CMS highlights at DESY

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on behalf of the DESY-CMS group

92nd PRC meeting
3rd November, 2021

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

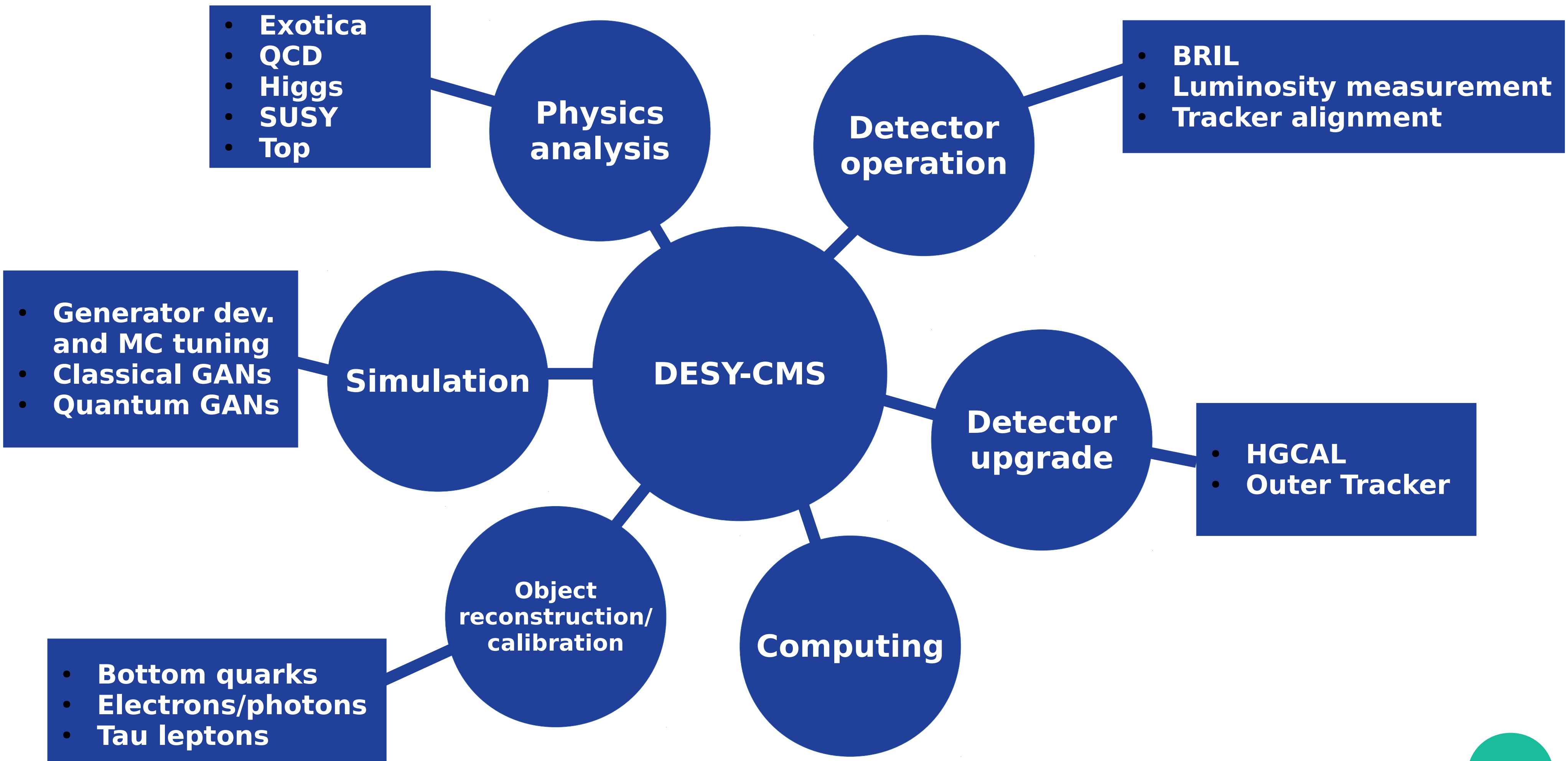
We dedicate this talk to

Nicolas Tonon

1993-2021

Introduction

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.**

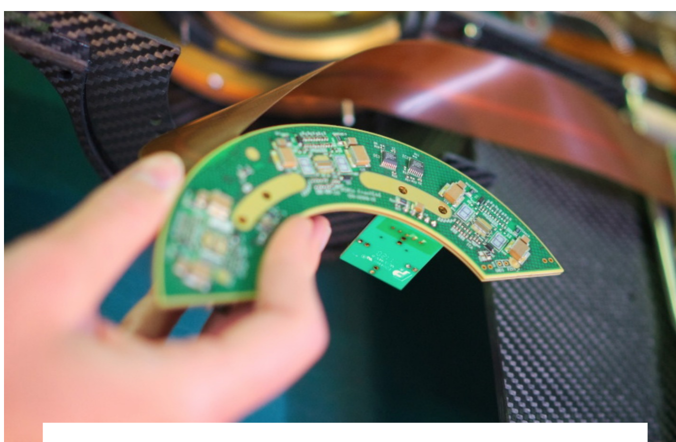
BRIL and Luminosity

Luminosity Detector

Fast Beam Condition Monitor (BCM1F)

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

July 2021: Installation



BCM1F “C-shape”
Assembly and testing at DESY

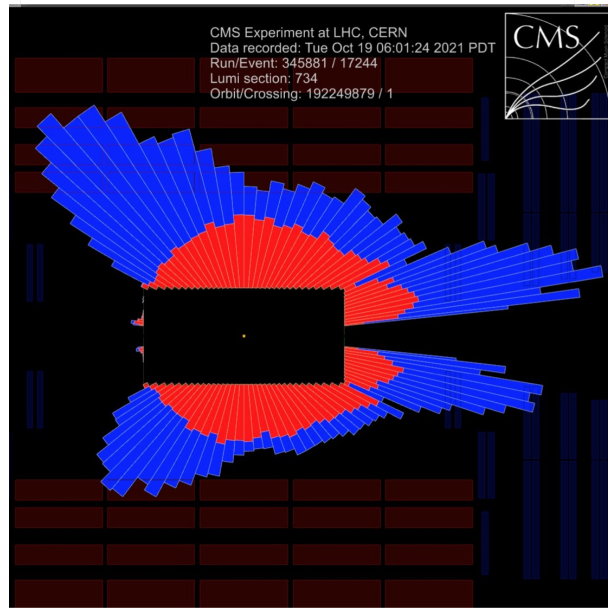
May/June 2021: Integration with Pixel Luminosity Telescope (at CERN)

CMS Online Luminosity Measurement

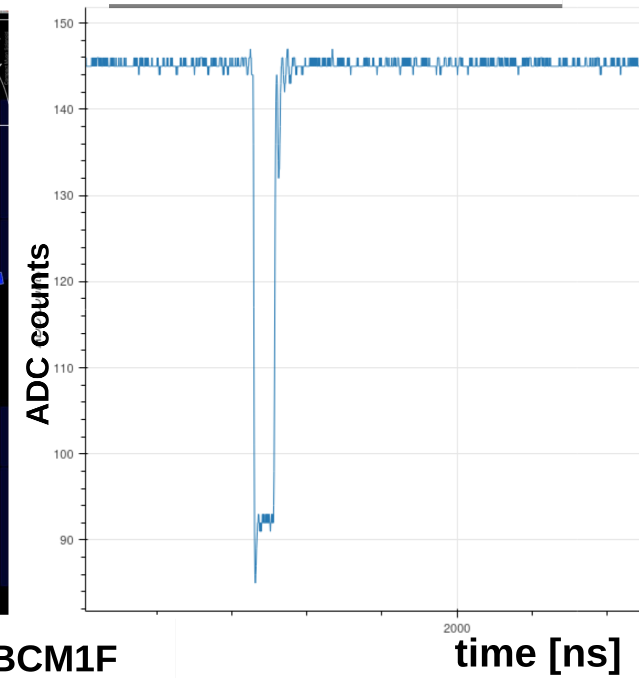
BCM1F: Stable Operation during Test Beams End of October

- **1st week: splash events**
- **2nd week: collisions, 900 GeV, overnight**
- **BCM1F delivers realtime luminosity to CMS and LHC, ~2×10^{28} cm^{-2}s^{-1}.**

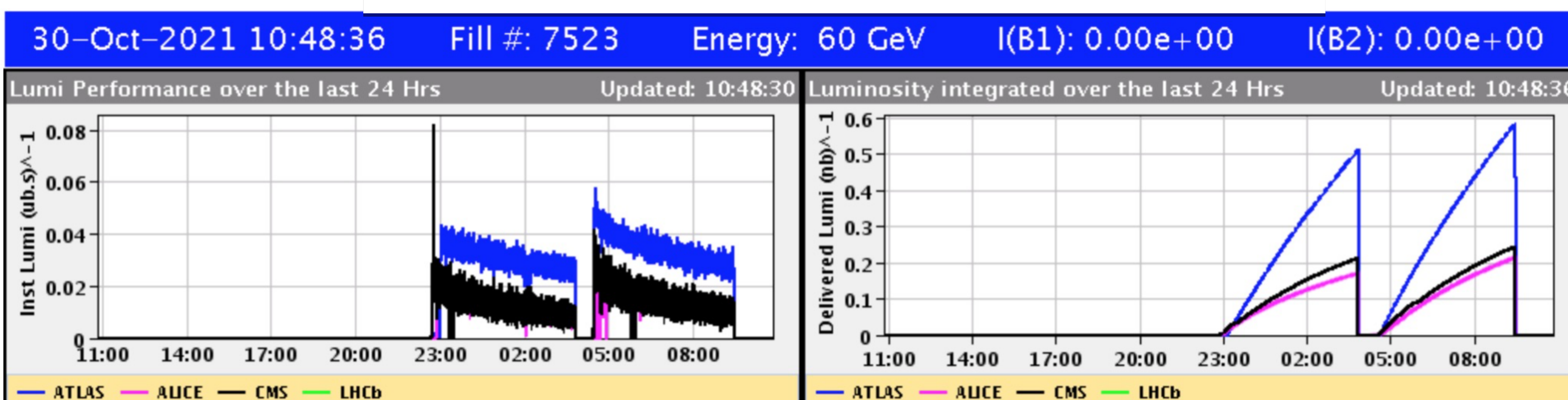
Splash in CMS Calorimeter



Splash in BCM1F



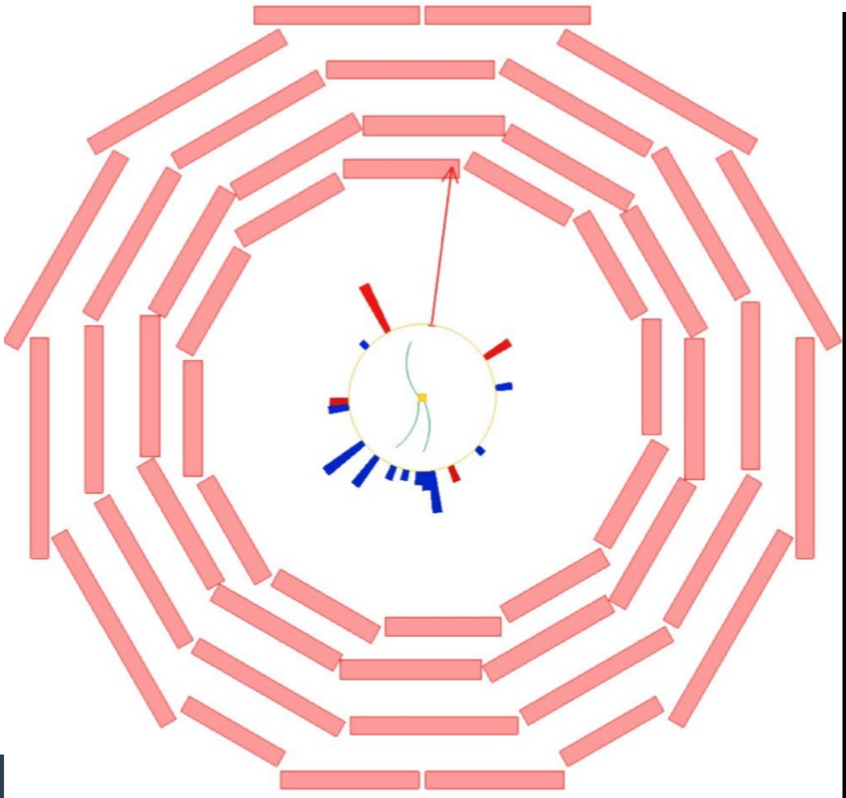
Public CMS luminosity (black line) as measured by BCM1F

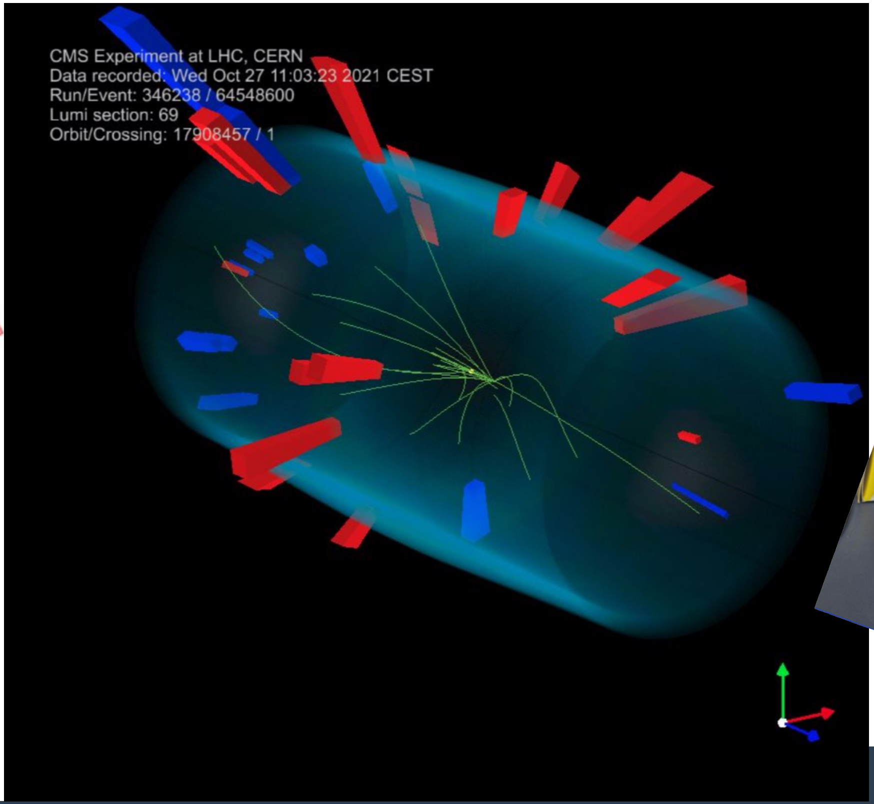


CMS Experiment

Recommissioning for Run-3

- **Stable collisions.**
- **Tracker, ECAL, HCAL, and BRIL are performing well.**
- **The CMS detector is ready for Run-3.**

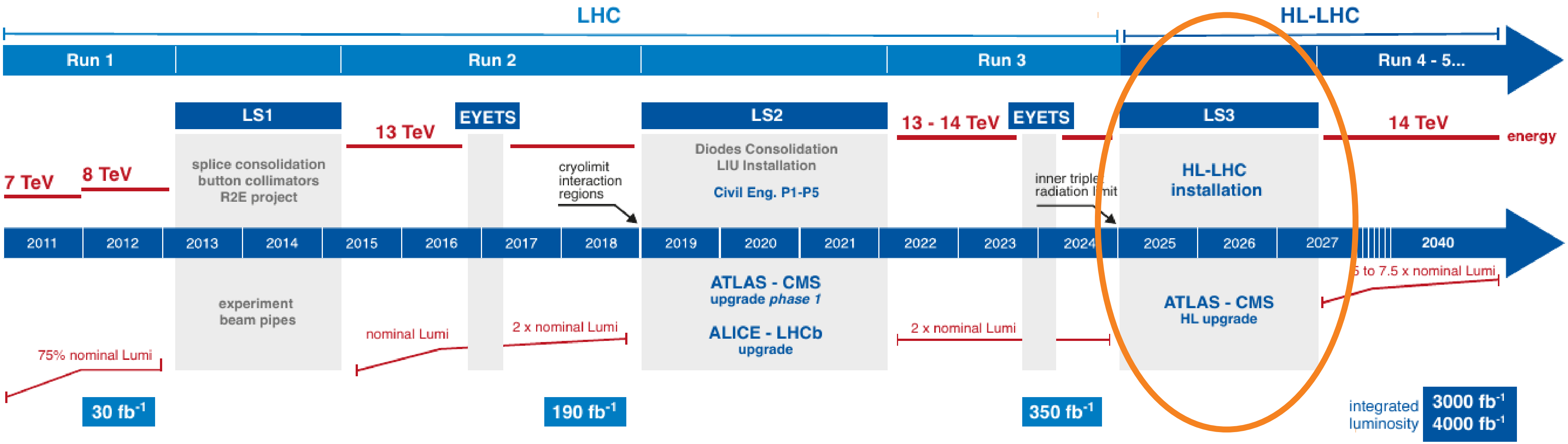




Phase-2 Upgrade: Overview

Phase-2 Upgrade

Overview



- **Instantaneous luminosity will increase by a factor of 5-7 (up to 7.5×10^{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

Endcap Calorimeter Upgrade

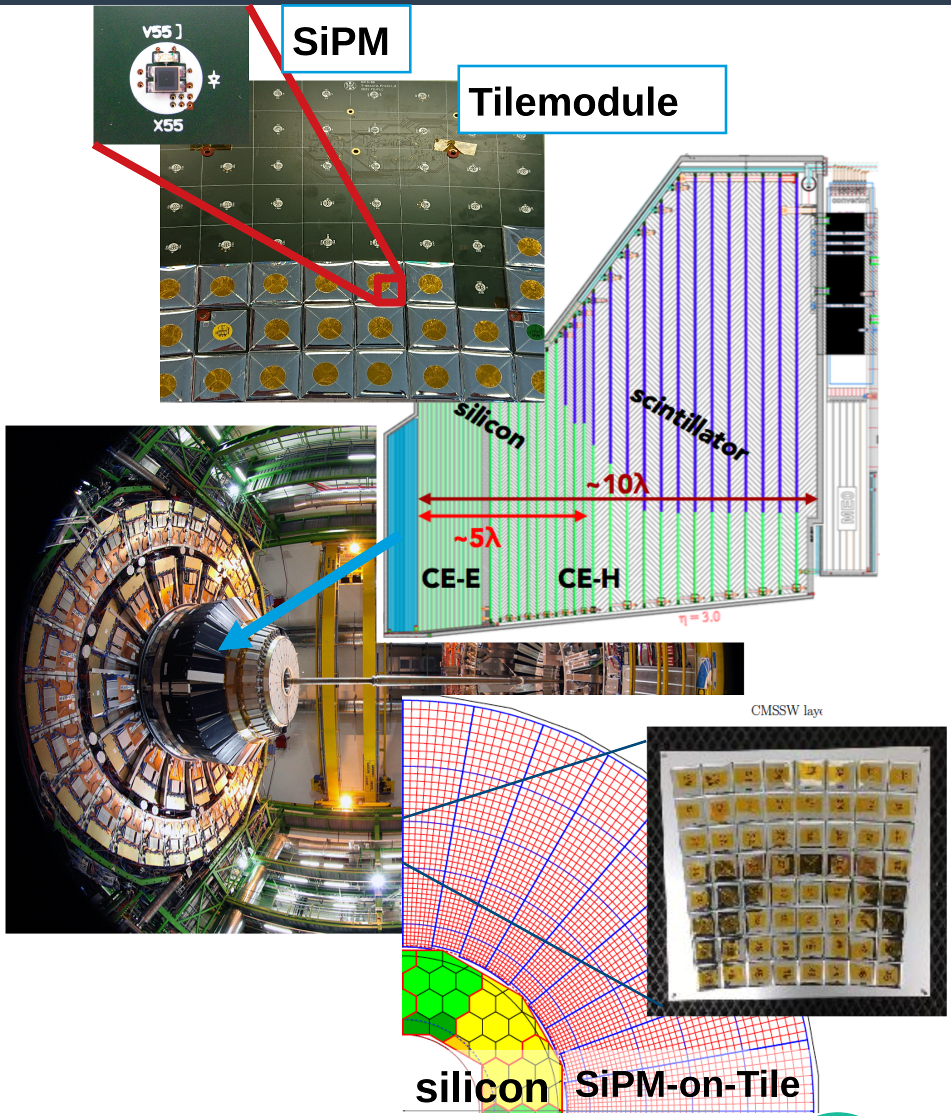
Active SiPM-on-Tile Read-out Modules

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)

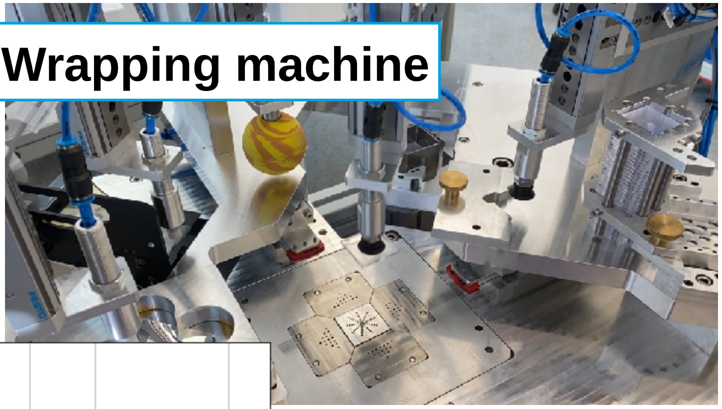
- **Development of active Tilemodules.**
  - Board-level electronics and automated assembly techniques.
- **Tilemodule Assembly Centre.**
  - Production and QC of Tilemodules for one endcap.

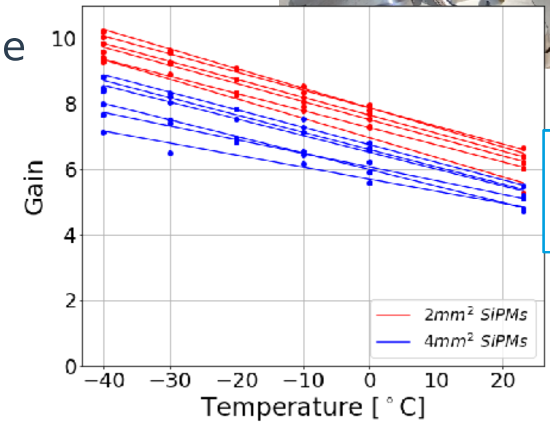


HGCAL Recent Highlights

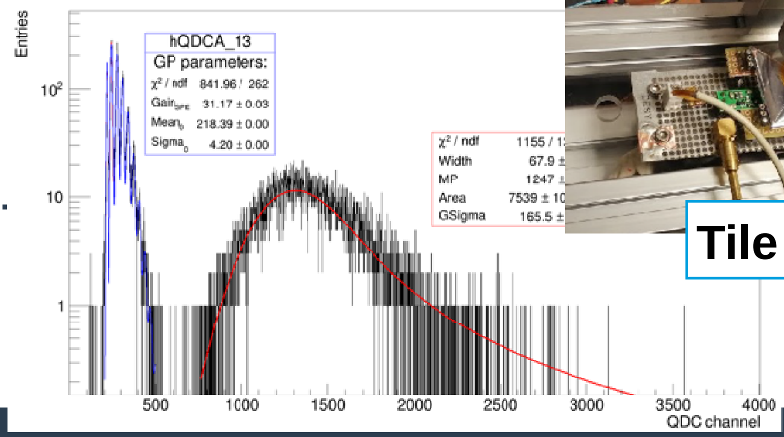
Preparing for the Production Phase

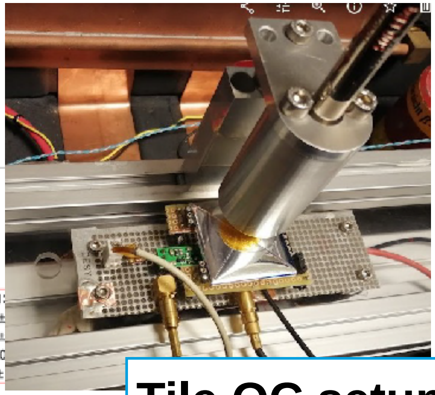
- **Tile wrapping and module assembly procedure:**
  - Now fully automated, wrapping 4 tiles per minute.
  - Gluing with pick & place: 1 module in < 10 minutes.
  - Procedure videos: [link1], [link2]
  - Scaling to other formats and large series still to be done.
- **New climate chamber in e-Lab.**
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





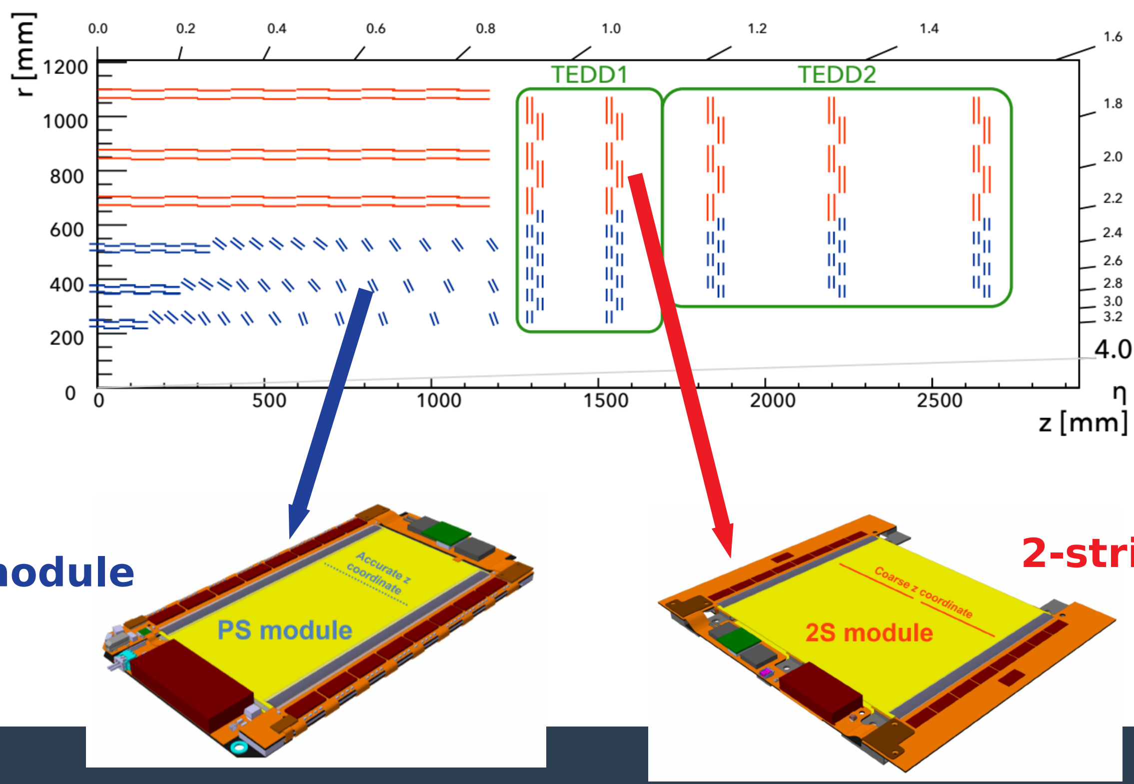
Climate Chamber:
Gain vs. Temperature





Tile QC setup

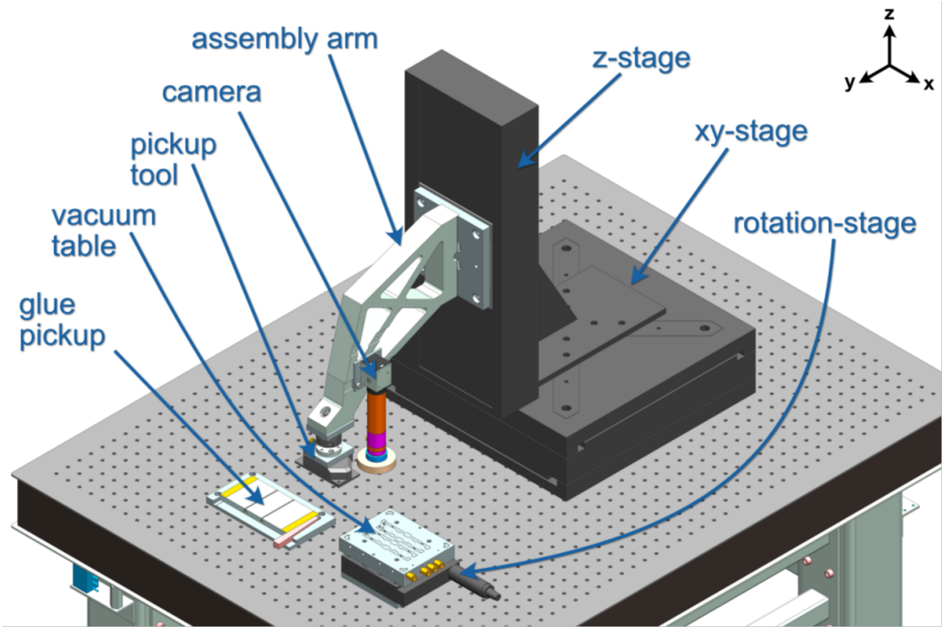
Phase-2 Upgrade: Outer Tracker

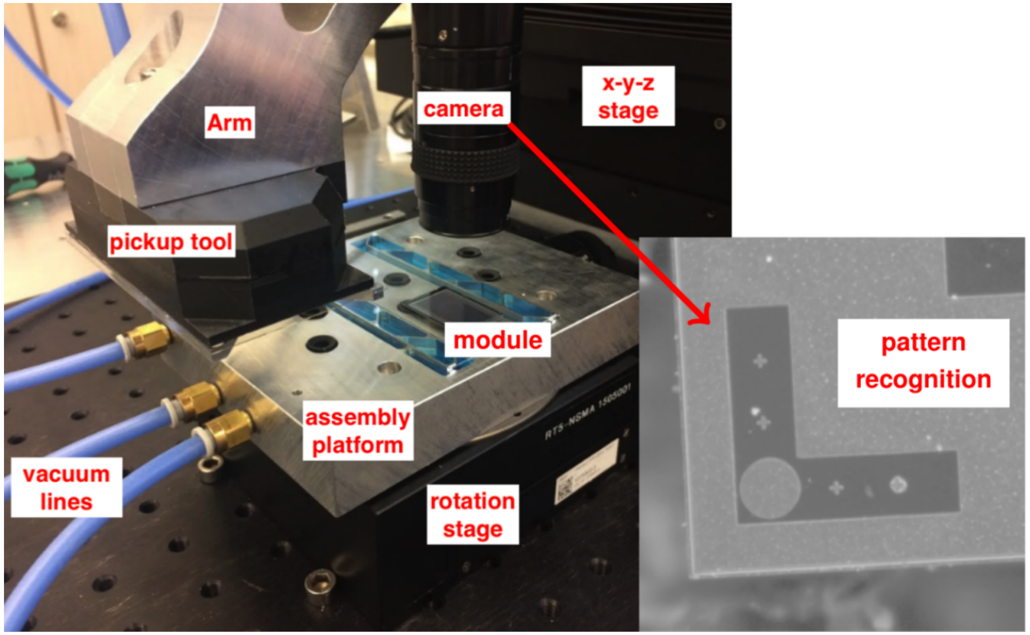


PS (Pixel Strip) module

2-strip (2S) module

PS Module Automated Assembly

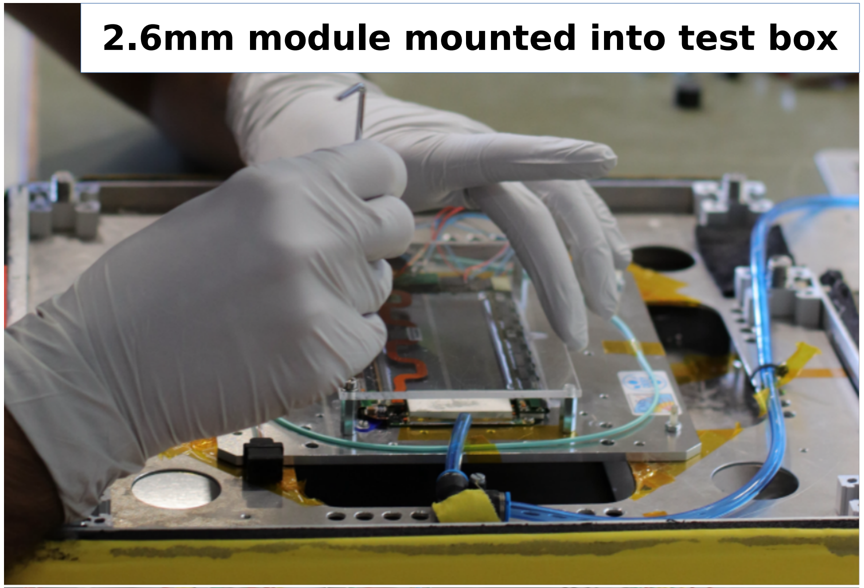


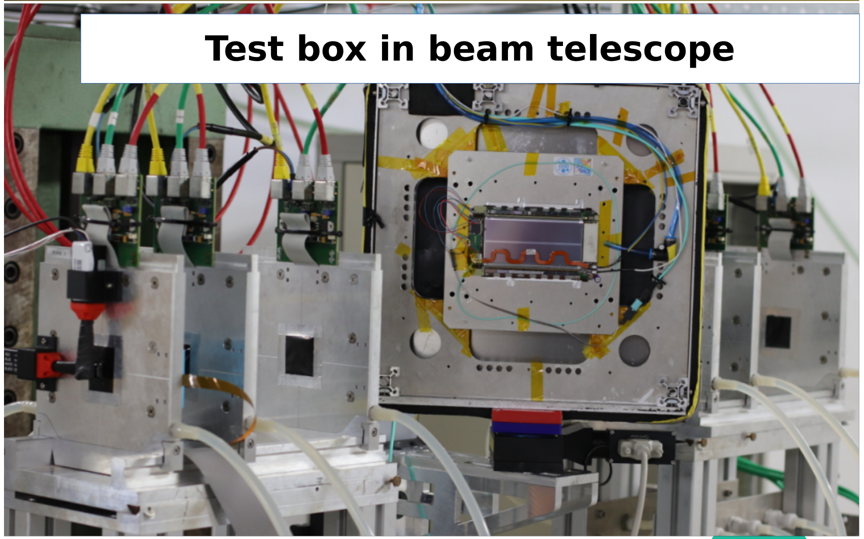


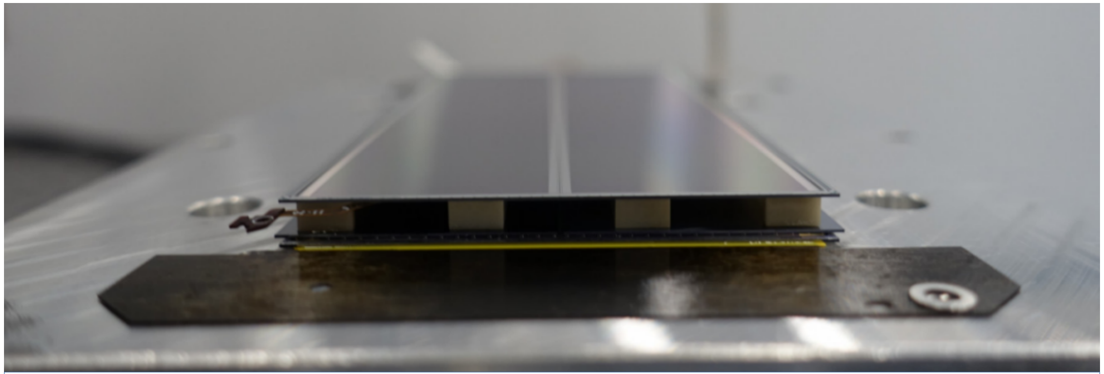
- **p_T discrimination on module requires sensor to be precisely aligned during assembly.**
  - Rotational misalignment below 800 µrad.
- **Sensor sandwich is assembled on a robotic stage.**
  - Relative alignment of object is measured with microscope camera and pattern recognition

PS Module Prototyping

- **Built two fully functional modules within specifications.**
- **2.6 mm sensor spacing:**
  - x=10µm (≤50µm)
  - y=53µm (≤100µm)
  - α=17µrad (≤800µrad)
- **4.0 mm sensor spacing:**
  - x=6µm (≤50µm)
  - y=66µm (≤100µm)
  - α=200µrad (≤800µrad)
- **Progress in debugging and setting up DAQ and test software.**
- **Preparing for data taking in beam mid-November.**

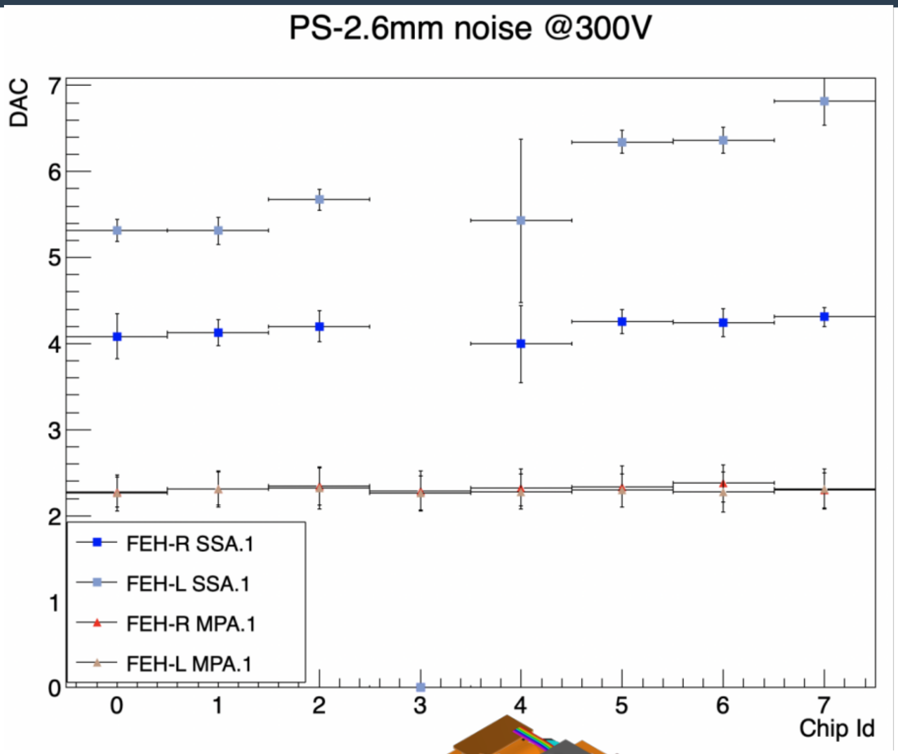

2.6mm module mounted into test box

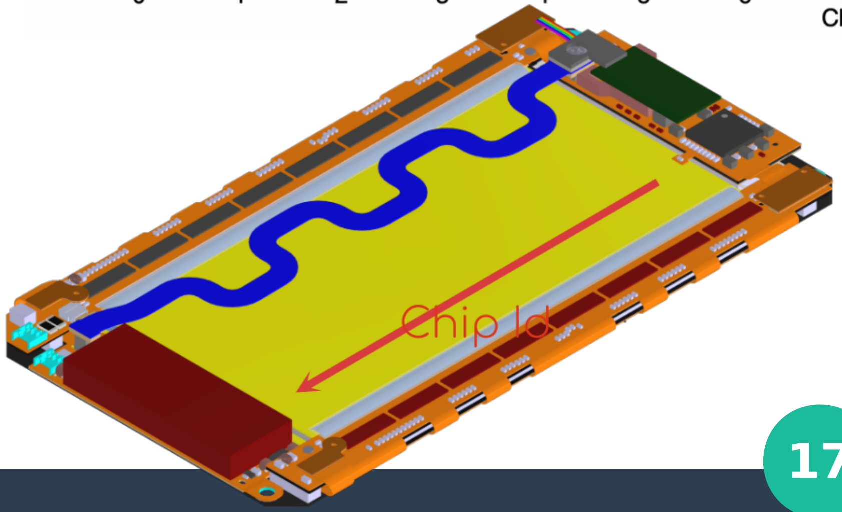

Test box in beam telescope


First 4.0 mm PS Sensor Sandwich assembled at DESY

Results from first functional 2.6 mm PS Module

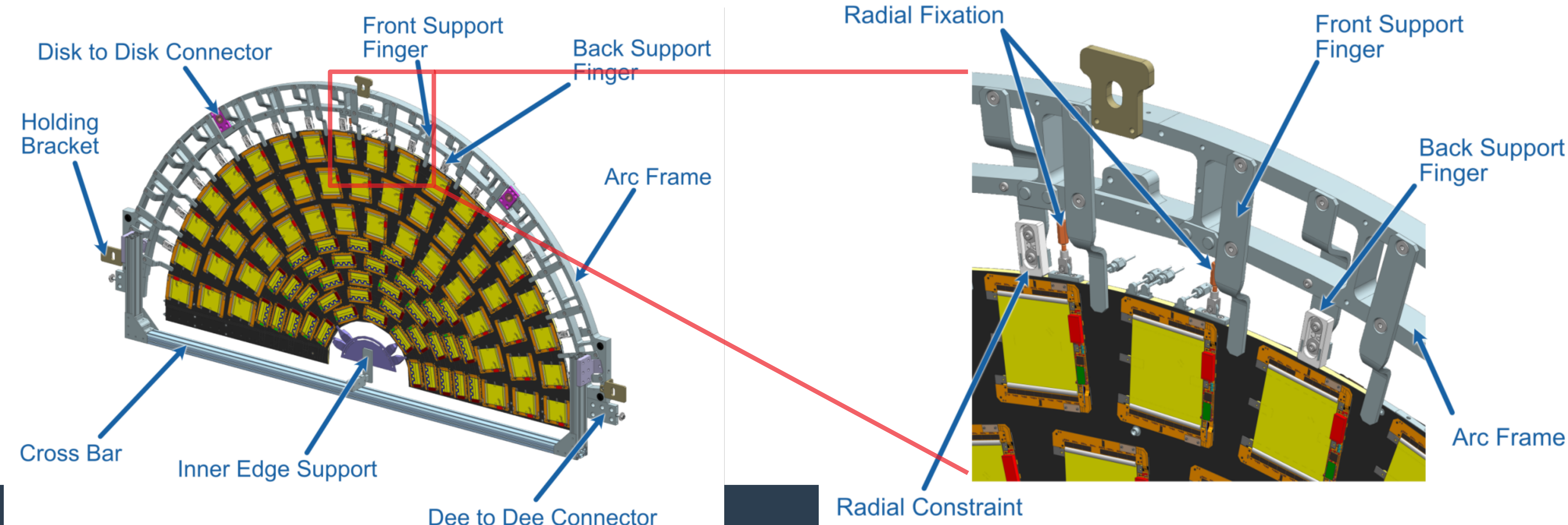
- **One of the first functional modules built within the collaboration.**
- **Module equipped with some preliminary components.**
- **Some hardware patches required with respect to final versions of electronics.**
- **Successful communication with the different components.**
- **Noise measurement at 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

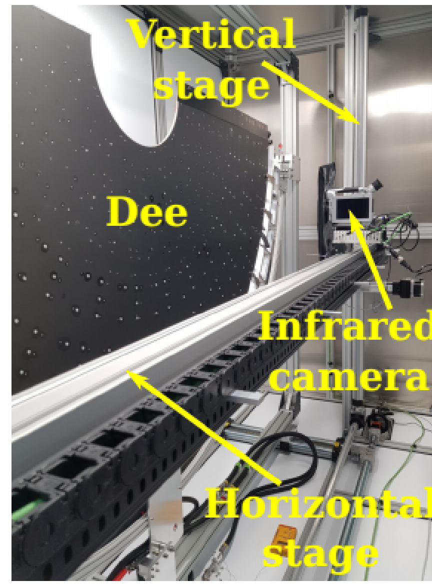
- **Local support structure in end caps is a half-disk (Dee).**
- **Modules are as close as ~1.3 mm to the Dee edges.**
  - Modules are offset in phi angle between front and back side of Dees to create overlaps.
- **Dee with modules cannot be manually handled.**
- **Dedicated holding structure - Arc 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.**

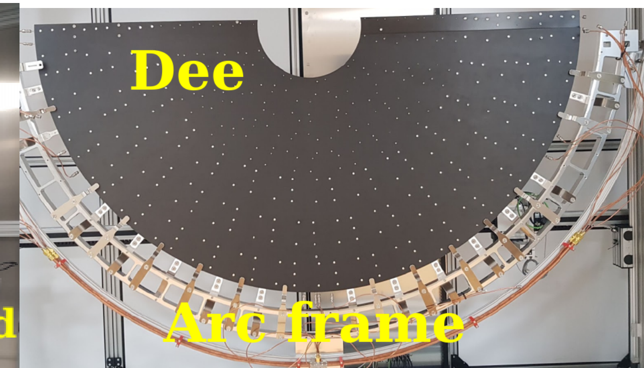


Infrared measurement of TEDD Dees

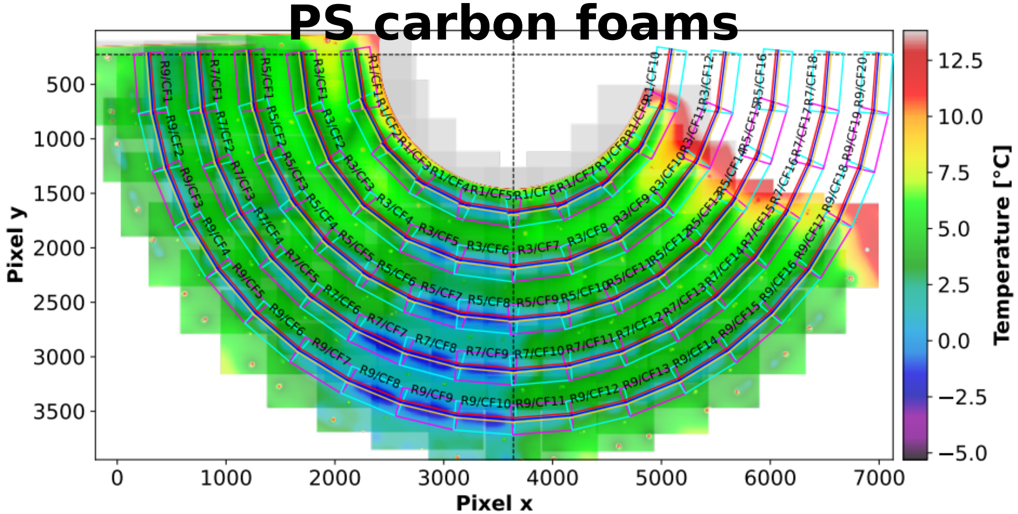
Setup overview

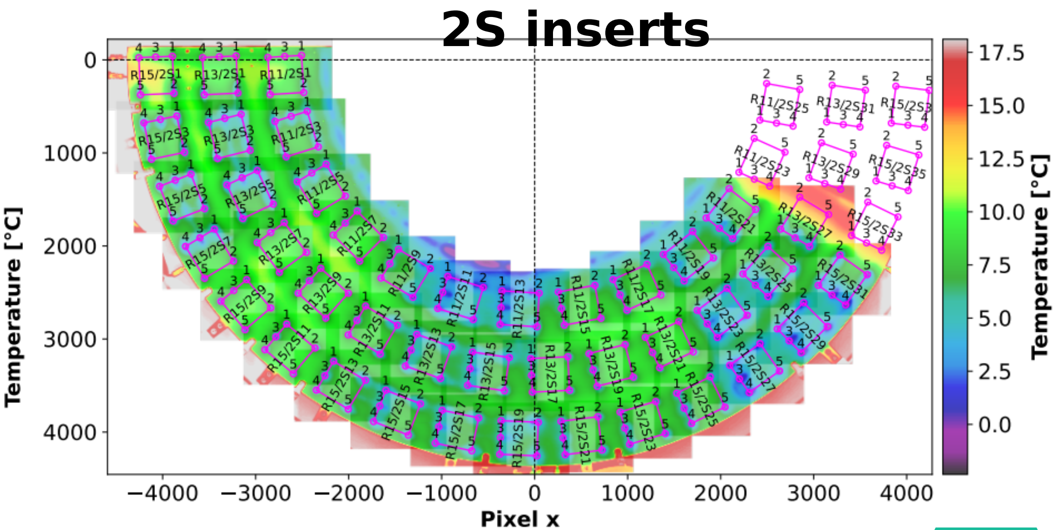
- **Important for thermal qualifications of the TEDD Dees – for testing and QC only.**
- **The Dee is mounted on an arc frame with a cooling manifold.**
- **The sectors are cooled simultaneously with a conventional cooling fluid.**
- **Infrared (IR) camera:**
  - Mounted on motorized stages.





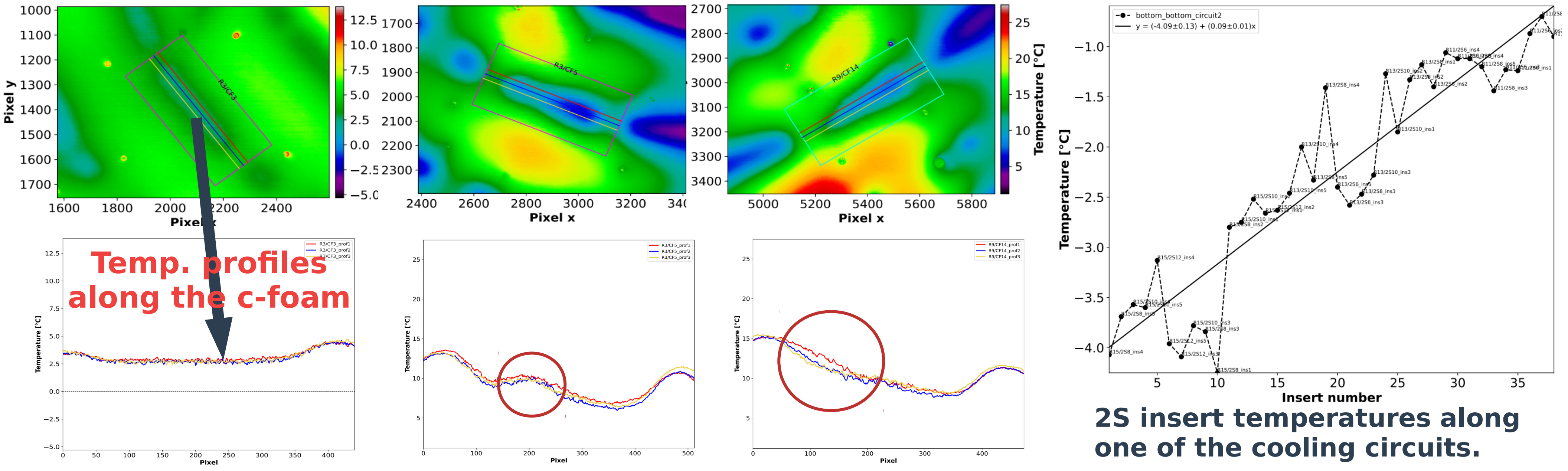
DESY dee prototype





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.

2S insert temperatures along one of the cooling circuits.

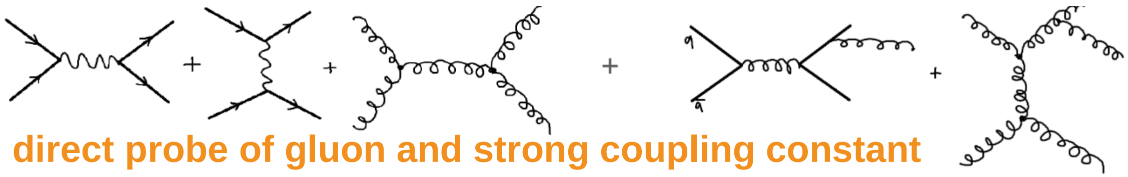
- **Automated extraction of features (PS c-foam temp. profiles, 2S insert temp.) from images.**
- **Impact of the defects on the cooling performance is being studied.**
- **Important to establish QC procedure – ongoing.**

Physics analyses

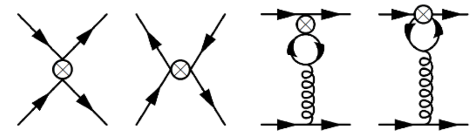
Simultaneous constraints on QCD and BSM

SMEFT interpretation of the inclusive jet production in pp collisions at 13 TeV.

SMEFT: Standard Model enhanced Effective Field Theory.



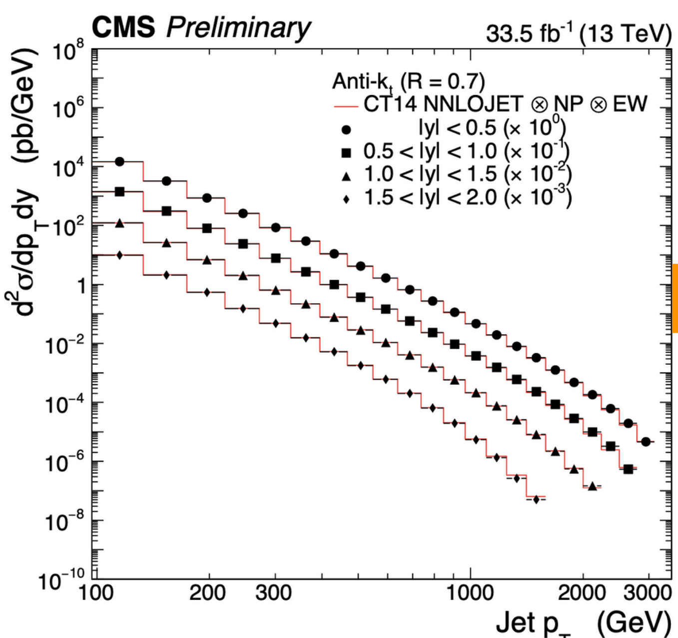
direct probe of gluon and strong coupling constant

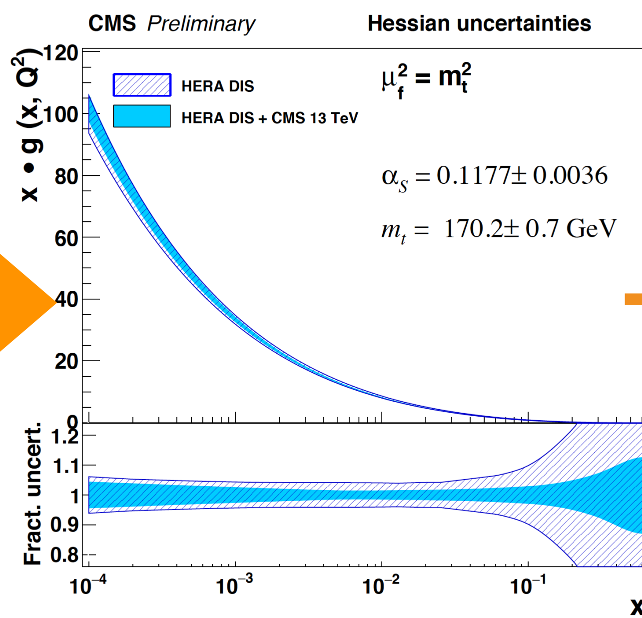


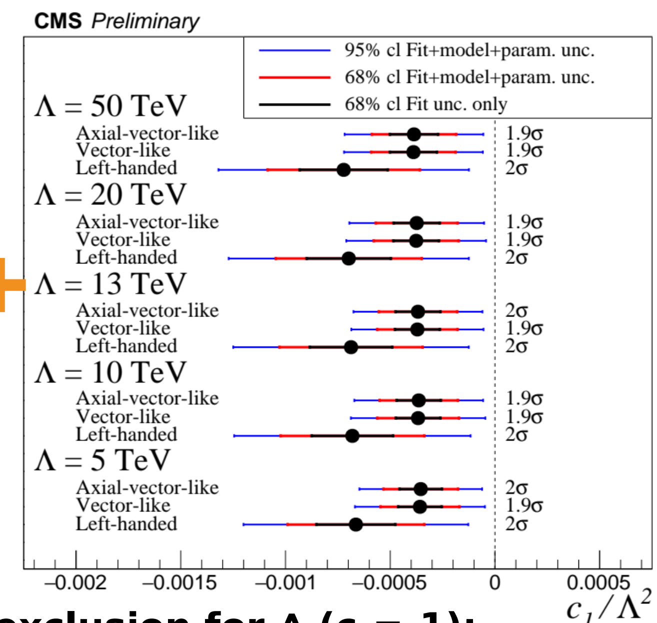
contact interactions

CMS-SMP-PAS-20-011

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







95% CL exclusion for Λ (c_1=-1):

Left-handed: Λ > 24 TeV

Vector like: Λ >32 TeV

Axial-vector like: Λ > 31 TeV

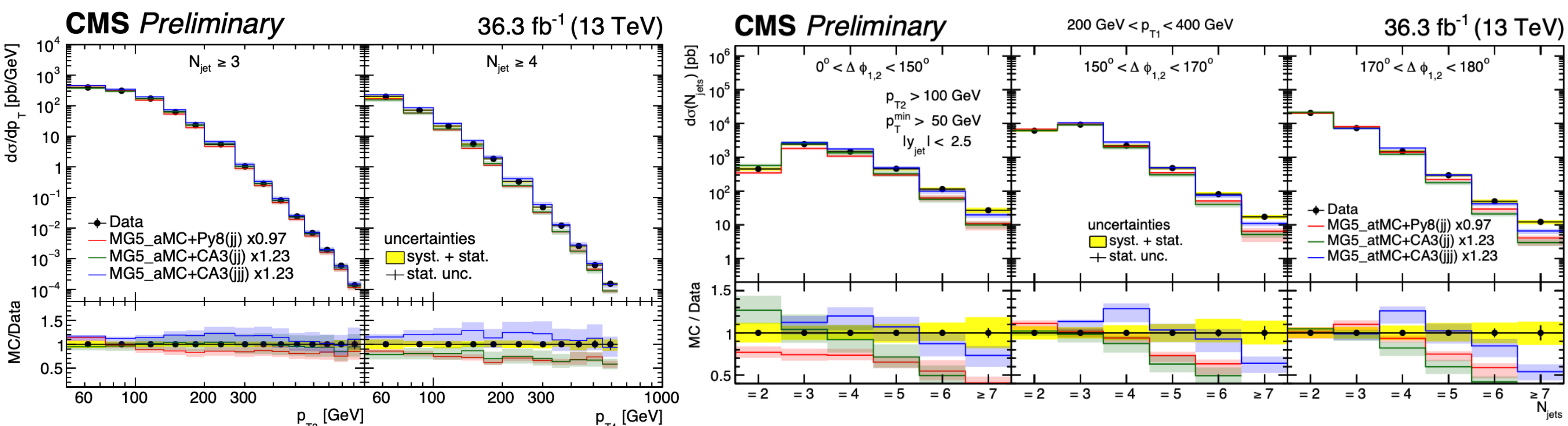
- **Improvement in PDF accuracy at high x**
- **Simultaneous extraction of QCD and BSM parameters**
- **No risk of absorbing BSM into PDFs**

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**

CMS-SMP-PAS-21-006

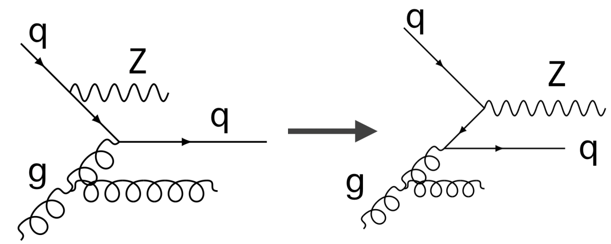


- **Measurements compared to LO (MadGraph, Pythia8, Herwig++)**
- **Comparison to NLO (MADGRAPH5_MC@NLO) with Pythia8 and CASCADE3 predictions**
- **For high jet multiplicities the lack of higher order contributions can be observed**

Azimuthal correlations in Z+jets events

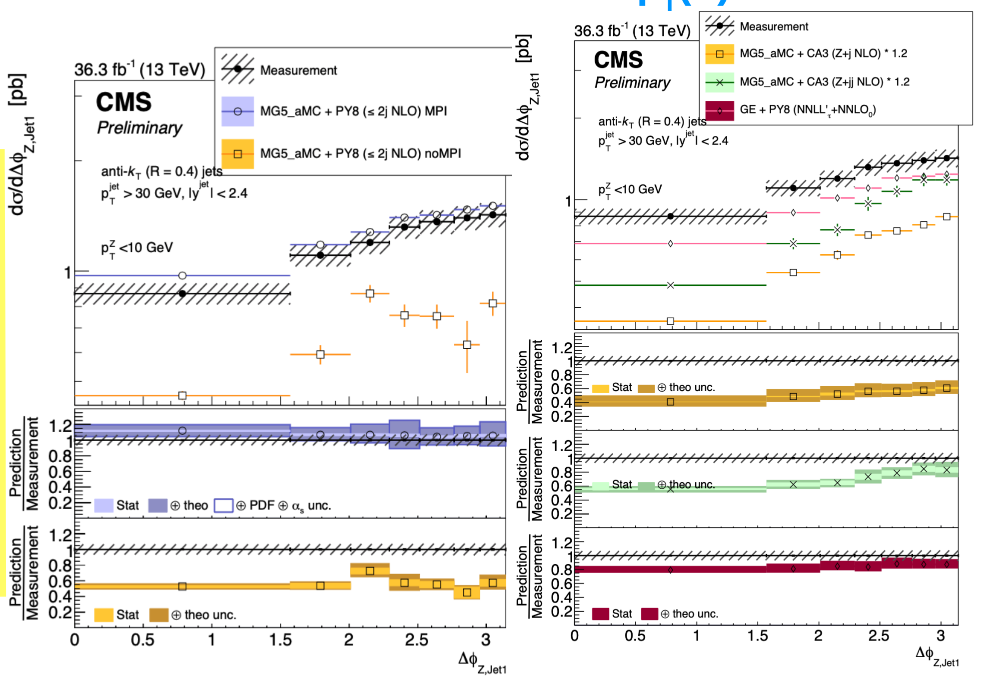
Particular interest in Parton Branching (PB) predictions

- **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

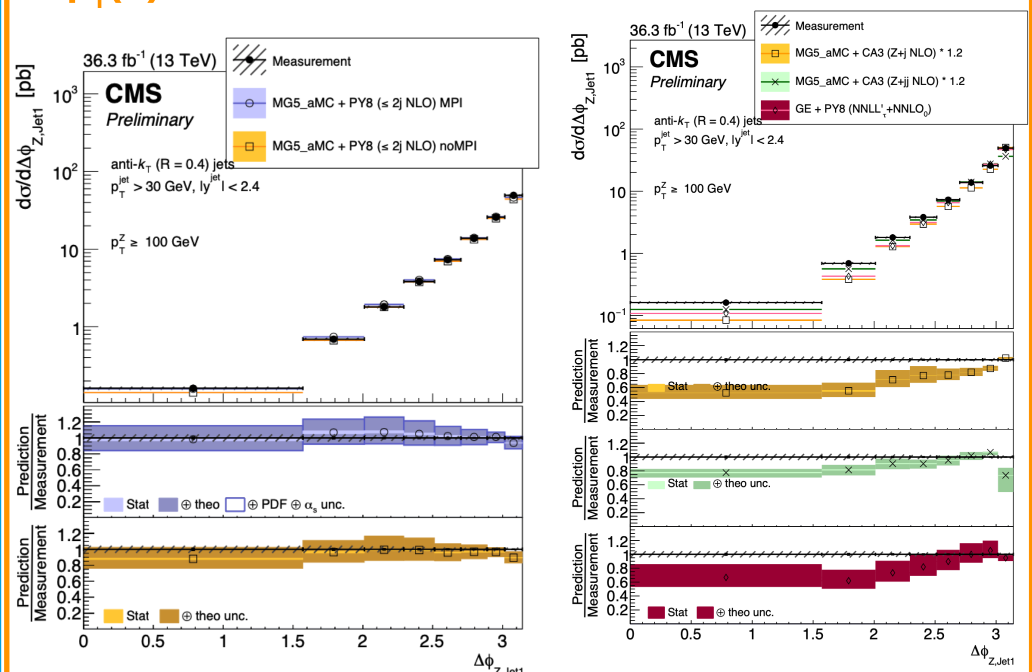


CMS-SMP-PAS-21-003

$p_T(Z) < 10$ GeV



$p_T(Z) > 100$ GeV

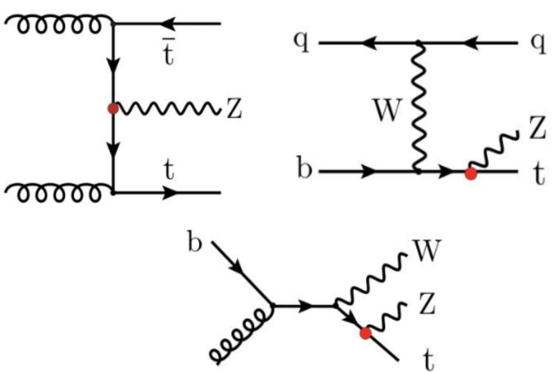


- **Z + jet measurements challenge theoretical predictions**
- **Good agreement achieved incl. contr. of multiparton interactions, parton shower, PB**

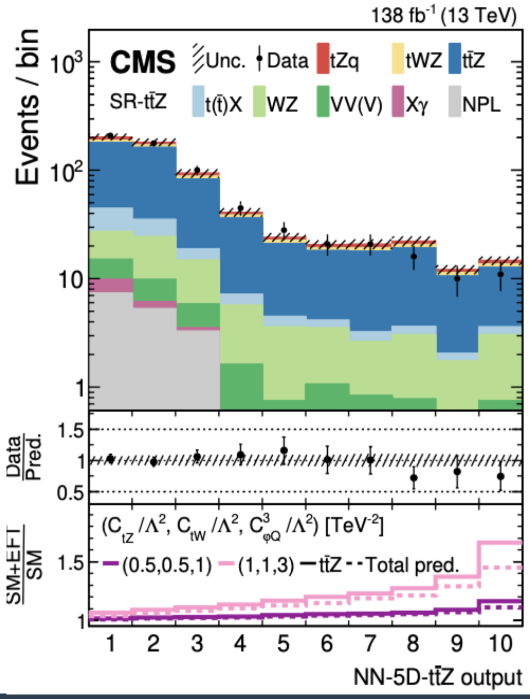
Probing t-Z couplings with EFT and ML

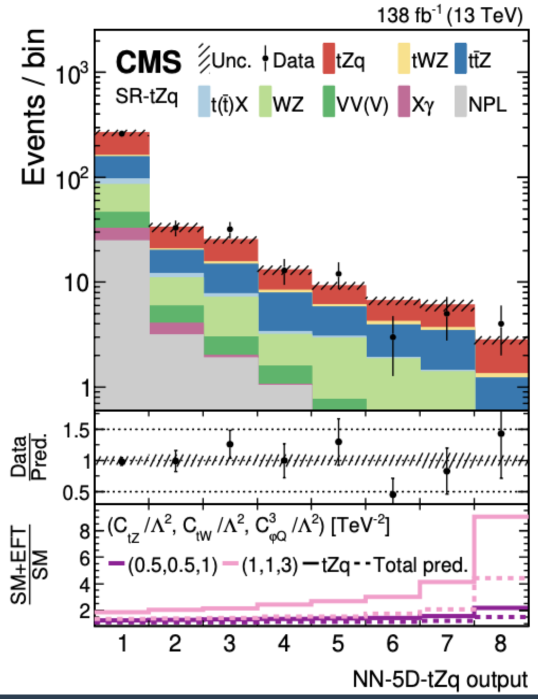
CERNCOURIER
Volume 61 Number 5 September/October 2021

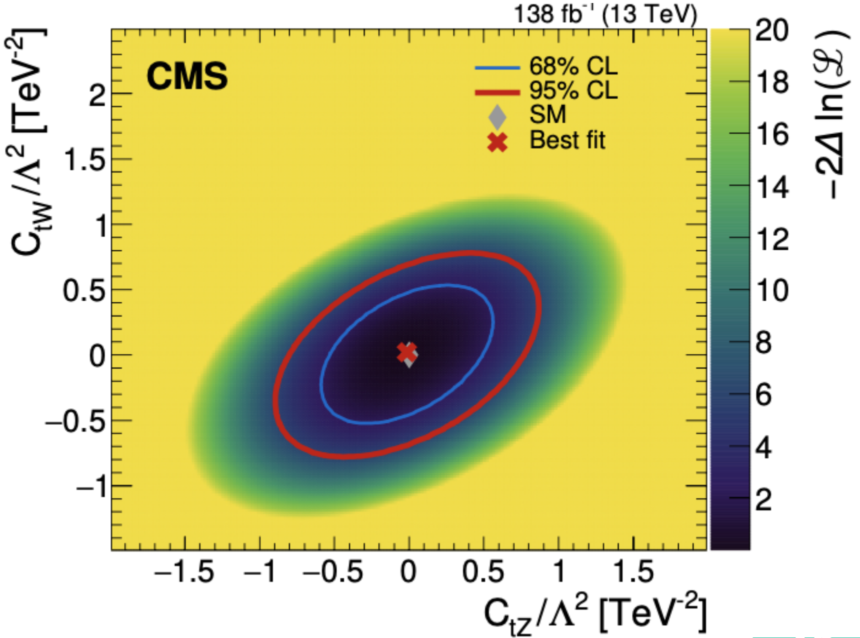
- t-Z coupling modified by various BSM scenarios.
- **Novel approach:** constrain several t-Z EFT operators in a simultaneous analysis of ttZ, tWZ, & tZq events:
  - Consider up to 5 operators simultaneously
  - Pioneer use of Deep Learning techniques



TOP-21-001, arXiv:2107.13896 (sub. to JHEP)



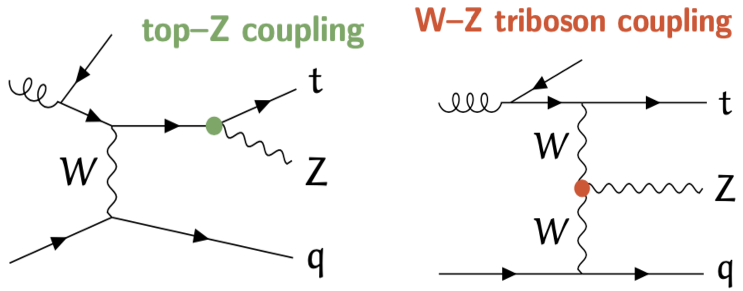




tZq production in final states with 3 leptons

Rare process, connects top with EWK sector

- EWK production → polarized top
- Sensitive to many EFT operators

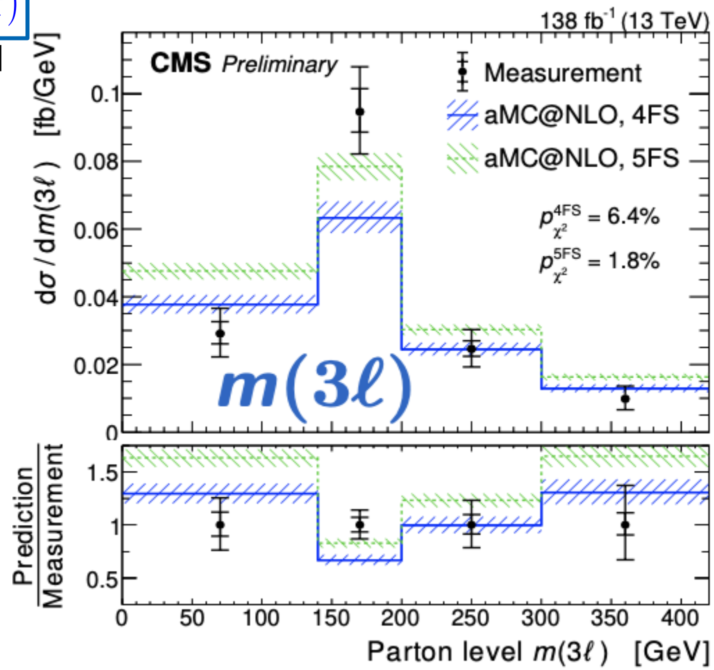


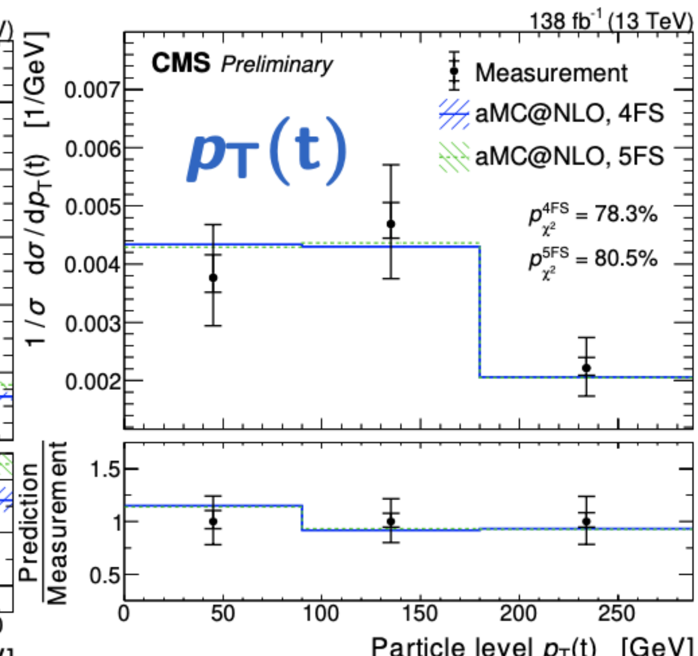
- First ever tZq differential measurements of top & Z observables, top-Z system, leptons
- First ever measurement of top spin asymmetry (A_ℓ) in tZq (proportional to polarization)

$$\boxed{A_\ell = 0.58^{+0.15}_{-0.16}(stat) \pm 0.06(syst)}$$

[consistent with SM prediction]

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





CMS-PAS-TOP-20-010

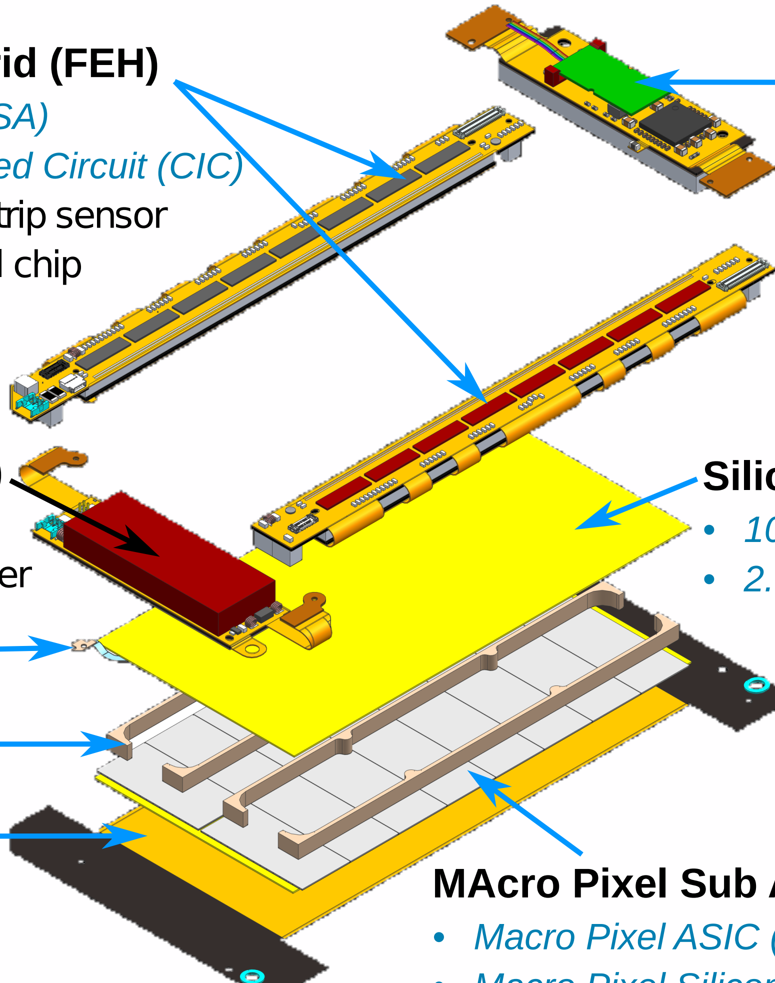
Summary

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

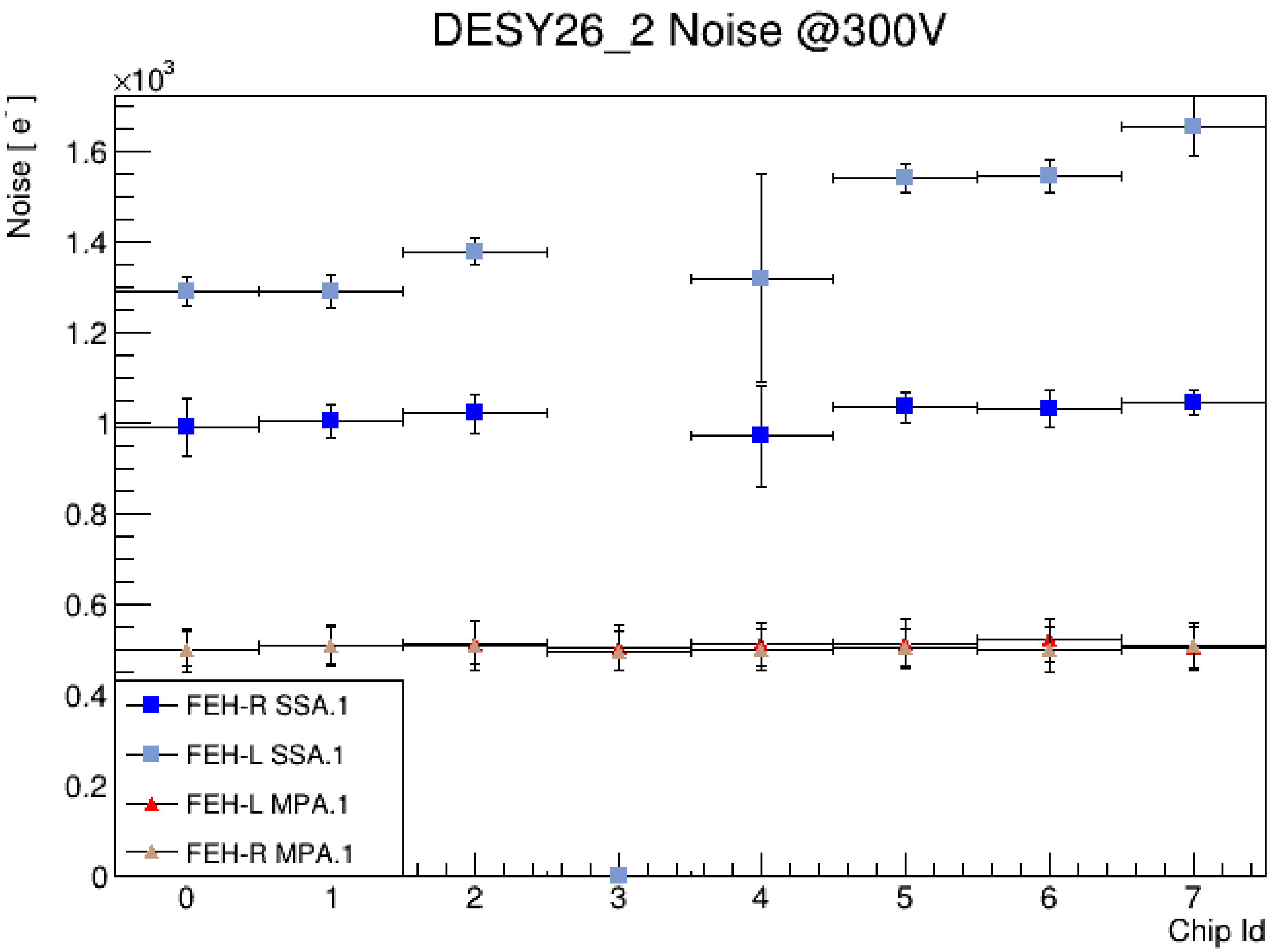
Silicon Strip Sensor
- *10 x 5 cm Silicon Strip Sensor*
- *2.5 cm long strips, 100 um pitch*

HV tail

AlN spacers

Carbon Foam (CF) baseplate

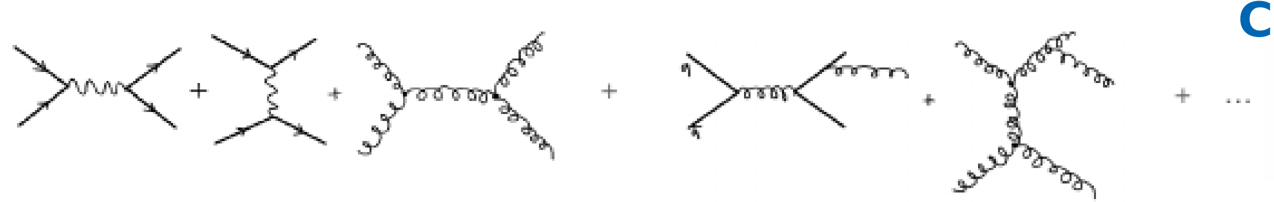
MAcro Pixel Sub Assembly (MaPSA)
- *Macro Pixel ASIC (MPA)*
- *Macro Pixel Silicon sensor 1400 x 100 um*
- Correlates signal from both sensors



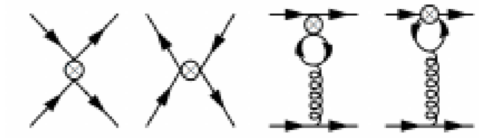
DESY26_2 Noise @300V
×10^3
Noise [e^-]
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
7
Chip Id
FEH-R SSA.1
FEH-L SSA.1
FEH-L MPA.1
FEH-R MPA.1

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



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

f(x, μ): PDF
(parton density function)

Tree-level x-sec SM+BSM

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{4\pi}{2\Lambda^2}\sum_n c_n O_n$$

Type of CI	c_1	c_3	c_5
Purely left-handed:	free	0	0
Vector-like:	free	$2c_1$	c_1
Axial-vector-like:	free	$-2c_1$	c_1

SM: Standard Model
EFT: Effective Field Theory
SMEFT: EFT-improved SM

- **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 χ^2 : $\mathbf{b^{th(min)}}$
  - PDF profiling performed using: **CT14 NLO and NNLO PDF sets.**
  - **Gluon PDF uncertainty is significantly reduced.**
  - Impact on α_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 ± 0.5(fit) + 0.2(scale) 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.

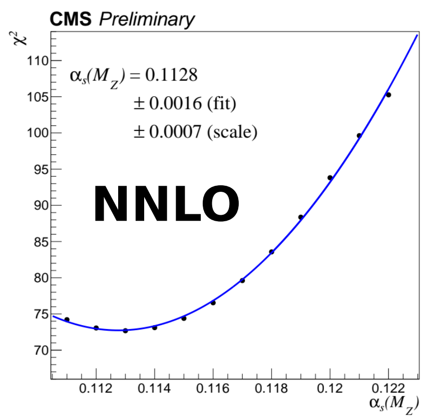
General PDF parametrization

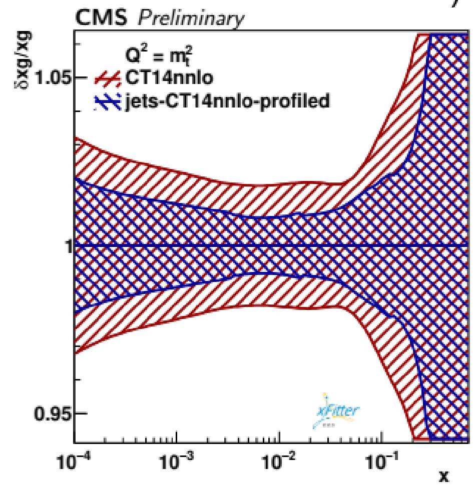
$$xf(x) = A_f x^{B_f}(1-x)^{C_f}(1+D_f x + E_f x^2)$$

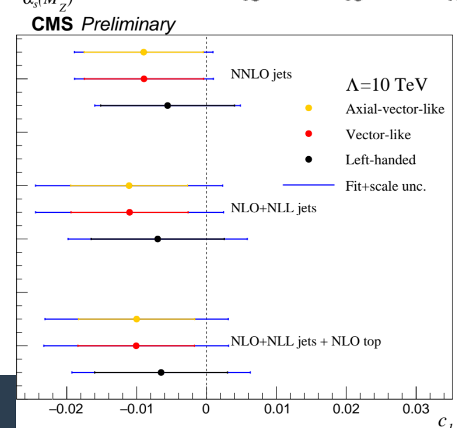
$$\chi^2 = \sum_{i=1}^{N_{\rm data}} \frac{\left(\sigma_i^{\rm exp} + \sum_\alpha \Gamma_{i\alpha}^{\rm exp} b_\alpha^{\rm exp} - \sigma_i^{\rm th} - \sum_\beta \Gamma_{i\beta}^{\rm th} b_\beta^{\rm th}\right)^2}{\Delta_i^2} + \sum_\alpha (b_\alpha^{\rm exp})^2 + \sum_\beta (b_\beta^{\rm th})^2$$

$$f_0' = f_0 + \sum_\beta b_\beta^{\rm th(min)} \left(\frac{f_\beta^+ - f_\beta^-}{2} - b_\beta^{\rm th(min)} \frac{f_\beta^+ + f_\beta^- - 2f_0}{2} \right)$$

Original central PDF







Measurement and QCD analysis of double-differential inclusive jet cross sections

Analysis strategy and results [2]

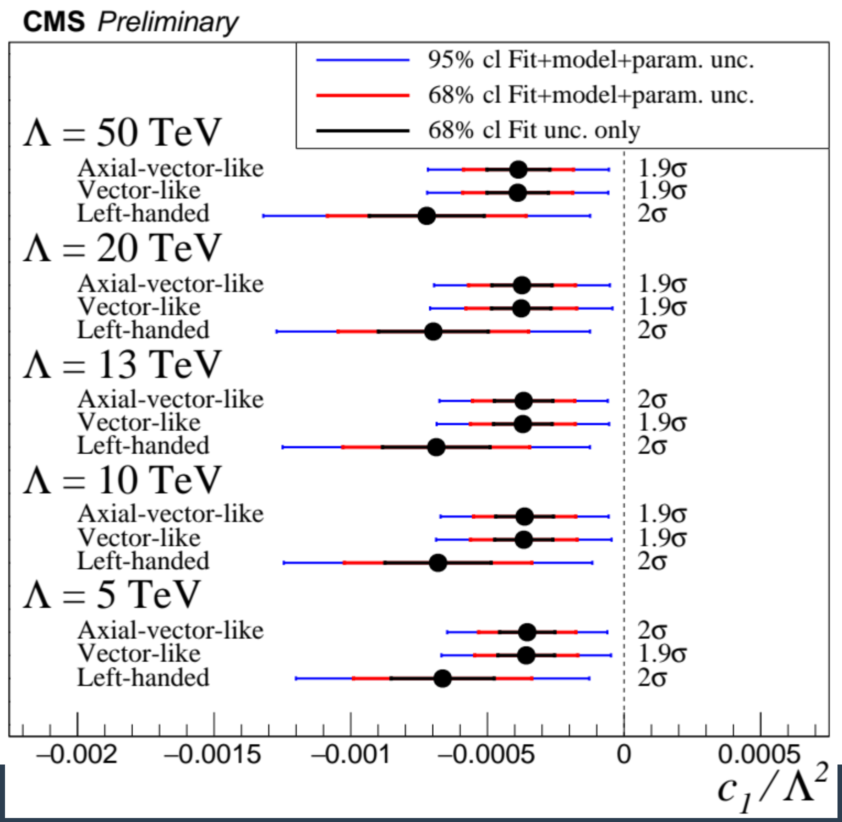
- **SMEFT interpretation at NLO:**
  - Simultaneous extraction of PDFs, α_S, m_t, and the CI Wilson coefficient c_1.
  - Perform (i) **SM only fit** (ii) **SMEFT fit**.
    - Resulting PDFs with both fits are consistent.
    - α_S and m_t values for both fits are consistent.
  - SMEFT fit:
    - Smaller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

SM fit

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

SMEFT fit

$$\alpha_S = 0.1187 \pm 0.0016(\text{fit}) \pm 0.0030(\text{model and param.})$$
$$m_t^{\text{pole}} = 170.4 \pm 0.6(\text{fit}) \pm 0.3(\text{model and param.})\,\text{GeV}.$$



Probing EFT operators in the associated production of top quarks with a Z boson

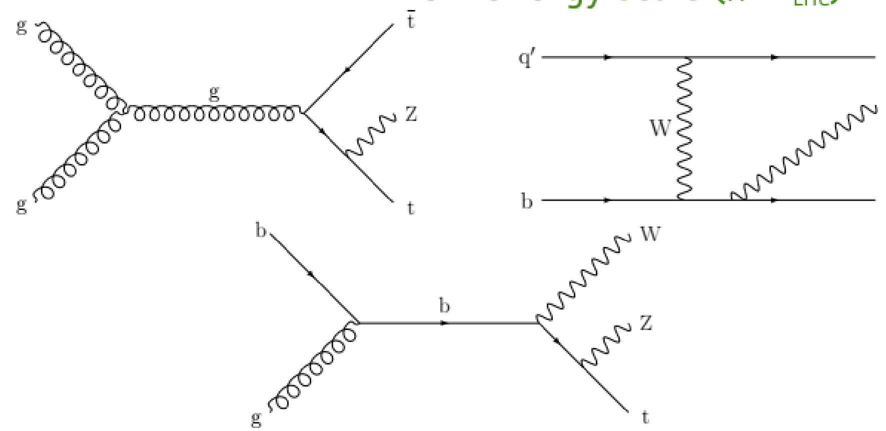
- **CMS-TOP-21-001: arXiv 2107.13896 (submitted to JHEP)**
- **Featured in the CERN Courier (Sep/Oct 2021): Learning to detect new top-quark interactions**
- **No BSM particles observed at the LHC: possible that $E_{BSM} >> E_{LHC}$.**
- **Effective Field Theory (EFT) – low energy approximation of a theory characterized by a large energy scale (Λ).**
- **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 ↔ interaction strengths

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{d,i} \frac{c_i^d}{\Lambda^{d-4}} \mathcal{O}_i^d$$

Higher-order operators

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



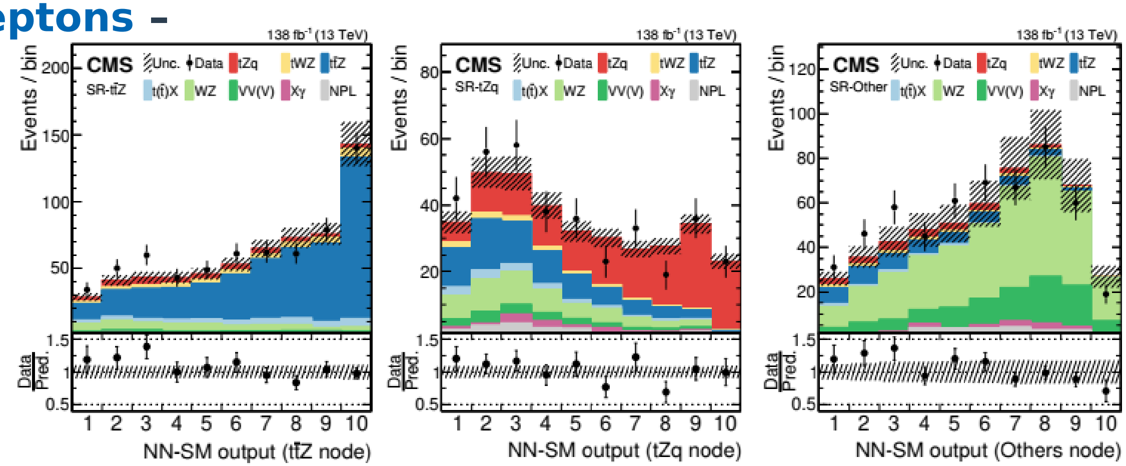
- **Focus on a subset of 5 operators:**
  - O_{tZ} , O_{tW} : induce electroweak dipole moment of the top quark.
  - $O^{3}_{\varphi Q}$: left-handed SU(2) triplet current operator.
  - $O^{-}_{\varphi Q}$, $O_{\varphi t}$: neutral current operators that modify the ttZ coupling for left and right handed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

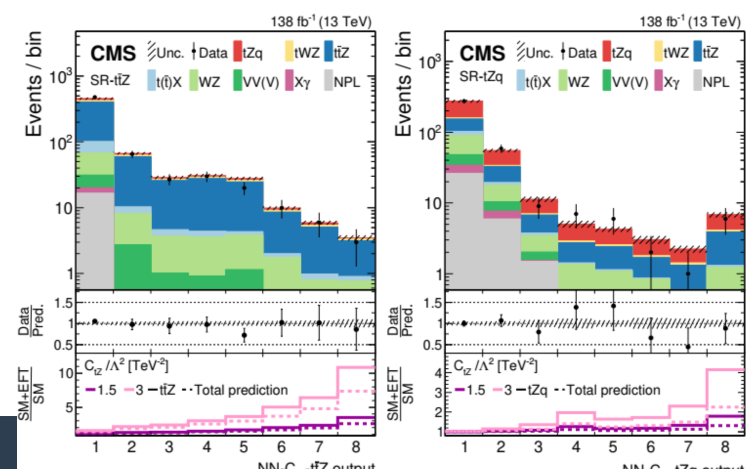
Probing EFT operators in the associated production of top quarks with a Z boson

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.

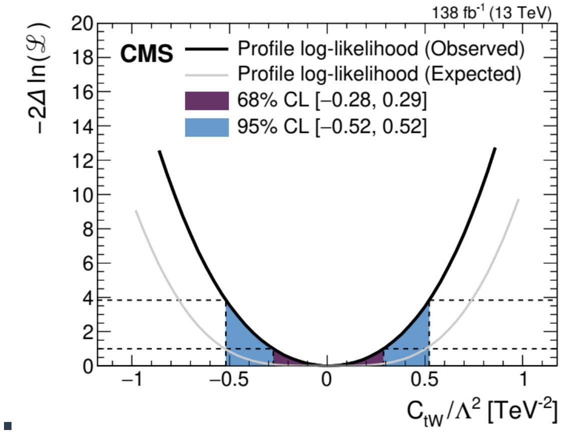
Selection requirement	SR-3ℓ	SR-$t\bar{t}$Z-4ℓ	WZ CR	ZZ CR
Lepton multiplicity	=3	=4	=3	=4
$m_{3\ell} - m_Z$	—	—	>15 GeV	—
Z boson candidates multiplicity	=1	=1	=1	=2
Jet multiplicity	≥2	≥2	—	—
b jet multiplicity	≥1	≥1	=0	—
p_T^{miss}	—	—	>50 GeV	—

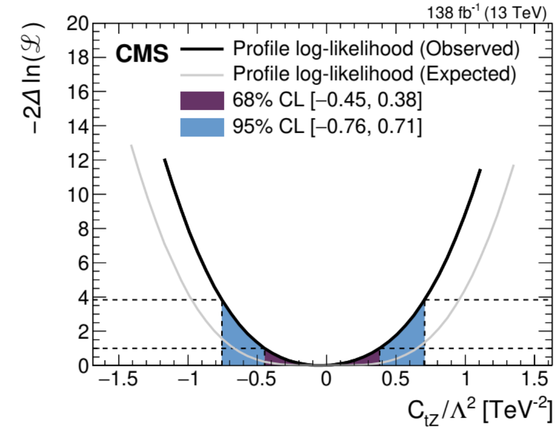




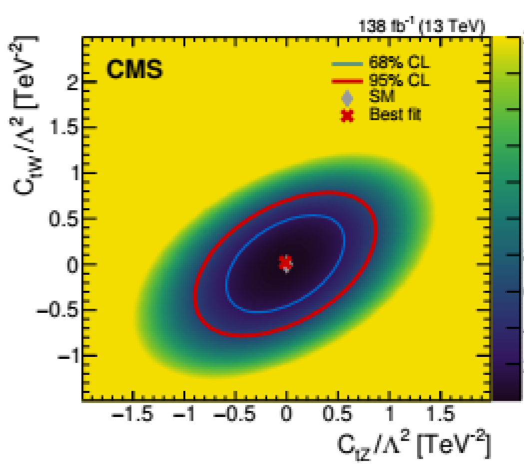
Probing EFT operators in the associated production of top quarks with a Z boson
Results

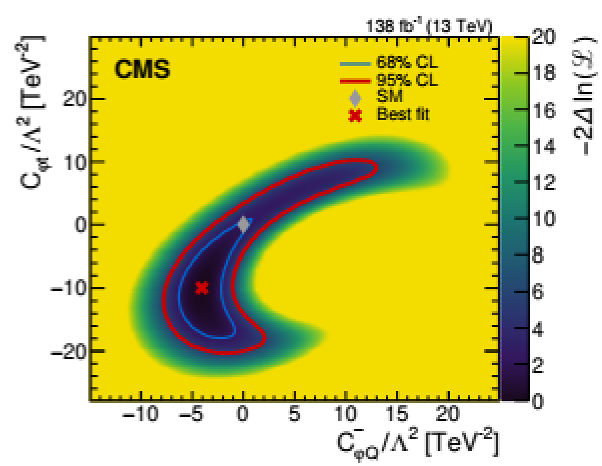
- **Results are extracted from a simultaneous fit to data in 6 categories (4 signal and 2 bkg).**
- **1D fit: Values of other WCs set to the SM value of 0.**
- **5D fit: All WCs fitted simulataneously.**
- **2D scans for the most correlated WCs.**
- **Results are consistent SM expectations.**
- **First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





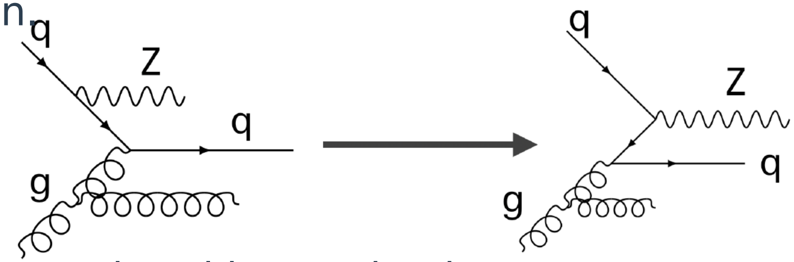
WC/Λ^2 [TeV^{-2}]	95% CL confidence intervals: Other WCs fixed to SM, Expected	Other WCs fixed to SM, Observed	5D fit, Expected	5D fit, Observed
c_{tZ}	$[-0.97, 0.96]$	$[-0.76, 0.71]$	$[-1.24, 1.17]$	$[-0.85, 0.76]$
c_{tW}	$[-0.76, 0.74]$	$[-0.52, 0.52]$	$[-0.96, 0.93]$	$[-0.69, 0.70]$
$c^3_{\varphi Q}$	$[-1.39, 1.25]$	$[-1.10, 1.41]$	$[-1.91, 1.36]$	$[-1.26, 1.43]$
$c^-_{\varphi Q}$	$[-2.86, 2.33]$	$[-3.00, 2.29]$	$[-6.06, 14.09]$	$[-7.09, 14.76]$
$c_{\varphi t}$	$[-3.70, 3.71]$	$[-21.65, -14.61] \cup [-2.06, 2.69]$	$[-16.18, 10.46]$	$[-19.15, 10.34]$





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.**

Fixed-order perturbative QCD calculation at NLO

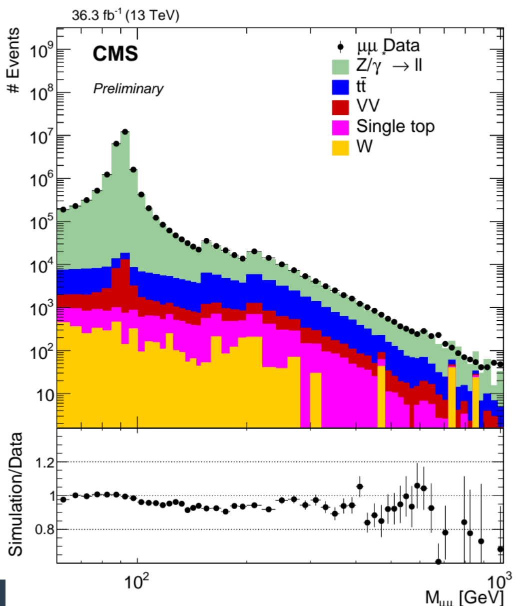
With PB TMD

generator	PDF	matrix element	tune
MG5_AMC+PY8 ($\leq 2j$ NLO) [33]	NNPDF 3.0 (NLO) [37]	NLO ($2 \to Z + 0, 1, 2$)	CUETP8M1 [35]
MG5AMC+CA3 ($Z + 1$) NLO [33]	PB-NLO-set2 (NLO) [19]	NLO ($2 \to Z + 1$)	–
MG5AMC+CA3 ($Z + 2$) NLO [33]	PB-NLO-set2 (NLO) [19]	NLO ($2 \to Z + 2$)	–
GENEVA NNLO [21–24]	NNPDF 3.1 (NLO) [39]	NNLO ($2 \to Z$)	CUETP8M1

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}, $\Delta\varphi(Z, jet_1)$, $\Delta\varphi(jet_1, jet_2)$.**
  φ: 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 → Particle level x-sec.



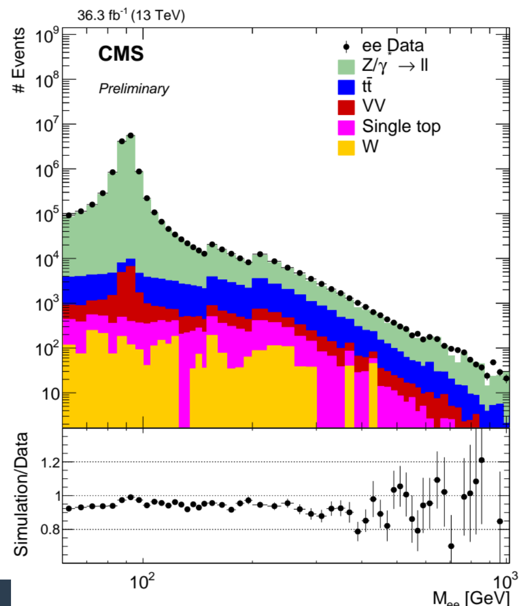


Table 2: Phase space of the measurement at particle level.

selection	cut	
electron: leading (subleading)	$p_T > 25(20)$ GeV	$\lvert\eta_e\rvert < 2.4$
muon: leading (subleading)	$p_T > 25(20)$ GeV	$\lvert\eta_\mu\rvert < 2.4$
lepton-jet isolation	$\Delta R_{l,j} > 0.4$	
$m_{l^+l^-}$	$76 < m_{l^+l^-} < 106$ GeV	
jet	$p_T > 30$ GeV	$\lvert\eta_{jet}\rvert < 2.4$

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.**

$\Delta\varphi(Z, jet_1)$

$p_T(Z)<10$ GeV **$30<p_T(Z)<10$ GeV** **$p_T(Z)>10$ GeV**