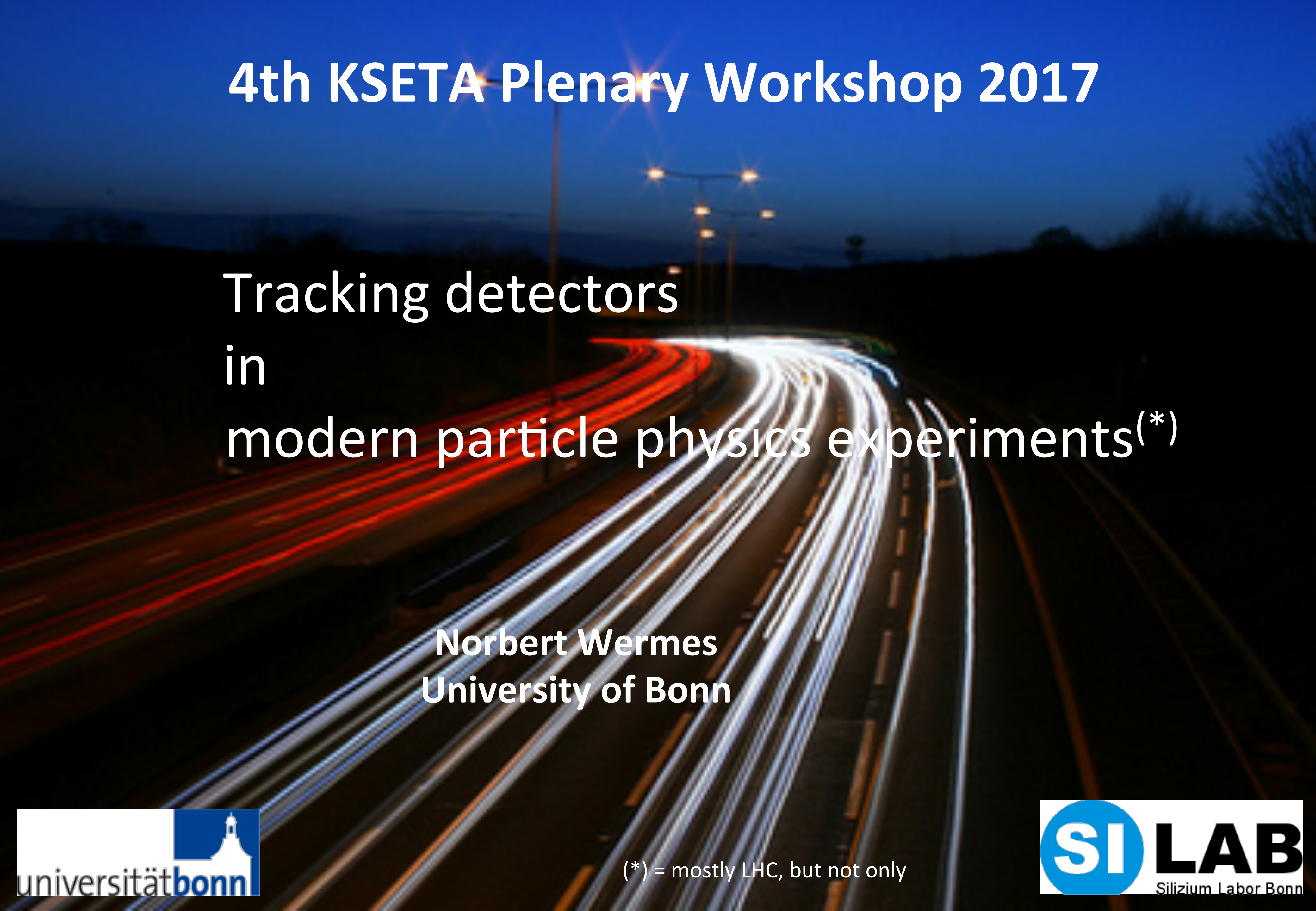


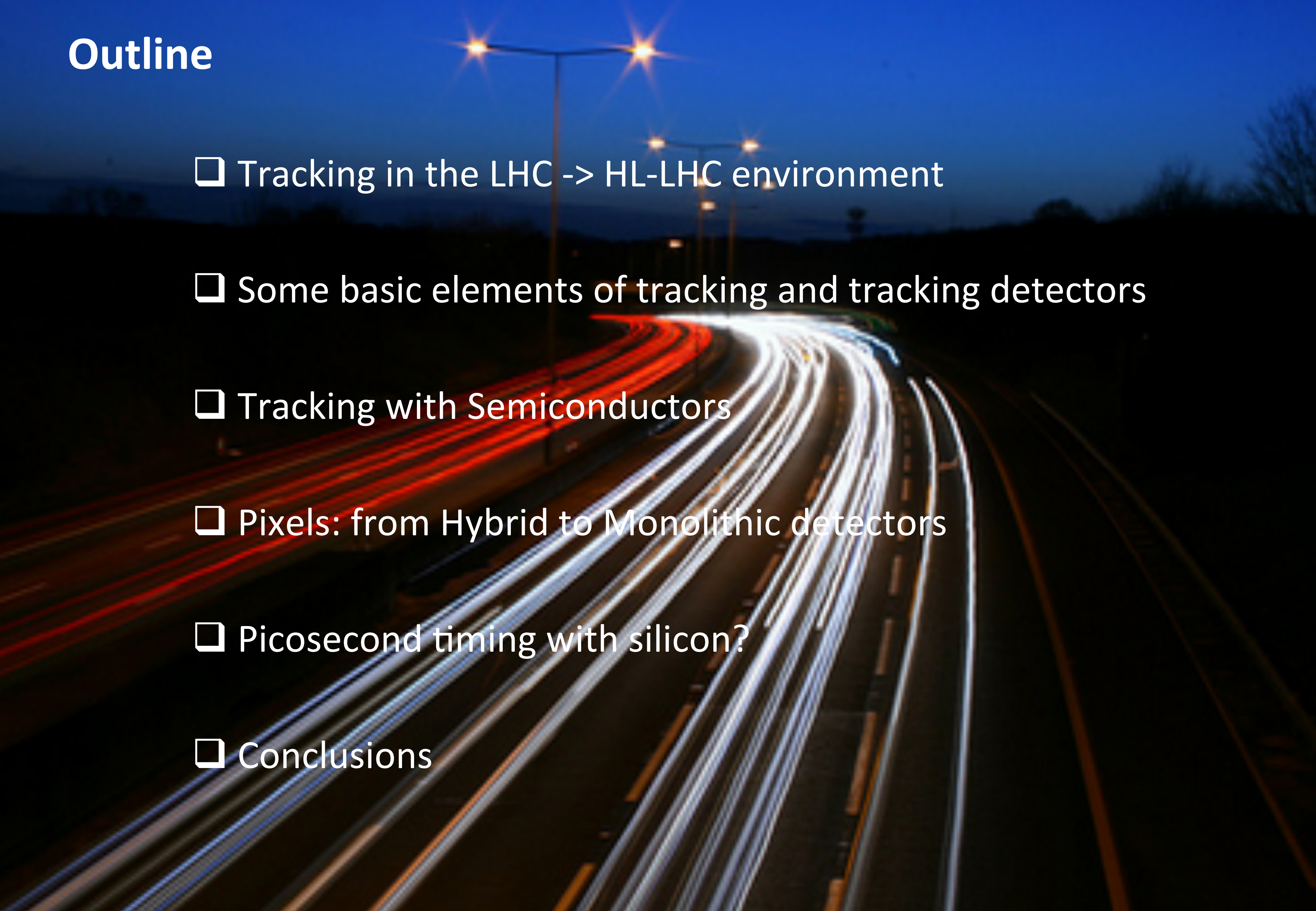
4th KSETA Plenary Workshop 2017

Tracking detectors in modern particle physics experiments(*)

Norbert Wermes
University of Bonn

(*) = mostly LHC, but not only

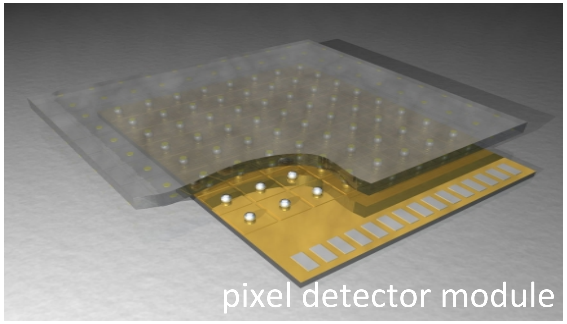
Outline



- ☐ Tracking in the LHC -> HL-LHC environment
- ☐ Some basic elements of tracking and tracking detectors
- ☐ Tracking with Semiconductors
- ☐ Pixels: from Hybrid to Monolithic detectors
- ☐ Picosecond timing with silicon?
- ☐ Conclusions

Where are we? ... or ... “from chips to Higgs and back”

detector development



pixel detector module

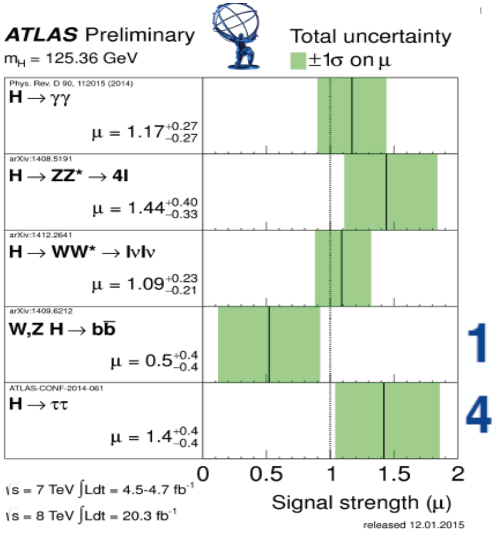
Run 1 (2010-12)

LHC ≅ 10^6 x LEP in track rate !

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

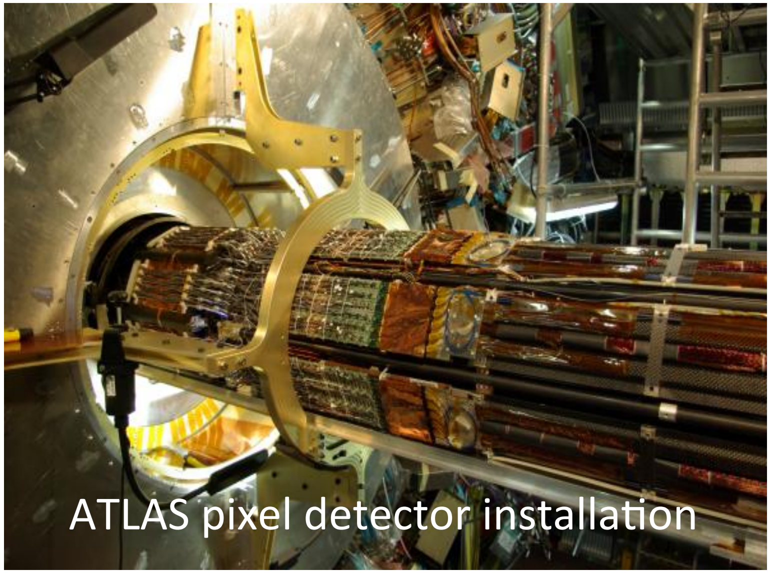
2018 + ... Run 1 **x 10 ?**

2026 + ... Run 1 **x 10 – 20 ?**

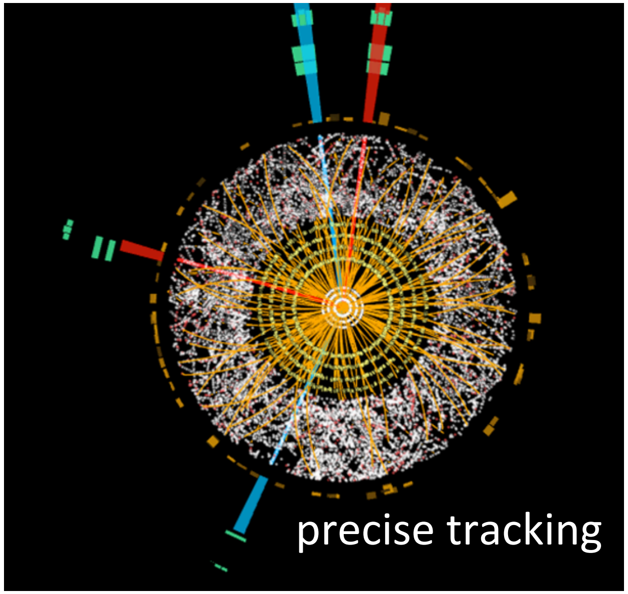


1.4σ

4.5σ

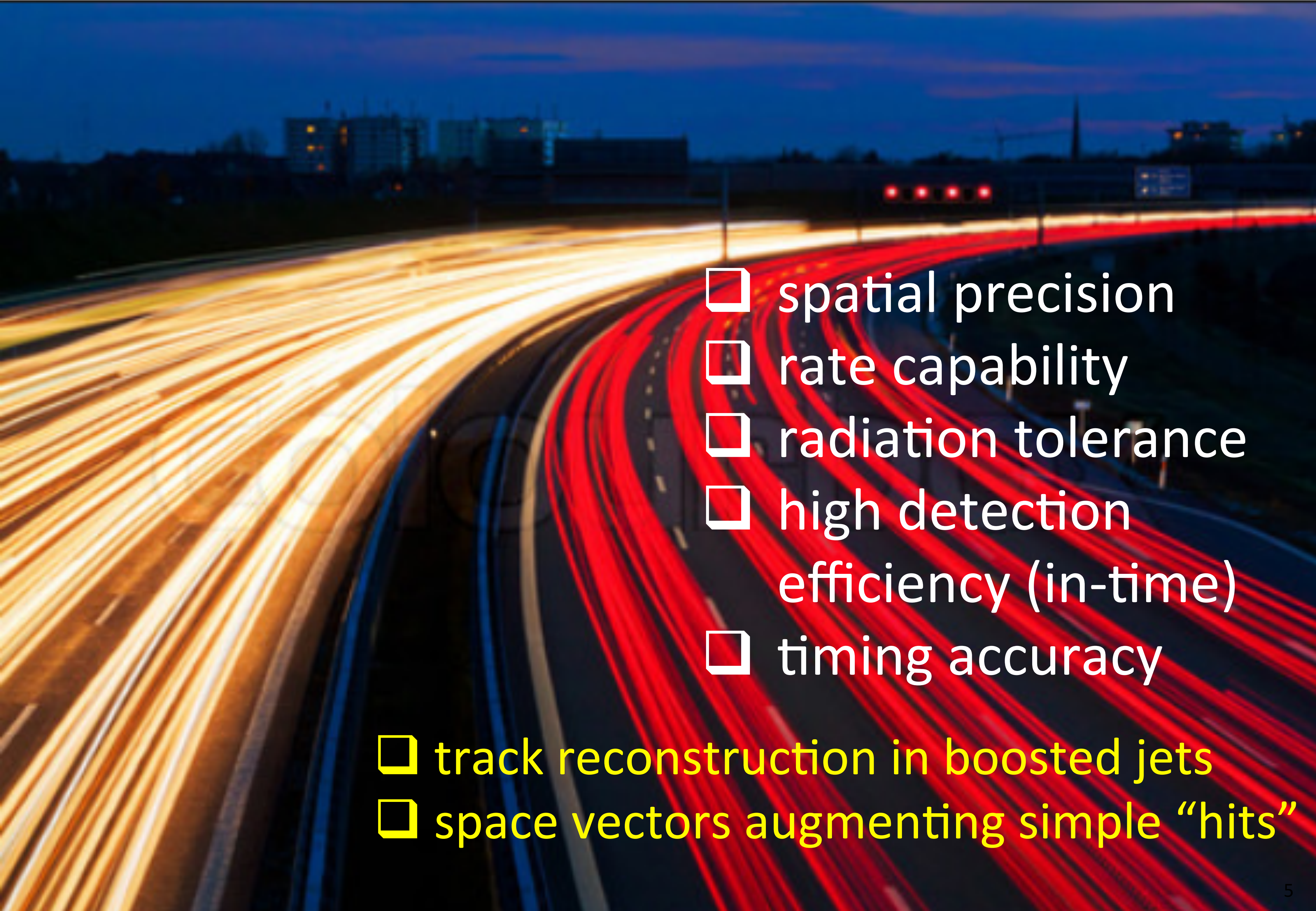


ATLAS pixel detector installation



precise tracking

N. Wermes, Desy Kolloquium 2016



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

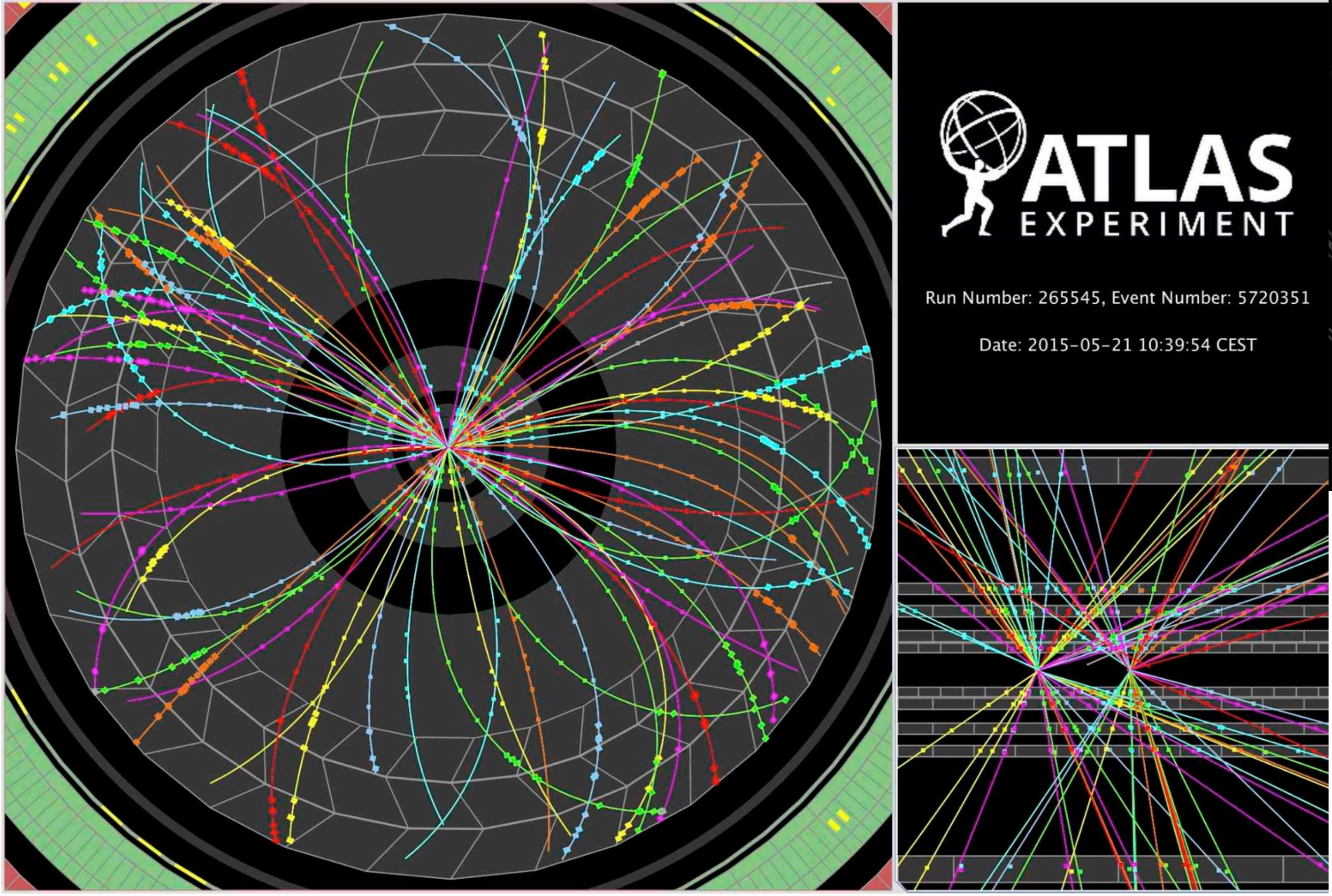
- ☐ track reconstruction in boosted jets
- ☐ space vectors augmenting simple “hits”

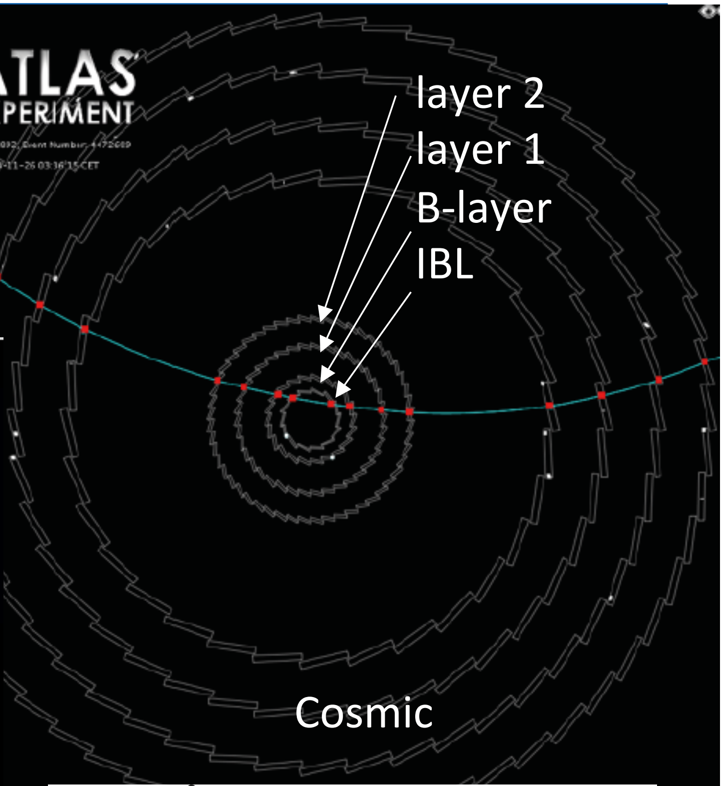
ATLAS Pixel Detector in operation

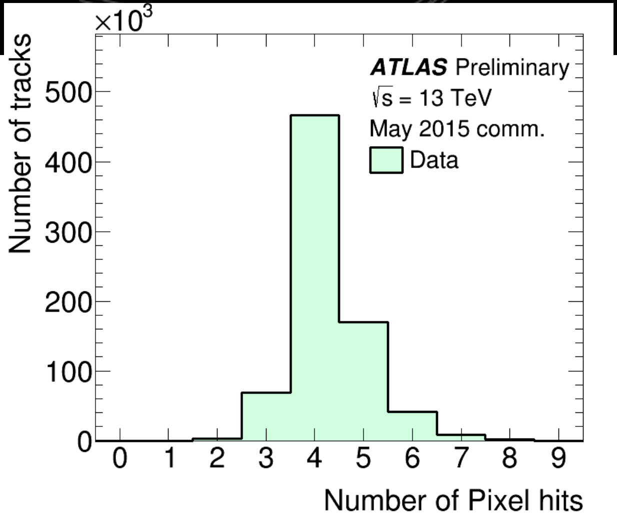
4-hit pixel system!

important for b-quark tagging

low luminosity, 2 interactions

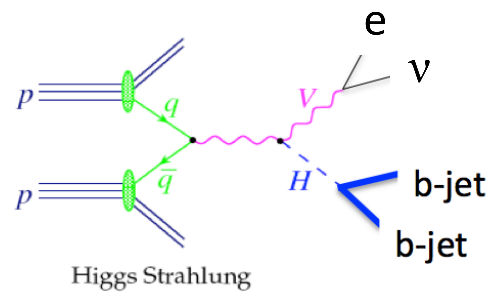


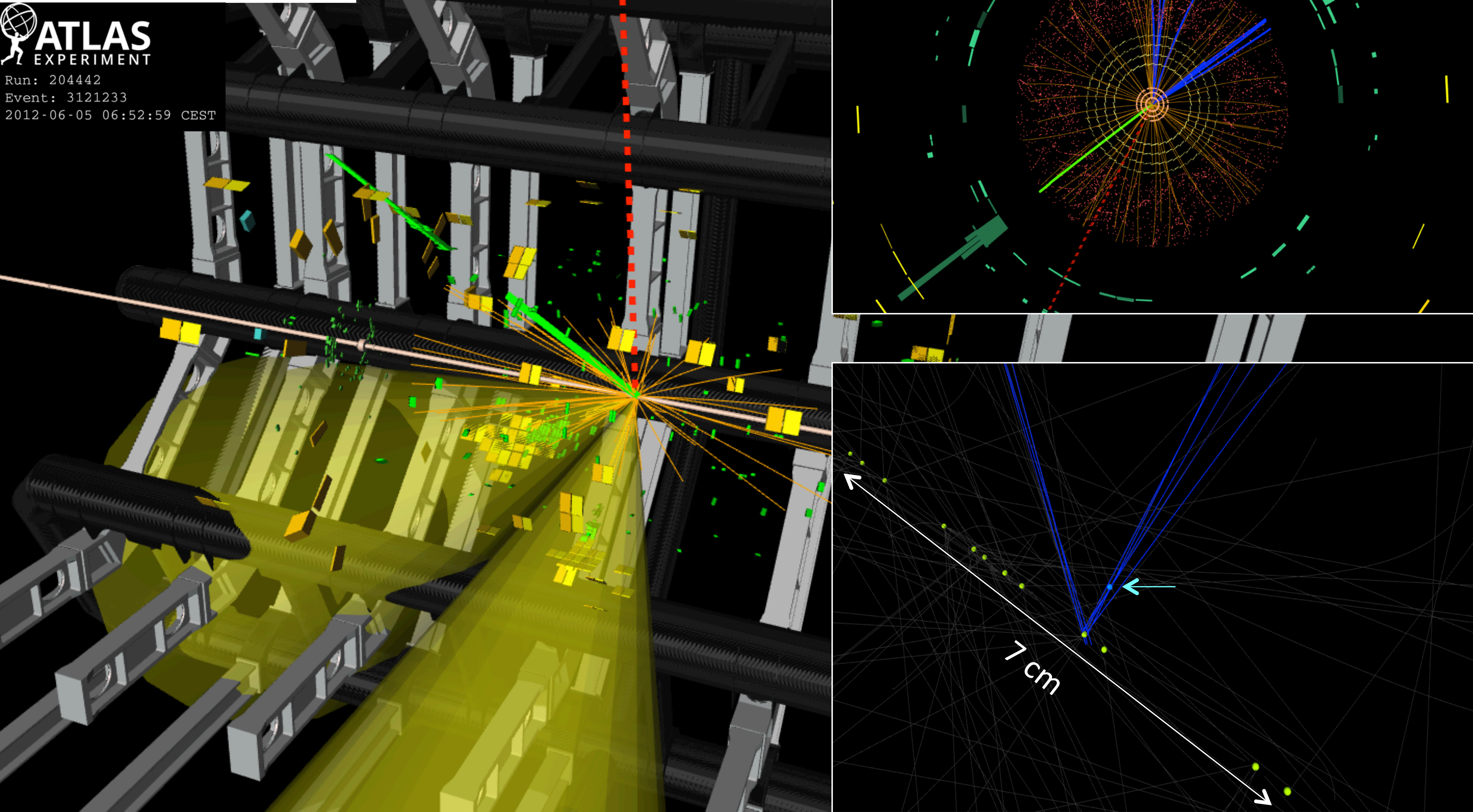


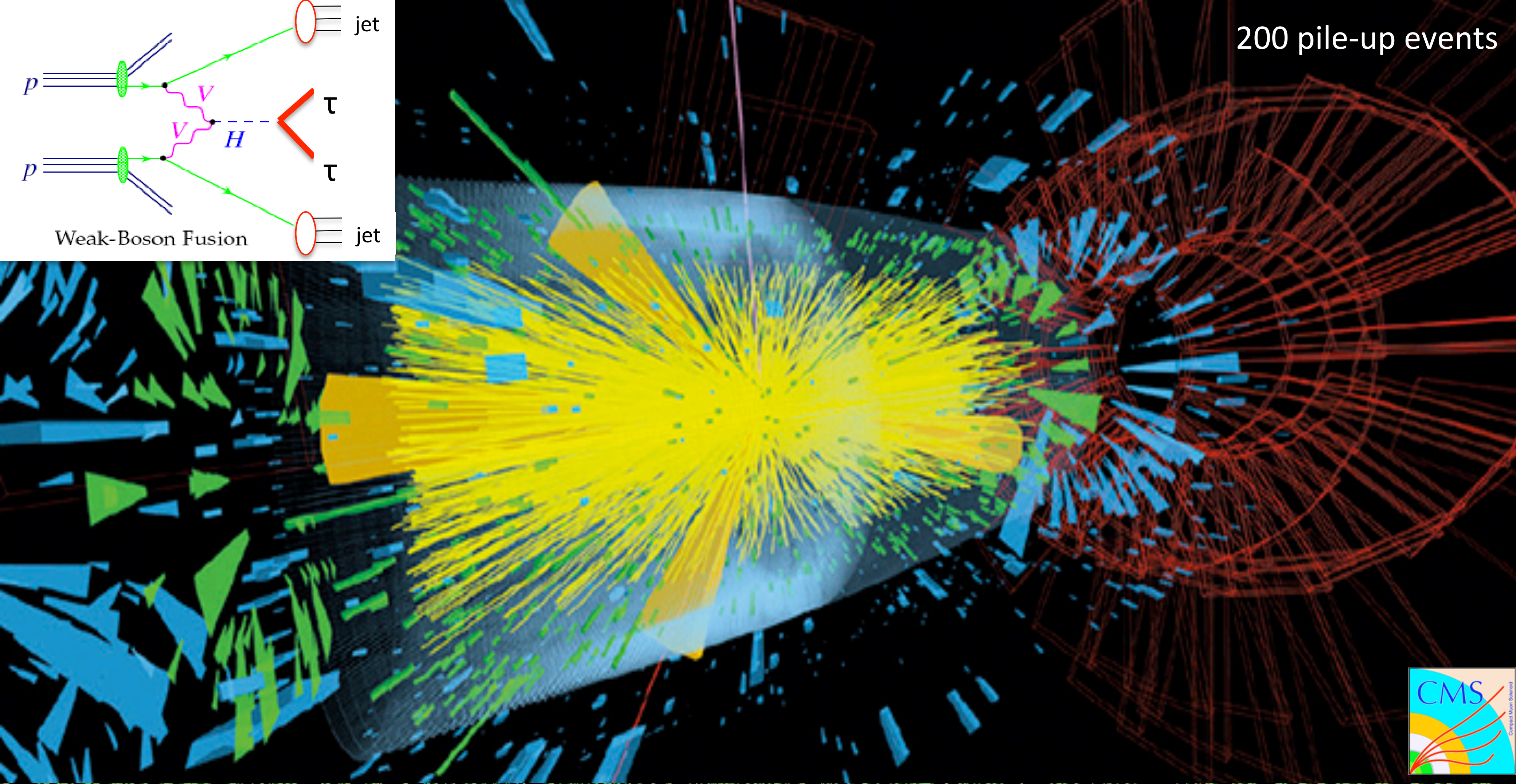


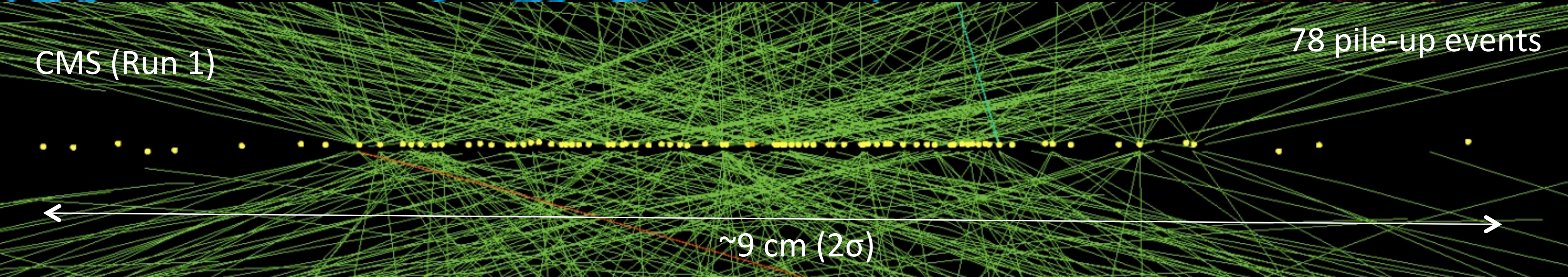
pp -> WH -> νl + bb

universitätbonn

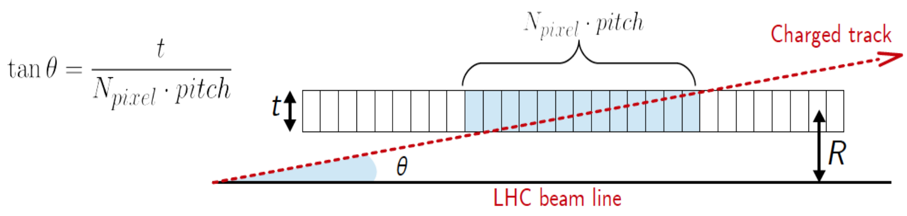




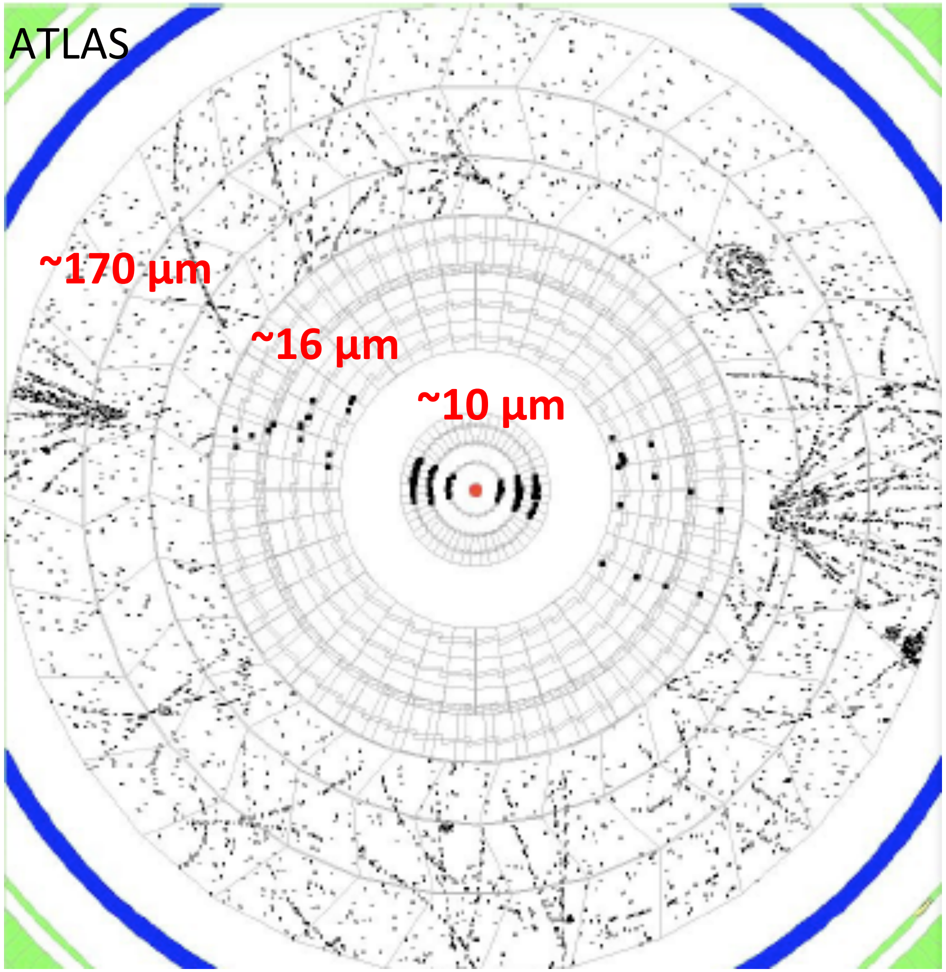

p
p
V
V
H
τ
τ
jet
jet
Weak-Boson Fusion
200 pile-up events
CMS


CMS (Run 1)
78 pile-up events
~9 cm (2σ)

Tasks of Tracking Detectors



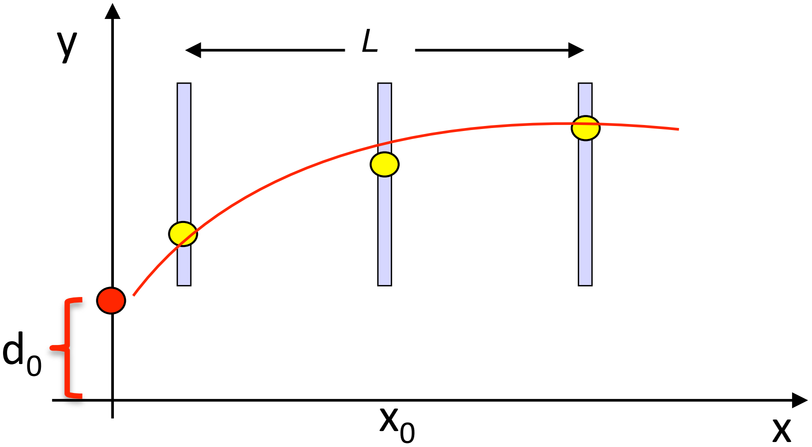
$$\tan\theta = \frac{t}{N_{pixel}\cdot pitch}$$



- 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

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

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

Gluckstern NIM 24 (1963) 381

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

$r = x_0/L$ = 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 $1/\sqrt{N}$

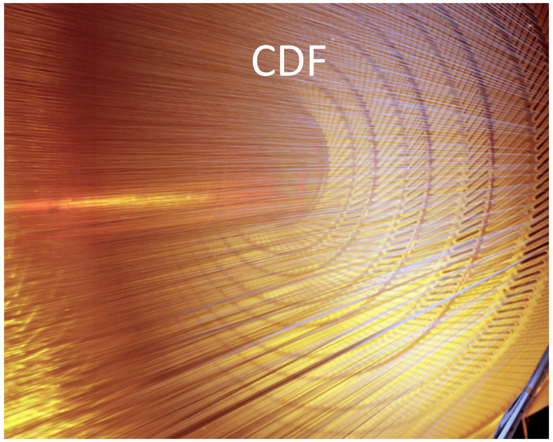
Technology most often used: Si - detectors

PRO – high resolution $\sigma_{\text{meas}} \sim 10$ µm

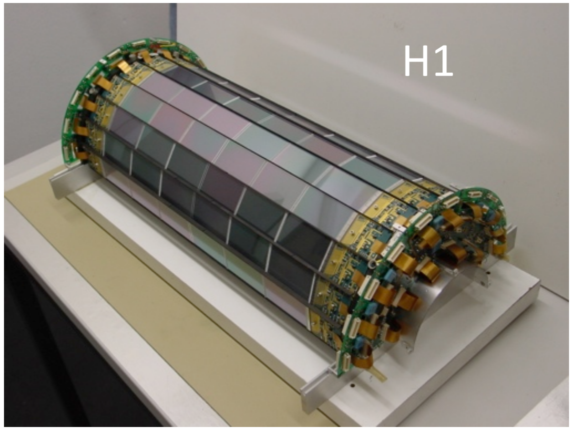
CON – expensive
– small *N*
– small *L*
– small X_0 => large mult. scatt.

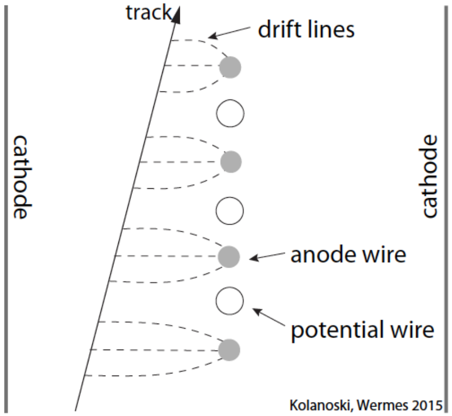
PRO – high rate capability

Gas-filled versus semiconductor detectors



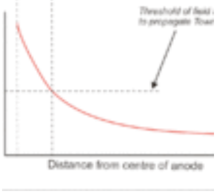
++	material	-
+	N_{meas}	--
low	cost	high
--	rate/speed	++
100 µm	resolution	10 µm



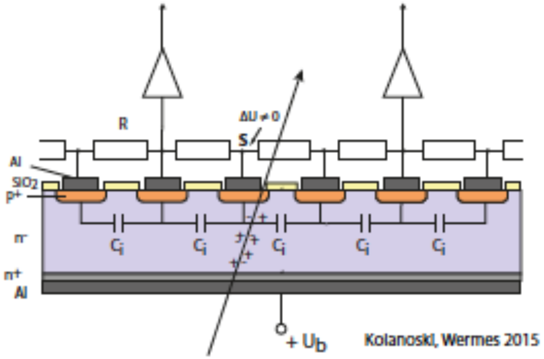


Kolanoski, Wermes 2015

field near wire
E(r) ~ 1/r

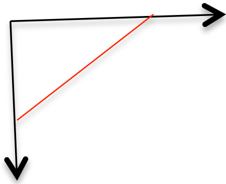


⇒ gas amplification



Kolanoski, Wermes 2015

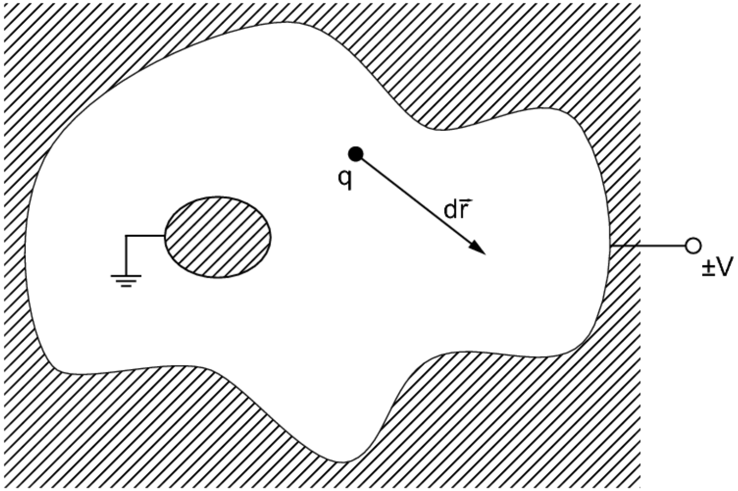
linear E



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

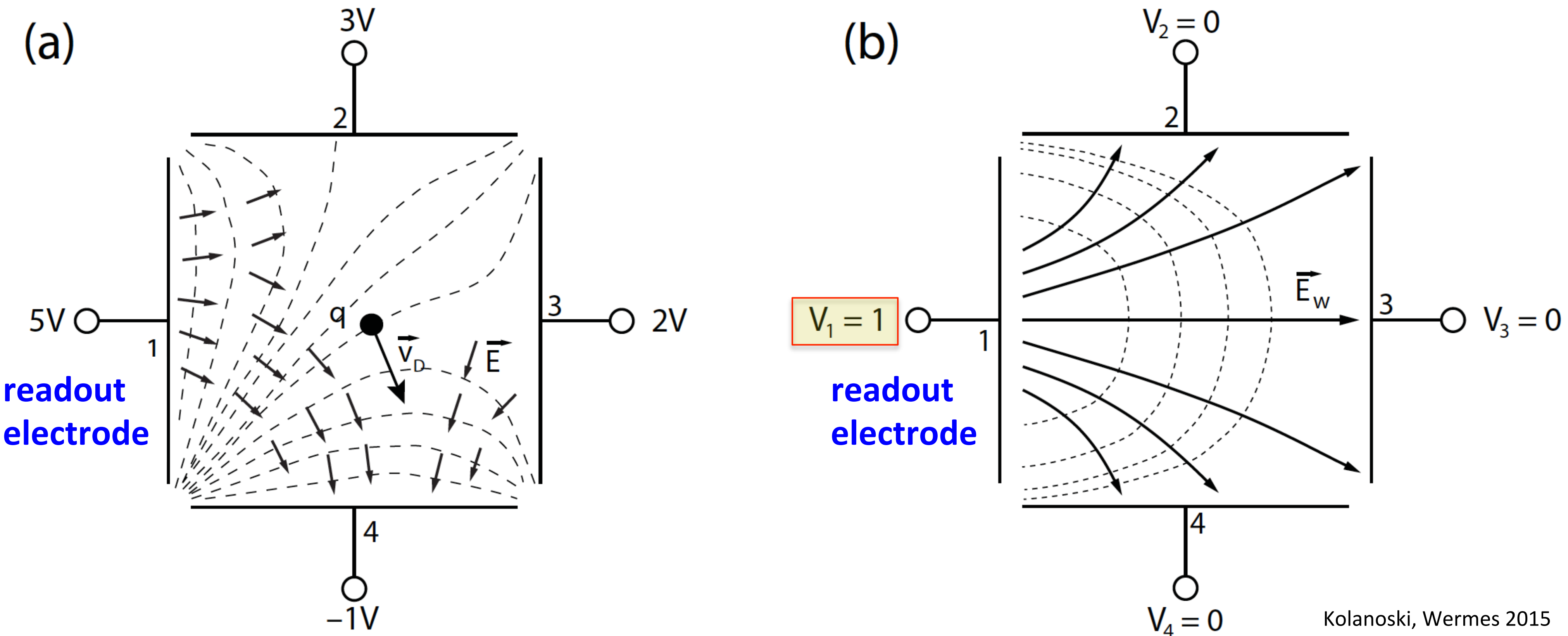
$$dQ = q\vec{\nabla}\phi_w d\vec{r}$$

they determine how charge movement couples to a specific electrode

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

weighting field

Normal Field and Weighting Field



Kolanoski, Wermes 2015

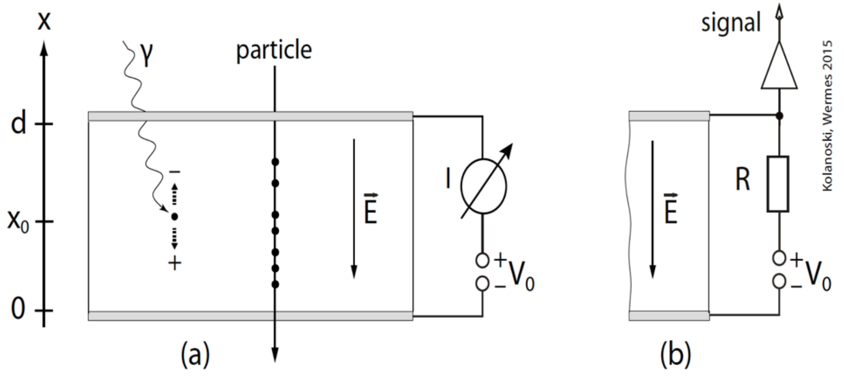
$$i_S = -\frac{dQ}{dt} = q\vec{E}_w\vec{v}$$

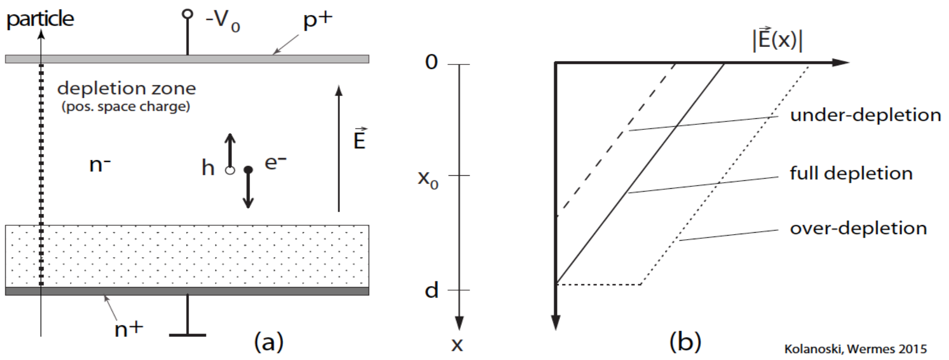
Recipe: To compute the weighting field of a readout electrode i, set voltage of electrode i to 1 and all other electrodes to 0.

Examples

parallel plate detector (gas filled)

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



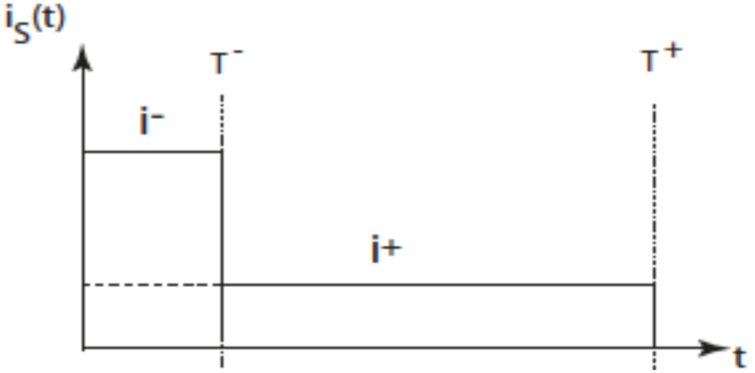


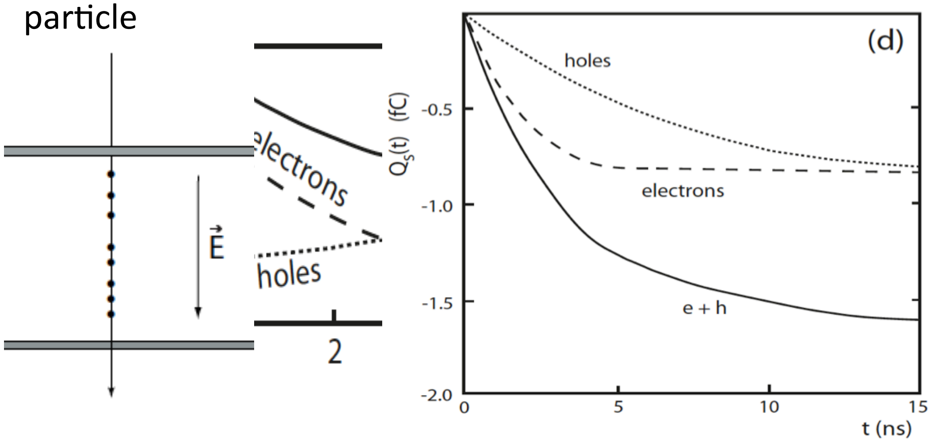
$$\vec{E}_w = -\frac{1}{d}\vec{e}_x$$

velocity (v=μE) almost const.

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

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

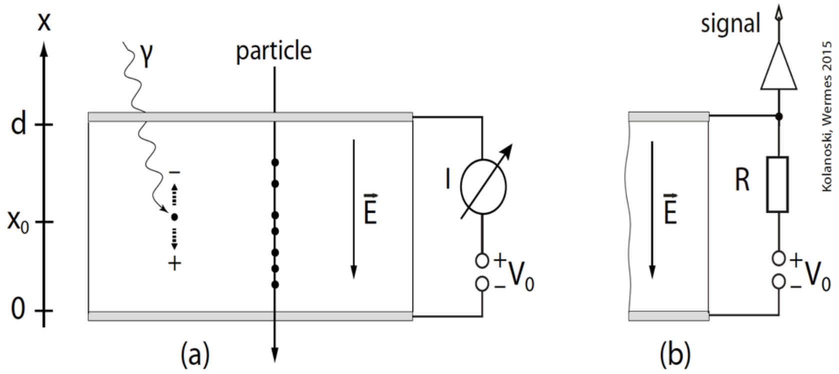




$$Q_{tot} = \int_0^{T^{\substack{+\\-}}} i(t)dt = Q_s^+ + Q_s^- = \pm e$$

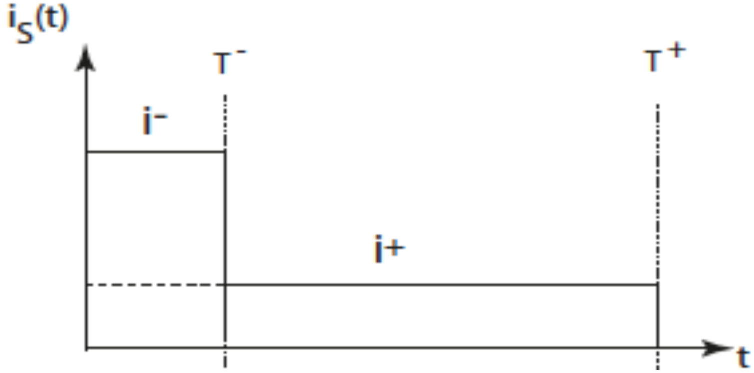
Examples

parallel plate detector (gas filled)



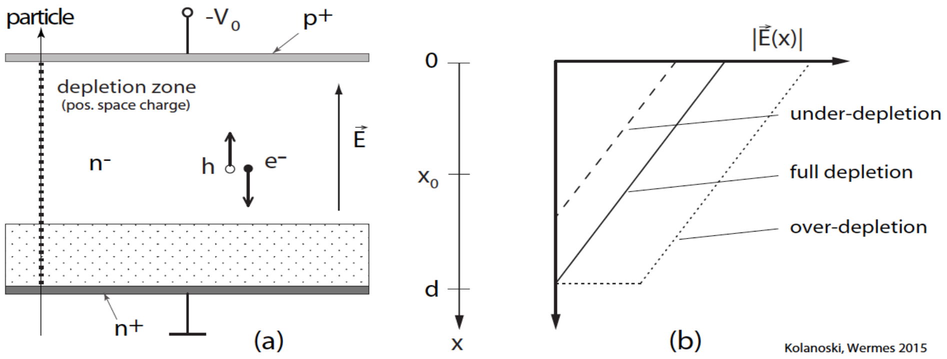
$$\vec{E}_w = -\frac{1}{d}\vec{e}_x$$

velocity (v=μE) almost const.



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

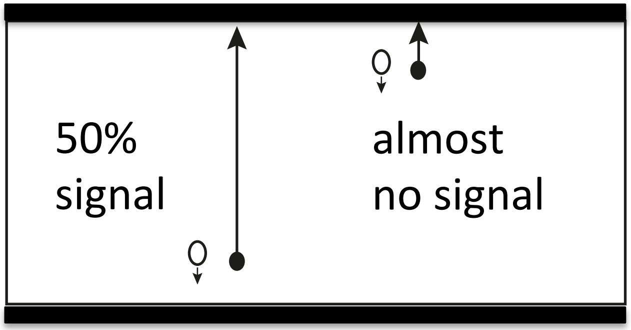
parallel plates with space charge (i.e. Si)



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

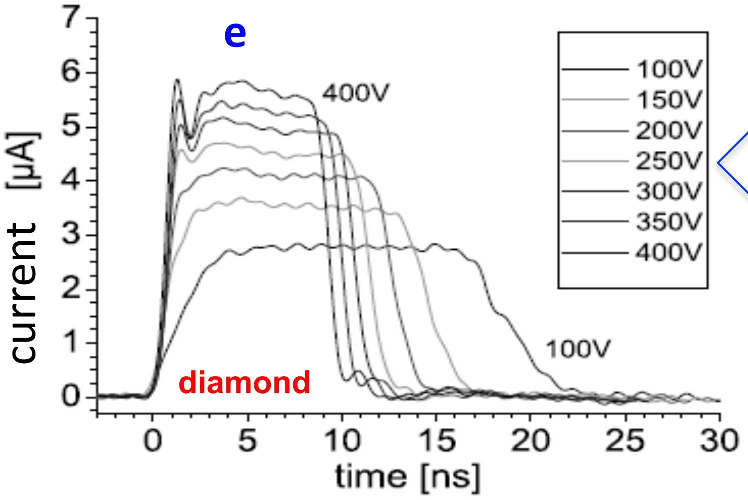
$$v_e = \dot{x}_e = -\mu_e E(x) = +\mu_e(a - bx)$$
$$\dot{x}_h = \qquad = -\mu_h(a - bx)$$

dangerous e.g. in CdTe



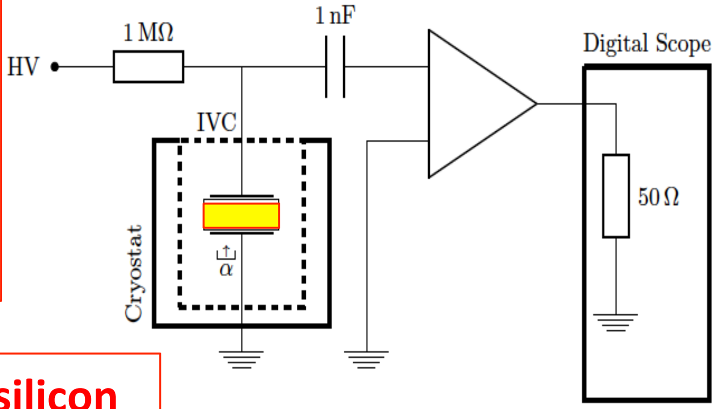
transient current

Current pulse measurements: TCT technique

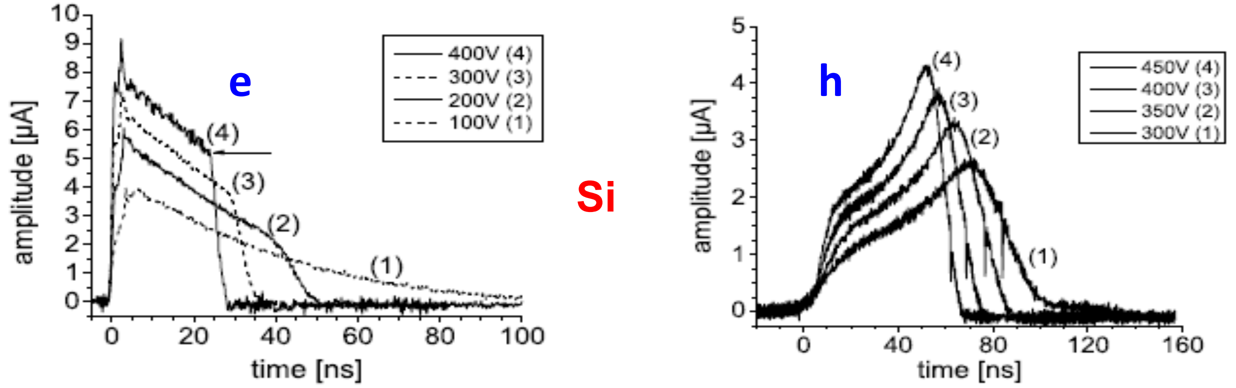


Fink, Lodomez, Krüger, Pernegger, Weilhammer, NW, NIM A 565 (2006), 227

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



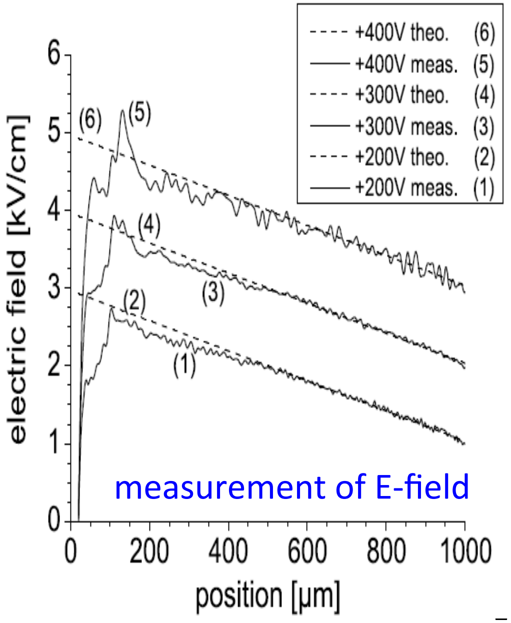
1mm pn – Diode **silicon**
- same weighting field
- different electric field



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

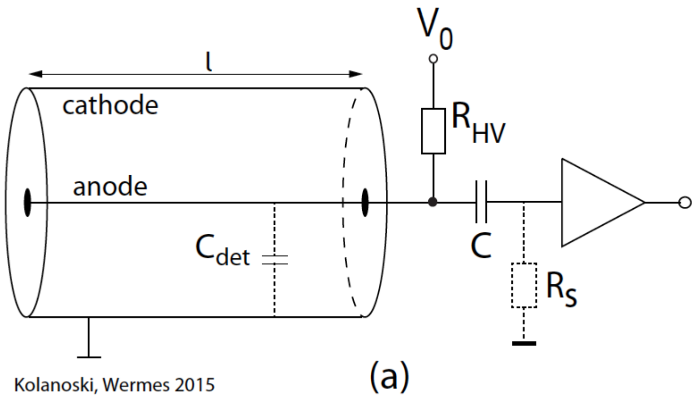
(b) Hole signals from α-particles impinging on the anode.

=>

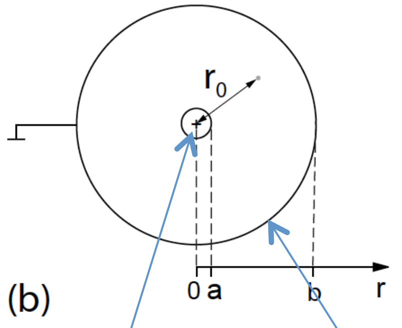


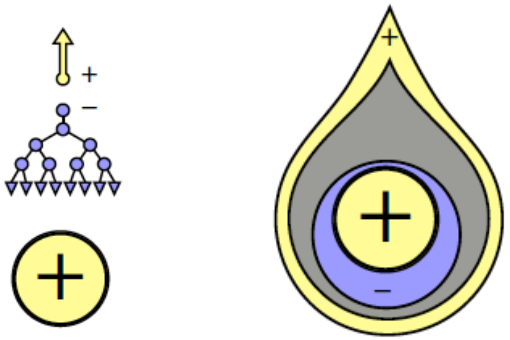
measurement of E-field

Signal development in a wire configuration



Kolanoski, Wermes 2015





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

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

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

which fulfills (*)

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

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

far away from wire

(a=10 µm, b=10 mm)

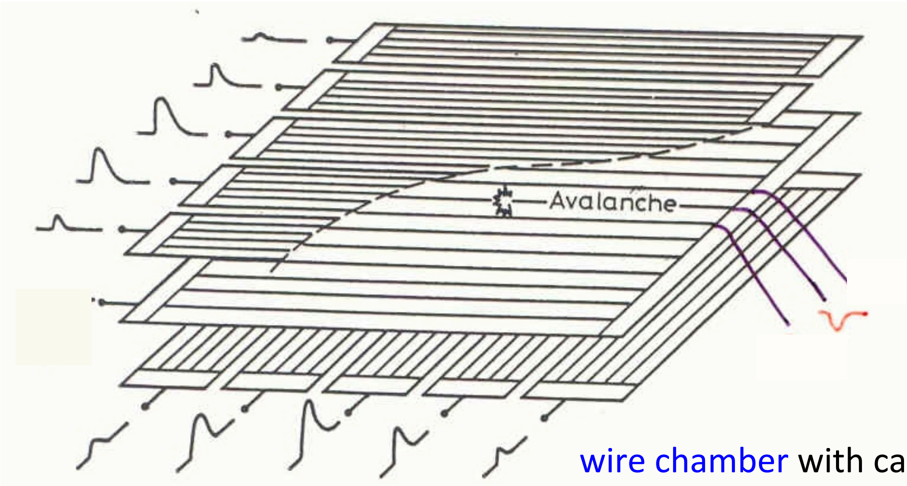
$$\left(\frac{Q_S^-}{Q_S^+}\right)_{r_0=a+\epsilon} \approx 0.01 - 0.02$$

near wire

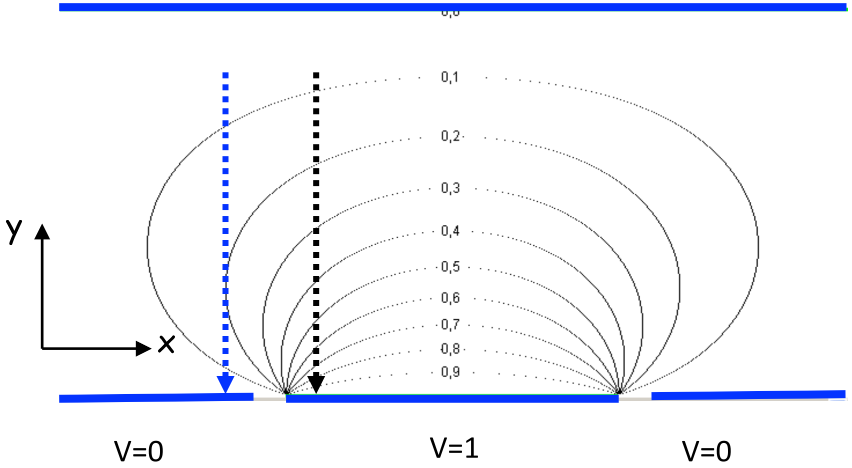
wire chamber signals are governed by away moving ions

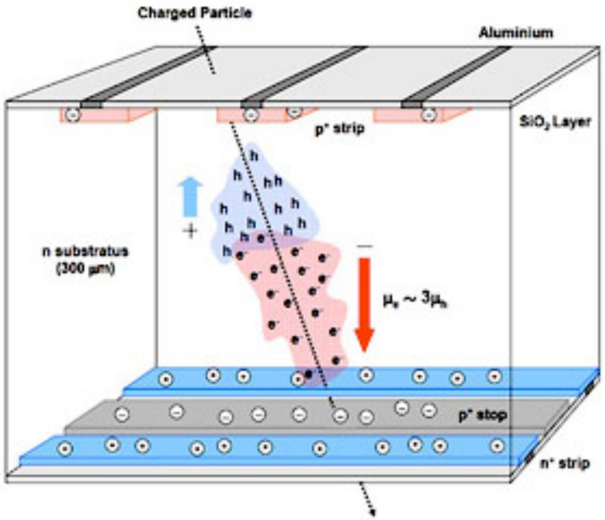
Structured electrodes

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

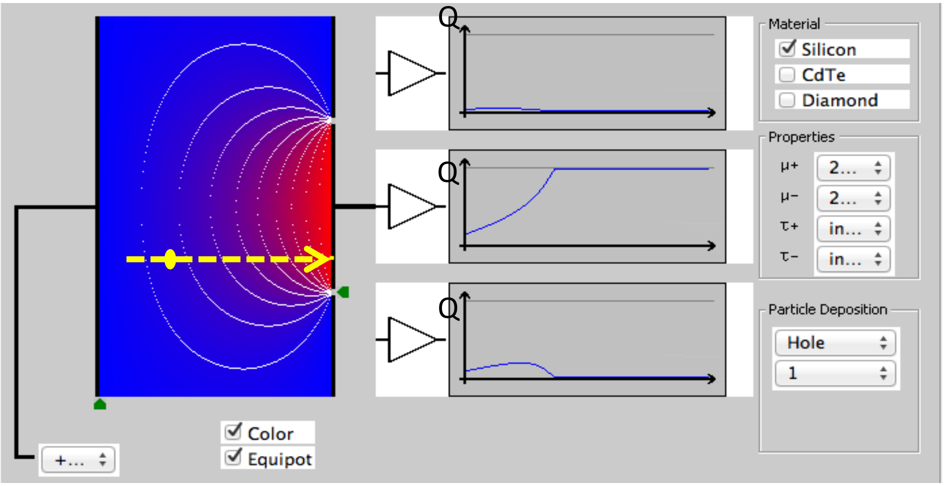


wire chamber with cathode R/O





double sided silicon strip detector



Material
☑ Silicon
☐ CdTe
☐ Diamond

Properties
μ+ 2...
μ− 2...
τ+ in...
τ− in...

Particle Deposition
Hole
1

☑ Color
☑ Equipot

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

❑ 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 × 10^{34} cm^{-2}s^{-1} × 120 ≈ 10^{11} tracks/s in 4π = 10^{6} × LEP
- @ r = 5cm => 9.5 tracks/cm^2/25 ns, but only 10^{-4} per pixel (100x100 μm^2)

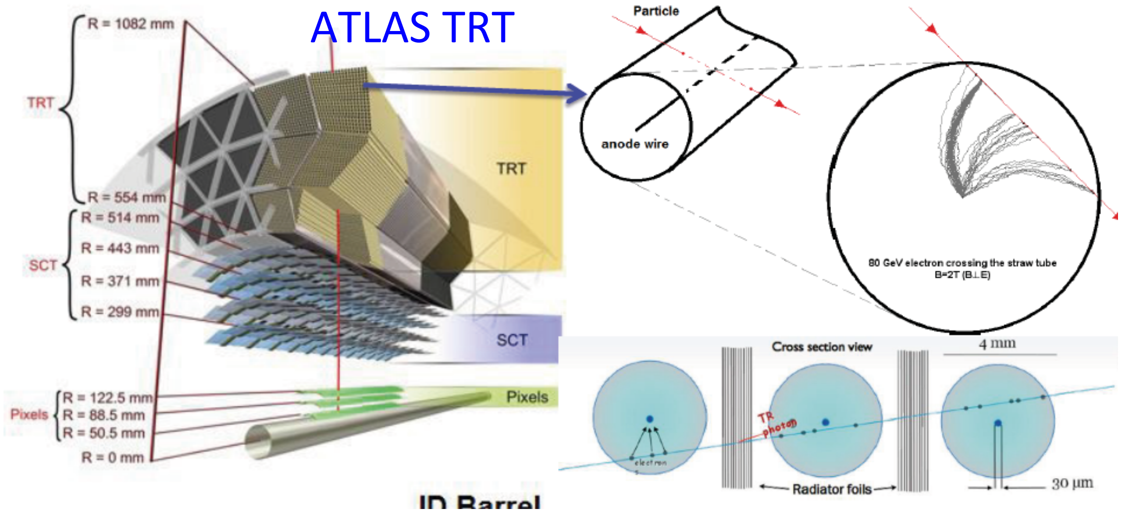
❑ radiation level (@ r = 5cm, per detector lifetime)

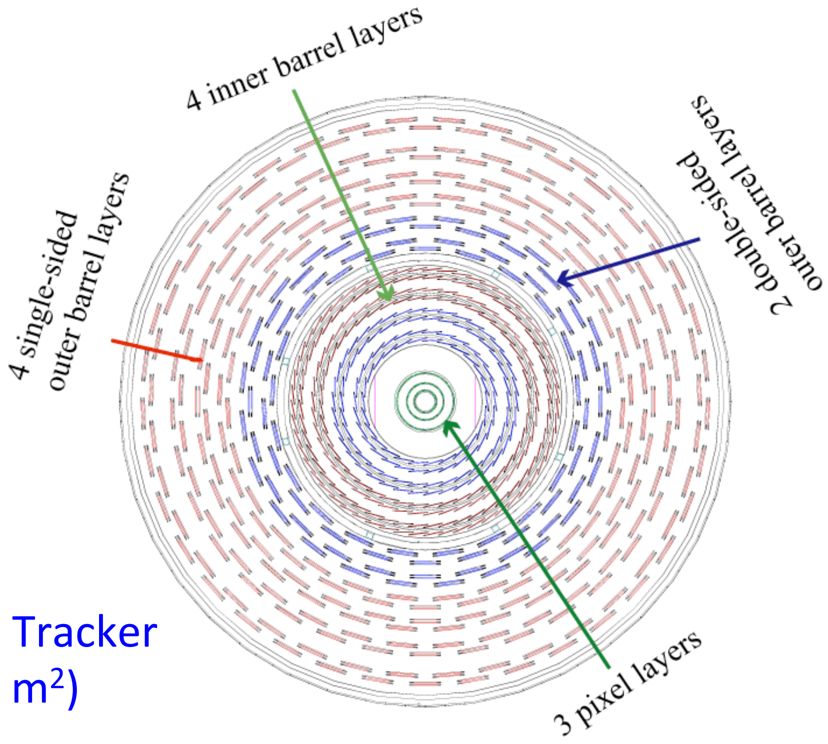
- total ionizing dose (TID) = energy/mass (J/kg) = 100 Mrad -> 1 Grad
- non ionizing fluence (NIEL, breaks the lattice) = 10^{15} particles per cm^2 -> 10^{16} cm^{-2}
- effects: ageing on wires, lattice damage, glue brittle, electronics, …

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

- way out
  - gas-filled detectors with small cells
  - timing precision $\ll$ 25 ns
  - solid state detectors
    - micro structuring => finest granularity
    - but: sensitive to radiation

ATLAS TRT

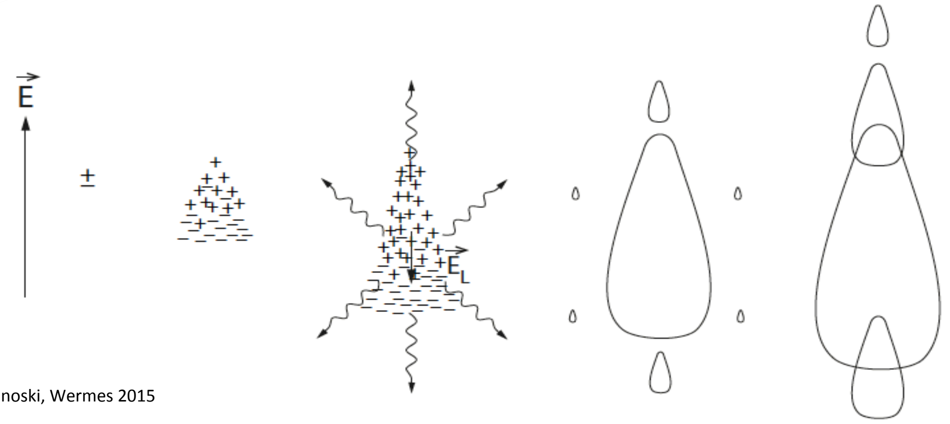




CMS Tracker
(200 m^2)

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

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

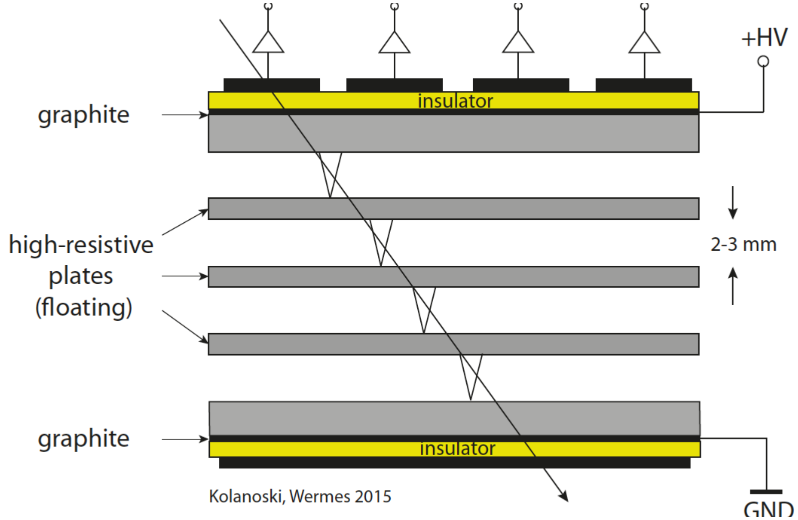


Kolanoski, Wermes 2015

"avalanche" <-> "streamer"

v_{drift} <-> photon emission

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

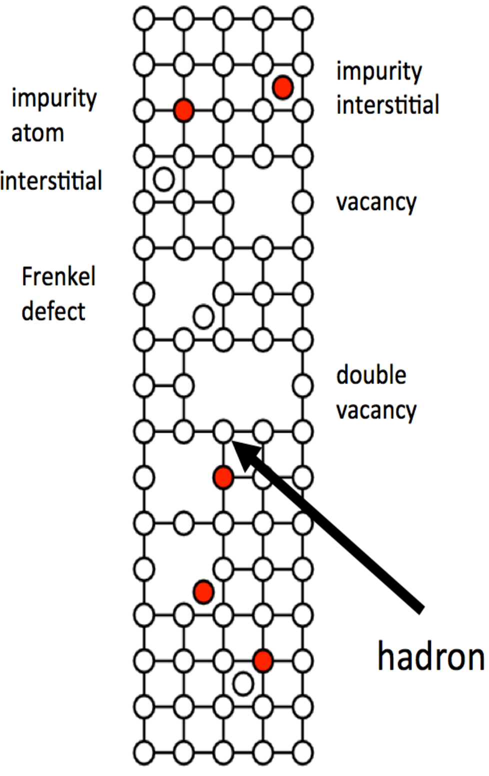


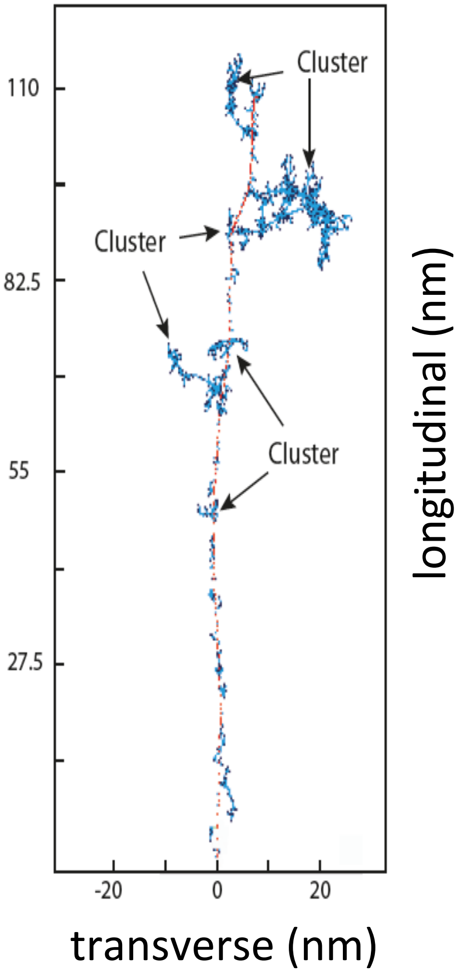
Kolanoski, Wermes 2015

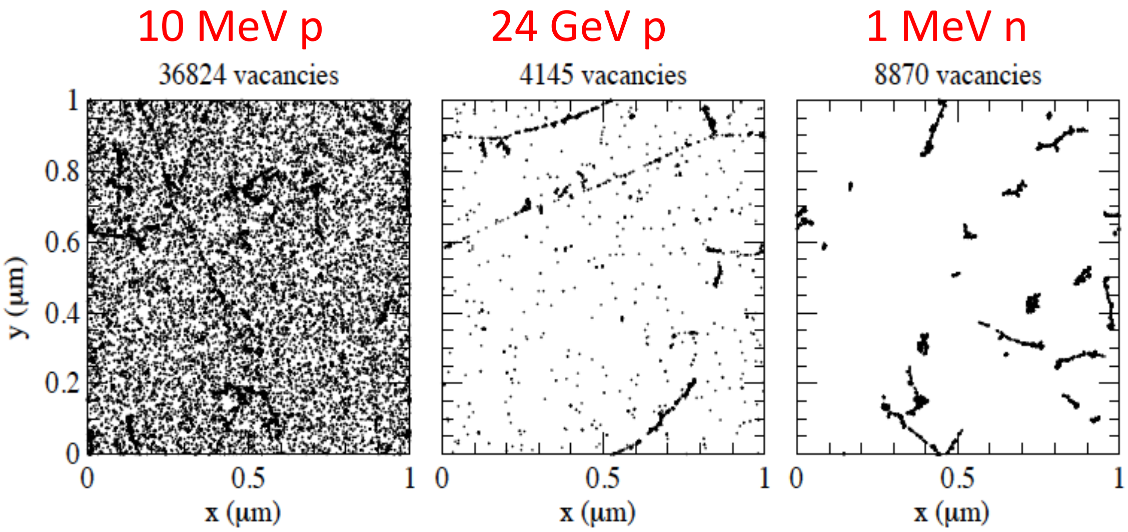
- ☐ gas filled chambers w/ large signals
  - operated in avalanche mode (≥10 kV/cm) or in streamer mode (~100kV/cm)
- ☐ gas with high ionisation density and high quenching efficiency
  e.g. 94.7% $C_2H_2F_4$ + 5% iC_4H_{10} + 0.3% SF_6

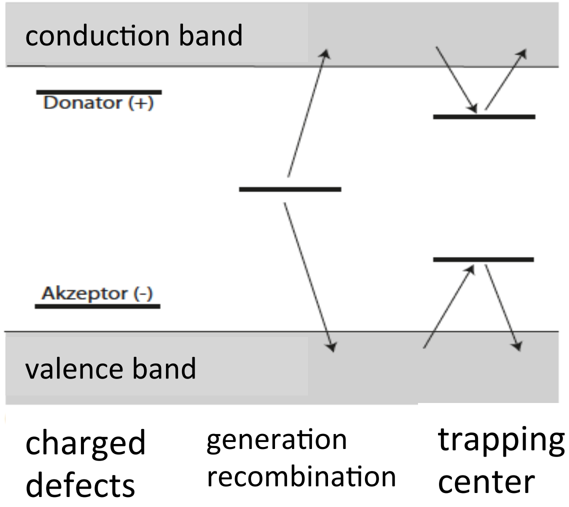
	Trigger RPC	**Timing RPC**
el. Feld	20-50 kV/cm	~100 kV/cm
op. mode	avalanche	streamer
signal	< 10pC	< 100pC
quench times	shorter	longer
σ_t	**1 ns**	**50 ps**
efficiency	98%	75%

… “special” at the LHC: the radiation environment





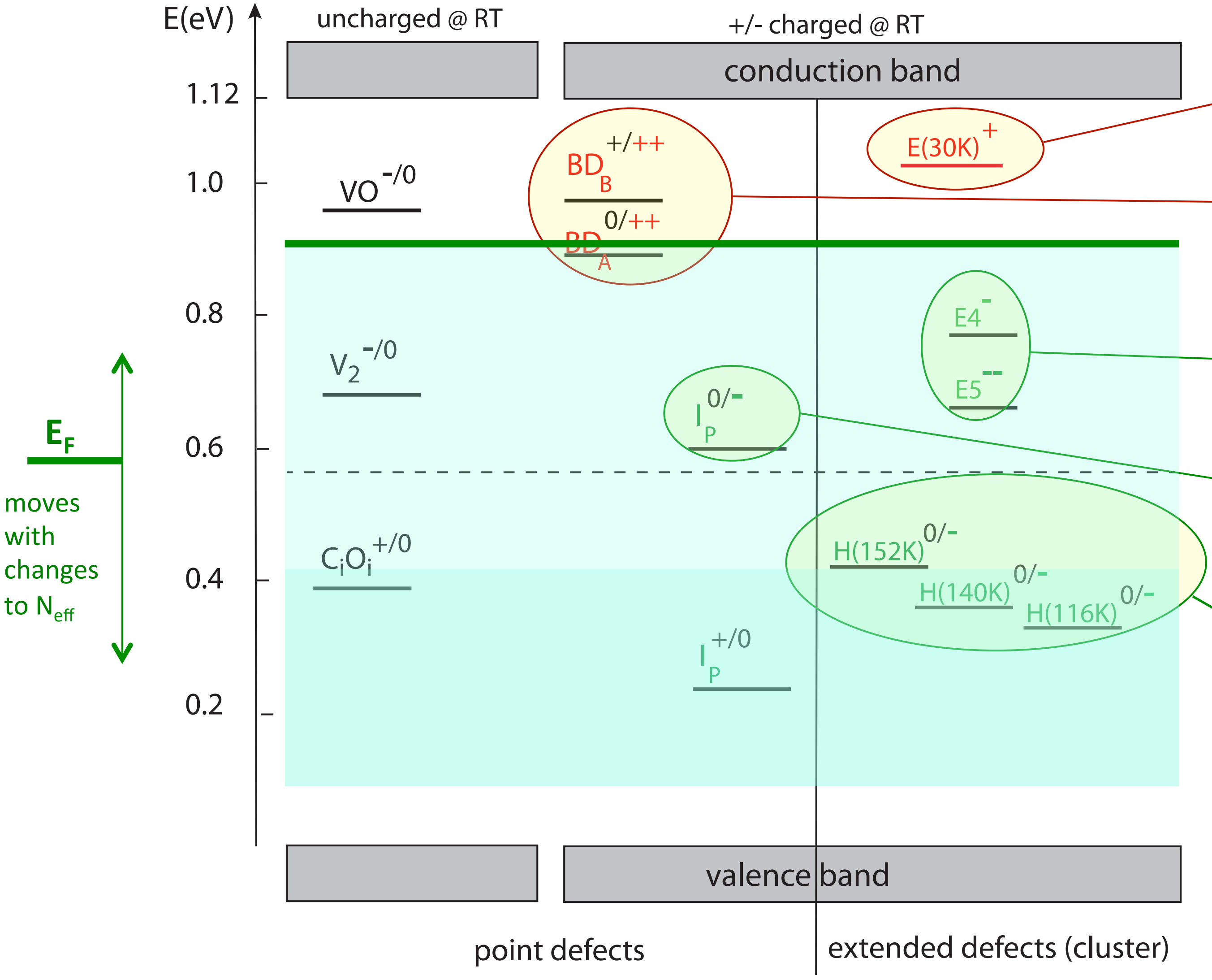




threshold energy to remove an atom:

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

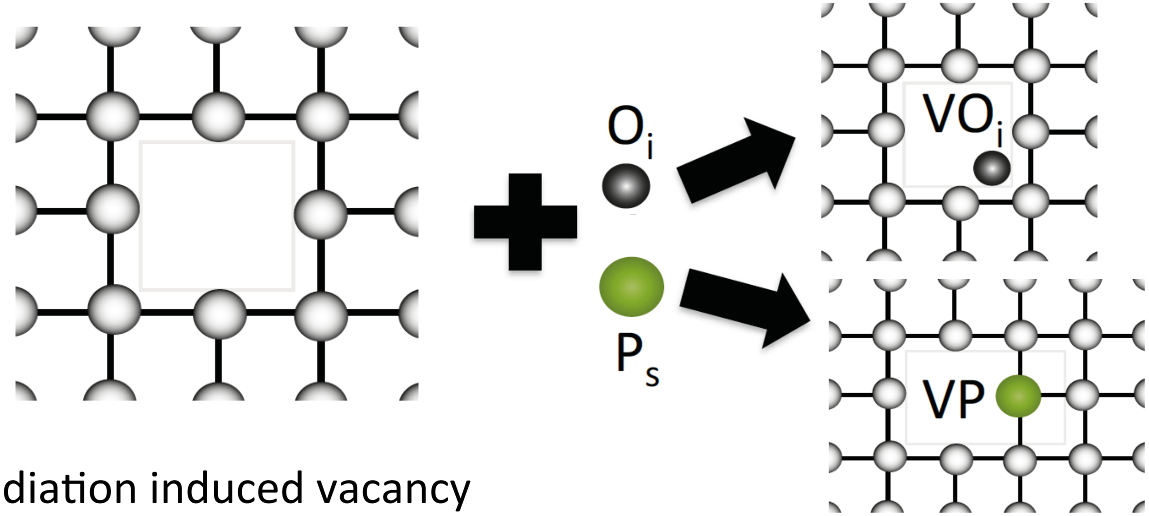
extended acceptor defects
produced equally by n,p
negative space charge
-> **reverse annealing**

- 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)

- 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}

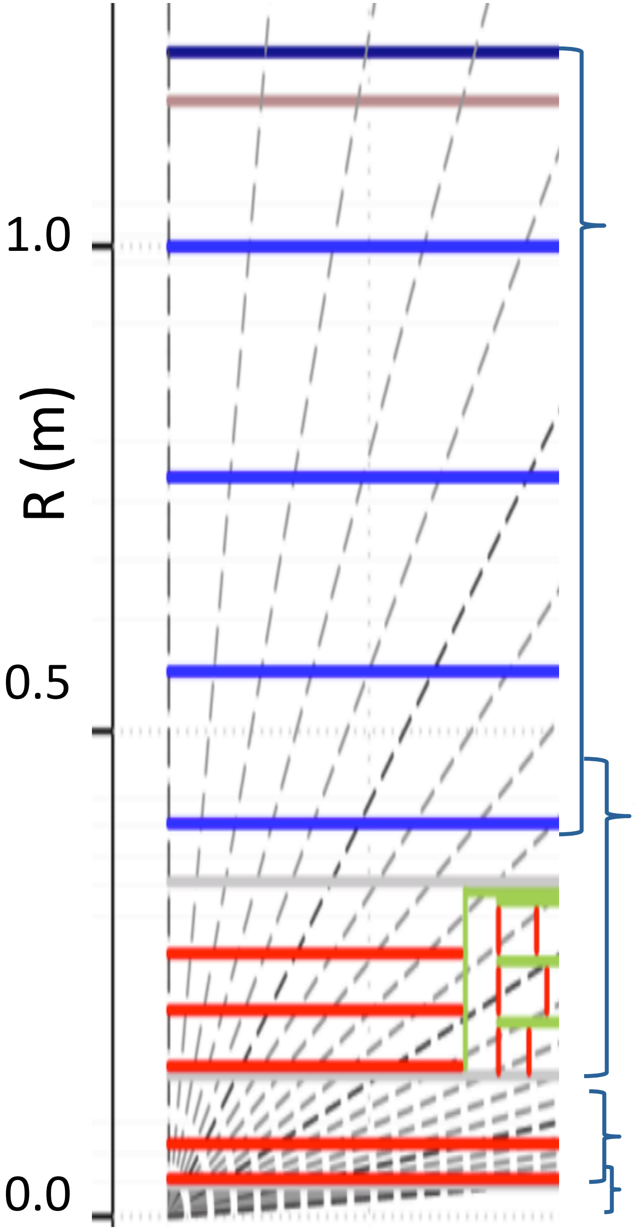
⇩

$[O] \gg [P]$

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 …

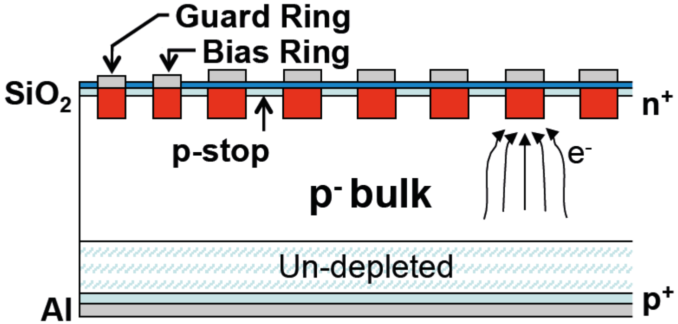


strips

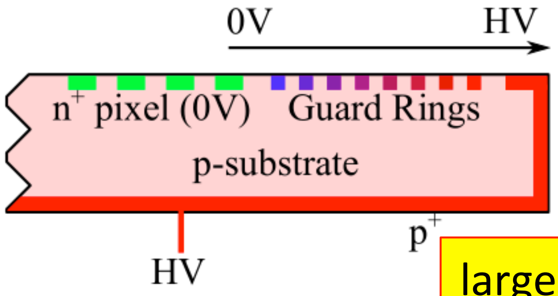
outer pixel

inner pixel

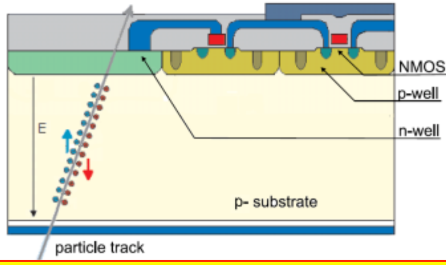
innermost pixel



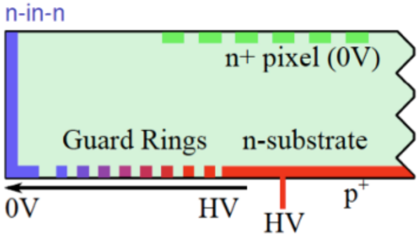
n^+ in p
strip modules

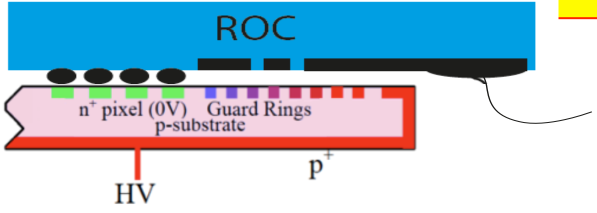


depl. CMOS pixels

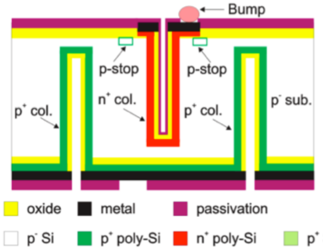


large modules
planar n^+ in n (or p) pixels / CMOS?





3D silicon



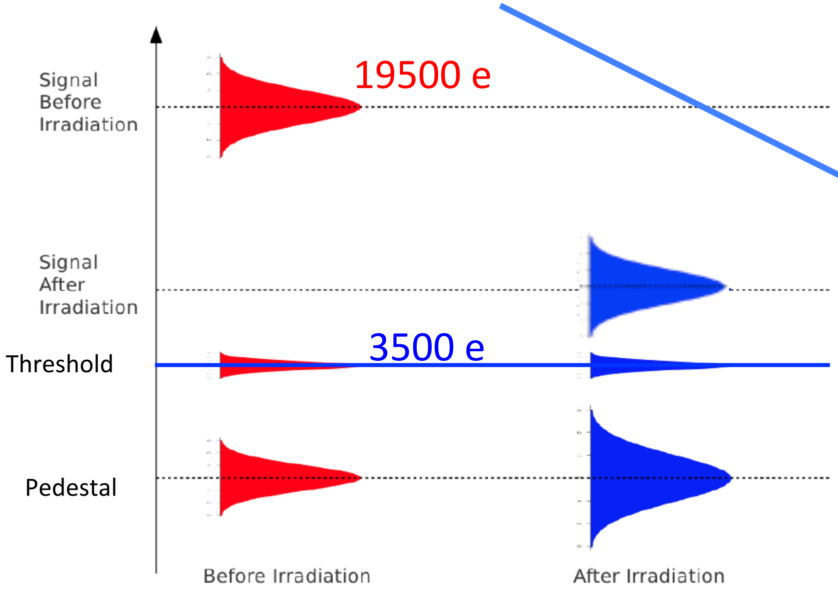
dedicated
rad.-hard
detectors

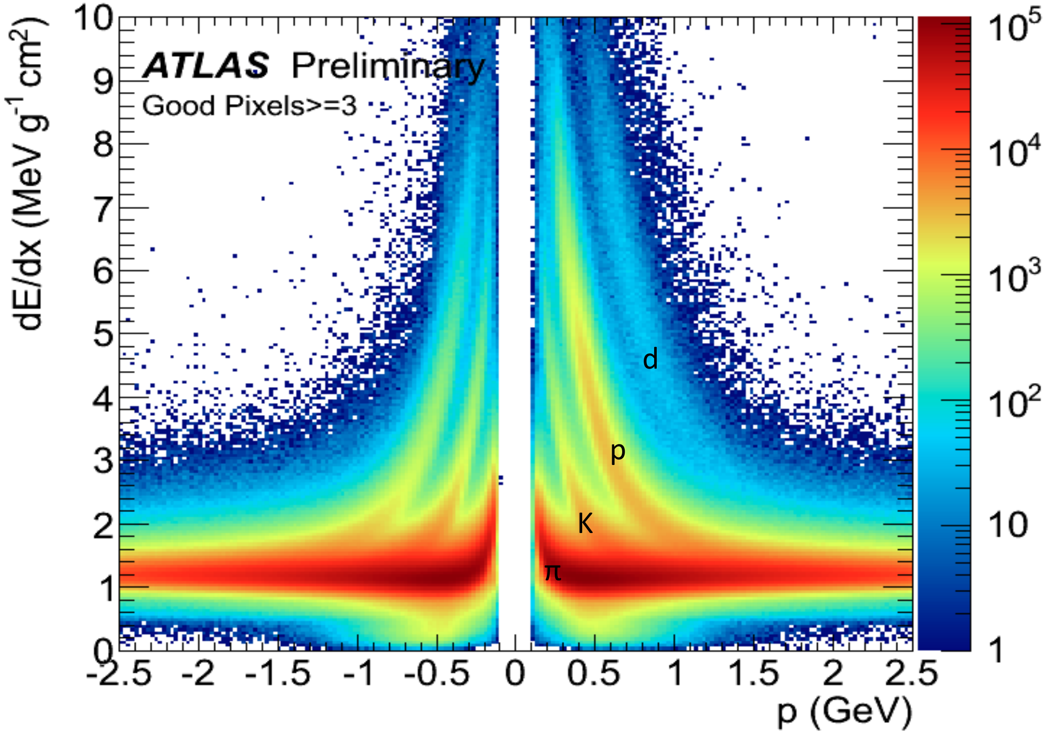
The typical S/N situation (... here ATLAS)

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



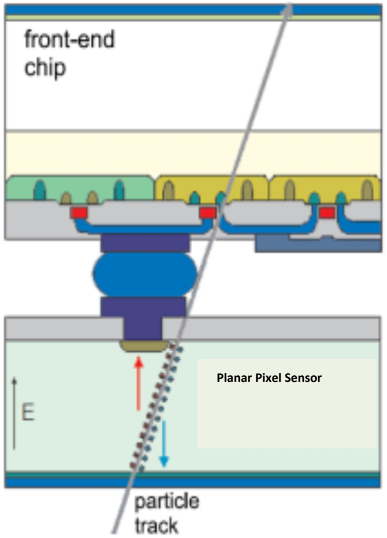


C. Gemme et al., ATLAS-CONF-2011-016

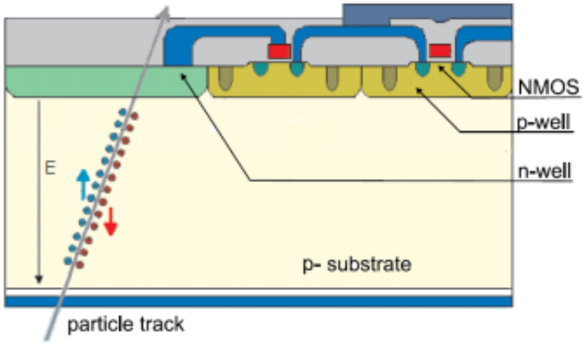
New Developments (Pixels)
... for LHC and others

Is there life after “hybrid pixels”? ... monolithic?

Hybrid Pixels

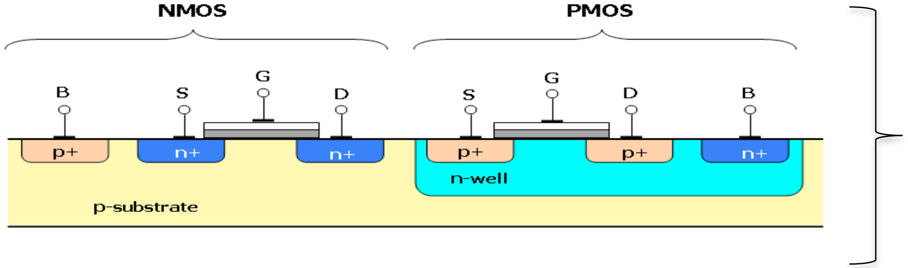


Depleted (fully) Monolithic Active Pixel Sensors (DMAPS)



(commercial CMOS Technology)

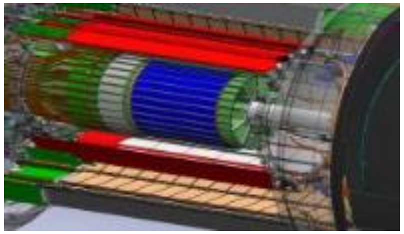
Peric et al., NIM A582 (2007) 876-885 & NIM A765 (2014) 172-176
Mattiazzo, Snoeys et al., NIM A718 (2013) 288-291
Havranek, Hemperek, Krüger, NW et al. JINST 10 (2015) 02, P02013



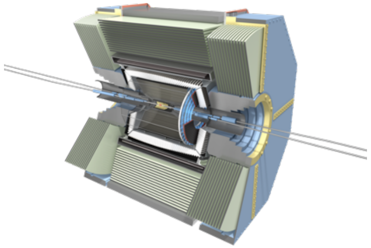
CMOS

Rate and Radiation Levels

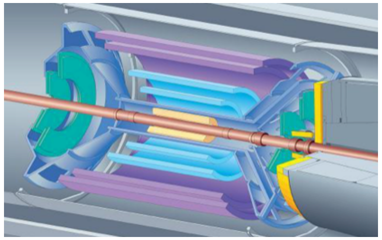
STAR



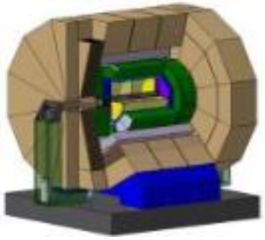
Belle II



ALICE-(HL)-LHC

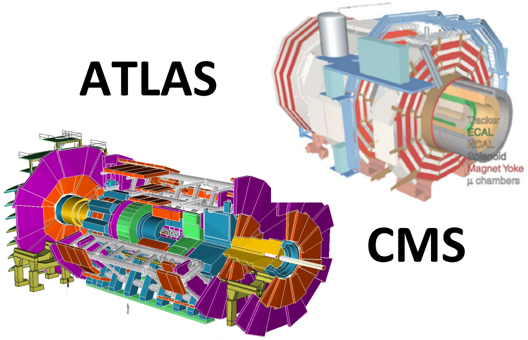


ILC



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

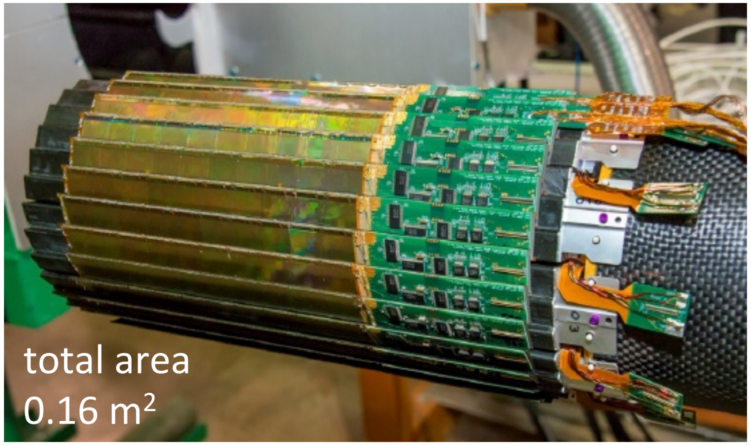
state of the art
- large area strips
- hybrid pixels

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

(Semi)-Monolithic Pixel Detectors

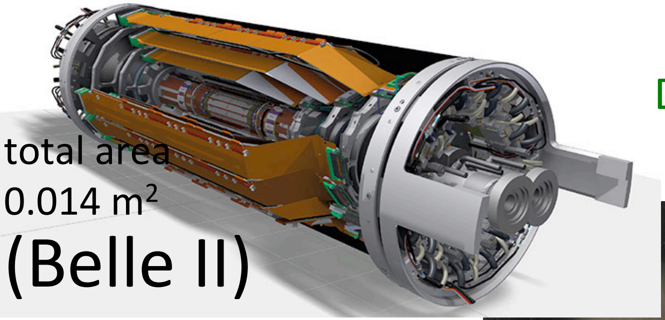
STAR / RHIC

MAPS



total area
0.16 m^2

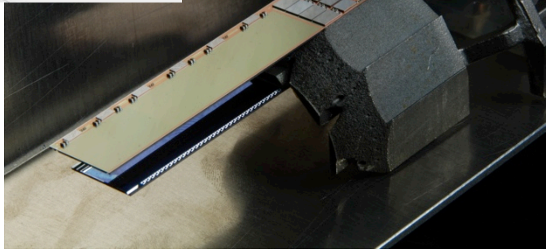
operated 2014-2015



total area
0.014 m^2

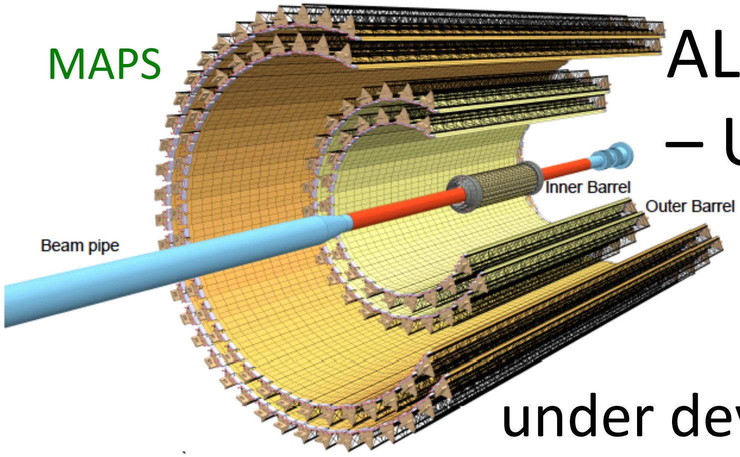
(Belle II)

DEPFET pixels



in production
for 2017

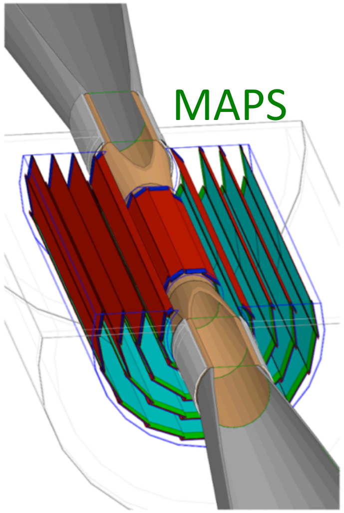
MAPS



ALICE
– Upgrade

total area
~10 m^2

under development
target: 2018



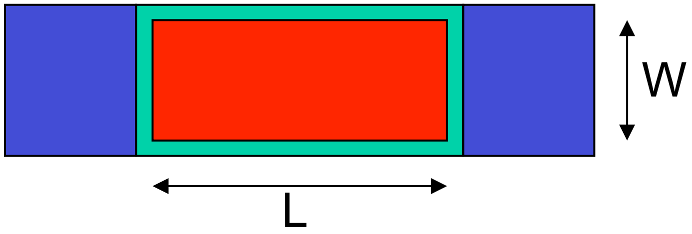
MAPS

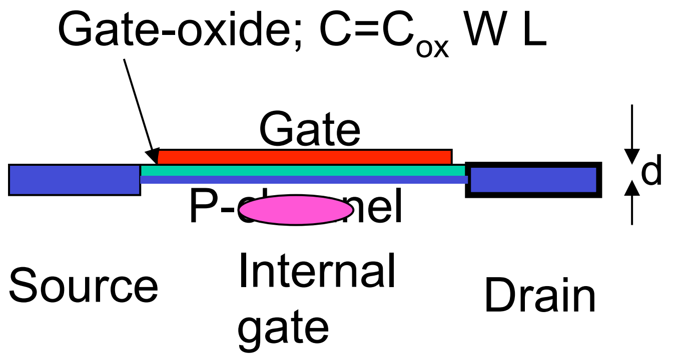
ILC

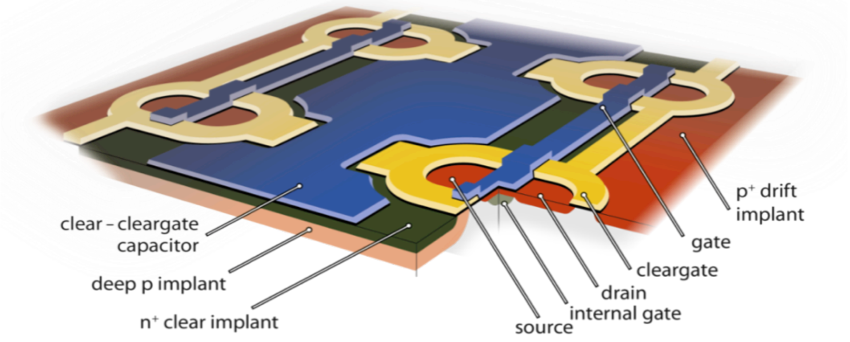
total area
? m^2

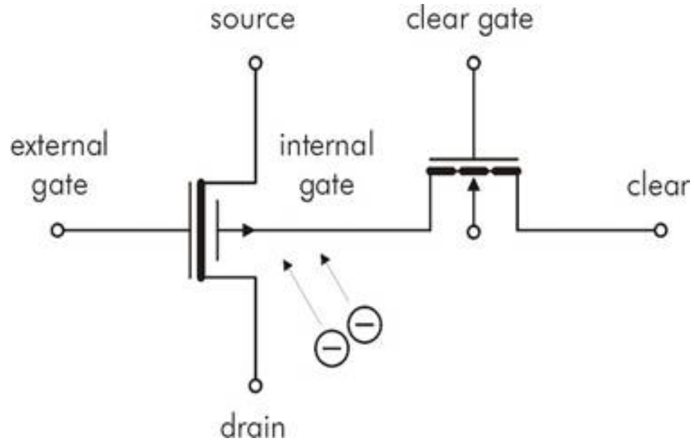
current
baseline

How does a DEPFET work?









A charge **q** in the internal gate is – via the capacitance to the channel – a voltage which “steers” the channel current I_d together with the external gate voltage, which hence effectively changes by: $\Delta V = \alpha\, q / (C_{ox}\, W\, L)$.
$\alpha < 1$ due to stray capacitances

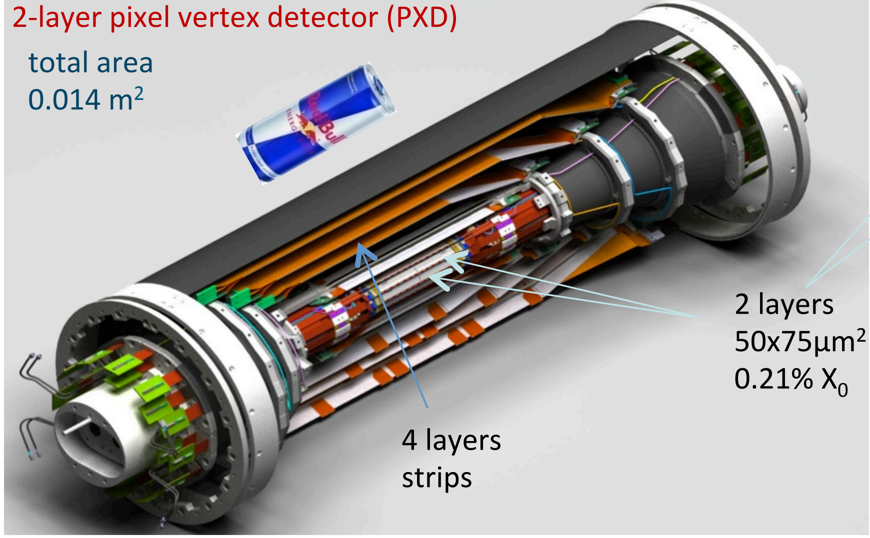
q

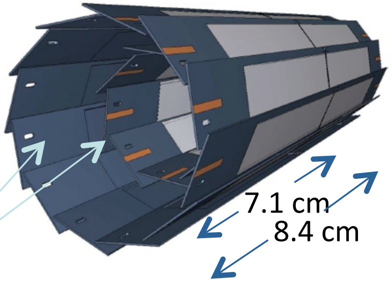
features:

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

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

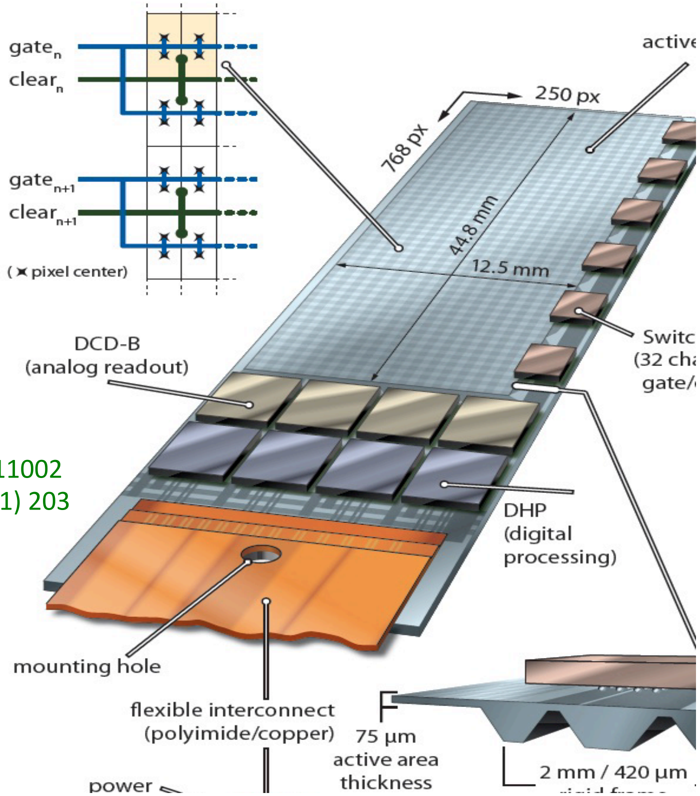
BELLE II DEPFET Pixel Detector

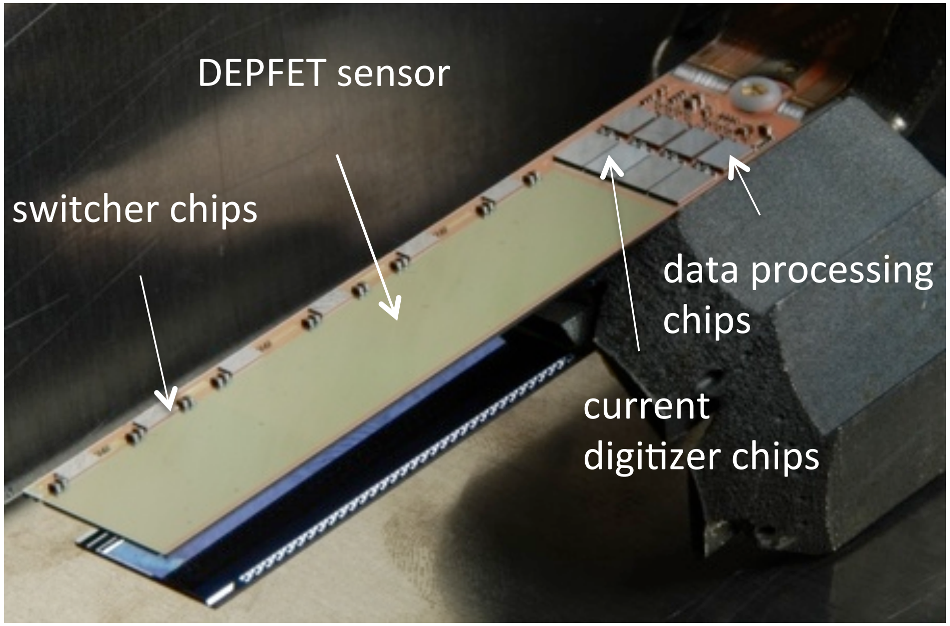


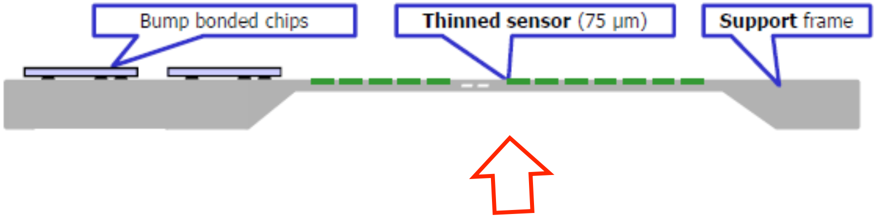


2 layers
50x75µm² pixels
0.21% X_0

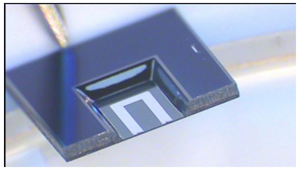
C. Marinas et al., JINST 10 (2015) 11, C11002
C. Kiesling et al., PoS EPS-HEP2011 (2011) 203







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

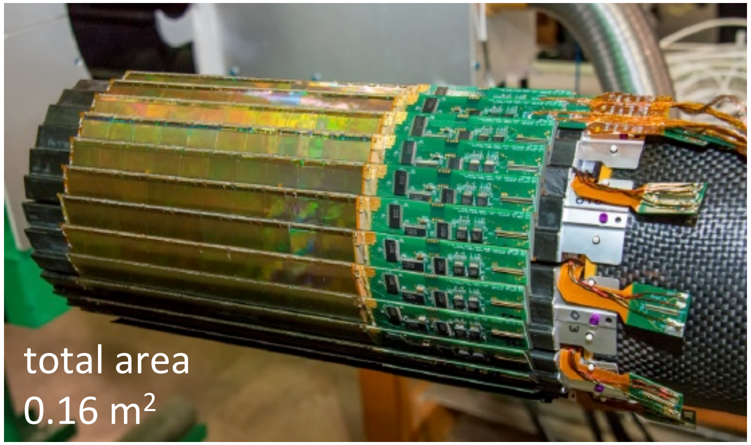


N. Wermes, SSI 2016, Tracking Detectors

(Semi)-Monolithic Pixel Detectors

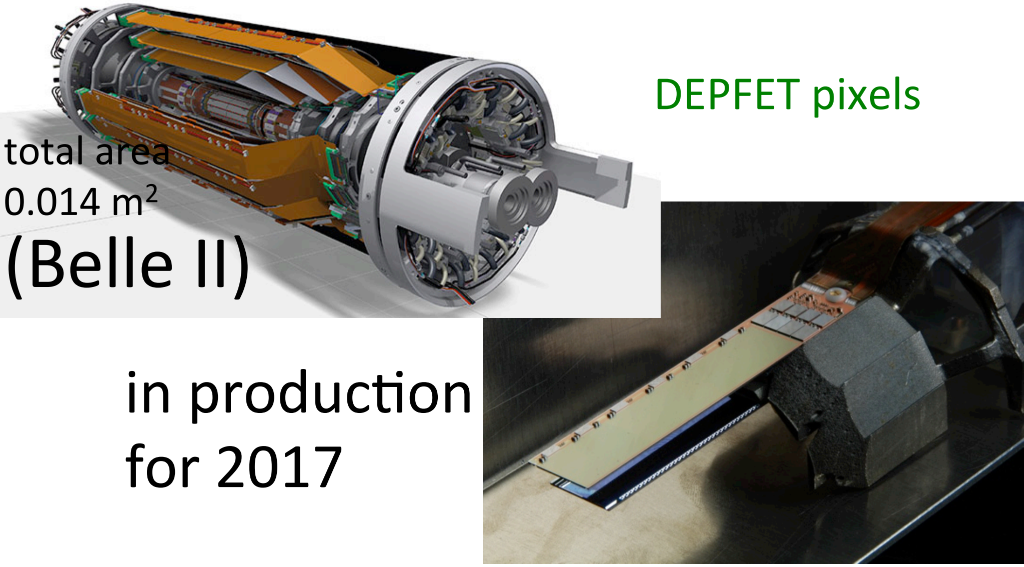
STAR / RHIC

MAPS



total area
0.16 m^2

operated 2014-2015



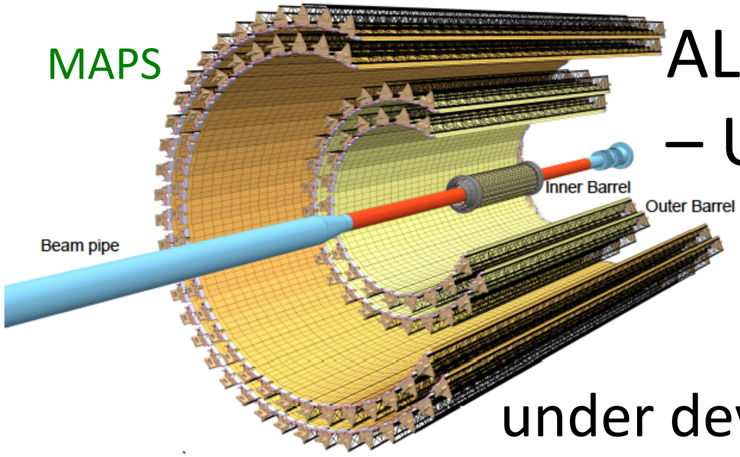
total area
0.014 m^2

(Belle II)

DEPFET pixels

in production
for 2017

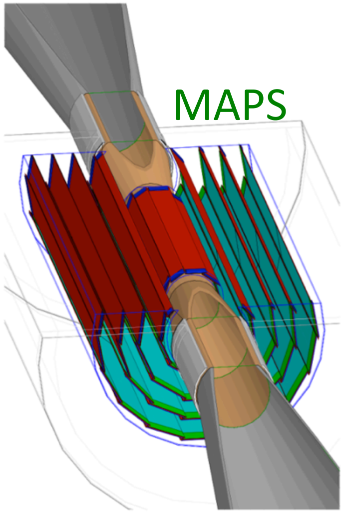
MAPS



ALICE
– Upgrade

total area
~10 m^2

under development
target: 2018



MAPS

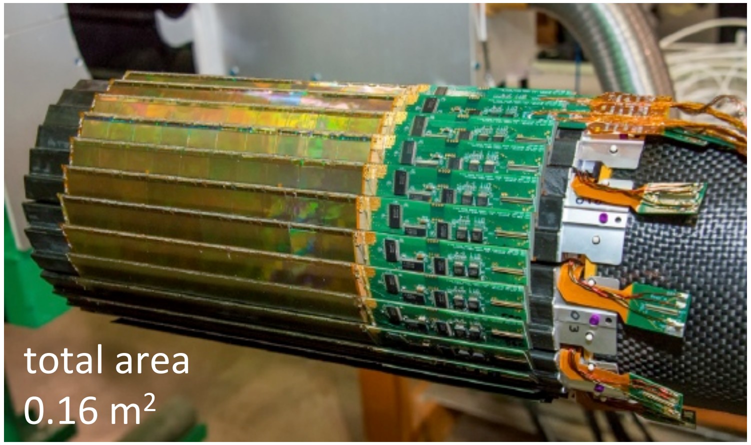
ILC

total area
? m^2

current
baseline

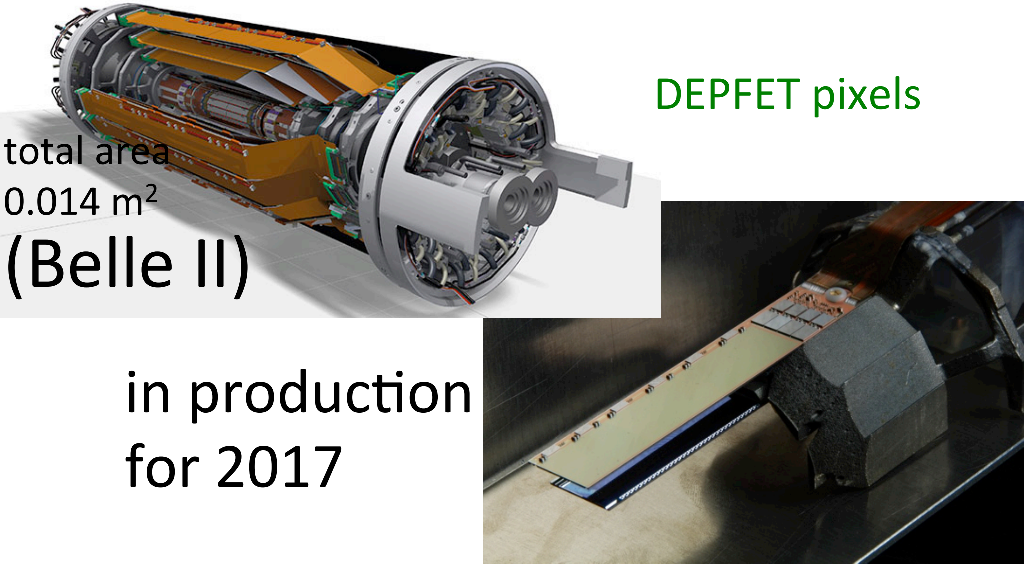
(Semi)-Monolithic Pixel Detectors

STAR / RHIC MAPS



total area 0.16 m^2

operated 2014-2015

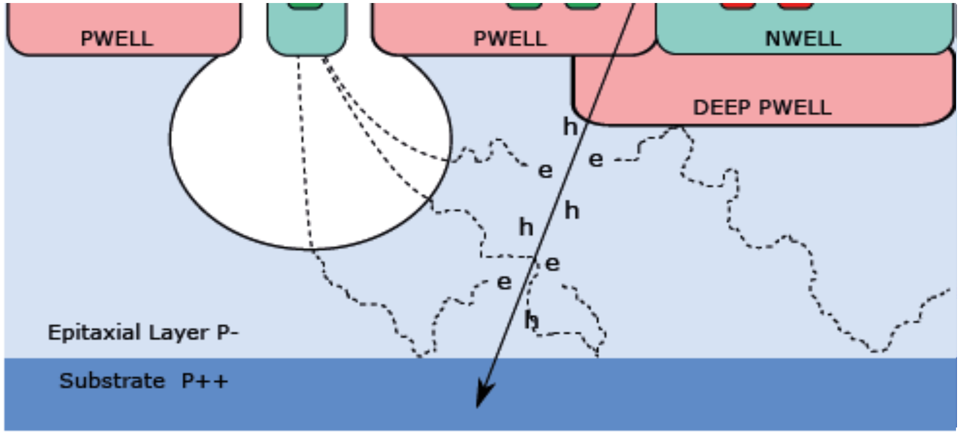


DEPFET pixels

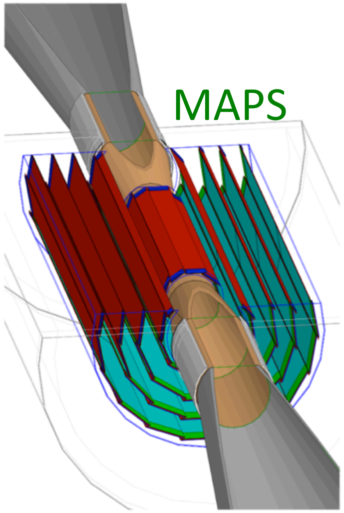
total area 0.014 m^2

(Belle II)

in production for 2017



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



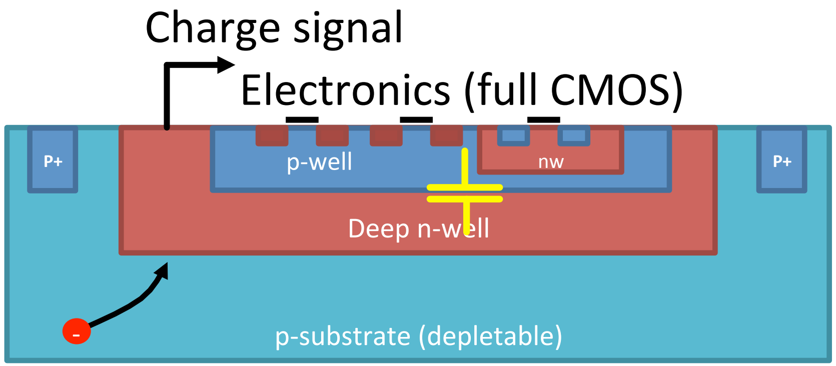
ILC

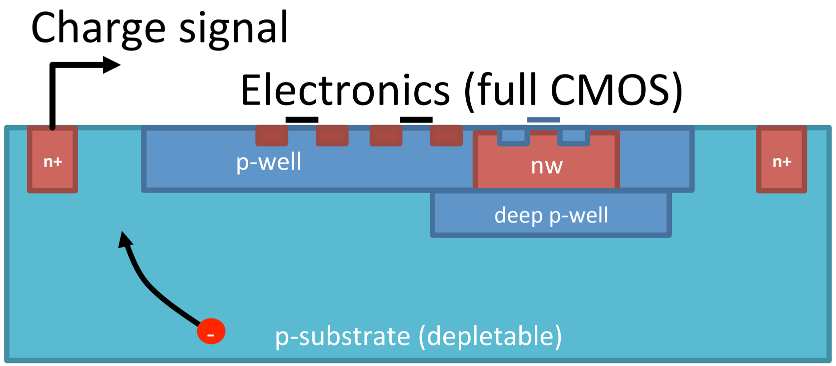
total area ? m^2

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 ??

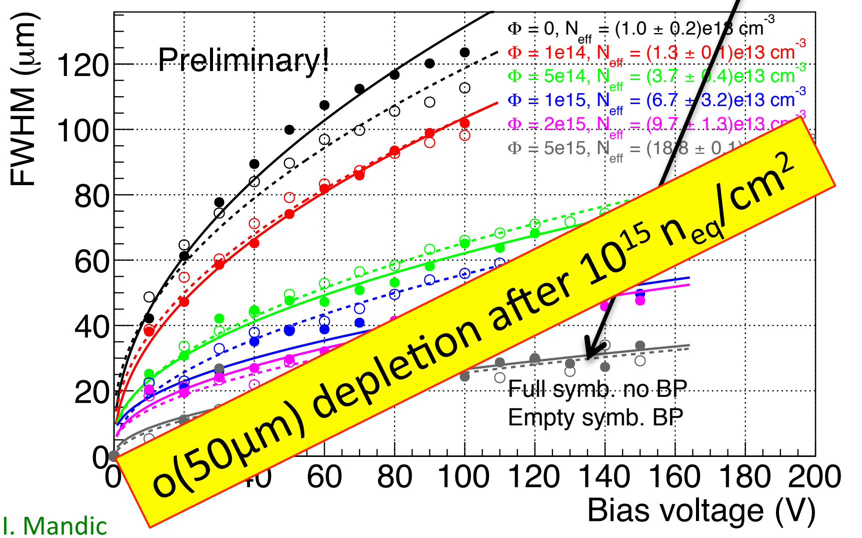
Goal-1 ... S/N ≈ 20, i.e. N ≲ 200e$^-$ => S = 4000e$^-$ (≙50µm)

universitätbonn

• radiation hardness

LFoundry

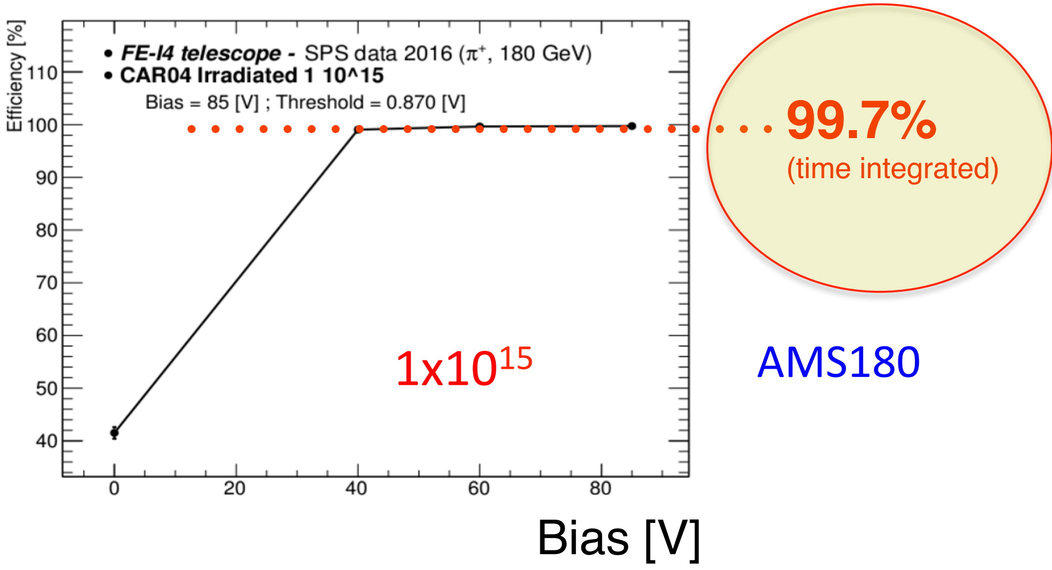
edge-TCT measurements



o(50µm) depletion after 10^{15} n_{eq}/cm^2

I. Mandic

• efficiency



99.7%
(time integrated)

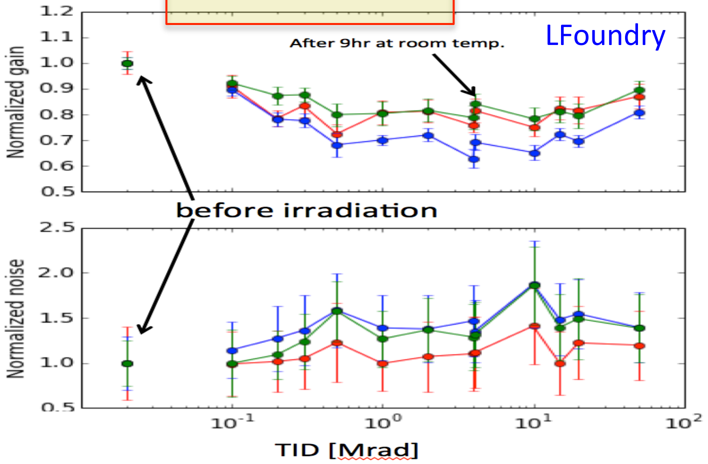
$1x10^{15}$

AMS180

TID 100 Mrad

gain

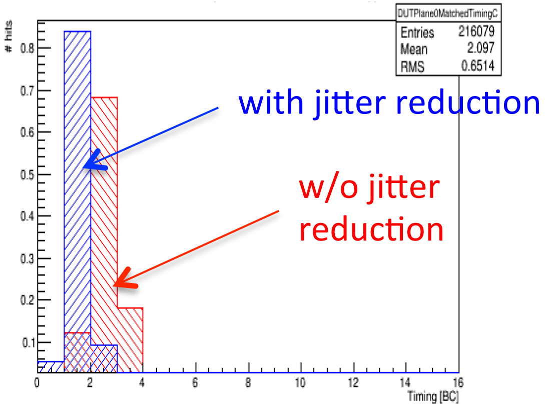
noise



N. Werme

• timing

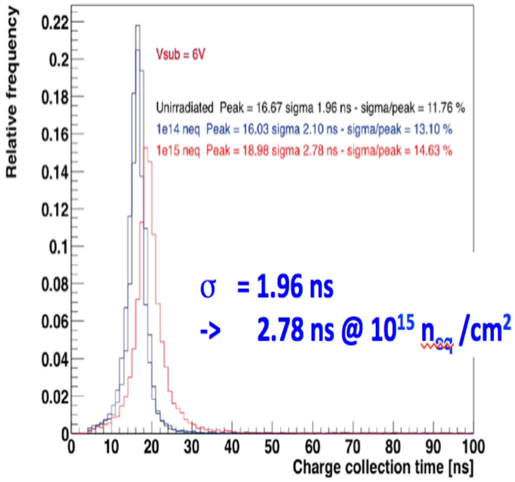
AMS180 after 1 x 10^{15} n_{eq}/cm^2



with jitter reduction

w/o jitter reduction

TowerJazz (small fill factor)



σ = 1.96 ns

-> 2.78 ns @ 10^{15} n_{eq} /cm^2

4D with LGADs?

Low Gain Avalanche Detectors

30 ps timing precision?

New: How to obtain fast timing with Si detectors?

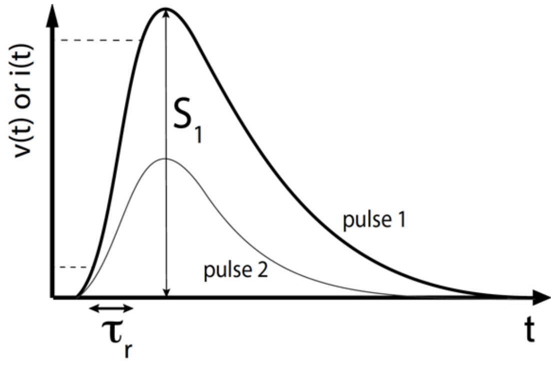
- ☐ 10 - 30 ps with (structured) Si detectors ??
- ☐ => exploit “in-silicon” charge amplification
  - in “Geiger Mode” fashion (like in gas **RPCs**) → σ_t governed by avalanche fluctuations

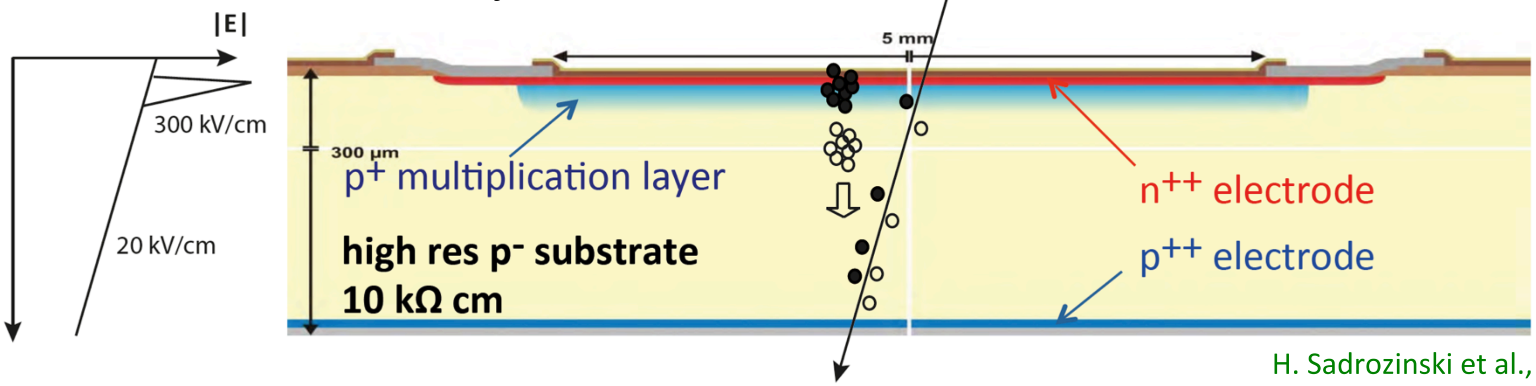
OR .... in “linear mode” fashion (lower E-fields, lower shot noise, no dark counts)
-> Low Gain Avalanche Detectors

“slew rate”

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

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)

New: How to obtain fast timing with Si detectors?

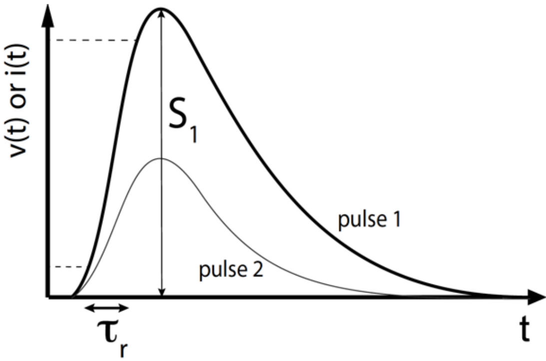
- ☐ 10 - 30 ps with (structured) Si detectors ??
- ☐ => exploit "in-silicon" charge amplification
  - in "Geiger Mode" fashion (like in gas **RPCs**) → σ_t governed by avalanche fluctuations

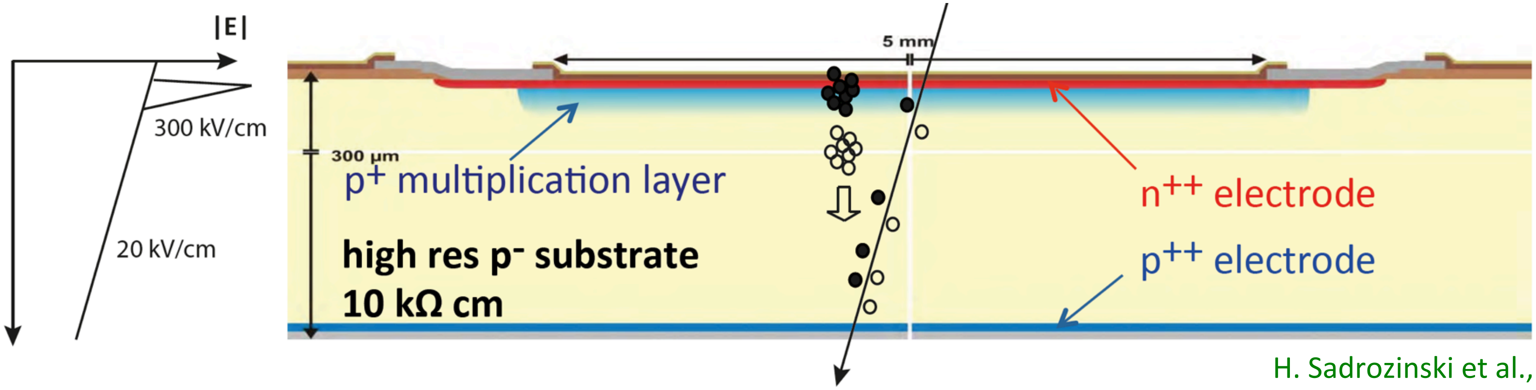
OR .... in "linear mode" fashion (lower E-fields, lower shot noise, no dark counts)
-> Low Gain Avalanche Detectors

"slew rate"

$$\sigma_t^2 = \underbrace{\left(\frac{V_{th}}{\boxed{dV/dt}}\bigg|_{rms}\right)^2}_{\sigma^2_{\text{time walk}}} + \underbrace{\left(\frac{\text{Noise}}{\boxed{dV/dt}}\right)^2}_{\sigma^2_{\text{noise}}} + \sigma^2_{\text{arrival}} + \sigma^2_{\text{dist}} + \sigma^2_{\text{TDC}}$$

TDC binning
can be made negligibl





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

H. Sadrozinski et al., NIM A730 (2013) 226-231
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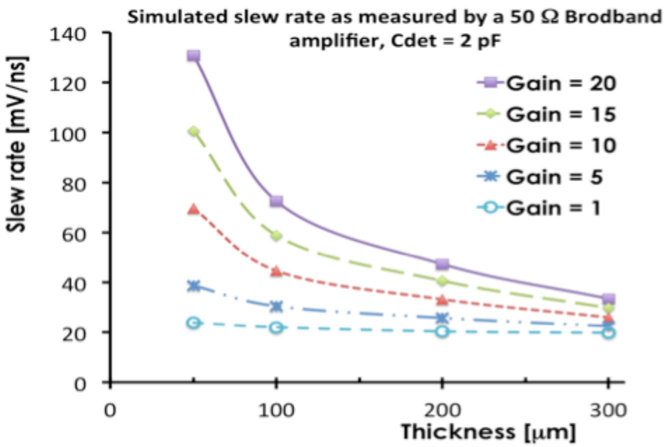
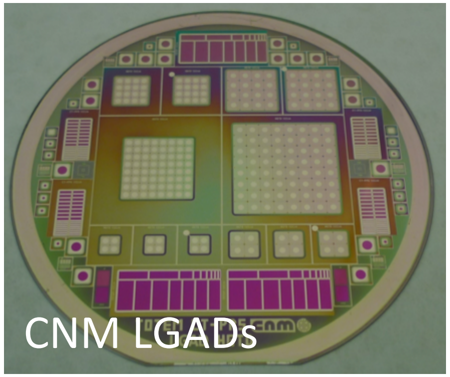
- ☐ Ultimate Goal: simultaneous space (~10µm) and time resolution (< 50 ps)
- ☐ Options for ATLAS (HighGranularityTimingDetector; Forward) -> pile-up killer and CMS-TOTEM (in Roman Pots)

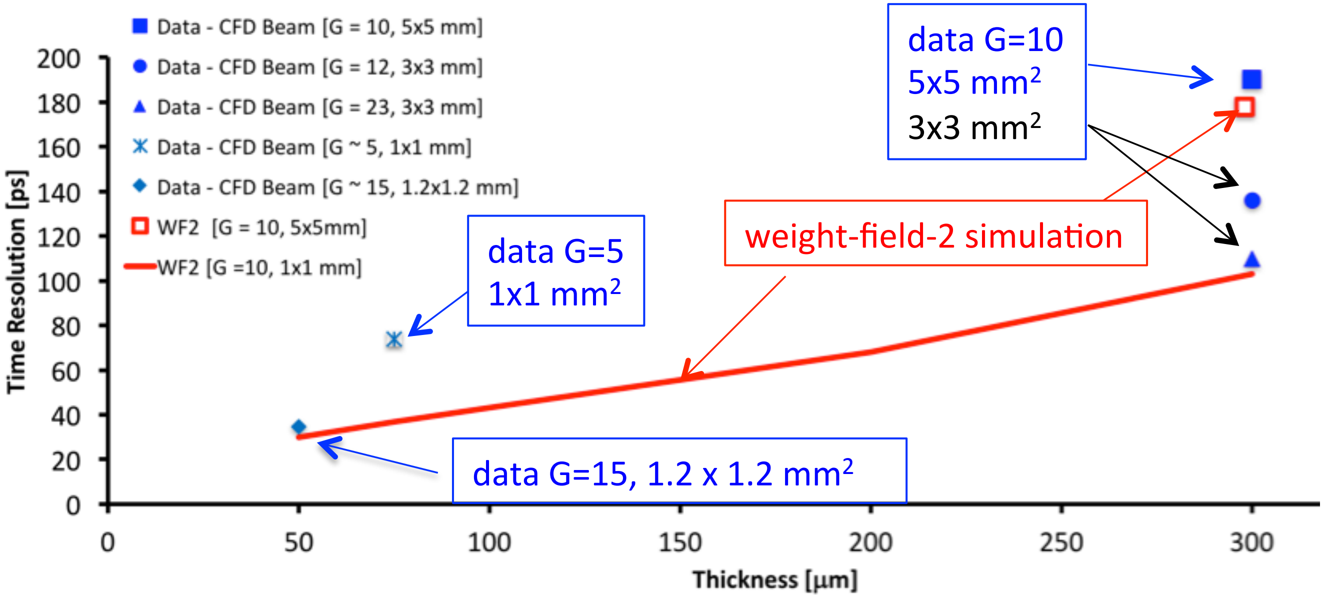
LGAD – starting with PAD detectors

- ☐ high voltage (800 - 1000 V)
  - high field -> fast e^-
- ☐ thin (50 µm)
  - higher field for given voltage
  - steeper signal
  - rad harder
  - smaller Landau spread
- ☐ gain ~10-20
  - lower E-fields
  - lower shot noise,
  - no/few dark counts





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



data G=10
5x5 mm^2
3x3 mm^2

data G=5
1x1 mm^2

weight-field-2 simulation

data G=15, 1.2 x 1.2 mm^2

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.

2016

Hermann Kolanoski
Norbert Wermes

Teilchendetektoren

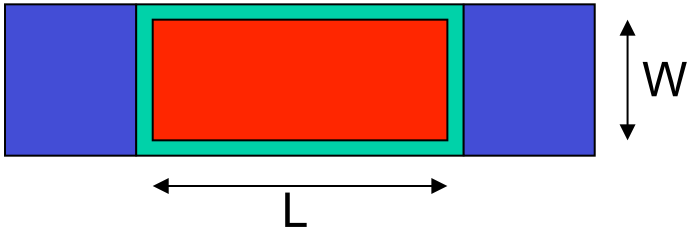
Grundlagen und Anwendungen

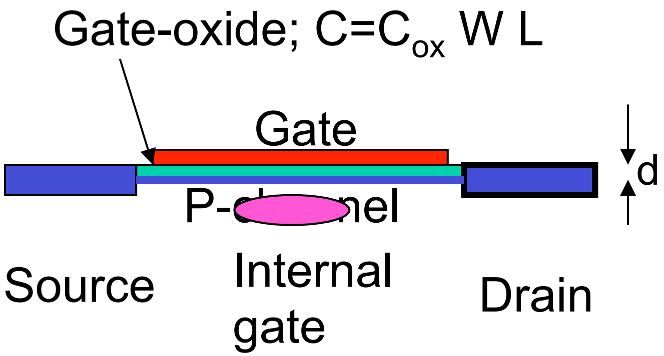
Springer Spektrum

BACKUP

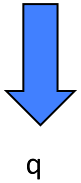
DEPFET

How does a DEPFET work?





A charge q in the internal gate induces a mirror charge αq in the channel (α <1 due to stray capacitance). This mirror charge is compensated by a change of the gate voltage: ΔV = α q / C = α q / (C$_{ox}$ W L) which in turn changes the transistor current I$_d$.



FET in saturation:

$$I_d = \frac{W}{2L}\mu C_{ox}\left(V_G + \frac{\alpha q_s}{C_{ox}WL} - V_{th}\right)^2$$

I_d: source-drain current
C_{ox}: sheet capacitance of gate oxide
W,L: Gate width and length
μ: mobility (p-channel: holes)
V_g: gate voltage
V_{th}: threshold voltage

Conversion factor:

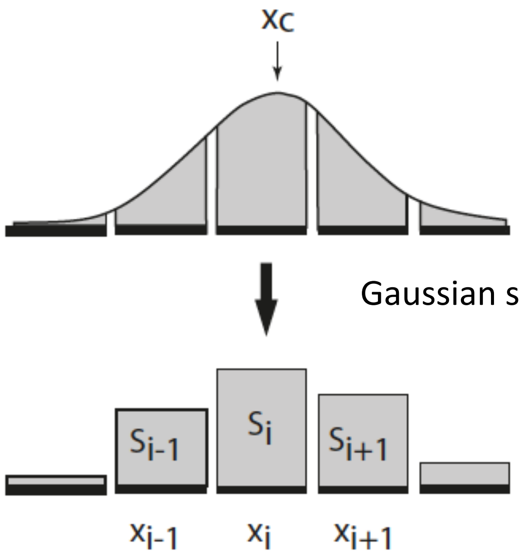
$$g_q = \frac{dI_d}{dq_s} = \frac{\alpha\mu}{L^2}\left(V_G + \frac{\alpha q_s}{C_{ox}WL} - V_{th}\right) = \alpha\sqrt{2\frac{I_d\mu}{L^3WC_{ox}}}$$

$$g_m \boxed{: g_q = \alpha\frac{g_m}{WLC_{ox}} = \alpha\frac{g_m}{C}}$$

Spatial Resolution

Spatial Resolution in segmented electrode configurations

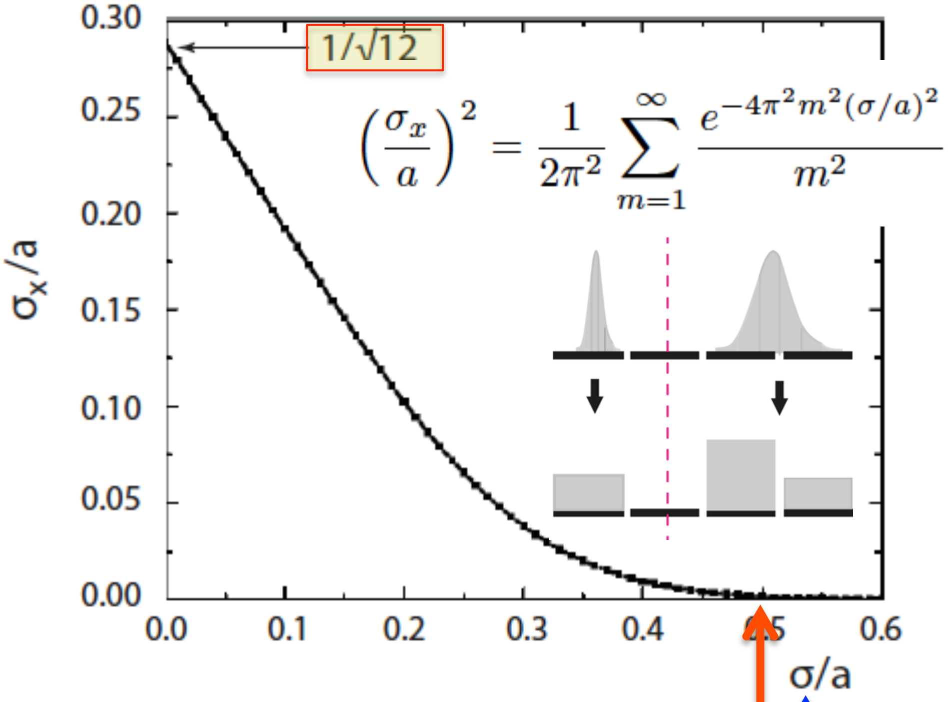
with analog information
and spread over more
than one electrode



Gaussian signal

center of gravity

$$\boxed{x_c = \frac{\sum S_i\, x_i}{\sum S_i}}$$



$$\left(\frac{\sigma_x}{a}\right)^2 = \frac{1}{2\pi^2}\sum_{m=1}^{\infty}\frac{e^{-4\pi^2 m^2 (\sigma/a)^2}}{m^2}$$

perfect resolution
but only w/o noise

width of charge cloud

$$x_{rec} = \frac{\sum (S_i + n_i)\, x_i}{\sum (S_i + n_i)} = \frac{x + \sum n_i x_i}{1 + \sum n_i} = \left(x + \sum n_i x_i\right)\left(1 - \sum n_i + \mathcal{O}(n_i^2)\right)$$

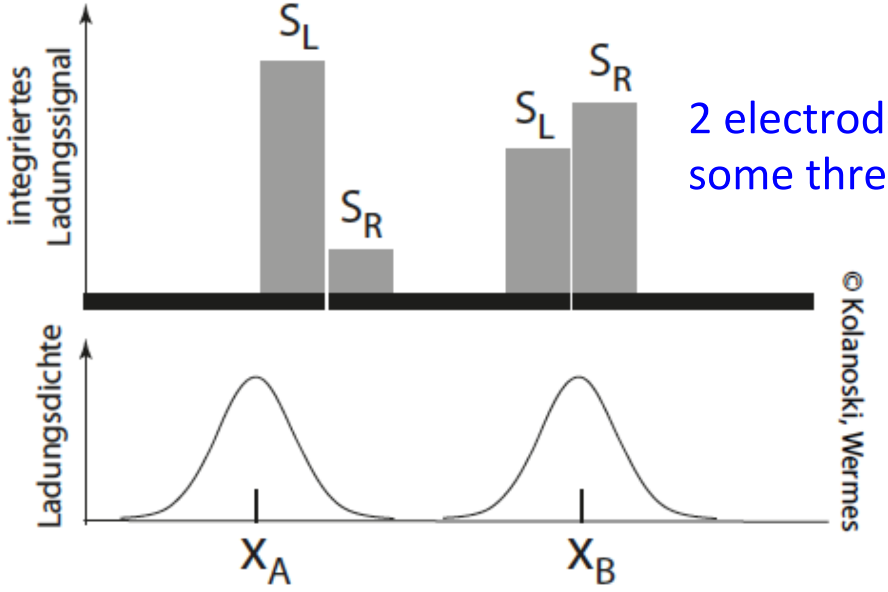
with uncorrelated noise
(normalized to signal)

$$\langle n_i^2 \rangle = \sigma_n^2, \quad \Rightarrow \boxed{\sigma_x^2 = \sigma_n^2 \left[\left(\sum_{i=1}^{N} x_i^2\right) + N\langle x^2 \rangle\right] + \mathcal{O}(\sigma_n^3)}$$

Arbitrary detector response ("data driven method")

typical for semiconductor detectors
and patterned gaseous detectors
channels have different gains

$N_{electrodes}$ = 2-3, S/N ~ 10



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2 electrodes have signal over some threshold

$$S_L(x) = Q\,\eta(x)$$

$$S_R(x) = Q - S_L(x) = Q\,(1 - \eta(x))$$

η = response function, indep. of Q
can be determined from signals themselves

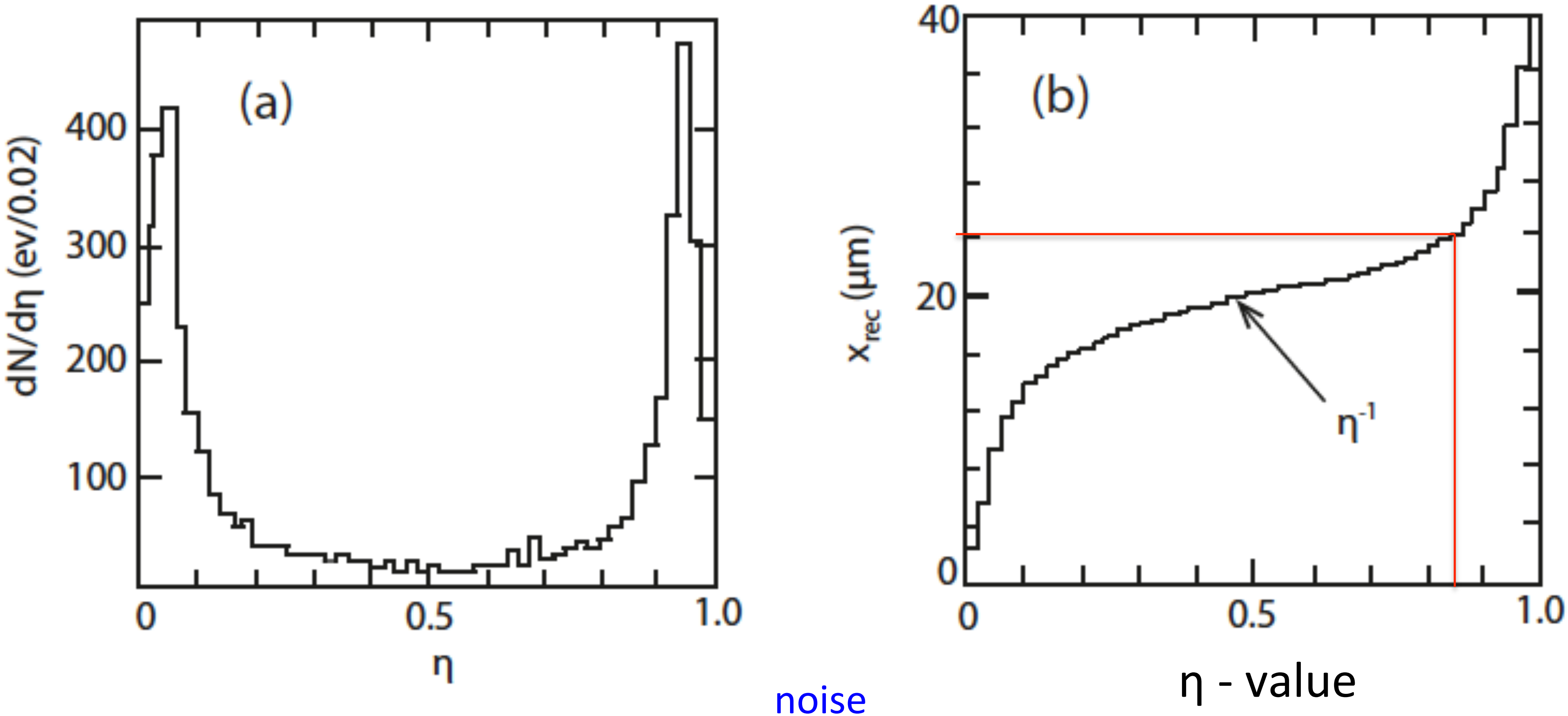
$$\boxed{\eta = \frac{S_L}{S_L + S_R}}$$

- assume a constant hit probability density
- => can build inverse of η-function (η -> x)
- pick best estimate of position from a measured distribution
- algorithm can also be extended to three – electrode situations

$$\boxed{x_{rec} = \eta^{-1}\left(\frac{S_L}{S_L + S_R}\right) = \frac{a}{N}\int_0^{\eta} \frac{dN}{d\eta'} d\eta'}$$

Arbitrary detector response

Belau, E. et al.: NIM 214 (1983) 253–260



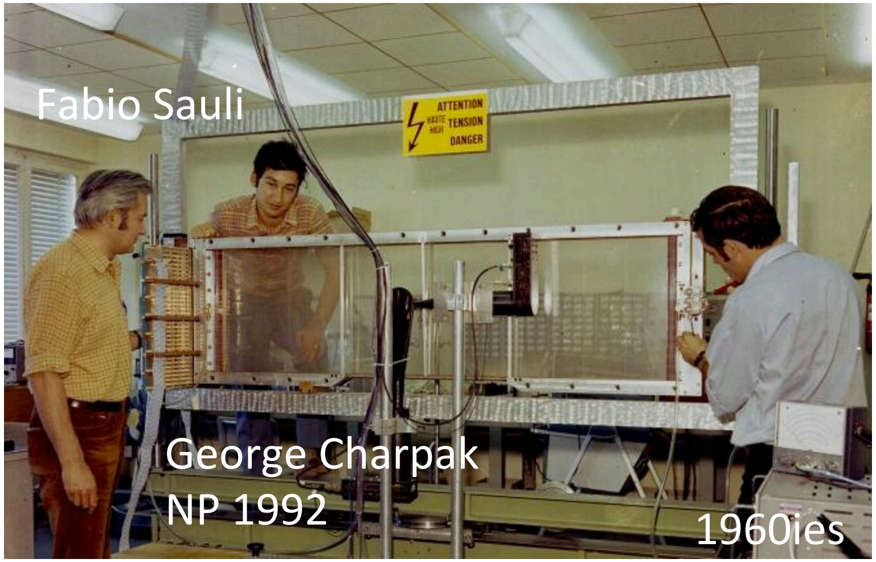
noise

resolution

$$\sigma_x^2 = 2\,\sigma_n^2 \left\langle \frac{\eta^2}{\eta'^{\,2}} \right\rangle$$

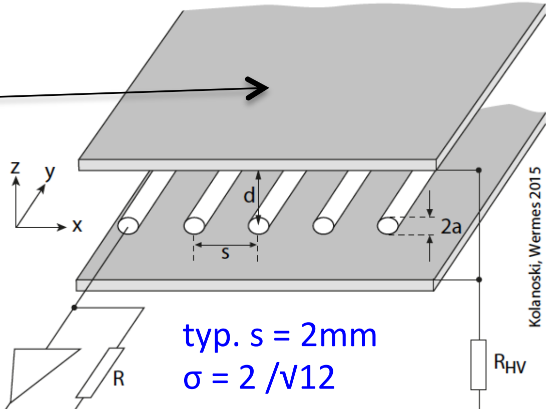
Gas-Filled Detectors

Multi Wire Proportional Chamber



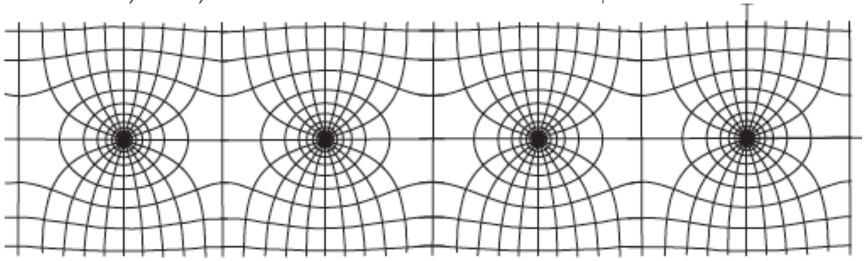
- mother of all wire chambers (1960ies)
- break through in tracking, because tracks became electronically recordable
- Nobel Prize 1992

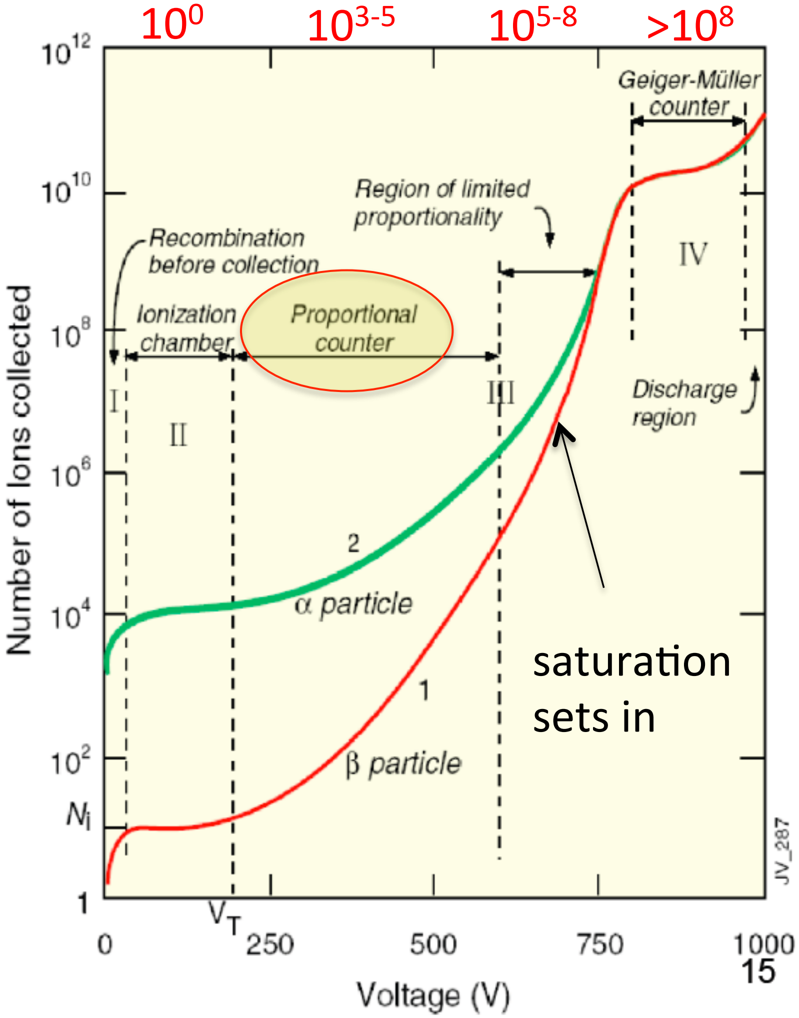
cathodes often patterned for 2nd coordinate



Kolanoski, Wermes 2015

typ. s = 2mm
σ = 2 /√12



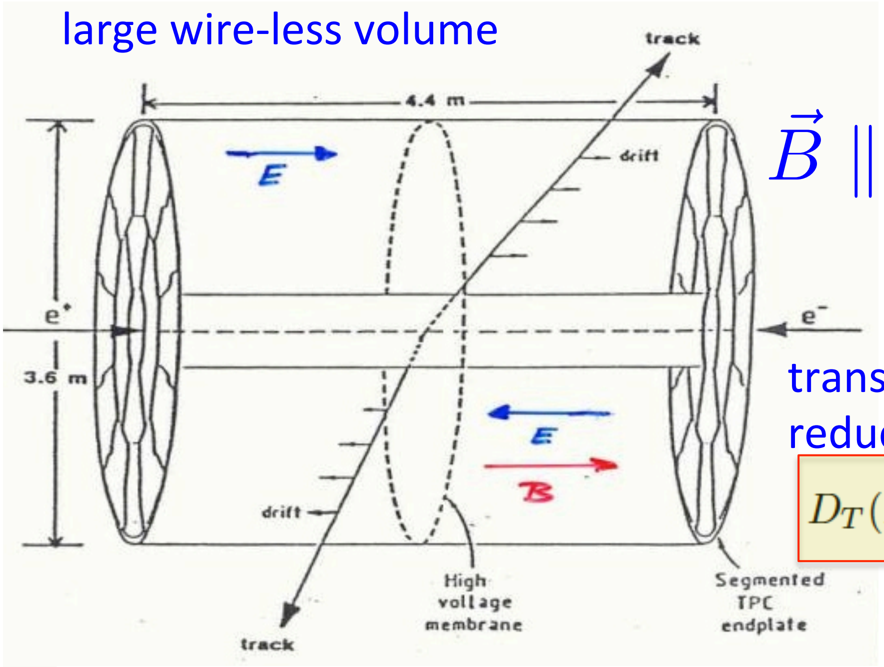


saturation sets in

Time Projection Chamber

invented by D. Nygren (1976)

large wire-less volume

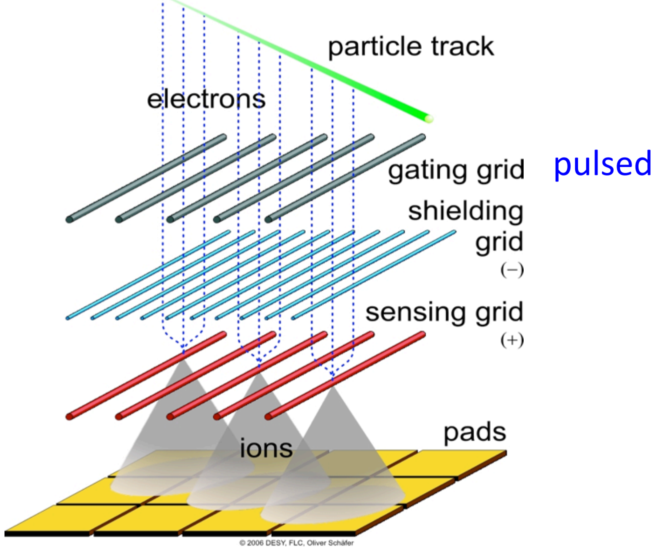


$\vec{B} \parallel \vec{E}$

transverse diffusion reduced

$$D_T(B) = \frac{D_T(0)}{1+\omega^2\tau^2}$$

long drift along , amplification at end of long drift

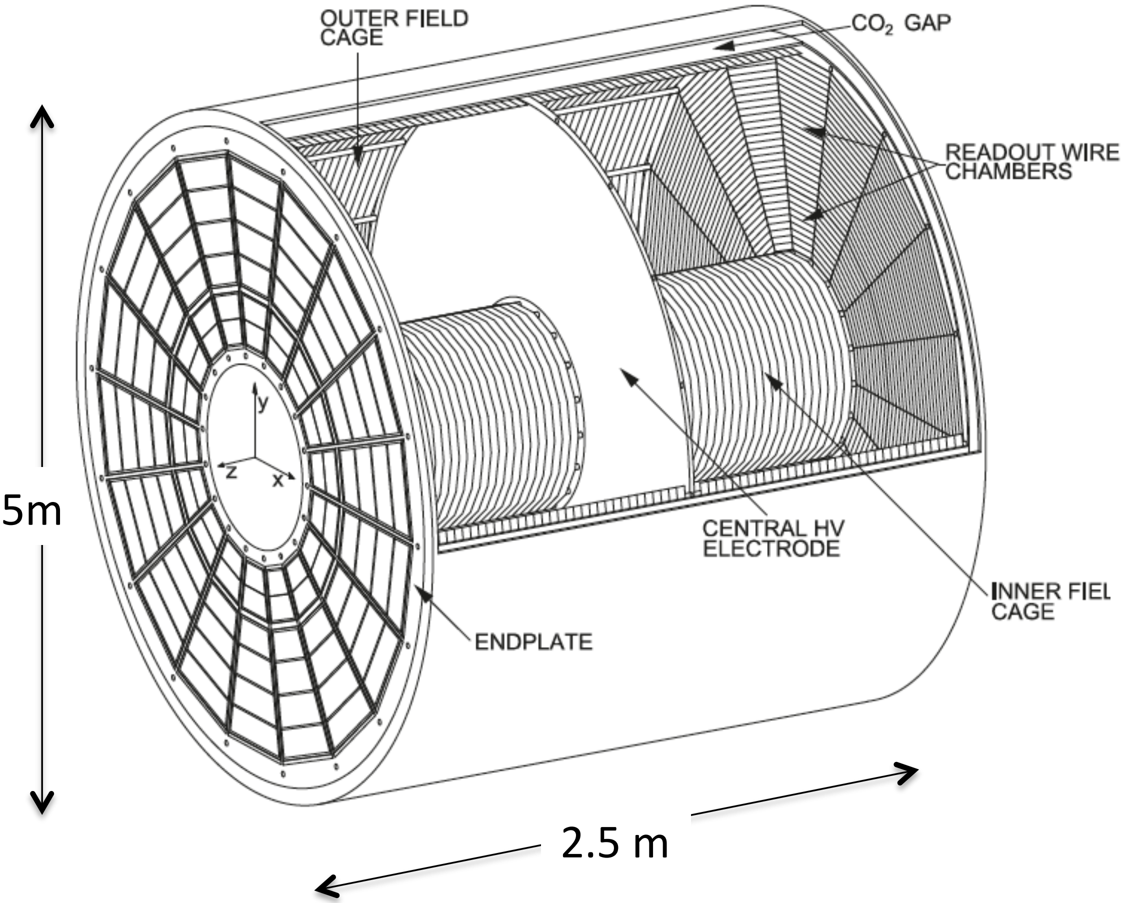


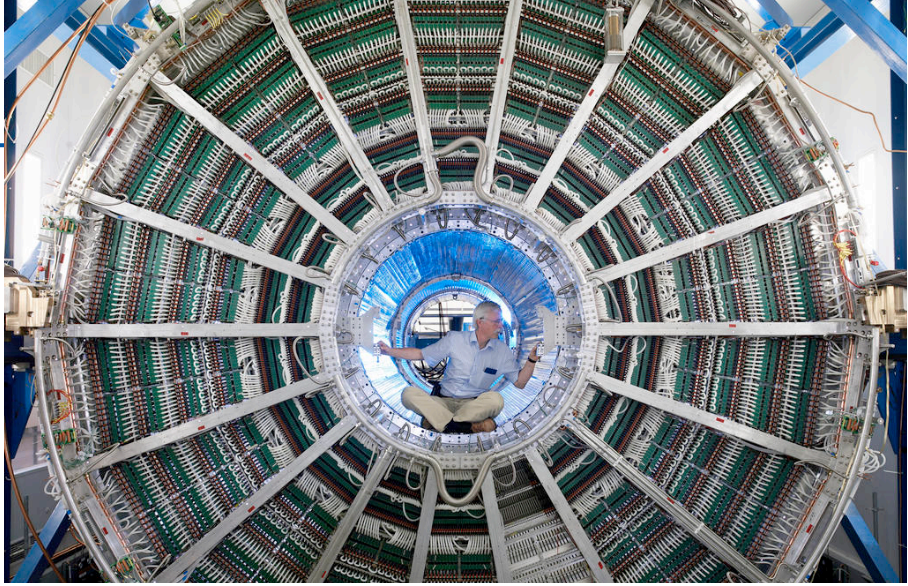
pulsed

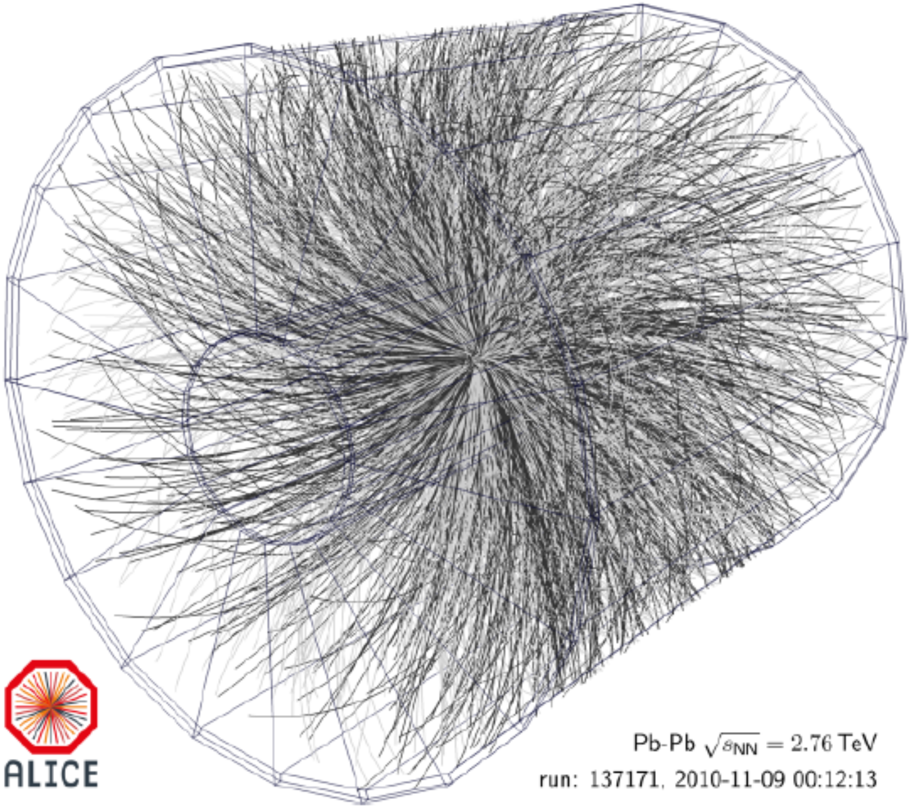
prevent ion-feedback by gating grid

- full 3-D reconstruction (voxels): xy from wire/pad geometry at the end flanges; z from drift time
- 3D track information recorded -> good momentum resolution
- also dE/dx measurement easy -> particle ID (not topic of this lecture)
- large field cage necessary
- typical resolutions: in rφ = 150-400 μm in z ≈ mm
- challenges
    - long drift time -> limited rate capability
    - large volume -> geometrical precision
    - large voltages -> potential discharges

ALICE TPC

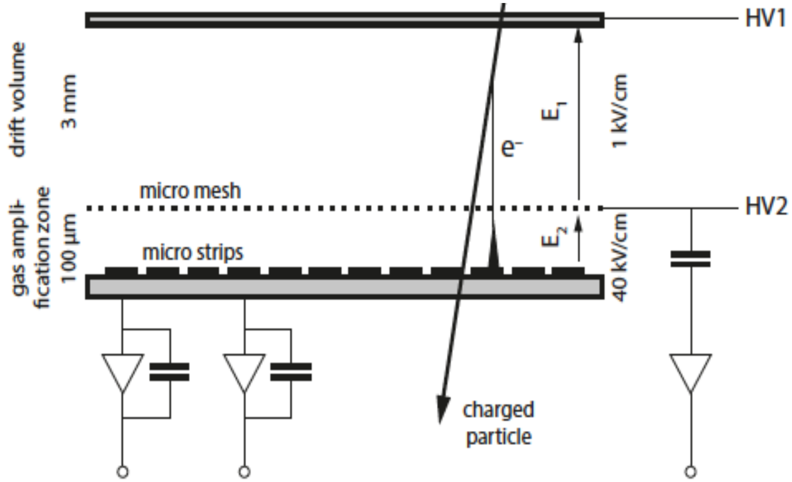


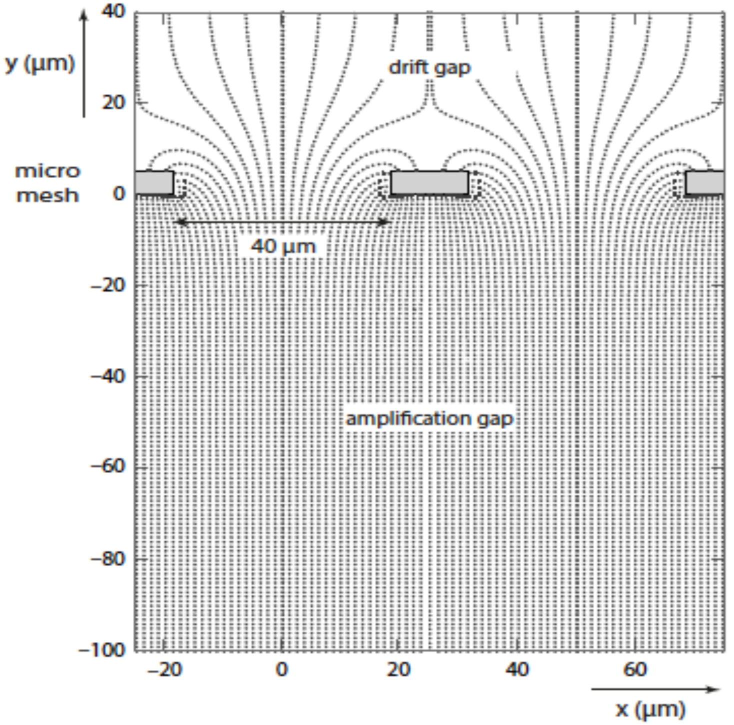




$$\sigma_{x,y,z} \approx 1\,mm^3$$

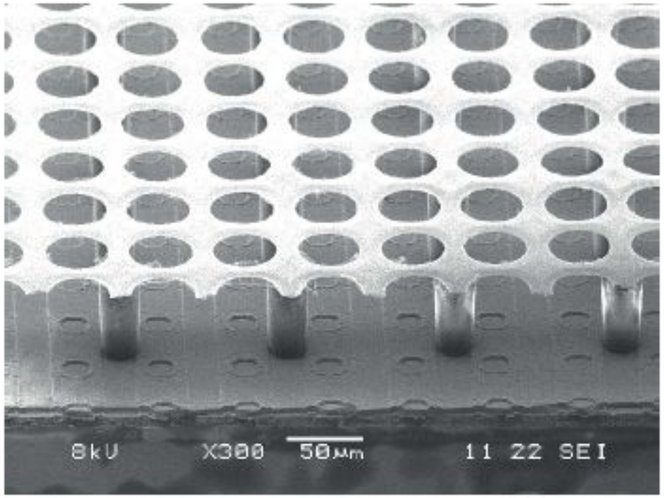
MICROMEGAS (MICRO MEsch GASeous Structure)





- ☐ separation of drift region and (short) amplification region by a micro grid
- ☐ R/O of induced charges by patterned electrode
- ☐ fast induced signals
- ☐ need precise grid alignment
- ☐ new development: INGRID structure obtained by “post processing” of grid directly on R/O chip

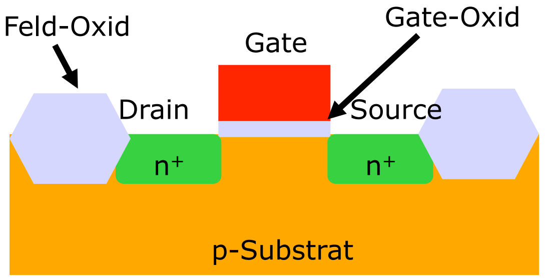
INGRID structure



Radiation Damage

Radiation damage to the FE-electronics … and cure

Effects: generation of positive charges in the SiO_2
and defects in Si - SiO_2 interface

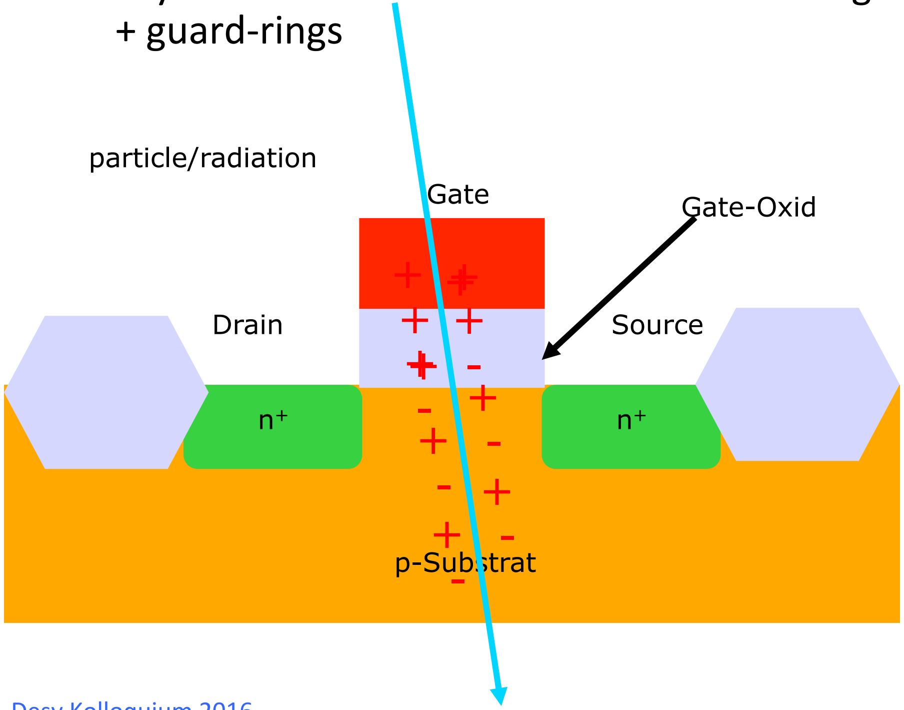


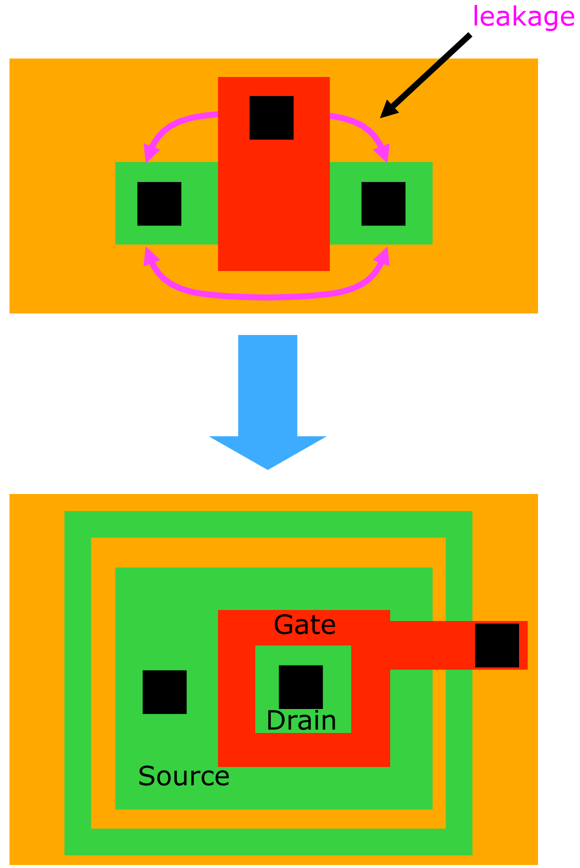
1. Threshold shifts of transistors

➔ Deep Submicron CMOS technologies with small structure sizes (≤ 350 nm) and thin gate oxides (d_{ox} < 5 nm) → holes tunnel out

2. Leakage currents under the field oxide

➔ Layout of annular transistors with annular gate-electrodes + guard-rings

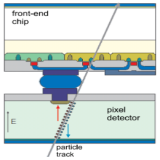




Else

Can one do better than “hybrid”?

Hybrid Pixel Detectors



☐ **PROs**

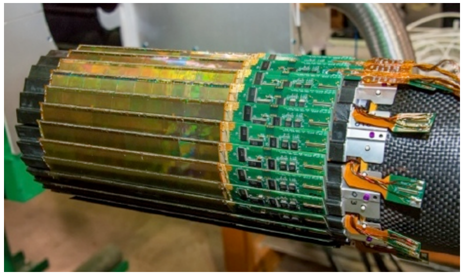
- complex signal processing already in pixel cells possible
- zero suppression
- temporary storage of hits during L1 latency
- radiation hard to >10^{15} n_{eq}/cm^2
- high rate capability (~MHz/mm^2)
- spatial resolution ~ 10 – 15 µm

☐ **CONs**

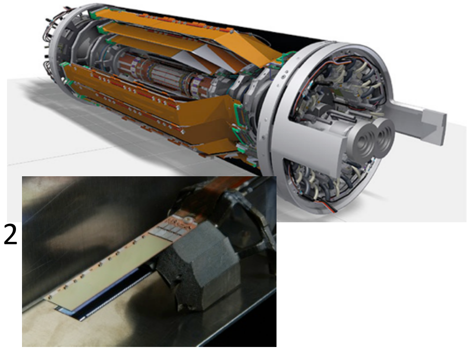
- relatively large material budget: ~3% X_0 per layer (1% X_0 @ ALICE)
- sensor + chip + flex kapton + passive components
- support, cooling (-10°C operation), services
- resolution could be better
- complex and laborious module production
- bump-bonding / flip-chip
- many production steps
- expensive

☐ hence: (Semi-)Monolithic pixels in part relying on commercial CMOS processes have come in focus (at first outside LHC-pp)

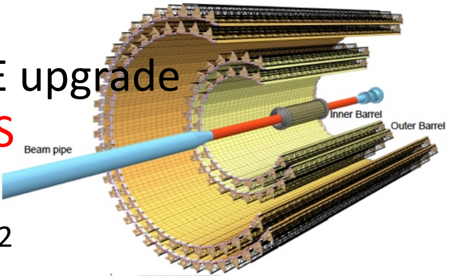
STAR
MAPS
2014
0.16 m^2



Belle II
DEPFET
2017
0.014 m^2



ALICE upgrade
MAPS
2018
10 m^2



ILC
DEPFET
MAPS
SOIPIX
20??