QCD Studies at the LHC

Klaus Rabbertz, University of Karlsruhe, CMS
Some Search at LHC

Why my observation channel is important, unique, complimentary, the most promising ...

What to look for ...

How to select the signal events ...

What NOT to look for: QCD Background!

What are the systematic uncertainties ...

How good is the signal to noise ratio ...

Summary

Somehow the general outlay of many LHC talks ... :-)

Real Outline

- Warming up
  - The LHC
  - The Experiments
  - Possible Commissioning Scenario

- Selected Topics (Personally biased → CMS, Start-up Physics)
  - High $p_T$ Jet Cross Section & PDFs
  - LHC Standard Candle
  - Event Shapes (Time permitting)

- Outlook

I don't have to convince this audience of the importance of QCD...
The Large Hadron Collider

Four interaction points with the experiments:

- ALICE
- CMS/TOTEM
- ATLAS
- LHCb

Lake Geneva

CERN Meyrin Site

Geneva Airport

LHC Design Parameters:

<table>
<thead>
<tr>
<th></th>
<th>pp</th>
<th>AA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy/Nucleon/TeV:</td>
<td>7.0</td>
<td>2.76</td>
</tr>
<tr>
<td>Bunch separation/ns:</td>
<td>25</td>
<td>100</td>
</tr>
<tr>
<td>Design Luminosity/cm²m⁻¹:</td>
<td>10⁻³⁴</td>
<td>10⁻²⁷</td>
</tr>
<tr>
<td>Number of bunches:</td>
<td>2808</td>
<td>592</td>
</tr>
<tr>
<td>No. of particles/bunch:</td>
<td>1.15·10¹¹</td>
<td>7.0·10⁷</td>
</tr>
</tbody>
</table>

All pictures and schematics pp. 4 – 16 are taken from CERN or the experiments!
LHC Construction Schedule

June 2006
LHC Installation (1/2)

26.04.2005: Installation of first LHC dipole
30.05.2006: Last cryoline section to be installed
06.06.2006: Shown by R. Bailey from the LHC Progress Dashboard.

Due to problems with the cryolines in the beginning the dipole installation was delayed. Now we are just in time ...

Need 1232
The ALICE Detector

General purpose heavy-ion experiment:
Study of strongly interacting matter and the quark-gluon-plasma

For details see e.g.:
The LHCb Detector

B-Physics experiment: Study of CP violation and precision measurement of other rare phenomena in B meson decays

For details see e.g.: LHCb Technical Design Report, Vol. 9, 2003
18.11.2005: Arrival of LHCb RICH2 detector
The ATLAS Detector

General purpose pp collider experiment:
Searches for Higgs bosons, other new particles (SUSY, ...) and new phenomena;
Precision measurement of SM parameters like top and W masses, ...;
Heavy ion program.

For details see e.g.:
ATLAS Installation

23.09.2005
ATLAS cavern with last toroid coil installed

04.11.2005
The CMS Detector

General purpose pp collider experiment: Searches for Higgs bosons, other new particles (SUSY,...) and new phenomena; Precision measurement of SM parameters like top and W masses, ...; Heavy ion program.

Plus TOTEM: Total cross section, elastic pp scattering, diffractive dissociation

12.05.2006: Insertion of CMS tracker for magnet test and cosmic challenge (in surface hall)

Note: In 2007, CMS will start without the pixel detectors and the endcap elm. calorimeter.
2007 Pilot run scenario (LHC-OP-BPC-0001 rev 1):

<table>
<thead>
<tr>
<th>Beam energy (TeV)</th>
<th>6.0, 6.5 or 7.0</th>
<th>6.0, 6.5 or 7.0</th>
<th>6.0, 6.5 or 7.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of bunches (per beam)</td>
<td>43</td>
<td>43</td>
<td>156</td>
</tr>
<tr>
<td>$\beta^*$ in IP 1, 2, 5, 8 (m)</td>
<td>18,10,18,10</td>
<td>2,10,2,10</td>
<td>2,10,2,10</td>
</tr>
<tr>
<td>Crossing Angle ($\mu$R)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Transverse emittance ($\mu$m)</td>
<td>3.75</td>
<td>3.75</td>
<td>3.75</td>
</tr>
<tr>
<td>Bunch spacing ($\mu$s)</td>
<td>2.025</td>
<td>2.025</td>
<td>0.525</td>
</tr>
<tr>
<td>Bunch Intensity</td>
<td>$1 \times 10^{10}$</td>
<td>$4 \times 10^{10}$</td>
<td>$4 \times 10^{10}$</td>
</tr>
<tr>
<td>Luminosity in IP 1 &amp; 5 (cm$^{-2}$ s$^{-1}$)</td>
<td>$\sim 3 \times 10^{28}$</td>
<td>$\sim 5 \times 10^{30}$</td>
<td>$\sim 2 \times 10^{31}$</td>
</tr>
<tr>
<td>Luminosity in IP 2 (cm$^{-2}$ s$^{-1}$)</td>
<td>$\sim 6 \times 10^{28}$</td>
<td>$\sim 1 \times 10^{30}$</td>
<td>$\sim 4 \times 10^{30}$</td>
</tr>
</tbody>
</table>

Dedicated runs for TOTEM or with heavy ions have to fit in

Not very probable to happen in 2007
CMS interpretation (CMS Physics TDR Vol. I):

<table>
<thead>
<tr>
<th></th>
<th>Pilot Run 2007</th>
<th>1st Physics Run 2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch separation/ns:</td>
<td>2025 → 525</td>
<td>75 → 25</td>
</tr>
<tr>
<td>Number of bunches:</td>
<td>43 → 156</td>
<td>936 → 2808</td>
</tr>
<tr>
<td>No. of particles/bunch:</td>
<td>$10^{10} \rightarrow 4 \cdot 10^{10}$</td>
<td>$4 \cdot 10^{10}$</td>
</tr>
<tr>
<td>Luminosity/cm$^{-2}$m$^{-1}$:</td>
<td>$3 \cdot 10^{29} \rightarrow 2 \cdot 10^{31}, 10^{32}$</td>
<td>$10^{32} \rightarrow 2 \cdot 10^{33}$</td>
</tr>
</tbody>
</table>

CMS assumptions on integrated luminosity:

- Pilot run 2007: 1/fb
- Low luminosity phase: 10 – 30 /fb
- High luminosity phase: 100 – 300 /fb
Many more details can be found in the talks of the current HERALHC workshop at CERN:

http://indico.cern.ch/conferenceDisplay.py?confId=186

<table>
<thead>
<tr>
<th>Time</th>
<th>Talk</th>
<th>Speaker</th>
</tr>
</thead>
<tbody>
<tr>
<td>14:00</td>
<td>Introduction to the workshop, prospects and the future (30')</td>
<td>A. De Roeck (CERN)</td>
</tr>
<tr>
<td>14:30</td>
<td>status of LHC machine (30')</td>
<td>Roger Bailey (CERN)</td>
</tr>
<tr>
<td>15:00</td>
<td>Status and startup for physics with CMS (30')</td>
<td>Maria Spiropulu (CERN)</td>
</tr>
<tr>
<td>15:30</td>
<td>Status and startup for physics with ATLAS (30')</td>
<td>Marina Cobal (Udine)</td>
</tr>
<tr>
<td>16:00</td>
<td>Coffee break</td>
<td></td>
</tr>
<tr>
<td>16:20</td>
<td>Status and startup for physics with ALICE (30')</td>
<td>Jean Pierre Revol (CERN)</td>
</tr>
<tr>
<td>16:50</td>
<td>Status and startup for physics with LHCb (20')</td>
<td>Giovanni Passaleva (Firenze)</td>
</tr>
<tr>
<td>17:10</td>
<td>Diffraction with TOTEM (20')</td>
<td>Risto Orava (Helsinki)</td>
</tr>
<tr>
<td>17:30</td>
<td>HERA program until 2007 (45')</td>
<td>Elisabetta Gallo (INFN Firenze/DESY)</td>
</tr>
<tr>
<td>18:15</td>
<td>ep program at LHC (30')</td>
<td>Emmanuelle Perez (Saclay/DESY)</td>
</tr>
</tbody>
</table>
Selected Topics

- Concentrate on start-up physics probably possible in 2007, hence:
  - Neither heavy ions, nor forward physics with TOTEM
  - No ECAL in CMS endcaps, no pixel detectors
  - No Higgs :-) ?

- But see the informative talks from D. d´Enterria on Monday: “... from RHIC to LHC”, or from Chr. Weiss on “GPDs ... at LHC” on Tuesday
High $p_T$ Jets

- Statistically, no problem even with only a pilot run in 2007 (up to $\approx 1.5$ TeV in $p_T$)
- Important to study the detector behaviour
- Improve understanding and estimates of QCD background to other processes
- Useful to measure the jet cross sections \textit{(ok)}
- Improve on PDFs, especially the gluon at high $x$ \textit{(not so simple)}
- Extract running of strong coupling in new $p_T$ range \textit{(slope decreases)}
- Precisely determine the strong coupling (curr. rel. uncertainty $\approx 2\%$, HERA goal: 1%; probably \textit{not competitive} with inclusive jets, but with \textit{jet rates} ? To be investigated ...)
Statistical Uncertainties

Est. statistical uncertainty for $L_{\text{int}} = 0.1 \text{ fb}^{-1}$
(Pythia LO high $p_T$ event cross section, all rap.)

Est. statistical uncertainty for $L_{\text{int}} = 300 \text{ fb}^{-1}$
(Pythia LO high $E_T$ jet cross section, hadrons)

Sizeable statistical uncertainties only at very high $p_T$
Knowledge on PDFs

Much insight has been gained, especially due to HERA, more to come from HERA II, see talk from D. Saxon on Monday.

Prospected reduction in uncertainty on PDF fits from ZEUS (F2 + jets) for HERA II.
Subprocess Decompositions

Decomposition of high $p_T$ jet cross sections into partonic subprocesses depending on $x_T = 2p_T/\sqrt{s}$ in central rapidity region.

**Tevatron**

- (1) $gg \rightarrow$ jets
- (2) $gq, g\bar{q} \rightarrow$ jets, $x_g < x_q$
- (3) $q\bar{q}, g\bar{q} \rightarrow$ jets, $x_g > x_q$
- (4) $q\bar{q} \rightarrow$ jets
- (5) $q\bar{q} \rightarrow$ jets
- (6) $q\bar{q} \rightarrow$ jets
- (7) $q\bar{q} \rightarrow$ jets

**LHC**

- (1) $gg \rightarrow$ jets
- (2) $gq, g\bar{q} \rightarrow$ jets, $x_g < x_q$
- (3) $gq, g\bar{q} \rightarrow$ jets, $x_g > x_q$
- (4) $q\bar{q} \rightarrow$ jets
- (5) $q\bar{q} \rightarrow$ jets
- (6) $q\bar{q} \rightarrow$ jets
- (7) $q\bar{q} \rightarrow$ jets

**fastNLO**

- Tevatron scenario: $0.1 \leq |y| < 0.7$
- LHC scenario: $0.00 \leq |y| < 0.75$
Recent Progress

- One of the most important developments in the last years are the error PDF sets, e.g. from the CTEQ group
- But their evaluation and especially PDF fits require:
  - Availability of reasonably fast theory calculations
  - Often needed: Repeated computation of same cross section
- Sometimes NLO predictions can be computed fast, but some are very slow, esp. for jets
- New procedure for fast repeated computations of NLO cross sections:
  Project fastNLO (T.Kluge, M.Wobisch, KR)
  - Useable for any observable in hadron-induced processes (hh, DIS, ...)
  - Does not include theor. calculation itself, here: NLOJET++ (Zoltan Nagy)
- No computation time saved at first run, repetition with e.g. another PDF set takes only milliseconds
- Involves one single approximation with quantifiable precision
PDF Approximation

- Introduce set of discrete $x^{(i)}$ with $x^{(n)} < \ldots < x^{(i)} < \ldots < x^{(0)} = 1$

- Around each $x^{(i)}$ define eigen function $E^{(i)}(x)$ with:
  
  $E^{(i)}(x^{(i)}) = 1$, $E^{(i)}(x^{(j)}) = 0$ ($i \neq j$), $\Sigma_i E^{(i)}(x) = 1$ for all $x$

- Express PDF $f(x)$ by lin. combination of eigen functions with coefficients given by PDF values at discrete points:
  
  $f(x) = \sum_i f(x^{(i)})E^{(i)}(x)$  => Integration only over $E^{(i)}(x)$, not $f(x)$!

For more info see: [http://hepforge.cedar.ac.uk/fastnlo](http://hepforge.cedar.ac.uk/fastnlo)

(T.Kluge,M.Wobisch,KR)

Similar project: NLO-GRID
(D.Clements, C.Gwenlan, C.Buttar, G.Salam, T.Carli, A.Cooper-Sarkar, M.Sutton)

Equidistant binning in:

$$\sqrt{\log(1/x)}$$

cubic interpolation of reweighted CTEQ6.1M gluon

$$w(x) = x^{-3/2}(1 - 0.99 x)^3$$

$\mu_f = 500$ GeV
fastNLO Application

CTEQ6.1 PDFs, $\alpha_s(M_Z) = 0.118$

No jet data used for PDF fits

H1 2000 PDFs, $\alpha_s(M_Z) = 0.118$
Dominant Uncertainties at high $p_T$

PDF uncertainty on high $p_T$ jet cross section acc. to evaluation of the 40 CTEQ6 error PDFs

E scale uncertainty on high $p_T$ jet cross section as derived from full CMS detector simulation
CDF hep-ex/0512062:

- **Dom. uncertainty**: Jet energy scale $\pm 3\% \rightarrow 10\%$ at low $p_T$ up to $60\%$ at high $p_T$
- Energy resolution, unfolding and luminosity: Below $10\%$ each
- UE: $-22\%$ up to $-4\%$
- Hadr.: $+13\%$ up to $+3.5\%$

D0 hep-ex/0012046 (Run I, new Run II results only preliminary):

- **Dom. uncertainty**: Jet energy scale $15\%$ at low $p_T$ up to $30\%$ at high $p_T$
Absolute scale of high $p_T$ jet cross section uncertain by 6% due to luminosity measurement

Investigate processes like $pp \rightarrow W + X$ and $pp \rightarrow Z + X$ as "Standard Candles" (CMS Physics TDR, Vol. II):

- Well measurable in case of subsequent leptonic decays $W \rightarrow l\nu$ resp. $Z \rightarrow l^+l^-$ with $l = e$ or $\mu$
- High cross sections above 10nb (1nb) expected in fiducial volume of CMS for $W \rightarrow l\nu$ ($Z \rightarrow l^+l^-$) channel
- $W$ channel more difficult, but more statistics available
- Most dangerous background from QCD events with decay leptons, tractable with isolation criteria against jets
- Like high $p_T$ jets very useful for detector, jet calibration ($Z + jets$, also $\gamma + jets$)
- Acceptance uncertainty is at 2-3% level already at start-up (nevermind the PDF!)
Standard Candle (2/2)

- Measures directly the quark and anti-quarks densities in the proton via

\[ \int_{q, \bar{q} \text{ partons}} dx_1 dx_2 \sigma_{q\bar{q} \rightarrow W,Z} \times L_{pp} \times PDF(x_1, x_2, Q^2) \]

- Theoretically well understood, BUT global rate uncertain to about 6 - 7% because of PDF uncertainties
- Clever combination (rates) of cross sections can be determined much more precise since uncertainties cancel
- Would be interesting to try combined fit with high $p_T$ jets
- Drell-Yan could add even more information on PDFs into common fit procedure (Calculation in NNLO exists)
Event Shapes (1/2)

Event Shapes have been used since a long time with great success in $e^+e^-$ scattering.

Since about ten years similarly applied in ep collisions, latest results from H1, ZEUS: hep-ex/060432v2

Power Corrections as alternative method for MC hadronization corrections

H1 exhibits them even on their www start page!

David Gross, David Politzer and Frank Wilczek awarded the 2004 Nobel Prize in Physics for the discovery of asymptotic freedom

Twenty years ago, David Gross, David Politzer and Frank Wilczek discovered asymptotic freedom in the theory of the strong interactions. Measurements published by H1 in the year 2005 beautifully illustrate this effect: the strong coupling $\alpha_s$ is seen to decrease as the hard scale at which it is measured, $Q$, increases.
Event Shapes (2/2)

ZEUS: Compatible results for event shape distributions, but less favourable of power correction concept

Shift of PT distribution by power corr.: (see papers by Dokshitzer, Webber, Dasgupta, Salam, Zanderighi, ...)

\[
\frac{1}{\sigma_{\text{tot}}} \frac{d\sigma(F)}{dF} = \frac{1}{\sigma_{\text{tot}}} \frac{d\sigma^{\text{pert}}(F - \mathcal{P})}{dF}
\]

\[
\mathcal{P} = a_F \frac{4C_F}{\pi} \mathcal{M}^I \left( \frac{\mu_I}{Q} \right)^p
\]

\[
[\bar{\alpha}_{p-1}^{I}(\mu_I) - \alpha_s(Q) - \frac{\beta_0}{2\pi} \left( \ln \frac{Q}{\mu_I} + \frac{K}{\beta_0} + \frac{1}{p} \right) \alpha_s^2(Q)]
\]

Averaged coupling up to infrared matching scale \(\mu_I\):

\[
\alpha_0(\mu_I) \equiv \int_0^{\mu_I} \frac{dk_t}{\mu_I} \alpha_s(k_t)
\]

H1 common fits of strong coupling and non-perturbative \(\alpha_0\) parameter for five different event shape distributions

Klaus Rabbertz  |  QNP06, Madrid, Spain  |  10.06.2006  |  33
Event Shapes in pp?

- Suggestion from theory to look for event shapes in pp collisions as well (e.g. directly global transverse thrust): (A. Banfi, G. Salam, G. Zanderighi: hep-ph/0605332, hep-ph/0407287)

\[ T_{\perp,g} \equiv \max_{\vec{n}_{\perp}} \sum_i \frac{|\vec{p}_{\perp i} \cdot \vec{n}_{\perp}|}{\sum_i |\vec{p}_{\perp i}|}, \quad \tau_{\perp,g} \equiv 1 - T_{\perp,g} \]

- Needs to include emissions in complete phase space, problematic with limited detector acceptance
- Two alternative definitions exist with either addition of a global recoil term or exponentially suppressed forward terms
- Can be used to study jet hadronization and underlying event properties
Outlook

The LHC start-up phase will probably be rather painful ...

And also the experiments will have a hard time getting things up and running (and keeping it there)

In any case I talked about a near future facility!

QCD will be among the first topics to be studied with real data

Already with just a pilot run a rich field of results with jets, W and Z production, Drell-Yan can be expected

The connecting point of all these are the parton densities

Very interesting times lie ahead and maybe some surprises with “standard” physics ... even without an early Higgs

Thank you!
Partonic Subprocesses

- Don't want to deal with 13 X 13 PDFs
- For hh → jets **seven** relevant partonic subprocesses

1) \( gg \Rightarrow \) jets \( \propto H_1(x_1, x_2) \)
2) \( qg, \bar{q}g \Rightarrow \) jets \( \propto H_2(x_1, x_2) \)
3) \( gq, g\bar{q} \Rightarrow \) jets \( \propto H_3(x_1, x_2) \)
4) \( q_i q_j, \bar{q}_i \bar{q}_j \Rightarrow \) jets \( \propto H_4(x_1, x_2) \)
5) \( q_i q_i, \bar{q}_i \bar{q}_i \Rightarrow \) jets \( \propto H_5(x_1, x_2) \)
6) \( q_i \bar{q}_i, \bar{q}_i q_i \Rightarrow \) jets \( \propto H_6(x_1, x_2) \)
7) \( q_i \bar{q}_j, \bar{q}_i q_j \Rightarrow \) jets \( \propto H_7(x_1, x_2) \)

- Need only seven linear combinations \( H_i \) of PDFs
Symmetries

In addition, symmetries can be exploited:

\[ H_n(x_1, x_2) = H_n(x_2, x_1) \quad \text{for} \quad n = 1, 4, 5, 6, 7 \]

\[ H_2(x_1, x_2) = H_3(x_2, x_1) \]

For hadron anti-hadron collisions, replace:

\[ H_4(x_1, x_2) \leftrightarrow H_7(x_1, x_2) \]

\[ H_5(x_1, x_2) \leftrightarrow H_6(x_1, x_2) \]

Minimize required table size and computing time!
Actual Usage

Our actual interpolation is:

- Two-dimensional \((x_1, x_2)\)
- Cubic, linear at the edges
- Spaced in \(x\) with points \(\sim \sqrt{\log(1/x)}\)

Example use case:
D0 incl. jets (hep-ex/0011036)
- No. of bins in rap. y: 5
- No. of bins in \(p_T\): 24 – 8
- Total no. of bins: 90
- No. of events (NLO): 49G
- CPU time for first run: \(> 4000h\)
- Table size (10 x bins, 4 scal.): 5.5MB
- Reading of table: \(O(1s)\)
- Execution time/PDF set: \(< O(0.01s)\)
- Stat. precision, y bins 1-3: 0.1 - 0.3%
- y bins 4,5: 0.2 - 1.0%

( Depending on used PC! )
Jet cross sections in hadron-hadron collisions

General cross section formula:

\[ \sigma_{hh} = \sum_n \alpha_s^n(\mu_r) \sum_{\text{flavour } i} \sum_{\text{flavour } j} c_{i,j,n}(\mu_r, \mu_f) \times f_i(x_1, \mu_f) \times f_j(x_2, \mu_f) \]

which depends on:

- Strong coupling constant \( \alpha_s \) to the power of \( n \)
- Perturbative coefficients \( c_{i,j,n} \)
- Parton density functions (PDFs) of the hadrons \( f_i(x) \), \( f_j(x) \)
- Renormalization scale \( \mu_r \), factorization scale \( \mu_f \)
- Momentum fractions \( x \)

▶ Standard procedure: Integration over phase space in \( (x_1, x_2) \)
(usually MC method) => Dependency on PDFs!

▶ New: Interpolation between fixed support points in \( x \) for PDFs
=> Evaluation a posteriori possible
**K Factors**

- **gg subprocess** dominant at low $p_T$
- **$q_i q_j$ subprocess** dominant at high $p_T$

**Graphs:**
- Comparison of $\sigma_{NLO}/\sigma_{LO}$ for different $p_T$ regions and subprocesses, showing the relative cross-sections.

**Legend:**
- fastNLO NLO (CTEQ6.1)
- Incl. $k_T$, $D=1.0$
- $gg \rightarrow$ jets
- $q_i q_j \rightarrow$ jets

**Axes:**
- $p_T/GeV$ on the x-axis
- $\sigma_{NLO}/\sigma_{LO}$ on the y-axis
Event shapes in Breit frame

Example: Thrust

\[ \tau := 1 - \frac{\sum_{i \in \text{CH}} |p_i^* \cdot \hat{n}|}{\sum_{i \in \text{CH}} |\vec{p}_i^*|} = 1 - \frac{\sum_{i \in \text{CH}} |p_{li}^*|}{P^*} \]