

CMS Experimental Results



Isabel Pedraza

Faculty of Physical & Mathematical Sciences
Benemérita Universidad Autónoma de Puebla

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XVIII Mexican Workshop on Particles and Fields

Overview

- 1 Introduction
- 2 CMS Highlights
- 3 Run 3 Expectations

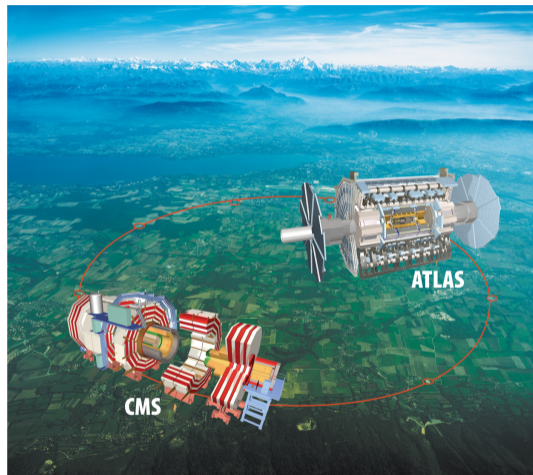


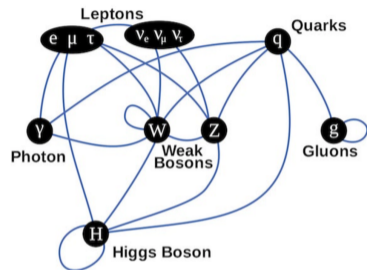
Image from CDS CERN server

Standard Model

Standard Model of Elementary Particles

	three generations of matter (fermions)			interactions / force carriers (bosons)	
	I	II	III		
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
	u up	c charm	t top	g gluon	H higgs
	d down	s strange	b bottom	γ photon	
	e electron	μ muon	τ tau	Z Z boson	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	

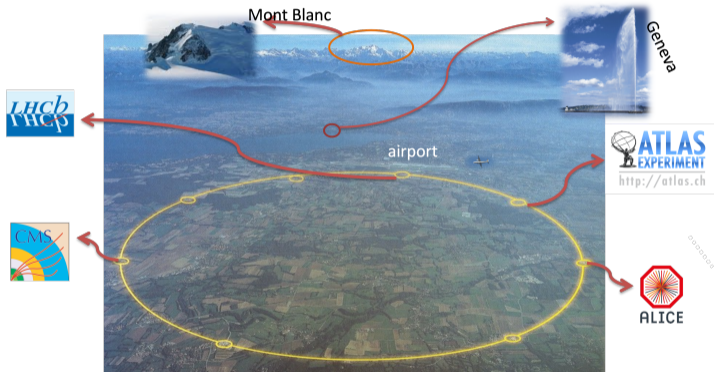
QUARKS (left side of fermion table)
LEPTONS (left side of fermion table)
GAUGE BOSONS VECTOR BOSONS (right side of boson table)
SCALAR BOSONS (right side of boson table)



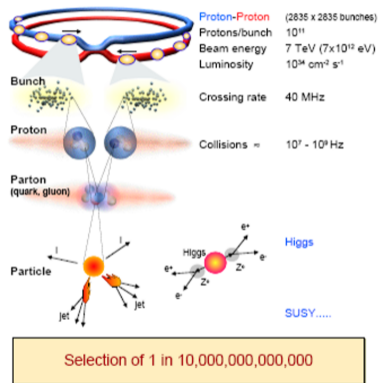
Elementary-particle interactions. Credit: Wikimedia

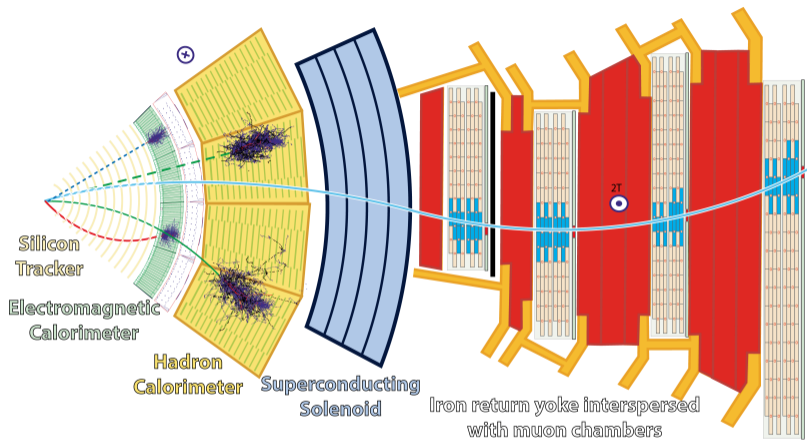
- Describing three of the four known fundamental forces.
- Classifies all known elementary particles.

Wikipedia



CERN CDS





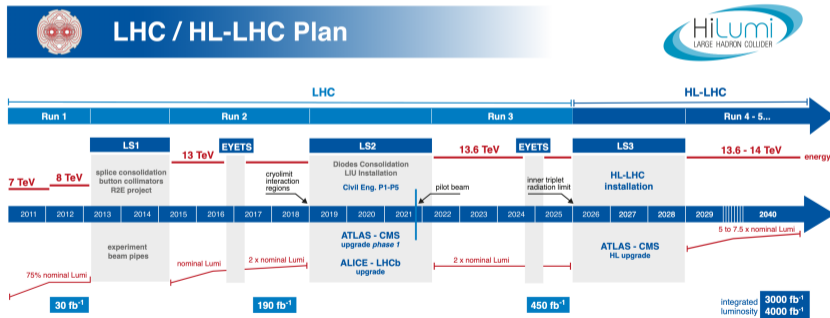
- Muon
- Electron
- Charged hadron (e.g. pion)
- - - Neutral hadron (e.g. neutron)
- - - Photon

CERN CDS

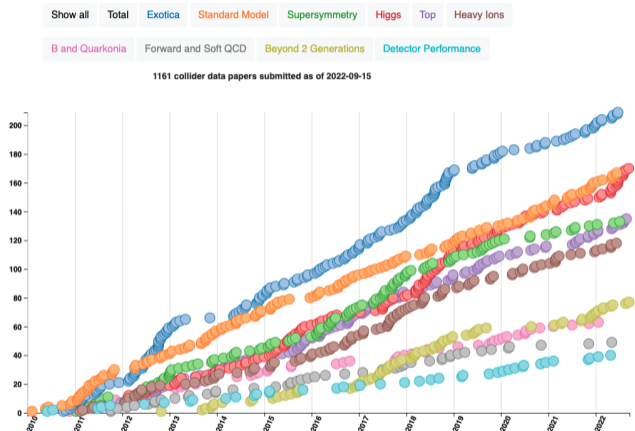
LHC Operations

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 $\sim 27 \text{ fb}^{-1}$
- 2015–2018: Run–2 13 TeV. Collected by CMS $\sim 150 \text{ fb}^{-1}$

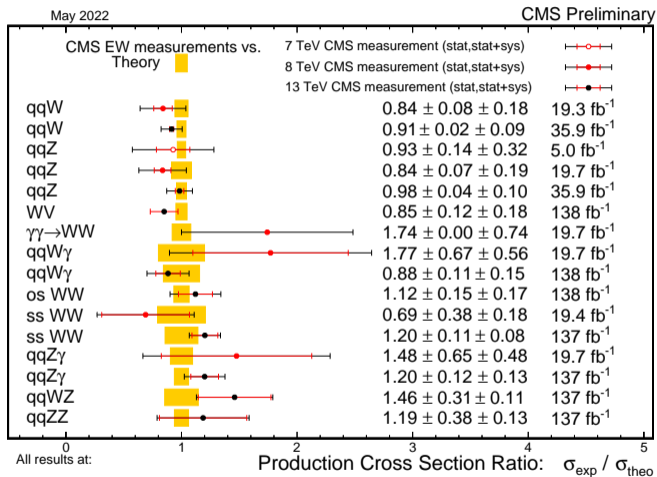


Physics results and publications



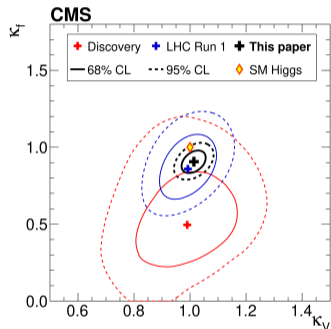
- 1159 papers on collider data published or submitted to a journal.
- Run 2 data analysis continues > 100 analysis.
- Run 3 early data analysis foresee 100 analysis in the first couple of years.
- First preliminary results with Run 3 data presented on September 4th at TOP2022.

CMS Cross Section measurements

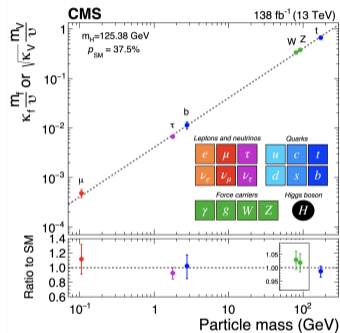


Physical Results Combined

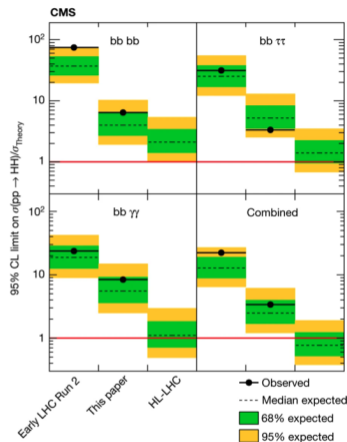
10 years of Higgs



Nature 607 (2022) [4].



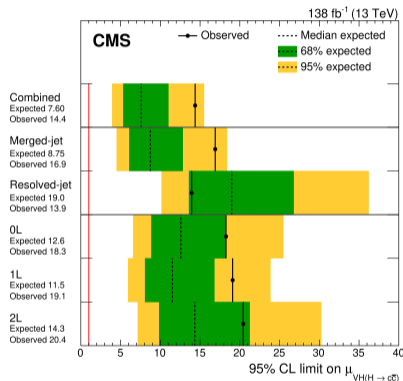
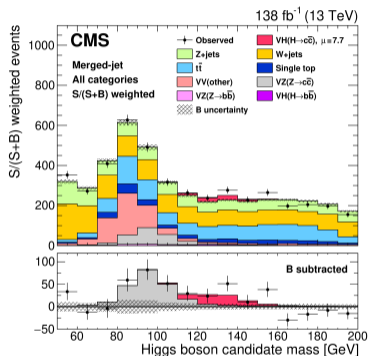
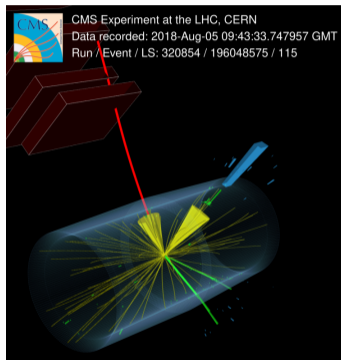
Physics briefing.



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

Astonishing achievements! Higgs coupling to charm

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

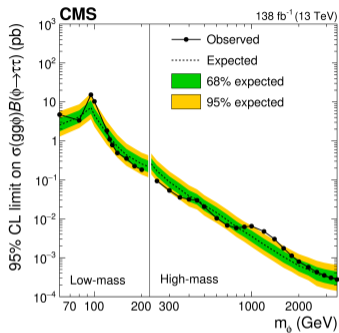


Physics briefing

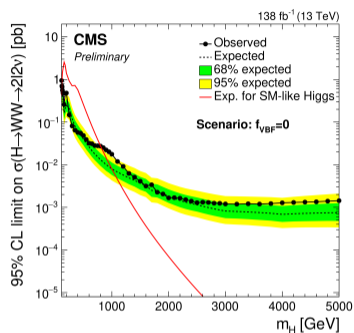
CMS-HIG-21-008 [7]

- Observation of $Z \rightarrow cc$ 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 strength.
- World's most stringent constraint on the coupling Higgs boson to charm quark.

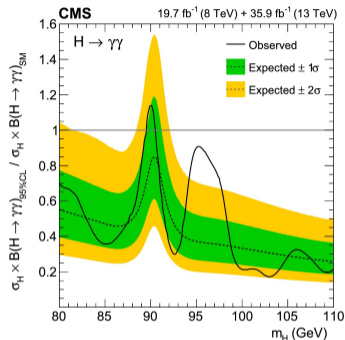
Hints for new physics with Higgs



CMS-HIG-21-001 [14].



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



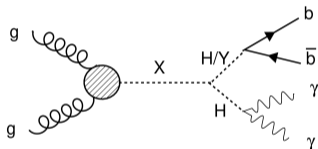
Phys. Let. B 793 [9].

Interesting excess with Higgs observed from CMS:

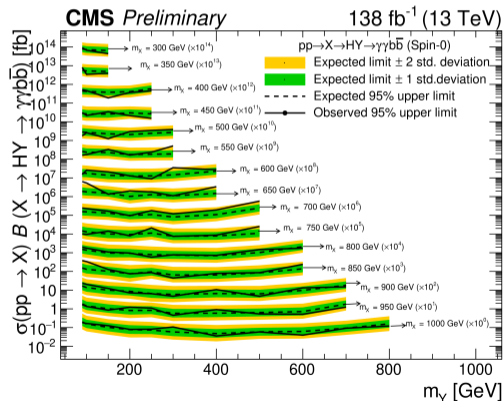
- $H \rightarrow \tau\tau$; excess 3.1σ (local), 2.7σ (global) at $M_\phi = 90 - 100$ GeV.[14]
- $H \rightarrow WW$; excess 3.8σ (local), 2.6σ (global) at $M_\phi = 650$ GeV.[10]
- $H \rightarrow \gamma\gamma$; excess 2.8σ (local), 1.3σ (global) at $M_\phi = 95$ GeV.[9]

New Physics Searches with Higgs

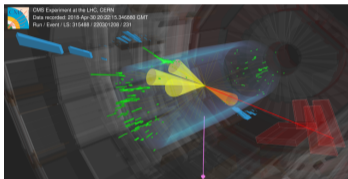
Search for resonances (X) decaying to $H/Y(bb)H(\gamma\gamma)$ First time looking at the Next-to-minimal Supersymmetric Standard Model (NMSSM) and the Two-real-scalar-singlet Model TRSM: ($X \rightarrow YH$) where $M_X > M_Y + M_H$. -0.5cm



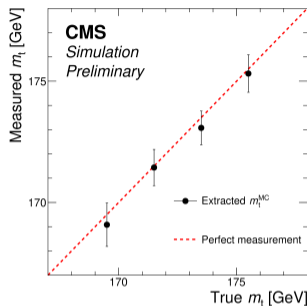
Largest deviation from background—only hypothesis Local significance 3.8σ , Global 2.8σ
 $M_Y = 9 \text{ GeV}$ and $M_X = 650 \text{ GeV}$.



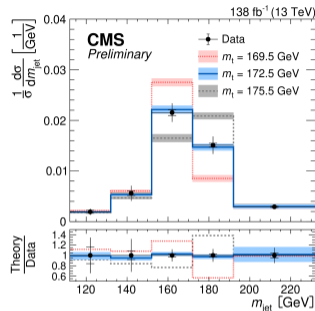
Jet mass measurement in boosted top



Physics briefing.

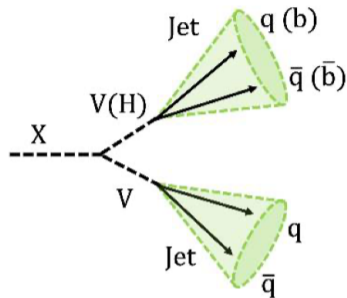


CMS-PAS-TOP-21-012.

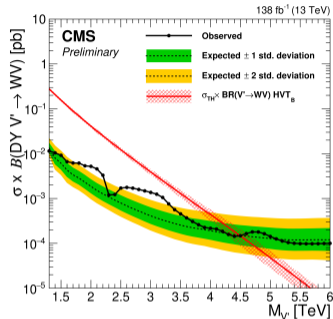


- We use X Cone, and it allows us to reconstruct a large jet with three subjects inside.
- Fully merged top decays contained in $R = 1.2$ jets with $p_T > 400$ GeV.
- Jet mass sensitive to m_t
- Data are described best by the top quark mass of $m_t = 172.76 \pm 0.1$ GeV

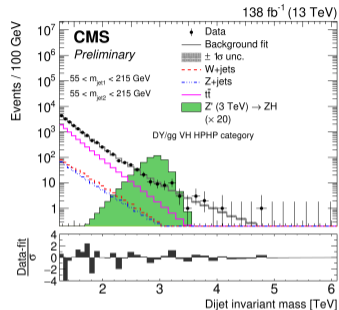
Multi-dimensional diboson (all-hadronic) search



© Agapitos.



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

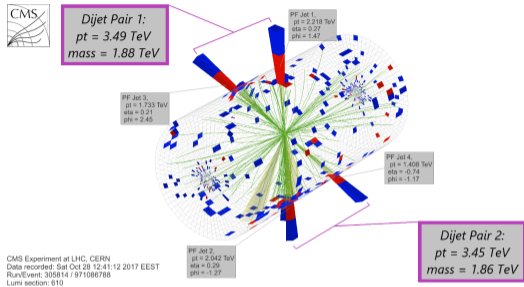


Physics briefing.

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

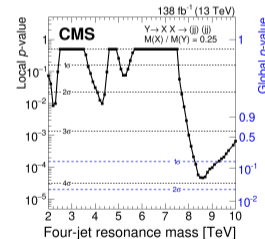
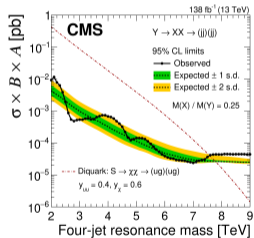
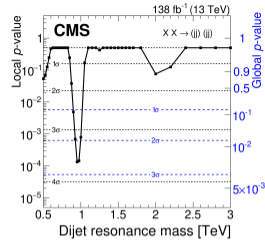
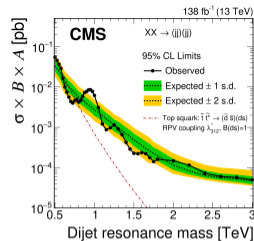
Model		Observed limit (TeV)
Radion DY/gg	VV	2.7
HVT model B, W'	WZ / WH	4.4 / 4.0
HVT model B, Z'	WW / ZH	(1.3-3.1, 3.3-3.5) / 3.9
HVT model B, V'	VV+VH / VV / VH	4.8 / 4.5 / 4.2
$G_{\text{bulk}} (\tilde{\kappa} = 0.5)$ DY/gg	VV	1.4

Paired dijet resonances



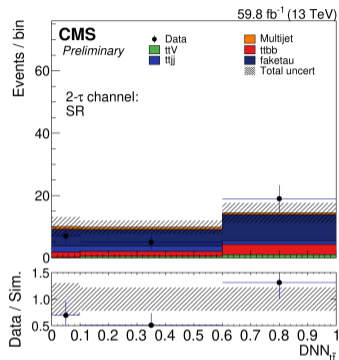
Excesses observed

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

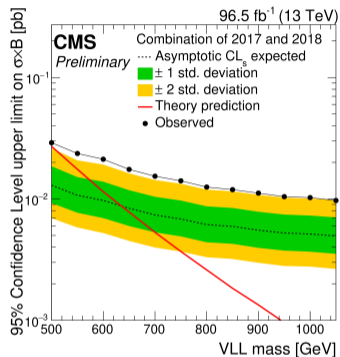
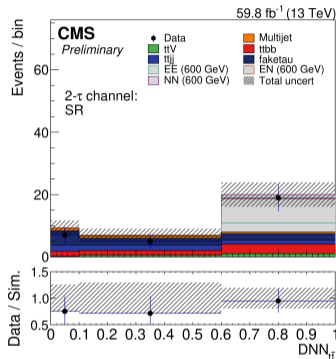


EXO-21-010 [13]

Vector-like leptons 3rd generation



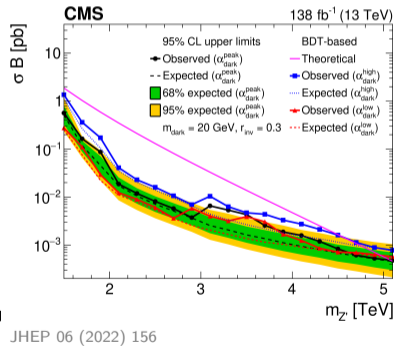
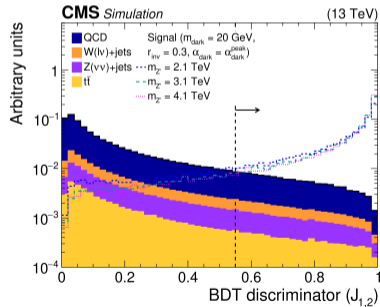
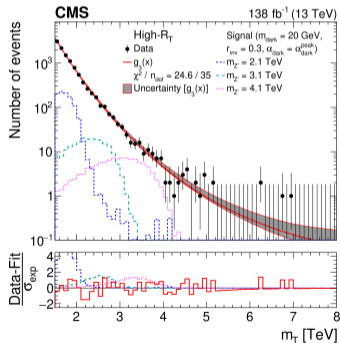
CMS-PAS-B2G-21-004[12]



- 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 2.9σ (2.8σ) 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

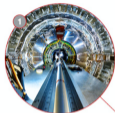
95% exclusion limits extend to $1.5 < Z' < 5.1$ TeV with DBT

Run 3 expectations

CMS Hardware Updates

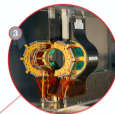
BEAM PIPE

Replaced with an entirely new one compatible with the future tracker upgrade for HL-LHC, improving the vacuum and reducing activation.



PIXEL TRACKER

All-new innermost barrel pixel layer, in addition to maintenance and repair work and other upgrades.



BRIL

New generation of detectors for monitoring LHC beam conditions and luminosity.



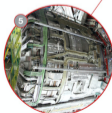
CATHODE STRIP CHAMBERS (CSC)

Read-out electronics upgraded on all the 180 CSC muon chambers allowing performance to be maintained in HL-LHC conditions.



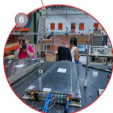
HADRON CALORIMETER

New on-detector electronics installed to reduce noise and improve energy measurement in the calorimeter.



SOLENOID MAGNET

New powering system to prevent full power cycles in the event of powering problems, saving valuable time for physics during collisions and extending the magnet lifetime.



GAS ELECTRON MULTIPLIER (GEM) DETECTORS

An entire new station of detectors installed in the endcap-muon system to provide precise muon tracking despite higher particle rates of HL-LHC.

Developments done for Run3

B-parking

- in 2018 we used low p_T displaced triggers to save a sample of unbiased B hadron recoiling wrt the triggered muon
 - Parked trigger rate $\sim 2\text{kHz}$ 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 ($\sim 1\text{ kHz}$ of Particle Flow scouting)

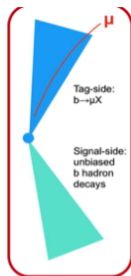
For Run 3 aim at running PF on higher rate, possible adding additional L1 triggers (use GPUs and pixel tracks)

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

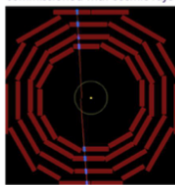
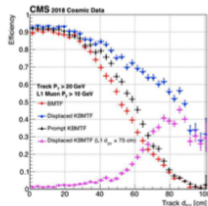


Collected billions of unbiased B decays
12 billion events total

Mode	N_{2018}	f_B	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			
$B^0 \rightarrow K^+ \ell^+ \ell^-$	2600	0.4	6.6×10^{-7}
$B^\pm \rightarrow K^\pm \ell^+ \ell^-$	1800	0.4	4.5×10^{-7}

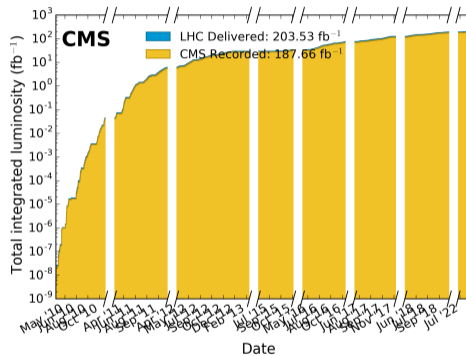
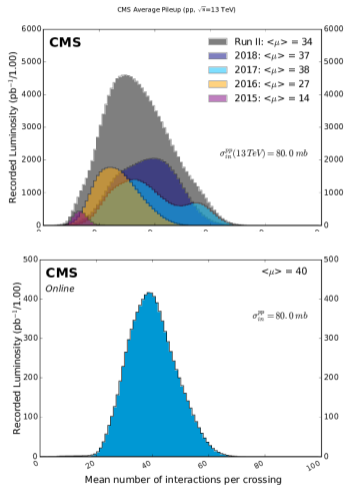
Kalman filter at L1

tested in parallel in 2018 and commissioned with cosmic rays



CMS Status

LHC restarted on July 5th, 2022. Expected to deliver 240–250 fb^{-1} for 4-year Run. [15][3]



- Over 10 fb^{-1} delivered at 13.6 TeV
- 90.2% data taking efficiency. [1]

Run3 Event at 13.6 TeV: New world record!

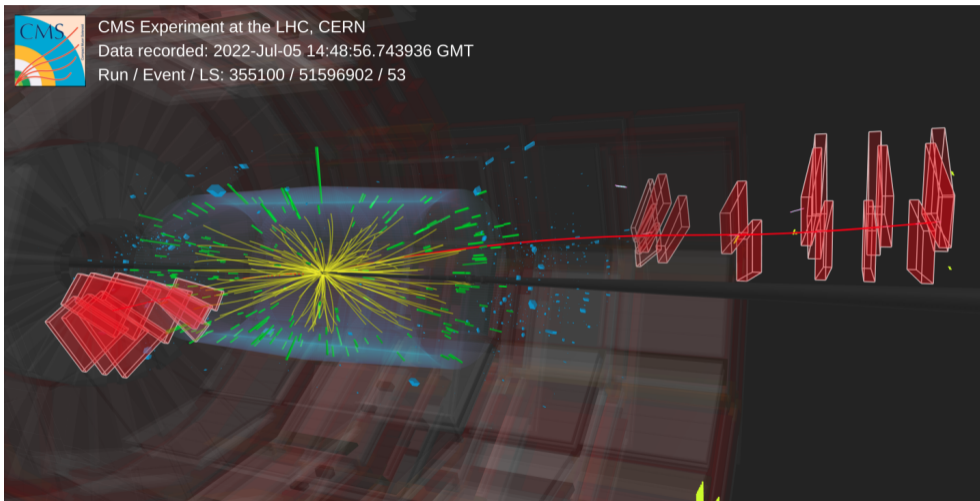
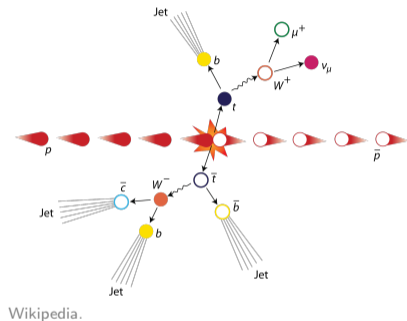
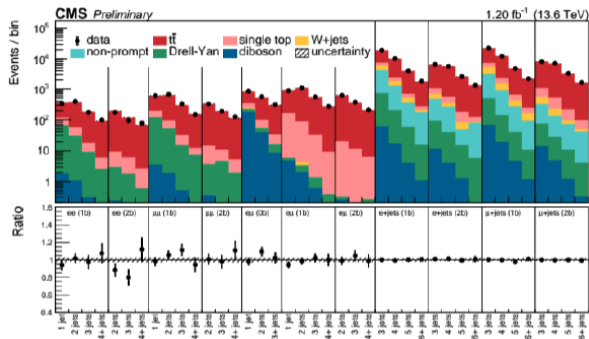


Image from CMS News

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



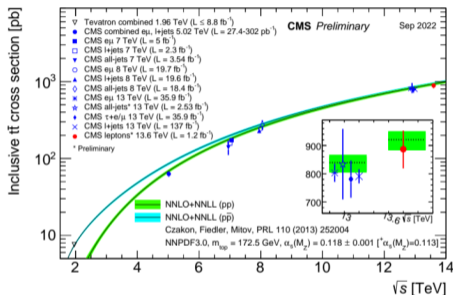
Wikipedia.

TOP-22-012.

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

$\sigma_{t\bar{t}}$ 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! $\sigma_{t\bar{t}} = 887_{-68}^{+66}$ 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 which uses multiple channels to constrain efficiencies *in situ*.
- Agreement with the Standard Model prediction.

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 produced every week.
- 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 attention to Long Lived Particle searches.

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



Calorimeter Endcap

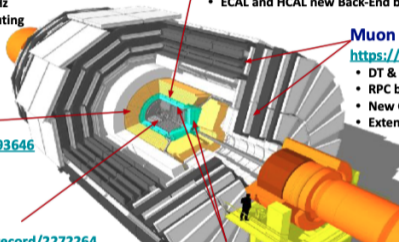
<https://cds.cern.ch/record/2293646>

- 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 $\eta = 3.8$



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>

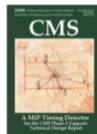
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta = 3$



Beam Radiation Instr. and Luminosity

<http://cds.cern.ch/record/2759074>

- Bunch-by-bunch luminosity measurement: 1% offline, 2% online



MIP Timing Detector

<https://cds.cern.ch/record/2667167>

Precision timing with:

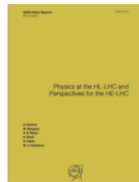
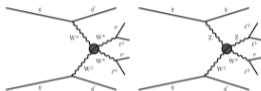
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes



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 $l = e, \mu$**

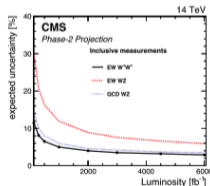


Mode	WW reference frame fraction (%)	Parton-parton reference frame fraction (%)
$W_L^\pm W_L^\pm$	10.9	7.3
$W_L^\pm W_T^\pm$	31.9	37.4
$W_T^\pm W_T^\pm$	57.2	55.3

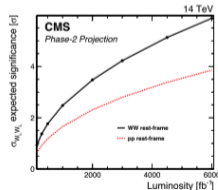
- Extrapolated from full Run 2 analysis
- Contributions of $W_L^\pm W_L^\pm$, $W_L^\pm W_T^\pm$ and $W_T^\pm W_T^\pm$ are measured in the $W^\pm W^\pm$ CM reference frame or in the initial-state parton-parton one

CMS-PAS-FTR-21-001

Uncertainty for inclusive measurements



Expected significance for the detection of $W_L W_L$



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 ~ 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.

References

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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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- [4] CMS Collaboration. “A portrait of the Higgs boson by the CMS experiment ten years after the discovery”. In: *Nature* 607 (2022), pp. 60–68. URL: <https://doi.org/10.1038/s41586-022-04892-x>.

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- [5] CMS Collaboration. *CMS Luminosity - Public Results*. 2022. URL: https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults#Multi_year_plots.
- [6] LHC Collaboration. *LHC Status Report at the 151st LHCC Meeting - OPEN Session*. <https://indico.cern.ch/event/1192325/>. Accessed: 2022-09-19. 2022.
- [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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- [9] The CMS Collaboration. “Search for a standard model–like Higgs boson in the mass range between 70 and 110 GeV in the diphoton final state in proton-proton collisions at $\sqrt{s} = 8$ and 13 TeV”. In: *Physics Letters B* 793 (June 2019), pp. 320–347. URL: <https://www.sciencedirect.com/science/article/pii/S0370269319302904?via%3Dihub>.
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- [12] The CMS Collaboration. *Search for pair-produced vector-like leptons in $\geq 3b + N_\tau$ final states.* Tech. rep. CMS-PAS-B2G-21-004. 2022. URL: <https://cds.cern.ch/record/2803736?ln=en>.
- [13] The CMS Collaboration. *Search for resonant and nonresonant production of pairs of dijet resonances in proton-proton collisions at $\sqrt{s} = 13$ TeV.* Tech. rep. CMS-EXO-21-010. 2022. URL: <http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO-21-010/>.

References V

- [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**

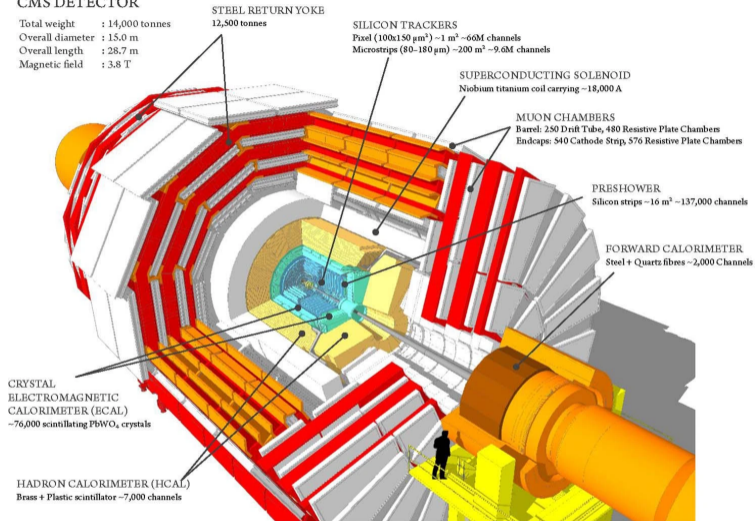


More info LMC #446 - <https://indico.cern.ch/event/1190674/>

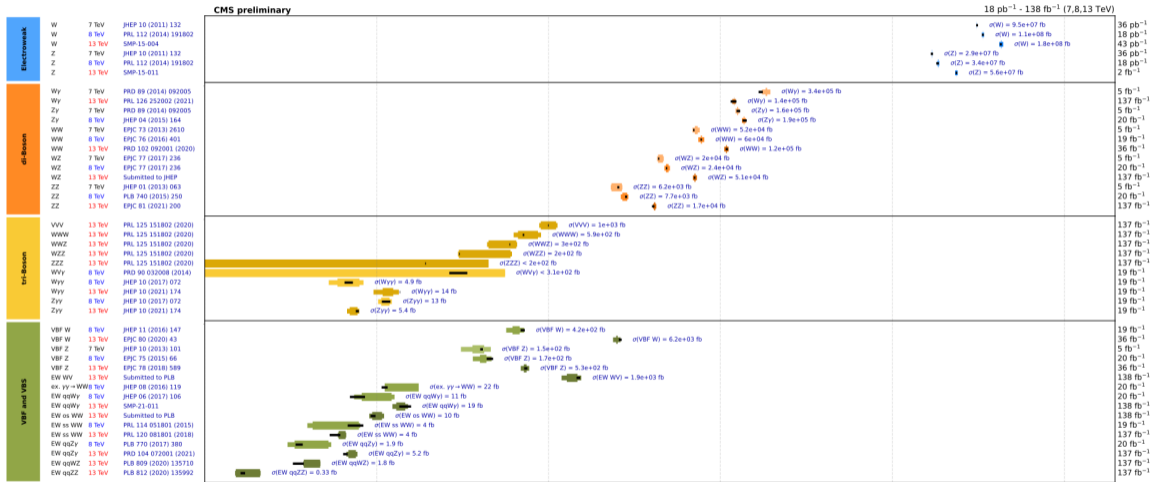


CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15,0 m
Overall length : 28,7 m
Magnetic field : 3.8 T

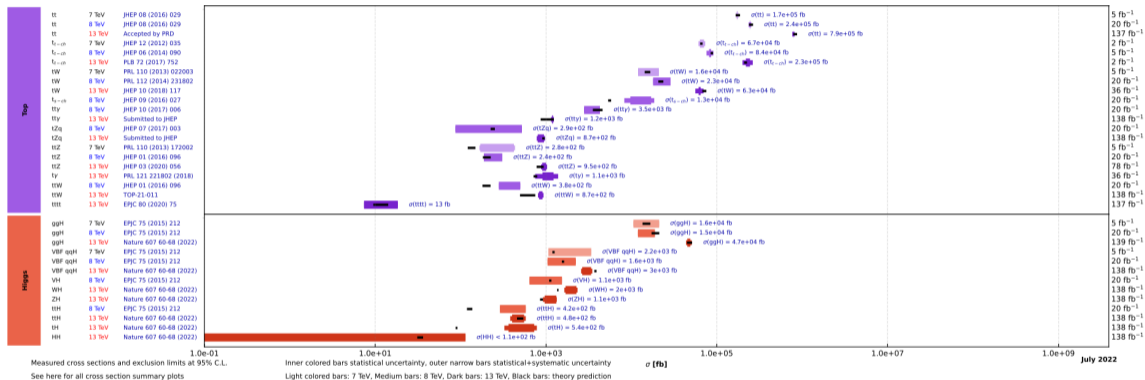


CMS Cross Section measurements



Physical Results Combined

CMS Cross Section measurements

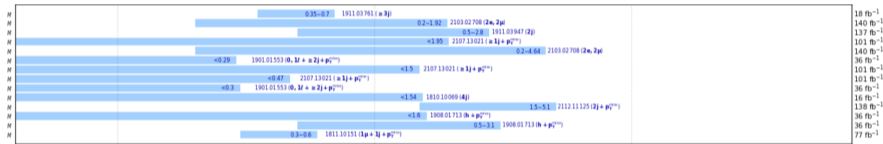


Physical Results Combined

Dark Matter

Dark Matter

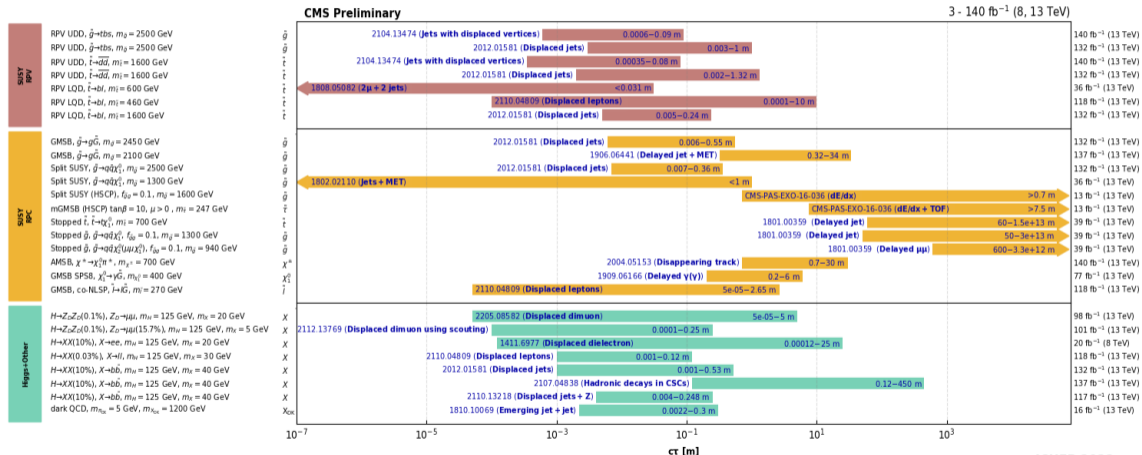
vector mediator (iq), $g_v = 0.25, g_{DM} = 1, m_\nu = 1$ GeV
 vector mediator (if), $g_v = 0.1, g_{DM} = 1, g_t = 0.01, m_\nu > 1$ TeV
 (axial)-vector mediator (iq), $g_a = 0.25, g_{DM} = 1, m_\nu = 1$ GeV
 (axial)-vector mediator (if), $g_a = 0.25, g_{DM} = 1, m_\nu = 1$ GeV
 (axial)-vector mediator (if), $g_a = 0.1, g_{DM} = 1, g_t = 0.1, m_\nu > m_{DM}/2$
 scalar mediator ($+if$), $g_s = 1, g_{DM} = 1, m_\nu = 1$ GeV
 scalar mediator (Hermitian port.), $g_s = 1, m_\nu = 1$ GeV
 pseudoscalar mediator ($+jV$), $g_p = 1, g_{DM} = 1, m_\nu = 1$ GeV
 pseudoscalar mediator ($+if$), $g_p = 1, g_{DM} = 1, m_\nu = 1$ GeV
 complex sc. med. (dark QCD), $m_{DM} = 5$ GeV, $r_{DM} = 25$ mm
 Z mediator (dark QCD), $m_{DM} = 20$ GeV, $r_{DM} = 0.3, a_{DM} = a_{DM}^{max}$
 Baryonic Z, $g_b = 0.25, g_{DM} = 1, m_\nu = 1$ GeV
 Z - 2HDM, $g_b = 0.8, g_{DM} = 1, \tan\beta = 1, m_\nu = 100$ GeV
 Leptoquark mediator, $\beta = 1, B = 0.1, a_{DM} = 0.1, 800 < M_{LQ} < 1500$ GeV



CMS Exotica Summary plots for 13 TeV data

Long Lived Particles

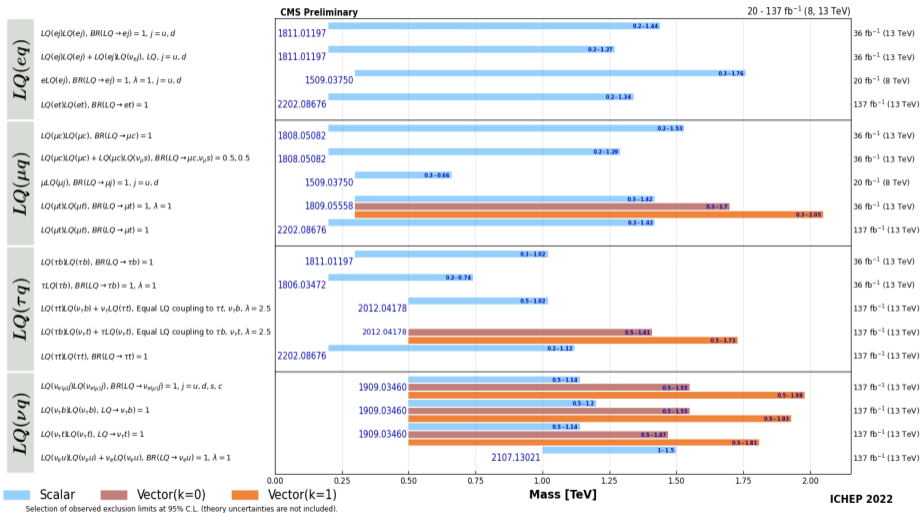
Overview of CMS long-lived particle searches



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.

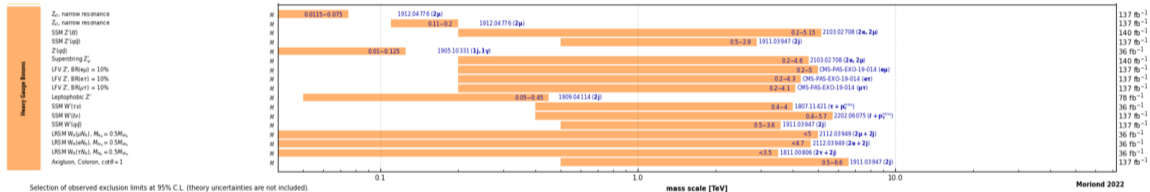
ICHEP 2022

Overview of CMS leptoquark searches



CMS Exotica Summary plots for 13 TeV data

Heavy Bosons Searches



CMS Exotica Summary plots for 13 TeV data