Search for new physics in CMS in events with jets, leptons and photons in the final state

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IISER PUNE

CMS

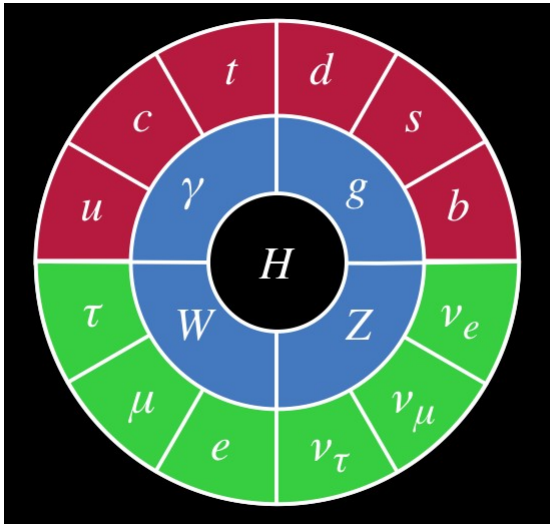
LEPTON PHOTON 2021 MAN

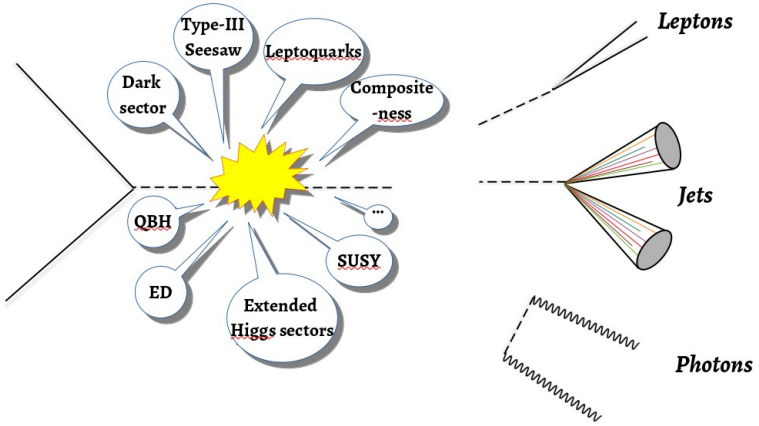
30th International Symposium on Lepton Photon Interactions at High Energies

Introduction

Standard Model (SM)

- A very successful theory towards understanding the universe. Unites three out of the four fundamental fources of the nature in an elegant effective field formulation.
- Doesn't completely describe every phenomena such as the existence of dark matter, neutrino oscillations and their small masses, baryon asymmetry, and so on.





Beyond-SM & signatures

- Many other theories proposed as a solution to complete the puzzle.
- New physics can be produced in collider experiments, and therefore can manifest themselves in final states with leptons, jets, and photons.
- A variety of handles with these simple objects for enhanced signal sensitivity and rejecting SM background. Let's take a look at how...

Today from CMS-EXOTICA...

...Published results

Strongly coupled DM CMS-EXO-19-020
- *Decaying to semi-invisible jets*
- *Produced via leptophobic Z'*

Dec 2021

Right-handed W boson and a heavy neutrino CMS-EXO-20-002
- *Final state with dileptons and dijets*

Dec 2021

Monojet and mono-V (had)
CMS-EXO-20-004
- *Energetic jets and large missing transverse energy*

Nov 2021

Exclusive diphoton production at high mass with tagged protons
CMS-EXO-18-014
- *First search!*

Oct 2021

...Preliminary results

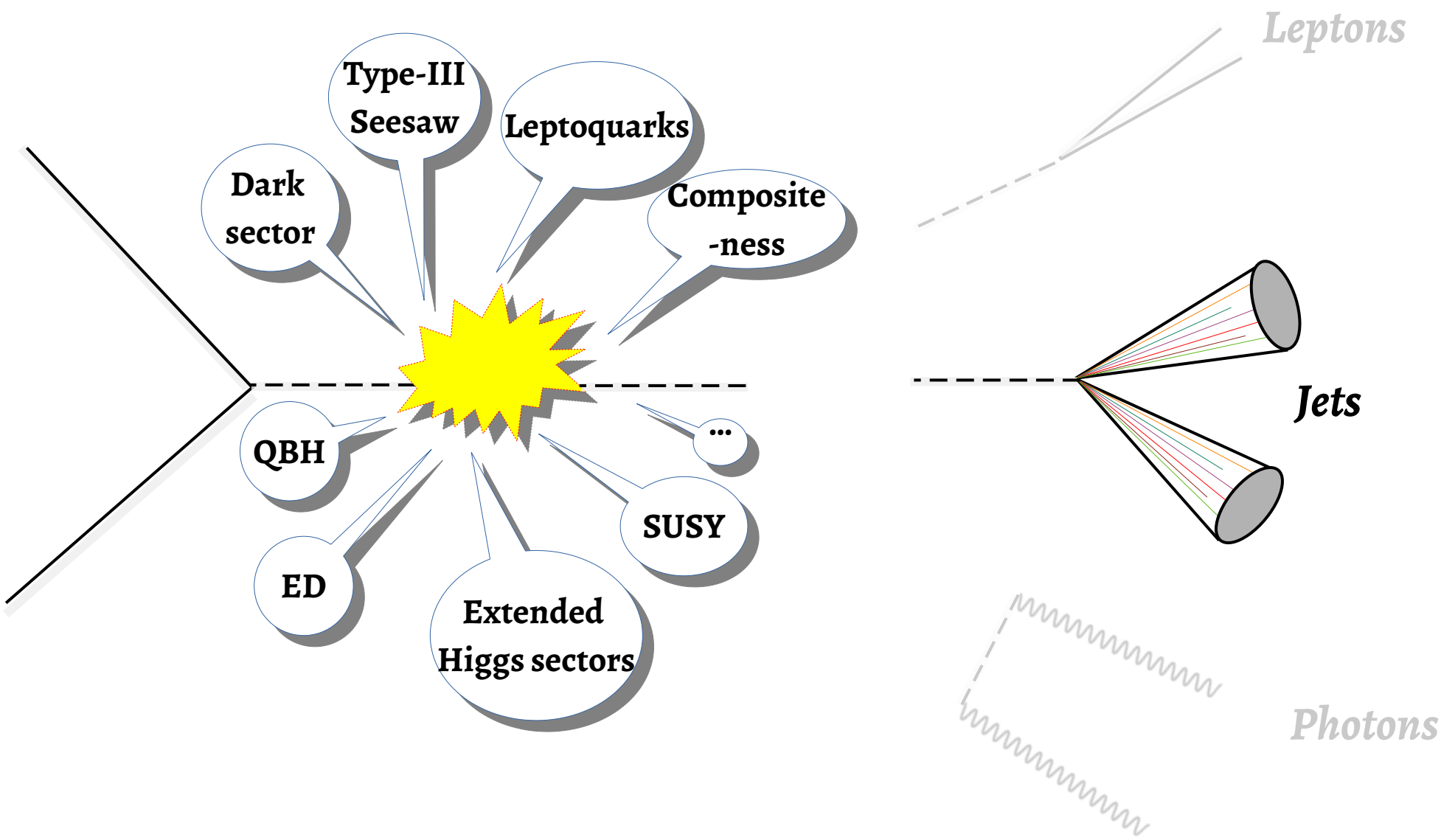
Type-III Seesaw, Vector-like leptons and Scalar leptoquarks
CMS-PAS-EXO-21-002
- *Three- and four-lepton final states ($e/\mu/\tau_h$)*

Aug 2021

QBH in eτ/μτ/eμ CMS-PAS-EXO-19-014
Dijet CMS-PAS-EXO-20-008 **& trijet resonances** CMS-PAS-EXO-20-007
DM + dark higgs to W+W- CMS-PAS-EXO-20-013
Wɣ resonances using hadronic decays of lorentz-boosted W bosons
CMS-PAS-EXO-20-001

Full list of CMS publications can be found here (EXO-XX-YYY).

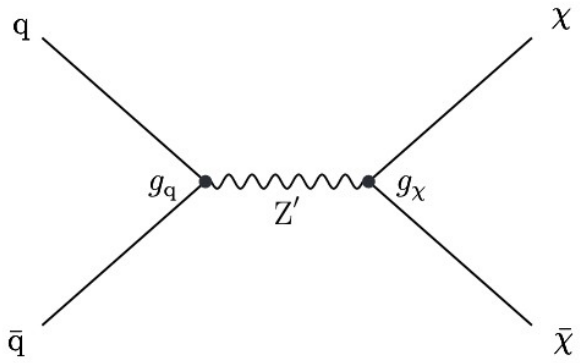
BSM theories with jets



arXiv:2112.11125

Strongly coupled DM

- **New physics:** Search for resonant production of strongly coupled dark matter in proton-proton collisions at 13 TeV
- **Manifests as:** Two "semivisible" jets containing visible SM matter, and invisible dark matter. Hence, missing energy aligned with one of the jets. Produced via a leptophobic Z' mediator.
- **Production & decay:** $pp \rightarrow Z' \rightarrow \chi\bar{\chi}$ (χ = Dark quarks)
- ***Final states:*** **jj+MET**



Data analyzed: 138 fb^{-1}

Major SM backgrounds:
QCD multijet, $t\bar{t}$, W($\rightarrow \ell\nu$)+jets, and Z($\nu\nu$)+jets

More about the model

- Dark quarks → unstable or stable dark hadrons (π_{dark},ρ_{dark}).
- Unstable dark hadrons decay promptly to SM quarks. Stable dark hadrons are DM candidates.
- $r_{inv} = N_{stable}/(N_{stable}+N_{unstable}) \in [0,1]$.
- Leptophobic Z' signal HV model parameters: $\sigma_{Z'}(m_{Z'},g_q)$, $m_{Z'}$, m_{dark}, α_{dark}, and r_{inv}.

arXiv:2112.11125

Strongly coupled DM

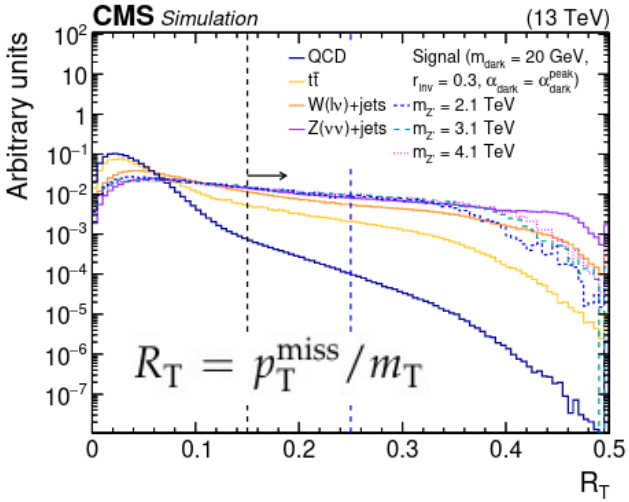
Analysis requirements

- **Objects:** PF objects with good identification criteria are used. Such as,

Signal jets	SM or "narrow" jets
pT > 200 GeV, |η|<2.4, AK8. Jet pT corrected with PUPPI probability.	pT > 30 GeV, |η|<3.0, AK4. Area-based PU subtraction.

Trigger: A narrow jet with pT > 450 (500) GeV or H_T (scalar sum of pT of all narrow jets) > 900 (1050) GeV in the year 2016 (2017-2018).

- **Event selection:**



Preselection requirements

$p_T(J_{1,2}) > 200\,\text{GeV},\ \eta(J_{1,2}) < 2.4$

Rejects 99% of t-channel QCD dijet events.

$R_T > 0.15$

$\Delta\eta(J_1, J_2) < 1.5$

$m_T > 1.5\,\text{TeV}$

$$m_T^2 = [E_{T,JJ} + E_T^{miss}]^2 - [\vec{p}_{T,JJ} + \vec{p}_T^{miss}]^2 = m_{JJ}^2 + 2p_T^{miss}\left[\sqrt{m_{JJ}^2 + p_{T,JJ}^2} - p_{T,JJ}\cos(\phi_{JJ,miss})\right]$$

$N_\mu = 0$

pT > 10 GeV, |η|<2.4, isolated.

$N_e = 0$

To reject instrumental backgrounds (85%).

p_T^{miss} filters

$\Delta R(j_{1,2}, c_{dead}) > 0.1$

Undermeasured jets due to nonfunctional ECAL readout channel (c_{dead}).

Final selection requirements

Misreconstructed jets. ← veto $f_\gamma(j_1) > 0.7$ & $p_T(j_1) > 1.0\,\text{TeV}$

HEM failure. ← veto $-3.05 < \eta_j < -1.35$ & $-1.62 < \phi_j < -0.82$ *

MET close to signal jets. ← $\Delta\phi_{min} < 0.8$

arXiv:2112.11125

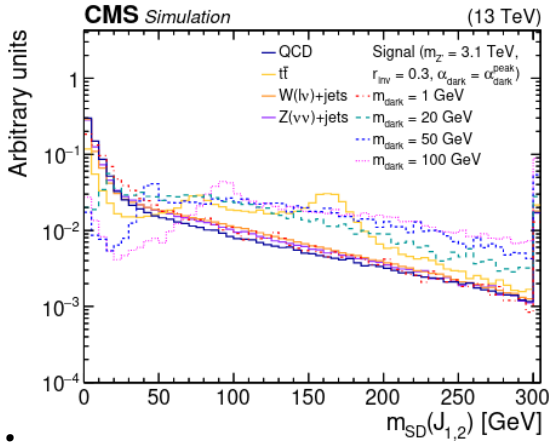
Strongly coupled DM

- **BDT-based identification of 'semivisible' jets:**

Total 15 input variables.

Signal samples for training: Various scans of $m_{Z'} \geq 1.5$ TeV, $m_{dark} \geq 10$ GeV, $0.1 \leq r_{inv} \leq 0.8$, at various α_{dark}. pT-weighted input variable distributions.

Background samples for training: QCD + tt in equal proportion.

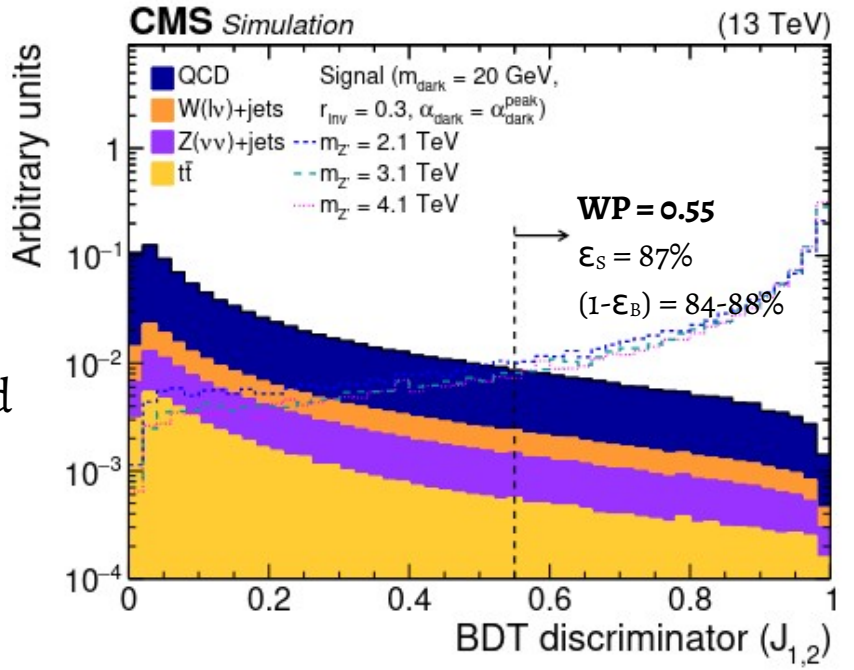


Category	Input variables
Heavy object identification	N-subjettiness ratios τ_{21} and τ_{32}, energy-correlation functions, and soft-drop mass m_{SD}.
Quark-gluon discrimination	Jet girth g_{jet}, the major (σ_{major}) & minor (σ_{minor}) axes, and pT dispersion $D_{pT.}$
Flavor and other	Jet-energy fractions: $f_{h\pm}$, f_e, f_μ, f_{ho}, and f_γ. $\Delta\phi$(J,MET).

- **Signal regions:**

i. Two signal regions for the inclusive search: **Low-R_T [0.15,0.25], and High-R_T (>0.25).** $R_T = p_T^{miss}/m_T$

ii. For the BDT-based search: Requiring both jets to be tagged as "semivisible" from BDT WP in each of the two inclusive signal regions, known as **"High-SVJ2"** and **"Low-SVJ2"**.



- **Background estimation:** Fit the observed m_T distribution in each signal region with a functional form following from traditional dijet seaches: $g(x) = \exp(p_1 x) x^{p_2[1+p_3 \ln(x)]}$ $x = m_T/\sqrt{s}$

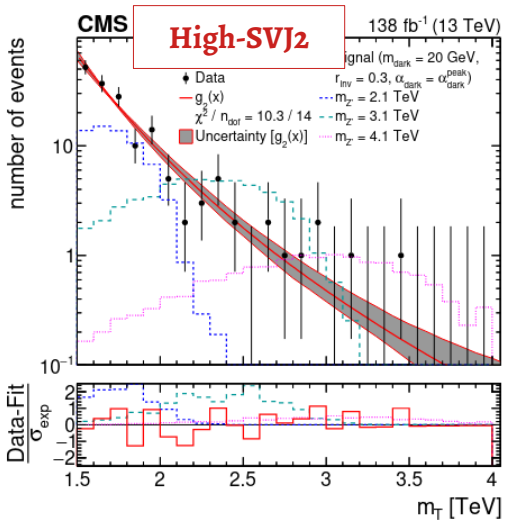
arXiv:2112.11125

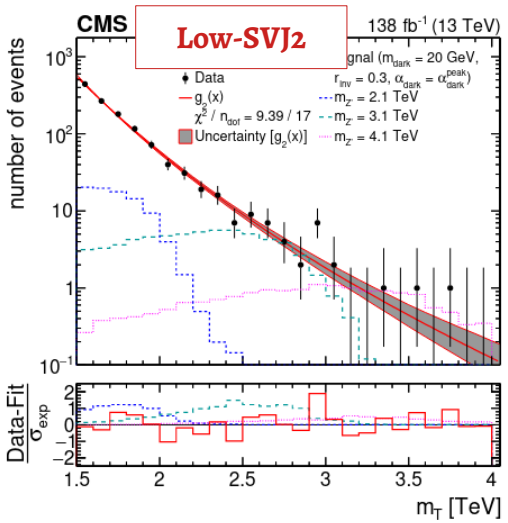
Strongly coupled DM

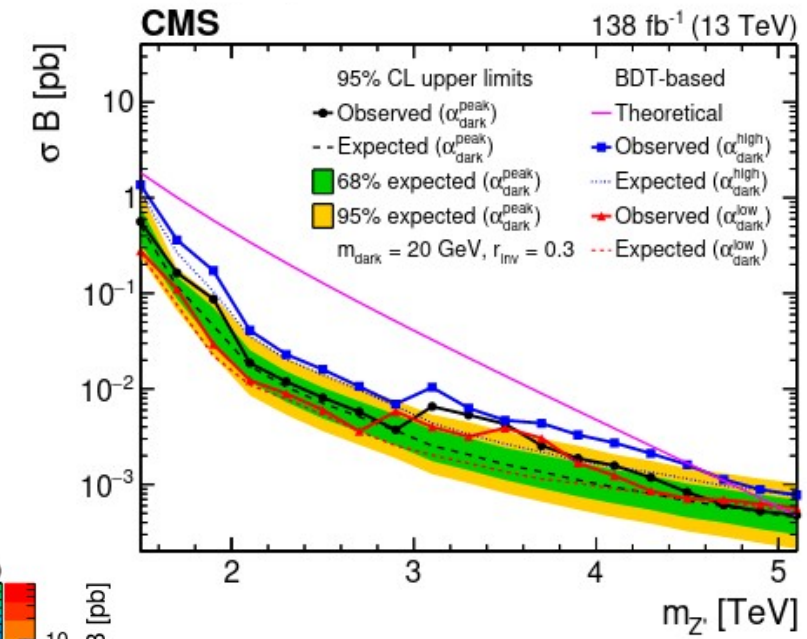
Results:

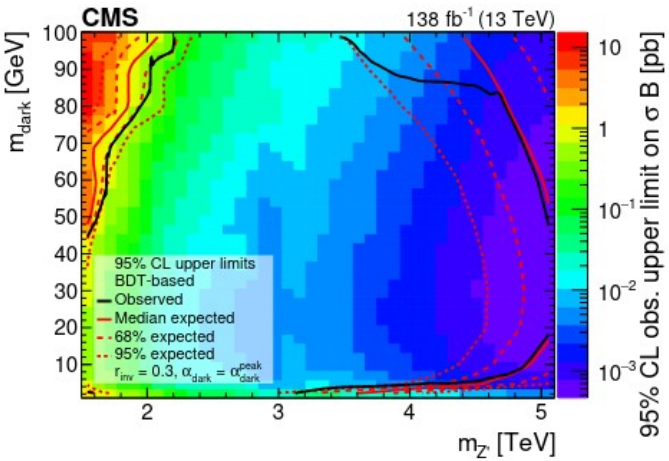
BDT-based signal regions:

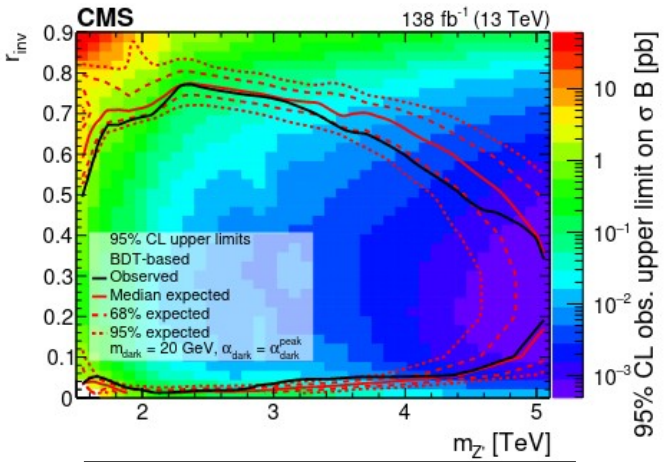
The combined likelihood for each pair of signal regions is computed as the product of the likelihood from each bin in the mT distributions.











$r_{inv} = N_{stable}/(N_{stable}+N_{unstable})$

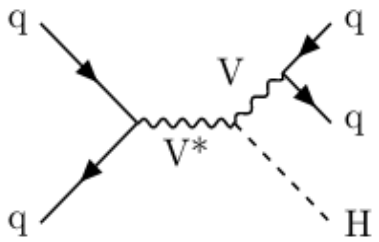
Limits on the effective cross section $\sigma_{Z'} \cdot B_{dark}$ at 95% confidence level (CL) using the modified frequentist CLs approach.

Assuming the Z′ and SM Z bosons have the same couplings to the SM quarks, these strongly-coupled hidden sector models are excluded for mediator masses of 1.5–5.1 TeV at 95% CL for the *first* time.

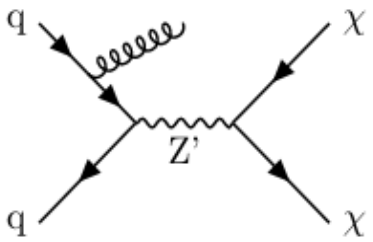
Monojet, and monoV (hadronic)

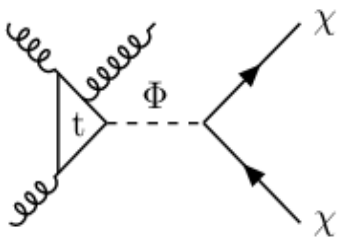
- **New physics:** Search for new particles in events with energetic jets and large missing transverse momentum in proton-proton collisions at √s= 13 TeV.

- **BSM models:** DM via "higgs portal", simplified DM production via new bosonic mediators (spin 0 or 1), and also via "fermion portal". ADD model of large extra dimensions, and single- as well as pair-produced first generation of leptoquarks (LQ).

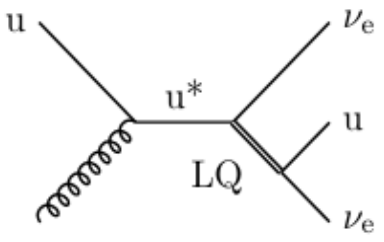


DM via higgs





DM via new bosonic mediators



Single LQ production

- **Manifests as:** Energetic hadronic jets accompanying invisible particles. Jets are derived from initial-state gluon radiation or hadronic decays of energetic SM vector bosons (V).

- ***Final states:*** **j+MET**

Data analyzed: 101 fb^{-1} (+statistical combination of previous 36 fb^{-1} result)
Major SM backgrounds: QCD multijet, Z→νν+jets, W(→ℓν)+jets, and Z(νν)+jets

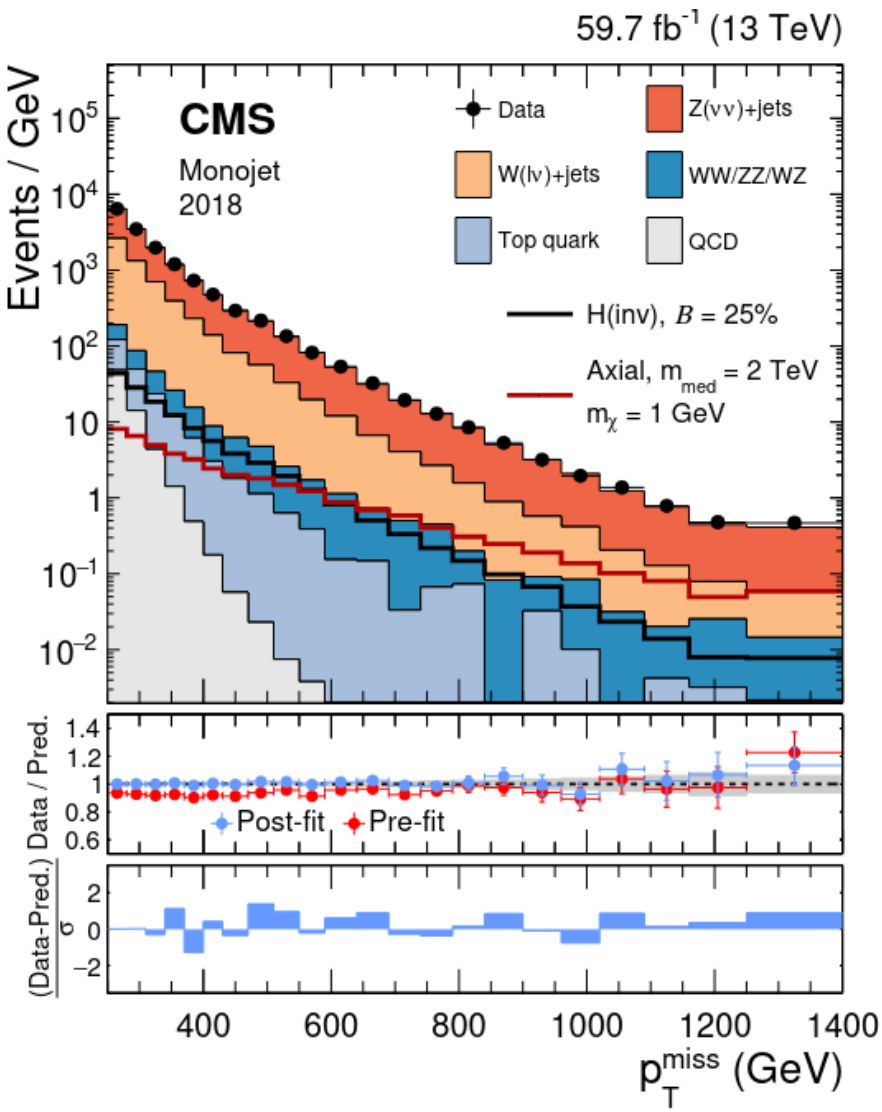
Monojet, and monoV (hadronic)

- **Object & event selection:** PF-based pT^{miss} > 250 GeV (>95% trigger efficiency).

Trigger: pT^{miss} > 120 GeV. The control samples with electrons selected with single isolated and non-isolated triggers, as well as a single photon trigger (200 GeV).

Events rejected if:

- Isolated electron (photon) of pT>10(15) GeV & $|\eta|$<2.5 or pT>10 GeV & $|\eta|$<2.4 muon or pT>18 GeV & $|\eta|$<2.3 τ_h.
- AK4 jets with pT>20 GeV & $|\eta|$<2.4 "b-tagged" using DeepCSV.
- Azimuthal angle difference requirements on pT^{miss} are failed.



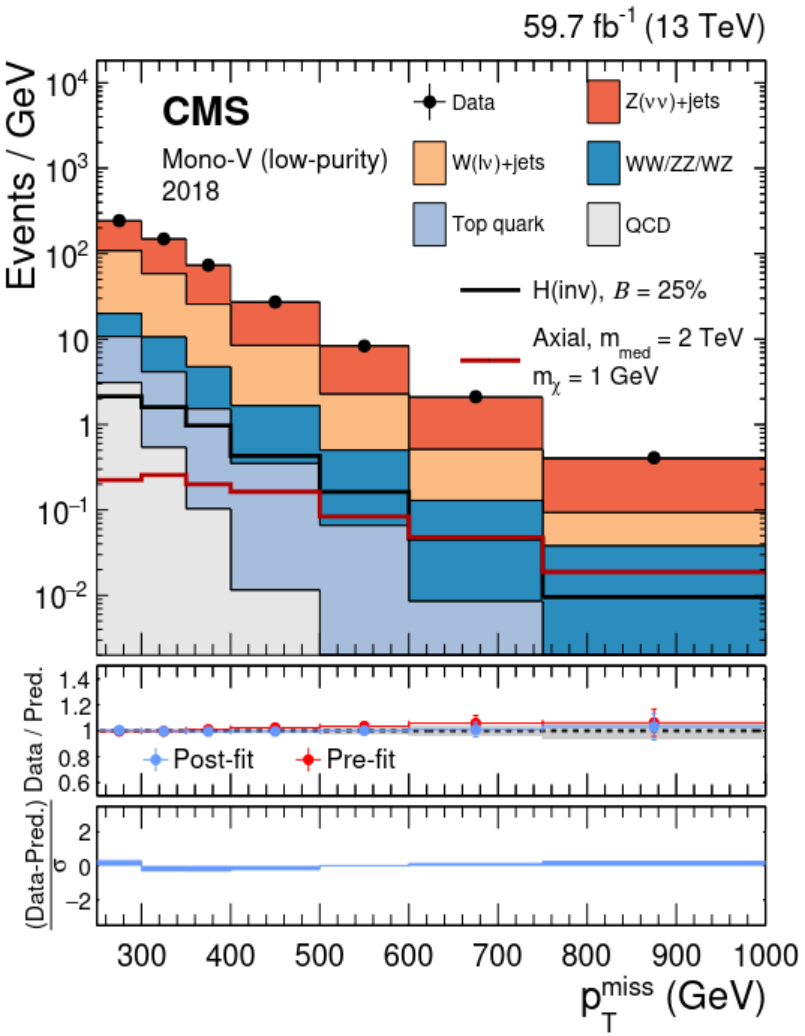
SR (1): Monojet

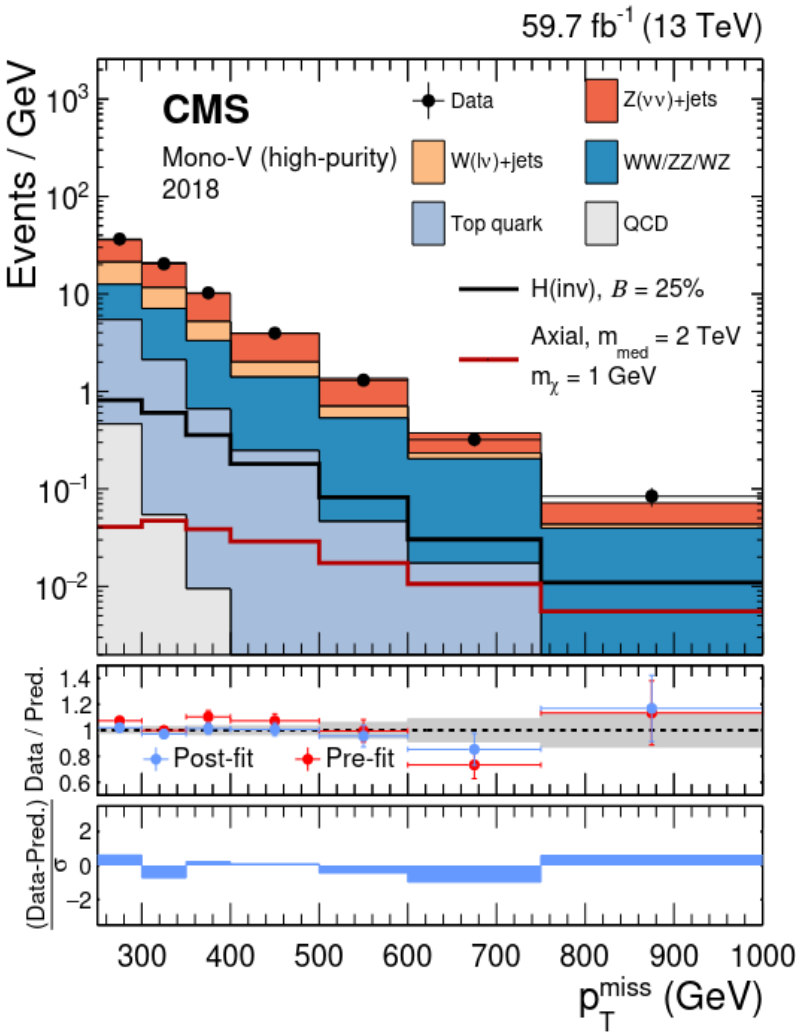
- AK4 jet pT>100 GeV, $|\eta|$<2.4.
- Additional quality criteria on the composition of the jet (e.g. charged hadron energy fraction>10%, neutral-hadron energy fraction<80%).

Monojet, and monoV (hadronic)

SR (2): Low-purity and SR (3): high-purity mono-V

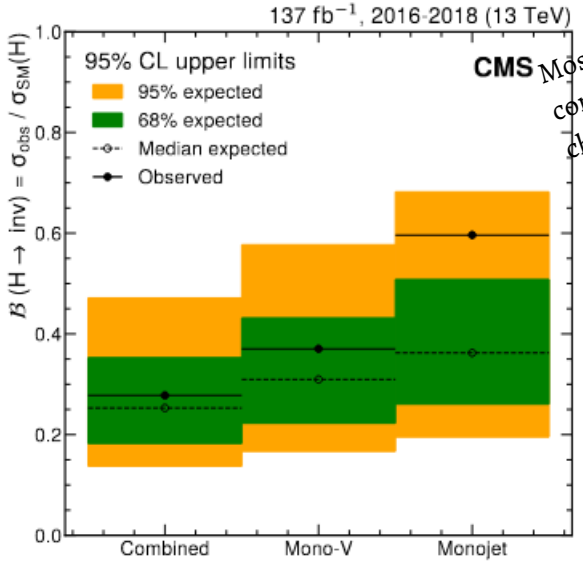
- AK8 jet pT>250 GeV, $|\eta|$<2.4. 'V' tagged with DeepAK8 algorithm, and 65 < m_{SD} < 120 GeV.
- NN output converted into a binary score (=vector boson score / vector boson + QCD score).





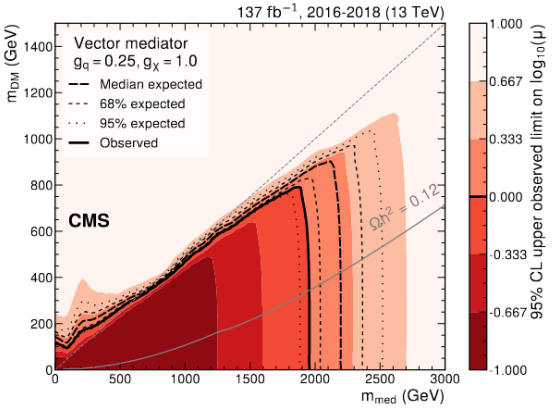
Monojet, and monoV (hadronic)

DM via Higgs-portal interpretation

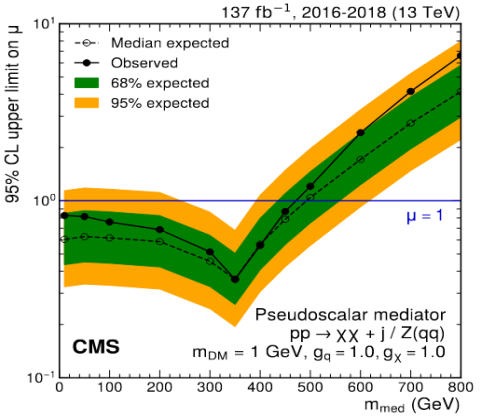


Most stringent limit from the combined gluon-fusion and V (qq)H channels to date.

Interpretation in a DM simplified model with a colorless mediator

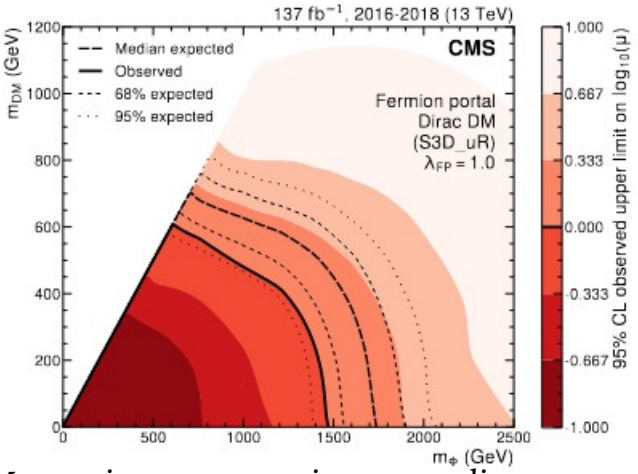


Spin-1 mediator. Combined limits improve previous exclusion of mediator mass by 20%.



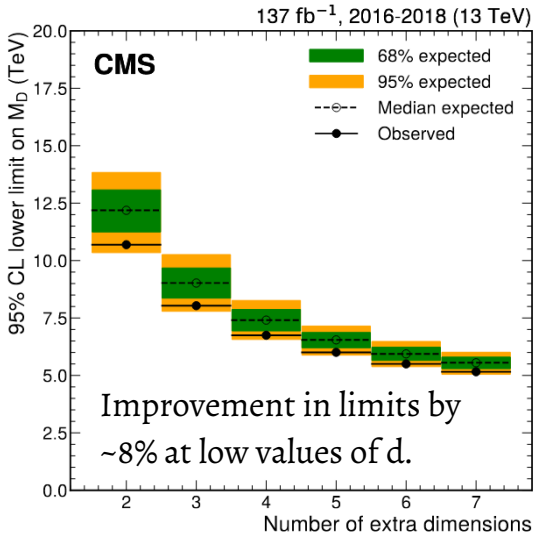
Most stringent constraints on the pseudoscalar spin-0 mediator.

DM via Fermion-portal interpretation

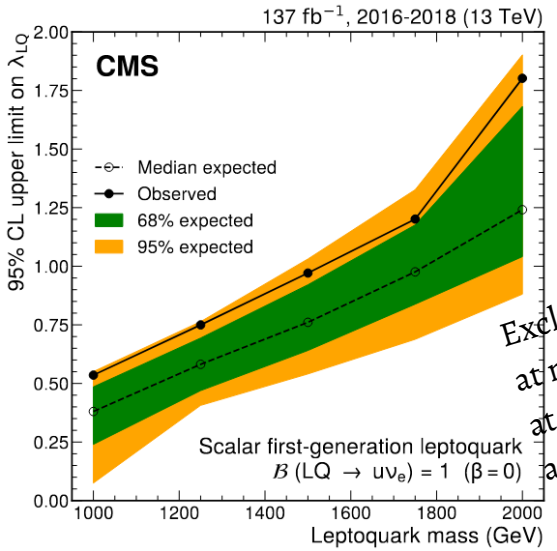


Most stringent constraints on mediator masses of up to 1.5 TeV at low m_{DM}.

ADD interpretation

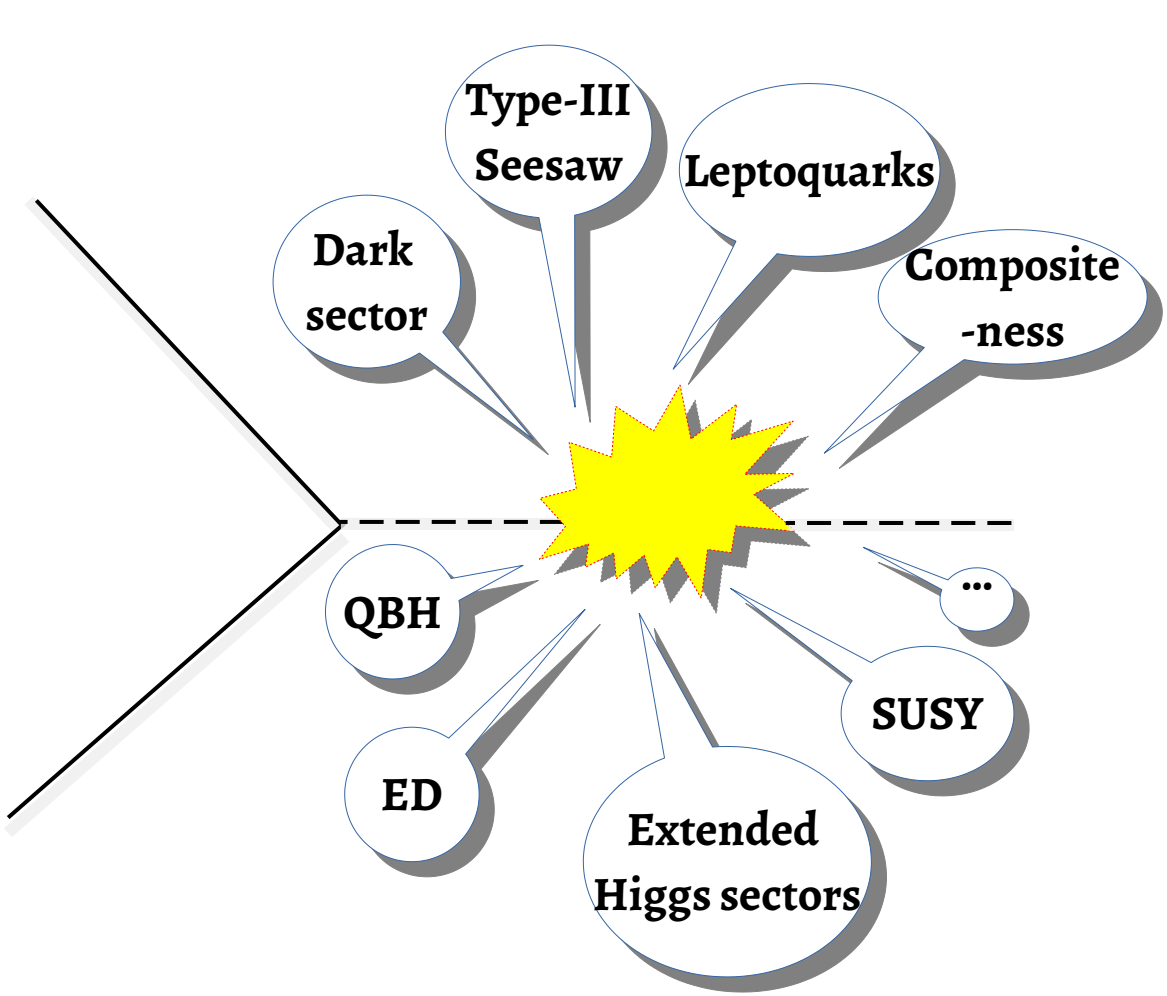


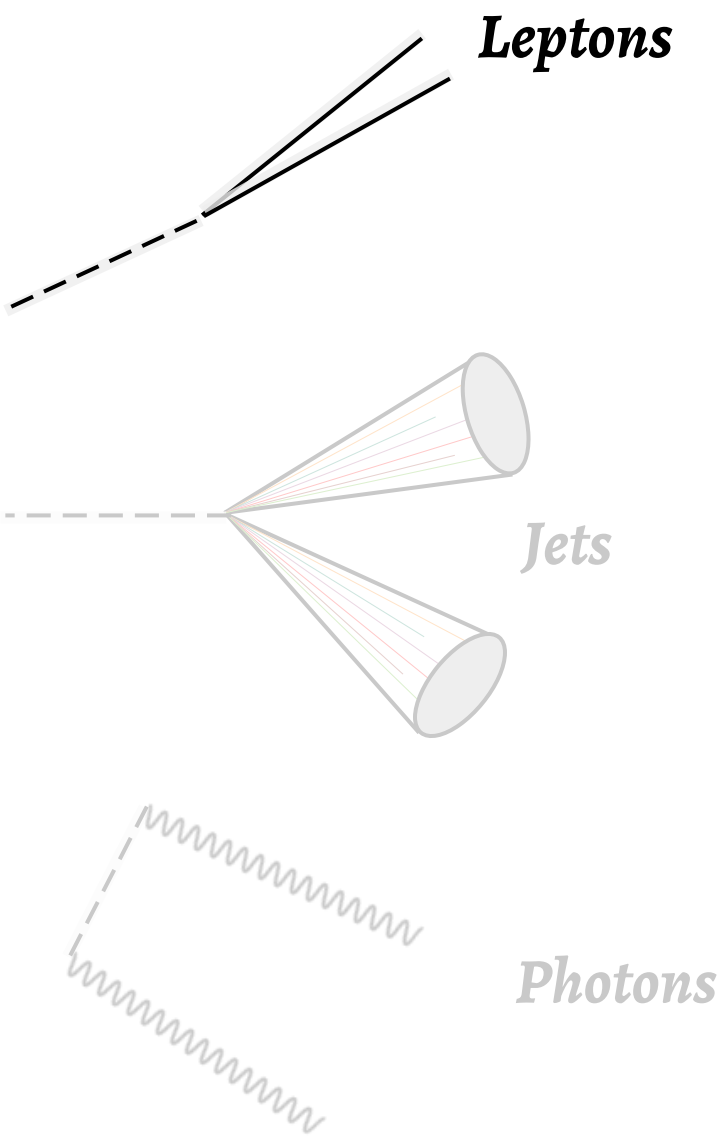
First-gen. Leptoquark interpretation



Excluded λ_{LQ} ~0.5 at m_{LQ} = 1 TeV, ~1.0 at m_{LQ} = 1.5 TeV and ~1.8 at 2 TeV.

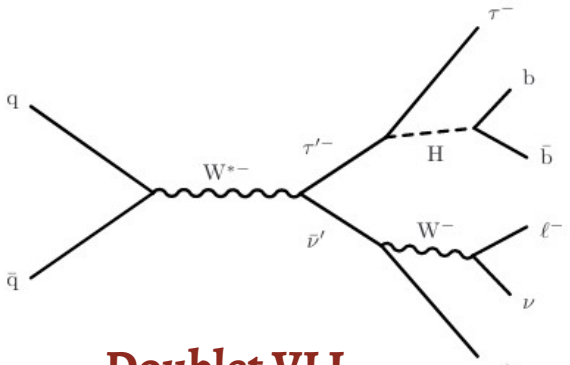
BSM theories with leptons



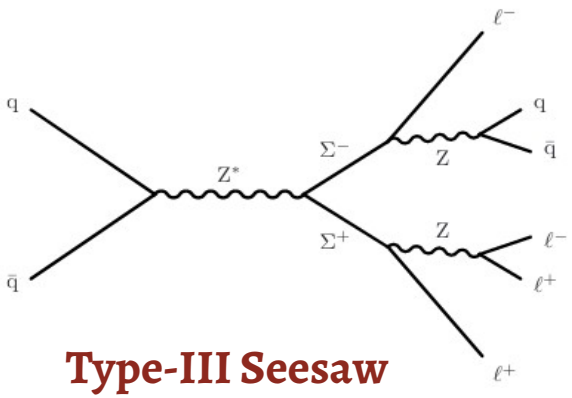


Multileptons with taus

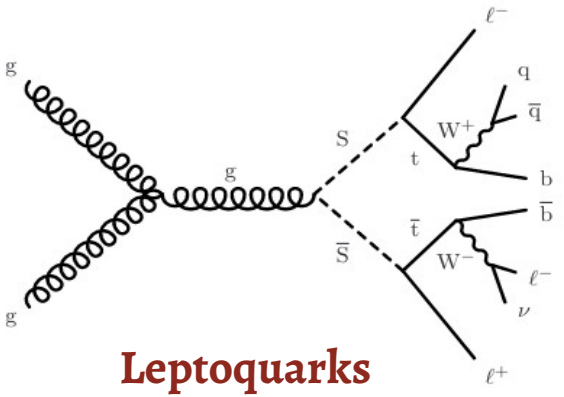
- **New physics:** Inclusive nonresonant multilepton probes of new phenomena at $\sqrt{s} = 13$ TeV.
- **BSM models:** Vector-like tau lepton in the doublet & singlet scenario, type-III Seesaw mechanism and pair-produced third-gen. scalar leptoquarks.
- **Manifests as:** Final states with multiple leptons ($e/\mu/\tau_h$), b-quark jets and missing energy.



Doublet VLL



Type-III Seesaw



Leptoquarks

Poster presentation here

Data analyzed: 138 fb^{-1}

Major SM backgrounds:

- WZ, ZZ, Zɣ, ttZ (irreducible).
- Misidentified leptons from jets, or arising from heavy flavor decays (reducible).

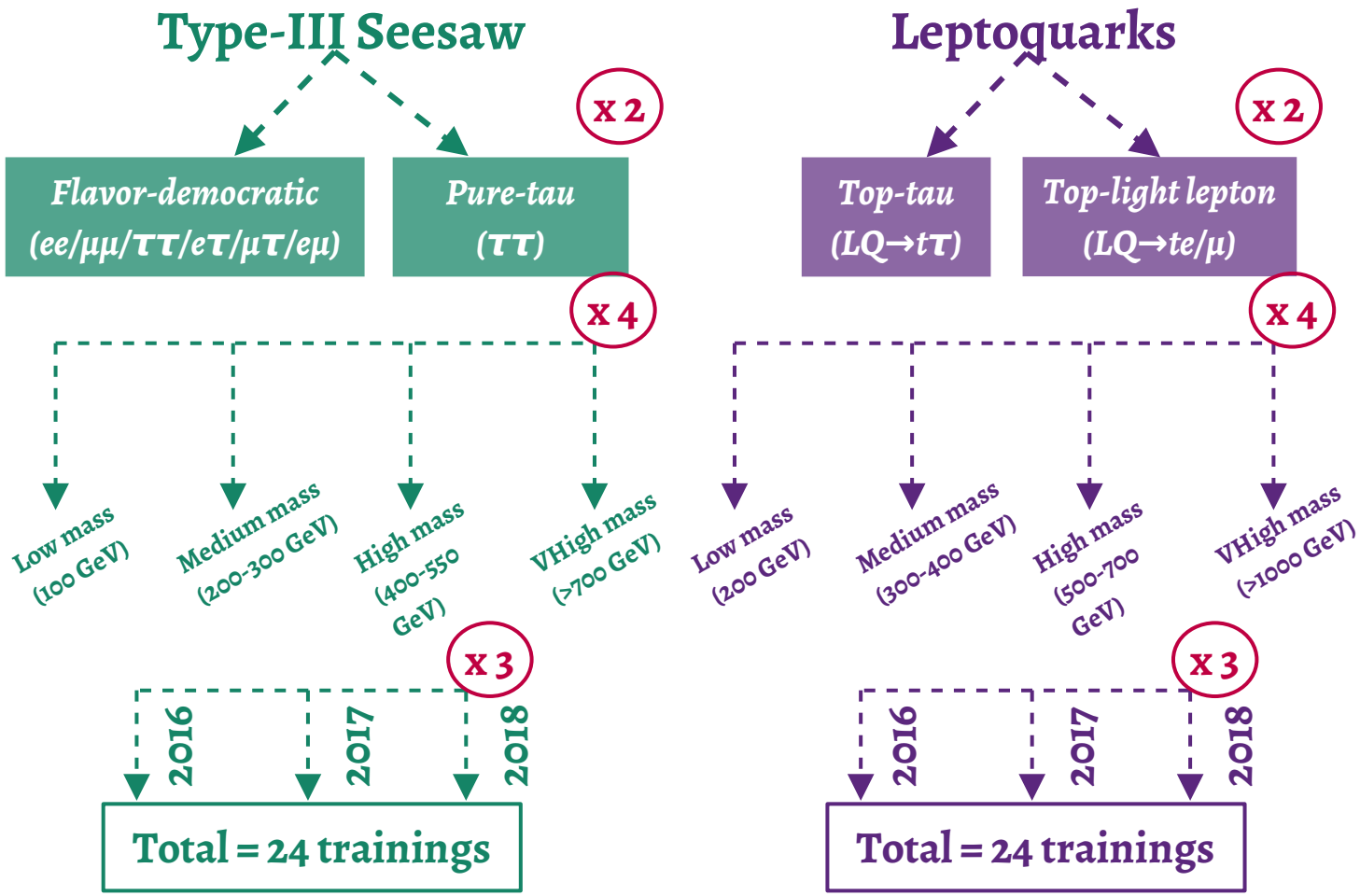
- **Final states:**

Objects	1ℓ	2ℓ	3ℓ	4ℓ
0τ_h	-	-	3ℓ	4ℓ
1τ_h	-	2ℓ1τ_h	3ℓ1τ_h	4ℓ
2τ_h	1ℓ2τ_h	2ℓ2τ_h	3ℓ1τ_h	4ℓ
3τ_h	1ℓ3τ_h	2ℓ2τ_h	3ℓ1τ_h	4ℓ

Multileptons with taus

- **Model-dependent search:** 57 distinct BDT trainings. Input variables are lepton properties, global event variables, angular distributions, and invariant & transverse masses (total 48).

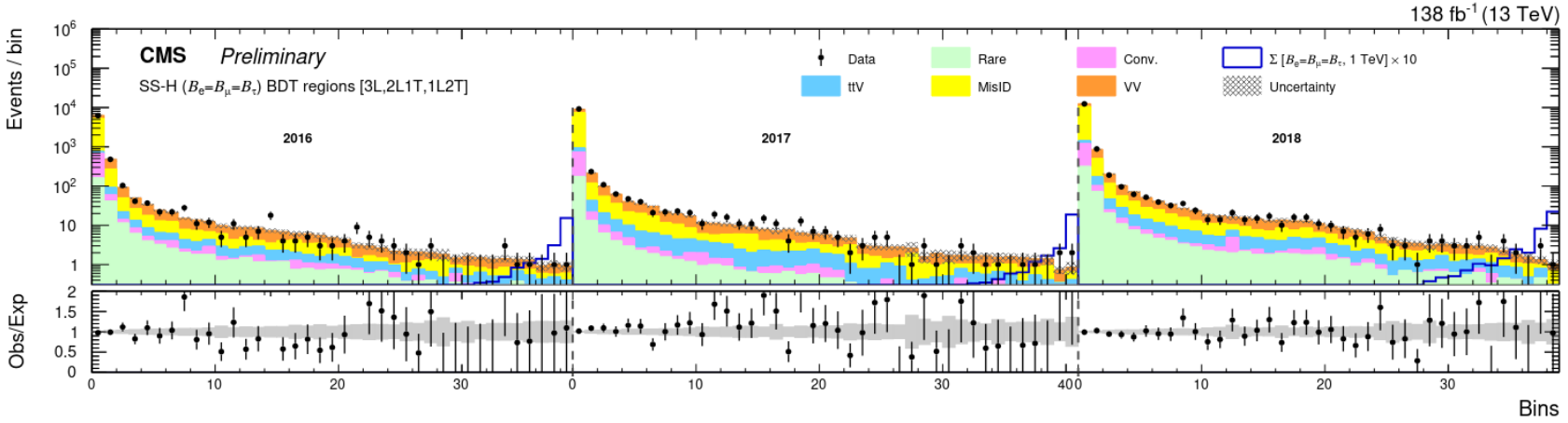
One BDT output spectra per training; **"adaptive" binning** (stretch high end BDT score, compress low end BDT score).



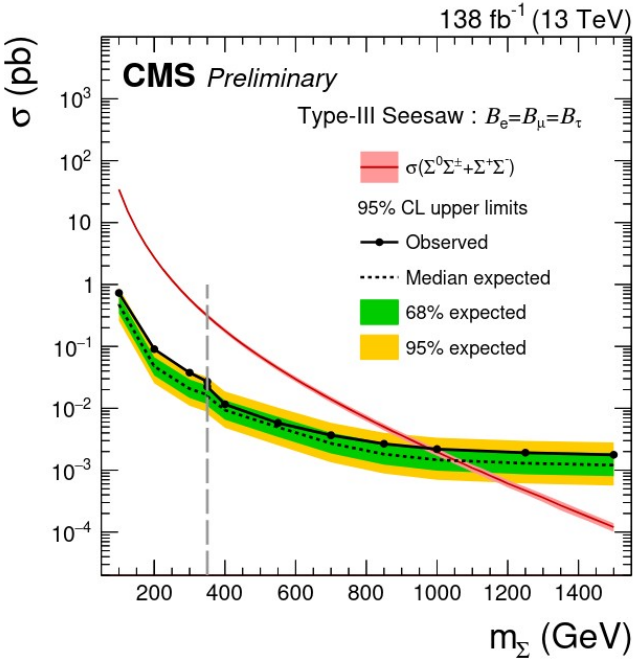
+ 9 VLL trainings

Multileptons with taus

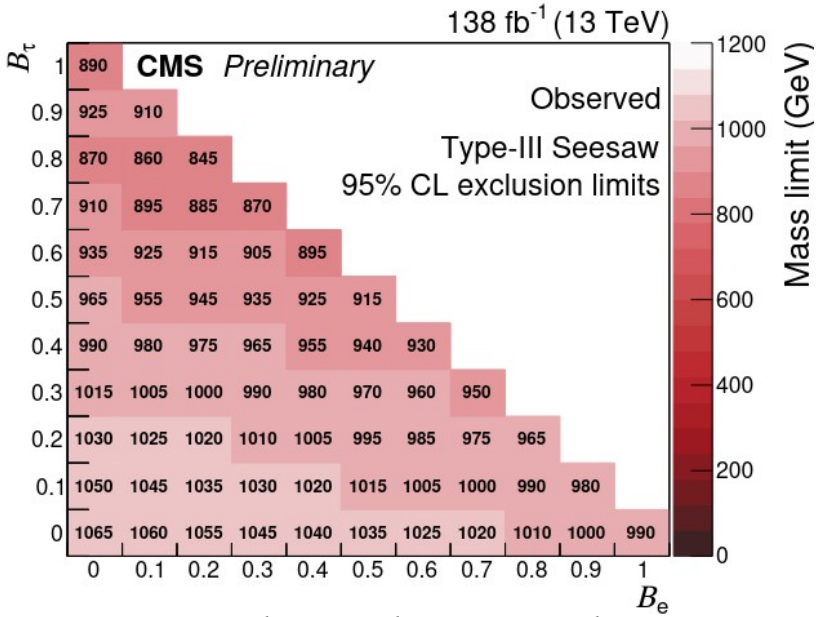
Type-III Seesaw results:



SS-H (B_e=B_μ=B_τ) BDT signal region bins in 3ℓ, $2\ell 1\tau_h$ and $1\ell 2\tau_h$ channels.



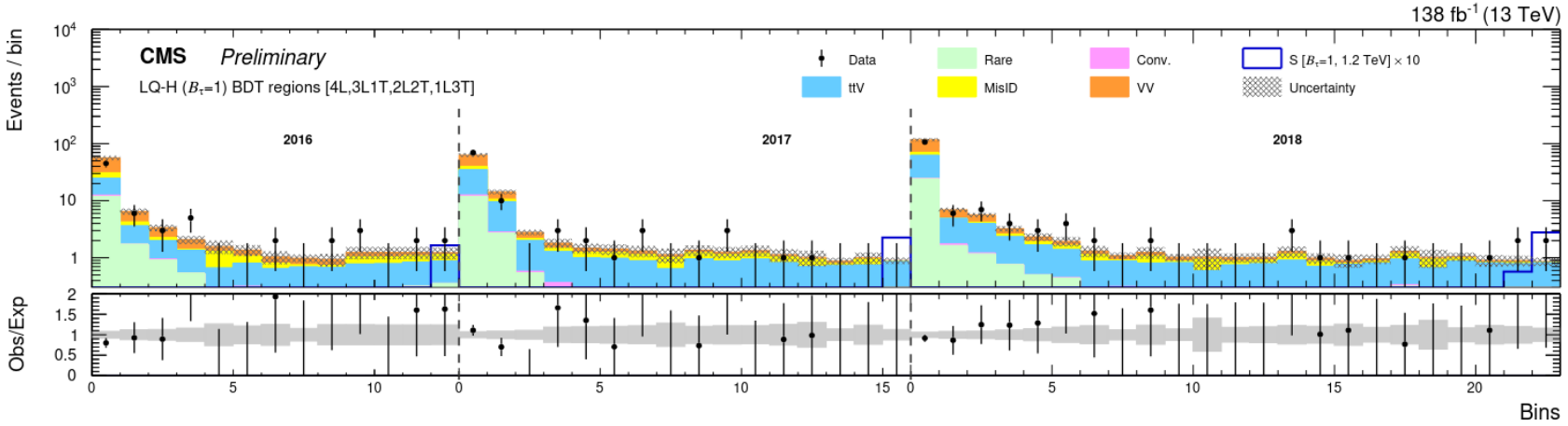
- Seesaw fermions excluded below 980 GeV (B_e=B_μ=B_τ), 990 Gev (B_e=1), 1065 GeV (B_μ=1), and 890 GeV (B_τ=1).
- Improvement by a factor of 100 in cross section limit for mixing to taus!!
- *Best* constraints from LHC at all branching ratios.



2D mass exclusion limits on the seesaw fermions in the B_e-B_τ plane (B_e+B_μ+B_τ=1).

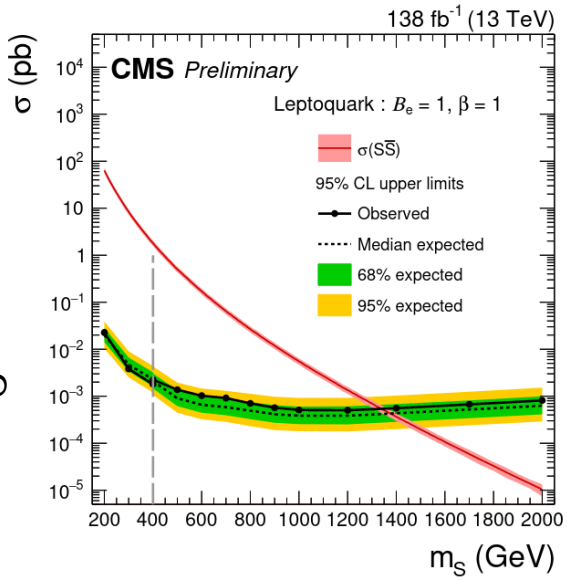
Multileptons with taus

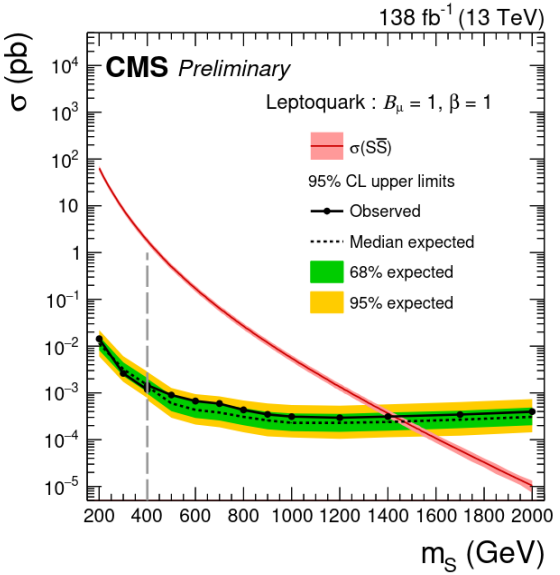
Third-gen. Leptoquarks results:

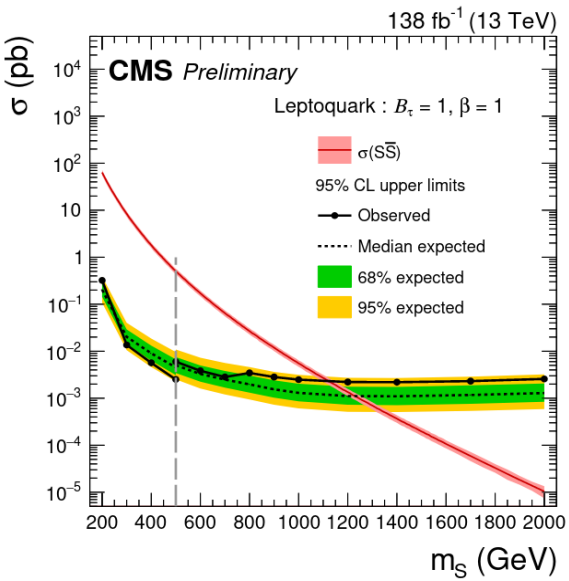


LQ-H (B_τ=1) BDT signal region bins in 4ℓ, $3\ell 1\tau_h$, $2\ell 2\tau_h$ and $1\ell 3\tau_h$ channels.

Excluded LQ below 1120 GeV (top + tau), 1340 GeV (top + electron), and 1420 GeV (top + muon) coupling scenario.

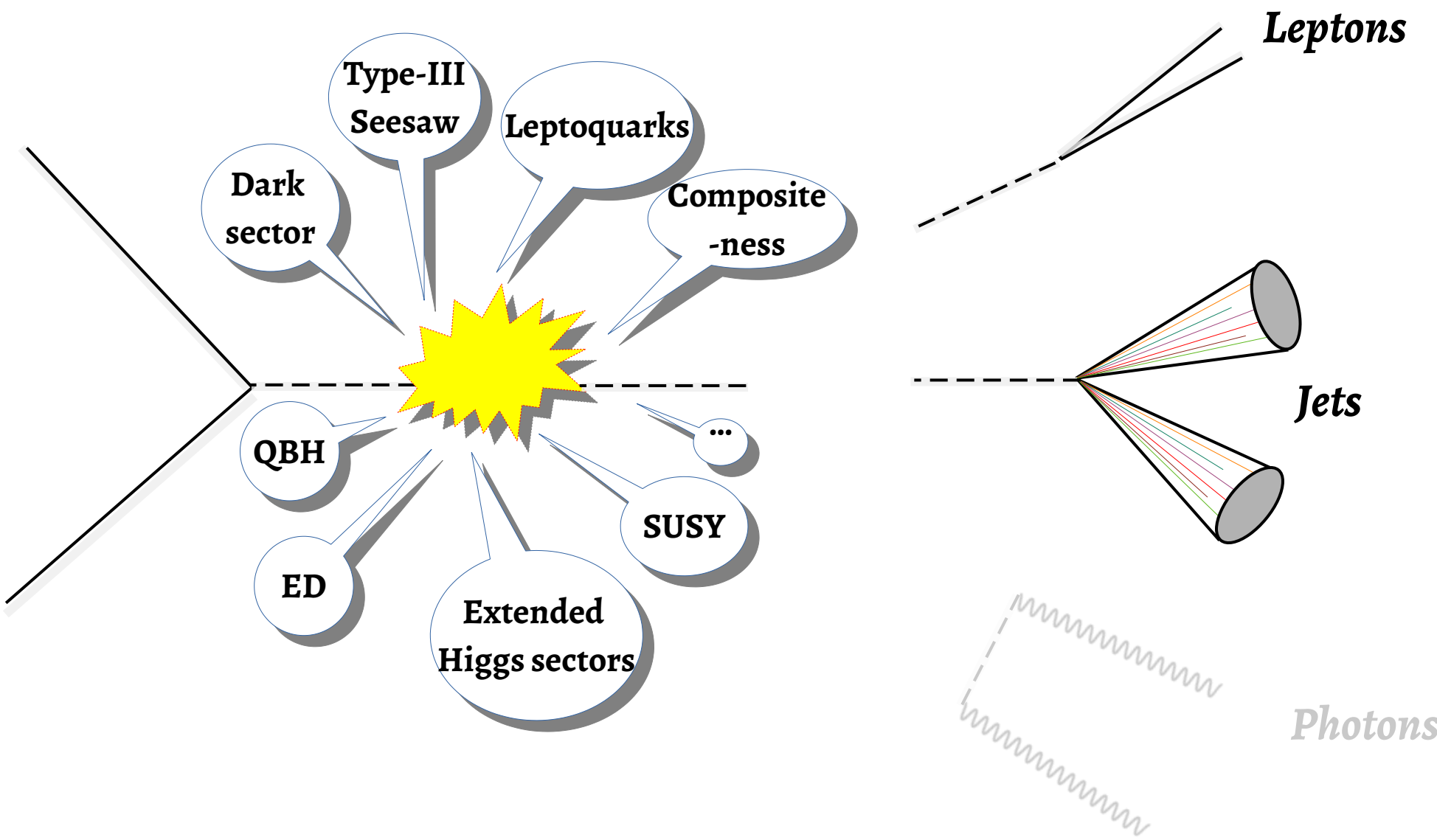






- *First* constraints from CMS on LQ → top+e coupling.
- *First* direct multilepton search for LQs. Comparable sensitivity with the dilepton results.

BSM theories with leptons & jets



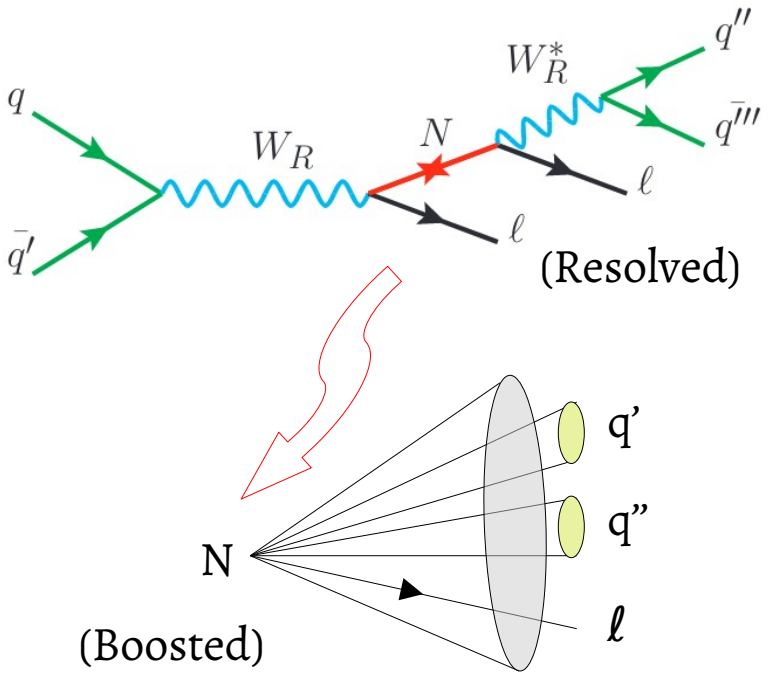
arXiv:2112.03949

W_R and a heavy neutrino

- **New physics:** Search for a right-handed W boson and a heavy neutrino in proton-proton collisions at $\sqrt{s}$ = 13 TeV.

- **About the model:** W_R resulting from a right-handed SU(2) group of the left-right symmetric models (LRSM). These models explain parity violation as the consequence of spontaneous symmetry breaking at a multi-TeV mass scale. Also, provides an explanation for the small mass of SM neutrinos through seesaw mechanism via a heavy right-handed neutrino (N).

- ***Final states:***
  ee+jj, μμ+jj (resolved)
  e+j, μ+j (boosted)



Data analyzed: 138 fb^{-1}
Major SM backgrounds: DY+jets, dileptonic $t\bar{t}$, tW (estimated from simulation, and modeling is corrected using CRs).

"Resolved" jets
pT > 40 GeV, |η|<2.4, AK4 CHS jets.

"Boosted" jets
pT > 200 GeV, |η|<2.4, AK8, PUPPI. M_{SD} > 40 GeV. LSF_3 > 0.75.

Leptons
ee (μμ) pT > 60, 53 GeV, |η|<2.4. Isolated within a cone of 0.3.

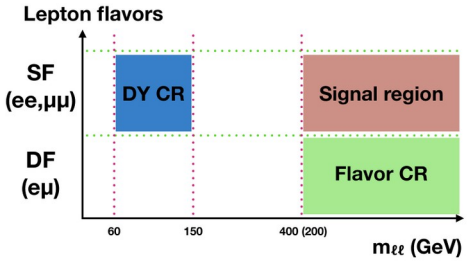
arXiv:2112.03949

W_R and a heavy neutrino

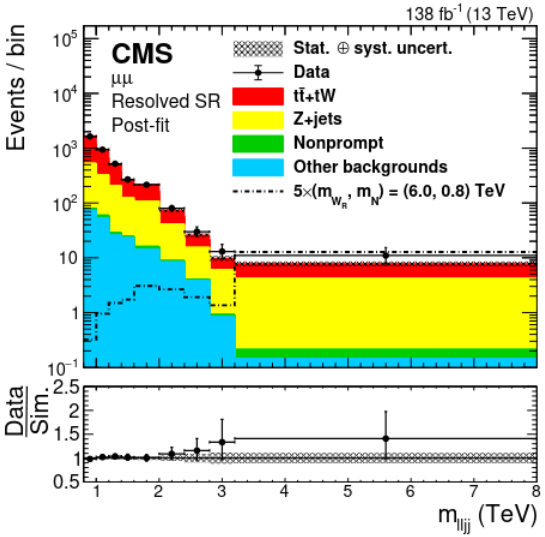
- **Event selection:**

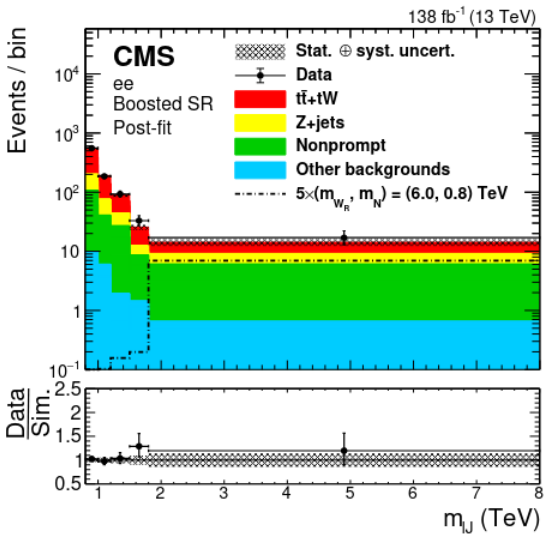
  Resolved topology → ee (μμ) + jj, ΔR between all objects > 0.4. Veto events with 2+ leptons. Leading two AK4 jets are used. $M_{\ell\ell}$ > 0.4 TeV.

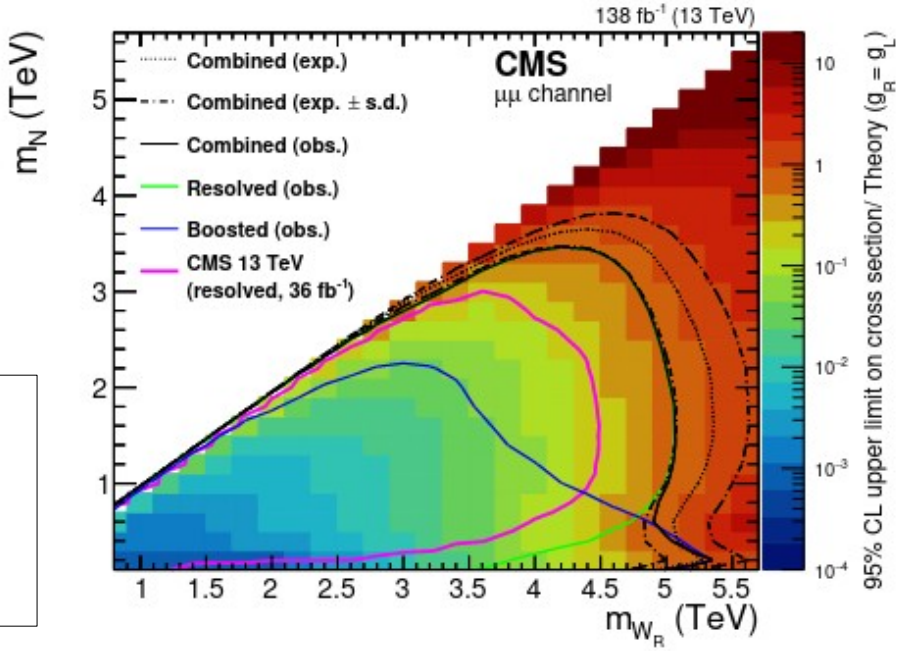
  Boosted topology → e (μ) + j, $\Delta\phi(\ell,j)$ > 2.0. Subleading lepton removed, falls inside the AK8 jet cone. $M_{\ell j}$ > 0.2 TeV.



- **Results:**

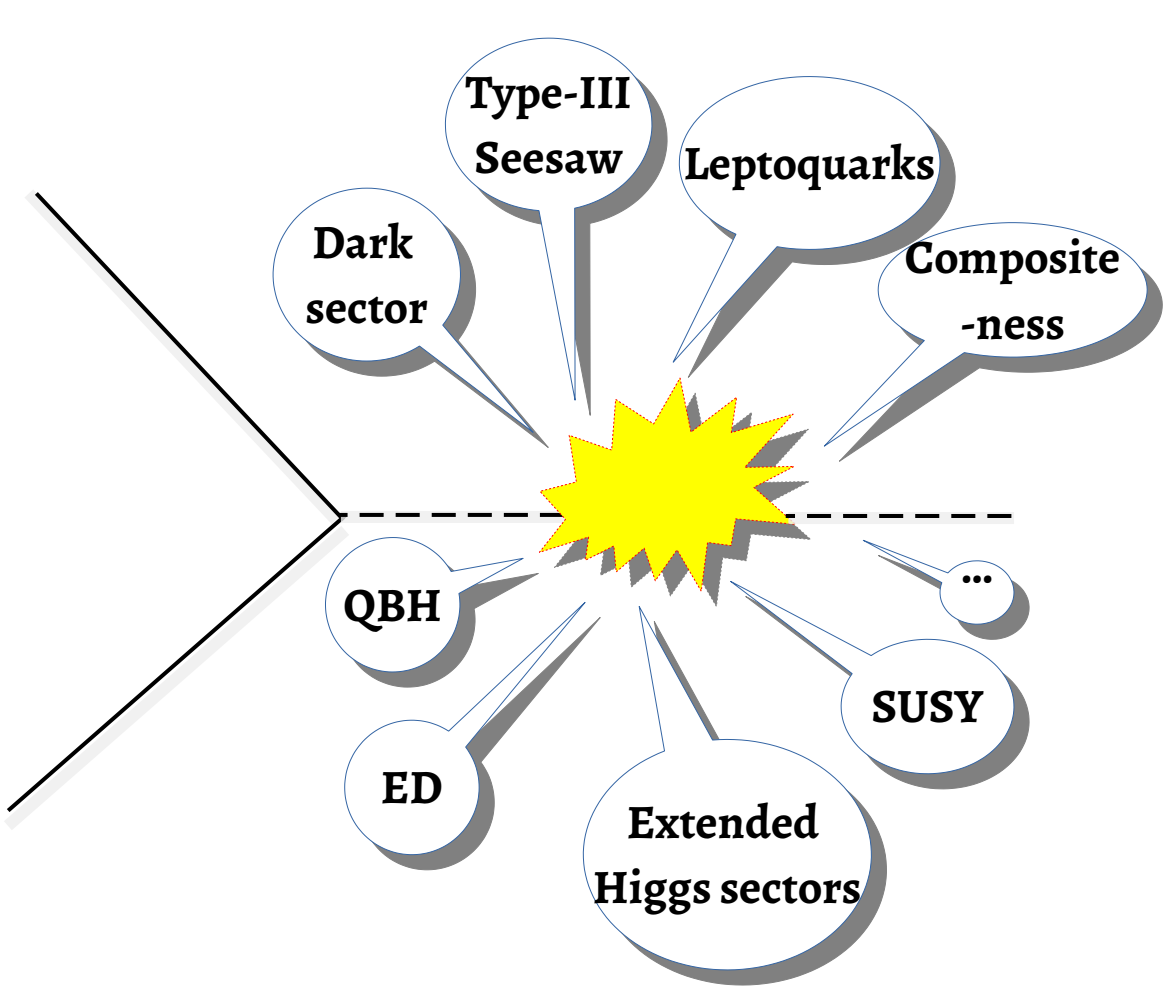


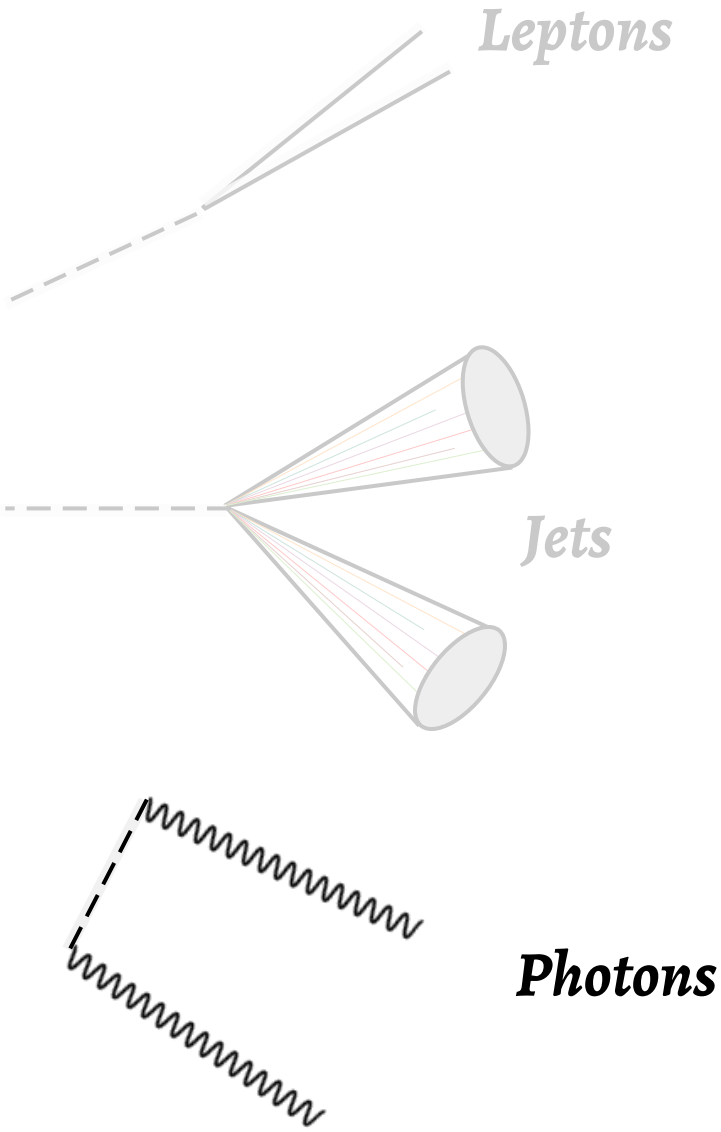




- For $m_N = m_W/2$, W_R observed to be excluded below 4.7 (5.2) TeV for the e (μ) channels.
- For m_N = 0.2 TeV, W_R excluded in the phase space up to 4.8 (5.0) TeV for the e (μ) channels.

BSM theories with photons

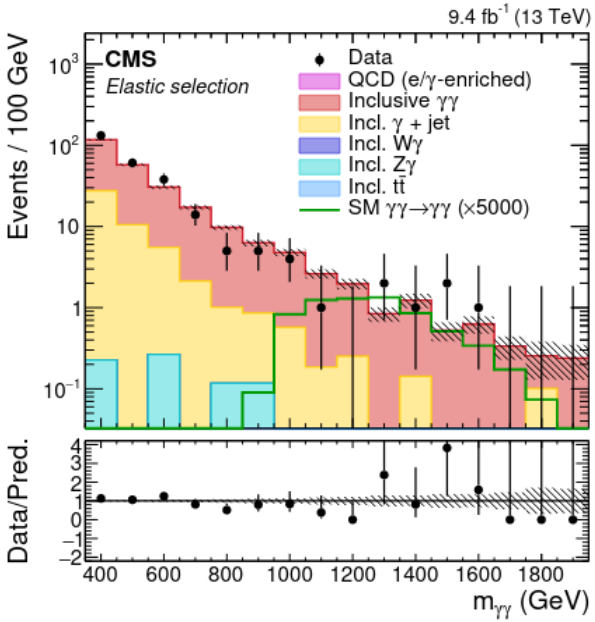




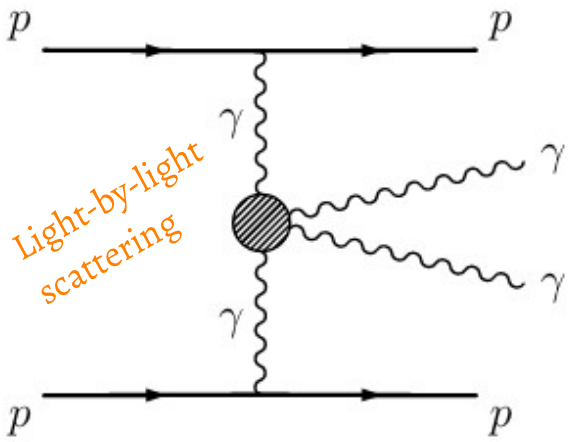
arXiv:2110.05916

Exclusive diphoton with tagged protons

- **New physics:** First search for exclusive diphoton production at high mass with tagged protons in proton-proton collisions at √s = 13 TeV.
- **Manifests as:** Two-photon production via photon exchange, with both protons intact. Effective extension of the SM Lagrangian, leading to dimension-8 term for four-photon coupling. $L_8^{\gamma\gamma\gamma\gamma} = \zeta_1 F_{\mu\nu}F^{\mu\nu}F_{\rho\sigma}F^{\rho\sigma} + \zeta_2 F_{\mu\nu}F^{\mu\rho}F_{\rho\sigma}F^{\sigma\nu}$

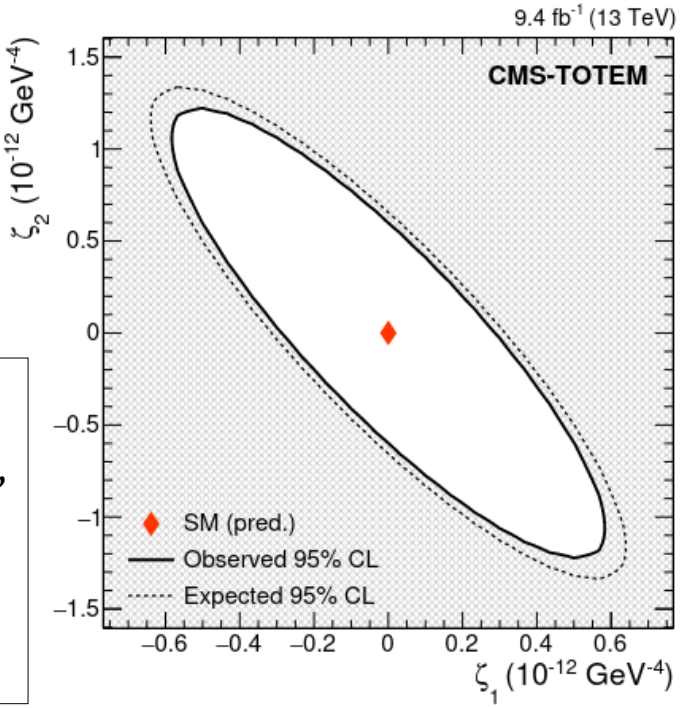


Data analyzed: 9.4 fb^{-1} collected in 2016 by CMS and TOTEM.
Major SM backgrounds: Inclusive γγ, Wγ, Zγ, and γ+jet.



Event selection:
Photons with pT>75 GeV, |η|<2.5,
$m_{\gamma\gamma} > 350$ GeV.
Diphoton acoplanarity,
$a = 1 - |\Delta\phi_{\gamma\gamma}/\pi| < 0.005$.

$|\zeta_1| < 2.88 \times 10^{-13}\,\text{GeV}^{-4} (\zeta_2 = 0)$,
$|\zeta_2| < 6.02 \times 10^{-13}\,\text{GeV}^{-4} (\zeta_1 = 0)$.

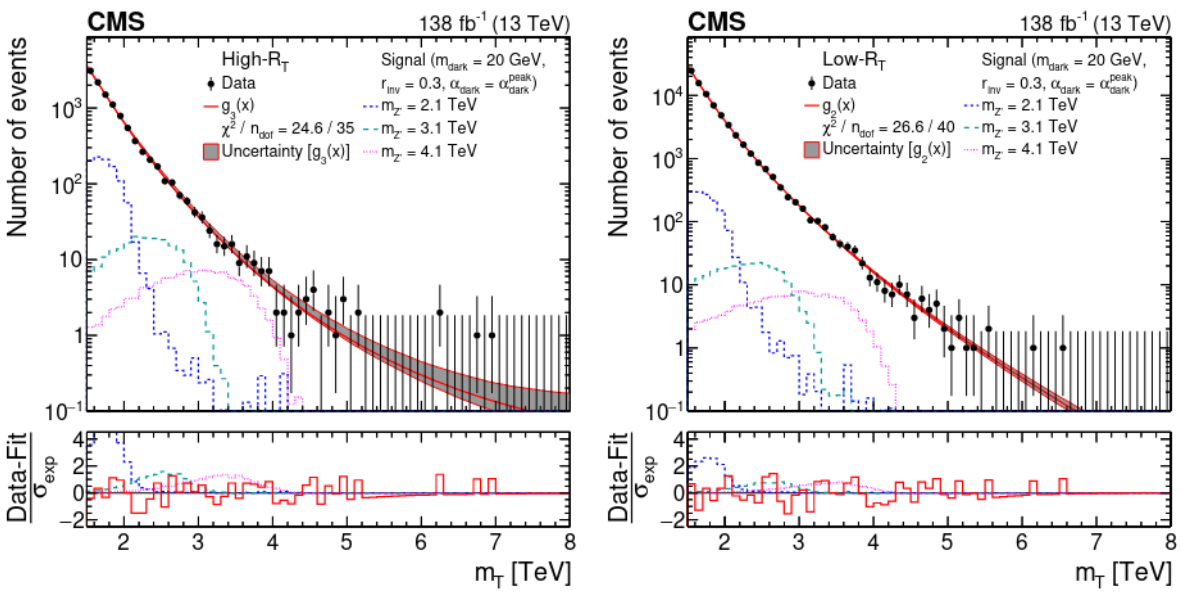


Scope for reinterpretation

Strongly coupled DM (arXiv:2112.11125)

- Inclusive signal regions doesn't rely on the details of jet substructure.
- Hence, can be applied to many signal models with a resonance producing jets aligned with pT^{miss}.

HEPDATA record for this analysis.



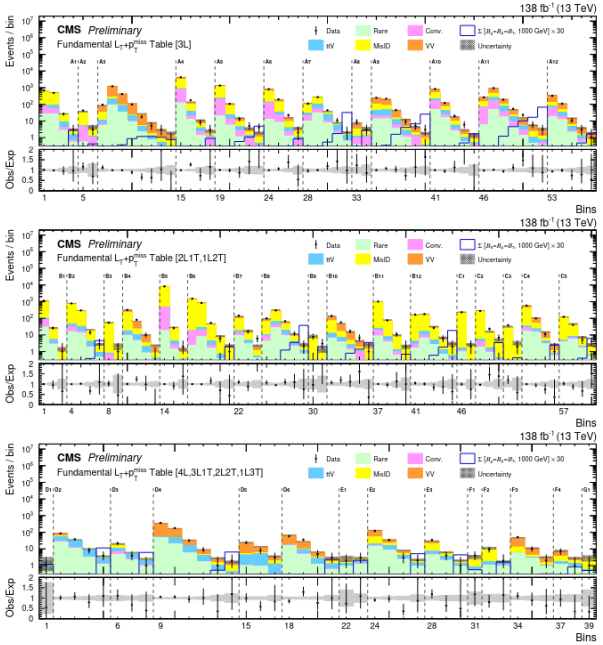
Multilepton with taus (CMS-PAS-EXO-21-002)

- Fundamental 43 model-independent categories:

		OSSF0			OSSF1				OSSF2		
		BelowZ	AboveZ	SS	OnZ	BelowZ	AboveZ	MixedZ	Single-OnZ	Double-OnZ	OffZ
3L	Low p_T/M_T	A1*		A2	A3	A4	A5	A6	–	–	–
	High p_T/M_T	A7*		A8	A9	A10	A11	A12	–	–	–
2L1T	Low p_T	B1	B2	B3	B4	B5	B6	–	–	–	–
	High p_T	B7	B8	B9	B10	B11	B12	–	–	–	–
1L2T		C1	C2	C3	–	C4	C5	–	–	–	–
4L		D1*			D2	D3*			D4	D5	D6
3L1T		E1*			E2	E3*			–	–	–
2L2T		F1*			F2*			–	F3	–	F4
1L3T		G1*			–	G1*		–	–	–	–

- Additional dimensionality from b tagged jets, H_T, and pT^{miss} – advanced scheme (204 categories)!

HEPDATA in preparation.



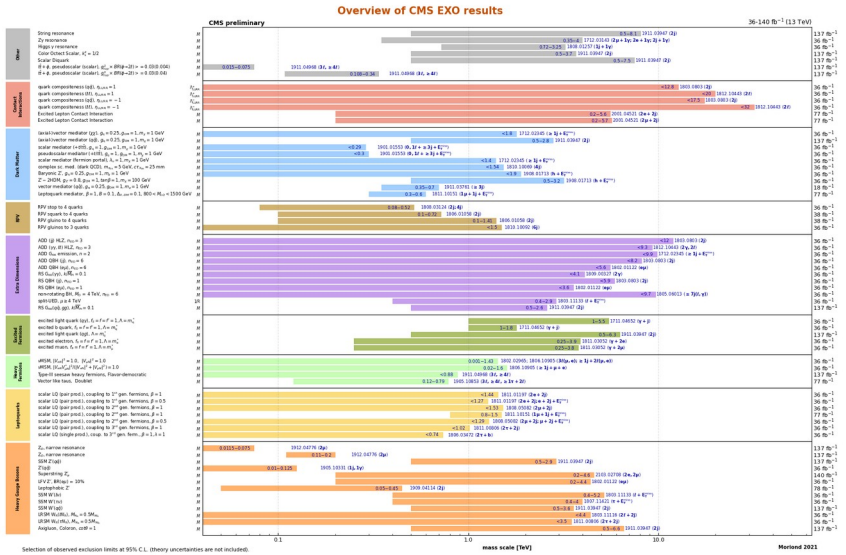
15 SRs (combined 2016–2018) in L_T+pT^{miss}.

257 SRs in S_T, and **2415** SRs in an advanced scheme!

Conclusion

- CMS has a widespread research program for understanding SM as well as BSM physics.
- Many exotic signals, both resonant and non-resonant, manifest themselves in final states with jets, leptons, and photons.
- Good reconstruction and comparatively low noise from SM allows us to span a wider phase space, thereby improving the exclusions. Use of innovative techniques including machine learning are also pushing the frontiers.
- Many new and existing results using better estimation procedures for SM processes with full Run2 data are already on the way.

Take a look at the impressive CMS-EXO reach so far here.

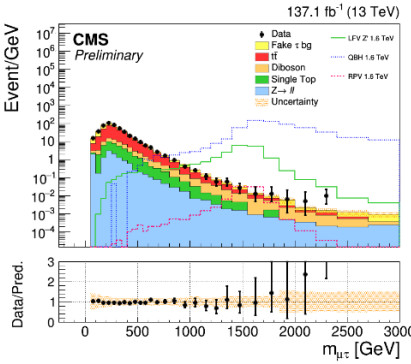


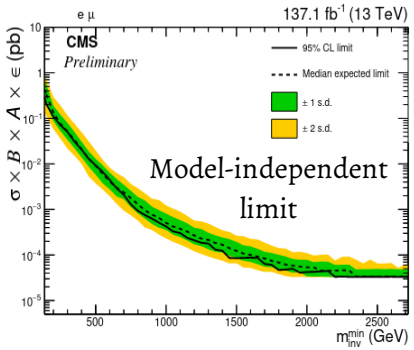
Stay tuned for Run3 and beyond... and let's keep hunting for new physics!

A few more highlights from CMS-EXO...

QBH, LFV Z', RPV τ sneutrino in eμ, eτ, μτ

CMS-PAS-EXO-19-014



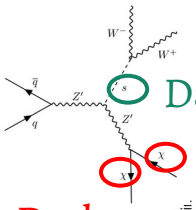


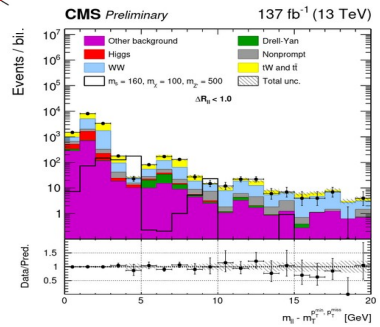
Channel	RPV (TeV) $\lambda = \lambda' = 0.01$	RPV (TeV) $\lambda = \lambda' = 0.1$	Z′ (TeV)	QBH (TeV)
eμ	2.2 (2.2)	4.2 (4.2)	5.0 (4.9)	5.6 (5.6)
eτ	1.6 (1.6)	3.7 (3.7)	4.3 (4.3)	5.2 (5.2)
μτ	1.6 (1.6)	3.6 (3.7)	4.1 (4.2)	5.0 (5.0)

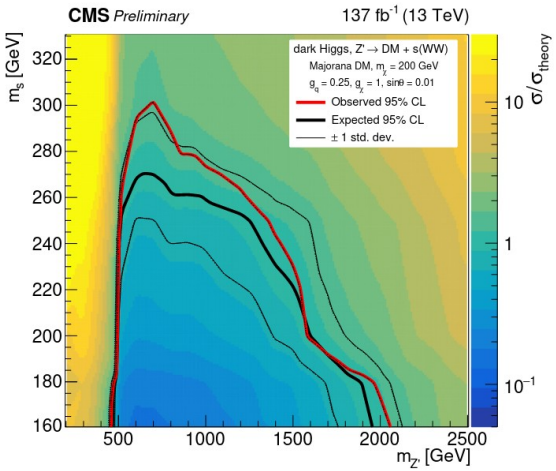
Best collider limits on these models to date.

DM + dark higgs → W+W-(→ℓℓνν)

CMS-PAS-EXO-20-013

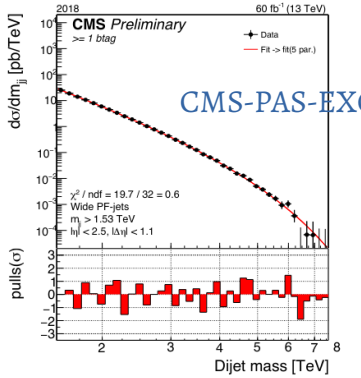


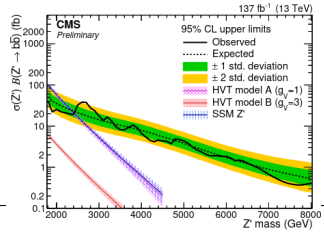




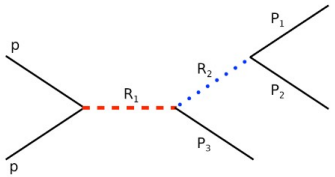
Heavy resonances to b quark pair

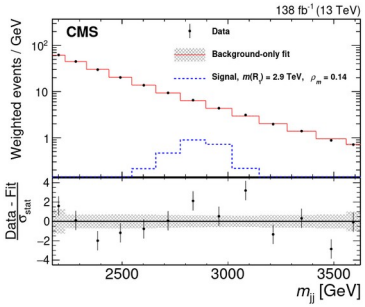
CMS-PAS-EXO-20-008



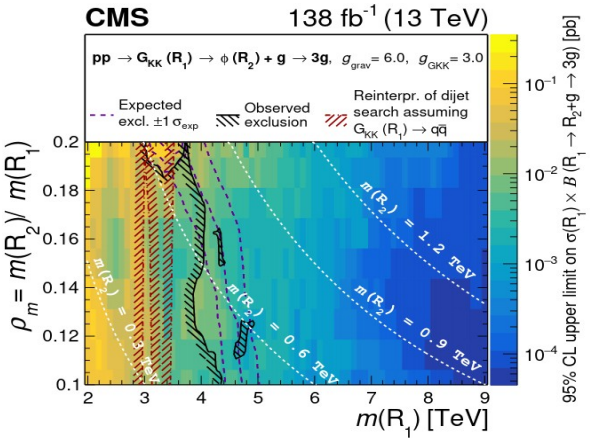


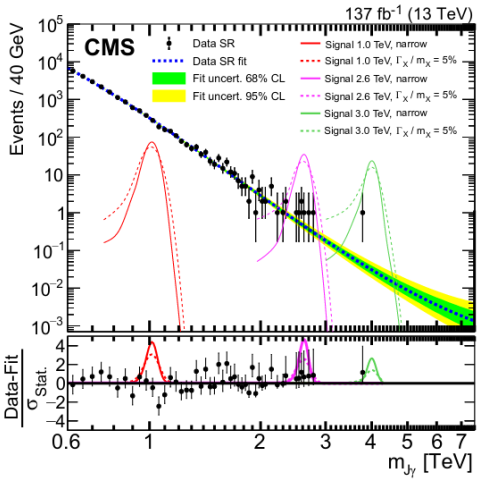
High mass trijet resonances with boosted dijet resonances





CMS-PAS-EXO-20-007





Wχ resonance

arXiv:2106.10509