Sagitta bias estimation using electrons in the ATLAS ID detector

Flip Physics, Valencia

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IFIC

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Context

The ATLAS detector

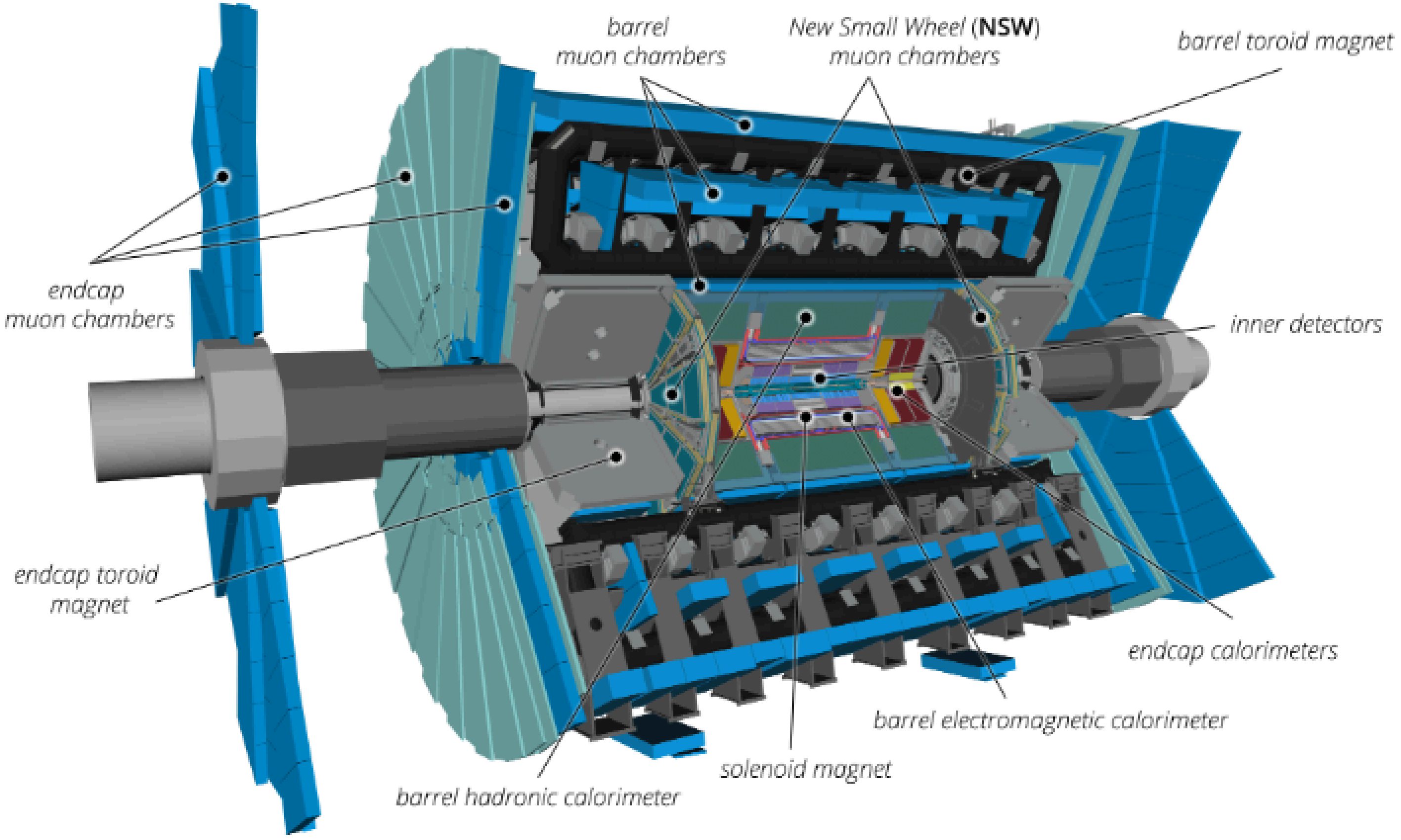


Fig. 3.1: ATLAS detector scheme for Run 3 [arxiv:2305.16623]

- General purpose LHC detector.
- Characterization of leptons and baryons:
  - Inner Detector
  - Electromagnetic Calorimeter
  - Hadronic Calorimeter
  - Muon chambers

The ATLAS Inner Detector (ID)

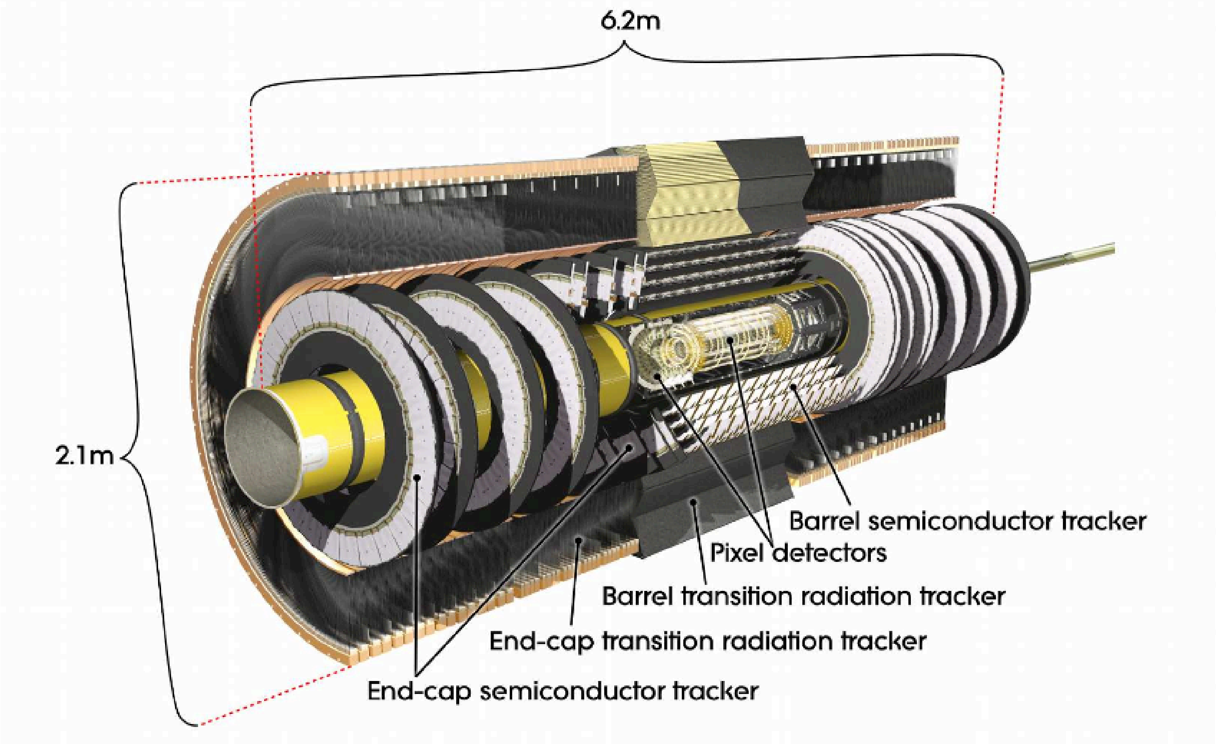


Fig. 4.1: ID detector scheme.

- Composoed by the **IBL, Pixel, SCT and TRT**.
- Reconstruct **tracks of particles** crossing the ID.
- Also reconstruct momentum of charged particles, thanks to the magnetic field $B = 2T$

ATLAS Coordinate system

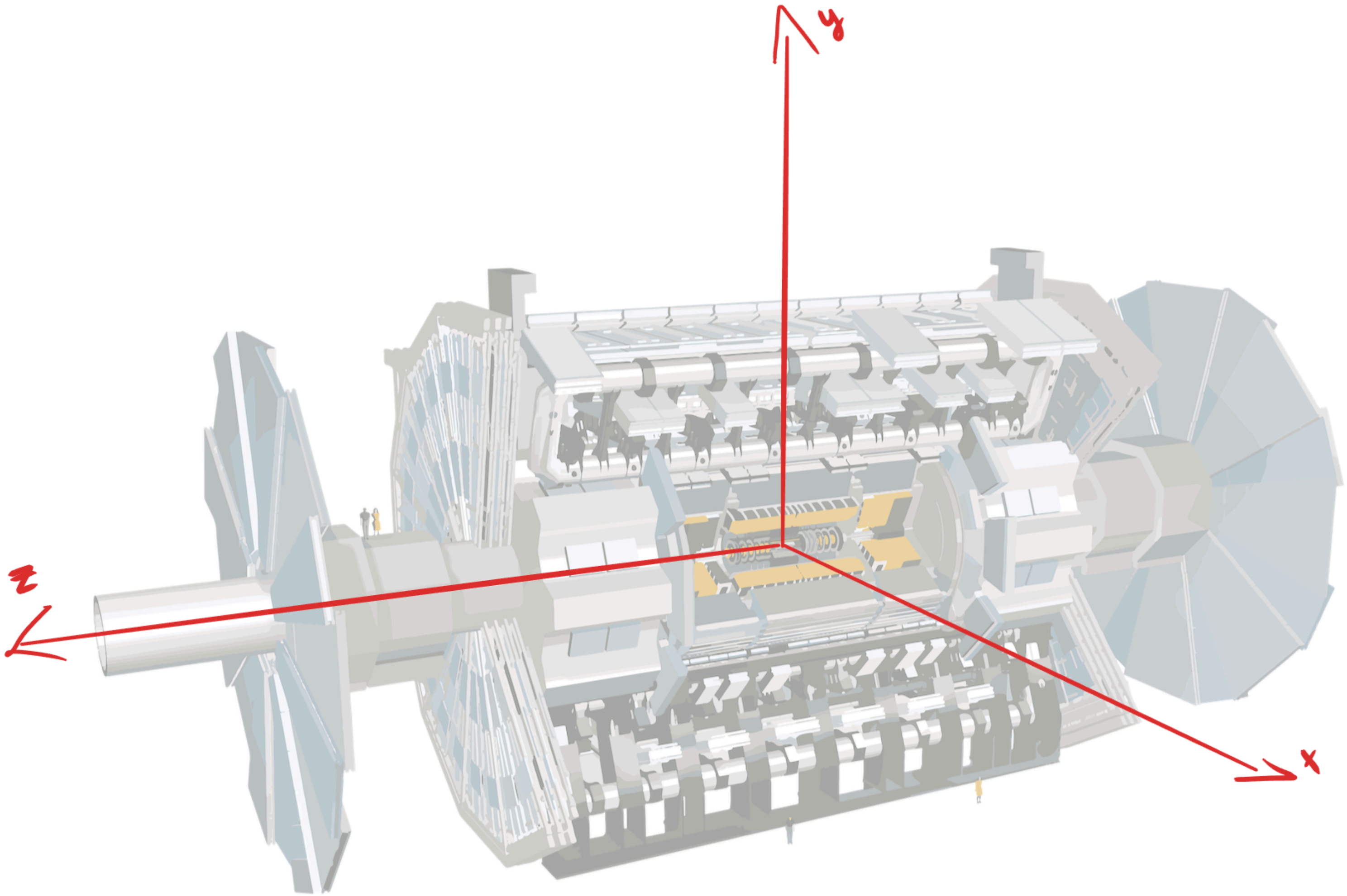


Fig. 5.1: ATLAS Global frame

ATLAS Coordinate system

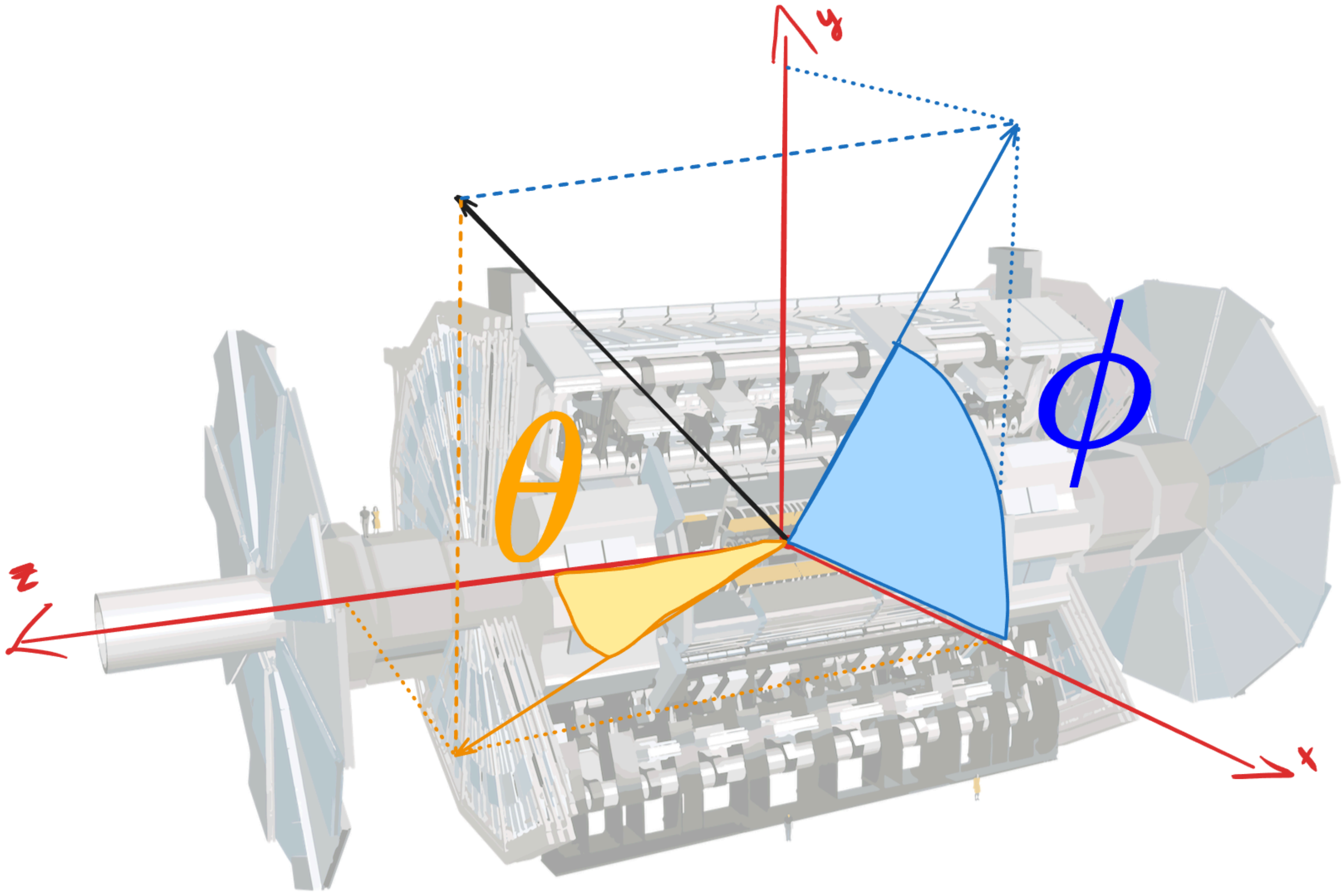


Fig. 6.1: ATLAS Global frame in spherical coordinates.

Spherical coordinates are usually used.
Due to detector **azimuthal symmetry**, ϕ is usually a free parameter.

Not θ but η

- η is Lorentz invariant.

$$\eta = -\ln\left[\tan(\theta/2)\right]$$

ID Tracking

ID Tracking principles

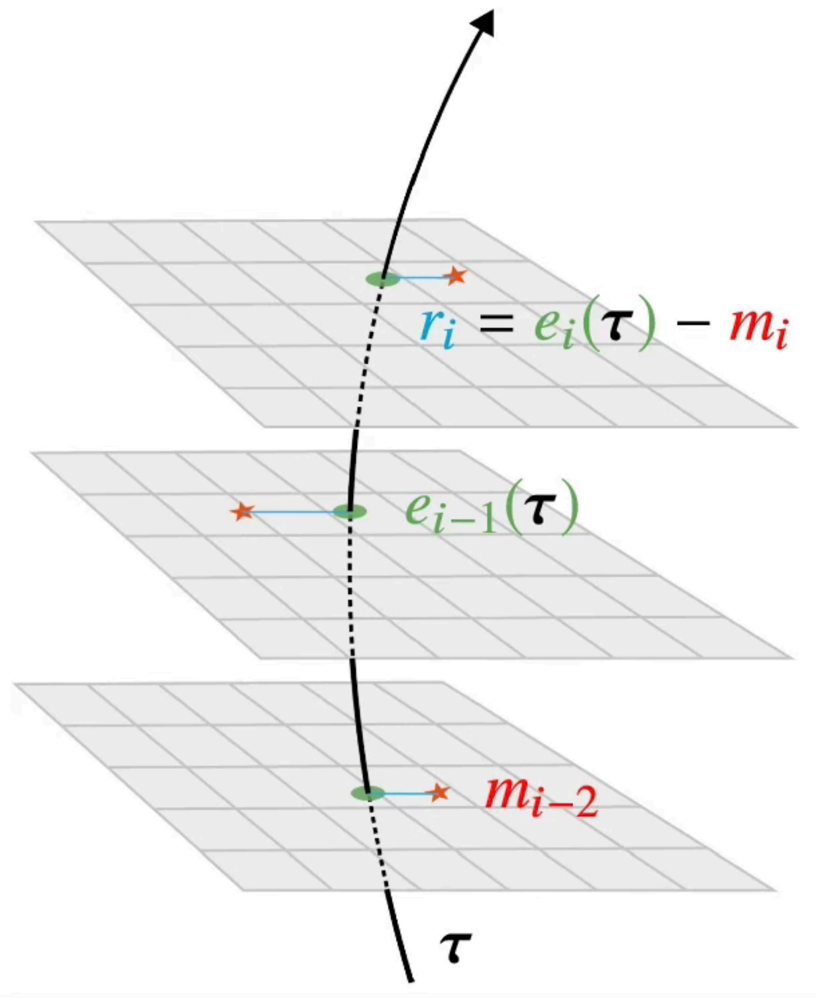


Fig. 8.1: Tracking representation

- Optimization of residuals between **hits** and **tracks**
- Different possible configurations due to overlap of event hits.

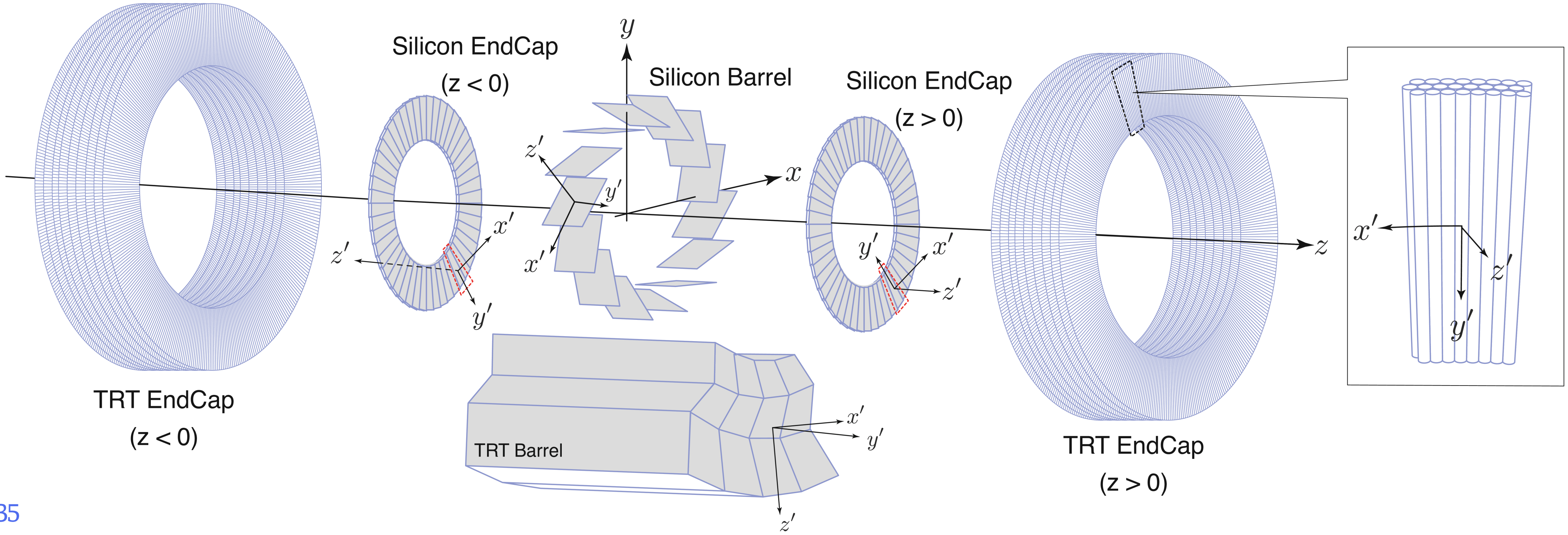
$$\chi^2 = \mathbf{r}^T(\tau)\Omega^{-1}\mathbf{r}(\tau)$$

where $\mathbf{r}$ is the vector of residuals,
Ω the covariance matrix, and
τ is the vector of track parameters

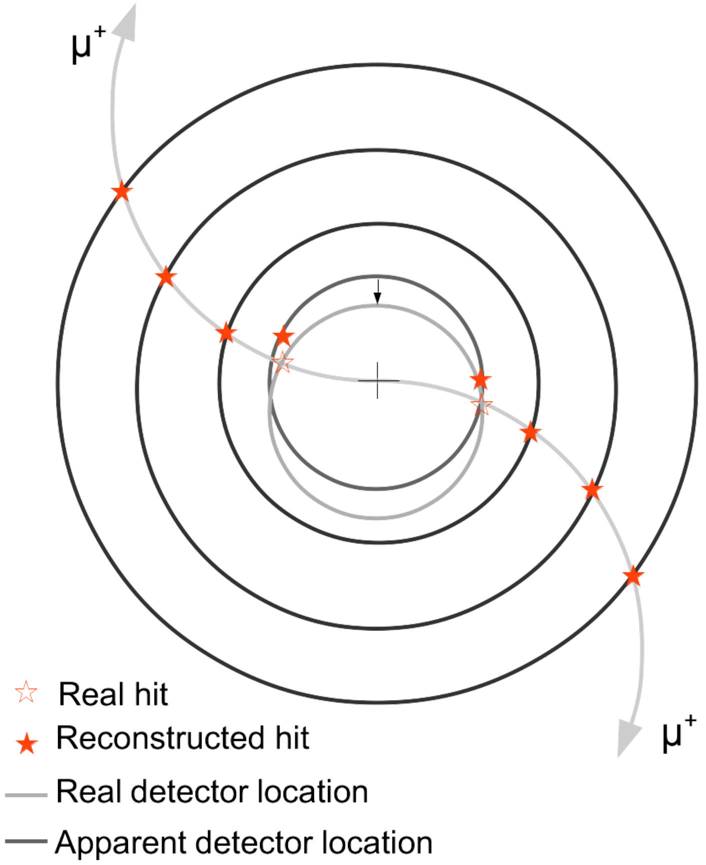
ID Alignment

In Alignment, the **position** of the **detectors**, **a**, is also a **parameter** to fit.
Distortions in the ID may affect track reconstruction.

$$\chi^2 = \mathbf{r}^T(\tau, \mathbf{a})\Omega^{-1}\mathbf{r}(\tau, \mathbf{a})$$



Weak Modes



- Certain deformations cause local χ^2 minima
  They are the ***weak modes***
- Cannot be corrected with the standard χ^2, constraints have to be applied.
- Radius invariant distortions produce what is called **sagitta bias**, δ_s

Fig. 10.1: Scheme of an ID distortion that bias the reconstructed

p.

Weak modes

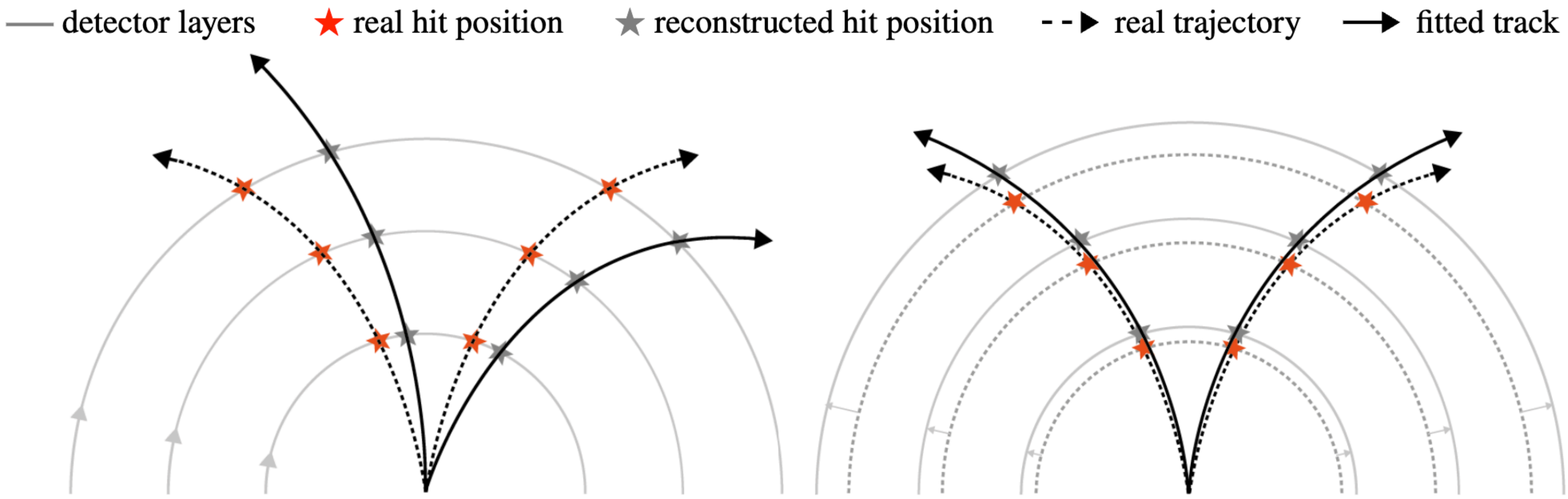


Fig. 11.1: At left there's sagitta deformation, and at right radial one

Sagitta bias δ_s

Sagitta bias δ_s definition

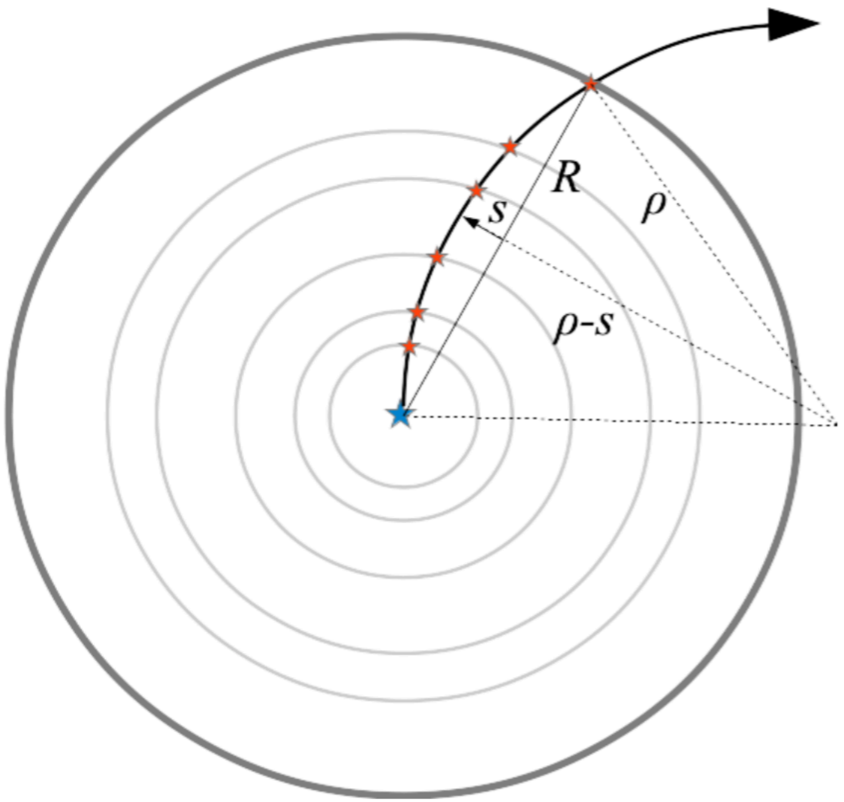


Fig. 13.1: Sagitta definition

s distortion = p distortion

$$p_T \propto \rho \propto s^{-1}$$

$$p = p' \cdot (1 - q p'_T \delta_s)^{-1}$$

- $\delta_s \equiv$ **Sagitta bias**
- $p' \equiv$ Reconstructed momentum
- $p \equiv$ "True" momentum
- $q \equiv$ Charge ($q = \pm 1$)

The sagitta bias δ_s corrects momentum p' anti-symmetrically in q

Run2 Method to compute δ_s

Calculating Sagitta Bias with $Z \to e^+e^-$ events

$\langle E/p \rangle$ of both positrons and electrons is compared.
The bias will emerge from the charge dependent asymmetries of $p'_{\pm}$.
An important assumption: $E_+ \approx E_-$

$$\delta_s = \frac{\langle E/p' \rangle_+ - \langle E/p' \rangle_-}{2\langle E_T \rangle}$$

$E_T = E/\cosh\eta$: Transverse energy, η: Pseudorapidity

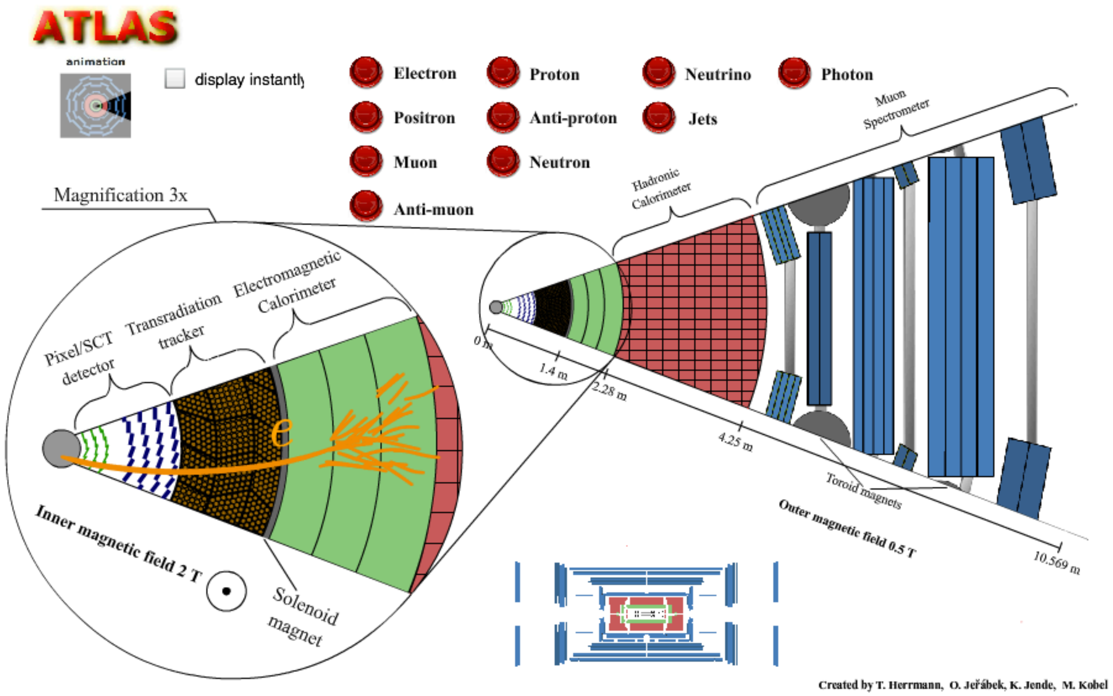


Fig. 14.1: Scheme of electron signature in the ID + Electromagnetic calorimeter

Toy MC E/p

Let's study the E/p pdf with a **simple toy MC** generation. E and p histograms are **gaussian** pdf with equal μ and σ.

As E/p is not a Gaussian, and has a tail to the right, an empirical approach to get the peak was to perform a **Crystal Ball fit**.

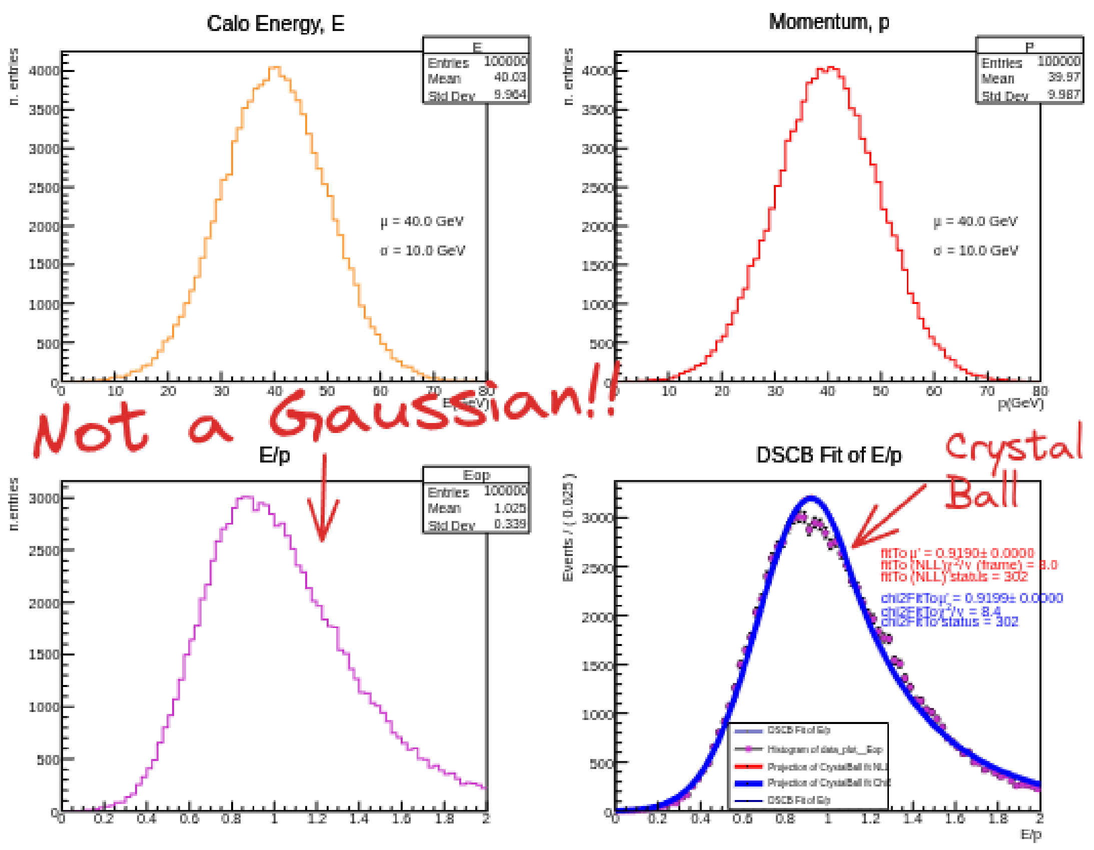
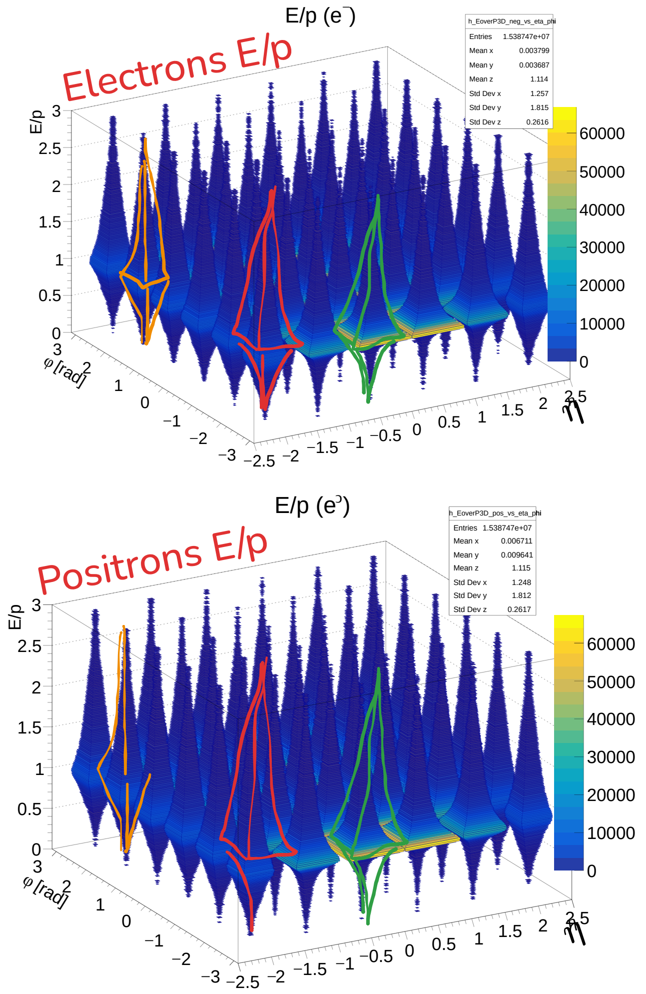


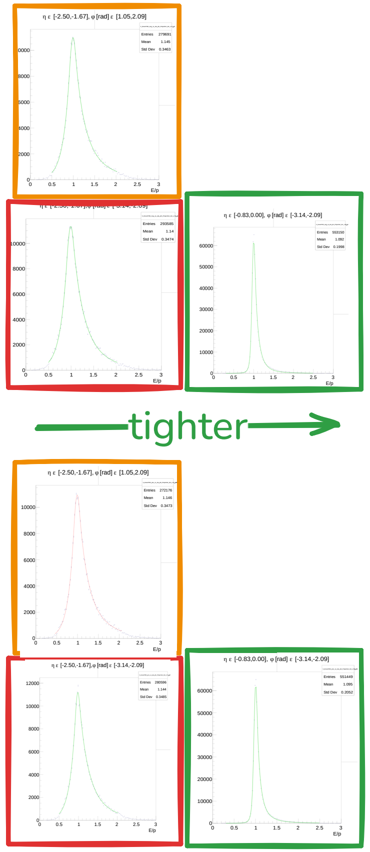
Fig. 15.1: E and P Gaussian, randomly generated distributions, and E/p at right

Fit E/p to Crystal Ball

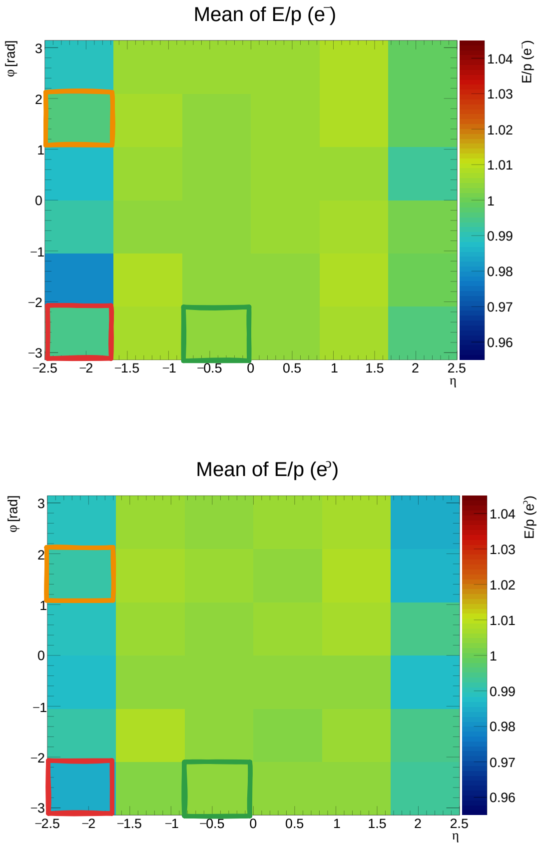
TH3 E/p histograms



CrystalBall fits to each tile



Mean of each (η, ϕ) tile's E/p



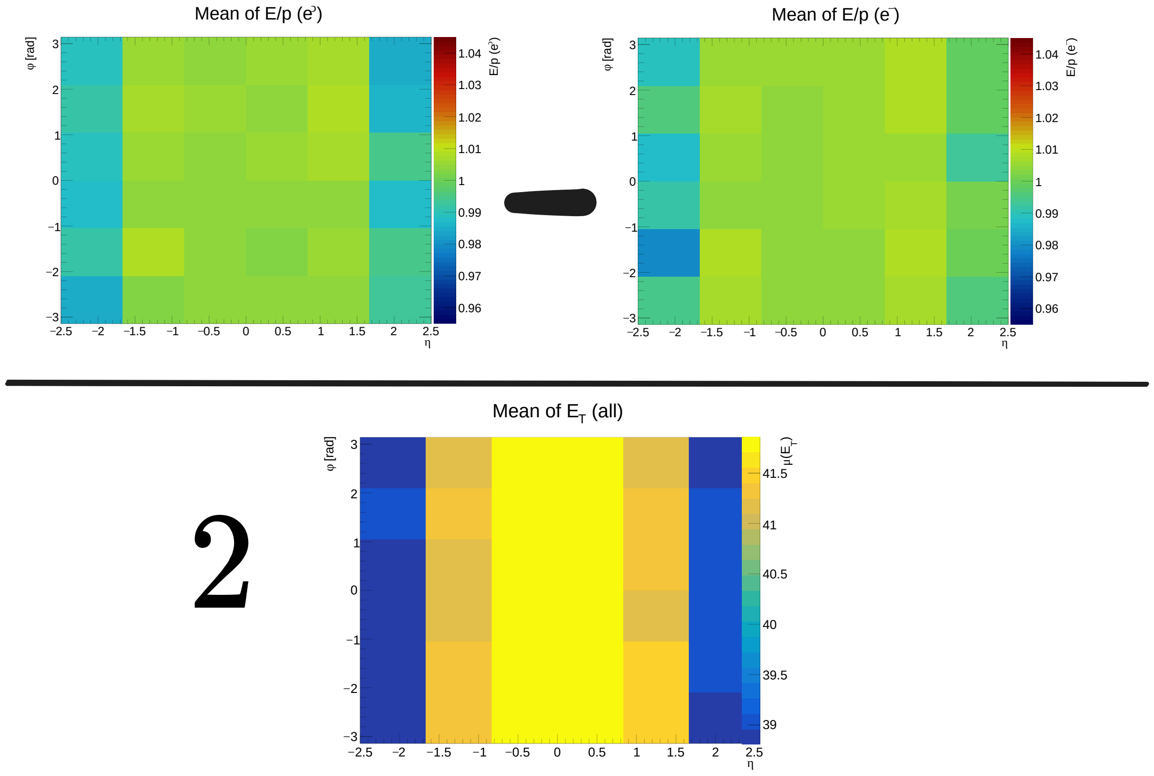
Filling $\delta_s(\eta, \phi)$ maps

δ_s Run2 method

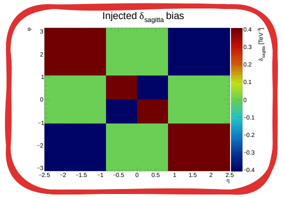
$$\delta_\text{s} = \frac{\langle E/p' \rangle_+ - \langle E/p' \rangle_-}{2\langle E_T \rangle}$$

For each (η, ϕ) tile
a local calculation of the
sagitta bias δ_s
is performed via a loop.

$\delta_s =$



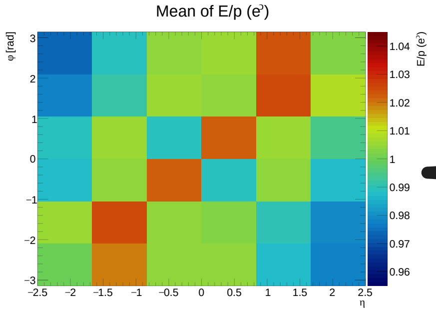
Injecting a δ_s on the Monte Carlo data Run2Method

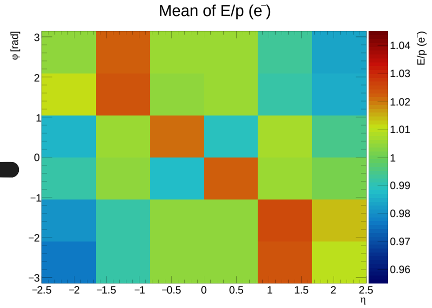


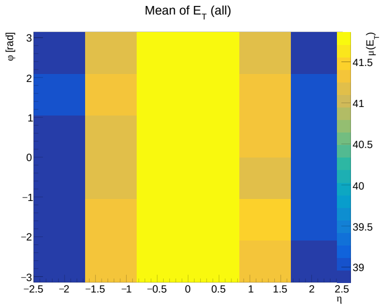
Injected sagitta bias

$$\delta_s = \frac{\langle E/p\rangle_+ - \langle E/p\rangle_-}{2\langle E_T\rangle}$$

$\delta_s =$







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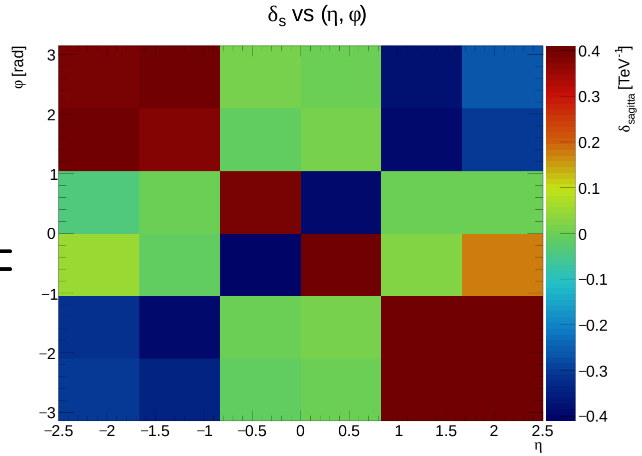

An artificial δ_s is injected on the Validation, similar to a chessboard.

Run2 method succeeds in computing it.

Conclusion

- I updated the E/p method used in Run 2 for to compute δ_s using events involving e^-e^+
- Now it can be used as a crosscheck for the *VarMin* method that uses muons.
- Studying the E/p fit, it can be interesting to do a convolution of a division of two gaussians, to improve it and it may be applicable to other performance related problems in ATLAS.

References

1. QP on jira: https://its.cern.ch/jira/browse/ATLIDTRKCP-734
2. Alignment of ATLAS ID in Run2 paper: The ATLAS Collaboration (2020). Alignment of the ATLAS Inner Detector in Run 2. *The European Physical Journal C*, *80*(12). doi:10.1140/epjc/s10052-020-08700-6

Repositories

3. InnerDetector: https://gitlab.cern.ch/atlas/athena/-/tree/main/InnerDetector/InDetMonitoring/InDetPerformanceMonitoring/InDetPerformanceMonitoring?ref_type=heads
4. InDetAlignExample development branch: https://gitlab.cern.ch/atlas-idalignment/InDetAlignExample/-/tree/development?ref_type=heads
5. Slides MarpX: https://github.com/cunhapaulo/MarpX/tree/main

Backup

The Large Hadron Collider at CERN

Fig. 22.1: LHC ring extension in Switzerland and France border. The flagship experiments are also shown.

One Ring to rule them all...

A hundred meters underground in Geneva and France, the **L**arge **H**adron **C**ollider lies.

It is 27 km long, so it **accelerates hadrons** $0.999999c$

With a energy of collision of

$$\sqrt{s} = 13.6 \text{ TeV}$$

The Large Hadron Collider at CERN

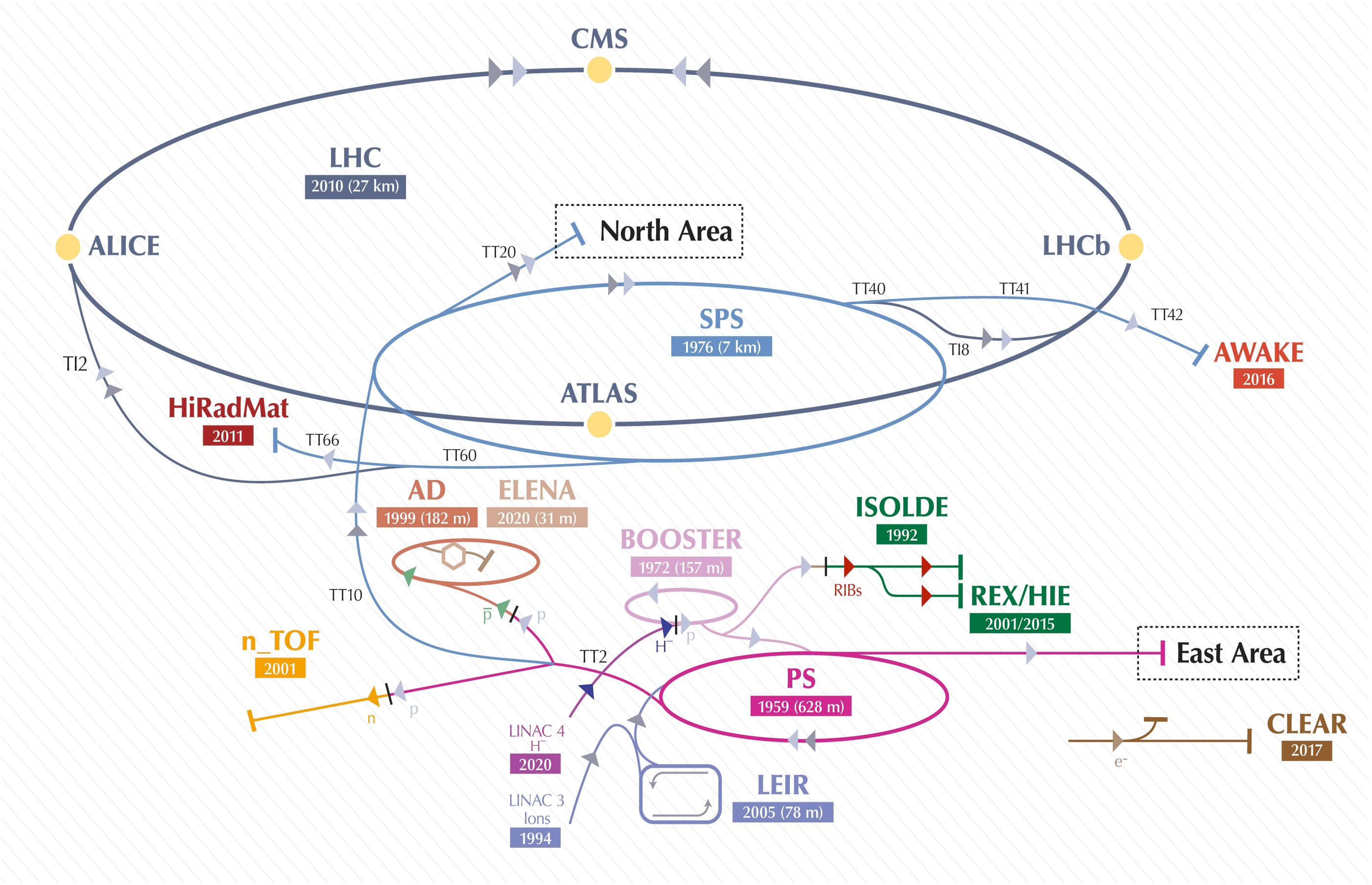

Fig. 23.1: LHC complex scheme. Ancient accelerators are reused to escalate the energy of the hadrons.

Ancient rings are used to feed the One Ring

Two hadrons beams are **accelerated** through larger and larger accelerators until they reach LHC **and collide**.

Four experiments cover the **four collision points**: ALICE, ATLAS, CMS and LHCb.

The ATLAS detector

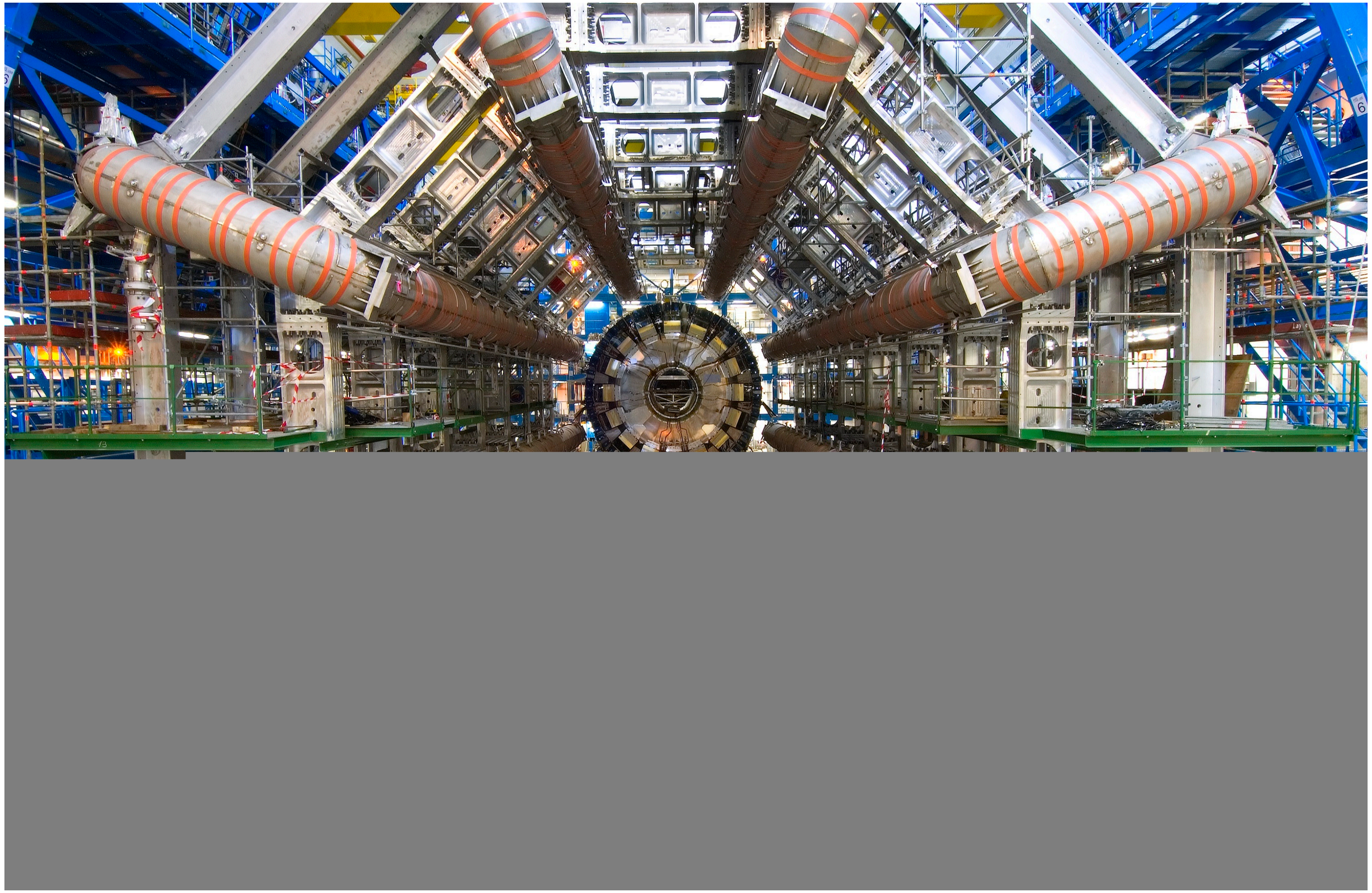

Fig. 24.1: ATLAS detector magnet system. Note the comparison with a person.

Momentum reconstruction in ATLAS

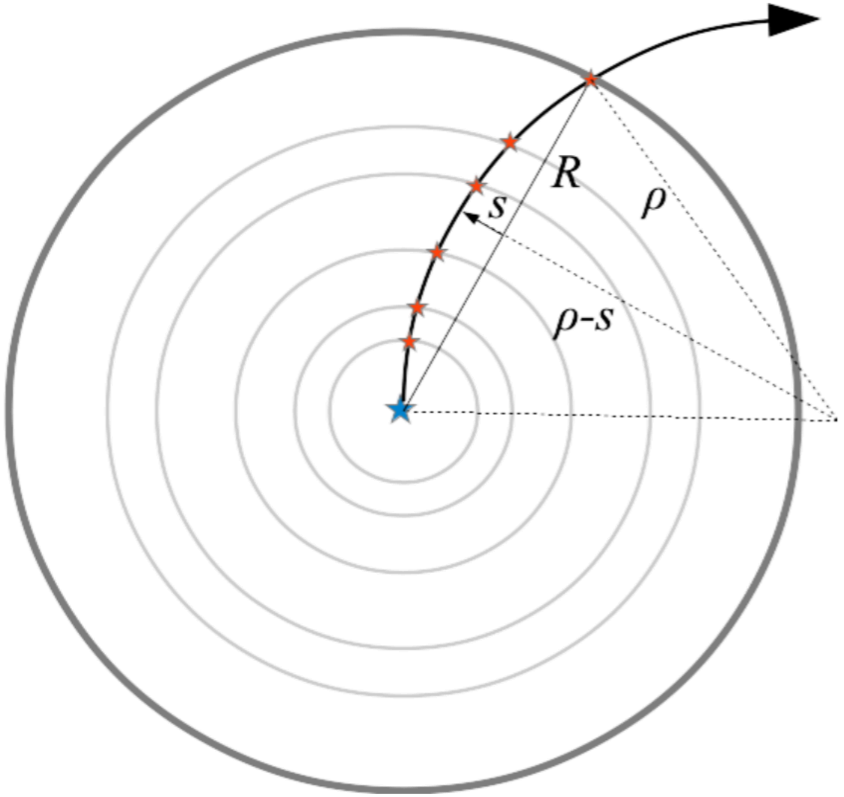

Fig. 25.1: Representation of a charged particle in an ATLAS-like detector. The cut is transverse to the B axis

Momentum of a **charged particle** in an uniform **magnetic field** B

$$p_T[\mathrm{GeV/c}] = 0.3 \cdot q[\mathrm{e}] \cdot B[\mathrm{T}] \cdot \rho[\mathrm{m}]$$

where

- $p_T \equiv$ transverse momentum
- $q \equiv$ charge of particle in e units
- $B \equiv$ magnetic field
- $\rho \equiv$ trajectory radius

Momentum reconstruction from sagitta

p_T reconstruction with s

Now momentum can be reconstructed with sagitta instead of the trajectory radius

$$p_T \simeq 0.3qB \cdot \frac{L^2}{8s}$$

$$p_T \simeq q\frac{\kappa}{s}$$

Sagitta distortion = Momentum distortion

p_T bias from s bias

Now we defined δ_s as the **sagitta bias**
In the **alignment group**, the goal is to **recover the true momentum p removing any biases**. That explains the inverse definition of the signs from usual analysis where the reconstructed momentum is what it is desired.

$$\frac{1}{p_T} \simeq \frac{1 - qp'_T\delta_s}{p'_T}$$

$$p_T = p'_T \cdot (1 - qp'_T\delta_s)^{-1} \underset{\delta_s \ll}{\approx} p'_T \cdot (1 + qp'_T\delta_s)$$

Sagitta distortion = Momentum distortion

Sagitta distortion

A geometrical distortion in the transversal plane of a track may produce a bias in the sagitta, i.e. a bias in the reconstructed momentum ($x' \equiv$ biased x from now on)

$$s' = s + \epsilon_s$$

p_T bias from s bias

Momentum is therefore affected by this sagitta bias. We can recover the true momentum p_T then: (note that $q = \pm 1$ then $\frac{1}{q} = q$)

$$\frac{1}{p_T} \simeq \frac{(s' - \epsilon_s)}{q\kappa} \simeq q\frac{s'}{\kappa} - q\frac{\epsilon_s}{\kappa} = \frac{1}{p'_T} - q\delta_s$$

Sagitta distortion = Momentum distortion

p bias from s bias

Considering the components of coordinate system (Transverse, Longitudinal) (T, z)

$$p_z = \cot\theta \cdot p_T = \cot\theta \cdot p'_T \cdot (1 + q p'_T \delta_s)$$

$$p_z = p'_z \cdot (1 + q p'_T \delta_s)$$

Considering that **$\cot\theta$ is not affected by δ_s**, we can see p'_z is affected in the same way by this bias than p'_T. Then:

$$p = \sqrt{(p_T)^2 + (p_z)^2} = p' \cdot (1 + q p'_T \delta_s)$$

Where $p \equiv p_{true}$ and $p_T \equiv p_{T,true}$

Run2 Method to compute δ_s

Using $Z \to e^+e^-$ Events

Currently in **Run3** alignment campaign, **muons** are being **used to correct sagitta bias** with the VarMin method.

Nonetheless, the usage of **electrons** have the **pro** that the **EM Calorimeter** from ATLAS detector can **reconstruct their E**.

Considering the energy-level of the collisions in LHC ($\sim$ TeV), we can approximate $p \underset{m_e \ll}{\approx} E$. And **$E$ is not affected by the sagitta bias**

Assumptions

- Assume calorimeter response q independent: that is **unbiased $E' = E$**
- Expected **charge dependent p' bias** for e^+ and e^-.

Run2 Method to compute δ_s

Calculating Sagitta Bias

The average value of the distributions of E/p of both **positrons** and **electrons** is **compared**. One can derivate this from $p = p' \cdot (1 - qp'_T\delta_s)^{-1}$

$$\langle E/p \rangle = \langle E/p' \rangle - q\,\langle E_T \rangle \delta_s$$

The bias is expected to emerge from the charge dependent asymmetries of the reconstructed momenta.

$$\delta_\mathrm{s} = \frac{\langle E/p' \rangle_+ - \langle E/p' \rangle_-}{2\langle E_T \rangle}$$

where q : Particle charge , $E_T = E/\cosh\eta$: Energy scale factor, η: Pseudorapidity

Run2 Method: Error propagation

From the equation $\delta_{\mathrm{s}} = \frac{\langle E/p' \rangle_{+} - \langle E/p' \rangle_{-}}{2\langle E_T \rangle}$, the partial derivatives wrt. each mean variable are performed:

$$\frac{\partial \delta_s}{\partial(\langle E/p' \rangle_{+})} = -\frac{\partial \delta_s}{\partial(\langle E/p' \rangle_{-})} = \frac{1}{2\langle E_T \rangle}$$

$$\frac{\partial \delta_s}{\partial(\langle E_T \rangle)} = \frac{\langle E/p' \rangle_{+} - \langle E/p' \rangle_{-}}{-2\langle E_T \rangle^2} = -\frac{1}{\langle E_T \rangle}\delta_s$$

Then:

$$\sigma_{\delta_s} = \sqrt{\left(\frac{1}{2\langle E_T \rangle} \cdot \sigma_{\langle E/p' \rangle_{+}}\right)^2 + \left(-\frac{1}{2\langle E_T \rangle} \cdot \sigma_{\langle E/p' \rangle_{-}}\right)^2 + \left(-\frac{\delta_s}{\langle E_T \rangle} \cdot \sigma_{\langle E_T \rangle}\right)^2}$$

Toy MC E/p

Let's study the E/p pdf with a **simple toy MC** generation. E and p histograms are **gaussian** pdf with equal μ and σ

Parameter	Value
N events	100000
μ_E	40
μ_p	40
σ_E	10
σ_p	10
Nbins	500

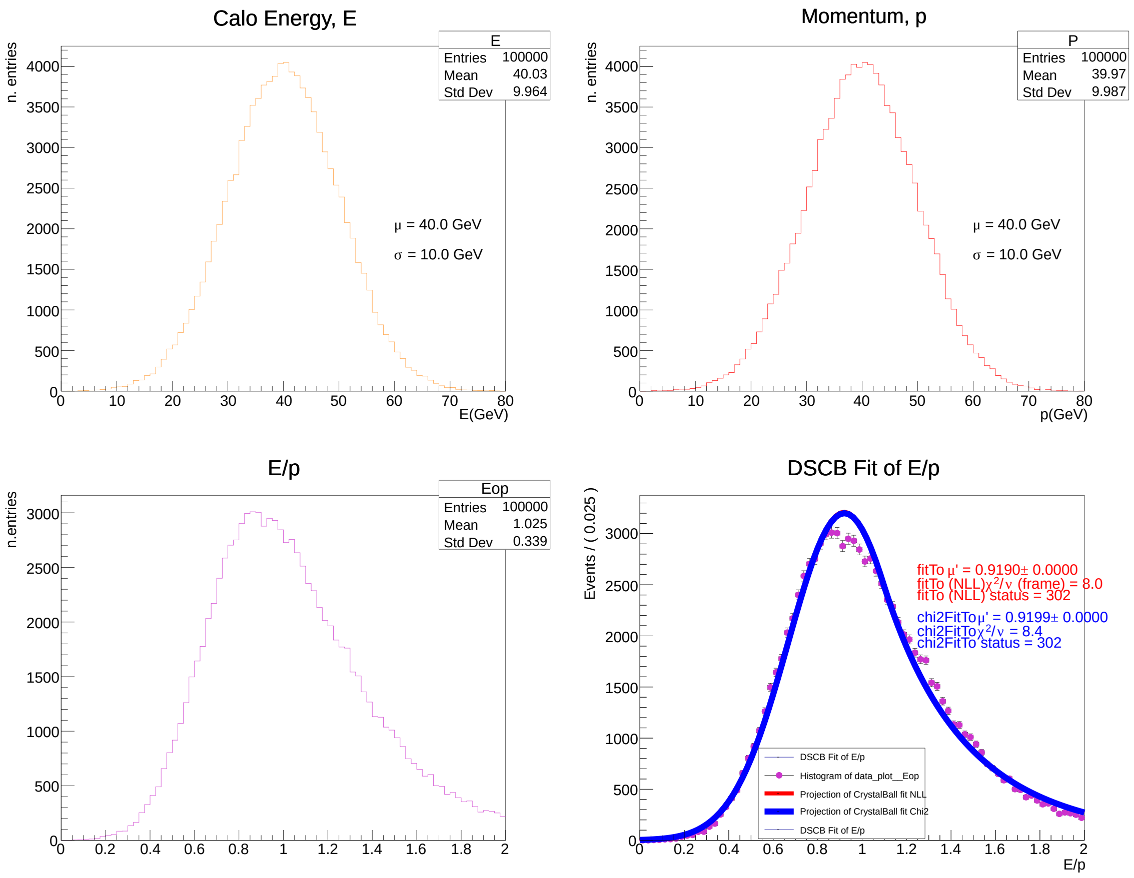

Fig. 33.1: E and P Gaussian, randomly generated distributions, and E/p at right

Toy MC E/p

First, we observe that the **tail** of the distribution **emerges** as a pure effect from the pdf.

Also, the mean from Crystal Ball fit is a bit below 1. Whereas the mean of the histogram is above.

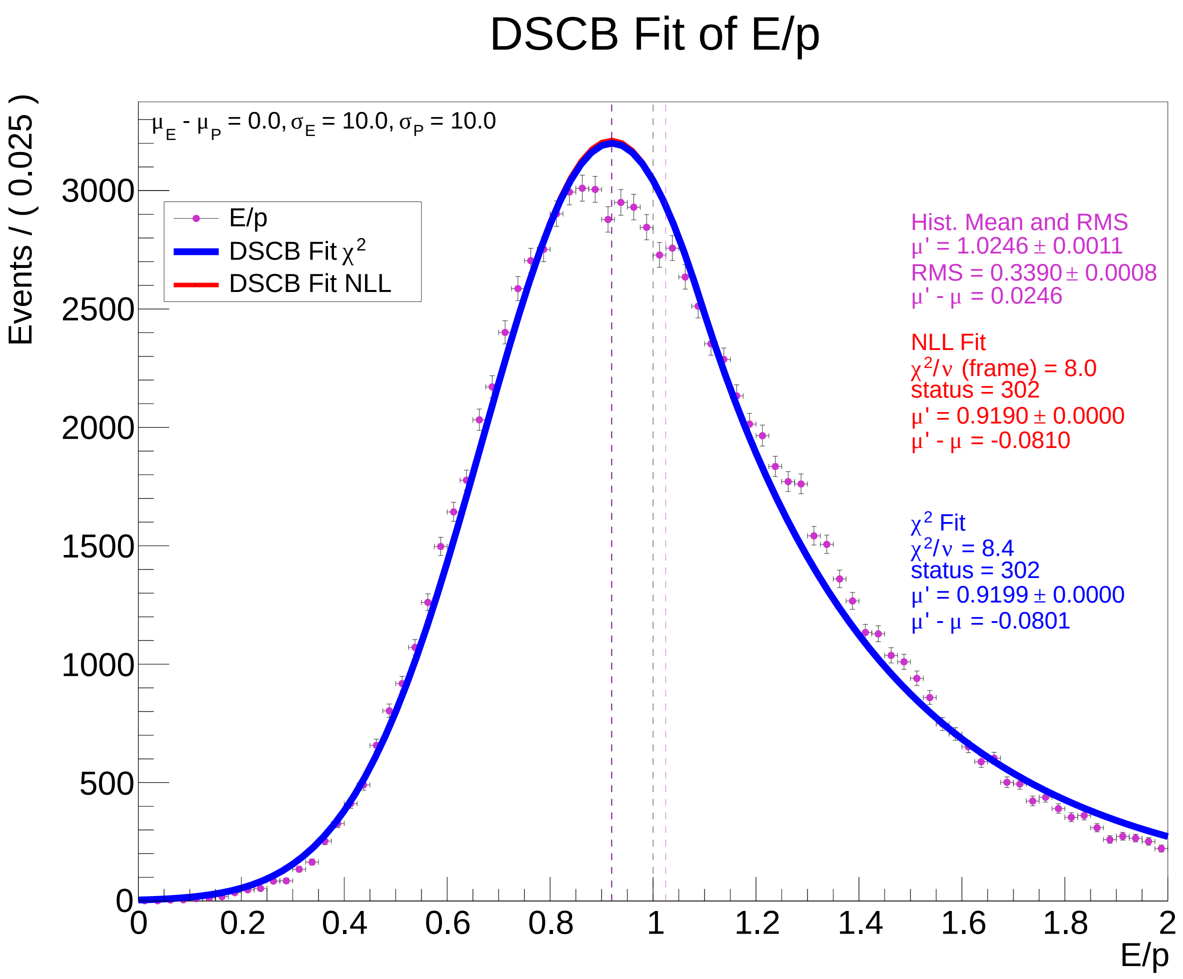

Fig. 34.1: CB Fit of MC Toy E/p. Pink is the TH1 mean, and red and blue are RooFit's fits

Toy MC E/p

The parameter σ from the E and p distributions is proportional to this biased means behaviour.

This supports the importance of using variable binning in the endcaps.

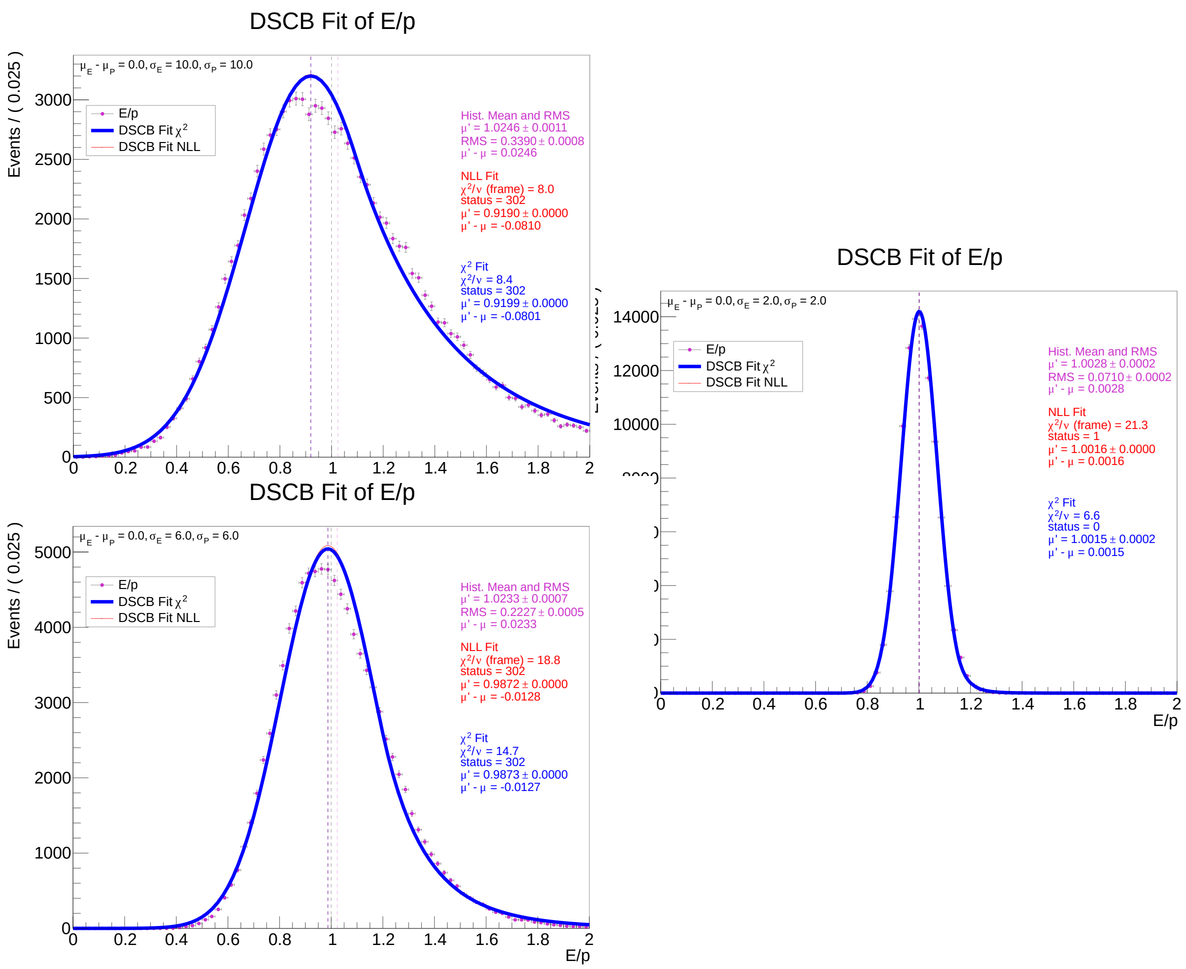

Fig. 35.1: CB fits of MC Toy E/p with different sigmas in E and p pdf