Experiments at the Large Hadron Collider

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DESY

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Outline

- The Large Hadron Collider
- The experiments
- Some examples for (early) physics
  - SM tests
  - SM Higgs search
  - SUSY(MSSM)
- LHC status and prospects
The Large Hadron Collider (LHC)

- Proton-proton collider in the former LEP tunnel
- Highest ever energy per collision
  
  14 TeV in the pp-system

  cf. Tevatron at 2 TeV

- High luminosity
  
  up to $10^{34}$/cm$^2$/s

- Conditions as $10^{-13}$ – $10^{-14}$ s after the Big Bang

- 4 experiments:
  
  ATLAS
  CMS
  LHCb specialised on b-physics
  ALICE specialised for heavy ion collisions

- LHC and experiments were constructed in global collaborations
The Large Hadron Collider (LHC)

LHC time table:

- Early 1980’s: first ideas about a multi-TeV proton collider at CERN
- Oct 1990: ECFA workshop on LHC in Aachen
- 16 Dec 1994: CERN council approves the LHC
- Feb 1996: approval of ATLAS and CMS
- Apr 1998: start civil engineering
- 7 Mar 2005: first dipole magnet installed
- 26 Apr 2007: last dipole installed
- 10 Sep 2008: first circulating beams
- Oct 2009: first pp-collisions expected
Challenges for the LHC: Magnets

- Superconducting dipole magnets to keep 7 TeV protons on a circular path ($r \approx 3$ km)
  
  $|B| = 8.33$ Tesla

- 1232 dipole magnets needed each is 15 m long (+ quadrupoles, sextupoles, etc.)
  - 1.9 K operating temperature
  - Supraliquid Helium
  - Largest cryogenic facility in the world

- Quench protection
  - Stored energy in one dipole: 8 MJ corresponds to a 40 t truck at 50 km/h

- LHC dipole design incorporates reversed field for oppositely rotating proton beams
LHC Dipoles

- Around 1999: construction of dipoles start
Cryogenics

- First cool down of an LHC sector (> 3 km) in April 2007
- 1.9 K: coldest place in the universe
Challenges for LHC Detectors

- **Protons are composite particles**
  - LHC collides protons on protons
  - But collisions of quarks and gluons are the fundamental processes
  - Screened by interactions of other quarks & gluons (underlying event)

- **LHC is filled with 2835 + 2835 proton bunches**
  - Collisions every 25 ns
  - 40 MHz crossing rate

- **$10^{11}$ protons per bunch**
  - 25 pp interactions per crossing (pile-up)
  - Each bunch collision produces $\approx 1600$ charged particles
A Collision Producing a Higgs Boson

- Identify each track requires a highly granular detector
- Reconstruct every track takes a lot of computing power

- with 25 pile-up interactions

- Remove low energy tracks ($p_T < 25$ GeV)
- $H \rightarrow ZZ \rightarrow 4$ muons
Example: CMS Tracking Detector

- Silicon strip detector

- 16000 such modules built
- 220 m² of silicon surface (almost a tennis court…)
- Largest silicon detector ever built
A Dream Becomes Reality...
Low luminosity phase

\[ 10^{33}/\text{cm}^2/\text{s} = 1/\text{nb/s} \]

approximately

- \( 10^8 \) pp interactions
- \( 10^6 \) bb events
- 200 W-bosons
- 50 Z-bosons
- 1 tt-pair

will be produced per second and

- 1 light Higgs per minute!

The LHC is a b, W, Z, top, Higgs, … factory!

The problem is to detect the events!

Cross Section of Various SM Processes
Experimental Signatures

1. Hadronic final states, e.g. quark-quark
   - no high $p_T$ leptons or photons in the final state
   - holds for the bulk of the total cross section

2. Lepton/photons with high $p_T$, example Higgs production and decay
   - Important signatures for interesting events:
     - leptons and photons
     - missing transverse energy
Detector Design Aspects

- **good measurement of leptons (high $p_T$)**
  - muons: large and precise muon chambers
  - electrons: precise electromagnetic calorimeter and tracking

- **good measurement of photons**

- **good measurement of missing transverse energy ($E_T^{\text{miss}}$)**
  requires in particular good hadronic energy measurements down to small angles, i.e. large pseudo-rapidities ($\eta \approx 5$, i.e. $\theta \approx 1^\circ$)

- **in addition identification of b-quarks and $\tau$-leptons**
  precise vertex detectors (Si-pixel detectors)

**Very important: radiation hardness**
  e.g. flux of neutrons in forward calorimeters $10^{17}$ n/cm$^2$ in 10 years of LHC operation
Trigger of interesting events at the LHC is much more complicated than at $e^+e^-$ machines

- interaction rate: $\approx 10^9$ events/s
- max. record rate: $\approx 100$ events/s  
  
  event size $\approx 1$ MByte $\Rightarrow$ 1000 TByte/year of data

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

- collision rate is 25 ns  (corresponds to 5 m cable delay)
- trigger decision takes $\approx$ a few $\mu$s

$\Rightarrow$ store massive amount of data in front-end pipelines  
  while special trigger processors perform calculations
The ATLAS experiment
A Toroidal LHC ApparatuS

ATLAS in a nutshell:
- Large air toroid with $\mu$ chambers
- HCAL: steel & scintillator tiles
- ECAL: LAr
- Inner solenoid (2 T)
- Tracker: Si-strips & straw tubes (TRD)
- Si-pixel detector
  $10^8$ channels
  15 $\mu$m resolution
ATLAS with inner Detectors
CMS in a nutshell:
- 4 T solenoid
- $\mu$ chambers in iron yoke
- HCAL: copper & scintillator
- ECAL: $\text{PbWO}_4$ crystals
- All Si-strip tracker
  220 m², $10^7$ channels
- Si-pixel detector similar to ATLAS
### Comparison ATLAS and CMS

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>length</td>
<td>≈ 46 m</td>
<td>≈ 22 m</td>
</tr>
<tr>
<td>diameter</td>
<td>≈ 25 m</td>
<td>≈ 15 m</td>
</tr>
<tr>
<td>weight</td>
<td>≈ 7000 t</td>
<td>≈ 12000 t</td>
</tr>
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</table>
LHC Jet Physics

- Jet rates will be one of the first LHC results: statistical precision

Jet rates will be one of the first LHC results: statistical precision

- compare to CDF result run II

100 pb\(^{-1}\) = few weeks (or months) at 14 TeV

10 fb\(^{-1}\) = 1 year

- detector systematic effects expected to be similar to Tevatron
- provides handle on PDF
Jet Physics

Jet physics at the LHC
- $E_T$ spectrum, rate varies over 11 orders of magnitude
- Test QCD at the multi-TeV scale

Inclusive jet rates for 300 fb$^{-1}$:

<table>
<thead>
<tr>
<th>$E_T$ of jet</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&gt; 1$ TeV</td>
<td>$4 \times 10^6$</td>
</tr>
<tr>
<td>$&gt; 2$ TeV</td>
<td>$3 \times 10^4$</td>
</tr>
<tr>
<td>$&gt; 3$ TeV</td>
<td>400</td>
</tr>
</tbody>
</table>
**W/Z Physics at the LHC**

- Very clean selection of W and Z boson possible
e.g. CMS study of $W \rightarrow e\nu$ and $Z \rightarrow ee$

Recall rates (initial phase $10^{33}$/cm$^2$/s):

$\approx 200 \; W/s \rightarrow \approx 20 \; W \rightarrow e\nu \;/s$

$\approx 50 \; Z/s \rightarrow \approx 1.5 \; Z \rightarrow ee \;/s$

plus the same rates for muon decays!

- $W$ and $Z$ events will provide an excellent tool for detector calibration
W Mass at the LHC

CMS: detailed study of statistical and systematic errors

- 1 fb\(^{-1}\): early measurement
- 10 fb\(^{-1}\): asymptotic reach, best calibrated & understood detector, improved theory etc.

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>uncertainty</th>
<th>(\Delta M_W) [MeV/c(^{2})] with 1 fb(^{-1})</th>
<th>uncertainty</th>
<th>(\Delta M_W) [MeV/c(^{2})] with 10 fb(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>statistics</td>
<td>40</td>
<td>10</td>
<td>2%</td>
<td>2</td>
</tr>
<tr>
<td>background</td>
<td>10%</td>
<td>10</td>
<td>2%</td>
<td>2</td>
</tr>
<tr>
<td>electron energy scale</td>
<td>0.25%</td>
<td>10</td>
<td>0.05%</td>
<td>2</td>
</tr>
<tr>
<td>scale linearity</td>
<td>0.00006/ GeV</td>
<td>30</td>
<td>0.00002/ GeV</td>
<td>&lt;10</td>
</tr>
<tr>
<td>energy resolution</td>
<td>8%</td>
<td>5</td>
<td>3%</td>
<td>2</td>
</tr>
<tr>
<td>MET scale</td>
<td>2%</td>
<td>15</td>
<td>&lt;1.5%</td>
<td>&lt;10</td>
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<tr>
<td>MET resolution</td>
<td>5%</td>
<td>9</td>
<td>&lt;2.5%</td>
<td>&lt;5</td>
</tr>
<tr>
<td>recoil system</td>
<td>2%</td>
<td>15</td>
<td>&lt;1.5%</td>
<td>&lt;10</td>
</tr>
<tr>
<td>total instrumental</td>
<td>40</td>
<td>&lt;20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PDF uncertainties</td>
<td>20</td>
<td></td>
<td>&lt;10</td>
<td></td>
</tr>
<tr>
<td>(\Gamma_W)</td>
<td>15</td>
<td></td>
<td>&lt;15</td>
<td></td>
</tr>
<tr>
<td>(p_T^W)</td>
<td>30</td>
<td></td>
<td>30 (or NNLO)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>transformation method applied to (W \rightarrow \mu\nu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>statistics</td>
</tr>
<tr>
<td>background</td>
</tr>
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<td>momentum scale</td>
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<td>(1/p_T^*) resolution</td>
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<td>acceptance definition</td>
</tr>
<tr>
<td>calorimeter (E_T^{miss}), scale</td>
</tr>
<tr>
<td>calorimeter (E_T^{miss}), resolution</td>
</tr>
<tr>
<td>detector alignment</td>
</tr>
<tr>
<td>total instrumental</td>
</tr>
<tr>
<td>PDF uncertainties</td>
</tr>
<tr>
<td>(\Gamma_W)</td>
</tr>
</tbody>
</table>
Di-Boson Production at the LHC

- very interesting: WW, ZZ final states not yet observed at the Tevatron
  first WZ events observed early 2007
- test triple gauge boson couplings (TGC)
  - $\gamma$WW and ZWW precisely fixed in SM
  - $\gamma$ZZ and ZZZ do not exist in SM!

- deviations from SM are amplified with E
- also $W\gamma$ and $Z\gamma$ final states can be used

**SM**

**New physics**

**CMS**

$L = 10 \text{ fb}^{-1}$

$ZZ \rightarrow e^+e^- e^+e^-$

$1 \text{ fb}^{-1}$ sufficient to observe both processes
Top Physics at the LHC

- LHC is a top factory
  - at $10^{33}$/cm$^2$/s
  - 1 $\bar{t}t$ per second or
  - 10 million per year

- Cross section $\approx$ 100 times larger than at the Tevatron
  - 7 pb Tevatron
  - $> 800$ pb LHC

- LHC will eclipse existing knowledge on the top despite problems like
  - pile-up
  - less striking signatures
Why Top Physics at the LHC?

- **ttbar production** is a standard candle at high $Q^2$
  - relatively precisely measureable and calculable
  - cross checks impact of pdf, underlying event, pile-up, ...

- **ttbar production**
  - $\approx 90\%$ gluon fusion
  - $\approx 10\%$ quark annihilation

i.e. similar to e.g. Higgs production

- Important background reaction for many New Physics channels
  - high cross section
  - presence of high $p_T$ lepton(s)
  - multi-jet final states

![Diagram showing ttbar production and Higgs production comparison](image.png)
Top Quark Decay

- **Top decay:**  $\approx 100\% \ t \rightarrow bW$
- **Other rare SM decays:**
  - CKM suppressed $t \rightarrow sW, dW$: $10^{-3} - 10^{-4}$ level
- **& non-SM decays, e.g.** $t \rightarrow bH^+$

In SM topologies and branching ratios are fixed:
- expect two b-quark jets
- plus $W^+W^-$ decay products:
  - 2 charged leptons + 2 neutrinos
  - 1 charged lepton + 1 neutrino + 2 jets
  - 4 jets (no b-quark!)

<table>
<thead>
<tr>
<th>$t\bar{t}$ decay modes</th>
<th>tt decay modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>5% $(e + \mu)$</td>
<td>lepton + jets</td>
</tr>
<tr>
<td>30% $(e + \mu)$</td>
<td>tau + jets</td>
</tr>
<tr>
<td>46%</td>
<td>dilepton</td>
</tr>
</tbody>
</table>
Top Pairs at the LHC

- Re-discovery of top possible with low luminosity (< 100 pb⁻¹)
- Semi-leptonic events

Observation of top quarks demonstrates that the full detector works:
  - electrons/ muons
  - jets
  - b-tagging
  - missing ET
Top Mass at the LHC

Example: detailed studies by CMS:

- **di-leptonic** ± 1.2 GeV
- **semi-leptonic** ± 1.2 GeV
- **fully hadronic** ± 2 GeV
- **$t \rightarrow J/\Psi + l + X$** ± 1.5 GeV

→ total top mass error ≤ 1 GeV possible with O(10 fb$^{-1}$) of well understood data
Some general considerations on LHC early phase

- time scale for discoveries not necessarily determined by ramp-up of integrated luminosity
- but progress and level of detector understanding
  - malfunctions, calibration, alignment

- difficult issues
  - jets
  - missing ET
  - forward detectors

- less critical
  - lepton based measurements
    - in particular muons
Understanding of the Detector

- Example for an easy case: muon pairs

**Drell-Yan production**

![Drell-Yan Production](image1)

**CMS**

Systematic error $\sim 10\%$

"At 100 pb$^{-1}$: 1 TeV $Z'$ with initial alignment"
Difficult example: missing ET
- is a very powerful tool to look for new physics
- but very complicated variable and difficult to understand:
  - collision effects
    - pile-up
    - underlying event
  - beam related background
    - beam halo
    - cosmic muons
  - detector effects
    - instrumental noise
    - dead/hot channels
    - inter-module calibration
SM Higgs Boson Production at the LHC

Once the mass is known all other Higgs properties are fixed!

- Gluon-gluon fusion and W, Z fusion are dominant
- Cross section at the Tevatron almost factor 100 smaller!
**Higgs Boson Decay**

Higgs couples proportional to masses
⇒ preferentially decaying into heaviest particle kinematically allowed

**Branching ratio versus $m_H$:**

- **Low mass** ($115 < m_H < 140$ GeV)
  $H \rightarrow bb$ make up most of the decays
  problem at the LHC because of the huge QCD background!

- **Intermediate** ($140 < m_H < 180$ GeV)
  $H \rightarrow WW$ opens up
  use leptonic $W$ decay modes

- **High mass** ($m_H > 180$ GeV)
  $H \rightarrow ZZ \rightarrow 4$ leptons
  golden channel!
Higgs Boson Decay

What to do in the preferred low mass region, i.e. $m_H < 140$ GeV?

- use $H \rightarrow \gamma \gamma$
- very low branching ratio $O(10^{-3})$
- but clean signature

Total width of the Higgs (= inverse lifetime)

- at low masses Higgs is a very sharp resonance
  \[ \Gamma_H \ll 1 \text{ MeV} \]
- $\Gamma_H$ explodes once $H \rightarrow WW, ZZ$ open up
  for $m_H \rightarrow 1$ TeV
  \[ \Gamma_H \approx m_H \]
Early Higgs Searches

- e.g. $H \rightarrow ZZ \rightarrow ee\mu\mu$ with 0.1 fb$^{-1}$
Search for the Higgs Boson at LHC

Possible future Higgs discovery plots:

H → γγ:
\( m_H = 130 \text{ GeV} \)
\( \sigma_{m_H} \approx 1 \text{ GeV} \)

H → ZZ → 4μ:
\( m_H = 200 \ (300, 500) \text{ GeV} \)

Note the increasing signal width
Search for the Higgs Boson at the LHC

Combine all search channels and determine expected significance as function of the luminosity and Higgs mass:

10 fb\(^{-1}\) sufficient for 5 \(\sigma\) discovery of the Higgs corresponds to 1 year at a luminosity of 10\(^{33}\)/cm\(^2\)/s

- CMS
- ATLAS (no K-factors)
**Production of SUSY particles at the LHC**
- squarks and gluinos are pair-produced through strong interaction, i.e. high cross sections
- but also sleptons and other SUSY particles can be pair-produced
- SUSY particles decay in a chain to SM particles plus the LSP

**Signature:**
- leptons, jets and missing $E_T$
- depend of SUSY particles produced, on their branching ratios etc.

**Strategy to discover SUSY at the LHC:**
- look for deviation from SM in distributions e.g. multi-jet + $E_T^{\text{miss}}$, multilepton+ $E_T^{\text{miss}}$
- establish SUSY mass scale
- try to determine model parameters (difficult!)
**Squarks and Gluinos**

- Strongly produced, cross sections comparable to QCD cross sections at the same mass scale

- If R-parity conserved, cascade decays produce distinctive events: multiple jets, leptons, and $E_T^{\text{miss}}$

- Typical selection: $N_{\text{jet}} > 4$, $E_T > 100, 50, 50, 50$ GeV, $E_T^{\text{miss}} > 100$ GeV

- Define: $M_{\text{eff}} = E_T^{\text{miss}} + P_T^1 + P_T^2 + P_T^3 + P_T^4$ (effective mass)

LHC reach for Squark- and Gluino masses:

- $1$ fb$^{-1}$ $\Rightarrow$ $M \sim 1500$ GeV
- $10$ fb$^{-1}$ $\Rightarrow$ $M \sim 1900$ GeV
- $100$ fb$^{-1}$ $\Rightarrow$ $M \sim 2500$ GeV

TeV-scale SUSY can be found rather quickly!

**example:** mSUGRA

$m_0 = 100$ GeV, $m_{1/2} = 300$ GeV
$tan b = 10$, $A_0 = 0$, $m > 0$
Early SUSY Searches

- Low mass SUSY ($M_{sp} \approx 500$ GeV) accessible with $O(100$ pb$^{-1}$)
- However time to discovery will be determined by
  - time to understand detector performance, e.g. $E_T^{miss}$
  - time to collect control samples e.g. W+jets, Z+jets, top,...
Early SUSY Searches

- Control over physics background
- Example $E_T^{\text{miss}} + \text{jets}$:
  - background from $Z \rightarrow \nu\nu (+\text{jets})$
  - normalise to $Z \rightarrow \mu\mu (+\text{jets})$

- Inclusive searches for 1 fb$^{-1}$
SUSY Search at LHC

Example: discovery reach as function of luminosity and model parameters which fix the mass scale of SUSY parameters

- achievable limits exploiting $E_T^{\text{miss}}$ signatures
- requires very good understanding of detectors

Conclusion:
- LHC will eclipse today’s limits on SUSY particles and parameters
- or discover SUSY if it exists at the TeV scale
Where are we today? Status and Expectations

- First circulating beams on September 10, 2008
LHC Accident

- Major accident on September 19, 2008
  - Bad connection between 2 magnets (resistance $\gg 1 \text{n}\Omega$)
  - Heat load $\approx 10 \text{ W}$ cannot be cooled away
  - Thermal runaway
- Quench protection of magnets worked well
- But light arc between magnets
  - Destroyed a Helium vessel
  - 2 tons of He effused
  - Shock wave in tunnel
53 magnets inspected, repaired & reinstalled
**Plans**

- Improve protection systems
- Restart LHC in September 2009
- First collisions in October 2009
- Operation until end 2010
  - reduced energy (4-5 TeV)
- Detectors are ready and preparing for data taking with cosmic rays
Summary & Outlook

- LHC start second half 2009
  - Collisions at 4-5 TeV energy (single beam)
  - 1st run continuously until end 2010
  - expected luminosity: a few 100 pb-1
- Detectors are ready for data taking
- The LHC experiments will
  - further improve knowledge on W boson, top quarks, QCD
  - will probe physics at the smallest distance scale
  - will answer the question if there is a Higgs boson or not
  - probe models like SUSY on the (multi-)TeV scale

Very exciting times are ahead of us!
Backup slides
A Collider for the Terascale

- **Electron-Positron Collider**
  - Like DORIS & PETRA at DESY or LEP at CERN
  - Point-like particles
  - But limited in energy by synchrotron radiation

- **Proton-(anti)proton collider**
  - Higher energy reach limited by magnet bending power
  - But much harder for experiments
Comparison of ATLAS and CMS

Physics performance: comparison in terms of mass resolutions

<table>
<thead>
<tr>
<th>System</th>
<th>ATLAS ((\text{GeV} \cdot \text{c}^{-2}))</th>
<th>CMS ((\text{GeV} \cdot \text{c}^{-2}))</th>
<th>LHCb ((\text{GeV} \cdot \text{c}^{-2}))</th>
<th>ALICE ((\text{GeV} \cdot \text{c}^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B \rightarrow \pi \pi)</td>
<td>0.070</td>
<td>0.031</td>
<td>0.017</td>
<td>—</td>
</tr>
<tr>
<td>(B \rightarrow J/\psi K_S^0)</td>
<td>0.019</td>
<td>0.016</td>
<td>0.010</td>
<td>—</td>
</tr>
<tr>
<td>(Y \rightarrow \mu \mu)</td>
<td>0.152</td>
<td>0.050</td>
<td>—</td>
<td>0.107</td>
</tr>
<tr>
<td>(H(130 \text{ GeV c}^{-2}) \rightarrow \gamma \gamma)</td>
<td>1.55</td>
<td>0.9</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>(H(150 \text{ GeV c}^{-2}) \rightarrow ZZ^* \rightarrow 4\mu)</td>
<td>1.60</td>
<td>1.35</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>(A(500 \text{ GeV c}^{-2}) \rightarrow \tau \tau)</td>
<td>50.0</td>
<td>75.0</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>(W \rightarrow \text{jet jet})</td>
<td>8.0</td>
<td>10.0</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>(Z'(3 \text{ TeV c}^{-2}) \rightarrow \mu \mu)</td>
<td>240</td>
<td>170</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>(Z'(1 \text{ TeV c}^{-2}) \rightarrow ee)</td>
<td>7.0</td>
<td>5.0</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

LHCb

- Experiment to address the question of matter-antimatter asymmetry
ALICE

- Experiment addresses new state of matter: the quark-gluon plasma

- Heavy ion collisions, eg. Pb-Pb
QCD and Jet Physics

- Hard scattering processes dominated by QCD jet production
- Originating from quark-quark, quark-gluon and gluon-gluon scattering
- Colored objects fragment
  \[ \rightarrow \text{observation of jets with high } p_T \text{ in the detectors} \]
- Studies of jet production is important
  - test of the experiment
  - test of the theory, down to the smallest distances
  - new physics, e.g. quark substructure?
QCD

Measurement of $\alpha_s$ at LHC limited by

- PDF (3%)
- Renormalisation & factorisation scale (7%)
- Parametrisation (A,B)

\[
\frac{d\sigma}{dE_T} \sim \alpha_s^2(\mu_R)A(E_T) + \alpha_s^3(\mu_R)B(E_T)
\]

- 10% accuracy $\alpha_s(m_Z)$ from incl. jets
- Improvement from 3-jet to 2-jet rate?

Verification of running of $\alpha_s$ and test of QCD at the smallest distance scale

- $\alpha_s = 0.118$ at $m_Z$
- $\alpha_s \approx 0.082$ at 4 TeV (QCD expectation)
W Mass at the LHC

- Any improvement at the LHC requires control of systematic error to $10^{-4}$ level
  - take advantage from large statistics $Z \rightarrow e^+e^-, \mu^+\mu^-$
  - most experimental and theoretical uncertainties cancel in $W/Z$ ratio
    e.g. Scaled Observable Method

\[ O_v = E^7, M^T \] distributions are scaled according to

\[ \frac{d\sigma^w}{dO_w}(O_w = XM_w) = \frac{M_z}{M_w} R(X) \frac{d\sigma^z}{dO_z}(O_z = XM_z) \]


- Another method:
  generate $W \rightarrow e(\mu)\nu$ „Monte Carlo“ from data by removing a lepton from $Z \rightarrow e^+e^-, \mu^+\mu^-$ events

- NNLO calculations ($p_T$ spectra) probably needed to achieve the required precision
Top Quarks at the LHC

Examples of simulated $tt \rightarrow bb qq \mu \nu$ events from CMS & ATLAS
Massive gauge bosons have three polarization states

At LEP in $e^+e^- \rightarrow W^+W^-$:

- determine $W$ helicity from lepton (quark) decay angle in $W$ rest frame $\theta^*$
  - $(1 \pm \cos \theta^*)^2$ transverse
  - $\sin^2\theta^*$ longitudinal

- Fraction of longitudinal $W$ in $e^+e^- \rightarrow W^+W^-$
  - $0.218 \pm 0.031$
  - SM: 0.24

- Tevatron:
  - Longitudinal $W$ in top decays
    - $0.91 \pm 0.52$ CDF
    - $0.56 \pm 0.31$ D0
    - SM: 0.7
Very short lifetime, no top bound states
⇒ Spin info not diluted by hadron formation

\[
A = \frac{N(t_L \bar{t}_L + t_R \bar{t}_R) - N(t_L \bar{t}_R + t_R \bar{t}_L)}{N(t_L \bar{t}_L + t_R \bar{t}_R) + N(t_L \bar{t}_R + t_R \bar{t}_L)}
\]

Distinguishes between
• quark annihilation
  \( A = -0.469 \)
• and gluon fusion
  \( A = +0.431 \)

Use double leptonic decays
\( tt \rightarrow bb \ell^+ \ell^- \)

\[ A = 0.311 \pm 0.035 \pm 0.028 \] (using 30 fb\(^{-1}\))
Early Higgs Searches

- Best chances around $m_H \approx 2m_W$ in $H \rightarrow WW \rightarrow 2l + 2\nu$ channel
Search for the Higgs Boson

**LEP:**

- $H \rightarrow bb$
- $H \rightarrow \gamma\gamma$
- $H \rightarrow W^+W^-$
- $H \rightarrow ZZ$

**LHC:**

- $H \rightarrow bb$
- $H \rightarrow \gamma\gamma$
- $H \rightarrow W^+W^-$
- $H \rightarrow ZZ$

- enormous QCD bkgd
- low $m_H$ (BR $\approx 10^{-3}$)
- medium $m_H$
- high $m_H$

$H \rightarrow \gamma\gamma$

$H \rightarrow ZZ \rightarrow 4\mu$ (golden channel)
Why SUSY?

1. Quadratically divergent quantum corrections to the Higgs boson mass are avoided

\[ \Delta m_H = f(m_B^2 - m_f^2) \]

(Hierarchy or naturalness problem)

2. Unification of coupling constants of the three interactions seems possible

3. SUSY provides a candidate for dark matter,

The lightest SUSY particle (LSP)

4. A SUSY extension is a small perturbation, consistent with the electroweak precision data

\[ m_{\text{SUSY}} \sim 1 \text{ TeV} \]
Early SUSY Searches

Inclusive searches for 1 fb⁻¹

\[ \tan \beta = 10, \ A_0 = 0, \ \mu > 0 \]

\[ m_h = 120 \text{ GeV} \]

\[ m_\chi = 103 \text{ GeV} \]

\[ m_\chi = 114 \text{ GeV} \]

\[ \text{NO EWSB} \]
SUSY Searches

LHC Strategy: End point spectra of cascade decays

Example: \( \tilde{q} \rightarrow q\tilde{\chi}_2^0 \rightarrow q\ell^+\ell^- \rightarrow q\ell^+\ell^-\tilde{\chi}_1^0 \)

\[ M_{\ell^+\ell^-}^{\text{max}} = \frac{\sqrt{(m_{\tilde{\chi}_2^0}^2 - m_{\ell}^2)(m_{\ell}^2 - m_{\tilde{\chi}_1^0}^2)}}{m_{\tilde{\chi}_2^0}} \]

\[ M_{\ell^+l^-}^{\text{max}} = \frac{\sqrt{(m_{\tilde{\chi}_2^0}^2 - m_{\ell}^2)(m_{\ell}^2 - m_{\tilde{\chi}_1^0}^2)}}{m_{\tilde{\chi}_2^0}} \]

[Graph showing event distribution with signal, SM background, and SUSY background]
SUSY signals

Second lighest neutralino $\chi^0_2$
- cascade decay
- leptons + $E_T^{miss}$

- cascade decay with $h$
- b-jets + $E_T^{miss}$

CMS

1 fb$^{-1}$

number of lepton pairs

$M(\tilde{\chi}^0_2)$ (GeV/c$^2$)

Events

$M_{h\gamma}$ (GeV)

$\chi^0_2 \rightarrow \ell \chi^0_1$

$\chi^0_2 \rightarrow h \chi^0_1$

$\tilde{\chi}^0_2 \rightarrow \chi^0_1 + \ell$

$\tilde{\chi}^0_2 \rightarrow h \ell$

$\tilde{\chi}^0_2 \rightarrow \chi^0_1 + b\ell$

$\tilde{\chi}^0_2 \rightarrow h b$

$\tilde{\chi}^0_2 \rightarrow \chi^0_1 + b\bar{b}$

$\tilde{\chi}^0_2 \rightarrow h b$
Extra Dimensions: $Z'$/ Randall-Sundrum

With 1 fb$^{-1}$:
- $Z'$ discovery up to 2 - 2.5 TeV
- most of RS parameter space covered