HIGGS HUNTING 2011
THEORY VIEWS

Babis Anastasiou
ETH Zurich
THE LHC IS MAKING HISTORY

• unearthing extremely rare phenomena
• making a classic contribution to science
• writing the most dramatic chapter in particle physics history
• proving a complete story in particle physics to tell for the next generations
• ….or getting us to an exciting frontier in physics governed by different laws.

John Ellis

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.
A TRIUMPH OF EXPERIMENTAL PHYSICS

- A technology marvel has been created.
- The LHC machine and detectors have proven themselves with amazing confidence.
- Performing excellent.
- At first LHC workshops, it was not anticipated that one can get so close to a Higgs boson discovery as we are now with only 7TeV.

Zoltan Kunszt,
“limited audience” dinner talk
CONGRATULATIONS

• As “theory bystanders” we are amazed with what has been achieved so far in the experimental frontier and congratulate.

• Not only the LHC teams, but also LEP and the TEVATRON.

• CDF and D0 have paved the way and brought sophistication and maturity into Higgs boson searches at hadron colliders.
• hypotheses, models and ideas on what to search for
• ideas on how to best search for certain signatures
• simulation tools
• a little bit of healthy “paranoia”
• precision and confidence
• “final” interpretation
HYPOTHESES

WHAT TO SEARCH FOR?
THE STANDARD MODEL
STANDARD MODEL TESTS

- A light Standard Model Higgs hypothesis is in agreement with all indirect tests

- More important: no spectacular novel phenomenon has emerged yet at the new LHC energy frontier.

M. Schott, for Gfitter
Higgs mechanism is the most plausible solution
(not a surprise)

A discovery not to be trivialized:
• A new guise of the gauge principle
• A new force of nature (non-gauge?)
• Propagating particles do not share the full
  symmetry of interactions
• Boost for precision studies at a LC
• New information from Higgs mass and couplings

G. Giudice
HIGGS MASS

• The last missing parameter in the Standard Model

• But its value may matter a lot for physics at many orders of magnitude higher than the LHC reach and cosmology. G. Giudice
LOW ENERGY SUPERSYMMETRY

• A beloved theory by both theorists and experimentalists

• A conceptually beautiful idea which makes physics at very high energies simple and largely explicable.

• It offers the opportunity for a bonus discovery at the LHC, by explaining dark matter and electroweak symmetry breaking simultaneously.
THE MERRY AND LONGEVITY

“Longevity Project participants who were the most cheerful and had the best sense of humor as kids lived shorter lives, on average, than those who were less cheerful and joking. It was the most prudent and persistent individuals who stayed healthiest and lived the longest.” The Longevity Project

• SUSY models are very exciting, offering an explanation about (almost) everything.
• The SM is also exciting but less cheerful and a little bit conservative…
LHC IS A MODEL ASSASSIN... 

...BUT

• it is early for SUSY to be pronounced “dead”

• well motivated scenarios yet to be constrained
  - almost degenerate sparticle spectrum
  - only third family squarks are light
  - also studies by A. Weiler

• Exciting interplay of Higgs physics and direct supersymmetry searches

Example: “Lambda-SUSY”

\[ W_\lambda = \lambda S H_1 H_2 \]

Barbieri, Hall, Nomura, Rychkov


• Rather strongly coupled scalar chiral multiplet

• Higgs bosons from \(\sim 200-700\) GeV

• heavier squarks, small \(\tan\beta\), ...

• “sacrifices”:
  - not complete theory as it requires a new threshold at \(\sim 10-20\) TeV,
  - not manifest gauge coupling unification
COMPOSITE HIGGS

- Light Higgs from strong dynamics at the TeV scale
- No elementary scalar.
- Cures the hierarchy problem.
- Similar mechanism from QCD (pion mass)
- UV completions with warped extra dimensions.

\[ \Delta m_\pi^2 \approx 3 \frac{\alpha_{em}}{4\pi} m_\rho^2 \]

R. Contino
COMPOSITE HIGGS

R. Contino

- Suppressed coupling of the Higgs boson to EWK gauge bosons
- Higgs-fermion couplings are model dependent.
- A fermiophobic Higgs is also possible
- Discovery of the Higgs boson may be more challenging (reduced production cross-sections)
- but not a “nasty” model... one generally expects additional signatures (top-quark partners)
Higgs pair production is typically enhanced (non-standard Higgs self-coupling)
NO HIGGS OR INVISIBLE HIGGS

- The Higgs boson in the Standard Model tames the cross-section growth for the scattering of longitudinal W’s.

- If no Higgs, then something else must be happening:
  - Higgs is in the theory, but it is the portal of the SM to a hidden sector and thus invisible *G. Giudice*

- Higgs is not in the theory, but other visible phenomena take place
NO HIGGS

- Forming of extended longitudinal W field configurations, decaying into multiple W,Z bosons. 
  R. Gupta

- Spin-1 resonances at the TeV scale  A. Kaminska
HOW TO SEARCH FOR “STUFF”?
THEORY INPUT FOR SEARCH STRATEGIES

• An optimal search strategy is usually shaped through hands on experience, which is lacking from the classical education of a typical theorist.

• But synergy and collaboration among theorists and experimentalists on search strategies has boosted progress.

• An important example is the classic paper of Dittmar and Dreiner on finding a Higgs signal in the WW channel.

• Many other examples: Higgs coupling extractions, reweighting methods, jet substructure,...
FAT JETS

T. Plehn

Fat jets — made for the LHC

- $VH$: bringing back 2/3 of light Higgses
- $t\bar{t}H$: curing combinatorics and backgrounds
- SUSY cascades: curing lack of analysis idea...
- $Z'$ etc: improving mass resolution
- $t\bar{t}^*$: curing backgrounds...
- $H \rightarrow aa \rightarrow 4g$: making it possible...

- The anatomy of boosted jets (collimated hadrons) can reveal heavy fast moving parent particles, such as a Higgs boson or a top-quark
- Has revived the WH and ZH channels at the LHC, and brings hope for the $ttH$
- Ideas to deal with increasing pile-up
SIMULATIONS
A SIMULATION OF MANY SCALES

- Non-perturbative parton densities
- Hard scattering cross-sections
- Radiative collinear cascades
- Hadronization, underlying event, ...
<table>
<thead>
<tr>
<th>set</th>
<th>order</th>
<th>data</th>
<th>(\alpha_s(M_Z))</th>
<th>uncertainty</th>
<th>HQ</th>
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<tr>
<td>MSTW 2008</td>
<td>NNLO</td>
<td>global</td>
<td>fitted (+ external variations)</td>
<td>Hessian (dynamical tolerance)</td>
<td>GM-VFN (ACOT +TR’)</td>
<td>Martin, Stirling, Thorne, Watt</td>
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<tr>
<td>CT10</td>
<td>NLO</td>
<td>global combined HERA</td>
<td>external (several values &amp; older fit)</td>
<td>Hessian (dynamical tolerance)</td>
<td>GM-VFN (SACOT-X)</td>
<td>CTEQ, Lai et al.</td>
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<td>NNPDF 2.1</td>
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<td>global combined HERA</td>
<td>external (several values &amp; recent fit)</td>
<td>Monte Carlo (pdf replicas)</td>
<td>GM-VFN (FONLL)</td>
<td>NNPDF, Ball et al.</td>
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<td>NNLO</td>
<td>DIS+DY(f.t.)</td>
<td>fitted</td>
<td>Hessian</td>
<td>FFN +matching</td>
<td>Alekhin, Blümlein, Klein, Moch</td>
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<tr>
<td>(G)JR</td>
<td>NNLO</td>
<td>DIS+DY(f.t.) + some jet</td>
<td>fitted</td>
<td>Hessian</td>
<td>FFN (VFN massless)</td>
<td>Glück, Jimenez Delgado, Reya</td>
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<tr>
<td>HERA PDF</td>
<td>NNLO</td>
<td>only DIS HERA</td>
<td>external</td>
<td>Hessian</td>
<td>GM-VFN (ACOT +TR’)</td>
<td>H1 &amp; Zeus collaborations</td>
</tr>
</tbody>
</table>

Each group one provides a number of sets to compute central values and pdfs, pdf+coupling uncertainties

*D. de Florian*
PDF ISSUES

• A generally very good precision.

• But with some discrepancies beyond the estimated uncertainties: strong coupling, gluon density.

• Affect mainly Tevatron gluon-fusion, but also LHC
Conclusions  D. de Florian

- Everything looks pretty solid and coming LHC data will help to constrain PDFs much better!

- PDFs play a role in setting exclusion limits for Higgs, but limit can not depend of pdf set used

- We know recent examples (e.g. MRST-06 vs MSTW-08) where TH improvements produced considerable change in PDFs (and Higgs cross section)

Do not expect such big modification in the future. But to be safer, I would recommend try PDF4LHC prescription with larger uncertainty to leave room for possible TH/EXP improvements (mostly on jets!)
FANTASTIC LEAP FORWARD:
TWO COMPLETE ORDERS IN THE PERTURBATIVE
EXPANSION ALWAYS ACCOUNTED FOR.

L. Reina  F. Maltoni
AUTOMATION

• Cost saving
  Trade human time and expertise spent on computing one process at the time with time on physics and pheno.

• Robustness
  Programs are modular and computations based on elements that can be systematically and extensively checked. Trust can be easily built.

• Wide accessibility
  One framework for all. Available to everybody for an unlimited set of applications for all. Suitable to EXP collaboration.

F. Maltoni
MadGraph
FKS
CutTools
MC@NLO

aMC@NLO

Hirshi, Frederix, Frixione, Maltoni, Garzelli, Pittau, Torrielli
STANDING OF SIMULATIONS

• The precision of generic Monte-Carlo tools is improving continuously and it is already impressive!

• including NLO (POWHEG, MC@NLO), improving parton showers (J.Lopez-Villarejo), etc

• Still, some vigilance is needed for “special” effects.

• Very recent example, finite width and signal-background interference effects.

Campbell,Ellis,Williams
Formally equivalent matching methods treat differently sub-leading effects. These are important in Higgs physics and generally processes with significant NLO corrections.

“Artificial” enhancement at large pt:
By chance on the NLO result for this observable.

Well known agreement between MC@NLO +HERWIG and the resummed result. Not quite for POWHEG.
Higgs observables are typically predicted with two and three-loop accuracy

- gluon-fusion, vector boson fusion, bottom-quark fusion, associated Drell-Yan total cross-sections are known at NNLO in the Standard Model

- Higgs decays are mostly known at NNNLO.

- In BSM, it is not always possible to reach completely NNLO (Heavy Higgs, more complicated virtual corrections).

- In the MSSM, all ingredients are there for NLO and even NNLO for a light Higgs (Muehlleitner, Rzhak, Spira; Degrassi, Slavich, Pak, Steinhauser, Zerf, Harlander, Hofman, Mantler,...)

- If it can be done for the MSSM, it can be done for any other model!
Total cross section is thus OK but....more exclusive observables are needed!

At LO we don’t find problems: compute the corresponding matrix element and integrate it numerically over the multiparton phase-space

Beyond LO the computation is affected by **infrared singularities**

Although these singularities cancel between real and virtual contributions, they prevent a straightforward implementation of numerical techniques

In particular, at NNLO, only few fully exclusive computations exist, due to their extreme technical complications

- $g g \rightarrow H$ **FEHLP, HNNLO**
  - C.Anastasiou, K.Melnikov, F.Petrello (2005)
  - S.Catani, MG (2007)
  - MG(2008)
- Drell-Yan **FEWZ, DYNNOLO**
  - R.Gavin et al. (2010)
  - L.Cieri et al. (2009)
Catani, Cieri, de Florian, Ferrera, Grazzini

FIRST EVER DIFFERENTIAL “2 TO 2” NNLO CROSS-SECTION

NEW: \[ pp \rightarrow \gamma\gamma \text{ at NNLO} \]

Two loop amplitude available
\( \gamma\gamma + \text{jet at NLO available} \)

\[ \Rightarrow \text{We can perform the NNLO calculation using hard coefficients obtained for Drell-Yan} \]

Use Frixione isolation \( \Rightarrow \) no fragmentation contribution

PRELIMINARY RESULTS \( \text{LHC, } \sqrt{s}=14 \text{ TeV} \)

\( p_T^\gamma \geq 40 \text{ GeV} \quad |\eta| \leq 2.5 \)

\( 60 \text{ GeV} \leq M_{\gamma\gamma} \leq 180 \text{ GeV} \)

\[ E_T^{\text{had}}(\delta) \leq \chi(\delta) \]

\[ \chi(\delta) = \epsilon_r E_T^{\gamma} \left( \frac{1 - \cos(\delta)}{1 - \cos(R_0)} \right)^n \]

\( n = 1 \quad \epsilon_r = 0.5 \quad R_0 = 0.4 \)

\[ \mu_R = \mu_F = M_{\gamma\gamma} \]
ASSOCIATED WH, ZH PRODUCTION

NEW: \textbf{WH at NNLO}

Results at the Tevatron

Cuts:
- lepton: $p_T > 20$ GeV and $|\eta|<2$
- $p_T^{miss} > 20$ GeV

Jets: $k_T$ algorithm with $R=0.4$

We require exactly 2 jets with $p_T > 20$ GeV and $|\eta|<2$

One of the jets has to be a $b$-jet with $|\eta|<1$

<table>
<thead>
<tr>
<th>$\sigma$ (fb)</th>
<th>LO</th>
<th>NLO</th>
<th>NNLO</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_F = \mu_R = (m_W + m_H)/2$</td>
<td>$4.266 \pm 0.003$</td>
<td>$4.840 \pm 0.005$</td>
<td>$4.788 \pm 0.013$</td>
</tr>
<tr>
<td>$\mu_F = \mu_R = m_W + m_H$</td>
<td>$3.930 \pm 0.003$</td>
<td>$4.808 \pm 0.004$</td>
<td>$4.871 \pm 0.013$</td>
</tr>
<tr>
<td>$\mu_F = \mu_R = 2(m_W + m_H)$</td>
<td>$3.639 \pm 0.002$</td>
<td>$4.738 \pm 0.004$</td>
<td>$4.908 \pm 0.010$</td>
</tr>
</tbody>
</table>

Fixed-order results appear to be under good control

Scale dependence at the 1\% level both at NLO and NNLO

Shape of $p_T$ spectrum of dijet system is stable
A "NON-SUMMARY" SLIDE
FULLY DIFFERENTIAL NNLO H->BB

Herzog, Lazopoulos, CA

- Yet another method for real radiation at NNLO (non-linear mappings)
- First physical application
- Radiation from the final state in the Higgs decay to bottoms may play a role for jet substructure, etc
- The NNLO revolution is growing with the influx of a bright younger generation in the field.
WE HAVE A PARTIAL VIEW OF PARTICLE PHYSICS

- but we should not worry or be anxious.

it already looks beautiful!
And the LHC will reveal a full picture which...
WILL REMAIN CLASSIC
...WHATEVER IT IS!