2025 LIP INTERNSHIP PROGRAM

SEARCH FOR RARE PHENOMENA WITH ATLAS OPEN DATA

Rediscovering the Higgs Boson: An Analysis of $H \to ZZ^* \to 4\ell$ Decays

ATLAS open data

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LIP

What we'll talk today

01 **The Big Picture:** The Standard Model, LHC, and the Higgs Boson

02 **Our Toolkit:** The ATLAS Detector and ATLAS Open Data

03 **The Golden Channel:** $H \rightarrow ZZ^* \rightarrow 4\ell$

04 **Our Analysis:** Reconstructing Z Bosons with Three Different Methods

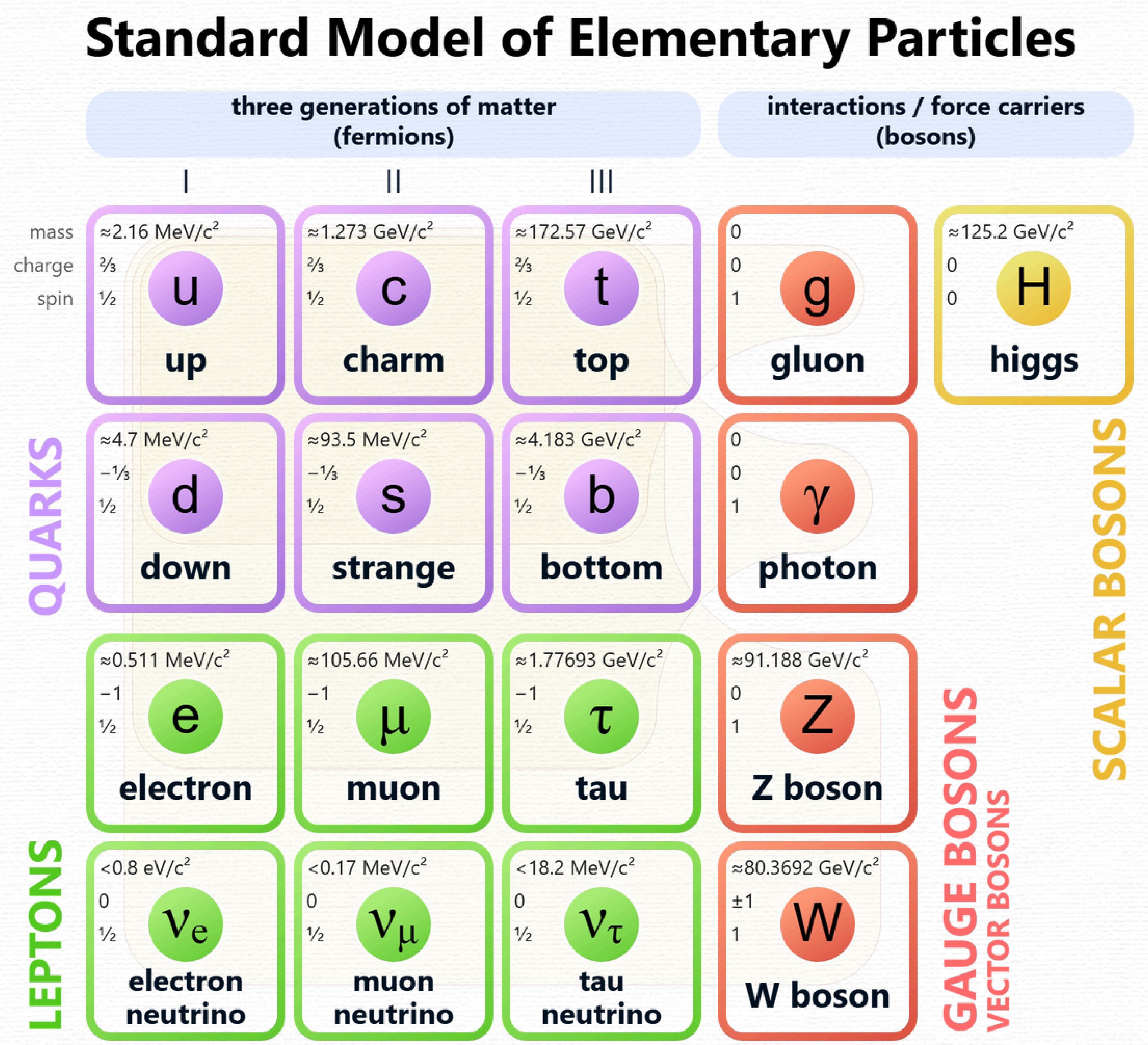
05 **Beyond Leptons:** The Role of Jets

06 **Key Findings & Conclusions**

The Standard Model and the Higgs Boson

The Theoretical Framework

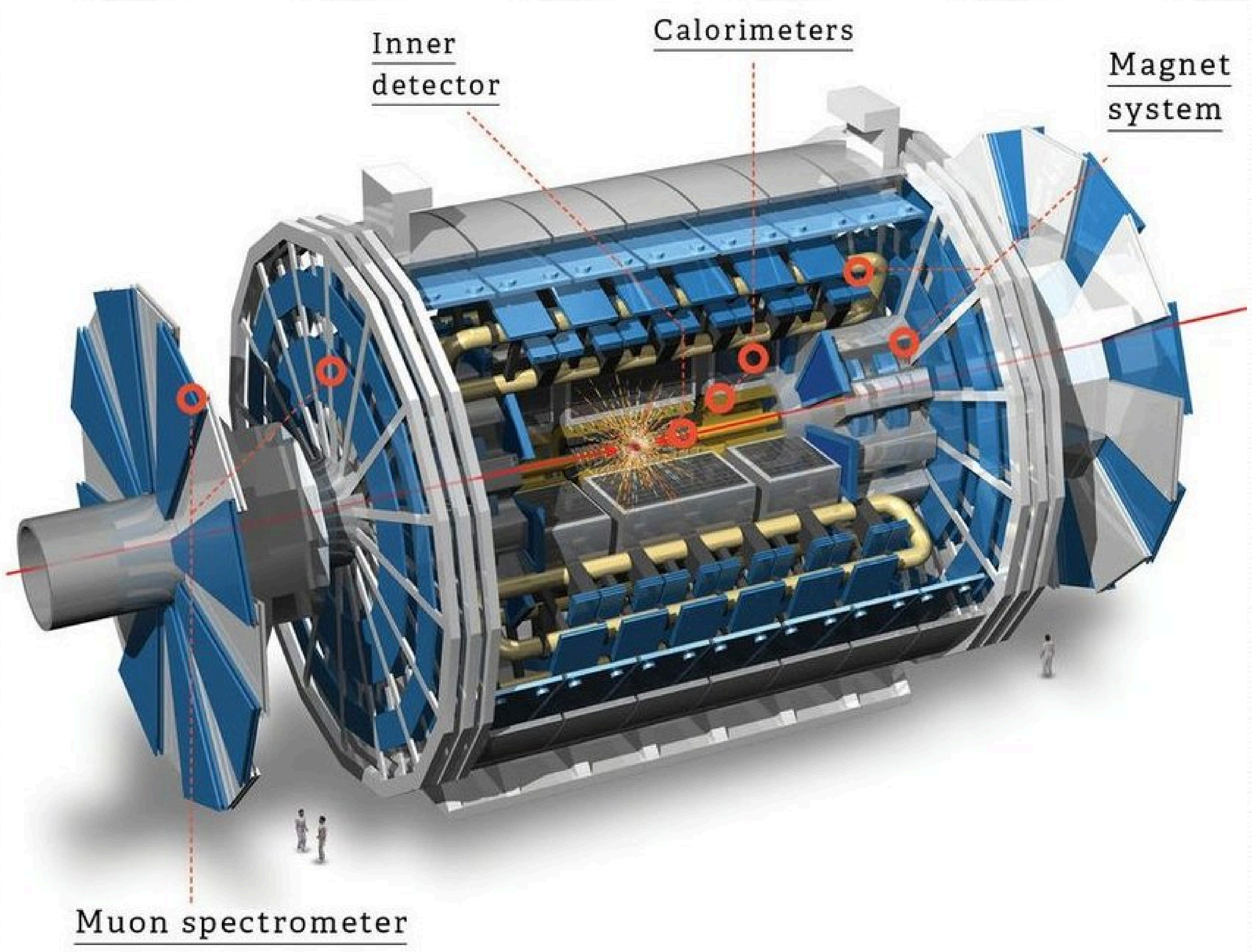
- The SM describes all known fundamental particles and forces (except gravity);
- **Fermions** (quarks, leptons) are the building blocks of matter;
- **Bosons** (photon, W, Z, gluon) mediate the forces;
- The **Higgs Boson** is the manifestation of the Higgs field, which gives mass to elementary particles;
- Its discovery in 2012 was a monumental achievement for the LHC.



The LHC & ATLAS

How We See the Invisible

The LHC accelerates two beams of particles, like protons, in opposite directions to nearly the speed of light within its 27-kilometer-long ring. We study the debris of the collisions detected by the **ATLAS detector.**

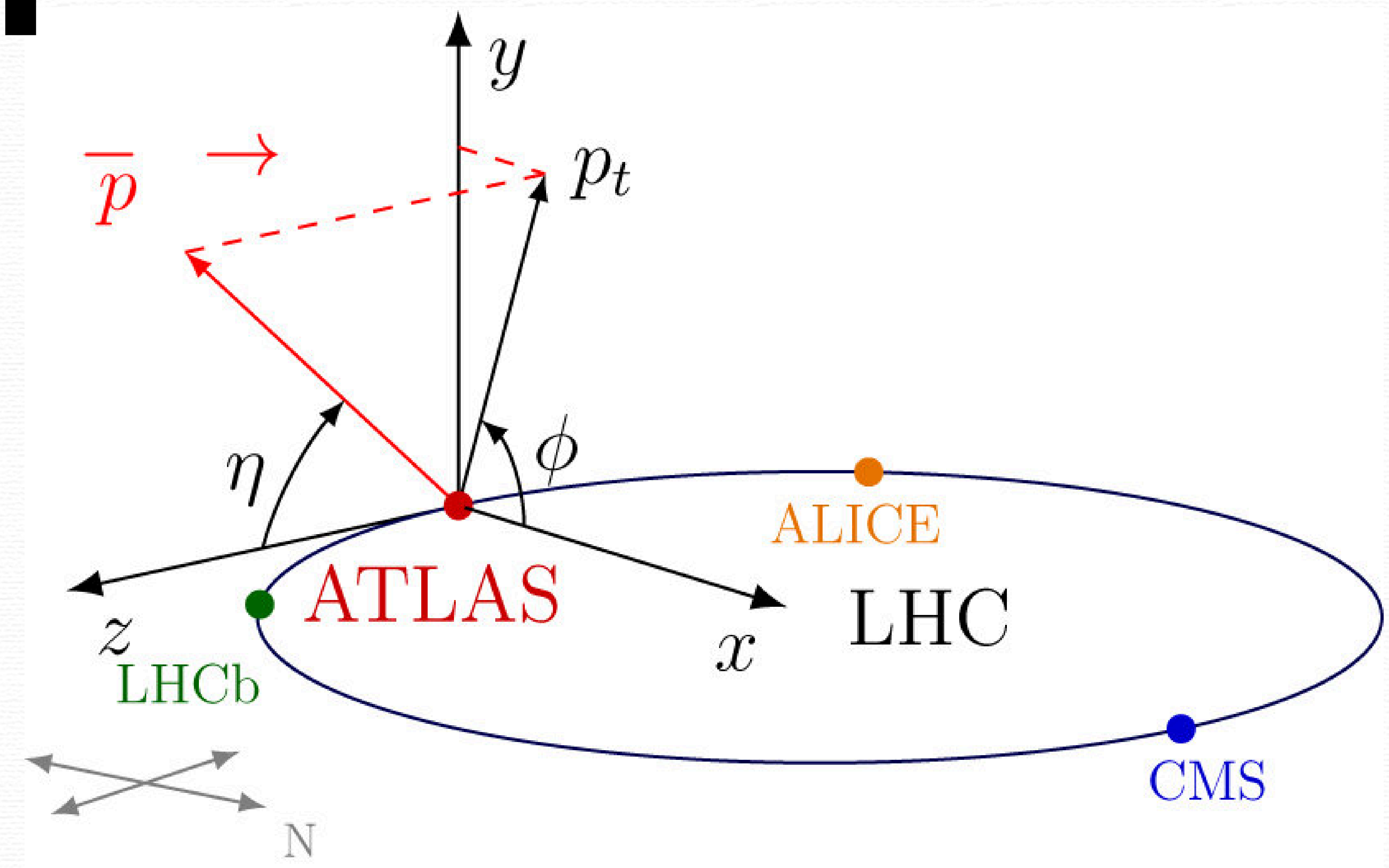


ATLAS Detector Layers:

- **Inner Detector:** Measures the position and momenta of charged particles.
- **Calorimeters**: Measure energy (stop most particles).
- **Muon Spectrometer**: Measures the position and momenta of muons (which pass through calorimeters).
- **Magnets**: Bend particle paths to measure momentum.

The Geometry of a Particle Collision

ATLAS uses a cylindrical coordinate system centered on the proton beamline. Since the partons initial collision momentum along the beam is unknown, physicists rely on transverse momentum (pT)—the component perpendicular to the beam—which is zero before collision and is therefore a crucial conserved quantity for analysis.



Our Data: ATLAS Open Data

Public Datasets from ALAS Open Data

Exactly4lep educational skim

Provides optimized subsets from curated datasets from proton-proton collisions at $\sqrt{s} = 13$ TeV, with pre-selected events to contain four leptons (electrons or muons).

Data Composition

Data (and MC) includes kinematic variables: pT, η, φ, E for each particle

ATLAS Open Magic

Python package which provides programmatic access to metadata and remote storage locations (URLs) for ATLAS Open Data resources.

General analysis

What's in our plots?

Data: Real proton-proton collisions from ATLAS.
MC Simulation: Predictions for both the Higgs Signal and Background Processes.:

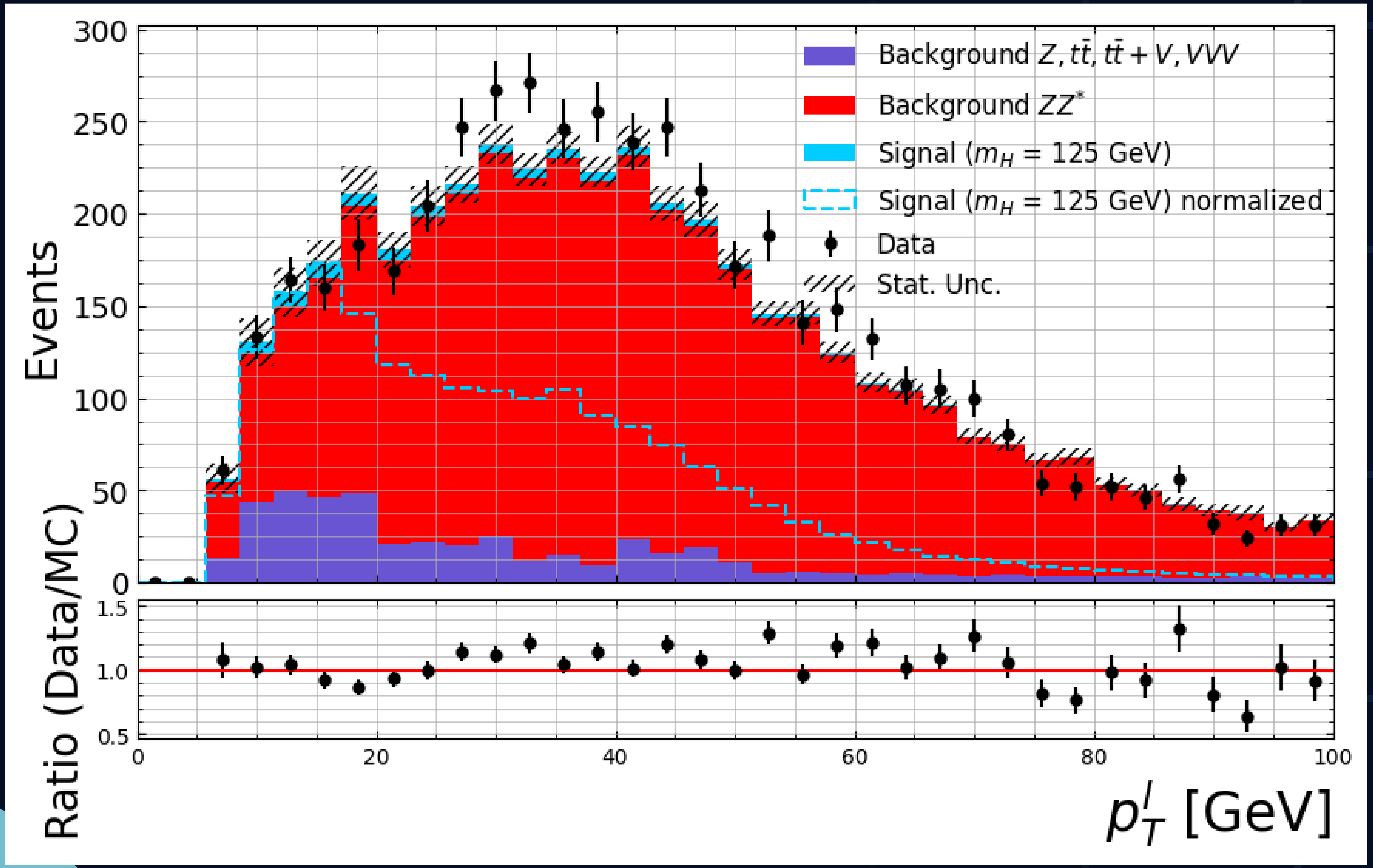
- Main Background: ZZ* production
- Other Backgrounds: $\bar{t}t$, Z+jets, VVV

How do we find the needle in the haystack?

- The Higgs signal is very rare compared to backgrounds.
- We apply kinematic filters (e.g., lepton pT > 7, 10, 15, 25 GeV).
- Why? These cuts suppress background more than signal, thus increasing the S/B rati0.

General analysis

Transverse momentum (pT) distribution for all individual leptons in all events from both experiment and Monte Carlo simulations.

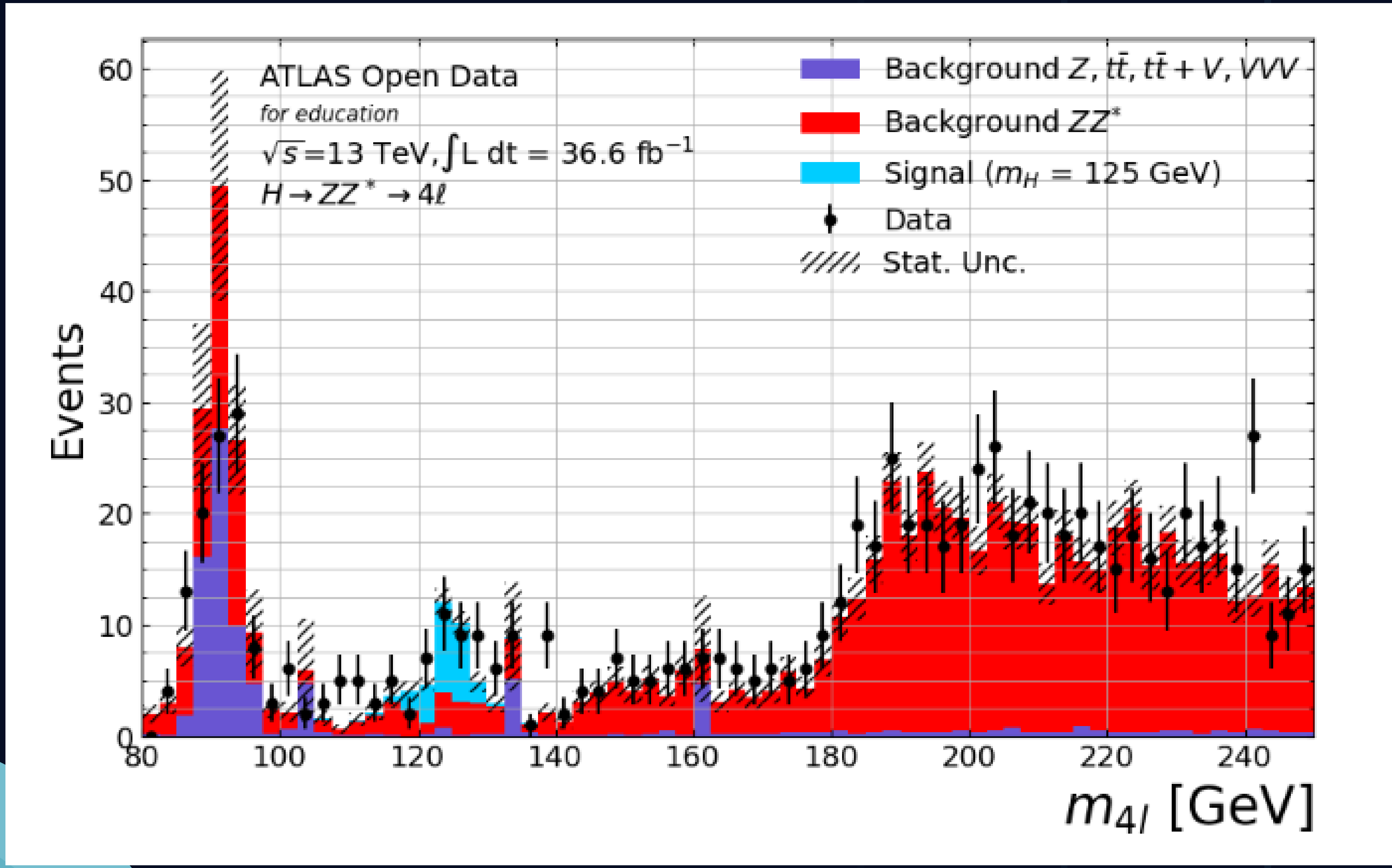


First Look: Single Leptons

- We first examined basic properties (lepton pT, η, multiplicity).
- Observation: After filtering, the data agrees well with the Background MC.
- Conclusion: Our cuts work! But these simple variables can't separate the Higgs from the background. We need to look deeper.

General analysis

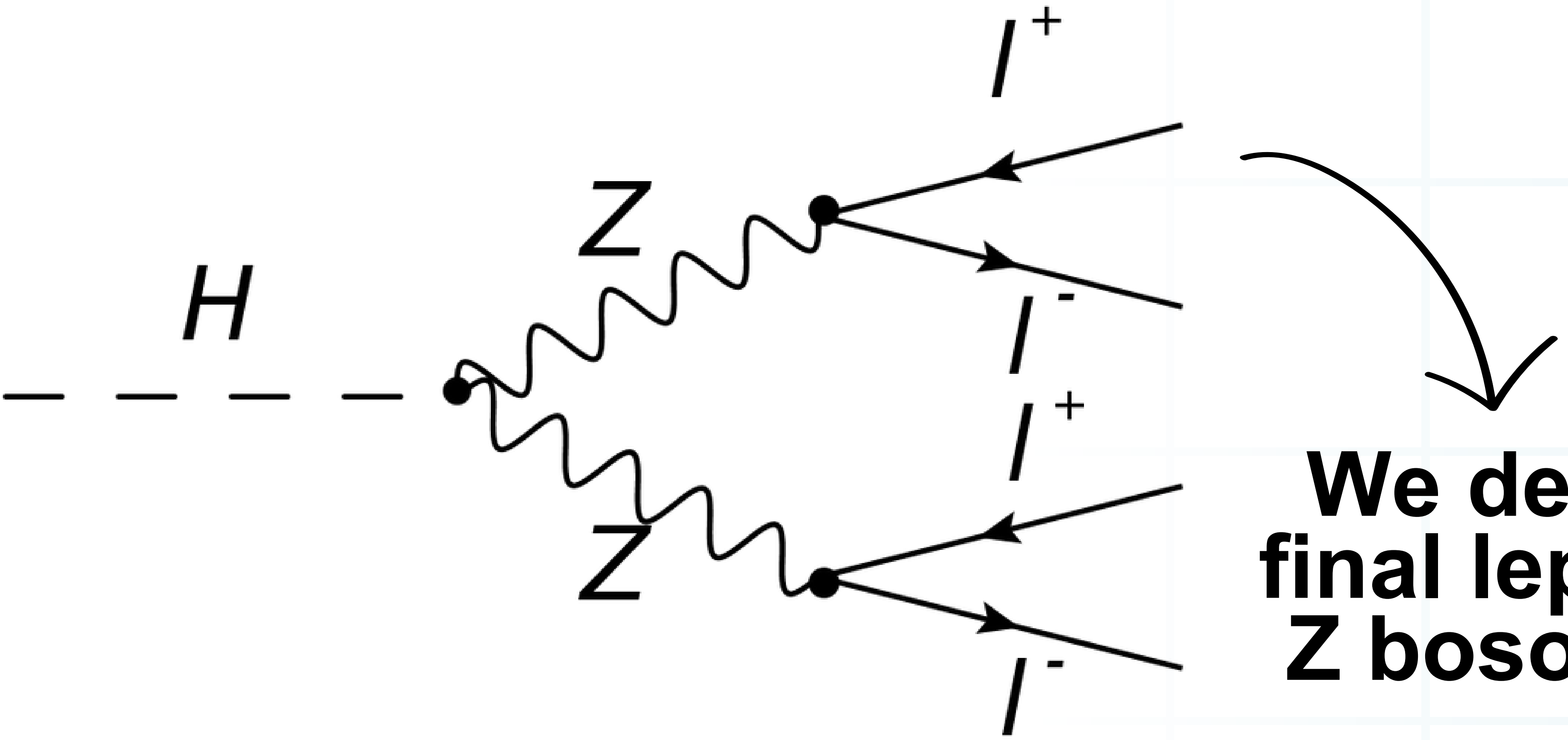
4 lepton system invariant mass distribution for each event from both experimental data and Monte Carlo simulations.



The Higgs Boson Signature: The 4-Lepton Invariant Mass

- We calculated the invariant mass of the 4-lepton system, since that should correspond to the Higgs mass.
- Observation: There is an overall agreement between the data and the combined ZZ* + Signal MC.
- Z Boson Peak: Peak at ~90 GeV from known ZZ* background.
- The Higgs Boson Signal: A clear excess of data events at $m_{4\ell}$ = 125 GeV!
- Conclusion: We found Higgs boson!

The Reconstruction Problem



We detect the four final leptons, but the Z bosons are gone.

- One Z boson is **on-shell** ("real", mass ~91 GeV)
- One Z boson is **off-shell** ("virtual", mass is different)

We must work backwards to find the correct pairing.

Why is this hard?

Example: e_1^-, e_2^-, e_3^+, e_4^+

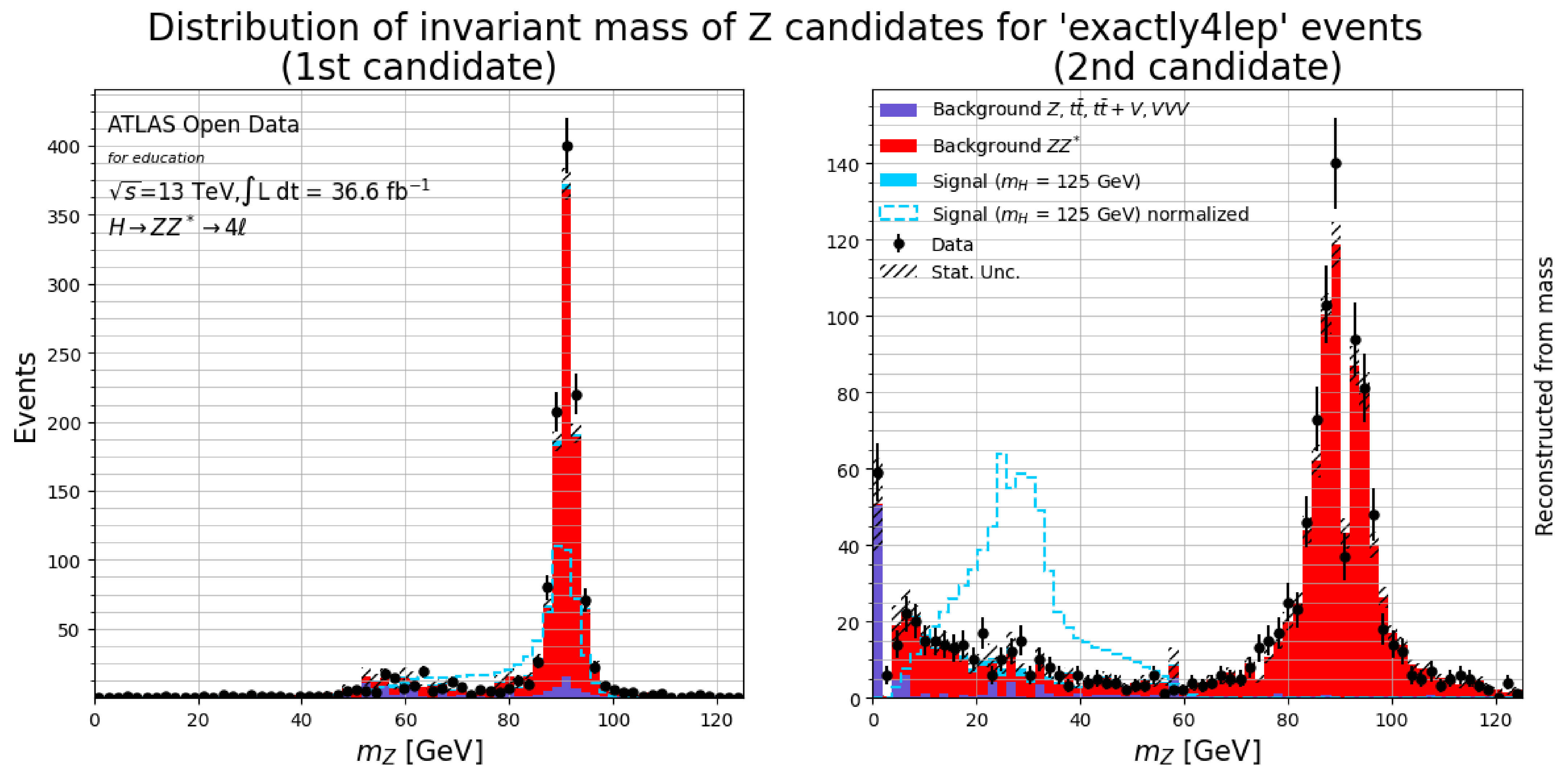
1. Option A: (e_1^- + e_3^+) & (e_2^- + e_4^+)
2. Option B: (e_1^- + e_4^+) & (e_2^- + e_3^+)

- Which pair is the **real Z** (mass ~91 GeV)?
- Which pair is the **virtual Z*** (mass is different)?

We Tested Three Methods

Z pair reconstruction

Mass criterion

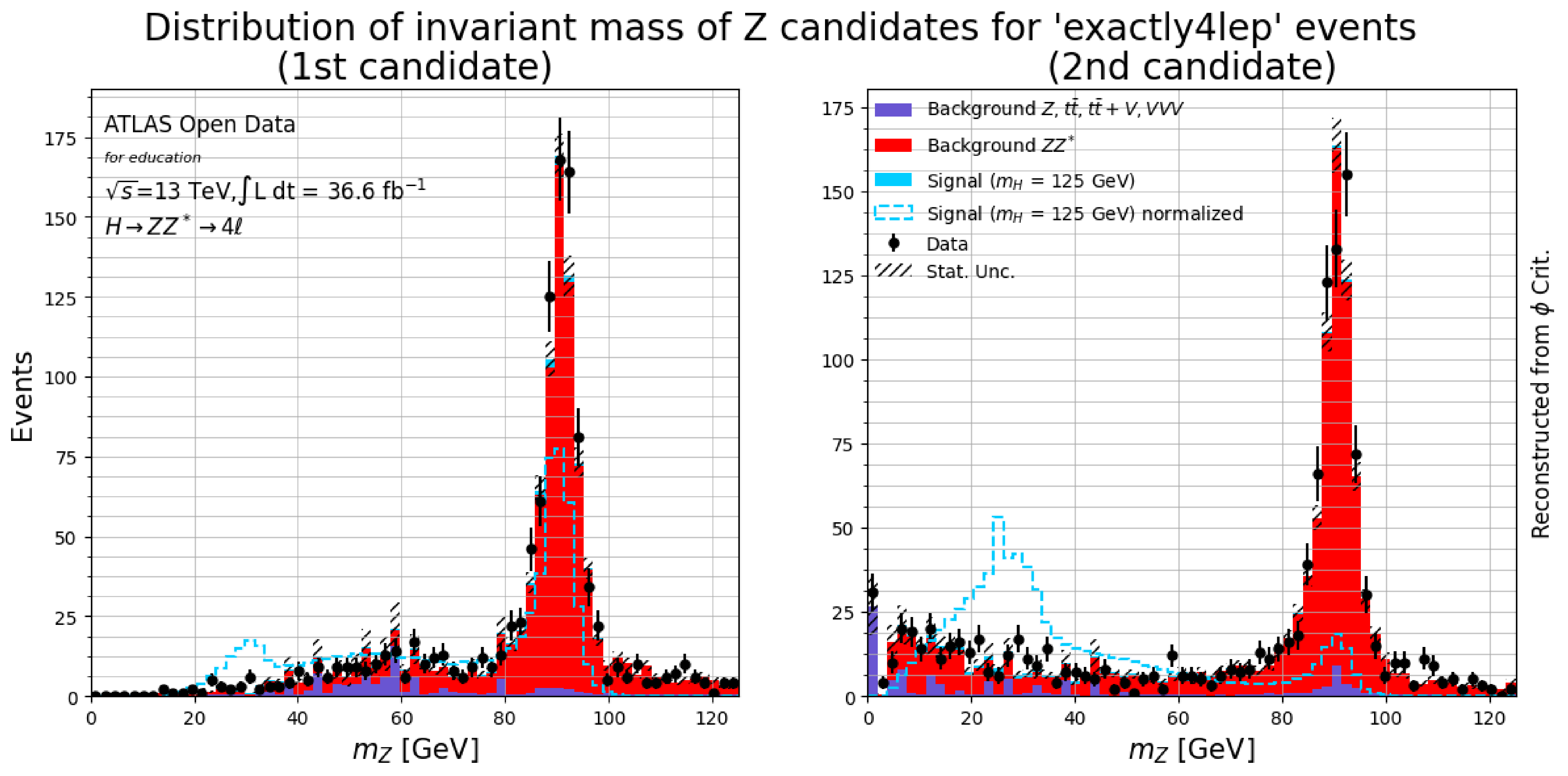


Caculate the invariant mass for all the six possible pairwise combinations of the four leptons that satisfy the OSSF criteria.

The pair with mass closest to the nominal Z boson mass of 91.188 GeV was considered the first Z candidate.

Z pair reconstruction

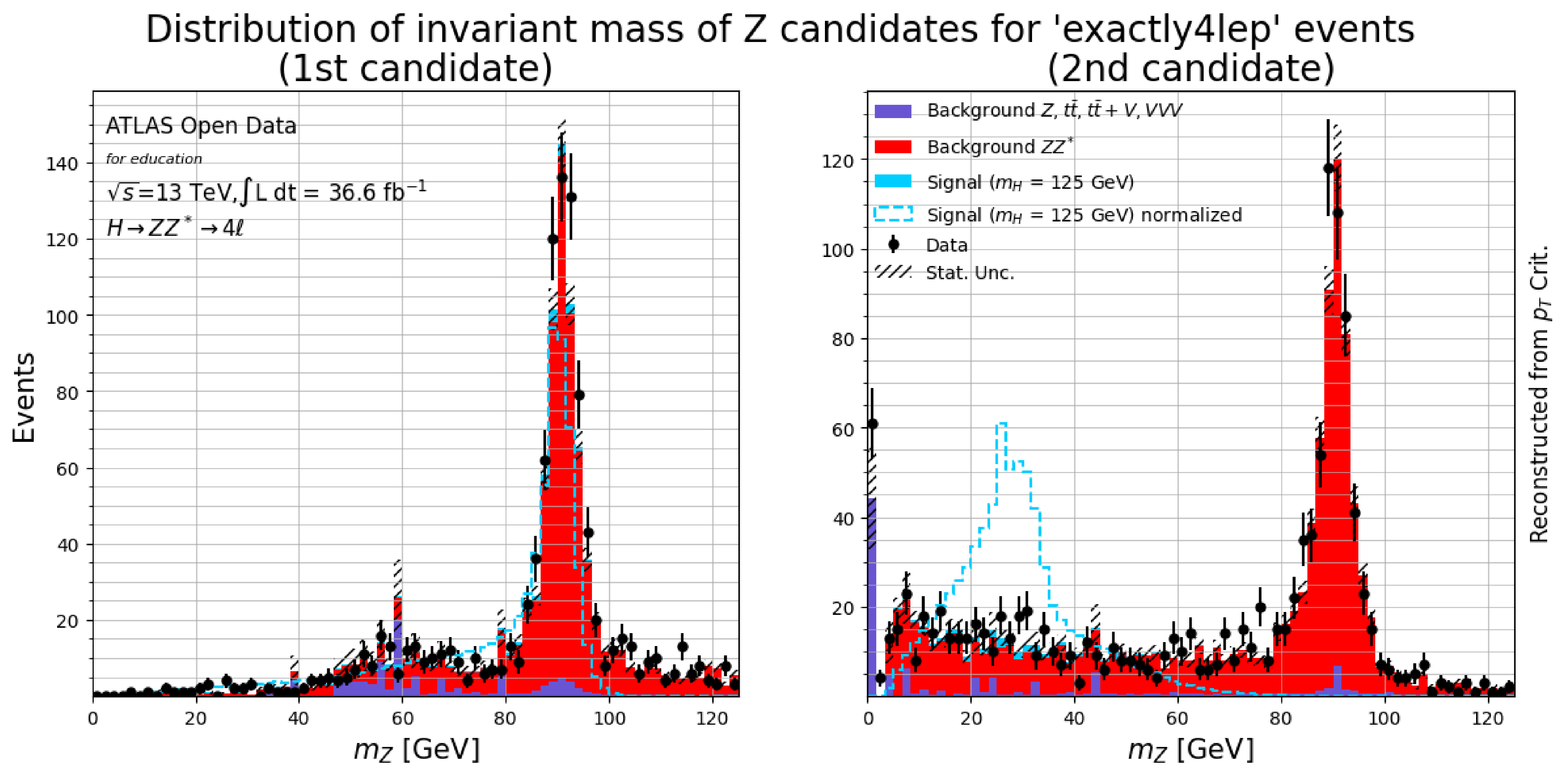
Angular separation criterion



The pair exhibiting a | Δϕ | value closest to π was selected as the first Z candidate.

Z pair reconstruction

Momentum criterion



The pair exhibiting the largest scalar sum of lepton transverse momenta was designated as the first candidate.

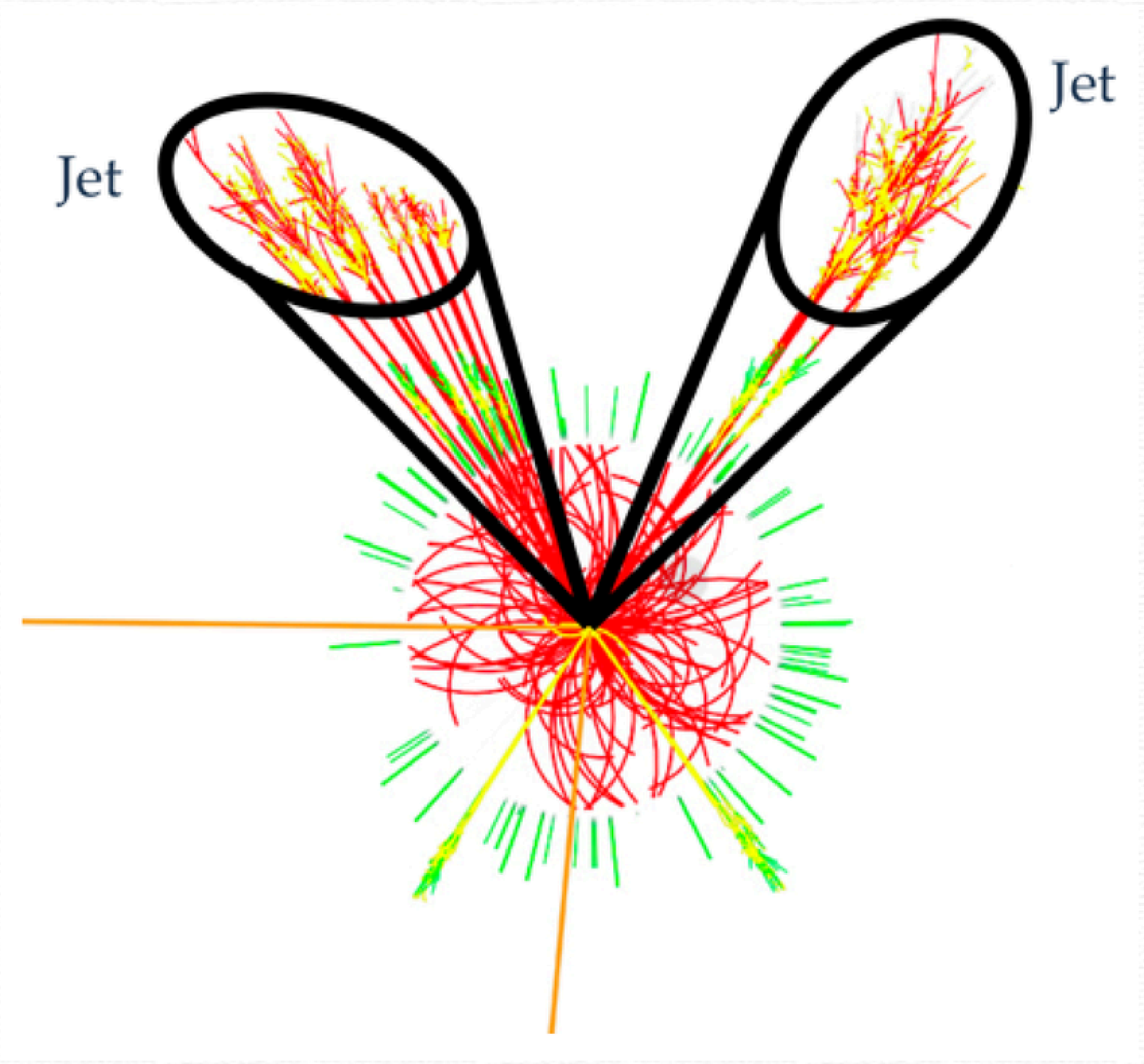
The influence of jets in particle kinematics??

The Theoretical Framework

Our signal is 4 leptons, but we often see jets (sprays of particles from quarks/gluons). They come from:

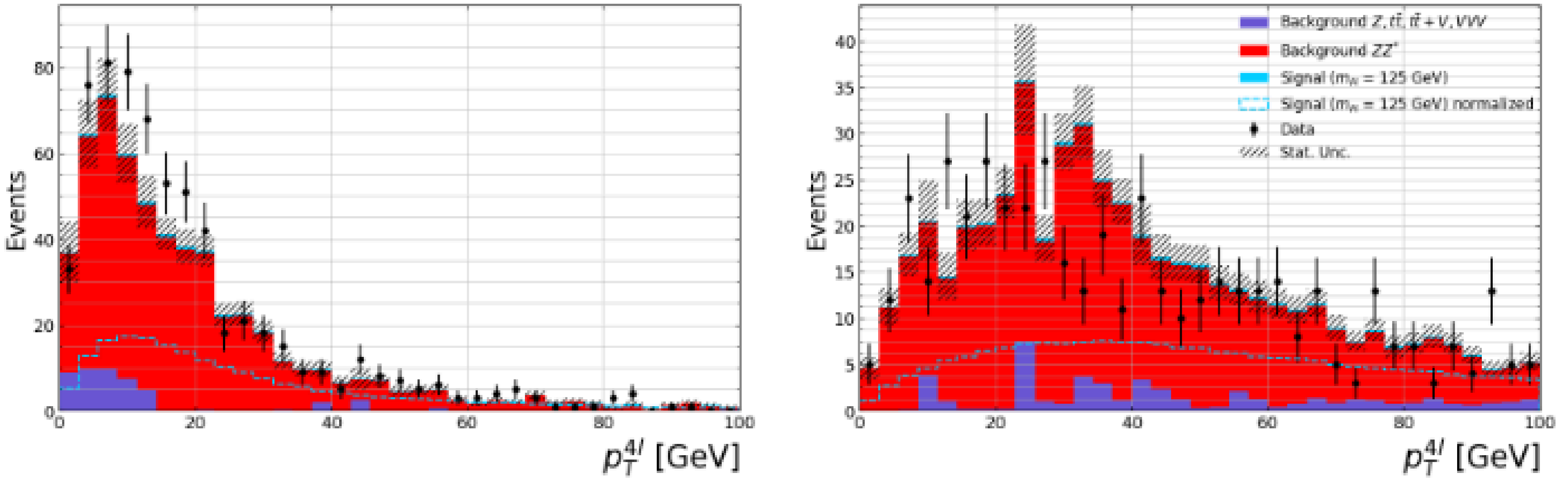
- Initial radiation before the Higgs was produced.
- Additional "pile-up" collisions in the detector.

Question: How do these jets affect our measurements?



The influence of jets in particle kinematics

4-lepton sytem



(a) Zero jets

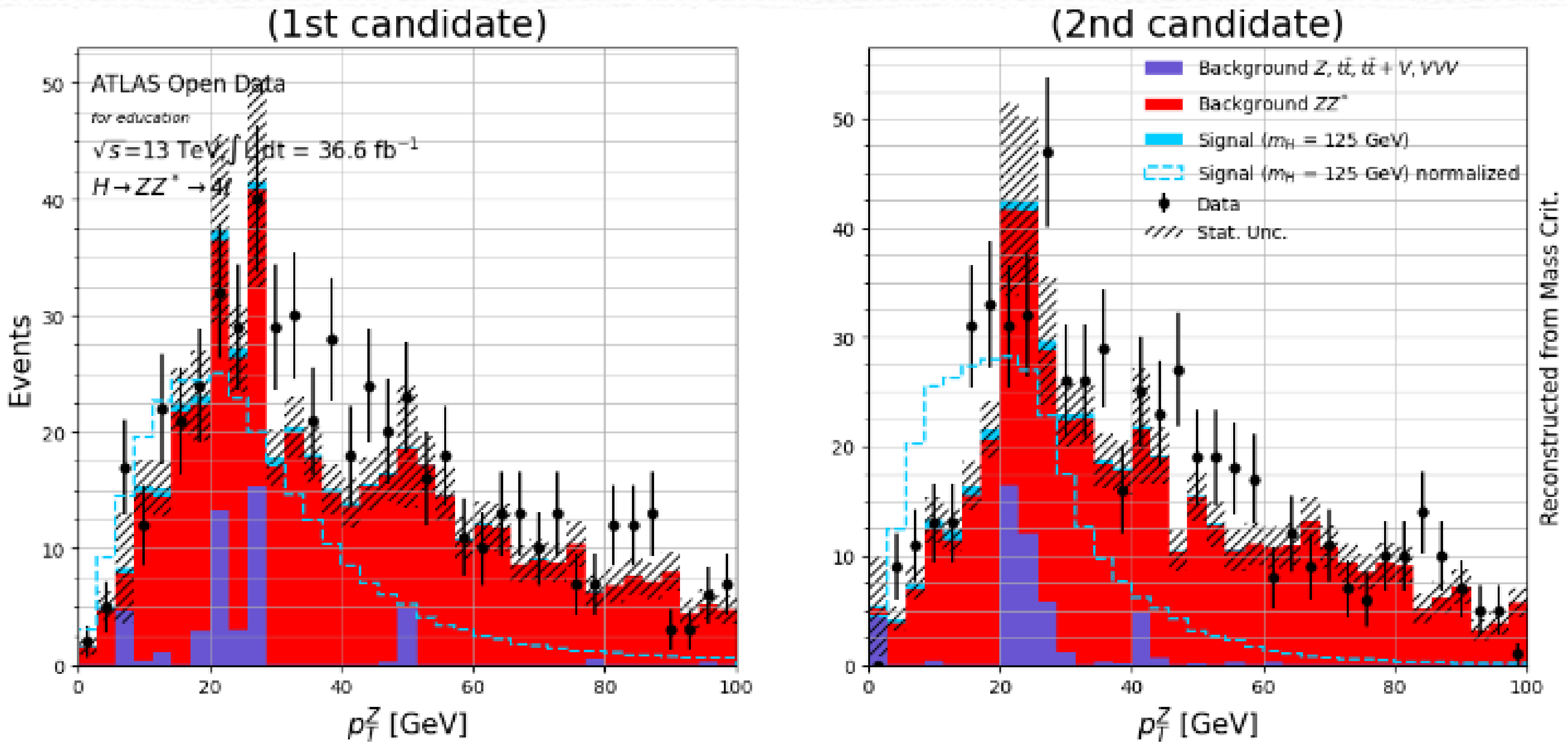
(b) Nonzero jets

- With zero jets, the 4-lepton system (our Higgs candidate) has low pT – it has nothing to balance against.
- With jets present, the Higgs candidate must have high pT to balance the transverse momentum of the jets.

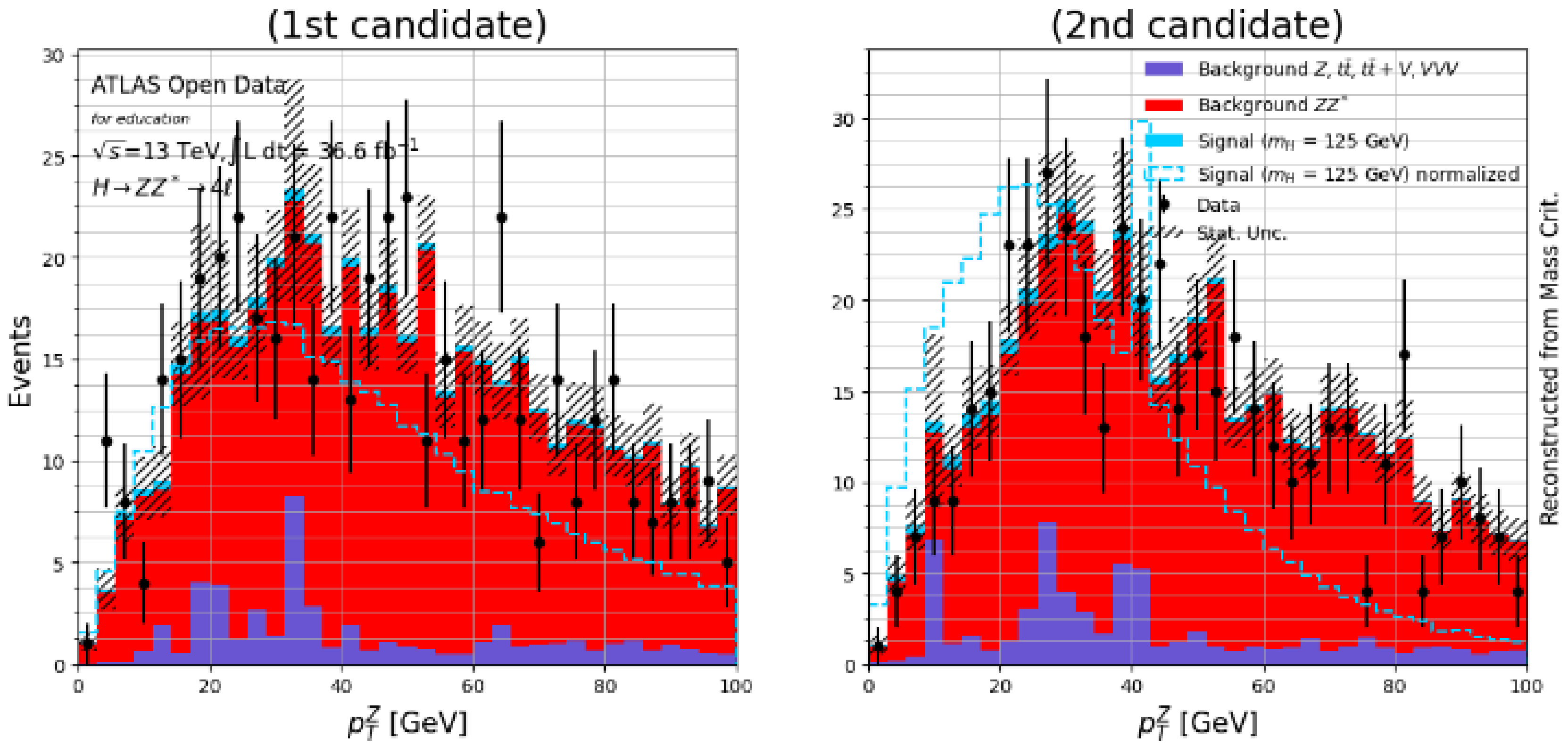
The influence of jets in particle kinematics

Z boson subsytem

- Less pronounced effects for events with and without jets than for the 4-lepton system.
- Many objects interfere with the final result due to the reconstruction

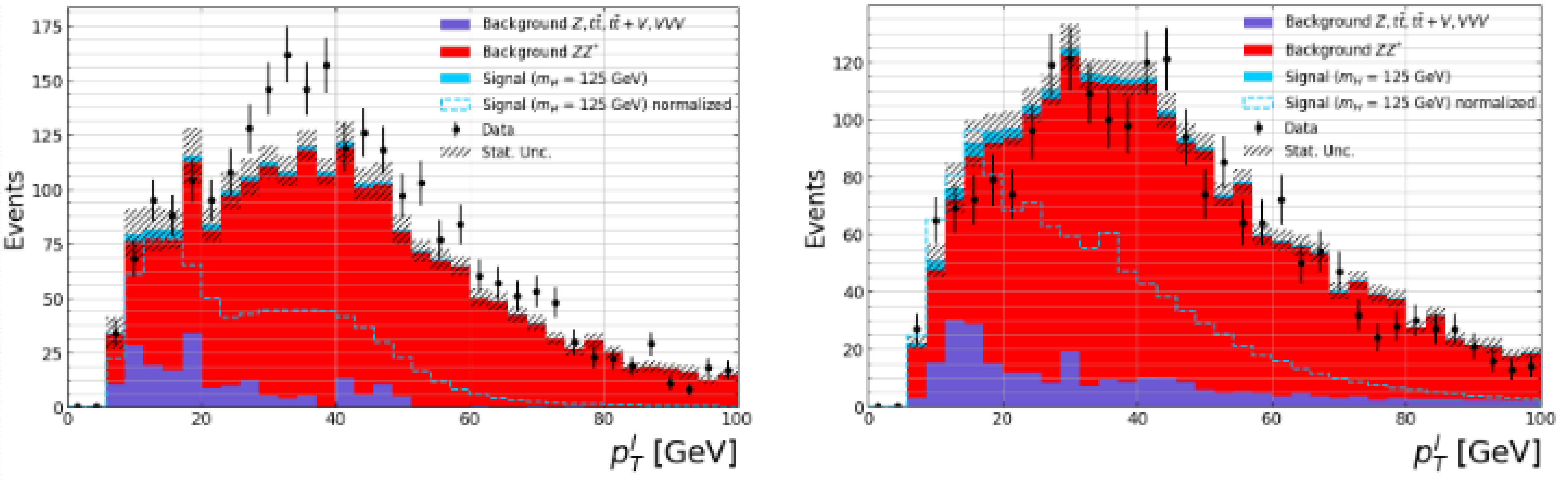


(a) Zero jets



The influence of jets in particle kinematics

Individual leptons

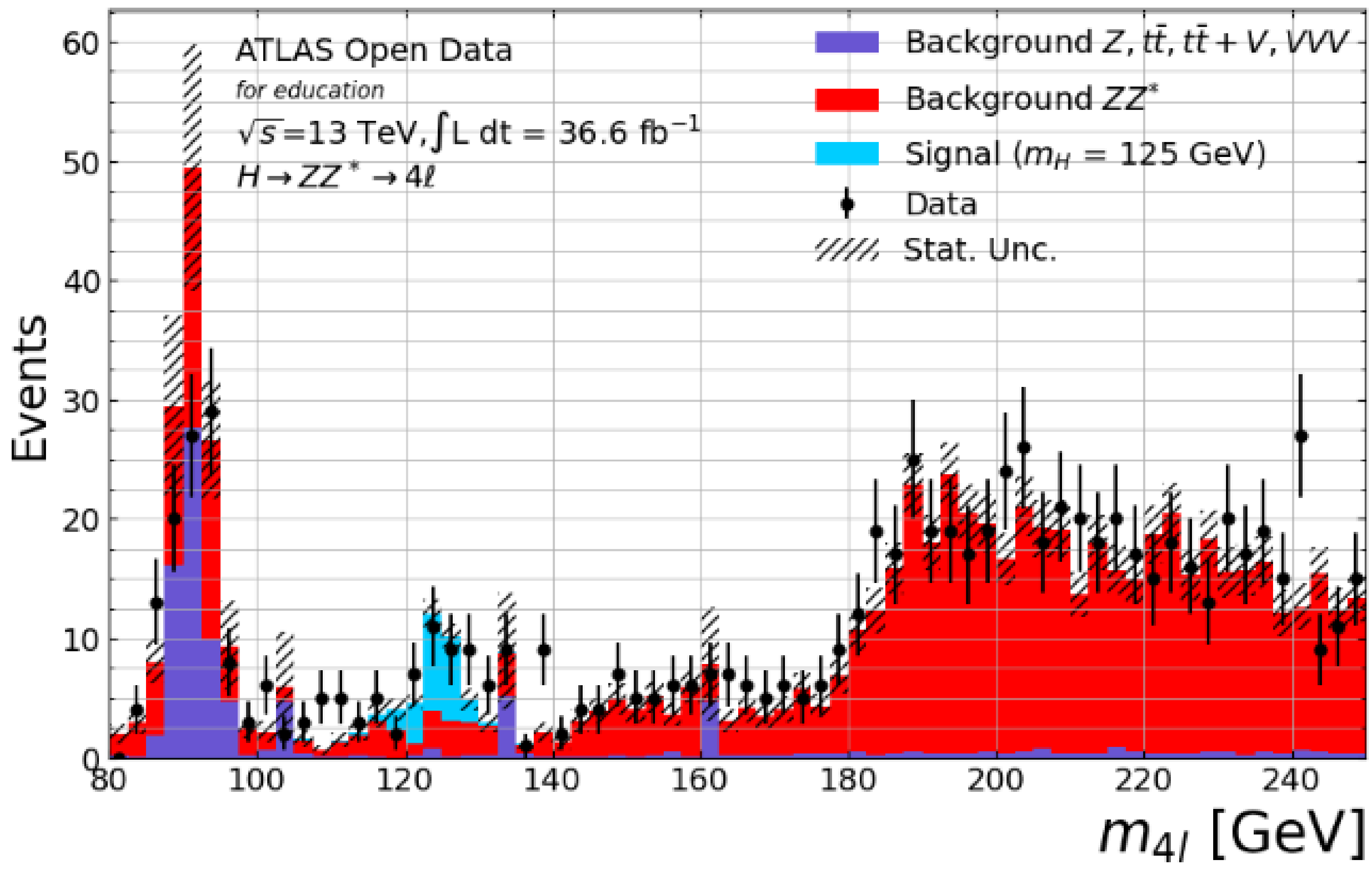


(a) Zero jets (b) Nonzero jets

- With zero jets, the individual lepton have higger pT– they are the final products of the decay, so there are more objects to compensate the pT.
- Small difference between events with or without jets - presence of jets has a smaller effect

Conclusions and future work

- We successfully rediscovered the Higgs boson signature using ATLAS Open Data, observing a clear excess of events at $m_{4\ell} \approx 125$ GeV.
- We implemented and compared three novel reconstruction techniques for identifying the Z boson pairs from the Higgs decay, with different degrees of precision.
- We investigated the impact of jet activity and demonstrated how it affects the kinematics of the Higgs candidate, providing a real-world example of transverse momentum conservation.
- This analysis showcases the power of public data initiatives to provide authentic research experiences and deepen our understanding of particle physics.


ATLAS Open Data
for education
$\sqrt{s}$=13 TeV, $\int$L dt = 36.6 fb^{-1}
$H \to ZZ^* \to 4\ell$
Background $Z, t\bar{t}, t\bar{t}+V, VVV$
Background ZZ^*
Signal (m_H = 125 GeV)
Data
Stat. Unc.
Events
m_{4l} [GeV]

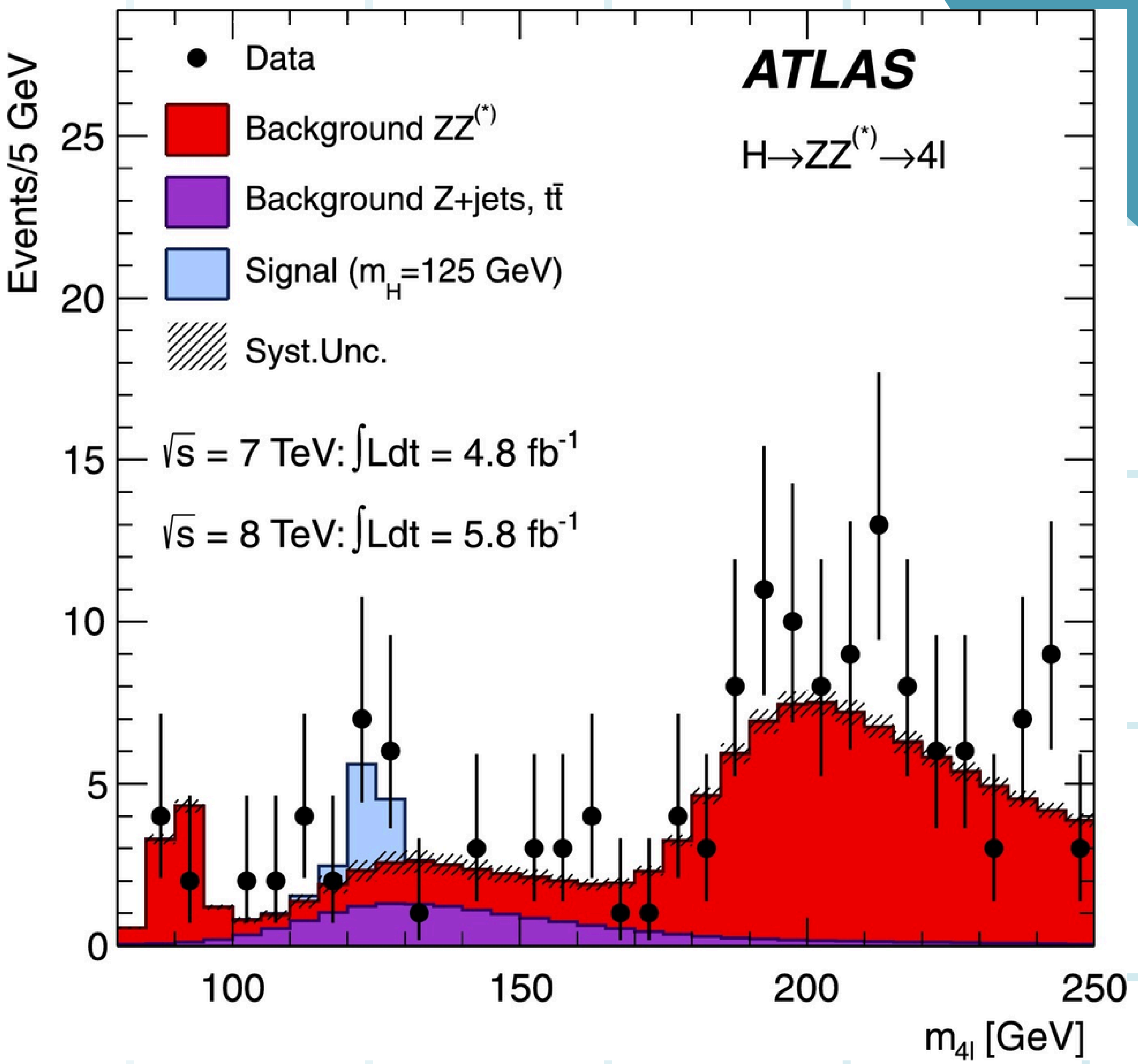

Data
Background ZZ$^{(*)}$
Background Z+jets, $t\bar{t}$
Signal (m_H=125 GeV)
Syst.Unc.
ATLAS
$H \to ZZ^{(*)} \to 4l$
$\sqrt{s}$ = 7 TeV: $\int$Ldt = 4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV: $\int$Ldt = 5.8 fb^{-1}
Events/5 GeV
m_{4l} [GeV]

IMAGE CREDITS

- slide 3: Wikipedia;
- slide 4: Research Gate;
- slide 5: Research Gate;
- slide 10: Wikipedia;
- slide 16: MDPI;
- slide 20: Higgs Official discovery.