The challenge of explaining new physics concepts and phenomena

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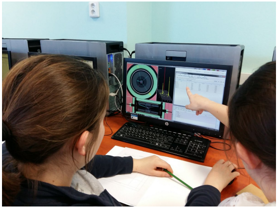
- an educational activity developed within IPPOG[a] to bring cutting-edge particle physics research into the classroom
  - since 2010 real proton-proton, proton-lead and lead-lead collision data from the LHC has been used in the IMC
  - the program follows the heartbeats of the LHC:
    - since the discovery of the Higgs Boson it has been part of both the Z-path and W-path
    - the discovery of quark-gluon plasma is covered in the exercise *Looking for strange particles in ALICE*
- the IMC and the data released through the CERN Open Data Portal triggers an extension of the educational material to
  - give a more researched based approach in introducing particle physics
  - introduce more concepts through hands-on activities
  - prepare for whatever will be discovered in the coming years

[a] the International Particle Physics Outreach Group

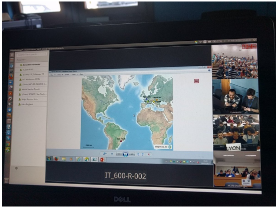
High-school students from all geographical regions master real event-display programmes, software tools and analysis methods. Having been introduced to the problem, they identify electrons, muons, photons and jets by exploiting their characteristic signals in various detector elements, perform event selection and categorization, and achieve the final analysis goals. (Image credits, left to right: Caroline Hamilton/CoEPP/University of Melbourne, Jayne Ion/iON creative, Franziska Viebach/TU Dresden.)

International Masterclasses in the LHC era

from CERN Courier, June 2014



from twitter (@physicsIMC)



from twitter (@physicsIMC)

The Z-path masterclass event

What the students are confronted with

- Z-path is one of the most popular exercises that are part of the IMC
  - using real proton-proton collision events recorded by the ATLAS detector at the LHC students identify particles and calculate the invariant mass
- typically the first few hours of the day are spent introducing what the students need to know to perform the experimental exercise later in the day
  - idea is that Masterclass should be self-contained (with some basic physics knowledge)

Typical IMC-day (10 am - 5 pm)

1. Introduction to particle physics (45 min.)
   - particle properties (mass, charge and spin)
   - introduction to the Standard Model (SM) (classification of particles and interactions)
   - unsolved problems in SM and some proposed new physics scenarios
2. The LHC and ATLAS (45 min.)
   - how to study very small particles and the early universe
   - what happens in a proton-proton collision ($E = mc^2$)
   - how are particles detected and identified in ATLAS
   - unstable particles and how to reconstruct the mass from the decay products
3. Invariant mass and how it is used to discover particles (30 min)
4. Measurements - each pair of students analyze $\sim$ 50 event displays (1.5 h)
5. Discussion of results in video conference with CERN and the other institutes (1 h)

Obviously a quite ambitious program given that these are high school students with little or no prior knowledge of particle physics or statistics

Do high school students have the necessary background to understand the ambitious program of the LHC Masterclasses?

Important concepts to master the Z-path (and other LHC-physics activities)

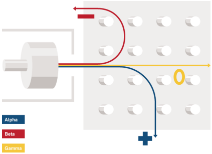
Particles and their intrinsic properties

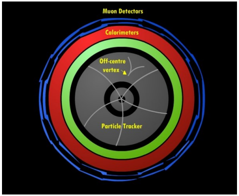
What is a particle?

By starting from the fundamental forces and the intrinsic properties of a particle (charge, mass, spin) . . .

Charge

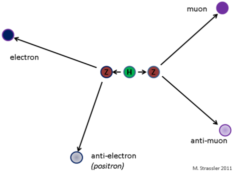
can be measured in a magnetic field





Mass

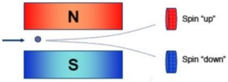
can be calculated from measurements of energy and momentum

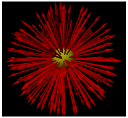


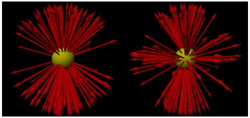
$$m_{1,2} = \sqrt{\left(\frac{E_1+E_2}{c^2}\right)^2 - \left(\frac{\vec{p}_1+\vec{p}_2}{c}\right)^2}$$

Spin

measured by looking at decay angles







... we build the Standard Model of particle physics
(analogues to the periodic table of elements)

THE STANDARD MODEL

CHARGE | MASS | SPIN

Matter: spin ½ (fermions)			Electric charge	Particle type	Interacts through
Up (u)	Charm (c)	Top (t)	+2/3	Quarks	• Electro-magnetic • Strong • Weak
Down (d)	Strange (s)	Bottom (b)	-1/3		
Electron-neutrino (ν_e)	Muon-neutrino (ν_μ)	Tau-neutrino (ν_τ)	0	Leptons	• Electro-magnetic • Weak
Electron (e^-)	Muon (μ^-)	Tau (τ^-)	-1		

Forces: spin 1 (bosons)	Electric charge	Mass	Responible for
Photon (γ)	0	0	Electromagnetic force
Gluon (g)	0	0	Strong force
Z-boson (Z)	0	91 GeV	Weak force
W-boson (W^-)	- 1	80 GeV	Weak force
spin 0			
Higgs (h)	0	125 GeV	Gives mass to Z and W

Light → Heavy

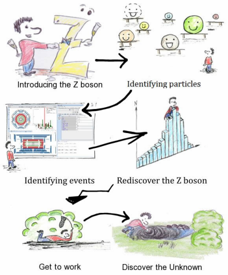
How to make the event learning-effective and attractive?

Students at masterclasses

- for some students almost everything presented at the IMC is new
- others may have heard of some of the concepts before, but on a very general level
- a full bottom to top introduction is hard to give in a 2×45 min lecture
- most optimal would be if students already had worked on some of the topics prior to the IMC participation

already have a web page that can be used pre- and/or post-masterclass:

`http://atlas.physicsmasterclasses.org/en/zpath.htm`



Z-Path

- Introducing the Z boson
- Introducing the Higgs boson
- New Physics
  - The Z' boson
  - The Graviton
- Identifying particles
- Identifying Events
- Search and discover with mass
- Get to work!

Knowledge Center

- Research at the LHC
- The Standard Model
- More about the Z boson
- Extra Space Dimensions and Gravity
- Supersymmetry
- Momentum
- Spin
- Energy units
- Vectors
- Histogram
- Radioactivity
- Feynman diagrams

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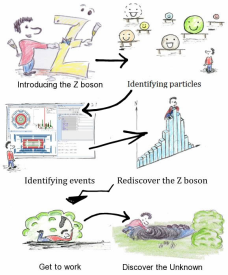

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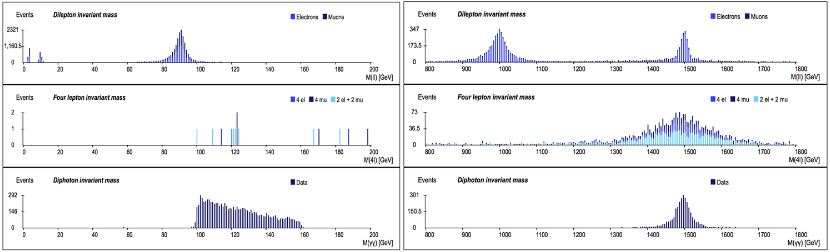
Extending the program

New physics and concepts in the masterclasses

- to prepare the students for new discoveries simulation of hypothetical particles have been mixed into the IMC data
    - a Z'at 1 TeV (spin-1) and a Graviton at 1.5 TeV (spin-2)
- the students look for decays of heavy particles into $\gamma\gamma$, $\mu^+\mu^-$, e^+e^- and four leptons and plot the invariant mass:



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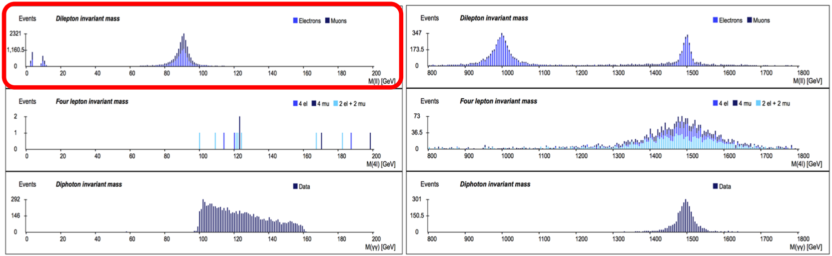

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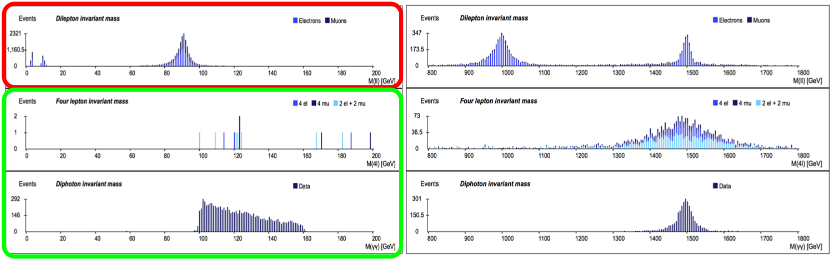

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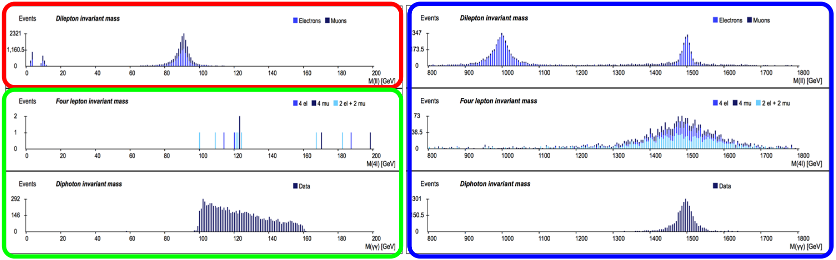

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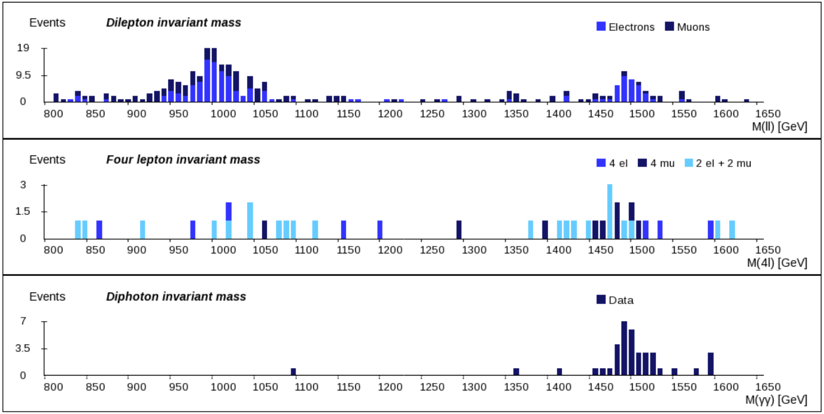
- students identify Higgs candidates ($\gamma\gamma$, 4-lepton dist.)
  - they experience the concept of statistics related to the discovery of the Higgs Boson
- they observe *unexpected* peaks at 1 and 1.5 TeV
  - first reaction is that this must be wrong!
  - how to understand the nature of the newly discovered particles?

- students experience that the technique they have learned can be (is) used to find new particles. . .
- . . . but the high invariant mass distributions opens up many other interesting discussions
  - why are the decay pattern different?
  - what does this tell us about the new particle's properties (spin-1 vs. spin-2)
    - this is usually something completely new to the students and hard to grasp with no prior knowledge about particles and spin



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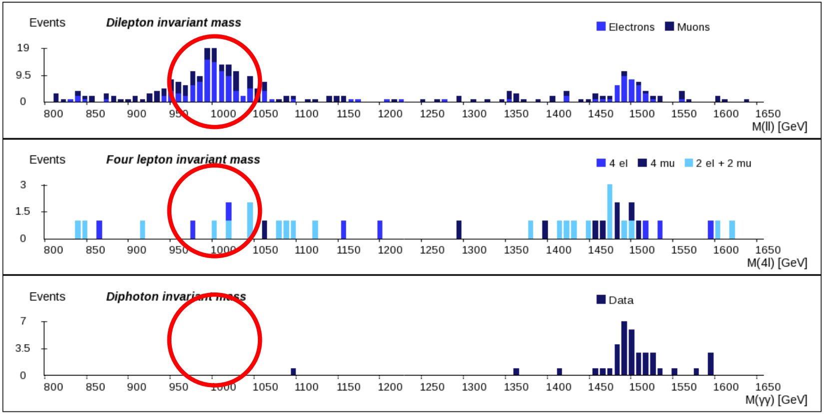

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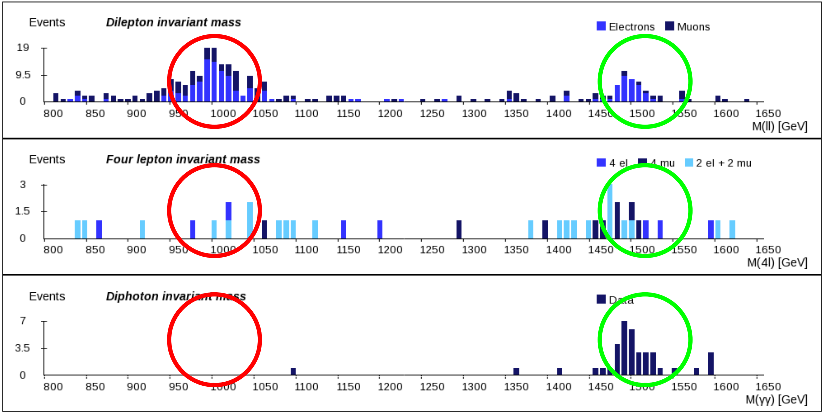


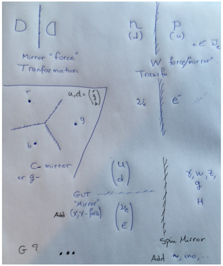
Previous slide showed one example on how a better understanding of the fundamental concepts in particle physics can make the masterclass even more interesting and attractive. In fact...

- ... understanding the concept of spin opens up a better understanding of many important topics
  - the spin-symmetry (matter-force) sets the basis for *Supersymmetry*
  - spin tells us a lot about the properties of the particle and its role in the creation and evolution of the universe
  - important quantity when trying to incorporate gravity in a particle physics context
  - important also to explain properties of macroscopic phenomena
    - the periodic table of elements
    - lasers
- what probably makes spin difficult is that it is a purely quantum mechanical property

There are many more concepts to bring in if we want to go beyond *buzz-words* in the way we teach young people about particle physics

Plans for extending the educational material

- we do not want to hide interesting physics!
  - quantum physical properties (like e.g. spin, color)
  - the concept of fields
  - the concept of symmetries
    - a natural way to understand the SM and theories beyond the SM (supersymmetry, heavy gauge bosons)
  - . . . and many others
- equipped with data from IMC and from the CERN Open Data portal there is an urgent need to extend the educational material to
  - be able to follow the LHC heartbeats
  - share whatever LHC (and future experiments) will discover
  - support both theoretical and experimental lectures at universities and high schools



explaining symmetries

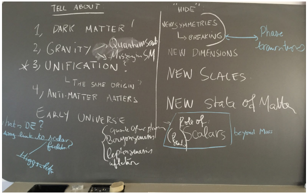
- investigating a more professional and research-based view on methods and ideas for introducing and explaining new physics concepts
  - in close contact with high school teachers and university departments of education

brainstorming with people from the Faculty of Educational Sciences at UiO

Conclusion, plans and outlook

- the international masterclasses bring cutting-edge particle physics research to the classroom
- this as well as the larger data sets recently released from the various LHC experiments triggers an extension of the educational material
    - through hands-on activities important concepts can be introduced in a new way (e.g. spin, invariant mass, missing energy)

- the Experimental Particle Physics group at the University of Oslo received 150k€ from `Thon Stiftelsen` to further develop tools and material to be used in the IMC and beyond
    - goal is to include the use of real LHC data in particle physics courses at the universities as well as develop the Z-`path` to be an independent resource to be used at high schools (not necessarily as part of a masterclass)
    - will hire students to contribute to the development of the tools
    - collaborate with local experts in education and didactic as well as high school teachers



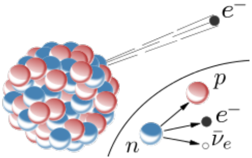
- in parallel fruitful discussions are ongoing within IPPOG on how to introduce important concepts in particle physics

BACKUP

- high school students that specialize in physics in Norway are taught physics the two last years of high school
- first year they have general natural science which includes some physics

first year physics

- electron, electron-neutrino, photon (and anti-particles) are known
- atoms taught as being constructed by protons, neutrons and electrons (no mention of quarks!)
- β-decay is known, but no explanation

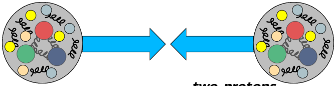


second year physics

- the Standard Model is introduced
    - (anti-)particles
    - force carriers
    - conservation laws (baryon and lepton number, charge, energy, momentum etc.)
    - all mostly presented as *facts* without much explanation

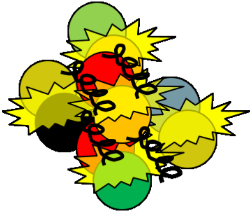
Important concepts to master the *Z*-path (and other LHC-physics activities)

Collisions and the invariant mass technique



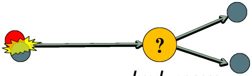
two protons

- protons consists of many particles ((anti-)quarks and gluons)
- additional collisions from other protons in same bunch (pile-up)



quarks and gluons interacting

- more than one of the partons in each of the protons can collide at the same time



hard process

- only interested in one of the collisions (the hard scattering process)
- goal for students is to calculate the invariant mass of the particle from the hard process

Students need to know that:

- heavy particles are unstable (decays almost immediately)
- energy and momentum are conserved
- the more energy the heavier particles can be produced in the collision

$$m_? = \sqrt{\left(\frac{E_1+E_2}{c^2}\right)^2 - \left(\frac{\vec{p}_1+\vec{p}_2}{c}\right)^2}$$

Important concepts to master the Z-path (and other LHC-physics activities)

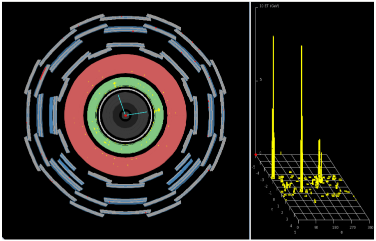
Theoretical

- Particles and their intrinsic properties
  - charge, mass, spin
  - interaction between particles
- Energy and momentum of particles
  - conservation of energy and momentum
  - invariant mass
  - vectors
- Statistics
  - histograms and bumps
  - significance
  - simulation and modeling

these topics are introduced to the students through lectures at the beginning of the masterclass day

Practical

- How the LHC and ATLAS work
  - proton-proton collisions ($E = mc^2$)
  - what is an *event* and how to interpret the digital reproduction of such events in displays
  - identification of particles that immediately disappear



Hands-on

Histograms, bumps and statistics

- Higgs "discovery" through the $H \to \gamma\gamma$ channel
- students look for events with di-photons and calculate the invariant mass

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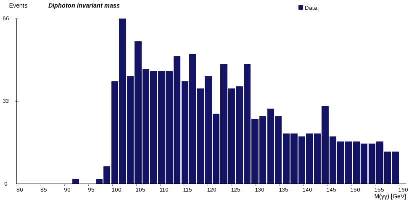
Student's results (0.36fb^{-1})



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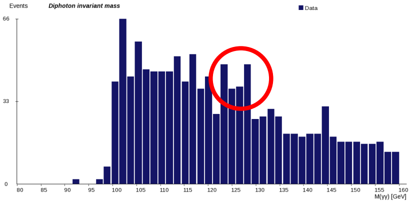

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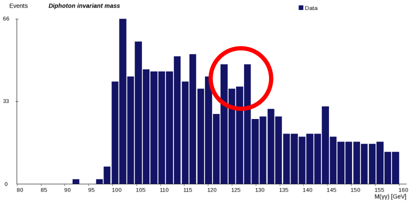
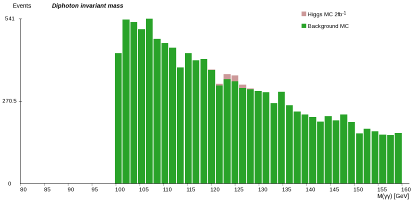


"Perfect results" with 2fb^{-1}



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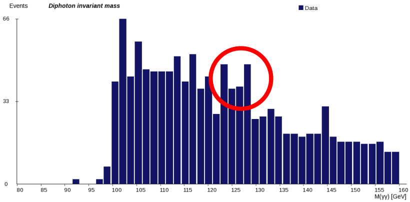

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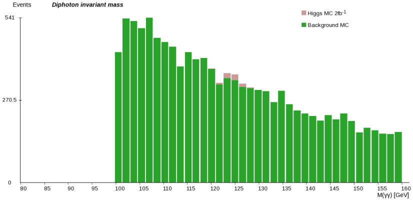
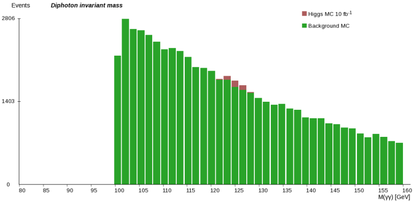


"Perfect results" with 10fb^{-1}



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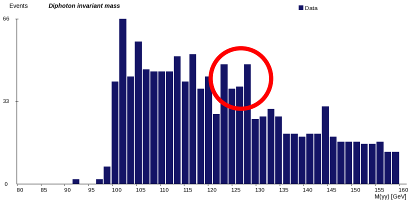

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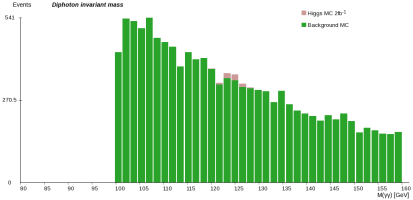

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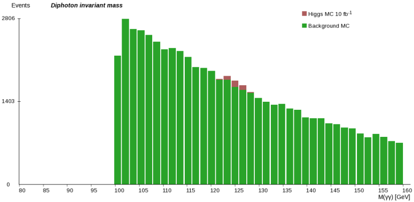
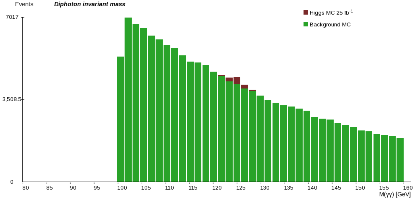


"Perfect results" with 25fb^{-1}



This is exactly how ATLAS and CMS discovered the Higgs!