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European network for developing new horizons for RIs

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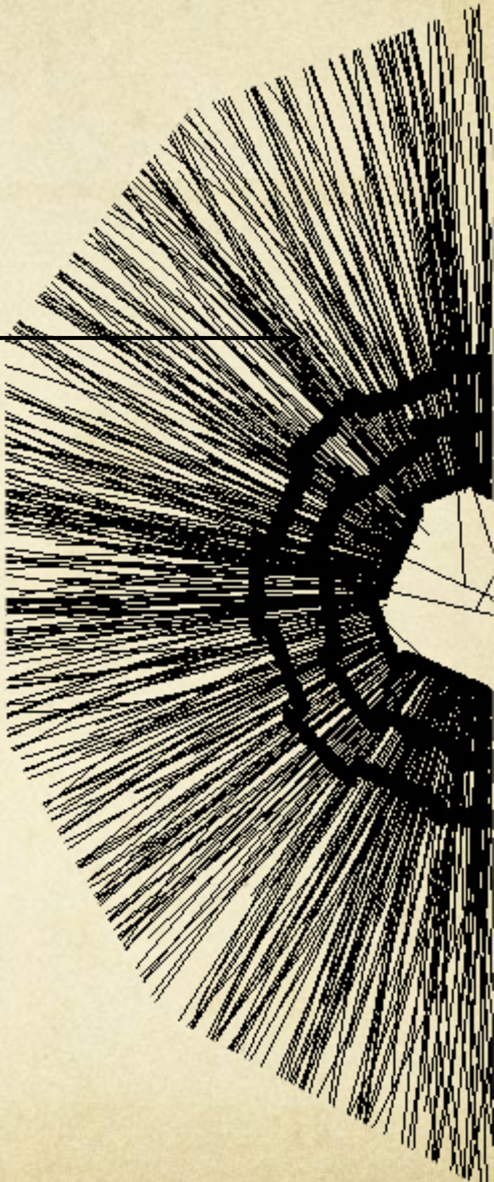
Tracking 3/3

3. Fitting algorithms

- Least square method (global)
- Kalman filter (local)
- Alignment



FITTING

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.

Nb of measured points to start?

The rule

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

Measurements

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

Models

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

Minimal #points needed

⇐ 2 points in 2D

⇐ 2 points in 3D

⇐ 3 points in 2D

⇐ 3 points in 3D

Least Square Method (LSM)

Linear model hypothesis

- P track parameters **p**, with N measurements **c**

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

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

"N measurements" means:
- K points (or layers)
- D coordinates at each point
- N = KxD

Sum of squares:

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

Best estimator (minimizing variance)

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

- Variance (= uncertainty) of the estimator:

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

- Estimator p follows a χ^2 law with N-P degrees of freedom

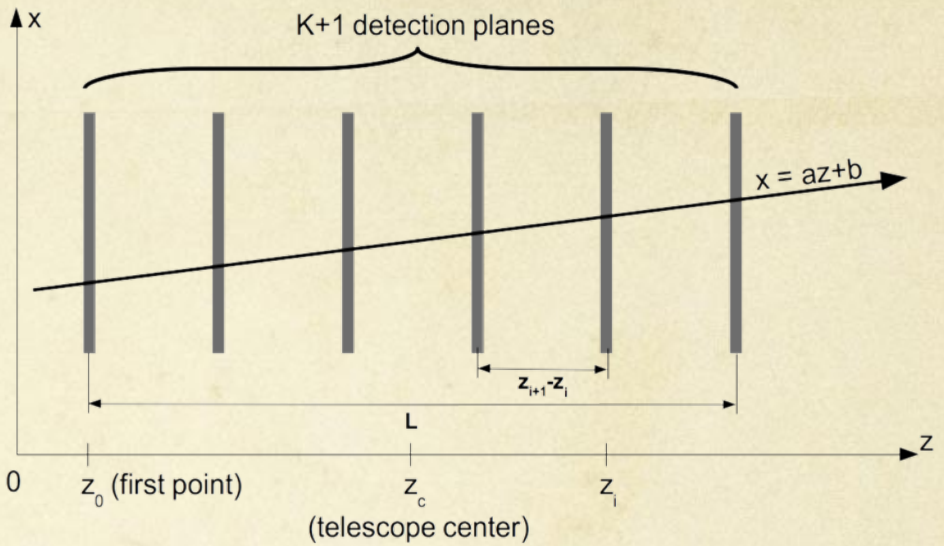
Generic tool for fitting: https://genfit.sourceforge.net

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

- But real difficulty could be computing **V** (NxN matrix)
  <= layer correlations if multiple scattering non-negligible if $\sigma_{\text{mult. scatt.}} \gtrsim \sigma_{\text{meas}}$

LSM on straight tracks

- Straight line model
  - 2D case ➞ D=2 coordinates (z,x)
  - 2 parameters: a = slobe, b = intercept at z=0



- General case
  - K+1 detection planes (i=0…k)
    - located at z_i
    - Spatial resolution $\boldsymbol{\sigma}_i$
  - Useful definitions

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

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

  - Uncertainties

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

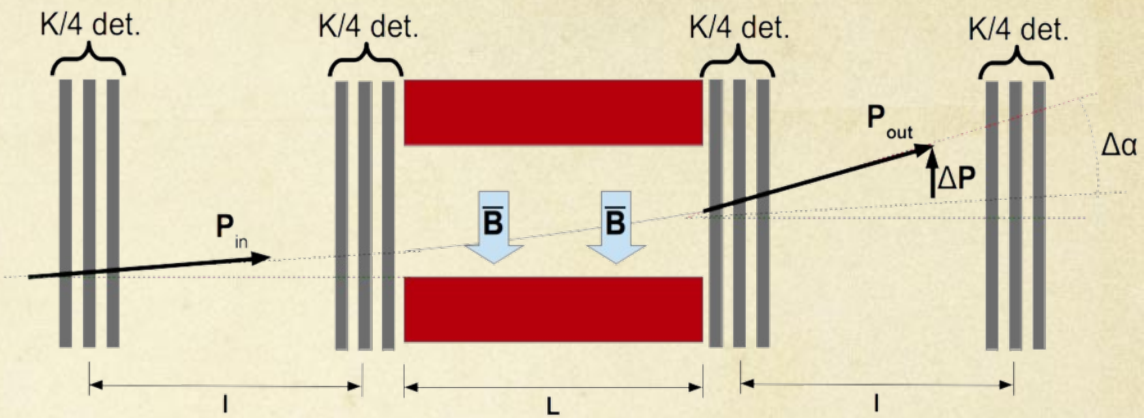
! correlation $\mathrm{cov}_{a,b} = \dfrac{-S_z}{S_1 S_{z^2} - (S_z)^2}$

- Case of uniformly distributed (K+1) planes
  - $z_{i+1} - z_i = L/K$ et $\boldsymbol{\sigma}_i = \boldsymbol{\sigma}$ $\forall i$
  - $S_z = 0$ ➞ a,b uncorrelated

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

  - Uncertainties :
    - $\boldsymbol{\sigma}_a$ and $\boldsymbol{\sigma}_b$ improve with $1/\sqrt{(K+1)}$
    - $\boldsymbol{\sigma}_a$ and $\boldsymbol{\sigma}_b$ improve with 1/L
    - $\boldsymbol{\sigma}_b$ improve with z_c

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

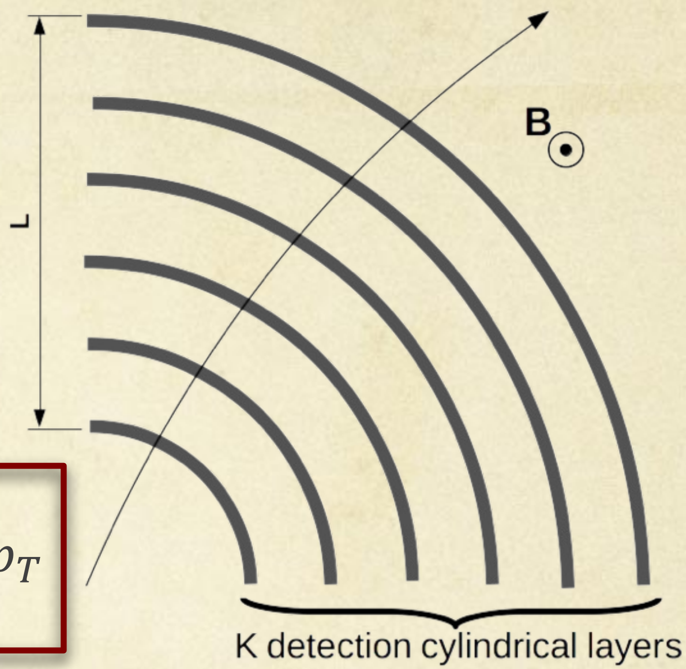
and $\sigma_\theta = \frac{13.6\ (\mathrm{MeV/c})}{\beta p}\sqrt{\frac{\mathrm{thickness}}{X_0}}$

$$\frac{\sigma_p}{p}(ms) = A_K\frac{13.6\ (\mathrm{MeV/c})}{\beta}\sqrt{\frac{\mathrm{total\ thickness}}{X_0}}$$

=> Constant with p!

A_K = factor depending on geometrical arrangement

LSM on collider geometry



- **Hypothesis**
  - K detectors uniformly distributed each with σ single point accuracy
  - Uniform field over path length L
- **Without multiple scattering**
  - Uncertainty on transverse momentum (Glückstern formula)

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

  - Works well with large K > 20

=> Proportional to p and to $\frac{1}{BL^2}$!

- **Multiple scattering contribution**
  - Brings additive contribution

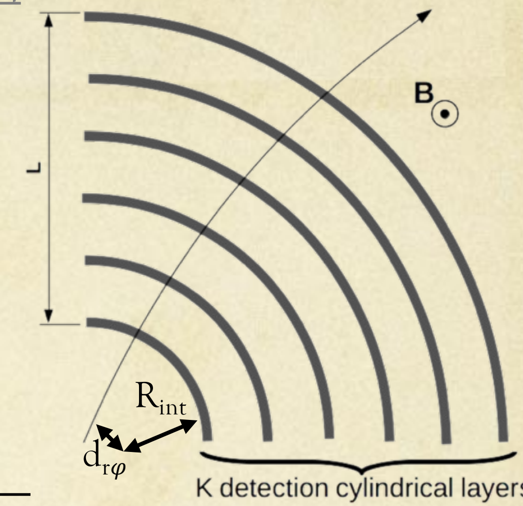
$$\frac{\sigma_{p_T}}{p_T} = \frac{1.43}{0.3q}\frac{1}{BL}\sqrt{\frac{13.6\ (\mathrm{MeV/c})}{\beta}\frac{\text{total thickness}}{X_0}}$$

*Numerical factors $\sqrt{\frac{720}{K+6}}$ and 1.43 can be refined
⟶ see https://arxiv.org/abs/1805.12014

=> Constant with p!
=> Depends on K through total thickness!

LSM for impact parameter ($d_{r\varphi}$)

⟶ see https://arxiv.org/abs/1805.12014



- Hypothesis
  - K detectors uniformly distributed over L
  - each with σ single point accuracy
  - First layer is close to PV / L => $r = R_{int}/L < 1$
- Without multiple scattering $\sigma_{d_{r\varphi}} = \frac{\sqrt{3}\sigma}{\sqrt{K+4}}\sqrt{1+8r+28\,r^2}$
- Multiple scattering contribution
  - Brings additive contribution proportional to $\sigma_\theta = \frac{13.6\ (\mathrm{MeV/c})}{\beta p_T}\sqrt{\frac{\mathrm{thickness}}{X_0}}$

$$\sigma_{d_{r\varphi}}(ms) = r\sigma_\theta\sqrt{1+\frac{1}{2}r+\frac{K-1}{4}r^2}\text{cv}$$

=> Proportional to r and K!

- Key points
  - Minimising R_{int}/L ↔ getting close & keeping lever arm
  - Multiple scattering destroys statistical gain of K>2

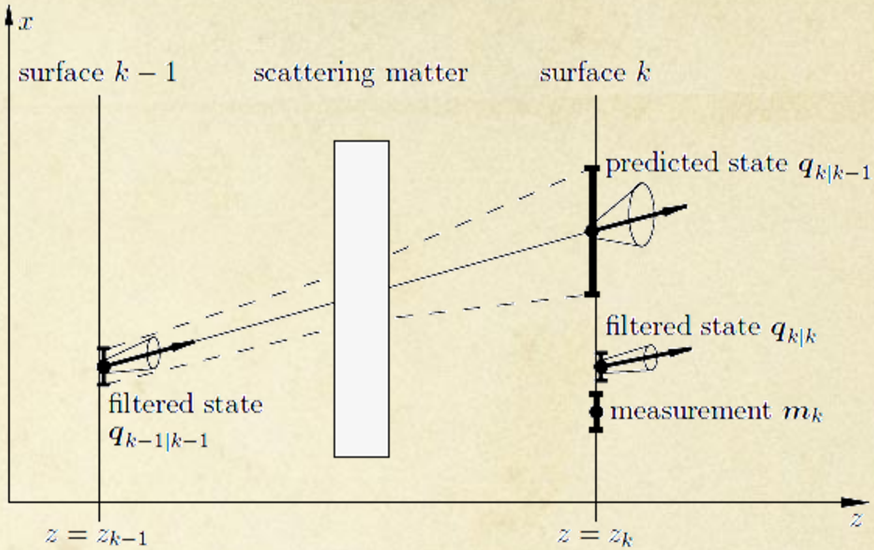
- Final parametrisation

$$\sigma_{d_{r\varphi}} = a \oplus \frac{b}{p_T \sin^{\frac{1}{2}}\theta}$$

$a \propto \sigma$
$b \propto \sigma_\theta$

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 $\vec{m}_k = H\,\vec{p}_k + \vec{\varepsilon}_k$
    - H=DxP matrix, **ε**= measure error associated with diagonal covariance DxD matrix V_m
    - Weighted means of prediction and measurement using variance ⇔χ^2 fit
  - Iterate…

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

Kalman filter 2/2

Forward and backward filters

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

Computation complexity

- only PxP, DxP or DxD matrices computation (≪NxN)

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

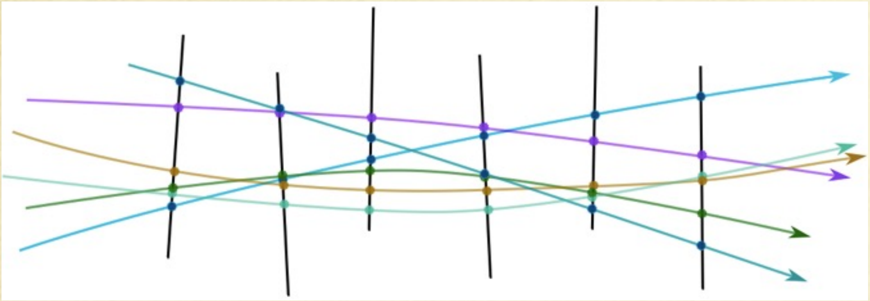
- Like dE/dx, correlated to momentum
- Additional measurement equation $\vec{m}'_k = H'\,\vec{p}_k + \vec{\varepsilon}'_k$

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

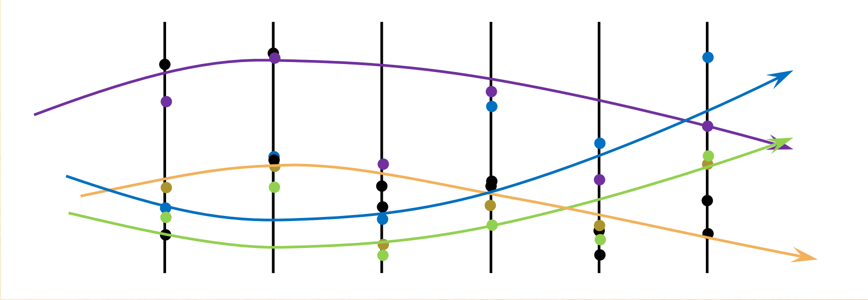
Need for Alignment

- Let's come back to one initial & implicit hypothesis
  - "We know were the point are located."
  - True to the extent we know were 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!

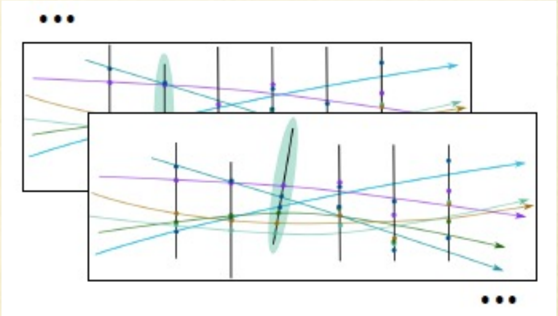
Alignment strategy 1/2

Alignment parameters

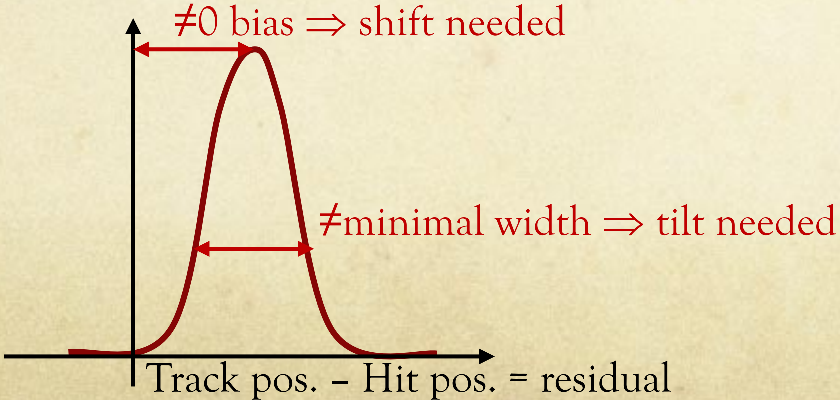
- Track model depends on additional “free” parameters, i.e. the sensor positions

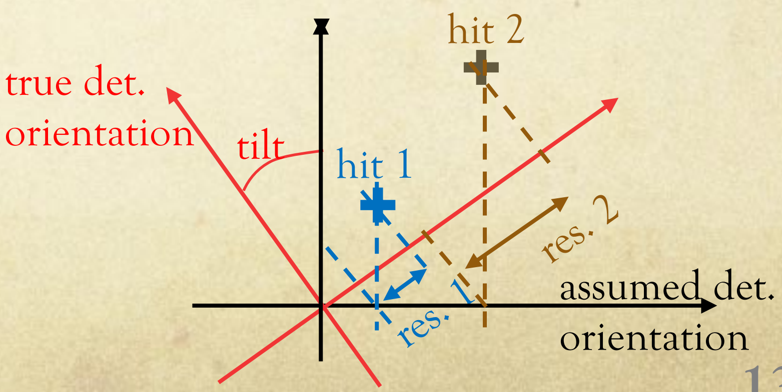
Methods to find the relative position of individual sensors

- 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.



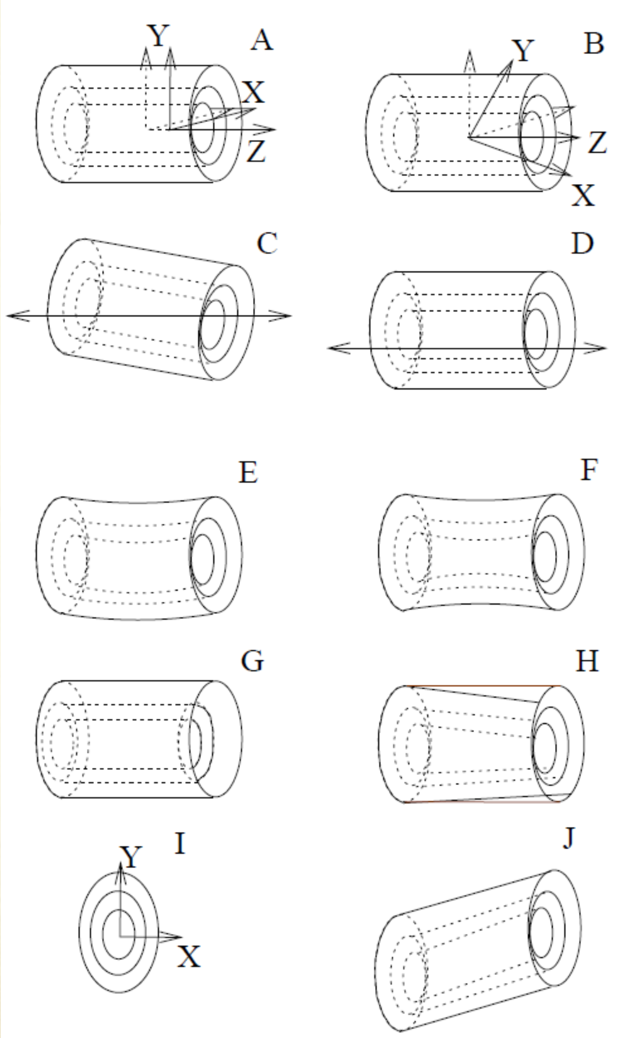
- Local alignment:
  - Use tracks reconstructed with reference detectors
  - Align other detectors by minimizing the “residual” (track-hit distance) width





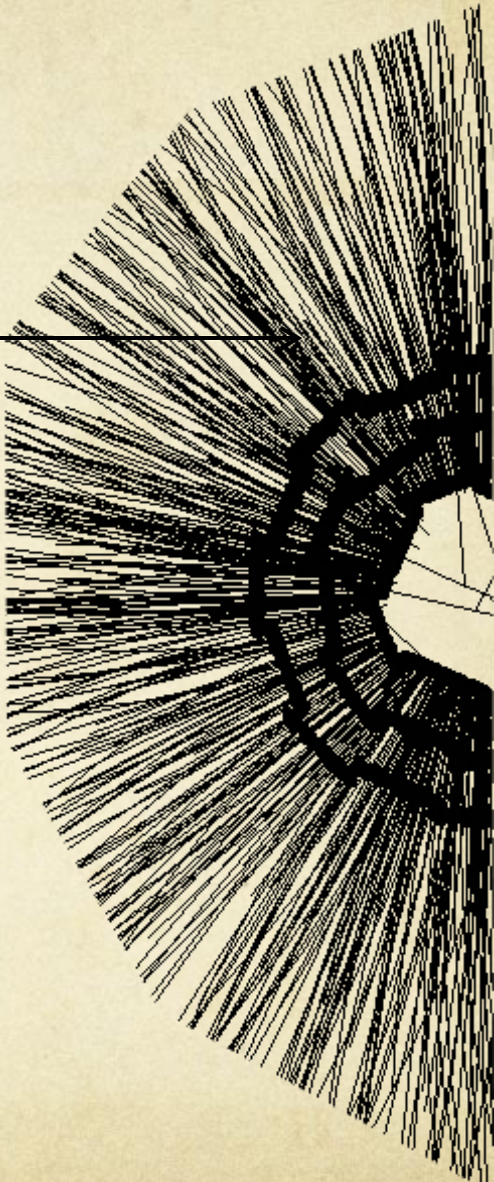
Alignment strategy 2/2

- In both methods (global or local alignment)
  - Use a set of well know tracks and tracking-"friendly" environment to avoid bias
    - Muons (very traversing) and no magnetic field
    - Low multiplicity events
- Global deformations also possible
  - Invisible through single track χ^2 investigation
  - affect overall positions & momentum
  - Corrected through observing
    - Mass peak positions
    - Systematic differences at various track angles or detector positions



4. Deconstructing some tracking systems

- **Collider setups:**
  - CBM, LHCb
  - ALICE, Belle II, CMS
- **Telescope setups:**
  - AMS, ANTARES, OPERA
- **Something totally(?) different**
  - AGATA



Lessons from figures of merit

- Excellent track finder requires
  - Granular sensors in space & time
  - Layer close to each other

Can a single algorithm all track search?

NO
real tracking is done with many steps

- Excellent momentum resolution requires
  - Many measurement points
  - Measurement over large lever arm
  - Low material budget
    (depending on momentum range)

Can we get all that with a single sub-detector?

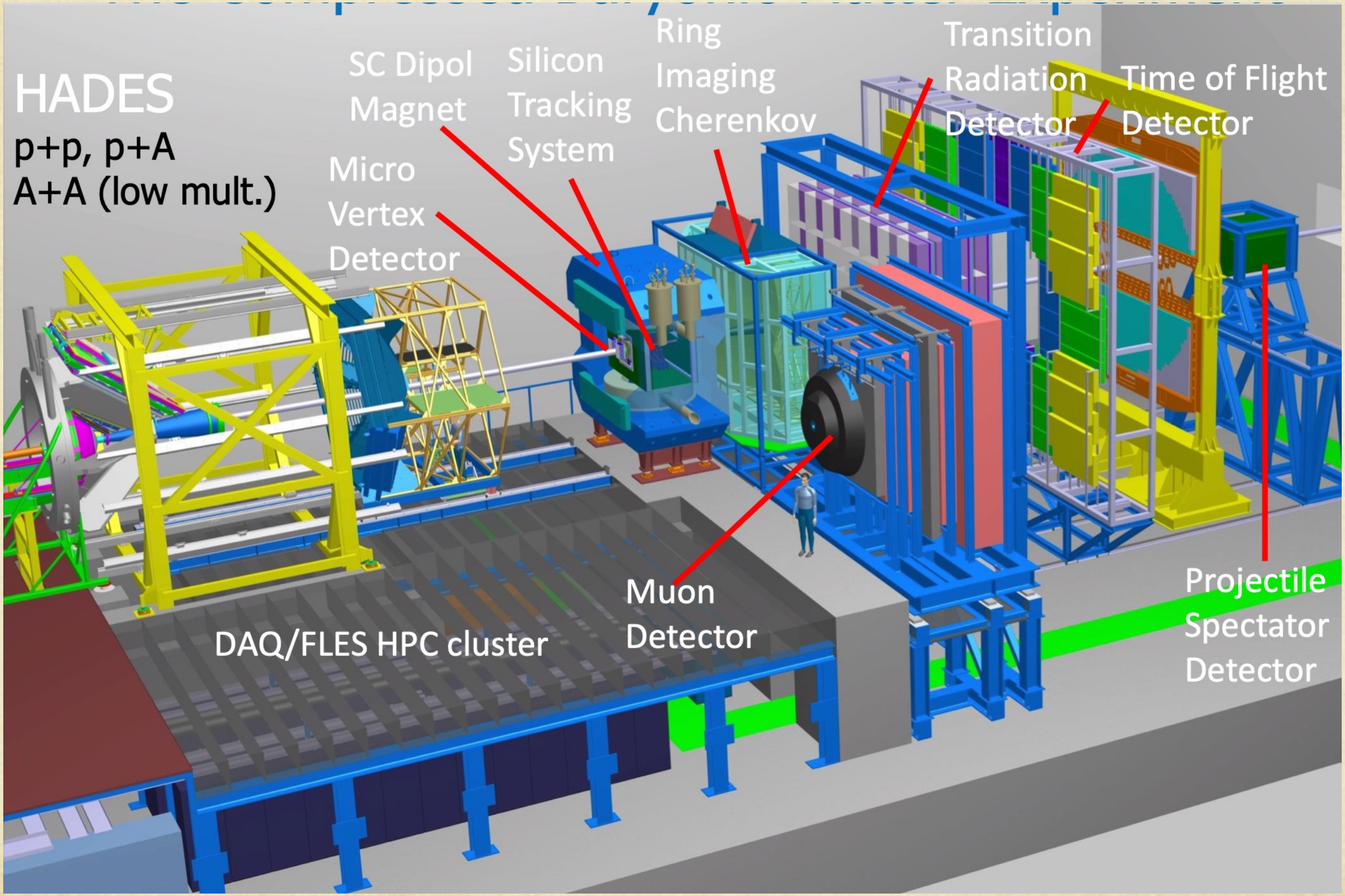
NO
(though they are similarities)

Trackers / Vertex locators

- Excellent vertexing requires
  - Very granular sensors in space
  - Short & long distances
  - Low material budget

4. Some tracking systems:

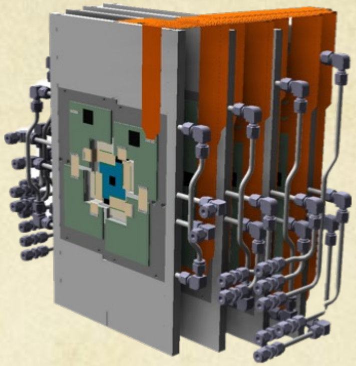
CBM @ FAIR/SIS setup

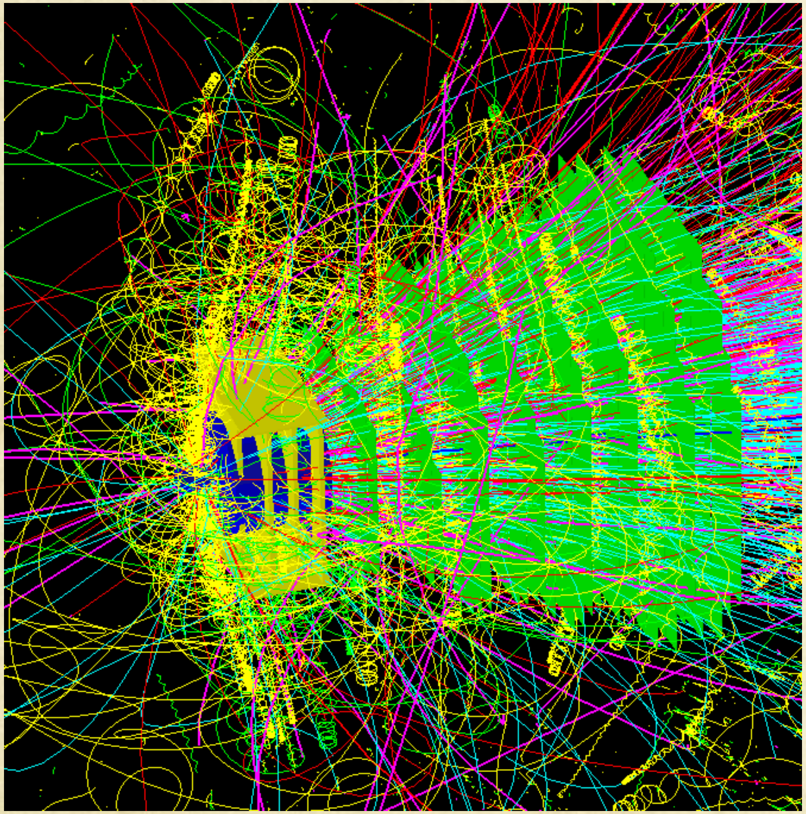


CBM @ FAIR/SIS setup

- 10^5-10^7 Au+Au/sec, 10^9 p+Au/sec

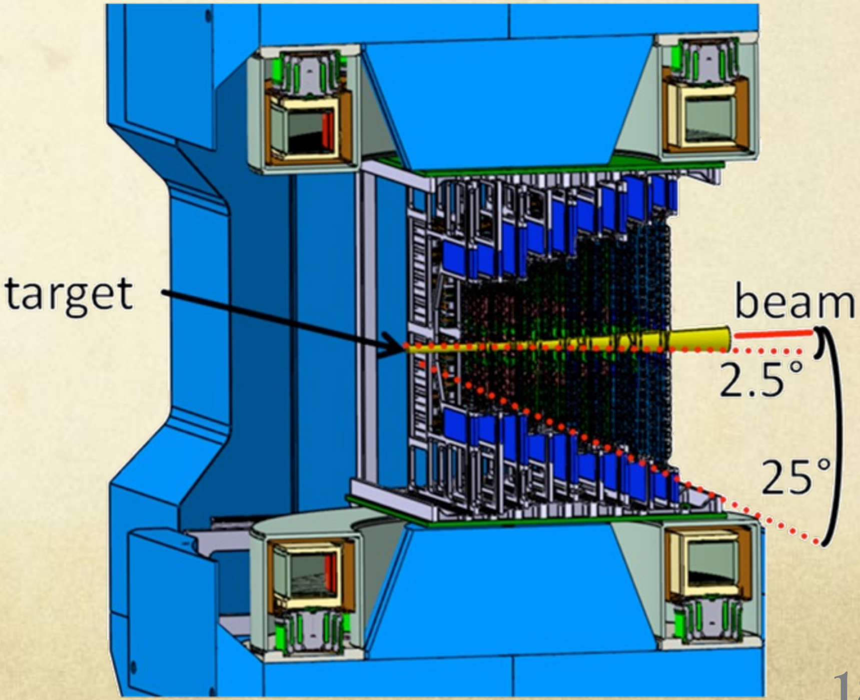
Micro Vertex Detector
(MAPS)





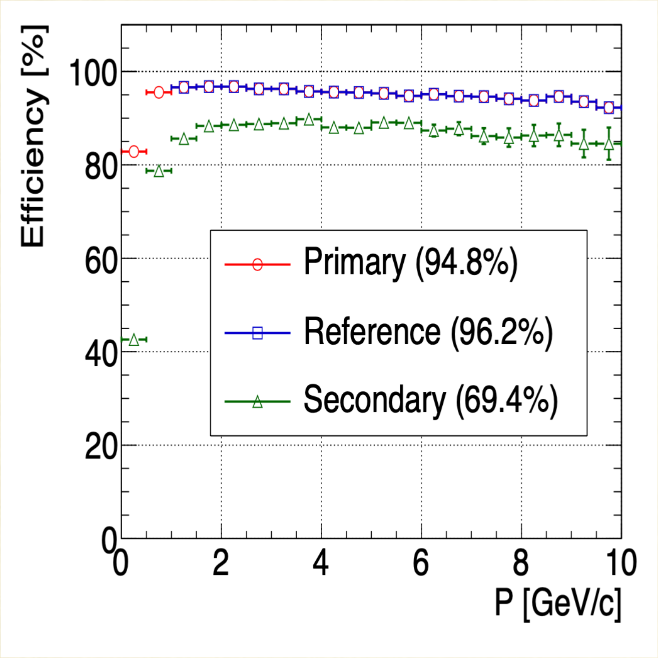
Simulated Au+Au collision at 8 A GeV

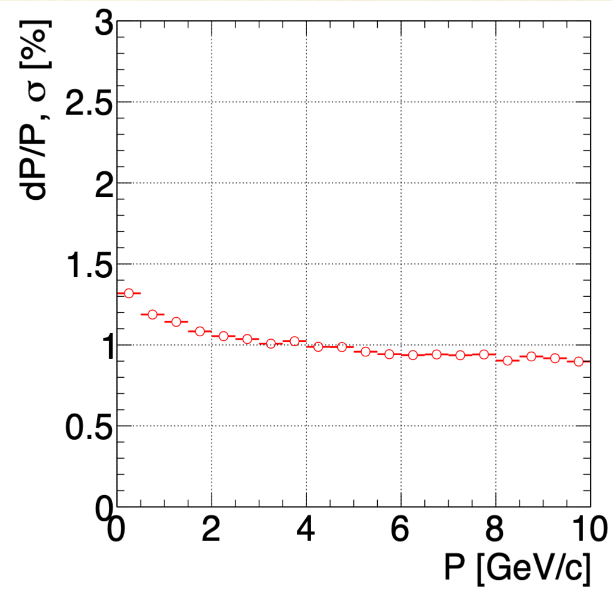
Silicon Tracking System
(double-sided strip sensors)

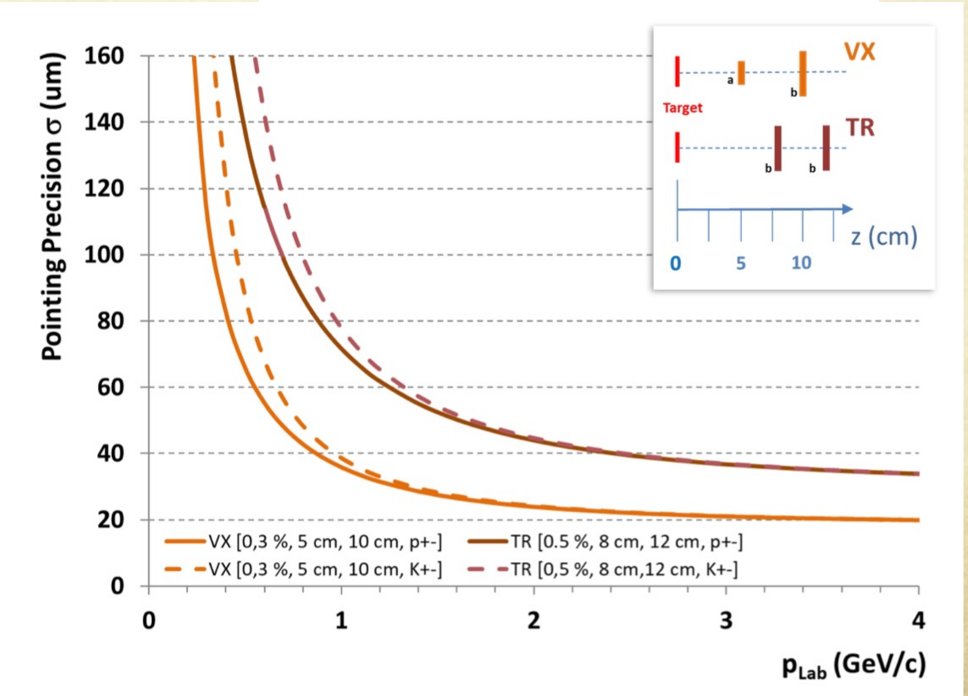


CBM @ FAIR/SIS performance

Track finder: cellular automaton
~700 tracks/event

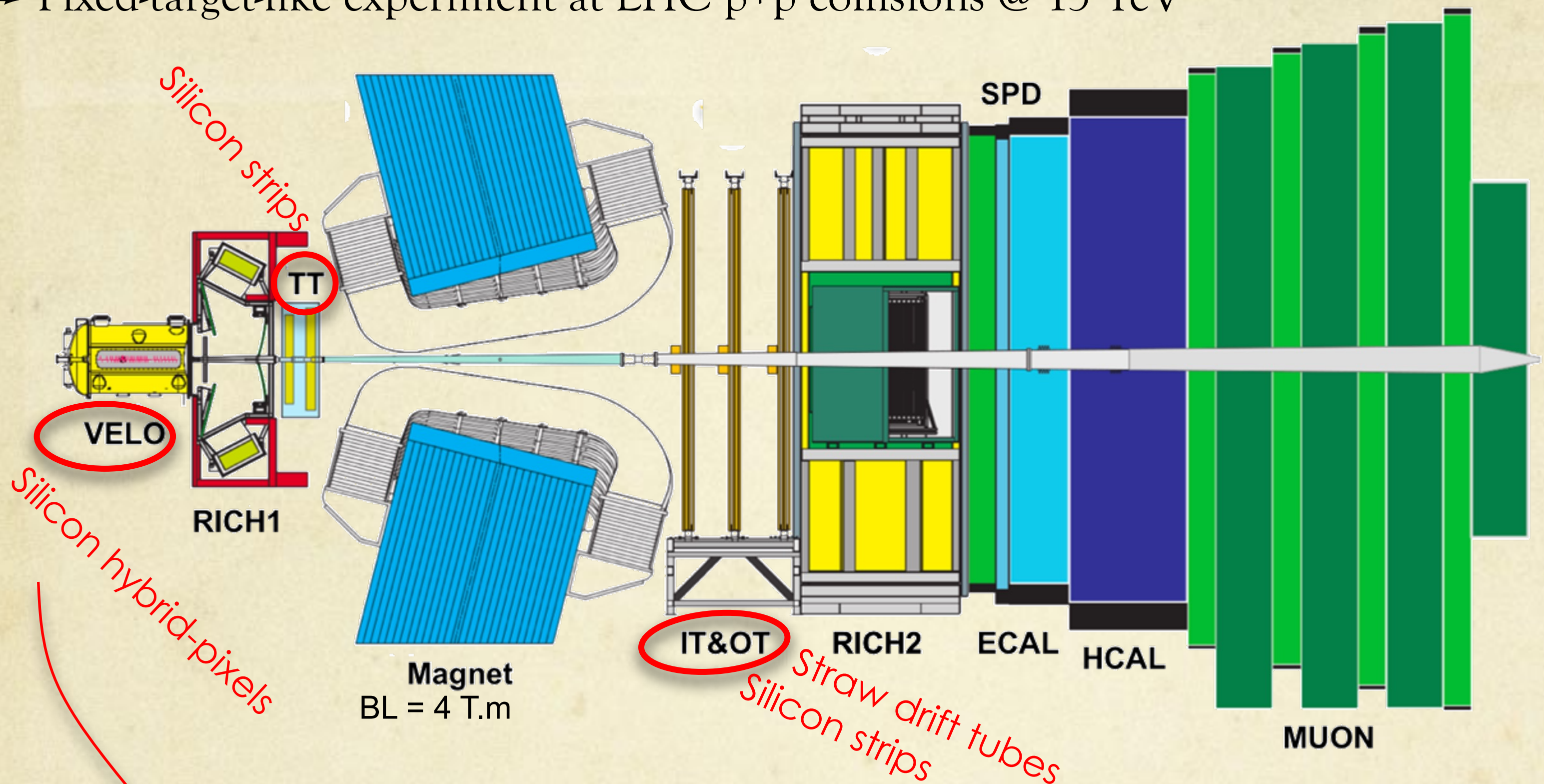


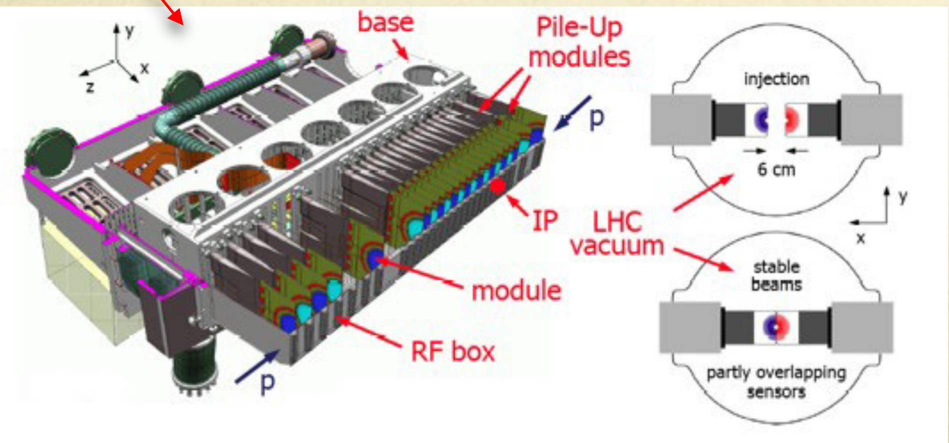




LHCb setup

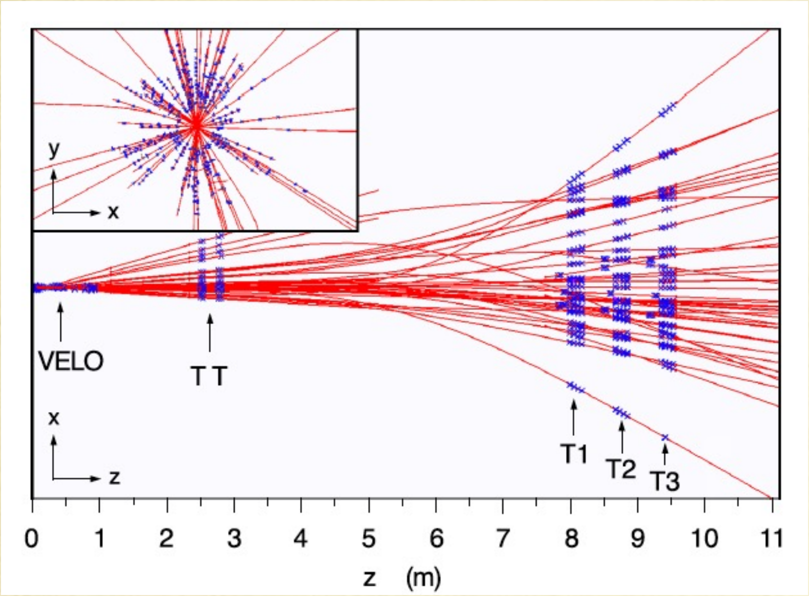
- Fixed-target-like experiment at LHC p+p collisions @ 13 TeV

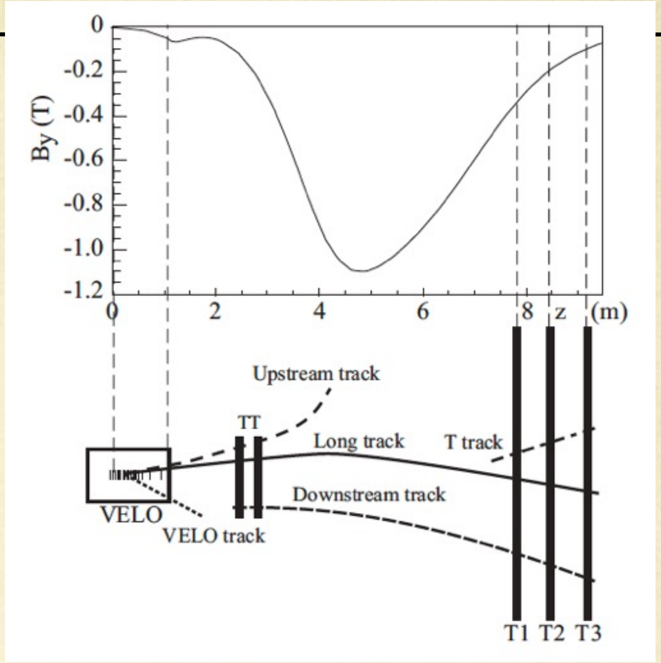


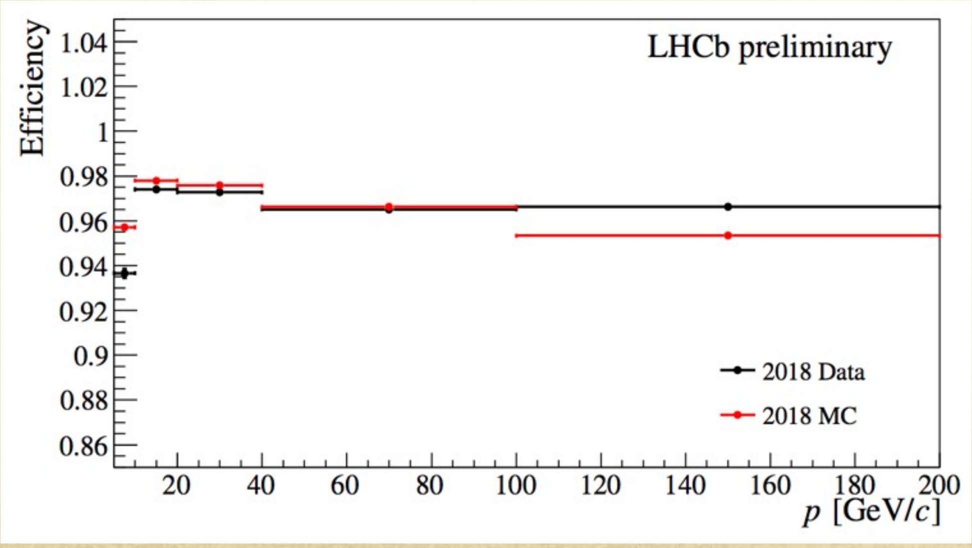


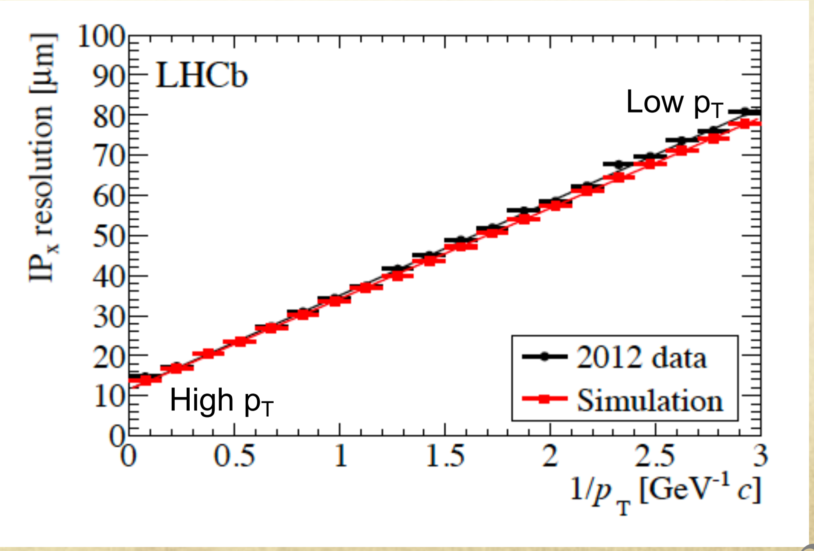
- Collision rate 40 MHz
- Trigger rates (hw & sw)
  1 MHz / 100 KHz / 12 Khz

LHCb performance



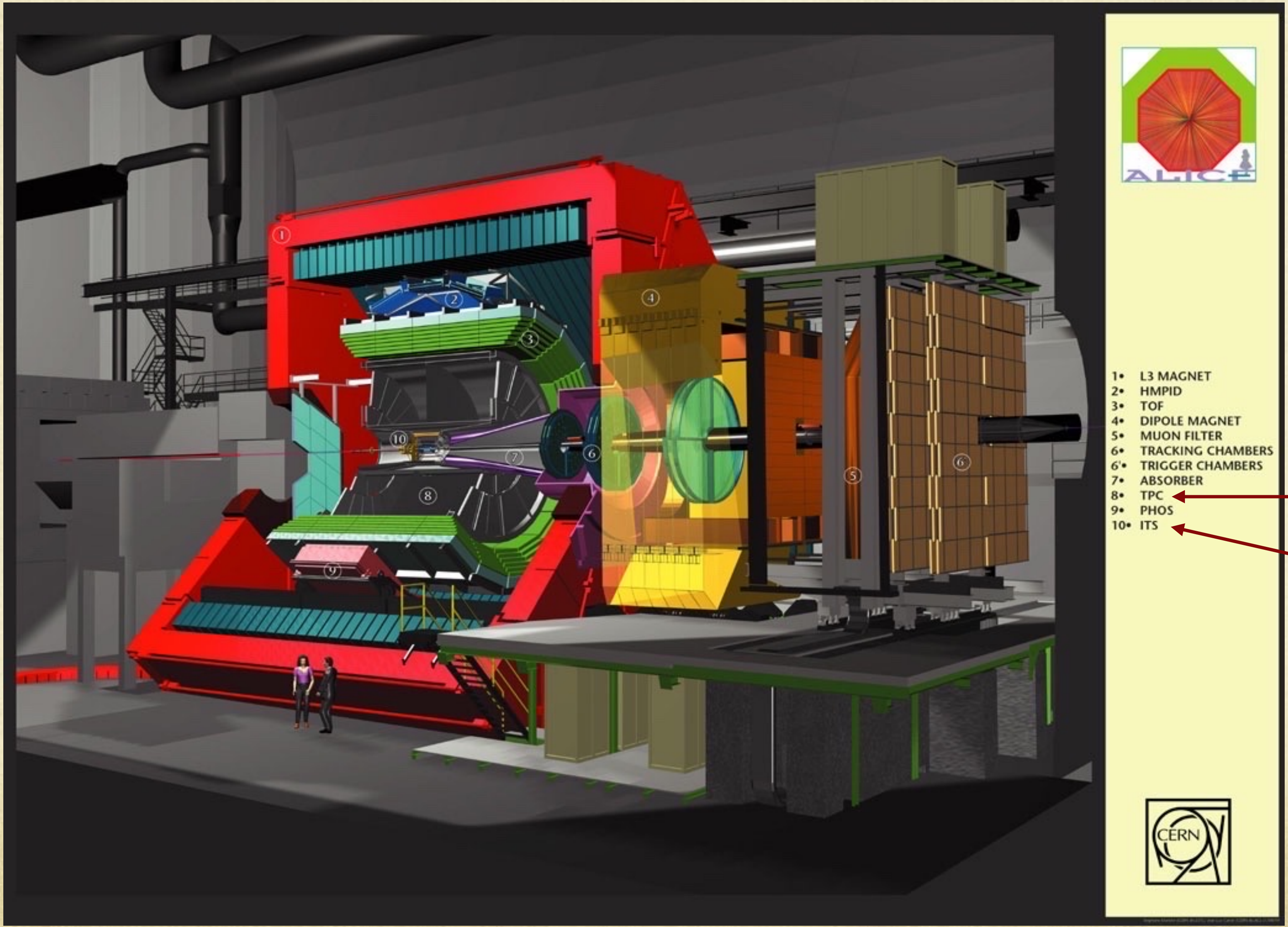






ALICE @ LHC setup

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

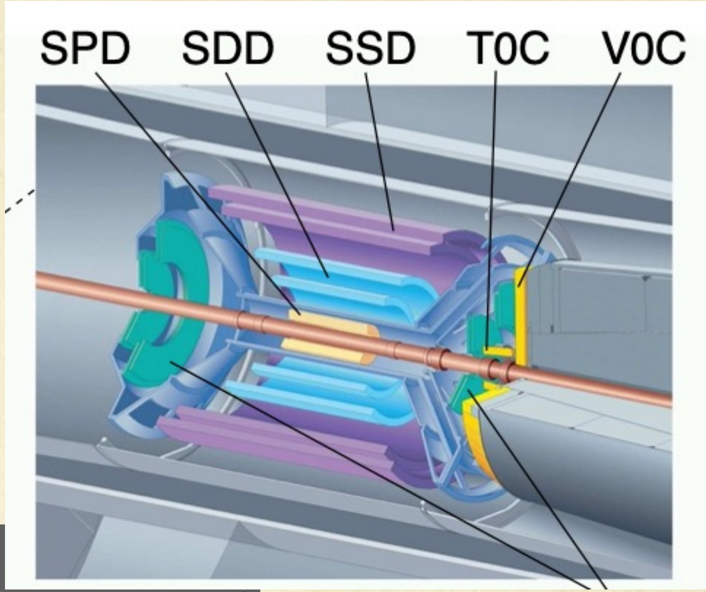


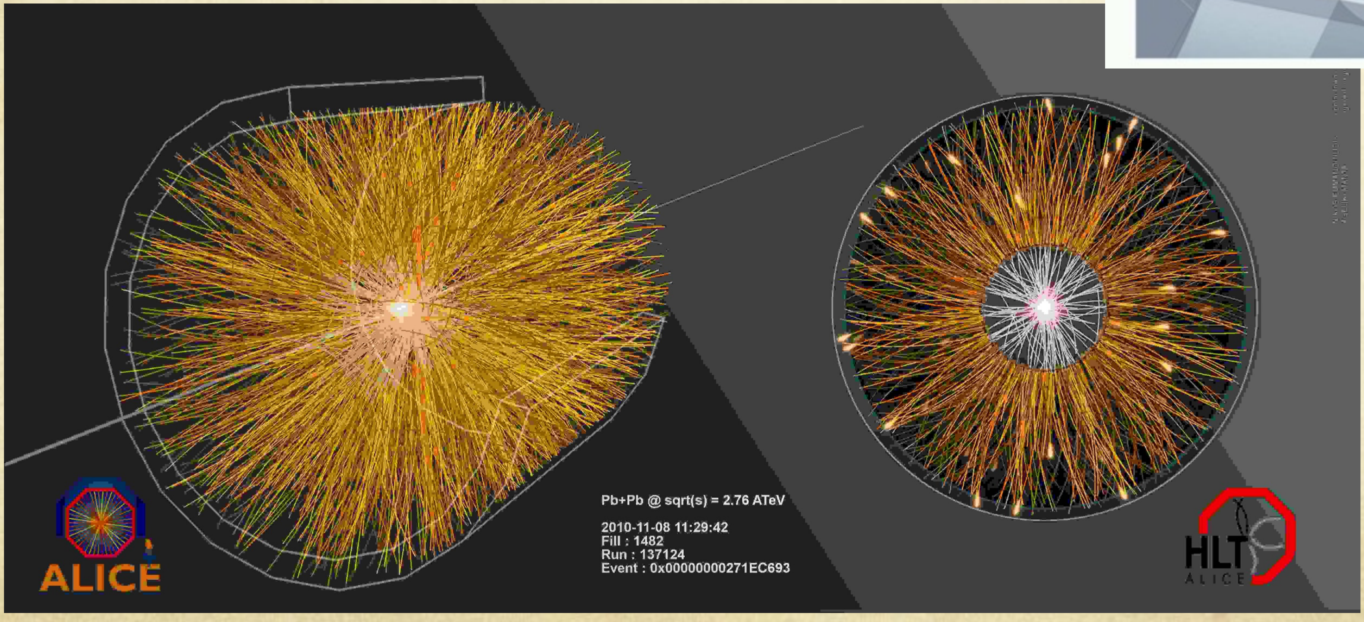
Largest TPC

Since 2022, largest MAPS area (10 m2, 13 Gpixels)

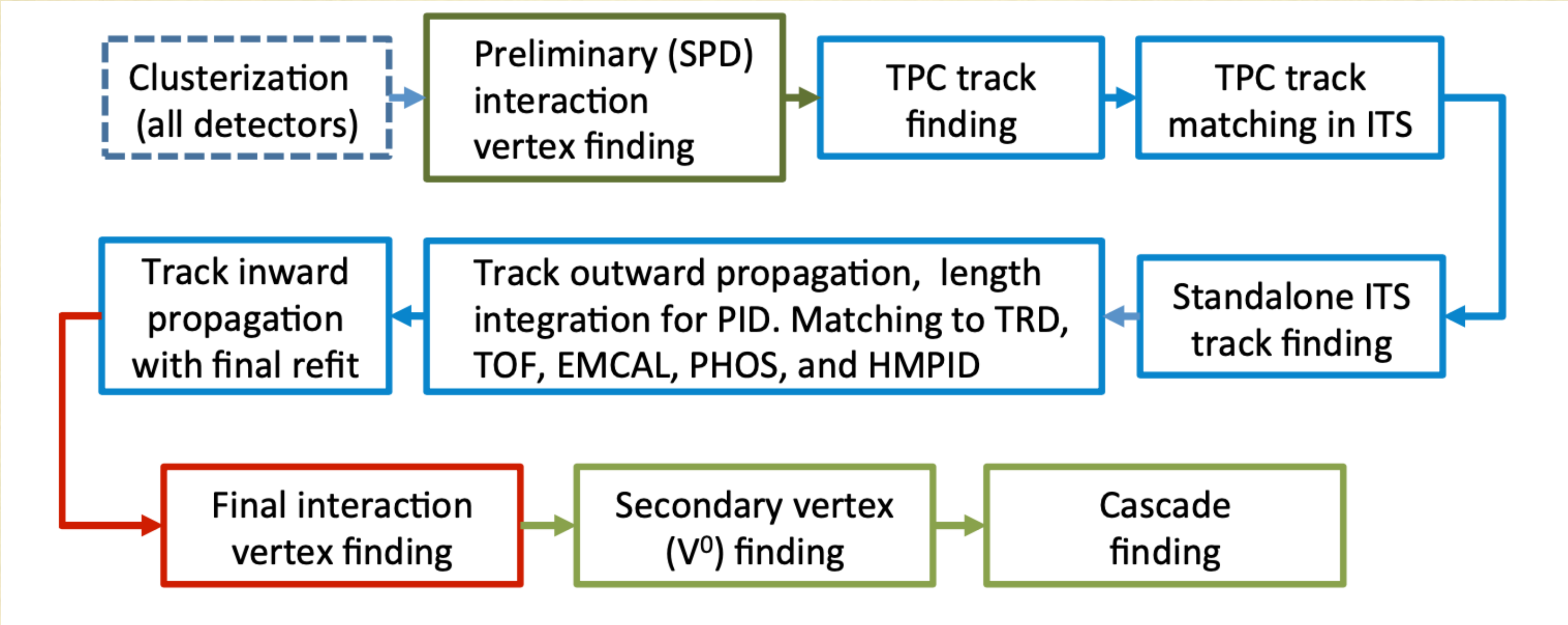
ALICE setup

- **Inside the large TPC, the Inner Tracking System**
  - Radius < 43 cm
  - Hybrid pixels: SPD
  - Silicon drift detector SDD
  - Double-sided strips SSD

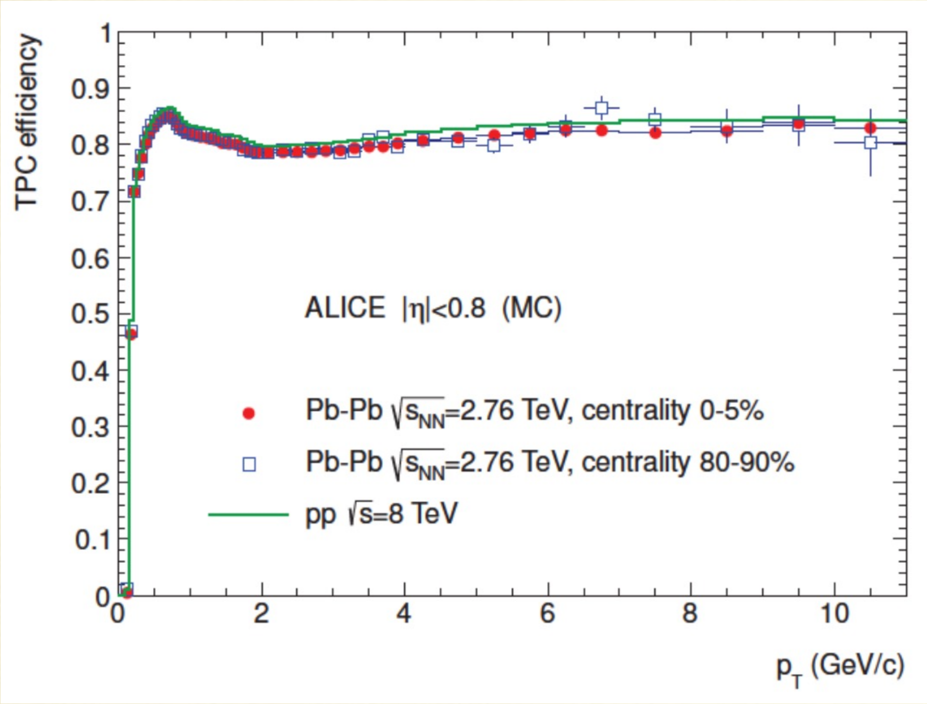


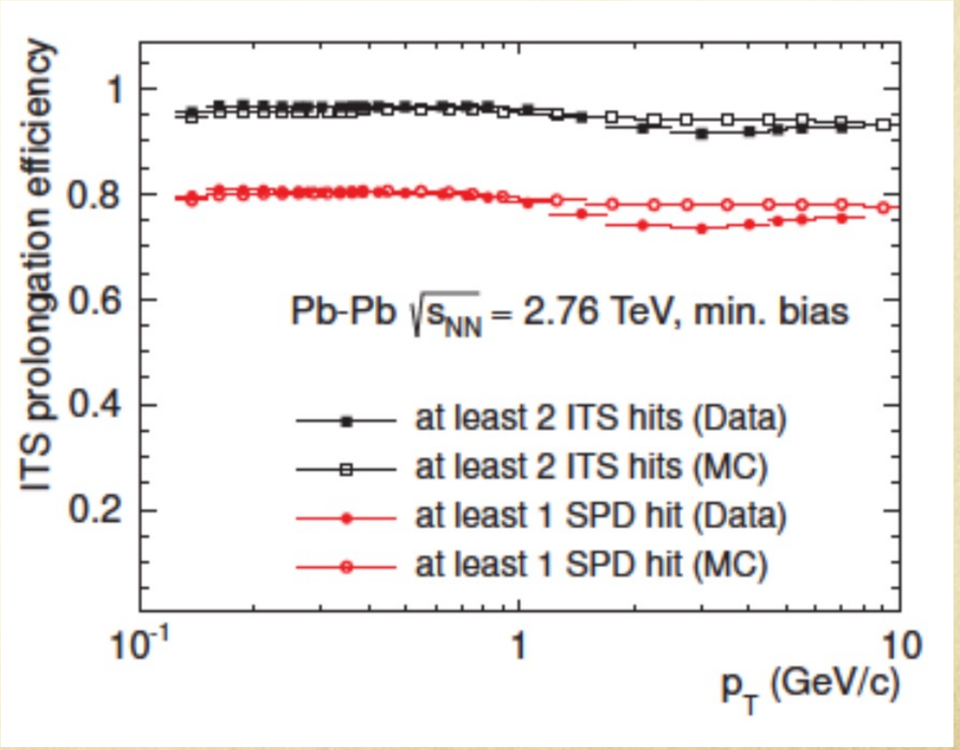


ALICE algorithm

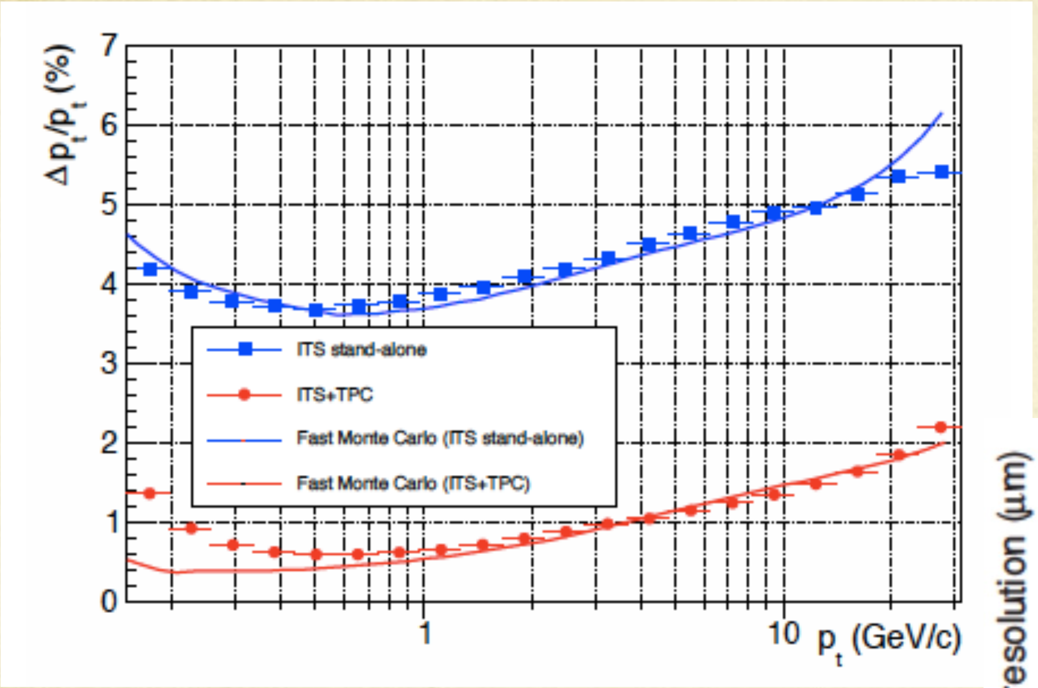


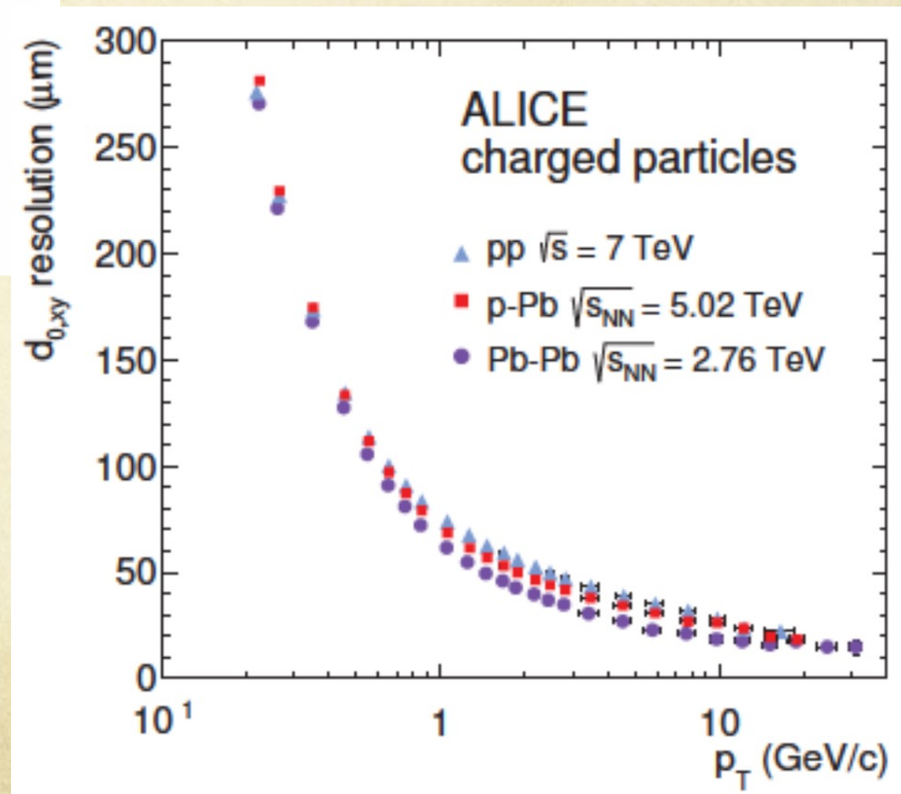
ALICE performance



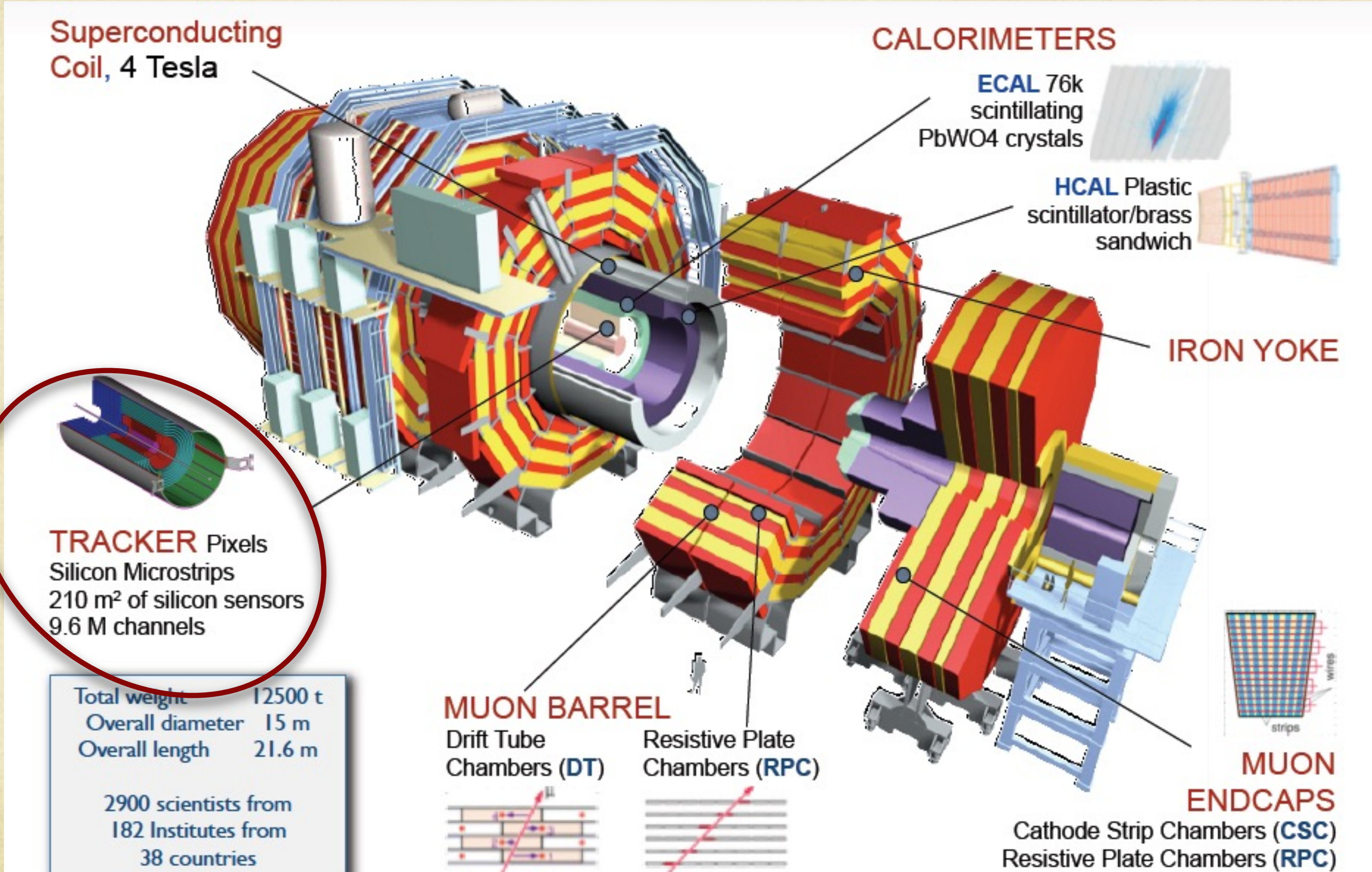


ALICE performance



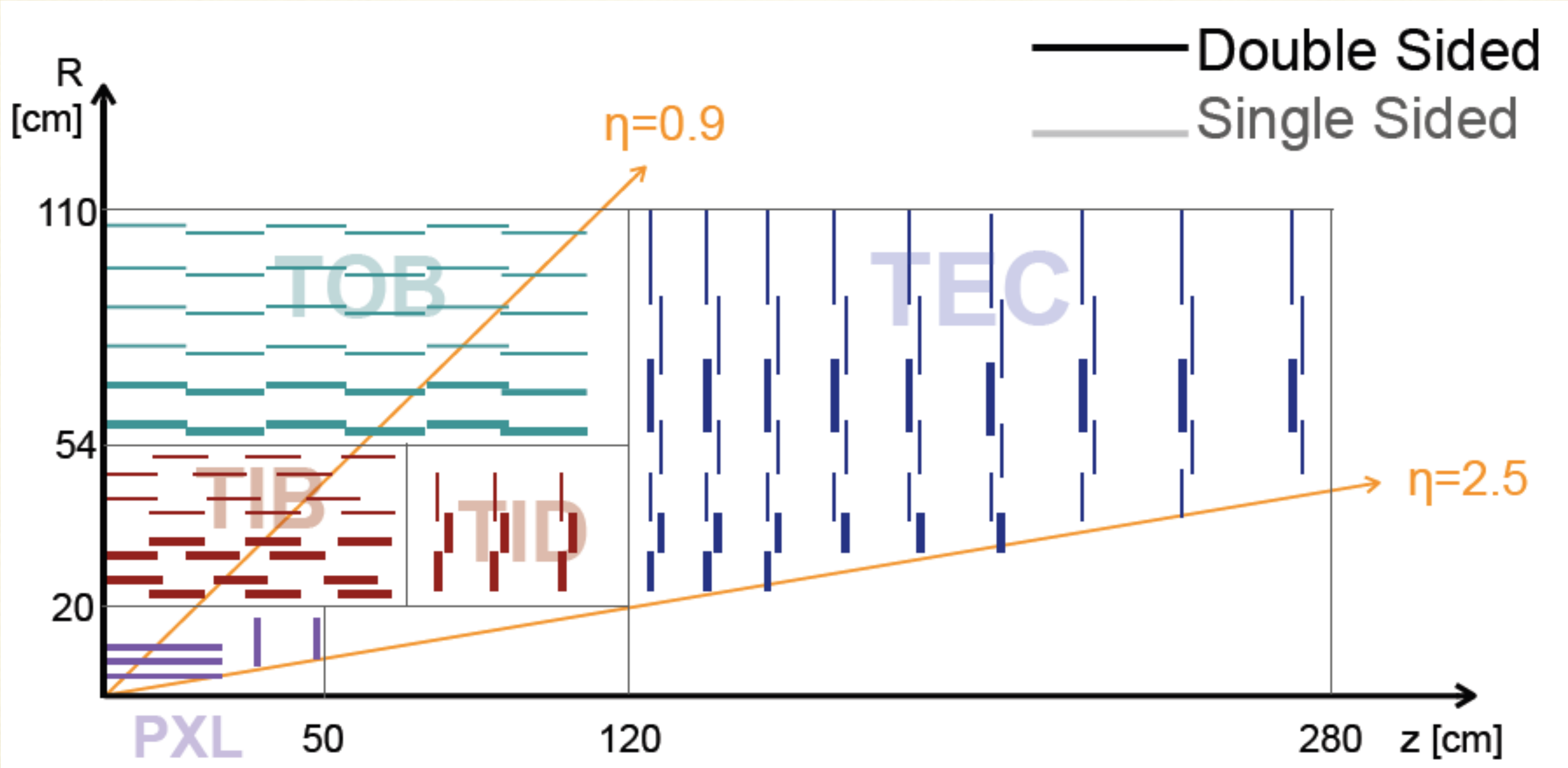


CMS @ LHC setup



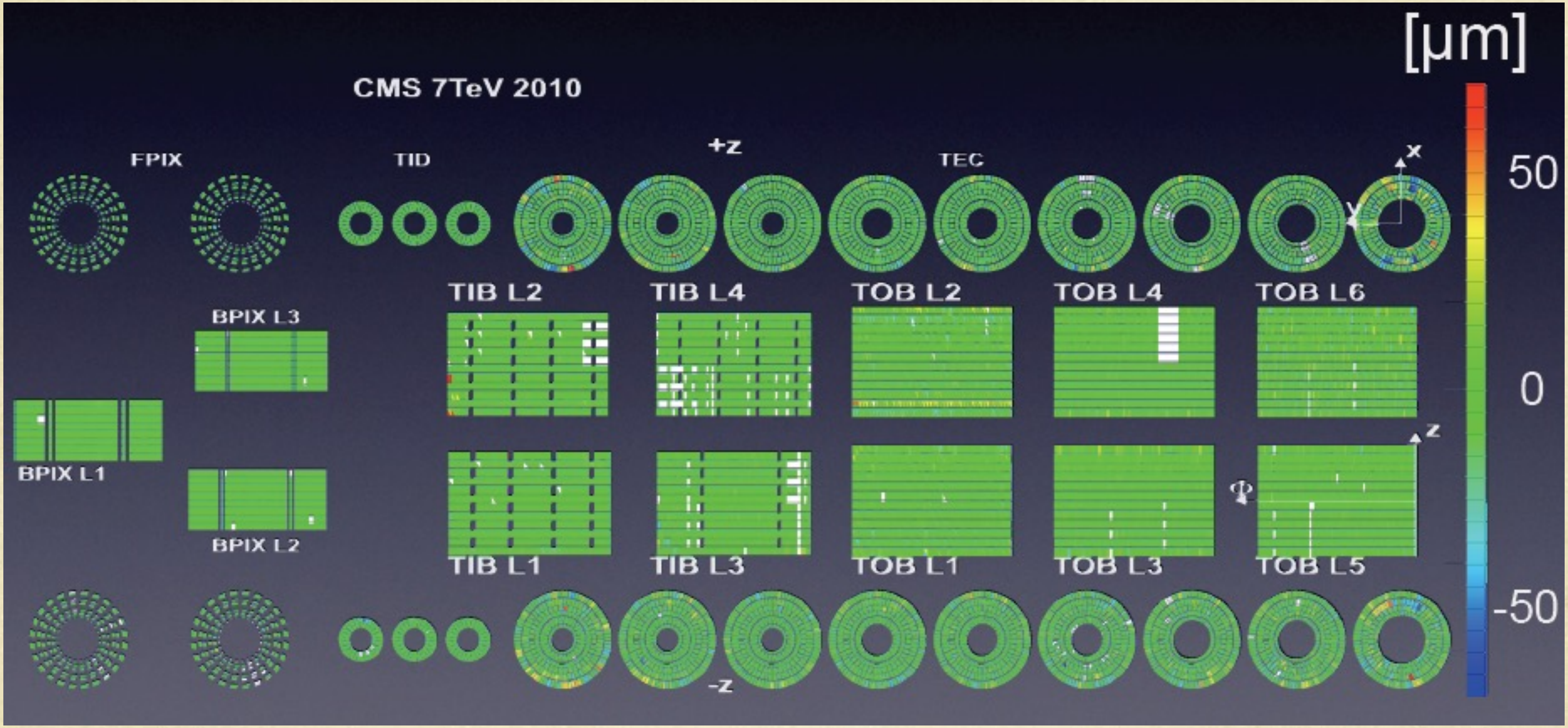
CMS setup

- The trackerS



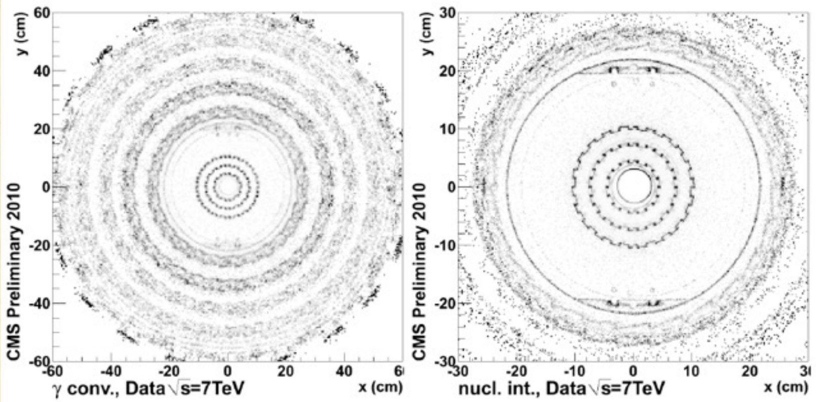
CMS alignment

- Alignment residual width

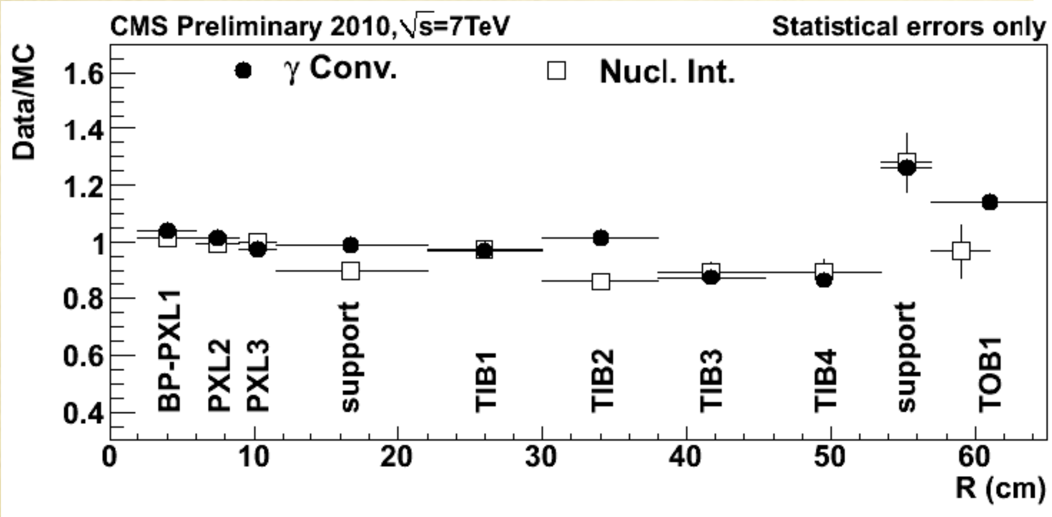


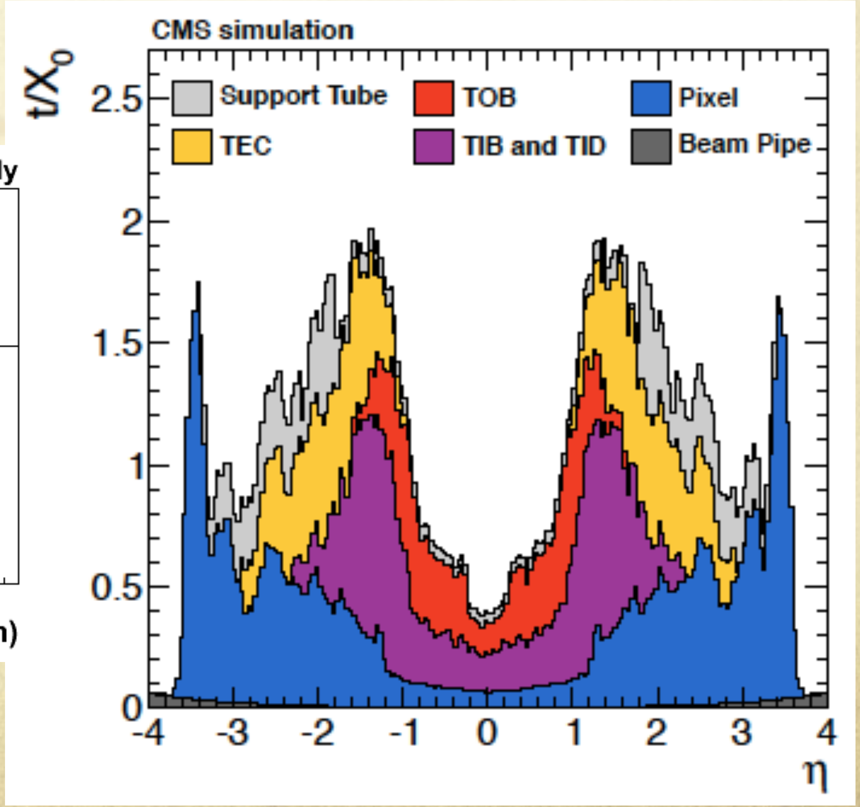
CMS material budget

- Taking a picture of the material budget
  - Using secondary vertices from $\gamma \rightarrow e^+e^-$



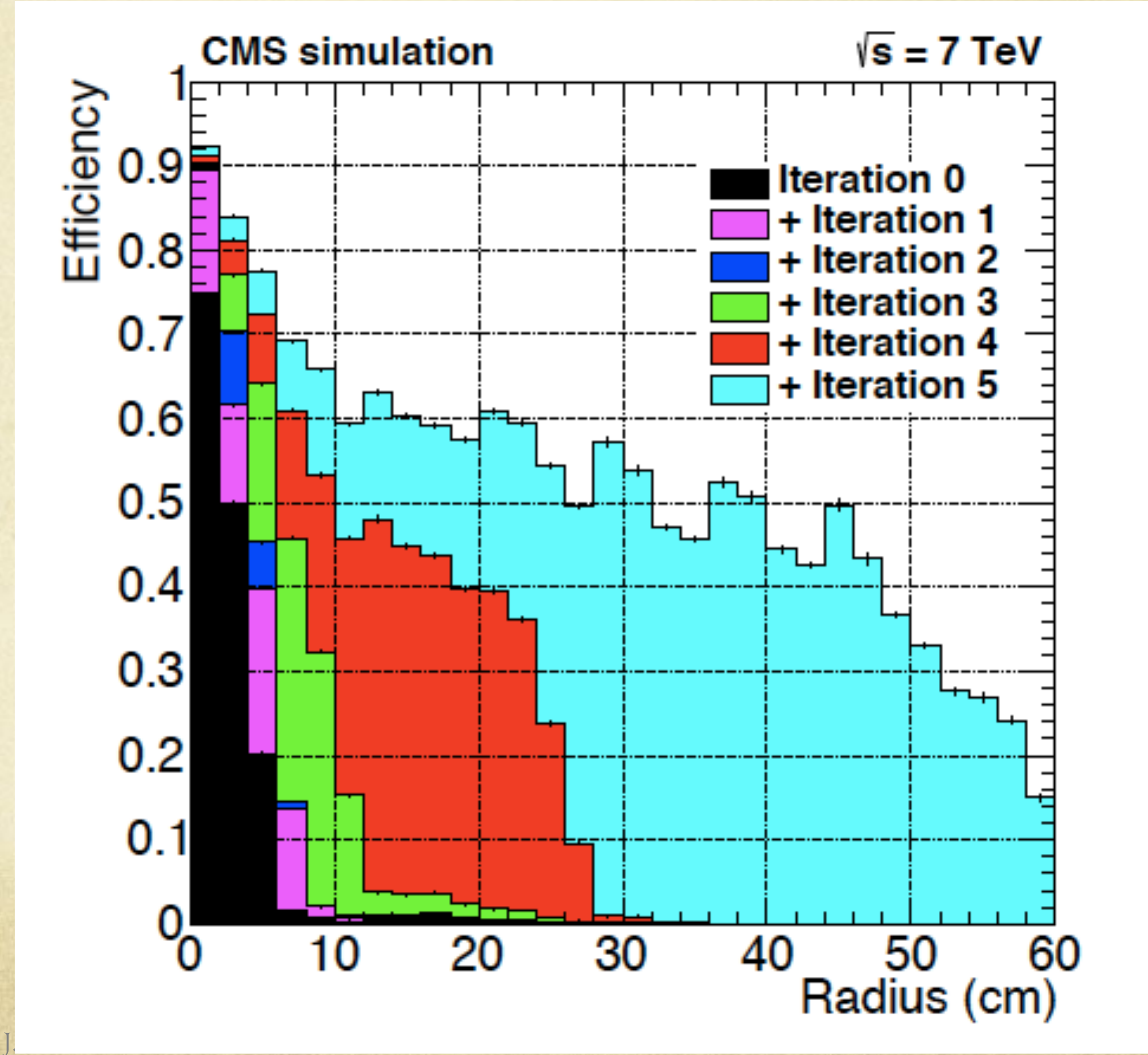
- Measuring it by data/simulation comparison





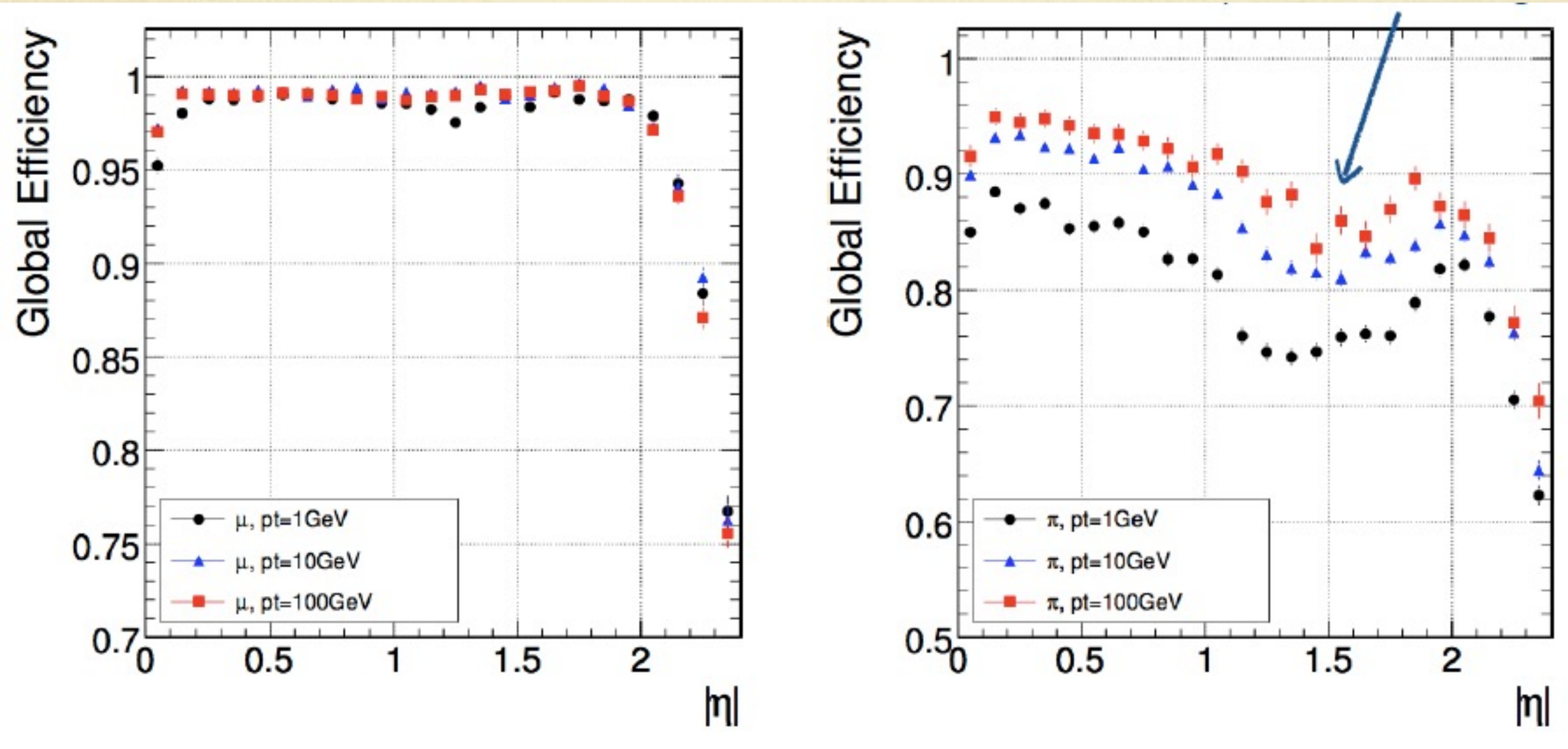
CMS performance

- Tracking algorithm = multi-iteration process



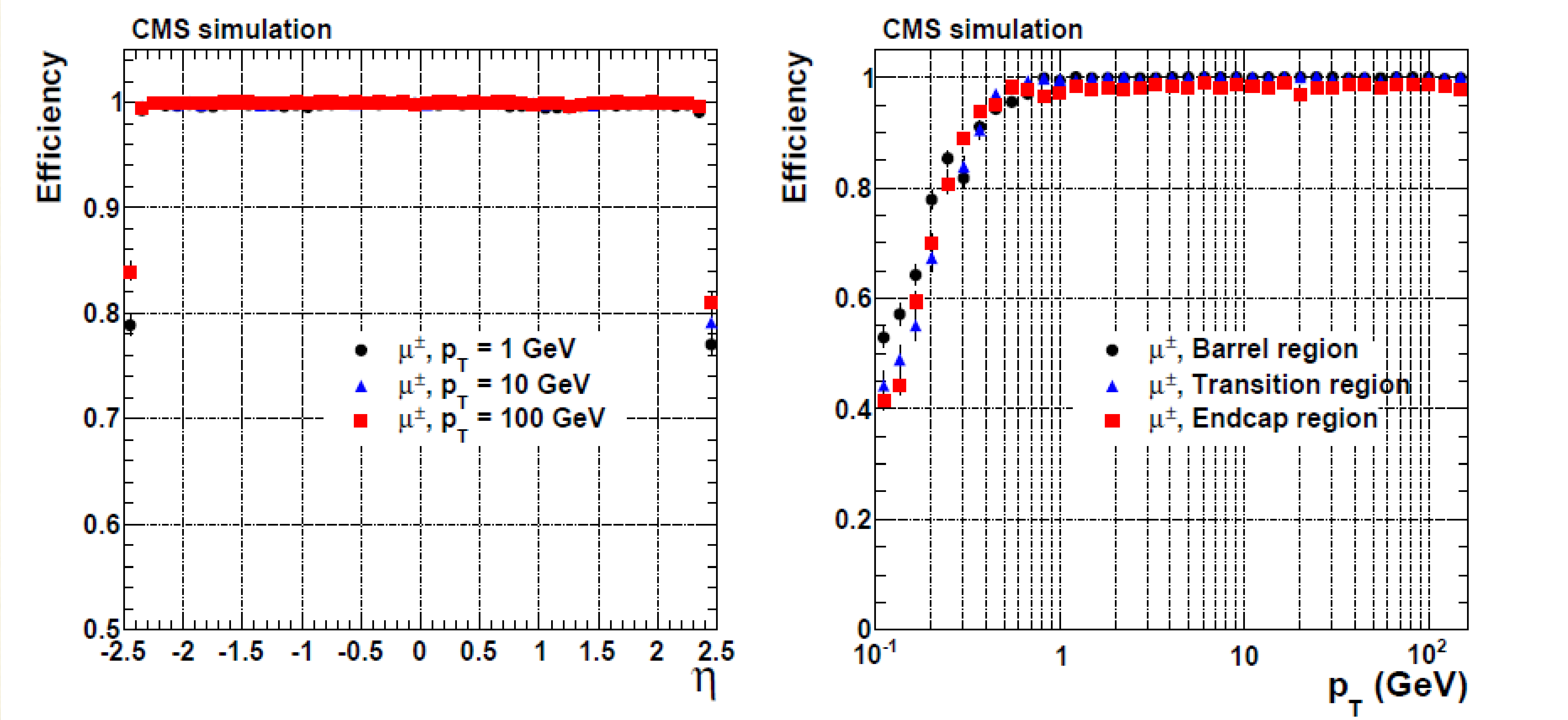
CMS performance

- Tracking efficiency



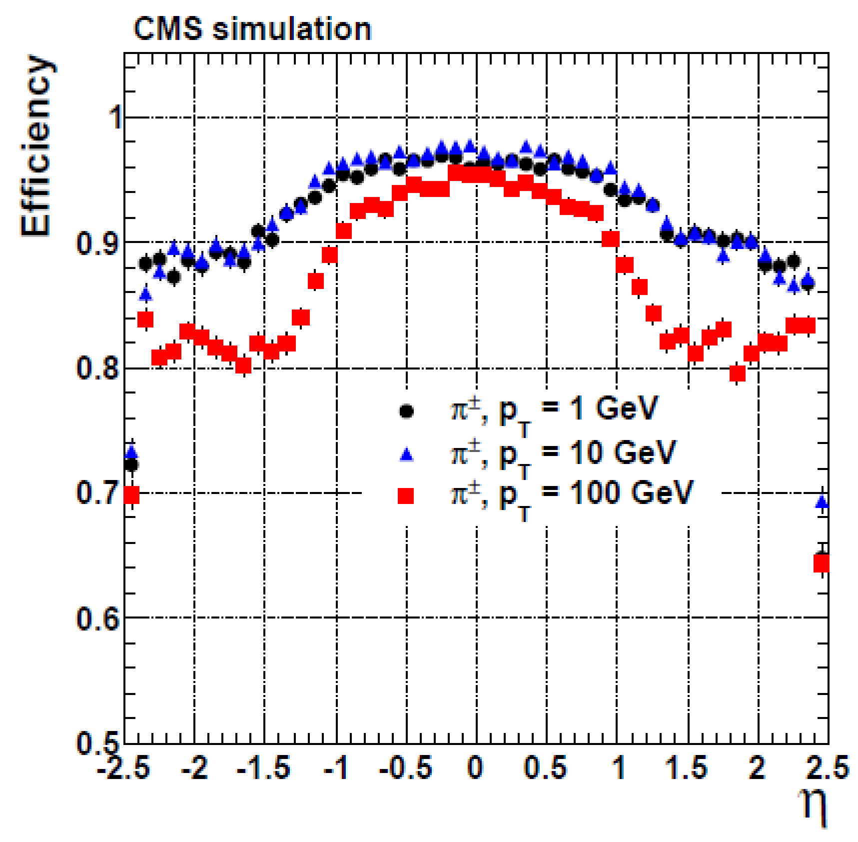
CMS performance

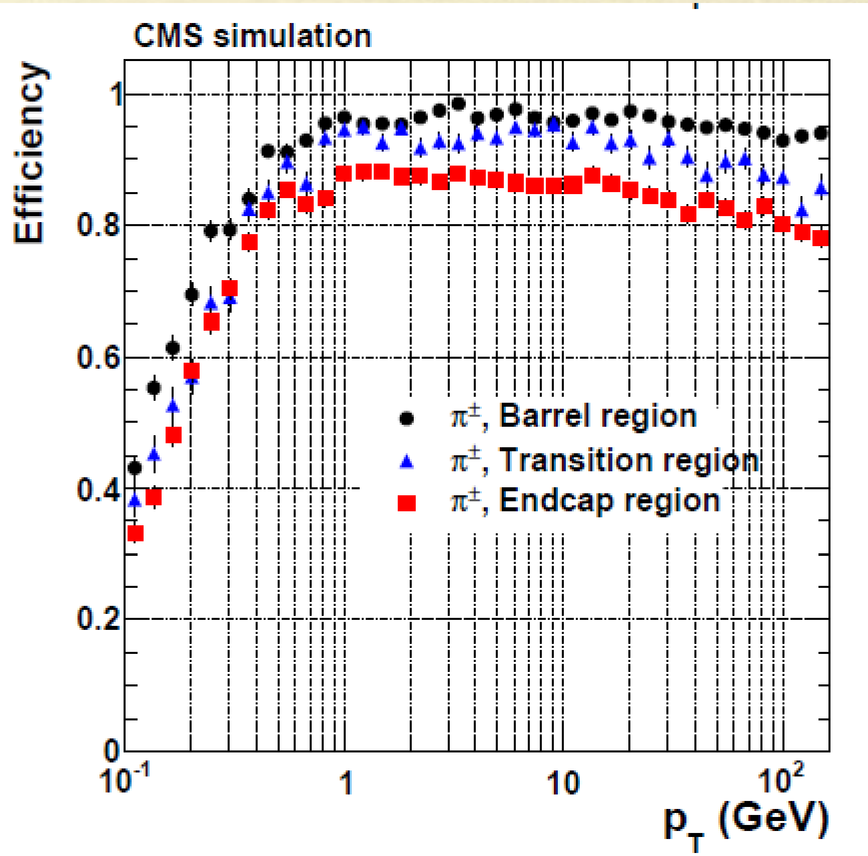
- Tracking efficiency
  - Single, isolated muons



CMS performance

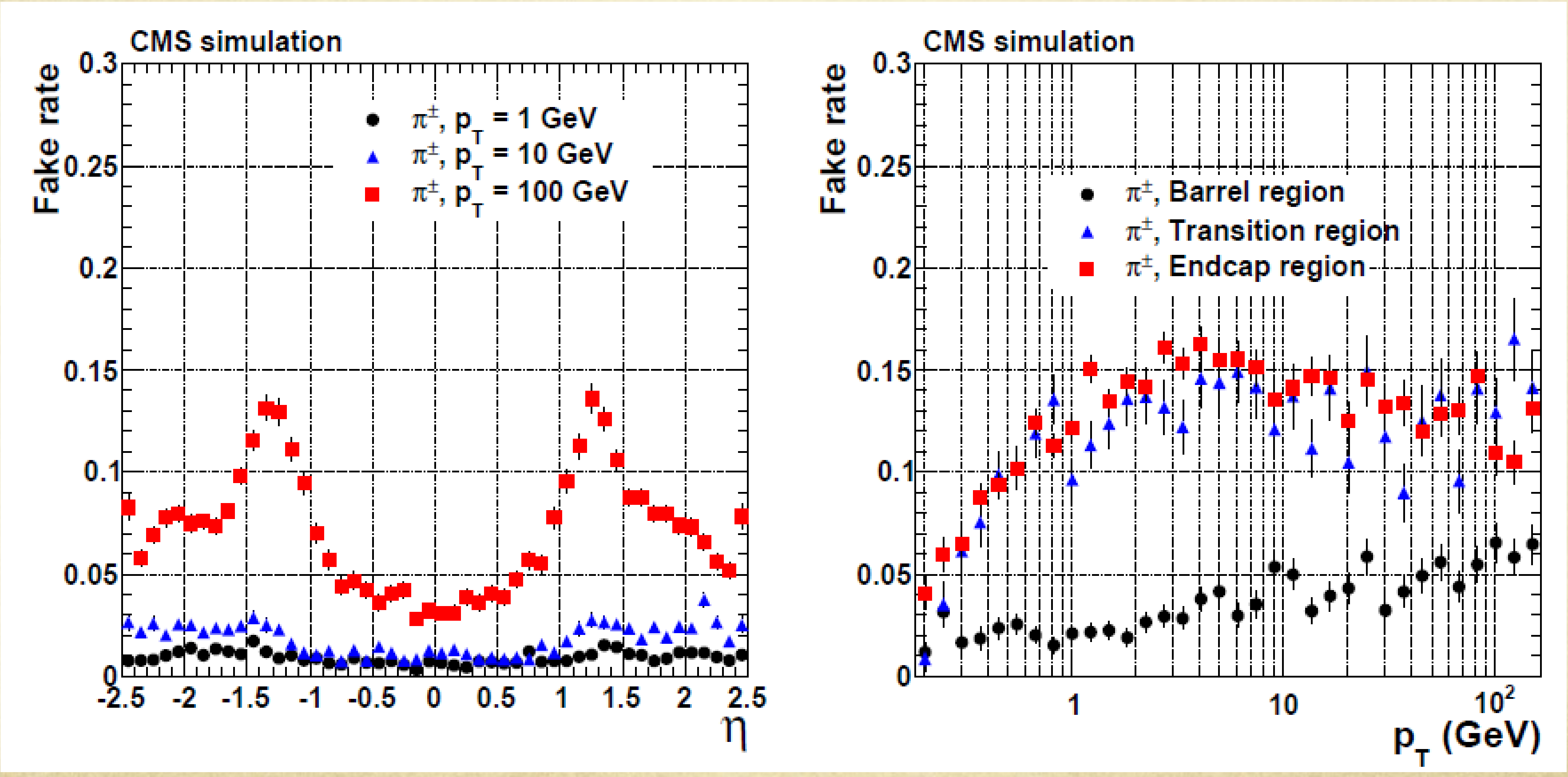
- Tracking efficiency
  - All pions





CMS performance

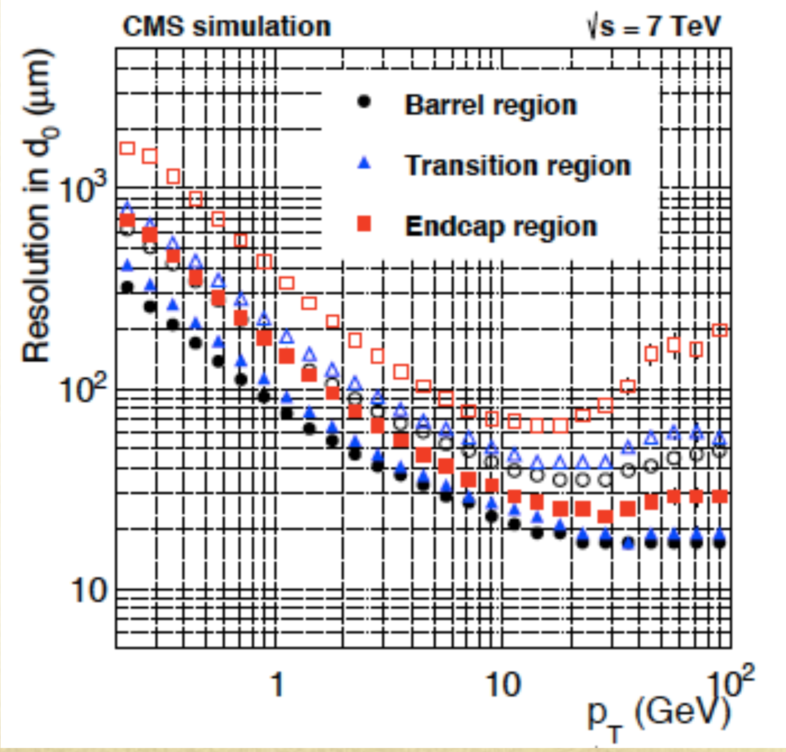
- Tracking purity
  - All pions

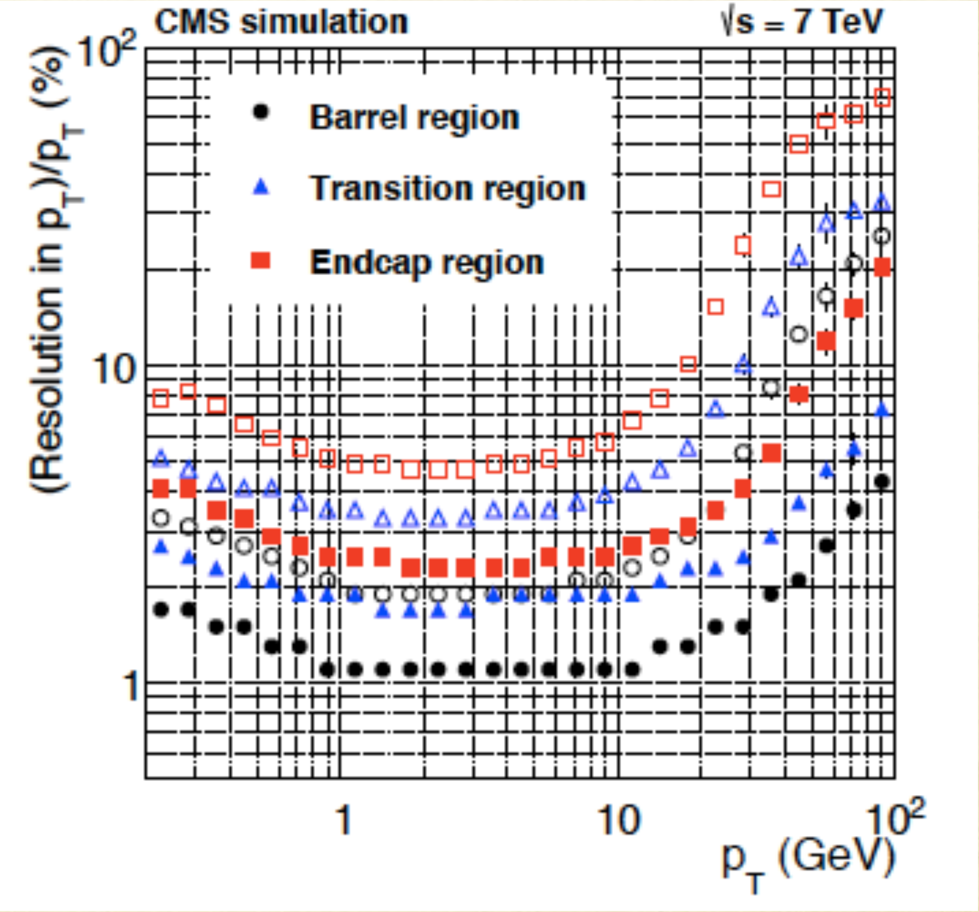


CMS performance

- Tracking resolution

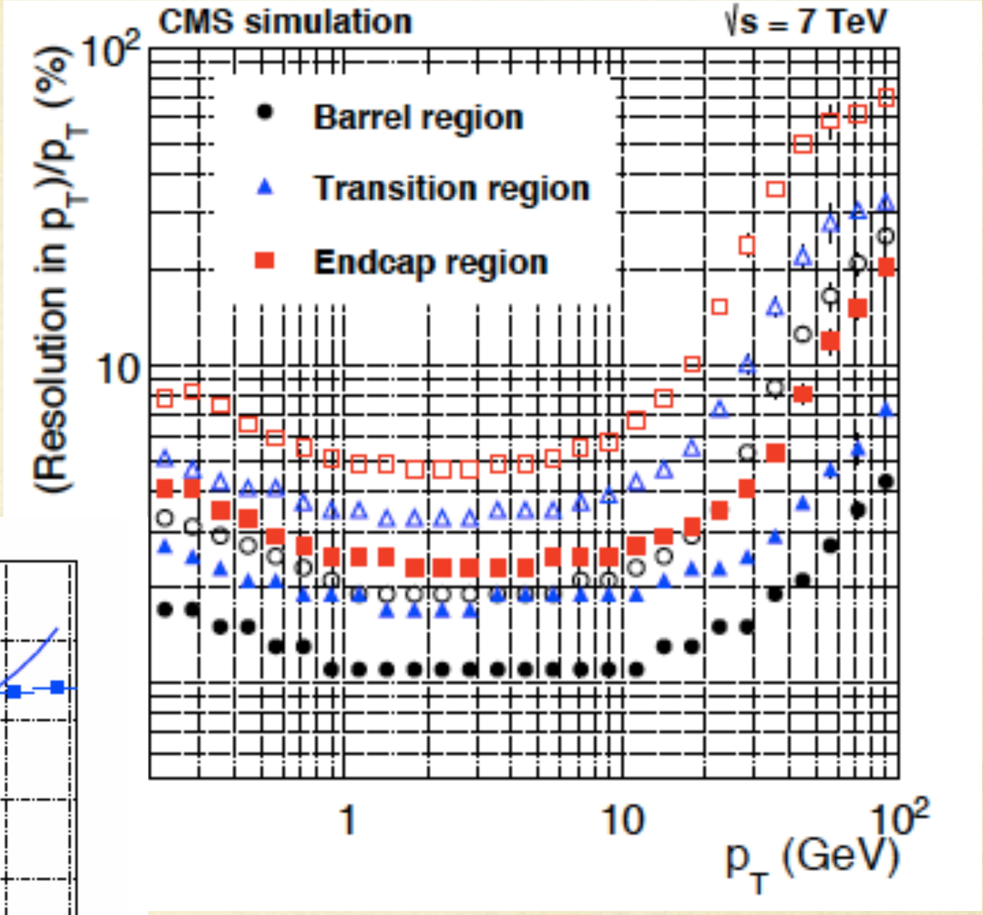
d0 = transverse impact parameter



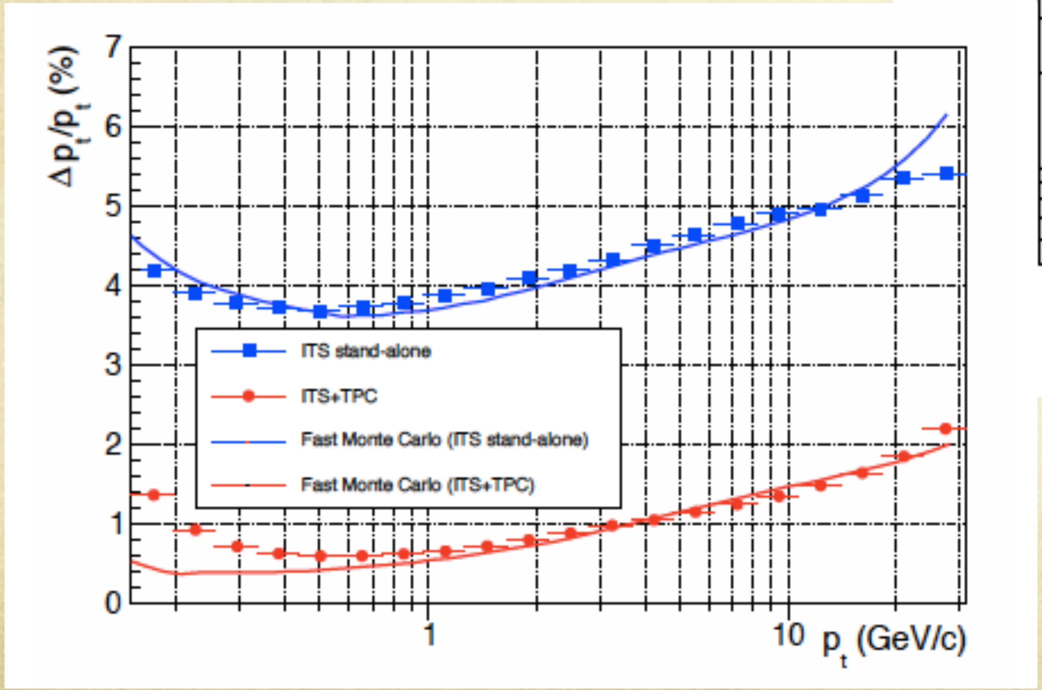


CMS performance

- Tracking resolution



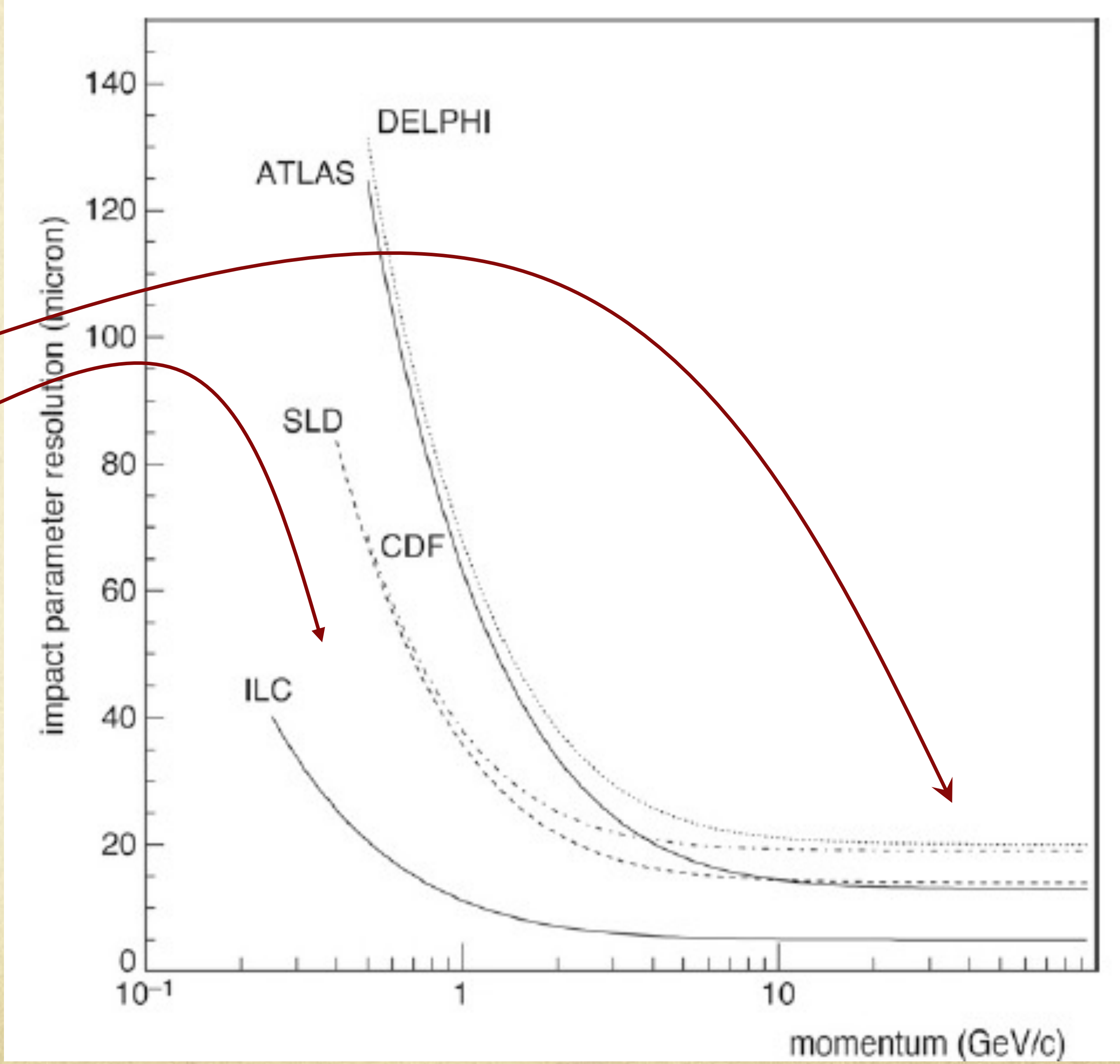
ALICE figure



4. Some tracking systems:

Impact parameter resolution

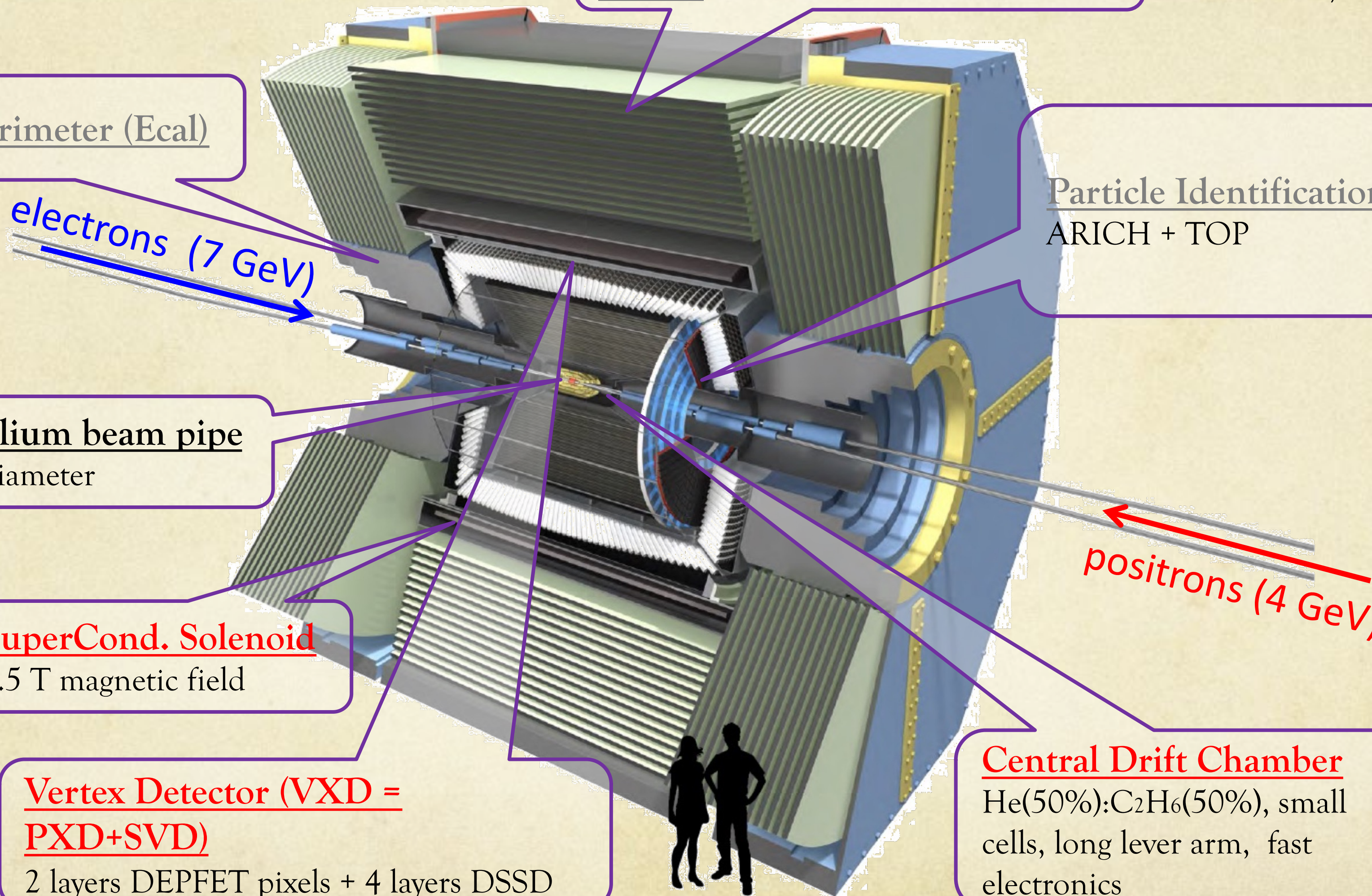
$$\sigma_{d_{r\varphi}} = a \oplus \frac{b}{p_T \sin^{\frac{1}{2}} \theta}$$



Belle II @ SuperKekB setup

- e^+e^- collisions
- Belle II ~7x7x7 m^3

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



KLong and muon detector (KLM)

EM Calorimeter (Ecal)

Particle Identification
ARICH + TOP

Beryllium beam pipe
2cm diameter

SuperCond. Solenoid
1.5 T magnetic field

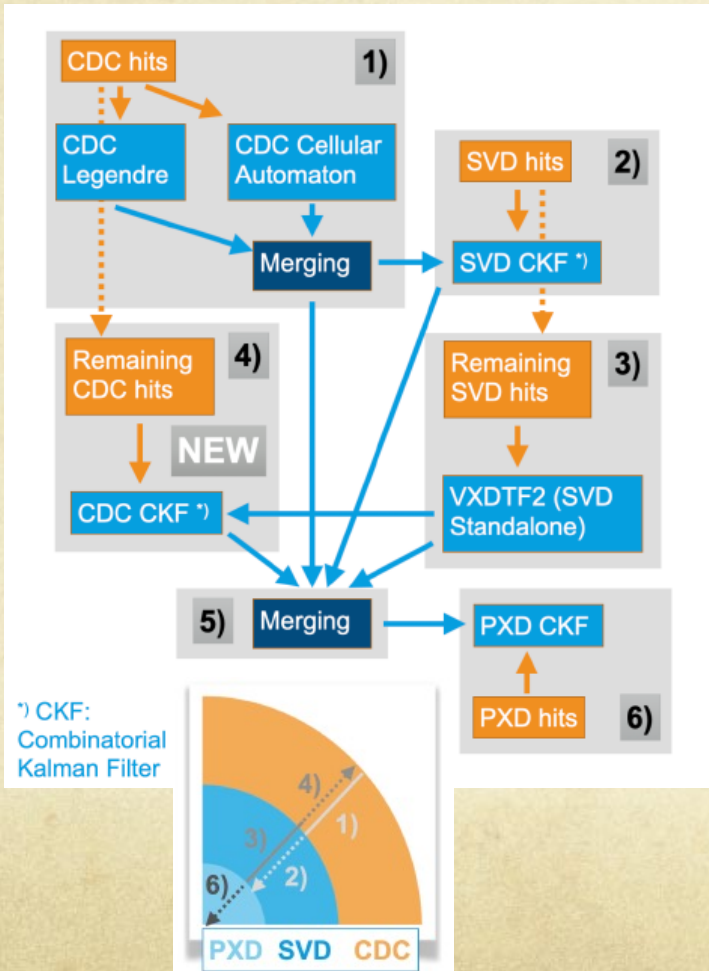
Vertex Detector (VXD = PXD+SVD)
2 layers DEPFET pixels + 4 layers DSSD

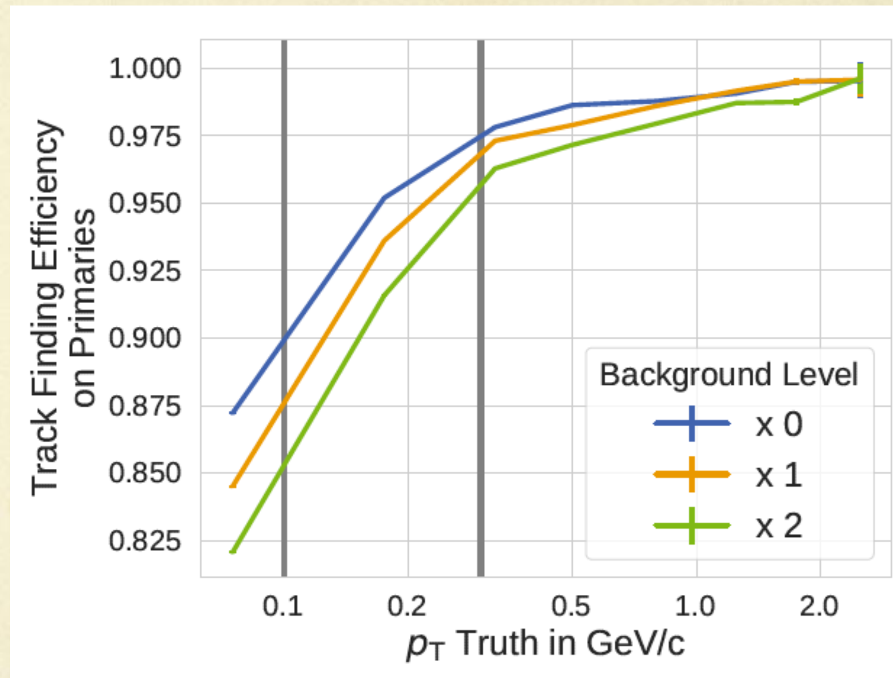
Central Drift Chamber
He(50%):C_2H_6(50%), small cells, long lever arm, fast electronics

Belle II algorithm

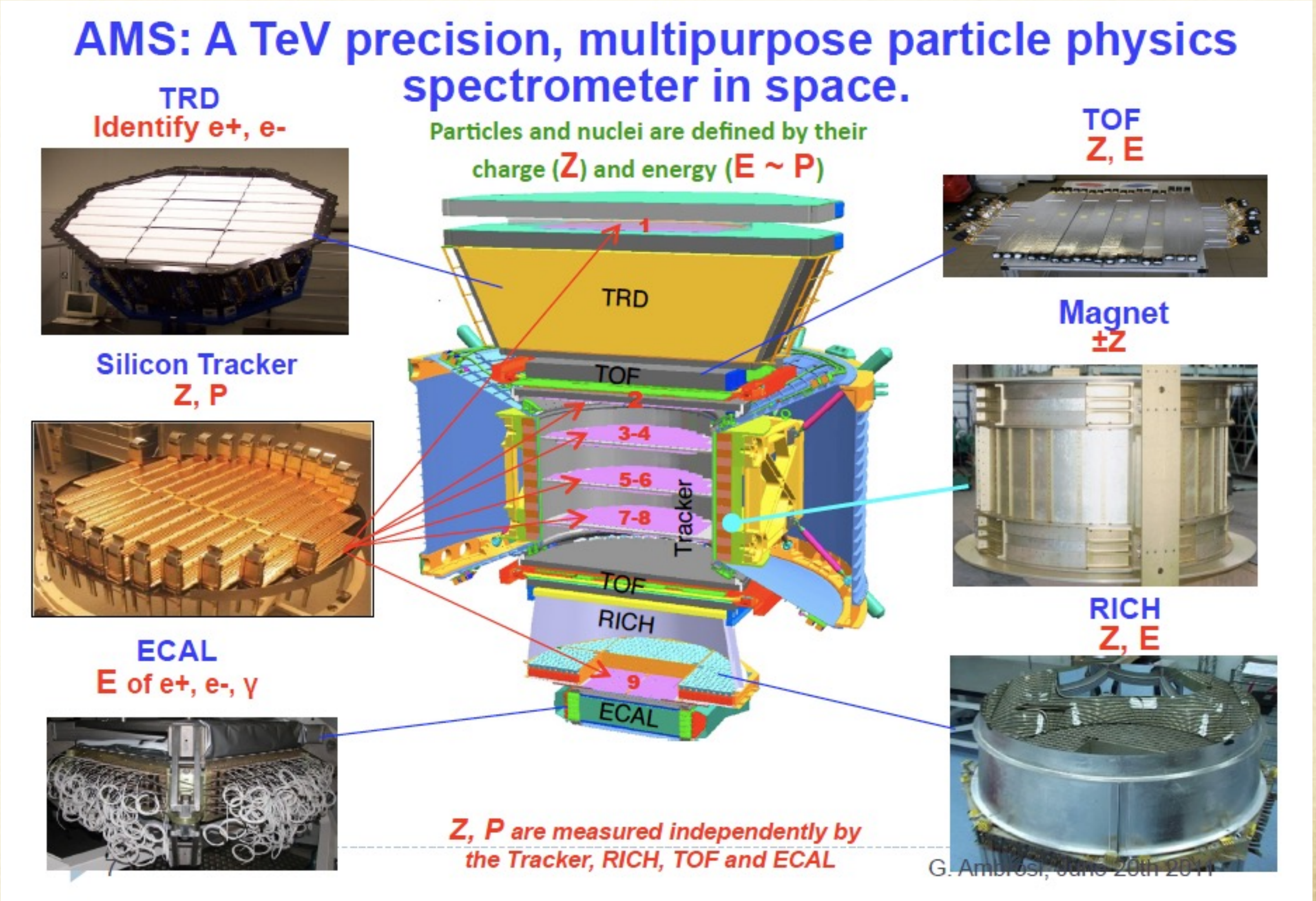
- Elementary collisions produce few tracks (~10/evts)
- Beam induced background largely dominates occupancies. => at peak luminosities > 10^{35} $cm^{-2}.s^{-1}$

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





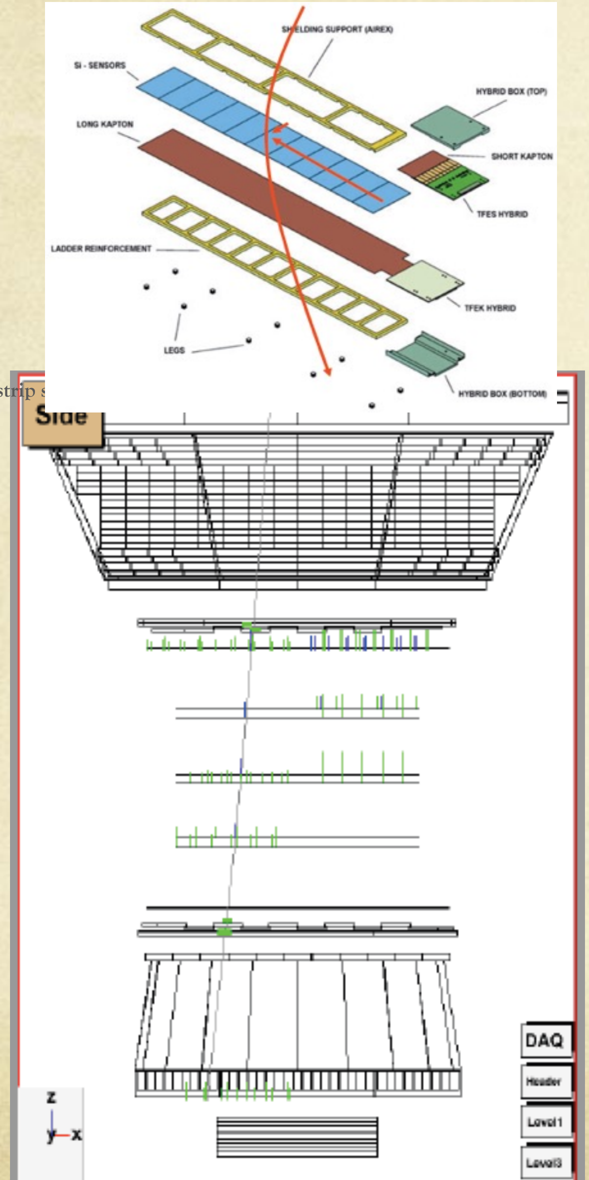
AMS


AMS: A TeV precision, multipurpose particle physics spectrometer in space.
Particles and nuclei are defined by their charge (Z) and energy (E ~ P)
TRD
Identify e+, e-
TOF
Z, E
Magnet
±Z
Silicon Tracker
Z, P
RICH
Z, E
ECAL
E of e+, e-, γ
TRD
TOF
1
2
3-4
5-6
7-8
Tracker
TOF
RICH
9
ECAL
Z, P are measured independently by the Tracker, RICH, TOF and ECAL

4. Some tracking systems:

AMS

Silicon strip s



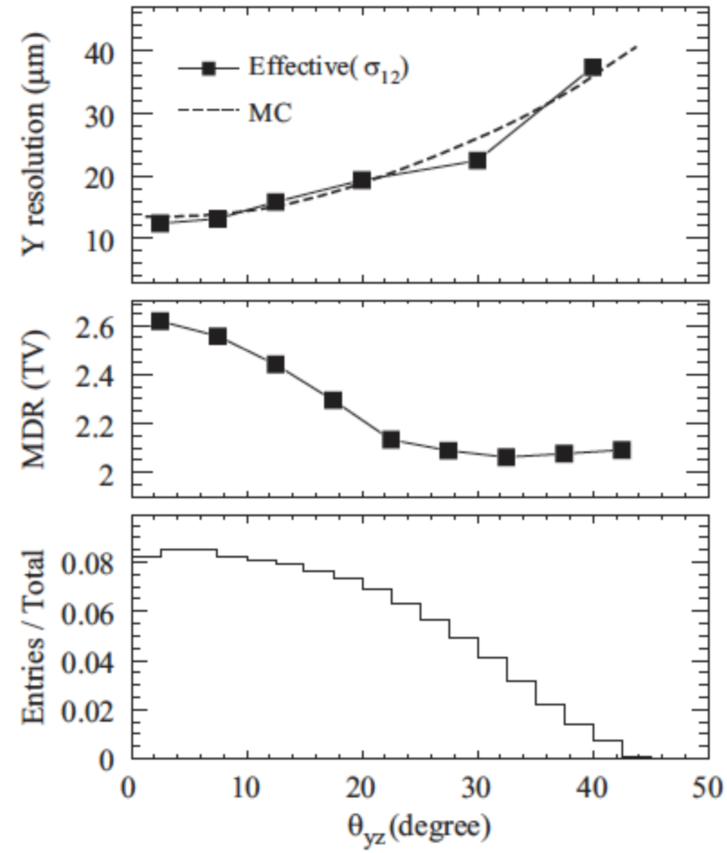
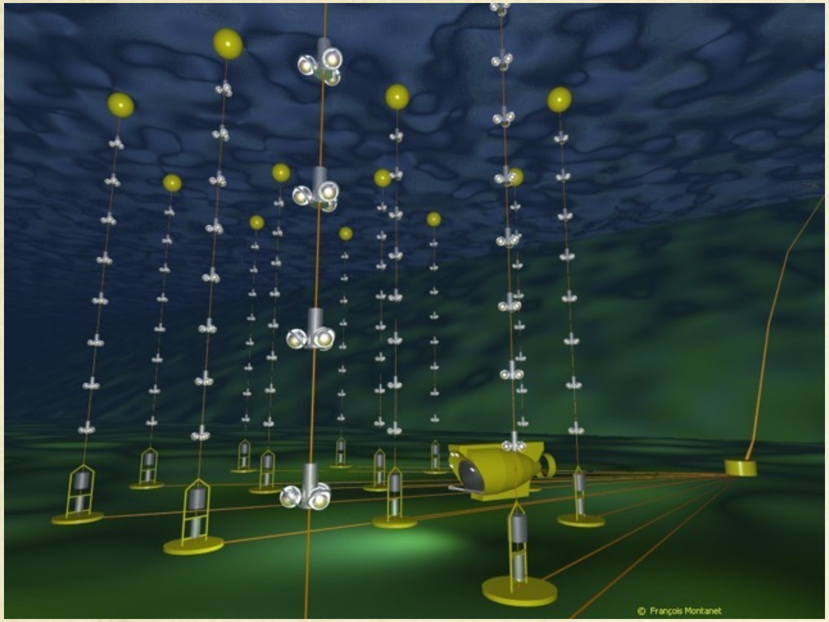
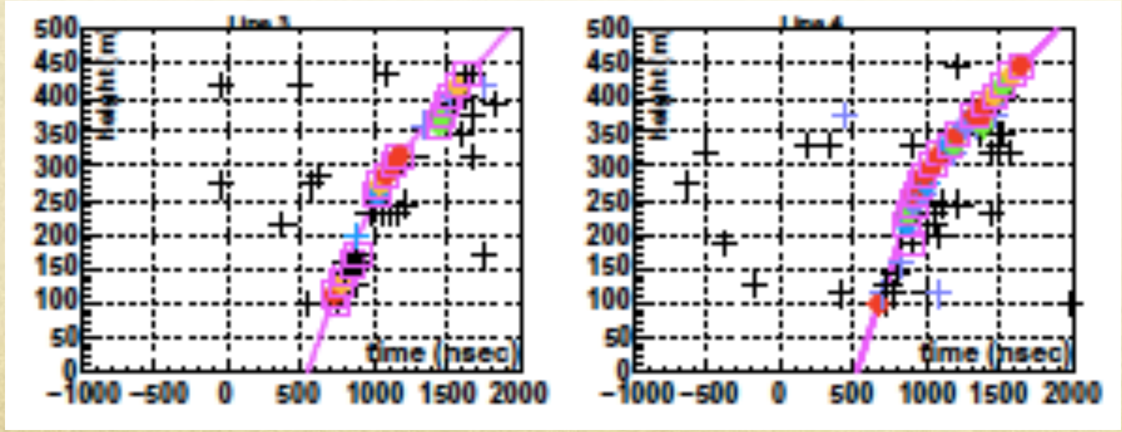


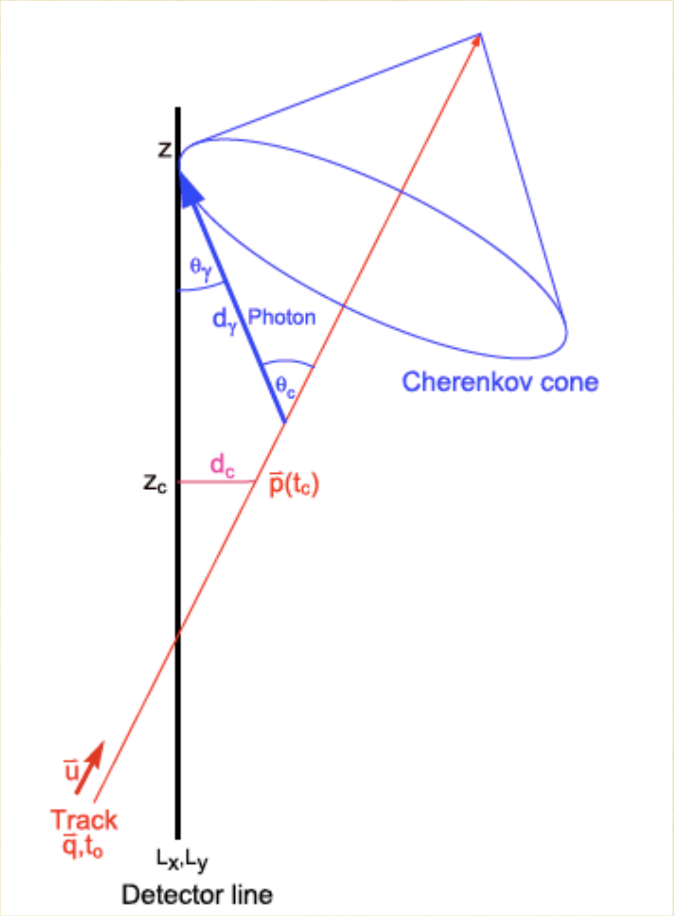
Fig. 5. The effective position resolution (weighted average of two Gaussian widths) in the *y*-coordinate for different inclination angles (top), the Maximum Detectable Rigidity (MDR, 100% rigidity measurement error) as a function of the inclination angle estimated for 1 TV proton incidence with the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

4. Some tracking systems:

ANTARES



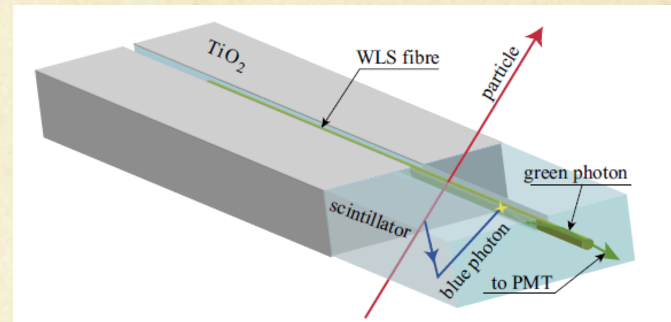


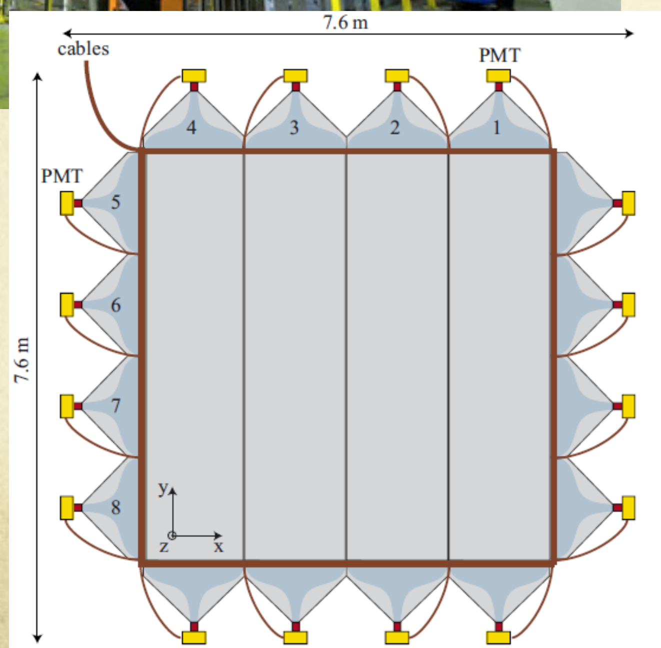


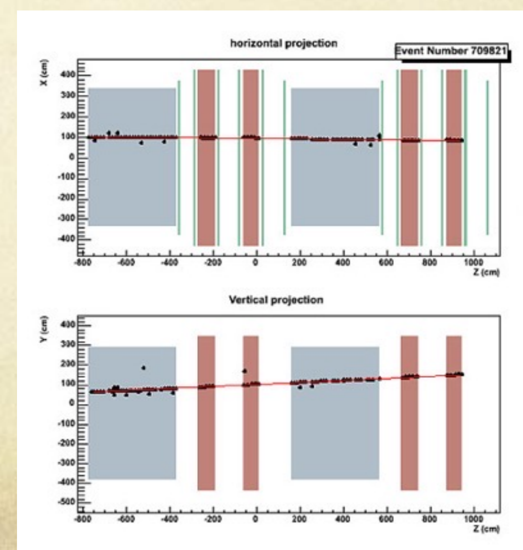
OPERA

Detecting ν created 700 km away

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

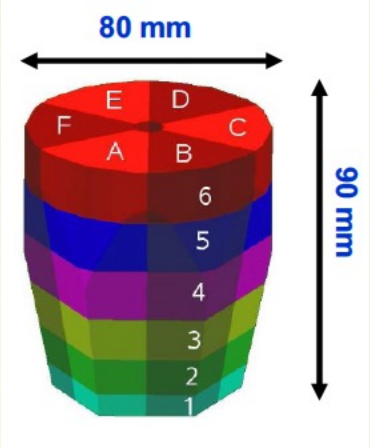


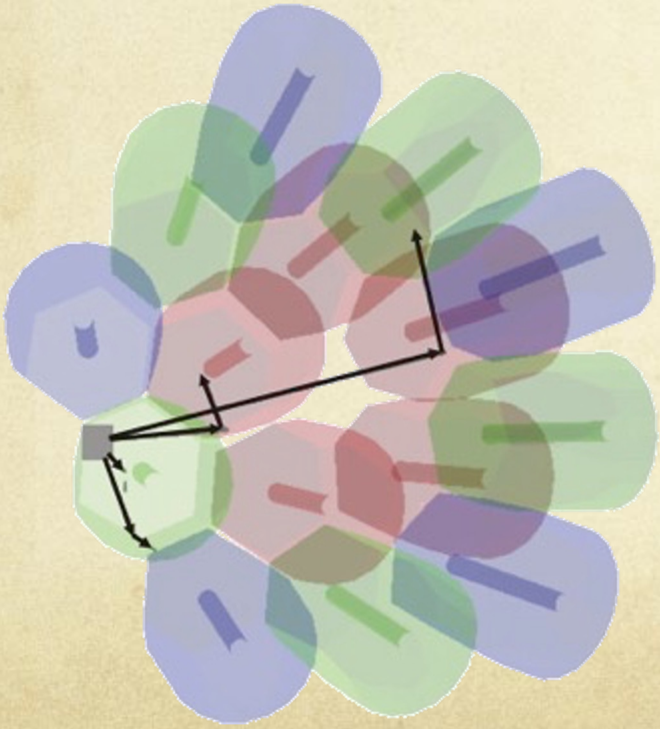


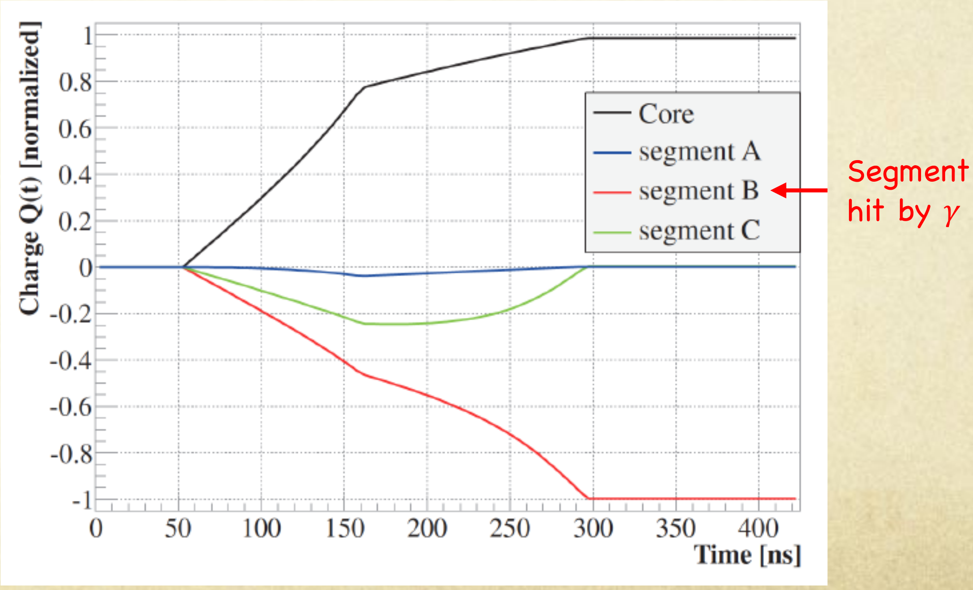


AGATA

- Advanced GAmma Tracking Array
  - European gamma-ray spectrometer ⟶ nuclear structure studies
  - Photon energy: 150 keV ⟶10 MeV
  - Physical effect = multiple Compton scattering
  - Sensors = segmented germanium

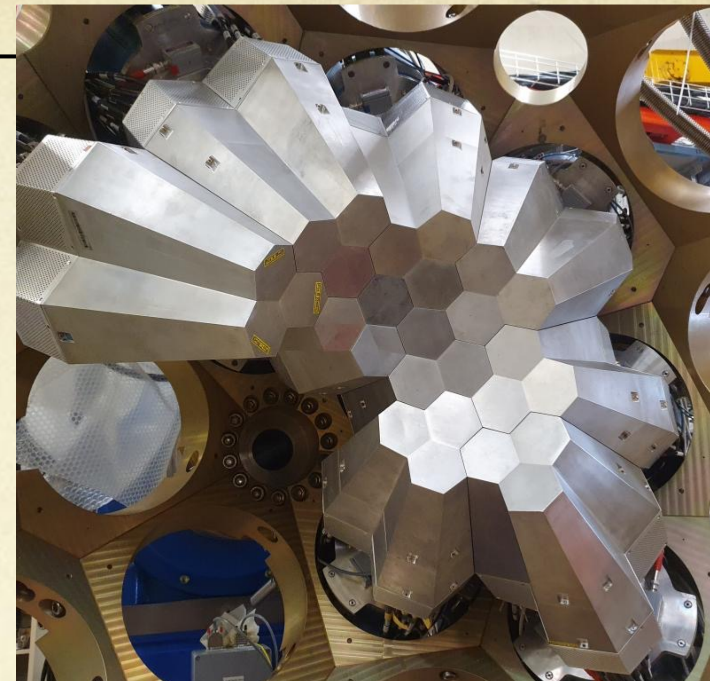




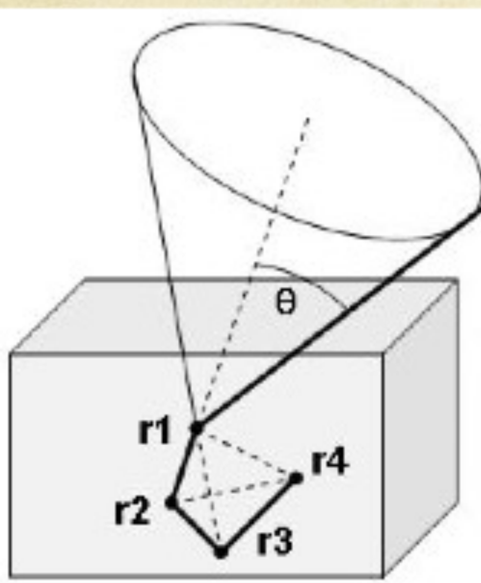


4. Some tracking systems:

AGATA

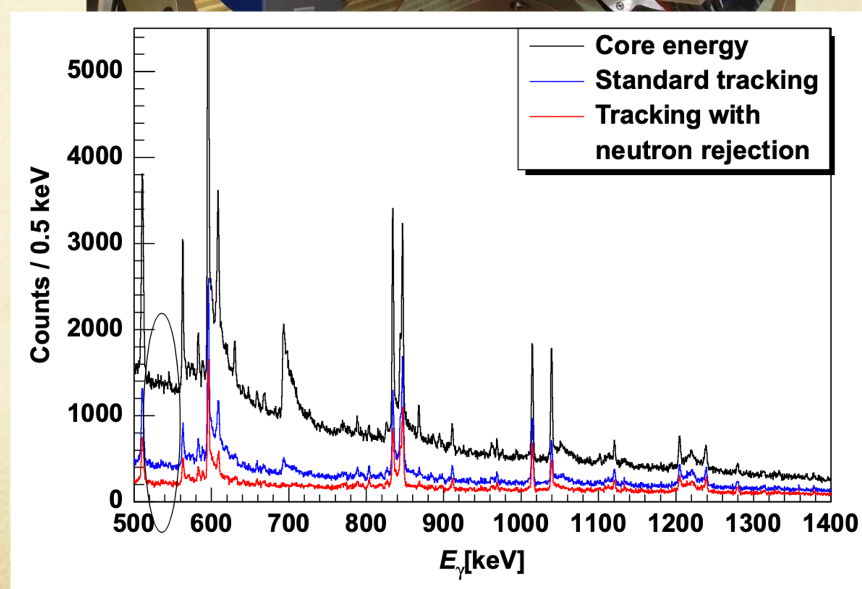


- Tracking algorithm
  - Various methods: standard iterative to adaptative
  - 2 steps (similar to charged particle tracking)
    - Grouping energy deposits
    - Ordering of energy => Initial E_γ



$$\cos\theta = 1 - \frac{E_1 m_0 c^2}{E_\gamma (E_\gamma - E_1)}$$

$$E_\gamma = E_1 + E_2 + E_3 + E_4$$



Summary

- **Fundamental characteristics of any tracking & vertexing device:**
  - (efficiency), granularity, material budget, power dissipation, “timing”, radiation tolerance
  - All those figures are correlated!

- **Reconstruction algorithms**
  - Enormous boost (variety and performances) in the last 10 years
  - Each tracking system has its optimal method: usually requires several algorithms

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

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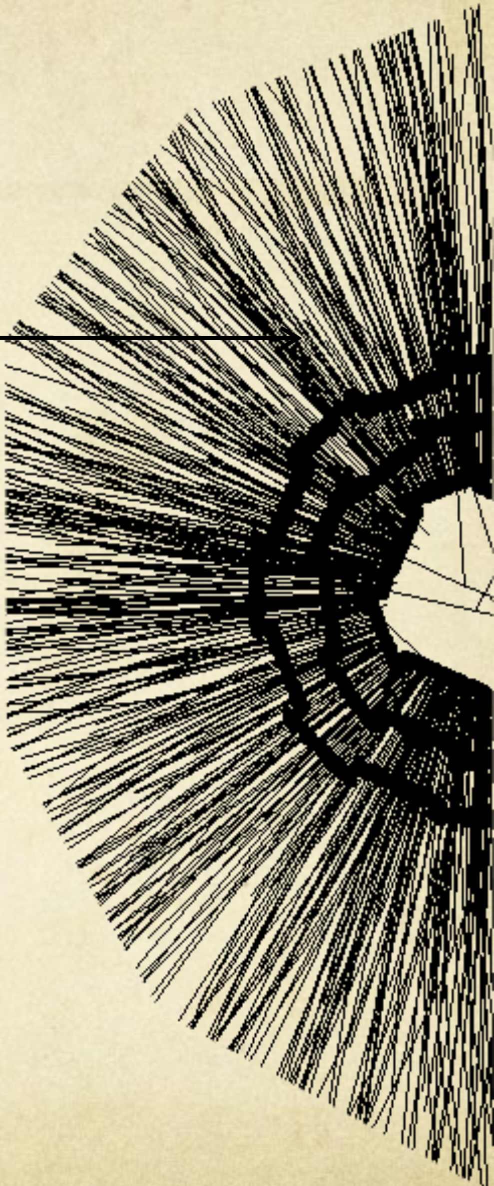

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