Physics at Hadron Colliders

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Rathen
15-17/09/09
Day 1:
1. Introduction (“Why?”)
2. Hadron Collider basics
3. Colliders
4. Detectors

Day 2:
5. Data reconstruction + Analysis
6. Physics
   6.1 QCD + Electroweak
   6.2 Top Quark

Day 3:
6.3 Higgs Bosons
6.4 Beyond SM Physics

• I’m happy to answer questions at any time
• Any selection of topics is biased – in these lectures as well…
1. Introduction

„Why?“
1. Introduction

In a nutshell: the big questions of microscopic physics

- Standard Model is extremely successful
- Experimental discovery of all of its matter constituents and force carriers
- Simple common approach to describe all (relevant) forces: QFT with a gauge principle
- Self-consistent at the level of quantum corrections
1. Introduction

In a nutshell: the big questions of microscopic physics

1st “but”:

The SM’s suggestion how to break electro-weak symmetry is not verified

Higgs mechanism (i.e. the SM approach) is a viable solution and evidence is compelling:

Experimental challenge #1:

Find this Higgs (or its relatives) or exclude it!

something in the loops mimics a light Higgs
or it is a light Higgs…
2nd ‘but’:

Even if we find a light Higgs:
why is it so light?

If there are no new phenomena which protect radiative corrections to the Higgs mass, it will receive un-naturally large (quadratic) corrections:

\[ m_H = m_{\text{bare}} - \delta m \approx (200 \text{ GeV}) \]

\[ \delta m \sim \Lambda^2 \quad m_{\text{bare}} \text{ and } \delta m \text{ are both } o(\Lambda^2) \text{ but almost equal!} \]

‘fine tuning’

We know this since so long that some of us are even willing to accept it (e.g. split SUSY, …)

Nevertheless, there are very good ideas how to protect the Higgs mass

Experimental challenge #2:

Find out what protects the Higgs mass at the TeV scale
1. Introduction

In a nutshell: the big questions of microscopic physics

3rd ‘but’:

Our beloved SM contains only a tiny fraction of what’s in our universe today! (how embarrassing)

The Universe:
- 5% SM matter
- 25% dark matter
- 70% dark energy

Experimental challenge #3:
What is the microscopic nature of dark matter (and dark energy?)
1. Introduction

In a nutshell: the big questions of microscopic physics

4th ‘but’:

We would probably not be happy with the answers to ‘but’s 1-3 unless they tell us something about physics at even higher energy scales!

a) unification of forces
b) connection between families (flavour physics)

We do have hints to very high scale physics

- a) unification of forces?
- b) heavy neutrinos?

$$m_N = \frac{m_D}{m_{\nu}} \approx \frac{1 \text{GeV}^2}{10^{-2} \text{eV}^2} = 10^{11} \text{GeV}$$

Experimental challenge #4:

Can precise measurements at the TeV-scale yield information about unification at very high scales?
The SM was to a large extent established at (hadron+lepton) colliders

The road ahead of us will need a broader set of exp. techniques:

- neutrino physics (from space + from accelerators/reactors)
- astro(particle)physics experiments (CMB, cosmic rays, DM searches, …)
- ultra-high precision at low energy (rare decays, g-2, …)

- but of course again colliders!

Which energy?

The TeV scale looks very interesting!

Why? →
1. Introduction

Why is the TeV scale interesting?

1. SM without Higgs violates unitarity (in $W_L W_L \rightarrow W_L W_L$) at 1.3 TeV! (something must happen!)

2. Higgs field vacuum expectation value $v = 246$ GeV

3. Evidence for light Higgs

4. Dark Matter consistent with (sub) TeV-scale WIMP (e.g. SUSY-LSP)

5. $2m_{\text{top}} = 350$ GeV

6. “Fine tuning” can be mitigated with TeV-scale new physics (SUSY,...)
1. Introduction

Experiments at high energy

- \[ E = \frac{hc}{\lambda} \]
  resolve small structures

- \[ E = mc^2 \]
  directly produce new particles

Relevant energy: centre-of-mass energy

\[ \rightarrow \text{colliders} \quad E_{\text{cm}} = 2 E_{\text{beam}} \]

(fixed target: \( E_{\text{cm}} = \sqrt{2}(E_{\text{beam}} m_{\text{target}}) \))
would need \( 10^{17} \text{eV} (= 100000 \text{ TeV}) \)
to have same c.m.s.
(+ cms system extremely boosted in laboratory)
1. Introduction

High energy accelerators vs. Cosmic Rays

Cosmics $> 10^{17}$ eV:
$\sim 10^{12}$ particles / earth / year

LHC:
$10^{16}$ collisions / year

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2. Basics
Rate of events for a given physics process with cross section $\sigma$:

$$N = L \cdot \sigma$$

units: $s^{-1} = cm^{-2} \cdot s^{-1} \cdot cm^2$

Luminosity depends on machine parameters:

$$\mathcal{L} = \frac{N_1 N_2 f}{4\pi \sigma_x \sigma_y}$$

#particles / bunch

repetition frequency

$\sim$ #colliding bunches

beam dimensions at IP

$L = 3.5\cdot10^{32} \, cm^{-2} \, s^{-1}$ peak luminosity reached at Tevatron Run II

$L = 10^{30} - 10^{32} \, cm^{-2} \, s^{-1}$ luminosity at LHC startup (1st year)

$L = 10^{33} \, cm^{-2} \, s^{-1}$ years 2-n of the LHC

$L = 10^{34} \, cm^{-2} \, s^{-1}$ LHC design luminosity (after n years)

(1000 x larger than LEP-2, 30 x Tevatron Run II)

Integrated Luminosity per “year”:

$$\int L dt = 10^7 \, s \ast L$$

$L_{int/year} = L[cm^{-2} \, s^{-1}] / 10^{32} \, fb^{-1}$
Two complementary approaches

- **p** = composite particle
  - unknown c.m.s. of initial system
  - parasitic collisions

- **p** = strongly interacting
  - huge SM backgrounds
  - not possible to reconstruct all f.st.
  - need highly selective trigger

- **e** = pointlike particle
  - c.m.s. = lab system
  - can use kinematic constraints

- **e** = electro-weakly interacting
  - low SM backgrounds
  - can reconstruct all final states
  - no trigger needed!

- **e** = easier to reach high energies
  - difficult to reach high energies (synchrotron radiation)
Hadron Collisions are a big mess

Idea stolen from K. Jakobs

why are we interested in that?
The (most) simplified view:

A fraction of the hadron-hadron-collisions contain a **hard scattering** process:

Collisions of two partons (with momentum fractions $x_1$, $x_2$) collide in a $2 \to 2$ (or $2 \to 1$, $2 \to 3$, ...) scattering process at parton c.m.s. energy

If $\sqrt{s} = \sqrt{x_1 x_2 s}$ is large the partonic process

- can be calculated perturbatively
- dominates the observable final state

(high $p_T$ – process)

<table>
<thead>
<tr>
<th>To produce a mass of:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>LHC</td>
</tr>
<tr>
<td>100 GeV: $x \sim 0.007$</td>
</tr>
<tr>
<td>5 TeV: $x \sim 0.36$</td>
</tr>
</tbody>
</table>
2. Basics | Examples for hard scattering processes

<table>
<thead>
<tr>
<th>QCD</th>
<th>Electro-Weak</th>
<th>New Physics</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="QCD Diagram" /></td>
<td><img src="image" alt="Electro-Weak Diagram" /></td>
<td><img src="image" alt="New Physics Diagram" /></td>
</tr>
</tbody>
</table>

...
2. Basics

Hadron – Hadron Collisions – more realistic view

Very complex process
Many approximations
→ MC Generators
→ data driven modelling
• hard scattering
• parton shower
• initial + final state rad.
• hadronisation
• hadron decays
• underlying event
  (multi-parton int.)
not shown:
virtual higher order correctionss

[Krauss]
2. Basics

Higher orders are important (→ QFT)

Figure 2: Sample two-loop diagrams contributing to the virtual corrections at NNLO.

[Harlander,Kilgore]
A busy multi-particle event can be revealed to be a „clean“ Higgs event after a $p_T$ cut.

Reconstructed tracks with $pt > 25$ GeV

note: it´s not always that simple…
c.m.s. of the hard scattering is unknown (even in the simple picture) 
\((x_1, x_2 \text{ unknown} \rightarrow \text{unknown longitudinal momentum of parton system})\)

\(\rightarrow\) use variables which are insensitive to longitudinal boosts

**Transverse momentum (invariant)**

\[ p_T = p \sin \theta \]

**Pseudorapidity (differences are invariant)**

\[ \eta = -\ln \tan \theta/2 \]
2. Basics

Cross section for hard processes

\[
\sigma = \sum_{a,b} \int d\alpha_a \int d\alpha_b \ f_a(\alpha_a, Q^2) \ \hat{\sigma}_{ab}(\alpha_a, \alpha_b) f_b(\alpha_b, Q^2)
\]

\(\hat{\sigma}_{ab}(\alpha_a, \alpha_b)\): hard scattering (parton) cross section for \(ab \rightarrow cd\)

\(f_a(\alpha_a, Q^2), f_b(\alpha_b, Q^2)\): parton density functions

\(a, b = q, \bar{q}, g\)

\(Q^2\): "energy scale" of hard process (\(p_T, \hat{s}, \ldots\)) not very well defined
2. Basics

Parton density functions

Have to be measured – mainly from deep inelastic scattering:
H1 & ZEUS at the HERA ep collider at DESY (1992-2007)

- Gluons dominate at low $x$
- Also (sea)quarks + antiquarks rise towards low-$x$ for larger $Q^2$

$Q^2$ evolution follows DGLAP eqn. can be extrapolated
2. Basics  

“Soft” processes

Hard processes are only a tiny fraction of total cross section

Most interactions due to interactions at large distance between incom. protons

Small momentum transfer, particles in the final state have large longitudinal, but small transverse momentum

\[ < p_T > \approx 600 \text{ MeV} \]  (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”

They dominate the total rate
Their properties cannot be calculated from pQCD!
Need to be measured
“Interesting“ cross sections highly suppressed w.r.t. \( \sigma_{\text{tot}} \) or even \( \sigma_b \)

But huge rates:

- min. bias \( 10^9 \) Hz
- \( \text{bb pairs} \) \( 5 \times 10^6 \) Hz
- \( \text{tt pairs} \) \( 8 \) Hz
- \( W \to e \nu \) \( 150 \) Hz
- \( Z \to e e \) \( 15 \) Hz
- Higgs (150 GeV) \( 0.2 \) Hz
- SUSY (1 TeV) \( 0.03 \) Hz
2. Basics

Parton Luminosities

[Stirling]
End of Day 1
3. Colliders

(very short)
3. Colliders

Tevatron

- Proton-Antiproton

Pro:
Annihilation processes with valence quarks (high $x \rightarrow$ large $\sqrt{s'}$)

Con:
Antiproton production + recycling tedious (limits luminosity)

- 36x36 bunches
- bunch crossing 396 ns
- Run II started in March 2001
3. Colliders

Tevatron

- Peak Luminosity: $3.5 \times 10^{32}$ cm$^{-2}$ s$^{-1}$
- Run II delivered: $\sim 7$ fb$^{-1}$

Run II Goal: 12 fb$^{-1}$ by end of 2011

note: most analyses by now only use 50% or less of recorded data
3. Colliders

The Large Hadron Collider LHC

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton - Proton</td>
<td></td>
</tr>
<tr>
<td>Design beam energy</td>
<td>7 TeV</td>
</tr>
<tr>
<td>Design luminosity</td>
<td>$10^{34}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>25 ns</td>
</tr>
<tr>
<td>Particles/Bunch</td>
<td>$10^{11}$ x 2808 bunches</td>
</tr>
<tr>
<td>SC Dipoles</td>
<td>1232, 15 m, 8.33T</td>
</tr>
<tr>
<td>Stored Energy</td>
<td>350 MJ/Beam</td>
</tr>
<tr>
<td>Stored Energy (magnets)</td>
<td>10 GJ</td>
</tr>
<tr>
<td>(10 GJ melt 24 tons of Cu)</td>
<td></td>
</tr>
<tr>
<td>3. Colliders</td>
<td>LHC Status</td>
</tr>
<tr>
<td>--------------</td>
<td>------------</td>
</tr>
<tr>
<td>Sept 10, 2008: first beam day</td>
<td></td>
</tr>
<tr>
<td>Sept 10-12, 2008: very successful commissing - „feels like an old friend“ (L. Evans)</td>
<td></td>
</tr>
<tr>
<td>beam life times ~ hours!</td>
<td></td>
</tr>
<tr>
<td>Sept 19, 2008: electrical connection between two magnets („busbar“) in S34 had too high R (200 nΩ instead of 0.3 nΩ) produced too much heat → SC quench → more heat → melting connection → insulation vacuum damaged → LHe into vacuum → mechanical damage, 400 MJ dissipated, 6t He into tunnel</td>
<td></td>
</tr>
<tr>
<td>June 2, 2009 39 dipoles and 14 quadrupoles repaired/replaced, electrical connection finished</td>
<td></td>
</tr>
<tr>
<td>improved diagnostics, many measurements, add. pressure release valves, improved mech. anchoring, enhanced quench protection system: avoid reoccurrence!</td>
<td></td>
</tr>
</tbody>
</table>

[Burkhardt LP09]

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3. Colliders | Prospects

Restart with beam planned in mid-November (long run until end 2010)
Collisions at injection energy $2 \times 0.45$ TeV = 0.9 TeV
2. physics run at $2 \times 3.5$ TeV = 7 TeV
3. physics run at increased energy, max. $2 \times 5$ TeV = 10 TeV (H.Ions end 2010)
Luminosity?

<table>
<thead>
<tr>
<th>Energy</th>
<th>TeV</th>
<th>No crossing angle</th>
<th>Crossing angle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.45</td>
<td>0.45</td>
<td>3.50</td>
</tr>
<tr>
<td></td>
<td>0.45</td>
<td>3.50</td>
<td>3.50</td>
</tr>
<tr>
<td>Bunch intensity</td>
<td>1.0E+10</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Bunches</td>
<td>4</td>
<td>43</td>
<td>43</td>
</tr>
<tr>
<td>Emittance</td>
<td>$\mu$m</td>
<td>3.75</td>
<td>3.75</td>
</tr>
<tr>
<td>$\beta^*$</td>
<td>m</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>Luminosity</td>
<td>cm$^{-2}$s$^{-1}$</td>
<td>4.2E+26</td>
<td>7.2E+28</td>
</tr>
<tr>
<td>Protons</td>
<td></td>
<td>4.0E+10</td>
<td>1.7E+12</td>
</tr>
<tr>
<td>% nominal</td>
<td></td>
<td>0.0</td>
<td>0.5</td>
</tr>
<tr>
<td>Stored energy</td>
<td>MJ</td>
<td>0.0</td>
<td>0.1</td>
</tr>
<tr>
<td>Monthly (0.2)</td>
<td>pb-1</td>
<td>0.00</td>
<td>0.04</td>
</tr>
<tr>
<td>Pile-up, $\sigma_\text{in} = 75$ mb</td>
<td></td>
<td>0.09</td>
<td>0.5</td>
</tr>
</tbody>
</table>

[Burkhardt LP09]
4. Detectors
4. Detectors  CDF @ Tevatron

New in Run II:

Tracking system

- Silicon vertex detector (SVXII)
- Intermediate silicon layers
- Central outer tracker (COT)
- End plug calorimeter
- Time of flight system
- Front-end electronics
- Trigger and DAQ systems

12 countries, 59 institutions
706 physicists
19 countries, 83 institutions

664 physicists

New for Run II

Inner detector
magnetic field added

Preshower detectors
Forward muon detector

Front-end electronics
Trigger and DAQ
4. Detectors

LHC Detectors

LHCb

ATLAS

b-quark physics

CMS

ALICE

heavy ion collisions
<table>
<thead>
<tr>
<th>4. Detectors</th>
<th>LHC Detectors - Requirements</th>
</tr>
</thead>
</table>

Principles of particle detection + Overall structure similar to previous detectors (LEP, HERA, Tevatron) - **BUT**

**Specific challenges at LHC**

- **Huge absolute collision rate** (25 ns, up to 40 minimum bias events per BX)
  - fast detectors (identify each bunch crossing)
  - radiation hardness (tolerate up to $10^{17}$ n/cm$^2$ trackers: $10^{14}$ n/cm$^2$)
  - high granularity (handle pile-up)
  - trigger (suppress to $10^{-7}$ of input), DAQ, reconstruction, analysis

- **Small Signal/Background ratio**
  - e.g. $\sigma_{\text{Higgs}}/\sigma_{\text{tot}} \sim 10^{-9}$ - visible $\sigma_{\text{Higgs}}$ even smaller
  - very powerful object identification / jet background suppression needed
  - mass reconstruction of leptonic/photon (H,Z) and jet (top→bqq) objects

- **Higher energies than previously**
  - large B-Field (→ tracking up to 3-5 TeV)
  - larger calorimeters (→ containment of had. showers → muon ID)
## 4. Detectors

### LHC Detectors - Targets

**Physics object identification – suppression of QCD jets**

<table>
<thead>
<tr>
<th>Object</th>
<th>Efficiency</th>
<th>BG suppr.</th>
<th>Motivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>electrons</td>
<td>&gt;70%</td>
<td>100000</td>
<td>Z,W,top,H→4ℓ,...</td>
</tr>
<tr>
<td>photons</td>
<td>80%</td>
<td>1000</td>
<td>H→γγ</td>
</tr>
<tr>
<td>muons</td>
<td>&gt;97% for p_T&gt;1GeV</td>
<td></td>
<td>H→4ℓ,...</td>
</tr>
<tr>
<td>tau leptons</td>
<td>50%</td>
<td>100</td>
<td>H/A→ττ, SUSY,…</td>
</tr>
<tr>
<td>b-jets</td>
<td>50%</td>
<td>100</td>
<td>top, H→bb,SUSY,…</td>
</tr>
</tbody>
</table>

**Mass resolution (calorimetric)**

(to suppress ~flat backgrounds)

- Photons, Electrons: 1%
  - (H→γγ, high mass resonances)

- B-Jets, Jets: 10%
  - W, top, high mass resonances

\[ S/B = 0.027 \]
4. Detectors

The ATLAS Experiment

Muon Detectors  Tile Calorimeter  Liquid Argon Calorimeter

Diameter 25 m
Barrel toroid length 26 m
Total length 46 m
Overall weight 7000 t

~2800 physicists
169 institutions
37 countries
5 continents

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SC Toroid: installation of last coil
4. Detectors               The ATLAS Experiment

Pixel detector: ~ 80 million channels
50\(\mu\)m x 400\(\mu\)m long

700 Muon Chambers
(Monitored Drift Tubes)
600 Muon Trigger Chambers (RPCs)

LAr calorimeter in final position
4. Detectors

The CMS Experiment

- Diameter: 15 m
- Total length: 22 m
- Overall weight: 12,500 t

>2500 physicists
183 institutions
38 countries
4 continents
CMS completed and closed for beams in Sept 2008
4. Detectors

CMS – Si tracker: from design…
4. Detectors

| CMS Si tracker - … to reality |

![CMS Si tracker image](Image)
### 4. Detectors

**ATLAS vs. CMS – complementary technology choices**

<table>
<thead>
<tr>
<th></th>
<th><strong>ATLAS</strong></th>
<th><strong>CMS</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Solenoidal B-Field</td>
<td>2T in front of ECAL</td>
<td>4T behind HCAL</td>
</tr>
<tr>
<td>Tracking</td>
<td>Si (Pixel+Strips)+Gas (TRT)</td>
<td>all Si (Pixel+Strips)</td>
</tr>
<tr>
<td>ECAL</td>
<td>L-Ar (high granularity)</td>
<td>PbWO(_4) crytsals (high E-resolution)</td>
</tr>
<tr>
<td>HCAL</td>
<td>Fe – Scintillator (10(\lambda))</td>
<td>Brass – Scintillator (7(\lambda))</td>
</tr>
<tr>
<td>Muons</td>
<td>SC air-core toroid (standalone)</td>
<td>Instrumented iron</td>
</tr>
</tbody>
</table>

Suggested reading on comparison of ATLAS and CMS:

**General-purpose detectors for the Large Hadron Collider.**

4. Detectors

ATLAS vs. CMS – dimensions
• Active sensors and mechanics: only ~ 10% of material budget
• 70 kW power into tracker and to remove similar amount of heat
• complex layout of services

[Froidevaux]
4. Detectors  

Material – Design and Reality

<table>
<thead>
<tr>
<th>Date</th>
<th>ATLAS $\eta \approx 0$</th>
<th>ATLAS $\eta \approx 1.7$</th>
<th>CMS $\eta \approx 0$</th>
<th>CMS $\eta \approx 1.7$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994 (Technical Proposals)</td>
<td>0.20</td>
<td>0.70</td>
<td>0.15</td>
<td>0.60</td>
</tr>
<tr>
<td>1997 (Technical Design Reports)</td>
<td>0.25</td>
<td>1.50</td>
<td>0.25</td>
<td>0.85</td>
</tr>
<tr>
<td>2006 (End of construction)</td>
<td>0.35</td>
<td>1.35</td>
<td>0.35</td>
<td>1.50</td>
</tr>
</tbody>
</table>

The numbers are given in fractions of radiation lengths ($X/X_0$). Note that for ATLAS, the reduction in material from 1997

- Material increased by ~ factor 2 from 1994 (approval) to now (end constr.)
- Electrons lose between 25% and 70% of their energy before reaching ECAL
- Between 20% and 65% of photons convert into $e^+e^-$ pair before ECAL
- Need to know material to ~ 1% $X_0$ for precision measurement of $m_W$ ($< 10$ MeV)

[Froidevaux]
4. Detectors  LHC detectors - commissioning

- Both ATLAS and CMS were ready to take data in Sept 08 (and still are!)

"Beam splash" event (dump beam into close-by upstream collimator) → 1000s of muons seen in ATLAS and CMS
4. Detectors  LHC detectors - status

Example: ATLAS (CMS very similar)

<table>
<thead>
<tr>
<th>Sub-detector</th>
<th>N. of channels</th>
<th>Fraction of working detector (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixels</td>
<td>80x10⁶</td>
<td>98.5</td>
</tr>
<tr>
<td>Silicon strip detector (SCT)</td>
<td>6x10⁶</td>
<td>~99.5</td>
</tr>
<tr>
<td>Transition Radiation Tracker (TRT)</td>
<td>3.5x10⁵</td>
<td>98.2</td>
</tr>
<tr>
<td>LAr electromagnetic calorimeter</td>
<td>1.7x10⁵</td>
<td>99.5</td>
</tr>
<tr>
<td>Fe/scintillator (Tilecal) calorimeter</td>
<td>9800</td>
<td>~99.5</td>
</tr>
<tr>
<td>Hadronic end-cap LAr calorimeter</td>
<td>5600</td>
<td>99.9</td>
</tr>
<tr>
<td>Forward LAr calorimeter</td>
<td>3500</td>
<td>100</td>
</tr>
<tr>
<td>Muon Drift Tube chambers (MDT)</td>
<td>3.5x10⁵</td>
<td>99.3</td>
</tr>
<tr>
<td>Barrel muon trigger chambers (RPC)</td>
<td>3.7x10⁵</td>
<td>~ 95.5</td>
</tr>
<tr>
<td>End-cap muon trigger chambers (TGC)</td>
<td>3.2x10⁵</td>
<td>&gt; 99.5</td>
</tr>
</tbody>
</table>

(aim: > 98.5 by first beams)
ATLAS recorded ~600 M of global cosmics ( > 1PB of data) with full detector operational → commission detector for collisions
4. Detectors

Cosmics calibration: example ATLAS pixels

Pixels, SCT: achieved with cosmics:
- alignment precision: ~ 20 μm (ultimate goal 5-10 μm)
- alignment stability Oct-2008-June-2009: few microns
- layer hit efficiency: > 99% ; occupancy: 10^{-10}
4. Detectors

Cosmics calibration: example ATLAS Tracker

Impact parameter resolution

Transition radiation $\sim \gamma$
($E \sim 100$ GeV for muons)

Momentum resolution

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Electron(!) candidates in ATLAS Transition Radiation Tracker (TRT) from $\delta$-electrons from cosmic muons

32/36 candidates have neg. charge!
5. Object reconstruction
Main objects to identify and reconstruct high-$p_T$ events:

<table>
<thead>
<tr>
<th></th>
<th>Tracker</th>
<th>ECAL</th>
<th>HCAL</th>
<th>Muon-System</th>
<th>Vertex-Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrons</td>
<td>++</td>
<td>+++</td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Photons</td>
<td>+</td>
<td>+++</td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Muons</td>
<td>+(+)</td>
<td>+</td>
<td>+</td>
<td>+++</td>
<td>(+)</td>
</tr>
<tr>
<td>Taus</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>B-Jets</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+++</td>
</tr>
<tr>
<td>Jets</td>
<td>+</td>
<td>+++</td>
<td>+++</td>
<td>(+)</td>
<td>-</td>
</tr>
<tr>
<td>Missing $E_T$</td>
<td>+</td>
<td>+++</td>
<td>+++</td>
<td>+</td>
<td>-</td>
</tr>
</tbody>
</table>

Most physics objects require many of the detector components to achieve the required/desired performance: combined performance
### 5. Reconstruction

<table>
<thead>
<tr>
<th>Object</th>
<th>Efficiency</th>
<th>BG suppr.</th>
<th>Motivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>electrons</td>
<td>&gt;70%</td>
<td>100000</td>
<td>Z,W,top,H→4ℓ,…</td>
</tr>
<tr>
<td>photons</td>
<td>80%</td>
<td>1000</td>
<td>H→γγ</td>
</tr>
<tr>
<td>muons</td>
<td>&gt;97% for p_T&gt;1GeV</td>
<td>1000</td>
<td>H→4ℓ,…</td>
</tr>
<tr>
<td>tau leptons</td>
<td>50%</td>
<td>100</td>
<td>H/A→ττ, SUSY,…</td>
</tr>
<tr>
<td>b-jets</td>
<td>50%</td>
<td>100</td>
<td>top, H→bb,SUSY,…</td>
</tr>
</tbody>
</table>

Some examples (from ATLAS – sorry) how this is achieved…
Electron candidates
- Calorimeter seeded → sliding window algorithm
- Matching track → exclude conversion tracks,
  → matching window 0.05x0.1 in $\Delta\eta\Delta\phi$
- E/p < 10 (loose)
Cut-based selection („simple“) for loose-medium-tight „electrons“, e.g.
track isolation, hadronic leakage, matching quality, TRT transition radiation,…

<table>
<thead>
<tr>
<th>Cuts</th>
<th>$E_T &gt; 17$ GeV</th>
<th>$E_T &gt; 8$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Efficiency (%)</td>
<td>Jet rejection</td>
</tr>
<tr>
<td></td>
<td>$Z \rightarrow ee$</td>
<td>$b,c \rightarrow e$</td>
</tr>
<tr>
<td>Loose</td>
<td>87.96 ± 0.07</td>
<td>50.8 ± 0.5</td>
</tr>
<tr>
<td>Medium</td>
<td>77.29 ± 0.06</td>
<td>30.7 ± 0.5</td>
</tr>
<tr>
<td>Tight (TRT)</td>
<td>61.66 ± 0.07</td>
<td>22.5 ± 0.4</td>
</tr>
<tr>
<td>Tight (isol.)</td>
<td>64.22 ± 0.07</td>
<td>17.3 ± 0.4</td>
</tr>
</tbody>
</table>

Likelihood selection can do better – but needs understanding of correlations

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5. Reconstruction  

**Tau leptons**

- **Branching ratios:**
  - **leptonic:**
    - $e/\mu \sim 35\%$
  - **hadronic:**
    - 1-prong $\sim 48\%$
    - 3-prong $\sim 14\%$
    - others $\sim 3\%$

  *where for 1-prong:*
  - $\pi^\pm \sim 23\%$
  - $\pi^\pm n\pi^0 \sim 74\%$

  *and for 3-prong:*
  - $3\pi^\pm \sim 62\%$
  - $3\pi^\pm n\pi^0 \sim 34\%$

- Leptonic decay hard to distinguish from prompt lepton (except lifetime)
  $\Rightarrow$ concentrate on hadronic tau’s

$m = 1.78$ GeV, $c\tau \sim 90$ $\mu$m
A hadronic tau is a narrow, low-multiplicity jet of hadrons ("tau-jet")
Main (serious!) background: QCD (quark, gluon) jets of low multiplicity

Seeding: Calorimeter-based or track-based (or from combined objects)

Discriminating variables:

1. $emRadius$: radius of the cluster in the EM calorimeter,

2. $isolationFraction$: fraction of the transverse energy deposited in a hollow cone of $0.1 < \Delta R < 0.2$
   around the tau cluster over the total energy in a cone of $\Delta R = 0.4$.

3. $ntrack$: number of associated tracks,

4. $charge$: absolute tau electric charge,

5. $numStripCells$: number of hits in the eta-strip with $E_T > 200$ MeV,

6. $stripWidth2$: energy weighted width in strips,

7. $ipSigLeadTrack$: lifetime signed impact parameter (2D) of the leading track,

8. $etOverPtLeadTrack$: ratio of the transverse energy of tau candidate to the transverse momentum
   of the leading track.
### 5. Reconstruction

**Tau leptons**

#### Performance:

<table>
<thead>
<tr>
<th>Selection</th>
<th>Efficiency</th>
<th>Rejection cuts</th>
<th>Rejection TMVA cuts</th>
<th>Rejection NN</th>
<th>Rejection PDRS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$E_T = 10-30$ GeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>one-prong</td>
<td>0.33</td>
<td>225 ± 10</td>
<td>435 ± 30</td>
<td>510 ± 40</td>
<td>460 ± 40</td>
</tr>
<tr>
<td>three-prong</td>
<td>0.28</td>
<td>360 ± 25</td>
<td>470 ± 40</td>
<td>740 ± 70</td>
<td>670 ± 60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$E_T = 30-60$ GeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>one-prong</td>
<td>0.42</td>
<td>140 ± 10</td>
<td>170 ± 10</td>
<td>440 ± 40</td>
<td>320 ± 30</td>
</tr>
<tr>
<td>three-prong</td>
<td>0.45</td>
<td>60 ± 2</td>
<td>90 ± 10</td>
<td>160 ± 10</td>
<td>130 ± 10</td>
</tr>
</tbody>
</table>
5. Reconstruction

Missing transverse energy

Particles which are neutral and interact only via weak interaction are invisible to the detector. Their presence can be only inferred indirectly from „missing energy“ (E/p- conservation). Since longitudinal momentum p_L cannot be measured at a hadron collider, only transverse momentum conservation can be used:

\[
0 = \sum_i p_{x,i} \quad 0 = \sum_i p_{y,i} \quad E_{T}^{\text{miss}} = \sqrt{\left(\sum_i p_{x,i}\right)^2 + \left(\sum_i p_{y,i}\right)^2}
\]

E_{T}^{\text{miss}} does not know why a particle was missed in the sum:

- because it did not interact (neutrino, neutralino, ...) : good
- because it escaped through a crack: bad
- because it escaped through the beampipe: bad (but low p_T)
- because it was misidentified (e.g. muon as hadron): bad
- because its energy was mismeasured (resolution,homogeneity):bad

fake E_{T}^{\text{miss}}
Example: QCD dijet events $560 < p_T < 1120$ GeV
5. Reconstruction  

**Missing transverse energy: Algorithms**

Calorimeter cell based:

\[
E_T^{miss} = \sqrt{\left( \sum_{i=cell} p_{x,i} \right)^2 + \left( \sum_{i=cell} p_{y,i} \right)^2}
\]

Advantage: no need to reconstruct particles, jets

Disadvantage: - have to calibrate calo response at the cell level
  (different for em and had showers)
  - potentially sensitive to noise
  - sensitive to min. bias pile-up
  - correct for muons (which do not leave much \( E \) in calorimeter)
  - correct for energy deposited in dead material (e.g. cryostat)

Object based:

\[
E_T^{miss} = \sqrt{\left( \sum_{i=objects} p_{x,i} \right)^2 + \left( \sum_{i=objects} p_{y,i} \right)^2}
\]

Objects = Electrons, Photons, Muons, Taus, Jets, low-\( p_T \) objects

Advantage: can calibrate each object individually

Disadvantage: - \( E_T^{miss} \) depends on (many) object definitions, all have to be understood
Both algorithms perform very similarly on Monte Carlo → interesting to compare them with data…

Resolution:

\[
\frac{\Delta E_T^{\text{miss}}}{E_T^{\text{miss}}} = \frac{53 - 57\%}{\sqrt{E_T^{\text{miss}} / \text{GeV}}}
\]
5. Reconstruction

Missing Et: a word of warning

**Missing ET in MHT30 skim**

MET includes cells with $E > 0$ (no CH)
- No correction
- Bad runs were removed
- Noisy events were removed
- Bad cells/towers were removed

![Graph showing Missing ET distribution](image)

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End of Day2
6. Physics

QCD
Electroweak
Top
Higgs

no time for BSM physics 😞
<table>
<thead>
<tr>
<th>6. Physics</th>
<th>Electroweak</th>
</tr>
</thead>
</table>

**QCD & Electroweak**
## LO cross sections in pb, inclusive

<table>
<thead>
<tr>
<th>$E_{cm}$ [TeV]/Process</th>
<th>7</th>
<th>10</th>
<th>14</th>
<th>Evt.s (7 TeV) in 200/pb</th>
<th>Ratio 7/14</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCD pt&gt;100 GeV</td>
<td>3.2E+05</td>
<td>6.8E+05</td>
<td>1.4E+06</td>
<td>6.4E+07</td>
<td>0.2</td>
</tr>
<tr>
<td>Z incl</td>
<td>2.5E+04</td>
<td>3.6E+04</td>
<td>5.7E+04</td>
<td>5.0E+06</td>
<td>0.4</td>
</tr>
<tr>
<td>W incl</td>
<td>9.5E+04</td>
<td>1.4E+05</td>
<td>2.1E+05</td>
<td>1.9E+07</td>
<td>0.5</td>
</tr>
<tr>
<td>ttbar</td>
<td>8.4E+01</td>
<td>2.2E+02</td>
<td>4.8E+02</td>
<td>1.7E+04</td>
<td>0.2</td>
</tr>
<tr>
<td>H(150 GeV)</td>
<td>4.0</td>
<td>8.2</td>
<td>16.0</td>
<td>8.0E+02</td>
<td>0.3</td>
</tr>
</tbody>
</table>

no branching ratios included!

[Dissertori]
6. Physics  QCD – Jet production

QCD jet production: largest (hard) cross section at a hadron collider
• highest $p_T$ reach
• test of pQCD – sensitivity to pdf’s
• sensitivity to new physics (new particles $\rightarrow$ jets, compositeness, extra dim…)

![Diagram of jet production](image)

excellent description by NLO QCD cross section varies over $10^{10}$

[Wobisch LP09]
6. Physics

QCD – Jet production: strong coupling constant

Compare inclusive jet cross section with NLO + 2-loop threshold corrections

→ sensitivity to strong coupling constant
→ observe running of $\alpha_s$
→ demonstration of asymptotic freedom
6. Physics                  Electro-weak gauge bosons

Z/W discovery by UA1 and UA2 (1983/84) at the CERN SpS (√s = 900 GeV)
6. Physics  

Electro-weak gauge bosons

At Tevatron and LHC W/Z production is/will be

• a major tool for detector calibration & alignment
• a tool to measure luminosity
• an important background
• a process for QCD studies

\[
\begin{align*}
\text{W/Z+jets(!)}
\end{align*}
\]

Keep in mind: at LHC(14) for 1fb⁻¹ you expect 1000 events with Z+3 jets(pt>40)

„Yesterday´s discovery is today´s calibration and tomorrow´s background…“
6. Physics

Modelling of extra jets

- $2 \to 2$ process at LO + parton shower (PS) (e.g. PYTHIA) fails at high jet multiplicities + large emission angles/$p_t$'s

- $2 \to n$ process at LO ("Matrix element") + PS (e.g. ALPGEN, SHERPA,...) needs careful "matching" algorithms "CKKW", "MLM", ... (avoid double counting of partons from ME and PS)

- $2 \to 3$ processes at NLO (MC@NLO,...) + PS ("correct" for $W+1$jet, $Z+1$jet, ... but similar problem as LO + PS for higher jet multiplicities good for total cross section ("K-factor")

⇒ even "state-of-the-art" Monte Carlo programs have large uncertainties
⇒ prepare to measure these cross sections with data

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| 6. Physics | Top Quark |

**Top Quark**
6. Physics

Top Quark

- Heaviest quark
- Discovered at Tevatron Run-I in 1995
- Tevatron Run-II measurements so far consistent with SM but: top is a „gate to new physics“
At discovery (1995)

17 events

DØ

19 events

CDF

Today: ~ 1000 tt pairs

LHC: 1 top pair /second
6. Physics  Top – processes and cross sections

**Top pair production (strong)**

<table>
<thead>
<tr>
<th></th>
<th>Tevatron</th>
<th>LHC (14 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>qq</td>
<td>85%</td>
<td>5%</td>
</tr>
<tr>
<td>gg</td>
<td>15%</td>
<td>95%</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>7 pb</td>
<td>600 pb</td>
</tr>
</tbody>
</table>

**Single top production (electro-weak)**

<table>
<thead>
<tr>
<th></th>
<th>Tevatron</th>
<th>LHC (14 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$ (s) (pb)</td>
<td>0.9</td>
<td>10</td>
</tr>
<tr>
<td>$\sigma$ (t) (pb)</td>
<td>2.4</td>
<td>250</td>
</tr>
<tr>
<td>$\sigma$ (tW) (pb)</td>
<td>0.1</td>
<td>60</td>
</tr>
</tbody>
</table>
**top decay:**

\[ \sim 100\% \]

\[ t \rightarrow W^+ b, v, q, \ell^+, \bar{q}' \]

*b-tagging important*

[Dias Schwanenberger]
6. Physics

Top: “Golden” Lepton + Jets Channel

\[ \text{3000 times higher rate} \]

\[ \text{10}^{10} \text{ times higher rate} \]

\[ \text{multijets} \]

[Schwanenberger]
6. Physics

Top-Antitop cross section

Measurements performed in $l_l$, $l_{(\text{incl } \tau)}+\text{jets}$, all-jets channels
Good agreement with NLO-QCD
6. Physics  Single top production

Extremely challenging analysis
bbℓν final state – W + 2 (b-)jets background!
complex multivariate analysis needed
important benchmark/milestone for (light) Higgs search
assume SM production → observed rate $\sim |V_{tb}|^2$

$|V_{tb}| = 1.07 \pm 0.12$

$|V_{tb}| = 0.91 \pm 0.13$
**template method:**

- reconstruct $m_{\text{top}}$
- compare data to MC with different $m_{\text{top}}$ hypotheses

**matrix element method:**

- probability densities for every event as function of $m_{\text{top}}$

$$P_{\text{sig}}(x; m_{\text{top}}, \text{JES}) = \frac{\text{Acc}(x)}{\sigma} \int d^n \sigma(y; m_{\text{top}}) dq_1 dq_2 f(q_1) f(q_2) W(x, y; \text{JES})$$

- Acceptance (selection, trigger, ...)
- LO-Matrix element x phase space
- PDF's
- Transfer Functions (Probability to measure x when y was produced)

[Schwanenberger]
6. Physics

Top mass

CФD Run II Preliminary (2.9 fb⁻¹)

≥ 2 tags events $m_{t}^{\text{rec}}$

Data

Fitted tt

Fitted Bkg

$\chi^2$/Ndo = 20.2 / 22

Prob = 0.589

CФD Run II Preliminary 3.2 fb⁻¹

likelihood fit method

$\Delta J_{ES} (c^2)$

$\Delta (ln L) = -0.5$

$\Delta (ln L) = -2.0$

$\Delta (ln L) = -4.5$

Mass of the Top Quark (*Preliminary)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF-I di-l</td>
<td>167.4 ± 10.3 ± 4.9</td>
</tr>
<tr>
<td>D0-I di-l</td>
<td>168.4 ± 12.3 ± 3.6</td>
</tr>
<tr>
<td>CDF-II di-l</td>
<td>171.2 ± 2.7 ± 2.9</td>
</tr>
<tr>
<td>CDF-I l+j</td>
<td>174.7 ± 2.9 ± 2.4</td>
</tr>
<tr>
<td>D0-II di-l</td>
<td>176.1 ± 5.1 ± 5.3</td>
</tr>
<tr>
<td>D0-I l+j</td>
<td>180.1 ± 3.9 ± 3.6</td>
</tr>
<tr>
<td>CDF-II l+j</td>
<td>172.1 ± 0.9 ± 1.3</td>
</tr>
<tr>
<td>D0 II l+j</td>
<td>173.1 ± 0.8 ± 1.6</td>
</tr>
<tr>
<td>CDF-I all-j</td>
<td>186.0 ± 10.0 ± 5.7</td>
</tr>
<tr>
<td>CDF-II all-j</td>
<td>174.8 ± 1.7 ± 1.9</td>
</tr>
<tr>
<td>CDF-II trk</td>
<td>175.3 ± 6.2 ± 3.0</td>
</tr>
<tr>
<td>Tevatron March '09</td>
<td>173.1 ± 0.6 ± 1.1</td>
</tr>
</tbody>
</table>

$\chi^2$/dof = 8.3/10.0 (79%)
systematic limit reached

further improvement will be slow
The SM (with $G_F$, $m_Z$, $\sin^2\theta_W$ as input) can predict $m_W$ vs. $m_{\text{top}}$ from quantum corrections.
Top Physics Timeline at the LHC

**Top for commissioning:**
The first observation of the top quark is a landmark event for the initial detector commissioning.

**Early Measurements:**
$\bar{t}t$ cross section will be among the first top physics measurements to be made.

**Top for calibration:**
The top mass and the $\bar{t}t$ topology are strong tools for understanding the detector.

**Top as background:**
Good understanding of the top is crucial to the discovery of new physics.

**Precision measurements:**
Precision-measurement of top properties and single top can be performed with accumulated data.

**Discovery through top:**
Study of the top quark may itself lead to the discovery of new physics.
Top-physics topics of interest

**tT cross section:**
- tT semileptonic (lepton + jets)
- tT dileptonic
- tT fully hadronic

**Top mass:**
- tT semileptonic (using hadronic jets)
- tT dileptonic (using leptons)

**Top property:**
- top charge
- top width
- tT spin correlation
- W helicity
- Yukawa coupling
- anomalous coupling
- resonance production

**Single top measurement:**
- s-, t-, Wt cross section
- Vtb measurement
- top polarization

A rich collection of physics programs.

Figure by Dhiman Chakraborty

Akiya Shibata@nyu.edu

HCPS2008 - May 27, 2008
LHC: The first top quarks to be seen in Europe

Rediscovery possible with 10 pb\(^{-1}\) at 10 TeV

\[ \sqrt{s} = 10 \text{ TeV}, \text{ after cuts:} \]

~ 15 l=e,\(\mu\) events per pb\(^{-1}\)

but ~ 3x less at \(\sqrt{s} = 7 \text{ TeV}\)

Ideal calibration source for most physics objects:
e,\(\mu\),\(\tau\),jets,b-jets,miss.-E
Higgs Bosons
Quantum field theory with massive exchange particles fails at high energies:

\[ \sigma \sim s^2 \]

violates unitarity at \( \sqrt{s} \sim 1.3 \) TeV

"if nothing happens, something must happen..."

**The Standard Model Solution:**
(rescue plan for the gauge principle)
Introduction of a new scalar field with non-vanishing field strength in the vacuum: the Higgs field.
**Paradigm:**
All (elementary) particles are massless

⇒ gauge principle works
⇒ renormalizable theory (finite cross sections)

permanent interaction with the Higgs field acts, as if the particles had a mass (effective mass)

\[
\frac{1}{q^2} = \left(\frac{gv}{\sqrt{2}}\right)^2 \left(\frac{1}{q^2}\right) = \left(\frac{gv}{\sqrt{2}}\right)^4 \left(\frac{1}{q^2}\right)^2
\]

\[
\frac{1}{q^2 - M^2} \text{ with } M^2 = g^2 \frac{v^2}{2}
\]
How to add such a field in a gauge invariant way?

"Mexican hat-Potential"

\[ V(\Phi) = -\mu^2|\Phi|^2 + \lambda|\Phi|^4 \]

most simple case: \( \Phi \) = complex doublet of weak isospin (=SM)

but this is a pure guess

many more possibilities, e.g.: 2 doublets (minimal SUSY), triplets,…

models with "true" and "effective" mass are not equivalent:

formulation with the help of Higgs mechanism:
  - is gauge invariant
  - postulates at least 1 scalar, massive Higgs boson
6. Physics  
Why Higgs?

**Theory:**
Upper bound: perturbativity (\(l<1\))
Lower bound: vacuum stability
Models: minimal SUSY: \(m<135\) GeV
GUT’s: \(m<180\) GeV

**Experiment:**
Precision measurements (LEP,SLC,Tevatron) are sensitive to virtual corrections:

\(m<250\) GeV (95% CL) within SM

The Higgs boson is probably “light”!
6. Physics

Higgs production at hadron colliders

\[ \sigma [fb] \]

\[ m_H (GeV) \]

100 120 140 160 180 200

LHC

10^4 10^3 10^2

100 200 300 400 500

TeV II

10^3

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Only few combinations of production and decay can be used at hadron colliders
"good" signatures (γγ, ℓℓℓℓ) have small BR's
for light (<130 GeV) Higgs, bb-mode can only be used in assoc. production
<table>
<thead>
<tr>
<th>at low mass (&lt;135 GeV)</th>
<th>at high mass (&gt;135 GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow b\bar{b}$</td>
<td>$H \rightarrow WW^\ast$</td>
</tr>
<tr>
<td>$WH \rightarrow \ell \nu b\bar{b}$</td>
<td>$WW \rightarrow \ell \nu \ell' \nu'$</td>
</tr>
<tr>
<td>$ZH \rightarrow \ell^+\ell^- b\bar{b}$</td>
<td></td>
</tr>
<tr>
<td>$ZH \rightarrow \nu\bar{\nu} b\bar{b}$</td>
<td></td>
</tr>
</tbody>
</table>

**Critical experimental issues:**

- **Low mass:** b-tagging, jet-energy resolution (di-jet mass = $m_H$)
- **High mass:** missing transverse energy, background modelling
Starting point: $W(\to \ell\nu)+2$jet events:

look at many observables and make sure, they are modelled correctly (Higgs negligible at this stage)
Next: apply b-tagging (2 categories: 1 b-tag, 2 b-tags)

→ Higgs x10 becomes visible
6. Higgs search at Tevatron: example $WH \rightarrow b\bar{b}\ell\nu$ @ D0

in addition look at $W+3$jets (different BG composition...)

**Graphs:**
- **DØ Preliminary** 
  - $L = 5.0$ fb$^{-1}$
  - **W + 3 jet / 1 b-tag**
  - **W + jet**
  - **Multi Jet**
  - **Wb$\bar{b}$/$c\bar{c}$**
  - $t\bar{t}$
  - s-top
  - Diboson
  - $WH$ 115 GeV (x10)

**Events vs Dijet Mass (GeV):**
- **Left Panel:**
  - Events (y-axis) vs Dijet Mass (x-axis)
- **Right Panel:**
  - Events (y-axis) vs Dijet Mass (x-axis)
6. Higgs search

at Tevatron: example WH → bbℓν @ D0

Then apply $m_H$-dependent neural network to check for compatibility with HW production.

check that the NN does what it should on the sample before b-tagging.
6. Higgs search at Tevatron: example $WH \rightarrow b\bar{b}\ell\nu$ @ D0

no significant excess at high NN-outputs
→ calculate CL for exclusion in this channel with log-likelihood ration using poisson-statistics (+bg-systematics in each bin of the NN output)

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6. Higgs search at Tevatron: high mass: \( H \rightarrow WW \)

Main mode: \( gg \rightarrow H \rightarrow WW^* \rightarrow l^+l^-\ell^+\ell^- \) (\( l, \ell \) = e, \( \mu \))
- two high \( p_T \) isolated leptons, missing \( E_T \)
- three main channels (ee, \( e\mu \), \( \mu\mu \))
- start probing other channels (\( \mu\tau \))

No direct reconstruction of the Higgs mass (\( \nu \)'s)

Main background:
Dibosons
- \( WW \) separated from the signal based on angular correlation \( \Delta \phi(l, l') \)
  - Higgs is a scalar!
  - \( \Delta \phi \) best background discriminant, used as one of the input variables to the NN

Other Backgrounds:
- \( W^+ \) jets and multijets
  - need good lepton identification
- \( Z \rightarrow \tau \tau \) : specific for \( e\mu \) channel and channels involving taus
6. Higgs search at Tevatron: high mass: $H \rightarrow WW$

Note: Higgs signal x1 (!!)
6. Higgs search at CDF and DØ: status summer 2009

CDF combination from Winter 2009 → Summer 2009
- $M_H = 115$ GeV
  - Expected limit $3.2 \sigma_{SM} \rightarrow 2.5 \sigma_{SM}$
  - Observed limit $3.8 \sigma_{SM} \rightarrow 3.6 \sigma_{SM}$
- $M_H = 165$ GeV
  - Expected limit $1.7 \sigma_{SM} \rightarrow 1.2 \sigma_{SM}$
  - Observed limit $1.6 \sigma_{SM} \rightarrow 1.2 \sigma_{SM}$

DØ combination from Winter 2009 → Summer 2009
- $M_H = 115$ GeV
  - Expected limit $3.6 \sigma_{SM} \rightarrow 3.1 \sigma_{SM}$
  - Observed limit $3.7 \sigma_{SM} \rightarrow 3.2 \sigma_{SM}$
- $M_H = 165$ GeV
  - Expected limit $1.7 \sigma_{SM}$
  - Observed limit $1.3 \sigma_{SM}$

most CDF/DØ low mass updates finalized only last week, DØ still analyzing extended dataset at high mass (5.4 fb⁻¹) → all finalized analyses are included in the combinations above but NO update of Tevatron combination [Bernardi LP09]
6. Higgs search at Tevatron: status winter 2009

**Low Mass analyses:**
$L = 0.9 - 2.7 \text{fb}^{-1}$
(results with more luminosity as presented before are **NOT** yet included in this combination)

@ $M_H = 115$
- Observed $\Rightarrow 2.5 \times \sigma_{SM}$
- Expected $\Rightarrow 2.4 \times \sigma_{SM}$

**High Mass analyses:**
Higgs cross sections use most recent theoretical inputs including MSTW 2008 NNLO PDF set

We exclude the SM Higgs from 160 to 170 GeV at 95% C.L.

These Moriond '09 CDF-DØ combined limits are obtained with an "effective" luminosity of $2.5/4.0 \text{ fb}^{-1}$ at low/high mass

Gregorio Bernardi / LPNHE-Paris

[Bernardi LP09]
6. Higgs search at Tevatron: projection

Assume CDF+DØ, and projected improvements:

2009: precision EW measurements + Tevatron → SM Higgs 115 – 160 GeV
2010: with Tevatron luminosity, expects upper limit to go down to ~145 GeV
≥2011: @ Tevatron, direct exclusion from 115 to 185 GeV, or first evidence?
  @ LHC requires several fb⁻¹ to have evidence for the low mass Higgs
  → LHC/Tevatron complementarity H → γγ vs H → bb

2xCDF Preliminary Projection, m_H=115 GeV

The race is on…
Cross section for Higgs (120 GeV) ~ xx x larger than at Tevatron - can exploit other (cleaner) channels.

But Higgs – due to large backgrounds – Higgs search is not „early LHC physics“

Low mass (<~ 135 GeV):

• $H \to \gamma\gamma$ (inclusive)

• Vector boson fusion ($H \to \tau\tau, H \to \gamma\gamma, H \to W^+W^-$)

• $ttH$ associated production $\to$ no longer considered „discovery channel“

• new idea: $WH, ZH$ at high $p_T(H)$
6. Higgs search \[ H \rightarrow \gamma\gamma \] @ LHC

\[ \text{BR}(H \rightarrow \gamma\gamma) = 0.2\%, \text{narrow peak} \]

huge, but smooth background  
\rightarrow \text{mass resolution is the key}

- Photon energy resolution & calibration
- Photon direction \rightarrow \text{granularity}

Mass resolution (ATLAS): 1.4 GeV

Problem:
60% of \( H \rightarrow \gamma\gamma \) events have at least one conversion

need to be identified
tail in resolution
need precise knowledge of material to obtain reliable simulation of signal & bg
6. Higgs search \[ H \rightarrow \gamma\gamma \] @ LHC

additional get better S/B (but lower rate)

**+1 jet analysis**

\[
\frac{S}{B} = 0.082
\]

**+2 jets analysis**

\[
\frac{S}{B} = 0.50
\]
6. Higgs search

Vector Boson Fusion

smaller rate than inclusive production but forward "tagging jets" + rapidity gap can be used to improve S/B

$m_{\tau\tau}$ can be reconstructed in collinear approximation

important discovery channel
6. Higgs search

HW, HZ production was considered not a discovery channel for a long time. Very recent new investigation: H+W/Z production at high p_T(H)

2 b-quarks from Higgs decay will be reconstructed in single jet

Look at “jet – substructure”

ATLAS (prel.) sensitivity for 30 fb⁻¹
(m_H = 120 GeV)

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<th>Channel</th>
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<th>w_i</th>
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</tbody>
</table>

5. Higgs search

Combined discovery prospects

ATLAS

L = 10 fb⁻¹

CMS

Luminosity for 5σ discovery, fb⁻¹

M_{H}, GeV/c²

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