ALICE project:
Introduction and hands-on

Outline of the proposed study

Reconstruct the decay of two charm hadrons:

- $D^0 \rightarrow K^-\pi^+$
- $\Lambda_c^+ \rightarrow pK^-\pi^+$

analysing proton-proton collision data from the ALICE experiment

- real data
- data from Monte Carlo simulations with enhanced signal

These particles are relatively rare and without selections the signal-to-background ratio is quite low

I will give you a series of root files containing root trees

After some first explanations and instructions, and a first ~hands-on session together,
I will give you some practical goals (mainly plots you should produce) and let you free to play with the data

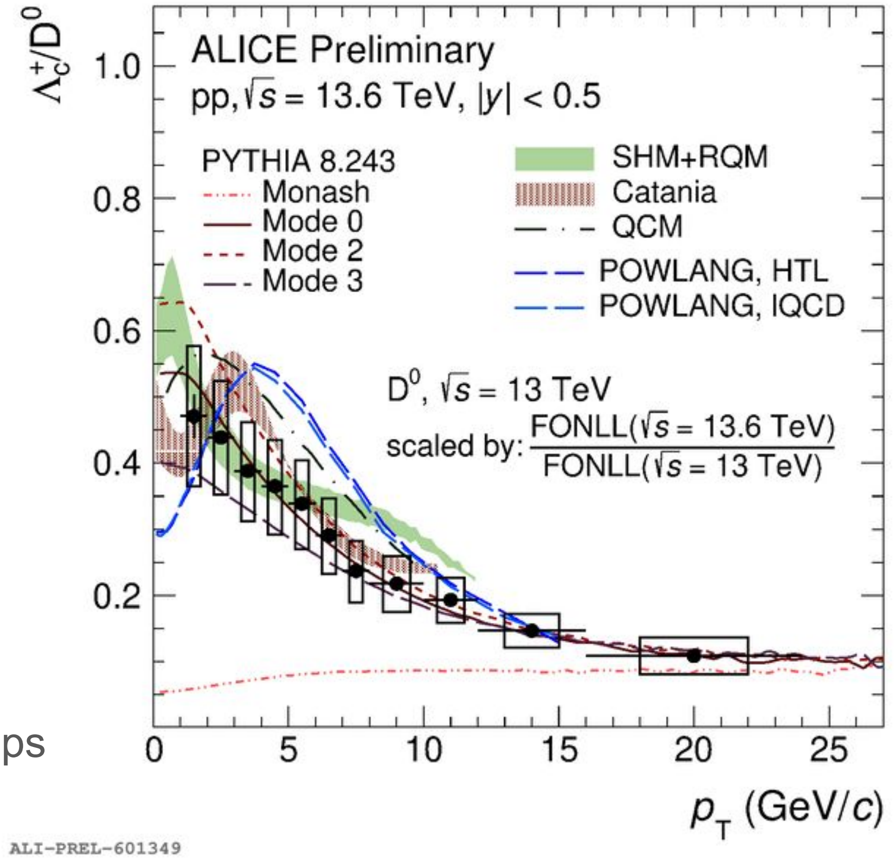
Outline of the proposed study

Ultimate goal would be to measure
the production cross section of the two particles
and compare them like in this result

Ratio of the production cross sections of these
two particle is a sensitive observable to investigate
the hadronisation process, i.e. the transition from
a system of quarks to one of hadrons

However, we cannot repeat the full analysis
- time limitation
- data-size needed too large

We will study and reproduce (some of) the main steps



Objectives

1) Become familiar with data-analysis techniques typically used in particle and (high-energy) nuclear physics
   - few concepts of data reconstruction
   - PID, vertexing, invariant mass analysis
2) Apply Machine Learning classification to reject background
3) Touch concepts and problems typical of the measurements done in this (and not only) context:
   - selection efficiency
   - statistical significance
   - systematic uncertainties

Data and software tools

Data files are root files containing trees (flat tables)
You will find them in the Cloud Veneto space at this directory:
/home/ubuntu/ALICEphyisicsOfData/

Right now, just one file in: /home/ubuntu/ALICEphyisicsOfData/FirstFile/AO2Dtree.root
For today, you can access the file we need, also via this google link:
https://drive.google.com/file/d/1CCHq1R24JuJqKFkmelCuJgnrQEcXzAYK/view?usp=drive_link

You can analyse them via ROOT(*) or with whatever programme/language you prefer: use UPROOT, transform in pandas dataframe, use python.

If you like to use Jupyter notebook, that's more than welcome!

(*) it might help to look at Root documentation and tutorial, https://root.cern/doc/master/group__Tutorials.html
but my advice is to do it when you need specific information. Learn by doing things.

What we do together

1) Introduction:
    i) main goals of ALICE experiment related to this project
    ii) basic concepts of data reconstruction
    iii) quick introduction to the physics case that you will explore
2) Hands-on session:
    i) data structure
    ii) first steps:
        - look at main single-track variables used in analysis
        - produce figures related to PID and tracking performance
        - build by hand candidates of decay particles (K^0_s, D^0)
3) Second appointment:
    i) look at files with already produced and filtered candidates
    ii) introduction to the main variables used to distinguish signal and background
    iii) discuss concepts of signal extraction, selection efficiency, statistical significance
    iv) systematic uncertainties

Brief introduction to what ALICE looks at in pp and Pb-Pb collisions

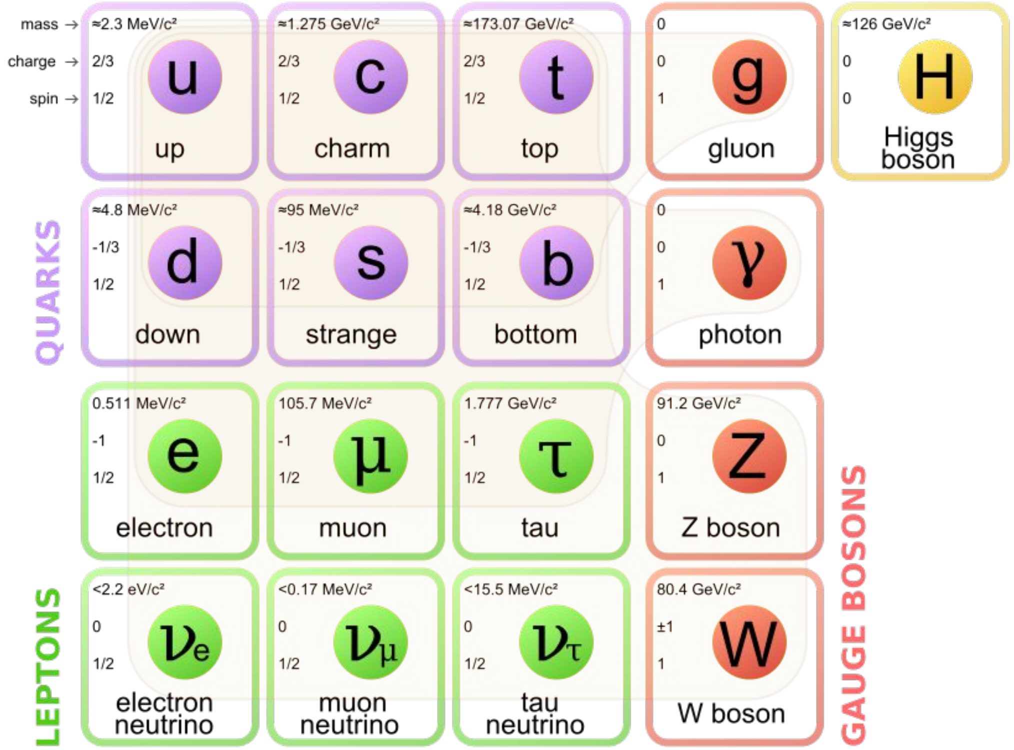
Recall: Elementary particles in the Standard Model

Elementary = no internal structure, pointlike (no dimension) opposite of “composite”
→ fundamental building blocks of all known matter

6 quarks
6 leptons
1 Higgs boson
4 gauge bosons (interaction messengers)

3+1 interactions:

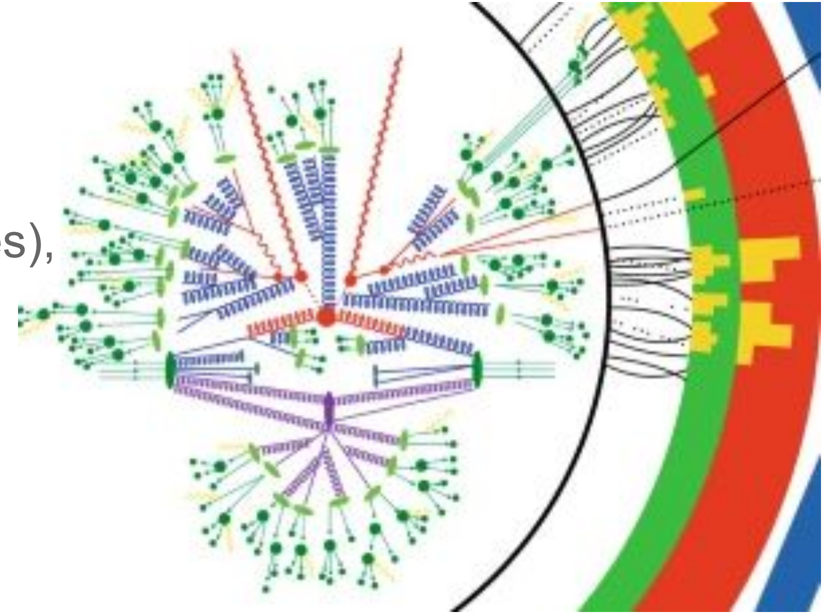
- strong → g
- electromagnetic → γ
- weak → $W^{\pm}$,Z^0
- (gravitation → graviton?)



[https://commons.wikimedia.org/wiki/File:Standard_Model_of_Elementary_Particles.svg]

Investigating the strong force at high-energy at colliders

What happens in **proton-proton collisions at high energies** like those accessible at the **Large Hadron Collider at CERN**?



Quarks and gluons inside protons
interact and produce
several quarks and gluons (rarely other particles),
i.e. a system of interacting partons,
which **evolves until hadrons are formed**

ALICE goal:
study the properties and evolution of the partonic and hadronic systems
→ learn properties of strong force and of some fundamental processes in nature

Picture from: Georgescu, I. Simulating parton showers. *Nat Rev Phys* 3, 73 (2021)

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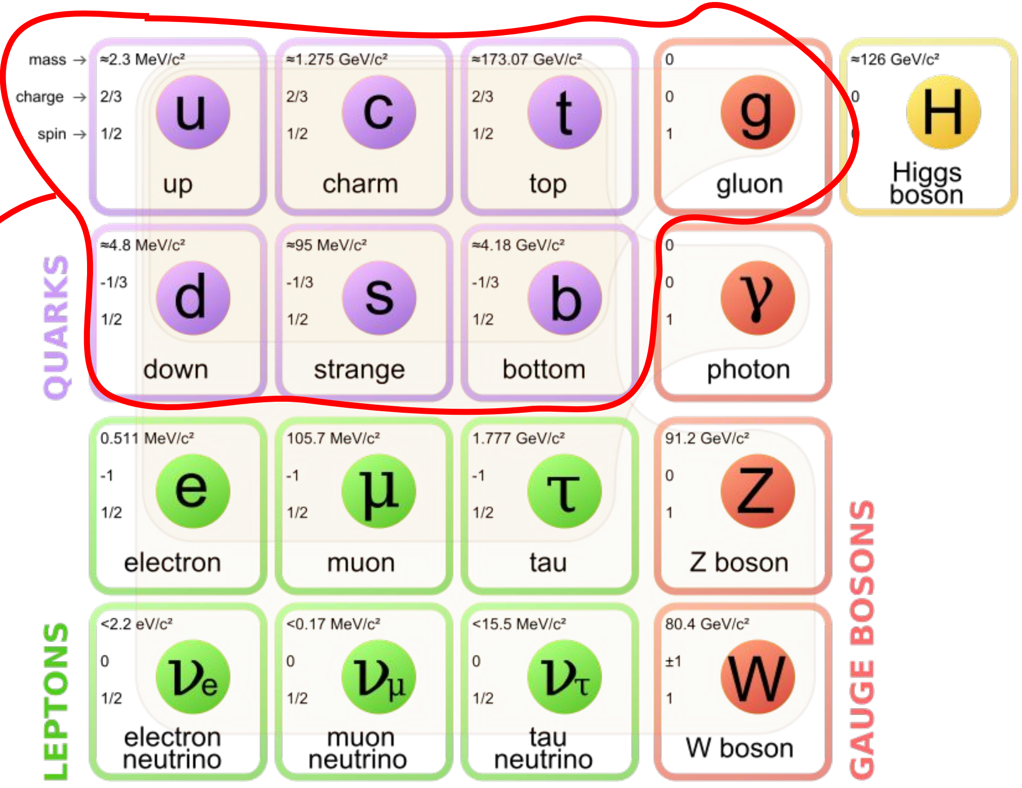
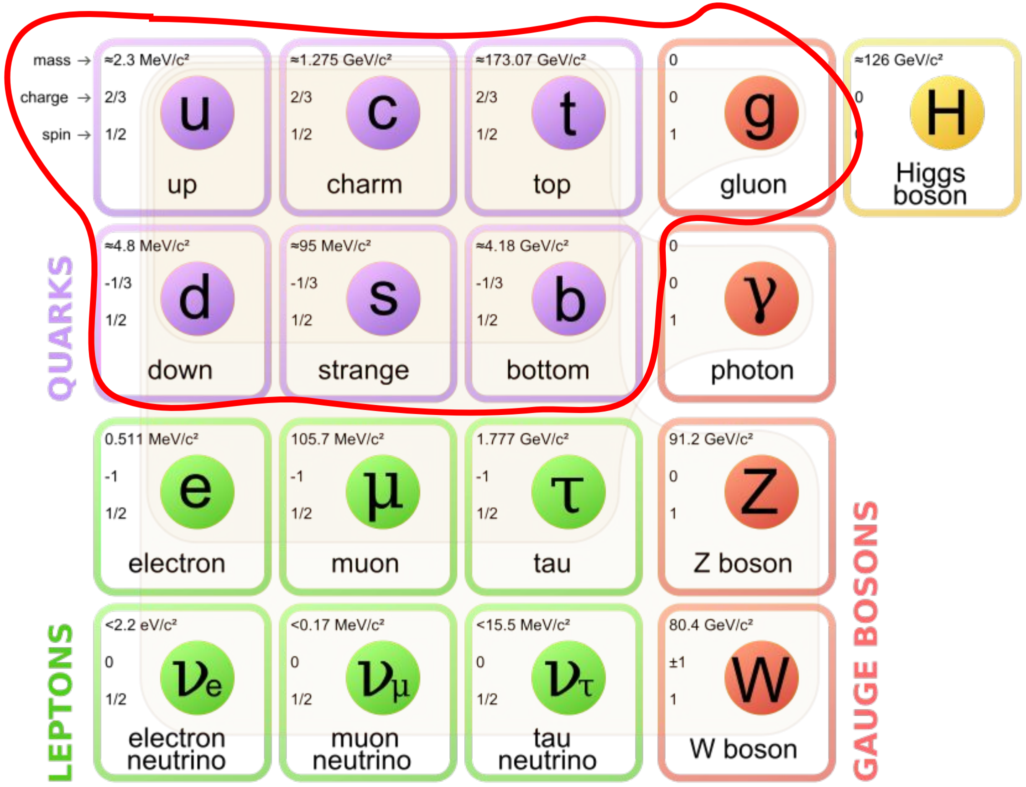
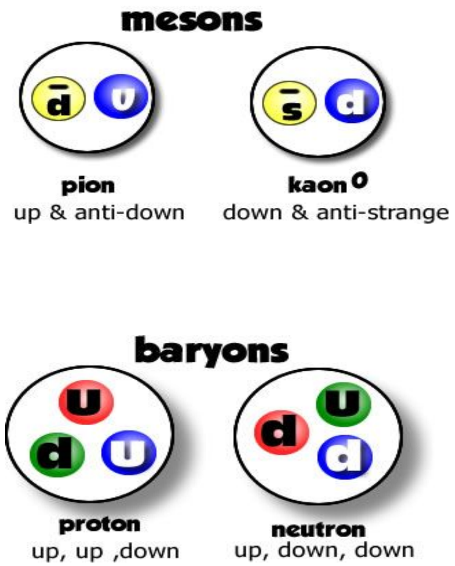


[https://commons.wikimedia.org/wiki/File:Standard_Model_of_Elementary_Particles.svg]

(Elementary particles and hadrons)

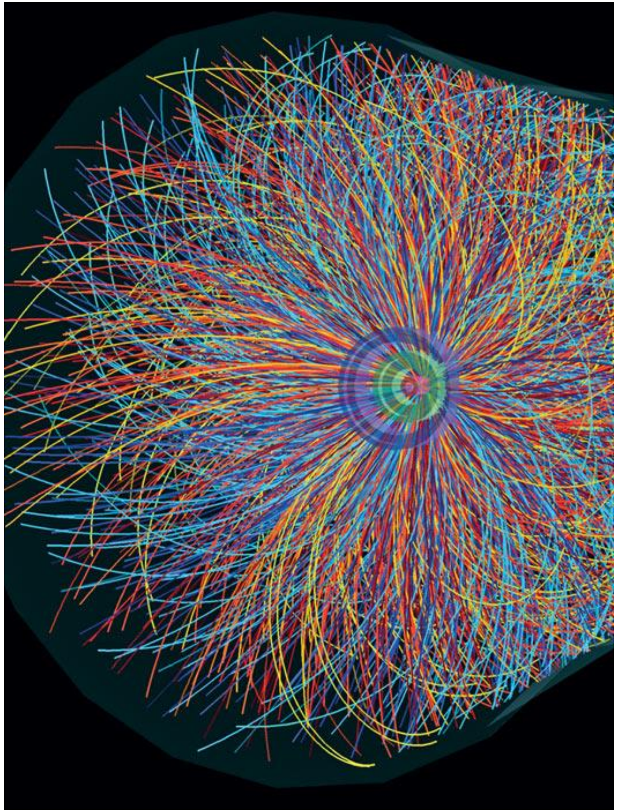
We never observe free quarks, only composite objects called hadons, in which quarks are bound and confined to stay by the strong nuclear force





Investigating the strong force at high-energy at colliders

What happens in Pb-Pb collisions at high energies like those accessible at the Large Hadron Collider at CERN?



Something similar to proton-proton collisions

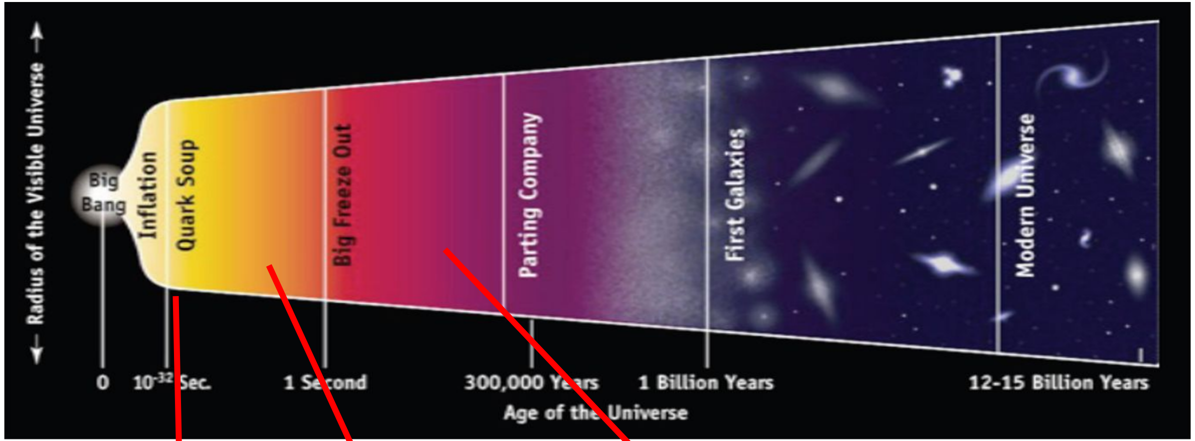
but the **number of produced quarks and gluons (and then hadrons) is much higher** (about x1000)

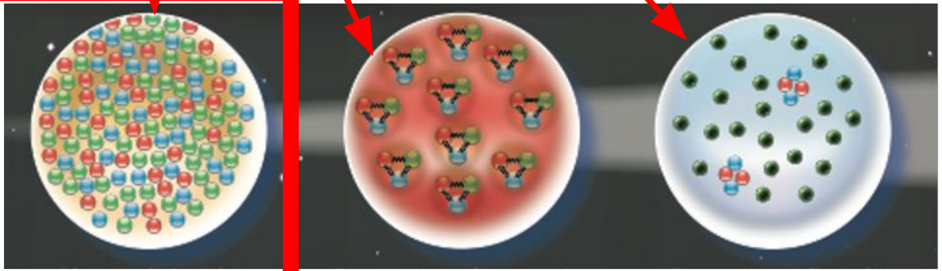
Partonic system with very high energy density

which behaves for a very short time (few 10^{-23} s) as a **quark-gluon plasma (QGP) state**

in which quarks and gluons behave and interact as free particles

Quark-gluon matter in the Early Universe …





quark-gluon plasma

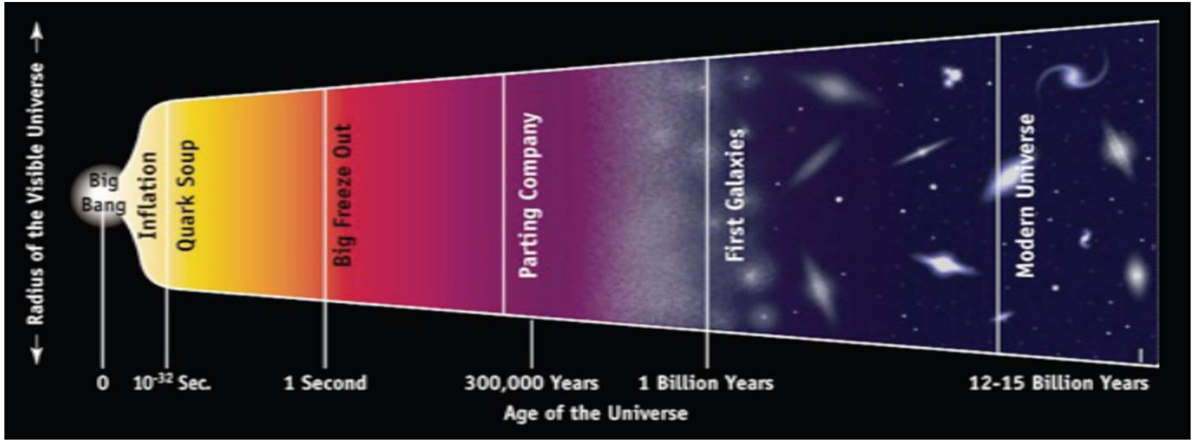
formation of protons, neutrons

formation of atomic nuclei

The transition from quarks to hadrons occurred in the expanding & cooling early Universe
~10 μs after the Big Bang

→ Before: **Quark Gluon Plasma**

Quark-gluon matter in Neutron Stars…



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→ Before: **Quark Gluon Plasma**

QGP **may** characterise also the core of neutron stars.

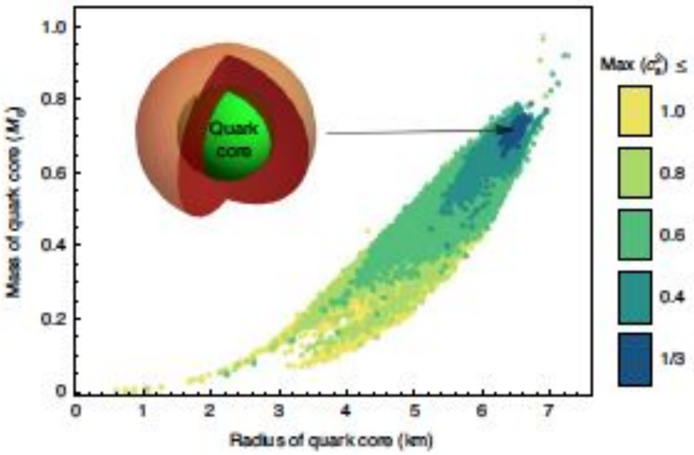
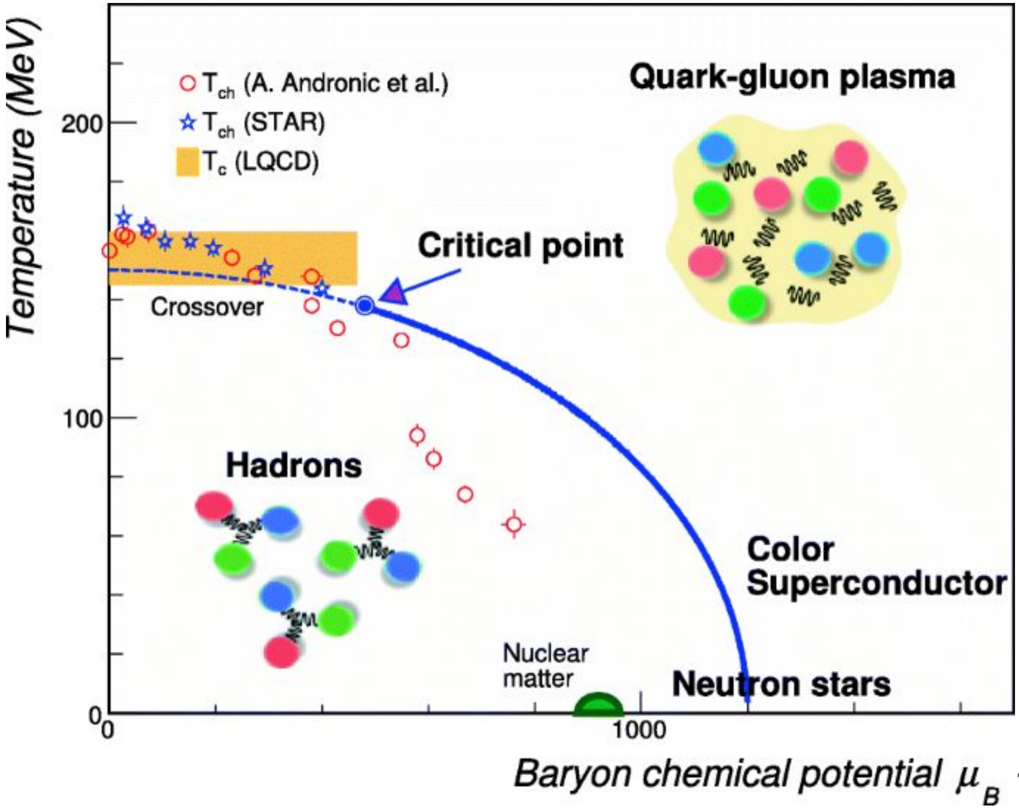
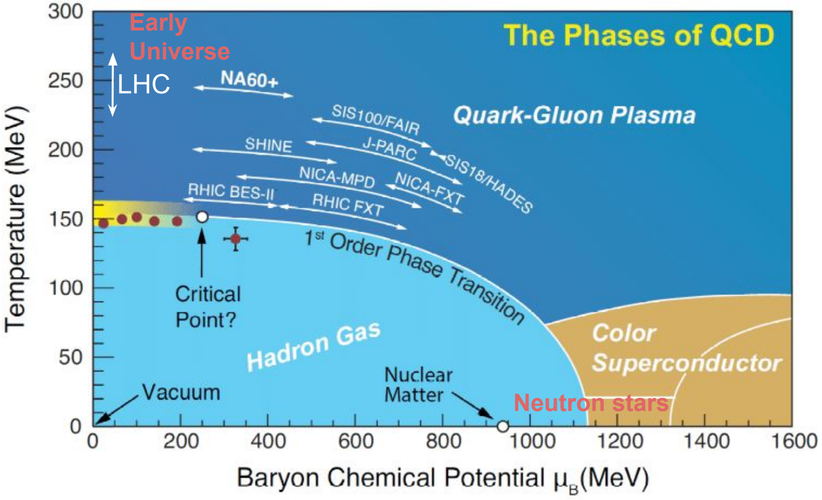


figure from Nature Physics, 16, 907-910 (2020),
https://www.nature.com/articles/s41567-020-0914-9

Exploring the strong-interaction phase diagram

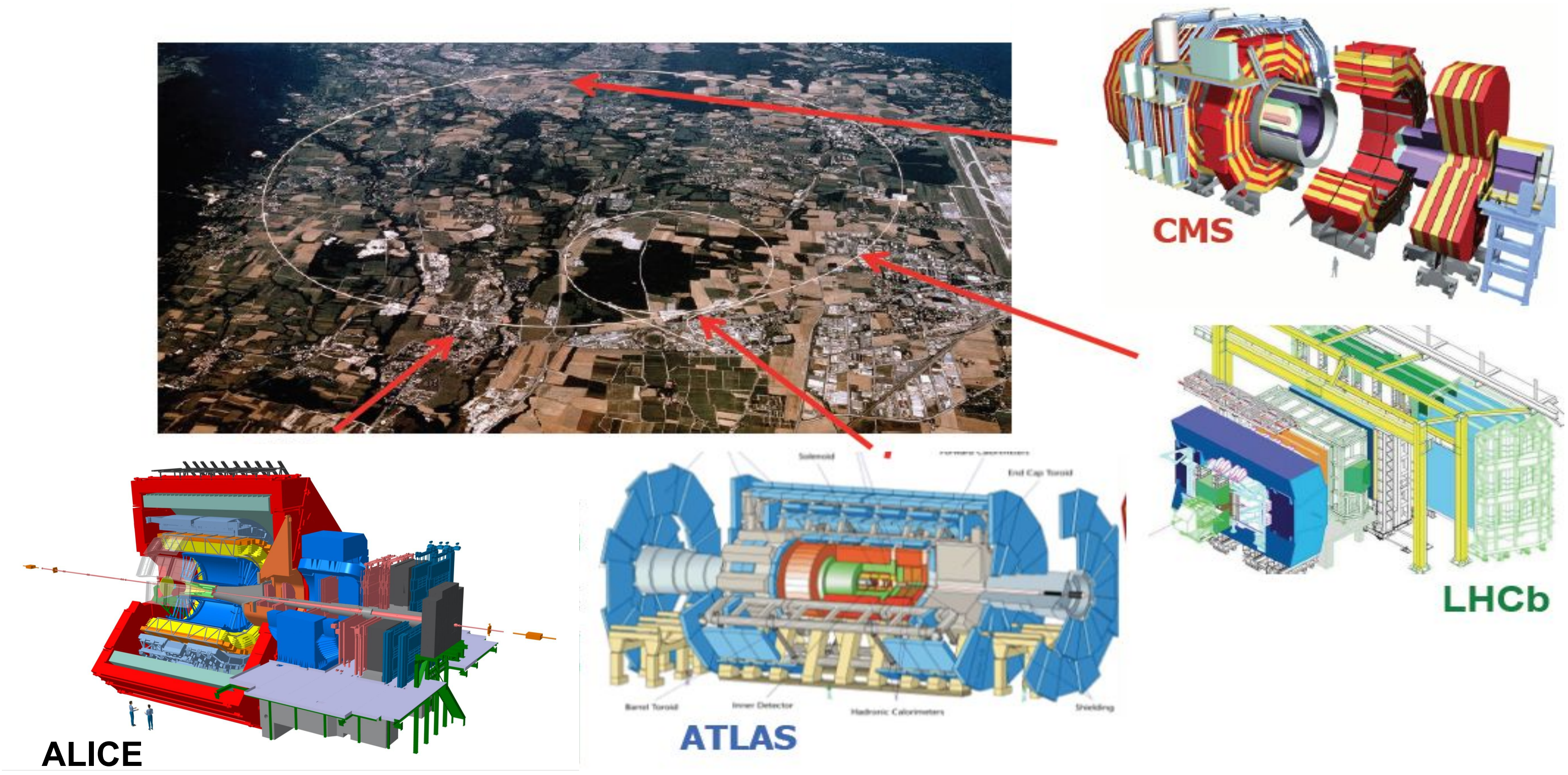




~ net-baryon density
(=density of protons - density of antiprotons)

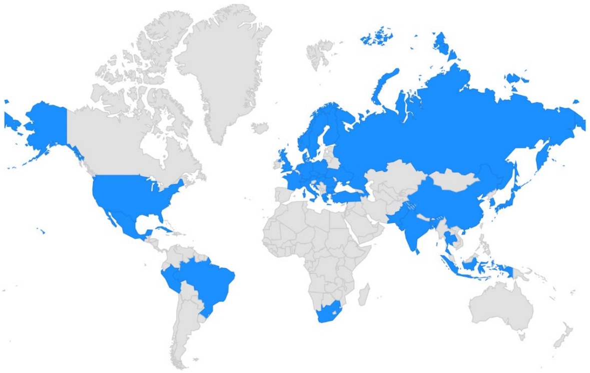
Quark-gluon matter on Earth

The ALICE experiment at the Large Hadron Collider

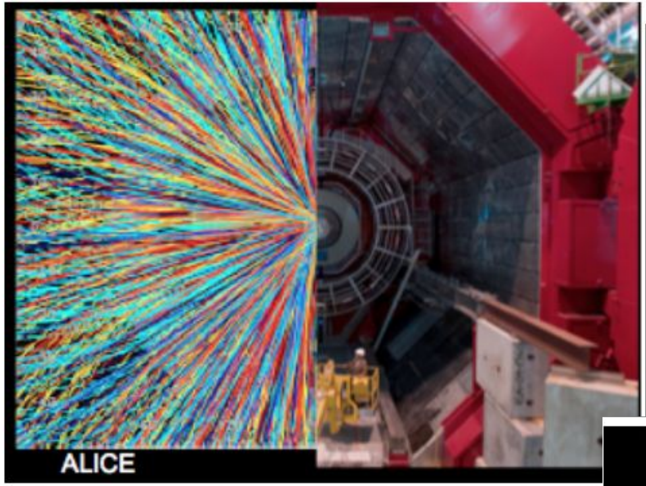


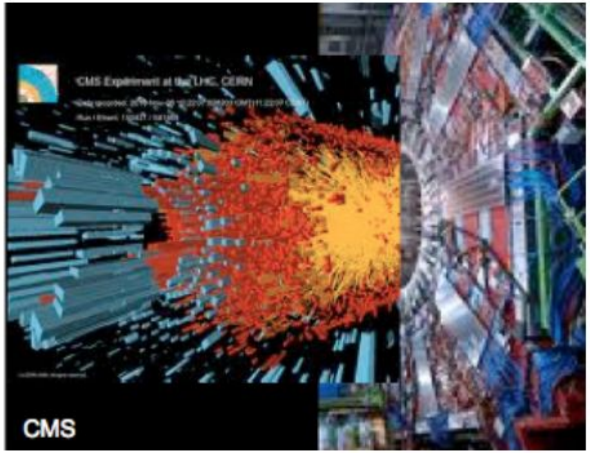
The ALICE experiment at the Large Hadron Collider

40 countries, 170 institutes, ~2000 members



What we see in Pb-Pb collisions

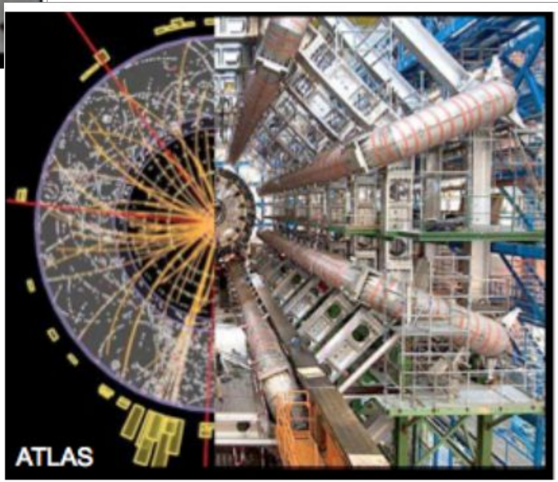


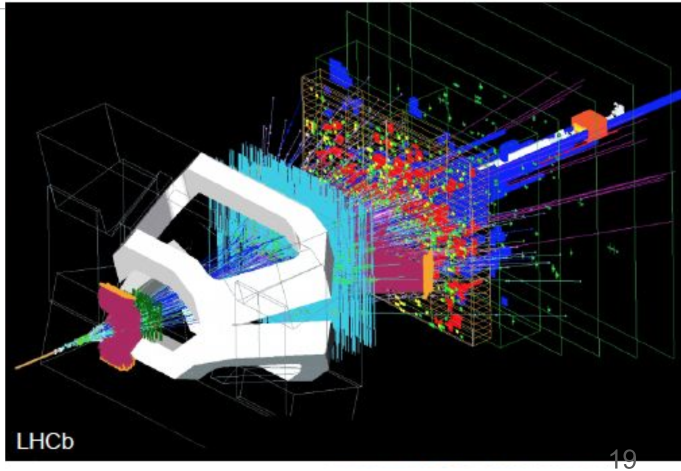


Coloured lines and boxes: visualisation of particle tracks or calorimeter energy deposits

From “event display” (so from real data)

Thousands of particles produced in a head-on Pb-Pb collision at the LHC
A lot of energy involved





“Artistic representations” of various features: MADAI webpage: https://madai.phy.duke.edu/indexaae2.html?page_id=503

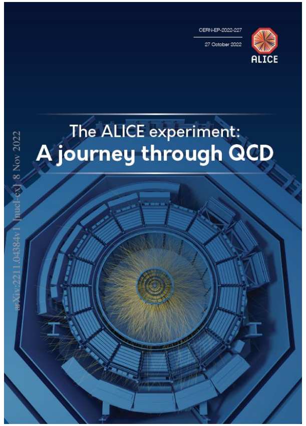
What do we want to know?

*What are the **global properties (e.g. temperature, density, volume, viscosity)** of the system?*

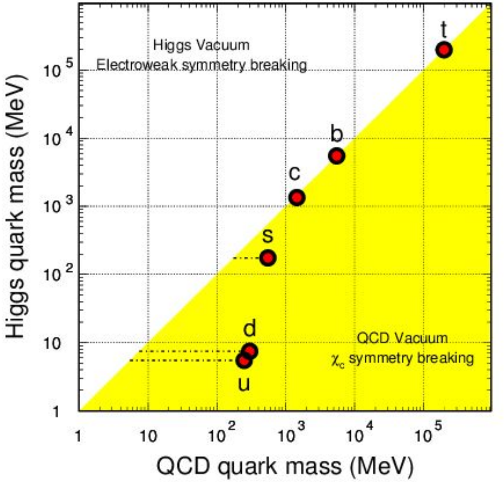
*Can we model the evolution of the quark-gluon system **from proton-proton to Pb-Pb collisions**?*

*How do **hadrons form out of a system of quarks** (hadronisation process)?*

… many more questions



https://arxiv.org/pdf/2211.04384.pdf



N.B.

- Higgs boson accounts only for a few % of the matter mass:
  M(proton) ~ 938 MeV/c^2
  M(up, down) ~ few MeV/c^2

- Most of matter mass is generated dynamically during the transition from quarks to hadrons

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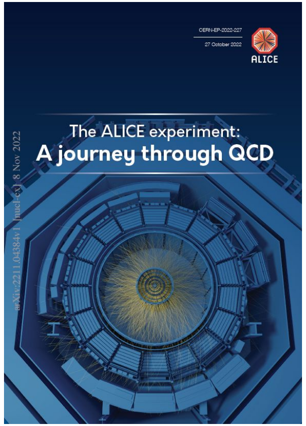

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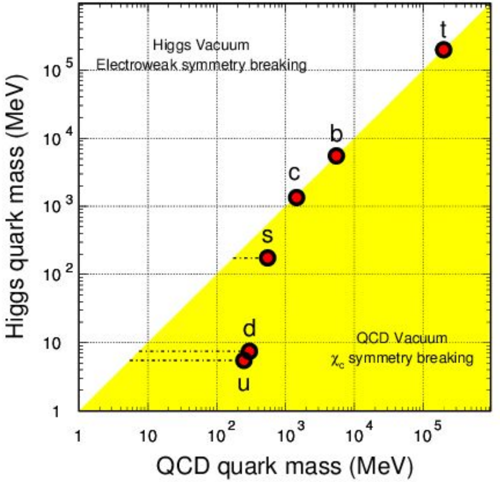

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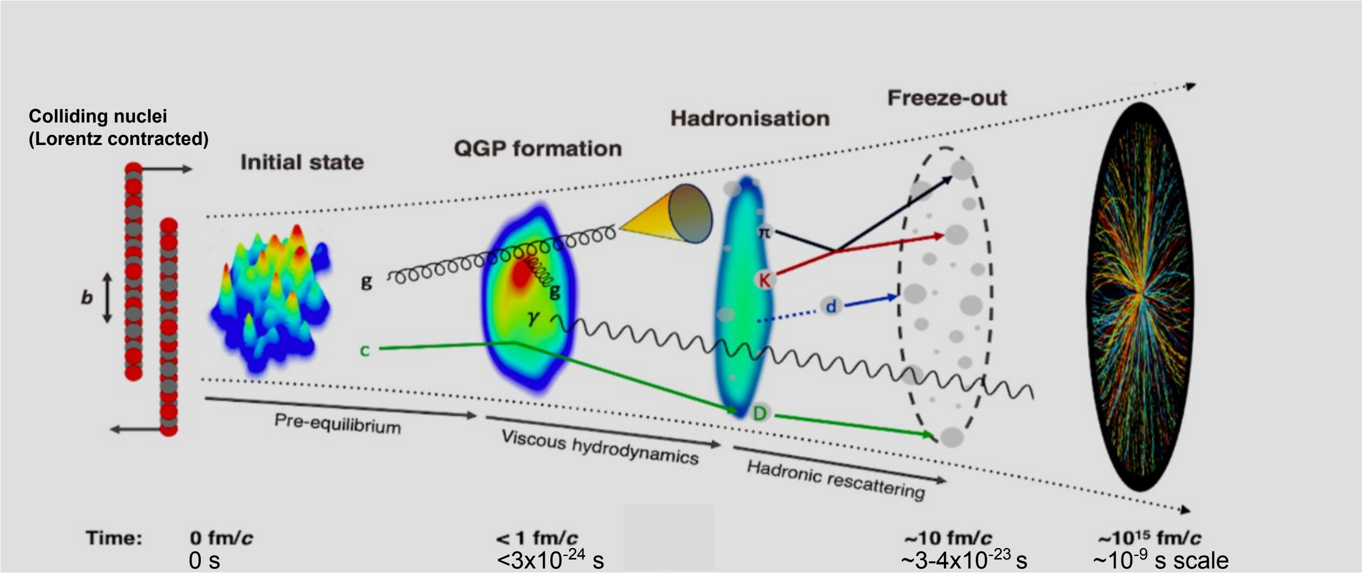
Back to nuclei collisions: system evolution and phases



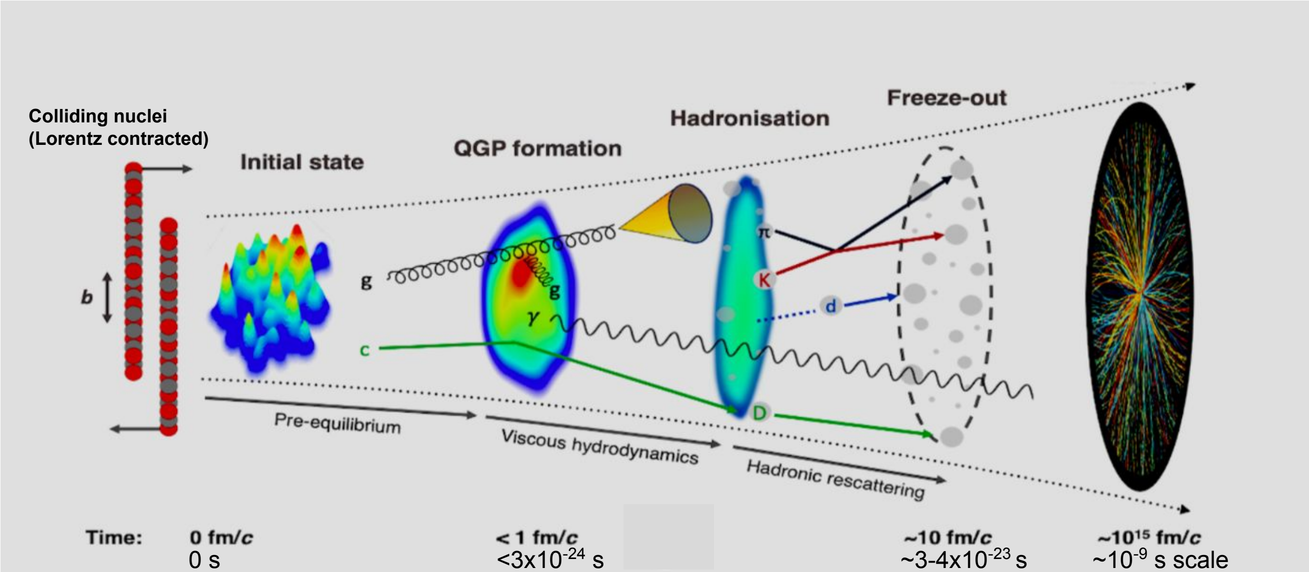
Temperature

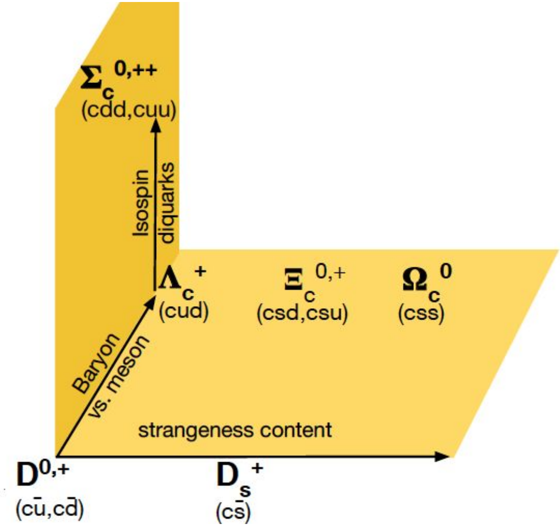
Phase transition critical temperature: T_c=156 MeV ~ $1.8{\cdot}10^{12}$ K

Sun core: $1.5 \cdot 10^7$ K

Sun surface: 5778 K

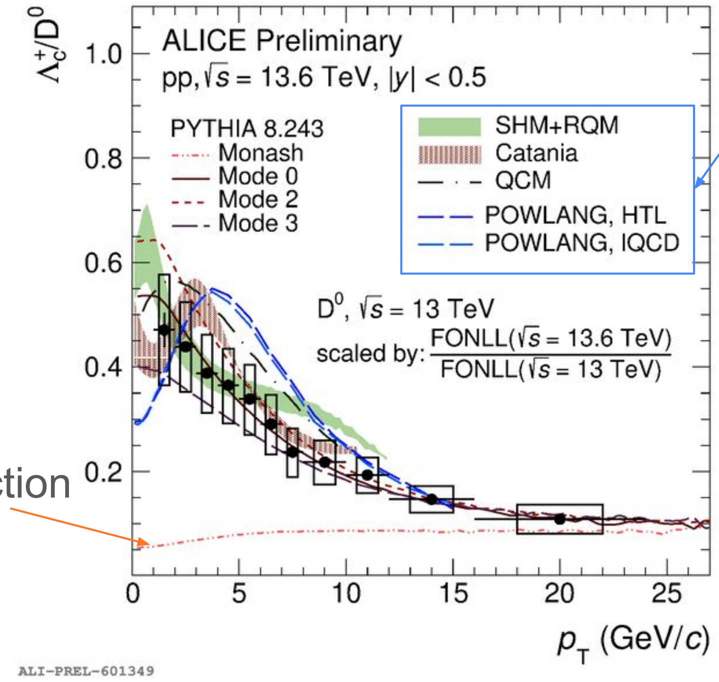
The role of charm quarks to study hadronisation





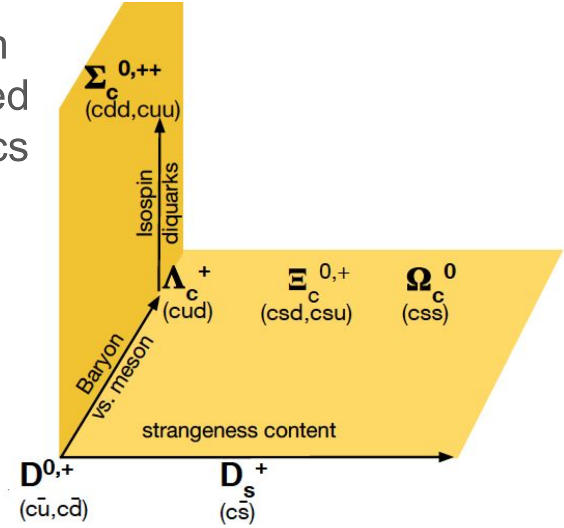
Massive quarks (mass >> temperature) as charm and beauty are produced only in hard-scattering processes occurring in the **very first instants** (before QGP formation, before hadronisation)
The production rate and quark kinematics can be calculated with perturbative QCD techniques
→ theoretically under control
→ we can use these quarks as probes to investigate the medium and the hadronisation process
In Pb-Pb collisions, but also in proton-proton collisions
How? by looking at hadrons with different quark composition

The role of charm quarks to study hadronisation



Models based on concepts inherited from QGP physics

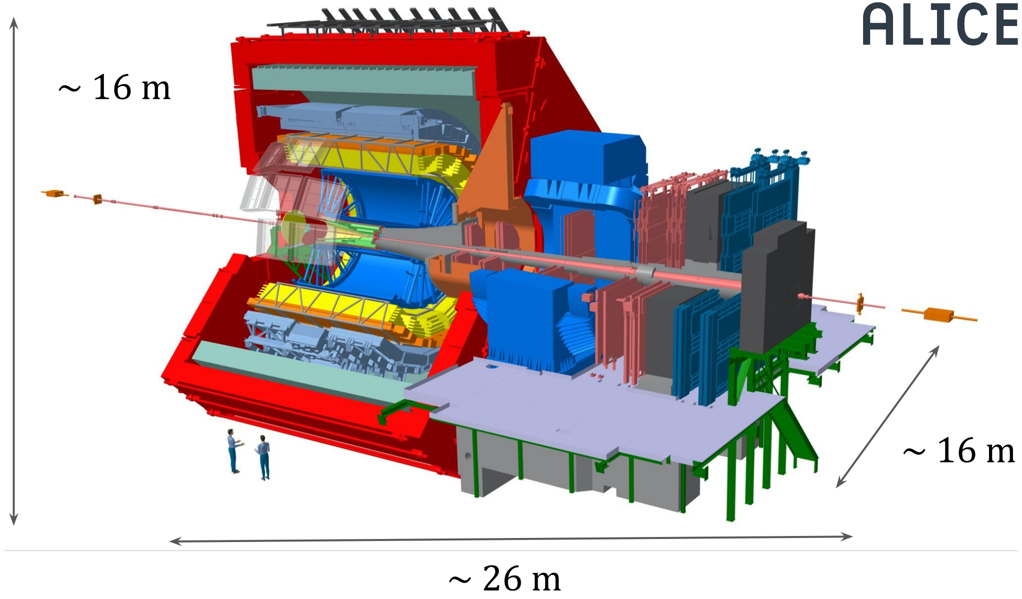
initial prediction



We started looking at proton-proton collisions as the needed reference to interpret Pb-Pb results
… but it turned out that the modelling of hadronisation in pp was naïve

The ALICE experiment at the Large Hadron Collider

ALICE

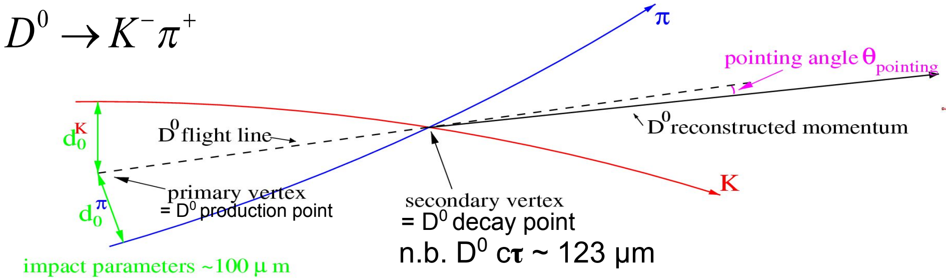


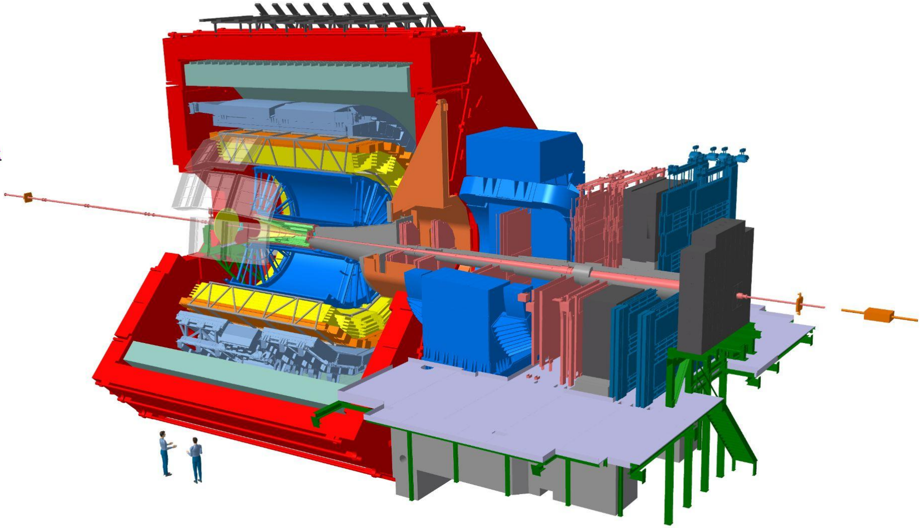
“Gigantic” particle accelerator (LHC) with gigantic apparatus

Magnets, trackers, muon-chambers, calorimeters… and several other detectors

ALICE public webpages (just look for “ALICE CERN”): https://alice-collaboration.web.cern.ch/ https://alice.cern/alice-physics

D^0 meson reconstruction





How much this signal is rare and the signal-to-background ratio (S/B) low?

Rough rough estimate:

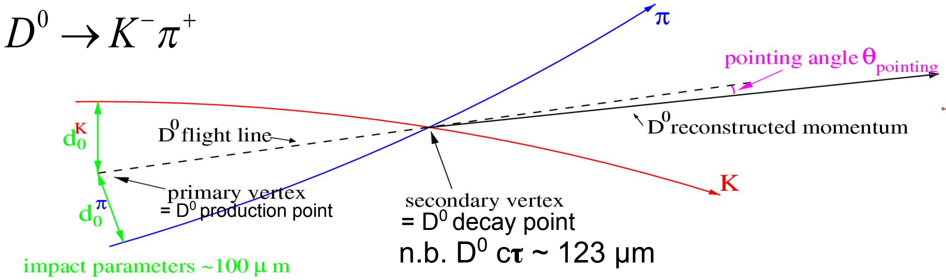
- Number of D^0/collision in detector acceptance ~1/100
- Branching ratio (fraction of decays in the specific decay channel)~4% → **S/collision~4/10000**
- Number of charged particles/collision in pp at 13 TeV in relevant detector acceptance: ~12, half positive, half negative → **B/collision ~ 36 → S/B ~ 10^{-5}**

A similar estimate, for the $\Lambda_c^+ \to pK^-\pi^+$ gives S/B~ 10^{-6}

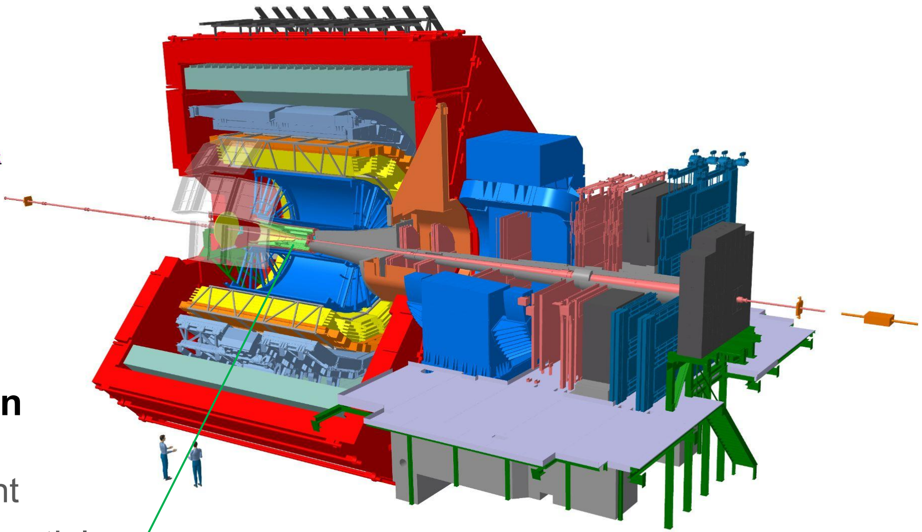
How do we improve it?

D^0 meson reconstruction

$D^0 \to K^- \pi^+$



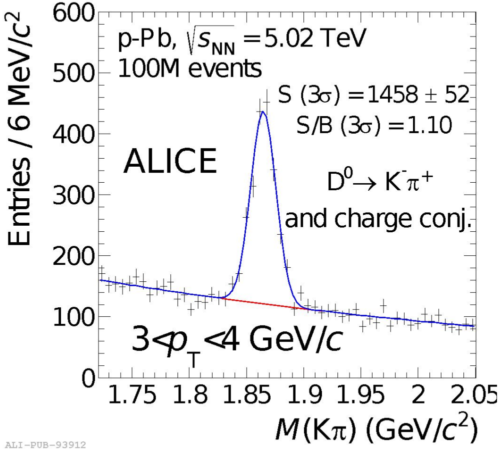
n.b. D^0 cτ ~ 123 μm



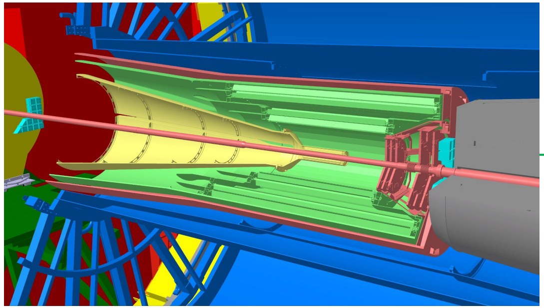
Exploit **invariant mass**, **secondary vertex reconstruction** and **particle ID (PID)**

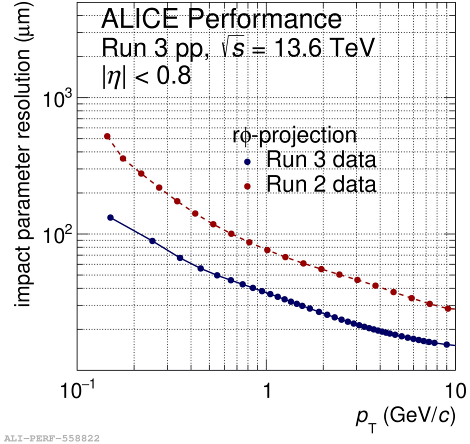
- d_0 = impact parameter ~ distance of a track from collision point
- decay length ~ hundreds micron

vs. most background particles produced at collision point

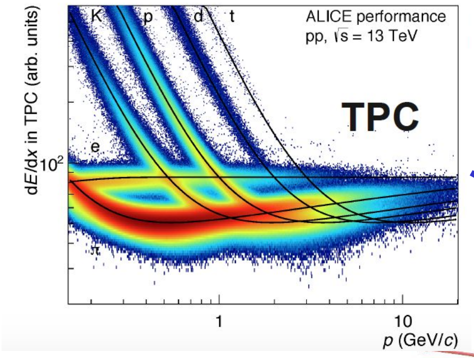


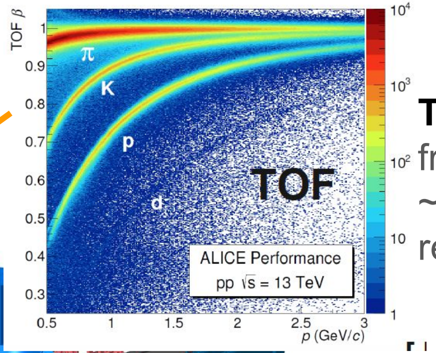
ITS (pixel detector with resolution ~ 5-10 μm



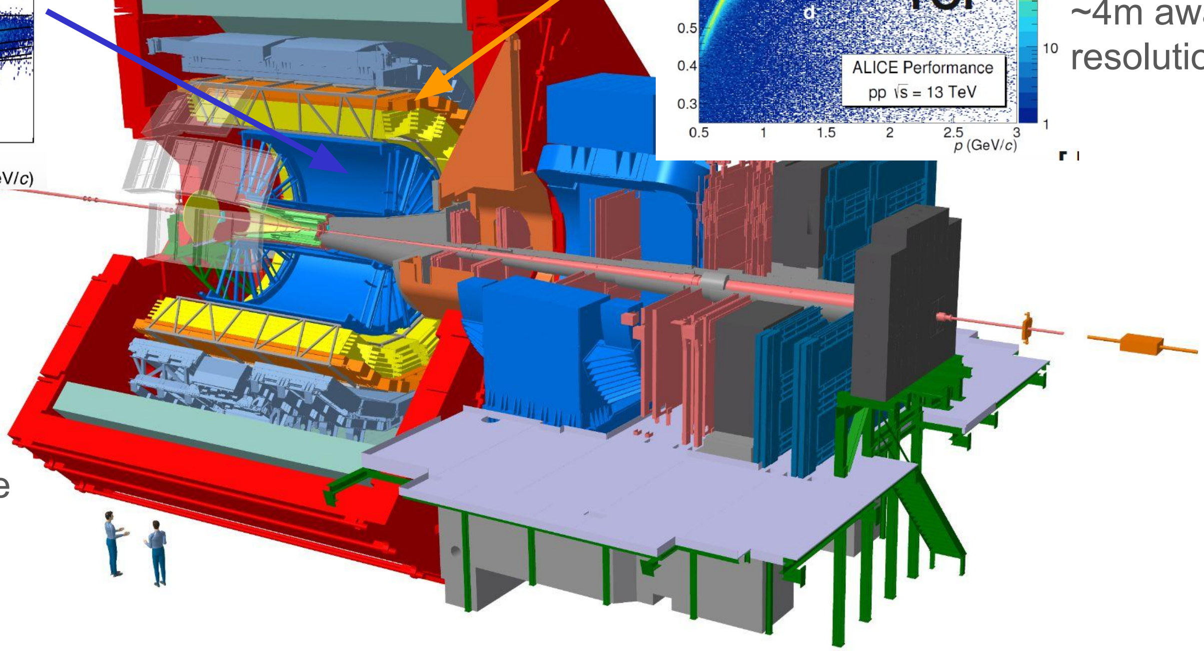


Particle IDentification (PID) in the ALICE experiment





Time Of Flight
from collision point to ~4m away
resolution ~80 ps



Time Projection Chamber
PID signal: specific energy loss in detector gas

Described by Bethe-Block formula (black lines in above figure)

Particle IDentification (PID) in the ALICE experiment

PID with Time Of Flight (TOF)

Measurement of arrival time t_{track} w.r.t. collision “start time” $t_{0\ \text{event}}$

Distance covered (L) is known

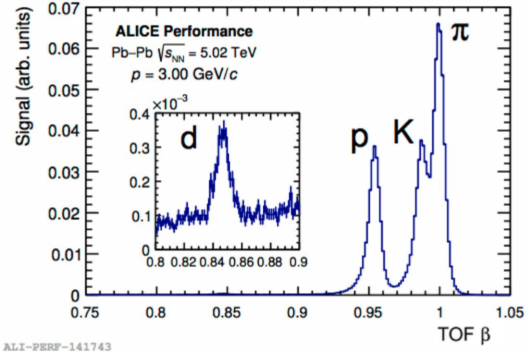
→ measure particle velocity ($\boldsymbol{\beta}$ =v/c)
$\boldsymbol{\beta} = L_{\text{track}} / (t_{\text{track}} - t_{0\ \text{event}})c$

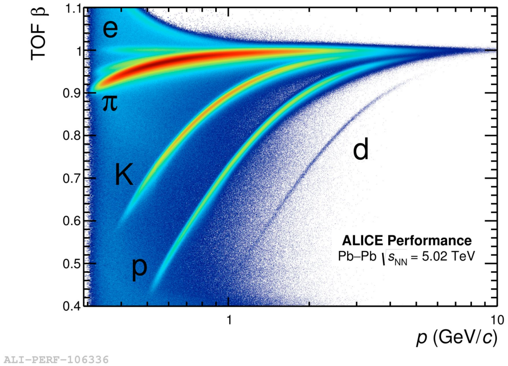
L~4 m ; $\boldsymbol{\Delta} t$ ($\boldsymbol{\beta}$ =1) = c/L = 13.3 ns

Detector + $t_{0\ \text{event}}$ resolution ~ 100 ps

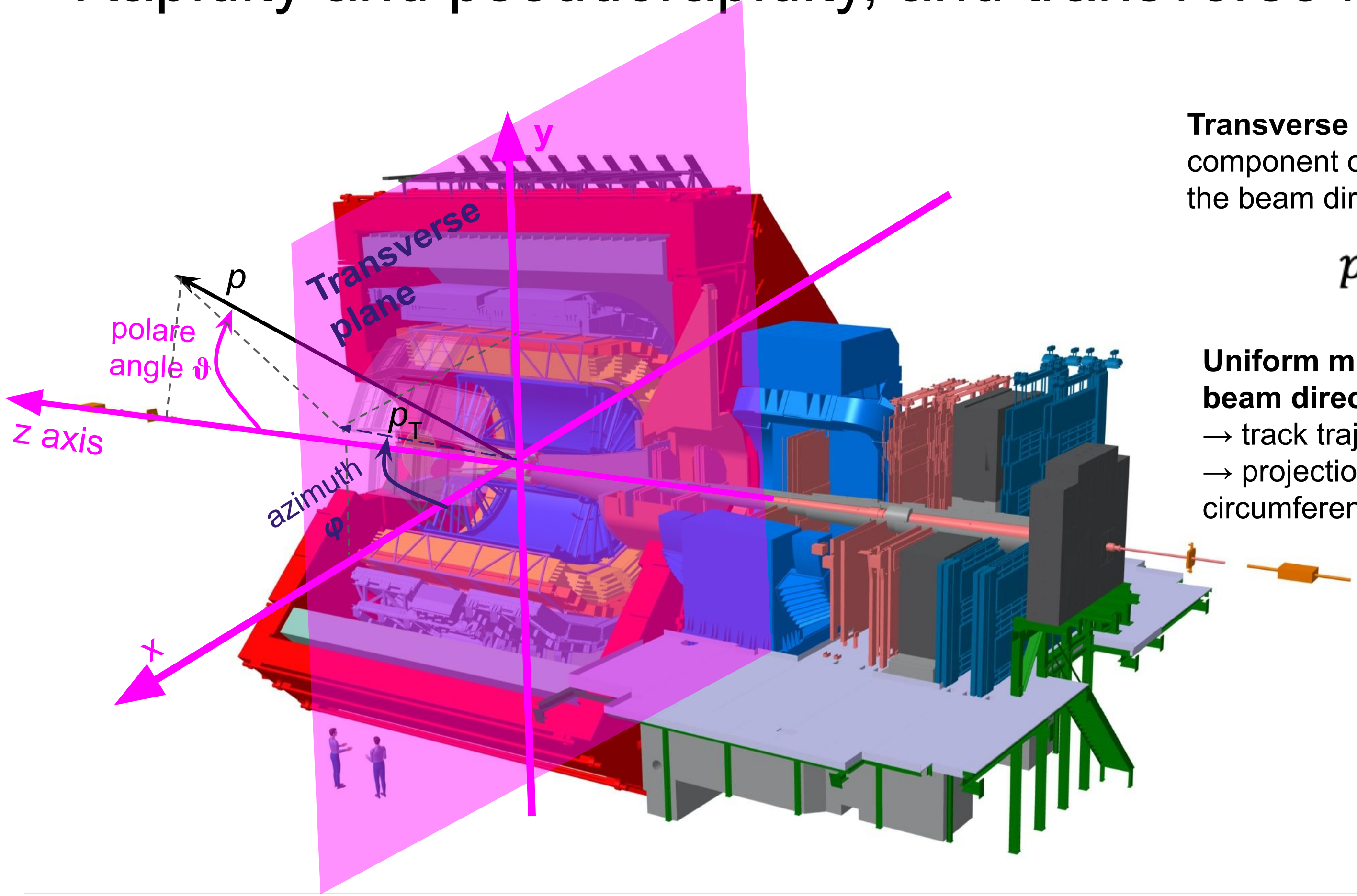
Knowing momentum (TPC) → mass ID

E.g. pion with p= 0.600 [2] GeV/c → $\boldsymbol{\Delta} t$ = *13.691 ns [13.366 ns]*
E.g. kaon with p= 0.600 [2] GeV/c → $\boldsymbol{\Delta} t$ = *17.3 ns [13.734 ns]*





Rapidity and pseudorapidity, and transverse momentum

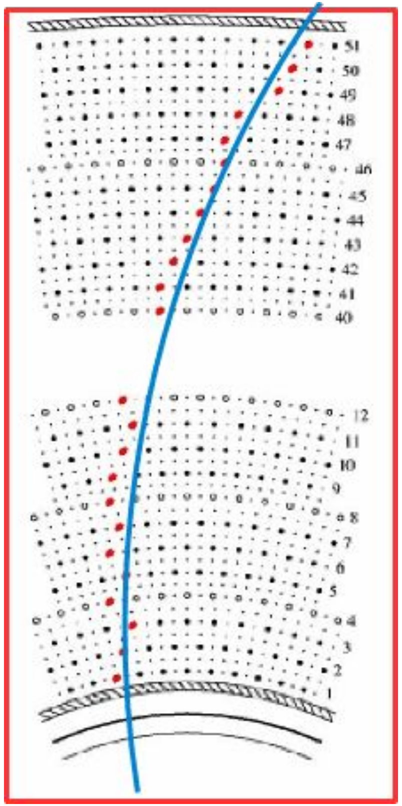


Transverse momentum (p_T): component of momentum transverse to the beam direction

$$p_T = \sqrt{p_x^2 + p_y^2}$$

Uniform magnetic field parallel to beam direction, B=0.5 T)
→ track trajectories are helix
→ projection on transverse plane is a circumference

Measuring particle trajectories and momentum



A series of **experimental "points"** that must be identified as belong to a given particle (→ "**track finding**") and **fitted** to reconstruct the particle trajectory ("**tracking**").

Curvature in magnetic field B and transverse momentum (p_T) related by:

$$p_T \,[\text{GeV}/c] = 0.3\, R\, [\text{m}]\;\; B\, [\text{T}]\; z\, [\text{charge, in proton-charge units}]$$

→ measurement of radius R (actually what is measured is the sagitta) → p_T

Examples

1) what is the radius of the track of a particle with p_T=1 GeV/*c* (assume z=1, B=0.5 T)?

R=1/(0.3*0.5) = 6.67 m

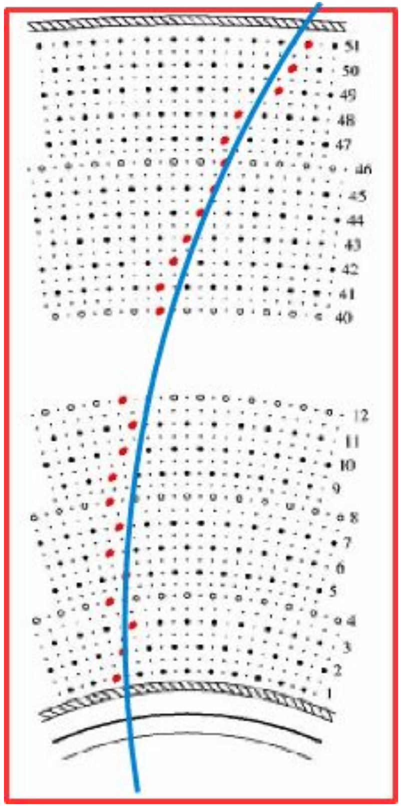
2) what is the minimum p_T a track must have to reach a detector located 4 m away from the collision point, assuming z=1 and B=0.5 T?

diameter =4 m → R=2 m → p_T = 0.3 * 2 *0.5 = 300 MeV/*c*

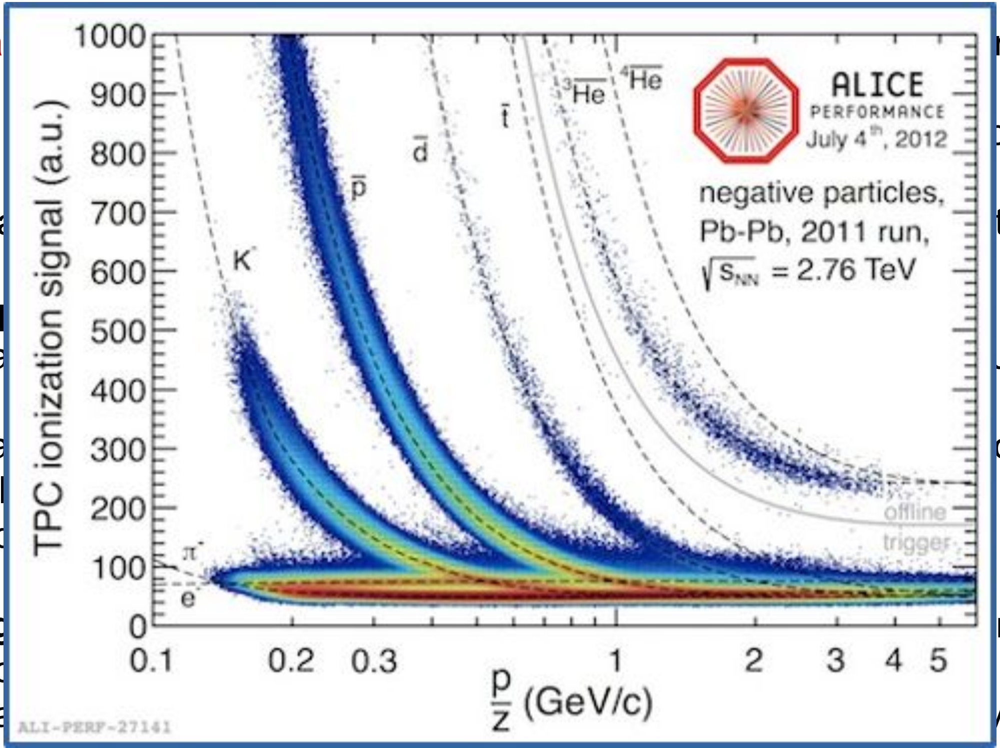
Ambiguity for particles with different charges (what we get from *R* is p_T/z) :

- charge sign from curvature sign
- ambiguity remains but particles with Z>1 (e.g. He nuclei) very rare
  - PID information helps removing ambiguity

Measuring particle trajectories and momentum



A series of **experimental “points”** that must be identified as belong to a given particle (→ “**track finding**”) and **fitted** to reconstruct the particle trajectory (“**tracking**”).



Curva related by:

charge units]

→ mea tta) → p_T

Examp

1) wha ume z=1, B=0.5 T)?

2) wha cated 4 m away from the col

c

Ambig m ***R* is p_T/z**) :

- c
- a rare
- PID information helps removing ambiguity

Introductory concepts: Rapidity and pseudorapidity

Velocities in different reference systems:

non-relativistic case: $v = v_1 + v_2$ relativistic case: $\beta = \dfrac{\beta_1 + \beta_2}{1 + \beta_1 \beta_2}$

Rapidity: $y = \tanh^{-1}\beta = \dfrac{1}{2}\log\left(\dfrac{1+\beta}{1-\beta}\right)$ relativistic and non-relativistic cases: $y = y_1 + y_2$

(in the non-relativistic limit: $y = \beta$)

Just need to remember what rapidity and pseudorapidity refer to

In accelerator physics, one usually defines rapidity along the beam direction (z axis)

$$y = \frac{1}{2}\log\frac{E + p_z}{E - p_z}$$

it depends on particle mass, in the sense that you need to know both momentum and energy or one of the two and the particle species (→ mass) to calculated it
But can be used to define *y* for any 4-vector, even that of a system of particles

And a connected variable, pseudorapidity:

does not depend on particle mass, it has a direct interpretation in terms of "direction" in the apparatus

$$\eta = \frac{1}{2}\log\frac{p + p_z}{p - p_z} = -\log\tan\frac{\vartheta}{2}$$

$\eta \approx y$ when E>>m

Introductory concepts: Rapidity and pseudorapidity

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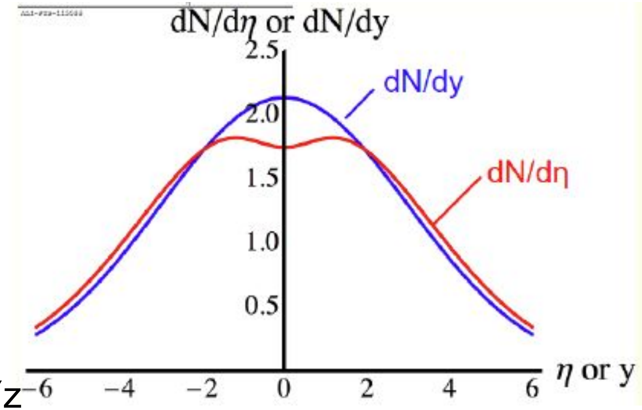

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But can be used to define *y* for any 4-vector, even that of a system of particles

→ Always keep in mind: Rapidity and pseudo-rapidity are not the same, especially at low transverse momenta!

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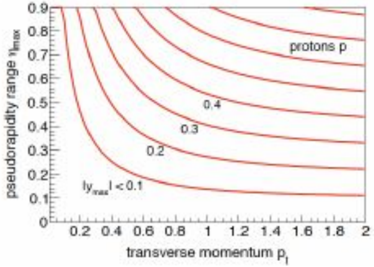
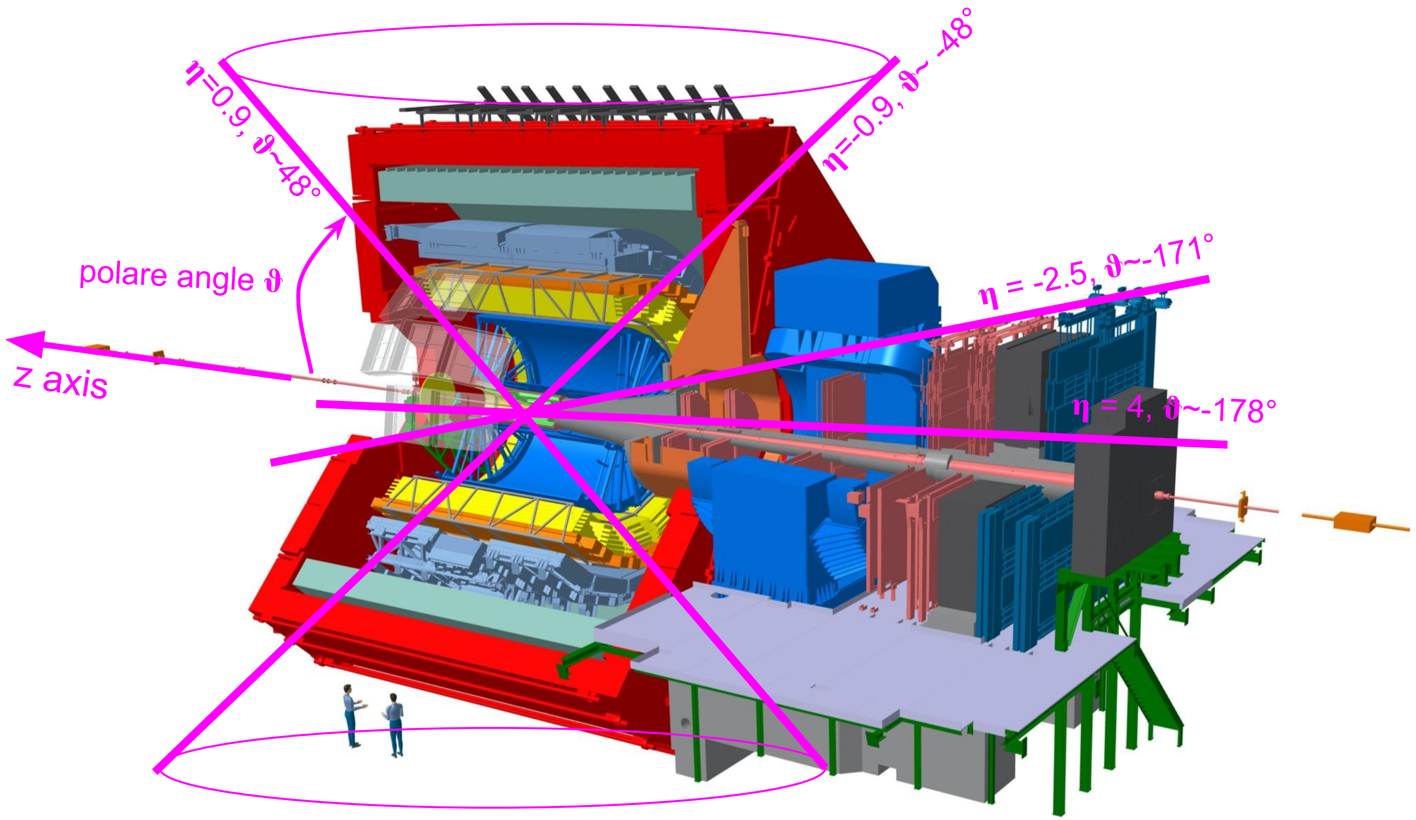


Rapidity and pseudorapidity, and transverse momentum



First part: understand single track variables

Single track, output data format

ALICE has a dedicated software based on C++, ROOT, and other packages, among which Apache Arrow (https://arrow.apache.org/)

Main need: most signal under study are rare but with limited possibility of being selected via “online” triggers
→ large data samples to be analysed

Data output based on flat tables

- fast analysis
- modular handling of information: more info needed → new table added

Typically:

- tables with track infos
- tables with collision infos

collision index

Single track, output data format

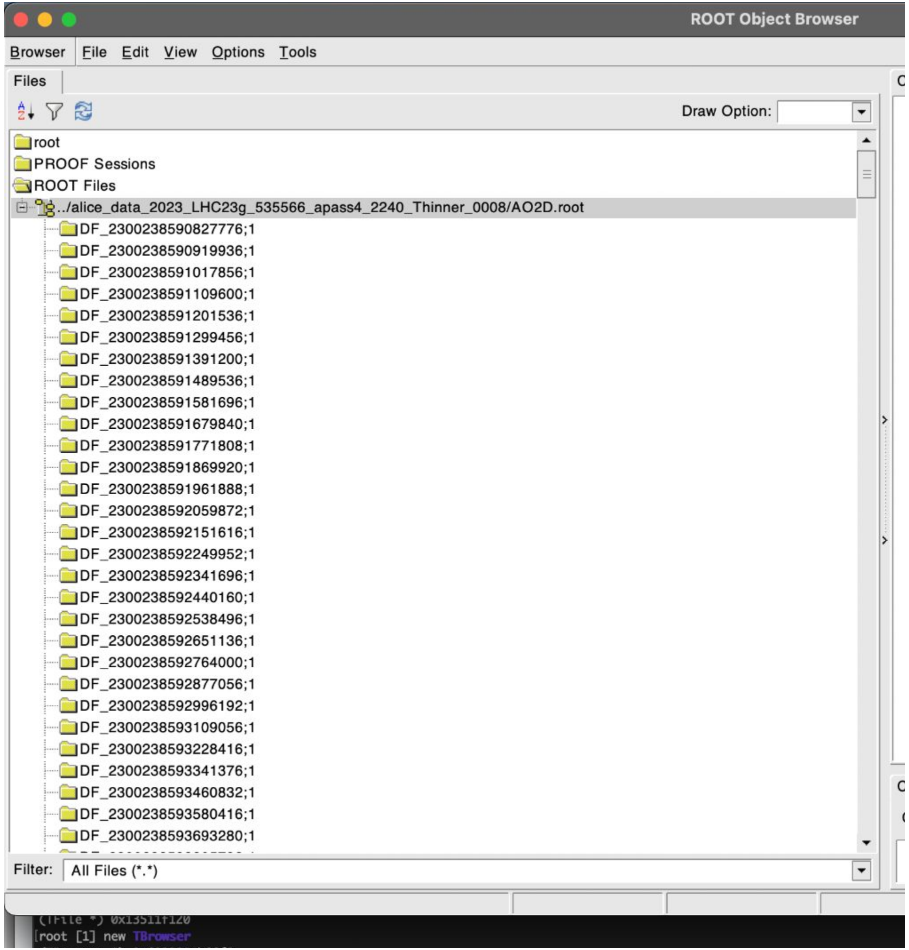
Data taken in “continuous readout” (peculiar of ALICE and few other experiments):

- no central event trigger sent by a dedicated detector to all subdetectors for starting readout.
- data continuously streamed
- events reconstructed in a second step
    - track reconstruction → primary vertices (~collision points) identified (position, time) by grouping of tracks in space and time

Time beat for data reconstruction: dataframe
Dataframe (DF): bunch of data readout contiguously in time that get reconstructed together (ALICE specific concept, you need to know it only for practical purposes!)

Subsequent procedures of “thinning” for data reduction (including track selections).
Final structures: files (called AO2D.root) with flat trees (tables) organised in DF.

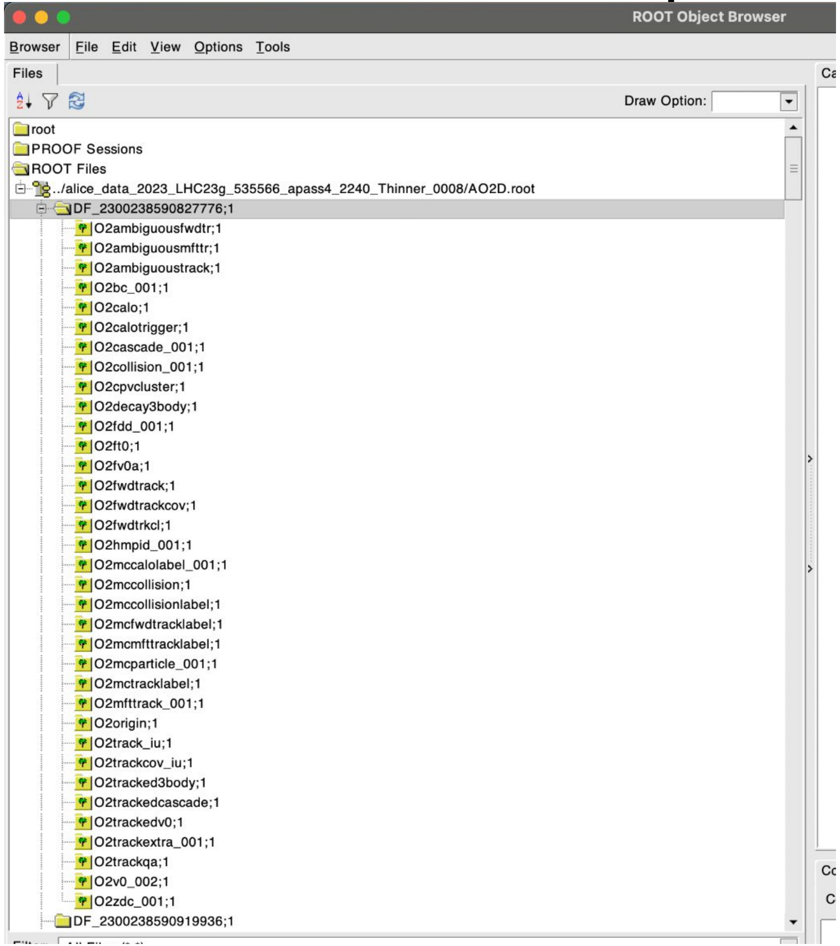
ALICE data format in practice



Let’s open a AO2D.root file with ROOT and look at it with a TBrowser

We see several directories, each corresponding to a different Data Frame

ALICE data format in practice



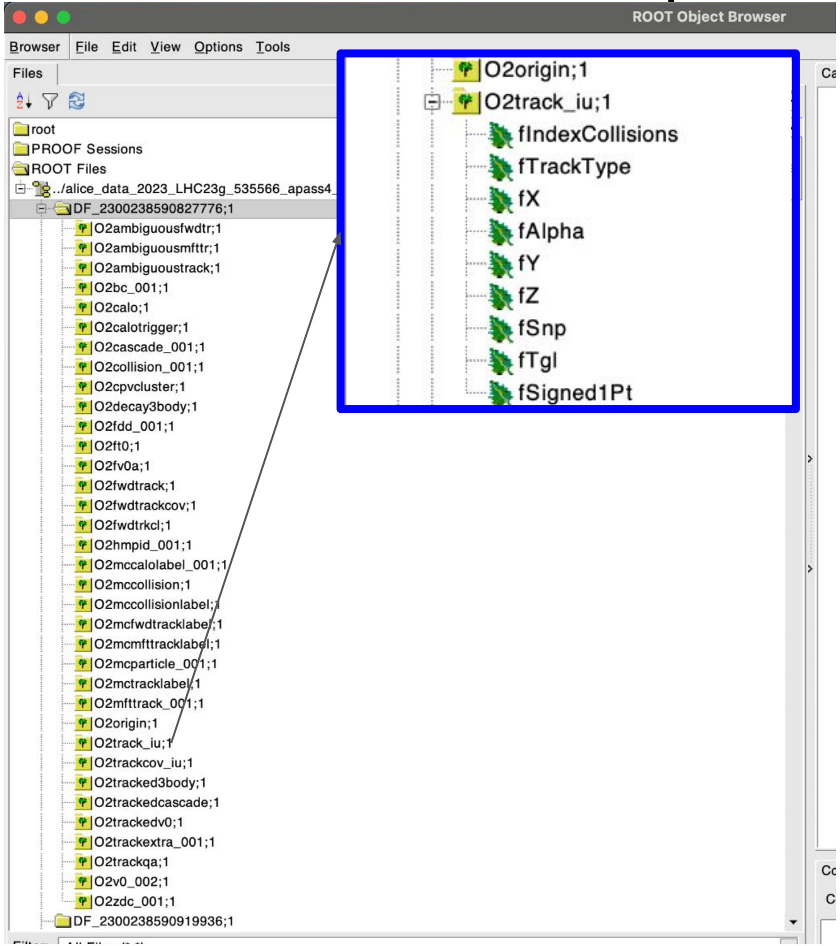
Inside a AO2D.root file (I open one with ROOT and look at it with a TBrowser)

We see several directories, each corresponding to a different Data Frame

If we open one, we see the list of tables

Their names start with O2: name of ALICE software, irrelevant for you…

ALICE data format in practice



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Main tables:

- table with track parameters

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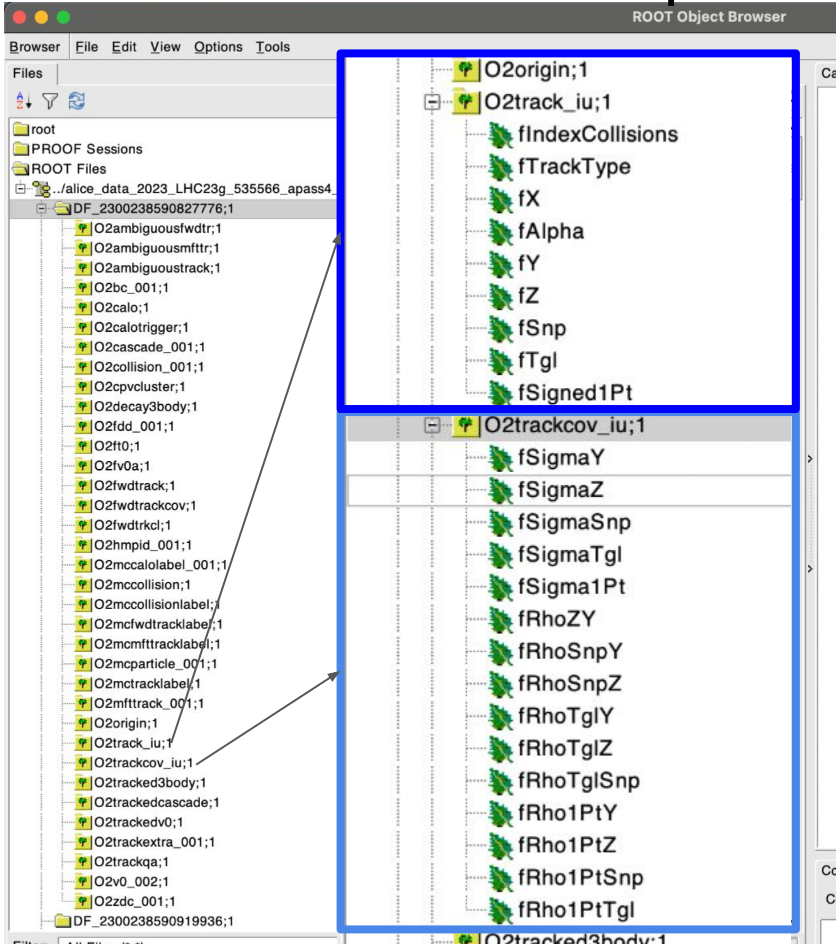

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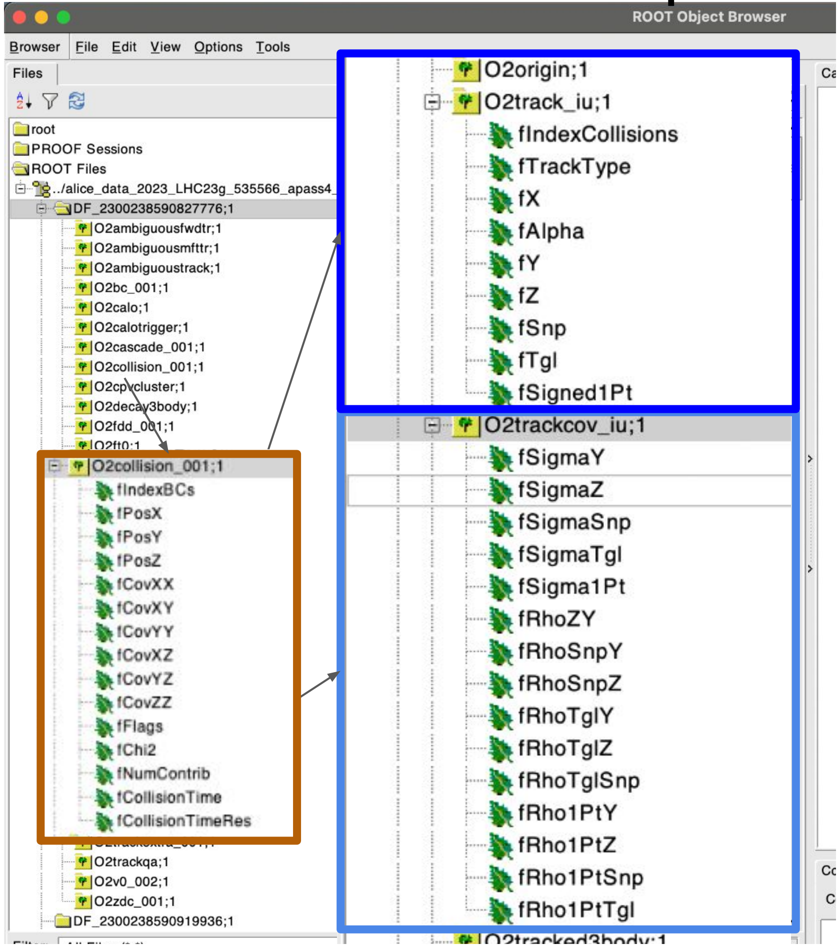
- table with track parameters
- related table with covariance matrix of track parameters

ALICE data format in practice



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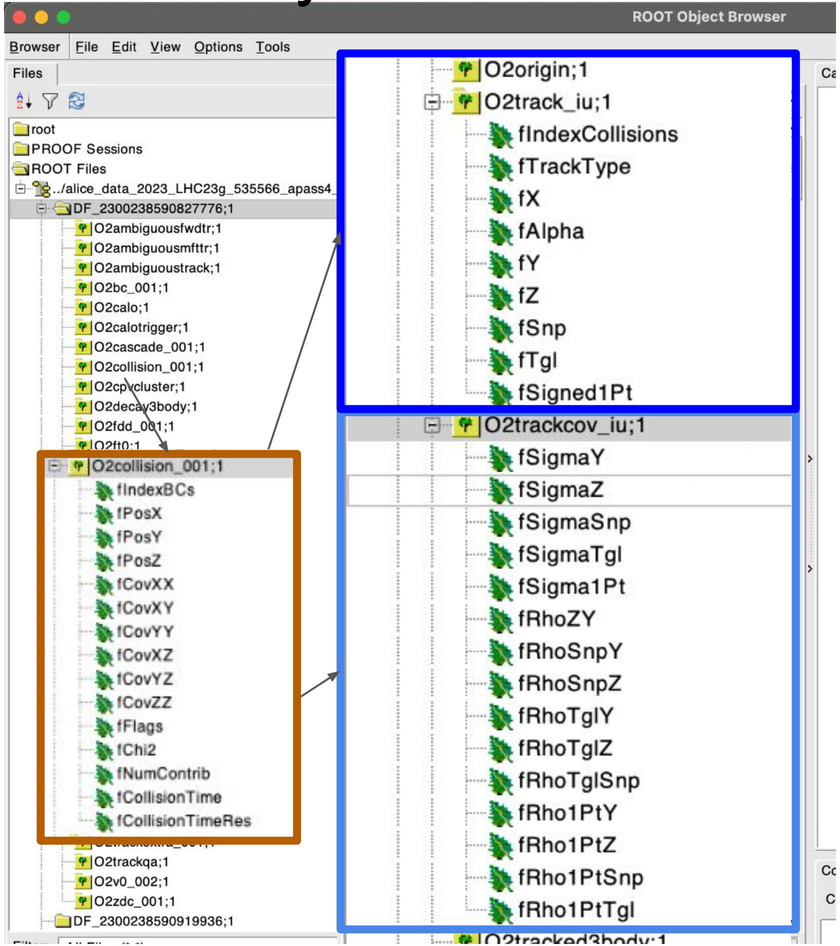
Main tables for us:

- table with track parameters
- related table with covariance matrix of track parameters
- table with collision and primary vertex information

Practically…



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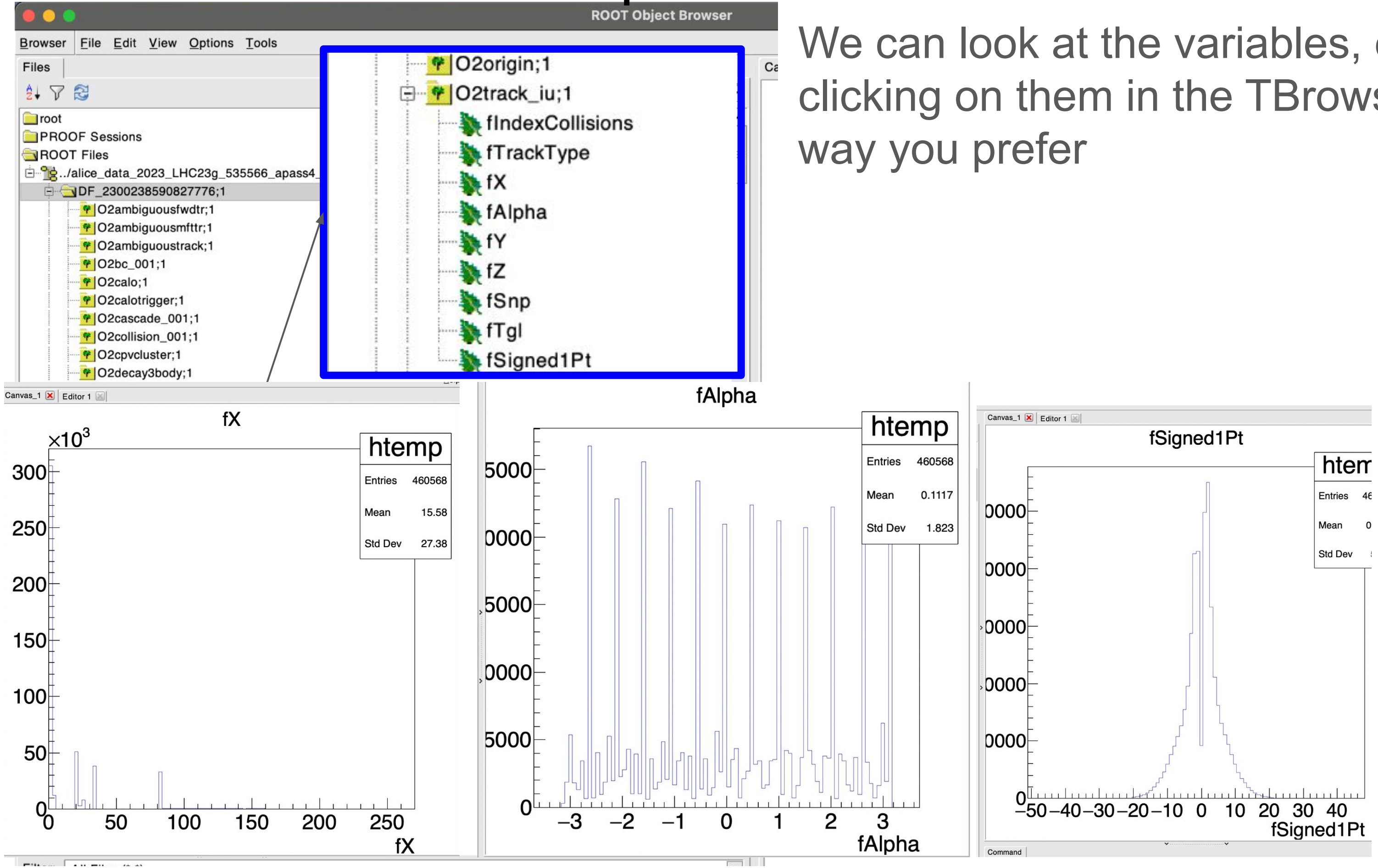
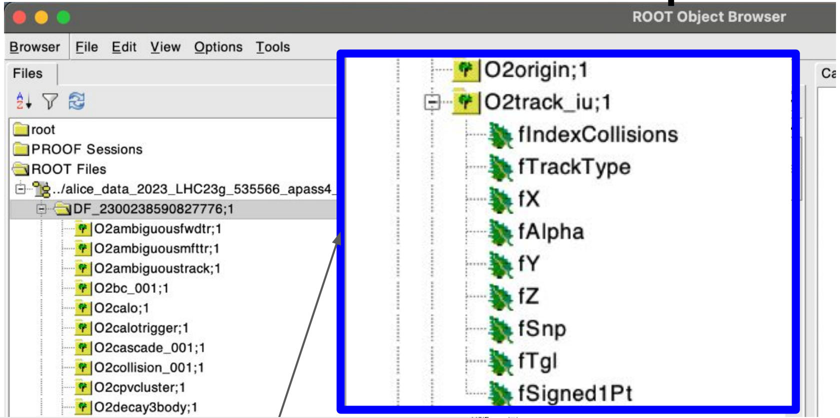
- table with collision and primary vertex information
- ... tables with PID information (later)

ALICE data format in practice



We can look at the variables, even by just clicking on them in the TBrowser or in whatever way you prefer

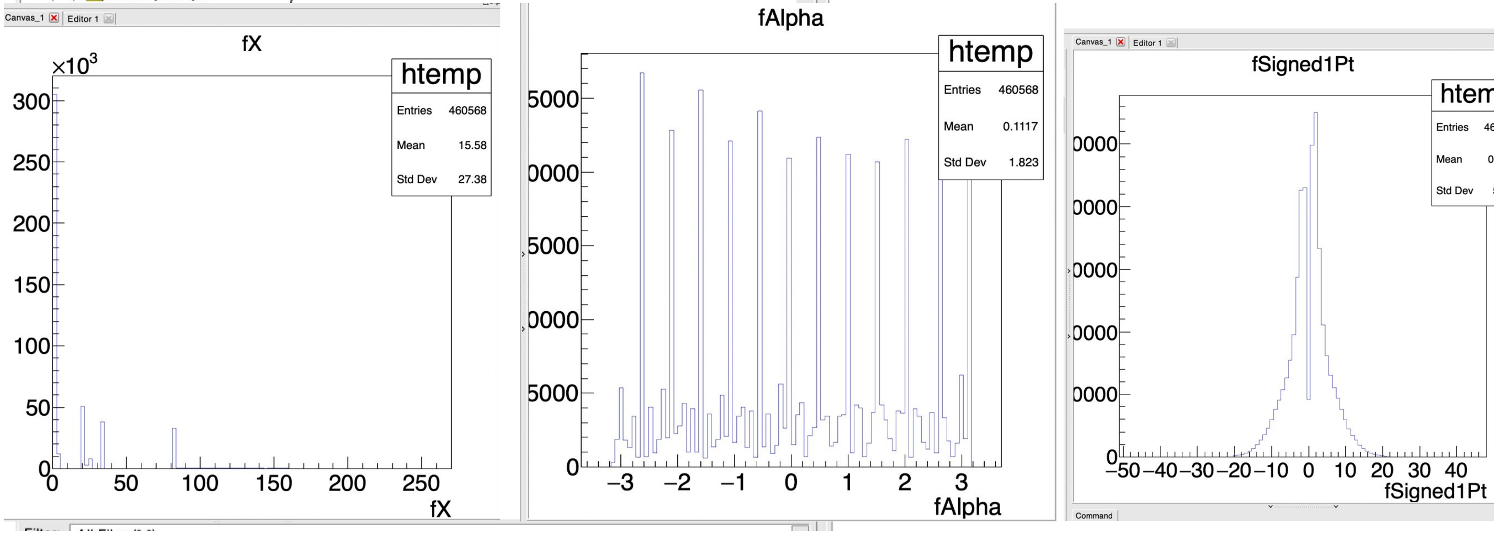
ALICE data format in practice



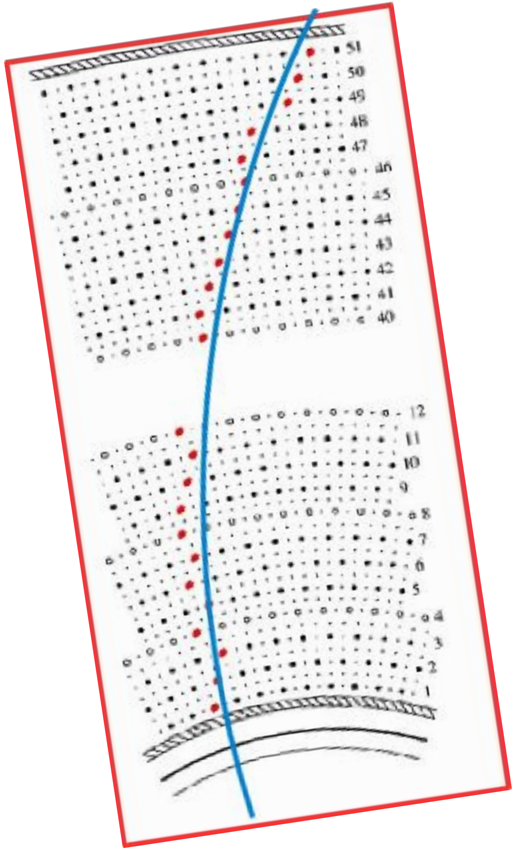
Note the name of the tree: O2track_iu

"iu" stands for "innermost update" point →

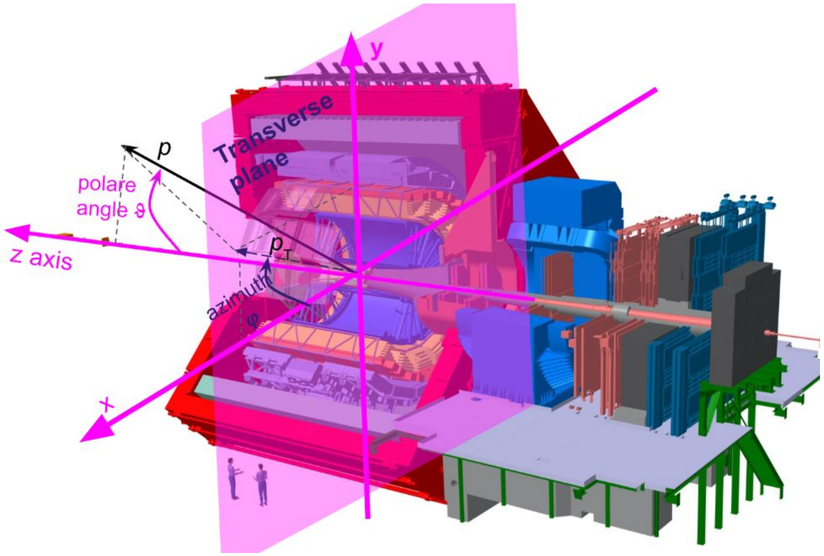
- these are the track parameters at the latest experimental point: this is not what we need (discussed later)
- in the **tracking reference system**

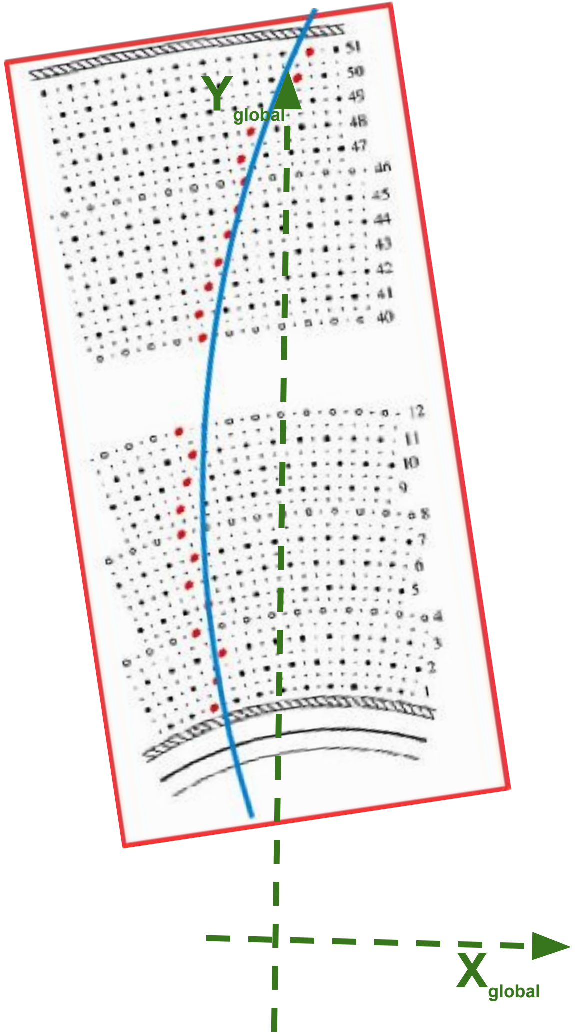


Tracking and global reference systems



Tracking and global reference systems





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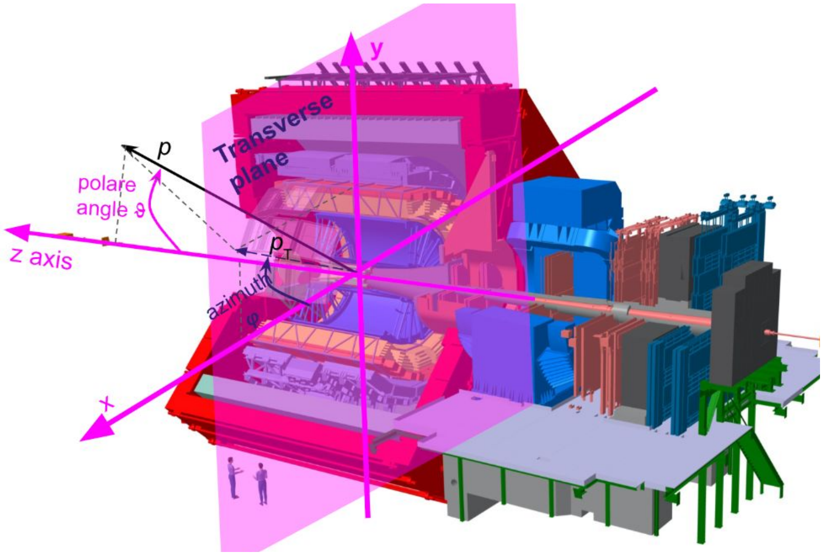
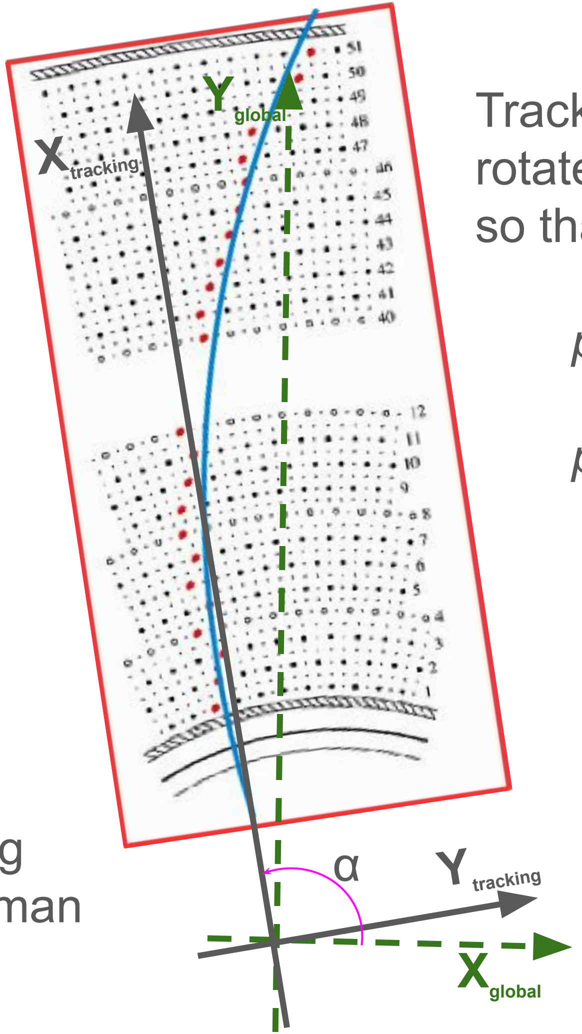


Why is it useful to use a track-dependent reference system?
Just because calculations related to tracking are easier (allows for approximation in Kalman filter used)

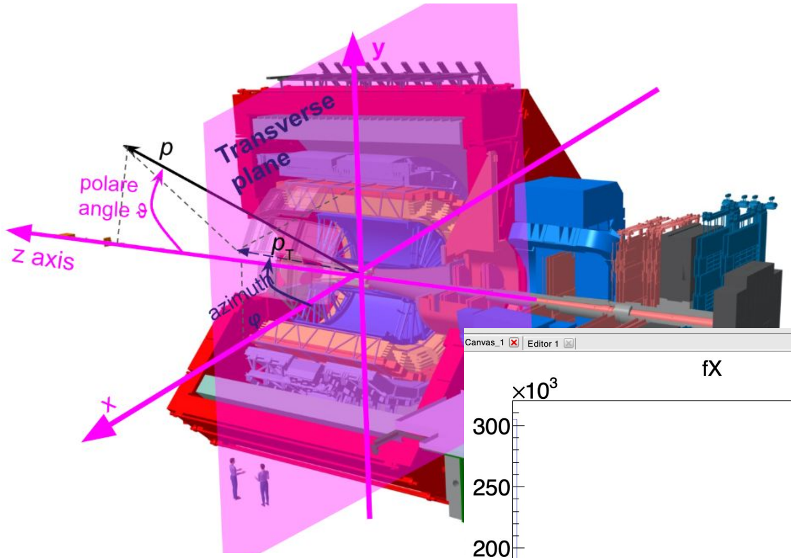


Tracking ref. system: rotated by an angle α so that

$$p_{x\ \mathrm{global}} = p_T \cos\alpha$$

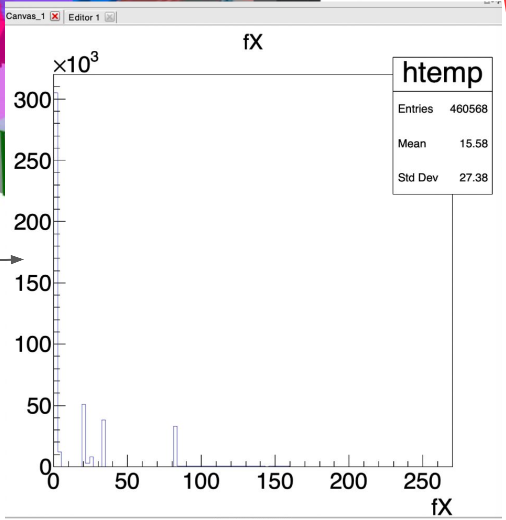
$$p_{y\ \mathrm{global}} = p_T \sin\alpha$$

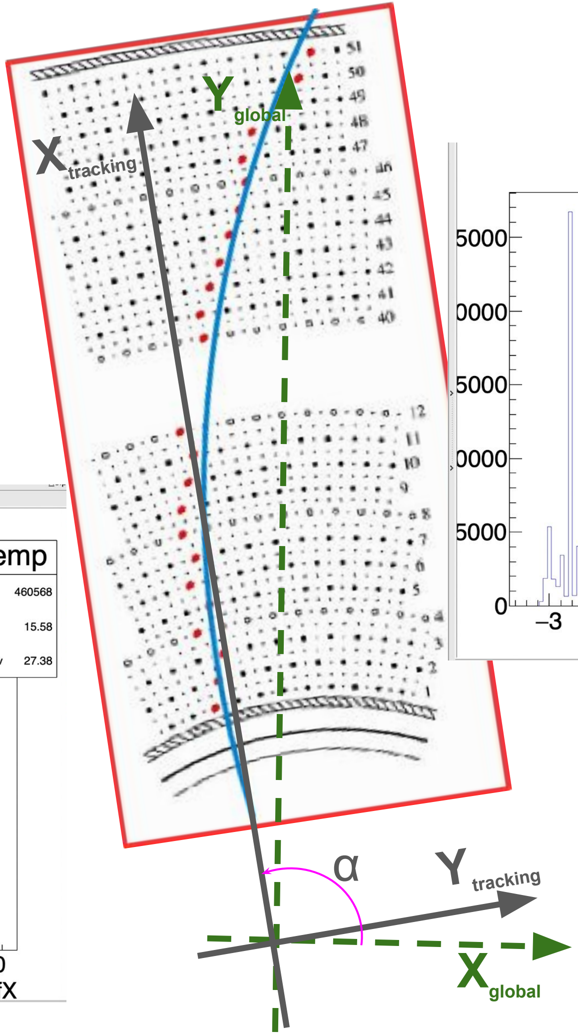
Tracking and global reference systems

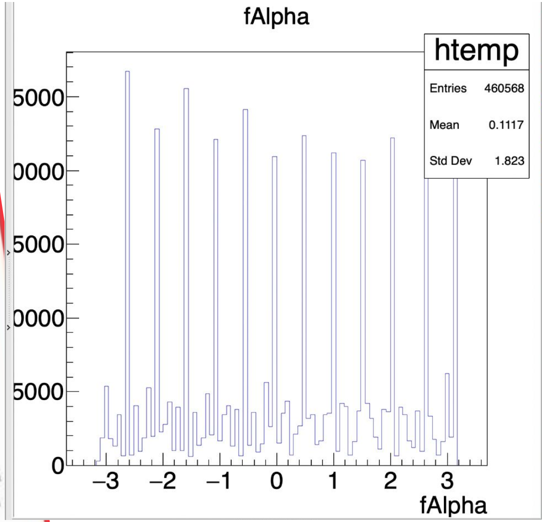


fX = $X_{tracking}$

not really a track parameter, is the “free” reference coordinate at which the track parameters are reported

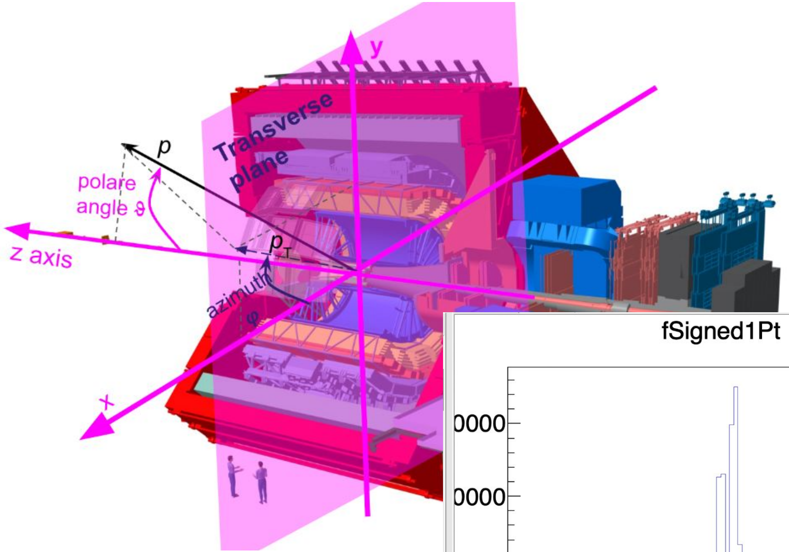


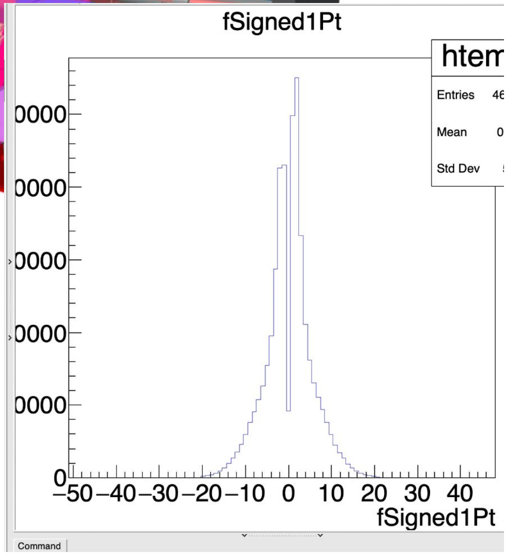


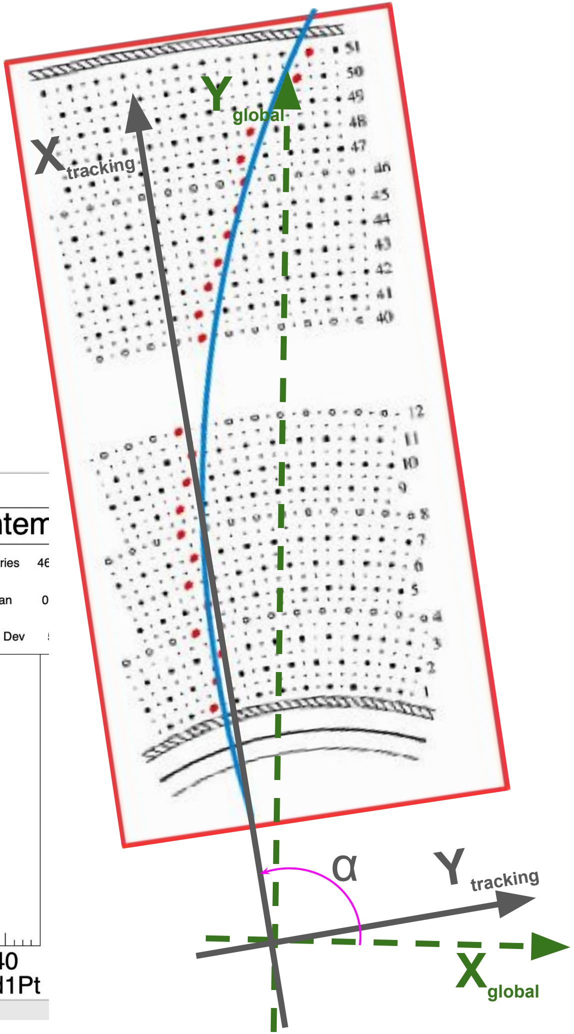


Angle between global and tracking system

Tracking and global reference systems







charge sign/p_T

N.B. 1/p_T

$\propto$ curvature

same in global and tracking system

Tracks at primary vertex

In a AO2D.root file there is too much information for our needs.
Moreover, having the tracks at the "innermost update" (IU) point is not that useful for us.

Usually, for most analyses and physics observables, **the parameters (e.g. the momentum components)** of a given track **must be evaluated where the original particle is produced**:

- **collision point** (→ "**primary vertex**"): vast majority of produced particles
- **decay point of parent particle**, for particles from weak decays, like daughters of
    - strange hadrons: K^0_s ($c\tau$ ~ 2.68 cm), Λ ($c\tau$ ~ 7.8 cm)
    - charm hadrons: D^+ ($c\tau$ ~ 310 μm), Λ_c^+ ($c\tau$ ~ 60 μm)
    - beauty hadrons: B^+ ($c\tau$ ~ 491 μm), Λ_b^+ ($c\tau$ ~ 441 μm)

N.B. timescale of strong and electromagnetic decay of elementary particles: 10^{-24} - 10^{-20} s
(τ~8×10^{-17} s for π^0, $c\tau$ ~ 25 nm) → decay point basically coincides with primary vertex

We save (in ALICE) tracks at the IU point because of possible ambiguities in the association of tracks to events (primary vertices).

Tracks at primary vertex

What we primarily need are the track parameters at the primary vertex (PV).

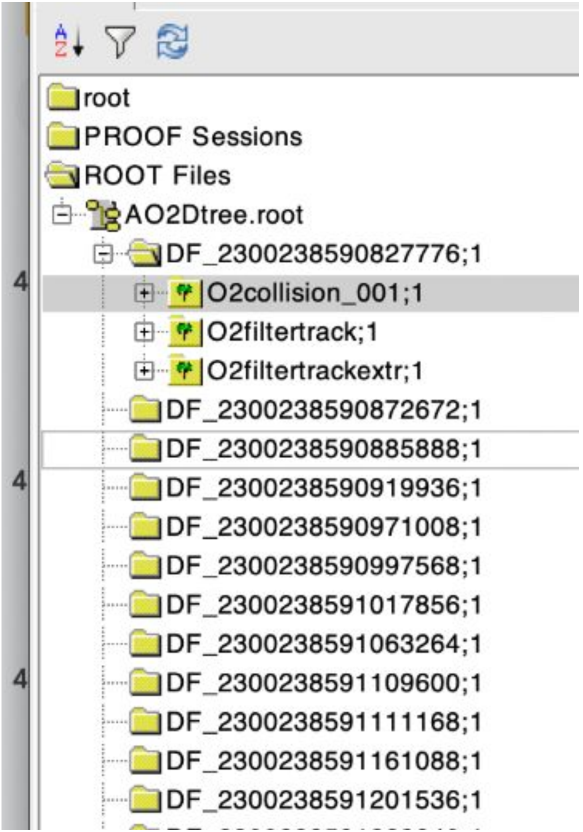
Propagation from IU to PV is not as trivial as it may seem: for best description of trajectories the material crossed must be taken into account: average energy loss (deterministic correction), multiple coulomb scattering (accounted for in track covariance matrix)
→ requires detailed knowledge of detector geometry + accurate modeling of interaction with material.
→ we can't do this without ALICE specific software

Data reduction/filtering operation

I prepared you files with

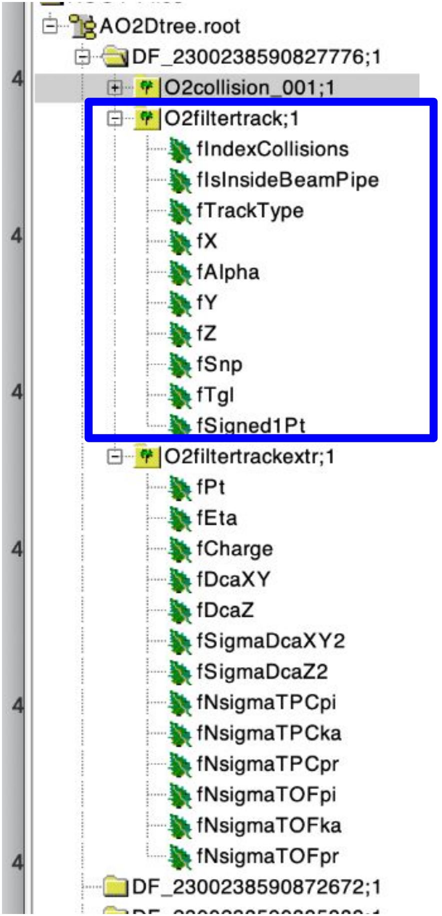
- tracks already propagated at the PV, i.e. at the point of closest approach (PCA) to the PV
    - tracking reference system, with X axis parallel to track direction (momentum vector) at PV
- selection of tracks (e.g. discaring tracks without points in the ITS, p_T>0.3 GeV/c)
- reduced info stored

The data files you will use



Same data-frame based structure than original files but only three tables inside:

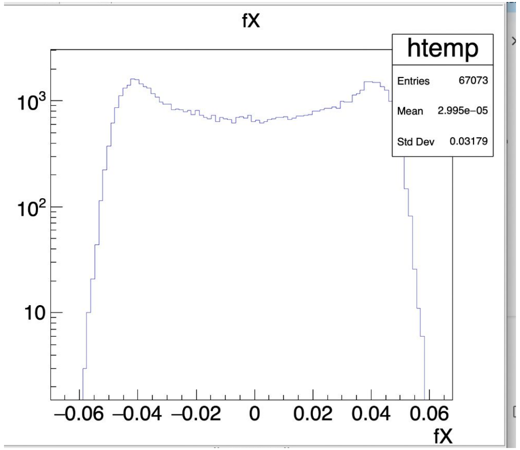
The data files you will use

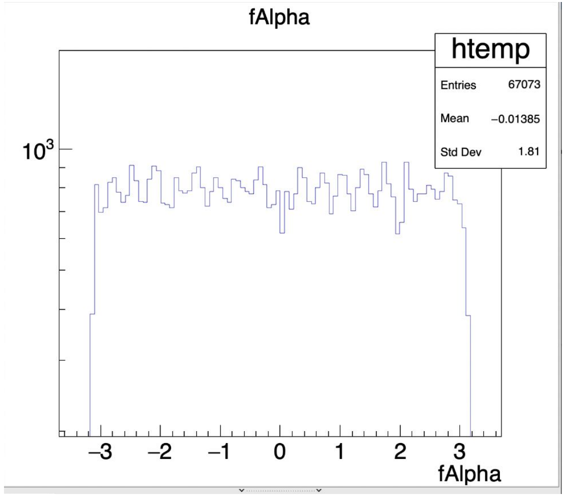


Same data-frame based structure than original files but only three tables inside:

- **O2filtertrack**: same track table presented before but now track parameters are at the PCA to the PV

  Still in tracking reference system!





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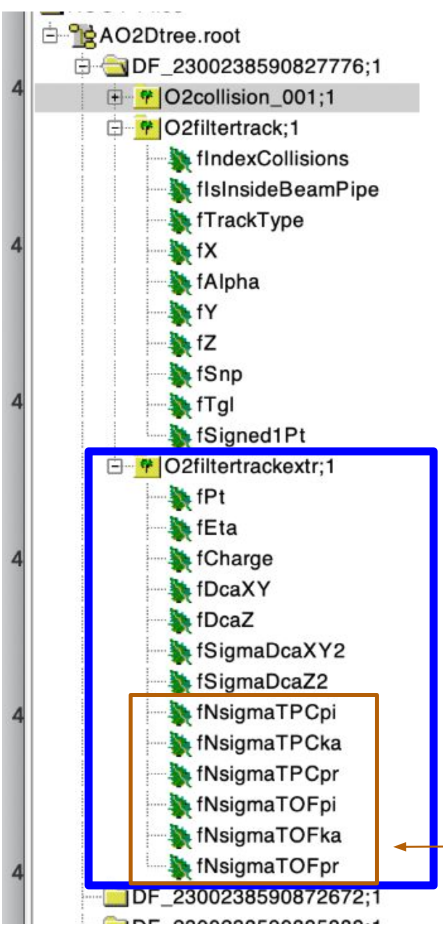
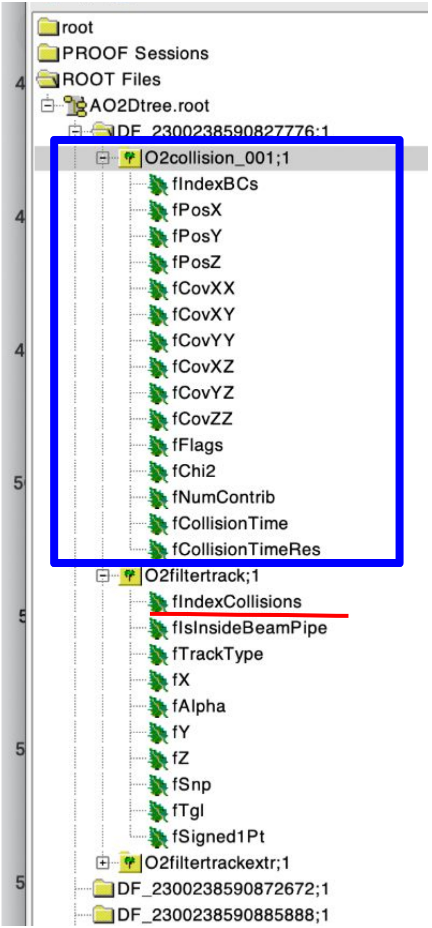


Same data-frame based structure than original files but only three tables inside:

- O2filtertrack: same track table presented before but now track parameters are at the PCA to the PV
- **O2filtertrackextr**: table with further track parameters you need
  - fEta = η (pseudorapidity)
  - fDcaXY = track impact parameter (w.r.t. the primary vertex) in the XY plane
  - fDcaZ = track distance to the the PV at the XY DCA pont (~ impact parameter along z)
  - fSigmaDcaXY2 = variance of fDCAxy
  - TPC and TOF PID variables

The <u>data</u> files you will use



Same data-frame based structure than original files but only three tables inside:

- O2filtertrack: same track table presented before but now track parameters are at the PCA to the PV
- O2filtertrackextr: table with further track parameters you need
- **O2collision_001**: table with PV information
  - coordinates (in global ref. system)
  - covariance matrix, chi2 of PV fit, ….
    (no selection/data reduction of this table since number of collisions << number of tracks)

Most important: **fIndexCollisions** in track table is the index of the collision to which the track is associated
→ **variable which allows to link the two tables**

let’s start playing with the data….

Let’s get familiar with the data

Take 1 file, access the trees and obtain what follows:

Goal 1:

- produce histogram of track pt distribution, first from a single DF, than using all DF in the file. Check that p_T and abs(fSigned1Pt) give the same.

Goal 2:

- produce plots with TPC and TOF PID information

Goal 3:

- calculate dcaXY variable from “local coordinates” (aka those of tracking reference system) and check your calculation comparing what you get with the available dcaXY
    - need to handle primary vertex coordinates (in global reference system) stored in collision table

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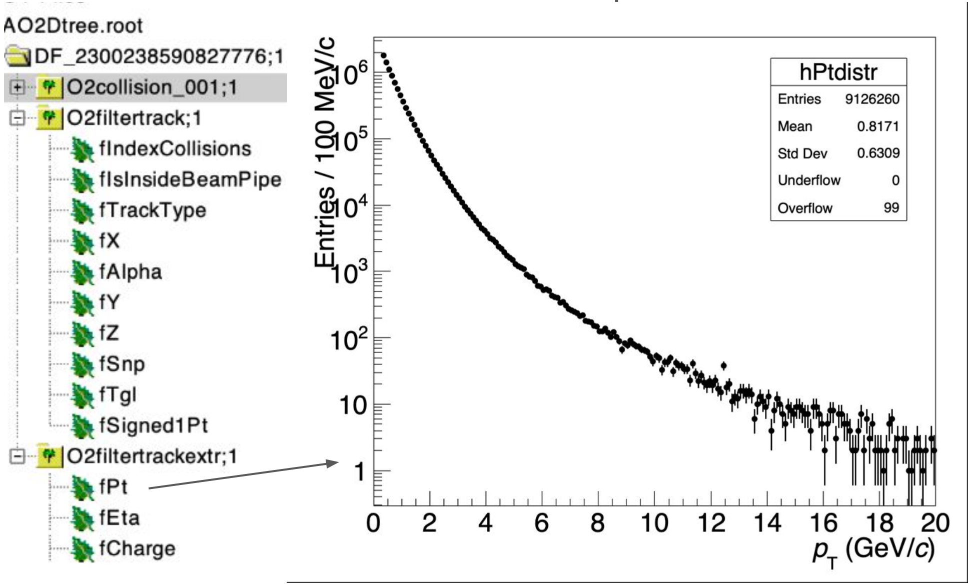

I used Root but you can use what you prefer!

Jupyter notebook is more than welcome!

Check that you get the same counts!

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Goal 1:

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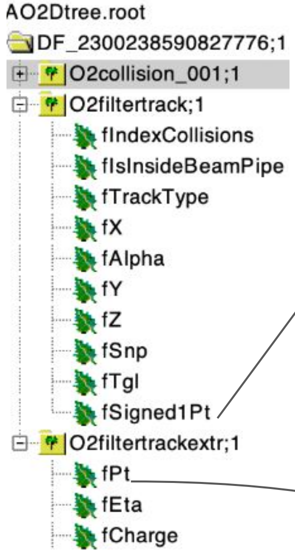
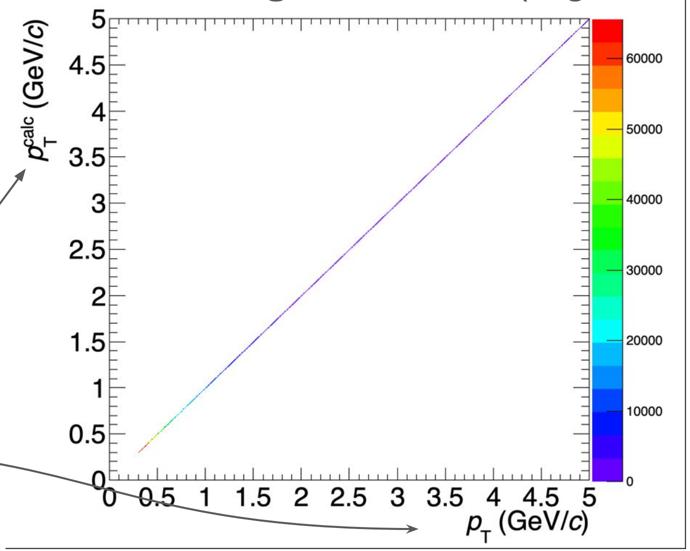
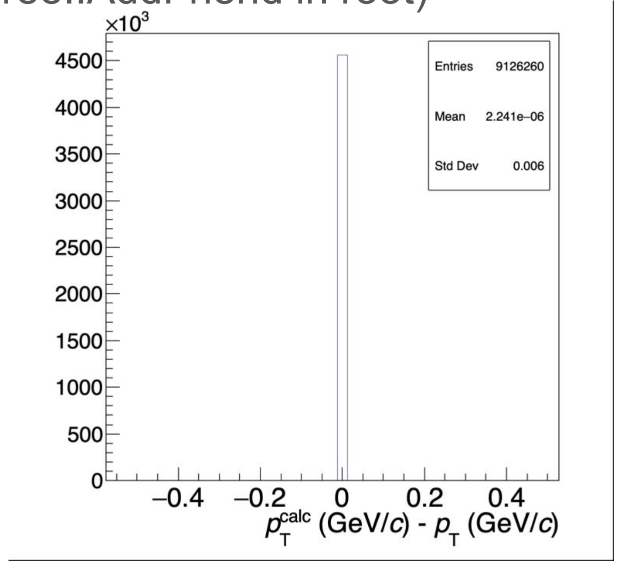
You need to **merge the trees** (e.g. using TTree::AddFriend in root)





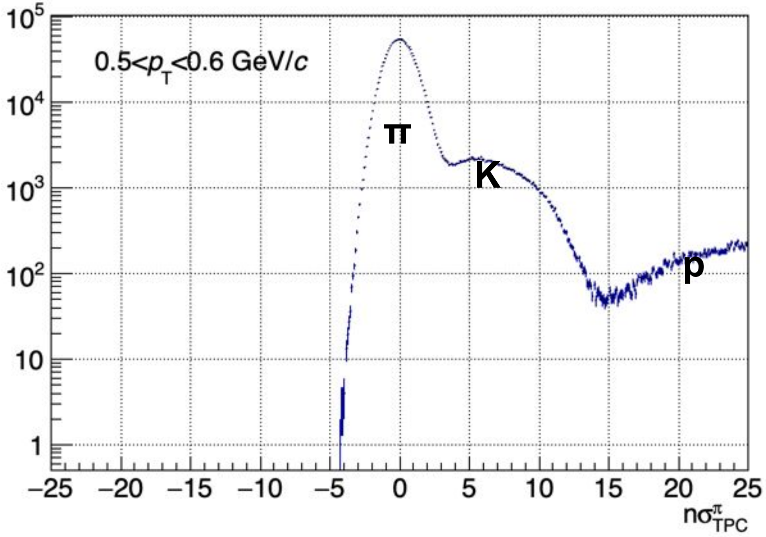


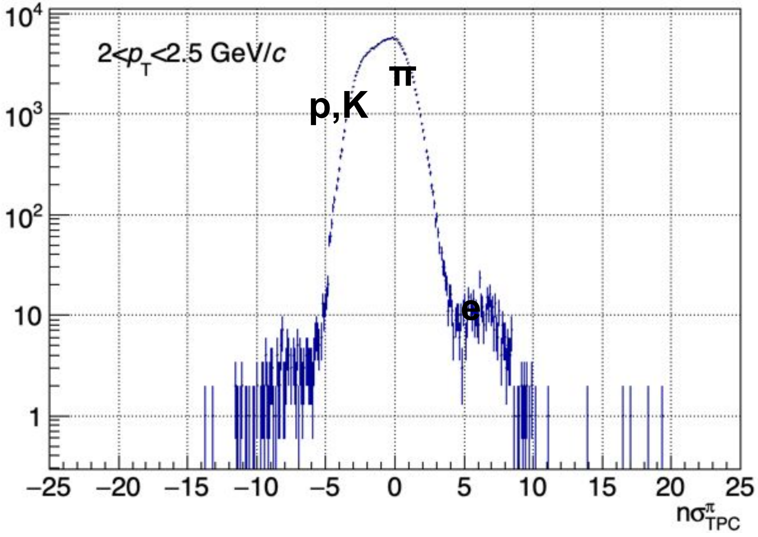
Let's get familiar with the data

Take 1 file, access the trees and obtain what follows:

Goal 2:

- produce plots with TPC and TOF PID information

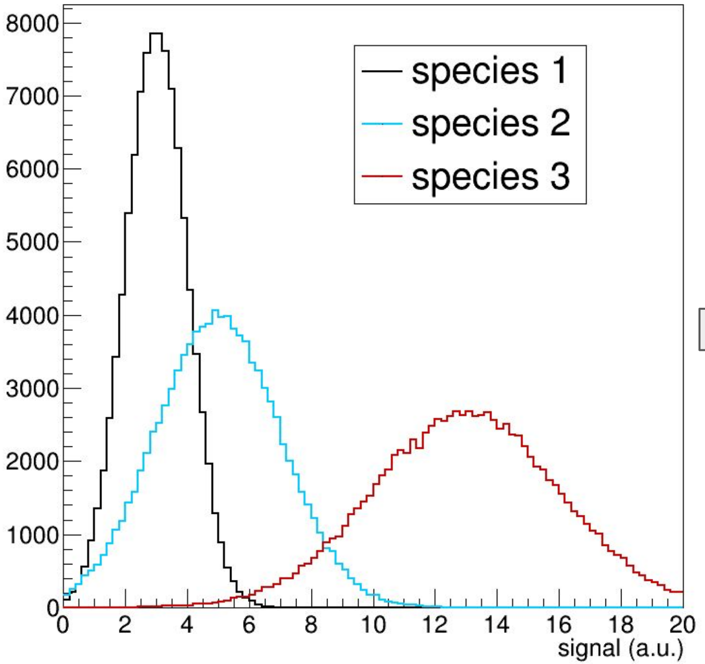




nσ = (measured signal - expected signal)/σ

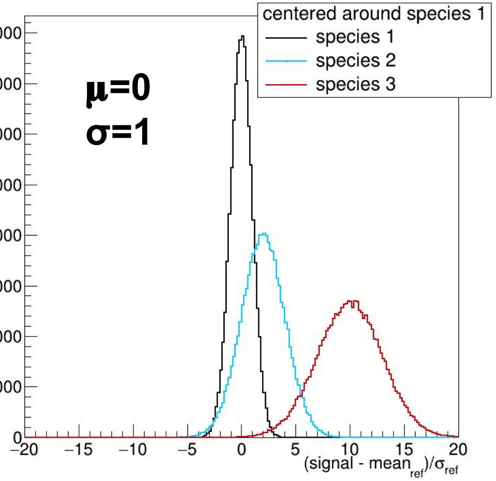
$n\sigma^{\pi}$ (p_T) → expected signal = expected signal for a pion with given p_T

Parenthesis: from signals to nσ

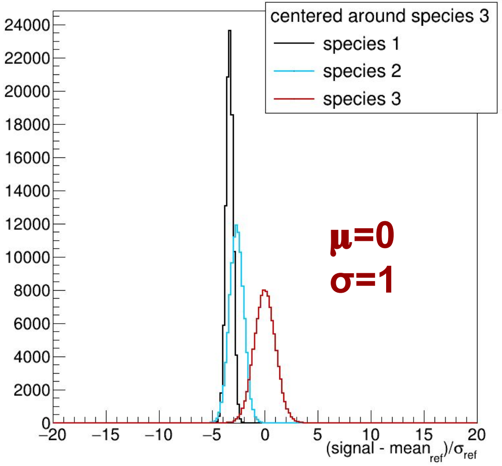


(signal - expected)/sigma

mean = mean1
sigma = sigma1



mean = mean3
sigma = sigma3

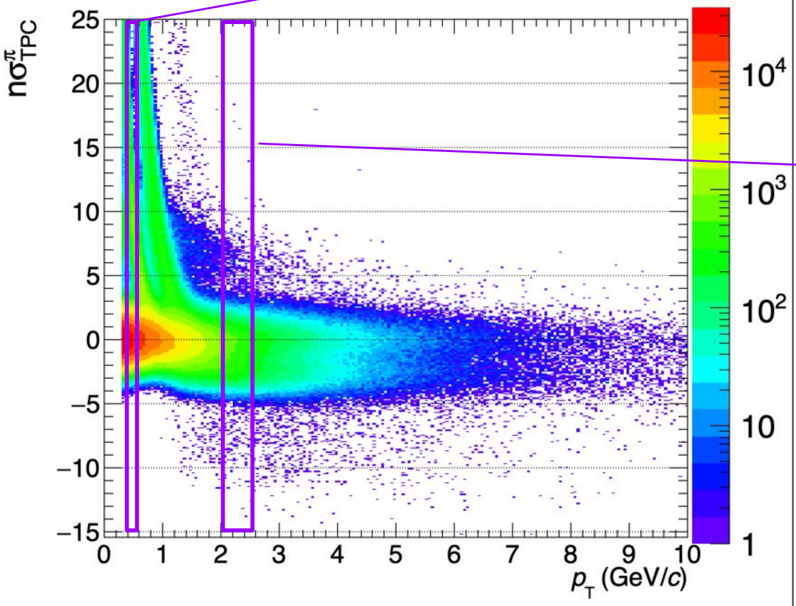


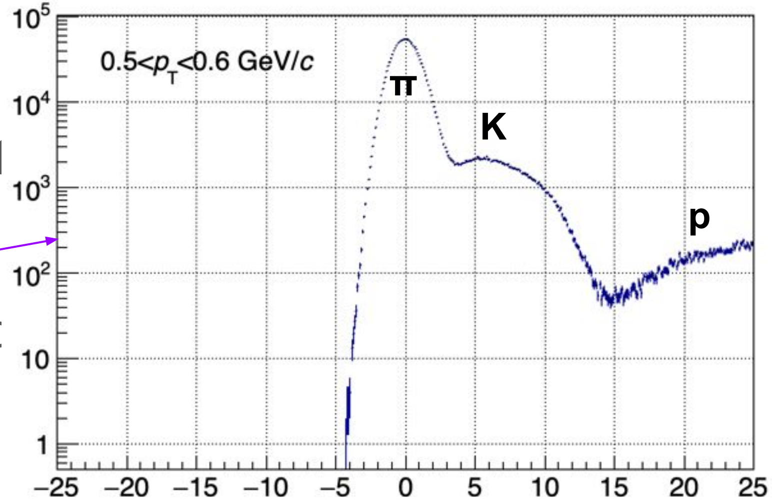
Let’s get familiar with the data

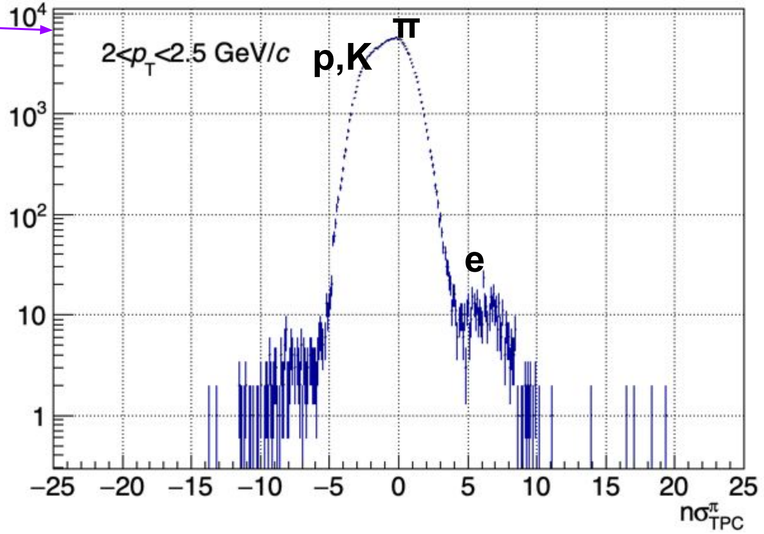
Take 1 file, access the trees and obtain what t

Goal 2:

- produce plots with TPC and TOF PID infc







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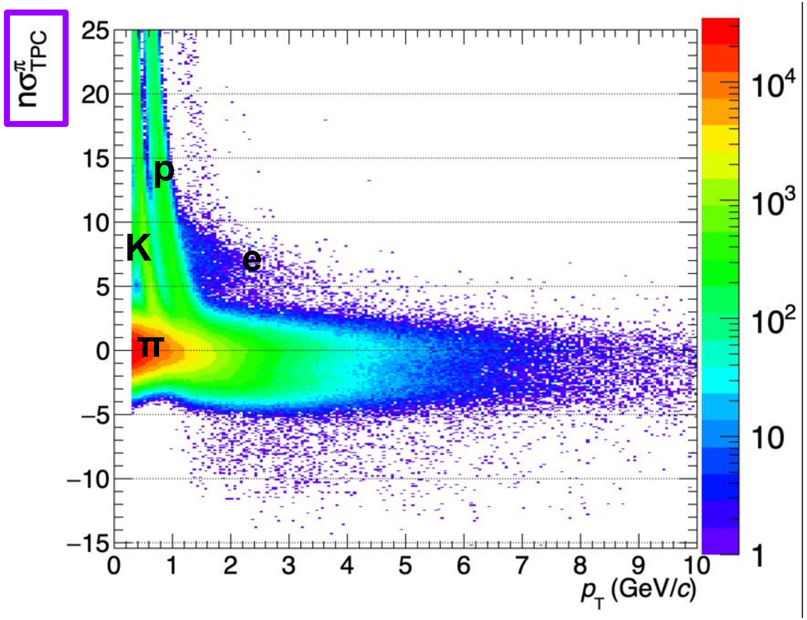
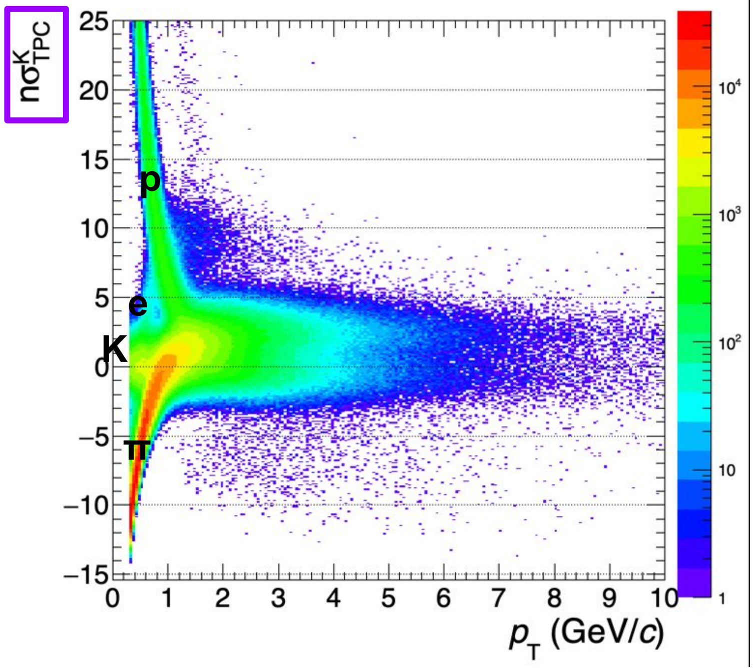
Take 1 file, access the trees and obtain what follows:

Goal 2:

- produce plots with TPC and TOF PID information



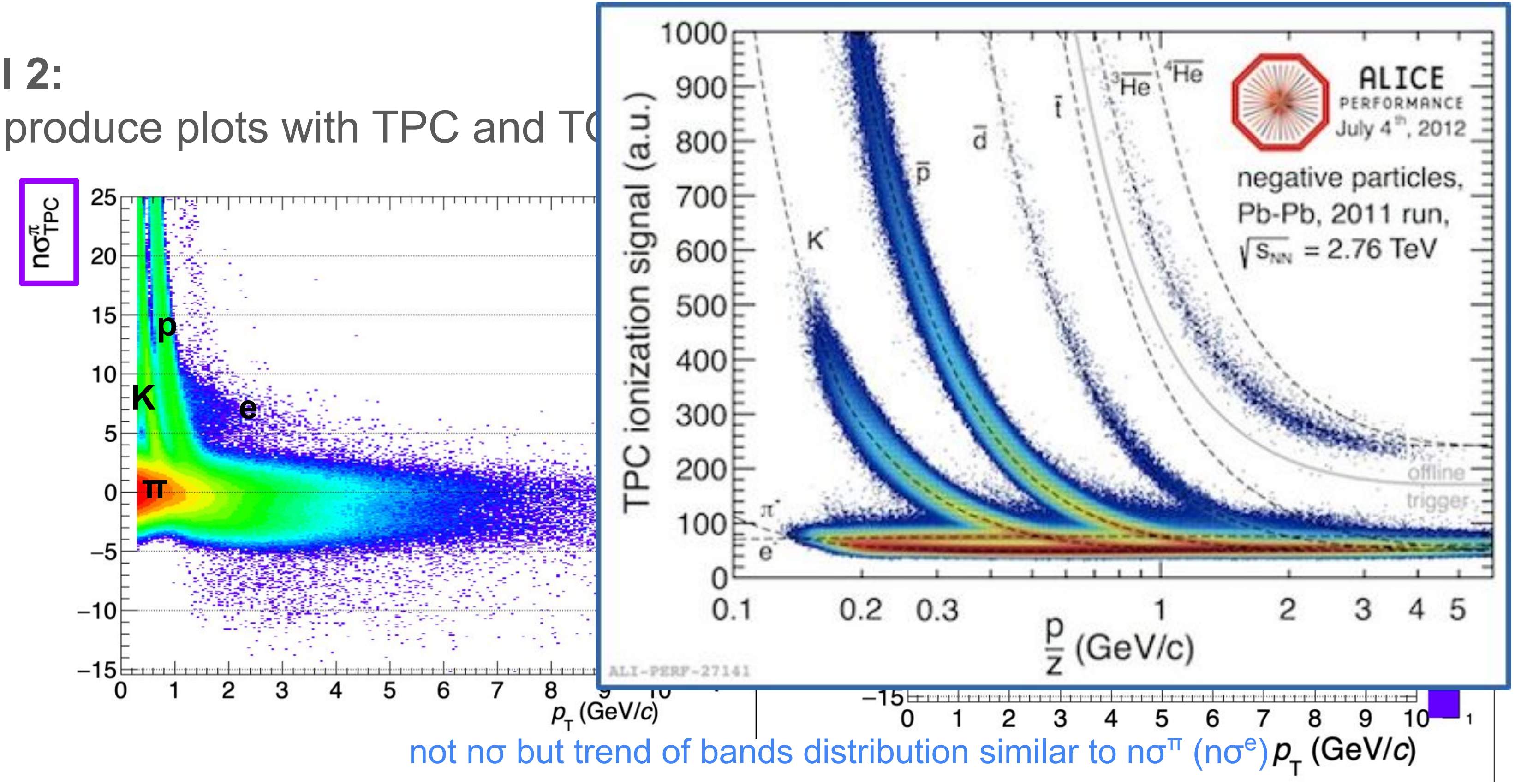


Let’s get familiar with the data

Take 1 file, access the trees and obtain what follows:

Goal 2:

- produce plots with TPC and TO



not nσ but trend of bands distribution similar to $n\sigma^{\pi}$ ($n\sigma^{e}$)

Let's get familiar with the data

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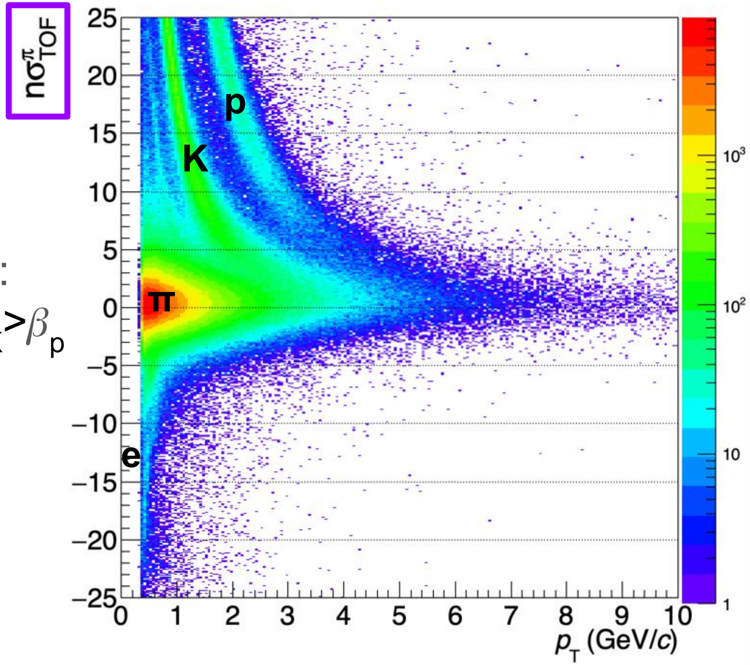
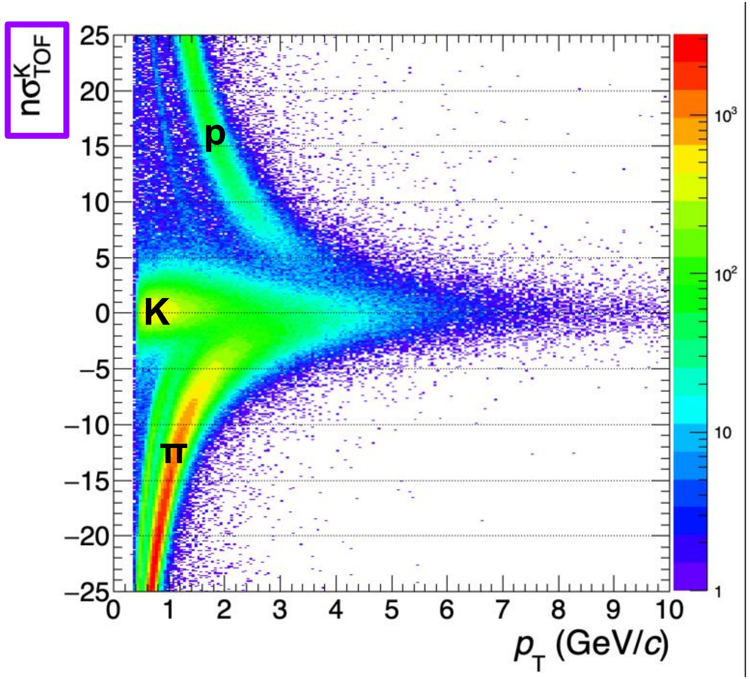
For a given momentum:
$1 \sim \beta_e > \beta_\pi > \beta_K > \beta_p$





Let's get familiar with the data

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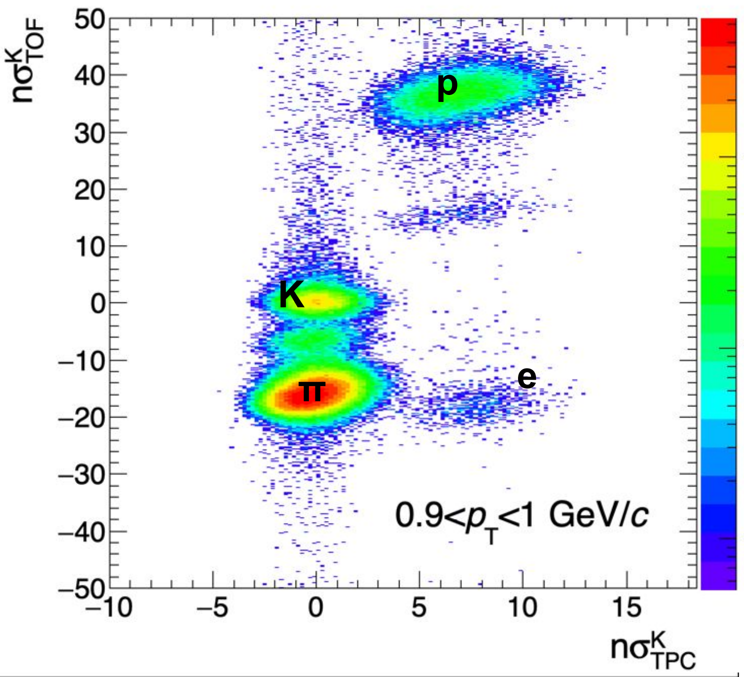
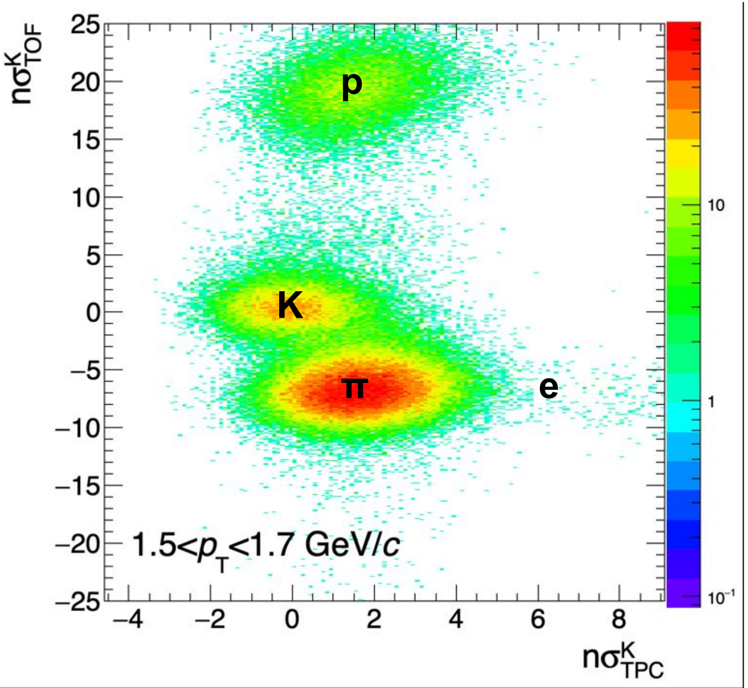


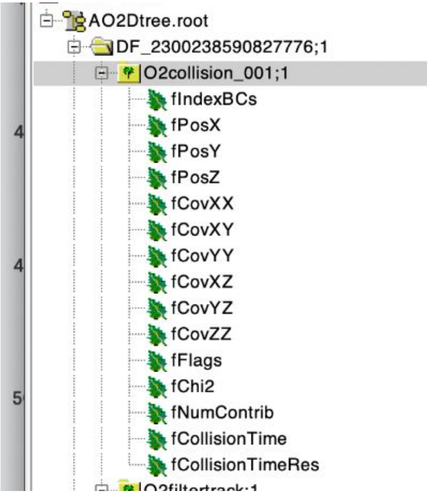


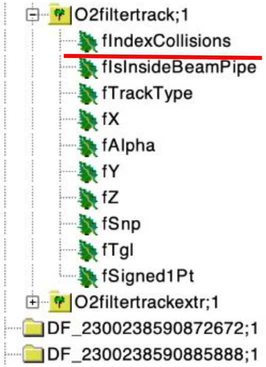
Let's get familiar with the data

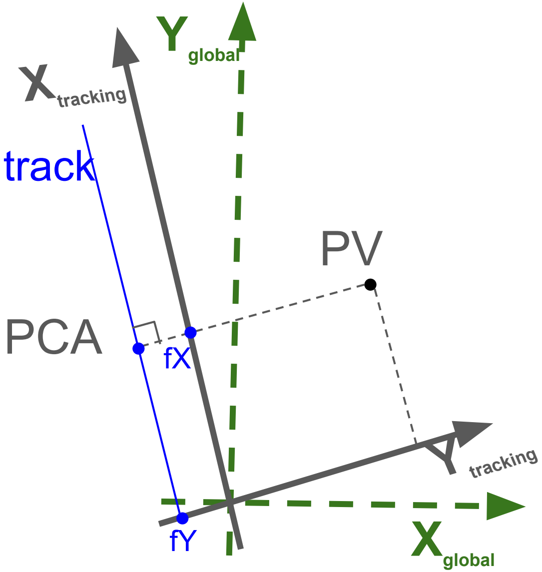
Take 1 file, access the trees and obtain what follows:

Goal 3:

- calculate dcaXY variable from "local coordinates" (those of tracking reference system) and check your calculation comparing what you get with the available dcaXY variable
    - in tracking system: dcaXY ~ Y_{track} - $Y_{PV\ (in\ tracking\ system)}$
    - need to handle primary vertex coordinates stored (in global reference system) in collision table:







dcaXY= (signed) distance of closest approach in XY plane
= track impact parameter
(d_0, see before)
= distance between PCA and PV points in XY plane
Relation dcaXY = Y_{track} - Y_{PV} with Y_{PV} in tracking system gives proper sign convention

Let’s get familiar with the data

Take 1 file, access the trees and obtain what follows:

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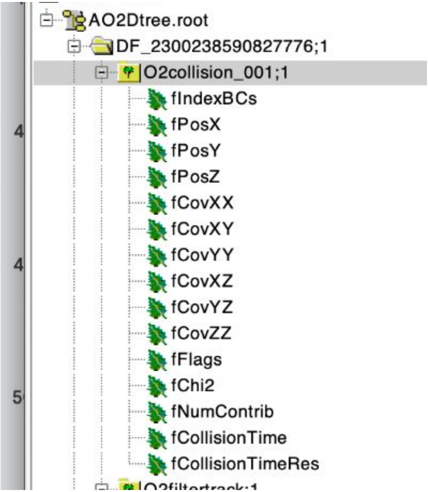
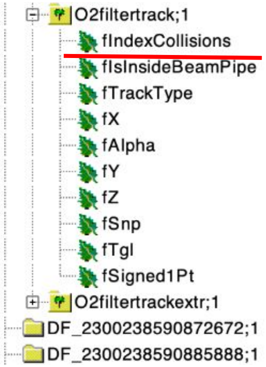




Remember:
fIndexCollisions gives the position in the O2collision tree of the primary vertex to which the track is associated

Let’s get familiar with the data

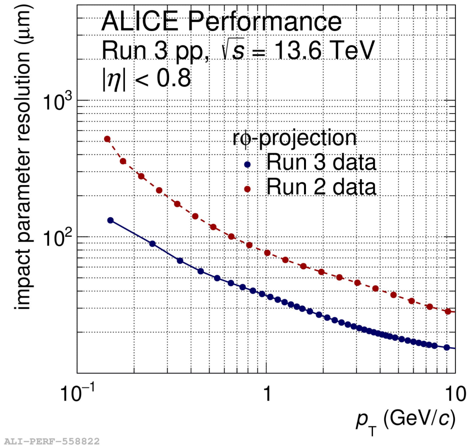
Goal 4:

- look at the dcaXY distribution in narrow pt intervals:

- take the rms of the distribution around the peak, i.e. calculate the rms’ that you get when you restrict the distribution to (approximately) the range [mean -2.5 rms, mean +2.5 rms]
    - alternatively: fit the distribution in a wider range (~5 rms) with a function composed of a Gaussian term (for the peak) and symmetric exponential tails:

- plot rms’ (or the Gaussian sigma) as a function of pt.
  You should get something like the figure on the right.

- repeat isolating pions, kaons, and protons



Let’s get familiar with the data

Goal 5:

- let’s find K^0_s signal! (mass = 497.614 MeV/c^2)
- K^0_s decays with a BR~69.2% (see PDG) in two opposite charge pions, $K^0_s \rightarrow \pi^+\pi^-$
- relatively large lifetime, τ ~ 0.896×10^{-10} s (~90 ps) → $c\tau$ is large (2.6844 cm)
    - exponential distribution of decay time in particle rest frame

$$\text{prob}(t) = 1/N\ dN/dt\ (t) = 1/\tau\ e^{-t/\tau}$$

    - decay length (L) in lab frame is distributed as:

$$\text{prob}(L) = 1/(\beta\gamma c\tau)\ e^{-L/\beta c\gamma\tau}$$

where βc: K^0_s velocity in lab frame (β = v/c = p/E)

$\gamma\tau$: decay time in lab frame; $\gamma = 1/\sqrt{(1-\beta^2)}$ =E/m, relativistic boost factor determining time-dilation

→ average decay lenght, $\langle L \rangle = \beta\gamma c\tau$

Similarly to single-particles, K^0_s are formed with a given momentum distribution dN/dp

(we checked dN/dp_T for single particles but at midrapidity dN/dp and dN/dp_T are similar)

→ decay length distribution determined by the convolution of dN/dp and dN/dt

Let's get familiar with the data

Without refining too much the analysis selections, let's try to find them

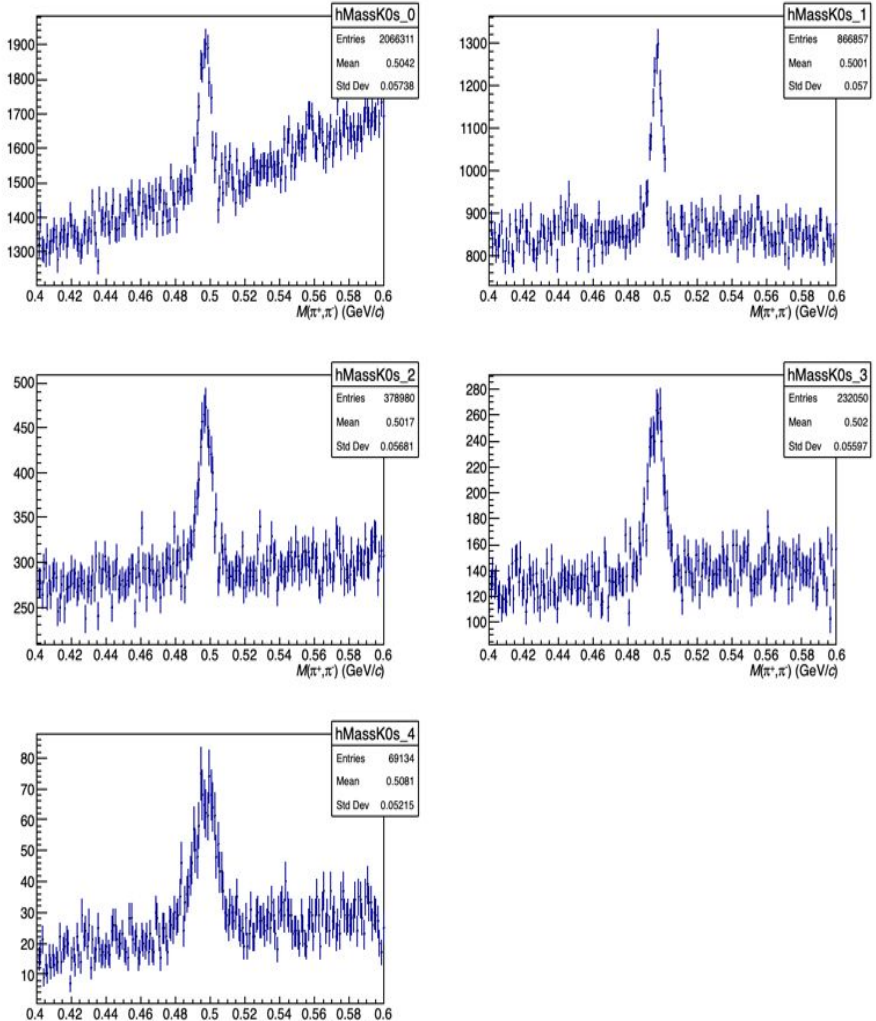
Combine positive and negative tracks to build candidates of K^0_s decay
- take tracks from the same event!
- calculate invariant mass and plot it

- you can play with some selections (PID: do you expect it to help a lot? dcaXY, …) and plot the invariant mass distribution in different pt intervals (e.g. 0-1,1-1.5,1.5-2,2-3,3-5).

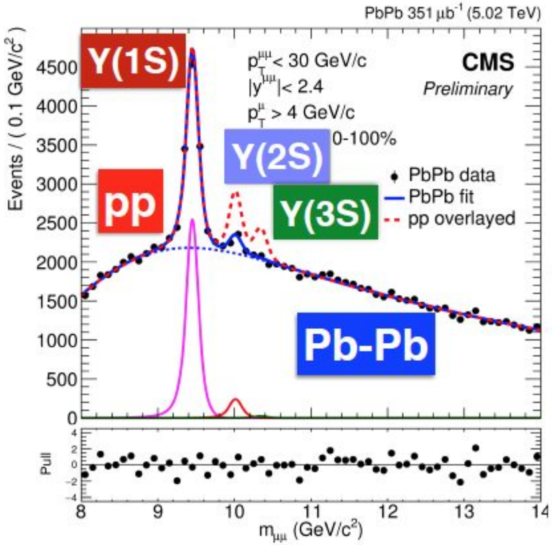
- train yourself in counting the yield (i.e. the number of K0s): fit the invariant mass distribution with a Gaussian term for the signal and another function (straight line, parabola, exponential… whatever you like and makes sense) for the background

Let’s get familiar with the data

You should get something like this



Invariant mass



Invariant mass analysis: a procedure to count particles that decay.

Mass + quantum numbers (spin, quark content) = particle identity card

$p^{\mu}_{\text{Mother}} = p^{\mu}_{\text{Daughter 1}} + p^{\mu}_{\text{Daughter 2}}$ (in any frame, for a N-body decay the sum is over the N daughters)

$p^{\mu}_{\text{Mother}} p_{\mu\text{,Mother}}$ is a Lorentz-invariant quantity

In Mother rest frame:

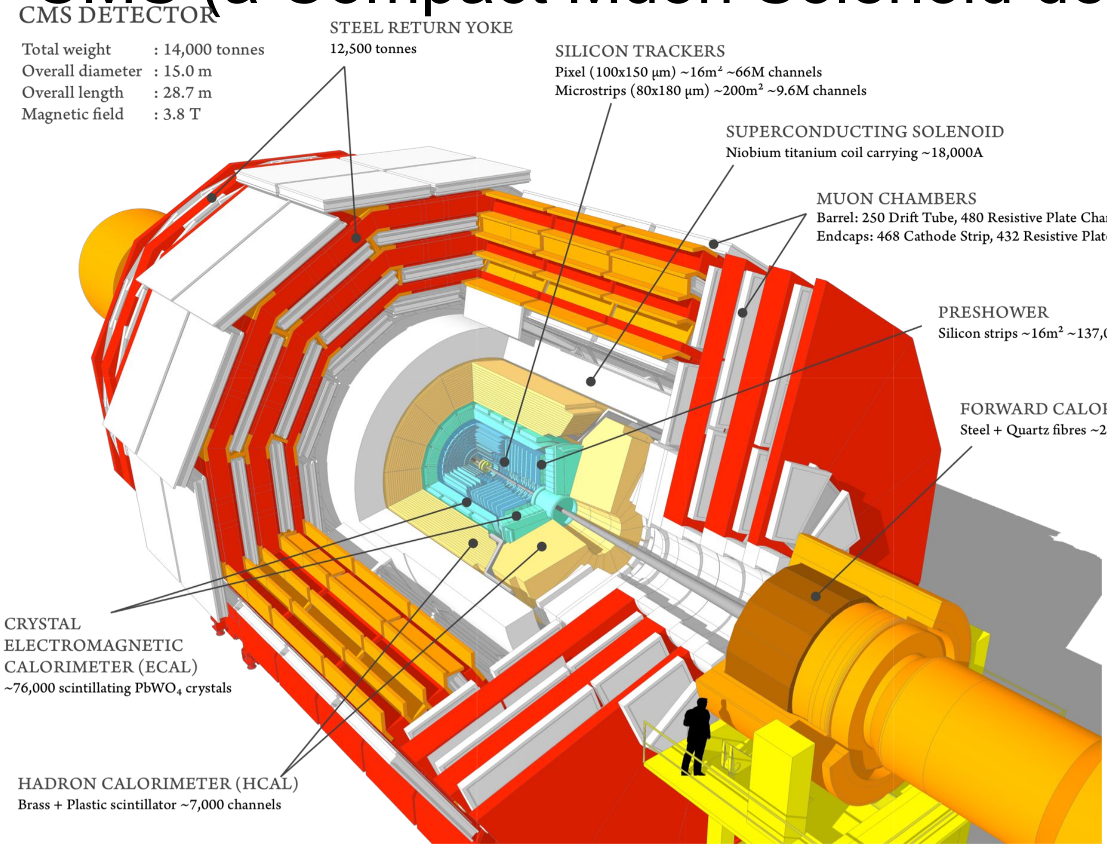
$p^{\mu}_{\text{Mother}} = (M, 0,0,0), \quad p^{\mu}_{\text{Daughter 1}} = (E_1, \vec{p_1}) \quad , \quad p^{\mu}_{\text{Daughter 2}} = (E_2, \vec{p_2})$ N. B.: $\vec{p_2} + \vec{p_1} = 0$

$\sqrt{p^{\mu}_{\text{Mother}} p_{\mu\text{,Mother}}} = M$ in any frame

$\sqrt{\left(p^{\mu}_{\text{Daughter 1}} + p^{\mu}_{\text{Daughter 2}}\right)\left(p_{\mu\text{,Daughter 1}} + p_{\mu\text{,Daughter 2}}\right)} = M$ in any frame

Extra

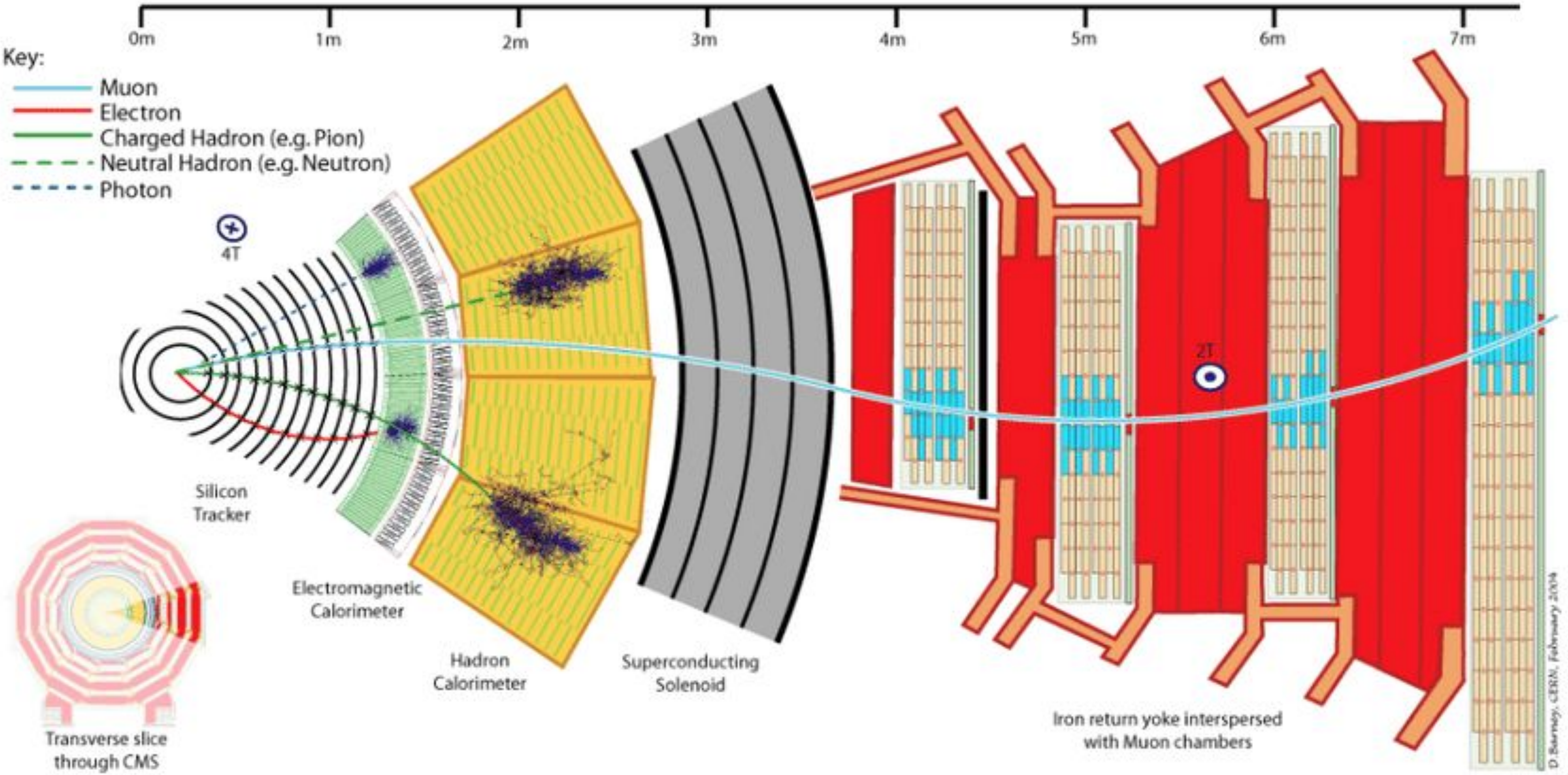
CMS (a Compact Muon Solenoid detector)



Muon detectors are always “external” because **muon identification exploits their penetrating power**. Muons do not interact much with material:

- they do lose energy and suffer from multiple Coulomb scattering, but these processes do not destruct them/not lead to absorption.
- they do not interact strongly
- cannot annihilate (there are no muons/antimuons in the material)
- Bremsstrahlung is a rather minor effect (differently from electrons, due to the x200 larger mass)

C


0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004