Standard Model (backgrounds) at the LHC

(part I)

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Introduction

• The study of SM backgrounds at the LHC relies on the general understanding of hard processes at the LHC. This understanding is crucial not just to calculated bgs, but to calculate BSM processes as well, and, more in general, to interpret any kind of LHC measurement, both within and beyond the SM.

• Examples:
  • $m(\text{top}) \Rightarrow m(\text{gluino}), m(\text{stop}), ....$
  • $\sigma(\text{Higgs}) \Rightarrow \text{BR}(H \rightarrow xx), \sigma(\text{gluinos}), ....$
  • kinematical distributions $\Rightarrow$ impact of selection cuts to improve $S/B$, particles’ properties (spin), ...
• Extracting and interpreting BSM signals from LHC physics is not only an issue of SM backgrounds

• Detailed experimental studies and theoretical modeling of production and decay properties, which may be challenging even in absence of bg’s, will be crucial for example to:
  • assess whether the Higgs is SM or not
  • pin down the origin of an anomalous missing ET signal at the LHC (neutralino from SUSY? neutrino from decay of new heavy quarks of new gauge bosons? ... ?? )
  • understand the origin of anomalies like $A_{FB}(\text{top})$ at the Tevatron
  • .....
• With very few exceptions, all BSM particles decay to a collection of SM states, plus possibly a neutrino-like WIMP

• Direct BSM searches therefore typically rely on inclusive observables built out of SM objects: leptons, jets, photons, neutrinos

• Good detectors, and “tagging” techniques, allow to use also “unstable” SM objects, like W/Z bosons, tau, charm, bottom quarks, as well as top quarks, and to define observables out of them (e.g. $p_T(Z)$, $p_T(b\text{-jet})$, etc)

• Thus most BSM searches boil down to studies of the properties of SM-like final states
  • W/Z+jets, jets+MET, ttbar+bbar+jets, VV+jets, ....
Even SM processes have backgrounds

Example:
$pp \rightarrow W \rightarrow \mu \nu$

Example:
$pp \rightarrow c\ c\ bar \rightarrow (c \rightarrow \mu X) + (c \rightarrow \nu X)$
**Ex: SM Backgrounds to SUSY in jets+MET**

**Missing energy** ⇒ **νs** ⇒ **W/Z production**

**“Irreducible”:** individual events cannot be distinguished from the signal

\[ Z + 4 \text{jets}, \; Z \rightarrow \nu \nu \]

**“Reducible”:** individual events feature properties which distinguish them from the signal, but these can only be exploited with limited efficiency

\[ W + 3 \text{jets}, \; W \rightarrow \tau \nu, \; \tau \rightarrow \text{hadrons (jet)} \]

\[ W + 4 \text{jets}, \; W \rightarrow e/\mu \nu, \; \text{lepton undetected} \]

\[ tt \rightarrow W + \text{jets, with } W \rightarrow \text{leptons as above} \]

- **τ jet** has low multiplicity, and originates from a displaced vertex, because of **τ**s lifetime
- **e/μ** can be detected, but cannot be vetoed with 100% efficiency, else the signal would be killed as well (**e/μ** may come from π conversions or decays)
- In addition to the above, top decays have **b**’s, but these cannot be detected and vetoed with 100% efficiency
“Instrumental”: individual events resemble the signal because of instrumental “effects” (namely instrumental deficiencies)

**Multijets**

The missing ET may originate from several sources:

- Mismeasurement of the energy of individual jets
- Incomplete coverage in rapidity (forward jets undetected)
- Accidental extra deposits of energy (cosmic rays on time, beam backgrounds, electronic noise, etc., etc., etc.)

![Graph](image)

It is sufficient that these effects leave a permille fraction of the QCD rate for the signal to be washed away!
• Successful searches and analyses of BSM phenomena require a good understanding of the properties of SM objects:
  • how do the quarks produced in BSM decays turn into jets?
  • what are the sources of leptons?
  • ....

• Goal of these lectures is to introduce the key ideas and techniques in the modeling of hard processes produced in high-energy hadronic collisions:
  • how can we possibly hope to describe accurately final states where hundreds of particles are produced?
The structure of the proton

Inside the proton we can find, in addition to the component $uud$ quarks, also \textbf{gluons} as well as \textbf{quark-antiquark} pairs.

If we probe the proton at energies high enough, we take a picture of the proton with a very sharp time resolution, and we can “detect” the presence of these additional components. In particular, the gluons and antiquarks present inside will participate in the reactions involving proton.

Notice that, if $\Delta t$ is small enough, even pairs of quark-antiquark belonging to the heavier generations (e.g. s-sbar, c-cbar) can appear!! The proton can contain quarks heavier than itself!!
Factorization Theorem

\[ \frac{d\sigma}{dX} = \sum_{j,k} \int f_j(x_1, Q_i) f_k(x_2, Q_i) \frac{d\hat{\sigma}_{jk}(Q_i, Q_f)}{d\hat{X}} F(\hat{X} \rightarrow X; Q_i, Q_f) \]

- sum over all initial state histories leading, at the scale Q, to:
  \[ \vec{p}_j = x \vec{P}_{\text{proton}} \]

- transition from partonic final state to the hadronic observable (hadronization, fragm. function, jet definition, etc)
- Sum over all histories with X in them

\( f_j(x, Q) \) Parton distribution functions (PDF)

\( F(\hat{X} \rightarrow X; Q_i, Q_f) \)
Universality of parton densities and factorization, an intuitive view

1) Exchange of **hard gluons** among quarks inside the proton is suppressed by powers of $(m_p/Q)^2$

\[ q \xrightarrow{q > Q} \int_Q^\infty \frac{d^4q}{q^6} \sim \frac{1}{Q^2} \]

Assuming asymptotic freedom!

2) **Typical time-scale of interactions binding the proton** is therefore of \( \mathcal{O}(1/m_p) \) (in a frame in which the proton has energy \( E, \tau = \gamma/m_p = E/m_p^2 \))

3) If a hard probe \( (Q >> m_p) \) hits the proton, on a time scale \( = 1/Q \), there is no time for quarks to negotiate a coherent response. The struck quark receives no feedback from its pals, and acts as a free particle
As a result, to study inclusive processes at large $Q$ it is sufficient to consider the interactions between the external probe and a single parton:

1) calculable in perturbative QCD (pQCD)
2) do not affect $f(x)$: $x_{\text{before}} = x_{\text{after}}$

However, since $T(q \approx 1 \text{GeV}) \gg 1/Q$, the emission of low-virtuality gluons will take place long before the hard collision, and therefore cannot depend on the detailed nature of the hard probe. While it is not calculable in pQCD, $f(q \ll Q)$ can be measured using a reference probe, and used elsewhere.

$\Rightarrow$ Universality of $f(x)$
Q dependence of parton densities

The larger is $Q$, the more gluons will not have time to be reabsorbed.

PDF’s depend on $Q$!

$$f(x, Q) = f(x, \mu) + \int_{x}^{1} dx_{in} f(x_{in}, \mu) \int_{\mu}^{Q} dq^{2} \int_{0}^{1} dy P(y, q^{2}) \delta(x - yx_{in})$$
\[ f(x, Q) = f(x, \mu) + \int_x^1 dx_{in} f(x_{in}, \mu) \int_\mu^Q dq^2 \int_0^1 dy P(y, q^2) \delta(x - yx_{in}) \]

f(x,Q) should be independent of the intermediate scale \( \mu \) considered:

\[ \frac{df(x, Q)}{d\mu^2} = 0 \quad \Rightarrow \quad \frac{df(x, \mu)}{d\mu^2} = \int_x^1 \frac{dy}{y} f(y, \mu) P(x/y, \mu^2) \]

One can prove that:

\[ P(x, Q^2) = \frac{\alpha_s}{2\pi} \frac{1}{Q^2} P(x) \]

and finally (Dokshitzer-Gribov-Lipatov-Altarelli-Parisi DGLAP equation):

\[ \frac{d f(x, \mu)}{d \log \mu^2} = \frac{\alpha_s}{2\pi} \int_x^1 \frac{dy}{y} f(y, \mu) P(x/y) \]
More in general, one should consider additional processes which lead to the evolution of partons at high $Q$ ($t=\log Q^2$):

\[
\frac{dq(x, Q)}{dt} = \frac{\alpha_s}{2\pi} \int_x^1 \frac{dy}{y} \left[ q(y, Q) P_{qq}(\frac{x}{y}) + g(y, Q) P_{qg}(\frac{x}{y}) \right]
\]

\[
\frac{dg(x, Q)}{dt} = \frac{\alpha_s}{2\pi} \int_x^1 \frac{dy}{y} \left[ g(y, Q) P_{gg}(\frac{x}{y}) + \sum_{q, \bar{q}} q(y, Q) P_{qg}(\frac{x}{y}) \right]
\]

\[
P_{qq}(x) = C_F \left( \frac{1 + x^2}{1-x} \right)_+
\]

\[
P_{qg}(x) = \frac{1}{2} \left[ x^2 + (1-x)^2 \right]
\]

\[
P_{gg}(x) = 2N_c \left[ \frac{x}{(1-x)_+} + \frac{1-x}{x} + x(1-x) \right] + \delta(1-x) \left( \frac{11N_c - 2n_f}{6} \right)
\]

\[
[g(x)]_+ : \int_0^1 dx f(x) g(x)_+ \equiv \int_0^1 [f(x) - f(1)] g(x) dx
\]
Examples of PDFs and their evolution

Valence up

Sea up

Gluon

All, at $Q=1\,\text{TeV}$

Note: $\text{sea} \approx 10\%$ glue

Note: charm$\approx$up at high $Q$