

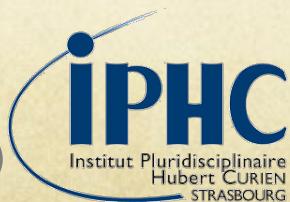


European School of Instrumentation
in Particle & Astroparticle Physics

2022

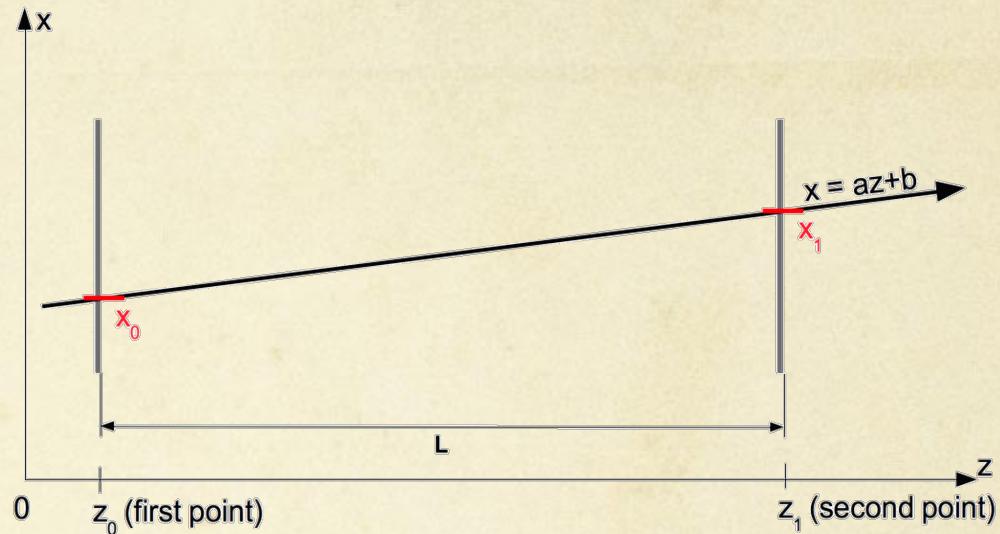


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○ Hypothesis:

- Two sensors
 - perfect positions
 - Infinitely thin
- 1 straight tracks
 - 2 parameters (a,b)



○ Estimation of track parameters

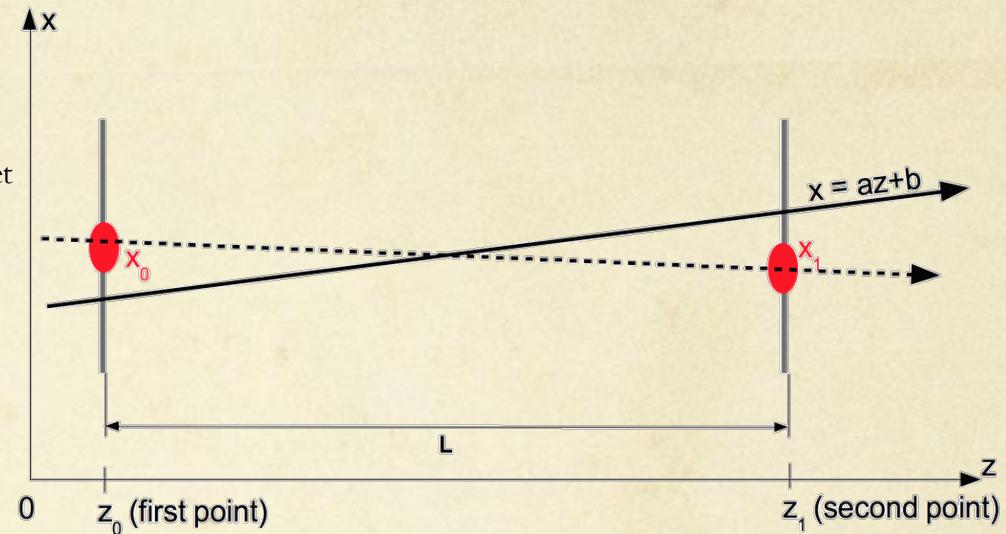
- Assuming track model is straight

- No uncertainty !

$$a = \frac{x_1 - x_0}{z_1 - z_0} , b = \frac{x_0 z_1 - x_1 z_0}{z_1 - z_0}$$

○ Hypothesis:

- Two sensors
 - Positions with UNCERTAINTY σ_{det}
 - Infinitely thin
- 1 straight tracks
 - 2 parameters (a,b)



○ Estimation of track parameters

- Assuming track model is straight
- Uncertainties from error propagation

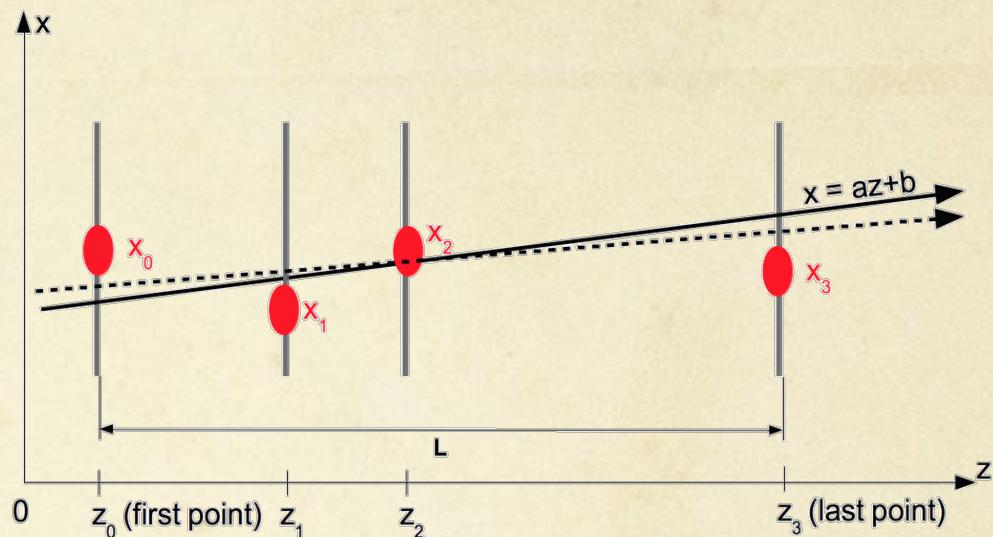
$$a = \frac{x_1 - x_0}{z_1 - z_0}, \quad b = \frac{x_0 z_1 - x_1 z_0}{z_1 - z_0}$$

$$\sigma_a = \frac{\sqrt{2}}{z_1 - z_0} \sigma_{\text{det}}, \quad \sigma_b = \frac{\sqrt{z_1^2 + z_0^2}}{z_1 - z_0} \sigma_{\text{det}}$$

$$\text{cov}_{a,b} = -\frac{\sqrt{z_1 + z_0}}{z_1 - z_0} \sigma_{\text{det}}$$

○ Hypothesis:

- More than two sensors
 - Positions with uncertainty σ_{det}
 - Infinitely thin
- 1 straight tracks
 - 2 parameters (a,b)



○ Estimation of track parameters

- Assuming track model is straight
 - Need **FITTING PROCEDURE** least square
 - Need covariance matrix of measurements
(here diagonal)
- Uncertainties from error propagation
 - Detail depends on geometry
- ➡ Both estimation & uncertainties improve

$$a = \frac{S_1 S_{xz} - S_x S_z}{S_1 S_{z^2} - (S_z)^2}, \quad b = \frac{S_x S_{z^2} - S_z S_{xz}}{S_1 S_{z^2} - (S_z)^2}$$

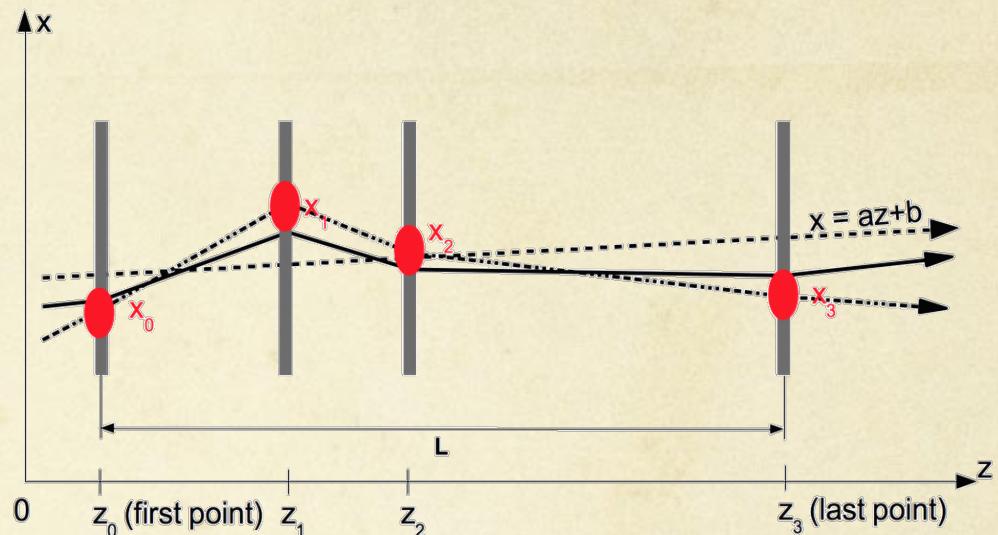
$$\sigma_a^2 = \frac{S_1}{S_1 S_{z^2} - (S_z)^2}, \quad \sigma_b^2 = \frac{S_{z^2}}{S_1 S_{z^2} - (S_z)^2}$$

$$\text{cov}_{a,b} = \frac{-S_z}{S_1 S_{z^2} - (S_z)^2}$$

$S_{f(x,z)} = \sum_{i=\text{first point}}^{\text{last point}} \frac{f(x_i, z_i)}{\sigma_{\text{det}}^2}$

○ Hypothesis:

- More than two sensors
 - Positions with uncertainty σ_{det}
 - With some THICKNESS
 - physics effect
- 1 straight tracks
 - 2 parameters (a,b)



○ Estimation of track parameters

- Assuming track model is straight
 - Need fitting procedure least square
 - Need covariance matrix of measurements
 - physics effect → **NON DIAGONAL** terms
- Uncertainties from error propagation

➡ same estimators but increased uncertainties

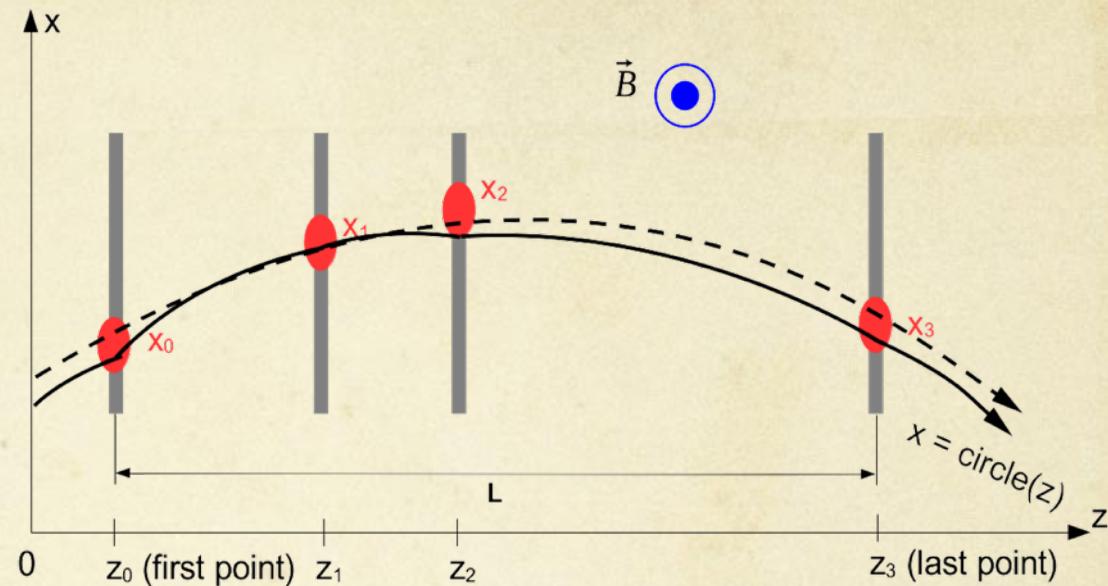
$$a = \frac{S_1 S_{xz} - S_x S_z}{S_1 S_{z^2} - (S_z)^2}, \quad b = \frac{S_x S_{z^2} - S_z S_{xz}}{S_1 S_{z^2} - (S_z)^2}$$

Complex covariant matrix expression

- correlation between sensors
- Various implementations possible

○ Hypothesis:

- More than two sensors
 - Positions with uncertainty σ_{det}
 - With some THICKNESS
 - physics effect
- No more straight track
 - Magnetic field → helix
 - 5 parameters → one is \vec{p}



○ Estimation of track parameters

- As before
 - Non diagonal covariance matrix
 - Increased uncertainties from physics effect
- BUT fitting more complex
 - Higher dimensions from 5 params
 - Non-linearities from model

Influence of geometry from

- Overall layout
- Shape of sensing layers

What are we talking about?

○ Hypothesis:

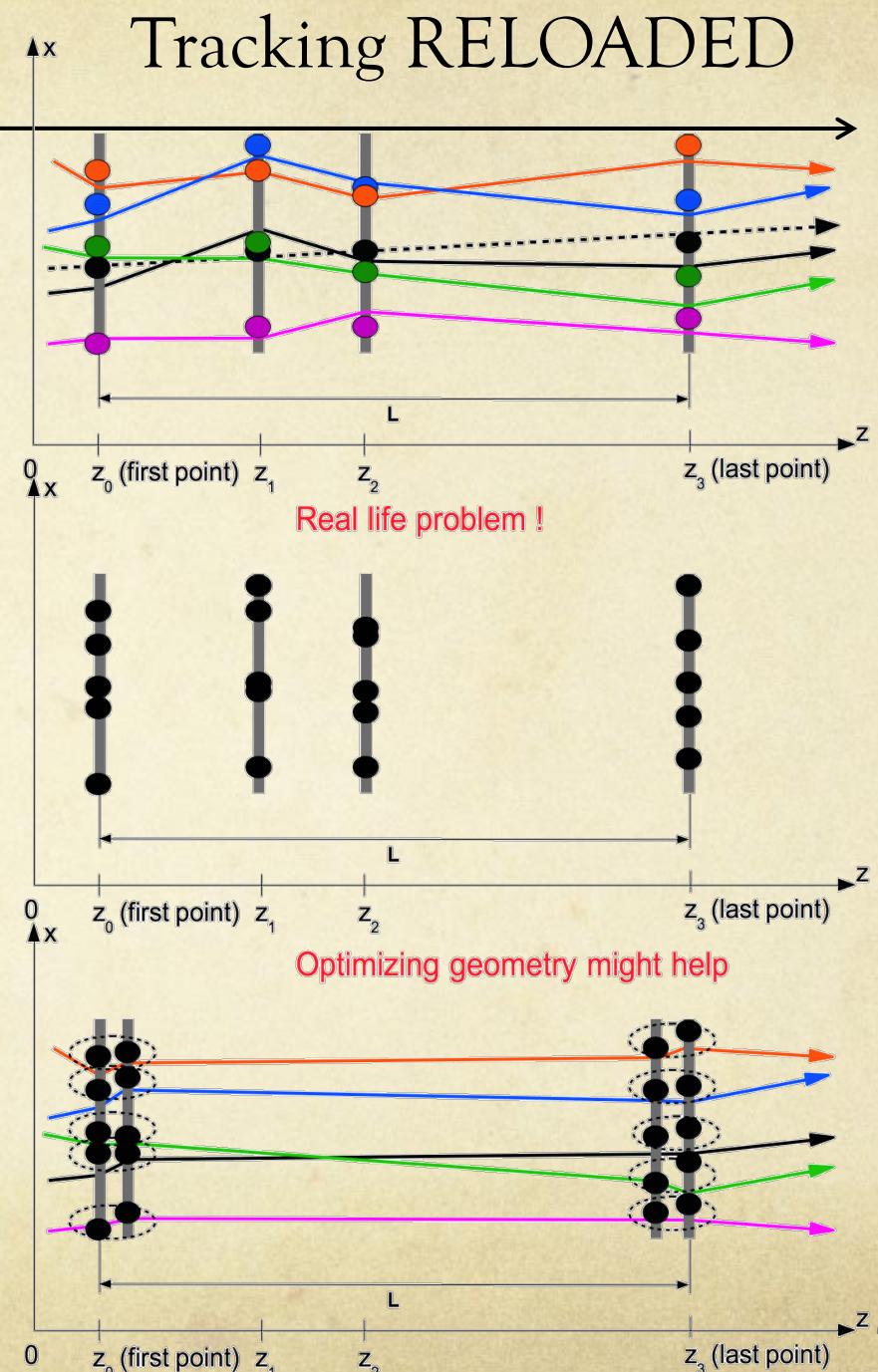
- More than two sensors
 - Positions with uncertainty σ_{det}
 - With some thickness
- MANY straight tracks
 - Still 2 parameters (a,b)...per track!
 - But may change along track path

○ New step = FINDING

- Which hits to which tracks ?
- Strongly depends on geometry

○ Estimation of track parameters

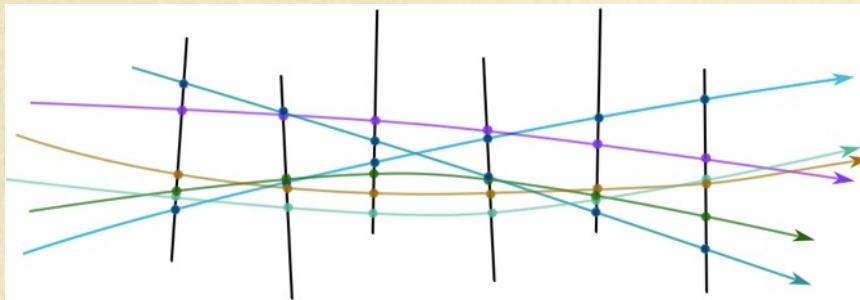
- Happens after finder
- Uncertainties involve correlation



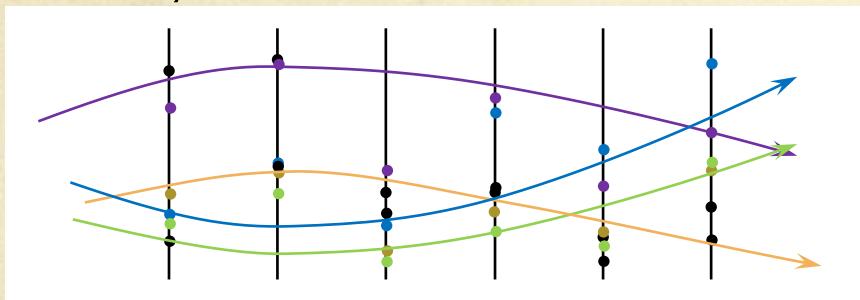
What are we talking about?

○ Alignment:

- What was mechanically constructed



- What you think is there !



Alignment procedure needed

Additional real-life troubles

○ Radiation environment

- Intensity & energy frontiers => large radiation exposure
- Total ionizing dose
 - Possible effects starting $\sim 1 \text{ kGy}$
 - Worst conditions $\sim \text{Ggy}$
- Non ionizing energy loss fluence
 - Possible effects starting $\sim 10^{12} \text{ n}_{\text{eq}(1\text{MeV})}/\text{cm}^2$
 - Worst conditions $\sim 10^{17} \text{ n}_{\text{eq}(1\text{MeV})}/\text{cm}^2$



Hardening/Monitoring needed

○ Temperature

- Electronics heat-up => perf. can degrades with temp.
- Radiation tolerance depends on temperature



cooling => additional material

Lecture outline

1. Basic concepts

2. Position sensitive detectors

3. Standard algorithms

4. Advanced algorithms

5. Optimizing a tracking system

6. References



first lecture

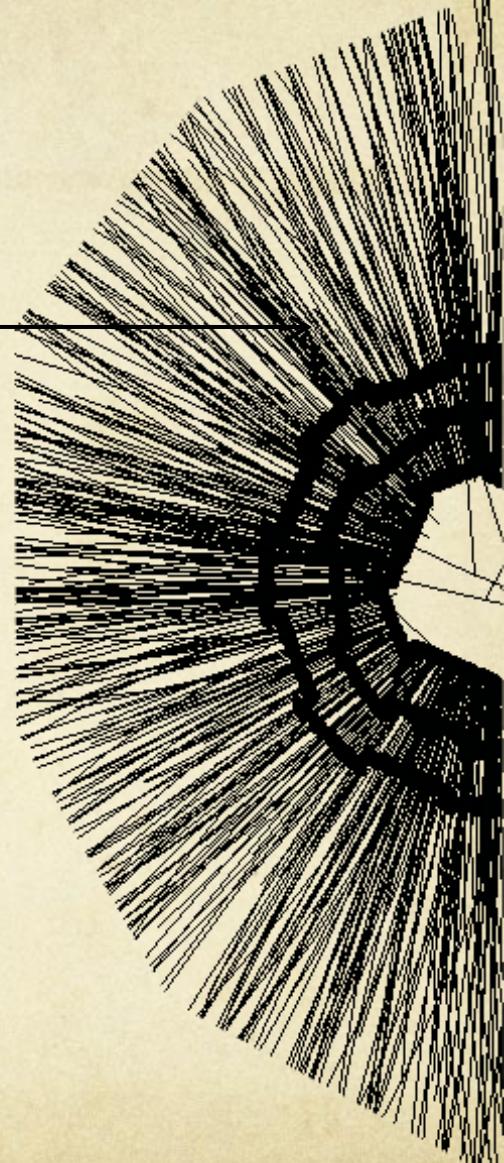


second lecture

third lecture

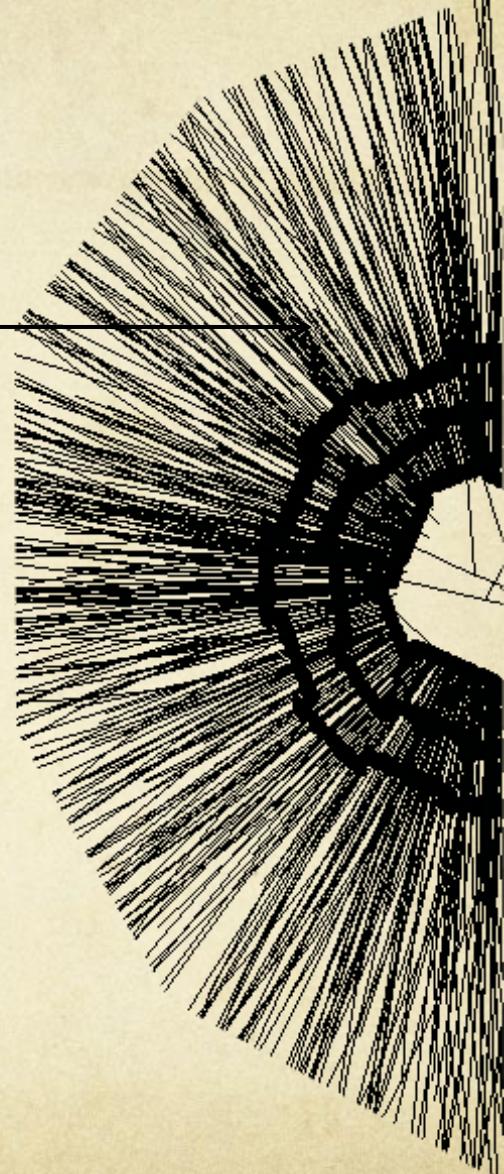


Tutorial



1. Motivations & basic concepts

- Motivations
- Types of measurements
- The 2 main tasks
- Environmental considerations
- Figures of merit

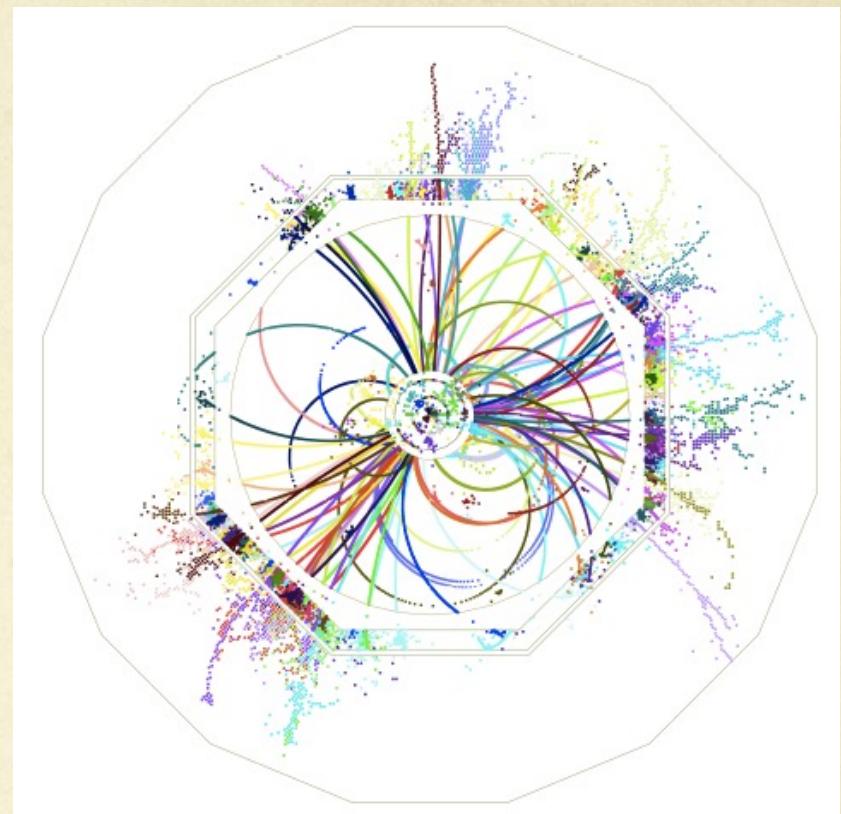


○ Understanding an event

- Individualize tracks \simeq particles
- Measure their properties
- LHC: ~ 1000 particles per 25 ns “event”

○ Track properties

- **Momentum** \Leftrightarrow curvature in B field
 - Reconstruct invariant masses
 - Contribute to jet energy estimation
- **Energy** \Leftrightarrow range measurement
 - Limited to low penetrating particle
- **Mass** \Leftrightarrow dE/dx measurement
- **Origin** \Leftrightarrow vertexing (connecting track)
 - Identify decays
 - Measure flight distance
- **Extension** \Leftrightarrow particle flow algorithm (pfa)
 - Association with calorimetric shower



8 jets event ($t\bar{t}$ -bar h) @ 1 TeV ILC

1. Motivations & Basic Concepts

Momentum measurement

○ Magnetic field curves trajectories $\frac{d\vec{p}}{dt} = q\vec{v} \times \vec{B}$

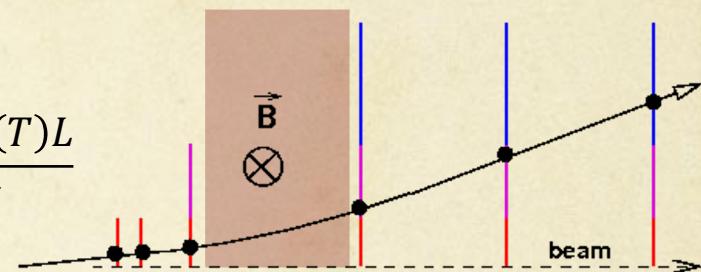
$$\left. \begin{array}{l} (\text{r-}\varphi) \text{ plane circle } p_T = 0.3zBR \\ (\text{r-}z) \text{ plane Straight line } p_T = p \cos \lambda \end{array} \right\} \vec{p} = \vec{p}_T + \vec{p}_z$$

- In $B=4\text{T}$ a $10\text{ GeV}/c$ particle will get a sagitta of 1.5 cm @ 1m

○ Fixed-target experiments

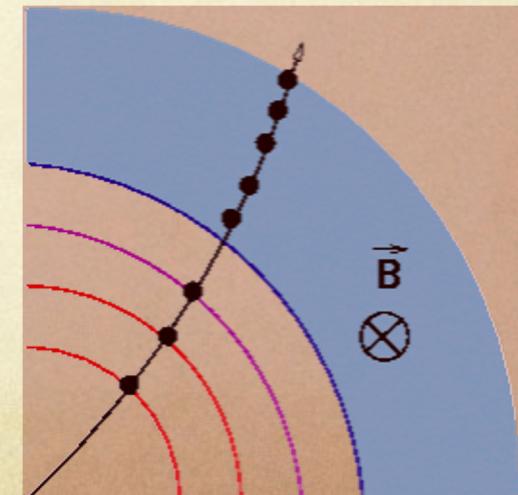
- Dipole magnet on a restricted path segment
- Measurement of deflection (angle variation)

$$\frac{p_T}{q} = \frac{0.3 \cdot B(T)L}{\Delta\alpha}$$



○ Collider experiment

- Barrel-type with axial B over the whole path
- Measurement of curvature (sagitta) $\frac{p_T(\text{GeV}/c)}{q} = 0.3 \cdot B(\text{T}) \cdot R(\text{m})$



○ Other arrangements

- Toroidal B... not covered

○ Two consequences

- Position sensitive detectors needed
- Perturbation effects on trajectories limit precision on track parameters

O Identifying through topology

→ Short-lived weakly decaying particles

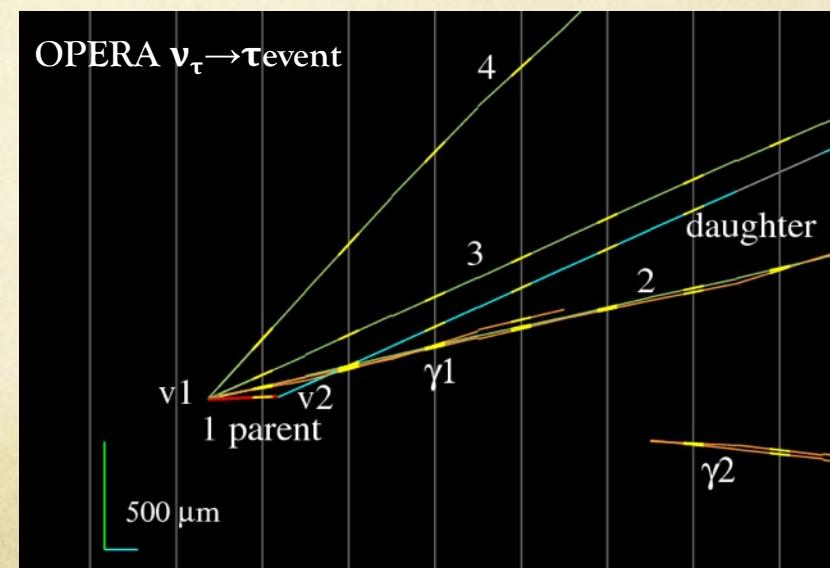
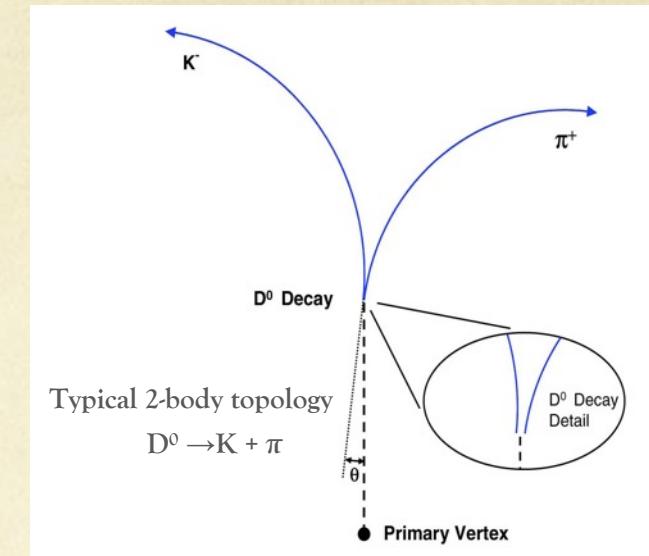
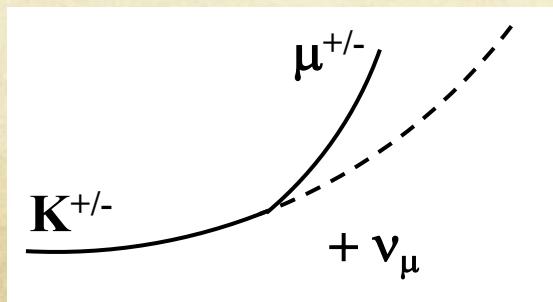
- Charm $c\tau \sim 120 \mu\text{m}$
- Beauty $c\tau \sim 470 \mu\text{m}$
- τ , strange (K_S, Λ)/charmed (D)/beauty (B) particles

O Exclusive reconstruction

- Decay topology with secondary vertex
- Exclusive = all particles in decay associated

O Inclusive “kink” reconstruction

- Some particles are invisible (ν)

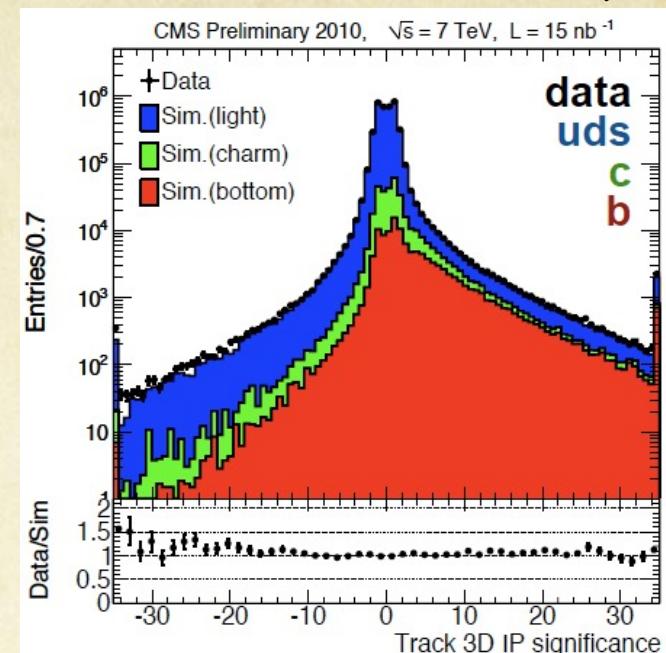


Inclusive reconstruction

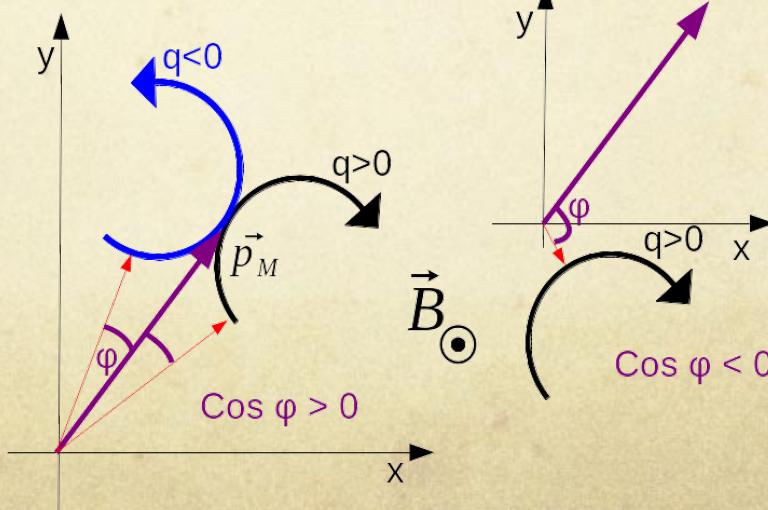
- Selecting parts of the daughter particles
= flavor tagging for high energy colliders
- based on impact parameter (IP)
- $\sigma_{\text{IP}} \sim 20\text{-}100 \mu\text{m}$ requested

Definition of impact parameter (IP)

- Also **DCA** = distance of closest approach from the trajectory to the primary vertex
- Full 3D or 2D (transverse plane d_p) + 1D (beam axis z)
- Sign extremely useful for flavor-tagging

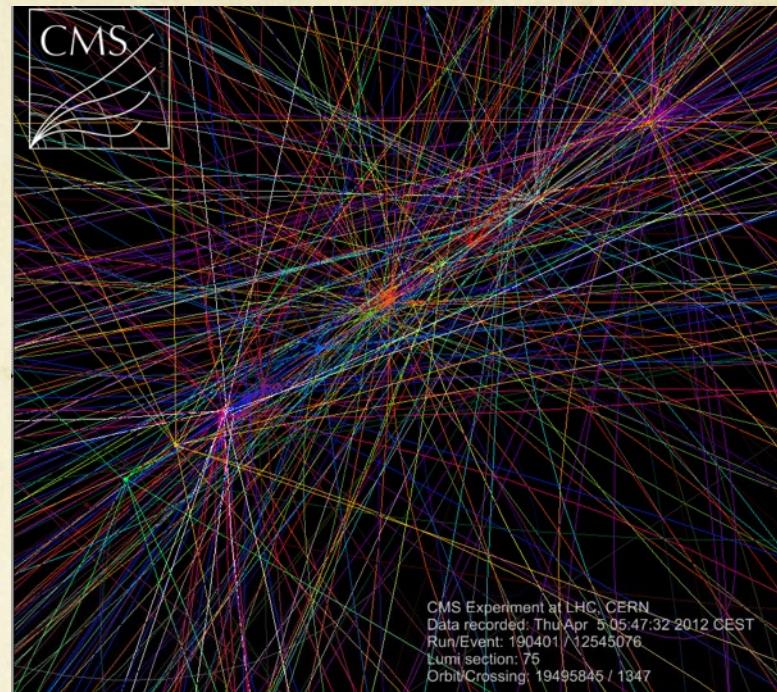


Sign defined by
angle dca / jet momentum



○ Finding the event origin

- Where did the collision did occur?
= Primary vertex
- (life)Time dependent measurements
 - CP-asymmetries @ B factories ($\Delta z \approx 60\text{-}120 \mu\text{m}$)
- Case of multiple collisions / event
 - $\gg 10$ (100) vertex @ LHC (HL-LHC)

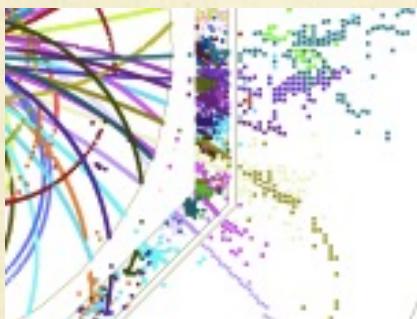


○ Remarks for collider

- Usually no measurement below 1-2 cm / primary vertex
 - Due to beam-pipe maintaining vacuum
- Requires **extrapolation** → expect “unreducible” uncertainties

○ Usually not a tracker task

- CALORIMETERs (see dedicated lecture)
- Indeed calorimeters gather material to stop particles while trackers try to avoid material (multiple scattering)
- however...calorimetry tries to improve granularity \Rightarrow track-cal are “trendy”



○ Particle flow algorithm

- Colliders (pp and ee)

○ Energy evaluation by counting particles

- Clearly heretic for calorimetry experts
- Requires to separate E_{deposit} in dense environment

○ Range measurement for low energy particles

- Stack of tracking layers
- Modern version of nuclear emulsion

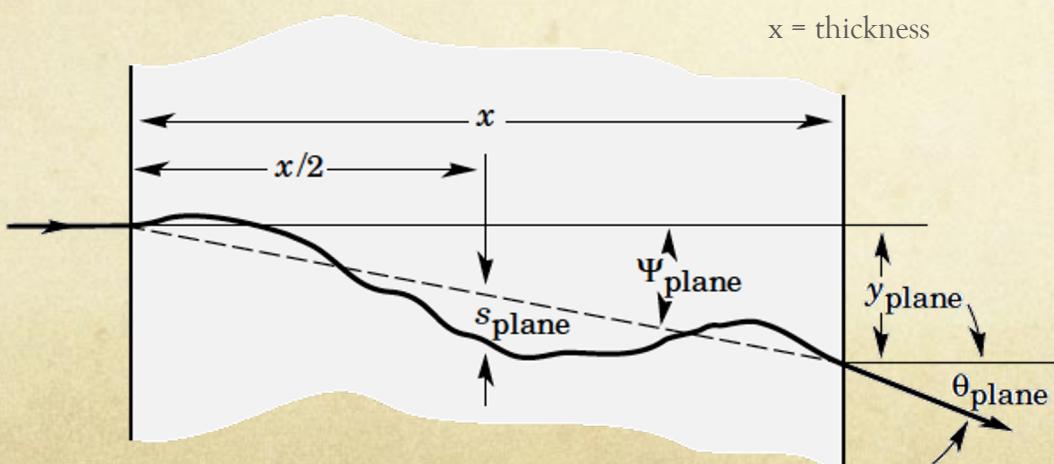
NOT COVERED

○ Reminder on the physics (see other courses)

- Coulomb scattering mostly on nuclei
- Molière theory description as a **centered gaussian process**
 - the thinner the material, the less true → large tails

○ In-plane description (defined by vectors \mathbf{p}_{in} , \mathbf{p}_{out})

- Corresponds to $(\varphi, \theta = \theta_{plane})$ with $\mathbf{p}_{in} = \mathbf{p}_z$ and $p_{out}^2 = p_{out,z}^2 + p_{out,T}^2$
- $$\left. \begin{array}{l} p_{out} \cos \theta \approx p_{out,z} \\ p_{out,T} = p_{out} \sin \theta \approx p_{out} \theta \end{array} \right\}$$
- Highland formula: $\sigma_\theta = \frac{13.6 \text{ (MeV/c)}}{\beta p} \cdot z \cdot \sqrt{\frac{\text{thickness}}{X_0}} \cdot \left[1 + 0.038 \ln\left(\frac{\text{thickness}}{X_0}\right) \right]$ (note: $\phi \in [0, 2\pi]$ uniform)
 z = particle charge)



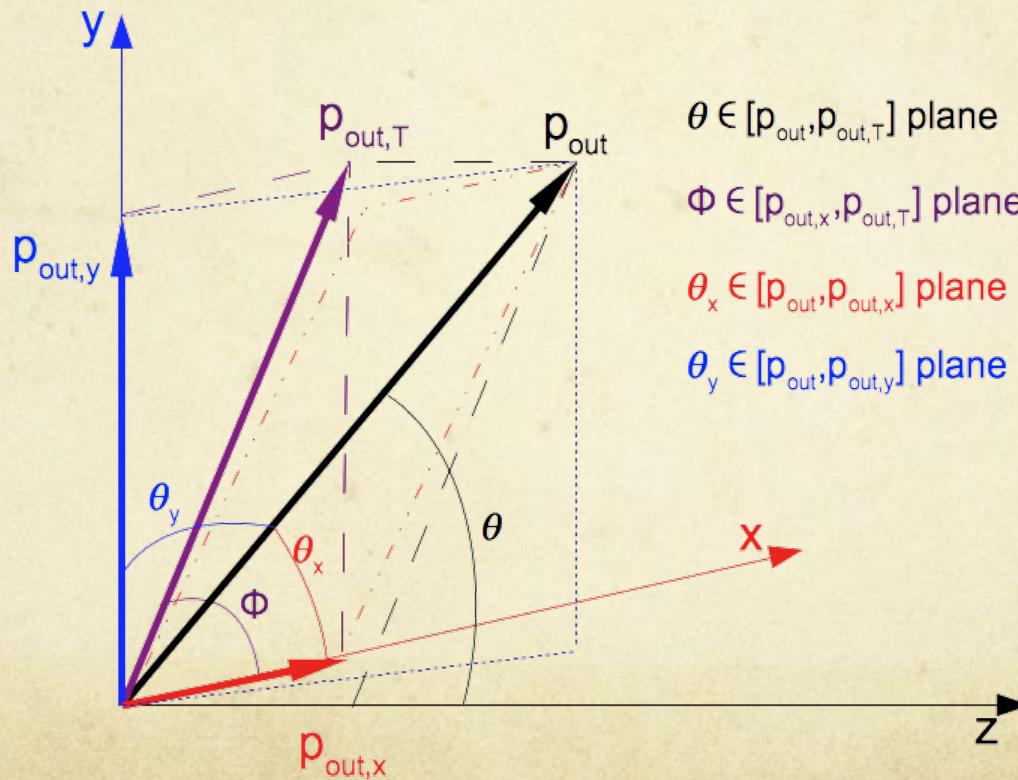
Xo = radiation length
 Same definition as in calorimetry
 ... though this is accidental

○ In-space description (defined by fixed x/y axes)

→ Corresponds to (θ_x, θ_y) with $p_{out,T}^2 = p_{out,x}^2 + p_{out,y}^2$ $\begin{cases} p_{out} \sin \theta_x \approx p_{out} \theta_x \\ p_{out} \sin \theta_y \approx p_{out} \theta_y \end{cases}$ → $\theta_{plane}^2 = \theta_x^2 + \theta_y^2$

→ θ_x and θ_y are independent gaussian processes

$$\sigma_{\theta_x} = \sigma_{\theta_y} = \frac{\sigma_{\theta_{plane}}}{\sqrt{2}}$$



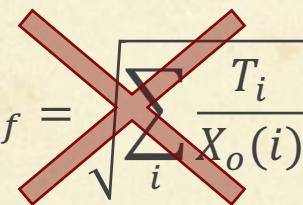
○ Important remark when combining materials

→ Total thickness $T = \sum T_i$, each material (i) with $X_0(i)$

→ Definition of effective radiation length $\rightarrow X_{0,eff} = \frac{\sum_i T_i X_0(i)}{T}$

→ Consider **single gaussian** process $\sigma_{eff} = \sqrt{\frac{T}{X_{0,eff}}}$

and never do variance addition
(which minimize deviation)

$$\sigma_{eff} = \sqrt{\sum_i \frac{T_i}{X_0(i)}}$$


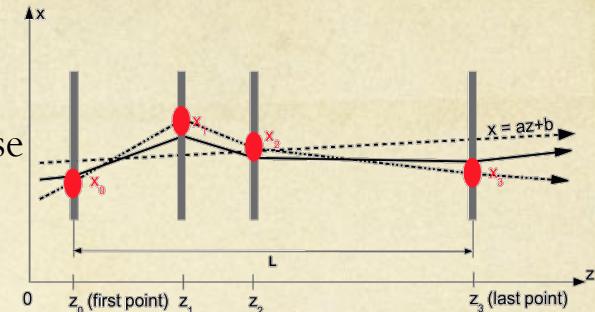
○ Some common materials in trackers

material	X0	Deviation for protons at 1 GeV		
		thickness	Budget	Shit @ 10 cm
Silicon	9.4 cm	100 μm	0.1 %	50 μm
Epoxy	30 cm	1 mm	0.3 %	90 μm
NaI	2.6 cm	1 mm	3.8%	350 μm
Gas (air-CH4)	300-700 m	10 cm	<10 ⁻³	-

Impact on tracking algorithm

- The track **parameters evolves** along the track !
- May drive choice of reconstruction method

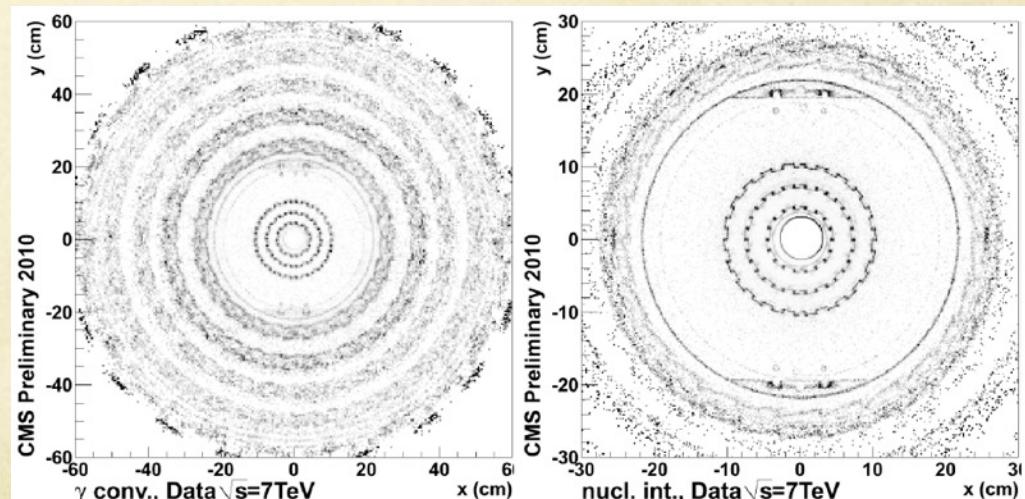
Remember
this simple case



Photon conversion

- Alternative definition of radiation length probability for a high-energy photon to generate a pair over a path dx :
- $\gamma \rightarrow e^+e^-$ = conversion vertex
- Generate troubles :
 - Additional unwanted tracks
 - Decrease statistics for electromagnetic calorimeter

$$\text{Prob} = \frac{dx}{\frac{9}{7} X_0}$$



CMS “picture” of material budget through photon conversion vertices (silicon tracker only)

The collider paradigm

- Basic inputs from detectors

- Succession of 2D or 3D points (or track segments)
➡ Who's who ?

- 2 steps process

- Step 1: track identification = **finding** = pattern recognition
 - Associating a set of points to a track
 - Step 2: track **fitting**
 - Estimating trajectory parameters → momentum

- Both steps require

- **Track model** (signal, background)
 - Knowledge of **measurement uncertainties**
 - Knowledge of **materials traversed** (Eloss, mult. scattering)

- Vertexing needs same 2 steps

- Identifying tracks belonging to same vertex
 - Estimating vertex properties (position + 4-vector)



The Telescope mode

○ Beam test

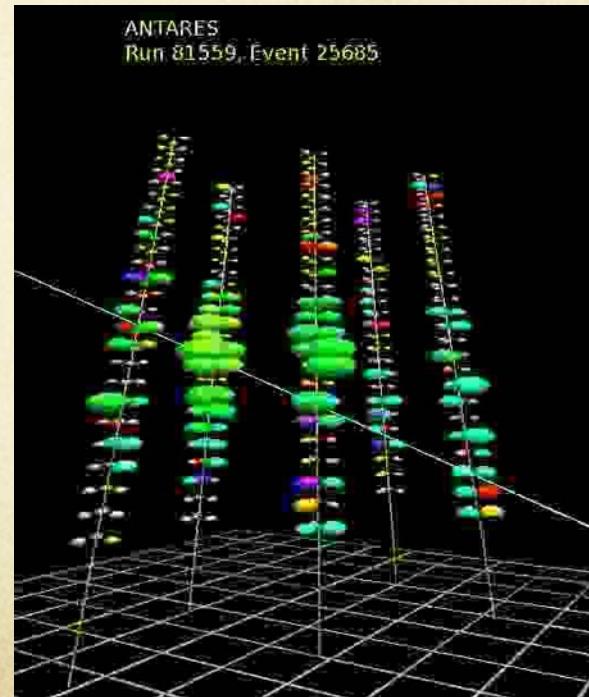
- Single particle at a time
 - Sole nuisances = noise and material budget
- Trigger from beam
 - Often synchronous
- Goal = get the particle incoming direction



EUDET- beam telescope

○ The astroparticle way

- Similar to telescope mode
- No synchronous timing
- Ex: deep-water ν telescopes



=> For 2 last cases: mostly a fitting problem

- Usually with straight track model



○ Life in a real experiment is tough (*for detectors of course, students are welcome!*)

- Chasing small cross-sections → large luminosity and/or energy
 - Short interval between beam crossing (LHC: 25 ns)
 - Pile-up of events (HL-LHC >100 collisions / crossing)
 - Large amount of particles (could be > 10^8 part/cm²/s)
⇒ background, radiation
 - Vacuum could be required (space, very low momentum particles (CBM, LHCb))
- } ⇒ Finding more complicated!
⇒ Requirements on detectors:
 - Fast timing
 - High granularity

○ Radiation tolerance

- Two types of energy loss
 - Ionizing (generate charges): dose in Gy = 100 Rad
 - Non-ionizing (generate defects in solid): fluence in $n_{eq}(1\text{MeV})/\text{cm}^2$
- The innermost the detection layer, the harder the radiation (radius² effect)
- Examples for most inner layers:
 - LHC: 10^{15} to $<10^{17} n_{eq}(1\text{MeV})/\text{cm}^2$ with 50 to 1 MGy
 - ILC: $<10^{12} n_{eq}(1\text{MeV})/\text{cm}^2$ with 5 kGy



○ Timing consideration

- **Integration time** drives occupancy level (important for finding algorithm)
- **Time resolution** offers time-stamping of tracks
 - Tracks in one “acquisition event” could be associated to their proper collision event if several have piled-up
- Key question = triggered or not-triggered experiment?

○ Heat concerns

- Spatial resolution → segmentation → many channels
- Readout speed → power dissipation/channel
- Efficient cooling techniques exist BUT
 - add material budget and may not work everywhere (space)

} Hot cocktail!

○ Summary

- Tracker technology driven by environmental conditions: hadron colliders (LHC)
- Tracker technology driven by physics performances: lepton colliders (B factories, ILC), heavy-ion colliders (RHIC, LHC)
- Of course, some intermediate cases: superB factories, CLIC

1. Motivations & Basic Concepts:

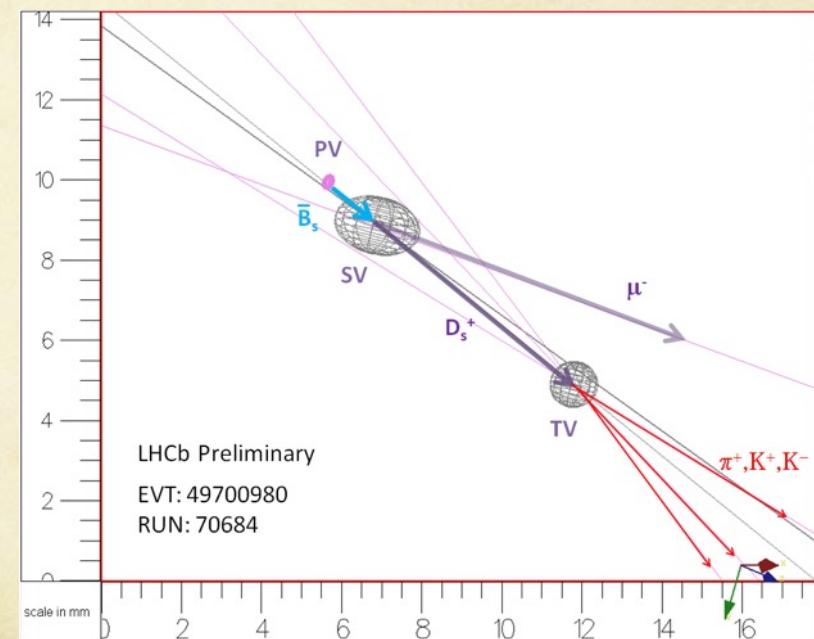
Figures of Merit

○ For detection layer

- Detection efficiency
 - Mostly driven by Signal/Noise
 - Note: Noise = signal fluctuation \oplus readout (electronic) noise
- Intrinsic spatial resolution
 - Driven by segmentation (not only)
 - Useful tracking domain $\sigma < 1\text{mm}$
- Linearity and resolution on dE/dx for PID
- Material budget

○ For detection systems (multi-layers)

- Track finding efficiency & purity
- Two-track resolution
 - Ability to distinguish two nearby trajectories
 - Mostly governed by signal spread / segments
- Momentum resolution $\frac{\sigma(p)}{p}$
- Impact parameter resolution
 - Sometimes called “distance of closest approach” to a vertex



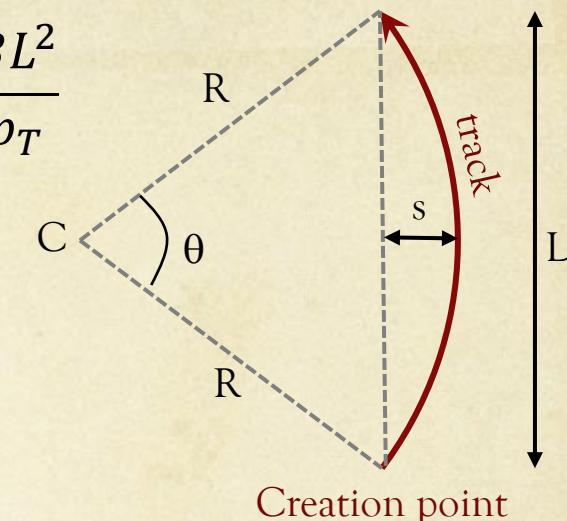
○ Momentum resolution

- Based on sagitta (s) measurement in collider geometry
- L = lever arm of measurements
- R = curvature radius $p_T/0.3B \gg L$

$$s \approx \frac{L^2}{8R} = 0.038 \frac{BL^2}{p_T}$$

↓

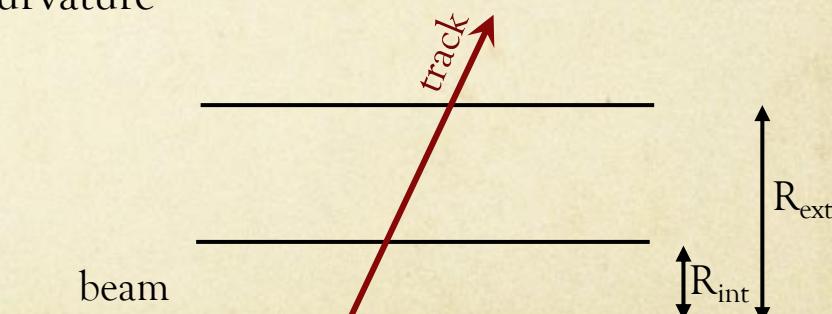
$$\frac{\sigma_{p_T}}{p_T} = \frac{\sigma_s}{s}$$



○ Impact parameter resolution

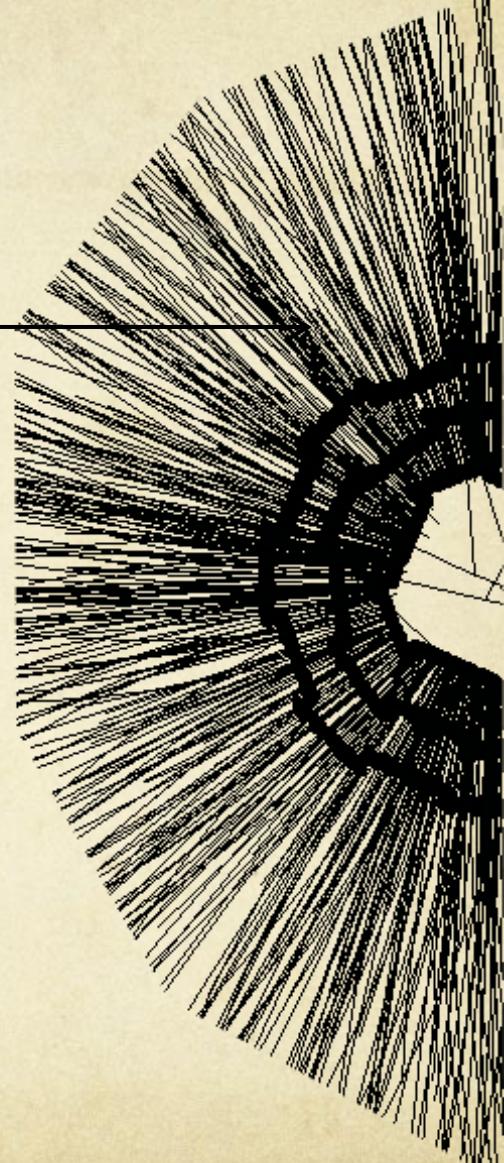
- Based on two layers measurements
- assume track straight over small distance: $R_{\text{ext}} \ll$ curvature
- Each layer with spatial resolution: σ_{int} , σ_{ext}
- Material budget → σ_θ
- Telescope equation:

$$\sigma_{IP} \propto \frac{\sqrt{R_{\text{ext}}^2 \sigma_{\text{int}}^2 + R_{\text{int}}^2 \sigma_{\text{ext}}^2}}{R_{\text{ext}} - R_{\text{int}}} \oplus \frac{R_{\text{int}} \sigma_{\theta(\text{ms})}}{p \sin^{3/2}(\theta)}$$



2. Detection technologies

- Signal formation, Spatial & Time resolution
- Single layer systems
 - Silicon & gas sensors, scintillators
- Multi-layer systems
 - Drift chambers and Time projection chambers
- Tentative simplistic comparison
- Magnets
- Practical considerations
- Leftovers



○ Basic signal formation with ionization:

- key parameters for initial nb of primary charges
- W_i = average energy for charge pair generation
- F = fano factor (<1) => variance_{#charges} = $F \langle \# \text{charges} \rangle$
- Schockley-Ramo theorem: current on electrode INDUCED by charge movement
=> electric field required

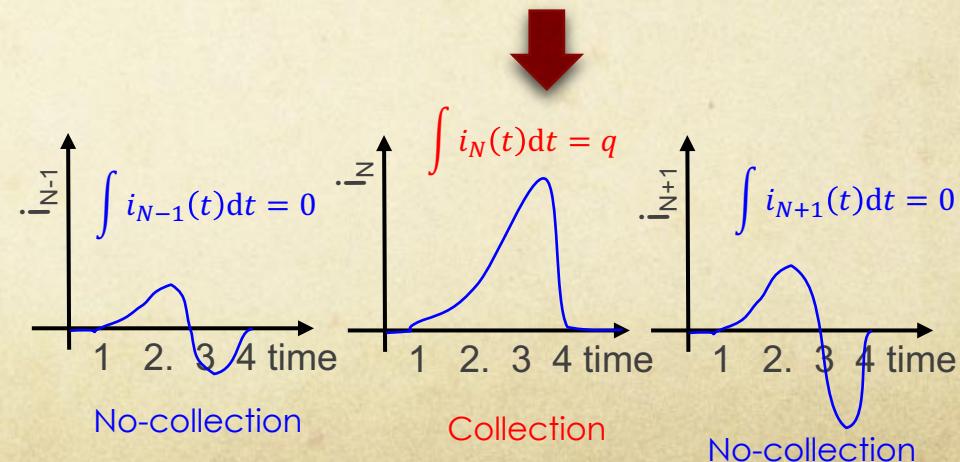
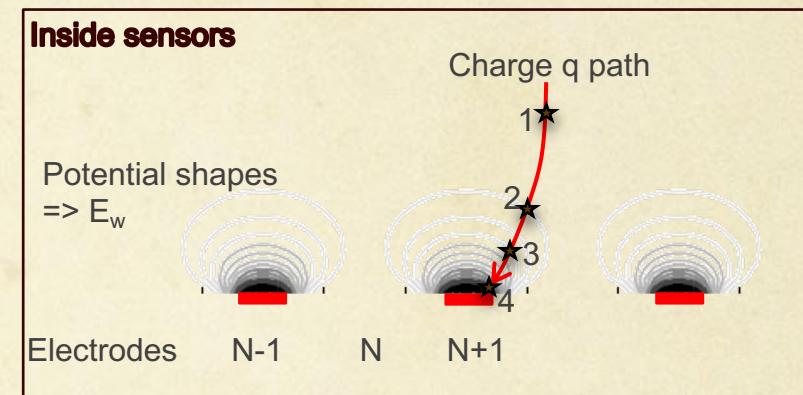
○ Collection and segmentation?

- $E_W(\vec{r})$ = field associated to ONE electrode at a position \vec{r}
- obtained with: THIS electrode has potential=1, all other electrodes have potential 0
- Current generated on THIS electrode for particle at \vec{r} and with velocity $v(\vec{r})$

$$i(\vec{r}) = q E_W(\vec{r}) v(\vec{r})$$

Charge sharing:

- Many charges generated by one particle
 - BUT their collection are shared among electrodes
- => each electrode collecting some charges and has some signal!



2. Detector Technologies:

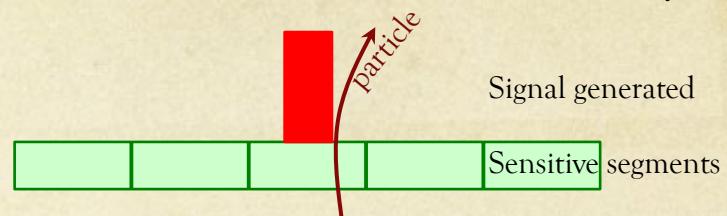
Spatial resolution

- Position measurement comes from segmentation

- Pitch

$$\sigma = \frac{\text{pitch}}{\sqrt{12}}$$

- Digital resolution



- Improvement from signal sharing

- Position = charge center of gravity

$$\sigma \propto \frac{\text{pitch}}{\text{signal/noise}}$$

- Effects generated by

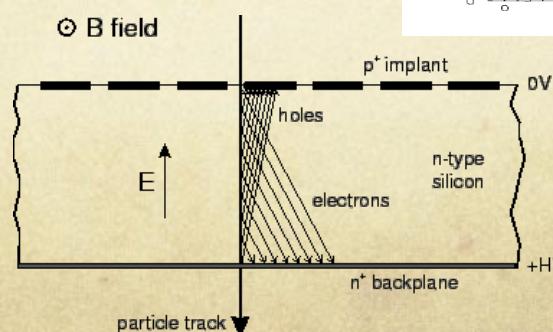
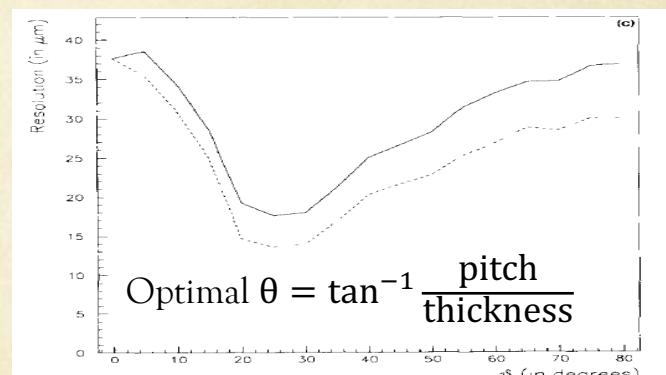
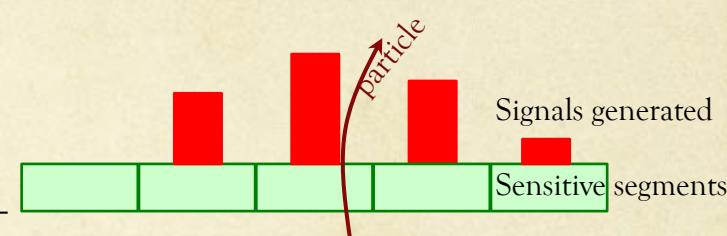
- Secondary charges spread inside volume
- Inclined tracks (however, resol. limited at large angles)

- Potential optimization of segmentation / sharing

- Work like signal sampling theory (Fourier transform)

- Warnings:

- Lorentz force from B mimic the effect
- counterproductive / 2-track resolution





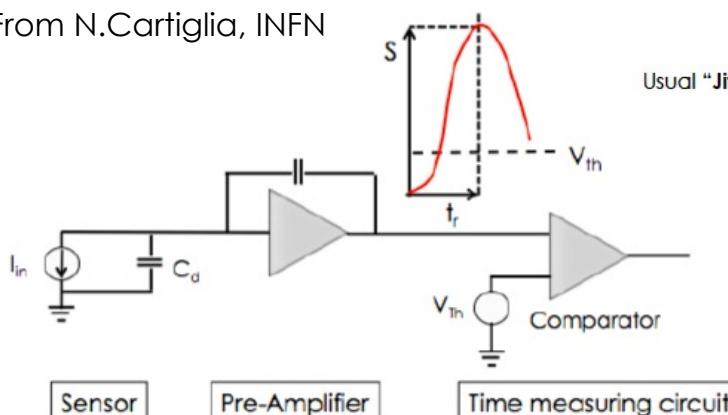
○ Various ways to qualify timing performance

- Integration time => Hit rate, potential bottleneck at data taking
- Time resolution => Track finder step

○ Time resolution for single layer

- Here from the silicon point of view (but similar for thin gas detectors)

From N.Cartiglia, INFN



Usual "Jitter" term

$$\sigma_t^2 = \left(\frac{\text{Noise}}{dV/dt} \right)^2 + (\Delta \text{ionization})^2 + (\Delta \text{shape})^2 + (\text{TDC, Clock ...})^2$$

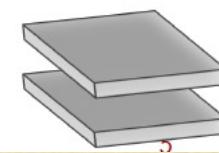
Subleading, ignored here

Amplitude variation:

Sensor design: very uniform signals

Encouraging remark by the expert 😊

This is the ONLY
good geometry



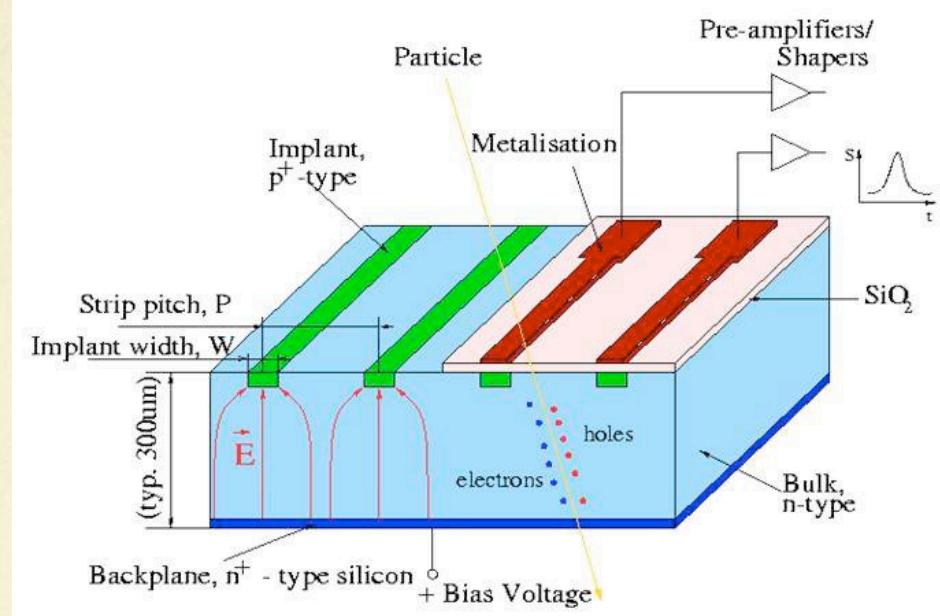
Time is set when the signal crosses the comparator threshold

○ Signal generation

- e-h pairs are generated by ionization in silicon
 - Average energy needed / e-h pair = 3.6 eV
 - 300 μm thick Si generates ~ 22000 charges for MIP
BUT beware of Landau fluctuation

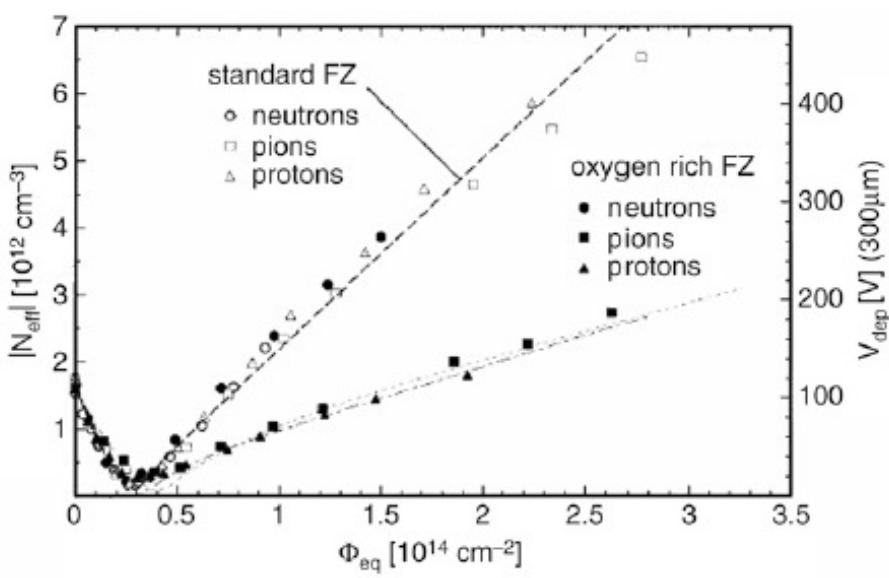
- Collection: P-N junction = diode
 - **Full depletion** (10 to 0.5 kV) generates a drift field (10^4 V/cm)
 - Collection time $\sim 15 \text{ ps}/\mu\text{m}$

$$\text{depth}_{\text{depleted}} \propto \sqrt{\text{resistivity} \times V_{\text{bias}}}$$



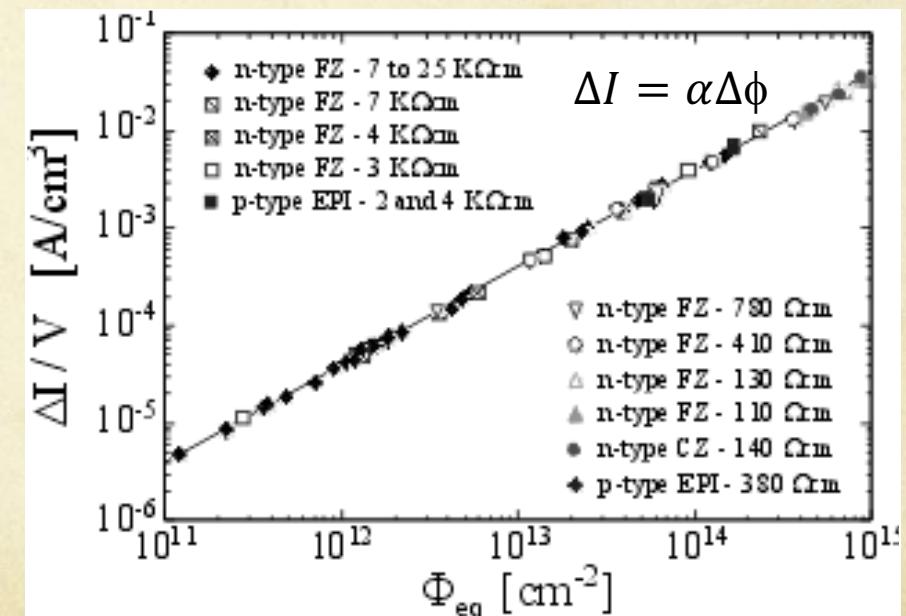
○ Non-ionizing energy loss

- Damage crystal network
 - Generates higher leakage current (noise)
 - Generates charge traps (lower signal)
- Modifies doping



○ Cumulated ionizing dose

- Parasitic charges trapped at interface with oxides
- Released randomly \Rightarrow Noise !



2. Detector Technologies:

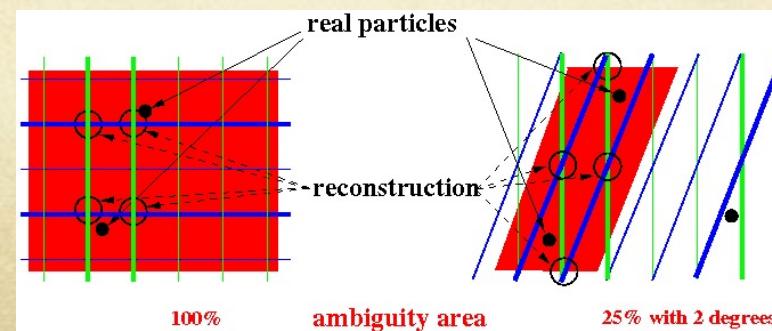
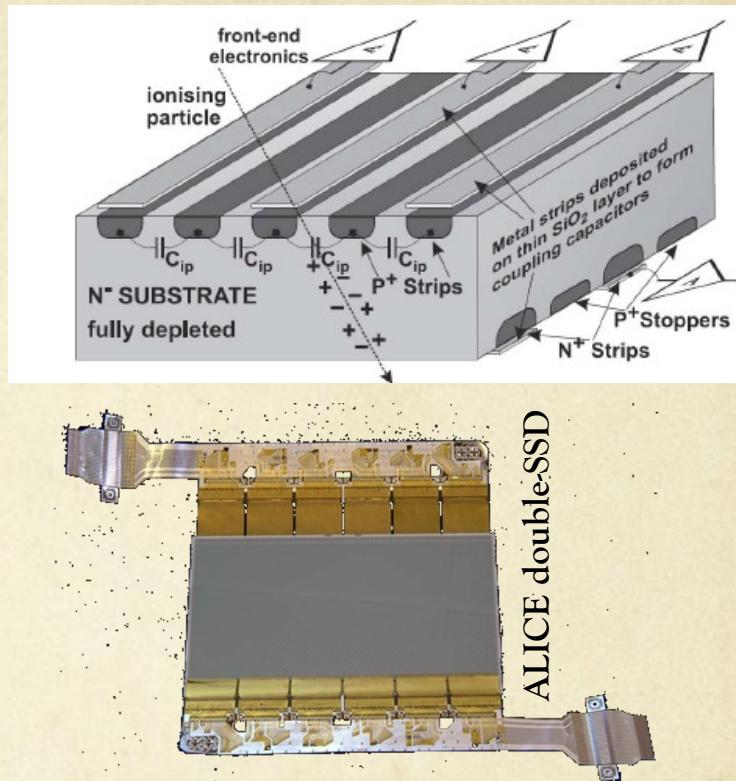
Silicon sensors: strips

○ Concept

- Pattern P-N junction as collection electrodes
- Exploit silicon industry lithographic technique

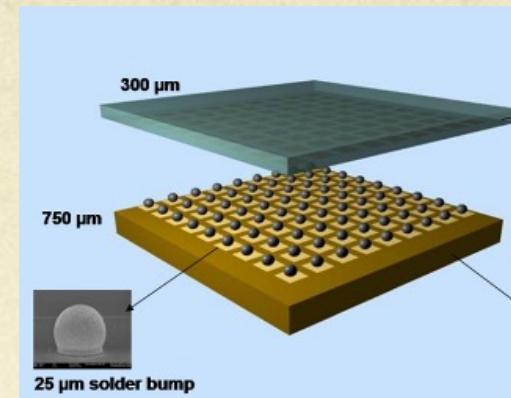
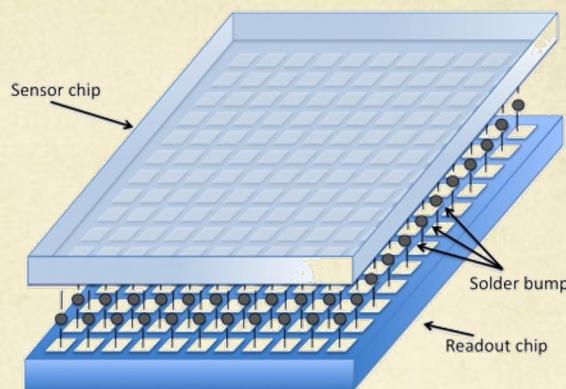
○ Silicon strip detectors

- Sensors “easily” manufactured with pitch down to $\sim 25 \mu\text{m}$
- 1D if single sided
- Pseudo-2D if double-sided
 - Stereo-angle useful against ambiguities
- Difficult to go below $100 \mu\text{m}$ thickness (low SNR)
- Speed and radiation hardness: LHC-grade



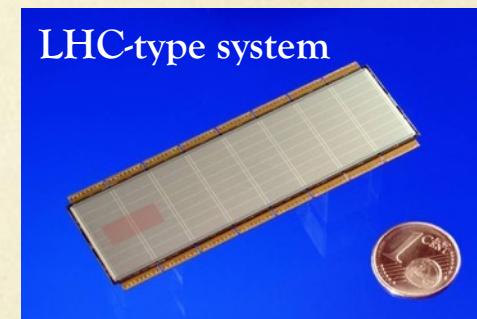
○ Concept

- Strips → pixels on sensor
- One to one connection from electronic channels to pixels



○ Performances

- Real 2D detector & keep performances of strips
 - Can cope with LHC rate => speed & radiation ($>> 10^{15} n_{eq(1\text{ MeV})}/\text{cm}^2$)
 - Strong development in sensor techno., e.g. 3D-sensors
- Pitch size limited by physical connection and #transistors for treatment
 - minimal (today): $25 \times 25 \mu\text{m}^2$
 - typical: $100 \times 150/400 \mu\text{m}^2$
 - spatial resolution about $10 \mu\text{m}$
- Material budget
 - Minimal(today): $100(\text{sensor})+100(\text{elec.}) \mu\text{m}$
- Power budget: $10 \mu\text{W}/\text{pixel}$
 - Very active cooling strategies



Currently the only technology surviving LHC innermost layers environment

2. Detector Technologies:

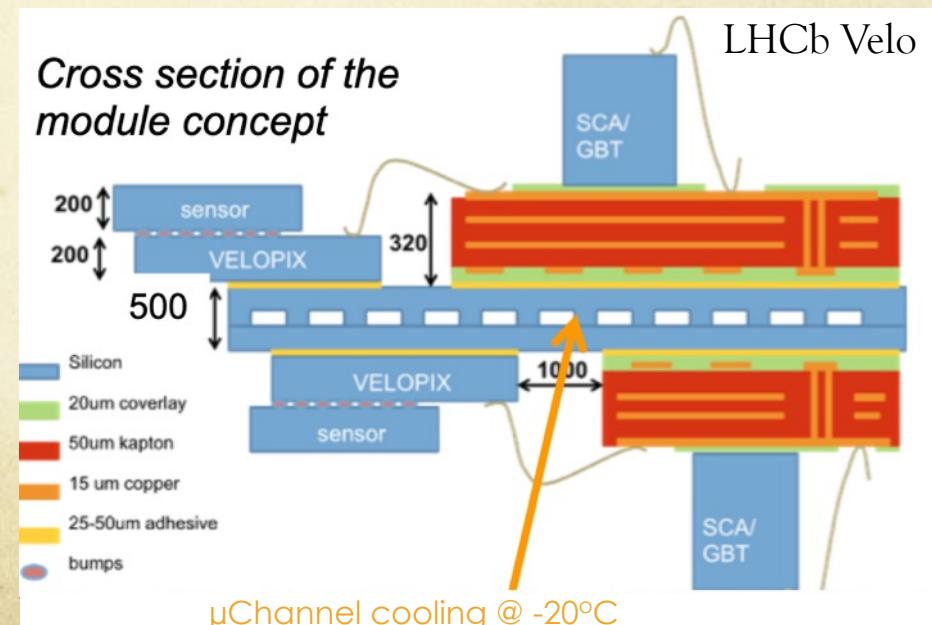
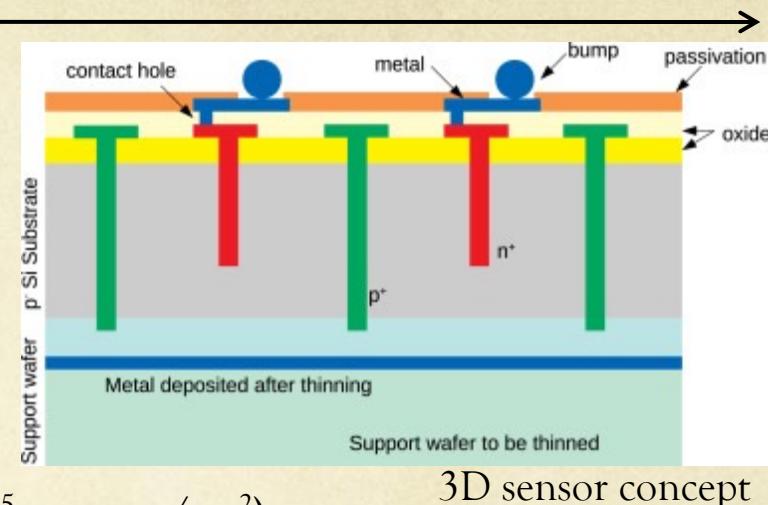
Silicon sensors: hybrid-pixels

○ Concept

- Strips → pixels on sensor
- One to one connection from electronic channels to pixels

○ Performances

- Real 2D detector & keep performances of strips
 - Can cope with LHC rate => speed & radiation ($>> 10^{15} n_{eq(1\text{ MeV})}/\text{cm}^2$)
 - Strong development in sensor techno., e.g. 3D-sensors
- Pitch size limited by physical connection and #transistors for treatment
 - minimal (today): $25 \times 25 \mu\text{m}^2$
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 - spatial resolution about $10 \mu\text{m}$
- Material budget
 - Minimal(today): $100(\text{sensor})+100(\text{elec.}) \mu\text{m}$
- Power budget: $10 \mu\text{W}/\text{pixel}$
 - Very active cooling strategies



2. Detector Technologies:

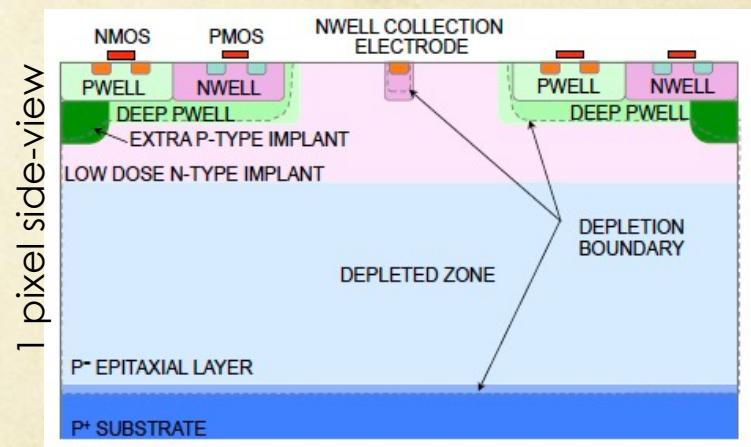
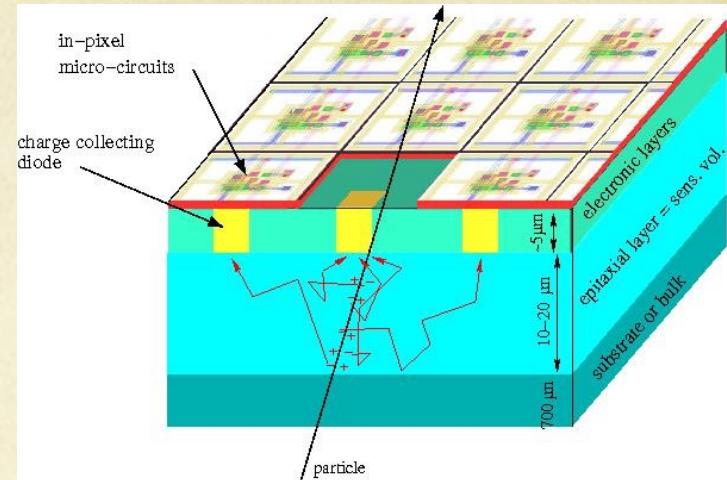
Silicon sensors: CMOS Pixel Sensors (Also dubbed MAPS)

○ Concept

- Use industrial CMOS process
 - Implement an array of sensing diode
 - Amplify the signal with transistors near the diode
- Benefit to
 - granularity: pixel pitch down to $\sim 10 \mu\text{m}$
 - material: sensitive layer thickness as low as 10-20 μm
- Known as Monolithic Active Pixel Sensors (MAPS)

○ Sensitive layer

- If undepleted & thin (10-20 μm)
 - Slow (100 ns) thermal drift of charges
 - non-ionizing rad. tolerance $\lesssim 10^{13} \text{ n}_{\text{eq}(1\text{MeV})}/\text{cm}^2$
- If fully depleted (from 10 to 100 μm)
 - Fast (few ns) field-driven drift of charges
 - non-ionizing rad. tolerance $\gtrsim 10^{15} \text{ n}_{\text{eq}(1\text{MeV})}/\text{cm}^2$



⇒ Main choice when multiple scattering & granularity are required (heavy-ion & e⁺e⁻ collisions)

2. Detector Technologies:

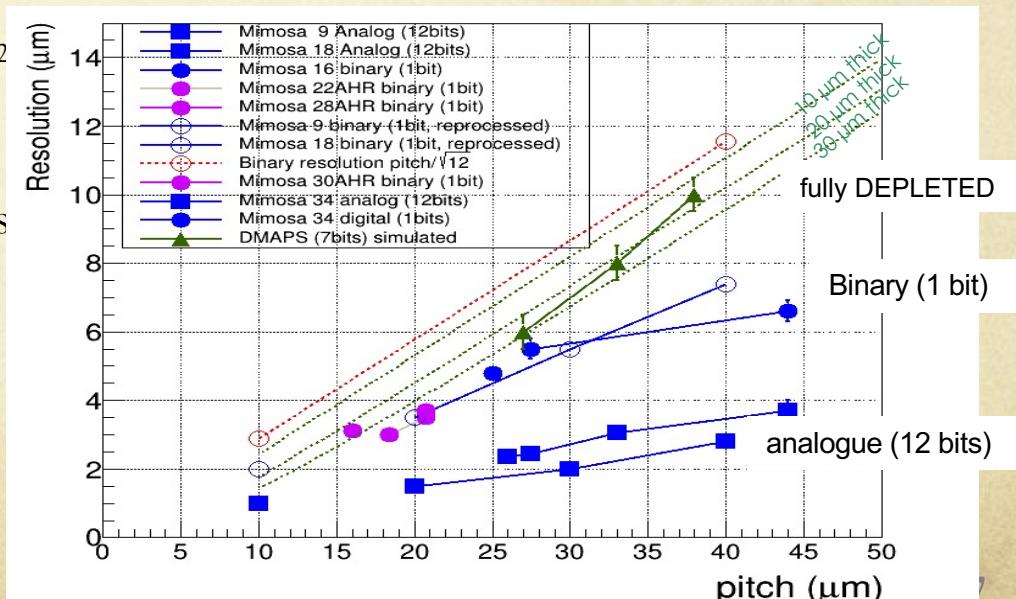
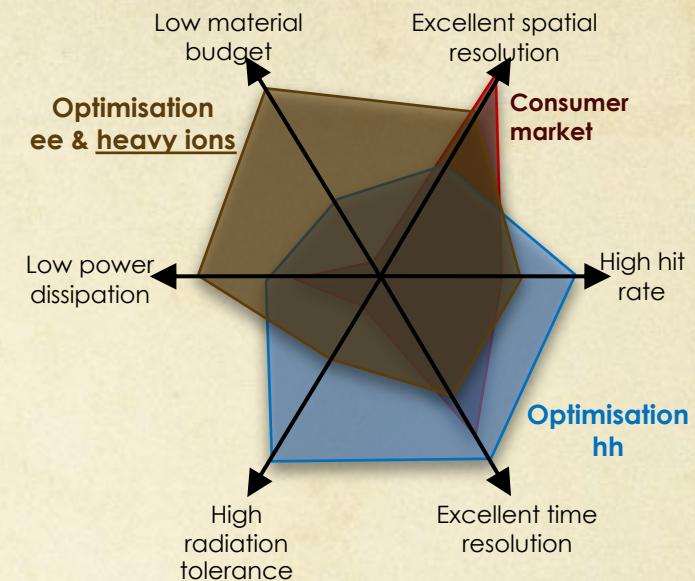
CMOS Pixel Sensor

Concept

- Use industrial CMOS process
 - Implement an array of sensing diode
 - Amplify the signal with transistors near the diode
- Gain in granularity: pitch down to $\sim 10 \mu\text{m}$
- Gain in sensitive layer thickness $\sim 10\text{-}20 \mu\text{m}$
- For undepleted thin sensitive layer
 - Slow (100 ns) thermal drift of charges
 - non-ionizing rad. tolerance $\lesssim 10^{13} \text{n}_{\text{eq}(1\text{MeV})}/\text{cm}^2$
- For fully depleted thin to thick sensitive layer
 - Fast (few ns) field-driven drift of charges
 - non-ionizing rad. tolerance $> 10^{15} \text{n}_{\text{eq}(1\text{MeV})}/\text{cm}^2$

Performances

- Spatial resolution 1-10 μm (in 2 dimensions)
- Material budget: $\lesssim 50 \mu\text{m}$
- Power budget: $< \mu\text{W}/\text{pixel}$
- Integration time $\simeq 5\text{-}100 \mu\text{s}$ demonstrated
 - $\sim 1 \mu\text{s}$ in development
- Timestamping @ ns level in development

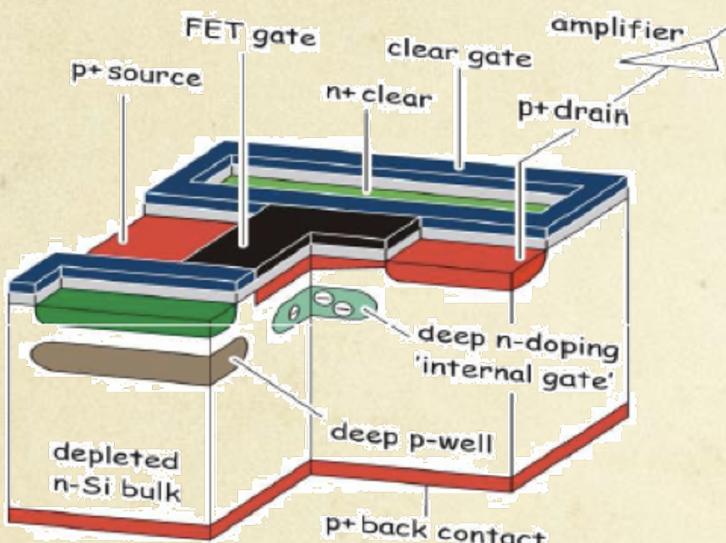


2. Detector Technologies:

Other active pixel sensors

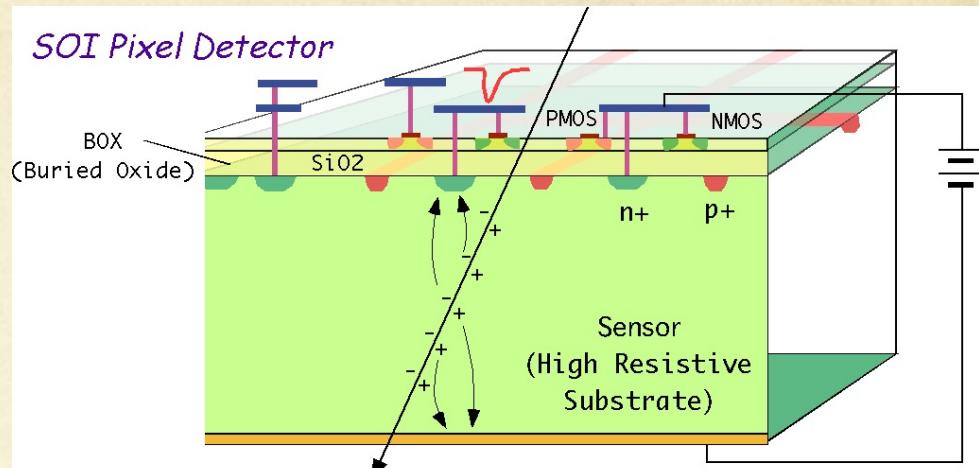
○ DEPFET

- Depleted p-channel FET



- Fully depleted sensitive layer
- Large amplification
- Still require some read-out circuits
 - Not fully monolithic
 - Possibly limited in read-out speed

○ Silicon On Insulator (SOI)



- Fully depleted sensitive layer
- Fully monolithic
- Electronics similar to MAPS
 - R&D for Belle II
 - 40 μm pitch for 60 ns time resolution low power expected
 - SOIPix R&D for ILC
 - 20 μm pitch for ~1 μm resolution



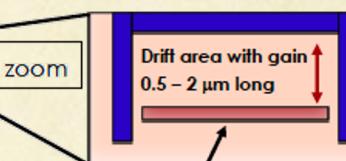
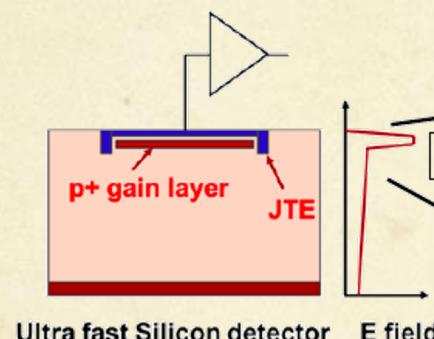
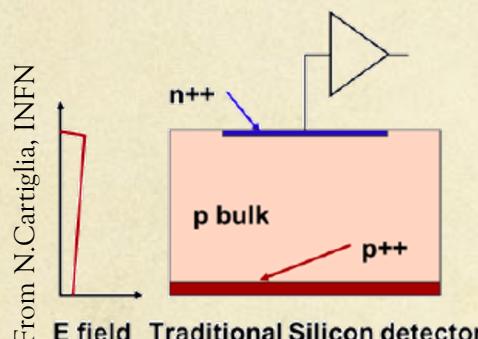
2. Detector Technologies:

Low Gain Avalanche Detector

Goal

- Reach time resolution 10 ps range, still with some segmentation < 100 μm
 - Current R&D to reach 1 μm with 1 ps combined!!

Principle: generate a controlled avalanche

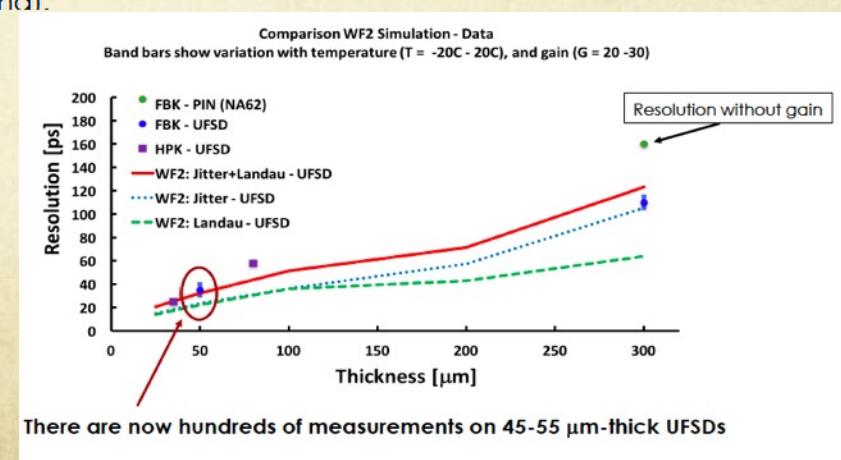


The gain layer:
a parallel plate
capacitor with high
field

The LGAD sensors, as proposed and first manufactured by CNM

(National Center for Micro-electronics, Barcelona):

- LGAD chosen by ATLAS & CMS for current upgrade
- Connected technology: SPADS (basic elements of SiPM)
 - Still suffer large dark count (temperature)



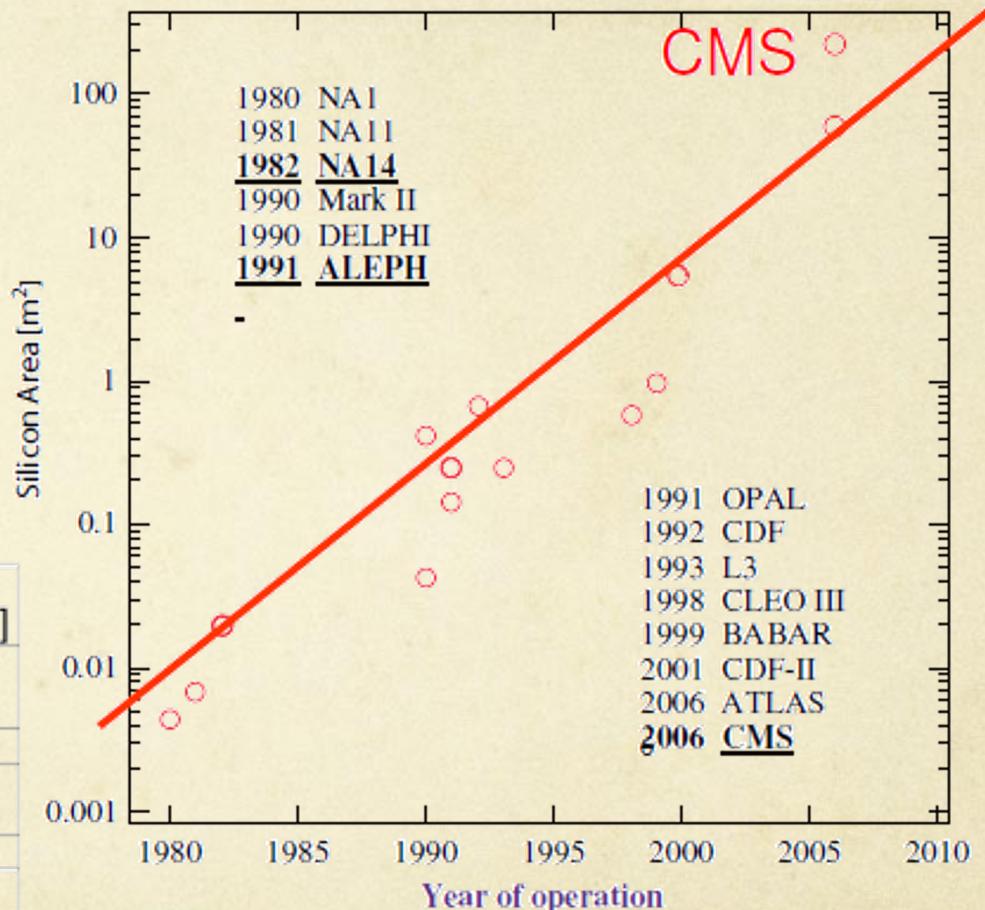
2. Detector Technologies:

Silicon sensors

Increasing popularity

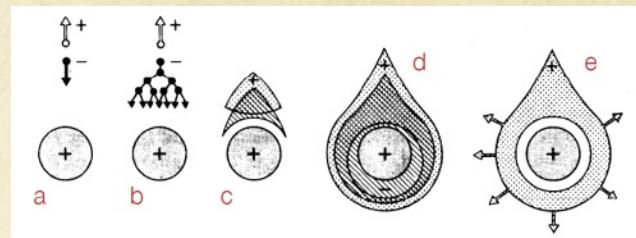
- Initially restricted to vertexing
 - LEP, B-factories
- Gradually introduced for tracking
 - LHC
 - Possible due to development of integration techniques (bonding, ...)

experiment	nb. of detectors	nb. of channels	silicon area [m^2]
CMS	15.95 k	10×10^6	223
ATLAS	16.0/2 k	6.15×10^6	60
AMS 2	2.3 k	196 k	6.5
DO 2		793 k	4.7
CDF SVX II	720	405 k	1.9
Babar		140 k	0.95
Aleph	144	95 k	0.49
L3	96	86 k	0.23



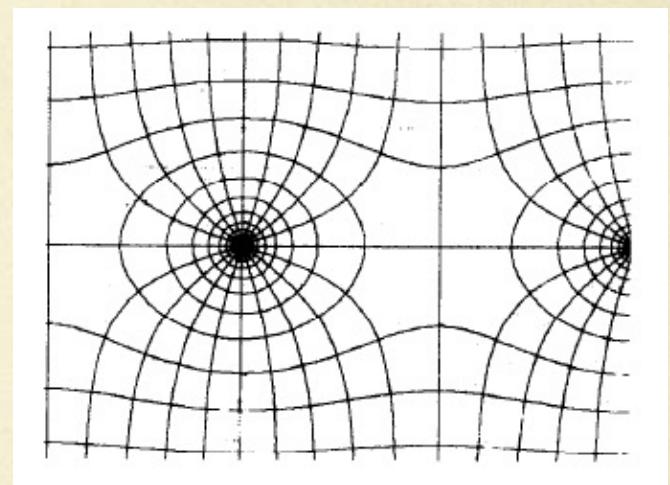
○ Basic sensitive element

- Metallic wire, $1/r$ effect generated an avalanche
- Signal depends on gain (proportional mode) typically 10^4
- Signal is fast, a few ns



○ Gas proportional counters

- Multi-Wire Proportional Chamber
 - Array of wires
 - 1 or 2D positioning depending on readout
 - Wire spacing (pitch) limited to 1-2 mm
- Straw or drift tube
 - One wire in One tube
 - Extremely fast (compared to Drift Chamber)
 - Handle high rate
 - Spatial resolution <200 μm
 - Left/right ambiguity



Electric fields line
around anode wires

2. Detector Technologies:

Wire chambers “advanced”

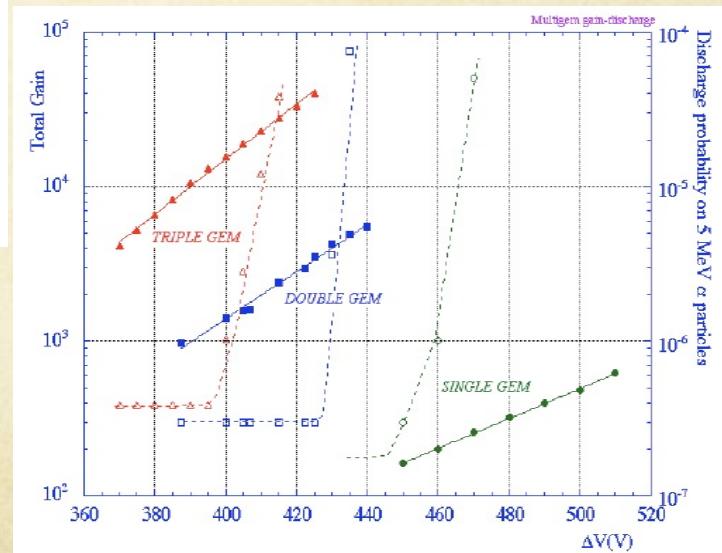
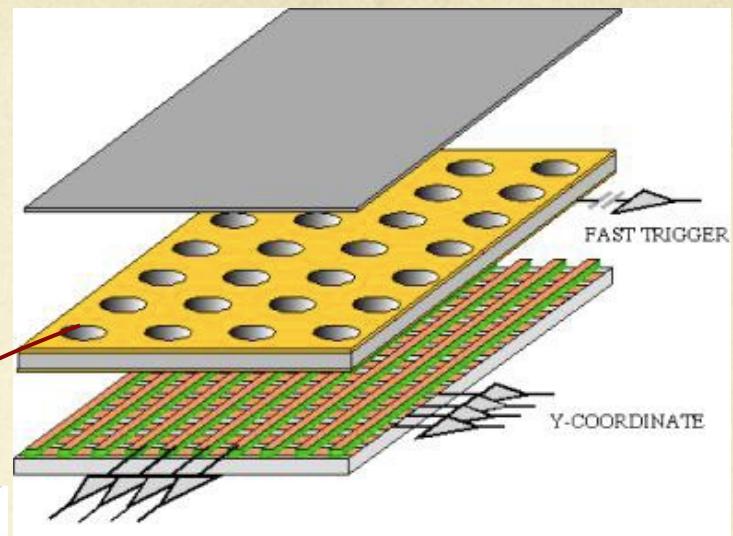
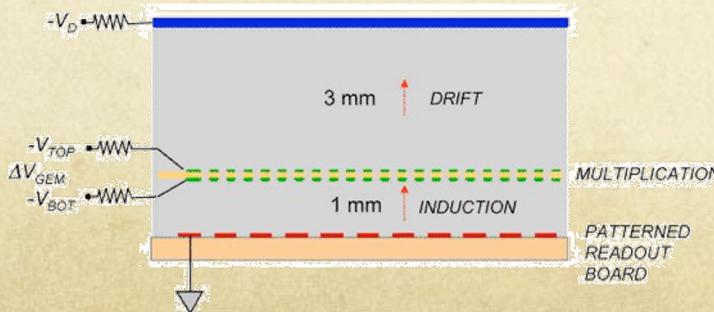
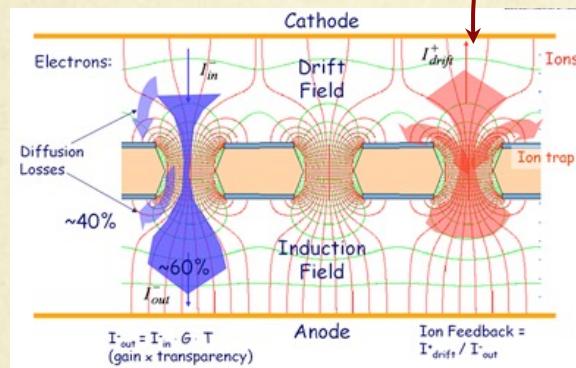
○ Micro-pattern gas multipliers

→ MSGC

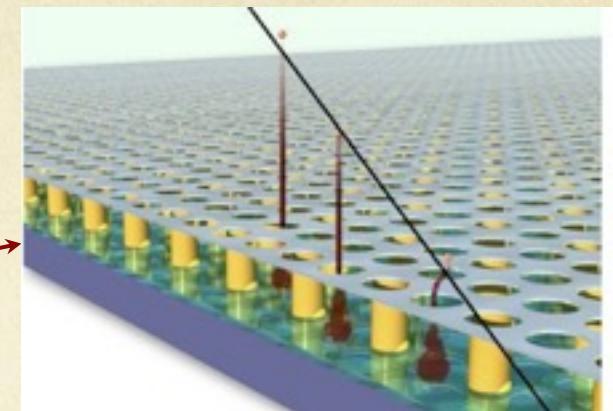
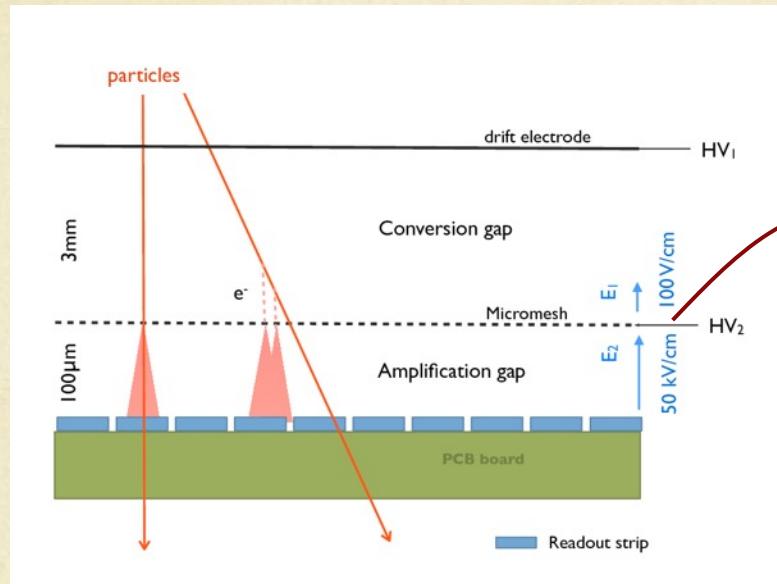
- Replace wires with lithography micro-structures
- Smaller anodes pitch 100-200 μm
- BUT Ageing difficulties due to high voltage and manufacturing not so easy

→ GEM

- Gain 10^5
- Hit rate 10^6 Hz/cm^2

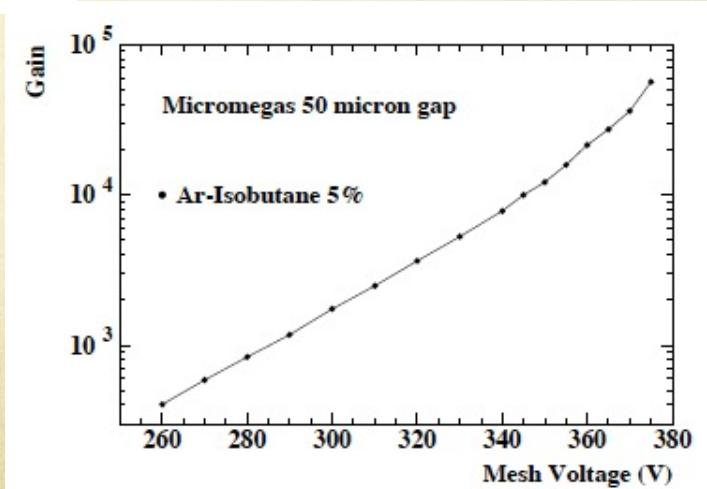


○ Micro-pattern gas multipliers



→ MICROMEGAS

- Even smaller distance anode-grid
 - Hit rate 10^9 Hz/cm²
- More development
- Electron emitting foil working in vacuum!



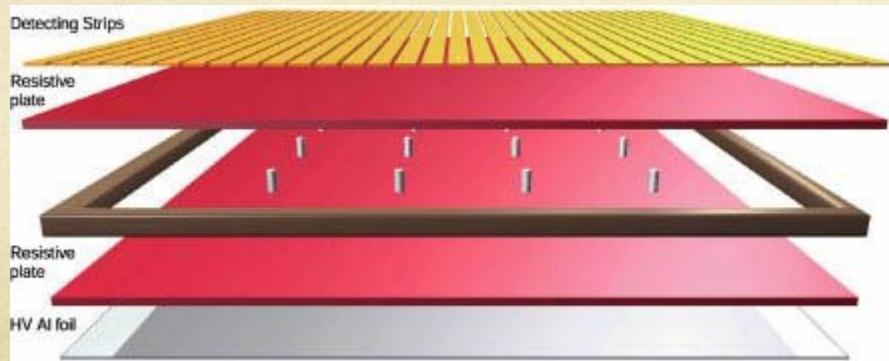
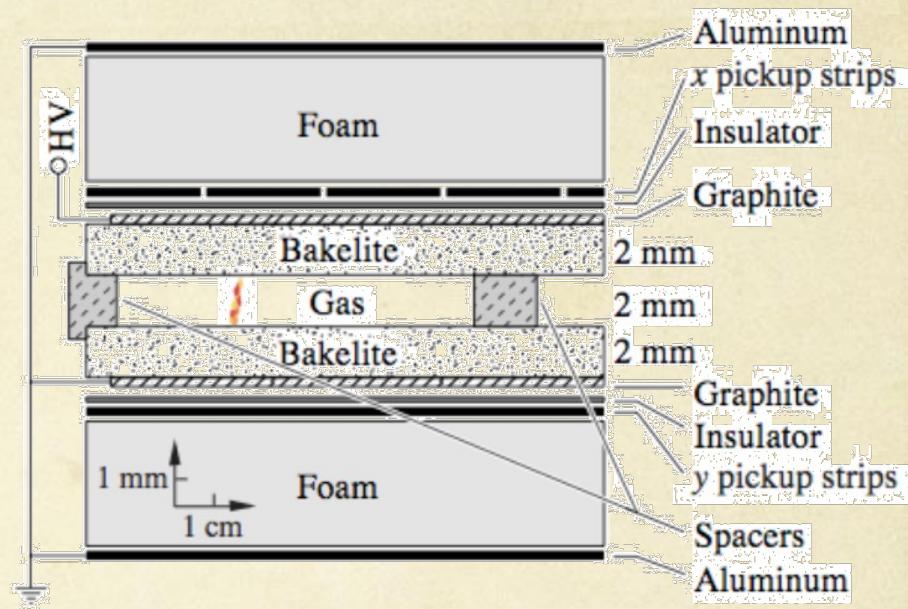
2. Detector Technologies:

Resistive Plate Chamber

- Getting to large planar area & being very fast

○ Principle

- Electrodes = highly resistive material
 - Insulator => potential built up by static charge accumulation
 - Easy to built over many m²
- Small distance
 - large field => avalanche
 - fast collection => time resolution << ns



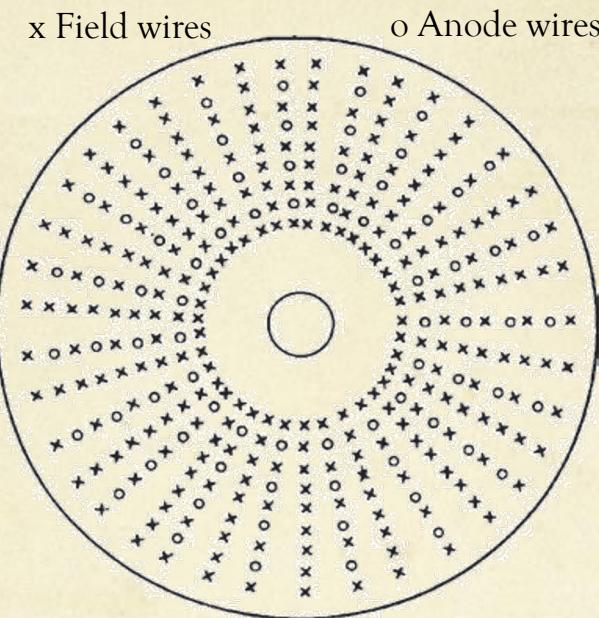
- Used in CMS, COMET, ... for large area muon chambers

2. Detector Technologies:

Drift chambers

○ Basic principle

- Mix field and anode wires
 - Generate a drift
- Pressurize gas to increase charge velocity (few atm)
- 3D detector
 - 2D from wire position
 - 1D from charge sharing at both ends



Belle II drift Chamber

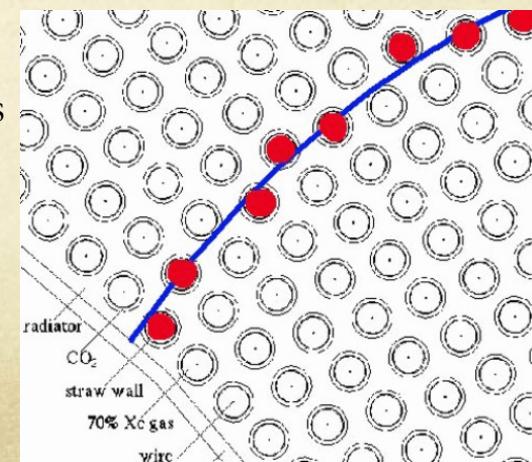
○ Spatial Resolution

- Related to drift path

$$\sigma \propto \sqrt{\text{drift length}}$$

- Typically 100-200 μm

Same principle
with straw tubes



○ Remarks

- Could not go to very small radius

2. Detector Technologies:

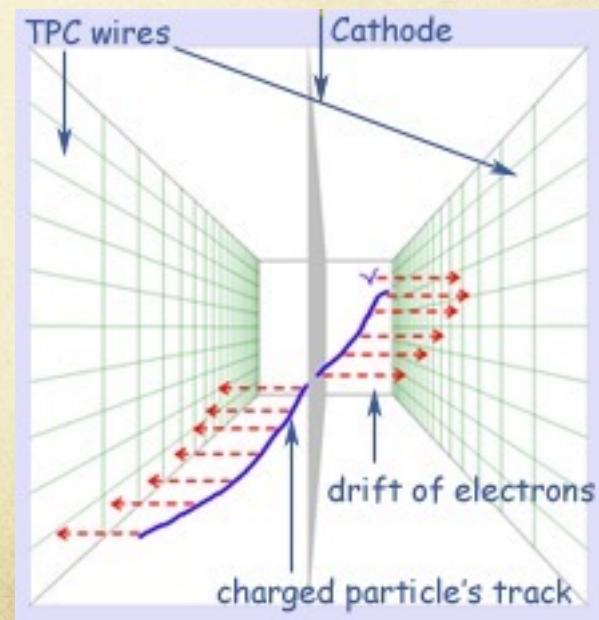
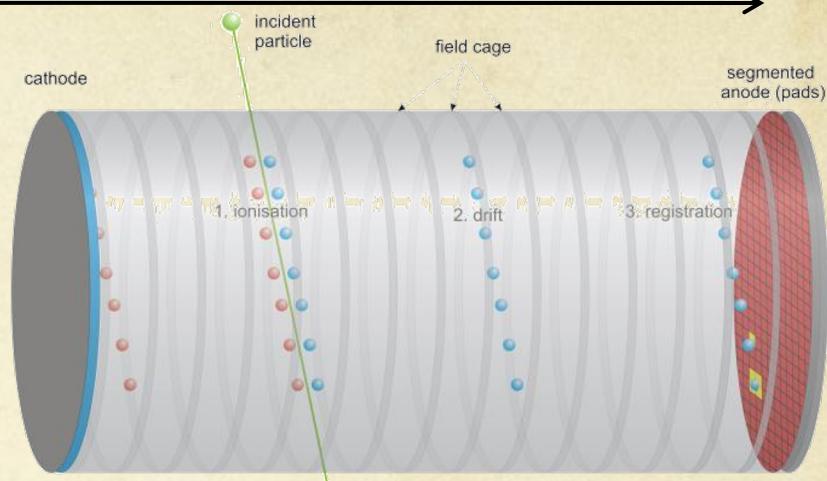
Time Projection Chambers 1/2

○ Benefits

- Large volume available
- Multi-task: tracking + Part. Identification

○ Basic operation principle

- Gas ionization → charges
- Electric field → charge drift along straight path
- Information collected
 - 2D position of charges at end-cap
 - 3rd dimension from drift time
 - Energy deposited from #charges
- Different shapes:
 - rectangles (ICARUS)
 - Cylinders (colliders)
 - Volumes can be small or very large

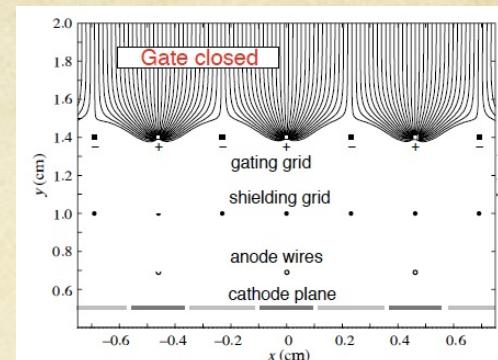
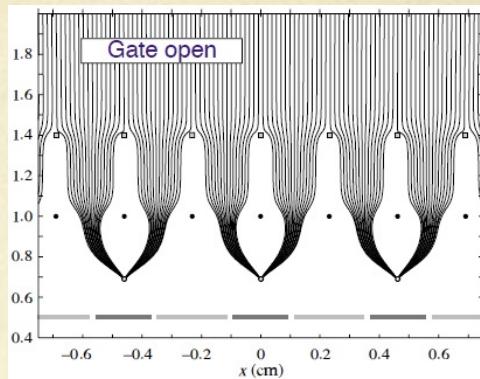


2. Detector Technologies:

Time Projection Chambers 2/2

○ End cap readout

- Gas proportional counters
 - Wires+pads, GEM, Micromegas



○ Performances

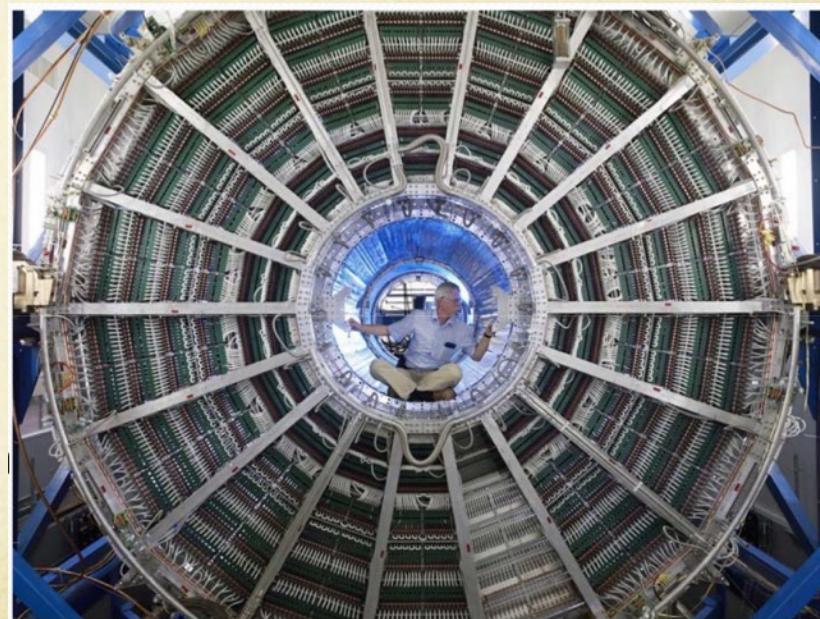
- Two-track resolution $\sim 1\text{cm}$
- Transverse spatial resolution $\sim 100 - 200 \mu\text{m}$
- Longitudinal spatial resolution $\sim 0.2 - 1 \text{ mm}$
- Longitudinal drift velocity: 5 to 7 cm/ μs
 - ALICE TPC (5m long): 92 μs drift time

→ Pro

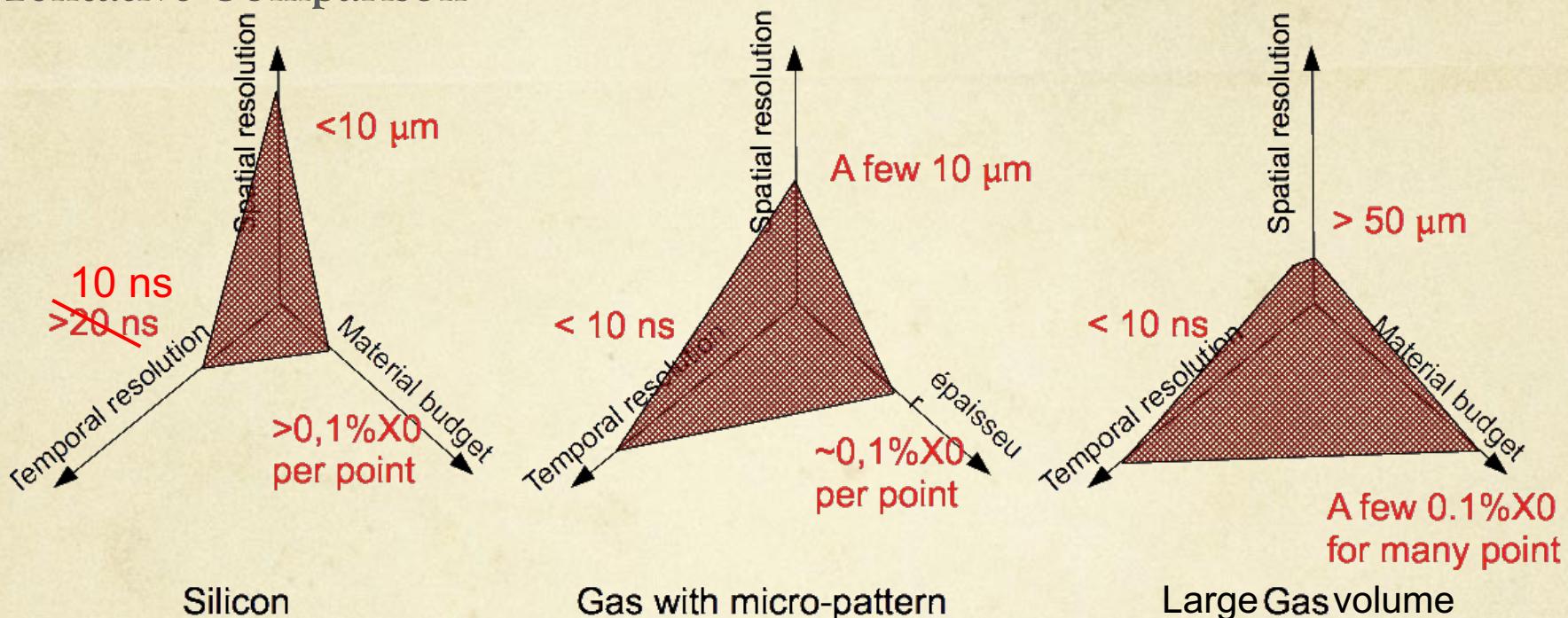
- Nice continuously spaced points along trajectory
- Minimal multiple scattering (inside the vessel)

→ Cons

- Limiting usage with respect to collision rate



○ Tentative Comparison



○ Trend

- Faster collision rates and higher particle multiplicities favour
 - Fast silicon sensors and micro-pattern gas chambers
 - pixelisation
 - Still large gas ensemble for
BelleII (SuperKEKB) => CDC and ALICE or ILD (ILC) => TPC

○ Solenoid

- Field depends on current I, length L, # turns N
 - on the axis $B = \frac{\mu_0 NI}{\sqrt{L^2 + 4R^2}}$
- Typically: 1 T needs 4 to 8 kA
→ **superconducting** metal to limit heat
- Field uniformity needs flux return (iron structure)
 - Mapping is required for fitting (remember $B(x)$?)
 - Usually performed with numerical integration
- Calorimetry outside → limited material → **superconducting**
- Fringe field calls for compensation



○ Superconduction

- cryo-operation → quenching possible !
- Magnetic field induces energy: $E \propto B^2 R^2 L$
 - Cold mass necessary to dissipate heat in case of quench

	Field (T)	Radius (m)	Length (m)	Energy (MJ)
ALICE	0.5	6		150
ATLAS	2	2.5	5.3	700
CMS	4	5.9	12.5	2700
ILC	4	3.5	7.5	2000

○ From a detection principle to a detector

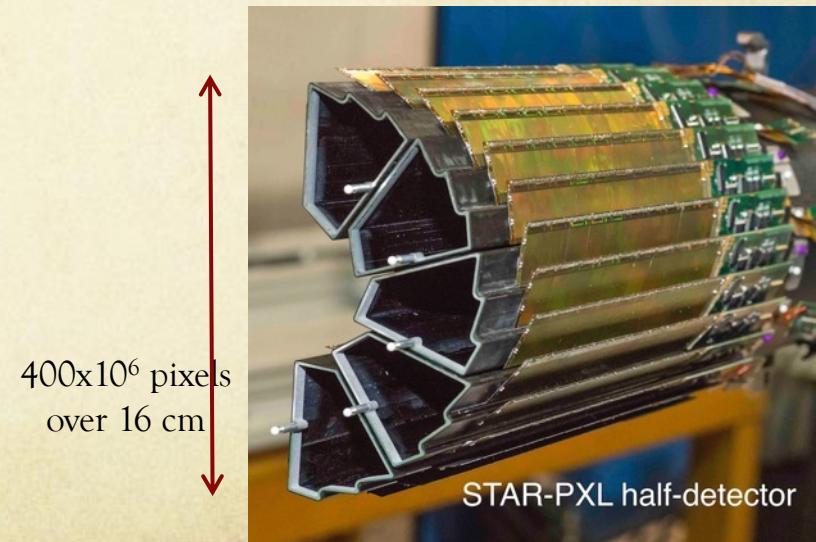
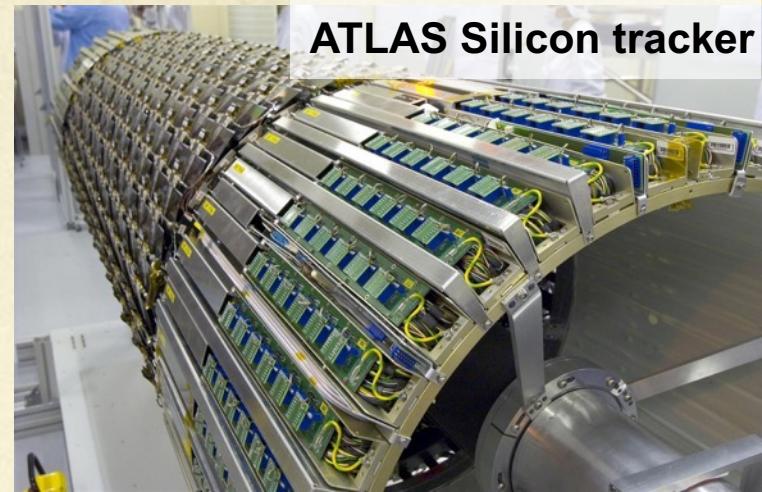
- Build large size or many elements
 - Manufacture infrastructures
 - Characterization capabilities
 - Production monitoring
 - New monolithic silicon pixel detector tend to replace silicon strip technology

→ Integration in the experiment

- Mechanical support
- Electrical services (powering & data transmission)
- Cooling (signal treatment dissipates power)

→ Specific to trackers

- Internal parts of multi-detectors experiment
→ limited space
- Material budget is ALWAYS a concern
- ⇒ trade-offs required



STAR-PXL half-detector

○ Signal generation

- see Ramo's theorem

○ Silicon drift detectors

- Real 2D detectors made of strips
- 1D is given by drift time

○ Diamond detectors

- Could replace silicon for hybrid pixel detectors
- Very interesting for radiation tolerance
- Used in beam monitoring

○ Charge Coupled Devices (CCD)

- Fragile/ radiation tolerance
- Used once in SLD VTX (~ 2000)

○ Nuclear emulsions

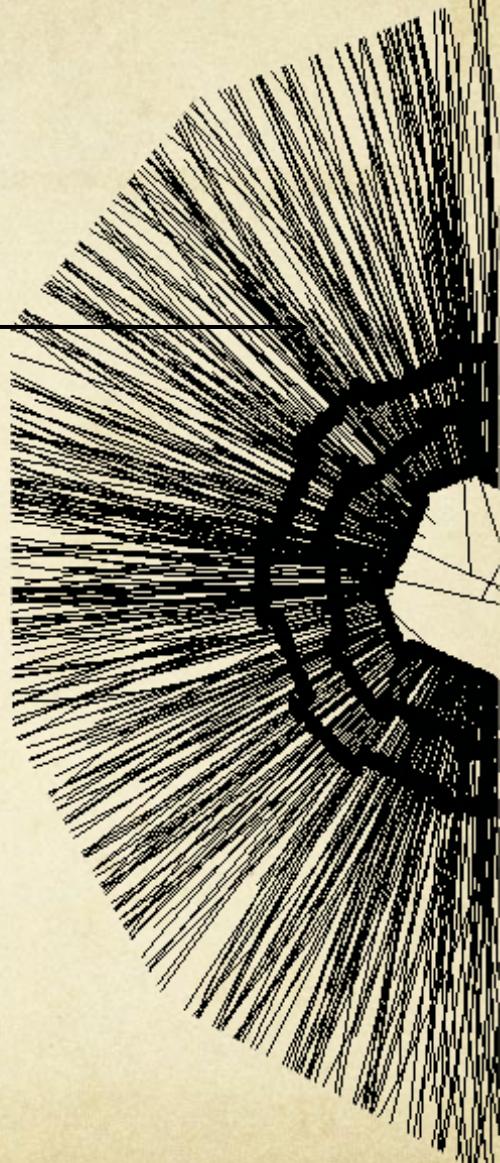
- One of the most precise $\sim 1\mu\text{m}$
- No timing information → very specific applications

○ Scintillators

- Extremely fast (100 ps)
- Could be arranged like straw tubes
- But quite thick ($X_0 \sim 2 \text{ cm}$)
- Used in LHCb SciFi

3. Standard algorithms

- Finders
- First evaluation of momentum resolution
- Fitters
- Alignment





○ Global methods

- Transform the coordinate space into **pattern space**
 - “pattern” = parameters used in track model
- Identify the “best” solutions in the new phase space
- Use all points at a time
 - No history effect
- Well adapted to evenly distributed points with same accuracy

○ Local methods

- Start with a **track seed** = restricted set of points
 - Could require good accuracy from the beginning
- Then extrapolate to next layer-point
 - And so on...**iterative procedure**
- “Wrong” solutions discarded at each iteration
- Possibly sensitive to “starting point”
- Well adapted to redundant information

**FINDING drives
tracking efficiency
fake track rate**



O A simple example

- Straight line in 2D: model is $x = a^*z + b$
- Track parameters (a, b); N measurements x_i at z_i ($i=1..N$)

O A more complex example

- Helix in 3D with magnetic field
- Track parameters ($\gamma_0, z_0, D, \tan\lambda, C=R$)
- Measurements (r, φ, z)

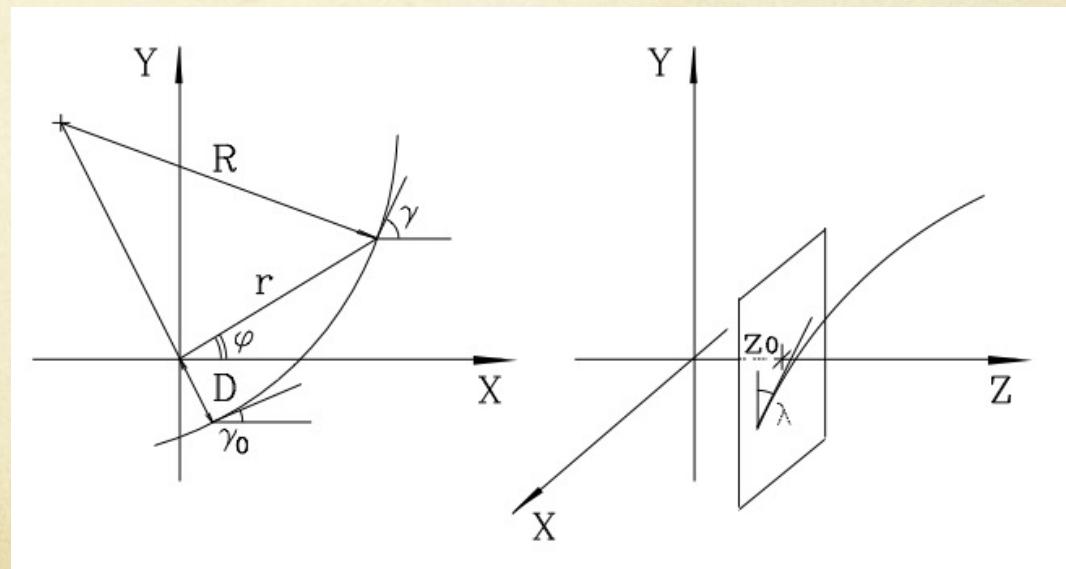
$$\varphi(r) = \gamma_0 + \arcsin \frac{C r (1 + CD) D / r}{1 + 2CD}$$

$$z(r) = z_0 + \frac{\tan\lambda}{C} \arcsin \left(C \sqrt{\frac{r^2 - D^2}{1 + 2CD}} \right)$$

O Generalization

- Parameters: P-vector \mathbf{p}
- Measurements: N-vector \mathbf{c}
- Model: function $f(\mathcal{R}^P \rightarrow \mathcal{R}^N)$

$$f(\mathbf{p}) = \mathbf{c} \Leftrightarrow \text{propagation}$$



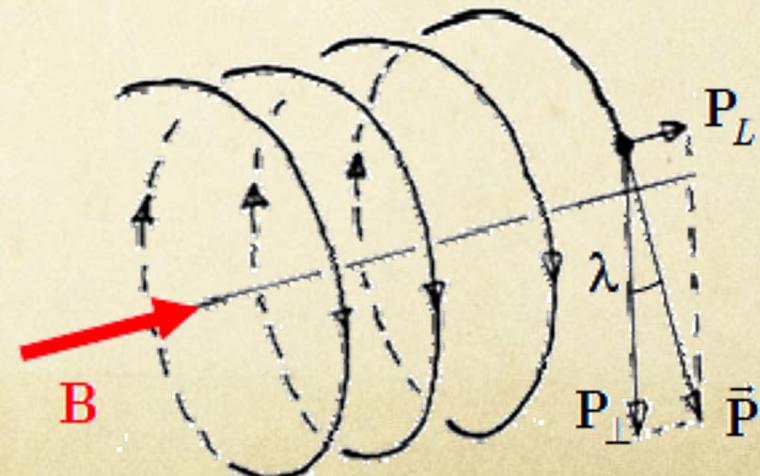
O Another view of the helix

- s = track length
- h = rotation direction
- λ = dip angle
- Pivot point (s=0):
 - position (x_0, y_0, z_0)
 - orientation φ_0

$$x(s) = x_o + R \left[\cos\left(\Phi_o + \frac{hs \cos \lambda}{R}\right) - \cos \Phi_o \right]$$

$$y(s) = y_o + R \left[\sin\left(\Phi_o + \frac{hs \cos \lambda}{R}\right) - \sin \Phi_o \right]$$

$$z(s) = z_o + s \sin \lambda$$

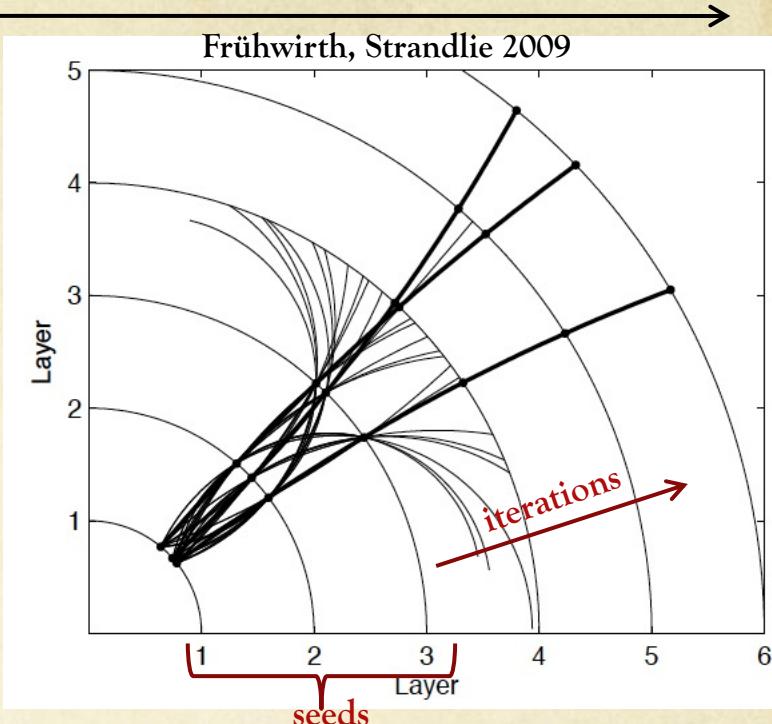


- Track seed = initial segment

- Made of few (2 to 4) points
 - One point could be the expected primary vtx
- Allows to initialize parameter for track model
- Choose most precise layers first
 - usually inner layers
- But if high hit density
 - Start farther from primary interaction
@ lowest density
 - Limit mixing points from different tracks

- Extrapolation step

- Out or inward (=toward primary vtx) onto the next layer
- Not necessarily very precise, especially **only local model** needed
 - Extrapolation uncertainty \lesssim layer point uncertainty
 - Computation speed important
- Match (associate) nearest point on the new layer
 - Might skip the layer if point missing
 - Might reject a point: if worst track-fit or if fits better with another track



○ Variant with track segments

- First build “tracklets” on natural segments
 - Sub-detectors, or subparts with same resolution
- Then match segments together
- Typical application:
 - Segments large tracker (TPC) with vertex detector (Si)
 - layers dedicated to matching

○ Variant with track roads

- Full track model used from start

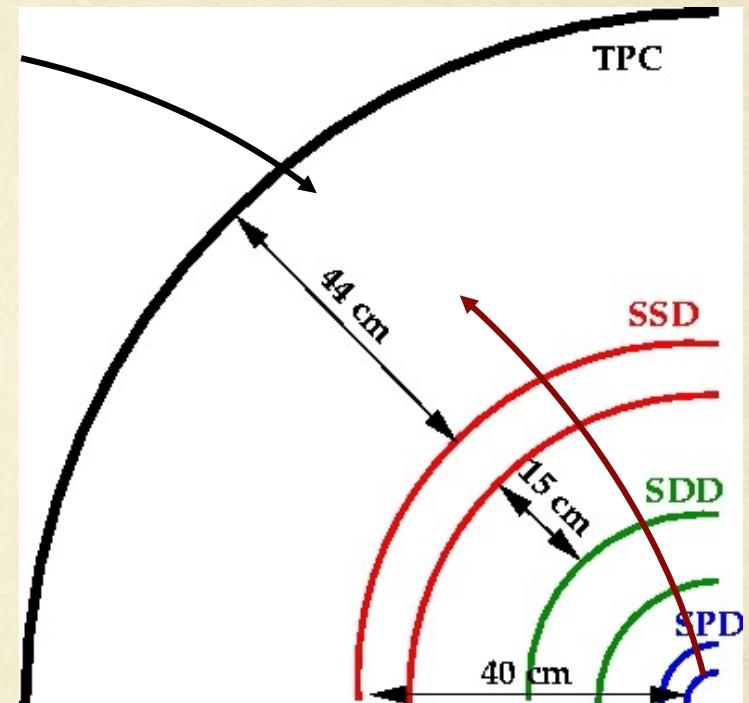
○ Variant with Kalman filter

- See later

○ Figure of merit

$$\sigma_{eff,\phi} \times \sigma_{eff,z} \times \rho_{bckgrnd}$$

- $\sigma_{eff} = \sigma(\text{sensor}) \oplus \sigma(\text{track extrapolation})$ = effective spatial resolution
- ρ = background hit density

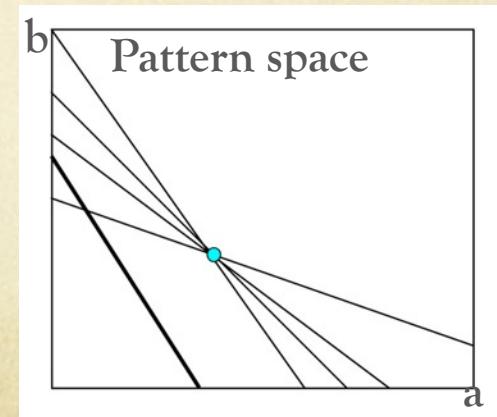
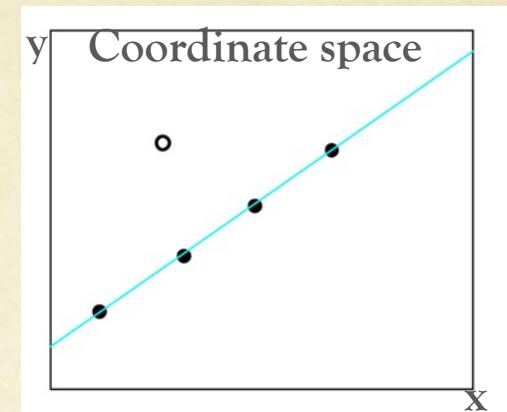


○ Brute force = combinatorial way

- Consider all possible combination of points to make a track
- Keep only those compatible with model
- Usually too time consuming...

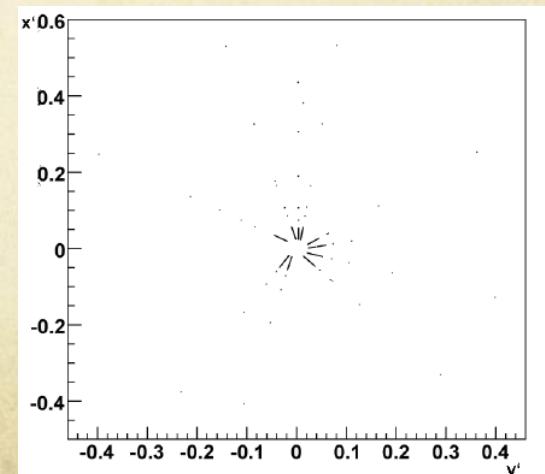
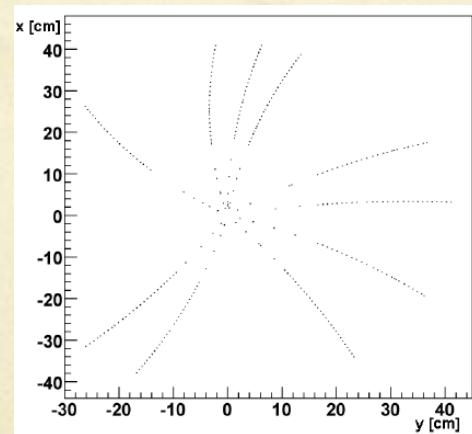
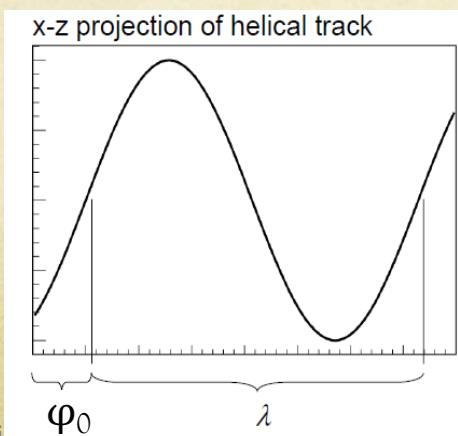
○ Hough transform

- Example straight track:
 - Coord. space $y = a^*x + b \Leftrightarrow$ pattern space $b = y - x^*a$
 - Each point (y,x) defines a line in pattern space
 - All lines, from points belonging to same straight-track, cross at same point (a,b)
 - In practice:
discretize pattern space and search for maximum
- Applicable to circle finder
 - needs two parameters as well (r, φ of center)
if track is assumed to originate from $(0,0)$
- More difficult for more than 2 parameters...



○ Conformal mapping for helix

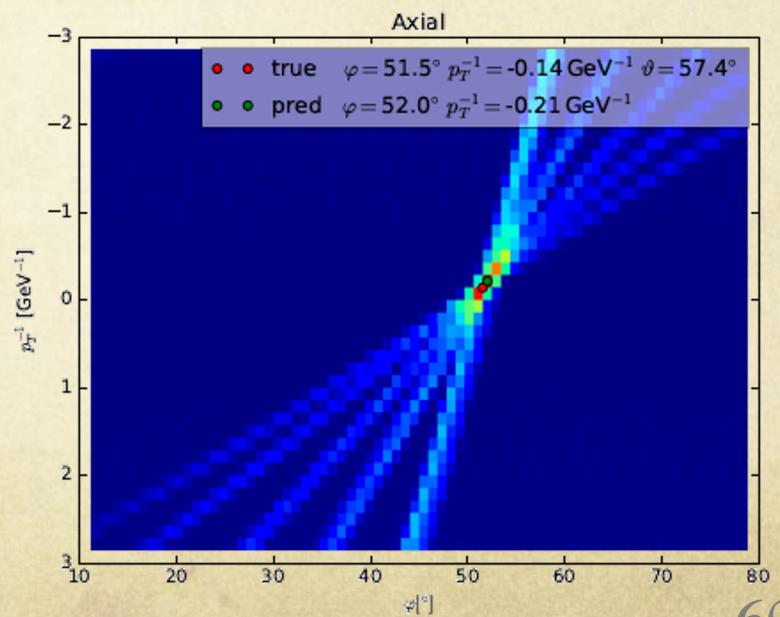
- (x_0, y_0, z_0) a (pivot) point on the helix with (a, b) the center of the projected circle of radius r
 - $(x-a)^2 + (y-b)^2 = r^2$
- Transforming to $x' = \frac{x-x_0}{r^2}$, $y' = \frac{y-y_0}{r^2}$ leads to $y' = -\frac{a}{b}x' + \frac{1}{2b}$ i.e. a line!
 - So all measured points (x, y) in circles are aligned in (x', y') plane
- Use Hough transform $(x', y') \rightarrow (r, \theta)$ so that $r = x' \cos \theta + y' \sin \theta$
 - To find the lines corresponding to true circles with $a = r \cos \theta$ and $b = r \sin \theta$
- Repeat for different z_0
 - New Hough transforms
 - λ = dip angle
 - φ_0 = orientation of pivot point



○ Figure of merit

- Search precision in pattern space depends on bin-size in the pattern space
 - Such bin-size \sim uncertainty on the measurements

$$\sigma_\phi(\text{sensor}) \times \sigma_z(\text{sensor}) \times \rho_{bckgrnd}$$



○ Why do we need to fit?

- Measurement error
- Multiple scattering error

○ Global fit

- Assume knowledge of:
 - all track points
 - full correlation matrix
 - difficult if $\sigma_{\text{mult. scatt.}} \gtrsim \sigma_{\text{meas.}}$
- Least square method

○ Iterative (local) fit

- Iterative process:
 - points included in the fit one by one
 - could be merged with finder step
- Kalman filter

FITTING drives
track extrapolation
& momentum res.



O The rule

- For the fit: nb of constraints > nb of free parameters in the track model

O Measurements

- 1 point in 2D = 1 constraint ($x \leftrightarrow y$) or ($r \leftrightarrow \phi$)
- 1 point in 3D = 2 constraints ($x \leftrightarrow z$ & $y \leftrightarrow z$)

O Models

- Straight track in 2D = 2 parameters
 - 1 coordinate @ origin ($z=0$), 1 slope
- Straight track in 3D = 4 parameters
 - 2 coordinates @ origin, 2 slopes
- Circle in 2D = 3 parameters
 - 2 coordinates for center, 1 radius
- Helix in 3D = 5 parameters
 - 3 coordinates for center, 1 radius, 1 dip angle

O Minimal #points needed

\Leftarrow 2 points in 2D

\Leftarrow 2 points in 3D

\Leftarrow 3 points in 2D

\Leftarrow 3 points in 3D



○ Linear model hypothesis

- P track parameters \mathbf{p} , with N measurements \mathbf{c}

$$\vec{c} = \vec{c}_s + A(\vec{p} - \vec{p}_s) + \vec{\epsilon}$$

- \mathbf{p}_s = known starting point (pivot), \mathbf{A} = **track model** NxP matrix,
 $\mathbf{\epsilon}$ = error vector corresponding to \mathbf{V} = covariance NxN matrix

"N measurements" means:

- K points (or layers)
- D coordinates at each point
- N = KxD

○ Sum of squares:

$$\sum \frac{(\text{model} - \text{measure})^2}{\text{uncertainty}^2} \quad \rightarrow \quad S(\vec{p}) = (\vec{c}_s + A(\vec{p} - \vec{p}_s) - \vec{c})^T V^{-1} (\vec{c}_s + A(\vec{p} - \vec{p}_s) - \vec{c})$$

○ Best estimator (minimizing variance)

$$\frac{dS}{d\vec{p}}(\underline{\vec{p}}) = 0 \quad \rightarrow \quad \underline{\vec{p}} = \vec{p}_s + (A^T V^{-1} A)^{-1} A^T V^{-1} (\vec{c} - \vec{c}_s)$$

- Variance (= uncertainty) of the estimator:

$$\underline{V_{\vec{p}}} = (A^T V^{-1} A)^{-1}$$

- Estimator \mathbf{p} follows a χ^2 law with N-P degrees of freedom

○ Problem \Leftrightarrow inversion of a PxP matrix ($A^T V^{-1} A$)

- **But real difficulty could be computing \mathbf{V} (NxN matrix)**

⬅ layer correlations if multiple scattering non-negligible if $\sigma_{\text{mult. scatt.}} \gtrsim \sigma_{\text{meas}}$

3. Standard algorithms:

LSM on straight tracks

○ Straight line model

- 2D case → D=2 coordinates (z,x)
- 2 parameters: a = slope, b = intercept at z=0

○ General case

- K+1 detection planes (i=0...k)

- located at z_i
- Spatial resolution σ_i

- Useful definitions

$$S_1 = \sum_{i=0}^K \frac{1}{\sigma_i^2}, \quad S_z = \sum_{i=0}^K \frac{z_i}{\sigma_i^2}, \quad S_{xz} = \sum_{i=0}^K \frac{x_i z_i}{\sigma_i^2}, \quad S_{z^2} = \sum_{i=0}^K \frac{z_i^2}{\sigma_i^2}$$

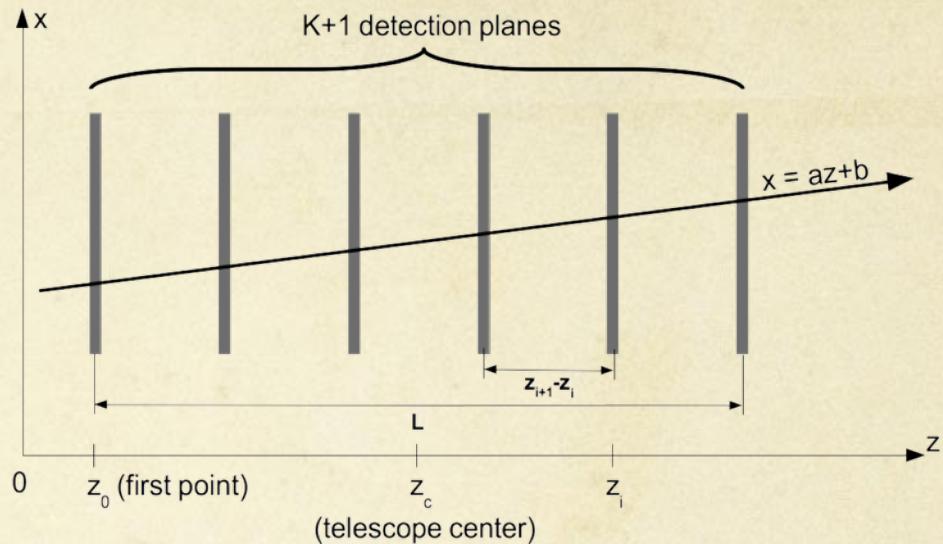
$$\rightarrow \text{Solutions} \quad a = \frac{S_1 S_{xz} - S_x S_z}{S_1 S_{z^2} - (S_z)^2}, \quad b = \frac{S_x S_{z^2} - S_z S_{xz}}{S_1 S_{z^2} - (S_z)^2}$$

- Uncertainties

$$\sigma_a^2 = \frac{S_1}{S_1 S_{z^2} - (S_z)^2}, \quad \sigma_b^2 = \frac{S_{z^2}}{S_1 S_{z^2} - (S_z)^2}$$

! correlation

$$\text{cov}_{a,b} = \frac{-S_z}{S_1 S_{z^2} - (S_z)^2}$$



○ Case of uniformly distributed (K+1) planes

$$\rightarrow z_{i+1} - z_i = L/K \text{ et } \sigma_i = \sigma \quad \forall i$$

$$\rightarrow S_z = 0 \rightarrow a, b \text{ uncorrelated}$$

$$\sigma_a^2 = \frac{12K}{(K+2)L^2} \frac{\sigma^2}{K+1}, \quad \sigma_b^2 = \left(1 + 12 \frac{K}{K+2} \frac{z_c^2}{L^2}\right) \frac{\sigma^2}{K+1}$$

- Uncertainties :

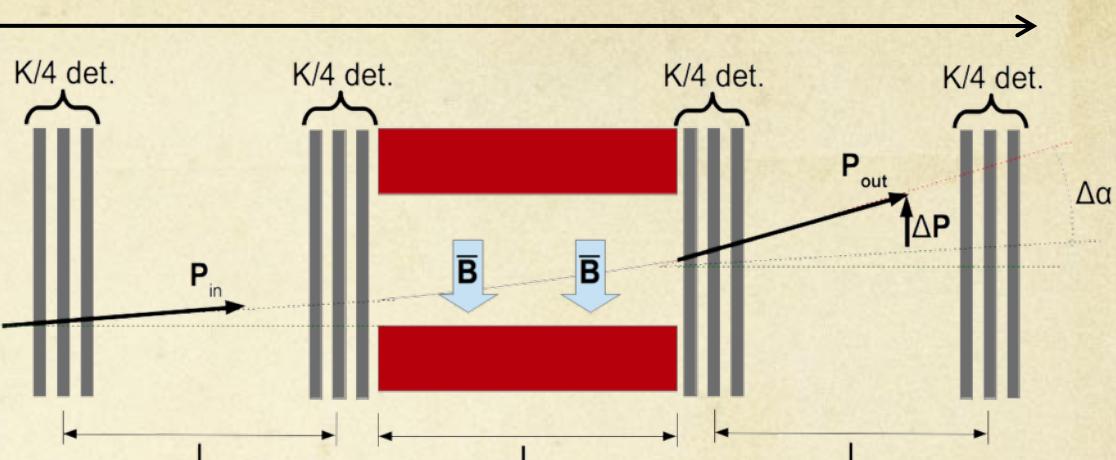
- σ_a and σ_b improve with $1/\sqrt{K+1}$
- σ_a and σ_b improve with $1/L$
- σ_b improve with z_c

3. Standard algorithms:

LSM on fixed target geometry

○ Hypothesis

- K detectors, each with σ single point accuracy
- Uniform field over L from dipole
 - Trajectory: $\Delta\alpha = \left| \frac{0.3qBL}{p} \right|$
 - Bending: $\Delta p = p \Delta\alpha$
- Geometrical arrangement optimized for resolution
 - Angular determination on input and output angle: $\sigma_\alpha^2 = \frac{16 \sigma^2}{K l^2}$



○ Without multiple scattering

- Uncertainty on momentum
- Note proportionality to p and to $\frac{1}{BL}$



$$\frac{\sigma_p}{p} = \frac{8}{0.3q} \frac{1}{BL} \frac{\sigma}{l\sqrt{K}} p$$

○ Multiple scattering contribution

- Bring **additive** term proportional to K



$$\frac{\sigma_p}{p} (MS) = A_N \frac{13.6 \text{ (MeV/c)}}{\beta} \sqrt{\frac{\text{thickness}}{X_0}}$$

Constant with p!

$$\text{and } \sigma_\theta = \frac{13.6 \text{ (MeV/c)}}{\beta p} \sqrt{\frac{\text{thickness}}{X_0}}$$

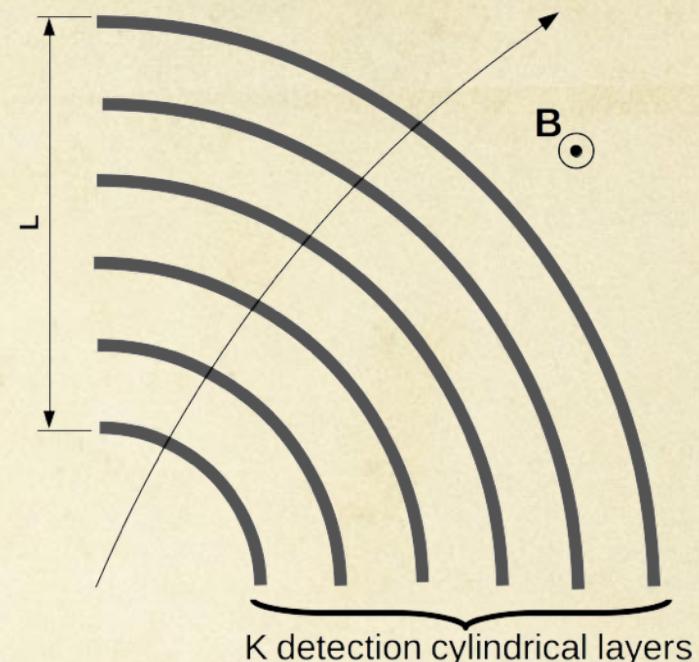
O Hypothesis

- K detectors uniformly distributed each with σ single point accuracy
- Uniform field over path length L

O Without multiple scattering

- Uncertainty on transverse momentum (Glückstern formula)

$$\frac{\sigma_{p_T}}{p_T} = \frac{\sqrt{720}}{0.3q} \frac{1}{BL^2} \frac{\sigma}{\sqrt{K+6}} p_T$$



Note proportionality to p and to $\frac{1}{BL^2}$!

- Works well with large $K > 20$

O Multiple scattering contribution

- Brings additive contribution

$$\frac{\sigma_{p_T}}{p_T} = \frac{1.43}{0.3q} \frac{1}{BL} \sqrt{\frac{13.6 \text{ (MeV/c) thickness}}{\beta} \frac{X_0}{X_0}}$$

Constant with p!

3. Standard algorithms:

Kalman filter 1/2

○ Dimensions

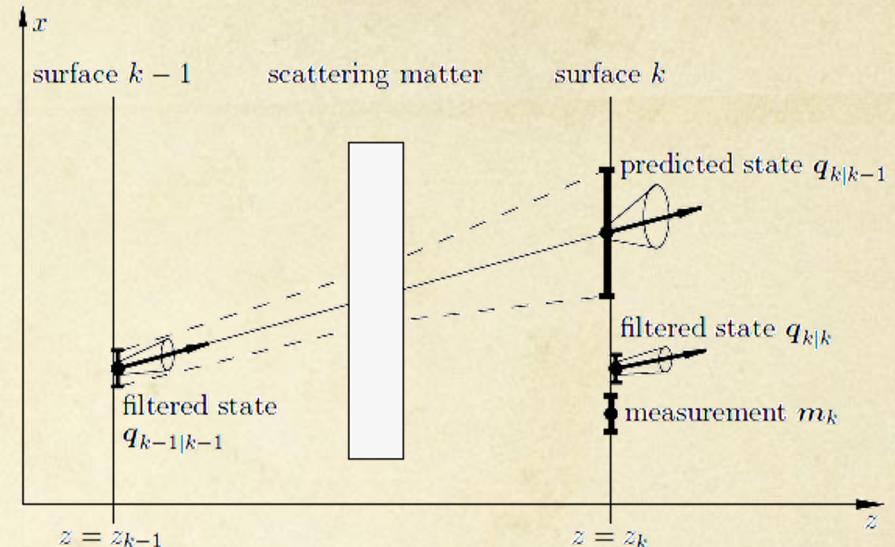
- P parameters for track model
- D “coordinates” measured at each point (usually D<P)
- K measurement points (# total measures: N = KxD)

○ Starting point

- Initial set of parameters: first measurements
- With large uncertainties if unknowns

○ Iterative method

- Propagate to next layer = prediction
 - Using the **system equation** $\vec{p}_k = G \vec{p}_{k-1} + \vec{\omega}_k$
 - G = PxP matrix, ω = perturbation associated with covariance PxP matrix V_ω
 - Update the covariance matrix with additional uncertainties
(ex: material budget between layers) $V_{k|k-1} = V_{k-1} + V_{\omega_k}$
- Add new point to update parameters and covariance, using the **measure equation** $\vec{m}_k = H \vec{p}_k + \vec{\epsilon}_k$
 - H =DxP matrix, ϵ = measure error associated with **diagonal** covariance DxD matrix V_m
 - Weighted means of prediction and measurement using variance $\Leftrightarrow \chi^2$ fit
- Iterate...



$$\vec{p}_k = \left(V_{k|k-1}^{-1} \vec{p}_{k|k-1} + H^T V_{m_k}^{-1} \vec{m}_k \right) \cdot \left(V_{k|k-1}^{-1} + H^T V_{m_k}^{-1} H \right)^{-1}$$



○ Forward and backward filters

- Forward estimate of \vec{p}_k : from $1 \rightarrow k-1$ measurements
- Backward estimate of \vec{p}_k : from $k+1 \rightarrow K$ measurements
- Independent estimates → combination with weighted mean = smoother step

○ Computation complexity

- only PxP, DxP or DxD matrices computation ($\ll N \times N$)

○ Mixing with finder

- After propagation step: local finder
- Some points can be discarded if considered as outliers in the fit (use χ^2 value)

○ Include exogenous measurements

- Like dE/dx , correlated to momentum
- Additional measurement equation

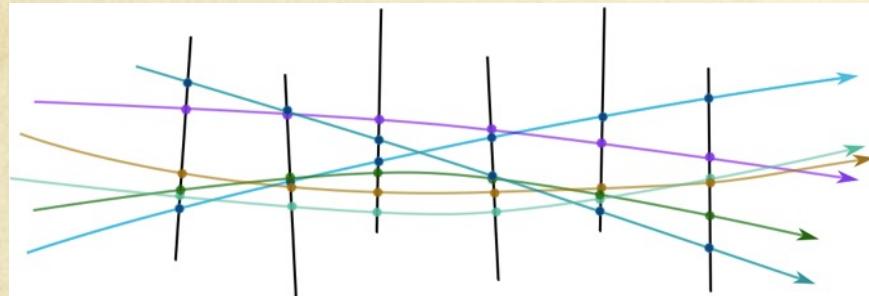
$$\vec{m}'_k = H' \vec{p}_k + \vec{\varepsilon}'_k$$

$$\vec{p}_k = \left(V_{k|k-1}^{-1} \vec{p}_{k|k-1} + H^T V_{m_k}^{-1} \vec{m}_k + H'^T V_{m'_k}^{-1} \vec{m}'_k \right) \cdot \left(V_{k|k-1}^{-1} + H^T V_{m_k}^{-1} H + H'^T V_{m'_k}^{-1} H' \right)^{-1}$$

Let's come back to one initial & implicit hypothesis

- “We know where the points are located.”
- True to the extent we know where the detector is!
- BUT, mechanical instability (magnetic field, temperature, air flow...) and also drift speed variation (temperature, pressure, field inhomogeneity...) limit our knowledge
- Periodic determination of positions and deformations needed = alignment

True tracks & True detector positions



Initial assumption for detector positions & tracks built from these assumptions



Note hit position relative to detector are the same
 tracks reconstructed are not even close to reality...
 and this assuming hits can be properly associated
 together!

○ Alignment parameters

- Track model depends on additional “free” parameters, i.e. the sensor positions

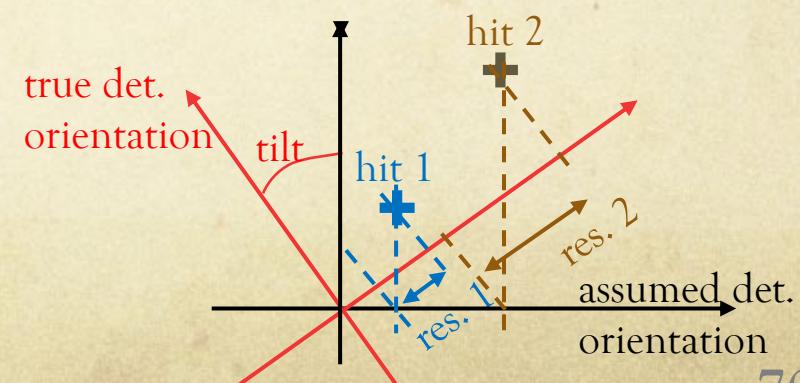
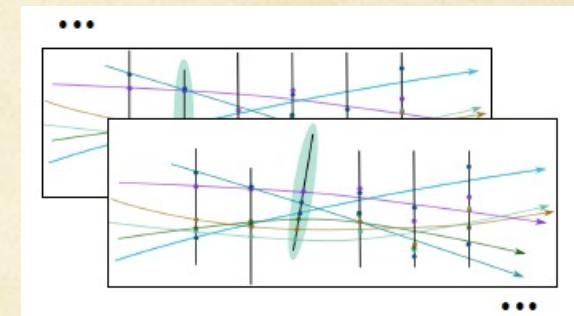
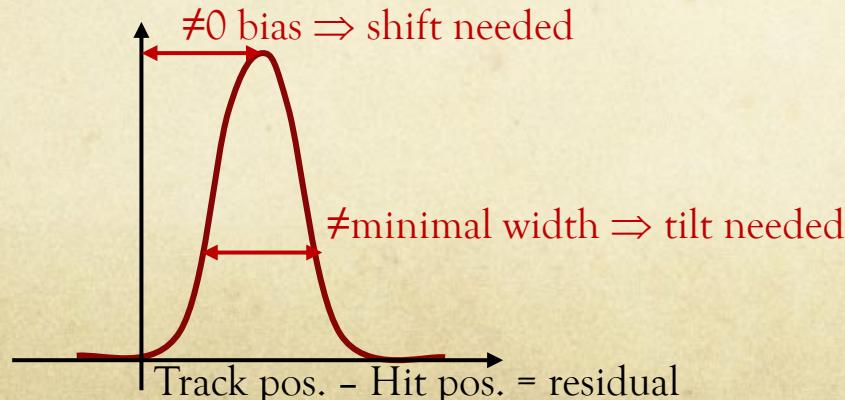
○ Methods to find the relative position of individual sensors

→ Global alignment:

- Fit the new params. to minimize the overall χ^2 of a set of tracks
- Beware: many parameters could be involved (few 10^3 can easily be reached) → Millepede algo.

→ Local alignment:

- Use tracks reconstructed with reference detectors
- Align other detectors by minimizing the “residual” (track-hit distance) width

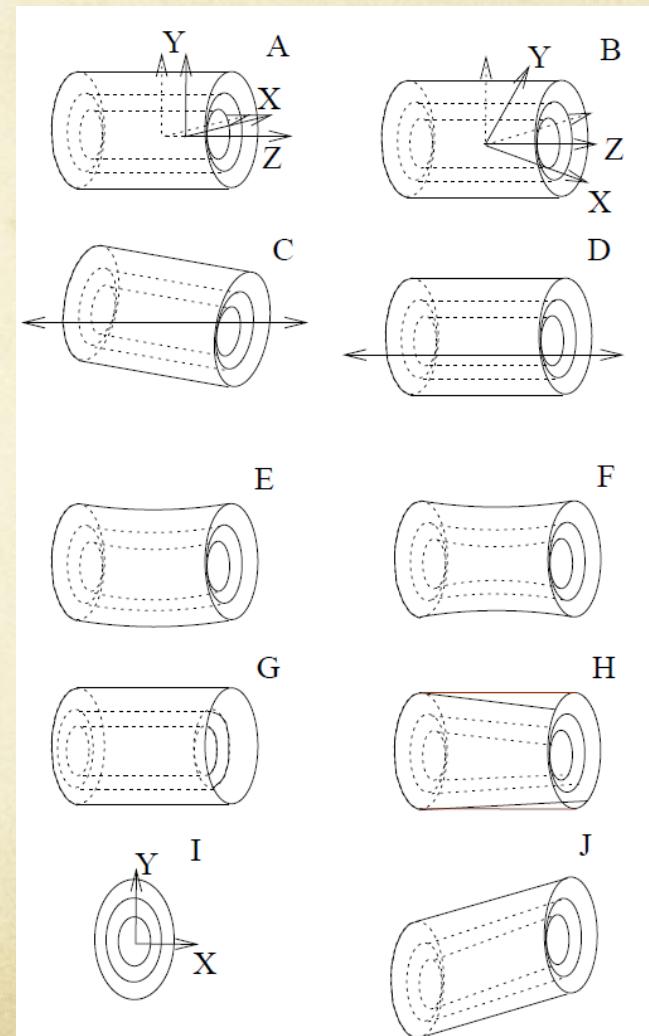


○ In both methods (global or local alignment)

- Use a set of well known tracks and tracking-”friendly” environment to avoid bias
 - Muons (very traversing) and no magnetic field
 - Low multiplicity events

○ Global deformations also possible

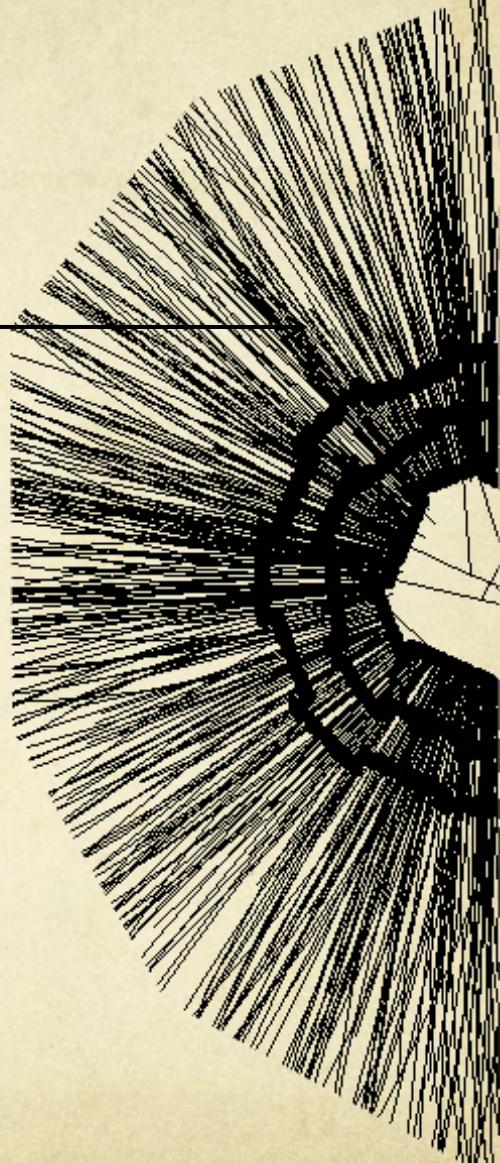
- affect overall positions & momentum
- Corrected through observing
 - Mass peak positions
 - Systematic differences at various track angles or detector positions



4. Advanced methods

(brief illustrations)

- Why ?
- Neural network
- Cellular automaton

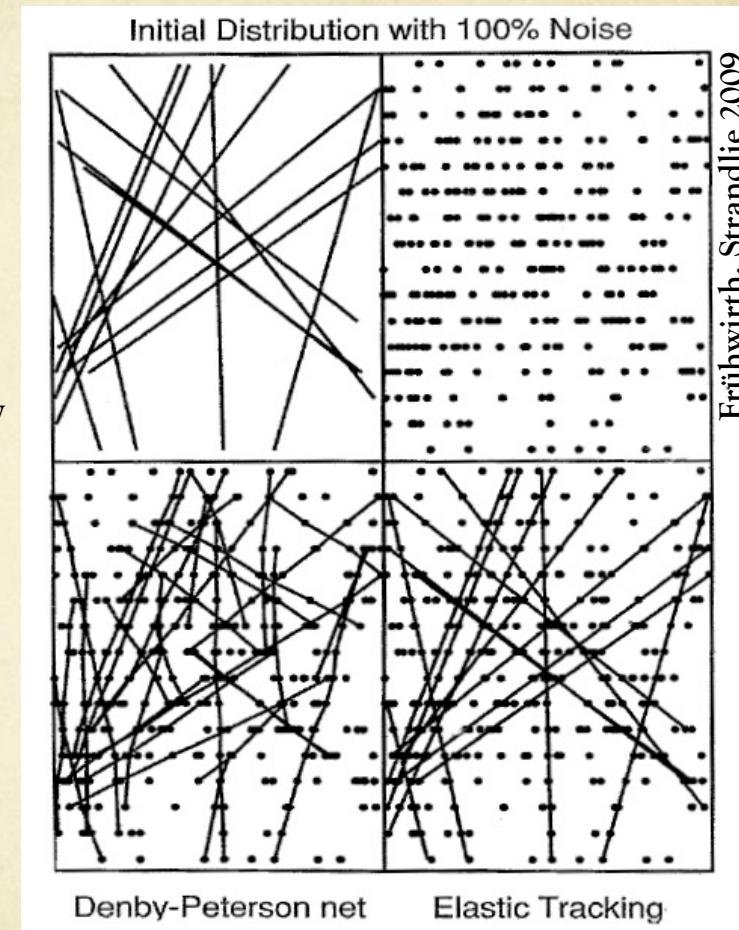


○ Shall we do better?

- Higher track/vertex density,
less efficient the classical method
- Allows for many options and best choice

○ Adaptive features

- **Dynamic change** of track parameters during finding/fitting
- Measurements are weighted according to their uncertainty
 - Allows to take into account several “normally excluded” info
- **Many hypothesis are handled simultaneously**
 - But their number decrease with iterations (annealing like behavior)
- Non-linearity
- Often CPU-time costly (is that still a problem?)



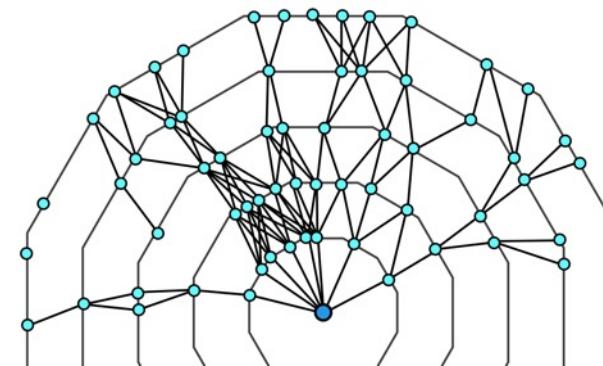
○ Examples

- Neural network, Elastic nets, Gaussian-sum filters, Deterministic annealing, Cellular automaton

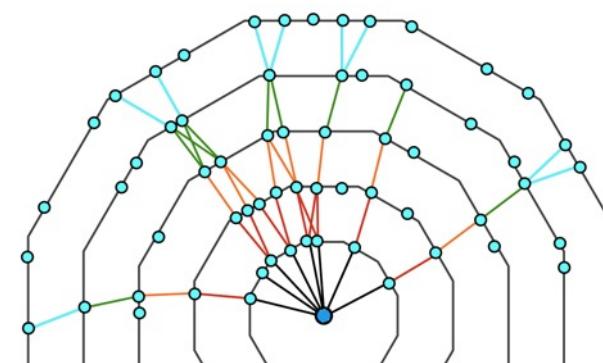
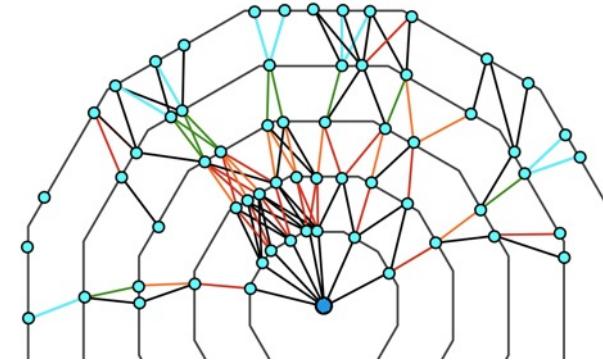
○ Cellular automaton

- Initialization
 - built any cell (= segment of 2 points)
- Iterative step
 - associate neighbour cells (more inner)
 - Raise “state” with associated cells
 - Kill lowest state cells

J. Lettenbichler *et al.*, 2013

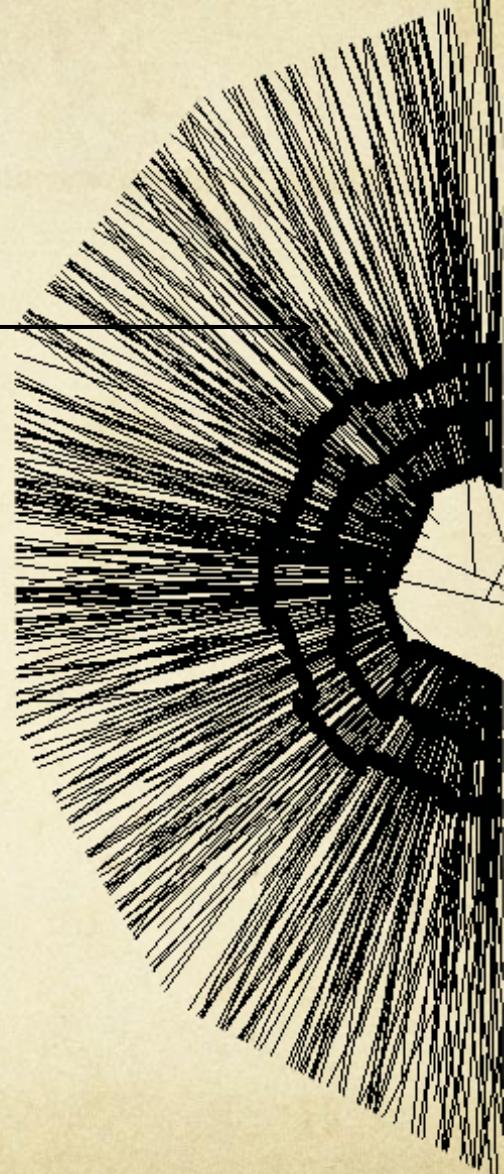


0 (black), 1 (red), 2 (orange), 3 (green), 4 (cyan)



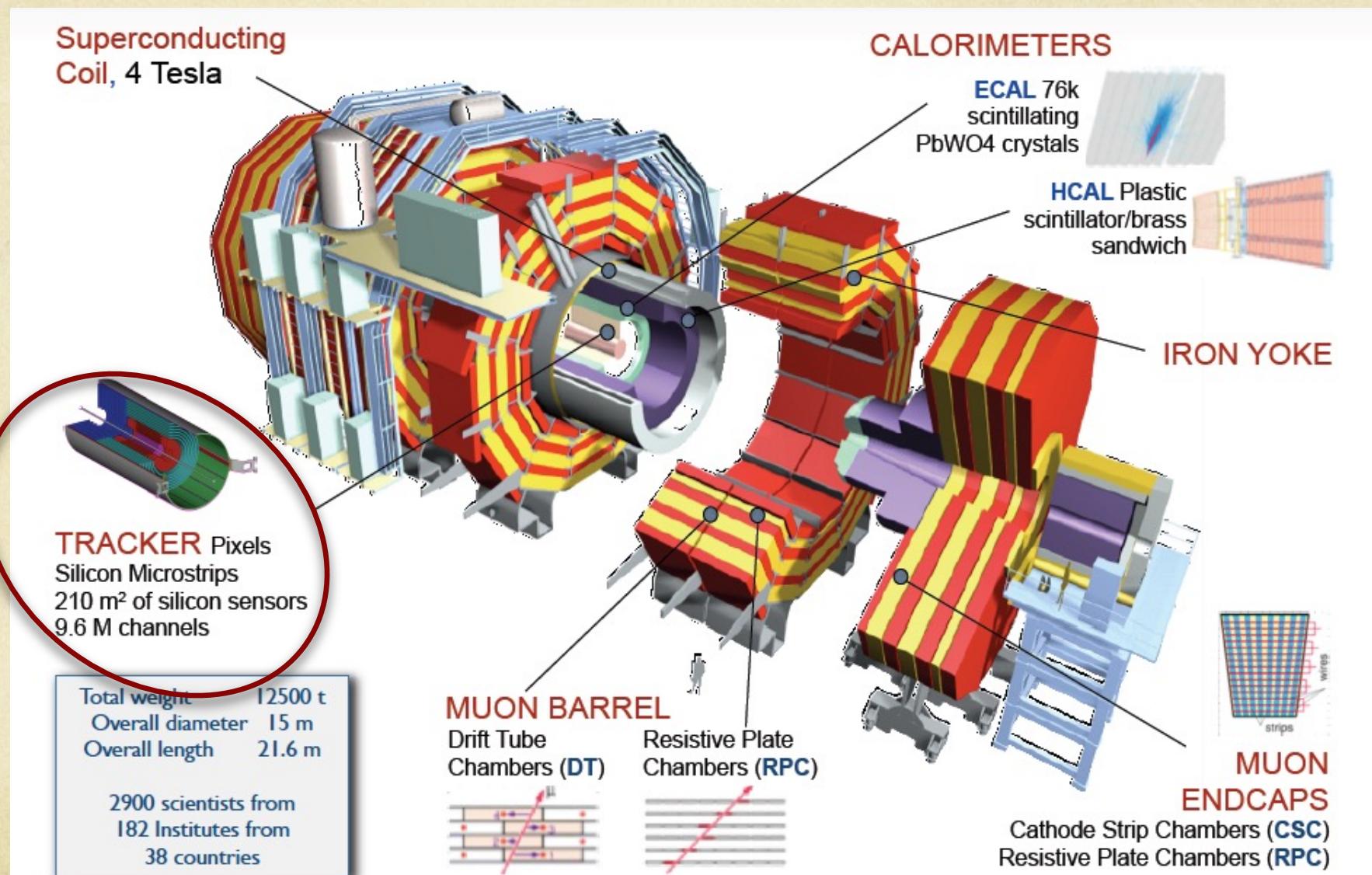
5. Deconstructing some tracking systems

- Collider setups:
 - CMS, ALICE, LHCb, Belle II
- Telescope setups:
 - AMS, ANTARES, OPERA



5. Some tracking systems:

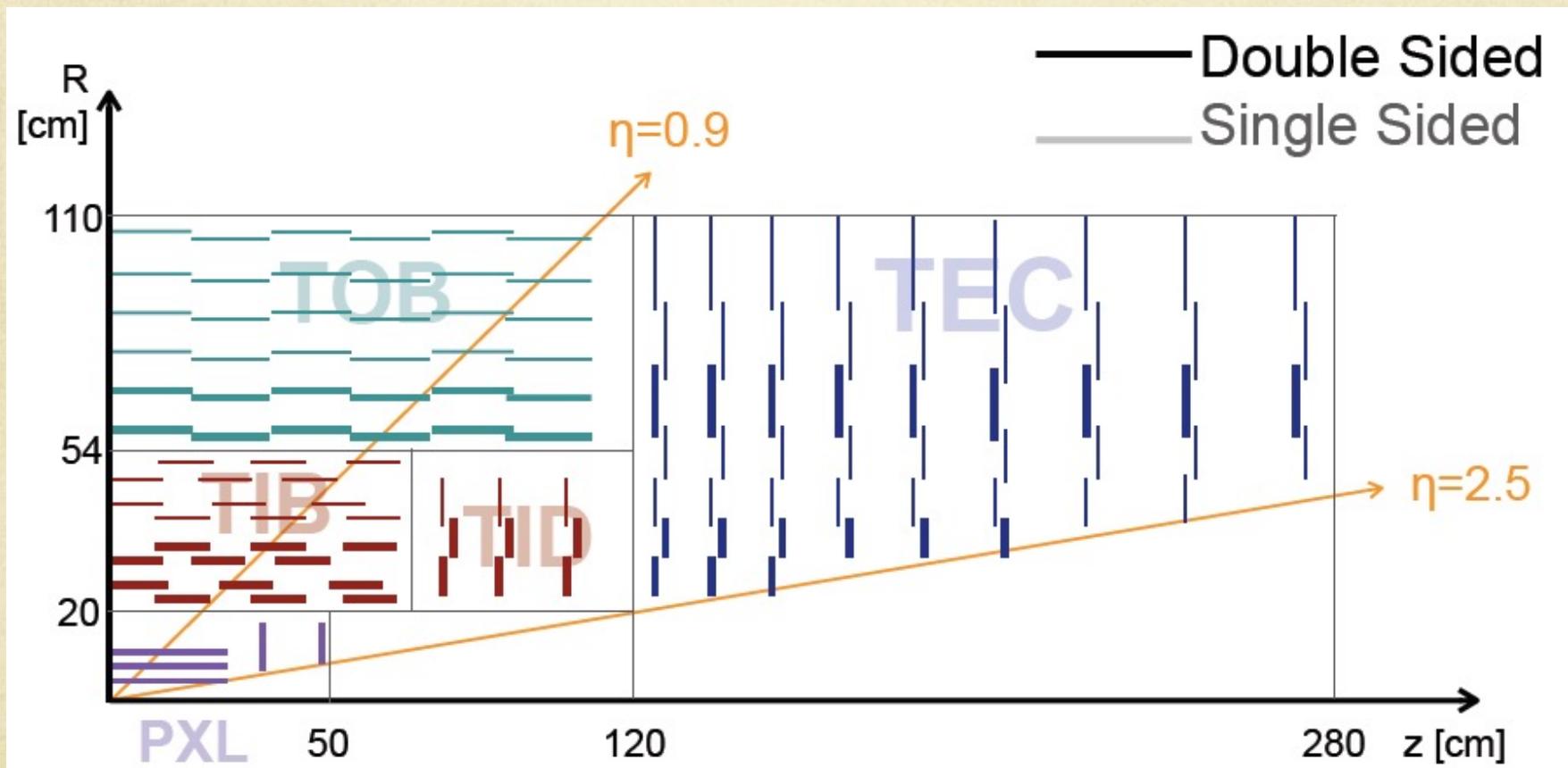
CMS setup



5. Some tracking systems:

CMS setup

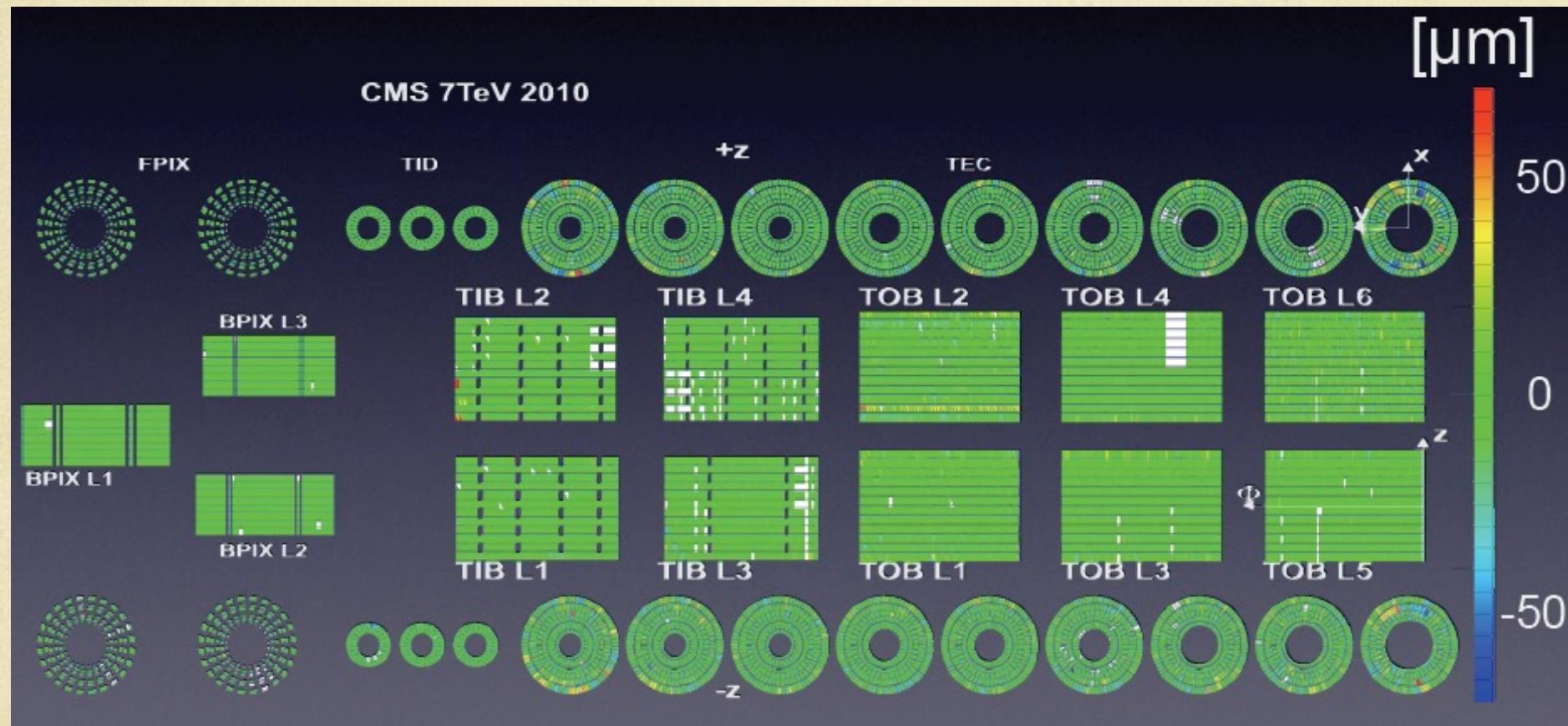
○ The trackerS



5. Some tracking systems:

CMS alignment

○ Alignment residual width

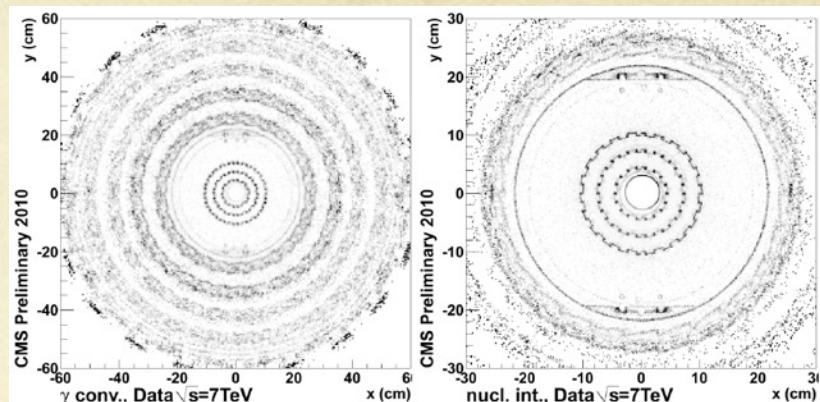


5. Some tracking systems:

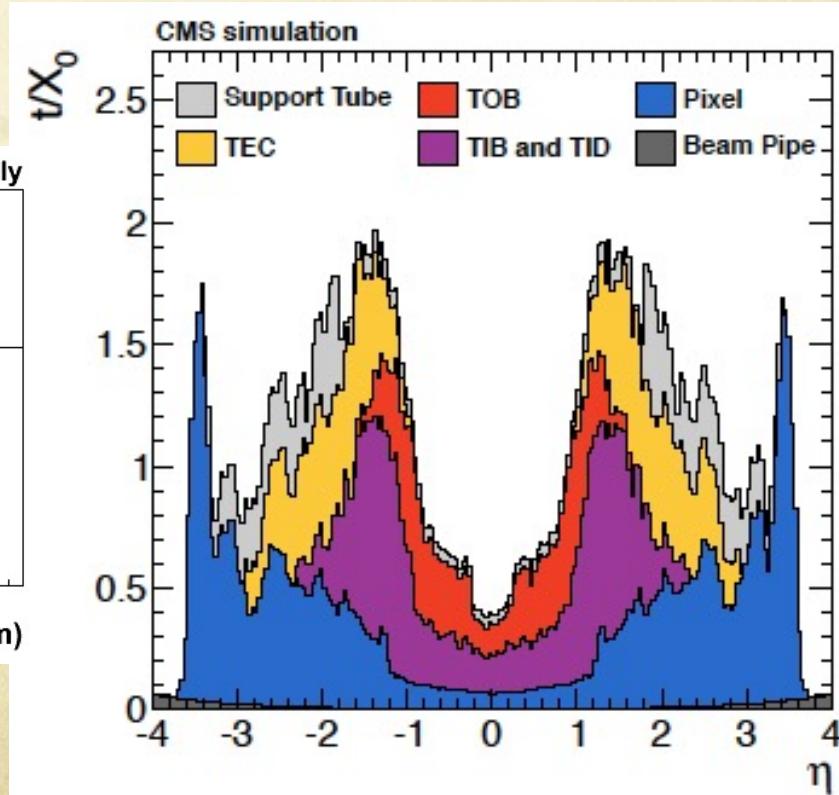
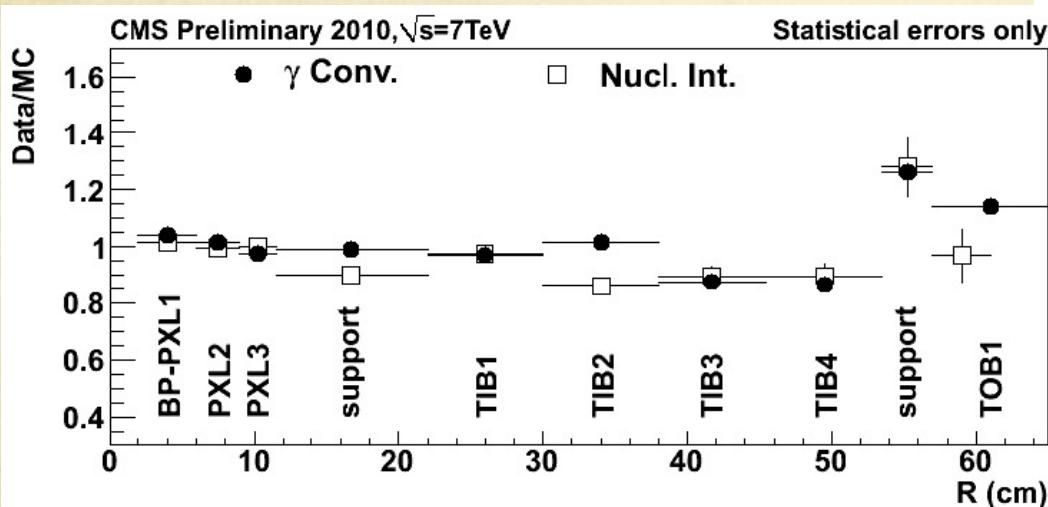
CMS material budget

○ Taking a picture of the material budget

- Using secondary vertices from $\gamma \rightarrow e^+e^-$

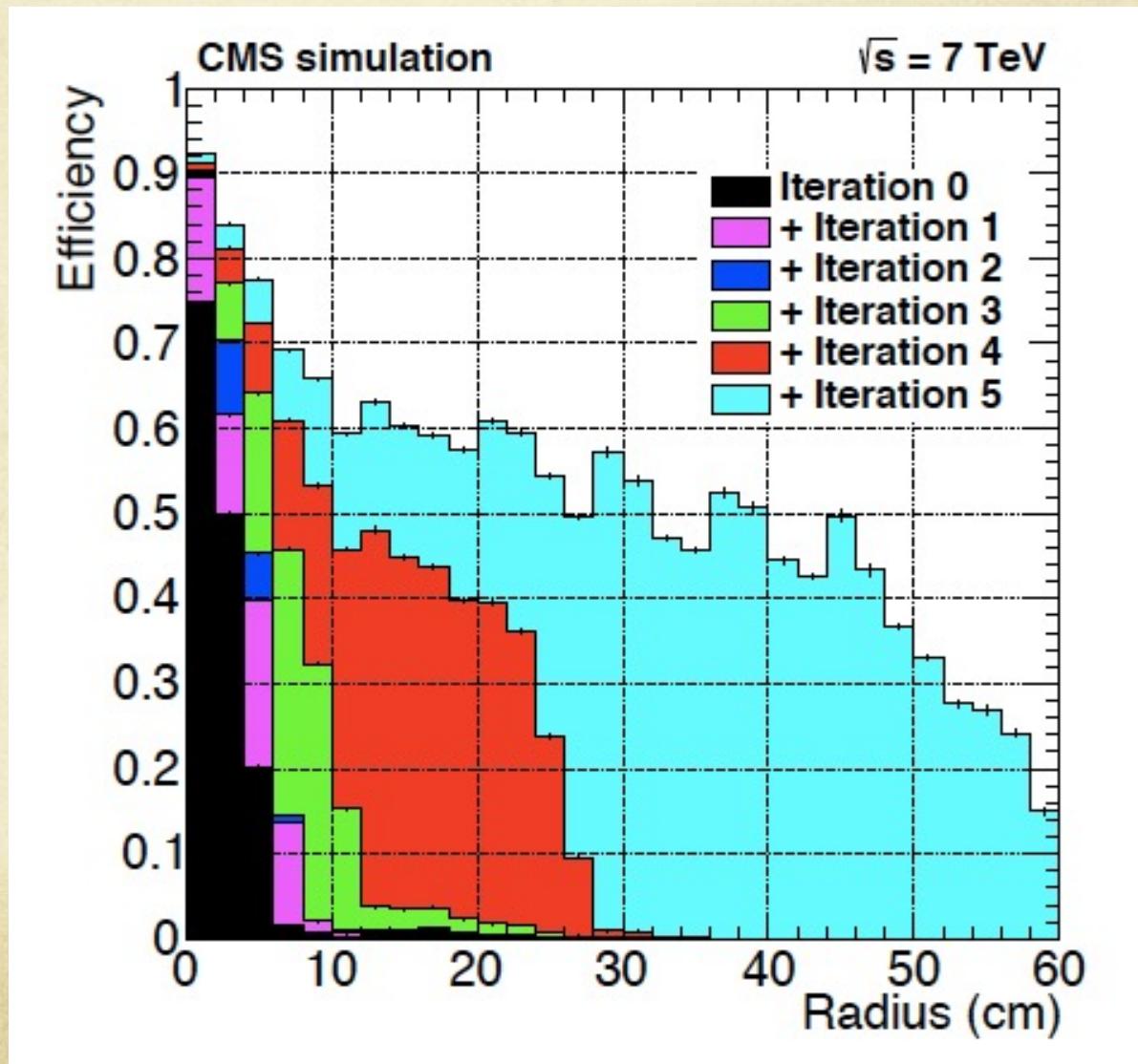


○ Measuring it by data/simulation comparison





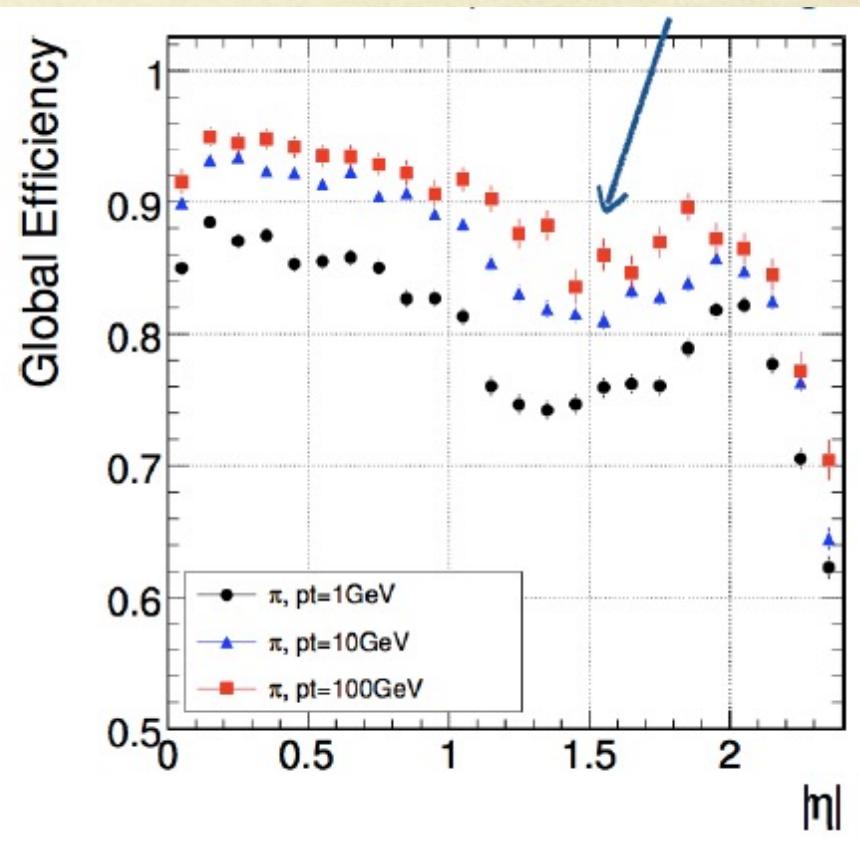
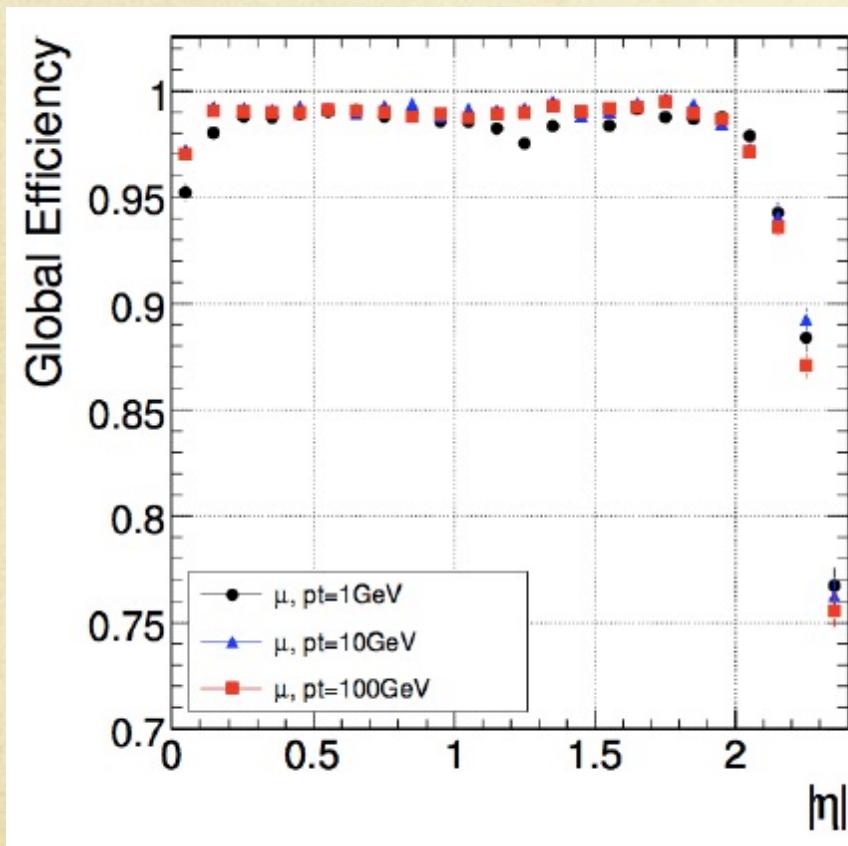
- Tracking algorithm = multi-iteration process



5. Some tracking systems:

CMS performance

○ Tracking efficiency

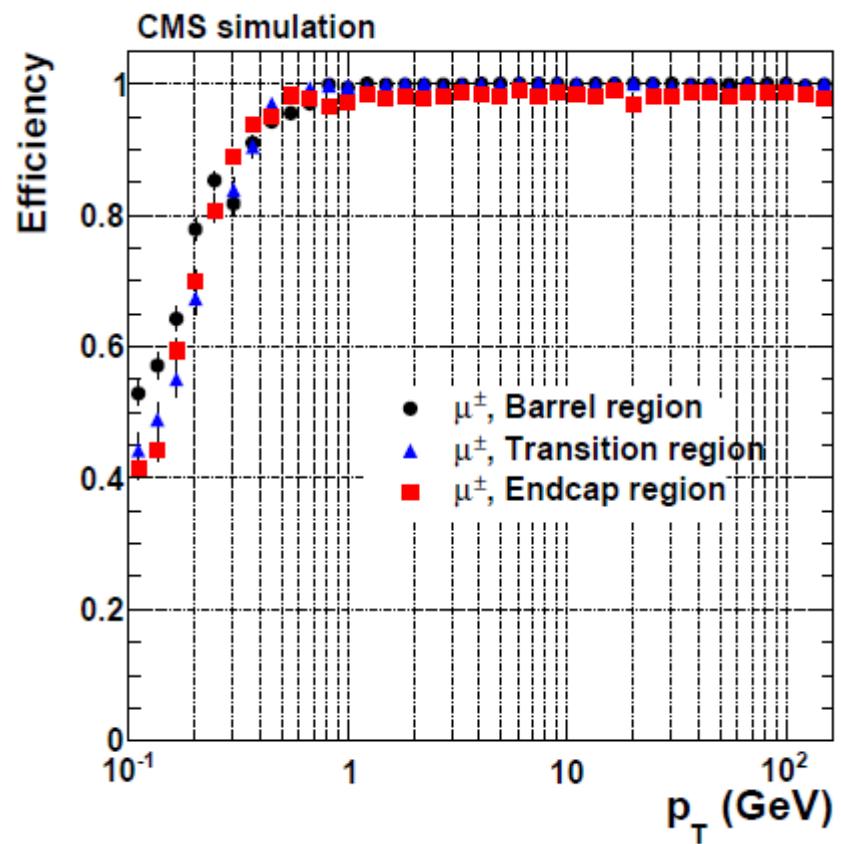
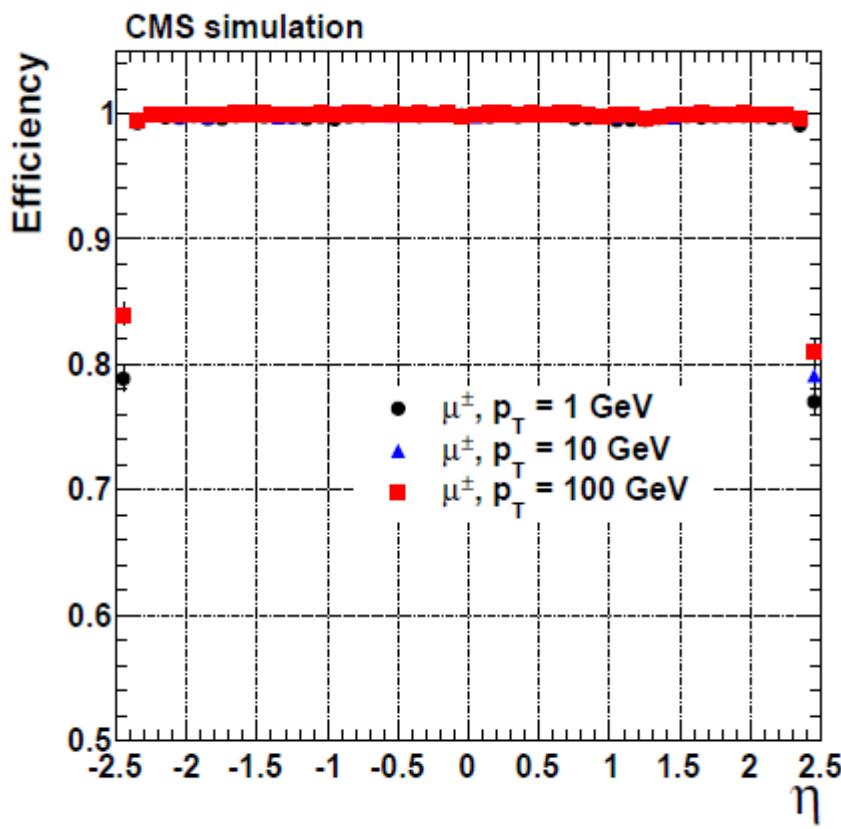


5. Some tracking systems:

CMS performance

○ Tracking efficiency

- Single, isolated muons

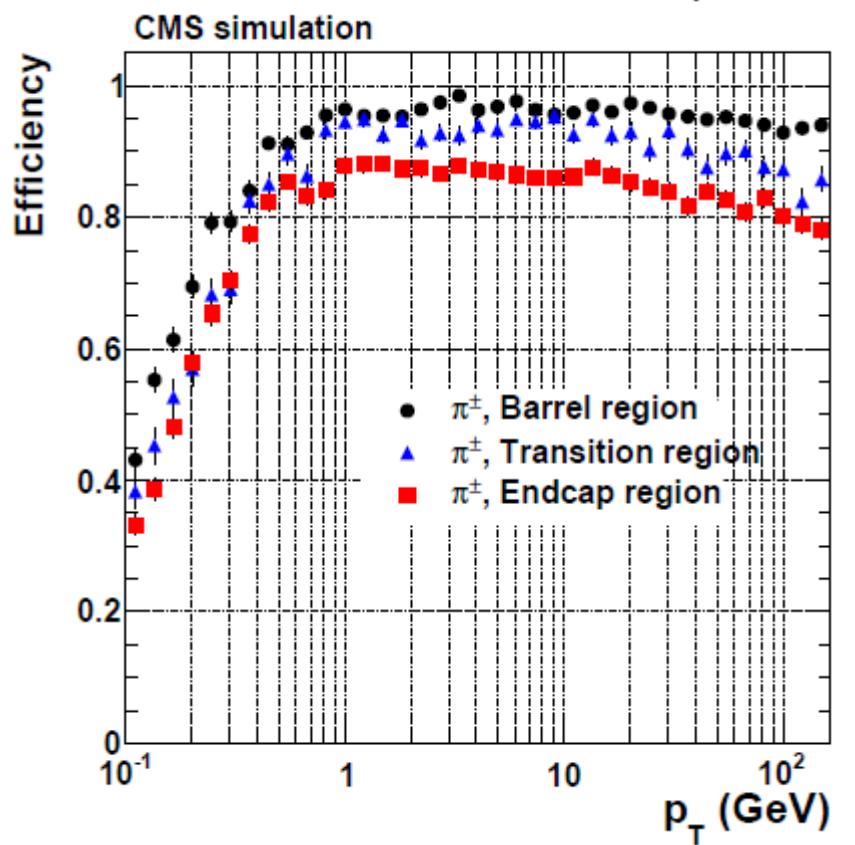
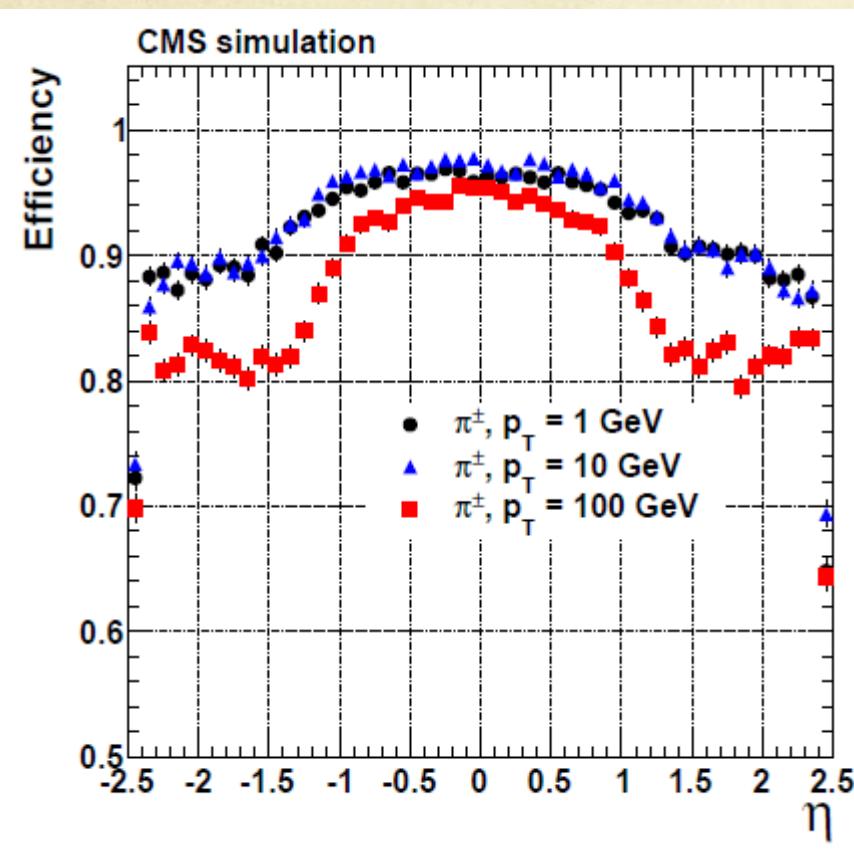


5. Some tracking systems:

CMS performance

○ Tracking efficiency

→ All pions

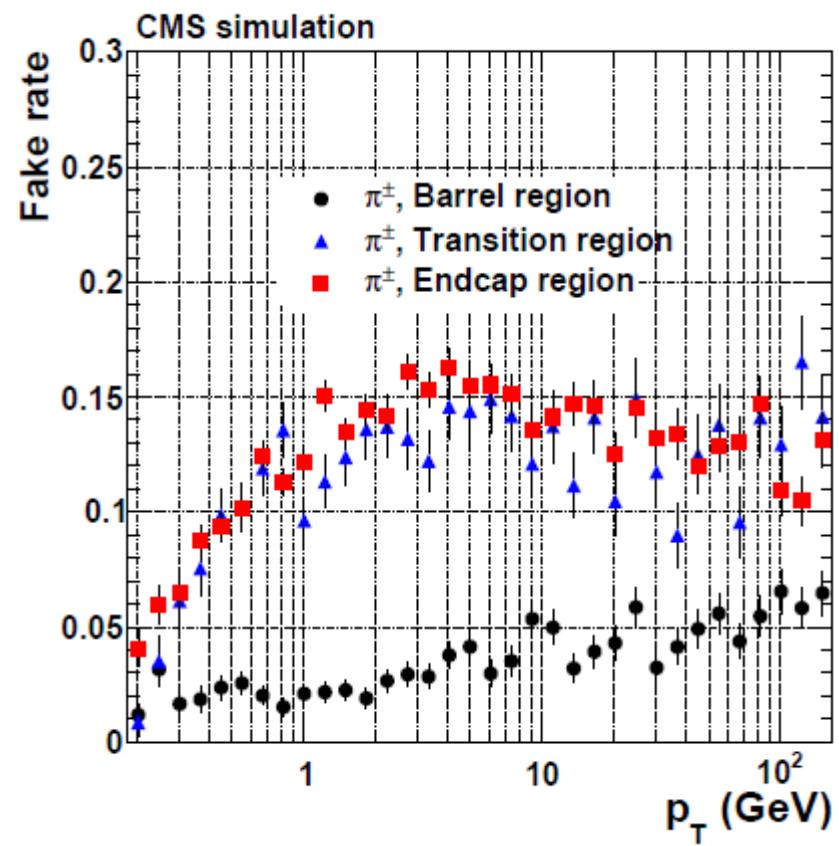
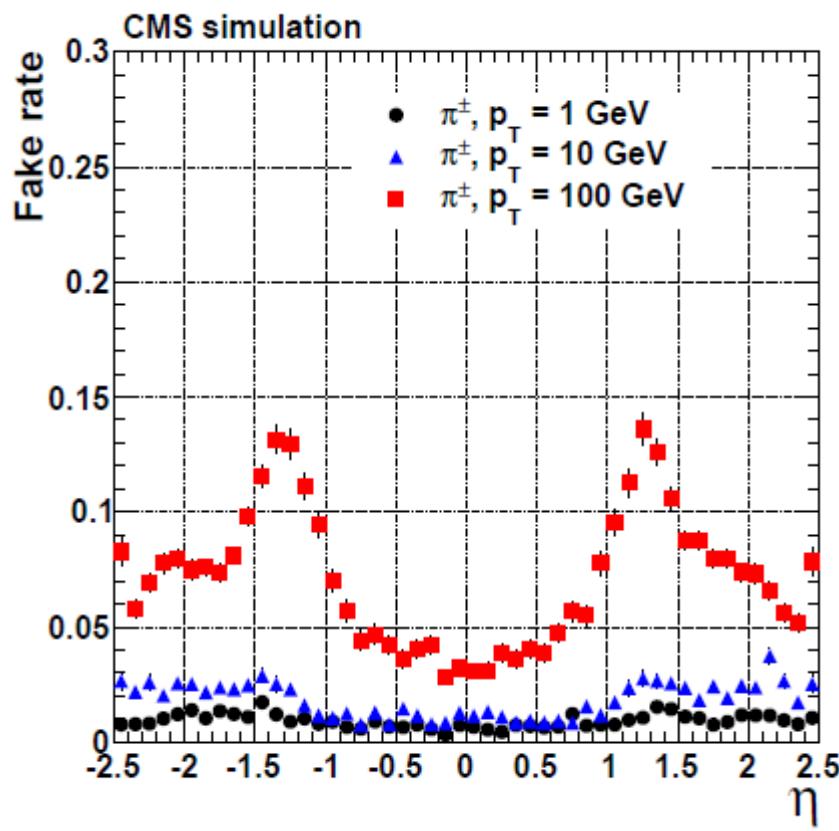


5. Some tracking systems:

CMS performance

○ Tracking purity

→ All pions

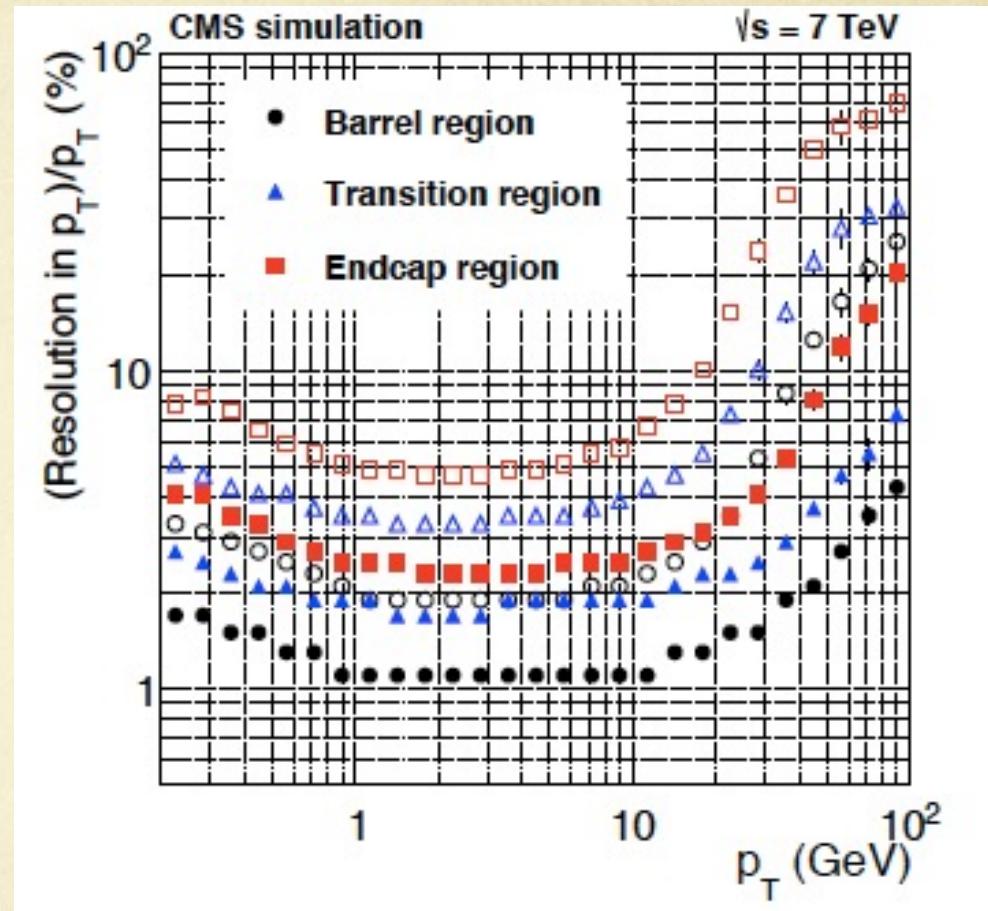
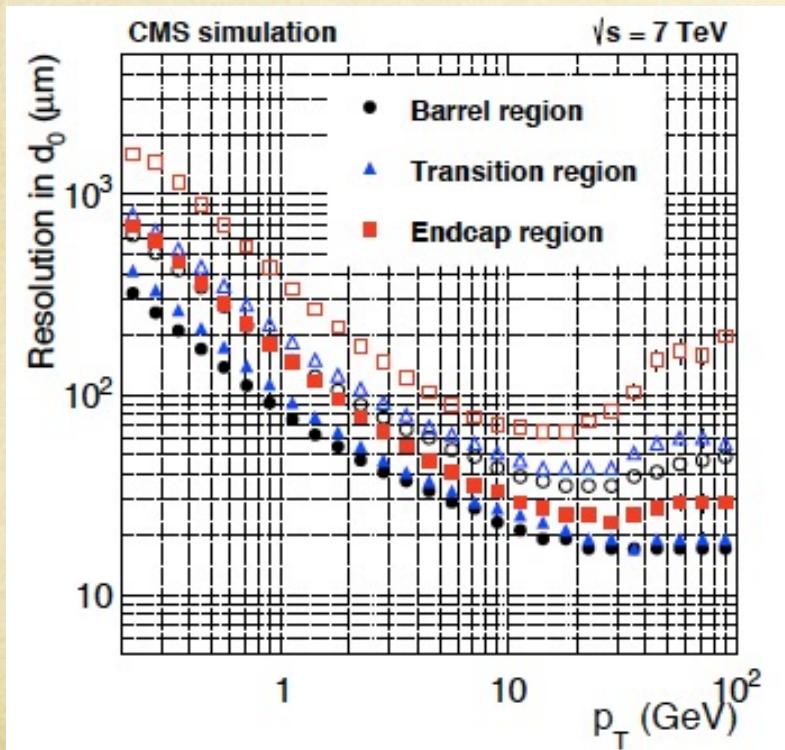


5. Some tracking systems:

CMS performance

○ Tracking resolution

d_0 = transverse impact parameter

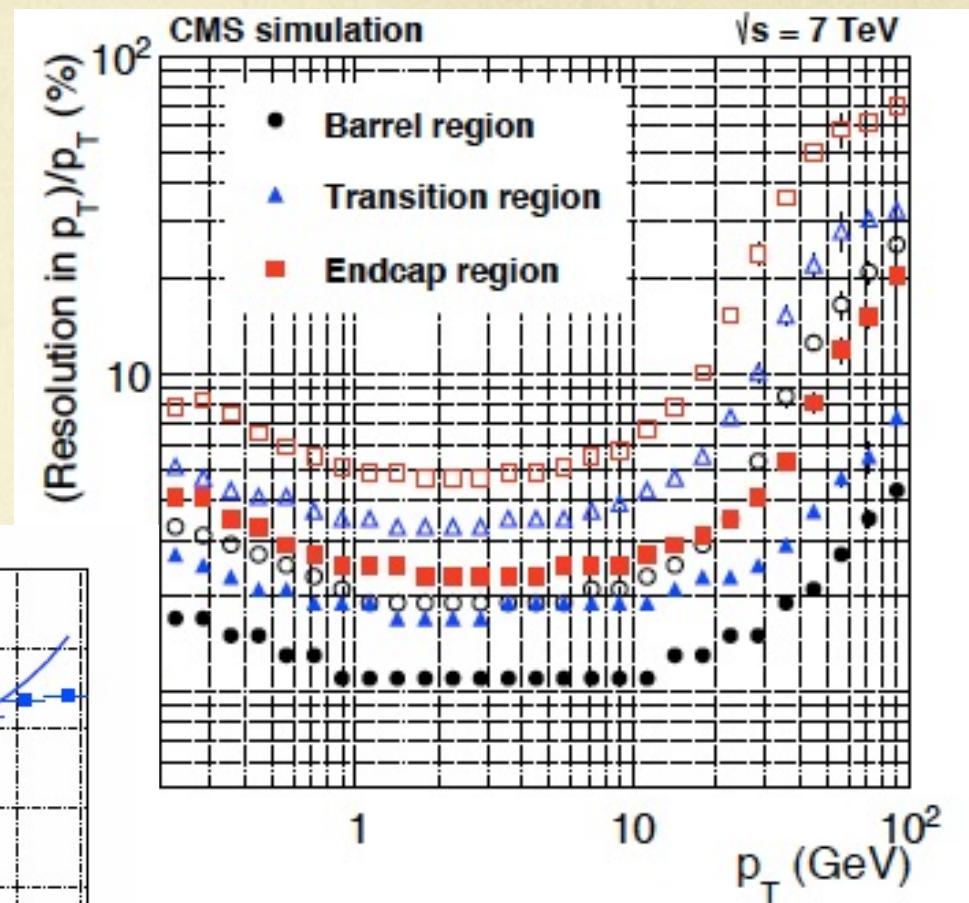
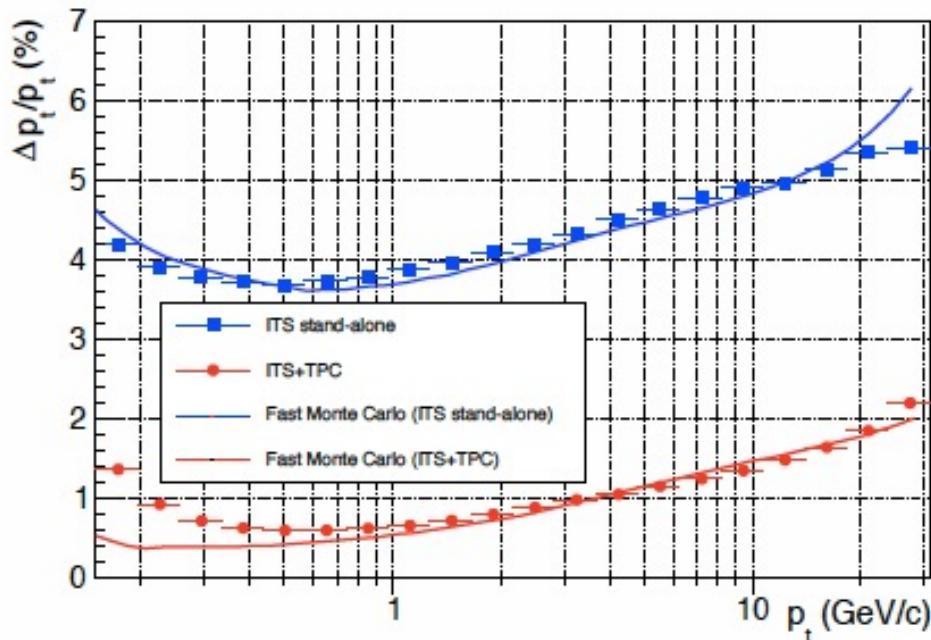


5. Some tracking systems:

CMS performance

○ Tracking resolution

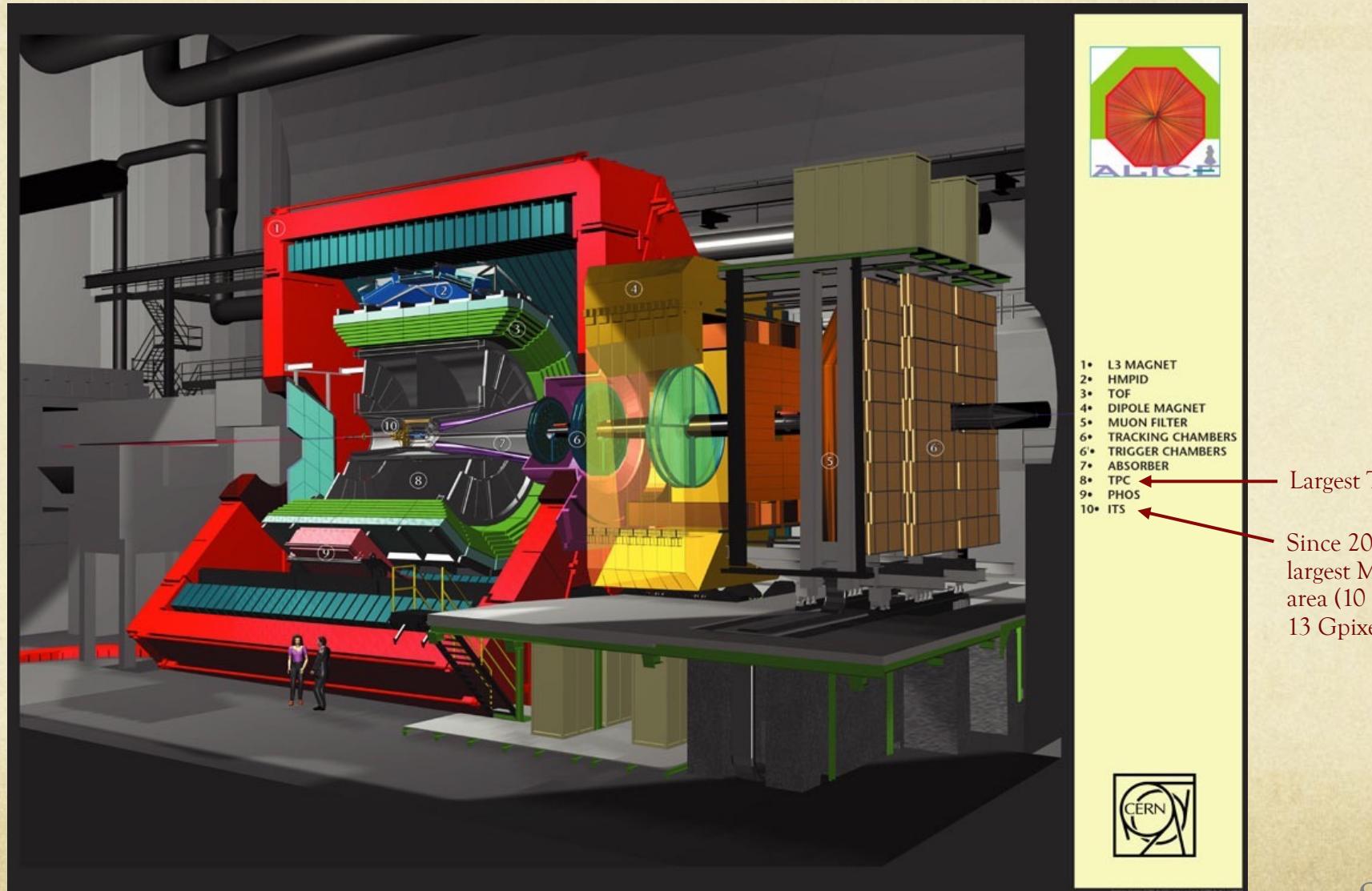
ALICE figure



5. Some tracking systems:

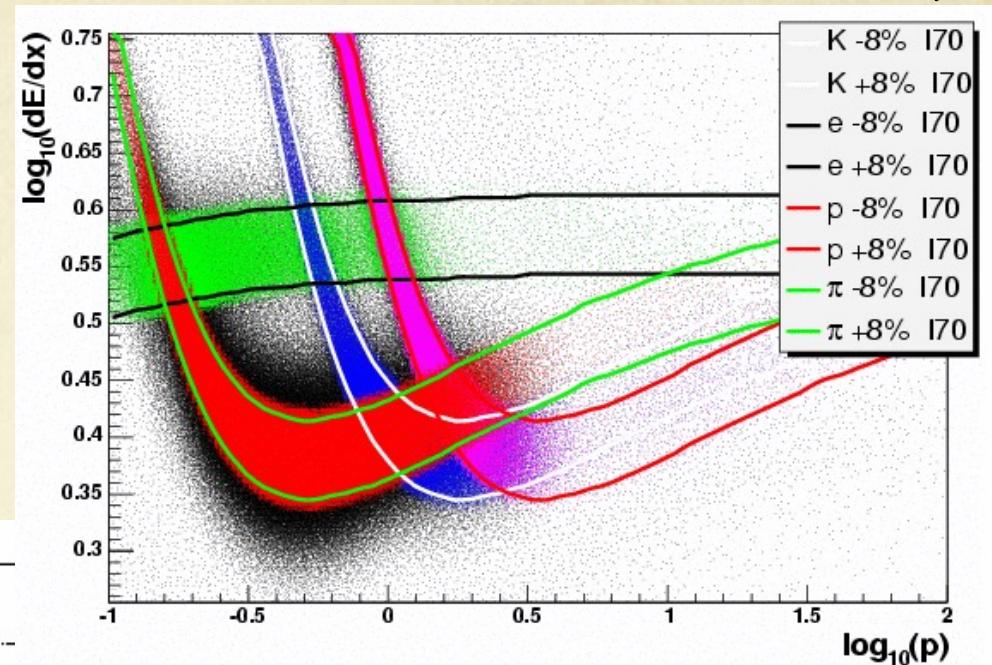
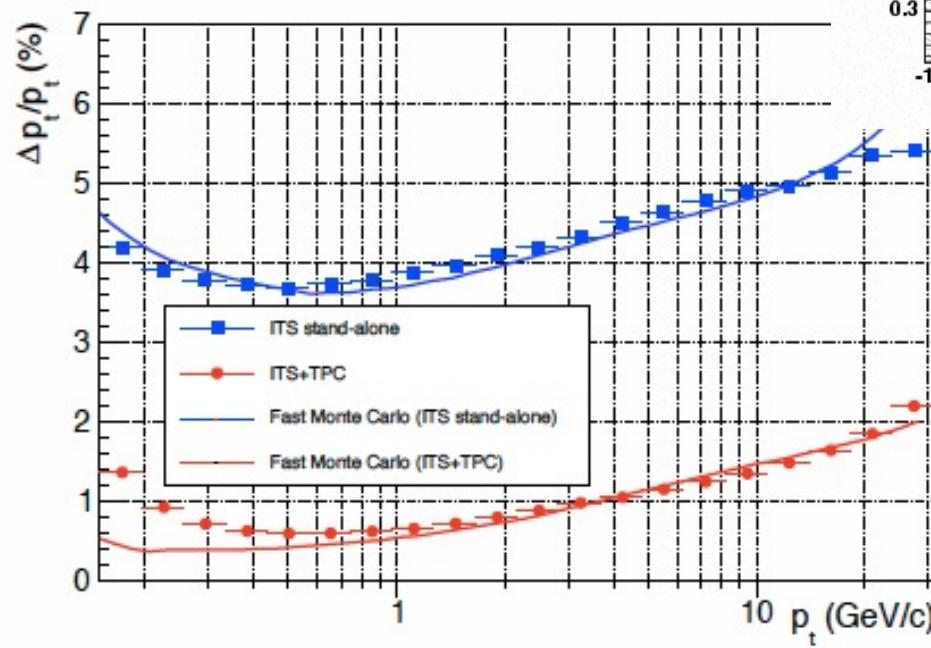
ALICE setup

A+A, A+p, p+p collisions



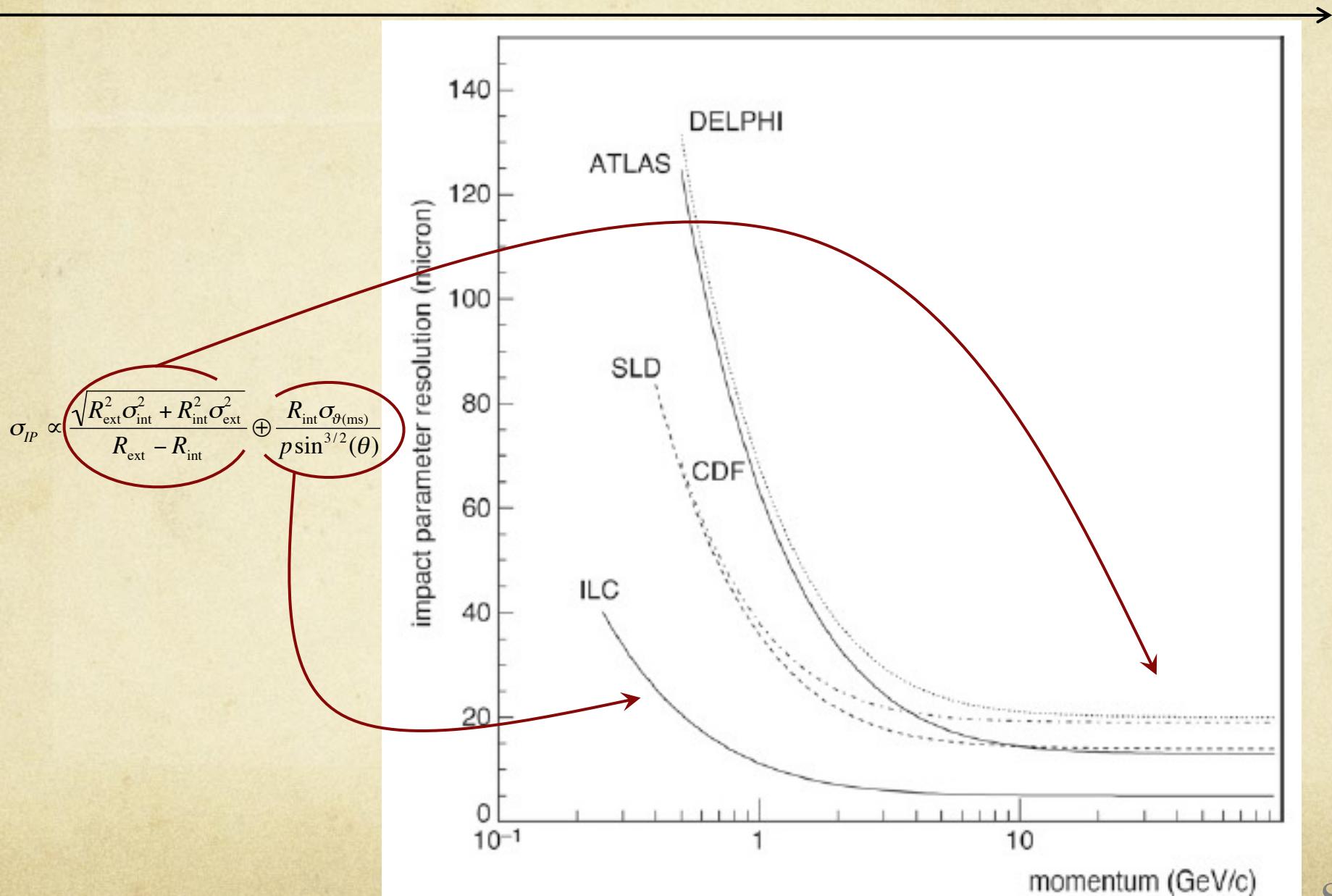
5. Some tracking systems:

ALICE performance



5. Some tracking systems:

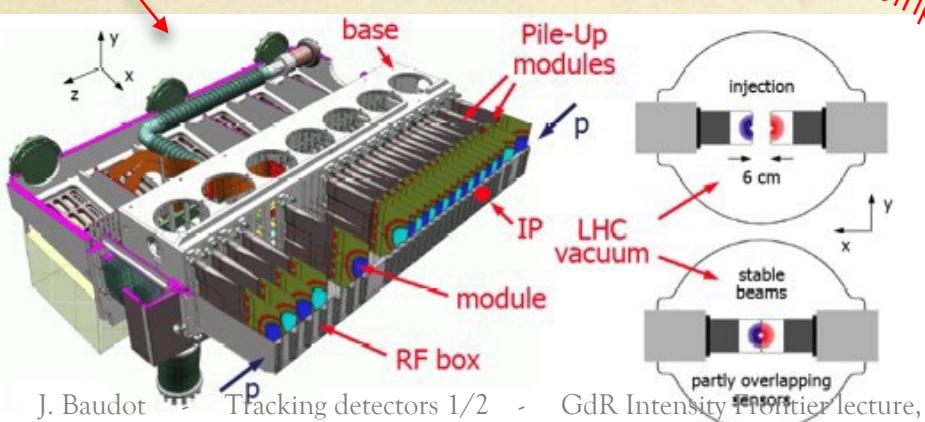
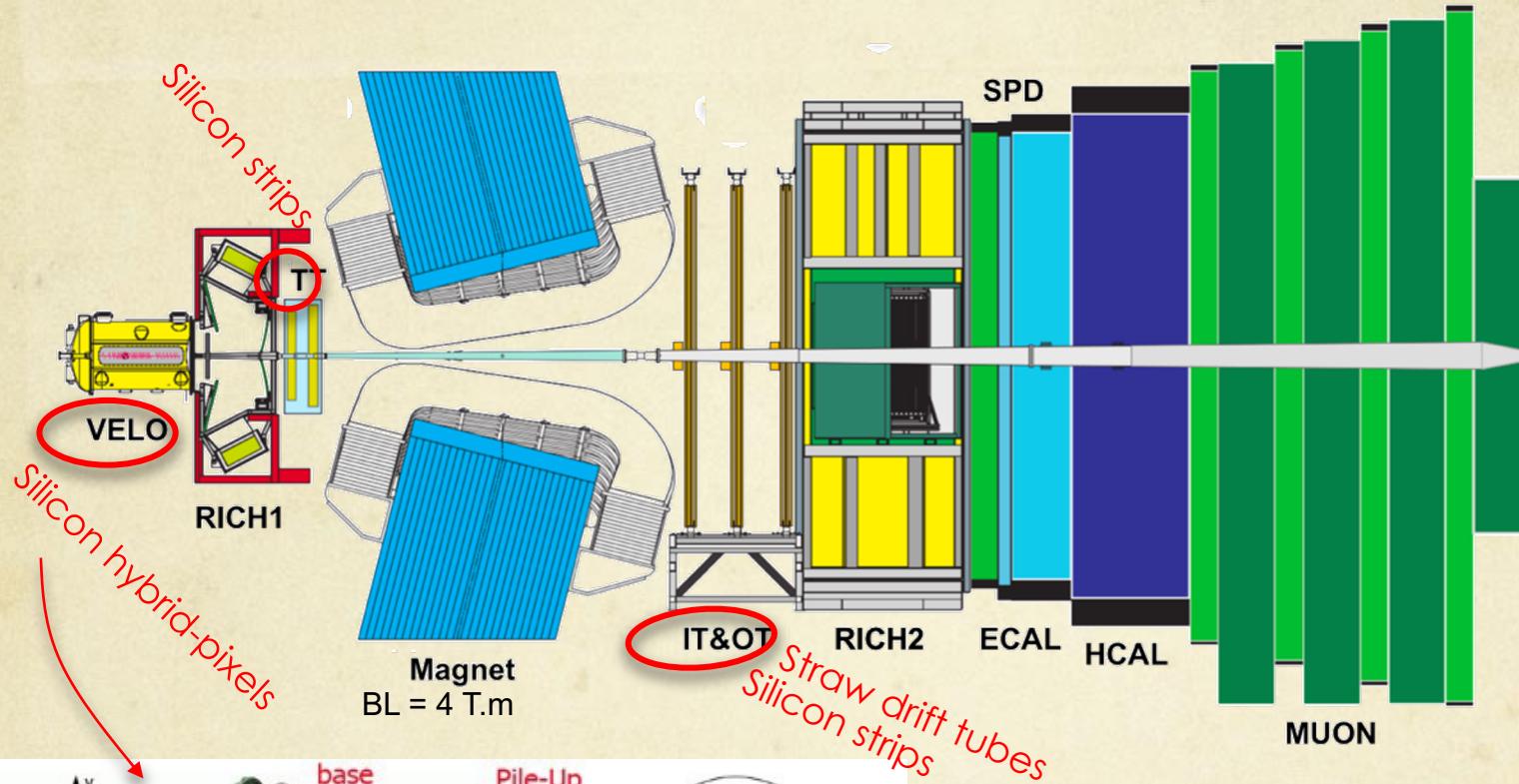
Impact parameter resolution



5. Some tracking systems:

LHCb setup

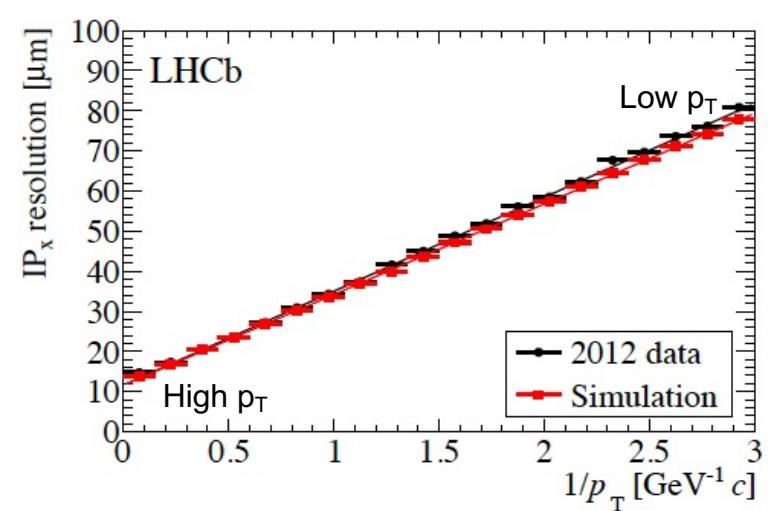
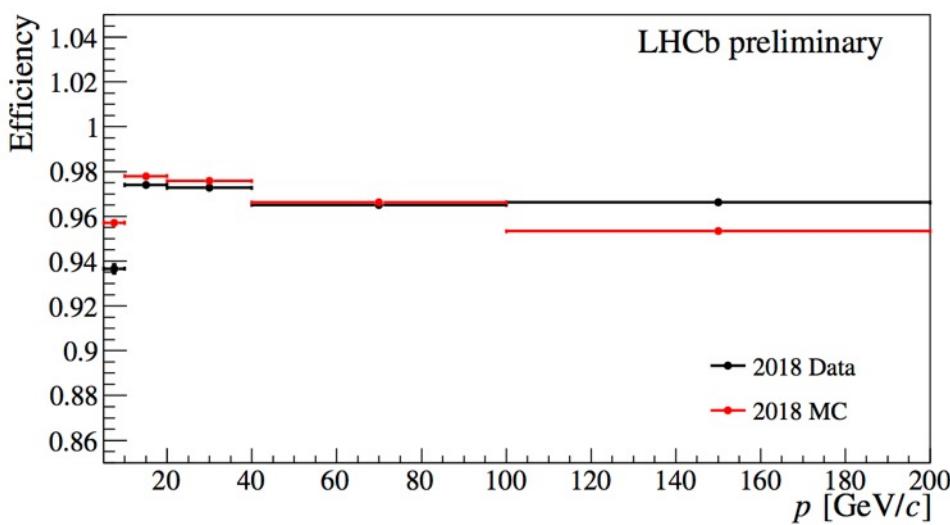
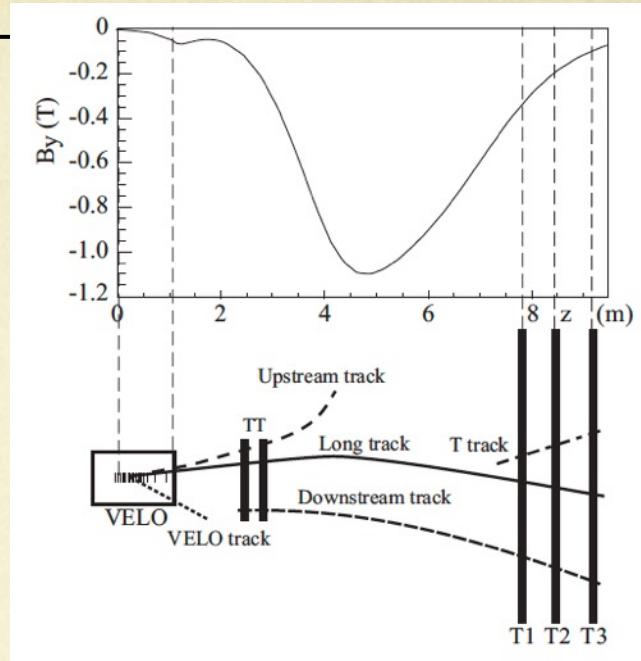
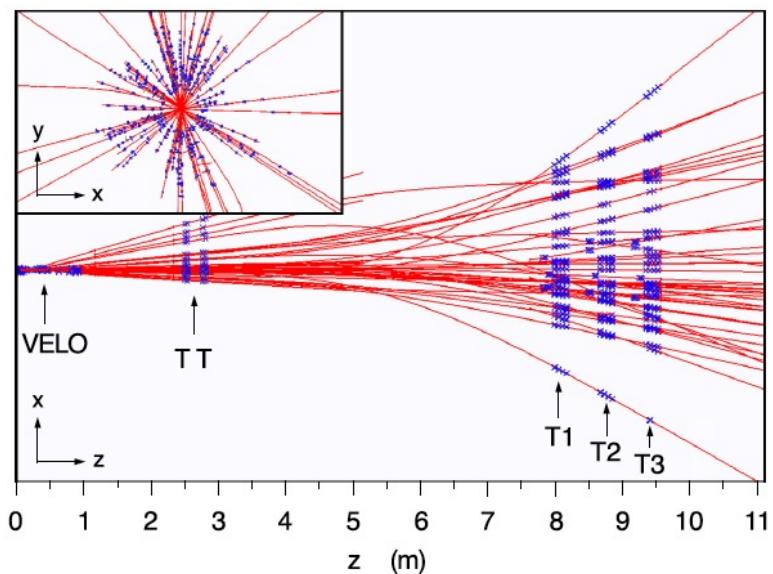
- Fixed-target-like experiment at LHC p+p collisions @ 13 TeV



- Collision rate 40 MHz
- Trigger rates (hw & sw)
1 MHz / 100 KHz / 12 KHz

5. Some tracking systems:

LHCb performance

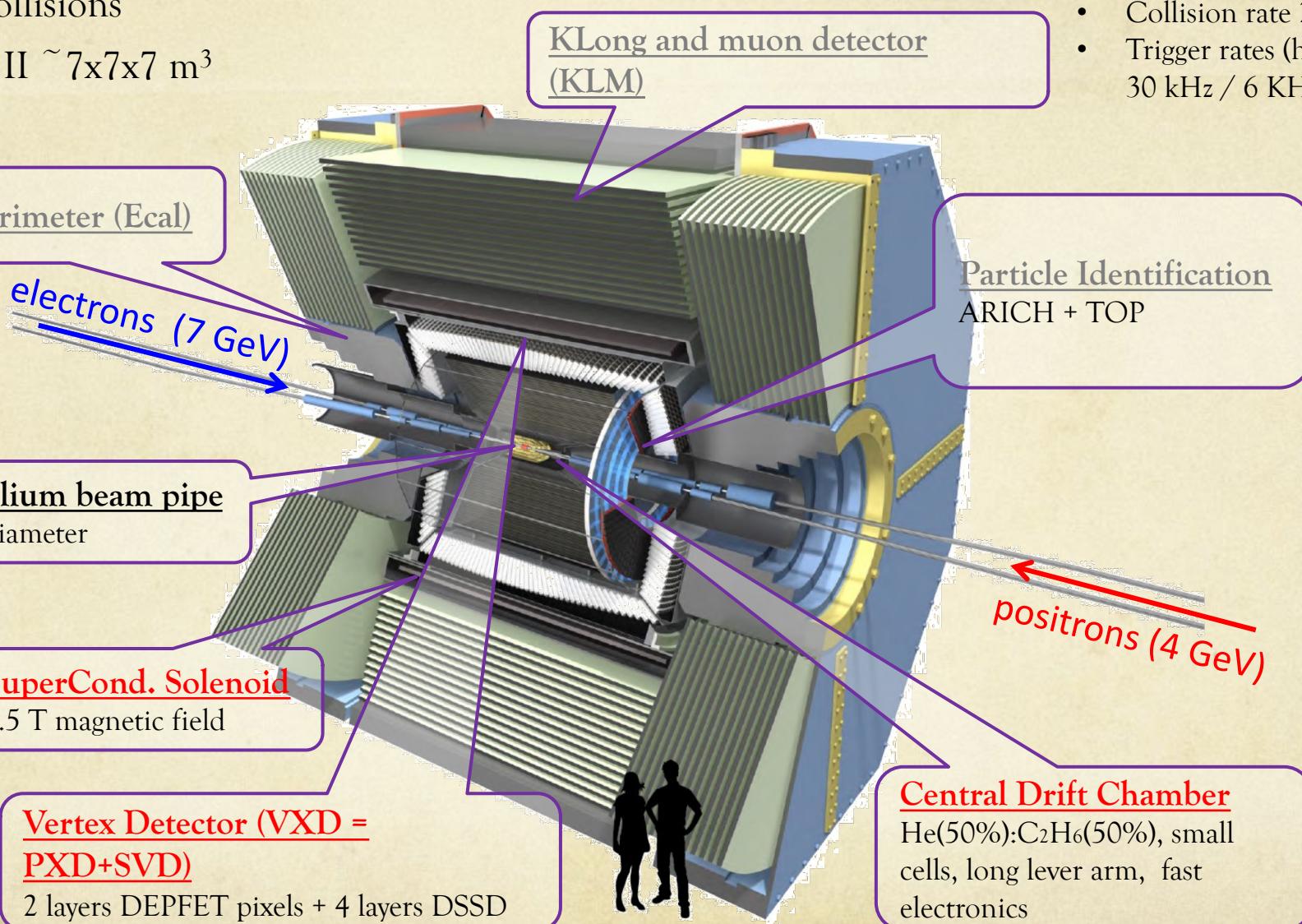


5. Some tracking systems:

Belle II setup

- e^+e^- collisions
- Belle II $\sim 7 \times 7 \times 7 \text{ m}^3$

- Collision rate 250 MHz
- Trigger rates (hw & sw)
30 kHz / 6 kHz



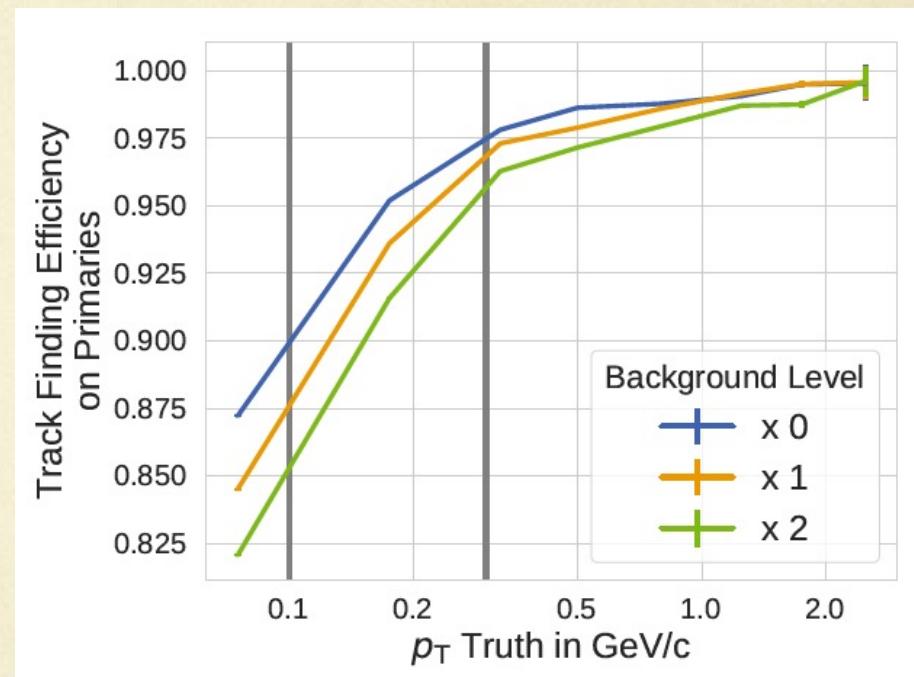
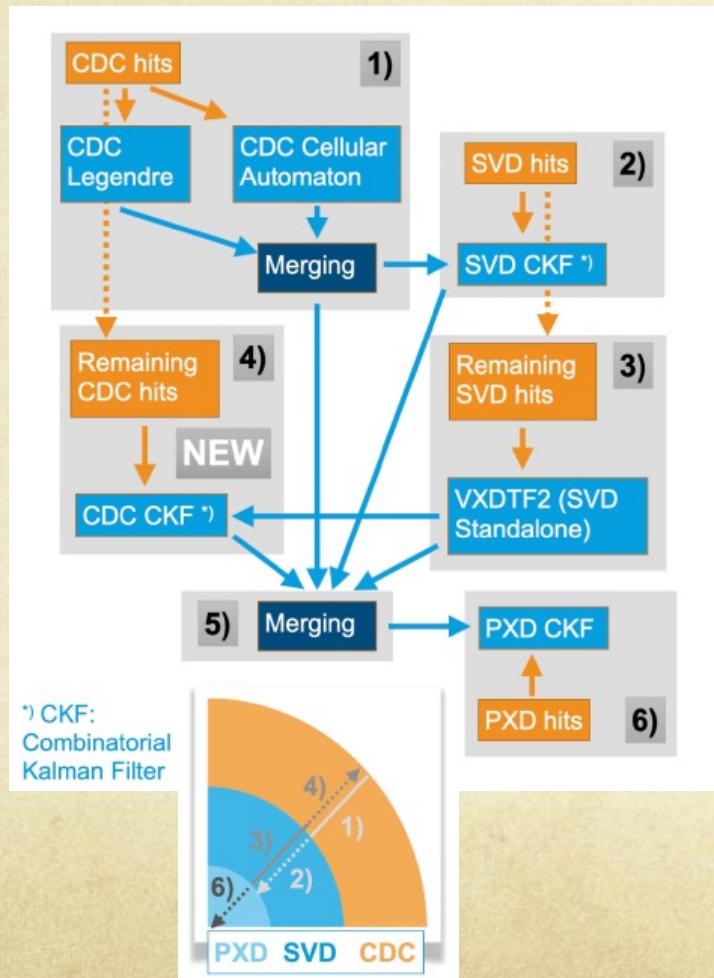
5. Some tracking systems:

Belle II algorithm

→ Elementary collisions produce few tracks ($\sim 10/\text{evts}$)

→ Beam induced background largely dominates occupancies.
at peak luminosities $> 10^{35} \text{ cm}^{-2}.\text{s}^{-1}$

Occupancies for Lumi $> 10^{35} \text{ cm}^{-2}.\text{s}^{-1}$
PXD: $\sim 1\%$, SVD: 1-3 %



AMS: A TeV precision, multipurpose particle physics spectrometer in space.

TRD Identify e+, e-



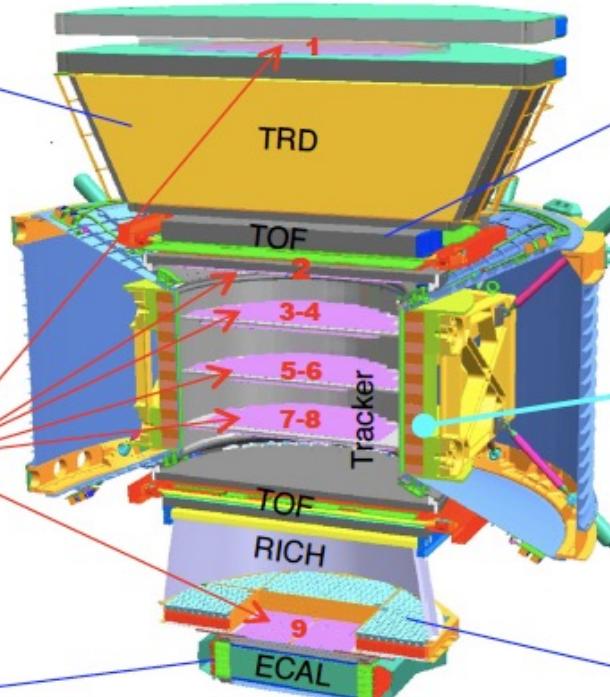
Silicon Tracker
Z. P



ECAL
E of e+, e-, ν



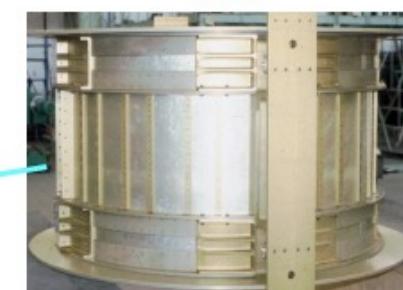
Particles and nuclei are defined by their charge (Z) and energy ($E \sim P$)



TOF
Z.E.



Magnet
+7



RICH
Z, E



Z, P are measured independently by the Tracker, RICH, TOF and ECAL

5. Some tracking systems:

AMS

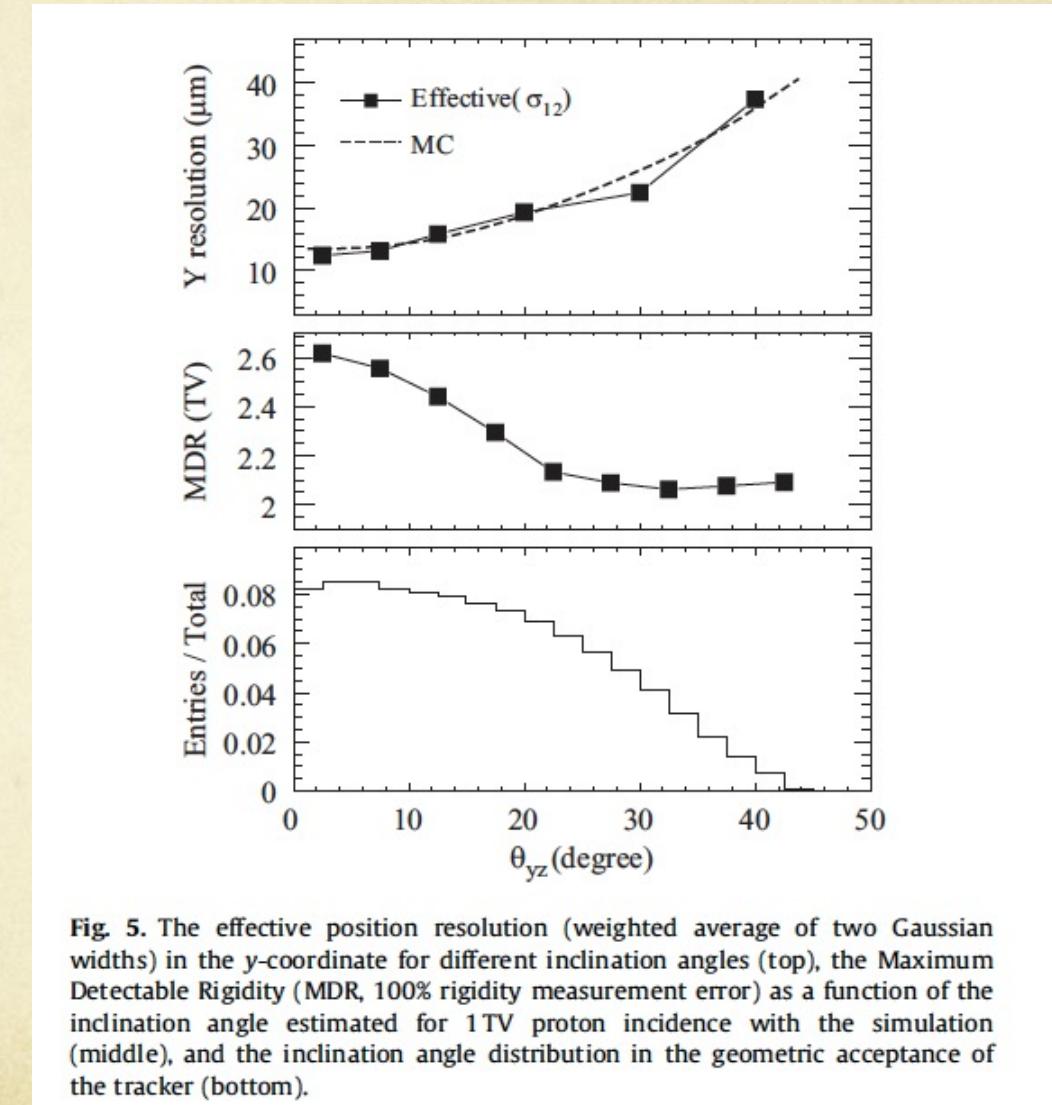
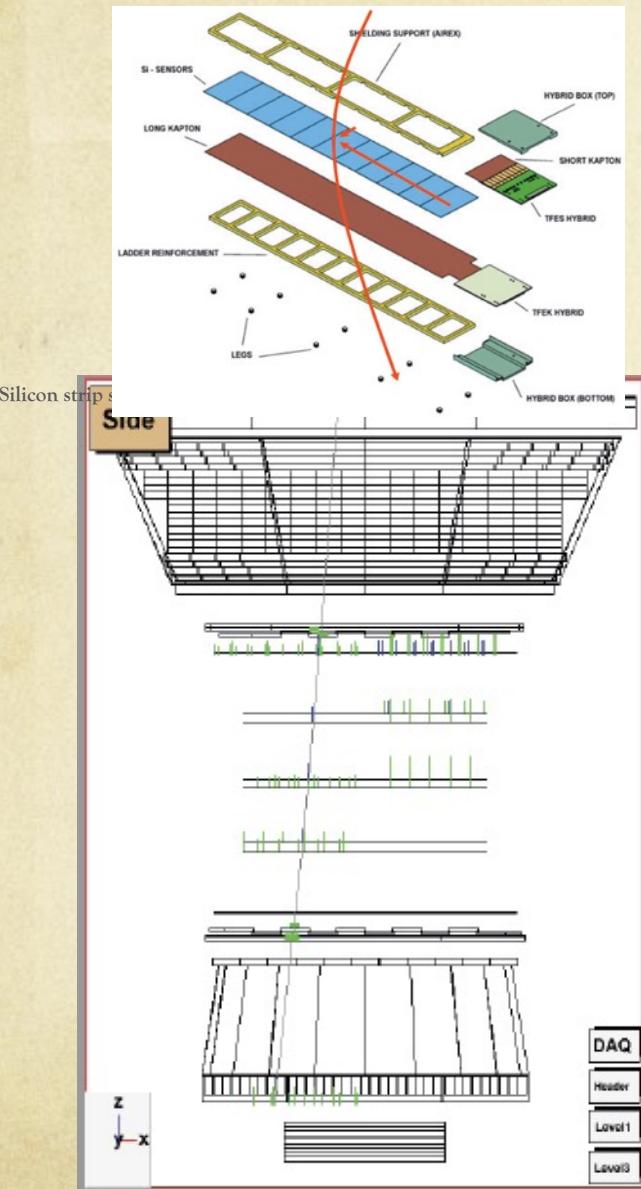
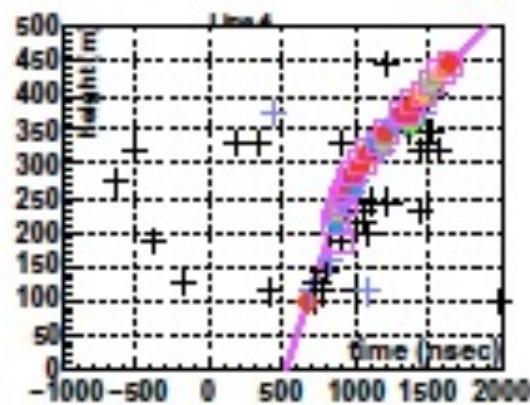
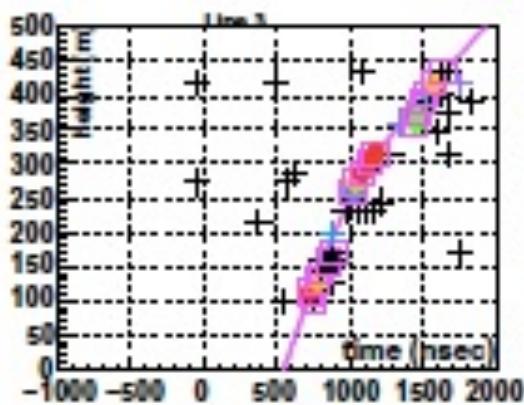
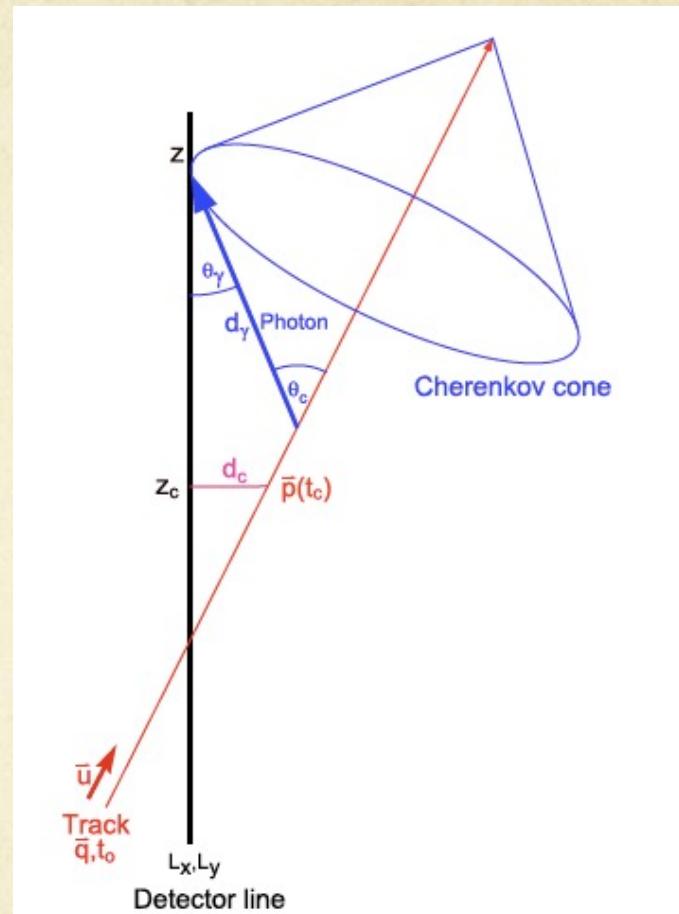
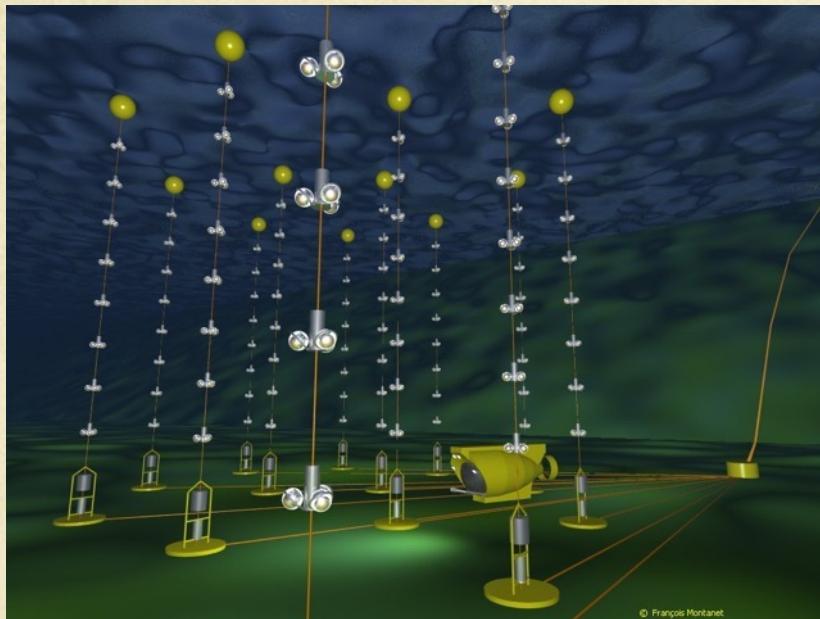


Fig. 5. The effective position resolution (weighted average of two Gaussian widths) in the y -coordinate for different inclination angles (top), the Maximum Detectable Rigidity (MDR, 100% rigidity measurement error) as a function of the inclination angle estimated for 1TV proton incidence with the simulation (middle), and the inclination angle distribution in the geometric acceptance of the tracker (bottom).

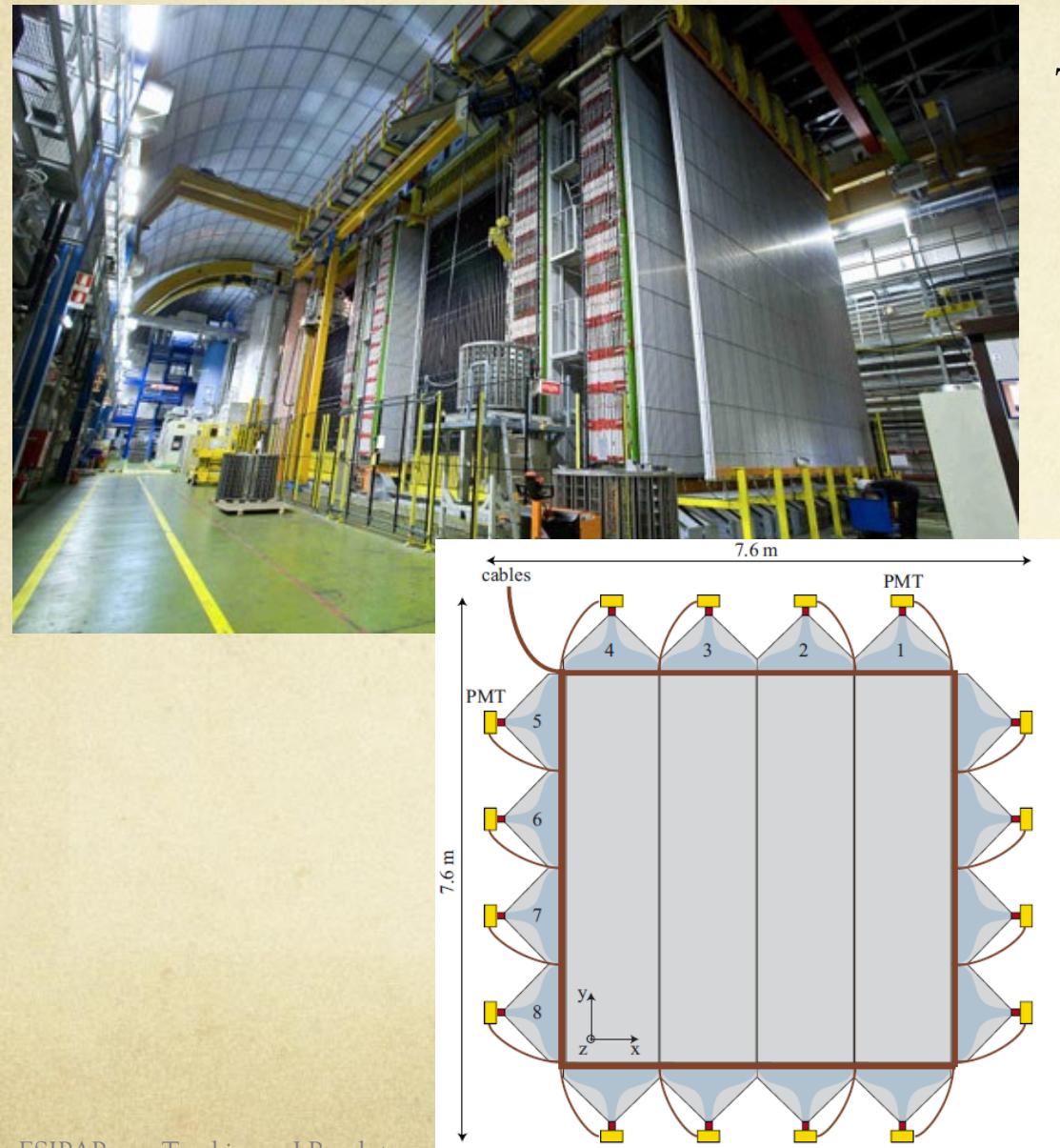
5. Some tracking systems:

ANTARES

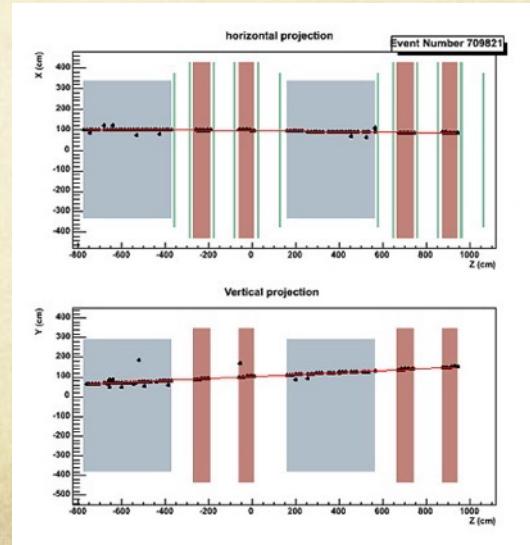
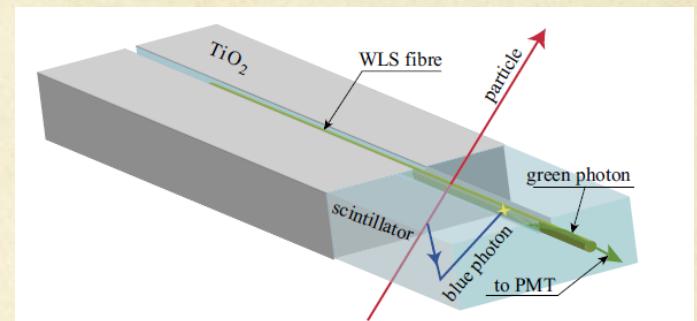


5. Some tracking systems:

OPERA



Target Tracker with scintillator strips:
1 strip = 6.86m long,
10.6mm thick, 26.3mm wide



Summary

○ Fundamental characteristics of any tracking & vertexing device:

- (efficiency), granularity, material budget, power dissipation, “timing”, radiation tolerance
- All those figures are intricated: each technology has its own limits

○ Many technologies available

- None is adapted to all projects (physics + environment choose, in principle)
- Developments are ongoing for upgrades & future experiments
 - Goal is to extent limits of each techno. → convergence to a single one?

○ Reconstruction algorithms

- Enormous boost (variety and performances) in the last 10 years
- Each tracking system has its optimal algorithm

○ Development trend

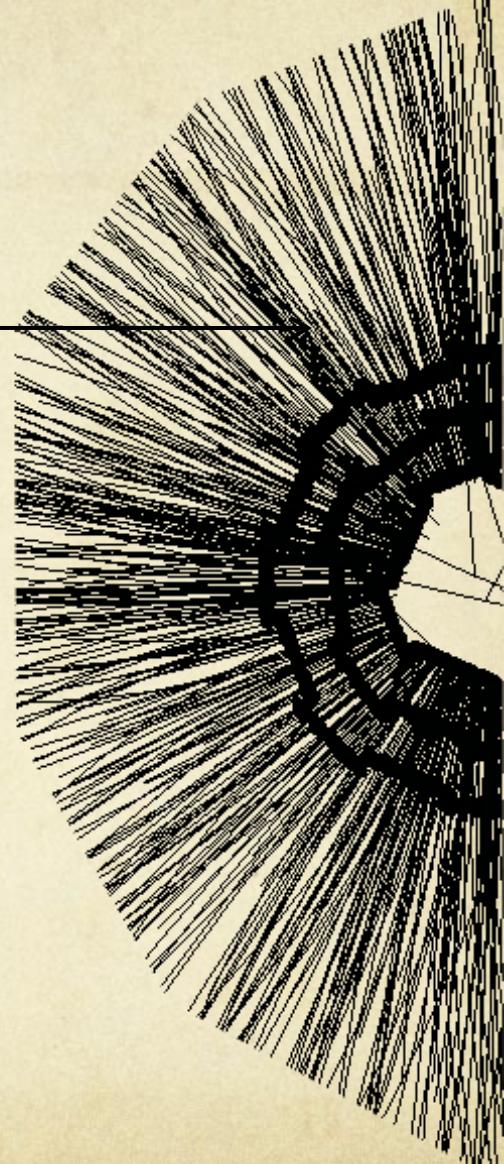
- Always higher hit rates call for more data reduction
- Tracking info in trigger → high quality online tracking/vertexing

○ Link with:

- PID: obvious with TPC, TRD, topological reco.
- Calorimetry: Particle flow algorithm, granular calo. using position sensors

References

- R.Frühwirth, M.Regler, R.K.Bock, H.Grote, D.Notz
Data Analysis Techniques for High-Energy Physics
Cambridge University Press, 2nd edition 2000
- P. Billoir
Statistics for trajectometry,
proceedings of SOS 2012, [doi:10.1051/epjconf/20135503001](https://doi.org/10.1051/epjconf/20135503001)
- ...and of course the Particle Data Group review
<http://pdg.web.cern.ch>, “Reviews, Tables, Plots” section
- D. Green
The Physics of Particle Detectors
ed. Cambridge University Press 2005
(some sections describing tracking)



- Detector technologies
 - H.G.Moser: *Silicon detector systems in high energy physics*, Progress in Particle and Nuclear Physics 63 (2009) 186237, [doi:10.1016/j.ppnp.2008.12.002](https://doi.org/10.1016/j.ppnp.2008.12.002)
 - V.Lepeltier: Review on TPC's, Journal of Physics: Conference Series 65 (2007) 012001, [doi:10.1088/1742-6596/65/1/012001](https://doi.org/10.1088/1742-6596/65/1/012001)
- Fabio Sauli
Gaseous Radiation Detectors: Fundamentals and Applications
ed. Cambridge University Press 2014
- Helmut Spieler,
Semiconductor Detector Systems,
ed. Oxford Univ. Press 2005
- Leonardo Rossi, Peter Fischer, Tilman Rohe and Norbert Wermes
Pixel Detectors: From Fundamentals to Applications,
ed. Springer 2006

o Reconstruction algorithm & fit

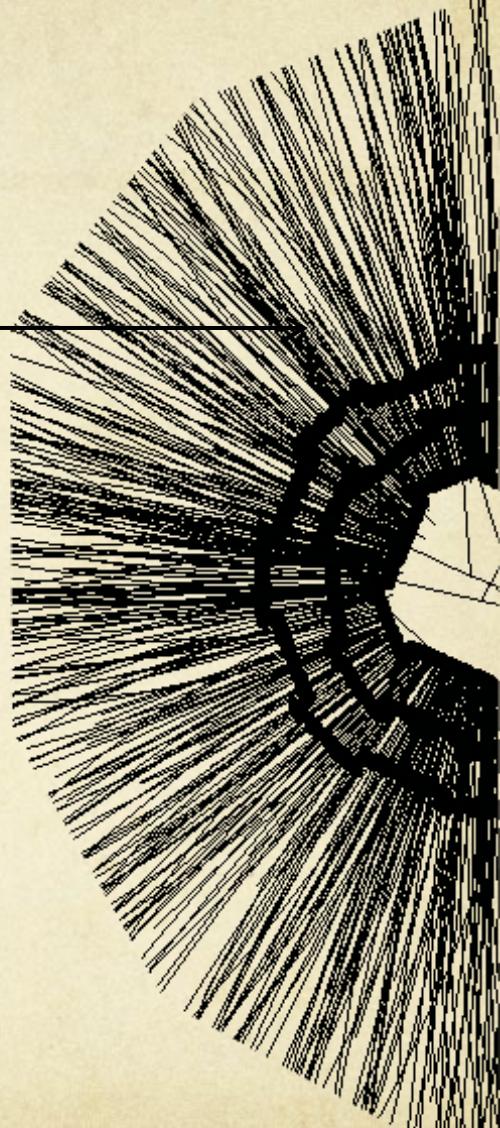
- A.Strandlie & R.Frühwirth : *Track and Vertex Reconstruction: From Classical to Adaptive Methods*, Rev. Mod. Phys. 82 (2010) 1419–1458, [doi:10.1103/RevModPhys.82.1419](https://doi.org/10.1103/RevModPhys.82.1419)
and many references therein.
- R Mankel : *Pattern recognition and event reconstruction in particle physics experiments*,
Rep. Prog. Phys. 67 (2004) 553–622, [doi:10.1088/0034-4885/67/4/R03](https://doi.org/10.1088/0034-4885/67/4/R03)
- C.Höpner, S.Neubert, B.Ketzer, S.Paul ; A New Generic Framework for Track Fitting in Complex Detector Systems (GENFIT),
Nucl.Instr.Meth. A 620 (2010) 518-525,2010, [doi:10.1016/j.nima.2010.03.136](https://doi.org/10.1016/j.nima.2010.03.136)
- V. Karimäki : *Effective circle fitting for particle trajectories*
Nucl. Instr. Meth. A 305 (1991) 187-191
- M. Valantan, M. Regler, R. Frühwirth : Generalization of the Gluckstern formulas I & II
Nucl. Instr. Meth. A 589 (2008) 109–117 & A 606 (2009) 728–742
- Proceedings of the first LHC Detector Alignment Workshop, report CERN-2004-007,
cdsweb.cern.ch/search?p=reportnumber%3ACERN-2007-004
also consult lhc-detector-alignment-workshop.web.cern.ch

○ Contributions from experiments

- S.Haino et al., *The performance of the AMS-02 silicon tracker evaluated during the pre-integration phase of the spectrometer*, Nuclear Instruments and Methods in Physics Research A 630 (2011) 78–81, [doi:10.1016/j.nima.2010.06.032](https://doi.org/10.1016/j.nima.2010.06.032)
- G.Piacquadio, ATLAS Alignment, Tracking and Physics Performance Results, proceedings of VERTEX 2010, [PoS\(VERTEX 2010\)015](https://pos.sissa.it/15/015)
- J.Aguilar et al., A fast algorithm for muon track reconstruction and its application to the ANTARES neutrino telescope, J. Astro. Phys. 34 (2011) 652-662, [doi10.1016/j.astropartphys.2011.01.003](https://doi.org/10.1016/j.astropartphys.2011.01.003)
- S.Amerio, Online Track Reconstruction at Hadron Collider, Proceedings of ICHEP 2010, [PoS\(ICHEP 2010\)481](https://pos.sissa.it/48/1)
- F.Arneodo et al., Performance of a liquid argon time projection chamber exposed to the CERN West Area Neutrino Facility neutrino beam, Phys.Rev. D 74(2006)112001, [doi:10.1103/PhysRevD.74.112001](https://doi.org/10.1103/PhysRevD.74.112001)
- J.Abdallah et al., b-tagging in DELPHI at LEP, <https://arxiv.org/abs/hep-ex/0311003v1>

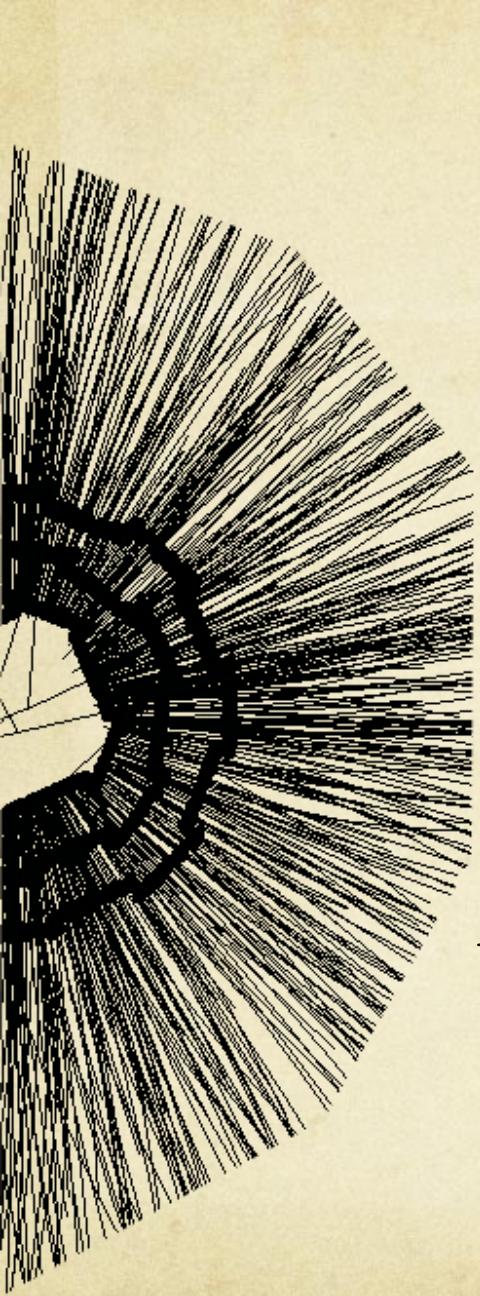
Was not discussed

- Particle interaction with matter
- The readout electronics
- Cooling systems
- Triggering
- Vertexing



10

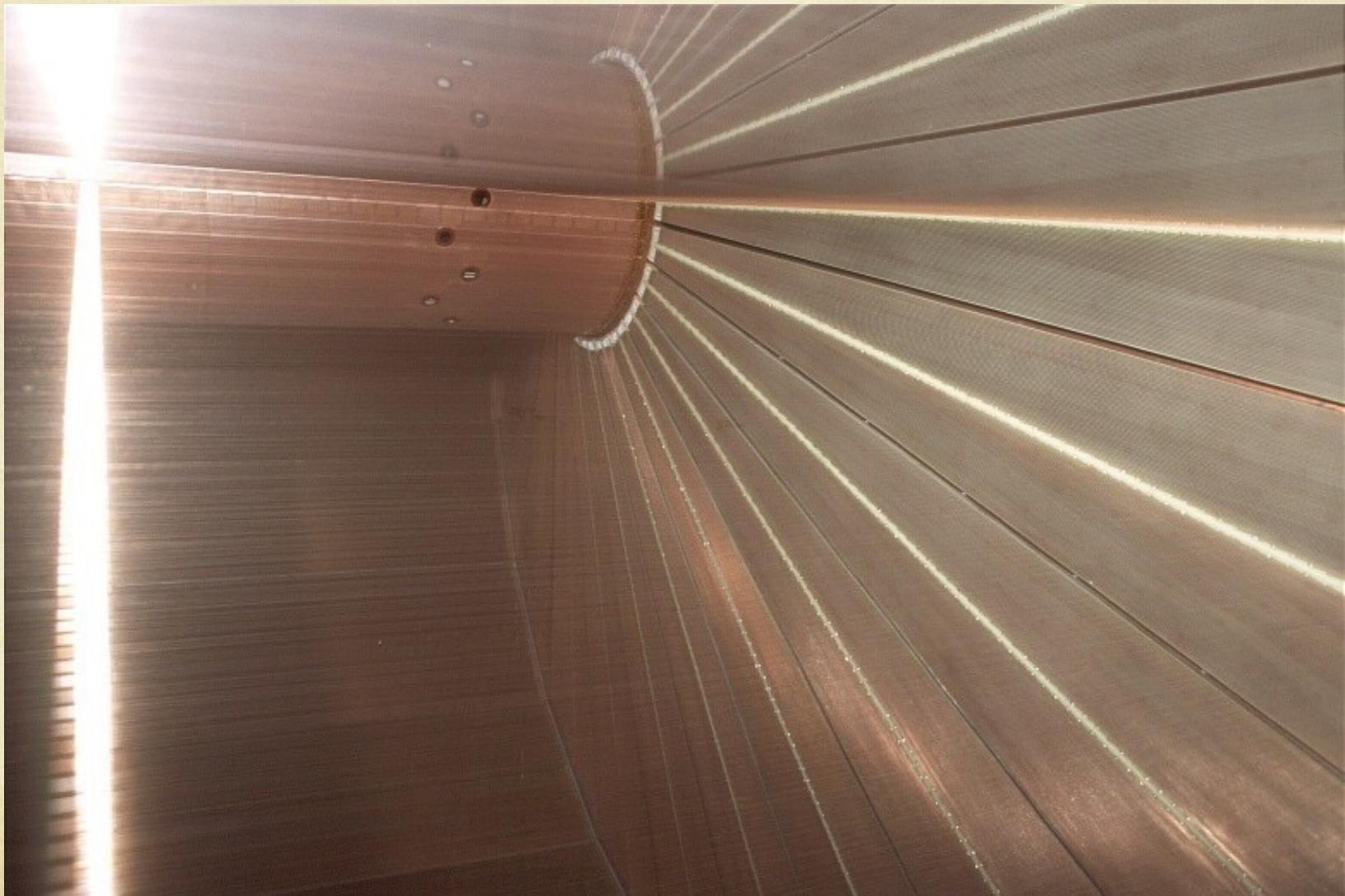
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Backups

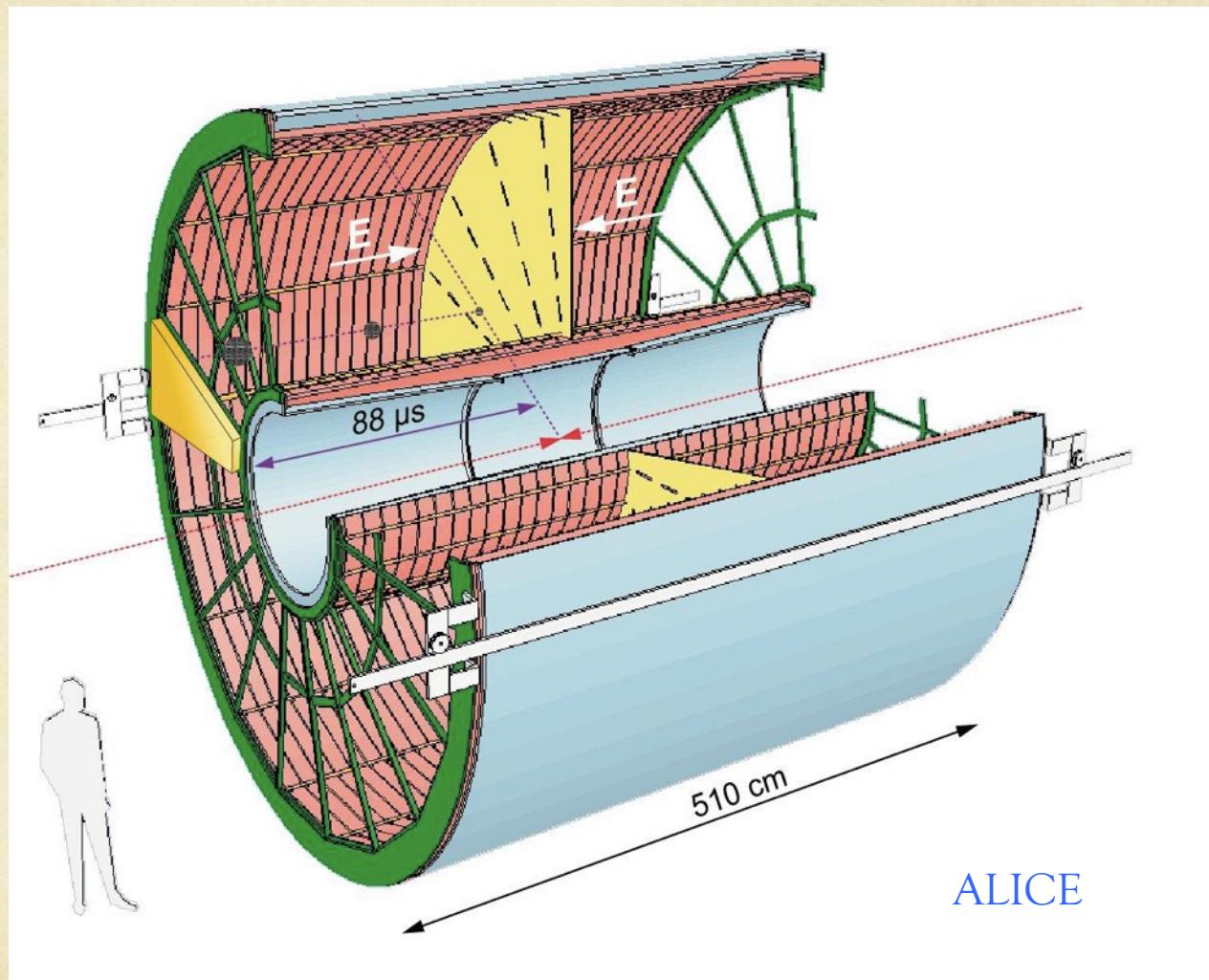
Backups:

OPAL drift chamber



10

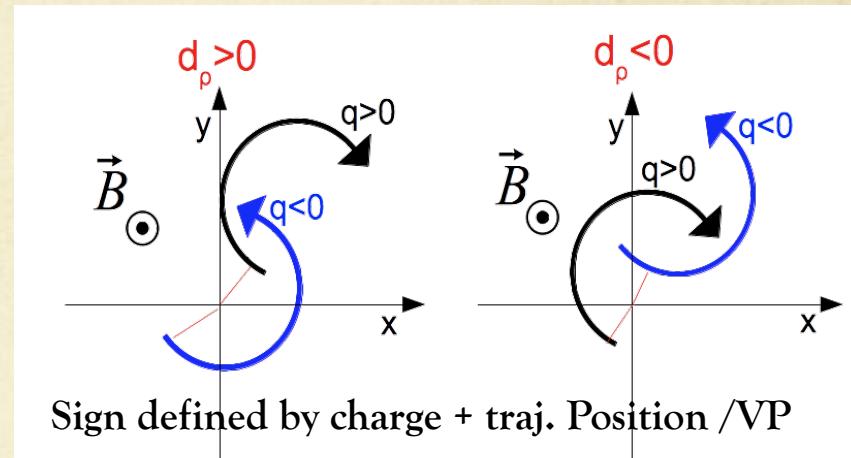
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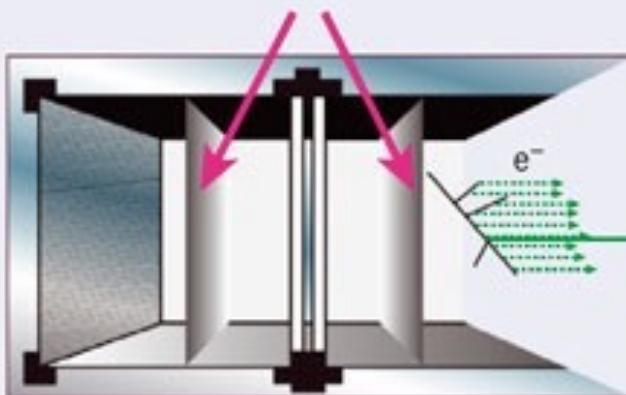
Sign of Impact Parameter

○ Geometrical sign

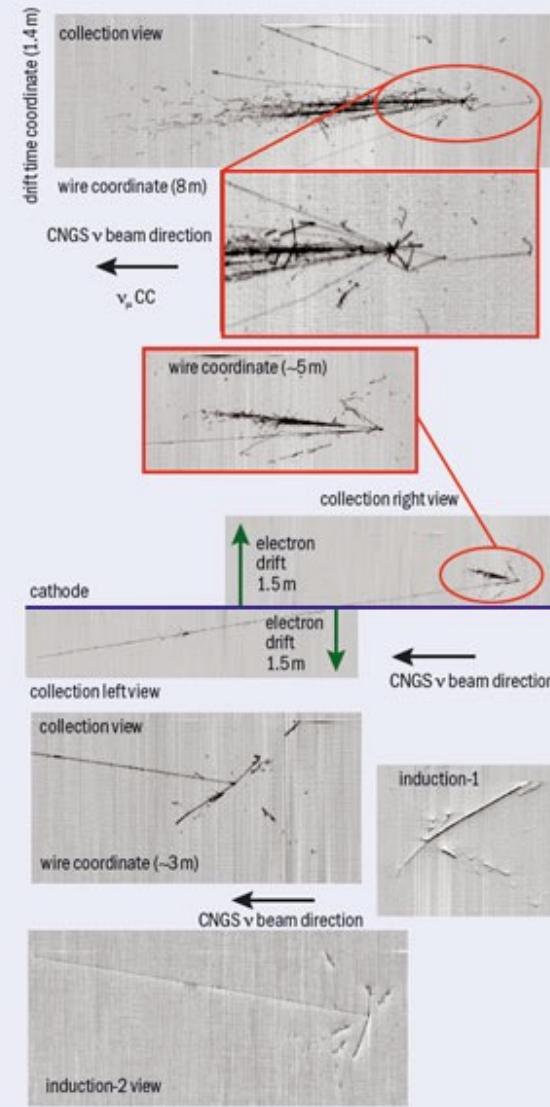
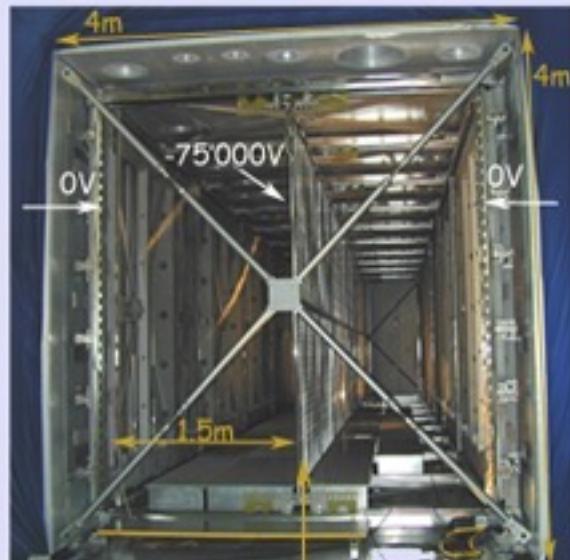
- Not helpful for b-tagging long-lived particles



cathodes

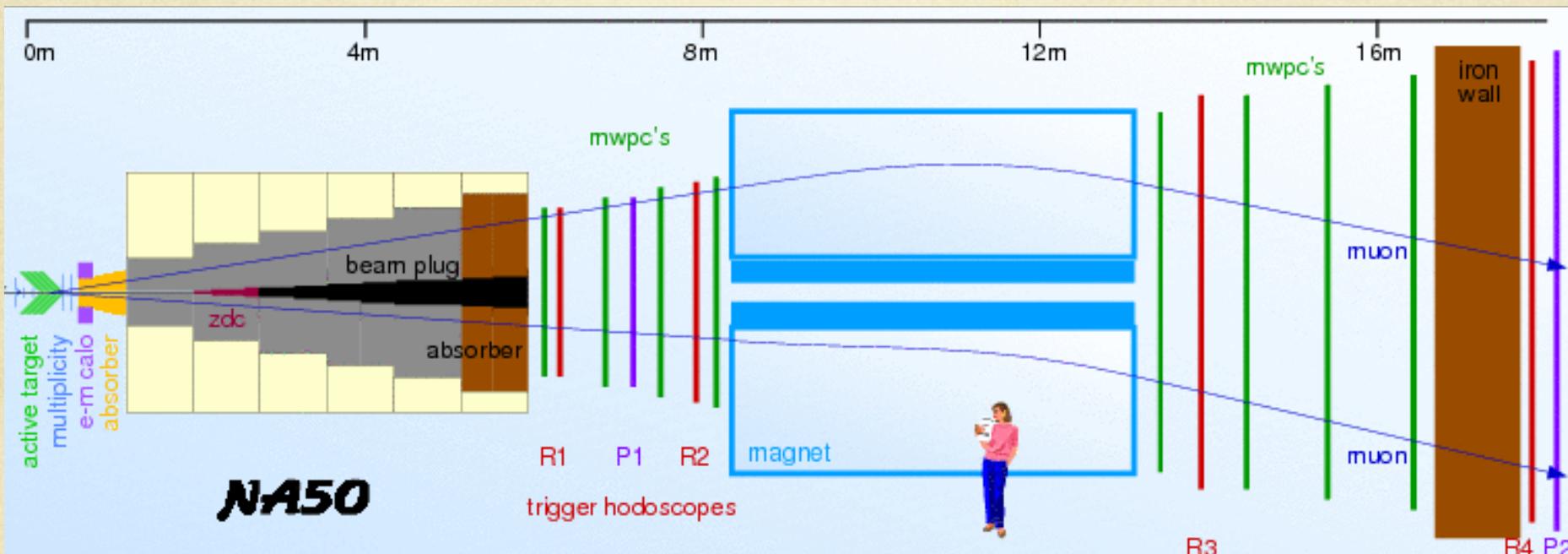


front view of the detector

wire planes
anode

Backups:

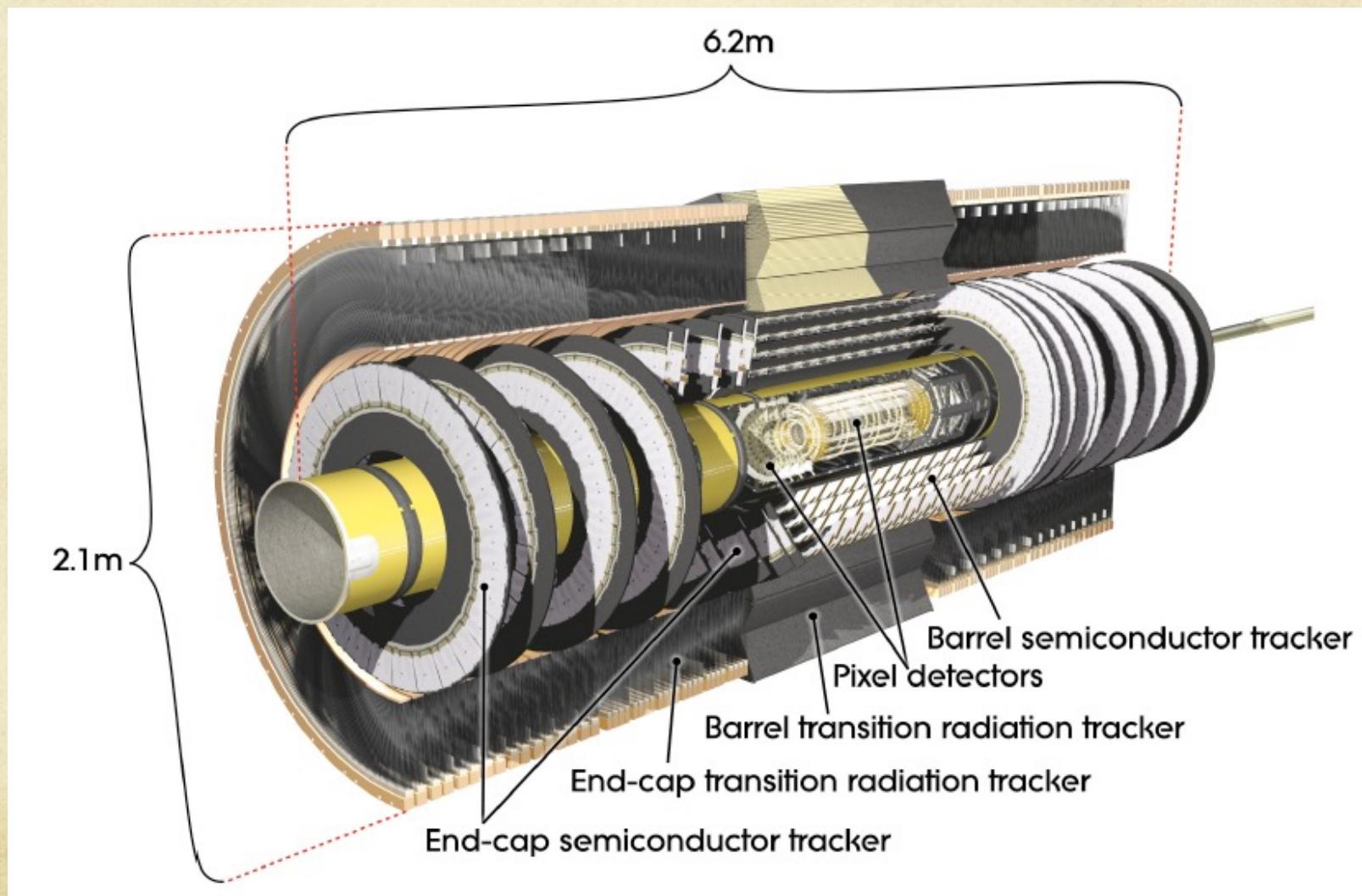
NA-50 fixed target

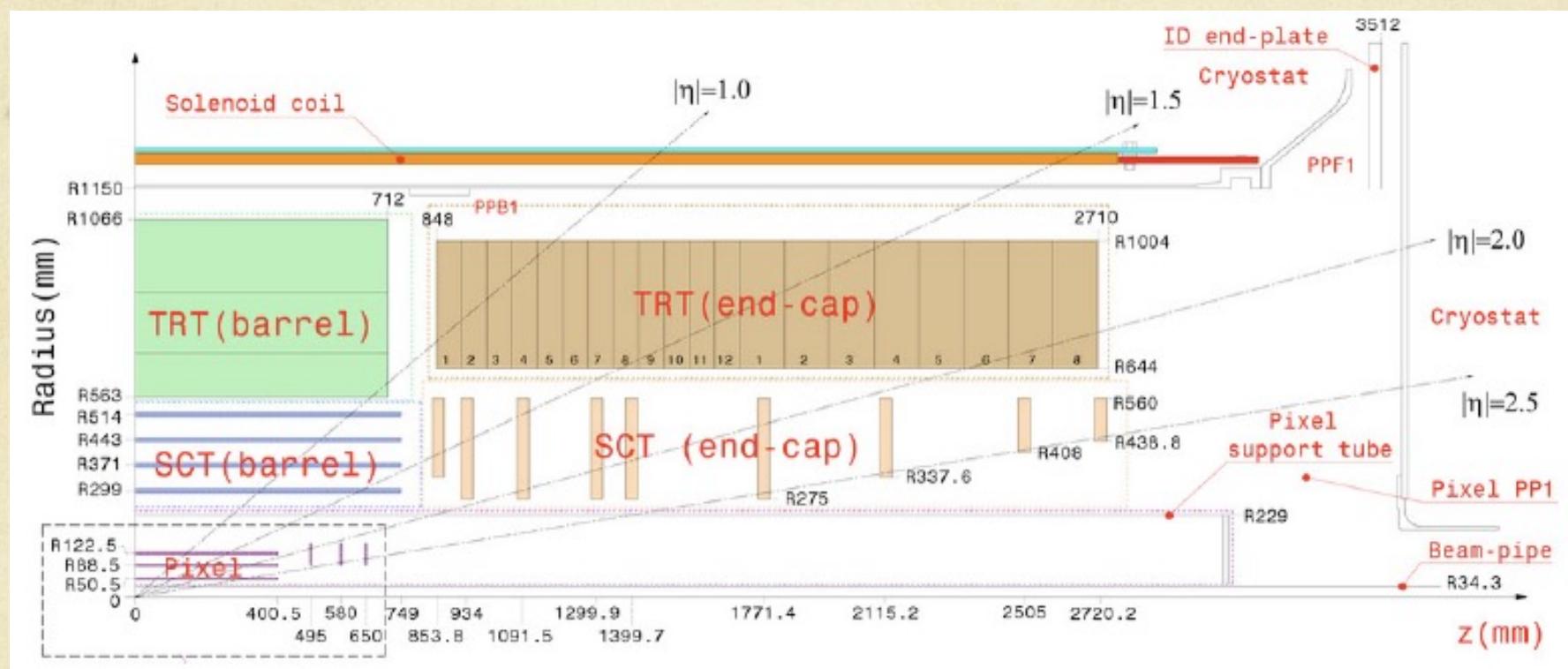


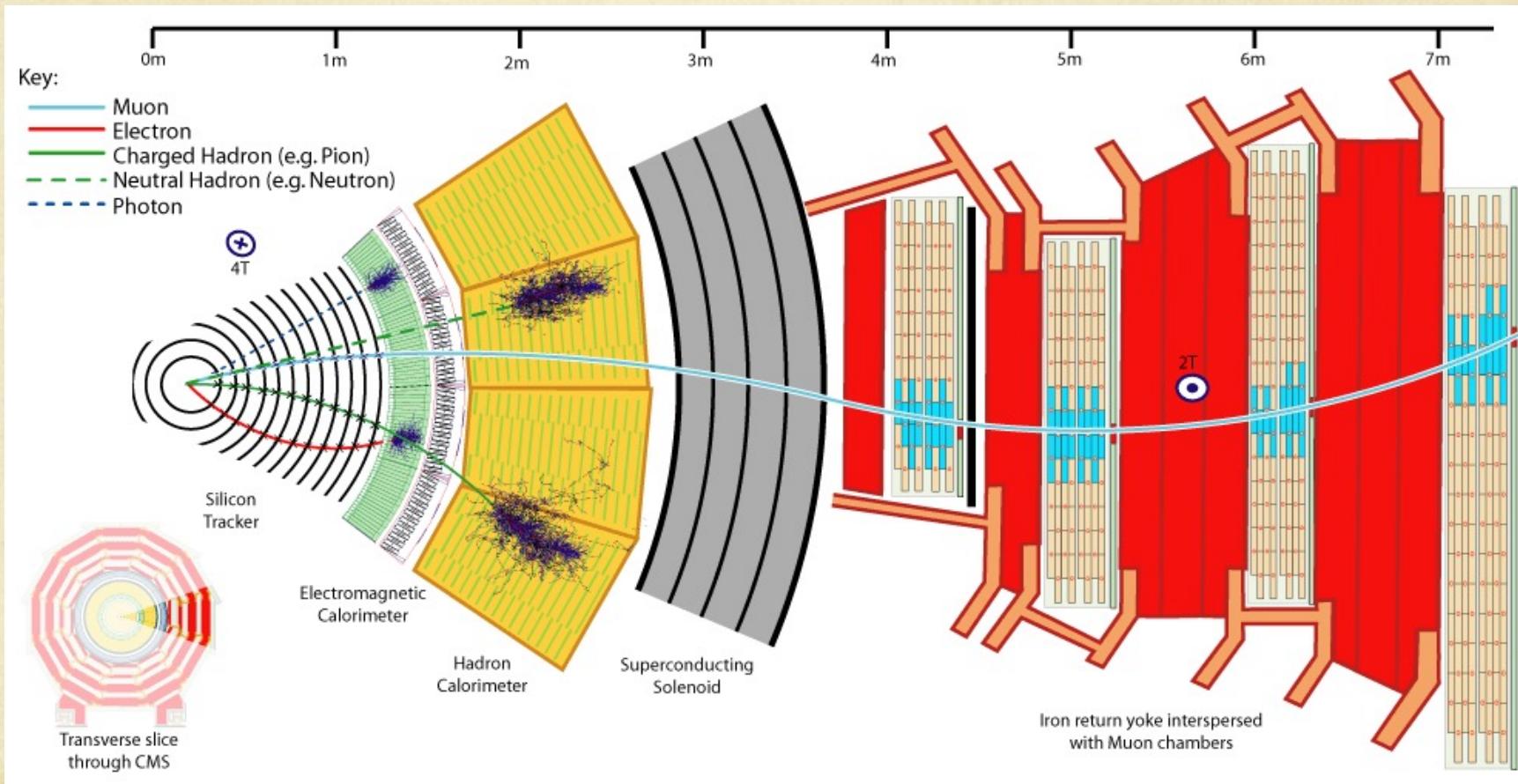
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9

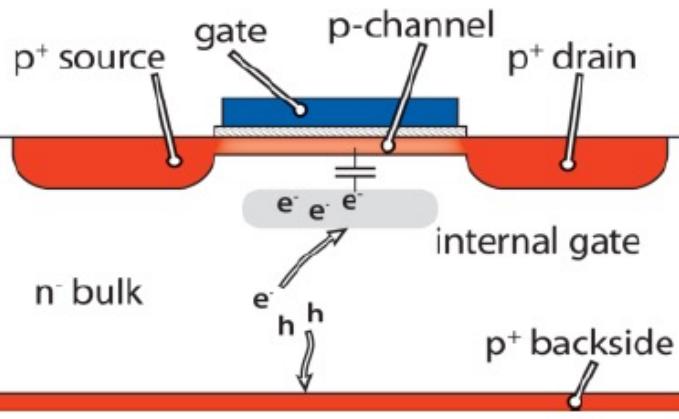
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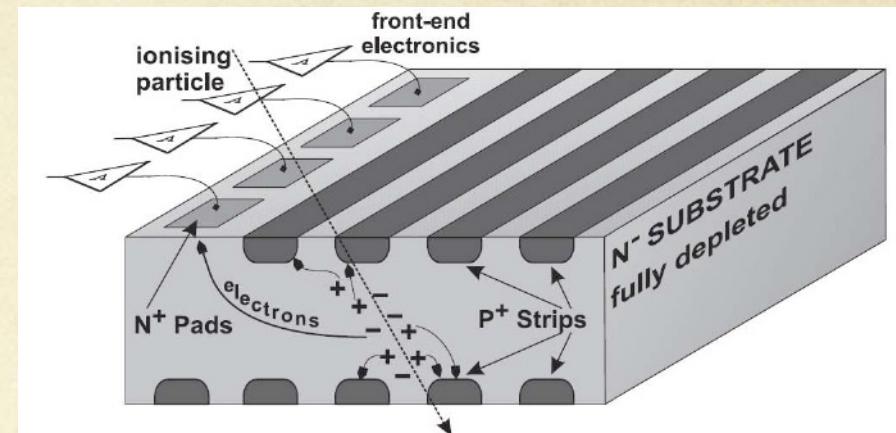




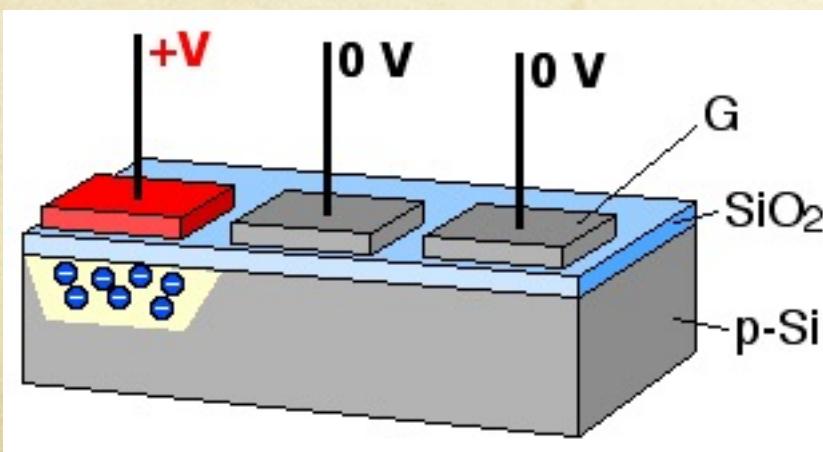
DEPFET



Silicon drift



CCD



MICROMEGAS

