Dynamics of EW & Strong Interactions

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HEP data analysis (continued)

The Higgs field

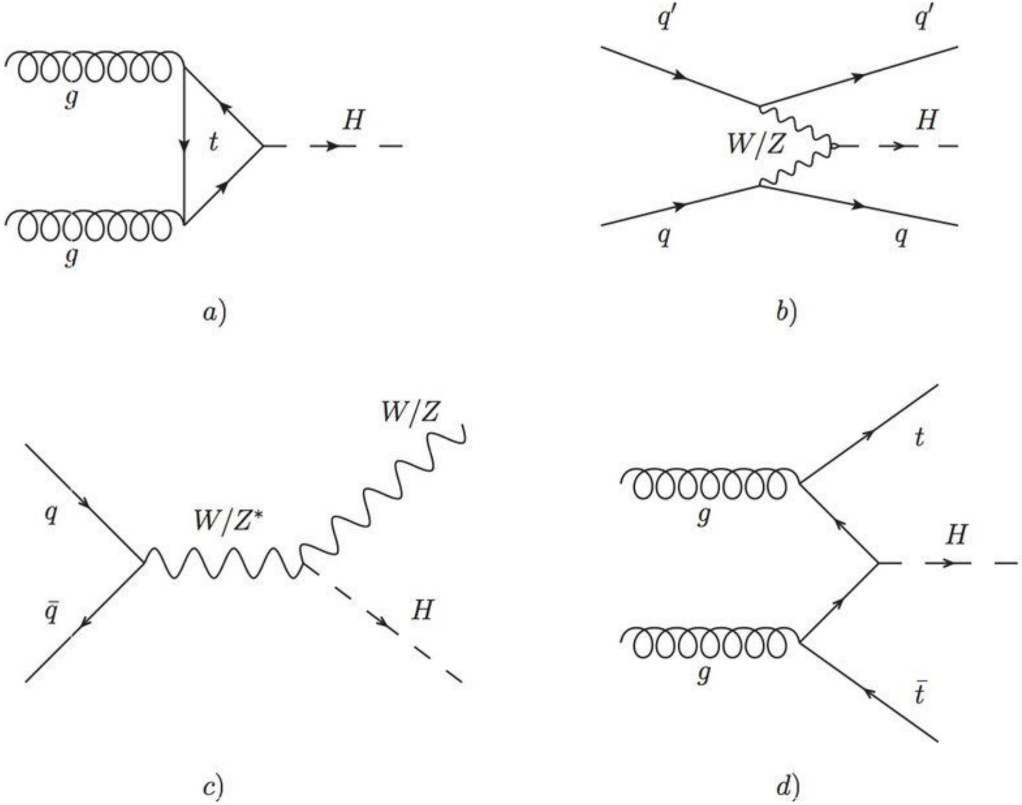
- Reminder of Higgs mechanism:
  - Higgs field added to SM lagrangian:
  - Higgs potential shape ⇒ ground state ≠ 0:
  - covariant derivative acting on ϕ
    → mass terms for EW gauge bosons
    → Higgs-boson coupling with gauge bosons proportional to their mass squared
  - Yukawa coupling added between ϕ and fermions
    → mass terms for fermions
    → Higgs-boson coupling with fermions proportional to their mass

Searching and measuring the Higgs boson

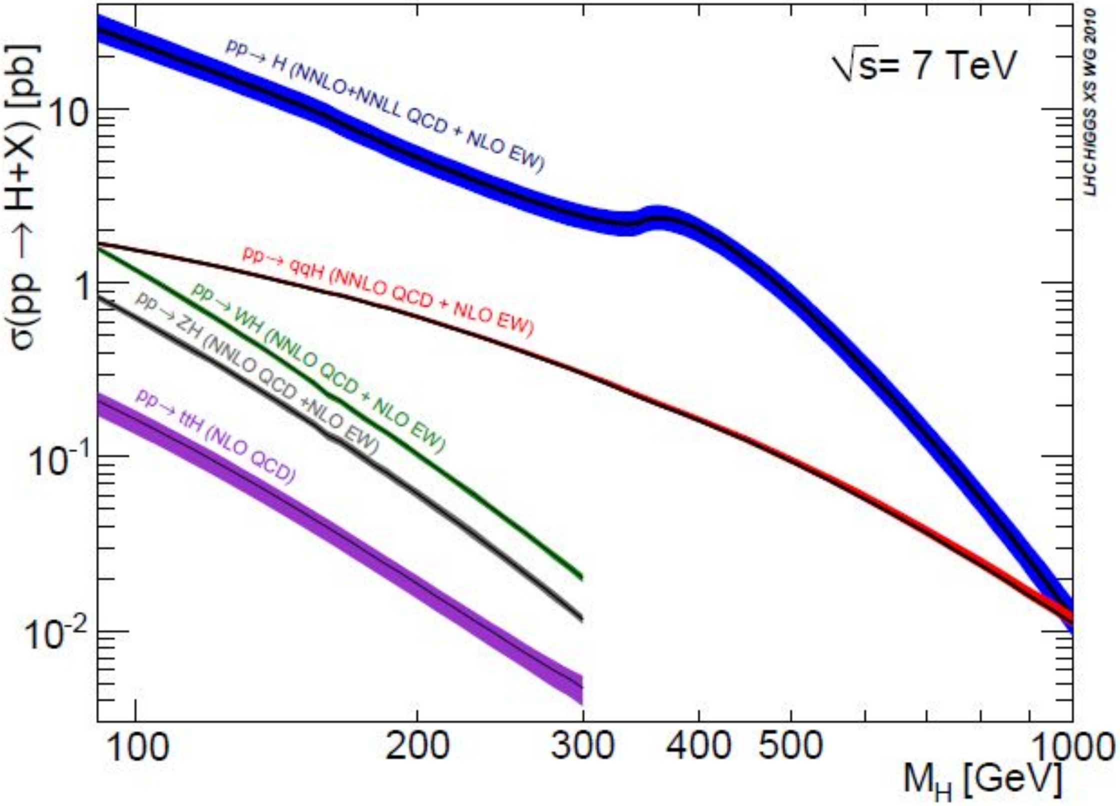
- Higgs boson couplings and mass only depend on 1 extra free parameter w.r.t. Higgs-less SM
    - ⇒ for a given Higgs mass, all production and decay properties of Higgs boson fixed (for a minimal Higgs sector, i.e. single-doublet model)

- Two main consequences:
    - before its observation, very clear where to look at (also thanks to EW precision fits)
    - once Higgs observed and measured, overconstrained system ⇒ deviations from precise predictions = evidence for new physics

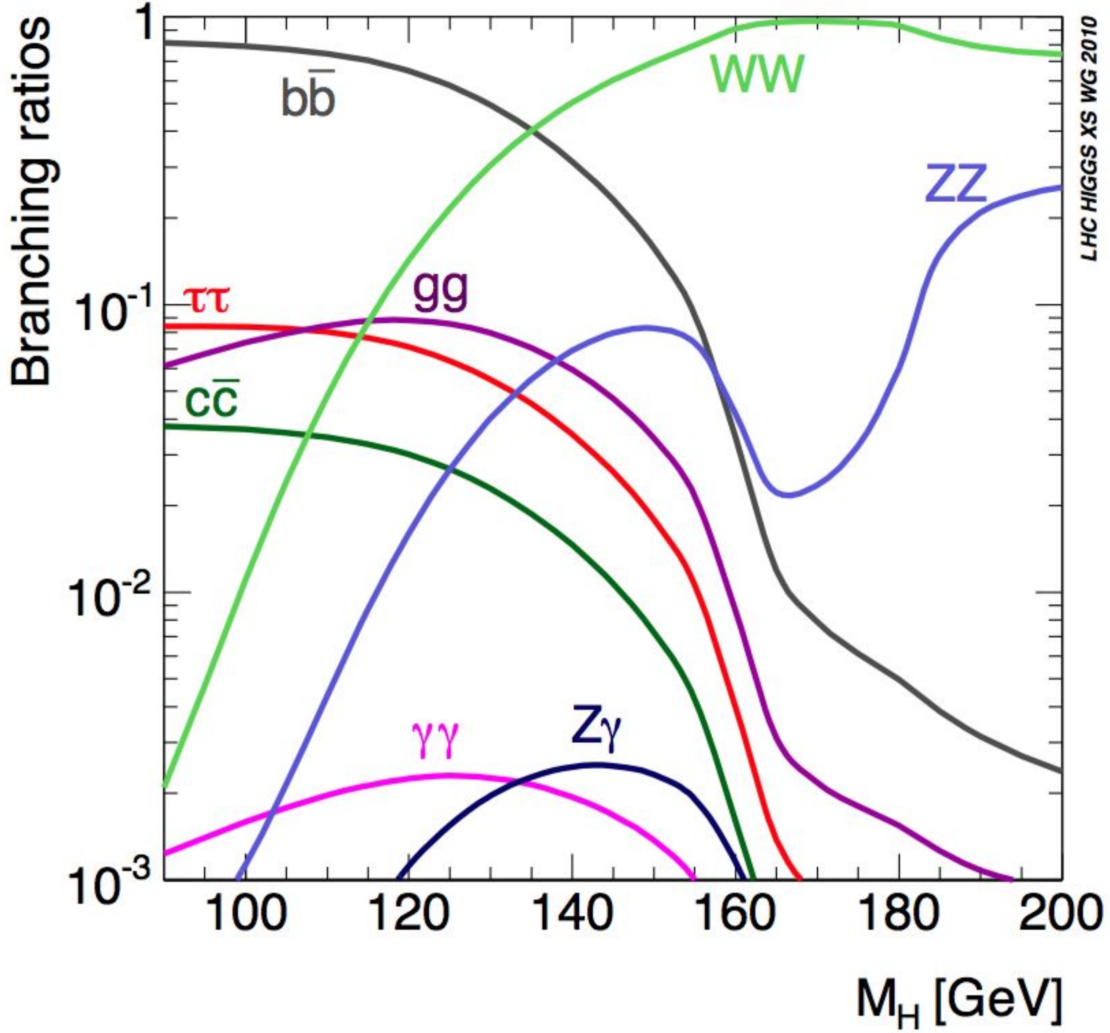
Producing Higgs bosons



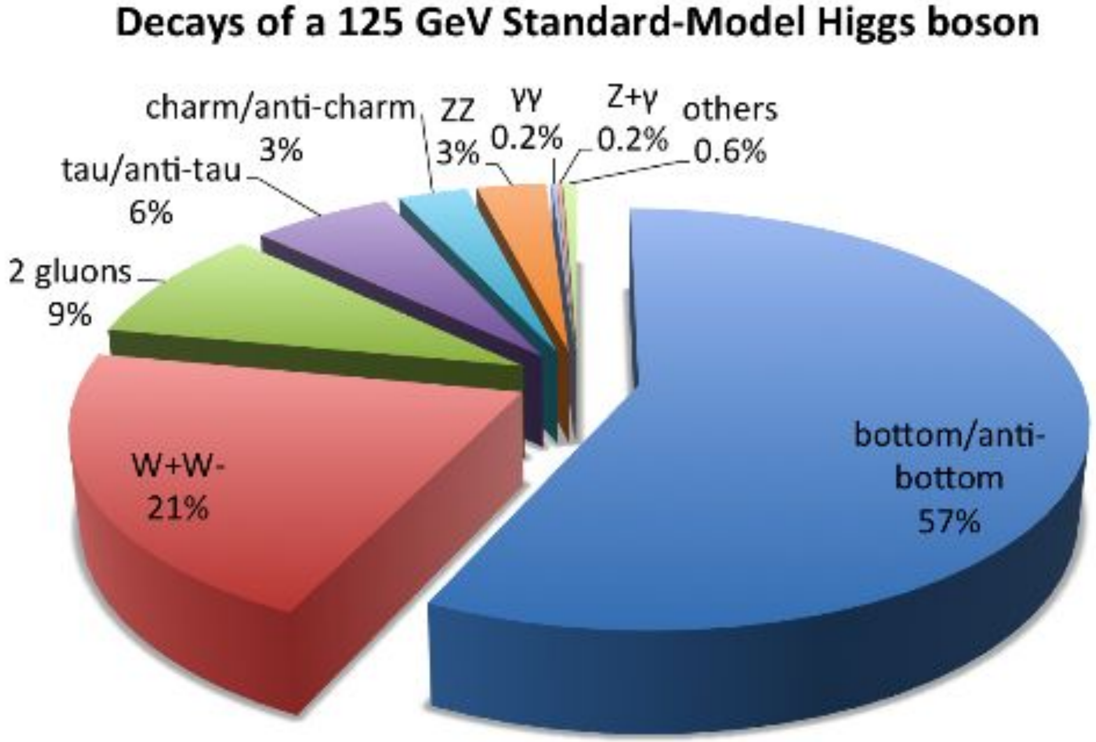
Producing Higgs bosons



Higgs decays

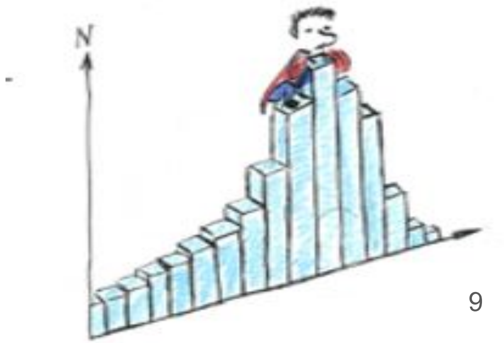


Higgs decays

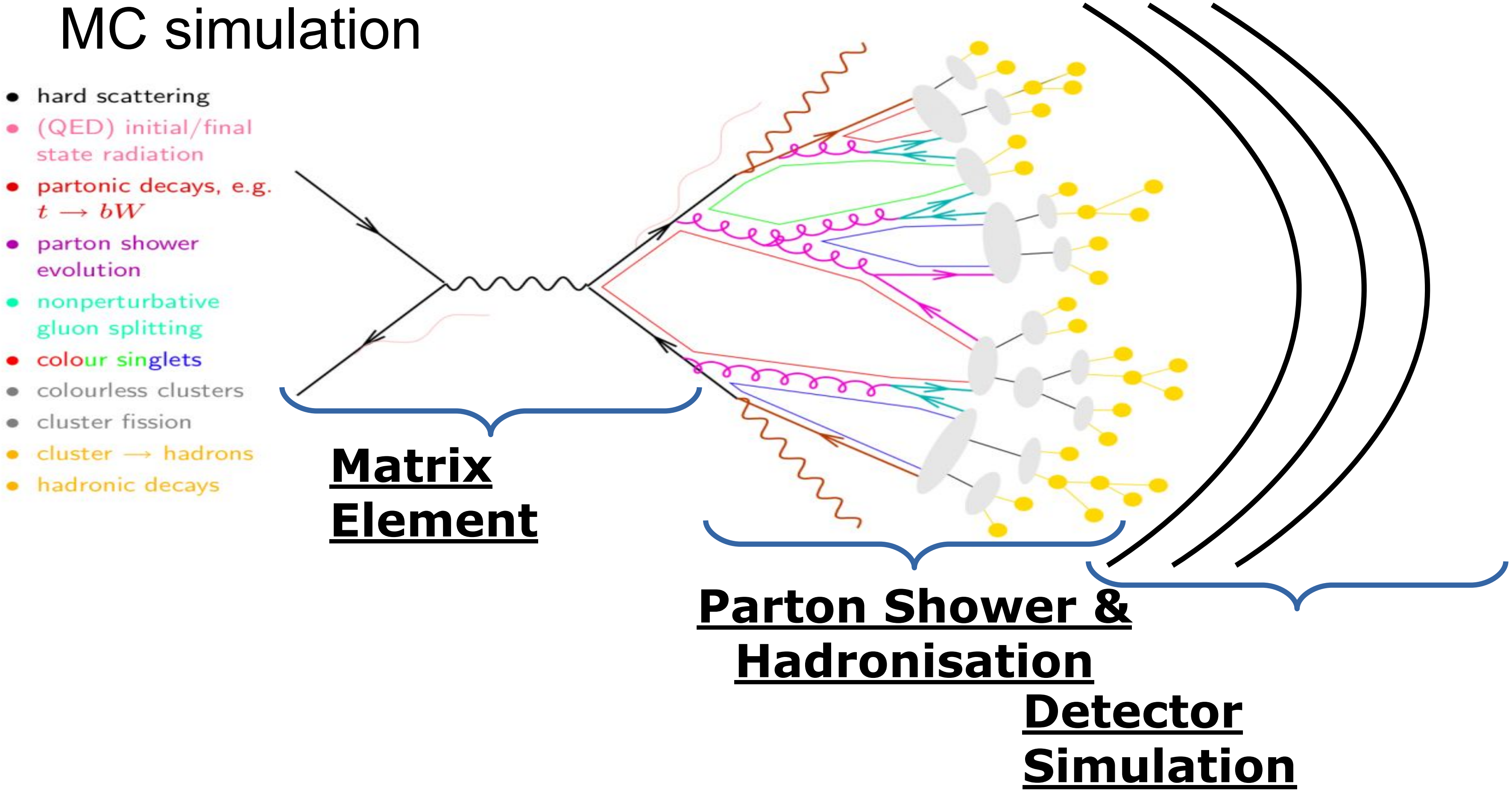


Analysis steps

1. Define **what** we want to measure
2. Choose a “**final state**” or “channel”
3. Identification of **background** processes
4. Define an “**event selection**” (and an “object selection”)
5. Look at the “**observable**”:
   number of events, invariant mass, asymmetry...
   - usually build histogram(s)
6. **Extract** the measurement & it's uncertainty
   - from the comparison of data histograms with a model (built from theory, assumptions, simulation...)
   - statistical interpretation

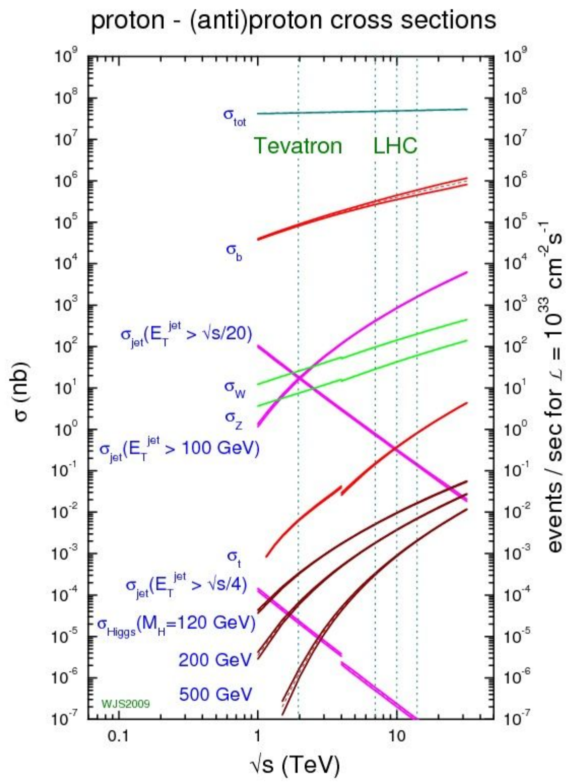


MC simulation



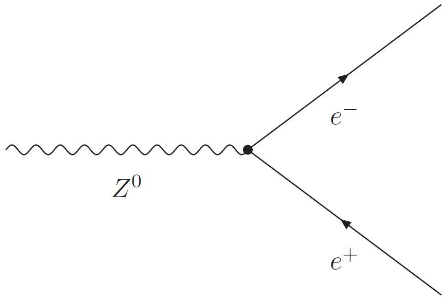
Why choosing a certain decay channel?

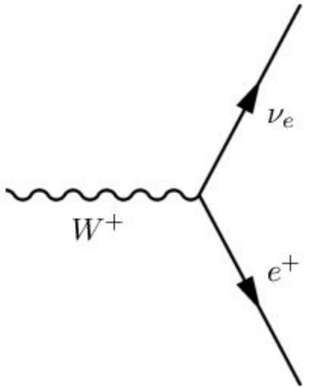
- Two aspects to consider:
  - how easy to distinguish target process from background processes?
    - all-hadronic final states hard to see just because of huge hadronic background
    - presence of high-energy lepton(s) / photon(s) preferred
  - how easy to measure particles in final state?
    - electrons, muons and photons measured with much better accuracy than jets, taus or *neutrinos*



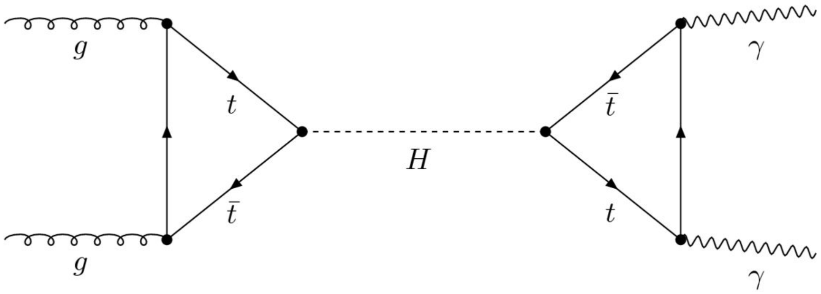
Choosing decay channels

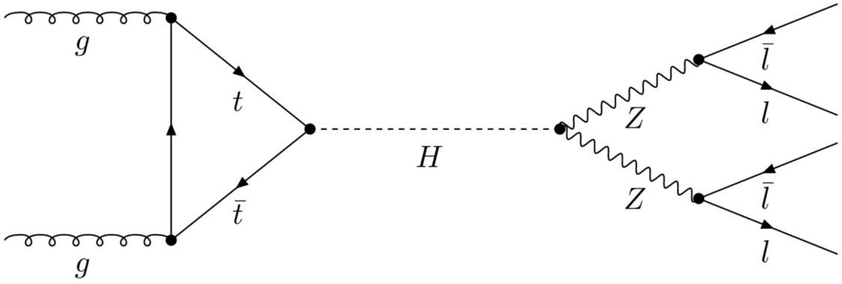
- W and Z:
  - leptonic decay channels preferred at hadron colliders (ℓ = e or μ):

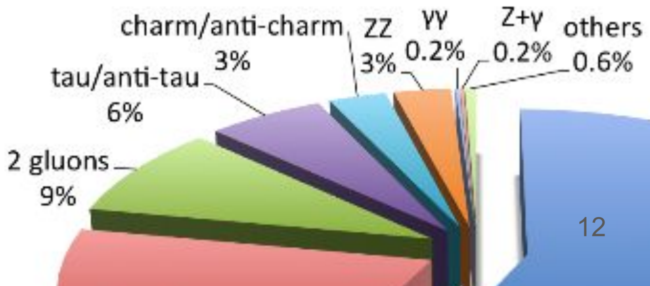




- Higgs boson - best channels to look at:
  - H → ZZ* → 4ℓ
  - H → γγ







Which backgrounds and how do they contribute?

- Once final state / channel chosen, need to evaluate backgrounds
  - background = any process that can produce similar final state, i.e. mimic signal (if cross-section large enough)

- How to evaluate background?
  - theory predictions
  - Monte Carlo simulation
  - "data-driven" methods, based on known difference between signal and background process events (from first principles, simulation...)

- What to do with background predictions?
  - will need to "subtract" prediction from observed data:

$$\text{Signal}^{\text{measured}} = \text{Data}^{\text{observed}} - \text{Background}^{\text{estimated}}$$

Why event selection?

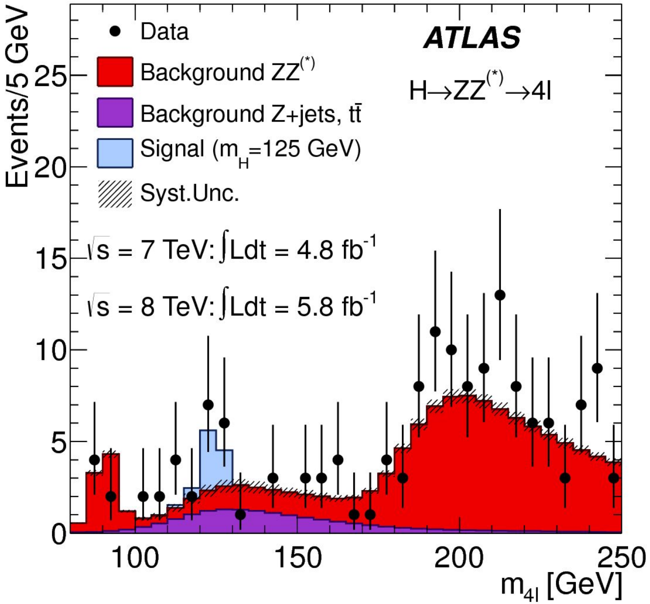
- Compute **statistical uncertainty** of measurement:
  - suppose measuring $N^{signal} = S$ (produced at LHC, in a certain dataset, in a certain channel - e.g. resonance decay mode)
  - can extract S by counting $N^{data} = D = S + B$ ($B = N^{background}$)
  - statistical uncertainty $\sigma_S = \sigma_D = \sqrt{D} = \sqrt{(S + B)}$
  - relative stat. uncertainty $\sigma_S/S = \sqrt{(S + B)}/S$
  - minimize rel. stat. unc. means maximizing $S/\sqrt{(S + B)}$:
    - if B is large ⇒ bad stat. precision, even with large D
    - if $B \to 0$ ⇒ maximal stat. precision, with given D

- Applying selection to minimize B while keeping large expected S:
  - e.g. maximizing $S/\sqrt{(S + B)}$

- With event selection (**efficiency** $\varepsilon < 1$) need to modify equation to extract S:
  - $S_0 = 1/\varepsilon \cdot (D - B)$

Observables and histograms

- In general, measurements most of the times extracted from histograms:
  - essentially counted number of events in each bin of one (or more than one) observable
  - observable means measured quantity: p_T of a reconstructed particle or jet, invariant mass, angular separation, ...
  - observed data in each bin compared with predicted background and predicted signal



- Why needs predicted signal?
  - remind:

$$S_0 = 1/\varepsilon \cdot (D - B)$$

Measuring cross-sections

- Production cross section of certain process can be measured as:

$$\sigma(S) = \frac{D - B}{\varepsilon \int L}$$

selection efficiency (can include branching ratio, acceptance...)

integrated luminosity: i.e. "amount of data" expressed in inverse-barn (e.g. pb^{-1}, fb^{-1}...)

- Can measure differential cross sections
  - in bins of certain observable(s)

Uncertainties in cross-section measurements

- Keep in mind the master formula:

$$\sigma(S) = \frac{D - B}{\varepsilon \int L}$$

- Statistical uncertainty:
    - affecting D (as seen before)

- Systematic uncertainties:
    - what? every uncertainty that is not a statistical uncertainty
    - affecting all the other ingredients: B, $\varepsilon = S/S_0$, $\int L$

Systematic uncertainties

- Can distinguish between:
  - experimental systematics:
    - integrated luminosity
    - detector resolution
    - detector calibration
    - identification and reconstruction efficiency for particles and jets
  - theory & modelling systematics:
    - background predicted cross-section(s)
    - branching ratios
    - prediction of shapes of observables used for event selection
      - for both signal and background
      - via MC simulation
      - precision in predicting energy and angular spectra, jet multiplicities etc. → crucial

(reminder from last time)

Uncertainties in MC simulation

- Typical systematic uncertainties affecting a NLO+PS MC prediction:
  - ME:
    - scale variations (see later)
    - PDF uncertainties
  - ME+PS:
    - matching scheme / matching scale
  - PS:
    - choice of algorithm ordering, recoil...
    - scale variations / effective α_S
  - Hadronization:
    - choice of hadronization model
    - uncertainties on hadronization parameters (e.g. in fragmentation functions)
  - All:
    - colour reconnection model
    - theory parameters: masses and couplings (such as α_S)

Other types of measurements

- At HEP experiments not measuring just cross sections:
  - discovery significance
  - exclusion limits
  - ratio of cross-sections / decay branching ratios
  - mass and width of resonances and particles
  - angular production asymmetries
  - polarizations and spin correlations (via angular distributions of decay products)
  - extraction of parameters from cross-section measurements (e.g. α_s, PDFs, fragmentation function parameters...)

Bonus exercise

- Madgraph MC simulation: https://launchpad.net/mg5amcnlo

End of lectures