Issues in Standard Model Physics and Higgs Searches as seen by an experimentalist

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Contents

- Introductory comments
- CMS Construction status
- Standard Model Physics
- Higgs Searches
- Further Remarks
- Summary / Conclusions

Note: Tomorrow Ian Hinchliffe (ATLAS) will talk about SUSY and other searches...
Introduction

- The richness of the LHC/CMS physics program is outstanding

- I cannot cover all, will show a few examples

- **Main aim**: to point out where I see a further need for combined efforts by *theoretical AND experimental* particle physicists

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**CMS Construction Status**
The CMS Detector

SUPERCONDUCTING COIL

CALORIMETERS
ECAL
Scintillating PbWO4 crystals
HCAL
Plastic scintillator/brass sandwich

IRON YOKE

TRACKER
Silicon Microstrips Pixels

MUON BARREL
Drift Tube Chambers (DT)
Resistive Plate Chambers (RPC)

MUON ENDCAPS
Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)

Total weight: 12,500 t
Overall diameter: 15 m
Overall length: 21.6 m
Magnetic field: 4 Tesla

Trial Test of Coil Insertion

Simulation of coil radial extent

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KITP, Collider Physics, Jan 04
Experimental area: Point 5

Main Shaft PX56

Experimental Caverns

Service Cavern

to be delivered to CMS in March 04

Experiment Cavern

to be delivered to CMS in July 04
Magnet Coil: ~ 50% done

- Expect the 5 coil modules at CERN by 1.6.04
- Start cooling on 1.3.05
- Complete magnet test on 15.8.05

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Magnet Yoke

Metallic structures have been completed

Subdetectors
Tracker

- 210 m² of silicon sensors
- 9,648,128 electronics channels

- All-Silicon Tracking
- Good progress on mechanics, electronics and associated system tests
- difficulties in startup of module production due to hybrids, now started
- Hamamatsu sensors OK, problems with quality of ST sensors

Electromagnetic Calorimeter

- ~ 76000 Lead-Tungstate Crystals
- Trigger Tower, 5x5 ch.

- Excellent results from tests of new 0.25 μm electronics
- Electronics mass production and integration starting
- 22000 crystals delivered (35%), Supermodule production ongoing
- > 50% of photodetectors (APDs) ready
Hadronic Calorimeter

- Both half barrels (HB) and end-caps (HE) completed
- On-board electronics installation in Q2-04, then start comissioning
- HF (very forward): All 36 wedges complete in Jan 04 (instead of Apr 04 target); mount them on final support structure in 2004.

Muon System

- Four stations
- Three types of chambers:
  - Drift tubes (barrel)
  - Cathode strip chambers (endcap)
  - Resistive plate chambers (barrel+endcap)
- Chamber production well on track
  - CSC: ~90% complete
  - DTs: ~40% assembled
  - RPCs: ~23% assembled for barrel
- Installation started
CMS Schedule

Objective: Complete Initial CMS for April 2007

Pixel detector ready but not installed for machine commissioning run ('pilot run')

- US and UX area delivered to CMS: Mar 04, Jul 04
- Magnet test on surface: Mid 2005
- ECAL barrel (EB) installation (partial): Q3 2005
- Lowering CMS: 2nd Half 2005
- Tracker installation + cabling: by mid-2005
- ECAL: EB- installation + EB cabling: Q3 2006
- EE installation: Q1 2007
- Det/Trig/DAQ Integration and Commissioning: Apr 06-Apr 07
- CMS closed ready for beam: Apr 07
- Collisions: mid – 2007
- Start Physics Run: Q3 2007
Event rates

Event production rates at $L = 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ 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>$W \rightarrow e\nu$</td>
<td>15</td>
<td>$10^8$</td>
</tr>
<tr>
<td>$Z \rightarrow e\nu$</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>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>
<tr>
<td>Minimum bias</td>
<td>$10^8$</td>
<td>$10^7$</td>
</tr>
<tr>
<td>$b\bar{b} \rightarrow \mu X$</td>
<td>$10^3$</td>
<td>$10^7$</td>
</tr>
<tr>
<td>QCD jets $p_T &gt; 150 \text{ GeV/c}$</td>
<td>$10^2$</td>
<td>$10^7$</td>
</tr>
</tbody>
</table>

$\Rightarrow$ statistical error negligible after few days!
$\Rightarrow$ dominated by systematic errors (detector understanding, luminosity, theory)

HLT performance: signal efficiency

- Efficiency of the Higher Level Trigger selection for some typical physics channels:

<table>
<thead>
<tr>
<th>Channel</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W \rightarrow e\nu$</td>
<td>67%</td>
</tr>
<tr>
<td>$W \rightarrow \mu\nu$</td>
<td>69%</td>
</tr>
<tr>
<td>$\text{Top} \rightarrow \mu X$</td>
<td>72%</td>
</tr>
<tr>
<td>$H(115 \text{ GeV}) \rightarrow \gamma\gamma$</td>
<td>77%</td>
</tr>
<tr>
<td>$H(160 \text{ GeV}) \rightarrow WW^* \rightarrow 2\mu$</td>
<td>92%</td>
</tr>
<tr>
<td>$H(150 \text{ GeV}) \rightarrow ZZ \rightarrow 4\mu$</td>
<td>98%</td>
</tr>
<tr>
<td>$A/H(200 \text{ GeV}) \rightarrow 2\tau$</td>
<td>45%</td>
</tr>
<tr>
<td>SUSY ($\sim 0.5 \text{ TeV sparticles}$)</td>
<td>$\sim 60%$</td>
</tr>
</tbody>
</table>
Issues to be addressed

Our Master Equation

\[ \sigma_{\text{meas}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\varepsilon L} \]

- Stat vs syst errors, backgrounds from data or MC? Signal Significance
- Reduce error?
- Understand isolation, jet veto; \( p_T \) distributions at NLO; need calculations for detectable acceptance.

\[ \sigma_{\text{theo}} = \text{PDF}(x_1, x_2, Q^2) \times \sigma_{\text{hard}} \]

- Constrain, define uncertainties
- HO calculations, implement in MC

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Standard Model Physics

Why SM physics

- Interesting in its own right
  - measure (calculable) event rates, cross sections (relative, differential, absolute)
  - establish (dis)agreement with SM, constrain SM
  - challenge theoretical calculations at high $Q^2$
  - demonstrate “working” experiment with well known processes

- Understanding of detector, calibration

- Backgrounds to many searches

- Constrain (relative) PDFs

- Alternative measurements of luminosity
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Issues in Standard Model Physics and Higgs Searches

Main systematics:

- backgrounds
- gluon radiation (ISR, FSR)
- b-regeneration
- need good E-Flow
- non-linearities, E inflict regeneration, radiation
- p-jet energy scale
- knowledge of light- and heavy-flavored quarks

Requiring: isolated lepton + Emiss: \( M_V \) <= 250 MeV

Top Quark Physics

Single top production

Branching ratios \(|V/\bar{V}|^2\)

Parton-shower decay

Production

Inclusive cross section

Charge

Spin

Top Mass

Width

V-Heftcy

Production

CP Violation

Non-minimal couplings!
Top Mass Measurement

- Why not from cross section?
  - huge statistics
  - totally different systematics

- Uncertainty on PDFs
  - $\Delta$PDF of 10% translates into $\Delta m_{\text{top}} \approx 4 \text{ GeV}$
  - need to constrain PDFs

- Luminosity
  - $\Delta L \approx 5\%$
  - can we do better?

\[ \Delta \sigma/\sigma \approx 5 \Delta m_{\text{t}}/m_{\text{t}} \]

\[ \begin{align*}
pp \rightarrow t\bar{t}, & \quad \sqrt{s}=14 \text{ TeV} \\
\sigma & \ (p\bar{p}) \ \text{(ref)} \ \text{at NLO+NLL QCD} \\
\alpha_s(M_Z) & = 0.1175, \quad k_T=0.4 \text{ GeV} \\
\alpha_s & = \alpha_s(M_Z)
\end{align*} \]

Lower inset:
- $\delta m_{\text{t}}/m_{\text{t}} = 0.21 \delta \sigma/\sigma$

Luminosity Measurement

- Expected uncertainty from luminosity monitors $= 5\%$
- Alternative: use W/Z counting as luminosity monitor

\[ N_{pp \rightarrow Z} = L_{pp} \cdot PDF(x_1, x_2, Q^2) \cdot \sigma_{q\bar{q} \rightarrow Z} (+HO) \]

count extract from theory

- or better: normalize processes to number of Zs (parton-parton luminosity)

\[ N_{pp \rightarrow WW} = N_{pp \rightarrow Z} \cdot \frac{\sigma_{q\bar{q} \rightarrow WW}}{\sigma_{q\bar{q} \rightarrow Z}} \cdot \frac{PDF(x_1', x_2', Q^2)}{PDF(x_1, x_2, Q^2)} \]

$\Delta L_{pp} = 0!$

Calculate ratios.
Reduced uncertainties(?)
Constraining PDFs

- at the same time: precise PDFs from $W^+/W^-/Z$ rapidities

Note:

if we want precise measurement of Luminosity or some parameter in hard-interaction cross section, it is essential to have HO calculation restricted to measurable acceptance

⇒ avoid extrapolation errors (extrapolation to large $y_W$)

Constraining PDFs

- particularly well suited: $W^+/W^-$ cross section ratio $\sim u(x)/d(x)$
- even small PDF differences observable
Direct photons

\[ \delta_{\text{stat}} \text{ after 10 days at } L=10^{32} \]

Fast simulation

\begin{align*}
\text{CMS Note 2000-063} \\
40 < E_T^\gamma < 50 \text{ GeV} \\
2.0 < \eta_{\text{jet}} < 2.5
\end{align*}

Very useful tool:

- energy scale calibration
- understanding of photon isolation
- constrain gluon and test SM predictions

\[ \eta_{\text{v}} \text{ for direct photons and background} \]

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Messages 1

- compute ratios of cross sections
- have new ideas/proposals for such ratios
- normalize processes to the well known W/Z production, and extend this method to gluon-initiated processes
- get (N)NLO predictions for measureable acceptance, or better, differential predictions
- direct photons: get best possible theoretical input (isolation criteria, higher order predictions) and constrain the gluon
The Underlying Event

see CDF study, R. Field et al.

The Underlying Event:
beam-beam remnants
initial-state radiation
multiple-parton interactions

Issues:
- modelling (min bias, multiple interactions)
- extrapolation to LHC energies
- impact on selection efficiencies?

The Underlying Event

"Transverse" Charged $p_{T\text{max}}$

- **TransMax region** defined event-by-event: contains highest $p_T$ charged particle
- In this comparison: PYTHIA has multiple interactions, HERWIG not
- **CDF data show** "jet structure" in UE: more activity in TransMax region (without $p_{T\text{max}}$ track) than on average in transverse region
- **Correlations** between the two transverse regions, described by ‘PY Tune A’.
**UE : Extrapolation to LHC**

by R. Field, see LHC MC WS

12% of "Min-Bias" events have $P_T$(hard) > 10 GeV/c!

1% of "Min-Bias" events have $P_T$(hard) > 10 GeV/c!

Note:
- will have 10-20 "minimum bias" events per beam crossing at high luminosity
- PY Tune A describes well the "underlying event", but not so well the properties of the leading jets!

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**Example : Impact on jet studies**

Reconstructed jet energy, $E_T$=50 GeV

| $|\eta|<1$ | 2.5 $< |\eta| < 3$ |
|---------|------------------|

- To get good jet energy resolution, such an effect has to be corrected for
- algorithms try to obtain corrections from the data
- however, calibration/testing of algorithms will be done using MC
  - have to understand well MB + UE
need models and data for understanding of underlying event

try to learn as much as possible at the TEVATRON

understand impact on “other” physics, such as isolation efficiencies for searches, jet resolution, MET resolution

further issue: fragmentation (in particular b-fragmentation): we need not only N(N)LO calculations, but also progress on fragmentation side

Higgs Searches
Searches: general remarks

- as significance (number of ‘sigmas’) one usually sees the definition \( \alpha_{\text{stat}}(\text{background}) = \sqrt{n_b} \) for large enough statistics.

\[
\tilde{n}_\sigma = \frac{n_s}{\sqrt{n_b + f^2 n_b^2}}
\]

- Adding a relative systematic uncertainty \( f \), \( \alpha_{\text{syst}}(\text{background}) = f n_b \), in quadrature to the statistical uncertainty, this becomes:

\[
\tilde{n}_\sigma = n_\sigma \cdot \left[ 1 + \left( \frac{f \cdot n_\sigma}{n_s / n_b} \right)^2 \right]^{-\frac{1}{2}}
\]

- limiting cases:

\[
\frac{n_s}{n_b} \ll f \cdot n_\sigma \quad \Rightarrow \quad \tilde{n}_\sigma \approx \frac{n_s / n_b}{f}
\]
dominated by systematics

\[
\frac{n_s}{n_b} \gg f \cdot n_\sigma \quad \Rightarrow \quad \tilde{n}_\sigma \approx n_\sigma
\]
dominated by statistics
Searches: general remarks...

- a concrete example (10% background uncertainty)

<table>
<thead>
<tr>
<th>$n_s$</th>
<th>$n_b$</th>
<th>$n_s/n_b$</th>
<th>$n_\sigma$</th>
<th>$\tilde{n}_\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>100</td>
<td>0.5</td>
<td>5</td>
<td>3.5</td>
</tr>
<tr>
<td>500</td>
<td>10000</td>
<td>0.05</td>
<td>5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

- in the second case, more luminosity will not improve the significance! (unless more data help to better understand the background)

SM Higgs
(see CMS Note 2003/033, Nov 03)
Production and Decay

2-photon final states (gg → H, qqH, WH, ttH)
- excellent detector resolution, isolation, QCD jets rejection

Lepton final states (4\ell, \mu, e or \tau)
- isolation, momentum resolution, tau identification

Lepton + neutrino final states
- lepton identification, WW and tt background rejection, MET resolution

Associated Higgs production (bbH, ttH)
- b-tagging, ttjj backgrounds

Higgs production via Vector Boson Fusion
- very forward jet tagging, tt(j) background
Classes of Final States

- Mass can be fully reconstructed ($\gamma\gamma$, 4 leptons, $b\bar{b}$)
  - background from sidebands
  - for hadronic final state: need excellent jet $E_T$ resolution

- Neutrinos in final state, no exact mass reconstruction possible
  (eg. $H \rightarrow WW \rightarrow \gamma\nu\bar{\nu}$ or $H/A \rightarrow \tau\tau$)
  - Jacobian peaks
  - background from ‘sidebands’ if possible
  - background from MC
  - extrapolation of background from non-signal region using data and MC (shape)
  - extrapolation of background using data and theory (ratio of cross section)

---

**$H \rightarrow \gamma\gamma$**

$S/B \approx 1/10$
(for inclusive search)

- enormous background, but smooth sidebands (need excellent resolution and high efficiency)

- Important issue: Isolation criterion
  - how to match theoretical and experimental definitions of photon isolation?

1. smooth cone isolation (S. Frixione)
   $E_T < p_T(\gamma) < (1-\cos R)(1-\cos R)^n, \ r < R$

2. "standard" theor. cone isolation (L. Dixon)
   $E_T < E_{T\text{out}}$ inside cone R

3. "standard" exp. cone isolation (CMS / ATLAS)
   no tracks $p_T < 1-2$ GeV/c inside cone R
   $E_T$ in calorimeter inside cone $R < E_{T\text{out}}$

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k-factors included

Bkg : Fast simulation

in bckg : irreducible pp → $\gamma\gamma$+X, pp → $\gamma$ jet with FSR

not in : QCD multi-jet, pp → $\gamma$ jet →isol. $\pi^0$ (~20-30% of irreducible)

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**H → ZZ(∗) → 4 leptons**

- Backgrounds: ZZ(∗), Zbb, ttbar
- Issues: lepton isolation; tracking (‘no’ impact parameter); uncertainties from UE regarding efficiencies, thresholds?

**H → WW(∗) → ℓνℓν**

- Backgrounds: WW, tt (WWbWb)
- central jet veto (suppresses WbWb)
- lepton isolation
- use different dynamics of signal and background, eg. lepton angles → good MCs needed!
- differential NNLO Higgs cross section as function of Higgs p_T would be nice

**Issues**:
- best channel for M_H~160-170 GeV. 10 fb^{-1} enough
Background extrapolation

Backgrounds to $H \rightarrow WW \rightarrow \ell\nu\nu \ell\nu\nu$: $t\bar{t}$ for gluon fusion, $t\bar{t}j$ for qqH

40-50% scale uncertainty at LO

Idea of extrapolation:

Cavelli, Kauer, Zeppenfeld

$\sigma_{bkg} \approx \left( \frac{\sigma_{bkg, LO}}{\sigma_{ref, LO}} \right) \cdot \sigma_{ref}$

low theor. uncertainty

low experim. uncertainty

Reference selection:
- like background, but
- no central jet veto
- no lepton pair cuts
- require b-tag

⇒ gives expt. stat. uncertainty of 1-2%

⇒ ~ 5% background uncertainty
Associated Higgs production

S/B < 1  (\sim 0.6-0.8)

Issues (very challenging):

- Backgrounds: ttbb, ttjj, Ztt, W+jets
  (from LO CompHEP)
  - sidebands-method not safe
- ttbb: dominant bckg. after selection. Very large scale uncertainties.
- additional jets (at NLO) can change the shape
- background extrapolation applicable (a' la Kauer et al.)?

one leptonic + one hadronic top decay

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Further information:

ttjj background

- Another approach: learn from TEVATRON (recent CMS talk by R. Demina)
  - production and ISR different, but
  - FSR very similar, jet E_\gamma spectrum very similar
  - eg. CDF RUN1: ttj gives a 5% contribution to W+njets (\geq 1b-tag) data
  - note: ttbb rate too small at TEVATRON

- Proposal for TEVATRON contribution
  - Monte Carlo verification and tuning for ttjj production
  - Study initial state radiation on gluon fusion dominated processes, e.g. bb prod.
  - Separation can be done with invariant mass selection:
    - M(bWj)=M(t) – b-jet radiation
    - M(jjj)=M(WW) – W decay products radiation
    - Forward jets – ISR
  - Analyses methods development and verification

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SM Higgs sensitivity

BUT NOTE: no systematic errors included!

MSSM Higgs

(one example of recent studies)

(see CMS Note 2003/033, Nov 03)
pp → b¯b H/A, H/A → ττ

looked for in τ decays: e+μ, ℓ+jet and jet+jet

Very challenging: hadronic τ-decays (isolation); S/B ~ 1.7-2.7 (large tanβ)

→ full trigger simulation performed

- Backgrounds: Z decays, QCD multijet, ttbar and Wt → veto 2. central jet
- Note: use this channel to precisely measure tanβ, with Δstat < Δtheo ~ 20%?

Roadmap

- 10 fb⁻¹:
  - SM-like Higgs discovery in H→ZZ(γ), H→WW(γ)

- 30-60 fb⁻¹ at low luminosity:
  - observation of other Higgs channels, such as H→γγ
  - first measurements of Higgs properties

- 100-300 fb⁻¹ at high luminosity:
  - observation of more Higgs channels
  - precise measurements of Higgs properties
  - in what model are we?
Messages

- same isolation criterion in experiment and theory

- differential (N)NLO cross sections needed (signal + backgr)
  - eg. as function of Higgs $p_T$ or rapidity
  - in particular, need more theory-input for important channel $H \to WW^{(*)} \to \ell\nu\ell\nu$

- very important and difficult background:
  - ttbb, $t\bar{t}j(j)$, $WW$
  - need NLO, associated systematic uncertainties, and/or

- clever background estimations, such as
  - extrapolation via ratios of cross sections from theory
  - use TEVATRON: understand where useful, where NOT (eg. different colour structure)

- CMS Physics TDR to come out in 2005
  - if you theorists do a good job, you will get a lot of citations .... d; -)
Further remarks

- Try from the very beginning
  - to establish an excellent collaboration theorists - experimentalists
  - in order to avoid (to have for years), eg.
  - improper usage of MCs
  - different definitions of systematic uncertainties
  - example: only about 12 years after LEP startup there has been an agreement between experiments (and theorists) on the theoretical uncertainty of $\alpha_s$ from event shapes...

Summary

- CMS is getting ready for exciting and challenging data taking at the LHC
  - detector construction at full steam, will be ready in April 07
  - see WEBCAM: http://cmsinfo.cern.ch/Welcome.html/cmseye/index.html
  - many (stat. only) studies have shown that CMS is well designed for addressing the very rich LHC program

- Now entering new period of analyses preparation
  - Physics TDR by 2005: write/debug/learn necessary software tools
  - concentrate carefully on ALL aspects of the analyses, such as
  - calibrations, systematic uncertainties due to detector
  - theoretical uncertainties

- Need good collaboration between experimentalists and theorists in order to
  - improve predictions
  - validate MCs
  - invent new/clever approaches where ‘standard’ methods appear hopeless
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