Desy Kolloquium, 5.10.2016

From chips to Higgs and back

... tracking detectors in modern particle physics experiments(*)

Norbert Wermes
University of Bonn

(*) = mostly LHC, but not only

"From chips to Higgs and back"

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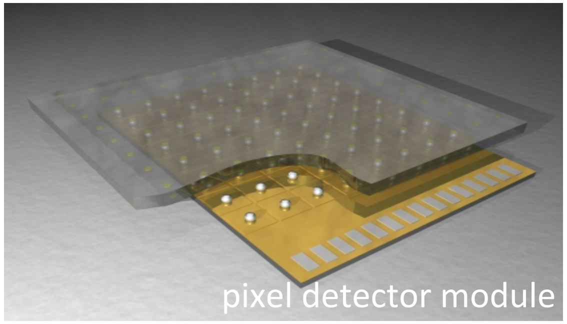
detector development



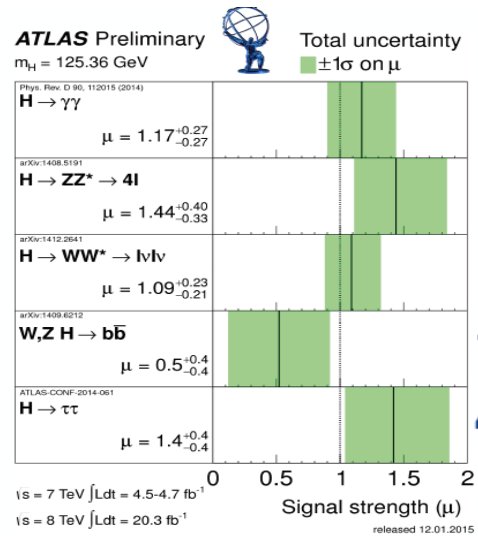
Run 1 (2010-12)

LHC ≅ 10^6 x LEP in track rate !

Run 2 (2015-18): Run 1 **x 5**

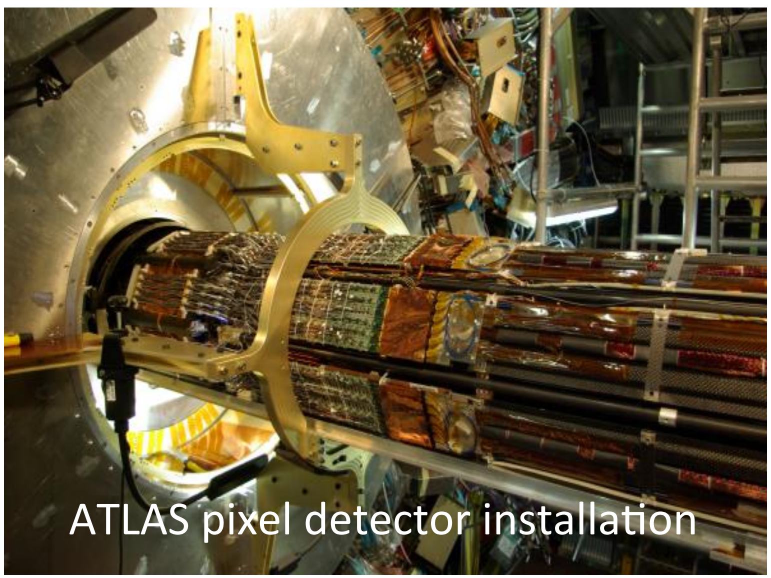
2018 + ... Run 1 **x 10 ?**

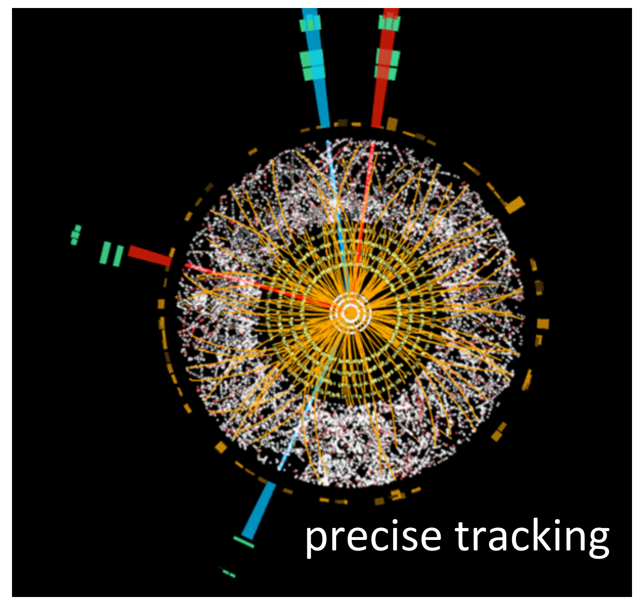
2026 + ... Run 1 **x 10 – 20 ?**

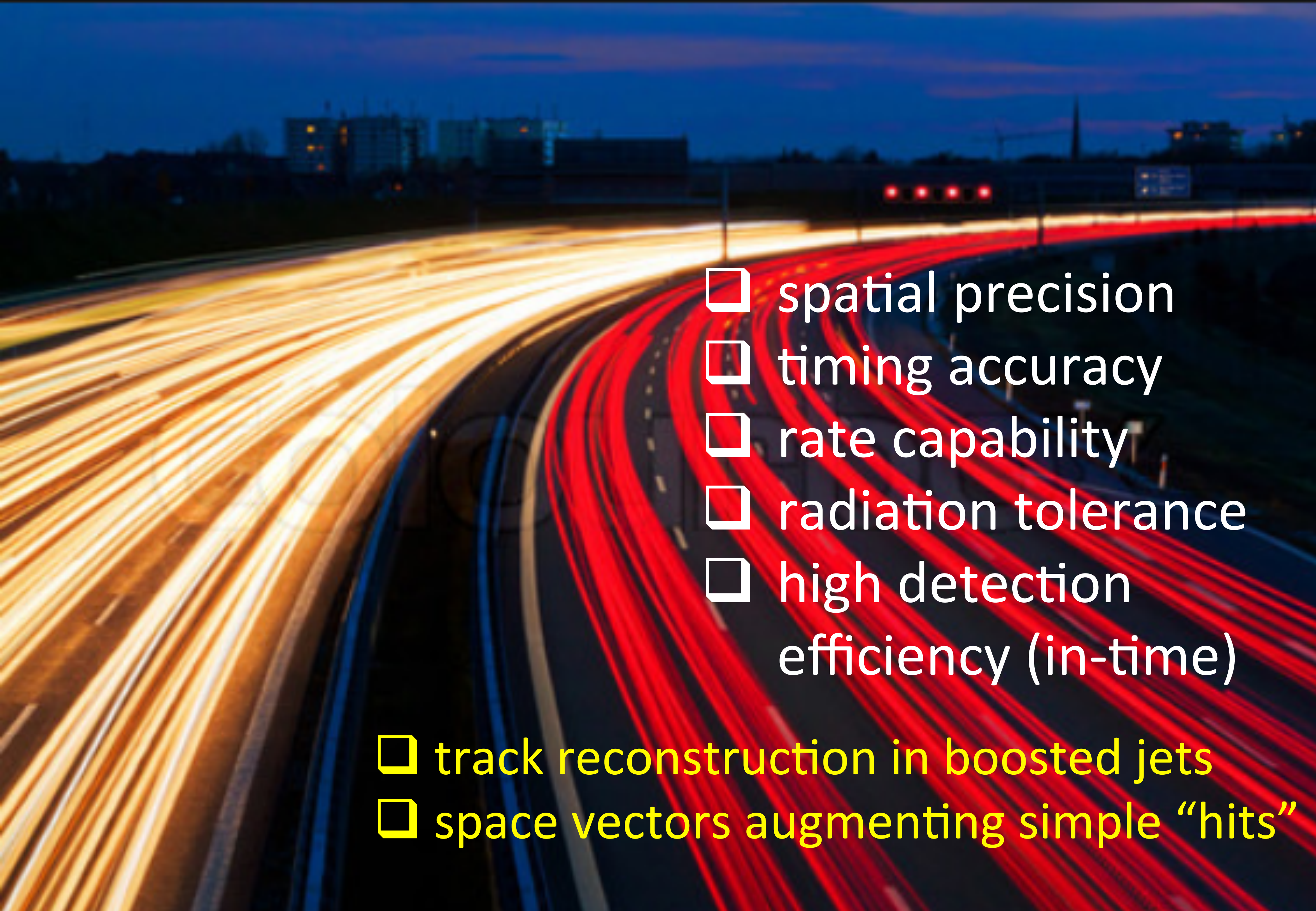


1.4σ

4.5σ







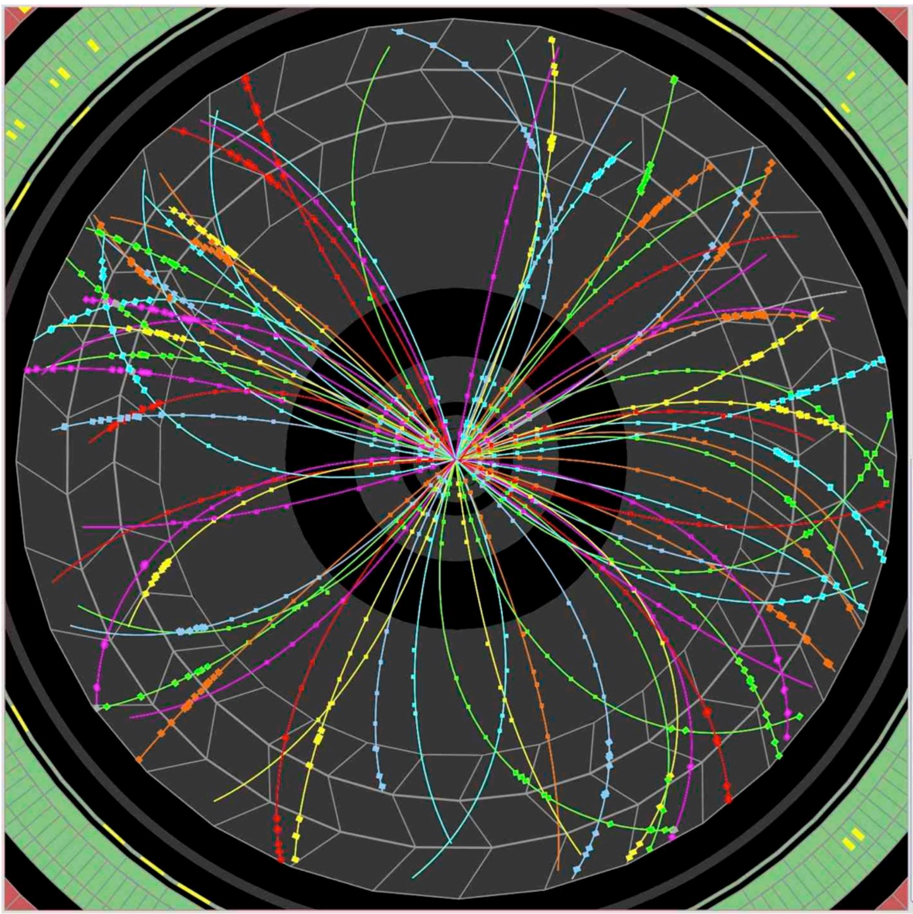
- ❑ spatial precision
- ❑ timing accuracy
- ❑ rate capability
- ❑ radiation tolerance
- ❑ high detection efficiency (in-time)

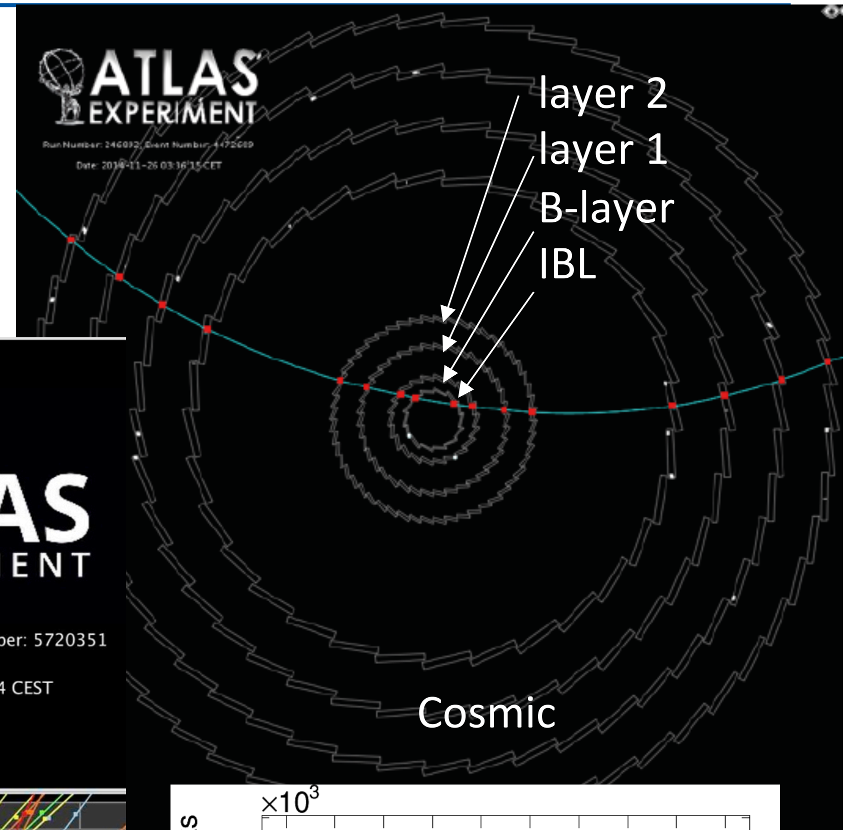
- ❑ track reconstruction in boosted jets
- ❑ space vectors augmenting simple “hits”

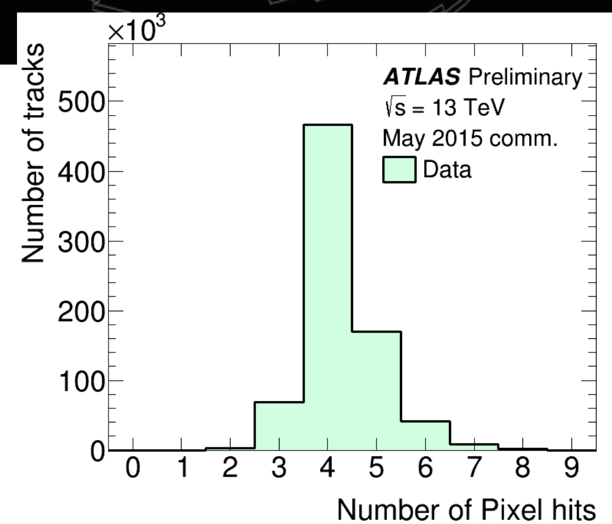
ATLAS Pixel Detector in operation

4-hit pixel system!
important for b-quark tagging

low luminosity, 2 interactions







pp -> WH -> νl + bb

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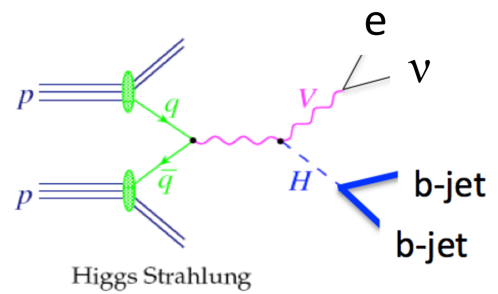
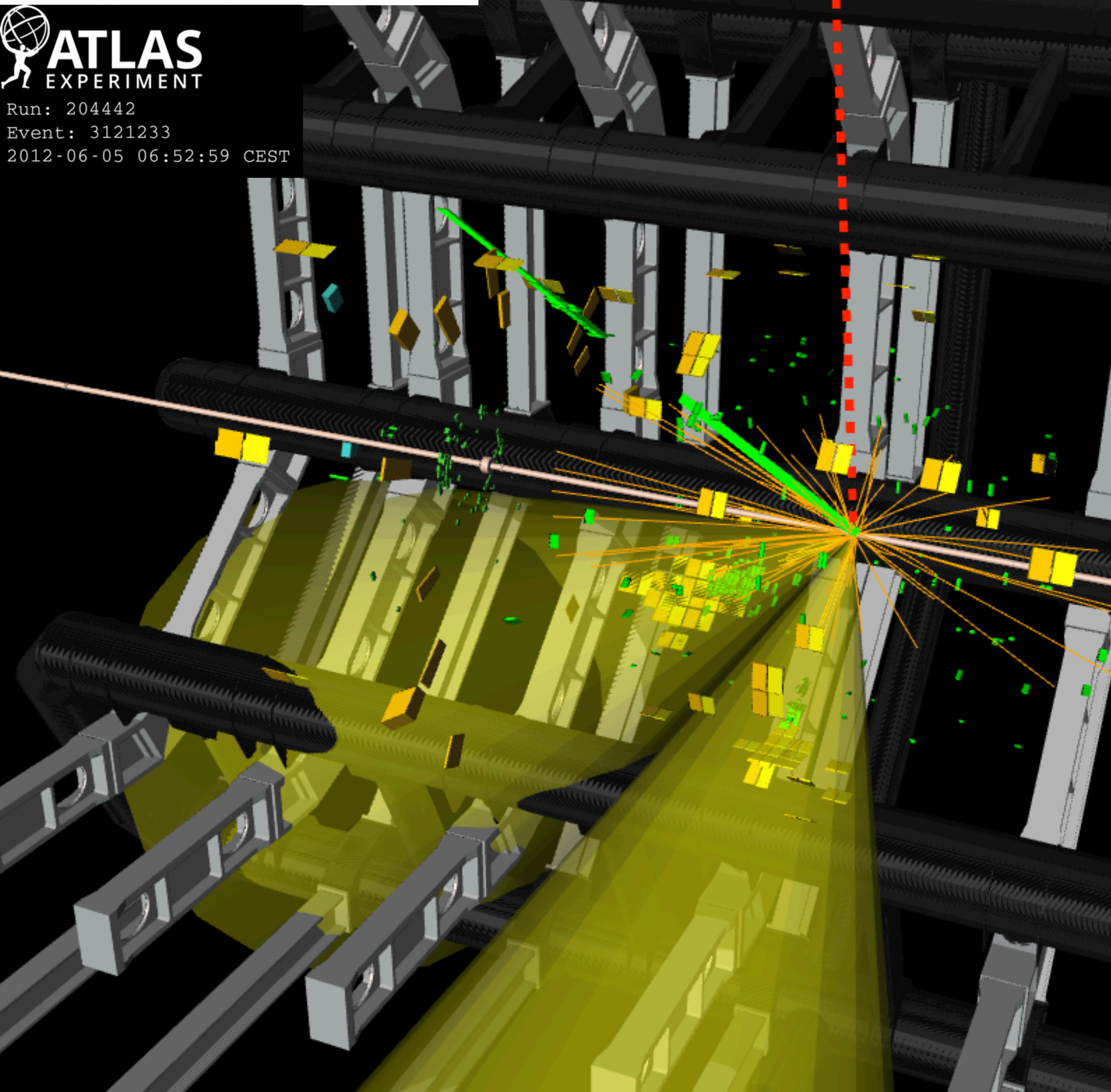
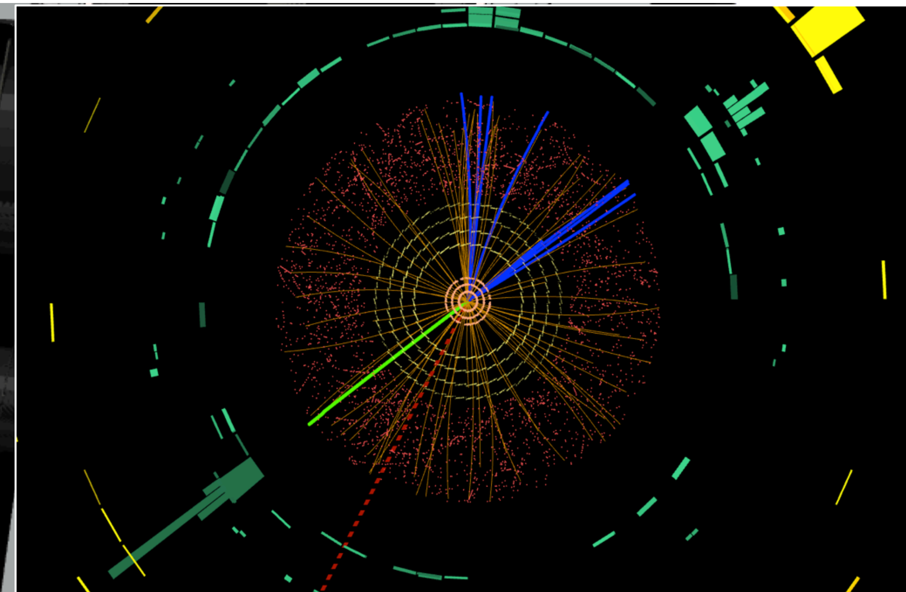
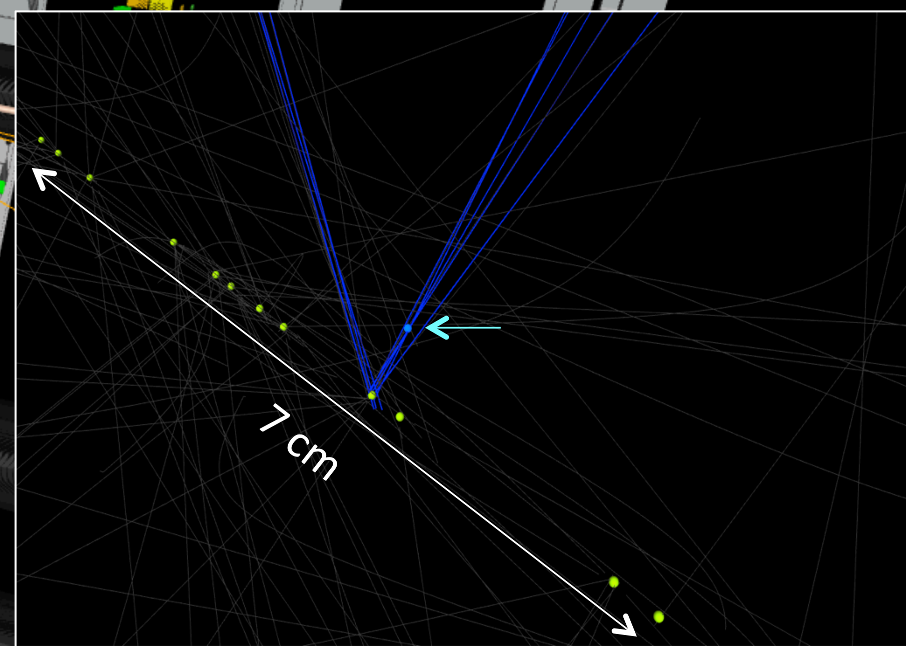
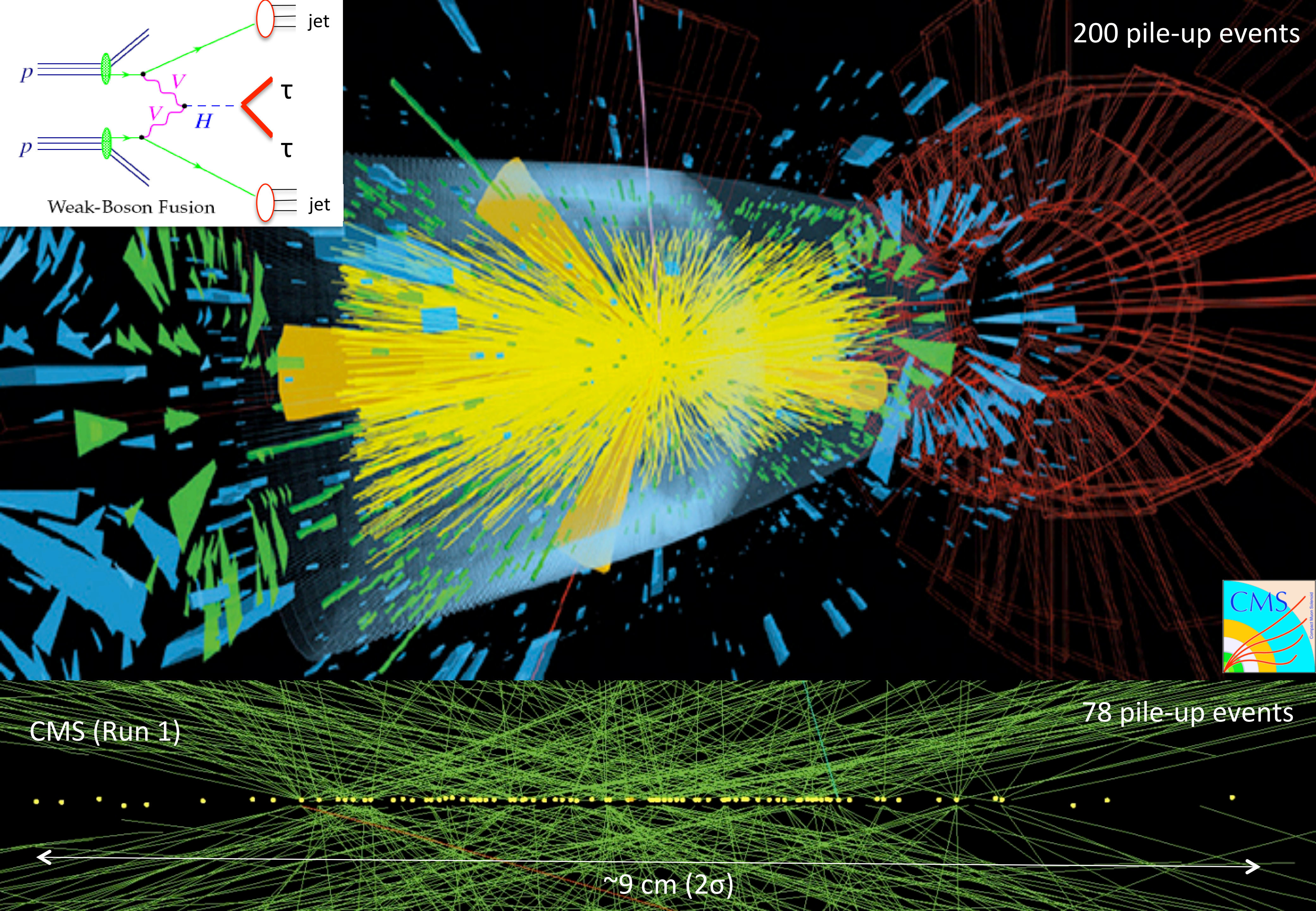


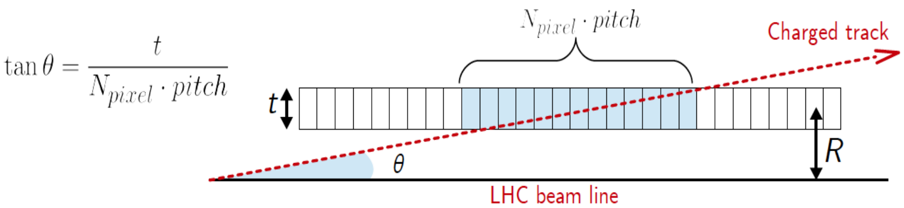


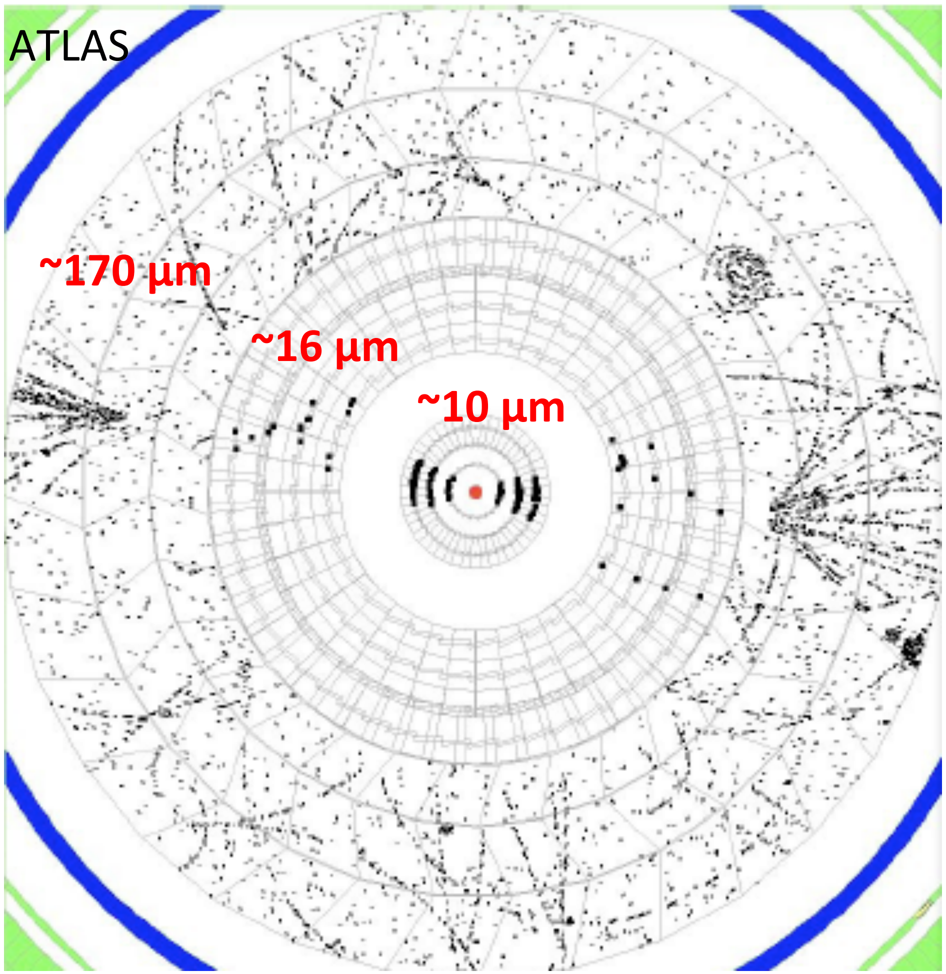





jet
p
V
τ
V
H
p
τ
jet
Weak-Boson Fusion
200 pile-up events
CMS
78 pile-up events
CMS (Run 1)
~9 cm (2σ)

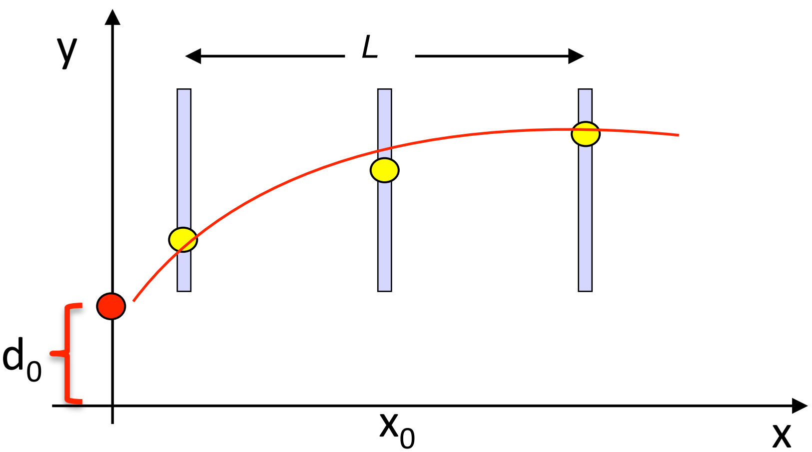
Tasks of Tracking Detectors





- provide precise space points or space point clusters (vectors) originating from ionizing charged particles
  - particle track finding from patterns of measured hits (at large background & pile-up)
  - momentum (B-field) and angle measurement
  - measurement of primary and secondary vertices
  - multi-track separation and vertex-ID in the core of (boosted) jets
  - for low momentum tracks: measurement of the specific ionization (dE/dx)
- keep the material influencing the paths of particles to a minimum to avoid scattering in the material and secondary interactions

Good tracking ... p_T and IP measurement as example



approximate helix by a linearized circle
and perform a least square fit

$$\left(\frac{\sigma_{p_T}}{p_T}\right)_{\text{meas}} = \frac{p_T}{0.3|z|}\frac{\sigma_{\text{meas}}}{L^2 B}\sqrt{\frac{720}{N+4}} \otimes \sigma_{MS}$$

$$[p_T] = \text{GeV/c},\ [L] = \text{m},\ [B] = \text{T}$$

Gluckstern NIM 24 (1963) 381

$$\sigma_{d_0} = \frac{\sigma_{\text{meas}}}{\sqrt{N}}\sqrt{1 + r^2\frac{12(N-1)}{(N+1)} + r^4\frac{180(N-1)^3}{(N-2)(N+1)(N+2)} + r^2\frac{30N^2}{(N-2)(N+2)}} \otimes \sigma_{MS}$$

$r = x_0/L$ = extrapolation parameter

- optimize σ_{meas} until other effects dominate (e.g. MS)
- $1/L^2$: the longer *L* the better
- place first plane as near as possible to the prod. point
- p_T resol. linearly better with B-field strength … but more confusion if many tracks
- Increasing N improves the resolution, but only as $1/\sqrt{N}$

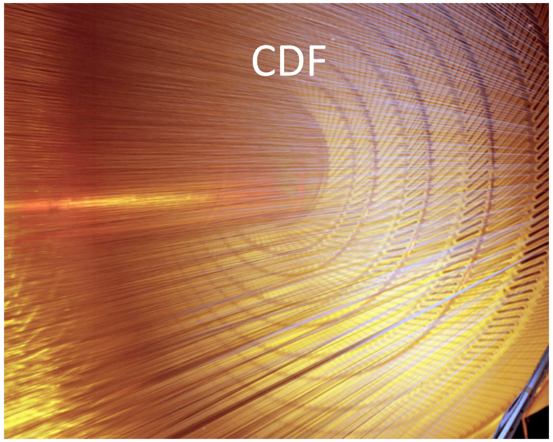
Technology most often used: Si - detectors

PRO – high resolution σ_{meas} ~ 10 µm

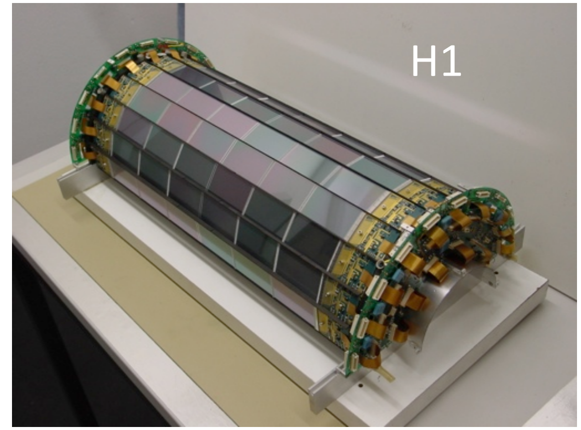
CON – expensive
– small *N*
– small *L*
– small X_0 => large mult. scatt.

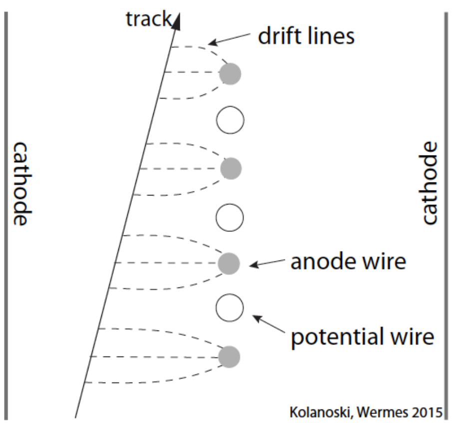
PRO – high rate capability

Gas-filled versus semiconductor detectors



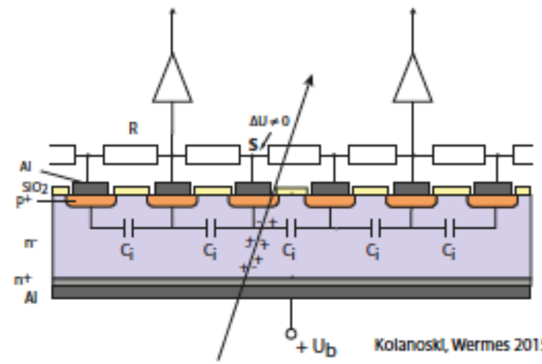
++	material	-
+	N_{meas}	--
low	cost	high
--	rate/speed	++
100 µm	resolution	10 µm

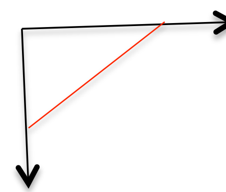




field near wire
E(r) ~ 1/r

⇒ gas amplification

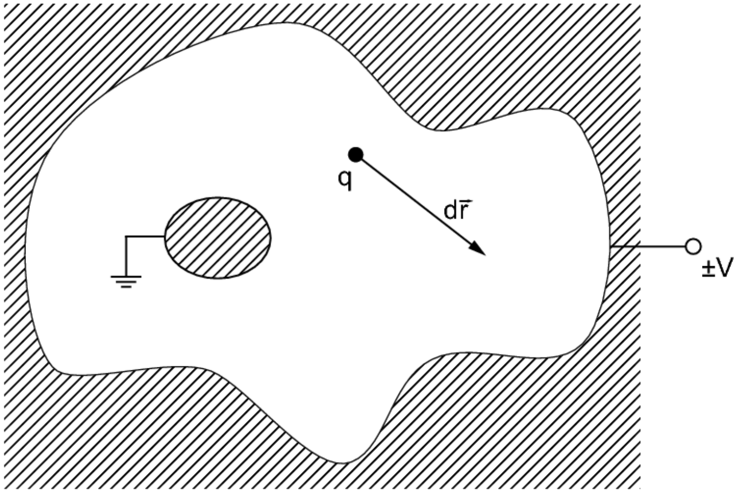




26 eV needed (Ar) per e/ion pair
94 e/ion pairs per cm
intrinsic amplification typ. 10^5
typ. noise: > 3000 e- (ENC)

3.65 eV (Si) needed per e/h pair
~10^6 e/h pairs per cm (20 000/250µm)
no intrinsic amplification
typ. noise: 100 e- (pixels) to 1000 e- (strips)

Some basics: How the signal is generated in a detector ...



how does a moving charge couple to an electrode ?

- respect Gauss' law and find

Shockley- Ramo theorem
(Shockley: J Appl.Phys 1938, Ramo: 1939)

induction (weighting) potential

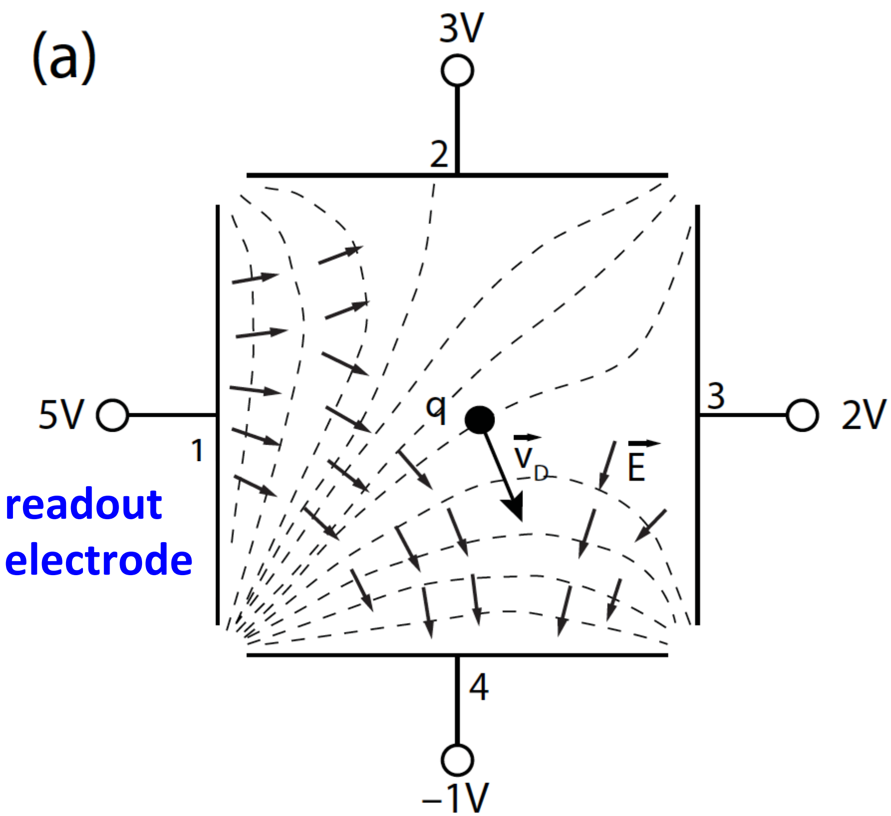
$$dQ = q\vec{\nabla}\phi_w d\vec{r}$$

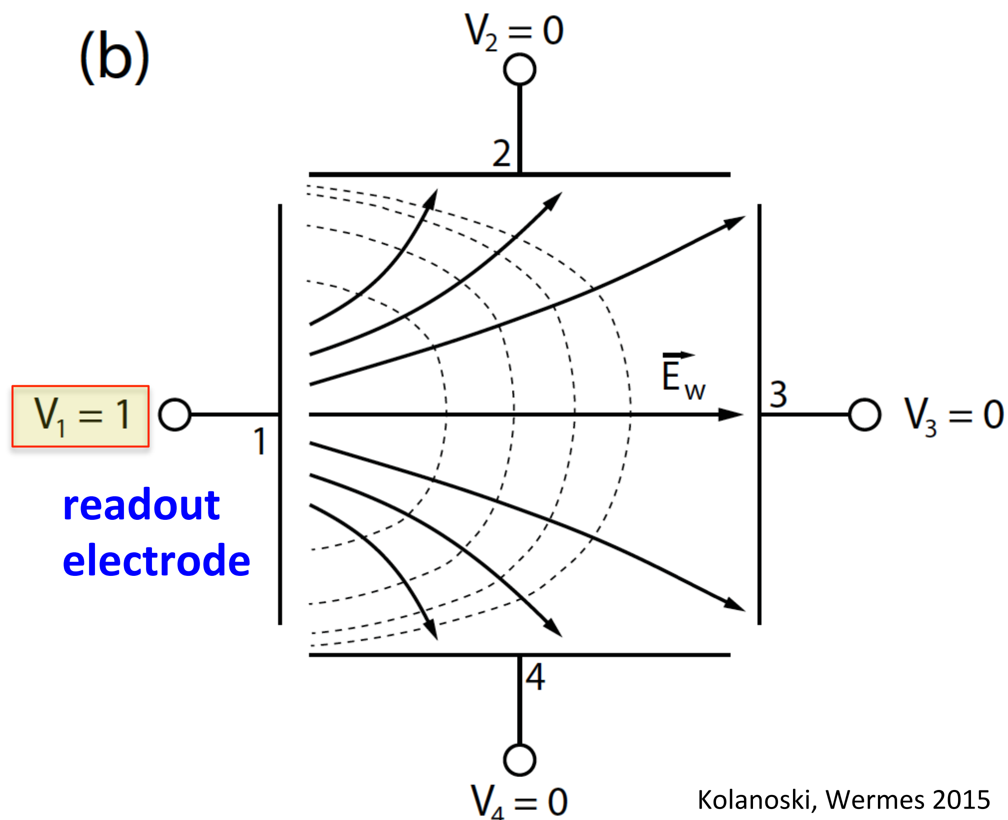
$$i_S = -\frac{dQ}{dt} = q\vec{E}_w\vec{v}$$

weighting field

they determine how charge movement couples to a specific electrode

Normal Field and Weighting Field





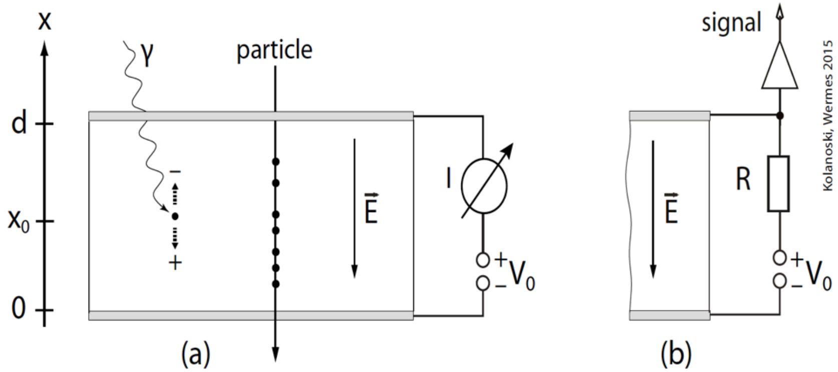
Kolanoski, Wermes 2015

$$i_S = -\frac{dQ}{dt} = q\vec{E}_w\vec{v}$$

Recipe: To compute the weighting field of a readout electrode i, set voltage of electrode i to 1 and all other electrodes to 0.

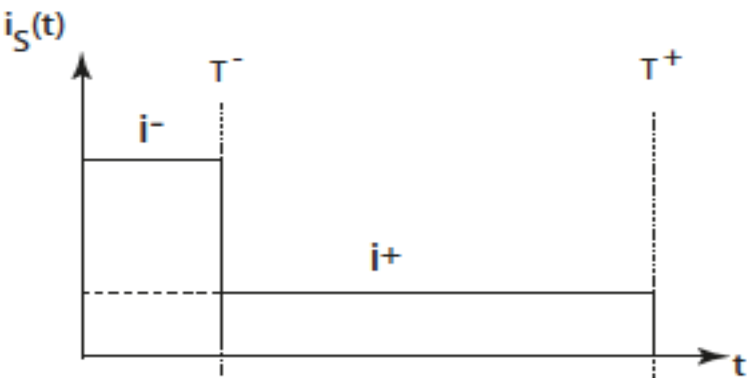
Examples

parallel plate detector (gas filled)



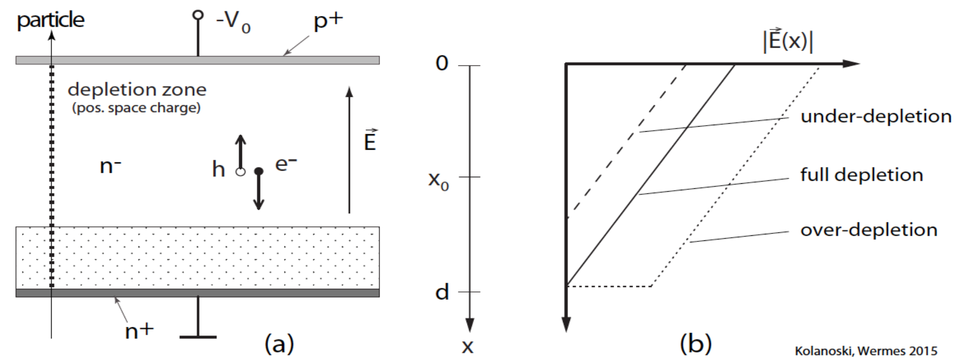
$$\vec{E}_w = -\frac{1}{d}\vec{e}_x$$

velocity (v=μE) almost const.



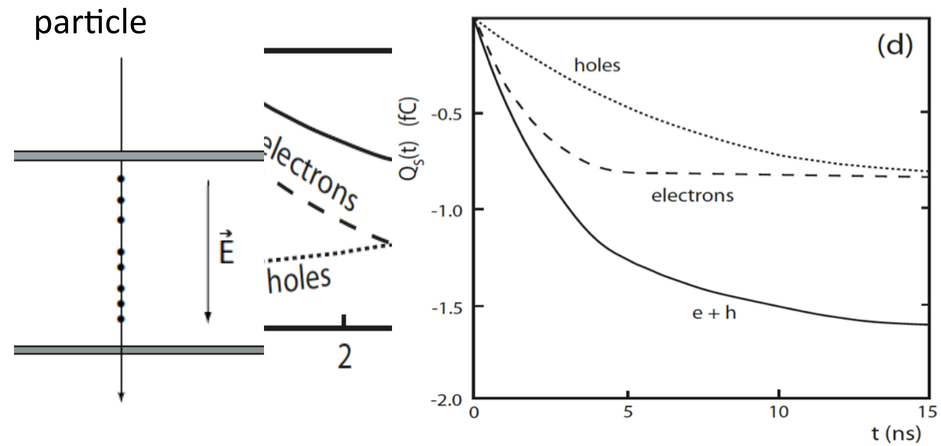
$$Q_{tot} = \int_0^{T^{\pm}} i(t)dt = Q_s^+ + Q_s^- = \pm e$$

parallel plates with space charge (i.e. Si)



$$\vec{E}_w = -\frac{1}{d}\vec{e}_x$$

$$v_e = \dot{x}_e = -\mu_e E(x) = +\mu_e(a - bx)$$
$$\dot{x}_h = \qquad = -\mu_h(a - bx)$$



Examples

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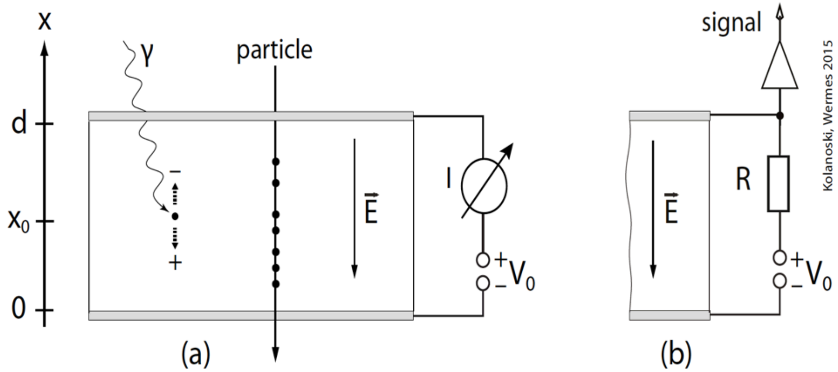

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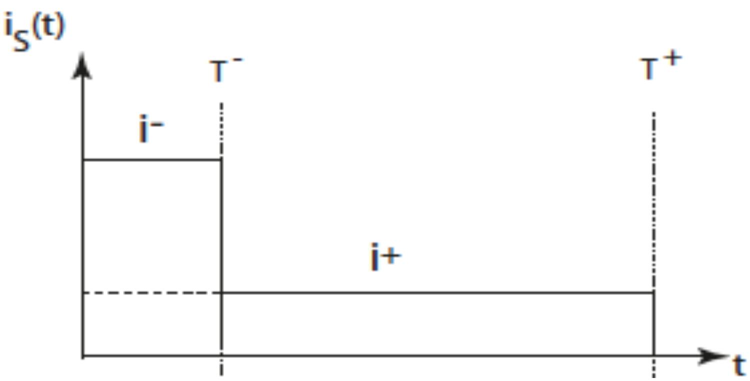

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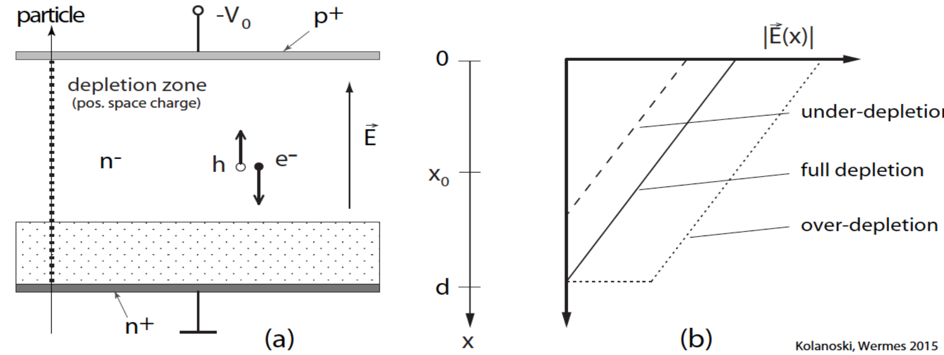

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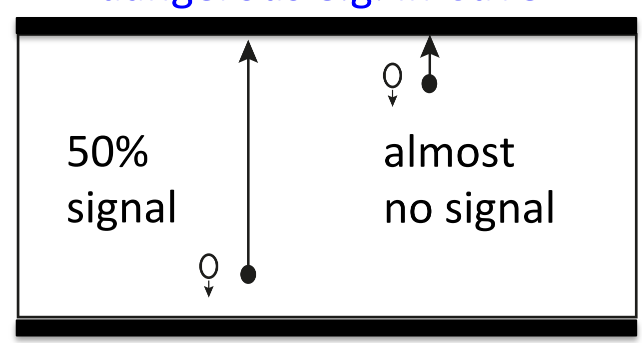
$$\dot{x}_h = \qquad = -\mu_h(a - bx)$$

dangerous e.g. in CdTe



transient current

Current pulse measurements: TCT technique

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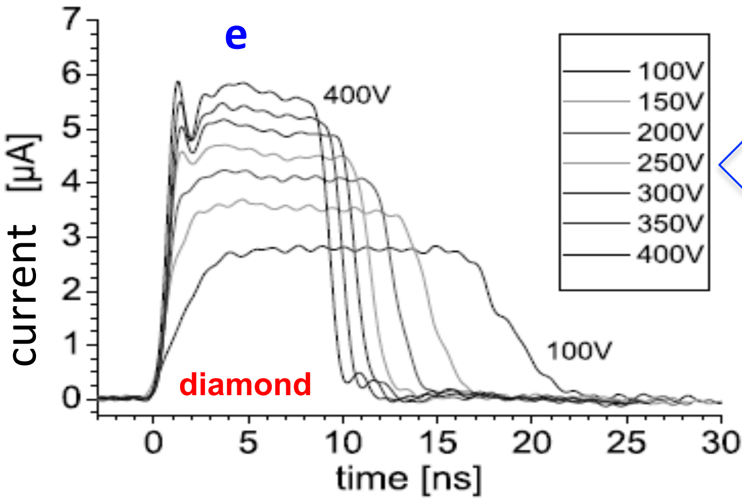
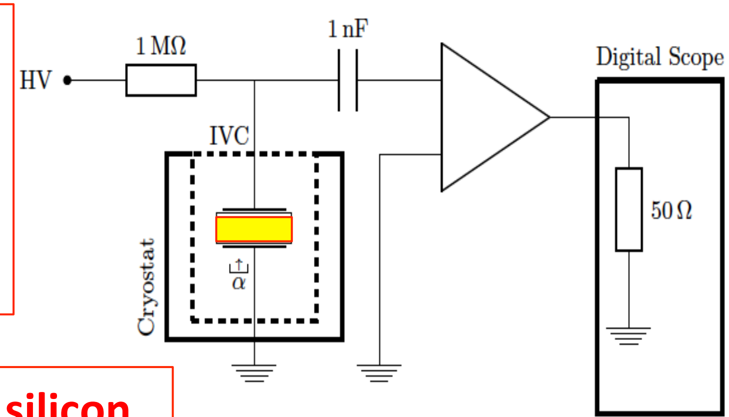


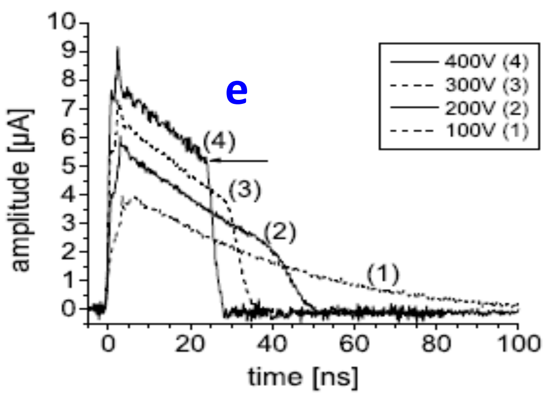
single crystal **diamond** is like a parallel plate detector filled with a dielectric w/o space charge



Fink, Lodomez, Kruger, Pernegger, Weilhammer, NW, NIM A 565 (2006), 227

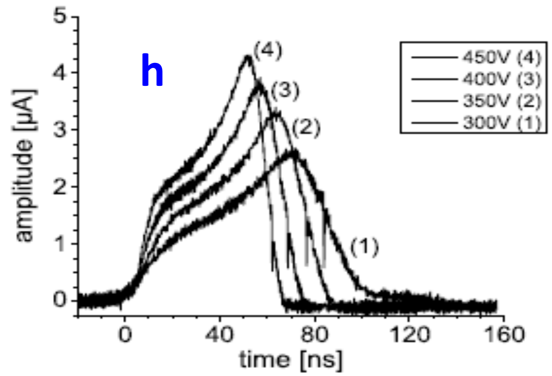
1mm pn – Diode **silicon**

- same weighting field
- different electric field



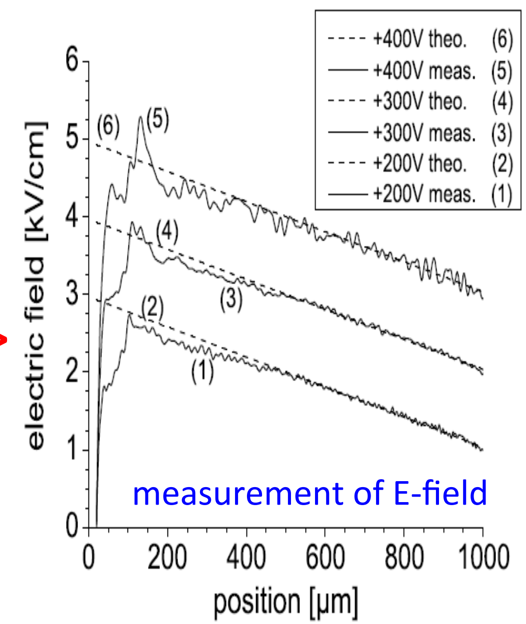
(a) Electron signals from α-particles impinging on the cathode.

Si

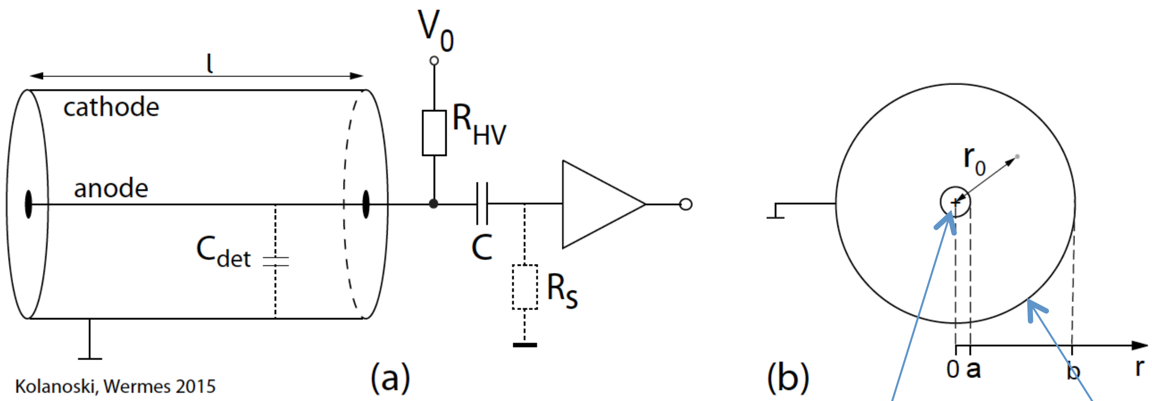


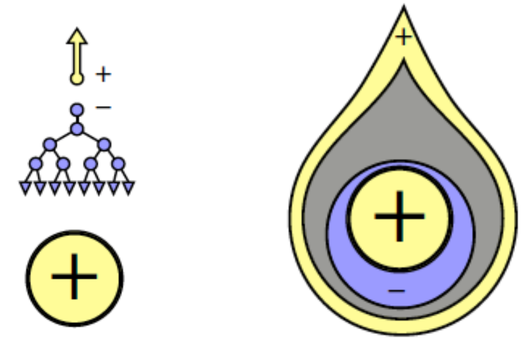
(b) Hole signals from α-particles impinging on the anode.

=>



Signal development in a wire configuration





- E(r) ~ 1/r => gas amplification => "signal" current starts only close to the wire
- Shockley-Ramo-recipe: $\phi_w(a) = 1\,, \quad \phi_w(b) = 0$ (*)

$$\vec{E}_W(r) = \frac{\mathbf{1}}{\mathbf{r}} \frac{1}{\ln\frac{b}{a}} \vec{e}_r$$

$$\phi_W(r) = -\frac{\mathbf{\ln r}/b}{\ln\frac{b}{a}}$$

which fulfills (*)

$$Q_S^{tot} = Q_S^- + Q_S^+ = -Ne$$

$$\left(\frac{Q_S^-}{Q_S^+}\right)_{r_0} = \frac{\ln r_0/a}{\ln b/r_0}$$

$$\left(\frac{Q_S^-}{Q_S^+}\right)_{r_0=b/2} \approx 9$$

far away from wire
(a=10 µm, b=10 mm)

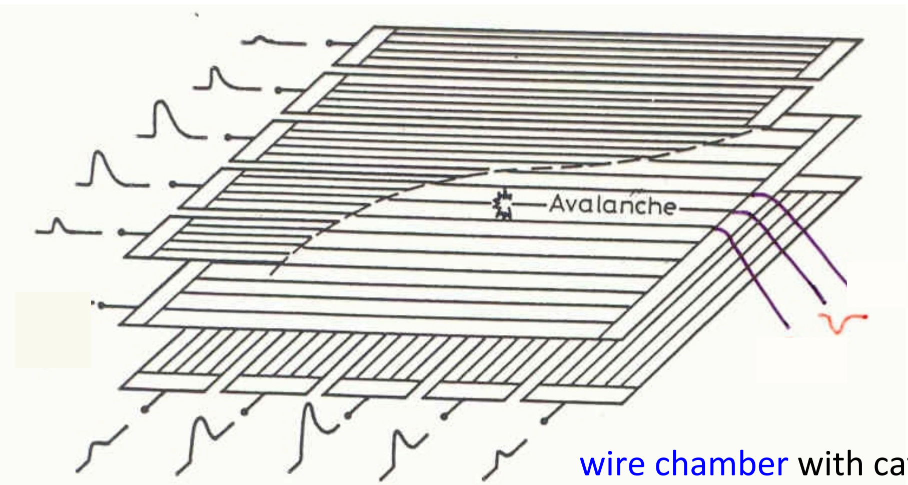
$$\left(\frac{Q_S^-}{Q_S^+}\right)_{r_0=a+\epsilon} \approx 0.01 - 0.02$$

near wire

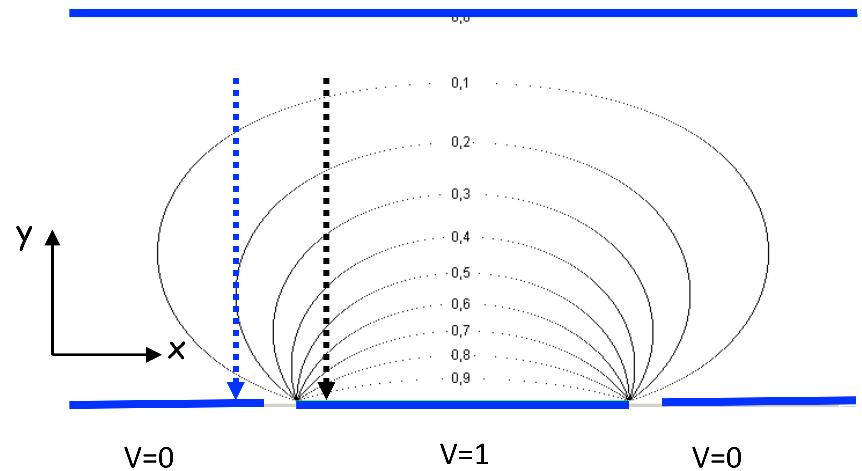
wire chamber signals are governed by away moving ions

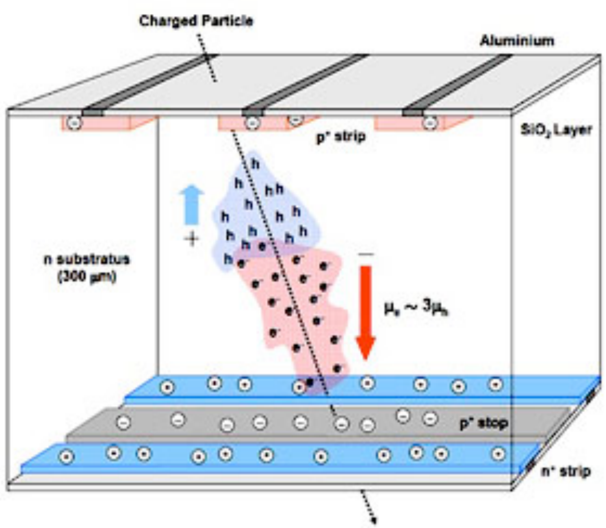
Structured electrodes

signals are induced on BOTH (ALL) electrodes => exploit for second coordinate readout

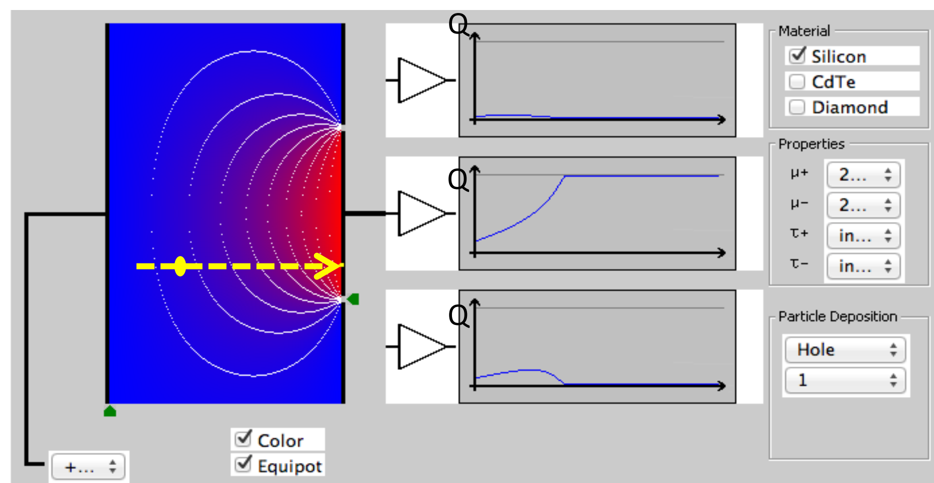


wire chamber with cathode R/O





double sided silicon strip detector



How to meet the LHC rate and radiation challenges ...

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❑ particle rates ($\mathcal{L} = 10^{34}$ cm^{-2} s^{-1})   note: heavy ions: $\mathcal{L} = 10^{27}$ cm^{-2} s^{-1}

- bunch crossing every 25 ns
- $N_{trk} = \sigma \mathcal{L} = 100$ mb $\times 10^{34}$ cm^{-2}s^{-1} $\times$ 120 ≈ 10^{11} tracks/s in 4π = $10^6 \times$ LEP
- @ r = 5cm => 9.5 tracks/cm^2/25 ns, but only 10^{-4} per pixel (100x100 μm^2)

❑ radiation level (@ r = 5cm, per detector lifetime)

- total ionizing dose (TID) = energy/mass (J/kg) = 100 Mrad -> 1 Grad
- non ionizing fluence (NIEL, breaks the lattice) = 10^{15} particles per cm^2 -> 10^{16} cm^{-2}
- effects: ageing on wires, lattice damage, glue brittle, electronics, …

How to meet the LHC rate and radiation challenges ...

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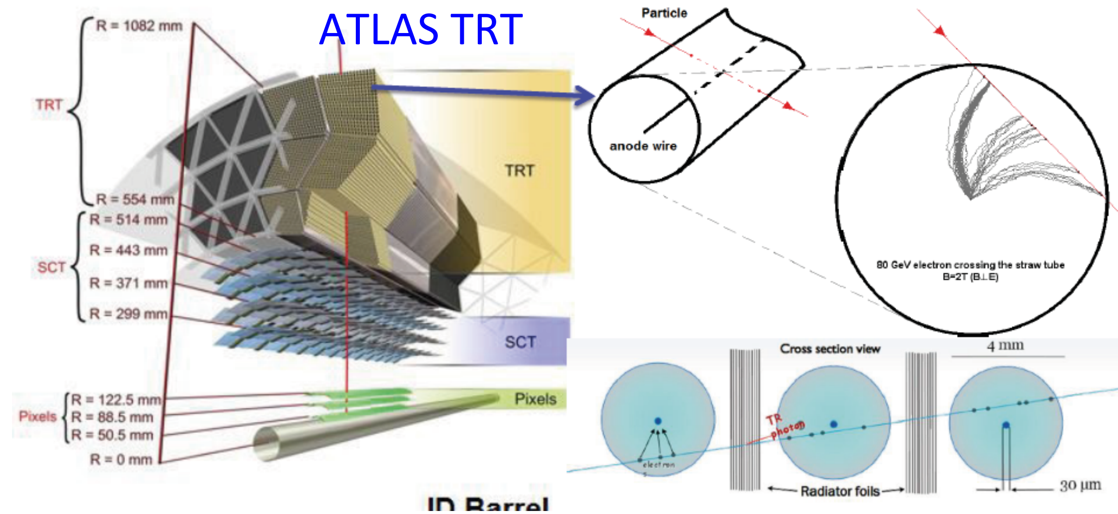
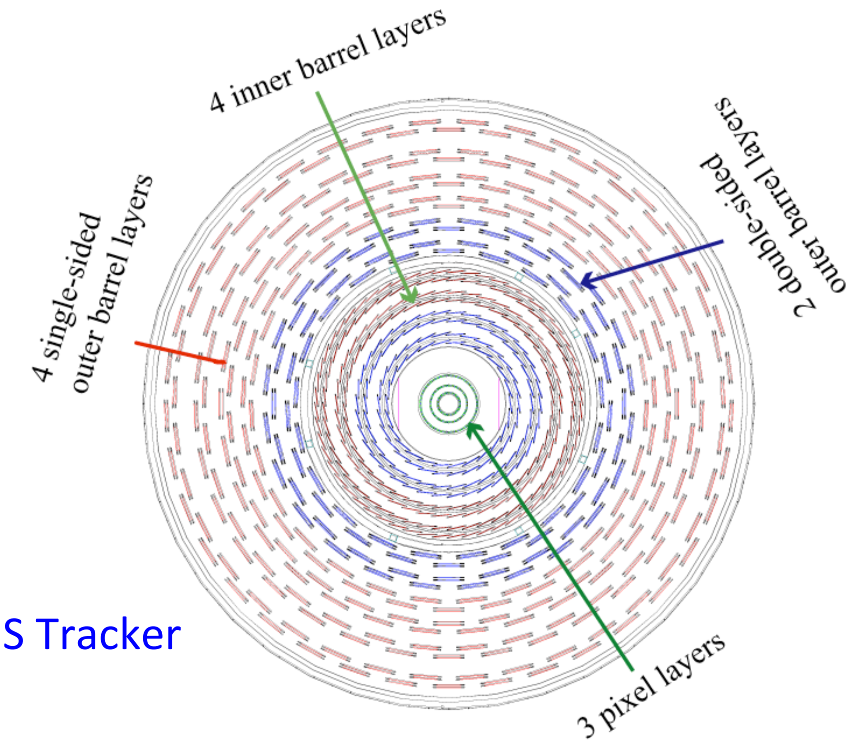
❑ way out

- gas-filled detectors with small cells



- timing precision ≪ 25 ns

- solid state detectors
  - micro structuring
    => finest granularity
  - but: sensitive to radiation



CMS Tracker

Example for "timing": RPCs (resistive plate chambers)

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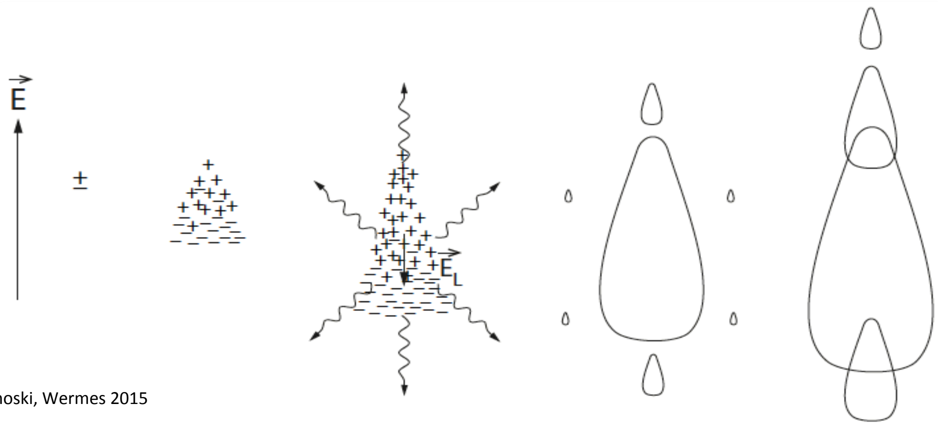
- target: **high timing precision** (trigger and timing chambers, e.g. ATLAS Muon Spectrometer)



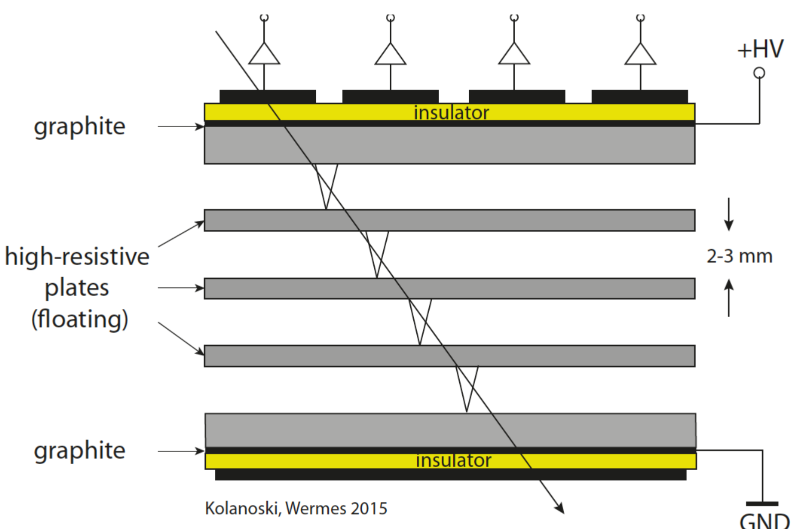
Kolanoski, Wermes 2015

- gas filled chambers w/ large signals
  - operated in avalanche mode (≥10 kV/cm) or in streamer mode (~100kV/cm)
- gas with high ionisation density and high quenching efficiency
  e.g. 94.7% $C_2H_2F_4$ + 5% iC_4H_{10} + 0.3% SF_6

"avalanche" <-> "streamer"

v_{drift} <-> photon emission

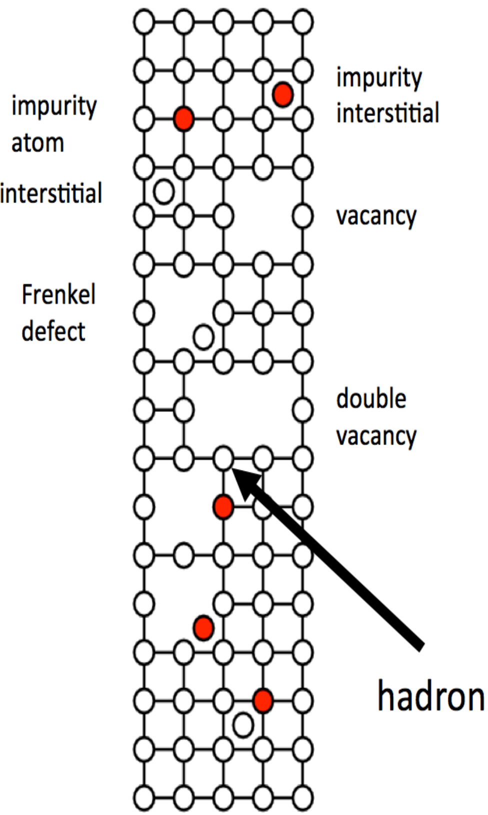
10^5 m/s <-> 10^6 m/s

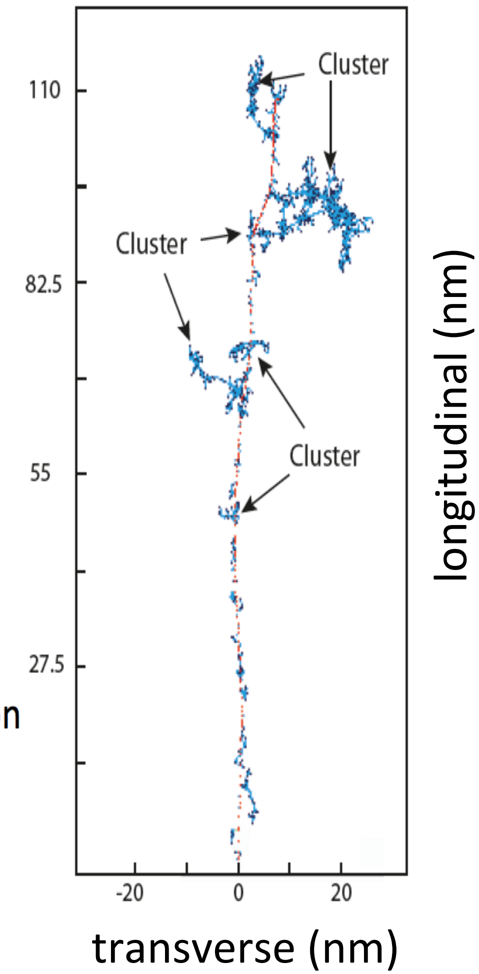


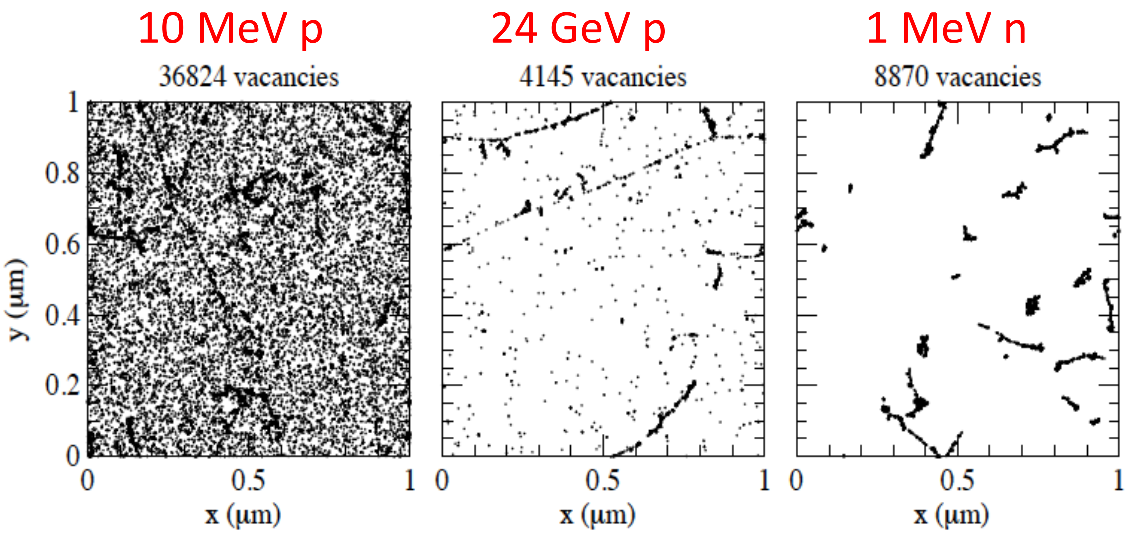
Kolanoski, Wermes 2015

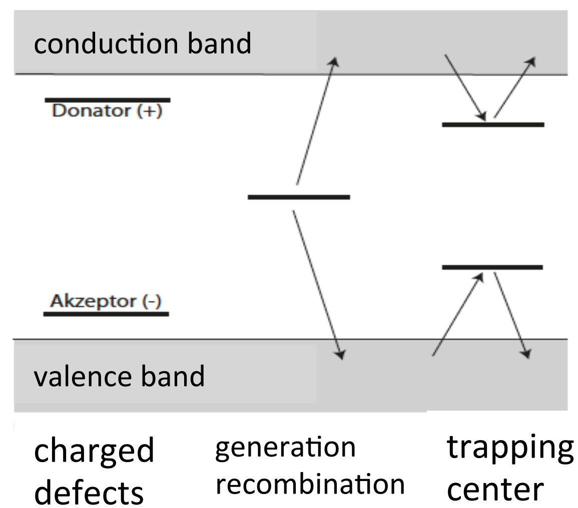
	Trigger RPC	Timing RPC
el. Feld	20-50 kV/cm	~100 kV/cm
op. mode	avalanche	streamer
signal	< 10pC	< 100pC
quench times	shorter	longer
σ_t	**1 ns**	**50 ps**
efficiency	98%	75%

... special at the LHC is the radiation environment





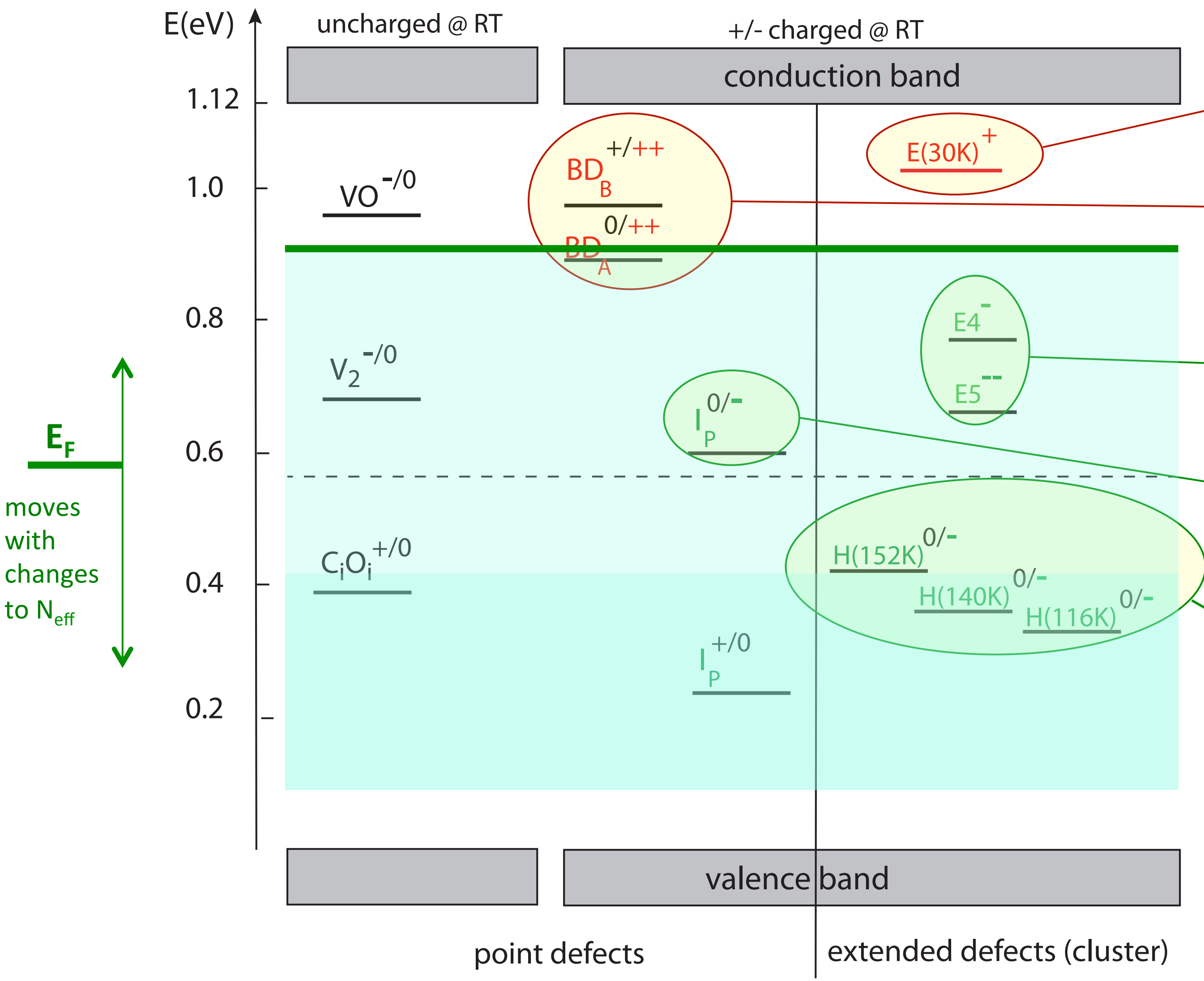




threshold energy to remove an atom:

Si: 25 eV, diamond: 43 eV

Much progress in understanding radiated Si-sensors



e- trap
positive space charge
higher conc. after proton than neutron irradiation
depends on oxygen content

BD=bistable donor (e- trap)
positive space charge
strongly produced in oxygen rich DOFZ material

triple vacancy, small cluster
negative space charge
-> **high leakage current**

V_2O complex (?)
negative space charge
causes **leakage current**, strongly produced in oxygen lean STFZ

extended acceptor defects produced equally by n,p
negative space charge
-> **reverse annealing**

- most defects show linear fluence dependence
- cooling helps to keep I_{leak} and rev. annealing smaller
- N_{eff} changes

Radu et al., J. Appl. Phys. 117, 164503 (2015)
RD50, M. Moll et al., PoS (Vertex 2013) (2013) 026

… and cures (defect engineering … examples)

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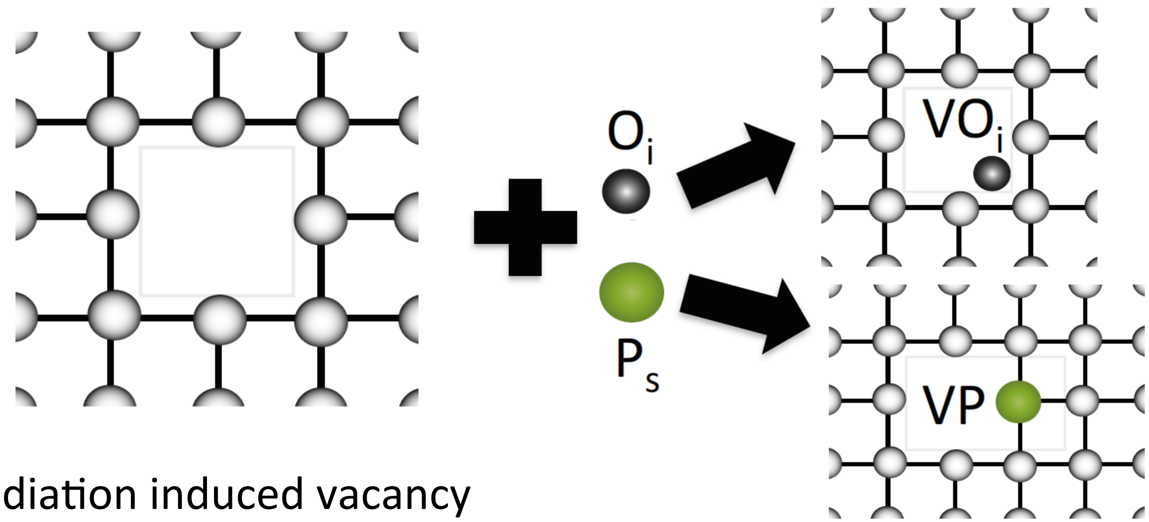
- low temperature (-10 °C) operation
- oxygenated silicon
- start with n-implant (e^- collection) in p-substrate material (not available ~1998)



radiation induced vacancy
(mobile even below RT)

harmless
VO_i defect

harmful
removes donor (P)
decreases N_{eff}

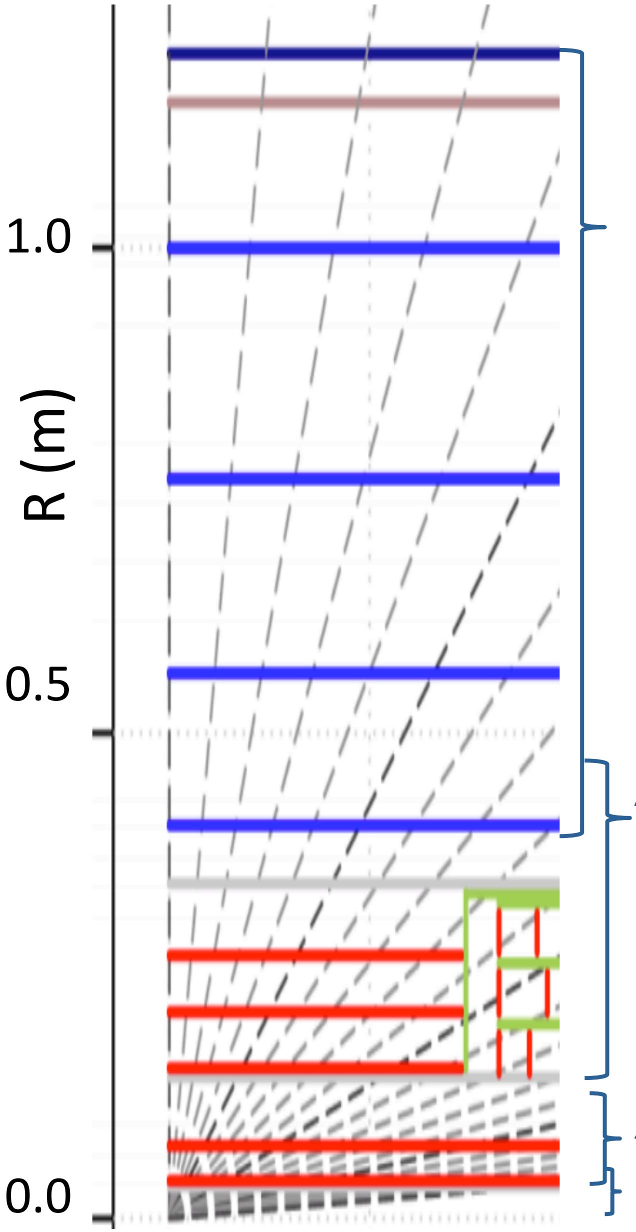
⇩

$[O] \gg [P]$

A. Junkes, PoS Vertex 2011 (2011) 035
I. Pintilie et al., Nucl.Instrum.Meth. A611 (2009) 52-68

- for: chip electronics (TID) use thin oxides and special designs

Typical tracker arrangements for the HL-LHC Upgrade …

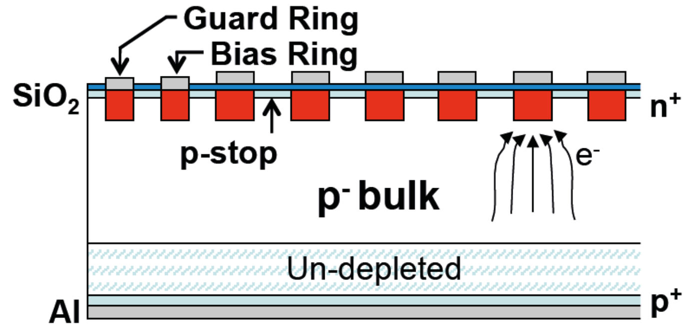


strips

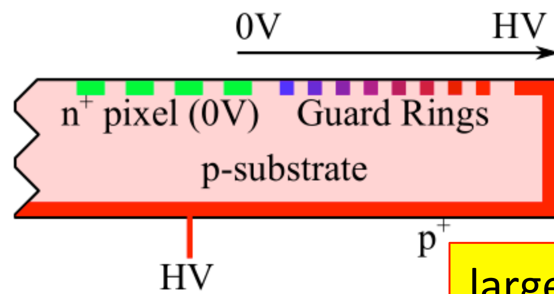
outer pixel

inner pixel

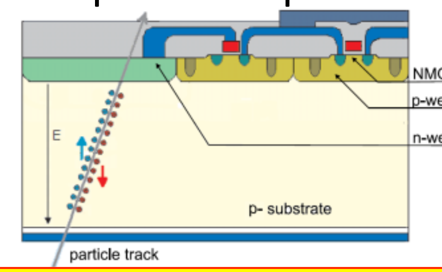
innermost pixel



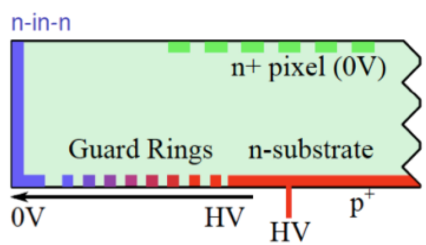
n+ in p
strip modules

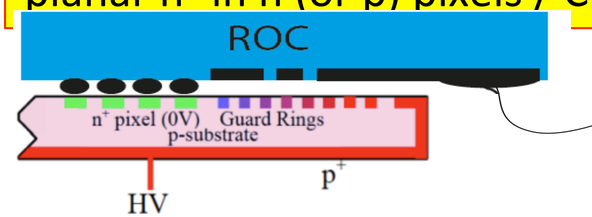


depl. CMOS pixels

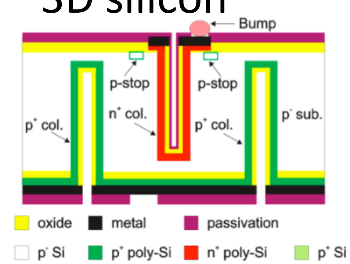


large modules
planar n+ in n (or p) pixels / CMOS?





3D silicon



dedicated
rad.-hard
detectors

The typical S/N situation (... here ATLAS)

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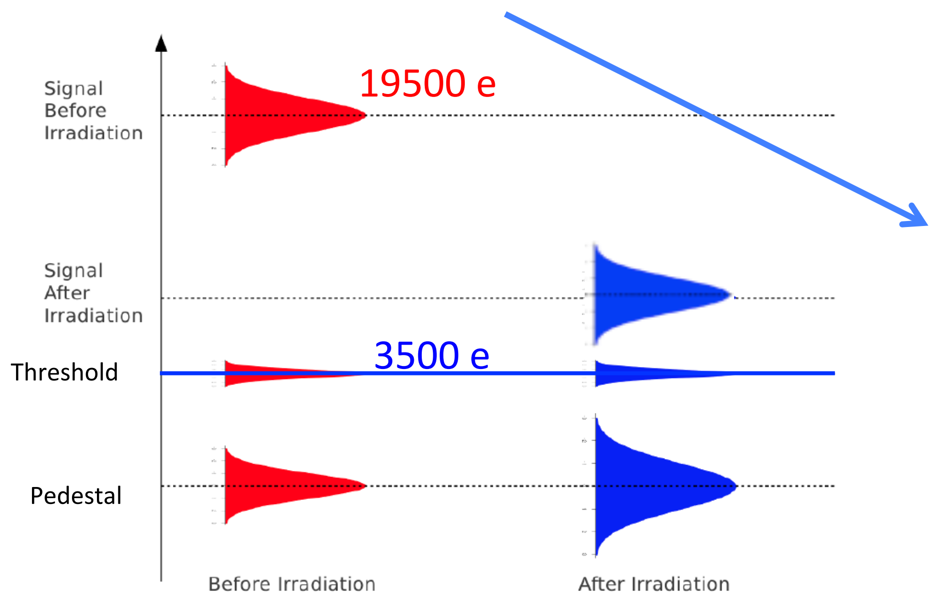
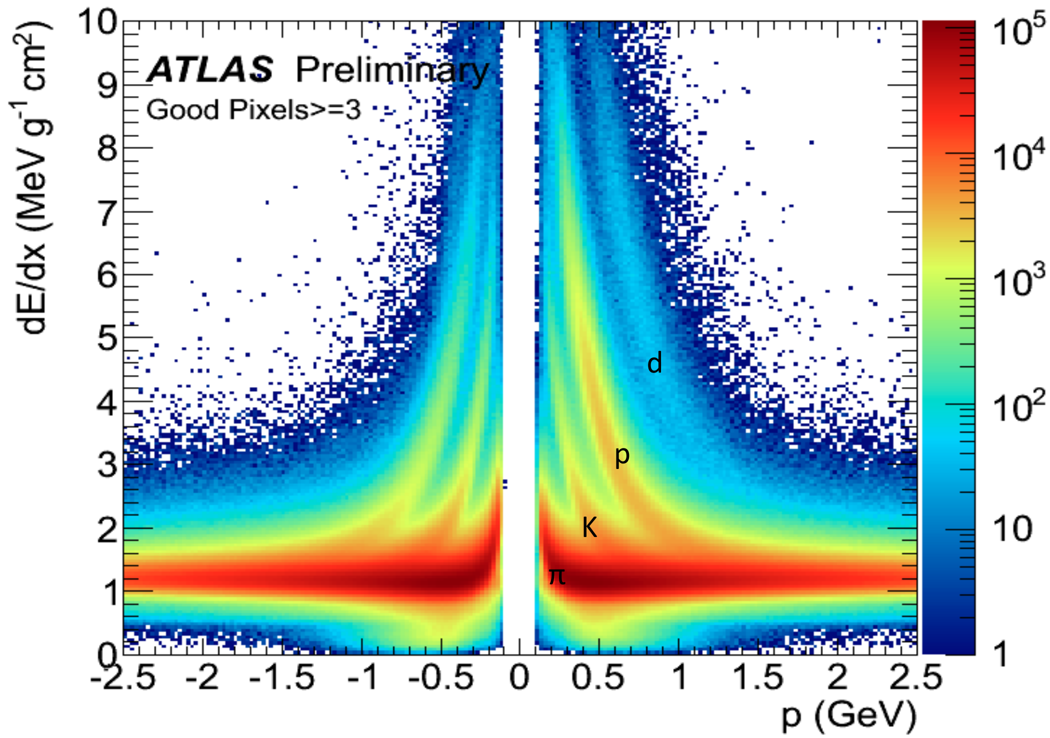
Signal of a mip in 250µm Si ≙ 19500 e^- → <10000 e^- after irradiation

Charge on more than 1 pixel => S/N > 30 → S/N ~ 10

- ❑ Discriminator thresholds = 3500 e, ~40 e spread, ~170 e noise
- ❑ 99.8% data taking efficiency
- ❑ 95.9% of detector operational
- ❑ ca. 10 µm x 100 µm resolution (track angle dependent)
- ❑ 12% dE/dx resolution





C. Gemme et al., ATLAS-CONF-2011-016

New Developments (Pixels)
... for LHC and others

Is there life after "hybrid pixels"? ... monolithic?

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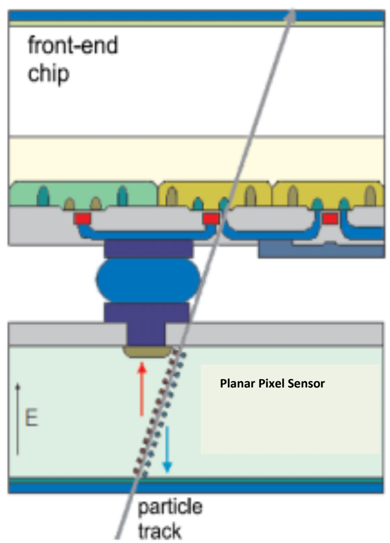
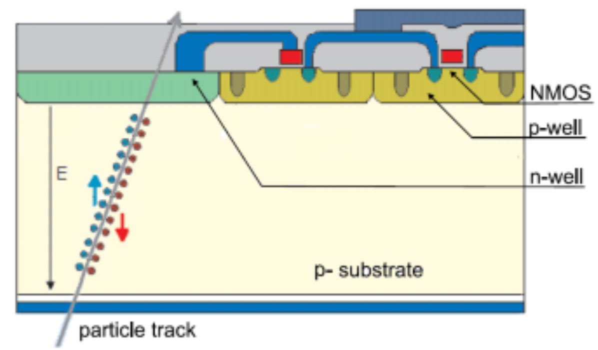
Hybrid Pixels

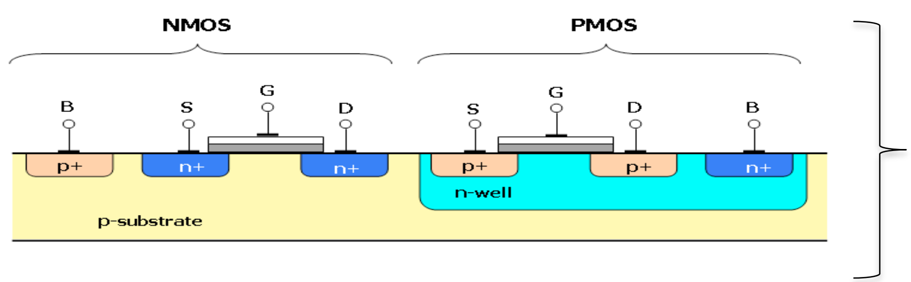


Depleted (fully) Monolithic Active Pixel Sensors (DMAPS)



(commercial CMOS Technology)

Peric et al., NIM A582 (2007) 876-885 & NIM A765 (2014) 172-176
Mattiazzo, Snoeys et al., NIM A718 (2013) 288-291
Havranek, Hemperek, Krüger, NW et al. JINST 10 (2015) 02, P02013



CMOS

Rate and Radiation Levels

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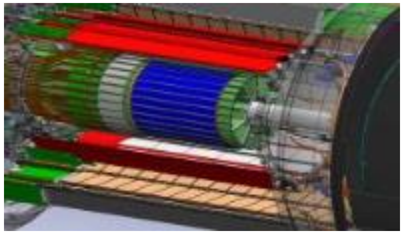
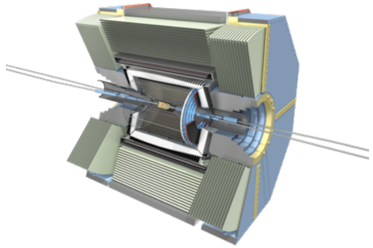
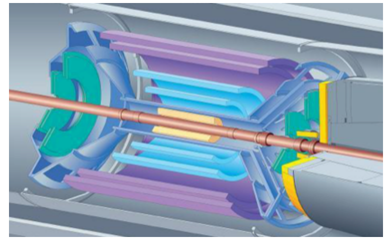
STAR



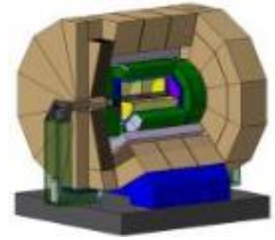
Belle II



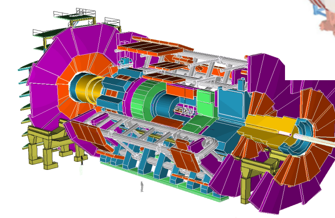
ALICE-(HL)-LHC

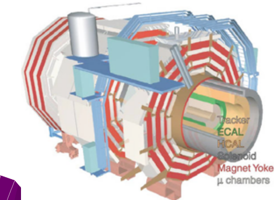


ILC



ATLAS





CMS

Numbers for innermost layers (r ≈ 5cm,) -> scale by 1/10 for typical strip layers (r > 25 cm)

	STAR	Belle II	ALICE-LHC heavy ion	ILC	LHC pp	HL-LHC-pp	
						Outer	Inner
BX-time (ns)	110	2	20 000	350	25	25	25
Particle Rate (kHz/mm^2)	4	400	10	250	1 000	1 000	10 000
Φ (n_{eq}/cm^2)	few 10^{12}	3×10^{12}	$> 10^{13}$	10^{12}	2×10^{15}	10^{15}	2×10^{16}
TID (Mrad)*	0.2	20	0.7	0.4	80	50	> 1000

Monolithic Pixels MAPS

Hybrid Pixels -> DMAPS

*per (assumed) liftetime
LHC, HL-LHC: 7 years
ILC: 10 years
others: 5 years

in need for
- much less material
- higher resolution
- thinner strips & monolithic pixels

state of the art
- large area strips
- hybrid pixels

- even larger area
- radhard sensors
- higher rates R/O

(Semi)-Monolithic Pixel Detectors

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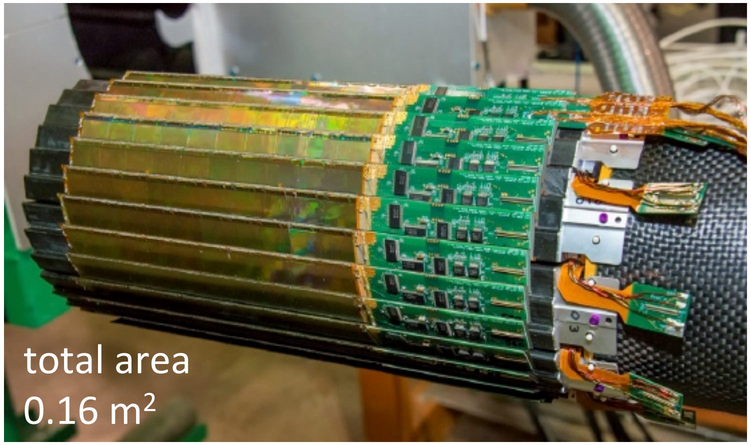
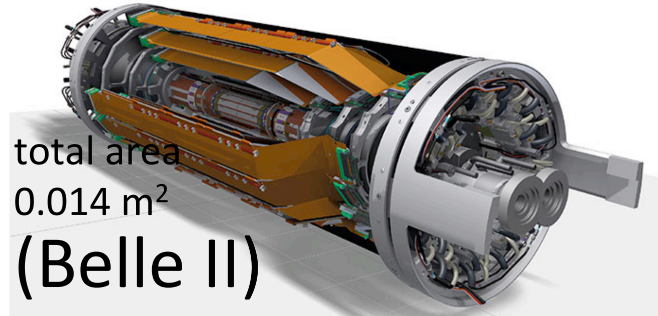
STAR / RHIC

MAPS



total area
0.16 m^2

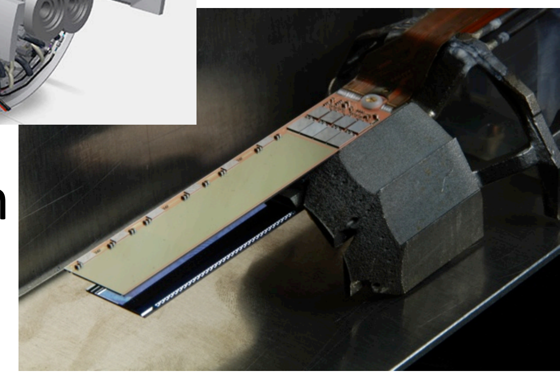
operated 2014-2015



total area
0.014 m^2

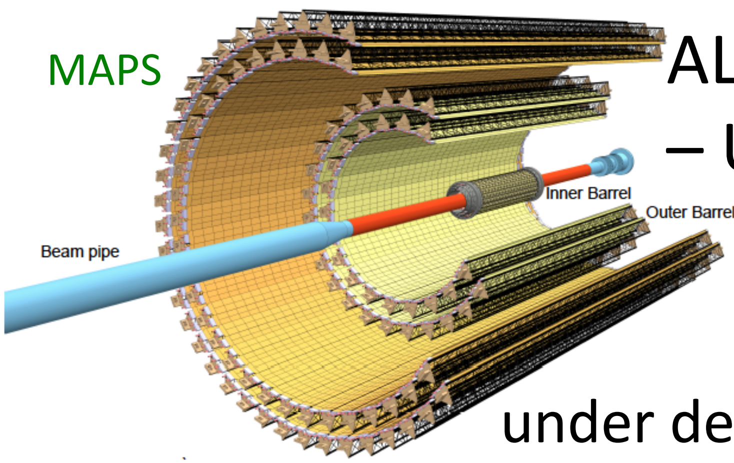
(Belle II)

DEPFET pixels



in production
for 2017

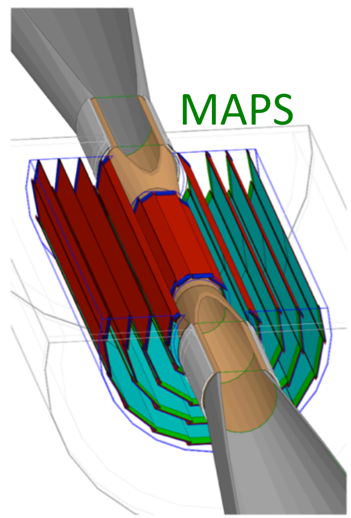
MAPS



ALICE
– Upgrade

total area
~10 m^2

under development
target: 2018



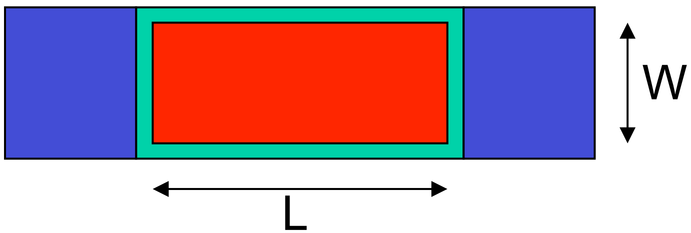
MAPS

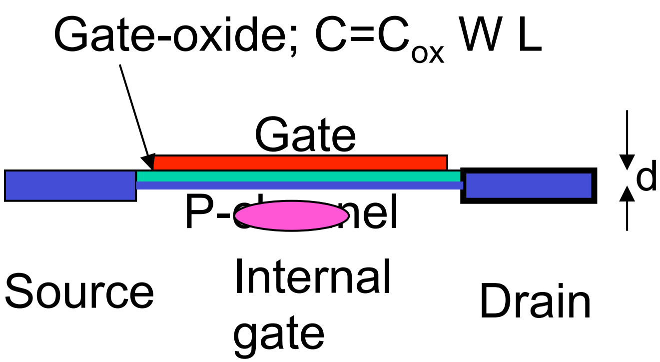
ILC

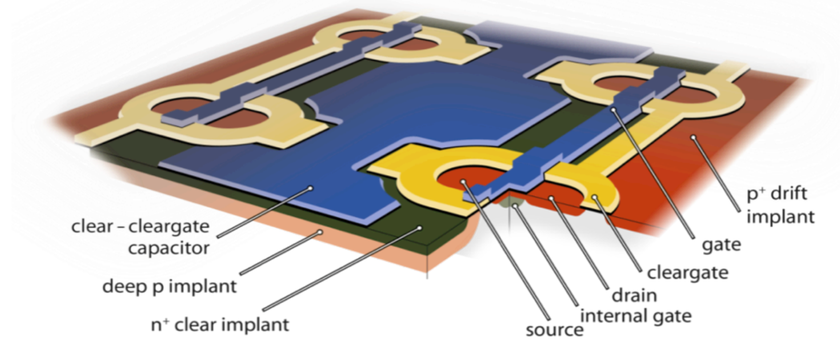
total area
? m^2

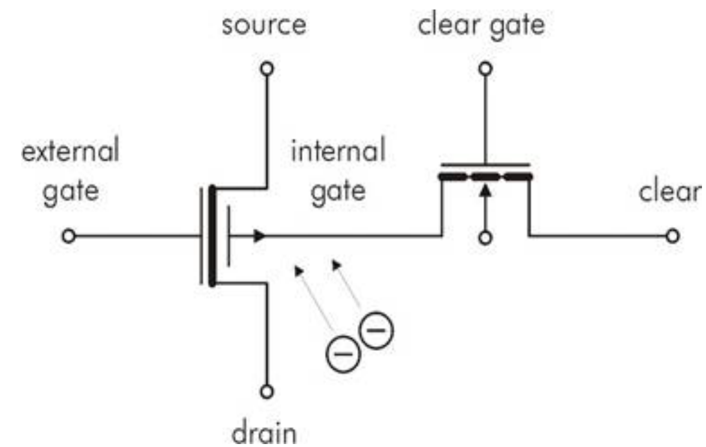
current
baseline

How does a DEPFET work?

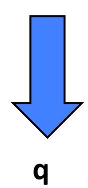








A charge q in the internal gate induces a (mirror) charge αq in the channel/external gate (α <1 due to stray capacitance) changing the gate voltage: $\Delta V = \alpha\, q / (C_{ox}\, W\, L)$ which in turn changes the transistor current I_d .



features:

- $g_q \sim 700$ pA/e$^-$
- small intrinsic noise
- sensitive off-state, w/o power used

Kemmer, J., G. Lutz et al., Nucl. Inst. and Meth. A 288 (1990) 92

BELLE II DEPFET Pixel Detector

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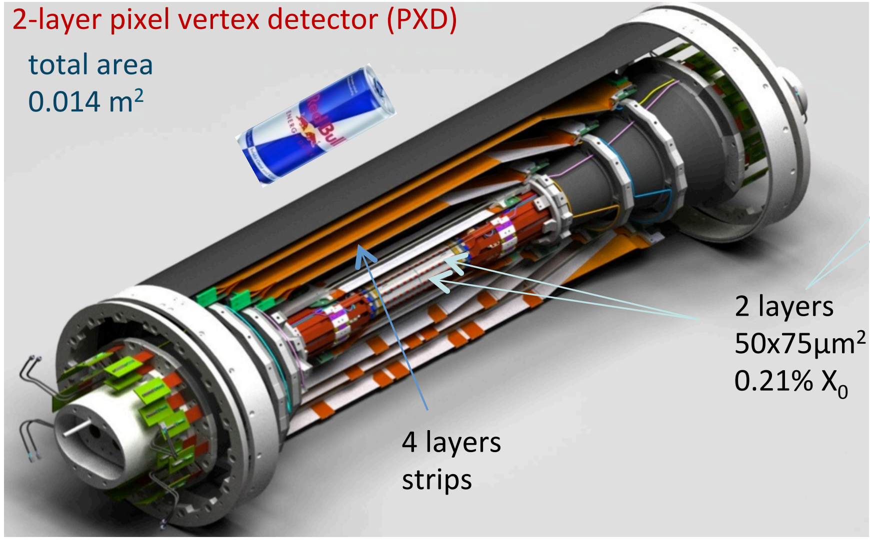
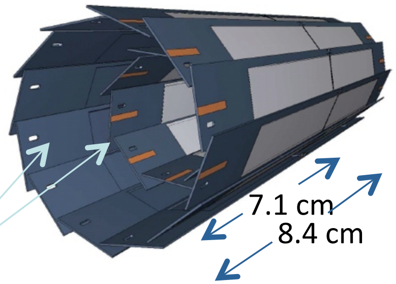
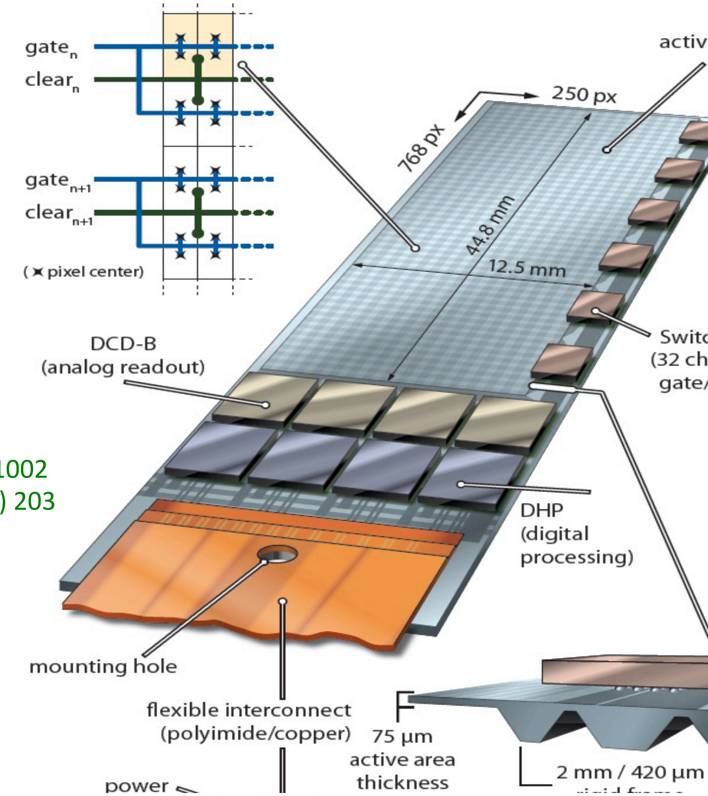
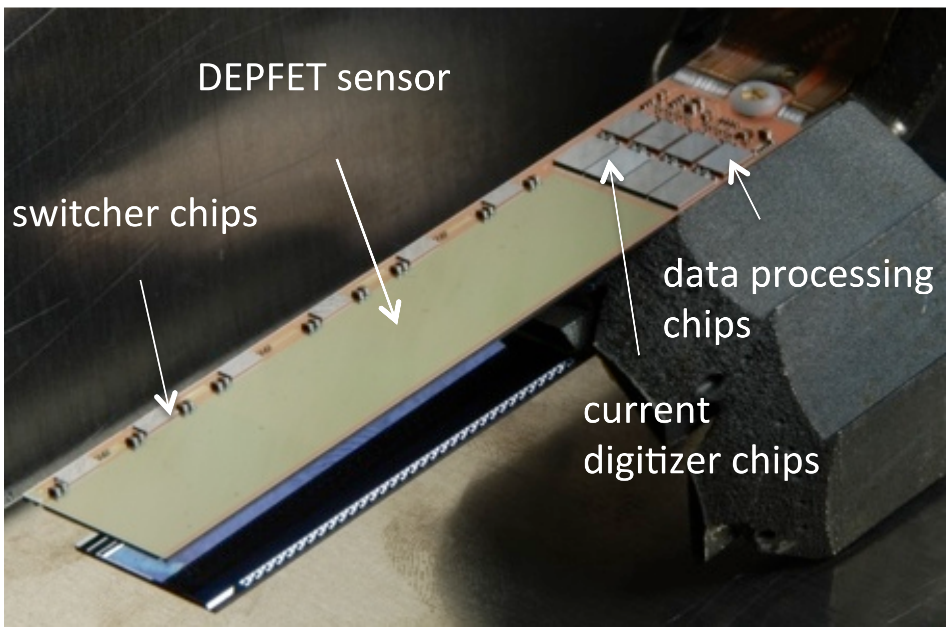
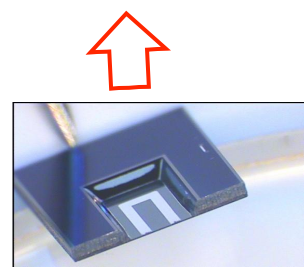






C. Marinas et al., JINST 10 (2015) 11, C11002
C. Kiesling et al., PoS EPS-HEP2011 (2011) 203

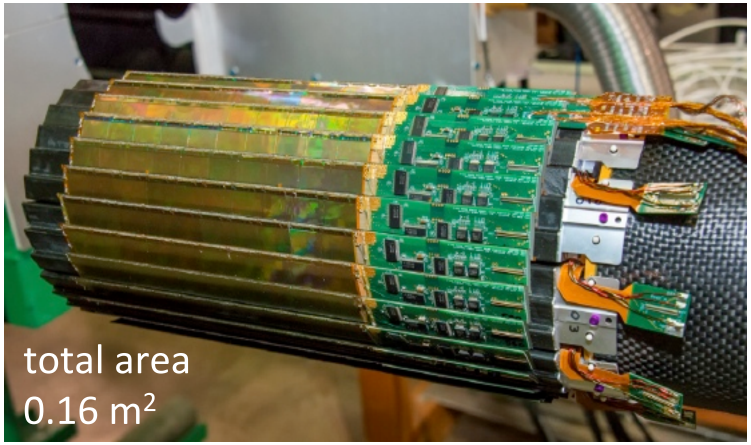




L. Andricek,
IEEE Trans.Nucl.Sci. 51 (2004) 1117-1120

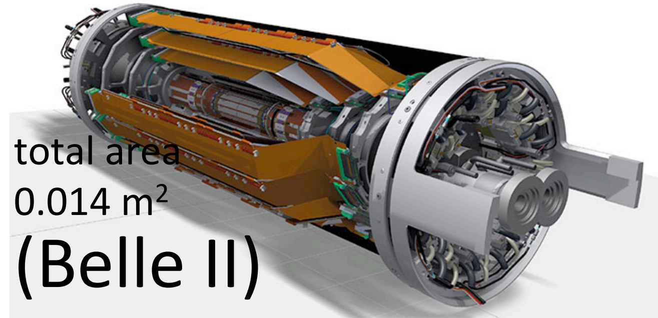
(Semi)-Monolithic Pixel Detectors

STAR / RHIC MAPS



total area
$0.16\ m^2$

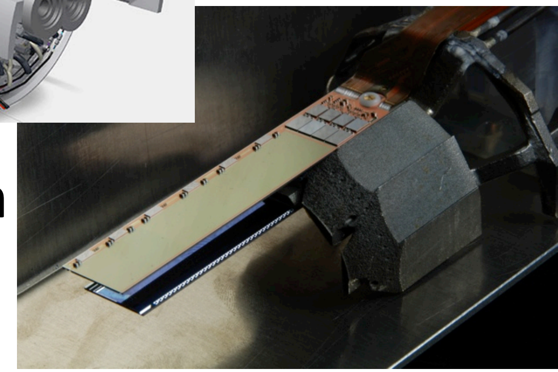
operated 2014-2015



total area
$0.014\ m^2$

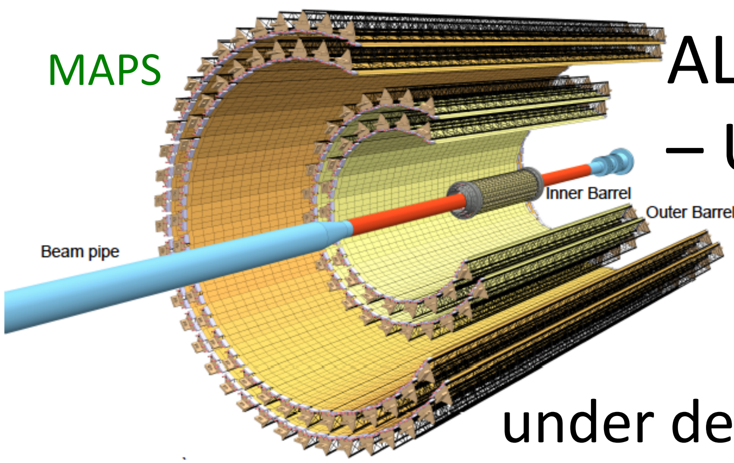
(Belle II)

DEPFET pixels



in production
for 2017

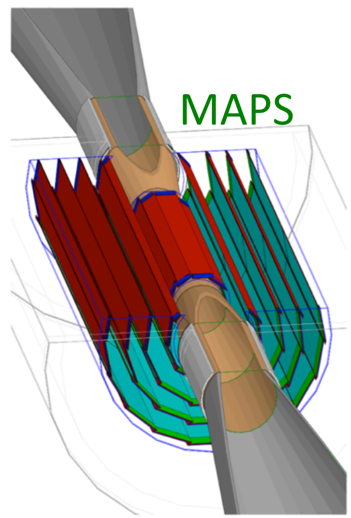
MAPS



ALICE
– Upgrade

total area
$\sim 10\ m^2$

under development
target: 2018



MAPS

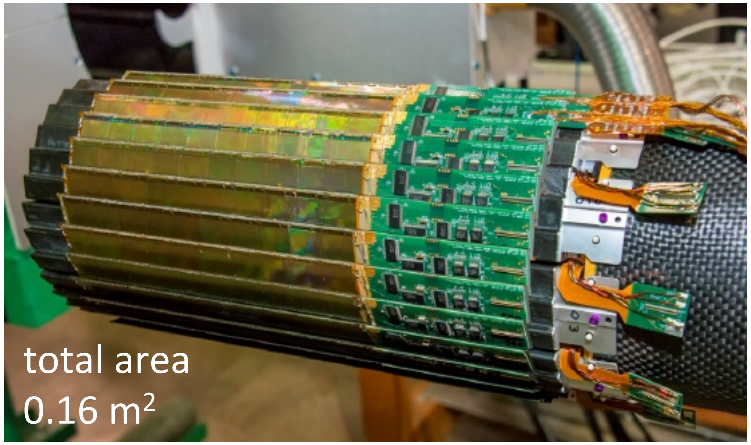
ILC

total area
$?\ m^2$

current
baseline

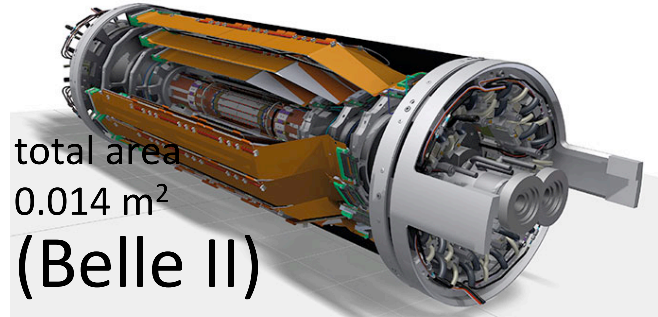
(Semi)-Monolithic Pixel Detectors

STAR / RHIC MAPS



total area 0.16 m^2

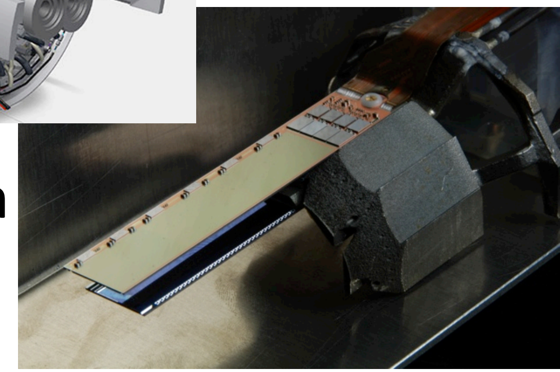
operated 2014-2015



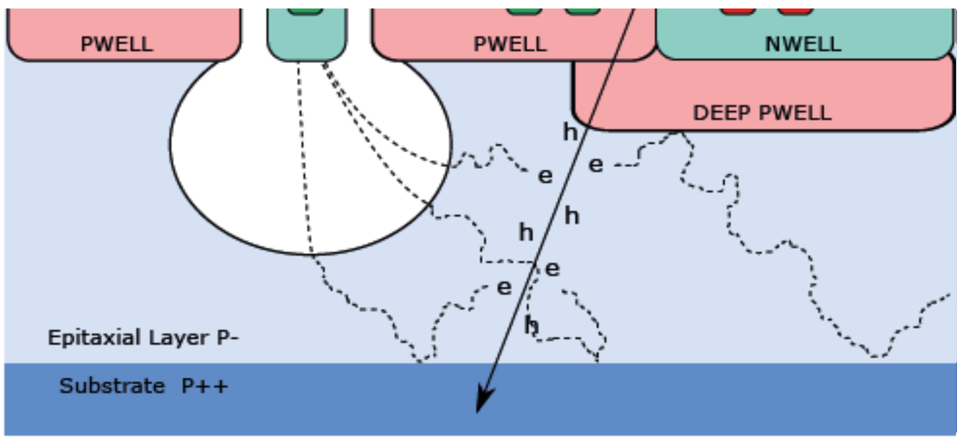
total area 0.014 m^2

(Belle II)

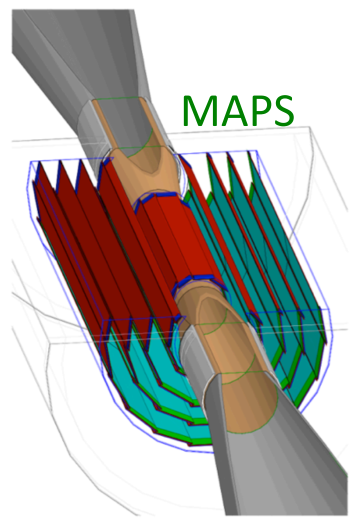
DEPFET pixels



in production for 2017



radiation tolerant to 1/1500 of HL-LHC-pp



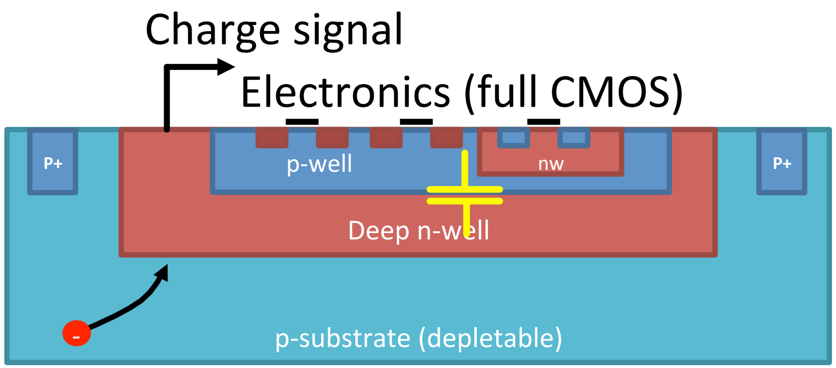
ILC

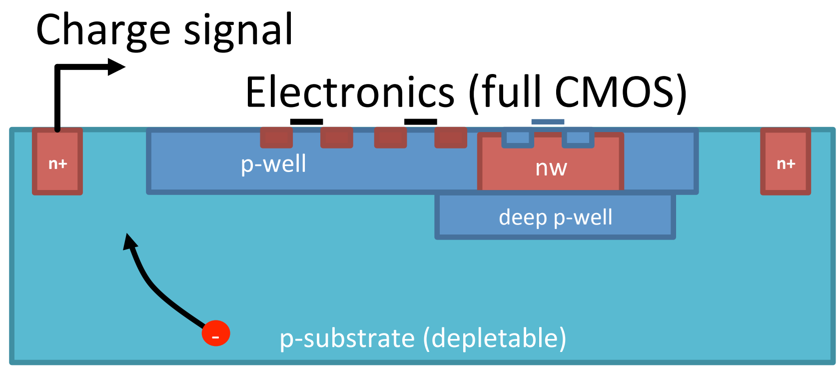
total area ? m^2

current baseline

J.P. Crooks, ..., R. Turchetta et al. IEEE TNS 2007 & Sensors (2008), ISSN 1424-8820

Large S/N versus radiation hardness ...





Electronics **inside** charge collection well

- **large fill factor**
  → no low field regions
  → on average **short(er) drift** distances
  → less trapping -> **radiation hard**

- **Larger (100 fF)** sensor **capacitance**
- **additional well-well capacitance** (~100 fF)
  → noise & speed/power penalties
  → x-talk easier (from digital to sensor)

Electronics **outside** charge collection well

- **small fill factor**
  -> very small sensor capacitance (~5 fF)
  → noise low, speed high, power low

- on average longer drift distances and low field regions
  → **not radhard ? or ??**

Goal-1 ... S/N ≈ 20, i.e. N ≲ 200e⁻ => S = 4000e⁻ (≙50µm)

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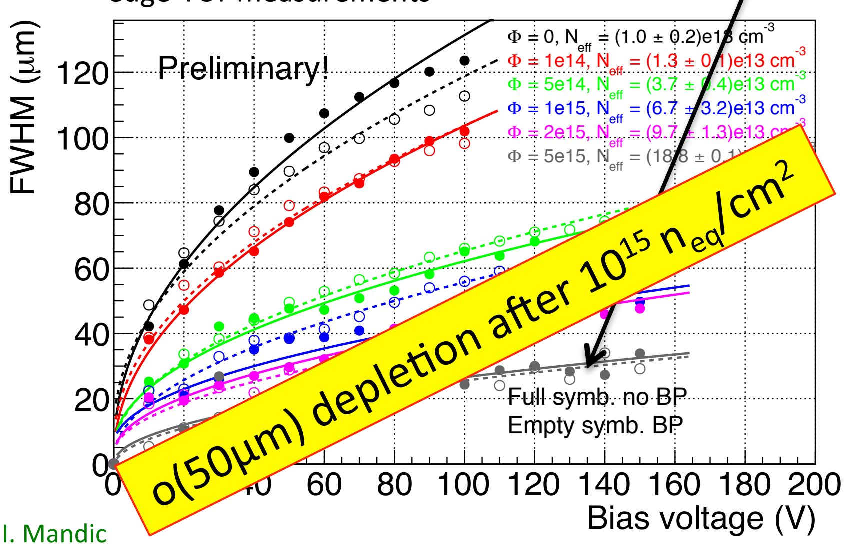
- radiation hardness

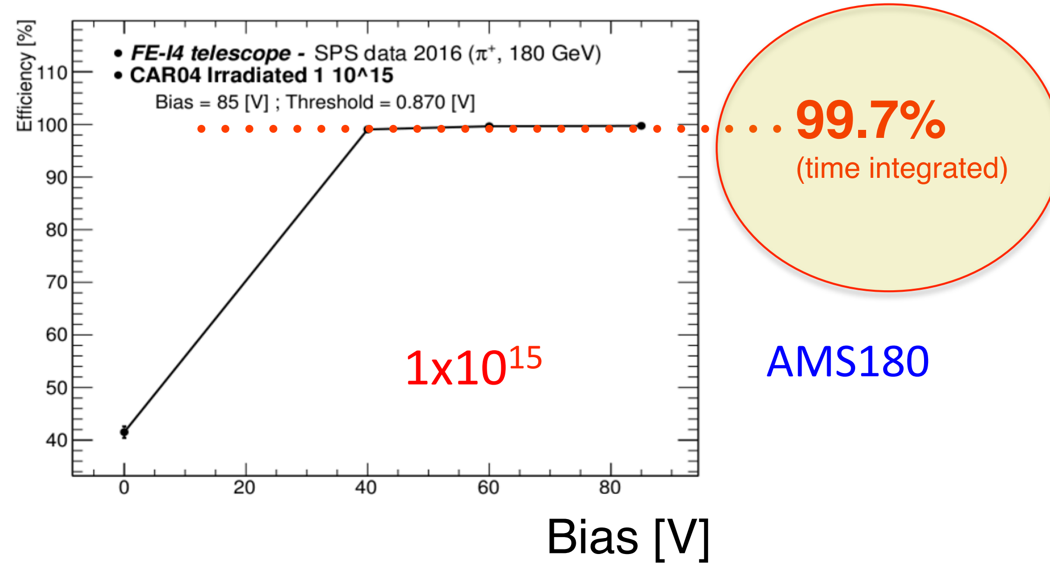
LFoundry

edge-TCT measurements

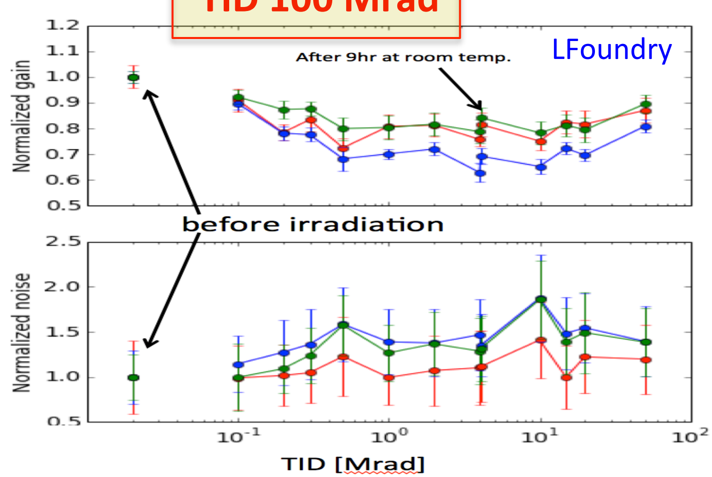


I. Mandic

- efficiency



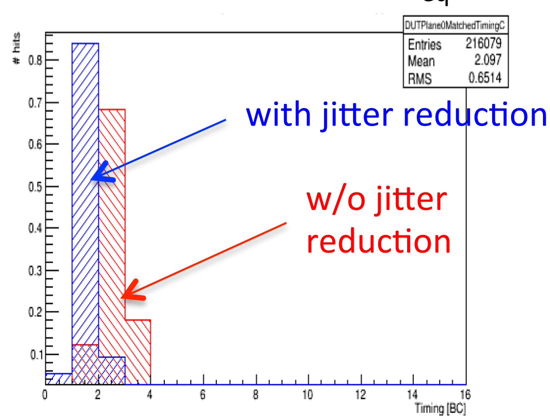
TID 100 Mrad



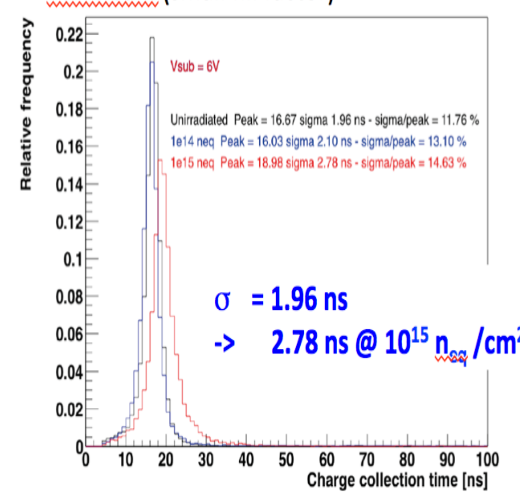
N. Wermes

- timing

AMS180 after 1 x 10^{15} n_{eq}/cm^2



TowerJazz (small fill factor)



4D with LGADs?

Low Gain Avalanche Detectors

30 ps timing precision?

New: How to obtain fast timing with Si detectors?

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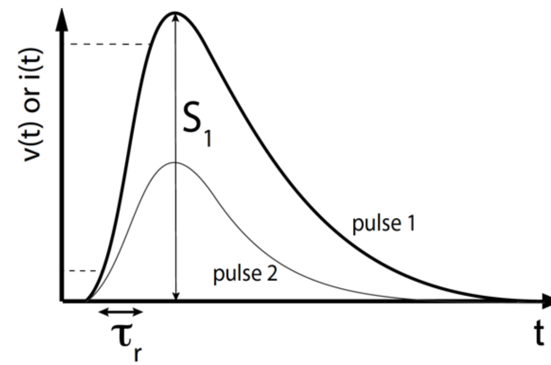
- 10 - 30 ps with (structured) Si detectors ??
- => exploit "in-silicon" charge amplification
  - in "Geiger Mode" fashion (like in gas **RPCs**) → σ_t governed by avalanche fluctuations

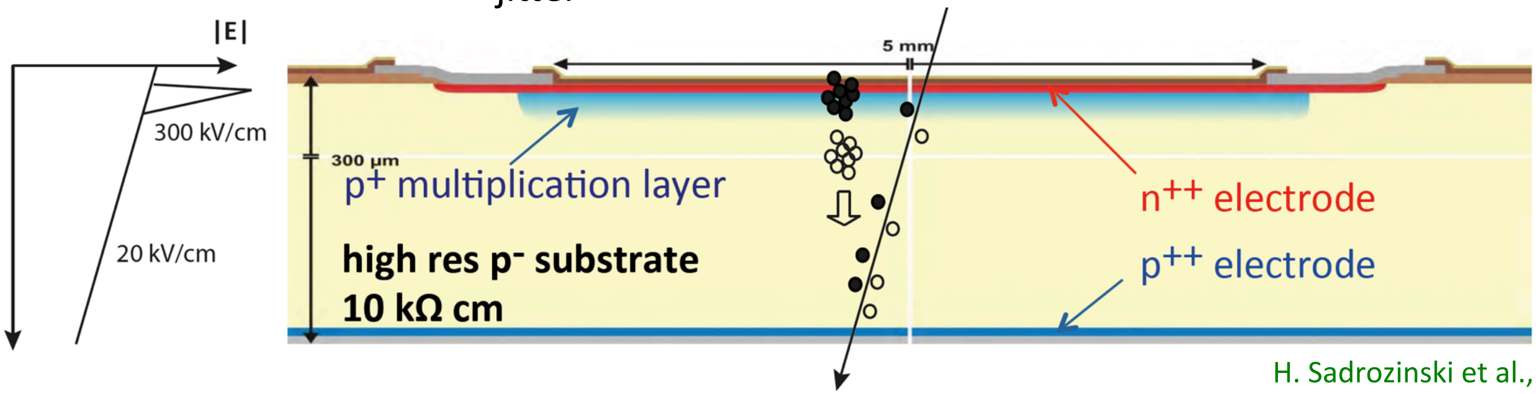
OR .... in "linear mode" fashion (lower E-fields, lower shot noise, no dark counts)
-> Low Gain Avalanche Detectors

"slew rate"

$$\sigma_t^2 = \underbrace{\left(\frac{V_{th}}{dV/dt}\Big|_{rms} \right)^2}_{\text{signal time walk}} + \underbrace{\left(\frac{\text{Noise}}{dV/dt} \right)^2}_{\text{noise time jitter}} + \underbrace{\left(\frac{TDC_{bin}}{\sqrt{12}} \right)^2}_{\text{TDC binning}}$$

TDC binning can be made negligible





$$i_S = q\vec{E}_w \cdot \vec{v}$$

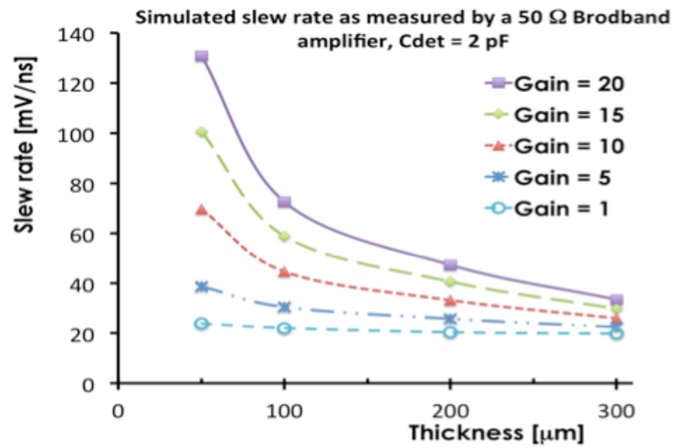
H. Sadrozinski et al., NIM A730 (2013) 226-231
N. Cartiglia et al., JINST 9 (2014) C02001
A. Seiden et al, Vertex2015, Proceedings

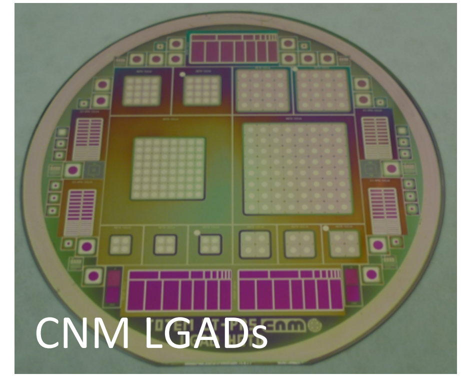
- Ultimate Goal: simultaneous space (~10µm) and time resolution (< 50 ps)
- Options for ATLAS (HighGranularityTimingDetector; Forward) -> pile-up killer and CMS-TOTEM (in Roman Pots)

LGAD – starting with PAD detectors

- high voltage (800 - 1000 V)
  - high field -> fast e^-

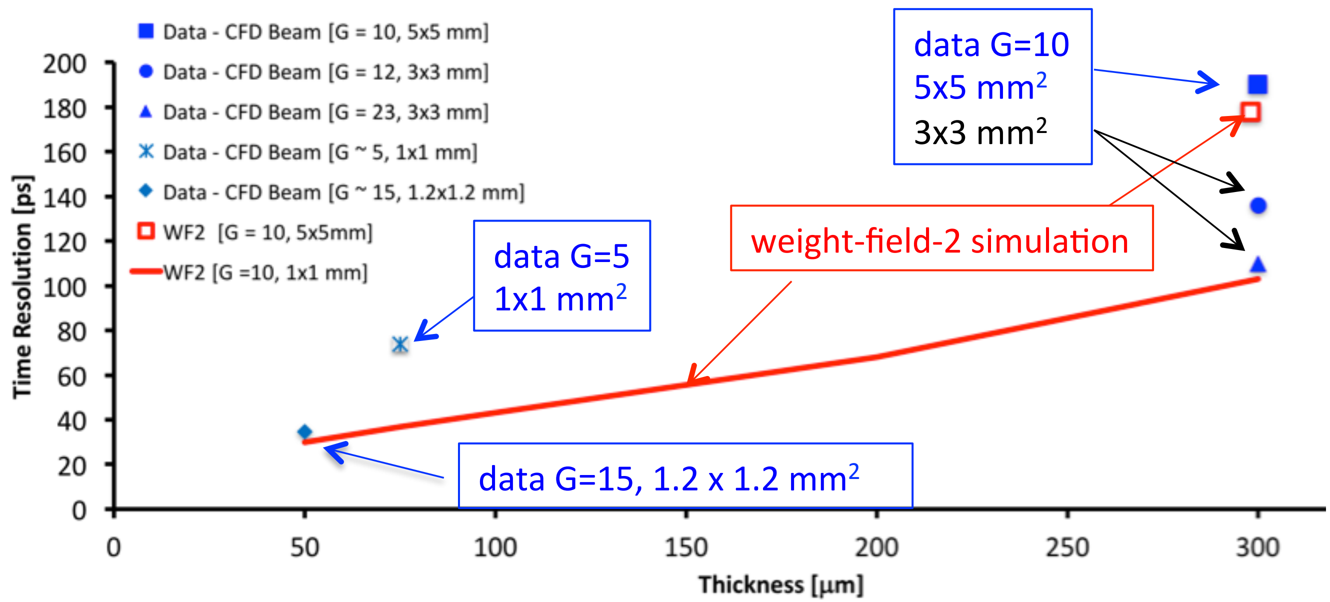
- thin (50 µm)
  - higher field for given voltage
  - steeper signal
  - rad harder
  - smaller Landau spread





G. Pellegrini et. al, NIM A 765 (2014) 12–16.

- gain ~10
  - lower E-fields
  - lower shot noise,
  - no/few dark counts



still pad detectors

Conclusions

- ❑ Tracking Detectors (gas-filled, semiconductors, fibres) are facing highest challenges with HL-LHC upgrades and also generally.
- ❑ This will advance the physics potential at the (almost newly built) HL-LHC experiments.
- ❑ As usual almost certainly spin-offs (bio-medical) will emerge.
- ❑ “Detector Physics” has become a field of its own.