The Z and Higgs bosons:
let's discover them with the ATLAS detector!

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Particle Physics Summer School 2018, University of Udine
23/07/2018

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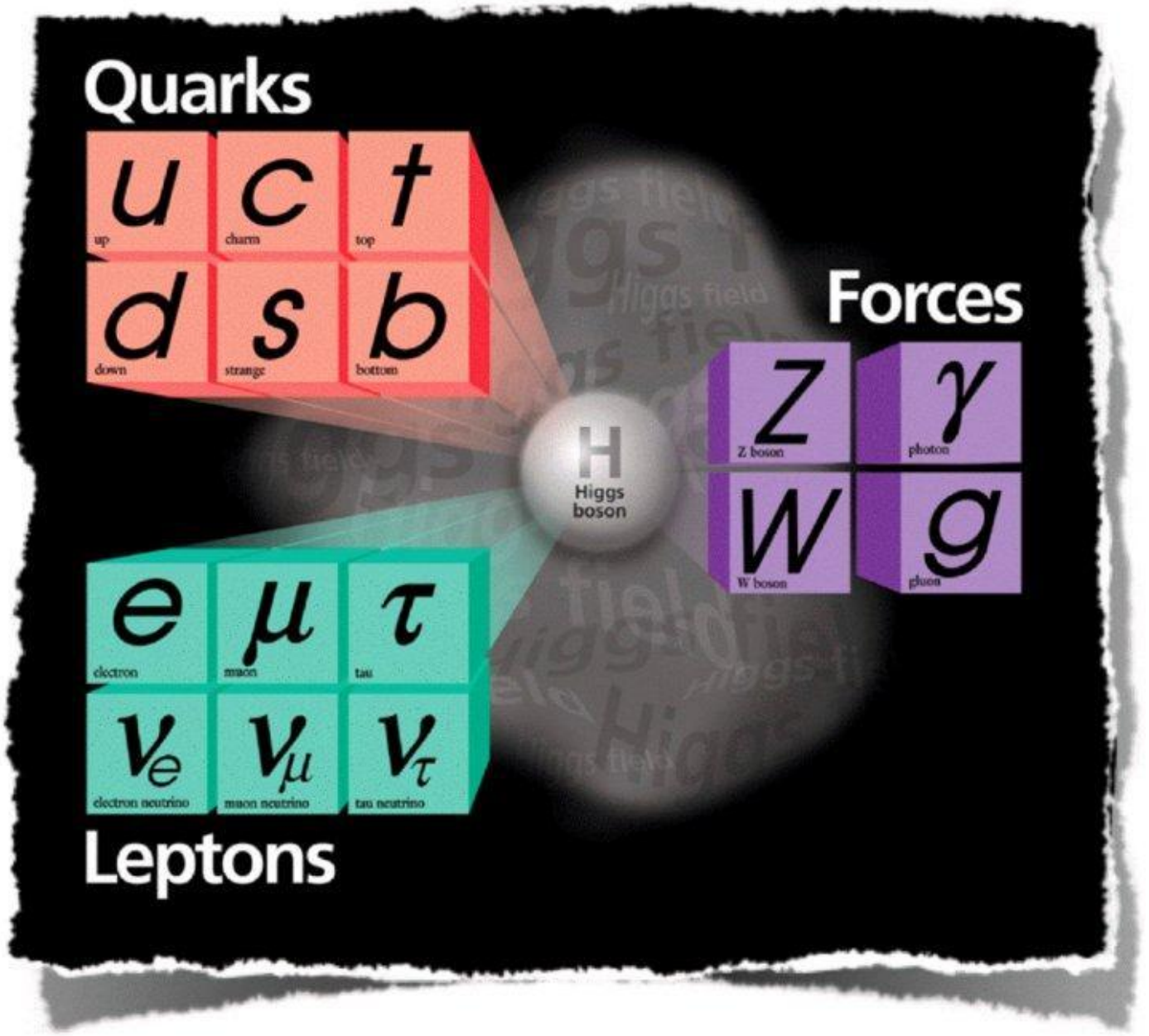
THE SM PARTICLES



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THE SM PARTICLES

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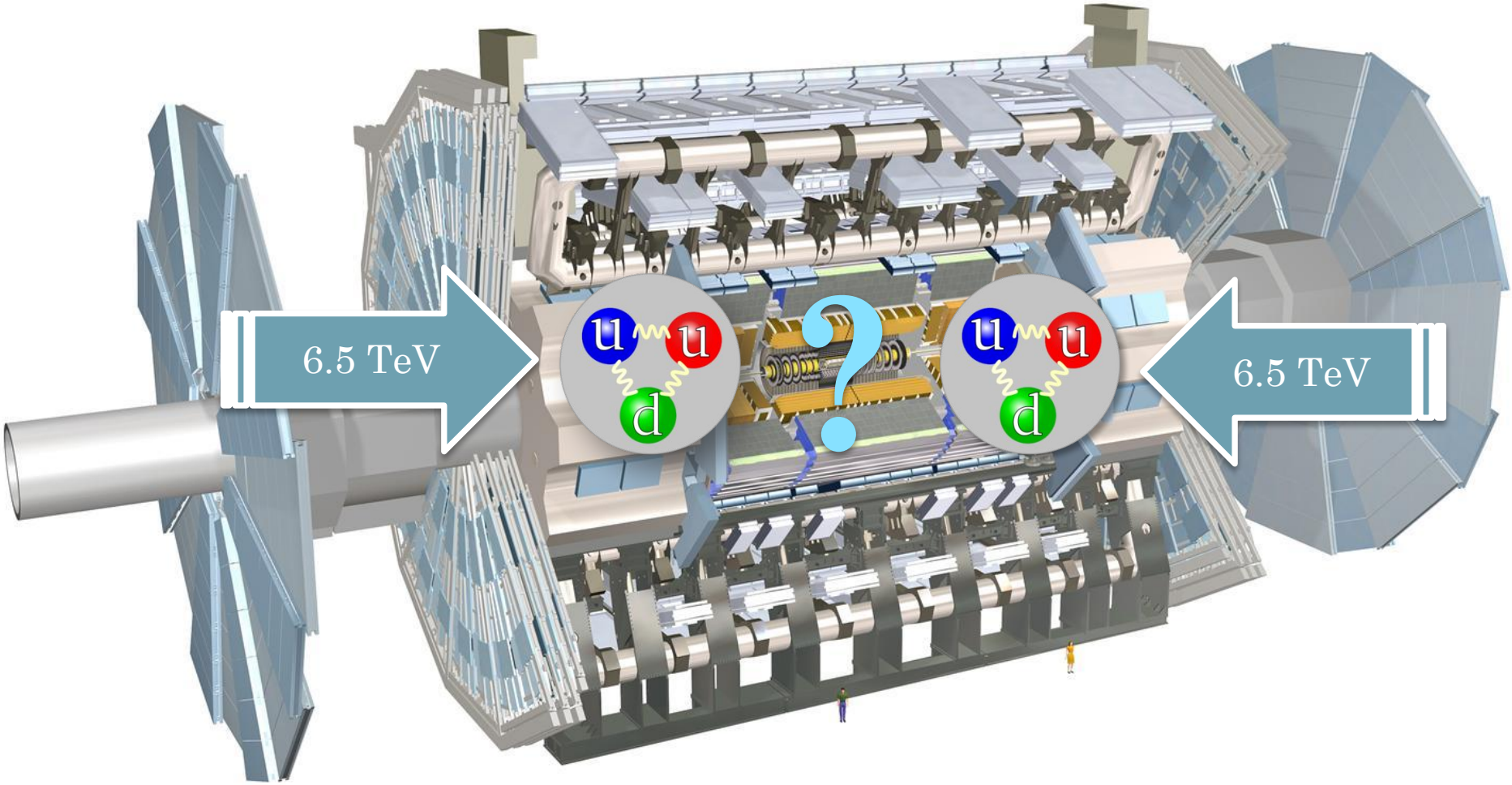
WHAT HAPPENS IN P-P COLLISIONS?



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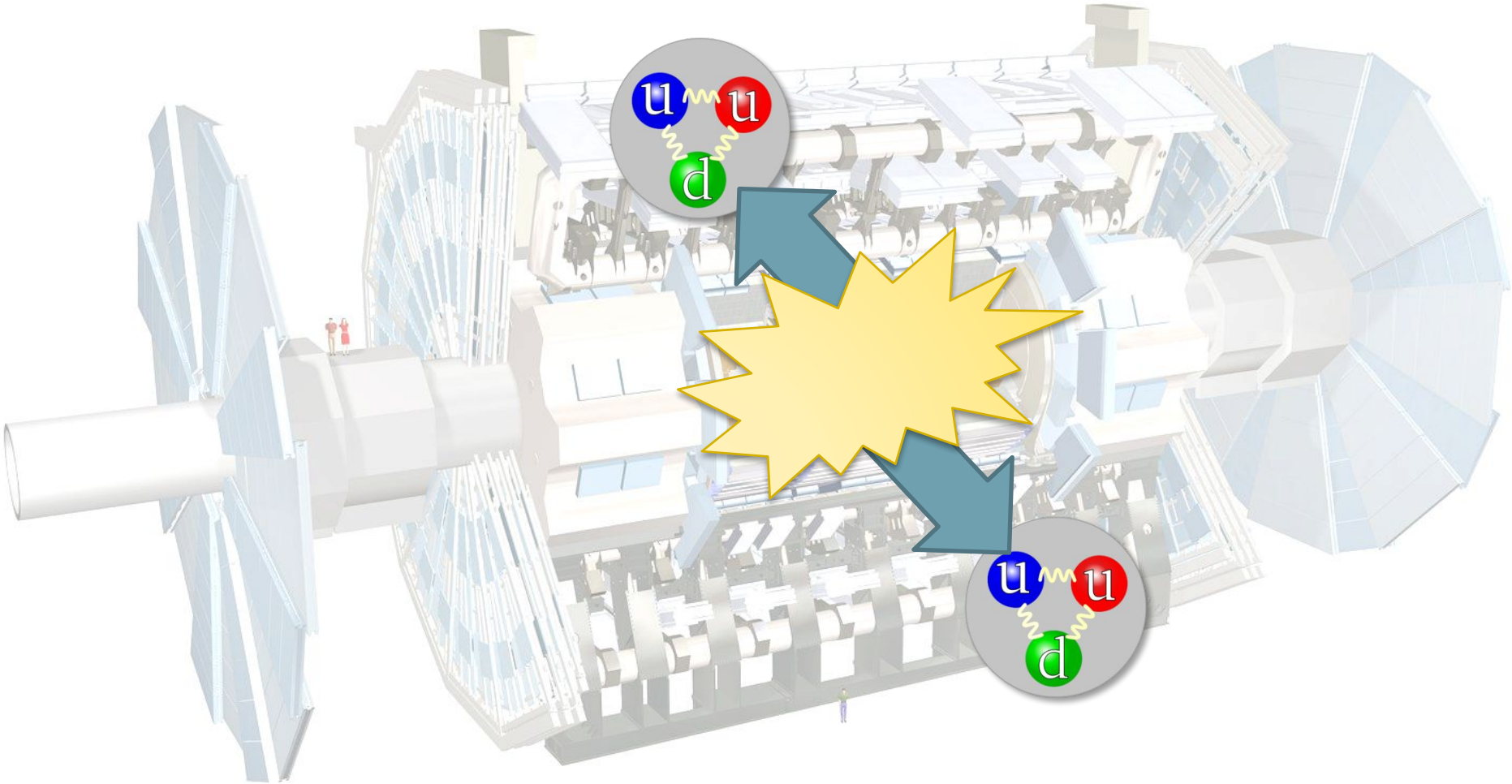
WHAT HAPPENS IN P-P COLLISIONS?

- Elastic scattering



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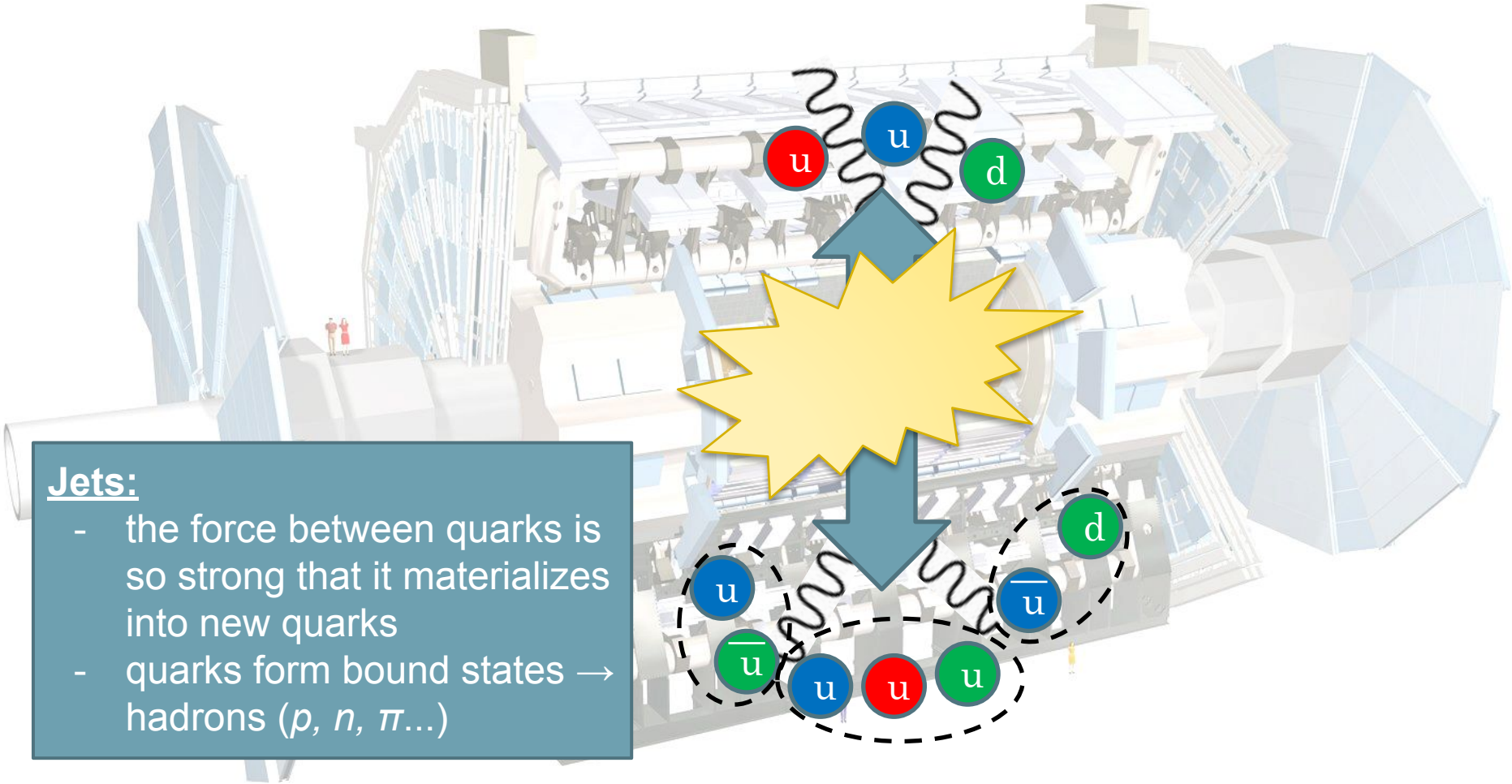
WHAT HAPPENS IN P-P COLLISIONS?

- Elastic scattering
- Inelastic scattering



Jets:

- the force between quarks is so strong that it materializes into new quarks
- quarks form bound states → hadrons (*p*, *n*, *π*...)

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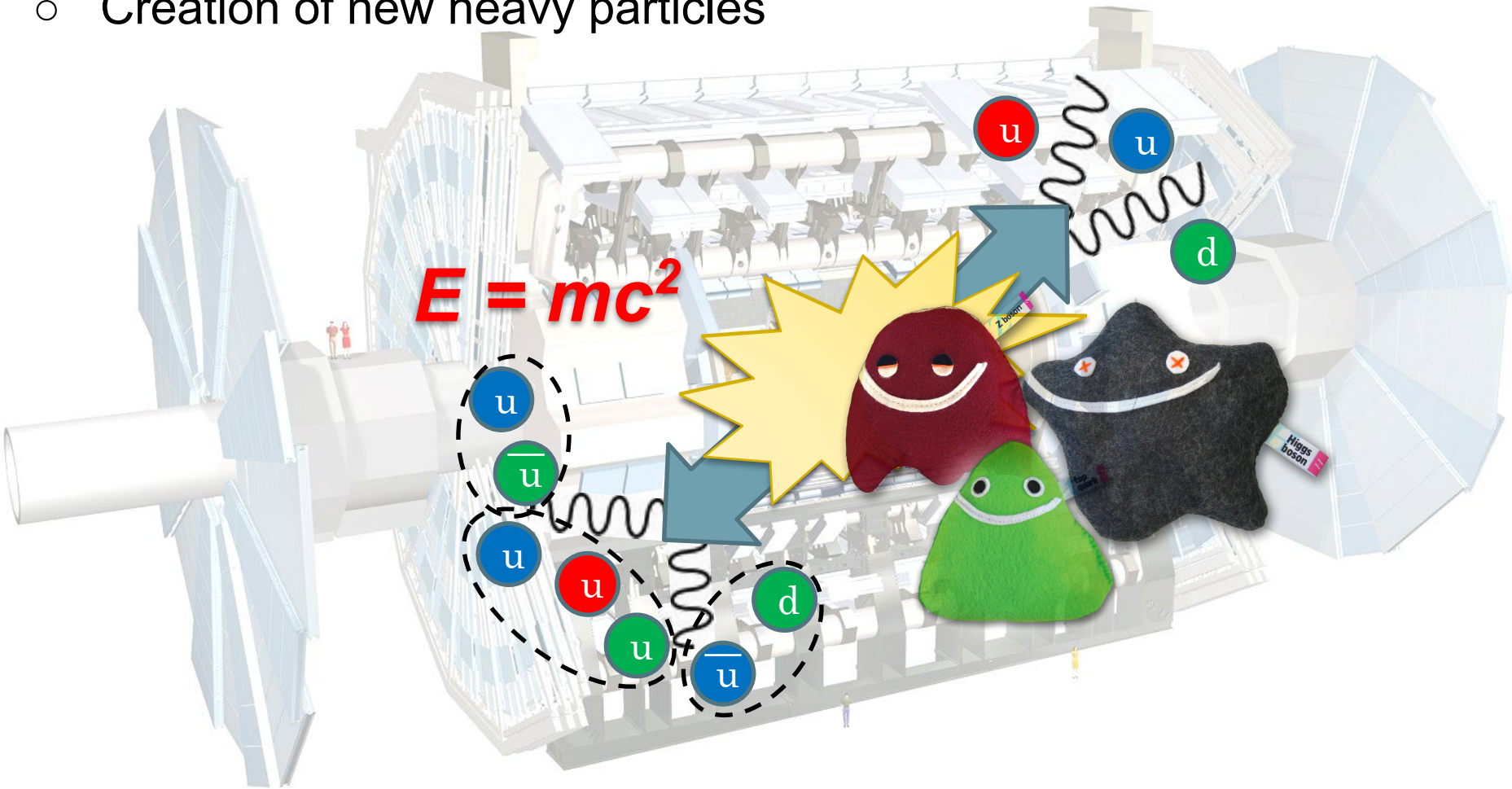
WHAT HAPPENS IN P-P COLLISIONS?

- Elastic scattering
- Inelastic scattering
- Creation of new heavy particles



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HOW CAN WE SEE PARTICLES?

- Most of the particles are unstable
- Very heavy particles (like the Z and Higgs bosons) decay immediately (after 3×10^{-25} = 0.000000000000000000000003 sec)
- The decay conserves:
  - ➜ the electric charge
  - ➜ the energy

Z boson:

- electric charge = 0
- mass = 91 GeV/c^2

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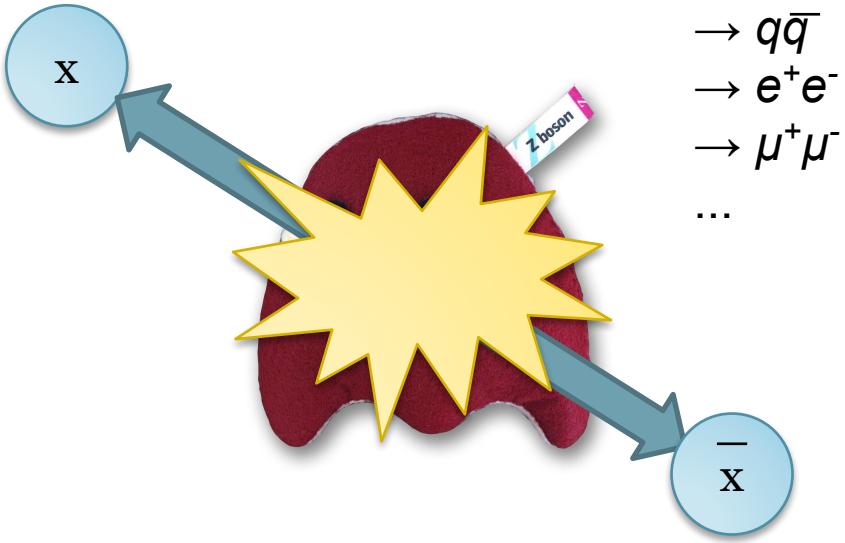

$\rightarrow q\bar{q}$
$\rightarrow e^+e^-$
$\rightarrow \mu^+\mu^-$
...

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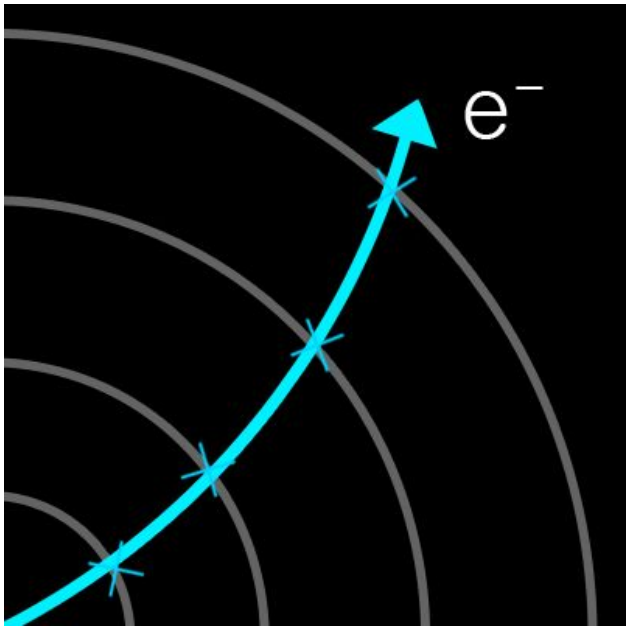
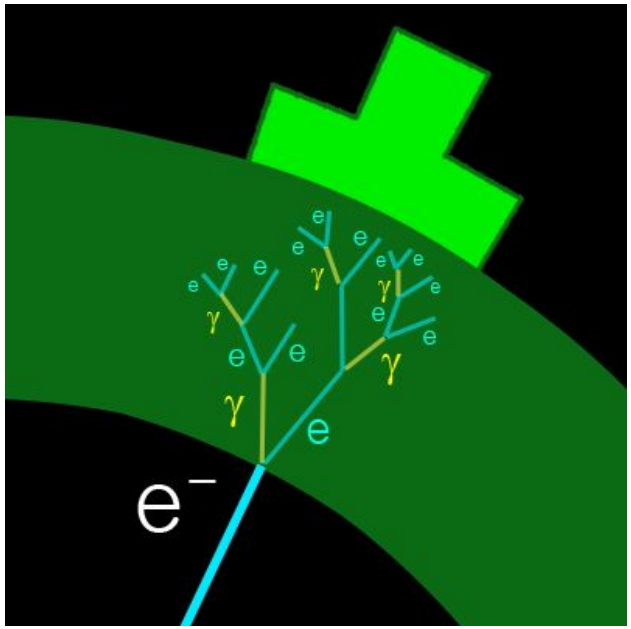
HOW CAN WE SEE PARTICLES?

- To see and measure stable particles we use **particle detectors**
  ➜ many different types and technologies, that can:
    - see different types of particles, of different energies
    - measure different properties (energy, direction, charge...)
- Two main types of detectors:

“Trackers”



“Calorimeters”



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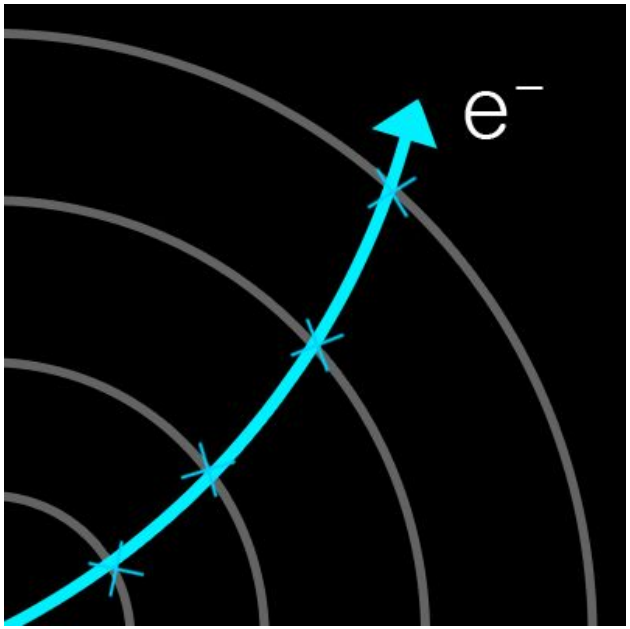
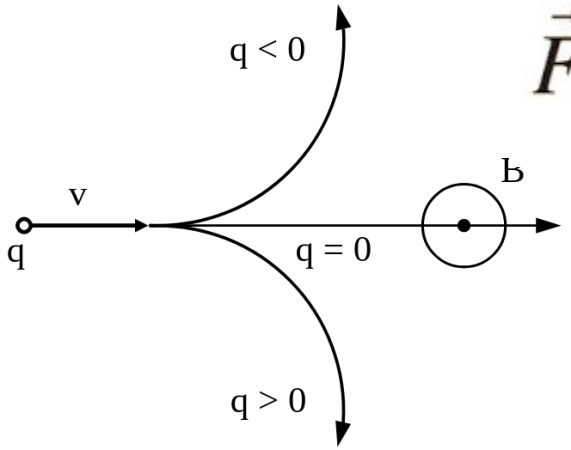
HOW CAN WE SEE PARTICLES?

- ➜ thin layers ⇒ small perturbation of particle motion
- ➜ precise **trajectory** determination
- ➜ immerse in **magnetic fields** ⇒ measure **momentum**
  - direction of curvature ⇒ sign of electric **charge**

"Trackers"





$$\vec{F} = q\vec{v} \; x \; \vec{B}$$

Technology:
- silicon detectors (e.g. pixel)
- proportional chambers (gas detectors)

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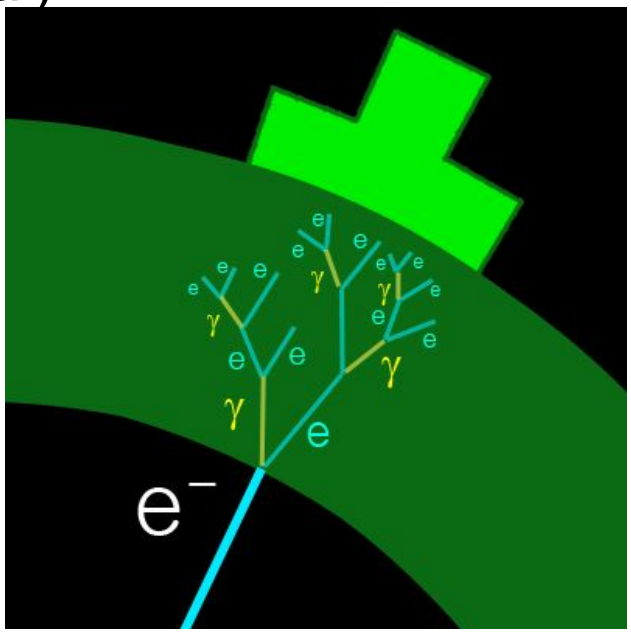
HOW CAN WE SEE PARTICLES?

- ➜ heavy and thick ⇒ **stop** particles
- ➜ particles interact with material and dissipate their entire kinetic energy → collected and measured

- ➜ often built to stop and measure:
  - either electrons and photons (EM-Cal)
  - or hadronic particles (Had-Cal)

“Calorimeters”



Technology:
- heavy materials as “absorbers” (metals)
- active materials often scintillators

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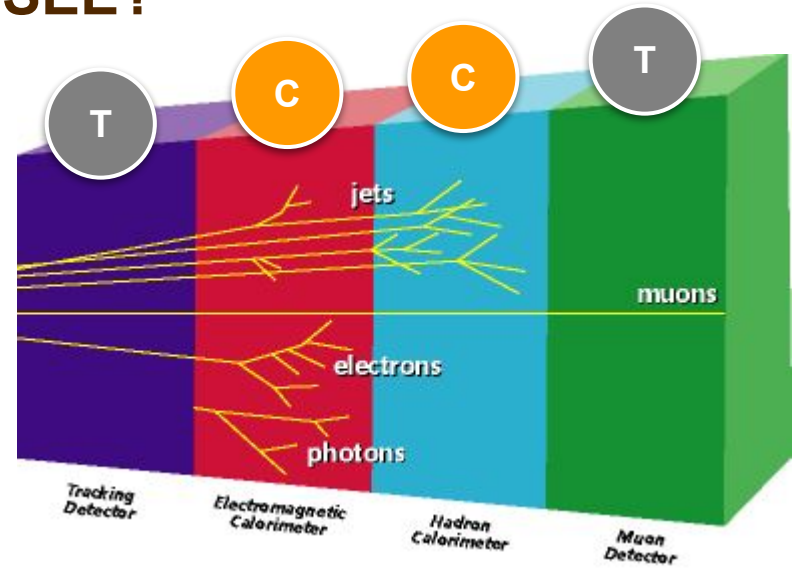
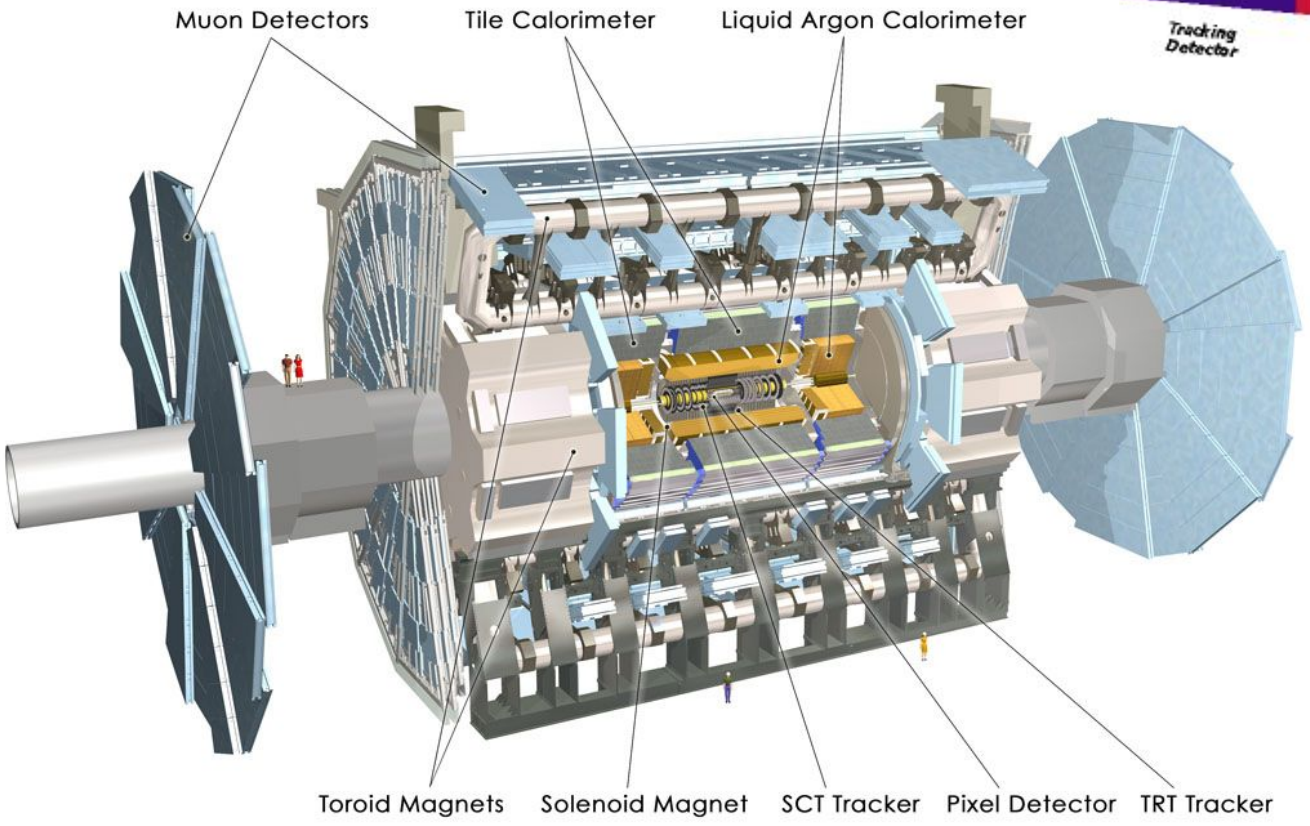
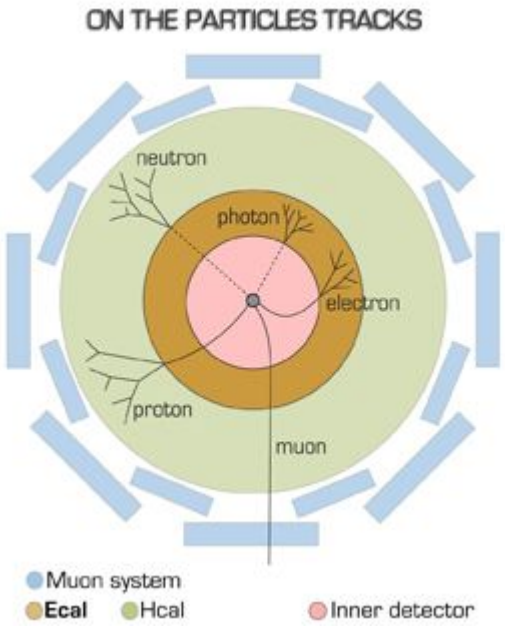
WHAT CAN ATLAS SEE?

- ATLAS is built with several layers of different detectors
  - ➜ can see and measure almost all stable particles







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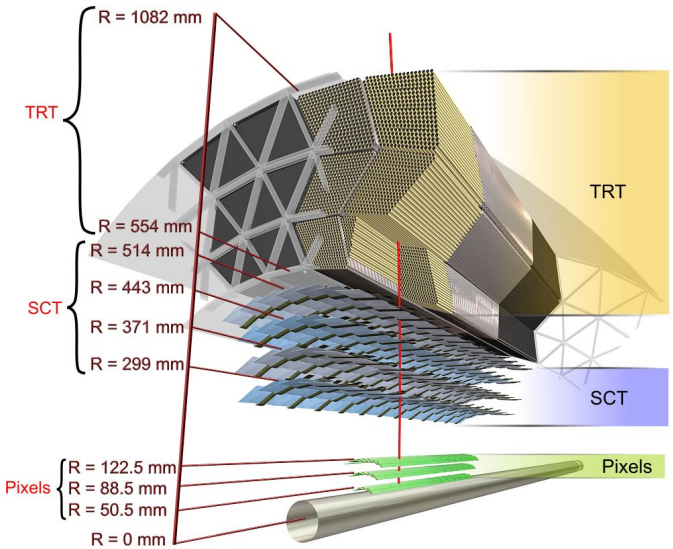
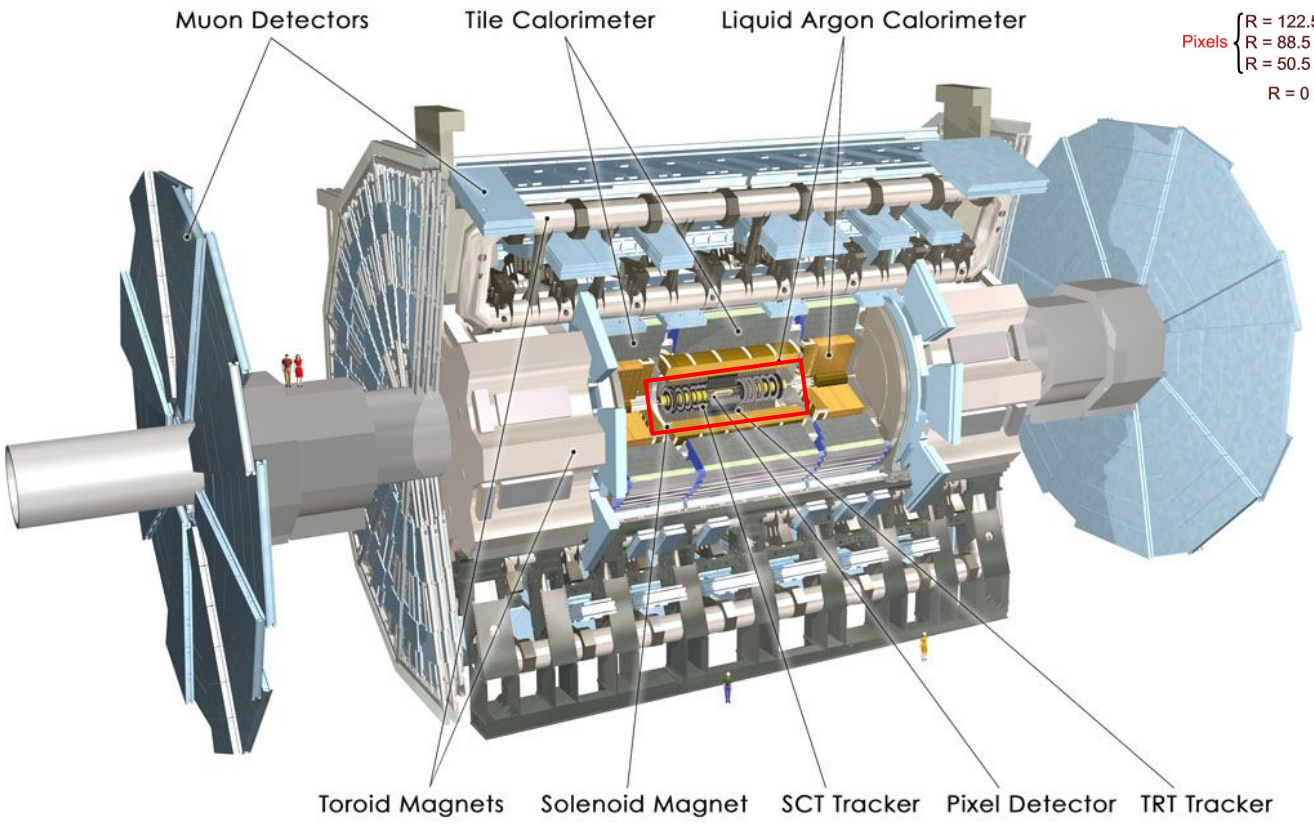
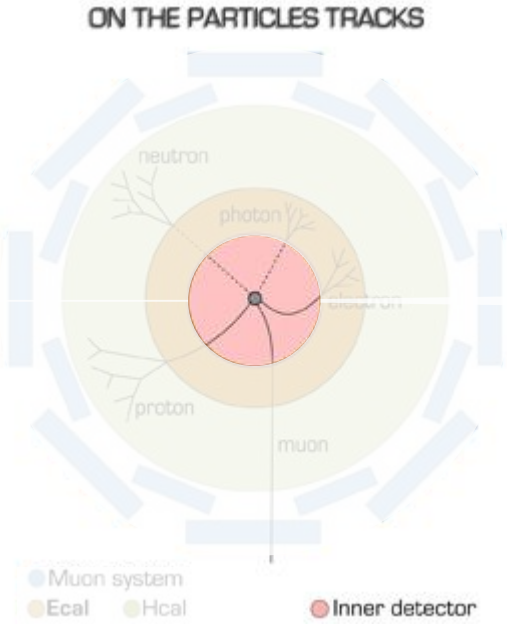
ATLAS SUB-DETECTORS

The Inner Detector







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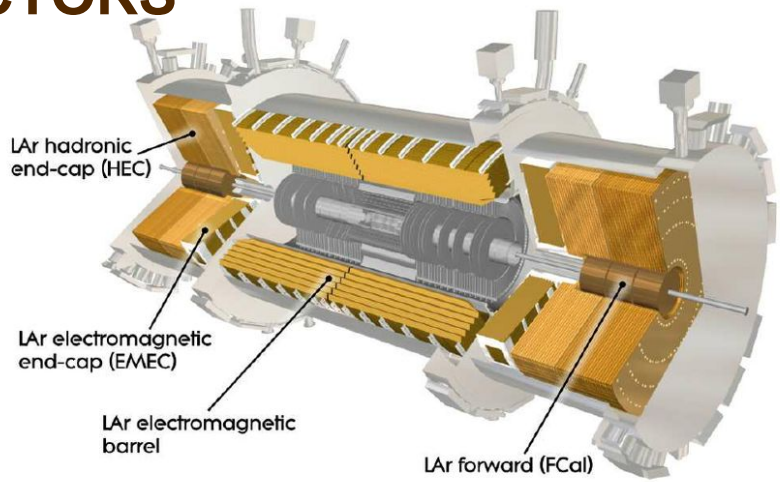
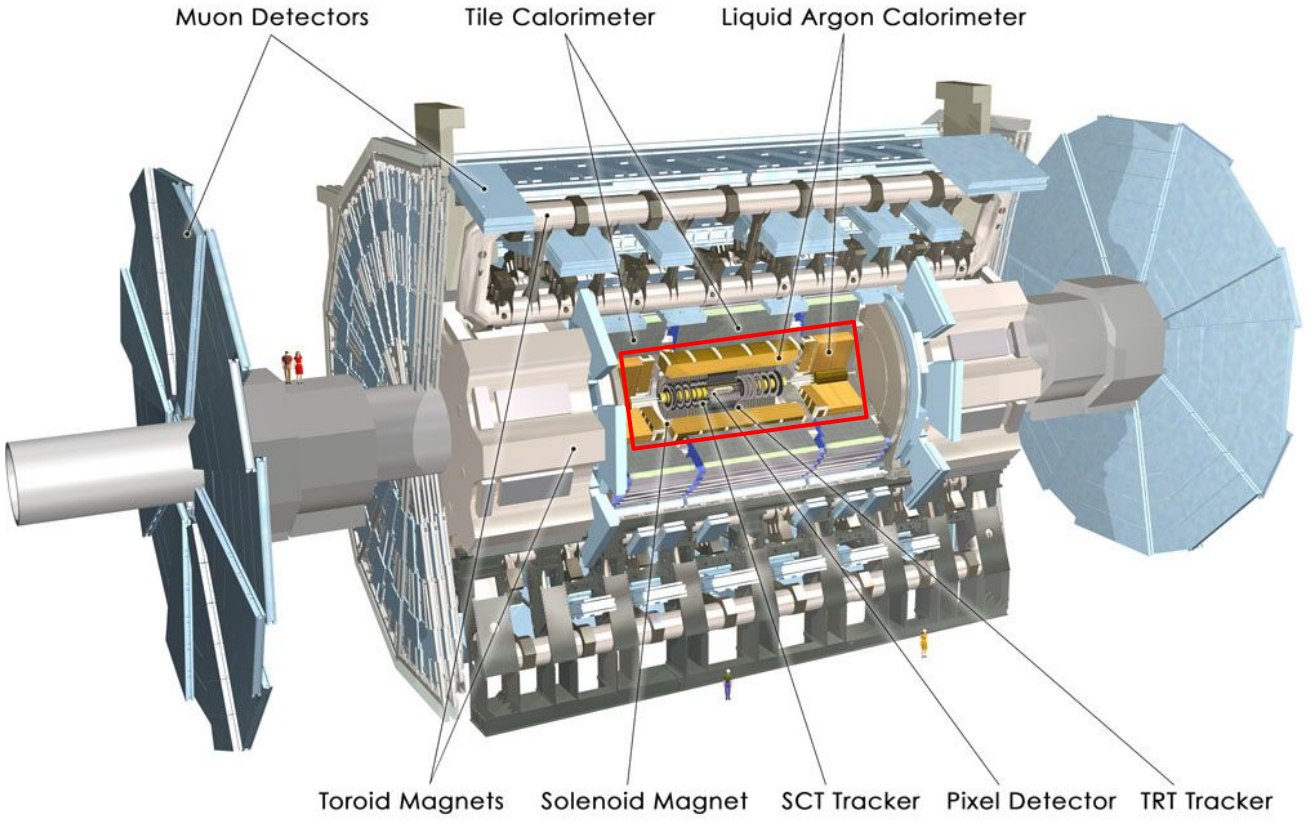
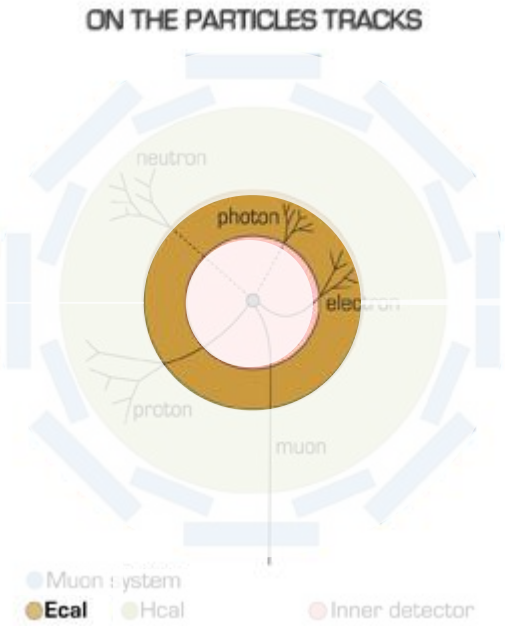
ATLAS SUB-DETECTORS

c The EM-Calorimeter







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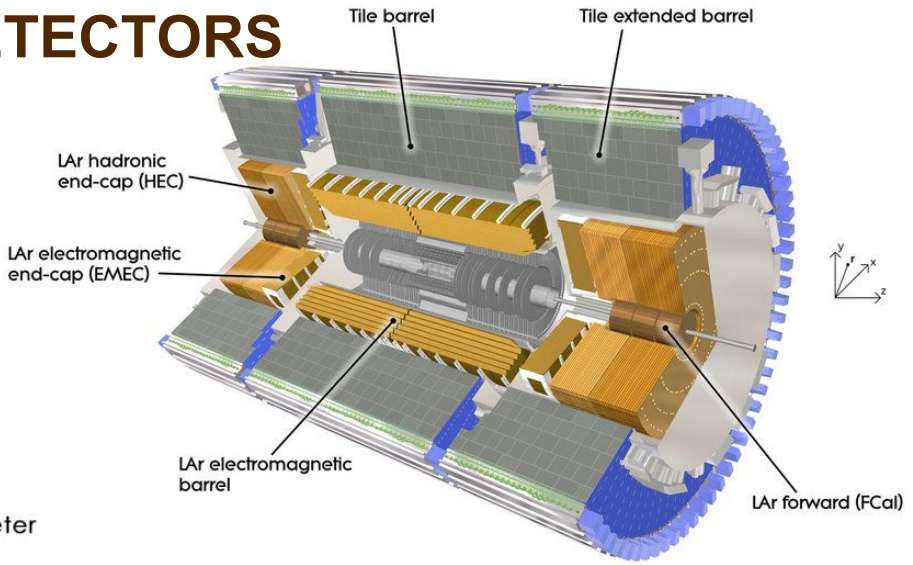
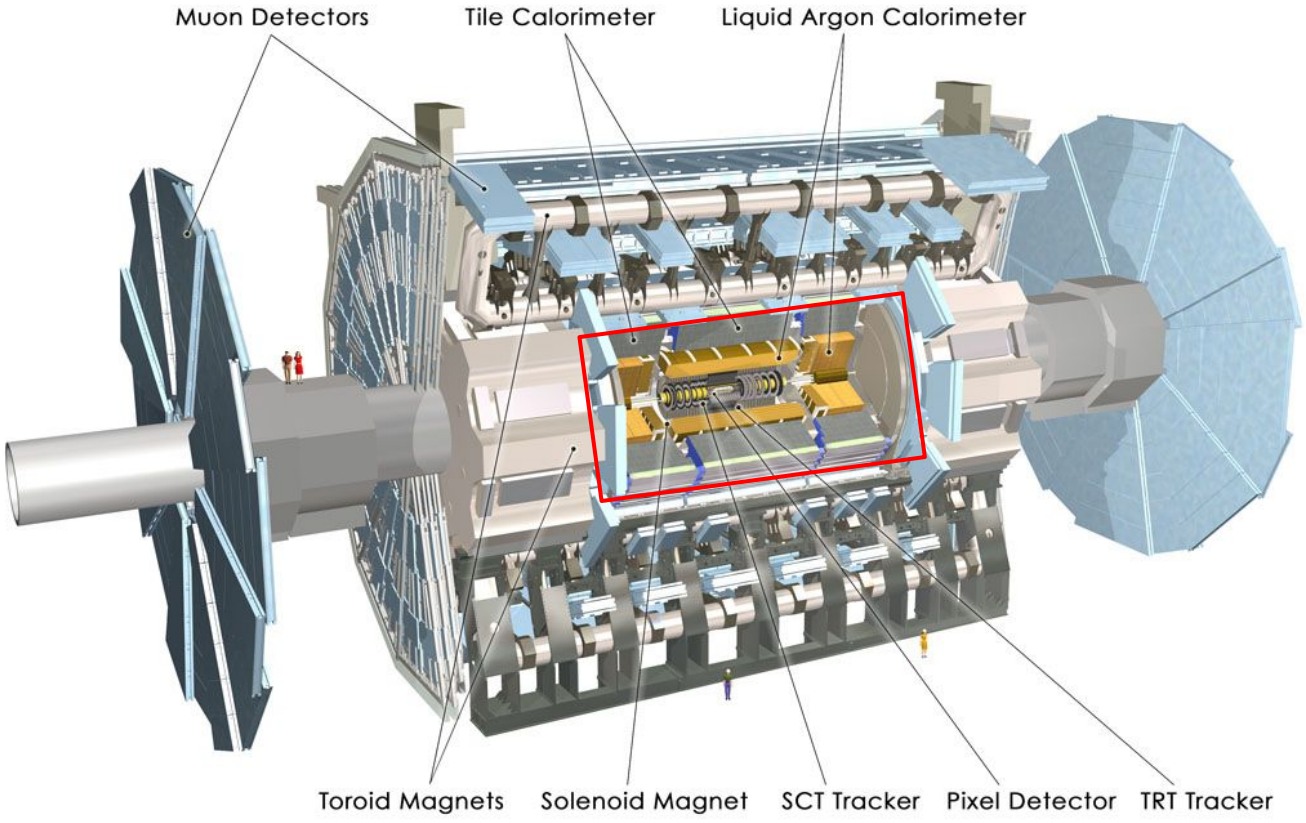
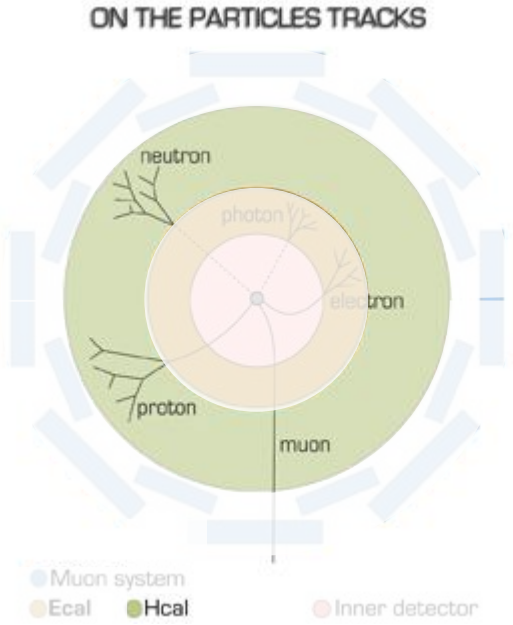
ATLAS SUB-DETECTORS

c The Hadronic-Calorimeter







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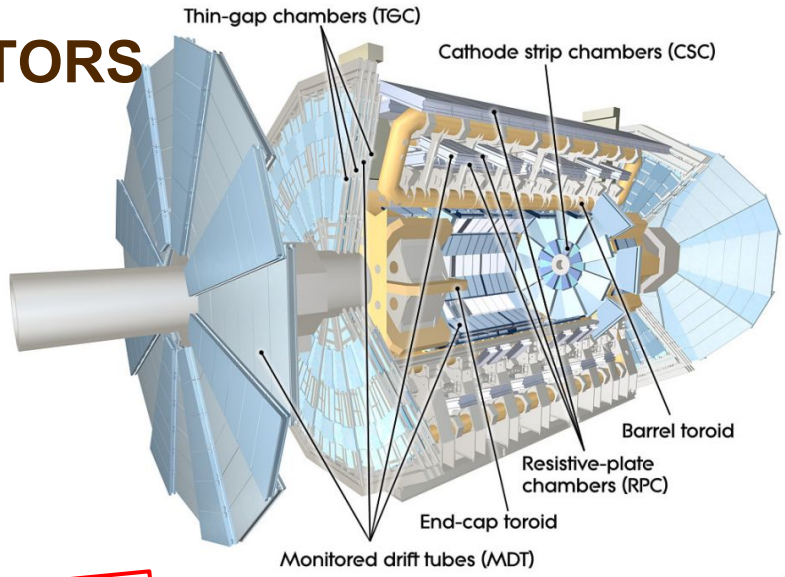
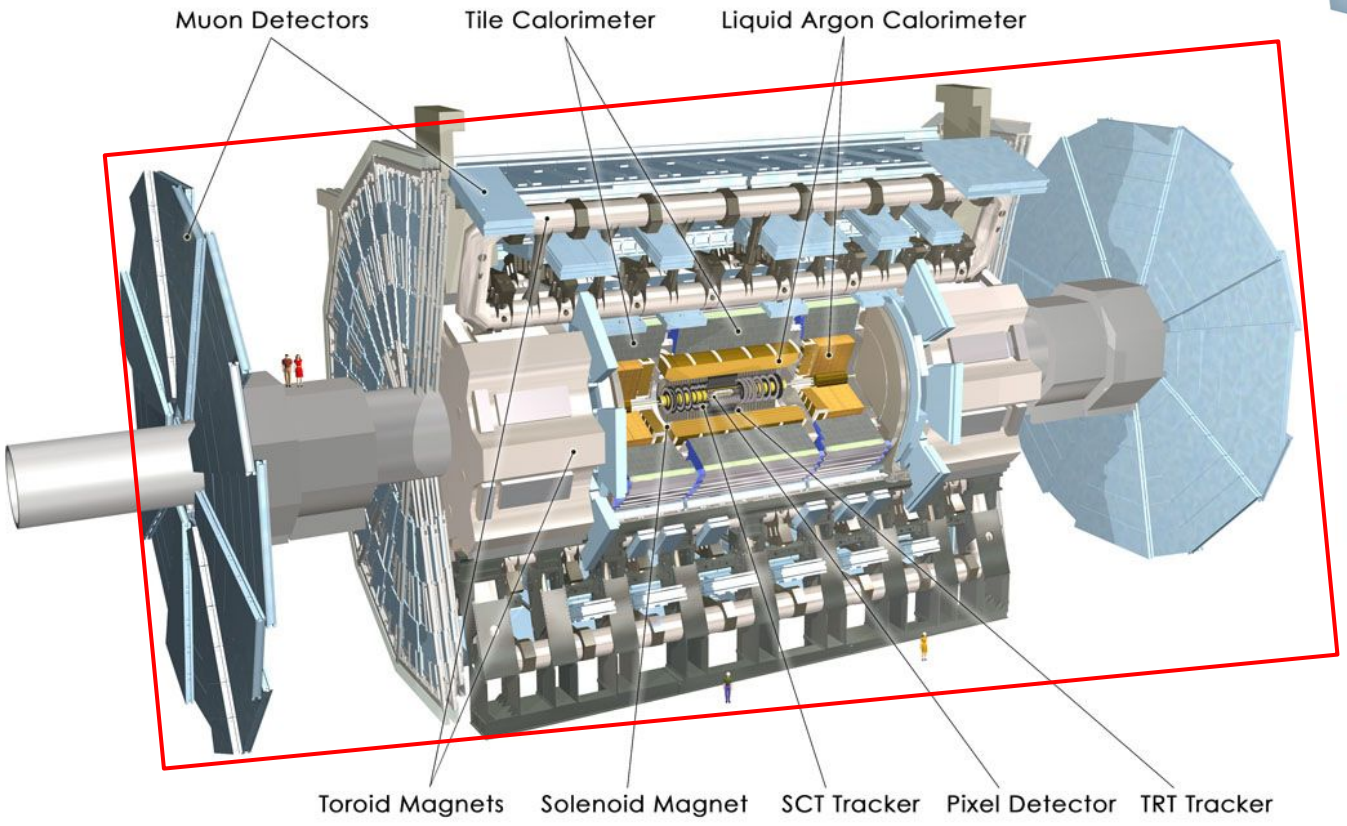
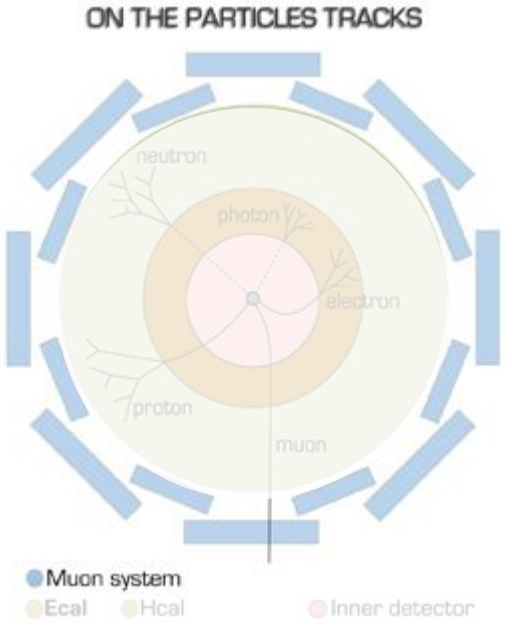
ATLAS SUB-DETECTORS

The Muon Spectrometer







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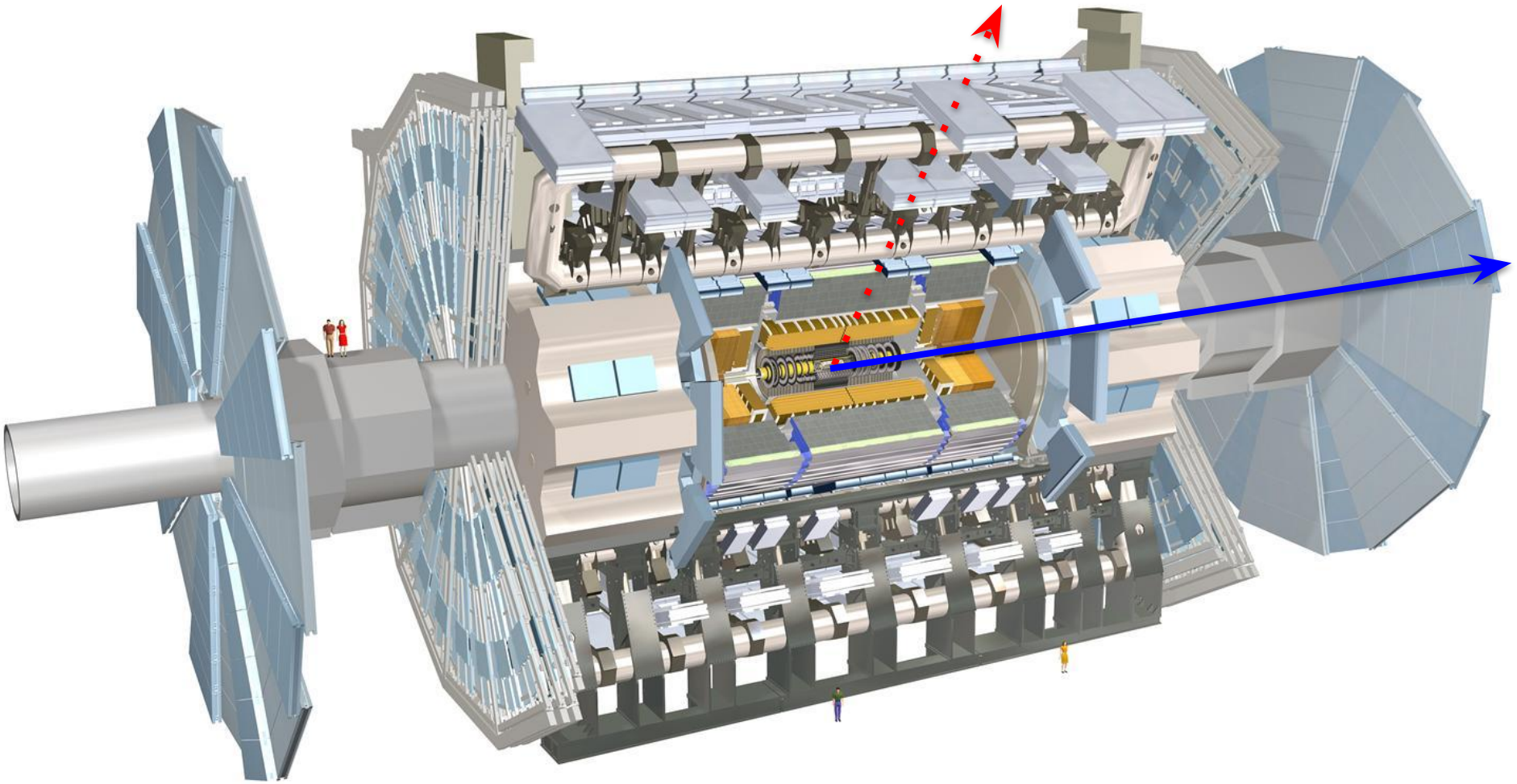
WHAT ATLAS CANNOT SEE

- Neutrinos (or new particles that interact only via weak interaction)
- Particles that are too forward / too close to the beam directions



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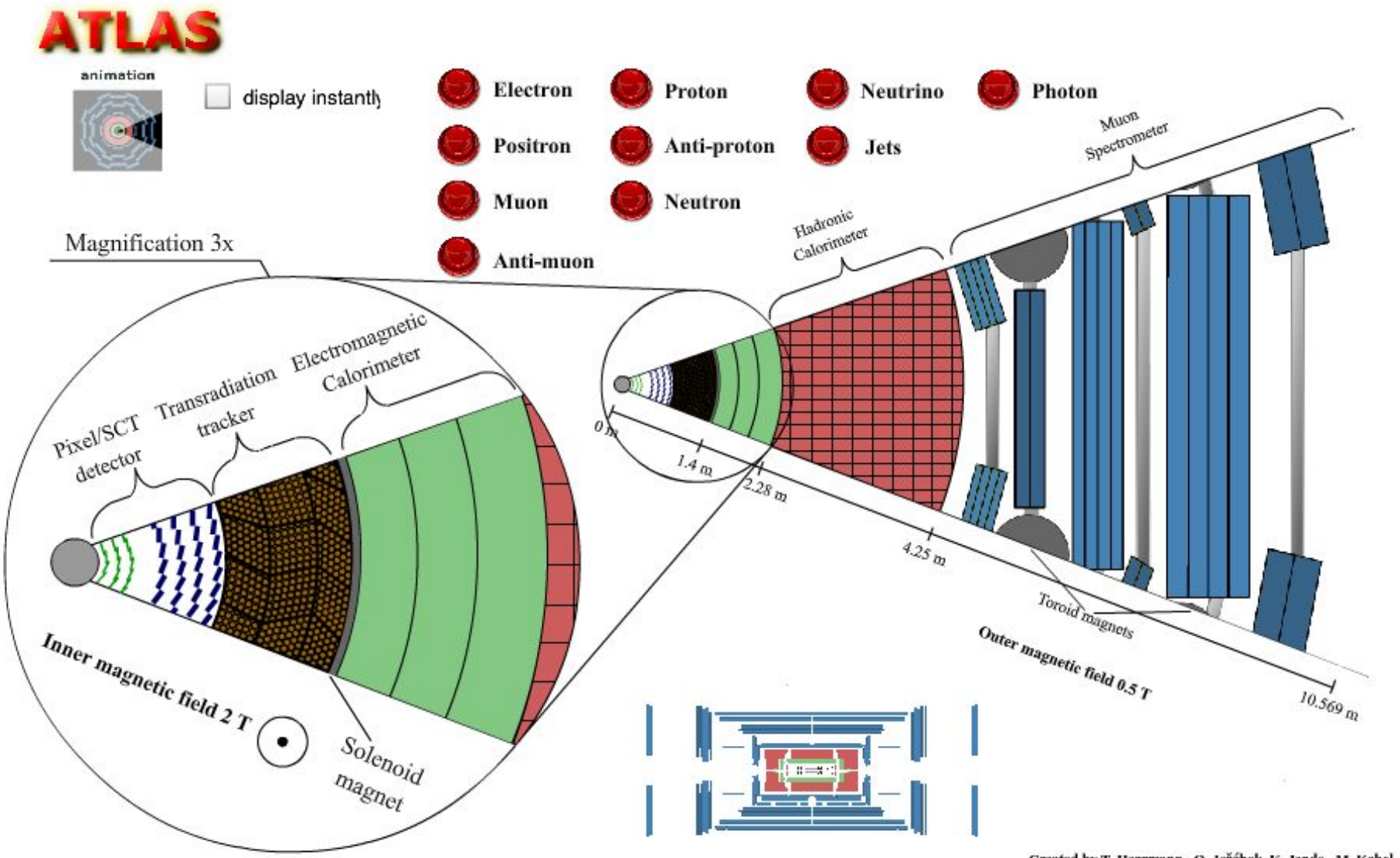
HOW PARTICLES LOOK LIKE IN ATLAS



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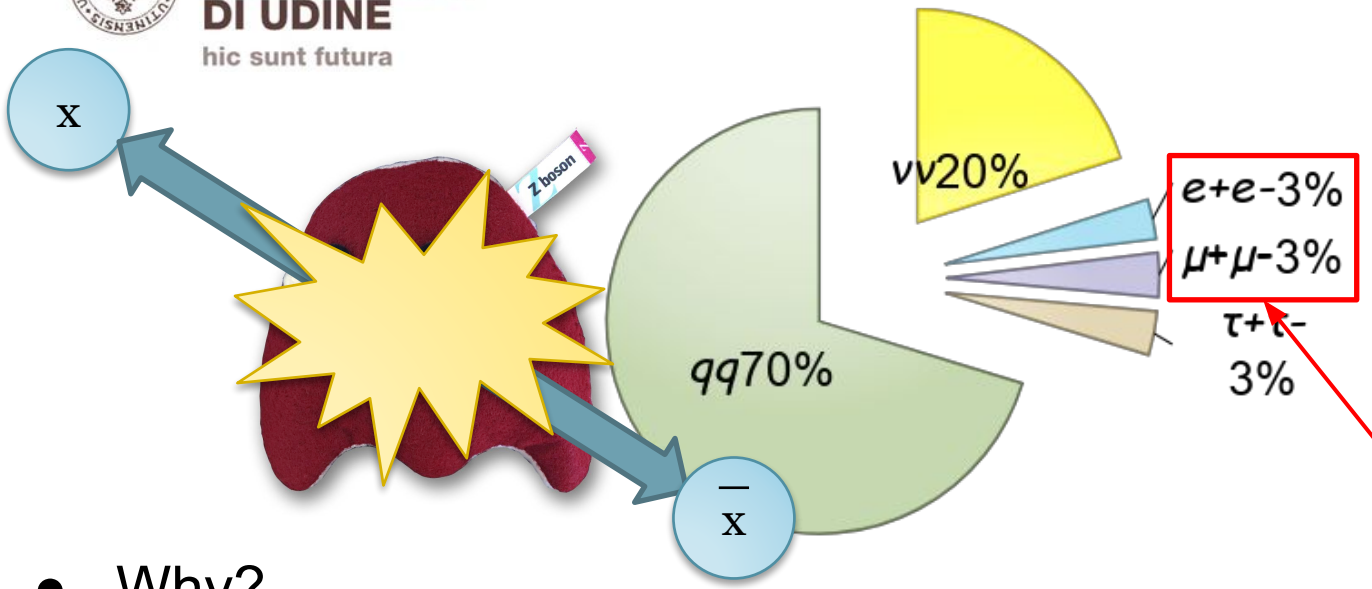
HOW CAN WE RECONSTRUCT THE Z BOSON?



- Why?
  - Out of the possible decays of the Z boson, we choose **these ones**

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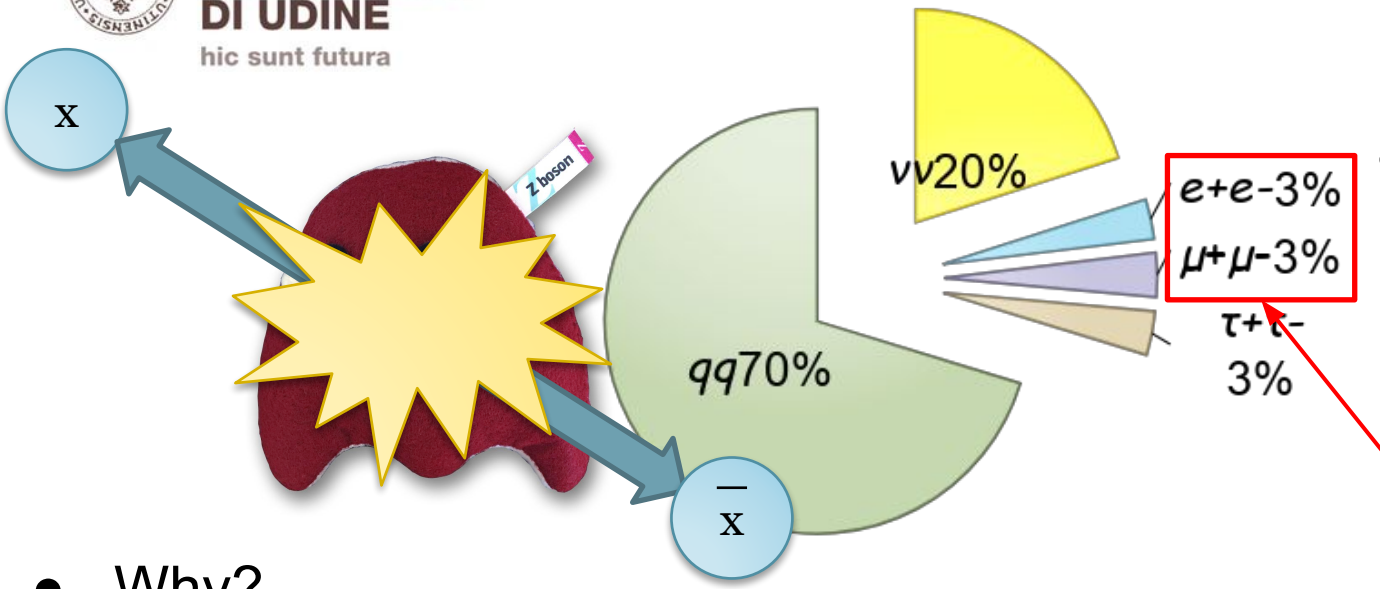
HOW CAN WE RECONSTRUCT THE Z BOSON?



- Out of the possible decays of the Z boson, we choose **these ones**

- Why?
  - ATLAS can measure electrons and muons with high precision
  - can distinguish Z → ee / μμ events from "background" events with production of just jets

- Invariant mass reconstruction:
  - use conservation of energy and momentum
  - can determine mass of parent particle from 4-momenta of its decay products

$$m_0^{(Z)} = \sqrt{\left(\frac{(E_{e^-} + E_{e^+})}{c^2}\right)^2 - \left(\frac{\vec{p}_{e^-} + \vec{p}_{e^+}}{c}\right)^2}$$

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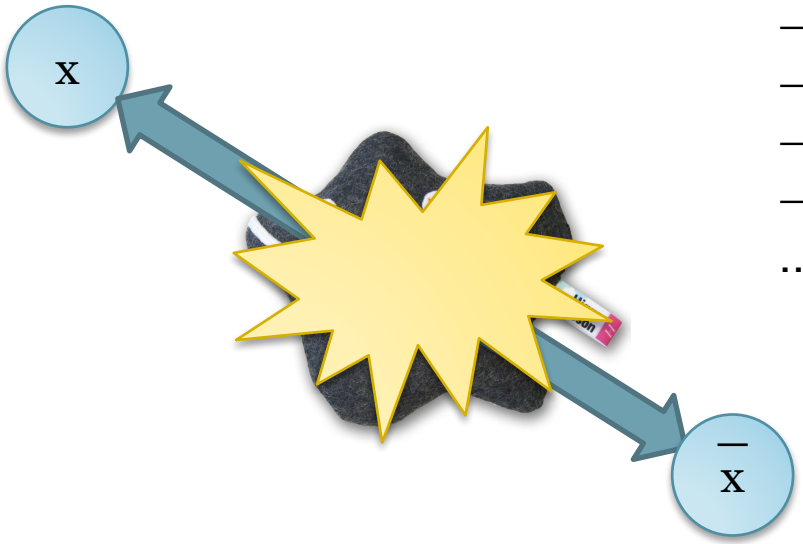
AND WHAT ABOUT THE HIGGS BOSON?

- The Higgs boson is special:
  - ➜ he prefers to decay into heavy particles



$\rightarrow b\bar{b}$
$\rightarrow \tau^+\tau^-$
$\rightarrow W^+W^-$
$\rightarrow ZZ$
$\rightarrow \gamma\gamma$
…

Higgs boson:

- electric charge = 0
- mass = 125 GeV/c^2

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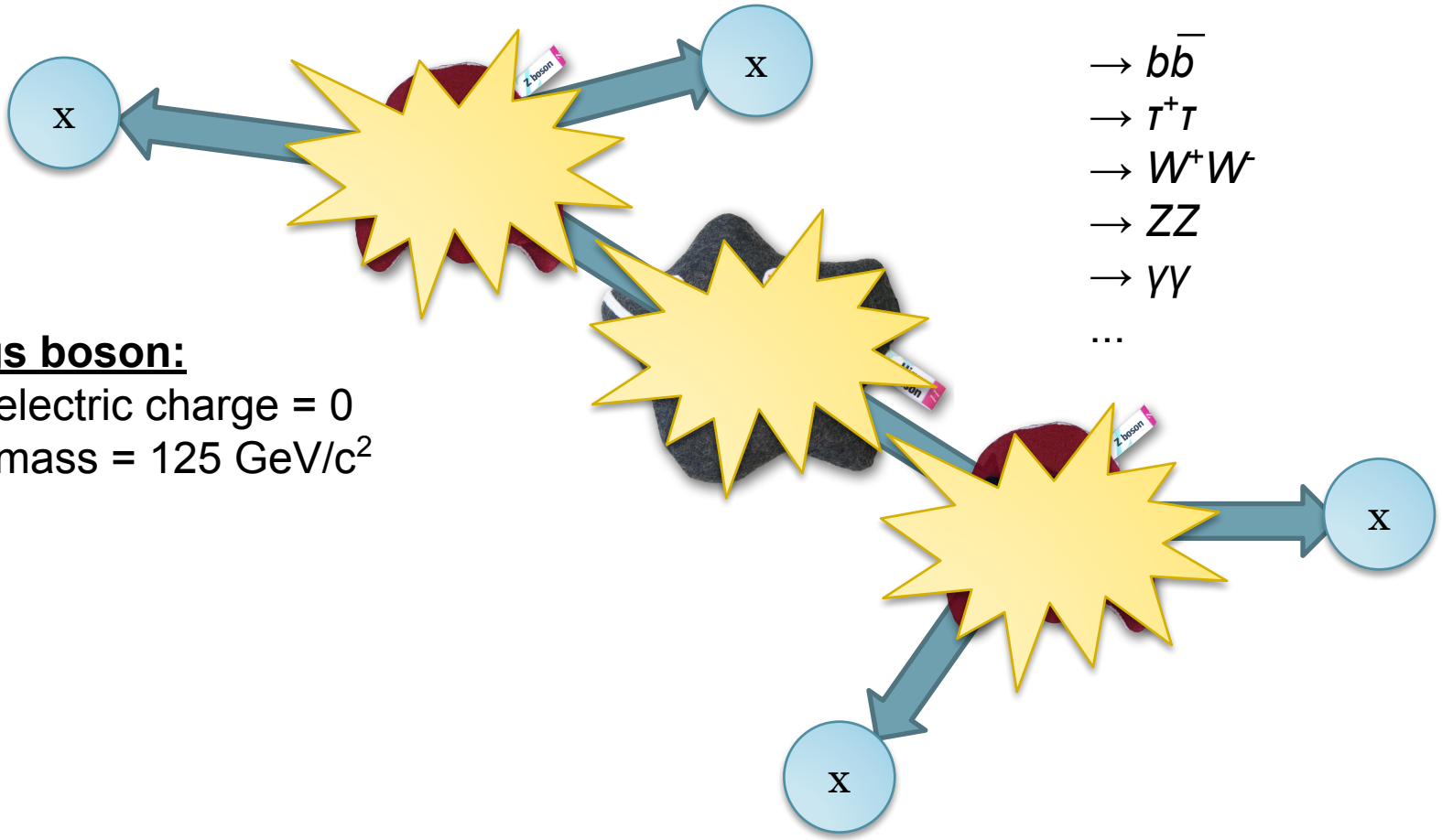
AND WHAT ABOUT THE HIGGS BOSON?

- The Higgs boson is special:
  - ➜ he prefers to decay into heavy particles
  - ➜ some of these heavy particles can also be unstable and decay



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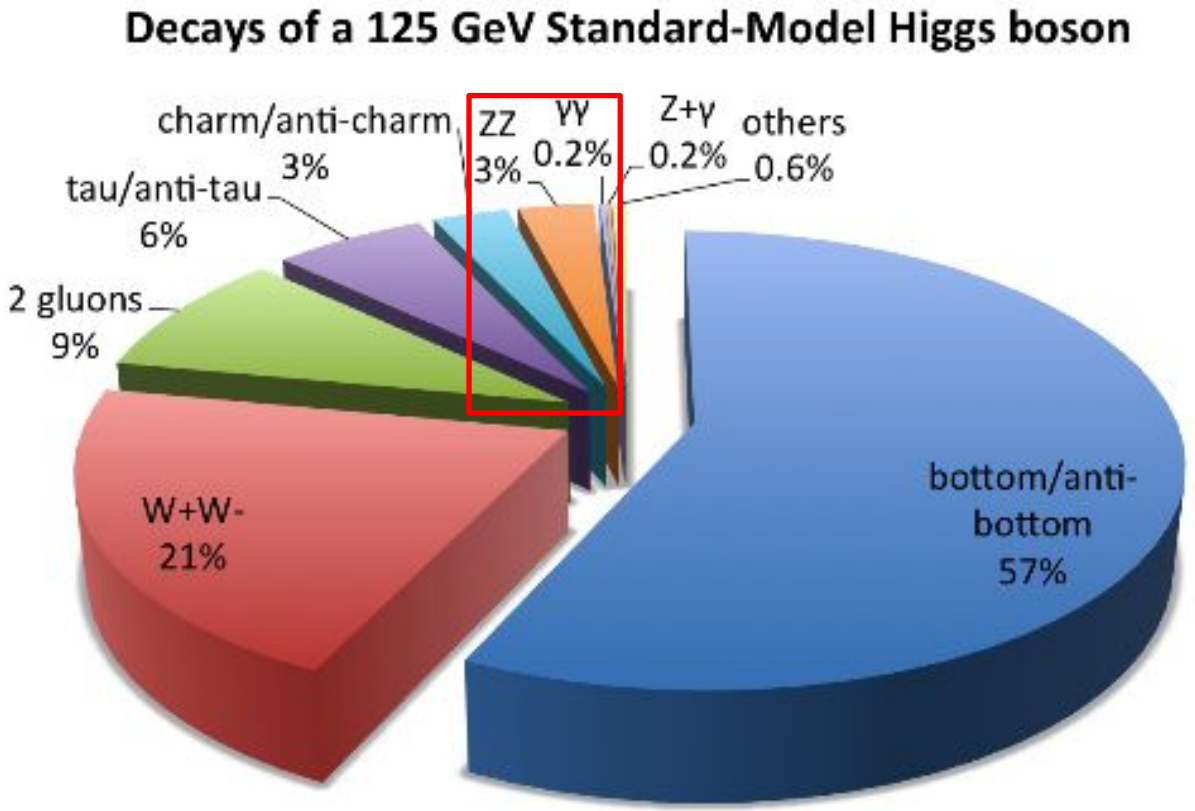
AND WHAT ABOUT THE HIGGS BOSON?

- Again, we like rare (but clean!) processes, so we look for:
  - ➜ H → two photons
  - ➜ H → ZZ → four leptons (electrons or muons)



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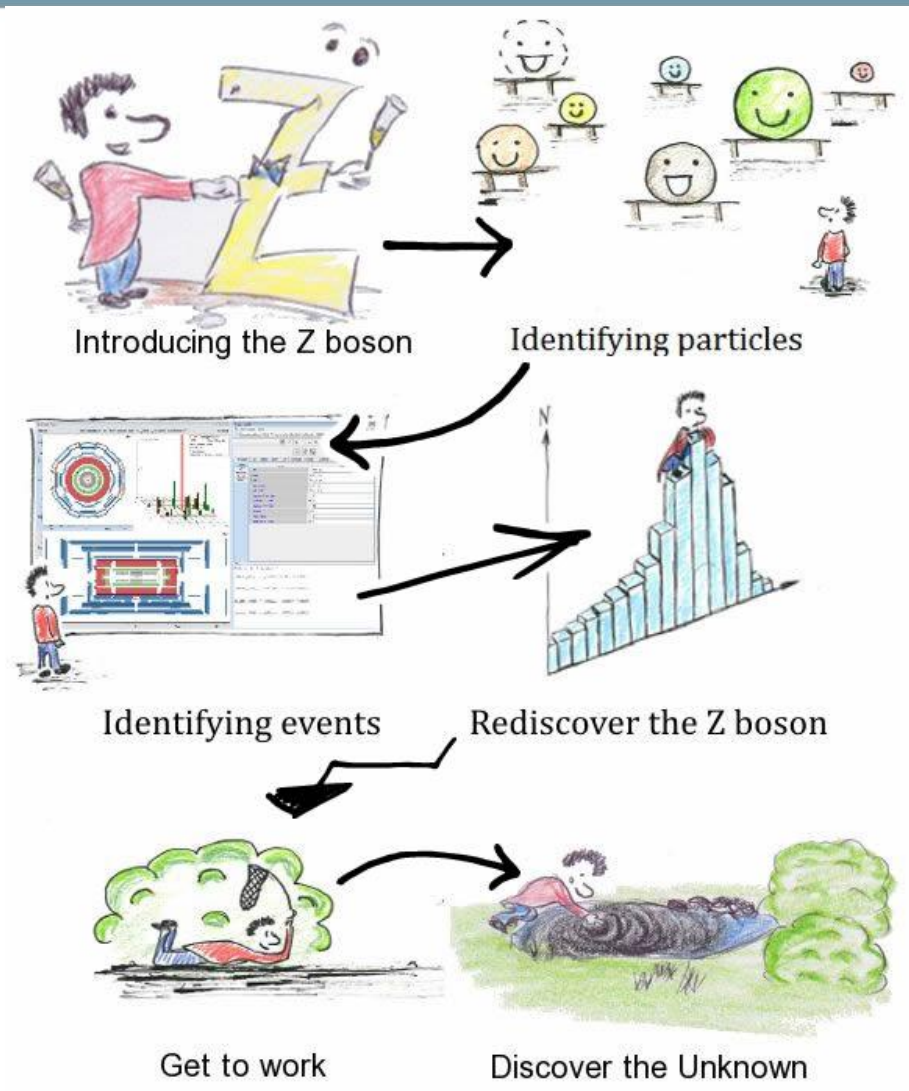
HANDS ON

- We will use the software Hypatia
  - ➜ an “event viewer”
- For each collision event (even real ATLAS data!) it shows as an interactive picture, with which we can:
  - ➜ see revealed particle trajectories
  - ➜ distinguish different types of particles
  - ➜ combine pairs of particles to see hypothetical parent particle (Z or Higgs bosons?)



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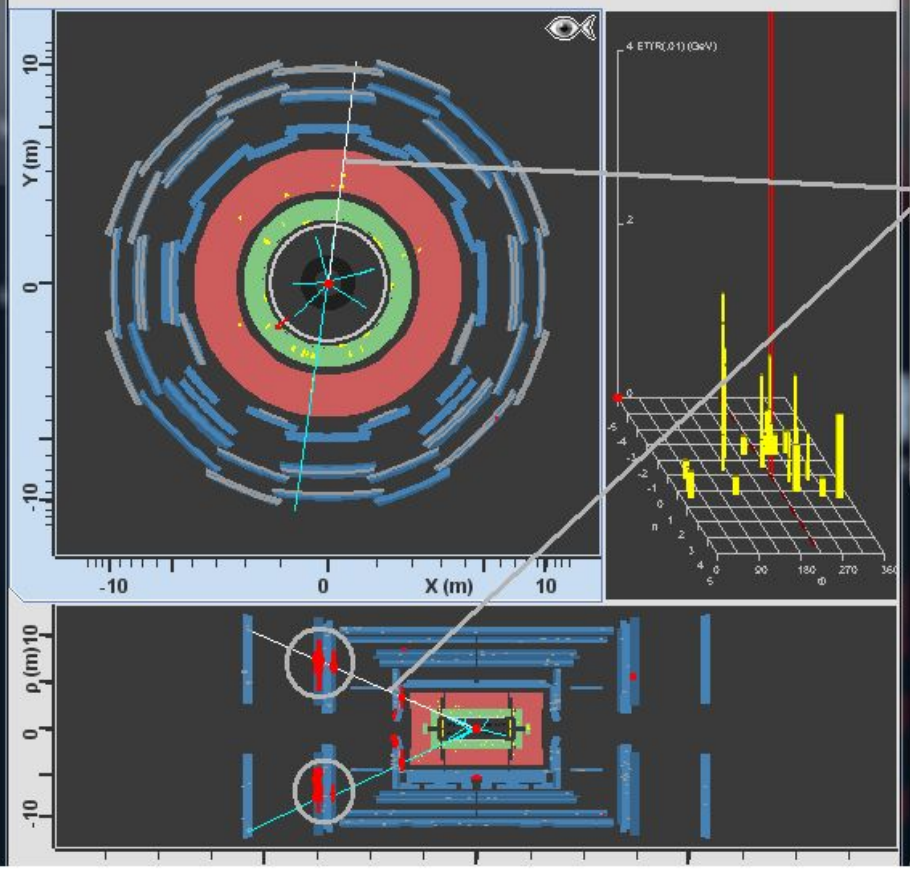
HYPATIA

Hybrid pupils' analysis tool for interactions in ATLAS - version 6.0 - Invariant Mass Window

File View Histograms Preferences Help

File Name	ETMis [GeV]	Track	P [GeV]	+/-	Pt [GeV]	φ	η	M(2l) [GeV]	M(4l) [GeV]	e/μ
00036_JiveXML_166964_987982.xml	19.626	Tracks 3	112.6	+	49.4	1.441	-1.464	95.325		μ
		Tracks 69	96.8	-	45.9	-1.720	-1.378			μ

Canvas Window - File: 00036_JiveXML_166964_987982.xml Run: 166964 Event: ...



HYPATIA - Track Momenta Window

File | Previous Event | Next Event | Insert Electron | Insert Muon | Delete Track | Reset Canvas

ETMis: 20.808 GeV φ: -2.415 rad Collection: MET_RefFinal

C:\installers\HYPATIA\groupA\00036_JiveXML_166964_987982.xml

Reconstructed Tracks

Track	+/-	P [GeV]	Pt [GeV]	φ	θ
Tracks 3	+	112.57	49.42	1.441	2.687
Tracks 69	-	96.83	45.88	-1.720	2.648
Tracks 127	-	37.93	30.81	1.803	0.948
Tracks 128	+	25.73	12.70	0.303	2.625
Tracks 134	+	121.30	89.22	-0.597	2.315
Tracks 136	-	34.18	8.63	-3.123	0.255
Tracks 154	+	14.19	8.35	-2.346	2.513
Tracks 176	-	13.53	12.74	0.259	1.915

HYPATIA - Control Window

Parameter Control | Interaction and Window Control | Output Display

Projection | Data | Cuts | InDet | Calo | MuonDet | Objects | Geometry

InDet | Calo | MuonDet | Objects | ATLAS

Name		Value
✔ |Pt|	>	5.0 GeV
|d0|	<	2.5 mm
|z0|	<	20.0 cm
|d0 Loose|	<	2.0 cm
|z0-zVtx|	<	2.5 mm

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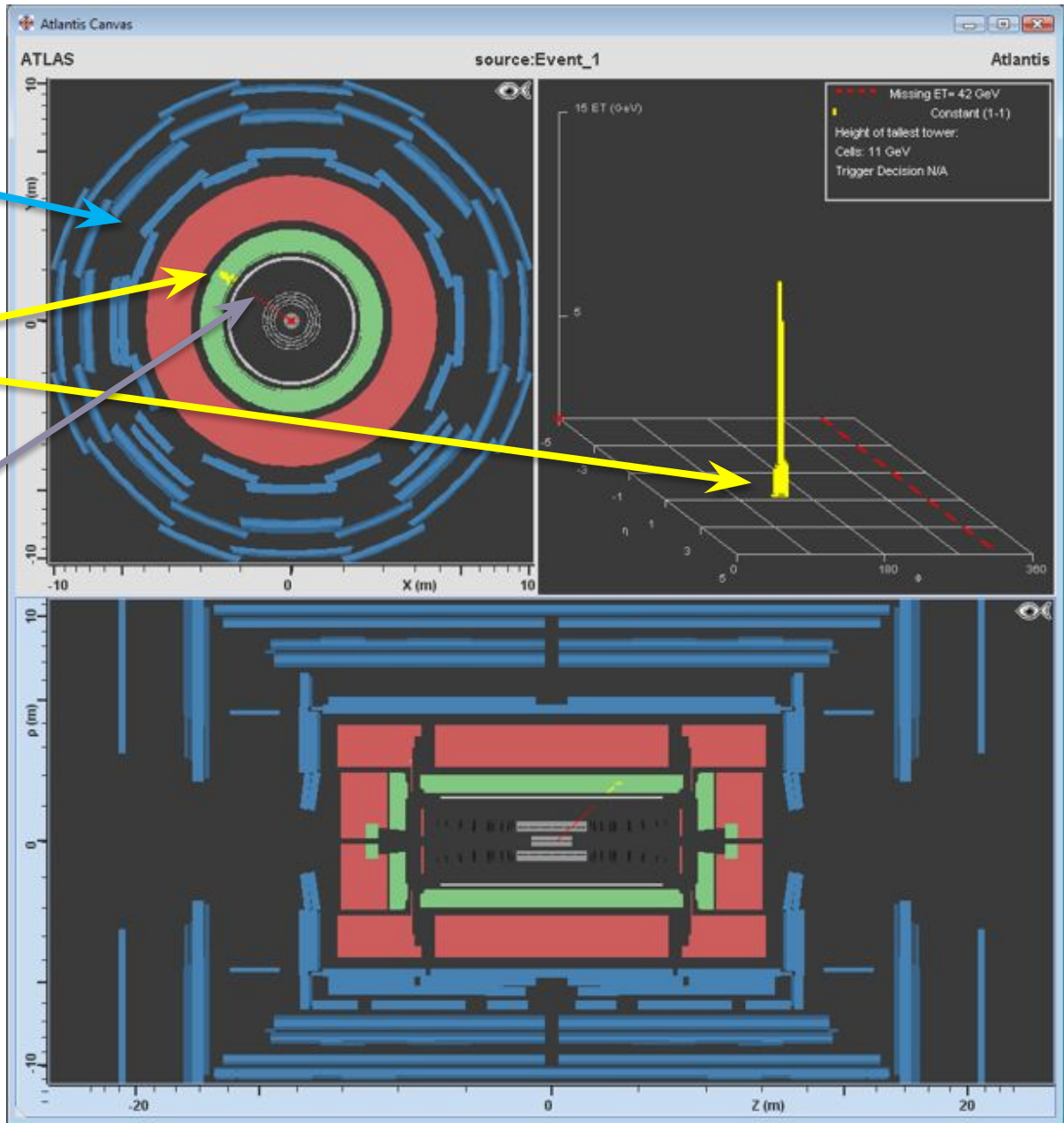
ELECTRON

no energy in the Had-Cal

energy in the EM-Cal

isolated track



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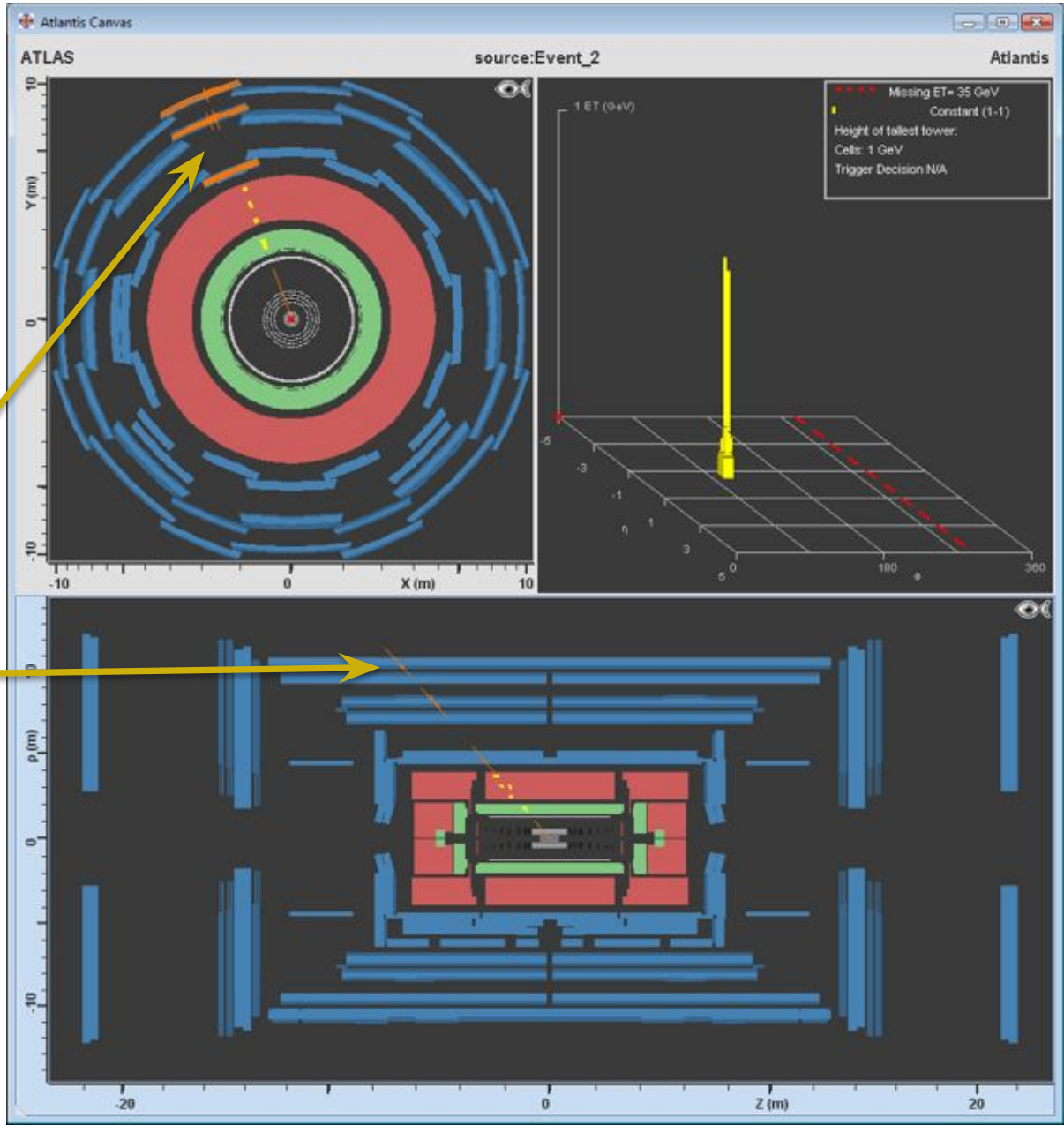
MUON

isolated track in the muon spectrometer



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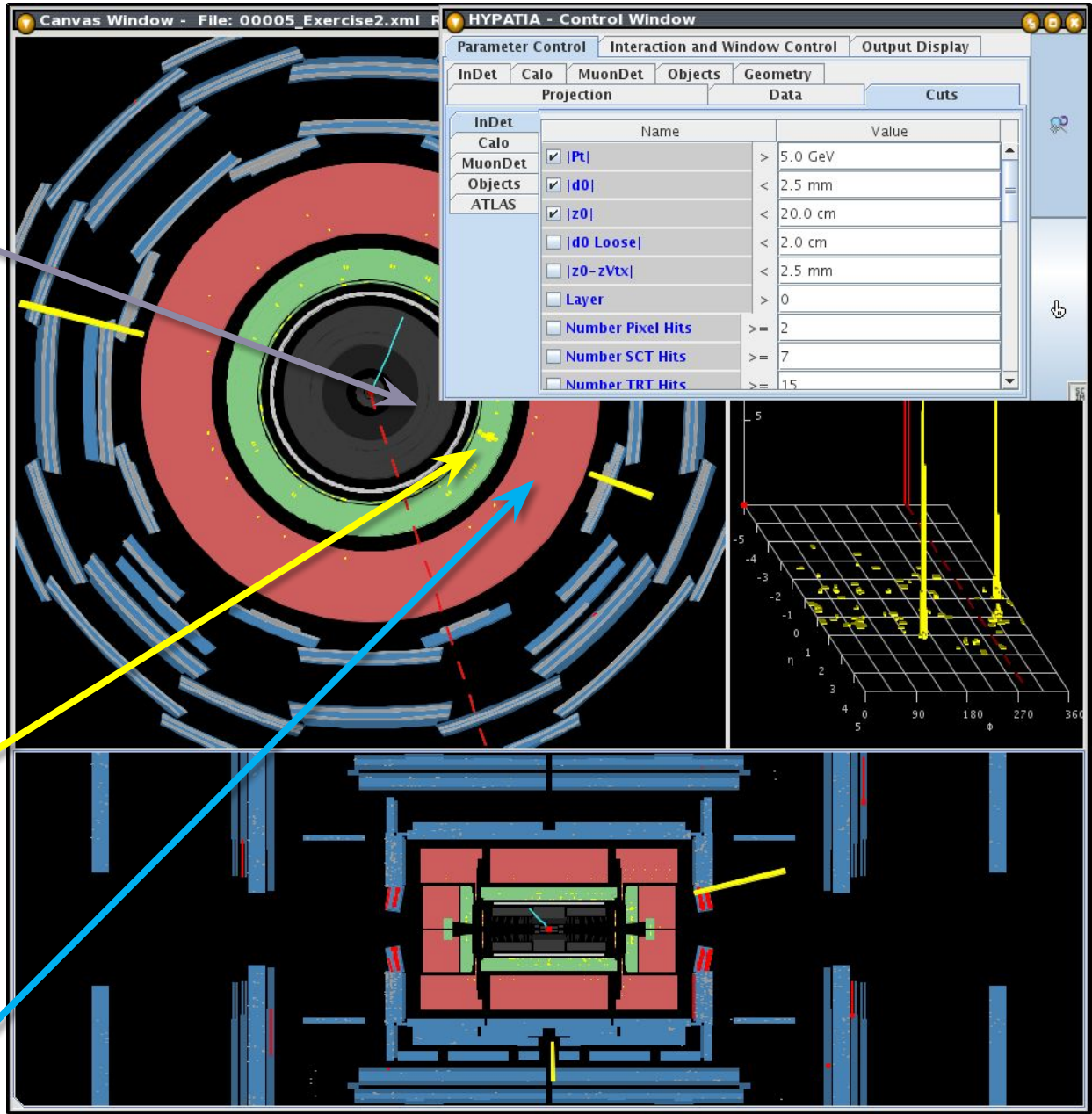
PHOTON

no energetic track associated

energy in the EM-Cal

no energy in the Had-Cal



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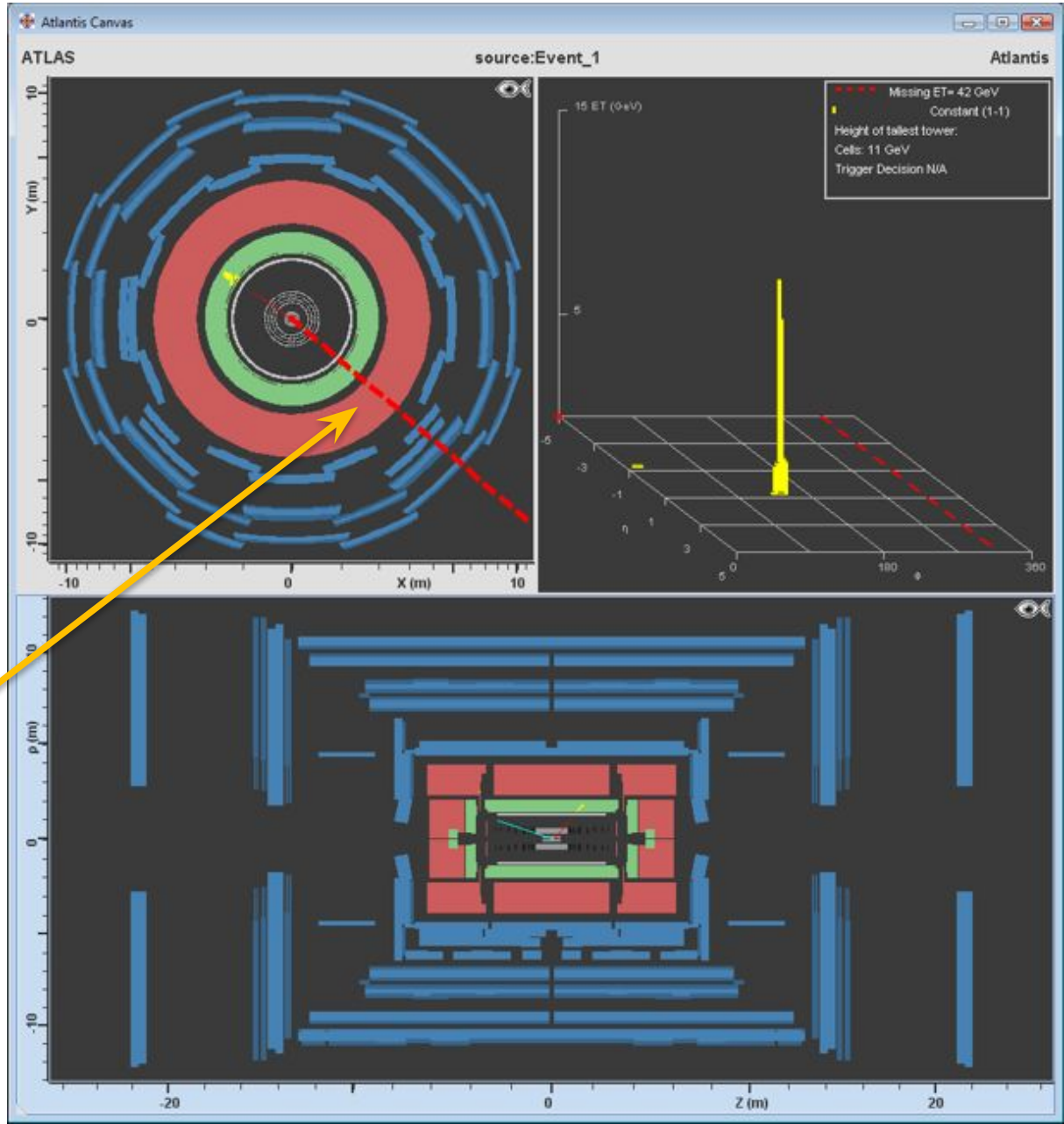
NEUTRINO

- Neutrinos are not revealed by ATLAS
  - ➜ but can be seen / reconstructed as missing energy or momentum (in the transverse plane)

look at the value of the EtMiss!



- Our Z and Higgs event shouldn't have EtMiss...

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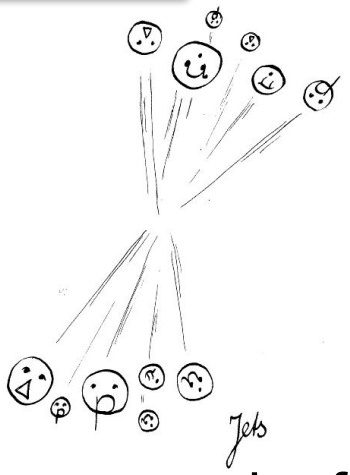
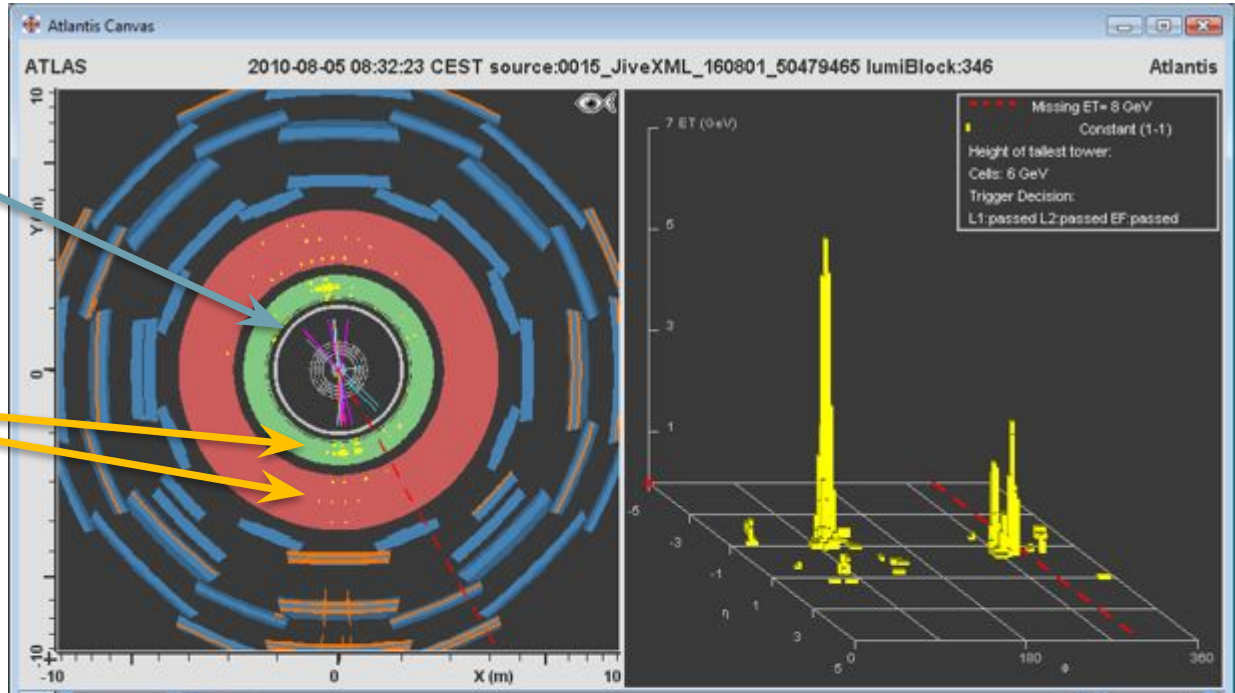
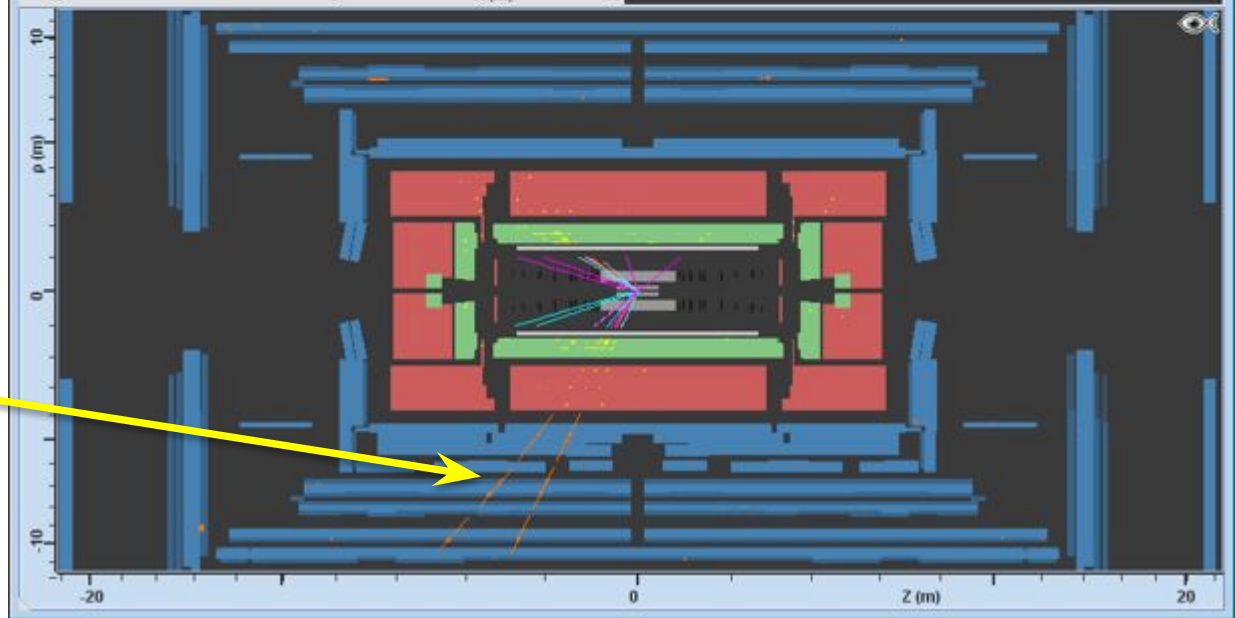
JET

many nearby tracks

energy in both EM and Had-Cal







- Muons can be found inside jets:
  - ➜ we don't want to take them as real muons!

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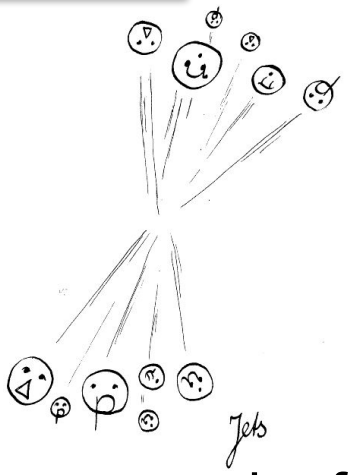
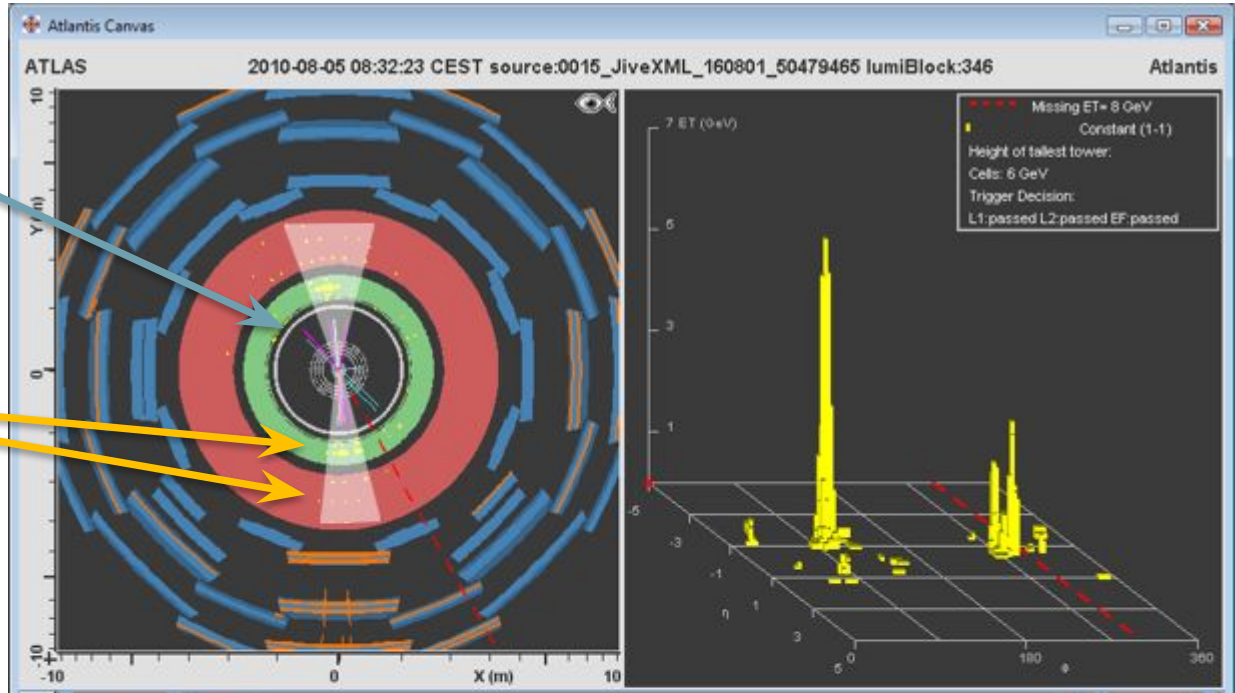
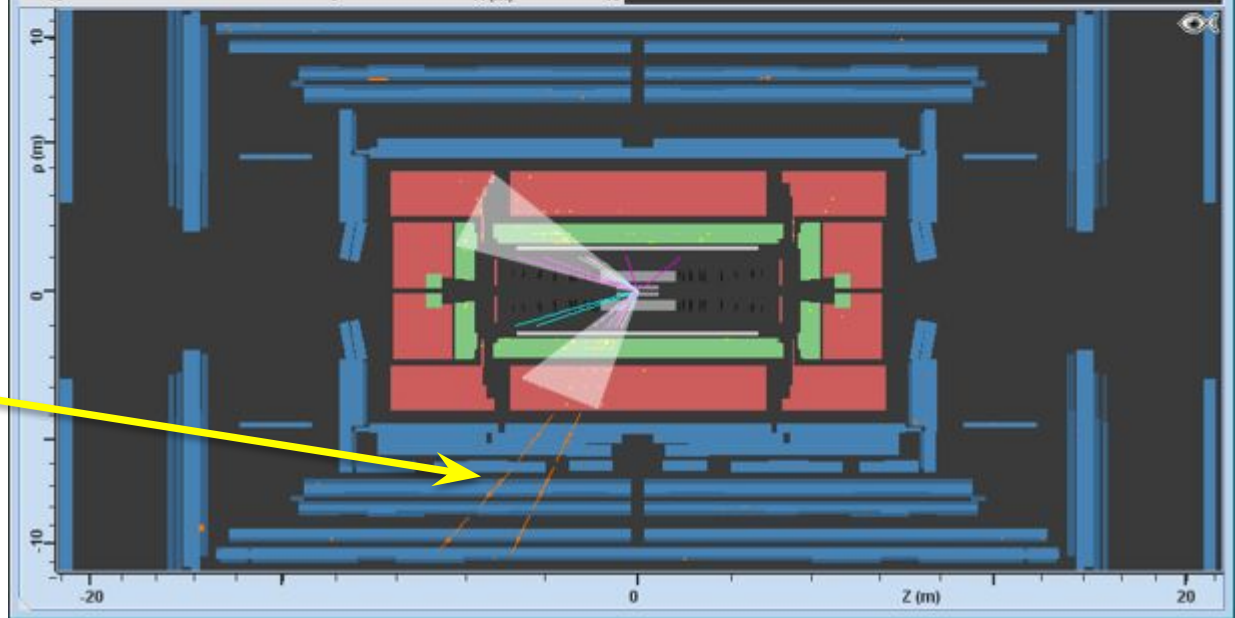
JET

many nearby tracks

energy in both EM and Had-Cal







- Muons can be found inside jets:
  - ➜ we don't want to take them as real muons!

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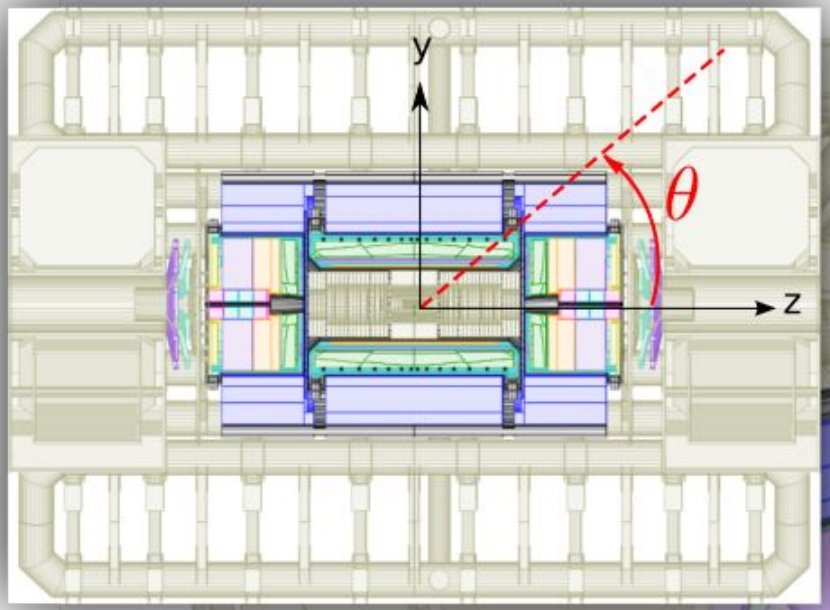
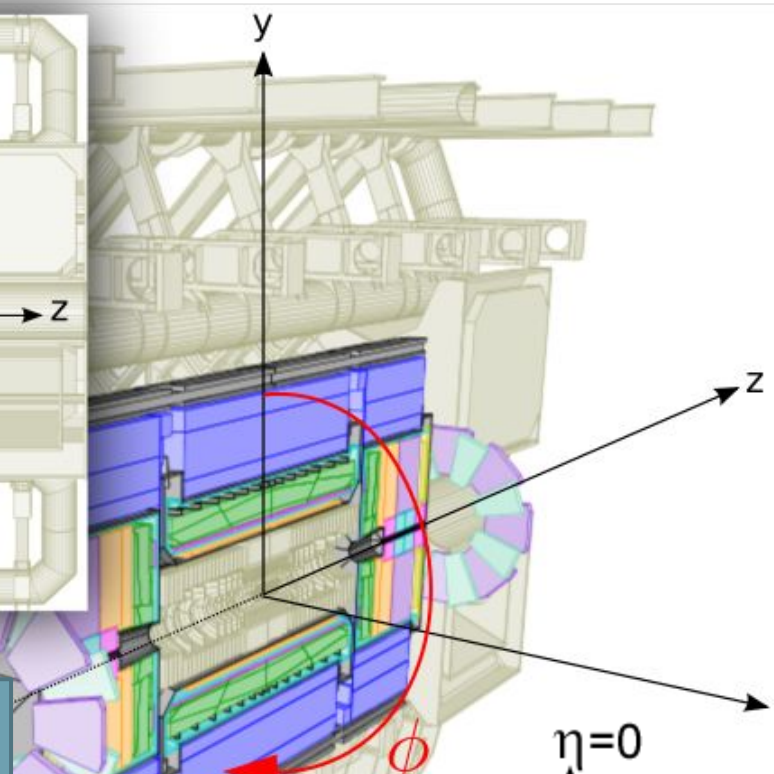
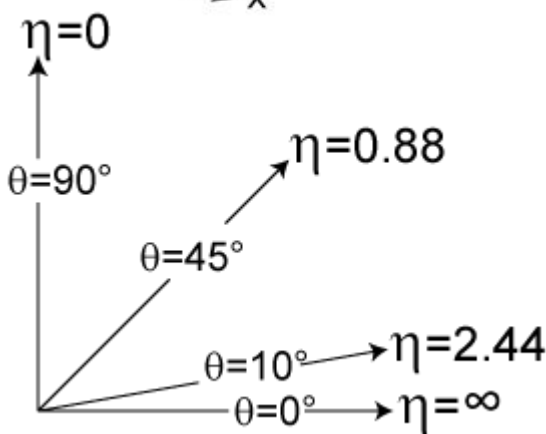
COORDINATES IN ATLAS







We will use:

- Momentum: p
- Transverse momentum: p_T
  $p_T = \sqrt{p_x^2 + p_y^2}$
- Angle in the transverse plane: φ
- Angle with respect to z: θ
  $\eta = -\ln(\tan(\theta/2))$

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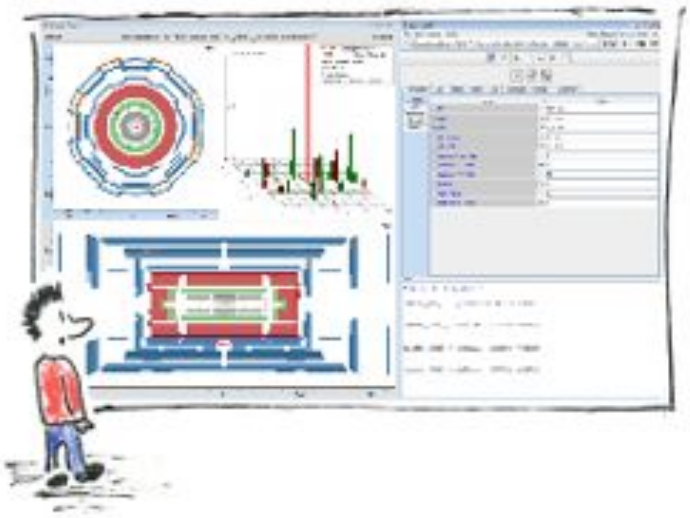
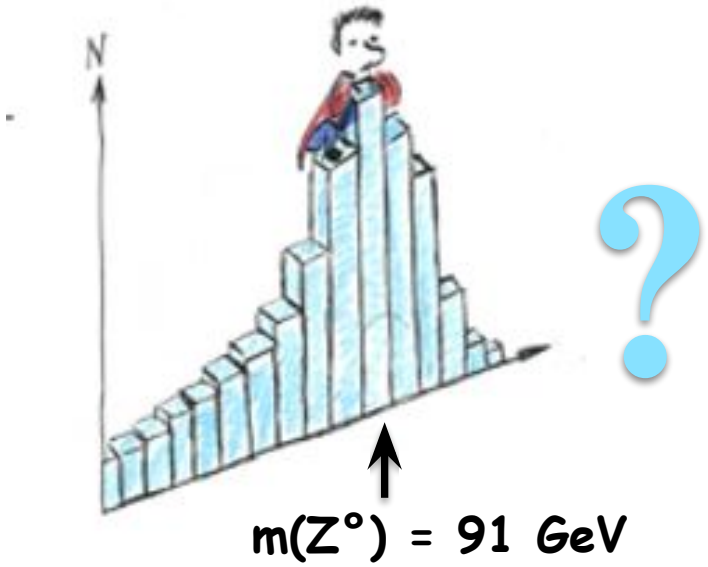
RE-DISCOVER THE Z BOSON



- Our exercise will consist in:
  - ➜ select “good” events
  - ➜ select electron, muon, photon pairs
  - ➜ fill histograms with invariant mass values



- if we do things correctly we should see a “peak” around the Z-boson mass
- but we might see something else or something more!

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... AND THE HIGGS BOSON

- Higgs-boson-production events are very rare
  ➜ you will see few of them

- To obtain the Higgs boson discovery it took time!

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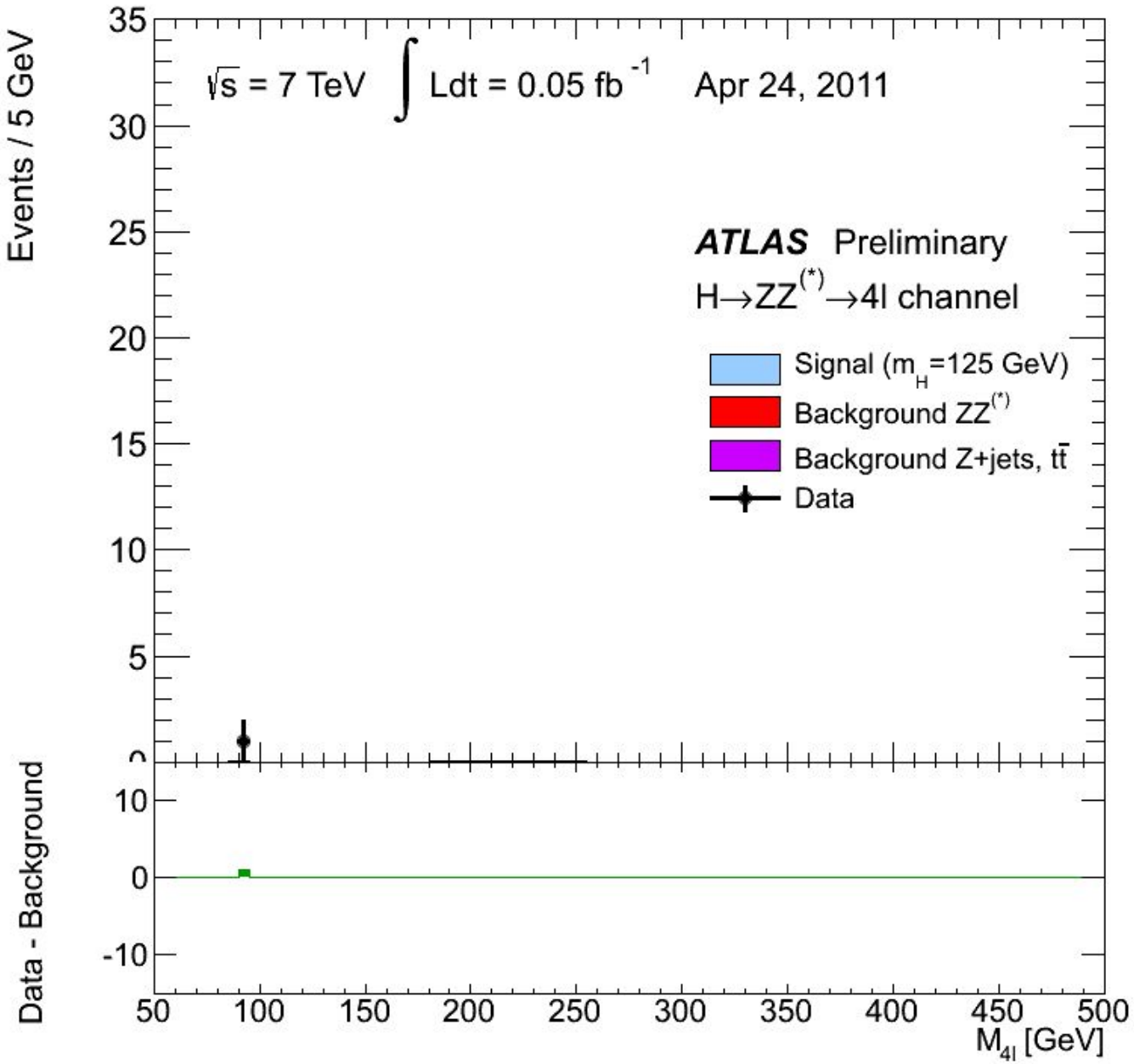

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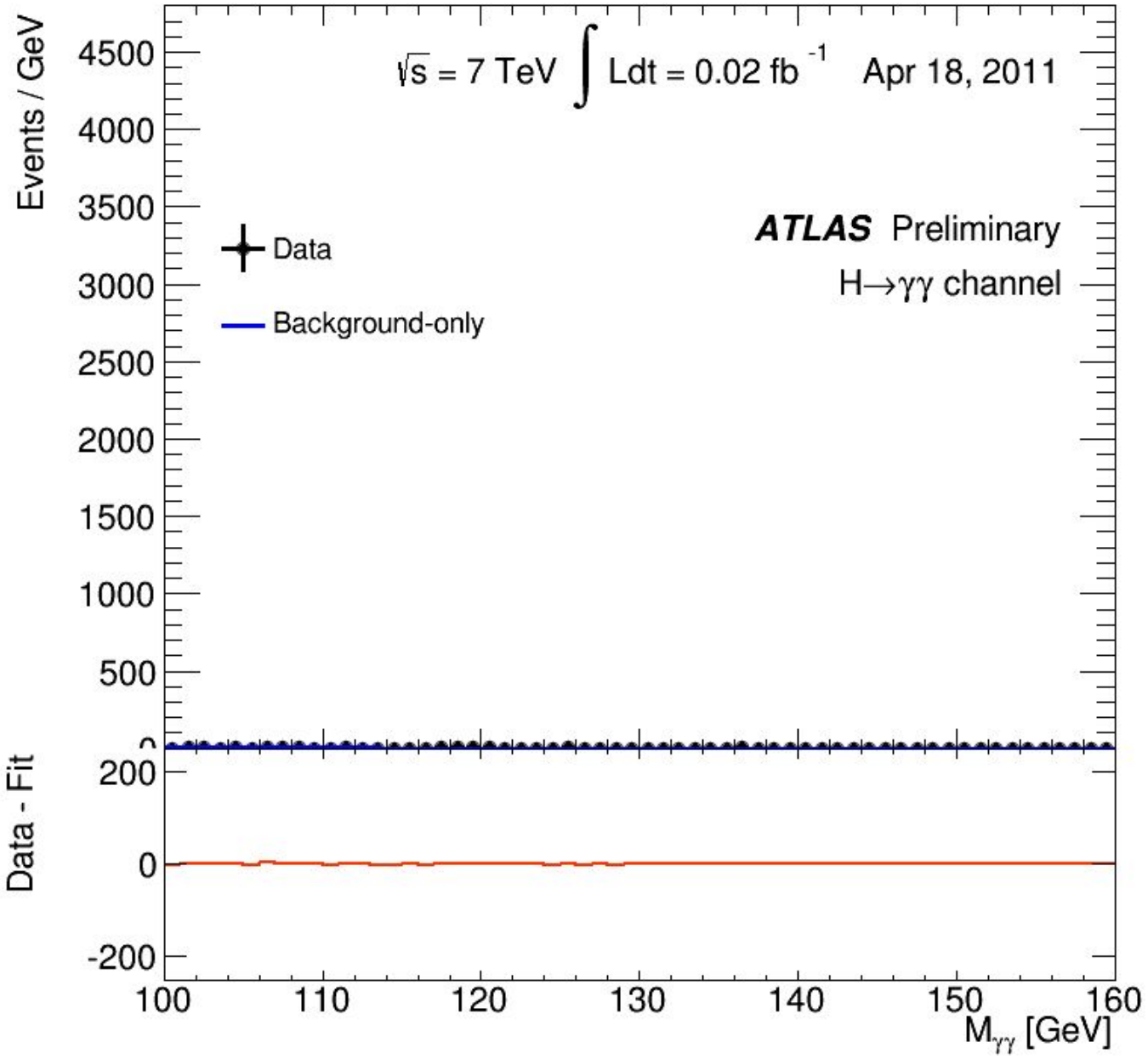

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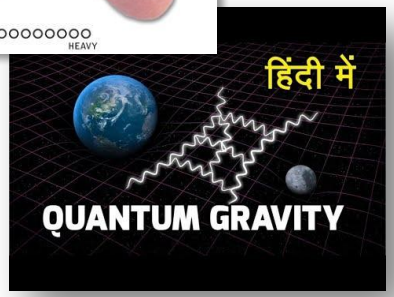
DISCOVERING NEW PHYSICS

- Many new theories predict new particles...
  - ➜ ... even heavier than the Z and the Higgs!

- The Z' boson:
  - ➜ heavy brother of the Z boson (how heavy?)
  - ➜ same decays of the Z boson
    - how to distinguish the two?



- The graviton:
  - ➜ excited states of the graviton might have large masses and be produced at the LHC
    - ... and decay in a similar way as the Higgs boson!

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TO WORK!

- And keep in mind:
  - ➜ work together
  - ➜ it takes time to practise
  - ➜ let's think critically
  - ➜ don't be shy: ask questions and ask for suggestions!

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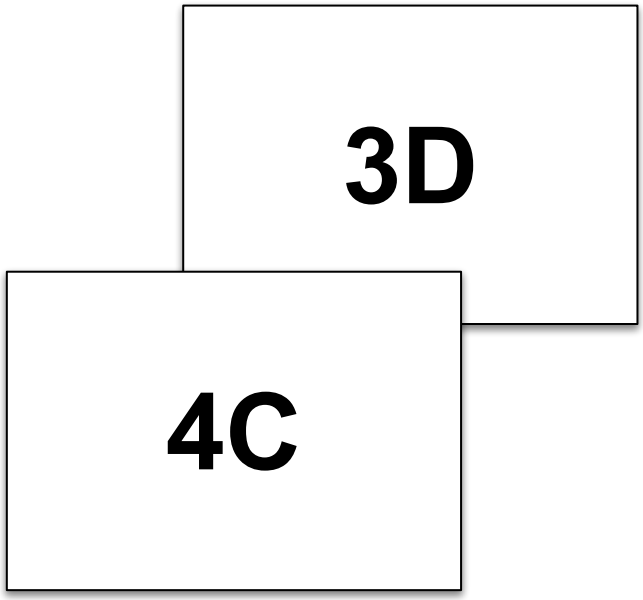
WELCOME

- Work in groups of two people
  - ➜ every group has:
    - one PC
    - two pieces of paper with a letter and a number (these are the identifiers for the data you will analyse!)



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ACCESS CREDENTIALS

- PC accounts:
  - ➜ username = masterclass
  - ➜ password = Uniud2018

- For Masterclass web-site (when requested):
  - ➜ username = ippog
  - ➜ password = imc

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CREATE YOUR WORKSPACE

- Create a new directory (on your Desktop) with an identifier of your group (i.e. one of the two letter+numbers you have)

- Every time you copy something or create a new file, do it inside there!

7D

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ACCESS THE SHARED DIRECTORY

- Open the file manager and look for the shared directory “masterclass” under “Computer”

- Go to the sub-directory “SummerSchool2018”:
  - ➜ inside there you have:
    - the Hypatia software
    - the data to analyze (including a common test data-set)
    - a text file with two web links

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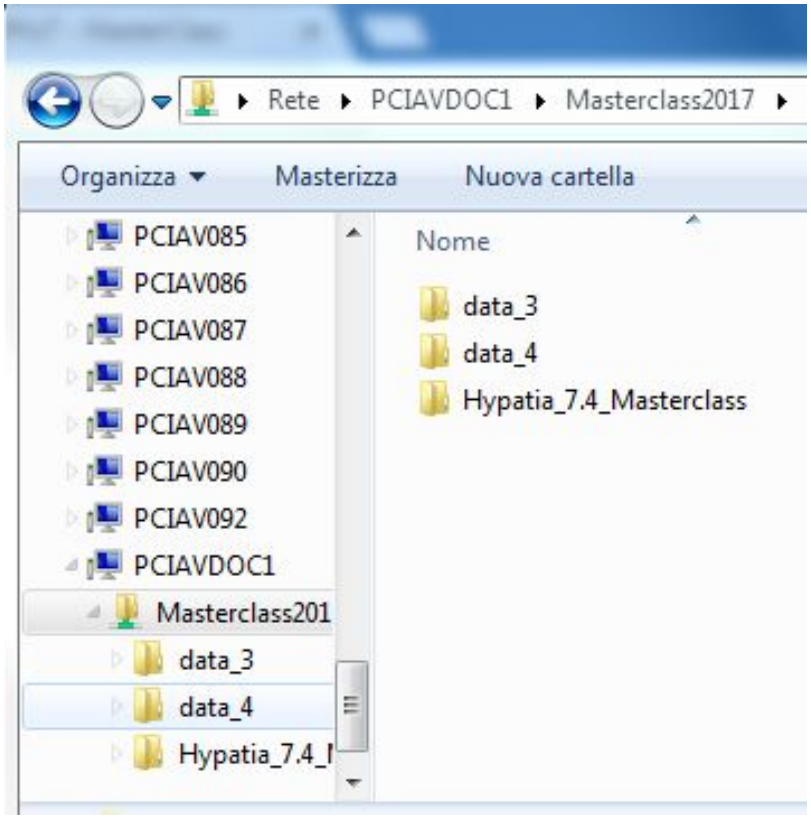
COPY NEEDED FILES

- Copy the following things to your directory:
  - ➜ The Hypatia directory “Hypatia_7.4_Masterclass”
  - ➜ The “Test” directory
  - ➜ The data-set directories corresponding to the letter/numbers you are assigned
    - under “Set 9” or “Set 10”
  - ➜ the text file “link”



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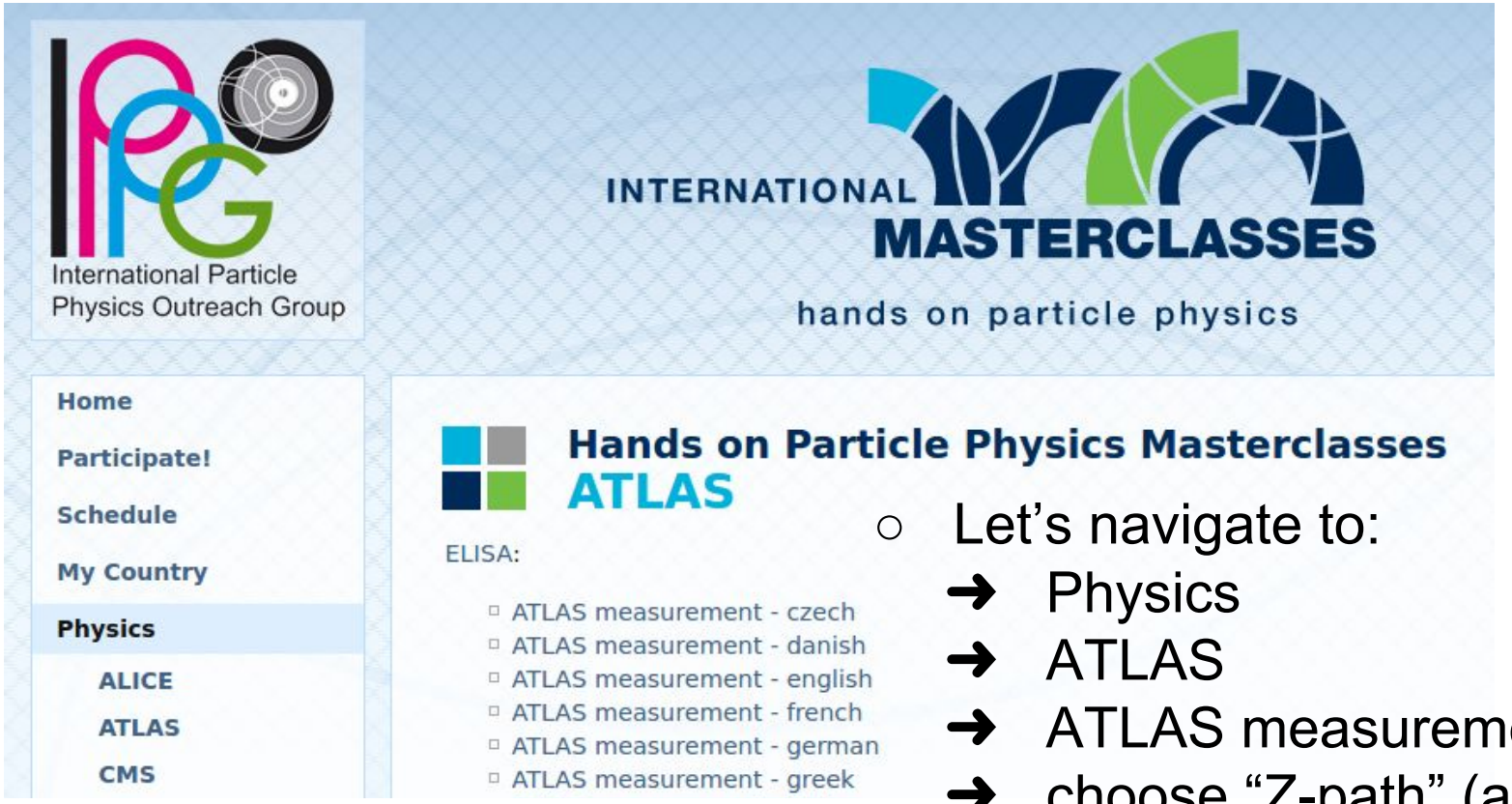
THE MASTERCLASS WEBSITE

- Open a web browser (better Internet Explorer)
- Go to this address:
  - ➜ http://physicsmasterclasses.org/



- Let's navigate to:
  - ➜ Physics
  - ➜ ATLAS
  - ➜ ATLAS measurement - english
  - ➜ choose "Z-path" (at the top)

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THE MASTERCLASS WEBSITE

- Now let's spend some time going through the material on the website

- Stop at "Visualization with Hypatia"

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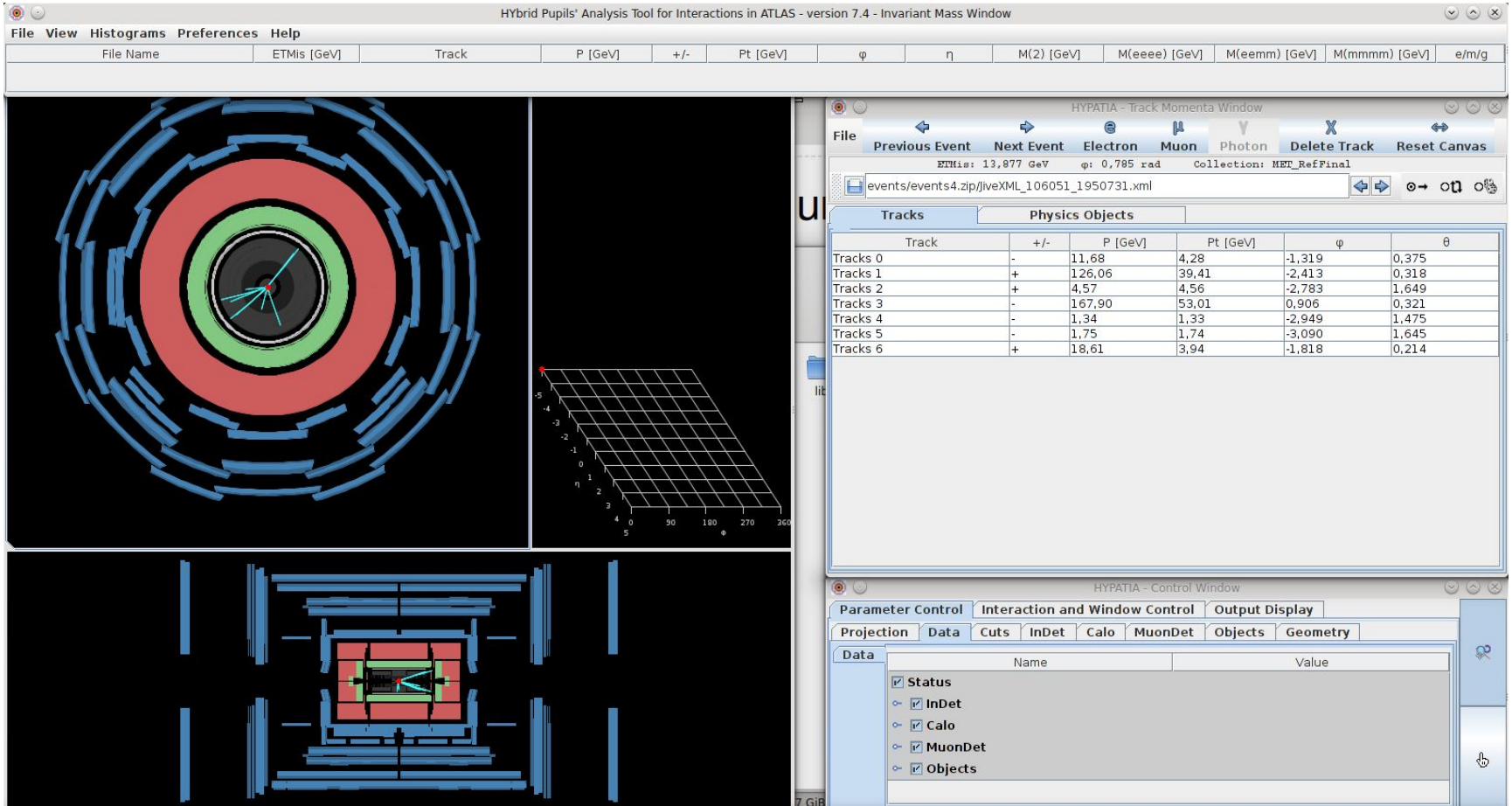
HYPATIA

- To start Hypatia:
  - ➜ go to the Hypatia directory you copied into your directory
  - ➜ double-click on Hypatia_7.4_Masterclass\Hypatia_7.4_Masterclass.jar



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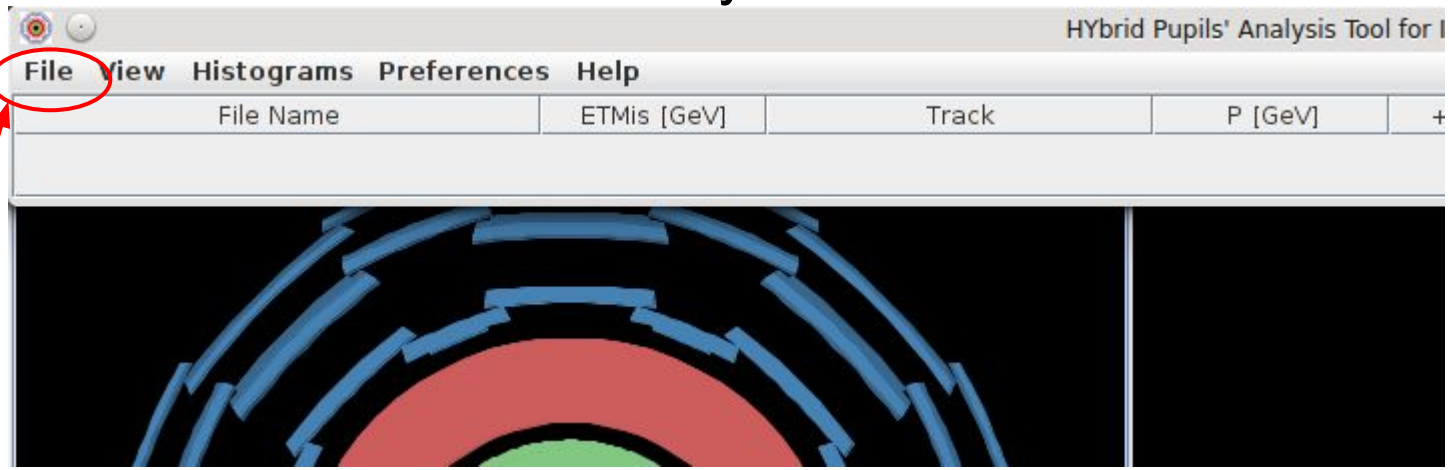
HYPATIA

- Not consider the events that are there by default!



- Go to:
  - ➜ File
  - ➜ Read event locally

- Navigate until you find the “test” dataset you copied to your directory
- Select the first .xml file there

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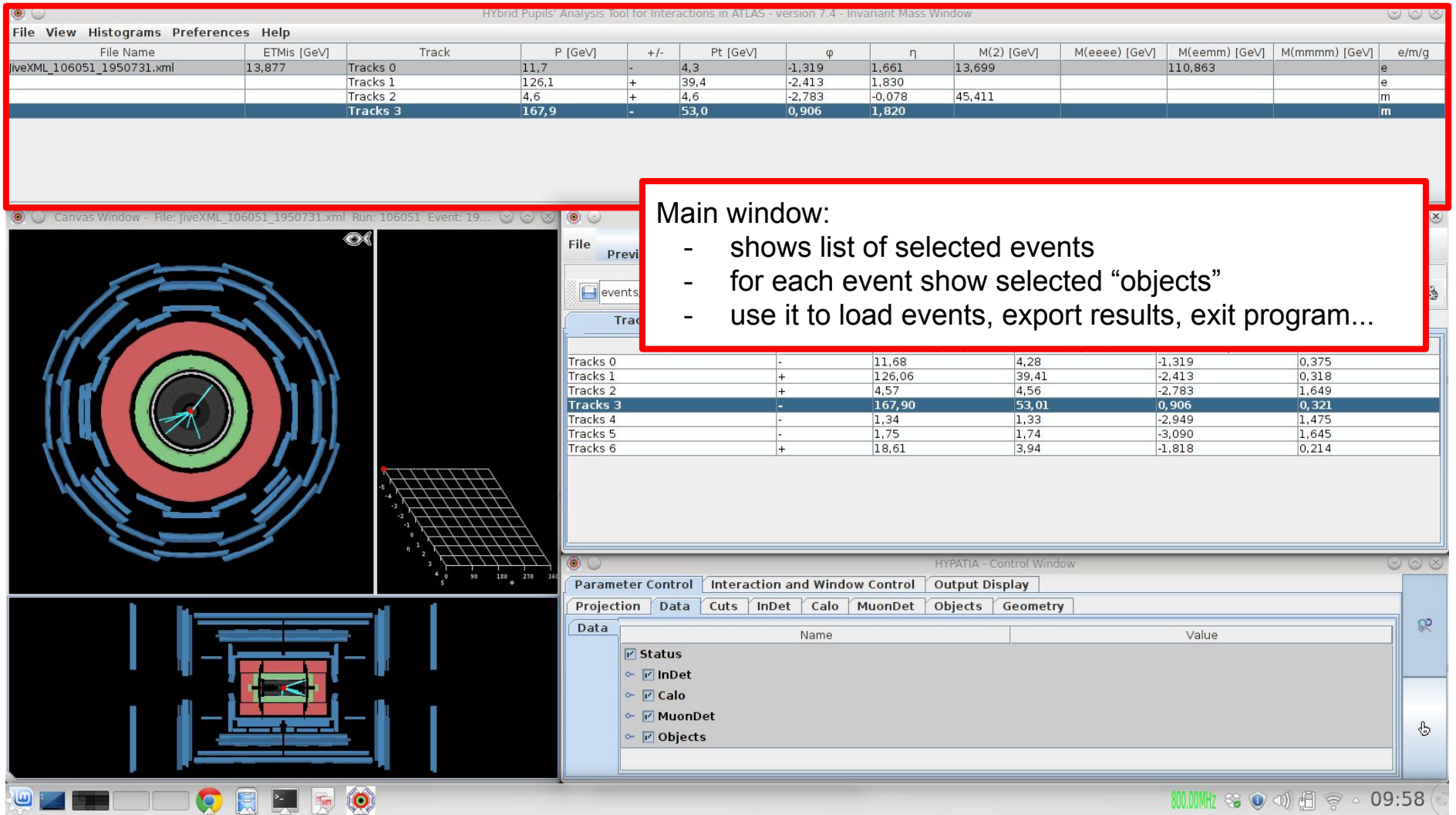
THE HYPATIA WINDOWS

- Hint adjust the windows!



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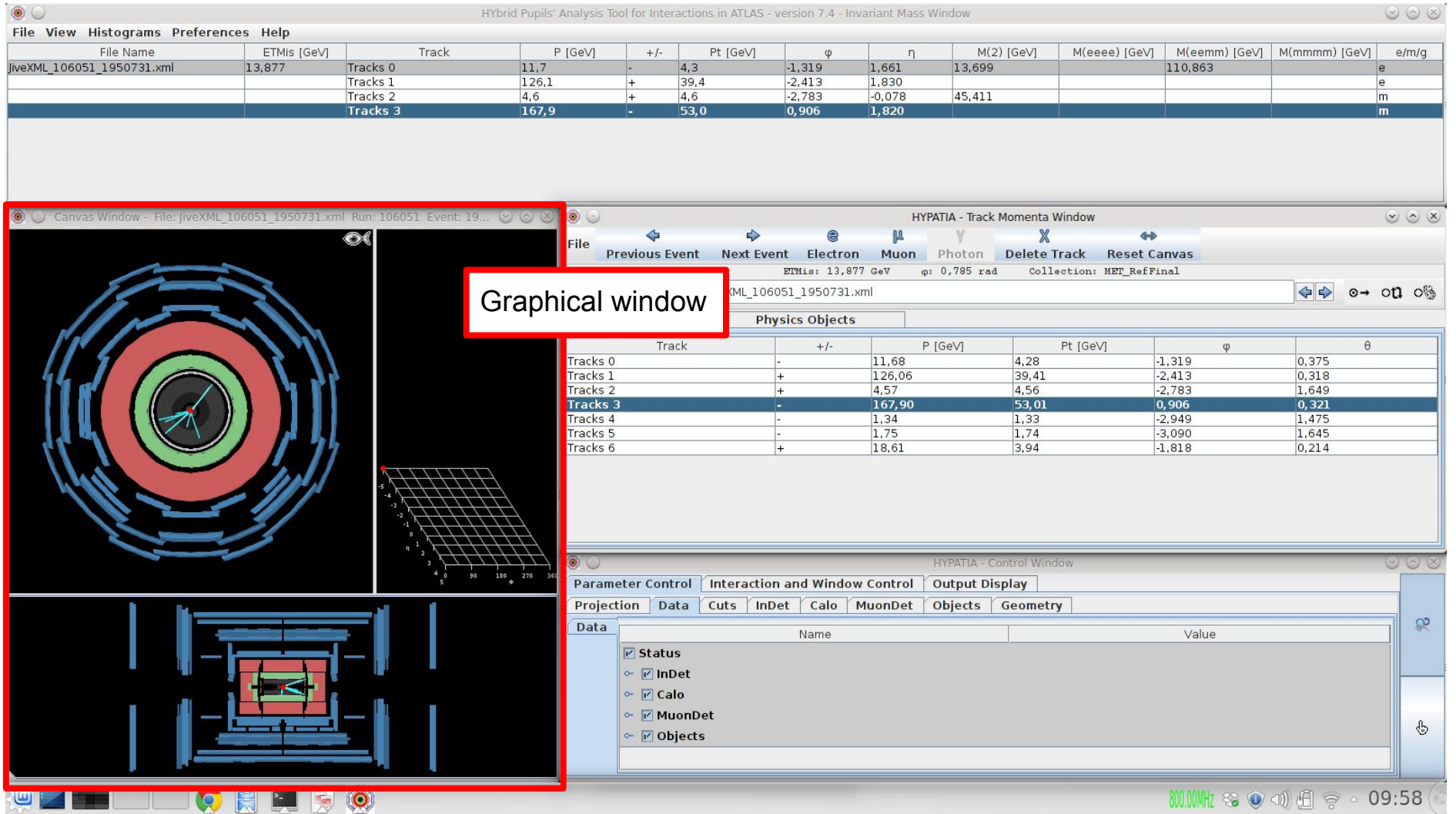

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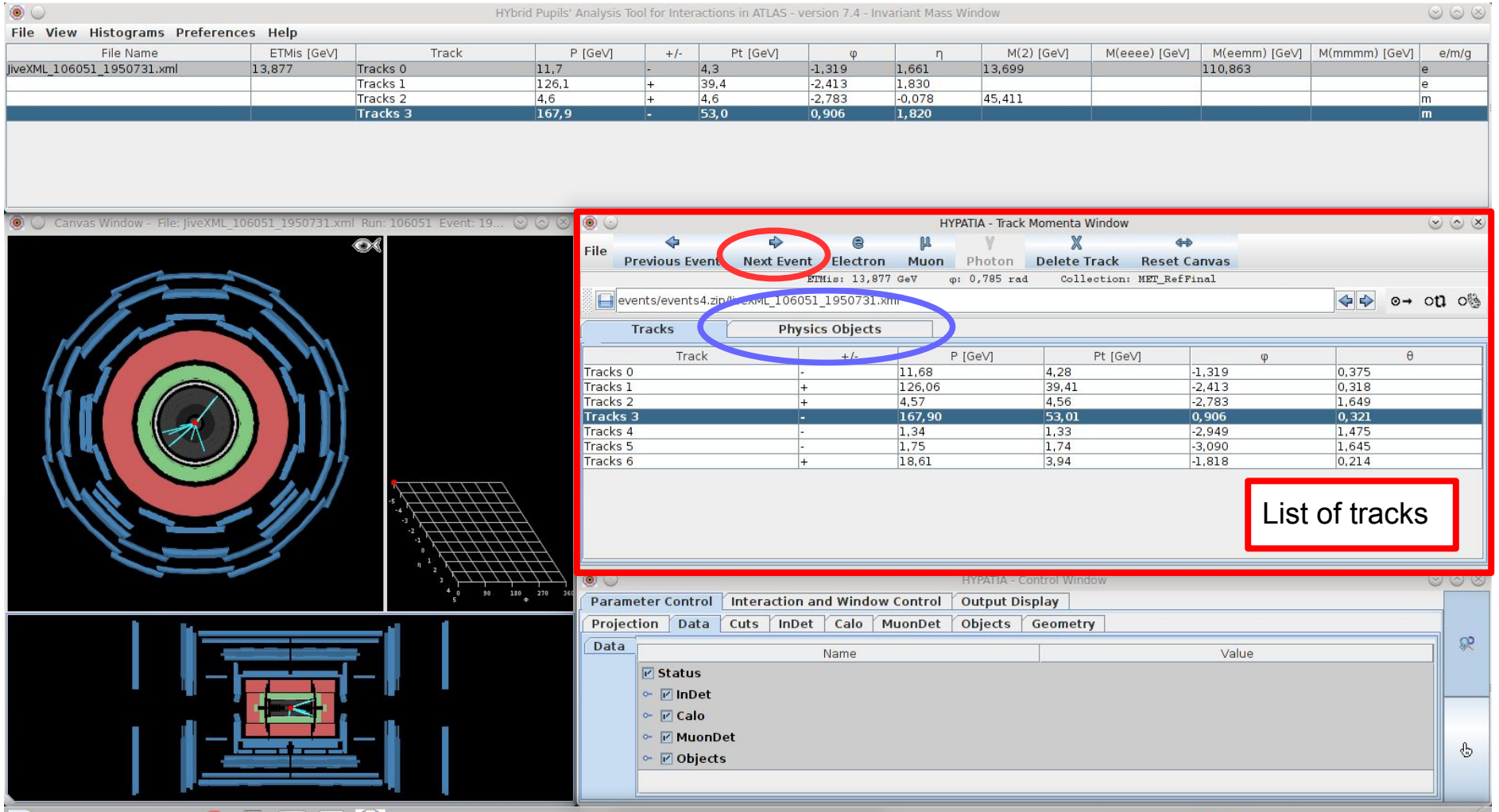

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THE HYPATIA WINDOWS

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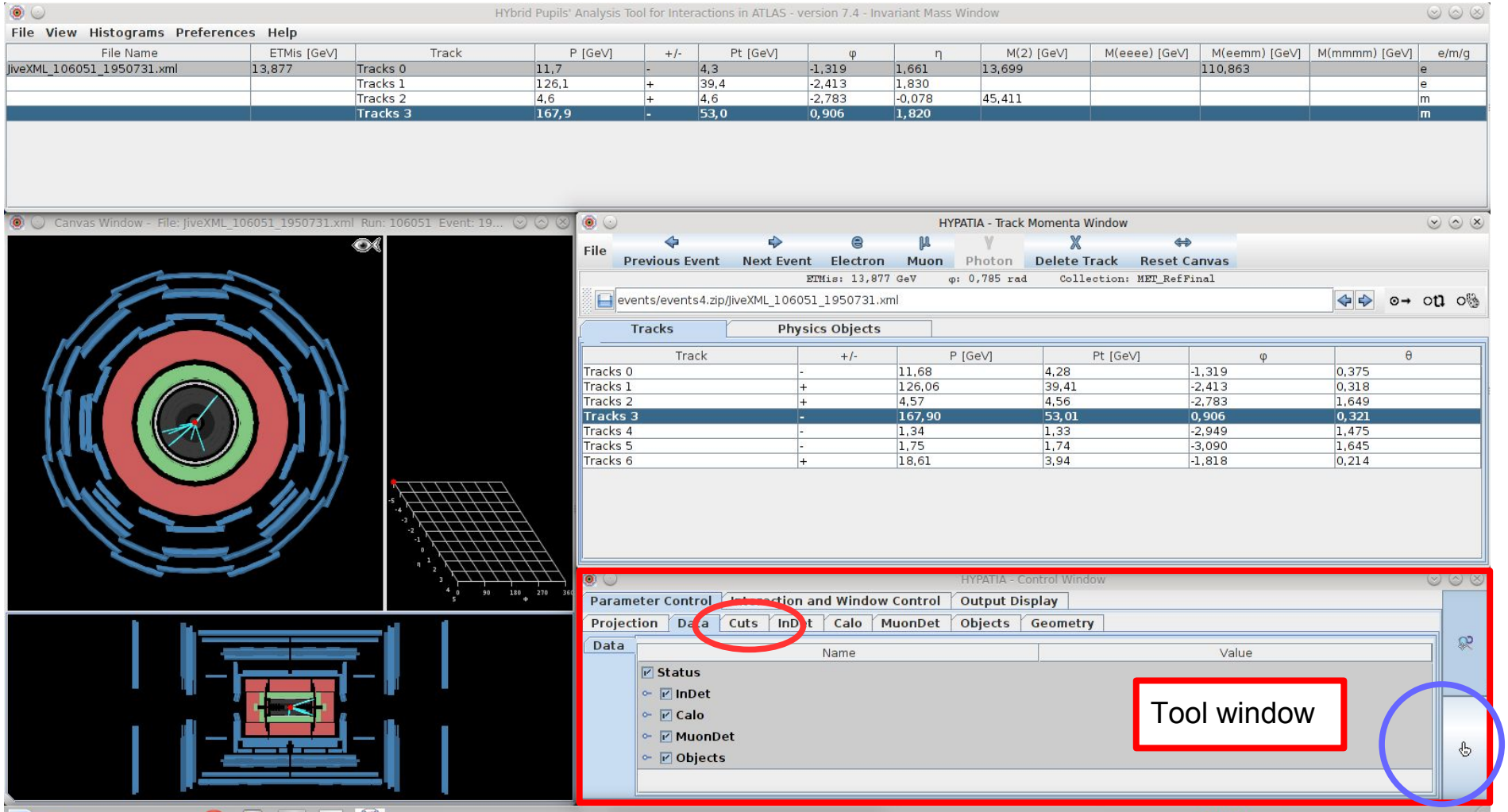

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PRACTISE

- Go back to the web-site
- Spend some time to go over the preliminary exercises:

➜ **Z-Path**

1.

Introducing the Z boson
Introducing the Higgs boson
New Physics
Identifying particles
ATLAS detector
Play!
Visualization with HYPATIA
Particle footprint visualization
Practice!

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Z-Path

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Introducing the Z boson
Introducing the Higgs boson
New Physics
Identifying particles
ATLAS detector
Play!
Visualization with HYPATIA
Particle footprint visualization
Practice!

2.

Identifying Events
When protons collide
Z events
Higgs events
Background events
Visualization
Practice!
Search and discover with mass
Get to work!

For this exercise we need few more slides....

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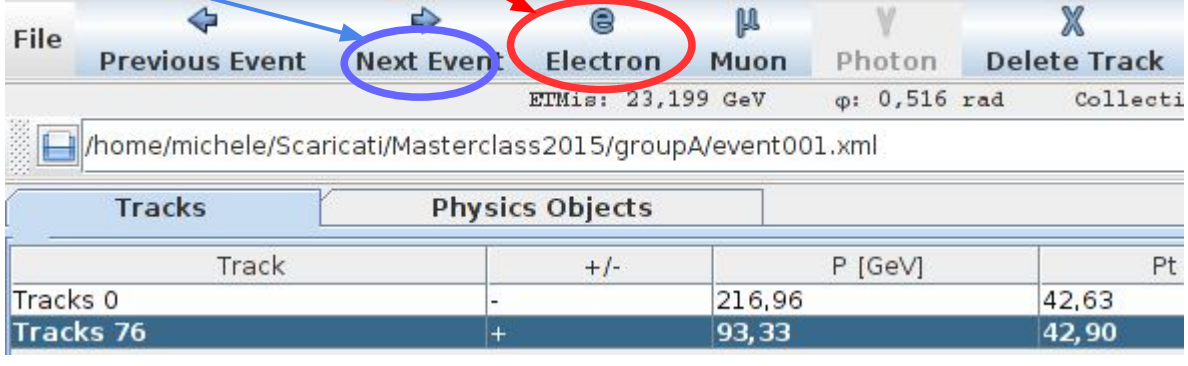
HOW TO PROCEED

- For every event, you will have to:
  - ➜ look for electrons, muons or photons
  - ➜ decide if the event is one of the following:
    - type $Z \rightarrow e^+e^-$ / $\mu^+\mu^-$
    - type $H \rightarrow ZZ \rightarrow$ 4-leptons
    - type $H \rightarrow \gamma\gamma$
  - ➜ if yes (!!), **select** the proper objects
    - they will be saved in the upper window
  - ➜ if not, the event is “background”
    - pass to **next event**

to remove objects wrongly inserted



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FEW TRICKS

- Check pT of objects:
  - ➜ Z and Higgs boson decay products are typically high-pT
  - ➜ relatively high pT means > 10 GeV/c
  - ➜ in case of doubt between different tracks to select, choose the higher pT one

- Check the electric charge:
  - ➜ pair of particles have to be oppositely-charged
  - ➜ in Higgs → 4-lep events the order is important:
    - +-+- → yes
    - +--+ → yes
    - ++-- → no!

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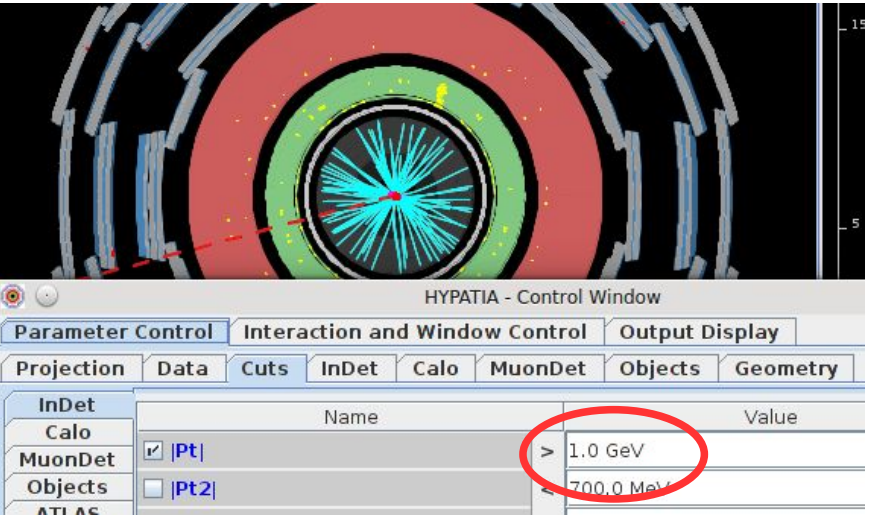
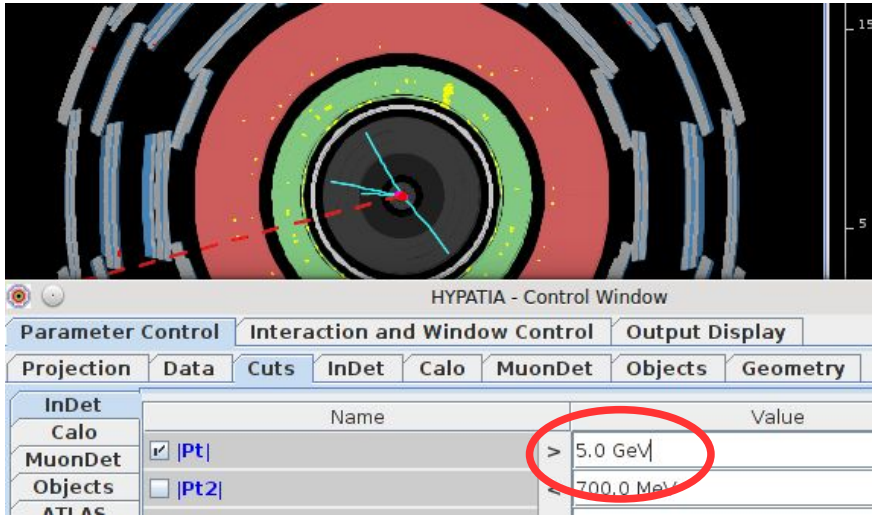
FEW TRICKS

- Rise the pT cut on the tracks to clean-up the view!
  ➜ to do it, go to the tools window, “Parameter Control”, “Cuts”





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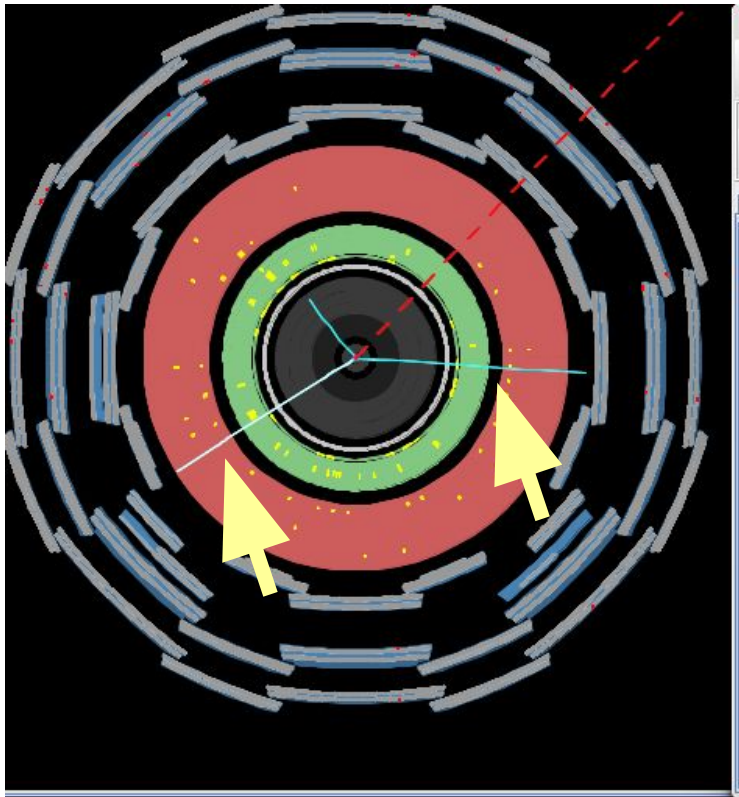
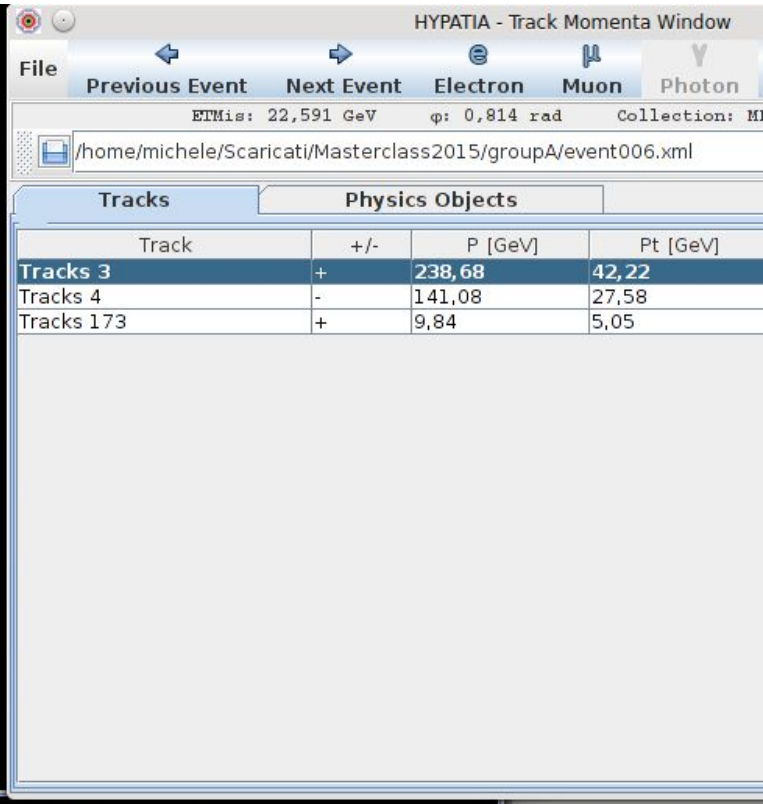
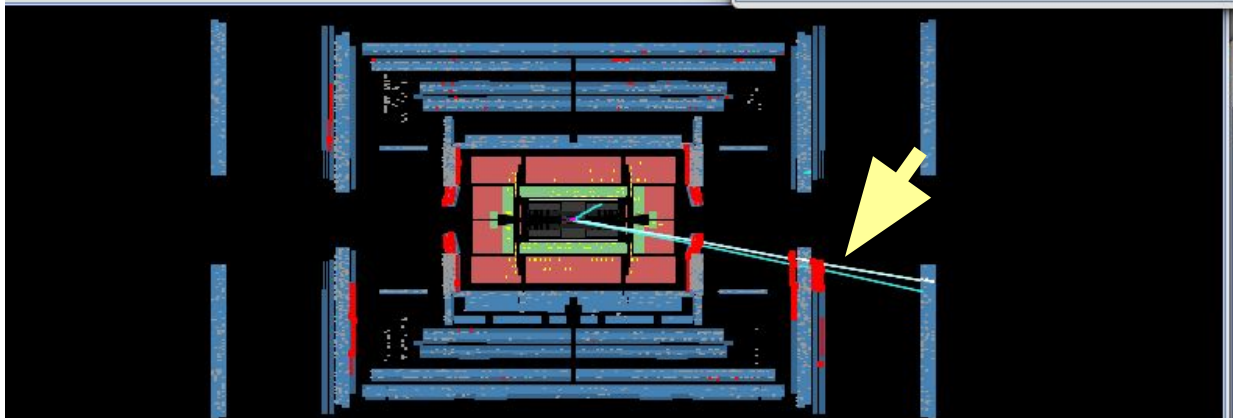
FEW TRICKS

- Pay attention to non-central muons, electrons, photons...







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FINAL INDICATIONS

- Don't look at the "invariant mass" values when collecting events!
  - ➜ select events regardless of the invariant mass values
  - ➜ e.g. keep events even if 4-lepton invariant mass is 10 GeV, or 1000 GeV!!

event004.xml	173,818	Tracks 0	605,3	-	582,0	2,195	-0,282	944,102			m
		Tracks 2	383,5	+	380,6	-0,908	-0,123				m
event005.xml	26,783	Tracks 3	58,2	-	37,7	0,707	-1,001	88,235		109,073	m
		Tracks 4	79,7	+	57,0	-1,794	-0,864				m
		Tracks 13	14,5	+	11,7	-2,513	-0,686	18,954			e
		Tracks 180	9,8	-	9,3	-0,295	-0,348				e

  - ➜ we will look at the invariant mass later

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READY STEADY, GO!

- You have two sets of 50 events each group
- And 2 hours to analyse them

➜ have fun!

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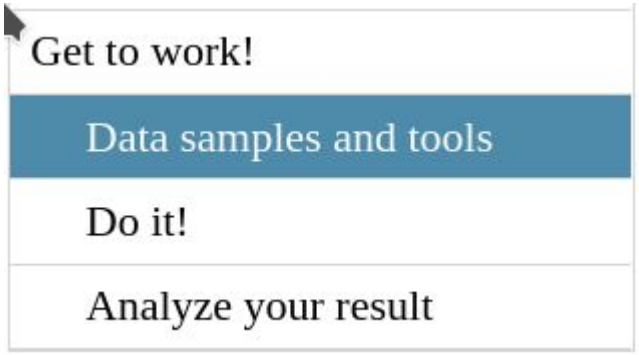
EXPORT THE RESULTS

- "File" → "Export invariant masses"
  - ➜ save the file in your working directory

- Then, from the web-site:
  - ➜



  - ➜ 3. Open the plot submission page from here
    - select "student" and upload your file(s)