Expectations for Run 3 with the CMS detector

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Overview

1. Introduction
2. Run 3
3. CMS Highlights

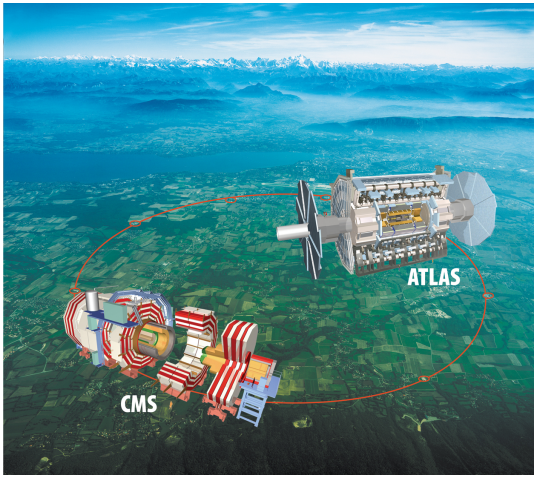
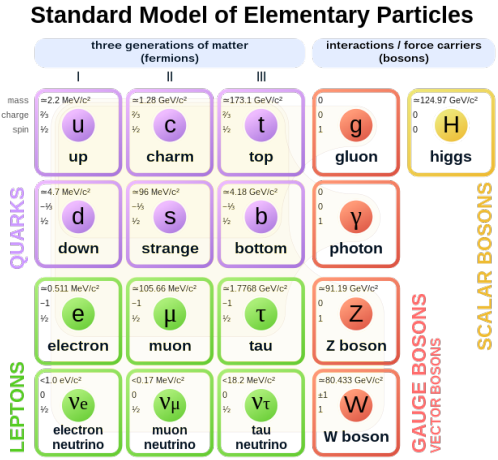
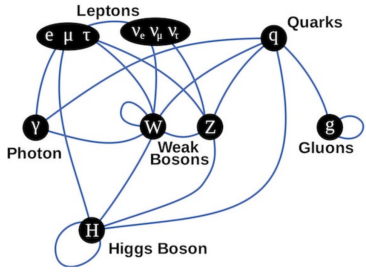


Image from CDS CERN server

Standard Model



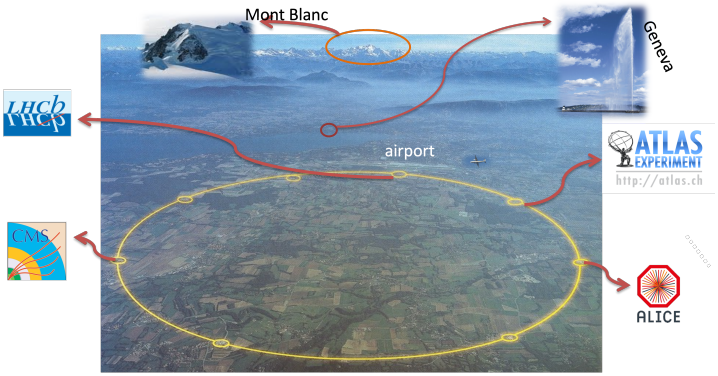
Wikipedia



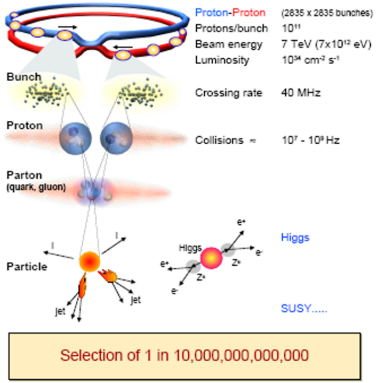
Elementary-particle interactions. Credit: Wikimedia

- Describing three of the four known fundamental forces.
- Classifies all known elementary particles.

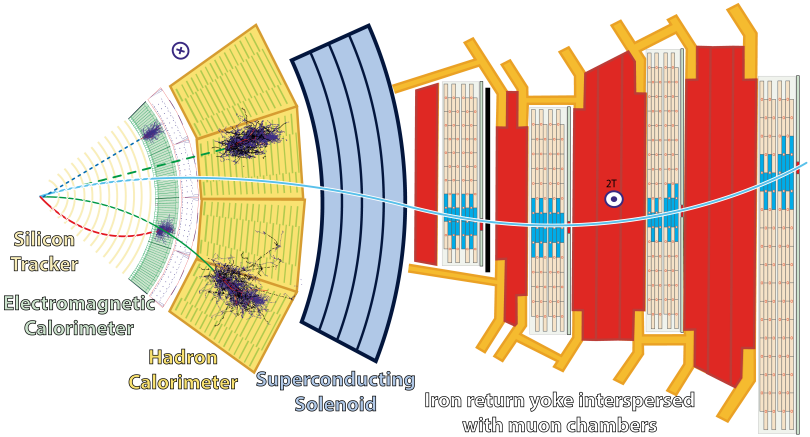
LHC


Mont Blanc
Geneva
airport
LHCb
ATLAS EXPERIMENT
http://atlas.ch
CMS
ALICE

CERN CDS


Proton-Proton (2835 x 2835 bunches)
Protons/bunch 10^{11}
Beam energy 7 TeV (7×10^{12} eV)
Luminosity 10^{34} cm^{-2} s^{-1}
Bunch
Crossing rate 40 MHz
Proton
Collisions ≈ 10^7 - 10^9 Hz
Parton (quark, gluon)
Particle
Higgs
SUSY.....
Selection of 1 in 10,000,000,000,000

CMS

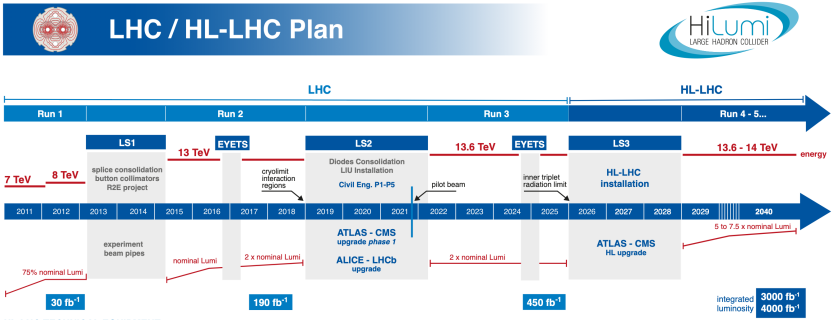

Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with muon chambers
2T
Muon
Electron
Charged hadron (e.g. pion)
Neutral hadron (e.g. neutron)
Photon

CERN CDS

LHC Operations

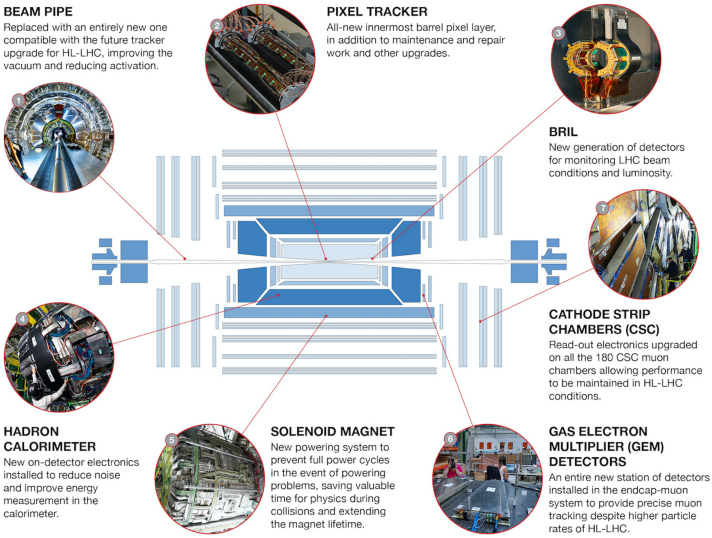
Amazing LHC performance! Thanks to the LHC Collaboration. pp Run−2 finished on October 24, 2018 at 6:00 a.m. [5]

- 2010−2012: Run−1 7/8 TeV. Collected by CMS ~ 27 fb^{-1}
- 2015−2018: Run−2 13 TeV. Collected by CMS ~ 150 fb^{-1}



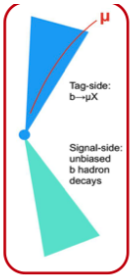
High Luminosity Project

CMS Hardware Updates



Developments done for Run3

- B-parking
  - in 2018 we used low p_T displaced triggers to save a sample of unbiased B hadron decays recoiling wrt the triggered muon
    - Parked trigger rate ~2kHz was reconstructed after the end of the run
  - **Enables several analyses on LFU violation** currently in progress
    - Expect first approved results soon
  - **Studying how to further optimize the trigger in Run 3**
- Scouting
  - Analysis based on a reduced data format and on the online reconstruction in the HLT farm (do not save the full event data)
  - In Run 2 all analyses based about 5 kHz (~1 kHz of Particle Flow scouting)
  - **For Run 3 aim at running PF on higher rate, possible adding additional L1 triggers (use GPUs and pixel tracks)**
- LLP improvements
  - **Ongoing developments in the L1 trigger** area with the aim to increase efficiency for displaced signatures
    - Increase efficiency for displaced muons
    - Extend muon triggers to hadronic showers
    - Out of time ECAL and HCAL at L1
    - Using HCAL depth information
  - **HLT developments also ongoing**

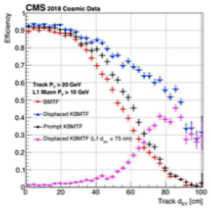


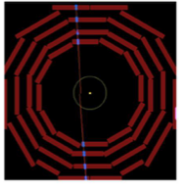
Collected billions of unbiased B decays
12 billion events total

Mode	N_{2018}	f_B	$\mathcal{B}$
Generic b hadrons			
B_d^0	4.0×10^9	0.4	1.0
$B^\pm$	4.0×10^9	0.4	1.0
B_s	1.2×10^9	0.1	1.0
b baryons	1.2×10^9	0.1	1.0
B_c	1.0×10^7	0.001	1.0
Total	1.0×10^{10}	1.0	1.0
Events for R_K and R_{K^*} analyses			
$B^0 \to K^* \ell^+ \ell^-$	2600	0.4	6.6×10^{-7}
$B^\pm \to K^\pm \ell^+ \ell^-$	1800	0.4	4.5×10^{-7}

Kalman filter at L1

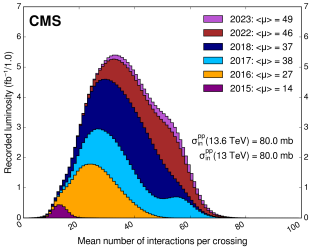
tested in parallel in 2018 and commissioned with cosmic rays

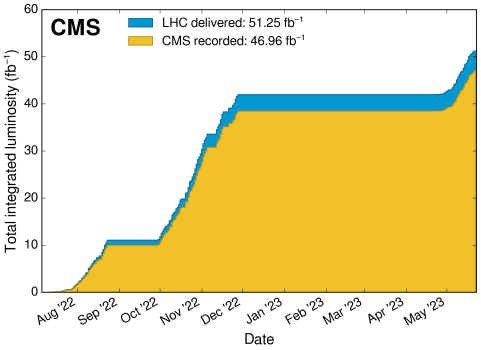




CMS Status

Run 3 started on July 5th,2022. Expected to deliver 240−250 fb^{-1} for 4-year Run. [15][3]
Run 3 2023, started on April 22nd at 7:00 p.m.





- Over 47 fb^{-1} delivered at 13.6 TeV
- 90.2% data taking efficiency. [1]

CMS Luminosity Public Results

Run3 Event at 13.6 TeV: New world record!

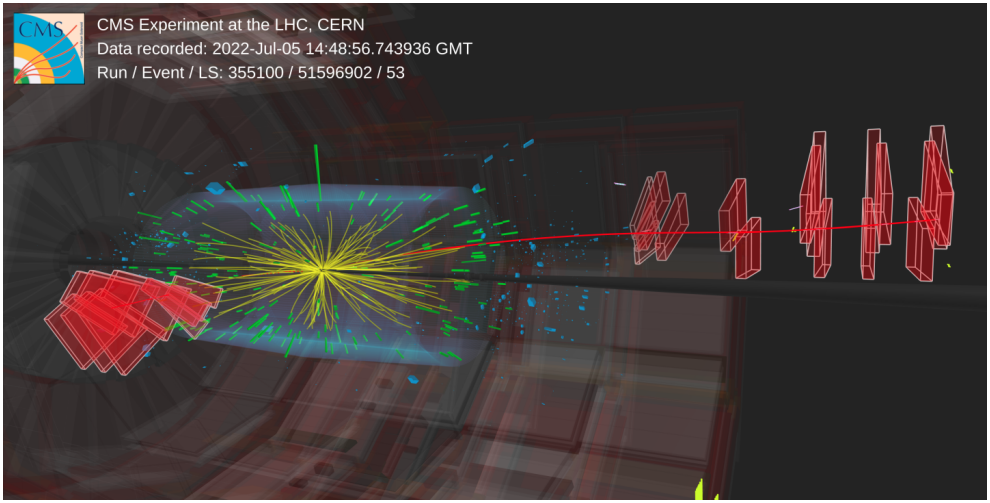
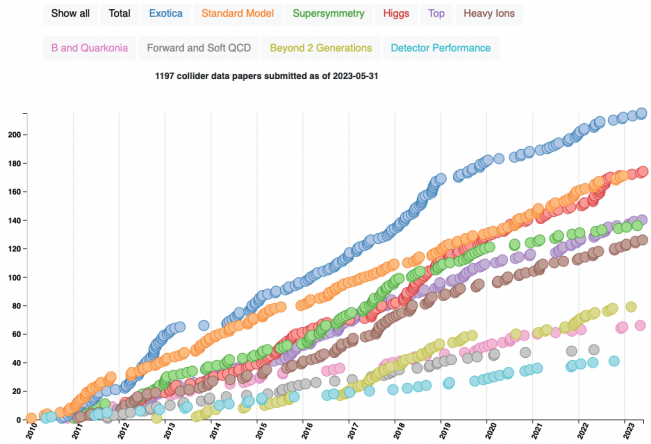


Image from CMS News

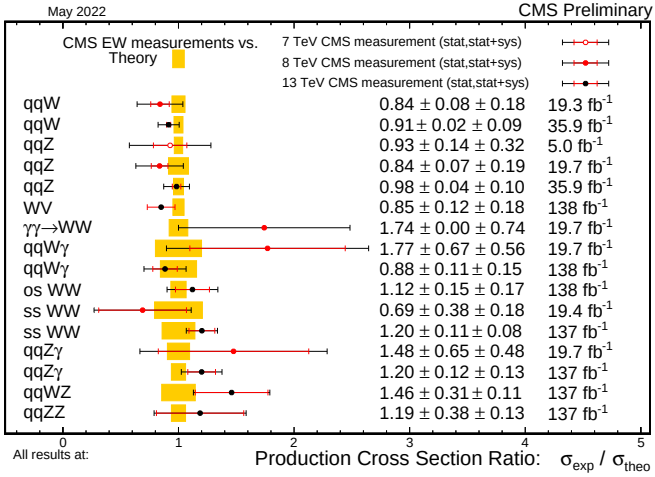
Physics results and publications



- 1197 papers on collider data published or submitted to a journal.
- Run 2 data analysis continues $>$ 100 analysis.
- Run 3 early data analysis foresee 100 analysis in the first couple of years.
- First preliminary results with Run 3 data presented on September 4th at TOP2022.

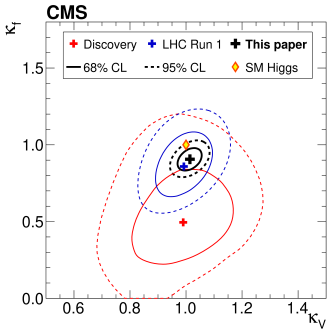
CMS Publications vs Time

CMS Cross Section measurements

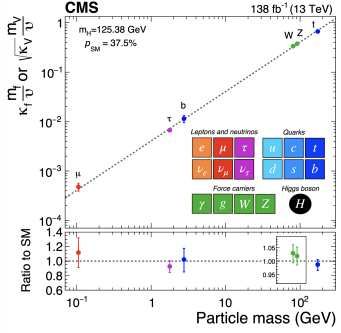


Physical Results Combined

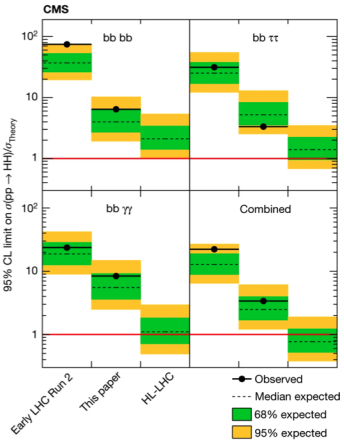
10 years of Higgs



Nature 607 (2022) [4].



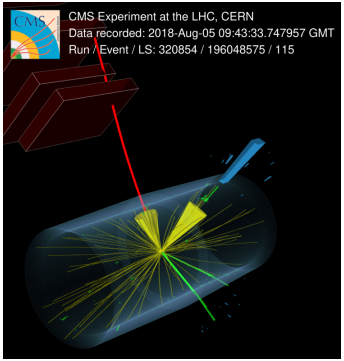
Physics briefing.



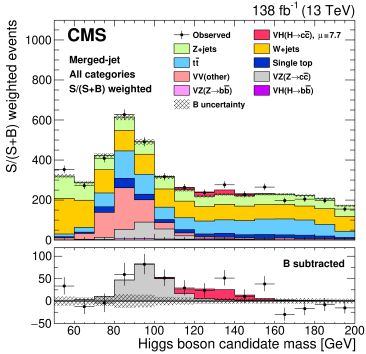
- SM tested over many orders of magnitude
- The Higgs couples with the particle mass.
- HH production decay $\sigma(HH) < 3$ SM.

Astonishing achivements! Higgs coupling to charm

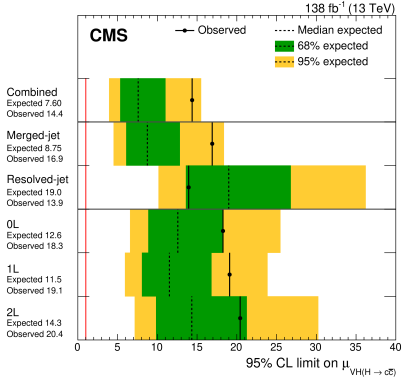
Coupling with the 2nd generation quarks. Search for $H \to cc$ in VH events



Physics briefing

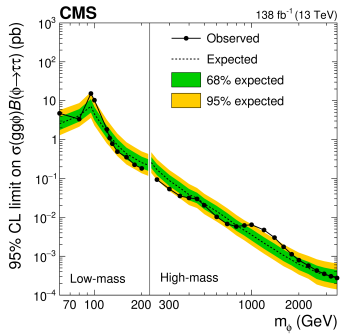


CMS-HIG-21-008 [7]

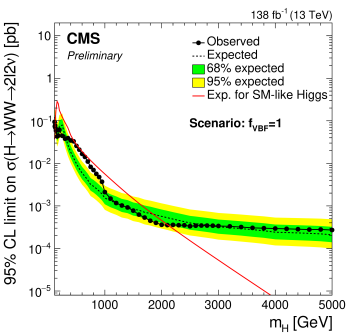


- Observation of $Z \to cc$ with more than 5σ. Its first observation at a hadron collider!
- $\mu = 1.002 \pm 0.036$ (th) ± 0.033 (exp) ± 0.029 (stat)
- Agreement with the Standard Model signal strenght.
- World's most stringent constraint on the coupling Higgs boson to charm quark.

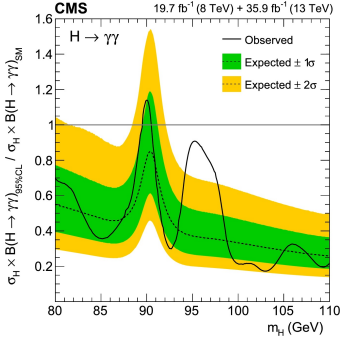
Hints for new physics with Higgs



CMS-HIG-21-001 [14].



CMS-PAS-HIG-20-016 [10].



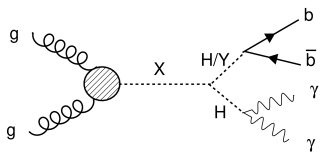
Phys. Let. B 793 [9].

Interesting excess with Higgs observed from CMS:

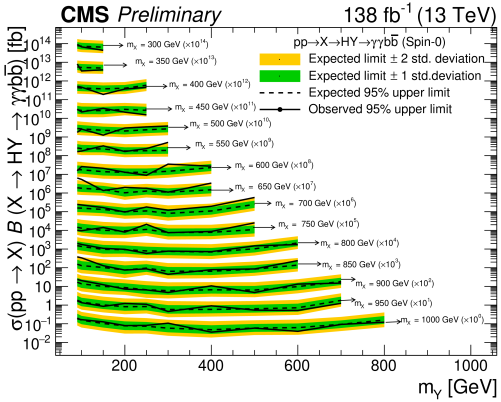
- $H \to \tau\tau$; excess 3.1σ (local), 2.7σ (global) at $M_\phi = 90 - 100$ GeV.[14]
- $H \to WW$; excess 3.8σ (local), 2.6σ (global) at $M_\phi = 650$ GeV.[10]
- $H \to \gamma\gamma$; excess 2.8σ (local), 1.3σ (global) at $M_\phi = 95$ GeV.[9]

New Physics Searches with Higgs

Search for resonances (X) decaying to $H/Y(bb)H(\gamma\gamma)$ First time looking at the Next-to-minimal Supersymmetric Standard Model (NMSSM) and the Two-real-scalar-singlet Model TRSM: ($X \to YH$) where $M_X > M_Y + M_H$. -0.5cm

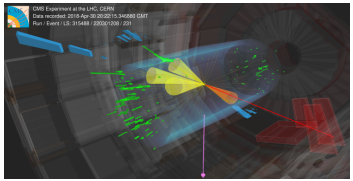


Largest deviation from background−only hypotesis Local significance 3.8σ, Global 2.8σ $M_Y = 9$ GeV and $M_X = 650$ GeV.

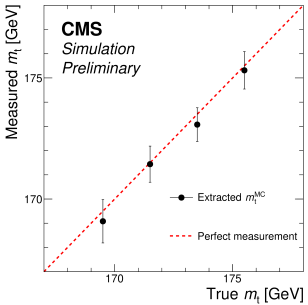


CMS−HIG−21−011 [8].

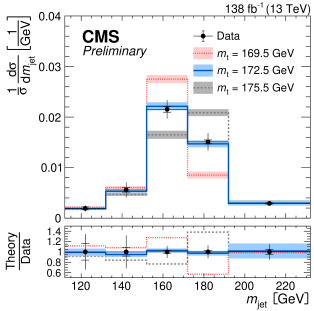
Jet mass measurement in boosted top



Physics briefing.

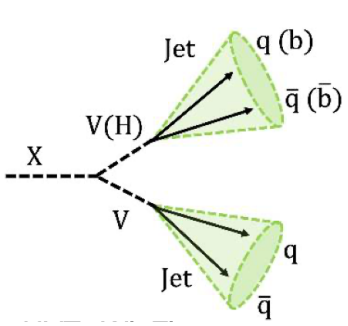


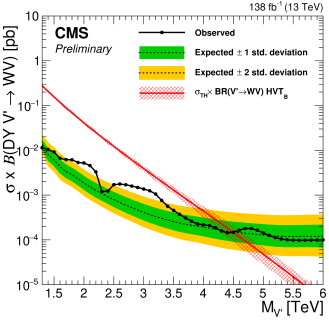
CMS-PAS-TOP-21-012.

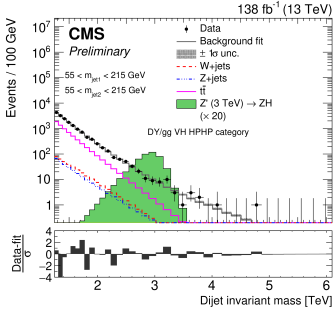


- We use XCone, and it allows us to reconstruct a large jet with three subjets inside.
- Fully merged top decays contained in $R = 1.2$ jets with $p_T > 400$ GeV.
- Jet mass sensitive to m_t
- Data are described best by the top quark mass of $m_t = 172.76 \pm 0.1$ GeV

Multi-dimensional diboson (all-hadronic) search







©Agapitos.

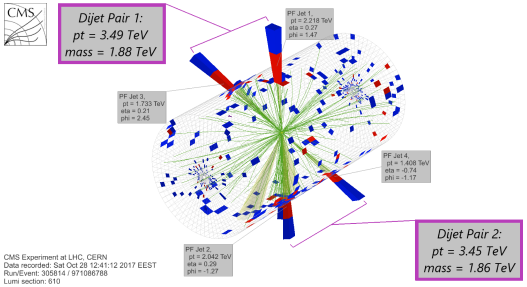
CMS-PAS-B2G-20-009[11].

Physics briefing.

- Best limits to date
- Excesses for $W' \to WZ$ at ~ 2.1 and ~ 2.9 TeV
- First result with spin-1 VBF production.
- Most stringent limits on spin-1 V'.

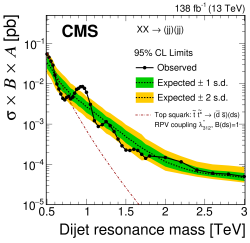
Model		Observed limit (TeV)
Radion DY/gg	VV	2.7
HVT model B, W′	WZ / WH	4.4 / 4.0
HVT model B, Z′	WW / ZH	(1.3–3.1, 3.3–3.5) / 3.9
HVT model B, V′	VV+VH / VV / VH	4.8 / 4.5 / 4.2
G_{bulk} ($\tilde{\kappa} = 0.5$) DY/gg	VV	1.4

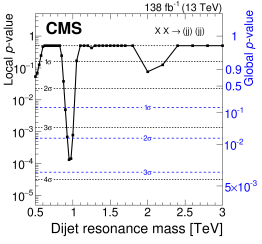
Paired dijet resonances

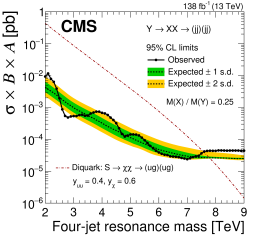


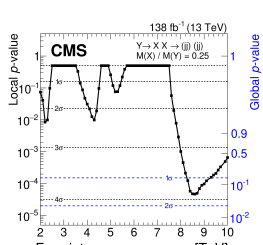
Excesses observed

- Resonant $m(S_u u) = 8.6$ TeV, $3.9\sigma(1.6\sigma)$ local (global).
- Non resonant $m(\tilde{t}) = 0.95$ TeV, $3.6\sigma(2.5\sigma)$ local (global).



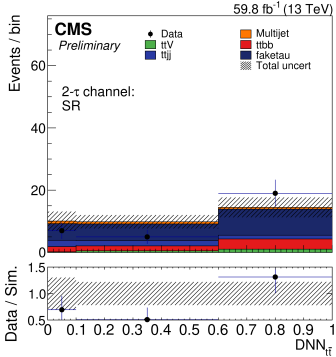


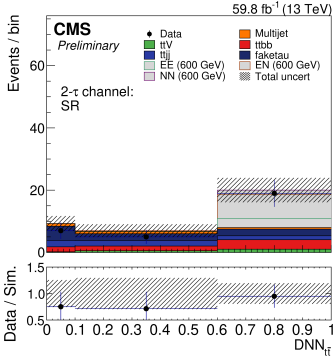


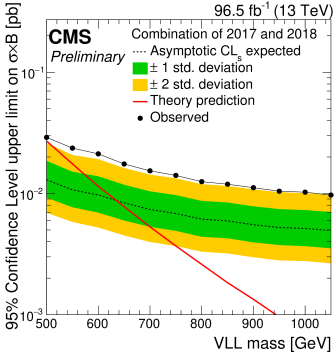


EXO-21-010 [13]

Vector-like leptons 3rd generation





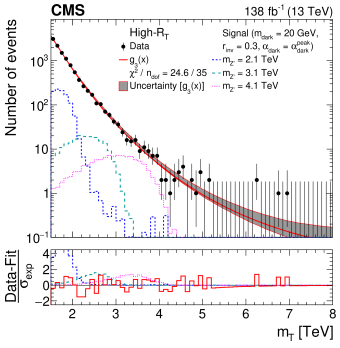


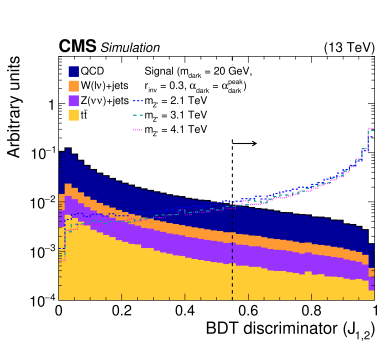
CMS-PAS-B2G-21-004[12]

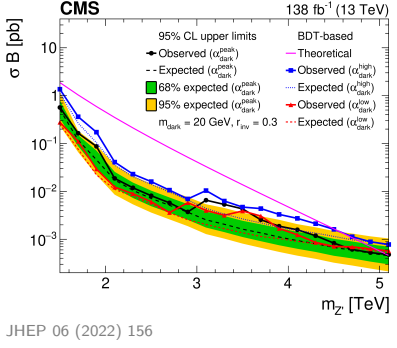
- 4321 (UV−complete) model with the potential to explain existing B−physics measurements.
- New techniques for τ and b: DeepTau[TAU-20-001], DeepJet[arXiv 2008.10519].
- Mild excess at $2.9\sigma(2.8\sigma)$ local(global) at 600 GeV.

Resonant production of strongly coupled dark matter

- First search for resonant production of DM from a strongly coupled hidden sector
- Dark quarks production through a Z' mediator $q\bar{q} \rightarrow Z' \rightarrow \chi\bar{\chi}$.
- Boosted Decision Tree (BDT) to improve signal-BKG rejection.
- Two signal regions based on transverse ratio $R_T = P_T^{miss}/m_T$







JHEP 06 (2022) 156

95% exclusion limits extend to $1.5 < Z' < 5.1$ TeV with DBT

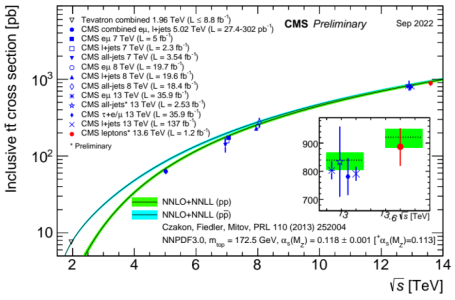
Run 3 results

Run 3 opportunities for Physics

- Run-2 data analysis is still ongoing (W mass included)
- New things with Run-3 data: new triggers, scouting(high rate trigger-objects analysis) and parking (opportunistic reco)[2]
- 1 billion fully-simulated (GEN to RECO) events are produced weekly.
- Machine Learning applications, streamlining the analysis process, heterogeneous computing (GPUs+CPU in use for HLT for Run3)
- Exotic searches have some gain with $13 \rightarrow 13.6$ GeV.
- Development of better methods for tagging, BG estimations, MC.
- Special item attention to Long-Lived Particle searches.

$\sigma_{t\bar{t}}$ at $\sqrt{s} = 13.6$ TeV with 1.2 ± 0.07 fb^{-1} (2/2)

First measurement of top quark production by CMS at $\sqrt{s} = 13.6$ TeV! $\sigma_{t\bar{t}} = 887^{+66}_{-68}$ pb



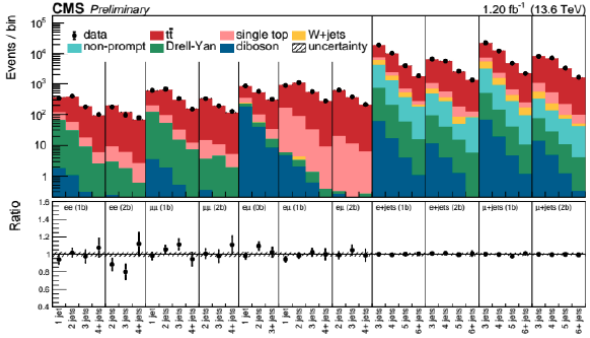
TOP−22−012.

Dominant uncertainties:

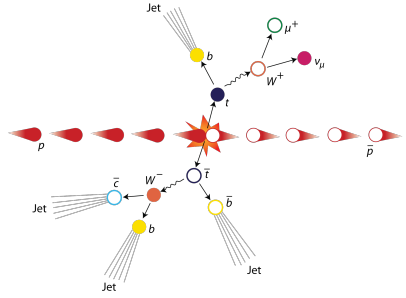
Source	Uncertainty (%)
Lepton ID SF	3.4
Jet energy scale	1.6
b tagging SF	1.5
ME/PS matching	1.1
Drell-Yan background	0.9
Pileup	0.7
combined likelihood fit	4.0
Jet calibration (external)	2.1
luminosity (external)	6.0

- Combination of five channels $e\mu$, ee, $\mu\mu$, e+jets, μ+jets.
- Events are selected with one or two charged leptons and additional jets.
- A novel early measurement using multiple channels to constrain efficiencies in *situ*.
- Agreement with the Standard Model prediction.

$\sigma_{t\bar{t}}$ at $\sqrt{s} = 13.6$ TeV with 1.2 ± 0.07 fb^{-1} (1/2)



TOP−22−012.

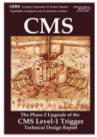


Wikipedia.

Comparison between simulation and data in the final analysis binning post fit agreement and uncertainties after performing the fit. The Lepton ID efficiency uncertainties are not included in the uncertainty band.

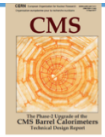
HL-LHC preparation

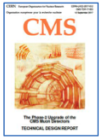
HL−LHC preparation



L1-Trigger HLT/DAQ
https://cds.cern.ch/record/2714892
https://cds.cern.ch/record/2759072
- Tracks in L1-Trigger at 40 MHz
- PFlow selection 750 kHz L1 output
- HLT output 7.5 kHz
- 40 MHz data scouting

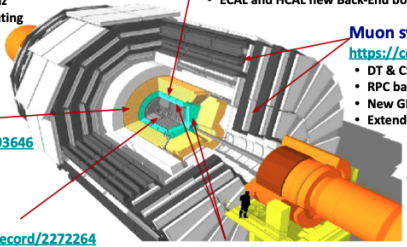
Barrel Calorimeters
https://cds.cern.ch/record/2283187
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards



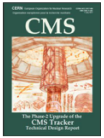


Muon systems
https://cds.cern.ch/record/2283189
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta = 3$

Calorimeter Endcap
https://cds.cern.ch/record/2293646
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

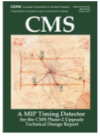


Beam Radiation Instr. and Luminosity
http://cds.cern.ch/record/2759074
- Bunch-by-bunch luminosity measurement: 1% offline, 2% online



Tracker https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta = 3.8$

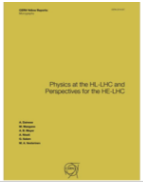
MIP Timing Detector
https://cds.cern.ch/record/2667167
Precision timing with:
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes



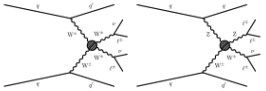
©Rizzi [2]

HL−LHC preparation

- The 2019 Yellow report gives a comprehensive review of the physics at the HL-LHC:
  - https://cds.cern.ch/record/2703572?ln=en
- More studies starting to appear the context of the Snowmass activities
- First CMS public results here:

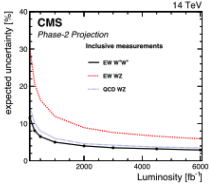


- **VBS measurement of $W^{\pm}W^{\pm}$ and WZ at HL-LHC uses leptonic decay modes of both W and Z where l = e, μ**
  - Extrapolated from full Run 2 analysis
  - Contributions of $W_L^{\pm}W_L^{\pm}$, $W_L^{\pm}W_T^{\pm}$ and $W_T^{\pm}W_T^{\pm}$ are measured in the $W^{\pm}W^{\pm}$ CM reference frame or in the initial-state parton-parton one

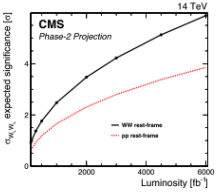


Mode	WW reference frame fraction (%)	Parton-parton reference frame fraction (%)
$W_L^{\pm}W_L^{\pm}$	10.9	7.3
$W_L^{\pm}W_T^{\pm}$	31.9	37.4
$W_T^{\pm}W_T^{\pm}$	57.2	55.3

Uncertainty for inclusive measurements



Expected significance for the detection of W_LW_L



CMS-PAS-FTR-21-001

Summary

- more than 1000 SM measurements and new physics searches available with Run1 and Run2 data.
- Many of them are precision measurements.
- Large number of BSM scenarios and signatures explored with LHC Run-2 data.
- New challenging models/signatures have been proven for the first time.
- Run-2 is a huge dataset and many analyses are still ongoing.
- CMS is publishing $\sim$80 analysis per year
- CMS is already taking Run-3 data.
- Few 2-3 sigma to be clarified with Run-3.
- Preparing for HL-LHC: new detectors to be installed.

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[2] CMS Collaboration Andrea Rizzi. *CMS Highlights at ICHEP*. https://agenda.infn.it/event/28874/contributions/171902/. Accessed: 2022–09-19. 2022.

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[7] The CMS Collaboration. *Direct search for the standard model Higgs boson decaying to a charm quark-antiquark pair*. Tech. rep. CMS-PAS-HIG-21-008. 2022. URL: http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-21-008/index.html.

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[14] The CMS Collaboration. *Searches for additional Higgs bosons and for vector leptoquarks in $\tau\tau$ final states in proton−proton collisions at $\sqrt{s} = 13$ TeV*. Tech. rep. CMS-HIG-21-001. Aug. 2022. URL: https://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-21-001/index.html.

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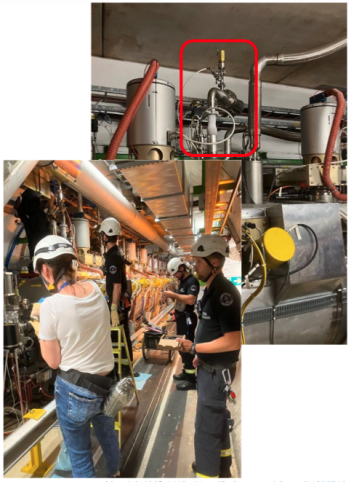
Backup

23rd August incident

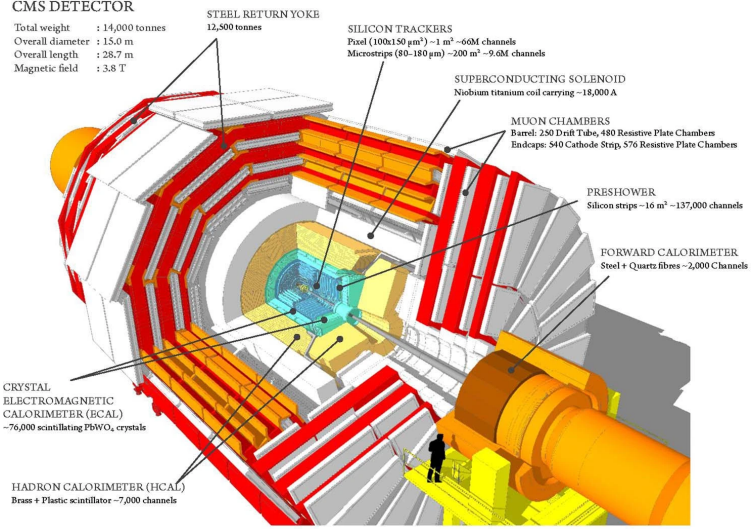
- ~ 18:00 lost communication SF4 cooling water flow PLC
  - Cryo compressor stopped in P4
  - RF cryo went in safe mode → controlled He release
- ~ 22:00 cryo system back online, start of recovery
- Fast response time of all involved teams !

- RF cavities pressure release disks ruptured
  - Cold He release lowered the burst disk rupture threshold
  - Disks replaced during the night by RF and Fire Brigade
  - Warm up to 300K is needed due to contaminated atmosphere in the RF cryo module

- **Expected downtime ~4 weeks**

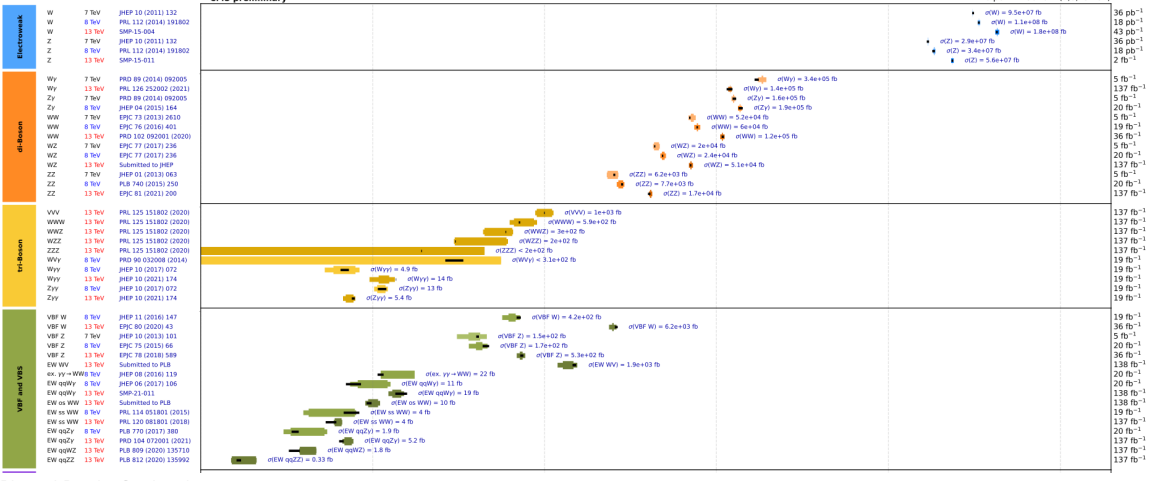


More info LMC #446 - https://indico.cern.ch/event/1190674/

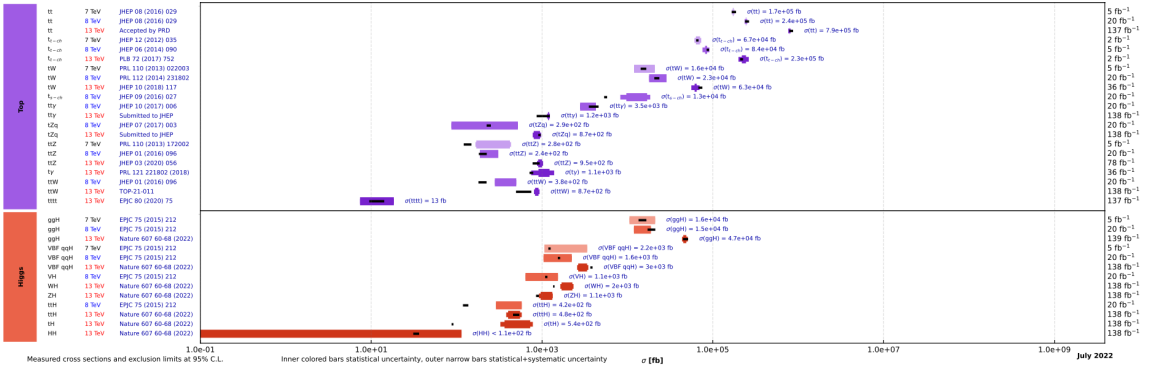


Nature 607, 60-68 (2022)[4]

CMS Cross Section measurements

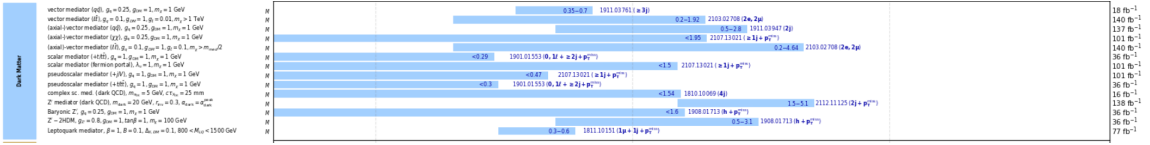


CMS Cross Section measurements



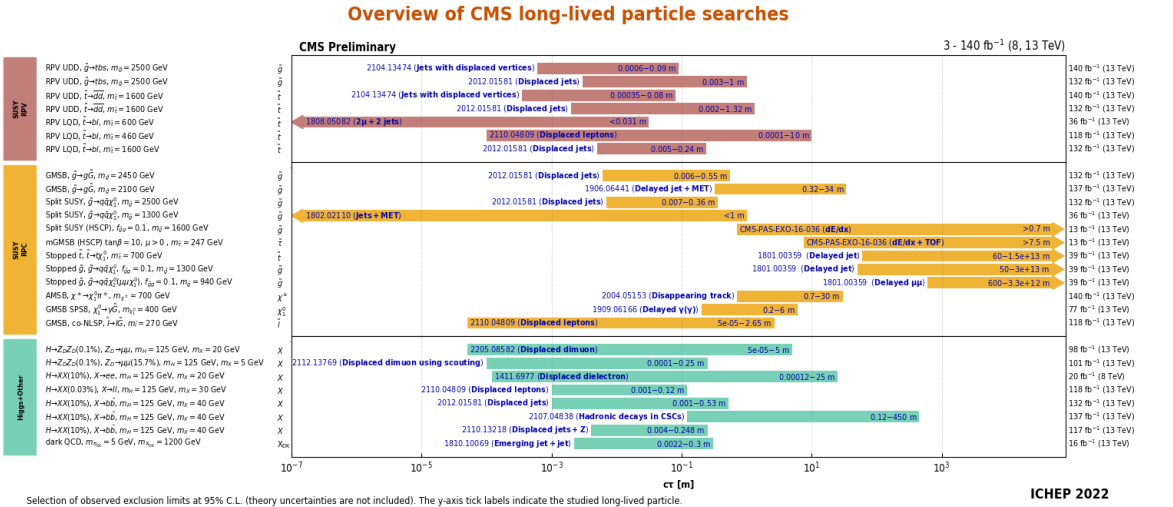
Physical Results Combined

Dark Matter



CMS Exotica Summary plots for 13 TeV data

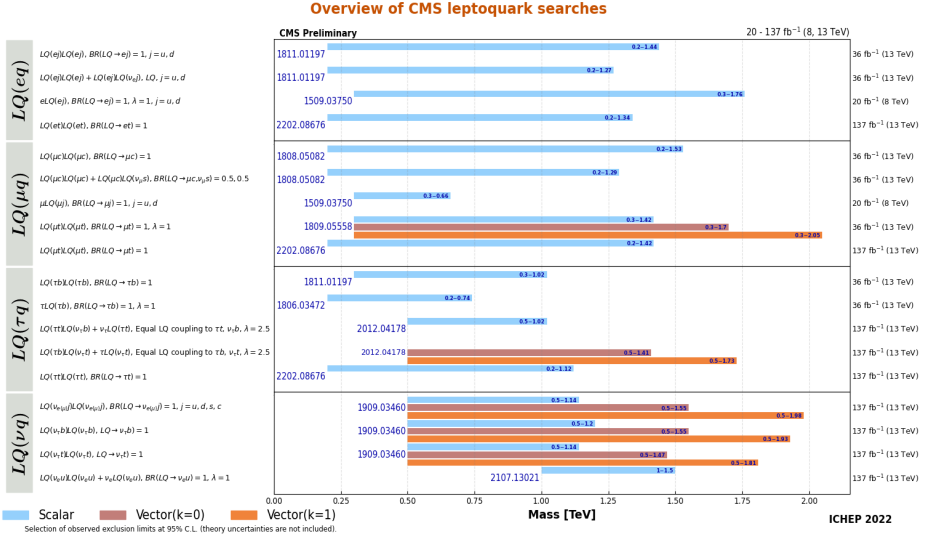
Long Lived Particles



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

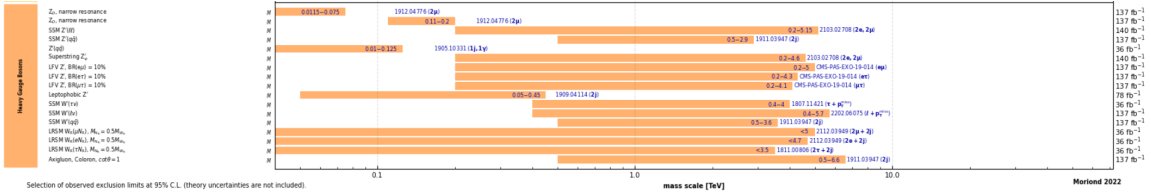
CMS Exotica Summary plots for 13 TeV data

Leptoquarks



CMS Exotica Summary plots for 13 TeV data

Heavy Bosons Searches



CMS Exotica Summary plots for 13 TeV data

Possible topologies of events at the production of long-lived particles