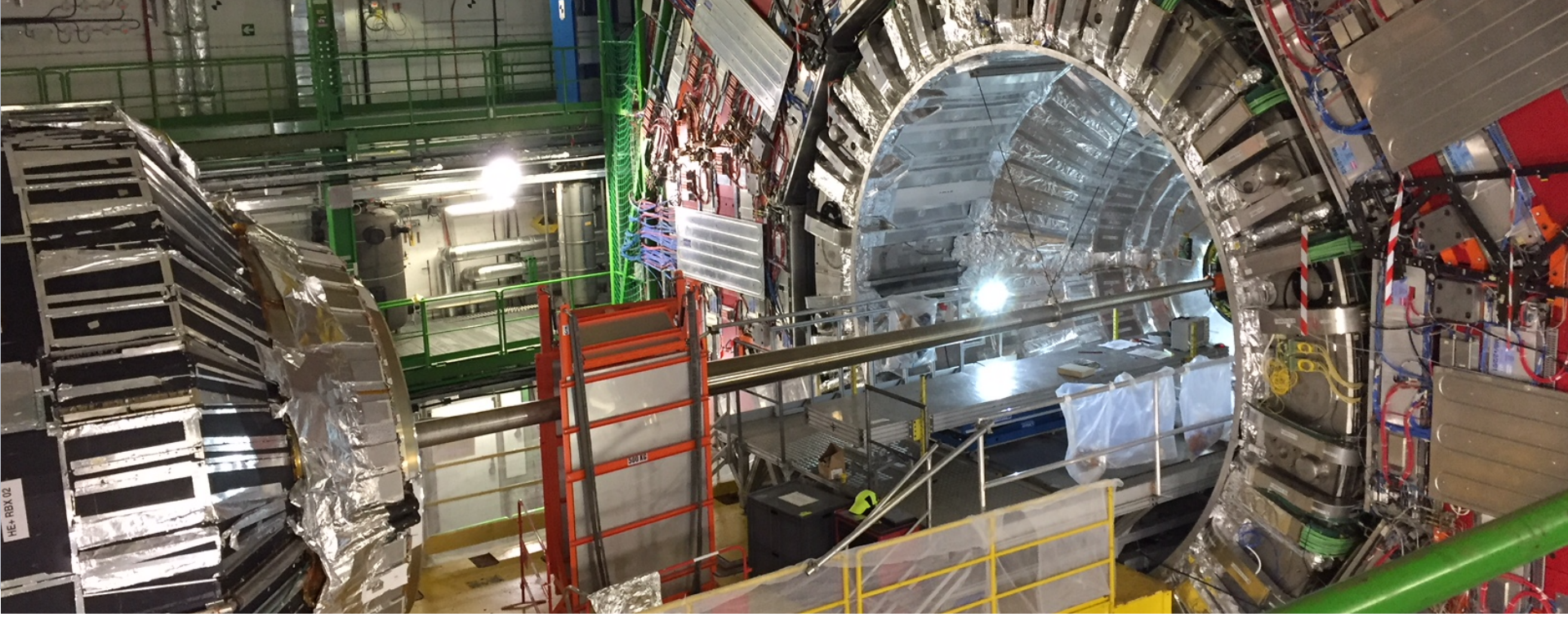


CMS highlights and LHC status

A. de Wit on behalf of the DESY CMS group

87th meeting of the DESY Physics Review Committee

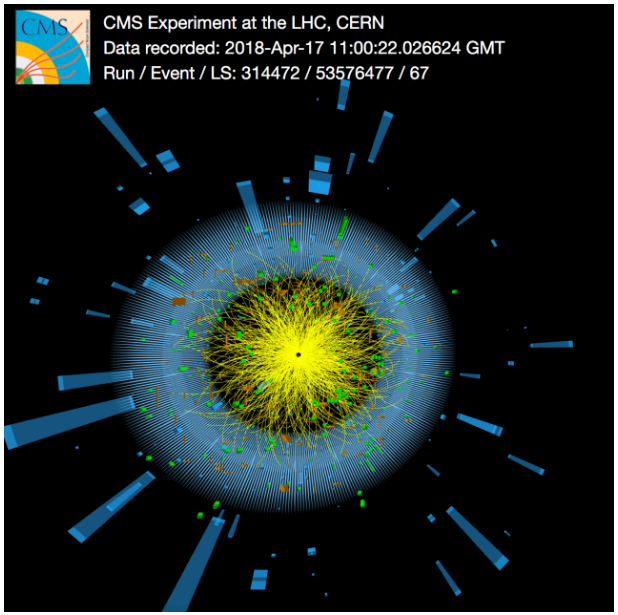
Open session, May 21st 2019

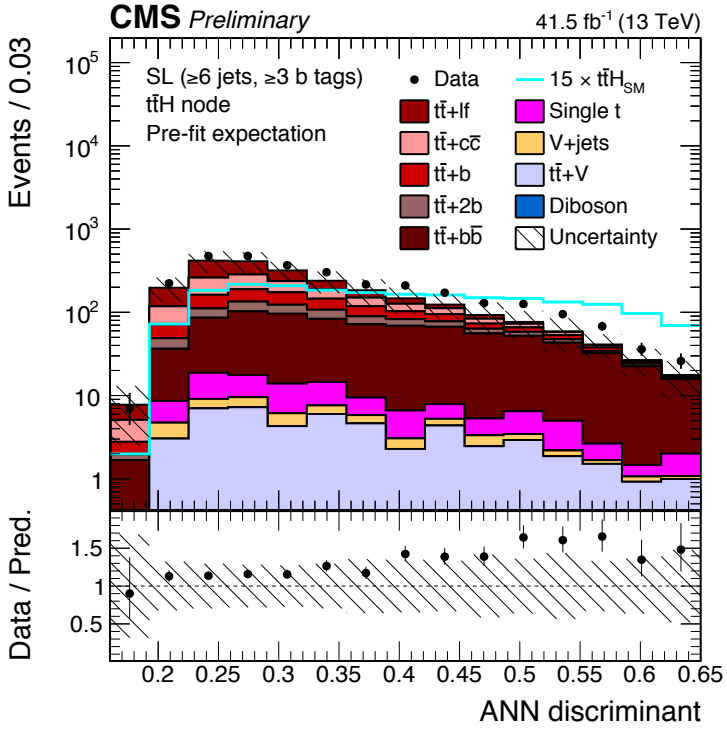
HELMHOLTZ SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN

DESY.

Outline

- **LHC status**
- **Tracker alignment**
- **Online luminometer: BCM1F detector**
- **Endcap calorimeter upgrade**
- **Phase-2 outer tracker upgrade**
- **Physics analysis highlights**
  - Top
  - Exotic new physics
  - SUSY
  - Higgs
  - QCD
  - Future
- **Summary**

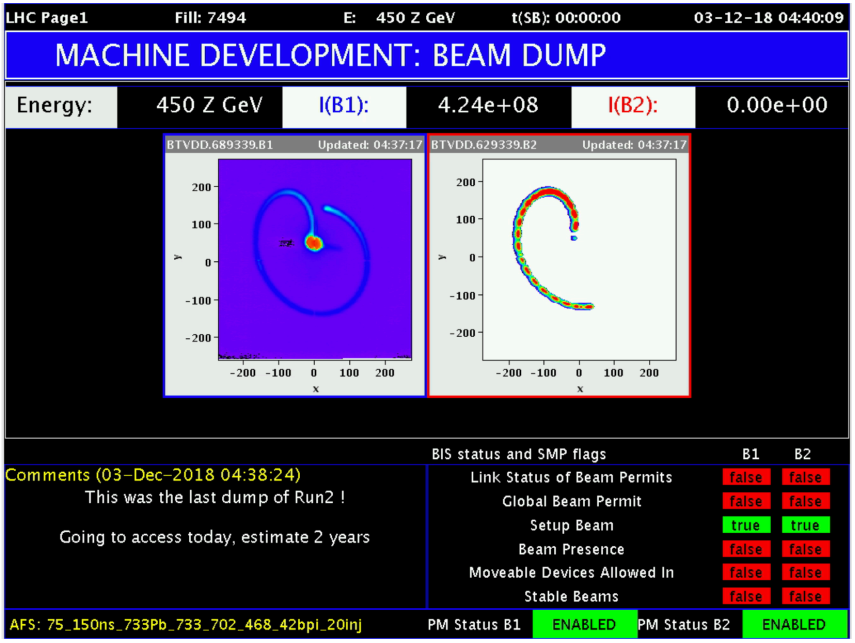


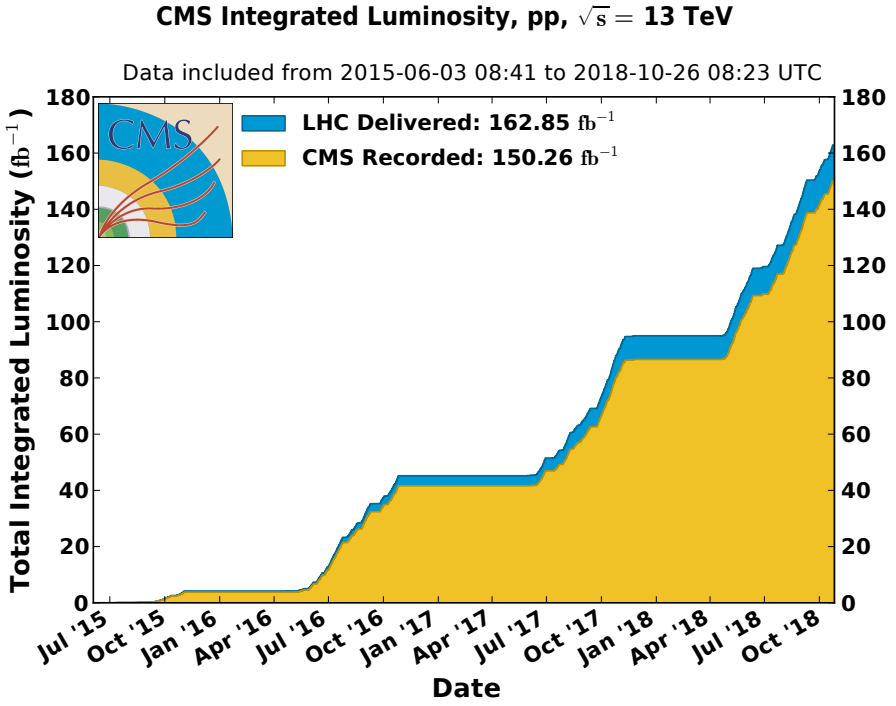


LHC Status

Summary of Run 2

- **A very successful Run 2 has come to an end**
  - p-p collisions: more than 160 fb^{-1} delivered to both ATLAS and CMS @ $\sqrt{s}$=13 TeV
  - Many PbPb, pPb, and special low-pileup runs taken throughout Run 2
- LS 2 under way until re-start in 2021
  - Increase in centre-of-mass energy from 13 to 14 TeV under discussion
  - Expect ~20/fb delivered to both ATLAS and CMS in 2021, ~100/fb per year in following years



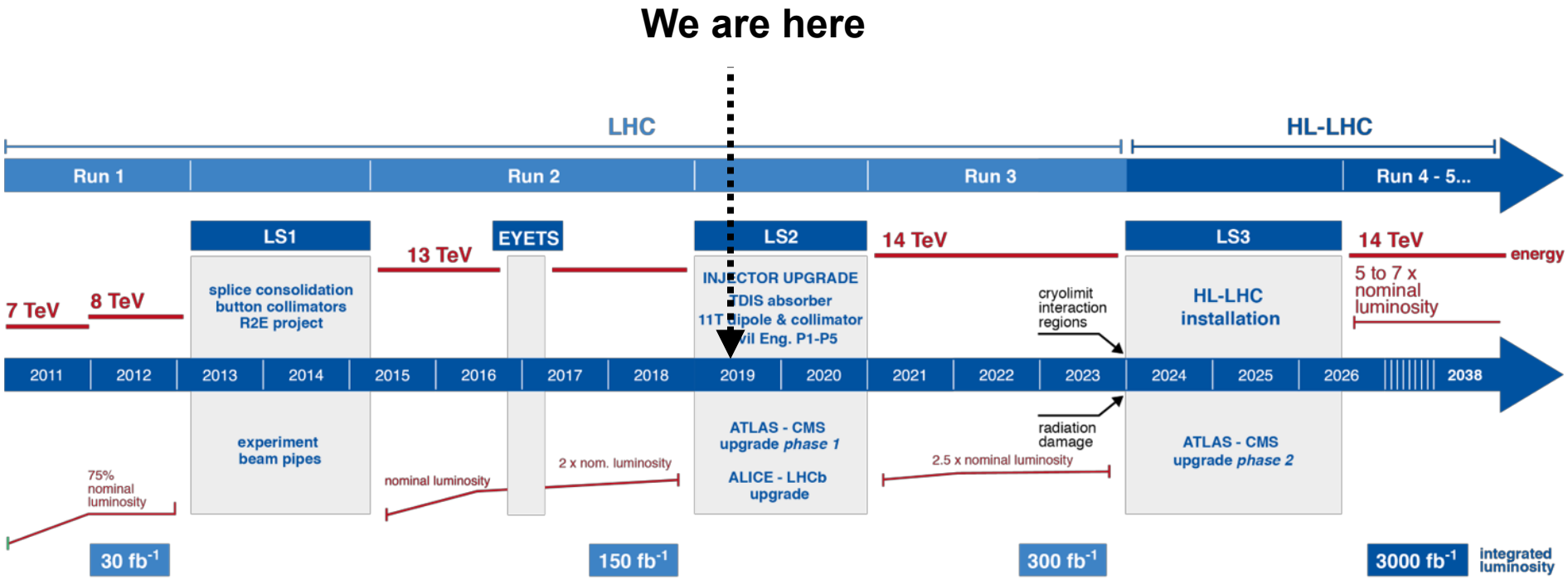


https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults

LHC status

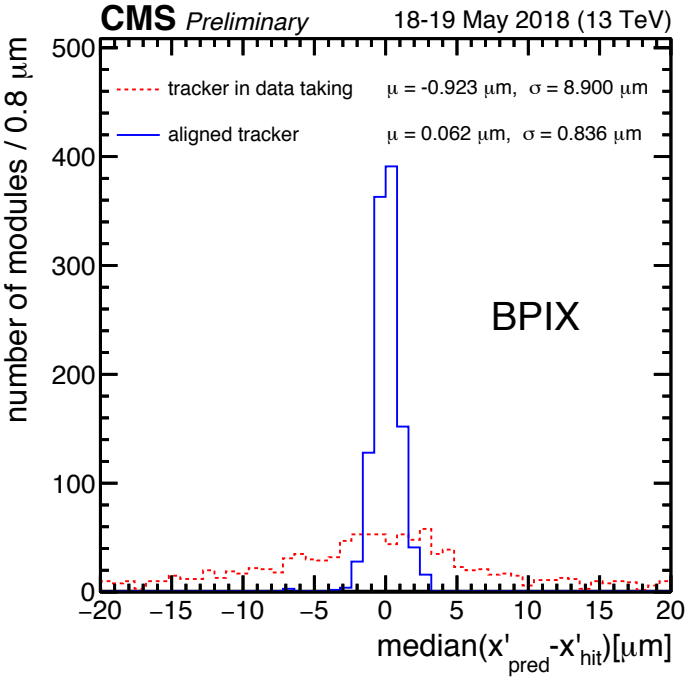
The road ahead

- So far we have collected ~5% of the total integrated luminosity the LHC and HL-LHC will deliver
- Preparations for high luminosity era continue to be in full swing

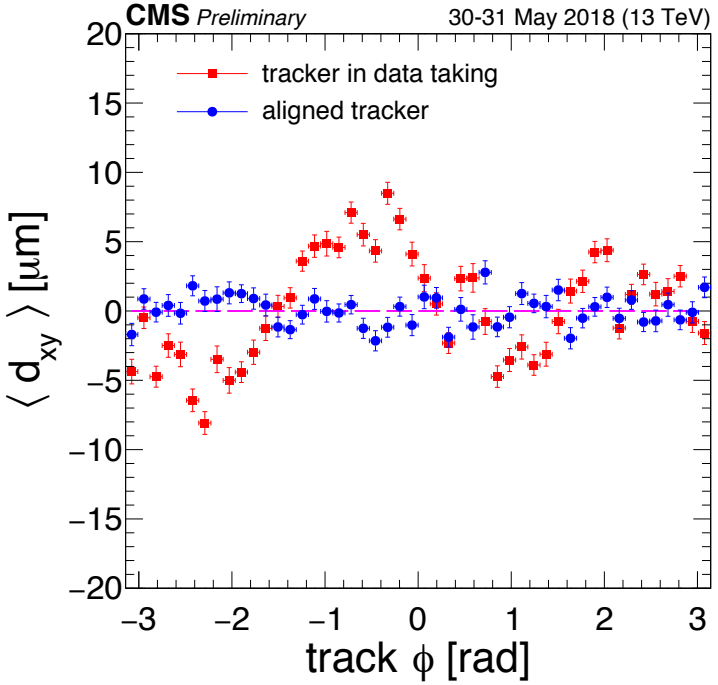


Alignment of the CMS tracker

- DESY-CMS group is a major contributor to the alignment of the tracker
  - Using MillePede-II, developed and supported at DESY
- Alignment group not just active during data-taking
  - Important input for re-reconstruction of already collected data
  - Good alignment performance for early re-processing of 2018 data
  - Work ongoing to determine “legacy” alignment for 2016-2018



distribution of median track-hit residuals in the barrel pixel detector



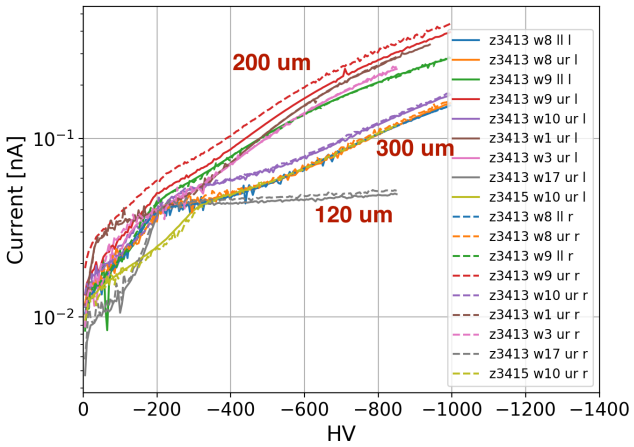
average unbiased track-PV impact parameter as a function of azimuth

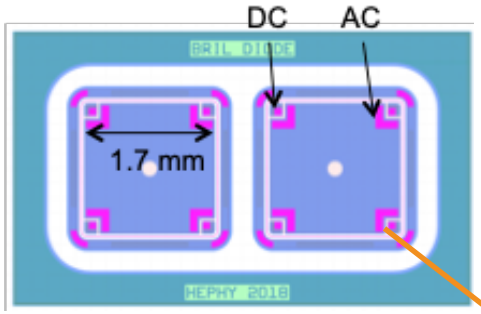
Online luminosity measurement: BCM1F detector

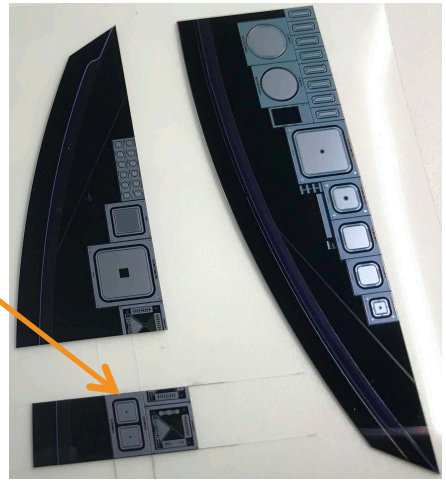
- BCM1F: silicon and diamond sensors near beam pipe
  - For Run-3: Refurbish BCM1F detector with improvements

Silicon sensors (cooled, A/C coupled)

- First batch produced with HGCal sensors
- Diced and characterised at DESY: **all good**





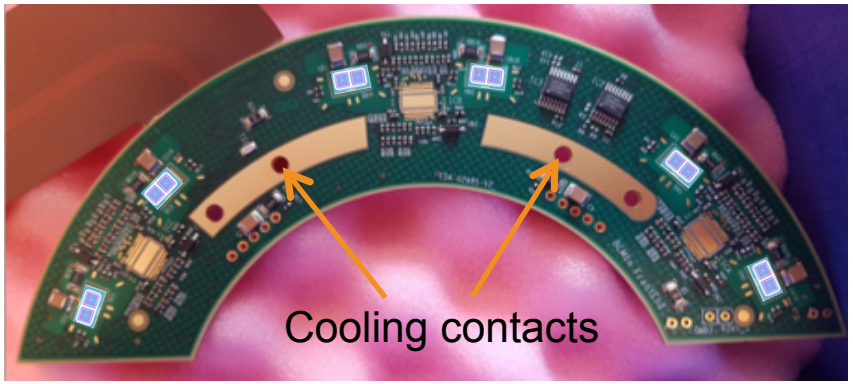


Double-diodes produced on HGCal wafers

6 double-diodes per C-shape

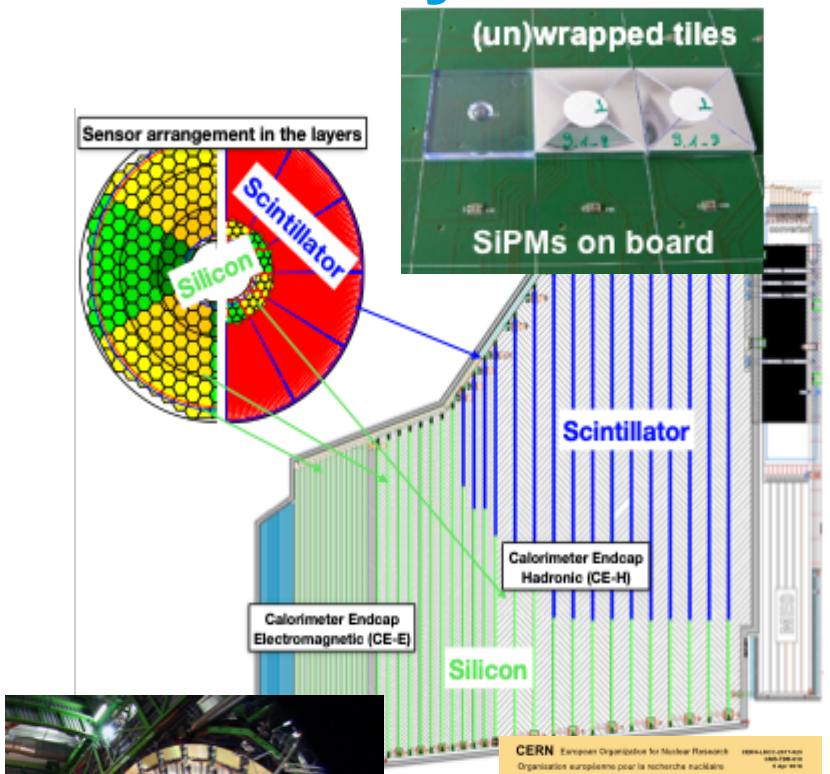
PCB board ("C-shape")

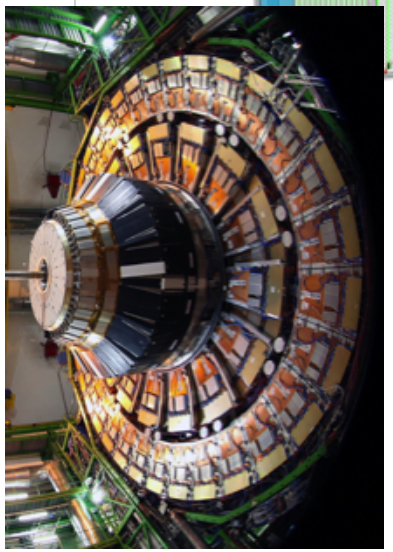
- Two C-shape prototypes built at CERN
- Assembly and electrical testing at DESY: **no faults found**
- Full-system beam tests 20-26 May at DESY

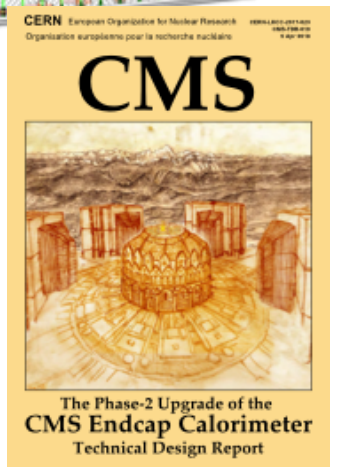


HGCAL: Highly Granular Calorimetry for CMS

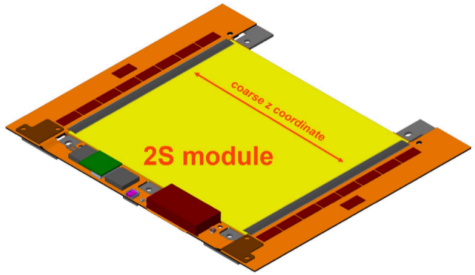
- Capitalising on CALICE developments for Linear Collider calorimeters
- **DESY's SiPM-on-Tile technology largely adopted for CMS endcap upgrade** where radiation levels permit
- New challenges
  - Radiation hardness
  - Data rates
  - Cooling
- **DESY (FLC group) contributes to engineering design (EDR due 2021)**
- SiPM-on-Tile read-out boards
  - Electronics integration, prototypes
- Automated assembly and QC procedures
  - Assembly centre demonstrator

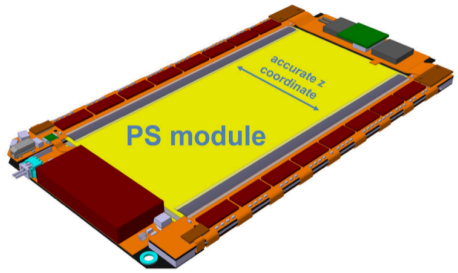


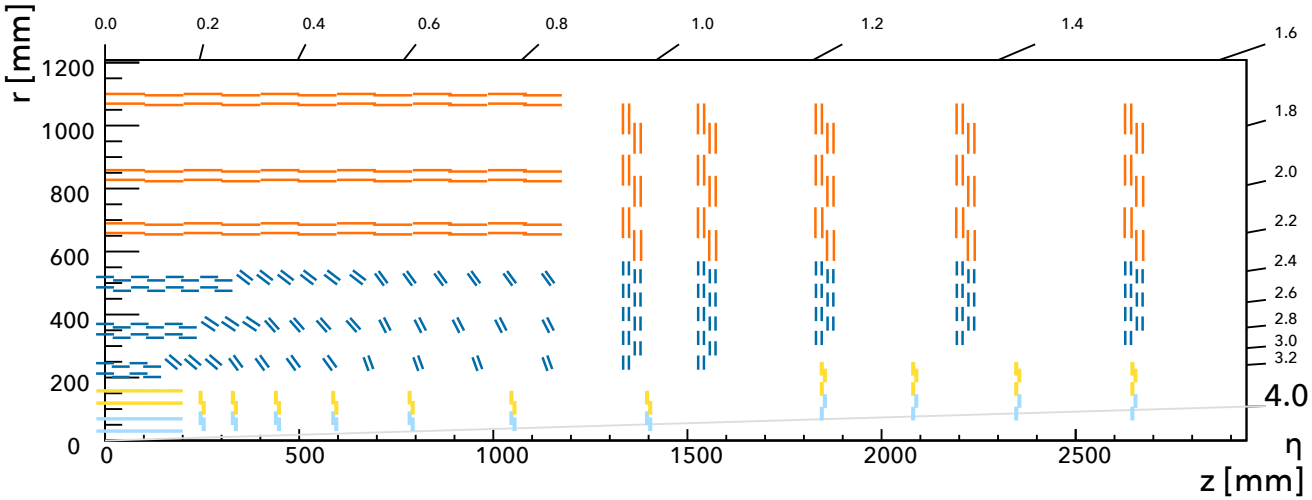


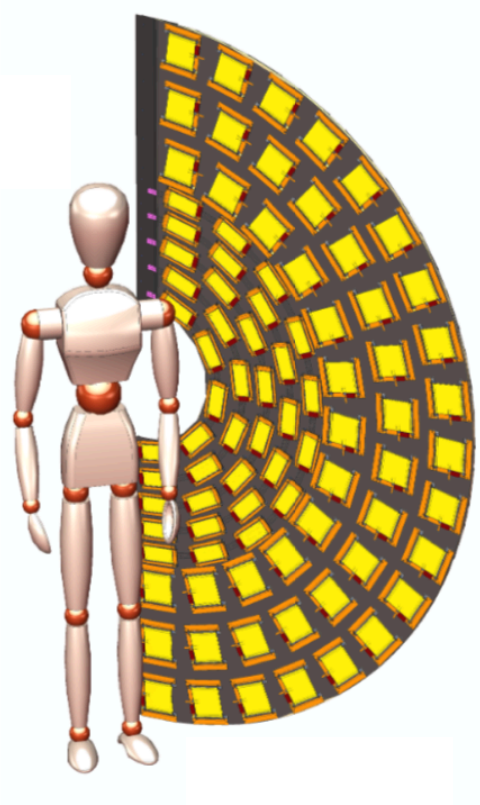


Phase-2 outer tracker upgrade





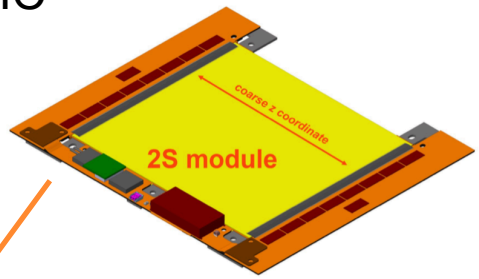


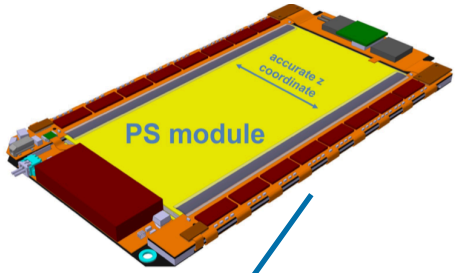


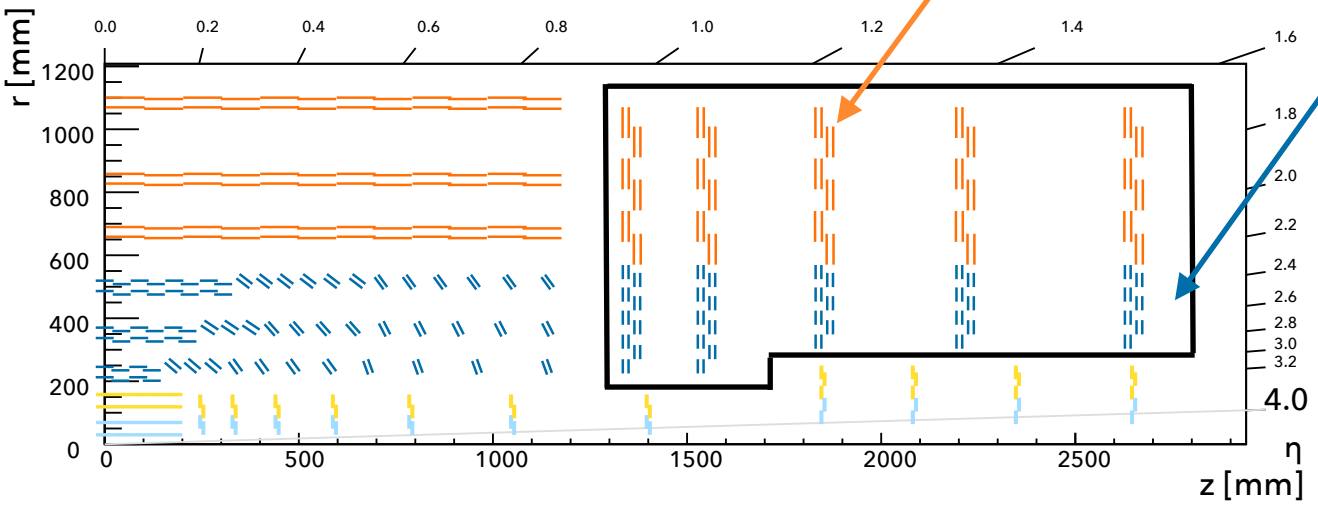
Phase-2 Outer Tracker

- Upgraded tracker to be installed during LS3 for the HL-LHC
  Outer tracker consist of
  - 6 barrel layers
  - 5 endcap double-disks

- 2 types of modules:
  - Pixel-strip (PS)
  - Two-strip (2S)





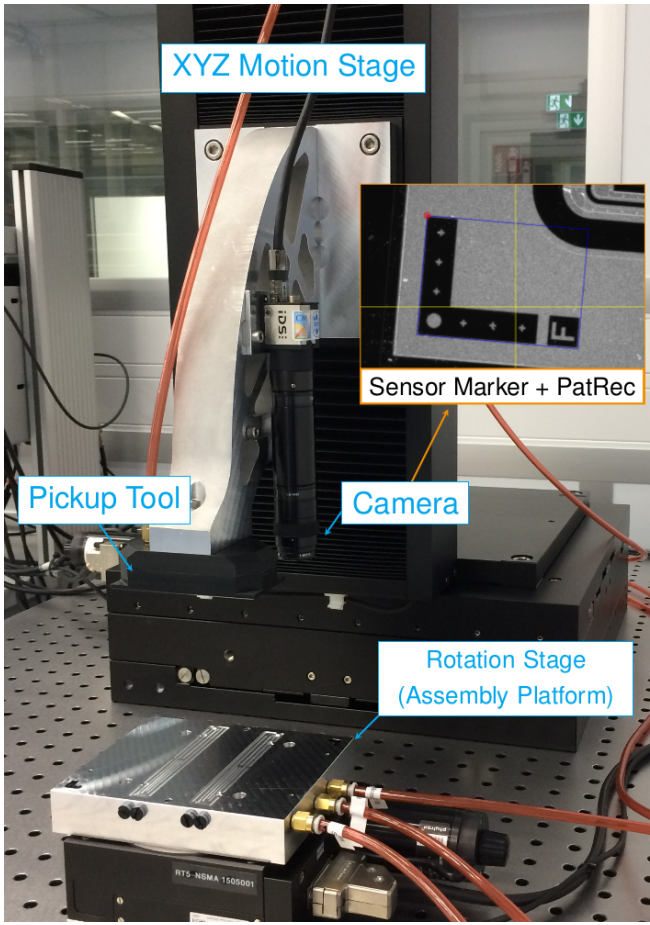


Automated PS module assembly

- Semi-automated procedure for high-precision steps of assembly of Pixel-Strip modules
- 1250 modules to be assembled at DESY
- Required sensor mis-alignment < 800 µrad
  - Achieved by applying pattern recognition on camera images of sensor markers ➔ **Method designed and developed at DESY**
- Setup is fully integrated in the DAF
- Production of glass-based mechanical prototypes
  - Method for simultaneously dispensing slow- and fast-curing glues on assembly components developed and under control
  - Reproducible assembly procedure; time being optimised
  - Alignment under control in latest prototypes

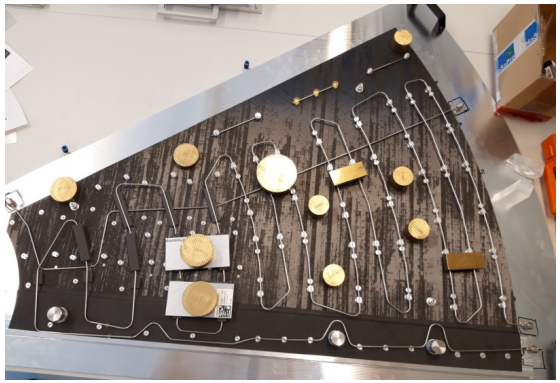
PSp-PSs (mis-)alignment

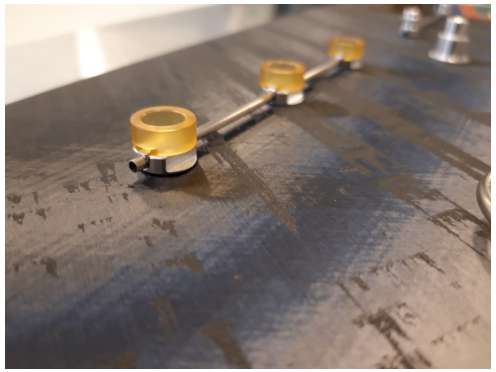
assembly	$\Delta\theta$ [μrad]
#1	**277**
#2	**197**
#3	**1440**
#4	**587**
#5	**372**
#6	**16**
#7	**205**
#8	**80**
#9	**24**

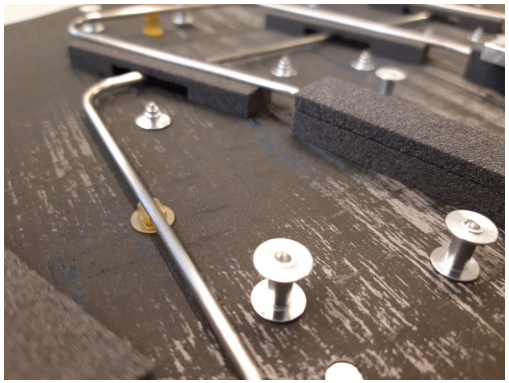


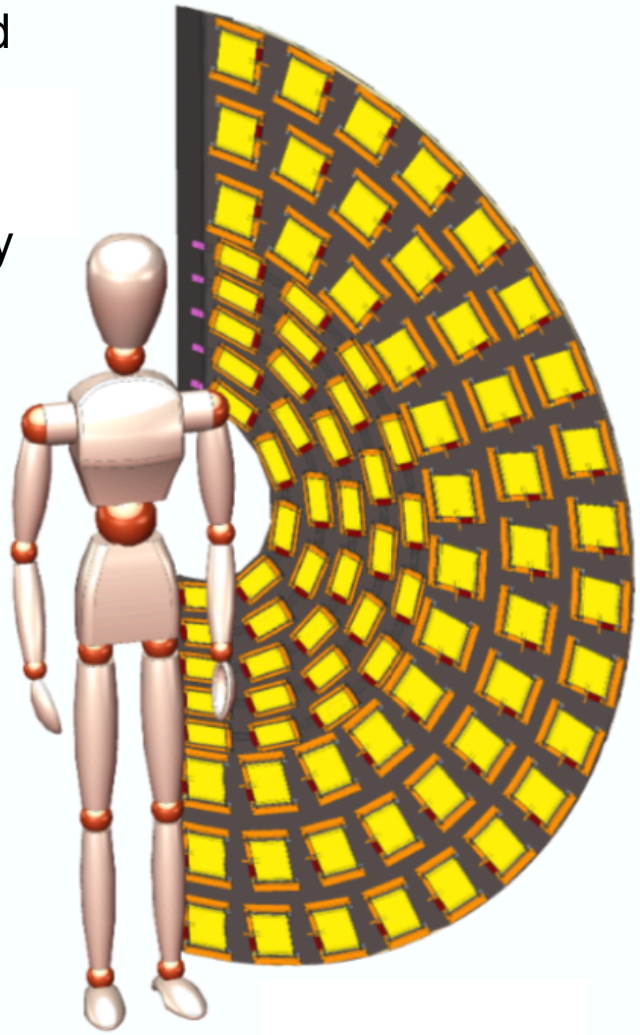
Tracker Endcap Double Disk (TEDD) - Dee prototype

- New iteration of the Dee prototype being assembled
  - Small scale version ~1/5 of final size will be produced at DESY
- Full-sized version of Dee to be produced by industry
  - Possible supplier identified, discussion ongoing







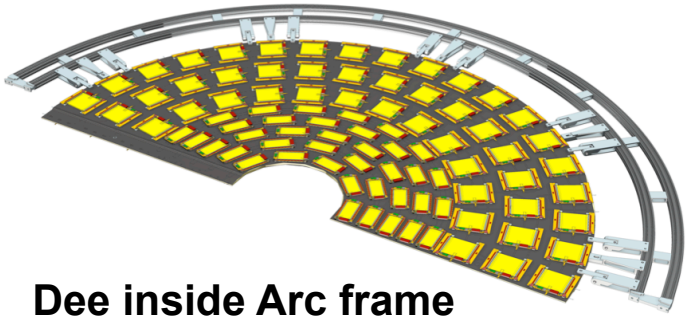


TEDD assembly

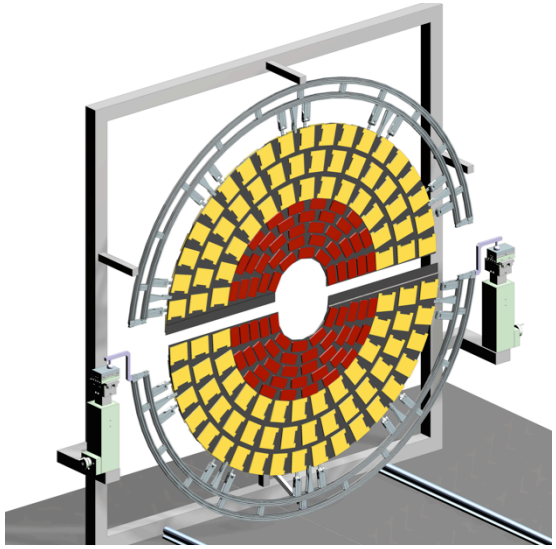
- **Endcap only reaches mechanical stability once all parts are connected**

- Individual Dees are fragile and not mechanically stable
  - Dees will be held by a dedicated **arc frame** during the integration and assembly procedure
  - Arc frame connects to all production stations (module mounting, disk assembly, storage, etc)

- Integration and assembly tooling being designed in collaboration with Lyon and Louvain



Dee inside Arc frame
- Installation of modules
- Thermal treatment
- Cold test



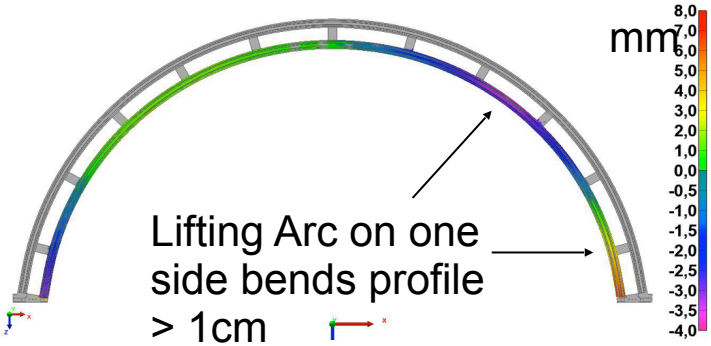
Disk and double disk assembly
- Relative alignment of Dees
- Installation of patch panels and cooling manifold

Arc frame development and prototype

- Arc frames include a universal interface to easily mount frame in any production station

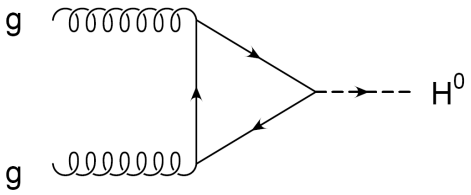
- First prototype arc frame has been produced
  - Testing of integration and assembly procedure
  - Verification of clamp design
  - Optimisation of arc geometry

- Laser scan measurement of prototype
  - Significant deformation from its own weight when lying flat ➔ need higher torsion stiffness

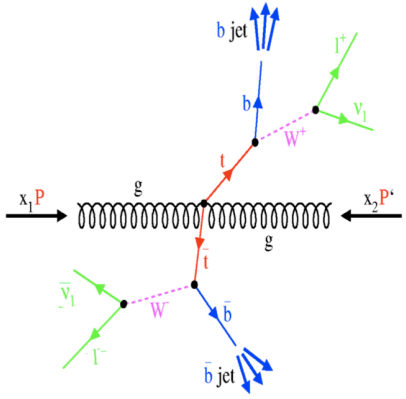


Physics analysis highlights

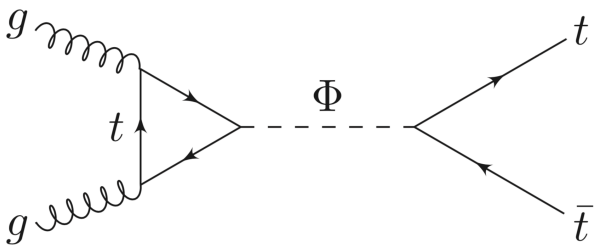
Higgs



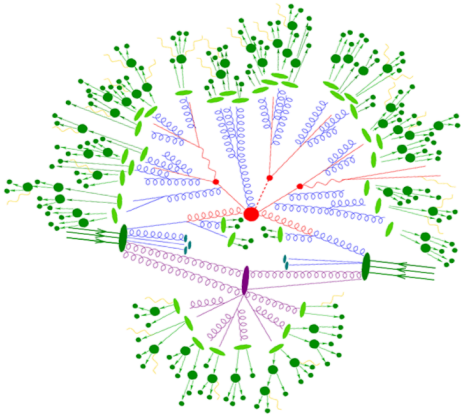
Top



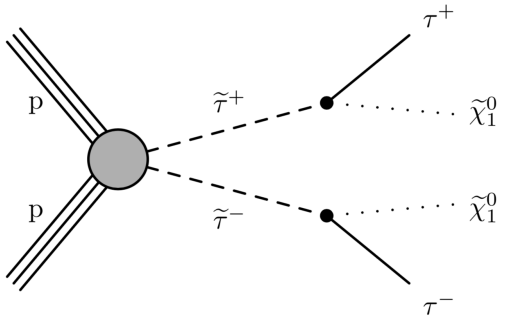
Exotic new physics



QCD and proton structure



Supersymmetry

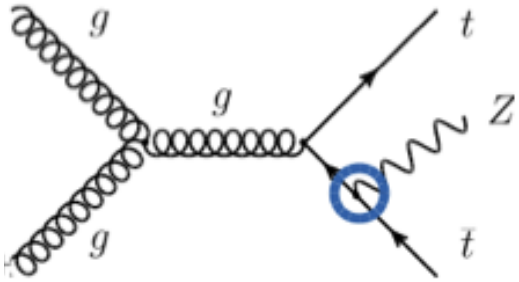


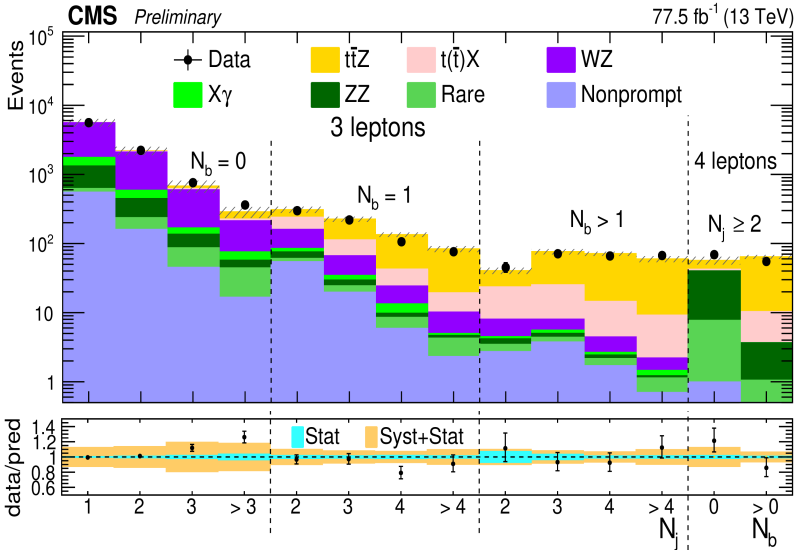
Top: Inclusive and differential $t\bar{t}Z$ cross sections

- Studying 3- and 4-lepton final states
- Categorisation based on numbers of jets and b-tagged jets
- **Most precise determination of inclusive cross section to date**

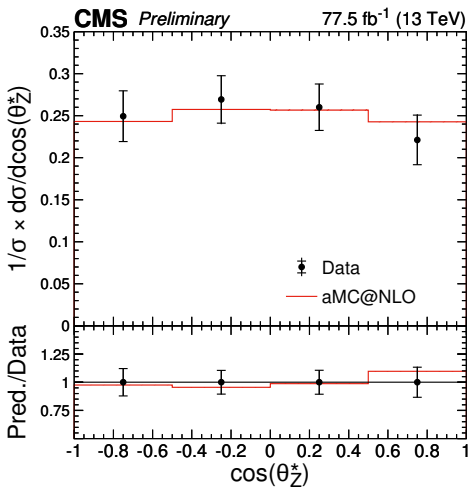
$$\sigma(\mathrm{pp} \to t\bar{t}Z) = 1.00^{+0.06}_{-0.05}\ (\mathrm{stat})\ ^{+0.07}_{-0.06}\ (\mathrm{syst})\ \mathrm{pb}$$

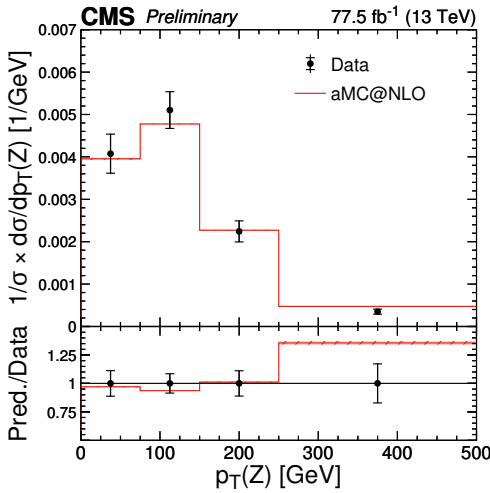
  - 9% precision ➔ better than NLO calculations
- **First ever measurement of ttZ differential cross-sections**
  - Interpret as constraints on EFT operators





Yields in the different analysis categories

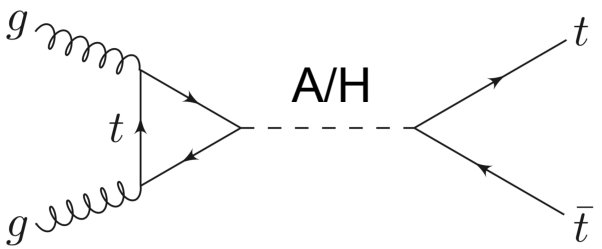


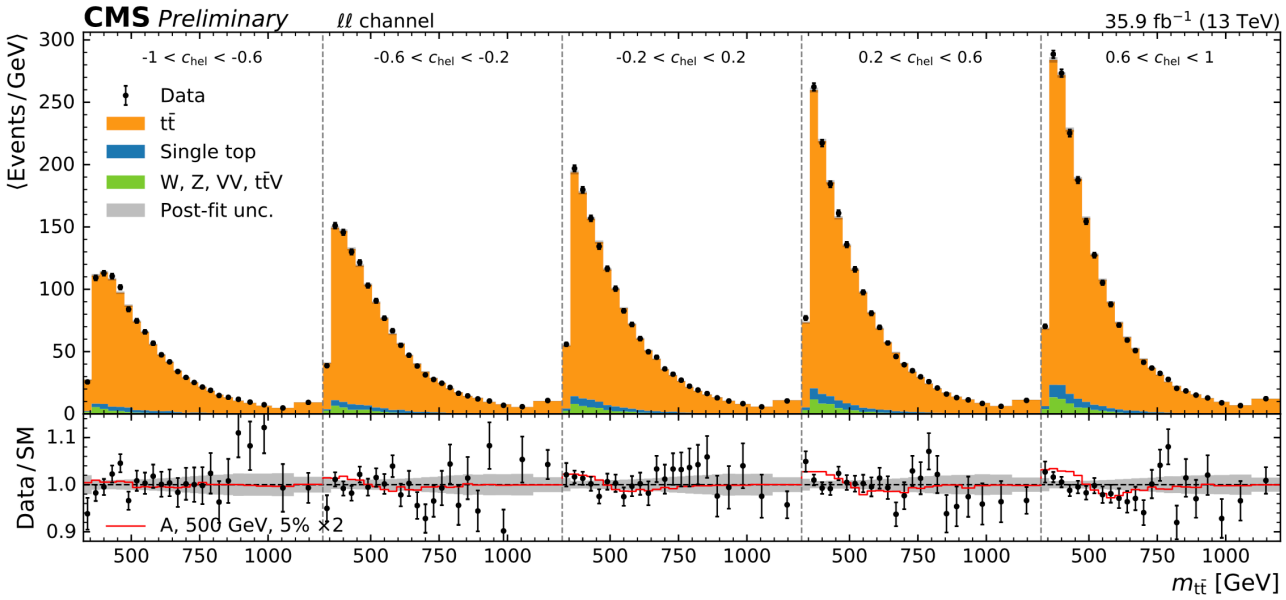


differential cross-sections as a function of $p_T(Z)$ and $\cos(\theta^*_Z)$

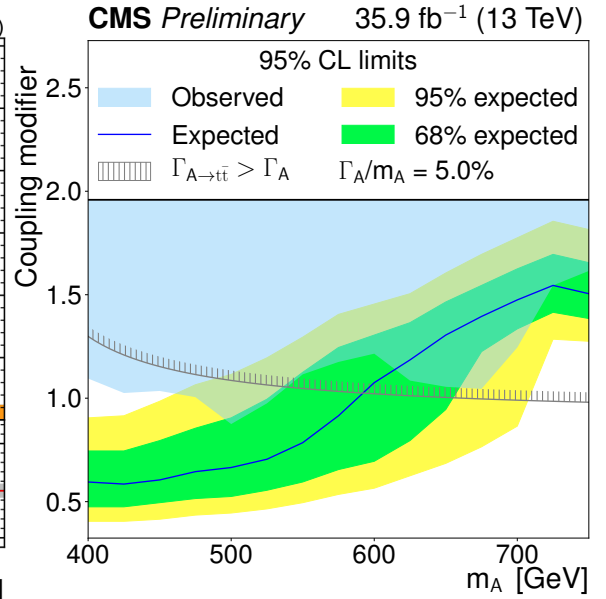
Exotica: Search for heavy A/H→$t\bar{t}$

- Search for heavy (pseudo)scalar Higgs boson decaying to a pair of top quarks in the di-lepton and lepton+jets channels
  - Heavy A/H could be DM mediator
- Analysis makes use of spin information in the decay to be able to set limits both on heavy pseudoscalar and on heavy scalar





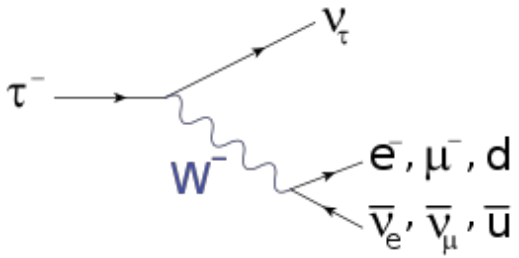
Unrolled distributions of discriminating variables



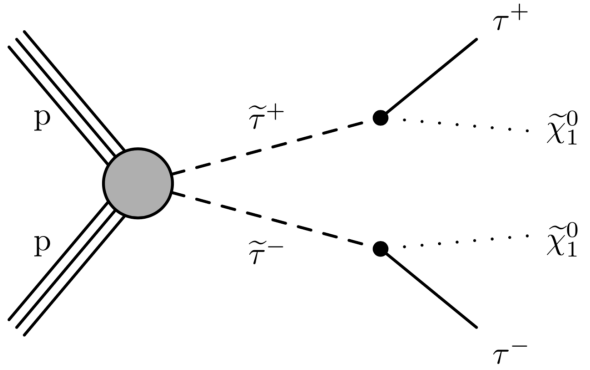
Observed and expected upper limits on the (A,$t\bar{t}$) coupling strength

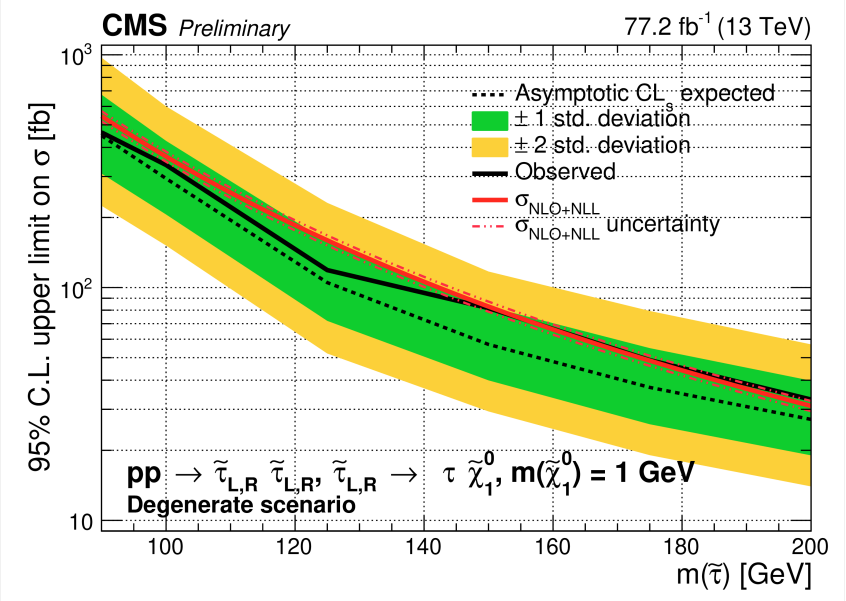
SUSY: search for stau pair production

- Analysis searches for direct stau pair production in final states with a pair of tau leptons and missing transverse momentum
- Final states studied:
  - One leptonically decaying tau lepton, one hadronically decaying tau lepton (DESY focus)
  - Two hadronically decaying tau leptons



- Analysis sensitivity improved using multivariate analysis techniques
- **Limits set on the stau pair production cross section**





Higgs: STXS measurements in H→ττ

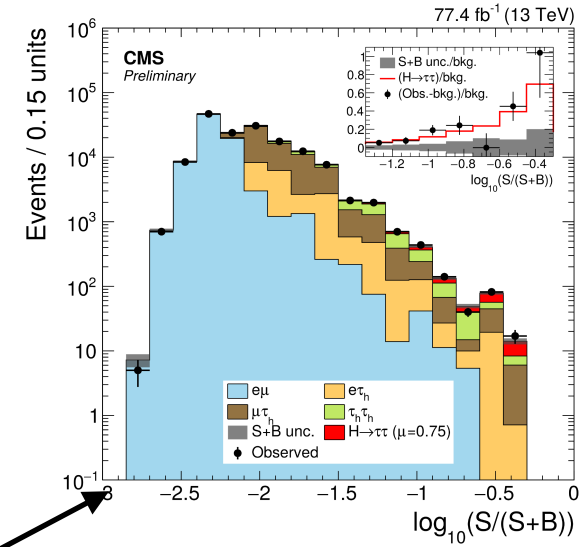
- Measurement of inclusive signal strength and simplified template cross sections (STXS)
- **STXS**: cross-section in exclusive phase-space bins

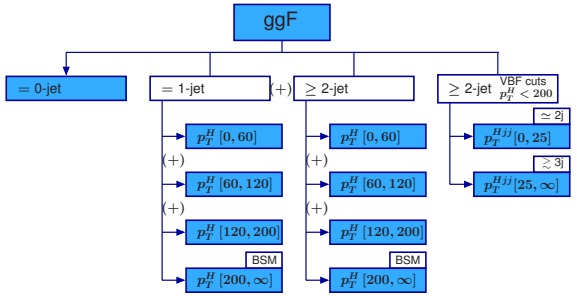
➔ Minimise model-dependence whilst retaining access to BSM effects

- **Machine learning approach:** multi-classifier neural networks used to maximally separate signal from backgrounds

➔ improvement in analysis sensitivity

- **Inclusive signal strength: μ = 0.75 $^{+0.18}_{-0.17}$**



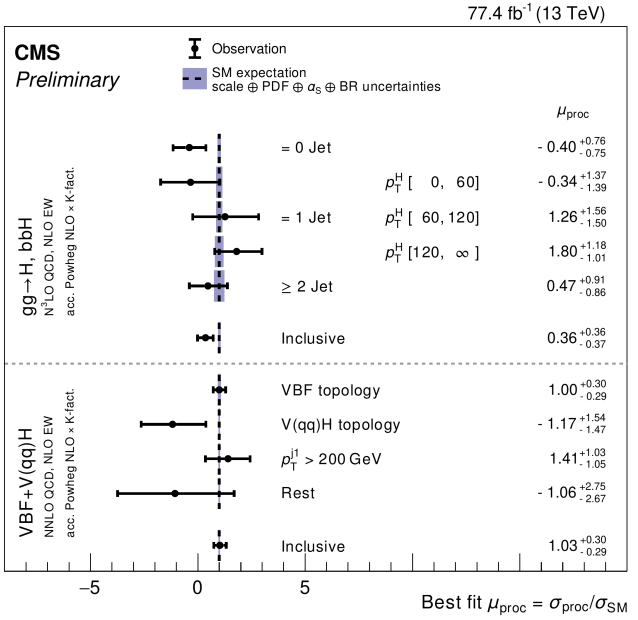


STXS classification used in gluon fusion production mode

gluon fusion

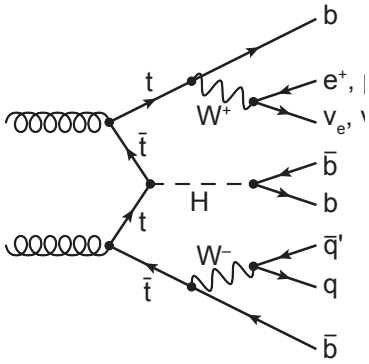
Measurements in STXS bins

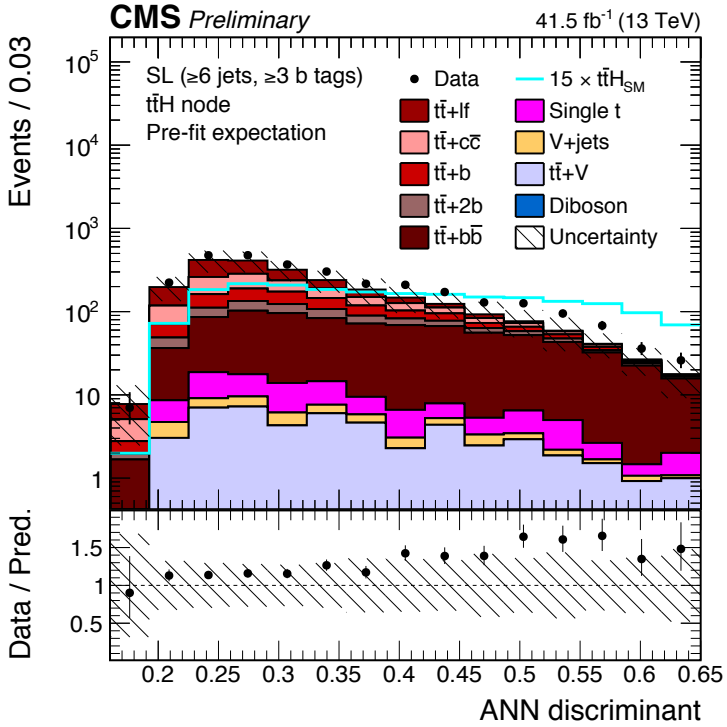
VBF

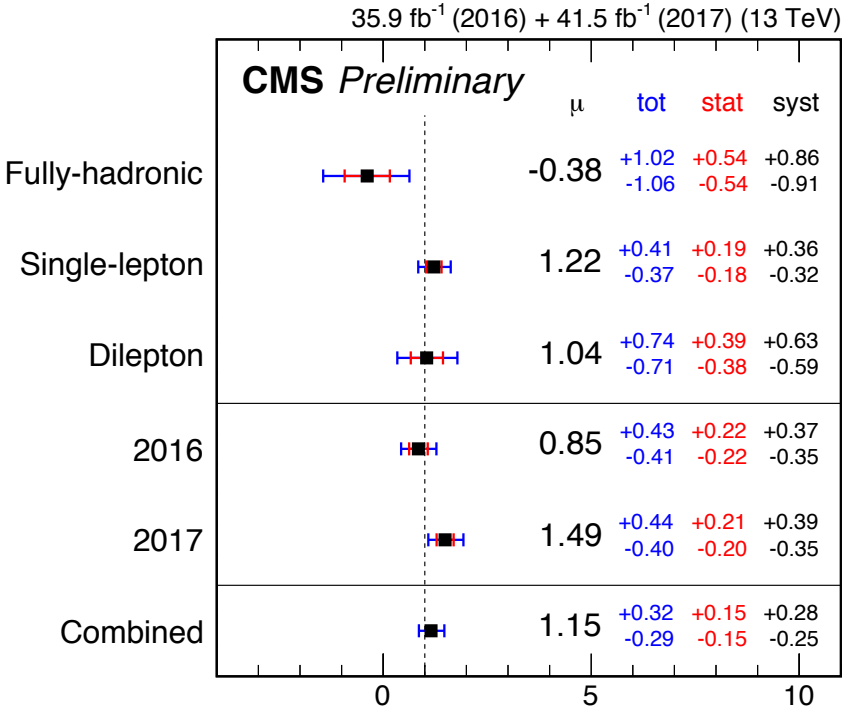


Top+Higgs: $t\bar{t}H(b\bar{b})$ with 2017 data

- Complex final state, can study many possible W decay modes:
  - Fully hadronic: higher rate
  - Fully or semi-leptonic: higher purity
- Analysis relies on **machine learning** and **matrix element** methods
- Combination with 2016 ttH(bb) analysis: **signal strength μ=1.15** $^{+0.32}_{-0.29}$





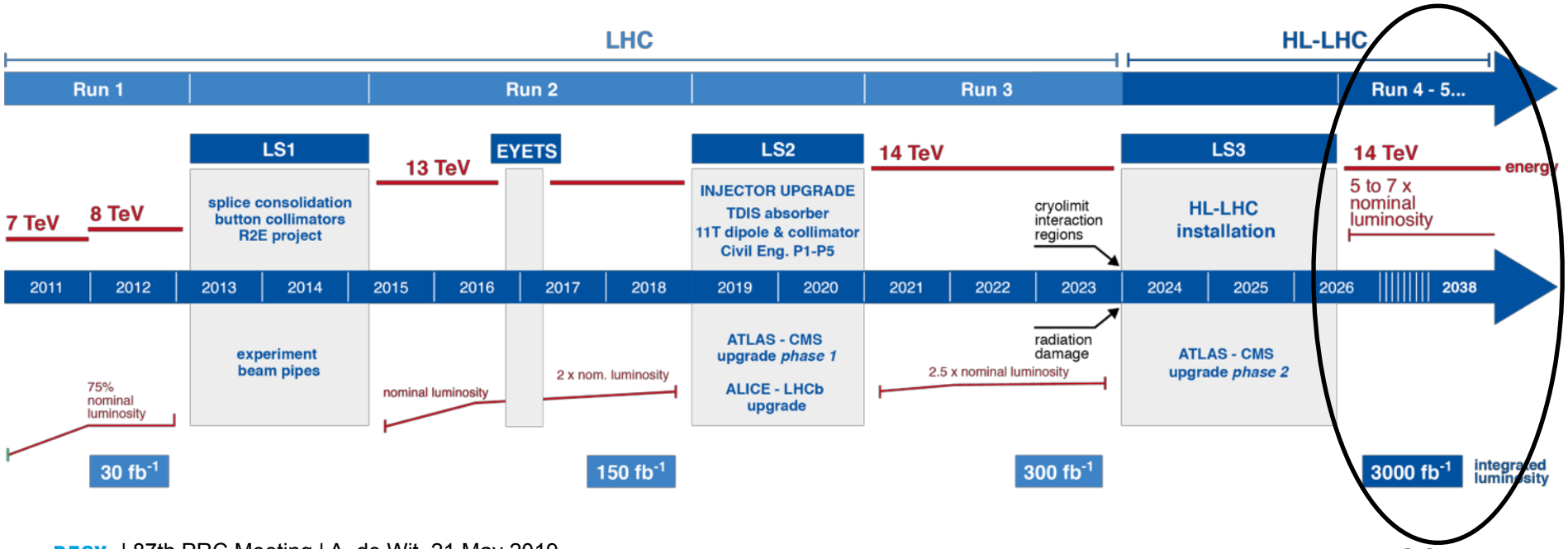


$\hat{\mu} = \hat{\sigma}/\sigma_{SM}$

Physics at the HL-LHC

- "Workshop on physics at the HL-LHC and perspectives on HE-LHC"
  - Major joint effort between experiments and theoretical community
  - Study of prospects for HL-LHC

- Several contributions from the DESY-CMS group
  - Extrapolation of existing analyses
  - Dedicated simulation studies

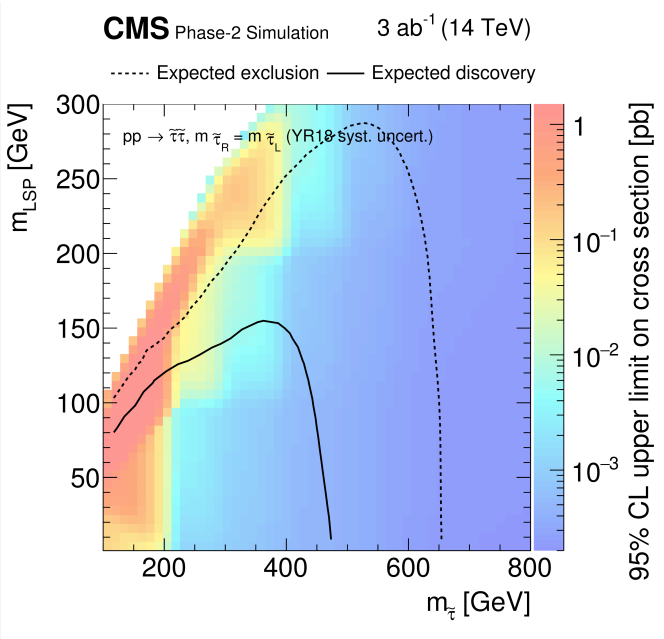


CERN-LPCC-2018-04
CERN-LPCC-2018-05
CERN-LPCC-2019-01

Physics at the HL-LHC

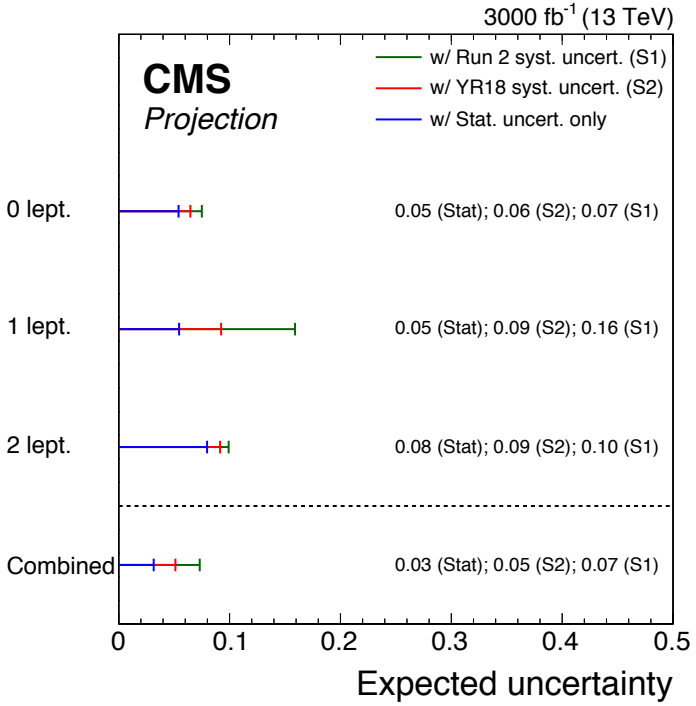
SUSY: stau pair production

- Analysis using dedicated simulated samples
- Study performed both for HL-LHC (3ab^{-1} @ 14 TeV, shown) and HE-LHC (15ab^{-1} @ 27 TeV)
- **Large area of (m_{LSP},m_{stau}) can be excluded**



Higgs: VH(bb)

- Extrapolation of existing analysis
- Precision @ 3ab^{-1}: ~5%, limited by theoretical uncertainties
- **All studied vector boson decay modes contribute ~equally**



Summary

- LHC Run 2 has finished after > 160 fb^{-1} delivered to ATLAS and CMS
  - LS2 is ongoing
- Good performance of tracker alignment for data re-processing
- BCM1F detector upgrade for Run 3 ongoing
  - Beam tests at DESY this week!
- HGCAL engineering design progressing
- Phase-II outer tracker upgrade project moving forward
  - Progress in automated module assembly and Dee and TEDD prototyping and assembly concept
- Many strong contributions from the DESY CMS group to physics analyses
  - Covering a wide range of topics in Top, Higgs, QCD, Supersymmetry and Exotica
  - Studies of prospects at HL-LHC

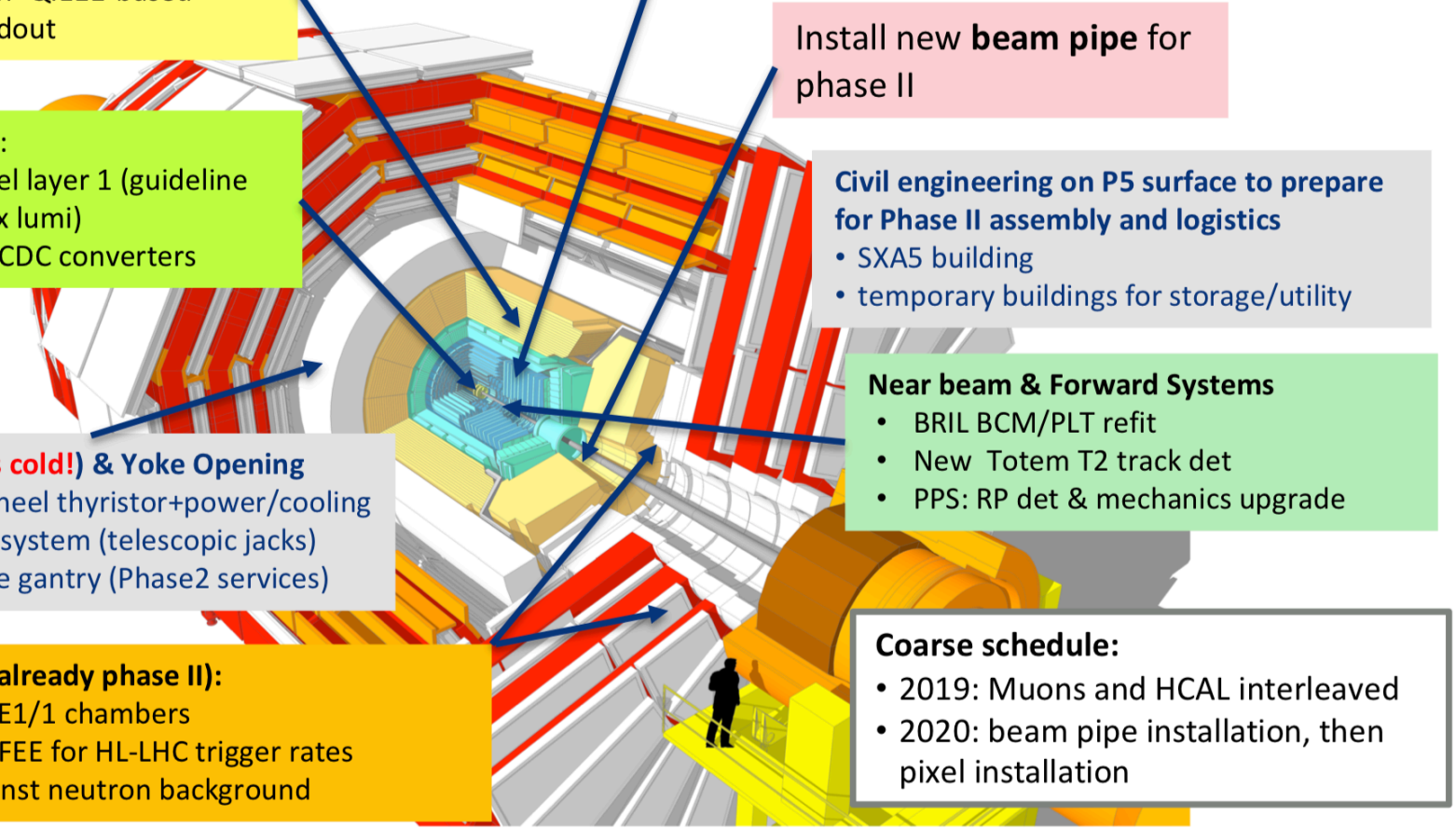
Backup

LHC status

- **Options for centre-of-mass energy**
  - Start at 14 TeV in 2021 ➔ need to start physics run later than planned as magnet training will take longer
  - Start at 13 TeV in 2021, finish magnet training in YETS 2021-2022 and start at 14 TeV in 2022
- **Performance estimates ATLAS/CMS**
  - ~20 /fb in 2021, ~100 /fb in following years of Run 3
  - Low machine availability expected in 2021, 50% availability thereafter.
  - Pile-up to increase ➔ significant number of bunches (30%) could have PU 70 or higher.

from R. Carlin, CMS week 04/2019

CMS upgrade work during LS2



Keep **strip tracker** cold to avoid reverse annealing

HCAL barrel (last phase I): install SiPM+QIE11-based 5Gbps readout

Install new **beam pipe** for phase II

Pixel detector:
- replace barrel layer 1 (guideline 250 fb-1 max lumi)
- replace all DCDC converters

Civil engineering on P5 surface to prepare for Phase II assembly and logistics
- SXA5 building
- temporary buildings for storage/utility

Near beam & Forward Systems
- BRIL BCM/PLT refit
- New Totem T2 track det
- PPS: RP det & mechanics upgrade

MAGNET (stays cold!) & Yoke Opening
- Cooled freewheel thyristor+power/cooling
- New opening system (telescopic jacks)
- New YE1 cable gantry (Phase2 services)

Muon system (already phase II):
- install GEM GE1/1 chambers
- Upgrade CSC FEE for HL-LHC trigger rates
- Shielding against neutron background

Coarse schedule:
- 2019: Muons and HCAL interleaved
- 2020: beam pipe installation, then pixel installation

HGCAL: Recent Progress

Prototyping Towards an Engineering Design

AHCAL prototype in joint CALICE CMS beam test

38 layers, 22000 SiPMs

Established performance and mass production concept

Electronics design of 1st tileboard prototype

Now in lay-out, HGCROC-SiPM in production

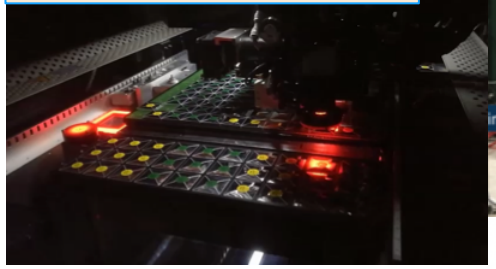
To establish electronic signal chain scintillator - SiPM - ASIC

Automated wrapping tools

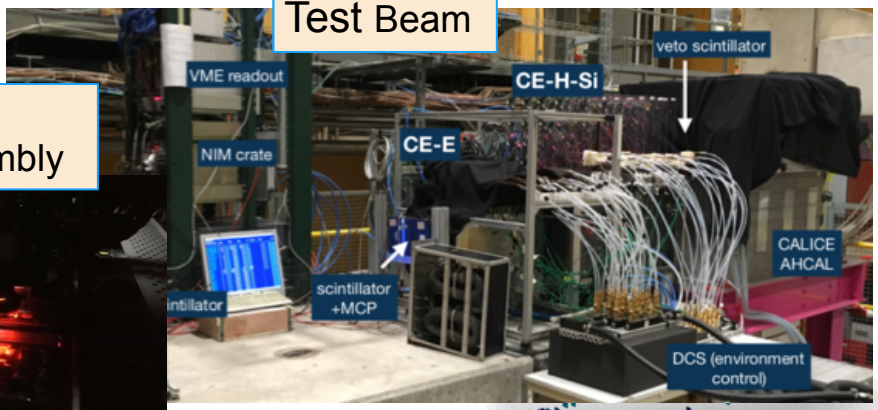
Tile wrapping machine built, now being optimised

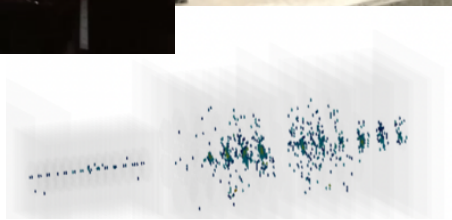
Tile placement tests in ZE group

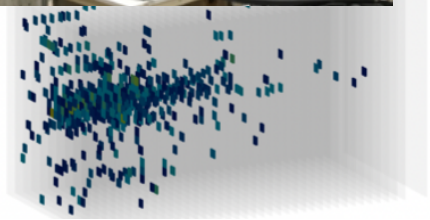
Production:
pick & place assembly

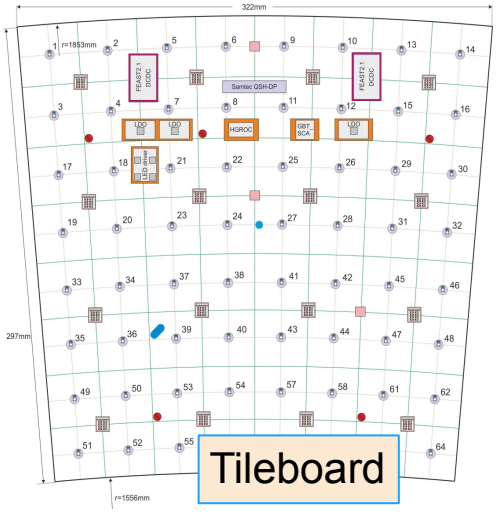


Test Beam

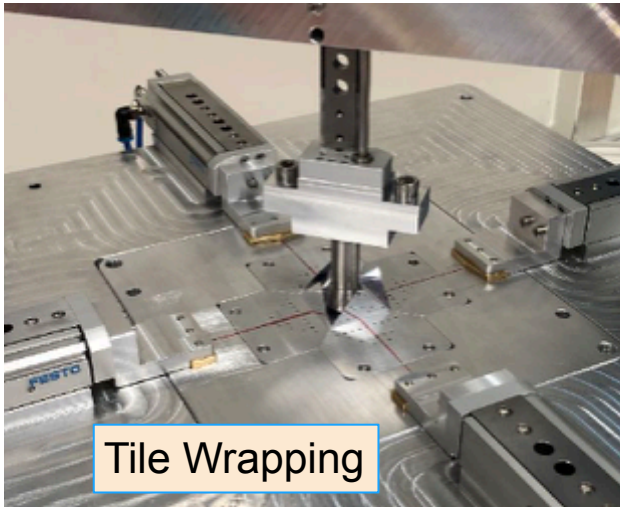








Tileboard

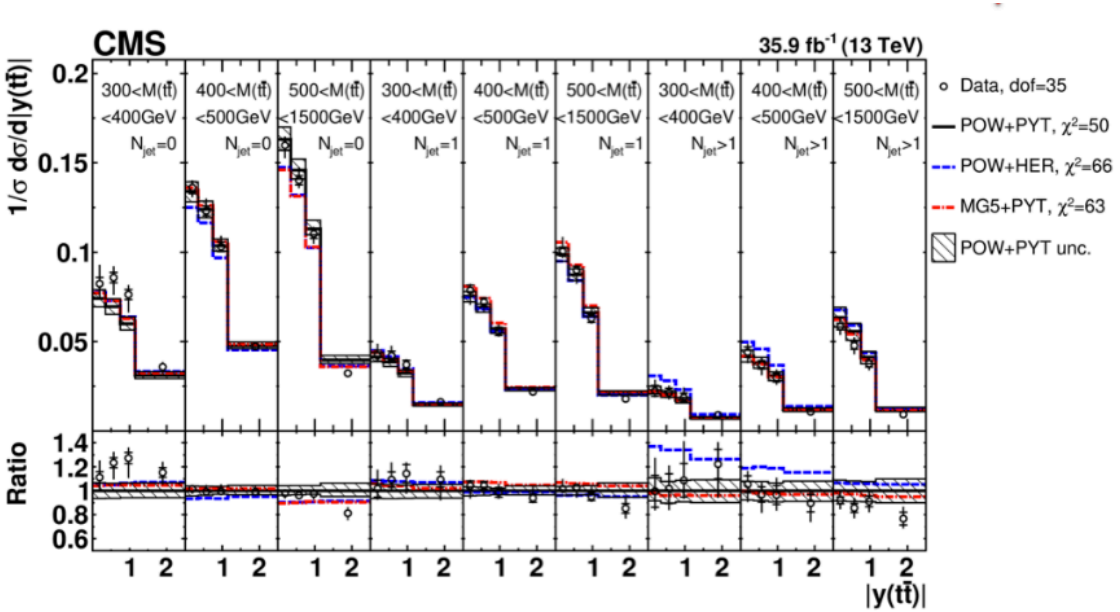


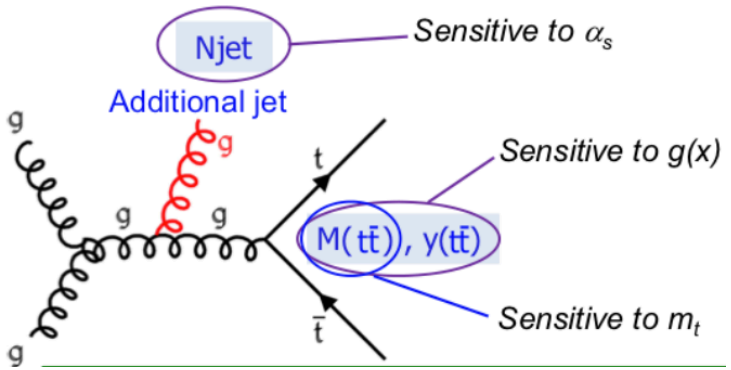
Tile Wrapping

arXiv 1904.05237, (sub'd to EPJC)

Top: Multi-differential tt cross-sections

- Use kinematical and topological observables to extract theory parameters
- **First ever 3D measurement of tt cross section as a function of M(tt), y(tt) and N_{jet}**
  - **Simultaneous fit of PDF+α_s+m_t^{pole}**





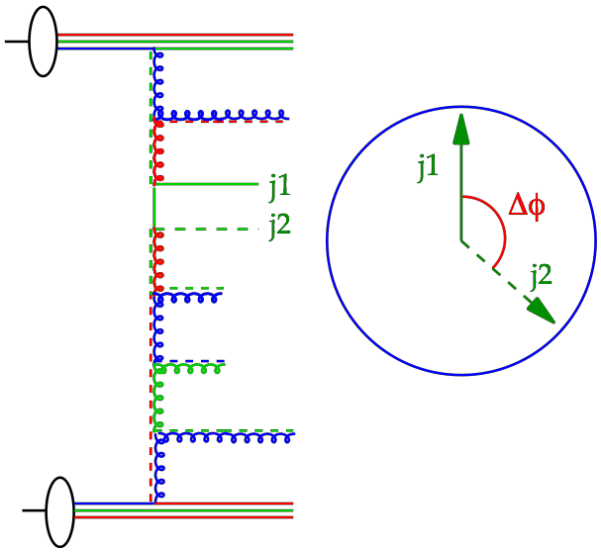
$$\alpha_S(m_Z) = 0.1135 \pm 0.0016(\text{fit})^{+0.0002}_{-0.0004}(\text{model})^{+0.0008}_{-0.0001}(\text{param})^{+0.0011}_{-0.0005}(\text{scale}) = 0.1135^{+0.0021}_{-0.0017}(\text{total}),$$

$$m_t^{\text{pole}} = 170.5 \pm 0.7(\text{fit}) \pm 0.1(\text{model})^{+0.0}_{-0.1}(\text{param}) \pm 0.3(\text{scale})\,\text{GeV} = 170.5 \pm 0.8(\text{total})\,\text{GeV}.$$

arXiv 1902.04374, (sub'd to EPJC)

QCD: Azimuthal separation in high p_T multi-jet events

- Measurement of azimuthal separation in nearly back-to-back jet topologies in 2- and 3-jet events in proton-proton collisions
- **Performed in a region never accessed before**
  - Sensitive to soft gluon and threshold resummation
  - ~15% discrepancy between measurement and models near $\Delta\varphi_{12} = 180^{o}$ ➔ important input for improving the models



Azimuthal correlations in the back-to-back region