Recent Exotics/BSM Results

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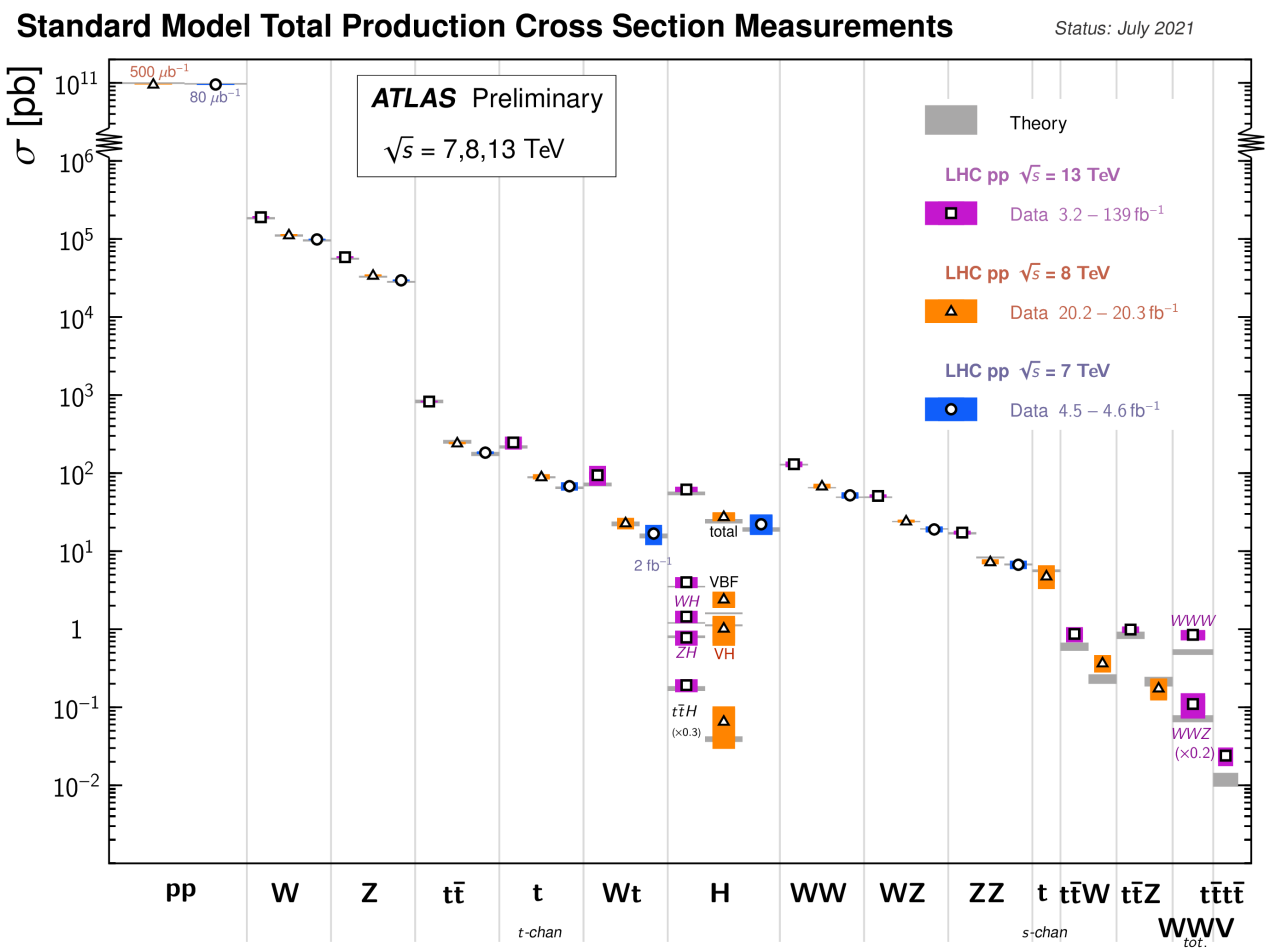
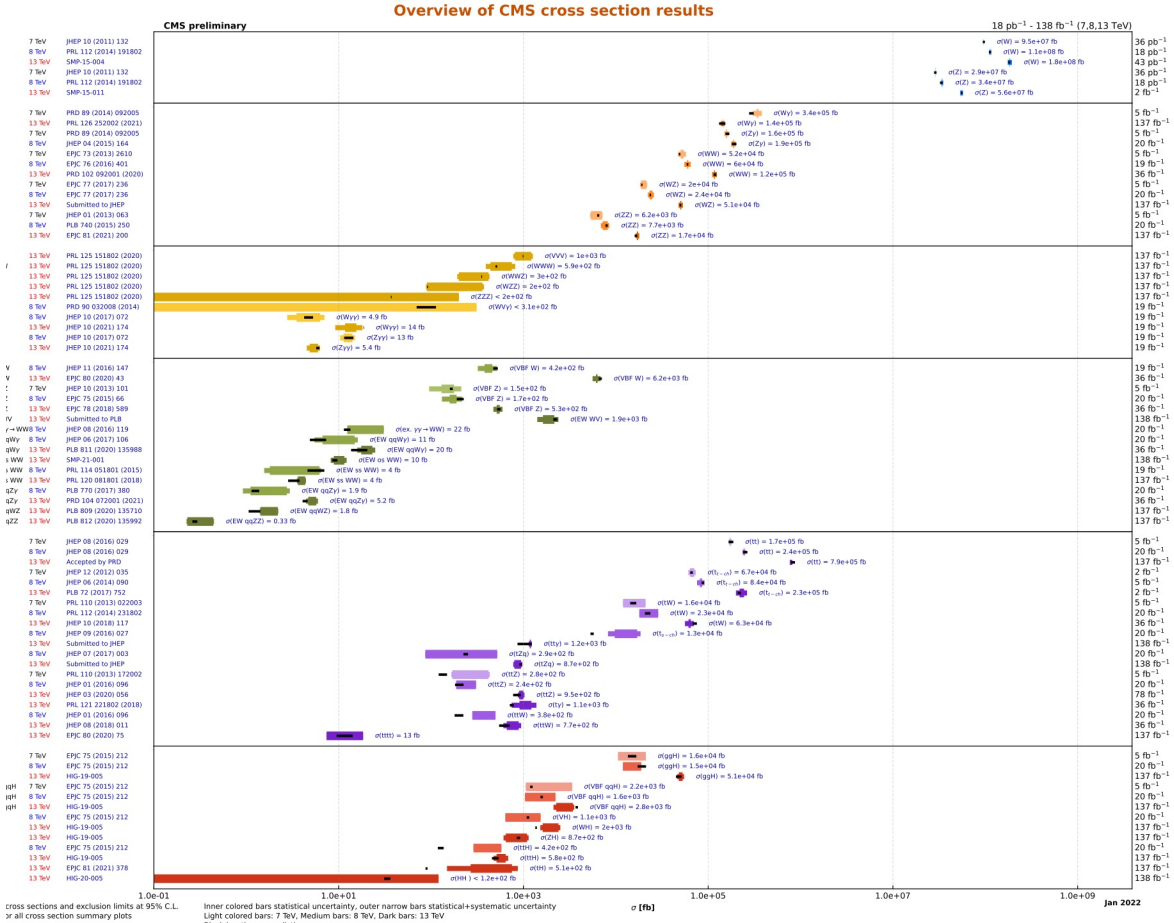
On behalf of ATLAS and CMS Collaboration

New methods and ideas at the frontiers of particle physics
20-Mar-2022

Triumph of the standard model

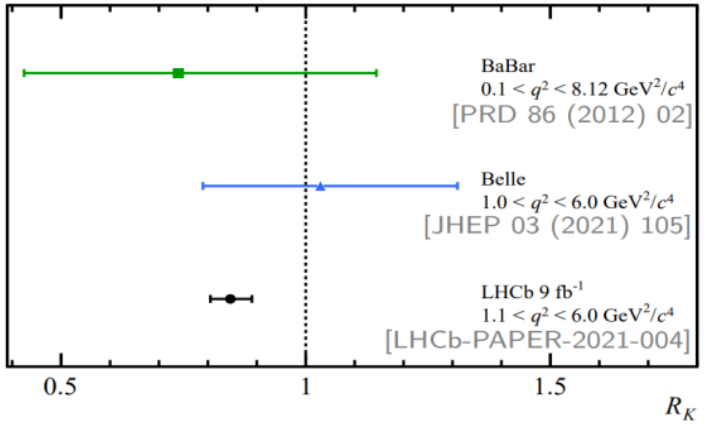
- So far, the standard model predicts pretty much everything we observed …

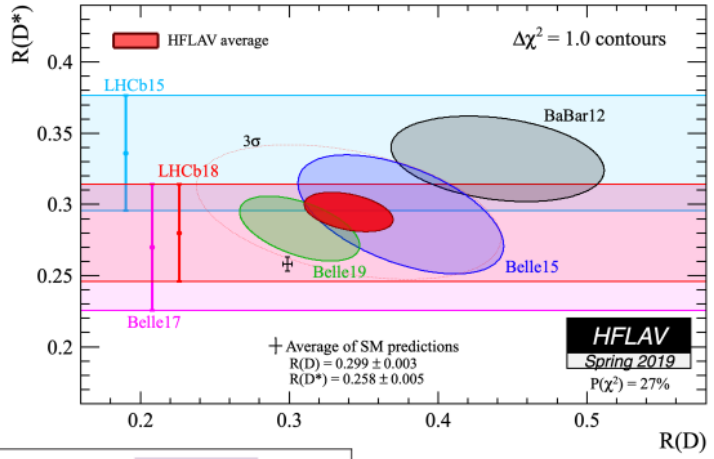


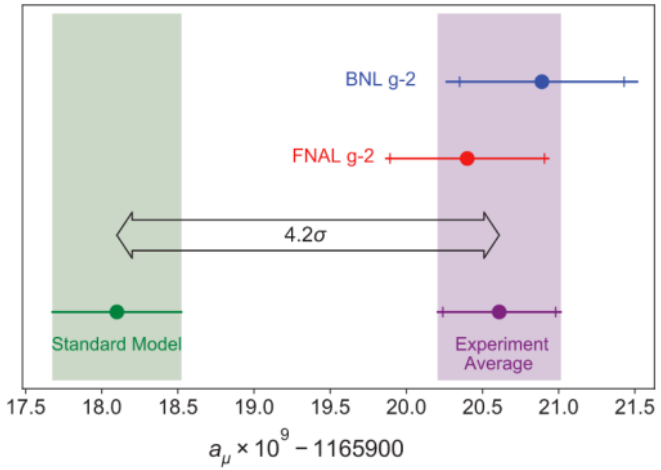


Quest for new physics

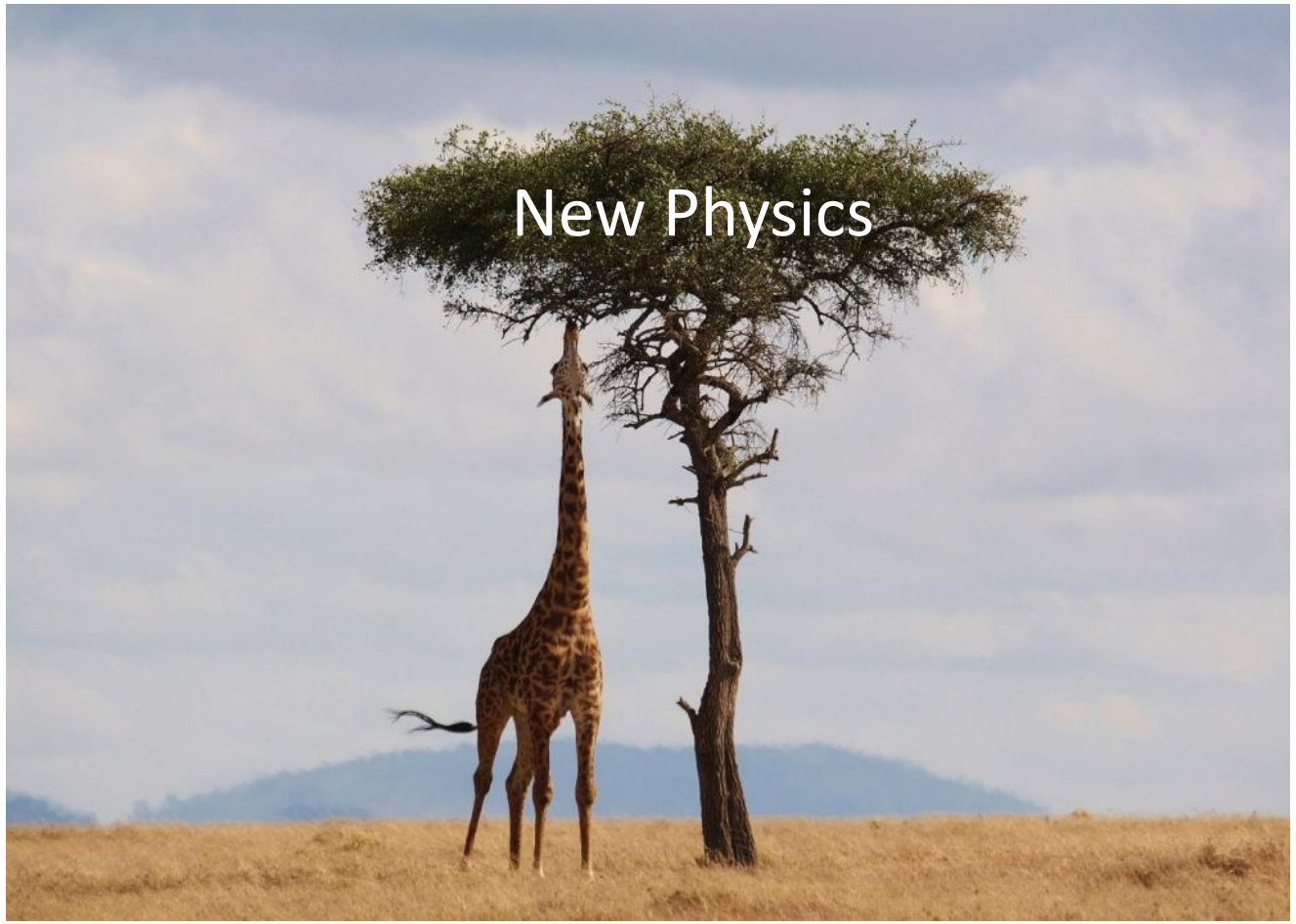
- The standard model is a low-energy approximation theory, and we were hopeful to find new physics early from the start of the new energy frontier
  - Dark matter candidate?
    - SUSY, Higgs → inv
  - What makes Higgs boson light?
    - SUSY, Vector-like quarks
  - Origin of neutrino masses?
    - Heavy neutrinos
  - Flavor anomalies, g-2, CKM…
    - LQs, Z'/W', vector-like leptons
- New fermions/scalars, new interactions





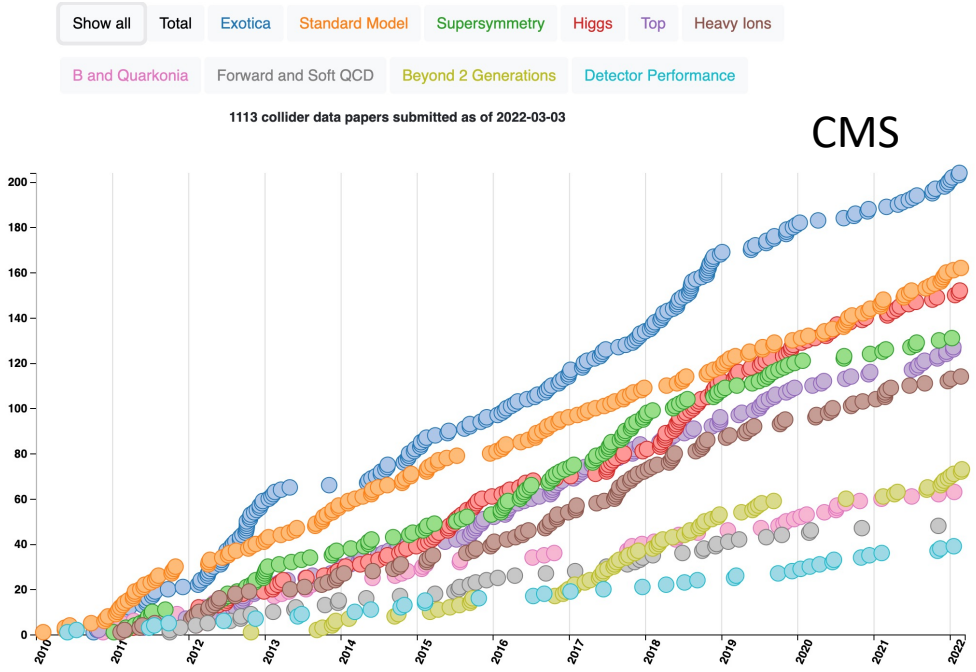


New methods and ideas at the frontier



Focus of this talk: new ideas in BSM

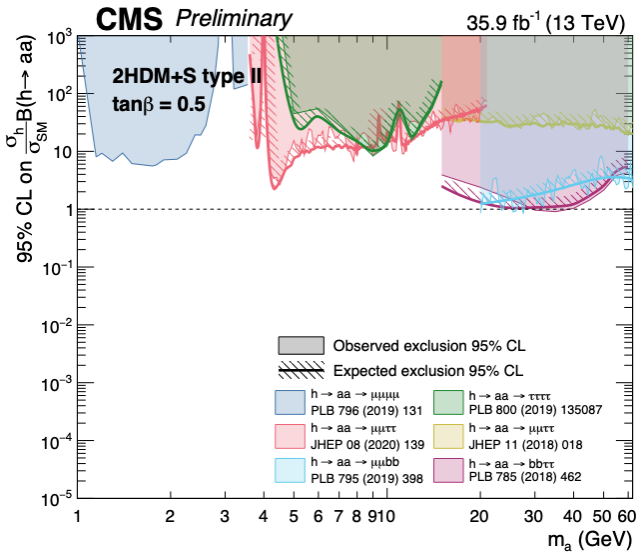
- Capitalize on full hardware and data analysis capabilities of the detectors
  - Advancement of data analysis tools allows expanding the sensitivity to experimentally challenging processes (DNN, graph CNN)
- Both ATLAS and CMS has a vibrant physics program with a lot of new results
  - Too many to present during this short talk. Here is a quick links to public results from the ATLAS and CMS
    - ATLAS public results
    - CMS public results: papers and preliminary results
- Here, I will focus mainly on recent results that use new techniques and ideas to search for new physics



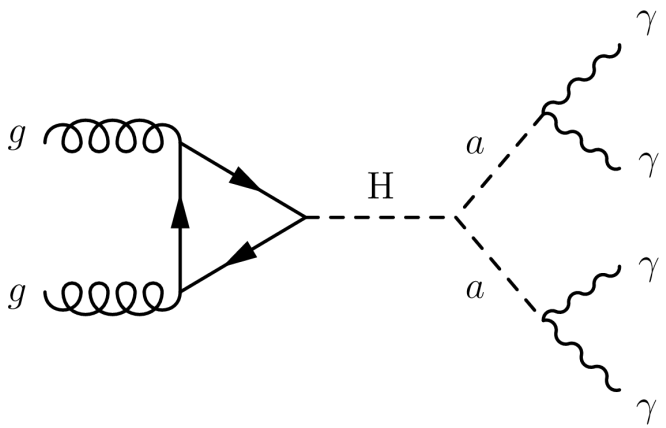
Search for H → $AA \to 4\gamma$

CMS-HIG-21-016

- Motivated by various extensions of the Higgs sector
  - A → $\ell\ell$ has been investigated in the past, but A → $\gamma\gamma$ has a clear experimental signature, and if A is fermiophobic, diphoton final state is the only process where A can be discovered
    - Higher mass pseudoscalar searches (above 10 GeV):
      ATLAS: Run 1 $3\gamma + X$ search EXOT-2013-24,
      CMS: Run 2 4γ CMS-HIG-21-003
  - No evidence for light resonance with masses above 10 GeV
    Limits are set at around 1 – 0.3 /fb for 15 – 60 GeV masses of A @ 95% CL



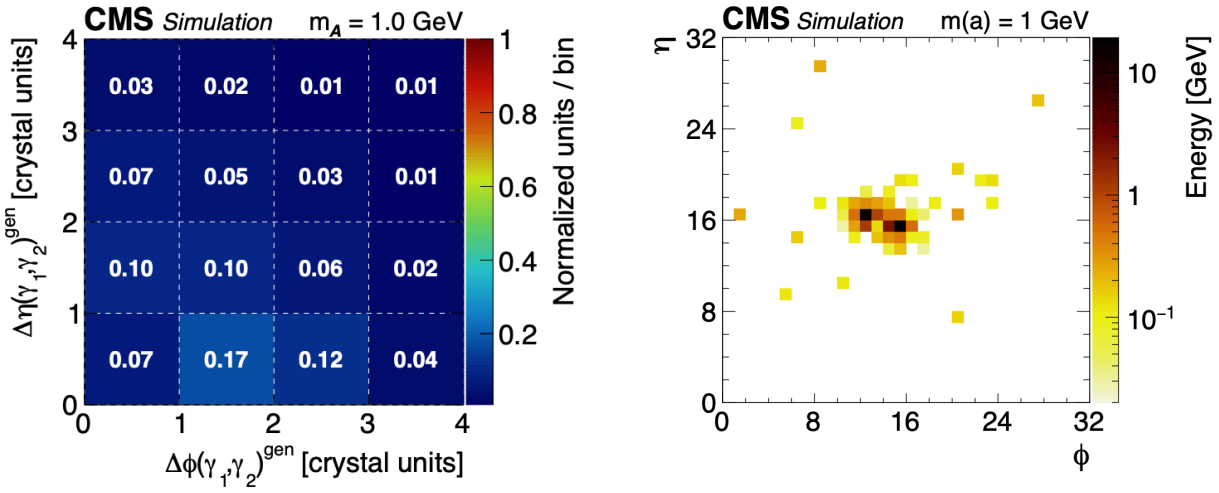
- Very low mass is unique as photon merge into a single shower
  - Could be impossible to separate from the vanilla H→ $\gamma\gamma$ process without a dedicated reconstruction
- New search in the boosted final state CMS-HIG-21-016



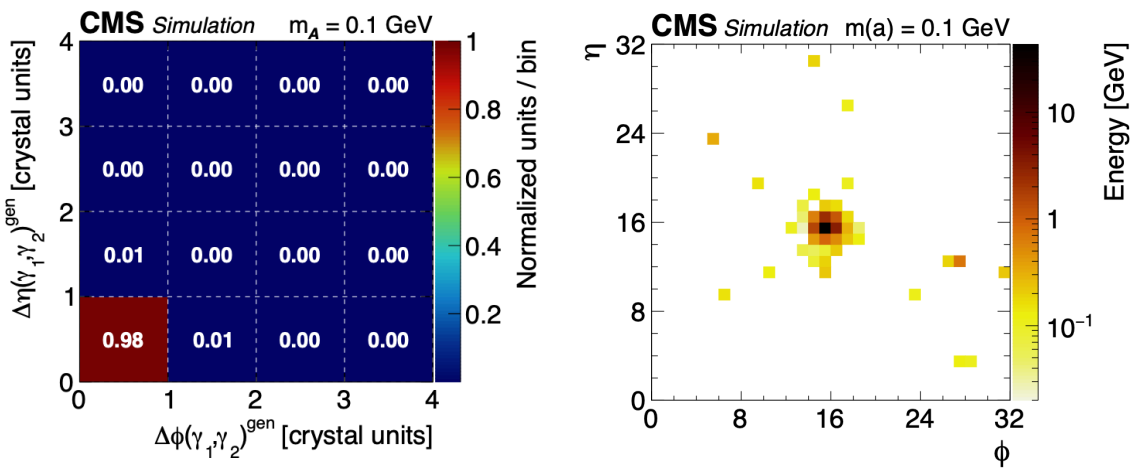
How do we reconstruct boosted γγ?

- Most of energy for higher mass resonance is deposited in a single crystal!

m_A = 1.0 GeV
$\gamma_L \approx 60$



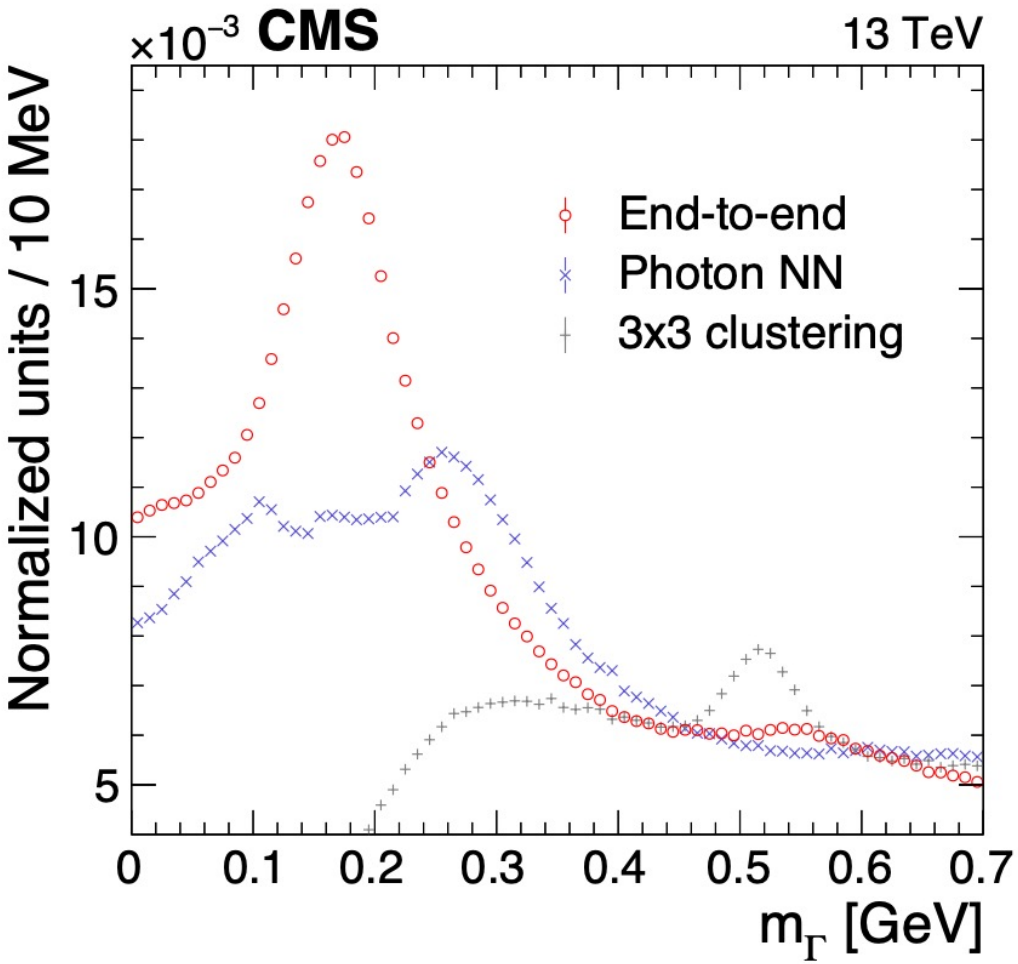
m_A = 0.1 GeV
$\gamma_L \approx 600$



- Develop a dedicated ResNet convolutional NN to reconstruct the mass of the diphoton candidate based on the energy deposition in the $\eta - \phi$ space
  - Validate on data by reconstructing π^0 candidates

Reconstruction of π^0 with CNN @ CMS

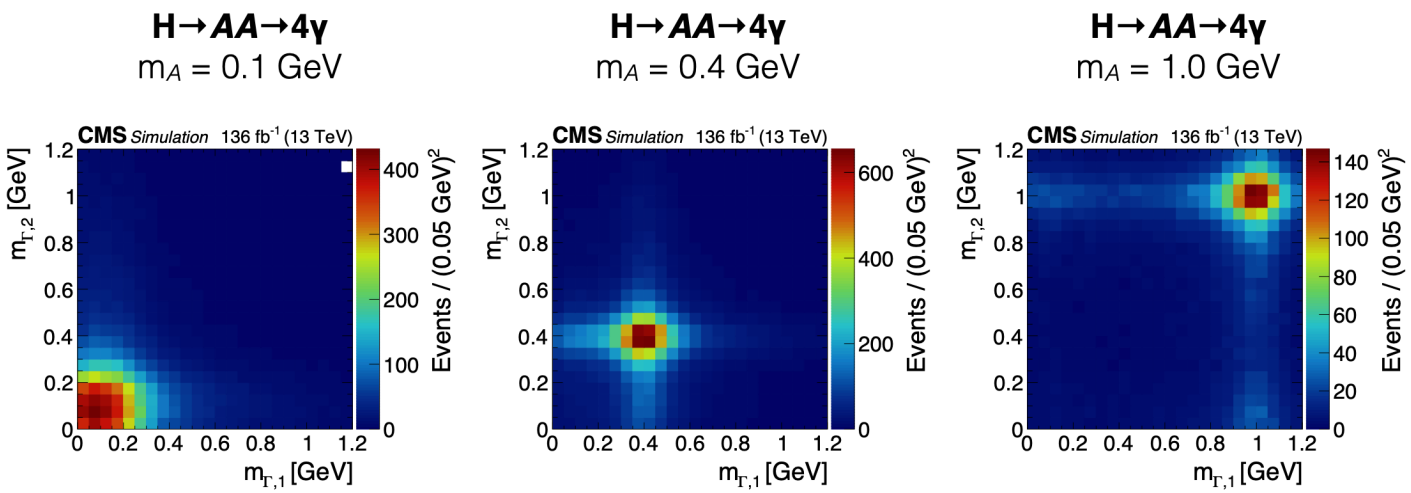
- Excellent performance of the CNN in data



Search for H → AA → 4γ

CMS-HIG-21-016

- Use 2D candidate mass (leading p_T vs. sub-leading p_T diphoton candidate)

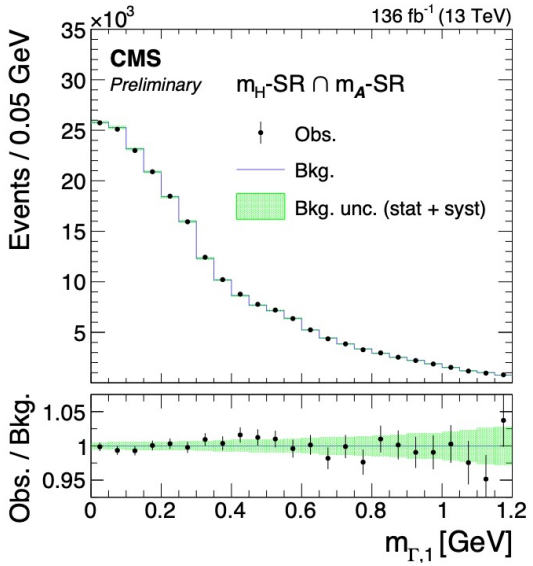


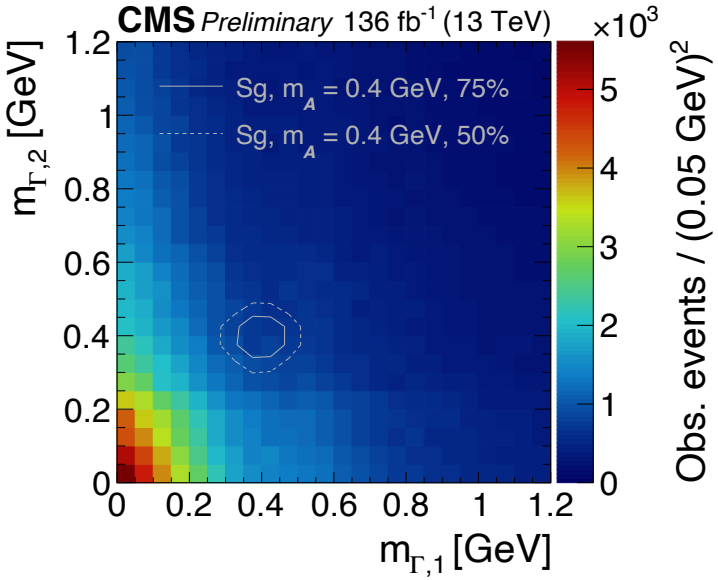
- Assumptions: identical mass hypothesis and prompt $A \to \gamma\gamma$ decay
- Use maximum likelihood estimation to determine the compatibility of observed template with signal and background models
  - Signal region: 110 GeV < m_A < 140 GeV
  - Signal template: 2D diagonal using simulation
  - Background template: binned 2D template from data and SM H → 2γ simulation in sidebands of diphoton invariant mass and 2D distributions

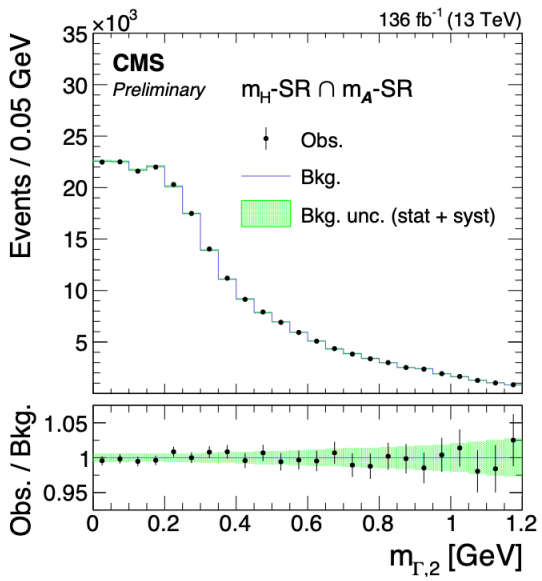
Search for H → $AA \rightarrow 4\gamma$

CMS-HIG-21-016

- No evidence for a resonant structure







Search for H → AA → 4γ

CMS-HIG-21-016

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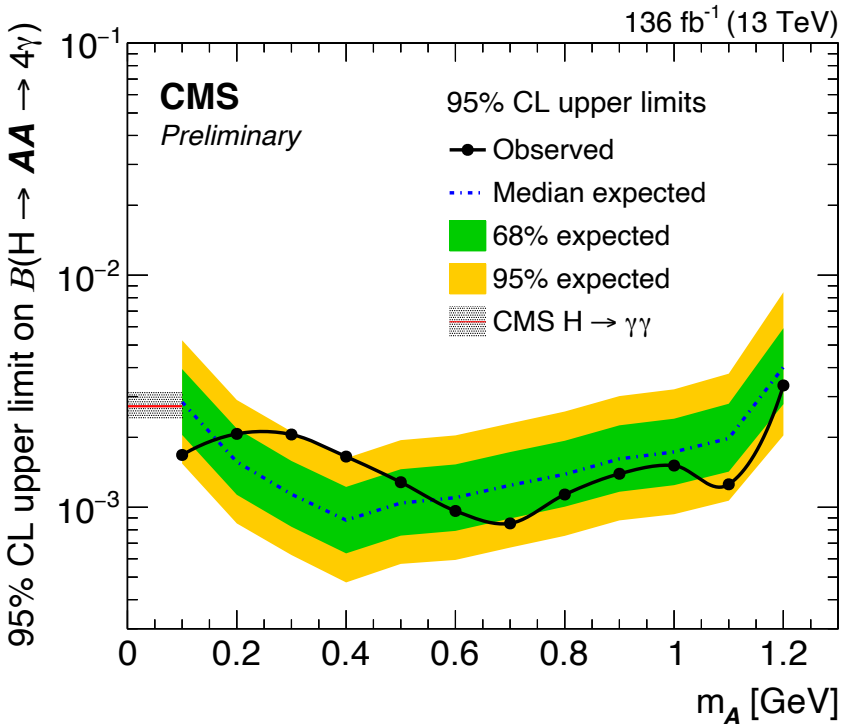
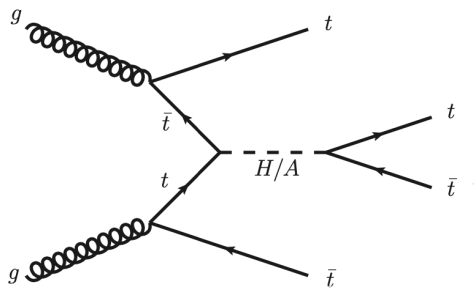


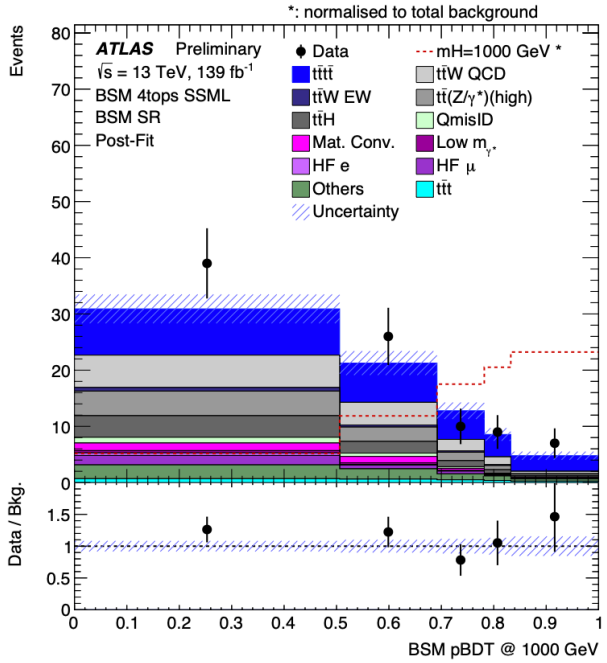
- Improves indirect constraints from Br(H→ $\gamma\gamma$)
- First CMS limits below $A \rightarrow \mu\mu$ threshold
- Future: adapt CNN to look for di-electron resonance; look at GNN

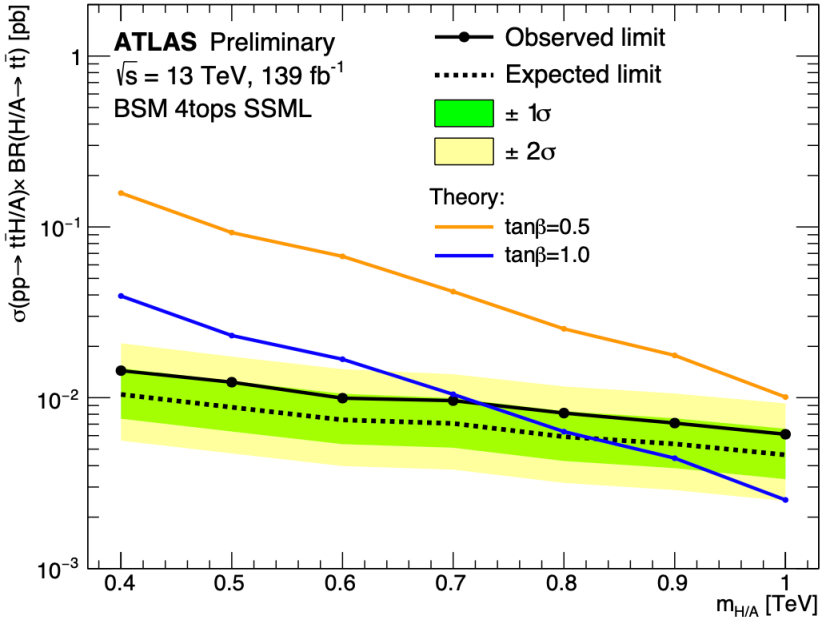
Search for new heavy H/A → $t\bar{t}$

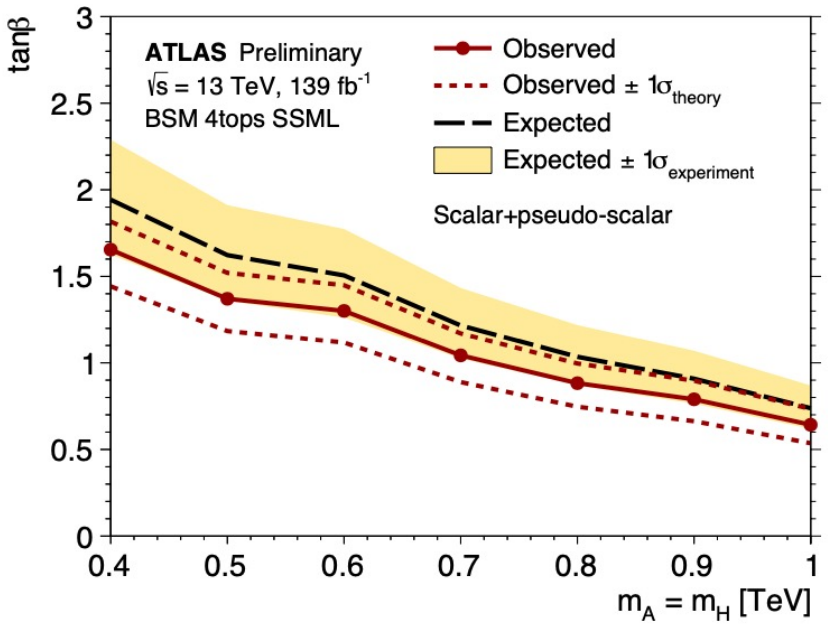
ATLAS-CONF-2022-008

- Search for SM-like boson predicted by MSSM, axion models, 2HDM
  - Dominant decay mode to a pair of top quarks: inclusive production has a negative interference with $gg \to t\bar{t}$: search in $t\bar{t}$H/A associative production instead
  - Final state: at lest 6 jets, ≥ 2 of which are b-tagged; H_T > 500 GeV
  - Sequential XGBoost BDT classifiers to separate
    - 4t final state from other backgrounds
    - SM 4t from signal (mass-parameterized BDT)







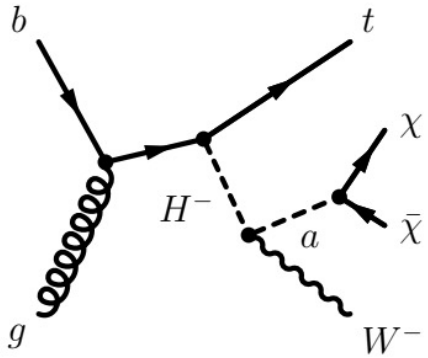


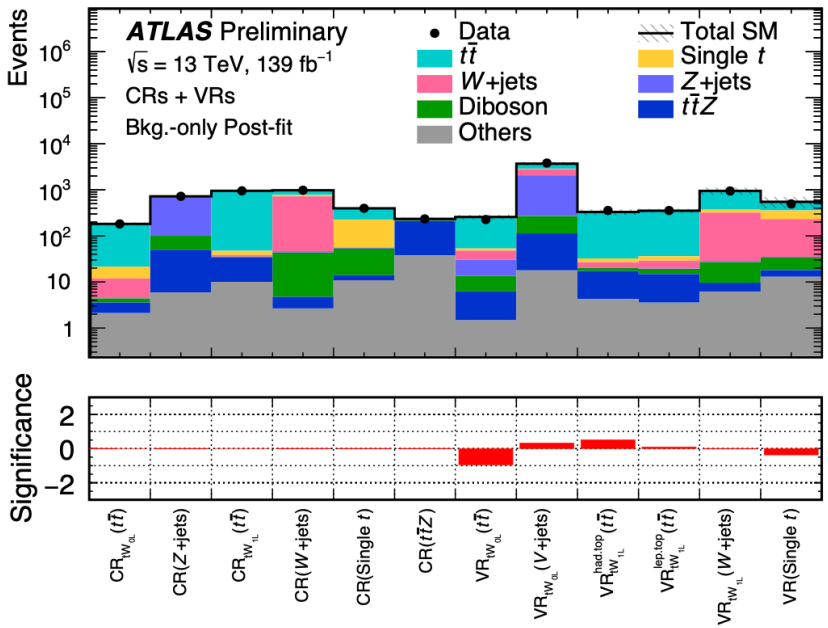
Search for dark matter in tW

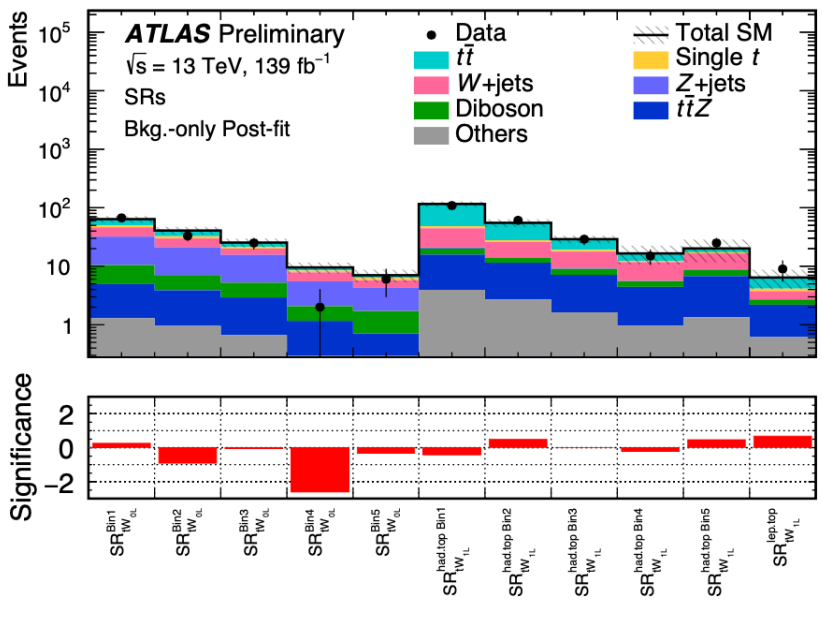
ATLAS-CONF-2022-012

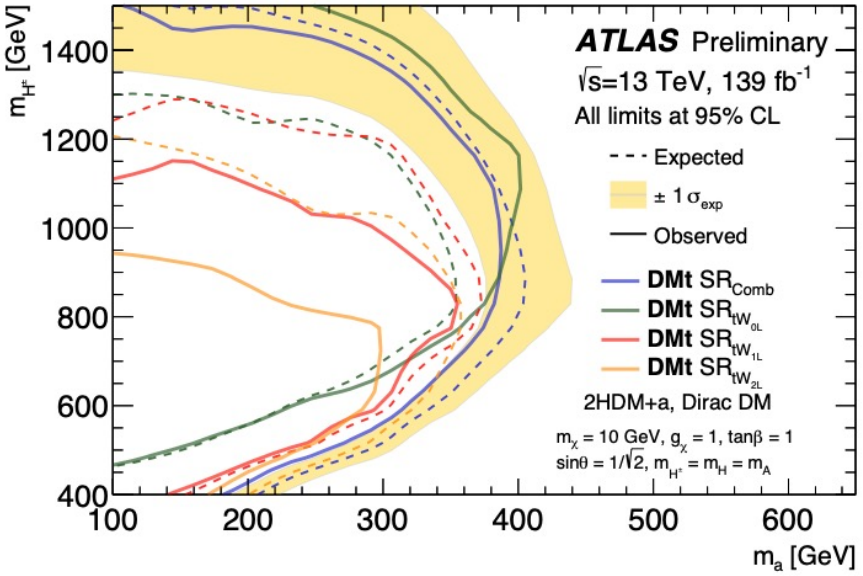
M. Bauer et al, 1701.07427

- Search for a DM candidate within the 2HDM
  - Complements the t+MET+X ATLAS analysis with Run 2 data and t/ttbar+MET CMS analysis with 2016 dataset
- Consider final states with 0 or 1 e/μ + at least one b-jet (DNN DL1r), high jet multiplicity, and significant MET due to χs
  - Backgrounds (V+jets, ttbar, tt+Z, single top) are estimated from data using CR
- Results are combined with the previous ATLAS analysis with two leptons in the final state





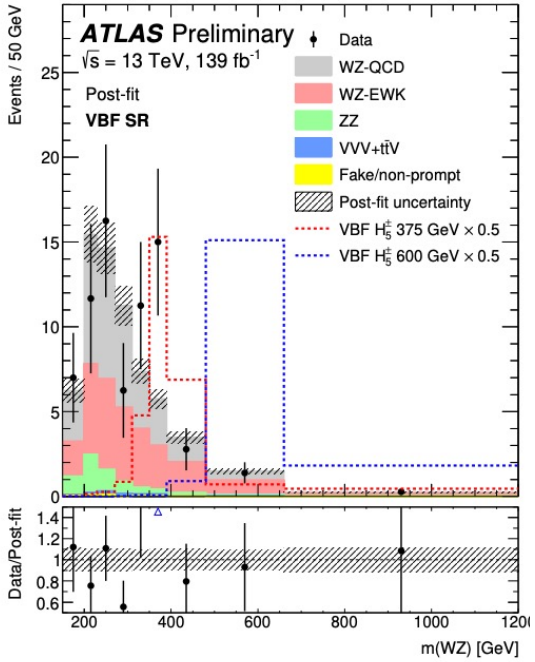


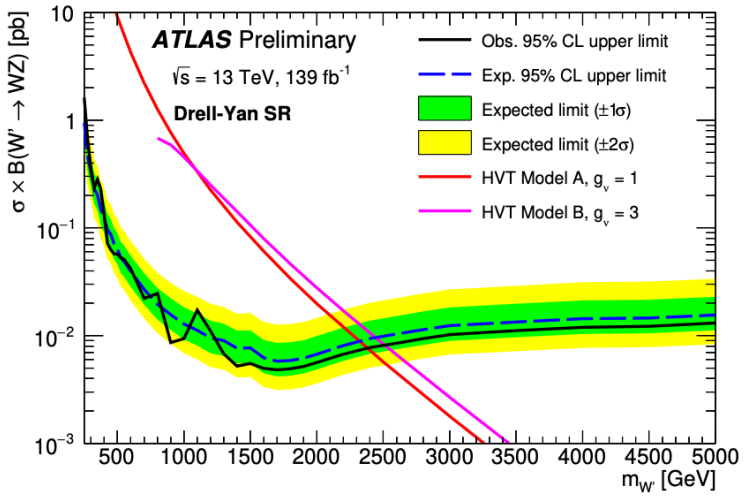


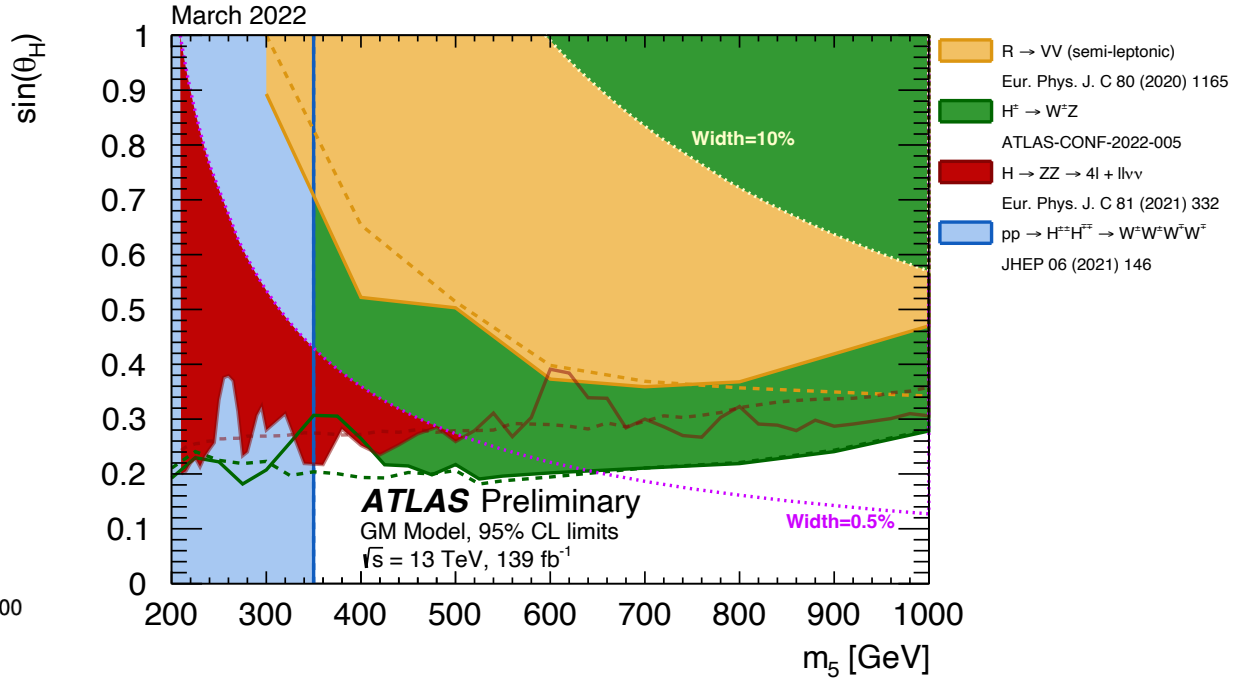
Search for resonant WZ → $\ell\nu\ell'\ell'$

ATLAS-CONF-2022-005
ATL-PHYS-PUB-2022-008

- Interpretation within a Georgi-Machacek model (VBF production) and a Heavy Vector Triplet (HVT) W' (both Drell-Yan and VBF)
  - Use Keras ANN to categorize events as coming from a VBF process or background
  - Use dedicated control regions to validate major backgrounds: WZ and ZZ
  - Final discriminant in all signal regions is the mass of the WZ system
- Interpretation of this and all previous heavy Higgs boson searches within GM model is documented as a separate note ATL-PHYS-PUB-2022-008



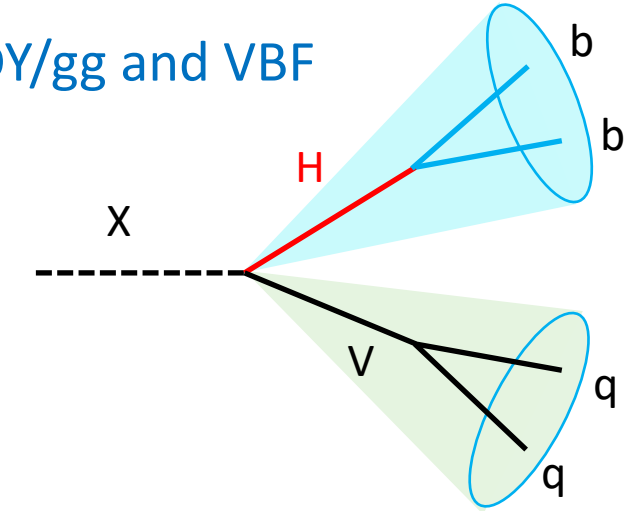


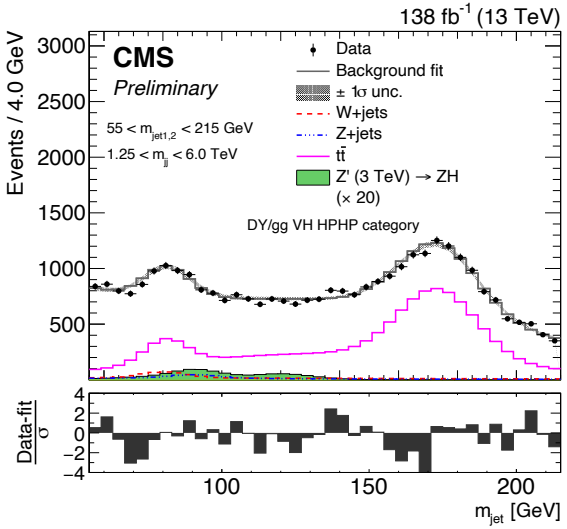


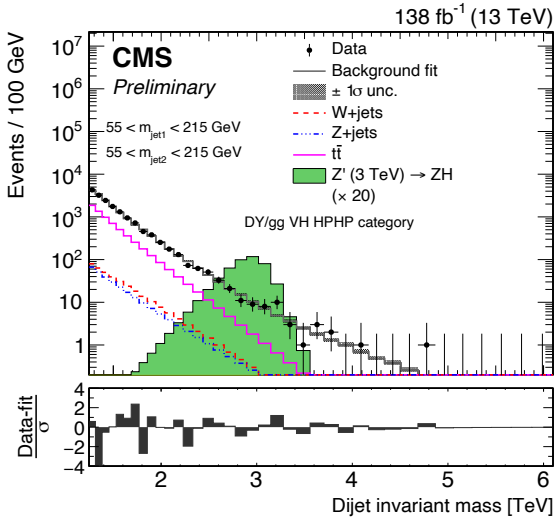
Search for VV → jets

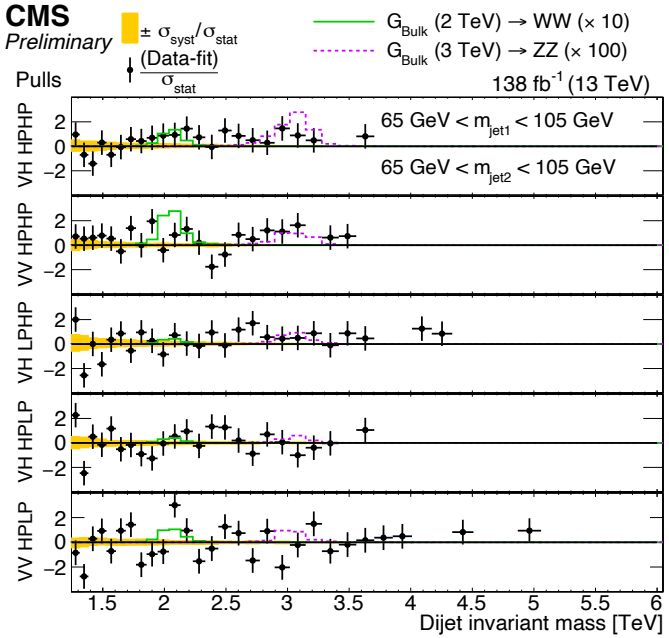
B2G-20-009

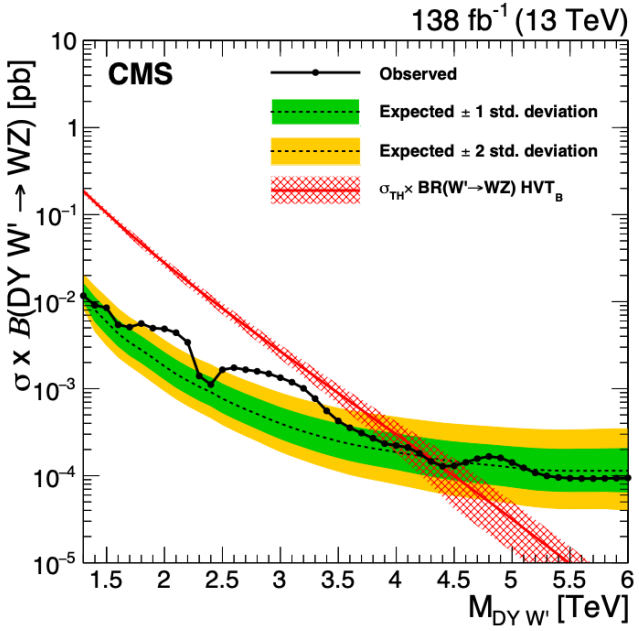
- Target heavy mass resonant production of WW, ZZ, WZ, WH, and ZH in DY/gg and VBF production
  - RS R/G, W' and Z' from composite/little Higgs models, HVT
  - Boosted regime: two "fat" AK8 jets (+2 jets for VBF)
    - Significant improvement wrt to previous results due to DeepAK8 to separate W/Z/H from gluon or quark jets
- 10 categories (VBF/ggH, high and low purity)
- 3D bump hunt in m_{jet1}, m_{jet2}, m_{jets}
- Mild 3.6σ (local) 2.3σ (global) excess at around 2.1 and 2.9 TeV









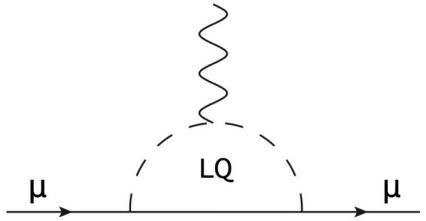


Search for cross-generational LQs

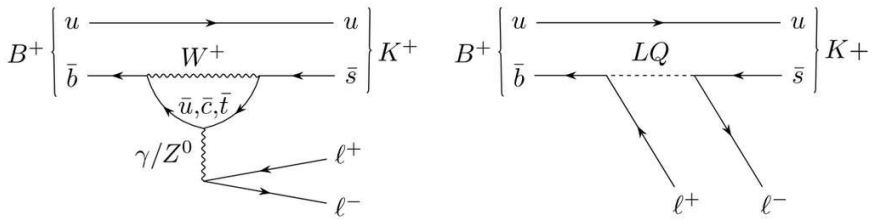
ATLAS-CONF-2022-009

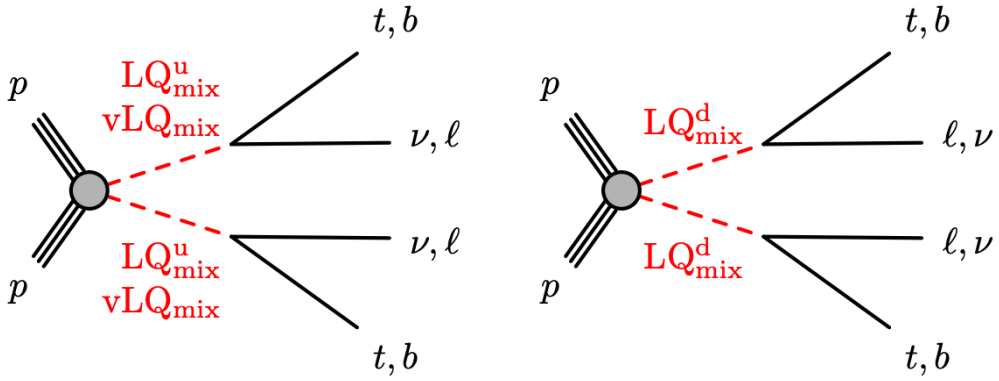
- Traditional LQ searches focused on scalars and decaying to the same generation leptons and quarks
  - Two charged leptons in the final state are easier
- Cross-generational vector LQs could accommodate both g-2 and existing $B \to K\ell\ell$ and $B \to D\tau\nu$ anomalies

R. Alonso et al: arXiv:1505.05164
R. Barbieri et al: arXiv:1512.01560



- Dedicated search for pairs of CG LQs with all possible decays to 3rd generation quarks (t, b) and 1st/2nd generation leptons (e, μ, ν) final state
  - Focus on single lepton (e, μ) final state; vector LQ optimization
  - One e or μ, high MET, at least 4 jets
  - Dedicated NNs to separate signal and backgrounds (tt, W+jets, single top) are trained on the orthogonal control regions in data

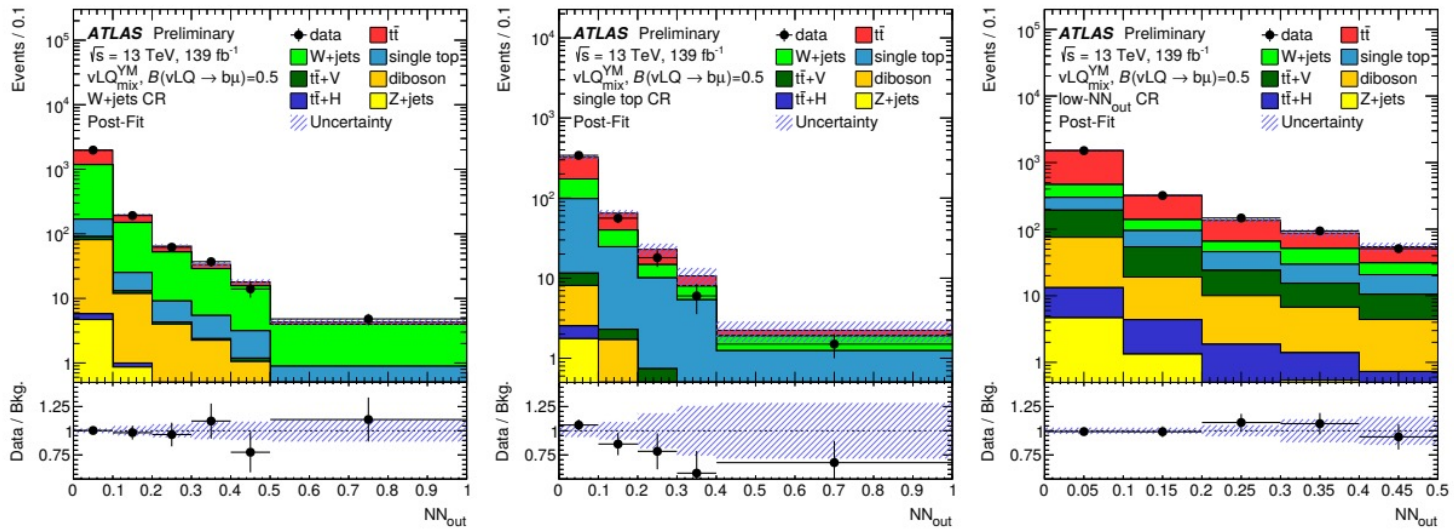




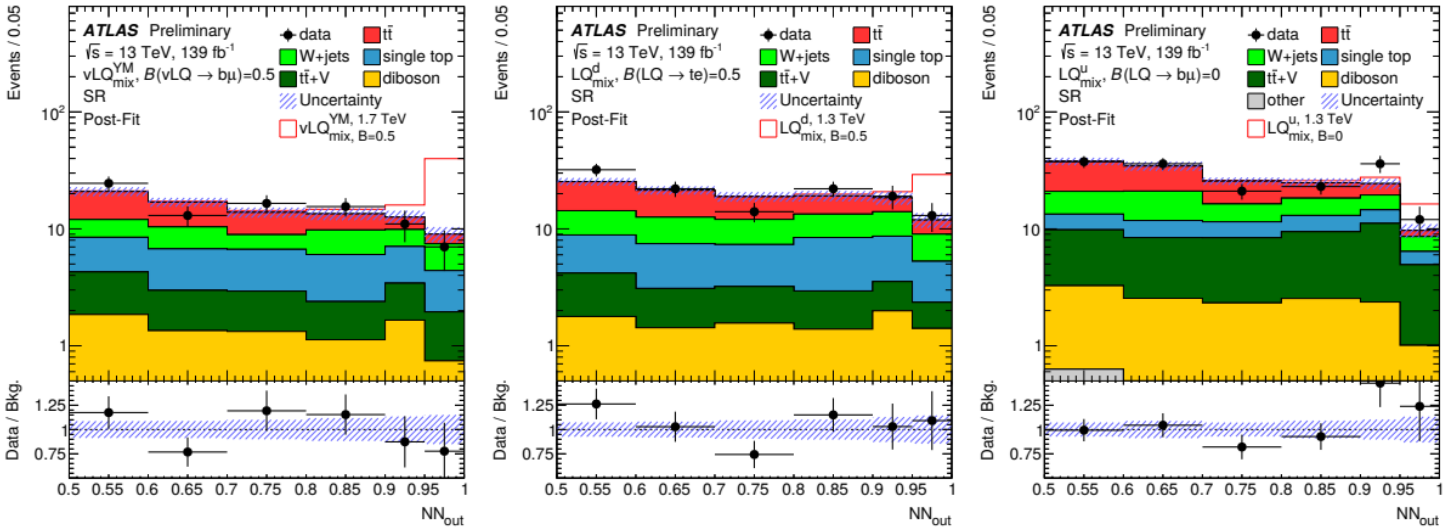
Search for cross-generational LQs

ATLAS-CONF-2022-009

- Data-background prediction for W+jets, single-top and low-NN (dominated by tt-bar) regions
  - $LQ^{YM}_{mix} \rightarrow b\mu/t\nu$ with B = 0.5



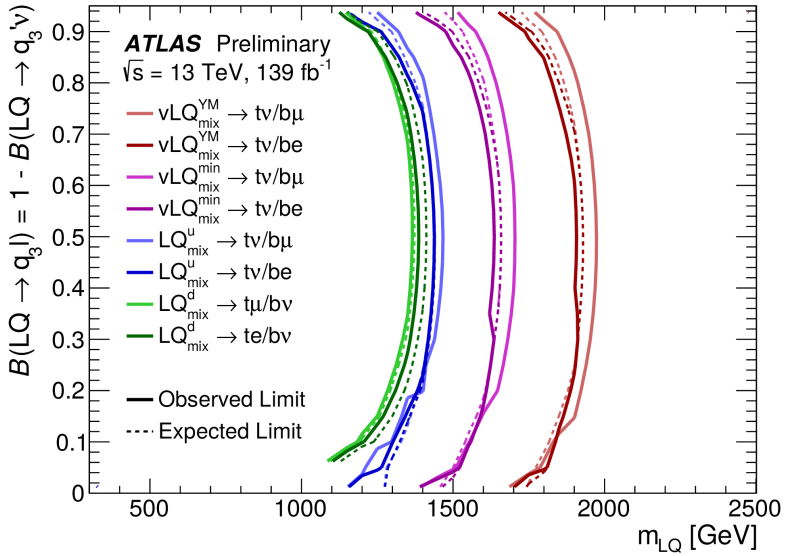
- Data-background prediction for signal regions

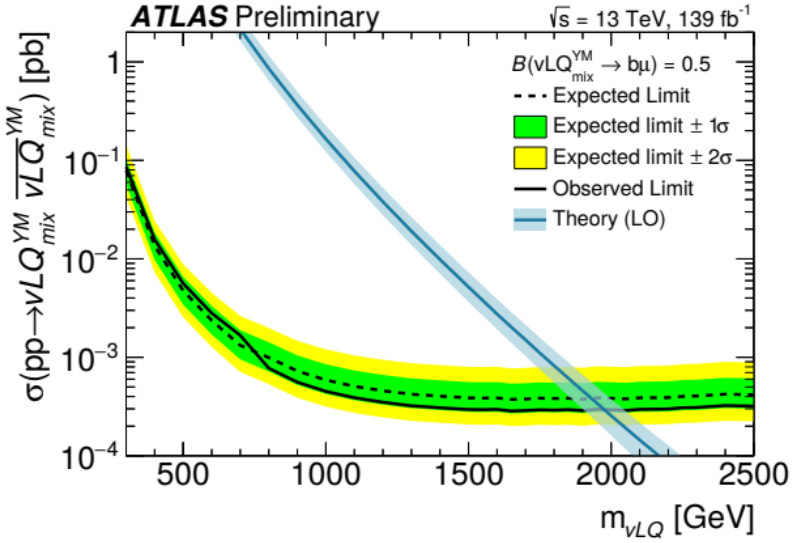


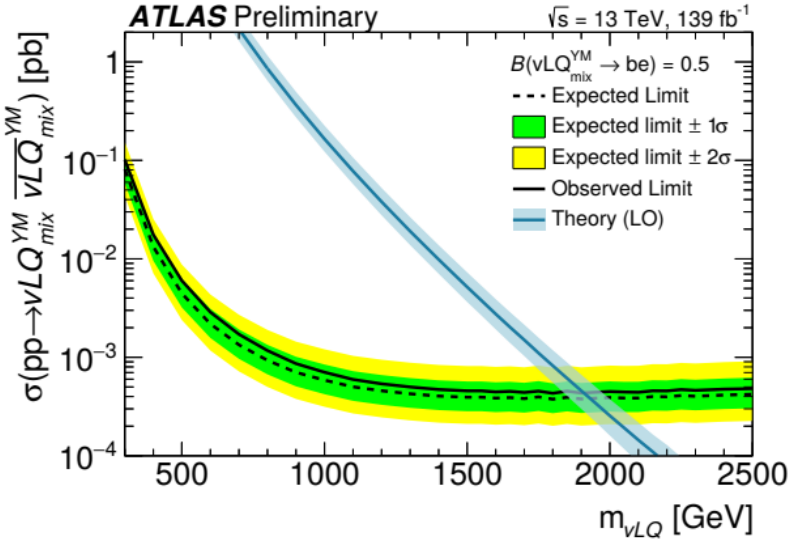
Search for cross-generational LQs

ATLAS-CONF-2022-009

- No significant excess observed. Limits at around 1.4 – 1.9 TeV were set on scalar and vector LQs for eight different models
  - Limits on the vector leptoquarks that could be responsible to B-anomalies are between 1.7 and 1.9 TeV depending on the coupling scenario







	Exp. limit [GeV]	Obs. limit [GeV]
$LQ^u_{mix} \to t\nu/b\mu$	1440^{+60}_{-60}	1460
$LQ^u_{mix} \to t\nu/be$	1440^{+60}_{-60}	1440
$LQ^d_{mix} \to t\mu/b\nu$	1380^{+50}_{-60}	1370
$LQ^d_{mix} \to te/b\nu$	1410^{+60}_{-60}	1390
$vLQ^{YM}_{mix} \to t\nu/b\mu$	1930^{+50}_{-60}	1980
$vLQ^{YM}_{mix} \to t\nu/be$	1930^{+50}_{-70}	1900
$vLQ^{min}_{mix} \to t\nu/b\mu$	1660^{+50}_{-50}	1710
$vLQ^{min}_{mix} \to t\nu/be$	1650^{+50}_{-60}	1620

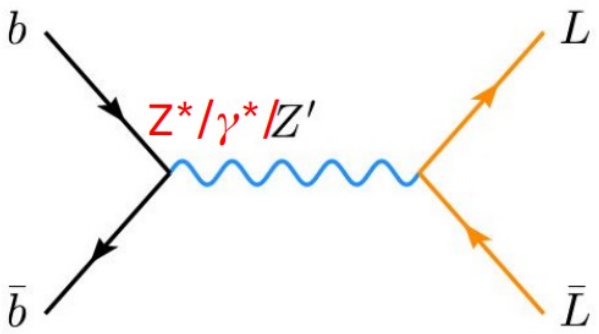
Search for vector-like leptons

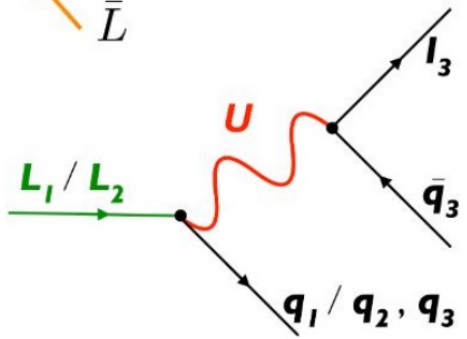
B2G-21-004

- 4321 model extending the SM sector provides a leptoquark for the source of the LFV and new families of vector-like fermions
  - Leptoquark U primarily decays to third generation leptons and quarks
  - The final state has at least 4 b-jets and various numbers of tau leptons, neutrinos and light jets from top quark decays

Di Luzio et al:
1708.08450
1808.00942

tau multiplicity	production + decay mode	final state
$0\,\tau$	$\mathrm{EE} \to \mathrm{b}(\mathrm{t}\nu_\tau)\mathrm{b}(\mathrm{t}\nu_\tau)$	$4\mathrm{b} + 4\mathrm{j} + 2\nu_\tau$
	$\mathrm{EN} \to \mathrm{b}(\mathrm{t}\nu_\tau)\mathrm{t}(\mathrm{t}\nu_\tau)$	$4\mathrm{b} + 6\mathrm{j} + 2\nu_\tau$
	$\mathrm{NN} \to \mathrm{t}(\mathrm{t}\nu_\tau)\mathrm{t}(\mathrm{t}\nu_\tau)$	$4\mathrm{b} + 8\mathrm{j} + 2\nu_\tau$
$1\,\tau$	$\mathrm{EE} \to \mathrm{b}(\mathrm{b}\tau)\mathrm{b}(\mathrm{t}\nu_\tau)$	$4\mathrm{b} + 2\mathrm{j} + \tau + \nu_\tau$
	$\mathrm{EN} \to \mathrm{b}(\mathrm{t}\nu_\tau)\mathrm{t}(\mathrm{b}\tau)$	$4\mathrm{b} + 4\mathrm{j} + \tau + \nu_\tau$
	$\mathrm{EN} \to \mathrm{b}(\mathrm{b}\tau)\mathrm{t}(\mathrm{t}\nu_\tau)$	$4\mathrm{b} + 4\mathrm{j} + \tau + \nu_\tau$
	$\mathrm{NN} \to \mathrm{t}(\mathrm{b}\tau)\mathrm{t}(\mathrm{t}\nu_\tau)$	$4\mathrm{b} + 6\mathrm{j} + \tau + \nu_\tau$
$2\,\tau$	$\mathrm{EE} \to \mathrm{b}(\mathrm{b}\tau)\mathrm{b}(\mathrm{b}\tau)$	$4\mathrm{b} + 2\tau$
	$\mathrm{EN} \to \mathrm{b}(\mathrm{b}\tau)\mathrm{t}(\mathrm{b}\tau)$	$4\mathrm{b} + 2\mathrm{j} + 2\tau$
	$\mathrm{NN} \to \mathrm{t}(\mathrm{b}\tau)\mathrm{t}(\mathrm{b}\tau)$	$4\mathrm{b} + 4\mathrm{j} + 2\tau$

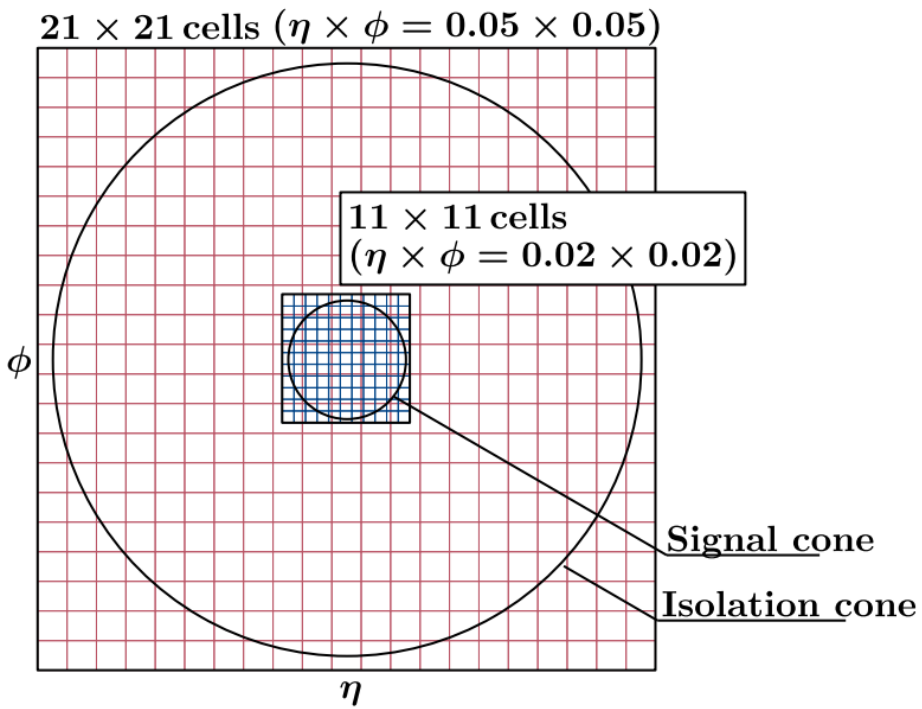


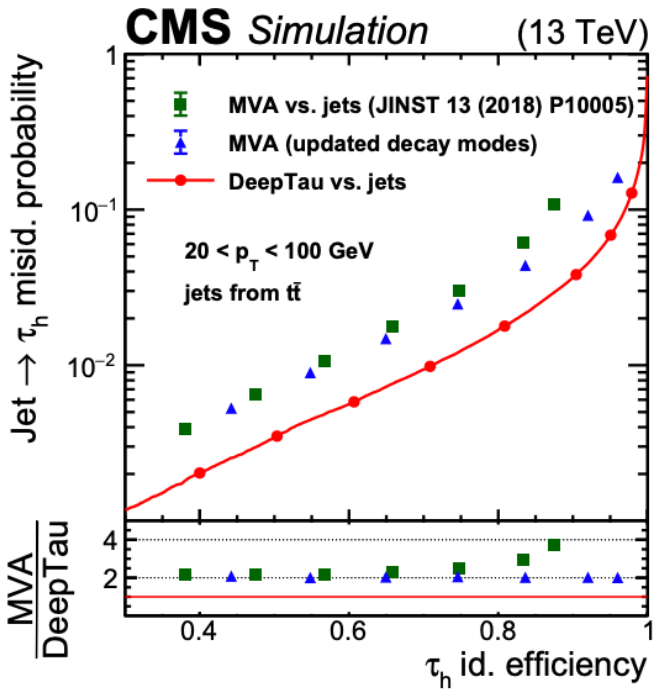


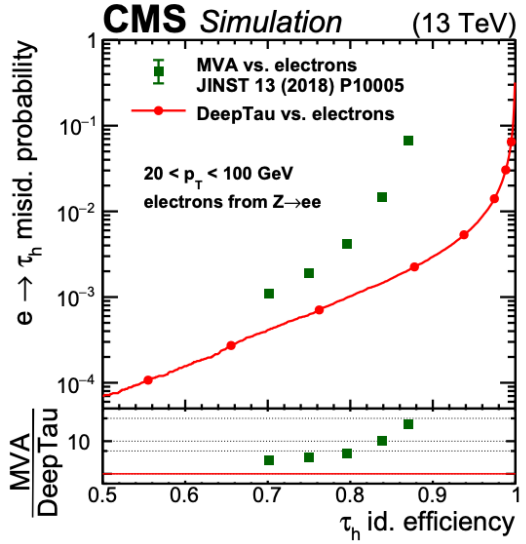
Machine learning tools: deep tau ID

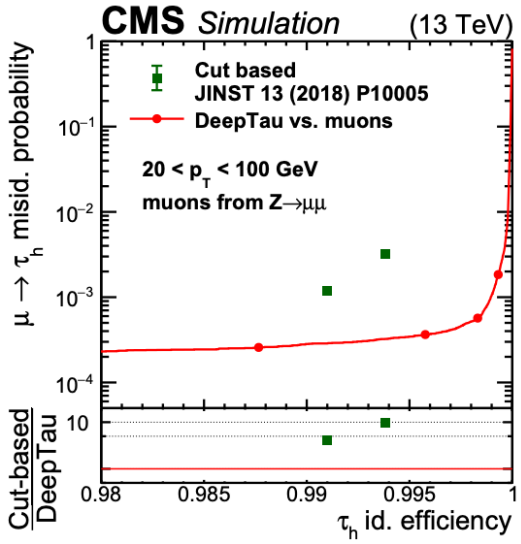
arXiv: 2201.08458

- Deep convolutional neural network for identification of tau leptons
  - About 100k input features used in training







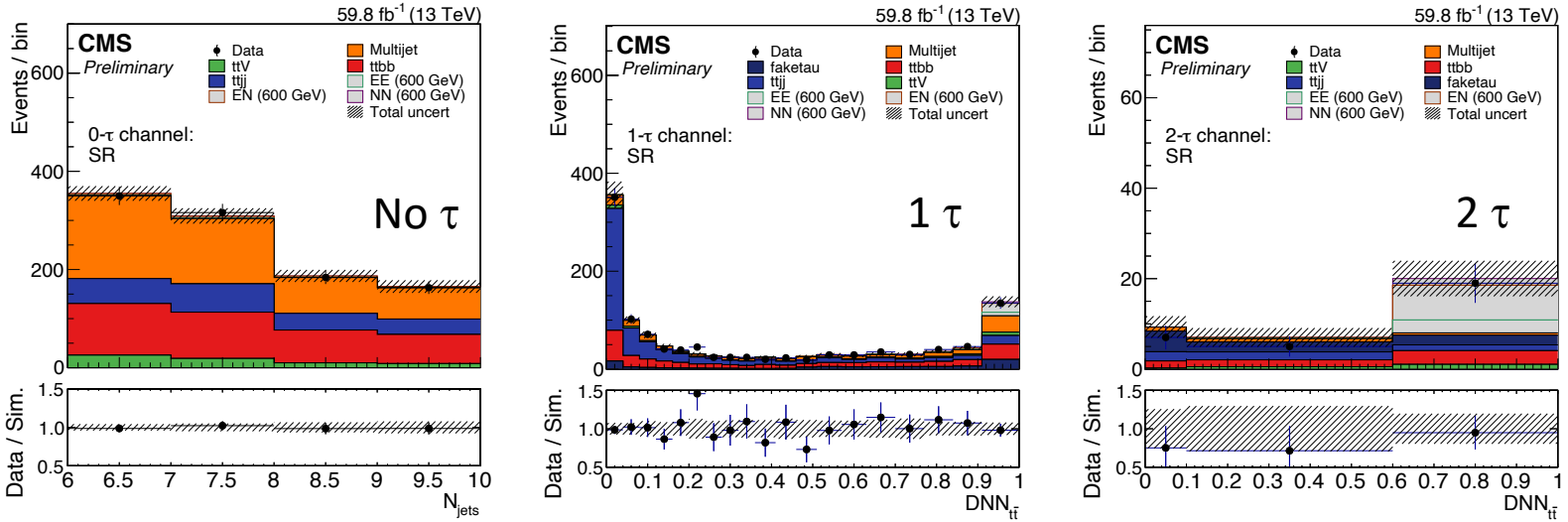


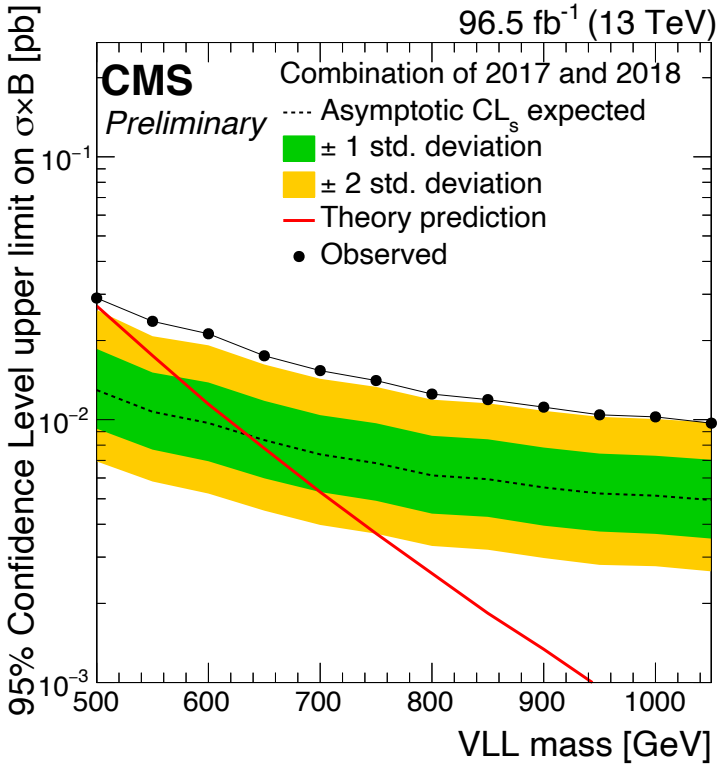
- Significant improvement in suppression of backgrounds

Search for vector-like leptons

B2G-21-004

- In addition to deep tau ID, use DeepCSV for b-jet identification at trigger level, DeepJET for offline selection
- ABCNet graph neural network is used to set up deep neural network classifiers to reject major QCD multijet and tt-bar backgrounds using dedicated control regions
  - Final fit is over number of jets, tau leptons, and DNN_{tt} classifier



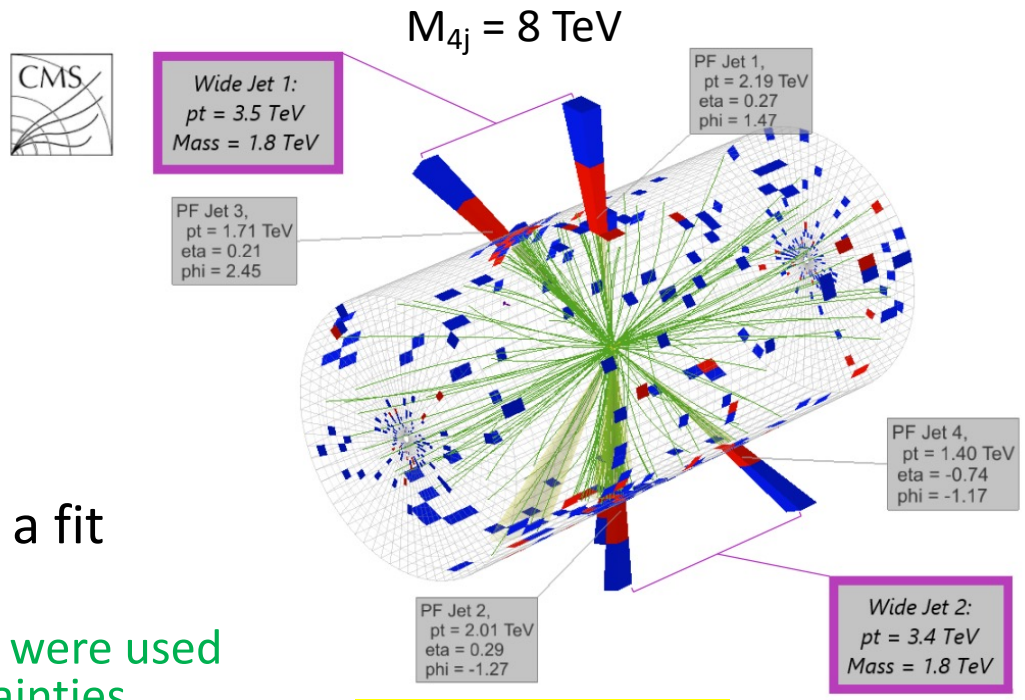


- 2.8σ for signal ~600 GeV with 2016+2017 data only

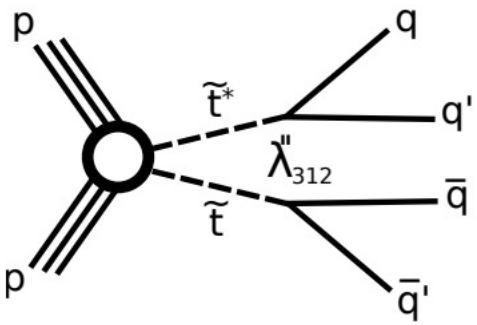
Search for $Y \to XX \to (jj)(jj)$

EXO-21-010

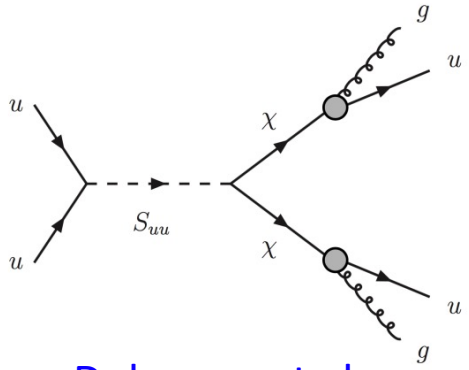
- Resolved jets final state: sensitivity to high mass X and Y
  - Interpretation: RPV SUSY or heavy di-quark that decays to vector-like quarks
- Final state: four highest-p_T jets paired to dijet pair
  - Minimize the sum ΔR_i- 0.8
  - Reduce QCD by imposing $\Delta R_i < 2$ and $\Delta\eta_{12} < 2$
  - Assume same X mass hypothesis $\frac{|m_1 - m_2|}{m_1 + m_2} < 0.1$
- Search over M_{4j} and average dijet mass m_{jj}
  - Background is estimated from a fit to ModDijet-3p function
    - Two other empirical functions were used to estimate systematic uncertainties



CMS-EXO-19-012



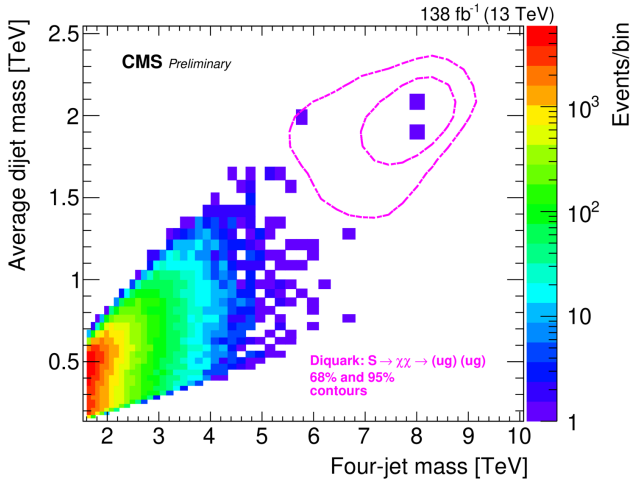
Evans et al, 1209.0764

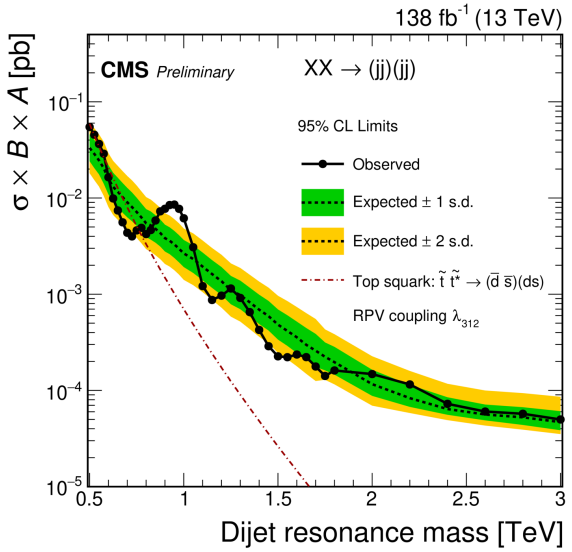


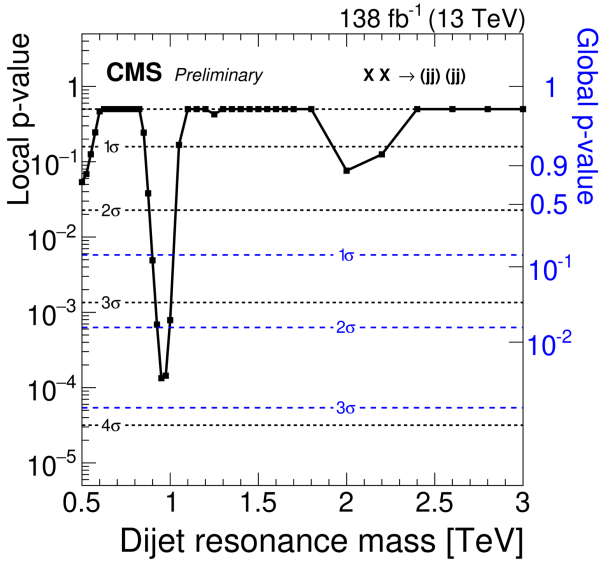
Dobrescu et al, 1810.09429

Search for $Y \to XX \to (jj)(jj)$

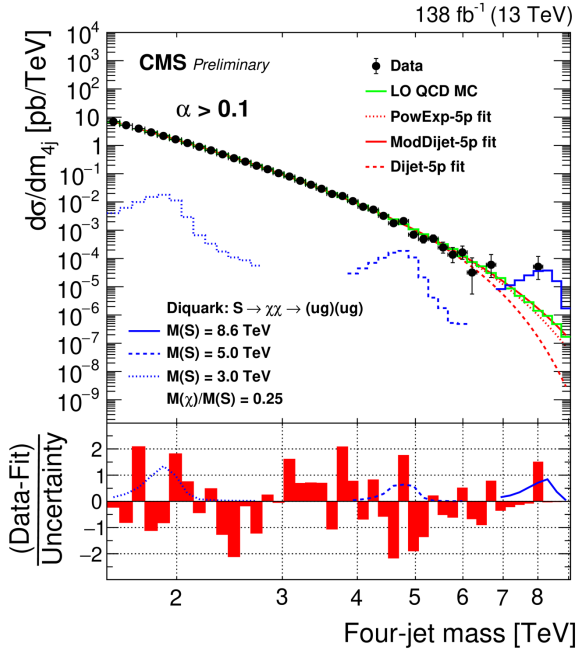
EXO-21-010

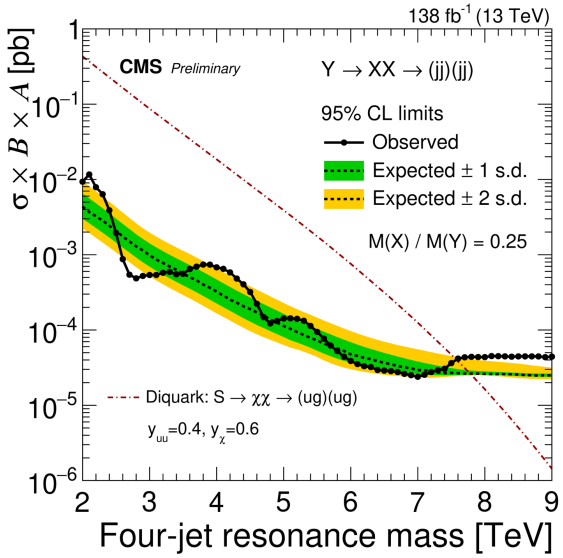


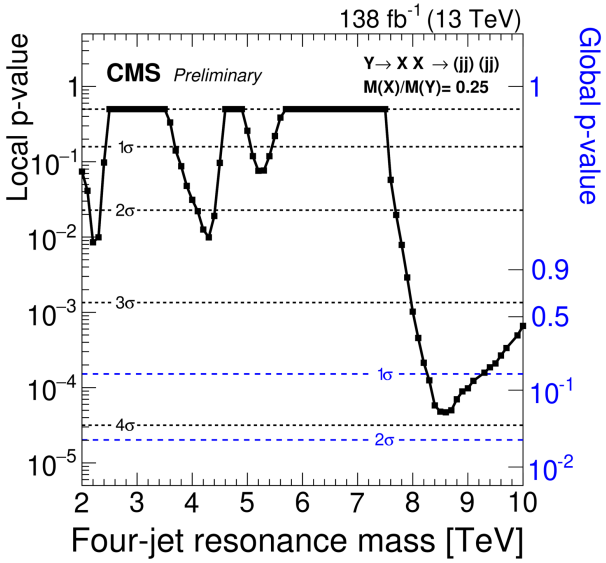




3.6σ Local
2.5σ Global



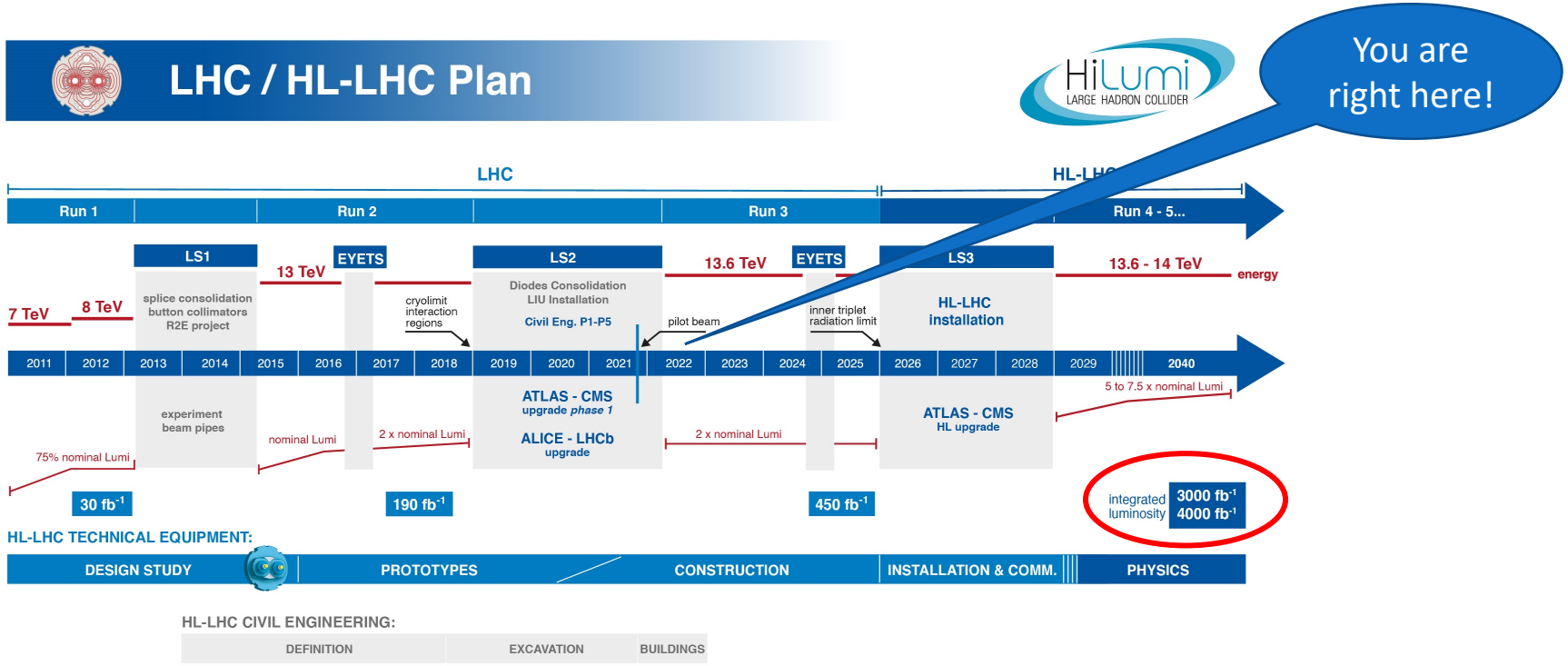




3.9σ Local
1.6σ Global

Summary

- Impressive number of new results with Run 2 data
  - Several very intriguing results!
- ATLAS and CMS collected about 138 /fb of integrated luminosity, and this is only about 5% of the expected luminosity from the LHC



Backup