Searches for Beyond the Standard Model Physics at the LHC

JeongEun Lee
Seoul National University

On behalf of the CMS Collaborations

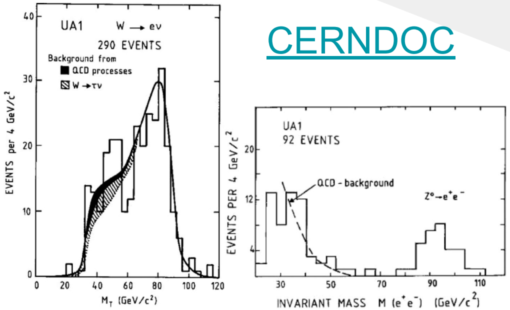
10 September 2022

RADPyC2022

XXXVI Particles and Fields Mexican Division Annual Meeting

Discovery of the Standard Model

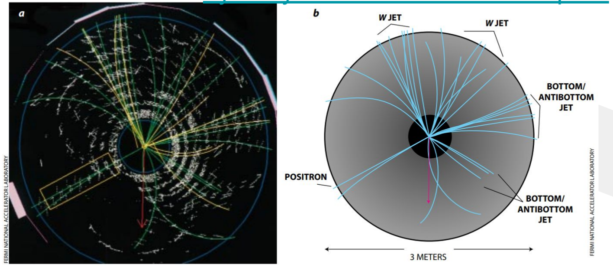
W and **Z** discovery at CERN(1983)

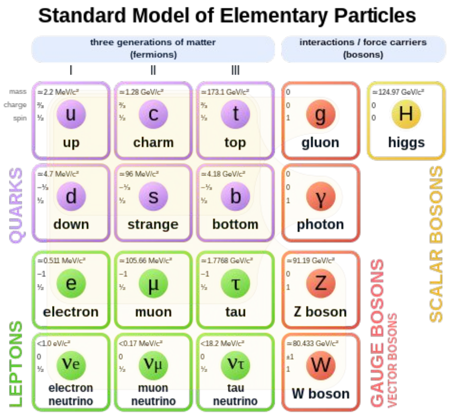


CERNDOC

Top quark discovery at Fermilab(1995)

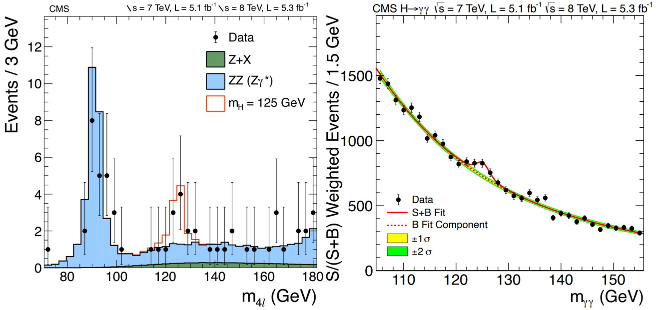
by Tony M. Liss and Paul L. Tipton





Higgs discovery at CERN (2012)

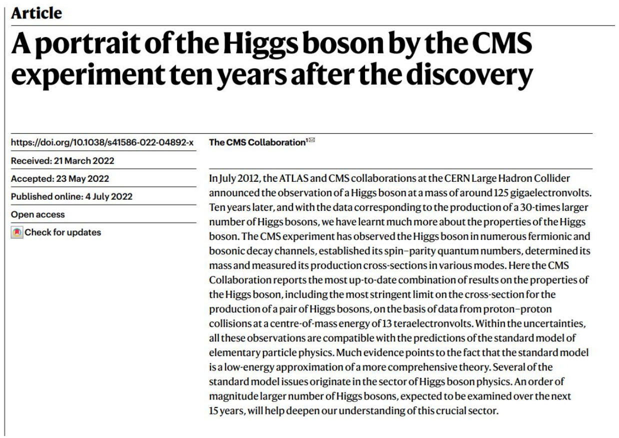
CERN 10 years HIGGS boson discovery



ATLAS Nature 607,52-59 (2022)
CMS Nature 607,60-68 (2022)

After the Higgs discovery 2012…

ParticleZoo.net



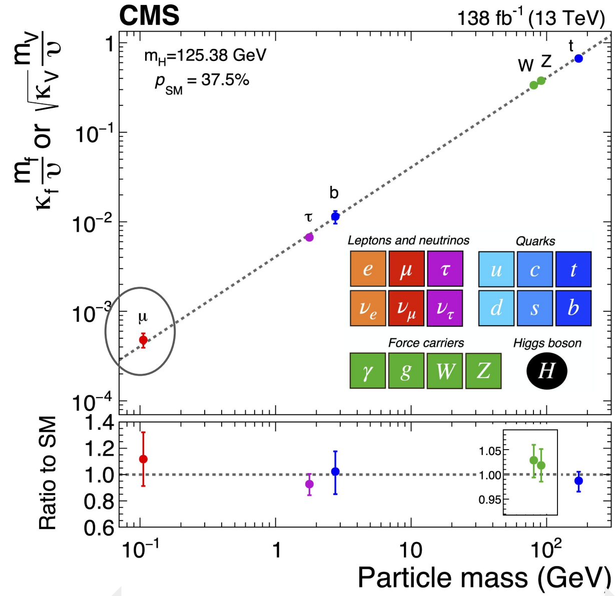
Article

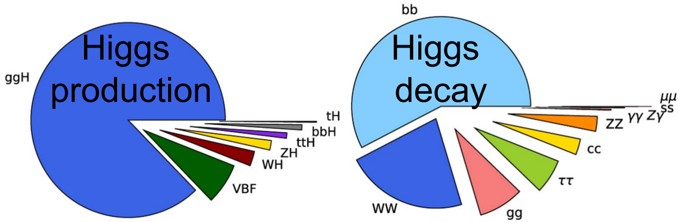
A portrait of the Higgs boson by the CMS experiment ten years after the discovery

https://doi.org/10.1038/s41586-022-04892-x
Received: 21 March 2022
Accepted: 23 May 2022
Published online: 4 July 2022
Open access
Check for updates

The CMS Collaboration[1]

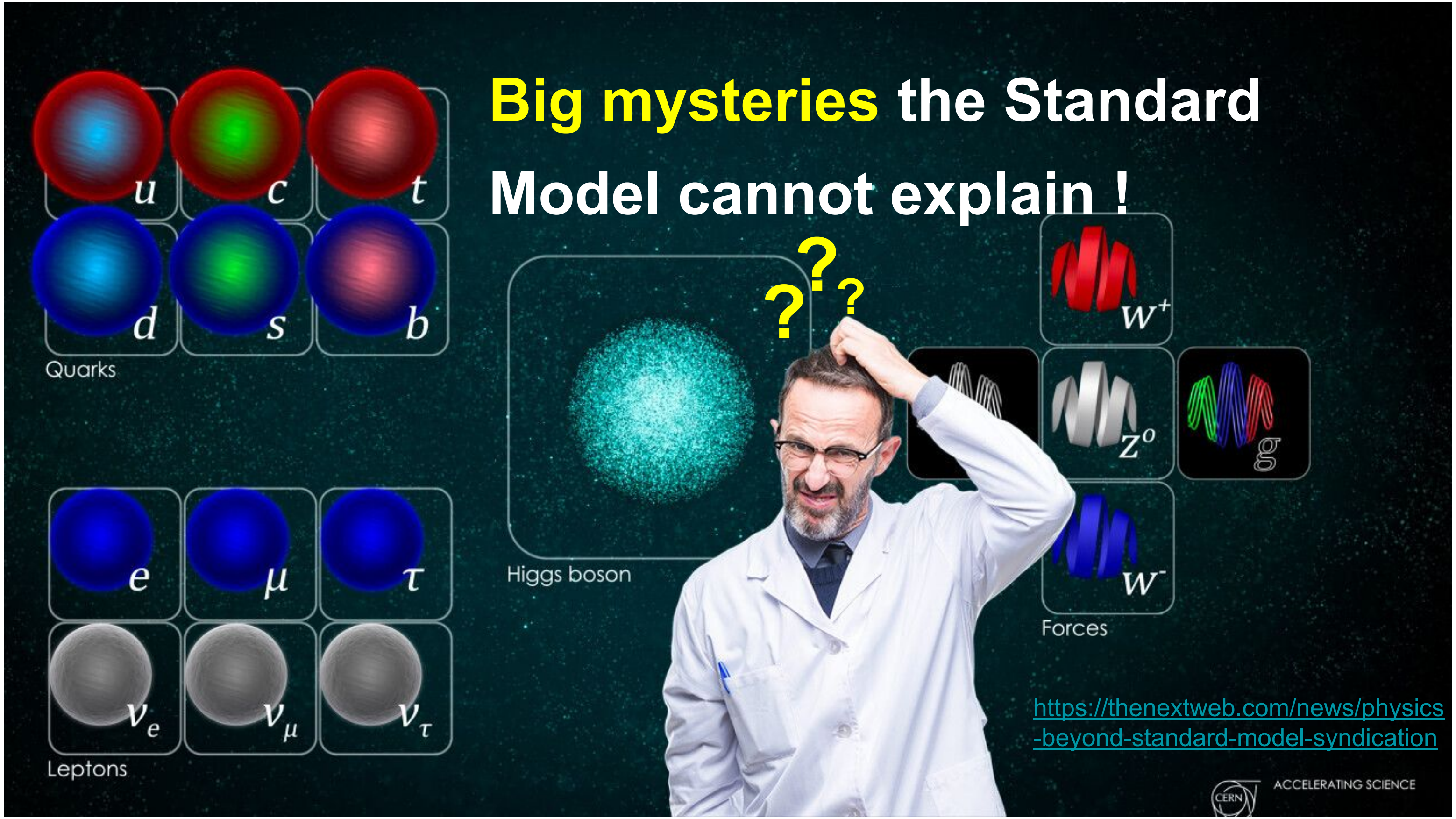
In July 2012, the ATLAS and CMS collaborations at the CERN Large Hadron Collider announced the observation of a Higgs boson at a mass of around 125 gigaelectronvolts. Ten years later, and with the data corresponding to the production of a 30-times larger number of Higgs bosons, we have learnt much more about the properties of the Higgs boson. The CMS experiment has observed the Higgs boson in numerous fermionic and bosonic decay channels, established its spin–parity quantum numbers, determined its mass and measured its production cross-sections in various modes. Here the CMS Collaboration reports the most up-to-date combination of results on the properties of the Higgs boson, including the most stringent limit on the cross-section for the production of a pair of Higgs bosons, on the basis of data from proton–proton collisions at a centre-of-mass energy of 13 teraelectronvolts. Within the uncertainties, all these observations are compatible with the predictions of the standard model of elementary particle physics. Much evidence points to the fact that the standard model is a low-energy approximation of a more comprehensive theory. Several of the standard model issues originate in the sector of Higgs boson physics. An order of magnitude larger number of Higgs bosons, expected to be examined over the next 15 years, will help deepen our understanding of this crucial sector.





- Exploit all production modes.
- Many decay channels accessible for 125 GeV Higgs.
- A new data point is updated (μ).
- Evidence-level measurement at the LHC.
- Particle mass range probed covers O(10^{-1}) to O(100) !

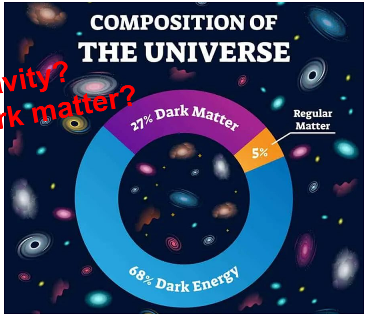
Beyond the **S**tandard **M**odel Physics : Open questions



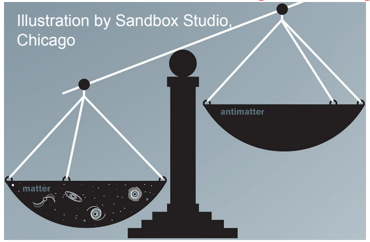
Big Open questions

Unknown Phenomena

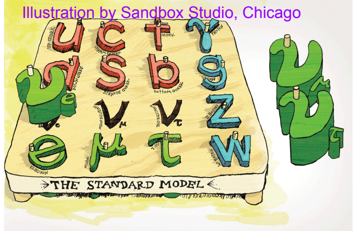
Gravity?
Dark matter?



Matter-antimatter asymmetry?

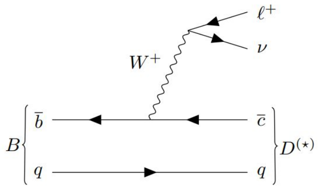


Neutrino mass?

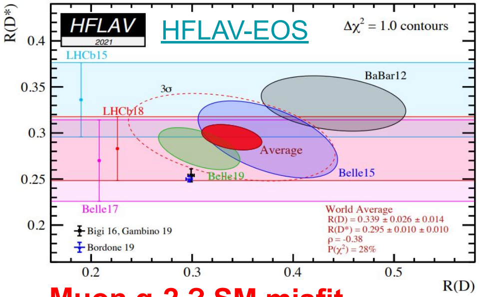


Experimental results-SM misfits

B-meson decays, Flavor Anomalies ?

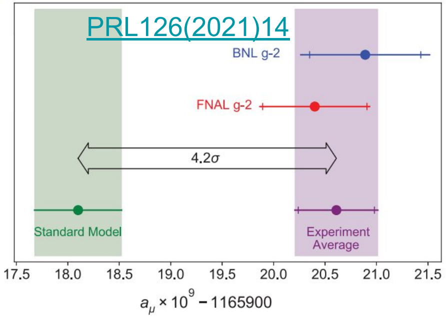


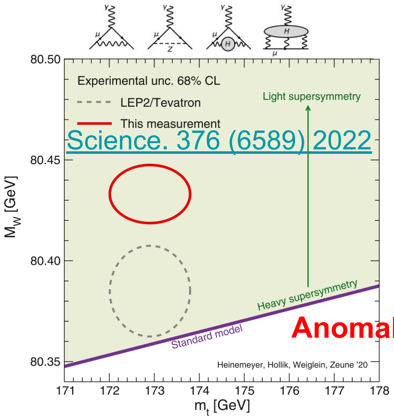
$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)} > SM$$



Muon g-2 ? SM misfit

$$\vec{\mu}_\ell = g_\ell \left(\frac{q}{2m_\ell}\right)\vec{s} \quad \text{where } g_\ell = 2(1 + a_\ell)$$

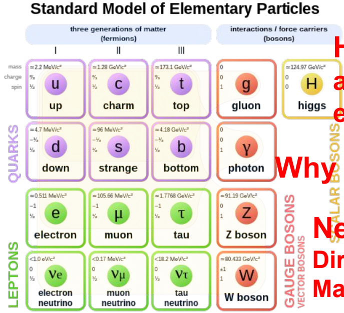




Anomalous W mass ?

Theory question

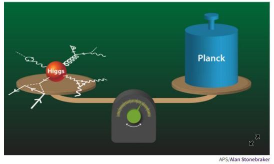
Too many SM parameters ?



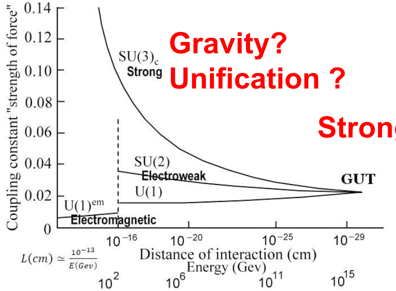
Higgs? alone? elementary?

Why 3 Gen?

Neutrino type? Dirac? Majorana?



Hierarchy Naturalness?



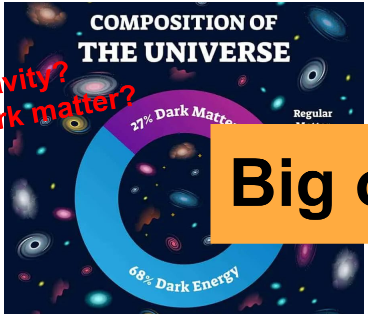
Gravity?
Unification ?

Strong CP?
etc…

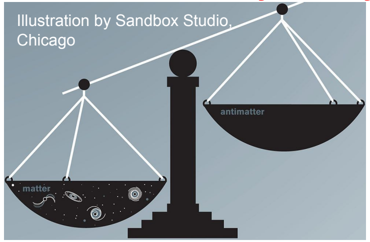
Big Open questions

Unknown Phenomena

Gravity?
Dark matter?



Matter-antimatter asymmetry?

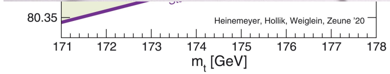


Neutrino mass?

Experimental results-SM misfits

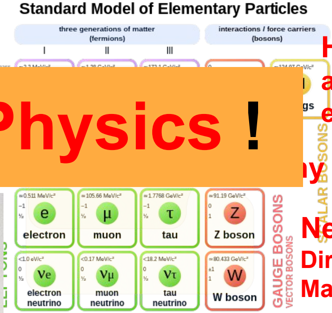
B-meson decays, Flavor Anomalies ?

Big opportunity to discover New Physics !

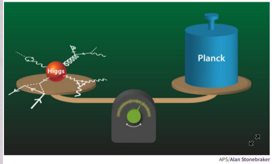


Theory question

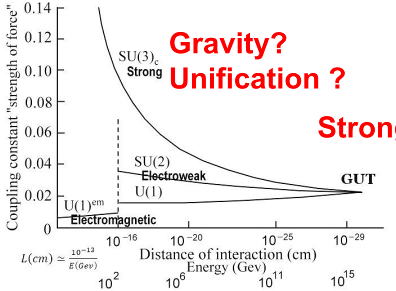
Too many SM parameters ?



Higgs?
alone?
elementary?
Why 3 Gen?
Neutrino type?
Dirac?
Majorana?



Hierarchy
Naturalness?

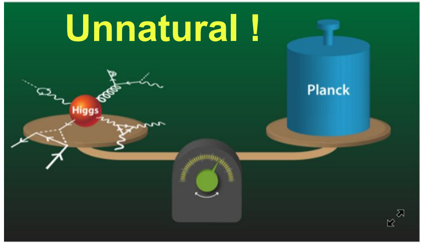


Gravity?
Unification ?

Strong CP?
etc…

New theoretical ideas and direction

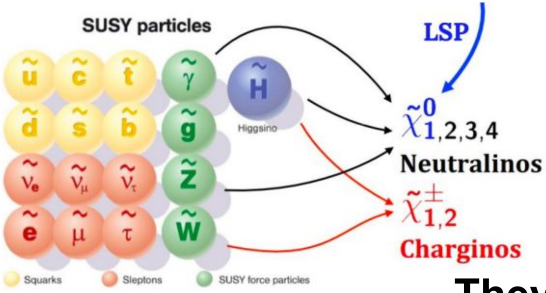
To solve Hierarchy problem,



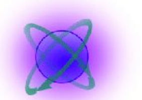
APS/Alan Stonebraker

$$\delta m_h^2 \sim \Lambda^2$$

Supersymmetry



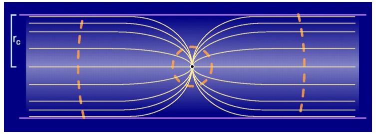
Compositeness


Composite Particle

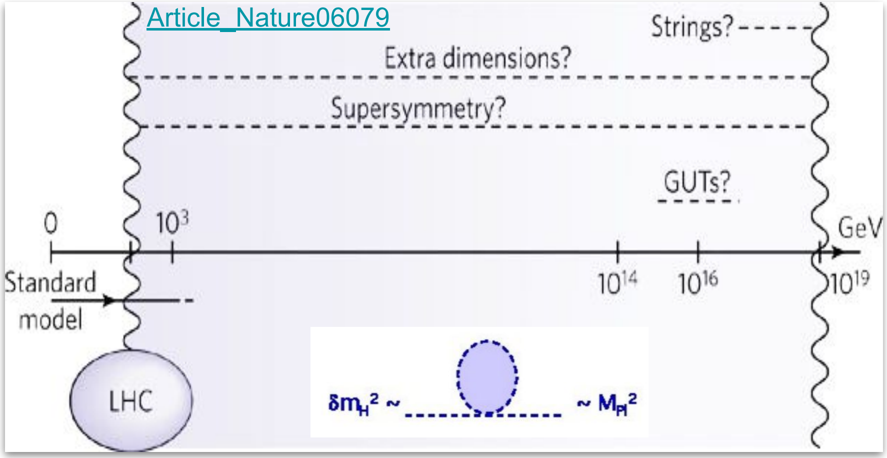
GUT

Many more…

Extra dimension



$$\Lambda_{wk} = M_{Pl}\, e^{-kr\pi}$$



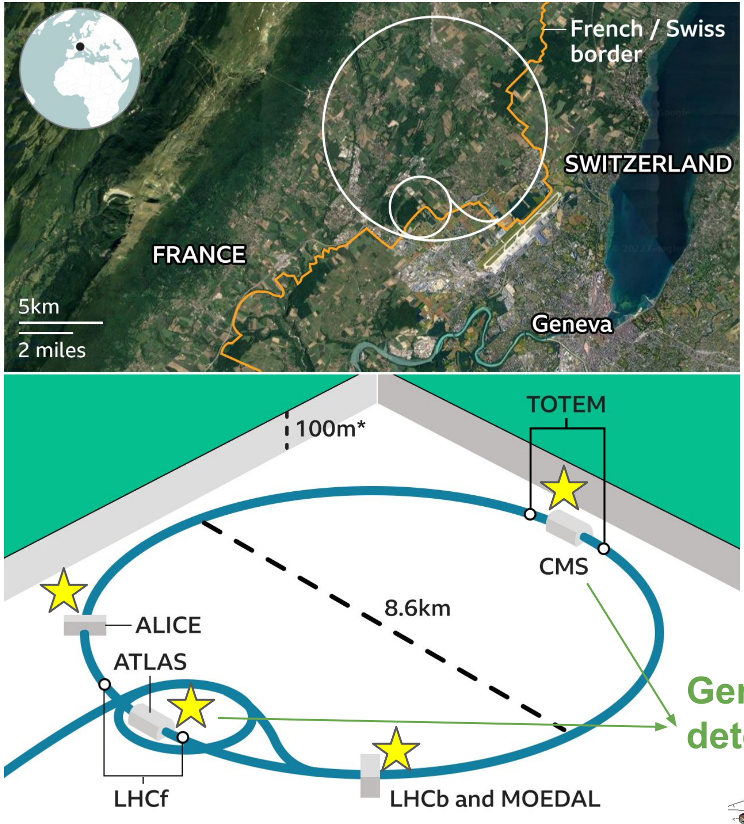
They predict new particles/interactions :

New interactions/Bosons
(Extended gauge sector V', Kaluza-klein V, Graviton, Leptoquarks, CI, ..)

New heavy quarks
(Excited quarks, Vector-like quarks, ..)

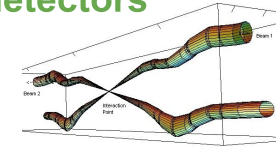
New heavy leptons/neutrinos
(Excited leptons, Vector-like leptons, heavy neutral lepton ..)

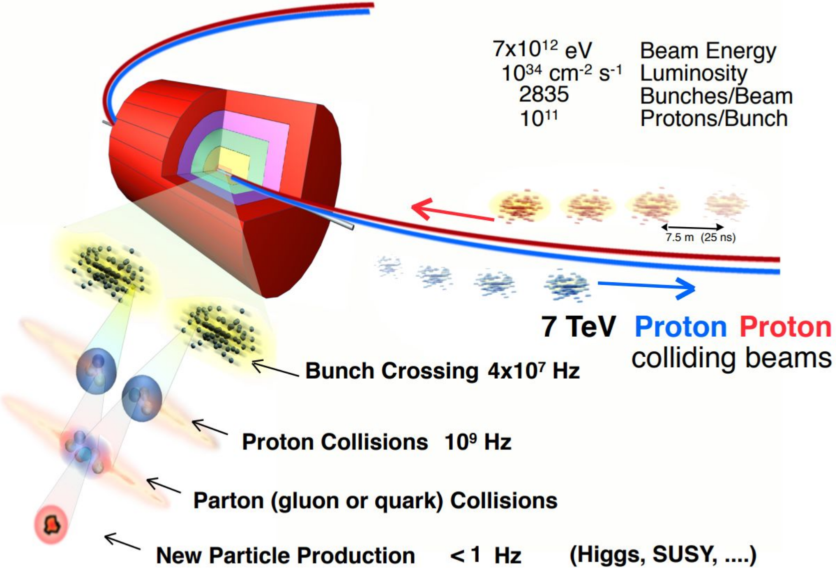
The Large Hadron Collider (LHC)



Source: CERN

General purpose detectors



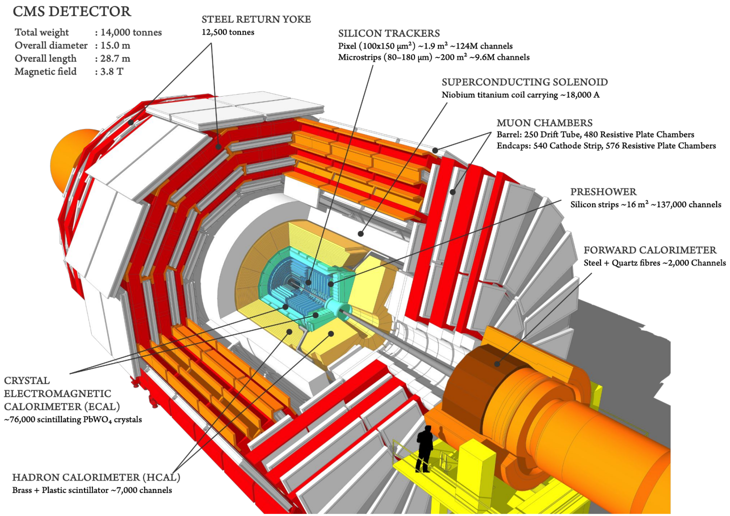


(Example) Rate : Run-2 (20Hz/nb)

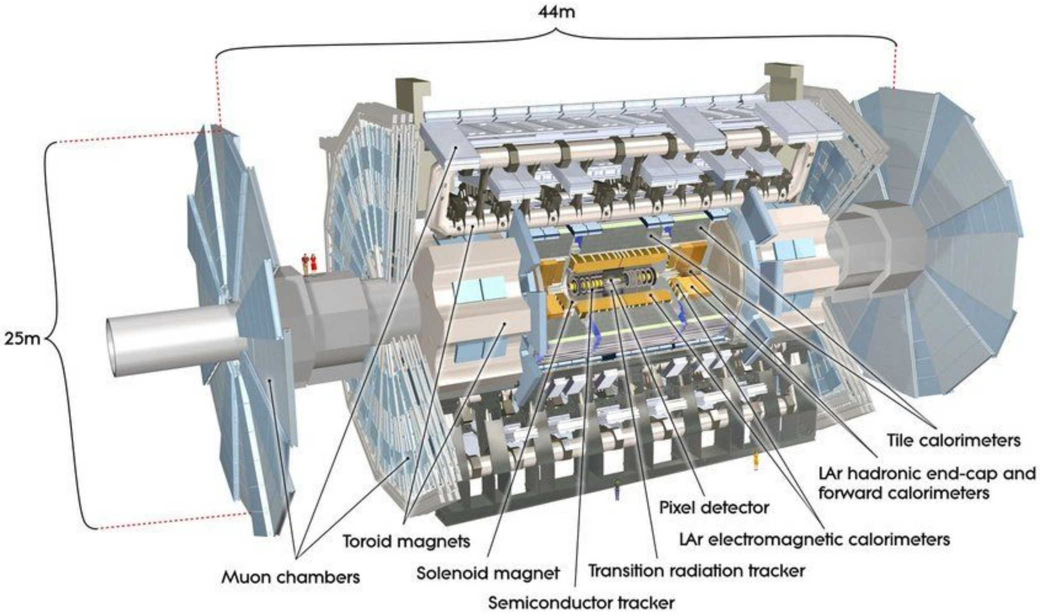
4000	W bosons/sec
1200	Z bosons/sec
17	ttbars/sec
1	Higgs bosons/sec

General Purpose Detectors at LHC

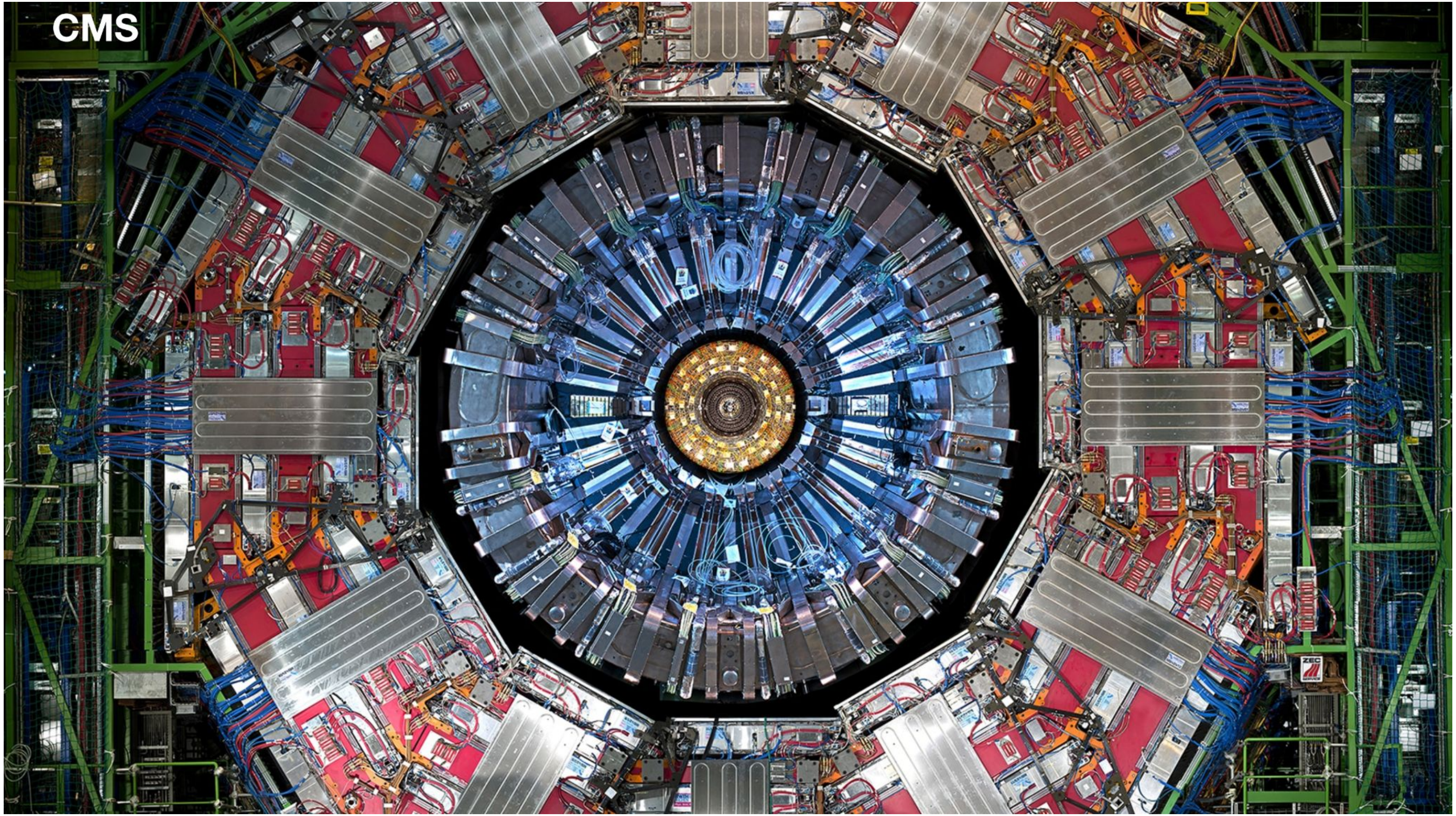
CMS
Compact Muon Solenoid



ATLAS
A Toroidal LHC Apparatus



Compact Muon Solenoid (CMS)



Data taking at LHC

LHC data taking

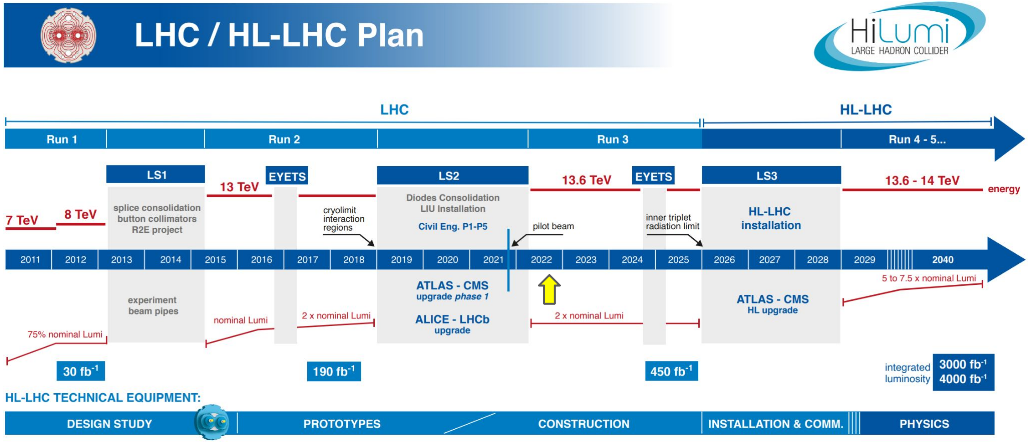
Run 1 : 7 TeV (2010-11), 8 TeV (2012)

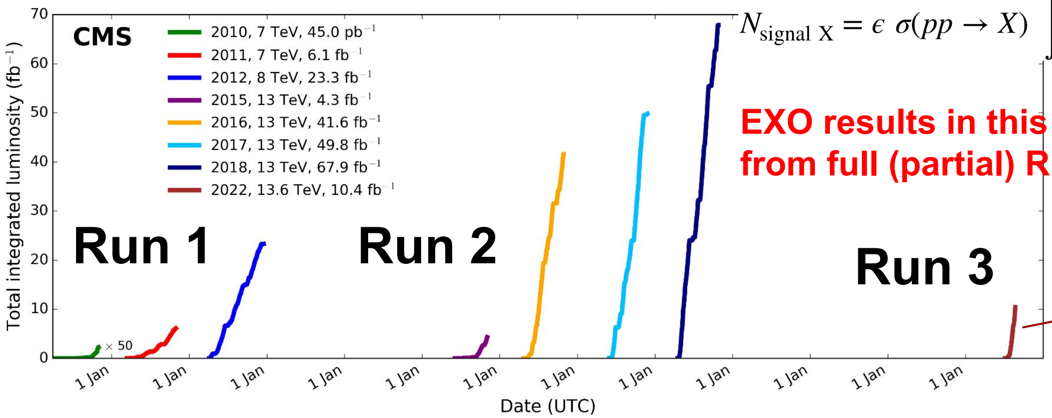
Run 2 : 13 TeV (2015-2018)

Run 3 : 13.6 TeV (2022-2025) ⇐ this July

High-Luminosity LHC (HL-LHC)

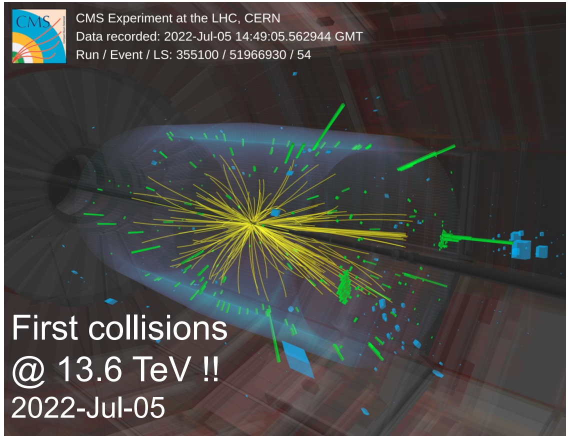
14 TeV (2029-42) 3000 fb^{-1}





$$N_{\text{signal X}} = \epsilon\ \sigma(pp \to X) \int dt\ \mathscr{L}$$

EXO results in this talk from full (partial) Run2 data

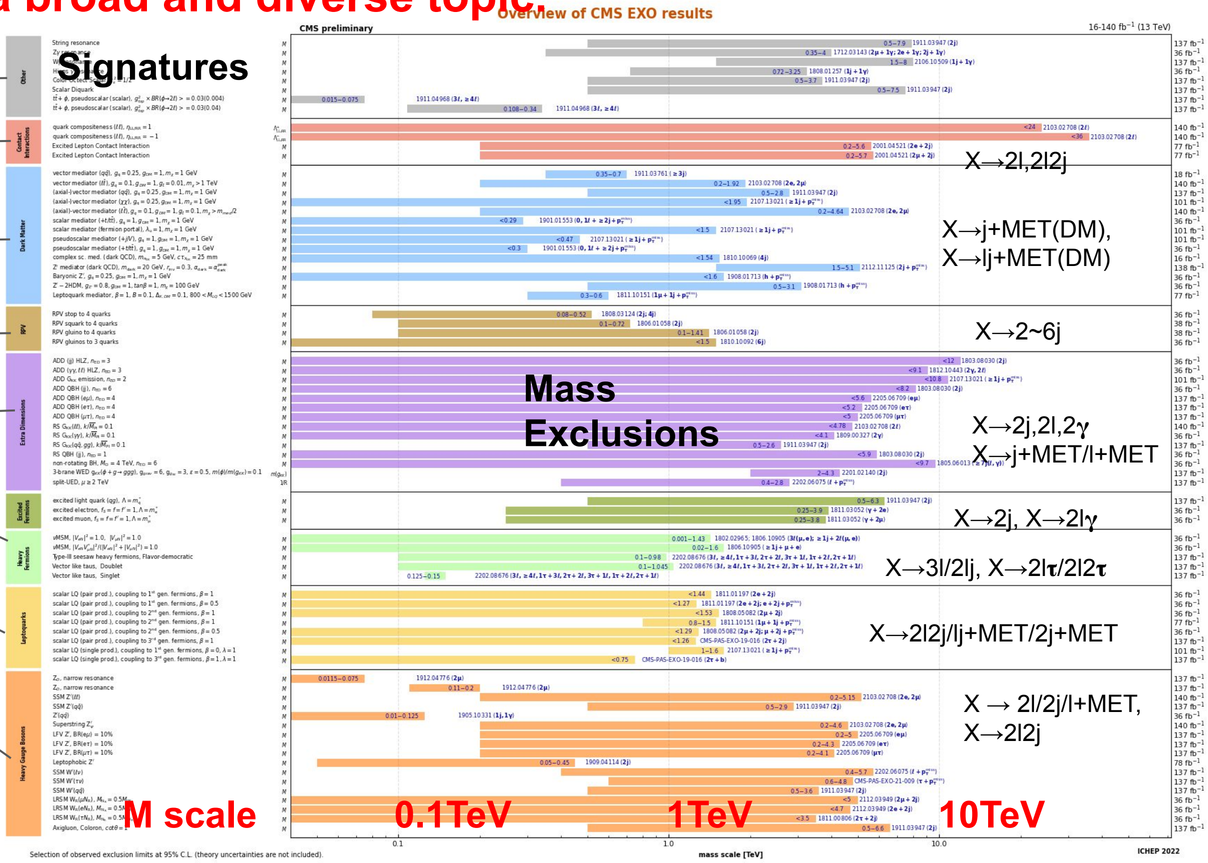


Overview of BSM searches at CMS

BSM program at the LHC has a broad and diverse topic.

BSM Model

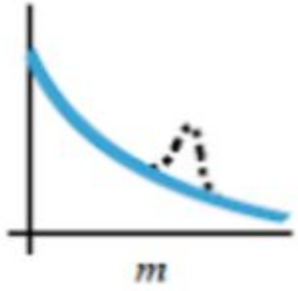
- Coloron/Diquark/…
- Contact Interactions
- Dark Matter
- R-Parity Violation
- Extra Dimensions
- Heavy Fermions
- Leptoquarks
- Heavy Gauge Bosons



In this talk, not cover large programs on Dark matter, SUSY, Long-lived particles

CMS EXO B2G SUSY public results   ATLAS EXOT HDBS SUSY public results   LHCb public results

Search Strategy

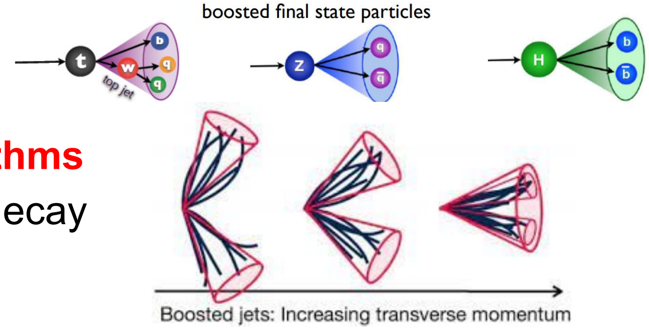


- **Target BSM signatures :**
  - New resonance will emerge at high mass spectra with various final states !
  - Single final state often can probes many BSM scenario,
    so analyses are mainly "**signature based**" :
    - Resonance search : dileptons, dijet, diboson (+lepton flavor violated, trijet, triboson .. etc)
  - Also, **Model-independent** result can be obtained and used to reinterpreted various models

- **Background Estimates :**
  - SM Backgrounds are evaluated with **Simulation**
  - Define **Control Region (CR)** in the data to evaluate a given SM background in most searches.
  - **Validation Regions (VR)** is used to cross-check a background method.

Advanced Identification algorithm

- **Jet Tagging technique :**
  - Exploiting the latest **jet substructure** and novel **ML algorithms**
  - Heavy resonances can produce **highly Lorentz boosted** decay products W/Z/H-tagged jet, t/b/q/g-tagged jet.



Soft drop algorithm

Removes soft and wide-angle radiation

$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0} \right)^{\beta}$$

N-subjettiness

Compatibility of a jet with having N-prong substructure

$$\tau_N = \frac{1}{d_0} \sum_i p_{\mathrm{T},i} \min \left[\Delta R_{1,i}, \Delta R_{2,i}, \ldots, \Delta R_{N,i} \right]$$

τ_2/τ_1 : 2-prong jet (W/Z like) τ_3/τ_2 : 3-prong jet (top-like)

Deep Learning Based algorithm at CMS:

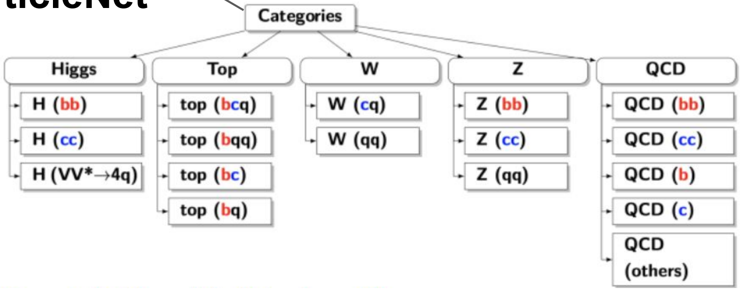
- DEEPJET
- CNN (ImageTop)
- **DEEPAK8**
- **ParticleNet**

…

JINST15(2020)P12012

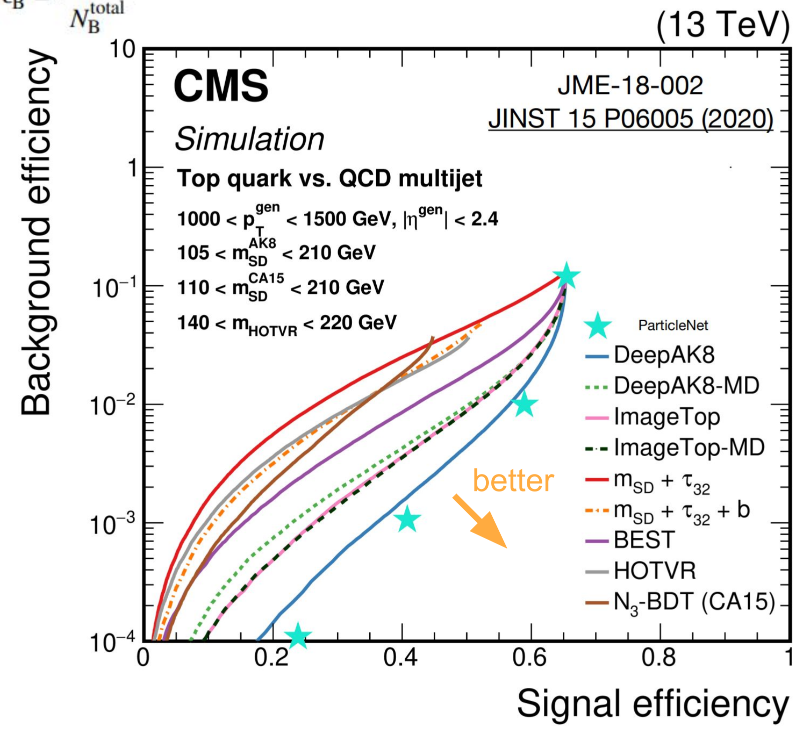
JINST15(2020)P06005

PR(2020)841



Jet Tagging evolution in CMS

$\epsilon_B = \frac{N_B^{tagged}}{N_B^{total}}$



$\epsilon_S = \frac{N_S^{tagged}}{N_S^{total}}$

Evolution (More Sophistication)

m_{SD}, τ_{32} , b
HOTVR → Traditional Jet Substructure

N_3-BDT → Boosted Decision Tree based

Boosted Event Shape Tagger (BEST) → Deep Neural Net (DNN) based

DeepJet
DeepAK8
ImageTop → Convolutional NN based

1D Convolutional neural network (CNN)
Mass decorrelated (MD) DeepAK8

ParticleNet → Graph NN based

Jet represented as “particle cloud”
Mass-decorrelated ParticleNet

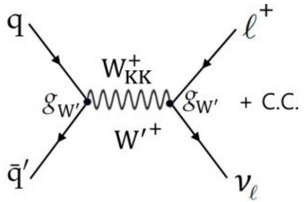
Search for New Force carriers/Boson

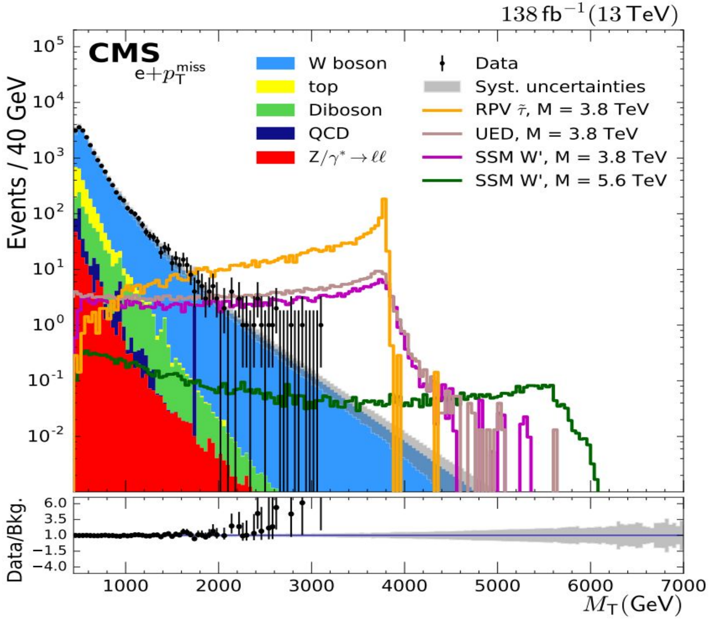
Spin-1 **W'/Z'**	in many model; Sequential Standard Model (SSM), Heavy Vector Triplet Model (HVT), composite Higgs model
Spin-2 **Graviton (G)** Spin-0 **Radion (ϕ)** Spin-1 **W_{KK}**	in extra dimension model (ED)
Spin-0 **h, H, $H^{\pm}$, A**	in the extended higgs sector introduce additional higgs 2 Higgs doublet model (2HDM), SUSY
Spin-0/1 **leptoquarks**	Possible explanation for flavor anomalies (B meson decay, muon g-2)
Spin-0 **Axion-like particle**	Possible solution to Strong-CP problem (DM candidate)

Heavy gauge boson W'→lν Search (1/5)

JHEP07(22)067

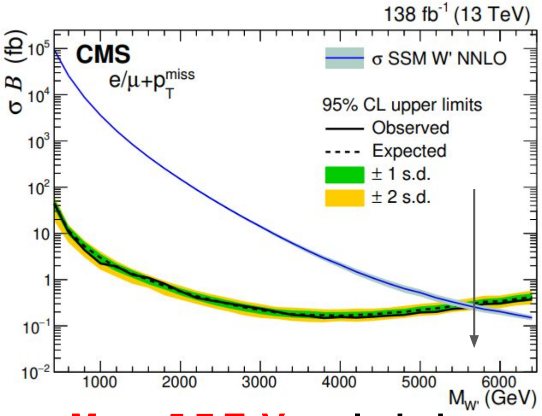
- Golden channel : High p_T l (e or mu) and p_T^{miss}
  - Search for excess in high M_T tail
  - Target BSMs : SSM, sUED model, RPV SUSY





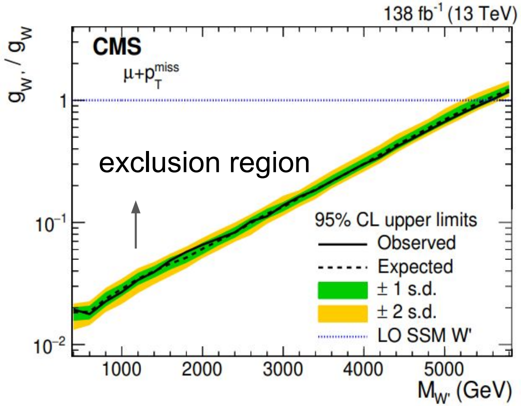
$$M_T = \sqrt{2p_T^\ell p_T^{miss}(1-\cos[\Delta\phi(\vec{p}_T^{\,\ell}, \vec{p}_T^{\,miss})])}$$

SSM W' benchmark Limit
(SM like $g_{W'} = g_W$)



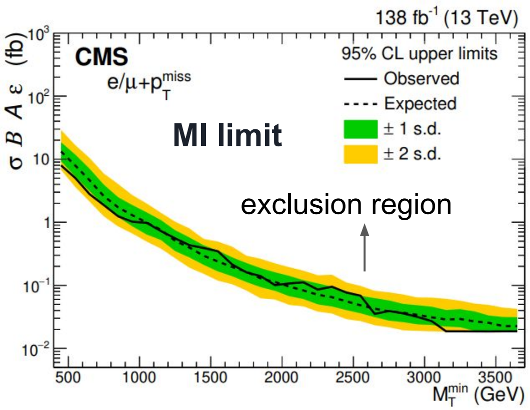
$M_{W'}$ < 5.7 TeV excluded
for e+μ channel

SSM W' Coupling Limit
($g_{W'}$/ g_W : 0.01 - 3)



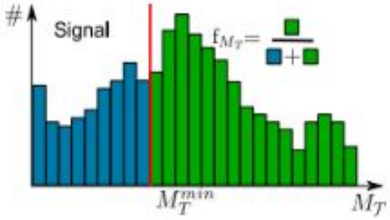
$g_{W'}/g_W$ > 0.03 excluded
($M_{W'}$ = 1 TeV)

Model independent Limit and application (2/5)



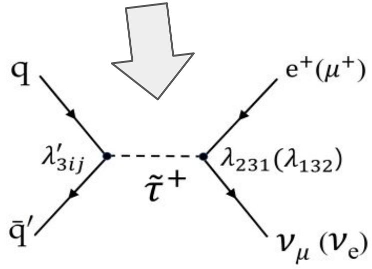
$(\sigma BA\varepsilon)_{excl}$ ranges 0.02 - 10 fb
M_T^{min} edge ranges 0.45 - 3.6 TeV

Using a single bin counting experiment ranging from M_T^{min} to infinity.
Limit on $(\boldsymbol{\sigma}BA\varepsilon)_{excl}$ can be used to test other BSM having same l+p_T^{miss} signature ;
$(\sigma\mathcal{B})_{theo} > (\sigma\mathcal{B})_{excl}$ can be exclude!

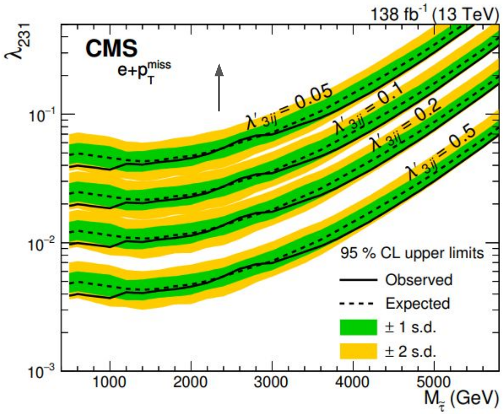


$$[\sigma\mathcal{B}\mathcal{A}\epsilon]_{excl}(M_T^{min}) = \frac{[\sigma\mathcal{B}\mathcal{A}\epsilon]_{MI}(M_T^{min})}{f_{M_T}(M_T^{min})}$$

Application to RPV SUSY model



scalar tau → l+p_T^{miss}



Test with 3 model parameters
M_{stau} : 0.4 - 6 TeV
Coupling λ'_{3ij}(production vertex) : 0.05 - 0.5
Coupling λ_{231}, λ_{132}(decay vertex) : 0.001 - 0.5

(ex) if M_{stau} =1 TeV, λ'_{3ij} =0.5
λ_{231}> 0.004 for eν,
λ_{132} > 0.005 for μν are excluded

First EFT Interpretation with lν data (3/5)

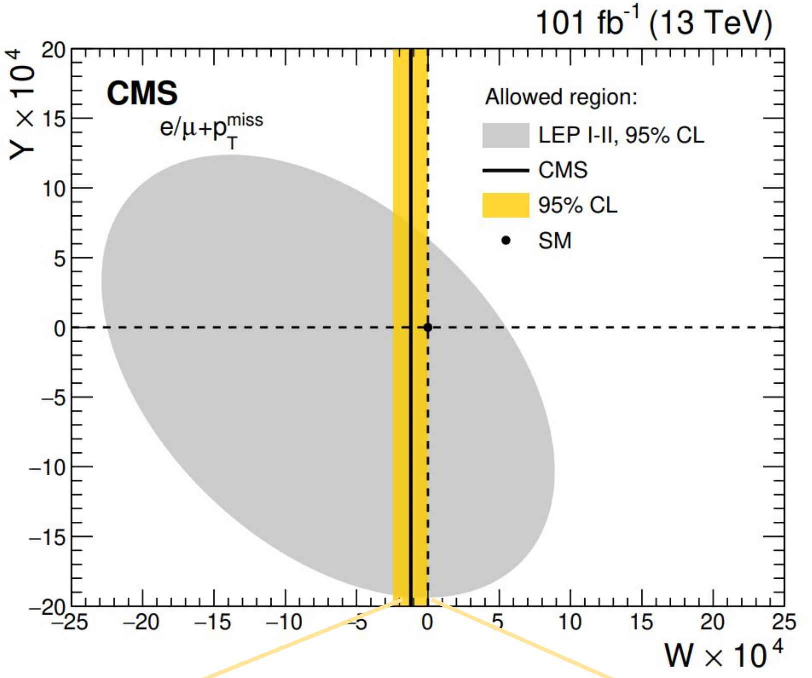
New

Indirect search in effective field theory (EFT)
NP can induce universal effect on SM predictions : the oblique EW parameters; S, T, W and Y.
Parameterizing in the framework of **EFT**

NP weight
$$\left|\frac{P_W}{P_W^{(0)}}\right|^2 = \left(1 + \frac{(2t^2-1)W}{1-t^2} + \frac{t^2 Y}{1-t^2} - \frac{W(q^2 - m_W^2)}{m_W^2}\right)^2$$

This is the first time using LHC data to constraint on *W* oblique parameter in $\ell\nu$ channel.

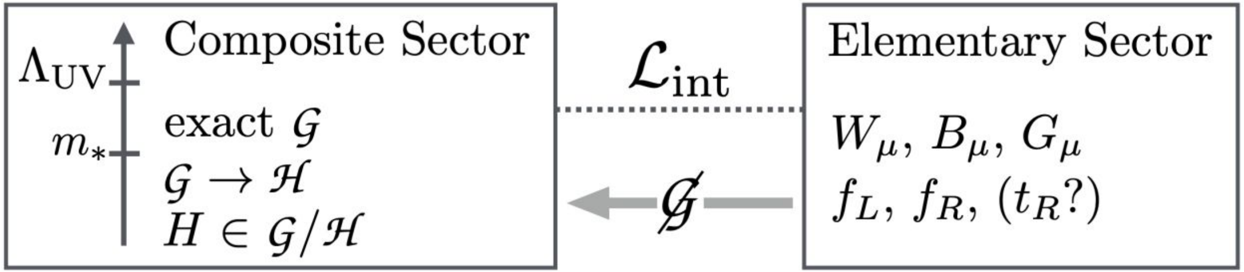
Significantly improving the constraint obtained from LEP data (gray).

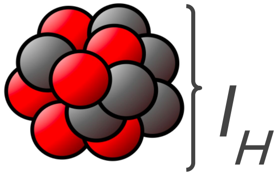


Most stringent to date! : $W = -1.2^{+0.5}_{-0.6} \times 10^{-4}$

Composite Higgs Model (4/5)

The basic structure of the composite Higgs scenario



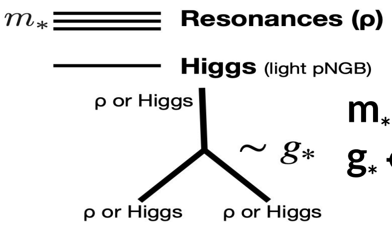


[arxiv:1506.01961](https://arxiv.org/abs/1506.01961)

JHEP06(2007)045

- ➔ Composite sector + Elementary sector (SM quarks, leptons, gauge bosons, no Higgs)
- ➔ Higgs boson = pseudo Nambu-Goldstone boson of broken symmetry
- ➔ It allows Higgs boson to be considerably lighter than confinement scale confinement scale m_*
- ➔ If EWSB effects small (m_* would be ~1 TeV or above)

Predicted new particles!
Additional heavy vector bosons from composite sector dynamics (analogs of **ρ** meson in QCD) and scalars



$m_* \simeq 1 / l_H$

$g_* \in [1, 4\pi]$

First Interpretation the Composite Higgs Model (4/5)

New

Exploiting Important interplay between **direct W' (coupling) limits** and **indirect constraints** from precise **Higgs measurements** and **EW *W* parameter**.

Set new constraints on composite Higgs model parameter (m*-g*) :

Direct search for **W' in SSM and HVT** models

$$g_{W'} = \frac{g^2}{g_*}$$

kinematically limited by the √s

Indirect constraint on **oblique *W* parameter**

$W = -1.2^{+0.5}_{-0.6} \times 10^{-4}$

$$g_*^2 = \frac{g^2 M_W^2}{W m_*^2}$$

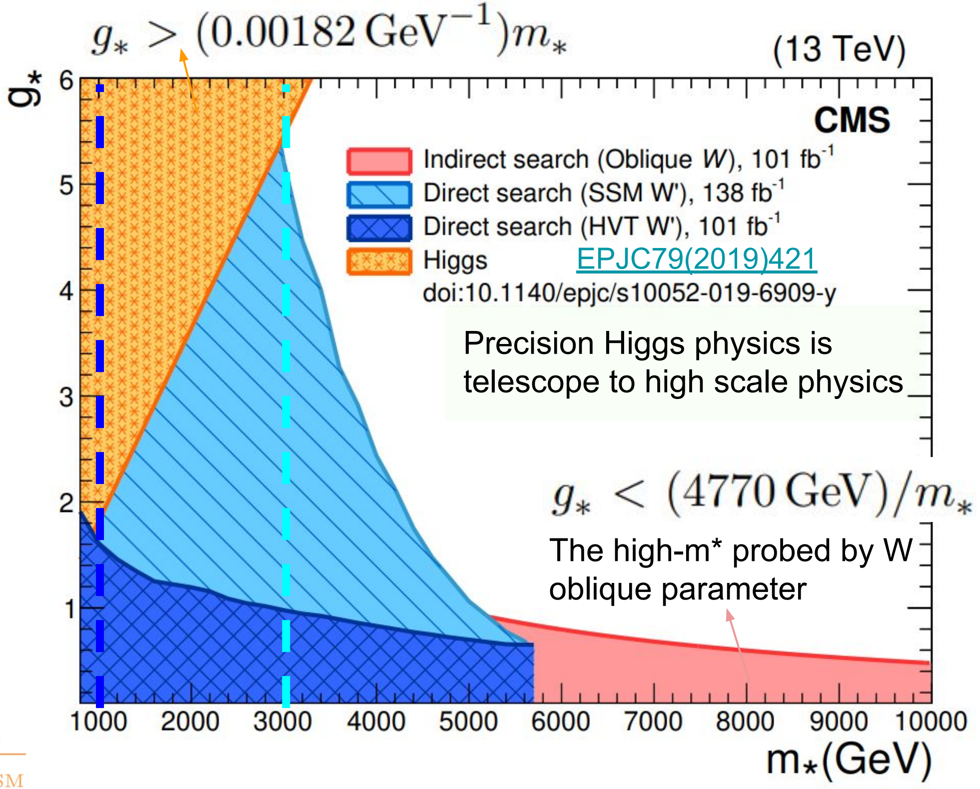
Indirect constraint on **Higgs measurement**

$\Delta\mu_H < 0.20$ at 95% CL

$$\Delta\mu_H = \frac{g_*^2 v^2}{m_*^2}$$

$$\mu = \frac{\sigma \cdot BR}{(\sigma \cdot BR)_{SM}}$$

Nature 607,60-68 (2022)



m_* < 3 (1) TeV excluded @95%CL the **SSM** (**HVT**) W' assumption.

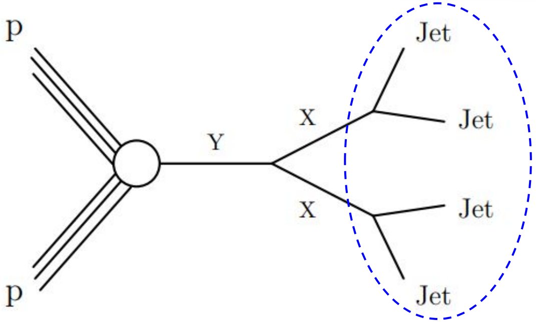
Paired-dijet Search (1/4)

CMS-EXO-21-010
arxiv:2206.09997

Resonant

$$pp \to Y \to XX \to (jj)(jj)$$

$$uu \to S \to \chi\chi \to (ug)(ug)$$

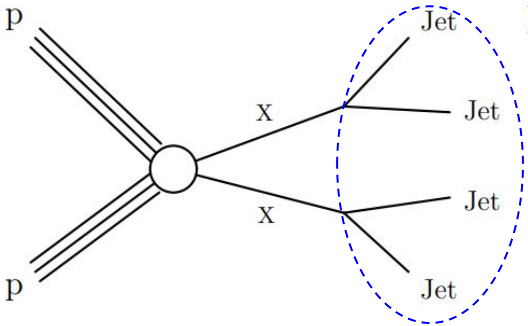


diquark model

Non-resonant

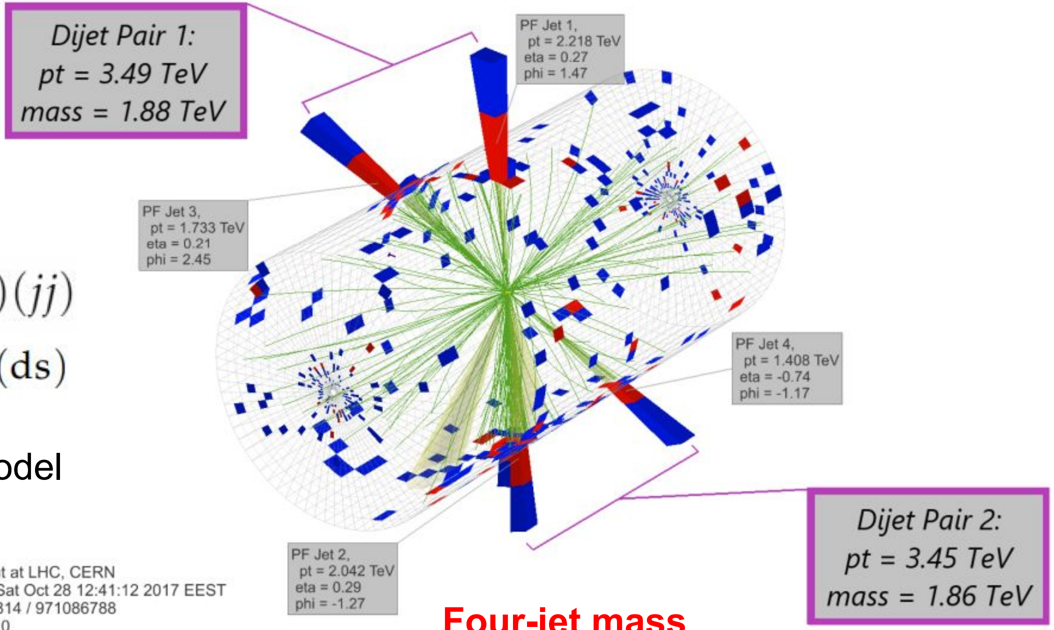
$$pp \to XX \to (jj)(jj)$$

$$pp \to \tilde{t}\tilde{t}^* \to (\bar{d}\bar{s})(ds)$$



RPV SUSY model

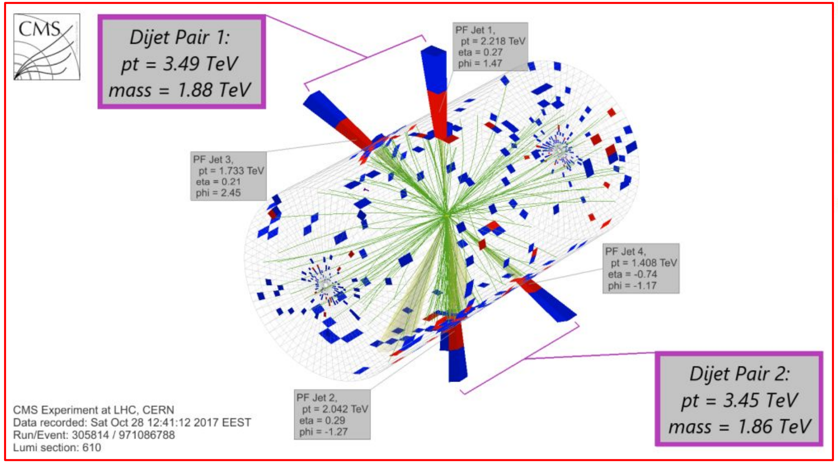
First signatures to explore

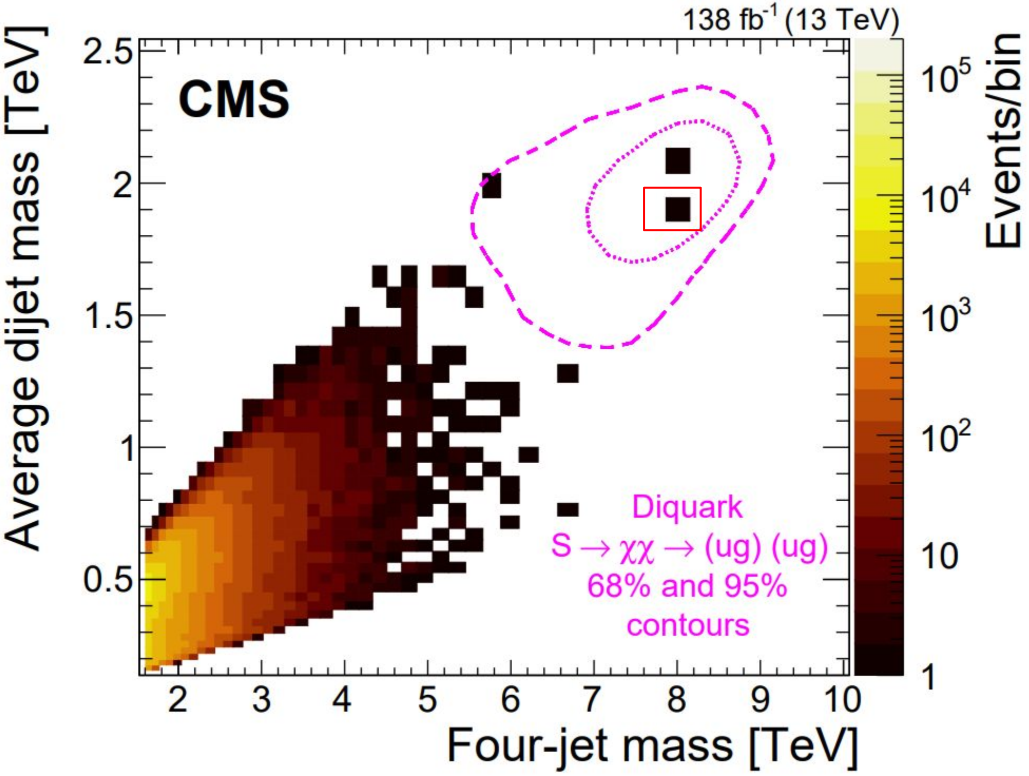


CMS Experiment at LHC, CERN
Data recorded: Sat Oct 28 12:41:12 2017 EEST
Run/Event: 305814 / 971086788
Lumi section: 610

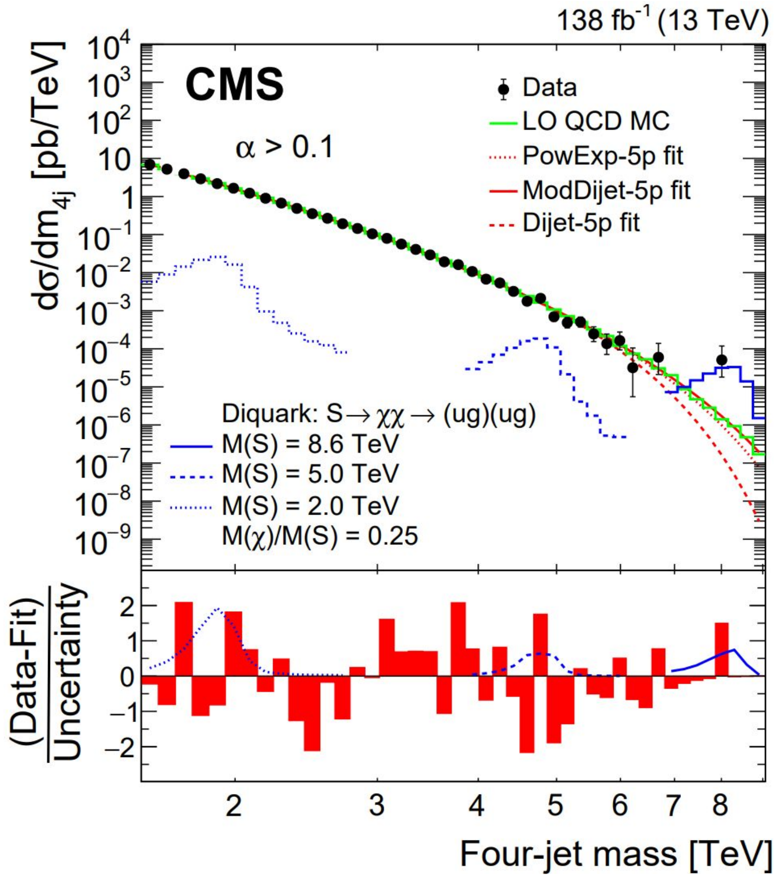
Four-jet mass 8 TeV

- Optimal **dijet pairing** with **small** $\Delta R^{pair}<2.0$, $\Delta\eta^{pair}<1.1$, $M_{Asym}<0.1$
- Background-fit in various α bins = $<m_{X=jj}>/m_{Y=4j}$
  (Scan various α bins)



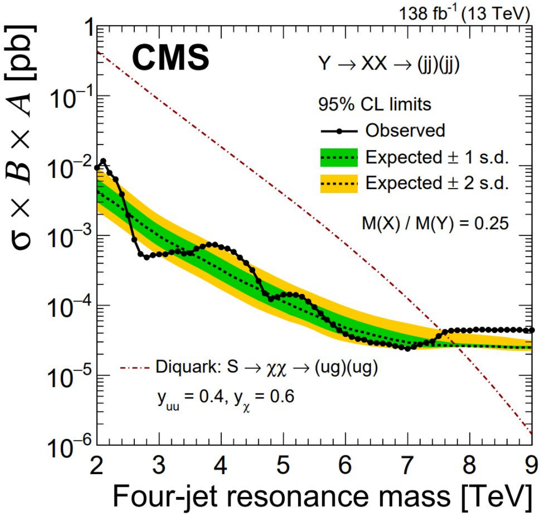


Paired-dijet Search (3/4)



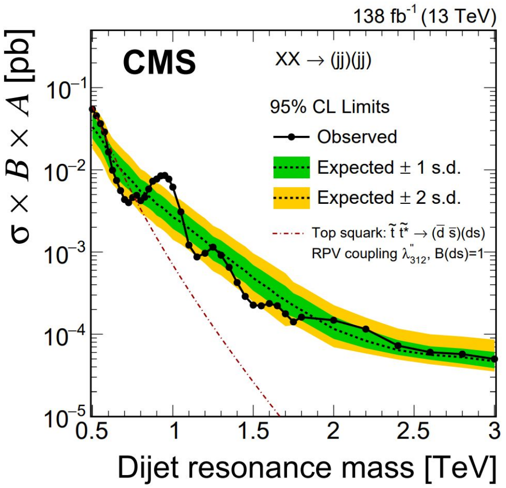
Scan α value (Avg. mass of the 2 dijets divided by the four-jet mass)

$$uu \to S \to \chi\chi \to (ug)(ug)$$

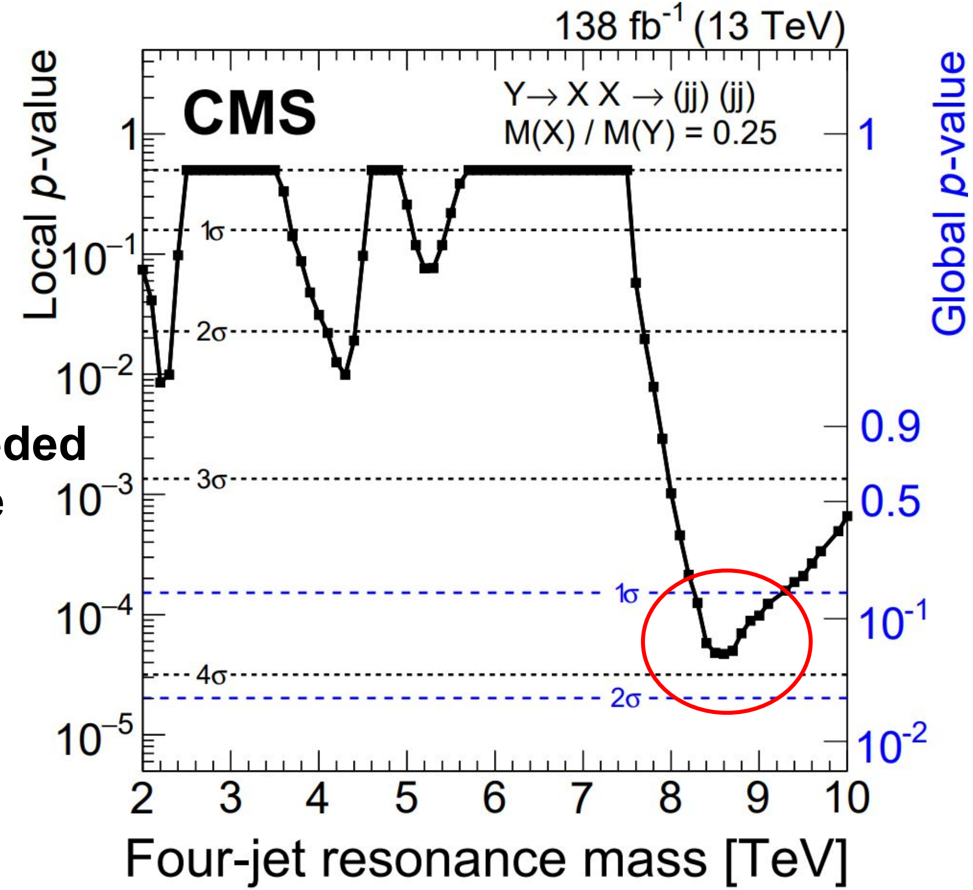


First model independent cross section upper limit at 95% CL

$$pp \to \widetilde{t}\widetilde{t}^{*} \to (\bar{d}\bar{s})(ds)$$



First paired-dijet resonances Search (4/4)



New

More data are needed to establish if these events are the first hints of a signal !!

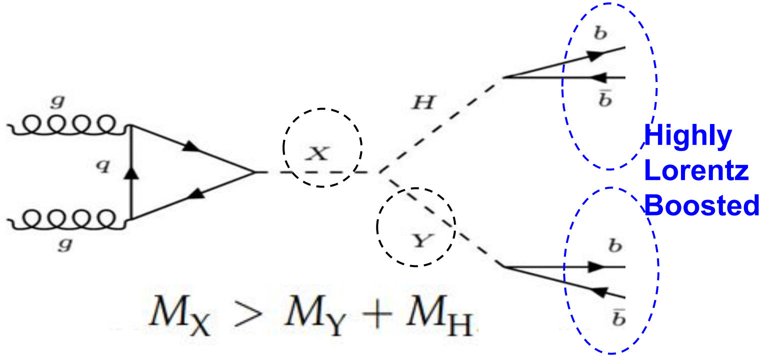
Resonant mass Local 3.9 σ

@ 4-jet Mass = 8.6 TeV dijet Mass = 2.15 TeV

Heavy resonance $X \rightarrow Y(bb)H(bb)$ Search (1/3)

CMS-B2G-21-003, arxiv:2204.12413

Search for **2 new scalars** (X, Y) in 4b
Motivated from NMSSM Higgs scalars model



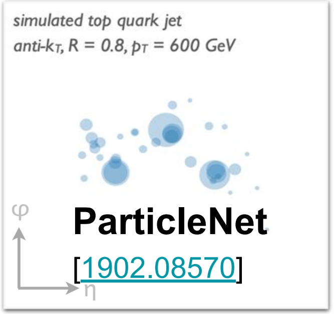
- **2 large-R b-pair jets from Y and H**
- $M_J(H)$: 110 - 140 GeV , $M_J(Y)$ > 60 GeV
- To increase signal sensitivity, special techniques are used to reconstruct the final states containing **the collimated bb pairs**

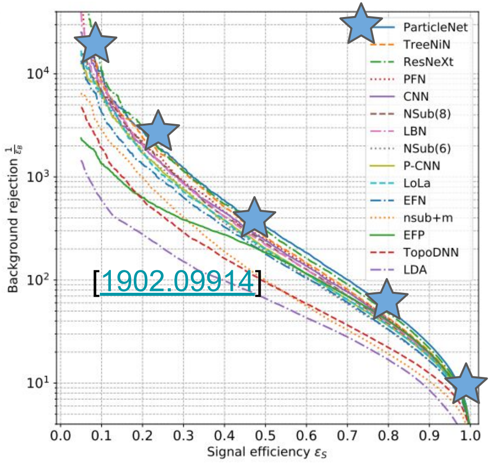
New jet substructure tool; ParticleNet

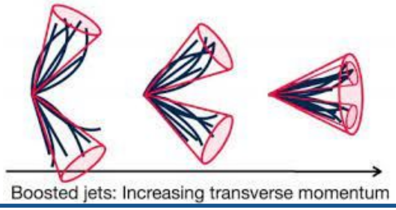
jet as kind of “particle cloud”, clustered to get information

ParticleNet is the state of art :
a GNN trained on jet particles that outputs
a classifier score for different signal jets.

New

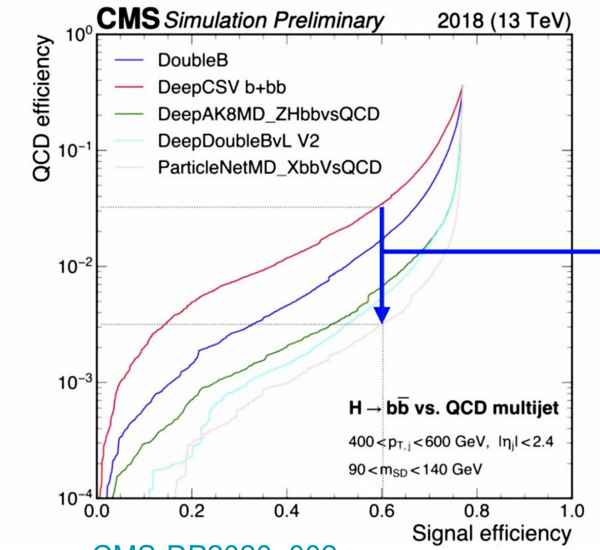






Boosted Boson tagging techniques :ParticleNet (2/3)

ParticleNet used for **tagging bb jets**

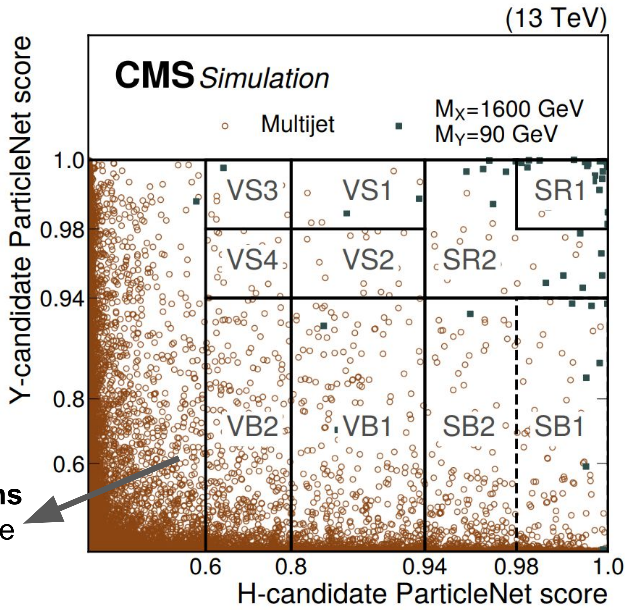


CMS-DP2020_002

Background rejection power 10 times increasing !

Event categorization based on **bb-tagging score**

$$P(\mathrm{R} \to \mathrm{b\bar{b}}) / (P(\mathrm{R} \to \mathrm{b\bar{b}}) + P(\mathrm{QCD}))$$

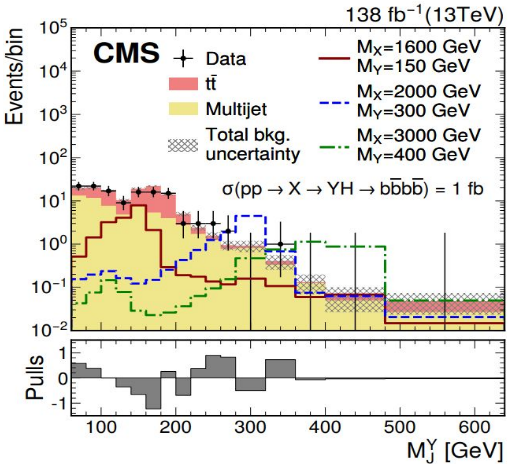


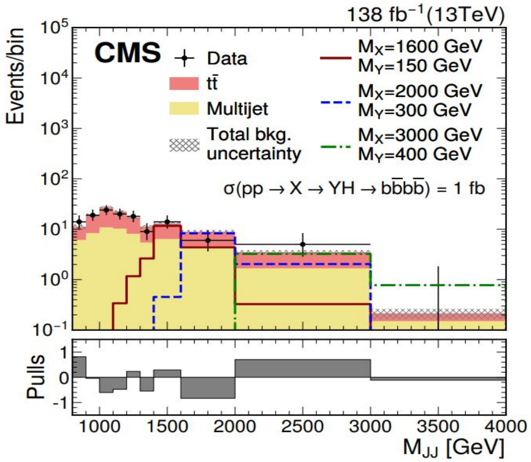
Signal Region (SR) has a ParticleNet tagger selection on both jets.

Sidebands (SB) used to estimate multijet background

Validation Regions used to validate the background estimation method

Heavy resonance $X \rightarrow Y(bb)H(bb)$ Search (3/3)





- 2D fit to (M_X - M_Y) in SR, SB, M_J(top) to estimate SM backgrounds.

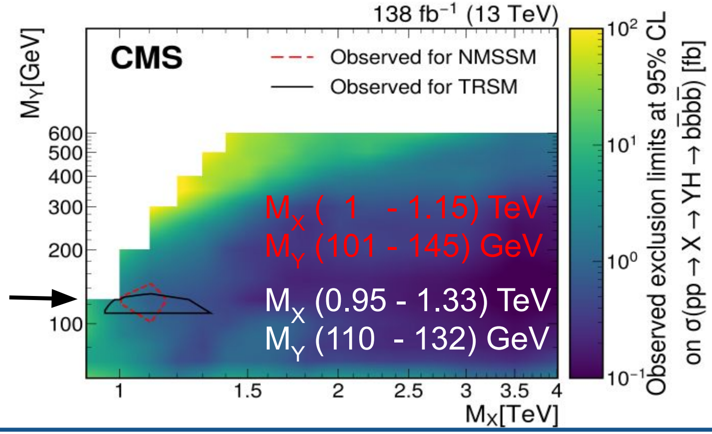
  Multijet background

  estimated in SRs "Pass to Fail Ratio"

  ttbar background

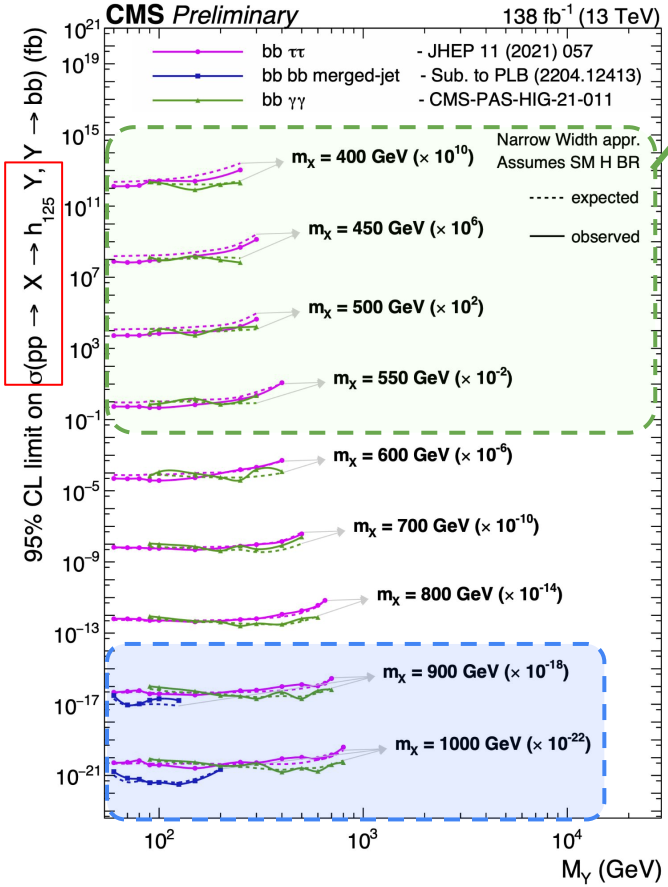
  estimated l+ 1 bjet + ptmiss + large-R jet (3 categories : bqq, bq, other)

  M_J(top) is fit to data with all-jet categories.



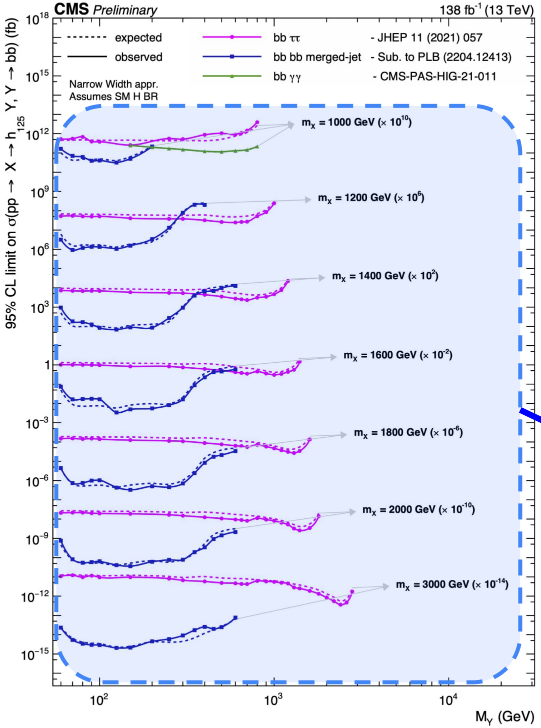
- Model-independent limit is interpreted in the NMSSM, TRSM.
- If M_Y= M_H (125 GeV), $\sigma_X \cdot B(H \rightarrow bb)$ ~ 5e-2 fb
- Factor 2 improved than previous HH→bbbb CMS result (ParticleNet)

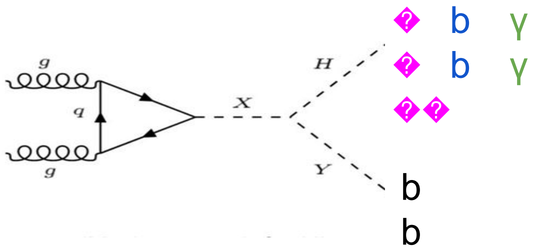
$X \rightarrow YH$ Complementary Sensitivity



Y(bb)H(γγ) channel
most sensitive for Mx < 600 GeV

CMS SummaryResultsHIG

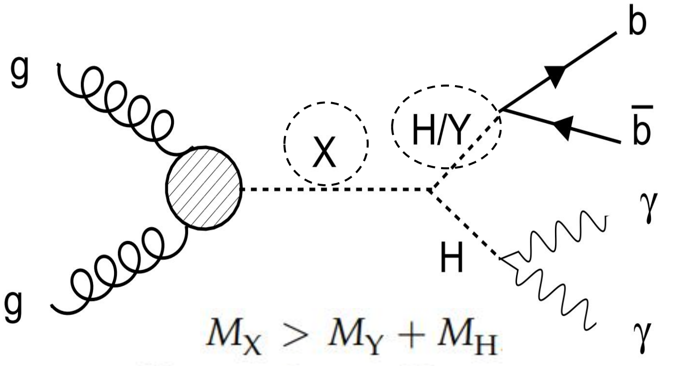




Y(bb)H(bb) channel
most sensitive for high Mx > 1 TeV

Heavy resonance $X \rightarrow Y(bb)H(\gamma\gamma)$ Search (1/3)

CMS-HIG-21-011

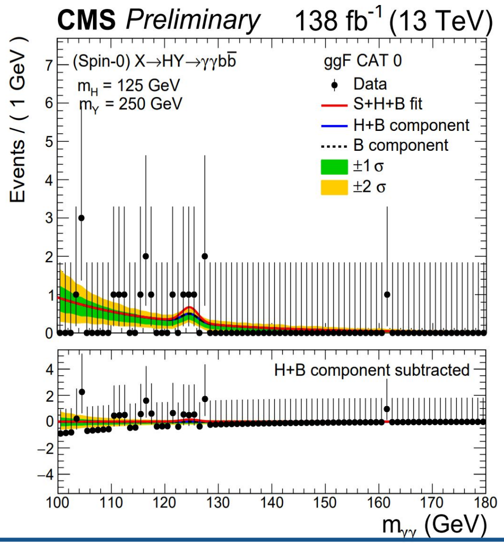


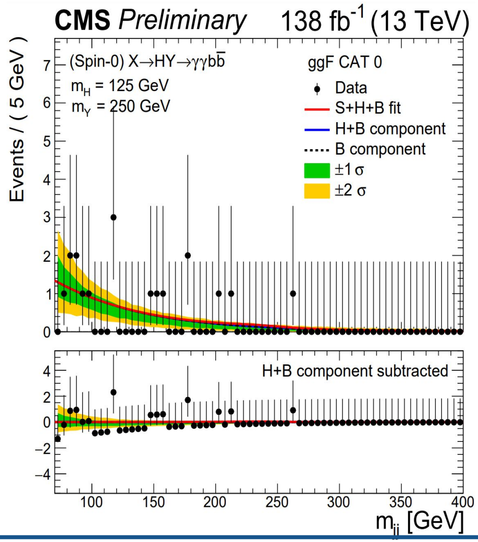
Signal identified with Neural Network (NN) training, Boosted Decision Tree (BDT) using b-jet ID, photon ID and kinematic variables.
Extract signal from 2D fit (M_Y-M_H) in window of $\tilde{M}_X$.

$$\tilde{M}_X \equiv m_{\gamma\gamma jj} - m_{\gamma\gamma} - m_{jj} + m_H + m_{H,Y}$$

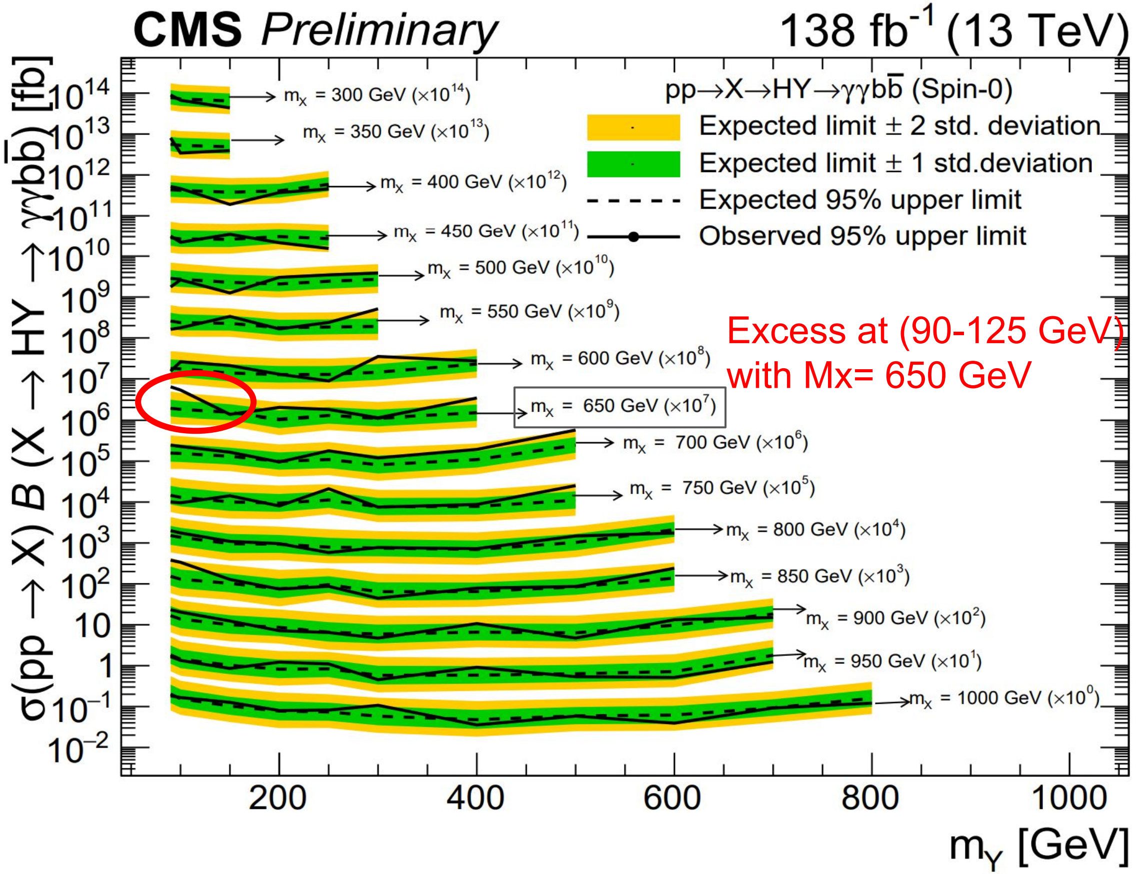
New

First time looking at NMSSM and TRSM ($X \rightarrow YH$) motivated searches also RS bulk ED ($X \rightarrow HH$).
X = Bulk Radion or KK Graviton





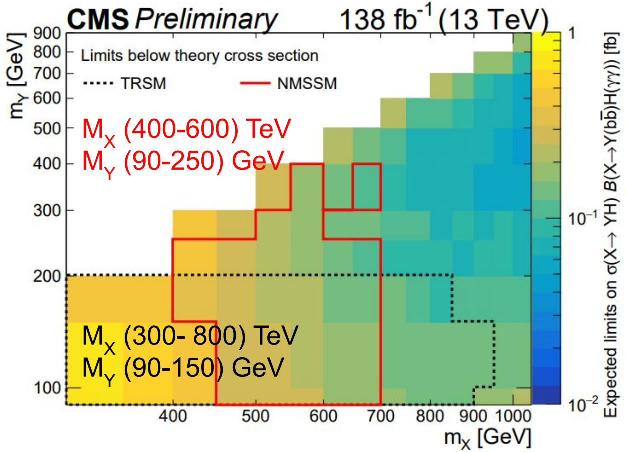
Heavy resonance $X \rightarrow Y(bb)H(\gamma\gamma)$ Search (2/3)



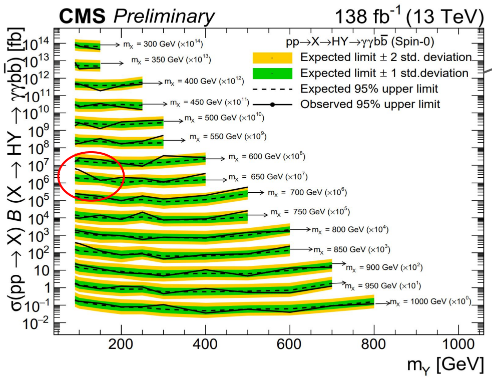
M_X = 650 GeV, M_Y = 90-125 GeV

Local 3.8σ, Global 2.6σ (M_Y < 150 GeV)
3.5σ (M_Y = 100 GeV)

Obs. Limits on the NMSSM and TRSM



Hints for New physics with Higgs (3/3)

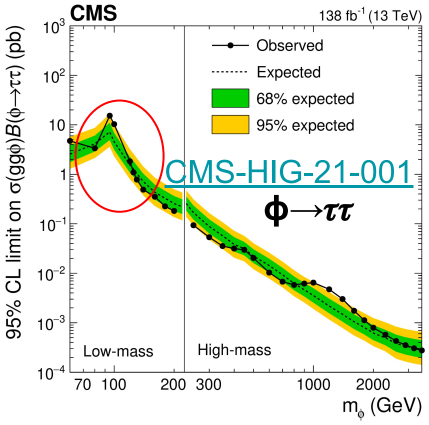


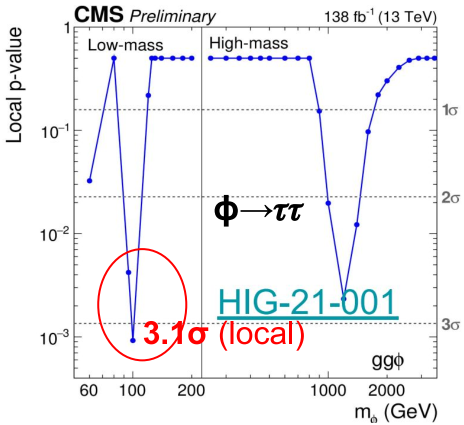
Heavy resonance X→H(bb)Y(γγ);
Excess 3.8σ (local), 2.8σ (global) at **M_Y = 90-125 GeV, M_X = 650GeV**

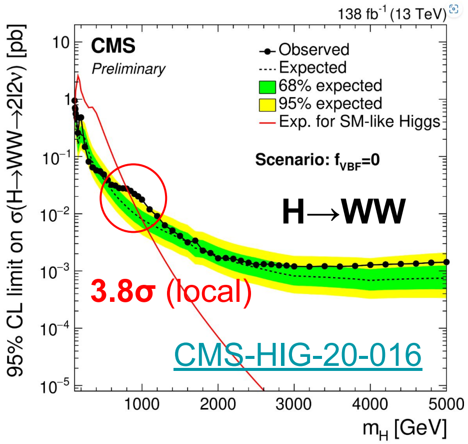
Interesting excess with Higgs observed from CMS :

H(ϕ)→ττ; **excess 3.1σ** (local), 2.7σ (global) at M_ϕ = **90-100** GeV CMS-HIG-21-001
H→WW ; **excess 3.8σ** (local), 2.6σ (global) at M_H = **650** GeV CMS-HIG-20-016
H→γγ ; **excess 2.8σ** (local), 1.3σ (global) at M_H = **95** GeV CMS-HIG-17-013

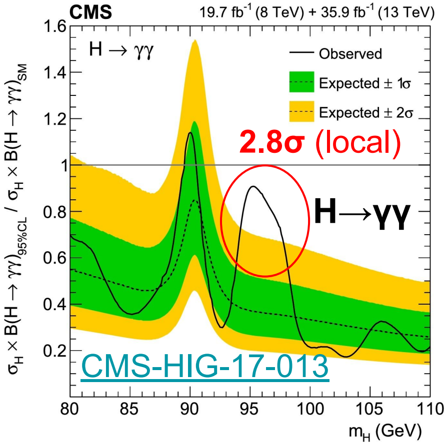
More data are needed to find out the origin !





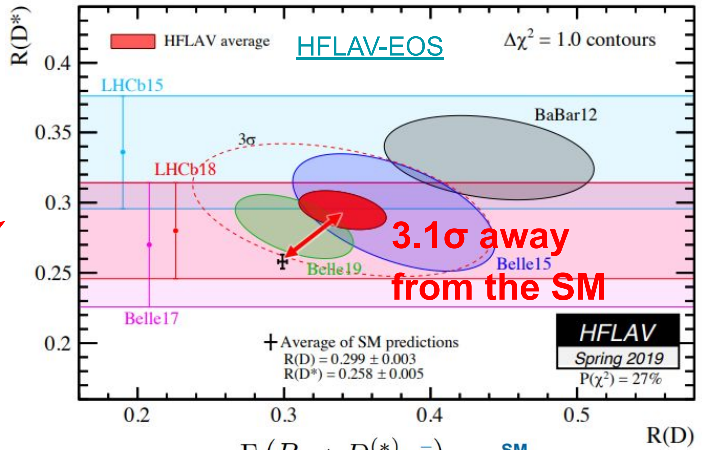


Phys. Lett. B 793 (2019) 320



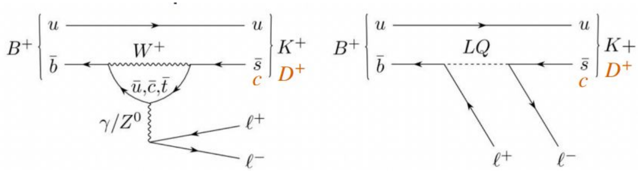
Leptoquarks (LQ)

- Leptoquarks can couple to both leptons and quarks
  - Both **scalar** and **vector** bosons are possible.
- Carry fractional electric charge
- Processes can violate lepton flavor universality (LFU)
  - Possible hints for **Flavor-anomalies in B decays**
  - strongly couple to **3rd generation SM fermions**
- Predicted in RPV SUSY, GUTs and Composite models.

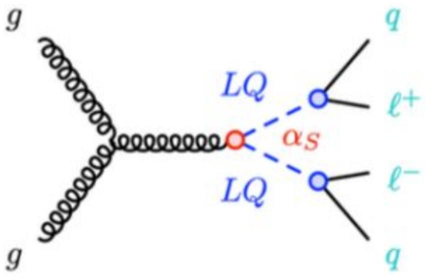


$$R_{D^{(*)}} = \frac{\Gamma\left(B \to D^{(*)}\tau\bar{\nu}\right)}{\Gamma\left(B \to D^{(*)}\ell\bar{\nu}\right)} \overset{\text{SM}}{>} 0.25$$

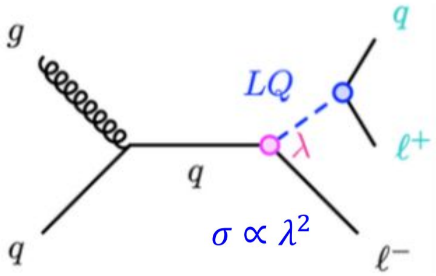
$$R_{K^{(*)}} = \frac{\Gamma\left(B \to K^{(*)}\mu\mu\right)}{\Gamma\left(B \to K^{(*)}ee\right)} \overset{\text{SM}}{<} 1$$



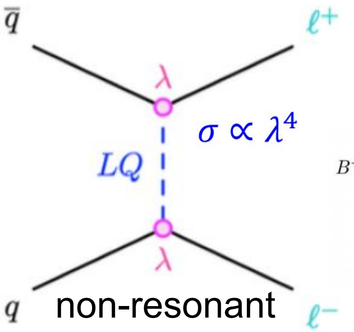
Pair LQ



Single LQ



LQ mediator



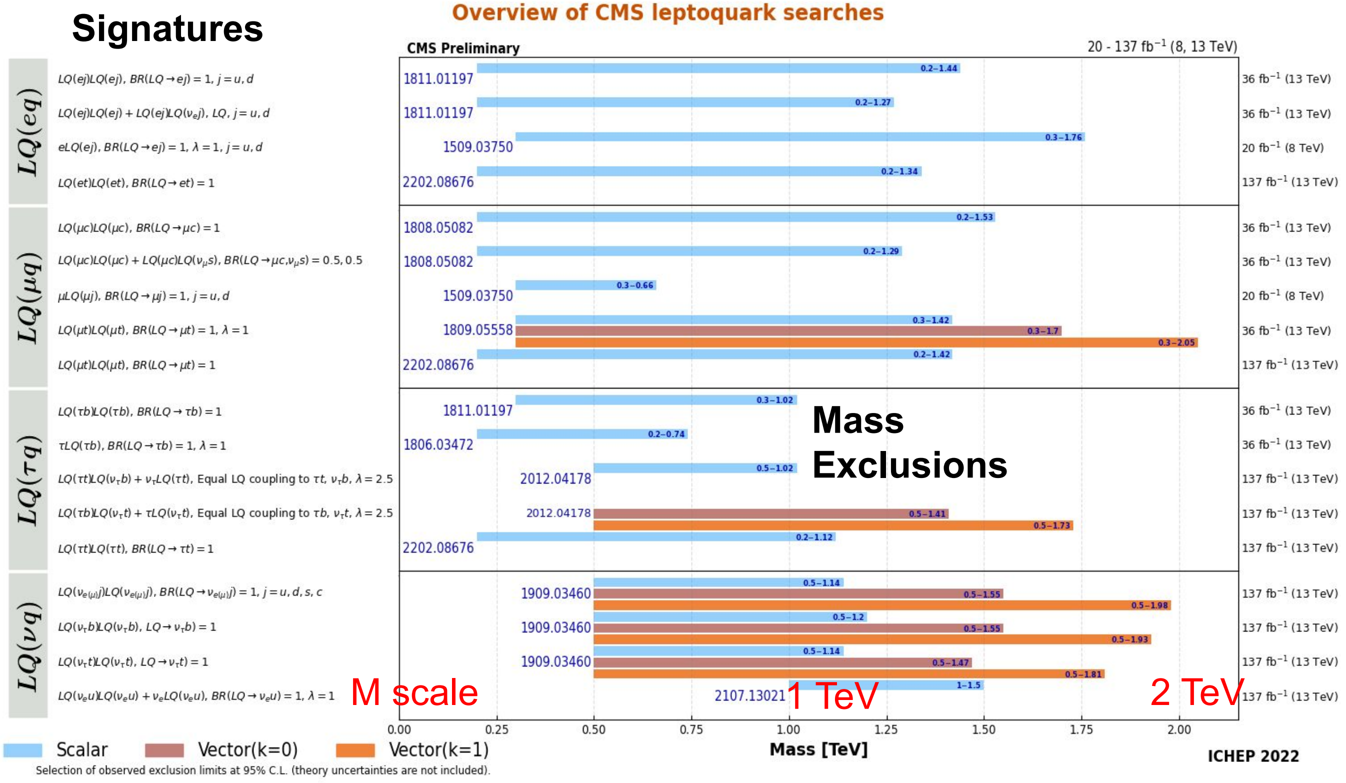
non-resonant (t-channel)

Overview of leptoquark searches at CMS

Scalar leptoquarks

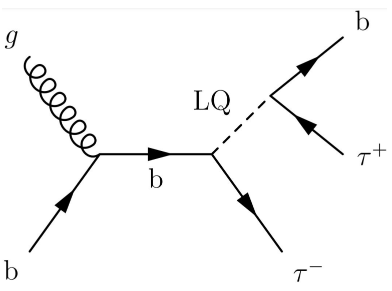
Vector leptoquarks (k=0)

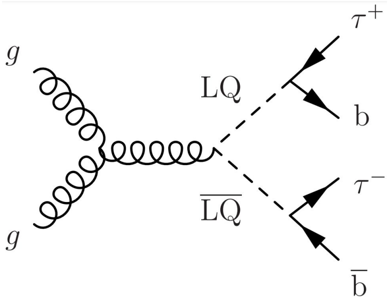
Vector leptoquarks (k=1)



3rd generation LQ with tau+b

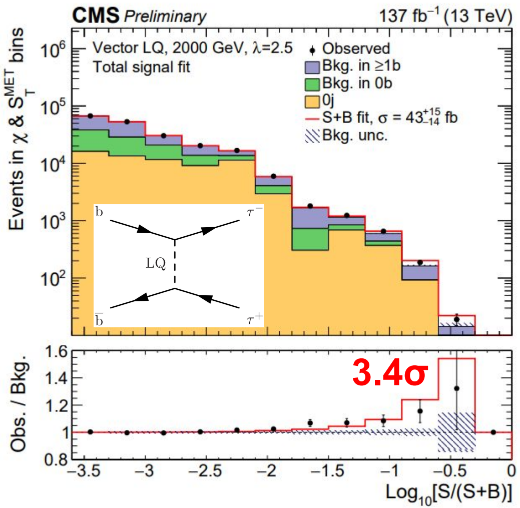
CMS-EXO-19-016

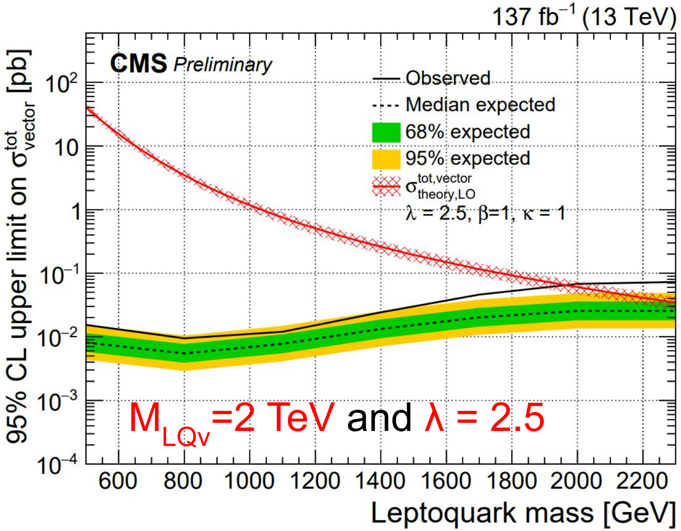


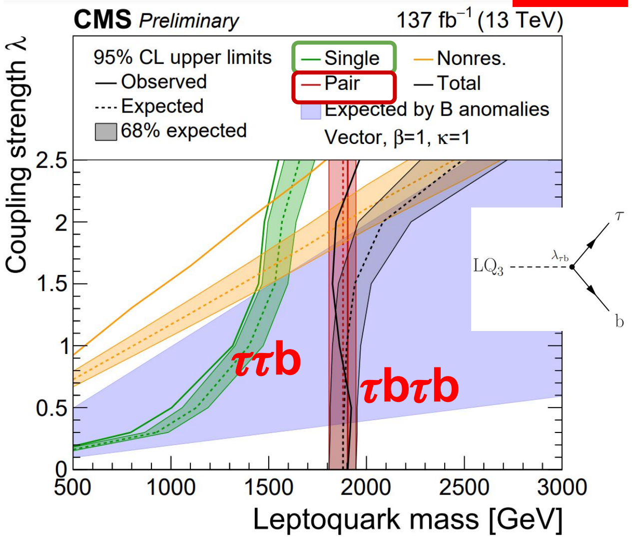


Events with τ and at least one b-jet selected.
Limits on scalar & vector LQs with various couplings λ and M are set.
Excess (3.4σ) for LQ→bτ at M_{LQ}=2 TeV and λ = 2.5 in combined channel.

New



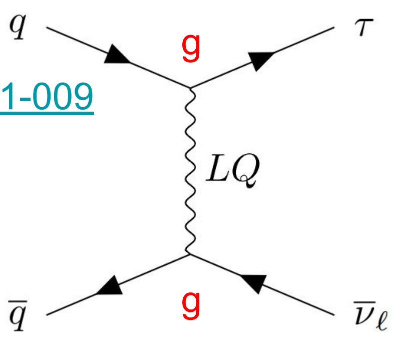




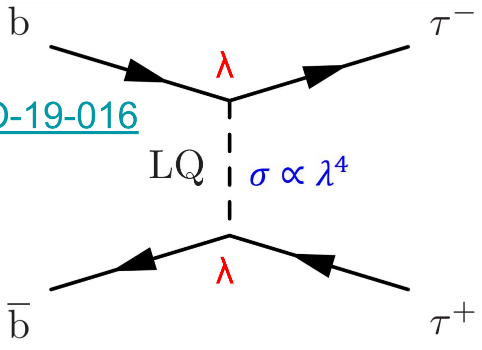
Non-resonant LQ in t-channel

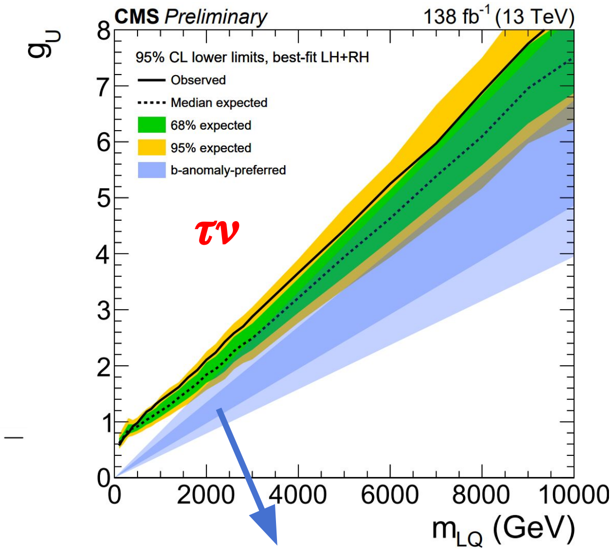
Newly search for the non-resonant production of $\tau\nu$ and $\tau\tau$ via t-channel **New**

CMS-EXO-21-009

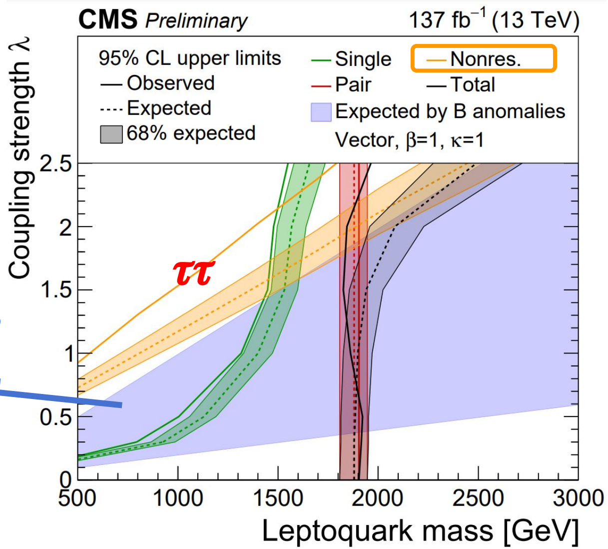


CMS-EXO-19-016





t-channel production
has higher sensitivity towards high coupling strengths

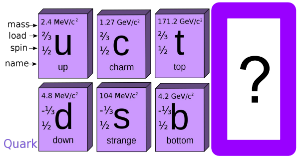


Region **B anomalies** preferred

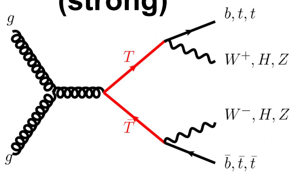
Gives access to upto **10 TeV M_{LQ} range !**

Search for New Fermions

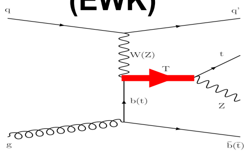
- **Vector-like quarks (VLQ)**
  - VLQs are colored spin ½ fermions
  - L/R-handed transform in the same way
  - Mass from mixing, not Higgs.
  - Many extensions of SM have VLQs



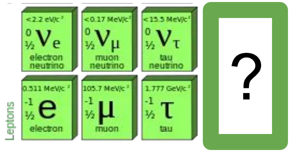
Pair production (strong)

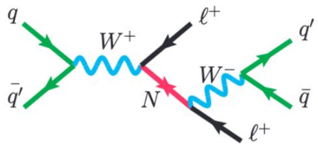


Single production (EWK)



- **Heavy Neutral Leptons (HNL)**
  - Potential BSM solutions for neutrino mass :
    - Type-I Seesaw models : HN mix with SM ν
    - Type-III Seesaw models : SU(2) triplet $\Sigma^0, \Sigma^+, \Sigma^-$ leptons
    - Left-Right Symmetry model (LRSM) : W_R, Z' along with 3 HN_R
    - Composite model
  - If HN is Majorana neutrino, Lepton Number Violation is possible



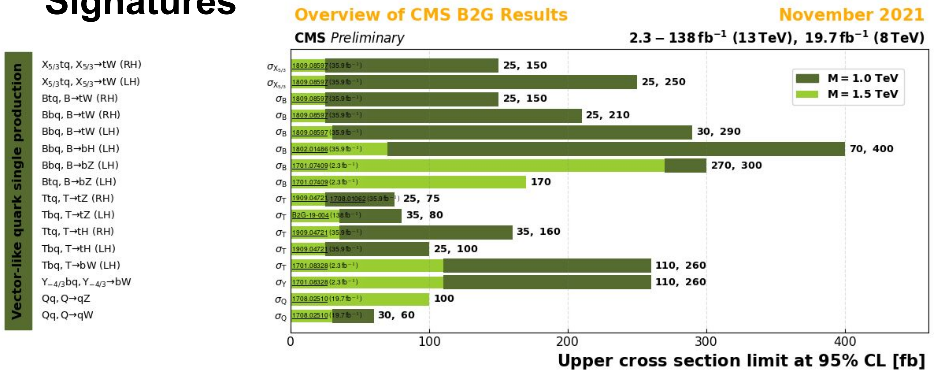


Overview of Vector-like Fermion searches at CMS

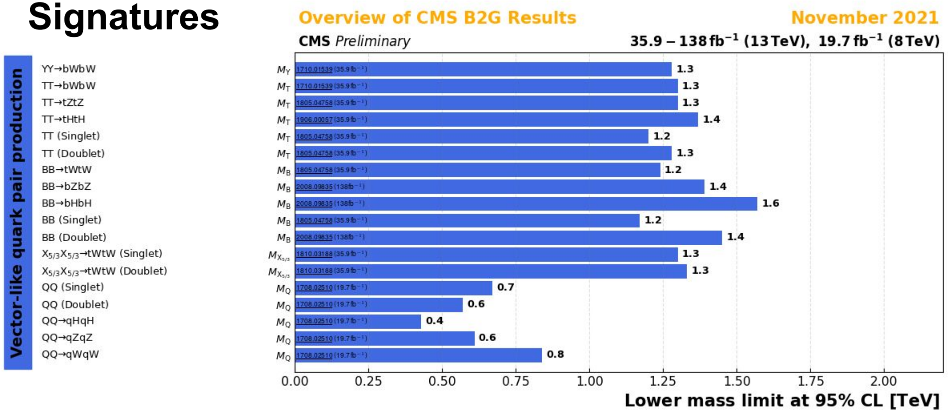
Single Vector-like quark production

Vector-like quark Pair production

Signatures



Signatures



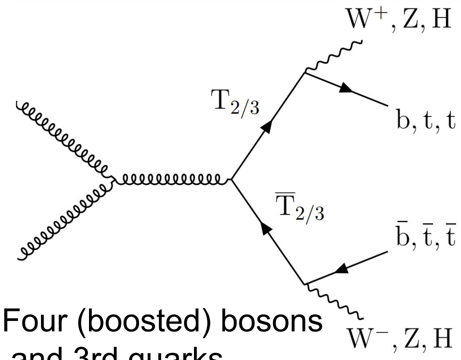
+

Vector-like Lepton

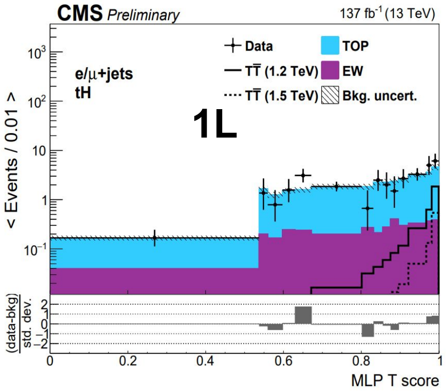
VLQ pair in leptonic states (TT, BB)

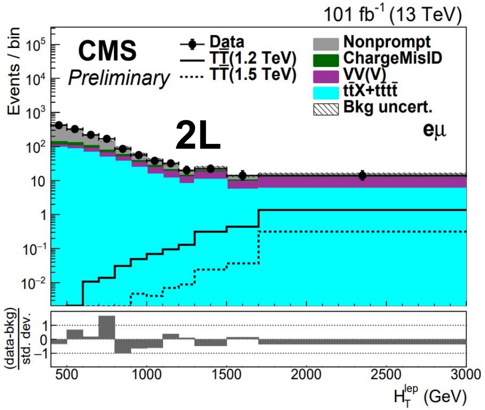
CMS-B2G-20-011

New



Four (boosted) bosons and 3rd quarks.





Scanning over VLQ Decay Branching Ratio

$T \rightarrow bW, tH$

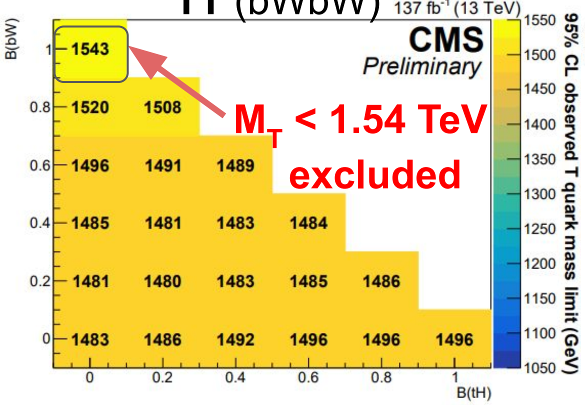
$B \rightarrow bH, tW$

1L : $W \rightarrow l + p_T^{miss}$
- ≥ 3 DEEPAK8 tagged jets, ΔR(l,j)>0.8
- **Multilayer perceptron network (MLP)**
- CR/SRs

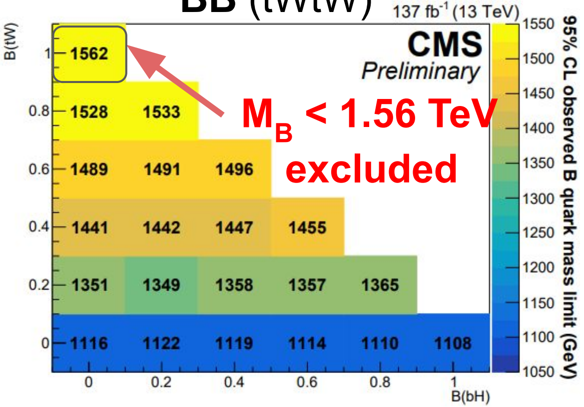
2L : Target T→tH (H→WW), and B→tW
- Dilepton with same-sign
- 3 SRs : ee, eμ, μμ

3L : Target T→tZ and B→tW
- 3 leptons and 3 small-R jets $+p_T^{miss}$
- SRs in high S_T

TT (bWbW)



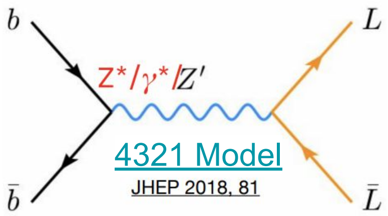
BB (tWtW)

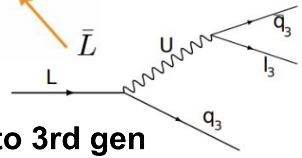


These are the strongest limits to date

Vector Like Lepton (VLL) pair in 4b+Nτ

arXiv:2208.09700





Decay of VLL to 3rd gen q+l (tt+τ/ν) via LQ(U)

Event categorization based on Nτ

- 0-τ (QCD dominated) fit w/ N(jets) =1
- 1-τ (QCD and tt) tight-τ, fit w/ DNN
- 2-τ (tt dominated) medium-τ, fit w/ DNN

2 event-wide Graph Networks:

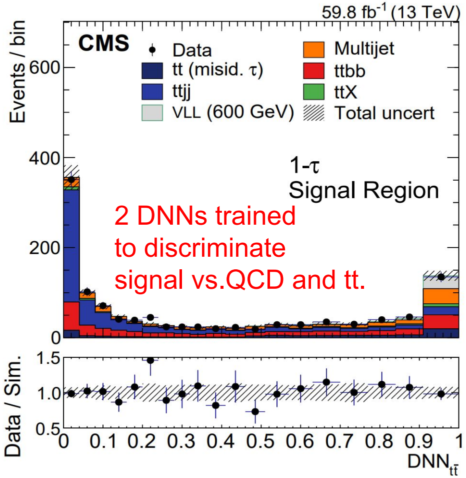
- QCD vs VLL : 0-τ region
- ttbar vs VLL : 1,2-τ regions

DNN inputs

Variable	Description
η	Pseudorapidity
ϕ	Azimuthal angle
$\log(\frac{p_T}{GeV})$	Logarithm of the p_T
$\log(\frac{m}{GeV})$	Logarithm of the mass
Q	Charge
DEEPJET score	b tagging discriminant

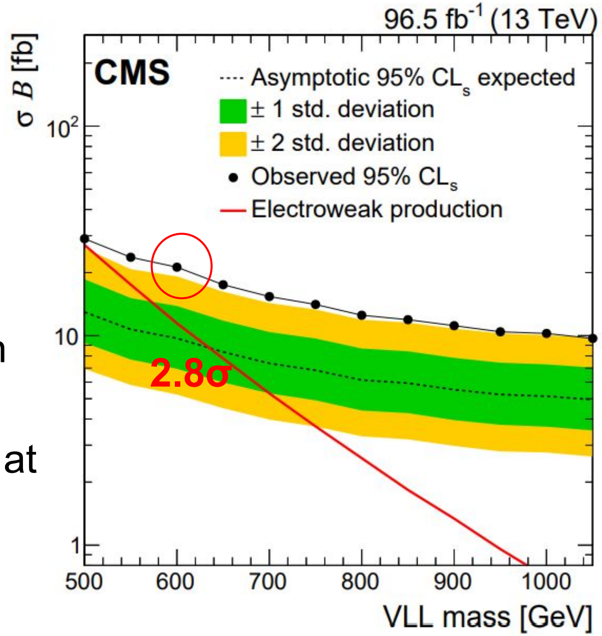
New

Tau multiplicity	VLL production + decay mode	Final state
0 τ	$EE \to b(t\nu_\tau)b(t\nu_\tau)$	$4b + 4j + 2\nu_\tau$
	$EN \to b(t\nu_\tau)t(t\nu_\tau)$	$4b + 6j + 2\nu_\tau$
	$NN \to t(t\nu_\tau)t(t\nu_\tau)$	$4b + 8j + 2\nu_\tau$
1 τ	$EE \to b(b\tau)b(t\nu_\tau)$	$4b + 2j + \tau + \nu_\tau$
	$EN \to b(t\nu_\tau)t(b\tau)$	$4b + 4j + \tau + \nu_\tau$
	$EN \to b(b\tau)t(t\nu_\tau)$	$4b + 4j + \tau + \nu_\tau$
	$NN \to t(b\tau)t(t\nu_\tau)$	$4b + 6j + \tau + \nu_\tau$
2 τ	$EE \to b(b\tau)b(b\tau)$	$4b + 2\tau$
	$EN \to b(b\tau)t(b\tau)$	$4b + 2j + 2\tau$
	$NN \to t(b\tau)t(b\tau)$	$4b + 4j + 2\tau$



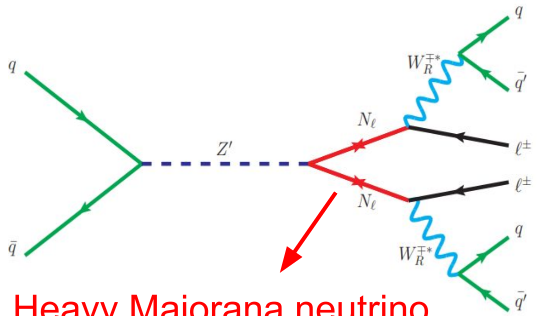
A mild excess in 1τ and 2τ SRs

2.8σ observed at M_{VLL}=600 GeV



Heavy Majorana neutrino (HN) pair in 2l+Nj

CMS-EXO-20-006



Heavy Majorana neutrino

HN can be pair produced from Z' in LR Symmetric Model

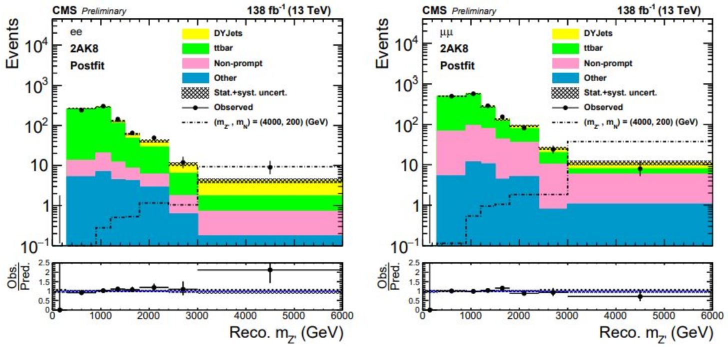
First result in CMS with 13 TeV (ATLAS 8 TeV)

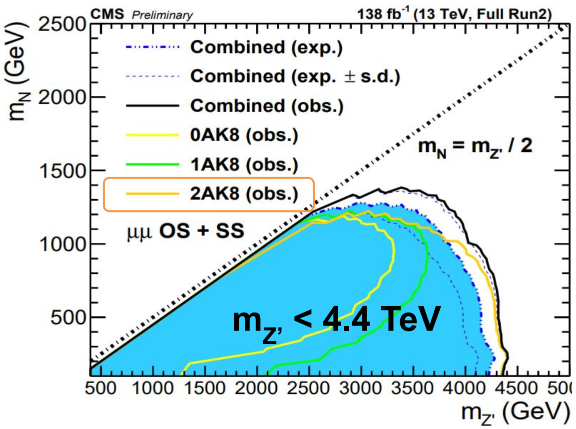
More complicated topology : 3 SRs

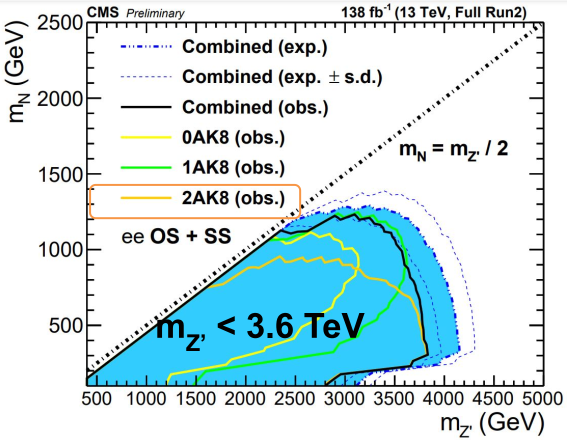
- 2 resolved (0 AK8Jet, 2 leptons) $m_N/m_{Z'}$ ~1
- 1 resolved + 1 boosted (1 AK8Jet, 1 or 2 leptons)
- 2 boosted (2 AK8Jet, 0-2 leptons) $m_N/m_{Z'}$ << 1

Combinations of dilepton(same-flavor)+jets

dominant effect in SR 3

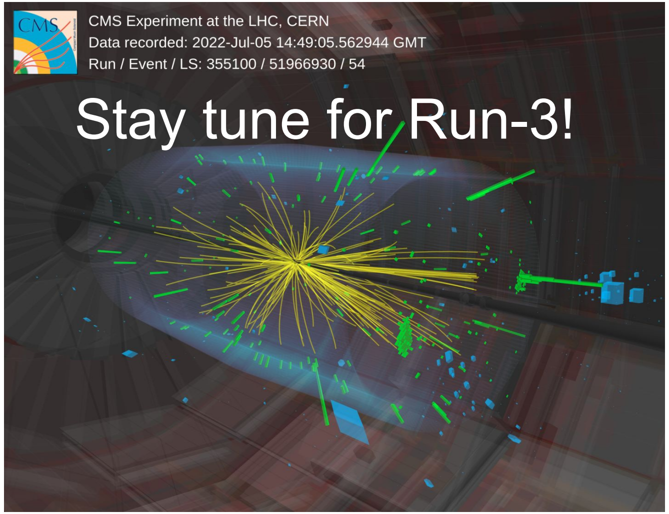


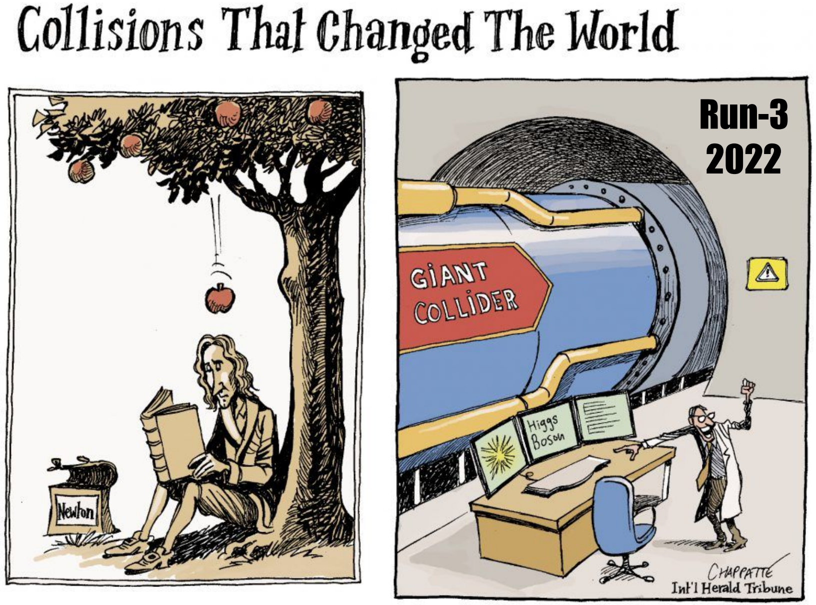




Summary

- Large number of BSM scenarios and signatures explored with LHC Run-2 data.
- No discovery yet, Sensitivity significantly improved with novel techniques.
- New challenging models/signatures are probed for the first time.
- Many intriguing results to follow up in Run-3 and beyond.
- More result in CMS publications.





Backup