Physics at Hadron Colliders
-From the Tevatron to the LHC-

• Introduction to Hadron Collider Physics

• The present Hadron Colliders
  - The Tevatron and the LHC
  - The experiments

• Test of the Standard Model
  - QCD: Jet, W/Z, top-quark production
  - W and top-quark mass measurements

• Search for the Higgs Boson

• Search for New Phenomena
Building blocks of the Standard Model

- **Matter**
  made out of fermions
  (Quarks and Leptons)

- **Forces**
  electromagnetism, weak and strong force
  + gravity
  (mediated by bosons)

- **Higgs field**
  needed to break (hide) the electroweak symmetry and to give mass to weak gauge bosons and fermions

→ **Higgs particle** (see lecture by C. Grojean)
  Theoretical arguments: \( m_H < \sim 1000 \text{ GeV/c}^2 \)
Where do we stand today?

e\text{e}^+\text{e}^- \text{ colliders LEP at CERN and SLC at SLAC } + \text{ the Tevatron pp collider} \\
+ \text{HERA at DESY} + \text{KEK in Japan} + \text{many other experiments (fixed target……..)} \\
have explored the energy range up to \sim 100 \text{ GeV} \text{ with incredible precision} \\

• The Standard Model is consistent with all experimental data !

• No Physics Beyond the SM observed

• No Higgs seen (yet)

Only unambiguous example of observed Higgs

(P. Higgs, Univ. Edinburgh)

Direct searches at LEP: \text{m}_H > 114.4 \text{ GeV}/c^2 (95\% CL)
Consistency with the Standard Model

Sensitivity to the Higgs boson and other new particles via quantum corrections:

\[ m_H = 90^{+36}_{-27} \text{ GeV}/c^2 \]
\[ m_H < 163 \text{ GeV}/c^2 \] (95 % CL)

Interpretation within the Standard Model (incl. new (2009) \( m_W \) and \( m_t \) measurements)

\[ m_H = 90^{+36}_{-27} \text{ GeV}/c^2 \]
\[ m_H < 163 \text{ GeV}/c^2 \] (95 % CL)
Constraints on the Higgs mass in a supersymmetric theory

O. Buchmüller et al., arXiv:0707.3447

\[ m_h = 110 \text{ (+8) (-10) ± 3 \ (theo) GeV/c}^2 \]

...watch the low mass region!

Includes:
- WMAP
- \( b \to s\gamma \)
- \( a_\mu \)
The Open Questions
Key Questions of Particle Physics

1. **Mass**: What is the origin of mass?
   - How is the electroweak symmetry broken?
   - Does the Higgs boson exist?

2. **Unification**: What is the underlying fundamental theory?
   - Can the interactions be unified at larger energy?
   - How can gravity be incorporated?
   - Is our world supersymmetric?
   - ....

3. **Flavour** or the generation problem
   - Why are there three families of matter?
   - Neutrino masses and mixing?
   - What is the origin of CP violation?
Problems at a larger scale

We are here

Surrounded by

- Mass
  (planets, stars, ..., hydrogen gas)
- Dark Matter
- Dark Energy

© Rocky Kolb
- Supersymmetry
- Extra dimensions
- ....
- Composite quarks and leptons
- ....

bosons

- New gauge bosons
- Leptoquarks
- Little Higgs Models
- ....
- Invisibly decaying Higgs bosons

Theoretical Models
….and they have still not finished

[Hitoshi Murayama]
The role of the present Hadron Colliders

1. Explore the TeV mass scale

- What is the origin of the electroweak symmetry breaking?

- The search for “low energy” supersymmetry
  Can a link between SUSY and dark matter be established?

- Other scenarios beyond the Standard Model
  - .......

  Look for the “expected”, but we need to be open for surprises

2. Precise tests of the Standard Model

- There is much sensitivity to physics beyond the Standard Model in the precision area

- Many Standard Model measurements can be used to test and to tune the detector performance

M. Battaglia, I. Hinchliffe, D. Tovey, hep-ph/0406147
Why a hadron collider?

e^+e^- colliders are excellent machines for precision physics!!
- e^+ e^- are point-like particles, no substructure → clean events
- complete annihilation, centre-of-mass system, kinematic fixed
Proton proton collision are more complex
Main drawbacks of $e^+e^-$ circular accelerators:

1. Energy loss due to synchrotron radiation
   (basic electrodynamics: accelerated charges radiate, dipole, x-ray production via bremsstrahlung, synchrotron radiation…….)

   - Radiated power (synchrotron radiation):
     (ring with radius $R$ and energy $E$)

   - Energy loss per turn:

   - Ratio of the energy loss between protons and electrons:

\[
P = \frac{2e^3 c}{3 R^2} \left( \frac{E}{mc^2} \right)^4
\]

\[
-\Delta E \approx \frac{4\pi e^2}{3 R} \left( \frac{E}{mc^2} \right)^4
\]

\[
\frac{\Delta E(e)}{\Delta E(p)} = \left( \frac{m_p}{m_e} \right)^4 \approx 10^{13}
\]

Future accelerators:
• pp ring accelerators (LHC, using existing LEP tunnel)

• or $e^+e^-$ linear accelerators, International Linear Collider ILC or CLIC (under study / planning)
2. Hard kinematic limit for $e^+e^-$ center-of-mass energy from the beam energy:

$$\sqrt{s} = 2 E_{\text{beam}}$$
How can interesting objects be produced?

Quarks and gluons in the initial state
Cross Sections

as a function of $\sqrt{s}$

Accelerators:
1. Proton-Antiproton Collider **Tevatron** at Fermilab, $\sqrt{s} = 1.96$ TeV
2. Large Hadron Collider (LHC) pp collider at CERN $\sqrt{s} = 10 - 14$ TeV

$$N_{\text{event}} = \sigma \cdot L \cdot \varepsilon \quad \text{(efficiency \cdot acceptance)}$$

$[s^{-1}] = [cm^2] \cdot [cm^{-2} \text{ s}^{-1}]$
Variables used in the analysis of pp collisions

Transverse momentum
(in the plane perpendicular to the beam)

\[ p_T = p \sin \theta \]

(Pseudo)-rapidity: \[ \eta = - \ln \tan \frac{\theta}{2} \]

- \( \theta = 90^\circ \rightarrow \eta = 0 \)
- \( \theta = 10^\circ \rightarrow \eta \approx 2.4 \)
- \( \theta = 170^\circ \rightarrow \eta \approx -2.4 \)
- \( \theta = 1^\circ \rightarrow \eta \approx 5.0 \)
Inelastic low-\( p_T \) pp collisions

Most interactions are due to interactions at large distance between incoming protons
→ small momentum transfer, particles in the final state have large longitudinal, but small transverse momentum

\(< p_T > \approx 500 \text{ MeV} \) (of charged particles in the final state)

\[ \frac{dN}{d\eta} \approx 7 \]
- about 7 charged particles per unit of pseudorapidity in the central region of the detector
- uniformly distributed in \( \Phi \)

These events are called “Minimum-bias events”
Some features of minimum bias events

- Features of minimum bias events cannot be calculated in perturbative QCD
- Experimental measurements / input needed
- Models / parametrizations are used to extrapolate from existing colliders (energies) to the LHC energy regime → large uncertainties
- Will be one of the first physics measurements at the LHC
- Needed to model other interesting physics (superposition of events,...)

\[ \langle p_T \rangle (\eta = 0): 550 – 640 \text{ MeV (15\%)} \]

\[ dN_{ch}/d\eta (\eta = 0): 5-7 (~ 33\%) \]
Hard Scattering Processes ….or QCD jet production

- Large momentum transfer, high $p_T$ in final state; qq, qg, gg scattering or annihilation

- Calculable in perturbative QCD → test of QCD (search for deviations)

- Constraints on the proton structure possible (parton distribution functions of the proton)

Tevatron, ppbar, $\sqrt{s} = 1.96$ TeV, central region $|\eta| < 0.4$
More details on the hard scattering process:

- Proton beam can be seen as a beam of quarks and gluons with a wide band of energies.
- The proton constituents (partons) carry only a fraction $0 < x < 1$ of the proton momentum.

The effective center-of-mass energy $\sqrt{\hat{s}}$ is smaller than $\sqrt{s}$ of the incoming protons.

\[
\begin{align*}
  p_1 &= x_1 p_A \\
  p_2 &= x_2 p_B \\
  p_A &= p_B = 7 \text{ TeV}
\end{align*}
\]

\[
\sqrt{\hat{s}} = \sqrt{x_1 x_2 s} = x \sqrt{s}
\]

(If $x_1 = x_2 = x$)

To produce a mass of:

- **LHC**
  - 100 GeV: $x \sim 0.007$
  - 5 TeV: $x \sim 0.36$

- **Tevatron**
  - 100 GeV: 0.05
  - 5 TeV: --
Where do we know the x-values from?

The structure of the proton is investigated in *Deep Inelastic Scattering* experiments:

Highest energy machine was the HERA ep collider at DESY/Hamburg (stopped operation in June 2007)

Scattering of 30 GeV electrons on 900 GeV protons:
→ Test of proton structure down to $10^{-18}$ m
How do the $x$-values of the proton look like?

Parton density functions (pdf):

- $u$- and $d$-quarks at large $x$-values
- Gluons dominate at small $x$!!

Uncertainties in the pdfs, in particular on the gluon distribution at small $x$
Parton densities depend on $x$ and momentum transfer (energy scale) $Q^2$

Impressive results achieved at HERA over the past years; Measurements of ep scattering cross sections (proton structure function $F_2(x,Q^2)$)

Evolution ($Q^2$ dependence) predicted by QCD (Altarelli-Parisi or DGLAP equation):

\[ \frac{d}{d \log Q^2} q(x, Q^2) = \frac{\alpha_s}{2\pi} \int_x^1 \frac{dy}{y} q(y, Q^2) P_{qq} \left( \frac{x}{y} \right). \]
Results from HERA

- Large data sets and combination of the two HERA experiments (H1 and ZEUS) improve the precision on the parton distribution functions

- Very important to reduce cross section uncertainties at hadron colliders
Calculation of cross sections

\[ \sigma = \sum_{a,b} \int dx_a \, dx_b \, f_a(x_a, Q^2) \, f_b(x_b, Q^2) \, \hat{\sigma}_{ab}(x_a, x_b) \]

Sum over initial partonic states \( a,b \)

\( \hat{\sigma}_{ab} \equiv \text{hard scattering cross section} \)

\( f_i(x, Q^2) \equiv \text{parton density function} \)

… + higher order QCD corrections (perturbation theory)

which for some processes turn out to be large
(e.g. Higgs production via gg fusion)

usually introduced as K-factors: \( K_{[n]} = \sigma_{[n]} / \sigma_{[LO]} \)

a few examples:

Drell-Yan production of W/Z: \( K_{NLO} \sim 1.2 \)
Higgs production via gg fusion: \( K_{NLO} \sim 1.8 \)
The accelerators

- LHC

K. Jakobs

XIV LNF Spring School “Bruno Touschek”, Frascati, May 2009
The Tevatron Collider at Fermilab

- Proton antiproton collider
  - 6.5 km circumference
  - Beam energy 0.98 TeV, $\sqrt{s} = 1.96$ TeV
  - 36 bunches, 396 ns separation (time between crossings)

- 2 Experiments: CDF and DØ

- Main challenges:
  - Antiproton production and storage
    → luminosity, stability of operation

Collider is running in so called Run II (since 2001)
[Run I from 1990 – 1996, int. luminosity: 0.125 fb⁻¹, Top quark discovery]

* March 2001 – Feb 2006: Run II a, $\int L \, dt = 1.2$ fb⁻¹
* July 2006 - 2010 (11)?: Run II b, $\int L \, dt = 10 - 12$ fb⁻¹
Tevatron performance

Peak luminosities of the machine as a function of time

- Peak luminosity of \( 3.5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \)
- Corresponds to \( \sim 10 \) interactions per bunch crossing
  (superposition of minimum bias events on hard collision)
The integrated Tevatron luminosity (until Apr. 2009)

- After a slow start-up (2001 – 2003), the Tevatron accelerator has reached an excellent performance
- Today, Tevatron delivers a data set equal to Run I (~100 pb\(^{-1}\)) every 2 weeks
- Integrated luminosity delivered to the experiments so far ~ 6.5 fb\(^{-1}\)
- Anticipate an int. luminosity of ~10 fb\(^{-1}\) until end of 2010, with a potential increase to 12 - 13 fb\(^{-1}\), if Tevatron will run until end of 2011
The Large Hadron Collider

... became a reality in 2008 after ~15 years of hard work

- Beam energy (nominal) 7 TeV
- SC Dipoles 1232, 15 m, 8.33T
- Stored Energy 362 MJ/Beam
- Bunch spacing 25 ns
- Particles/Bunch $1.15 \cdot 10^{11}$
- Design luminosity $10^{33} - 10^{34}$ cm$^{-2}$s$^{-1}$
- Int. luminosity 10- 100 fb$^{-1}$ / year
Descent of the last magnet, 26 April 2007
Work on installation, interconnection and testing underground
An excellent start: first beams – September 10, 2008
First beams at CERN – and everywhere else...
After September 10

- Successful continuation of commissioning with beam (low intensity, $10^9$ protons)

Sept 11:

Switched on RF for beam 2 circulating beam for 10 min

Many tests (orbit, dump, …)

Sept 12:

Measure horizontal beam profile with wire scanner

......

everything worked impressively well
The Event on 19. Sep 2008

- the present understanding
- ongoing repair work
- plans for 2009/2010
Sector 34: the event which started
**Actions ongoing and time schedule**

- **Repair work is well underway**  
  (all magnets in the incident area and in a buffer zone around have been removed, repaired and meanwhile lowered down in the tunnel again)

- **Quench detection system has been improved to generate both early warnings and interlocks and to encompass magnets, bus bars and interconnects;**  
  Relief devices on the cryostat vacuum vessels increased in discharge capacity (in the sectors that were warm).

- **Powerful techniques have been developed to spot resistive splices at low current;**  
  All sectors have been systematically verified to spot eventual defects.

- **It is expected that machine operation will be resumed in Oct. 2009, with first collisions towards the end of the year**

- **Physics run with beam energy of 5 TeV**

- **Start with low number of bunches / intensity, expect to deliver a few hundreds of pb\(^{-1}\) until end of 2010**
Physics implications of 10 vs 14 TeV

- At 10 TeV, more difficult to create high mass objects...

- Below about 200 GeV, this suppression is <50% (process dependent)

- Above ~2-3 TeV the effect is more marked

14 TeV simulation results will be shown throughout the lectures, unless stated otherwise

<table>
<thead>
<tr>
<th>Process</th>
<th>√s [TeV]</th>
<th>Cross section</th>
</tr>
</thead>
<tbody>
<tr>
<td>W→ℓν</td>
<td>14</td>
<td>20.5 nb</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>14.3 nb</td>
</tr>
<tr>
<td>Z→ℓℓ</td>
<td>14</td>
<td>2.02 nb</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1.35 nb</td>
</tr>
<tr>
<td>ttbar</td>
<td>14</td>
<td>833 pb</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>396 pb</td>
</tr>
</tbody>
</table>

James Stirling

pdfs: MSTW2007NLO
Comparison of the LHC and Tevatron machine parameters

<table>
<thead>
<tr>
<th></th>
<th>LHC (design)</th>
<th>Tevatron (achieved)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre-of-mass energy</td>
<td>14 TeV</td>
<td>1.96 TeV</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>2808</td>
<td>36</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>25 ns</td>
<td>396 ns</td>
</tr>
<tr>
<td>Energy stored in beam</td>
<td>360 MJ</td>
<td>1 MJ</td>
</tr>
<tr>
<td>Peak Luminosity</td>
<td>$10^{33-34}$ cm$^{-2}$s$^{-1}$</td>
<td>$3.5 \times 10^{32}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Integrated Luminosity / year</td>
<td>10-100 fb$^{-1}$</td>
<td>$\sim 2$ fb$^{-1}$</td>
</tr>
</tbody>
</table>

- 7 times more energy (after initial 5 TeV phase)
- Factor 3-30 times more luminosity
- Physics cross sections factor 10-100 larger
Cross Sections and Production Rates

Rates for $L = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$: (LHC)

- **Inelastic proton-proton reactions**: $10^9 / \text{s}$
- **bb pairs**: $5 \times 10^6 / \text{s}$
- **tt pairs**: $8 / \text{s}$
- **$W \rightarrow e \nu$**: $150 / \text{s}$
- **$Z \rightarrow e e$**: $15 / \text{s}$
- **Higgs (150 GeV)**: $0.2 / \text{s}$
- **Gluino, Squarks (1 TeV)**: $0.03 / \text{s}$

LHC is a factory for:
top-quarks, b-quarks, W, Z, ....... Higgs, .......

The only problem: you have to detect them!
Detector requirements from physics

- Good measurement of *leptons* and *photons* with large transverse momentum $P_T$

- Good measurement of *missing transverse energy* ($E_T^{miss}$) and energy measurements in the forward regions $\Rightarrow$ calorimeter coverage down to $\eta \sim 5$

- Efficient *b-tagging* and *$\tau$ identification* (silicon strip and pixel detectors)
Detector requirements from the experimental environment (pile-up)

• LHC detectors must have **fast response**, otherwise integrate over many bunch crossings $\rightarrow$ too large pile-up

Typical response time: 20-50 ns
$\rightarrow$ integrate over 1-2 bunch crossings
$\rightarrow$ pile-up of 25-50 minimum bias events
$\Rightarrow$ very challenging readout electronics

• **High granularity** to minimize probability that pile-up particles be in the same detector element as interesting object
$\rightarrow$ large number of electronic channels, high cost

• LHC detectors must be **radiation resistant**: high flux of particles from pp collisions $\rightarrow$ high radiation environment
e.g. in forward calorimeters: up to $10^{17}$ n/ cm$^2$ in 10 years of LHC operation
The ATLAS experiment

- Solenoidal magnetic field (2T) in the central region (momentum measurement)

High resolution silicon detectors:
- 6 Mio. channels (80 μm x 12 cm)
- 100 Mio. channels (50 μm x 400 μm)
  space resolution: ~ 15 μm

- Energy measurement down to 1° to the beam line

- Independent muon spectrometer (supercond. toroid system)

Diameter: 25 m
Barrel toroid length: 26 m
End-cap end-wall chamber span: 46 m
Overall weight: 7000 Tons
ATLAS Installation

October 2006
Muon detector system
In the forward region
A historical moment:
Closure of the LHC beam pipe ring on 16th June 2008
ATLAS was ready for data taking in August 2008
The very first beam-splash event from the LHC in ATLAS on 10\textsuperscript{th} September 2008, 10:19
ATLAS Commissioning

with cosmic rays.....
Commissioning with cosmics

more than 200 M events recorded since Oct. 08
A combined barrel + endcap track

- Hits in:
  - TRT (endcap)
  - SCT (endcap and barrel)
  - Pixels (endcap and barrel)

- Very useful for alignment
The Calorimeters

Commissioning since ~3 years

- Good performance, small number of "dead channels":
  - EM: ~0.01%
  - HEC: ~0.1%
    (+ Low voltage power supply problems, impacting ¼ of an endcap)
  - FCal: none
  - Tile Calorimeter: ~1.5%

Most of them recovered during the shutdown

- Effort is now more focussed on:
  * Long term stability
  * Prediction of the signal
  * Extraction of calibration constants

- Fine granularity in region of Inner Detector acceptance, |η| < 2.5:
  - σ/E ~ 10%/√E ⊕ 0.7%
  - Linearity to ~0.1%

- Coarser granularity in the other regions sufficient for jet reconstruction and $E_T^{\text{miss}}$ measurements
  - σ/E ~ 50% / √E ⊕ 3% (barrel / endcap)
  - σ/E ~ 100%/√E ⊕ 10% (forward)
Some calorimeter commissioning results

Precise knowledge is very important for an accurate calibration
**Superconducting Coil, 4 Tesla**

**Tracker**
- Pixels
- Silicon Microstrips
- 210 m² of silicon sensors
- 9.6M channels

**Muon Barrel**
- Drift Tube Chambers (DT)
- Resistive Plate Chambers (RPC)

**Calorimeters**
- **ECAL**
  - 76k scintillating PbWO₄ crystals
- **HCAL**
  - Plastic scintillator/brass sandwich

**Iron Yoke**

**Total weight** 12500 t
**Overall diameter** 15 m
**Overall length** 21.6 m

**Muon Endcaps**
- Cathode Strip Chambers (CSC)
- Resistive Plate Chambers (RPC)
CMS Installation

Experimental Hall, August 06

Coil inserted, 14. September 2005

Cathode Strip chambers and yoke endcaps

Hadronic calorimeter, endcap

Tracker, outer barrel
CMS Detector closed for 10\textsuperscript{th} Sep.
Back to the Tevatron

The CDF experiment

12 countries, 59 institutions
706 physicists

The DØ collaboration

19 countries, 83 institutions
664 physicists
The CDF detector in Run II

- Core detector operates since 1985:
  - Central Calorimeters
  - Central muon chambers

- Major upgrades for Run II:
  - Drift chamber (central tracker)
  - **Silicon tracking detector:**
    - SVX, ISL, Layer 00
      - 8 layers
      - 700k readout channels
      - 6 m²
      - material: 15% $X_0$
  - Forward calorimeters
  - Forward muon system
  - Time-of-flight system
  - Trigger and DAQ
  - Front-end electronics
Some new CDF subdetectors
The DØ Run II Detector

Retained from Run I
- LAr calorimeter
- Central muon detector
- Muon toroid

New for Run II
- Inner detector (tracking)
- Magnetic field added
- Preshower detectors
- Forward muon detector

Front-end electronics
- Trigger and DAQ

In addition: Inner B-layer (similar to CDF)
DØ Detector

Solenoid

Fiber Tracker

Silicon Detector
Data set

Tevatron delivers a data set equal to Run I (~100 pb\(^{-1}\)) every 2 weeks
+ Well understood detectors with data taking efficiencies of ~90%

Similar for CDF

\[ N_{\text{event}} \, [1/s] = \sigma \cdot L \cdot \varepsilon \, (\text{efficiency} \cdot \text{acceptance}) \]
Challenges with high luminosity

Min. bias pileup at the Tevatron, at $0.6 \cdot 10^{32} \text{ cm}^2\text{s}^{-1}$ ... and at $2.4 \cdot 10^{32} \text{ cm}^2\text{s}^{-1}$

Average number of interactions:

**LHC**: initial “low” luminosity run
(L=2 $\cdot 10^{33} \text{ cm}^2\text{s}^{-1}$): $\langle N \rangle = 3.5$

**TeV**: (L=3 $\cdot 10^{32} \text{ cm}^2\text{s}^{-1}$): $\langle N \rangle = 10$
How are the interesting events selected?

**TRIGGER:** much more difficult than at $e^+e^-$ machines

Interaction rate: $\sim 10^9$ events/s
Can record $\sim 200$ events/s (event size 1 MB)

$\Rightarrow$ trigger rejection $\sim 10^7$

Trigger decision $\sim \mu s$ $\rightarrow$ larger than interaction rate of 25 ns

store massive amount of data in **pipelines** while special trigger processors perform calculations
**Triggering at hadron colliders**

The trigger is the key at hadron colliders

---

**CDF Detector**

- 1.7 MHz crossing rate
- Dedicated hardware
  - 42 L1 buffers
  - 25 kHz L1 accept
  - Hardware + Linux PC's
    - 4 L2 buffers
    - 800 Hz L2 accept
  - Linux farm (200)
    - 200 Hz L3 accept
  - disk/tape

---

**DØ trigger:**

- L1: 1.6 kHz
- L2: 800 Hz
- L3: 50 Hz
LHC data handling, GRID computing

Trigger system selects ~200 “collisions” per sec.

LHC data volume per year:
10-15 Petabytes
= 10-15 \cdot 10^{15} \text{ Byte}

A typical Tier-2 GRID center
(example: Tokyo University)
Towards Physics:
some aspects of reconstruction of physics objects

- As discussed before, key signatures at Hadron Colliders are

  **Leptons:**
  - $e$ (tracking + very good electromagnetic calorimetry)
  - $\mu$ (dedicated muon systems, combination of inner tracking and muon spectrometers)
  - $\tau$ hadronic decays: $\tau \rightarrow \pi^+ + n \pi^0 + \nu$ (1 prong)
  - $\rightarrow \pi^+ \pi^- \pi^+ + n \pi^0 + \nu$ (3 prong)

  **Photons:**
  - $\gamma$ (tracking + very good electromagnetic calorimetry)

  **Jets:**
  - electromagnetic and hadronic calorimeters
  - **b-jets** identification of b-jets (b-tagging) important for many physics studies

**Missing transverse energy:** inferred from the measurement of the total energy in the calorimeters; needs understanding of all components… response of the calorimeter to low energy particles
Jet reconstruction and energy measurement

• A jet is NOT a well defined object
  (fragmentation, gluon radiation, detector response)

• The detector response is different for particles interacting electromagnetically (e,γ) and for hadrons
  → for comparisons with theory, one needs to correct back the calorimeter energies to the „particle level“ (particle jet)
  Common ground between theory and experiment

• One needs an algorithm to define a jet and to measure its energy
  conflicting requirements between experiment and theory (exp. simple, e.g. cone algorithm, vs. theoretically sound (no infrared divergencies))

• Energy corrections for losses of fragmentation products outside jet definition and underlying event or pileup energy inside
Main corrections:

• In general, calorimeters show different response to electrons/photons and hadrons

• Subtraction of offset energy not originating from the hard scattering (inside the same collision or pile-up contributions, use minimum bias data to extract this)

• Correction for jet energy out of cone (corrected with jet data + Monte Carlo simulations)
Jet Energy Scale

Jet response correction in DØ:

• Measure response of particles making up the jet

• Use photon + jet data - calibrate jets against the better calibrated photon energy

• Achieved jet energy scale uncertainty:
  
  DØ: $\Delta E/E \sim 1\text{-}2\%$

(excellent result, a huge effort)
Jet energy scale at the LHC

- A good jet-energy scale determination is essential for many QCD measurements (arguments similar to Tevatron, but kinematic range (jet $p_T$) is larger, $\sim 20$ GeV – $\sim 3$ TeV)

- Propagate knowledge of the em scale to the hadronic scale, but several processes are needed to cover the large $p_T$ range

<table>
<thead>
<tr>
<th>Measurement process</th>
<th>Jet $p_T$ range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z +$ jet balance</td>
<td>$20 &lt; p_T &lt; 100 - 200$ GeV</td>
</tr>
<tr>
<td>$\gamma +$ jet balance</td>
<td>$50 &lt; p_T &lt; 500$ GeV (trigger, QCD background)</td>
</tr>
<tr>
<td>Multijet balance</td>
<td>$500$ GeV $&lt; p_T$</td>
</tr>
</tbody>
</table>

Reasonable goal: 5-10% in first runs (1 fb$^{-1}$) 1- 2% long term

Example: $Z +$ jet balance

Stat. precision (500 pb$^{-1}$): 0.8%
Systematics: 5-10% at low $p_T$, 1% at high $p_T$