The road to the ElectroWeak Symmetry Breaking

18th January 2012
Seminar at Johns Hopkins University

S.Bolognesi (Johns Hopkins University)
Outline

- The Higgs boson and the ElectroWeak Symmetry Breaking (EWSB)
- **Status**: CMS results in a nutshell, focusing on high mass H->VV

- **What’s next?**
  - move to **larger mass (>600 GeV beyond SM)**
    - control of V+jets background
    - jet merging
    - signal characterization (angular analysis)
  - improve sensitivity to **smaller xsec -> Vector Boson Fusion**
    - control of VV background

- The final arbiter: **VV scattering**
Why we need the Higgs

The Higgs boson provides

1) an EXPLICATION of the W,Z mass (ie EWSB)

2) a DESCRIPTION of the fermions masses

• 1 is really fundamental to make the SM “working” (next slides)
  ... even if not less arbitrary!

• 2 is just another way of formulating the same question:
  why the fermions have those particular masses?
  why the fermions have those particular Higgs couplings?
  (SM works well without 2: just the fermio-phobic Higgs)
EWSB and the W, Z mass

\[ L_{\text{gauge}} = -\frac{1}{4} W_{\mu \nu}^i W^{i \mu \nu} - \frac{1}{4} B_{\mu \nu} B^{\mu \nu} + \frac{1}{2} m^2 W_{\mu \nu}^i W^{i \mu \nu} + \frac{1}{2} m^2 B_{\mu \nu} B^{\mu \nu} \]

Gauge invariance

Scalar potential \((\lambda > 0, \mu < 0)\)

\[ V(\Phi) = \mu^2 \left| \Phi^* \Phi \right| + \lambda \left( \Phi^* \Phi \right)^2 \]

with minimum (empty state) at

\( (v = \text{empty expectation value}) \)

\[ \langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \quad \text{or} \quad \langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v \\ 0 \end{pmatrix} \]

SU(2)

Complex scalar doublet of SU(2)

\[ \Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \]

SU(2) x U(1)

Goldstone bosons \(\omega_i\)

1 physical scalar field -> Higgs

4 Gauge fields combined into known vector bosons:

\[ W^\pm = \frac{1}{\sqrt{2}} \left( W_\mu^1 \pm i W_\mu^2 \right) \quad M_W^2 = \frac{1}{4} g^2 v^2 \]

\[ Z^\mu = \frac{-g' B_\mu + \mu W_\mu^3}{\sqrt{g^2 + g'^2}} \quad M_Z^2 = \frac{1}{4} \left( g^2 + g'^2 \right)^2 \]

\[ A^\mu = \frac{-g B_\mu + \mu W_\mu^3}{\sqrt{g^2 + g'^2}} \quad M_A^2 = 0 \]

U(1)_{EM}

generic Gauge

\[ \Phi = \frac{1}{\sqrt{2}} e^{i\omega_i x^i / 2v} \begin{pmatrix} 0 \\ v + h \end{pmatrix} \]

1 physical scalar field

\( \langle h \rangle = 0 \)

3 Goldstone bosons \(\omega_i\)

4 Gauge fields \(W_{\mu \nu}^i B_{\mu}^i\)

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Higgs and unitarity in VBF

W, Z mass (→ longitudinal degrees of freedom) arise from the Higgs mechanism:

without Higgs, $W_L^+ W_L^- \rightarrow W_L^+ W_L^-$

would break unitarity

$$A(W_L^+ W_L^- \rightarrow W_L^+ W_L^-) \approx \frac{1}{v^2} \left( -s - t + \frac{s^2}{s - m_H^2} + \frac{t^2}{t - m_H^2} \right)$$

Same behavior for all VV amplitudes

$$A(Z_L Z_L \rightarrow W_L^+ W_L^-) = \frac{1}{v^2} \left( -s + \frac{s^2}{s - m_H^2} \right)$$ (s channel only)

$$A(Z_L W_L^- \rightarrow Z_L W_L^-) = \frac{1}{v^2} \left( -t + \frac{t^2}{t - m_H^2} \right)$$ (t channel only)

$$A(W_L^- W_L^- \rightarrow W_L^- W_L^-) = \frac{1}{v^2} \left( -u - t + \frac{u^2}{u - m_H^2} + \frac{t^2}{t - m_H^2} \right)$$ (t and u channels)

VBF is the smoking gun of the EWSB!
VBF and VV scattering

- **VV scattering spectrum** $\sigma(VV\rightarrow VV)$ vs $M(VV)$
  - is the fundamental probe to test nature of Higgs boson or to find alternative EWSB mechanism

\[ a(s) \]

- Whatever we will see or not see at low mass ($<2\times m_W$), the EWSB mechanism must be probed in the VV final state
  - search for possible resonances in VBF
  - measurement of VV scattering spectrum

\[ \Lambda_{SB} < 1\text{TeV} \]
- SB sector weakly coupled

\[ \Lambda_{SB} > 1\text{TeV} \]
- SB sector strongly coupled

- $\Lambda_{SB} > 1\text{TeV}$
- SM No-Higgs
- Unitarity violation

- Other scenarios possible: eg, strongly interacting light Higgs

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Higgs production and decay

\[ \sigma(pp \to H+X) [\text{pb}] \]

\[ \sqrt{s} = 7 \text{ TeV} \]

Bringing ratios

\[ \begin{align*}
1 & \quad \text{bb} \\
10^1 & \quad \text{WW} \\
10^2 & \quad \text{ZZ} \\
10^3 & \quad \text{tt} \\
\end{align*} \]

\[ \begin{align*}
100 & \quad \text{cc} \\
200 & \quad \gamma\gamma \\
300 & \quad Z\gamma \\
500 & \quad \gamma\gamma \\
1000 & \quad \gamma\gamma \\
\end{align*} \]
**CMS results**

- **WW→lnqq, ZZ→llqq** limited by huge V+jets background, taken from simu/data with large theoretical/statistical error

- **WW→lnln** at high mass limited by signal << WW background ($\Delta\phi$ not effective)

- **ZZ→llnn**:  
  - 200-400 GeV limited by non-Z background (top, W+jets, WW)
  - >400 GeV limited by Z+jets tail at high MET: not large but not well known (controlled with $\gamma$+jets → statistical error+met uncertainty)

  → **drives the UL for mH>300-400**

- **ZZ→4l** limited by statistics (only ZZ background: small and well known)

  → **drives the UL for mH 200-300**
Future improvements?

- Combination of >5 different channels (ele, mu, btag, ...) Robust!

- Very optimized analyses, some space for further improvement. With higher lumi:
  - use shape analyses (where not yet done)
  - extract signal with multidimensional fit (now only mZZ fit)
  - extract background (norm and shape) from data with lower uncertainty
What's next?

CMS Preliminary, $\sqrt{s} = 7$ TeV
Combined, $L_{\text{int}} = 4.6-4.7$ fb$^{-1}$

95% CL limit on $\sigma/\sigma_{\text{SM}}$

95% CL: obs 127-600, exp: 117-543 GeV

higher mass

lower xsec
1 TeV masses: not anymore “the” Higgs

→ General search for $X \rightarrow VV \rightarrow 4f$: exotic models (eg, Technicolor, ExtraDimension, ...)

**RS Graviton vs SM Higgs:**

<table>
<thead>
<tr>
<th>Signal Channels</th>
<th>140 GeV</th>
<th>250 GeV</th>
<th>500 GeV</th>
<th>1 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(H_{SM} \rightarrow ZZ^{(*)})$</td>
<td>$9.26 \times 10^3$</td>
<td>$1.14 \times 10^3$</td>
<td>$2.40 \times 10^2$</td>
<td>-</td>
</tr>
<tr>
<td>$\sigma(G_{RS} \rightarrow ZZ)$ at $c = 0.01$</td>
<td>-</td>
<td>$1.94 \times 10^3$</td>
<td>$6.83 \times 10^1$</td>
<td>1.41</td>
</tr>
<tr>
<td>$\sigma(G_{RS} \rightarrow ZZ)$ at $c = 0.06$</td>
<td>-</td>
<td>$4.83 \times 10^4$</td>
<td>$1.89 \times 10^3$</td>
<td>$3.53 \times 10^1$</td>
</tr>
<tr>
<td>$\sigma(G_{RS} \rightarrow ZZ)$ at $c = 0.1$</td>
<td>-</td>
<td>$1.94 \times 10^5$</td>
<td>$6.76 \times 10^3$</td>
<td>$1.41 \times 10^2$</td>
</tr>
<tr>
<td>$B(H_{SM} \rightarrow ZZ^{(*)})$</td>
<td>0.068</td>
<td>0.295</td>
<td>0.260</td>
<td>-</td>
</tr>
<tr>
<td>$B(G_{RS} \rightarrow ZZ)$</td>
<td>-</td>
<td>0.052</td>
<td>0.049</td>
<td>0.046</td>
</tr>
<tr>
<td>$B(ZZ \rightarrow 4l)$</td>
<td>$\sim 0.007 \times 0.067 \simeq 4.48 \times 10^{-3}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B(ZZ \rightarrow 2\ell 2\nu)$</td>
<td>$\sim 2 \times 0.067 \times 0.699 \simeq 8.96 \times 10^{-2}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N(H_{SM} \rightarrow ZZ^{(*)} \rightarrow 4\mu)$</td>
<td>0.52</td>
<td>0.64</td>
<td>0.13</td>
<td>-</td>
</tr>
<tr>
<td>$N(H_{SM} \rightarrow ZZ^{(*)} \rightarrow 4e)$</td>
<td>0.52</td>
<td>0.64</td>
<td>0.13</td>
<td>-</td>
</tr>
<tr>
<td>$N(H_{SM} \rightarrow ZZ^{(*)} \rightarrow 2\mu 2\nu)$</td>
<td>1.04</td>
<td>1.28</td>
<td>0.27</td>
<td>-</td>
</tr>
<tr>
<td>$N(H_{SM} \rightarrow ZZ \rightarrow 2\mu 2\nu)$</td>
<td>-</td>
<td>22.4</td>
<td>38.9</td>
<td>-</td>
</tr>
<tr>
<td>$N(H_{SM} \rightarrow ZZ \rightarrow 2e 2\nu)$</td>
<td>-</td>
<td>21.5</td>
<td>45.5</td>
<td>-</td>
</tr>
<tr>
<td>$N(G_{RS} \rightarrow ZZ \rightarrow 4\mu)$ at $c = 0.01$</td>
<td>1.7</td>
<td>0.06</td>
<td>0.0013</td>
<td>-</td>
</tr>
<tr>
<td>$N(G_{RS} \rightarrow ZZ \rightarrow 4e)$</td>
<td>1.7</td>
<td>0.06</td>
<td>0.0013</td>
<td>-</td>
</tr>
<tr>
<td>$N(G_{RS} \rightarrow ZZ \rightarrow 2\mu 2\nu)$</td>
<td>3.4</td>
<td>0.12</td>
<td>0.0025</td>
<td>-</td>
</tr>
<tr>
<td>$N(G_{RS} \rightarrow ZZ \rightarrow 4\mu)$ at $c = 0.05$</td>
<td>42.9</td>
<td>1.4</td>
<td>0.028</td>
<td>-</td>
</tr>
<tr>
<td>$N(G_{RS} \rightarrow ZZ \rightarrow 4e)$</td>
<td>42.9</td>
<td>1.4</td>
<td>0.028</td>
<td>-</td>
</tr>
<tr>
<td>$N(G_{RS} \rightarrow ZZ \rightarrow 2\mu 2\nu)$</td>
<td>85.8</td>
<td>2.8</td>
<td>0.055</td>
<td>-</td>
</tr>
<tr>
<td>$N(G_{RS} \rightarrow ZZ \rightarrow 4\mu)$ at $c = 0.1$</td>
<td>162</td>
<td>5.3</td>
<td>0.11</td>
<td>-</td>
</tr>
<tr>
<td>$N(G_{RS} \rightarrow ZZ \rightarrow 4e)$</td>
<td>162</td>
<td>5.3</td>
<td>0.11</td>
<td>-</td>
</tr>
<tr>
<td>$N(G_{RS} \rightarrow ZZ \rightarrow 2\mu 2\nu)$</td>
<td>324</td>
<td>10.5</td>
<td>0.22</td>
<td>-</td>
</tr>
</tbody>
</table>

CMS AN-2010-35:
**Angular Analysis of Resonances pp → X → ZZ**
A. Bonato, A.V. Gritsan, Z.J. Guo, N.V. Tran, A. Whitbeck
Johns Hopkins University, Baltimore, MD, USA

xsec larger than Higgs:
first, repeat “Higgs” search for different spin, width resonance

→ at high mass still very low number of events per fb$^{-1}$

→ importance of semileptonic final states

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Available results: ZZ

- **CDF search for G→ZZ**: same features discussed for high mass Higgs @ LHC

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**ZZ→4l**: low statistics

**ZZ→llnn**

**MET control V+jets**

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**ZZ→lljj**: large V+jets

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**CDF, L=6 fb⁻¹**

- (a) electron channel
- (b) muon channel

---

**CDF, L=6 fb⁻¹**

- 4l + lljj + lvv expected
- 4l + lljj + lvv observed

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**arXiv:1111.3432v1**
Available results: W+2jets

CDF “bump”

ATLAS & D0 xchecks

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Control of V+jets

- Control region (e.g., $Z \rightarrow jj$ sidebands) has very low stat for $M(lljj) \sim 1$ TeV

- Improving theoretical tools (Blackhat, Madgraph, ...)
  - test them where we have statistics
  - rely on them to extrapolate at higher energy/multiplicity
QCD measurement (jet $p_T > 20-30$ GeV):
→ syst. dominated by jet scale, PileUp removal

Data unfolded for detector effects → compared to NLO ("hadron level")

ATLAS:
V+jets at Tevatron

At low $p_T$, low multiplicity:
interesting discrepancy data-NLO observed

but results limited by systematics
→ new variables

D0 novel measurement:
angular correlations have much lower systematics
High mass: what’s new?

- Can we simply keep the same Higgs analysis strategy? Not at very high masses!

- New experimental issues at very high mass (1 TeV and above)
  
  $X \rightarrow$ boosted $VV \rightarrow$ jet merging (and nearby leptons)

- Unknown signal and very small background $\rightarrow$ no point in pushed optimization! Keep model independent approach as much as possible

- How to disentangle the various models?
  
  - peak $\rightarrow$ mass and width, xsec and BR
  
  - spin! $\rightarrow$ angular analysis
Jet merging:

$$\Delta R_{qq} \approx \frac{1}{\sqrt{z(1-z)}} \frac{M_Z}{p_T^Z} \text{ approx}$$

$$\Delta R 0.8 \text{ (CA) } \rightarrow M_X > 600 \text{ GeV}$$

$$\Delta R 0.5 \text{ (Akt) } \rightarrow M_X > 900 \text{ GeV}$$

Handles to distinguish wrt to jets from QCD (e.g., $X \rightarrow ZZ \rightarrow 2l2j$ VS $Z+$jets):

- jet mass

![Graph showing mass distribution of W-Jet candidates with CMS EXO-11-006 data and MC fit.](image)
Jet merging (2)

Handles to distinguish wrt to jets from QCD (eg, $X \rightarrow ZZ \rightarrow 2l2j$ VS $Z+$jets):

- jet radiation:

  no singularity, just decay!

  soft/collinear singularity in QCD

JHU seminar: Path-Integral Jets  by David Krohn (Harvard)
Jet pruning

- Remove all parts of the jet which are soft and wide angle

- QCD jets mass substantially decreased \(\rightarrow\) lower backgrounds

Boosted objects mass reconstruction improved

Typically used for boosted top or boosted \(H\rightarrow bb\) ...
Example in $X \rightarrow ZZ \rightarrow 2l2j$

First look at Z boosted (no numbers yet) ...
preliminary, A.Bonato, R.Covarelli

- RS Graviton
- $M_G \ 1500 \ \text{GeV}$
- $CA \ 0.8$

$X \rightarrow ZZ \rightarrow 2l2q$ signal

Z+jets

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Angular analysis (1)

- $X \rightarrow ZZ \rightarrow 4f$ decay kinematic fully defined by 5 angles

Signal ($M_X 250$):

- $0^+, 0^-$
- $1^+, 1^-$
- $2^+ m, 2^+ L, 2^-$

X→ZZ

Z decays


MC from Johns Hopkins

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Angular analysis (2)

- Can be clearly used to disentangle different signals... but what about background?
- Already used in $H \rightarrow ZZ \rightarrow 2l2\nu$: cut on likelihood
  - signal: ideal × uncorr. accept
  - $Z$+jets from MC: no correlations, (background from jj sidebands)
- To optimize further (multidimensional fit), need full theoretical description of background:
  - $qq \rightarrow ZZ$:
    - $gg$ also available → can be used to disentangle $qq$-$gg$!!
What’s next?

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Combined, $L_{\text{int}} = 4.6-4.7$ fb$^{-1}$

95\% CL limit on $\sigma/\sigma_{\text{SM}}$

95\%CL: obs 127-600, exp: 117-543 GeV

higher mass

lower xsec
Improve sensitivity

- WHY? Models with lower xsec
  - Ex of (light) composite higgs:
    \[ \frac{1}{p^2-m_H^2} \rightarrow \frac{1}{1+\xi c_H} \frac{1}{p^2-m_H^2} \]
  - Factor 5 in luminosity wrt to present results
  - Improve theoretical control of
    - signal: \(\rightarrow\) NNLO&NNLL effects, precise mass shape prediction, signal-background interference (back-up)
      (studied in the Higgs Xsec WG and documented in 2 Yellow Report)
    - background: \(\rightarrow\) control of ZZ, WW ewk continuum

First LHC to Terascale Workshop (Sept 2011):
LCH at LHC by J.R. Espinoza

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Diboson production (WW,WZ,ZZ)

- qqbar → VV
- gg → VV

- SM test: TGC fixed by ewk gauge structure
  - any deviation from SM in VV xsec is direct hint of NP in bosonic sector

- Backgrounds for high mass Higgs → VV

LHC focused on leptonic final state, Tevatron looked at semileptonic but limited by systematics (V+jets)
VV: theoretical prediction

- Uncertainty dominated by QCD part

\[ \text{qq} \rightarrow \text{ZZ NLO} + \text{gg} \rightarrow \text{ZZ} \]

- WW in jet bins: uncertainty on \( \sigma(\geq N) \) + modeling: MC@NLO vs ALPGEN

<table>
<thead>
<tr>
<th>( \Delta \sigma_{\geq 0} ) (%)</th>
<th>( \Delta \sigma_{\geq 1} ) (%)</th>
<th>( \Delta \sigma_{\geq 2} ) (%)</th>
<th>( \Delta \sigma_{\geq 3} ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>6</td>
<td>42</td>
<td>100</td>
</tr>
</tbody>
</table>

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ZZ→4l: measurement

- 4l is 0.5% of ZZ xsec but very clean

Dedicated EWK analysis with very low luminosity, Higgs results much beyond that

\[
\sigma(ZZ) = 3.8^{+1.5}_{-1.2} \text{(stat)} \pm 0.2 \text{(syst)} \pm 0.2 \text{(lumi)} \text{ pb}
\]

\[
\sigma(pp \rightarrow ZZ + X) \times B(ZZ \rightarrow 4\ell) = 28.1^{+4.6}_{-4.0} \text{(stat.)} \pm 1.2 \text{(syst.)} \pm 1.3 \text{(lumi.) fb}
\]
WW->lnln: measurement

- Dedicated EWK results only with very low luminosity,

\[ \sigma_{W^+W^-} = 41.1 \pm 15.3 \text{ (stat)} \pm 5.8 \text{ (syst)} \pm 4.5 \text{ (lumi) pb} \]

- Higgs analysis much beyond that:

<table>
<thead>
<tr>
<th></th>
<th>data</th>
<th>all bkg.</th>
<th>qq → W^+W^-</th>
<th>gg → W^+W^-</th>
<th>tt+tW</th>
<th>W + jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-jet</td>
<td>1359</td>
<td>1364.8 ± 9.3</td>
<td>980.6 ± 5.2</td>
<td>58.8 ± 0.7</td>
<td>147.3 ± 2.5</td>
<td>99.3 ± 5.0</td>
</tr>
<tr>
<td>1-jet</td>
<td>909</td>
<td>951.4 ± 9.8</td>
<td>416.8 ± 3.6</td>
<td>23.8 ± 0.5</td>
<td>334.8 ± 3.0</td>
<td>74.3 ± 4.6</td>
</tr>
<tr>
<td>2-jet</td>
<td>703</td>
<td>714.8 ± 13.5</td>
<td>154.7 ± 2.2</td>
<td>5.1 ± 0.2</td>
<td>413.5 ± 2.7</td>
<td>37.9 ± 3.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>WZ/ZZ</th>
<th>Z/γ* → ℓ⁺ℓ⁻</th>
<th>Wγ</th>
<th>Z/γ* → τ⁺τ⁻</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-jet</td>
<td>33.0 ± 0.5</td>
<td>16.6 ± 4.0</td>
<td>26.8 ± 3.5</td>
<td>2.4 ± 0.5</td>
</tr>
<tr>
<td>1-jet</td>
<td>28.7 ± 0.5</td>
<td>39.4 ± 6.4</td>
<td>13.0 ± 2.6</td>
<td>20.6 ± 0.4</td>
</tr>
<tr>
<td>2-jet</td>
<td>15.1 ± 0.3</td>
<td>56.1 ± 11.7</td>
<td>10.8 ± 3.6</td>
<td>21.6 ± 2.1</td>
</tr>
</tbody>
</table>

Stat. and syst. errors included
From VBF to VV scattering

- First search for a VBF resonance, feasible in 2012
- Measurement of VV scattering spectrum with higher lumi (>50 fb⁻¹)

Tipical signature: forward-backward “spectator” jets with very high energy
Higgs-like resonance in VBF

- RE-DO all the analyses in VBF mode (eg, fermiophobic)

- Today only $WW \to \ln\ln$. **Expectations for next year:**
  - $lumi > 10 fb^{-1}$
  - $\sigma_{vbf} \sim 0.1\times\sigma_{gg}$
  - 0.5 effic. VBF cuts

VBF yields in 2012 ~ 0.5 $gg$ yields of 2011 summer results, with much less background:

- $ZZ \to 4l$ will be still limited by statistics
- $WW \to \ln\ln\ln$ will improve S/B ($signal/10, WW^*\alpha_s^2$)
- semileptonic final states will have **reasonable signal yields + much lower background** than inclusive analysis

eg, $ZZ \to lljj$:
  - signal yields for $m_H 300-500 \sim 15 \sim 5$ events
  - $V+(N+1)jets/V+N$ jets $\sim 0.15 \to$ asking 2 jets reduces **background to 2%**!
  - S/B may increase of a factor 2 (eff $0.5 \times \sigma_{0.1} / 0.02$)
VV scattering spectrum

- In no Higgs case: \[ A(W_L^+W_L^- \rightarrow W_L^+W_L^-) \approx \frac{1}{v^2} \left( -s - t + \frac{s^2}{s-m_H^2} + \frac{t^2}{t-m_H^2} \right) \]

BUT increasing of xsec at high VV is suppressed by

- PDF
- offshell bosons
- unpolarized bosons

→ small difference btw SM and violation of unitarity (no Higgs)

\[ \rightarrow W^\pm W^\pm \text{ scattering} \]

\[ \rightarrow \text{with proper cut (eg } \Delta \eta \text{ jets) can be enhanced } \rightarrow \text{ selection of the longitudinal } W \]
Longitudinal polarization

Angular analysis can boost LL-TT separation (new!):

partonic study in the center of mass of W

mH 500 GeV

noHiggs (unitarity violation)
VV scattering: interference effects

- Big interference effects considered only in **Phantom**

\[ qq \rightarrow 6f \, O(\alpha_{EW}^6) \]

\[ \text{signal} \quad + \quad \text{irreducible background (}\alpha_{EW}^6\text{)} \]

- WW approximated without interference
- WW signal with “a posteriori” cuts
- M(H) = 500 GeV

**JHEP 0603 (2006) 093**
Accomando, Ballestrero, Bolognesi, Maina, Mariotti
The first aim of the Higgs search is the understanding of the EWSB -> focus on H->VV final state

Main steps:
- search for generic resonance X->ZZ->4f
- search for VBF resonance and measuring of VV scattering spectrum

Ingredients along the EWSB road:
- experimental issue: control of V+jets (jet pruning)
- several theoretical uncertainties on VV EWK continuum
The road to the ElectroWeak Symmetry Breaking

18th January 2012
Seminar at Johns Hopkins University

S.Bolognesi (Johns Hopkins University)
Sources

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JHU seminar: **Path-Integral Jets** by David Krohn (Harvard)

First LHC to Terascale Workshop (Sept 2011):

**LCH at LHC** by J.R. Espinoza

**Boson Boson scattering analysis** by A. Ballestrero (INFN Torino)
Mass shape

- Present approx:
  - xsec for on-shell Higgs production and decay in zero width approx
  - acceptance from MC with ad-hoc BW distribution

10-30% uncertainty on xsec for mH 400–600 GeV

From Passarino talk at last LHC to Terascale WS

**The off-shell Higgs production**

Is currently computed according to

$$\sigma_{\text{os}}(\mu_H^2) \delta(z \hat{s} - \mu_H^2) \rightarrow \sigma_{\text{os}}(z \hat{s}) \text{BW}(z \hat{s}),$$

At least at lowest QCD order, where the so-called modified Breit–Wigner distributions is defined by

$$\text{BW}(s) = \frac{1}{\pi} \frac{s \Gamma_{H}^{\text{os}} / \mu_H^2}{[s - \mu_H^2]^2 + (s \Gamma_{H}^{\text{os}} / \mu_H^2)^2},$$

Where now $\mu_H = M_{H}^{\text{os}}$.

**This ad-hoc Breit–Wigner**

- Cannot be derived from QFT and also is not normalizable in $[0, +\infty]$.
- Its practical purpose is to enforce a *physical* behavior for low virtualities of the Higgs boson but the usage cannot be justified.
- This modified Breit–Wigner cannot be derived from QFT.
- Note that this Breit–Wigner for a running width comes from the substitution of $\Gamma \rightarrow \Gamma(s) = \Gamma s/M_H^2$ in the Breit–Wigner for a fixed width $\Gamma$. This substitution is not justifiable.

Study with QFT-consistent Higgs propagator in the YR2
Higgs qT

- **HqT**: \( q_T > m_H \) NNLO
  \( q_T << m_H \) NNLL (resumming \( \ln(m_H^2/q_T^2) \))

**Uncertainties:**
- factor/renorm scale
- non perturb. effects
  (smearing with NP form factor)

**PDF**

**large mt approximation**

---

LHC To Terascale Physics WS

S.Bolognesi (Johns Hopkins University)
Reweight to HqT

- HqT used to reweight full event generators (POWHEG at NLO)

<table>
<thead>
<tr>
<th>H p_T</th>
<th>mH 120 GeV</th>
<th>mH 500 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>arbitrary/normalization</td>
<td>arbitrary/normalization</td>
<td></td>
</tr>
<tr>
<td>H y</td>
<td>mH 120 GeV</td>
<td>mH 500 GeV</td>
</tr>
<tr>
<td>arbitrary/normalization</td>
<td>arbitrary/normalization</td>
<td></td>
</tr>
</tbody>
</table>

- Very small effect on acceptance in 4l: 1-2% (larger if jet veto!)

Powheg

Powheg re-weighted to Hqt
(to be redone before PS)

HNNLO
Signal: jet counting

- Analysis in exclusive jet bins (ex, WW+0,1,2 jets)

  → theoretical uncertain in jet bins to be combined with correlations

  - varying renormalization and factorization scales in the fixed-order predictions for each exclusive jet cross section \( \sigma_N \)

    (results as 100% correlated)

  - inclusive xsec \( (\sigma \geq N_{jets}) \), as source of perturbative uncertainties

    \[ \sigma_N = \sigma \geq N - \sigma \geq N + 1 \]

    with error propagation

- if background depends on \( N_{jets} \)

- for VBF

  different treatments of the uncontrolled higher-order \( O(\alpha^3s) \) terms

  i.e., different NNLO expansions

LHC To Terascale Physics WS

S.Bolognesi (Johns Hopkins University)
Resummation of jet-veto logarithms ($\ln(p_{\text{cut}}/m_H)$), induced by jet cut parameter $p_{\text{cut}}$

Presently doable only on beam thrust variable

$$T_{\text{cm}} = \sum_k |\vec{p}_{T_k}| e^{-|\eta_k|} = \sum_k (E_k - |\vec{p}_{k}^z|)$$

($\sim$ raw approx of $p_{\text{cut}}$)

and used to reweight MC@NLO
Signal-background interference

- Recent results for WW, but focused on low mass

\[ \text{Effect on } gg \rightarrow H \rightarrow WW \text{ at LO} \]

- 3 gens (solid)
- 2 gens (dashed)

\[ m_T < m_H \quad \text{non-resonant diagrams can be large for } m_T > m_H \]

\[ \Delta \phi_{ll} \text{ [rad.]} \]

- Also shape effects!

- Worth to investigate further at high mass?
ZZ: theoretical prediction

- ZZ fully from MC, well under control

Interference in the final state with identical leptons

- qq→ZZ NLO + gg→ZZ
ZZ: theoretical uncertainties

NLO Ratio $\sigma(Q) / \sigma(m_{j})$

$1 + \delta_{\text{QCD}}(NLO)$

$q\bar{q}$ Ratio $\sigma(Q) / \sigma(m_{j})$

$1 + \delta_{\text{QCD}}(gg)$

$0.5$ $1.0$ $1.5$

$0.85$ $0.9$ $0.95$ $1.0$ $1.05$ $1.1$ $1.15$ $1.2$

$0.5$ $1.0$ $1.5$

$0.85$ $0.9$ $0.95$ $1.0$ $1.05$ $1.1$ $1.15$ $1.2$

scale

PDF+$\alpha_{s}$

01/18/2012 seminar 45 S.Bolognesi (Johns Hopkins University)
WW: theoretical uncertainties

- WW taken from MC for large $m_H$
  - $gg+qq$ NLO available (MCFM)
    - PDF+$\alpha_s$ and scale uncertainty dominates

- in jet bins using uncert on $\sigma(\geq N)$ + modeling: MC@NLO vs ALPGEN

<table>
<thead>
<tr>
<th>$\Delta\sigma_{\geq 0}$ (%)</th>
<th>$\Delta\sigma_{\geq 1}$ (%)</th>
<th>$\Delta\sigma_{\geq 2}$ (%)</th>
<th>$\Delta\sigma_{\geq 3}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>6</td>
<td>42</td>
<td>100</td>
</tr>
</tbody>
</table>

- WW from control region for $m_H<200$ GeV ($m_{ll}$, $\Delta\phi_{ll}$)

<table>
<thead>
<tr>
<th></th>
<th>scale</th>
<th>pdf CTEQ 6.6 error set</th>
<th>pdf central (CTEQ6.6, MSTW2008, NNPDF2.1)</th>
<th>Modelisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_W^b$</td>
<td>2.5%</td>
<td>2.6%</td>
<td>2.7%</td>
<td>3.5%</td>
</tr>
<tr>
<td>$\alpha_W^l$</td>
<td>4%</td>
<td>2.5%</td>
<td>1.4%</td>
<td>3.5%</td>
</tr>
</tbody>
</table>

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WW→ℓνℓν measurement

- Complex analysis (no mass peak→counting experiment, many backgrounds)

- Main systematics:
  - **background estimate:**
    | Background  | Cuts                        |
    |-------------|-----------------------------|
    | W+jets      | tight lepton quality        |
    | top         | (b-)jet veto                |
    | Drell-Yan   | Z mass veto, missing $E_T$  |
    | WZ, ZZ, Wγ  | 2 leptons → estimated from MC |

- **signal acceptance:**
  - jet-veto efficiency
  - leptonic efficiency
  - missing $E_T$ uncertainty
  - theoretical (gg box, PDF)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>$gg \rightarrow W^+W^-$</td>
<td>349.7 ± 30.3</td>
</tr>
<tr>
<td>$gg \rightarrow W^+W^-$</td>
<td>17.2 ± 1.6</td>
</tr>
<tr>
<td>$W + \text{jets}$</td>
<td>106.9 ± 38.9</td>
</tr>
<tr>
<td>$t\bar{t} + tW$</td>
<td>63.8 ± 15.9</td>
</tr>
<tr>
<td>$Z/\gamma^* \rightarrow \ell\ell + WZ + ZZ$</td>
<td>12.2 ± 5.3</td>
</tr>
<tr>
<td>$Z/\gamma^* \rightarrow \tau\tau$</td>
<td>1.6 ± 0.4</td>
</tr>
<tr>
<td>$WZ/ZZ$ not in $Z/\gamma^* \rightarrow \ell\ell$</td>
<td>8.5 ± 0.9</td>
</tr>
<tr>
<td>$W + \gamma$</td>
<td>8.7 ± 1.7</td>
</tr>
<tr>
<td>signal + background</td>
<td>568.6 ± 52.2</td>
</tr>
<tr>
<td>Data</td>
<td>626</td>
</tr>
</tbody>
</table>
WW/WZ→lν2j at CDF

- First observation: $5.4\sigma$ (first evidence at D0 with $4.4\sigma$ in 2008)
- Much larger backgrounds, no resolution to distinguish W/Z→jj

**fit to Mjj (3.9 fb-1)**

+ matrix element method: (2.7 fb-1)
  
  - discriminant exploiting full kinematic information, based on calculations of differential xsec of signal and background
  
  - data-MC validation of input kinematic variables
  
  - fit to shape of discriminant

\[
\sigma(WW + WZ) = 16.0 \pm 3.3 (\text{stat} + \text{syst}) \text{ pb} \quad \text{(NLO expected} \quad 16.1 \pm 0.9 \text{ pb)}
\]
WZ/ZZ→lν/νν+2b at Tevatron

- Crucial for Higgs search (ZH→ννbb). Very complex analysis!
  - WZ → lνbb + ZZ → ννbb  
  - No leptons! → huge background: multijets QCD, V+jets (from data)
  - very sophisticated techniques:

Crisis (2b-tags)

CDF (2b-tags)

D0: \( \sigma(WZ, ZZ) = 6.9 \pm 1.3 \text{ (stat)} \pm 1.8 \text{ (syst)} \, \text{pb} \)

CDF: \( \sigma(WZ, ZZ) = 5.8^{+3.6}_{-3.0} \, \text{pb} \) (expected 4.6 pb)

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**ZZ at CDF**

- **ZZ→4ℓ** (6 fb-1) excess of events at high $M_{ZZ}$ (e.g., Randall Sundrum Graviton)
  - But xsec still compatible with SM
    \[
    \sigma(p\bar{p} \rightarrow ZZ) = (2.8^{+1.2}_{-0.9} \text{ (stat.)} \pm 0.3 \text{ (syst.)}) \text{ pb} \\
    (1.4 \pm 0.1) \text{ pb}
    \]
  - No excess in other final states

- **ZZ→2l2j**
  - Control of $Z+jets$ very challenging to measure
  - Control of $Z$ +jets is crucial

- **ZZ→2l2ν** (5.9 fb-1)
  - Shape analysis with fit to neural network
    \[
    \sigma(p\bar{p} \rightarrow ZZ) = 1.45^{+0.44}_{-0.42} \text{ (stat.)}^{+0.41}_{-0.30} \text{ (syst.)} \text{ pb} \\
    \sigma(ZZ) = 1.21^{+0.05}_{-0.04} \text{ (scale)}^{+0.04}_{-0.03} \text{ (PDF)} \text{ pb}.
    \]
WZ→3l+ν at LHC

Very clean, low background

CMS:

\[ \sigma(WZ) = 17.0 \pm 2.4 \text{(stat)} \pm 1.1 \text{(syst)} \pm 1.0 \text{(lumi)} \text{ pb} \]

(NLO expected \[ 18.75^{+1.1}_{-0.8} \text{ pb} \])

ATLAS:

\[ \sigma(WZ) = 21.1^{+3.1}_{-2.8} \text{(stat)} \pm 1.2 \text{(syst)}^{+0.9}_{-0.8} \text{(lumi)} \text{ pb} \]

(NLO expected \[ 17.2^{+1.2}_{-0.8} \text{ pb} \])
Recent $WZ \rightarrow 3l+\nu$ at Tevatron

- Possible only at hadron colliders (charged final state)
  - **D0 with 4.1 fb-1**
    - statistics 2 times smaller than LHC, while xsec is 6 times smaller
    - $\sigma(WZ) = 3.90^{+1.06}_{-0.90} \, pb$
    - (NLO expected $3.25 \pm 0.19 \, pb$
  - **CDF with 7.1 fb-1**
    - Shape analysis with fit to neural network
    - $\sigma(WZ) = 3.9^{+0.6\, (stat)}_{-0.5\,(stat)}^{+0.6\,(syst)} \, pb$
    - (NLO expected $3.46 \pm 0.2 \, pb$

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V+jets: ratios

CMS PAS EWK-10-011

- Many systematics cancel out

- Use high statistics W sample to predict Z+jets background for NP

- Very well known theoretically $\Rightarrow$ any deviation is hint of NP
Z+b jets

- Fixed flavor scheme: b only from gluon splitting

- Variable flavor scheme: gluon splitting integrated into the PDF (expected to coincide at NLO)

- Benchmark for MSSM Higgs: $\phi b b\bar{b}$ (large theoretical uncertainty on xsec)

- Background to $Z$H($H\to bb\bar{b}$), NP search with lept +b-jets

- b-jets analysis:
  - b-tagging with Secondary Vertex requirement or more sophisticated (eg Neural Network in D0)
  - b-tag eff. measured separately from data
  - b-tag purity extracted from data (eg SV mass fit)

  → measurement of $Z+b / Z+jets$ to cancel other (non-btag) systematics

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### Z+b results

**CMS**

No statistical power yet to disentangle fixed VS variable flavor scheme

#### b-tag eff. corrected results:

| Sample       | $\frac{p_{T,b} > 25 \text{ GeV}, |\eta| < 2.5}{p_{T}\text{-lead}} \times 10^{-3}$ |
|--------------|-------------------------------------------------|
| Data SSVHE   | 4.3 ± 0.6 (stat) ± 1.1 (syst)                   |
| Data SSVHP   | 5.4 ± 1.0 (stat) ± 1.2 (syst)                   |
| MadGRAPH     | 5.1 ± 0.2 (stat) ± 0.2 (syst) ± 0.6 (theory)    |
| MCFM         | 4.3 ± 0.5 (theory)                              |

**D0** (4.2 fb-1)

$$\frac{\sigma(Z + b \text{jet})}{\sigma(Z + \text{jet})} = 0.0193 \pm 0.0022 \text{(stat)} \pm 0.0015 \text{(syst)}$$

**CDF** (7.86 fb-1)

<table>
<thead>
<tr>
<th>Measured</th>
<th>NLO $Q^2 = m_Z^2 + p_{T,Z}^2$</th>
<th>NLO $Q^2 = &lt;p_{T,jet}^2&gt;$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{\sigma(Z+b)}{\sigma(Z)}$</td>
<td>2.84 ± 0.29 ± 0.29 × 10^{-3}</td>
<td>2.3 × 10^{-3}</td>
</tr>
<tr>
<td>$\frac{\sigma(Z+b)}{\sigma(Z+\text{jet})}$</td>
<td>2.24 ± 0.24 ± 0.26 × 10^{-2}</td>
<td>1.8 × 10^{-2}</td>
</tr>
</tbody>
</table>

TO BE UPDATED soon with 1 fb^{-1} → much better precision!
**W+c**

- Dominated by $s \rightarrow Wc$
  - $d \rightarrow Wc$ Cabibbo suppressed
  - $W+b$ even more suppressed
- $W_{c\bar{c}}$ (Wc) measures the $s$ PDF

- **CMS** (unexpected! just a first go):

  \[
  R_c^\pm = 0.92 \pm 0.19 \ (\text{stat.}) \pm 0.04 \ (\text{syst.}) \\
  R_c = \quad 0.143 \pm 0.015 \ (\text{stat.}) \pm 0.024 \ (\text{syst.})
  \]

- **Tevatron**: $W+c \sim 5\% \ W+jets$
  - Semileptonic charm decay + opposite charge $W$ and $c$

  **CDF** ($4.3 \ fb^{-1}$):

  \[
  \sigma(Wc) \cdot BR(W \rightarrow l\nu) = 33.7 \pm 11.4 \ (\text{stat}) \pm 4.7 \ (\text{syst}) \ \text{pb}
  \]

  (NLO calculation: $16.5 \pm 4.7 \ \text{pb}$)

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