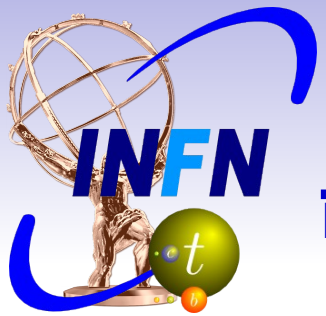

Fisica Nucleare e Subnucleare,
Dipartimento di Fisica, Università degli Studi di Trieste

High Energy Physics Monte Carlo & Data Analysis Tutorial

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INFN Trieste,
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ATLAS Udine Group

2015 December 7th, 14th, 15th

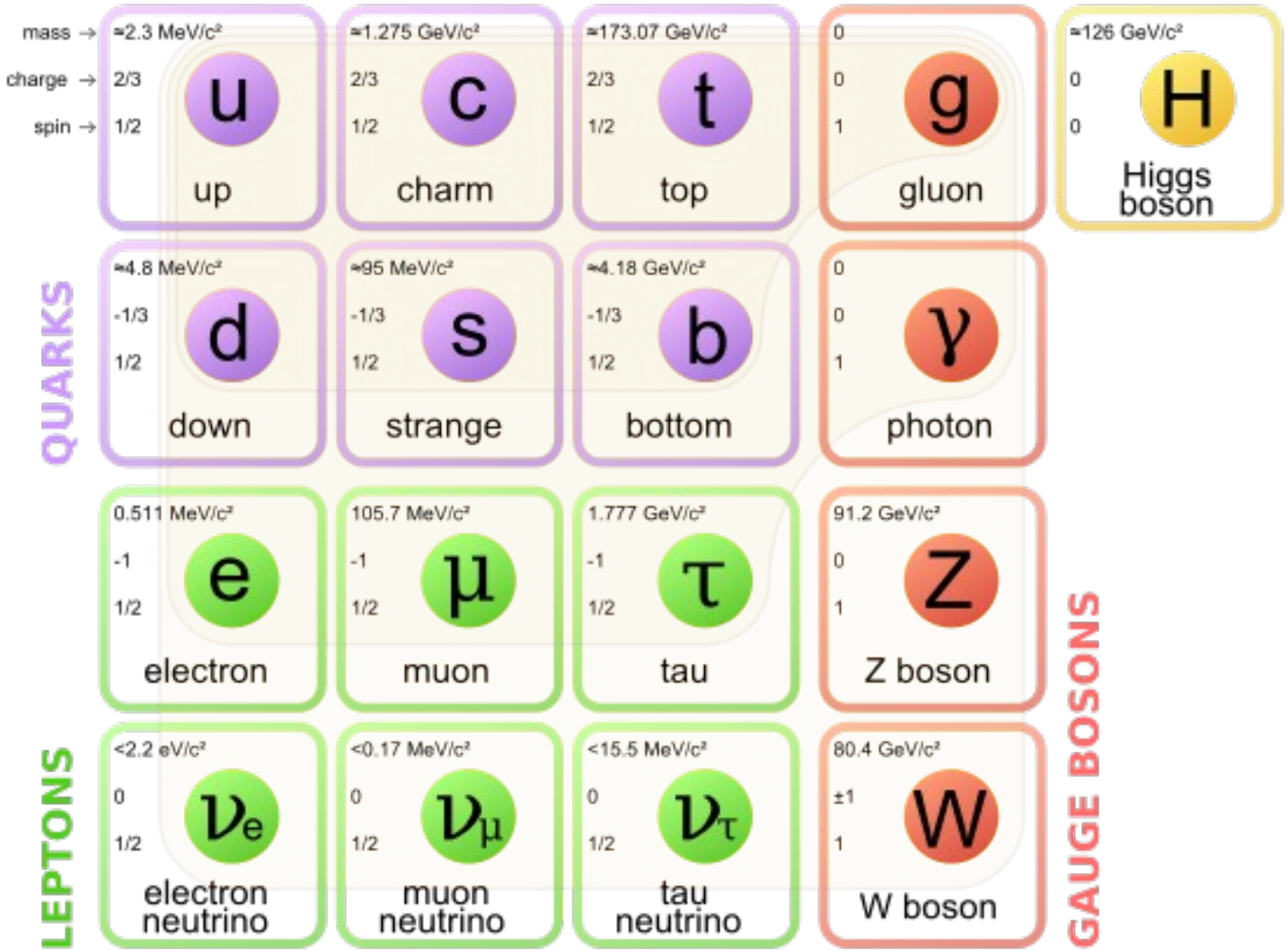
Lecture 1

- Introduction to HEP data analysis & Monte Carlo simulation
- Monte Carlo tools: MadGraph and Delphes
- Practise

What you should know

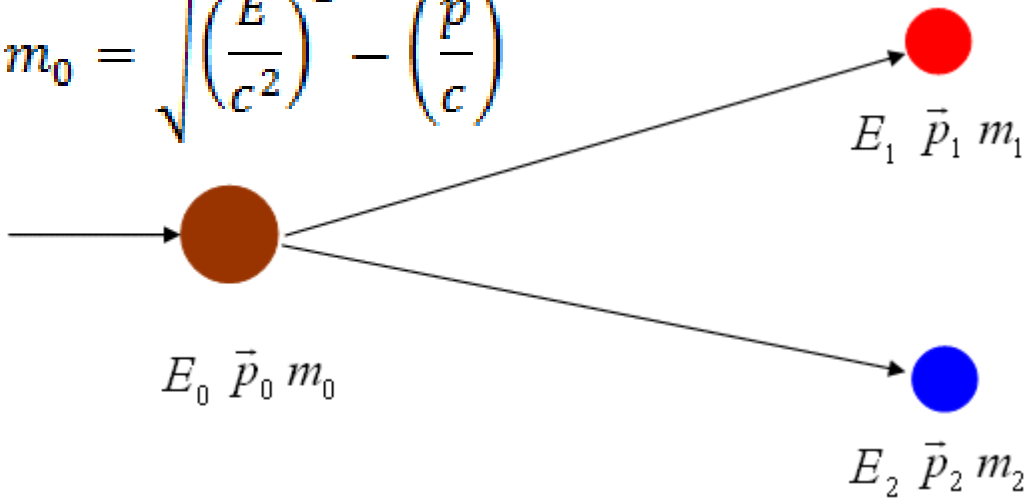
- Standard Model
- LHC @ CERN
- LHC detectors: ATLAS & CMS
- W and Z boson decays,
  top quark production & decays
- Higgs searches and discovery ?

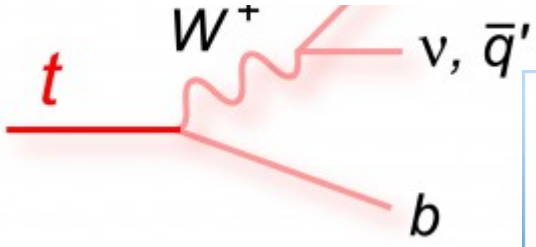
Reminder:
The Standard Model Particles

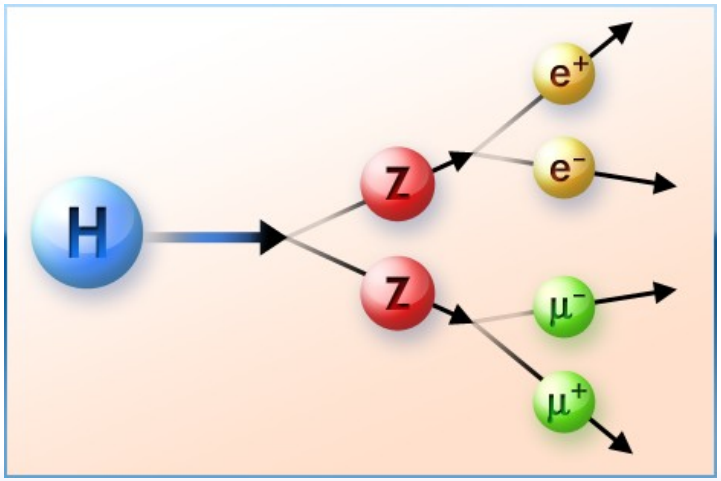


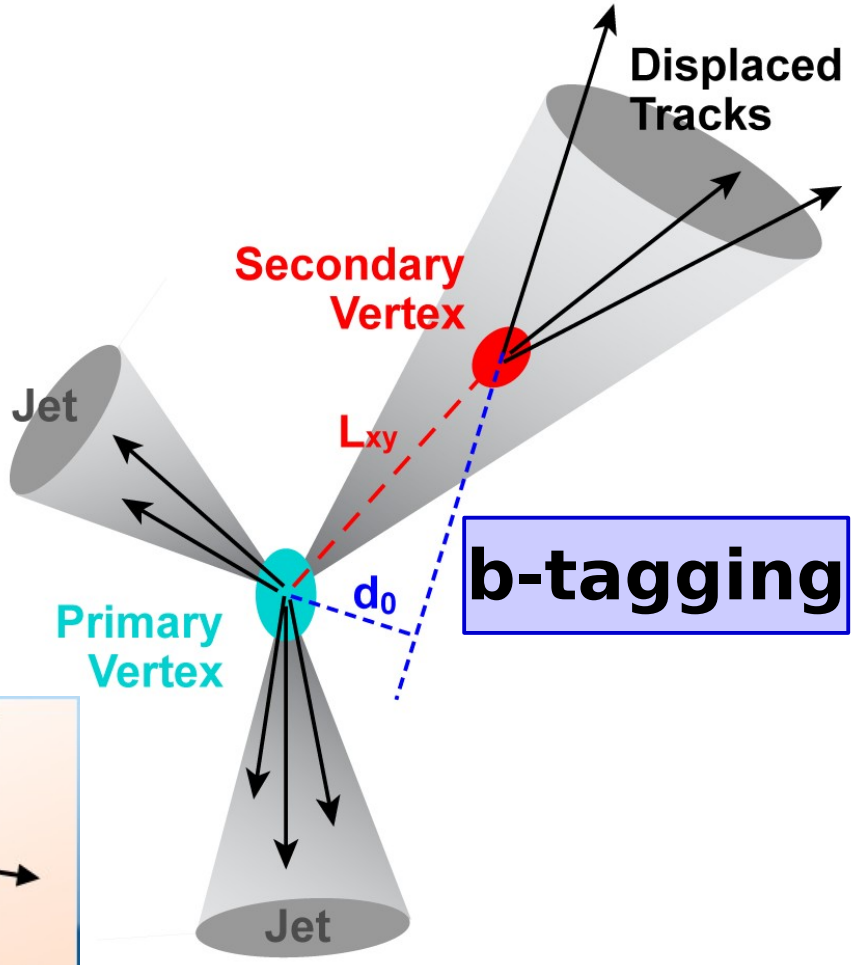
Reminder: Particle Decays

$$m_0 = \sqrt{\left(\frac{E}{c^2}\right)^2 - \left(\frac{\vec{p}}{c}\right)^2}$$

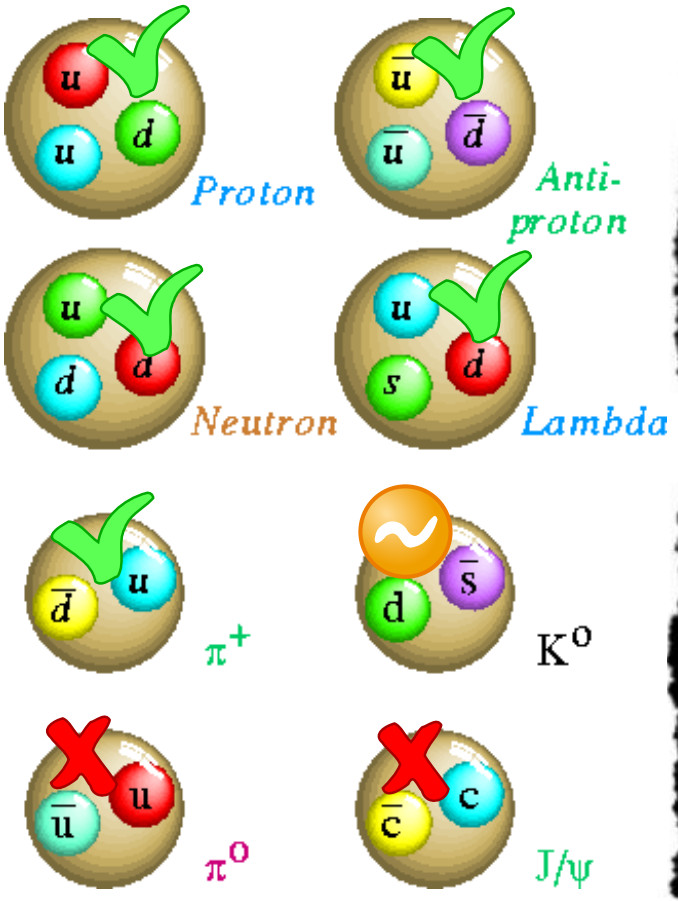


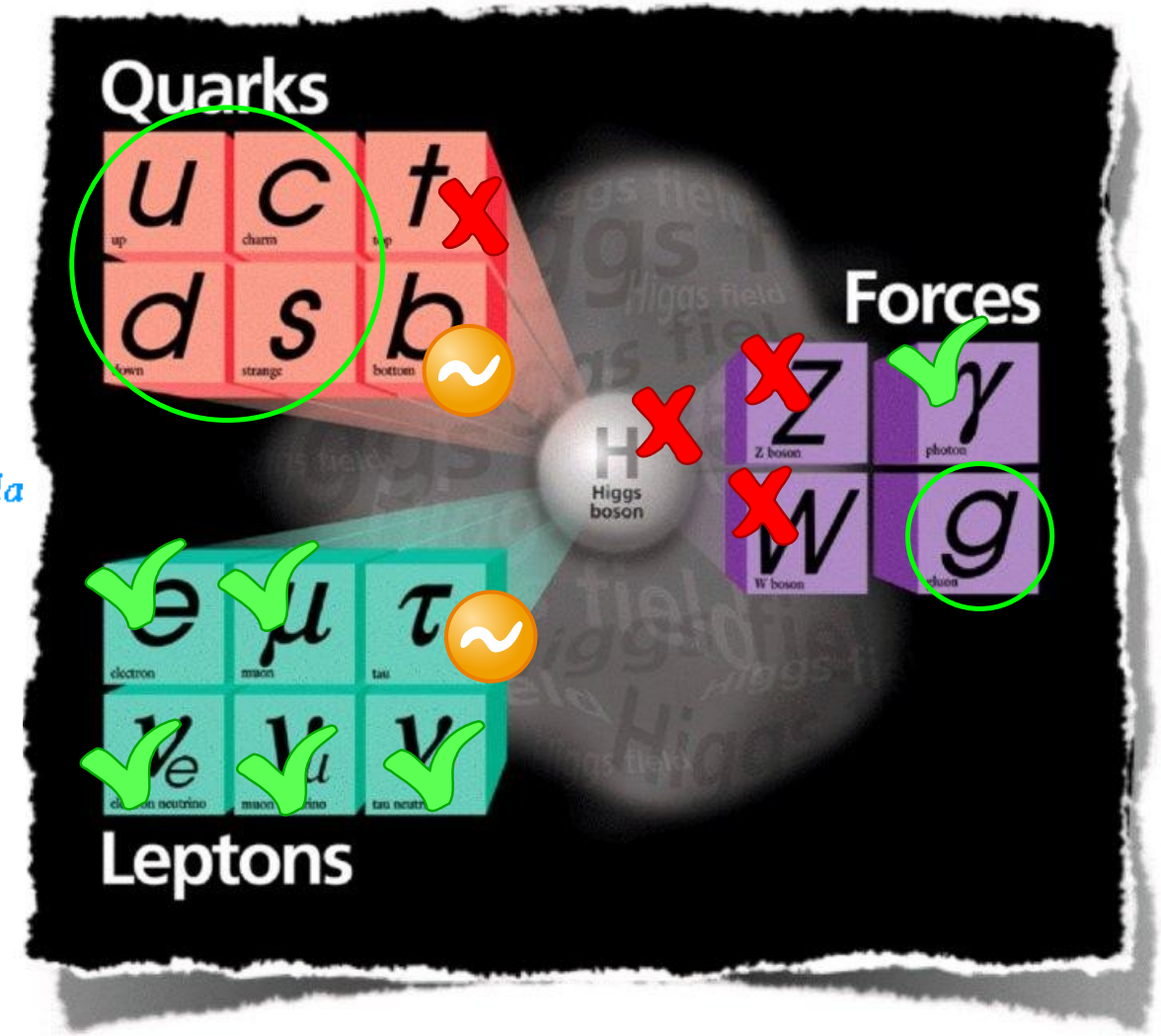




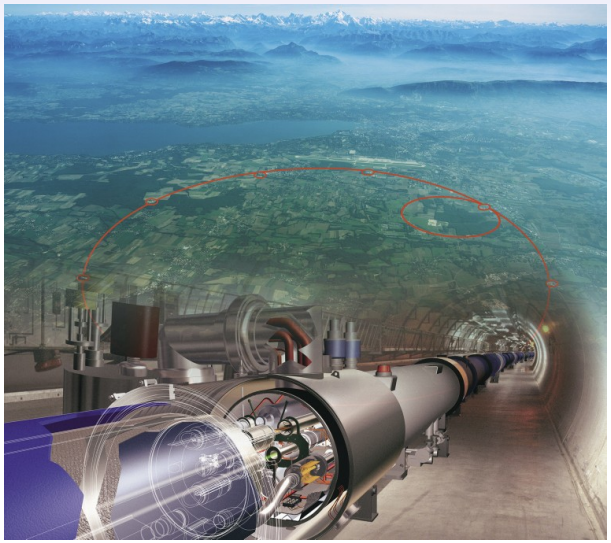


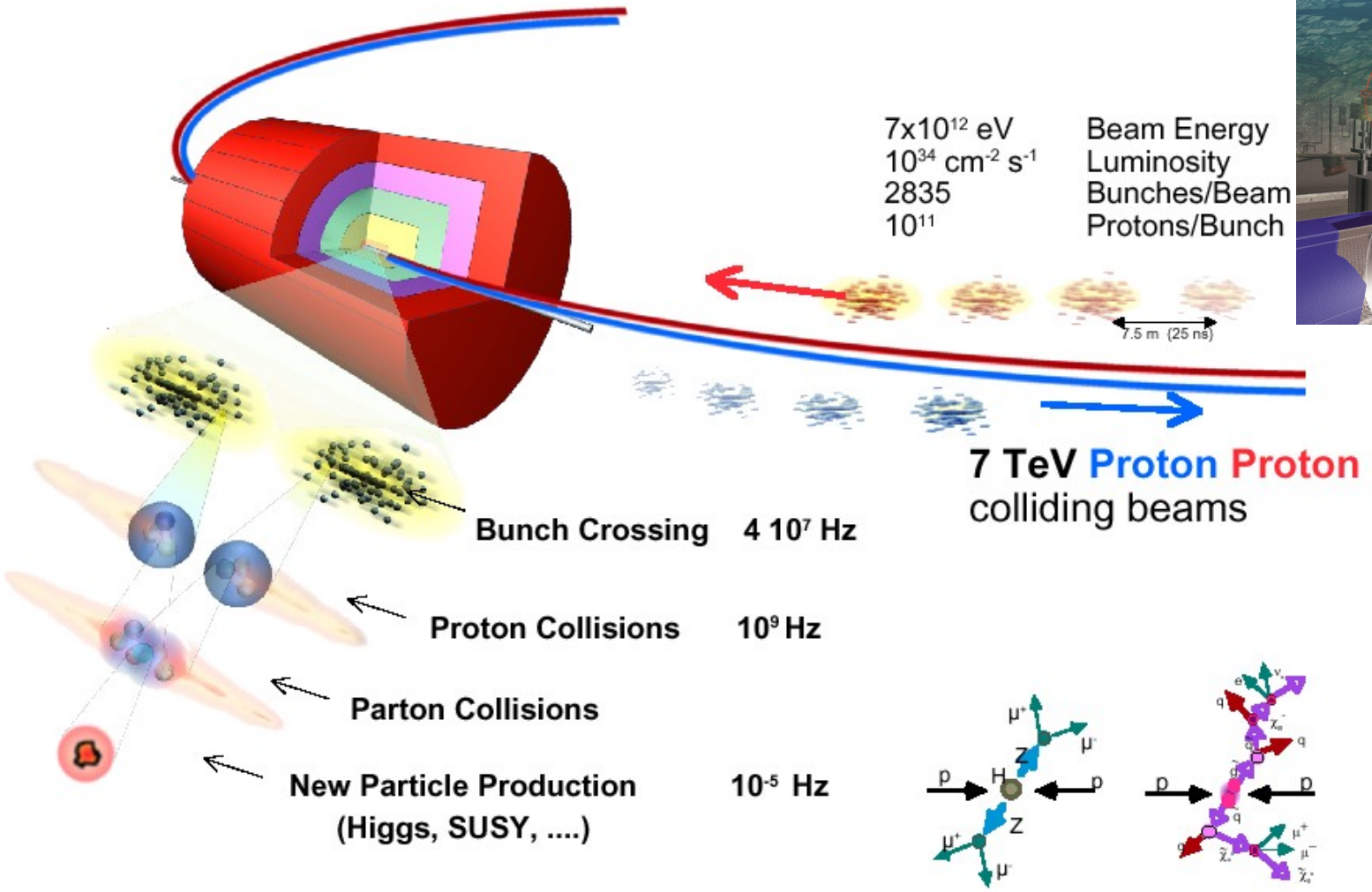
Reminder: stable and unstable particles





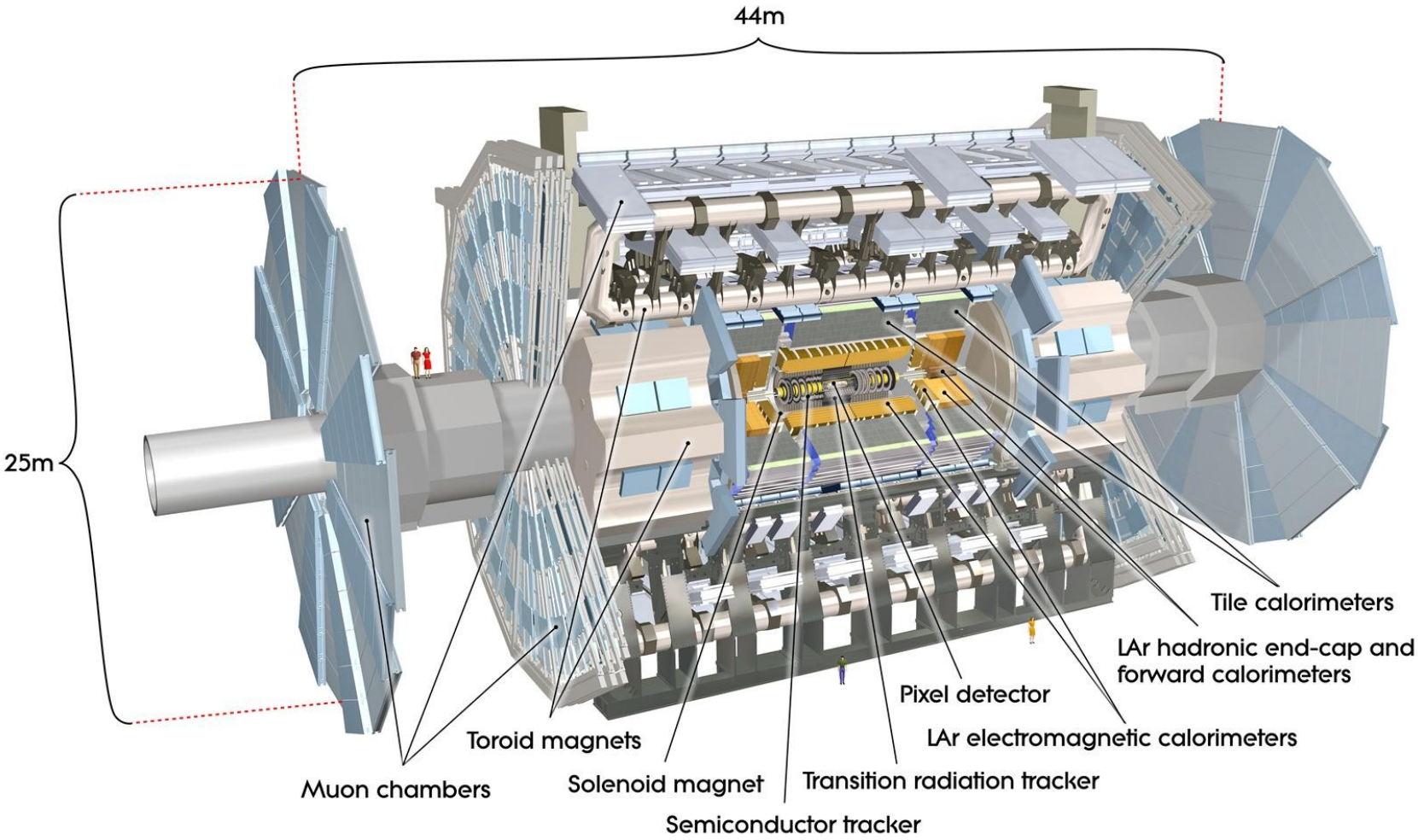
Reminder: pp collisions @ LHC

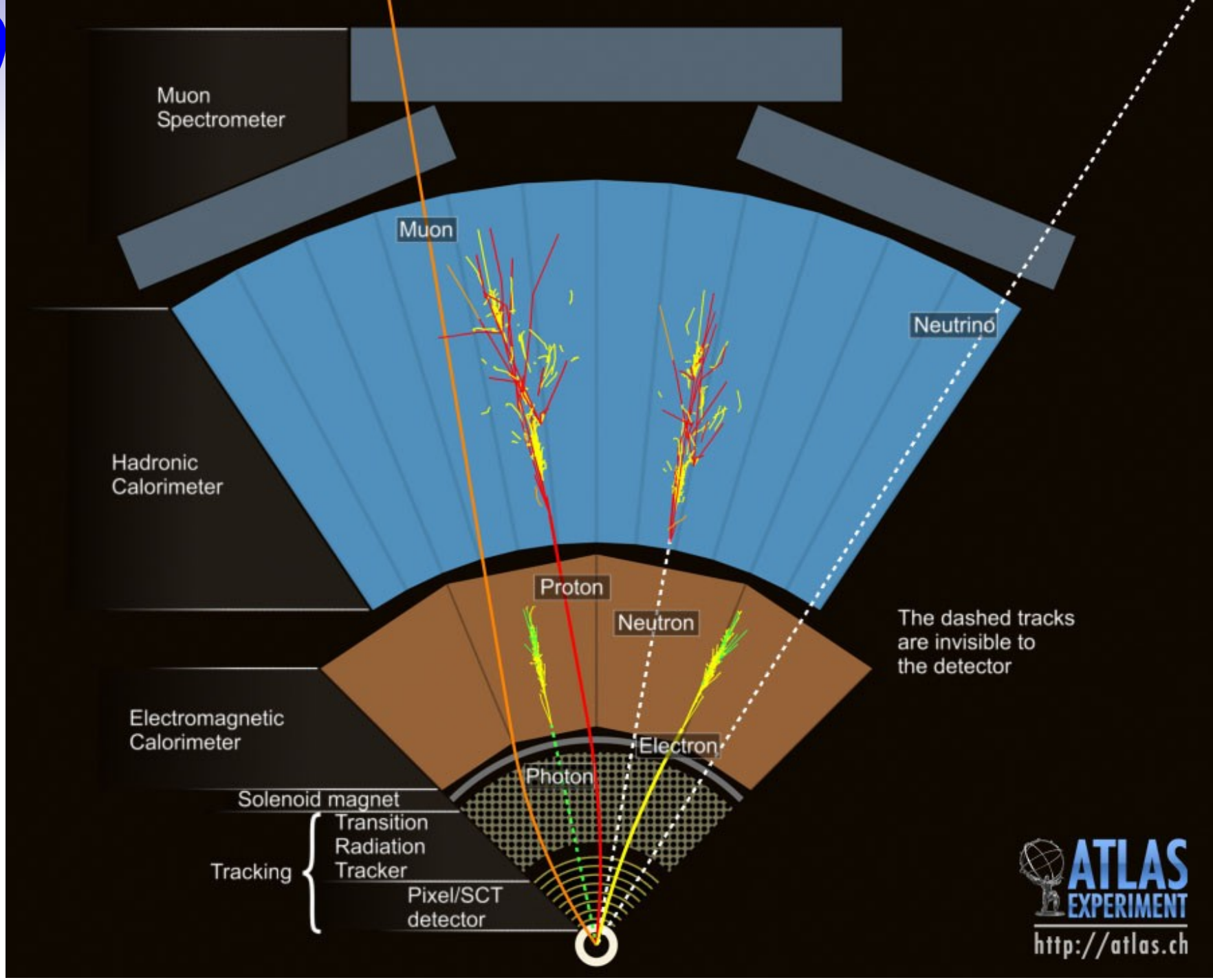




Selection of 1 event in 10,000,000,000,000

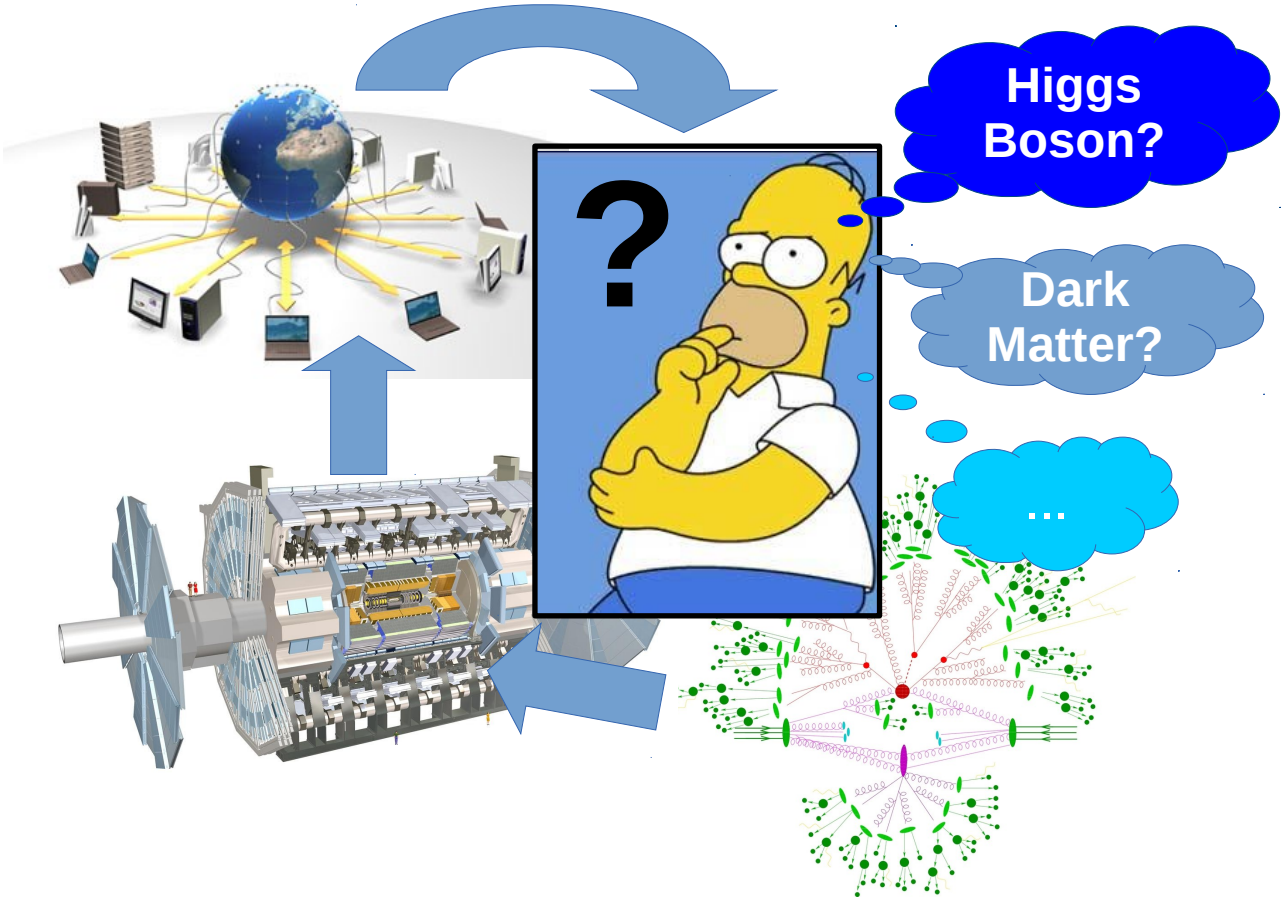
Reminder: ATLAS detector




Muon
Spectrometer
Muon
Neutrino
Hadronic
Calorimeter
Proton
Neutron
The dashed tracks
are invisible to
the detector
Electromagnetic
Calorimeter
Electron
Photon
Solenoid magnet
Tracking
Transition
Radiation
Tracker
Pixel/SCT
detector
ATLAS
EXPERIMENT
http://atlas.ch

The LHC-data-analyser job:

- What does it mean “analyse ATLAS data”?



The LHC-data-analyser job: The steps

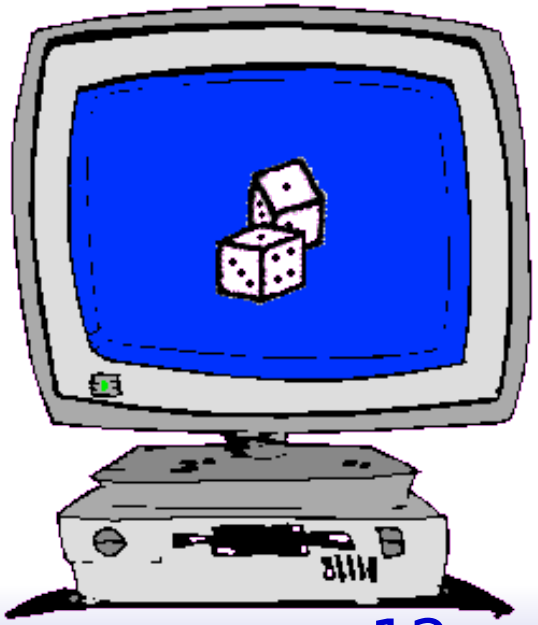
- Define what we want to measure
- Choose a “final state”
- Define an “event selection” (and an “object selection”)
- Look at the “observable”: number of events, invariant mass, asymmetry...
- Extract the measurement & it's uncertainty

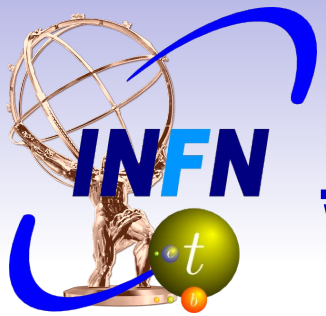
The LHC-data-analyser job: Data and Simulation

- "In parallel", the analyser should:
  - Get and read the Data from the detector
  - Compare with Simulated Data

- Detector system
- Trigger
- Data-acquisition
- Data distribution
- Reconstruction
- Calibration

- Monte Carlo generator development
- Simulated event production





Monte Carlo Simulation: Why Simulated Data?

- Monte Carlo simulation used to predict what we expect to see under certain conditions:
  - To perform studies before having the data
  - To compute event selection efficiency / acceptance
  - To predict the amount of background events
  - To distinguish different signals
  - ...

Monte Carlo Simulation: Different steps

“Matrix Element”

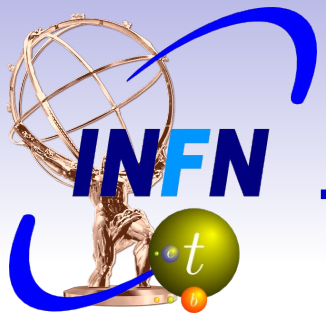
- Generation of the central process
- At “parton level”
- Usually no decays
- No hadrons
- No time-evolution

“Parton Shower & Hadronisation”

- Evolution of the final (and initial!) states
- Simulation non-perturbative QCD: gluon emission and gluon splitting
- From partons to parton-jets and hadrons
- Unstable particle decays

“Detector Simulation”

- Simulation of the particle-detector material interaction
- Full simulation very computationally expensive
- Often “fast simulation“ used



Monte Carlo Simulation: MadGraph

- Matrix Element MC generator
- Multi-leg LO processes (i.e. 2→N processes)
- Allows the user to ask for any process, at any order in QCD and EW
- Recently QCD-NLO functionality added with aMCatNLO
- Allows for any new model implementation: useful for new physics studies

- Online process generation: http://madgraph.hep.uiuc.edu/
- Download site for latest version: https://launchpad.net/mg5amcnlo
- MadGraph5 intro: http://indico.cern.ch/event/239005/material/slides/0.pdf
- Reference: arXiv:1405.0301 [hep-ph]

Monte Carlo Simulation: MadGraph

Code can be generated either by:

I. Fill the form:

Model: SM — Model descriptions

Input Process: — Examples/format

Example: p p > w+ j j QED=3, w+ > l+ vl

p and j definitions: p=j=d u s c d~ u~ s~ c~ g

sum over leptons: l+ = e+, mu+; l- = e-, mu-; vl = ve, vm, vt; vl~ = ve~, vm~, vt~

Submit

II. Upload the proc_card.dat

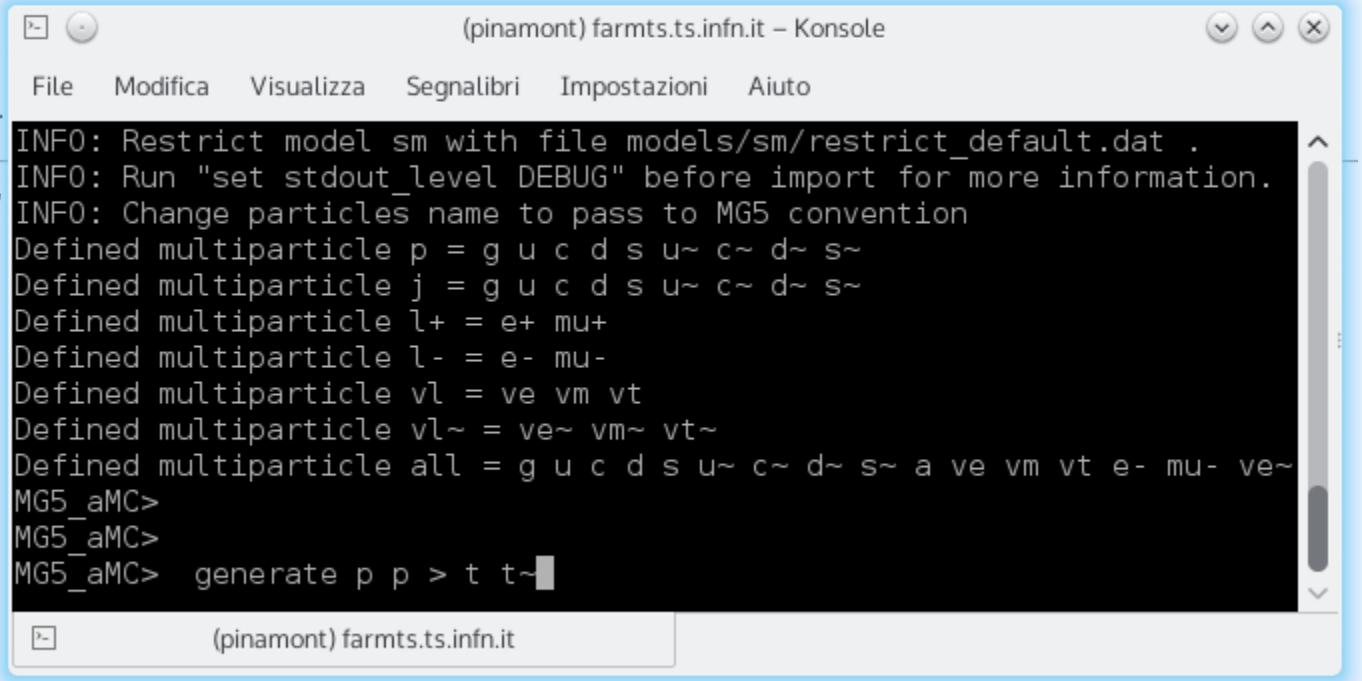
Process card examples

proc_card format MadGraph 5

Scegli file Nessun file selezionato and send it to the server.

III. Upload the full banner (all cards are uploaded as the "current"

Scegli file Nessun file selezionato and send it to the server.



Monte Carlo Simulation: MadGraph

- Model (particles, couplings, Lagrangian...)
- Process
- Collider properties

MadGraph5

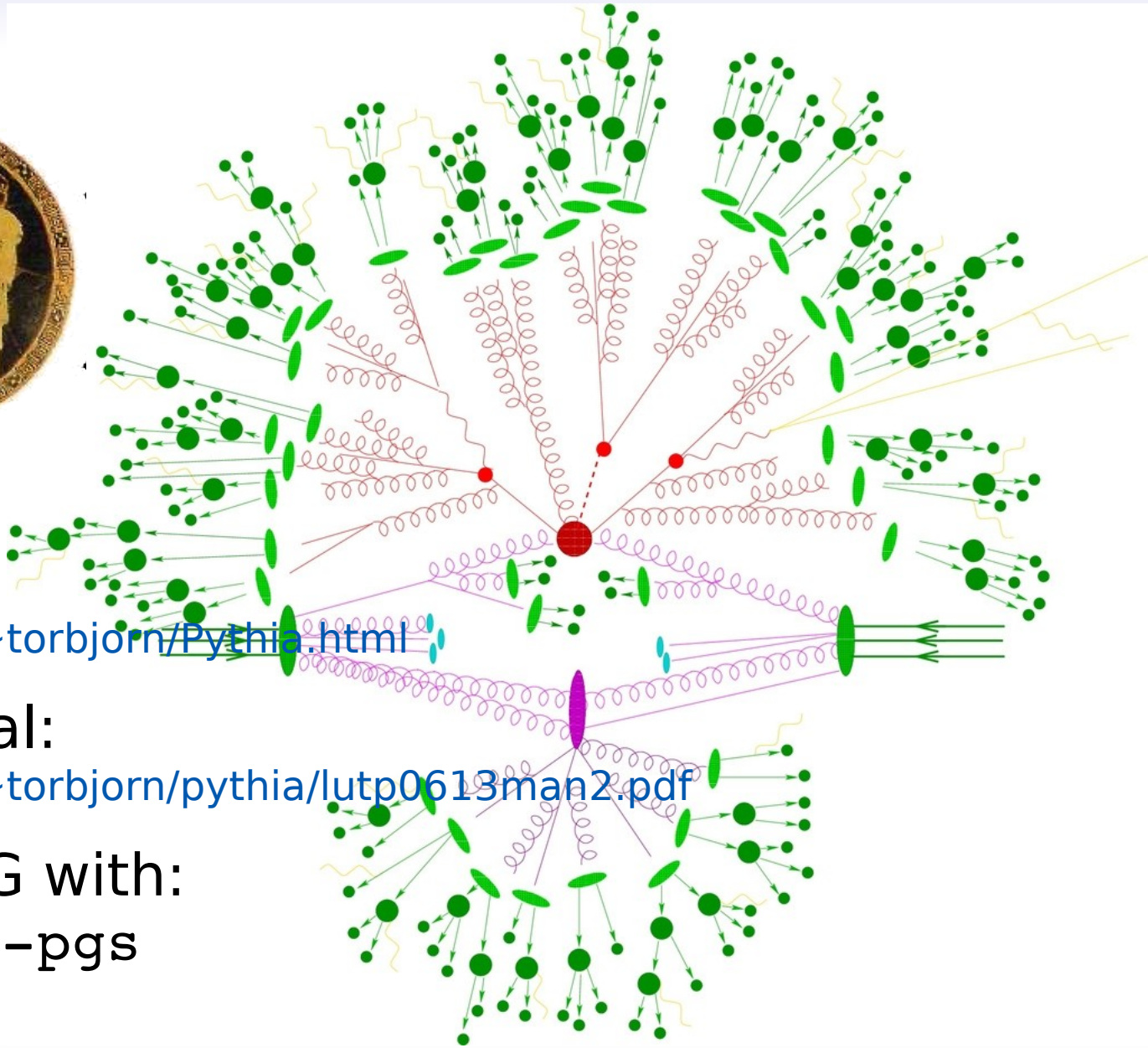
(+MadEvent, +MadSpin..)

- Feynman diagrams
- Cross-section
- Parton-level events

Automatically interfaced with:

- Pythia (parton-shower & hadronisation)
- Delphes (fast detector simulation and event reconstruction)

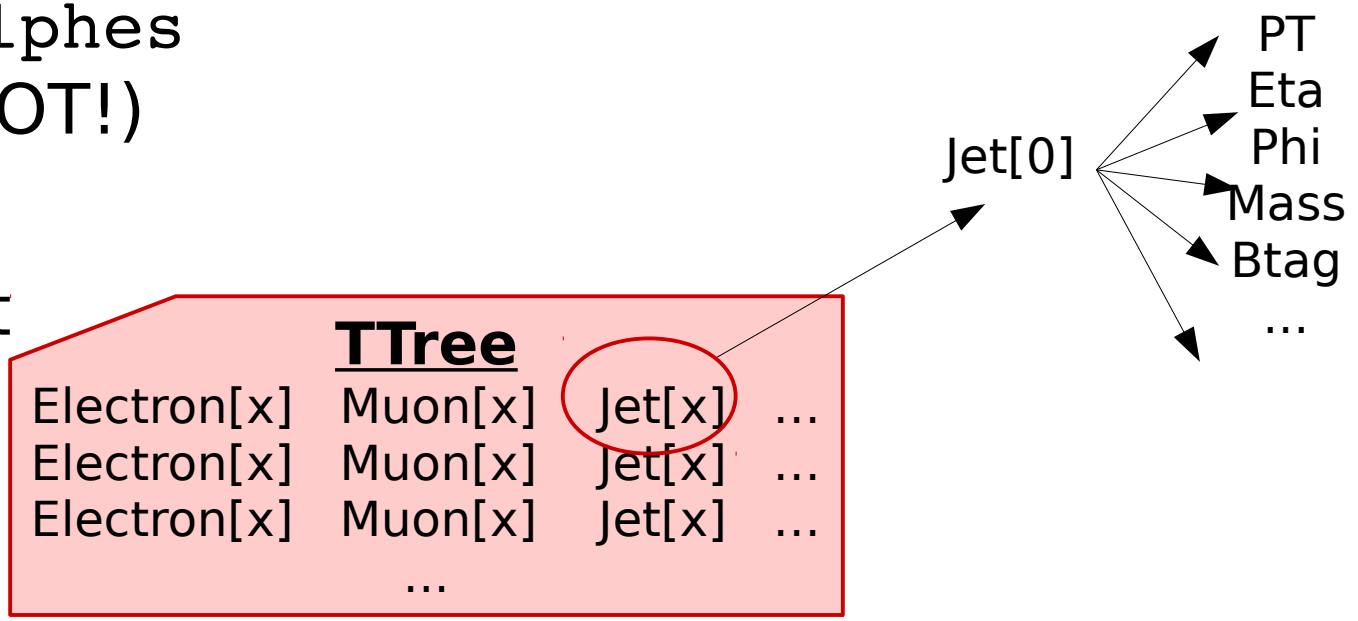
Monte Carlo Simulation: Pythia



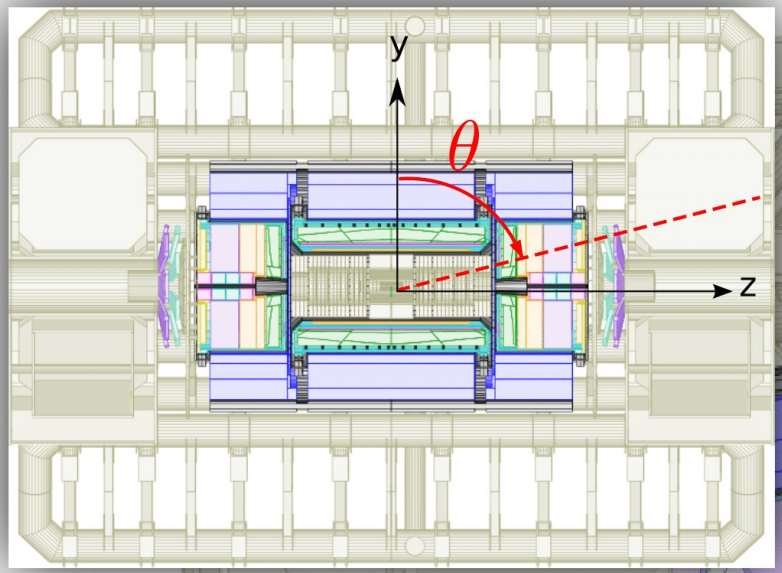
- Homepage:
  http://home.thep.lu.se/~torbjorn/Pythia.html
- Pythia 6.4 manual:
  http://home.thep.lu.se/~torbjorn/pythia/lutp0613man2.pdf
- Installed from MG with:
  `install pythia-pgs`

Monte Carlo Simulation: Delphes

- Homepage: https://cp3.irmp.ucl.ac.be/projects/delphes
- Installed in MG5 with just:
  `install Delphes`
  (requires ROOT!)
- Produce nice ROOT format outputs



Reminder: Coordinates and Quantities



- Transverse momentum: $pT = \sqrt{px^2+py^2}$
- Pseudorapidity: $\eta = -\ln(\tan(\theta/2))$
- Energies and momenta in GeV

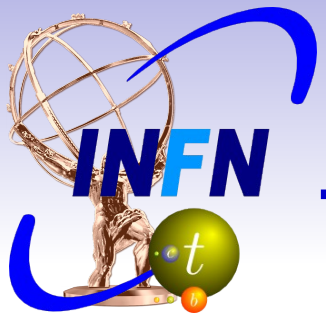
Monte Carlo Simulation
MG5 options and cards

- When running MG5, different cards (text files containing options) can be modified
- The most important ones:
  - run_card.dat
  - param_card.dat
  - madspin_card.dat
  - delphes_card.dat

```
#*********************************************************************
# Number of events and rnd seed                                      *
# Warning: Do not generate more than 1M events in a single run       *
# If you want to run Pythia, avoid more than 50k events in a run.    *
#*********************************************************************
  10000 = nevents ! Number of unweighted events requested
      0       = iseed   ! rnd seed (0=assigned automatically=default))
#*********************************************************************
# Collider type and energy                                           *
# lpp: 0=No PDF, 1=proton, -1=antiproton, 2=photon from proton,      *
#                                         3=photon from electron     *
#*********************************************************************
        1     = lpp1    ! beam 1 type
        1     = lpp2    ! beam 2 type
     6500     = ebeam1  ! beam 1 total energy in GeV
     6500     = ebeam2  ! beam 2 total energy in GeV
```

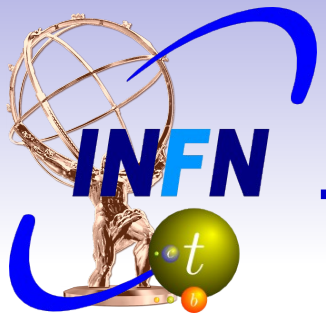
```
Block MASS      #  Mass spectrum (kinematic masses)
#       PDG        Mass
          5     4.70000000E+00   # bottom   pole mass
          6     1.74300000E+02   # top      pole mass
         15     1.77700000E+00   # tau      mass
         23     9.11880000E+01   # Z        mass
         24     8.04190000E+01   # W        mass
         25     1.20000000E+02   # H        mass
#             PDG       Width
DECAY         6     1.50833649E+00   # top width
DECAY        23     2.44140351E+00   # Z   width
DECAY        24     2.04759951E+00   # W   width
DECAY        25     5.75308848E-03   # H   width
```

```
# specify the decay for the final state particles
decay t > w+ b, w+ > l+ vl
decay t~ > w- b~, w- > l- vl~
decay w+ > l+ vl
decay w- > l- vl~
decay z > l+ l-
```



End of Lecture 1

- Open a browser
- Go to:
  https://twiki.cern.ch/twiki/bin/view/Main/UnitsHiggsTutorial
- Start to work!



Lecture 2

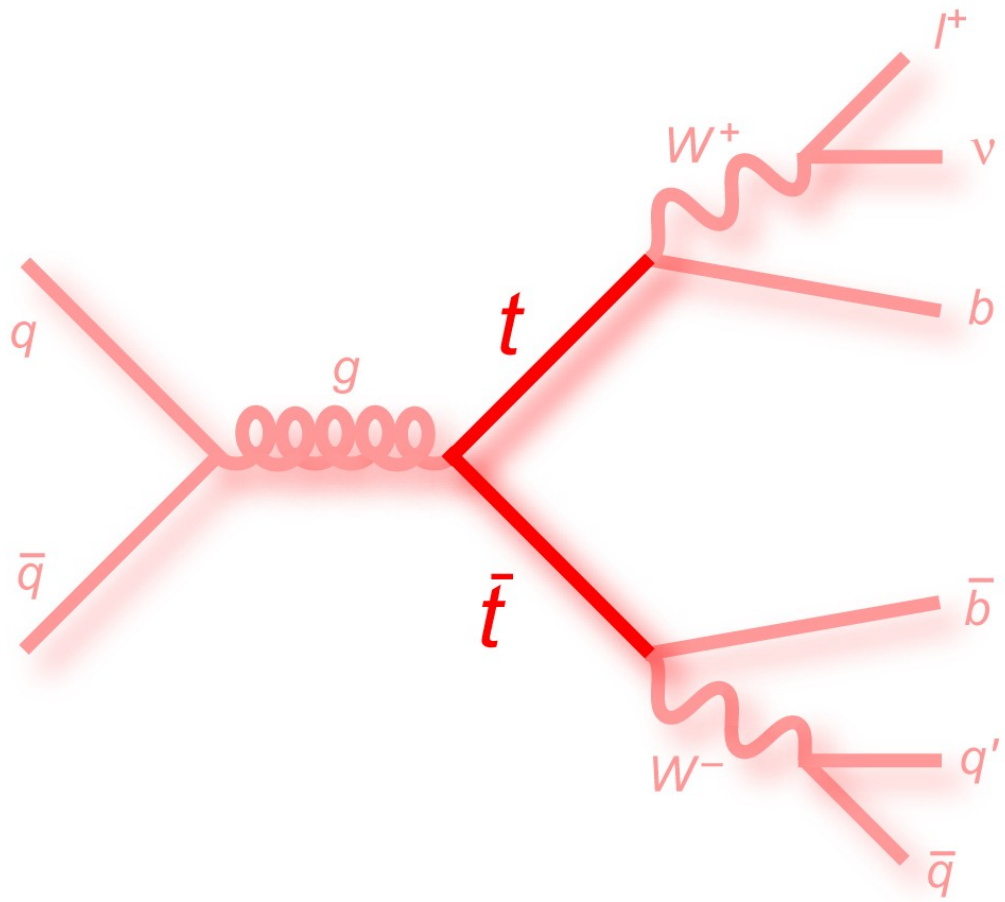
- tt cross-section measurement
  - Signal and background
  - How to measure a cross-section
  - Event selection
  - Statistical uncertainty

tt cross-section measurement
Top pair production

Top Pair Decay Channels

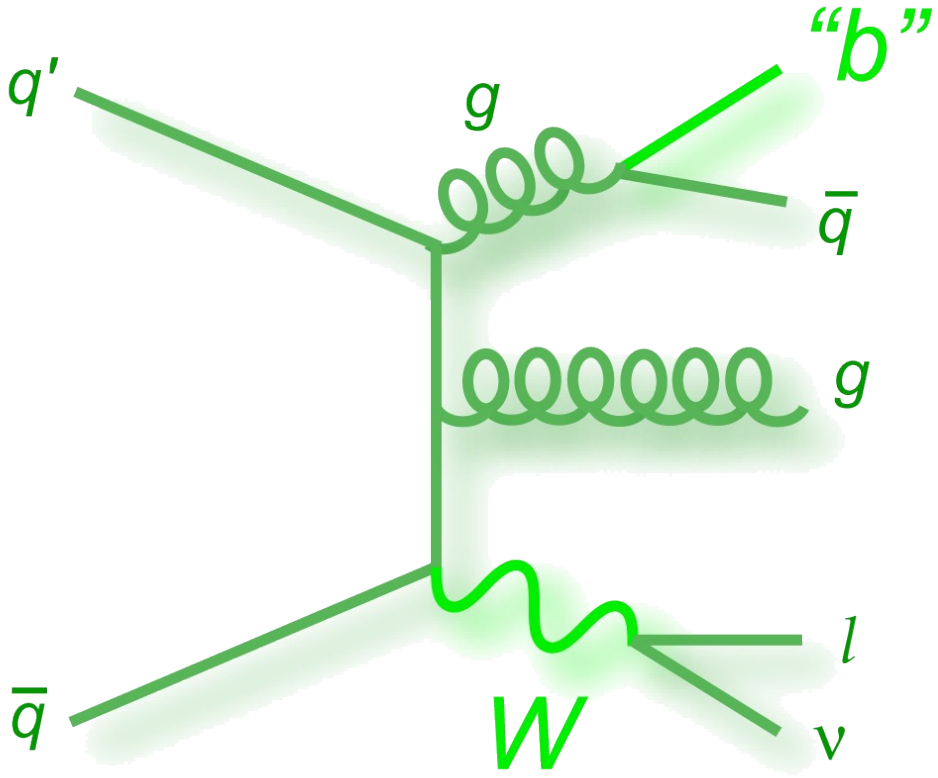
W decay	e^+	μ^+	τ^+	$u\bar{d}$	$c\bar{s}$
e^-	ee	eμ	eτ	electron+jets	
μ^-	eμ	μμ	μτ	muon+jets	
τ^-	eτ	μτ	ττ	tau+jets	
$\bar{u}d$	electron+jets	muon+jets	tau+jets	all-hadronic	
$\bar{c}s$					

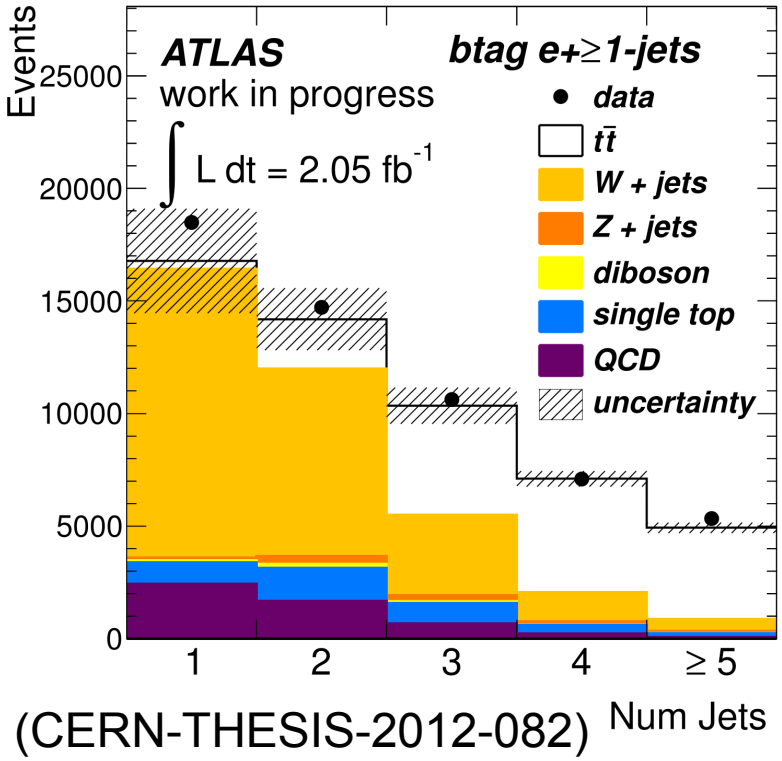
dileptons



tt cross-section measurement
Signal and Background

- Main background from W+jets production
  - X-sec >> than ttbar, but selection cuts can suppress it





tt cross-section measurement
The golden formula

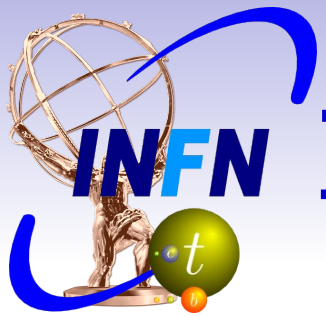
Number of expected events entering the selection (from MC simulation)

Number of selected events in Data

$$\text{X-section} = \frac{N - B}{\text{Lumi} * \text{eff}}$$

Integrated Luminosity

Signal selection efficiency: N(selected)/N(tot), from MC simulation



tt cross-section measurement
Event Selection

- Typical event selection for ttbar → l+jets:
  - Exactly 1 e / μ with pT>25 GeV, |eta|<2.5
  - 4 or more jets with pT>25 GeV, |eta|<2.5
  - Some Missing Transverse energy (>25 GeV?)
  - Eventually one or more jets tagged as coming from a b (“b-tagged”)

tt cross-section measurement
Statistical uncertainty

- Events counts are described by Poisson statistics
  - $\delta N = \sqrt{N}$
- From previous formula
  - $\delta X/X = \sqrt{N}/(N-B) = \sqrt{(S+B)}/S$
- Need optimal selection to balance between small B and large S!

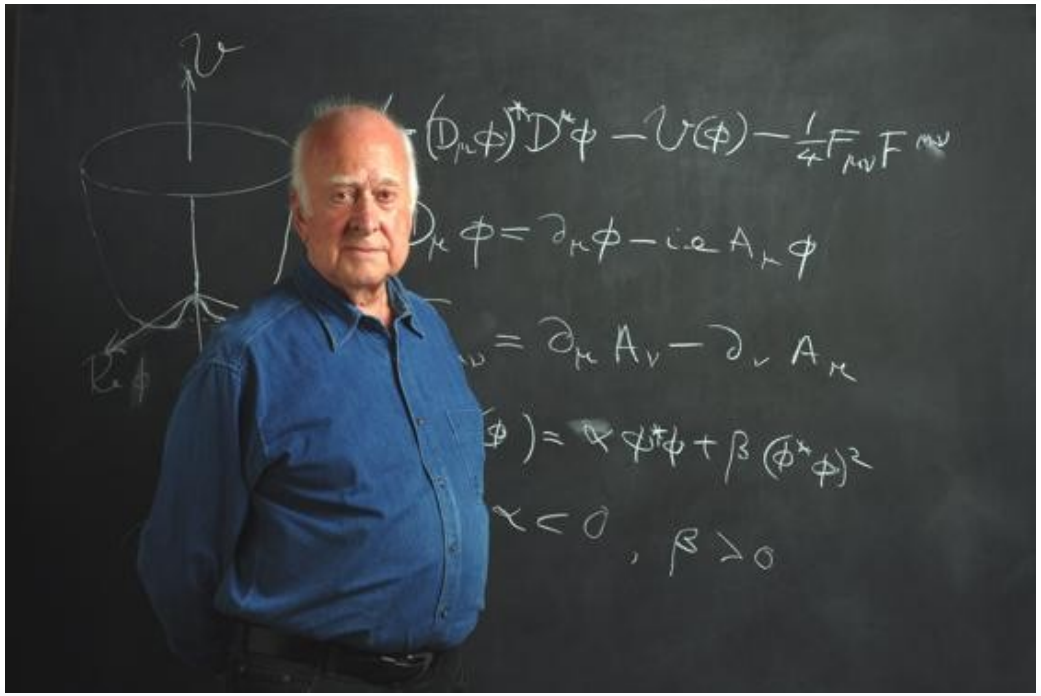
End of Lecture 2

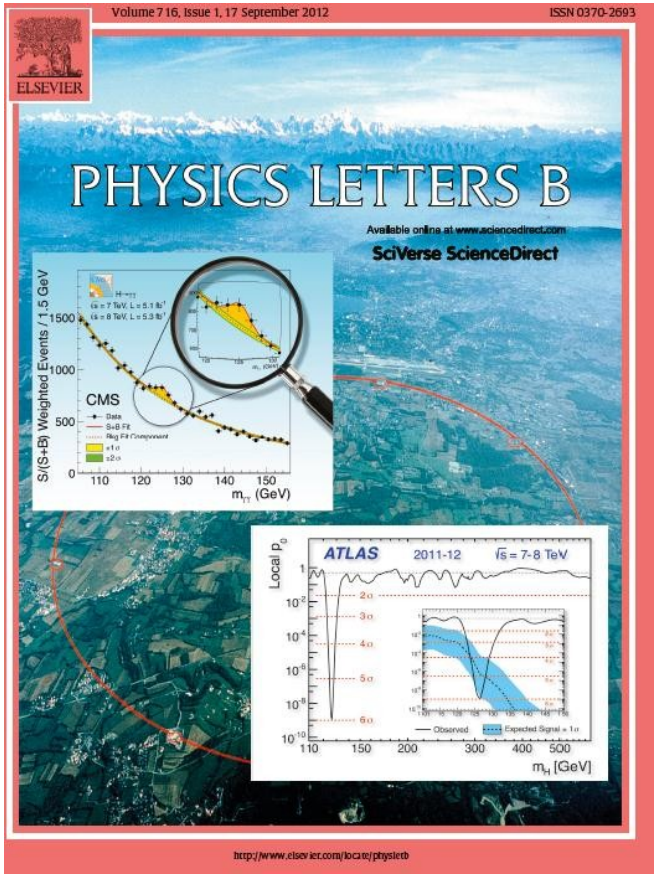
- Go to:
  https://twiki.cern.ch/twiki/bin/view/Main/UnitsHiggsTutorial
- Start the exercise

Lecture 3

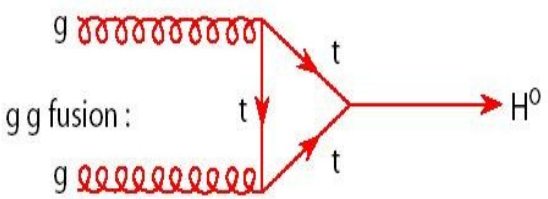
- Higgs reminder: production & decay
- The H → 4 lepton process:
  - Signal and background
  - Higgs mass reconstruction

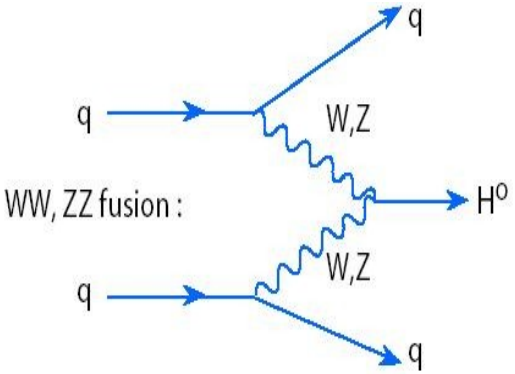
Reminder
The Higgs Boson

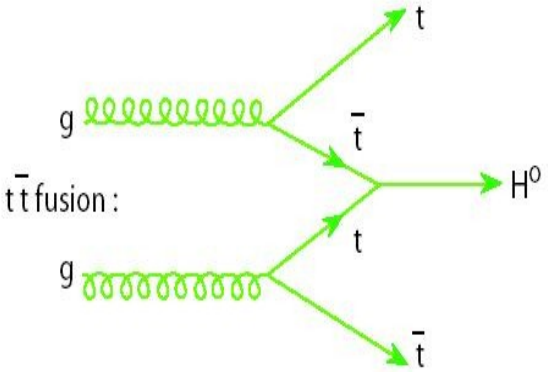


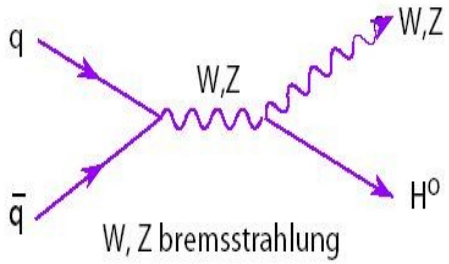


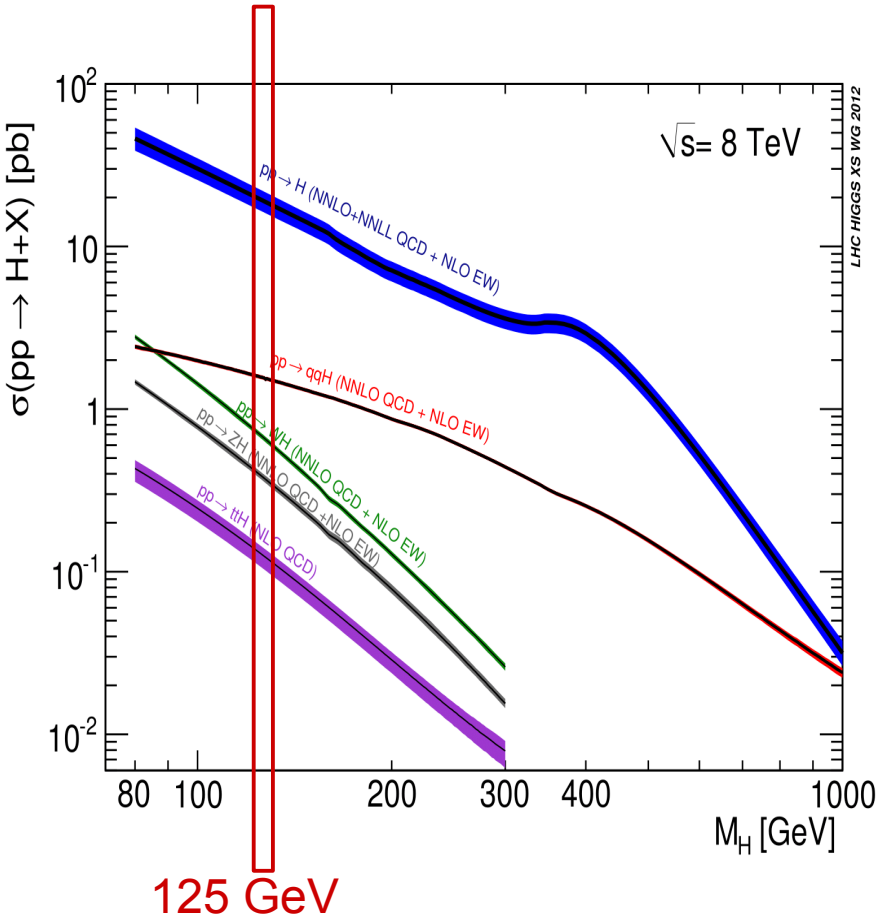
Reminder
Higgs Production



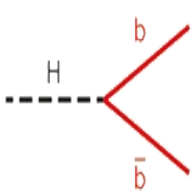








Reminder
Higgs Decay



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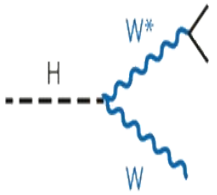

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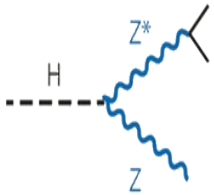
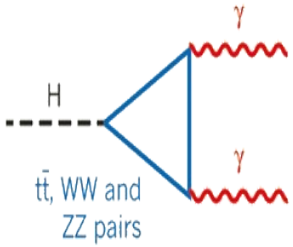


2.6%



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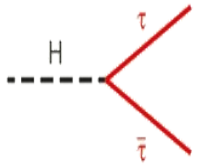
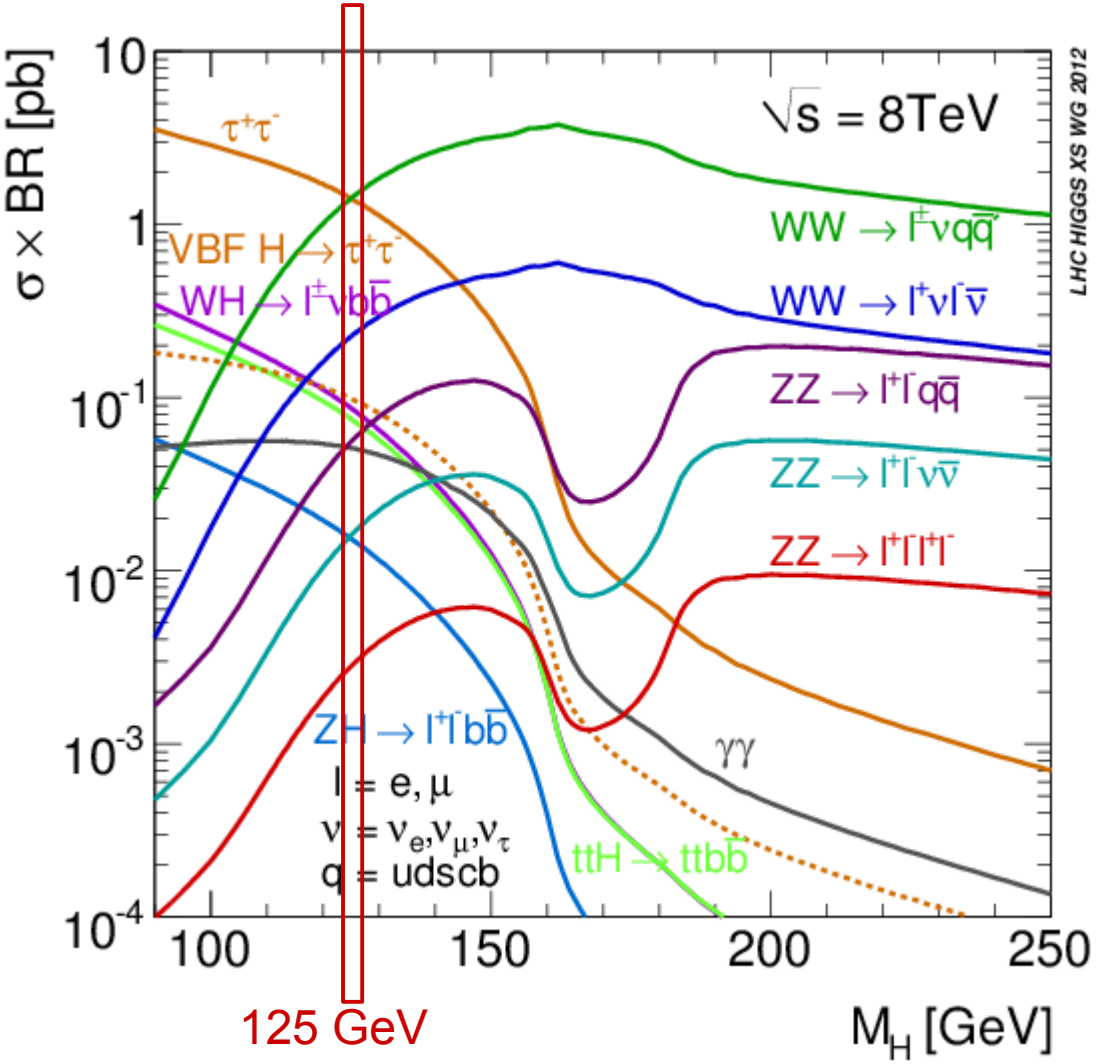
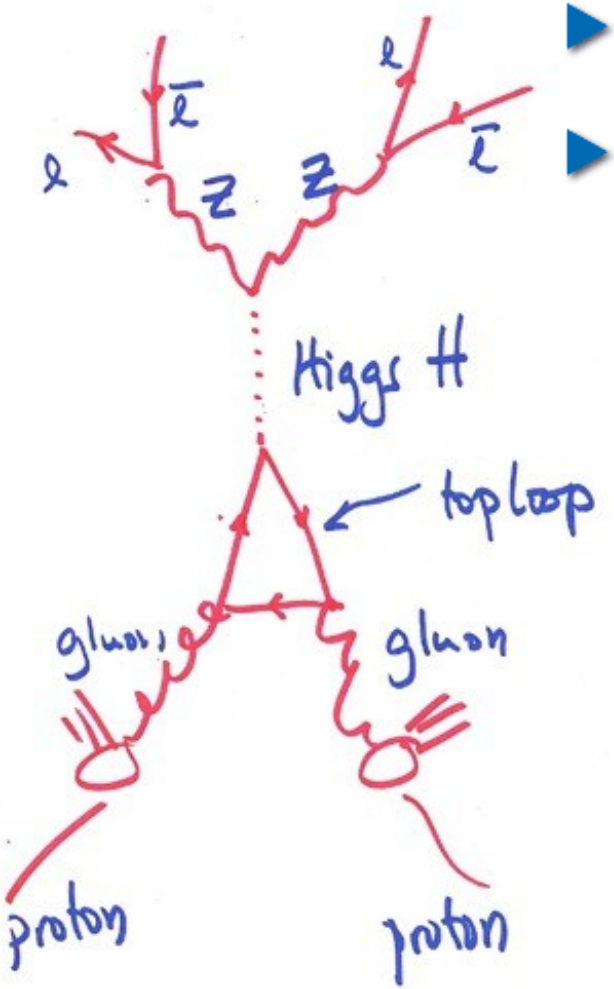


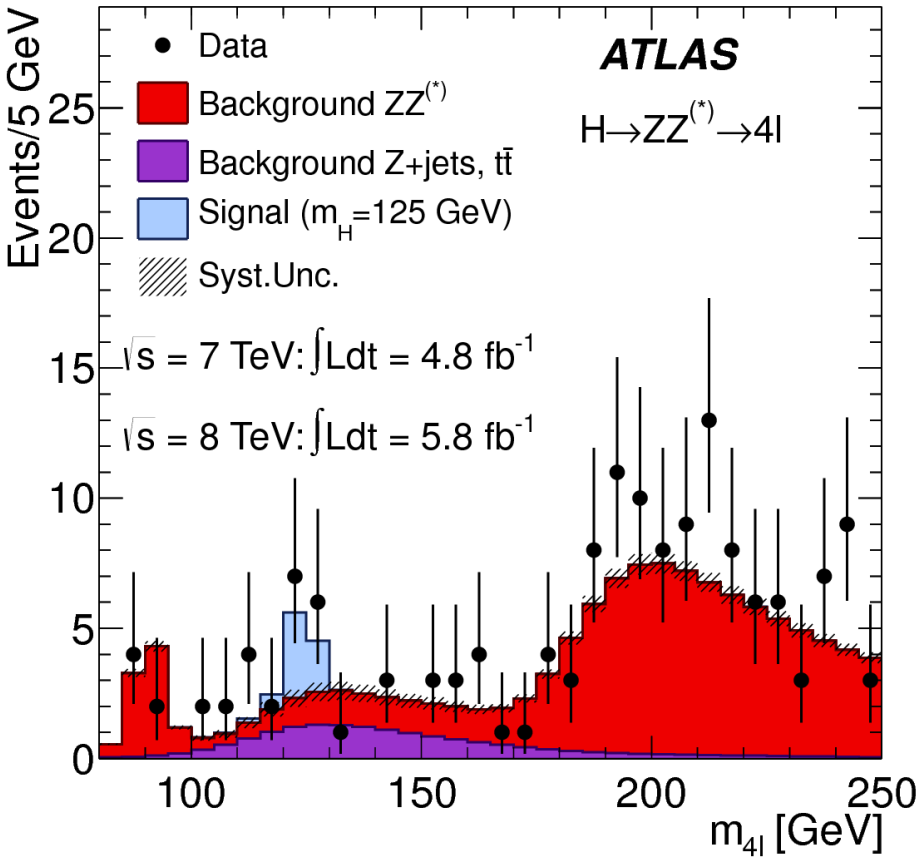
6.3%

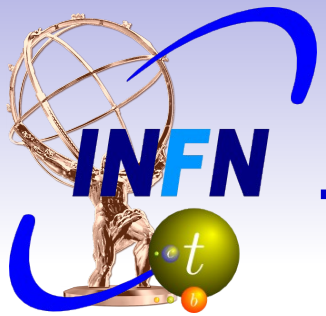


Reminder
The ZZ* → 4 lep channel



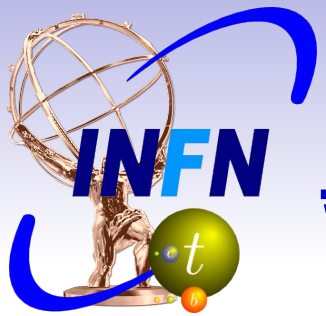
- Lowest BR, excellent signal purity
- One of the two Z is offshell (mH<2*mZ)





Exercise
Reconstruct the Higgs mass

- We will have a “data” sample
- Generate pp → H → ZZ* → 4 lep events
- Generate pp → ZZ → 4 lep background
- (neglect other background)
- Apply a simple event selection
- Reconstruct and plot the Higgs mass as the invariant mass of the 4 leptons
- Compare “data” with Signal + Background



Exercise
What can we measure?

- Higgs mass measurement by comparing different signal templates
- Higgs cross-section x BR(H→ZZ)
- Exclusion Limits
- Discovery Significance

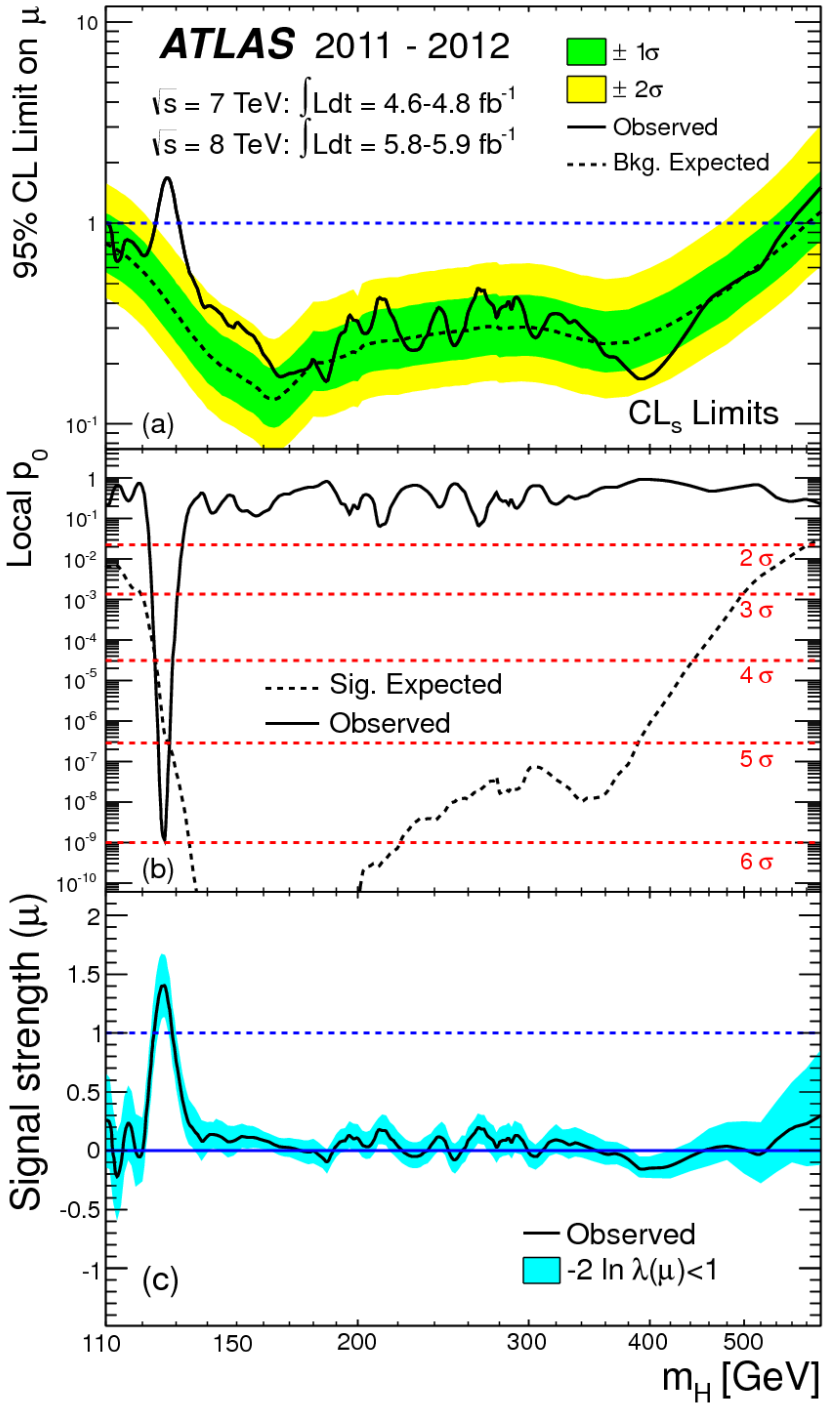
Bonus

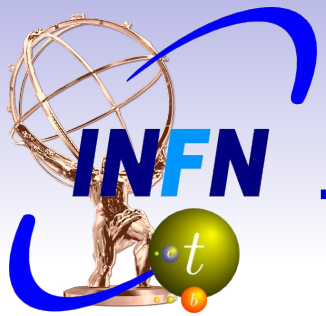
Exclusion limits

Discovery significance

Cross section

(μ = measured xs / SM predicted)





End of Lecture 3

- Go to:
  https://twiki.cern.ch/twiki/bin/view/Main/UnitsHiggsTutorial
- Start the exercise