Data-based particle physics courses & projects

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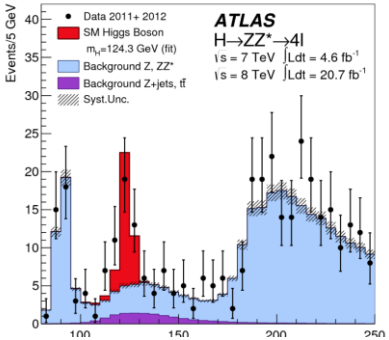
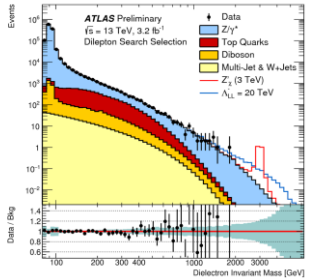
A successful program

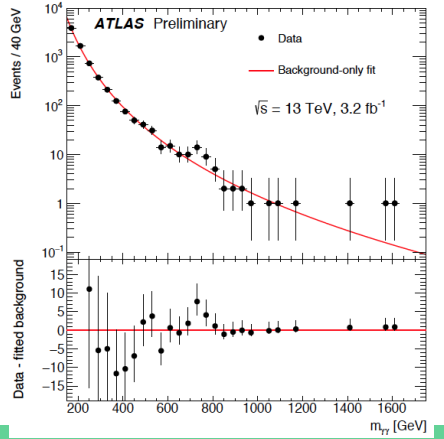
International Particle Physics Outreach Group

- IPPOG has developed an educational activity that brings the excitement of cutting-edge particle physics research into the classroom.
  - The LHC data have been successfully deployed since 2010 in International Masterclasses (IMC) where students perform various measurements based on proton-proton, lead-lead and proton-lead collisions.
  - The Higgs discovery, the investigation of the quark-gluon plasma phenomenon and other measurements and scientific methods could be shared with the students

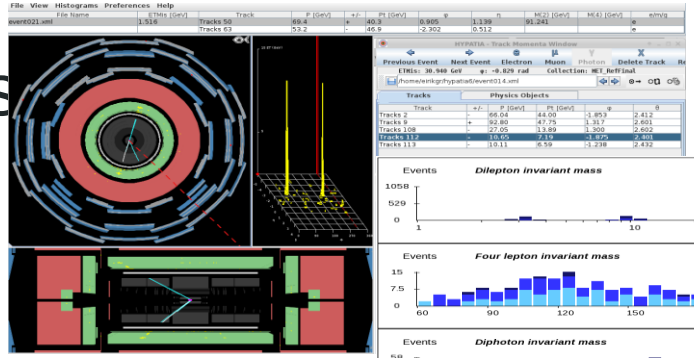


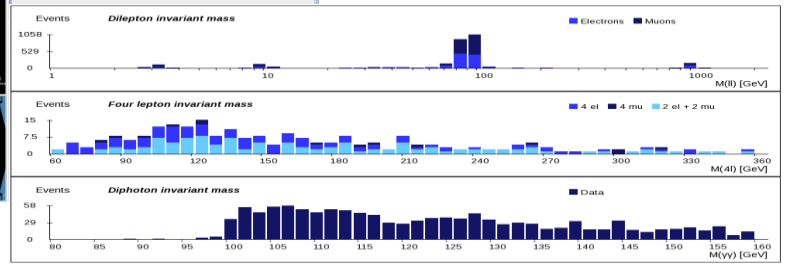
- The promises of the 13 TeV LHC era in terms of new discoveries and the opportunity offered by the CERN open data portal (⇒) triggered
  - the extension of the educational materials.
  - interesting discussions on how to introduce more concepts … should new phenomena be discovered at the LHC.





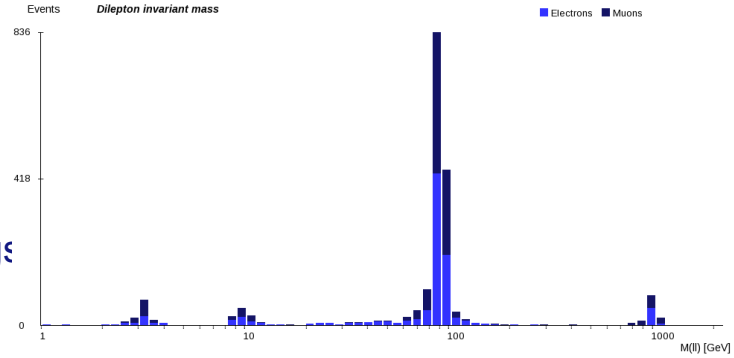
Zpath Masterclasses

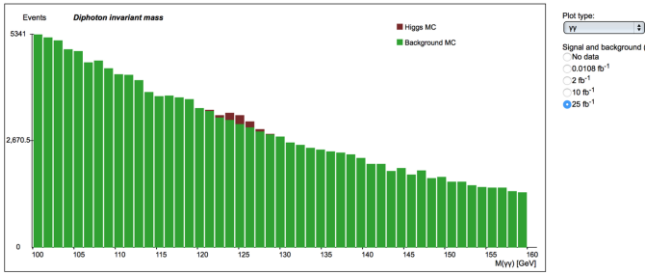




- Identify events: ll, 4l, γγ
- Calculate invariant mass
- Upload results to OPIoT
- Combine results, discuss, interpret

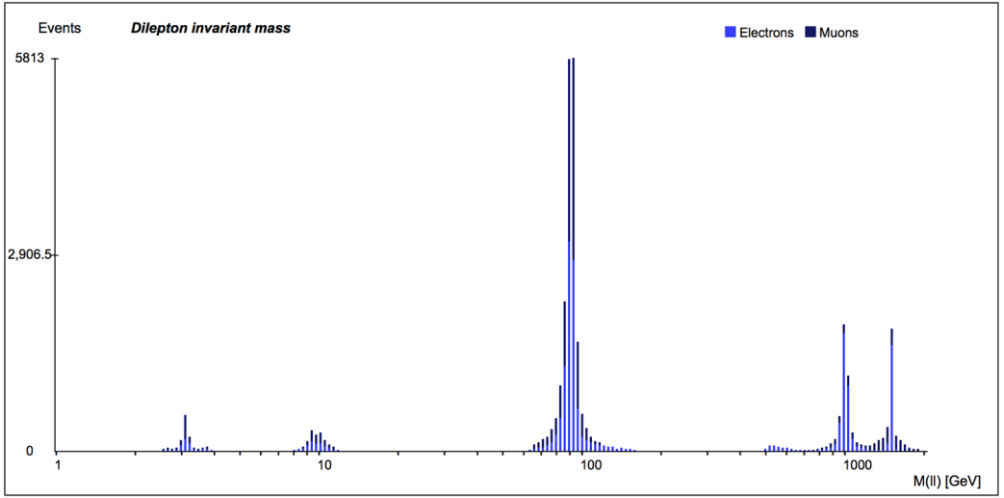
- ll → Measure mass and width of known particles: Z^0,J/ψ,Y
  - ➢ Search for new force / new gauge boson – Z‘
- 4l, γγ → Provide insight into the process of discovering the Higgs at CERN
  - ➢ Explain concepts of statistics, modeling, signal significance
- “Comparison” to results published by experiment:
  - ➢ slides for moderators and tutors

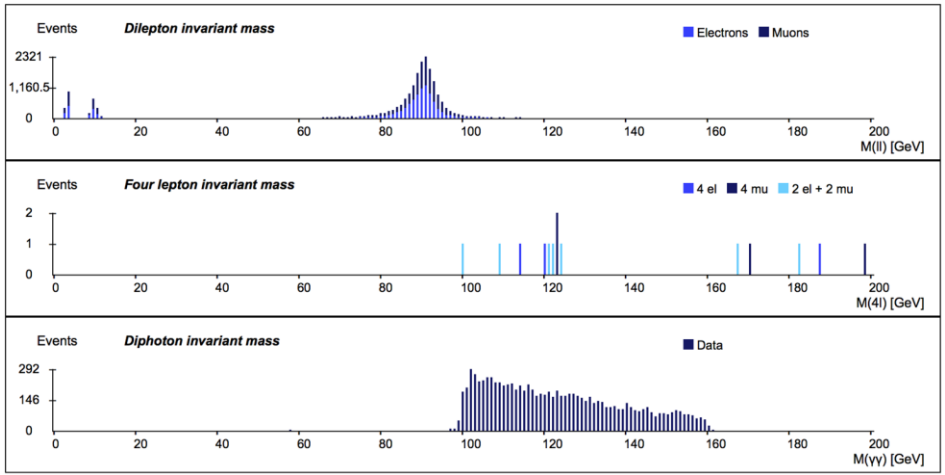


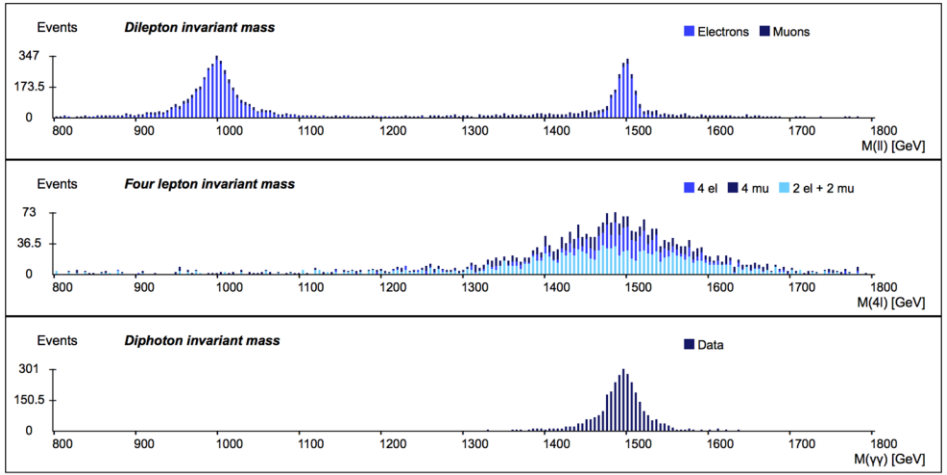


Zpath new features

- New physics
  - graviton → ll, ZZ/4l, di-photons → 2016 IMC
  - supersymmetry / dark matter → advanced projects
- More concepts added

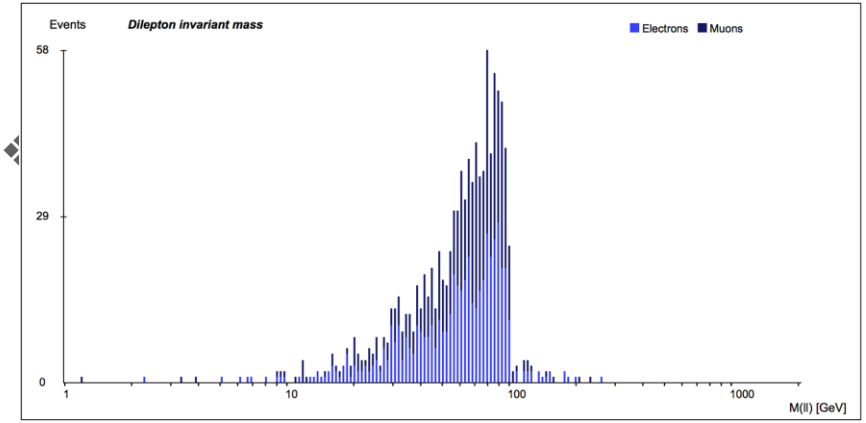


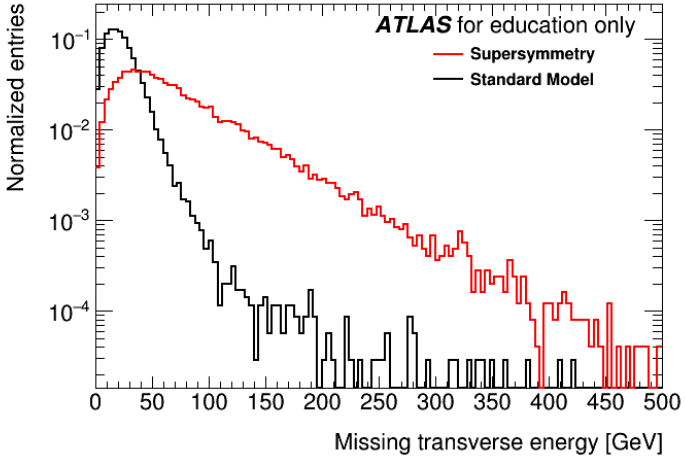


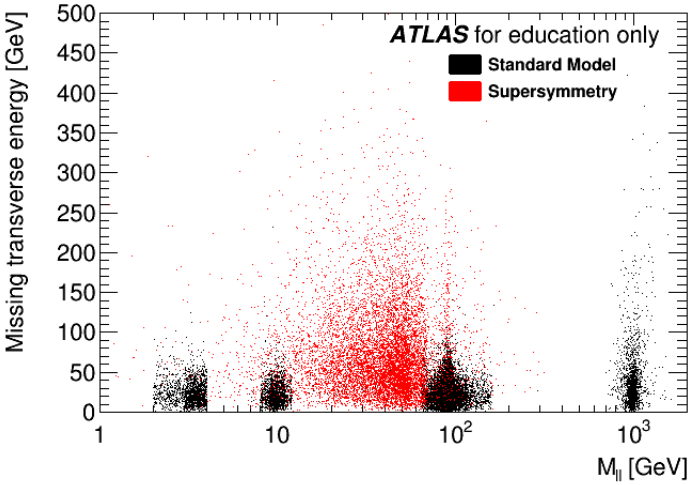


Zpath new features

- Supersymmetry with ETmiss and leptons or DM simplified model (mono Z)
  - ETmiss for SUSY signal and the “SM+Z’” masterclass sample ⇒

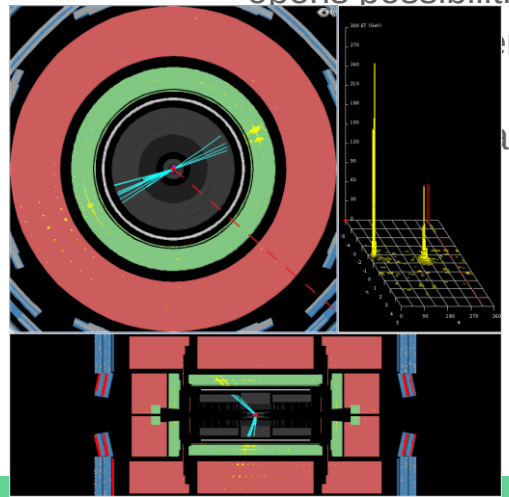


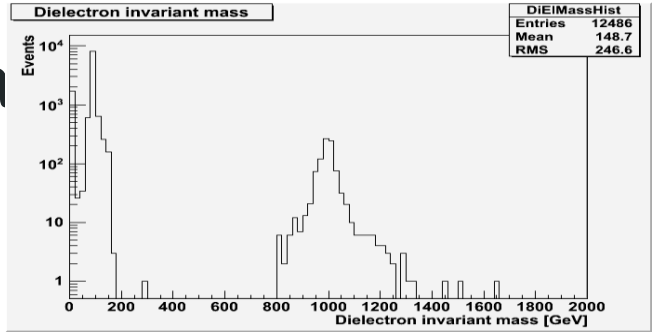


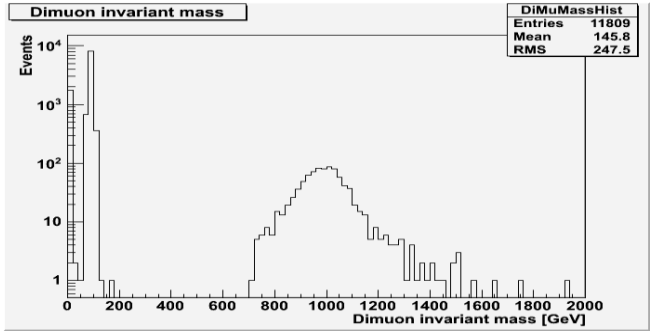


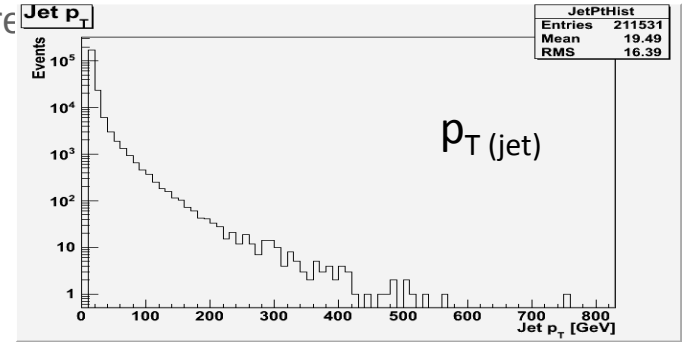
Batch analysis & high statistics data

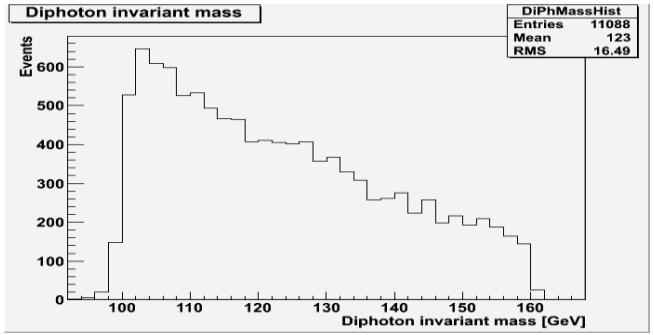
- after having studied a set of event displays
  - ➢ example of ATLAS data available for masterclasses ⇒
- more data made available by experiments - Cern open data portal ⇒
  - ➢ opens possibilities for detailed studies and projects for
    ents
    alre







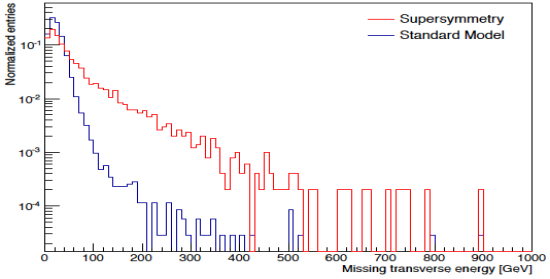


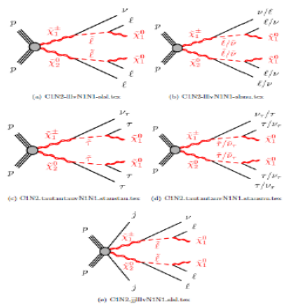


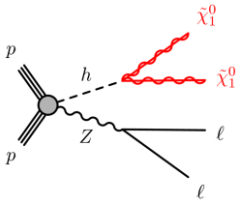
- **Z-path introduced in FYS3510 (Subatomic physics) and FYS4560 (Advanced particle physics) at University of Oslo**
  - Students calculate an electroweak process e+e- → l+l-, use CompHEP to include a Z' , and perform a pp → l+l- +X analysis and compare to ATLAS results: Z-path data, more recently atlas data portal
  - 4-leptons (IMC, 40 events) used in project work related to Higgs (production and decay) and weak gauge boson self-couplings (allowed and forbidden couplings) studies: recently with atlas data portal
  - Larger statistics allow beautiful "textbook" hands-on activities

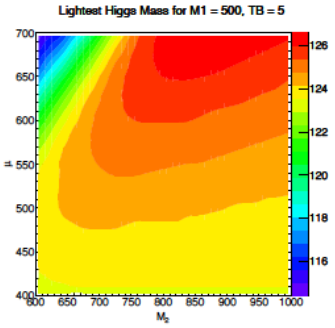
3-month student research projects within FYS4010 Bachelor Course

- 2015: Search optimisation with ATLAS using pMSSM parameter calculation and plotting tool
  - (IMC) data compared to generated and ATLFAST simulated MC samples resulting from a pMSSM search optimisation; ETmiss enhances the di-lepton endpoint distribution → results, *Alex Cameron*
- 2016 (2) Invisible Higgs in mono-Z processes and New Physics at the LHC – Search optimisation with ATLAS, *Max Delto*
- 2016 (1) ATLAS@home: A graphic design project for the ATLAS@home interface, *Giulio Isacchini*









Project descriptions - 2016

- Each analysis consists of
  - (i) selecting/studying particular final states made of particles measured by detector
  - (ii) identifying underlying proton-proton collision process(es),
  - (iii) interpreting results in terms of SM measurement or within some new theory

1. (i) Four charged lepton final state.
   (ii) $pp \rightarrow ZZ+X \rightarrow 4l+X$ or $pp \rightarrow H+X \rightarrow ZZ+X \rightarrow 4l+X$
   (iii) Test of the electroweak theory and production and study of the Higgs boson.
1. (i) Dilepton and diphoton final states
   (ii) $pp \rightarrow \gamma, Z, Z', G \rightarrow l^+l^- + X$, $pp \rightarrow H, G \rightarrow \gamma\gamma + X$
   (iii) Study of known particle resonances, search for new ones in M(ll) and M($\gamma\gamma$) distributions
   Make use of spin to distinguish various outcomes?
1. (i) Dilepton and missing transverse energy (MET) final state
   (ii) $pp \rightarrow \tilde{l}^+\tilde{l}^- + X \rightarrow l^+l^- + MET + X$, $pp \rightarrow Z + MET + X \rightarrow l^+l^- + MET + X$, $pp \rightarrow W^+W^- + X \rightarrow l^+l^- + MET + X$,
   $pp \rightarrow Z(\rightarrow l^+l^-)\ Z(\rightarrow \nu\nu) + X \rightarrow l^+l^- + MET + X$
   (iii) Search for SUSY particles (sleptons) and/or Dark Matter.
4. Final state characterisation and interpretation using machine learning algorithms (in progress)

Project 1 - What do 4-lepton final states tell us about the Standard Model and the Higgs boson?

(i) Select and study four charged lepton final states produced in proton-proton collisions at the LHC and collected by the ATLAS detector.

- Go to the Z-path web pages and download the event display program HYPATIA and one arbitrary data sample consisting of 50 events (dirXX/groupX.zip). Unzip your data sample and open it with HYPATIA (File→ Read Event Locally and open the first event "event001.xml"). Navigate through the data sample using the "Next Event" button and look for events with four charged leptons ($e^+e^-e^+e^-$, $\mu^+\mu^-\mu^+\mu^-$, $e^+e^-\mu^+\mu^-$) in the final state (these are quite rare). Use HYPATIA to calculate the invariant mass of individual electron and/or muon pairs as well as of the full 4-lepton system by inserting the leptons into the "Invariant Mass Window" using the "Electron" and/or "Muon" buttons.
- Go to the web-based Histograms Analyzer to learn how "cuts" are used in a particle physics analysis to select events of interest. Place cuts on any variable directly by clicking on the x-axis of the corresponding histogram, and see how the composition of the data sample in terms of the different physics processes changes.
- Go to the ATLAS Open Data portal and download the samples and analysis code to a computer which has PyROOT installed and at least 7 GB of free disk space. Follow the instructions to analyze the data and plot results, first using the predefined "ZZAnalysis", and later modifying this analysis to complete the below exercises.

(ii) Analyse the data in terms of the following processes (the Z boson can be on- or off-shell) by building the invariant masses, of 2 pairs of oppositely charged leptons, or of the four leptons. Information about the angular distribution of the leptons in the centre of mass of the decaying Z or H bosons may also be used.

- $pp \rightarrow ZZ+X \rightarrow 4l+X$.
- $pp \rightarrow H+X \rightarrow ZZ+X \rightarrow 4l+X$.

(iii) Test of the electroweak theory and production and study of the Higgs boson. Describe the features of the invariant mass distributions within a wide range of masses. Compare the right- (l^+l^-) and wrong- (l^+l^+, l^-l^-, $l^+l'^-$) lepton combinations. Does the SM describe well the data? Compare data and available MC. Draw your conclusions.

- SM predicts coupling between the Z boson & quarks or leptons, allowing scattering process quark-antiquark → ZZ through a quark exchange. The Z-self coupling and γ-Z coupling, leading to annihilation process quark-antiquark→ γ,Z→ ZZ, are forbidden.
- SM predicts the existence of a scalar (spin-0) boson. Higgs boson observed at mass 125 GeV by the ATLAS and CMS collaborations. The Higgs couples to massive particles.

Project 2 - Do new fundamental forces or extra space dimensions show up at the LHC the way the Z and Higgs bosons did?

(i) Select and study di-lepton and di-photon final states produced in proton-proton collisions at the LHC and collected by the ATLAS detector.

- Go to the Z-path web pages and download the event display program HYPATIA and one arbitrary data sample consisting of 50 events (dirXX/groupX.zip). Unzip your data sample and open it with HYPATIA (File -> Read Event Locally and open the first event "event001.xml"). Navigate through the data sample using the "Next Event" button and look for events with lepton pairs (e^+e^-, $\mu^+\mu^-$) or photon pairs ($\gamma\gamma$). Use HYPATIA to calculate the invariant mass of the pairs by inserting the particles into the "Invariant Mass Window" using the "Electron", "Muon", and "Photon" buttons.
- Go to the web-based Histograms Analyzer to learn how "cuts" are used in a particle physics analysis to select events of interest. Place cuts on any variable directly by clicking on the x-axis of the corresponding histogram, and see how the composition of the data sample in terms of the different physics processes changes.
- Go to the ATLAS Open Data portal and download the samples and analysis code to a computer which has PyROOT installed and at least 7 GB of free disk space. Follow the instructions to analyze the data and plot results, first using the predefined "ZAnalysis", and later modifying this analysis to complete the below exercises.

(ii) Analyse the data in terms of the following processes by building the invariant masses, of 2 pairs of oppositely charged leptons, or of 2 photons. Information about the angular distribution of the leptons in the centre of mass of the decaying Z or H bosons may also be used.

- $pp \rightarrow \gamma, Z, Z', G \rightarrow l^+l^- + X$
- $pp \rightarrow H, G \rightarrow \gamma\gamma + X$.

(iii) Study the known particle resonances and determine their properties, search for new ones in dilepton and diphoton invariant mass distributions, make use of spin to distinguish various outcomes. In addition to mass and electric charge, particles have a fundamental property called spin or "intrinsic angular momentum". The Higgs boson has spin 0, the Z' and Z bosons spin 1, and the Graviton, the hypothetical mediator of gravity, spin 2. Knowing the spin is a way to further characterise a newly observed resonance. This can be done by studying, in addition to the invariant mass, the angular distribution of the decay products in the reference frame of the decaying particle. A spin-0 particle would lead to an isotropic distribution. The higher the spin, the more complicated would be the pattern. The conservation of angular momentum and spin come in addition, and imposes constraints on allowed particle decays.

Project 3 - Is the world supersymmetric and/or where is Dark Matter?

(i) Select and study di-lepton final states - featuring important missing energy/momentum taken by weakly interacting particles such as Dark Matter - produced in proton-proton collisions at the LHC and collected by the ATLAS detector.

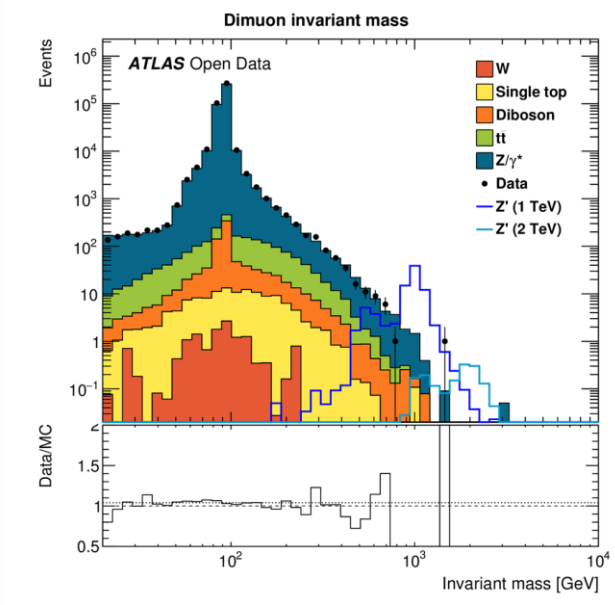
- Go to the Z-path web pages and download the event display program HYPATIA and one arbitrary data sample consisting of 50 events (dirXX/groupX.zip). Unzip your data sample and open it with HYPATIA (File -> Read Event Locally and open the first event "event001.xml"). Navigate through the data sample using the "Next Event" button and look for events with lepton pairs (e^+e^-, $\mu^+\mu^-$). Use HYPATIA to calculate the invariant mass of the pairs by inserting the particles into the "Invariant Mass Window" using the "Electron" and "Muon" buttons. Check the value of the MET in each event. If the MET is large enough, the direction will be shown as a red dashed line.
- Go to the web-based Histograms Analyzer to learn how "cuts" are used in a particle physics analysis to select events of interest. Place cuts on any variable directly by clicking on the x-axis of the corresponding histogram, and see how the composition of the data sample in terms of the different physics processes changes.
- Go to the ATLAS Open Data portal and download the samples and analysis code to a computer which has PyROOT installed and at least 7 GB of free disk space. Follow the instructions to analyze the data and plot results, first using the predefined "ZAnalysis", and later modifying this analysis to complete the below exercises.

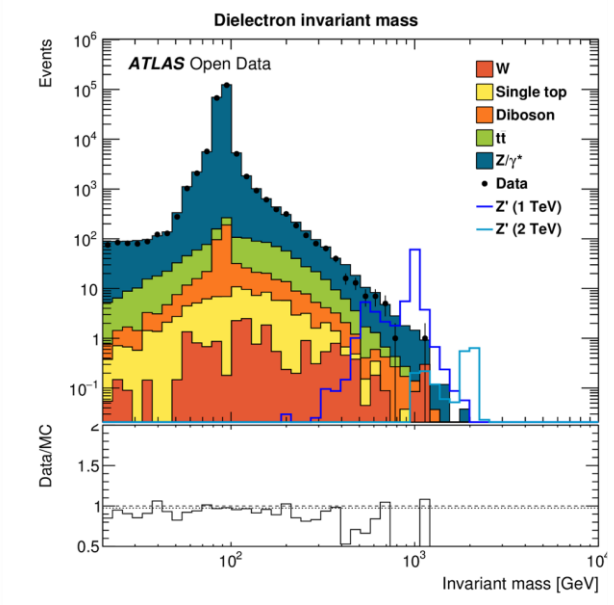
(ii) Analyse the data in terms of the following processes by building the invariant mass of 2 pairs leptons (ee, mumu, emu). In this particular search the information about the missing transverse energy (MET) will be decisive in separating signal from background

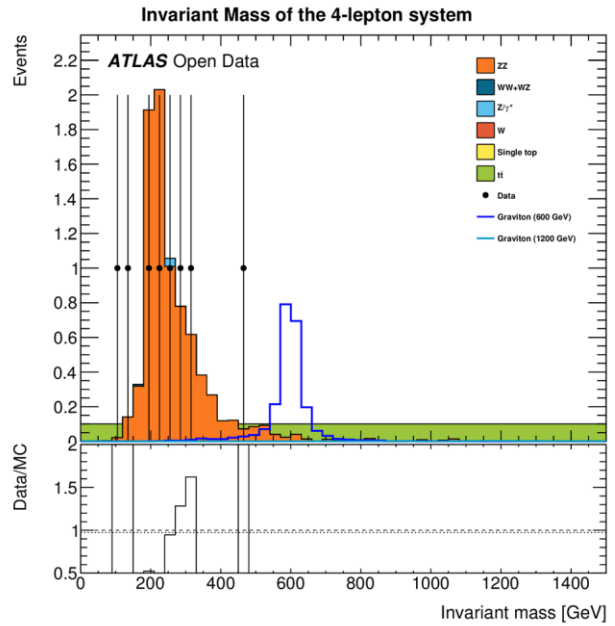
- $pp \rightarrow \tilde{l}^+\tilde{l}^- + X \rightarrow l^+l^- + MET + X$ (possible signal for supersymmetry)
- $pp \rightarrow Z + MET + X \rightarrow l^+l^- + MET + X$ (possible signal of DM)
- $pp \rightarrow W^+W^- + X \rightarrow l^+l^- + MET + X$, $pp \rightarrow Z(\rightarrow l^+l^-)\ Z(\rightarrow \nu\nu) + X \rightarrow l^+l^- + MET + X$ (SM background processes)

(iii) Describe the features of the dilepton invariant mass and MET distributions. Does the SM describe well the data? Compare data and the available MC samples. Draw your conclusions. Interpret the data in terms of searches for supersymmetric particles (sleptons) and/or Dark Matter.

Preliminary ll & 4l analysis







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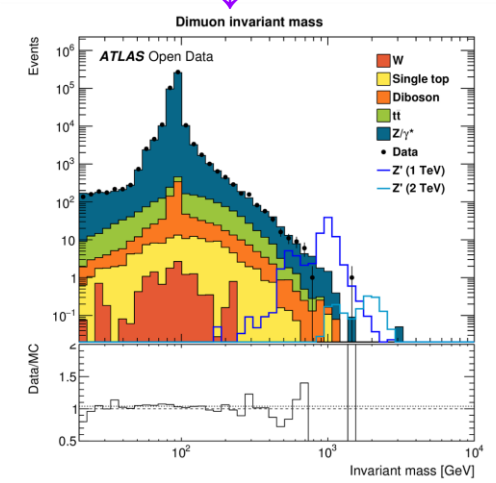
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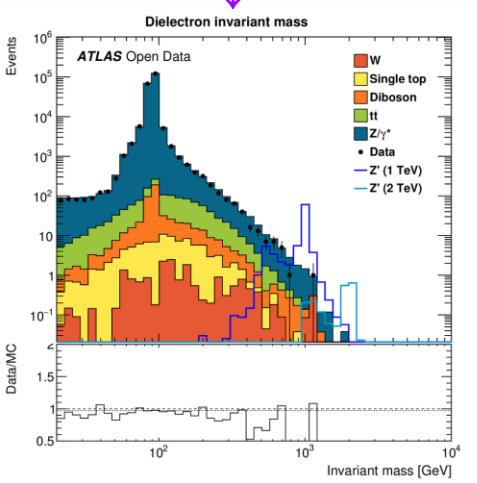
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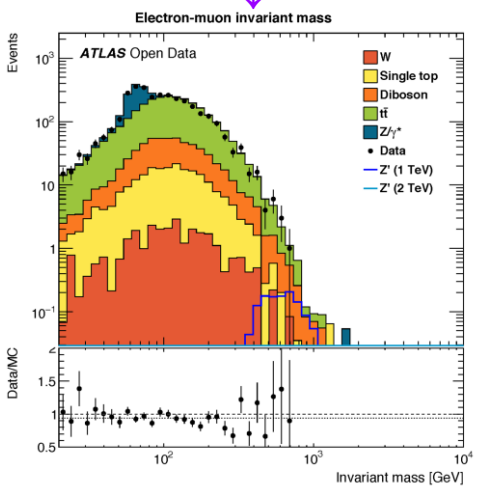
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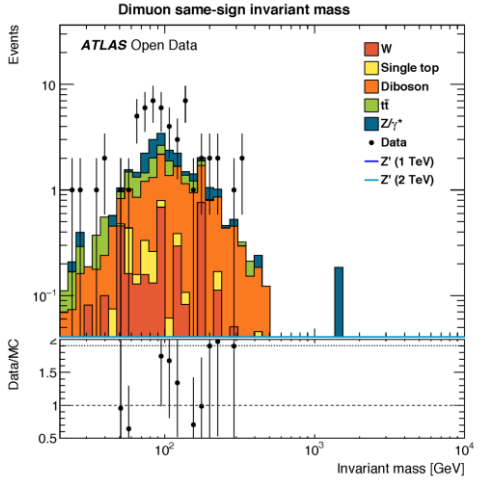
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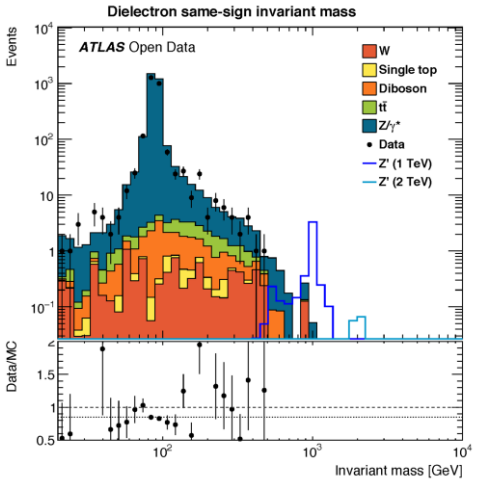
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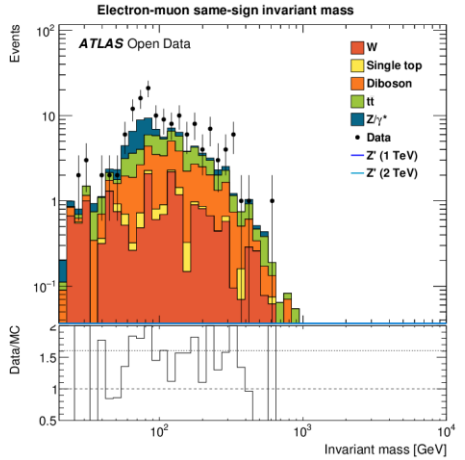
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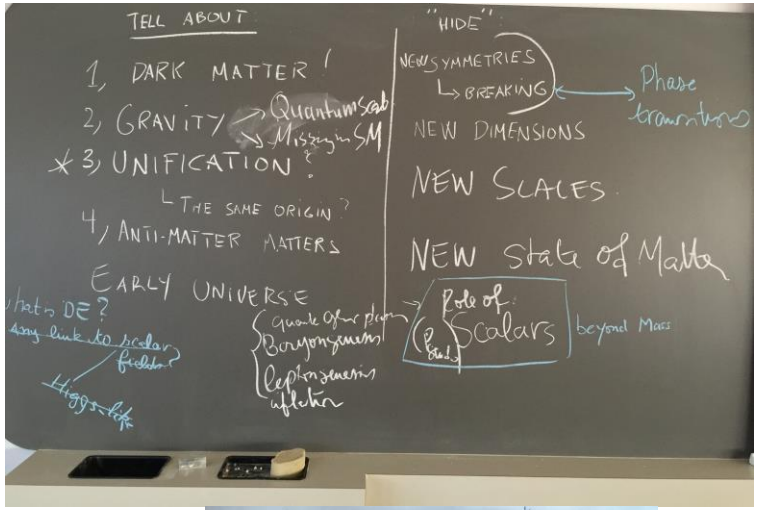
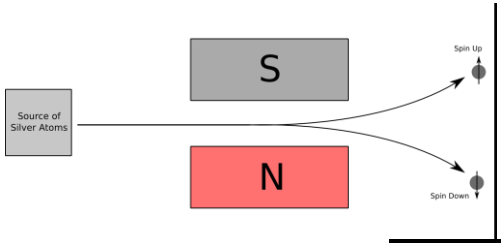
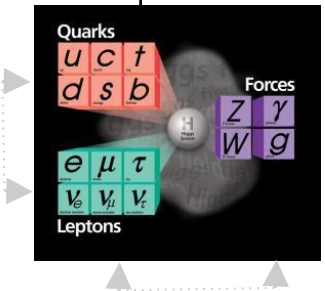
Invariant mass [GeV]

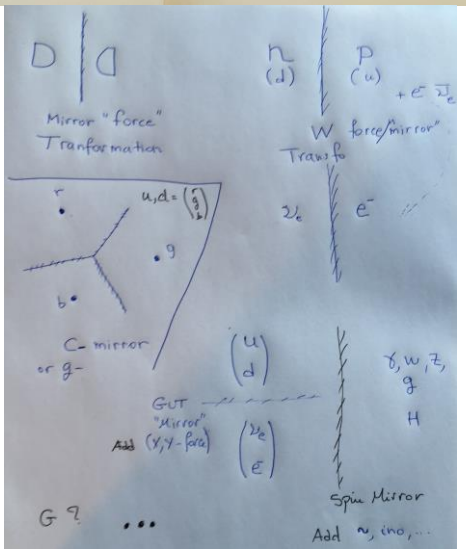
- There is an urgent need to extend the educational materials (IMC and more)
  - to follow LHC 'heartbeats',
  - to share any new future discoveries
  - and to influence textbooks and teaching methods.



- Which new concepts to introduce?
  - spin, C, P, T, ...
  - (new) symmetries
  - extra space dimensions
  - gravity and graviton
  - dark matter







- What to improve?
  - What is a particle? Intrinsic properties.
  - How to introduce matter and force particles? Classification and symmetry pattern

New Physics http://testatlas.physicsmasterclasses.org/en/zpath.htm in Zpath

By colliding protons at higher energies and higher collision rates the LHC continues the exciting voyage towards new physics, allowing physicists all over the world to explore a previously unexplored territory full of promise.

As part of the search for new physics phenomena at the LHC, we have introduced the ***Z' boson*** *(link). This particle is a heavy partner of the Z boson and is predicted by some theories beyond the Standard Model (SM) that require the introduction of a new weak force.*

Let us concentrate on two of the greatest enigmas in physics today: the nature of ***dark matter*** *(DM) and the behavior of Gravity (link) at the microscopic quantum scale.*

Astronomical observations based on gravitational effects tell us that 85 percent of the matter in the universe is dark, and normal matter (atoms made of electrons, and up- and down-quarks) only contributes to 5% of the content of the universe. Popular DM particle candidates are so-called weakly interacting massive particles, WIMPs for short. WIMP candidates are expected in ***supersymmetry*** *(link), the most popular extension of the SM.*

In analogy with other forces of nature, the force of gravity is carried by the hypothetical ***graviton****, which has not yet been observed. While no satisfactory quantum description of gravity exists, superstring theories elegantly propose to incorporate gravity into the theoretical framework. The notion of a particle is replaced by extended objects - strings - living in 10 or 11 spacetime dimensions, thus requiring 6 or 7* ***extra space dimensions*** *(link).*

Are there more space dimensions than the usual known 3, which would allow gravity-related phenomena, such as microscopic black holes and gravitons, to be discovered in the LHC era?

If accessible, the new phenomena above could be observed and studied by the ATLAS and CMS experiments at the LHC.

Knowledge Center

- ***Søknad om støtte til studentaktiv forskning innen prosjektet Z-path***
  - Project “A data-based path for education, research and discovery”
  - By/for students students, various levels
  - With department of education - more professional and research based view on methods and ideas for introducing and explaining new concepts
- Activities
  - New Website design
  - Library of new concepts and phenomena accessible to students and teachers
  - Analysis and development tools: data, simulation, calculations, …
  - Research projects and new courses based on LHC data and beyond

Aktivitet	Produkt	Milepæl	Periode/frist
A1. Nytt design og modernisering av websidene tilknyttet *Z-path*	D1. Ny *Z-path*-webside	M1.1. Åpne for bruk i IPPOG M1.2. Ta i bruk i fysikkurs ved UiO	høst 2017 vår 2018
A2. Gjøre en presentasjon av nye konsepter og fenomen i (partikkel) fysikk tilgjengelig for elever og lærere på videregående	D2. Presentasjon av nye konsepter i fysikken	M2.1 Utvide biblioteket av viktige konsepter og gjøre de tilgjengelig på websidene M2.2 Teste forståelsen av konseptene på elever og studenter på ulike nivå	vår 2018 vår 2019
A3. Utvikle verktøyene for analyse av data fra LHC og presentasjon av resultatene	D3. Verktøy for å analysere LHC-data og gjøre statistiske analyser	M3.1. Et fysikkbibliotek M3.2. Dynamisk, webbasert presentasjonsverktøy	høst 2018 høst 2018
A4. Organisere lokale og internasjonale masterclasses	D4. Masterclasses	M4.1. IMC 2018 M4.2. IMC 2019 M4.3. IMC 2020	vår 2018 vår 2019 vår 2020
A5. Ta i bruk undervisningsmateriell i universitetskurs og forskningsprosjekt for studenter	D5. LHC-data i høyere utdanning	M5.1. En forenklet prototyp M5.2. En ferdig prototyp M5.3. Ta i bruk materialet i to fysikkurs og i enkeltstående forskningsprosjekt	høst 2018 høst 2019 høst 2020
A6. Publisere i journaler for fysikkutdanning og på konferanser	D6. Publikasjoner, presentasjoner	M6.1. *Z-path* M6.2. Forklare nye konsepter M6.3. LHC-data og oppdagelser i høyere utdanning	vår 2018 høst 2019 høst 2020
A7. Utføre spørreundersøkelse blant nye fysikkstudenter	D7. *Z-path*s effekt på rekruttering	M7.1. Evaluere *Z-path* sin innvirkning på rekruttering M7.2. Bruke resultatene fra undersøkelsene i publikasjoner	høst 2017 - høst 2020 høst 2020