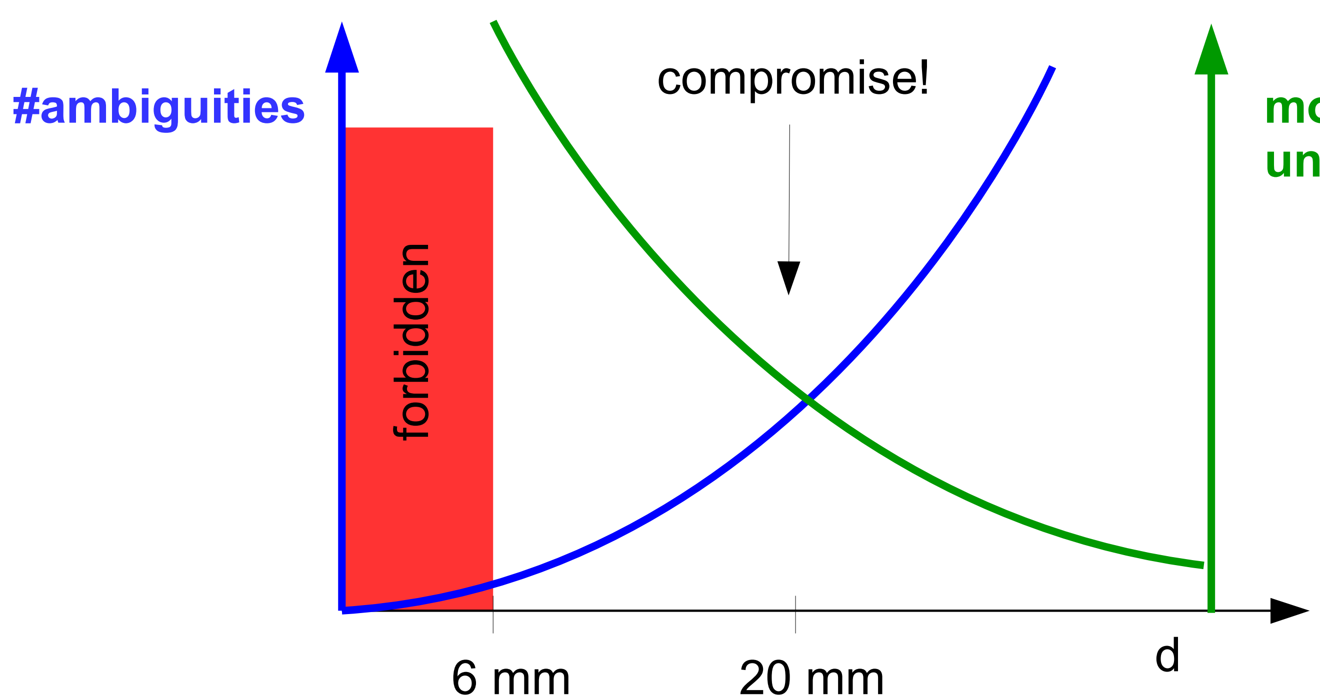
$d^2 > 8b^2 \chi^2_{cut}$ with $b = 45\,mm\,\frac{Tesla}{B}\sqrt{x/X_0}$

(multiple scattering limit for tracking → arXiv:1606.04990)

for $\chi^2_{cut} = 15\ ,\ B = 2\ Tesla\ ,\ \frac{x}{X_0} = 0.01$

follows: $d > 6\ mm$





Simulation Study

Simulation Setup

- fast simulation including all electromagnetic IA (brems, photon conversions)
- upgraded LHC scenario: proton-proton collision with 200 pileup events
- monolithic triplet layers with 40 x 40 μm^2 pixel size at radius = 100 cm with d=2cm
- Material per tracking layer 1.5% X_0
- cylindrical geometry

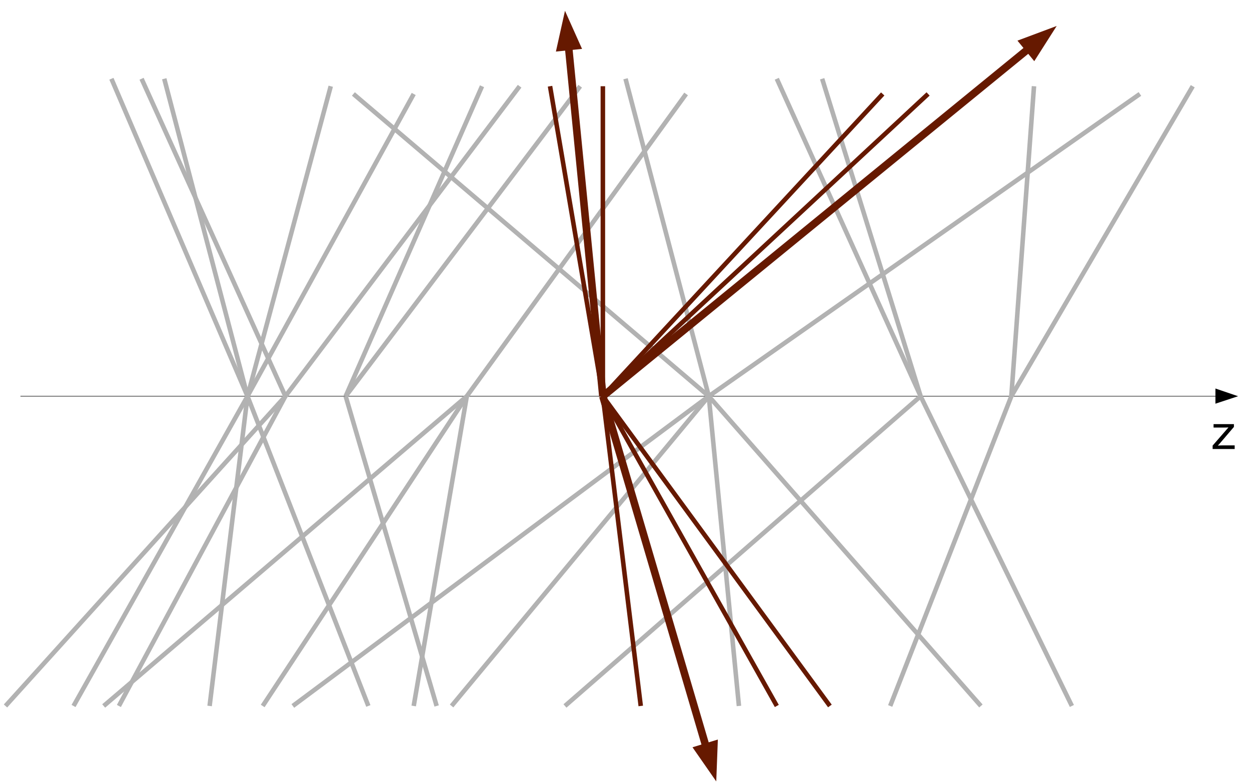
Monte Carlo Samples

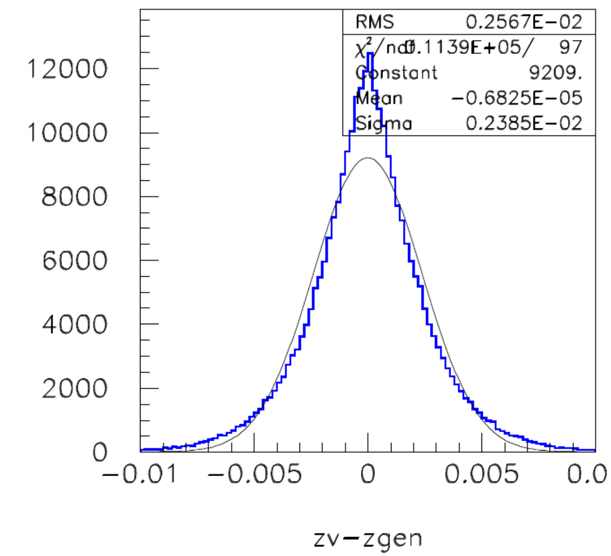
- Pythia 8 for MinBias events for purity studies
- Z' → ttbar with m(Z`)=3 TeV for efficiency studies
- (HH → bbar tau tau)

→ first preliminary results

Simulated Z_0 Resolution

event vertex can be reconstruction with a resolution
of a few mm in z-direction (depends on tracker material)



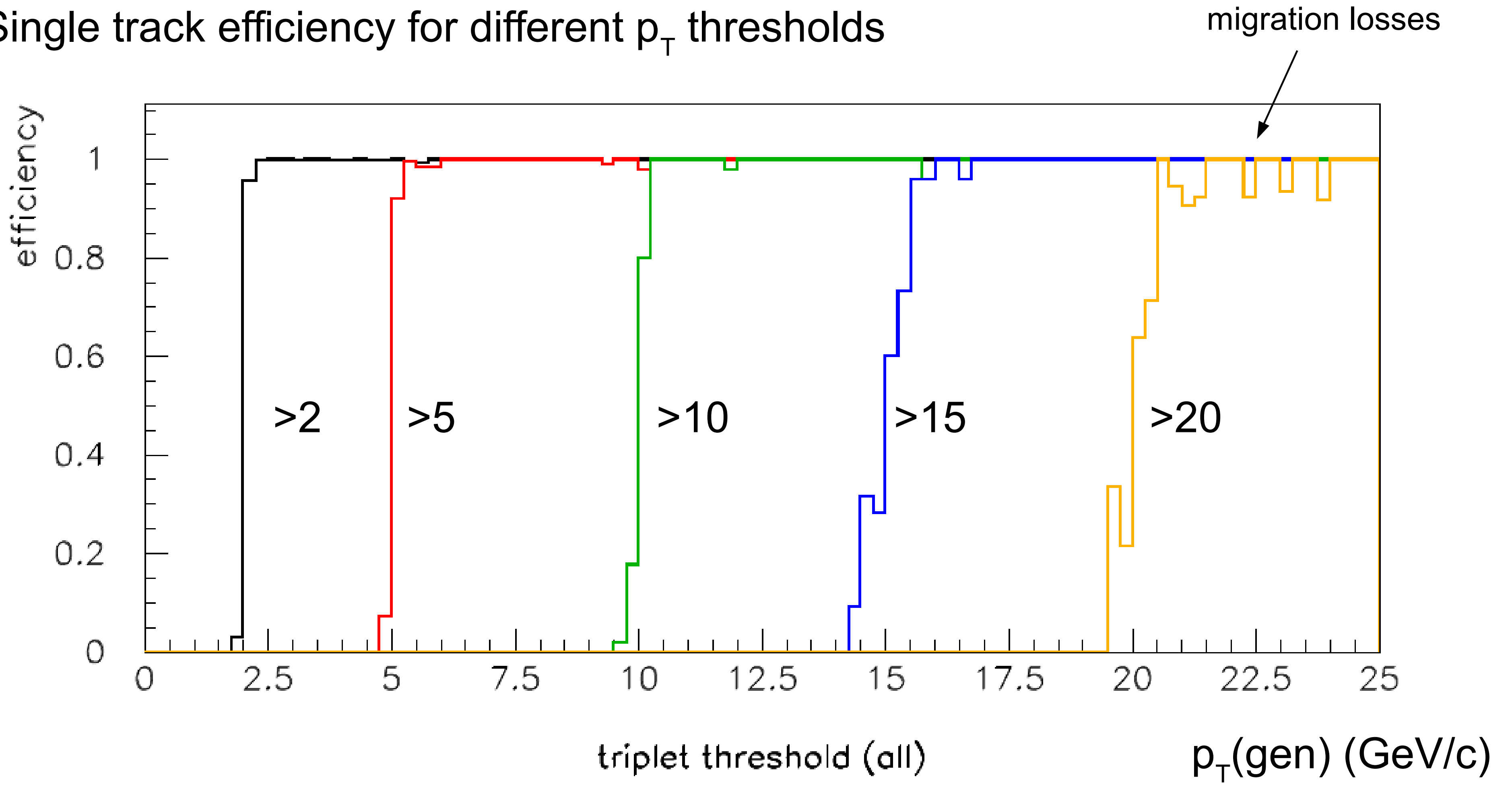


$\sigma(z_0) \sim 2.5$ mm

→ **good separation of pileup events possible!**

Track Finding Efficiency

Single track efficiency for different p_T thresholds



- Track reconstruction efficiency ~ 100% *
- Track purity is close to 100% (not shown)

* assuming 100% single hit efficiency

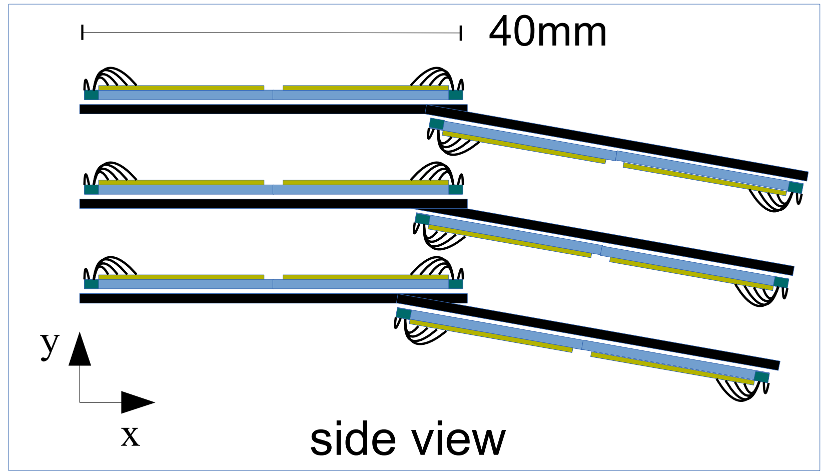
Conclusion

- **Monolithic pixel sensors are ideal for realizing track triggers**
- **Prototypes of depleted MAPS have been successfully qualified for HL-LHC within the ATLAS CMOS demonstrator project; new test chips are being produced**
- **Reconstruction of all tracks for PU=200 @ 40 MHz seems possible with high efficiency and purity using a special tracker design (stacked layers)**
- **Such a track trigger could trigger on isolated leptons, multi-jet topologies, etc.**
- **Studies are ongoing ...**

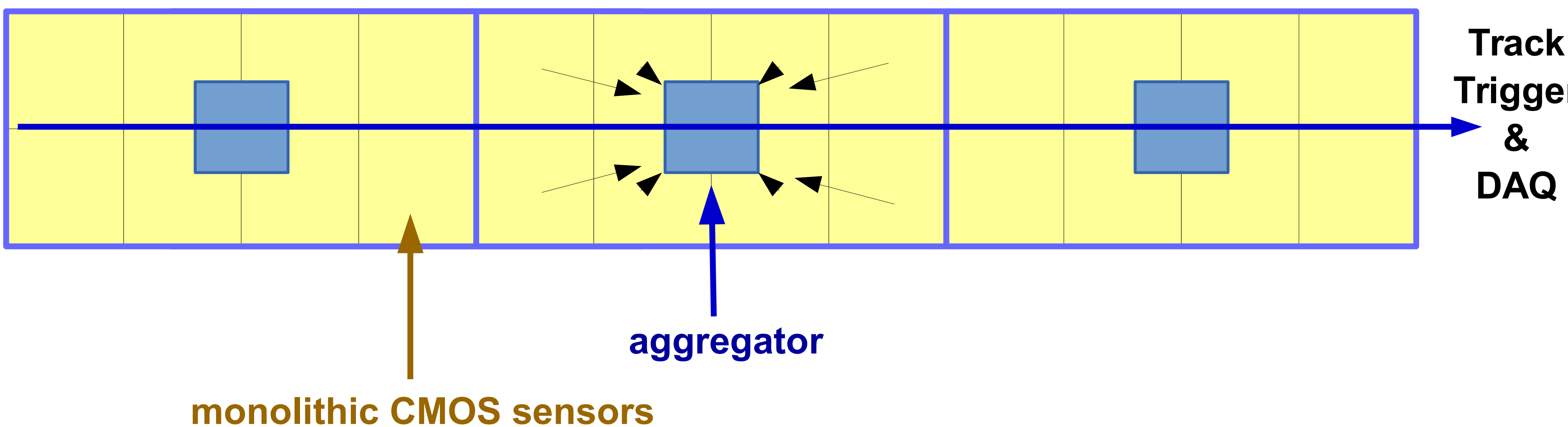
Outlook

Study concrete designs using full GEANT simulation:

example layout:

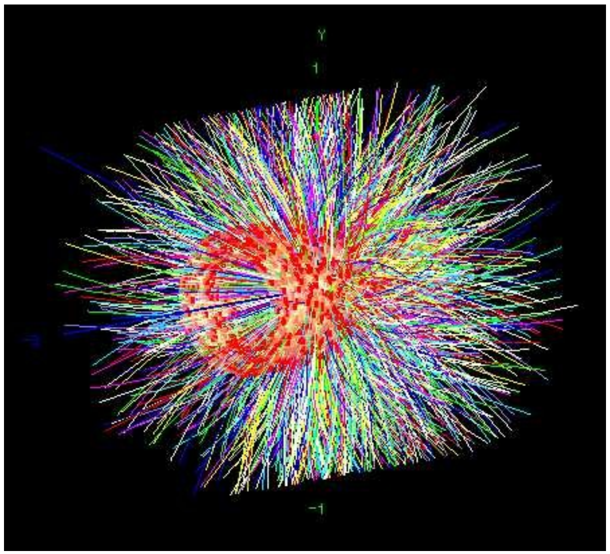


top view of one ladder:



Backup

Typical LHC Experiment



- O(10000) charged tracks at HL-LHC
- material budget ~ 2-3% / layer
- 10-12 layers per experiment for R≤1m

Uncertainties:

- hit resolution ~ 15 μm → $\sigma_\Theta \approx$ 0.15 mrad
- scattering: $\sigma_\Theta \propto \frac{1}{p}\sqrt{X/X_0}$ → p_{crit} = 15 GeV/c

p≤10 GeV/c	p≥10 GeV/c
• **multiple scattering** uncertainty dominates	• **hit uncertainty** dominates
• **~99% of particles**	• ~1% of particles