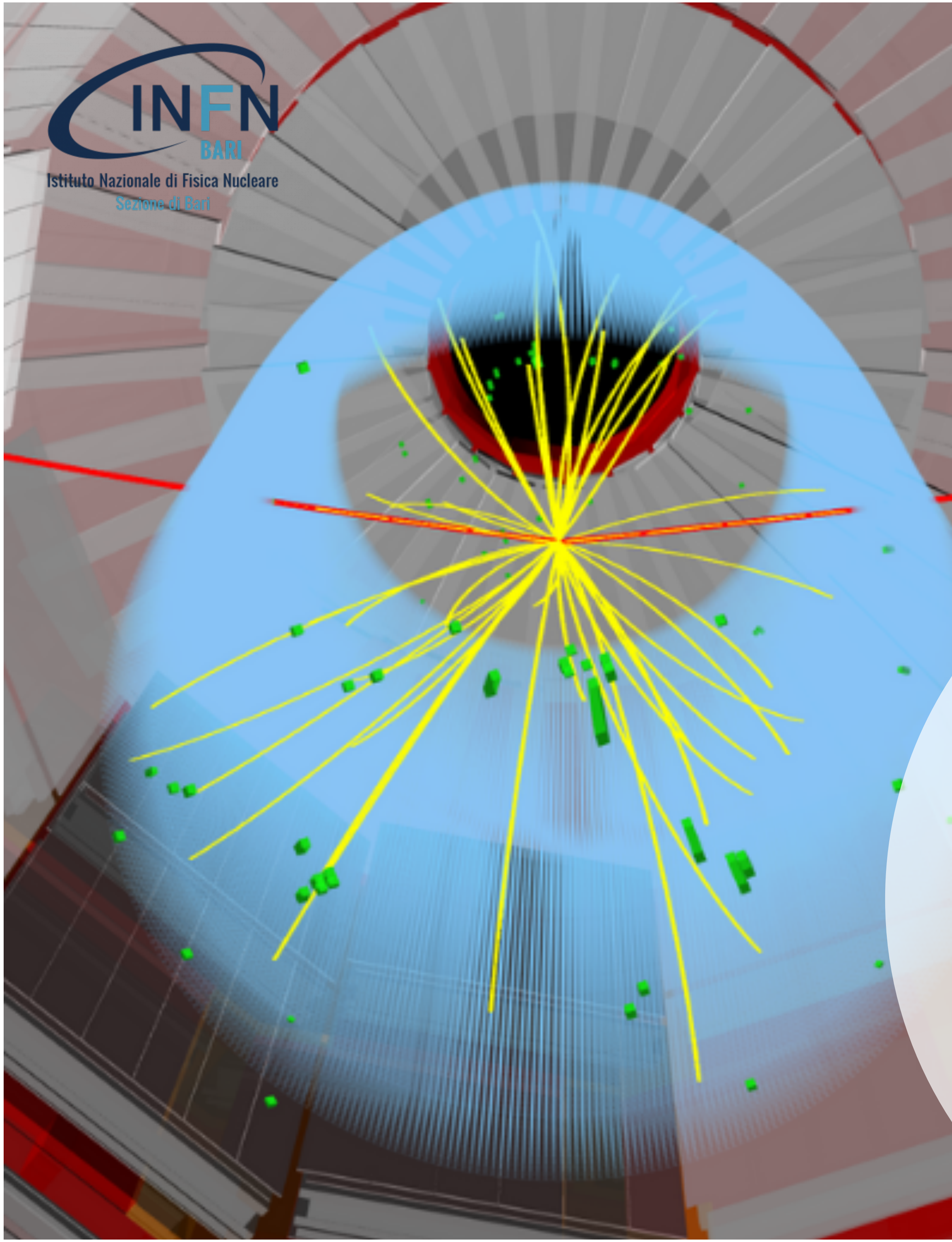


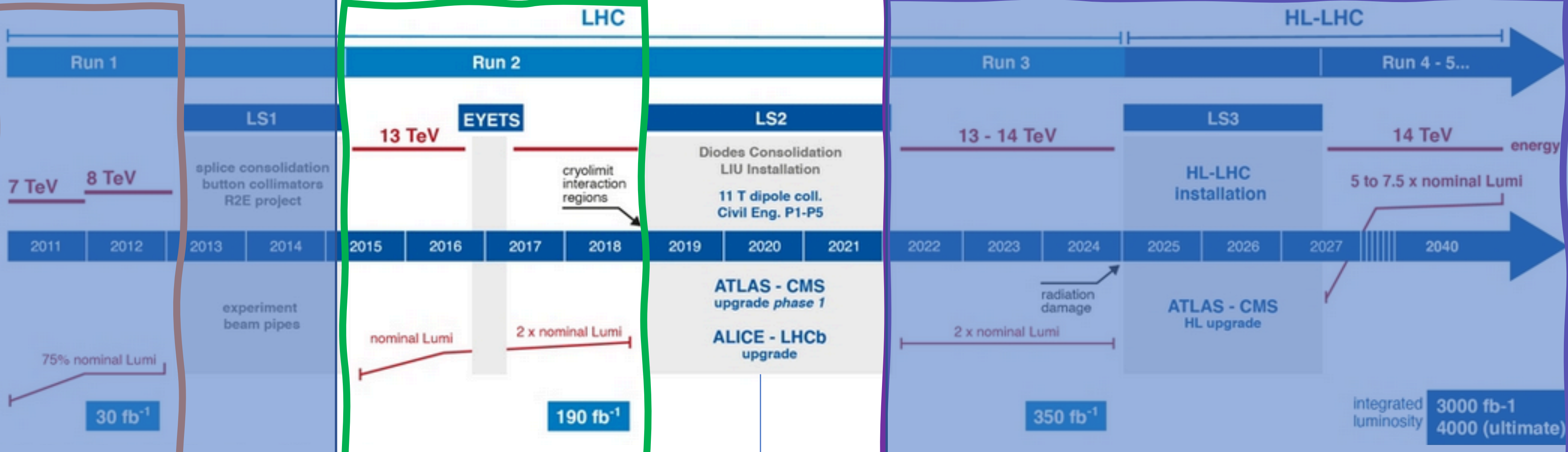
CMS Highlights

Rosamaria Venditti (INFN and University of Bari)

On behalf of the CMS Collaboration

ICNFP 2020- 9th International Conference on New Frontiers in Physics

Roadmap from past to future



Higgs boson discovery

Larger dataset and COM→ precision measurement on Higgs properties and new physics searches (this talk!)

The best is yet to come

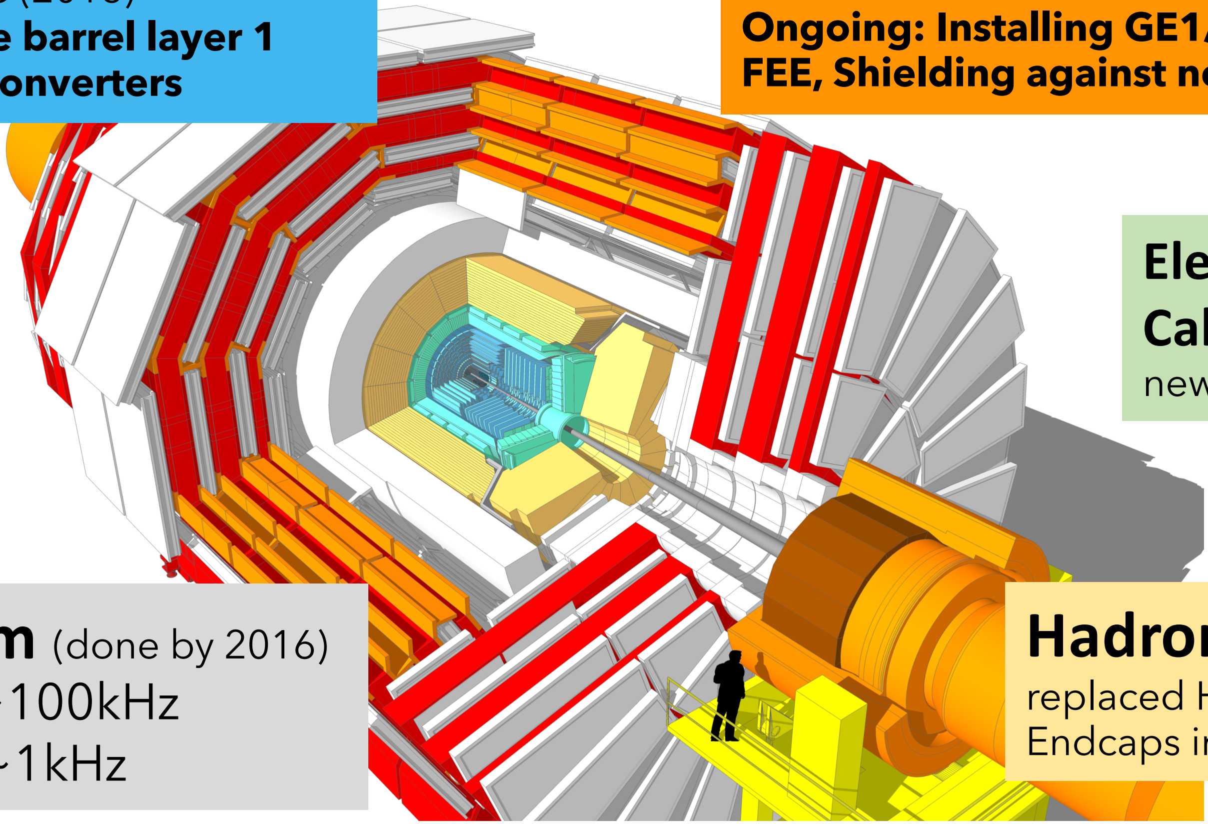
We are here! Just 4 months delay on the LHC schedule for the COVID emergency

The CMS Apparatus: status and activities

- The CMS detector Phase-1 upgrades started during the first Long Shutdown (2014) and concluded during the Run 2 end of the year technical stops (2019)

Silicon Tracker
• **Pixel upgraded** in 2017 (4th layer) replaced some electronics in 2018
• Microstrips running colder -15°C (2015-2017) -20°C (2018)
Ongoing: replace barrel layer 1
Replace DC-DC converters

Muon Detectors
• Drift tubes VME → μTCA readout in 2018
• New RPC stations
• GEM slice test (GE1/1) in 2018
Ongoing: Installing GE1/1, Upgrade CSC FEE, Shielding against neutron background



Electromagnetic Calorimeter
new DAQ links in 2018

Trigger System (done by 2016)
• L1 hardware ~100kHz
• HLT software ~1kHz

Hadron Calorimeter
replaced HPDs→**SiPMs** in Endcaps in 2018

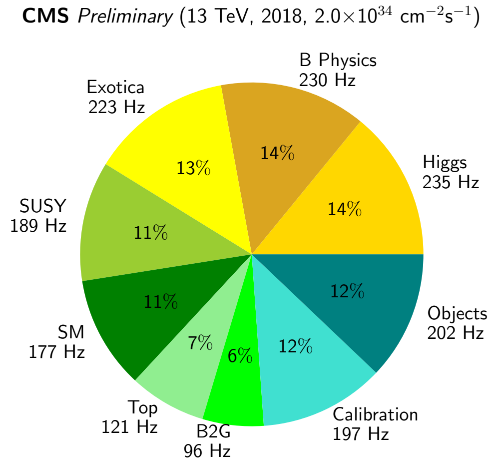
More on
Mia Tosi's talk

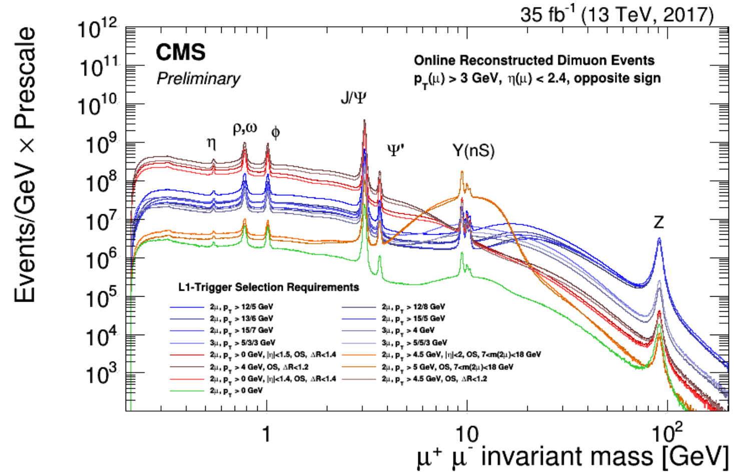
Catching particles: trigger and datasets

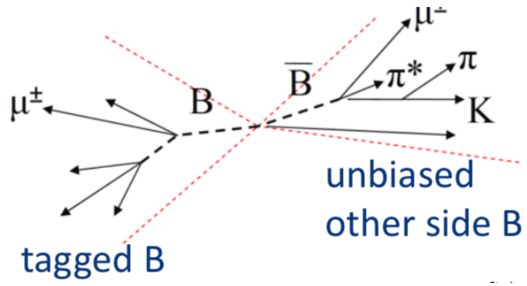
Multiple flavour of data allow to cover as much as possible the SM an BSM physics phase space

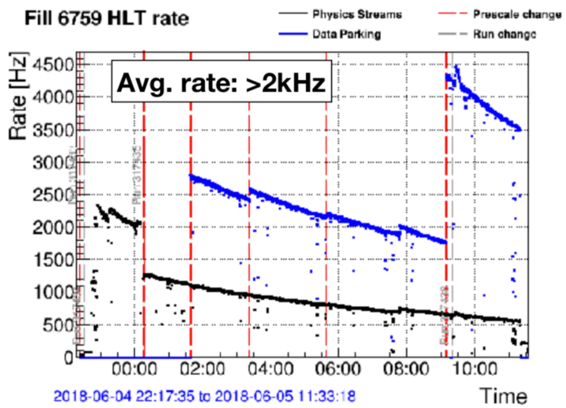
<u>pp collisions</u>

- "Standard triggers"
- B-parking: store data with lower trigger thresholds at end of fill, delay their processing → *11B* events enriched in **unbiased B-decays !!!**
- Scouting: lower pT threshold and mass selections thanks to a **reduction** of **event size to O(10kB) due to** physics objects reconstructed at the High Level Trigger (no full reco!)







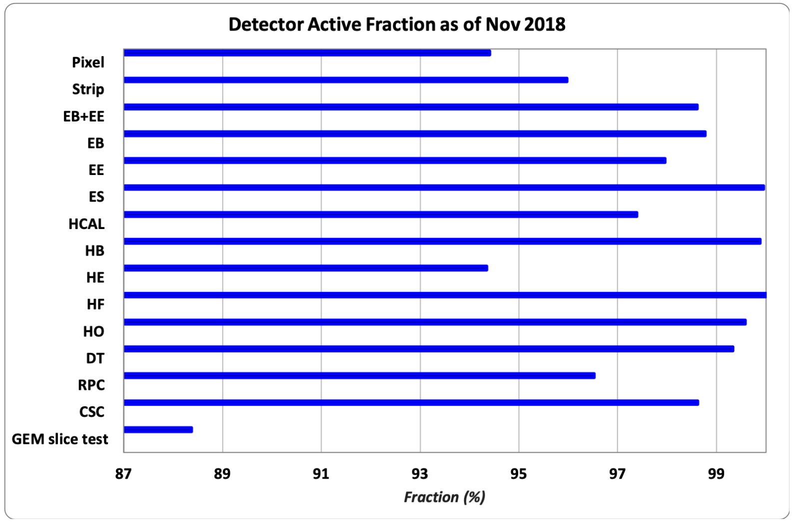


Other flavors:
<u>Heavy Ions, Low beta*, Low-PU</u>

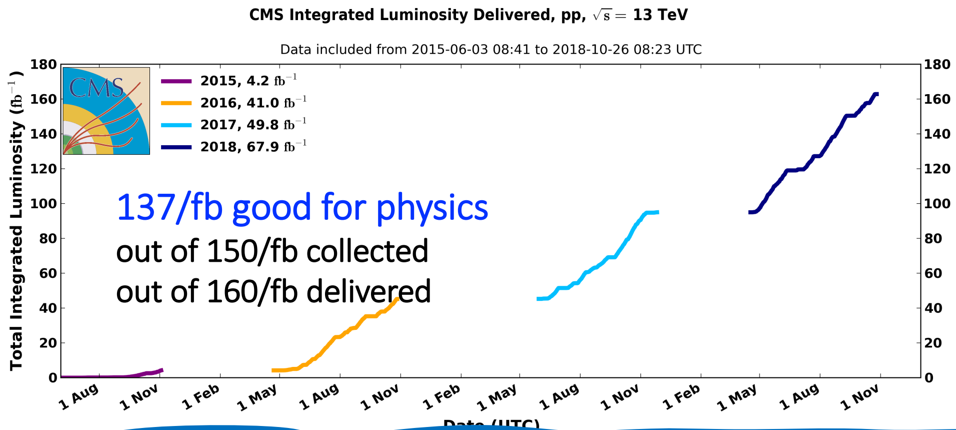
The CMS Run 2 data-taking

Few challenges successfully accomplished during Run2
→BX time from 50ns (Run1) to 25ns(Run2)
→Significant number of pile-up interactions

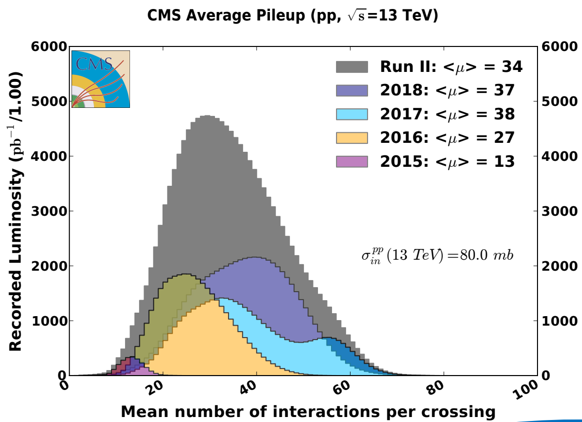
All sub-detectors performed excellently



pp collisions

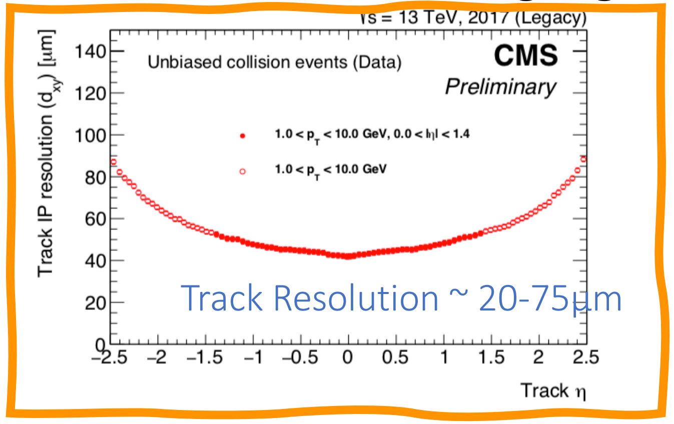


137/fb good for physics
out of 150/fb collected
out of 160/fb delivered

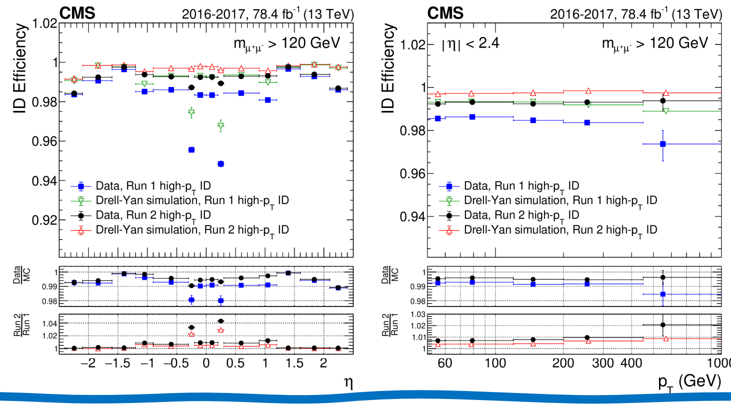


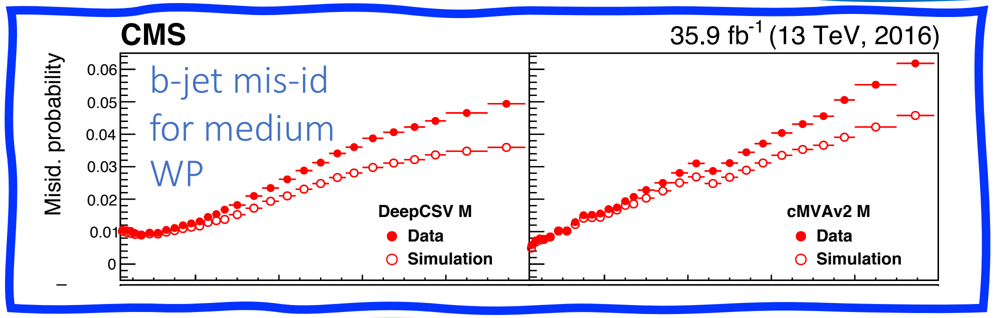
The Objects reconstruction - miscellanea

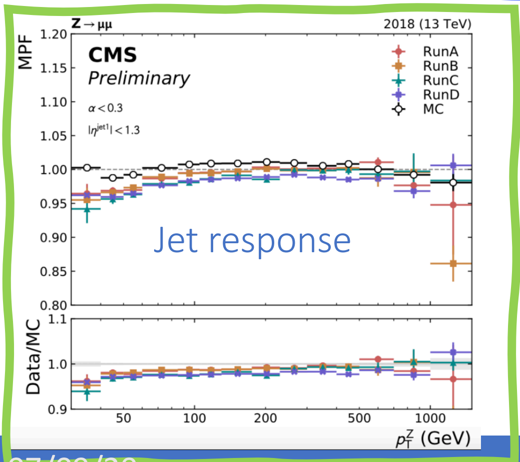
Consolidate existing algorithm thanks to a deep knowledge of the detector → excellent performance

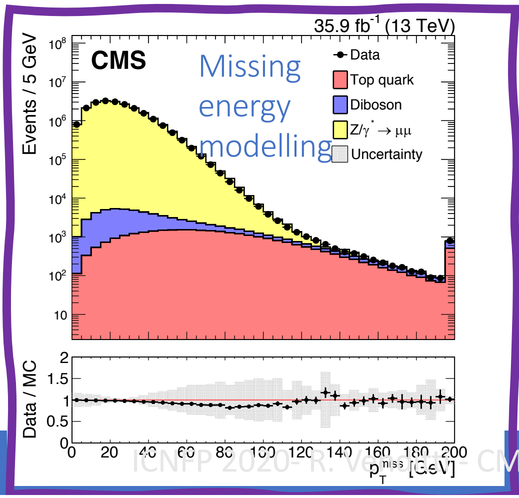


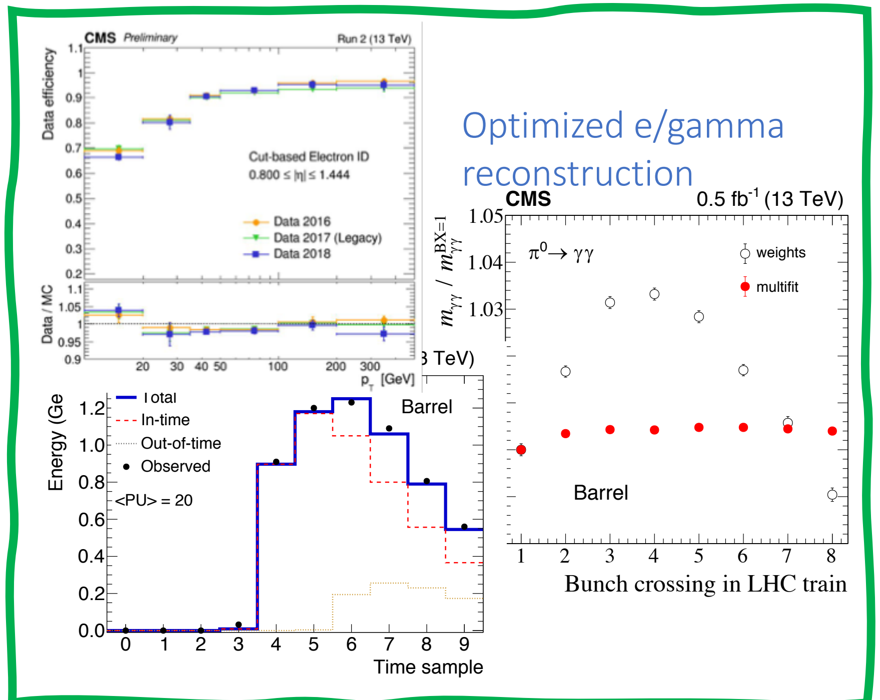
New tuning for High-pT muons ID









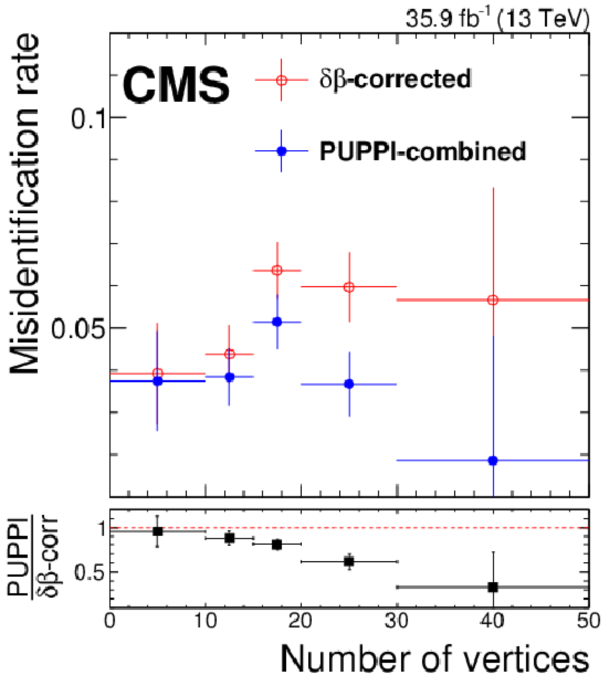


The Objects reconstruction

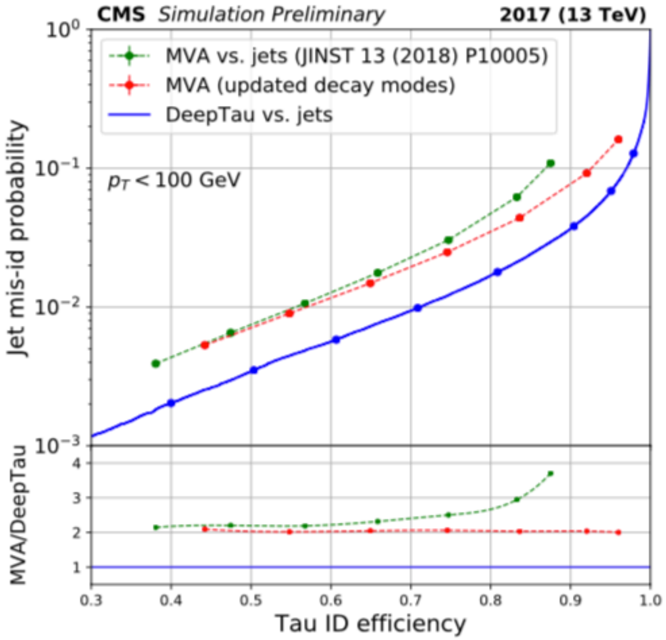
More on
Mia Tosi's talk

- Extensive use of MVA an Deep/ML techniques to consolidate and improve existing identification/reconstruction algorithms and explore new possibilities

Lepton/jet isolation with PUPPI

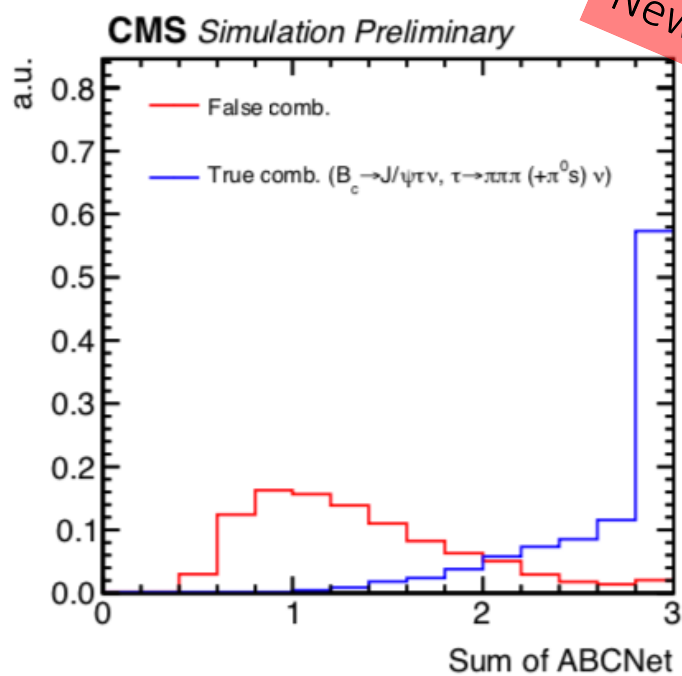


Jet to tau discrimination with Deep Learning



Low p_t tau identification

New



Improved performance with Deep/ML techniques!
New algorithms used in some of the full-Run 2 dataset based analyses showed in next slides

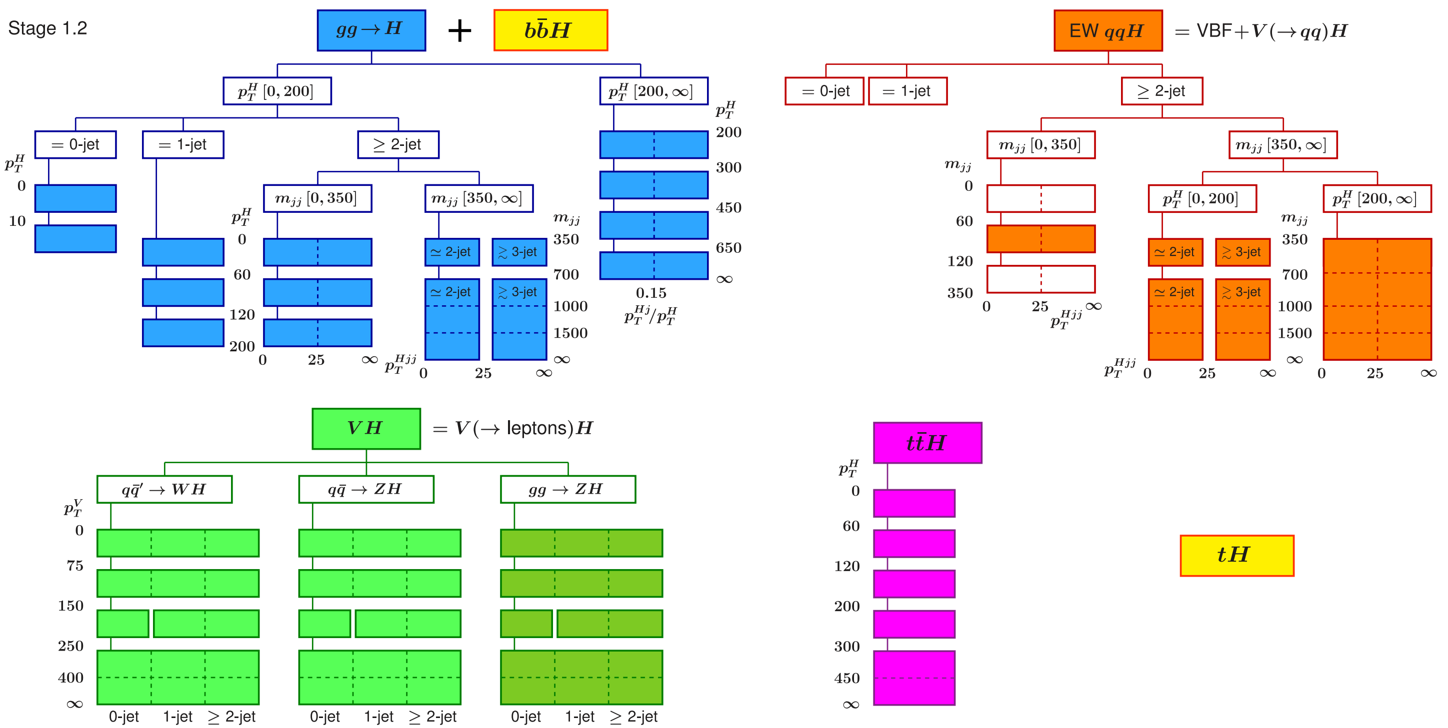
Developed in view of B-parking based analyses, impact of the physics will come soon!

Higgs bosons physics with full CMS Run II dataset

Measurement are performed with full Run II luminosity and results are interpreted in the STXS model

- Each Higgs boson production mode is split into numerous bins by kinematic features that are highly correlated with reconstruction-level objects.
- Reduce theory uncertainty and model dependence on measured bins

More on R. Seidita's talk



H→γγ

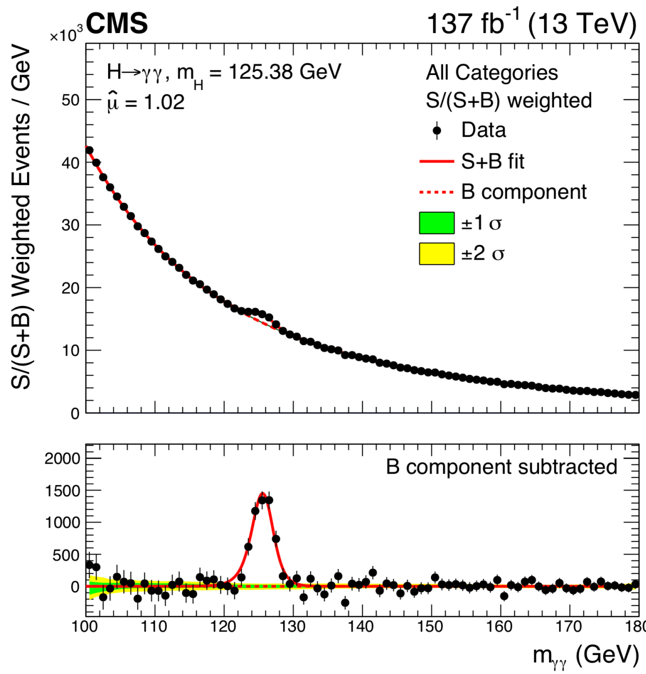
HIG-19-015

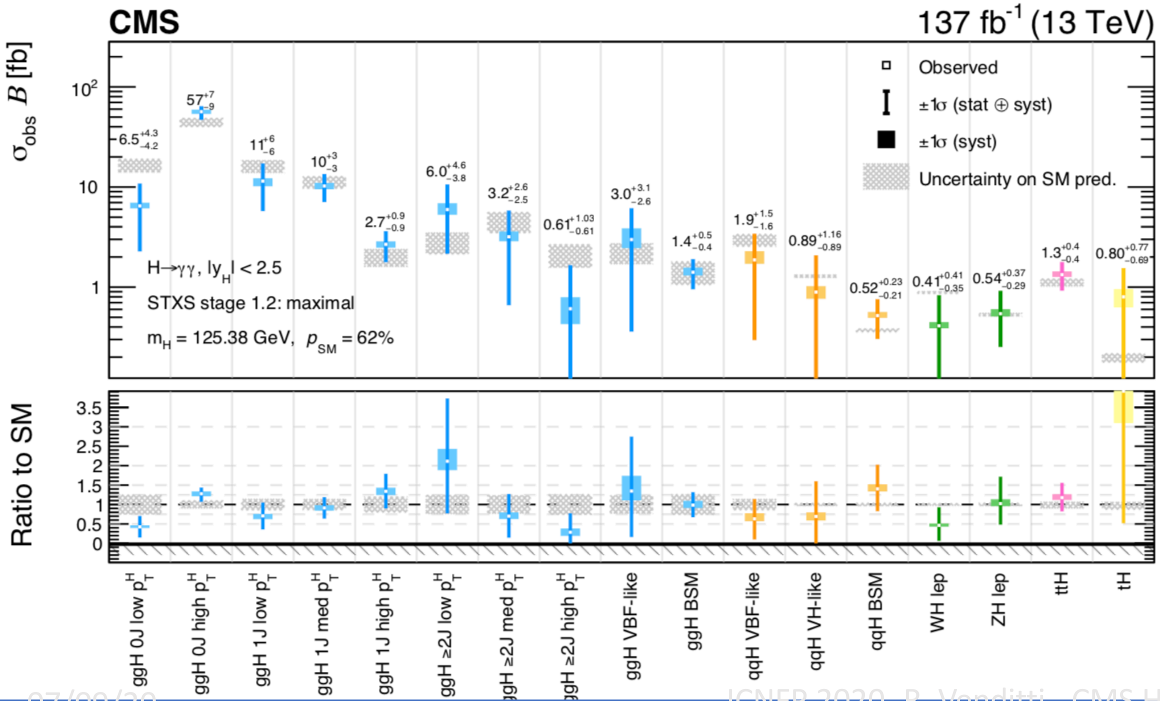
Full Run 2 dataset used to analyze H decays to photons

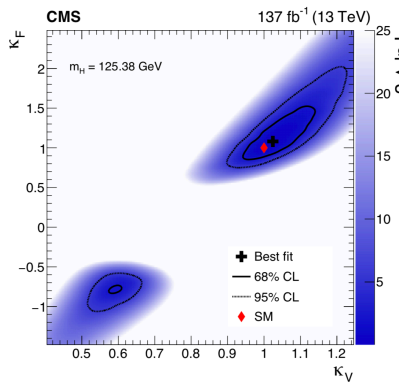
- covering ggH, VBF, and associate production modes (V, tt, tH)
- overall signal strength modifier $\mu = 1.02^{-0.11}_{-0.9}$

  →10% precision

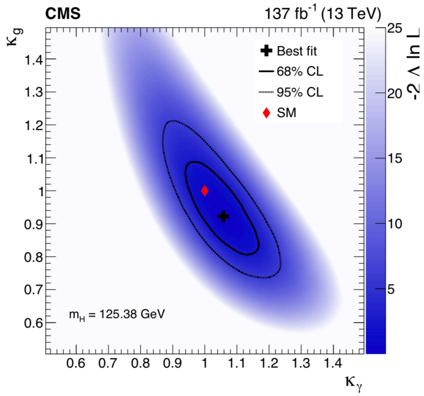
  →most precise measurement of associated production with single top (x12 SM)
- results also provided in terms of production signal strengths and coupling modifiers in the κ-framework







Couplings with fermions and bosons



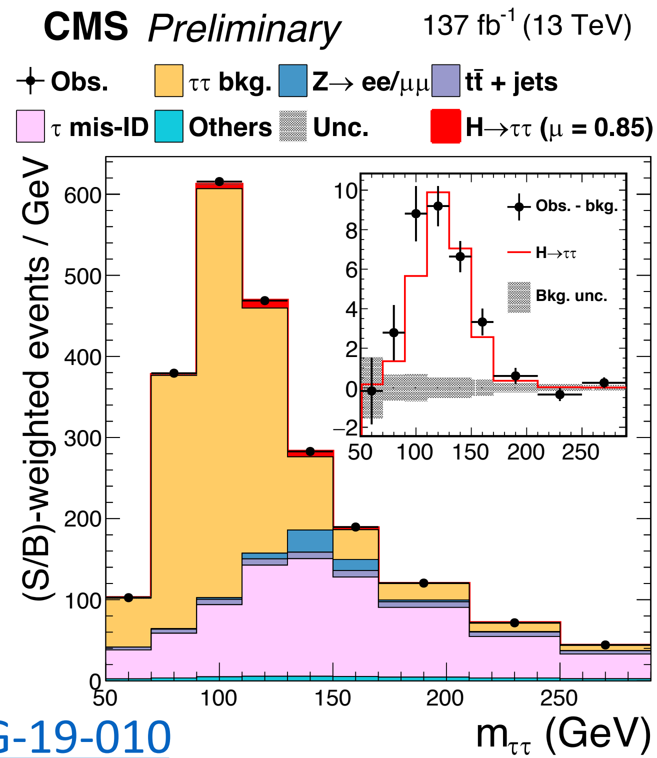
Effective couplings with gluons and photons

H→ττ

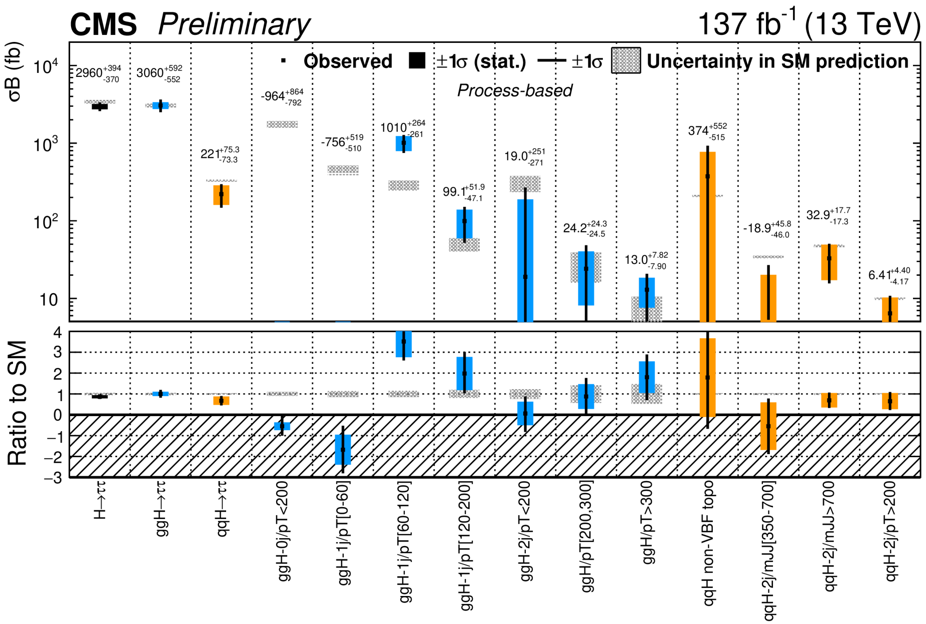
- Covering ggH, VBF in main final states (eμ, eτ_h, μτ_h, $\tau_h\tau_h$)
- Main background Z → ττ estimated with embedding
- Overall signal strength modifier

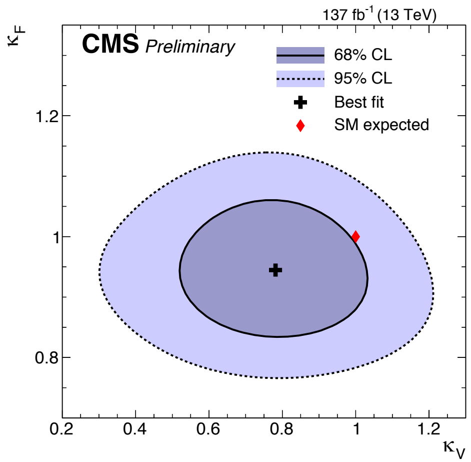
$$\mu = 0.85^{+0.07}_{-0.06}\,(th)^{+0.06}_{-0.06}\,(sys)^{+0.08}_{-0.07}\,(bbb)$$

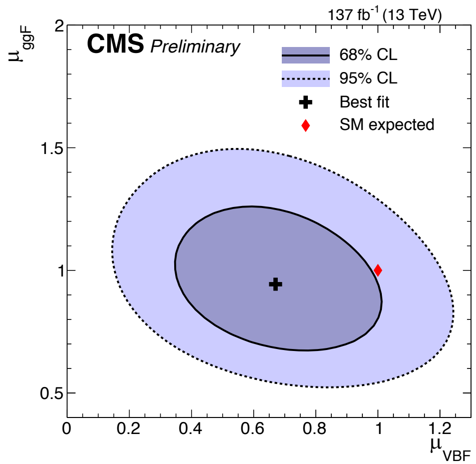
  - Significant improvement in precision wrt to previous measurment
  - Observed significance greater than 5sigma
  - Improvement driven by the improved jet-to-tau discrimination
- Results also provided in terms of production signal strengths and coupling modifiers in the κ-framework



CMS PAS HIG-19-010







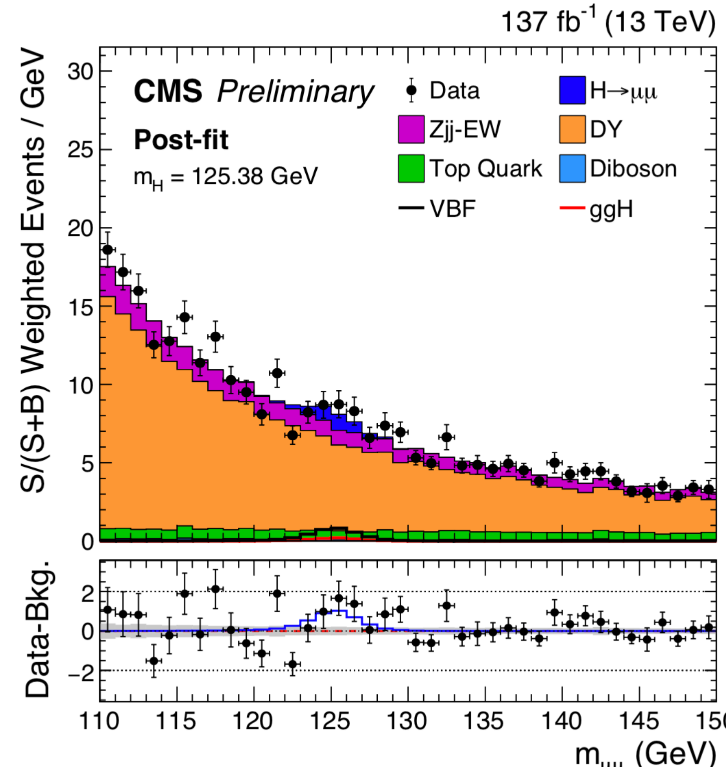
H→μμ

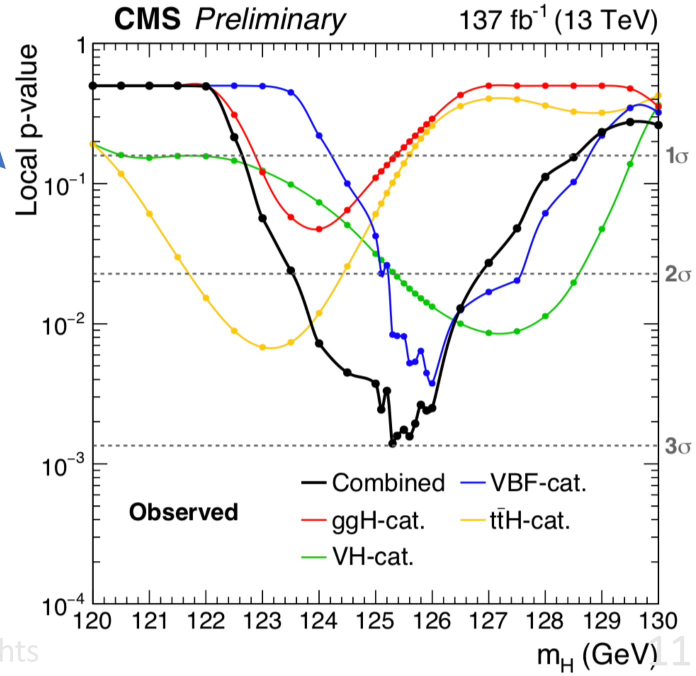
- First evidence for the Higgs boson decay to fermions of the second generation.
- Select events with two well-isolated opposite-signed muons.
- Events classified on the topology of the production modes: ggH, VBF, VH and ttH tagged
  - VBF: signal extracted from DNN discriminant using kinematic input variables of di-muon and di-jet system
  - ggH, VH, ttH: simultaneous fit of m(μμ) system in bins of dedicated BDT
- The observed (expected for μ = 1) significance at m_{H} =125.38 GeV is 3.0(2.5)σ
- Signal strenght:

$$\mu = 1.19^{+0.41}_{-0.39}\,(stat)^{+0.17}_{-0.16}\,(sys)$$

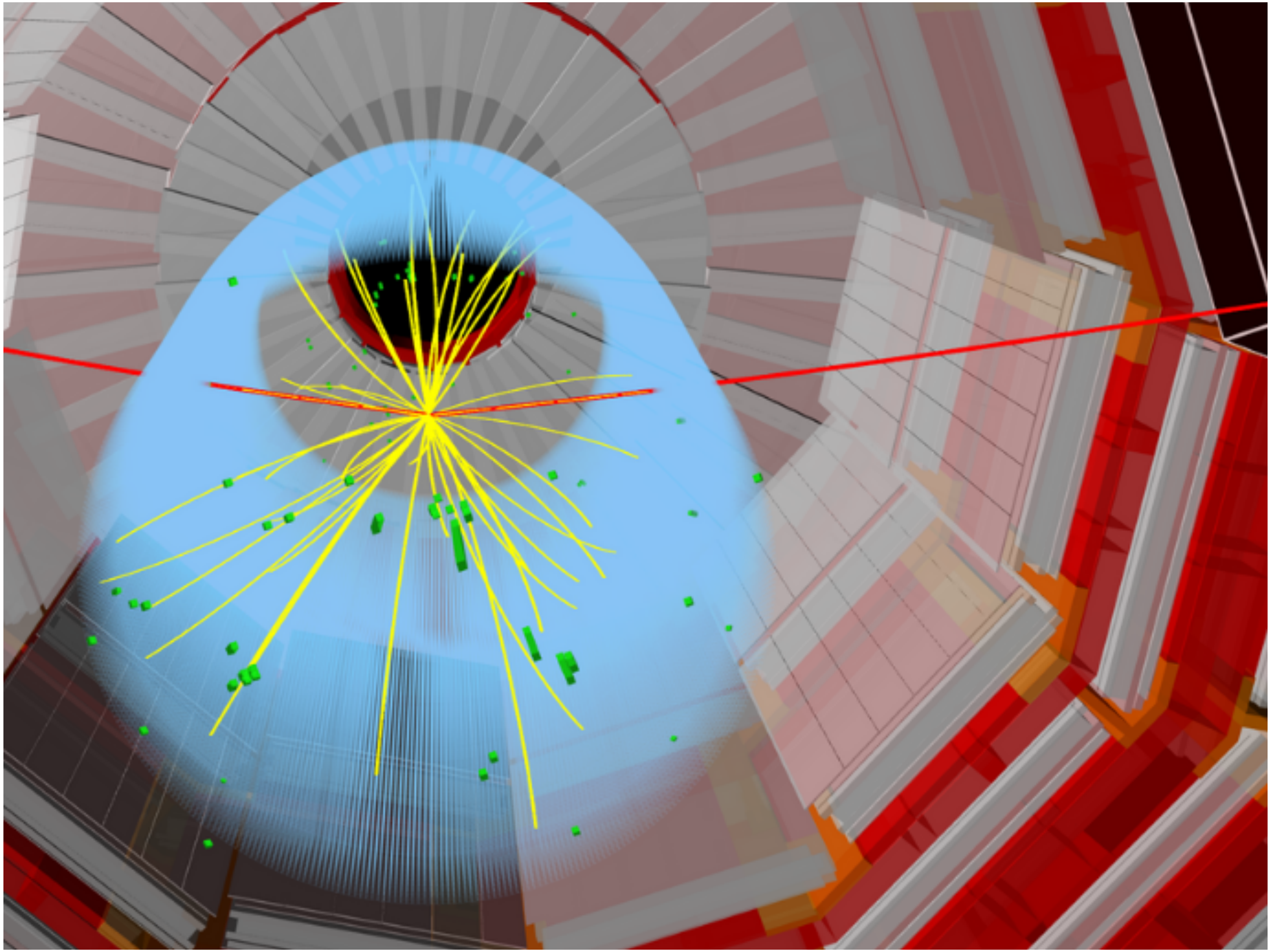
- Measured BR at 95% CL:

  $0.8 \times 10^{-4} < BR(H \to \mu\mu) < 4.5 \times 10^{-4}$



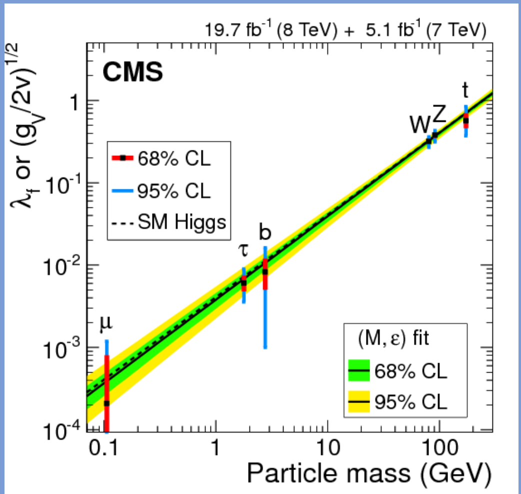


HIG-19-006

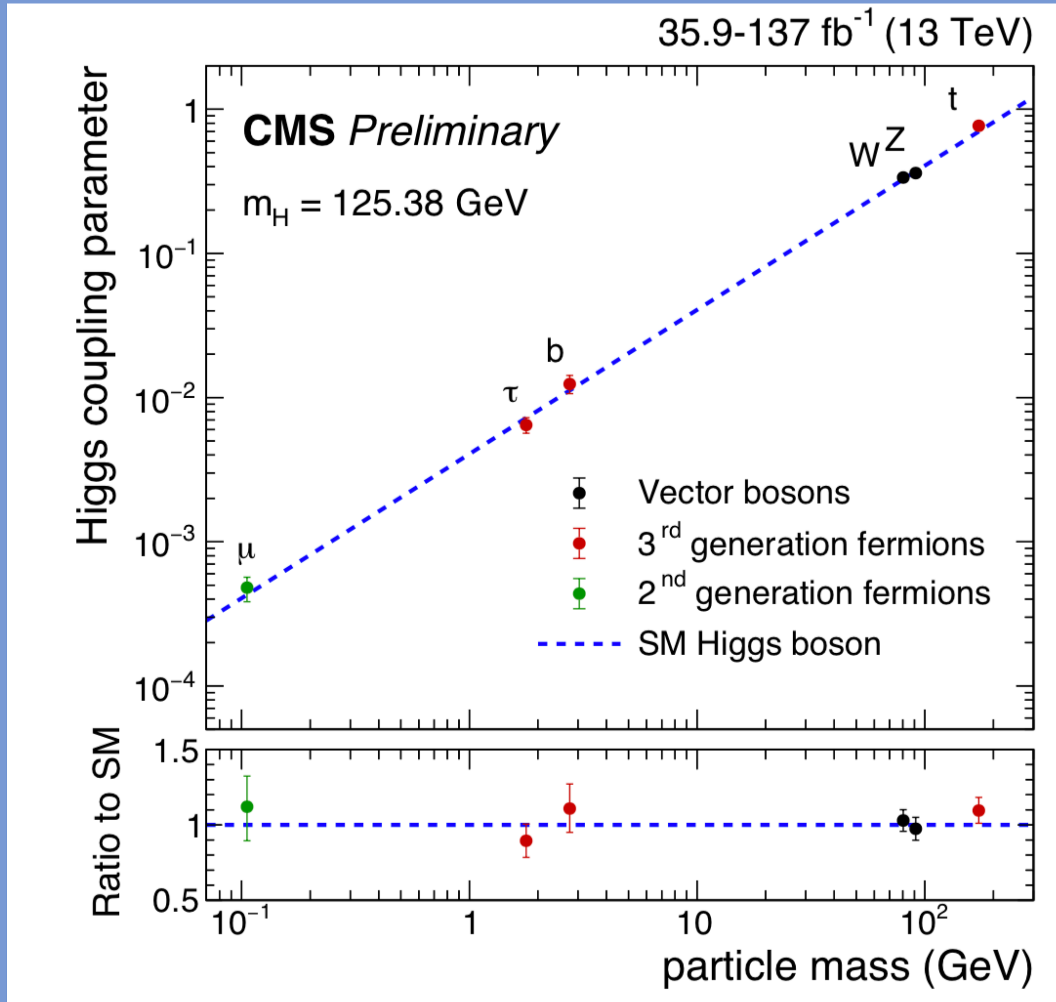


Towards completing the SM picture

From Run 1



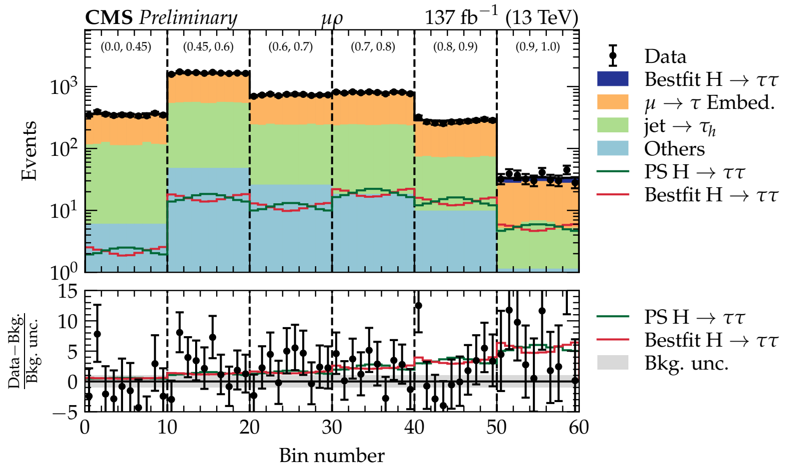
To Run 2



- Best-fit value for κ_μ at 95% CL $0.65 < \kappa_\mu < 1.53$ ($k\mu$=1.13)
- Higgs couplings with leptons and bosons are compatible with the SM prediction
- Significant increase in the precision wrt to Run1!

Probing the CP structure of the Higgs

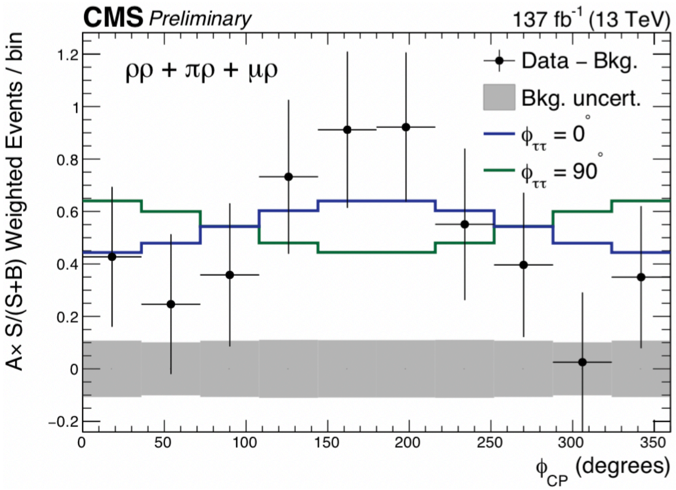
- CP violating effects expected to be more experimentally accessible in coupling with fermions
    - 27deg precision on effective mixing angle between scalar and pseudoscalar with full Run2

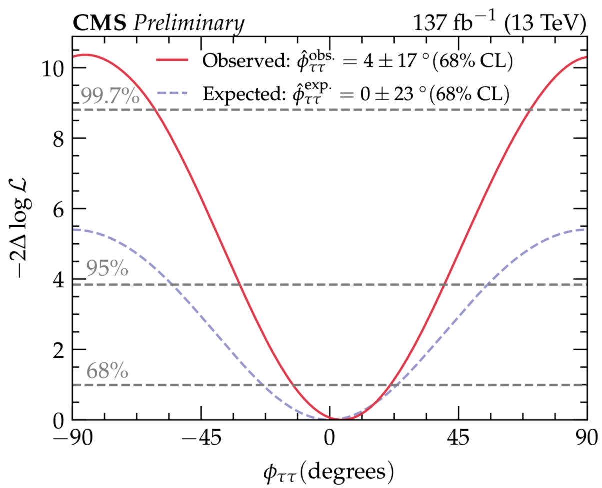


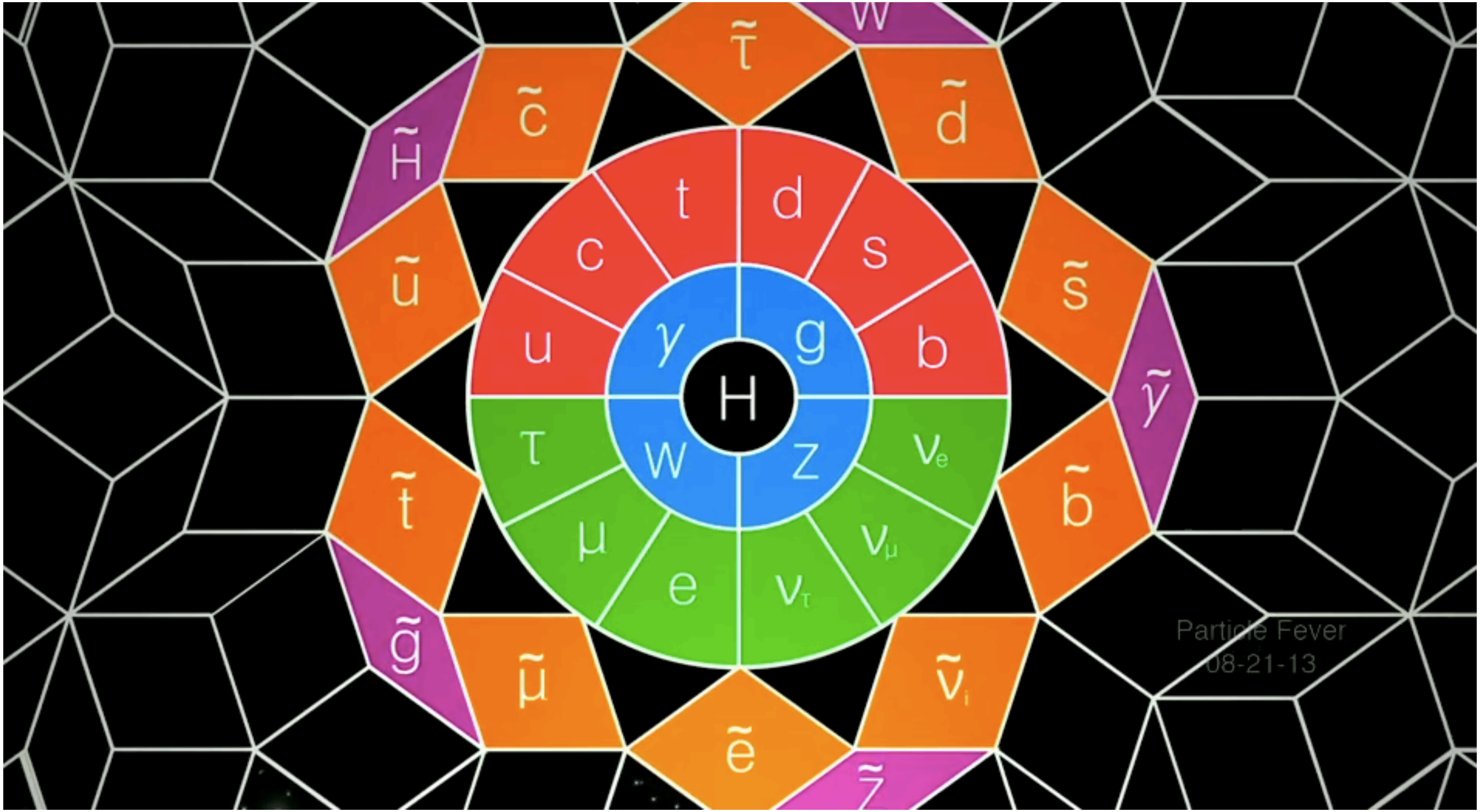
- Using $H \rightarrow \tau\tau$ decays, measuring angular correlation between decay planes Φ_{CP} in $\tau_\mu\tau_h$ and $\tau_h\tau_h$ channels
    - Measurement of the direction of the tau-leptons decay product → Dedicated MVA decay mode identification with a BDT
- Background rejection with dedicated BDT(NN)
    - High sensitivity bins used for signal extraction

- Obs. (exp.) sensitivity to distinguish between the scalar and pseudo-scalar hypotheses 3.2 (2.3) σ
- Obs. (exp.) for *the mixing angle between scalar and pseudoscalar hypotesis*

  4 ± 17◦ (0 ± 23◦) at the 68% CL.
    - uncertainties measured in ttH are ±55 (CMS) and ±43 (ATLAS)







Beyond Standard Model

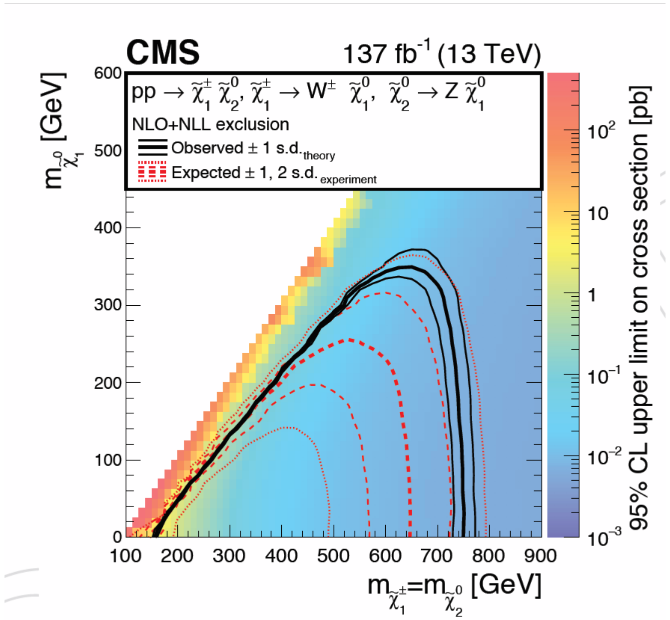
See talks by
L. Thomas (EXO), U. Sarkar (SUSY)

Exploring SUSY – electowikinos and s-leptons

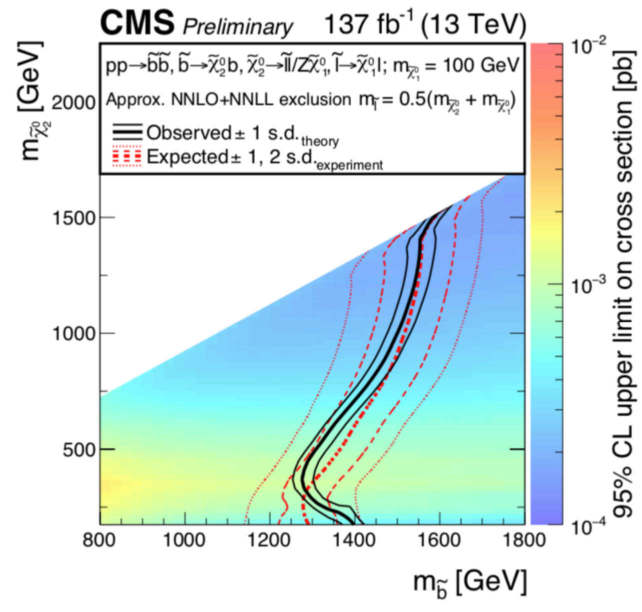
EWK sector: much lower xsect but sensitivity to lower sparticle masses.

1. Z (→ll)+2 jets and moderate Etmiss (confirm results on gluinos production)
2. a kinematic edge in the invariant mass distribution of the lepton pair
3. Direct s-lepton production: moderate E_{tmiss}, hadronic activity, Z-veto

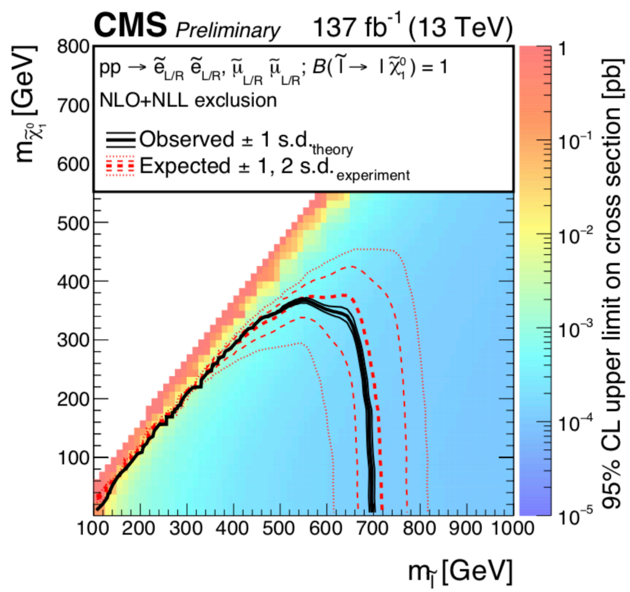
CMS-SUS-20-001



Excluded chargino (neutralino) masses up to 750 (800) GeV;



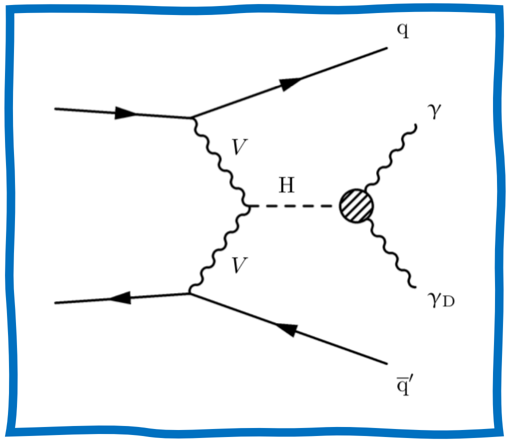
Excluded light-flavor (bottom) squark masses up to 1.7 TeV



Exclude Slepton masses up to 650 GeV

Search for dark photons in VBF Higgs events

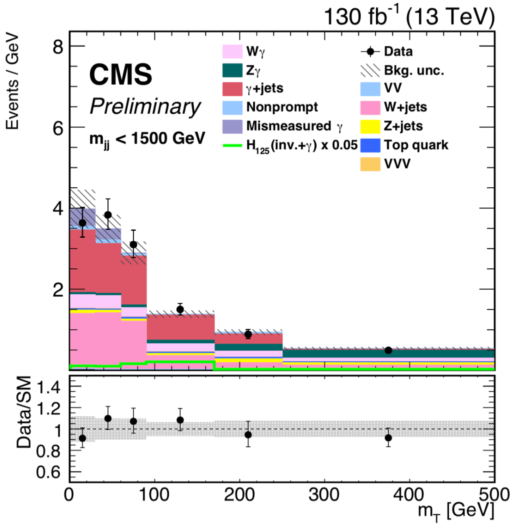
- 38% UL @95% CL on BR(H→BSM particles)
- SM Higgs + model independent search for Higgs bosons with mH in [125,1000] GeV, H→ $\gamma\ \gamma_D$
- H→ $\gamma\ \gamma_D$ in VBF events. Final state with >=2 VBF tagged jets, single isolated γ and large E_{tmiss}
- Bkg: W(→eν))+jets, W(→ lν) + γ with l outside acceptance
  - Bkg norm. to data in CRs

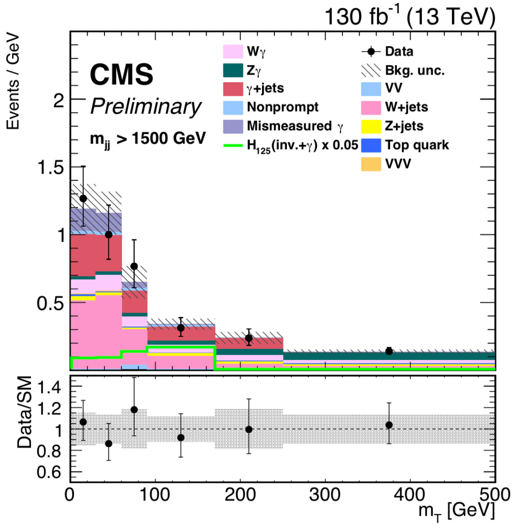


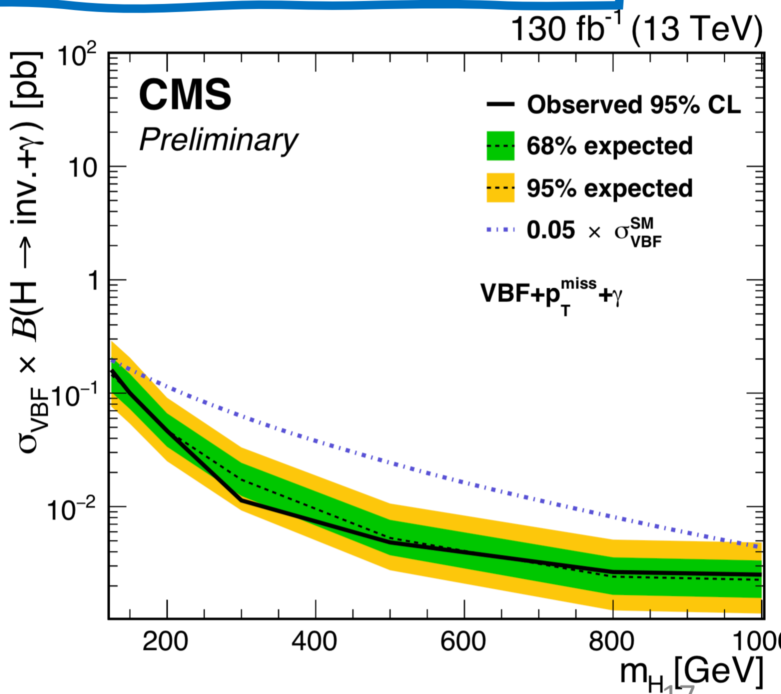
CMS-PAS-EXO-20-005

H → invisible+γ excluded for σxBR > 150-2 fb

Signal extracted from $m_T(\gamma + E_{tmiss})$

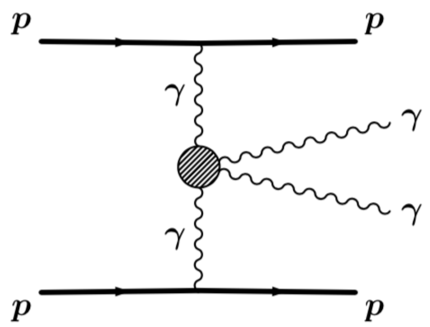






EXO-20-005

Exclusive diphoton production with intact protons



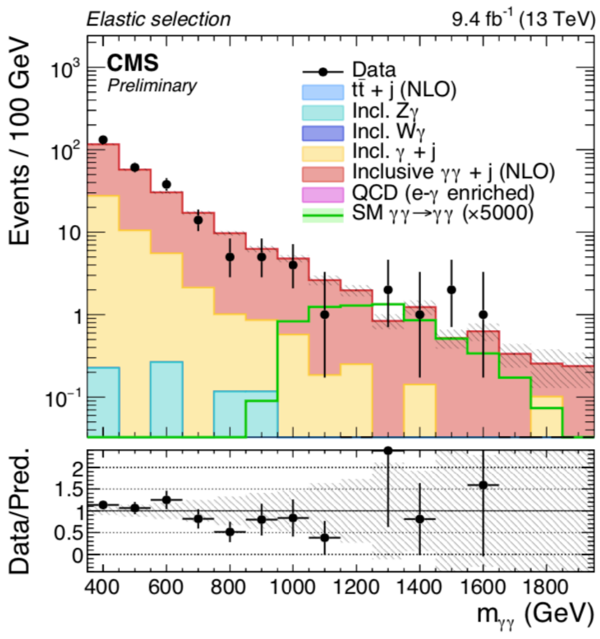
$$L_8^{\gamma\gamma\gamma\gamma} = \zeta_1 F_{\mu\nu}F^{\mu\nu}F_{\rho\sigma}F^{\rho\sigma} + \zeta_2 F_{\mu\nu}F^{\mu\rho}F_{\rho\sigma}F^{\sigma\nu}$$

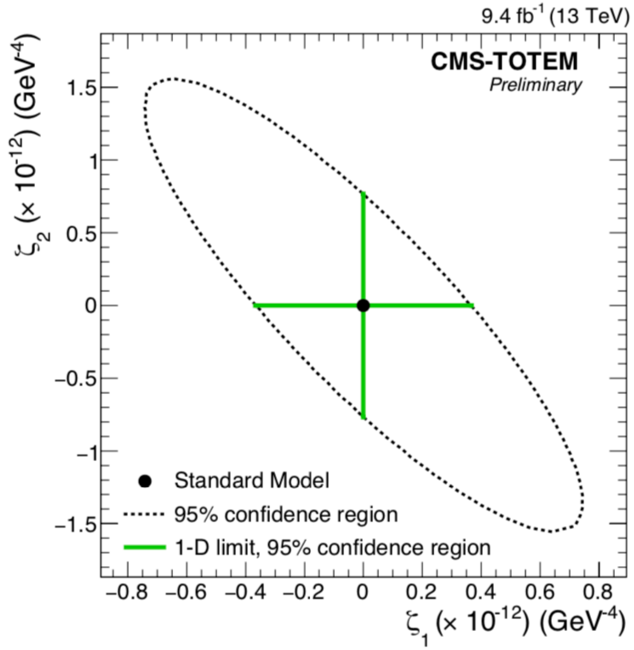
$$\zeta_{1,2} = a_{1,2}^{\gamma\gamma}/\Lambda^4$$

- Two γ interactions via charged particle loop, create two outgoing γ (light-by-light scattering)
- Effective extension of the SM Lagrangian using charge-parity conserving operators probed
- High diphoton mass spectrum (>350 GeV) explored
- Signature: 2p+2γ→studied using data collected by CMS and TOTEM in 2016 (9.6 fb^{-1})

- Trigger and offline selections on final state γ
- **Intact Protons events:** sensitivity enhanced requiring momentum conservation, thanks to the PPS measurement

CMS PAS EXO-18-014

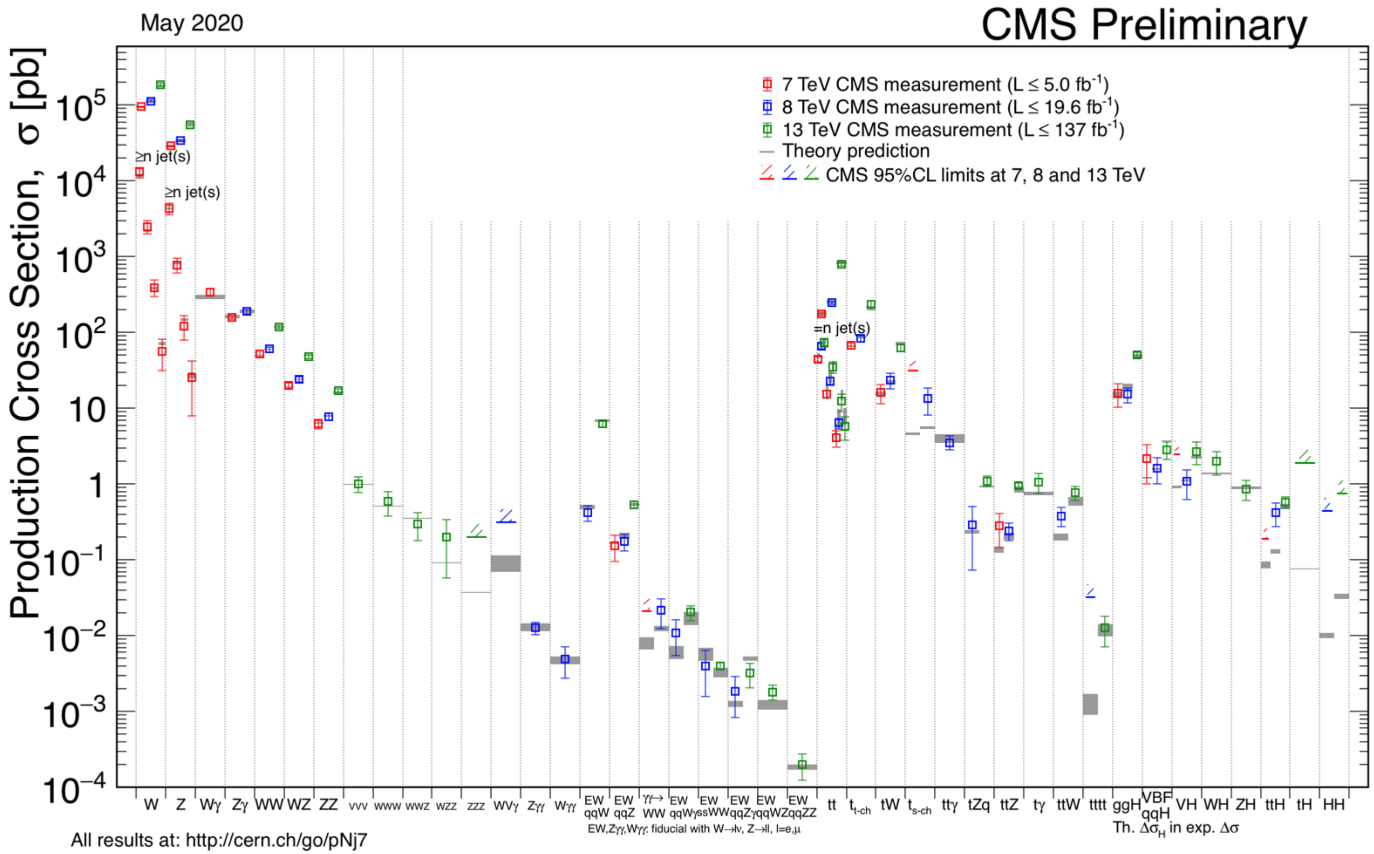




→No events observed Upper limits at 95% CL on the 4-photon anomalous quartic couplings set.

Standard Model

Good agreement for many processes, over 15 orders of magnitude



Testing the Standard Model through rare processes and differential/precision measurements

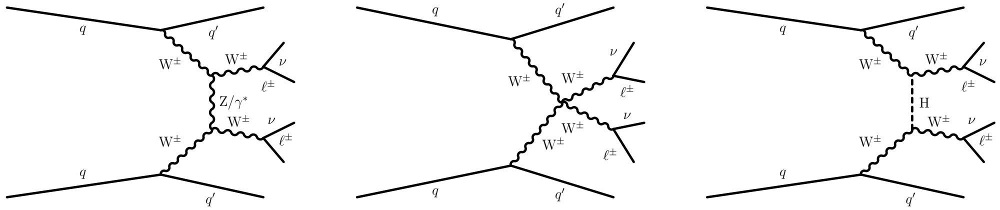
possible due to excellent reconstruction and calibration performance results

Production of polarized WW pairs in VBS – inspecting the EWSB

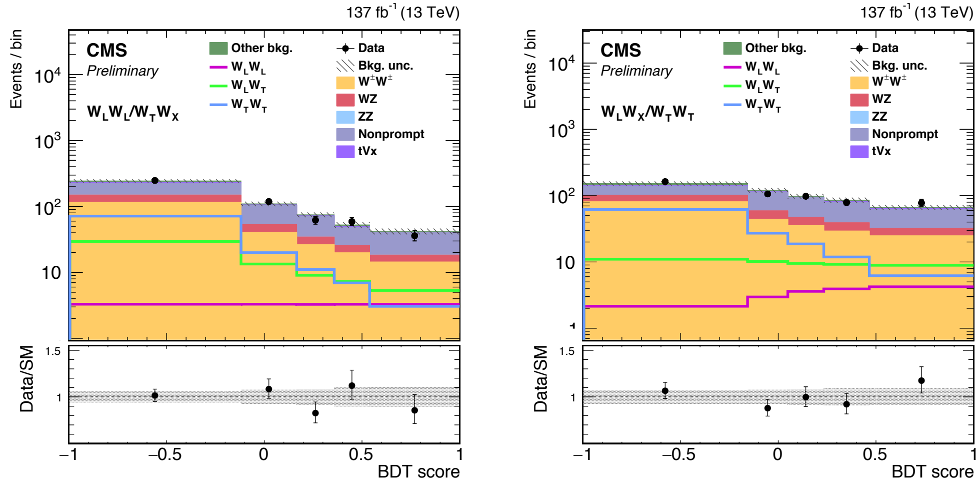
•Modifications of the production cross sections for the longitudinally polarized W are expected in BSM models, e.g., in scenarios involving additional Higgs bosons

Strategy:

- tag VBS events
  - → two energetic forward-backward tagging jets
  - → large m_{jj} and Δy_{jj}
  - → little hadronic activity between tagging jets in fully leptonic final states
- Isolate signal: EW polarized WW production with a BDT
  - → $W_L^\pm W_L^\pm$ & $W_T^\pm W_x^\pm$
  - → $W_T^\pm W_T^\pm$ & $W_L^\pm W_x^\pm$
- discriminate fake bkg from SM with another BDT
- Control regions used to constrain SM background (WZ, tZq, ZZ)
- Signal extraction with a simultaneous fit of 2D distribution of the 2 MVA discriminant in the SR and CRs



CMS-SMP-20-006



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

Measured and theoretical fiducial cross section agree within uncertainties (COM frame of the WW).

Double Z Production in VBS

inspecting the EWSB

- Search for ZZ production in VBS events allows to access to triple and quartic gauge boson couplings
    - anomalous modifications probed

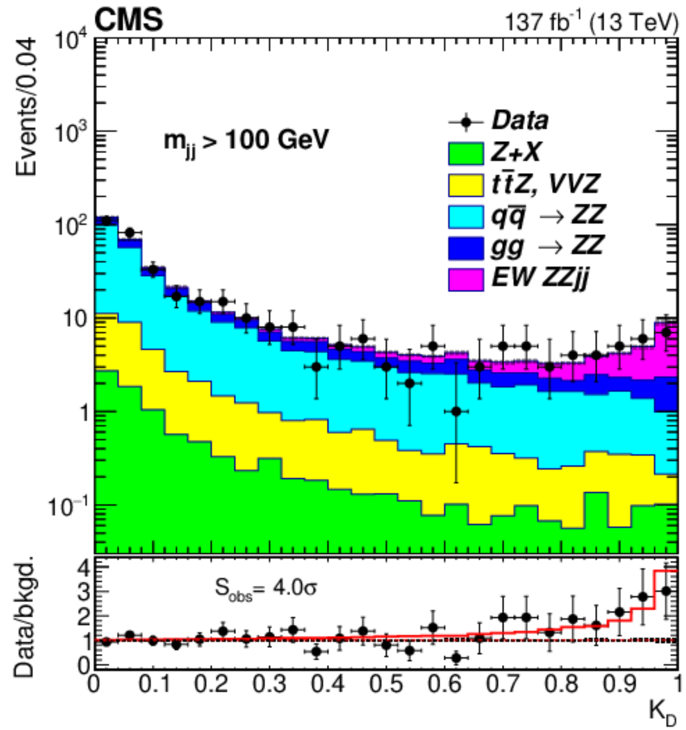
- Search strategy similar to Higgs-to-ZZ analysis, in addition to the VBS tagging

- Background mainly from dibosons production with QCD-induced jets
    - constrained by the data in the fit
- Main uncertainties:
    - QCD renormalization and factorization scales
    - Jet energy scale

- Signal strenght and significance of the EW signal determined using a matrix element discriminant (K_D) to separate the signal and the QCD background.
- **Measured fiducial cross section consistent with SM**

Evidence for VBS in events with 4l

4.0σ obs (3.5σ exp) from Run 2



SMP-20-001

UL at 95% CL set on aQGC in terms of EFT operators

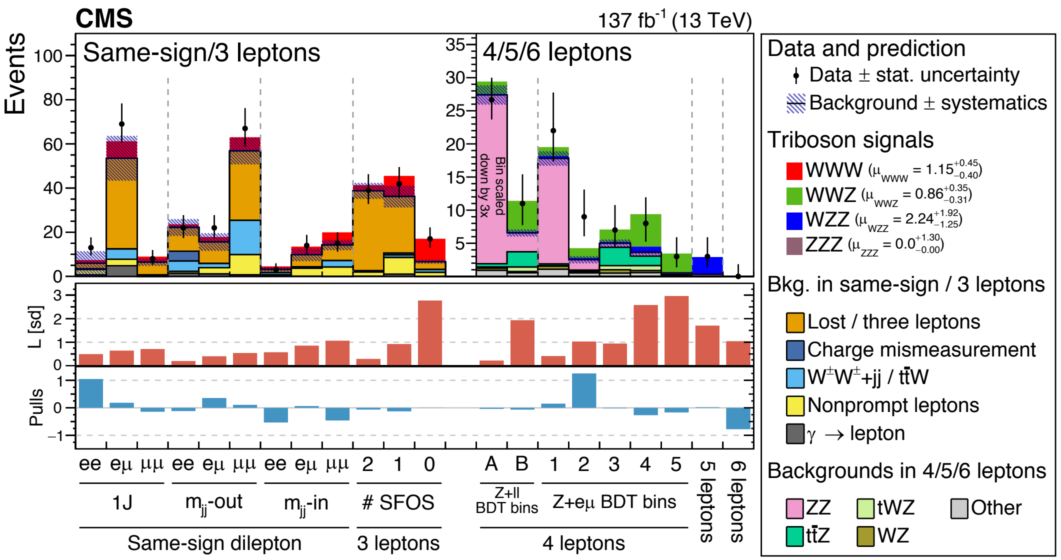
$$-0.24 < f_{T0}/\Lambda^4 < 0.22$$
$$-0.31 < f_{T1}/\Lambda^4 < 0.31$$
$$-0.63 < f_{T2}/\Lambda^4 < 0.59$$
$$-0.43 < f_{T8}/\Lambda^4 < 0.43$$
$$-0.92 < f_{T9}/\Lambda^4 < 0.92$$

Triple Boson Production

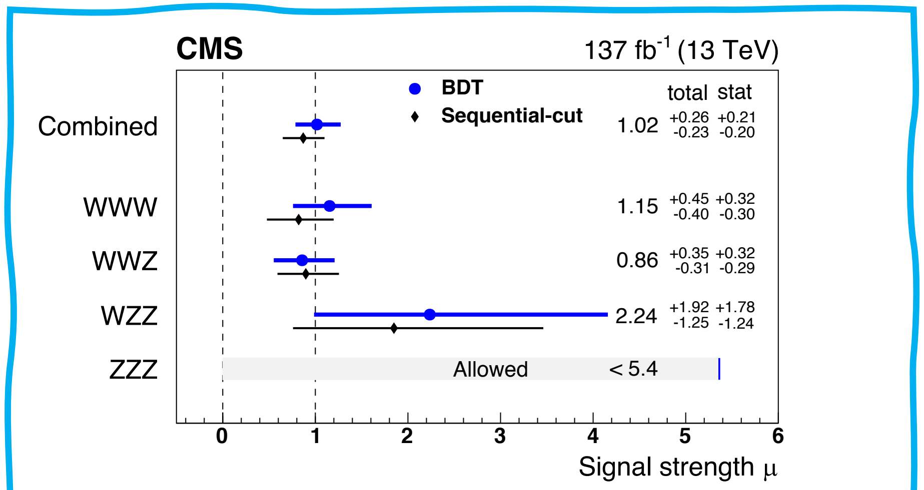
SMP-19-014

a tool to probe the quartic gauge coupling

- If BSM is present around 1 TeV, VVV cross section might deviate from SM predictions
- Full Run2 dataset used to probe such rare processes



- Five final states considered, with up to 6 leptons:
  - WWW $\rightarrow l^{\mp} l^{\pm} 2\nu qq'$,
  - $W^{\pm}W^{\pm}W^{\mp} \rightarrow l^{\pm}l^{\pm}l^{\mp}3\nu$
  - $W^{\pm}W^{\mp}Z \rightarrow l^{\pm}l^{\mp}2\nu\, l^{\pm}l^{\mp}$,
  - $W^{\pm}ZZ \rightarrow l^{\pm}\nu\, 2(l^{\pm}l^{\mp})$
  - ZZZ $\rightarrow 3(l^{\mp}l^{\mp})$.
- Background estimation: Non-isolated leptons from data, prompt lepton from MC



- Main systematic: estimation of background (limited stat.): 25% prompt, 50% non-prompt
- Analysis sensitivity in SS 3l and 4l channels is enhanced by using BDTs.
- Results in agreement with the SM!
- 5.7σ obs (5.9σ exp) significance for VVV

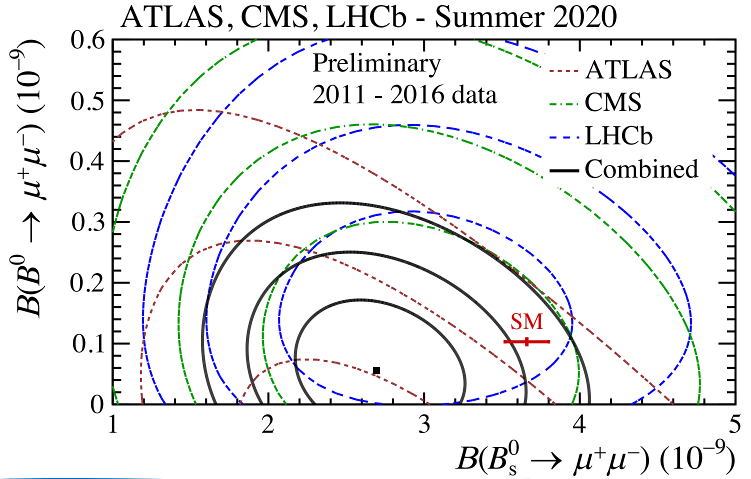
B-Physics

See Federica Simone's talk

Combination of the ATLAS, CMS and LHCb results on $B^0 \to \mu\mu$ and $B_s \to \mu\mu$

New!!

- $B^0 \to \mu\mu$ and $B_s \to \mu\mu$ via penguin loop diagrams helicity suppressed
  - any deviation from SM predicted values is hint for BSM physics → most sensitive FCNC (BRs ratio)
  - theoretical uncertainties significantly reduced
- Similar search strategy for the 3 analyses (di-muon triggers, rectangular cuts, BDT)

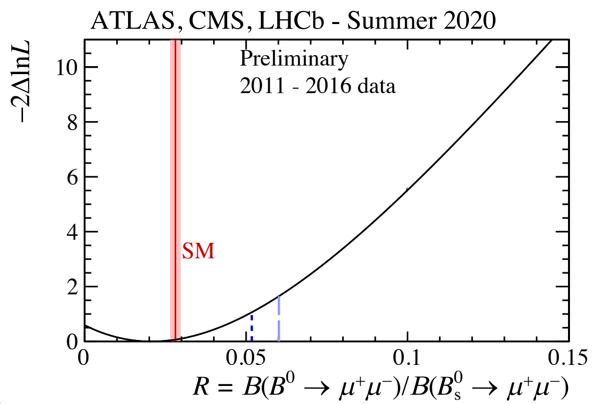


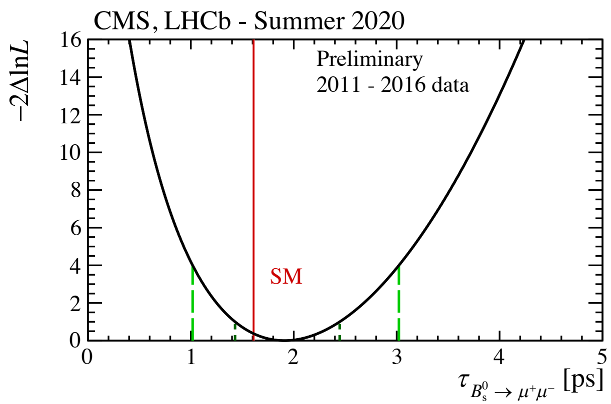
Combination performed using the binned two-dimensional profile likelihoods obtained by each experiment from their fit to the dimuon invariant mass distributions in the two channels

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.69\,^{+0.37}_{-0.35}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (0.6 \pm 0.7) \times 10^{-10}.$$

- BR ratio $\mathcal{R} = 0.021^{+0.030}_{-0.025}$
- Bs lifetime (CMS+LHCB data)

$$\tau_{B_s^0 \to \mu^+\mu^-} = 1.91^{+0.37}_{-0.35}\ \text{ps}.$$



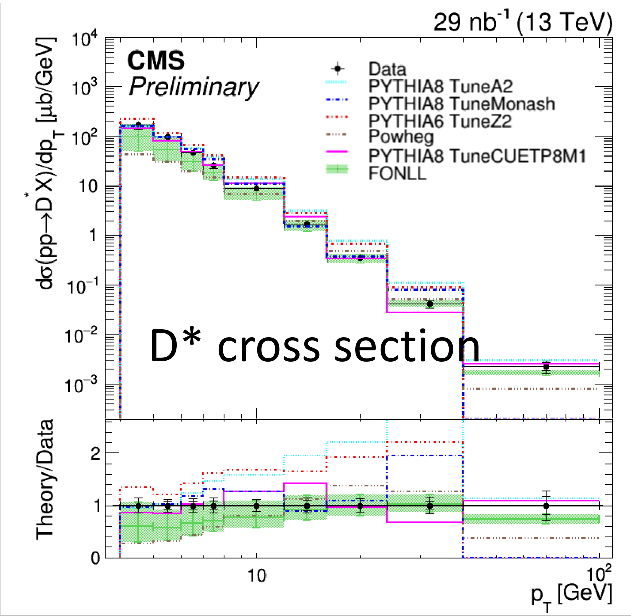


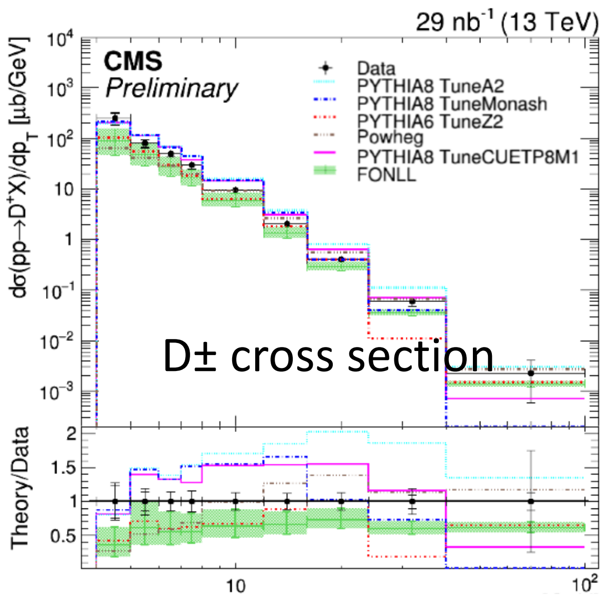
Prompt open charm production

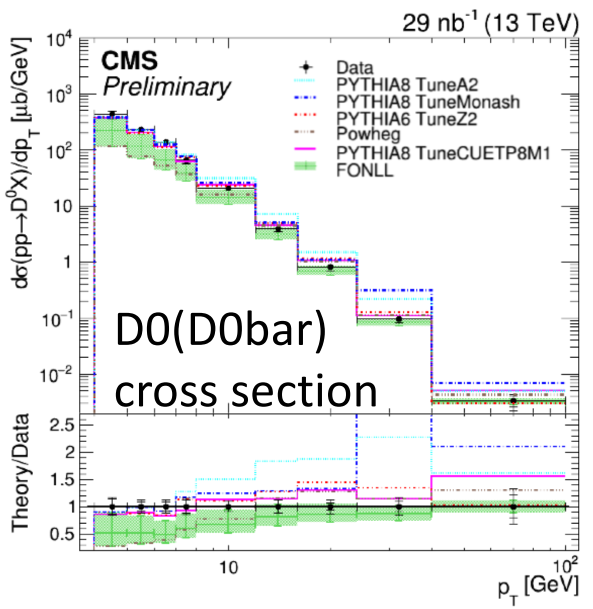
- Important tests of QCD, give insight into particle production at colliders
- Baseline/background for other physics studies
- Hadronization challenging to understand → measurements needed
- 29/nb pp collisions collected in 2016 collected with ZeroBias trigger
- Phase space: 4 < pT (D) < 100 GeV && $|\eta|$ < 2.1

Analyzed processes + c.c.

- $pp \to D^{*+}X \to D^0\pi^+{}_sX \to K^-\pi^+\pi^+{}_sX$
- $pp \to D^0X \to K^-\pi^+X,$
- $pp \to D^+X \to K^-\pi^+\pi^+X,$



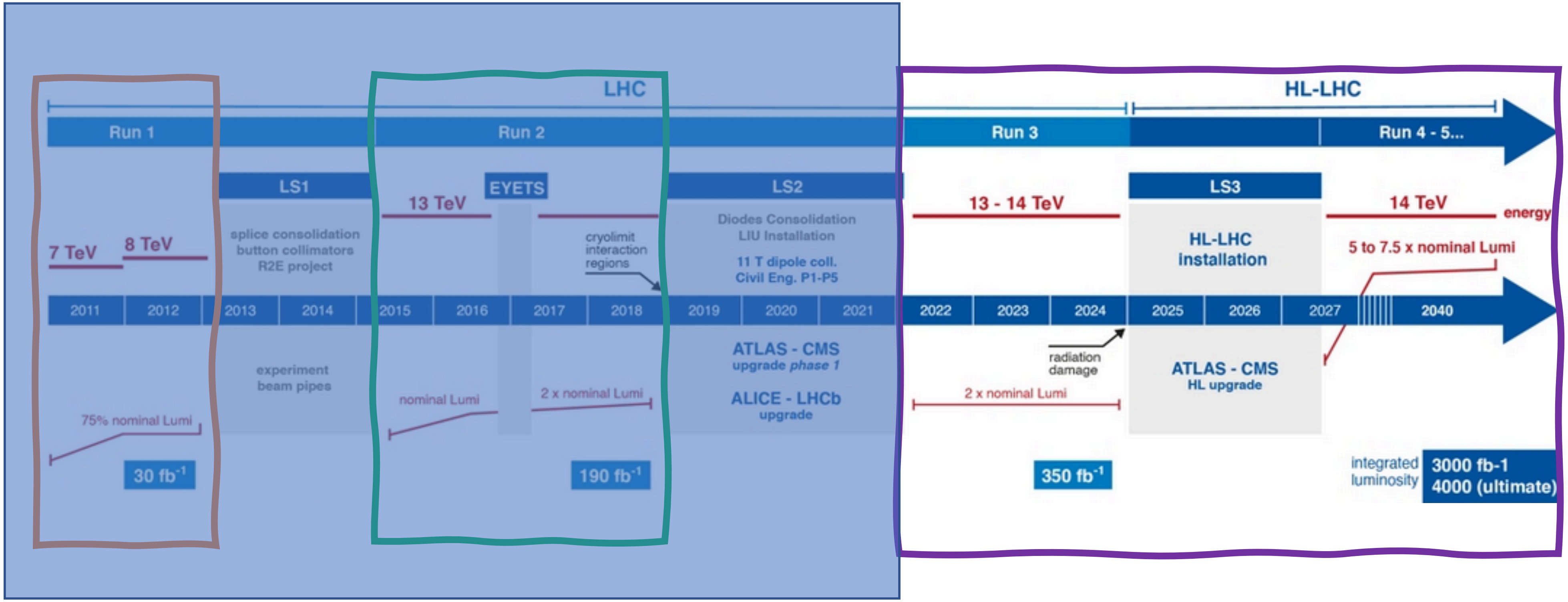




- Prompt cross section measured
  - non prompt contribution estimated with MC
- Fair agreement with the thoretical models tested
  - No MC or theoretical prediction describes the data well over the entire kinematic range

Towards next runs

See talks by:
R. M. Chatterjee, A. Savin,
C. Bino, C. Aruta, L. Cristella



Steps and Plans towards Run 3

Exploiting new detectors:

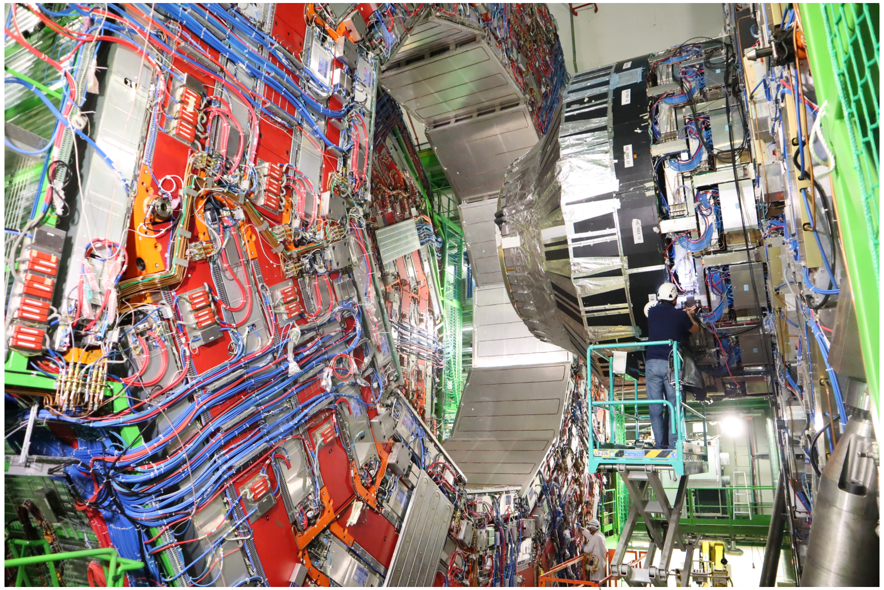
• Phase-1 pixel detector with updated Layer 1 electronics
• First layer of GEM muon detectors in the forward region
•New electrionics with depth segmentation in Hadronic Calorimeter

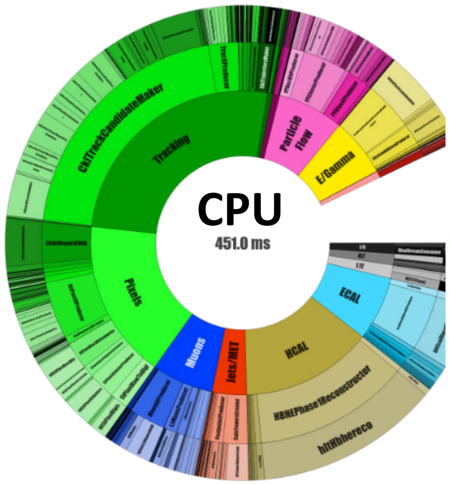
Planning to move to heterogeneous architecture in High Level Trigger, with mixed CPU/GPU

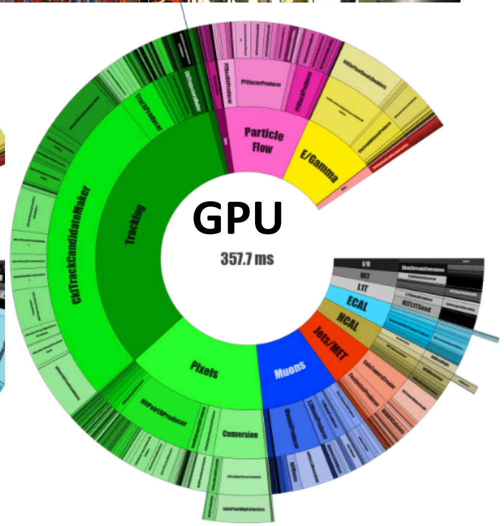
- Already achieved 25% reduction of CPU time
- Opens new possibilities for trigger algorithms leveraging on GPUs
- A testbed for HL-LHC Computing and triggering

Plan to improve Scouting and Parking data with more sophisticated approach

- The analysis of run2 dataset is ongoing, will tell us more abou the potential of these innovative data taking methods
- Design of the new triggers is ongoing with the goal of enlarge the phase space
    - Improve LLP triggers at L1 and HLT
    - Improve B-parking triggers, possibly parking Low MET data for SUSY searches?







HL-LHC: Detector upgrade

Upgrades at the forefront of the technology to cope challeging data taking conditions→aim to fully exploit the 3000/fb int. luminosity to reach unprecedent precision in SM measurement and further constraint (or even find) new physics

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

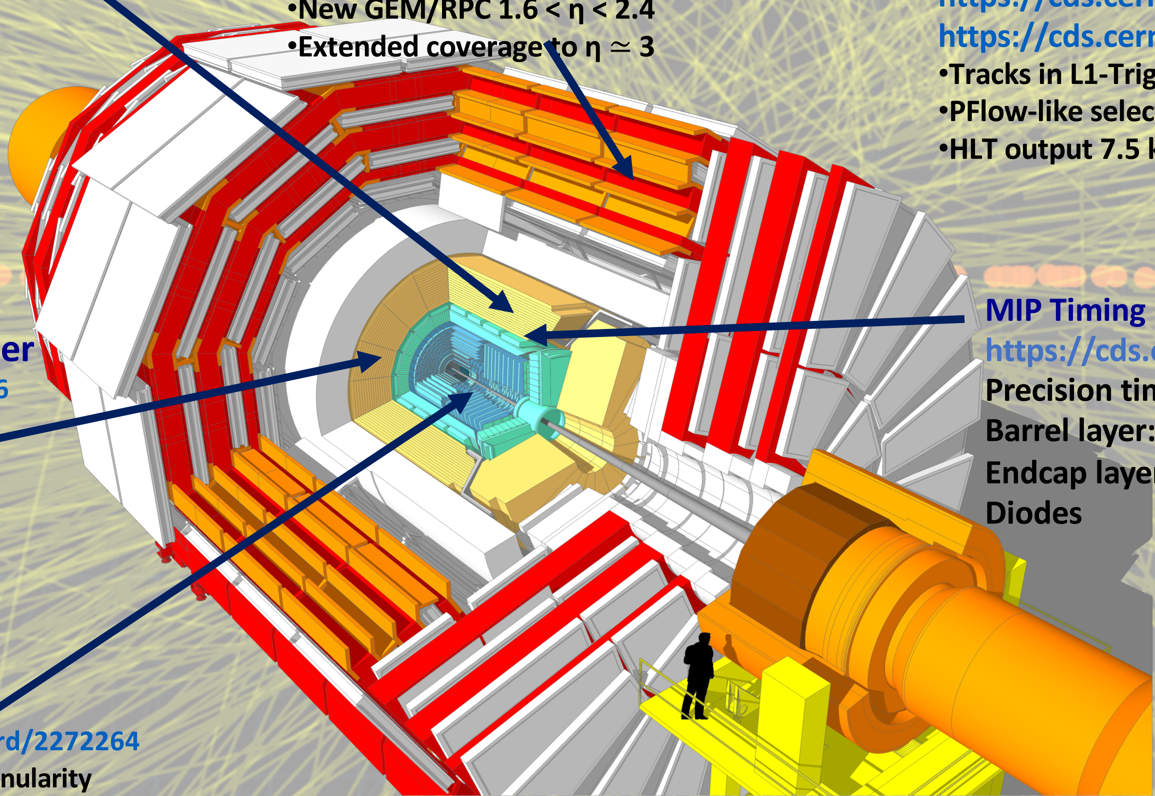
ECAL crystal granularity readout at 40 MHz with precise timing
ECAL and HCAL new Back-End boards

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 $\eta \simeq 3$

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



MIP Timing Layer
https://cds.cern.ch/record/2296612

Precision timing with:
Barrel layer: Crystals + SiPMs
Endcap layer: Low Gain Avalanche Diodes

High Granularity Calorimeter
https://cds.cern.ch/record/2293646

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

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

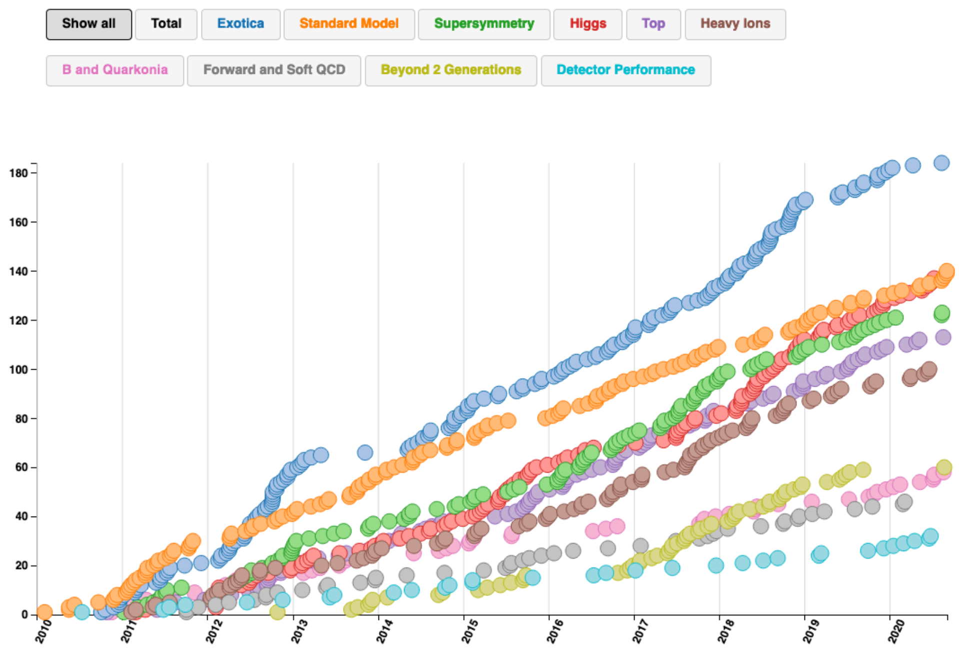
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$

Conlusions

- Deep knowledge of the CMS detector and reconstruction algorithms matured during Run 2
  - Exthensive use of ML/DeepL
- Many significant results provided explointing full Run 2 luminosity
  - Yukawa Coupling with the second generation of lepton measured with full run 2 statistics
  - Standard model and B-physics searches mainly used as a tool to probe the presence of new physics
  - BSM physics further constrained with direct searches, exploiting full Run 2 luminosity

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

- Work for Run 3 preparation ongoing, delay introduced by COVID was negligible
  - New detectors almost installed, new algorithm in tuning and validation phase
- Extensive work during Run2 for preparing the Phase 2 upgrade
  - Detector design in place, TDR finalized
  - HLT TDR in the pipeline, will come soon
- Incoming LHC runs will provide us much more data:
  - Less then 10% of the total (HL-)LHC luminosity delivered and analyzed so far



Thank you for your kind attention