UNIVERSITY OF SUSSEX

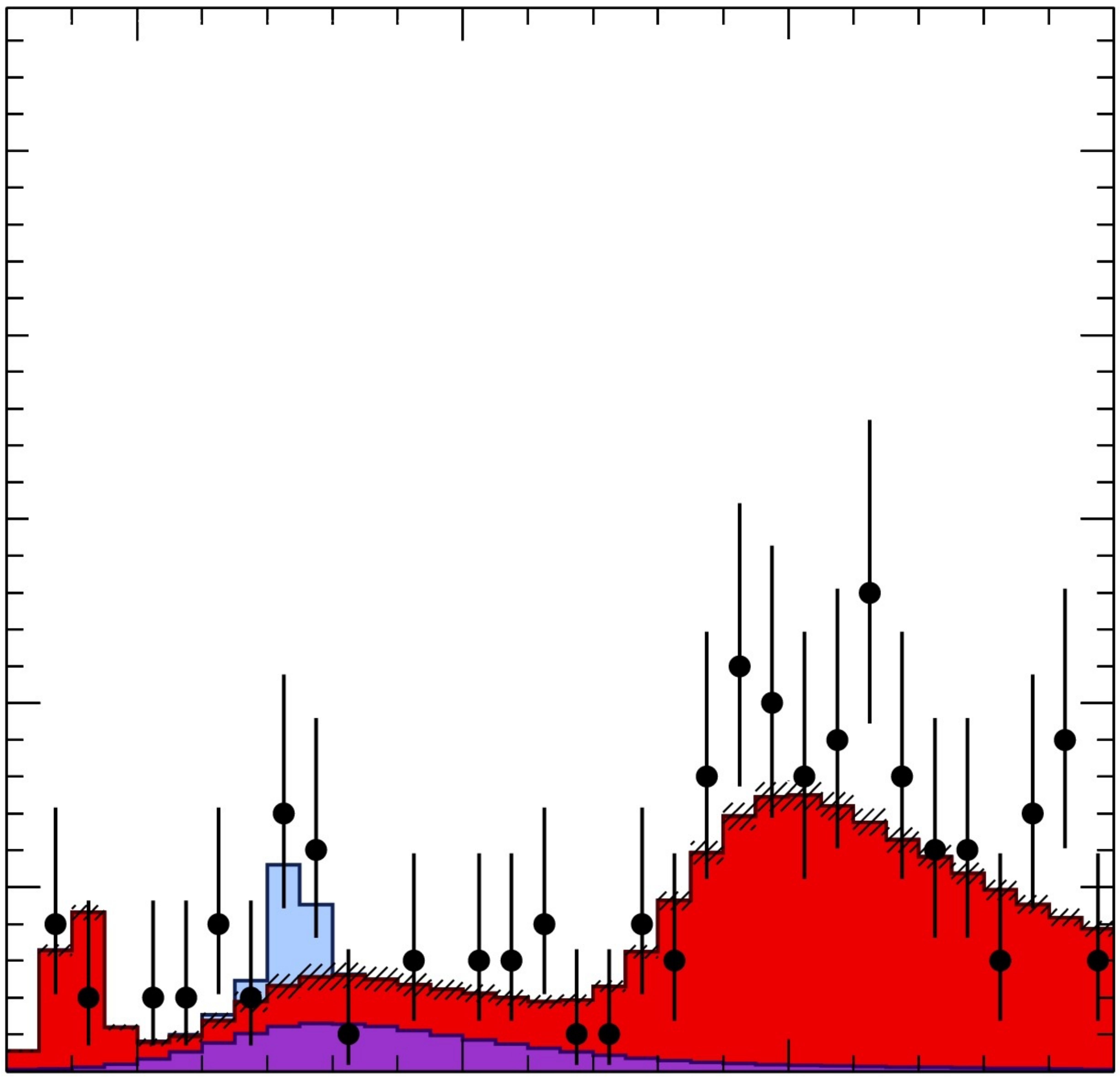
ATLAS EXPERIMENT

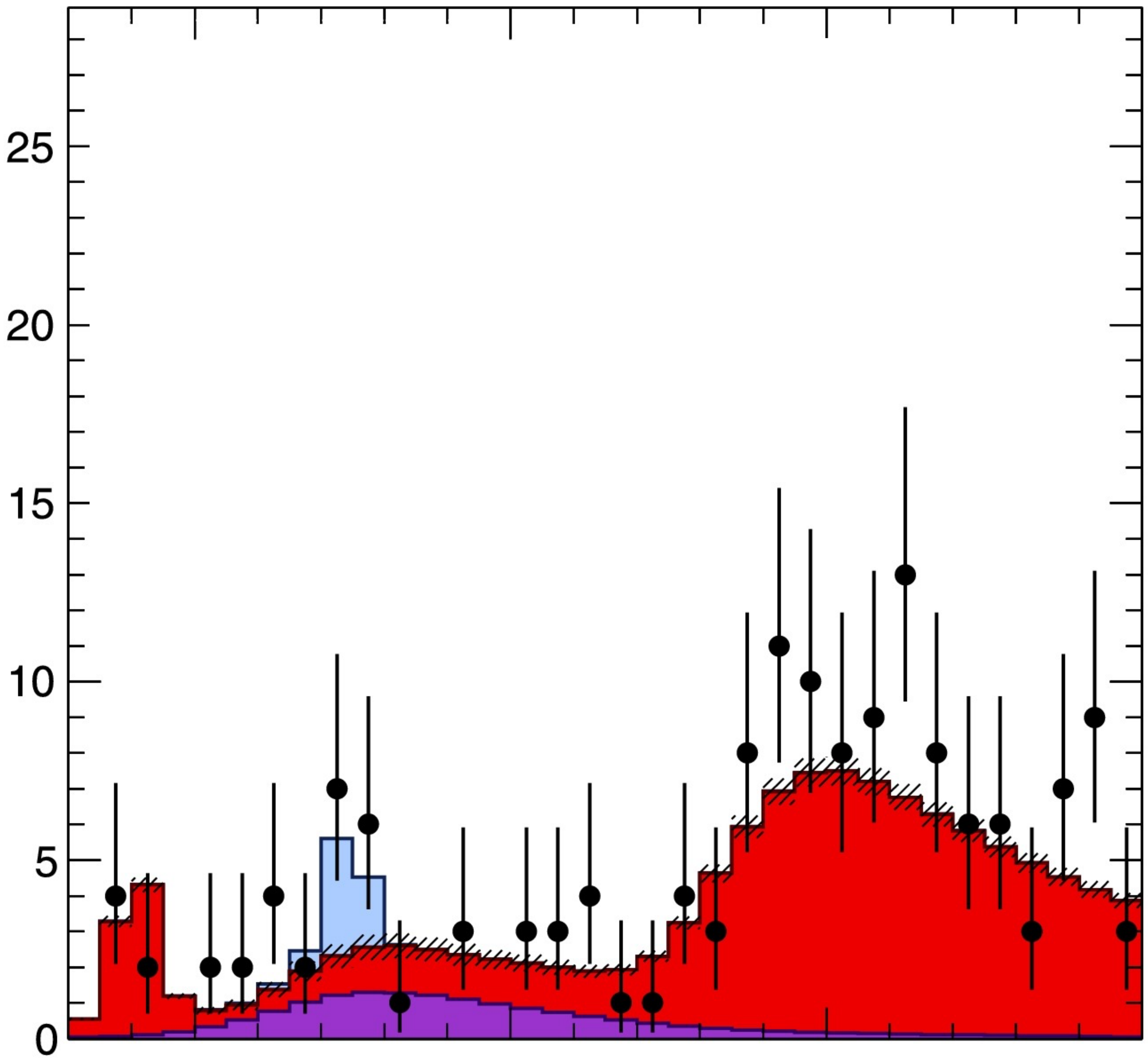
Meirin Oan Evans, Adam Powell (+ help of many people)

CAPS 2019 Abertawe

9th July 2019

How to rediscover the Higgs





25
20
15
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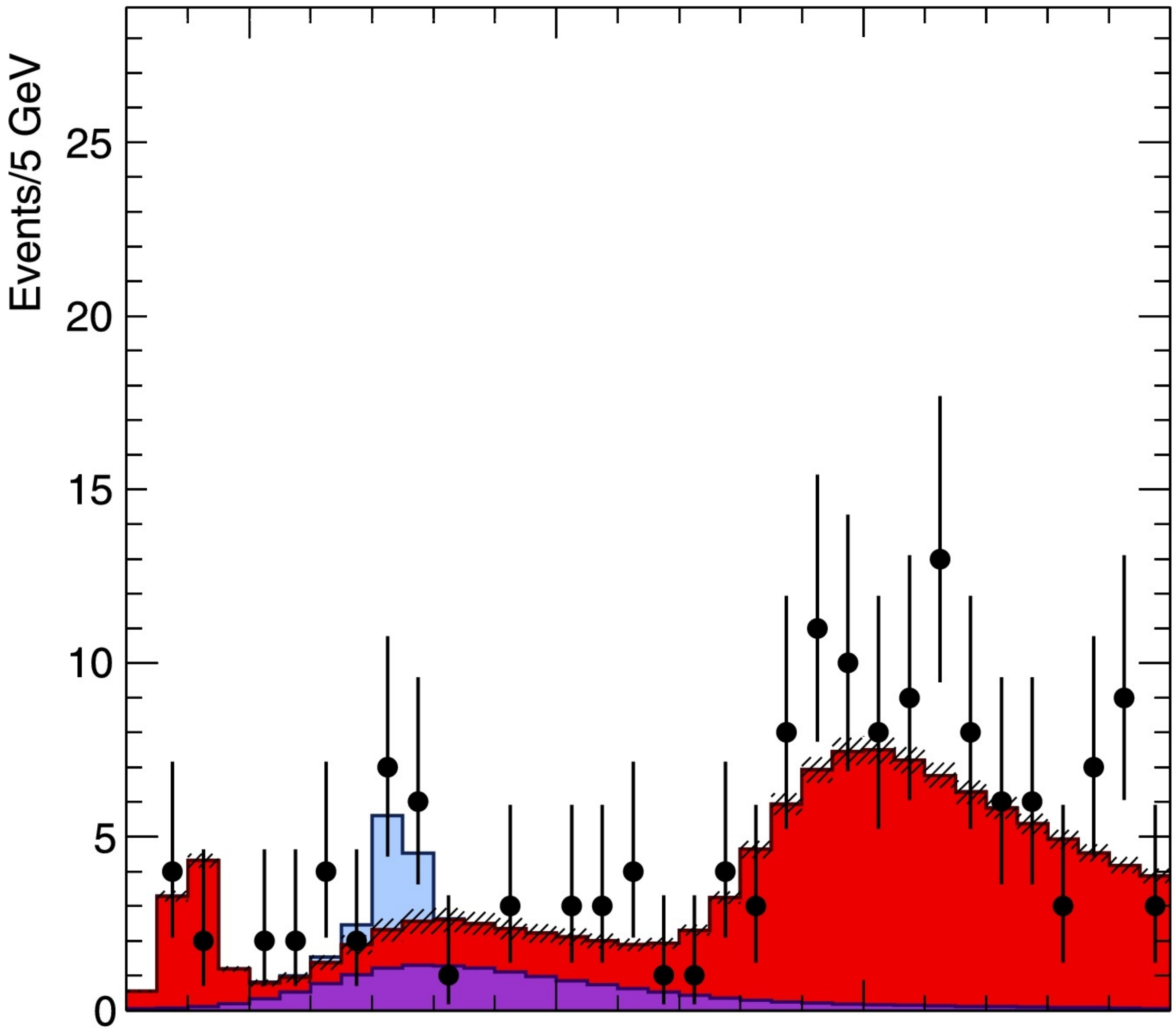
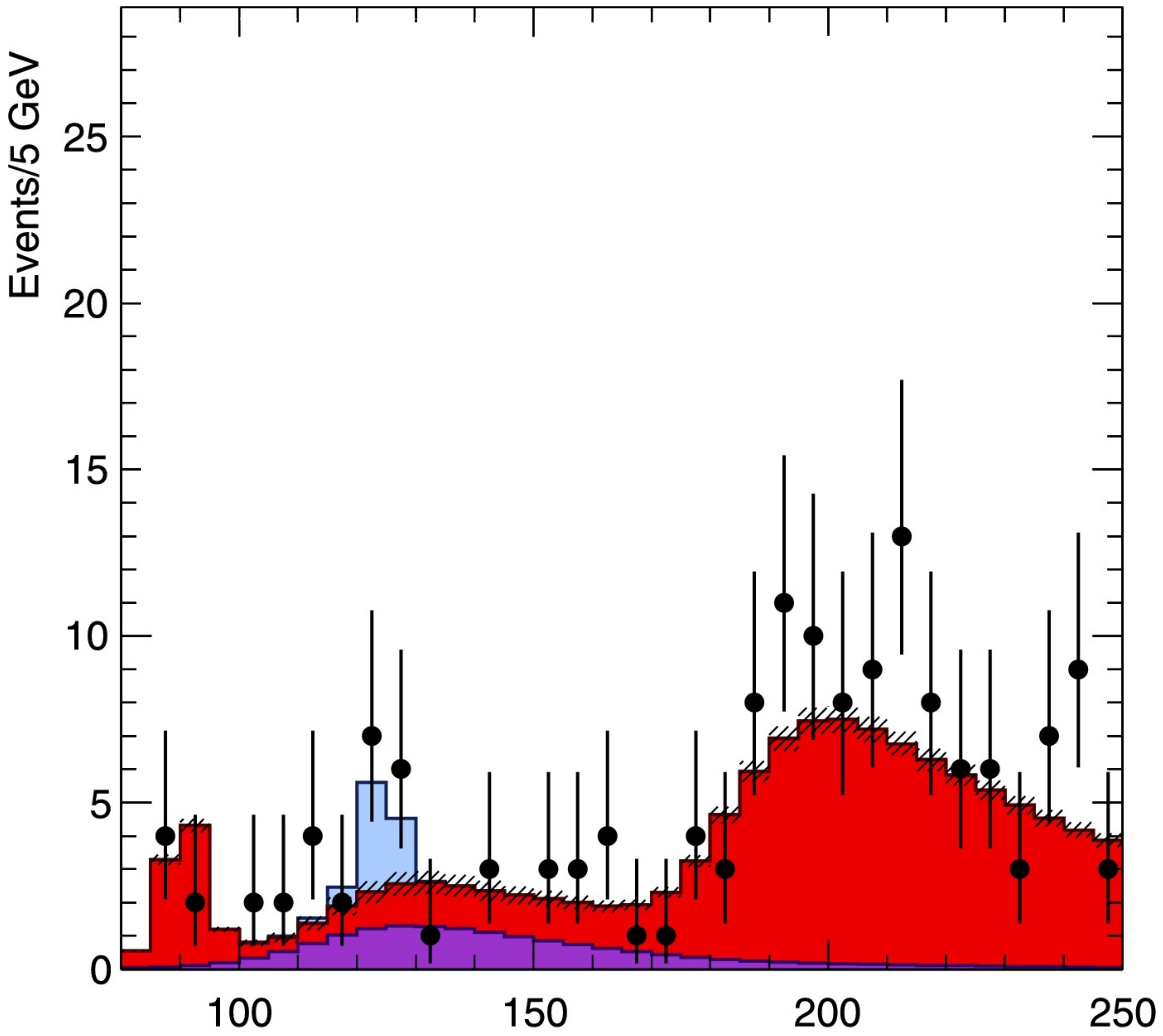
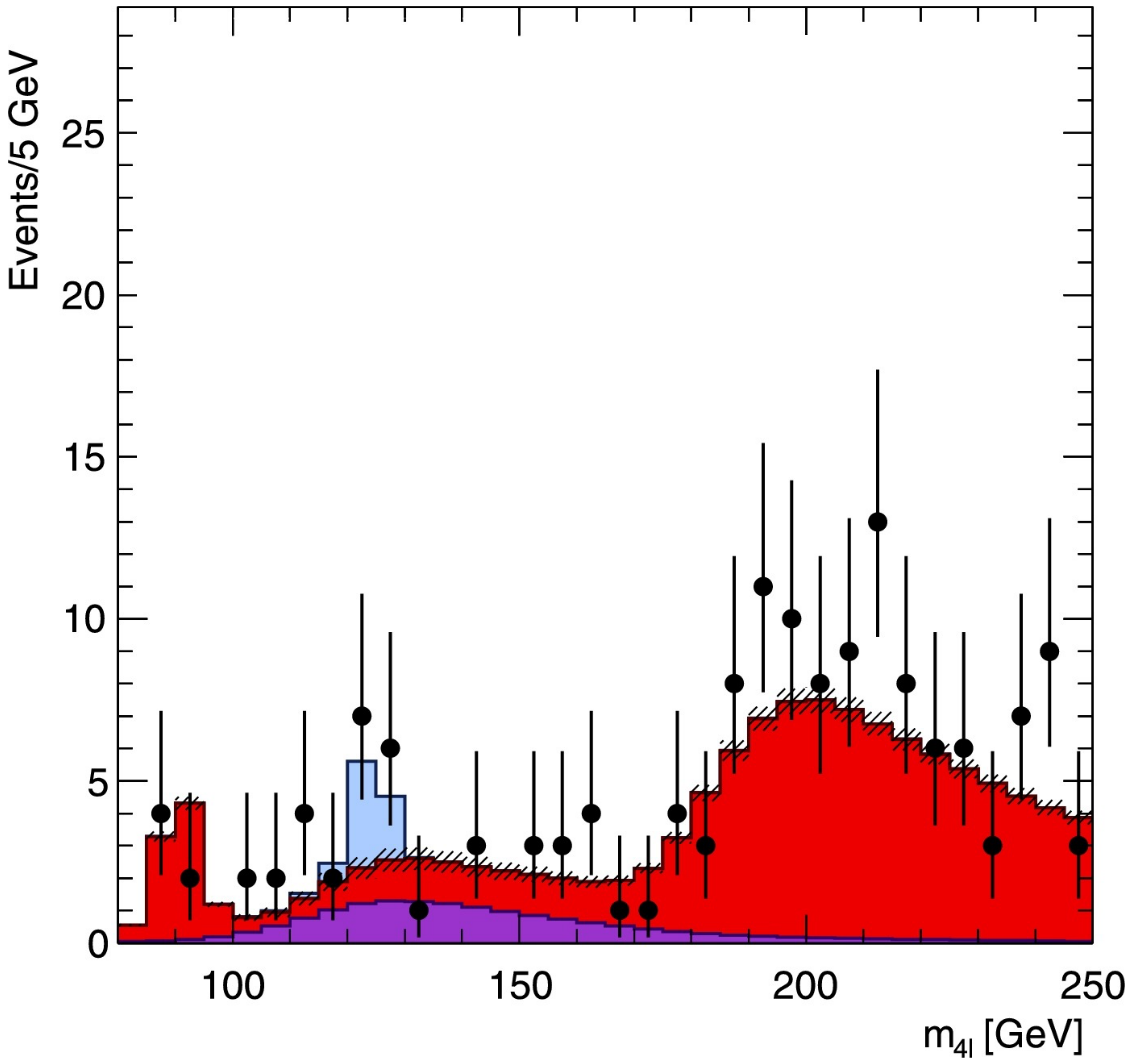
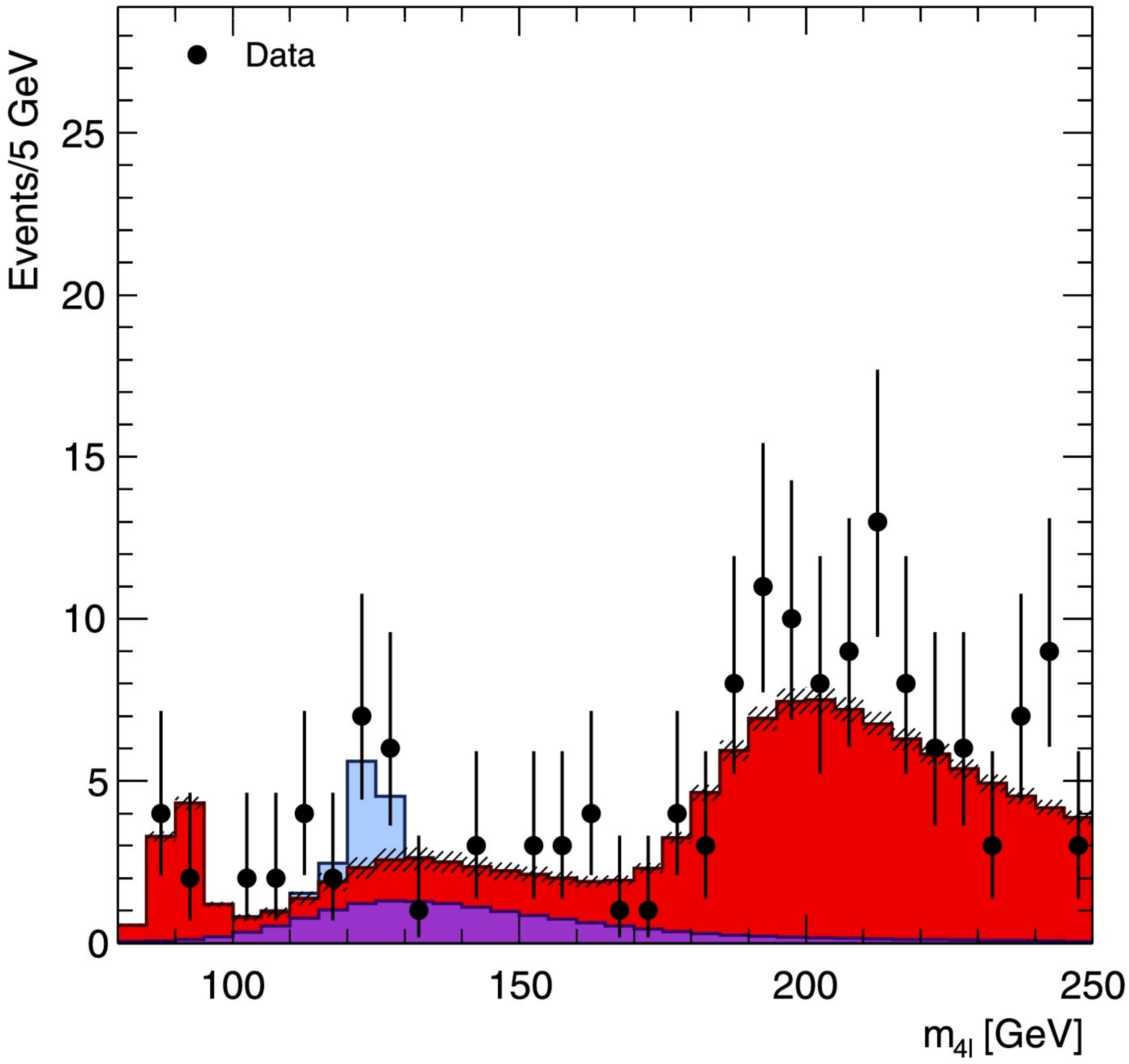
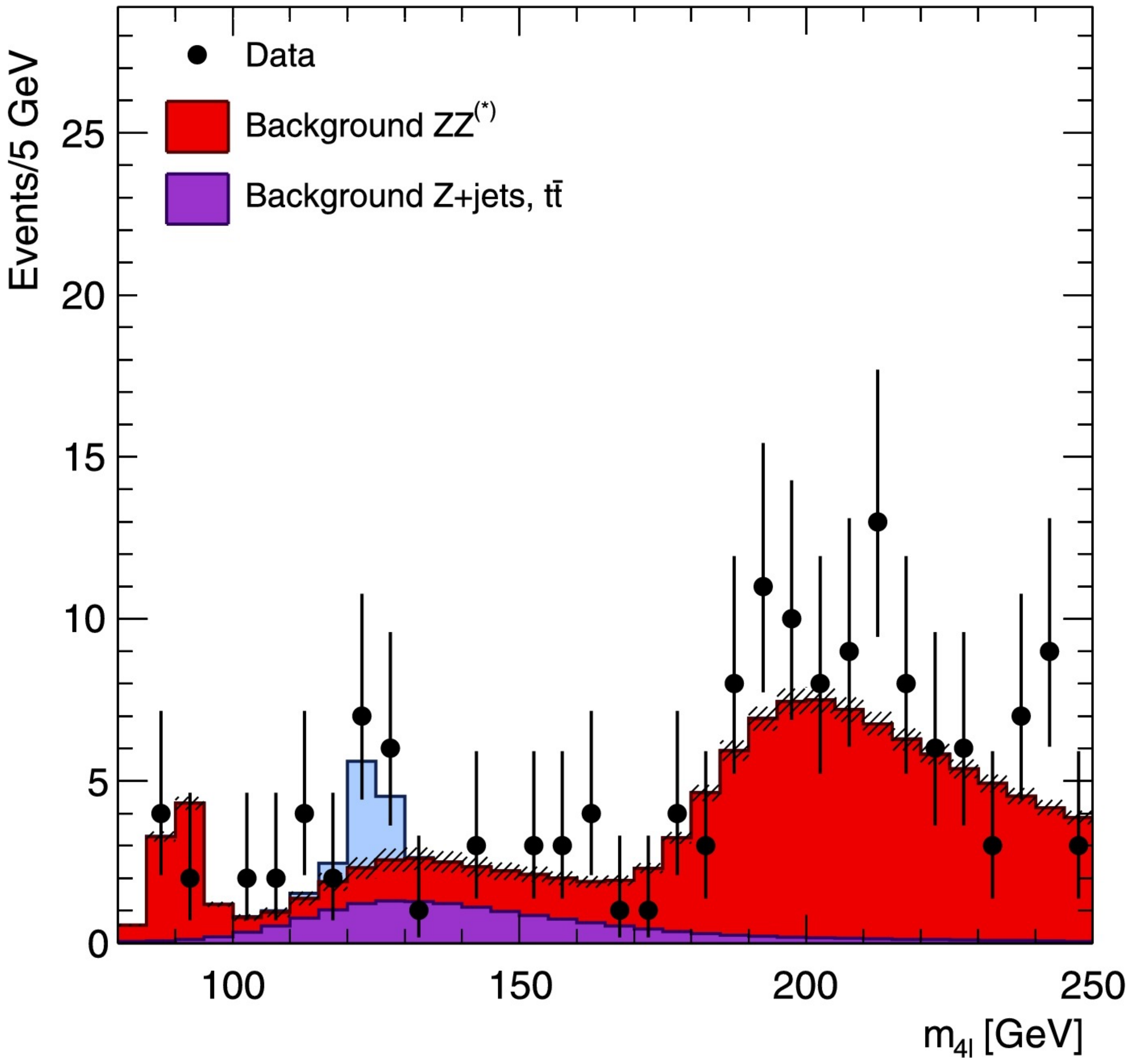

Events/5 GeV
25
20
15
10
5
0


Events/5 GeV
25
20
15
10
5
0
100
150
200
250


Events/5 GeV
25
20
15
10
5
0
100
150
200
250
m_{4l} [GeV]


Data
Events/5 GeV
25
20
15
10
5
0
100
150
200
250
m_{4l} [GeV]



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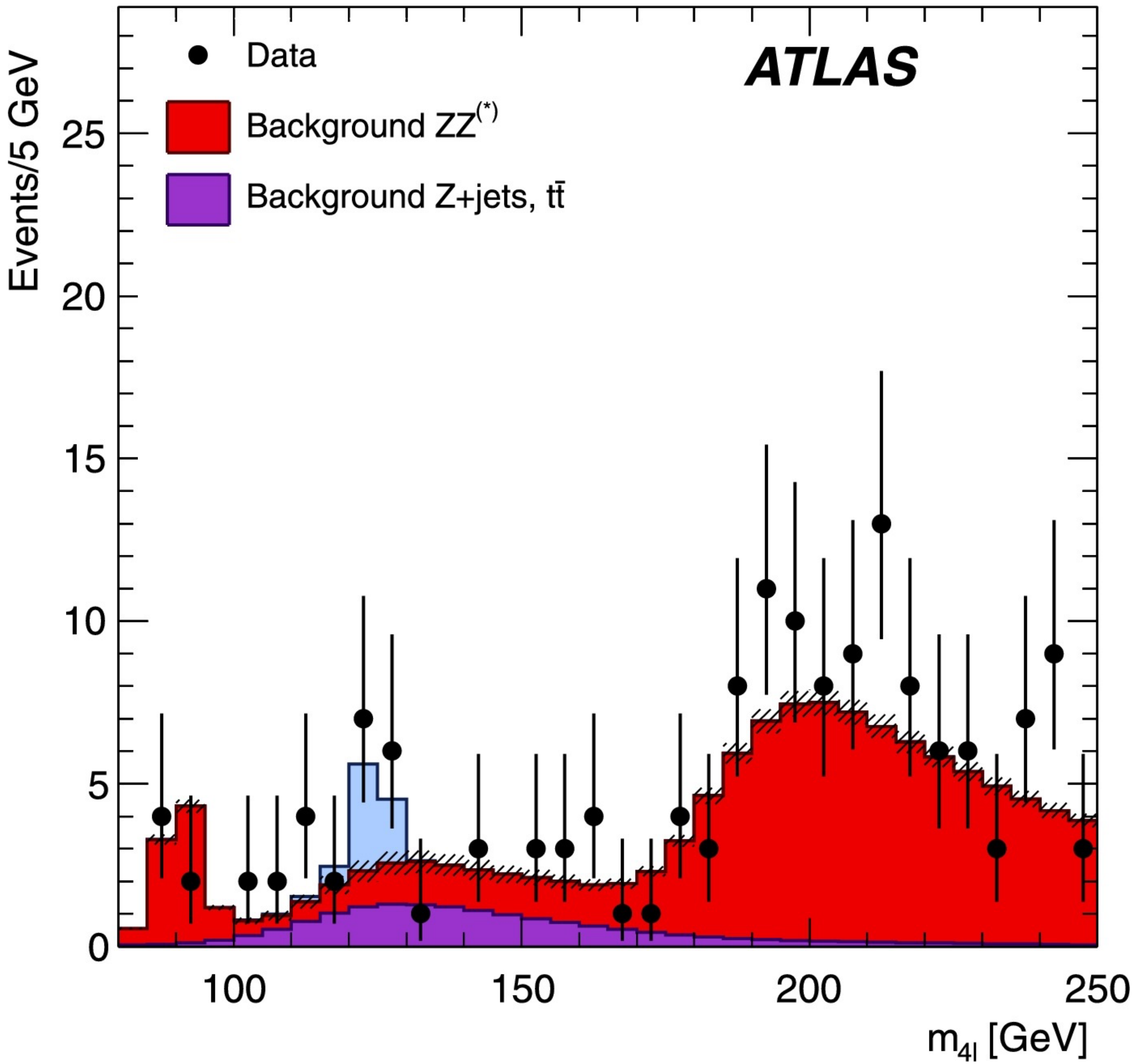
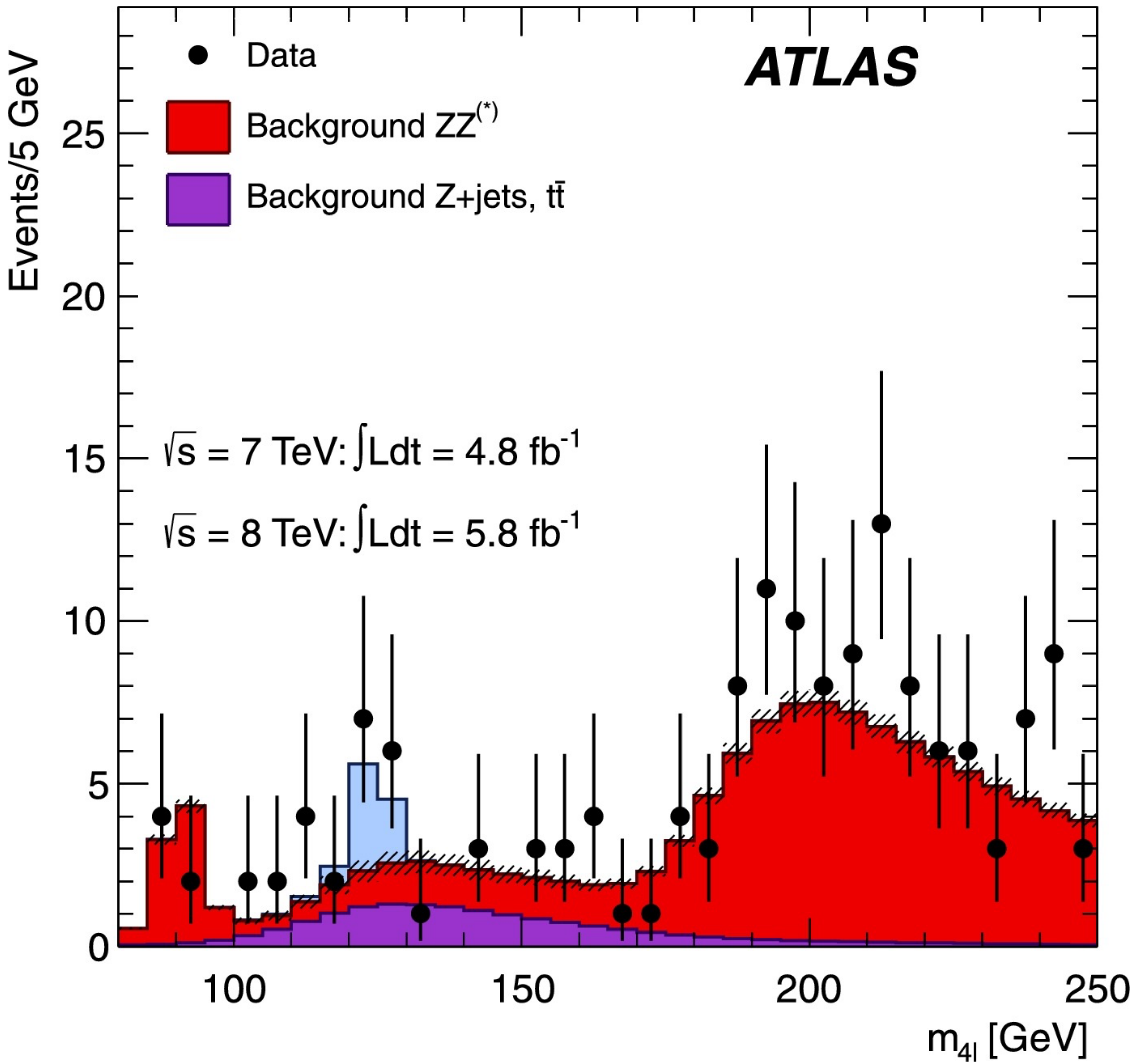


Data
Background $ZZ^{(*)}$
Background Z+jets, $t\bar{t}$
ATLAS
Events/5 GeV
25
20
15
10
5
0
100
150
200
250
m_{4l} [GeV]



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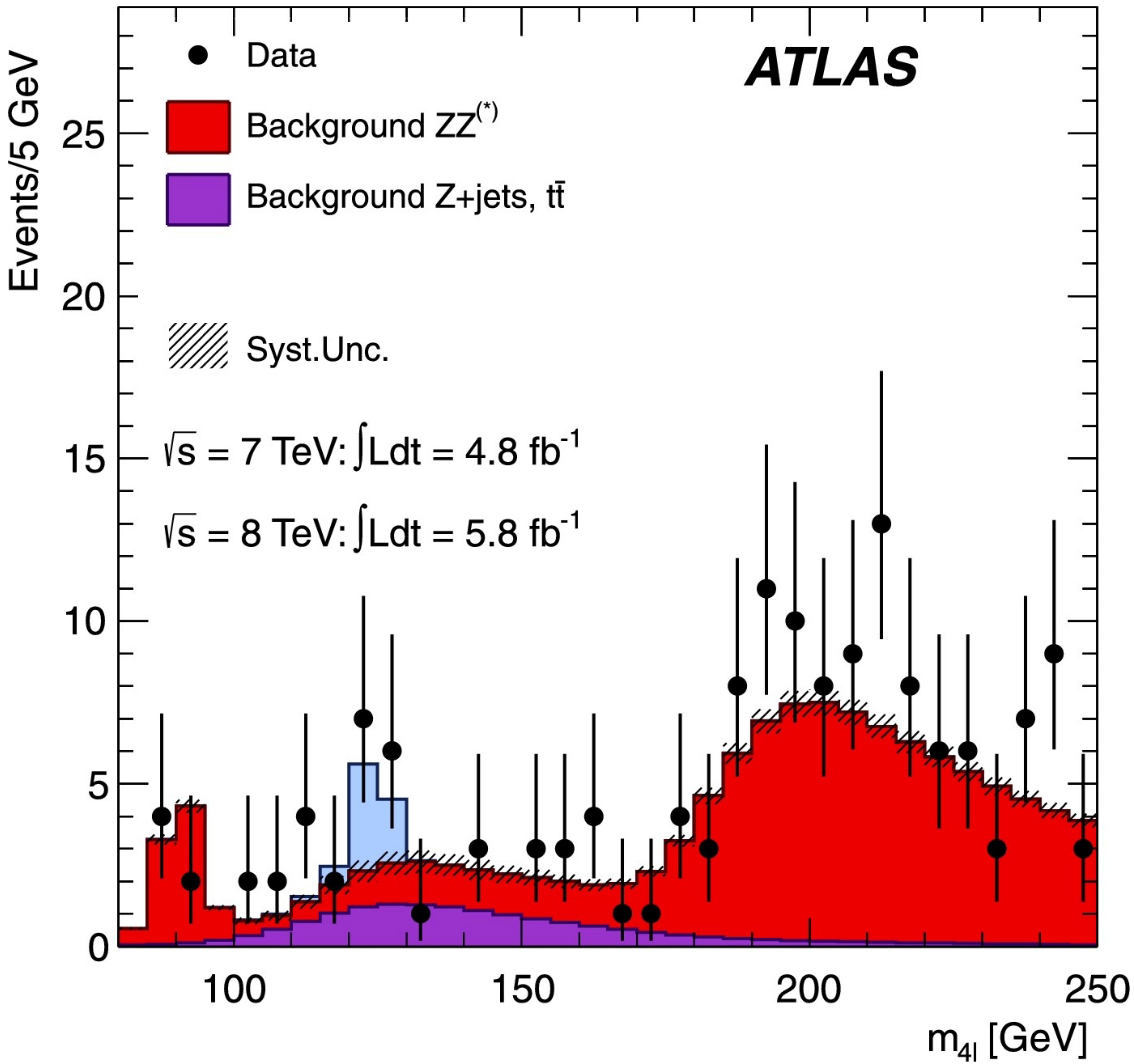
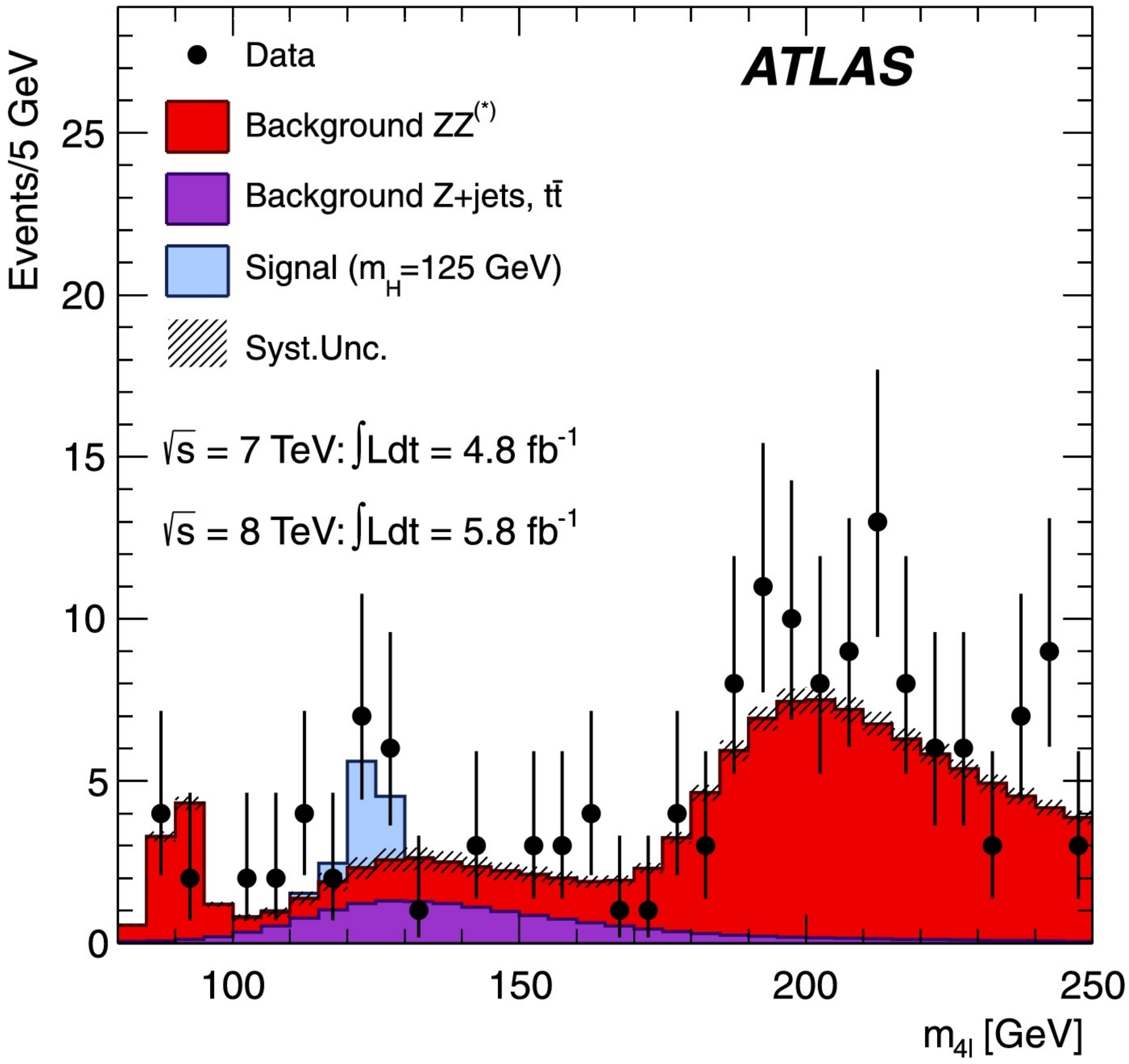
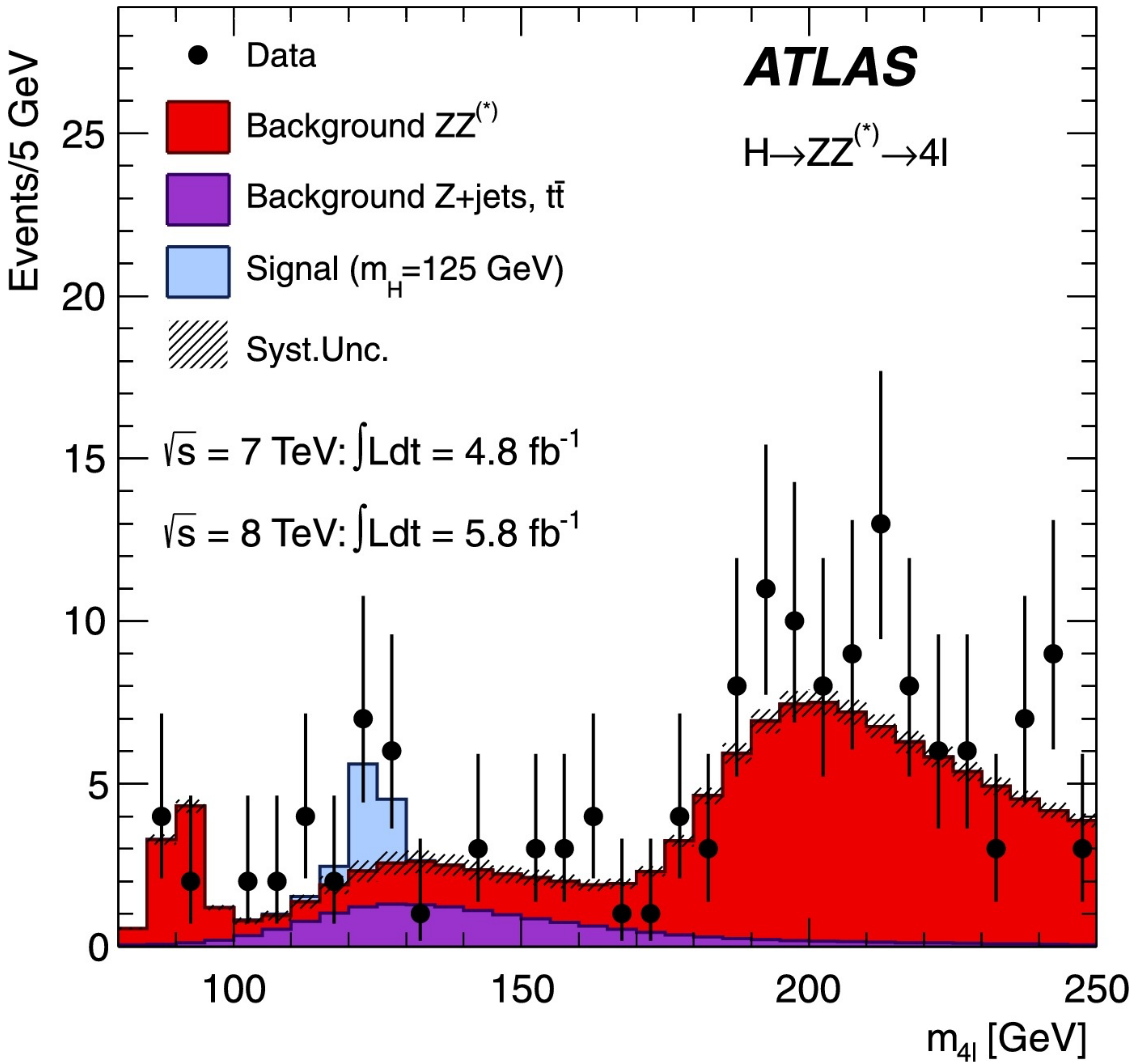
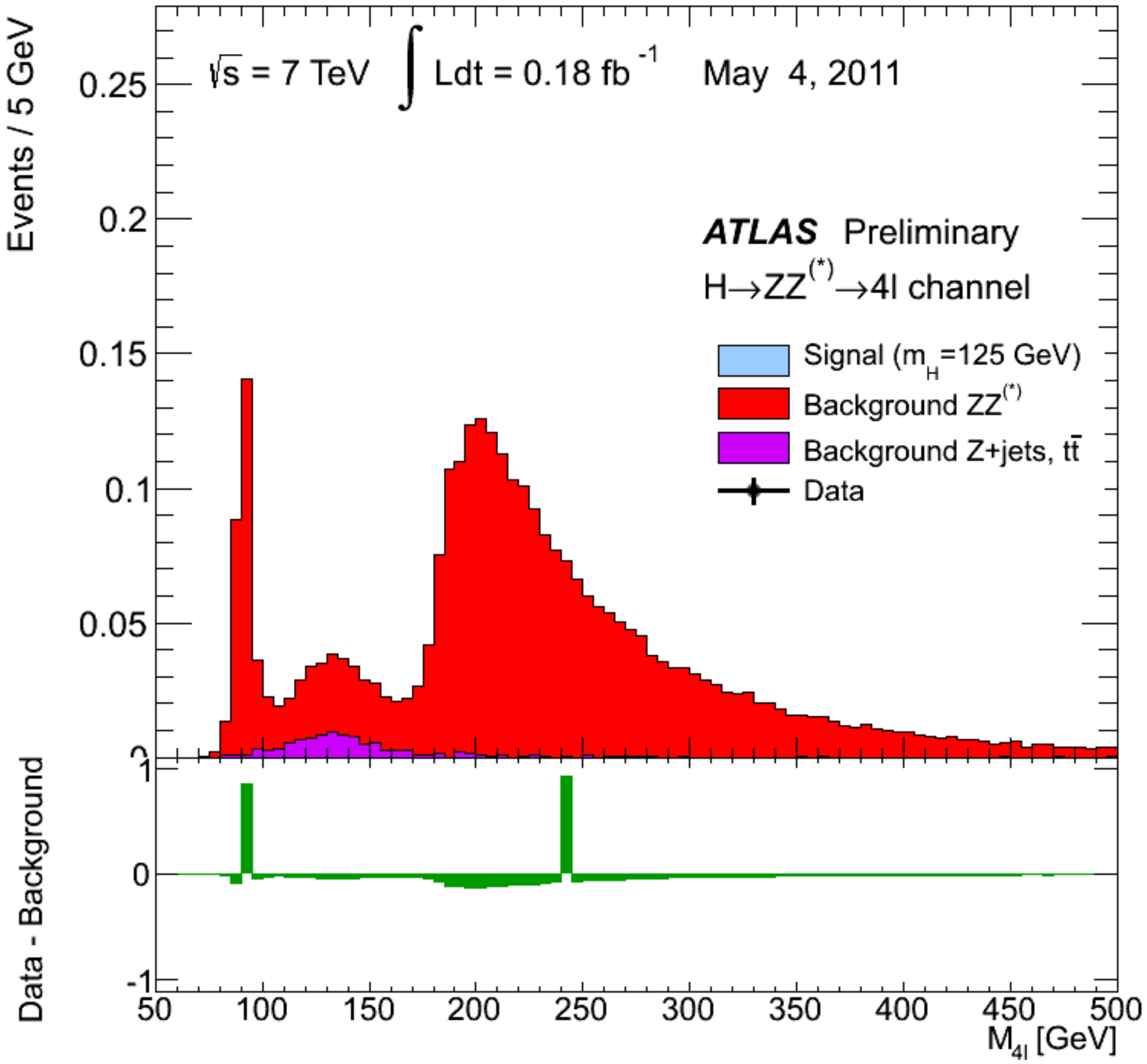


ATLAS
Data
Background ZZ(*)
Background Z+jets, tt̄
Syst.Unc.
√s = 7 TeV: ∫Ldt = 4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.8 fb-1
Events/5 GeV
m4l [GeV]
0
5
10
15
20
25
100
150
200
250


Data
ATLAS
Background ZZ(*)
Background Z+jets, tt̄
Signal (m_H=125 GeV)
Syst.Unc.
√s = 7 TeV: ∫Ldt = 4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.8 fb-1
Events/5 GeV
0
5
10
15
20
25
100
150
200
250
m4l [GeV]


Events/5 GeV
Data
Background $ZZ^{(*)}$
Background Z+jets, $t\bar{t}$
Signal (m_H=125 GeV)
Syst.Unc.
ATLAS
$H \rightarrow ZZ^{(*)} \rightarrow 4l$
$\sqrt{s}$ = 7 TeV: $\int Ldt$ = 4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV: $\int Ldt$ = 5.8 fb^{-1}
0
5
10
15
20
25
100
150
200
250
m_{4l} [GeV]



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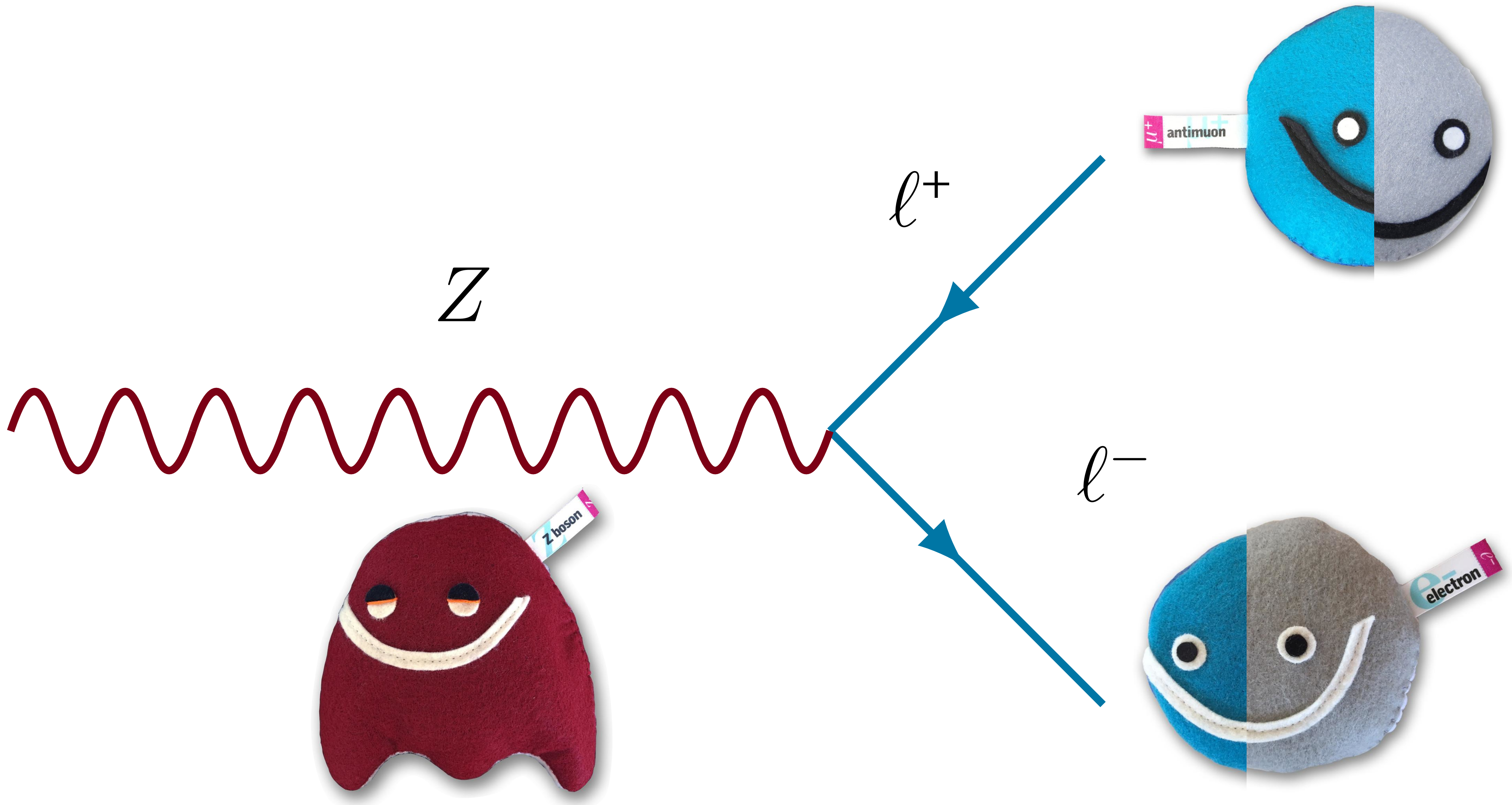
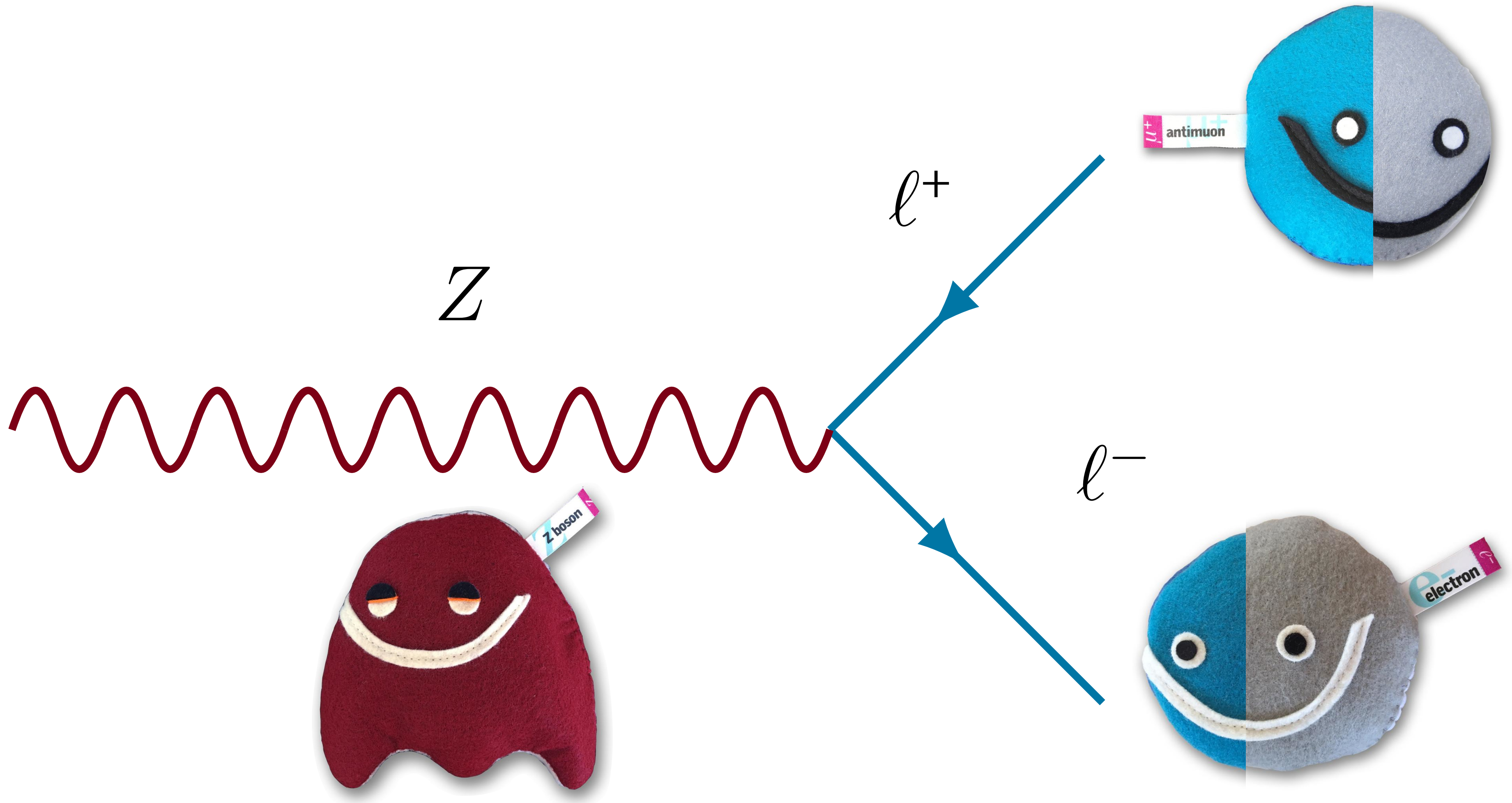
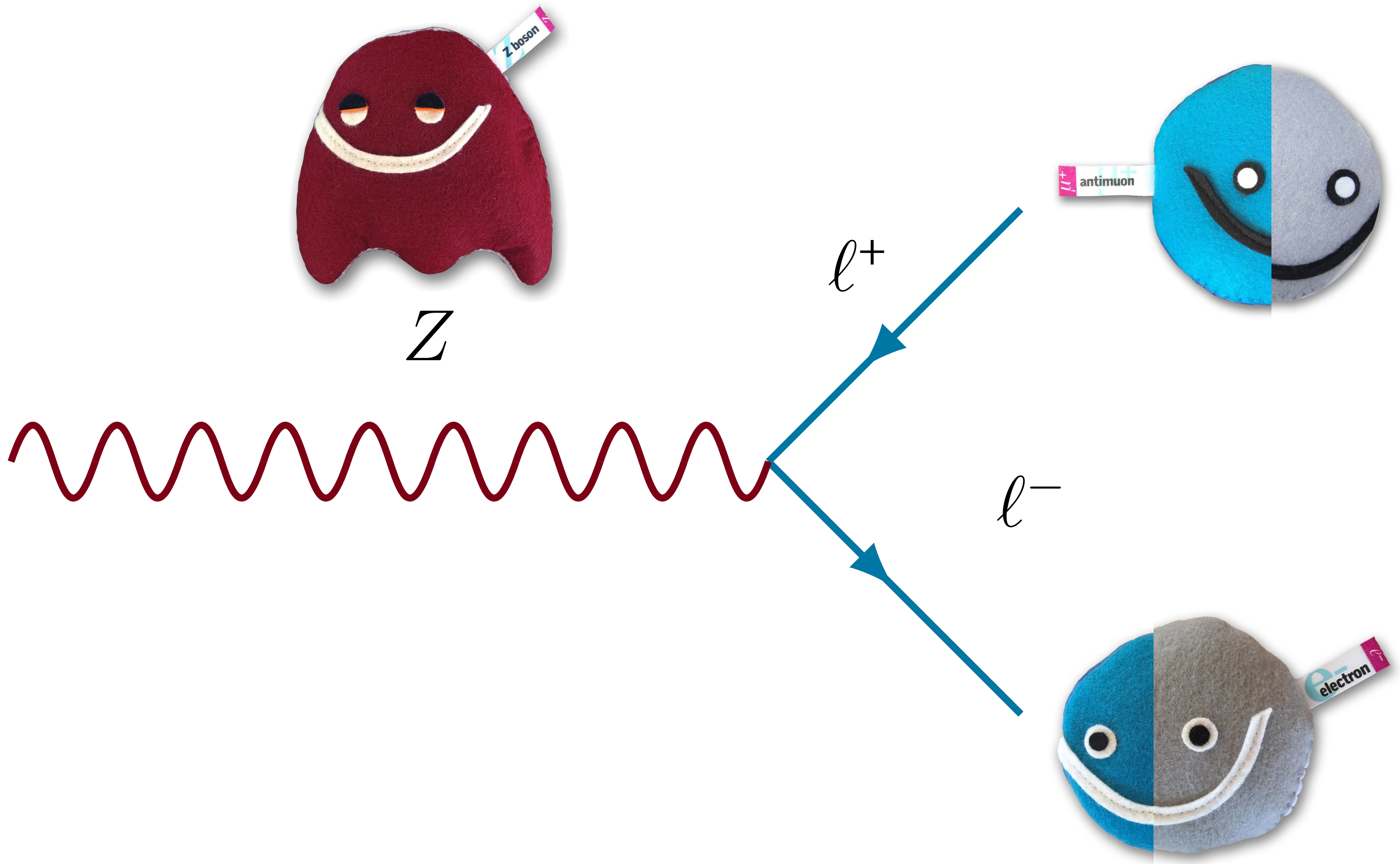
Z

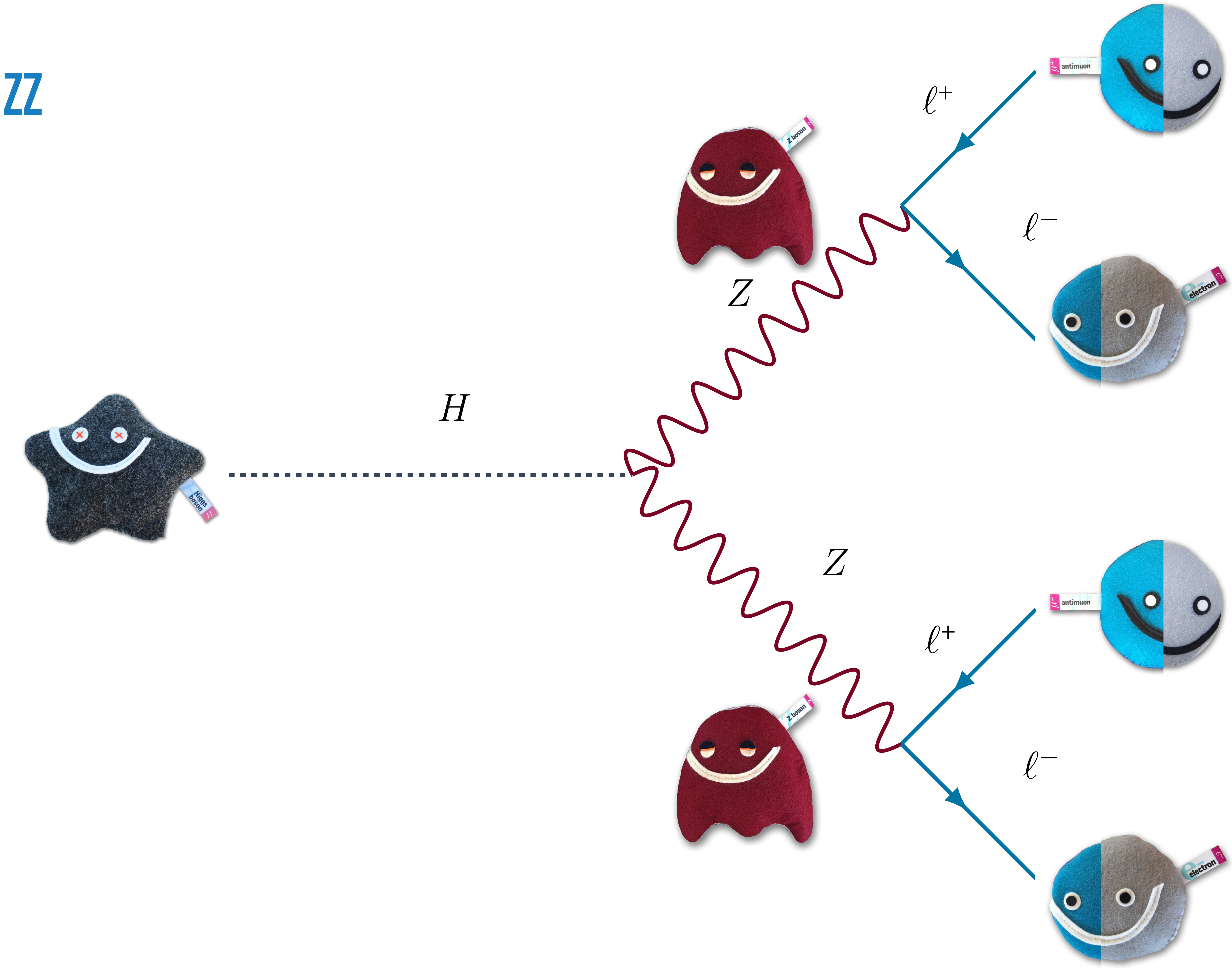


ZZ

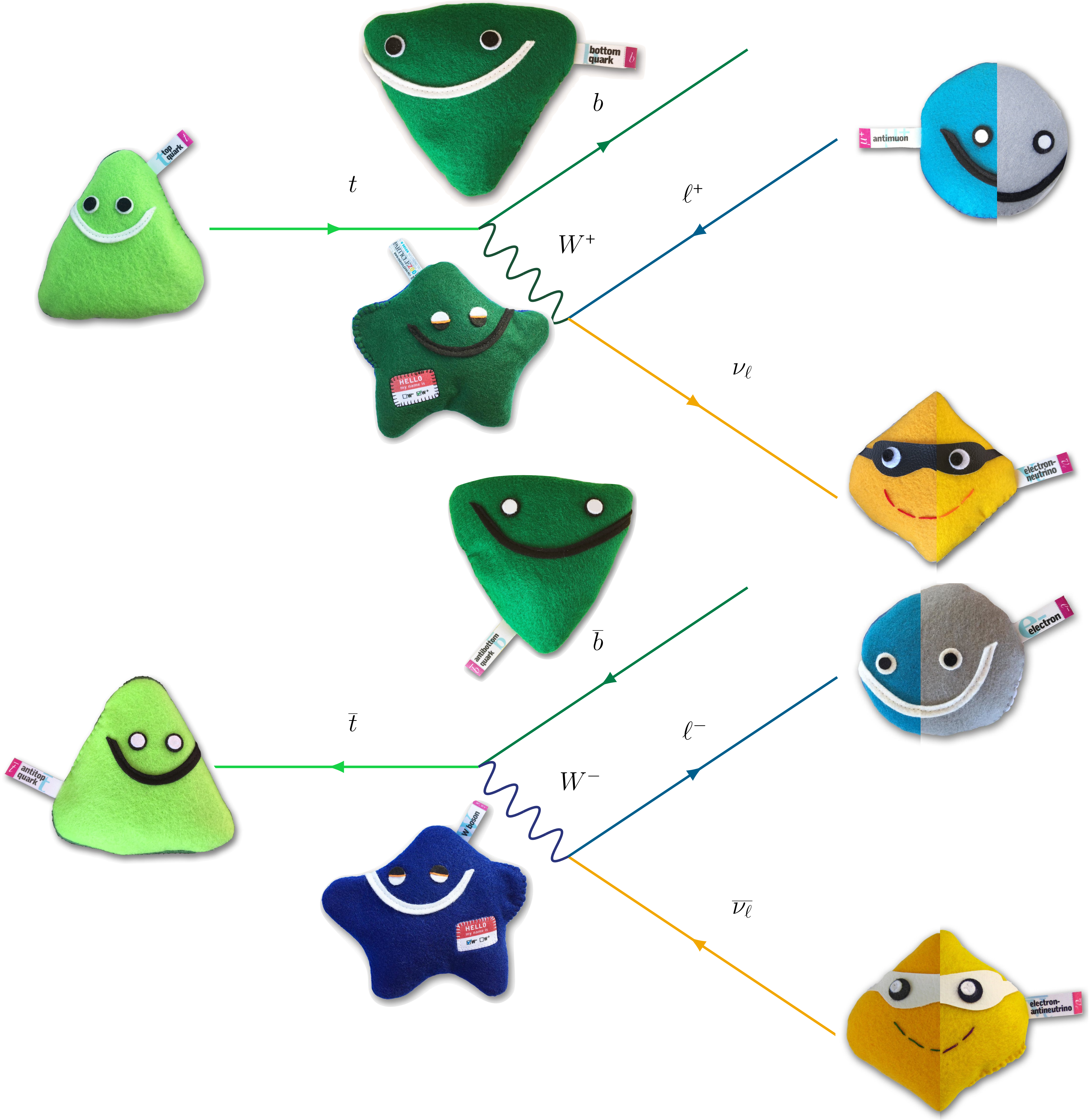

Z
ℓ^+
ℓ^-
Z boson
antimuon
electron


Z boson
Z
ℓ^+
ℓ^-
antimuon
electron

H → ZZ



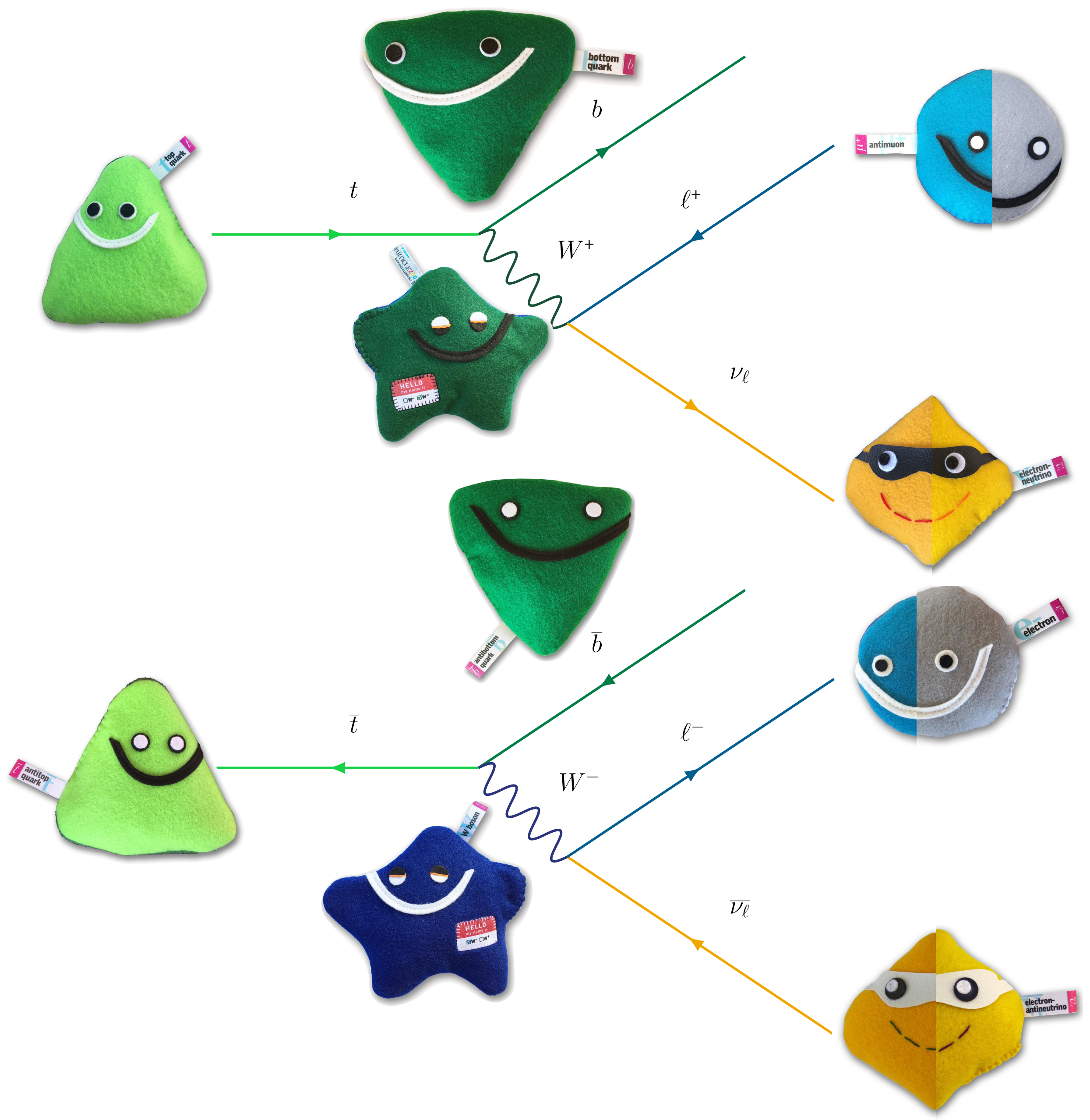
$t\bar{t}$



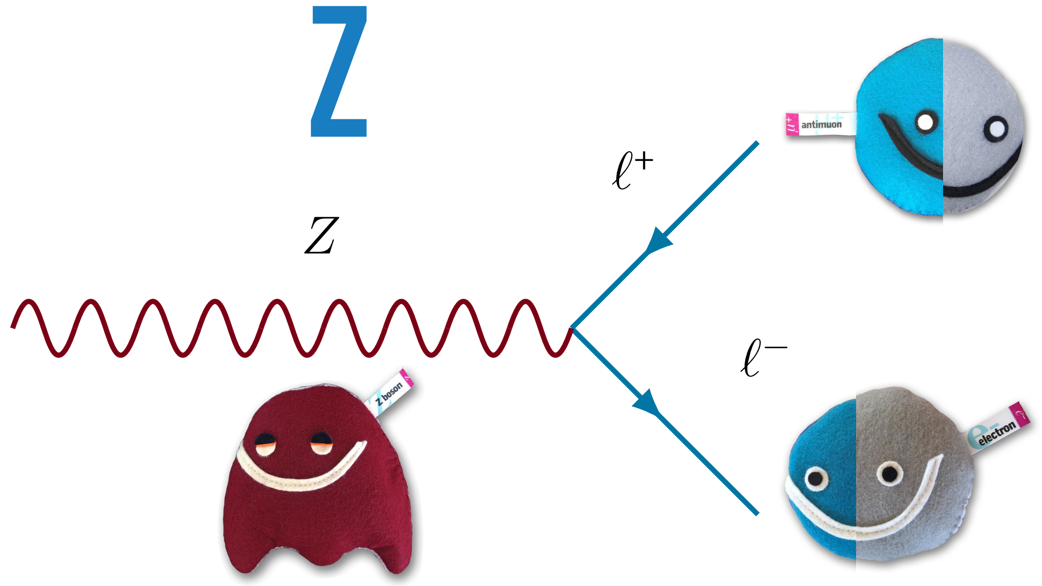
top quark
bottom quark
t
b
W^+
ℓ^+
antimuon
ν_ℓ
electron-neutrino
antibottom quark
$\bar{b}$
electron
antitop quark
$\bar{t}$
W^-
ℓ^-
W boson
$\overline{\nu_\ell}$
electron-antineutrino

SIGNAL VS BACKGROUND

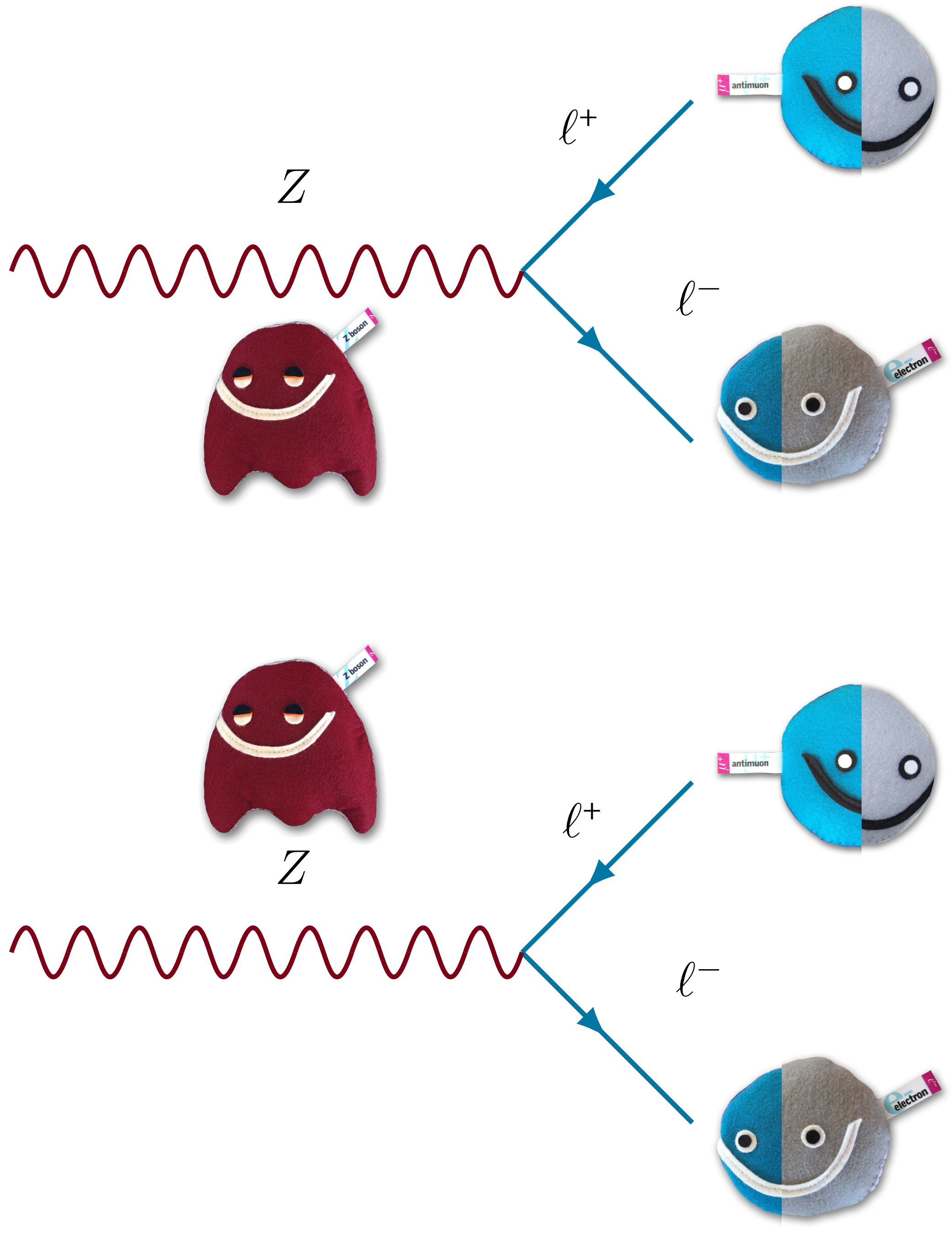
$t\bar{t}$



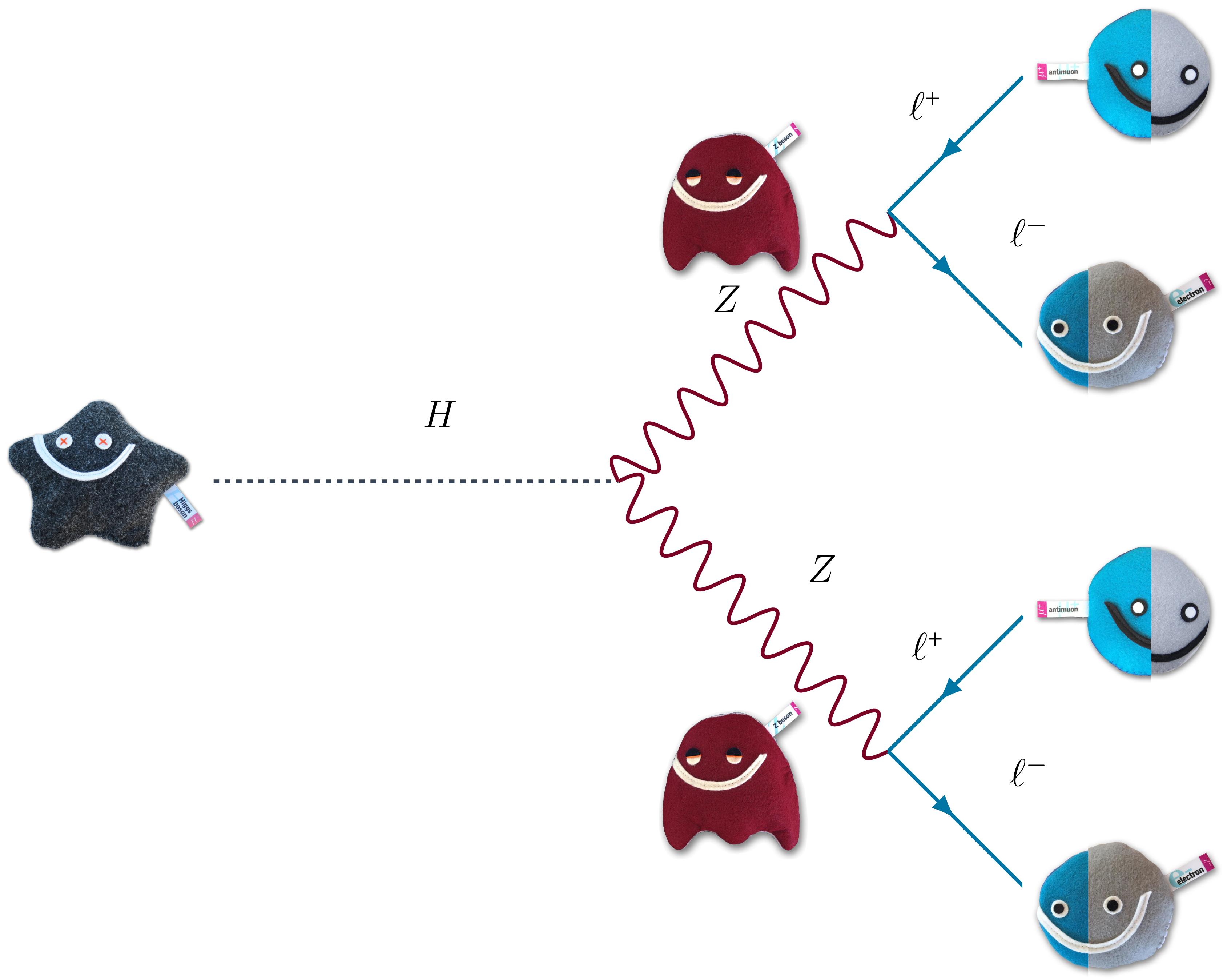
Z



ZZ



H → ZZ



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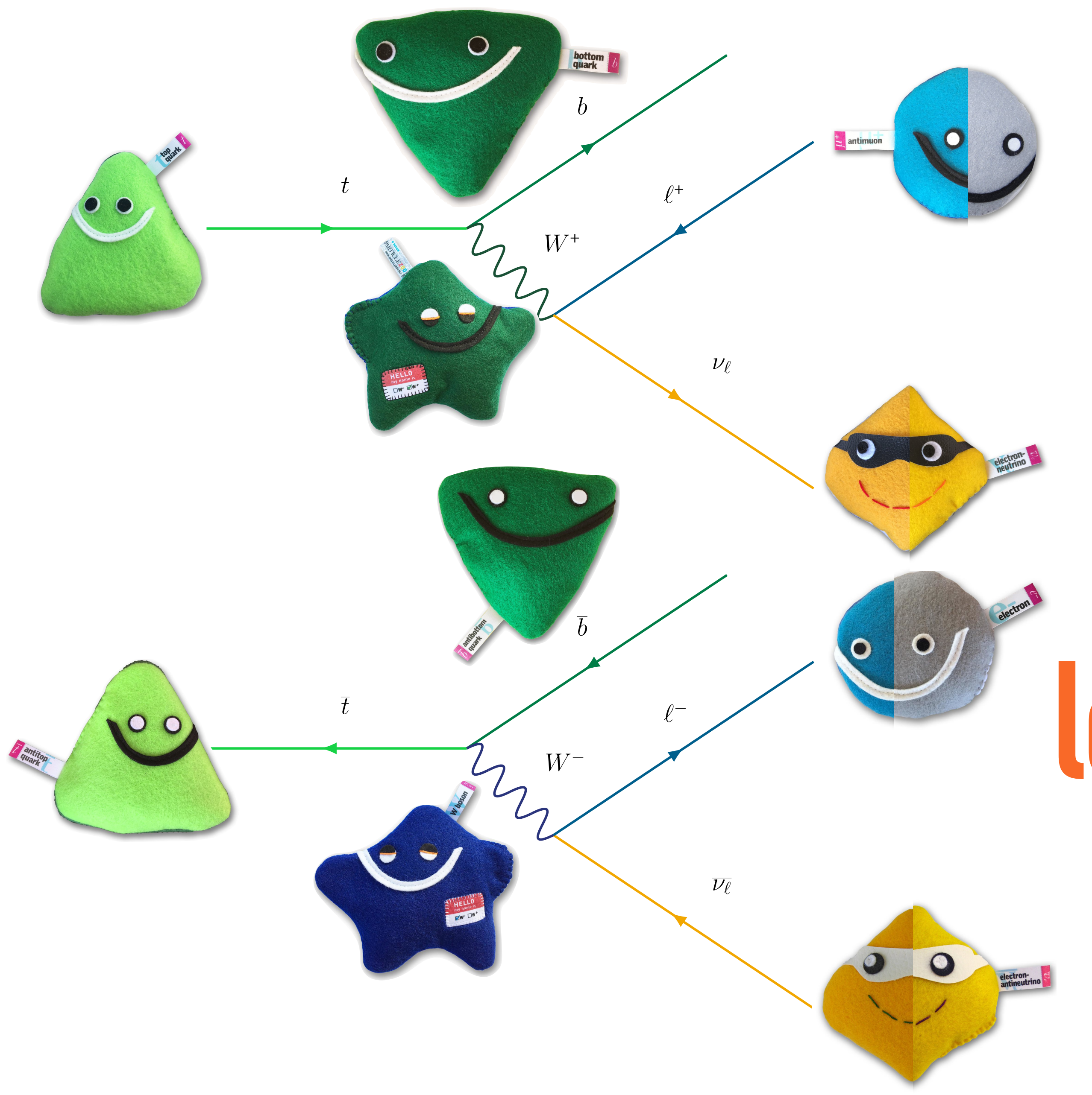
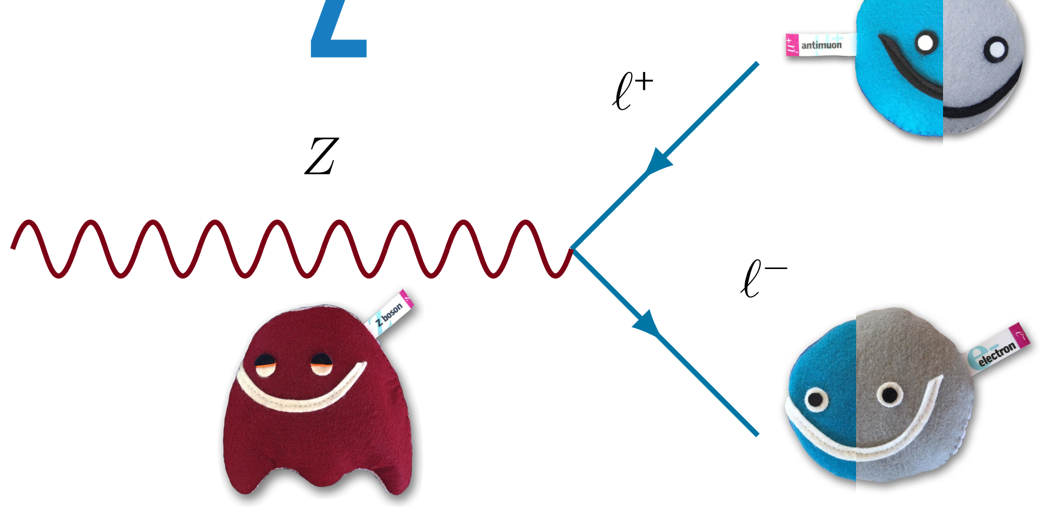
ATLAS EXPERIMENT

SIGNAL VS BACKGROUND

$t\bar{t}$

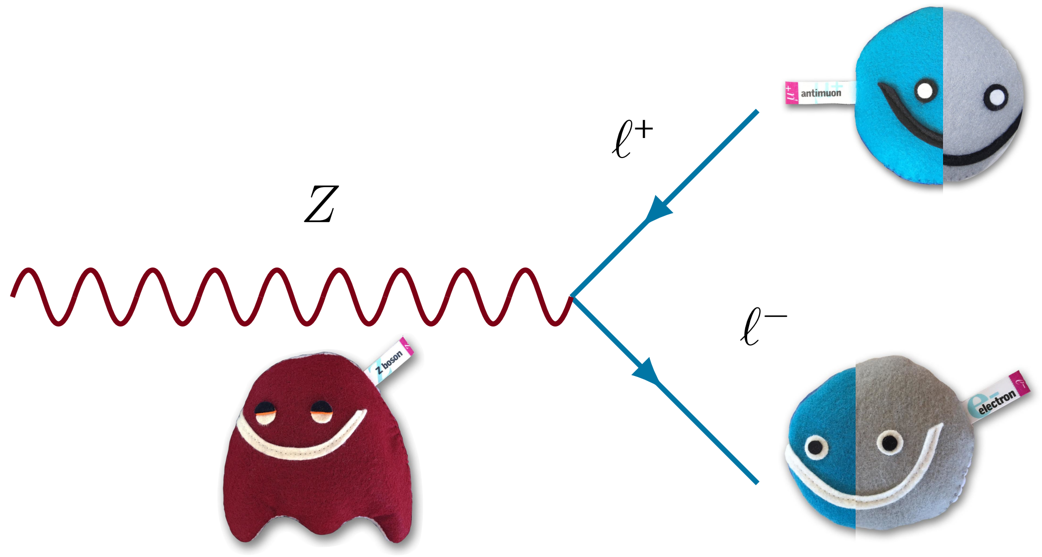


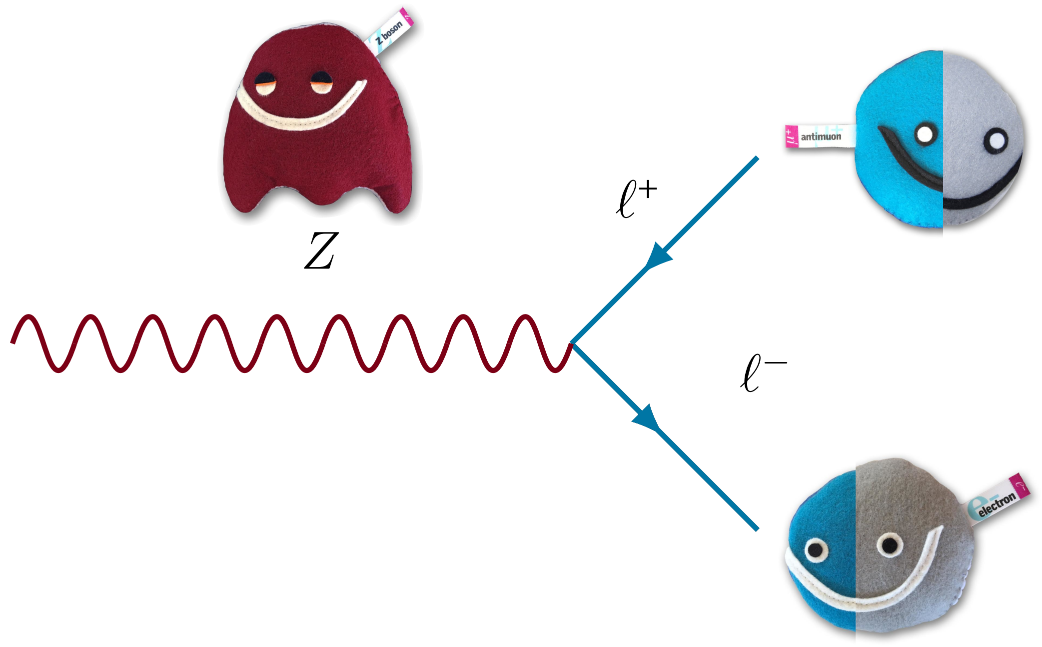
Z



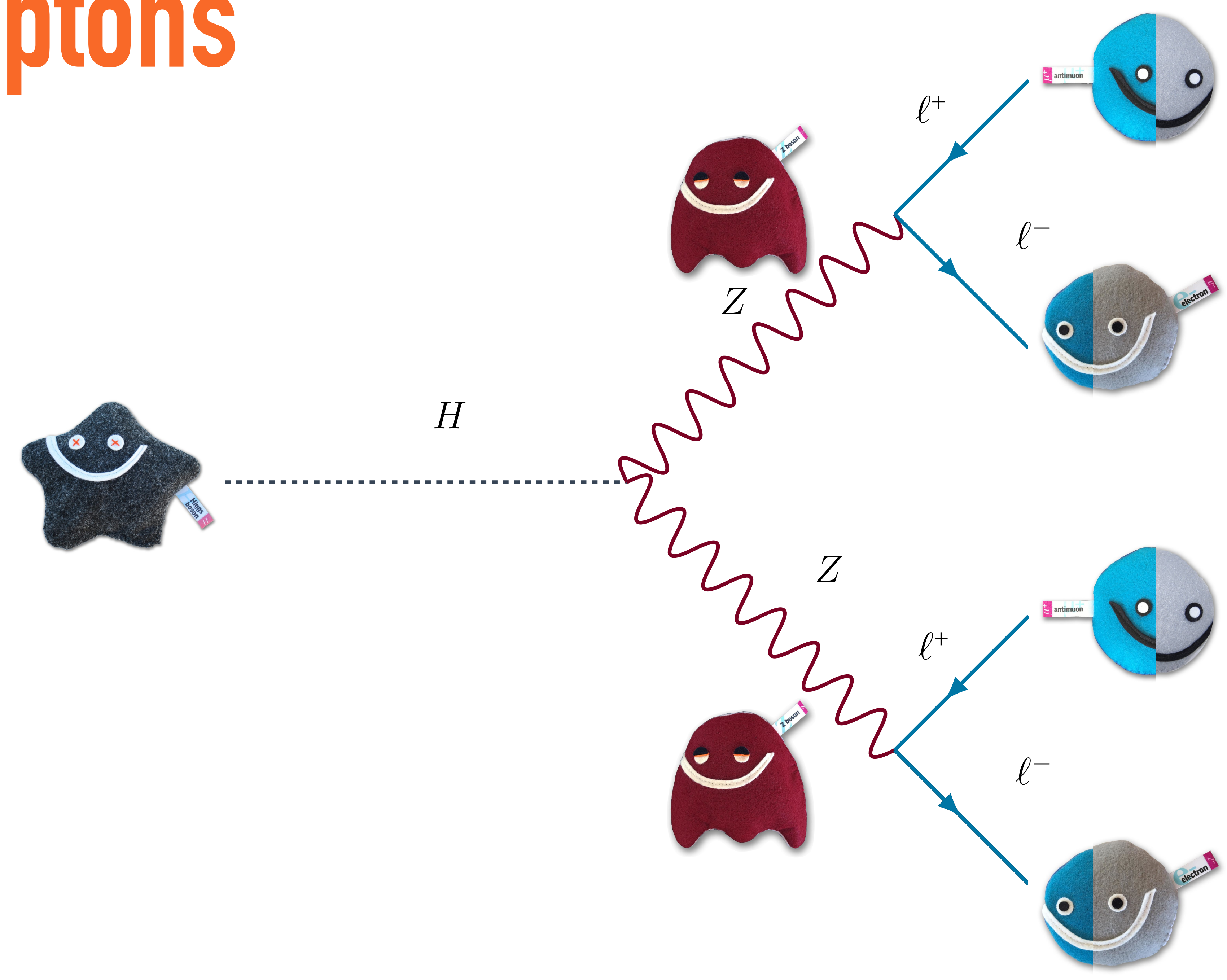
2 leptons

4 leptons





ZZ



H → ZZ

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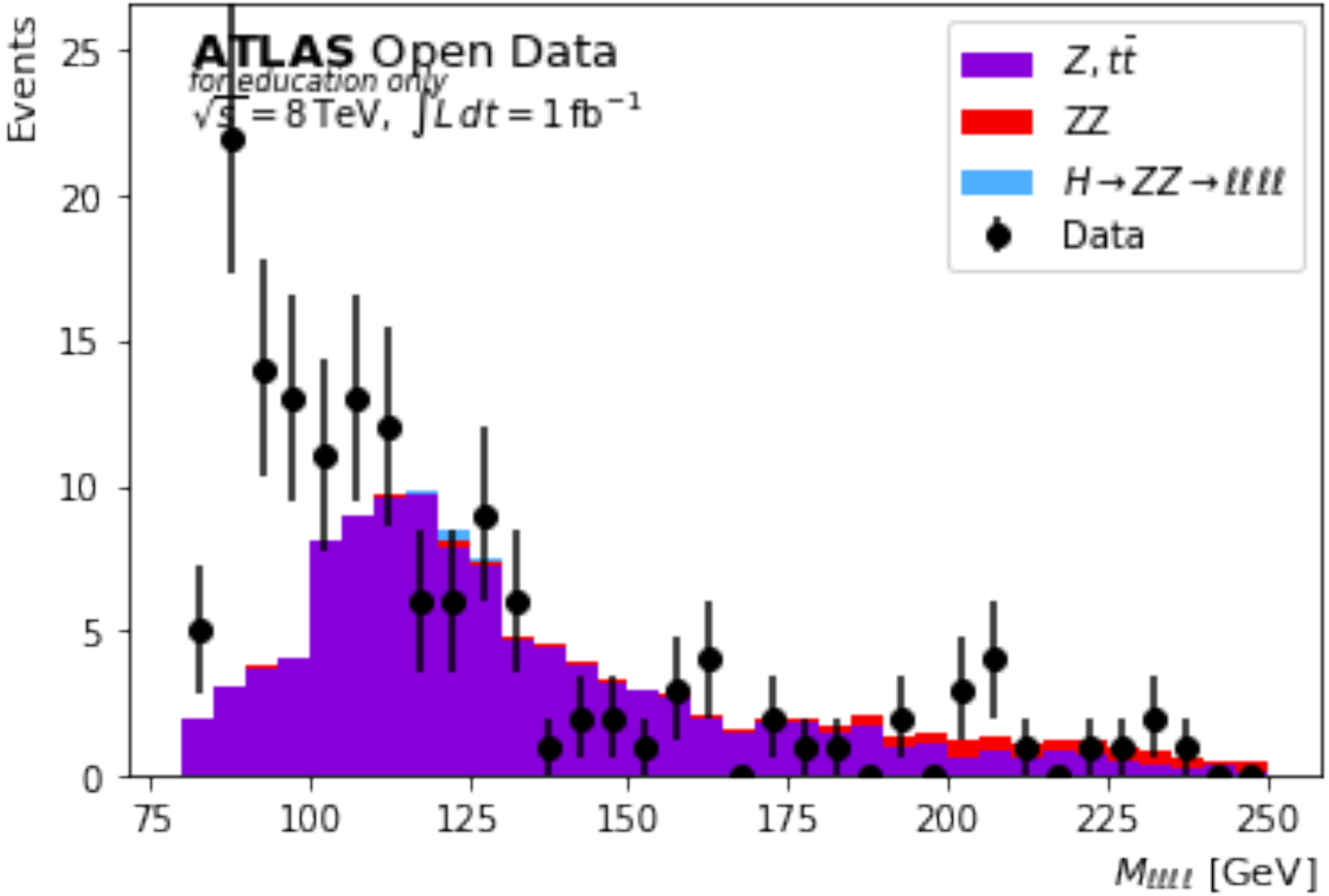
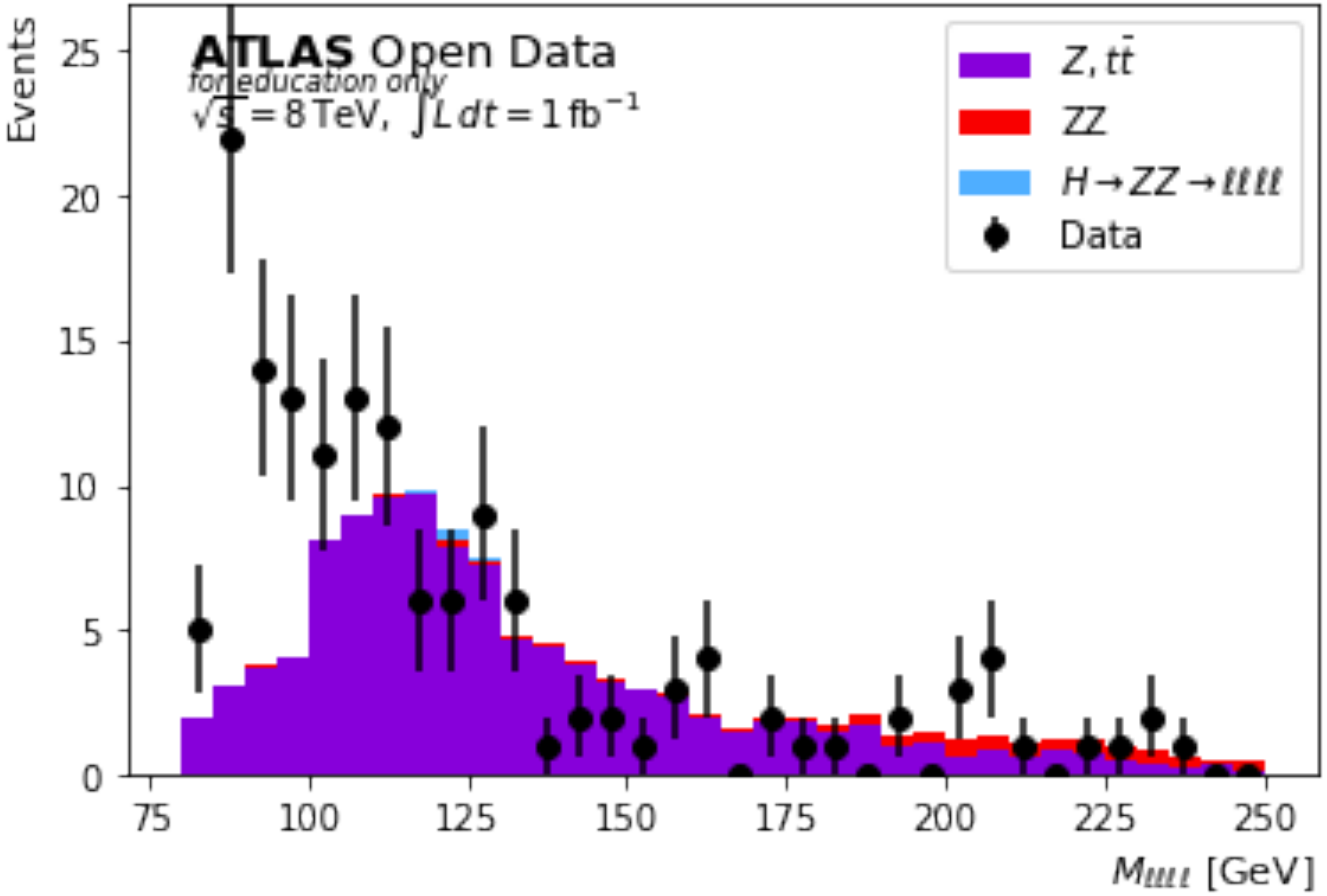
Run the template analysis

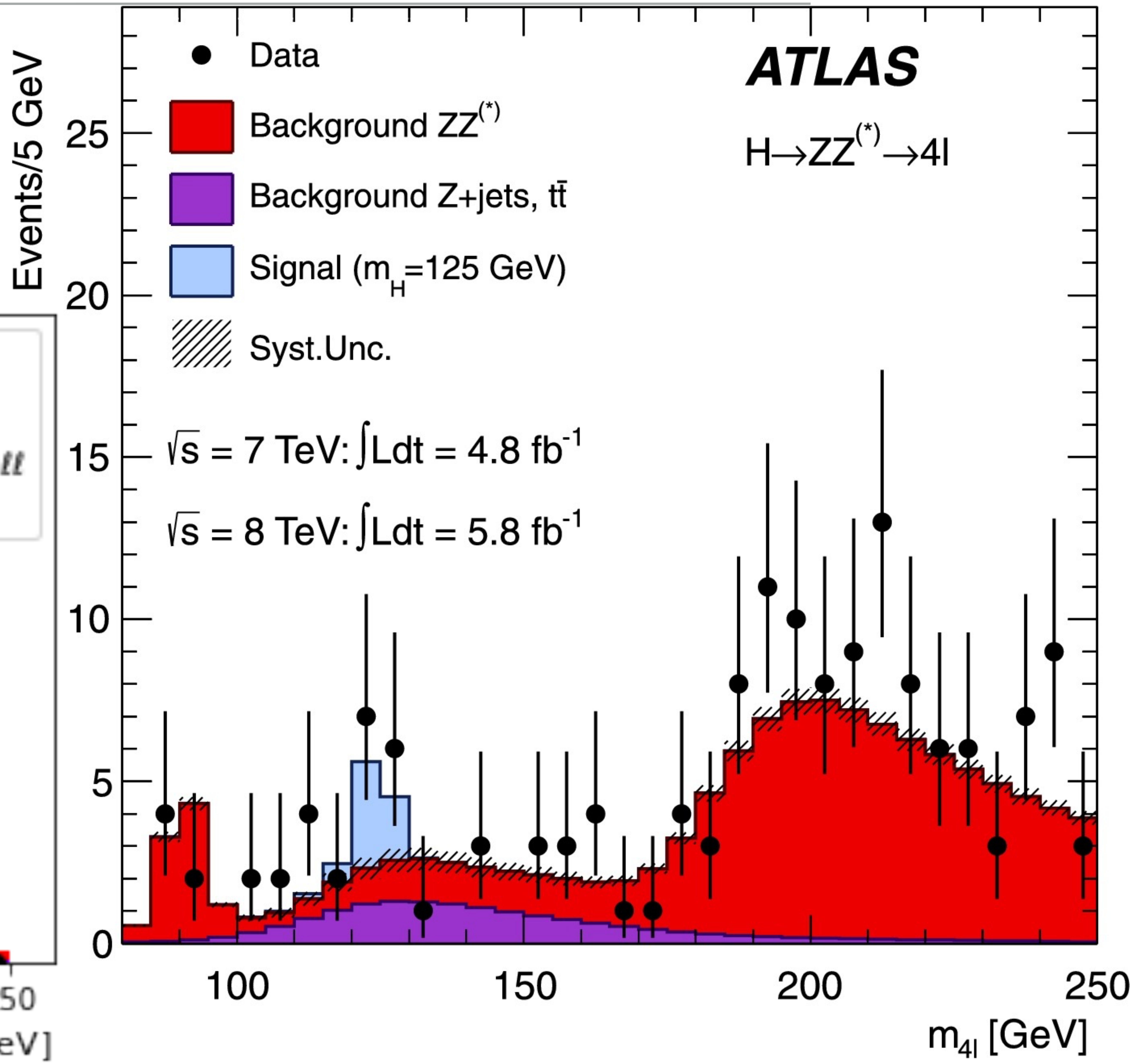
- Go to github.com/meevans1/How-to-rediscover-the-Higgs
- Follow the instructions to open the Jupyter notebook
- Cell -> Run All

Output from template analysis



Output from template analysis





Cut on more variables

- Variables described on the ATLAS Open Data website
- Try add your own cuts to improve the signal / background ratio
- I'll be updating the live google doc with hints

Competition time!

- Submit your team's notebook + its output for entry into our competition
- Winners' code will be modified to use for the upcoming release of new 13 TeV data
  - (+ a prize at the dinner Thursday)
- Instructions on the GitHub code page on how to enter

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Judgement criteria

- In this order:
  - Something crazy like Machine Learning
  - Code elegance
  - Number of cuts correctly implemented
  - Total elapsed time
  - Plot
  - $\text{Signal}/\sqrt{\text{Background}}$

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Diolch! (Thanks!)

- From this hackathon I hope you've got an insight into:
  - How Python, Pandas, Numpy & Matplotlib can be used for (really) big data analysis
  - How interesting (& challenging) particle physics can be
  - How the Higgs boson was discovered
  - How you can go onto rediscover the Higgs boson
  - How to (re-)win a Nobel Prize

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@meirinoanevans
@meirinoanevans
Meirin Oan Evans

DIOLCH! (THANKS!)

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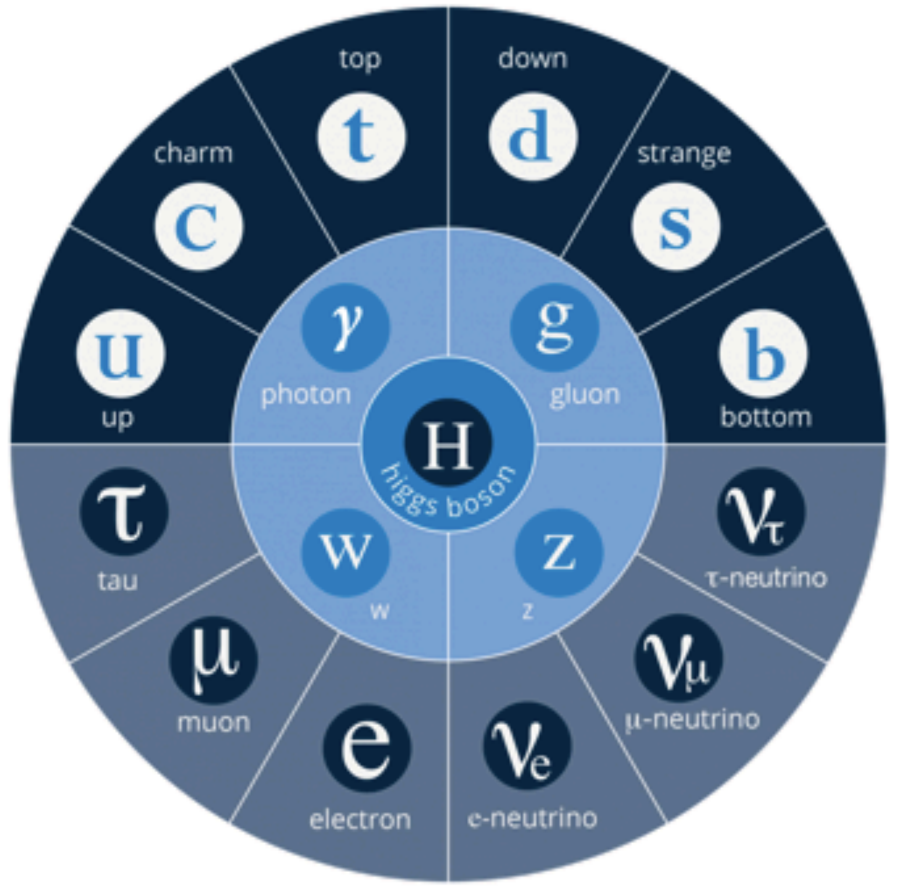
Experimental Particle Physics



What are the building blocks of matter?

What are the forces between them?

What happened to antimatter?

What's dark matter?

What was the early universe like & how did it evolve?

What about gravity?

Anything else?

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open data ATLAS

ATLAS data

- ATLAS is designed to observe up to 1.7 billion collisions a second
  - (> 60 million MB/s)
  - On a stack of standard 120mm 700MB CDs, it'd stretch from the Earth to the Sun every year!
- So a trigger system selects ~1000 of these collisions s^{-1}
  - Our CD stack now only stretches from Brighton to Oxford every year…

*not to scale

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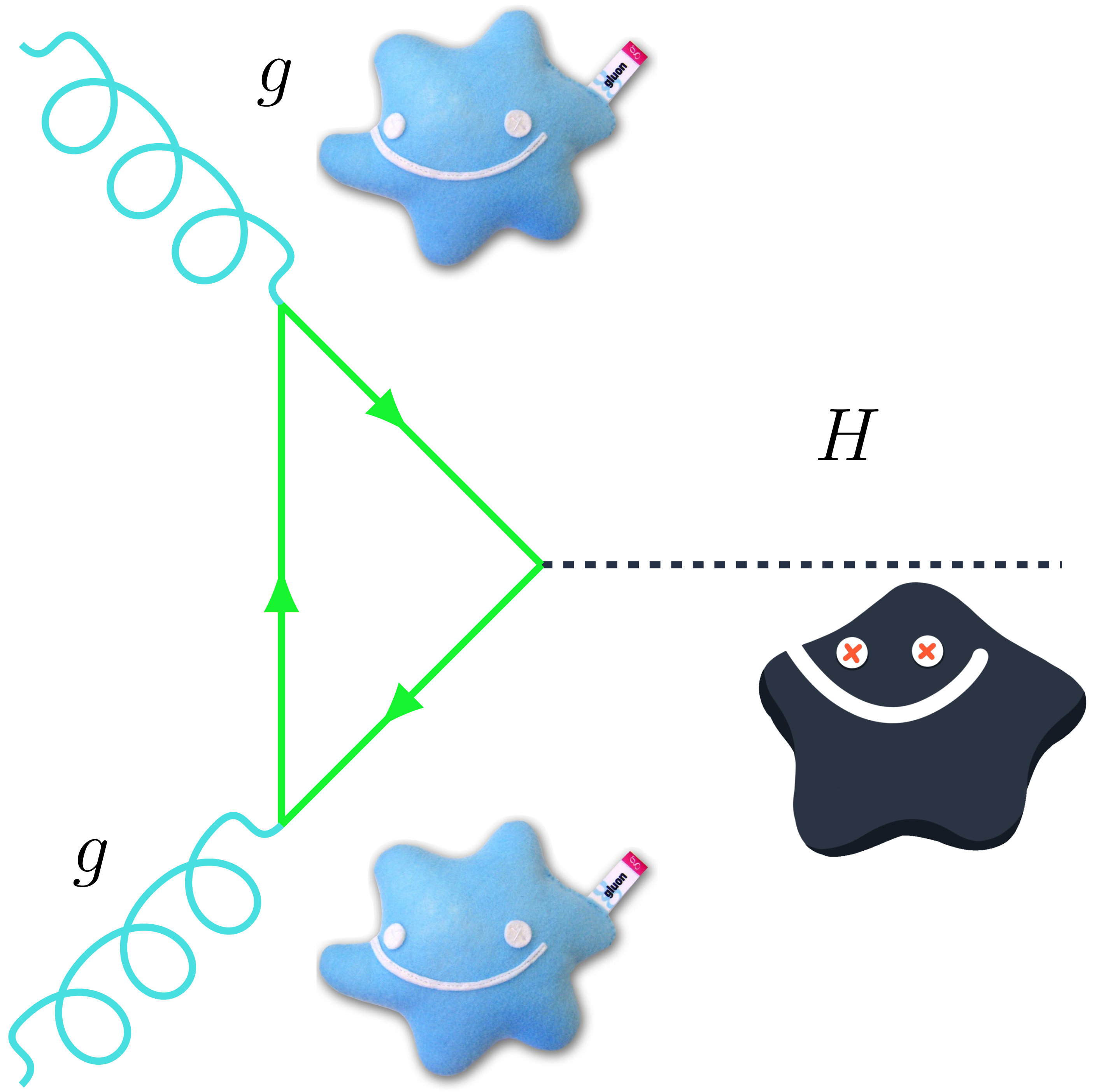
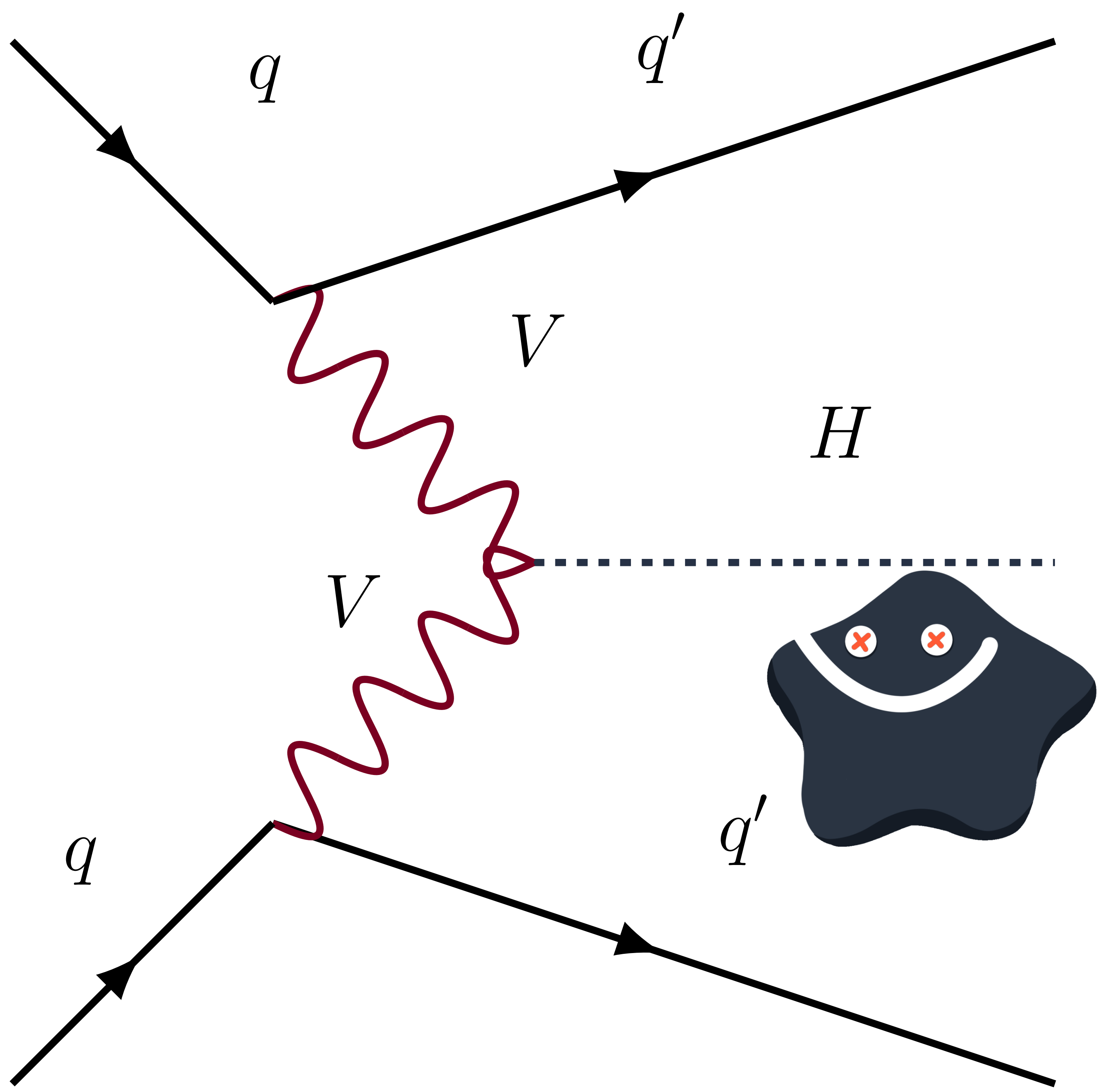
open data ATLAS

Higgs production

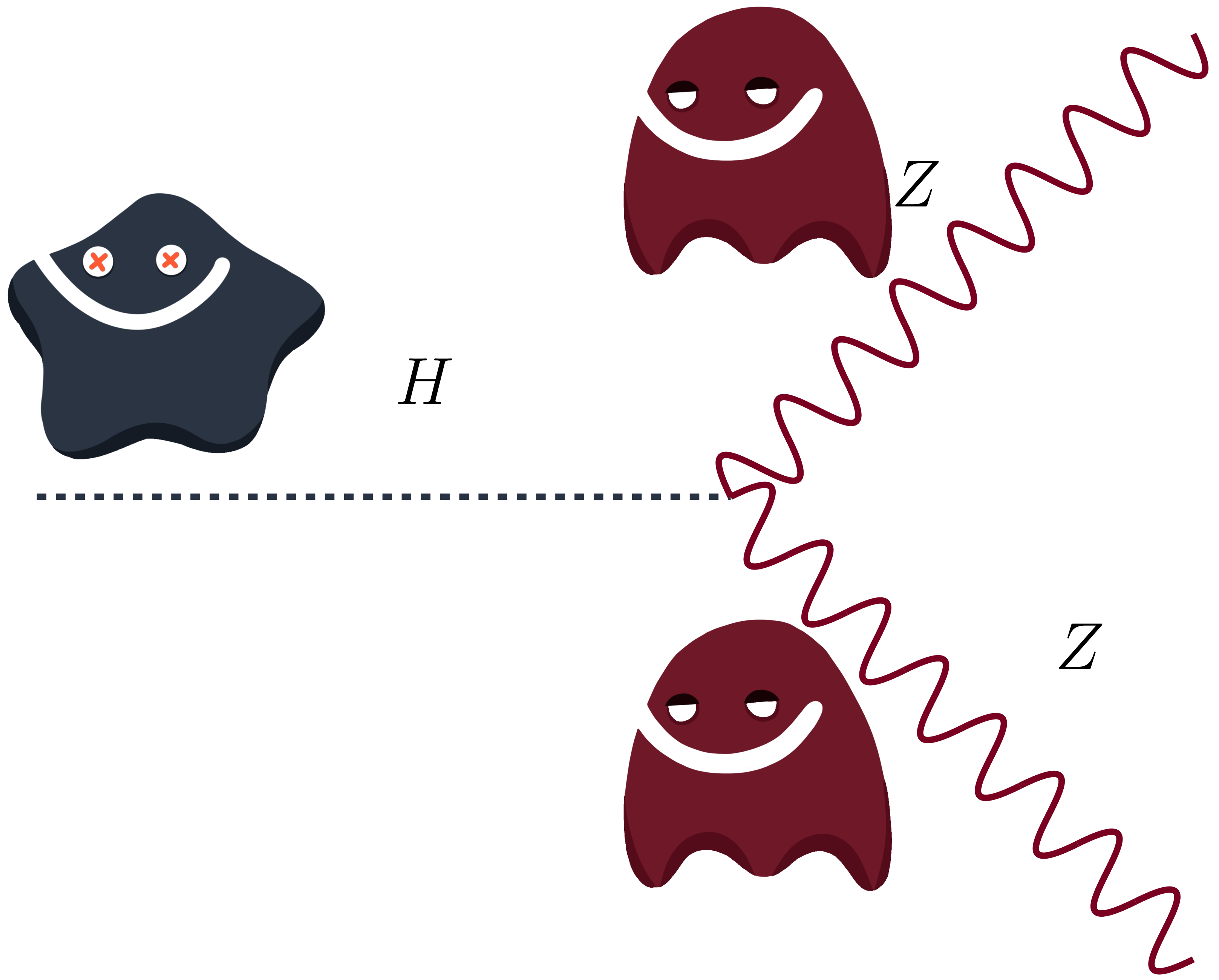


gluon-gluon (gg)

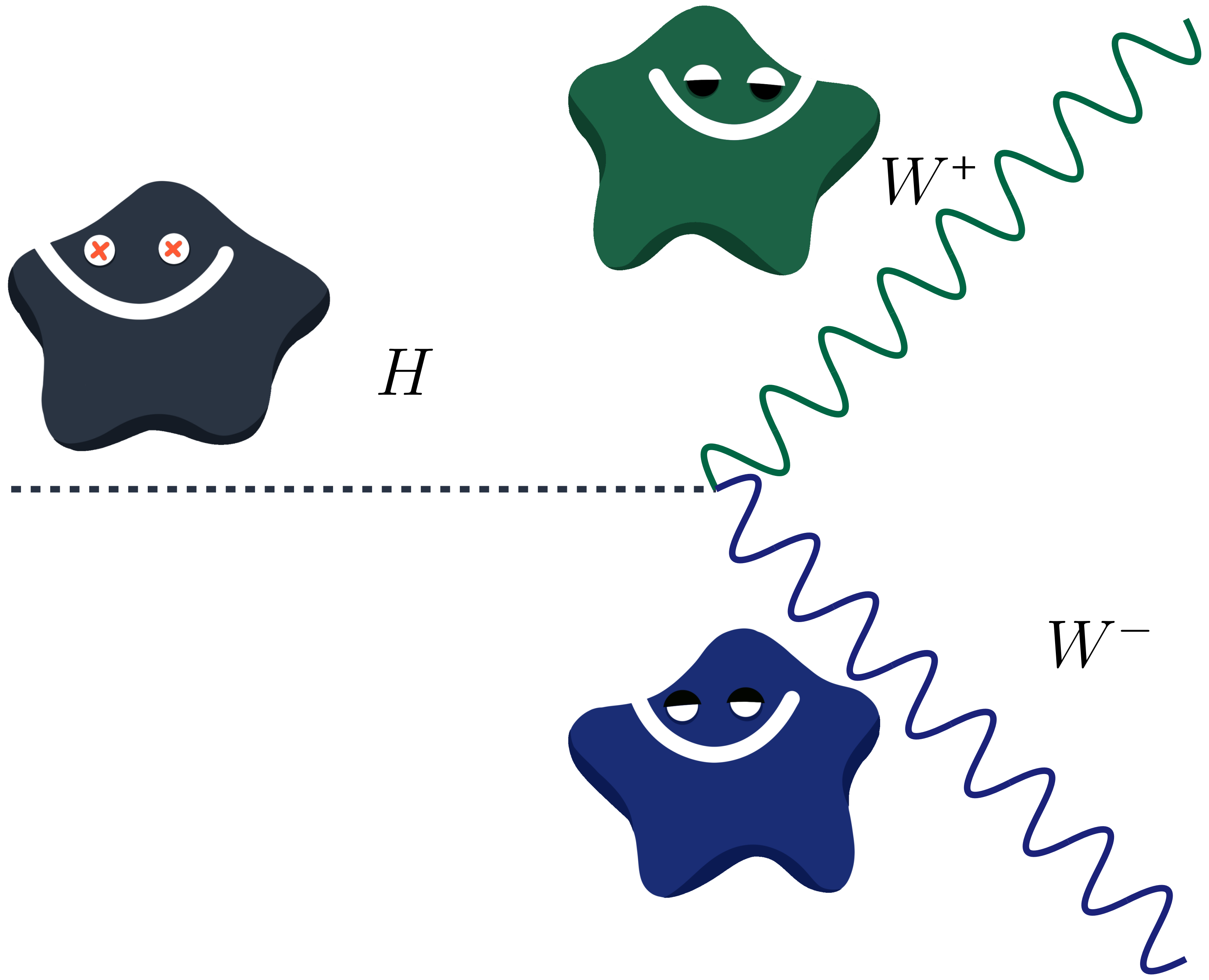


Vector Boson Fusion (VBF)

Higgs decay

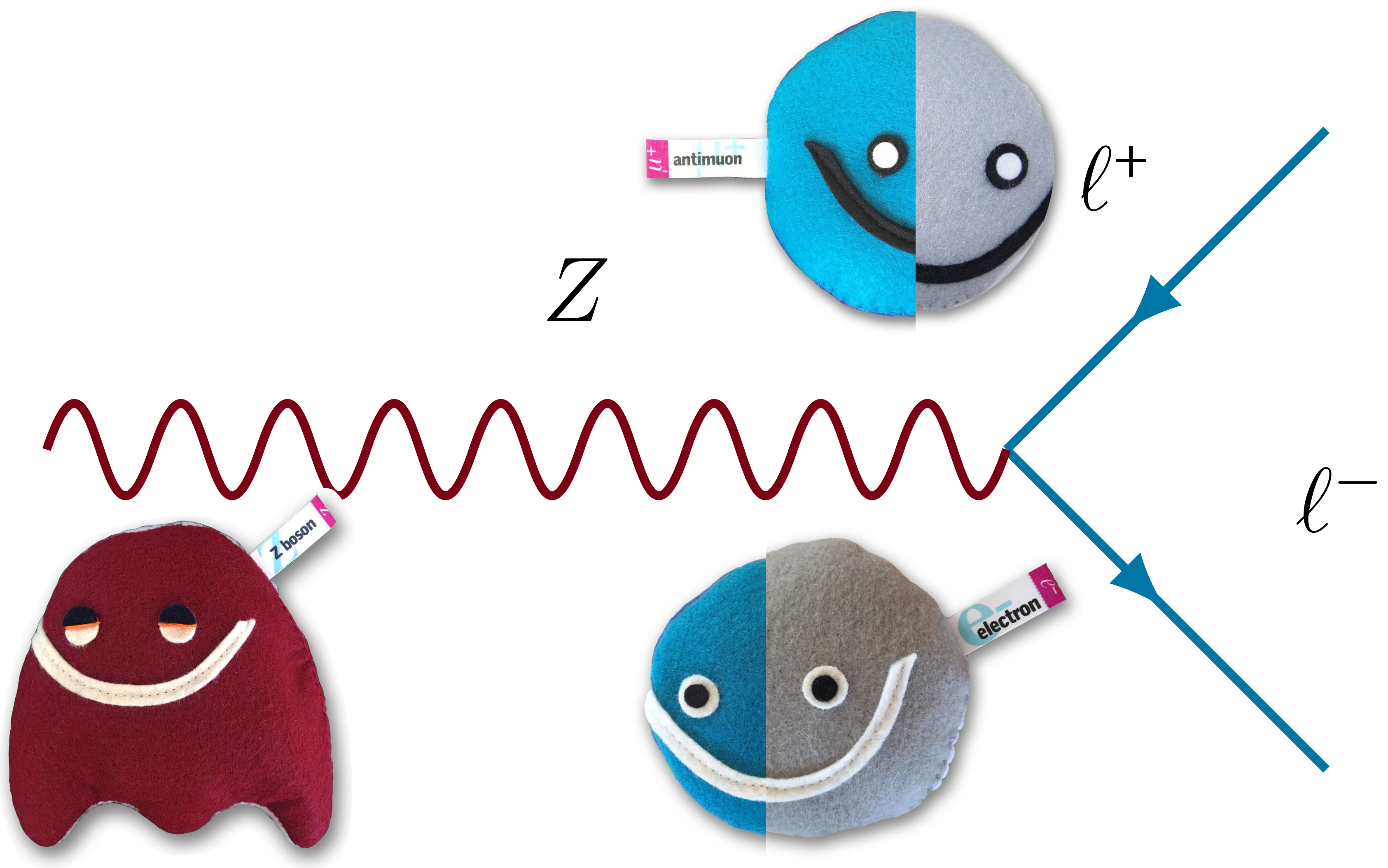


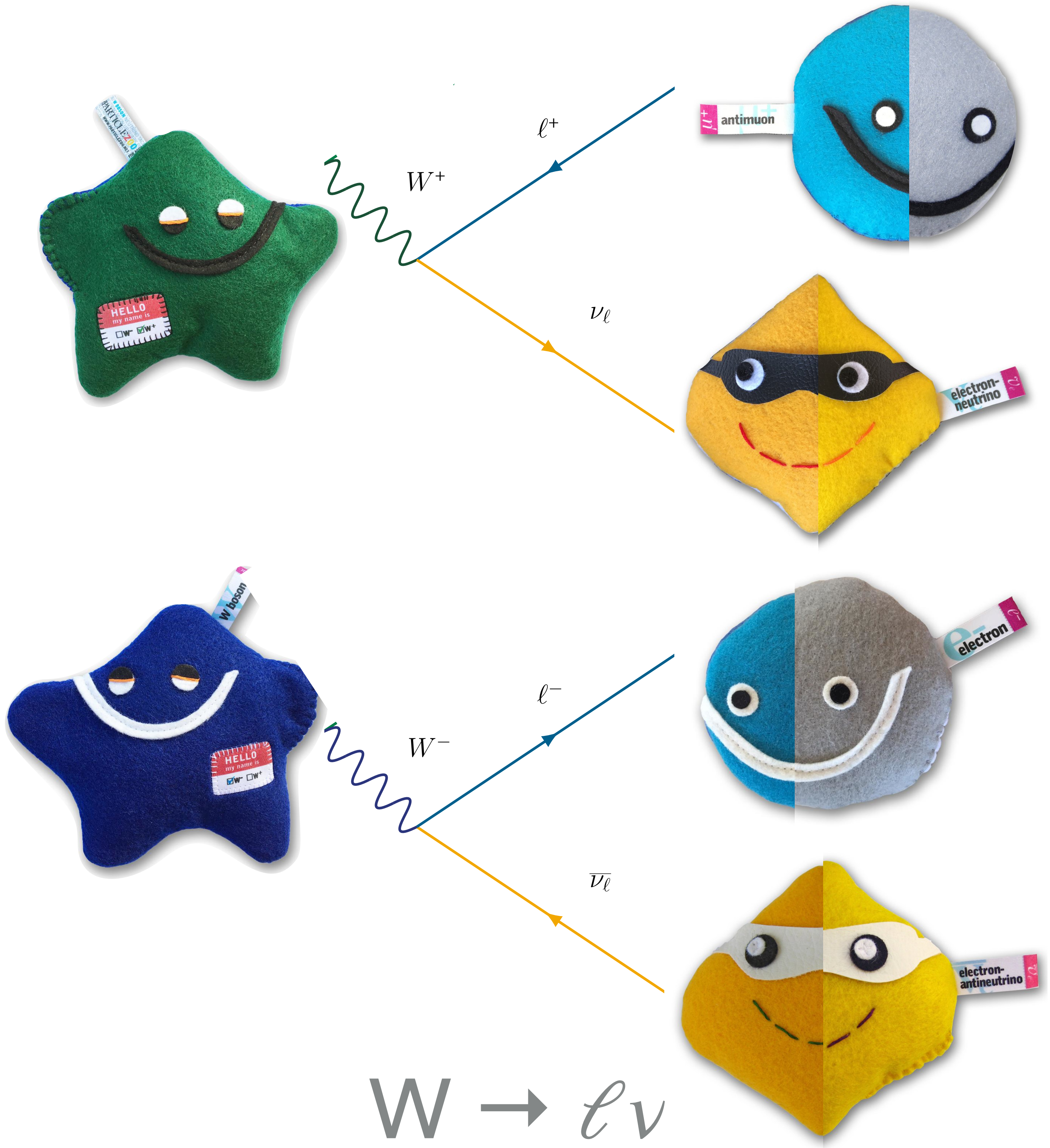
H → ZZ



H → WW

Z & W decay





$Z \rightarrow \ell\ell$

$W \rightarrow \ell\nu$

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open data ATLAS

Final state particles

- Of the particles we've talked about, only charged leptons ($\ell^{\pm}$) are directly measured by ATLAS
- Higgs, Z, W bosons have lifetimes < 10^{-22} s
  - They decay before being measured
  - They're measured indirectly by their final state particles

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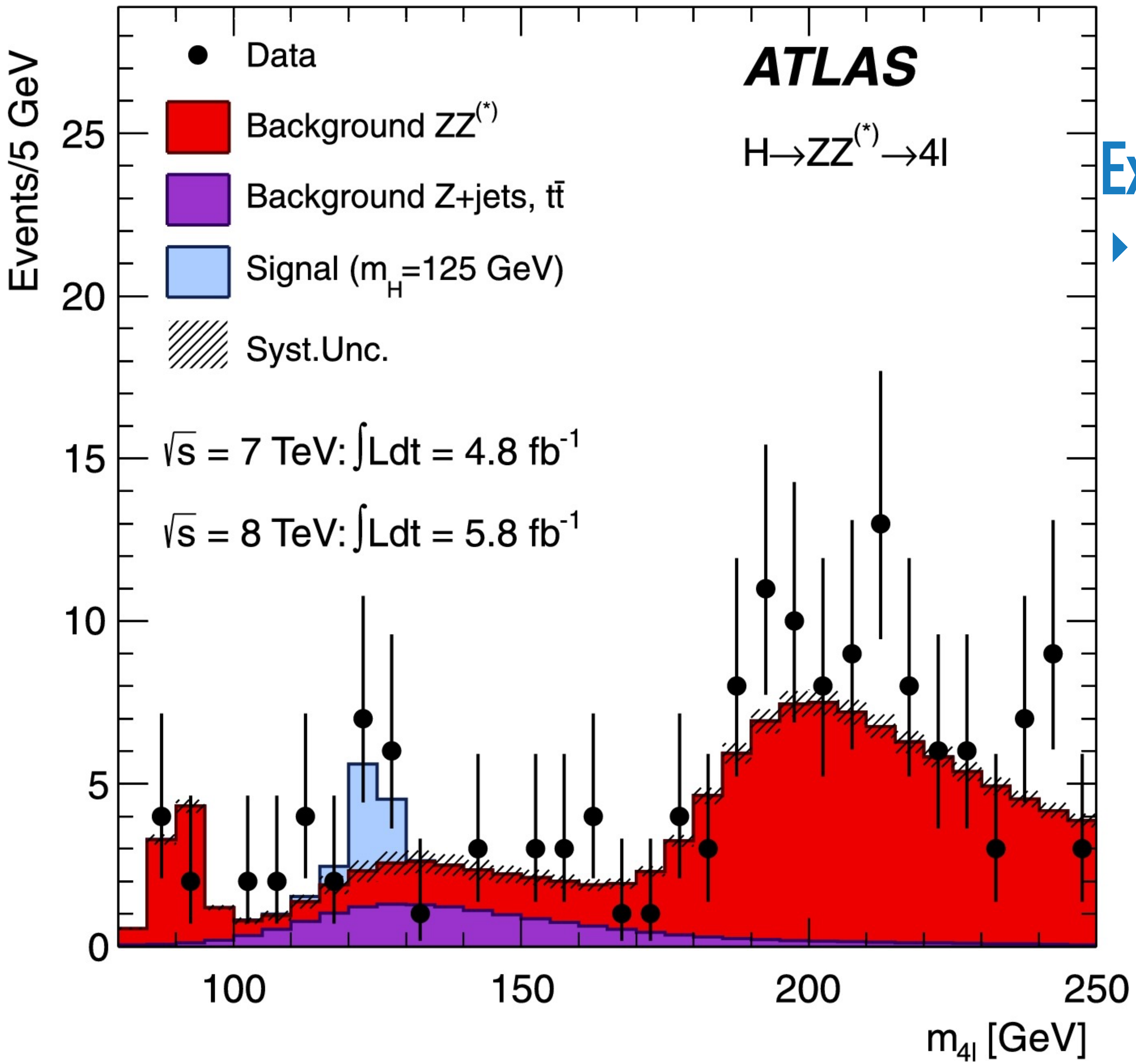
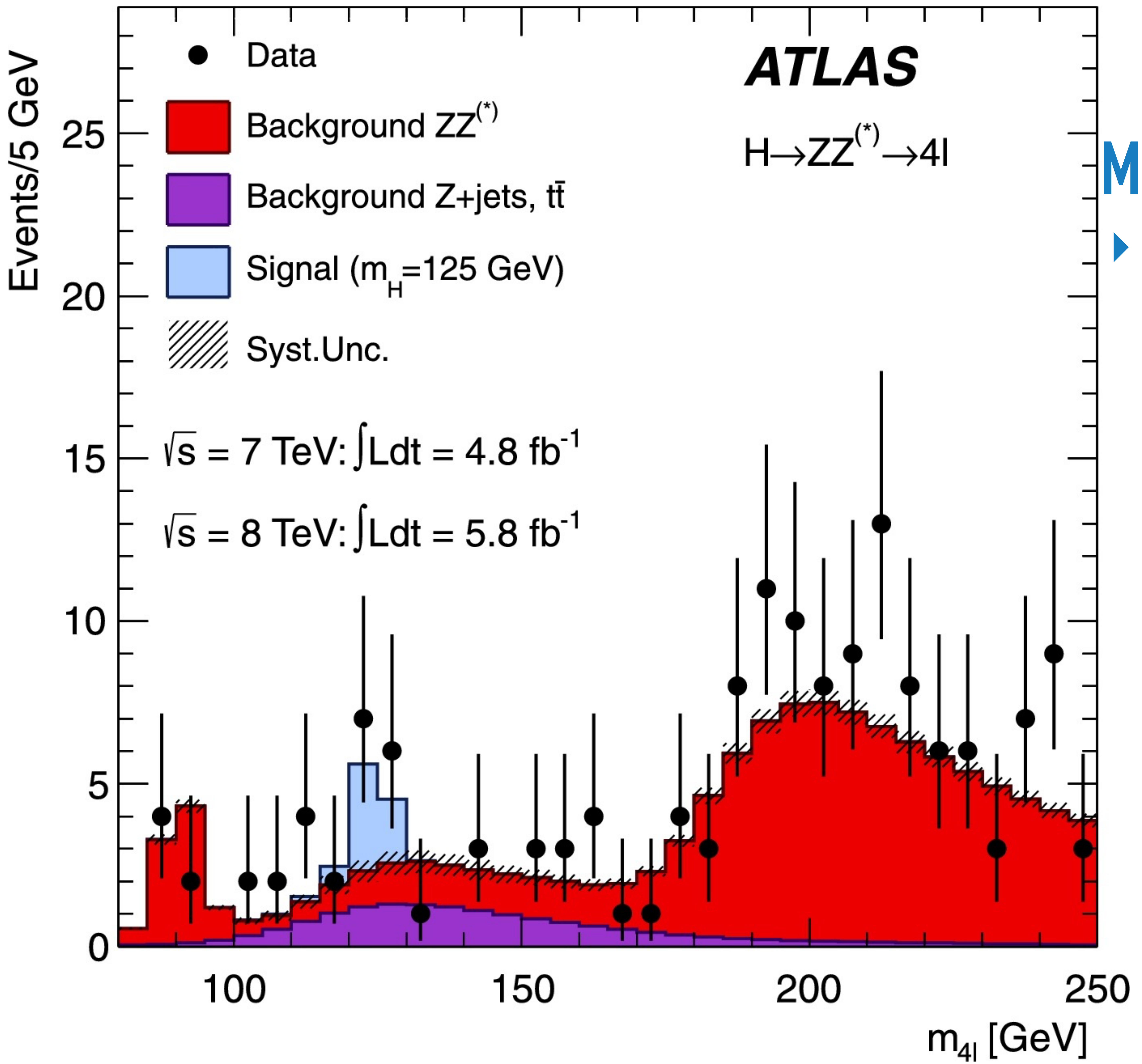
open data ATLAS



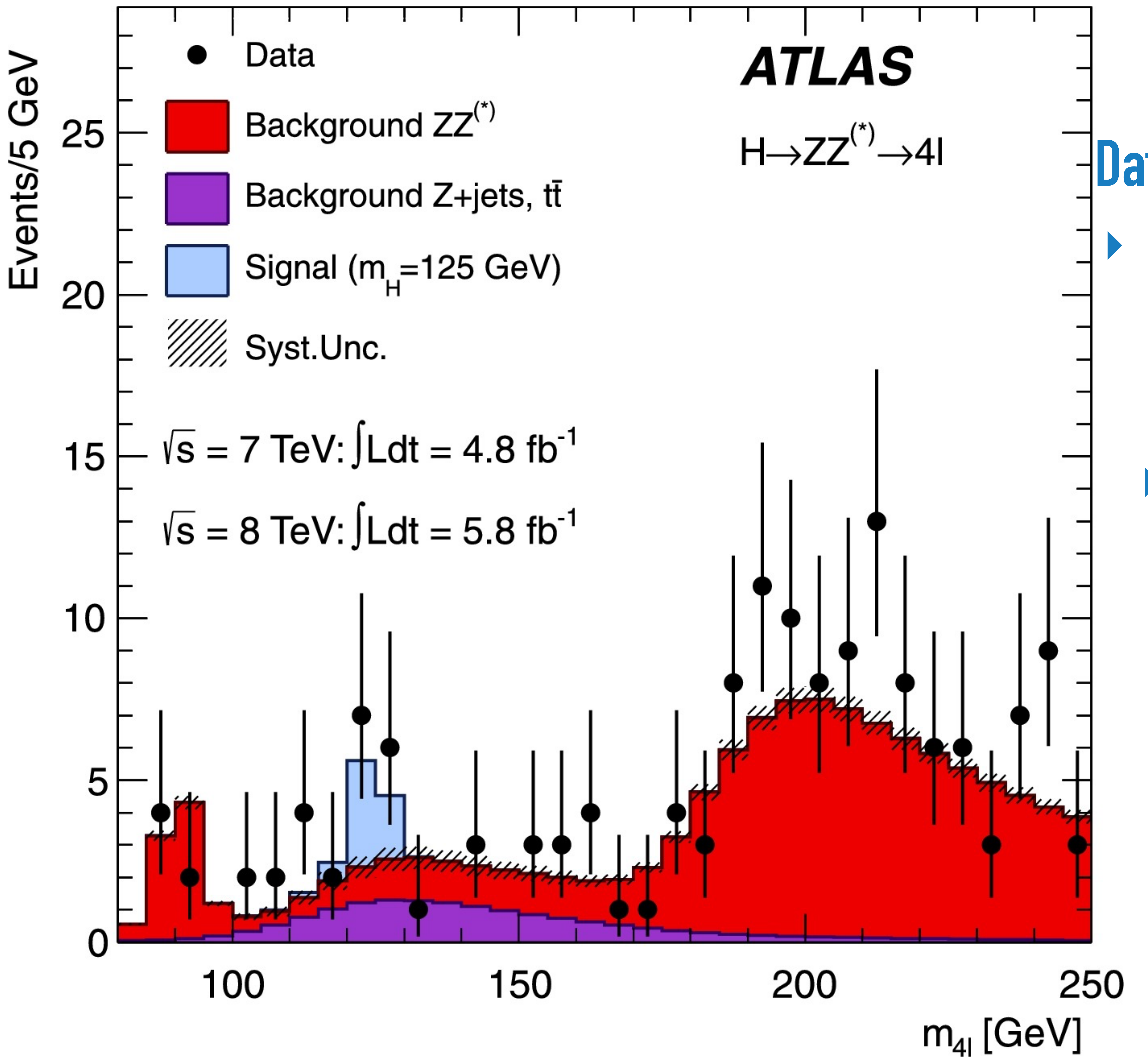
Experimental data

- Black points represent experimental data
  - Statistical uncertainty represented by error bars on the data points



MC simulation

- Filled histograms show the prediction from different MC simulations
  - The contributions are stacked



Data/MC discrepancy

- Any discrepancy between Data & MC is statistical
  - Like line-of-best-fit only passing through 67% of 1σ error bars

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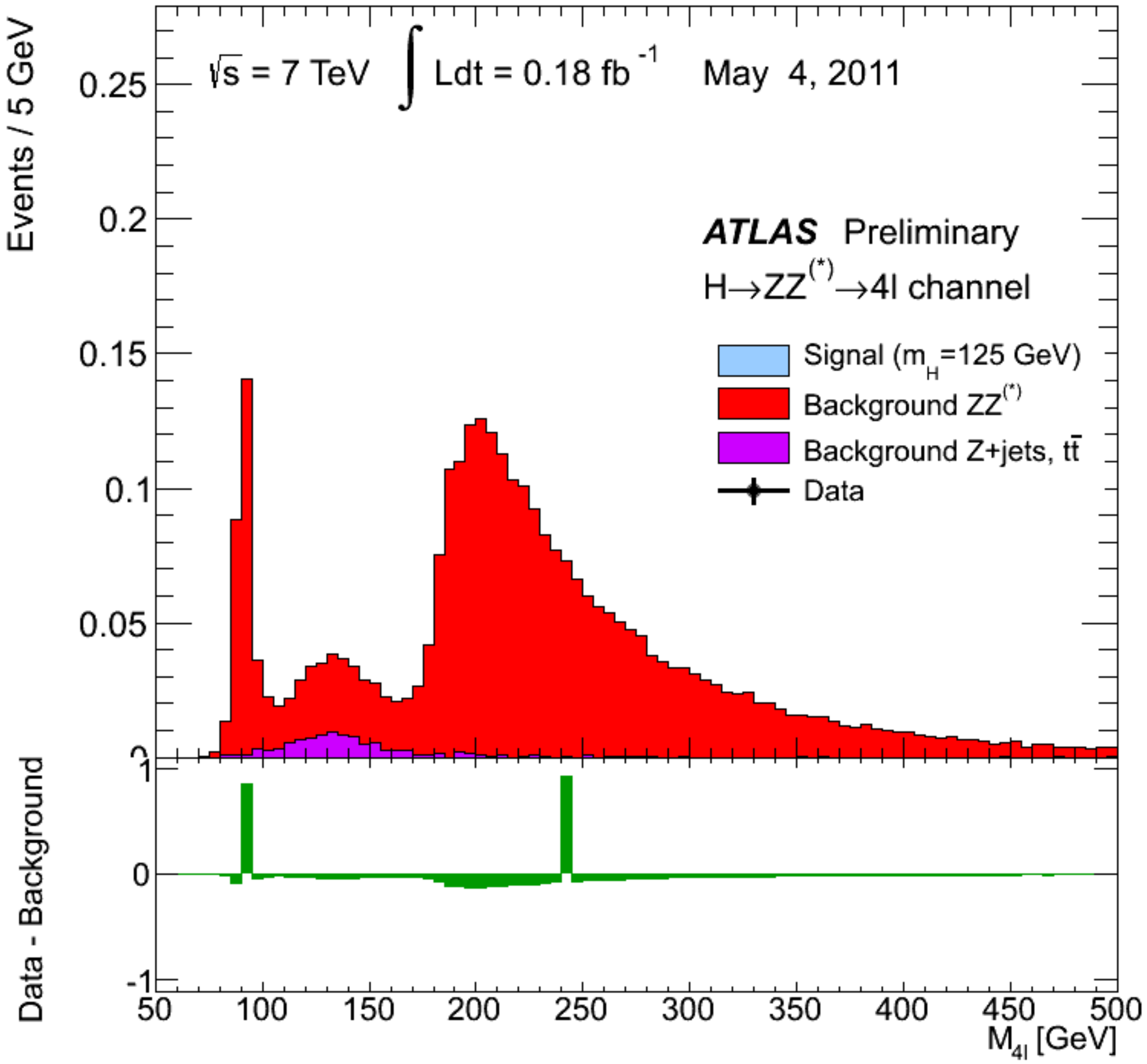
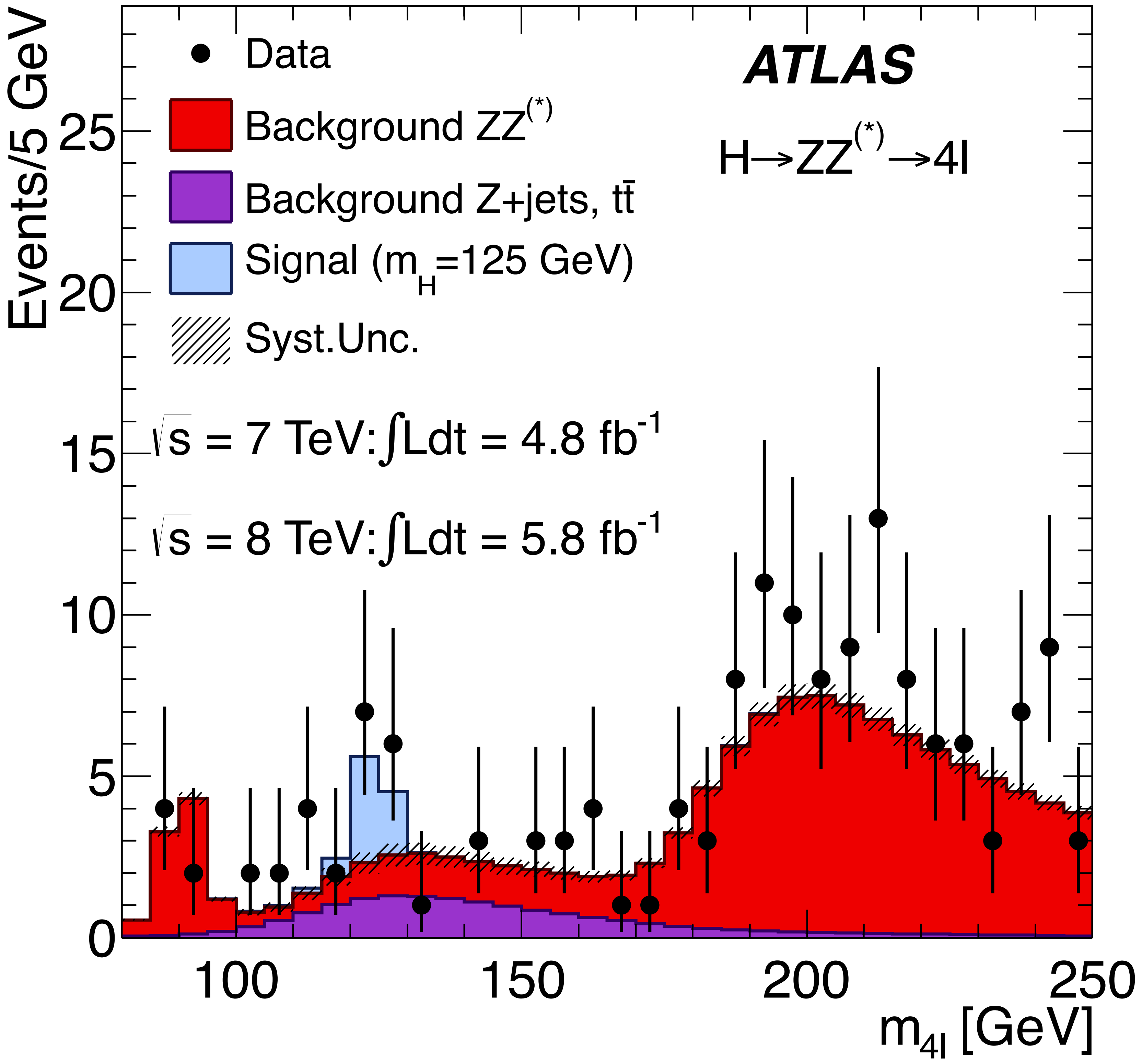
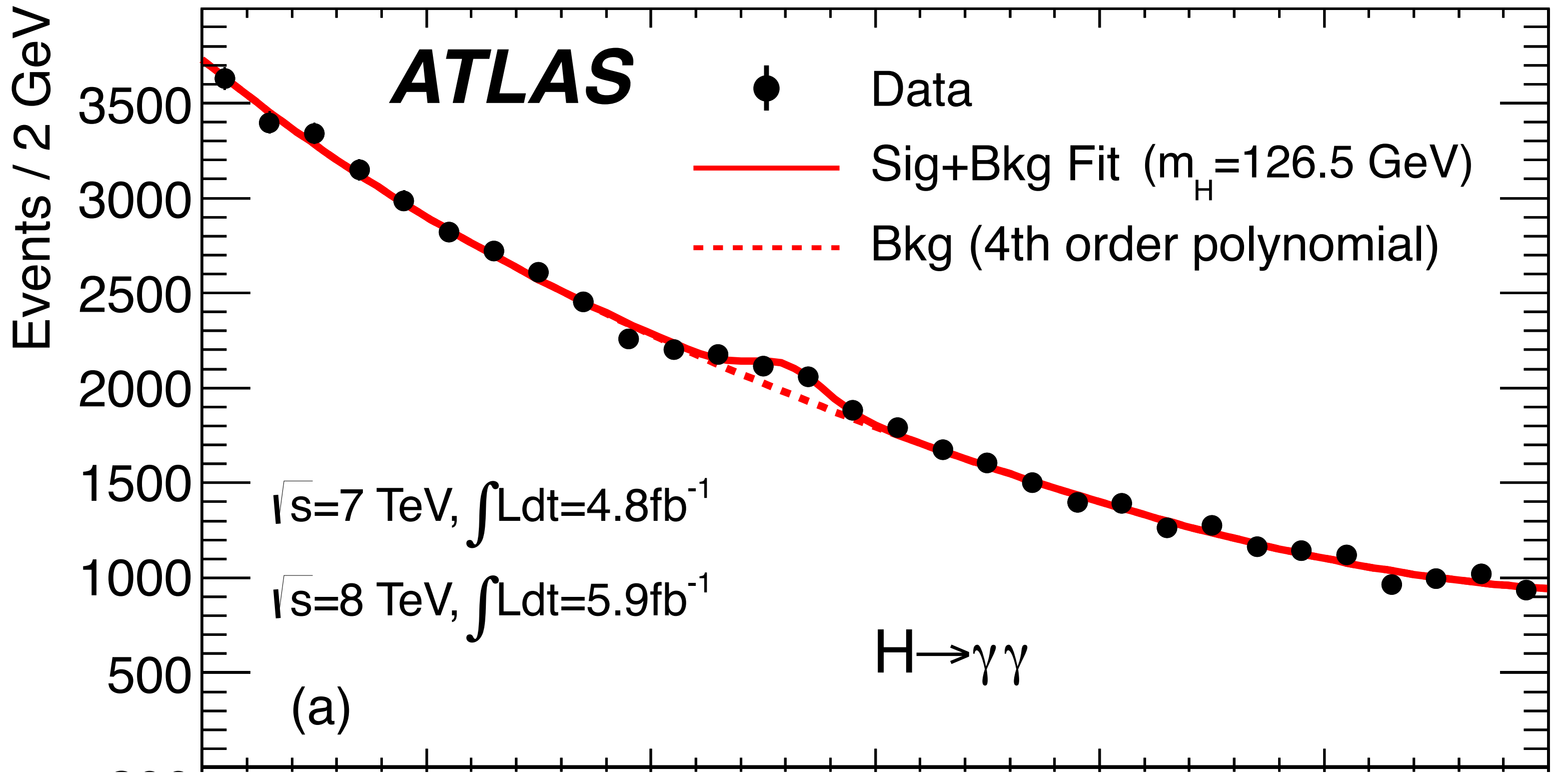
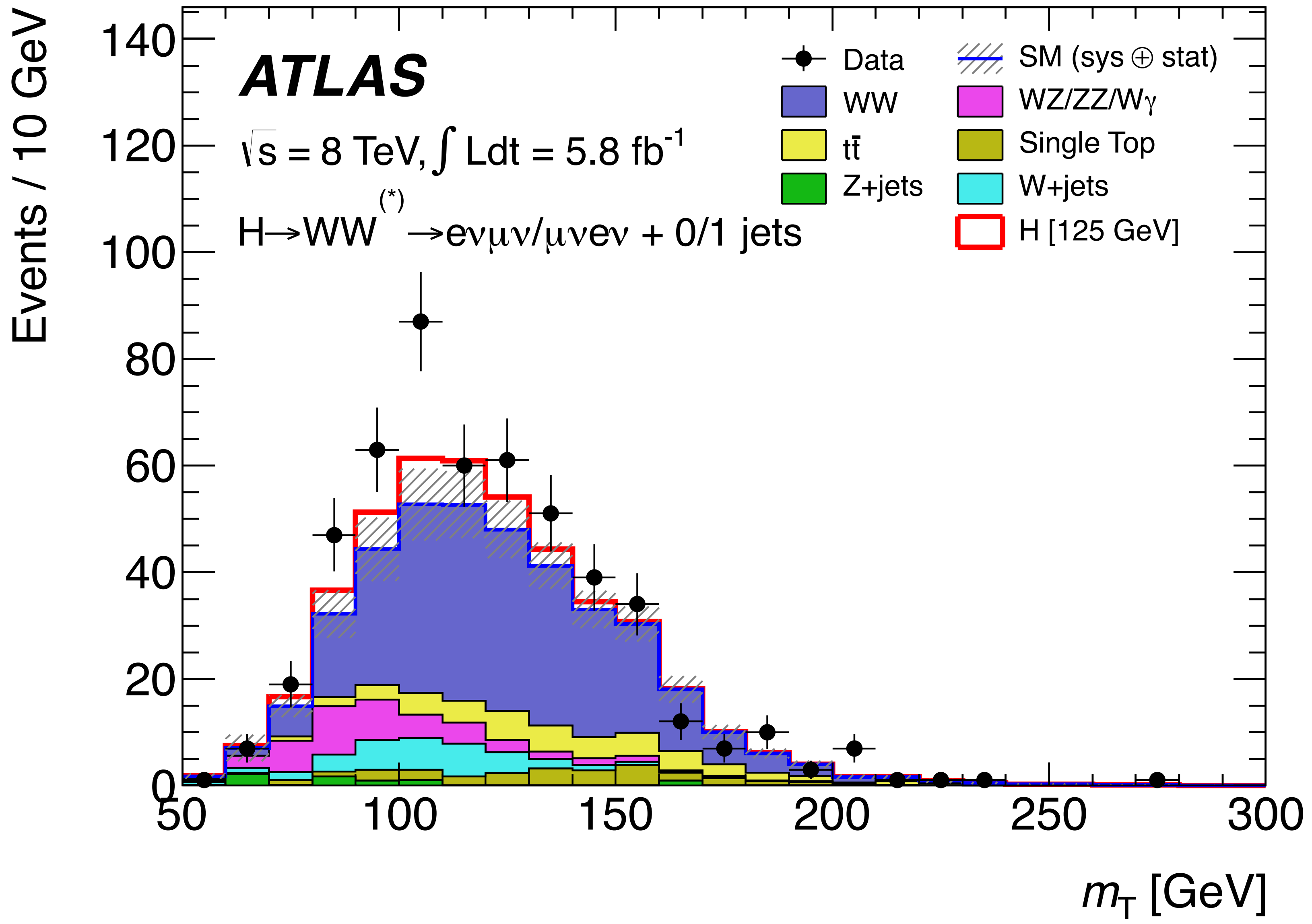
open data ATLAS


Events / 5 GeV
√s = 7 TeV
∫ Ldt = 0.18 fb^-1
May 4, 2011
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (m_H=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Data - Background
M_4l [GeV]
0.25
0.2
0.15
0.1
0.05
1
0
-1
50
100
150
200
250
300
350
400
450
500

How did this lead to a discovery?







- Combining $H \to ZZ$, $H \to \gamma\gamma$, $H \to WW$, gave total significance of 5σ in data over background-only

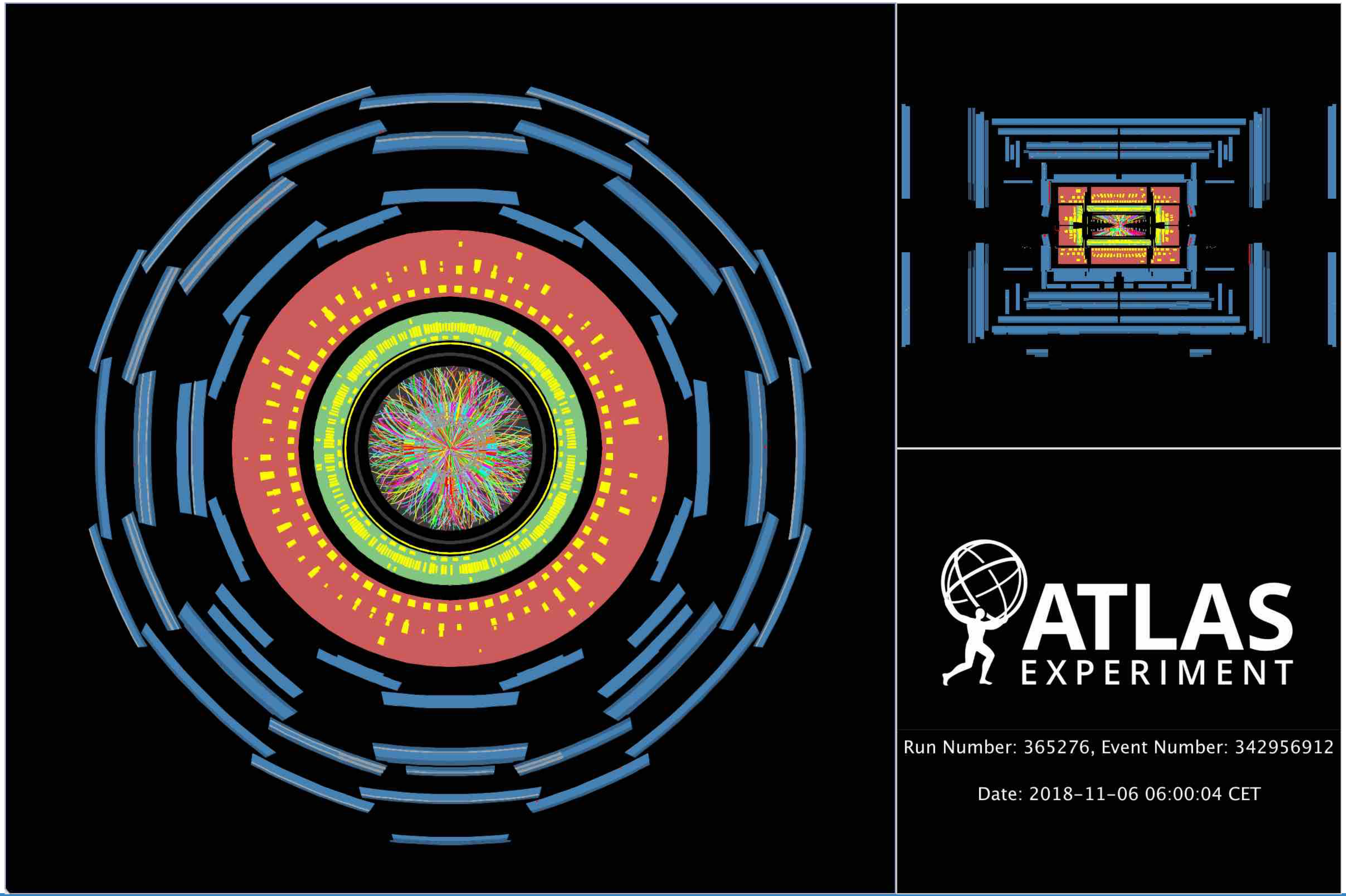
Why do Z & $t\bar{t}$ sometimes have > 2 leptons?

- From Higgs discovery paper: “Non-prompt leptons from heavy flavour decays, electrons from photon conversions and jets-misidentified as electrons…”

➡ Can have more than just the leptons from the leading order Feynman diagrams

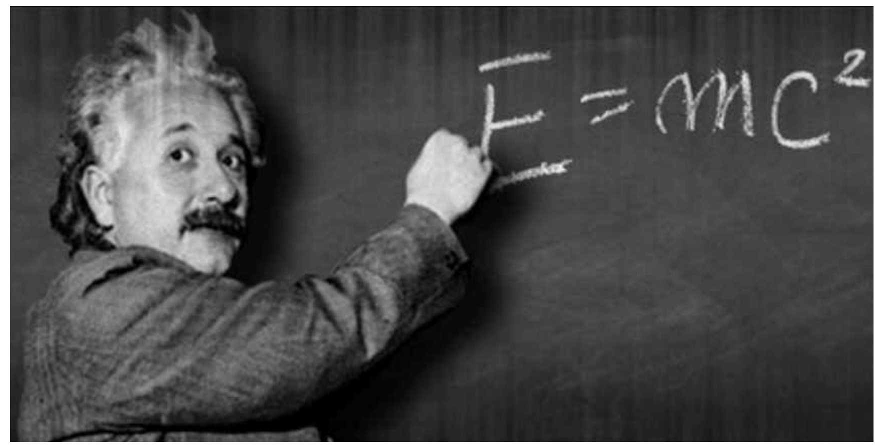
➡ e.g. any charged particle can radiate a photon, which decays into an electron-positron pair (2 extra leptons)

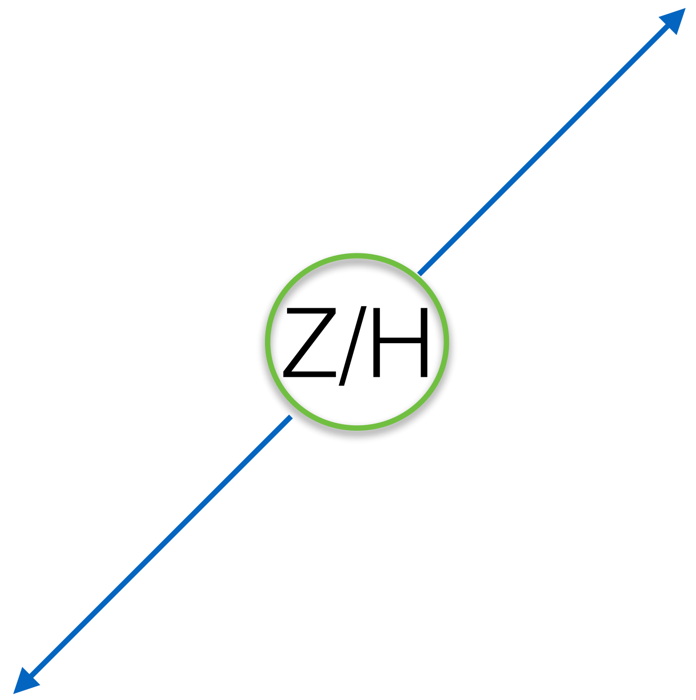
Transverse momentum? Why not momentum?



Transverse momentum? Why not momentum?

- Z and Higgs bosons are ~100x heavier than protons
  - ➡ ~all proton momentum goes to making Z/Higgs rest mass
  - ➡ Z/Higgs produced almost at rest
  - ➡ decay products move ~back-to-back in random direction
  - ➡ products often oriented in transverse plane
- Leptons are ~1000x lighter than Z/Higgs





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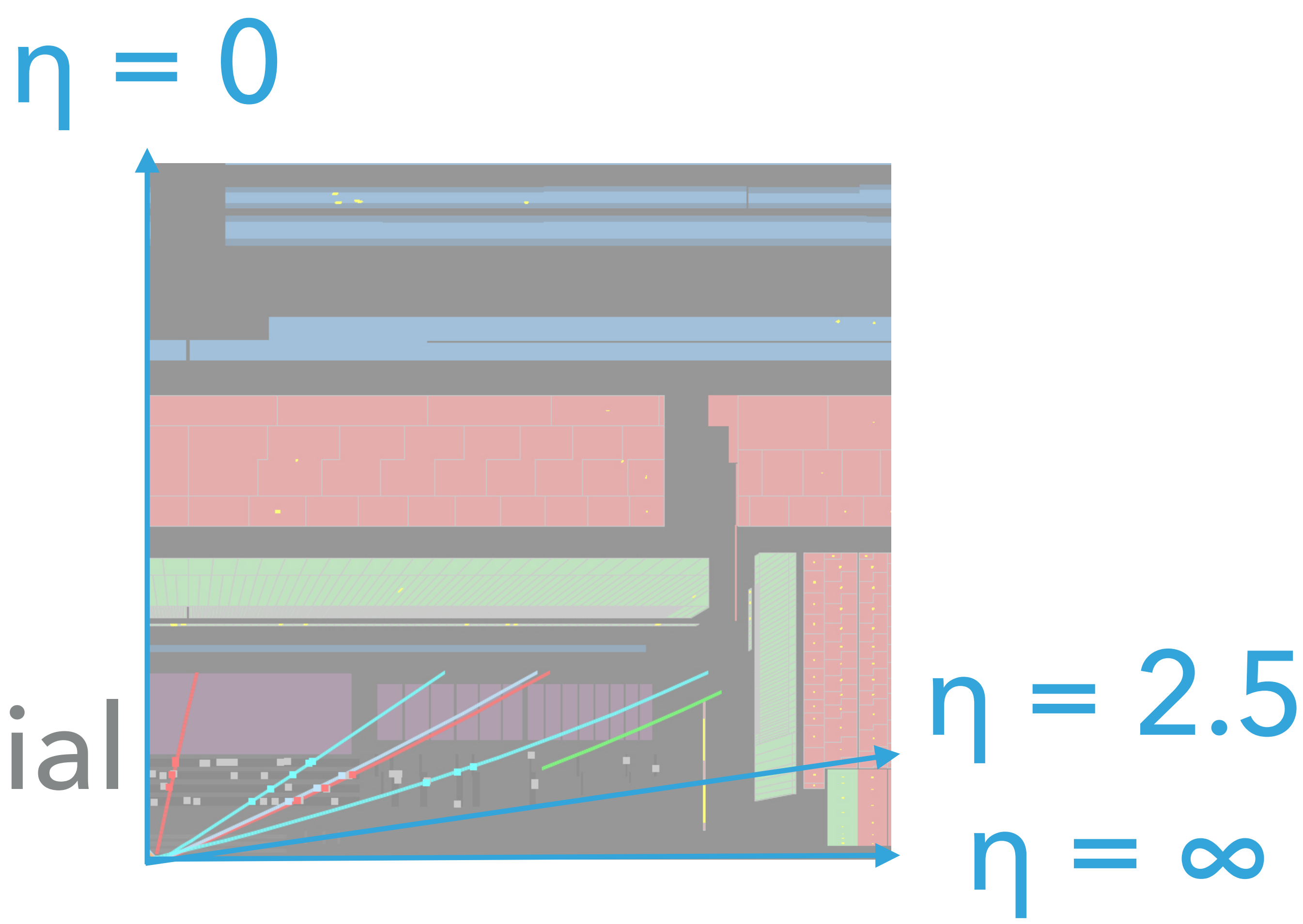
Pseudorapidity? Why not θ?

- $lep\_eta = -\ln\tan(\frac{\theta}{2})$.
- Differences in pseudorapidity are Lorentz invariant
- Differences in θ aren't

  ➡ difference in pseudorapidity gives handle on spatial separation



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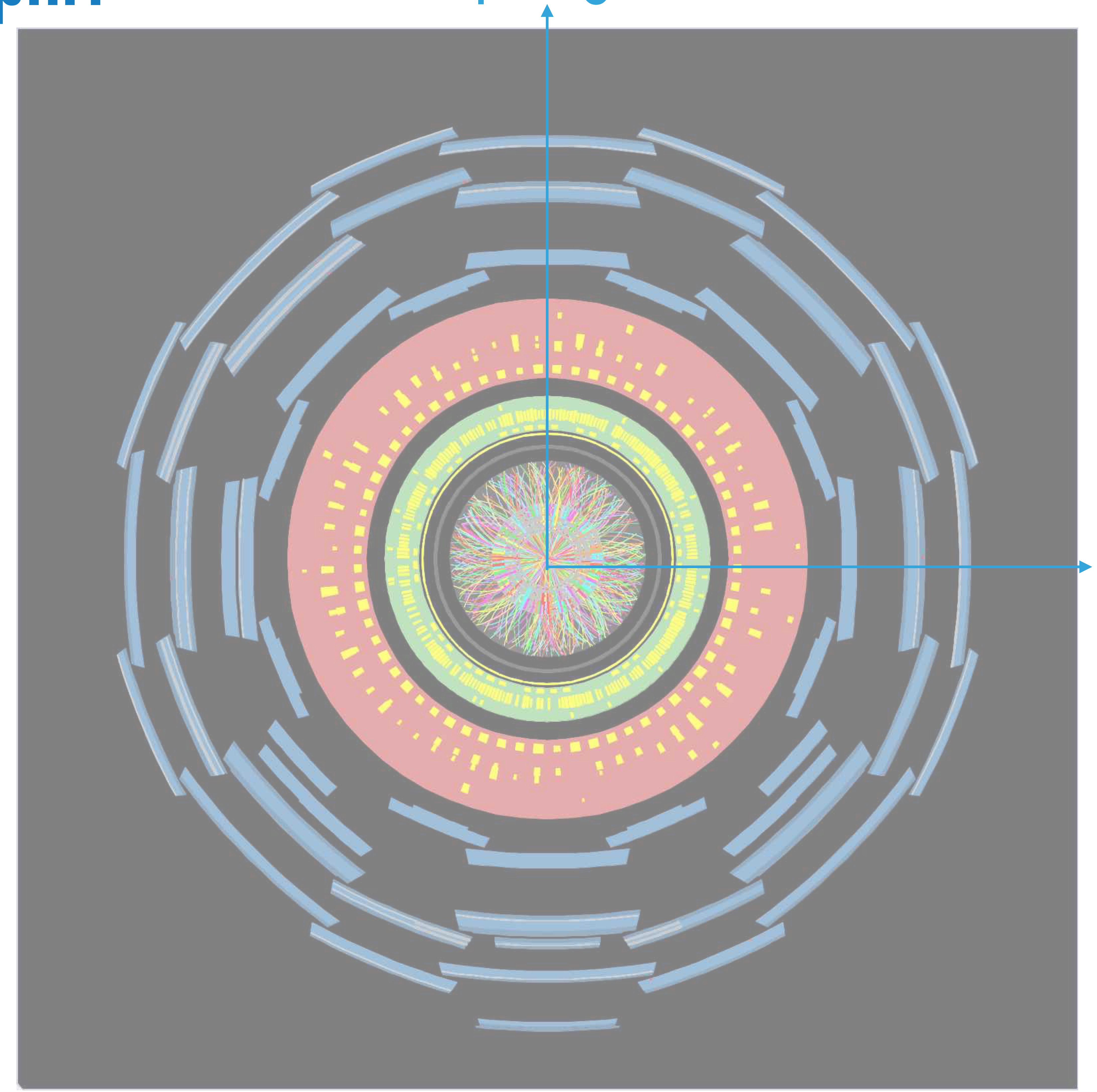
What's lep_phi?

$\Phi = 0^0$



$\Phi = 90^0$

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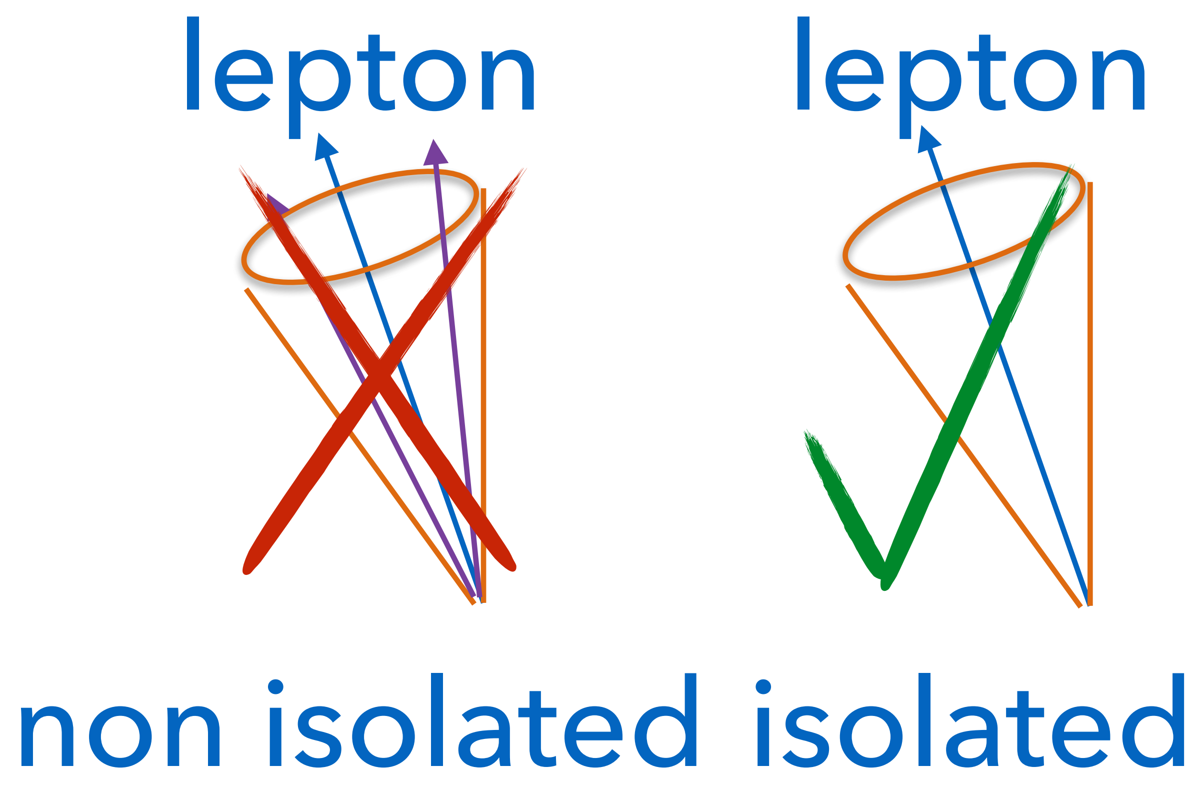
What's lep_etcone20?

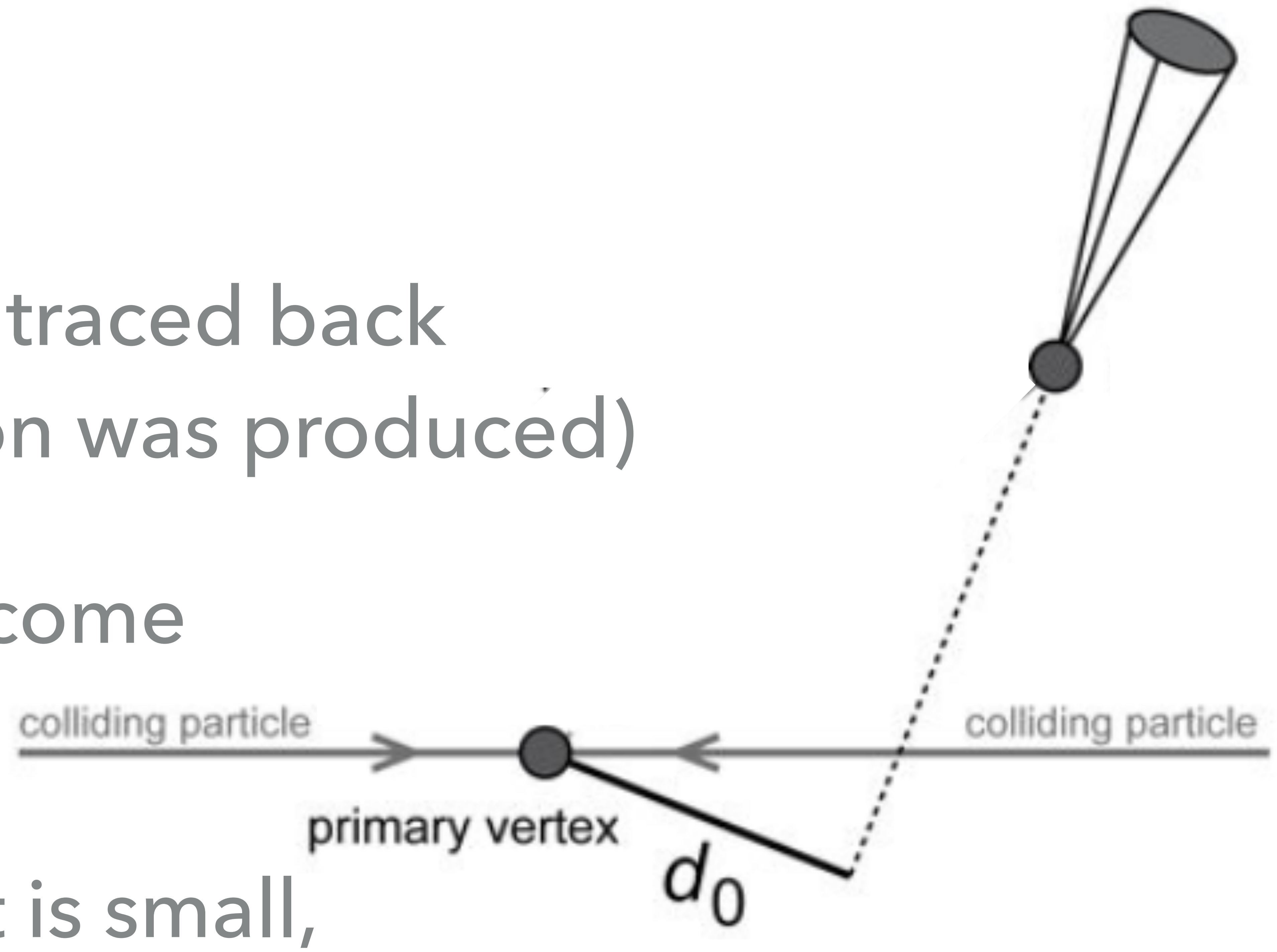
- A measure of the energy in a cone around the lepton, not including the lepton



- Leptons from boson decays are more likely to be isolated
- But we don't want to throw away leptons with really high pt, even if they aren't completely isolated
- So throw away leptons with etcone20/pt > 0.3 (e.g.)

What's lep_d0?

- Trace back the track of the lepton
- Take the minimum distance between the traced back track and primary vertex (where the boson was produced)
- Want to throw away leptons that haven't come from the primary vertex (large d0)
- If the significance of the d0 measurement is small, we can be confident of our d0 measurement
- So cut away leptons with d0/sigd0 > 6.5 (e.g.)



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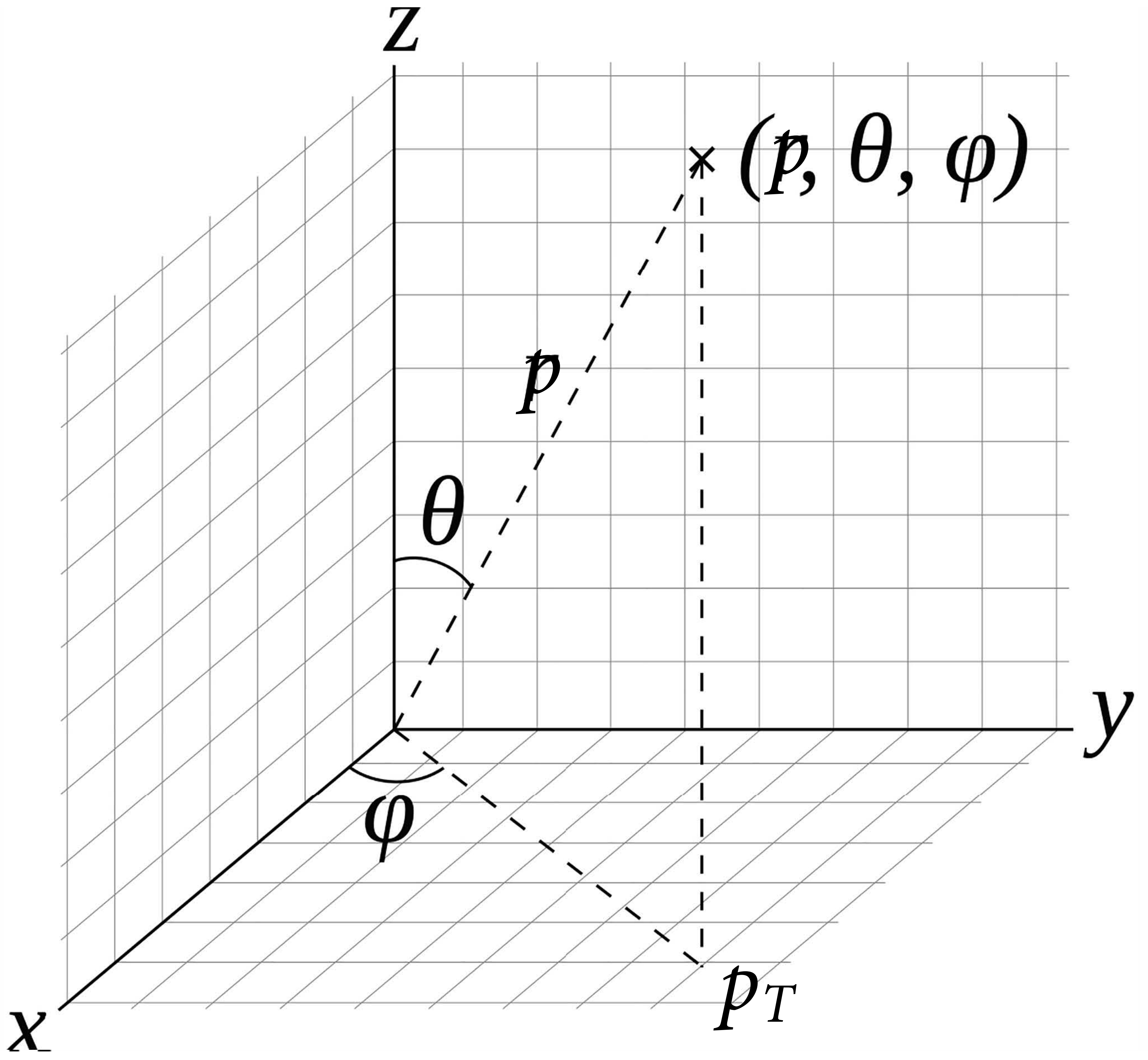
Momentum components

- $p_x = p_T \cos \phi$
- $p_y = p_T \sin \phi$
- $p_z = p \cos \theta, p_T = p \sin \theta$

➡ $p_z = \dfrac{p_T}{\sin \theta} \cos \theta$



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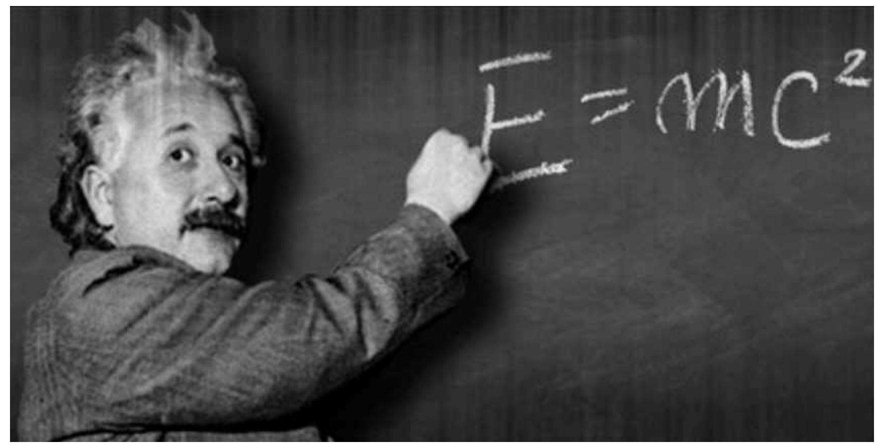
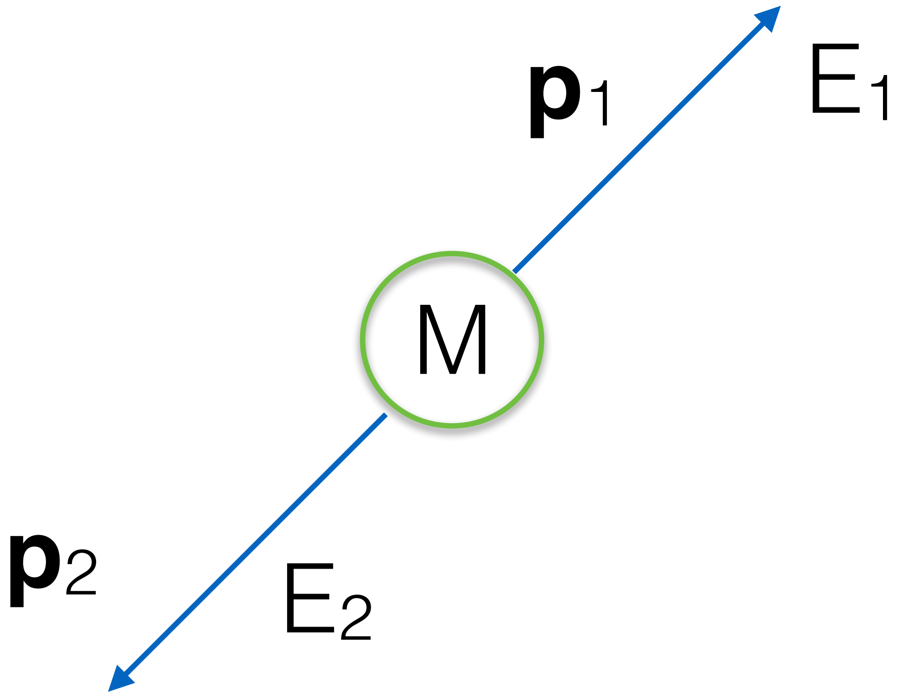
ATLAS EXPERIMENT

Invariant mass



- $E^2 = p^2 + M^2$
- $M = \sqrt{E^2 - p^2}$
- $M = \sqrt{(E_1 + E_2 + \ldots)^2 - (\vec{p_1} + \vec{p_2} + \ldots)^2}$



- Use final state leptons to find invariant mass of the boson from which they decayed
- Throw away if invariant mass very different to prediction

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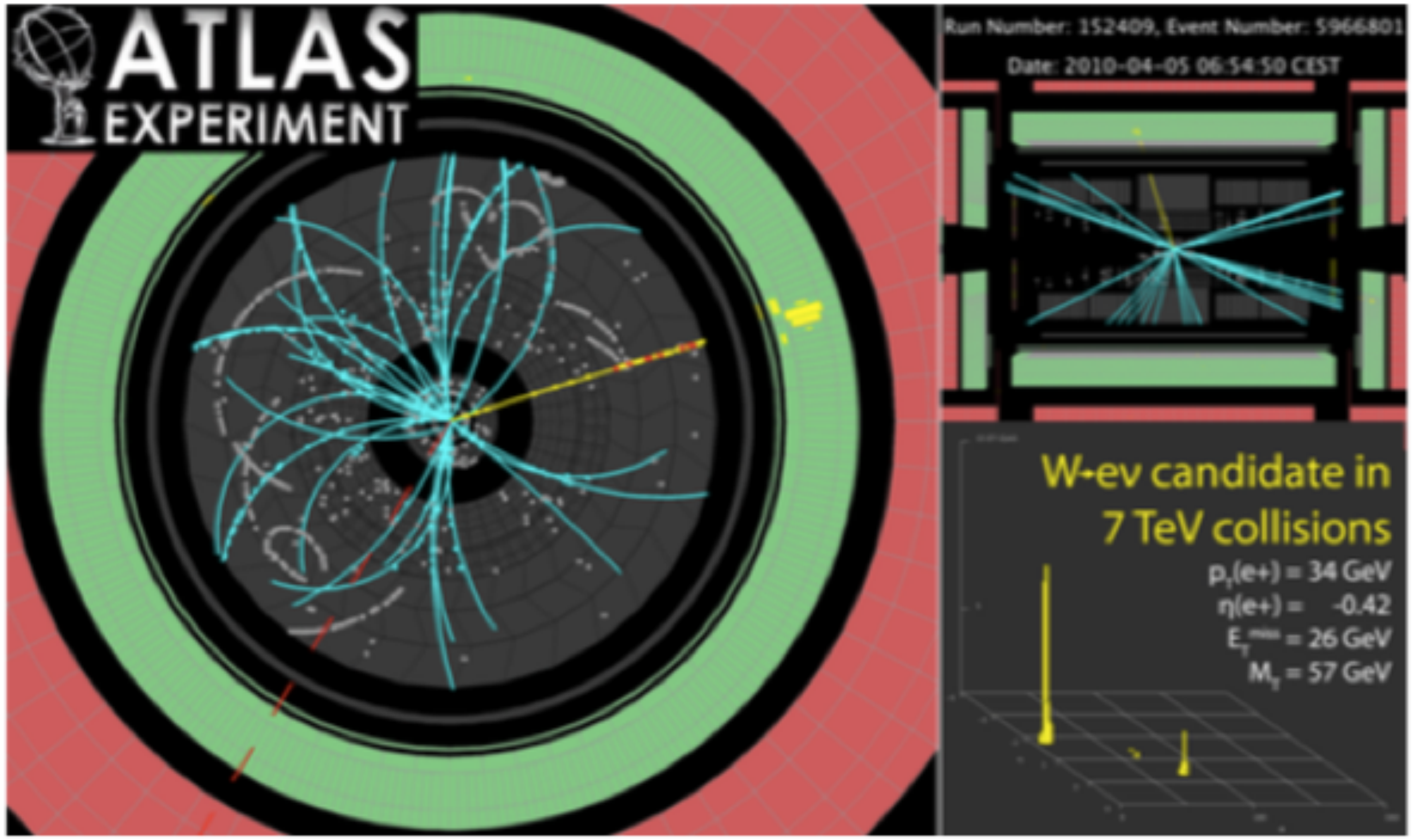
ATLAS EXPERIMENT

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

- Don't want the tracks of leptons to overlap
- If they did overlap, it'd be hard to say whether it was 1 or 2 tracks
- So throw away leptons that are very close together in ΔR



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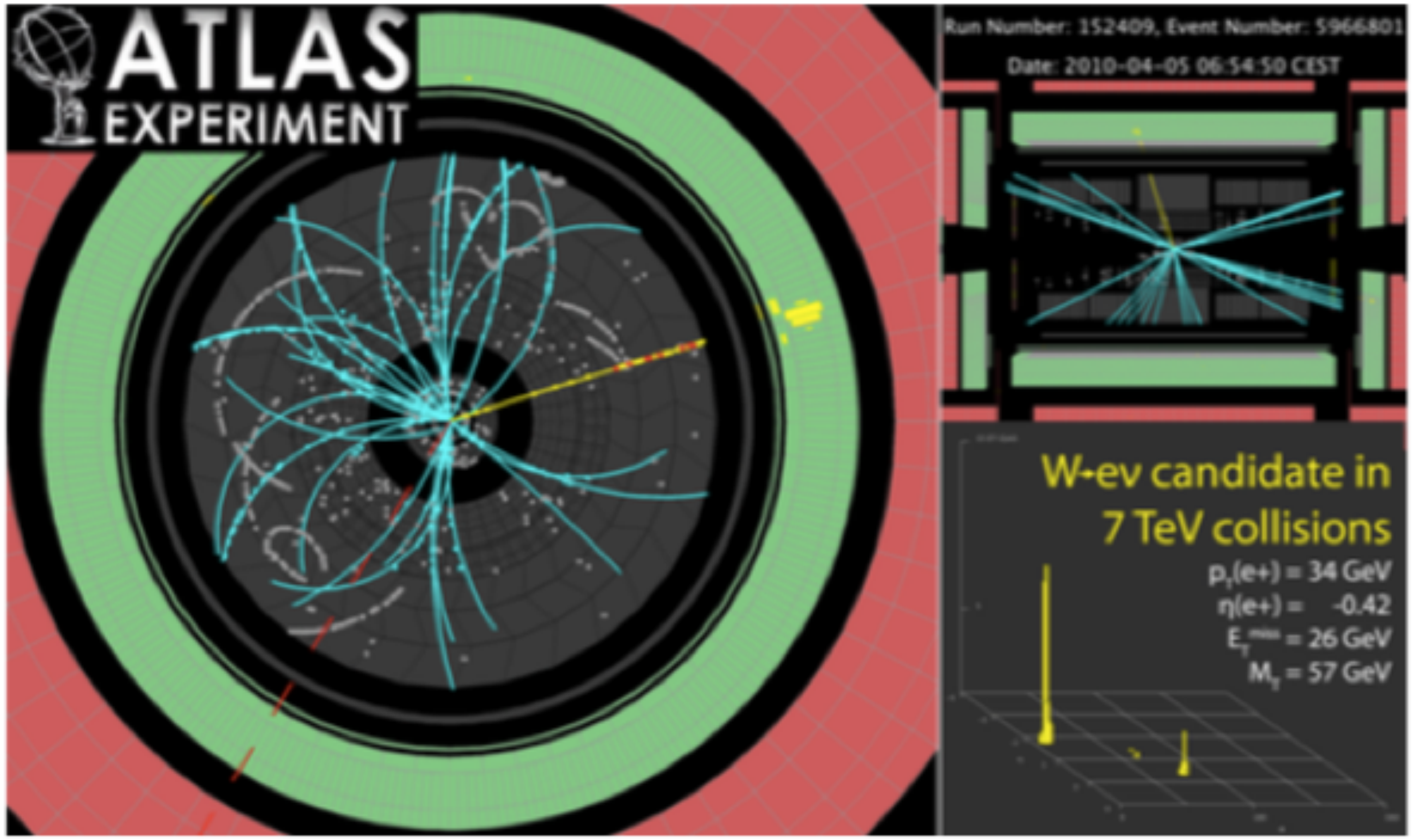
ATLAS EXPERIMENT

Why a stricter ΔR for leptons of same type?

- Electrons are detected by their energy deposited
- If electrons are really close together, you're not sure whether you're detecting 2 electrons, or a single high-energy electron
- Similar for muons



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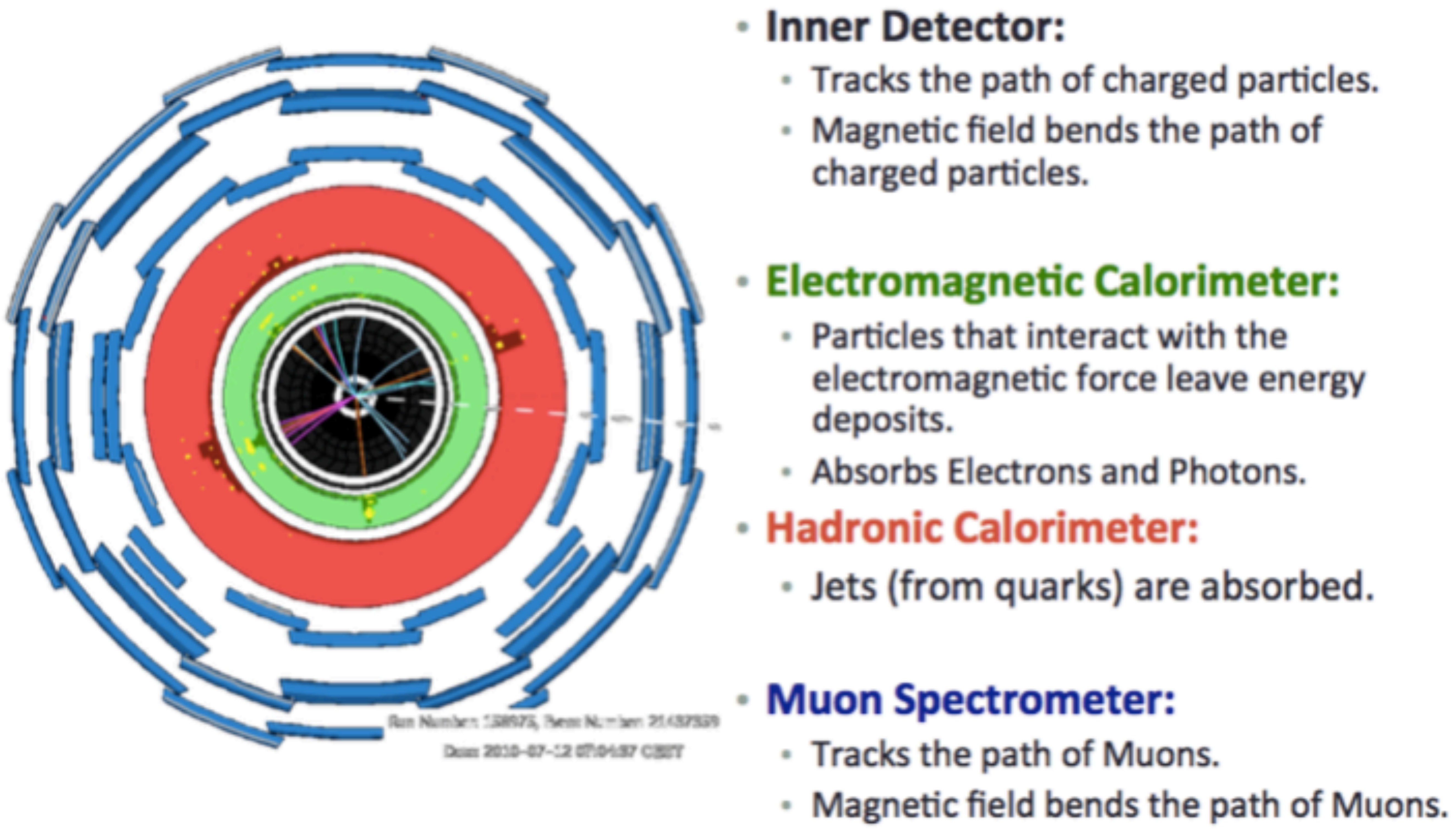
ATLAS EXPERIMENT

Why a lower p_T threshold for muons?

- Muons are the only particles detected in the outer part of ATLAS
- So if something is detected here, high chance it's a muon



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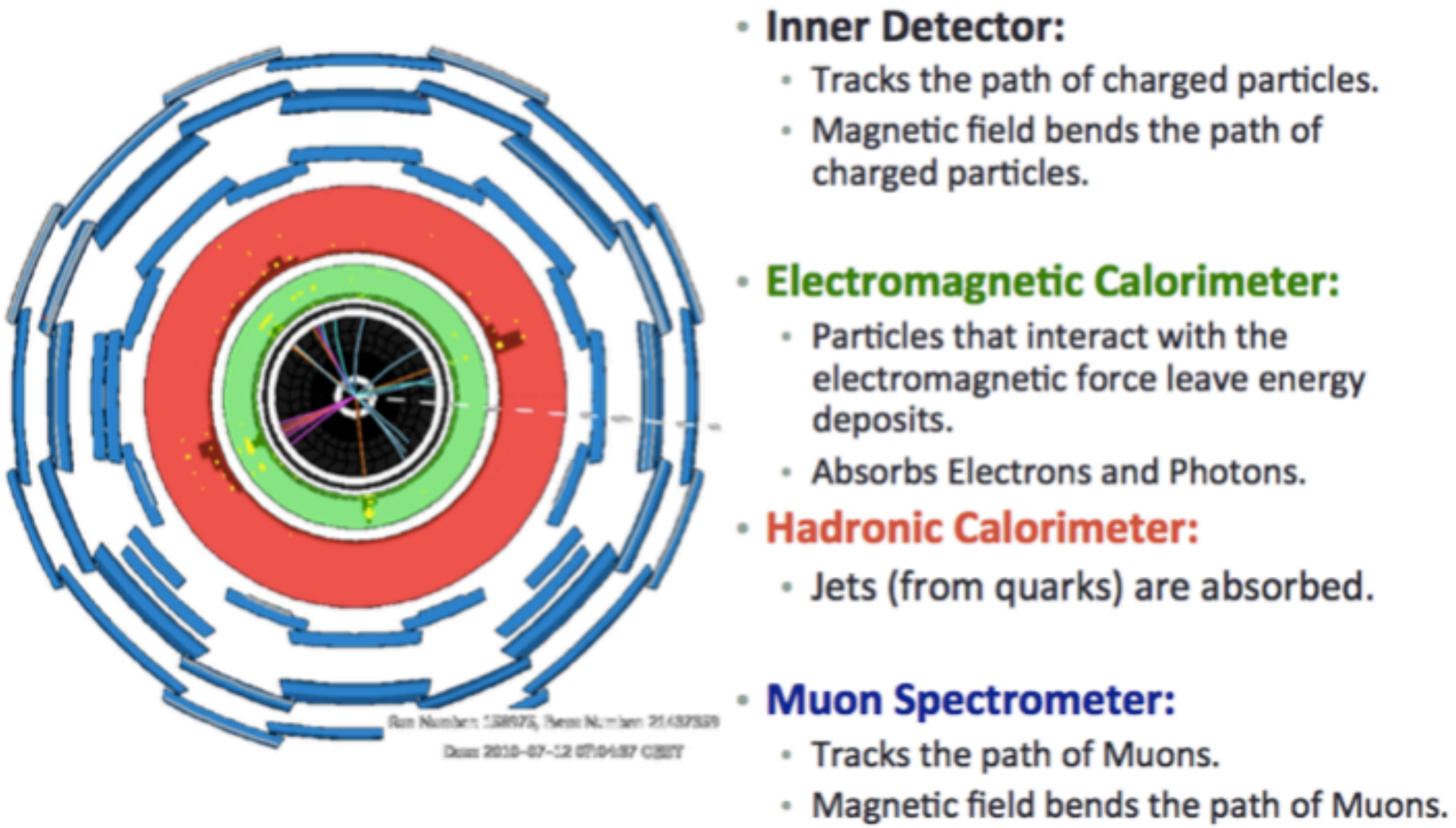
ATLAS EXPERIMENT

Why a lower etcone20 threshold for electrons?

- Electrons are detected in a busier part of ATLAS than muons
- Need to account for other energy in Electromagnetic Calorimeter when measuring electrons



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ATLAS EXPERIMENT

$\text{Signal}/\sqrt{\text{Background}}$

- $\text{Signal}/\sqrt{\text{Background}}$ is a statistical measure of how well you're separating signal and background
- It's an example of "significance"
- This is taking the statistical uncertainty on the number of background events as a Poisson distribution
- Only background in denominator because when searching for a new particle, you have to reject the background-only hypothesis

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ATLAS EXPERIMENT

Lepton p_T

- "the second (third) lepton in p_T order must satisfy $p_T > 15$ GeV ($p_T > 10$ GeV)"

Minimum opposite-charge-same-type lepton pair invariant mass

- "All possible lepton pairs in the quadruplet that have the same flavour and opposite charge must satisfy $m_{\ell\ell} > 5$ GeV in order to reject backgrounds involving the production and decay of J/ψ mesons"

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ATLAS EXPERIMENT

Invariant mass of Z boson candidate 1

- "The same-flavour and opposite-charge lepton pair with an invariant mass closest to the Z boson mass (m_Z) in the quadruplet is referred to as the leading lepton pair. Its invariant mass, denoted by m_{12}, is required to be between 50 GeV and 106 GeV"

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ATLAS EXPERIMENT

Invariant mass of Z boson candidate 2

- "The same-flavour and opposite-charge lepton pair with an invariant mass closest to the Z boson mass (m_Z) in the quadruplet is referred to as the leading lepton pair. The remaining same-flavour, opposite-charge lepton pair is the sub-leading lepton pair. Its invariant mass, m_{34} ,is required to be in the range $m_{min} < m_{34} < 115$ GeV, where the value of m_{min} depends on the reconstructed four-lepton invariant mass, $m_{4\ell}$. The value of m_{min} varies monotonically from 17.5 GeV at $m_{4\ell}$ = 120 GeV to 50 GeV at $m_{4\ell}$ = 190 GeV and is constant above this value."

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ATLAS EXPERIMENT

ΔR

- "leptons are required to be separated from each other by $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.1$ if they are of the same flavour and by $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.2$ otherwise."

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ATLAS EXPERIMENT

Minimum lepton p_T

- "Each electron (muon) must satisfy $p_T > 7$ GeV ($p_T > 6$ GeV)"

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ATLAS EXPERIMENT

Lepton etcone20

- "The … isolation for electrons is computed as the sum of the E_T of …energy … clusters … within a cone of size ΔR = 0.2 around the candidate electron …, divided by the electron E_T. … The … energy of the cells assigned to the electron … is excluded,…The … isolation for electrons is required to be less than 0.20. The … isolation …for muons is defined by the ratio to the p_T of the muon of the E_T sum of the calorimeter cells inside a cone of size ΔR = 0.2 around the muon direction minus the energy deposited by the muon. Muons are required to have a … isolation less than 0.30 "

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ATLAS EXPERIMENT

Lepton d0

- "Non-prompt leptons from heavy flavour decays, electrons from photon conversions and jets mis-identified as electrons have broader … impact parameter distributions than prompt leptons from Z boson decays and/or are non-isolated. Thus, the Z and $t\bar{t}$ background contributions are reduced by applying a cut on the … impact parameter significance, defined as the transverse impact parameter divided by its uncertainty, d_0/σ_{d_0}. This is required to be less than 3.5 (6.5) for muons (electrons). The electron impact parameter is affected by bremsstrahlung and thus has a broader distribution."

Significance

- $$\frac{\text{measurement}}{\text{error}}$$
- Quote this as a number of "σ"
  - (Not to be confused with a 1σ error bar!)
- Error can usually be estimated using Poisson (square root)
- What measures of significance do you use in your work?

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Significance measures

- $$\frac{N_{\text{signal}}}{\sqrt{N_{\text{background}}}}$$
- $$\frac{N_{\text{data}} - N_{\text{background}}}{\sqrt{N_{\text{background}}}}$$
- $$\frac{N_{\text{signal}}}{\sqrt{N_{\text{signal}} + N_{\text{background}}}}$$
- $$\frac{N_{\text{data}} - N_{\text{background}}}{\sqrt{N_{\text{signal}} + N_{\text{background}}}}$$
- $$\frac{N_{\text{data}} - N_{\text{background}}}{\sqrt{N_{\text{data}}}}$$
- $$\sqrt{2((N_{\text{signal}} + N_{\text{background}})\ln(1 + \frac{N_{\text{signal}}}{N_{\text{background}}}) - N_{\text{signal}})}$$

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If $N_{\text{background}}$ known

- $\dfrac{N_{\text{signal}}}{\sqrt{N_{\text{background}}}}$
- Profile likelihood ratio test

$$\sqrt{2((N_{\text{signal}} + N_{\text{background}})\ln(1 + \frac{N_{\text{signal}}}{N_{\text{background}}}) - N_{\text{signal}})}$$

- Useful resource: statistics presentation by Glen Cowan

Implement more cuts

- What results did you get?
- How does the new result compare with previous results?
- How would you measure the success of these cuts?
- How might you improve?

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Optimisation

- Cuts used in Higgs discovery paper will have been optimised for that dataset
- We only have a subset (~10%) of that dataset
  - So the optimised cuts for our dataset might be different
- Modify some cuts and see what happens
- How might you optimise your cuts?

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Machine Learning

- Neural Network (NN)
- Boosted Decision Tree (BDT)
- Support Vector Machine (SVM)
- Random Forest

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