LHC: Past, Present and Future

XX GIORNATE DI STUDIO sui RIVELATORI

Torino
February 23-26, 2010

Sergio Bertolucci
CERN, Geneva
LHC: a spectacular start!

- Experiments showing their readiness
- Excellent experiment-machine interface
- Very encouraging news from the side of the backgrounds.
- Fast data turnaround times
3 ways of reconstruction the vertex:
Pixels only; all ITS; TPC only.
TPC standalone resolution is of course much worse than the ITS, but gives the same position; i.e. the relative alignment is ok.
The x resolution is for all momenta and track multiplicities; the actual beamspot (after unfolding) is slightly less than 200 micron.

Impact parameter distribution (DCA) of SPD tracklets to the found vertex.
Sigma is about 190 micron for horizontal tracklets (all momenta and multipl.) (alignment error contribution < 15 micron).
It is worse for vertical tracklets (less statistics from cosmics available for alignment, to be done with collision events)
Particle Identification

TPC

ITS

TOF

Run: 164044, 104070, 104157
104316, 104083, 104321
Cuts: chi2<10, 4 points in SDD/SSD

0.30 < p_T < 2.00 GeV/c
10/12/2009, ALICE-TOF

Entries 8320
Integral 6587
Decay Reconstruction

\[ \bar{\Lambda} \rightarrow \pi p \]
\[ \mu = 1115.4 \pm 0.3 \text{ MeV} \]
\[ \sigma = 2.0 \pm 0.4 \text{ MeV} \]

\[ \Lambda \rightarrow \pi p \]
\[ \mu = 1115.5 \pm 0.2 \text{ MeV} \]
\[ \sigma = 1.6 \pm 0.2 \text{ MeV} \]

\[ K^0_s \rightarrow \pi\pi \]
\[ \mu = 496.7 \pm 0.2 \text{ MeV} \]
\[ \sigma = 4.6 \pm 0.2 \text{ MeV} \]
Online event display, event #0
First Collisions, 23 Nov 2009
Uncalibrated $E_T \sim 55$ GeV for both jets
Both jets at $\eta = -0.2$; \~\no\missing $E_T$
2-Jet Event at 2.36 TeV

Jet1: uncalibrated $E_T \sim 22$ GeV, $\eta = -2.1$
Jet2: uncalibrated $E_T \sim 11$ GeV, $\eta = 1.4$

ATLAS EXPERIMENT
2009-12-08, 21:40 CET
Run 142065, Event 116969

Villa Gualino, September 2010
Online determination of the primary vertex and beam spot using the Level-2 trigger algorithms

High-Level Trigger running with > 150 chains

Two pairs of colliding bunches
2 opposite-sign tracks:
- $p_T > 500$ MeV
- originating from common vertex
- impact parameter $d_0 > 4$ mm
- momentum sum along flight direction

Data and MC normalized to the same area

ATLAS Preliminary

Minimum Bias Stream, Runs 141749 & 141811

$K_S^0$ Invariant Mass

- Data
- Simulation (MC09)

Gauss (+poly) fit data

$\mu = 497.2 \pm 0.5$ MeV
$\sigma = 8.1 \pm 0.6$ MeV

Both tracks:
- $p_T > 500$ MeV, Si hits > 3, |D0| > 4 mm
- Pointing cut: $\cos(\theta) > 0.8$
$\pi^0 \rightarrow \gamma\gamma$

- 2 photons with $E_T(\gamma) > 300$ MeV
- $E_T(\gamma\gamma) > 900$ MeV
- shower shapes compatible with photons
- All combinations plotted.
- No correction for upstream dead material ($\sim 2.5 \times X_0$ at $\eta=0$)
- Data and MC normalised to the same area

**ATLAS preliminary**

Very good data-MC agreement for (very soft !) photon showers

Shower width (strip units)
γ → e⁺e⁻ conversions

Radial distribution of conversions occurring in Si layers. Location of the pixels layers at R=50, 90, 120 mm is clearly visible.

$\gamma \rightarrow e^+e^-$ conversions

$p_T(e^+) = 1.75$ GeV, 11 TRT high-threshold hits
$p_T(e^-) = 0.79$ GeV, 3 TRT high-threshold hits
Conversion R ~ 31 cm ($1^{st}$ SCT layer)

ATLAS preliminary

Data conversion candidate
MC conversion candidate
MC truth conversion
(Non diffractive minimum bias MC)
Electron candidates

**EM clusters** $E_T > 2.5$ GeV matched to a track

→ 47 candidates in 20000 minimum-bias events

Data and MC normalised to the same area

According to MC:

- Sample dominated by hadron fakes
- Most electrons from $\gamma$-conversions

**Very good data-MC agreement for (soft !) electrons and hadrons**

**Transition radiation hits in the TRT**

(transition radiation from electrons produces more high-threshold hits)
$\eta$ and $\phi$ distributions of (very low momentum $p \sim 3$ GeV) muon candidates are compatible with particles produced in the collisions (mainly coming from $K/\pi$ decays).
Energy flow in calorimeters...

Uncalibrated clusters
(topological clusters with noise suppression)

Excellent agreement data-MC at such low energies indicates very good description of material in simulation and G4 shower modeling.
... and missing transverse energy resolution

Energy resolution of the two components (METx, METy) of the missing $E_T$ vector vs the total transverse energy in the calorimeters

- Measurement over full calorimeter coverage, $|\eta| < 5$, ~ 200000 cells
- Calculated using clusters at EM-scale
- Noise contribution (from random triggers): 0.5 GeV
# CMS Experiment at the LHC, CERN

**Data recorded:** 2009-Dec-08 04:14:38.495160 GMT  
**Run:** 123592  
**Event:** 2003169  
**Lumi section:** 13  
**Orbit:** 12844863  
**Crossing:** 51

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**CMS Experiment at the LHC, CERN**  
**Date Recorded:** 2009-11-23 19:21 CET  
**Run/Event:** 122314/1514552  
**Candidate Collision Event**
Monday 23rd November

CMS Experiment at the LHC, CERN
Date Recorded: 2009-11-23 19:21 CET
Run/Event: 122314/1514552
Candidate Collision Event
First Di-photon Distribution in CMS

- $M(\pi^0)$ is low in both data and MC
- Mostly due to the readout threshold (100 MeV/Crystal).
- Conversions: part of the energy is deposited upstream of ECAL.
- Event timing is consistent

CMS 2009 Preliminary Uncorrected Distributions

- $M(\pi^0) = (119.1 \pm 3.4) \text{ MeV}$
- $\sigma = (10.4 \pm 2.9) \text{ MeV}$
- $N(\text{ev}) = 20.0 \pm 5.5$

MC (MinBias 900 GeV no B)

- $mass = (117.0 \pm 1.2) \text{ MeV}$
- $\sigma = (16.9 \pm 1.3) \text{ MeV}$
- $N(\text{ev}) = 509.1 \pm 38.2$
Sunday 6th Early Morning First: “Physics” Fill
4x4 bunches, \( \Sigma \sim e^{10} \) protons  Stable Beam Flag set for the first time

All CMS ON

Sunday 6th : 9am

Charged particle \( p_T \) spectrum produced a few hours after the first fill and compared with MC.

Monday 7th : 9am

**\( K^0 \) and \( \Lambda \)** (\( \eta \) and \( \phi \) have also been observed)
Secondary vertex and track reconstruction in good shape,
\( p/K \) hypotheses checked with Si \( dE/dx \),
magnetic field map is good
Anti-$K_T$ algorithm with cone size $R=0.7$

<table>
<thead>
<tr>
<th></th>
<th>Jet 1</th>
<th>Jet 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrected $p_T$ (GeV)</td>
<td>24</td>
<td>26</td>
</tr>
<tr>
<td>$\eta$</td>
<td>0.3</td>
<td>2.0</td>
</tr>
<tr>
<td>$\phi$</td>
<td>2.5</td>
<td>-0.7</td>
</tr>
<tr>
<td>EM Energy Fraction</td>
<td>0.5</td>
<td>0.6</td>
</tr>
</tbody>
</table>
Calibration and Monitoring: Examples

Saturday 12th: “Physics” Fills (250k minbias events)

Reconstructed Primary Vertex Distributions
Beam scan yielded a factor 3 increase in rate at CMS!

![Plot of reconstructed primary vertex distributions](image)

Workflow for ECAL calibration
Plot produced after a few hours

CMS 2009 Preliminary

- $\mu = (113.3 \pm 0.6)$ MeV
- $\sigma = (15.2 \pm 0.6)$ MeV
- $N = 2496.6 \pm 110.8$

Run 124024
Taken on Sat 12th 14:57-17:06
Workflow for ECAL calibration
Plot produced after a few hours
Performance of CMS

Good agreement with MC Expectation

Tracking

Calorimetry

CMS 2009 Preliminary

Particle Flow

Villa Gualino, September 2010
First Physics Distributions

$1/2\pi p_T \sigma^2 N_{ch} \frac{d^2 N}{dy dp_T}$ [(GeV/c)$^2$]

CMS NSD

Tsallis fit

$\sqrt{s}=900$ GeV, NSD

CMS

$\eta$

0 2

UA5 NSD

All three methods combined
Sunday 14th December @ 2.36 TeV

Ran from 4:17 to 5:49: Around 15k events taken
MultiJet Event at 2.36 TeV

CMS Experiment at the LHC, CERN
Date Recorded: 2009-12-14 05:41 CET
Run/Event: 124120/16701049
Candidate Multijet Event at 2.36 TeV

4 PFlow Jets $E_T > 7$ GeV, $p_T$ cut on tracks displayed > 0.4 GeV
Dimuon Event at 2.36 TeV

CMS Experiment at the LHC, CERN
Date Recorded: 2009-12-14 04:46 CET
Run/Event: 124120/5686693
Candidate Dimuon Event at 2.36 TeV

\[ p_T(\mu_1) = 3.6 \text{ GeV}, \quad p_T(\mu_2) = 2.6 \text{ GeV}, \quad m(\mu\mu) = 3.04 \text{ GeV} \]

Villa Gualino, September 2010
A few highlights from LHCb for SPC

11.12. 2009  5:50:50
Run 63691 Event 472  bld 2209
pp interaction vertex as seen by VELO

(VELO is halfway to nominal operation position: each side is 15 mm away from the nominal position)

### A-side

<table>
<thead>
<tr>
<th>Variable</th>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
<th>Underflow</th>
<th>Overflow</th>
<th>$\chi^2$/ndf</th>
<th>Prob</th>
<th>Constant</th>
<th>Mean</th>
<th>Sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>X, mm</td>
<td>26919</td>
<td>0.6229</td>
<td>0.442</td>
<td>11</td>
<td>684</td>
<td>1265/85</td>
<td>0</td>
<td>3333 ± 29.3</td>
<td>0.6025 ± 0.0019</td>
<td>0.2987 ± 0.0018</td>
</tr>
<tr>
<td>Y, mm</td>
<td>26919</td>
<td>-0.3537</td>
<td>0.3863</td>
<td>250</td>
<td>461</td>
<td>461/81</td>
<td>0</td>
<td>3540 ± 28.6</td>
<td>-0.3568 ± 0.0018</td>
<td>0.2923 ± 0.0015</td>
</tr>
<tr>
<td>Z, mm</td>
<td>26919</td>
<td>0.6973</td>
<td>86.59</td>
<td>10</td>
<td>35</td>
<td>853.3/94</td>
<td>0</td>
<td>5338 ± 41.8</td>
<td>4.868 ± 0.241</td>
<td>38.89 ± 0.19</td>
</tr>
</tbody>
</table>

### C-side

<table>
<thead>
<tr>
<th>Variable</th>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
<th>Underflow</th>
<th>Overflow</th>
<th>$\chi^2$/ndf</th>
<th>Prob</th>
<th>Constant</th>
<th>Mean</th>
<th>Sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>X, mm</td>
<td>25711</td>
<td>0.5431</td>
<td>0.4632</td>
<td>881</td>
<td>22</td>
<td>1376/85</td>
<td>0</td>
<td>3024 ± 27.9</td>
<td>0.5296 ± 0.0020</td>
<td>0.3092 ± 0.0020</td>
</tr>
<tr>
<td>Y, mm</td>
<td>25711</td>
<td>-0.408</td>
<td>0.418</td>
<td>269</td>
<td>274</td>
<td>573.5/87</td>
<td>0</td>
<td>3258 ± 27.6</td>
<td>-0.4092 ± 0.0019</td>
<td>0.3012 ± 0.0017</td>
</tr>
<tr>
<td>Z, mm</td>
<td>25711</td>
<td>0.246</td>
<td>92.9</td>
<td>10</td>
<td>35</td>
<td>950.5/96</td>
<td>0</td>
<td>4983 ± 40.3</td>
<td>4.119 ± 0.252</td>
<td>39.57 ± 0.20</td>
</tr>
</tbody>
</table>
Using all tracking power, especially VELO !!!

**Tracking without VELO**

### $K_S$ Invariant Mass (LHCb 2009 data, preliminary)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integral</td>
<td>375</td>
</tr>
<tr>
<td>$\chi^2$ / ndf</td>
<td>49.961 / 95</td>
</tr>
<tr>
<td>Prob</td>
<td>0.99996</td>
</tr>
<tr>
<td>constant</td>
<td>4.1092 ± 0.5318</td>
</tr>
<tr>
<td>slope</td>
<td>-0.0061707 ± 0.0006907</td>
</tr>
<tr>
<td>$N_{signal}$</td>
<td>272.61 ± 16.09</td>
</tr>
<tr>
<td>$m$</td>
<td>496.98 ± 0.30</td>
</tr>
<tr>
<td>$\sigma_m$</td>
<td>4.2274 ± 0.2392</td>
</tr>
</tbody>
</table>

### $\Lambda$ Invariant Mass (LHCb 2009 data, preliminary)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Integral</td>
<td>1871</td>
</tr>
<tr>
<td>$\chi^2$ / ndf</td>
<td>80.719 / 95</td>
</tr>
<tr>
<td>Prob</td>
<td>0.85176</td>
</tr>
<tr>
<td>constant</td>
<td>3.138 ± 0.0951</td>
</tr>
<tr>
<td>threshold</td>
<td>1077.5 ± 0.4</td>
</tr>
<tr>
<td>$N_{signal}$</td>
<td>302.28 ± 28.81</td>
</tr>
<tr>
<td>$m$</td>
<td>1114.4 ± 0.4</td>
</tr>
<tr>
<td>$\sigma_m$</td>
<td>3.6836 ± 0.3639</td>
</tr>
</tbody>
</table>
RICH identifies kaons

Orange points – photon hits
Continuous lines – expected distribution for each particle hypothesis (proton below threshold)
ECAL reconstructs $\pi^0$ signal

First data: 23 November 2009, No B-field

$$\langle m \rangle = (133 \pm 3) \text{ MeV/c}^2$$

$$\sigma = (11 \pm 4) \text{ MeV/c}^2$$

Now $\pi^0$ peak can be routinely monitored on-line:

LHCb data (preliminary)
MIP identification using ECAL, HCAL & Muon
First glance at the material distribution using $\gamma$ conversions upstream the magnet: Tracker system and ECAL

$M(e^+e^-) < 200 \text{ MeV}/c^2$ for any pair of the oppositely charged tracks

Z positions of the vertices reconstructed from 2 tracks with $M(\text{ee}) < 200 \text{ MeV} \& E/p > 0.7$ strongly peak at the location of the 2 stations of the Trigger Tracker: TT1 & TT2
What do we need to do to match the Tevatron, which aims for 9 fb$^{-1}$ by 2010? What is the minimum amount of data at a given energy that is needed to make the 2009 physics run useful? (assuming CM energy $8 < \sqrt{s} < 10$ TeV)

Integrated luminosity $\times$ cross section versus energy

- $\sigma_{W}(M_W=80$ GeV)
- $\sigma_{Z}(M_Z=91$ GeV)
- $\sigma_{\text{jet}}(E_T^{\text{jet}} > \sqrt{s}/20)
- \sigma_{\text{jet}}(E_T^{\text{jet}} > 100$ GeV)
- $\sigma_{\text{Higgs}}(M_H = 150$ GeV)
- $\sigma_{\text{Higgs}}(M_H = 500$ GeV)
Top quark

- Background to new physics searches – must measure cross-section & properties in data
- Expected Tevatron statistics provide a benchmark:
  - Cross-section statistical precision will then be comparable to other uncertainties
  - High-precision top physics will be underway

\[ \text{ATLAS estimate} \quad \text{Tevatron} \ \ell+\text{jets w. 8 fb}^{-1} \]

\[ \ell+\text{jets} \quad \ell\ell bb \quad \text{Tevatron} \ \ell\ell bb \ w. 8 fb}^{-1} \]

~50 pb\(^{-1}\)@14 TeV would match full Tevatron sample
- lose ~factor 2 in cross-section dropping to 10 TeV
- lose ~another factor 2 dropping to 8 TeV

Below 8 TeV samples will be rather small, with a few tens of pb\(^{-1}\)

Catch up with Tevatron with \( s^{1/2} = 8-10 \) TeV and \( \sim 200-100 \) pb\(^{-1}\) g.d.
**Z’**

**Z’: Heavy partner of the Z (SSM)**
- Very clean experimental signal: $Z’ \rightarrow ll$
- Tevatron 95% CL limit at $m_{Z’} = 1$ TeV

**ATLAS fast simulation**

**Needed luminosity for 95%CL exclusion at $m_{Z’} = 1$ TeV:**
- $s^{1/2}$: 14 $\rightarrow$ 10 $\rightarrow$ 6 TeV
- Lumi: 13 $\rightarrow$ 30 $\rightarrow$ 110 pb$^{-1}$
SUSY, an example

- $l$+jets+missing-$E_T$ channel
  - Not most sensitive, but will be usable before inclusive jets +missing-$E_T$ analysis

- Tevatron limit currently is 380 GeV in this model ($m_{\tilde{q}} = m_{\tilde{g}}$)
  - Plot shows 3 masses above this

- We will be sensitive to a region overlapping with ultimate Tevatron reach

- Below $E_{cm} \approx 8$ TeV, the sensitivity collapses

---

5σ discovery beyond current Tevatron limits is possible with $s^{1/2} = 8-10$ TeV and $\sim 30-15$ pb$^{-1}$ g.d.
Higgs 95% CL at LHC GPD, \(H \rightarrow\) weak bosons, indicative

- Luminosity for 95% CL exclusion (fb\(^{-1}\))

- Dependence from ATLAS G4 simulation of e\(\nu\mu\nu\) channel assuming gg\(\rightarrow\)H dominant

- Int. lumi scale uncertainty is \(\sim\)50%

- Tevatron expect 1.9\(\sigma\) sensitivity at \(m=160\) with 8 fb\(^{-1}\) (one expt)

- Massive loss of sensitivity below 6 TeV

To challenge Tevatron with \(s^{1/2} = 7-10\) TeV, we need \(\sim\)300-200 pb\(^{-1}\) g.d.
Physics reach for $\text{BR}(B_s^0 \rightarrow \mu^+ \mu^-)$

- as function of integrated luminosity (and comparison with Tevatron)

At $s^{1/2} = 8 \text{ TeV}$, need $\sim 0.3\text{-}0.5 \text{ fb}^{-1} \text{ g.d.}$ to improve on expected Tevatron limit

Collect $\sim 3 \text{ fb}^{-1}$ for $3\sigma$ observation of SM value
Heavy Ions: Flow at LHC

- one of the first and most anticipated answers from LHC
  - 2nd RHIC paper: Aug 24, 22k MB events, flow surprise (v_2)
    - Hydrodynamics: modest rise (Depending on EoS, viscosity, speed of sound)

BNL Press release, April 18, 2005:
Data = ideal Hydro
"Perfect" Liquid
New state of matter more remarkable than predicted – raising many new questions

LHC will either
confirm the RHIC interpretation
(and measure parameters of the QGP EoS)

OR

..........................

LHC?
LHC Physics in 2010

First beams: very early physics - rediscover SM physics
Detector synchronization, in-situ alignment and calibration

10 pb⁻¹: Standard Model processes
measure jet and lepton rates, observe W, Z bosons
first look at possible extraordinary signatures...

30 pb⁻¹ Measure Standard Model Processes (at 10TeV need ~ 30pb⁻¹):
~ \(10^4\) Z \(\rightarrow\) e+e- (golden Z’s for detector studies (1%))
~ \(10^5\) W \(\rightarrow\) eν
~ \(10^3\) ttbar (measure \(\sigma\) to 10%)

Initial Higgs searches and searches for physics beyond the SM

> 200 pb⁻¹ Entering Higgs discovery era and explore large part of SUSY and new resonances at ~ few TeV

Background for new physics
Need to understand very well
The hard scattering

To produce (at central rapidity, i.e. $x_1 \sim x_2$) a mass of

<table>
<thead>
<tr>
<th></th>
<th>LHC</th>
<th>TEVATRON</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 GeV</td>
<td>$x \sim 0.007$</td>
<td>0.05</td>
</tr>
<tr>
<td>5 TeV</td>
<td>$x \sim 0.36$</td>
<td>--</td>
</tr>
</tbody>
</table>

From where do we know these?

Hard Scattering = processes with large momentum transfer ($Q^2$)

Represent only a tiny fraction of the total inelastic pp cross section ($\sim 70$ mb)

eg. $\sigma(pp \rightarrow W+X) \sim 150$ nb $\sim 2 \cdot 10^{-6} \sigma_{tot}(pp)$
Parton Distribution functions

HERA ep accelerator, 6.3 km circumference

Scattering of 30 GeV electrons on 900 GeV protons:
→ Test of proton structure down to $10^{-18}$ m

→ the LHC is a gluon-gluon collider!
Kinematic regime for LHC much broader than currently explored
- for example, HERA covers most of the relevant $x$ range, but at much smaller values of $Q^2$

Is NLO DGLAP evolution sufficient for LHC?

Have to propagate correctly the uncertainties of PDF determinations into predictions of LHC processes
- important when comparing to data

Have to determine / constrain the PDFs at LHC itself
- what are useful processes for this?
### Event rates

Event production rates at $L=10^{33}$ cm$^{-2}$ s$^{-1}$ and statistics to tape

<table>
<thead>
<tr>
<th>Process</th>
<th>Events/s</th>
<th>Evts on tape, 10 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W\bar{e}e$</td>
<td>15</td>
<td>$10^8$</td>
</tr>
<tr>
<td>$Z \rightarrow ee$</td>
<td>1</td>
<td>$10^7$</td>
</tr>
<tr>
<td>$t \bar{t}$</td>
<td>1</td>
<td>$10^6$</td>
</tr>
<tr>
<td>Minimum bias</td>
<td>$10^8$</td>
<td>$10^7$</td>
</tr>
<tr>
<td>QCD jets $p_T &gt; 150$ GeV/c</td>
<td>$10^2$</td>
<td>$10^7$</td>
</tr>
<tr>
<td>$b \bar{b} \not X$</td>
<td>$10^3$</td>
<td>$10^7$</td>
</tr>
<tr>
<td>gluinos, $m=1$ TeV</td>
<td>$0.001$</td>
<td>$10^3$</td>
</tr>
<tr>
<td>Higgs, $m=130$ GeV</td>
<td>0.02</td>
<td>$10^4$</td>
</tr>
</tbody>
</table>

$10^7$ events to tape every 3 days, assuming 30% data taking efficiency, 1 PB/year/exp

Statistical error negligible after few days (in most cases)!

Dominated by systematic errors (detector understanding, luminosity, theory)
An example: Top production
Top Quark Physics

- Production cross section
- Resonance production
- Production kinematics
- Top Mass
  - Spin
  - Charge
- W Helicity
- Anomalous couplings;
  - CP violation
- Rare/non SM decays branching ratios, $|V_{tb}|$
- Single top production
Top as a “Tool”

- Tag and Lepton study tool
- Missing $E_T$ study tool
- b-tag study tool
- Light quark: jet energy scale from $M_W$ constraint
- b quark: jet energy scale from $M_{top}$ constraint
Top production

Pair production: $qq$ and $gg$-fusion

Electroweak production of single top-quarks (Drell-Yan and $Wg$-fusion)

<table>
<thead>
<tr>
<th></th>
<th>Run I 1.8 TeV</th>
<th>Run II 1.96 TeV</th>
<th>LHC 14 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$qq$</td>
<td>90%</td>
<td>85%</td>
<td>5%</td>
</tr>
<tr>
<td>$gg$</td>
<td>10%</td>
<td>15%</td>
<td>95%</td>
</tr>
<tr>
<td>$\sigma$ (pb)</td>
<td>5 pb</td>
<td>7 pb</td>
<td>600 pb</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Run I 1.8 TeV</th>
<th>Run II 1.96 TeV</th>
<th>LHC 14 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$ (qq) (pb)</td>
<td>0.7</td>
<td>0.9</td>
<td>10</td>
</tr>
<tr>
<td>$\sigma$ (gW) (pb)</td>
<td>1.7</td>
<td>2.4</td>
<td>250</td>
</tr>
<tr>
<td>$\sigma$ (gb) (pb)</td>
<td>0.07</td>
<td>0.1</td>
<td>60</td>
</tr>
</tbody>
</table>

K. Jakobs, CSS07
Top identification

4 jets $p_T > 40$ GeV
2 jets $M(jj) \sim M(W)$
Isolated lepton $p_T > 20$ GeV

$E_T^{\text{miss}} > 20$ GeV

b-tagging important: Need excellent Silicon Vertex and Pixel Detectors
Top Production (example: semi-leptonic case)

See the top immediately with simple selection:
Missed $E_T$, 1 lepton, ≥4 jets, even without b-tag (!), cut on hadronic W mass

Example (ATLAS study):
- Observe it with 30 pb$^{-1}$
- $\sigma(tt)$ to 20% with 100 pb$^{-1}$
- $M(t)$ to 7-10 GeV

Once b-tagging is understood:
Very high S/B achievable ~ 27!

Backgrounds:
- $W+4j$, $Wbb+2j(3j)$ (minor here)

relevant also for single-top

Study the top quark properties
- mass, charge, spin, couplings, production and decay,
- $M_{top} \sim 1$ GeV?

important background for searches
- Jet energy scale from $W\rightarrow$jet jet,
- commission b-tagging

Top pair events in 300 pb$^{-1}$

$N_{top} = 580 \pm 48$
$\sigma(m_{top}) = 15.4 \pm 1.2$

$M_{reco}$
Top Mass Measurement

Require: isolated lepton + $E_{T\text{miss}}$, $M_{JJ}=M_W$, two b-tag jets $\text{stat} \approx 250 \text{ MeV}$

Main systematics:

- knowledge of light- and b-jet energy scale
  - fragmentation, radiation, non-linearities, UE
  - need good energy-flow algorithms

- b-fragmentation

- gluon radiation (ISR, FSR)

- backgrounds

$\delta m_{\text{top}} \approx 1 \text{ GeV achievable}$?
Importance of $m_{top}$ (and $m_W$)

- Indirect constraint on Higgs
- Test overall consistency of SM (or something beyond), if Higgs is found
LHC:

the present and the (near) future
Next steps

- Technical stop until mid February 2010 to:
  - Fix connectors problem to the nQPS cables
  - Insert the nQPS in the Machine protection system
  - Allow CMS to fix a cooling circuit problem
  - Perform the Chamonix retreat

- Ramp to 3.5 TeV
- Commission beams for collisions
- Start Physics run at 7 TeV c.m
- Run until end of 2011
- Perform (two) ions runs (end 2010, end 2011)
Beam Energy; Chamonix

- Simulations for safe current used pessimistic input parameters (RRR......) but have no safety margins
- For 2010, 3.5 TeV is safe
  - Measure the RRR (asap) to confirm the safety margin for 3.5TeV/beam
- Without repairing the copper stabilizers, 5 TeV is risky

Decision from Management/detectors following Chamonix

- Run at 3.5 TeV/beam up to a predefined integrated luminosity with a date limit. Then consolidate the whole machine for 7TeV/beam.
Time lines (Very Preliminary)

<table>
<thead>
<tr>
<th>Activity</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC Operation</td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Injector Chain Operation</td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>LEIR/Linac3/Ions</td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Linac4 Project</td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Inner Triplet (Phase I Upgrade)</td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>LHC Upgrade &quot;cryo&quot; Collimation</td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Consolidation LHC</td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Consolidation Injectors</td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>SPS Upgrade</td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>PS Booster energy increase</td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td></td>
</tr>
</tbody>
</table>

3.5 TeV per beam

Start of 2 year cycle

High Energy Possible

Higher Intensity from injectors?

Next year we talk about the far future!
LHC Performance Pre-amble

• The nominal parameters of the LHC (as quoted in the LHC design report) are challenging both for the machine and the experiments. A staged approach to commissioning the LHC with proton beams was first proposed in Chamonix 2006.

• This approach aimed at finding a balance between robust operations (efficiency and machine protection) and satisfying the experiments (luminosity and event pileup). The number of bunches, bunch intensity and $\beta^*$ are the key parameters varied throughout the period of commissioning to ensure safe and efficient operation.

• The LHC commissioning will be carried out in stages with performance being gradually increased up to the nominal parameters. The 2009 run constituted a first stage, starting with a pilot run at 0.45 and 1.18 TeV/beam and low intensities.

• In 2010 and 2011 we will be operating at 3.5TeV/beam and pushing intensities and luminosities but along a safe line.
Nearly all the parameters are variable (and not independent)

- Number of particles per bunch \( N \)
- Number of bunches per beam \( k_b \)
- Relativistic factor \( \gamma \) (\( E/m_0 \))
- Normalised emittance \( \varepsilon_n \)
- Beta function at the IP \( \beta^* \)
- Crossing angle factor
  - Full crossing angle \( F \)
  - Bunch length \( \theta_c \)
  - Transverse beam size at the IP \( \sigma_z \) or \( \sigma^* \)

\[ F = \frac{\sqrt{1 - \left(\frac{\theta_c^2}{2\sigma_z^2}\right)}}{\gamma} \]
LHC performance drivers/limiters

Machine Protection is super critical

Interaction region ($\beta^*$, F)

Optics
Aperture
Machine protection

Intensity

Collimation
Injector chain
Electron cloud effect
Machine protection

Energy

Interconnects
Training
Machine protection

Presently we are here!!
$\beta^*$ and F in 2010

- Lower energy means bigger beams
  - Less aperture margin
  - Higher $\beta^*$

- > 150 bunches requires crossing angle (beam-beam)
  - Requires more aperture
  - Higher $\beta^*$

- Targets for 3.5TeV
  - 2/2.5 m without/with crossing angle in 2010
  - 2m with crossing angle in 2011
With > 150 bunches per beam, need a crossing angle to avoid parasitic collisions.
Collimator “limit” around $6 \times 10^{13}$ protons per beam at 3.5 TeV with “intermediate” settings (about 20% nominal intensity)

33.6 MJ stored beam energy

Soft limit, not yet well defined, 0.2%/s loss rate totally arbitrary (8 minute lifetime)
Strategy for Increasing the Beam Intensity

• The magic **number for 2010/11 is 1 fb⁻¹**. To achieve this, the LHC must **run flat out at 2x10^{32} cm⁻²s⁻¹ in 2011**,  
  • Correspond to 8e10 ppb, 700 bunches, with a stored energy of 35 MJ (with $\beta^*$=2 m and nominal emittance).
Special criteria before any intensity increase,

• **Stability** is an issue for going above 0.25 MJ.
  – The **optics stability** should be better than about ~10%
  – The **orbit stability** should be better than <0.5 mm to 0.2 mm. (The actual tolerances would depend on the measured “n1” and on the collimator setting.)
  – **1-2 MJ of beam energy** is close to 1% of nominal performance.
    • The **MPS performance should be reviewed at this beam energy.**

• **Bunch Spacing**
  – For most of the time one could operate with **50-ns trains**, initially based on 6, and then 12 bunches per train (and not 36).
Procedure

• How would the green light for an intensity increase be given?
  • The minimum running time at a given intensity is about 10 days with at least 10 fills/dumps.
  • A mini-review prior to every intensity step would discuss any issue and document the decision.
  • There was the exception of requiring at least 3-4 weeks of running at an intensity around 1-2 MJ, possibly in two different configurations (43 bunches and trains).
  • The losses should always be small enough to avoid the risk of frequent quench.
  • A number of tests or verifications are needed after each intensity increase:
    – the diagnostics should be shown to be fully operational, and t
    – beam cleaning adequate.
    – beam dump would be tested at injection.
  • Optics changes like introducing a crossing angle or squeeze would require additional verifications, e.g. related to the collimation set up (to be adjusted), and to the asynchronous dump failure check.
Intensity increase – Summary

- Maximum intensity increase versus stored energy:
  - Up to 0.25 MJ: typical factor ~2, max 4
  - Up to 1-2 MJ: max. factor ~2
  - Above 1-2 MJ: ≤ ~2 MJ per step
<table>
<thead>
<tr>
<th>Stage</th>
<th>lb (protons)</th>
<th>Nb</th>
<th>Stored E (kJ)</th>
<th>Stored E step</th>
<th>Peak L (Hz cm^-2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 pilots</td>
<td>5.00E+09</td>
<td>4</td>
<td>11.2</td>
<td>1.00</td>
<td>4.77E+27</td>
</tr>
<tr>
<td>4 bunches</td>
<td>2.00E+10</td>
<td>4</td>
<td>44.8</td>
<td>4.00</td>
<td>7.63E+28</td>
</tr>
<tr>
<td>4 bunches</td>
<td>5.00E+10</td>
<td>4</td>
<td>112.0</td>
<td>2.50</td>
<td>4.77E+29</td>
</tr>
<tr>
<td>8 bunches</td>
<td>5.00E+10</td>
<td>8</td>
<td>224.0</td>
<td>2.00</td>
<td>9.54E+29</td>
</tr>
<tr>
<td>4x4 bunches</td>
<td>5.00E+10</td>
<td>16</td>
<td>448.0</td>
<td>2.00</td>
<td>1.91E+30</td>
</tr>
<tr>
<td>8x4 bunches</td>
<td>5.00E+10</td>
<td>32</td>
<td>896.0</td>
<td>2.00</td>
<td>3.81E+30</td>
</tr>
<tr>
<td>43x43</td>
<td>5.00E+10</td>
<td>43</td>
<td>1204.0</td>
<td>1.34</td>
<td>5.13E+30</td>
</tr>
<tr>
<td>8 trains of 6 b</td>
<td>8.00E+10</td>
<td>48</td>
<td>2150.4</td>
<td>1.79</td>
<td>1.33E+31</td>
</tr>
<tr>
<td>50 ns trains</td>
<td>8.00E+10</td>
<td>96</td>
<td>4300.8</td>
<td>2.00</td>
<td>2.67E+31</td>
</tr>
</tbody>
</table>

\[ \beta^* = 2 \text{ m, nominal emittance} \]

2 weeks between energy steps = 10 days + margin for MD, access etc

Villa Gualino, September 2010
Progression (2)

- After 30 weeks: $\sim 1 \times 10^{32}$ cm$^{-2}$s$^{-1}$, 12 MJ.
Summary

- To reach a peak of luminosity of $2 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$ in 2010 there must be a rapid progression in stored beam energy in parallel to a lot of commissioning activities.
  - Much faster than in previous machines, with the potential to cause damage!
  - Coupled to an excellent machine uptime.
- Progress will depend on confidence in MPS.
  - Tests … + operational experience.
Luminosity estimates

• Calculate peak luminosity given the usual inputs
  – Bunch current, number of bunches, emittance, beta*, crossing angle

• Calculate luminosity lifetime given
  – Luminosity, cross-section
  – Beam-gas lifetime
  – IBS growth rates

• Optimize fill length given an assumed turnaround time

• Given fill length & luminosity lifetime – calculate integrated luminosity per fill (average luminosity per unit time)
Operation month/year

After a year or so...

- 30 days per month
- 3 day technical stop & recovery
- [~2 days machine development]
  - Absorbed into unavailability for this exercise
- **60% machine availability**
  - During which time we are dedicated to trying to do physics

- 4 weeks of ions (plus one week setup)
- Other requests e.g. Totem
- Assume around 7 months proton physics
  - approx. 200 days
One month: 720 bunches of 7 $e^{10}$ at $\beta^* = 2.5$ m. gives a peak luminosity of $1.2 \times 10^{32}$ cm$^{-2}$s$^{-1}$ and an integrated of about $105 \, pb^{-1}$ per month.

* Turn on crossing angle at IP1.
**Turn on crossing angle at all IPs.
2011

3.5 TeV: run flat out at ~100 pb$^{-1}$ per month

<table>
<thead>
<tr>
<th></th>
<th>No. bunches</th>
<th>ppb</th>
<th>Total Intensity</th>
<th>Beam Stored Energy (MJ)</th>
<th>beta*</th>
<th>Peak Lumi</th>
<th>Int Lumi per month [pb$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 ns</td>
<td>432</td>
<td>7 e10</td>
<td>3 e13</td>
<td>17</td>
<td>2</td>
<td>1.3 e32</td>
<td>~85</td>
</tr>
<tr>
<td>Pushing intensity limit</td>
<td>720</td>
<td>7 e10</td>
<td>5.1 e13</td>
<td>28.2</td>
<td>2</td>
<td>2.2 e32</td>
<td>~140</td>
</tr>
<tr>
<td>Pushing bunch current limit</td>
<td>432</td>
<td>11 e10</td>
<td>4.8 e13</td>
<td>26.6</td>
<td>2</td>
<td>3.3 e32</td>
<td>~209</td>
</tr>
</tbody>
</table>

With these parameters we should be able to deliver 1 fb$^{-1}$
Integrated is not totally dictated by the peak
16 bunches
In summary

SM physics at the LHC: we will have to re-discover the SM before going to other discoveries

Test the SM at an unprecedented energy scale
- lots of highly exciting and interesting physics
  - Jets, Ws and Zs, tops, ...

These are also important tools to
- understand, study, calibrate and improve the detector performance
- constrain physics input (pdfs, underlying event)
- necessary input for all other measurements
...and of course

...there might be welcomed surprises

...but never forget that....

...the only place in which success comes before work is in the dictionary