The Standard Model at LHC

1. Hadron interactions
2. QCD and parton densities
3. Monte Carlo generators
4. Luminosity and cross-section measurements
5. Minimum bias events
6. Jet physics
7. W and Z physics
Hadron Interactions
Kinematical variables

Relevant kinematic variables:

- Transverse momentum: $p_T$
- Rapidity: $y = \frac{1}{2} \cdot \ln \left( \frac{E - p_z}{E + p_z} \right)$
- Pseudorapidity: $\eta = -\ln \tan \frac{1}{2} \theta$
- Azimuthal angle: $\varphi$
Proton-Proton Scattering @ LHC

\[ \sigma = \sum_{ij} \int dx_1 dx_2 \ f_i(x_1, Q^2) f_j(x, Q^2) \hat{\sigma}(Q^2) \]

PDFs

Proton

\[ f_j(x_j) \]

\[ f_k(x_k) \]

\[ \hat{\sigma}(Q^2) \]

Proton

\[ p_1 \]

\[ x_j p_1 \]

Hard Process [calculable]

Product

Product

\[ q(x, Q^2) \]

\[ g(x, Q^2) \]
Example: Drell-Yan Process

Proton \rightarrow q \rightarrow \gamma (Z) \rightarrow \mu^+ \mu^-

Proton
### QCD Matrix Elements

| Subprocess       | $|M|^2 / g_s^4$ | $|M(90^\circ)|^2 / g_s^4$ |
|------------------|----------------|---------------------------|
| $qq' \rightarrow qq'$ | $\frac{4}{9} \frac{s^2 + \bar{u}^2}{\hat{t}^2}$ | 2.2                       |
| $qq' \rightarrow q\bar{q}'$ | $\frac{9}{9} \frac{s^2}{\hat{t}^2}$ | 3.3                       |
| $q\bar{q} \rightarrow q'\bar{q}'$ | $\frac{4}{9} \frac{\hat{t}^2 + \bar{u}^2}{s^2}$ | 0.2                       |
| $q\bar{q} \rightarrow q\bar{q}$ | $\frac{4}{9} \left( \frac{s^2 + \bar{u}^2}{\hat{t}^2} + \frac{\hat{t}^2 + \bar{u}^2}{\bar{u}^2} \right) \frac{8}{27} \frac{s^2}{\bar{u}\hat{t}}$ | 2.6                       |
| $q\bar{q} \rightarrow gg$ | $\frac{32}{27} \frac{\bar{u}^2 + \hat{t}^2}{\bar{u}\hat{t}} - \frac{8}{3} \frac{s^2}{\bar{u}^2}$ | 1.0                       |
| $gg \rightarrow q\bar{q}$ | $\frac{1}{6} \frac{s^2 + \hat{t}^2}{\bar{u}\hat{t}} - \frac{3}{8} \frac{s^2 + \hat{t}^2}{\bar{u}^2}$ | 0.1                       |
| $gg \rightarrow gg$ | $\frac{3}{4} \left( \frac{s^2 + \bar{u}^2}{\hat{t}^2} + \frac{s^2 + \hat{t}^2}{\bar{u}^2} + \frac{s^2 + \bar{u}^2}{\bar{u}^2} + 3 \right)$ | 6.1                       |
| $gg \rightarrow gg$ | $\frac{9}{4} \left( \frac{s^2 + \bar{u}^2}{\hat{t}^2} + \frac{s^2 + \hat{t}^2}{\bar{u}^2} + \frac{s^2 + \bar{u}^2}{\bar{u}^2} + 3 \right)$ | 30.4                      |
Proton-Proton Scattering @ LHC

\[ \sigma = \sum_{ij} \int dx_1 dx_2 \; f_i(x_1, Q^2) f_j(x, Q^2) \; \hat{\sigma}(Q^2) \]

⊗ Hadronization

\[ p_1 \rightarrow x_j p_1 \]

Hard Process [calculable]

PDFs

\[ f_j(x_j) \]

\[ f_k(x_k) \]

Proton

\[ x_k p_2 \]

Parton Shower

Hadronization [phenomenological]

Hadron-Jets Leptons ...

Couse on Physics at the LHC 2018
QCD & parton densities
Lepton-proton scattering

Cross Section:
\[ d\sigma \sim d\sigma_{eq} \times F_2 \]

\[ 4 \pi \alpha^2/q^4 \]
\[ x \cdot \sum e_q^2 q(x) \]

\[ Q^2 = -q^2 = -(k-k')^2 \]

SF
Structure function
describes proton structure
probability to find quark with mom. fraction x

Electron \((e^\pm)\)

k

k'

Quark

Proton Remnant

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Structure Function

Electron-Quark scattering (spinless case)

\[
\frac{d\sigma(eq)}{dq^2} = \frac{4\pi\alpha^2}{q^4} e_q^2
\]
Rutherford scattering on pointlike target

\[
\frac{d\sigma(ep)}{dq^2} = \frac{4\pi\alpha^2}{q^4} \left[2e_u^2 + e_d^2\right] = \frac{4\pi\alpha^2}{q^4}
\]

\[
\frac{d\sigma(ep)}{dx dq^2} = \frac{4\pi\alpha^2}{q^4} \left[e_u^2 u(x) + e_d^2 d(x) + \ldots\right]
\]

QPM: Structure Functions $F_2$ independent of $Q^2$

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Proton
Three valence quarks

Proton
Three bound valence quarks

Proton
Bound valence quarks + gluon radiation

[see e.g. Halzen/Martin]
Scaling violation

\[ F_2(x, Q^2) = \sum e_q^2 x q(x, Q^2) \]
Scaling violation

Proton quark dominated:
\[ Q^2 \uparrow \Rightarrow F_2 \downarrow \text{ for fixed } x \]

Proton gluon dominated:
\[ Q^2 \uparrow \Rightarrow F_2 \uparrow \text{ for fixed } x \]

\[ Q^2 \]-evolution described by DGLAP Equations
Proton parton densities

H1 and ZEUS HERA I+II Combined PDF Fit

$Q^2 = 10000 \text{ GeV}^2$

- $xg \times 0.05$
- $xS \times 0.05$
- $xu_v$
- $xd_v$

H1 and ZEUS Combined PDF Fit

$Q^2 = 10000 \text{ GeV}^2$

- HERAPDF1.0 (prel.)
- exp. uncert.
- model uncert.
- parametrization uncert.
- HERAPDF1.0
- HERAPDF1.5 (prel.)
- (HERA I+II)
Particle production @ LHC

\[ x_{1,2} = \left( M/14 \text{ TeV} \right) \exp( \pm y) \]

\[ Q = M \]

LHC parton kinematics

\[ M = 1 \text{ TeV} \]

\[ M = 10 \text{ TeV} \]

\[ M = 100 \text{ GeV} \]

\[ 100 \text{ GeV-Higgs} \]

\[ y = 6, 4, 2, 0, 2, 4, 6 \]

\[ x \]

\[ 10^{-7}, 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3}, 10^{-2}, 10^{-1}, 10^{0} \]

\[ pp \to X_M + \text{remnants} \]

\[ X_M: \text{particle with mass } M \]
\[ \text{e.g. Higgs} \]

\[ M^2 = x_1 x_2 \cdot s \]

i.e. to produce a particle with mass \( M \) at LHC energies (\( \sqrt{s} = 14 \text{ TeV} \))

\[ \langle x \rangle = \sqrt{x_1 x_2} = M/\sqrt{s} \]
\[ [x_1 = x_2: \text{mid-rapidity}] \]

LHC needs:

Knowledge of parton densities
Extrapolation over orders of magnitudes
Monte Carlo Generators
Monte Carlo overview

Monte Carlo simulation ...

- Numerical process generation based on random numbers
- Method very powerful in particle physics

Event generation programs:
- Pythia, Herwig, Isajet, Sherpa ...
- Hard partonic subprocess + fragmentation & hadronization ...

Detector simulation:
- Geant ...
- Interaction & response of all produced particles ...

MC simulations in particle physics

- Event Generator: simulate physics process (quantum mechanics: probabilities!)
- Detector Simulation: simulate interaction with detector material
- Digitization: translate interactions with detector into realistic signals
- Reconstruction/Analysis: as for real data

Couse on Physics at the LHC 2018
<table>
<thead>
<tr>
<th>No.</th>
<th>Subprocess</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1/f \to f' \to f W^+ z \to f W^+ f' \to f W^+ f \to f W^+ f \to f W^+ f' \to f W^+ f'</td>
</tr>
</tbody>
</table>
From Partons to Jets

From partons to color neutral hadrons:

**Fragmentation:**
Parton splitting into other partons
[QCD: re-summation of leading-logs]
[“Parton shower”]

**Hadronization:**
Parton shower forms hadrons
[non-perturbative, only models]

**Decay of unstable hadrons**
[perturbative QCD, electroweak theory]
Detector simulation

GEANT
Geometry And Tracking

Detailed description of
detector geometry
[sensitive & insensitive volumes]

Tracking of all particles through
detector material ...

⎯ Detector response

Developed at CERN since 1974 (FORTRAN)
[Today: Geant4; programmed in C++]
Luminosity and cross-section measurements
Cross section & Luminosity

Number of observed events
just count ...

Background
measured from data or calculated from theory

$\sigma = \frac{N^{\text{obs}} - N^{\text{bkg}}}{\int \mathcal{L} \, dt \cdot \varepsilon}$

Luminosity
determined by accelerator, triggers, ...

Efficiency
many factors, optimized by experimentalist
Cross section & Luminosity

\[ \hat{N} = L \cdot \sigma \]

\[ N = \sigma \cdot \int L \, dt \quad \sigma = N/L \]

integrated luminosity

Collider experiment:

\[ \Phi_a = \frac{\hat{N}_a}{A} = \frac{N_a \cdot n \cdot v}{U} = \frac{N_a \cdot n \cdot f}{A} \]

\[ L = f \frac{nN_aN_b}{4\pi\sigma_x\sigma_y} \]

\[ \hat{N} = \Phi_a \cdot N_b \cdot \sigma_b \]

\[ \Phi_a \]: flux
\[ n_a \]: density of particle beam
\[ v_a \]: velocity of beam particles

\[ \hat{N} \]: reaction rate
\[ N_b \]: target particles within beam area
\[ \sigma_a \]: effective area of single scattering center

\[ L \]: luminosity

LHC:

- \[ N_a \]: number of particles per bunch (beam A)
- \[ N_b \]: number of particles per bunch (beam B)
- \[ U \]: circumference of ring
- \[ n \]: number of bunches per beam
- \[ v \]: velocity of beam particles
- \[ f \]: revolution frequency
- \[ A \]: beam cross-section
- \[ \sigma_x \]: standard deviation of beam profile in x
- \[ \sigma_y \]: standard deviation of beam profile in y

\[ N_x \sim 10^{11} \]
\[ A \sim .0005 \text{ mm}^2 \]
\[ n \sim 2800 \]
\[ f \sim 11 \text{ kHz} \]
\[ L \sim 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \]
Van-der-Meer separation scan

Determine beam size ...

measuring size and shape of the interaction region by recording relative interaction rates as a function of transverse beam separation ...

First optimization scans at LHC performed for squeezed optics in all IPs [November 2009].
Minimum bias events
Characteristics of inelastic p-p collisions

Particle density in minimum bias events

Soft QCD (PT threshold on tracks: 50 MeV)

Particle density in data rises faster than in model predictions. Tuning of MC generators was needed.
Charged particle $p_T$ spectrum

$$\langle p_T \rangle = 0.545 \pm 0.005 \text{ (stat.)} \pm 0.015 \text{ (syst.) GeV/c}$$

$$dN_{ch}/dp_T$$

$p_T > 100 \text{ MeV}$
$|\eta| < 2.5$
$N_{ch} \geq 2$

\[ \sqrt{s} = 7 \text{ TeV} \]

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Jet physics
Jet production @ LHC

\[ \sigma = \sum_{ij} \int dx_1 dx_2 \ f_i(x_1, Q^2) f_j(x, Q^2) \ \hat{\sigma}(Q^2) \]

Available up to NLO
First NNLO calculations becoming available ...

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Jet properties measurement

**Calorimeter Jet**
[extracted from calorimeter clusters]
- Understanding of detector response
- Knowledge about dead material
- Correct signal calibration
- Potentially include tracks

**Hadron Jet**
[might include electrons, muons ...]
- Hadronization
- Fragmentation
- Parton shower
- Particle decays

**Parton Jet**
[quarks and gluons]
- Proton-proton interactions
- Initial and final state radiation
- Underlying event

**Measurement**

*From measured energy to particle energy*
- Compensate energy loss due to neutrinos, nuclear excitation ...

*From particle energy to original parton energy*
- Compensate hadronization; energy in/outside jet cone ...

Needs Calibration
Jet reconstruction

Iterative cone algorithms:

Jet defined as energy flow within a cone of radius $R$ in $(y,\phi)$ or $(\eta,\phi)$ space:

$$R = \sqrt{(y - y_0)^2 + (\phi - \phi_0)^2}$$

Sequential recombination algorithms:

Define distance measure $d_{ij}$ ...
Calculate $d_{ij}$ for all pairs of objects ...
Combine particles with minimum $d_{ij}$ below cut ...
Stop if minimum $d_{ij}$ above cut ...

e.g. $k_T$-algorithm:
[see later]

$$d_{ij} = \min\left(k_{T,i}^2, k_{T,j}^2\right) \frac{\Delta R_{ij}}{R}$$

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Jet energy calibration

Absolute calibration

Relative calibration

Photon
\[ p_T = 76.1 \text{ GeV/c} \]
\[ \eta = 0.0 \]
\[ \varphi = 1.9 \text{ rad} \]

Anti-\( k_T \) 0.5 PFJet
\[ p_T = 72.0 \text{ GeV/c} \]
\[ \eta = 0.0 \]
\[ \varphi = -1.2 \text{ rad} \]
Jet energy resolution

Resolution: \[ \frac{\sigma(p_T)}{p_T} = \sqrt{2} \sigma_A \]

using \( p_T \) asymmetry: \[ A = \frac{p_T^{\text{jet 1}} - p_T^{\text{jet 2}}}{p_T^{\text{jet 1}} + p_T^{\text{jet 2}}} \]

CaloJets (Anti-\( k_T \) \( R=0.5 \))
\( 0 < \ln|\eta| < 1.4 \)

Particle flow jets
Resolution unfolding

Measured spectrum = Real spectrum \[ \square \text{Experim. resolution} \]

\[ N_{\text{part}} = N_{\text{meas}} \cdot \frac{N_{\text{MC part}}}{N_{\text{MC meas}}} \]

**ATLAS**

- anti-\(k_t\) jets, \(R=0.6\)
  - 0.3 < |\(y\)| < 0.8

**ATLAS**

- anti-\(k_t\) jets, \(R=0.6\)
  - 2.1 < |\(y\)| < 2.8

Unfolding factor

\[ p_T [\text{GeV}] \]

\[ \text{Unfolding factor} \]

- PYTHIA 6, \(\sqrt{s} = 7 \text{ TeV}\)
- Unc. from shape (x10)
- Unc. from \(E\) resol. (x10)
- Unc. from \(y\) resol. (x10)
Inclusive jet cross-section

Cross section is huge
(\sim \text{Tevatron} \times 100)

Very good agreement with
NLO QCD over nine orders of magnitude

PT extending from 20 to 500 GeV

Main uncertainty:
Jet Energy Scale (3-4%)
Inclusive jet cross sections: 3-jet / 2-jet ratio

\[ H_T = \sum_{i=1}^{N} p_{T_i} \]
Jets: angular correlations

Difference in azimuth of the two leading jets
Probe of QCD high-order processes
Very slight dependence on JES
No dependence on luminosity
Dijet mass

Search for numerous resonances
BSM:
string resonance, excited quarks, axi-gluons, colorons, E6
diquarks, W’ and Z’, RS gravitons

Four-parameter fit to describe
QCD shape:

\[
\frac{d\sigma}{dm} = p_0 \left( \frac{1 - \frac{m}{\sqrt{s}}}{\sqrt{s}} \right)^{p_1} \frac{ \left( \frac{m}{\sqrt{s}} \right)^B }{ \left( \frac{m}{\sqrt{s}} \right)^{B+1} } \\
B = p_2 + p_3 \left( m / \sqrt{s} \right)
\]
W and Z bosons
Vector boson production

Direct $\gamma$-production:

Singel W/Z production:

$W^\pm$ production: 
(main contributions) $
\begin{cases} 
ud \rightarrow W^+ \\
d\bar{u} \rightarrow W^- 
\end{cases}$

$Z$ production: 
(main contributions) $
\begin{cases} 
\bar{u}u \rightarrow Z \\
d\bar{d} \rightarrow Z 
\end{cases}$

- At LHC energies these processes take place at low values of Bjorken-$x$
- Only sea quarks and gluons are involved
- At EW scales sea is driven by the gluon, i.e. x-sections dominated by gluon uncertainty

➡️ Constraints on sea and gluon distributions
W and Z boson decays

Leptonic decays ($e/\mu$): very clean, but small(ish) branching fractions
Hadronic decays: two-jet final states; large QCD dijet background
Tau decays: somewhere in between…


W and Z boson signatures

Missing transverse energy

$W \rightarrow \ell \nu$

$Z \rightarrow \ell\ell$

Additional hadronic activity $\rightarrow$ recoil, not as clean as $e^+e^-$
Precision measurements: only leptonic decays
Isolated High-$p_T$ Leptons

Starting point for many hadron collider analyses: isolated high-$p_T$ leptons $\rightarrow$ discriminate against QCD jets ...

- QCD jets can be mis-reconstructed as leptons (“fake leptons”)
- QCD jets may contain real leptons, e.g. from semileptonic B decays $[B \rightarrow lvX]$ $\rightarrow$ soft and surrounded by other particles

“Tight” lepton selection ...

- Require $e/\mu$ with $p_T > (at least) 20$ GeV
- Track isolation, e.g. $\sum p_T$ of other tracks in cone of $\Delta R=0.1$ less than 10% of lepton $p_T$
- Calorimeter isolation, e.g. energy deposition from other particles in cone of $\Delta R=0.2$ less than 10%
Dilepton mass spectrum at 7 TeV

CMS Preliminary
\(\sqrt{s} = 7\) TeV, \(L_{\text{int}} = 40\) pb\(^{-1}\)

CMS Preliminary 2010
\(\sqrt{s} = 7\) TeV, \(L_{\text{int}} = 35\) pb\(^{-1}\)

CMS Preliminary, \(\sqrt{s} = 7\) TeV
\(L_{\text{int}} = 3.1\) pb\(^{-1}\)
\(\sigma = 70\) MeV/c\(^2\)
\(|y| < 1\)
Example: CMS W Analysis

Select isolated electrons and muons ...
[muons: $p_T>9$ GeV; electrons: $p_T>20$ GeV]

Investigate transverse mass ...
[Use $E_{T,miss}$; $M_T = (p_{lep} + E_{T,miss})^{1/2}$]

The W signal yield is extracted from a binned likelihood fit to the $M_T$ distribution. Three different contributions:
- W signal
- QCD background
- other (EWK) backgrounds.
W/Z production at 7 TeV

Transverse Mass,

\[ M_T = \sqrt{2E_T^\mu E_T^{miss} (1 - \cos \Delta \phi_{e,miss})} \]
$W, Z$ cross-section v.s. $\sqrt{s}$

hep-ex 1012.2466, JHEP 01 (2011) 080
W+/W- charge asymmetry

NNLO cross sections: scale uncertainties very small

W rapidity: asymmetry [sensitivity to PDFs]

$$A_W(y) = \frac{d\sigma(W^+)/dy - d\sigma(W^-)/dy}{d\sigma(W^+)/dy + d\sigma(W^-)/dy}$$

Proton-Proton Collider: symmetry around y=0 ...

PDFs:

- $u(x) > d(x)$ for large $x$ ...
- more $W^+$ at positive rapidity
- $d/u$ ratio < 1 ...
- always more $W^+$ than $W^-$
W + Jets multiplicity

$|\eta| < 2.8$ and $p_T > 20$ GeV

arXiv:1012.5382
W + Jets $P_T$

Tails are important in several Exotica and SUSY searches
SM processes measured at LHC
**W Mass Determination**

**Template method:**

- Fit templates (from MC simulation) with different $m_W$ to data
- $\rightarrow$ W mass from best fit

Requires very good modeling of physics & detector

Templates for $m_W = 80.4 \pm 1.6$ GeV

Ultimate LHC goal:
$m_W$ uncertainty of 15 MeV
[via combination]
End of Lecture 2