Tracking

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University of California
Santa Barbara
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Plan

My intentions are to:

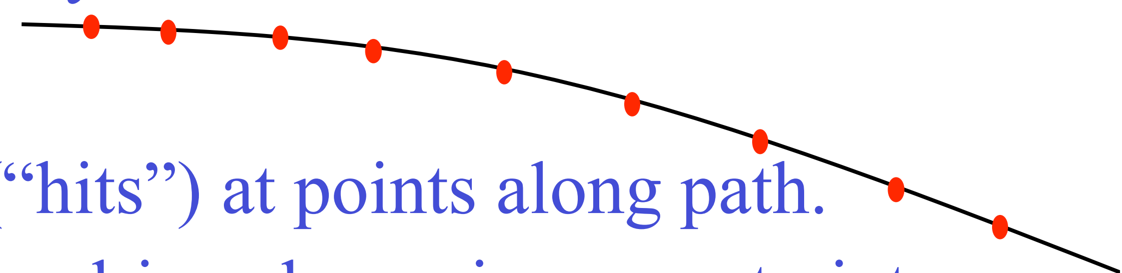
- Help you build intuition about the experimental role of tracking.
- Help you build intuition about tracking hardware.
- Help you build intuition about tracking software.

Outline

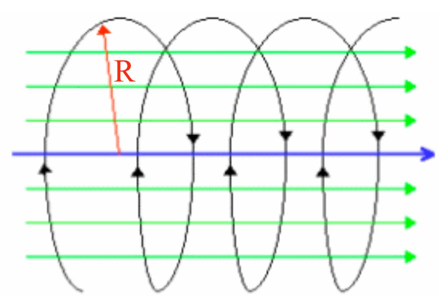
- Goals of tracking
- Hardware
- Software
- Design, commissioning, operation

NLO Outline

- Goals of tracking
  - Measure 4-vector and origin of particles.
  - As well as allowed by various constraints.
- Hardware
  - Measure position (“hits”) at points along path.
  - Various approaches, driven by various constraints.



- Software
  - Collect measured hits and fit a helix.
  - Various approaches, driven by various constraints.



$p_T = 0.3\ B\ R$

Physics Goals of Tracking

Measure 4-momenta and origin of particles.

Similar to goals of other detector components,
e.g., the calorimeter and muon detectors.

Redundant?

Physics Goals of Tracking

Measure 4-momenta and origin of particles.

Similar to goals of other detector components,
e.g., the calorimeter and muon detectors.

Redundant? Good!

- Complementarity, i.e., different strengths.
- Confirmation.

Redundancy = Confirmation

Electron: E/p and $\eta\phi$ match,

beamspot match

Muon: p/p and $\eta\phi$ match,

beamspot match

Jet: E and $\eta\phi$ match, (should contain charged particles)

beamspot match.

Redundancy: Electrons

Calorimeter:

Energy resolution ~ O(1)% / sqrt(E)

~ No pointing, but assume beam origin $\Rightarrow p_T$.

Large background from neutral pions.

Tracker:

Momentum resolution ~ O(1)% * p_T

Non-gaussian tails from bremstrahlung

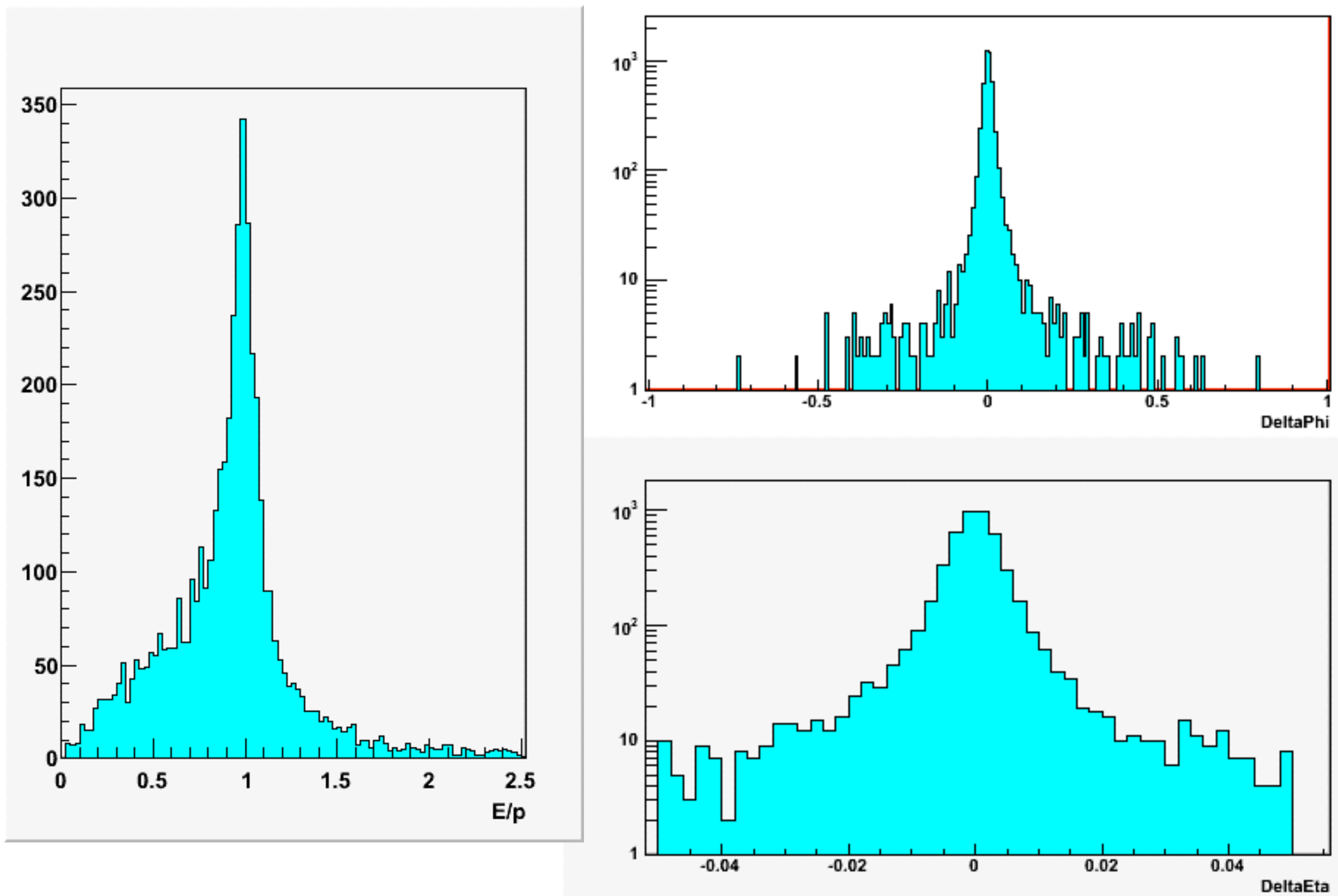
Large background from charged pions.

Redundancy: Electrons

E/p=1 for electron, while ≈ no EM energy for π^+ and ≈ no p for π^0.

η and ϕ of track and calorimeter measurements should match.

Once confirmed,
take |p| from cal,
take origin &
direction from track,
or refit all info.



Low pT electrons, in a CMS simulation. Wing To, UC Santa Barbara

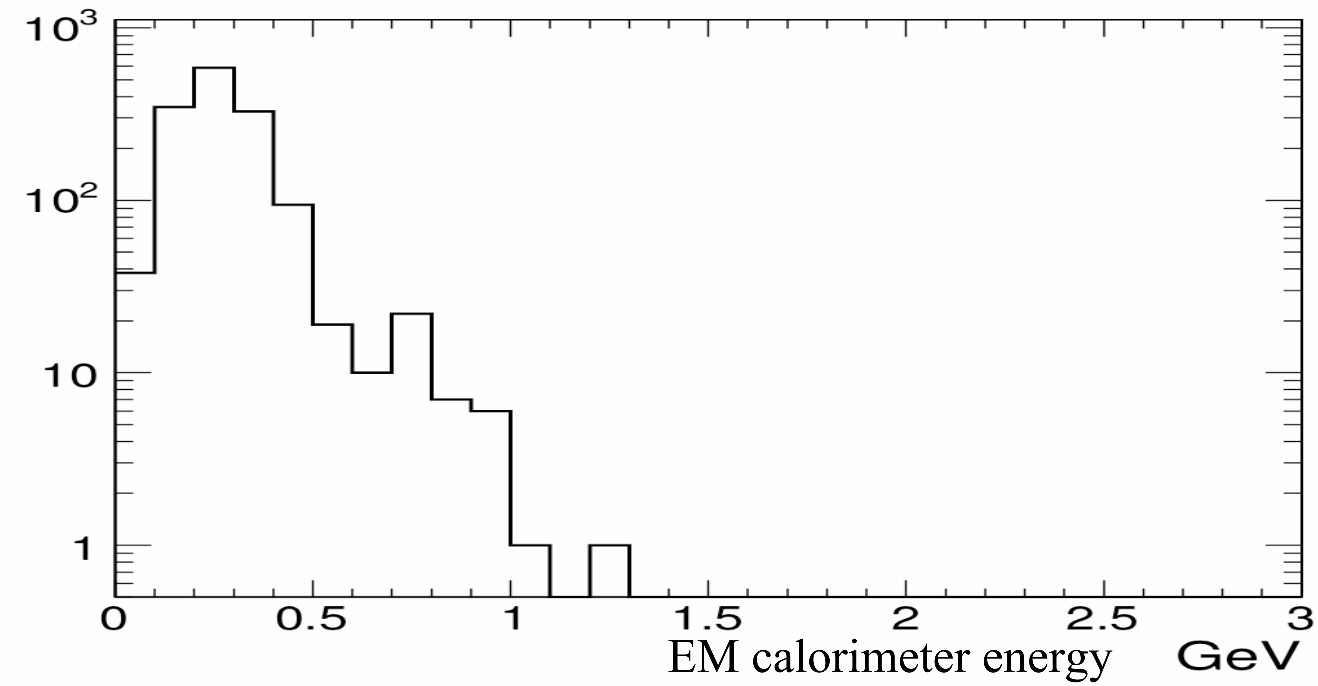
Redundancy: Muons

Momentum match between muon system and tracker.

η and ϕ of track and muon system

Calorimeter measurements should "match".

Once confirmed,
take p from track,
take origin &
direction from track,
or refit all info.

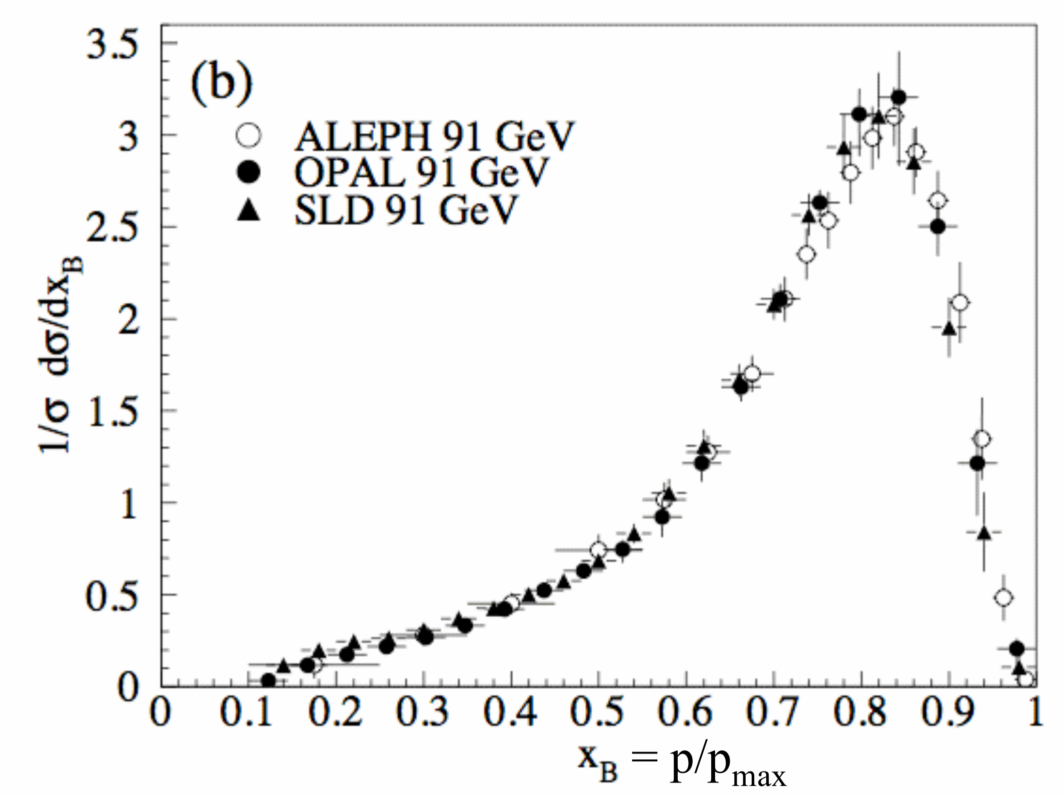


CMS TDR

Redundancy: Leptons

W or Z parent vs heavy flavor semileptonic decay?

Isolation: “Primary leptons,” e.g., from W’s have a fragmentation function peaked at 1. There is a small contribution there from semileptonic decay of heavy flavor there.



PDG

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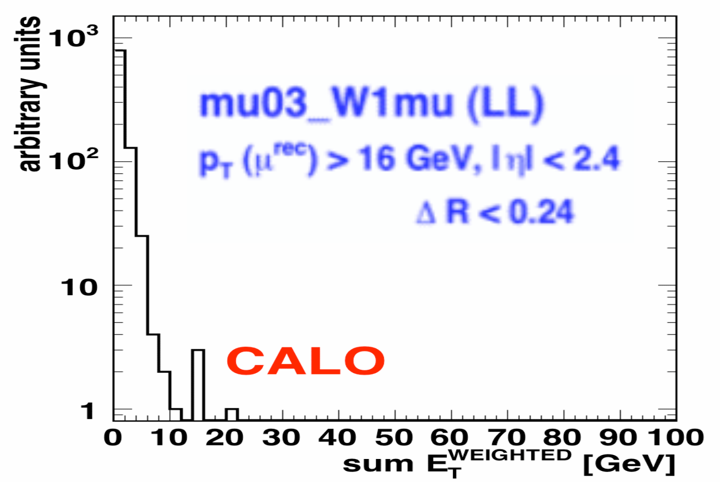
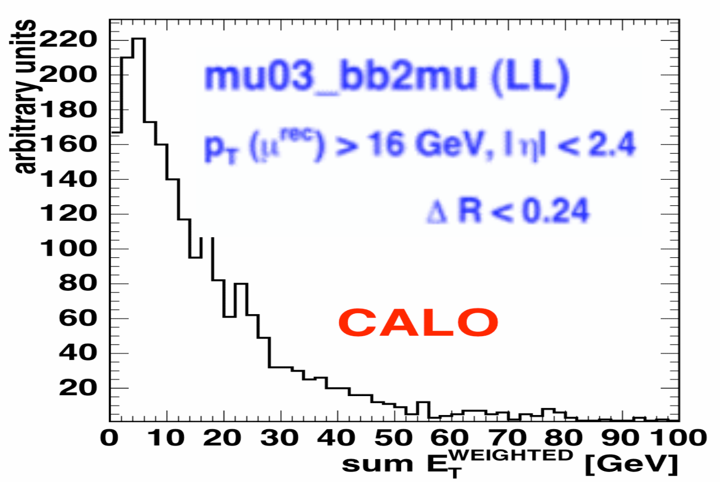
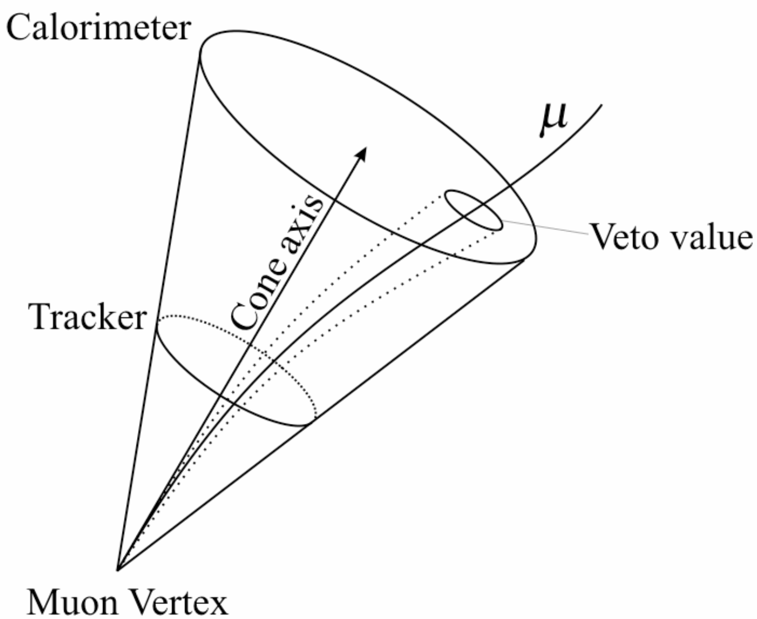




CMS TDR



Measuring low energy is done better by
The track than the calorimeter. So...

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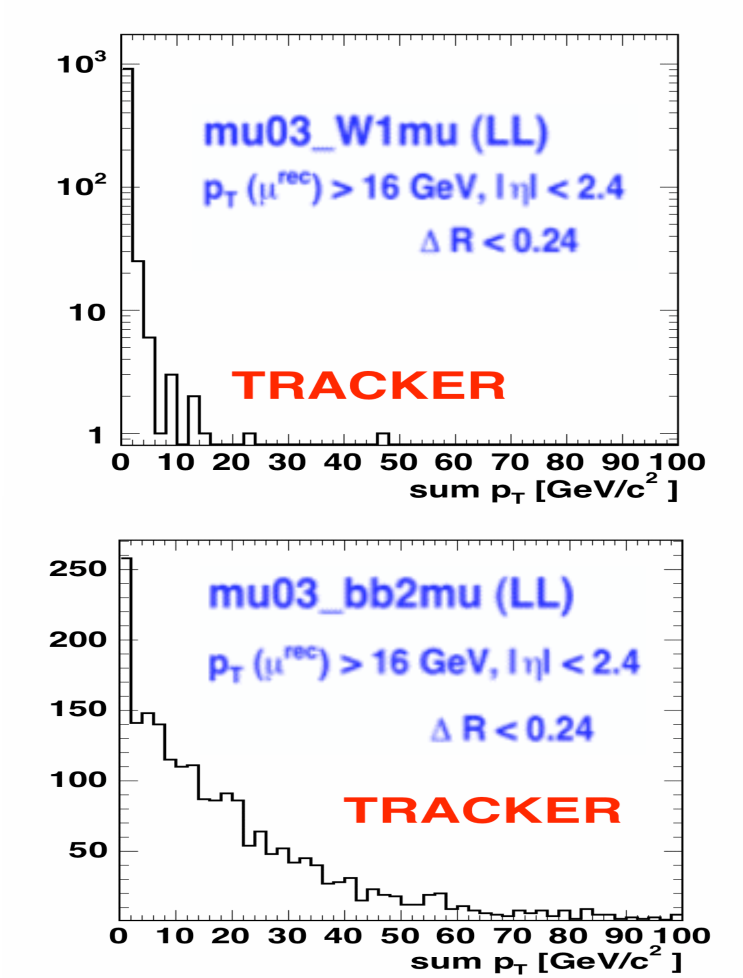
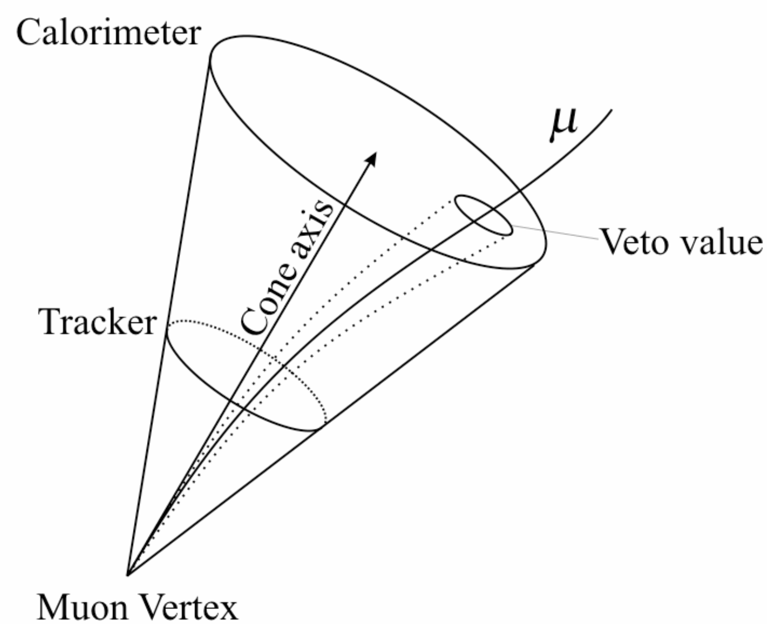




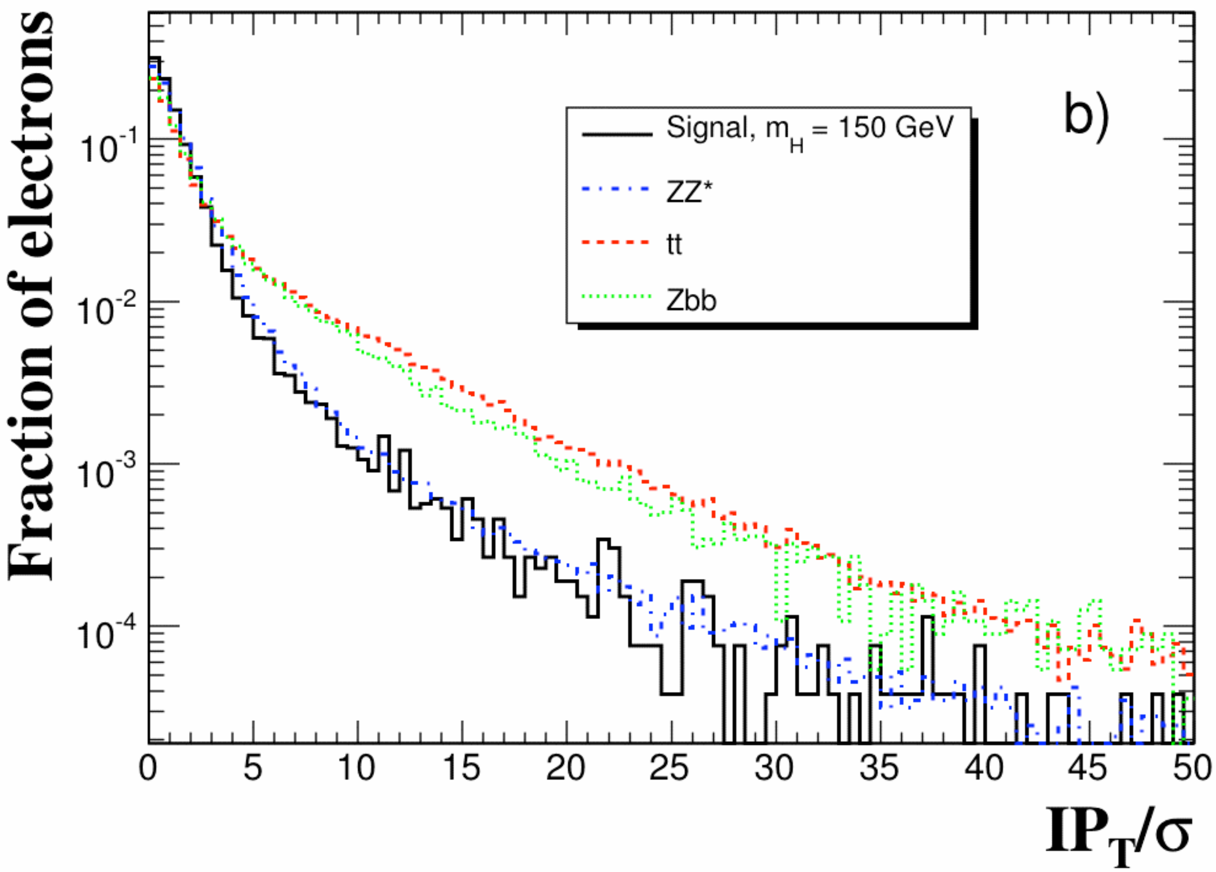
Measuring low energy is done better by
The track than the calorimeter. So use it *too*.

CMS TDR

Redundancy: Leptons

W or Z parent vs heavy flavor semileptonic decay?

- Impact parameter: "Primary leptons," e.g., from W's come from the collision point.
- Heavy flavor decay has $c\tau = O(100)\ \mu m$.
- π & K decay in flight larger. Cosmic muons flat.



CMS TDR

Redundancy: Jets as an example

Calorimeter:

~ Integrates out fragmentation

Energy resolution ~ O(100) % / sqrt(E)

Good at high momentum

Reasonable pointing, assuming beam origin.

Tracker:

Single particles

Momentum resolution ~ O(1)% * p_T.

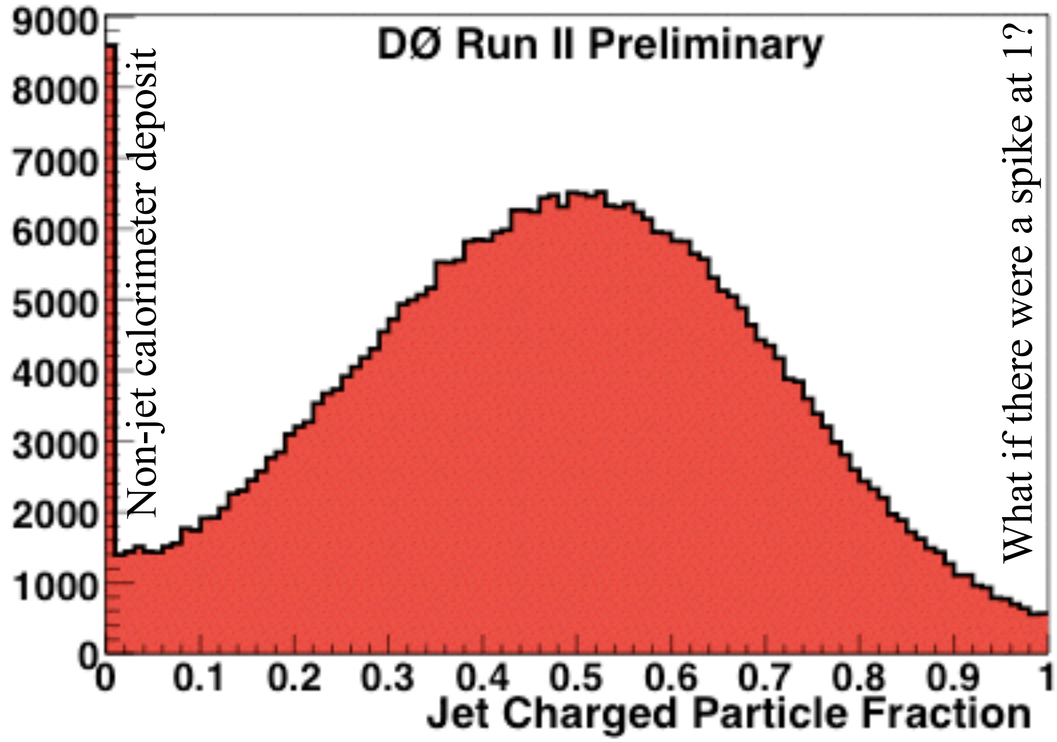
Good at low momentum.

Confirms beam origin.

Redundancy: Jets as an example

The ratio of charged particle momentum to calorimeter momentum is essentially a fragmentation function.

Useful to reject fake missing energy in a monojet search.



Redundancy: Jet energy resol. improvement

Tracking measurements can improve jet energy resolution:

- Better resolution at low pT
- Energy swept out of cone

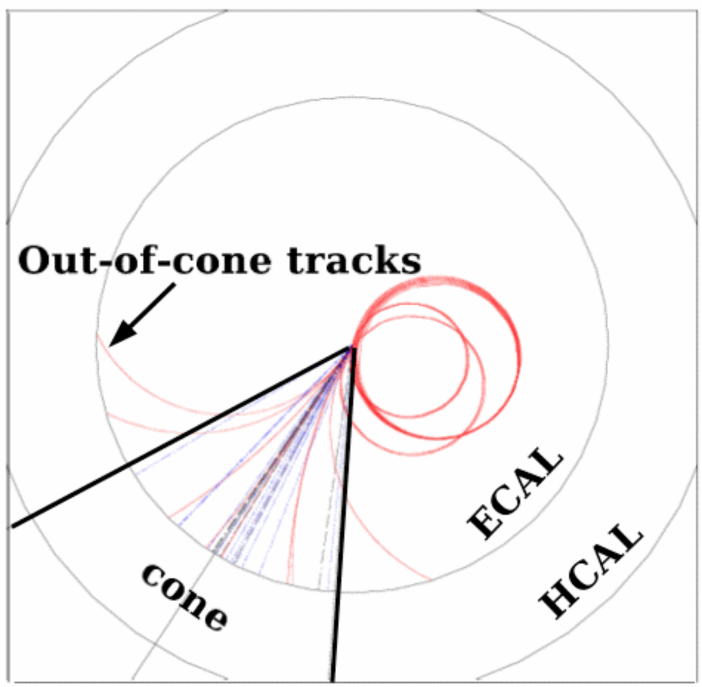


Fig. 1. Single jet in CMS (transverse view). The typical cone size of 0.5 is displayed as black straight lines. The tracks leaving the cone before reaching the calorimeter are called out-of-cone tracks

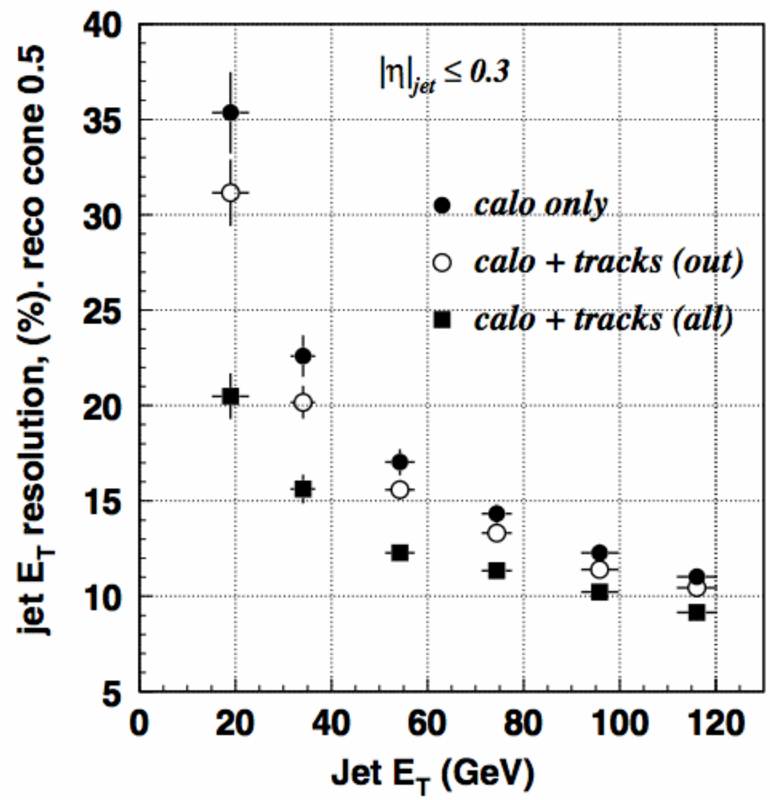
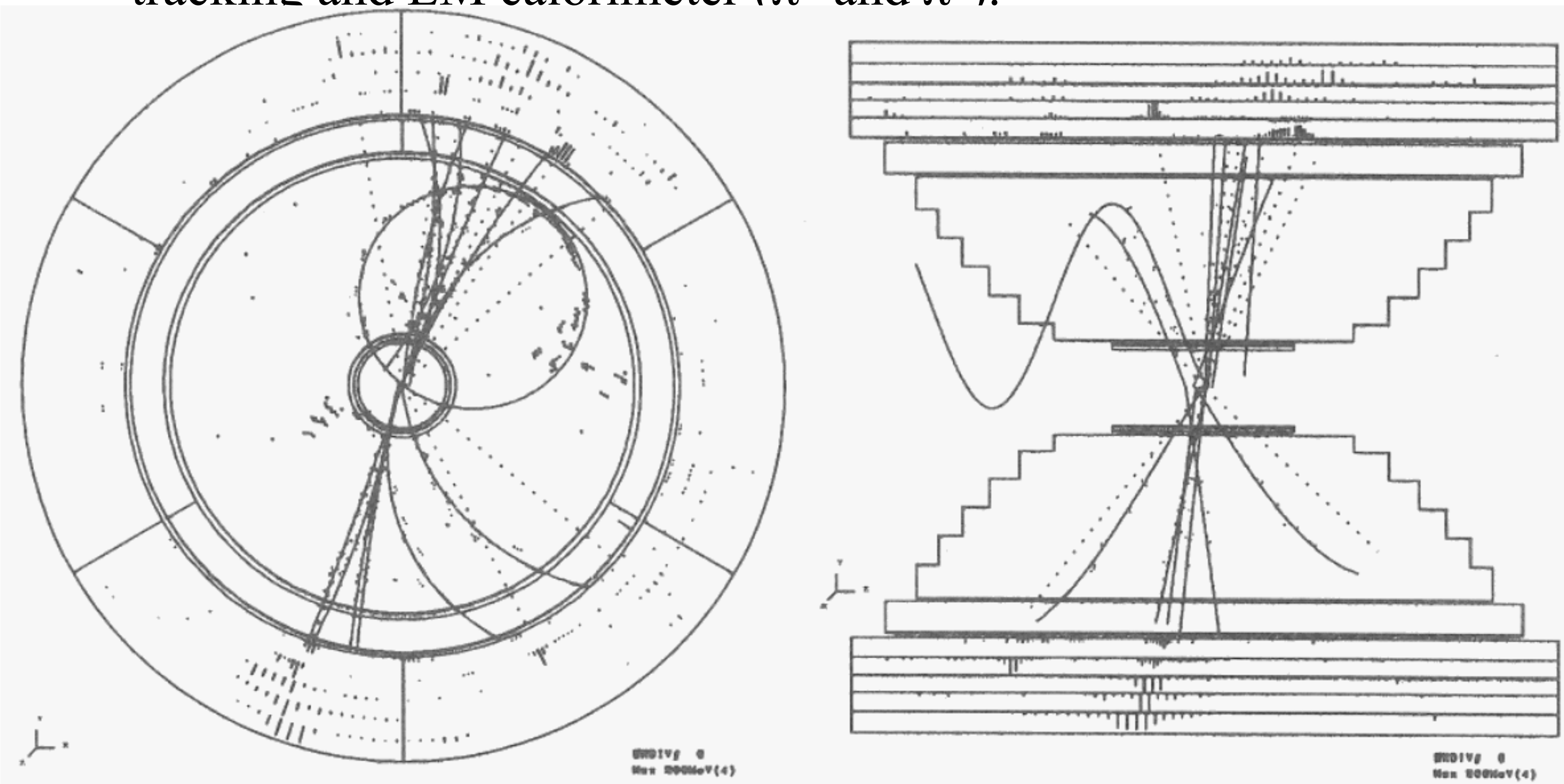


Fig. 8. The jet transverse energy resolution as a function of the original jet transverse energy in a single jet sample; reconstruction with calorimeter only (close circles), out-of-cone tracks (open circles), subtraction procedure of expected responses using library of responses (close squares)

O. Kodolova et al, Eur.Phys.J.C40S2:33,2005

Redundancy: Track based jets

At low energy, can measure jets without a hadronic calorimeter: tracking and EM calorimeter ($\pi^{\pm}$ and π^0).



E.g., event displays from AMY experiment (e^+e^- at 60 GeV). EM calorimeter only.

Redundancy: Track based jets

Best to measure low energy jets with tracking alone.

Can then stitch this together with calorimeter at high energy.

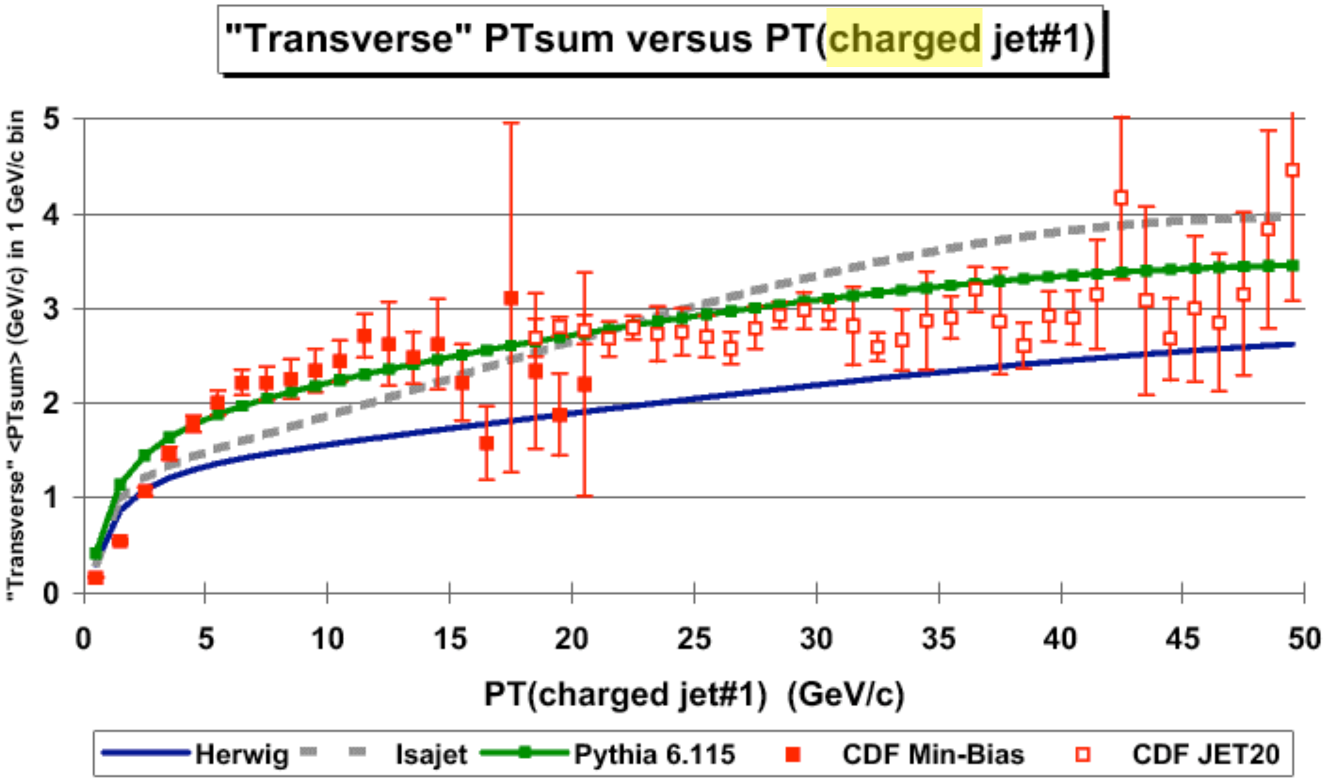


FIG. 29. Data from Fig. 22 on the average scalar p_T sum of charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$) as a function of P_{T1} (leading charged jet) for the transverse region defined in Fig. 14 compared with the QCD hard scattering Monte-Carlo predictions of HERWIG, ISAJET, and PYTHIA 6.115. The solid (open) points are the Min-Bias (JET20) data. Each point corresponds to the transverse $\langle P_T(\text{sum})\rangle$ in a 1 GeV/c bin.

Affolder et al, PRD65, 092002 (2002)

Redundant mad-lib

"If these are really ____________,
then measuring _____________
in the ____________
should show _________."

Redundancy and detector design

Redundancy was essential for:

- Confirmation
- Complementary measurement, better in some cases, worse in others.

No one detector has to do it all.

Relies on the general properties of the measurements more than the details of precision or fake rate.

What tracking doesn’t need to measure

High momentum jets

Far forward jets (= high E)

Everything--100% efficiency not required

Purely--100% purity not required

Efficiency and purity issues different for Tevatron & LHC.

Wish list for tracking

Adding a crude measure of something new may be better than improving the precision on something old.

Adding measures of quality may be better than improving the quality.

Driven by the physics that you want to do.

Hardware

Want to measure the particles' paths by having them leave bread crumbs as they go.

Actually, footprints in the sand is a better metaphor.

Only possible for charged particles due to (repeated) ionization.

Ionization energy loss, dE/dx

$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

Bethe-Bloch eq., just E&M

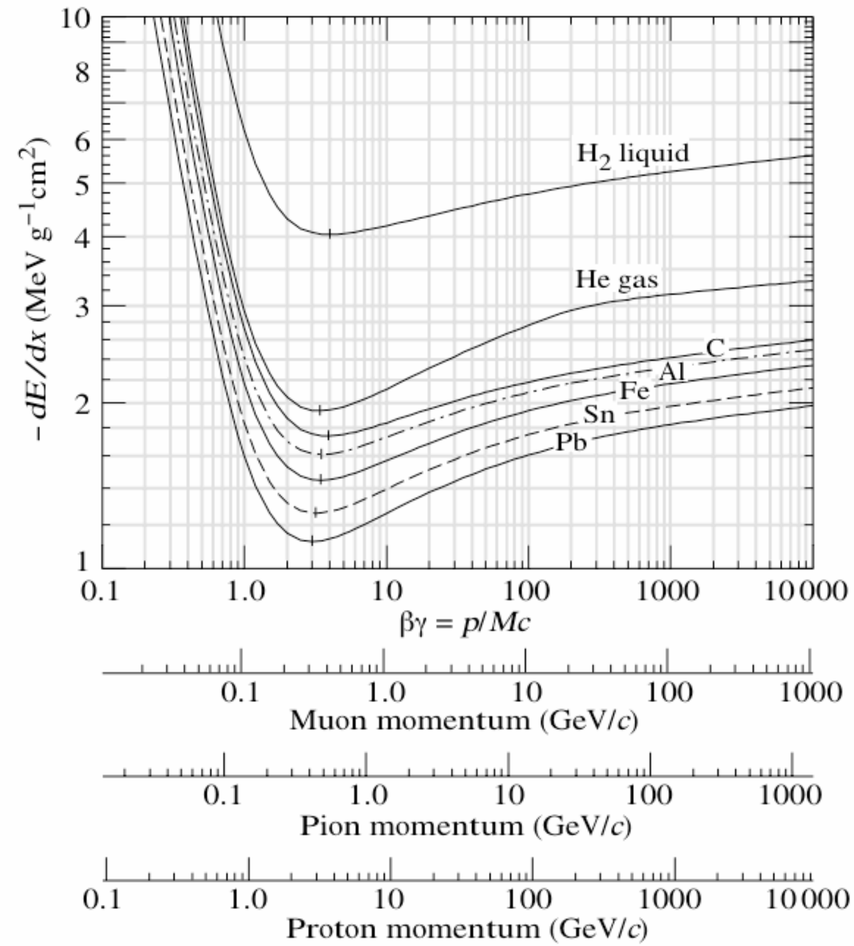
Function of $\beta\gamma$=p/M, since β=1.

Universal curve,

$\beta\gamma$=p/M indp. of pl type

$$T_{\max} = \frac{2m_e c^2\, \beta^2 \gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}$$

Relativistic rise & density effect.



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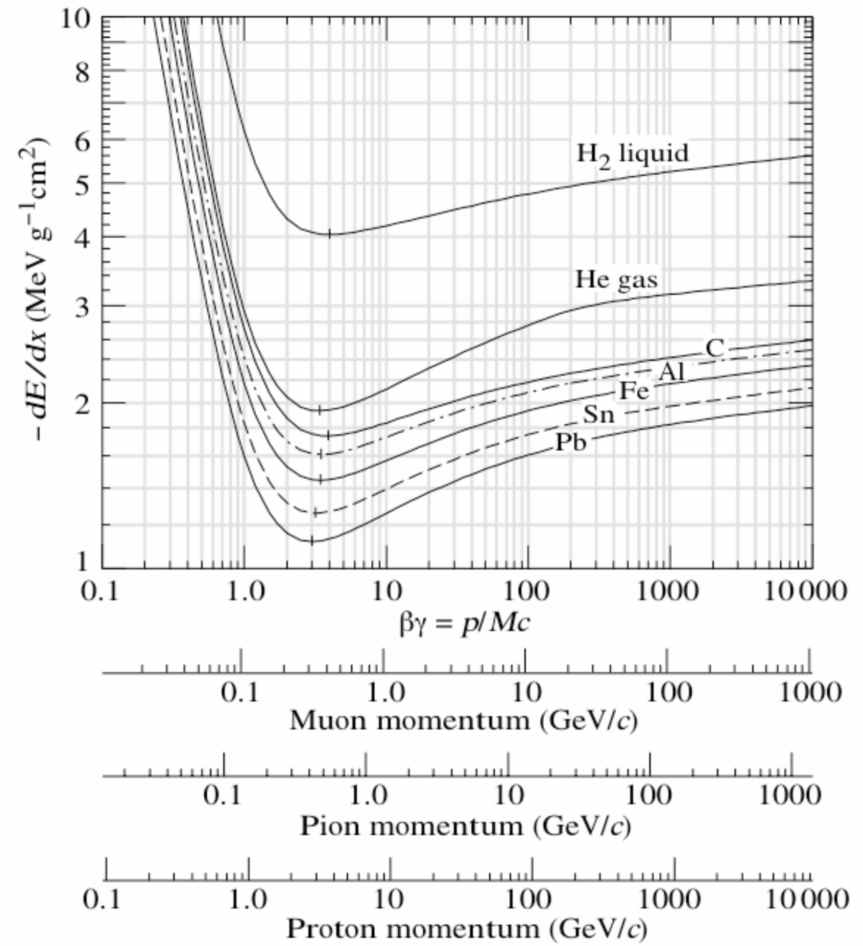
Depends on medium through I = O(10) eV
& density through Z/A.
Small variation among solids.
Dominant effect is density.
So, three categories:

Gas: ~0.5 keV/cm ~5 e$^-$/mm
Liquid: ~300 keV/cm ~3000 e$^-$/mm
Solid: ~4 MeV/cm ~ 50,000 e$^-$/mm

The ionization yield
drives the technology.



Gas

5 electrons/mm is hard!

- Resolution limited to ~1/5 mm
- Challenging to detect a small number of ions

That was for He; other gases have higher density, ~x10.
Can increase pressure for another factor of ~2.

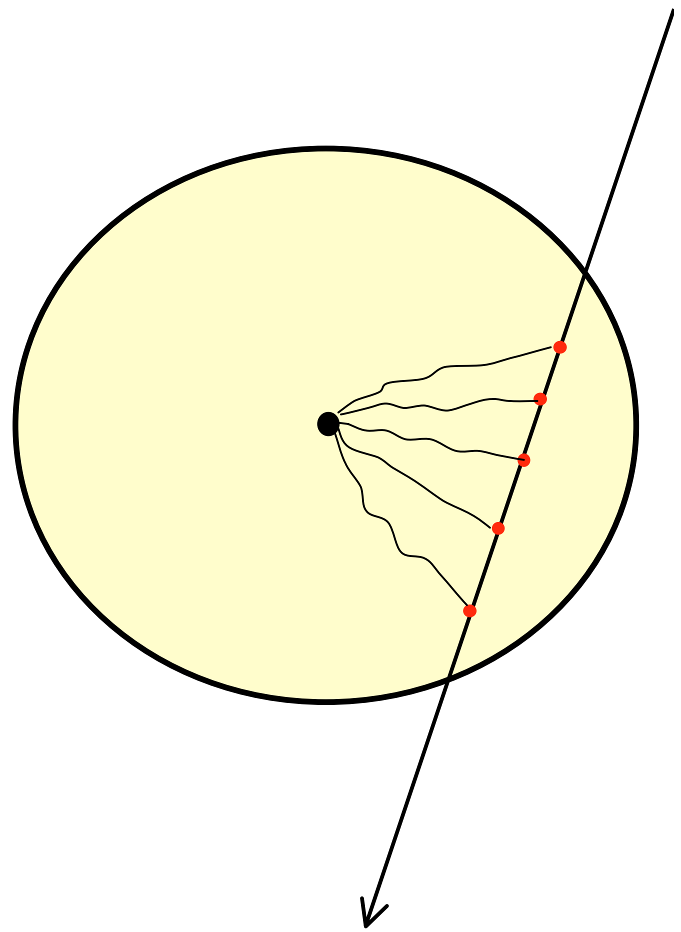
Need large amplification.

Gas Amplification

Single electrons amplified to detectable signal through gas amplification.
E.g., enclose gas in a cylinder with a thin central wire at +HV.

Liberated electrons drift toward wire.

- Repeatedly-scattered walk along E field lines.
- Constant drift speed, ≈ 50 μm/ns.



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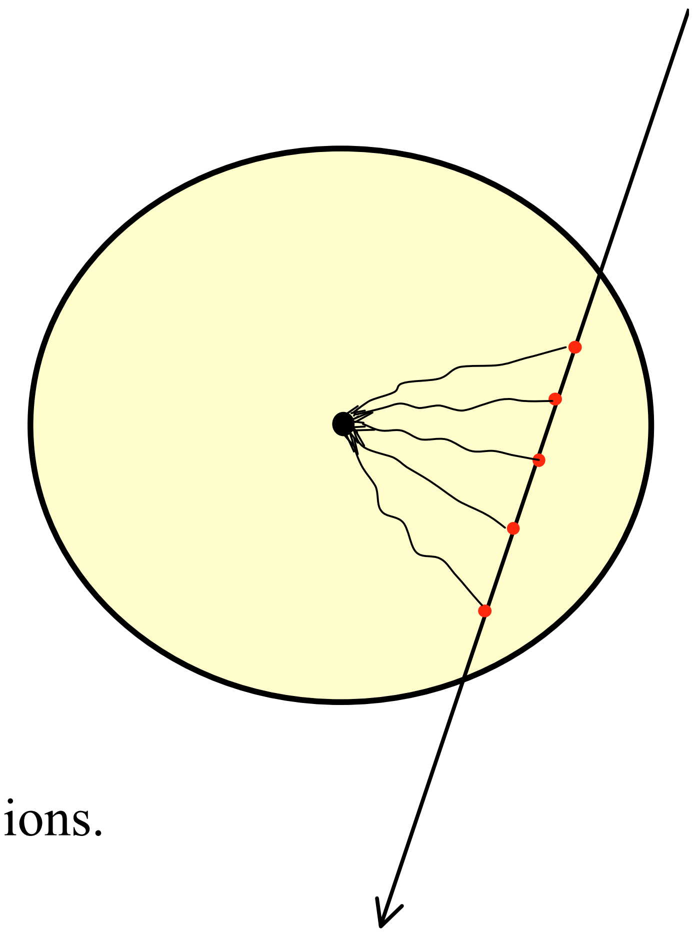
E field increases dramatically near wire.
Energy gained between scatters sufficient to further ionize gas.
⇒ Amplification

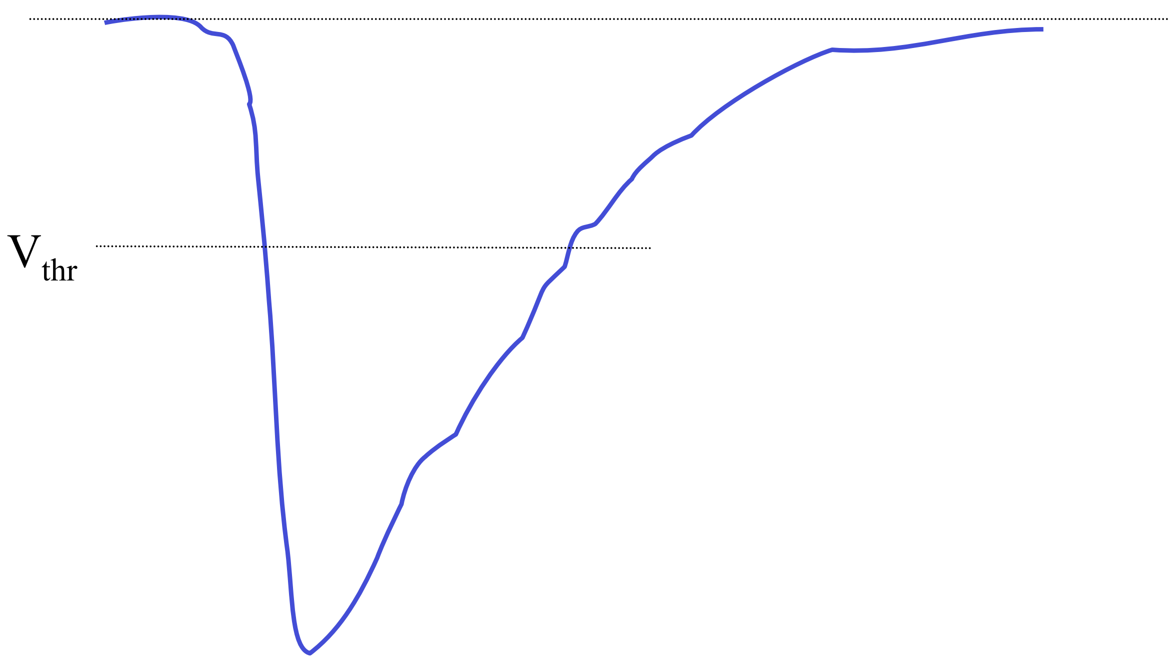


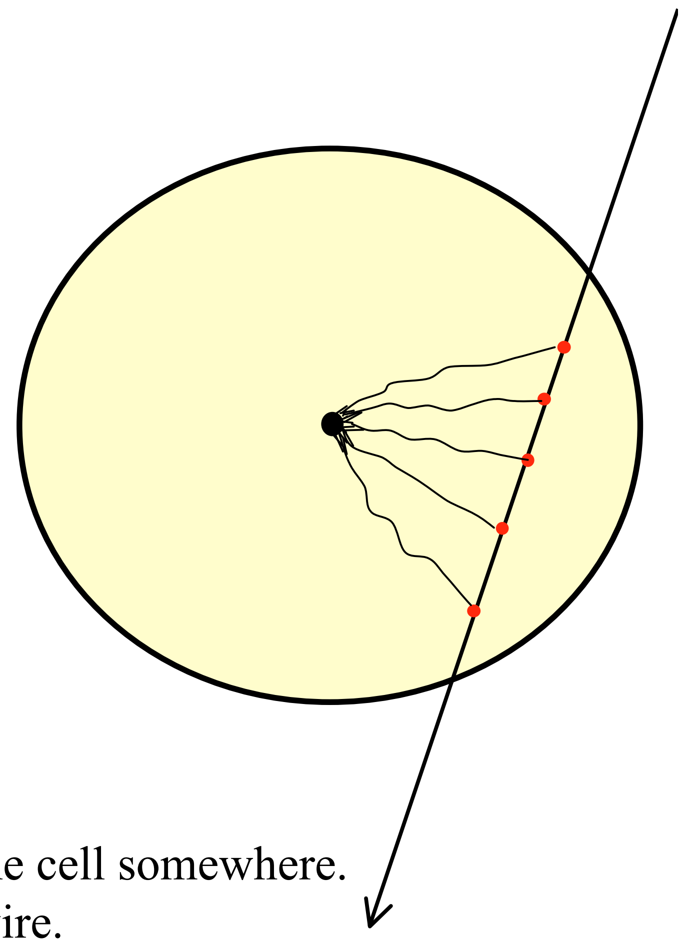
Amplification stabilized by "quencher."

Get a pulse of current from the moving electrons and ions.

Gas Drift Chambers

Current pulse…Each individual primary ionization, merges into one.
Fast rise from electrons, long decay from slow ions.

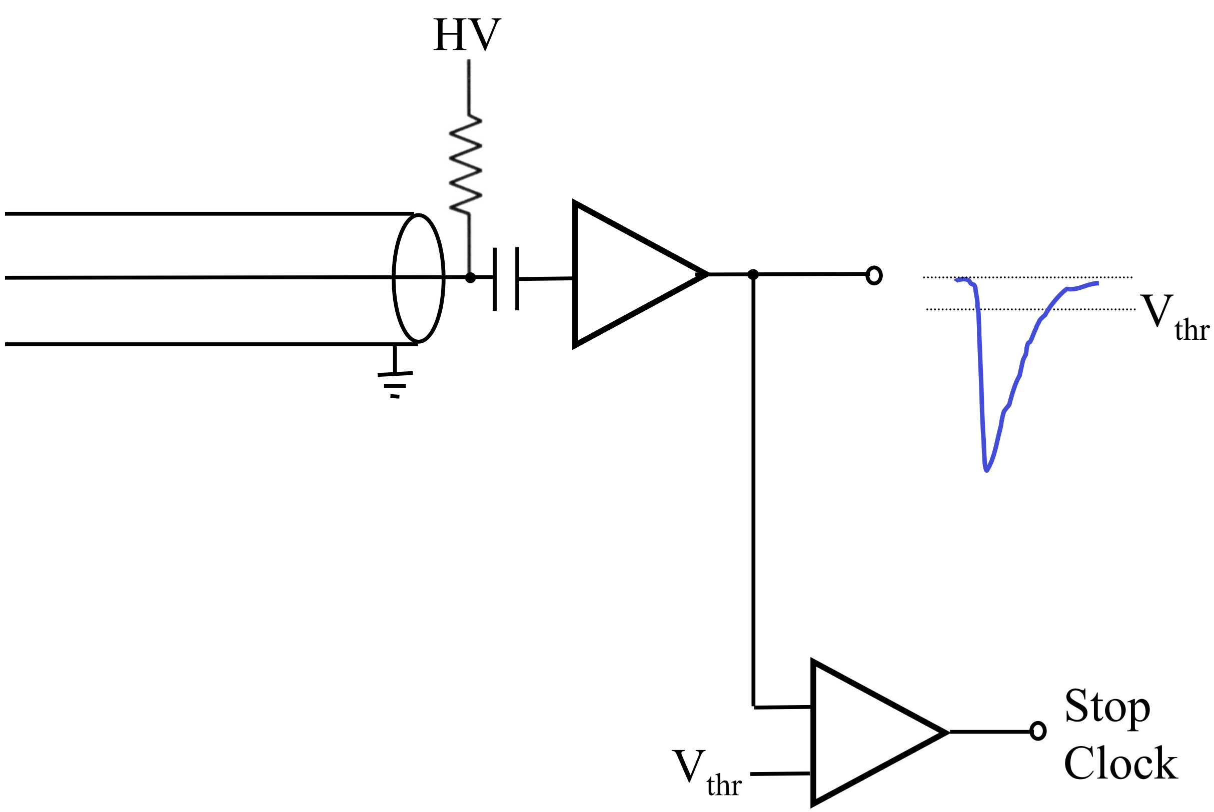


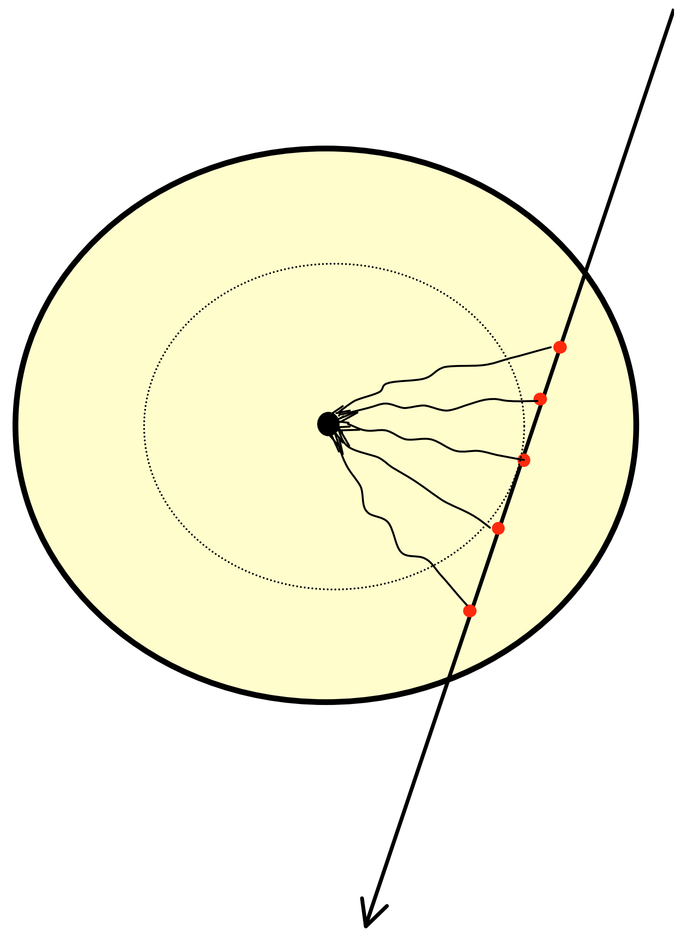


Charge above some threshold indicates a particle traversed the cell somewhere.
But, when the pulse occurred tells how close it came to the wire.

Drift Chamber Electronics

Need to detect and time stamp a current pulse from a HV wire.





Start the clock at beam crossing,
and subtract flight and signal propagation to get drift time.

Drift Chamber Resolution

Resolution at worst ≈ R, actually R/sqrt(12).

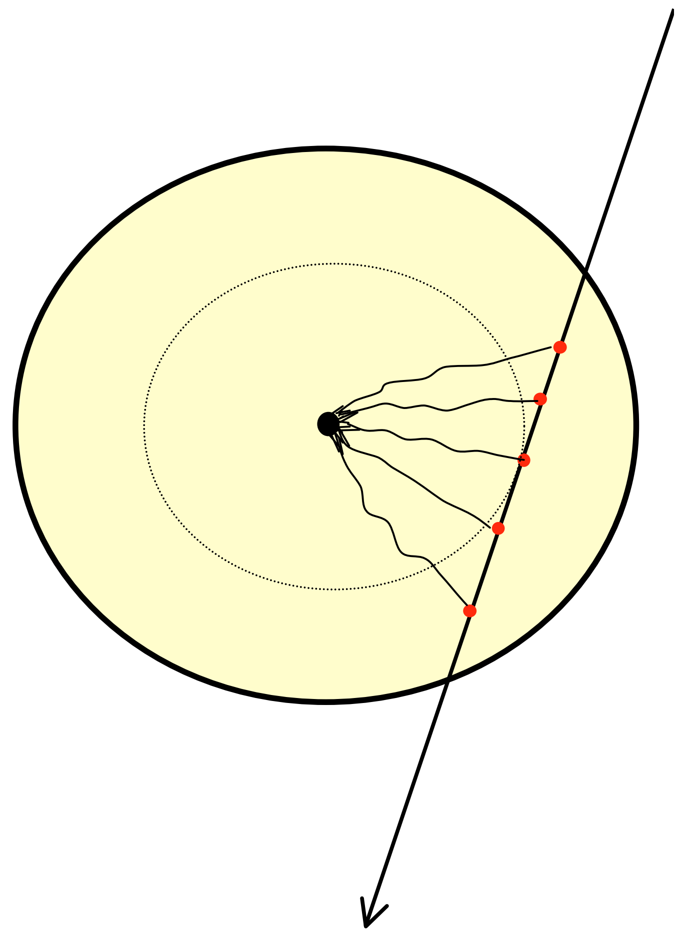
Timing based distance of closest approach limited by:

$\sigma_{timing} \approx$ 50 μm (for 1 ns)

$\sigma_{Diffusion} \approx$ 100 μm

$\sigma_{IonizFluct} \approx$ 100 μm

Typical resolutions are 100 - 200 μm.



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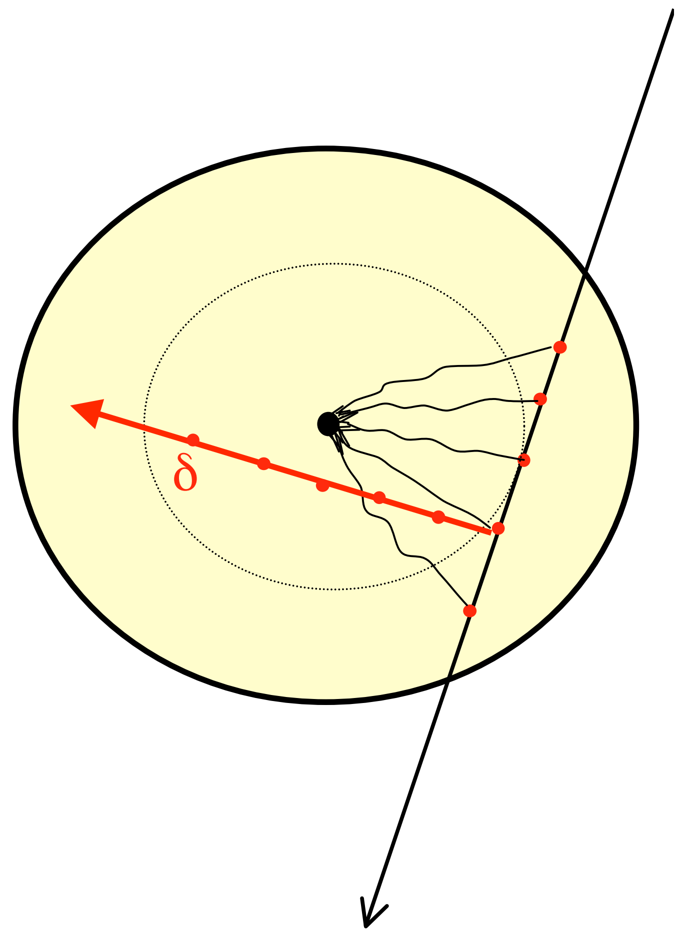
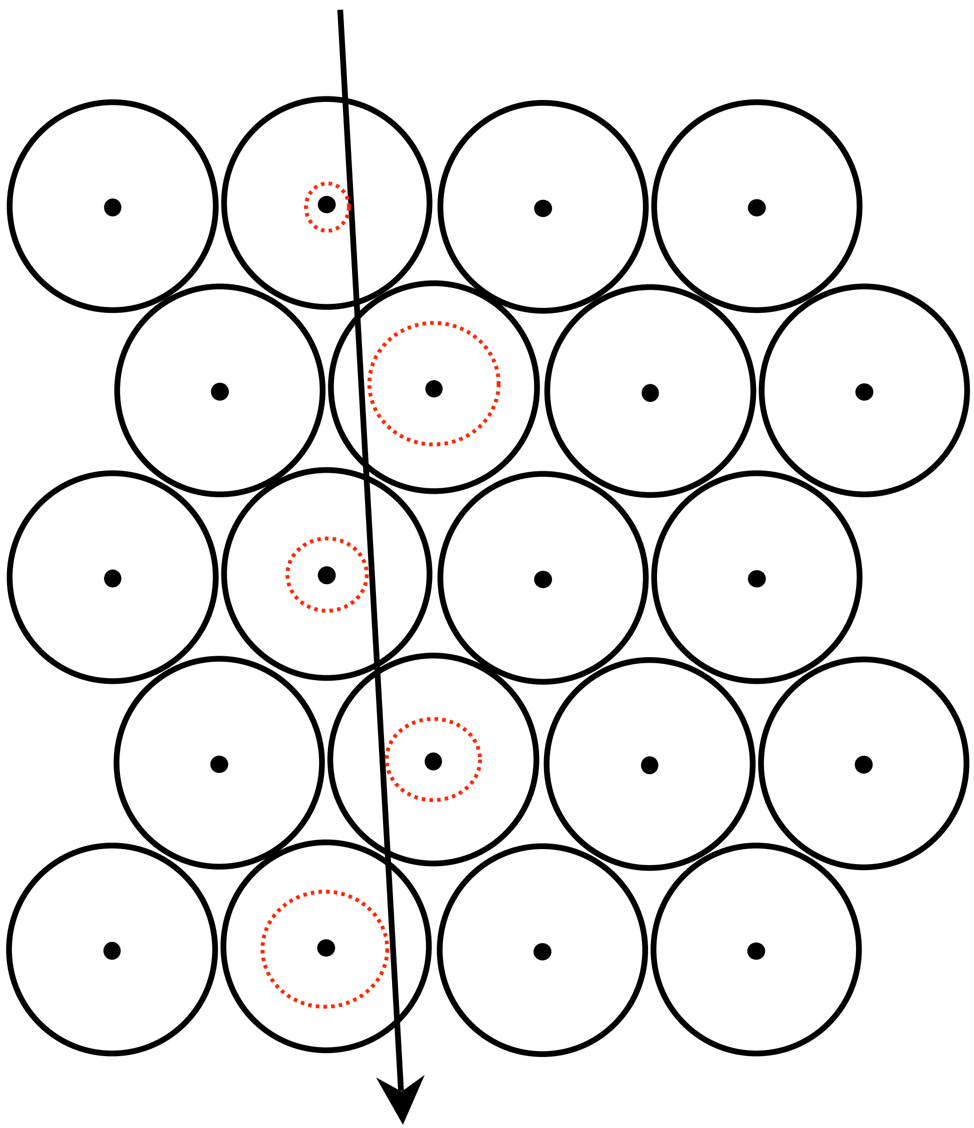
Systematics on resolution:

- Alignment, e.g., wire sag
- t0
- δ-rays
- Left-right ambiguity



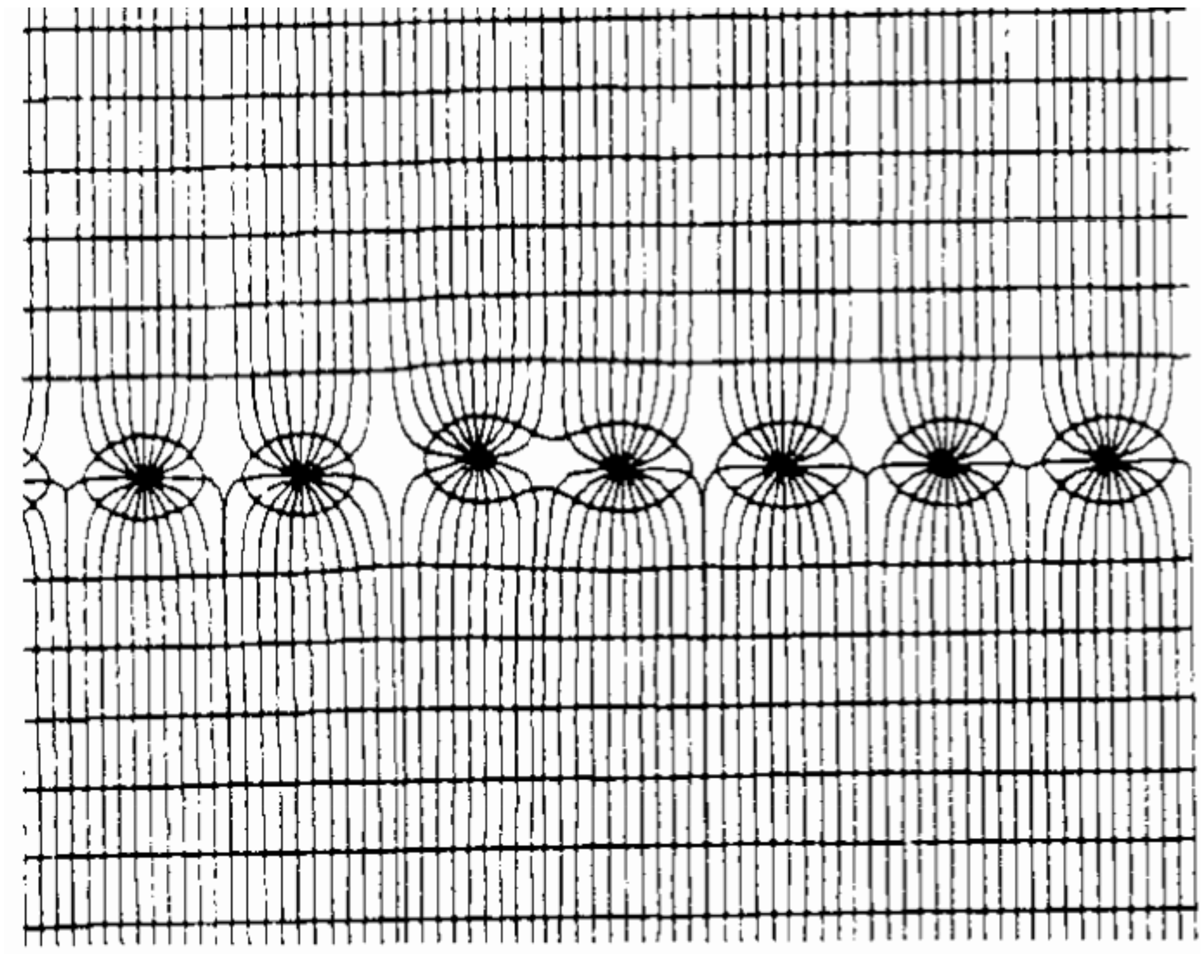
Drift Chamber Geometry

Can resolve left-right ambiguity with several staggered cells.



Drift Chamber Geometry

This basic principle can be applied in many different geometries.
The original was the **M**ulti **W**ire **P**roportional **C**hamber



G. Charpak, Nobel lecture '92

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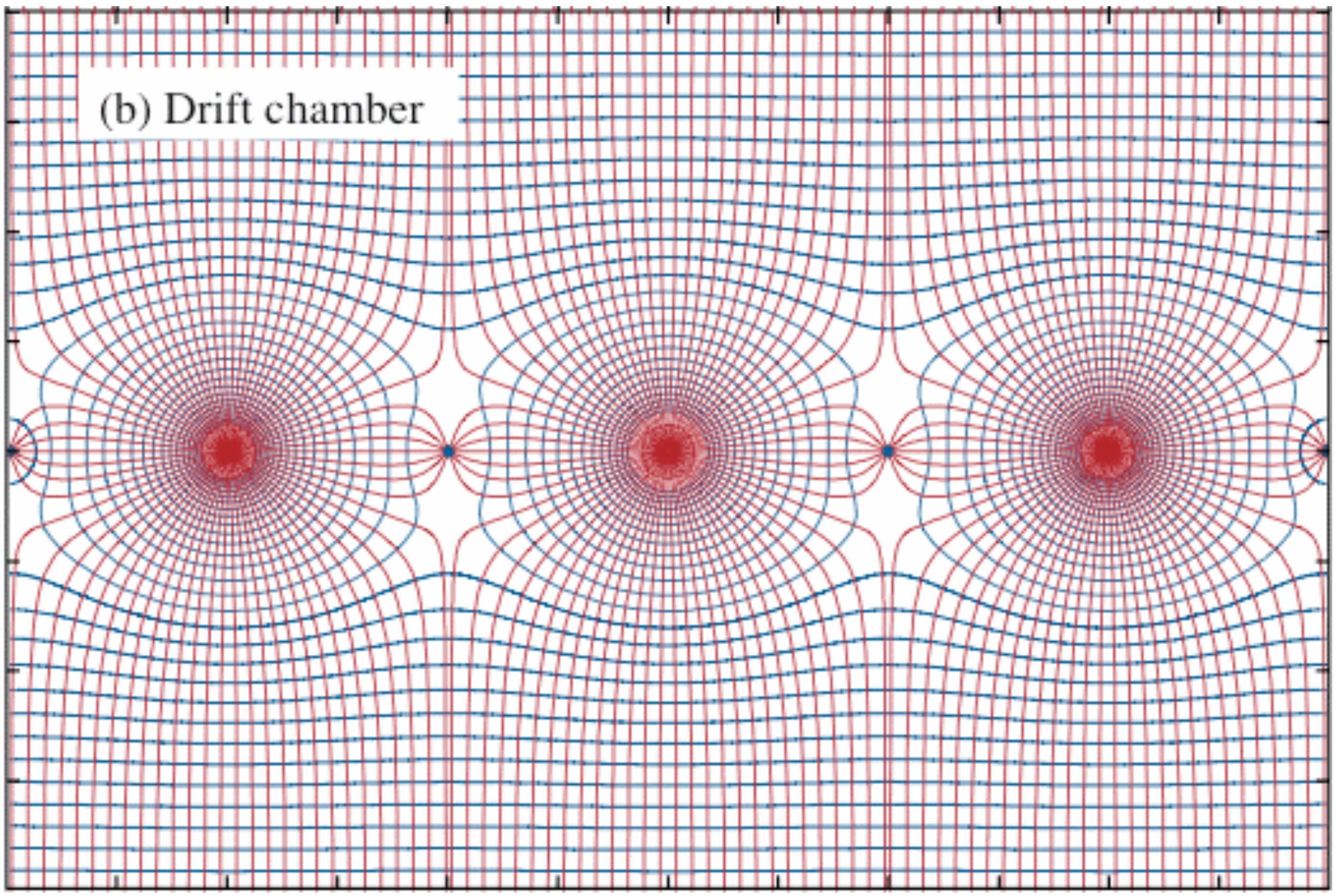
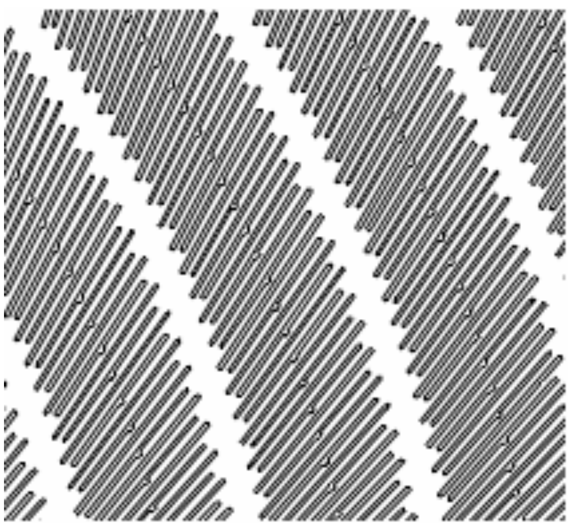
The original was the **M**ulti **W**ire **P**roportional **C**hamber
Drift chambers can shape field lines with ground wires and sheets.

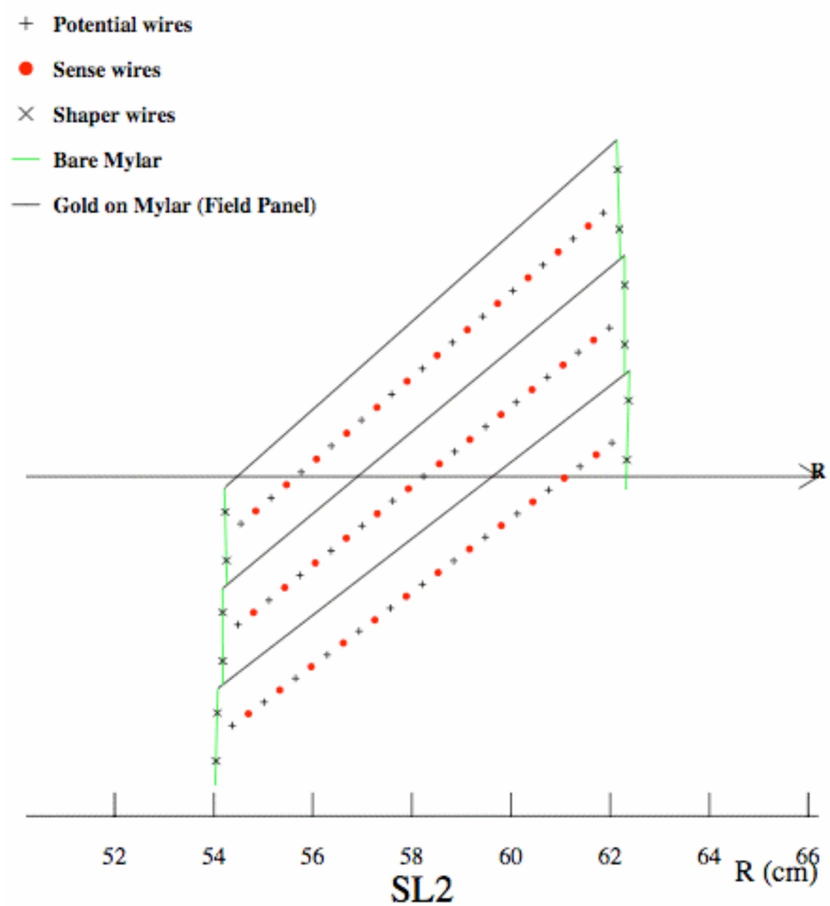


PDG

CDF's Drift Chamber Geometry

- Field shaped by wires and sheet.
- 40 mm diam Au plated W wire
- Cell tilted due to Lorentz angle





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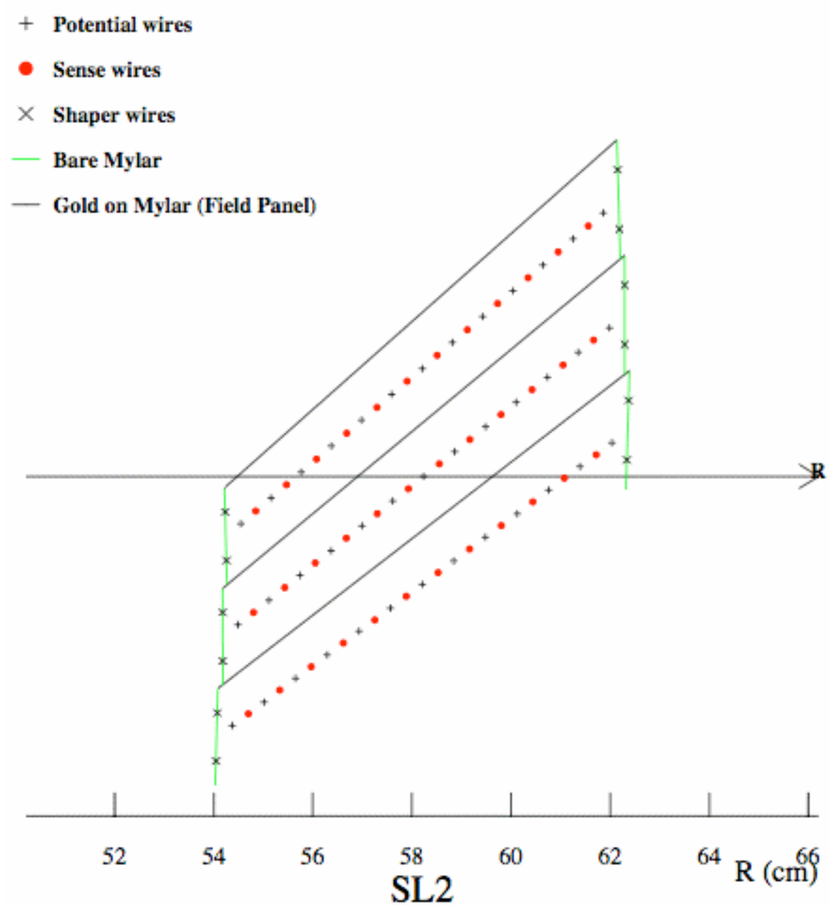

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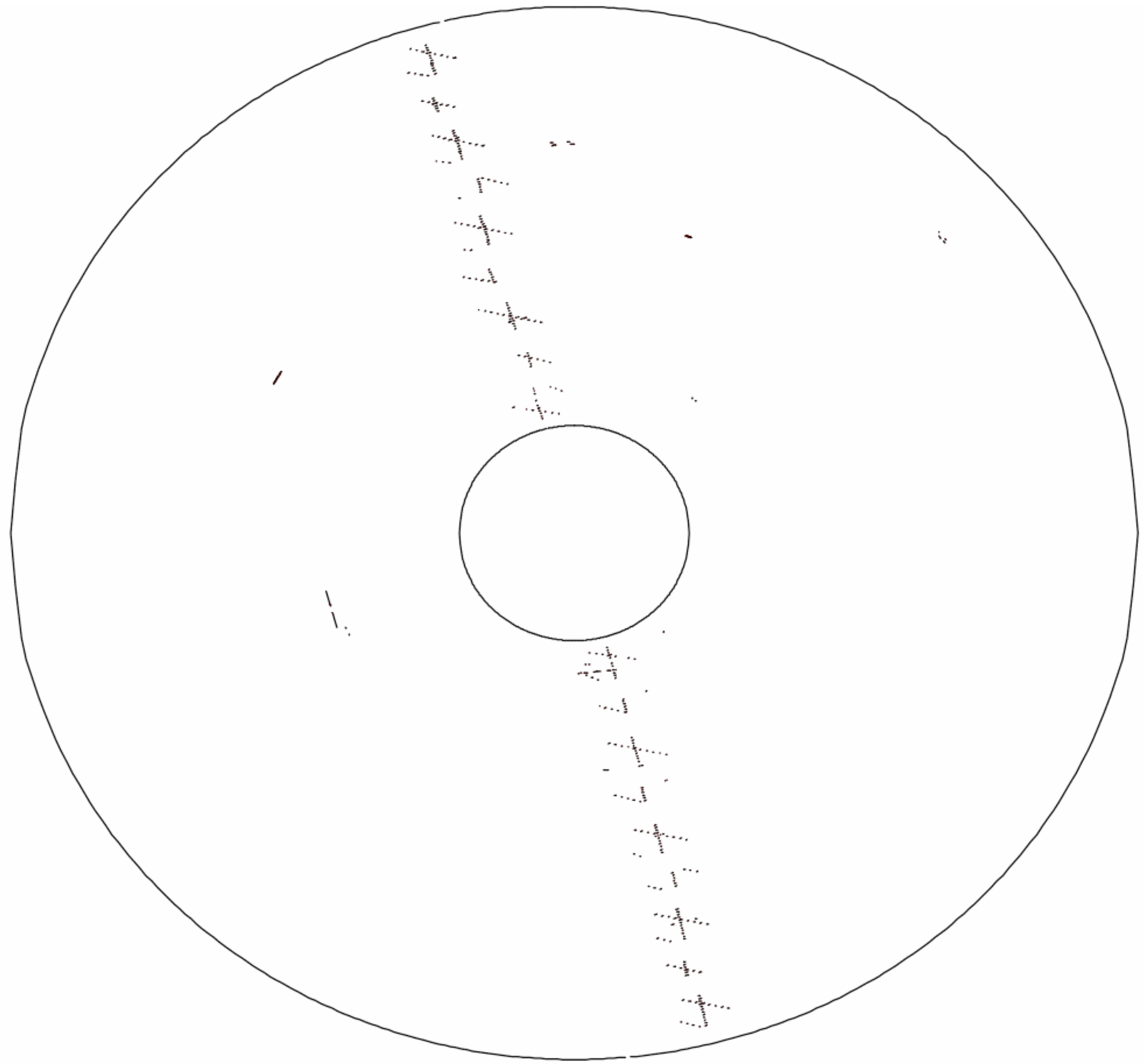
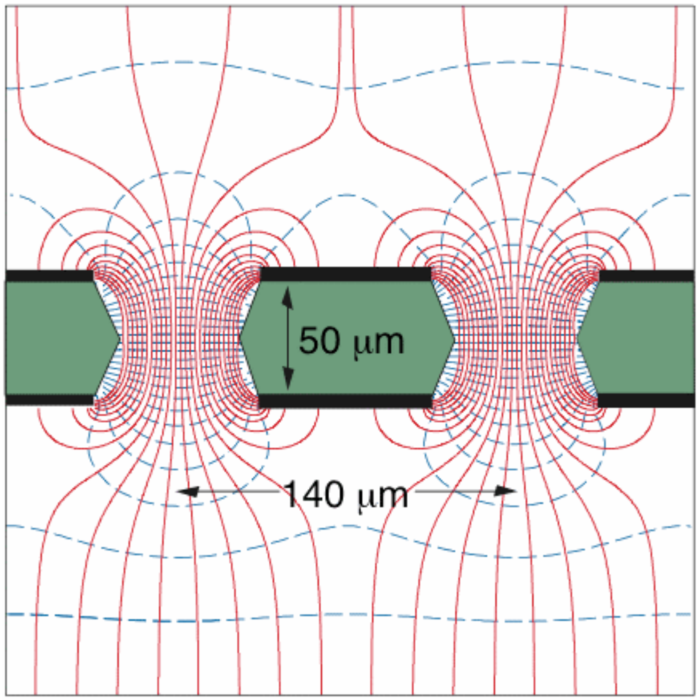
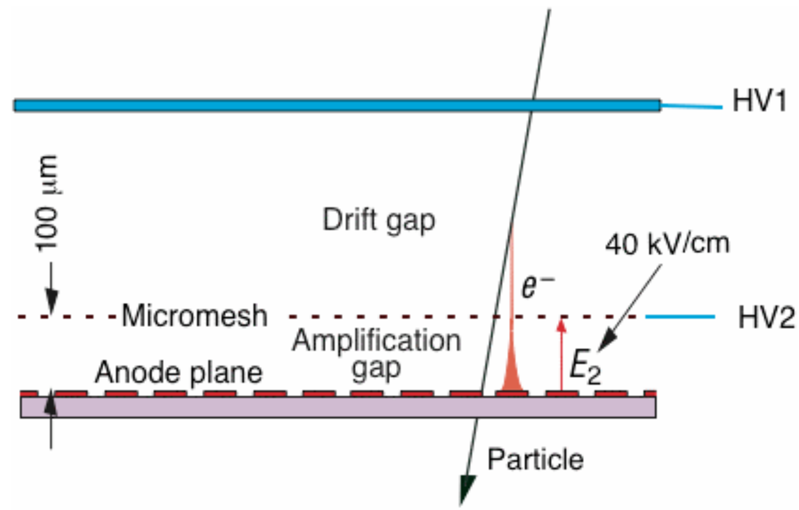


This is actually a Run 1 event, where there were some differences.

Other Drift Chambers Geometries

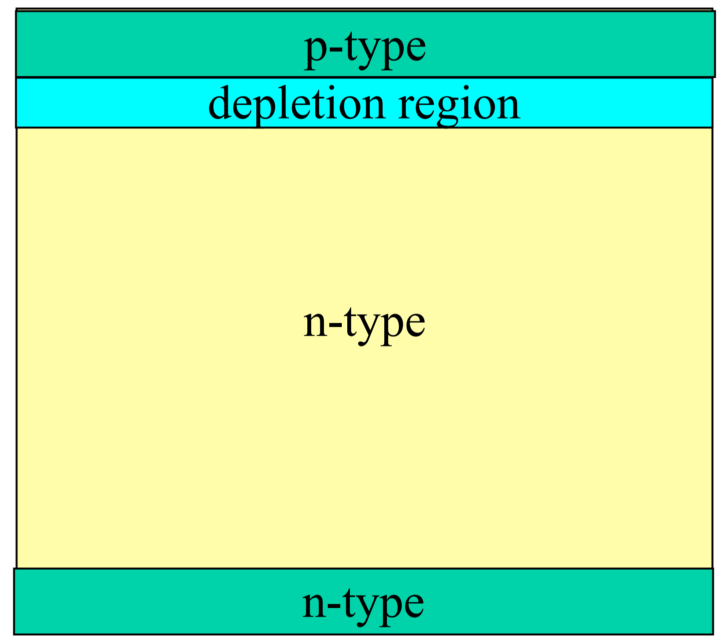




Solid State Detectors

Basic operation is similar to a photodiode

A pn diode has a natural depletion zone free of charge carriers.



Solid State Detectors

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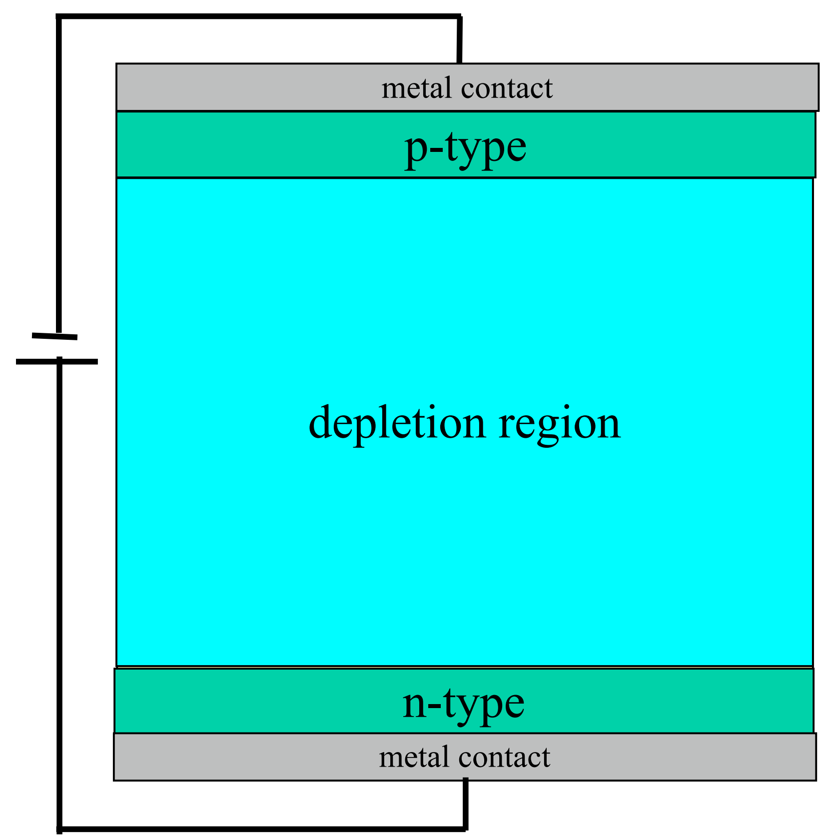
A pn diode has a natural depletion zone free of charge carriers.
Reverse biasing extends depletion region.

Small leakage current from thermally generated e-hole pairs.

Photons generate charge carriers ⇒ current.



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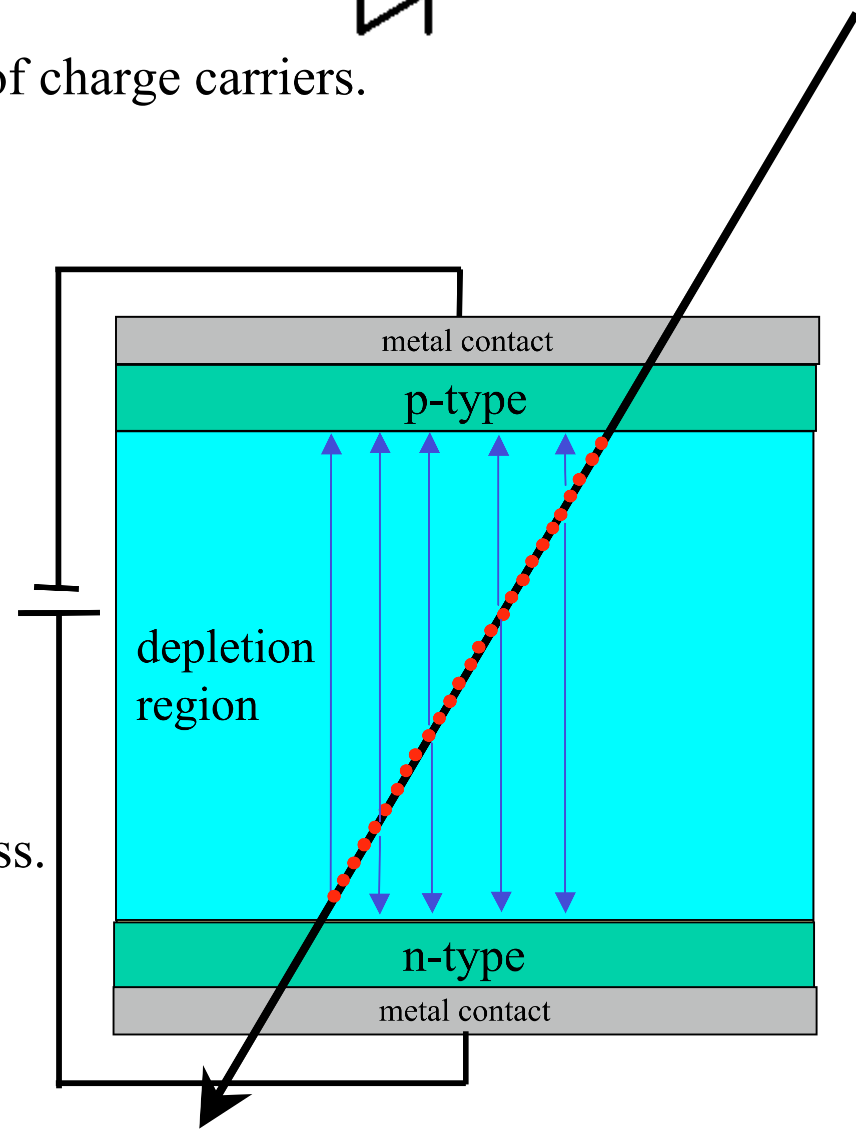
Charged particle ionization generates charge carriers ⇒ current.

≈ 20k electrons in ≈ 20ns for 300 μm thickness.
⇒ Electronics challenge.

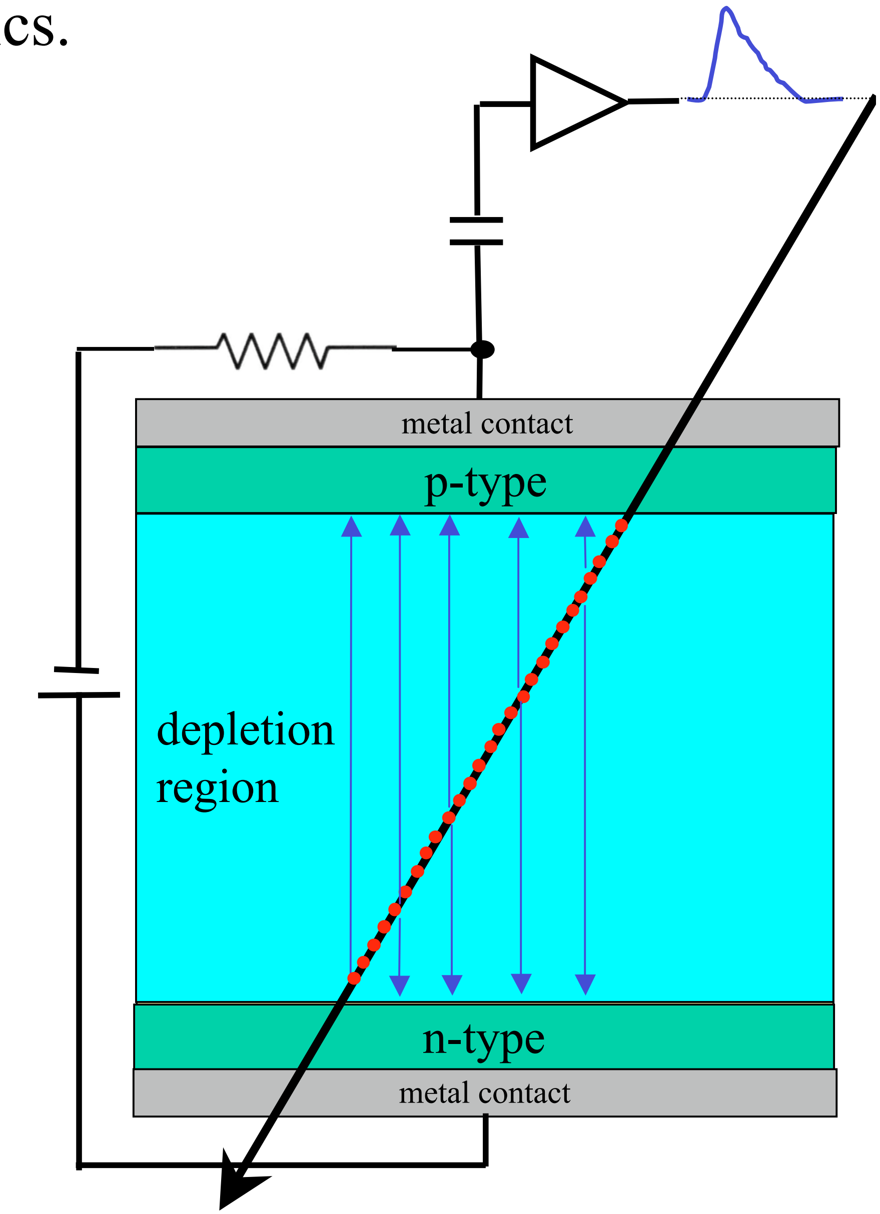


Solid State Detector Electronics

Signal amplification only in electronics.

$\Rightarrow$ Low noise amplifiers.

Current integrator gives total charge.



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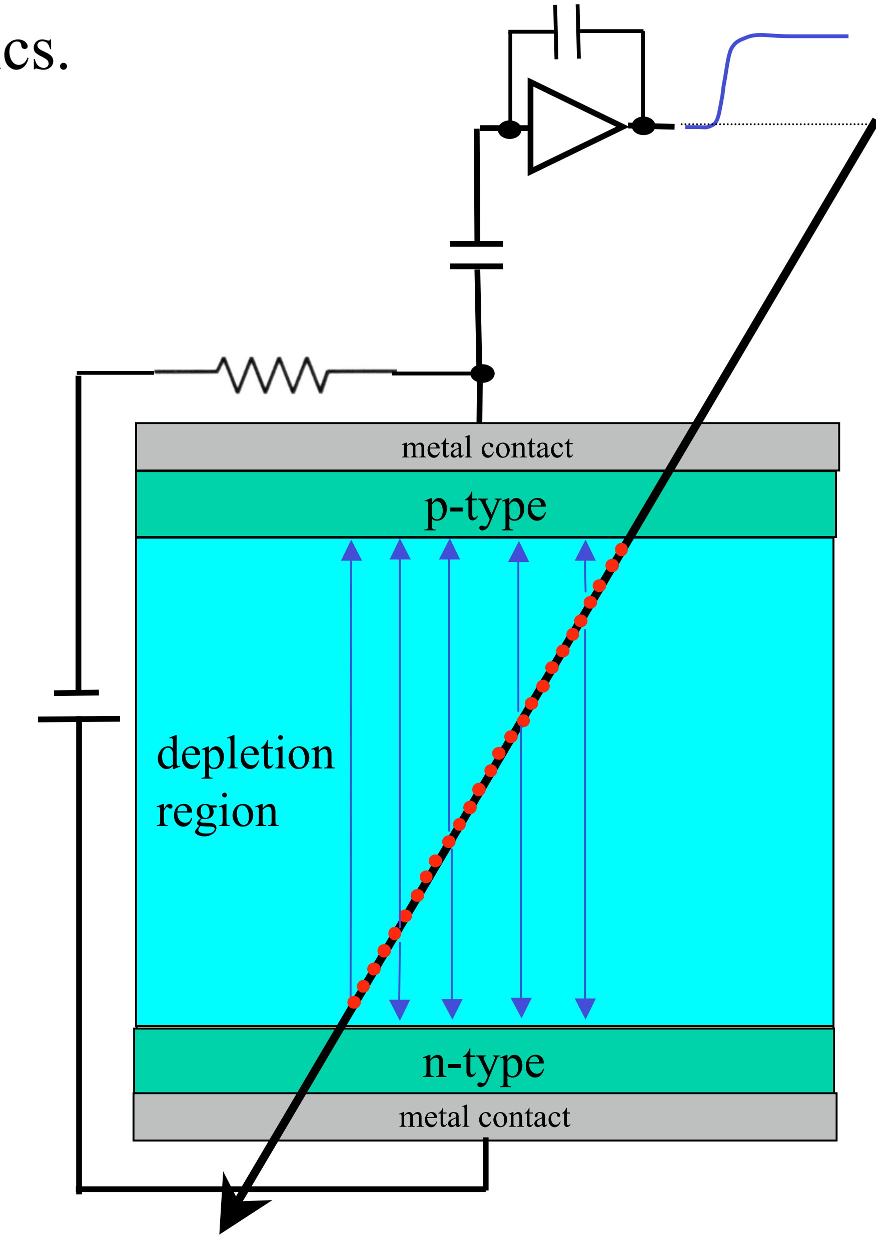
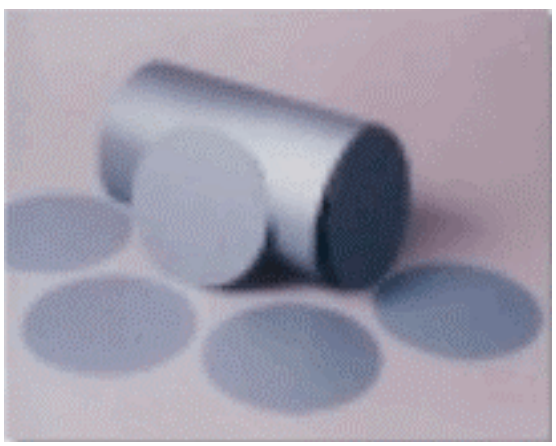
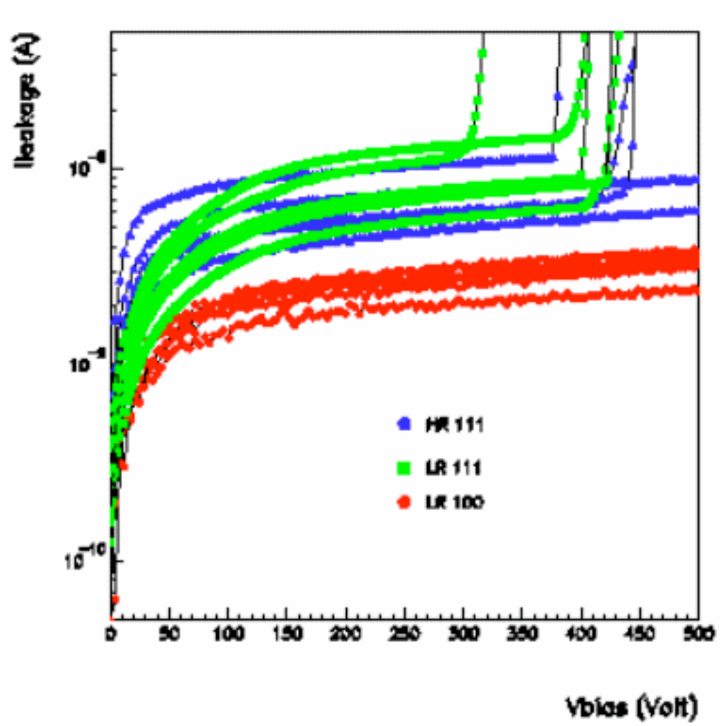
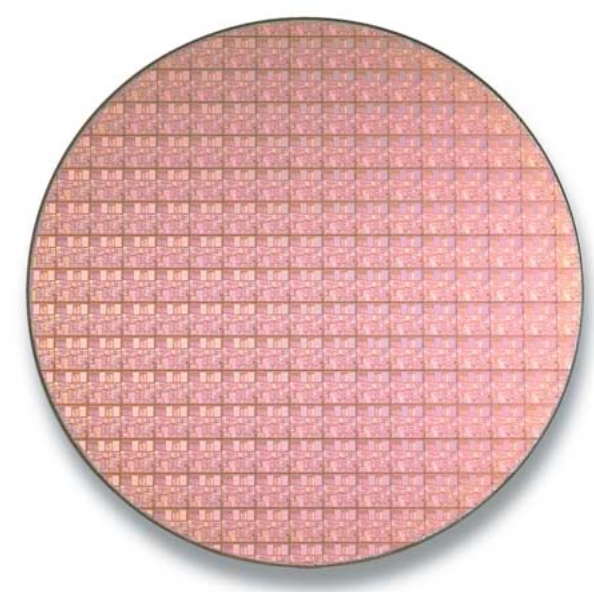


Sensor challenge

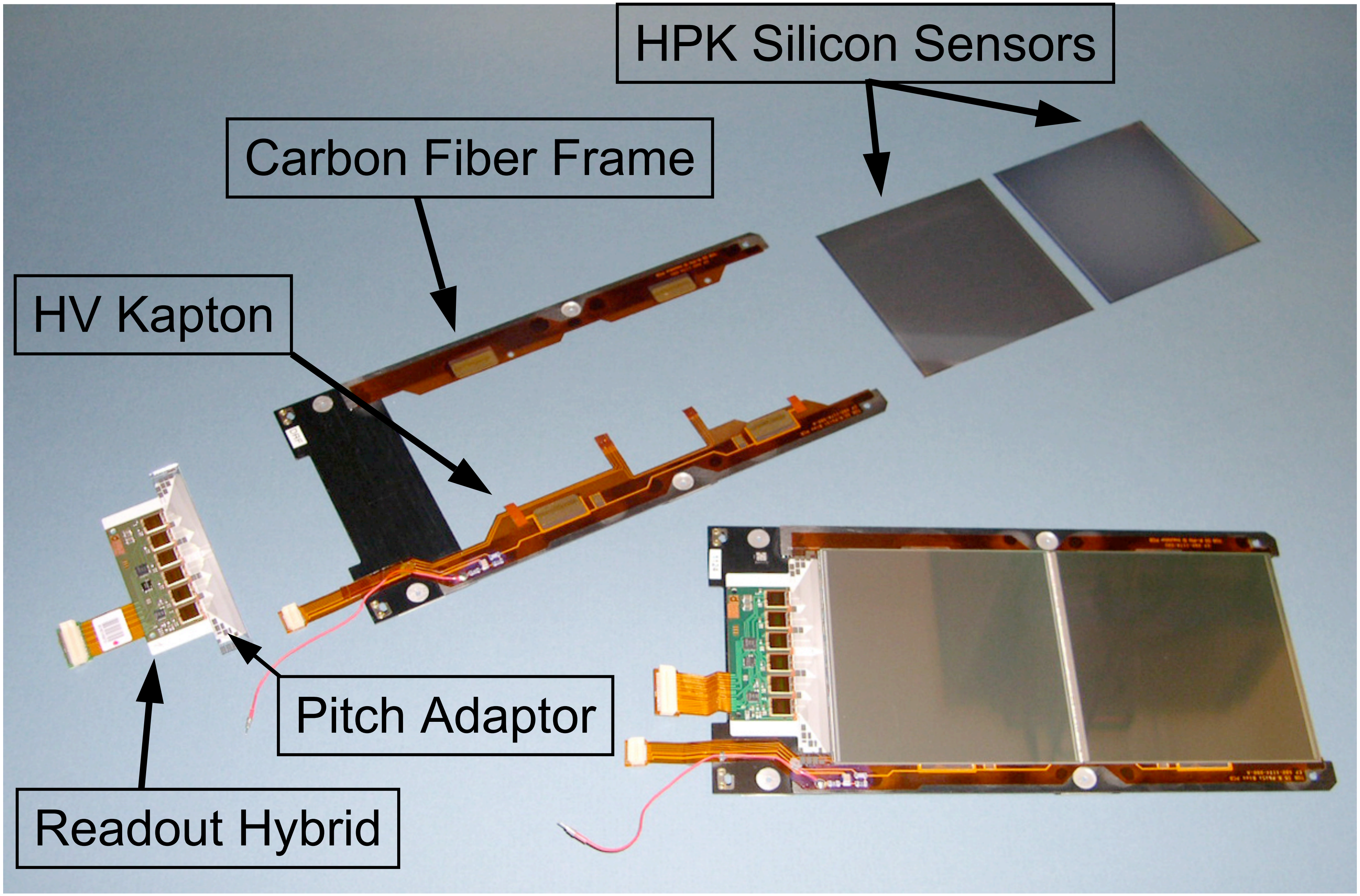
Possible to get O(1000) electron equivalent noise.
OK for 20k electron signal (300 μm).
Silicon structures normally O(1) μm thick.
Need O(100) V to deplete ⇒ high purity, high resistivity.
Using ≈ full sensor sensitive to even small defect rate.





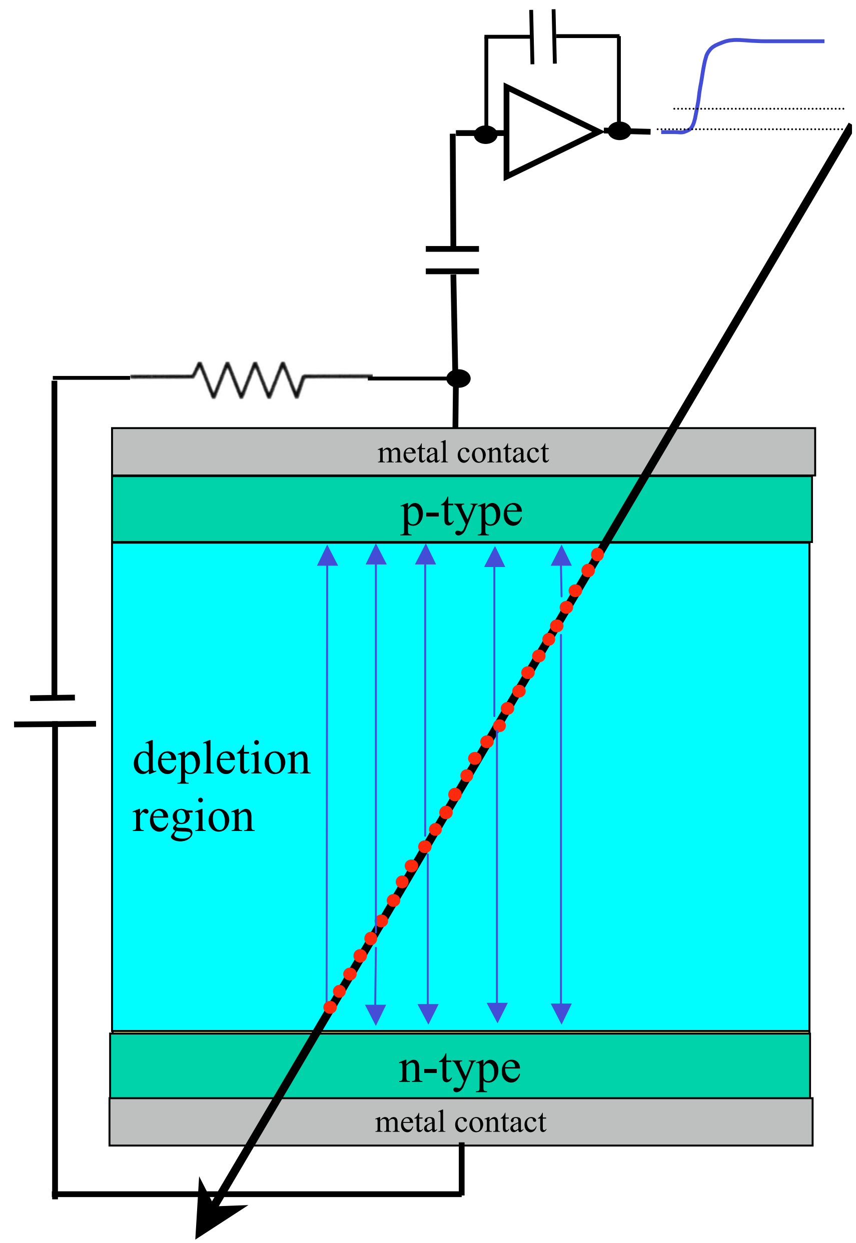


Mechanical challenge



Solid State Detector Resolution

Depends on size of diode…



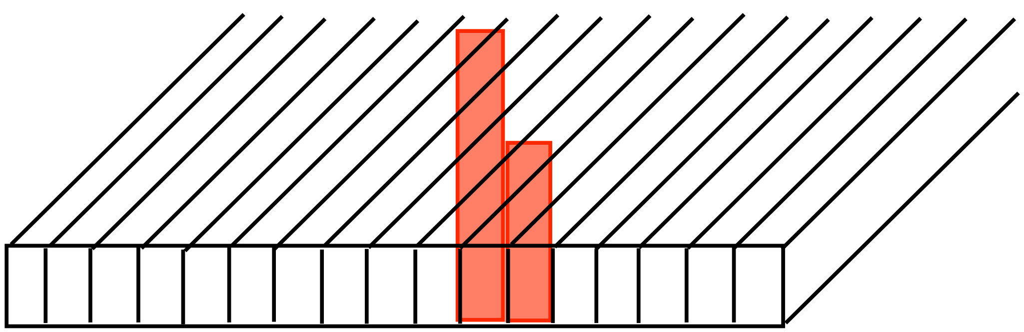
Solid State Detector Resolution

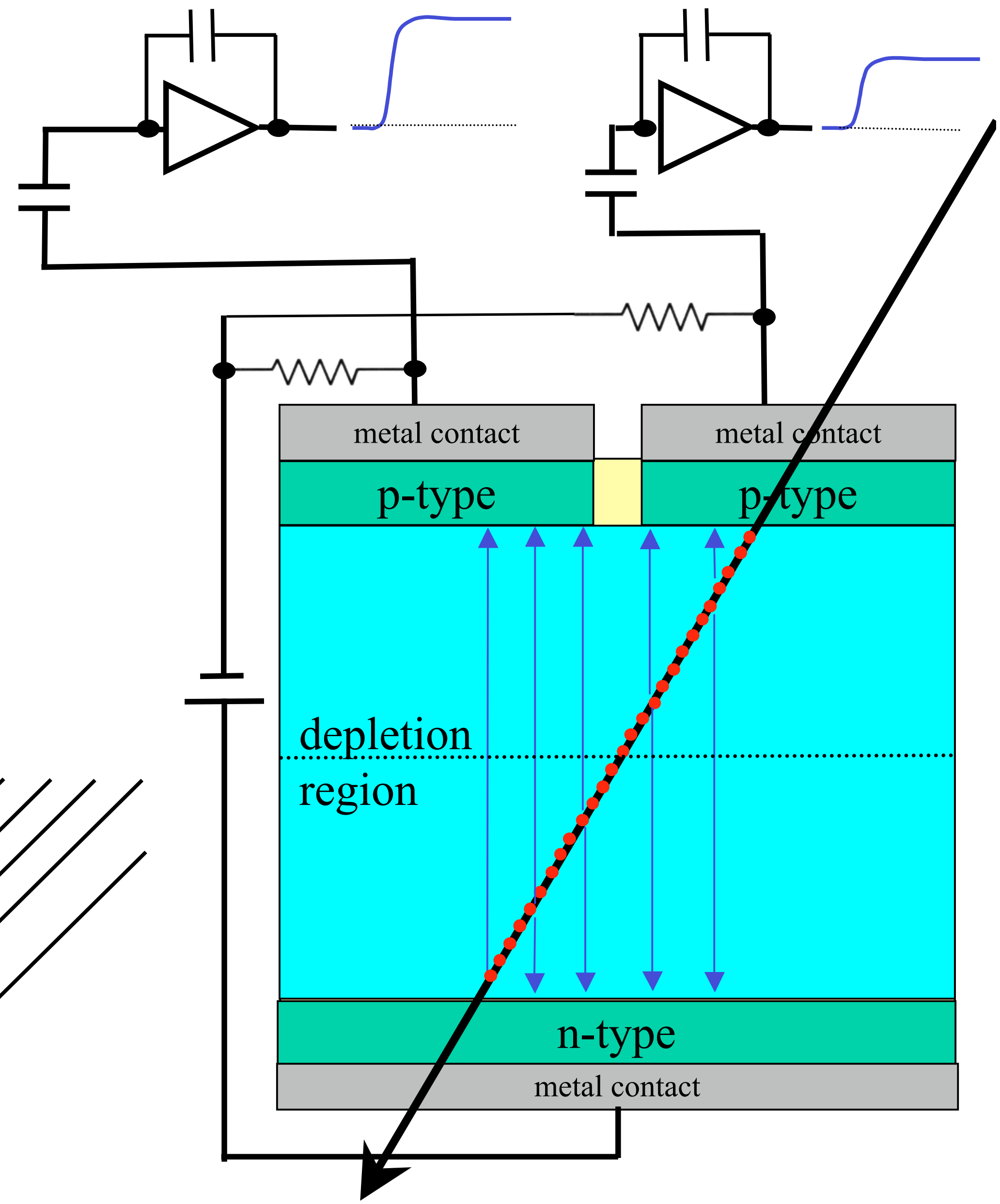
Depends on size of diode…

Lithography allows small diodes.

Charge weighting allows
more precise position determination

$$\bar{x} = \frac{\Sigma x_i q_i}{\Sigma q_i}$$





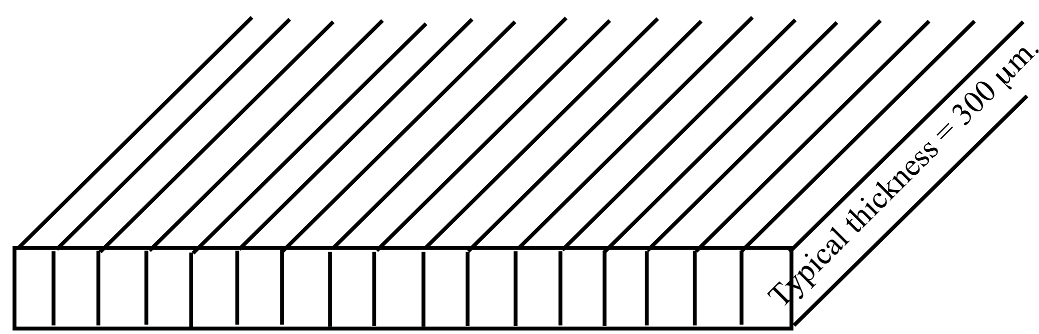
Solid State Detector Resolution

Depends on size of diode. Lithography allows small diodes.
Charge weighting allows more precise position determination

$\sigma_x \approx$ pitch/sqrt(12) if one channel
$\sigma_x \approx$ pitch/4 if two channels
$\sigma_x \approx$ pitch/2 if three channels

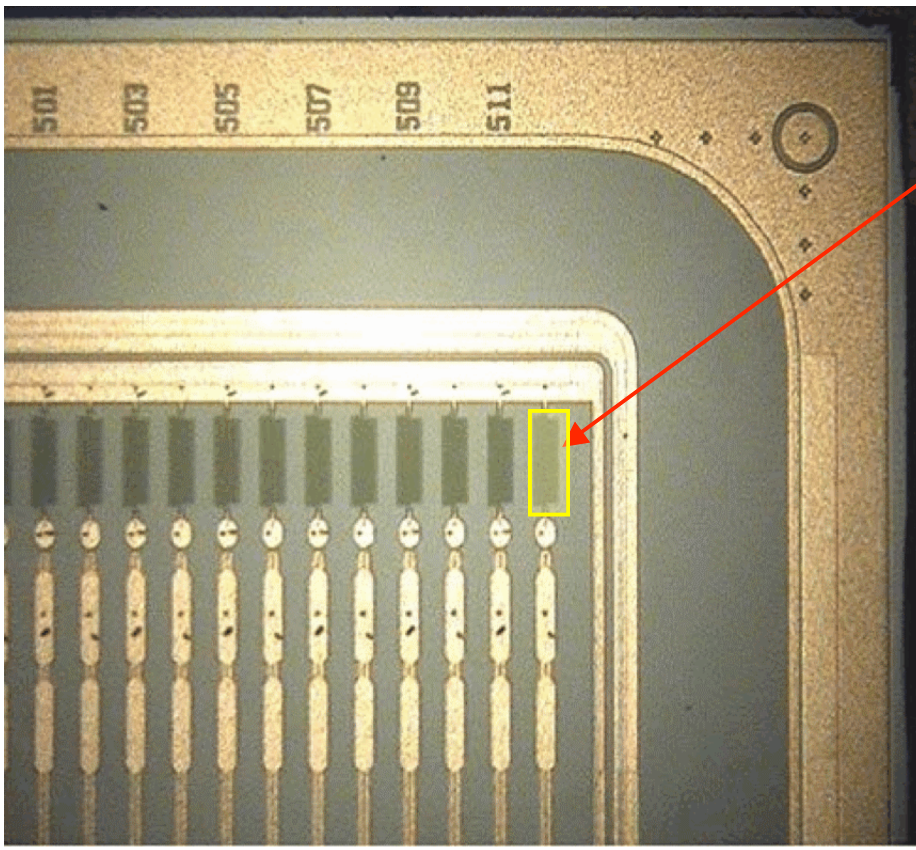
Make the pitch small.

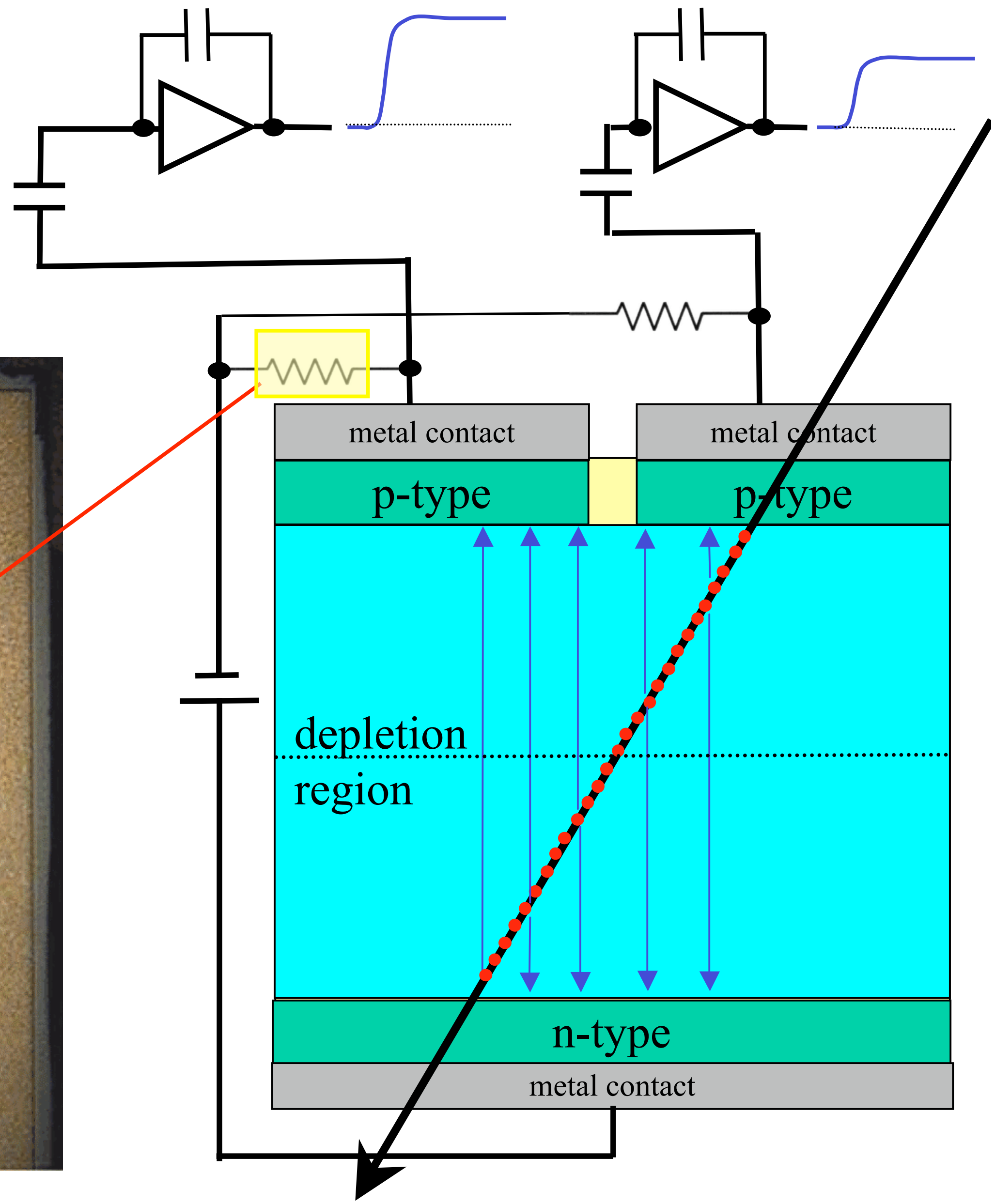
Typical pitch = 50 to 200 μm.
⇒ Many channels.



Many channel challenge

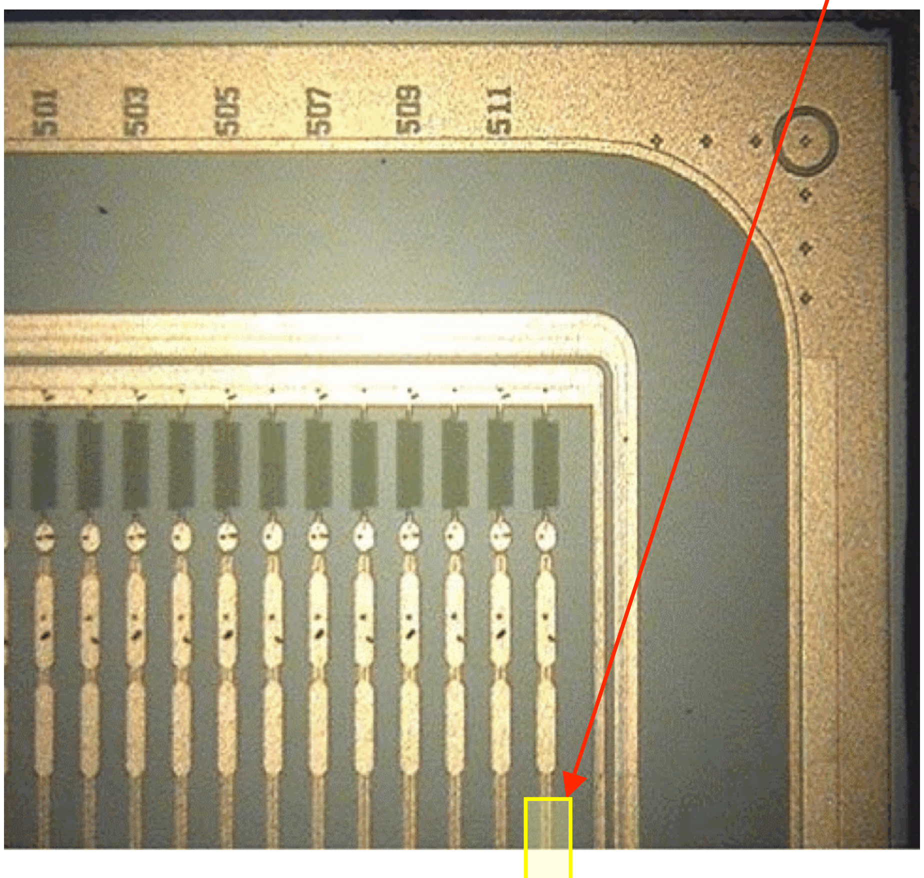
Build resistors into silicon.

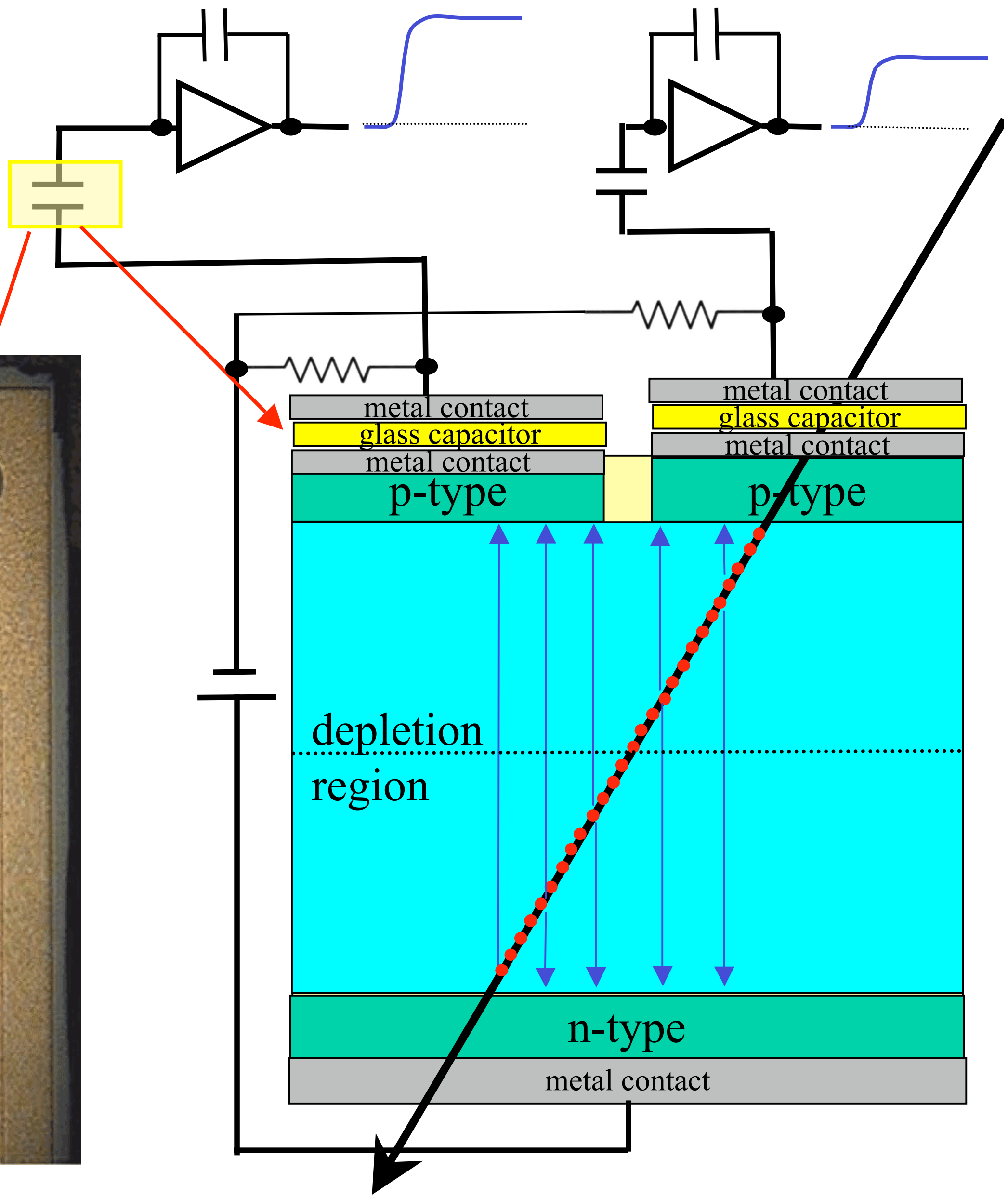




Many channel challenge

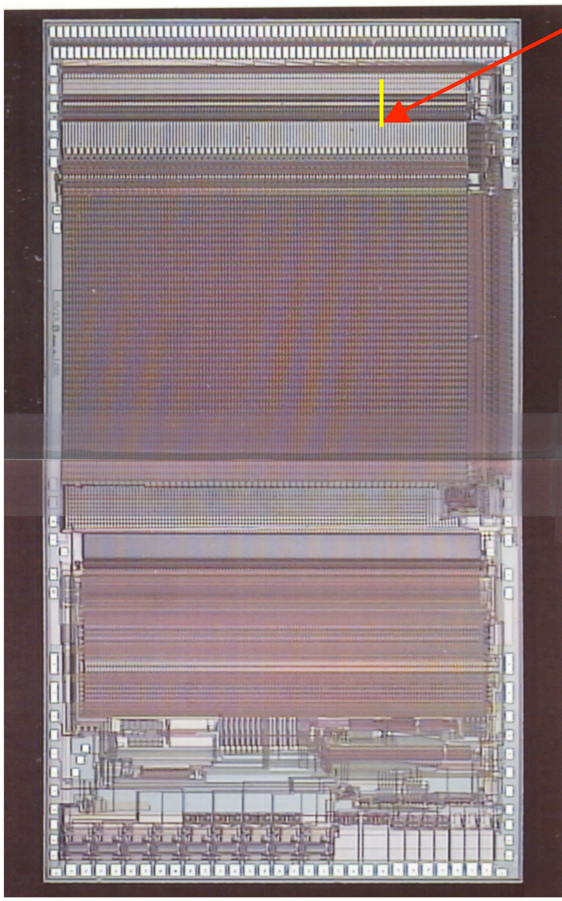
Build capacitors into silicon.

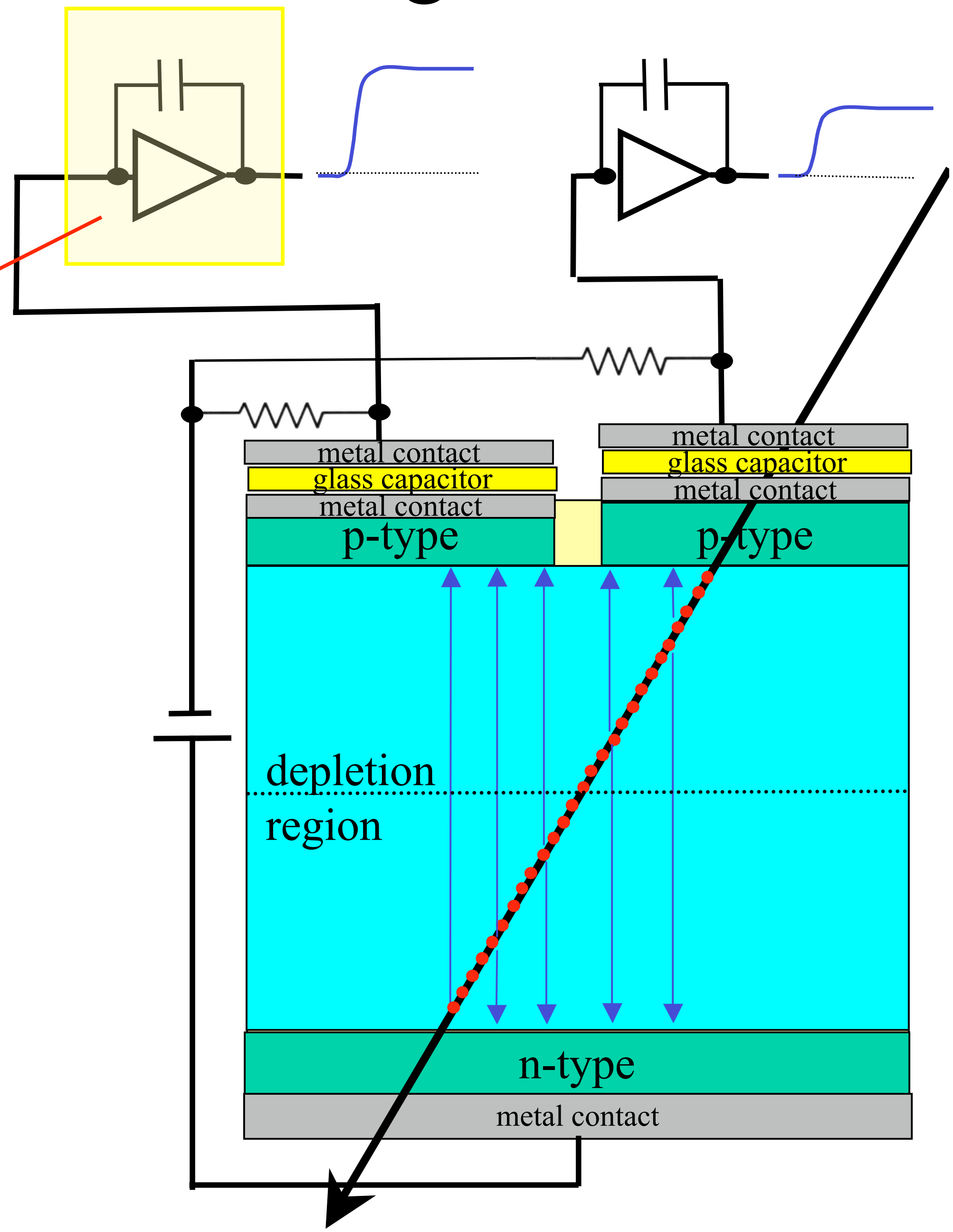




Many channel challenge

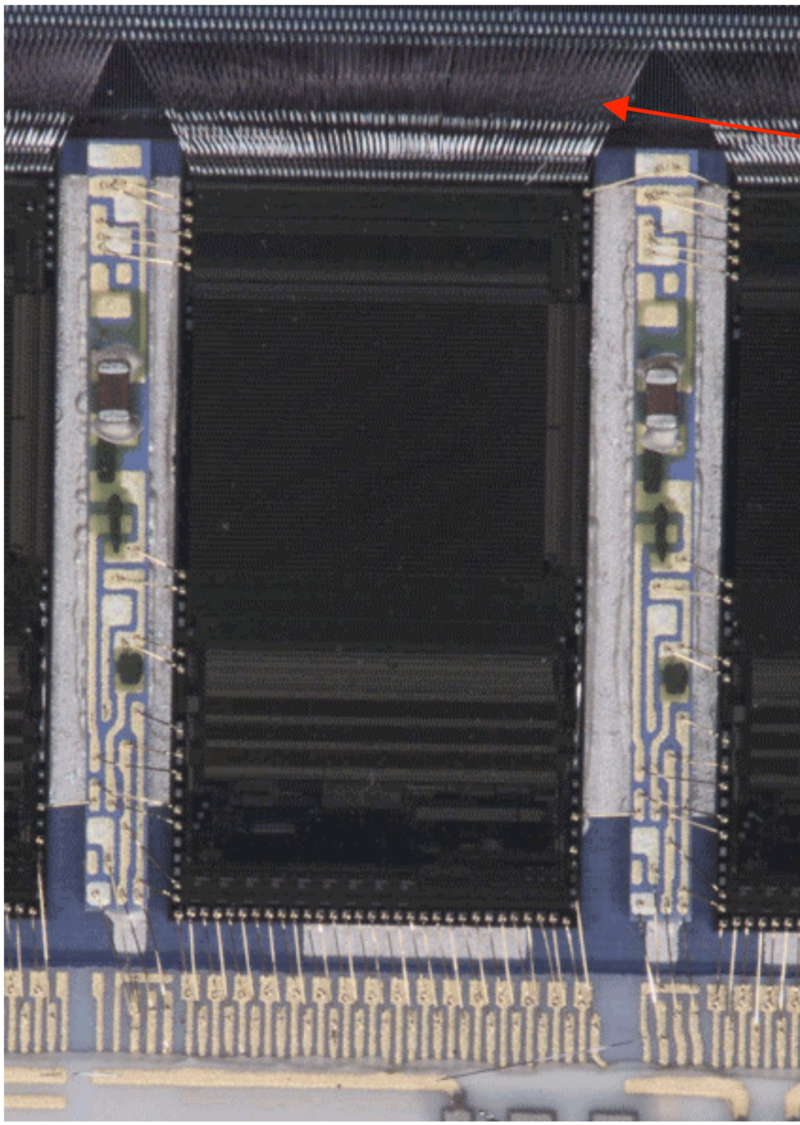
ICs for 128 channels

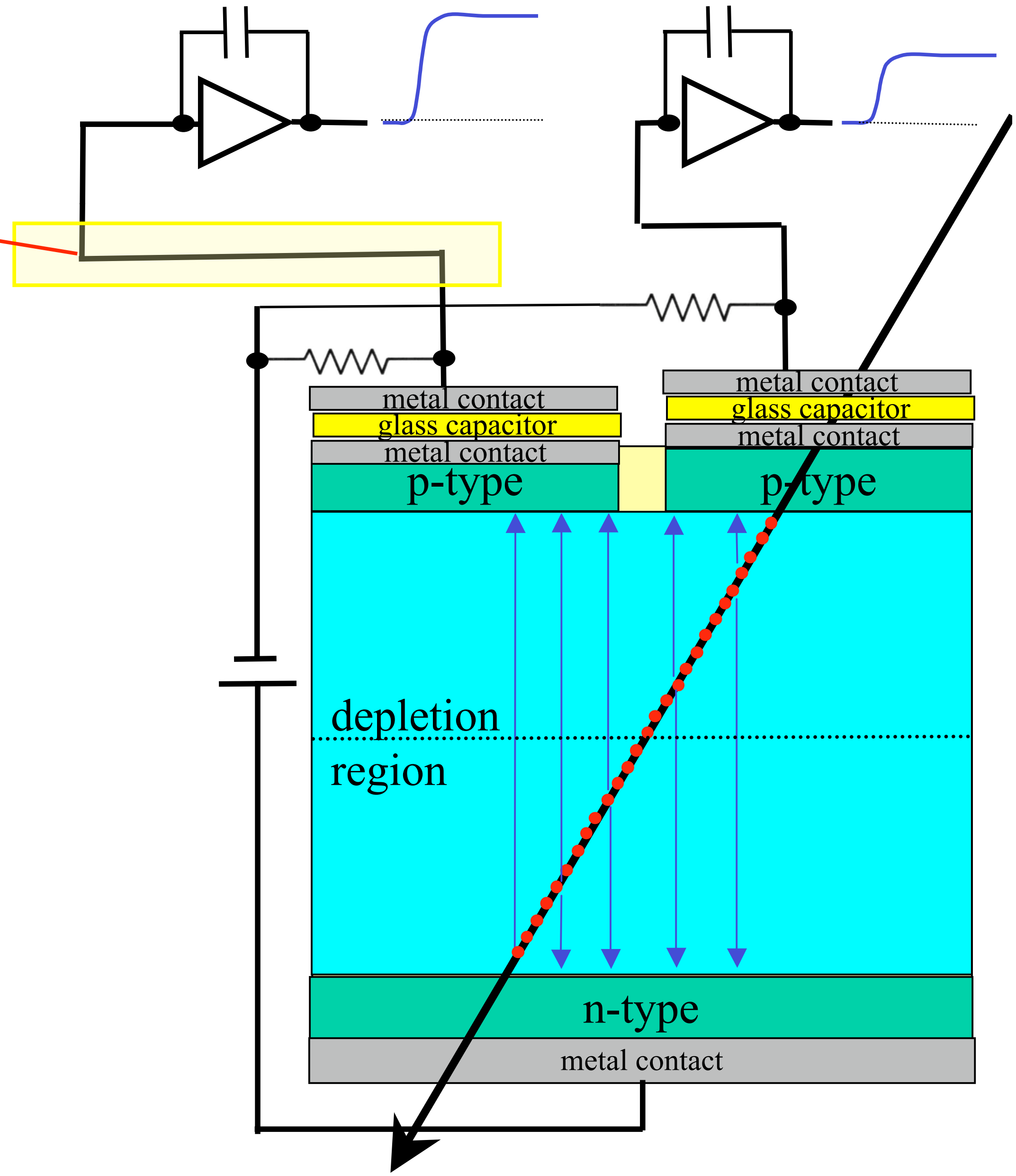




Many channel challenge

Make a lot of connections





Many channel challenge

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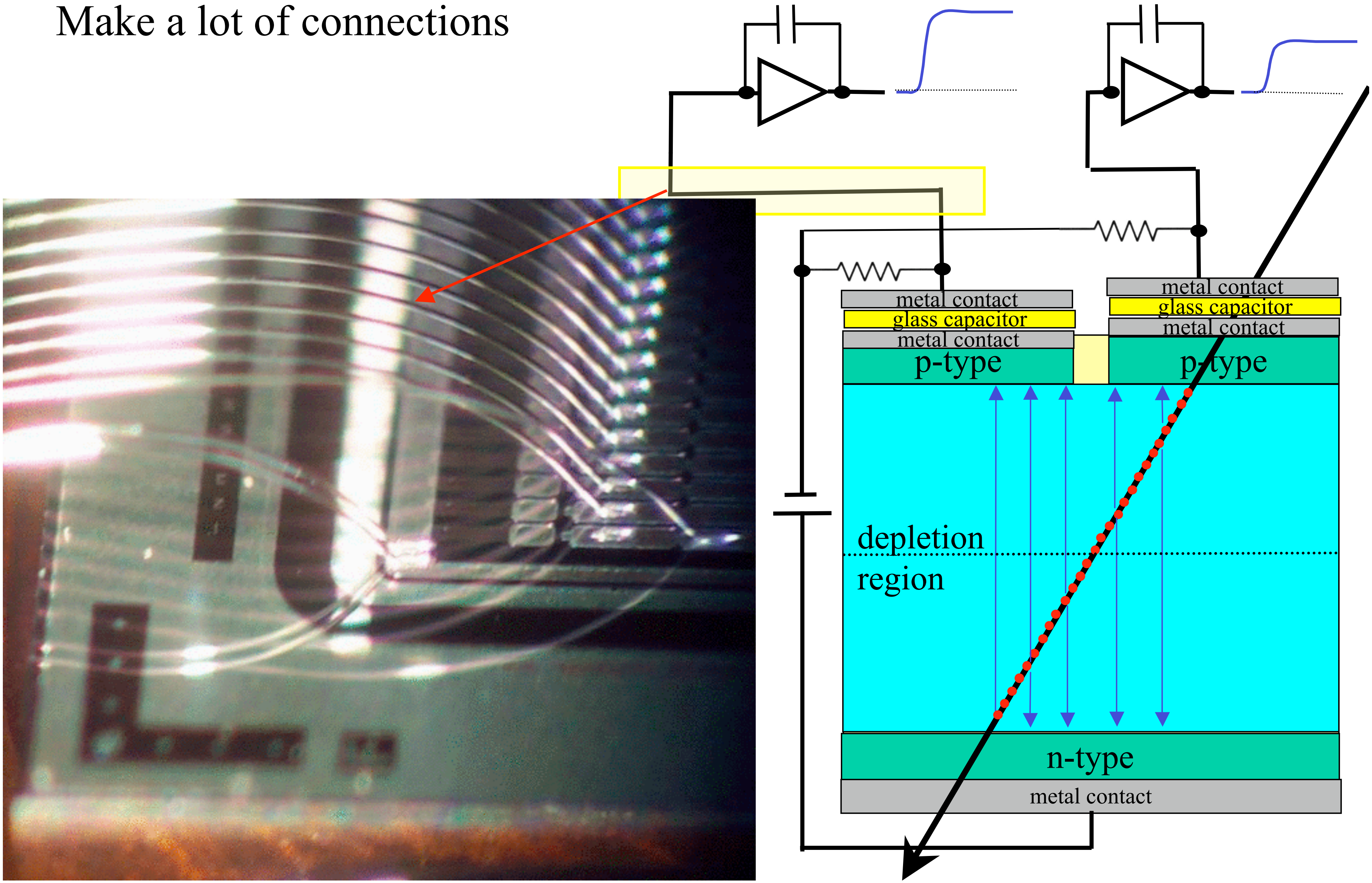
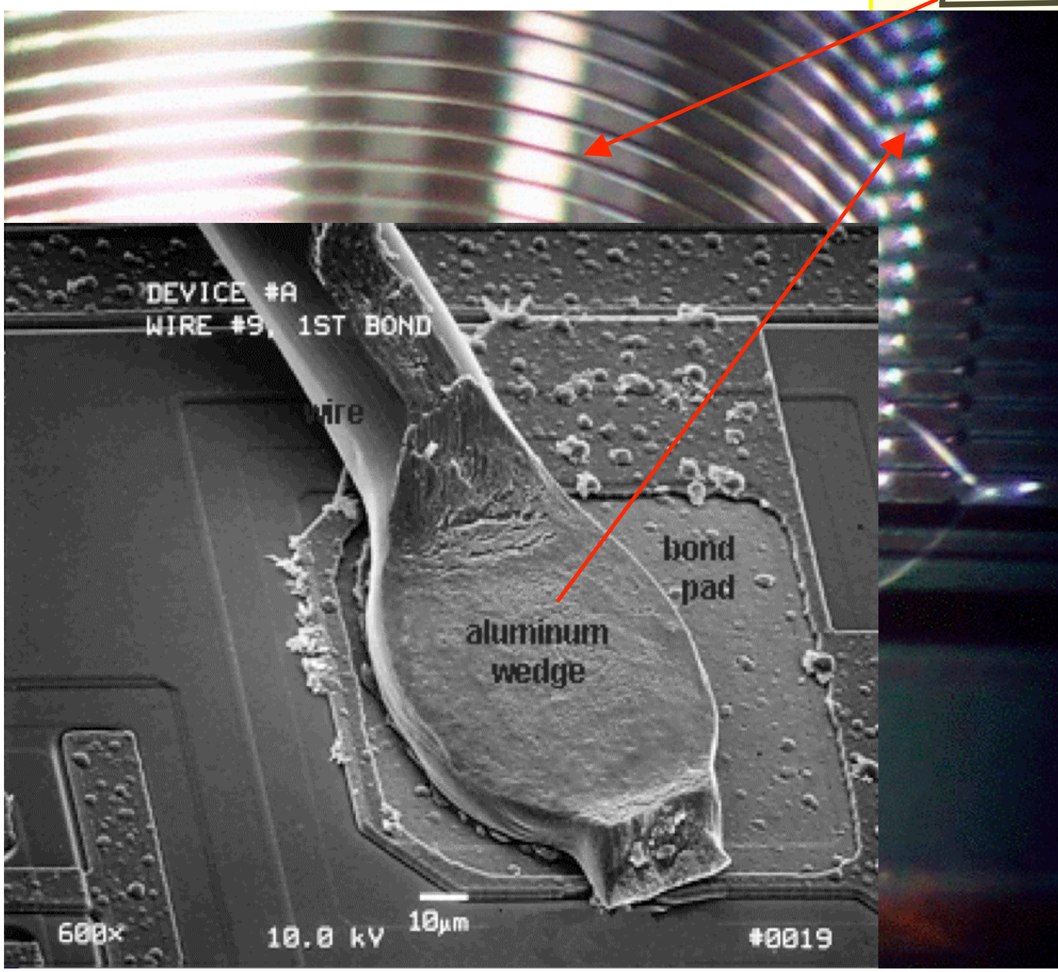
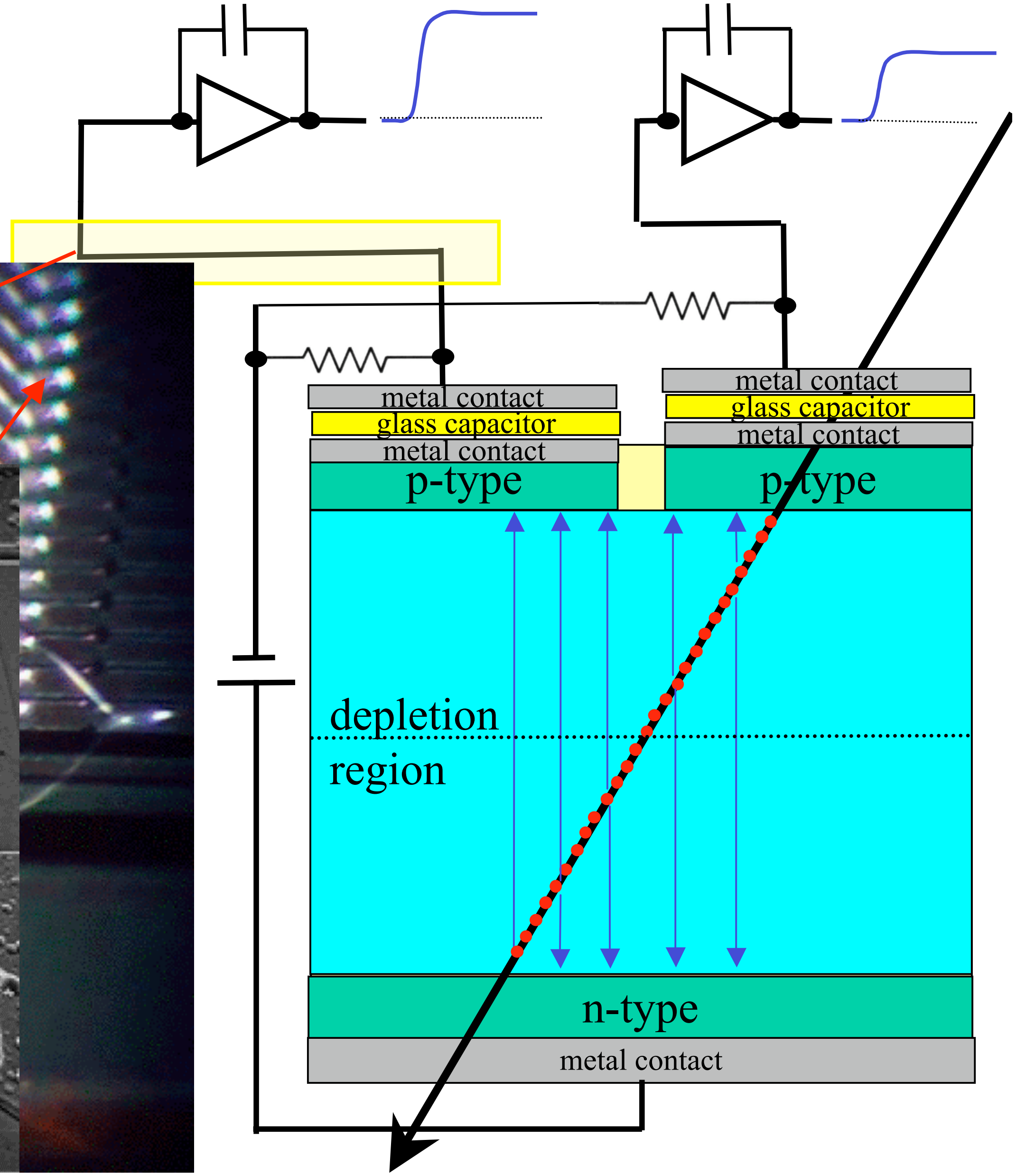


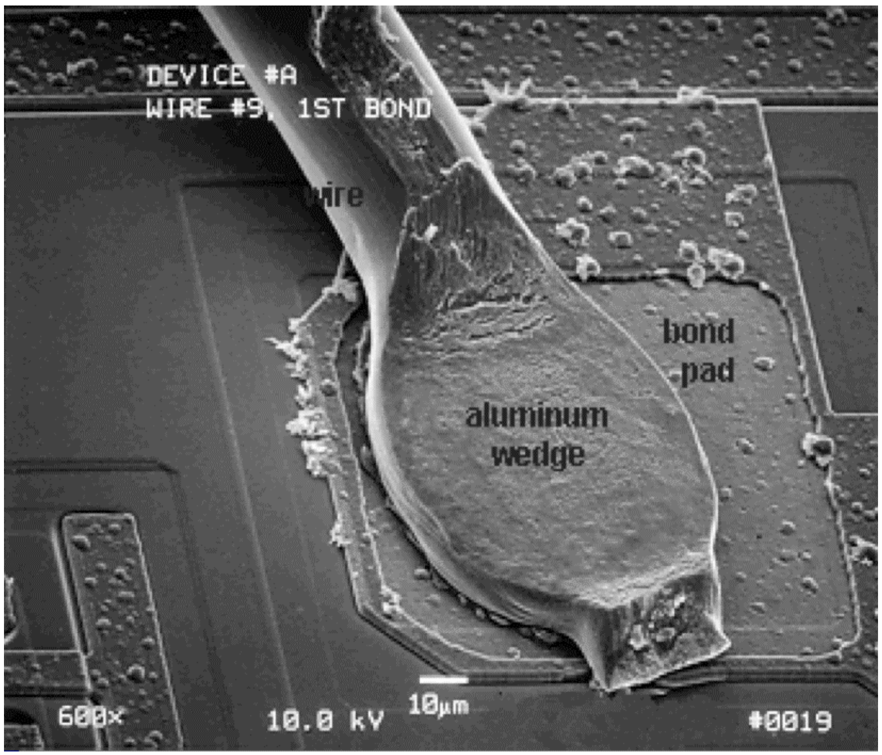
Many channel challenge

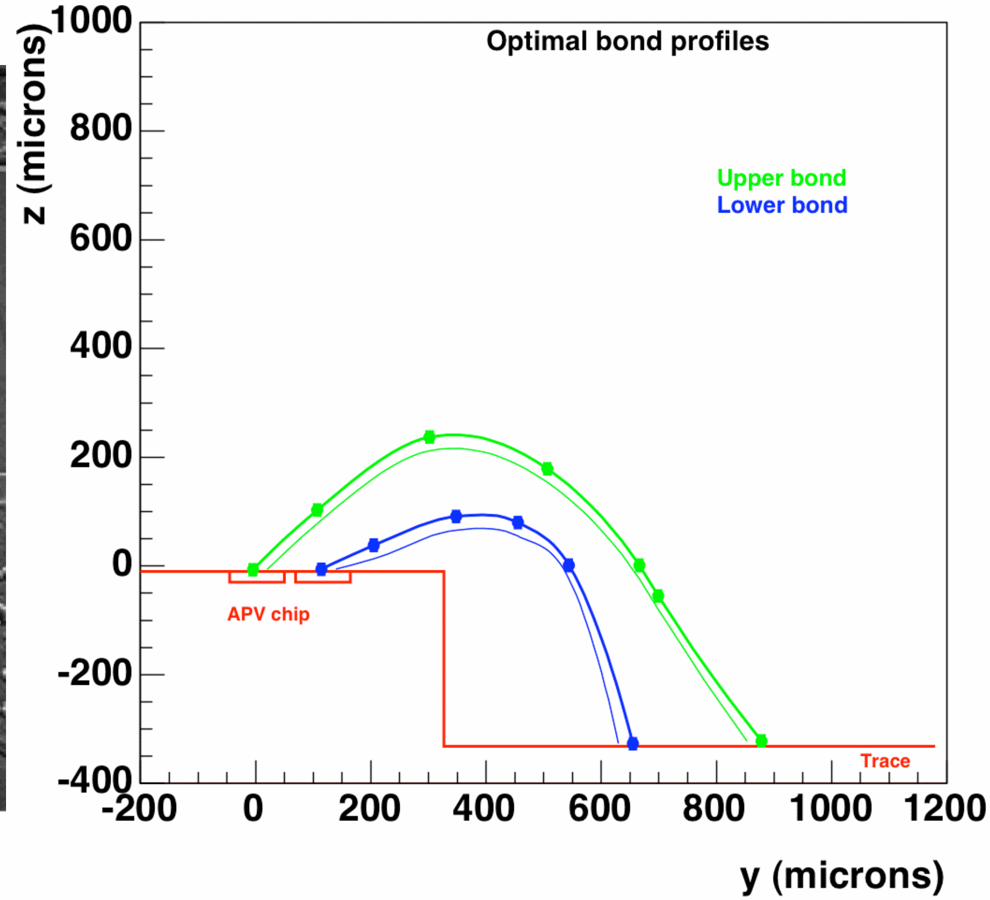
Make a lot of connections





Many channel challenge





Many channel challenge

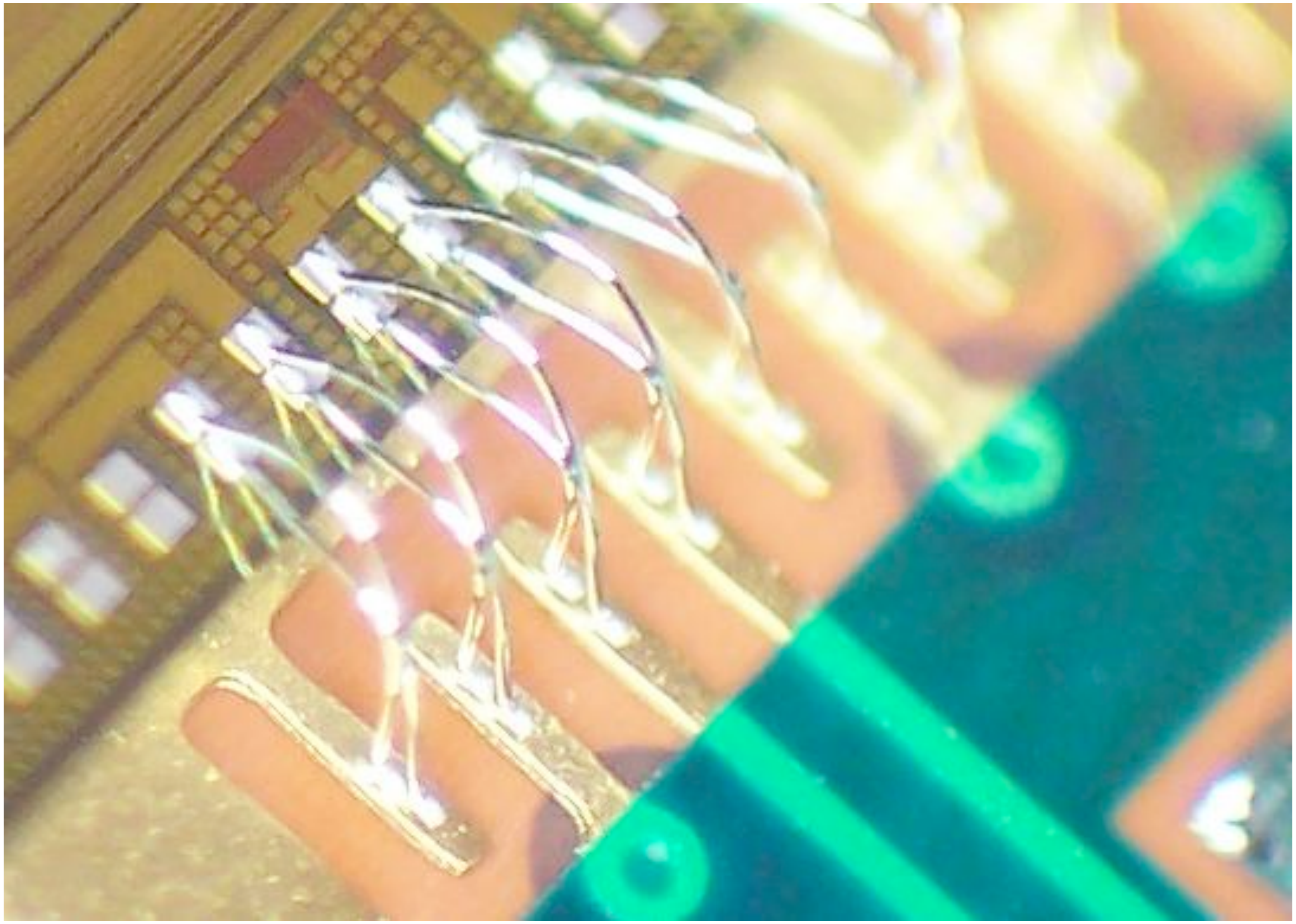
Kulicke and Soffa 8090 wirebonding machines

Many channel challenge

A plot of the wire bonding rate as a function of time during RunII? Well, maybe correlated.

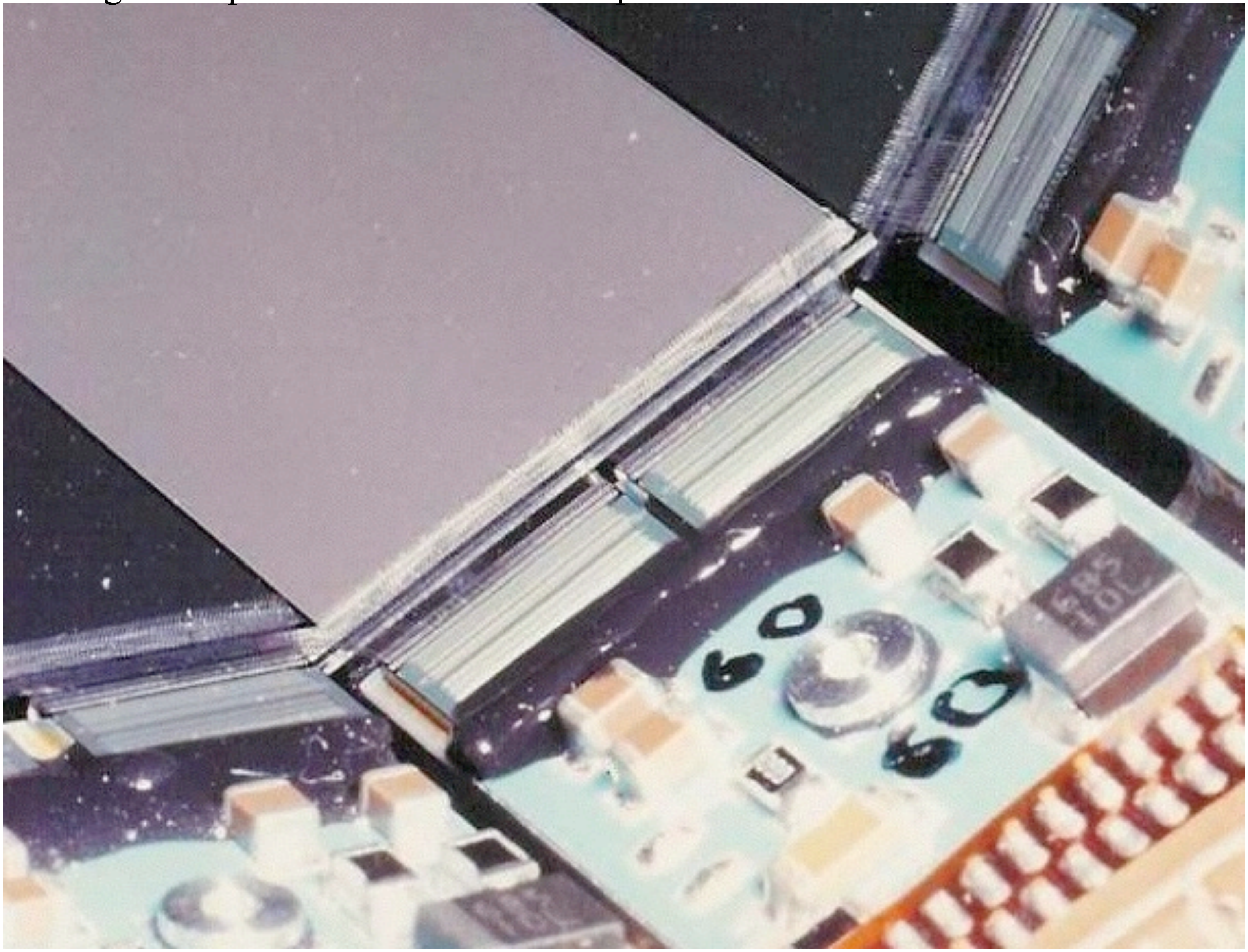
Many channel challenge

Also use microbonding on output of ASIC.



Many channel challenge

Also use microbonding on output of ASIC. Can be encapsulated once tested.



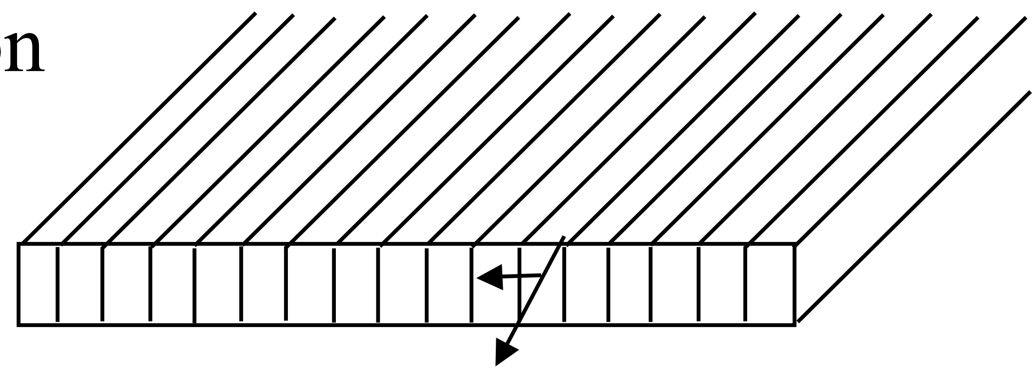
Solid State Detector Resolution

Resolution for pitch of 50 μm

- $\sigma_x \approx 15$ μm if one channel
- $\sigma_x \approx 10$ μm if two channels
- $\sigma_x > 20$ μm if three channels

Systematics on resolution

- δ-rays
- Noise
- Alignment



$$\bar{x} = \frac{\Sigma x_i q_i}{\Sigma q_i}$$

Solid State Detector Resolution

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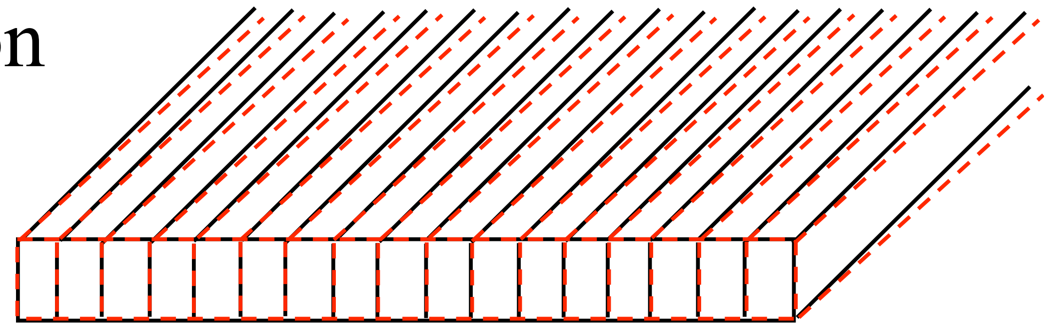


3D measurements

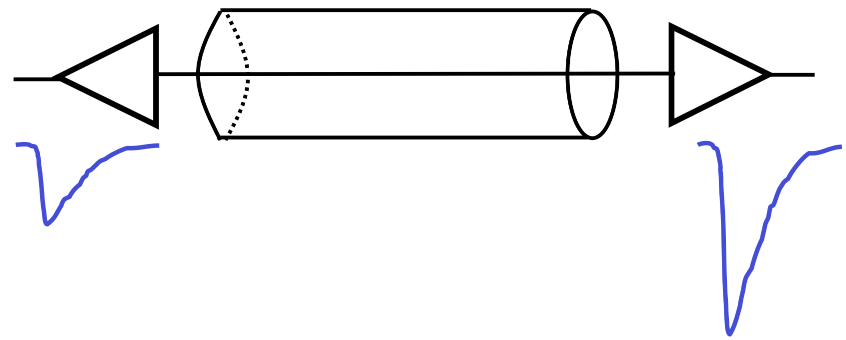
So far, only 2D ($r\phi$). Can get 3D measurements by:

Detector length / sqrt(12)

3D measurements

So far, only 2D (rϕ). Can get 3D measurements by:

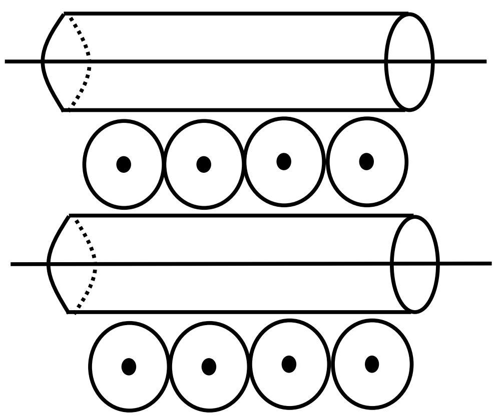
- Detector length / sqrt(12)
- Charge division



3D measurements

So far, only 2D (rϕ). Can get 3D measurements by:

- Detector length / sqrt(12)
- Charge division
- Use sets of orthogonal detectors
- Use sets of stereo detectors



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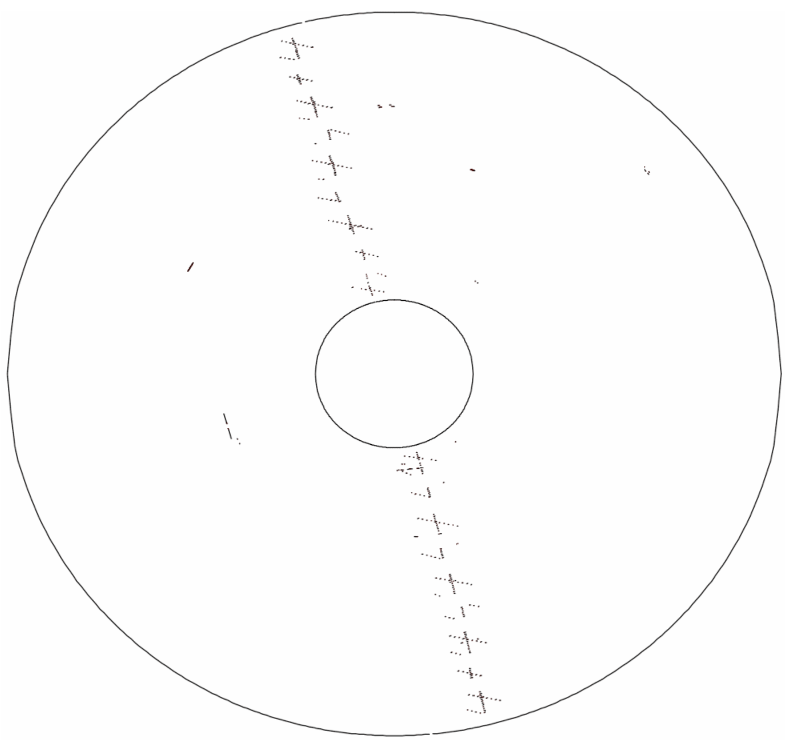

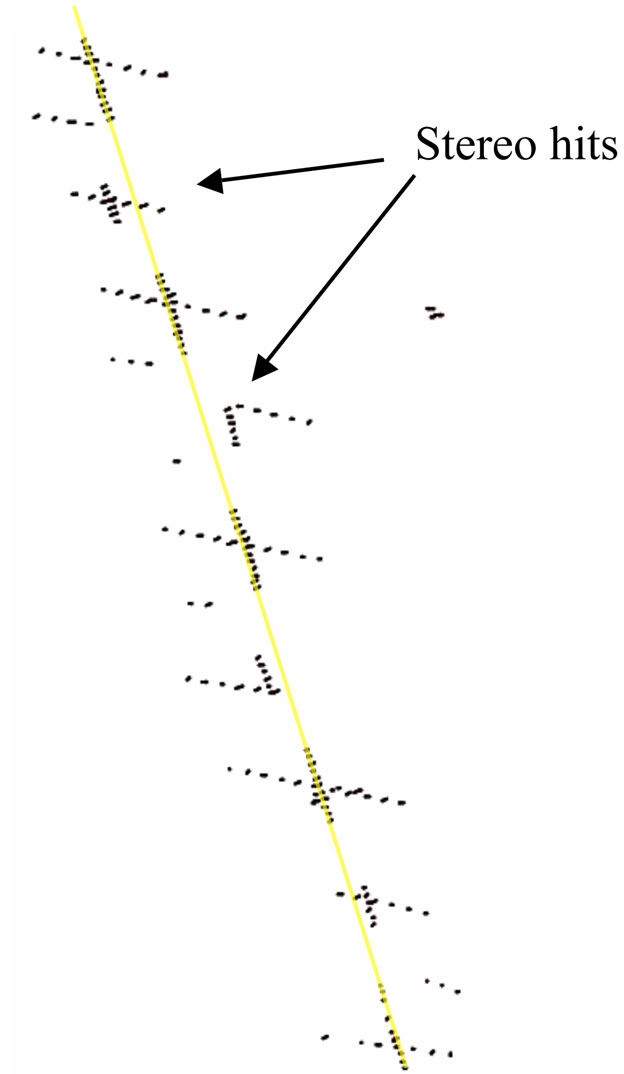

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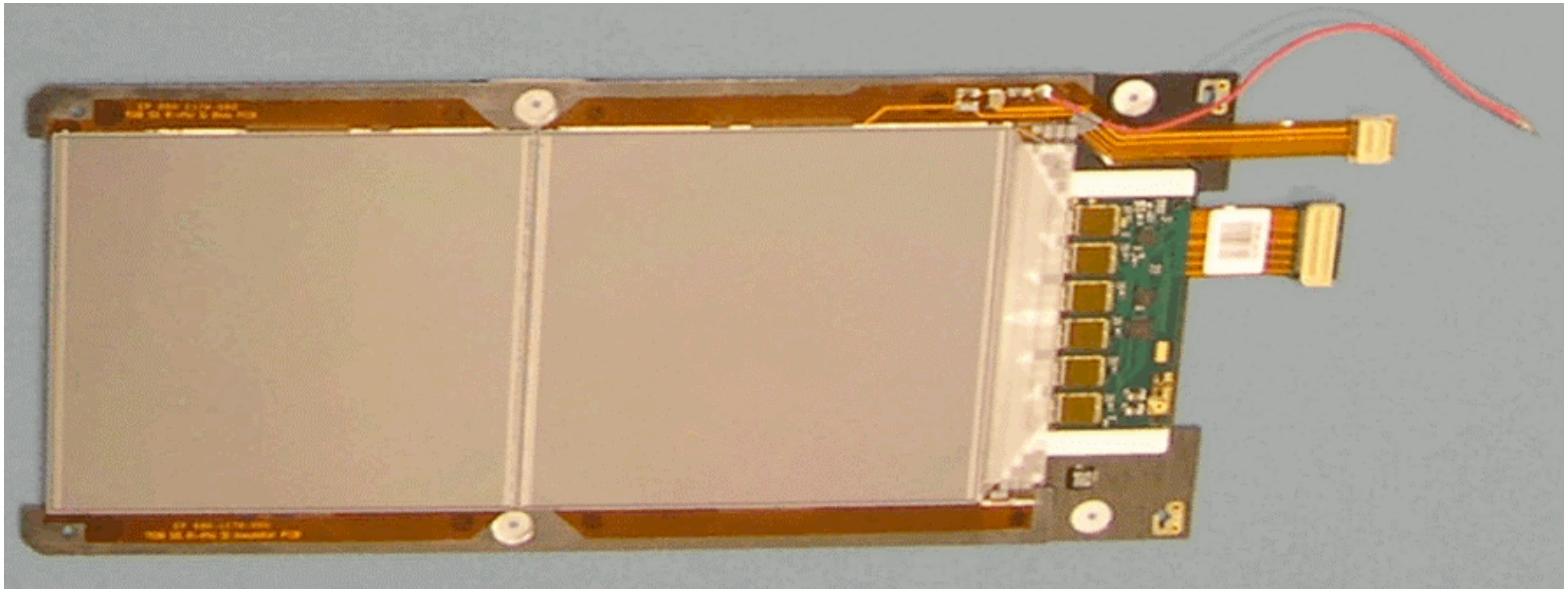
An axial silicon module for CMS



3D measurements

So far, only 2D (rϕ). Can get 3D measurements by:

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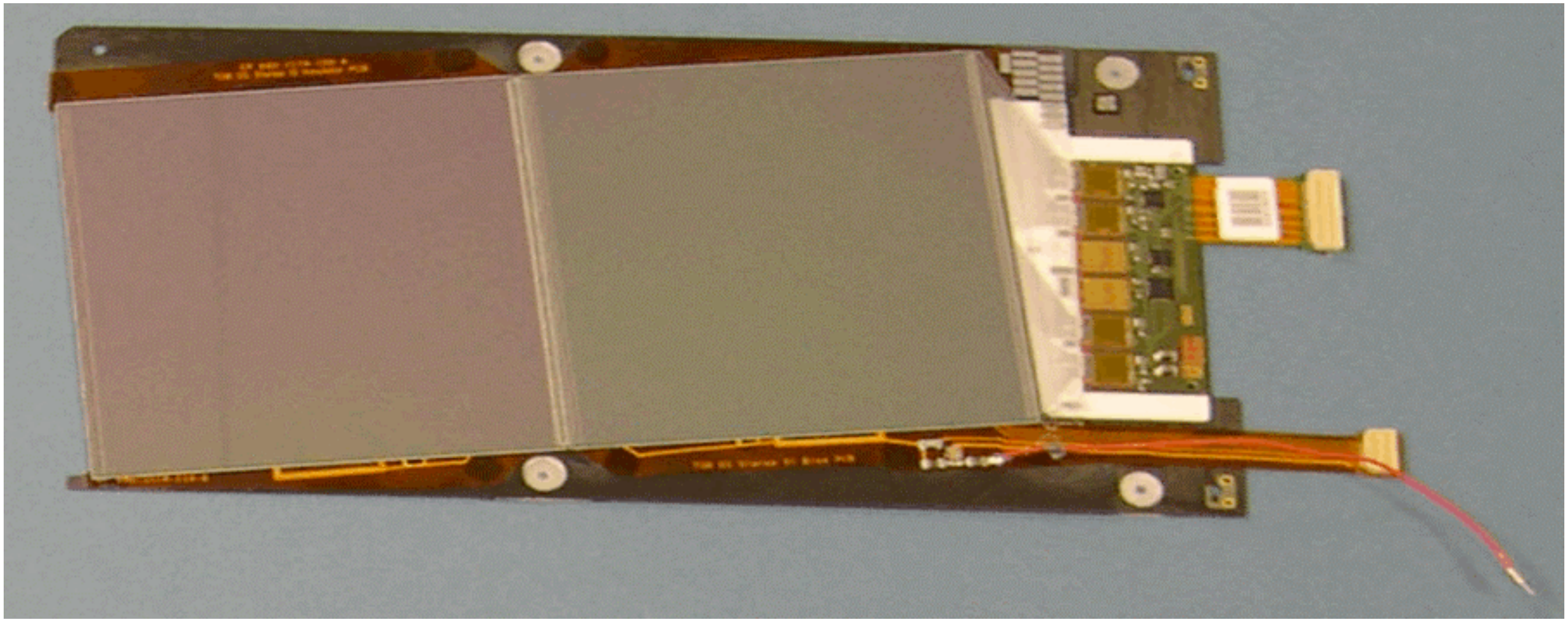
- Use sets of orthogonal detectors
- Use sets of stereo detectors

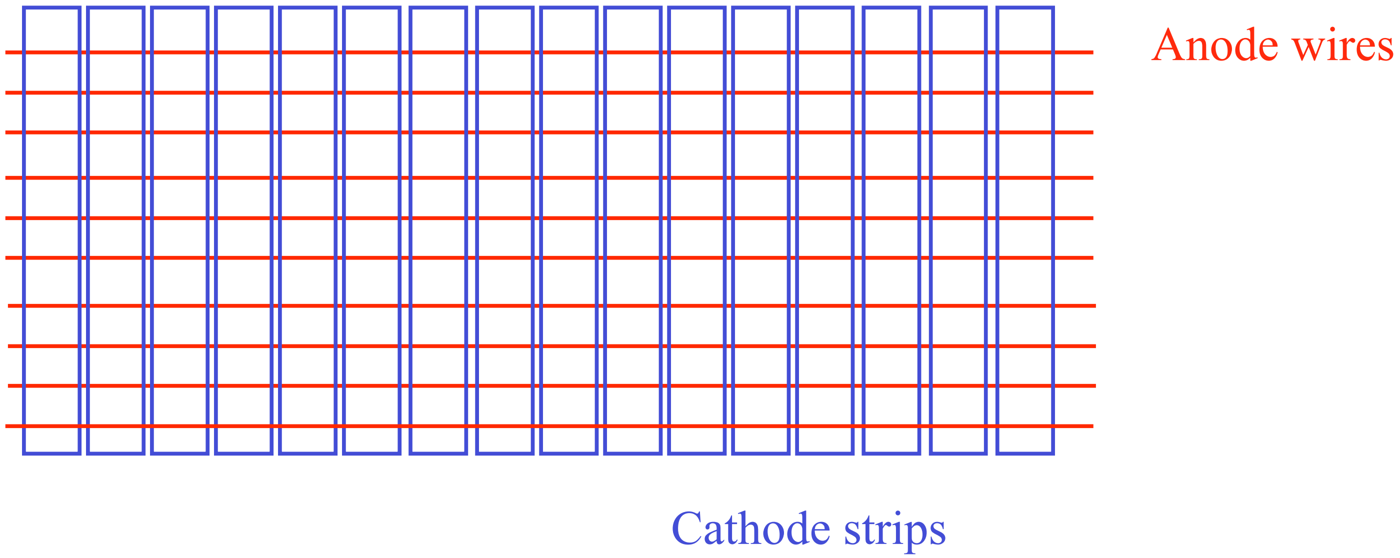
A stereo silicon module for CMS



3D measurements

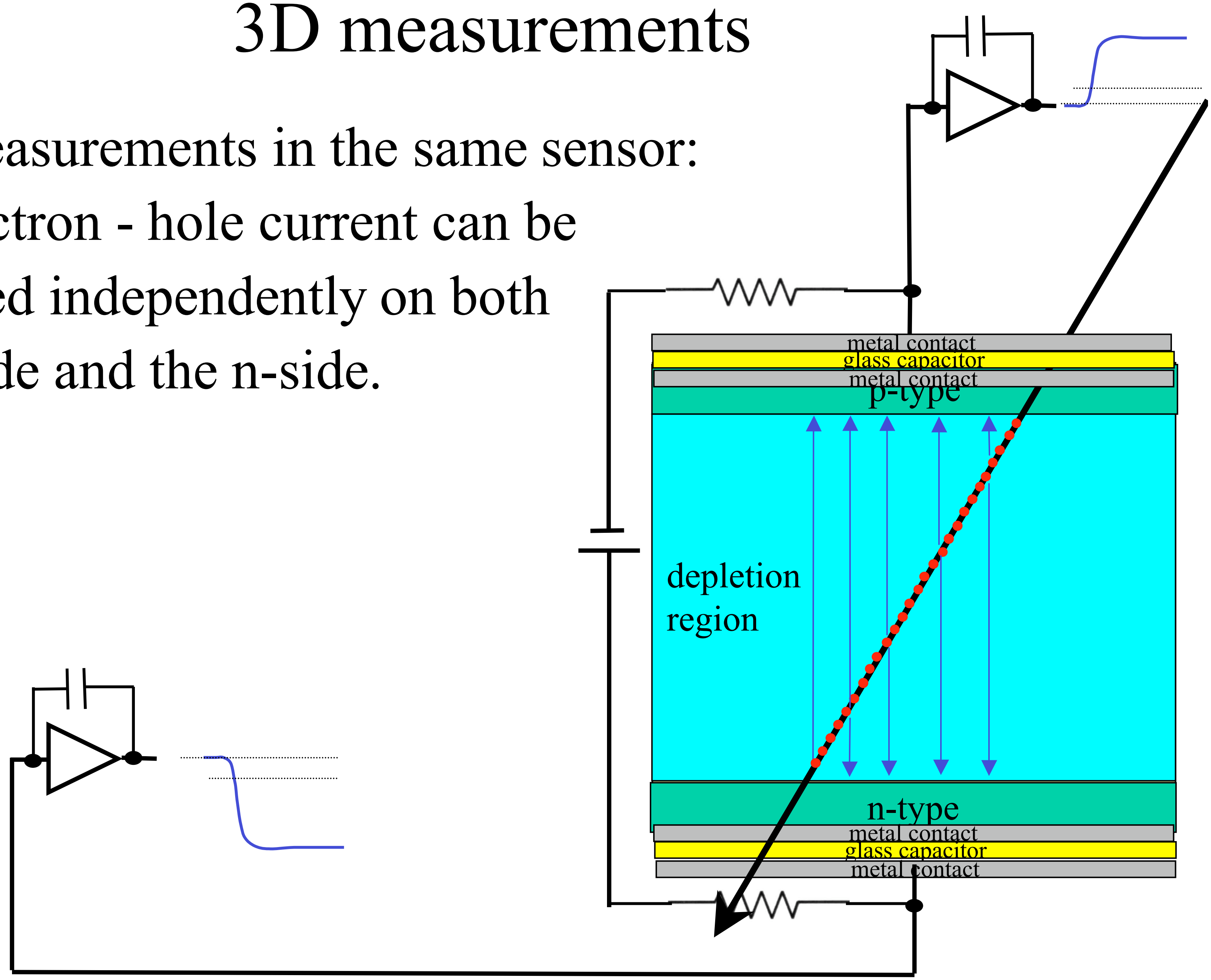
Two measurements in the same sensor.

The electron - ion current can be measured independently on both the anode and the cathode.



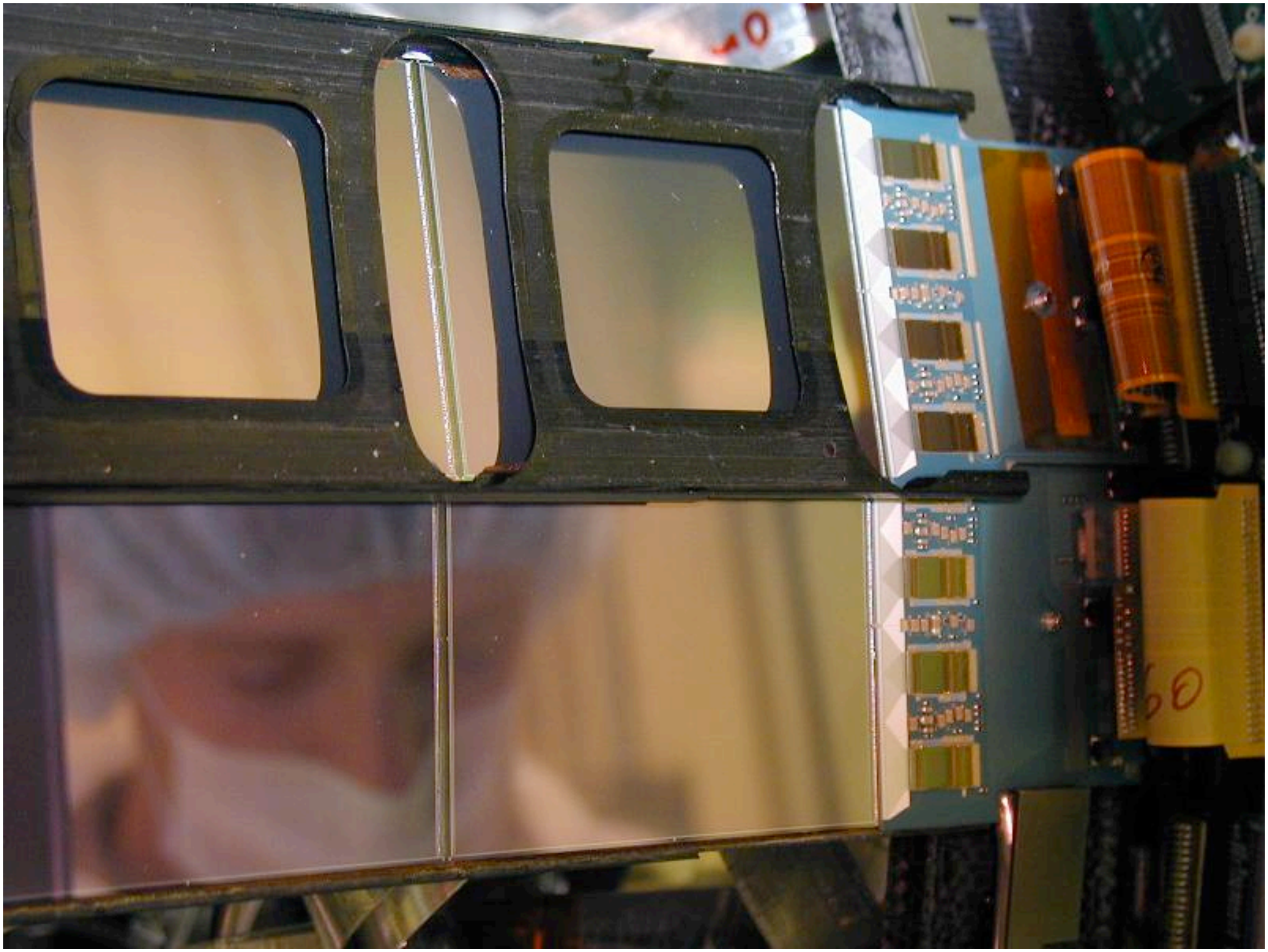
3D measurements

Two measurements in the same sensor:
The electron - hole current can be measured independently on both the p-side and the n-side.



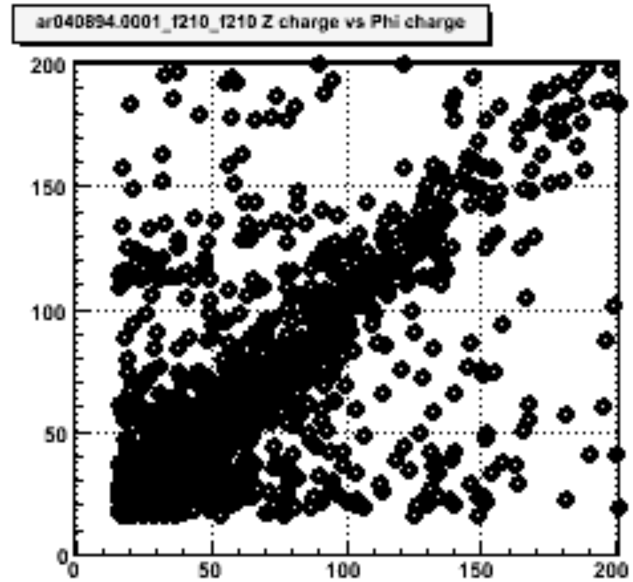
3D measurements

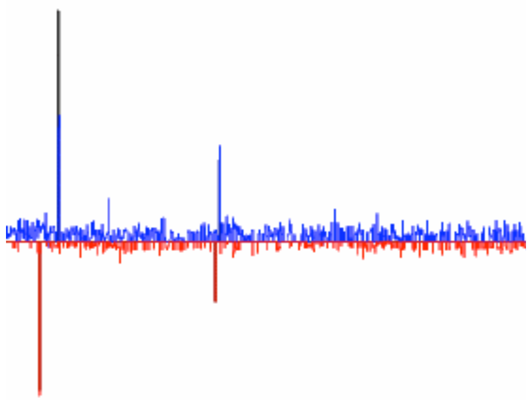
Two measurements in the same sensor.

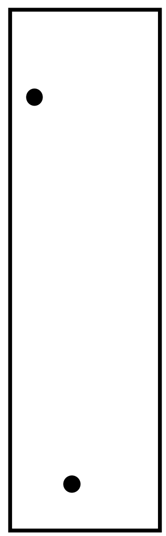


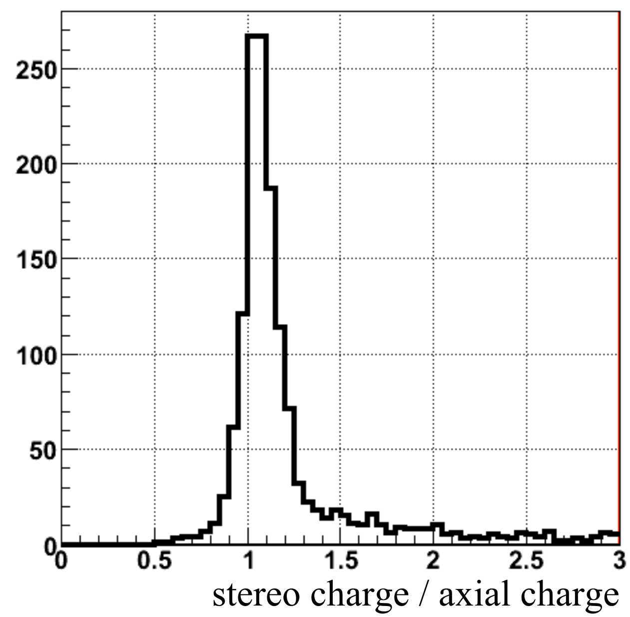
3D measurements

Two measurements in the same sensor.
O(1) degree stereo angle gives
O(1) mm resolution for
O(10) μm hit resolution.







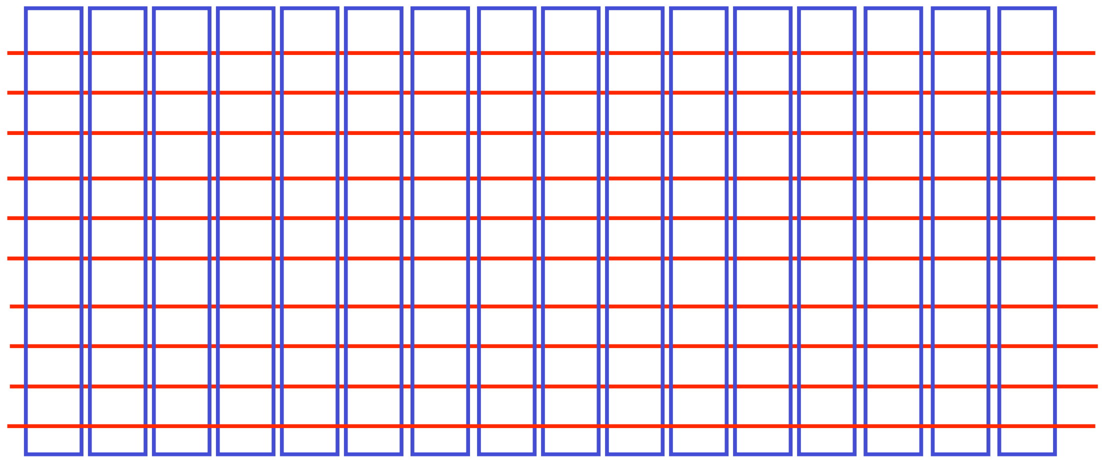


Larger angle gives smaller resolution but more combinatorics…

3D measurements

Two measurements in the same sensor.

Larger angle (e.g., 90^{o}) gives better resolution but more combinatorics…

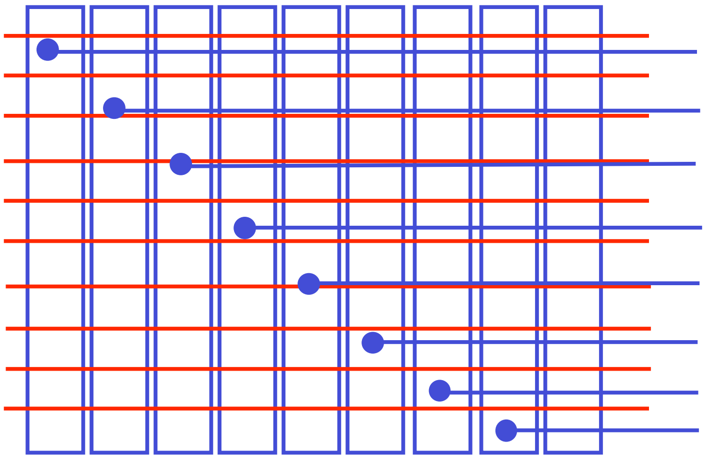


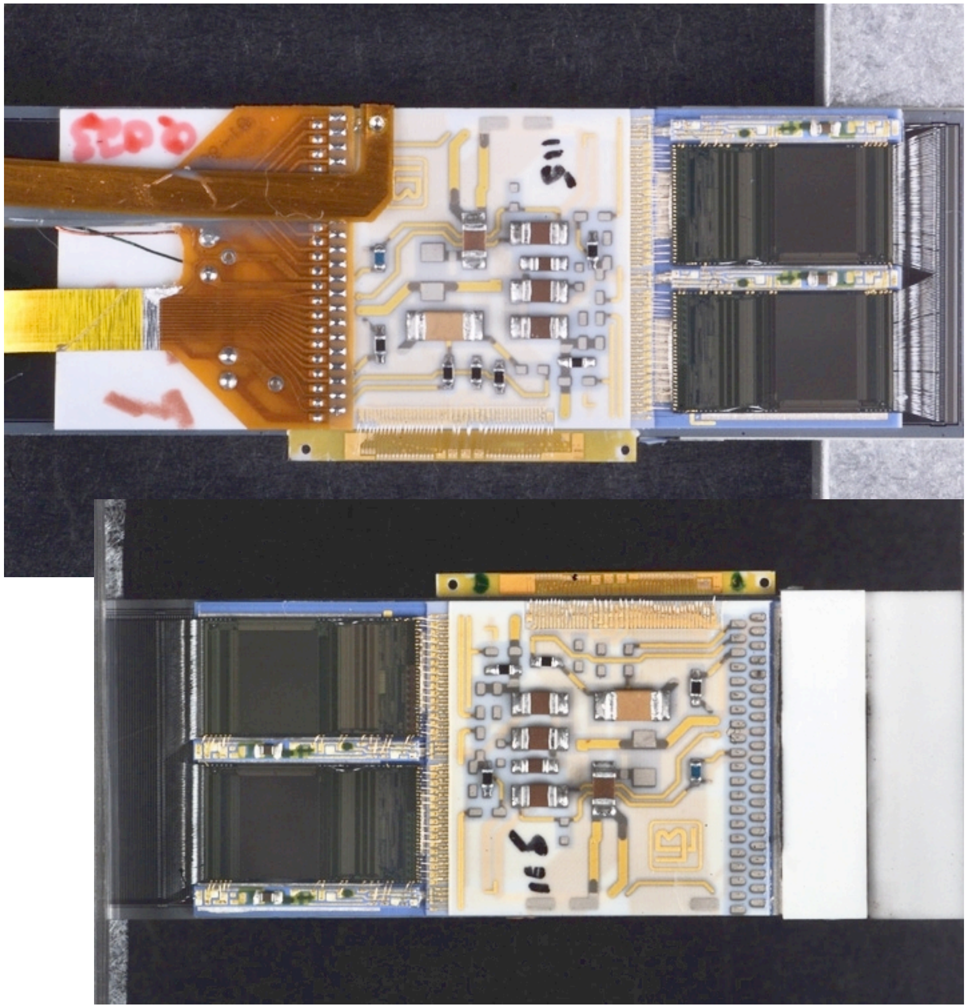
3D measurements

Two measurements in the same sensor.

Larger angle (e.g., 90°) gives better resolution but more combinatorics

"Double metal" to bring out connections

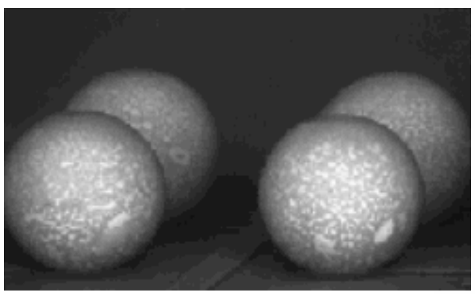


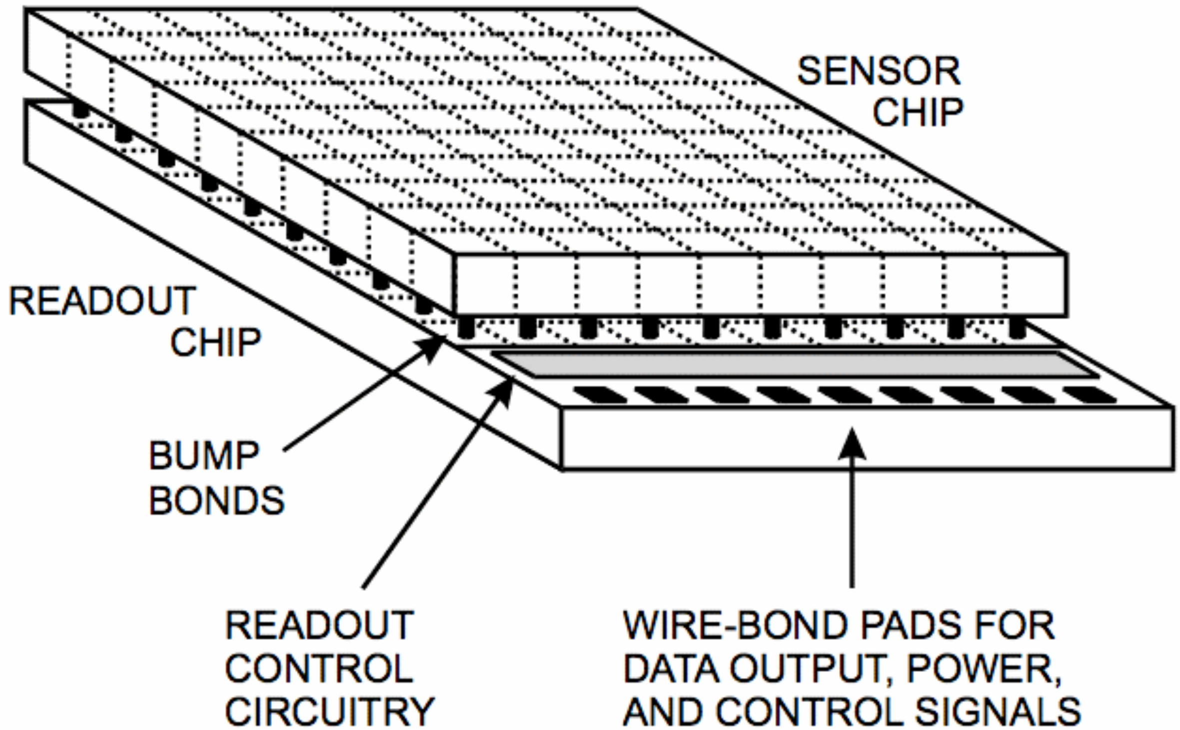


90° resolution similar to previous, if pitch is small.

3D measurements: Pixels

Two precise and unambiguous measurements in the same sensor!





But, motivated more by granularity (for robust track finding) than by resolution…

Helmut Spieler, “Semiconductor Detector Systems”


Next time…
Track finding

Bibliography

- nobelprize.org/nobel_prizes/physics/laureates/1992/charpak-lecture.pdf
- Gino Bolla, UTeV seminar
- Guido Tonelli, Tracking at the LHC, SLAC Summer Institute 2006
- Aaron Dominguez, HCPSS06 Lecture on Tracking
- CMS Technical Design Report
- CDF Technical Design Report
- Daniella Bortoletto, 11th Vienna Conference on Instrumentation, Feb. 2007
- Helmut Spieler, "Semiconductor Detector Systems"