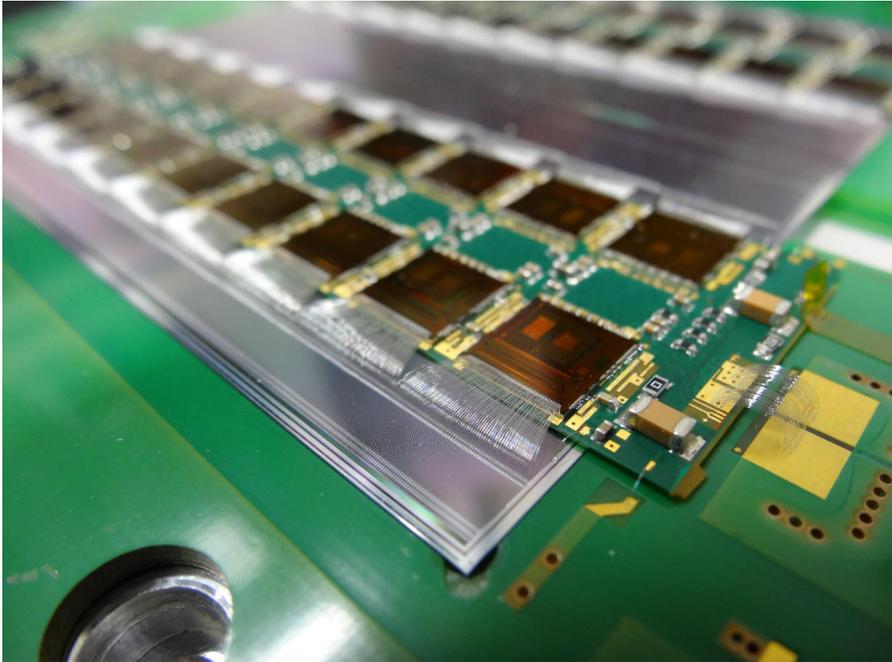


„Neue“ Detektor-Technologien

an Beschleunigern in der Teilchenphysik



Ingo Bloch

Technisches Seminar

DESY, 19. November 2013

> Kurze Einführung

> Beispiele für Anforderungen an Detektoren

- Im Proton-Proton Large Hadron Collider
- In einer möglichen Elektron-Positron Maschine

> Gasdetektoren, Beispiel MICROMEGA, GEM

> Silizium-Photomultiplier

- Anwendung in Calice

> Design für Energy-/Particle-Flow

» Kurze Particle-Flow Erläuterung

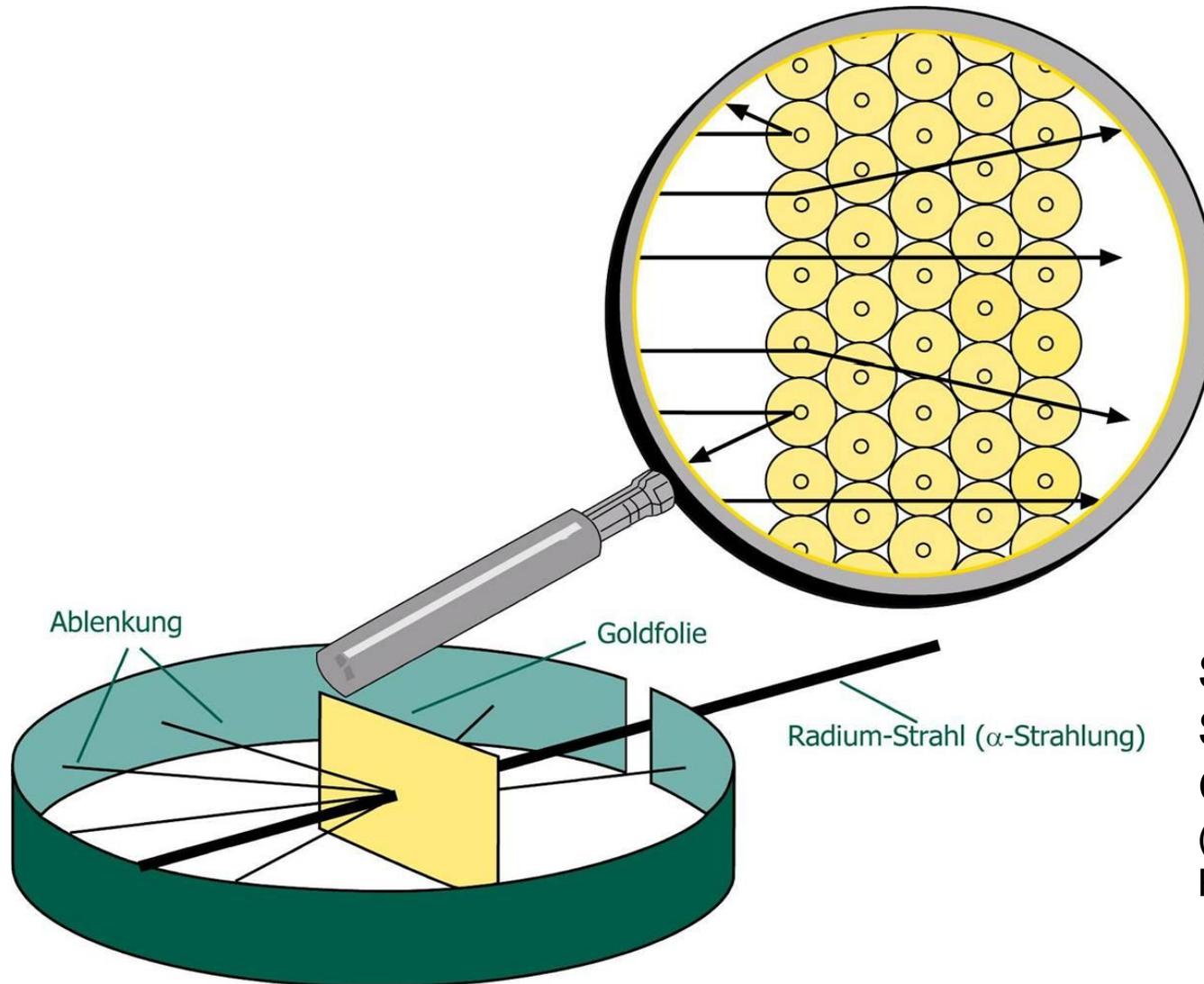
> Silizium Spurdetektoren

- Streifen (hier in Z :)) - mit CO₂ Kühlungs-Intermezzo
- Pixel

Sehr persönliche
Auswahl an Themen,
ganz und gar nicht
vollständig



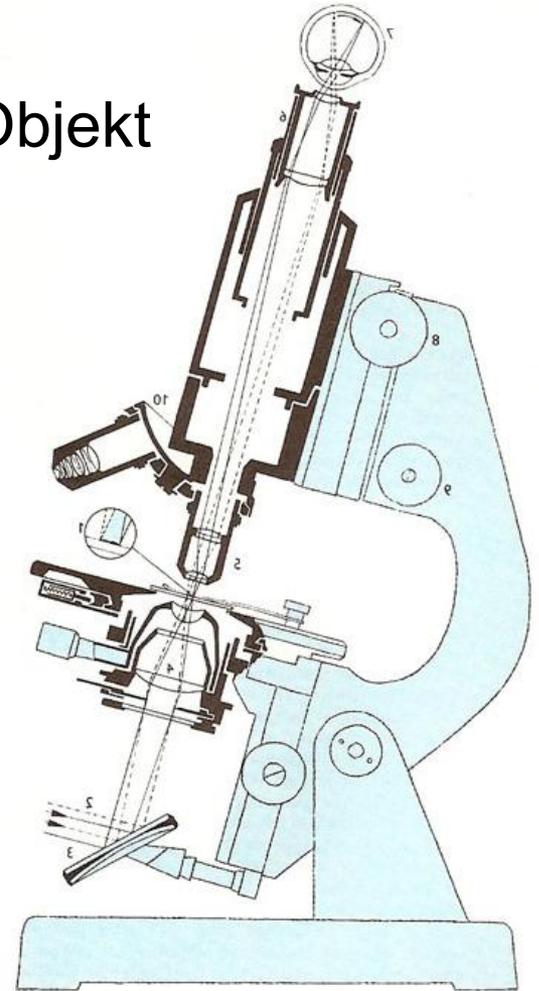
➤ Wir wollen das Kleinste vom Kleinsten „sehen“



Streuung von α -
Strahlung an einer
Goldfolie
(Geiger, Marsden,
Rutherford, 1911)

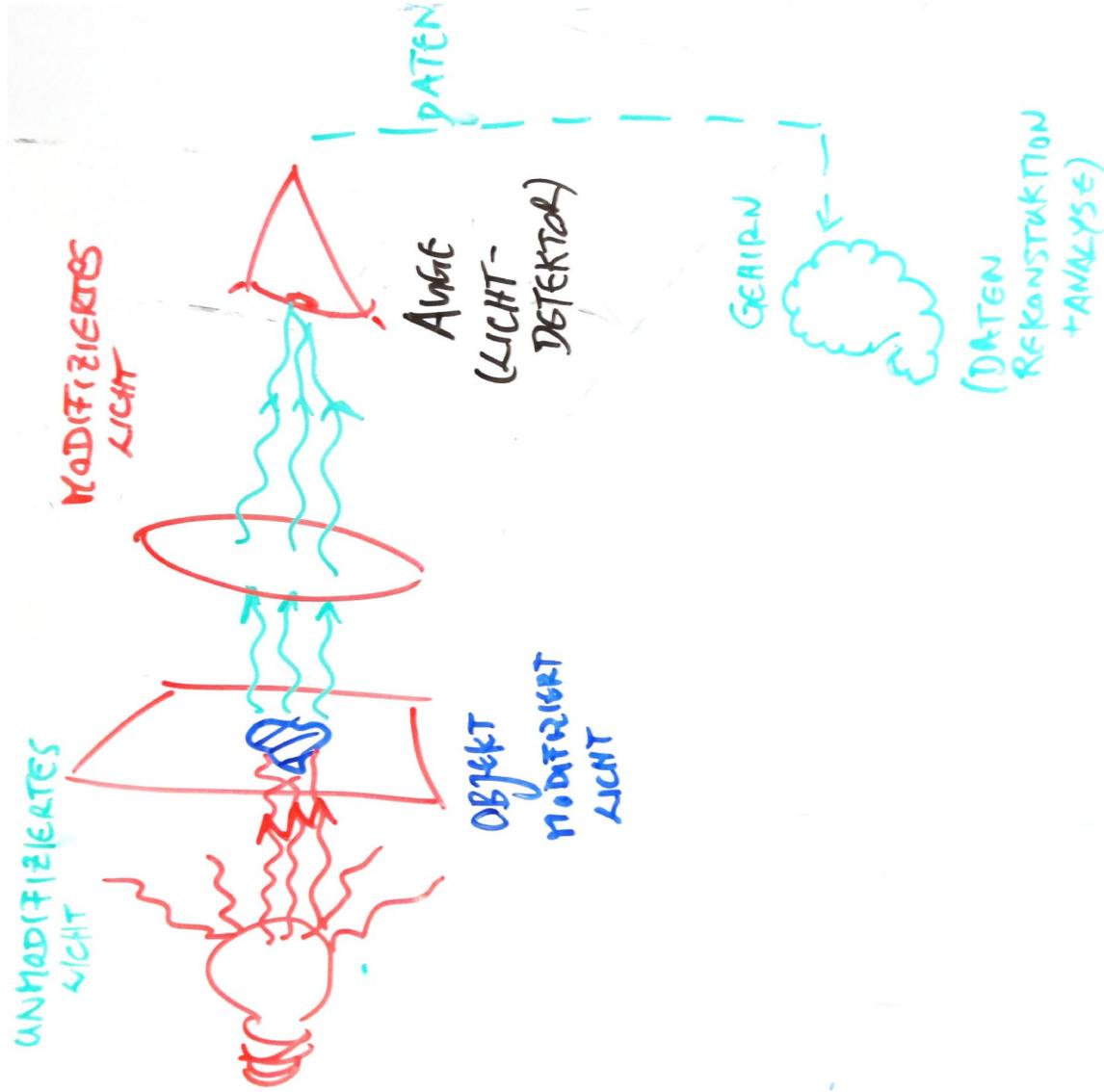
> Mikroskop

1. **Licht** scheint auf zu untersuchendes Objekt
2. **Objekt** (z.B. Zelle) **modifiziert Licht**
3. Modifiziertes Licht wird **zum Detektor** geführt (*zum Auge*)
4. Modifiziertes Licht wird **rekonstruiert** (*Gehirn*)
5. **Analyse** von rekonstruiertem Licht **erlaubt Rückschluss auf Ursprung der Lichtmodifikation** (*da war eine Zelle unterm Mikroskop!*)



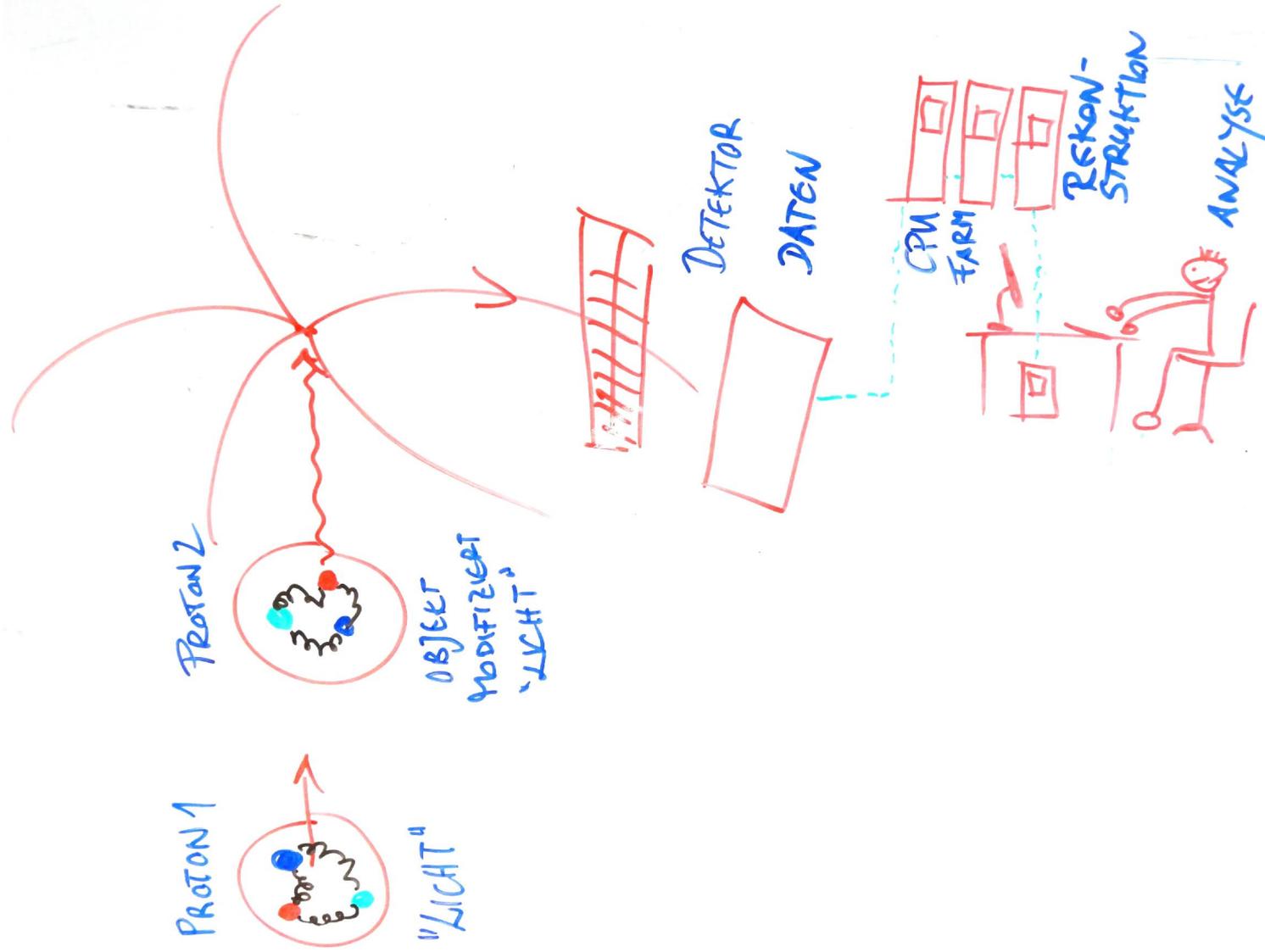
Teilchenphysik – Messprinzip

➤ Analogie zum Mikroskop



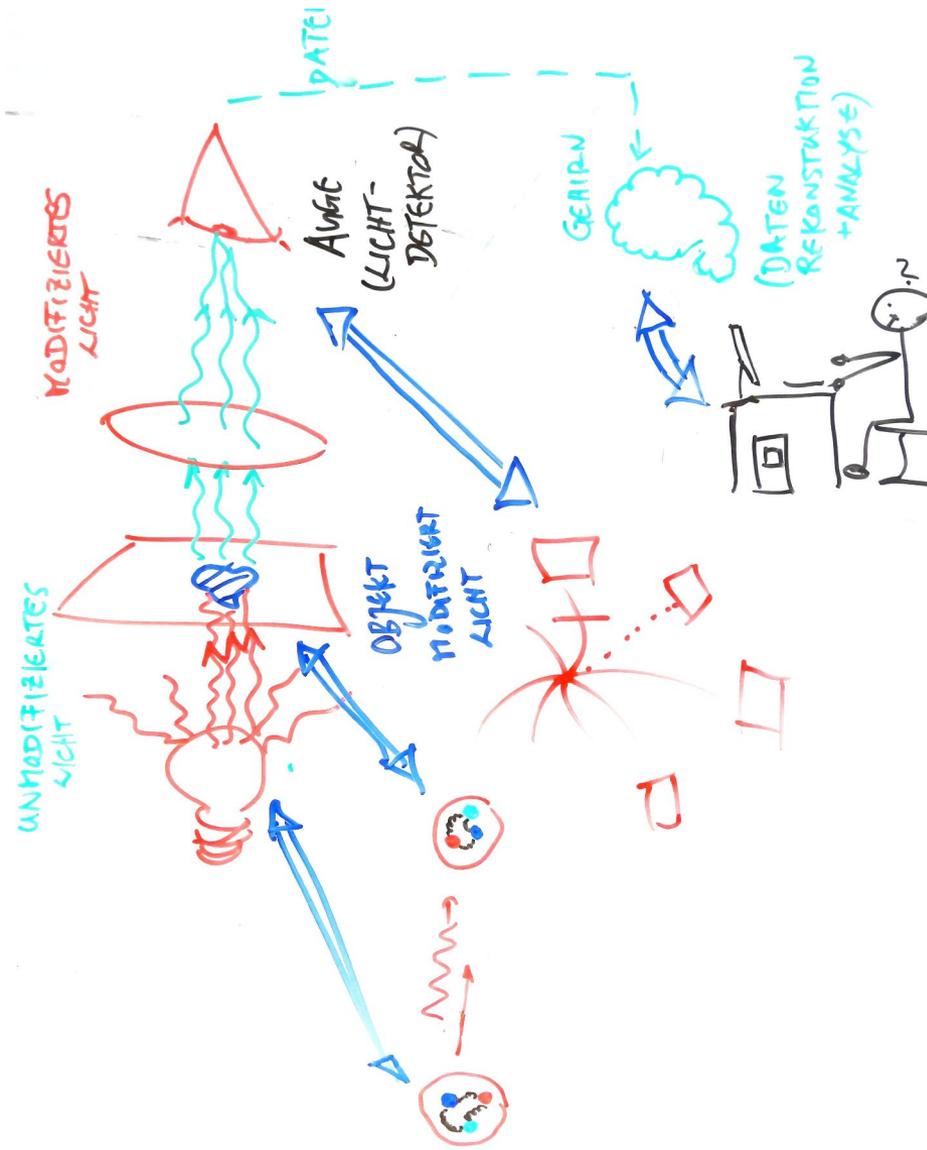
Teilchenphysik – Messprinzip

➤ Analogie zum Mikroskop



Teilchenphysik – Messprinzip

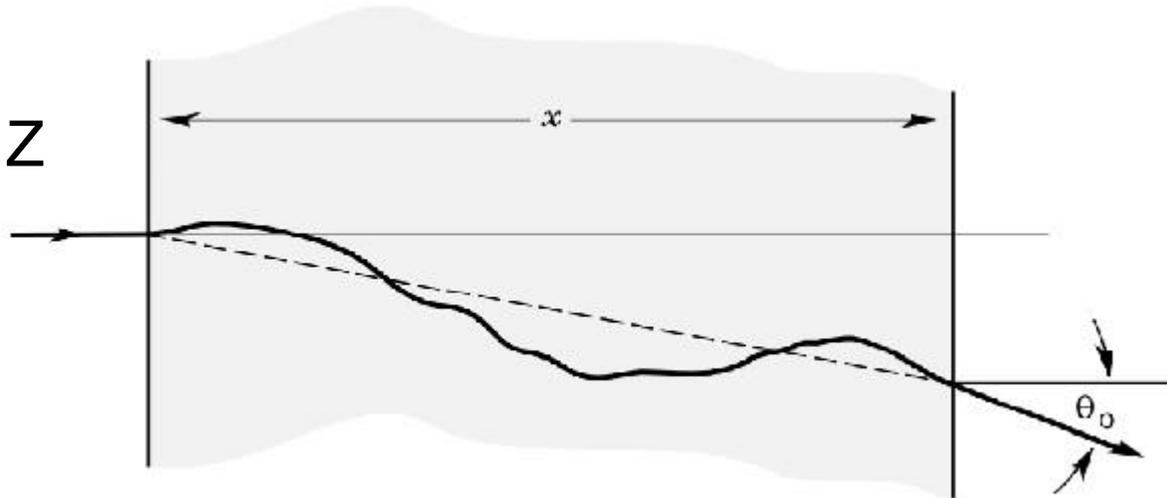
➤ Analogie zum Mikroskop



Teilchennachweis – grundsätzliche Methoden

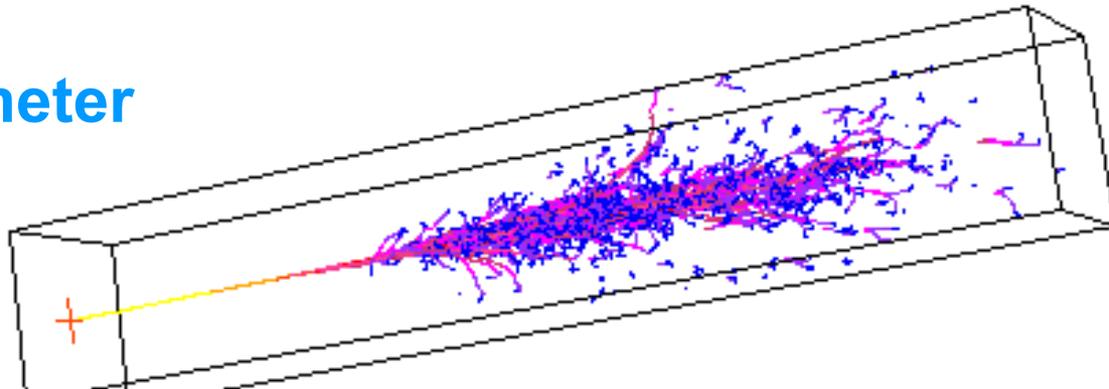
- > **Entweder** Spur von geladenen Teilchen mit wenig Störung der Flugrichtung verfolgen – Teilchen ionisieren und regen Atome/Moleküle an
→ Folge Spur mittels Material mit niedrigem Z und niedriger Dichte

→ **Spurdetektoren**



- > **Oder** Teilchen vollständig absorbieren und deponierte Energie messen, mittels Material mit hohem Z und hoher Dichte

→ **Kalorimeter**



Teilchennachweis – ein Ereignis



> Kurze Einführung

> **Beispiele für Anforderungen an Detektoren**

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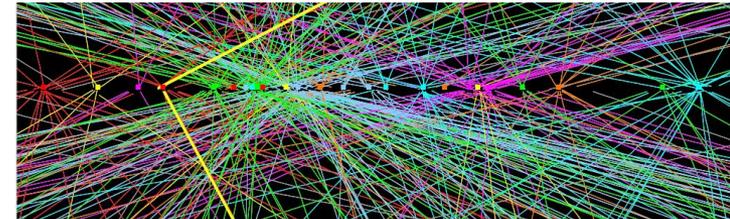
- Streifen (hier in Z :)) - mit CO₂ Kühlungs-Intermezzo
- Pixel



Beispiele – Anforderungen an Detektoren

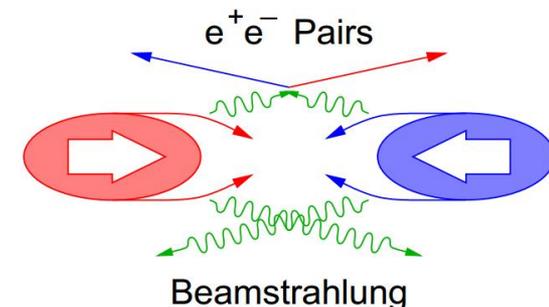
> Proton Proton (LHC)

- 20 / 40 MHz Kollisionsrate (50 / 25 ns zwischen 2 Ereignissen)
- 20 bis 150 Hintergrundereignisse überlagern das Hauptereignis (PileUp)
- Starke Strahlenbelastung durch hohen Teilchenfluss von Kollisionen
 - > Bis zu $\sim 10^{16}$ n_{eq}/cm^2
- Arbeitstemperaturen
 - > Im Spurdetektor $-30^\circ C$
 - > Ausserhalb Umgebungstemperatur



> Elektron Positron (ILC / CLIC)

- Kollisionen „mit Atempausen“
 - > Erlaubt triggerlose Auslese
 - > Ermöglicht Puls-Stromversorgung
- Kein Pileup, aber auch herausfordernde Untergründe, hauptsächlich durch Beam-Beam e^+e^- Erzeugung



- Kurze Einführung
- Beispiele für Anforderungen an Detektoren
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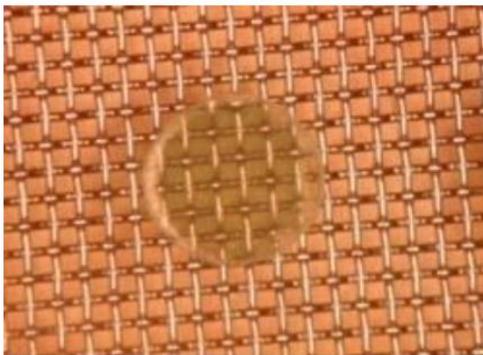
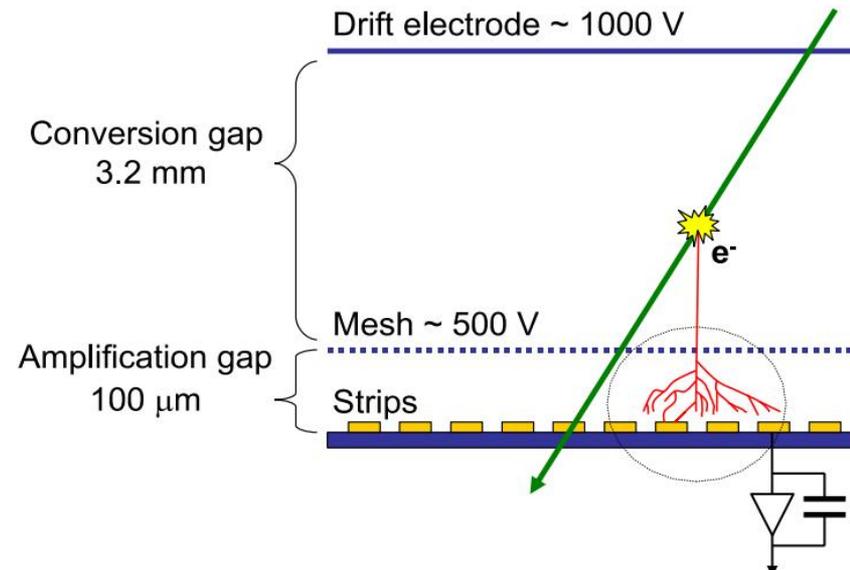
Gasdetektoren: MICROMEAGAs / GEMs

➤ Angelehnt an / Weiterentwicklung von Proportionaldriftkammern

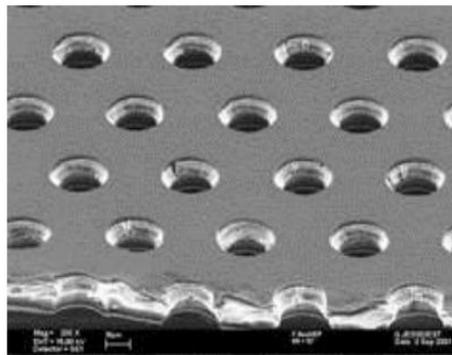
- MICROMESH Gaseous Structure, MICROMEAGAs (I. Giomataris, 1992)
- Gas Electron Multipliers, GEMs (F. Sauli, 1997)

➤ Verstärkungen 1k – 1M-fach

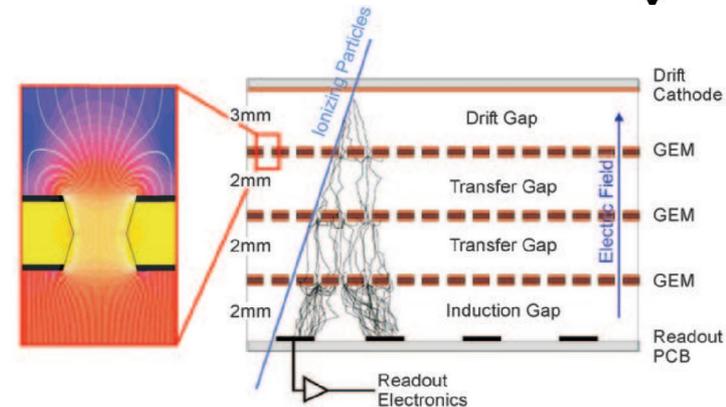
➤ Erlauben projektiv große Volumina auszulesen



MicroMegas



GEM



<http://arxiv.org/pdf/hep-ex/0703049v1.pdf>

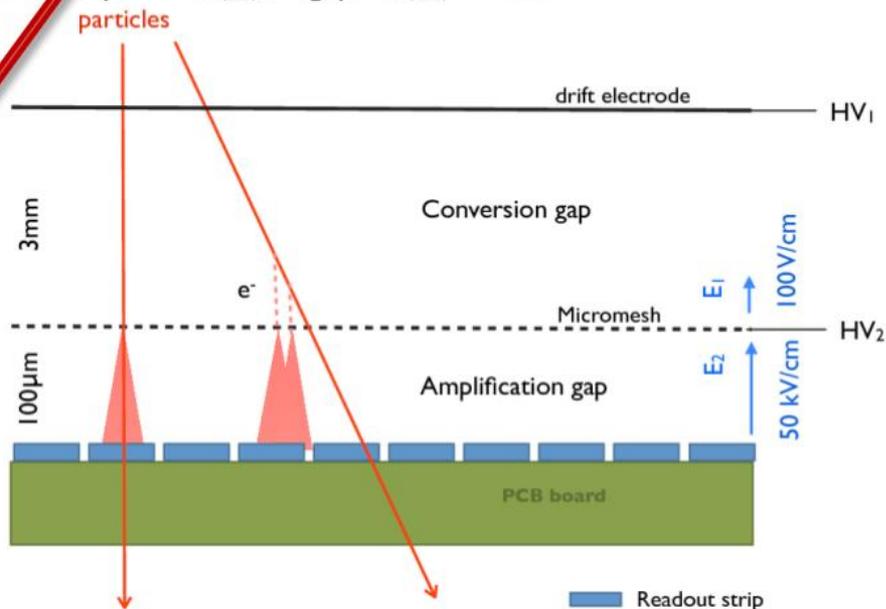
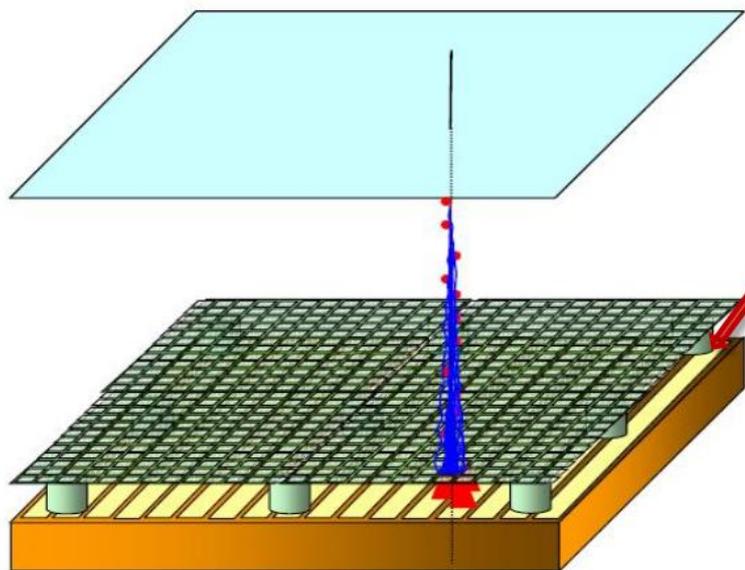
Figure 18. Schematic cross section of a triple GEM detector. The insert shows the electric field configuration for typical GEM voltages.



Gasdetektoren: Micromegas

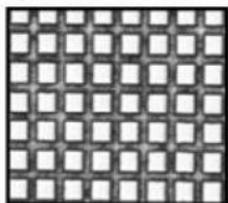
Y. Giomataris, PH. Rebourgeard, JP. Roberts and G. Charpak, NIM A 376 (1996) 29

Micromegas (MMs) are parallel-plate chambers where the amplification takes place in a **thin gap**, separated from the **conversion region** by a **fine metallic micro-mesh**, supported by 50-100 μm insulating pillars.

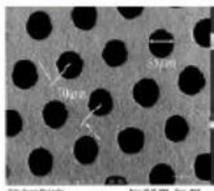


Practical operation of Micromegas

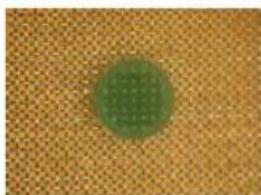
1, Feb.17, 2009



Electroformed



Chemically etched

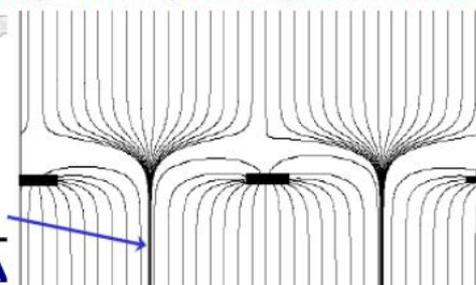


Woven

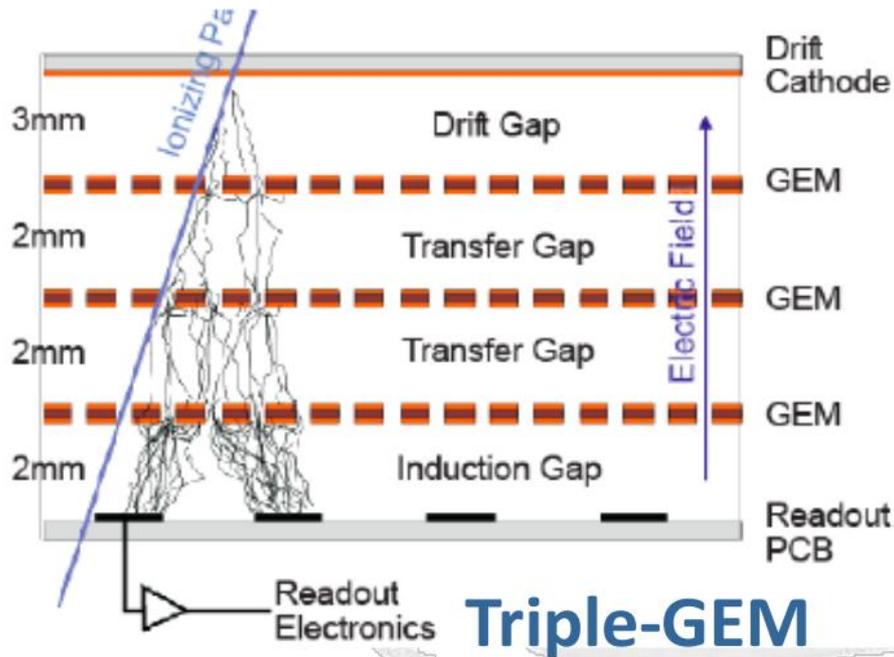


Deposited by vaporization

Funnel field lines: high transparency to electrons



Gasdetektoren: GEM Prinzip

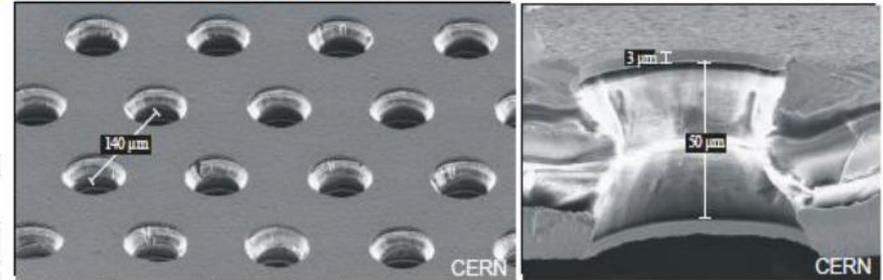


Invented by F. Sauli in 1997

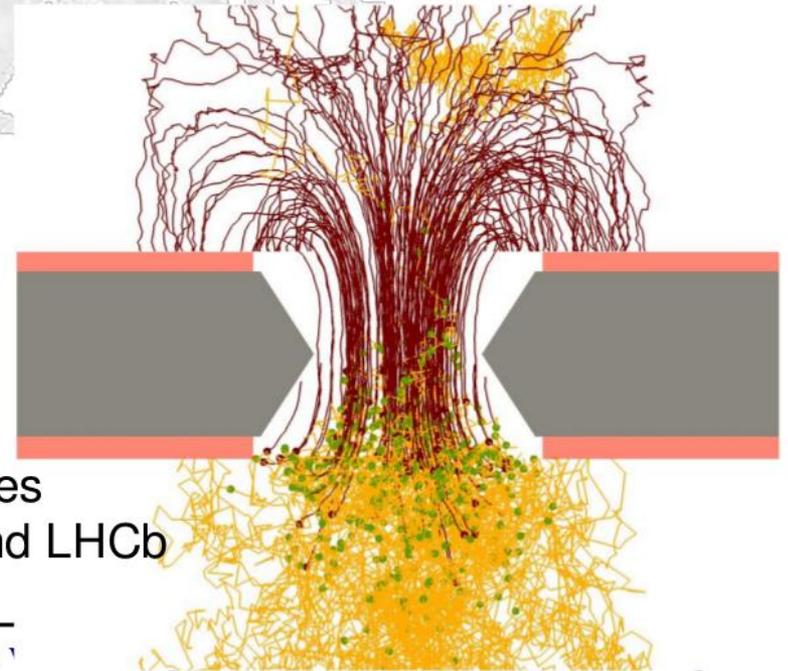
Main characteristics:

- ✓ Excellent rate capability: up to $10^5/\text{cm}^2$
- ✓ Gas mixture: Ar/CO₂/CF₄ – not flammable
- ✓ Large areas ~1 m x 2m with industrial processes
- ✓ Long-term operation in COMPASS, TOTEM and LHCb

Gas Electron Multipliers (GEMs) are made of a copper-kapton-copper sandwich, with holes etched into it



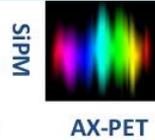
Electron microscope photograph of a GEM foil



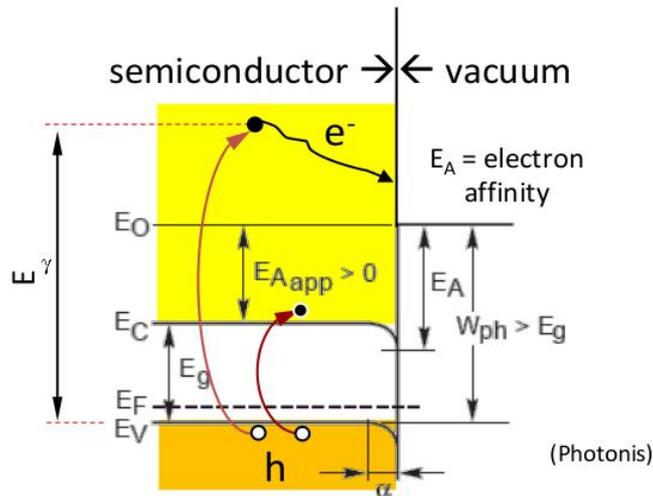
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 - Pixel



Basics of photodetection



Many photosensitive materials are semiconductors, but photoeffect can also be observed from gases and liquids.

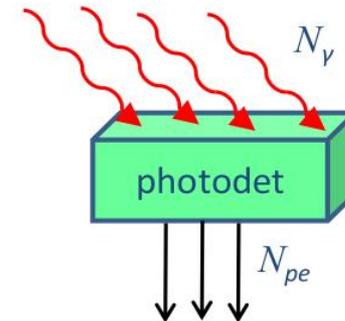
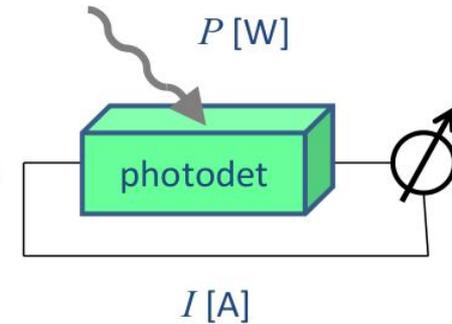


Internal photoeffect: $E_\gamma > E_g$

External photoeffect: $E_\gamma > E_g + E_A$

Internal photoeffect

External photoeffect



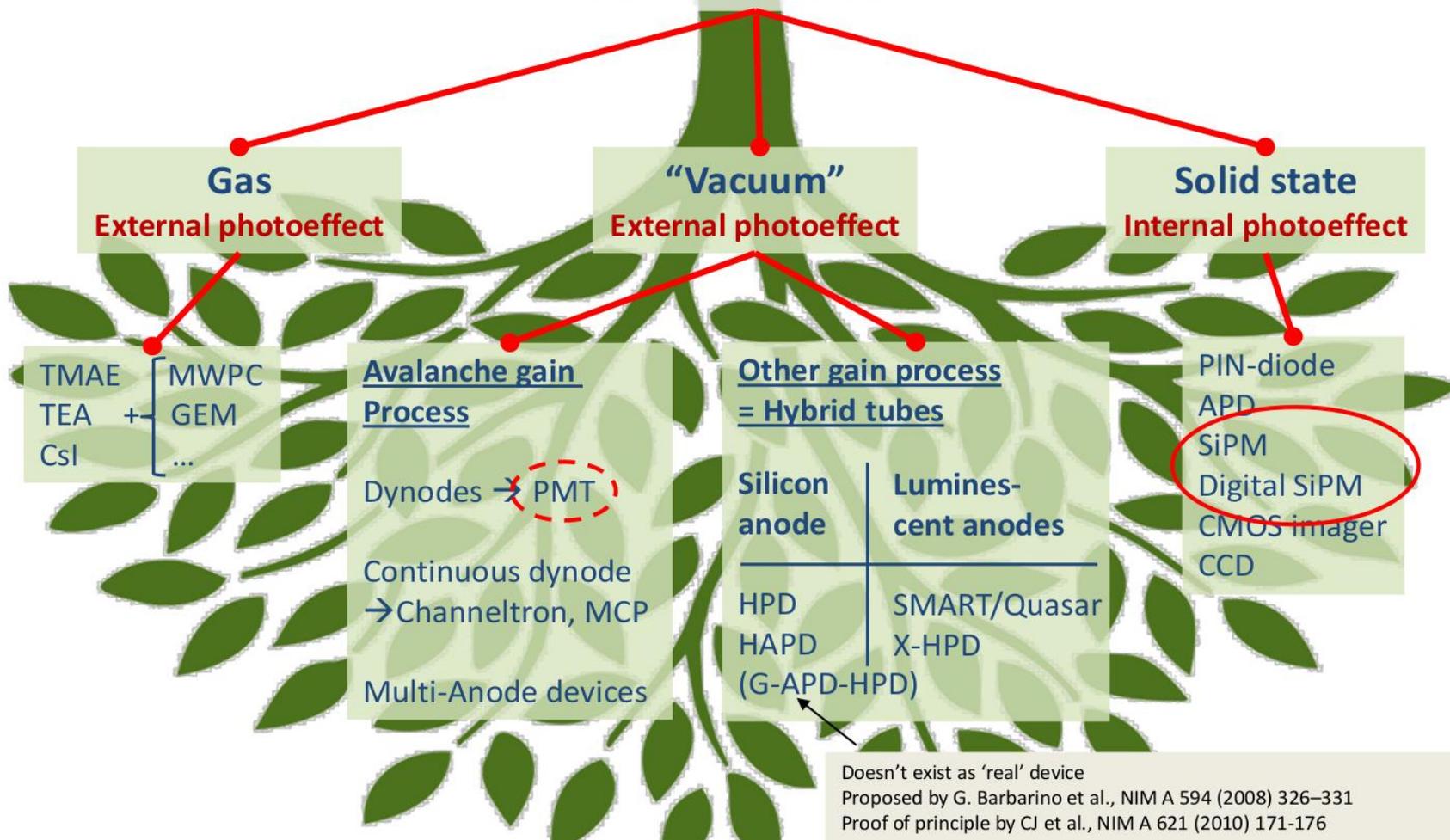
Silizium – SiPMs / GM-APD



Family tree of photo-detectors



Photodetectors



Doesn't exist as 'real' device
 Proposed by G. Barbarino et al., NIM A 594 (2008) 326–331
 Proof of principle by CJ et al., NIM A 621 (2010) 171-176

Silizium – SiPMs / GM-APD



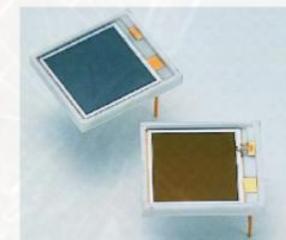
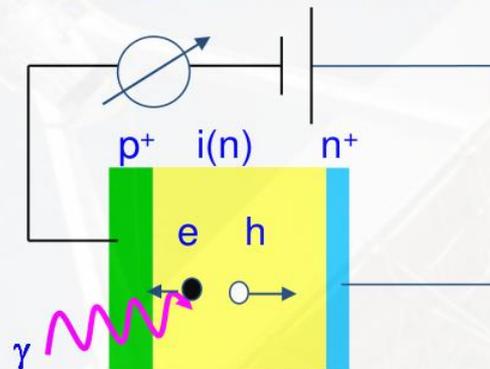
Solid-state photon detectors



AX-PET

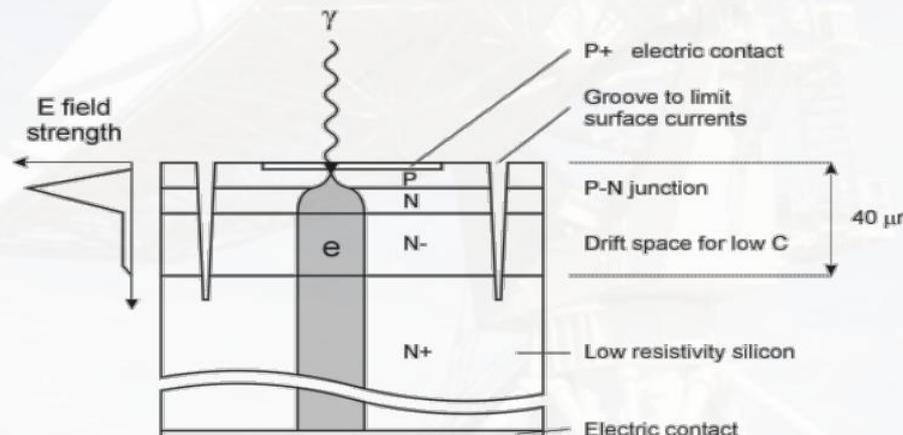
(Si) – Photodiodes (PIN diode)

- P(I)N type
- p layer very thin ($<1 \mu\text{m}$), as visible light is rapidly absorbed by silicon
- High QE (80% @ $\lambda \approx 700\text{nm}$)
- Gain = 1



Avalanche photodiode (APD)

- High reverse bias voltage: typ. few 100 V
- Special doping profile \rightarrow high internal field ($>10^5 \text{ V/cm}$) \rightarrow avalanche multiplication
- Avalanche stops due to statistical fluctuations.
- Gain: typ. $O(100)$
- Rel. high gain fluctuations (excess noise from the avalanche). CMS ECAL APD: $\text{ENF} = 2 @G=50$.
- Very high sensitivity on temp. and bias voltage $\Delta G = 3.1\%/V$ and $-2.4\%/K$



Hamamatsu S8148.
(140.000 pieces used
in CMS barrel ECAL).



Silizium – SiPMs / GM-APD



PIN → APD → Geiger mode Avalanche Photodiode (GM-APD)

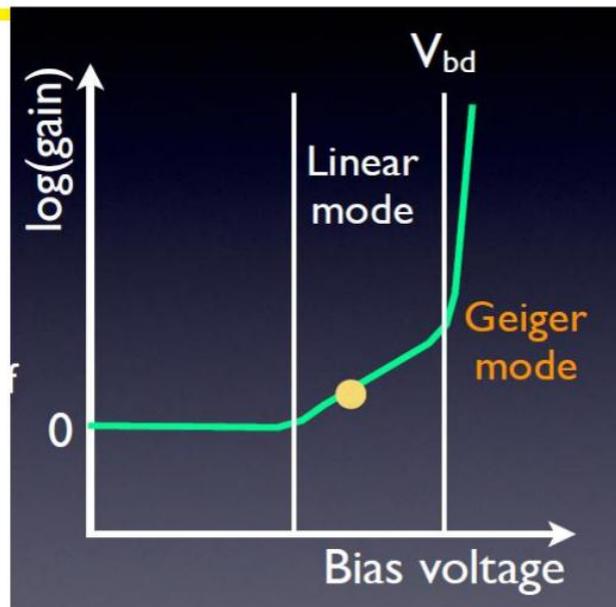


AX-PET

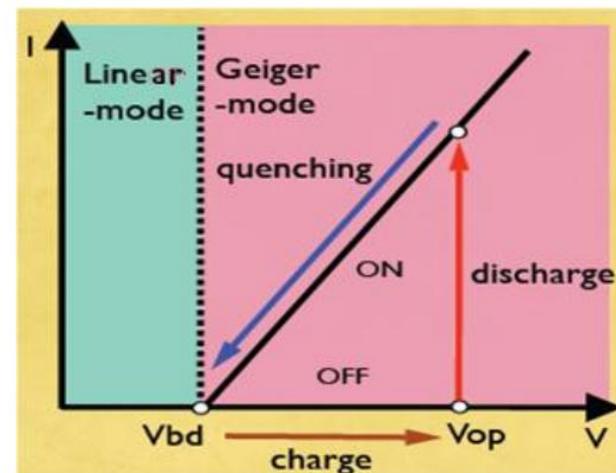
How to obtain higher gain (= single photon detection) without suffering from excessive noise ?

Operate APD cell in Geiger mode (= full discharge), however with (passive/active) **quenching**.

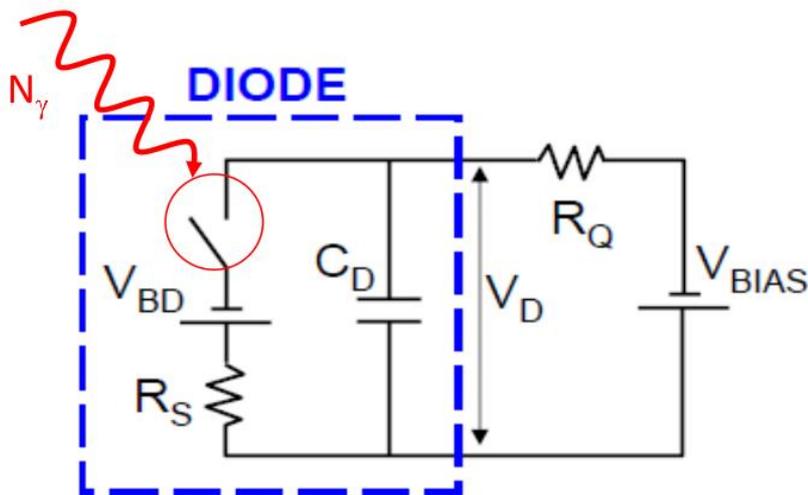
Photon conversion + avalanche short circuit the diode. A single photon (or anything else) is sufficient!



J. Haba, RICH2007



J. Haba, RICH2007

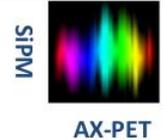


J. Haba, RICH2007

A single-cell GM-APD is just a **binary** device (=switch). Info on N_γ is lost by the Geiger avalanche. It will become more interesting when we combine many cells in one device ...



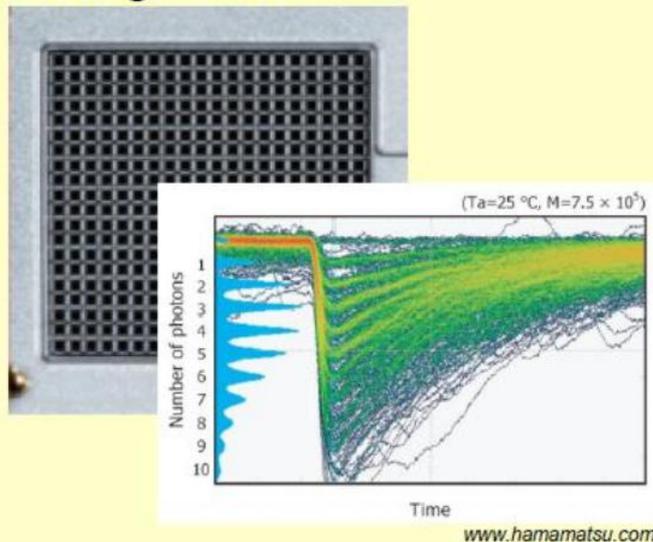
And finally ... Digital SiPM



With the GM-APD being a binary device...
one could also conceive a fully digital SiPM, where the output is just the digital count of the number of fired cells.

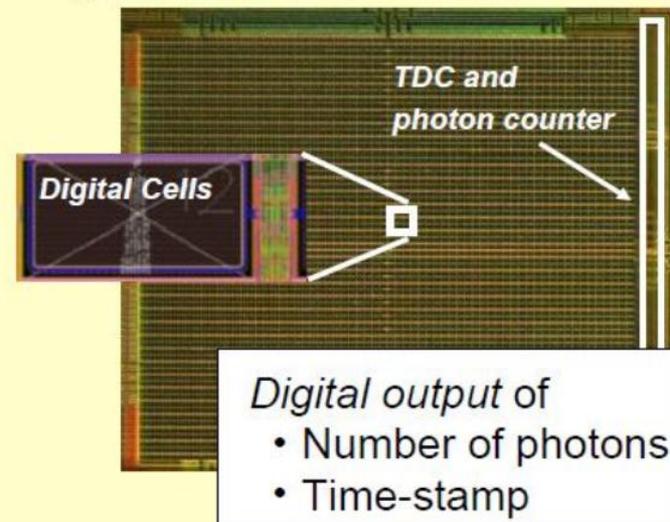
Philips

Analog SiPM



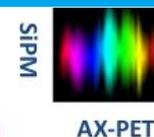
- Cells connected to common readout
- Analog sum of charge pulses
- Analog output signal

Digital SiPM

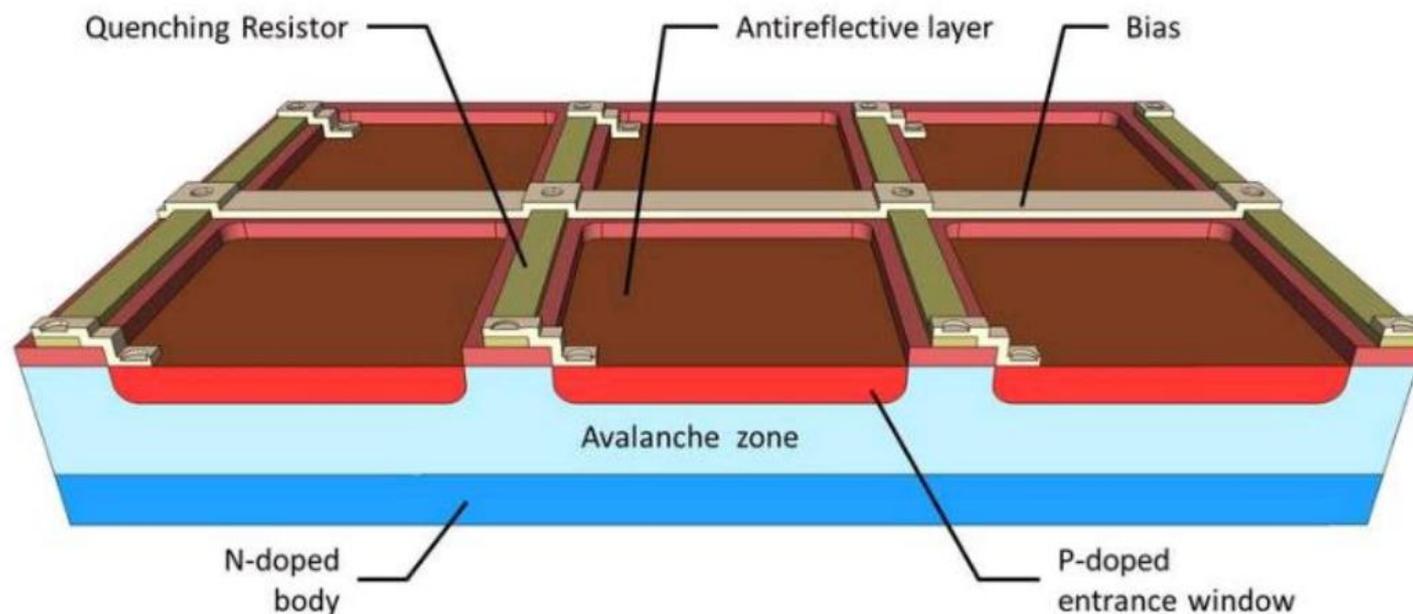


- Each diode is a digital switch
- Digital sum of detected photons
- Digital data output

Silizium – SiPMs / GM-APD



Schematic representation of a blue sensitive pn structure

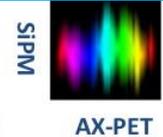


Source: <http://www.ketek.net/products/sipm-technology/microcell-construction/>

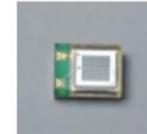
Silizium – SiPMs / GM-APD



PM vs SiPM

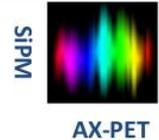


	PMT	SiPM
QE (VIS)	0.2-0.4	0.2-0.7
Gain	10^6 @ O(kV)	10^6 @ O(50V)
Timing	$T_r \sim O(1\text{ns})$ TTS $\sim O(100\text{ ps})$	$T_r \sim O(1\text{ns})$ TTS $O(100\text{ ps})$
Dynamic range	$O(10^6)$	$O(10^3)$
ENF	1.1-1.5	~ 1
Dark noise rate	$O(\text{kHz}/\text{cm}^2)$	$O(\text{MHz}/\text{mm}^2)$
Single photon sensitivity/ counting	☹/☹	☺/☺
Magnetic field immunity	☹	☺
Robustness & compactness	☹☹	☺☺





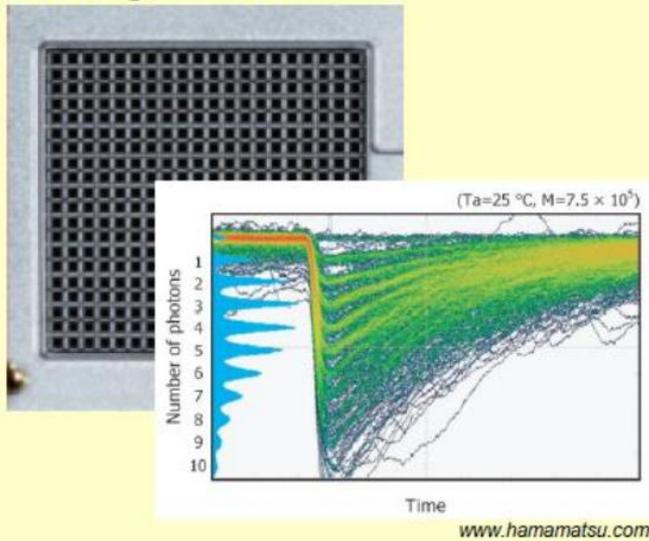
And finally ... Digital SiPM



With the GM-APD being a binary device...
one could also conceive a fully digital SiPM, where the output is just the digital count of the number of fired cells.

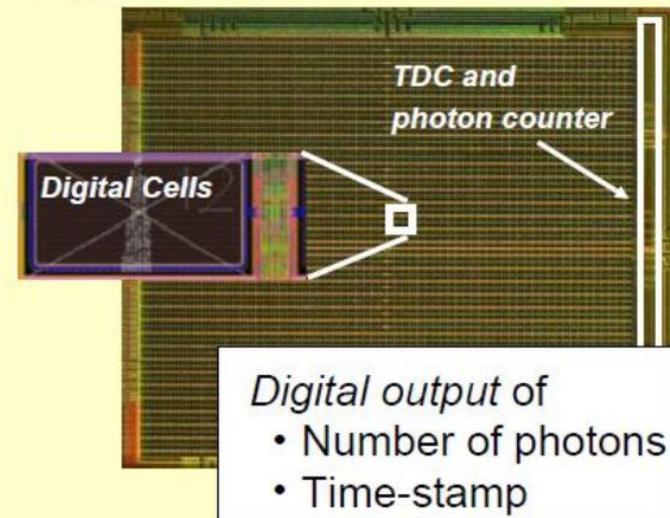
Philips

Analog SiPM



- Cells connected to common readout
- Analog sum of charge pulses
- Analog output signal

Digital SiPM



- Each diode is a digital switch
- Digital sum of detected photons
- Digital data output

Silizium – SiPMs / GM-APD



Digital SiPM



Compared to the analog technology, the digital one (so far only offered by Philips) has a number of

advantages

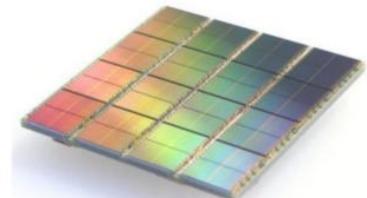
- + Integration of bias supply, amp, TDC, counter...
- + Fast active quenching → no afterpulses
- + Possibility to de-activate noisy cells → potentially lower dark noise
- + Reduced sensitivity to voltage and temperature variations
- + Compactness
- + Possibility to add local intelligence

... problems shared with analog

- High dark noise (a discharging cell doesn't know whether it is digital or analog)
- Signal saturation (limited number of cells)

... and also has some drawbacks

- The local electronics is a source of heat → cooling advisable
- The readout functionality is designed into the sensor. In case of mismatch with the needs, relatively expensive modifications of the sensor/FPGA may be required.

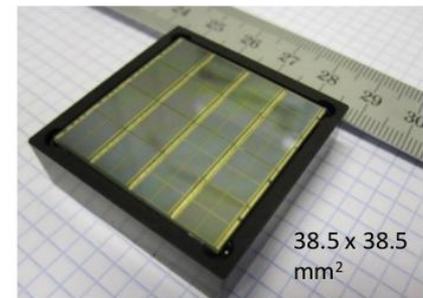


Front and back sides of a 64 channel digital tile (DPC6400-22-44) or (DPC3200-22-44)



Philips

Packaged module, as delivered to clients (DPC3400-22-44). Includes a 100 μm thick protective glass layer.

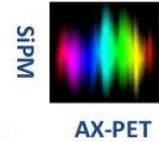


38.5 x 38.5 mm^2

Silizium – SiPMs / GM-APD



SiPM in the ILC HCAL and ECAL (R&D)

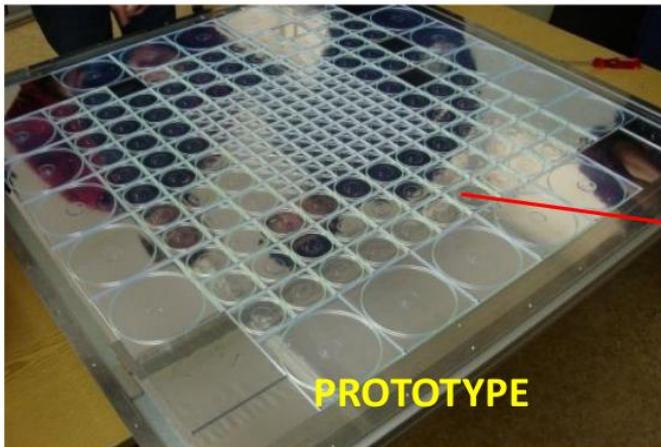


High granularity hadronic calorimeter optimised for the Particle Flow measurement of multi-jets final state at the ILC

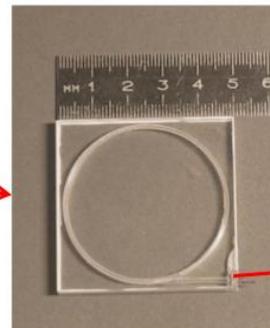
photo-detector requirements:

- insensitive to magnetic field ($\sim 5T$)
- coupling with a scintillator (blue emission)
- stability (T-control or T-monitoring)
- rel. large dynamic range
- low cost

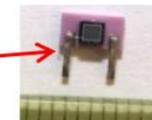
CALICE tests with MePHI/PULSAR, HAMAMATSU, KETEK SiPMs



216 tiles/layer (38 layers in total) ~ 8000 channels



3 x 3 cm² plastic scintillator tile with embedded WLS fiber + SiPM



SiPM
1 mm²

Readout of SiPMs by the SPIROC ASIC (LAL)

$e^+ e^-$ collider (1 TeV)

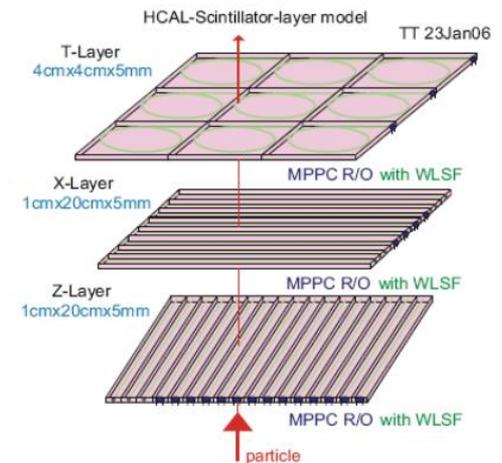
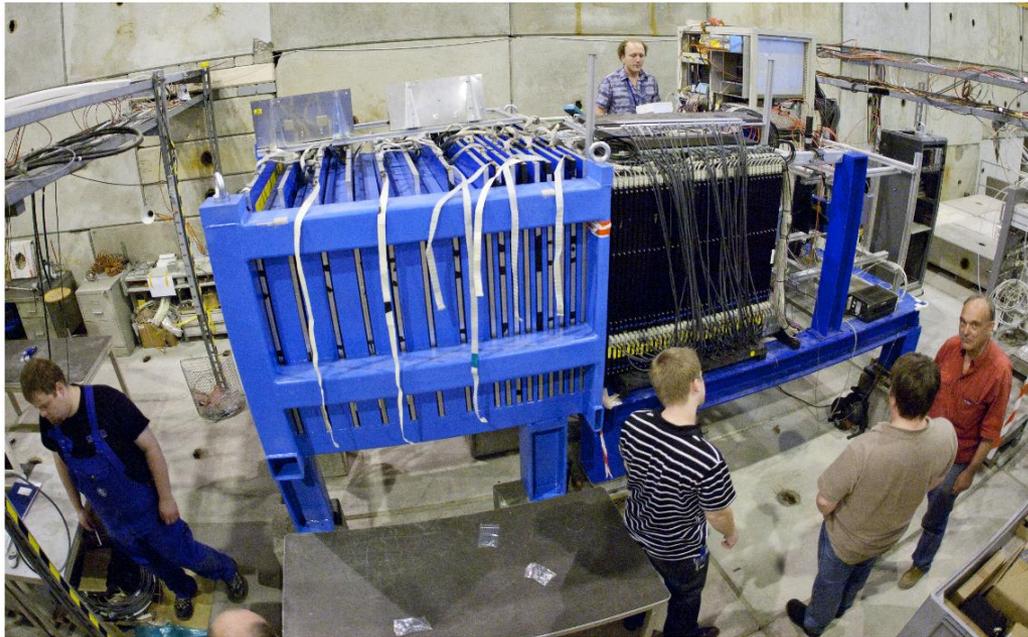


Fig. 6. A possible scintillator strip/tile sequence of the analog HCAL.

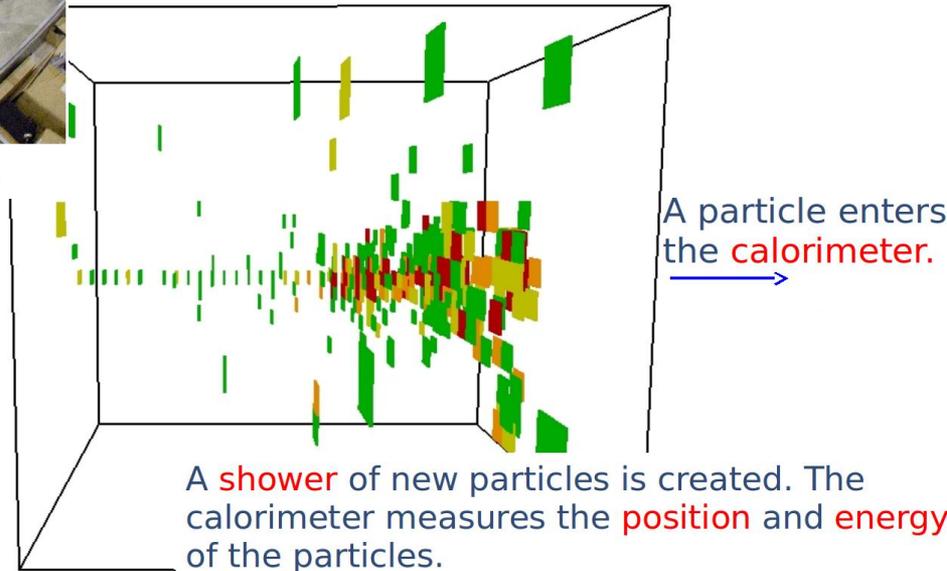
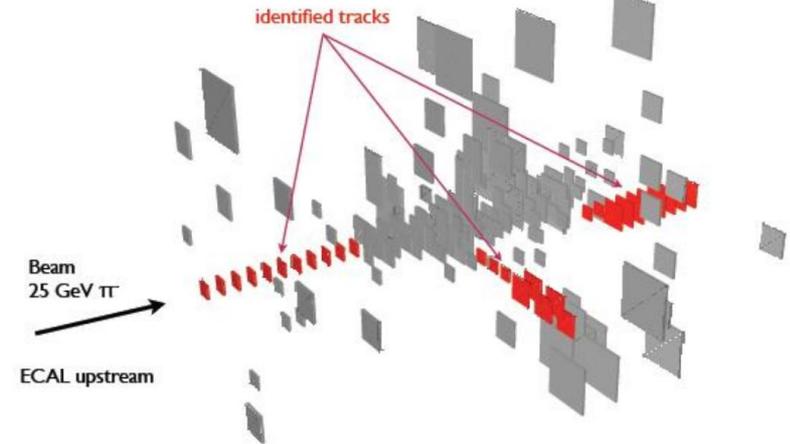
Silizium – SiPMs in Kalorimetern



Prototype of an **imaging calorimeter** for CLIC.

> Pixeliertes Kalorimeter

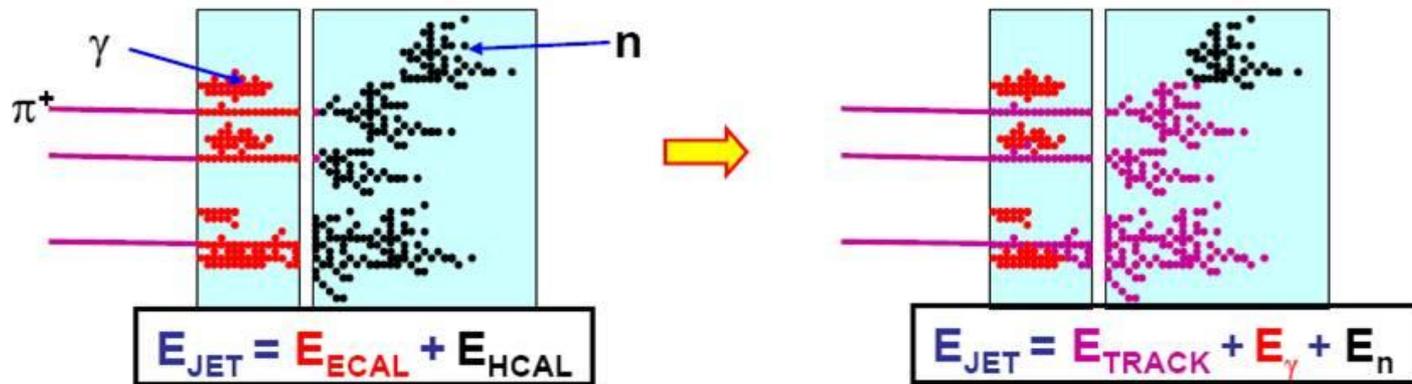
- Fast wie Spurdetektor – erlaubt „particle flow“ Messung, siehe naechste Seite



Particle Flow – verbesserte Energiemessung

> Traditionelle Datenrekonstruktion

- „Hits“ im Spurdetektor zu Spuren verbinden und Impuls der Teilchen bestimmen
- „Hits“ im Kalorimeter zu Jets zusammenfassen und damit Energie des ursprünglichen Teilchens messen



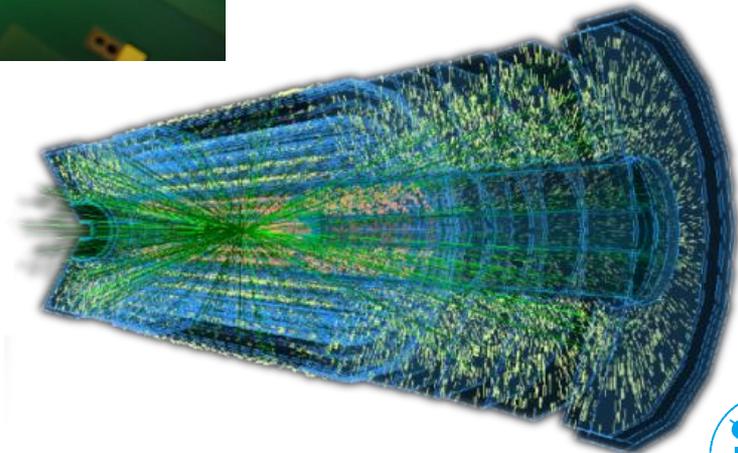
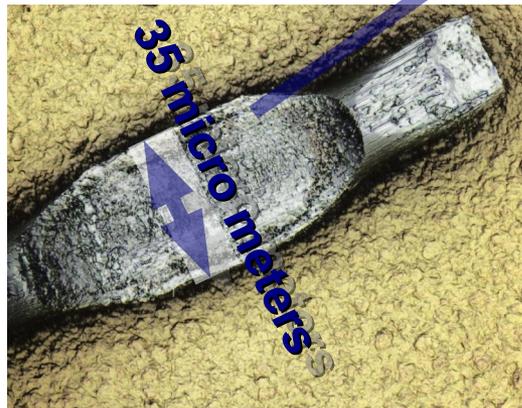
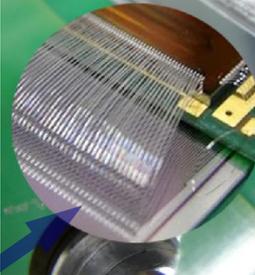
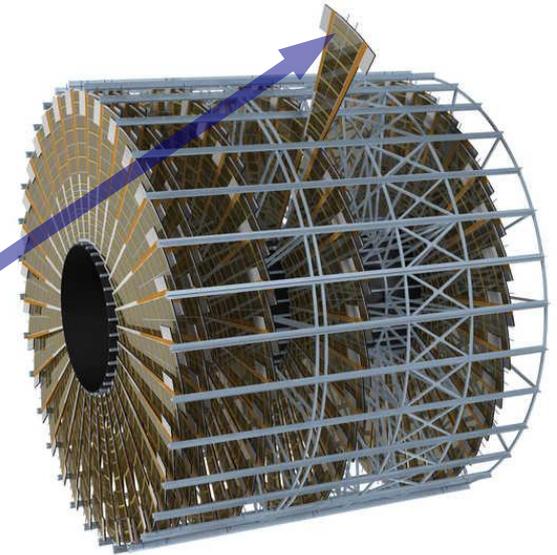
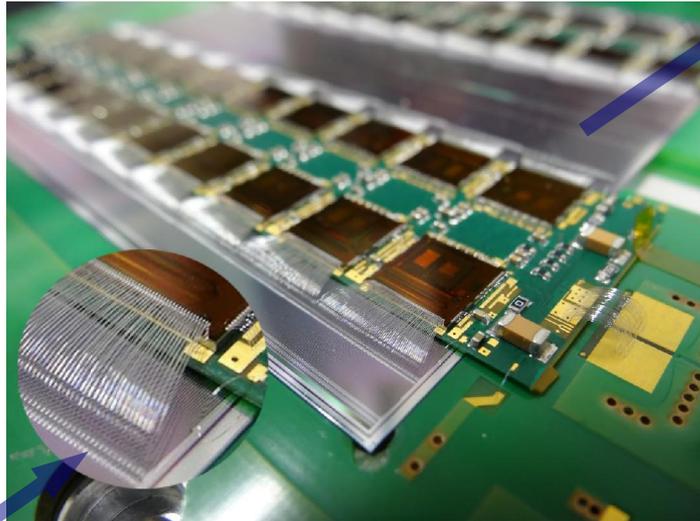
> Energy/Particle Flow

- Vor Zusammenfassung von Kalo-Hits zu Jets, erst mit Spuren kombinieren, besten Messwert bestimmen und dann für Jets bestbekanntesten Wert verwenden

- Kurze Einführung
- Beispiele für Anforderungen an Detektoren
 - Im Proton-Proton Large Hadron Collider
 - In einer möglichen Elektron-Positron Maschine
- Gasdetektoren, Beispiel MICROMEGA, GEM
- Silizium-Photomultiplier
 - Anwendung in Calice
 - Design für Energy-/Particle-Flow
 - » Kurze Particle-Flow Erläuterung
- **Silizium Spurdetektoren**
 - Streifen (hier in Z :)) - mit CO₂ Kühlungs-Intermezzo
 - Pixel

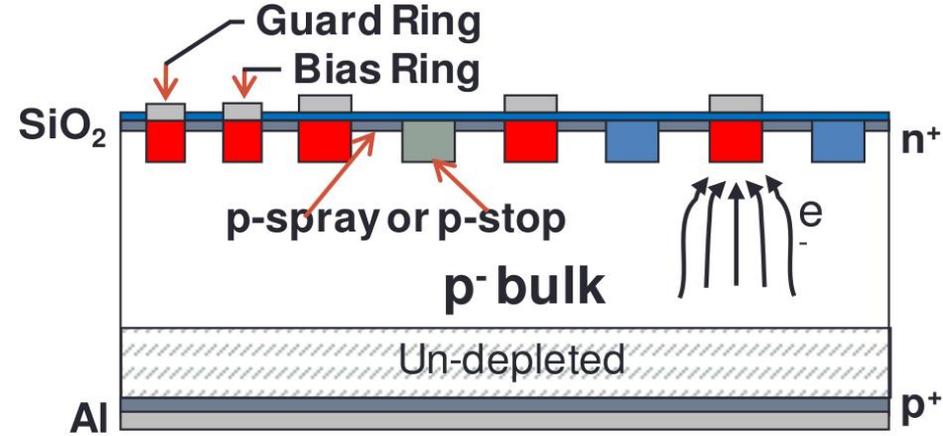


Silizium: Streifen und Pixel

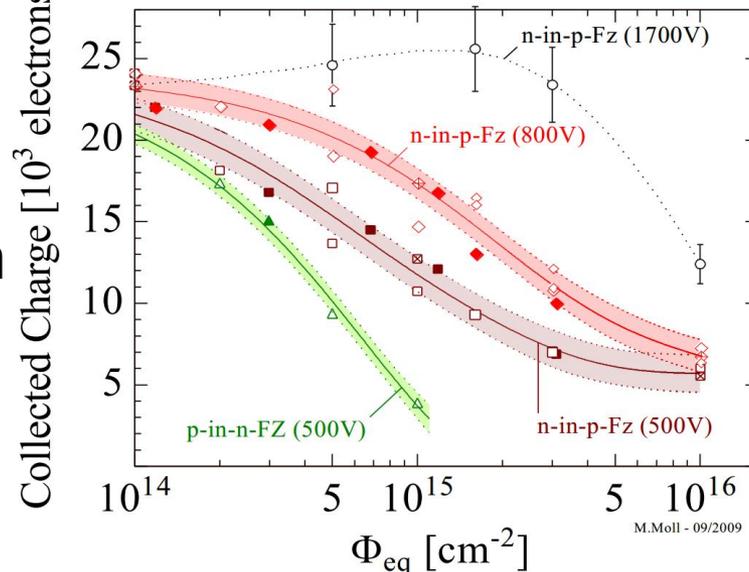


Silizium Streifendetektoren – n-Seiten Auslese

- > **Neu: n-in-p Sensoren**
- > Einseitiger Prozess bei Herstellung
→ **Günstiger**
- > Kann partiell verarmt betrieben werden, da p-n Übergang immer auf Ausleseseite
→ **Strahlenthart**
- > Es werden Elektronen und nicht wie bei trad. p-in-n Löcher von der Auslese gesammelt
→ **Schneller mit weniger Ladungsverlust an Störstellen**



N. Unno, Trento 2012



FZ Silicon Strip Sensors

- n-in-p (FZ), 300μm, 500V, 23GeV p [1]
- n-in-p (FZ), 300μm, 500V, neutrons [1,2]
- ⊠ n-in-p (FZ), 300μm, 500V, 26MeV p [1]
- ◆ n-in-p (FZ), 300μm, 800V, 23GeV p [1]
- ◇ n-in-p (FZ), 300μm, 800V, neutrons [1,2]
- ◊ n-in-p (FZ), 300μm, 800V, 26MeV p [1]
- n-in-p (FZ), 300μm, 1700V, neutrons [2]
- ▲ p-in-n (FZ), 300μm, 500V, 23GeV p [1]
- △ p-in-n (FZ), 300μm, 500V, neutrons [1]

References:

- [1] G.Casse, VERTEX 2008 (p/n-FZ, 300μm, -30°C, 25ns)
- [2] I.Mandic et al., NIMA 603 (2009) 263 (p-FZ, 300μm, -20°C to -40°C, 25ns)

G. Kramberger, Vertex 2012



Silizium Streifendetektoren – ATLAS

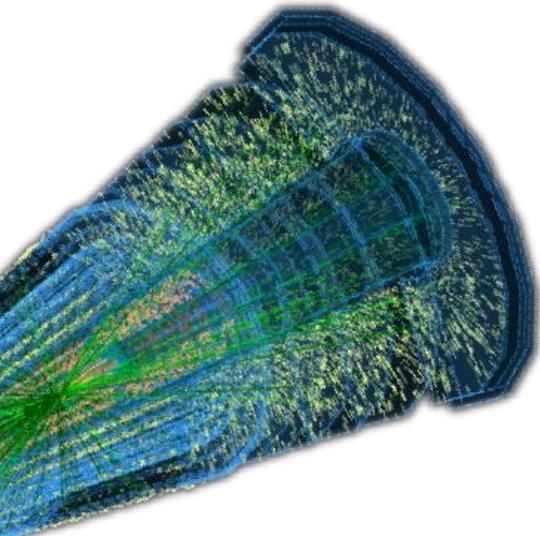
> ATLAS Streifendetektor für HL-LHC Upgrade:

- Extreme Strahlenbelastung; momentane Sensoren überstehen $\mathcal{L} \sim 300 \text{ fb}^{-1}$

> Problem: Ziel für HL-LHC ist $\mathcal{L} \sim 3000 \text{ fb}^{-1}$
→ **e.g. n-in-p Sensoren**

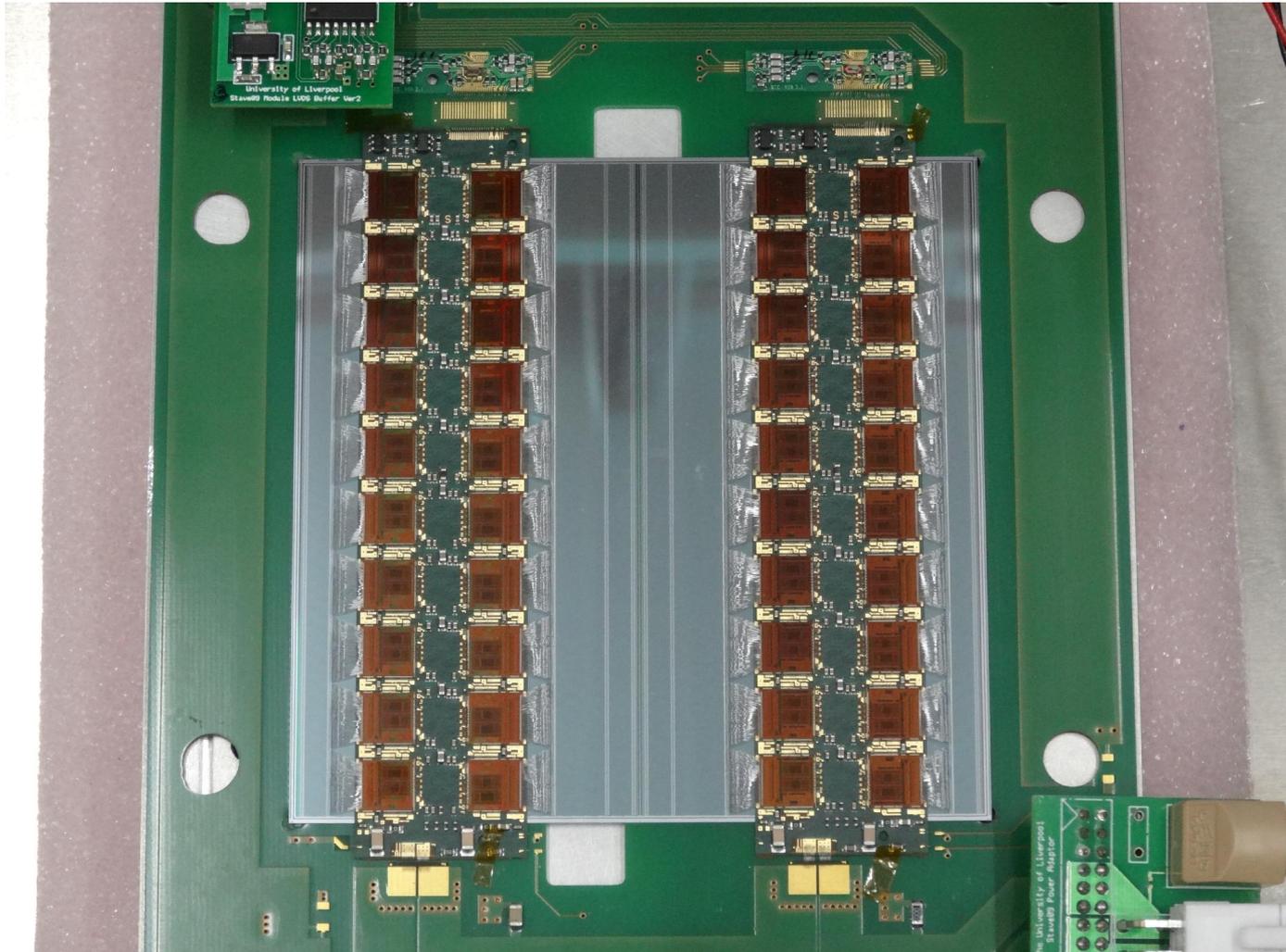
- ~140 PileUp Events überlagern Hauptereignis

> Problem: Mit momentaner Segmentierung / Streifenlänge erhält man potentiell mehrere Treffer pro Streifen
→ **Unterteilung in mehr kürzere Streifen**

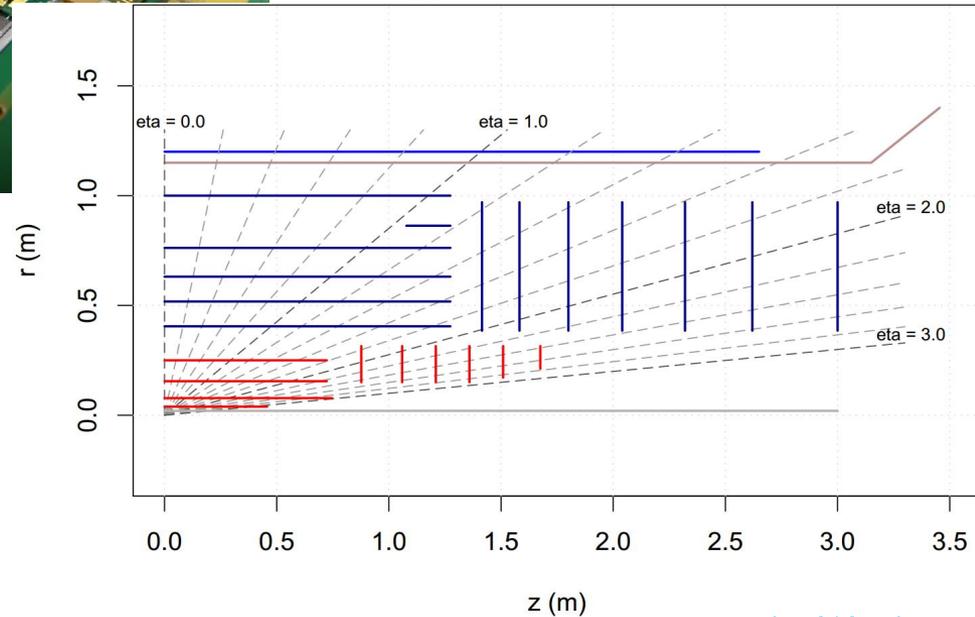
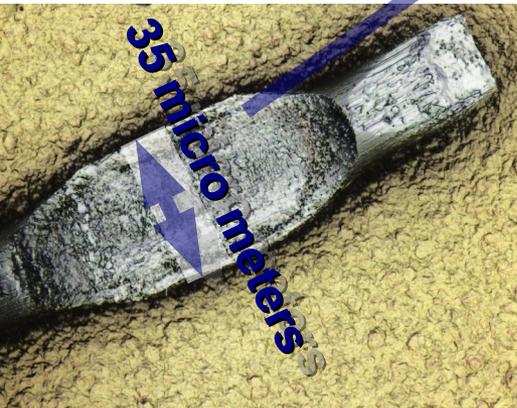
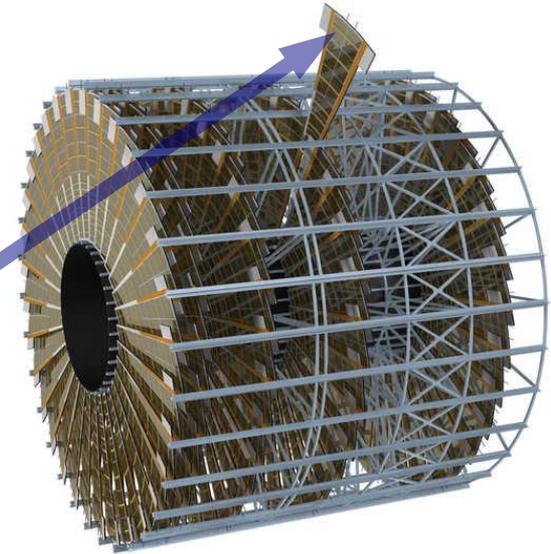
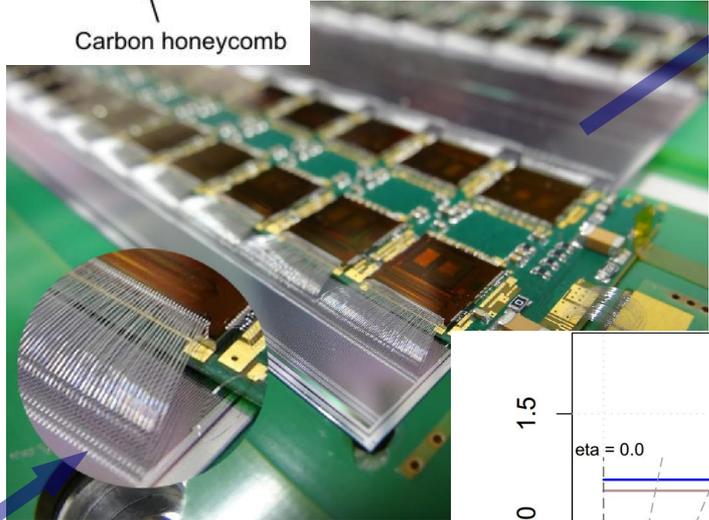
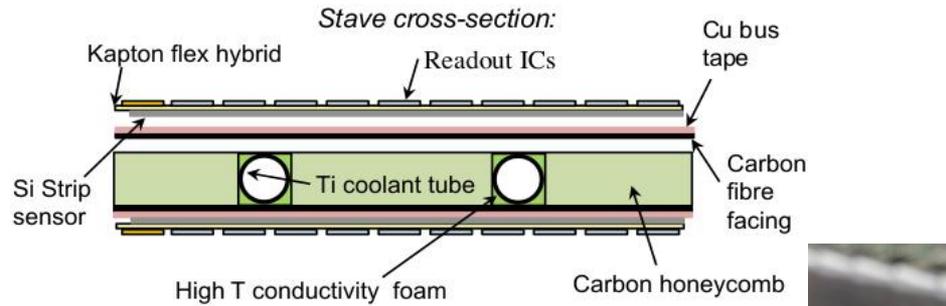


HL-LHC Si-Streifenmodule in Zeuthen

- Eins der ersten in DESY gefertigten ATLAS Streifenmodule



Silizium Streifendetektoren – ATLAS



Silizium Streifendetektoren – CMS

- > CMS verfolgt Selbst-Trigger Konzept
- > 2 sehr nah beieinander liegende Sensoren liefern Abschätzung der Spurkrümmung

- Outer tracker

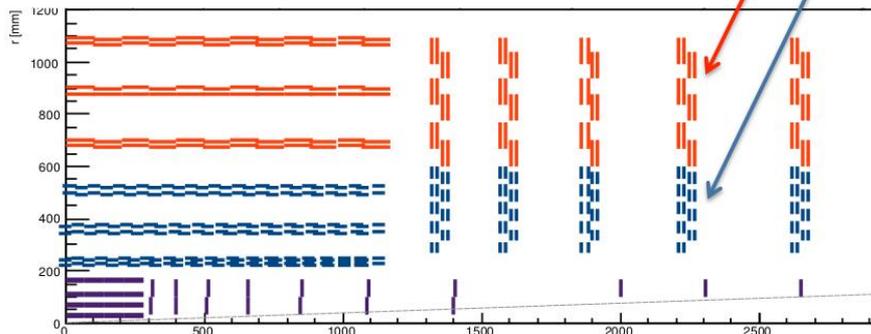
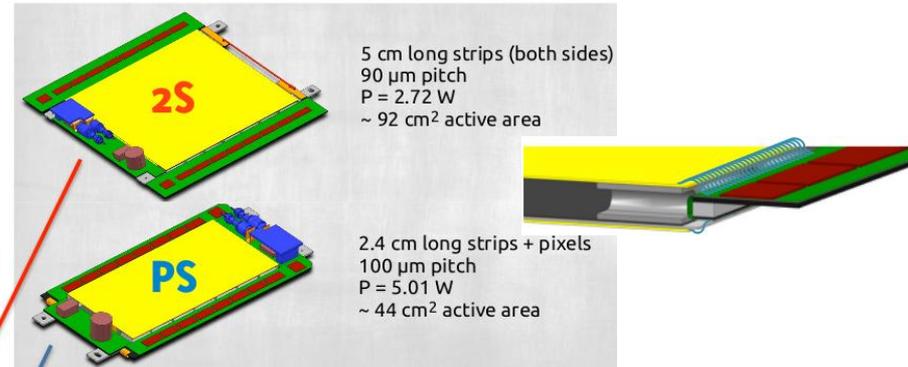
- High granularity for efficient track reconstruction beyond 140 PU
- Two sensor “Pt-modules” to provide trigger information at 40 MHz for tracks with $P_t \geq 2 \text{ GeV}$
- Improved material budget

- Pixel detector

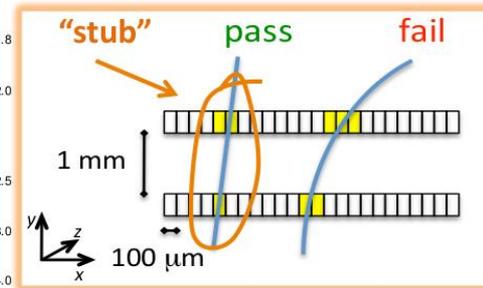
- Similar configuration as Phase 1 with 4 layers and 10 disks to cover up to $|\eta| = 4$
- Thin sensors 100 μm ; smaller pixels 30 x 100 μm

- R&D activities

- In progress for all components - prototyping of 2S modules ongoing
- BE track-trigger with Associative Memories



Trigger track selection in FE





- Für HL-LHC ist Kühlung sehr wichtig da Sensoren bei niedriger Temperatur weniger Schaden durch die Strahlung erhalten

CO₂ cooling

5th Detector Workshop of the
Helmholtz Alliance

"Physics at the Terascale"

CO₂ Kühlung



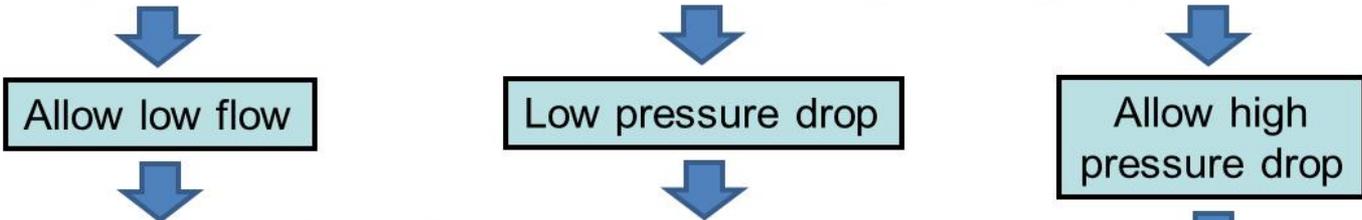
Why is evaporative CO₂ cooling good for HEP detectors?



CO₂ allows small tubing

Why?

Large latent heat & Low viscosity & High pressure



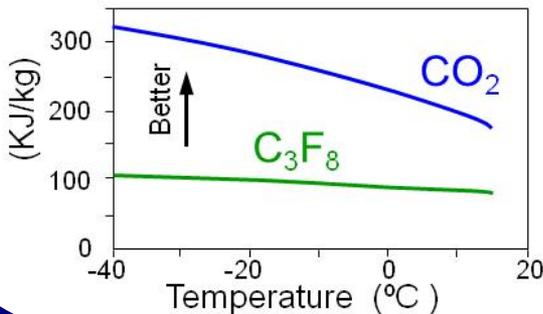
Low pressure drop

Lower pressure drop

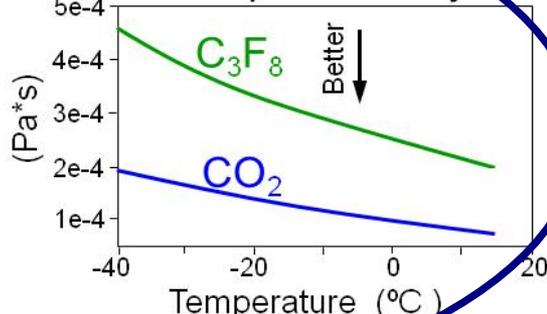
Allow very small tubing

But with very high heat transfer capability!

Latent Heat of Evaporation



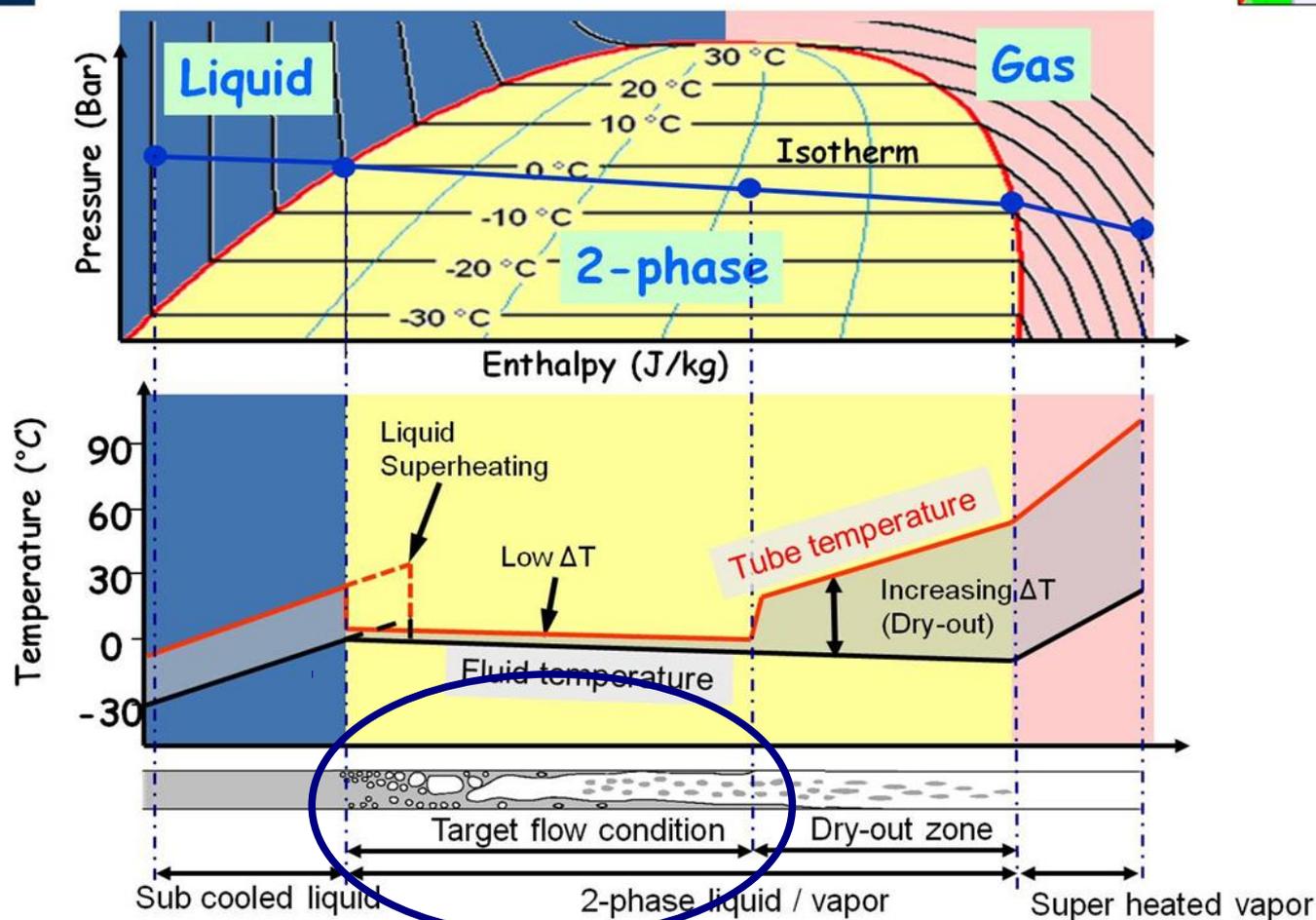
Liquid Viscosity





What happens inside a cooling tube?

Heating a flow from liquid to gas





CO₂ and safety



CO₂ has a high pressure (10-100bar) but this does not have to be an increased safety issue.

Pressure Equipment Directive (PED):

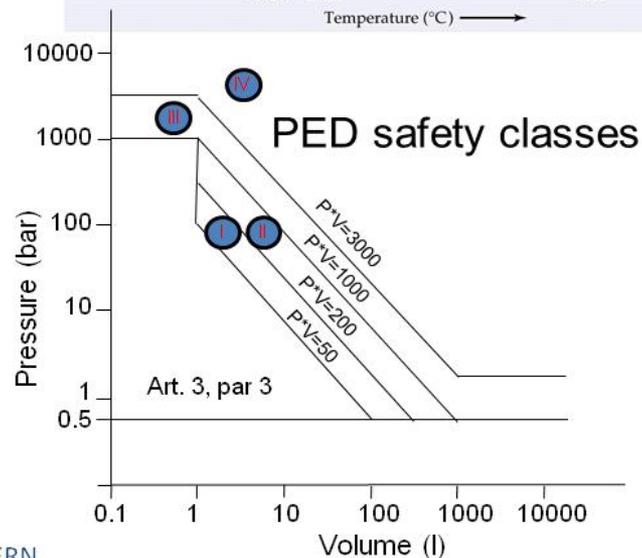
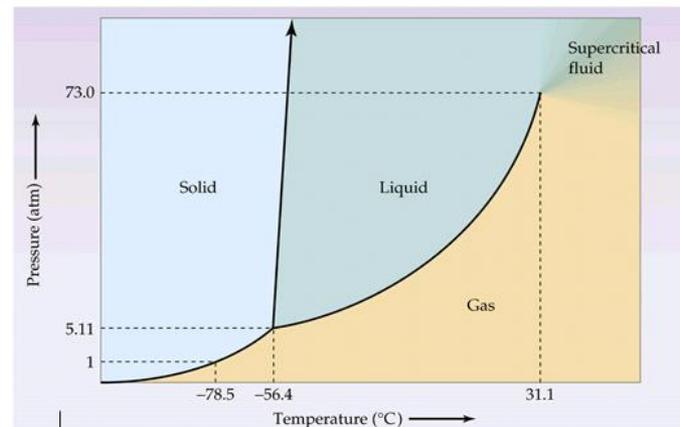
- Stored energy determines the safety class.
- Stored Energy = **Pressure x Volume**

CO₂ is environmental friendly, non-toxic and cheap

CO₂ in large concentrations is asphyxiating, be careful with venting CO₂ in unventilated small spaces.

CO₂ does not exist as liquid in atmospheric conditions. It is released as -78°C solid (Like a fire extinguisher). => Cold burn risk.

	ID	Design Pressure	Stored energy
CO ₂	1.4mm	100 bar	15.4 J/m
C ₃ F ₈	3.6mm	15 bar	15.3 J/m



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3D Sensors

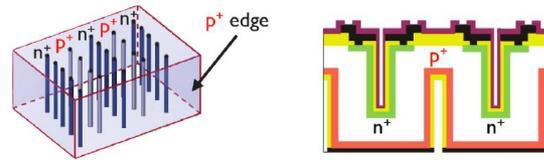
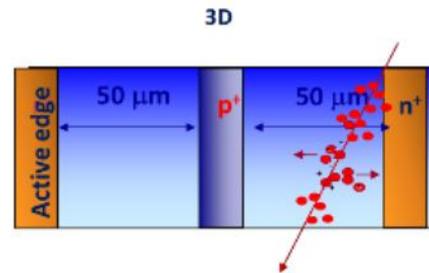
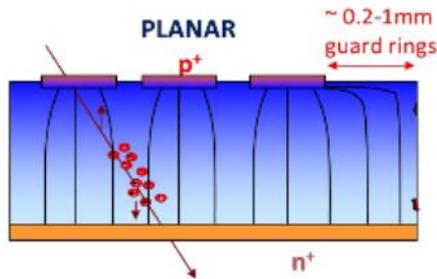
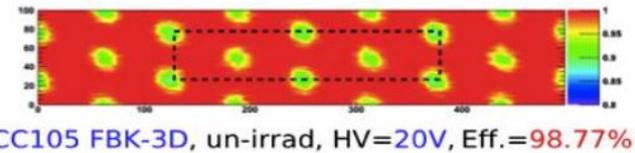


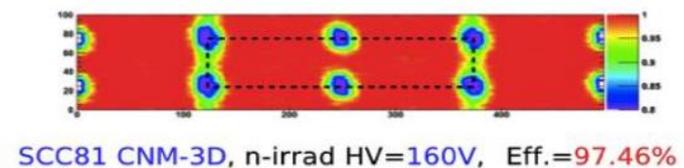
Figure 1: Schematic of full-3D sensor with n⁺ read-out and p⁺ bias electrodes (left) and partial-3D (right).



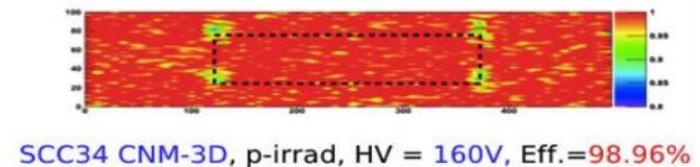
3D pixel sensors



0°



0°

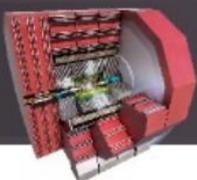


15°

- Both electrode types are processed inside the detector bulk
- Max. drift and depletion distance set by electrode spacing - **reduced collection time and depletion voltage**
- Very good performance at high fluences**
- Production time and complexity to be investigated for larger scale production
- Used in ATLAS IBL

ATLAS IBL Sensor (Threshold: 1600 e
 p-irrad: $5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ with 24 MeV protons
 n-irrad: $5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ by nuclear reactor)

Silizium Pixel – sehr dünne Sensoren



Thin sensor assemblies

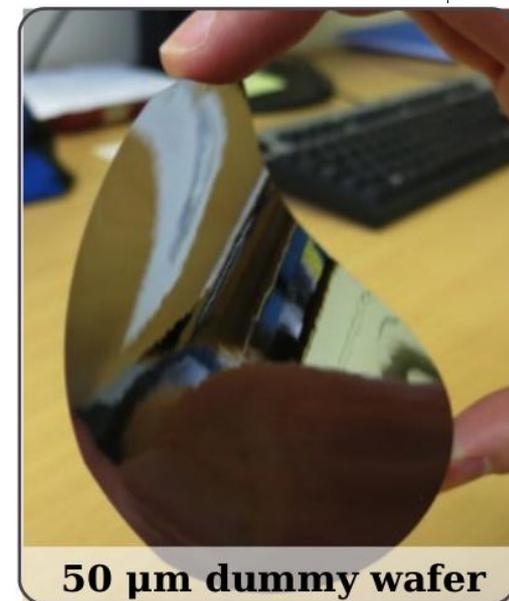


Advacam

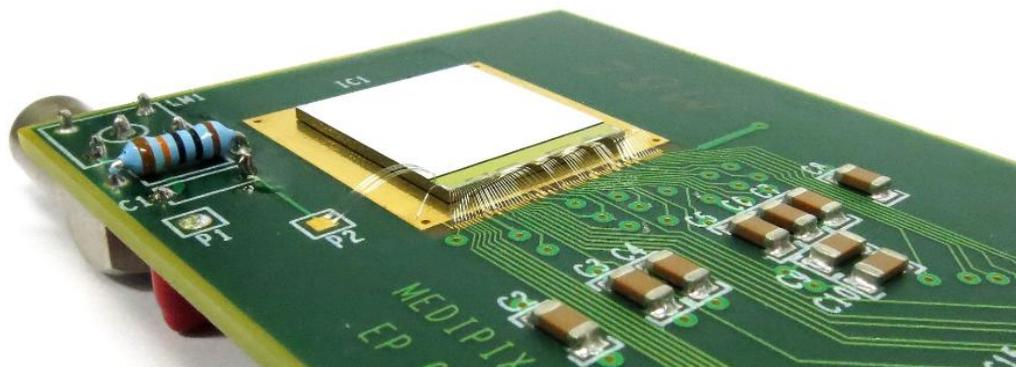
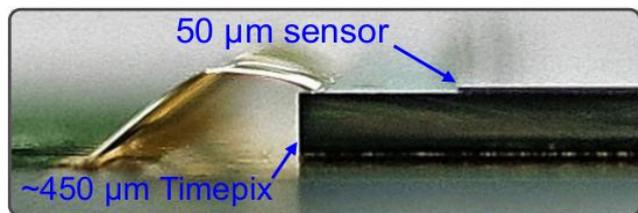
- **50 μm thin** with **20 μm and 50 μm active-edge** assemblies on standard thickness Timepix ASIC (*delivered July 2013*)
- **Excellent sensor quality**, few (<8) unconnected bumps
- Depletion at **15V**
- *5 x assemblies tested at DESY*

Micron Semiconductor + IZM

- **100, 150, 200 μm** pixel sensor (Timepix compatible)
- *3 x 100 μm assemblies tested at DESY*



50 μm dummy wafer



Conclusion & Ausblick

- Kleinere, schnellere, effizientere, strahlenhärtere, magnetfeldresistentere ... Sensoren. z.B.
 - GEMs statt Driftkammern
 - SiPMs statt PMs
 - 3D Pixel statt 2D Pixel
 - n-in-p statt p-in-n
- Fortschritt beim Verständnis von Strahlenschäden zusammen mit höherer Packungsdichte in Auslesechips erlaubt Silizium-Spur-Detektoren für HL-LHC
 - CO₂ Kühlung bringt notwendige niedrige Temperaturen bei gleichzeitiger Materialreduktion
- Weitere Integration (Auslese & Sensor in einem Guss) zu erwarten mit günstiger CMOS Technologie

