SPS-H2 ENERGY LOSS & MATERIAL IMPACT @HGCAL TESTBEAMS

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on behalf of the CMS Collaboration
Introduction

- The CMS-HGCAL calorimeter is being designed to replace the existing endcap calorimeters during the future HL-LHC “era”
  - Main driving factor: Dealing with the expected radiation / pileup @ HL-LHC era
  - Also: Improvement of the granularity & the detection resolution

- Key parameters:
  - ~620 m² of silicon sensors
  - ~400 m² of scintillators
  - ~6M Si channels, 0.5 or 1 cm² cell size

- Overall: A design that will offer much more information than any previous calorimeter – Therefore a challenging endeavor which needs simulations & test-beam data!
- For more detailed information please check Ludivine Cead’s talk ‘Beam-tests of CMS High Granularity Calorimeter prototypes at CERN’ on this workshop.
Most of the LHC test beams are taking place in North Area Facility.
CMS has two dedicated ‘zones’ there: -
PPE172 – H2 (HCAL) & PPE164 – H4 (ECAL)

HGCAL test beams during 2017 and 2018 have been taking place in PPE172 or H2 zone.
SPS H2 Beamline

Precise (< 2% dp/p acceptance), robust, flexible **magnetic spectrometer**

‘Primary’, 400 GeV/c beam from the SPS accelerator is extracted on a Beryllium target and produces all kinds of secondary particles, that can be transported to the test-beam zone.
Particle Production: Electron and Pion Beams

For the HGCAL test beams, Electrons & Pions are necessary in a wide range of energies (10 – 300 GeV/c). This is generally possible, however one should take into account that:

- The maximum *electron* production momentum @ the target is ~ 300 GeV *(selected via the beam line collimators)*

- Fortunately, Synchrotron Radiation helps towards a more pure beam (but, introduces an extra ‘momentum spread’ that needs to be understood)

- Also: The electrons are very sensitive to material present in the beam line *(bremsstrahlung, multiple scattering...)*

In order to better understand these effects and how they affect the beam delivered to the HGCAL prototype, we engaged in a very detailed, realistic Monte-Carlo study of the beam line.
Monte-Carlo Model (G4beamLine)

- **G4beamline** has been used to simulate the H2 beamline from the production target to HGCAL. ([http://www.muonsinternal.com/muons3/G4beamline](http://www.muonsinternal.com/muons3/G4beamline))

- Magnetic elements (quadrupoles, bending magnets, collimators) and other materials (scintillators, beam windows etc) have been added precisely to the model

- Corrector magnets and Halo/Veto counters upstream and inside PPE172 (HGCAL zone) are implemented

- Materials of fixed experiment NA61/SHINE on beamline also simulated, as well as HGCAL’s materials during the test beam.
Photos of the PPE172 Zone from HGCAL October TestBeam
Photos of the Experimental Area

The NA61 Experiment is located upstream the testbeam area! Beam is passing through the NA61 experiment, including their TPC, Detectors and instrumentation at \( \sim \% \chi_0 \)

- When H2 zone used, NA61 calorimeters out of beam line. But they can not move their TPC and some fixed materials from the beam line.
- Inside the PPE172 – H2 zone, there are also other materials such as beam halo and veto detectors, another \( \sim \% \chi_0 \)
Energy Loss on H2 Beamline - Electrons

- Main source of energy loss especially for the electron beams is the synchrotron radiation (SR)
  - The first question was if this effect is correctly calculated by G4beamline.
- Assuming an unphysical monochromatic, 250GeV/c positron pencil beam passing through all the beam line magnets and reaching to HGCAL:

Observations:

- SR effects are reproduced correctly by G4beamline
- The mean momentum in HGCAL is 243.7 GeV/c
- An (extra) momentum spread is introduced of the order of 0.1%
- For a realistic calculation, this effect needs to be convoluted with the initial emittance, the collimator settings & the material present in the line
- 10M initial particle (90 % e, 10 % proton) generated with G4beamline at the target position and with a realistic phase-space is transported to HGCAL prototype.
- A large particle tail down to very low momenta appears, of the order of ~1% of the total count rate @ HGCAL position.
- The effect is almost the same in all momenta.
The hadronic beam in H2 beam line depends on the secondary momentum chosen. Example for 50 GeV/c: 76.6% $\pi^+$, 17.2% proton, 6.2% kaon.

The lower energy tails demonstrated above, are particles created in the last ‘straight’ section of the beam line (cannot be cleaned out by the bending magnets).

The tail effect is less pronounced than in the electrons.
Investigation of Low Energy Particles – Where are they produced?

- Low energy particles defined as the particles with momentum less than 3% of nominal energy. After these definition we count them through the beam line from target to HGCAL to understand their behavior and where they are produced.

- The interactions in the apertures of the beam elements produce secondaries that are quite effectively cleaned by the beamline spectrometer & the cleaning collimators.

- However, in the NA61 + HGCAL zone, bremsstrahlung in the material produces $\gamma \gamma$ pairs and therefore more $e^- e^+$ pairs and showers!
The plots show the data points taken in the 2018 test beam, the previous simulation framework without the beam line elements introduced, and the full beam line simulation with G4beamline.

The origin of the differences between data/MC are still being investigated, towards the improvement of the model that will serve the better understanding of the beam conditions in the future test beams.
An improvement in the agreement between data / MC is observed, especially in the higher-momentum part of the energy resolution spectrum.

G4beamline result for momentum spread is slightly bigger than estimated which is expected since all the materials on the beamline modeled in detail.

<table>
<thead>
<tr>
<th>Initial $e^+$ Beam Energy (GeV/c)</th>
<th>Estimated Final Energy</th>
<th>Estimated dp/p (%)</th>
<th>Monte Carlo Final Energy</th>
<th>Monte Carlo dp/p (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>20</td>
<td>0.1009</td>
<td>19.91</td>
<td>0.561</td>
</tr>
<tr>
<td>30</td>
<td>30</td>
<td>0.1009</td>
<td>29.87</td>
<td>0.568</td>
</tr>
<tr>
<td>50</td>
<td>49.99</td>
<td>0.1009</td>
<td>49.79</td>
<td>0.573</td>
</tr>
<tr>
<td>80</td>
<td>79.93</td>
<td>0.1009</td>
<td>79.62</td>
<td>0.582</td>
</tr>
<tr>
<td>100</td>
<td>99.83</td>
<td>0.1009</td>
<td>99.45</td>
<td>0.589</td>
</tr>
<tr>
<td>120</td>
<td>119.65</td>
<td>0.161</td>
<td>119.2</td>
<td>0.598</td>
</tr>
<tr>
<td>150</td>
<td>149.16</td>
<td>0.2018</td>
<td>148.5</td>
<td>0.623</td>
</tr>
<tr>
<td>200</td>
<td>197.32</td>
<td>0.2018</td>
<td>196.3</td>
<td>0.642</td>
</tr>
<tr>
<td>250</td>
<td>243.61</td>
<td>0.605</td>
<td>242.5</td>
<td>0.651</td>
</tr>
<tr>
<td>300</td>
<td>287.18</td>
<td>0.605</td>
<td>286.02</td>
<td>0.671</td>
</tr>
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</table>
A detailed Monte-Carlo model of the full beam line, including the correct magnetic fields, collimator settings and materials has been developed in G4beamline - created towards understanding better the beam properties and also be able to fine-tune the setups in the future.

The beam reaching the HGCAL setup in the H2 beam line, is affected by the synchrotron radiation of the magnets as well as the upstream material. The beam purity (in hadronic and electron beams) is not heavily affected, however low energy tails can be seen by the high-resolution HGCAL prototype and need to be understood in detail, and their effects taken into account in the analysis.

The agreement between Data and MC seems improved with the detailed model, some differences are still being investigated.

The model is available for other experiments that can take place in H2 beam line, and can serve for better understanding of the beam properties.
BACK-UP
Particles With $P_{\text{Total}}$ Less Than %3.0 Of Nominal Energy [**30 GeV - e⁺**]

**Particles With $P_{\text{Total}}$ Less Than %3.0 Of Nominal Energy [**250 GeV - e⁺**]
Investigation of Low Energy Particles
Investigation of Low Energy Particles

- When we focus after the last H-magnet, we can clearly see the rise of low-energy photons and electrons/positrons with the wrong energy increasing just before the HGCAL Calorimeter (no magnetic elements to clean)
- Two very thick (2cm) Scintillators, DWCs in front of HGCAL play a key role by increasing the lower energy particles by a factor x2
NA61/SHINE Experimental Area & Materials

- The NA61/SHINE is a “Fixed target” experiment, permanently installed upstream PPE172, and spans over ~30 meters of beam line!
- They have a lot of materials present at the beamline. However, during the HGCAL test-beam, most of them were removed from the beam line (SX, VX counters, A/Z ...)
- Only Beam Position Detectors (BPDs) were considered for the simulation. These are gas detectors filled with Ar-CO2 and covered by two very thin mylar windows.
- Also Air regions inside NA61 are taken correctly into account.

<table>
<thead>
<tr>
<th>detector</th>
<th>dimensions [mm]</th>
<th>hole [mm]</th>
<th>position [m]</th>
<th>material budget [%(\Delta T)] [%(X_0)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>60 x 60 x 5</td>
<td></td>
<td>-36.42</td>
<td>0.635</td>
</tr>
<tr>
<td>S2</td>
<td>(\phi = 28 \times 2)</td>
<td></td>
<td>-14.42</td>
<td>0.254</td>
</tr>
<tr>
<td>S3</td>
<td>(\phi = 26 \times 5)</td>
<td></td>
<td>-6.58</td>
<td>0.635</td>
</tr>
<tr>
<td>S4</td>
<td>(\phi = 20 \times 5)</td>
<td></td>
<td>-2.11</td>
<td>0.635</td>
</tr>
<tr>
<td>S5</td>
<td>(\phi = 20 \times 5)</td>
<td></td>
<td>9.80</td>
<td>0.635</td>
</tr>
<tr>
<td>V0</td>
<td>(\phi = 80 \times 10)</td>
<td>(\phi = 10)</td>
<td>-14.16</td>
<td>1.175</td>
</tr>
<tr>
<td>V0p</td>
<td>300 x 300 x 10</td>
<td>(\phi = 20)</td>
<td>~-14</td>
<td>1.175</td>
</tr>
<tr>
<td>V1</td>
<td>100 x 100 x 10</td>
<td>(\phi = 8)</td>
<td>-6.72</td>
<td>1.175</td>
</tr>
<tr>
<td>V1p</td>
<td>300 x 300 x 10</td>
<td>(\phi = 20)</td>
<td>-6.74</td>
<td>1.175</td>
</tr>
<tr>
<td>A</td>
<td>150 x 5 x 15</td>
<td></td>
<td>~-146</td>
<td>1.904</td>
</tr>
<tr>
<td>Z</td>
<td>160 x 40 x 2.5</td>
<td></td>
<td>-13.81</td>
<td>0.562</td>
</tr>
<tr>
<td>BPD-1</td>
<td>48 x 48 x 32.6</td>
<td></td>
<td>-36.20</td>
<td>0.025</td>
</tr>
<tr>
<td>BPD-2</td>
<td>48 x 48 x 32.6</td>
<td></td>
<td>-14.90</td>
<td>0.025</td>
</tr>
<tr>
<td>BPD-3</td>
<td>48 x 48 x 32.6</td>
<td></td>
<td>-6.70</td>
<td>0.025</td>
</tr>
</tbody>
</table>

Results of NA61/SHINE Material Effects!

- NA61 Area has significant effect on high energy beams but for the low energy beams, the effects of the NA61/SHINE experiment is a slightly smaller (less momentum, less bhremstullung)
Results of NA61/SHINE Material Effects!

Particles With $P_{\text{Total}}$ Less Than %3.0 Of Nominal Energy [100 GeV - e$^+$]

- **With NA61 Materials**
  - 4 x DWCs in PPE172

- **Without NA61 Materials**
  - 4 x DWCs in PPE172

 Assuming that a vacuum pipe was in the place of NA61/SHINE
Results of NA61/SHINE Material Effects!

In higher momenta, the effect of the NA61/SHINE Experiment has significant effects on beam profile (higher momentum, more important bhremmstrahlung).
Magnetic elements and materials

- Quadrupole
- Bending Magnet
- Beam Window
- Collimator
- Scintillator