Heavy resonances at energy frontier colliders

Clement Helsens, CERN-EP
EPS 2019, Genf
Based on arXiv:1902.11217 (accepted by EPJC)
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
Expectation from hadron future collider

Guaranteed deliverables
- Study Higgs and top-quark properties and exploration of EWSB phenomena with unmatchable precision and sensitivity

Exploration potential (New machines are build to make discoveries!)
- Mass reach enhanced by factor $\sqrt{s}/14\text{TeV}$ (5-7 at 100TeV)
  - Statistics enhanced by several orders of magnitude for possible BSM seen at HL-LHC
- Benefit from both direct (large $Q^2$) and indirect precision probes

Could provide firm answers to questions like
- Is the SM dynamics all there at the TeV scale?
- Is there a TeV-Scale solution the hierarchy problem?
- Is DM a thermal WIMPS?
- Was the cosmological EW phase transition 1$^{\text{st}}$ order? Cross-over?
- Could baryogenesis have taken place during EW phase transition?
Circular hadron projects @CERN

**FCC-hh**
- Need a new 100km tunnel
- Need 16 Telsa magnet to reach 100TeV in 100km
- Baseline Luminosity (10y)
  - $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ (HL-LHC) $<\mu>200$
- Ultimate luminosity (15y)
  - $30 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ $<\mu>1000$
- 2.4MW sync rad/ring x300 HL-LHC
- Considering $30 \text{ ab}^{-1}$ for the study
Environment and detector requirements

@100TeV FCC-hh

- The radiation level increase mostly driven by the jump in instantaneous luminosity
  - pp cross-section from 14 to 100TeV only grows by a factor 2
  - 10 times more fluence compared with HL-LHC (x100 wrt to LHC)
  - Need radiation hard detectors

- More forward physics -> larger acceptance
  - Precision momentum spectroscopy and energy measurements up to \(|\eta|<4\)
  - Tracking and calorimetry up to \(|\eta|<6\) (at 10cm of beam line at 18m of IP)

- More energetic particles
  - colored hadronic resonances up to 40TeV -> Full containment of jets up to 20TeV
  - Resonances decaying to boosted objects (top, bosons) -> need very high granularity to resolve such sub-structure
FCC-hh detector
FCC-hh detector

Comparison to ATLAS & CMS
Direct discovery reach at 100TeV

- **To first approximation**
  - The discovery reach at the highest masses is driven by the energy increase wrt to LHC
  - For $\sqrt{s}=100$TeV we expect the reach to be extended by factors 5-7 wrt LHC for the same BSM parameters
Outline

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

• Hadronic resonances
  • $T\bar{t}$, $WW$, $jj$

• Summary
\[Z^- \rightarrow \gamma \pi^+ \pi^-\]
Z'→μ⁺μ⁻/e⁺e⁻

- **Z' model**
  - 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
$Z' \rightarrow \mu^+\mu^-/e^+e^- (30\text{TeV})$

As expected better mass resolution for electrons
Limits and discovery

Reach up to 40TeV this very simple case!

Considering 2.2fb⁻¹ per day for baseline

5σ 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.
\(Z' \rightarrow \tau \tau\)

- Analysis selection (hadronic taus only as most sensitive)
  - \(p_T(j1/2) > 1\, \text{TeV}, \ |\eta(j1/2)| < 2.5\)
  - At least 2 tau tags

<table>
<thead>
<tr>
<th>(Z') mass [TeV]</th>
<th>(\Delta \phi(\tau_1, \tau_2))</th>
<th>(\Delta R(\tau_1, \tau_2))</th>
<th>(E_T^{\text{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 $p_T$
$Z' \rightarrow tt$
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: \( p_T \sim 1\text{TeV} \rightarrow \Delta R = 0.5 \)

FCC: \( p_T \sim 10\text{ TeV} \rightarrow \Delta R = 0.05 \)
Multivariate discriminant

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

<table>
<thead>
<tr>
<th>variable</th>
<th>weight</th>
<th>variable</th>
<th>weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_3$ (track jet, R=0.2)</td>
<td>0.12</td>
<td>$\tau_1$ (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>$\tau_{31}$ (track jet, R=0.2)</td>
<td>0.10</td>
<td>$\tau_{31}$ (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>$\tau_2$ (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>$\tau_3$ (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>$\tau_{32}$ (track jet, R=0.2)</td>
<td>0.08</td>
</tr>
<tr>
<td>$\tau_{21}$ (track jet, R=0.2)</td>
<td>0.06</td>
<td>$\tau_{21}$ (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>$\tau_1$ (track jet, R=0.2)</td>
<td>0.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau_2$ (track jet, R=0.2)</td>
<td>0.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau_{32}$ (track jet, R=0.2)</td>
<td>0.02</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Z'->ttbar

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

- **Analysis selection**
  - $p_T(j_{1/2}) > 3\,\text{TeV}, \, |\eta(j_{1/2})| < 3$
  - Jet1,2 Soft Dropped mass $> 100\,\text{GeV}$
  - 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 substructure, and improve $m_{tt}$ 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 $tt$ 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: $p_T \sim 10\text{ TeV} \rightarrow \Delta R = 0.025$

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

\[
30 \text{ TeV } G_{RS} \rightarrow gg
\]
\[
30 \text{ TeV } G_{RS} \rightarrow q\bar{q}
\]
\[
30 \text{ TeV } G_{RS} \rightarrow VV
\]
**Di-boson resonance (only hadronic)**

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

- **Analysis Selection (Fully hadronic)**
  - Jet1/2 $p_T > 3\text{TeV}$, jet1/2 $|\eta| < 3$
  - $J1,2 \tau_{21}, \tau_{32} > 0$
  - $|\eta_{\text{jet}1} - \eta_{\text{jet}2}| < 2.4$
  - 2 $W$ jets from MVA discriminant

- **Norm uncertainties**
  - $t\bar{t}$ 20%  QCD 50%, $VV$ 20%, $VJ$ 40%
RSG $\rightarrow$ WW

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

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

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

- **Z’ model**
  - Same benchmark as Z’ -> 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
Discrimination of $Z'$ models within LHC reach
Bonus
Summary

- **Di-lepton (ee/μμ)**
  - Background free analysis
  - Discovery reach ~42TeV with full dataset for SSM model

- **Z’->ττ (hadronic taus)**
  - More complex final state
  - Discovery reach ~19TeV with full dataset
  - Need better high $p_T$ tau tagging techniques

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

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

- **Di-jet**
  - Reach up to 40TeV
  - Calorimeter containment for best resolution
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 Grid Packs

- **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
$Z' \rightarrow \tau \tau$

$p_T(j1/2) > 1\text{TeV}, \ |\eta(j1/2)| < 2.5$

<table>
<thead>
<tr>
<th>process</th>
<th>yield (30.0 ab$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{{Z}} = 15$ TeV</td>
<td></td>
</tr>
<tr>
<td>Drell-Yann</td>
<td>888.9</td>
</tr>
<tr>
<td>QCD</td>
<td>10237.8</td>
</tr>
<tr>
<td>$L = 30$ ab$^{-1}$</td>
<td></td>
</tr>
</tbody>
</table>

- FCC-hh Simulation (Delphes)

<table>
<thead>
<tr>
<th>process</th>
<th>yield (30.0 ab$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{{Z}} = 15$ TeV</td>
<td></td>
</tr>
<tr>
<td>Drell-Yann</td>
<td>781.0</td>
</tr>
<tr>
<td>QCD</td>
<td>10083.6</td>
</tr>
</tbody>
</table>

$\phi(Z',\text{met})$

$\Delta R(\tau,\tau_j)$

MET [GeV]

$0 \quad 100 \quad 200 \quad 300 \quad 400 \quad 500 \quad 600 \quad 700 \quad 800 \quad 900 \quad 1000$

$0 \quad 10 \quad 100 \quad 1000 \quad 10000 \quad 100000 \quad 1000000 \quad 10000000 \quad 100000000 \quad 1000000000 \quad 10000000000$
- 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)

$m_T = \sqrt{2 \vec{p}_T(Z') \cdot \text{MET} \cdot (1 - \cos(\Delta \phi(Z' - \phi_{\text{MET}})))}$

<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>
<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)

- $\sqrt{s} = 100$ TeV
- $L = 30$ ab$^{-1}$

- $m_\{Z\} = 5$ TeV
- Drell-Yann
- QCD

- $m_\{Z\} = 15$ TeV
- Drell-Yann
- QCD
Tracking in dense env.

- Tracker granularity
  - Defined in $(\eta \times \phi)$
  - Worst case scenario
    - pitch size in the first pixel layer:
      \[
      \text{reso} = (2-3) \times 10\text{um}/(0.025) \sim 0.001
      \]
- 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*->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
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)

Background rejection versus Signal efficiency

Variables used
Flow 1,2,3,4,5/5
Soft dropped mass
$\tau 32, \tau 21, \tau 1/2/3$
W versus QCD jet tagger

Variables used
Flow 1,2,3,4,5/5
Soft dropped mass
t32, t21, t1/2/3

TMVA overtraining check for classifier: BDT_Whad_vs_QCD

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