Resonant Di-Higgs Production: Probing Electroweak Phase Transition at LHC
Gazing beyond the Standard Model

❖ The Standard Model (SM) is the most fundamental theory we have in Physics
→ It describes the fundamental particles and their interactions

❖ The SM is great, but not perfect…
→ Neutrino Masses
→ Dark Matter
→ Hierarchy problem \( m_h^2 \sim m_{h0}^2 - \alpha \lambda_f^2 \Lambda^2 \)
→ Matter-Antimatter Asymmetry (baryogenesis) \( \frac{n_B - n_{\bar{B}}}{n_{\gamma}} \sim 10^{-9} \)

❖ Several solutions have been proposed:
→ No perfect solution
  (each model focuses on few aspects)
→ Generally based on the idea of adding more ingredients to the SM Lagrangian
→ As a result the Higgs sector is often extended
Extending the Higgs sector

- Higgs sector could result extended in many ways

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
<th>Higgs bosons</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM (one doublet of complex scalar fields)</td>
<td>3 d.o.f. give mass to $W^\pm$ and $Z$, Yukawa couplings generate fermion mass</td>
<td>$h$</td>
</tr>
<tr>
<td>SM + singlet (xSM)</td>
<td>Used in the context of EWK baryogenesis, DM…</td>
<td>$h, H$</td>
</tr>
<tr>
<td>2HDM (contains a second doublet)</td>
<td>Prerequisite for SUSY, natural in GUT, DM originating from 2HDM</td>
<td>$h, H, A, H^\pm$</td>
</tr>
<tr>
<td>2HDM + complex singlet (e.g. NMSSM)</td>
<td>Solve the mu-problem in MSSM (where $H(125)$ is unnaturally heavy)</td>
<td>$h_1, h_2, h_3, a_1, a_2, H^\pm$</td>
</tr>
<tr>
<td>SM + triplet</td>
<td>Natural explanation for small neutrino masses</td>
<td>$h, H, A, H^\pm, H^{\pm\pm}$</td>
</tr>
</tbody>
</table>

- We will chat about this one!
Baryogenesis, EWPT and xSM

- Dynamical generation of baryon asymmetry requires the Sakharov conditions:
  - B Violation (sphalerons)
  - C/CP Violation (CKM Matrix)
  - Departure from Thermal Equilibrium or a breakdown of CPT invariance (EW Phase Transition)

- But…
  - CKM Matrix does not provide enough C/CP violation (too feeble)
  - In minimal SM, for m(h)~125 GeV, EWPT occurred through a cross-over phase transition in the early Universe

- Possible solutions:
  - Extended Higgs sector would change the nature and properties of the EWPT
  - Universe could have undergone a strong first order EWPT even for a SM-like Higgs boson of mass m(h)~125 GeV.
  - Simplest solution.... xSM model (SM + singlet)
Higgs effective potential (with radiative and thermal corrections):

\[
V(h, T) \sim (aT^2 - \mu^2)h^2 - E(T)h^3 + \lambda(T)h^4
\]

1\textsuperscript{st} Order:

\[
\langle \phi \rangle = 0 \rightarrow \langle \phi \rangle = \phi(T) \quad \text{Discontinuous}
\]

2\textsuperscript{nd} Order:

\[
\langle \phi \rangle = 0 \rightarrow \langle \phi \rangle = \phi(T) \quad \text{Continuous}
\]

Higgs VEV Sudden Change

\[
\lambda(T)h^4 \quad \text{Large H mass} \quad \rightarrow
\]

\[
E(T)h^3 \quad \text{New bosons}
\]

In the SM (\(m_h = 125\,\text{GeV}\)) EW Phase Transition Smooth CrossOver


Luca Pernié

Resonant Di-Higgs production, 07. May. 2018
**xSM: resonant di-Higgs production**

- **xSM**: singlet scalar extension of the SM
  - Foreseen 2 Higgs bosons \( H \) and \( h \)
  - If \( m(H) > 215 \text{ GeV} \): \( H \rightarrow hh \) is allowed
  - Discovery mode if \( H \rightarrow ZZ \) is suppressed

- DiHiggs searches in general:
  - Resonant: xSM, MSSM, 2HDM
  - Non-Resonant: access Higgs self-coupling, destructive interference

- Several final states could be produced:
  - \( bbb \): high BR, high bkg
  - \( bb\gamma\gamma \): low BR, moderate bkg
  - \( bb\tau\tau \): moderate BR and \( tt \)
  - \( bbWW \): high BR, high bkg, neutrinos!

We will focus on:
- **Resonant Production**
- \( HH \rightarrow bbWW \rightarrow bb\mu\mu\nu \)
A glimpse at the topology

❖ Our final state:
  → Two isolated muons (electrons)
  → Two jets
  → Two neutrinos

❖ Typical signature:
  → Jets originating from b-partons
  → Invariant mass of b-jets close to 125 GeV
  → Missing Energy
  → Kinematic distributions (ΔR, ΔΦ…)

❖ SM backgrounds:
  → Top-pair production (tt): large σ, could produce the same final state
  → Drell-Yan (DY): very large σ, no jets at Leading Order, and no MET
  → tW: small σ, could produce the same final state
  → Non resonant hh: negligible

❖ We will only focus on:
  → Signal
  → tt
Signal cross section: what to expect?

- Among all strong first order EWPT points, two different benchmark models have been selected: Optimistic and Pessimistic scenario.

- If bbWW sensitivity is boosted could improve low/medium mass range.


Few numbers:

- Signal benchmark: maximize the $\sigma \cdot \text{BR}(H \rightarrow hh)$ at LHC

- Just to realize the difficulty of the analysis:
  - $\sigma(t\bar{t}) \cdot \text{Br}(\mu\mu\nu\nu b\bar{b}) \sim 9.53 \text{ pb}$ \quad \rightarrow N_{\text{ev}}(300 \text{ fb}^{-1}) \sim 3 \text{ M events}$
  - $\sigma(B1) \cdot \text{Br}(\mu\mu\nu\nu b\bar{b}) \sim 0.002 \text{ pb}$ \quad \rightarrow N_{\text{ev}}(300 \text{ fb}^{-1}) \sim 600 \text{ events (0.02\% N}_{tt})$
  - $\sigma(B6) \cdot \text{Br}(\mu\mu\nu\nu b\bar{b}) \sim 0.0001 \text{ pb}$ \quad \rightarrow N_{\text{ev}}(300 \text{ fb}^{-1}) \sim 30 \text{ events (0.001\% N}_{tt})$
  - $\sigma(B12) \cdot \text{Br}(\mu\mu\nu\nu b\bar{b}) \sim 1.5 \times 10^{-6} \text{ pb}$ \quad \rightarrow N_{\text{ev}}(300 \text{ fb}^{-1}) \sim 0.5 \text{ events (0.000002\% N}_{tt})$

<table>
<thead>
<tr>
<th>$\cos \theta$</th>
<th>$m_2$ (GeV)</th>
<th>$\Gamma_{h_2}$ (GeV)</th>
<th>$x_0$ (GeV)</th>
<th>$\lambda$</th>
<th>$a_1$ (GeV)</th>
<th>$a_2$ (GeV)</th>
<th>$b_3$ (GeV)</th>
<th>$b_4$ (GeV)</th>
<th>$\lambda_{111}$ (GeV)</th>
<th>$\lambda_{211}$ (GeV)</th>
<th>$\sigma$ (pb)</th>
<th>BR</th>
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<tbody>
<tr>
<td>B1</td>
<td>0.961</td>
<td>258</td>
<td>0.68</td>
<td>307</td>
<td>-0.52</td>
<td>-266</td>
<td>-138</td>
<td>0.26</td>
<td>3.43</td>
<td>-0.70</td>
<td>1.19</td>
<td>0.50</td>
</tr>
<tr>
<td>B2</td>
<td>0.976</td>
<td>341</td>
<td>2.42</td>
<td>257</td>
<td>0.92</td>
<td>-377</td>
<td>0.39</td>
<td>-403</td>
<td>0.77</td>
<td>204</td>
<td>-150</td>
<td>0.59</td>
</tr>
<tr>
<td>B3</td>
<td>0.982</td>
<td>353</td>
<td>2.17</td>
<td>265</td>
<td>0.99</td>
<td>-400</td>
<td>0.45</td>
<td>-378</td>
<td>0.69</td>
<td>226</td>
<td>-144</td>
<td>0.44</td>
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<tr>
<td>B4</td>
<td>0.983</td>
<td>415</td>
<td>1.59</td>
<td>54.6</td>
<td>0.17</td>
<td>-642</td>
<td>3.80</td>
<td>-214</td>
<td>0.16</td>
<td>44.9</td>
<td>82.5</td>
<td>0.36</td>
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<td>B5</td>
<td>0.984</td>
<td>455</td>
<td>2.08</td>
<td>47.4</td>
<td>0.18</td>
<td>-707</td>
<td>4.63</td>
<td>-607</td>
<td>0.85</td>
<td>46.7</td>
<td>93.5</td>
<td>0.26</td>
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<tr>
<td>B6</td>
<td>0.986</td>
<td>511</td>
<td>2.44</td>
<td>40.7</td>
<td>0.18</td>
<td>-744</td>
<td>5.17</td>
<td>-618</td>
<td>0.82</td>
<td>46.6</td>
<td>91.9</td>
<td>0.15</td>
</tr>
<tr>
<td>B7</td>
<td>0.988</td>
<td>563</td>
<td>2.92</td>
<td>40.5</td>
<td>0.19</td>
<td>-844</td>
<td>5.85</td>
<td>-151</td>
<td>0.08</td>
<td>47.1</td>
<td>104</td>
<td>0.087</td>
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<tr>
<td>B8</td>
<td>0.992</td>
<td>604</td>
<td>2.82</td>
<td>36.4</td>
<td>0.18</td>
<td>-898</td>
<td>7.36</td>
<td>-424</td>
<td>0.28</td>
<td>45.6</td>
<td>119</td>
<td>0.045</td>
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<td>B9</td>
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<td>662</td>
<td>2.97</td>
<td>32.9</td>
<td>0.17</td>
<td>-976</td>
<td>8.98</td>
<td>-542</td>
<td>0.53</td>
<td>44.9</td>
<td>132</td>
<td>0.023</td>
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<tr>
<td>B10</td>
<td>0.993</td>
<td>714</td>
<td>3.27</td>
<td>29.2</td>
<td>0.18</td>
<td>-941</td>
<td>8.28</td>
<td>497</td>
<td>0.38</td>
<td>44.7</td>
<td>112</td>
<td>0.017</td>
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<tr>
<td>B11</td>
<td>0.996</td>
<td>767</td>
<td>2.83</td>
<td>24.5</td>
<td>0.17</td>
<td>-920</td>
<td>9.87</td>
<td>575</td>
<td>0.41</td>
<td>42.2</td>
<td>114</td>
<td>0.0082</td>
</tr>
<tr>
<td>B12</td>
<td>0.994</td>
<td>840</td>
<td>4.03</td>
<td>21.7</td>
<td>0.19</td>
<td>-988</td>
<td>9.22</td>
<td>356</td>
<td>0.83</td>
<td>43.9</td>
<td>83.8</td>
<td>0.0068</td>
</tr>
</tbody>
</table>

Efficiency & Acceptance not included

Kinematic distributions

❖ MT2 variable is very powerful:
→ Estimates the $m_T$ in systems with more than one neutrino
→ Bound masses of unseen pair of particles which are presumed to have decayed semi-invisibly into particles which were seen
→ Treating the lepton and the b-jet as a single object
→ Not sensitive for B3 (H mass very similar to $2m_t$ mass)

❖ Better than simple transverse mass:

$$m_T = \sqrt{2p_T(\mu^-\mu^+)E_T^{miss}(1 - \cos(\phi_{\mu^-\mu^+} - \phi_{E_T^{miss}}))}$$
Heavy Mass Estimator (HME)

- To explain the method... let’s make some initial assumption:
  → All visible variables are perfectly measured (no pileup)
  → Both SM Higgs bosons on-shell
  → At least one of two W bosons off-shell ("1" marks the on-shell one: W₁ → µ₁ν₁)

- Under the above assumptions, kinematics described by:

\[
\begin{align*}
\hat{H}_{T_x} &= p_x(ν₁) + p_x(ν₂) \\
\hat{H}_{T_y} &= p_y(ν₁) + p_y(ν₂)
\end{align*}
\]

\[
\sqrt{p_4^2(ℓ₁, ν₁)} = M_W, \quad 20 < \sqrt{p_4^2(ℓ₂, ν₂)} < 45 \text{ GeV} \\
(p_4(ℓ₁) + p_4(ℓ₂) + p_4(ν₁) + p_4(ν₂))^2 = M_h^2
\]

- The momentum of each neutrino described by 3 unknown parameters: 6 unknowns
  → 4 constraints could reduce the number of unknowns to two
  → We randomly generate the two unknowns: η and φ of one neutrino
  → We solve the system
  → A single generation of the two unknowns is called one iteration, and, if the equations admit solution, it produces a MMC value (the estimator for M_H value)
Heavy Mass Estimator

- Produced **large amount of iterations**, the η and φ of neutrino, according to probability density function from simulation.

- To include resolution effects in MMC, correction on jets and $E_{T}^{miss}$ are applied with constraint that invariant mass of two jets equals to $m(h)$. In addition, the higgs boson mass and W boson mass used in MMC are generated according to gaussian function to take care of intrinsic width of H and W boson respectively.

![HME likelihood function of one typical event, B3](image)

- The maximum of the distribution estimates the true $M_{H}$ value.
- Each MMC iteration produce a value that fill this distribution.
- (Y axis value corresponding to maximum is the MMC probability.)

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Resonant Di-Higgs production, 07.May.2018
Heavy Mass Estimator

- The maximum of the MMC likelihood if the MMC value fore each event

- The final MMC distribution has a resolution that depends on the mass point

- In the case of tt MMC impose unnatural kinematic condition:
  → Equations have no solution
  → MMC value peak below tt mass

- MMC mass in the final discriminating variable we use to derive limits

![Graph showing MH from HME reconstruction with different mass points B3, B6, B9, and TTbar.]
DNN: a novel approach

- Parametric training of a Deep Neutral Network
  → Used in CMS-PAS-HIG-17-006*

- Solve several common issue:
  → Train a single mass point
  → Train a mix of unlabelled mass points
  → Train different DNNs using few mass points

- Plus allow:
  → Smooth interpolation
  → Optimal continuous performances

- Ongoing: adding HME (whole shape!) to DNN


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Resonant Di-Higgs production, 07.May.2018
A promising channel!

- Eventual discovery could be reached at HL-LHC (up to 700 GeV)
- Competitive channel (thanks to HME mass reconstruction)
  → Comparison made by normalizing to the same luminosity (300 fb⁻¹)
- HME technique will be brought to CMS analysis, interplay with DNN!

ElectroWeak Baryogenesis

The EW Baryogenesis Recipe:

1. CP Violation + Transport (diffusion)

2. Out of Equilibrium

\[ \Gamma_{\text{Sph}}^b \sim \exp(-E_{\text{Sph}}/T) \sim \text{SUPPRESSED} \]

(if \( \langle \phi \rangle / T \geq 1 \))

\[ n_B = n_b^L - n_b^L + n_b^R - n_b^R = 0 \]

\( \neq 0 \) and \( \neq 0 \)

Thanks to Jose Miguel
EWPT and xSM

- Several ways to modify the SM Higgs potential:
  
  **HOW TO MODIFY THE SM HIGGS POTENTIAL TO GET A SEWPT?**

  \[ V_{\text{eff}}(h, T) = V_0(h) + V_0^{\text{loop}}(h) + V_T(h, T) \]

  - **Tree-level effects:**
    → Add a scalar that modifies the tree-level potential and create a barrier
    → E.g. \(x\text{SM}, \text{NMSSM}\) (dominant effect tree-level)

  - **Loop effects:**
    → Add particles whose loops reduce vacua energy difference so \(W, Z\) thermal loops create a barrier
    → E.g. 2HDM (dominant effect is loop)

  - **Thermal effects:**
    → Add new boson to the plasma to generate a thermal barrier
    → E.g. MSSM (dominant effect is thermal)

*Thanks to Jose Miguel*
Thanks to the LHC for bringing $\sim 100 \text{ fb}^{-1}$ of $\mathrm{Lint} @ 13 \text{ TeV}$ to both CMS and ATLAS (and 50 more expected in 2018)!

Not enough? High-Luminosity LHC!
The High-Luminosity program

- LHC has an ambitious plan that foreseen a High-Luminosity period of data taking:
  - Up to 3000 fb\(^{-1}\) of Luminosity will be collected
  - Pileup: major challenge to face!
  - CMS and ATLAS detector need major detectors upgrade (rad-hard, pileup mitigation interesting, but not on this talk)
  - Also: more luminosity, more computational requirements!
Samples generation:

- Each of the xSM benchmark points generated with Herwig++
  - Parameter values chosen to maximize the $\sigma \cdot \text{BR}(H \rightarrow hh)$ at LHC (optimistic scenario)

- $tt$: simulated at next-to-leading order (NLO) accuracy with POWHEG,
  - subsequently processed with Herwig for parton showering and hadronization

- Detector simulation performed by **DELPHES 3.3.0**
  - Based on the CMS input cards
  - Simulated pileup = 40
  - Reconstruction and isolation are based on CMS muon performance
    - Muons: $|\eta| < 2.4$ and $p_T \geq 10$ GeV
    - Jets: $|\eta| < 2.5$ and $p_T \geq 30$ GeV
Basic selection:

- **Initial requirements:**
  - 2 isolated muons ($P_T > 10$ GeV and $|\eta| < 2.4$)
  - 2 jets ($P_T > 30$ GeV and $|\eta| < 2.5$)
  - Missing Transverse energy ($E_T^{\text{miss}} > 20$ GeV)
  - 1 b-tagged jet (CSV medium working point, WP)
  - 1 b-tagged jet (CSV medium or loose working point)

- **CSV algorithm:**
  - In delphes eff. and mistag are parametrized (vs $p_T$ and $\eta$)
  - Medium WP: eff.$\sim 70\%$, mistag$\sim 1.5\%$
  - Loose WP: eff.$\sim 85\%$, mistag$\sim 10\%$

- **Basic selection keep our signal still hidden by tt**
Machine Learning

- The search is difficult… but not impossible!
  Same final state between $tt$ and $Hhh$, but different kinematic!
  → Only a Multi Variate Analysis can efficiently exploit such differences

- Di-lepton and Di-jet invariant mass quite sensitive
The search is difficult... but not impossible!
Same final state between tt and Hhh, but different kinematic!
→ Only a Multi Variate Analysis can efficiently exploit such differences

ΔR variable also can differentiate signal and background
Preselection:

- **Basic selection:**
  - 2 isolated muons ($P_T > 10 \text{ GeV}$ and $|\eta| < 2.4$)
  - 2 b-jets [Medium and (Medium or Loose) WP]
  - $E_{T\text{miss}} > 20 \text{ GeV}$

Each bin is a different signal sample

<table>
<thead>
<tr>
<th>Variable</th>
<th>Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta R(l, l)$</td>
<td>$0.07 &lt; \Delta R(l, l) &lt; 3.3$</td>
</tr>
<tr>
<td>$\Delta R(j, j)$</td>
<td>$\Delta R(j, j) &lt; 5.0$</td>
</tr>
<tr>
<td>$M(l, l)$</td>
<td>$5 &lt; M(l, l) &lt; 100 \text{ GeV}$</td>
</tr>
<tr>
<td>$M(j, j)$</td>
<td>$M(j, j) &gt; 22 \text{ GeV}$</td>
</tr>
</tbody>
</table>

- Before training a Multivariate Analysis we perform a preselection:
  - Loose: we want the MVA to be tight
  - Highly efficient of the signal
  - The same for each signal mass point
  - tt efficiency $\sim 60$

- But still:
Multi Variate Analysis:

- Input variables (B7 shown):
  - Discriminant power change from signal to signal
  - A simple cut is not as efficient as letting a MVA to do the jobs
Multi Variate Analysis:

- Input variables (B7 shown):
  - Discriminant power change from signal to signal
  - A simple cut is not as efficient as letting a MVA to do the jobs
Multi Variate Analysis:

- Correlation:
  - Some methods are sensitive to correlated variables
  - In general we prefer to avoid them (also to simplify the categorization)
  - Only exception is $\Delta R(b_1b_2)$ and $m(b_1b_2)$

![Correlation Matrix (signal)](image1)

![Correlation Matrix (background)](image2)
Multi Variate Analysis:

- Final discriminator:
  - We trained a different MVA for each mass point
  - Several methods have been tested (BDT, Likelihood, KNN, Neural Network…)
  - Performance are similar
  - We selected Boosted Decision Tree (BDT) for low mass signals (B1-B7), and Likelihood for high masses (B8-B12)
Multi Variate Analysis:

- Cut chosen in order to maximize sensitivity:

<table>
<thead>
<tr>
<th>Classifier</th>
<th>(#signal, #backgr.)</th>
<th>Optimal-cut</th>
<th>S/sqrt(S+B)</th>
<th>NSig</th>
<th>NBkg</th>
<th>EffSig</th>
<th>EffBkg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Likelihood</td>
<td>(20.549999, 23461)</td>
<td>0.9990</td>
<td>0.884801</td>
<td>9.244946</td>
<td>99.92854</td>
<td>0.4499</td>
<td>0.004259</td>
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<td>KNN</td>
<td>(20.549999, 23461)</td>
<td>0.9001</td>
<td>0.768873</td>
<td>9.886247</td>
<td>155.4444</td>
<td>0.4811</td>
<td>0.006626</td>
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<td>MLP</td>
<td>(20.549999, 23461)</td>
<td>0.9214</td>
<td>0.972139</td>
<td>8.932808</td>
<td>75.50156</td>
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<td>0.003218</td>
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<td>BDT</td>
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<td>0.995324</td>
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<td>91.046</td>
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<td>BDTD</td>
<td>(20.549999, 23461)</td>
<td>0.0782</td>
<td>0.854258</td>
<td>9.982725</td>
<td>126.5761</td>
<td>0.4858</td>
<td>0.005395</td>
</tr>
</tbody>
</table>

Cut efficiencies and optimal cut value

- For 21 signal and 23461 background events the maximum S/S+B is 0.9953 when cutting at 0.1361

TMVA overtraining check for classifier: BDT

- Kolmogorov-Smirnov test: signal (background) probability = 0.149 (0.843)
MVA perform better at high mass…
… but the number of signal events
is much lower there!
(less sensitivity)
Sidebands:

- We need to know the tt distribution extremely well, especially the tails
  - Confident that future MC will represent the data with high precision (NNLO or more)
  - But we cannot simply set uncertainty on tt based on QCD scale etc…
    (10-15% unc. will affect drastically our sensitivity).

- Creating a control region (CR) to estimate tt:
  - Select events with \( M(b_1b_2) > 150 \text{ GeV} \) (tt enriched phase space)
  - Train the MVA in that region
  - Apply the MVA to the CR (in data and MC)
  - Estimate scale factors that correct MC distribution based on data
MMC before MVA cut

❖ The analysis so far:
  → Applying Selection and Preselection
  → Applying the MVA cut
  → Look at the MMC distribution
    (here MMC is before the MVA cut)

❖ We need to address systematics errors
Sidebands:

- Distributions after the MVA cut in CR and Signal Region (SR)
  - Uncertainty driven by the statistic in the CR

![Distributions after the MVA cut in CR and Signal Region (SR)](image-url)
MMC after MVA cut

- We derive limits using the core of our signal and the tail of tt distribution

- We can estimate tt from data before the MVA, but this is not relevant for us, we need to prove we control tt tails

\[
\begin{align*}
\text{HME \ [GeV]} & \quad \text{prob.} \\
\text{HME \ [GeV]} & \quad \text{prob.}
\end{align*}
\]

\[
\begin{align*}
\text{HME \ [GeV]} & \quad \text{prob.} \\
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\end{align*}
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\[
\begin{align*}
\text{HME \ [GeV]} & \quad \text{prob.} \\
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\end{align*}
\]

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\end{align*}
\]

\[
\begin{align*}
\text{HME \ [GeV]} & \quad \text{prob.} \\
\text{HME \ [GeV]} & \quad \text{prob.}
\end{align*}
\]
Systematics

❖ Scale Factors (SF) will be extracted in the CR and applied to the SR
  → Uncertainty on the SF will be drive by the statistic in the CR
  → Using more CR will allow to cross check the SF
  → Better to be conservative, we assume:
    B1-B2-B3: 3%
    B4: 5%
    B5: 10% B6-B7-B8-B9: 12%
    B10-B11-B12: 15%

❖ Signal uncertainty:
  → This is just a feasibility study,
    no data to compute realistic systematics
  → Assuming general CMS systematics
    for Higgs searches: ~ 10%

Example from:

<table>
<thead>
<tr>
<th>Source of uncertainties</th>
<th>Error, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated luminosity</td>
<td>2.6%</td>
</tr>
<tr>
<td>Muon HLT</td>
<td>1.5%</td>
</tr>
<tr>
<td>Muon ID</td>
<td>4 × 1%</td>
</tr>
<tr>
<td>Muon tracking</td>
<td>4 × 0.2%</td>
</tr>
<tr>
<td>Overlapping in Tracker</td>
<td>2 × 1.2%</td>
</tr>
<tr>
<td>Overlapping in Muon System</td>
<td>2 × 1.3%</td>
</tr>
<tr>
<td>Dimuons mass consistency</td>
<td>1.5%</td>
</tr>
<tr>
<td>NNLO Higgs $p_T$ re-weighting</td>
<td>2.0%</td>
</tr>
<tr>
<td>PDF+$\alpha_s$</td>
<td>3.0%</td>
</tr>
<tr>
<td>Total</td>
<td>7.3%</td>
</tr>
</tbody>
</table>
Performing a "cut and count" analysis (i.e. not having MMC mass available) result in a much worse sensitivity

→ Signal yield within the tt systematics

No HME shape

$L = 300 \text{ fb}^{-1}$

Using HME shape

$L = 300 \text{ fb}^{-1}$
Results

- Sensitivity of the analysis driven by $t\bar{t}$ knowledge
  → Better sensitivity if we have no systematic uncertainty (only MC statistic)
  → We choose a "conservative" systematic on $t\bar{t}$

L = 300 fb$^{-1}$

![Realistic uncertainty](image1)

![Statistic only uncertainty](image2)