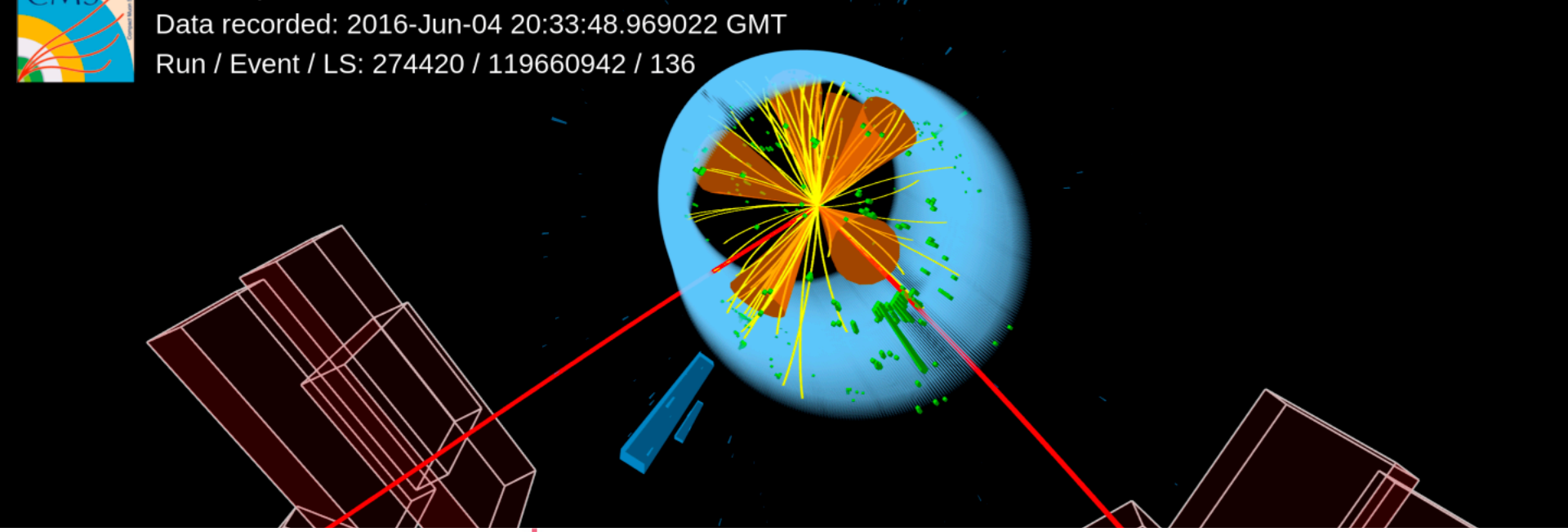


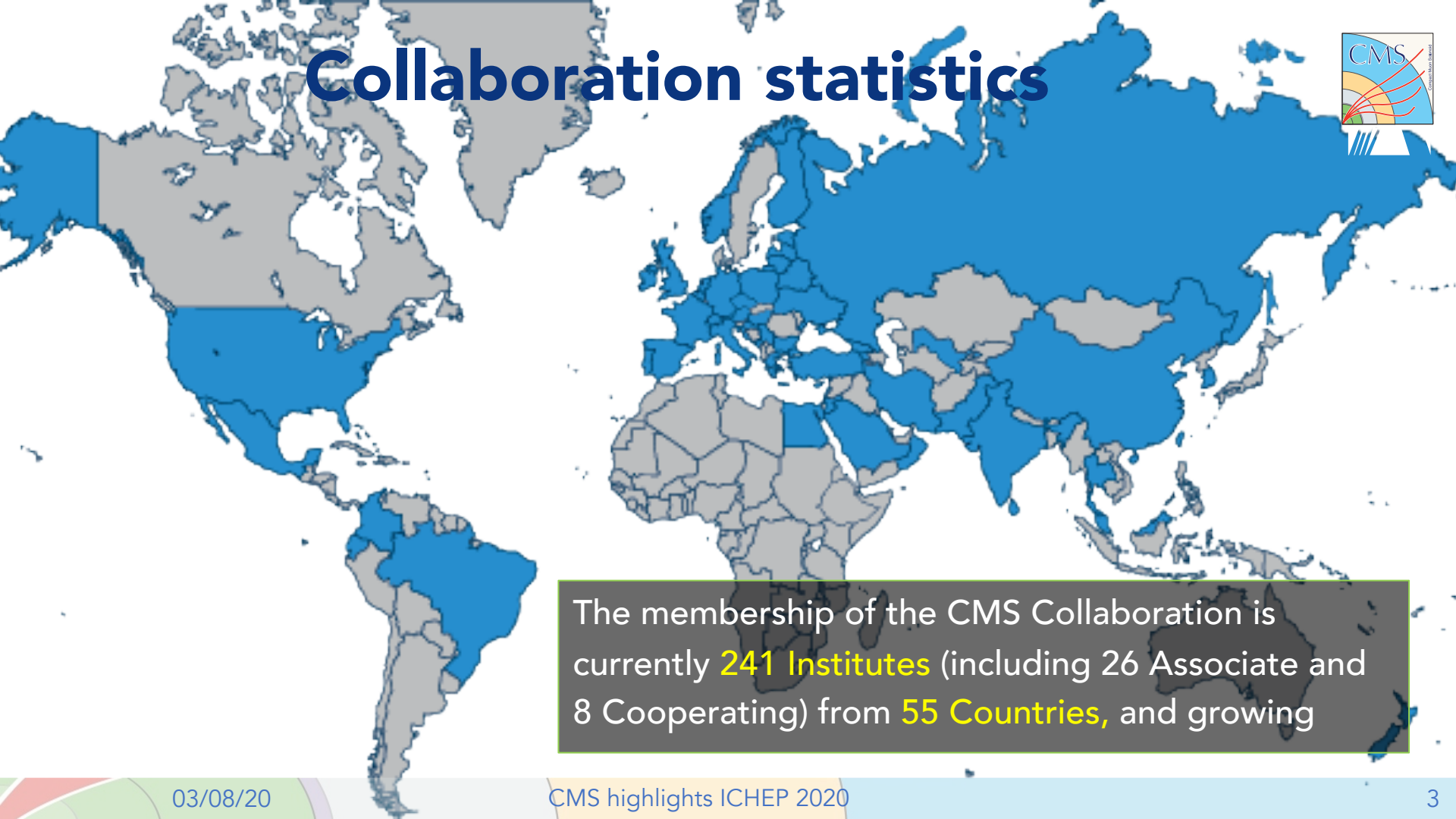
CMS highlights

Roberto Carlin, University of Padova, INFN and CERN

Aug 3 ICHEP 2020

Present status and short-term future

Collaboration statistics



The membership of the CMS Collaboration is currently 241 Institutes (including 26 Associate and 8 Cooperating) from 55 Countries, and growing

Civil engineering on P5 surface to prepare for Phase-2 assembly and logistics

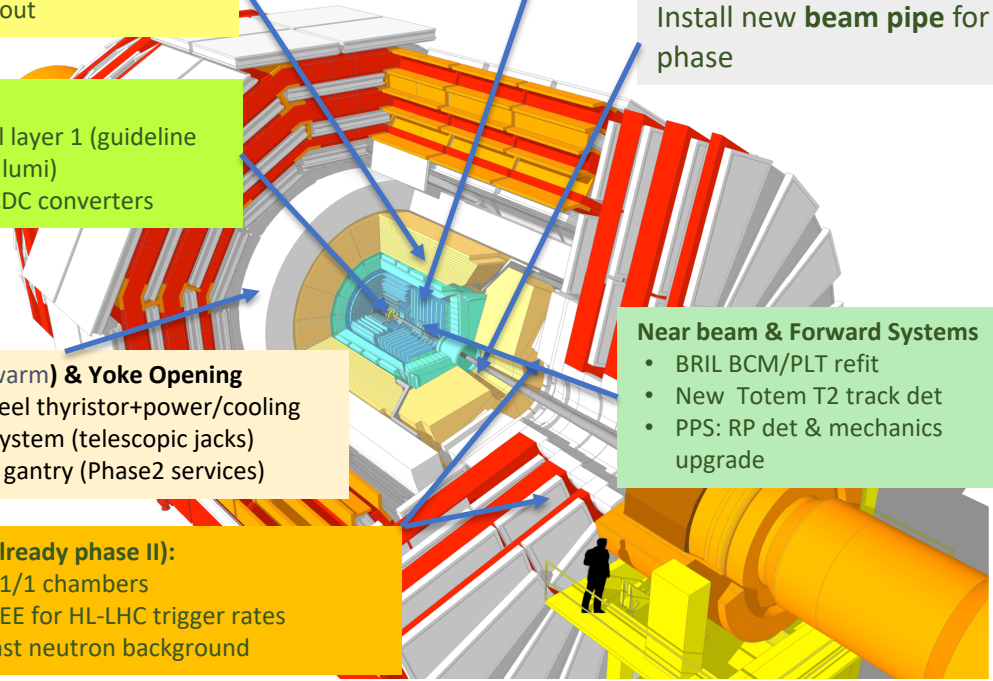
CMS LS2 Shutdown

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

HCAL barrel (completed): install SiPM+QIE11-based 5Gbps readout

Install new **beam pipe** for phase

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



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

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

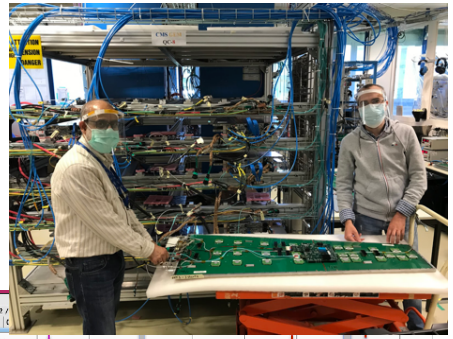
Muon system (already phase II):
- install GEM GE1/1 chambers
- Upgrade CSC FEE for HL-LHC trigger rates
- Shielding against neutron background

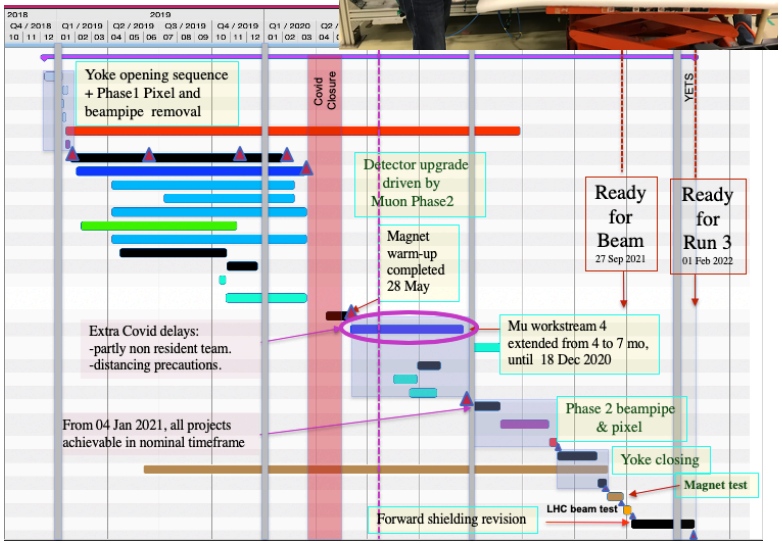
LS2 plan overview
- Some maintenance, improvement and Phase 1 upgrade
- Many activities already related to Phase 2 (HL-LHC) upgrades and related services and infrastructure

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

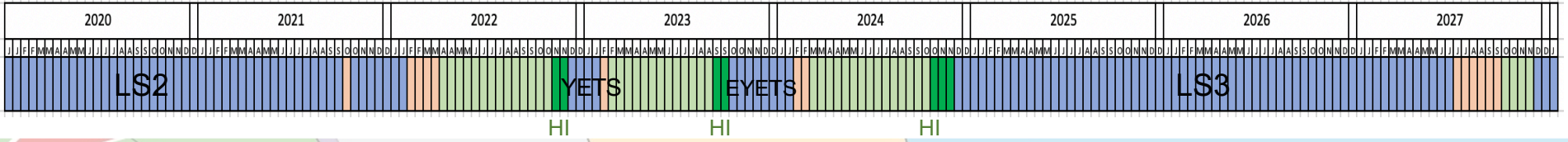
CMS plans after Covid-19

- We accumulated some delay in the lockdown, but we restarted in May, and only few of the many activities are expected to be slowed down by Covid-19 precautions
- A very constructive discussion with the other LHC experiment and with CERN lead to a plan in which LHC will restart early in 2022 (instead of mid '21 but with a long stop between '21 and '22)
  - The integrated luminosity of Run 3 is expected to be almost the same!
- CMS will be able to have all planned shutdown activities completed in time for a first short test beam in September 21





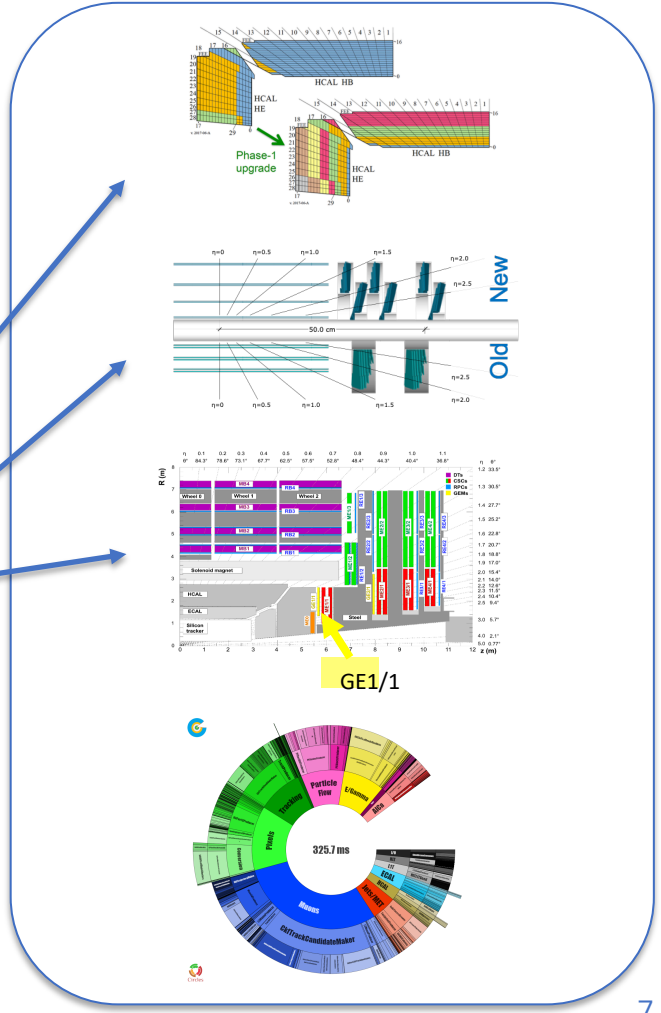
LHC Timeline



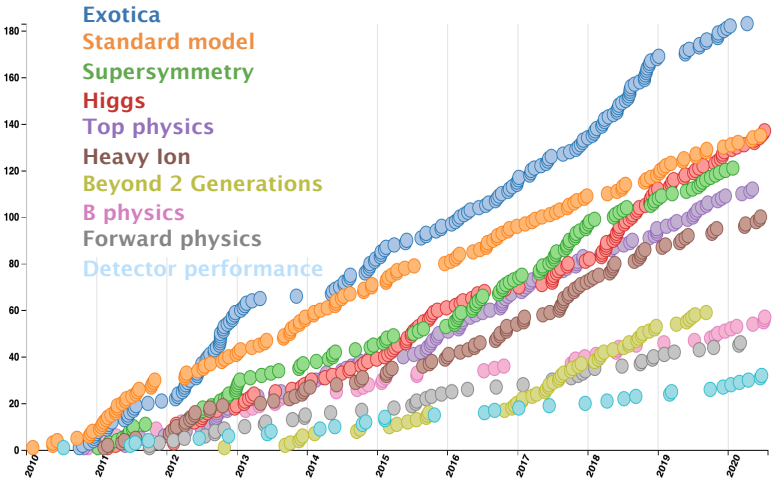
Plans for Run 3

Not only “more of the same”

- Certainly lots of statistics for searches and precision measurements
- Exploiting new detectors, some designed for Phase 2
  - Depth segmentation from new electronics in Hadronic Calorimeter
  - Phase-1 pixel detector with updated Layer 1 electronics
  - First layer of GEM muon detectors in the forward region
- Planning to move to heterogeneous architecture in High Level Trigger, with mixed CPU/GPU
  - Already achieved 25% reduction of CPU time
  - Opens new possibilities for trigger algorithms leveraging on GPUs
  - A testbed for HL-LHC Computing and triggering

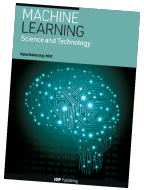


CMS publications

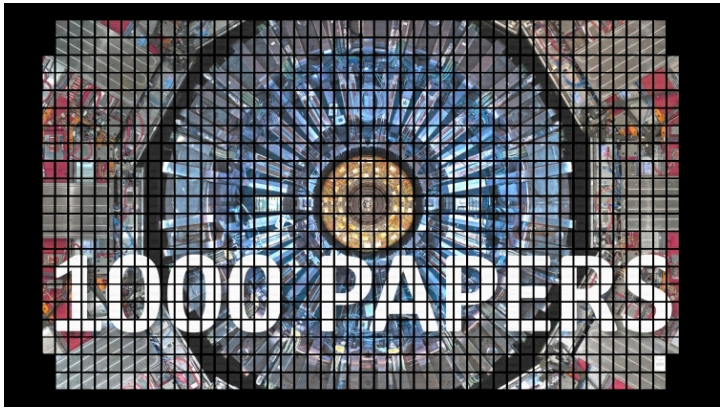


982 papers on collider data published or submitted to a journal

Overall, we submitted 1007 papers, having celebrated the 1000th paper on June 19th



We have now had several CMS papers accepted in Machine Learning journals



Some Highlight on Scientific Results

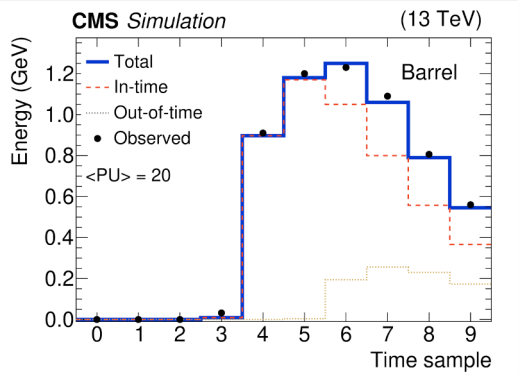
CMS made public 24 new results in time for ICHEP, covering all areas of physics related activities in CMS: detector performance, SM measurements, searches, Higgs, B-physics, HI.
Will not show all of them

arXiv:2006.14359
Submitted to Journal of Instrumentation

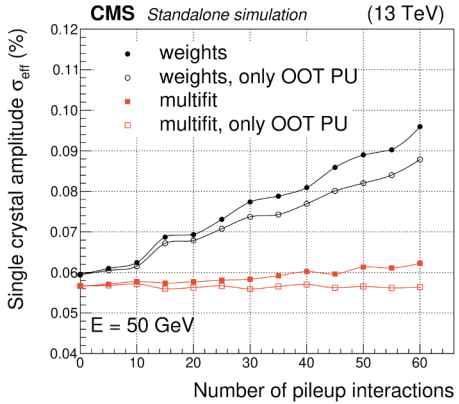
reconstruction of ECAL signal amplitudes in presence of large PU

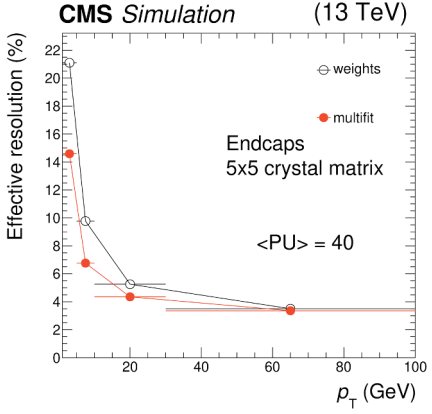
- ECAL signal amplitude reconstruction employed in Run 2
  - Template fitting technique, designed to subtract the signals of overlapping interactions from the multiple 25 ns spaced bunches
    - Large improvement compared to Run 1
    - Largely suppresses contribution from Out of time Pileup
  - Very fast, can be employed in the HLT (already adapted and running on GPUs in view of Run 3)

One in time and up to 9 OOT amplitudes are fitted

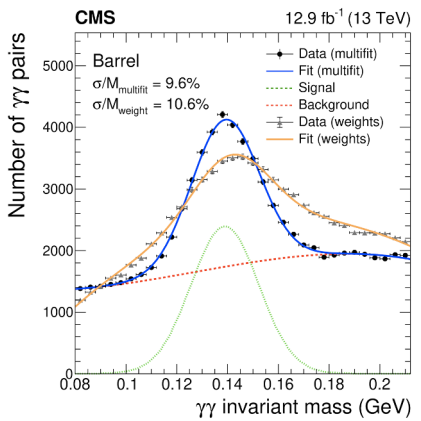


Large improvement in resolution compared to Run 1 method





π^0 mass

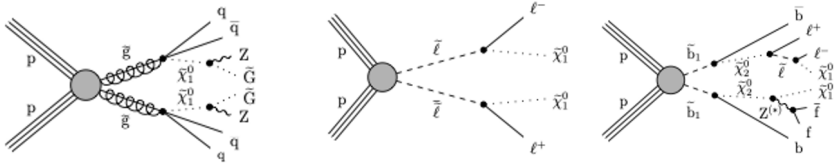


Direct searches

New results on strongly & weakly interacting sparticles

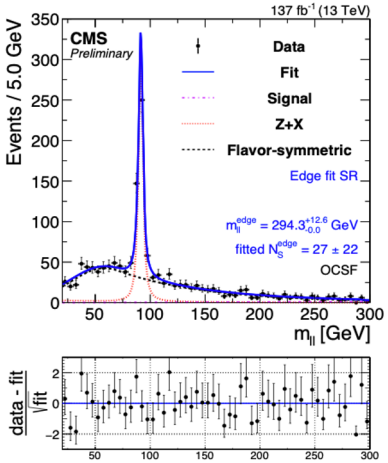
Continuing searches for SUSY with a generic analysis of events with 2 opposite-charge same-flavor leptons

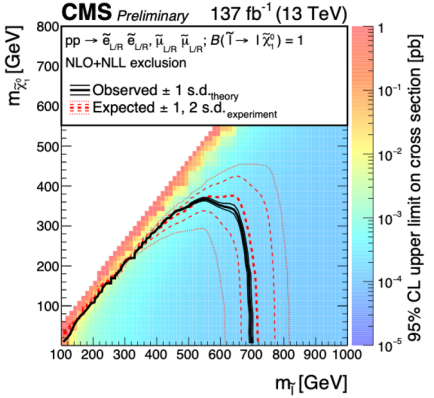
- "classical" signature - leptons could stem from Z-decays, from different decay branches, or a cascade decay



- interpretations based on yields in dedicated signal regions, and using the distinctive kinematic properties for leptons from cascades
- Upper limits at 95% CL are set on the production σ of SUSY particles, typically extending the reach of previous CMS results by hundreds of GeV

fit for kinematic edge



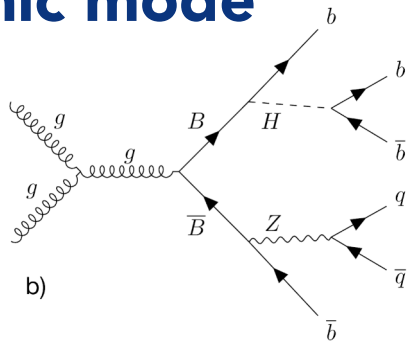


limit on slepton pair production, as a function of slepton and lightest neutralino masses

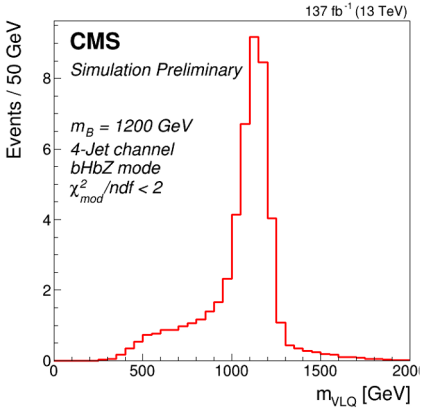
Recently, CMS also exploited hadronic decays of boosted Z's: SUS-19-013

Search for BB production in a fully hadronic mode

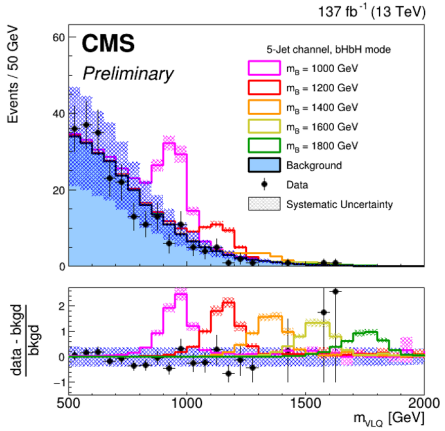
- Search for bottom-type ($q = -\frac{1}{3}$) vector-like quarks (VLQs)
  - decay into a b quark and a Higgs or a Z boson
- Due to the large boost jets from H or Z may be merged
  - Analysis considers events with 6, 5 (1 merged) and 4 jets (2 merged)
  - A combination of b-tagging and chi-squared is used for each mass hypothesis to select the best jet pairing and evaluate the VLQ mass



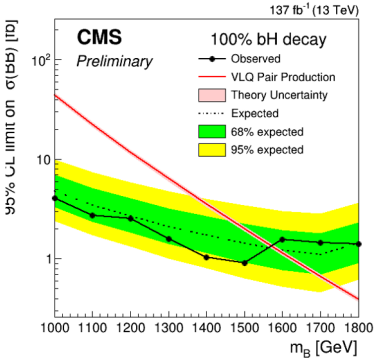
Signal mass resolution similar for different jet multiplicities



5-jet channel bH-bH



Upper limit on the cross section for BF (VLQ-bH)=100%



No signal observed
95% CL lower mass limits (GeV)

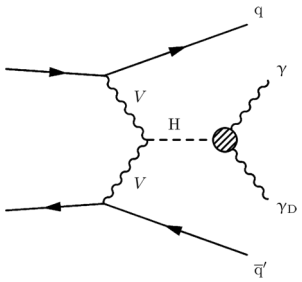
BF(bH) = 100%	BF(bZ) = 100%	BF(bH) = BF(bZ) = 50%
1570	**1390**	**1450**

previous limits were just above 1 TeV

CMS B2G-19-005

Search for dark photons in VBF Higgs events

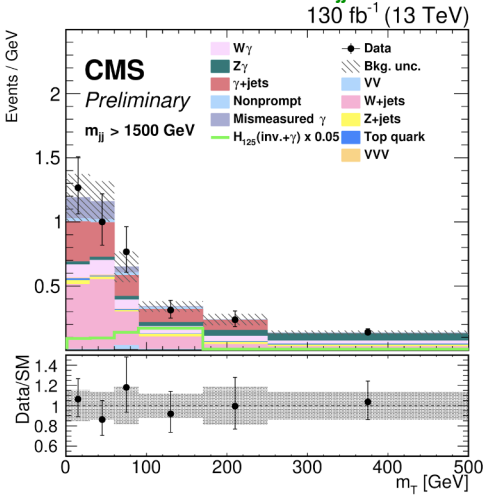
- Higgs decays into photon plus a dark photon (undetected) are searched in VBF events
  - Using 2016-2017-2018 dataset



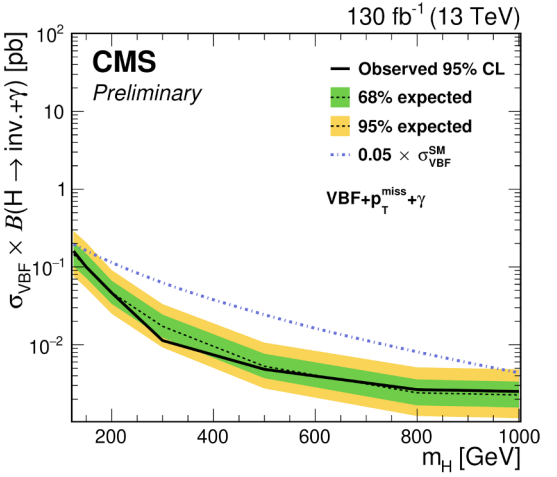
Several control regions defined to constrain the BG from data

Region	Bins	Range (GeV)
SR, $m_{jj} < 1500$ GeV	6	[0,30,60,90,170,250,inf]
SR, $m_{jj} \geq 1500$ GeV	6	[0,30,60,90,170,250,inf]
W + jets CR, $m_{jj} < 1500$ GeV	3	[0,90,250,inf]
W + jets CR, $m_{jj} \geq 1500$ GeV	3	[0,90,250,inf]
$Z(\ell\bar{\ell}) + \gamma$ CR, $m_{jj} < 1500$ GeV	1	[0,inf]
$Z(\ell\bar{\ell}) + \gamma$ CR, $m_{jj} \geq 1500$ GeV	1	[0,inf]
$W(\rightarrow \ell\nu) + \gamma$ CR, $m_{jj} < 1500$ GeV	1	[0,inf]
$W(\rightarrow \ell\nu) + \gamma$ CR, $m_{jj} \geq 1500$ GeV	1	[0,inf]
γ + jets CR, $m_{jj} < 1500$ GeV	1	[0,inf]
γ + jets CR, $m_{jj} \geq 1500$ GeV	1	[0,inf]

Signal region with M_{jj}>1500 GeV



95% CL upper limit on σ times $\mathcal{B}$

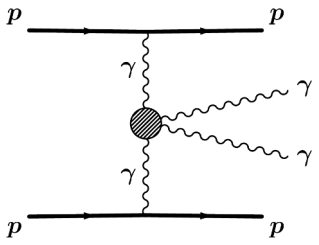


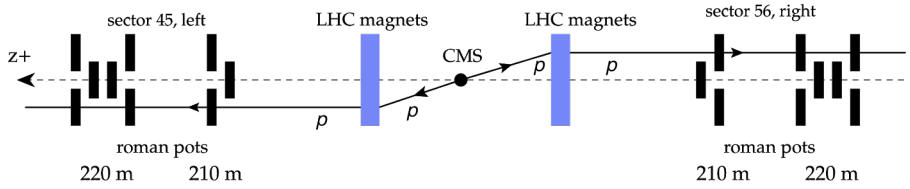
95% CL upper limit on $\mathcal{B}$(H->γγ$_D$) at m_H=125 GeV with the SM production

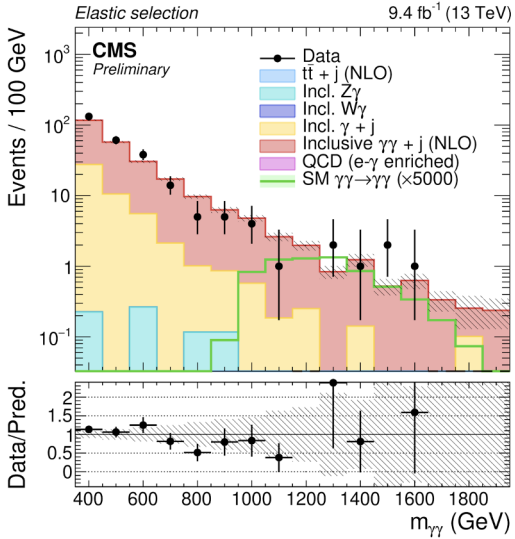
VBF		ZH		VBF+ZH	
Obs. (%)	Exp. (%)	Obs. (%)	Exp. (%)	Obs. (%)	Exp. (%)
3.4	$2.7^{+1.2}_{-0.8}$	4.6	$3.6^{+2.0}_{-1.2}$	2.9	$2.1^{+0.9}_{-0.6}$

CMS PAS EXO-20-005

Exclusive diphoton production with intact protons







Elastic selection: 1-$\Delta\phi/\pi$ <0.005
266 events

Search for exclusive diphoton production with intact protons detected in the TOTEM detector

- Data collected in 2016, IntL = 9.6 fb^{-1}, will extend to the total 110 fb^{-1} of Run 2
- Addressing high mass, M$\gamma\gamma$ > 350 GeV
- Extension of SM Lagrangian with 8-dim term of 4-photon interaction:

$$L_8^{\gamma\gamma\gamma\gamma} = \zeta_1 F_{\mu\nu}F^{\mu\nu}F_{\rho\sigma}F^{\rho\sigma} + \zeta_2 F_{\mu\nu}F^{\mu\rho}F_{\rho\sigma}F^{\sigma\nu} \quad \text{with} \quad \zeta_{1,2} = a_{1,2}^{\gamma\gamma}/\Lambda^4$$

No events observed when requiring matching between the mass and rapidity extracted from photons and protons.
Upper limits at 95% CL on the 4-photon anomalous quartic couplings:

$$|\zeta_1| < 3.7 \times 10^{-13}\ \text{GeV}^{-4} \quad (\zeta_2 = 0)$$
$$|\zeta_2| < 7.7 \times 10^{-13}\ \text{GeV}^{-4} \quad (\zeta_1 = 0)$$

CMS PAS EXO-18-014
TOTEM NOTE 2020-003

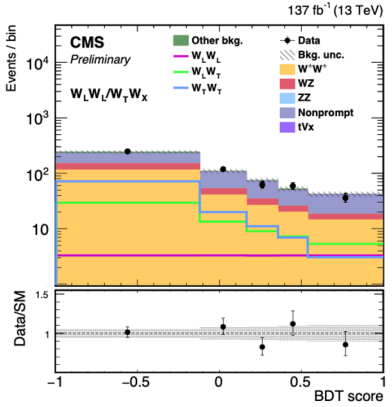
SM, mostly as a search for BSM

Production of polarized WW pairs

SMP-20-006

Motivation

- production of longitudinally polarized gauge bosons via vector boson scattering is tightly linked to the mechanism of EW symmetry breaking
- modifications of the production cross sections are expected in BSM models, e.g., in scenarios involving additional Higgs bosons
- the precise measurement of the cross section is a long-term goal of the LHC program



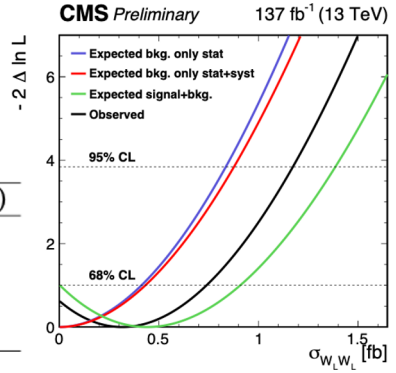
First measurement of production cross section of polarised $W^{\pm}W^{\pm}$ pairs in pp collisions

simultaneous measurement of W_LW_L&W_TW_X, or W_LW_X&W_TW_T production

- EW production with at least one W_L measured with 2.3σ (3.1σ) obs (exp)
- Upper limits (95% CL) for W_LW_L production at 1.17fb (0.88fb) obs (exp)

Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W_L^{\pm}W_L^{\pm}$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
$W_X^{\pm}W_T^{\pm}$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W_L^{\pm}W_X^{\pm}$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18
$W_T^{\pm}W_T^{\pm}$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21

fiducial cross sections in the WW frame



LH scan of the W_LW_L cross section

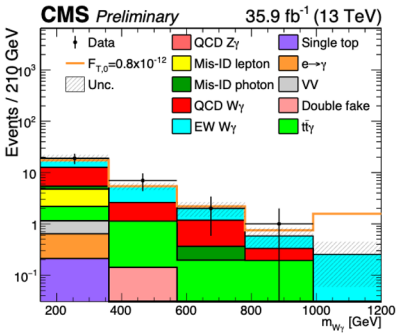
Multiboson production

The analysis of polarized WW pairs is part of a larger set of recent CMS results (EW) multiboson production

- Boson production via vector boson scattering gives access to triple and quartic gauge boson couplings (and anomalous modifications thereof)
- All these studies have to overcome the challenge of small production cross sections

1st Observation of EW Wγ production

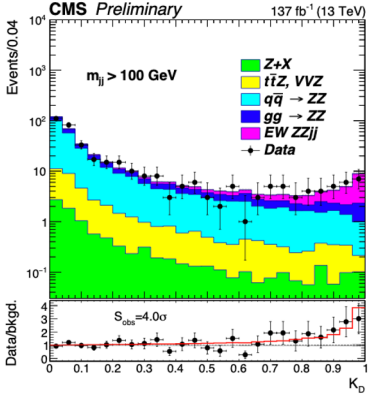
- 5.3σ obs (4.8σ exp) from a combination of 13 and 8 TeV data



SMP-19-008

Evidence for VBS in events with 4l

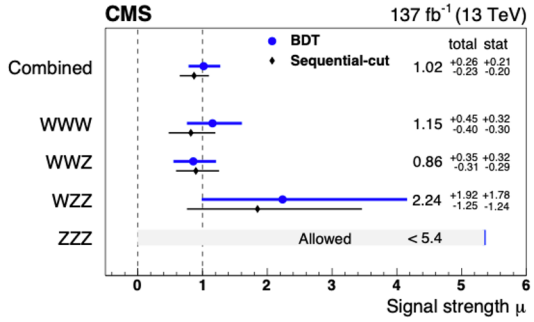
- 4.0σ obs (3.5σ exp) from Run 2



SMP-20-001

1st observation of the production of three massive gauge bosons

- 5.7σ obs (5.9σ exp) significance for VVV
- 3.3σ (3.4σ) obs for WWW (WWZ)



SMP-19-014, arXiv:2006.11191

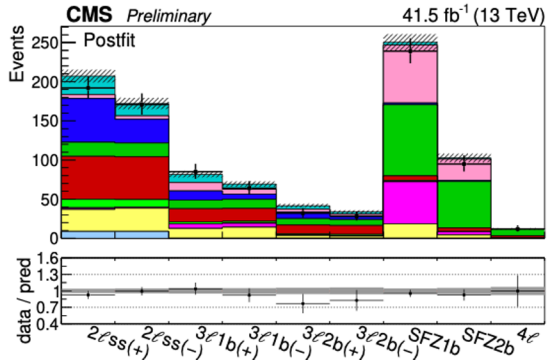
this is our 1000th submitted paper

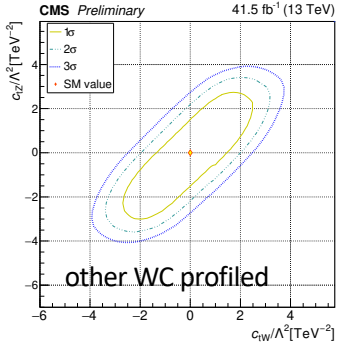
EFT interpretation of associated top quark production

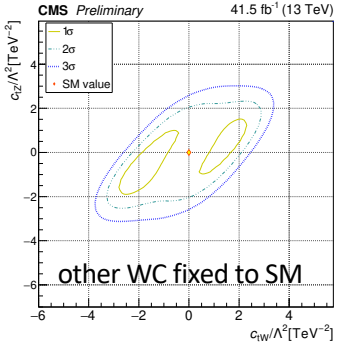
CMS-PAS-TOP-19-001

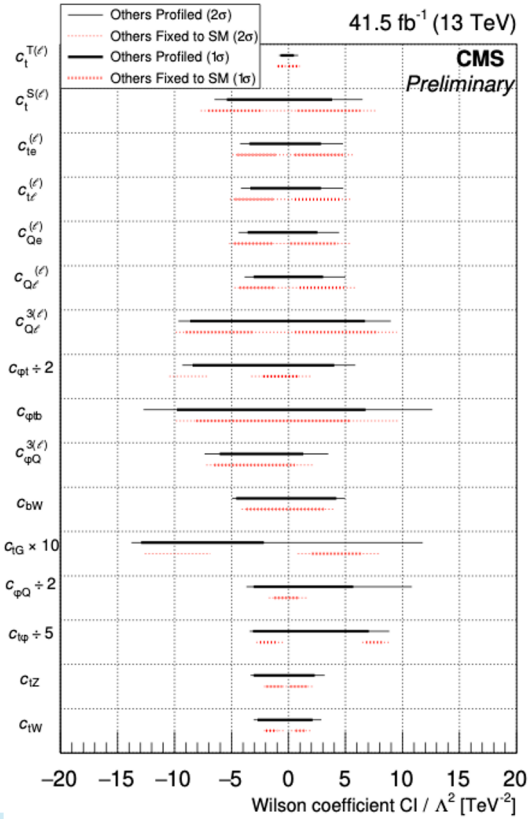
New approach to derive constraints on 16 Wilson coefficients from analysis of tt+X & t+X production

- using ttH, ttll, ttlv, tllq, and tHq in multilepton final states
- parameterization of the quadratic dependence of yields on 16 coefficients for a simultaneous fit:
  - 1D and 2D limits in two scenarios:
    all other coefficients profiled / all other coefficients fixed to SM (0)









Higgs

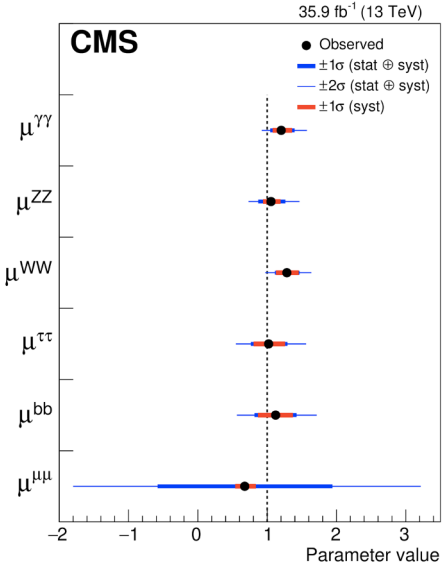
Higgs couplings to fermions

LHC Run 2 data gave us direct access to H couplings to 3rd generation fermions

- decays to tau leptons (PLB 779 (2018) 283, first observation by a single experiment, summer ‘17)
- associated production with top quarks (PRL 120 (2018) 231801, spring ‘18)
- decays to bottom quarks (PRL 121 (2018) 121801, summer ‘18)

The next challenge is to establish couplings to the 2nd generation

- currently best 95% CL limit on $\sigma(VH)\times B(H\to cc)$: 70 (expected: 37) x SM (JHEP 03 (2020) 131, winter ‘19)
- decays to muons: status before ICHEP 2020
  - CMS: < 2.9 x SM @ 95% CL (2016 + Run 1, PRL 122 (2019) 021801)
  - ATLAS: signal strength μ = 1.2 ± 0.6 (Run 2, arXiv::2007.07830)



signal strength modifiers per decay mode from HIG-17-031

Measurement of H → $\mu\mu$

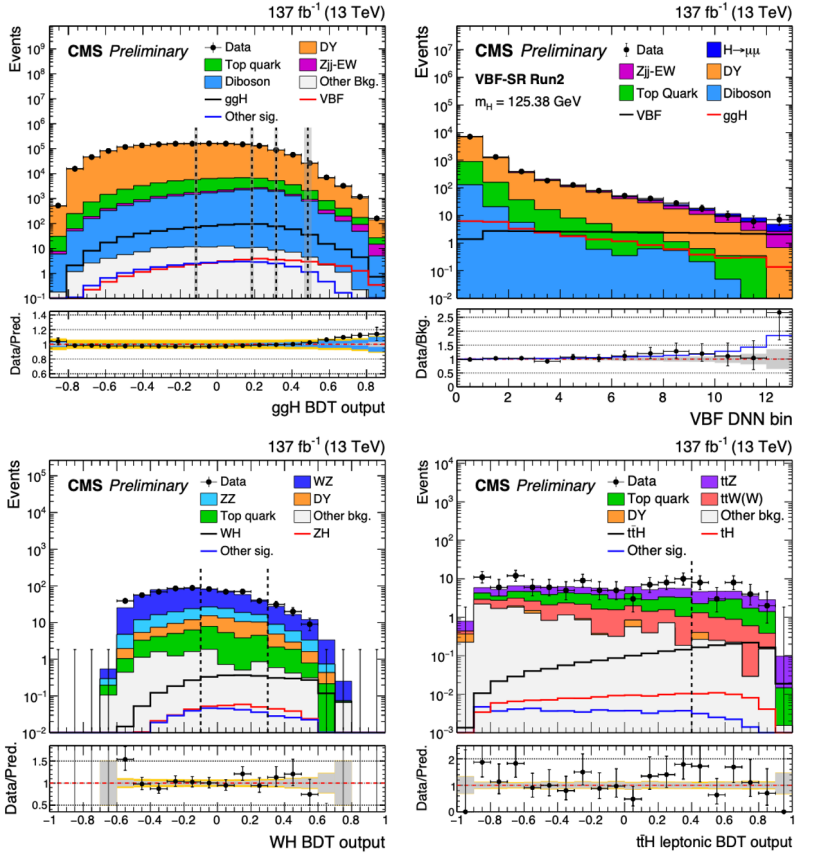
CMS HIG-19-006

- analysis of Run 2 data (137 fb^{-1})
  - four components targeting ggH, VBF, VH, and ttH
  - highest cross section in ggH and VBF modes
  - background suppression due to fwd. jets leads to highest sensitivity for VBF

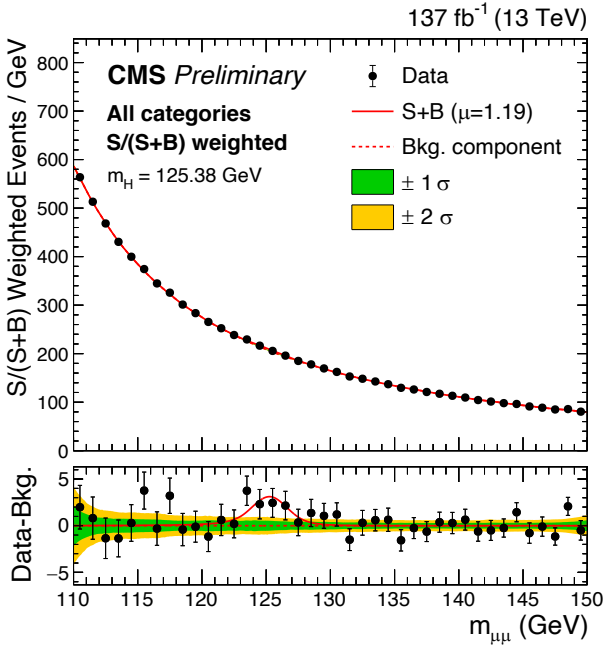
- result is combined with Run 1 data at 7 and 8 TeV
- results are reported at m_H = 125.38 GeV [Phys. Lett. B 805 (2020)]

significance: 3.0σ obs (2.5σ exp)

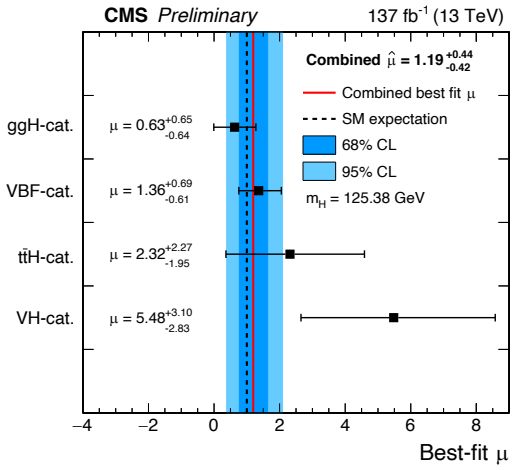
signal strength: $\mu = 1.19^{+0.41}_{-0.39}\,(\text{stat})^{+0.17}_{-0.16}\,(\text{syst})$



Measurement of H → μμ

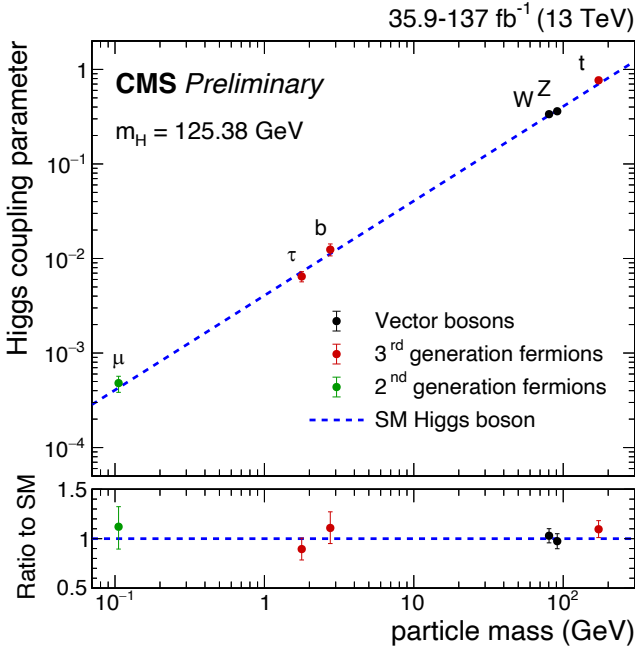


$m_{\mu\mu}$ distribution for the weighted combination of all event categories, with the best-fit SM H→μμ signal contribution with m_H = 125.38 GeV



combined signal strength

$\mu = 1.19^{+0.44}_{-0.42}$

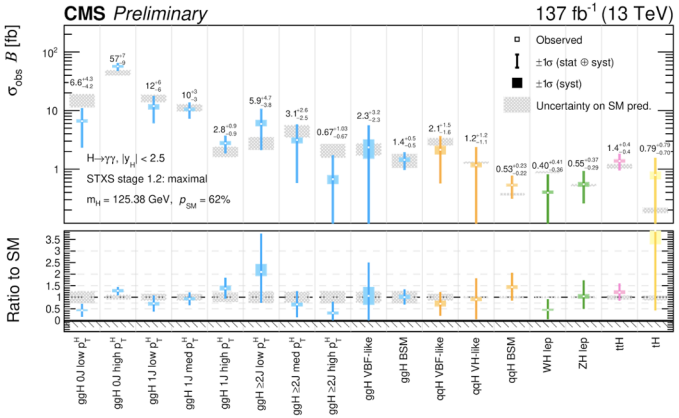


the best-fit estimates for the six reduced coupling strength modifiers as a function of particle mass. The best-fit value for k_μ is 1.13 and the corresponding observed 68% CL interval is $0.91 < k_\mu < 1.34$

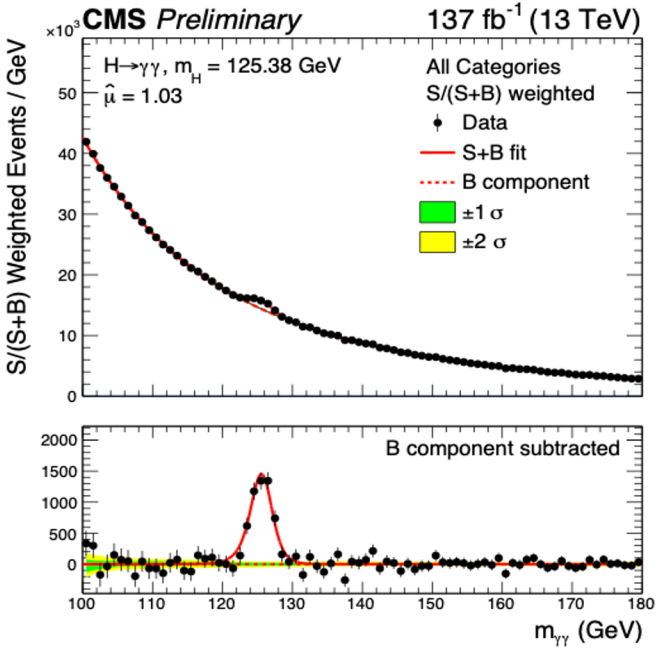
Higgs boson signal strengths and couplings from H→γγ

Full Run 2 dataset used to analyze H decays to photons

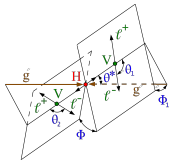
- covering ggH, VBF, and associate production modes (V, tt)
- overall signal strength modifier $\mu = 1.03^{+0.11}_{-0.09}$
- analysis categories tailored for kinematic regions in the "simplified template cross section scheme" STXS
- results also provided in terms of production signal strengths and coupling modifiers in the **κ**-framework



STXS Stage 1.2, maximal merging



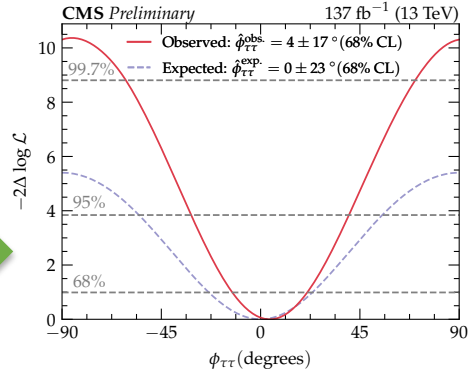
HIG-19-015



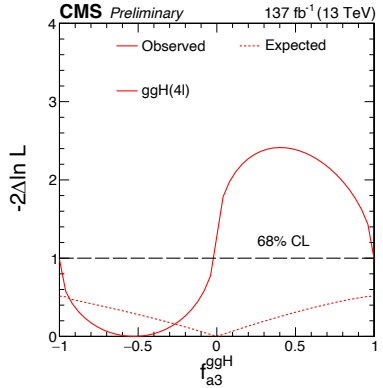
CP-structure and anomalous couplings of Higgs Bosons

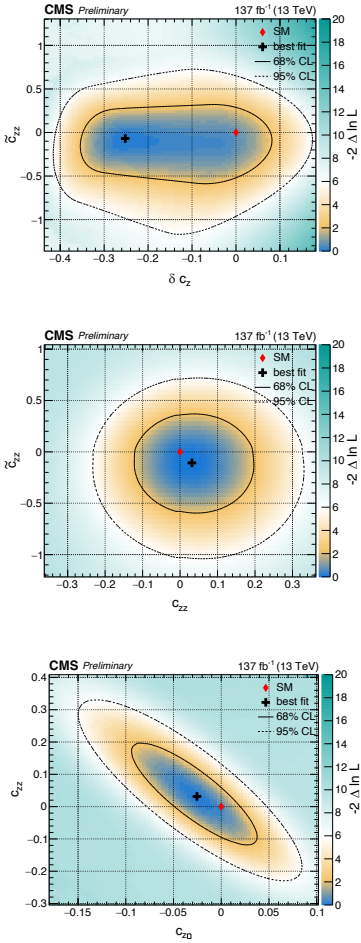
Two analyses (both 137 fb-1) were presented:

- CP structure of the Yukawa coupling between H and τ
  - Using $H \to \tau\tau$ decays, measuring angular correlation between decay planes in μh and hh channels
  - Mixing angle between CP-even (SM) and CP-odd coupling found to be 4±17°
  - Observed (expected) significance of separation between scalar and pseudoscalar hypotheses is 3.2 (2.3) σ
- Studies of CP-violation and anomalous H coupling to V and fermions in the $H \to 4l$ channel
  - using kinematics of the Higgs boson's *4l* decay and of its production in association with a vector boson, hadronic jets, or a top-quark pair
  - Simultaneous measurement of up to five HVV, two Hgg, and two Htt couplings, interpreted in the framework of effective field theory
  - CP-sensitive parameter f_{a3}^{ggH} in the H couplings to gluons best-fit value:
    - $f_{a3}^{ggH} = -0.53^{+0.51}_{-0.47}\,(obs)\;\; 0 \pm 1\,(exp)$



CMS-PAS-HIG-20-006

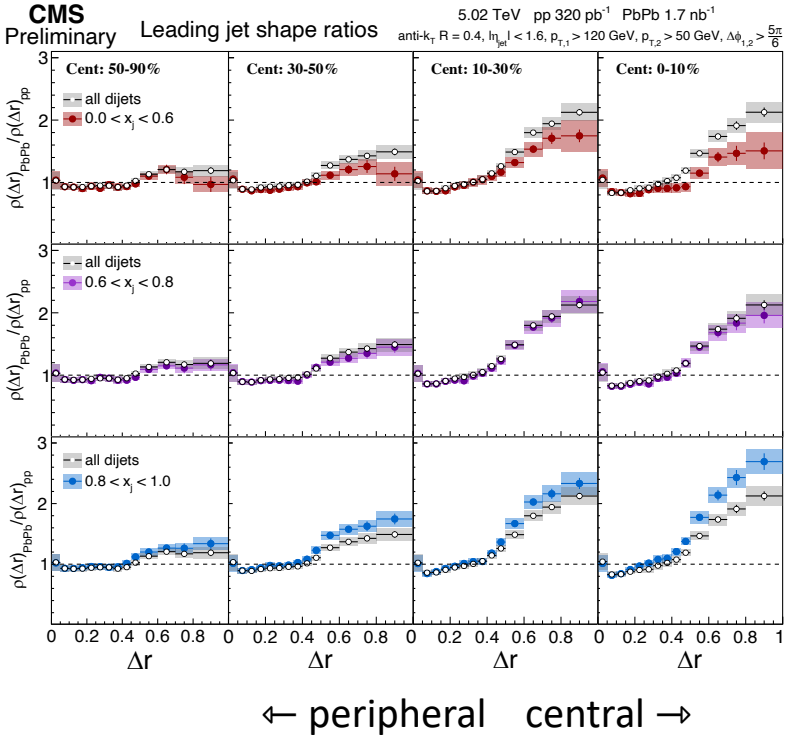




CMS-PAS-HIG-19-009

Heavy Ions in CMS

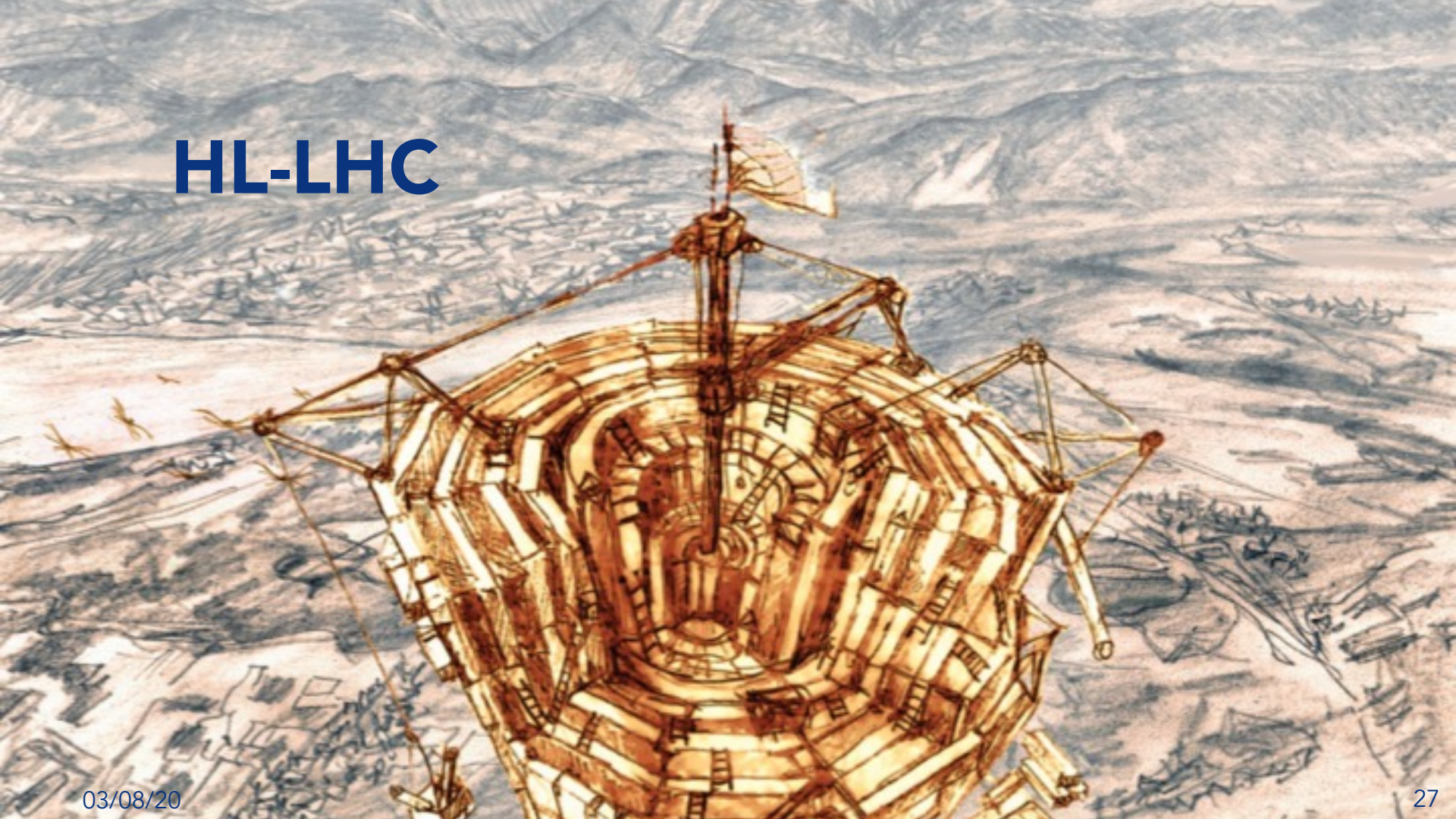
- **Measurement of charged particle yields and jet shapes in events containing back-to-back leading and subleading jet pairs**
  - Comparing PbPb and pp collisions
  - LHC data collected at a collision energy of $\sqrt{s_{NN}}$=5.02 TeV in 2017 and 2018, corresponding to integrated luminosities of 320 pb^{-1} for pp and 1.7 nb^{-1} for PbPb collisions
- Observe a redistribution of energy to large angles w.r.t. the jet axis in PbPb, and for the leading jet this is more pronounced in balanced dijets



PbPb to pp ratio for leading jet shapes ρ(Δr)PbPb/ρ(Δr)pp

CMS PAS HIN-19-013

HL-LHC



CMS HL-LHC upgrade

Technical proposal CERN-LHCC-2015-010 https://cds.cern.ch/record/2020886
Scope Document CERN-LHCC-2015-019 https://cds.cern.ch/record/2055167

L1-Trigger/HLT/DAQ

https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193

- Tracks in L1-Trigger at 40 MHz
- PFlow-like selection 750 kHz output
- HLT output 7.5 kHz

Barrel Calorimeters

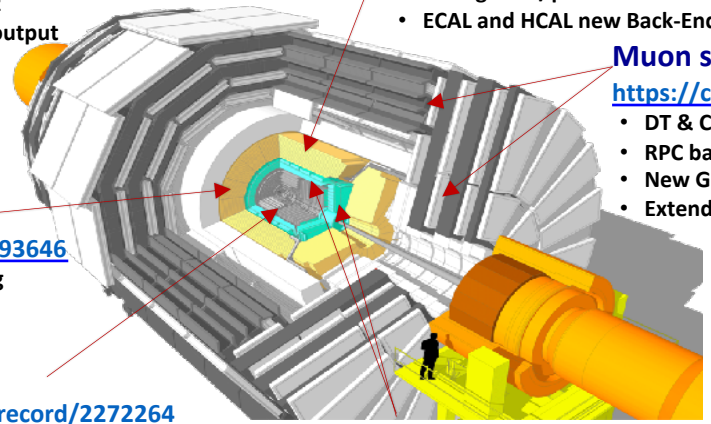
https://cds.cern.ch/record/2283187

- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

Muon systems

https://cds.cern.ch/record/2283189

- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$



Calorimeter Endcap

https://cds.cern.ch/record/2293646

- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

Beam Radiation Instr. and Luminosity, and Common Systems and Infrastructure

https://cds.cern.ch/record/002706512

Tracker https://cds.cern.ch/record/2272264

- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$

MIP Timing Detector

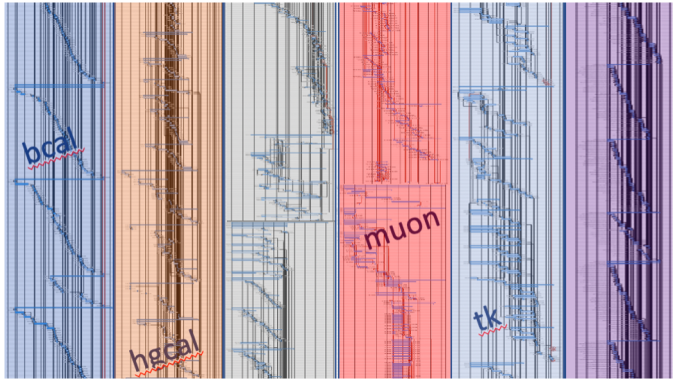
https://cds.cern.ch/record/2296612

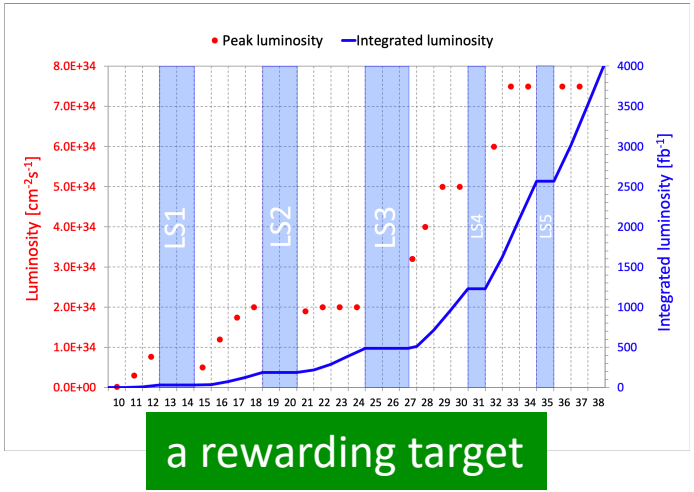
Precision timing with:

- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

New paradigms (design/technology) for an HEP experiment to fully exploit HL-LHC luminosity

A complex schedule

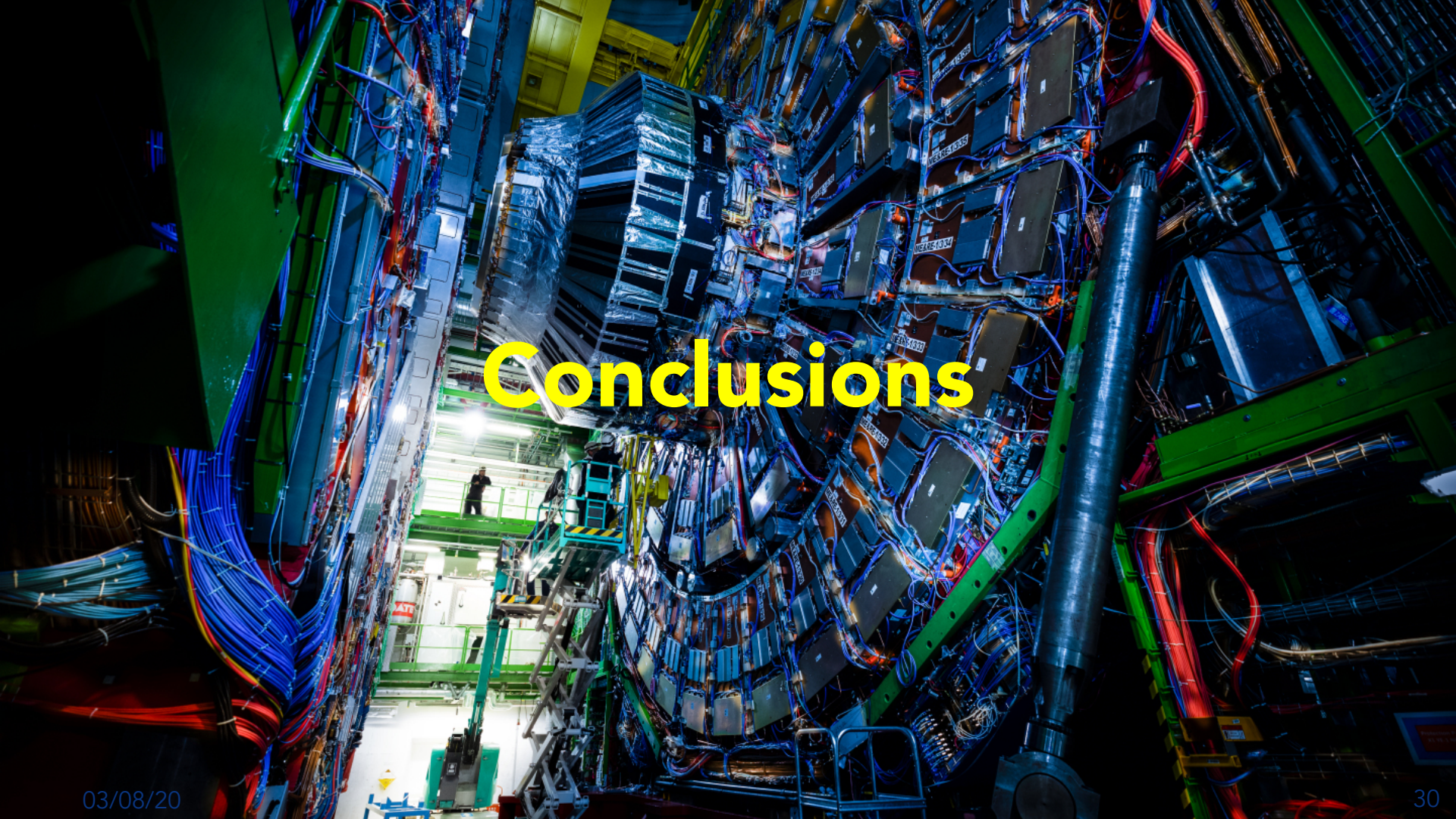




a rewarding target

TDRs for the main detector and L1 trigger approved,
Entering a new phase of engineering, prototyping, construction

- Covid-19 has generated delays up to 3 months, still absorbable in the present contingencies
  - A very long prolongation of present precautions (e.g to 2022 when we are going to start mass production) or further widespread lockdowns will have an impact



Conclusions

We celebrated the 10th anniversary of the first collisions @ CMS

Conclusions

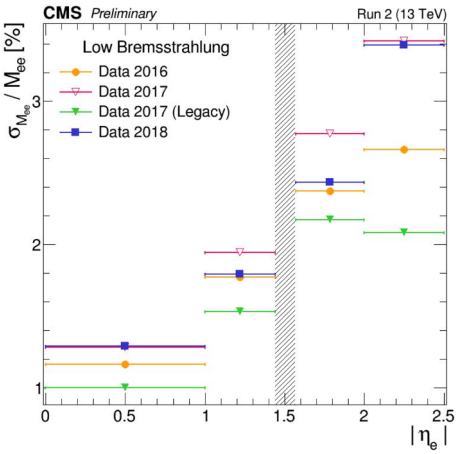
- We have been and are very productive with excellent results with a very large scope of physics results
- And we have still many years and luminosity in front of us
  - The large luminosity LHC delivered is about 5% of the total expected
- We are active in several different areas:
  - Analysis, development of new techniques which are needed to exploit the large luminosities that LHC delivers (thanks!), preparation and upgrades for the coming Run 3, HL-LHC upgrade
- It is an ideal opportunity for a young physicist to be part of an LHC collaboration, exposed at the same time to the different activities of an experimental physicist, all at the leading edge

Thanks for Listening (and, be safe!)

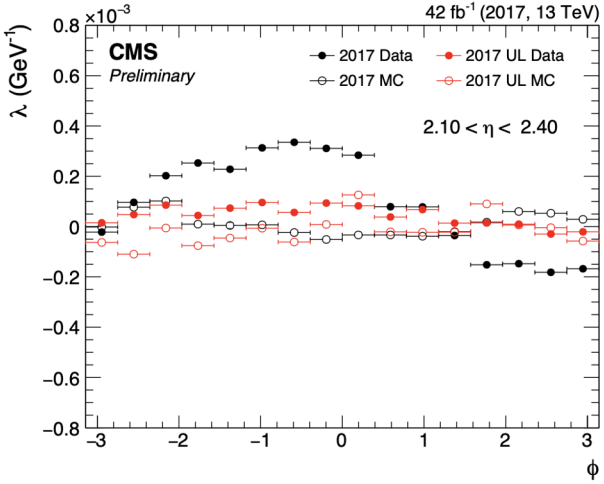
Backup Slides

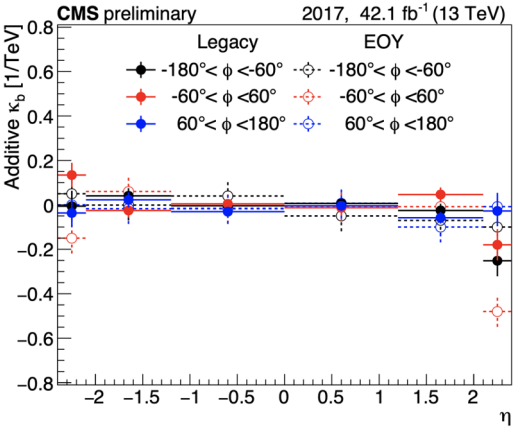
Detector performance

Improvements in performance for legacy reconstruction of Run 2 data



better mass resolution for electron pairs (in particular in the forward region)

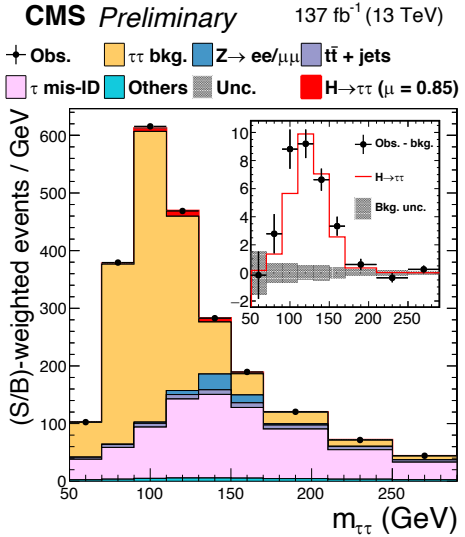




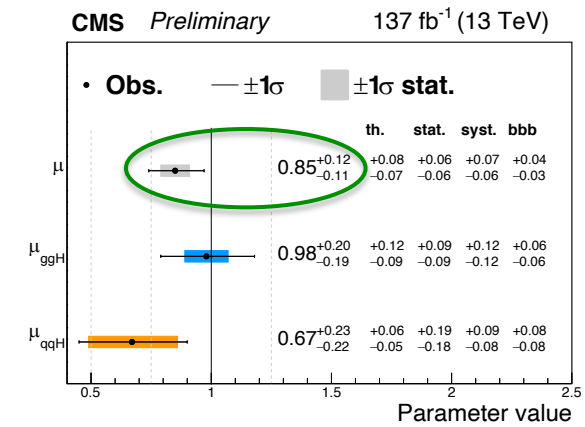
Measurement of Higgs boson production in the decay channel with a pair of τ leptons

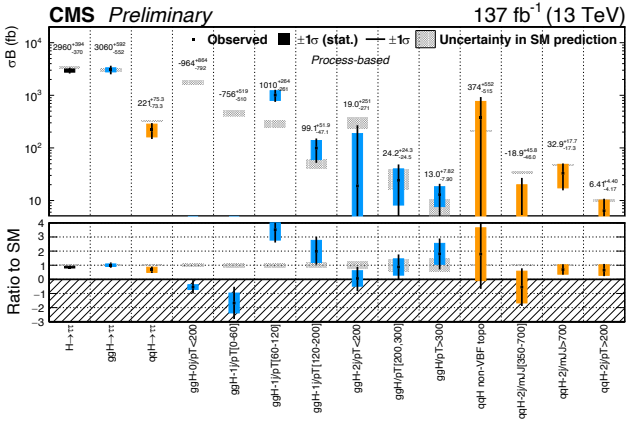
Measurement of H→$\tau\tau$ with the 2016-2018 Run 2 sample at 13 TeV

- targeting the ggH and VBF production modes
- Study performed also in the categories of the Simplified Template Cross section Scheme (STXS)



$m_{\tau\tau}$ distribution reweighting every category, year and final state





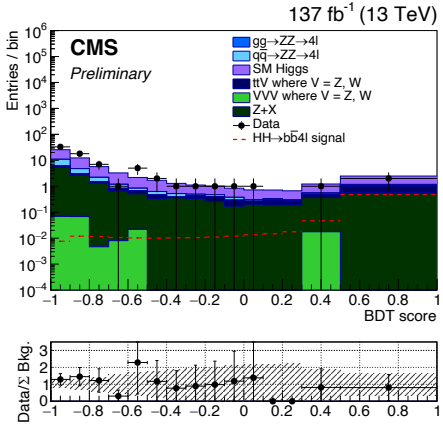
signal strengths (top) and product of $\sigma\mathcal{B}$ in Simplified Template Cross section Scheme (STXS) bins, for one of the merging schemes

CMS-PAS-HIG-19-010

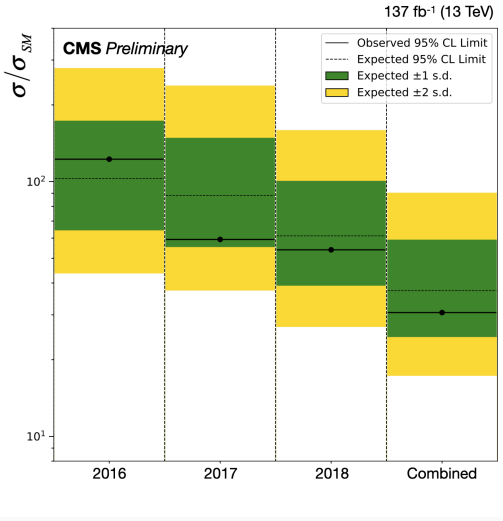
Search for $HH \to 4lb\bar{b}$

Search for non-resonant pair production of HH with $HH \to ZZ^*b\bar{b} \to 4lb\bar{b}$

- $H \to ZZ^*$ has small branching fraction but large S/B
- Search on 2016 to 2018 data sample (137 fb^{-1}) using multivariate analysis with BDT discriminator
- The observed (expected) upper limit on the signal strength modifier μ, defined as the ratio of the double-H boson rate in the $4lb\bar{b}$ channel to the Standard Model (SM) expectation, is 30 (37) at 95% CL

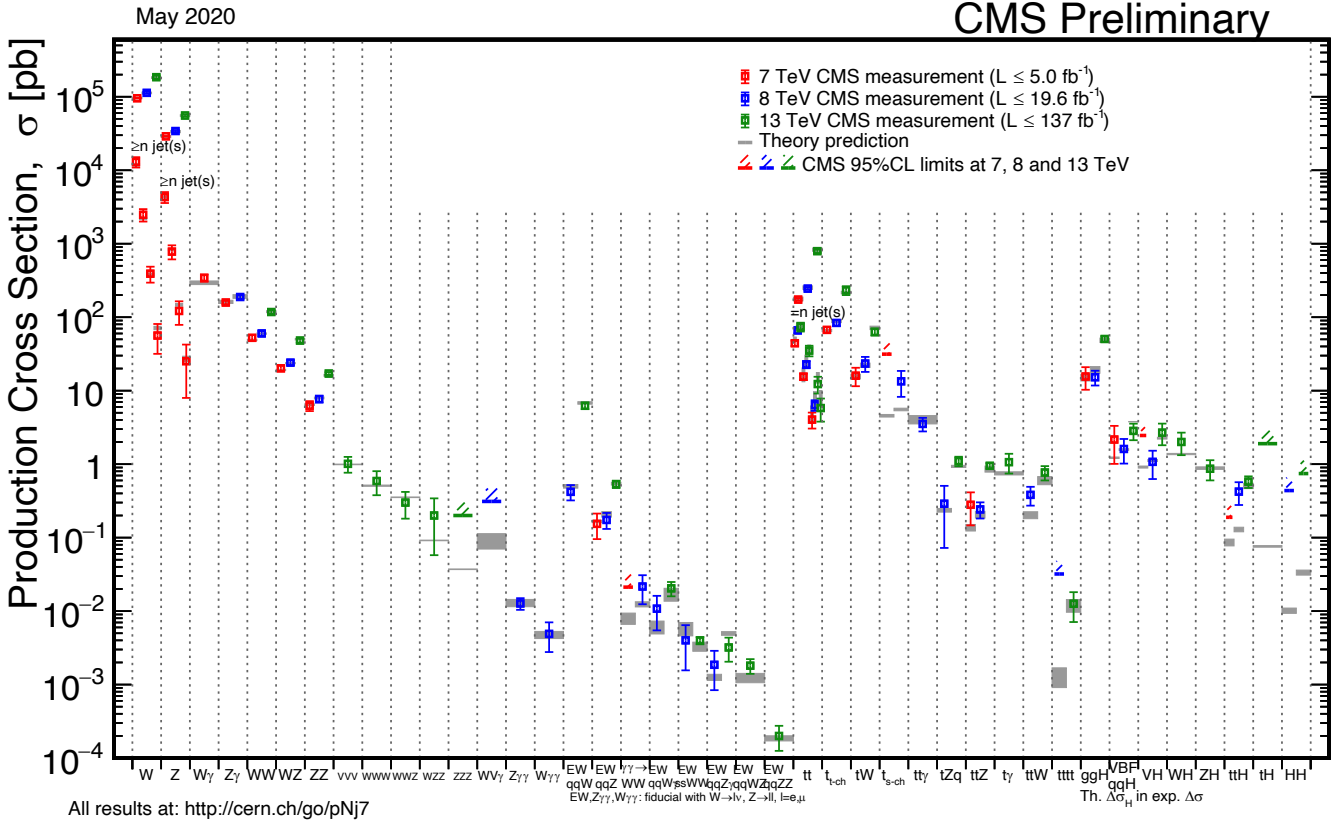


Inclusive BDT distributions for signal, estimated background components, and data for the three different leptonic final state (4μ, 4e, and 2e2μ) and data taking years



upper limit on the signal strength at 95% CL for each year and for the combination:

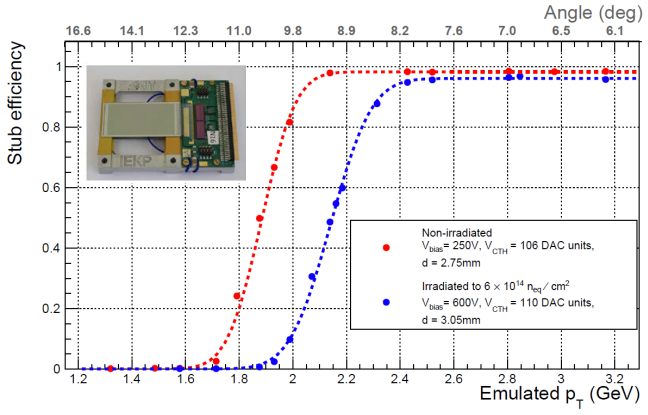
CMS PAS HIG-20-004

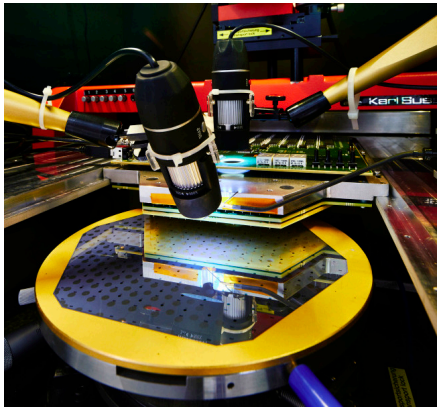


All results at: http://cern.ch/go/pNj7

HL-LHC progress

- Outer Trackers Stubs (input to L1 trigger from hit patterns in two sensor planes) good efficiency measured with beams in irradiated mini-module
  - Different turn-on are related to different sensor spacing
  - See more in K. Klein talk in the parallels





- HGCAL Silicon sensors are first use of 8" technology for large-scale HEP sensors
  - Comprehensive test program including full-sensor tests with custom probe cards and reactor based neutron irradiations
  - See more in J. Mans talk in the parallels