CMS highlights at DESY

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on behalf of the DESY-CMS group

92nd PRC meeting
3rd November, 2021
We dedicate this talk to

Nicolas Tonon

1993-2021
The CMS group at DESY has a very broad scope of activities.
Overview

This talk will highlight only a subset of several studies/results:

- **BRIL and Luminosity measurement (Run-3).**
- **Detector upgrade (Phase-2):**
  - High Granularity Calorimeter (HGCAL).
  - Outer Tracker.
- **Physics analyses (Run-2):**
  - Simultaneous constraints on QCD and BSM.
  - Insight into the structure of higher-order corrections.
  - Azimuthal correlations in Z+jet events.
  - Probing t-Z couplings with EFT and ML.
  - tZq production in final states with 3 leptons.
BRIL and Luminosity
Luminosity Detector
Fast Beam Condition Monitor (BCM1F)

- Rebuilt for Run3, using cooled silicon sensors.
- Successfully installed in July: [CERN bulletin], [youtube]
- Proven working immediately and stably during test beams 18-31 October.

BCM1F “C-shape”
Assembly and testing at DESY

July 2021: Installation

May/June 2021: Integration with Pixel Luminosity Telescope (at CERN)
CMS Online Luminosity Measurement

BCM1F: Stable Operation during Test Beams End of October

- 1st week: splash events
- 2nd week: collisions, 900 GeV, overnight
- BCM1F delivers realtime luminosity to CMS and LHC, \(\sim 2 \times 10^{28} \text{ cm}^{-2}\text{s}^{-1}\).

Public CMS luminosity (black line) as measured by BCM1F
Stable collisions.
Tracker, ECAL, HCAL, and BRIL are performing well.
The CMS detector is ready for Run-3.
Phase-2 Upgrade: Overview
Instantaneous luminosity will increase by a factor of 5-7 (up to $7.5 \times 10^{34}$ cm$^{-2}$s$^{-1}$).

Pileup will increase to ~200.

High particle multiplicity and radiation levels (among other things) dictate the detector designs.

DESY involved in:
- High granularity calorimeter (HGCAL).
- Outer Tracker (DESY will build one OT endcap).
Phase-2 Upgrade:
High Granularity Calorimeter
High Granularity Calorimeter (HGCAL)

- Offspring of future-collider targeted R&D (CALICE).
- SiPM-on-Tile technology where radiation permits.
- 400 m$^2$ scintillator, 240K SiPMs.
- 600 m$^2$ silicon, 6M channels.

DESY Contribution (FTX Group)

- Development of active Tilemodules.
  - Board-level electronics and automated assembly techniques.
- Tilemodule Assembly Centre.
  - Production and QC of Tilemodules for one endcap.
HGCAL Recent Highlights
Preparing for the Production Phase

- **Tile wrapping and module assembly procedure:**
  - Now fully automated, wrapping 4 tiles per minute.
  - Gluing with pick & place: 1 module in < 10 minutes.
  - Procedure videos: [link1], [link2]
  - Scaling to other formats and large series still to be done.

- **New climate chamber in e-Lab.**
  - Operation and characterization of Tilemodules at -30 °C.
  - Second chamber for production QC (thermo-cycling) ordered.

- **Setting up Quality Control.**
  - Scintillator tile light output QC set-up commissioned.
  - Cosmic test stand for full modules in preparation.

- **Pre-series in 2022, pre-production in 2023.**
Phase-2 Upgrade: Outer Tracker

PS (Pixel Strip) module

2-stripe (2S) module
PS Module Automated Assembly

- $p_T$ discrimination on module requires sensor to be precisely aligned during assembly.
  - Rotational misalignment below 800 μrad.
- Sensor sandwich is assembled on a robotic stage.
  - Relative alignment of object is measured with microscope camera and pattern recognition
PS Module Prototyping

- Built two fully functional modules within specifications.
- **2.6 mm sensor spacing:**
  - $x=10\,\mu m\, (\leq 50\,\mu m)$
  - $y=53\,\mu m\, (\leq 100\,\mu m)$
  - $\alpha=17\,\mu rad\, (\leq 800\,\mu rad)$
- **4.0 mm sensor spacing:**
  - $x=6\,\mu m\, (\leq 50\,\mu m)$
  - $y=66\,\mu m\, (\leq 100\,\mu m)$
  - $\alpha=200\,\mu rad\, (\leq 800\,\mu rad)$
- Progress in debugging and setting up DAQ and test software.
- Preparing for data taking in beam mid-November.
Results from first functional 2.6 mm PS Module

- One of the first functional modules built within the collaboration.
- Module equipped with some preliminary components.
- Some hardware patches required with respect to final versions of electronics.
- **Successful communication with the different components.**
- Noise measurement at 300 V bias.
- Higher noise is observed on left Front End Hybrid (FEH) Strip Sensor ASIC (SSA) and towards the DC-DC converters.
TEDD Integration Tooling - Arc Frame

- Local support structure in end caps is a half-disk (Dee).
- Modules are as close as ~1.3 mm to the Dee edges.
  - Modules are offset in phi angle between front and back side of Dees to create overlaps.
- Dee with modules cannot be manually handled.
- Dedicated holding structure - Arc frame - was designed for handling of Dees.
- Dee will rest in its own Arc frame up to almost the last integration step.
- Design has to be compatible with all integration steps.
- Substantial progress in the past months - design very close to final.
**Infrared measurement of TEDD Dees**

**Setup overview**

- **Important for thermal qualifications of the TEDD Dees** - for testing and QC only.
- **The Dee is mounted on an arc frame with a cooling manifold.**
- **The sectors are cooled simultaneously with a conventional cooling fluid.**
- **Infrared (IR) camera:**
  - Mounted on motorized stages.

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**PS carbon foams**

**2S inserts**
Infrared measurement of TEDD Dees

A few examples

Profiles looks good: Flat and uniform

Profiles have bumps.

Profiles have a strong slope, and are dissimilar.

- Automated extraction of features (PS c-foam temp. profiles, 2S insert temp.) from images.
- Impact of the defects on the cooling performance is being studied.
- Important to establish QC procedure – ongoing.
Physics analyses
Simultaneous constraints on QCD and BSM

SMEFT interpretation of the inclusive jet production in pp collisions at 13 TeV.
SMEFT: Standard Model enhanced Effective Field Theory.

Direct probe of gluon and strong coupling constant

Contact interactions

New CMS data used in QCD+CI fit at NLO with DIS (EPJC 75 (15)12) and CMS ttbar (EPJC 80 (2020) 7)

- Improvement in PDF accuracy at high $x$
- Simultaneous extraction of QCD and BSM parameters
- No risk of absorbing BSM into PDFs

95% CL exclusion for $\Lambda$ ($c_1=-1$):
Left-handed: $\Lambda > 24$ TeV
Vector like: $\Lambda > 32$ TeV
Axial-vector like: $\Lambda > 31$ TeV
Insight into the structure of higher-order corrections

Data compared to MG5_atMC NLO predictions interfaced with Pythia8 and CASCADE3

- For the first time measured jet multiplicity in bins of the leading jet $p_T$ & azimuthal angle between leading jets $\Delta\phi_{1,2}$
- Up to seven jets are measurable.
- Cross section of the four leading jets measured up to the TeV scale:
  - Benchmark for Standard Model multi-jet cross section calculations
  - Test simulations including parton showers for higher jet multiplicity

- Measurements compared to LO (MadGraph, Pythia8, Herwig++)
- Comparison to NLO (MADGRAPH5_MC@NLO) with Pythia8 and CASCADE3 predictions
- For high jet multiplicities the lack of higher order contributions can be observed
Azimuthal correlations in Z+jets events

Particular interest in Parton Branching (PB) predictions

- **Small** $p_T(Z)$: soft-gluon resummation and non-perturbative contributions essential
- **High** $p_T(Z)$: Z+jet production dominant, significant corrections from QCD processes

- **$p_T(Z) < 10$ GeV**
- **$p_T(Z) > 100$ GeV**

- **Z + jet measurements challenge theoretical predictions**
- **Good agreement achieved incl. contr. of multiparton interactions, parton shower, PB**
Probing t-Z couplings with EFT and ML

- t-Z coupling modified by various BSM scenarios.
- **Novel approach**: constrain several t-Z EFT operators in a simultaneous analysis of ttZ, tWZ, & tZq events:
  - Consider up to 5 operators simultaneously
  - Pioneer use of Deep Learning techniques
tZq production in final states with 3 leptons

Rare process, connects top with EWK sector
- EWK production $\rightarrow$ polarized top
- Sensitive to many EFT operators

- First ever tZq differential measurements of top & Z observables, top-Z system, leptons
- First ever measurement of top spin asymmetry ($A_\ell$) in tZq (proportional to polarization)

$$A_\ell = 0.58^{+0.15}_{-0.16} \text{ (stat)} \pm 0.06 \text{ (syst)}$$ [consistent with SM prediction]

- Exploit machine learning techniques (DNN) to enhance sensitivity to tZq signal

CMS-PAS-TOP-20-010
Summary
Summary

- Presented some of the highlights from the DESY-CMS group.
  - Refurbished BCM1F successfully installed and performing stably. CMS is ready for Run-3.
  - Significant progress in Phase-2 upgrade activities:
    - HGCAL: tile wrapping, module assembly and QC.
    - Outer Tracker: PS module assembly and prototyping; TEDD integration tooling and infrared measurements.
  - Recent physics analysis results:
    - Simultaneous constraints on QCD and BSM.
    - Insight into the structure of higher-order corrections.
    - Azimuthal correlations in Z+jet events.
    - Probing t-Z couplings with EFT and ML.
    - tZq production in final states with 3 leptons.
  - Many more exciting activities for Run-2, Run-3 and Phase-2 are ongoing.

Thank you!
Backup
SSA Front-End Hybrid (FEH)
• Strip Sensor ASIC (SSA)
• Concentrator Integrated Circuit (CIC)
• Handles signal from strip sensor
• Transfers data to pixel chip

Read-Out Hybrid (ROH)
• Low-power Gigabit Transceiver (lpGBT)
• VTRx+ optical module
• Transmits data over optical fibre

Power Hybrid (POH)
• DC-DC converter
• Used for module power

Silicon Strip Sensor
• 10 x 5 cm Silicon Strip Sensor
• 2.5 cm long strips, 100 um pitch

MACro Pixel Sub Assembly (MaPSA)
• Macro Pixel ASIC (MPA)
• Macro Pixel Silicon sensor 1400 x 100 um
• Correlates signal from both sensors
DESY26_2 Noise @300V
Measurement and QCD analysis of double-differential inclusive jet cross sections

- CMS-PAS-SMP-20-011: [link]

Jet production cross section can be sensitive to contributions from new physics.

Contact interactions

\[ \sigma_{pp \to \text{jet} + x} = \sum_{ij} f_i(x_1, \mu_F) f_j(x_2, \mu_F) \otimes \sigma_{ij \to \text{jet}}(x_1, x_2, \alpha_s(\mu_R), \frac{Q}{\mu_R}, \frac{Q}{\mu_F}) \]

\( f(x, \mu) \): PDF (parton density function)

Tree-level x-sec SM+BSM

\[ L_{\text{SMEFT}} = L_{\text{SM}} + \frac{4\pi}{2\Lambda^2} \sum_n c_n O_n \]

<table>
<thead>
<tr>
<th>Type of CI</th>
<th>( c_1 )</th>
<th>( c_3 )</th>
<th>( c_5 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purely left-handed</td>
<td>free</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Vector-like</td>
<td>free</td>
<td>( 2c_1 )</td>
<td>( c_1 )</td>
</tr>
<tr>
<td>Axial-vector-like</td>
<td>free</td>
<td>( -2c_1 )</td>
<td>( c_1 )</td>
</tr>
</tbody>
</table>

Contact interactions (CI) can appear as deviations from SM at low rapidity (y) and high \( p_T \).

However, such deviations can get absorbed into the parton density function (PDF) fits.

To avoid this: fit the PDF and CI couplings simultaneously.
Measurement and QCD analysis of double-differential inclusive jet cross sections

Analysis strategy and results [1]

- Impact of the CMS data on global PDF sets:
  - Profiling procedure.
  - Extract the nuisance param. values that minimize $\chi^2 : b^{th(min)}$
  - PDF profiling performed using: CT14 NLO and NNLO PDF sets.
  - Gluon PDF uncertainty is significantly reduced.
  - Impact on $\alpha_s$ using CMS inclusive jet xsec: Consistent with global avg.
  - Can also profile non-PDF quantities like: top mass ($m_t$), CI Wilson coeff. ($c_1$).
    - $m_t = 170.3 \pm 0.5 \text{(fit)} + 0.2 \text{(scale)} \text{ GeV}$
      - Consistent with CMS-TOP-18-004.
    - CI Wilson coeff. ($c_1$) values consistent with SM.
- [not shown] Impact at NLO based on HERA DIS (Deep Inelastic Scattering) measurements.
  - HERA+CMS PDF uncertainties significantly reduced compared to HERA-only.

\[ xf(x) = A_f x^{B_f (1-x)} c_f (1+D_f x + E_f x^2) \]
\[ \chi^2 = \sum_{i=1}^{N_{\text{data}}} \left( \sigma_i^{\text{exp}} + \sum_{\alpha} \Gamma_{i \alpha}^{\text{exp}} b_{\alpha}^{i} - \sigma_i^{\text{th}} - \sum_{\beta} \Gamma_{i \beta}^{\text{th}} b_{\beta}^{i} \right)^2 + \sum_{\alpha} (b_{\alpha}^{\text{exp}})^2 + \sum_{\beta} (b_{\beta}^{\text{th}})^2 \]

\[ f_0' = f_0 + \sum_{\beta} b_{\beta}^{\text{th(min)}} \left( \frac{f_\beta^+ - f_\beta^-}{2} - \frac{f_\beta^{th(min)} f_\beta^+ + f_\beta^- - 2 f_0}{2} \right) \]
Measurement and QCD analysis of double-differential inclusive jet cross sections
Analysis strategy and results [2]

- SMEFT interpretation at NLO:
  - Simultaneous extraction of PDFs, $\alpha_S$, $m_t$, and the CI Wilson coefficient $c_1$.
  - Perform (i) SM only fit (ii) SMEFT fit.
    - Resulting PDFs with both fits are consistent.
    - $\alpha_S$ and $m_t$ values for both fits are consistent.
  - SMEFT fit:
    - Smaller uncertainties w.r.t. the profiling method.
    - $c_1$ values are consistent with SM.

SM fit
$\alpha_S = 0.1188 \pm 0.0017$ (fit) $\pm 0.0022$ (model and param.)
$m_t^{\text{pole}} = 170.4 \pm 0.6$ (fit) $\pm 0.1$ (model and param.) GeV.

SMEFT fit
$\alpha_S = 0.1187 \pm 0.0016$ (fit) $\pm 0.0030$ (model and param.)
$m_t^{\text{pole}} = 170.4 \pm 0.6$ (fit) $\pm 0.3$ (model and param.) GeV.
Probing EFT operators in the associated production of top quarks with a Z boson

- CMS-TOP-21-001: arXiv 2107.13896 (submitted to JHEP)
- Featured in the CERN Courier (Sep/Oct 2021): Learning to detect new top-quark interactions
- No BSM particles observed at the LHC: possible that $E_{\text{BSM}} \gg E_{\text{LHC}}$.
- Effective Field Theory (EFT) - low energy approximation of a theory characterized by a large energy scale ($\Lambda$).
- EFT allows for a model independent interpretation of potential deviations from the SM prediction.
- Several BSM theories predict sizable modification of the $t$-$t$-$Z$ coupling.
- This coupling can be probed using $ttZ$, $tZq$, and $tWZ$ processes.
- Use novel Machine Learning techniques to improve sensitivity to the Wilson coefficients (WCs).

Wilson coefficients $\leftrightarrow$ interaction strengths

$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_{d,i} \frac{c^d_i}{\Lambda^4} O^d_i$

Higher-order operators

BSM energy scale ($\gg E_{\text{LHC}}$)

Focus on a subset of 5 operators:
- $O_{tZ}$, $O_{tW}$: induce electroweak dipole moment of the top quark.
- $O^3_{\varphi Q}$: left-handed SU(2) triplet current operator.
- $O^\varphi_{\varphi Q}$, $O^\varphi_{\varphi t}$: neutral current operators that modify the $ttZ$ coupling for left and right handed top quarks, respectively.
Probing EFT operators in the associated production of top quarks with a Z boson

Analysis strategy

- **Search in 3 lepton (3l) and 4 lepton (4l) final states.**
- **Main genuine lepton bkg. from WZ and ZZ processes:** define control regions (CRs) to use in the fit.
- **Data-driven estimation of the mis-ID leptons - Invert lepton isolation/ID.**
- **Train 2 neural networks (NNs):**
  - **NN-SM:** separate tZq and ttZ signal from backgrounds (WZ, ZZ, ttX, VVV).
    - Each category is quite pure.
  - **NN-EFT (binary):** separate between SM hypothesis and EFT.
    - 8 NNs trained, targeting different signal scenarios.
    - Sampled uniformly over a range of the WC values – NN learns to interpolate between WC values.
    - Last bins highly sensitive to EFT.

<table>
<thead>
<tr>
<th>Selection requirement</th>
<th>SR-3ℓ</th>
<th>SR-ttZ-4ℓ</th>
<th>WZ CR</th>
<th>ZZ CR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton multiplicity</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>$m_{3\ell} - m_Z$</td>
<td></td>
<td></td>
<td>&gt;15 GeV</td>
<td></td>
</tr>
<tr>
<td>Z boson candidates multiplicity</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Jet multiplicity</td>
<td>≥2</td>
<td>≥2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>b jet multiplicity</td>
<td>≥1</td>
<td>≥1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>$p_T^{miss}$</td>
<td></td>
<td></td>
<td>&gt;50 GeV</td>
<td></td>
</tr>
</tbody>
</table>
Probing EFT operators in the associated production of top quarks with a Z boson

Results

- Results are extracted from a simultaneous fit to data in 6 categories (4 signal and 2 bkg).
- 1D fit: Values of other WCs set to the SM value of 0.
- 5D fit: All WCs fitted simultaneously.
- 2D scans for the most correlated WCs.
- Results are consistent SM expectations.
- First application of NNs for a global fit of EFT.
- Some of the limits (e.g. $c_{tW}$) are the best experimental measurements till date.
Azimuthal correlations in Z+jets events

- CMS-PAS-SMP-21-003: [link]
- Z bosons are a standard candle at the LHC: can be measured very precisely in the leptonic channel.
- QCD corrections play an important role at non-zero $p_T(Z)$.
  - At small $p_T(Z)$:
    - Jet production is the dominant process.
    - The Z boson appears as an electroweak (EW) correction.
    - Soft gluon radiation is important.
  - At high $p_T(Z)$:
    - Z+1jet production is the dominant process.
    - QCD contribution to this process can be measured via associated jet production.
  - Particularly interesting for the newly developed Parton Branching (PB) transverse momentum dependent (TMD) parton densities.
    - Advantage: PB-TMD parton shower parameters fixed by PB-TMD parton densities.
  - Compare measurements with different calculations.

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**Fixed-order perturbative QCD calculation at NLO**

<table>
<thead>
<tr>
<th>generator</th>
<th>PDF</th>
<th>matrix element</th>
<th>tune</th>
</tr>
</thead>
<tbody>
<tr>
<td>MG5.AMC+PY8 ($\leq 2j$ NLO) [33]</td>
<td>NNPDF 3.0 (NLO) [37]</td>
<td>NLO ($2 \to Z + 0,1,2$)</td>
<td>CUETP8M1 [35]</td>
</tr>
<tr>
<td>MG5AMC+CA3 (Z + 1) NLO [33]</td>
<td>PB-NLO-set2 (NLO) [19]</td>
<td>NLO ($2 \to Z + 1$)</td>
<td>–</td>
</tr>
<tr>
<td>MG5AMC+CA3 (Z + 2) NLO [33]</td>
<td>PB-NLO-set2 (NLO) [19]</td>
<td>NLO ($2 \to Z + 2$)</td>
<td>–</td>
</tr>
<tr>
<td>GENEVA NNLO [21–24]</td>
<td>NNPDF 3.1 (NLO)[39]</td>
<td>NNLO ($2 \to Z$)</td>
<td>CUETP8M1</td>
</tr>
</tbody>
</table>
Azimuthal correlations in Z+jets events

Analysis strategy

- Select events with either 2 opposite sign electrons or muons.
- Veto events with any extra lepton.
- Electrons/muons required to satisfy certain isolation/identification criteria.
- Measure the following in different $p_T(Z)$ bins: $n_{jet}$, $\Delta \phi(Z, jet_1)$, $\Delta \phi(jet_1, jet_2)$.
  $\phi$: azimuthal angle; jet_1/jet_2: jets with the highest/second-highest $p_T$.
- Unfold the distributions using iterative D’Agostini method:
  - Corrects for detector effects: reconstructed (measured) x-sec $\rightarrow$ Particle level x-sec.

<table>
<thead>
<tr>
<th>Table 2: Phase space of the measurement at particle level.</th>
</tr>
</thead>
<tbody>
<tr>
<td>selection</td>
</tr>
<tr>
<td>electron: leading</td>
</tr>
<tr>
<td>(subleading)</td>
</tr>
<tr>
<td>muon: leading</td>
</tr>
<tr>
<td>(subleading)</td>
</tr>
<tr>
<td>lepton-jet isolation</td>
</tr>
<tr>
<td>$m_{l+j} &lt; 76 &lt; m_{l+j} &lt; 106 \text{ GeV}$</td>
</tr>
<tr>
<td>jet</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>
Azimuthal correlations in Z+jets events

Results

- Upper row colors:
  - MG5_aMC+PY8
  - MG5_aMC+PY8 [no multiparton interactions (MPI)]

- Lower row colors:
  - MG5_aMC+CA3 (Z+1)
  - MG5_aMC+CA3 (Z+2)
  - GENEVA NNLO

- MPI contributes significantly in the low $p_T(Z)$ regions. MPI becomes negligible for $p_T(Z)>100$ GeV.
- MG5_aMC+PY8 describes the measurements within scale uncertainties.
- MG5_aMC+CA3 (PB TMD) remarkably close to measurement. N.B. No MPI and and free parameters for parton shower here.