OUTLINE

• Big picture

• Higgs: Getting to know the newest member of the Standard Model

• Going beyond the Standard Model

• New analysis techniques: getting boosted
\[ \mathcal{L}_{SM} = D_\mu H^+ D_\mu H + \mu^2 H^+ H - \frac{\lambda}{2} (H^+ H)^2 - (y_{ij} H \bar{\psi}_i \psi_j + h.c.) \]

- Couplings to EW gauge bosons
- Higgs self-couplings
- Couplings to fermions
\[ \mathcal{L}_{SM} = D_\mu H^\dagger D_\mu H + \mu^2 H^\dagger H - \frac{\lambda}{2} (H^\dagger H)^2 - (y_{ij} H \bar{\psi}_i \psi_j + \text{h.c.}) \]

- **Couplings to EW gauge bosons**
- **Higgs self-couplings**
- **Couplings to fermions**

Diagram showing interactions of particles and fermions.
Reconstruction, Simulation, Calculations

\[ \mathcal{L}_{SM} = D_\mu H^\dagger D_\mu H + \mu^2 H^\dagger H - \frac{\lambda}{2} (H^\dagger H)^2 - (y_{ij} H \bar{\psi}_i \psi_j + h.c.) \]

- Couplings to EW gauge bosons
- Higgs self-couplings
- Couplings to fermions
REALITY (SORT OF)

Higher order processes

Fatjets?

Hard Scatter

underlying event

Multiple parton interactions

PDFs

Initial & Final State Radiation

Parton Shower

Hadronization
THE GENERAL QCD UNCERTAINTY FORMULA
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• Generate events with most precise MC available for your favorite process
  • Typically NLO, but some exceptions
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• Assess uncertainties by varying:
  • Generators (ex. PS(ISR/FSR), Matching scales, UE, MPI, Pileup)
  • Factorization & renormalization scales by 1/2, 2.
  • PDFs using PDF4LHC recommendations
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• Add any necessary analysis specific tweaks to this procedure!
  • e.g., $\alpha_s$ variations, Stewart-Tackmann and/or jet-veto-efficiency methods, quark mass treatments, variations of substructure variables
SUMMARY OF RUN I

- Run I stats:
  - 5 fb$^{-1}$ @7 TeV, 20 fb$^{-1}$ @ 8 TeV
  - ~95% detector uptime for CMS & ATLAS
  - Mean simultaneous collisions: 21
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CAN'T POSSIBLY COVER EVERYTHING!
WILL FOCUS ON MEASUREMENTS WITH IMPORTANT QCD EFFECTS
OUTLINE

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PORTRAIT OF A PARTICLE
PORTRAIT OF A PARTICLE

• What does it look like?
  • Mass, width, spin, parity

\[ m_H = 125.09 \pm 0.21 \text{ (stat.)} \pm 0.11 \text{ (scale)} \pm 0.02 \text{ (other)} \pm 0.01 \text{ (theory) GeV}, \]
PORTRAIT OF A PARTICLE

• What does it look like?
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• What’s its origin story?
  • Production processes
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• Does it act the way we think it should?
  • Cross-sections and differential distributions
WIDTH FROM $H \rightarrow ZZ$
WIDTH FROM $H \rightarrow ZZ$

- Use ratio of on-shell to off-shell $gg$ production cross-sections to measure width

\[
\sigma_{on-shell}^{gg \rightarrow H \rightarrow ZZ} \sim \frac{g^2_{gg} \delta_{H}^2}{m_H \Gamma_H} \quad \text{and} \quad \sigma_{off-shell}^{gg \rightarrow H^* \rightarrow ZZ} \sim \frac{g^2_{gg} \delta_{H}^2}{(2m_Z)^2}
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WIDTH FROM H→ZZ

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\[ \sigma_{\text{on-shell}}^{gg \to H \to ZZ} \sim \frac{\delta_{gg}^2 \delta_{HZZ}^2}{m_H \Gamma_H} \quad \text{and} \quad \sigma_{\text{off-shell}}^{gg \to H^* \to ZZ} \sim \frac{\delta_{gg}^2 \delta_{HZZ}^2}{(2m_Z)^2} \]

Data

WIDTH FROM H → ZZ

- Use ratio of on-shell to off-shell gg production cross-sections to measure width

\[ \sigma_{\text{on-shell}}^{\text{gg→H→ZZ}} \sim \frac{g^2 g H g H Z Z}{m_H \Gamma_H} \quad \text{and} \quad \sigma_{\text{off-shell}}^{\text{gg→H*→ZZ}} \sim \frac{g^2 g H g H Z Z}{(2m_Z)^2} \]

- Need to isolate gg component: Enhance gg contribution with MELA discriminant

\[ D_{gg} = \frac{p_{gg}^{\text{tot}}}{p_{gg}^{\text{tot}} + p_{qq}^{\text{bkg}}} = \left[ 1 + \frac{p_{qq}^{\text{int}} + p_{gg}^{\text{bkg}}}{a \times p_{gg}^{\text{sig}} + \sqrt{a} \times p_{gg}^{\text{int}} + p_{gg}^{\text{bkg}}} \right]^{-1} \]

\[ (m_{Z_1}, m_{Z_2}, \Omega) \]
Unbinned ML fit for $\Gamma_H, \mu_{ggH}, \mu_{VBF}$ using

\[
\begin{align*}
(m_{4l}, D_{\text{bkg}}^\text{kin}, p_T^{4l} \text{ or } D_{\text{jet}}) &: \quad 4l \text{ on } \text{–} \text{ shell} \\
(m_{4l}, D_{\text{gg}}) &: \quad 4l \text{ off } \text{–} \text{ shell} \\
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• Makes heavy use of MC & calculations for discriminants & PDF construction

• LO MC (gg2VV, MCFM) reweighted with NNLO (+NNLL) K-factors* of 2-2.5 (same applied to signal & bkgd)
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Relies on no new physics assumption (on-shell & off-shell couplings are the same)!

Would have tighter constraints if new physics existed: CMS arXiv:1507.06656
• By combining all Run I observations, can measure signal strength of different production processes
  
  • Assuming SM BR
• By combining all Run I observations, can measure signal strength of different production processes

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By combining all Run I observations, can measure signal strength of different production processes

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PRODUCTION

- By combining all Run I observations, can measure signal strength of different production processes.

- Assuming SM BR


<table>
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<th>Production</th>
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<tbody>
<tr>
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<td>$\sqrt{s} = 8$ TeV</td>
</tr>
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</tr>
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- Total uncertainty on production is $\sim$15% with different processes contributing 20-40% uncertainties.

- CMS: EPJC 75 (2015) 212

19.7 fb$^{-1}$ (8 TeV) + 5.1 fb$^{-1}$ (7 TeV)

$\mu = 1.00 \pm 0.13$

$\mu = 0.87 \pm 0.16$

$\mu = 1.14 \pm 0.27$

$\mu = 0.89 \pm 0.38$

$\mu = 2.76 \pm 0.99$

$\sigma/\sigma_{SM}$

$m_H = 125$ GeV

Preliminary
PRODUCTION

• By combining all Run I observations, can measure signal strength of different production processes

• Assuming SM BR


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PRODUCTION

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Total uncertainty on production is ~15% with different processes contributing 20-40 % uncertainties:

  • Theory uncertainties dominate ggF process determination
    • Current QCD scale in NNLO+NNLL (+7-8%) and PDF+alpha_s (+-8%) uncertainties
    • VBF uncertainties are comparable to experimental uncertainties: dominated by ggF contamination from jet veto

\[
\begin{array}{c|c|c|c}
\text{Process} & \mu \sqrt{s=8 \, \text{TeV}} & \mu \sqrt{s=7 \text{ and } 8 \text{ TeV}} \\
\hline
\text{ggF} & 1.23^{+0.25}_{-0.21} & 1.23^{+0.23}_{-0.20} \\
\text{VBF} & 1.55^{+0.39}_{-0.35} & 1.23 \pm 0.32 \\
\text{VH} & 0.93 \pm 0.39 & 0.80 \pm 0.36 \\
\text{ttH} & 1.62 \pm 0.78 & 1.81 \pm 0.80 \\
\end{array}
\]
• Production type determined by event jet properties
JET COUNTING & VETOS

- Production type determined by event jet properties

<table>
<thead>
<tr>
<th>Decay tag and production tag</th>
<th>Expected signal composition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>H → γγ [18], Section 2.1</strong></td>
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## JET COUNTING & VETOS

- Production type determined by event jet properties
- Large uncertainties on ggF contamination estimated with:
  - Active area for improvement in Run II

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<tr>
<td>Total</td>
<td>14.9%</td>
<td>10.7%</td>
<td>6.6%</td>
<td>5.9%</td>
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</table>

<table>
<thead>
<tr>
<th>ggF enriched category</th>
<th>( gg \rightarrow H, qq/gg \rightarrow b\bar{b}H/t\bar{t}H )</th>
<th>( qq' \rightarrow Hqq' )</th>
<th>( qq \rightarrow W/ZH )</th>
<th>ZZ*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical cross section</td>
<td>12%</td>
<td>4%</td>
<td>4%</td>
<td>4%</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>2.2%</td>
<td>6.6%</td>
<td>4.0%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Total</td>
<td>12.2%</td>
<td>7.7%</td>
<td>5.7%</td>
<td>4.1%</td>
</tr>
</tbody>
</table>
COUPLINGS

- Measuring fermionic couplings is a key part of Higgs program
- $b$s and taus branching ratios & top coupling targeted

<table>
<thead>
<tr>
<th>Couplings</th>
<th>Signal strength ($\mu$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS Prelim.</td>
<td>$m_H = 125.36$ GeV</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>$\mu = 1.17^{+0.27}_{-0.27}$</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^* \rightarrow 4l$</td>
<td>$\mu = 1.44^{+0.40}_{-0.33}$</td>
</tr>
<tr>
<td>$H \rightarrow WW^* \rightarrow l\nu l\nu$</td>
<td>$\mu = 1.09^{+0.23}_{-0.21}$</td>
</tr>
<tr>
<td>$W,Z H \rightarrow b\bar{b}$</td>
<td>$\mu = 0.5^{+0.4}_{-0.4}$</td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$</td>
<td>$\mu = 1.4^{+0.4}_{-0.4}$</td>
</tr>
</tbody>
</table>

$\sqrt{s} = 7$ TeV $\int Ldt = 4.5$-4.7 fb$^{-1}$
$\sqrt{s} = 8$ TeV $\int Ldt = 20.3$ fb$^{-1}$

$\mu = \frac{\sigma_{ob}}{\sigma_{SM}}$

Released 12.01.2015
• Measuring fermionic couplings is a key part of Higgs program

• $b\bar{s}$ and taus branching ratios & top coupling targeted
VH → bblν(ll)(νν)
VH → bblνν(νν)

- Challenging measurement with many signal regions & complex backgrounds
$VH \rightarrow bbl\nu(\bar{ll})(\nu\nu)$

- Challenging measurement with many signal regions & complex backgrounds
- Theory systematics dominate over experimental uncertainties

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$\sigma_\mu$</th>
</tr>
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<tbody>
<tr>
<td>Total</td>
<td>0.41</td>
</tr>
<tr>
<td>Statistical</td>
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<tr>
<td>Systematic</td>
<td>0.26</td>
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<table>
<thead>
<tr>
<th>Experimental uncertainties</th>
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<td>Jets</td>
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</tr>
<tr>
<td>$E_T^{\text{miss}}$</td>
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</tr>
<tr>
<td>Leptons</td>
<td>0.01</td>
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<td>$b$-tagging(*)</td>
<td>$b$-jets 0.07</td>
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<tr>
<td></td>
<td>$c$-jets 0.04</td>
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<td>light jets 0.04</td>
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<td>Luminosity</td>
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<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Signal</td>
<td>0.07</td>
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<tr>
<td>Floating normalisations</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$W$-jets 0.06</td>
</tr>
<tr>
<td></td>
<td>$Z$-jets 0.03</td>
</tr>
<tr>
<td></td>
<td>$t\bar{t}$ 0.04</td>
</tr>
<tr>
<td>Background modelling</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$W$-jets 0.11</td>
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<tr>
<td></td>
<td>$Z$-jets 0.08</td>
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<tr>
<td></td>
<td>$t\bar{t}$ 0.05</td>
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<tr>
<td>Single-top</td>
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<tr>
<td>Diboson</td>
<td>0.02</td>
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<tr>
<td>Multijet</td>
<td>0.06</td>
</tr>
</tbody>
</table>
Challenging measurement with many signal regions & complex backgrounds

Theory systematics dominate over experimental uncertainties

Largest uncertainty: V + hf

\[ \Delta \mu \]

\[ \mu \]

\[ \mu \]

ATLAS: JHEP01(2015)069
CMS: PRD 89 (2014) 012003
• New CMS measurement exploits lower energy QCD phenomena to enhance all hadronic final state

  • Quark-gluon discrimination (RMSs of jet constituents in $\eta$-$\Phi$, jet asymmetry pull, jet particle multiplicity, max energy fraction carried by constituent)

  • Scalar sum of soft hadronic activity built from soft track-jets

• Relies on good modeling of fragmentation and soft QCD effects!
- Use QGL, soft activity (HT & N_{softjets}), production & decay dynamics in BDT to define signal regions: best S/B 1.7%; 50-7% ggF contamination
- Use QGL, soft activity (HT & N_{softjets}), production & decay dynamics in BDT to define signal regions: best S/B 1.7%; 50-7% ggF contamination

- Fit $M_{bb}$ spectra to extract signal: $\mu = 2.8^{+1.6}_{-1.4}$
• Measurement of ttH allows direct access to top yukawa coupling

• Busy final state:
  • 4-6 jets, 1-2 leptons, missing energy from t & H decay

• Most dominant backgrounds include QCD production of multiple heavy flavor quarks (ttbb, ttb, ttcc)
  • Many scales involved for signal & backgrounds!

• Analyses use multivariate and matrix-element discriminants for highest sensitivity
CMS ANALYSIS EXAMPLE
CMS ANALYSIS EXAMPLE

- Test two sets of hypotheses with event discriminants:
  - $ttH$ vs QCD $tt+bb$ (kinematics & dynamics)
  - $tt+lf$ vs. $tt+hf$ (b-tagging information)
CMS ANALYSIS EXAMPLE

- Test two sets of hypotheses with event discriminants:
  - $ttH$ vs QCD $tt+bb$ (kinematics & dynamics)
  - $tt+lf$ vs. $tt+hf$ (b-tagging information)

- Discriminants built from MC:
  - $ttH$: Pythia 6 w/NLO x-section normalization
  - $tt+jet$: Madgraph+Pythia normalized to NNLO + NNLL
• Fit to extract ttH signal strength, $\mu$

\[ \hat{\mu} = 1.2^{+1.6}_{-1.5} \]
• Fit to extract ttH signal strength, $\mu$

$$\hat{\mu} = 1.2^{+1.6}_{-1.5}$$

• Fit uncertainties highlights:
• Fit to extract $ttH$ signal strength, $\mu$

\[ \hat{\mu} = 1.2^{+1.6}_{-1.5} \]

• Fit uncertainties highlights:

• Top $p_T$ reweighting: vary between none & 2x weighting factor
• Fit to extract ttH signal strength, $\mu$

$$\hat{\mu} = 1.2^{+1.6}_{-1.5}$$

• Fit uncertainties highlights:
  
  • Top pT reweighting: vary between none & 2x weighting factor
  
  • Normalization of tt+hf assigned 50% uncertainty so it can be fixed by fit
• Fit to extract ttH signal strength, $\mu$
  $$\hat{\mu} = 1.2^{+1.6}_{-1.5}$$

• Fit uncertainties highlights:
  • Top pT reweighting: vary between none & 2x weighting factor
  • Normalization of tt+hf assigned 50% uncertainty so it can be fixed by fit

<table>
<thead>
<tr>
<th>Source</th>
<th>Rate uncertainty</th>
<th>Shape</th>
<th>Process</th>
<th>ttH</th>
<th>tt+jets</th>
<th>Others</th>
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<tbody>
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<td><strong>Experimental uncertainties</strong></td>
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<tr>
<td>Integrated luminosity</td>
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<td>tt+bb normalisation</td>
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<tr>
<td>tt+b normalisation</td>
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<tr>
<td>tt+c\bar{c} normalisation</td>
<td>50%</td>
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<td>Background cross sections</td>
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<td>PDF</td>
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<td>✓</td>
<td>✓</td>
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<tr>
<td>Statistical uncertainty (bin-by-bin)</td>
<td>4–30%</td>
<td>Yes</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

FIDUCIAL CROSS-SECTIONS

• Most precise channels ($\gamma\gamma$, ZZ) give stringent tests of predictions
  • Still statistics limited!

• Experimental systematic errors roughly equivalent to theory uncertainties
  • PDF uncertainty significant for N$^3$LO calculation, but will be reduced to 2-3% with new PDF4LHC recommendations
FIDUCIAL CROSS-SECTIONS

- Most precise channels ($\gamma\gamma$, ZZ) give stringent tests of predictions
  - Still statistics limited!
- Experimental systematic errors roughly equivalent to theory uncertainties
  - PDF uncertainty significant for $N^3$LO calculation, but will be reduced to 2-3% with new PDF4LHC recommendations

![Graph showing fiducial cross-sections with CMS Preliminary results.](image-url)
• Sizeable differences in H +jet rates between MCs & data

• Important consequences for jet veto

• Data systematic uncertainties comparable theory uncertainties
Differential Distributions

- Shape comparison yields harder $H p_T$ spectrum in data
- Same true for leading jet spectrum

• Shape comparison yields harder H $p_T$ spectrum in data

• Same true for leading jet spectrum
• Also testing rapidity distributions in inclusive and H + jet events

• Higher statistics measurements will be quite important for Runs II & III
OUTLINE

• Big picture

• Higgs: Getting to know the newest member of the Standard Model

• Going beyond the Standard Model

• New analysis techniques: getting boosted
THE BSM FORMULA

Define Control Region

Input to fit machinery

Look in Signal region

Determine transfer factor to Signal Region from MC

Do simultaneous fits to signal & control regions to extract signal
Define Control Region

Input to fit machinery

GOOD MC MODELING IS CRITICAL TO THIS PROCESS!

Look in Signal region

Determine transfer factor to Signal Region from MC

Do simultaneous fits to signal & control regions to extract signal
• Most Run 1 searches are concluded, combinations in progress

<table>
<thead>
<tr>
<th>Process</th>
<th>Generator</th>
<th>Cross-section order in $\alpha_s$</th>
<th>Tune</th>
<th>PDF set</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W(\rightarrow l\nu)$+jets</td>
<td>SHERPA 1.4.1 [75]</td>
<td>NNLO [76]</td>
<td>SHERPA default</td>
<td>CT10 [77]</td>
</tr>
<tr>
<td>$Z/\gamma^*(\rightarrow \ell\ell)$+jets Drell–Yan (8 &lt; $m_{\ell\ell}$ &lt; 40 GeV)</td>
<td>SHERPA 1.4.1</td>
<td>NNLO [76]</td>
<td>SHERPA default</td>
<td>CT10</td>
</tr>
<tr>
<td>$Z/\gamma^*(\rightarrow \ell\ell)$+jets (10 &lt; $m_{\ell\ell}$ &lt; 60 GeV)</td>
<td>ALPGEN 2.14 [79] + HERWIG 6.520 [82, 83] + JIMMY [84]</td>
<td>NNLO [78]</td>
<td>AUET2 [80]</td>
<td>CTEQ6L1 [81]</td>
</tr>
<tr>
<td>$\gamma$+jets</td>
<td>SHERPA 1.4.1</td>
<td>LO</td>
<td>SHERPA default</td>
<td>CT10</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>Powheg-Box 1.0 [85–87] + PYTHIA 6.426 [90]</td>
<td>NNLO+NNLL [88, 89]</td>
<td>Perugia2011C [91, 92]</td>
<td>CT10</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>SHERPA 1.4.1</td>
<td>NNLO+NNLL</td>
<td>SHERPA default</td>
<td>CT10</td>
</tr>
<tr>
<td>Single top</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>$t$-channel</td>
<td>AcerMC 3.8 [93] + PYTHIA 6.426</td>
<td>NNLO+NNLL [94]</td>
<td>AUET2B [95]</td>
<td>CTEQ6L1</td>
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<tr>
<td>$s$-channel, $Wt$</td>
<td>mc@nlo 4.03 [96, 97] + HERWIG 6.520</td>
<td>NNLO+NNLL [98, 99]</td>
<td>AUET2B</td>
<td>CT10</td>
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<tr>
<td>$t\bar{t}$+W/Z boson</td>
<td>Madgraph 5 1.3.28 [100] + PYTHIA 6.426</td>
<td>NLO [101–103]</td>
<td>AUET2B</td>
<td>CTEQ6L1</td>
</tr>
<tr>
<td>Dibosons WW, WZ, ZZ, $W\gamma$ and $Z\gamma$</td>
<td>SHERPA 1.4.1</td>
<td>NLO [104, 105]</td>
<td>SHERPA default</td>
<td>CT10</td>
</tr>
</tbody>
</table>

• Most signal samples are LO generators, cross-sections at NLO + NLL
• Can combine many (13) analyses and test against both full and simplified models

• Typically, experimental errors slightly larger or on par with theory signal uncertainties
• Can combine many (13) analyses and test against both full and simplified models

• Typically, experimental errors slightly larger or on par with theory signal uncertainties
AN EXAMPLE: 3RD GEN SQUARKS IN ALL HADRONIC FINAL STATES

- Signal: 1 or 2 b-jets with large missing energy (MET)
  - Require high transverse mass (built from MET & subleading jet)
  - Signal regions binned in contransverse mass

\[(M_{CT})^2 = [E_T^{j1} + E_T^{j2}]^2 - [\vec{p}_T^{j1} - \vec{p}_T^{j2}]^2 = 2p_T^{j1}p_T^{j2} [1 + \cos \phi(j_1, j_2)]\]

- Include ISR search region with high $p_T$ non b-tagged jet
• Background estimation is key:
  • Dominated by Z/W+jets, ttbar

• For each signal region, define $W\rightarrow l\nu$ control region

$$N_{SR}^{\text{pred}}(Z \rightarrow \nu\bar{\nu}; M_{CT}, p_{T}^{\text{non-b}}, N_{b\text{jets}}) = N_{CR}^{\text{obs}}(M_{CT}, p_{T}^{\text{non-b}}) R_{MC}^{SR/CR}(M_{CT}, p_{T}^{\text{non-b}}, N_{b\text{jets}})$$

• Assess systematic on procedure by MC closure test, variations of non- $W$ contributions, Z+hf modeling, normalization of contributions taken from MC

<table>
<thead>
<tr>
<th>$N_{b\text{jets}}$</th>
<th>$M_{CT}$</th>
<th>$M_{CT}$</th>
<th>$M_{CT}$</th>
<th>$M_{CT}$</th>
<th>ISR</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>&lt;250</td>
<td>[250,350]</td>
<td>[350,450]</td>
<td>&gt;450</td>
<td></td>
</tr>
<tr>
<td>$Z(\nu\bar{\nu})$ +jets</td>
<td>1</td>
<td>848±12±79</td>
<td>339±8±52</td>
<td>48.0±3.0±6.0</td>
<td>8.1±1.6±1.7</td>
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<tr>
<td>$t\bar{t}$, $W(\ell\nu)$ +jets</td>
<td>1</td>
<td>645±24±57</td>
<td>381±17±38</td>
<td>36.0±4.9±5.7</td>
<td>7.8±2.6±2.0</td>
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<tr>
<td>QCD multijets</td>
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<td>25.0±9.4±5.2</td>
<td>16.0±7.4±2.8</td>
<td>0.0±1.0±1.2</td>
<td>negligible</td>
</tr>
<tr>
<td>Rare processes</td>
<td>1</td>
<td>18.0±9.2</td>
<td>18.0±8.9</td>
<td>1.1±0.5</td>
<td>0.3±0.1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>1</td>
<td>1540±100</td>
<td>754±68</td>
<td>85±10</td>
<td>16.0±4.1</td>
</tr>
<tr>
<td>$Z(\nu\bar{\nu})$ +jets</td>
<td>2</td>
<td>60.0±3.4±7.1</td>
<td>28.0±2.4±3.8</td>
<td>3.9±0.9±1.0</td>
<td>0.7±0.6±0.6</td>
</tr>
<tr>
<td>$t\bar{t}$, $W(\ell\nu)$ +jets</td>
<td>2</td>
<td>29.0±2.9±5.5</td>
<td>17.0±2.5±3.3</td>
<td>2.4±0.9±0.6</td>
<td>0.0±0.2±0.2</td>
</tr>
<tr>
<td>QCD multijets</td>
<td>2</td>
<td>1.9±0.7±0.4</td>
<td>1.2±0.8±0.2</td>
<td>0.0±0.1±0.1</td>
<td>negligible</td>
</tr>
<tr>
<td>Rare processes</td>
<td>2</td>
<td>1.8±0.9</td>
<td>3.4±1.7</td>
<td>0.1±0.1</td>
<td>0.1±0.1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>2</td>
<td>93±10</td>
<td>50.0±6.4</td>
<td>6.5±1.7</td>
<td>1.0±0.9</td>
</tr>
</tbody>
</table>
• Good data/MC agreement is found in signal regions
• Good data/MC agreement is found in signal regions

• Combine and set limits!
GENERIC DIBOSON RESONANCES
• Hint of excess @ 2 TeV in all hadronic di-boson resonance search
• Hint of excess @ 2 TeV in all hadronic di-boson resonance search

• Select events using jet mass, properties and substructure variables
**GENERIC DIBOSON RESONANCES**

- Hint of excess @ 2 TeV in all hadronic di-boson resonance search
- Select events using jet mass, properties and substructure variables
- Fit to smoothly falling dijet mass spectrum

![Graph showing events vs dijet mass with significance](image)

**ATLAS**

$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

- Data
- Background model
- 1.5 TeV Bulk $G_{RS}$, $k/\overline{M}_{Pl} = 1$
- 2.0 TeV Bulk $G_{RS}$, $k/\overline{M}_{Pl} = 1$
- Significance (stat)
- Significance (stat + syst)

**WW Selection**

ATLAS: arXiv:1506.00962
Generic Diboson Resonances

- Hint of excess @ 2 TeV in all hadronic di-boson resonance search
- Select events using jet mass, properties and substructure variables
- Fit to smoothly falling dijet mass spectrum
- Majority of uncertainties arise from use of jet properties

ATLAS: arXiv:1506.00962
OUTLINE

• Big picture
• Higgs: Getting to know the newest member of the Standard Model
• Going beyond the Standard Model

**New analysis techniques: getting boosted**

More details: BOOST 2015
NEW TOOLS FOR USING JETS

- Confluence of theory and experimental improvements and √s increase are making us sensitive to the details of jets
  - Jet mass, constituents properties
- Makes use of hadronic decays possible!
  - Used in several Run I analyses, many planned for Run II
- Wide open parameter space for taggers: tops, Higgs, W/Z bosons, quark-gluon

CMS Simulation, $\sqrt{s} = 8$ TeV

**Top Tag Efficiency**

- **Mistag Rate**
  - Matched parton $p_T > 400$ GeV/c
  - Matched parton $p_T > 600$ GeV/c
  - Matched parton $p_T > 800$ GeV/c

- **Top Tag Efficiency**
  - Distributions for different jet masses and efficiencies.
  - Comparison between CMS Top Tagger and HEP Top Tagger with various working points (WP).

**Events / 5 GeV**

- Data / Bkg
  - Data vs. Background comparison for different jet masses and efficiencies.

**CMS**

- Data, tf, W$\to l\nu$+jets, Others

**CMS-B2G-13-008**

- 19.7 fb$^{-1}$ (8 TeV)

- M$_{jet}$[GeV]
• However, uncertainties can be significant

\[
D^\beta_2 = \frac{e_3^\beta}{(e_2^\beta)^3} = \frac{\sum_{i<j<k} p_T^i p_T^j p_T^k (R^\beta_{ij} R^\beta_{ik} R^\beta_{kj})}{(\sum_{i<j} p_T^i p_T^j R^\beta_{ij})^3}
\]

W/Z-boson tagging using substructure variables
• However, uncertainties can be significant
• However, uncertainties can be significant

• Expected to be a very active development area in Run II with close collaboration with theorists!
CONCLUSIONS

• Wide range of QCD calculations and models used in Higgs & BSM measurements

• Run 1 analyses had important uncertainties due to PDFs, heavy flavor production, jet substructure and soft(ish) QCD effects

• Looking forward to pushing the limits in Run II!

  • Lots of recent theory improvements still to be incorporated
BACK-UP
ZZ K-FACTORS

• QCD ZZ production only known to LO:
  • CMS width analysis uses same k-factors as NNLO Higgs calculation based on arXiv: 1312.2397
  • ATLAS width measurement reported as function of unknown K-factor
  • Key place for theory development
• K-factor measured as a function $m_{4l}$, $p_{T_{4l}}$ in ATLAS-CONF-2015-031
• ATLAS width results as a function of relative K-factors
**Diboson Resonance**

Table 2: Parameters for the mass-drop filtering algorithm used to groom C/A jets. The choice of $\mu_f$ parameter corresponds to no mass-drop requirement being imposed in the grooming procedure.

<table>
<thead>
<tr>
<th>Filtering parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{y_f}$</td>
<td>0.2</td>
</tr>
<tr>
<td>$\mu_f$</td>
<td>1</td>
</tr>
<tr>
<td>$R_f$</td>
<td>0.3</td>
</tr>
<tr>
<td>$n_f$</td>
<td>3</td>
</tr>
</tbody>
</table>

\[ \sqrt{y} \equiv \min(\triangle_R^{(j_1, j_2)} \frac{\Delta R_{(j_1, j_2)}}{m_0} \geq \sqrt{y_f}, \text{ Boson Tagging Requirements} \]

\[ \sqrt{y} \geq 0.45, n_{trk} < 30, \text{ and } |m_j - m_{\nu}| < 13 \text{ GeV} \]

Figure 2: Event selection efficiencies as a function of the resonance masses for EGM $W' \rightarrow WZ$ and bulk $G_{RS} \rightarrow WW$ and ZZ for simulated events with resonance mass within 10% of the nominal signal mass. In (a), the event topology requirements are applied to EGM $W' \rightarrow WZ$, $G_{RS} \rightarrow WW$ and $G_{RS} \rightarrow ZZ$ samples, while in (b), the WZ, WW and ZZ boson tagging selections are also applied in the EGM $W' \rightarrow WZ$, $G_{RS} \rightarrow WW$ and $G_{RS} \rightarrow ZZ$ samples respectively and the efficiencies shown are corrected by the simulation-to-data scale factor. The width of the bands in each figure indicates both the statistical and systematic uncertainties.
FULL EVENT DISPLAY FROM FIRST SLIDE