Heavy resonances at 100TeV

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Based on arXiv:1902.11217 (accepted by EPJC) and in FCC CDRs
Motivation

• **Goal of the study**
  • Discovery reach for heavy objects
  • Find ways to discriminate QCD, top and boson jets
  • Being validated with calorimeter and tracker performances in full simulation

• **No pileup assumed**
  • For such heavy object the effect is hopefully not large
  • Effect on jet reconstruction and performance being studied in full simulation

• **In this talk**
  • Not discussing yet the physic models
  • Neither designing fully state of the art analyses
  • But rather study the performance of the FCC-hh detector
Outline

• **Leptonic resonances**
  • $ee, \mu\mu, \tau\tau$

• **Hadronic resonances**
  • $Ttbar, WW, jj$

• **Summary**
$Z' \rightarrow l^+l^-$
Z' -> μ⁺μ⁻/e⁺e⁻

• **Z' model**
  • From Pythia8, no k-factor
  • Simple benchmarks used to check detector performance
  • Helped to tune the muon resolution initially of 10%@10TeV given the reach of such heavy objects

• **Analysis selection**
  • $p_T(\text{lepton}_1)$ and $p_T(\text{lepton}_2) > 1$TeV
  • $|\eta_{\text{lepton}_1}|$ and $|\eta_{\text{lepton}_2}| < 4$
  • $M_{ll} > 2.5$ TeV (to bridge with HL-LHC reach of 6 TeV, start signal at 5 TeV)

• **Uncertainties**
  • 50% uncertainty on the Drell-Yan normalization
$Z' \rightarrow \mu^+\mu^-/e^+e^-$ (30 TeV)

As expected better mass resolution for electrons
Limits and discovery

Considering 2.2fb\(^{-1}\) per day for baseline 5\(\sigma\) discovery for:
- 20TeV after \(~50\) days (first year?)
- 33TeV after 10 years @ baseline
- 42TeV after full operation 25 years
Z’ flavour anomaly

Quick interpretation of Z’→μμ

Arxiv:1710.06363

We test this line
Discovery $\mu\mu$ degraded

Best sensitivity achieved with an assumed $\sigma_p/p \approx 5\%$ at $p_T = 20$ TeV corresponding to our target for the FCC-hh detector.

Worse results for projected CMS resolution of $\sigma_p/p \approx 40\%$.

Accurate reconstruction and momentum measurements of $p_T = 20$ TeV -> require large lever arm, excellent spatial resolution and precise alignment of the tracking plus muon systems.
Z' -> ττ

- Analysis selection (hadronic taus only as most sensitive)
  - $p_{T}(j1/2) > 1$ TeV, $|η(j1/2)| < 2.5$
  - At least 2 tau tags

<table>
<thead>
<tr>
<th>$Z'$ mass [TeV]</th>
<th>$Δφ(τ_1, τ_2)$</th>
<th>$ΔR(τ_1, τ_2)$</th>
<th>$E_{T}^{miss}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 – 8</td>
<td>&gt; 2.4</td>
<td>&gt; 2.5 and &lt; 3.5</td>
<td>&gt; 400 GeV</td>
</tr>
<tr>
<td>10</td>
<td>&gt; 2.4</td>
<td>&gt; 2.7 and &lt; 4</td>
<td>&gt; 300 GeV</td>
</tr>
<tr>
<td>12 – 14</td>
<td>&gt; 2.6</td>
<td>&gt; 2.7 and &lt; 4</td>
<td>&gt; 300 GeV</td>
</tr>
<tr>
<td>16 – 18</td>
<td>&gt; 2.7</td>
<td>&gt; 2.7 and &lt; 4</td>
<td>&gt; 300 GeV</td>
</tr>
<tr>
<td>&gt; 18</td>
<td>&gt; 2.8</td>
<td>&gt; 3 and &lt; 4</td>
<td>&gt; 300 GeV</td>
</tr>
</tbody>
</table>

- Uncertainties
  - 50% uncertainty on the Drell-Yann normalization
  - 50% uncertainty on the Di-jet normalization
Limit/significance

5σ discovery for:
- 12TeV after 10 years @ baseline
- 19TeV after full operation 25 years

Challenges: better tau tagging at high $p_T$
Z’ -> tt
Z'->ttbar

- **Z' model**
  - Signal with Pythia8
  - Important benchmark model for detector performance on sub-structure

$$\Delta R \approx 2m/p_T$$

**Top-quark**

- **LHC:** $p_T \sim 1$ TeV $\rightarrow \Delta R = 0.5$
- **FCC:** $p_T \sim 10$ TeV $\rightarrow \Delta R = 0.05$
Multivariate discriminant

- Developed MVA discriminant to disentangle overwhelming QCD jets from boosted W/tops

<table>
<thead>
<tr>
<th>$W$ tagger</th>
<th>weight</th>
<th>top tagger</th>
<th>weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_3$ (track jet, R=0.2)</td>
<td>0.12</td>
<td>$r_1$ (track jet, R=0.2)</td>
<td>0.21</td>
</tr>
<tr>
<td>$m_{SD}$ (track jet, R=0.2)</td>
<td>0.11</td>
<td>$m_{SD}$ (track jet, R=0.2)</td>
<td>0.17</td>
</tr>
<tr>
<td>$r_{31}$ (track jet, R=0.2)</td>
<td>0.10</td>
<td>$r_{31}$ (track jet, R=0.2)</td>
<td>0.11</td>
</tr>
<tr>
<td>$E_F(n=5, \alpha=0.05)$</td>
<td>0.09</td>
<td>$r_2$ (track jet, R=0.2)</td>
<td>0.10</td>
</tr>
<tr>
<td>$E_F(n=4, \alpha=0.05)$</td>
<td>0.09</td>
<td>$r_3$ (track jet, R=0.2)</td>
<td>0.09</td>
</tr>
<tr>
<td>$E_F(n=1, \alpha=0.05)$</td>
<td>0.08</td>
<td>$m_{SD}$ (track jet, R=0.8)</td>
<td>0.09</td>
</tr>
<tr>
<td>$E_F(n=2, \alpha=0.05)$</td>
<td>0.07</td>
<td>$m_{SD}$ (track jet, R=0.4)</td>
<td>0.09</td>
</tr>
<tr>
<td>$E_F(n=3, \alpha=0.05)$</td>
<td>0.06</td>
<td>$r_{32}$ (track jet, R=0.2)</td>
<td>0.08</td>
</tr>
<tr>
<td>$r_{21}$ (track jet, R=0.2)</td>
<td>0.06</td>
<td>$r_{21}$ (track jet, R=0.2)</td>
<td>0.06</td>
</tr>
<tr>
<td>$m_{SD}$ (track jet, R=0.8)</td>
<td>0.06</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{SD}$ (track jet, R=0.4)</td>
<td>0.06</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$r_{1}$ (track jet, R=0.2)</td>
<td>0.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$r_{2}$ (track jet, R=0.2)</td>
<td>0.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$r_{32}$ (track jet, R=0.2)</td>
<td>0.02</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Boosted topology

Jet $p_T \sim 10$ TeV

Background efficiency vs. Signal efficiency

$t_{had}$ vs. QCD tagger

$W_{had}$ vs. QCD tagger
Z’->ttbar

- **Z’ model**
  - Signal with Pythia8
  - Important benchmark model for detector performance on sub-structure

- **Analysis pre-selection**
  - $p_T(j_{1/2}) > 3\text{TeV}$, $|\eta(j_{1/2})| < 3$
  - Jet1,2 Soft Dropped mass > 100GeV
  - Jet1,2 $\tau_{21}$, $\tau_{32}$ > 0
  - $|\eta_{\text{jet1}} - \eta_{\text{jet2}}| < 2.4$
  - 2 b-tag jets, 2 top jets from MVA discriminant
  - Do not explicitly select leptons, but "correct" di-top mass for MET

- **Uncertainties**
  - 20% uncertainty on the ttbar normalization
  - 50% on di-jet 40% on Vj and 20% on VV
Z'->ttbar

5σ discovery for TC2:
- 17TeV after 10 years @ baseline
- 23TeV after full operation (25y)

5σ discovery for SSM:
- 11TeV after 10 years @ baseline
- 16TeV after full operation (25y)

Challenges: better top tagging from sub-structure, and improve $m_t$ mass resolution

SSM is obviously a benchmark for leptonic decays
High efficiencies ($\varepsilon_b > 60\%$) for corresponding low mis-identification probability ($\varepsilon_{u,d,s} < 1\%$) from light jets have to be achieved up to $p_T = 5\ $TeV.

For example, searches for heavy resonances decaying to hadronic $t\bar{t}$ pairs heavily rely on efficient $b$-tagging performance at such energies.

The discovery reach for a specific $Z'$ model assuming several scenarios for $b$-jet identification at very large $p_T$ are considered

- Nominal efficiency $(1-p_T/15)*85\%$
- scenarios 1, 2, 3 correspond to reduction of the slope by a factor 25%, 33% and 50%.

As expected the discovery reach strongly depends on the $b$-tagging performances.
RSG->WW
W->jj
**Di-boson resonance (only hadronic)**

- **Randall-Sundrum Graviton**
  - Signal with pythia8
  - Important benchmark model for detector performance on sub-structure

- **W/Z bosons**
  - LHC: $p_T \sim 1\text{TeV} \rightarrow \Delta R = 0.25$
  - FCC: $p_T \sim 10\text{ TeV} \rightarrow \Delta R = 0.025$

\[
\frac{n-1}{5} R \leq \Delta R(k, \text{jet}) < \frac{n}{5} R, \quad \text{Flow}_{n,5} = \sum_k \frac{|p_T^k|}{|p_T^{\text{jet}}|}
\]
Di-boson resonance (only hadronic)

- **Randall-Sundrum Graviton**
  - Signal with pythia8
  - Important benchmark model for detector performance on sub-structure

- **Analysis pre-selection (Fully hadronic)**
  - Jet1/2 $p_T>3$TeV, jet1/2 $|\eta|<3$
  - $J1,2 \tau_{21}, \tau_{32}>0$
  - $|\eta_{jet1} - \eta_{jet2}|<2.4$
  - 2 W jets from MVA discriminant

- **Norm uncertainties**
  - ttbar 20% QCD 50%, VV 20%, VJ 40%
RSG->WW

Challenges: better W tagging from substructure, and improve $m_{WW}$ mass resolution

5σ discovery for RSG:
- 10TeV after 1 year (~100fb$^{-1}$)
- 15TeV after 10 years @ baseline
- 22TeV after full operation 25 years
Q*->jj
**Q*/Z’-\to jj**

- **Q* model**
  - Strongly coupled
  - Wide, large cross section

- **Z’ model**
  - Same benchmark as Z’ -\to leptons
  - Narrow, small cross section

- **Analysis selection**
  - $p_T(j1)$ and $p_T(j2)>3$TeV
  - $Y^* = |y_{jet1} - y_{jet2}|/2 < 1.5$

- **Uncertainties**
  - 50% uncertainty on the Di-jet normalization
5σ discovery for Q* (wide and strongly coupled):
• 15TeV after 1 day (1fb⁻¹)
• 36TeV after 10 years @ baseline
• 40TeV after full operation 25 years

5σ discovery for Z’ (narrow and weakly coupled):
• <15TeV after 10 years @ baseline
• 19TeV after full operation 25 years

Smearing the mass (increasing the calorimeter constant term) has a large impact on the discovery potential
Summary

- **Di-lepton**(ee/\(\mu\mu\))
  - Background free analysis
  - Discovery reach \(\sim42\) TeV with full dataset for SSM model

- **Z’\(\rightarrow\)\(\tau\tau\)** (hadronic taus)
  - More complex final state
  - Discovery reach \(\sim19\) TeV with full dataset
  - Need better high \(p_T\) tau tagging techniques

- **Ttbar**
  - Discovery reach up to 23 TeV
  - Better top tagging from sub-structure, and improve \(m_{tt}\) mass resolution

- **Di-boson**
  - Discovery reach up to 22 TeV
  - Better W tagging from sub-structure, and improve \(m_{WW}\) mass resolution

- **Di-jet**
  - Reach up to 40 TeV
  - Calorimeter containment for best resolution
Bonus
Next steps

• **Di-lepton**(ee/μμ)
  • Interpretation with Lepto-Quarks
  • add other Z’ signal XS to limit
  • Di-elec results basically RSG-→γγ

• **Z’-→ττ (hadronic taus)**
  • Not fully optimised for m<10TeV
  • Further checks to be done in full sim

• **Ttbar**
  • Sub-structure performance to be checked with full sim
  • Include other benchmarks

• **Di-boson**
  • Sub-structure performance to be checked with full sim
  • Could add leptonic channels
  • Add other benchmarks and ZZ/WZ

• **Di-jet**
  • Possibly add other benchmarks
  Contact interaction, etc…
Technicalities

**Signals:**
- Mainly produced with Pythia8
- MG5 in some cases (interpretations)
- No k-factor assumed

**Backgrounds:**
- with MG5 LO
- k-factor of 2 assumed

**Software**
- Using FCC software with detector parameterization
- When setting limits, use full shape and profile likelihood ratio

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cut (TeV)</th>
<th>Statistic ($10^6$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Di-electron</td>
<td>$p_T(e)&gt;5$</td>
<td>10</td>
</tr>
<tr>
<td>Di-muon</td>
<td>$p_T(\mu)&gt;5$</td>
<td>10</td>
</tr>
<tr>
<td>Di-tau</td>
<td>$p_T(\tau)&gt;2.5$</td>
<td>10</td>
</tr>
<tr>
<td>Di-tau</td>
<td>$2.5&gt;p_T(\tau)&gt;1$</td>
<td>5</td>
</tr>
<tr>
<td>Di-jet</td>
<td>$p_T(j)&gt;2.5$</td>
<td>50</td>
</tr>
<tr>
<td>Di-jet</td>
<td>$2.5&gt;p_T(j)&gt;1$</td>
<td>30</td>
</tr>
<tr>
<td>Di-boson</td>
<td>$p_T(V)&gt;2.5$</td>
<td>15</td>
</tr>
<tr>
<td>V+jets</td>
<td>$m_{Vj}&gt;5$</td>
<td>10</td>
</tr>
<tr>
<td>Top pair</td>
<td>$p_T(t)&gt;2.5$</td>
<td>10</td>
</tr>
</tbody>
</table>
FCC-hh Analysis Framework

- **GridPack producer**
  - Makes MG5_aMC@NLO GridPacks

- **LHE Producer**
  - Produce LHE files on LSF/condor queues from GP or standalone MG5
  - About a 2 billion events produced

- **FCCSW**
  - Runs Pythia8 parton shower+hadronisation and Delphes with FCC detector

- **Analysis preselection and high level variable definitions**
  - Python framework produces flat ROOT trees

- **Analysis Final selection and plots**
  - Python framework for optimising analysis cut flows and producing

- **Limit setting**
  - Atlas inspired tool for limits and significance

- More info in my talk at the FCC software session Thursday afternoon
B-tagging

- **High $p_T$ b-tagging**
  - Very displaced vertices
  - After the 1$^{\text{st}}$, 2$^{\text{nd}}$, or even 3$^{\text{rd}}$ layer of the pixel detector
  - Used for this top pair resonance search

- **Estimate**
  - Need a first realistic estimate of how b-tagging will perform
  - Using results from full simulation study without tracks (hit multiplicity jump)
  - See Estel Perez talk at detector session
\(Z' \rightarrow \tau \tau\)

\(p_T(j_{1/2}) > 1 \text{ TeV}, \, |\eta(j_{1/2})| < 2.5\)

<table>
<thead>
<tr>
<th>process</th>
<th>yield (30.0 ab(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m_{{Z}} = 15) TeV Drell-Yann</td>
<td>888.9</td>
</tr>
<tr>
<td>QCD</td>
<td>10237.8</td>
</tr>
<tr>
<td></td>
<td>7116045.3</td>
</tr>
</tbody>
</table>

06/07/18

Heavy Resonances at 100 TeV

27/06/19
- Track jets seems to be more robust and better understood at high $p_T$
- Use those at high $p_T$ corrected by p-flow jet $p_T$ when using substructure
$Z' = \tau_1 + \tau_2$ (4 vectors)

$m_T = \sqrt{2p_T(Z')*MET*(1 - \cos(\Delta\phi(\Phi_{Z'} - \Phi_{MET}))})$

<table>
<thead>
<tr>
<th>Process</th>
<th>Yield (30.0 ab⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_Z = 5$ TeV</td>
<td>25345.8</td>
</tr>
<tr>
<td>Drell-Yann</td>
<td>2715.5</td>
</tr>
<tr>
<td>QCD</td>
<td>361221.2</td>
</tr>
</tbody>
</table>

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<th>Yield (30.0 ab⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_Z = 15$ TeV</td>
<td>686.2</td>
</tr>
<tr>
<td>Drell-Yann</td>
<td>3769.5</td>
</tr>
<tr>
<td>QCD</td>
<td>695272.8</td>
</tr>
</tbody>
</table>

FCC-hh Simulation (Delphes)

Events / 0.2 TeV

m_T [TeV]
Tracking in dense env.

- Tracker granularity
  - Defined in $(\eta \times \phi)$
  - Worst case scenario
    - pitch size in the first pixel layer:
      \[
      \text{reso} = (2-3) \times 10\mu m/(0.025) \sim 0.001
      \]
- Inefficiency
  - when two or more tracks hit same pixel
  - keep only highest $p_T$ track
  - Arbitrary and probably conservative, considering that this is only first pixel layer
- Conservative value
  - 0.001 used for FCC studies
$Q^* \rightarrow jj$

5σ discovery for $Q^*$:
- 15 TeV after 1 day (1 fb$^{-1}$)
- 36 TeV after 10 years @ baseline
- 40 TeV after full operation 25 years
Boosted objects

• **What is:**
  • Optimal jet collection
  • Minimal track angular resolution?

• **Assessed using:**
  • QCD, QCD+weak shower, W and Top jets
  • GenJets, CaloJets, Particle Flow Jets, Track Jets with 2-5-10-20 TeV

• **Outcome:**
  • Use track jets for sub-structure corrected to pf jets
  • More information in this talk [here](#)

• Performance of reconstructing such boosted objects is being further investigated in full simulation for the report
• Track jets seems to be more robust and better understood at high $p_T$
• Use those at high $p_T$ corrected by p-flow jet $p_T$ when using substructure

10TeV objects
W versus QCD jet tagger

Variables used:
Flow 1, 2, 3, 4, 5/5
Soft dropped mass
τ32, τ21, τ1/2/3

TMVA overtraining check for classifier: BDT_Whad_vs_QCD

Kolmogorov-Smirnov test: signal (background) probability = 0.358 (0.001)

Background rejection versus Signal efficiency

Variables used:
Flow 1, 2, 3, 4, 5/5
Sos dropped mass
τ32, τ21, τ1/2/3
W versus QCD jet tagger

Variables used:
- Flow 1,2,3,4,5/5
- Soft dropped mass
- $\tau_{32}, \tau_{21}, \tau_{1/2/3}$

TMVA overtraining check for classifier: BDT_Whad_vs_QCD

Kolmogorov-Smirnov test: signal (background) probability = 0.358 (0.001)

Top vs QCD
W versus QCD