A few basic facts theorists might want to know about an LHC experiment

Using the Search for lepton jets from Hidden Valley models as an example

Pauline Gagnon
CERN / Indiana University
Purpose of this talk:

- Use this opportunity to give you a chance to ask all those little questions you might not feel comfortable asking in a conference when 95% of the attendees are experimentalists (and not >95% theorists as here!)
- Give you an idea on how ATLAS has looked for lepton jets from Hidden Valley models so far
- Get ideas from you on specific aspects you would like us to test
- In case you don’t know, ATLAS offers short term associations for theorists to work on specific issues
Before I get started.....

Let me clarify a few points that might not always be clear
Why does it take so much time to analyze all the available data?

- Many analyses based on 2010 data only became available for the winter or even summer conferences.
- Many are only preliminary results:
  - Publications require a stringent and long review process in large collaborations.
  - With more than 3000 physicists on ATLAS or CMS, not easy to get everybody happy.
- Before completing any analysis, each sub-group working on data preparation has to provide their part:
  - Data quality group decides which data can be used.
  - Performance groups give calibration, energy scale corrections, etc.
  - Needed from each group: e/gamma, jet and Et miss, muon, b-tagging, trigger etc.
- Even with 3000 people, we are lacking people everywhere!
Data quality

- Data taking period is divided in small time interval of 1-3 minutes where the detector and LHC conditions are stable.
- These are called "luminosity blocks" in ATLAS.
- For each lumi block, the detector sub-groups check if their detector was fully or partially operational.
- This information is given to the performance groups. They determine which lumi block can be used to search for each separate physics object (electrons, muons, jets, missing $E_T$).
- Data quality group then issues "good run lists" which are used for each analysis.
- This explains why we sometimes publish results on 35 pb$^{-1}$, 37 pb$^{-1}$ or 40 pb$^{-1}$ depending on which physics objects are needed for each analysis.
Other reasons for delays

- The more data we have, the less forgiving it gets
- More data means the error bars go down
- We need more precise and more specialized cross-checks
- We are looking at hundreds of distributions! But even missing ET looks good

Very general (minimum bias)  Very specific (Z->ee events)
How much better will we do with the 2011 data?

- In 2010, CMS and ATLAS both had ~ 40 pb\(^{-1}\) of usable data
  - Most papers so far and preliminary results for Moriond
  - ATLAS just started showing some 2011 data at PLHC

- In 2011, we expect 2-3 fb\(^{-1}\) in total (1fb\(^{-1}\) already in)

- Assuming 2 fb\(^{-1}\) by the end of 2011 (conservative)
  - That’d be 50 times more data than in 2010
  - Signal will increase by 50 but so will the background
  - Uncertainty on the background would decrease by a factor of \sqrt{50}
  - The significance, \(S/\sqrt{B}\), will increase by a factor of \(\sim 7\)

- With 3 fb\(^{-1}\) by the end of 2011 (slightly optimistic)
  - That’d be 75 times more data than in 2010, improve limits by \(\sim 8.5\)

- Combining ATLAS and CMS is like having twice as much data
With 2-3 fb\(^{-1}\) per experiment, and combining CMS and ATLAS, we could exclude a SM Higgs in most of this whole range by end of 2011.
The trivial Higgs boson: first evidences from LHC arXiv:1106.4178

Their previous paper was rejected by the referee for not being solid enough to corroborate the great claims about the SM Higgs mass.

“We decided to leave to LHC the reply to the anonymous referee. Indeed, we feel that the time is coming to undertake a profound revision of the peer review process.

“It is remarkable that the experimental data do show an excess of three events in this region.”
Easy mistakes to be avoided(2)

How often should we see a 4.8σ fluctuation in our career?

- **Exclusion**: no signal observed at a 2σ-level (95% CL)
- **Observation**: signal observed at a 3σ-level (99% CL)
- **Discovery**: signal observed at a 5σ-level (99.9995% CL)
What could go wrong?

<table>
<thead>
<tr>
<th>system</th>
<th># of channels</th>
<th>Operation efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>pixels</td>
<td>80 M</td>
<td>96.9%</td>
</tr>
<tr>
<td>Silicon tracker</td>
<td>6.3 M</td>
<td>99.1%</td>
</tr>
<tr>
<td>Transition radiation tracker</td>
<td>350 k</td>
<td>97.5%</td>
</tr>
<tr>
<td>EM calorimeter barrel</td>
<td>170 k</td>
<td>99.5%</td>
</tr>
<tr>
<td>EM calorimeter end-cap</td>
<td>3.5 k</td>
<td>99.8%</td>
</tr>
<tr>
<td>Hadronic calorimeter</td>
<td>9.8 k</td>
<td>97.9%</td>
</tr>
<tr>
<td>Hadronic end-cap</td>
<td>5.6 k</td>
<td>99.6%</td>
</tr>
<tr>
<td>Muon system</td>
<td>1071 k</td>
<td>97.0-99.8%</td>
</tr>
</tbody>
</table>
Monte Carlo simulations

- Every time the LHC changes its running conditions, we need to generate a whole new set of MC events (it takes 1-2 months)
  - For each background and each signal
- Already, we had to go for a new production when:
  - LHC changed the center-of-mass energy
    - Higgs cross-sections go down by a factor of 4 between $E_{\text{CM}} = 14$ TeV and 10 TeV
  - Bunch spacing: going from 75 ns to 50 ns
    - meant more luminosity but also
    - more pile-up (# of low energy events occurring at the same time)
- We are constantly improving our reconstruction algorithms
  - 2-3 times a year, we do a new reconstruction software release when major bugs are found and fixed, or new features have been added
  - The entire data set and MC samples are reprocessed after a new release
  - We try to keep the same release for several months to avoid driving people insane
Estimating background and efficiency using data

- Much more reliable than using Monte Carlo simulations

**Tag & probe method:**
- Using for example $Z \rightarrow e^+e^-$ or $Z \rightarrow \mu^+\mu^-$
- Select a very clean sample of di-leptons under the Z peak
- Impose selection criteria to only one lepton (**tag**)
- Get the efficiency from the second lepton (**probe**):  
  - completely unbiased

- We often use events from J/ψ, Y or Z for various calibrations and cross-checks
Other tricks we like to play

ABCD-method

Have 4 regions in two variables so that:
• background is independent for the variables:
  \[
  \frac{n_A}{n_B} = \frac{n_C}{n_D}
  \]
• signal sitting in one region

Then it is possible to estimate number of background events in D via:

\[
\hat{n}_D^{est} = \frac{n_B \cdot n_C}{n_A}
\]

This can be done completely without Monte-Carlo information
• data driven background estimation

x-axis: missing transverse energy
y-axis: reconstructed transverse W-mass
A B C D: regions
n_A n_B n_C n_D: event counts
Trigger issues

- We are limited by how much data we can take in:

<table>
<thead>
<tr>
<th>Level 1</th>
<th>~75 KHz</th>
<th>Level 2</th>
<th>5 KHz</th>
<th>Level 3</th>
<th>400 Hz</th>
</tr>
</thead>
</table>

- As the luminosity goes up, we must tighten our selection criteria – increase the threshold or quality criteria
- Then we are forced to prescale our triggers:
  - Prescale factor of 100 means retain only 1 out of 100 such events

**Lowest unprescaled triggers**

<table>
<thead>
<tr>
<th>Minimum $p_T$</th>
<th>2010</th>
<th>now</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single electrons</td>
<td>15 GeV</td>
<td>20 GeV</td>
</tr>
<tr>
<td>Di-electrons</td>
<td>5 GeV each</td>
<td>12 GeV each</td>
</tr>
<tr>
<td>muons</td>
<td>13 GeV</td>
<td>18 GeV</td>
</tr>
<tr>
<td>Di-muons</td>
<td>6 GeV each</td>
<td>10 GeV each</td>
</tr>
<tr>
<td>photons</td>
<td>40 GeV</td>
<td>60 GeV</td>
</tr>
<tr>
<td>Di-photon</td>
<td>15 GeV each</td>
<td>20 GeV each</td>
</tr>
</tbody>
</table>
Trigger efficiency: should be stable measured using $Z \rightarrow ee$ (tag&probe)
Muon trigger rate as a function of luminosity

ATLAS Preliminary
\(\sqrt{s} = 7\) TeV, Data 2010

L1 Muon Trigger Rate [Hz]

Luminosity \([10^{29}\text{ cm}^{-2}\text{s}^{-1}]\)
Weekly data taking

- Max lumi in one day: 56.33/pb on Sunday 12th
- Colliding bunches: 1042; 144b per train
- $L \sim 1.1 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$
- Ready Rec: 218/pb in last week, total $> 0.9$/fb
Various LHC modes

**Main steps:**
- Setup
- Injection probe beam
- Injection
- Ramping
- Adjust
- Stable beams
- Preparing to dump
- Beam dump

**Additional steps occurring at any time:**
- Beam loss
- Cryo problems
- Recovering
- Access
- Power glitch
- Injection studies
- Beam studies
How to read LHC page 1

BEAM SETUP: INJECTION PROBE BEAM

| TED TI2 position: | BEAM | TDI P2 gaps/mm | up: 10.69 | down: 8.68 |
| TED TI8 position: | BEAM | TDI P8 gaps/mm | up: 9.53  | down: 8.90 |

FBCT Intensity and Beam Energy

Comments 23-06-2011 19:07:20:
INJECTION STUDIES
- injection studies

BIS status and SMP flags

<table>
<thead>
<tr>
<th>Link Status of Beam Permits</th>
<th>B1</th>
<th>B2</th>
</tr>
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<tr>
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<td>true</td>
</tr>
<tr>
<td>Setup Beam</td>
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<td>true</td>
</tr>
</tbody>
</table>

Pauline Gagnon, CERN / Indiana University
**Injection**

**BEAM SETUP: INJECTION PHYSICS BEAM**

<table>
<thead>
<tr>
<th>BCT T12: 0.00e+00</th>
<th>I(B1): 6.12e+10</th>
<th>BCT T18: 0.00e+00</th>
<th>I(B2): 1.85e+11</th>
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</thead>
<tbody>
<tr>
<td>TED T12 position: BEAM</td>
<td>TDI P2 gaps/mm</td>
<td>up: 40.12</td>
<td>down: 40.12</td>
</tr>
<tr>
<td>TED T18 position: BEAM</td>
<td>TDI P8 gaps/mm</td>
<td>up: 40.08</td>
<td>down: 40.11</td>
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</table>

**FRCT Intensity and Beam Energy**

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>0</th>
<th>500</th>
<th>1000</th>
<th>1500</th>
<th>2000</th>
<th>2500</th>
<th>3000</th>
<th>3500</th>
<th>4000</th>
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<tbody>
<tr>
<td>Intensity</td>
<td>1.4E13</td>
<td>1.2E13</td>
<td>8E12</td>
<td>6E12</td>
<td>4E12</td>
<td>2E12</td>
<td>0</td>
<td>0</td>
<td>0</td>
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**Comments 24–06–2011 01:16:07:**

The plan for the night is:

1) injection verification (DONE)

**BIS status and SMP flags**

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<tr>
<td>true</td>
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**Link Status of Beam Permits**

Global Beam Permit
Setup Beam

Pauline Gagnon, CERN / Indiana University
Ramping from 450 GeV to 3.5 TeV

Energy: 3500 GeV

I(B1): 1.84e+11
I(B2): 1.70e+11

The plan for the night is:
1) injection verification (DONE)
2) loss maps at 3.5TeV (soon)
3) PHYSICS fill with 1236 bunches

Comments 24-06-2011 02:41:55:

BIS status and SMP flags

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<td>false</td>
<td>false</td>
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<tr>
<td>false</td>
<td>false</td>
</tr>
</tbody>
</table>

AFS: Single_2b_1_1_1_wp
PM Status B1: ENABLED
PM Status B2: ENABLED
Human aspect

- There are >3000 physicists on ATLAS or CMS alone
  - 138 institutes
  - 37 participating countries
  - 70 nationalities
  - About 18% women

- Alice and LHCb have about 1000 physicists each

- It takes \(~20\) people at all times to staff the ATLAS control room

- Even more people are on call as system experts at all times
ATLAS control room on March 8, 2010
International Women’s Day
In 2010 alone, LHC experiments produced:
- 53 publications
- 1700 conference talks
- 179 student theses

Initial focus on performance and calibration
Confirmed the Standard Model solidity above 2 TeV
Already put limits or excluded several models for new physics (excited quarks, axigluons, leptoquarks…)
Limits on long-lived gluinos by CMS using quiescent time between fills
Already in October, we measured $t\bar{t}b\bar{t}$ cross-section
- This brings into play all the analysis tools: lepton id, b-tagging, MET
Observation of the quark-gluon plasma
Biggest surprise so far: asymmetric jets due to quark-gluon plasma
Switching gears

Searching for lepton jets from Hidden Valley models

(I also work on invisible Higgs if someone is interested)
Several models predict lepton jets in the framework of Hidden Valley models when a light gauge boson decays into leptons.

- ATLAS studied a particular class of such models using events generated by Itay Yavin (JHEP 1004 (2009) 116.)
- Weakly-interacting dark-sector with its own gauge bosons
- The LSP, here a neutralino ($N_1$) decays to a dark photon ($\gamma_d$) and a dark fermion ($f_d$)
- SPS1a SUSY parameters (Snowmass Points and Slopes from Snowmass 2001)

**SPS1a** | **mSUGRA**
--- | ---
$m_0$ | 100
$m_{\frac{1}{2}}$ | 250
$A_0$ | -100
$\tan \beta$ | 10
Model specificities

- Motivated in part by Pamela:
  - dark photons are assumed to be ~ 1 GeV
- Can decay only to $e^+e^-, \mu^+\mu^-$ or pion pairs depending on $m_{\gamma_D}$
- Dark photon is light and comes from cascade decay of heavy squarks: leptons are boosted and collimated, hence the lepton jet name
- The radiation parameter, $\alpha_d$, determines how many dark photons are produced

→ Look for events with many collimated lepton pairs
Current ATLAS analysis status

- Preliminary results obtained for the ~40 pb\(^{-1}\) 2010 data using only the muon channel

- Updates with ~1 fb\(^{-1}\) of 2011 data in progress
  - Lepton jets studies using electrons should be shown later this summer using 1 fb\(^{-1}\) hopefully by lepton-photon

- Electrons are more difficult to reconstruct in ATLAS:
  - Calorimeter closer to interaction point than muon spectrometer
  - Electromagnetic clusters tend to overlap, especially when coming from high \(p_T\) electrons \(\Rightarrow\) broader EM clusters
  - Standard electron identification techniques fail
MC event with 2 muon Lepton Jets

- EM calorimeter
- Tracker
- Hadronic calorimeter
- Muon system
Lepton jets Kinematics

- The heavier the dark photon, the higher the lepton $p_T$

- The more radiated lepton jets ($\alpha_d$), the softest the leptons

- # of muons and their separation depends on $m_\gamma$ and $\alpha_d$

- Some events have electrons or pion jets, so less muons
Event selection criteria

- Events must pass the di-muon trigger with $p_T > 6$ GeV
- Request at least 4 muons with $p_T > 7$ GeV
- 3 muons passing higher track quality criteria to reduce background from fakes
- Lepton jet is built from 2 muons found within $\Delta r < 0.1$ rad
- Lepton jet scaled isolation $E_T^{\text{cone}}/p_T < 0.7$
- Event must have at least 2 such lepton jets

Emanuel Strauss, SLAC
QCD background normalization

- QCD production cross-section not precisely known
- Compare data and MC in 3 separate regions to extract scaling factors for J/ψ, Y, and QCD from simultaneous fit

![Graph showing QCD, Y, J/ψ, and MC comparison](image-url)
Cutflow: main challenge is the QCD background

<table>
<thead>
<tr>
<th></th>
<th>≥ 2 muon</th>
<th>≥ 4 muons</th>
<th>≥ 4 muons w/ ≥ 3 HQ</th>
<th>2 LJets</th>
<th>2 Isolated LJets</th>
</tr>
</thead>
<tbody>
<tr>
<td>data</td>
<td>174450</td>
<td>246</td>
<td>84</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>all bkg</td>
<td>200000 ± 15000</td>
<td>200 ± 50</td>
<td>81 ± 20</td>
<td>1.74 ± 0.48</td>
<td>0.20 ± 0.19</td>
</tr>
<tr>
<td>QCD</td>
<td>160000 ± 14000</td>
<td>188 ± 50</td>
<td>73 ± 20</td>
<td>1.46 ± 0.42</td>
<td>0.19 ± 0.19</td>
</tr>
<tr>
<td>T</td>
<td>2100 ± 120</td>
<td>0.00 ± 0.00</td>
<td>0.00 ± 0.00</td>
<td>0.00 ± 0.00</td>
<td>0.00 ± 0.00</td>
</tr>
<tr>
<td>Ψ</td>
<td>22100 ± 3700</td>
<td>3.4 ± 1.9</td>
<td>0.95 ± 0.43</td>
<td>0.24 ± 0.23</td>
<td>0.00 ± 0.00</td>
</tr>
<tr>
<td>W+Jet</td>
<td>332 ± 11</td>
<td>0.40 ± 0.40</td>
<td>0.00 ± 0.00</td>
<td>0.00 ± 0.00</td>
<td>0.00 ± 0.00</td>
</tr>
<tr>
<td>Z+Jet</td>
<td>14420 ± 42</td>
<td>2.00 ± 0.50</td>
<td>1.37 ± 0.41</td>
<td>0.00 ± 0.00</td>
<td>0.00 ± 0.00</td>
</tr>
<tr>
<td>t̅t̅</td>
<td>357 ± 1.4</td>
<td>4.31 ± 0.16</td>
<td>3.47 ± 0.14</td>
<td>0.041 ± 0.016</td>
<td>0.012 ± 0.008</td>
</tr>
<tr>
<td>Diboson</td>
<td>16.577 ± 0.070</td>
<td>1.640 ± 0.013</td>
<td>1.557 ± 0.013</td>
<td>0.00033 ± 0.00019</td>
<td>0.00033 ± 0.00019</td>
</tr>
</tbody>
</table>

Squark Signal Samples

<table>
<thead>
<tr>
<th>α̅_t</th>
<th>m_α</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>300</td>
<td>8.26 ± 0.27</td>
<td>3.52 ± 0.18</td>
<td>2.38 ± 0.15</td>
<td>1.76 ± 0.12</td>
<td>1.38 ± 0.11</td>
</tr>
<tr>
<td>0.0</td>
<td>500</td>
<td>6.90 ± 0.25</td>
<td>2.62 ± 0.15</td>
<td>1.87 ± 0.13</td>
<td>1.35 ± 0.11</td>
<td>1.04 ± 0.10</td>
</tr>
<tr>
<td>0.1</td>
<td>300</td>
<td>15.16 ± 0.37</td>
<td>9.14 ± 0.28</td>
<td>7.58 ± 0.26</td>
<td>4.77 ± 0.21</td>
<td>2.90 ± 0.16</td>
</tr>
<tr>
<td>0.1</td>
<td>500</td>
<td>15.97 ± 0.38</td>
<td>8.38 ± 0.27</td>
<td>6.99 ± 0.25</td>
<td>4.08 ± 0.19</td>
<td>2.33 ± 0.14</td>
</tr>
<tr>
<td>0.3</td>
<td>300</td>
<td>9.60 ± 0.38</td>
<td>6.89 ± 0.32</td>
<td>5.99 ± 0.30</td>
<td>3.28 ± 0.22</td>
<td>1.25 ± 0.14</td>
</tr>
<tr>
<td>0.3</td>
<td>500</td>
<td>11.75 ± 0.32</td>
<td>7.88 ± 0.26</td>
<td>7.01 ± 0.25</td>
<td>3.29 ± 0.17</td>
<td>1.11 ± 0.10</td>
</tr>
</tbody>
</table>
Main analysis: at least 3 high quality muons

Here, relax this cut and instead assign an event weight $p(m|n)$: probability that $m$ high-quality muons are found when $n$ muons are present

Predicts $0.19 \pm 0.19$ QCD background event compared to $0.20 \pm 0.19$ from MC estimates
Define 4 separate regions:
A. **Signal region:**
   - 4 muons with $p_T > 7$ GeV
   - Jet isolation
B. $4 > p_T > 7$ GeV for 3rd and other muons
C. no isolation for one lepton jet
D. Reverse $p_T$ and isolation cuts

Isolation and $p_T$ cuts are uncorrelated
Assume $A/C = B/D$

Predicts **0.11 ± 0.11** background events in region A

<table>
<thead>
<tr>
<th></th>
<th># data events</th>
</tr>
</thead>
<tbody>
<tr>
<td>B: anti-$p_T$</td>
<td>1</td>
</tr>
<tr>
<td>C: anti-isolation</td>
<td>3</td>
</tr>
<tr>
<td>D: anti both</td>
<td>26</td>
</tr>
<tr>
<td>A: signal region</td>
<td>0</td>
</tr>
</tbody>
</table>
• Given no events are found in ~40 pb-1 of 2010 data, we can set limits on production cross-section*BR

• CMS obtains model-independent limits using a search for a low mass resonance for cross-sections*BR*acceptance between 0.1 and 0.5 pb with ~35 pb-1 of data
• This model seems like it’ll be ruled out soon
Stay tune! With the 2011 data, it should get really interesting!
Extra details
**Event selection criteria**

- Events must pass the di-muon trigger with $p_T > 6$ GeV
- Request at least 4 muons with $p_T > 7$ GeV
- 3 muons passing higher track quality criteria to reduce background from fakes
- Lepton jet is built from 2 muons found within $\Delta r < 0.1$ rad
- Lepton jet scaled isolation $E_T^{\text{cone}}/p_T > 0.7$
- Event must have at least 2 such lepton jets
Systematic uncertainties

<table>
<thead>
<tr>
<th>Systematic</th>
<th>Signal</th>
<th>QCD</th>
<th>J/Ψ</th>
<th>Y</th>
<th>W+Jet</th>
<th>Z+Jet</th>
<th>t¯t</th>
<th>Di-boson</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>3.4%</td>
<td></td>
<td></td>
<td>3.4%</td>
<td>3.4%</td>
<td>3.4%</td>
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<tr>
<td>Trigger</td>
<td>1%</td>
<td></td>
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<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>Reconstruction</td>
<td>2.9%</td>
<td></td>
<td></td>
<td>2.9%</td>
<td>2.9%</td>
<td>2.9%</td>
<td>2.9%</td>
<td>2.9%</td>
</tr>
<tr>
<td>ΔR Efficiency</td>
<td>8%</td>
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<td>Muon Smearing</td>
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</table>
Lepton jets Kinematics (2)

- # of muons and their separation depends on $m_\gamma$ and $\alpha_d$
- Some events have electrons or pion jets, so less muons
Given no events are found in ~40 pb-1 of 2010 data, we can set limits on production cross-section.