Searching Where The Light Isn't: Discovery Potential in LHC Anomalies

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January 13, 2023

Outline

LHC,
Standard Model,
& Beyond

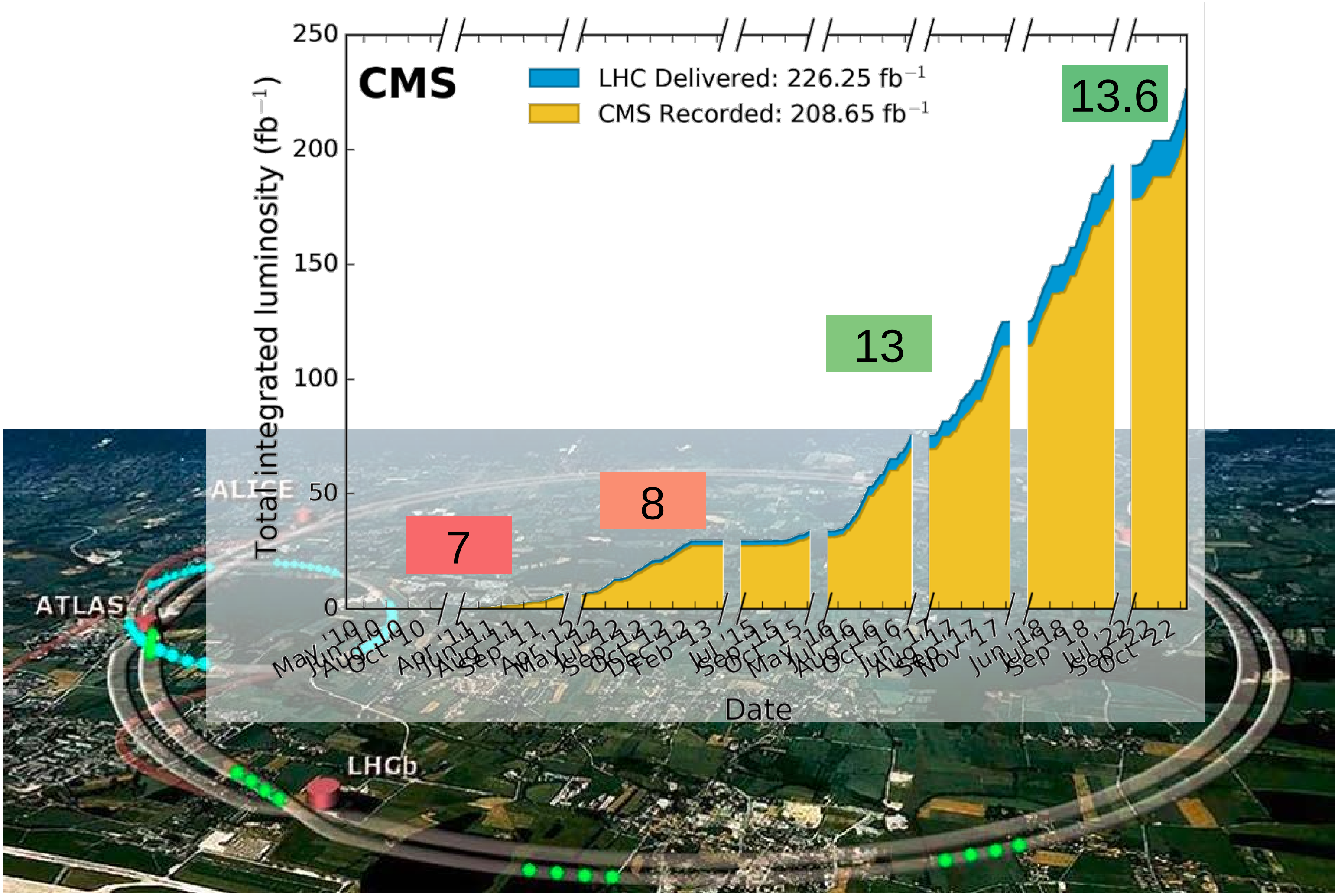
Excesses

Prospects

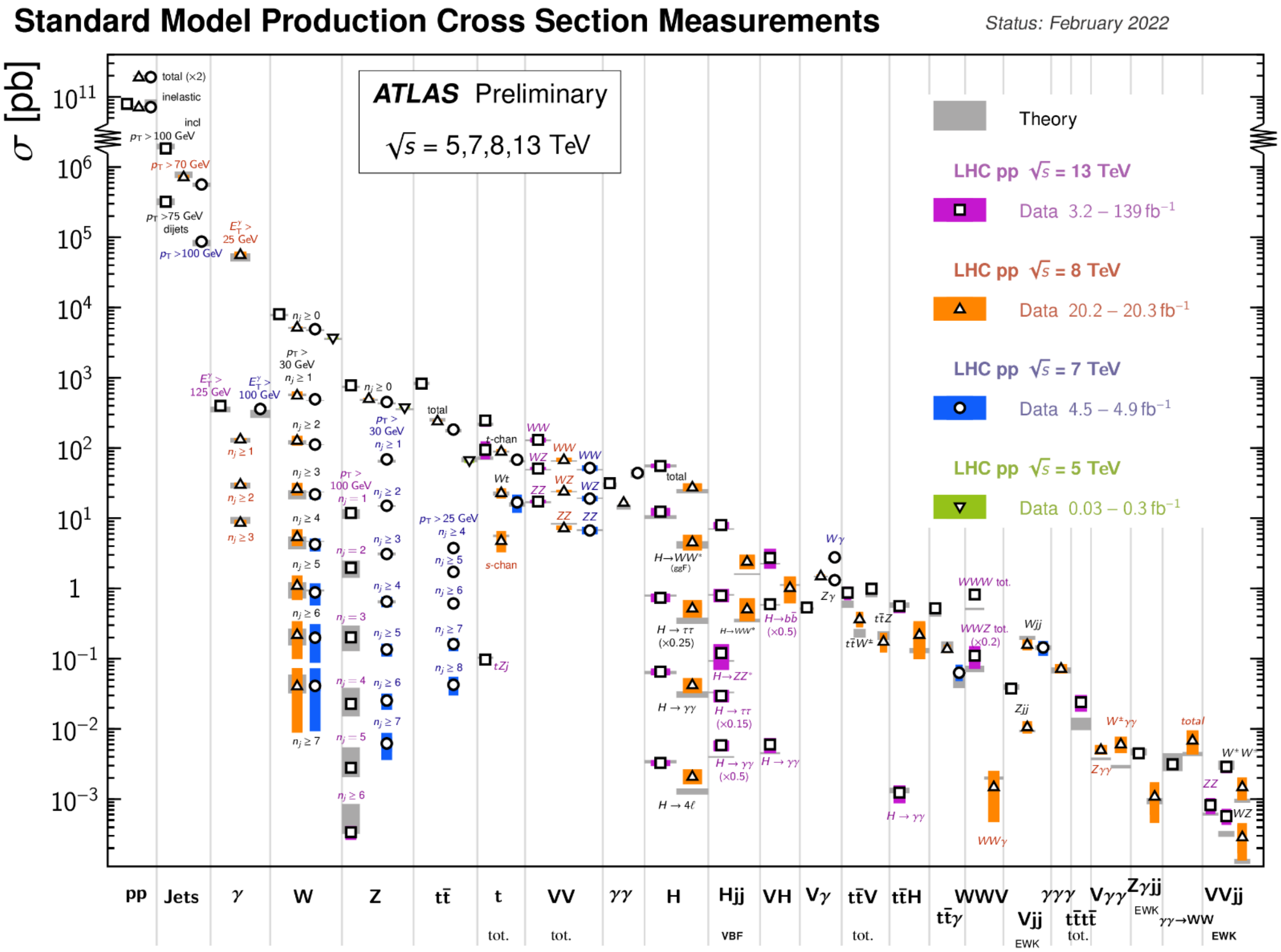
Anomaly Detection

LHC,
Standard Model,
& Beyond

The LHC So Far

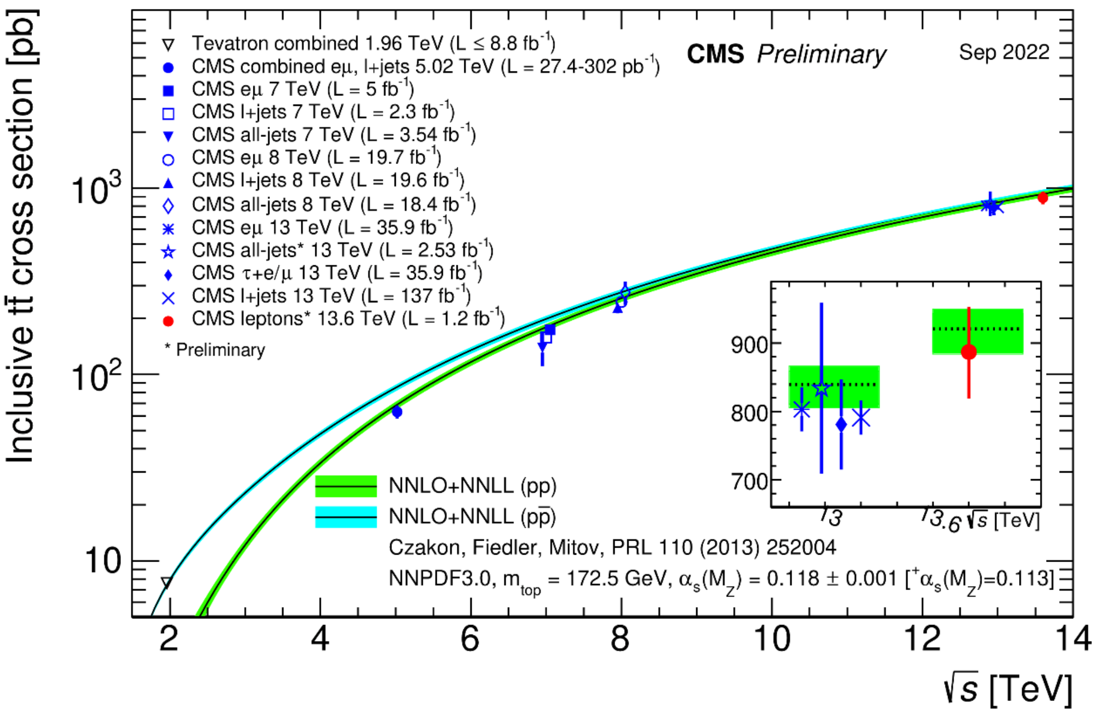


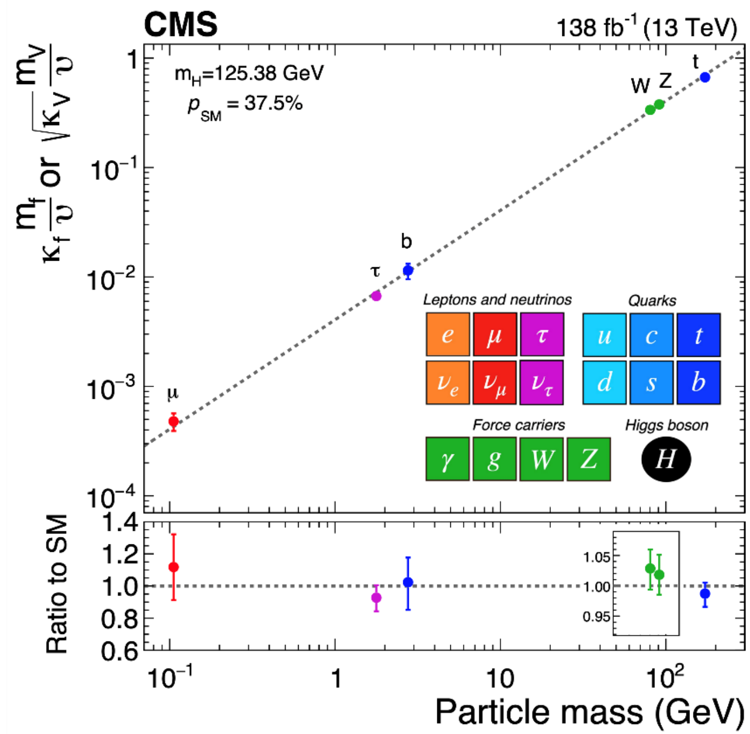
The Standard Model at the LHC



- Excellent agreement with theory across 14 decades of cross section values
- Measurements of weak bosons, Higgs, top, including multiparticle processes

More Standard Model

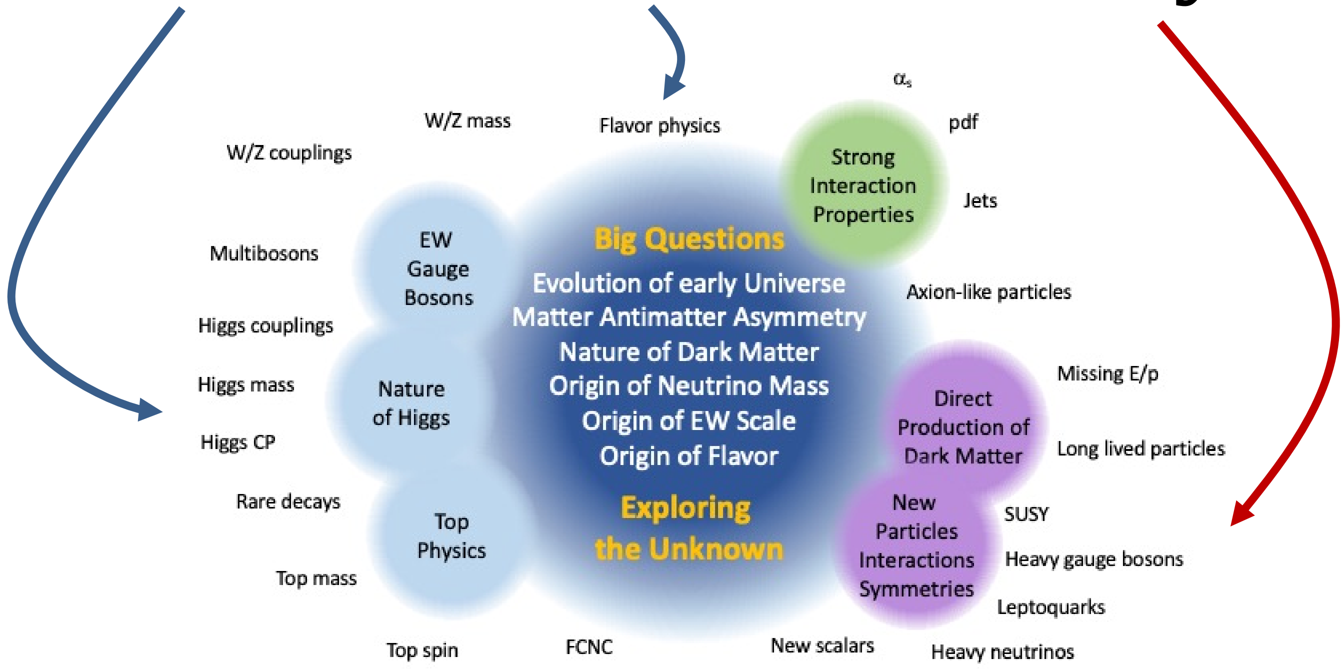




- Further excellent agreement with theory:
  - o $t\bar{t}$ cross section measurements from $\sqrt{s}$ = 1.96 to 13.6 TeV
  - o Higgs couplings (even in 2nd generation!)

➢ What is missing from the standard model?

The Standard Model & Beyond



- SM alone cannot answer the big questions

➢ Motivation to search for new particles & interactions

- What wouldn't we have seen yet?

High mass

Weakly interacting

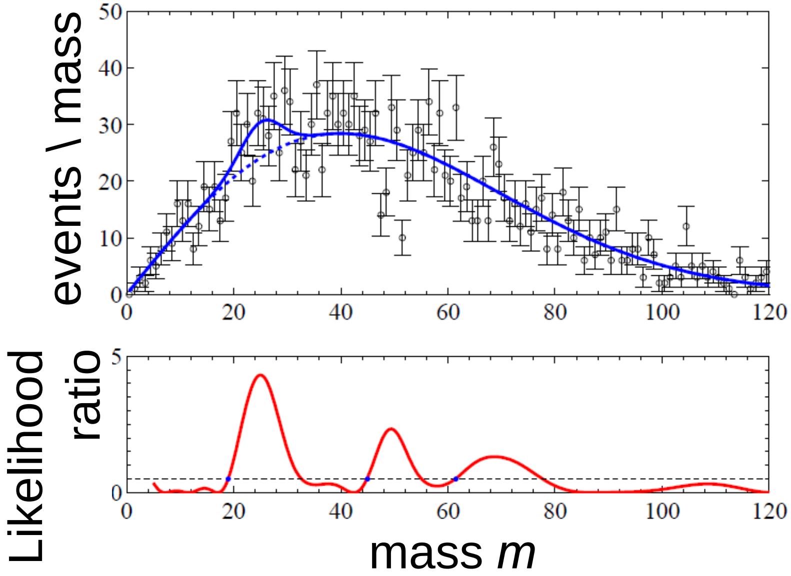
Unusual signatures

CMS Data Analysis School

- Celebrating a successful data analysis school!
  - First in-person school since 2020
- 8 speakers, 46 facilitators, 46 students

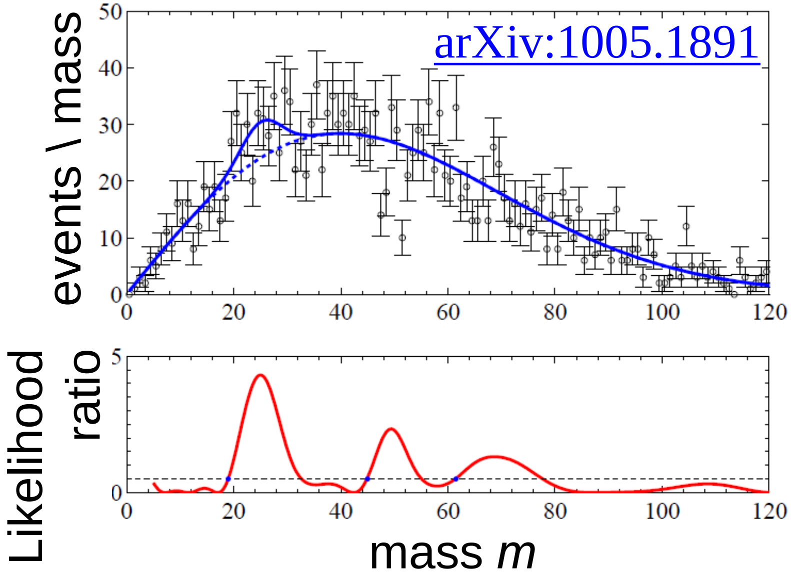
Excesses

Our First Excess



- Which of these resonances is real?

Look Elsewhere Effect

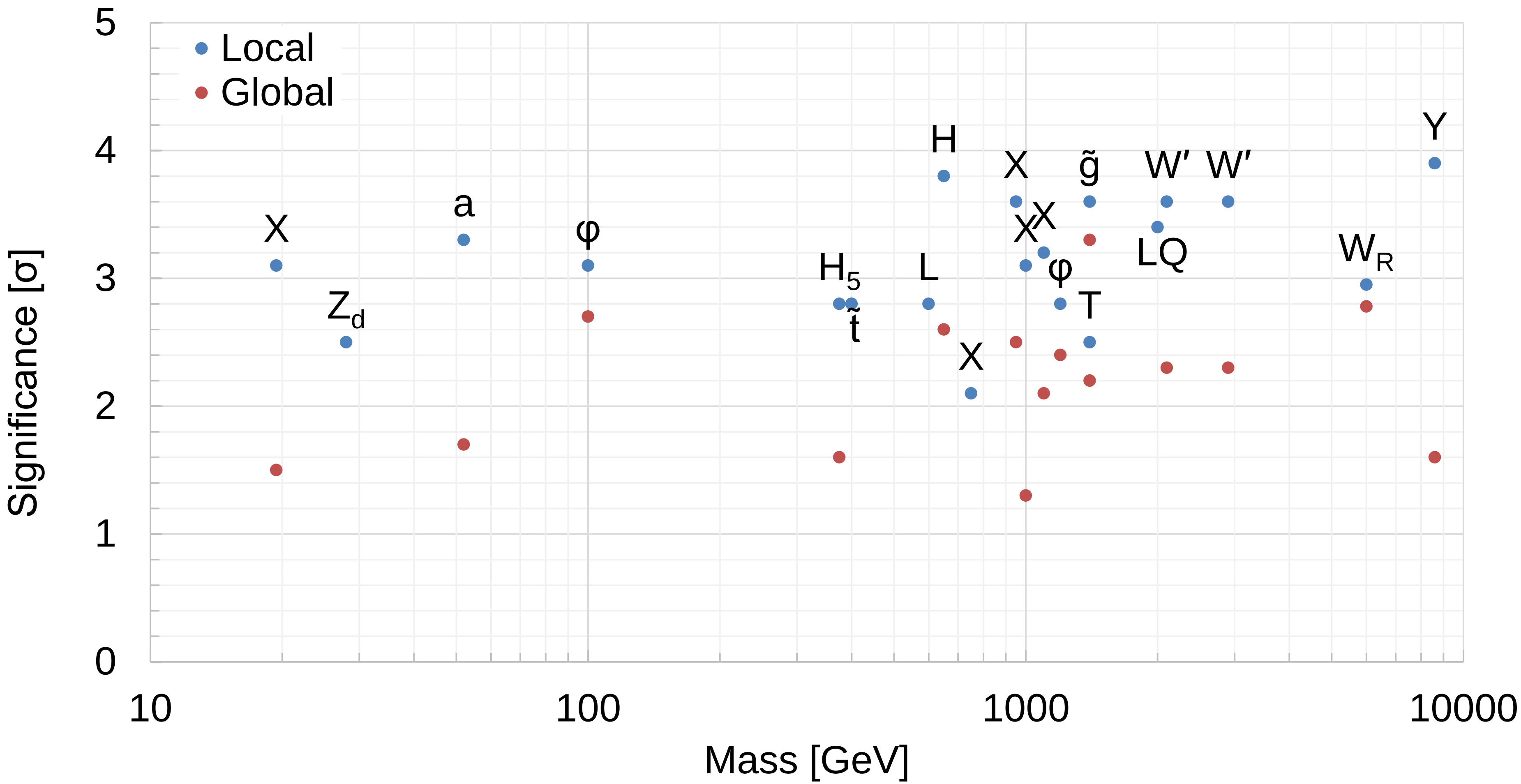


- Which of these resonances is real?
- None of them!
  - All points from toy dataset generated from background-only distribution
- Need to consider probability of statistical fluctuations
  - "Multiple comparison problem"

- Compute *trial factor*: $t = P$(my resonance)/P(any resonance) (for a given threshold)
- Local significance: before accounting for LEE
  - Divide local p-value by trial factor, then recompute z
- Global significance: after accounting for LEE
  - Always lower than local

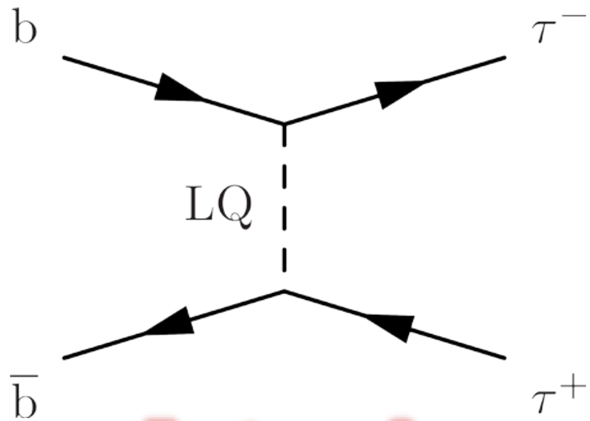
Recent Excesses

- Past ~year has seen a slew of results from the "full Run 2" dataset (~138 fb^{-1})
- Many intriguing excesses:

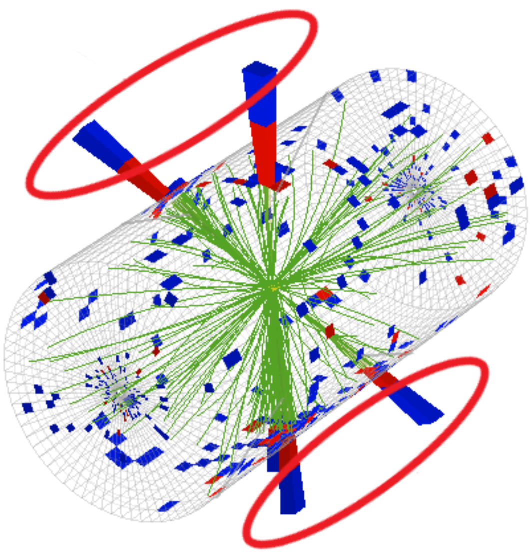


Today's Menu

- Focus on a few of the most significant excesses
- Brief details on others in backup

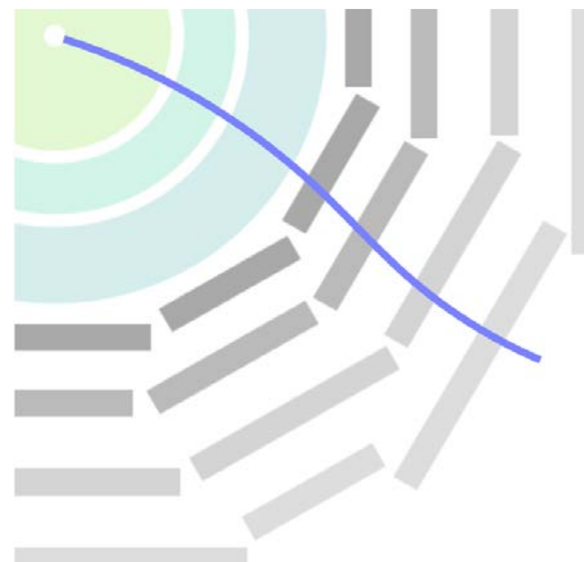


Dijet resonances

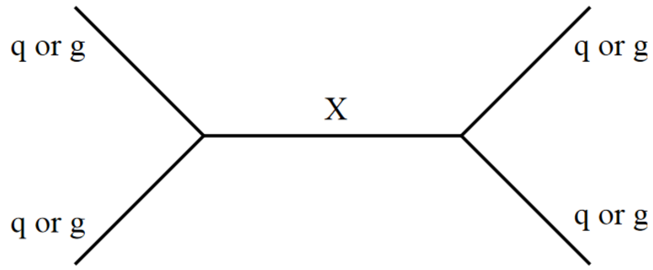


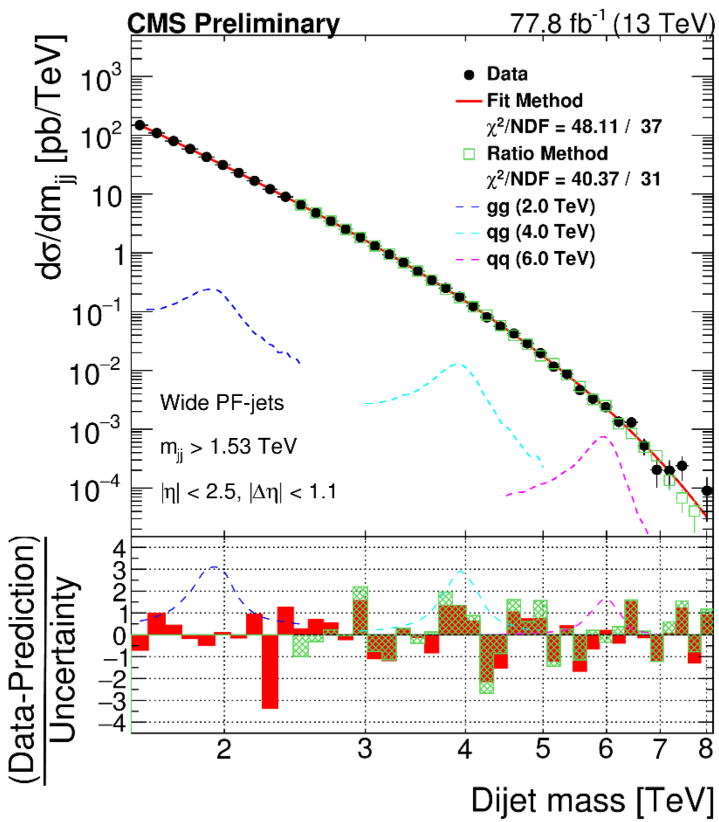
Leptoquarks

Heavy long-lived charged particles



Dijet Resonances





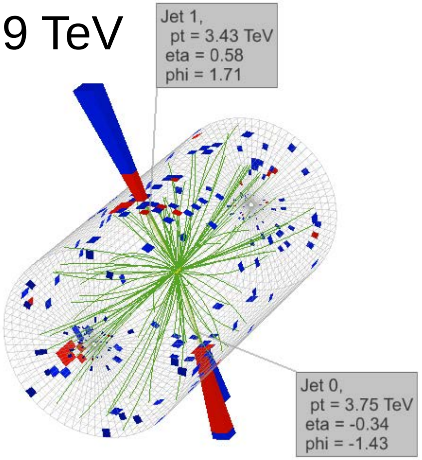
CMS-PAS-EXO-17-026

- One of the simplest and most generic signatures of new physics
- Applies to any resonance that can be produced in *s*-channel by gluon-gluon fusion, quark-antiquark annihilation, or quark-gluon scattering
- Benchmark models: W′, Z′, excited quarks, Randall-Sundrum gravitons, dark matter mediators, and more…
- CMS strategy:
  - Combine R = 0.4 jets into wide jets if they have $\Delta R < 1.1 \rightarrow$ collect final state radiation to improve mass resolution
  - Estimate background via analytic fit to observed data

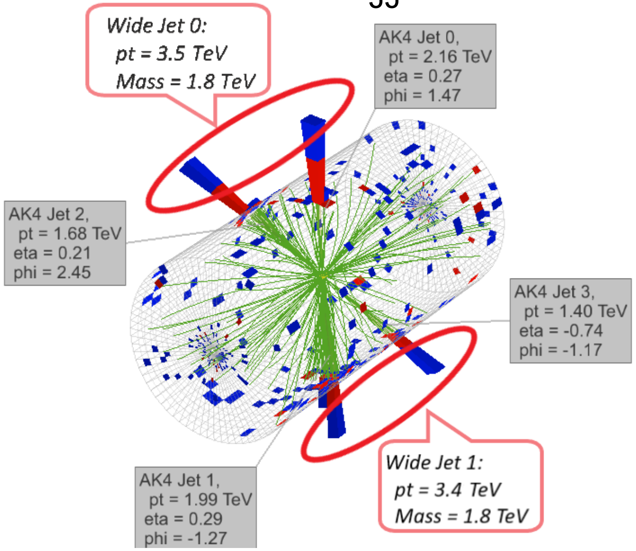
High Mass Events

- Our story begins in 2018:
  - Two events near 8 TeV
  - One with unexpected properties!
- Theoretical prediction for QCD background with m_{JJ} = 8 TeV, $m_{J_1} = m_{J_2}$ = 1.8 TeV: 4.5×10^{-5} events
  - Uncertainty: < 100%
- While dijet search is generic by design, it doesn't target this topology directly…

m_{JJ} = 7.9 TeV

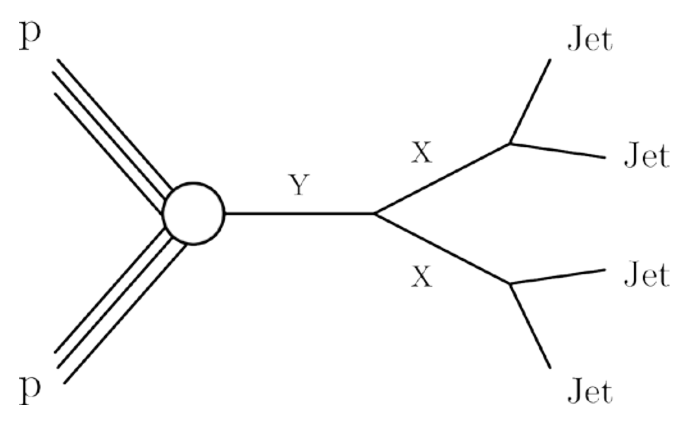


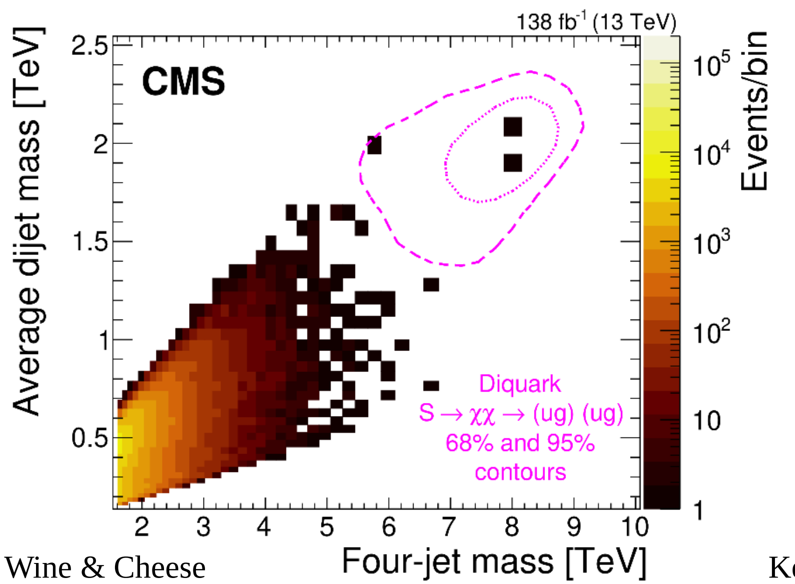
m_{JJ} = 8.0 TeV

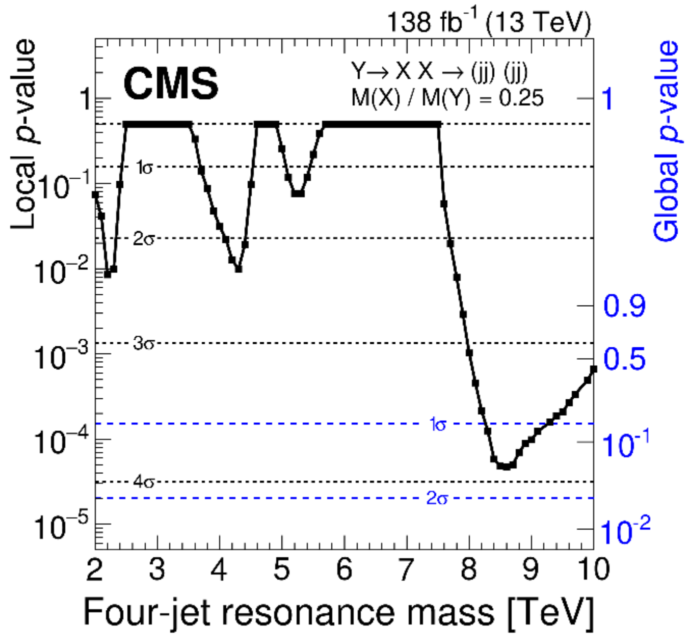


Dedicated Search

- Several signal models proposed: diquark, coloron
- 4 narrow jets *j*, paired to make 2 wide jets *J*
  - Require $\Delta R < 2.0$ to combine narrow jets (looser than dijet search) & low wide jet mass asymmetry
  - Bin in $\alpha = \overline{m}_{jj}/m_{4j}$ (avoid correlations), fit m_{4j}
- Result: a second event!
  - $m_Y = 8.6$ TeV, $m_X = 2.1$ TeV: 3.9σ local, 1.6σ global

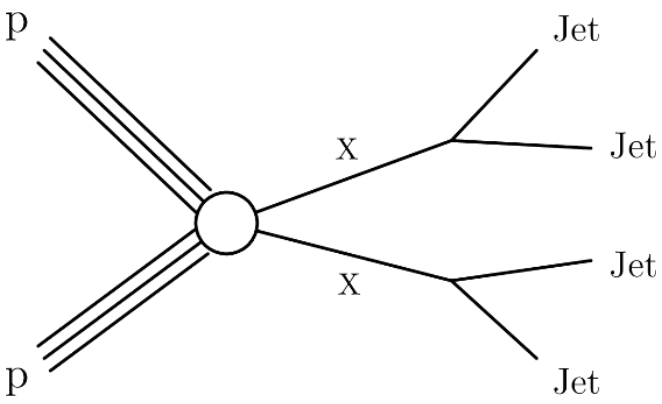


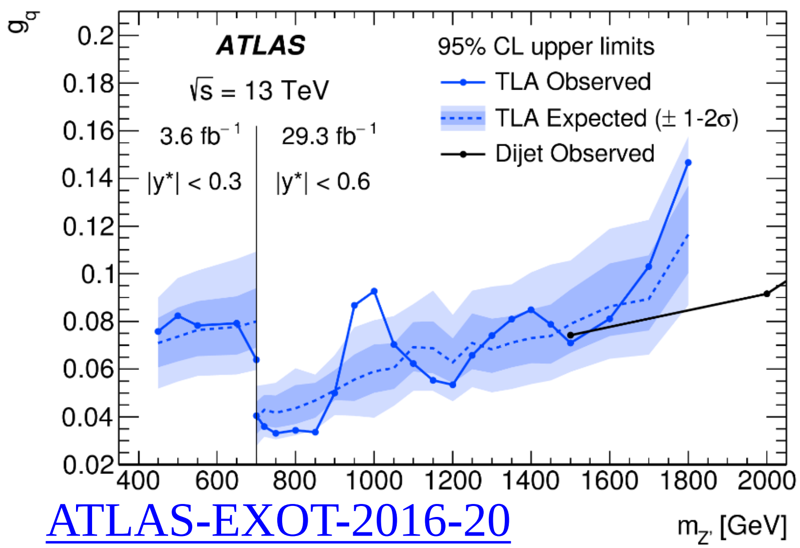


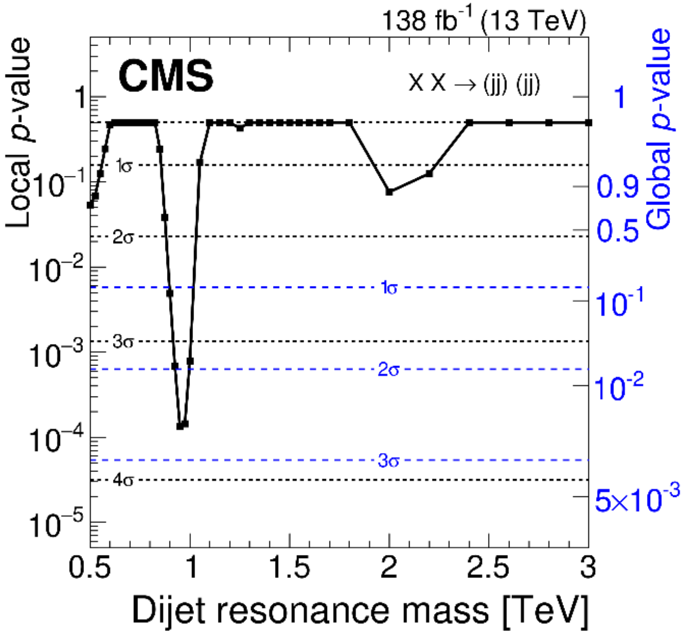


Nonresonant Excess

- Also search for nonresonant dijet pairs
  - e.g. from *R*-parity violating supersymmetry
- Same strategy, but fit $\overline{m}_{jj}$
- Another excess observed!
  - m_X = 0.95 TeV: 3.6σ local, 2.5σ global
- *Maybe* compatible with small excess from ATLAS trigger-level (scouting) search



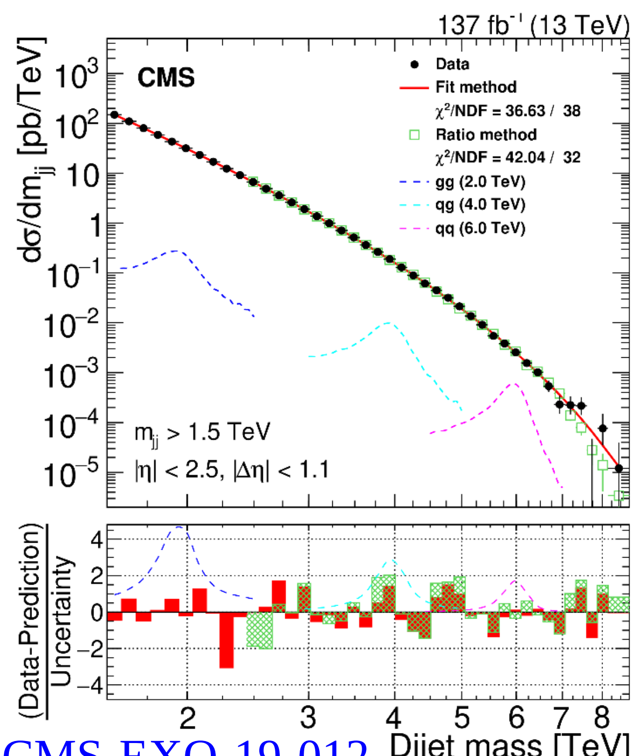




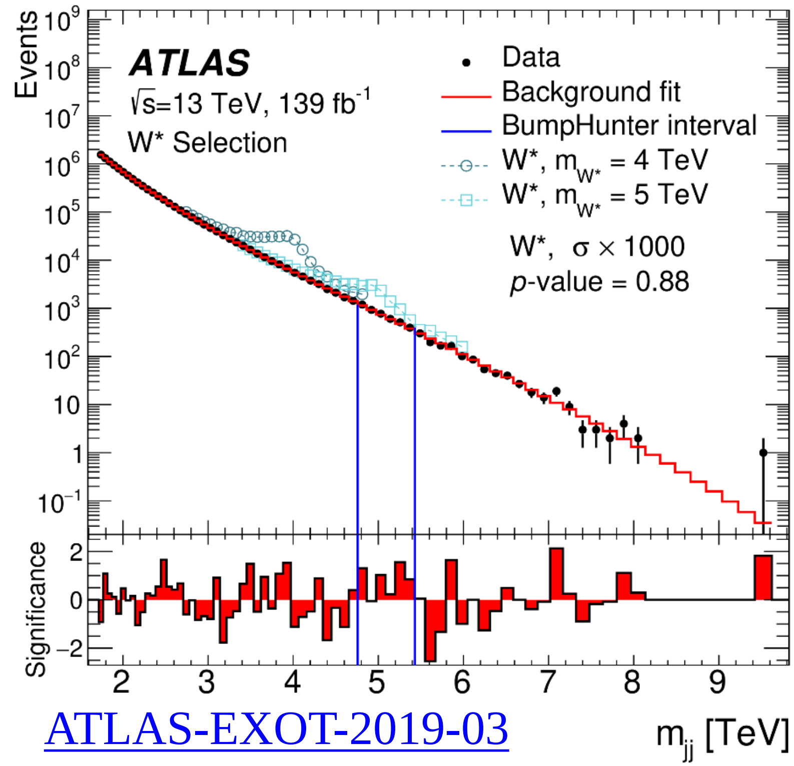
[ATLAS-EXOT-2016-20]

Meanwhile…

- Both CMS & ATLAS published full Run 2 dijet searches
- Each has a few events near or above 8 TeV
- Potentially consistent w/ resonant paired dijet signal models:
  if $q\bar{q} \rightarrow Y \rightarrow XX$, then also $q\bar{q} \rightarrow Y \rightarrow q\bar{q}$

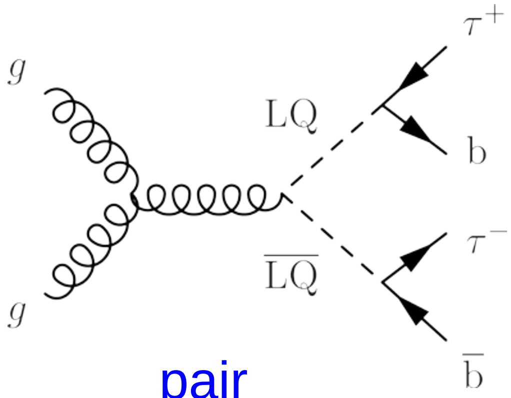


CMS-EXO-19-012

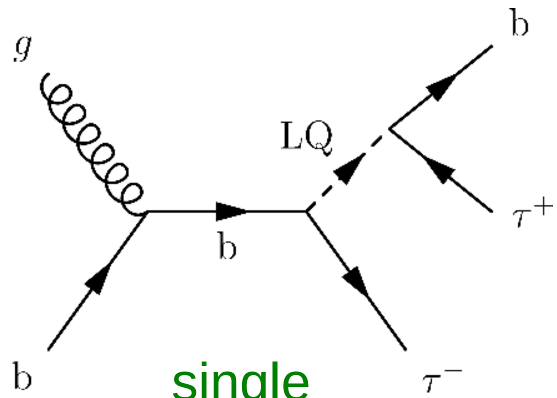


ATLAS-EXOT-2019-03

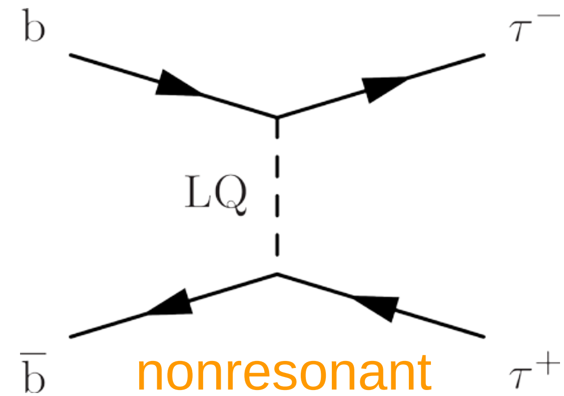
Leptoquarks



pair



single

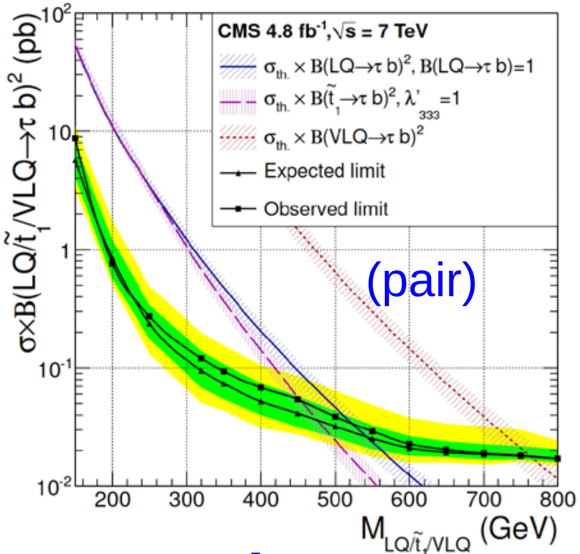


nonresonant

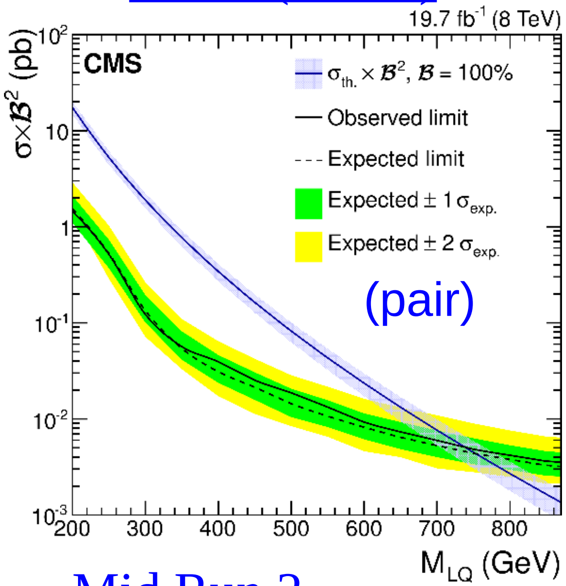
- Particles that couple to both leptons and quarks are predicted by many theories: grand unification, superstring theory, compositeness, etc.
- LQ properties:
  - Spin: scalar or vector
  - Yukawa couplings λ to lepton ℓ and quark q
  - Branching fractions β to given ℓ, q flavors
    - e.g. β(bτ) and β(tν_τ) for LQ shown above
  - Anomalous couplings κ to SM gauge fields

Leptoquarks: Then to Now

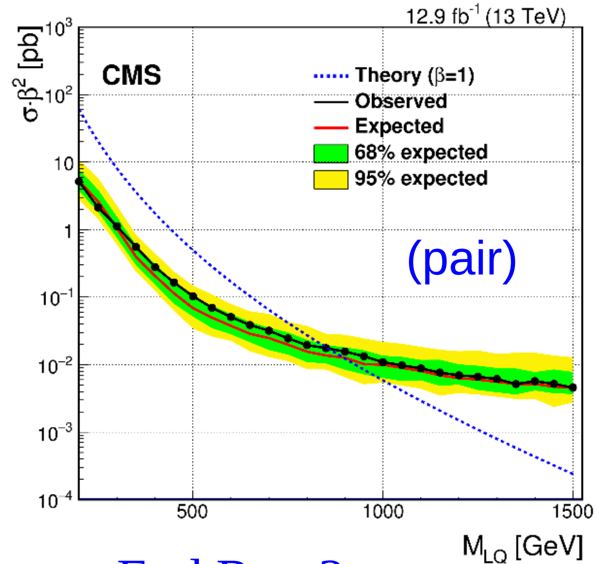
Run 1 (7 TeV)



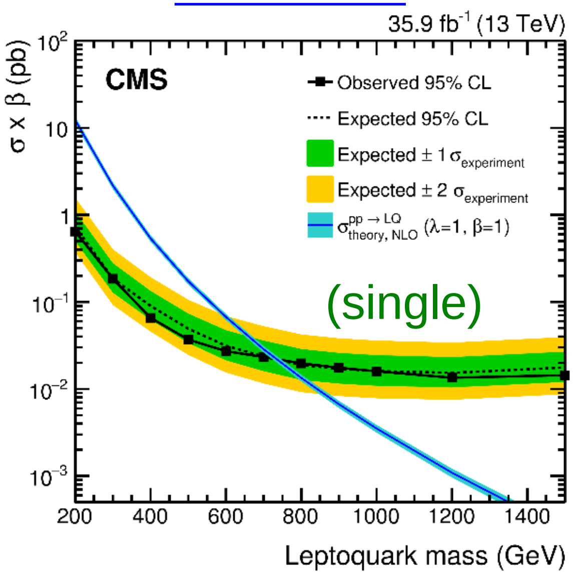
Run 1 (8 TeV)



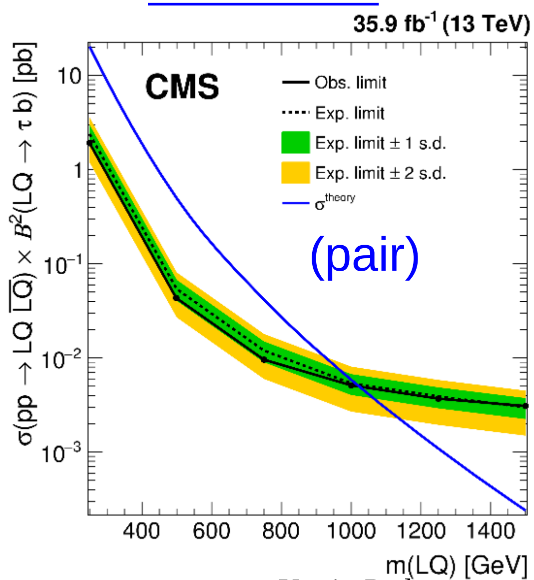
Early Run 2



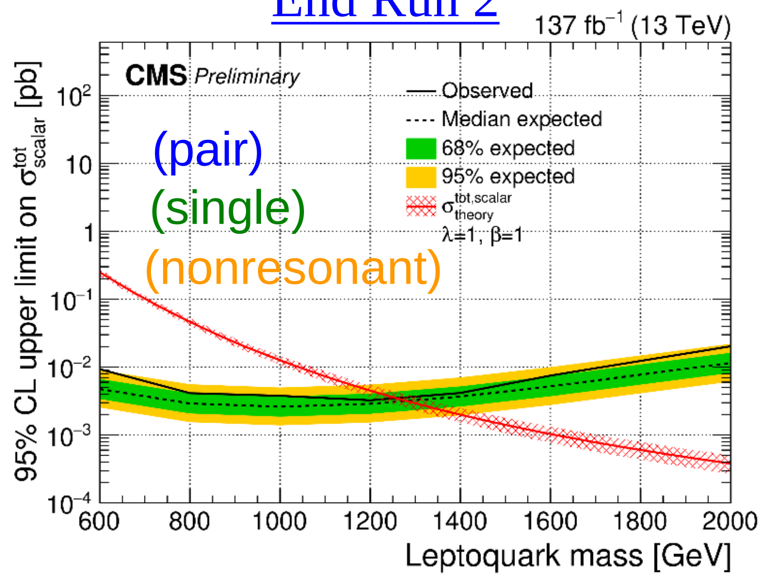
Mid Run 2



Mid Run 2



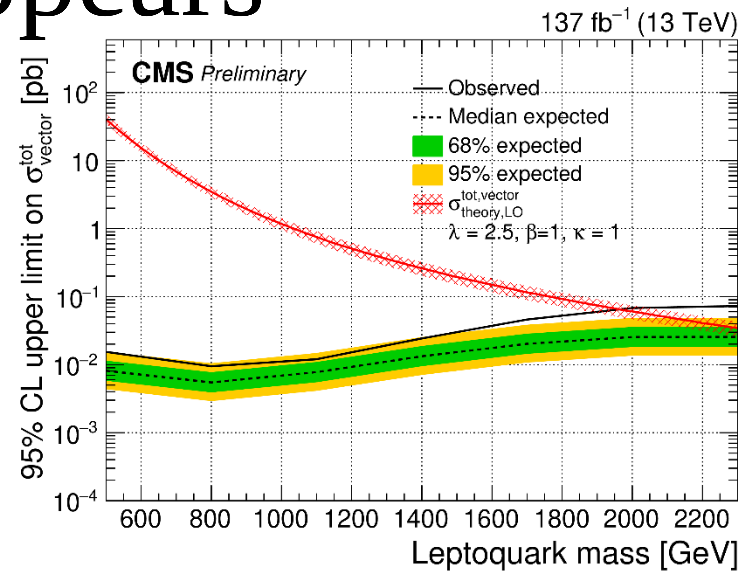
End Run 2

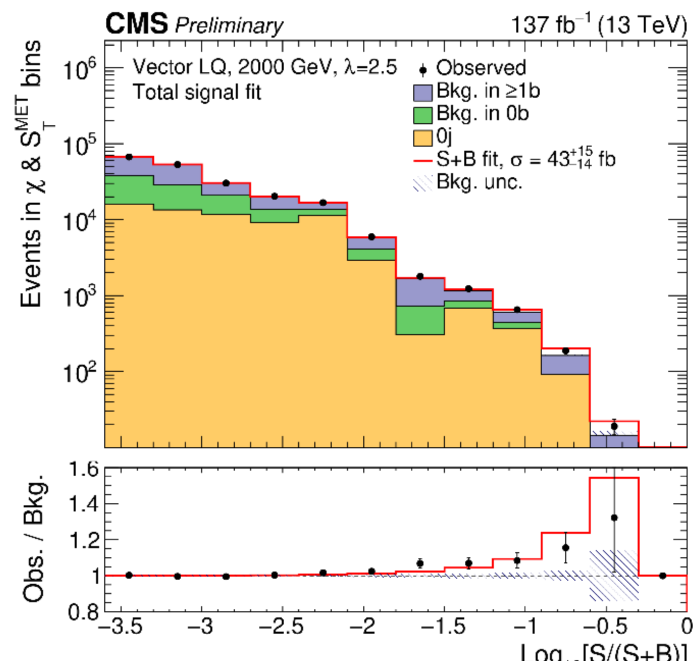


An Excess Appears

- Previous: scalar leptoquarks w/ $\lambda = 1$, $\kappa = 0$
- Here: choose signal parameters to fit excess (vector LQ, $\lambda = 2.5$, $\kappa = 1$)
  - o $m_{LQ} = 2$ TeV: 3.4σ local
- Sort search variables by sensitivity
  - o Resonant channels: $S_T = p_T(\tau_1) + p_T(\tau_2) + p_T(j_1) + p_T(j_2) + p_T^{miss}$
  - o Nonresonant channels: $\chi = \exp(|y(\tau_1) - y(\tau_2)|)$, y = rapidity
- Driven by nonresonant signal

Signal	$m_{LQ} = 1400$ GeV		$m_{LQ} = 2000$ GeV	
	σ [pb]	z	σ [fb]	z
Vector, $\kappa = 1$				
Pair	$0.24^{+0.46}_{-0.44}$	0.0	$0.24^{+0.41}_{-0.39}$	0.0
Single, $\lambda = 1$	$1.00^{+0.89}_{-0.85}$	1.2	$0.60^{+0.66}_{-0.63}$	1.0
Single, $\lambda = 2.5$	$9.1^{+6.5}_{-6.2}$	1.5	25^{+18}_{-17}	1.4
Nonres.	58^{+18}_{-17}	3.5	51^{+16}_{-15}	3.5
Total, $\lambda = 1$	$0.42^{+0.69}_{-0.66}$	0.0	$1.3^{+1.5}_{-1.4}$	0.5
Total, $\lambda = 2.5$	$12.2^{+7.1}_{-6.8}$	1.8	43^{+15}_{-14}	3.1

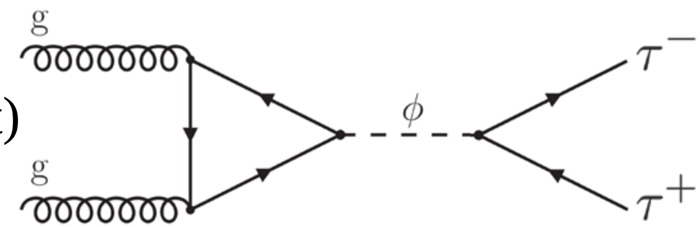


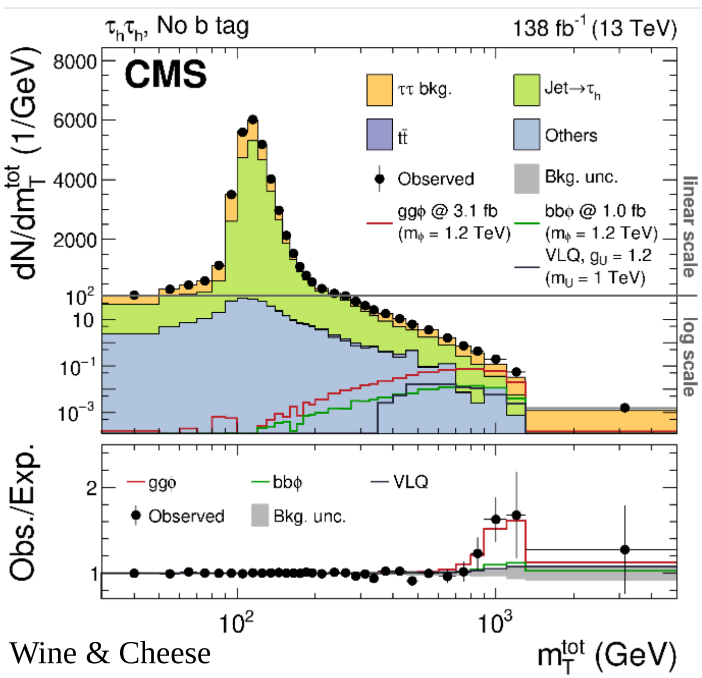


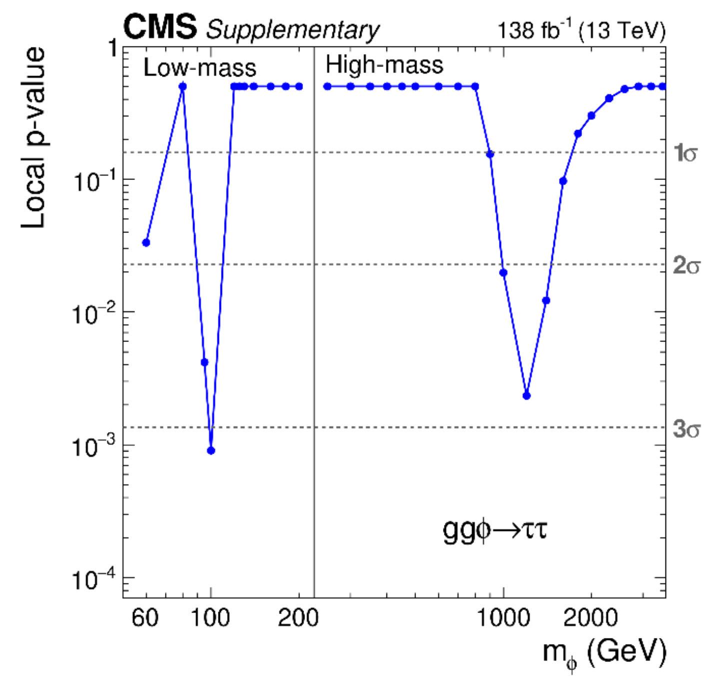
A Related Excess?

- Search for φ → ττ, using $m_{\mathrm{T}}^{\mathrm{tot}} = \sqrt{m_{\mathrm{T}}^{2}(\vec{p}_{\mathrm{T}}^{\,\tau_1}, \vec{p}_{\mathrm{T}}^{\,\tau_2}) + m_{\mathrm{T}}^{2}(\vec{p}_{\mathrm{T}}^{\,\tau_1}, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}) + m_{\mathrm{T}}^{2}(\vec{p}_{\mathrm{T}}^{\,\tau_2}, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}})}$
  - Also provides a vector LQ interpretation
- m_{φ} = 1200 GeV: 2.8σ local, 2.4σ global
- Driven by "no b tag region" (no jet requirement)
  - Search also has 1b region
- vs. LQ search: 0j (jet veto), 0b+≥1j, ≥1b regions

➢ Seemingly quite compatible… stay tuned!

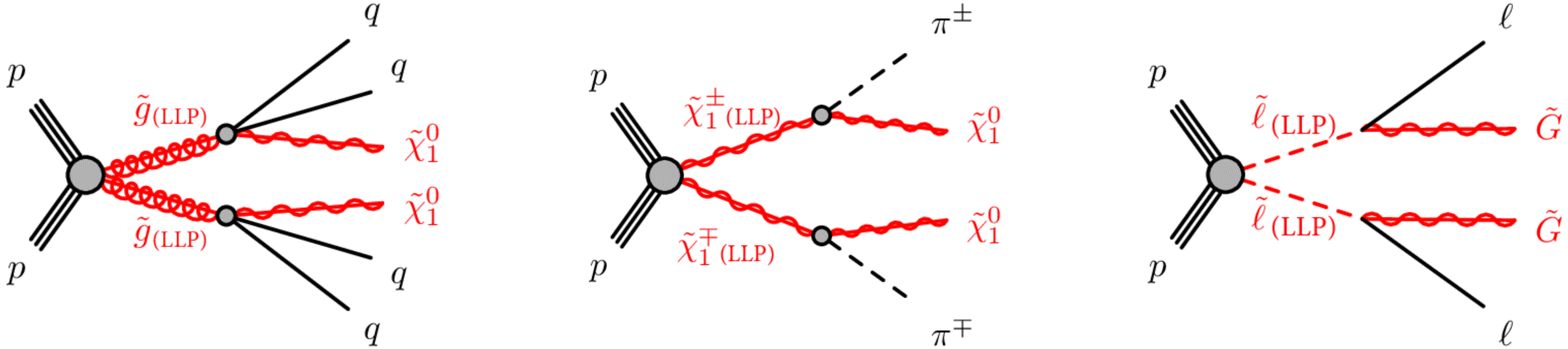






Heavy Long-Lived Charged Particles

- Predicted by many models of supersymmetry:
  - Charged superpartners (charginos $\tilde{\chi}^{\pm}$, sleptons $\tilde{\ell}$) make ionization deposits (dE/dx) as they traverse the detector
  - Gluinos are EM neutral but color-charged: can form R-hadrons w/ SM quarks, which can have EM charge

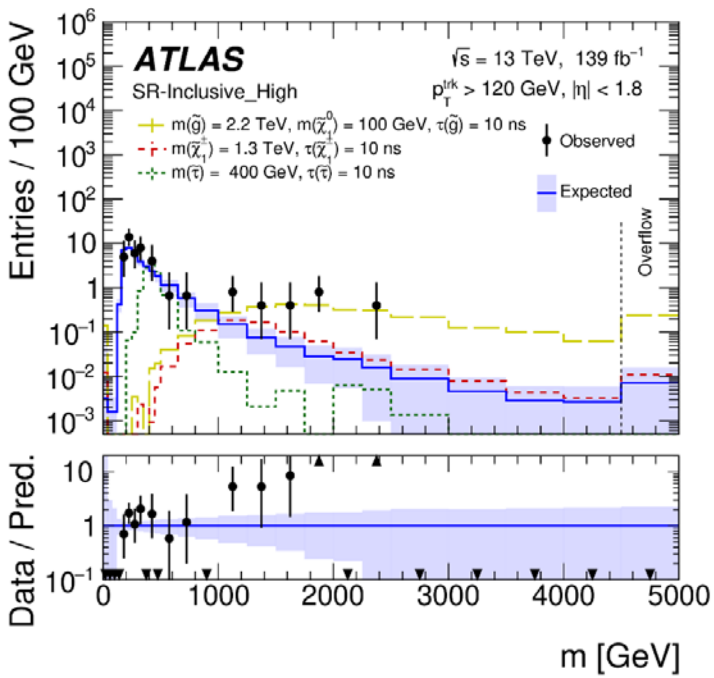


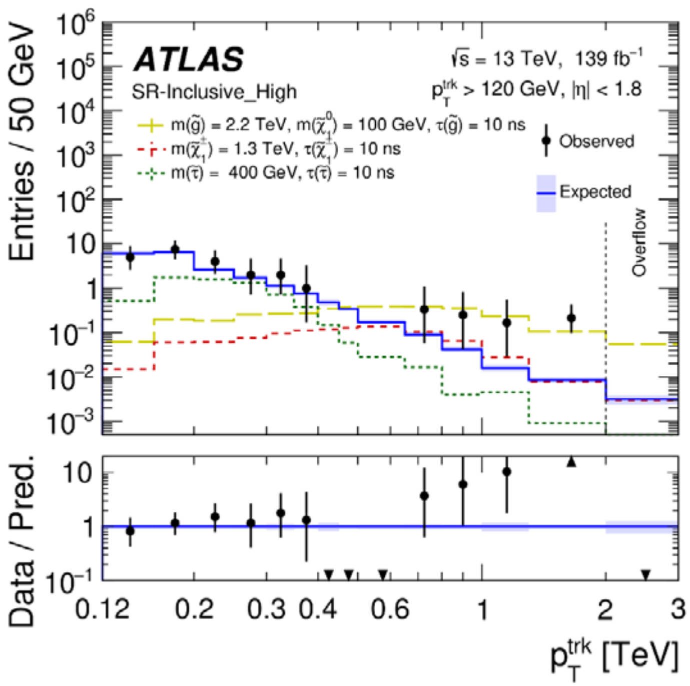
- Ionization: dE/dx depends on mass m, charge Q, velocity β

$$-\left\langle \frac{dE}{dx} \right\rangle = 4\pi m_e n_e r_e^2 Q^2 \left(-1 + \frac{2}{\beta^2} \ln \frac{\beta\gamma}{I_e} \right)$$

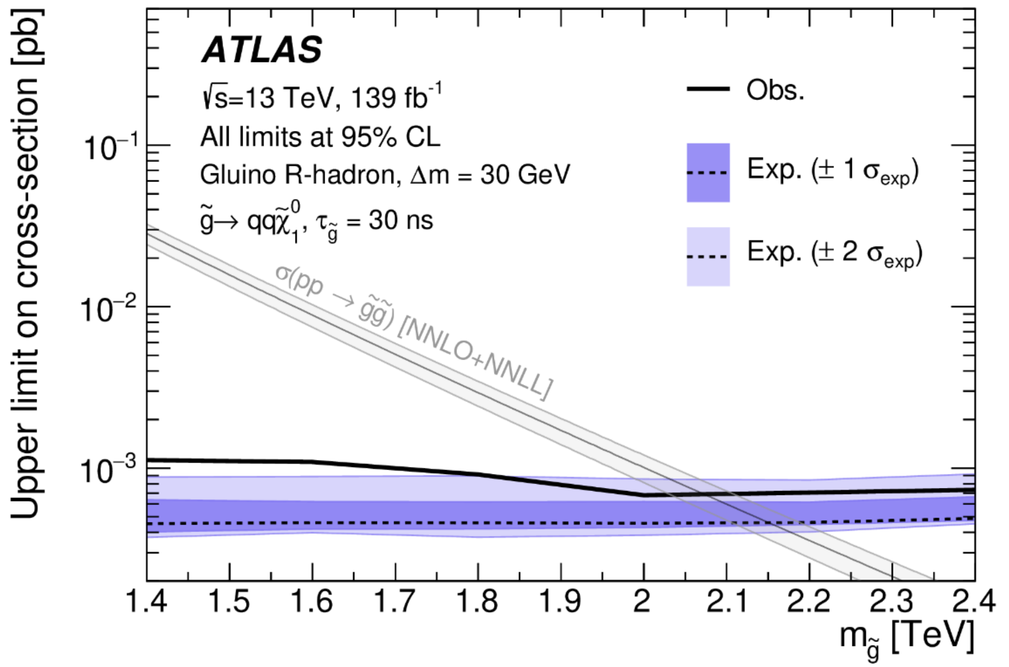
Heavy Long-Lived Charged Particles

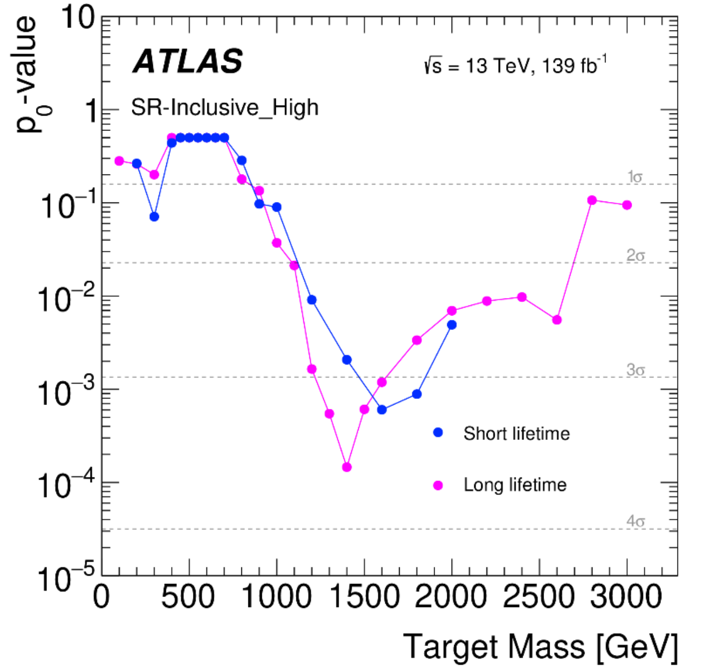
- Trigger on p_T^{miss} (from neutralinos or gravitinos)
- Require at least one high-p_T track with various quality & background rejection requirements
- Measure dE/dx (in MeV g^{-1} cm^2) using inner detector:
  - o Reconstruct track mass: $m_{\mathrm{d}E/\mathrm{d}x} \equiv p_{\mathrm{reco}}/\beta\gamma(\langle \mathrm{d}E/\mathrm{d}x \rangle_{\mathrm{corr}})$
  - o Signal regions: low (1.8 ≤ dE/dx ≤ 2.4), high (dE/dx > 2.4)





Statistical Analysis

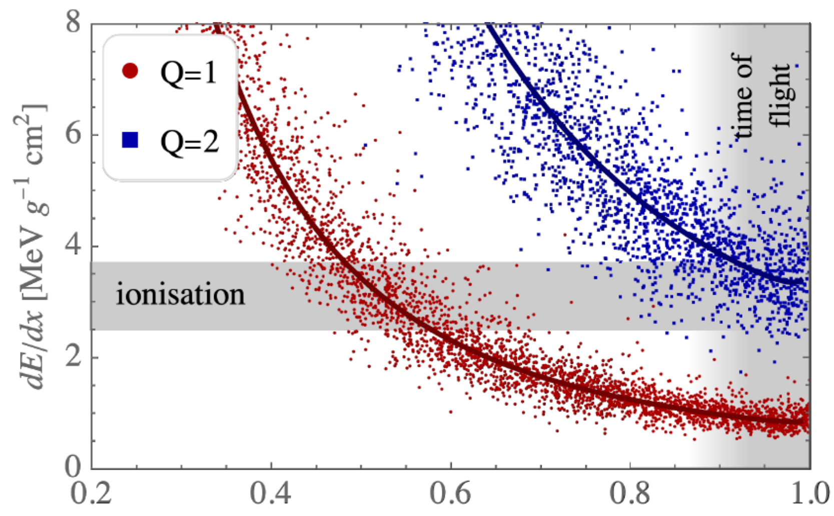


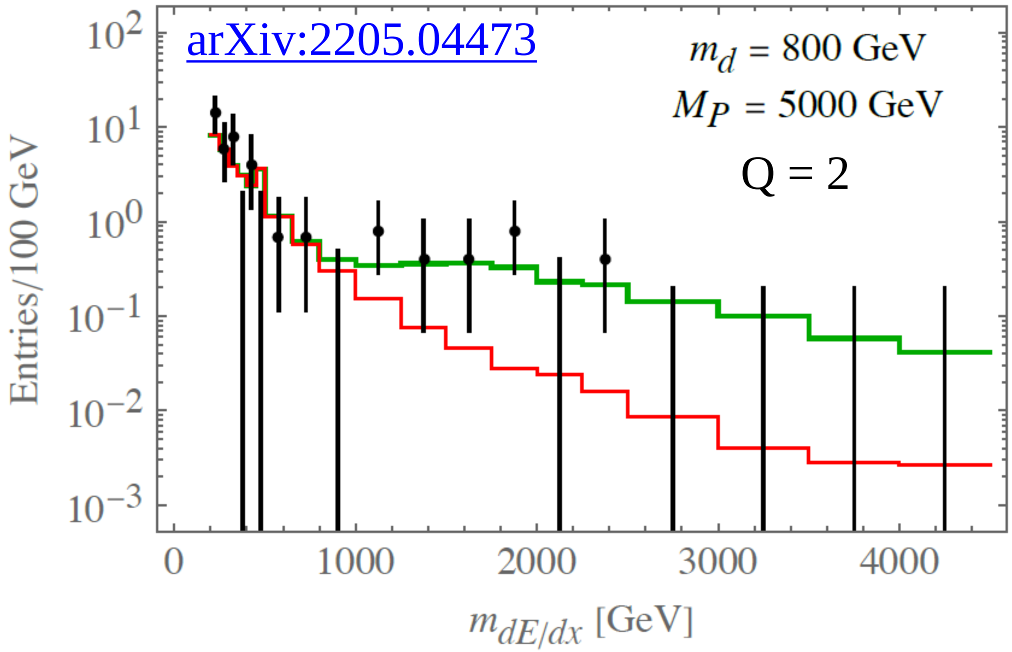


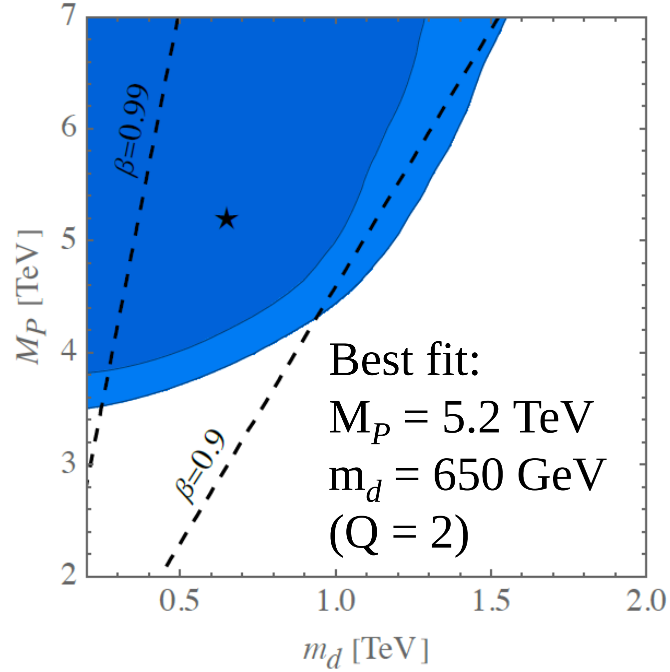
- $m_{\tilde{g}}$ = 1.4 TeV: 3.6σ local, 3.3σ global
- 7 excess events w/ 1100 < m < 2800 GeV:
  - 2 likely background (overflow in pixel tracker dynamic range)
  - Other 5: 2.4 ≤ dE/dx ≤ 3.7 MeV g^{-1} cm^2
    → predicted β = 0.5–0.6, but measured β ≈ 1 (from ToF, MS, Calo)
    - Not consistent with heavy LLP hypothesis…

Another Interpretation

- Doubly-charged particles have β values compatible w/ measured dE/dx!
- Resonant production of relatively light daughter particles *d* from massive parent particle *P* → boosted
- Good match for kinematic properties of excess events



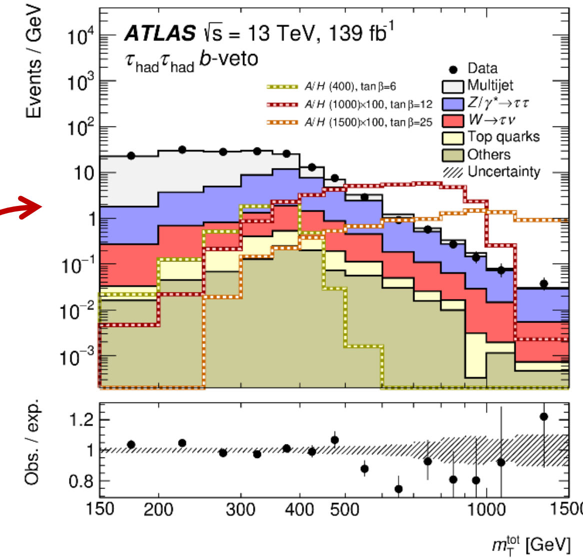


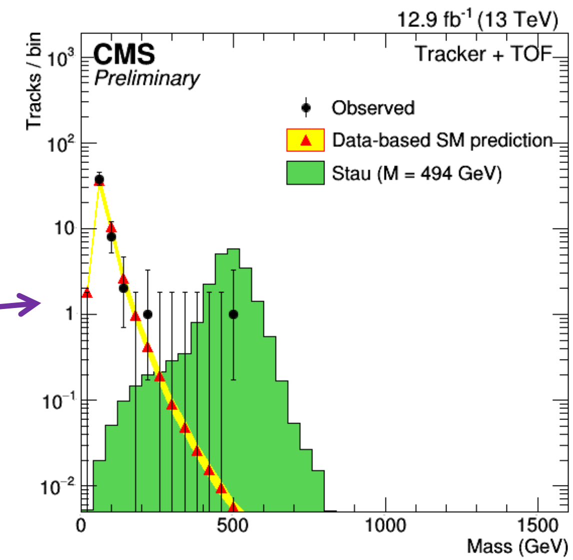


Prospects

Run 2 Prospects

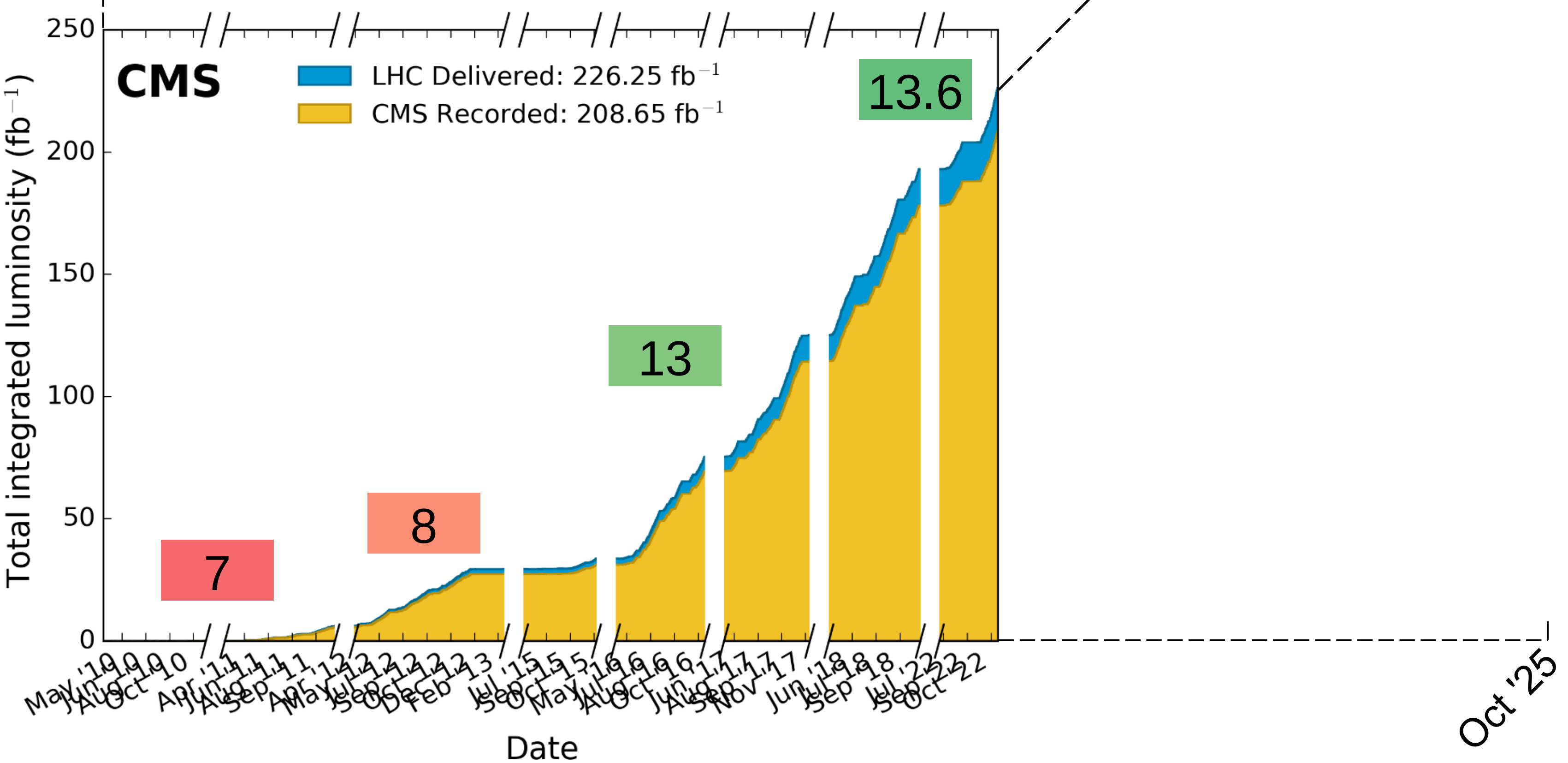
- A statistically independent dataset exists just on the other side of the ring…
- Paired dijet search:
  no corresponding result from ATLAS (yet)
- Leptoquark search:
  - ATLAS has full Run 2 results for [bτbτ](), [bℓbℓ](), or [bττ]() final states, but:
    - All require ≥1 b-jet in all signal regions
    - No nonresonant interpretations
      (only pair or single production)
  - ATLAS also has a search for [A/H → ττ]():
    - Very minor excess in last bin,
      potentially consistent but not convincing…
- Heavy charged LLP search:
  - Latest CMS result from [early Run 2]()
  - Updated result eagerly awaited!



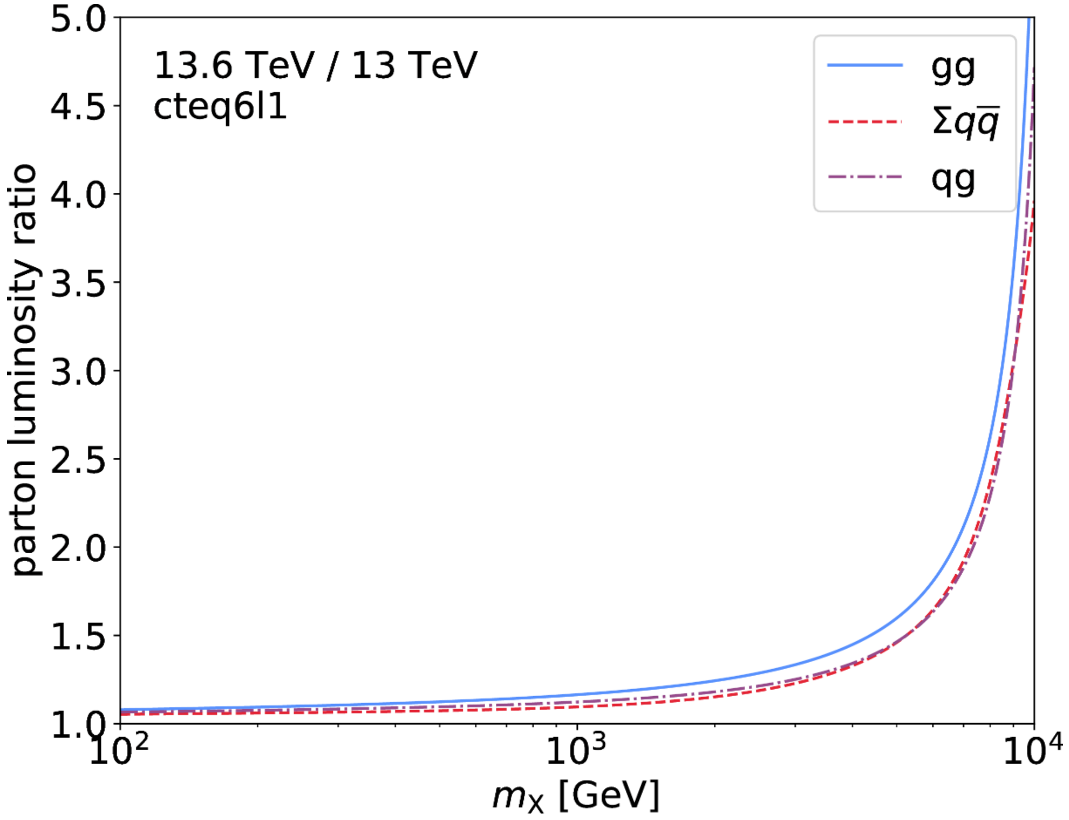


Run 3 Luminosity

- Strong performance in first year of Run 3: 41.5 fb^{-1} delivered
- Expect ~80 fb^{-1}/year for remaining 3 years of Run 3
- LHC dataset will double in size!



Run 3 Parton Luminosity



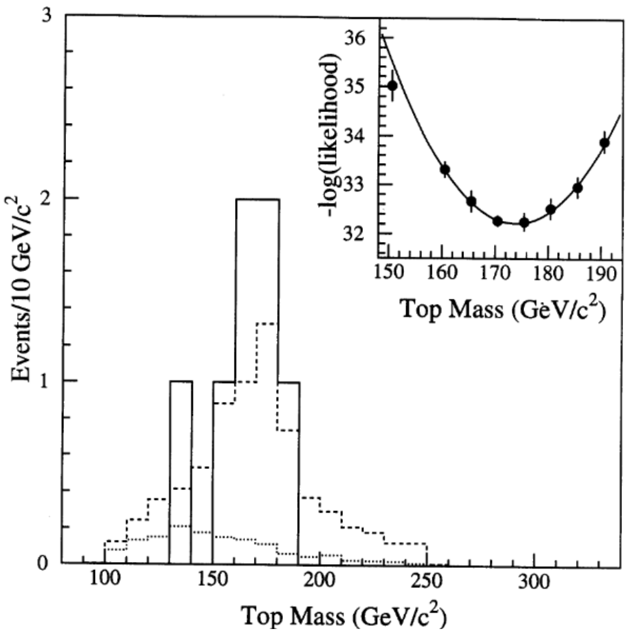
- Parton luminosity: generic cross section to produce an *s*-channel resonance
- √s increase to 13.6 TeV: especially impactful for massive resonances

➢ Production rates can increase by a factor of 2 or more in Run 3

Run 3 Prospects

Search	Mass [TeV]	Parton lumi ratio factor	Significance ↑: Run 2 lumi	Significance ↑: Full Run 3
Paired dijets	8	2	40%	100%
LQ, HCLLP	1–2	1.1–1.2	5–10%	50%
Boosted LLP pair	5	1.5	20%	70%

- Paired dijets, 2 events in Run 2 dataset:
  - 4 events in Run 3 w/ Run 2 lumi
  - 8 events in full Run 3 dataset
    - Almost 5σ, 8σ local
  - And no LEE! (search for specific mass)
- Parton luminosity increase less relevant for lower-mass excesses
- May need to wait for end of Run 3 to conclude…



First evidence of top quarks from CDF in 1994: only 12 events!

Searches: Imagination vs. Reality

Expected process: Theoretical prediction → Experimental search confirms theory → Nobel prize

Actual process: Theoretical prediction → Experimental search finds something different → ???

> **The most exciting phrase to hear in science, the one that heralds new discoveries, is not "Eureka!" but "That's funny…"**
>
> — Isaac Asimov

Observations from Our Survey

- For all three significant excesses we've studied today:
  - Signatures *don't match* signal models that initially motivated the searches
- Let's ask again: what wouldn't we have seen yet?
  - Something we weren't looking for!

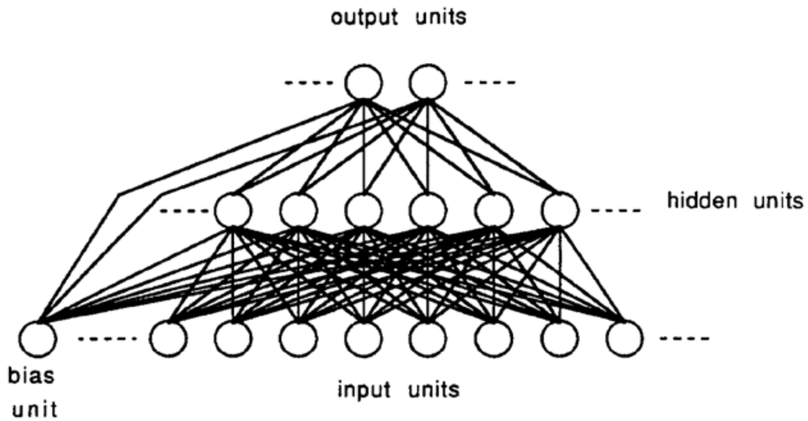
➢ Need to *search where the light isn't*

- So… how do we do that?

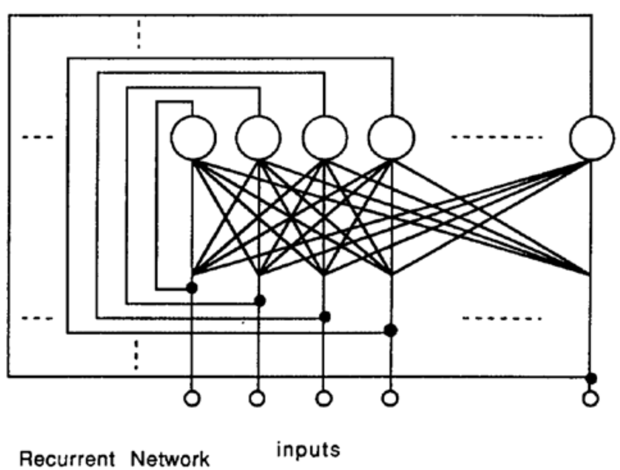
Anomaly Detection

Machine Learning

FROM THEN…

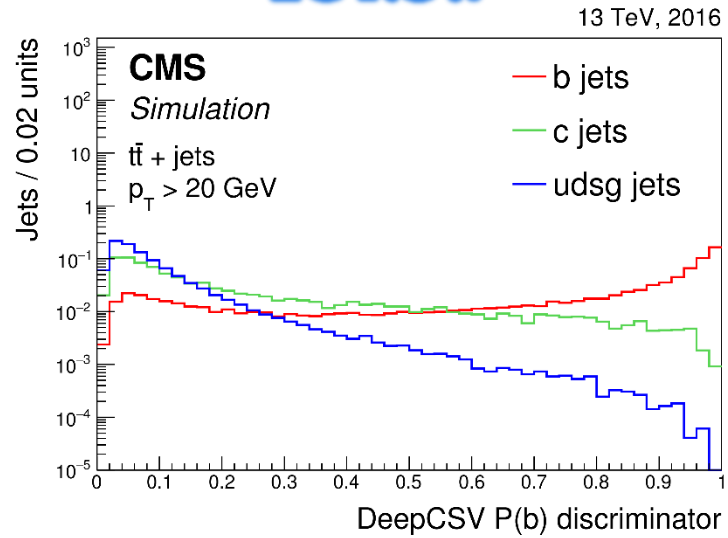


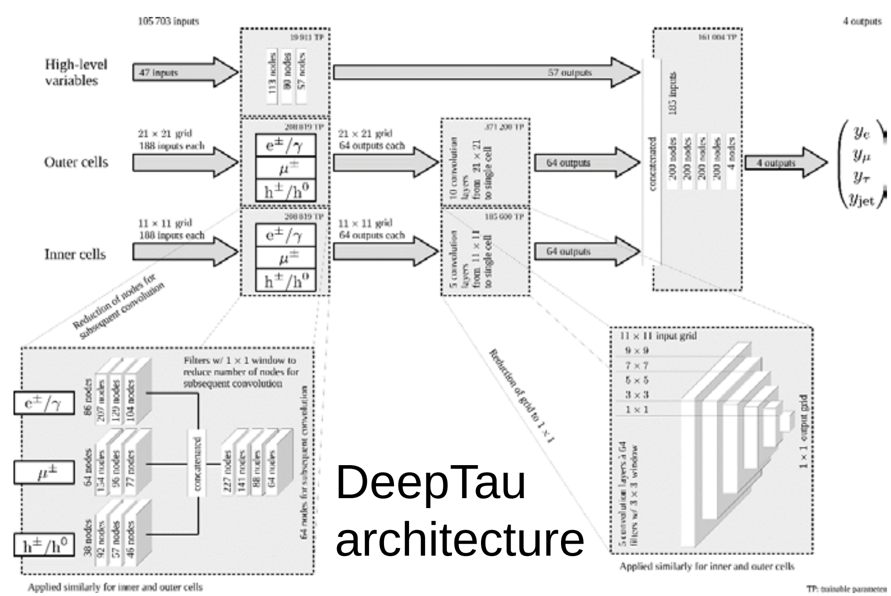
Feed forward neural network



B. Denby, "Neural Network Tutorial for High Energy Physicists", [FERMILAB-Conf-90/94](), May 1990

TO NOW





DeepTau architecture

ML for Searches

- Usage of ML in HEP is growing, including searches
- Most common usage: object or event classification
  - e.g. CMS leptoquark, $\varphi \rightarrow \tau\tau$ searches: deep neural networks for b- and τ-tagging
- Many searches develop custom classifiers for their signal models
  - Pros: higher sensitivity (reject more SM background, keep signal)
  - Cons: (potentially) lower sensitivity to other BSM signal models
- Can we get the pros without the cons?

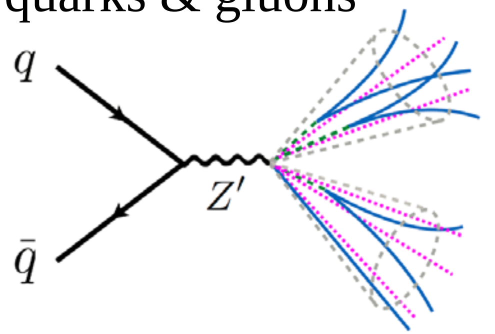
➢ *Anomaly detection*:

- Learn (train ML algorithm) based only on what we know (SM)
- Pick out what doesn't match or isn't recognized → something new?

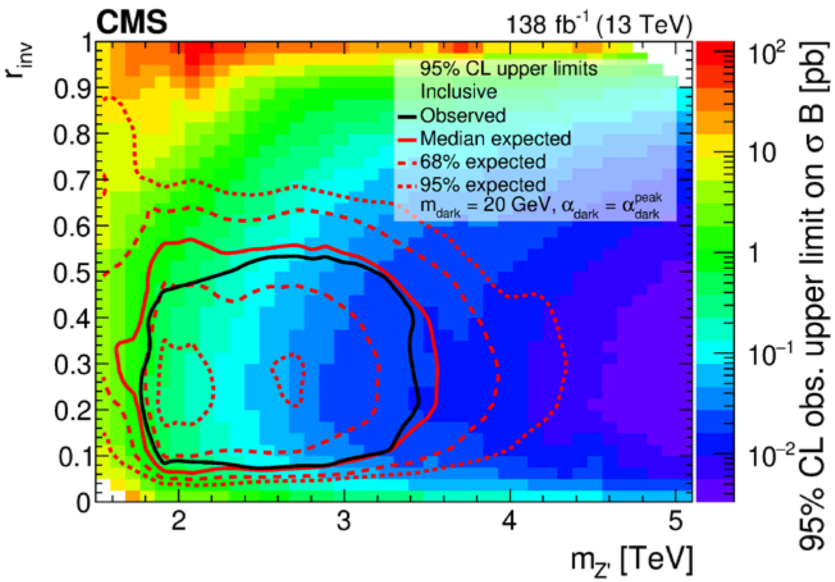
Case Study: Semivisible Jets

- What if dark matter is made up of composite particles, like visible matter?
- Strongly coupled hidden sector: dark QCD force with dark quarks & gluons
  - o Unstable dark hadrons: decay to SM quarks → jets
  - o Stable dark hadrons: dark matter candidates

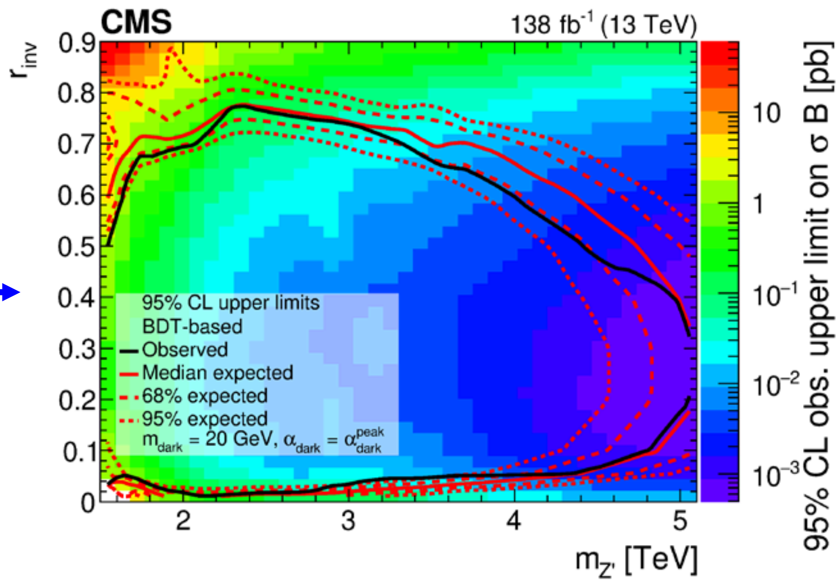
➢ Semivisible jets (SVJs): mixture of SM hadrons and DM!
  - o Look like mismeasured or neutrino-ful SM jets



- First CMS search: use BDT to tag SVJs, but also present results w/o tagger
  - o Dark QCD models have many undetermined parameters



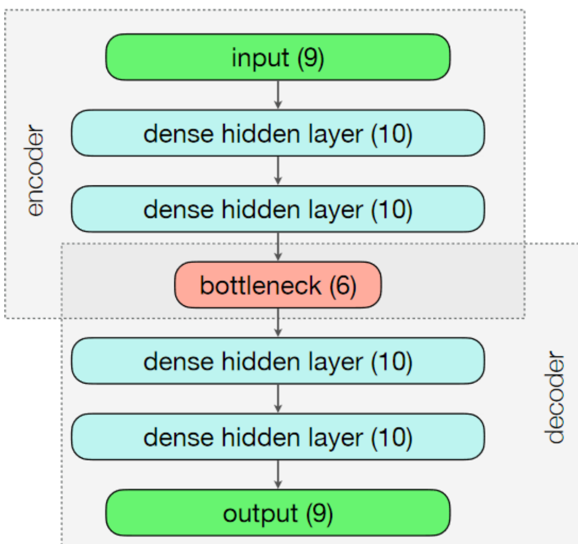
BDT →



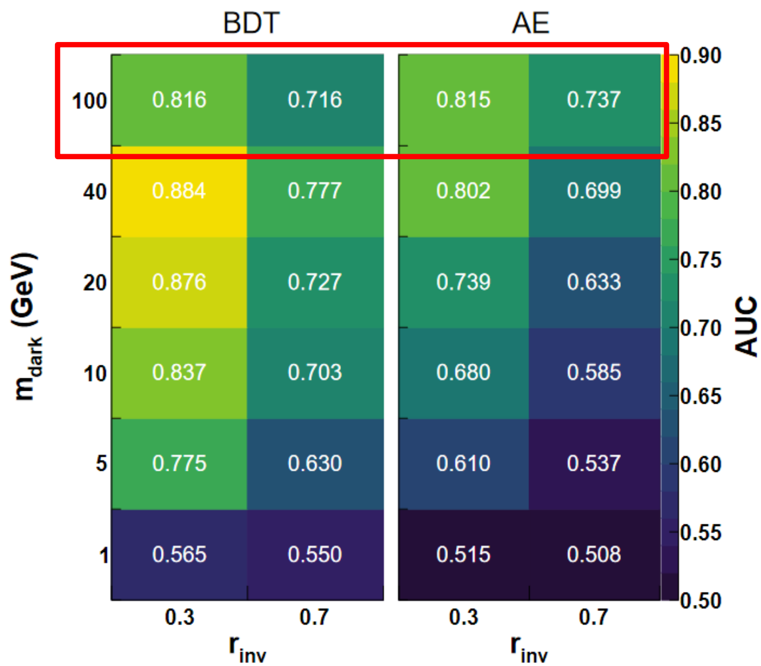
Autoencoders for Semivisible Jets

- Supervised classifier: trained on specific signal models (e.g. BDT) → may be insensitive to other signal model variations
- Autoencoder: creates latent representation that accurately reconstructs *background* → knows nothing about signal!
- Comparison: AE trained on QCD background, vs. BDT trained on signals w/ m_{dark} = 20 GeV

➢ Autoencoder can outperform BDT!

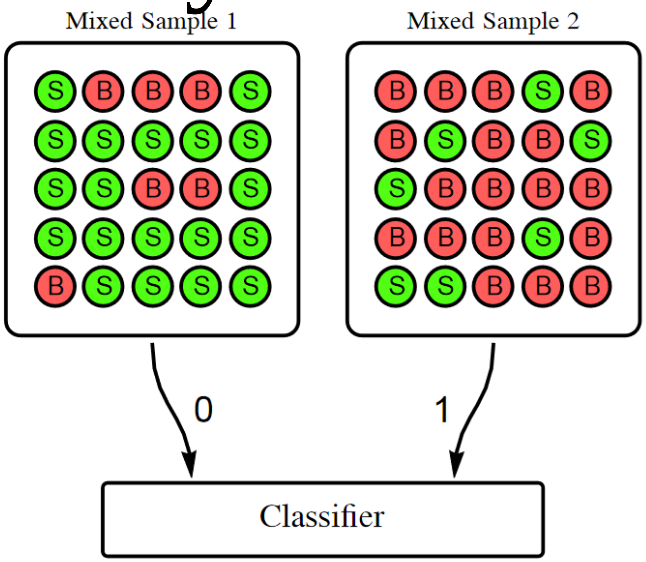


[arXiv:2112.02864](https://arxiv.org/abs/2112.02864)



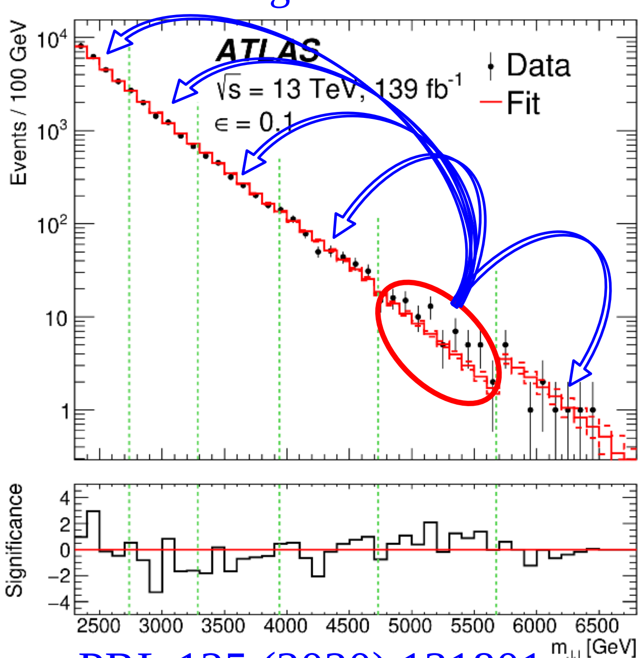
"invisible fraction"

First Experimental Anomaly Search



- Targets A → BC signatures
  - o A more general dijet search
- Uses "classification without labels" (CWoLa) technique: train on multiple data regions, assume different mix of processes in each

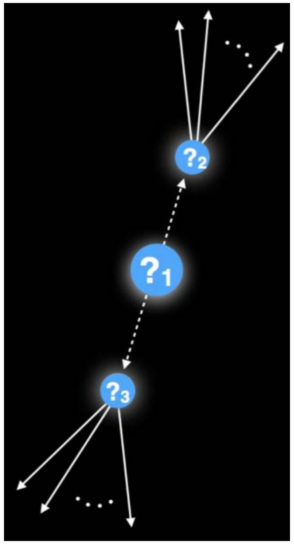
Training/validation

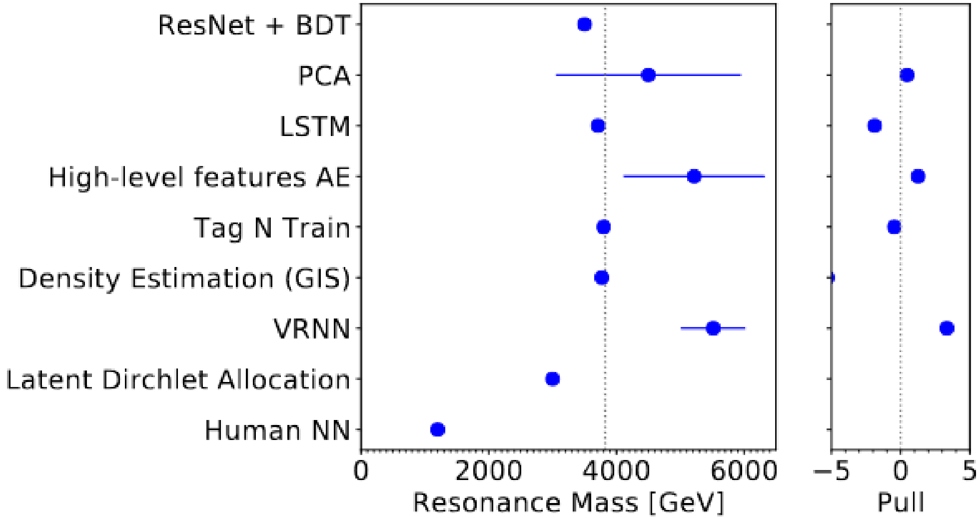


PRL 125 (2020) 131801

- No sign of a high-mass dijet excess…
  - o BUT: only considers $30 < m_J < 500$ GeV, $2.28 < m_{JJ} < 6.81$ TeV
- ➢ Need to be as inclusive as possible, even w/ anomaly detection!
- Newer ATLAS anomaly search for Y → XH uses autoencoder + Higgs tagger

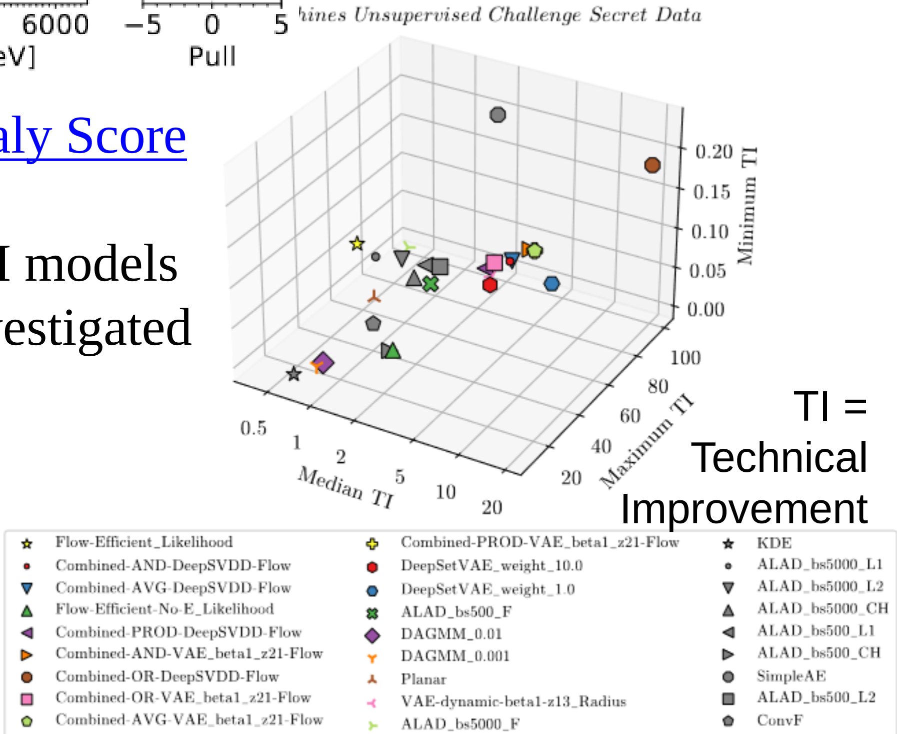
Anomaly Challenges





[LHC Olympics 2020](#):
- First challenge in this arena
- Led to new techniques like [Tag N Train](#), [QUAK](#)

[Dark Machines Anomaly Score Challenge 2021](#):
- Wider range of BSM models
- More techniques investigated

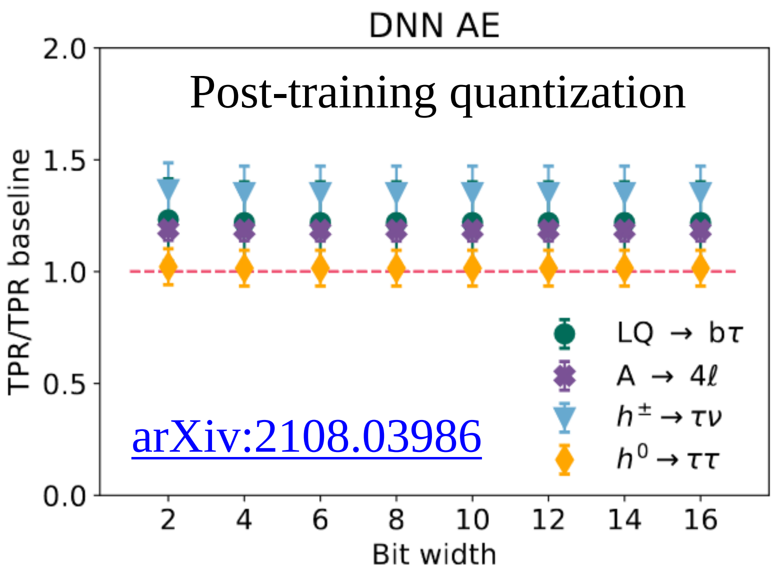


TI = Technical Improvement

- Challenges provide *open datasets*
  - o Crucial for benchmarks & comparisons of different methods
- See also: [Anomaly Detection Data Challenge 2021](#)

Anomaly Detection in Trigger

- Anomaly detection in offline analysis is a great way to extract more from existing datasets
- But can we take more interesting data in ongoing Run 3?
- Substantial work to accelerate ML inference on FPGAs for L1 trigger
  - Now applied to autoencoders!
- Effective models easily fit into ~1μs latency budget



arXiv:2108.03986

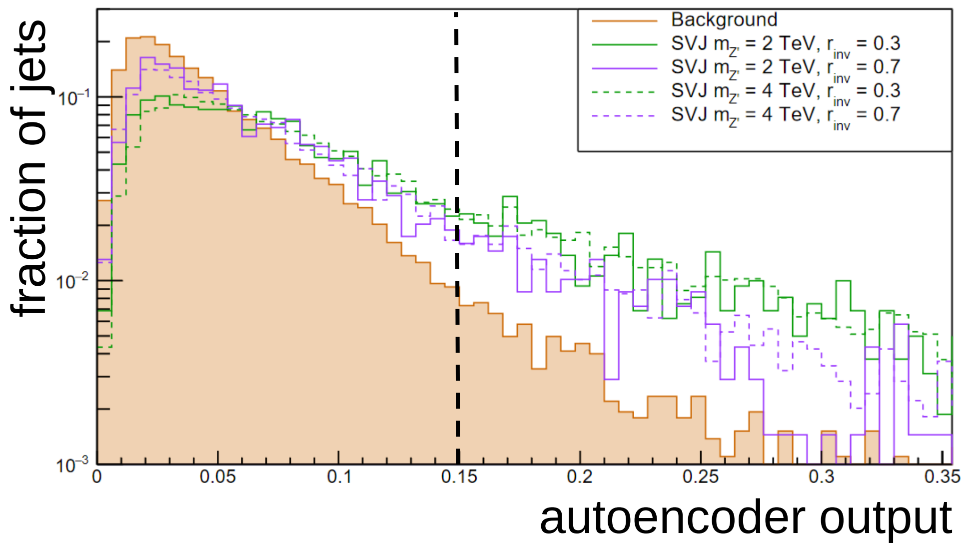
hls4ml

Model	Latency [ns]	II [ns]
DNN AE QAT 8 bits	130	5
CNN AE QAT 4 bits	1480	895
DNN VAE PTQ 8 bits	80	5
CNN VAE PTQ 8 bits	365	115

How to Use Anomaly Triggers

- AE from semivisible jet study:
- Turn it into a trigger:

1. Optimize threshold based on trigger rates & acceptance
2. Deploy on FPGA w/ hls4ml
3. Nobel prize?



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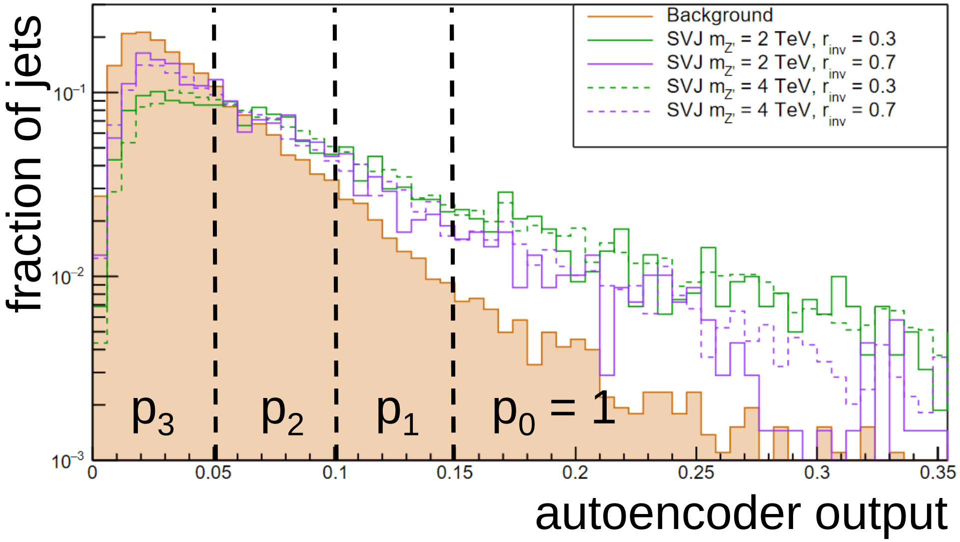
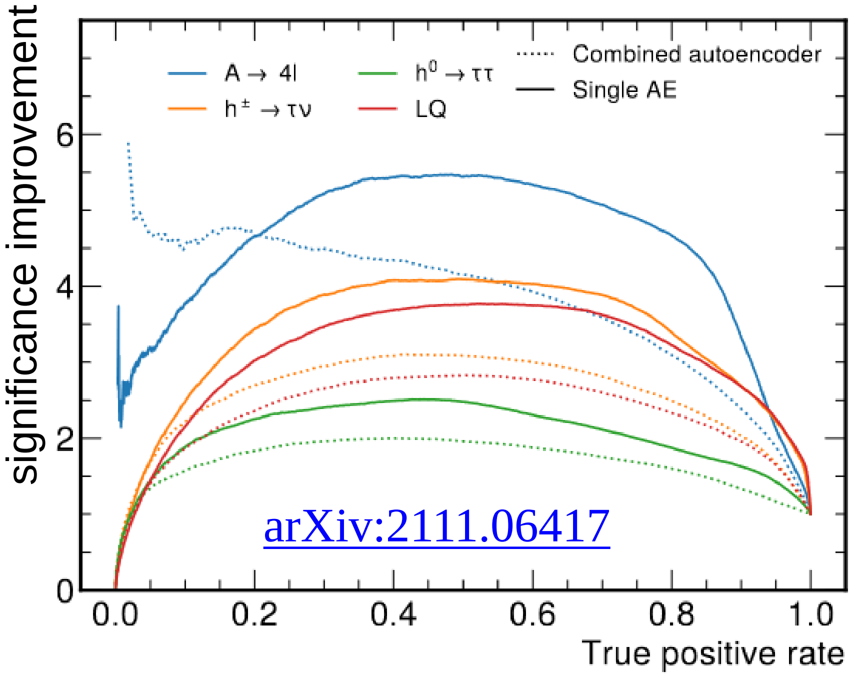
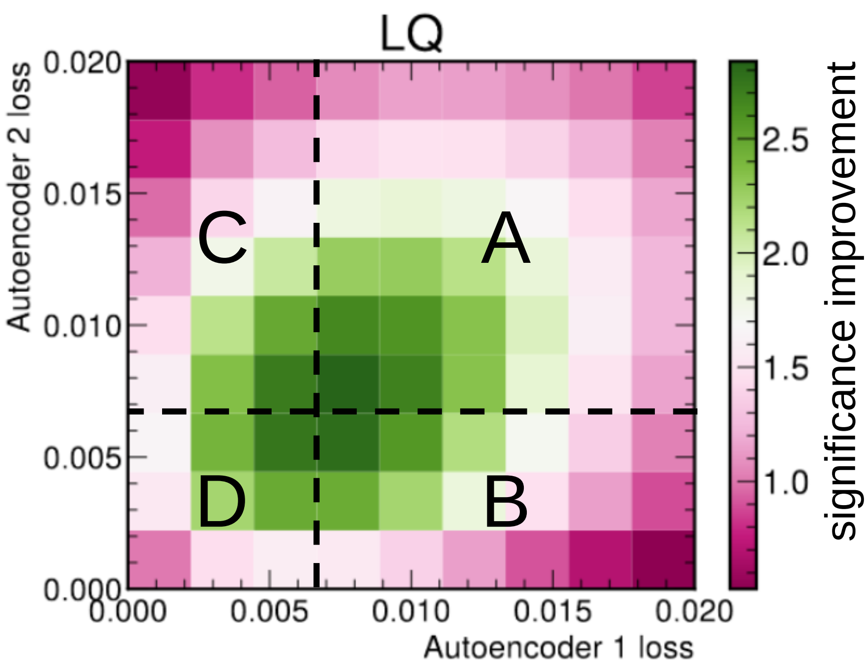


➢ Important part of science: convincing other scientists!
  - Are the triggered events signal or background?
- Need to characterize *entire* AE response: use different *prescales* to control rates, $p_3 > p_2 > p_1 > p_0 = 1$
  - Also need to *monitor* data: avoid collecting detector noise for 3 years

Another Way to Use Anomaly Triggers



- Related idea: 2 decorrelated AEs
  - Con: decorrelation procedure reduces sensitivity vs. single AE
  - Pro: facilitates "ABCD" background estimation



- Trigger strategy, as before:
  - Accept all events in signal region A
  - Prescaled triggers for regions B, C, D

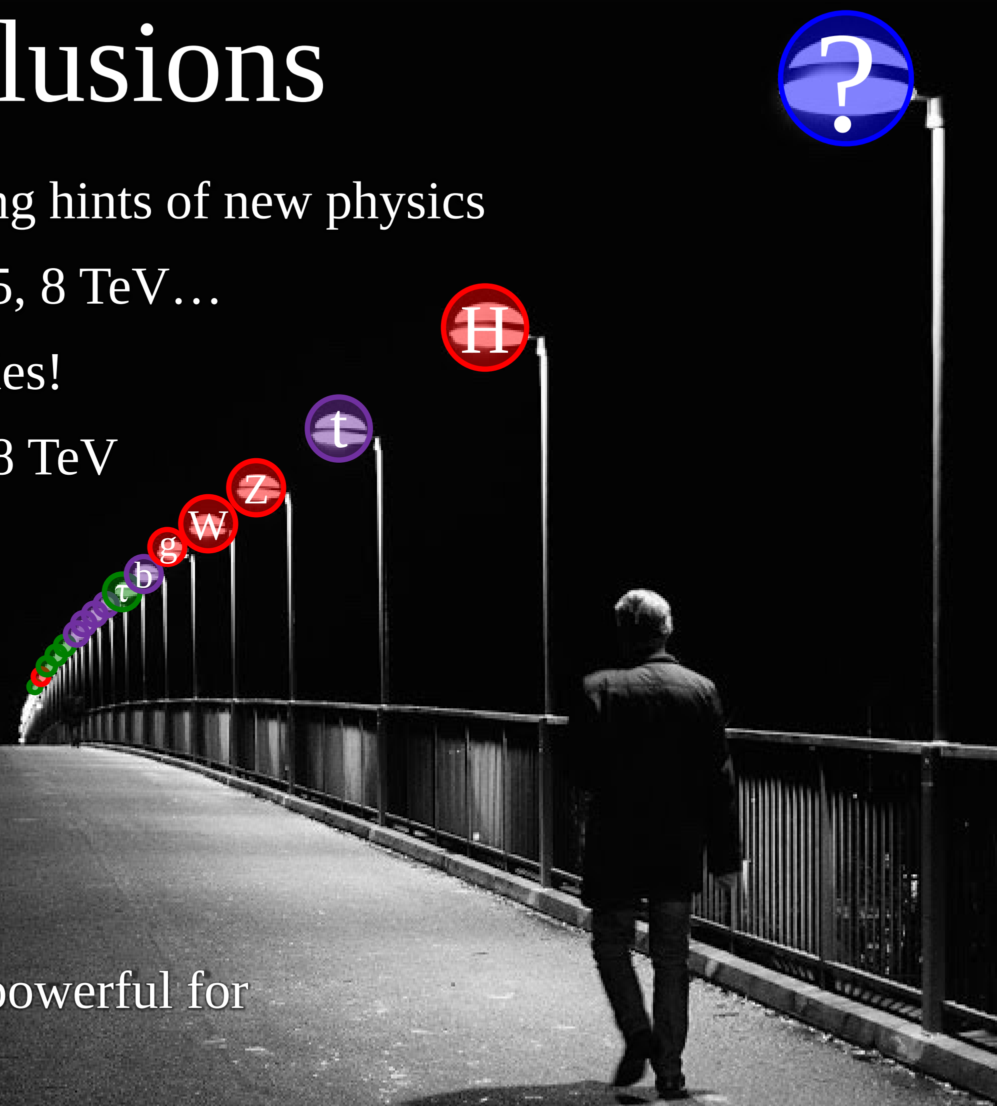
Conclusions

- Run 2 has produced many tantalizing hints of new physics
  - o Possible new resonances at 1, 2, 5, 8 TeV…
- Run 3 provides exciting opportunities!
  - o $\sqrt{s} \rightarrow 13.6$ TeV: ~2× increase @ 8 TeV
  - o Also 2× increase in luminosity
- Many excesses observed look quite different from motivating signal models

➢ Avoid the streetlight effect:
search where the light isn't

- Anomaly detection techniques are powerful for model-agnostic searches
  - o But they're also tricky: use with caution!

➢ Plenty of potential new physics still to be found in the LHC dataset



Backup

References

- https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults
- https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-009/
- http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/TOP-22-012/index.html
- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG
- https://arxiv.org/abs/2211.11084
- https://arxiv.org/abs/2209.13128
- https://lss.fnal.gov/archive/1994/pub/Pub-94-116-E.pdf
- See table (next slide) for links to search papers/conference notes
  - Subsequent slides have links to additional references, if any

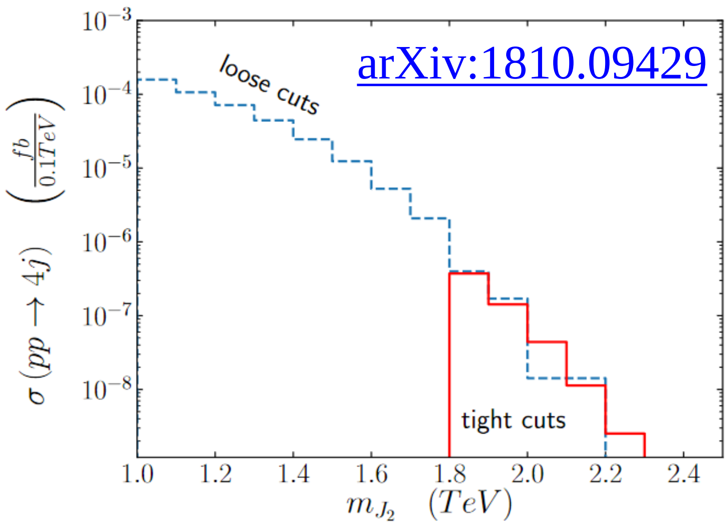
Table of Excesses

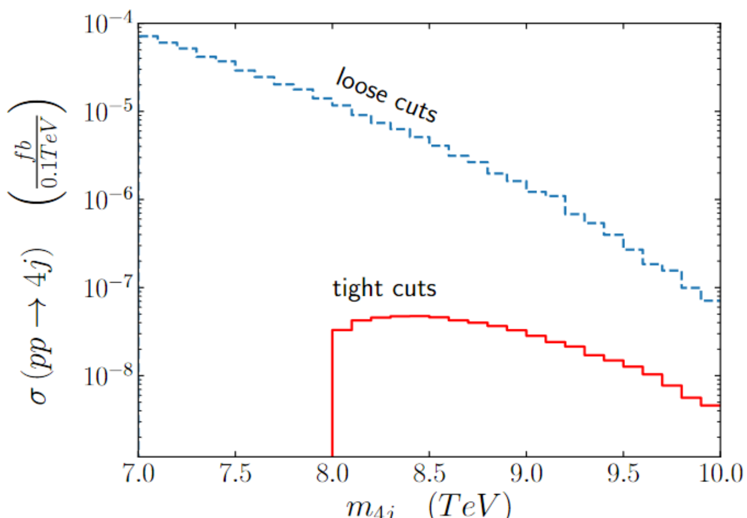
Experiment	Process	Mass(es)	Local σ	Global σ
CMS	$\varphi \to \tau\tau$	m_φ = 100 GeV	3.1	2.7
CMS	$\varphi \to \tau\tau$	m_φ = 1.2 TeV	2.8	2.4
CMS	$H \to WW$	m_H = 650 GeV	3.8	2.6
CMS	$Y \to XX \to (jj)(jj)$	m_Y = 8.6 TeV m_X = 2.1 TeV	3.9	1.6
CMS	$XX \to (jj)(jj)$	m_X = 0.95 TeV	3.6	2.5
CMS	$W' \to WZ$	$m_{W'}$ = 2.1 TeV	3.6	2.3
CMS	$W' \to WZ$	$m_{W'}$ = 2.9 TeV	3.6	2.3
ATLAS	$X \to HH \to bbbb$	m_X = 1.1 TeV	3.2	2.1
ATLAS	$H_5 \to WZ$	m_{H_5} = 375 GeV	2.8	1.6
CMS	$X \to \varphi\varphi \to bbbb$	m_X = 1 TeV m_φ = 75 GeV	3.1	1.3
ATLAS	Heavy Charged LLP	$m_{\tilde{g}}$ = 1.4 TeV	3.6	3.3
CMS	$X \to HH \to WWWW$	m_X = 750 GeV	2.1	
ATLAS	$X \to \gamma\gamma$	m_X = 19 GeV	3.1	1.5
CMS	$LL \to (qq\ell)(qq\ell)$	m_L = 600 GeV	2.8	
CMS	$LQ\ LQ \to (b\tau)(b\tau)$	m_{LQ} = 2 TeV	3.4	
ATLAS	$H \to Z_dZ_d \to \ell\ell\ell\ell$	m_{Z_d} = 28 GeV	2.5	
CMS	$W_R \to N\ell$	m_{W_R} = 6 TeV m_N = 0.8 TeV	2.95	2.78
ATLAS	$H \to aa \to bb\mu\mu$	m_a = 52 GeV	3.3	1.7
CMS	$\tilde{t} \to tqqq$ (pair)	$m_{\tilde{t}}$ = 400 GeV	2.8	
CMS	$T \to tZ$	m_T = 1.4 TeV	2.5	2.2

QCD at m_{JJ} = 8 TeV

Loose: m_{4j} > 7 TeV,
m_{J_1} > 1 TeV, m_{J_2} > 1 TeV
Tight: $m_{4j} \geq$ 8 TeV,
$m_{J_1} \geq$ 1.8 TeV, $m_{J_2} \geq$ 1.8 TeV

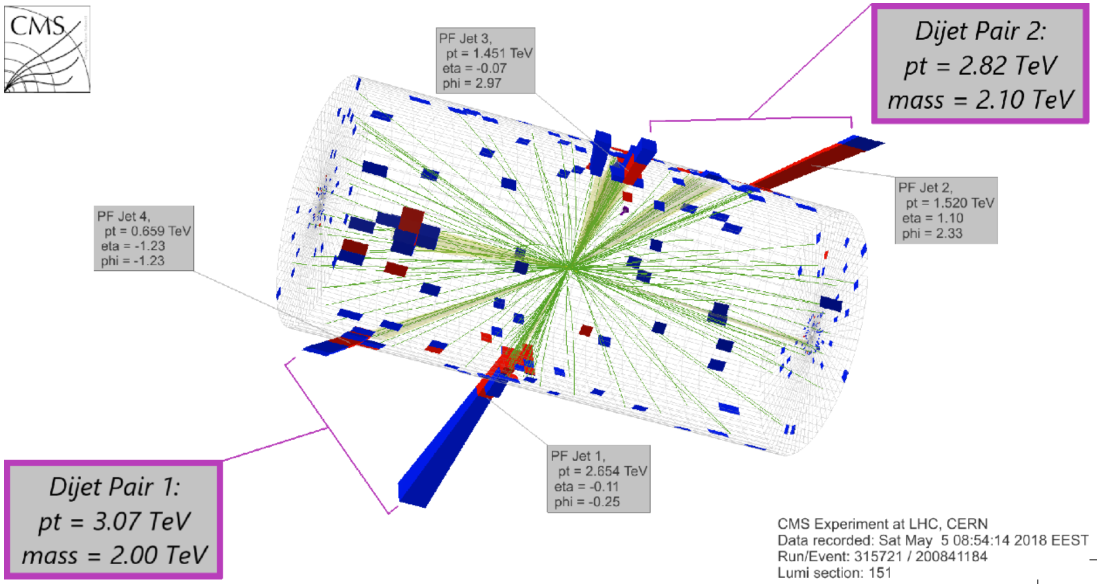
- pp → 4j in MadGraph5_aMC@NLO
- Uncertainties:
  - Cross section: NLO *k*-factor for 4j process is ~ 1
  - PDFs: 21% from NNPDF2.3LO (valence quarks dominate)
  - μ_R/μ_F: +72%, –40%
- Result: 4.5×10^{-5} events in 77.8 fb^{-1} (similar results for other PDFs)
- Observation: 2 wide jets w/ $m_J \geq$ 1.8 TeV less likely than $m_{4j} \geq$ 8 TeV
  - Kinematically constrained: $\overline{m}_J \approx \frac{m_{4j}}{2\sqrt{1+4/\Delta R_J^2}}$ for central jets



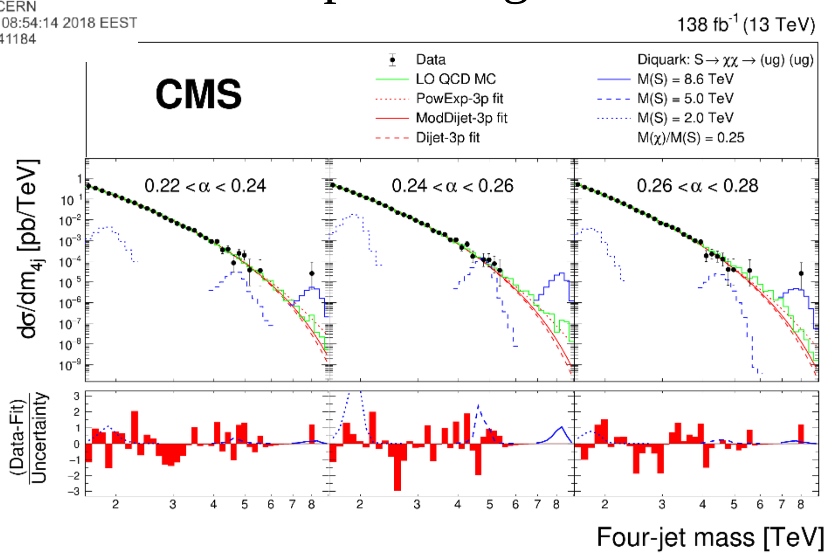


Paired Dijet Search

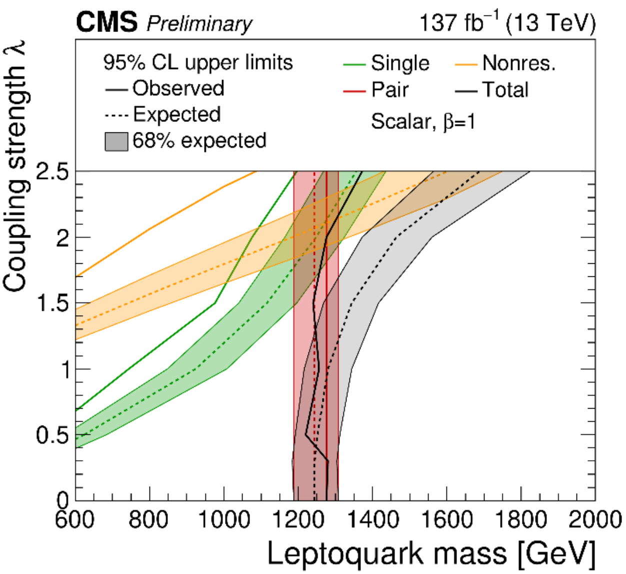
- 2nd event: $\Delta R_1 = 1.5$, $\Delta R_2 = 1.3$

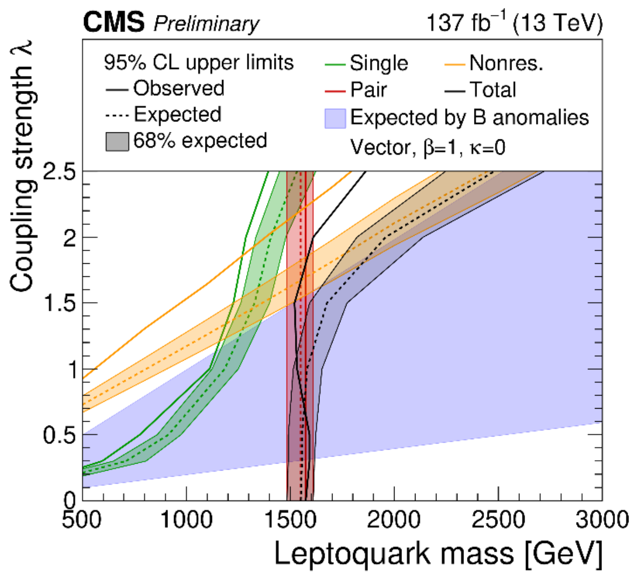


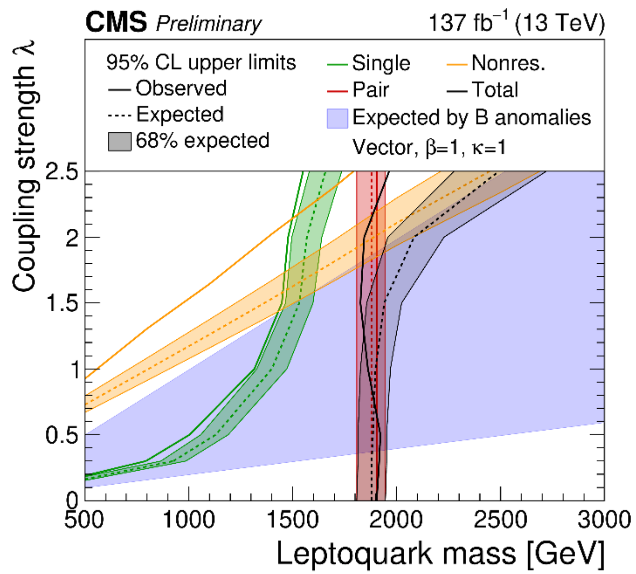
- Example background fits:

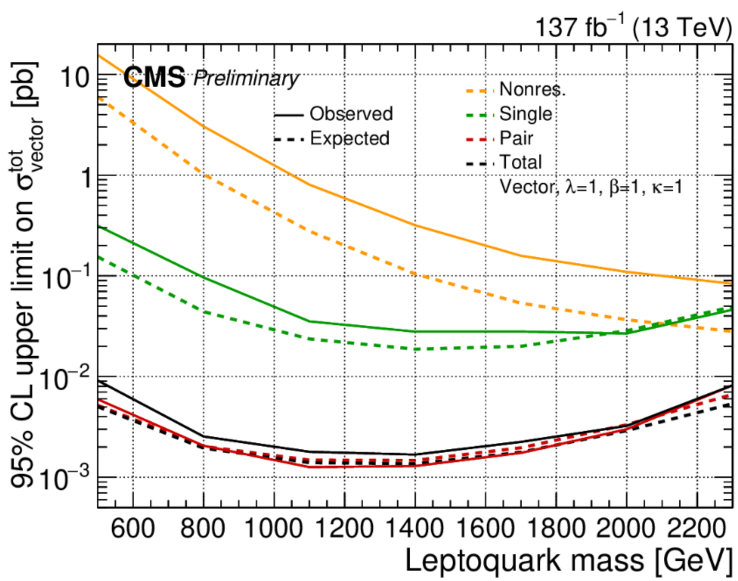


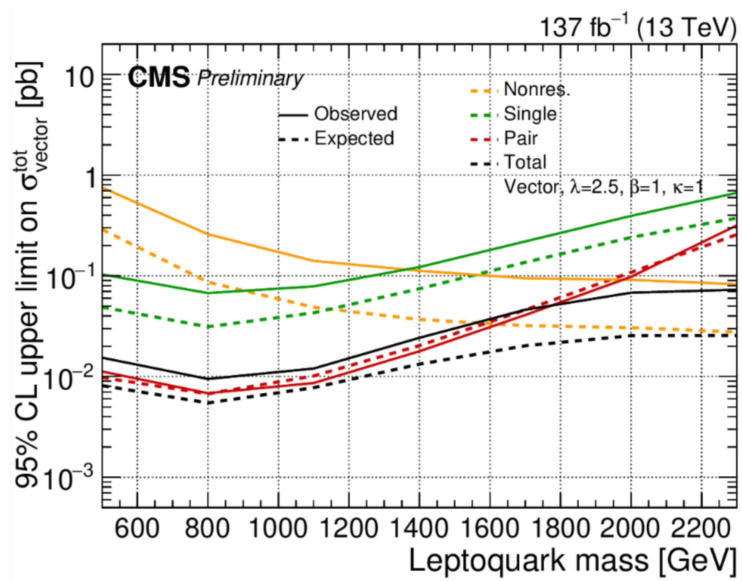
LQ Production Mode Contributions



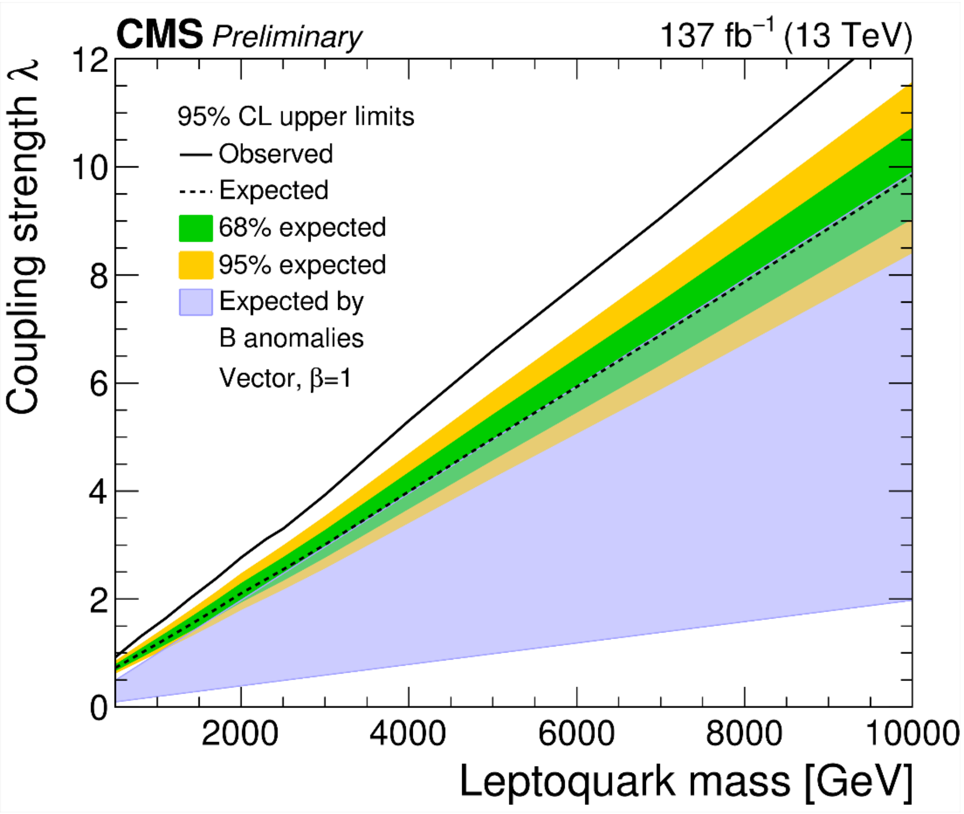




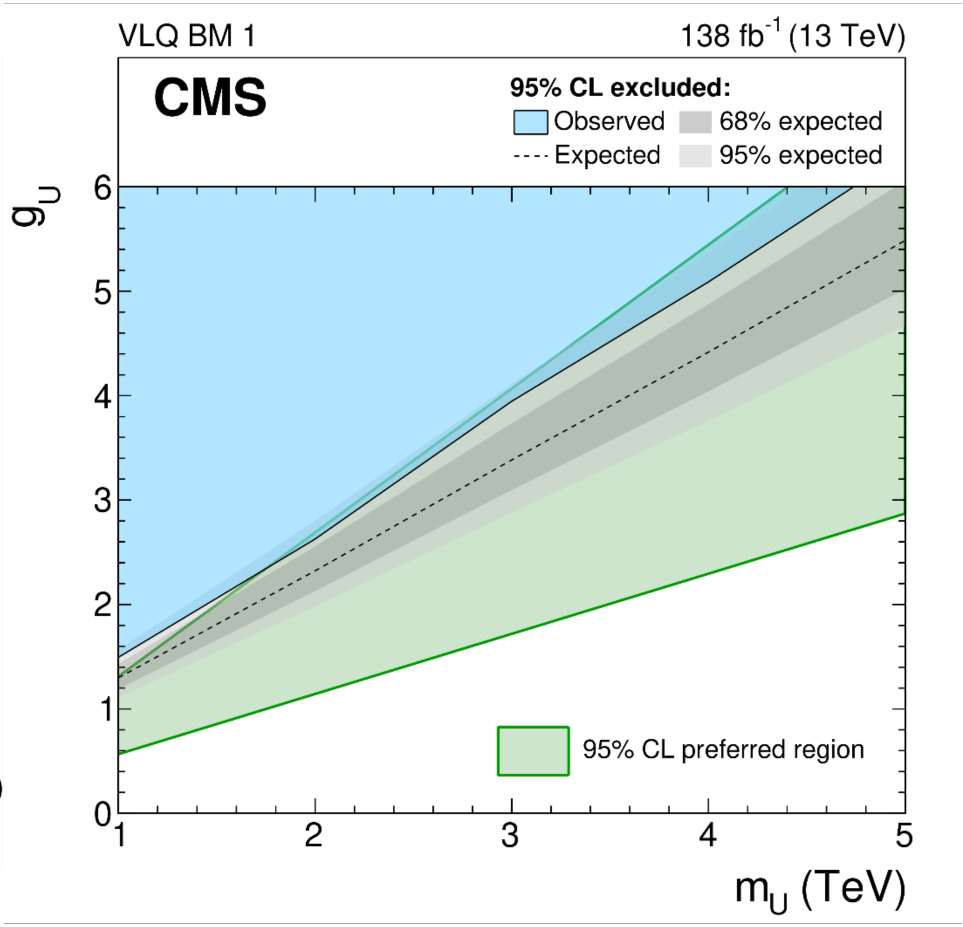




Nonresonant Vector LQs



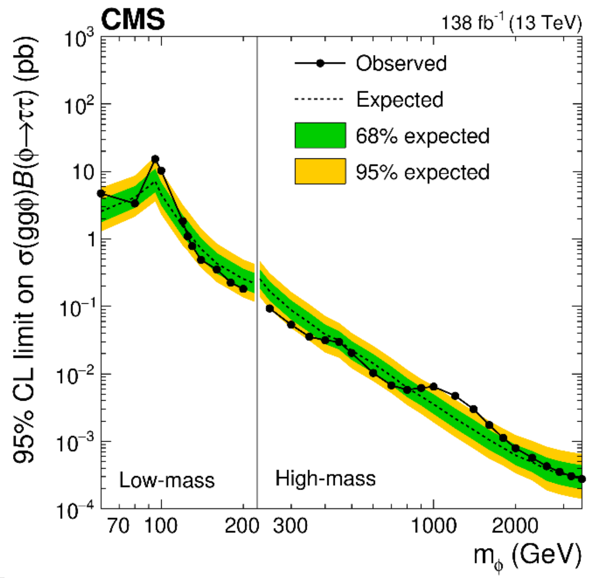
LQ search

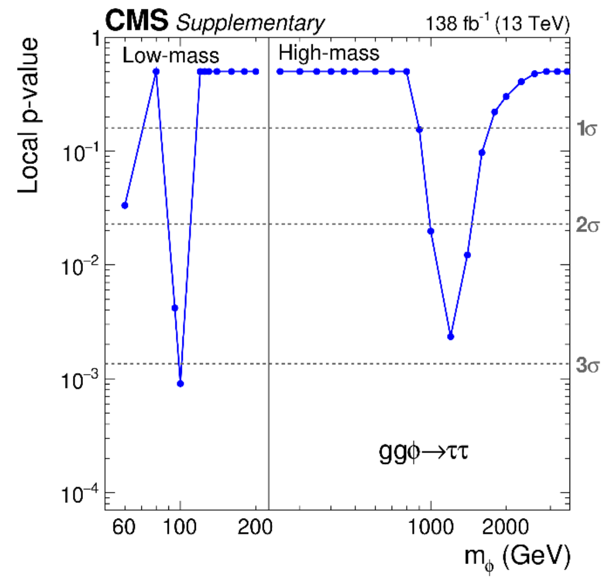


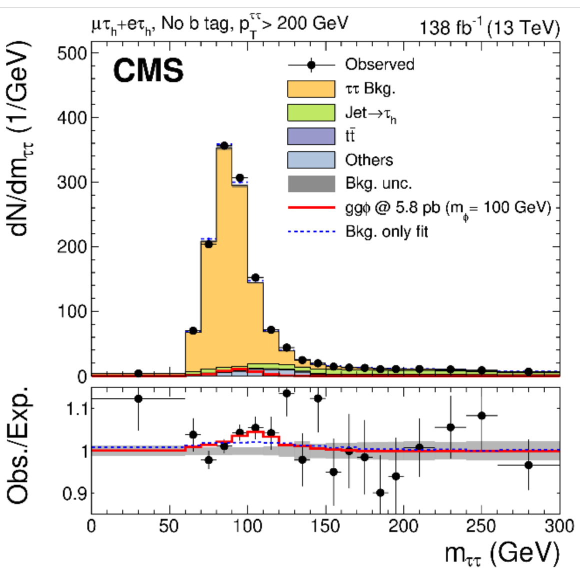
φ→ττ search

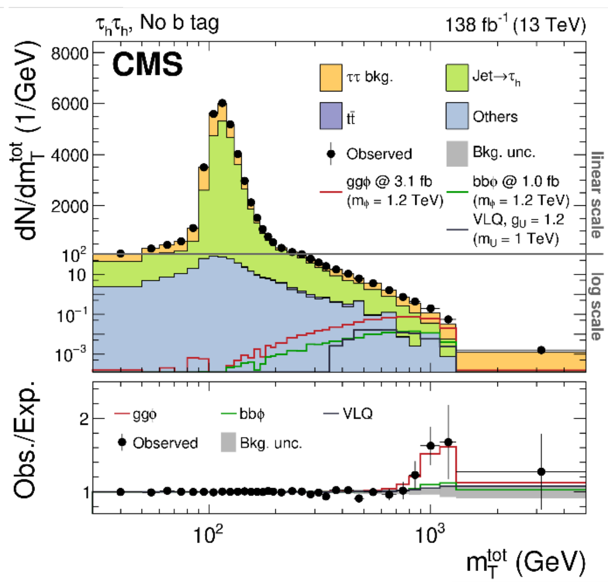
$\varphi \rightarrow \tau\tau$

- Final states:
  $e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$
- DeepTau, DeepCSV used
- m_φ = 100 GeV:
  3.1σ local, 2.7σ global
- m_φ = 1200 GeV:
  2.8σ local, 2.4σ global



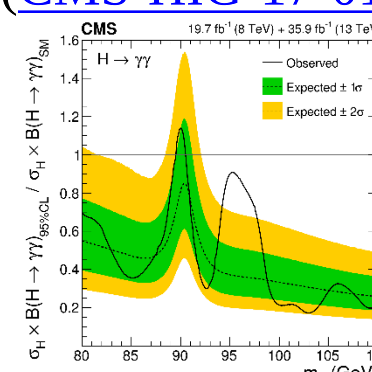




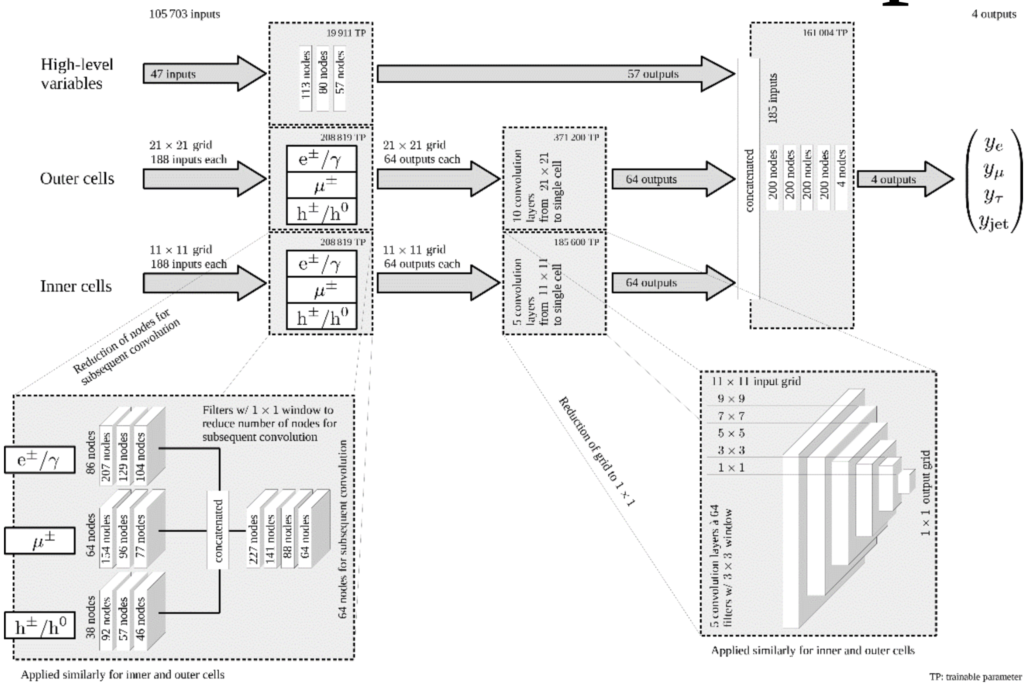


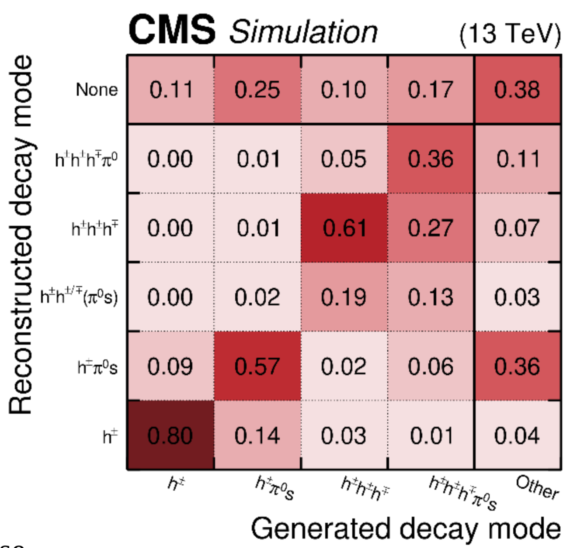
$$m_T^{tot} = \sqrt{m_T^2(\vec{p}_T^{\,\tau_1}, \vec{p}_T^{\,\tau_2}) + m_T^2(\vec{p}_T^{\,\tau_1}, \vec{p}_T^{\,miss}) + m_T^2(\vec{p}_T^{\,\tau_2}, \vec{p}_T^{\,miss})}$$

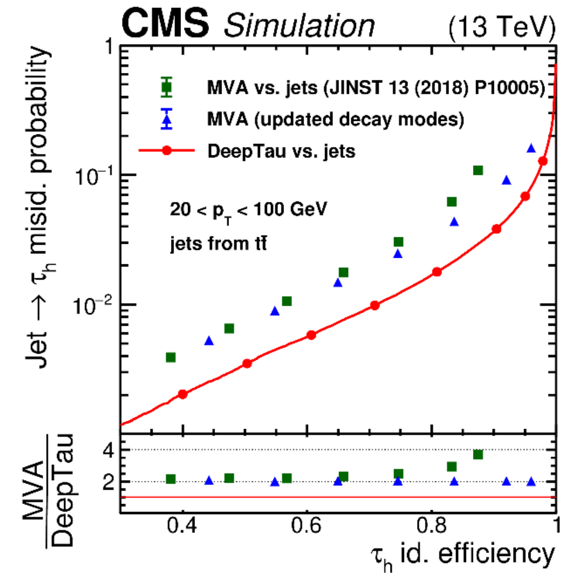
- m_φ = 95 GeV:
  2.6σ local, 2.3σ global
- Related to $H \rightarrow \gamma\gamma$ excess?
  2.8σ local, 1.3σ global
  (CMS-HIG-17-013)

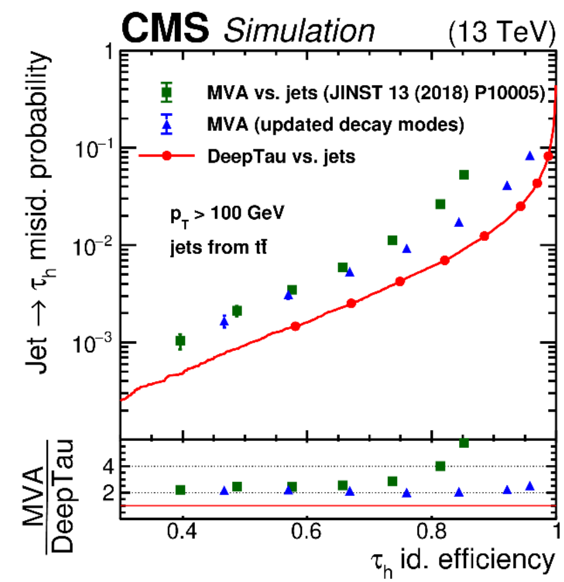


DeepTau


105 703 inputs
4 outputs
High-level variables
47 inputs
19 911 TP
113 nodes
80 nodes
57 nodes
57 outputs
Outer cells
21 × 21 grid
188 inputs each
208 819 TP
e±/γ
μ±
h±/h0
21 × 21 grid
64 outputs each
371 200 TP
10 convolution layers from 21 × 21 to single cell
64 outputs
Inner cells
11 × 11 grid
188 inputs each
11 × 11 grid
64 outputs each
185 600 TP
5 convolution layers from 11 × 11 to single cell
161 004 TP
concatenated
185 inputs
200 nodes
200 nodes
200 nodes
200 nodes
4 nodes
4 outputs
y_e
y_μ
y_τ
y_jet
Reduction of nodes for subsequent convolution
Filters w/ 1 × 1 window to reduce number of nodes for subsequent convolution
86 nodes
207 nodes
129 nodes
104 nodes
64 nodes
154 nodes
96 nodes
77 nodes
38 nodes
92 nodes
57 nodes
46 nodes
concatenated
227 nodes
141 nodes
88 nodes
64 nodes
64 nodes for subsequent convolution
Applied similarly for inner and outer cells
Reduction of grid to 1 × 1
11 × 11 input grid
9 × 9
7 × 7
5 × 5
3 × 3
1 × 1
5 convolution layers a 64 filters w/ 3 × 3 window
1 × 1 output grid
Applied similarly for inner and outer cells
TP: trainable parameter


CMS Simulation (13 TeV)
Reconstructed decay mode
None 0.11 0.25 0.10 0.17 0.38
h±h±h∓π0 0.00 0.01 0.05 0.36 0.11
h±h±h∓ 0.00 0.01 0.61 0.27 0.07
h±h±/∓(π0s) 0.00 0.02 0.19 0.13 0.03
h±π0s 0.09 0.57 0.02 0.06 0.36
h± 0.80 0.14 0.03 0.01 0.04
h±
h±π0s
h±h±h∓
h±h±h∓π0s
Other
Generated decay mode

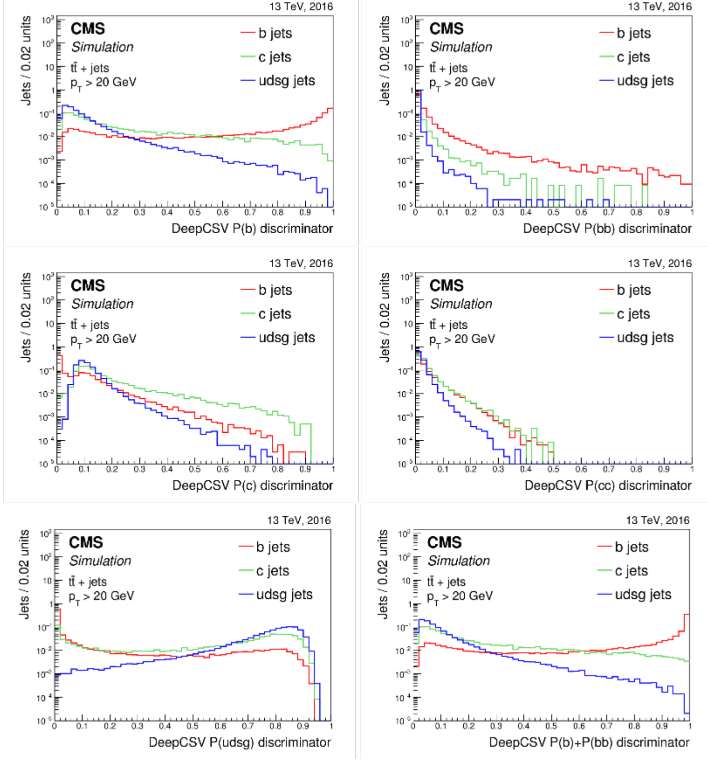

CMS Simulation (13 TeV)
MVA vs. jets (JINST 13 (2018) P10005)
MVA (updated decay modes)
DeepTau vs. jets
20 < p_T < 100 GeV
jets from tt̄
Jet → τh misid. probability
MVA / DeepTau
τh id. efficiency

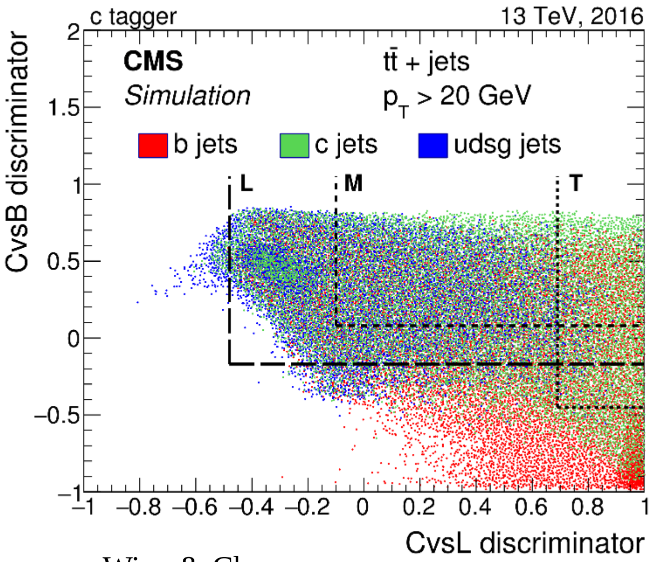

CMS Simulation (13 TeV)
MVA vs. jets (JINST 13 (2018) P10005)
MVA (updated decay modes)
DeepTau vs. jets
p_T > 100 GeV
jets from tt̄
Jet → τh misid. probability
MVA / DeepTau
τh id. efficiency

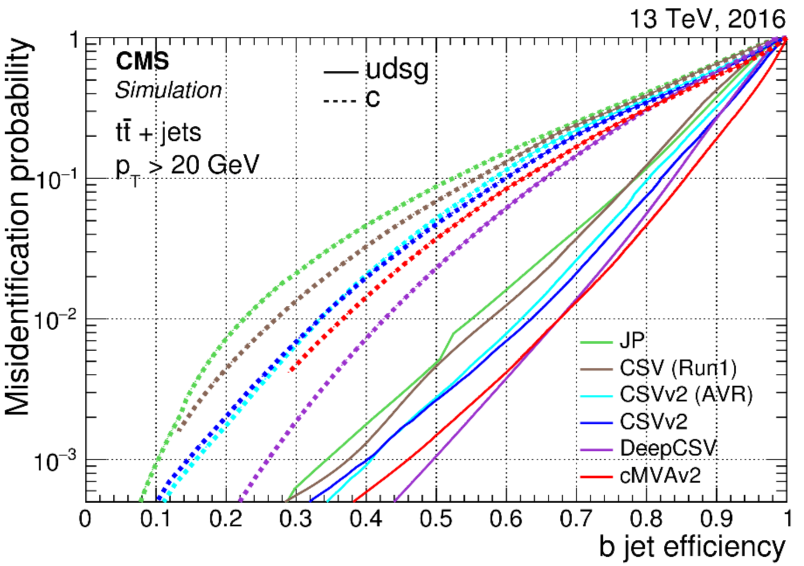
DeepCSV

4 hidden layers, 100 nodes each

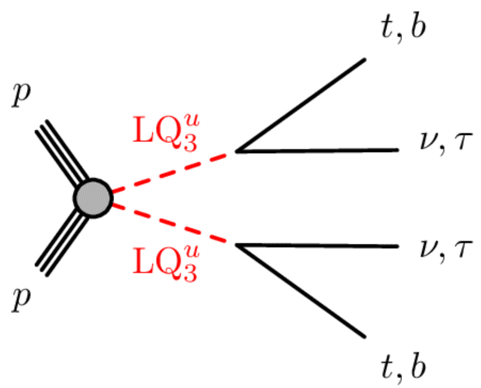
Input variable
SV 2D flight distance significance
Number of SV
Track η_{rel}
Corrected SV mass
Number of tracks from SV
SV energy ratio
$\Delta R(\mathrm{SV, jet})$
3D IP significance of the first six tracks
Track $p_{\mathrm{T,rel}}$
$\Delta R(\mathrm{track, jet})$
Track $p_{\mathrm{T,rel}}$ ratio
Track distance
Track decay length
Summed tracks E_{T} ratio
$\Delta R(\mathrm{summed\ tracks, jet})$
First track 2D IP significance above c threshold
Number of selected tracks
Jet p_{T}
Jet η



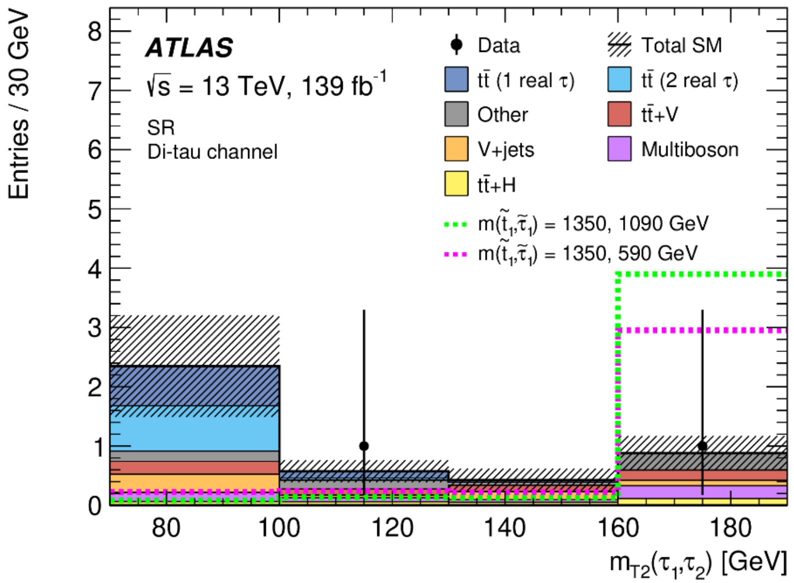


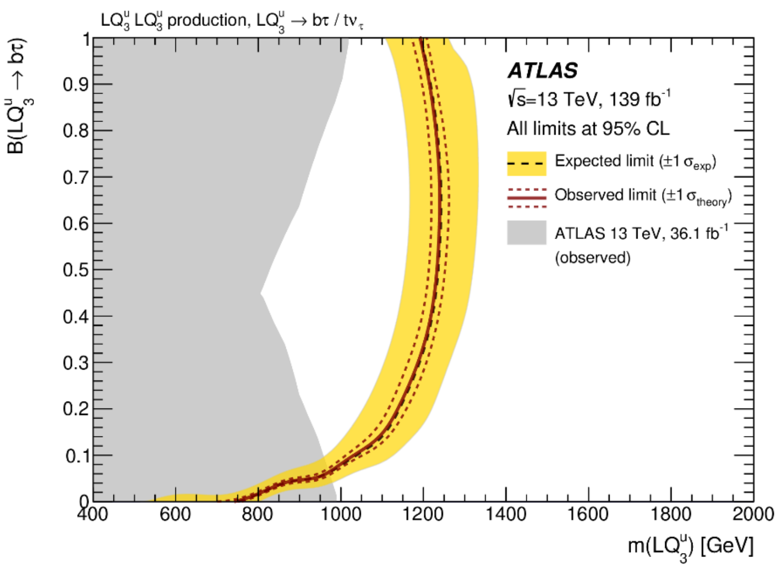


ATLAS bτbτ



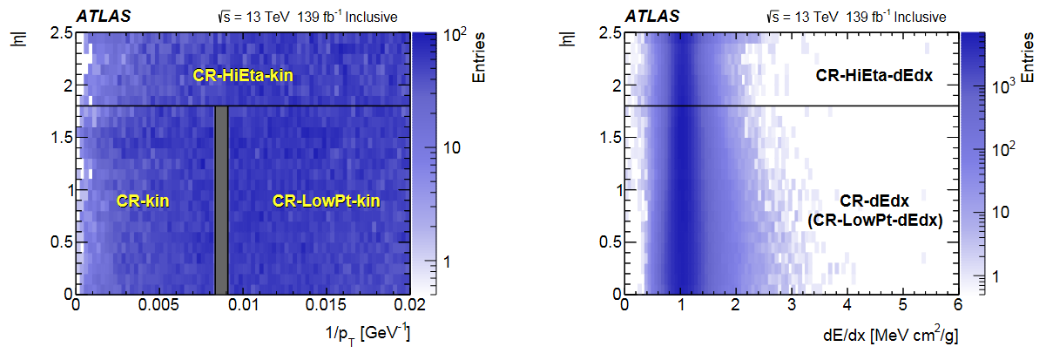
Di-tau preselection	Single-tau preselection
E_T^{miss}-trigger fired and $E_T^{miss} > 250$ GeV No light leptons (e/μ) At least two jets	
At least two hadronic tau leptons At least one b-tagged jet	Exactly one hadronic tau lepton At least two b-tagged jets



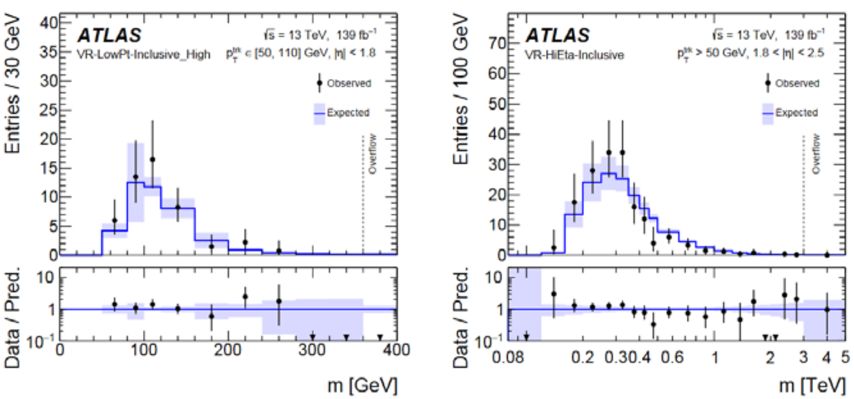


HCLLP Background Estimation

Region	p_T [GeV]	$\lvert\eta\rvert$	E_T^{miss} [GeV]	dE/dx [MeV g^{-1}cm^2]
SR	> 120	< 1.8	> 170	> 1.8
CR-kin			> 170	< 1.8
CR-dEdx			< 170	> 0
VR-LowPt	[50, 110]	< 1.8	> 170	> 1.8
CR-LowPt-kin			> 170	< 1.8
CR-LowPt-dEdx			< 170	> 0
VR-HiEta	> 50	[1.8, 2.5]	> 170	> 1.6
CR-HiEta-kin			> 170	< 1.6
CR-HiEta-dEdx			< 170	> 0



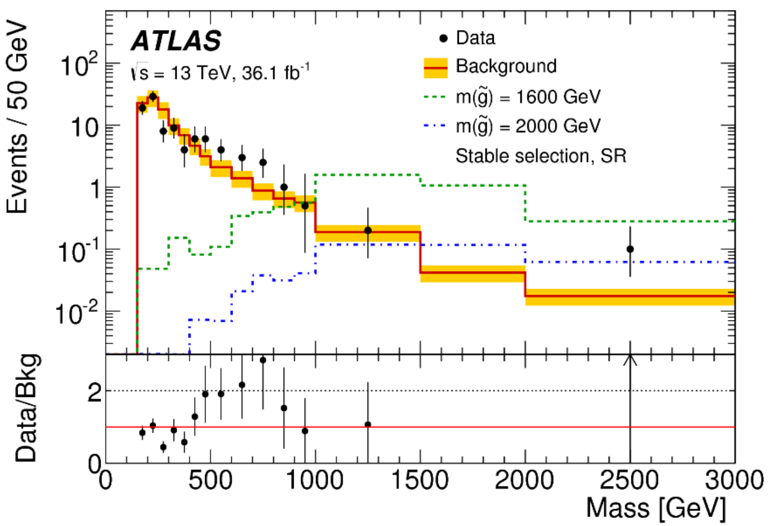
(a) Kinematic control regions (b) dE/dx control regions

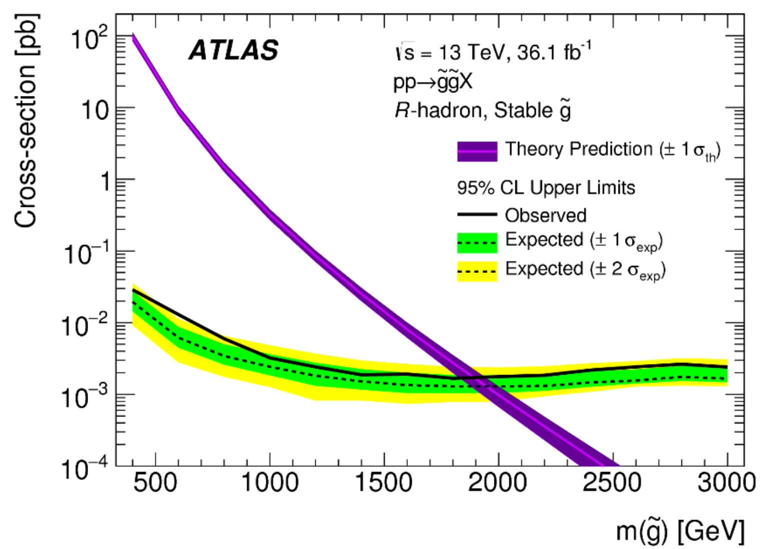


- Toy track generation:
1. Sample $1/p_T$, η from CR-kin
2. Sample dE/dx from η bin of CR-dEdx
3. Compute m using dE/dx–$\beta\gamma$ calibration
- 10–40M toy tracks sampled
- Validated in validation regions (bottom)

Previous HCLLP Search

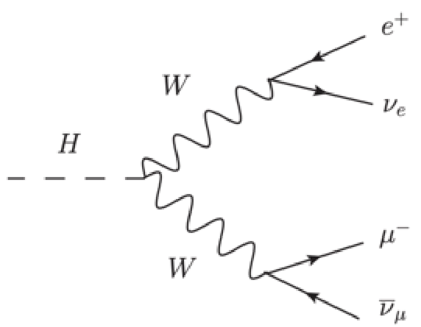
- Similar search previously conducted with mid Run 2 dataset
- Excess of events with mass 500–800 GeV
  → $m_{\tilde{g}}$ = 600 GeV: 2.4σ local
- *Not confirmed* in updated search
  - Excesses can be inspiring… but be careful placing bets until verification!

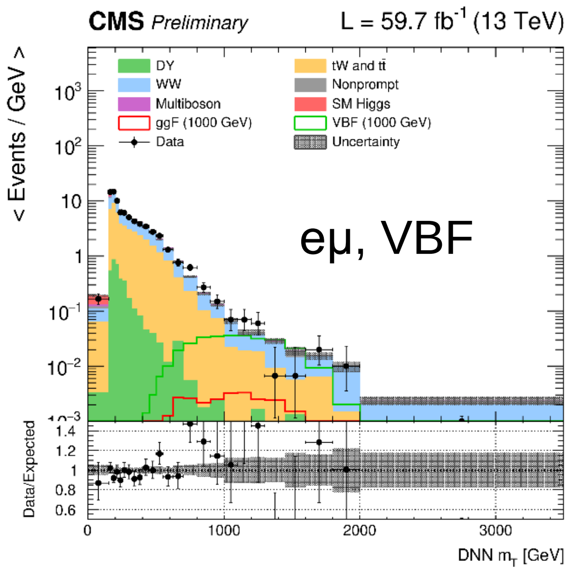


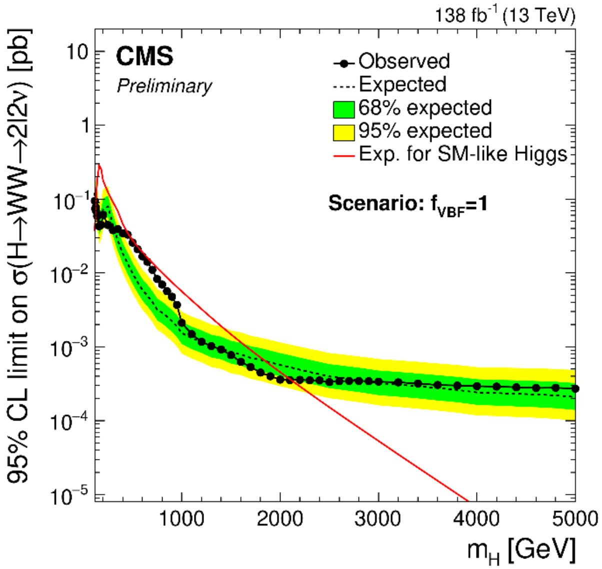


H → WW

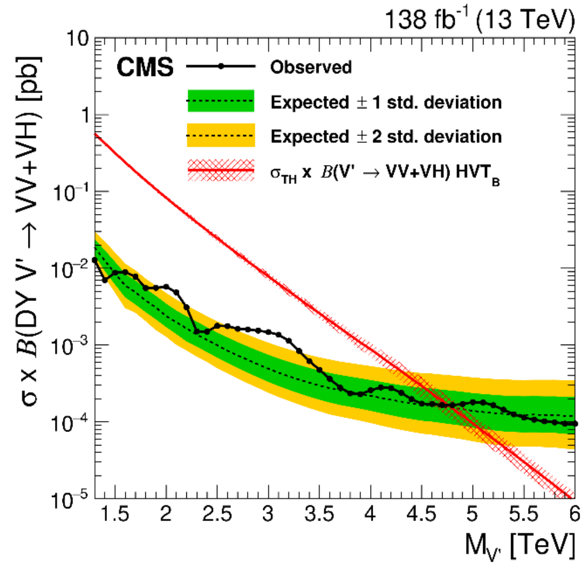
- Final states: eμ, μμ, ee
- DNN categorization into gluon-gluon fusion (ggF), vector boson fusion (VBF), or background
- Second DNN reconstructs resonance mass (regression)
- m_H = 650 GeV: 3.8σ local, 2.6σ global



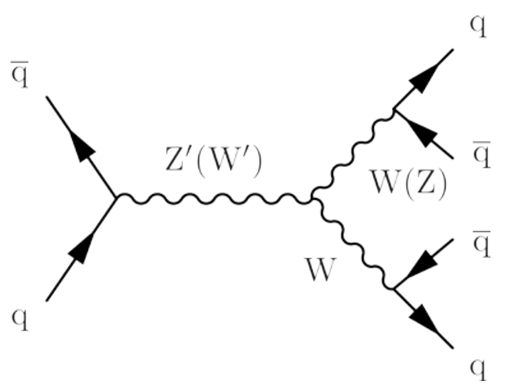


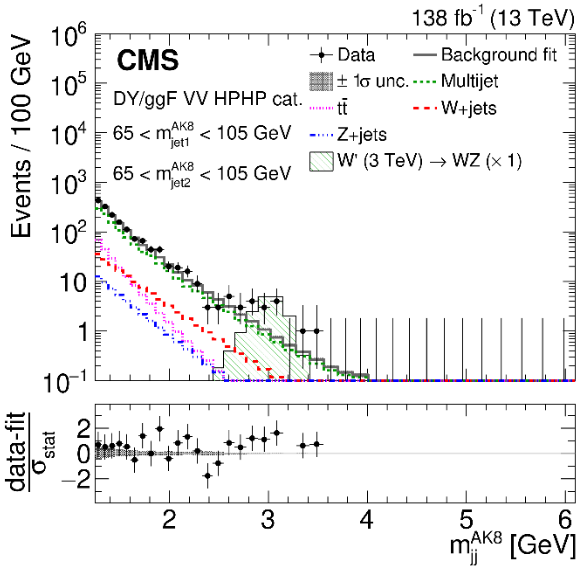


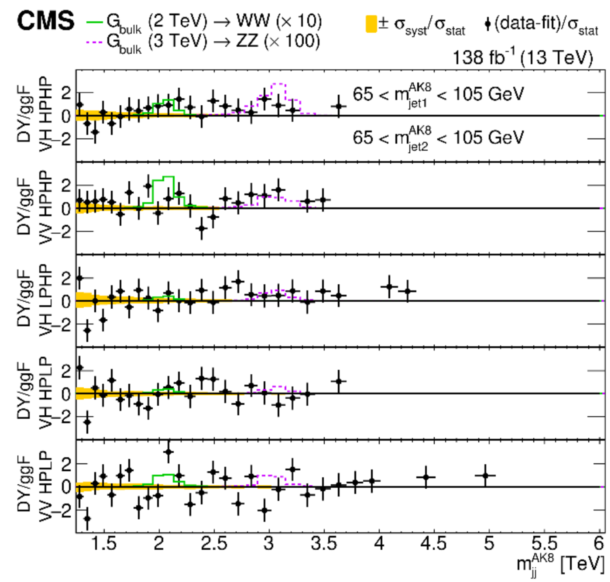
$W' \to WZ$



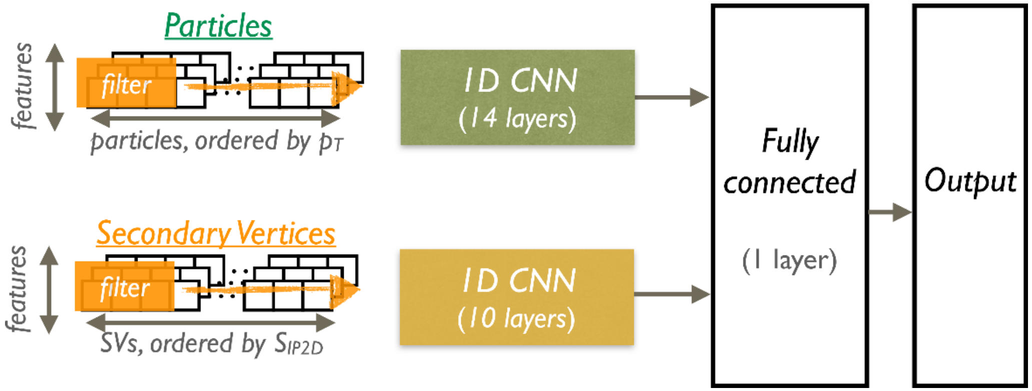
- Boosted jet reconstruction & categorization ($q\bar{q}$, $b\bar{b}$) with [DeepAK8](#) algorithm
- $m_{W'}$ = 2.1, 2.9 TeV: 3.6σ local, 2.3σ global
- No corresponding significant excesses in semileptonic final states ([CMS](#), [ATLAS](#))

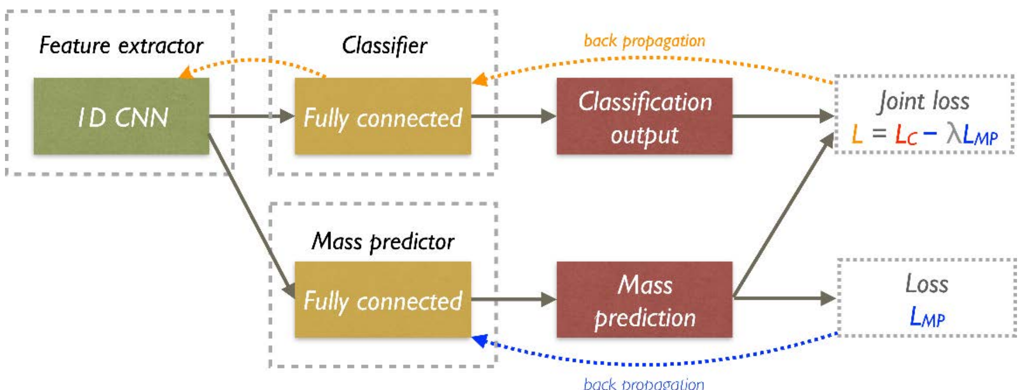


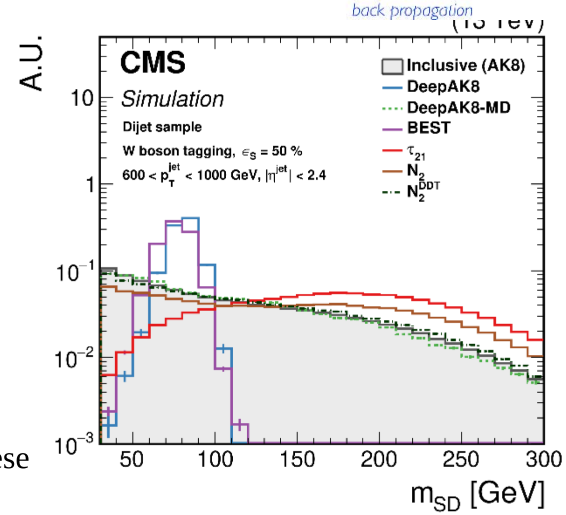


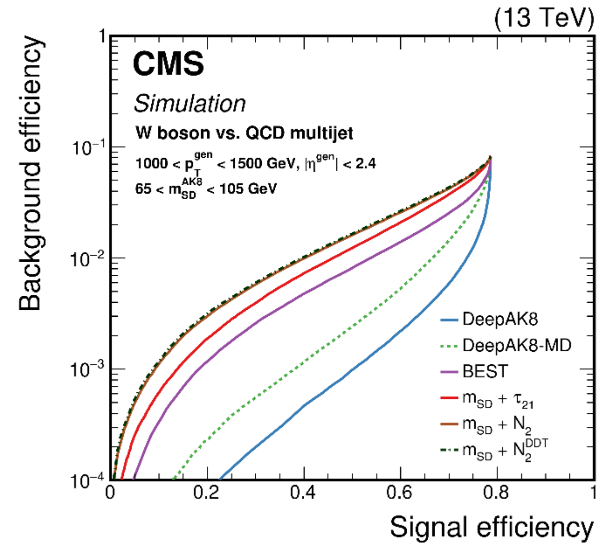


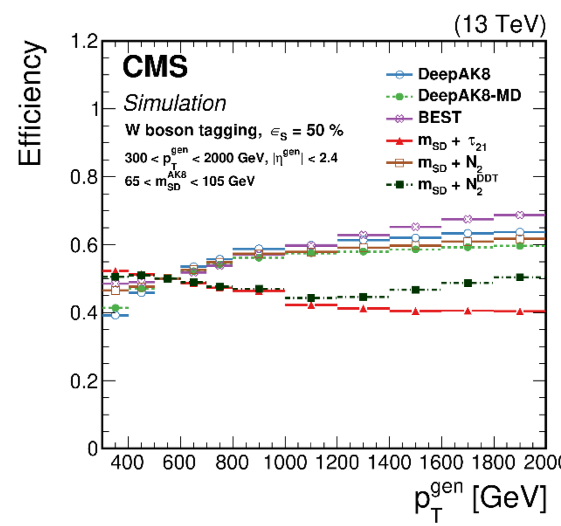
DeepAK8


Particles
features
filter
particles, ordered by p_T
1D CNN
(14 layers)
Secondary Vertices
features
filter
SVs, ordered by S_{IP2D}
1D CNN
(10 layers)
Fully connected
(1 layer)
Output

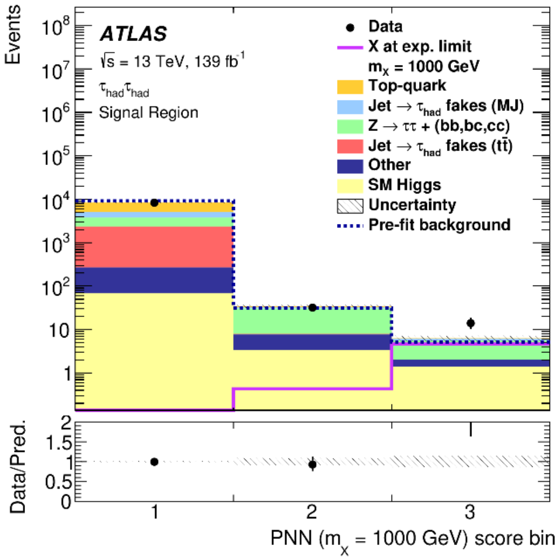

Feature extractor
1D CNN
Classifier
Fully connected
back propagation
Classification output
Joint loss
$L = L_C - \lambda L_{MP}$
Mass predictor
Fully connected
Mass prediction
Loss
L_{MP}
back propagation

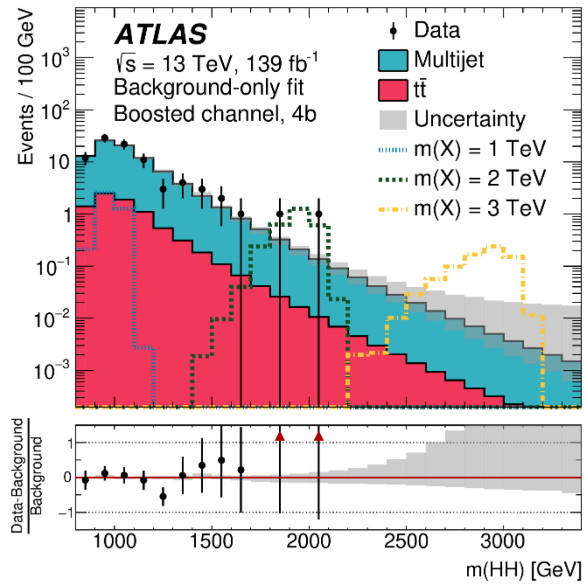

CMS
Simulation
Dijet sample
W boson tagging, ϵ_S = 50 %
$600 < p_T^{jet} < 1000$ GeV, $|\eta^{jet}| < 2.4$
Inclusive (AK8)
DeepAK8
DeepAK8-MD
BEST
τ_{21}
N_2
N_2^{DDT}
A.U.
m_{SD} [GeV]

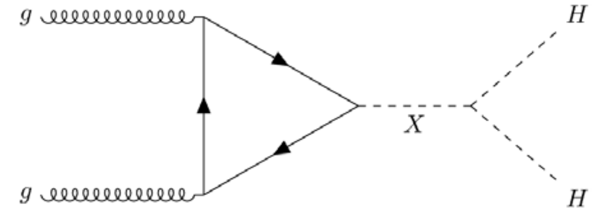

(13 TeV)
CMS
Simulation
W boson vs. QCD multijet
$1000 < p_T^{gen} < 1500$ GeV, $|\eta^{gen}| < 2.4$
$65 < m_{SD}^{AK8} < 105$ GeV
DeepAK8
DeepAK8-MD
BEST
$m_{SD} + \tau_{21}$
$m_{SD} + N_2$
$m_{SD} + N_2^{DDT}$
Background efficiency
Signal efficiency


(13 TeV)
CMS
Simulation
W boson tagging, ϵ_S = 50 %
$300 < p_T^{gen} < 2000$ GeV, $|\eta^{gen}| < 2.4$
$65 < m_{SD}^{AK8} < 105$ GeV
DeepAK8
DeepAK8-MD
BEST
$m_{SD} + \tau_{21}$
$m_{SD} + N_2$
$m_{SD} + N_2^{DDT}$
Efficiency
p_T^{gen} [GeV]

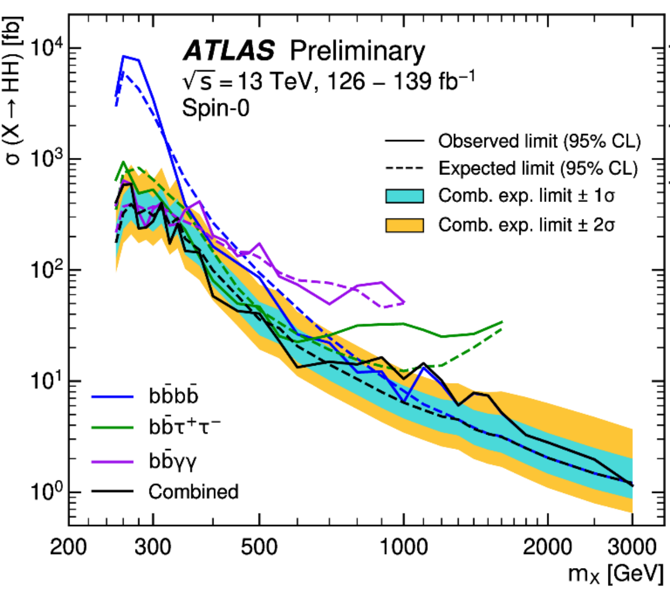
$X \to HH \to bb\gamma\gamma,\ bb\tau\tau,\ bbbb$

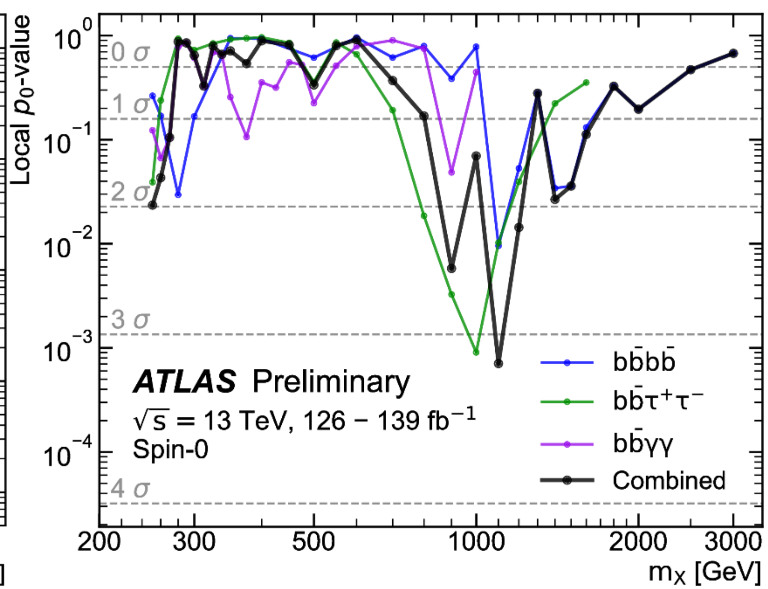






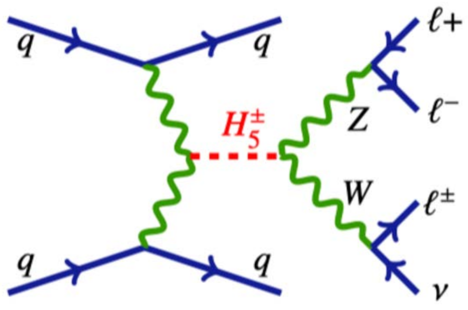
- [bbττ](): parametrized neural network w/ event-level variables (masses, angles, E_T^{miss}, etc.)
- [bbbb](): fit to m(HH) spectrum (boosted channel)



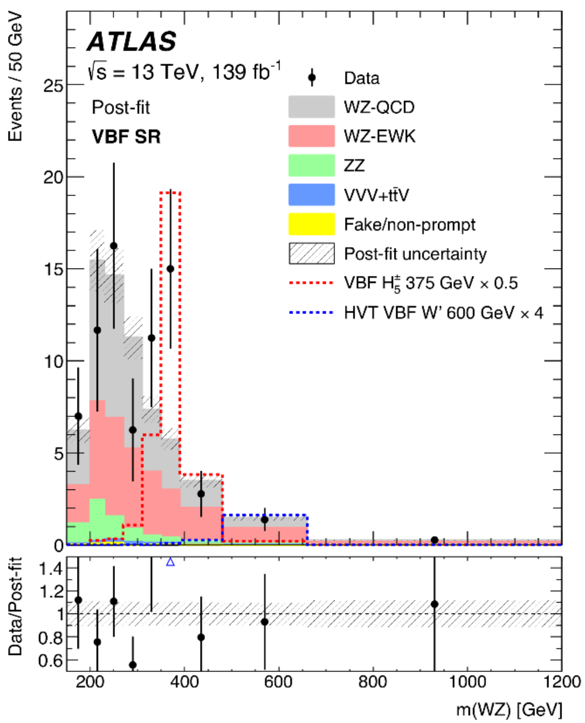


- m_X = 1.1 TeV: 3.2σ local, 2.1σ global

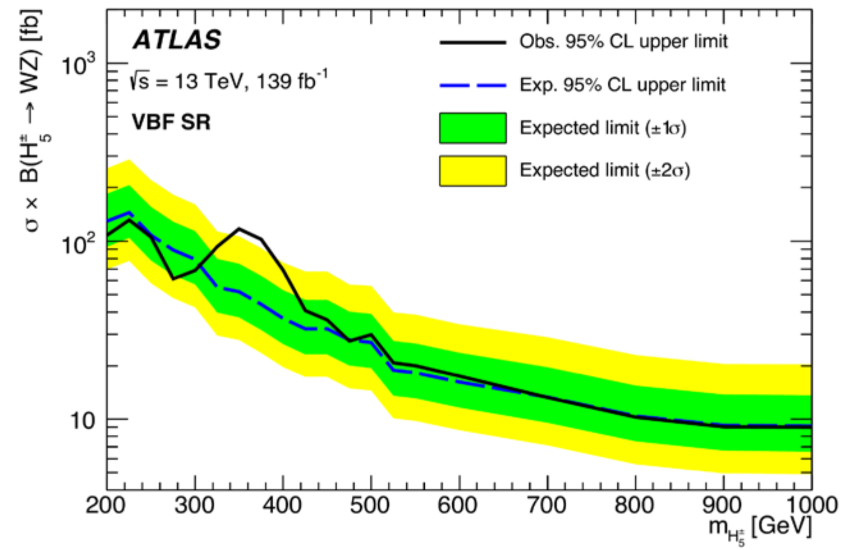
$H_5 \rightarrow WZ$

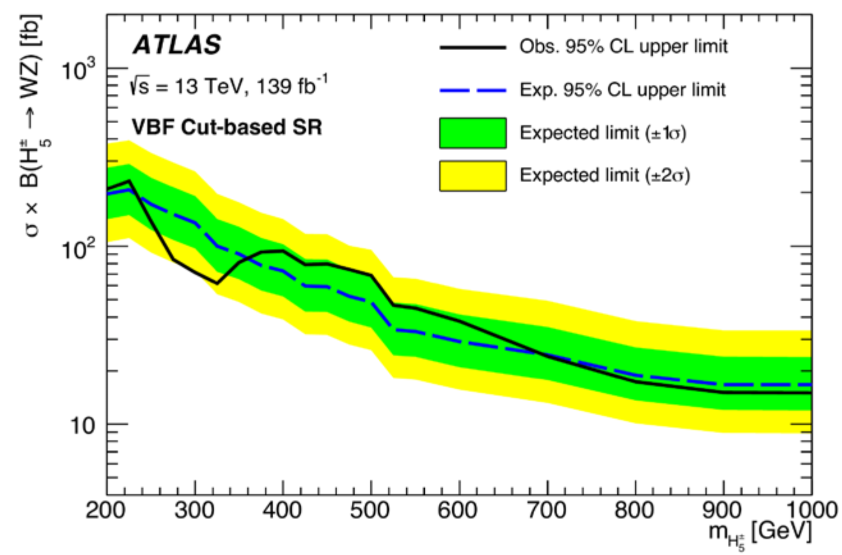


(c)



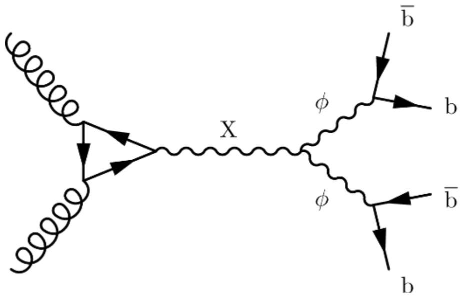
- ANN used to select VBF signal events
- m_{H_5} = 350 GeV: 2.8σ local, 1.6σ global
- No significant excess in alternative cut-based signal region
    - o But overall limits weaker by 30–50%

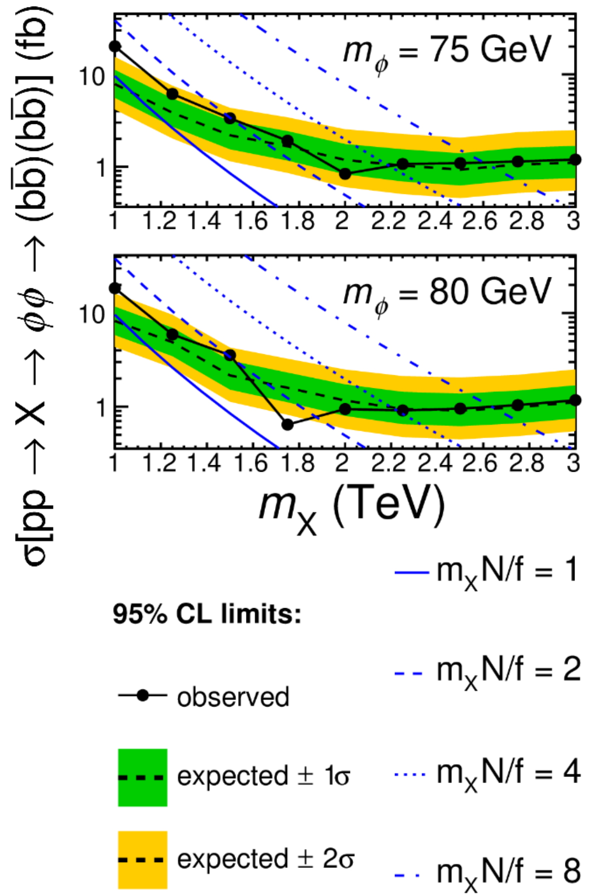


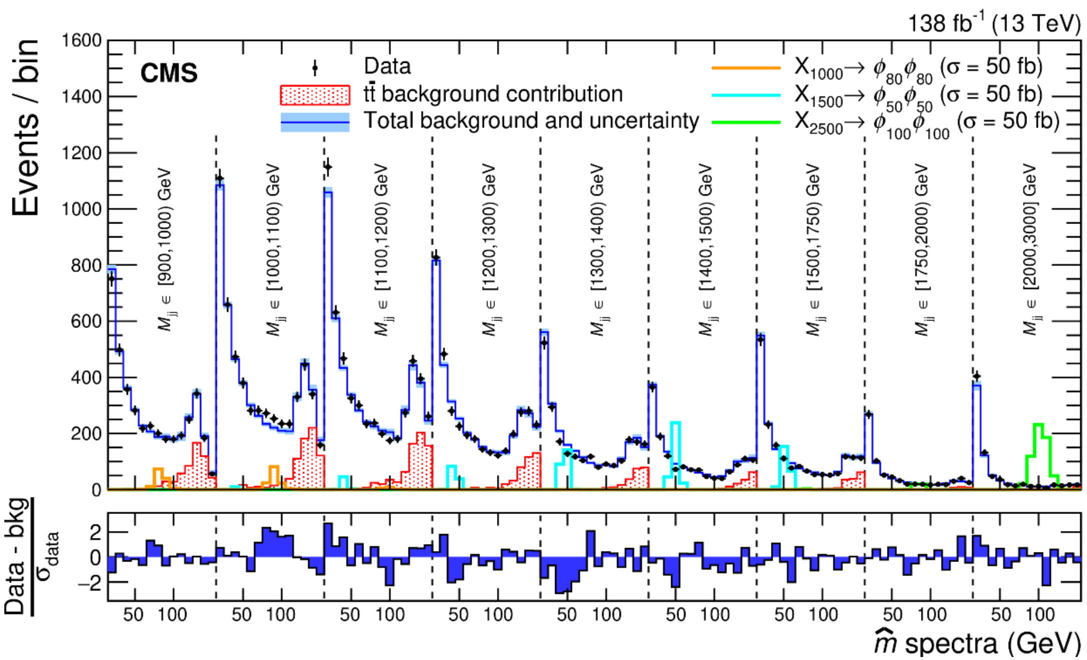


$X \to \varphi\varphi \to bbbb$

- Double-b tagger BDT used to identify merged $b\bar{b}$ jets from φ intermediate particles
- m_X = 1 TeV, m_φ = 75 GeV: 3.1σ local, 1.3σ global

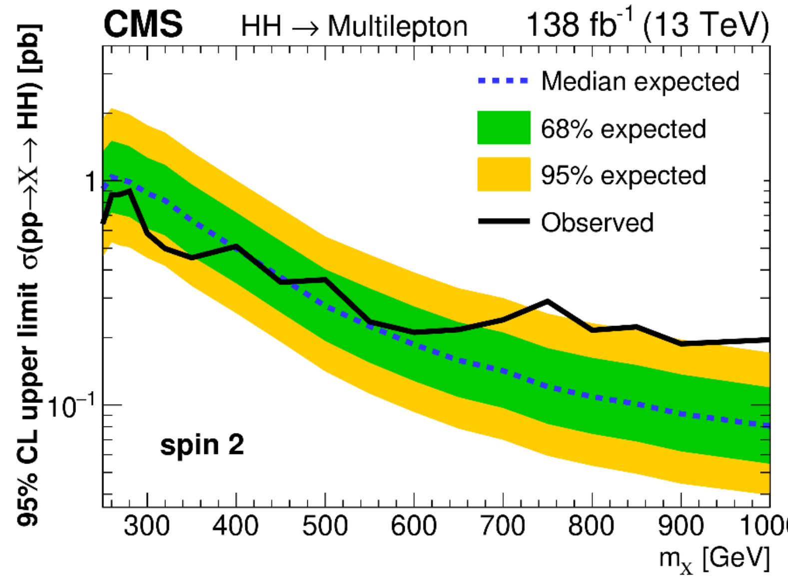


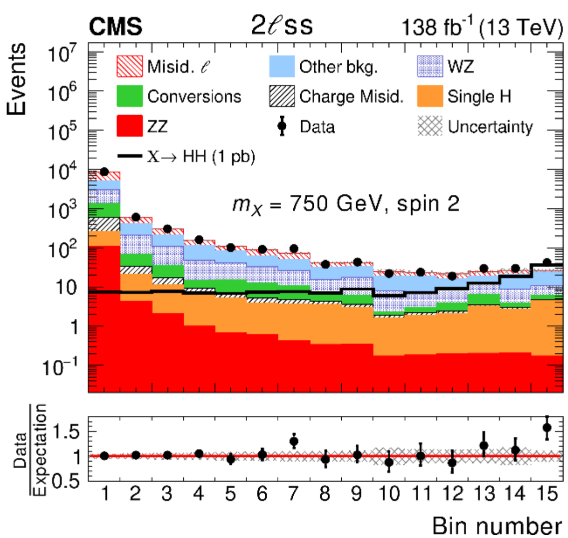


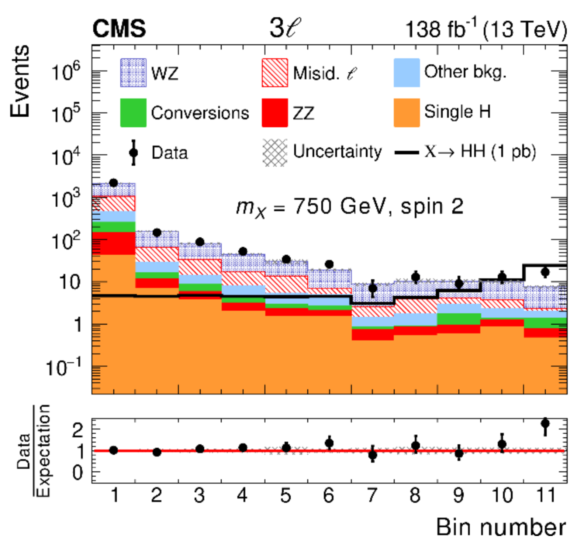


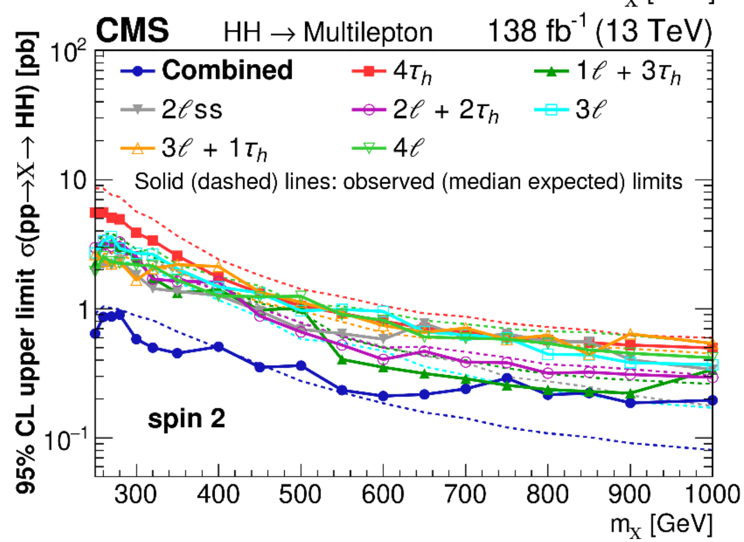
X → HH → WWWW, WWττ, ττττ

- BDT used to classify signal and background
- m_X = 750 GeV: 2.1σ local
- Driven by 2ℓ same sign & 3ℓ categories



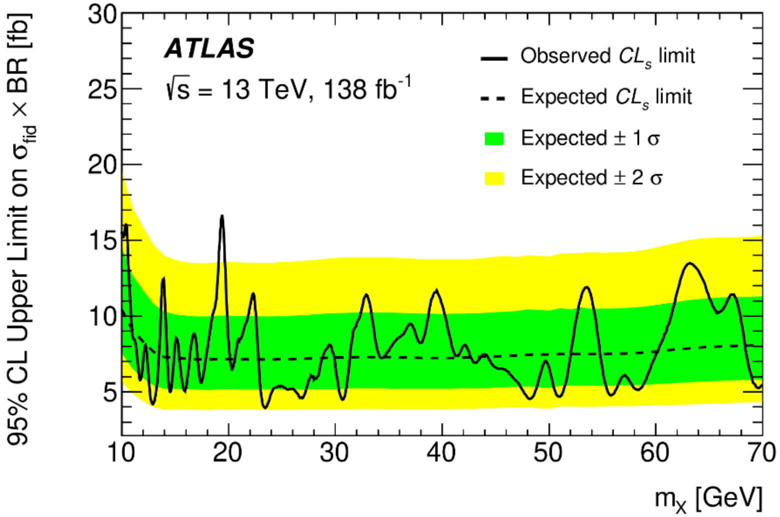


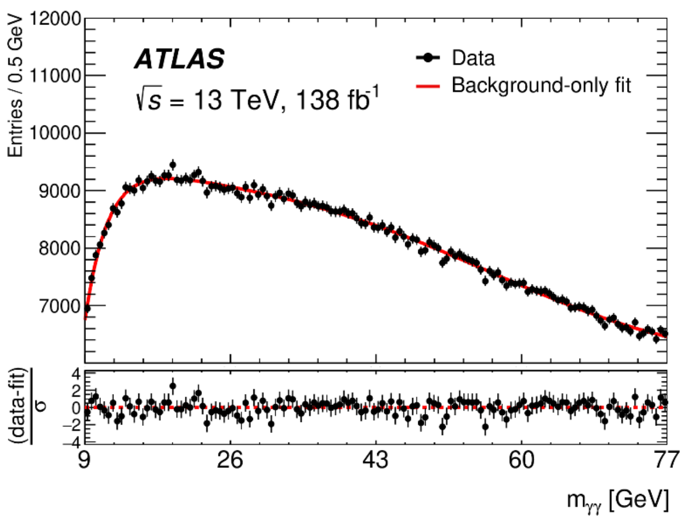


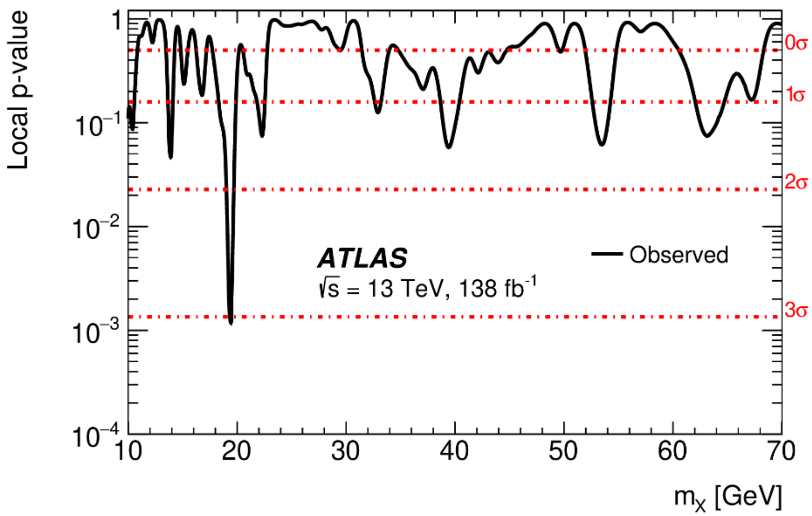


$X \rightarrow \gamma\gamma$

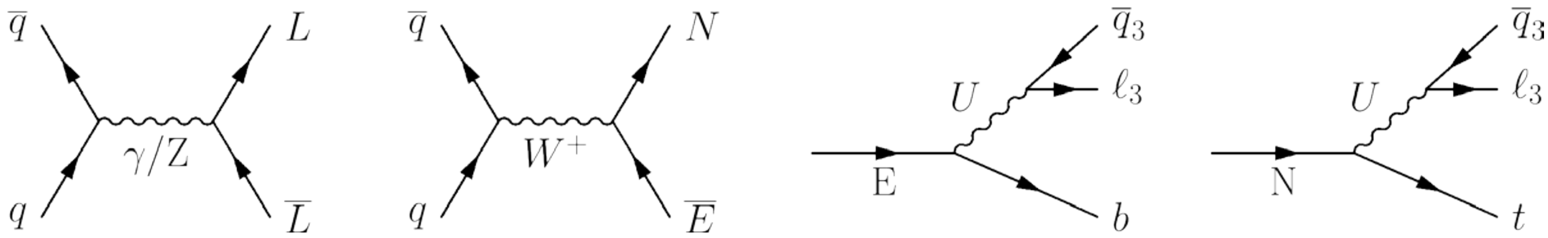
- Search for boosted diphoton resonances
- m_X = 19.4 GeV:
  3.1σ local, 1.5σ global



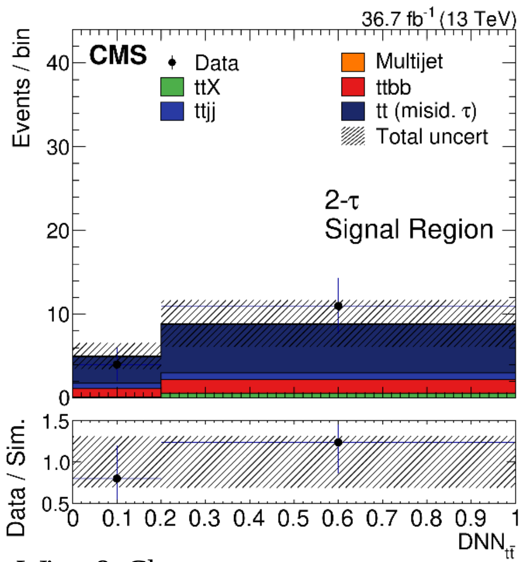


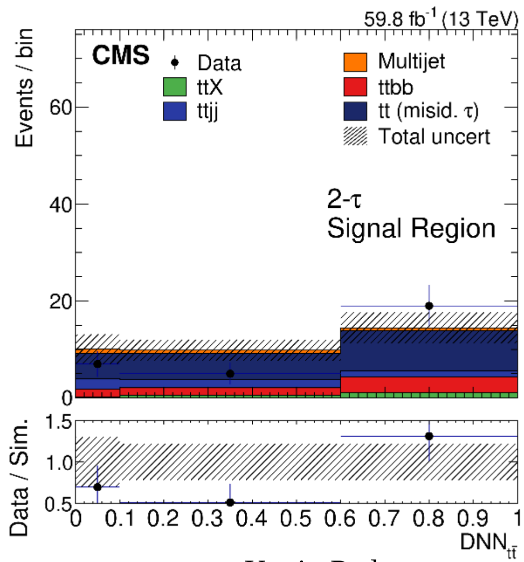


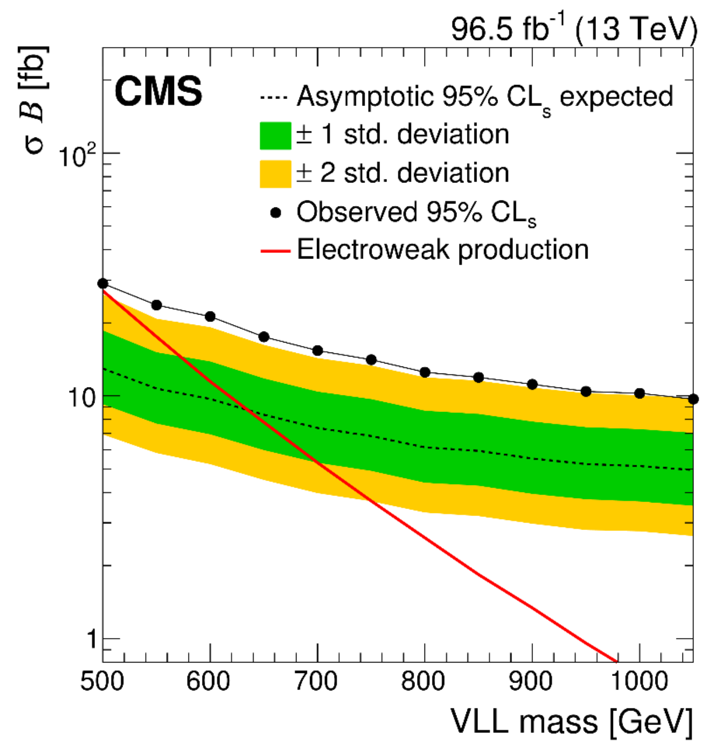
LL → (qqℓ)(qqℓ)



- L: vector-like lepton
- Two graph neural networks (ABCNet architecture) used to distinguish signal from QCD (for 0-τ_h) and $t\bar{t}$ (for 1-, 2-τ_h)
- m_L = 600 GeV: 2.8σ local
- Driven by 1- & 2-τ_h channels

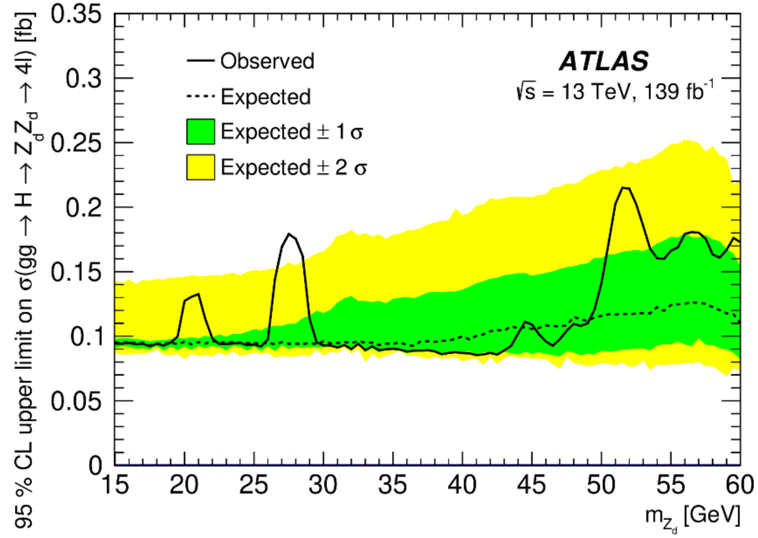


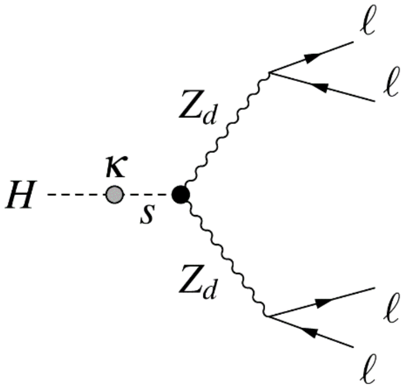


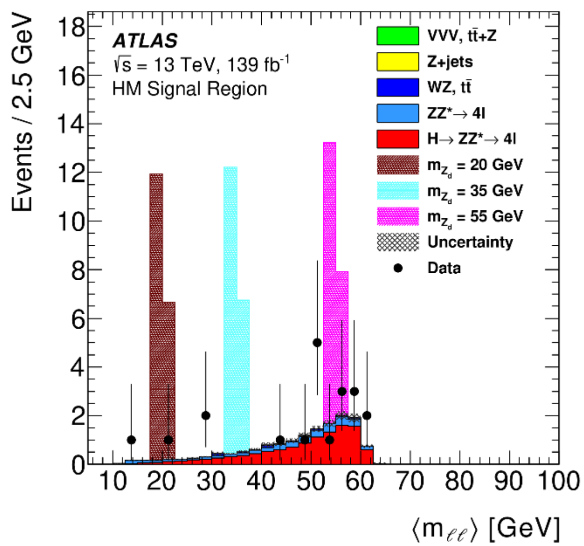


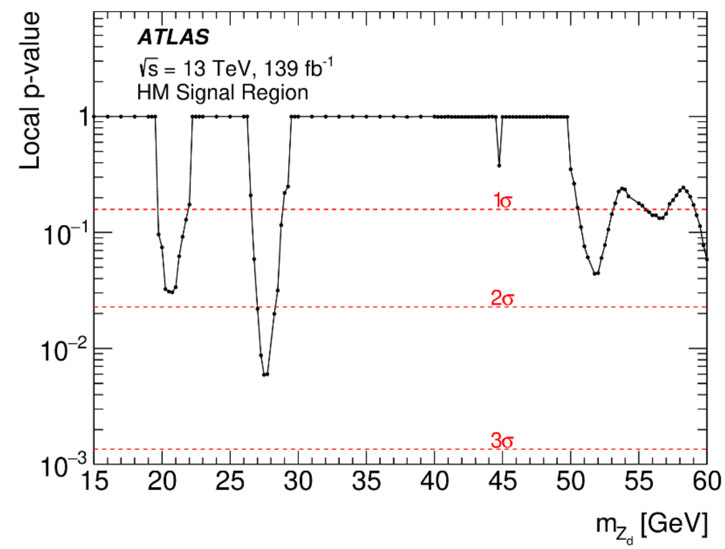
$H \to Z_d Z_d \to \ell\ell\ell\ell$

- Signal region yield:
  20 events observed
  15.6 ± 0.4 ± 1.2 expected
- m_{Z_d} = 28 GeV: 2.5σ local
- Limits shown for kinetic mixing parameter ε and Higgs mixing parameter κ both = 10^{-4}



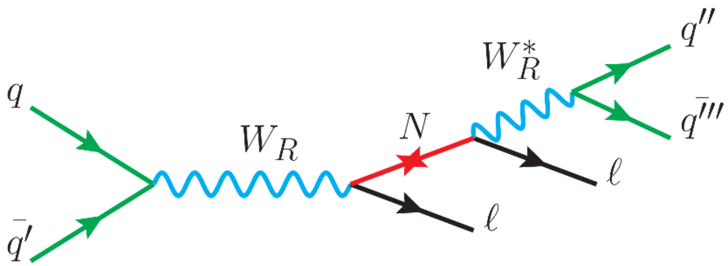


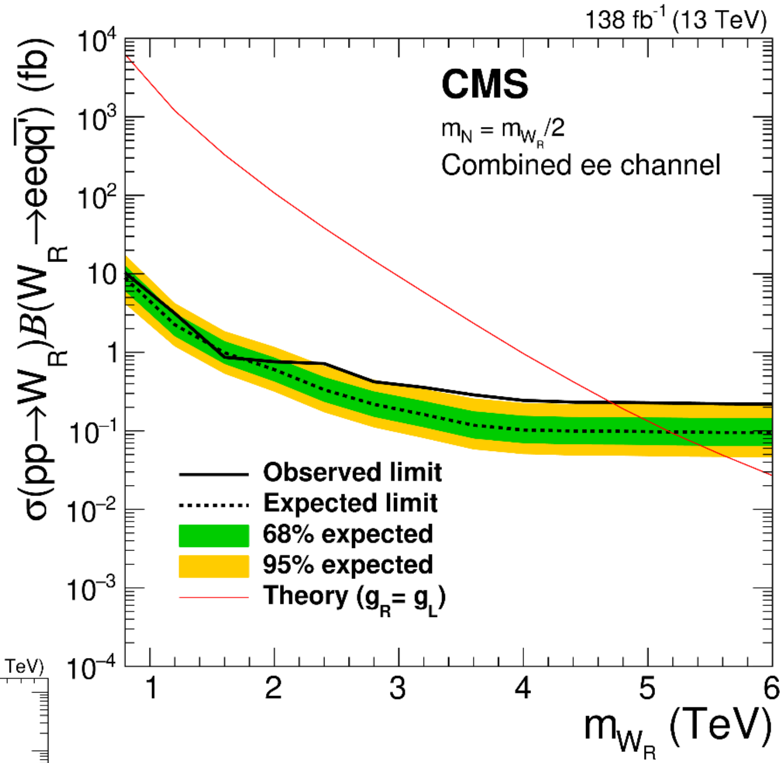


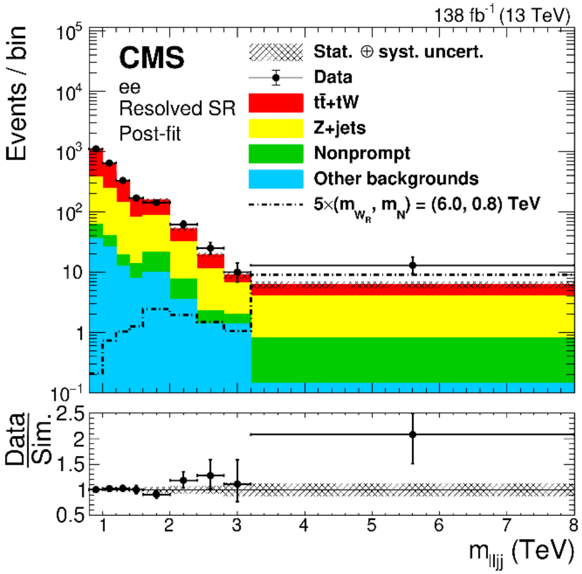


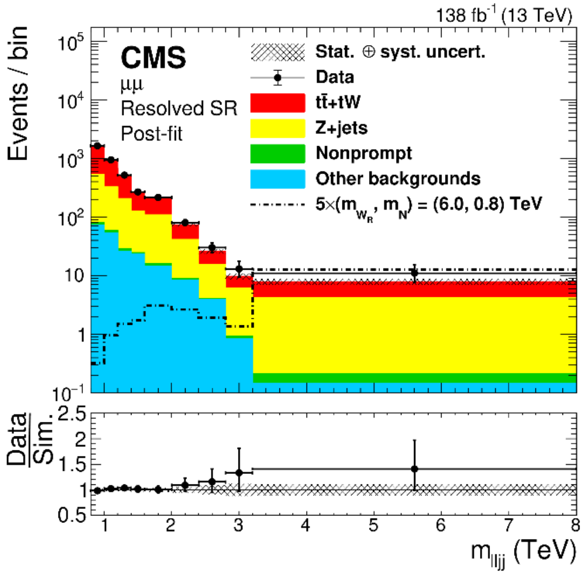
$W_R \to N\ell$

- Excess appears in resolved channels (primarily ee), not in boosted
- m_{W_R} = 6 TeV, m_N = 0.8 TeV: 2.95σ local, 2.78σ global



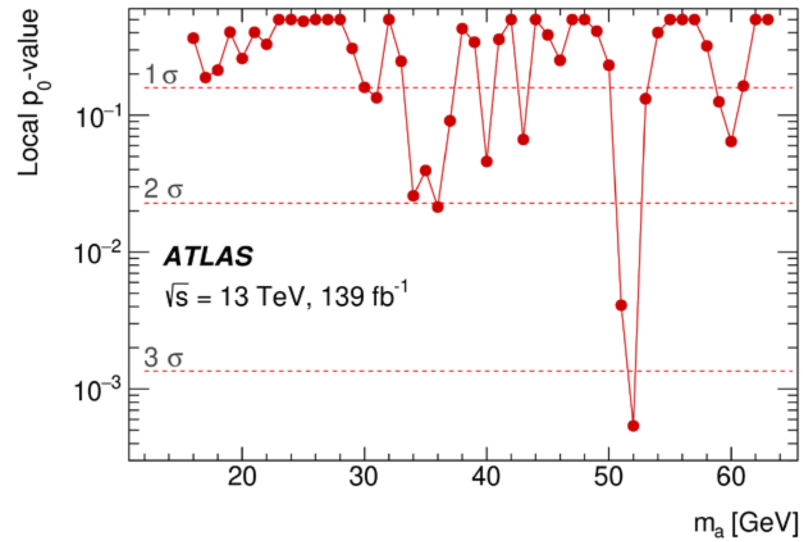


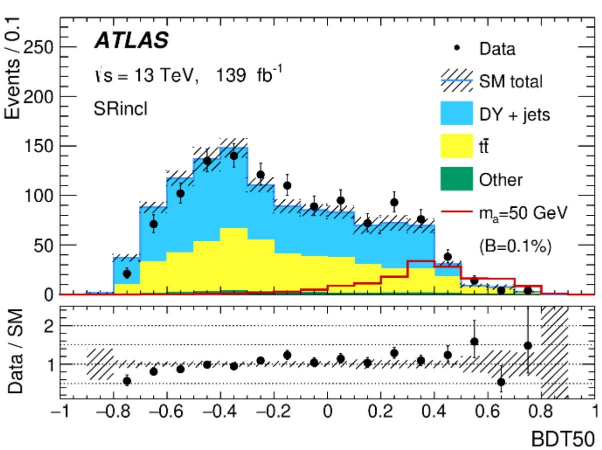


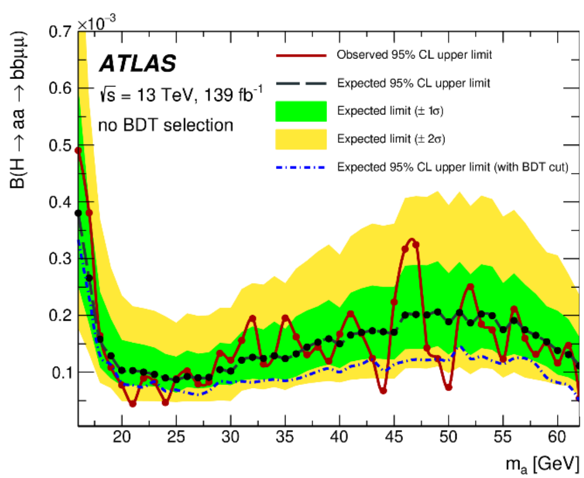


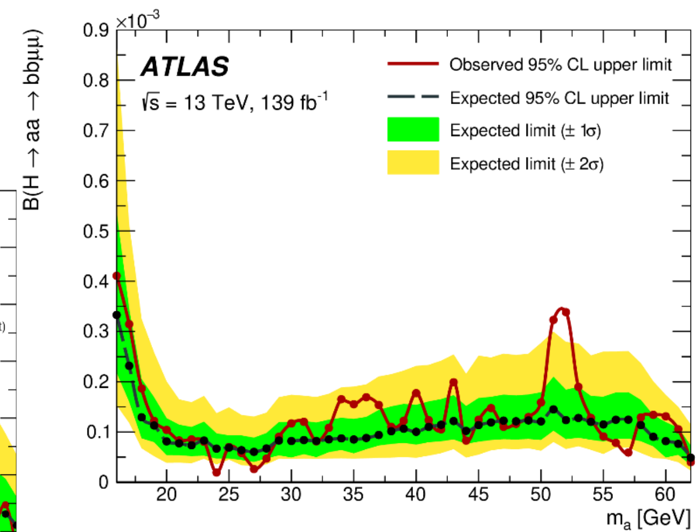
$H \to aa \to bb\mu\mu$

- BDT trained to distinguish signal from background, in overlapping bins of 8 GeV in $m_{\mu\mu}$
- m_a = 52 GeV:
  3.3σ local, 1.7σ global
- Excess not apparent if BDT not applied



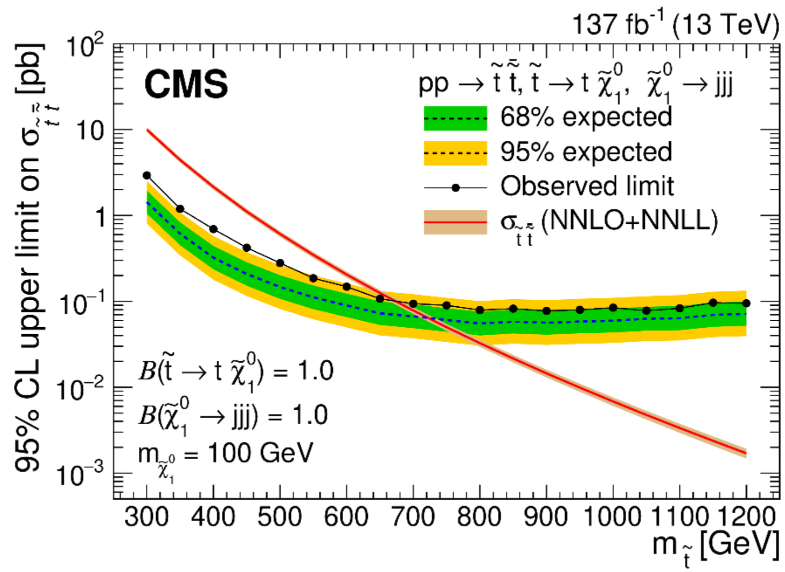


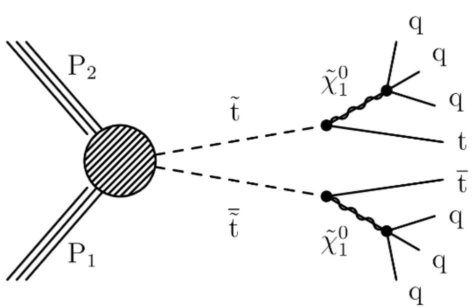


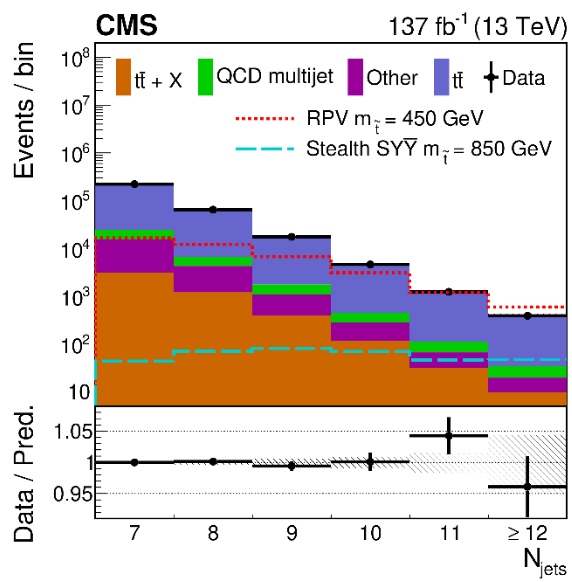


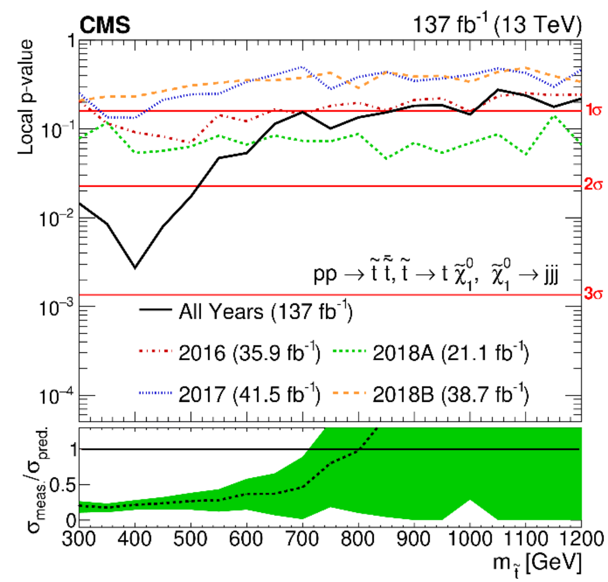
$\tilde{t} \rightarrow tqqq$ (pair)

- Semileptonic channel: one top decays to e or μ, other top decays to quarks
- Custom neural network distinguishes signal from background
  - o Gradient reversal used to decorrelate from N_{jets}
- $m_{\tilde{t}}$ = 400 GeV: 2.8σ local

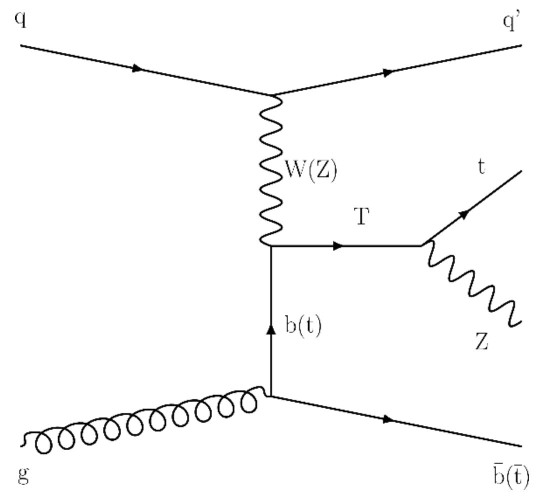




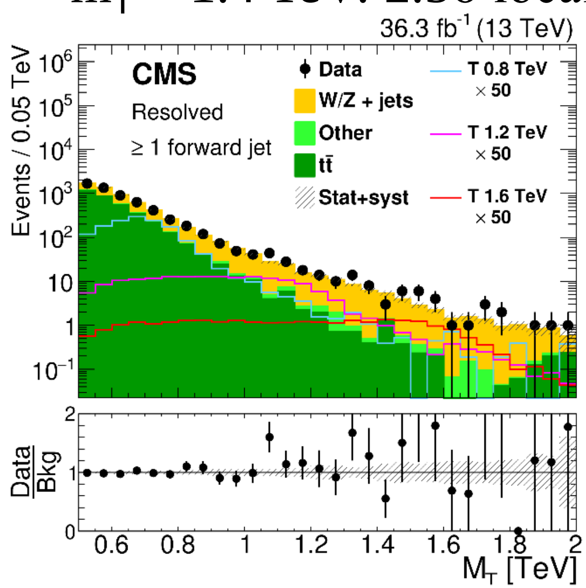


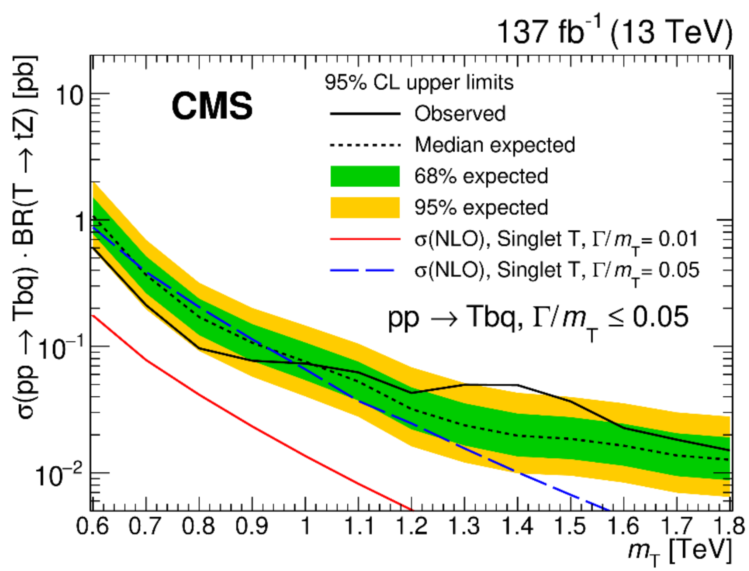


$T \to tZ$

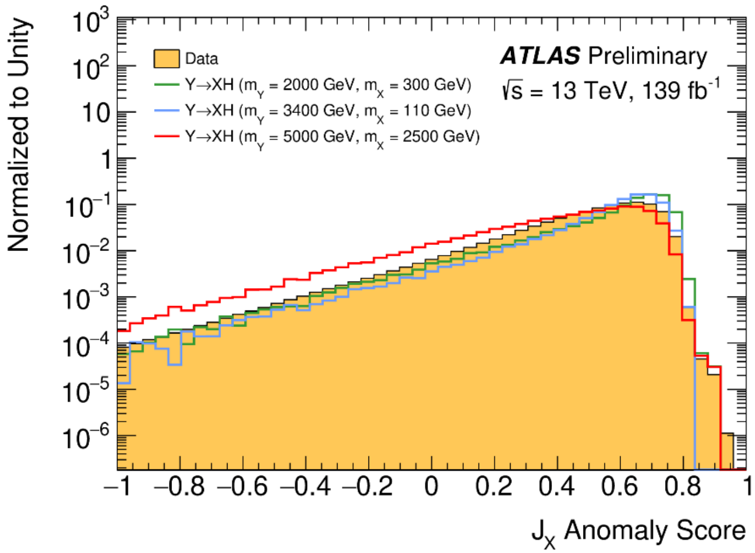


- Hadronic top + p_T^{miss} final state:
  - $t \to Wb \to (q\bar{q})b$, $Z \to \nu\nu$
- Merged: top tagging w/ subjet b-tagging, softdrop mass, Nsubjettiness ratio τ_{32}
- Partially merged: W tagging w/ softdrop mass, τ_{21}
- Resolved: take highest-p_T combination of 3 jets
- Excess driven by resolved + ≥1 forward jet category in 2016 data
- m_T = 1.4 TeV: 2.5σ local, 2.2σ global

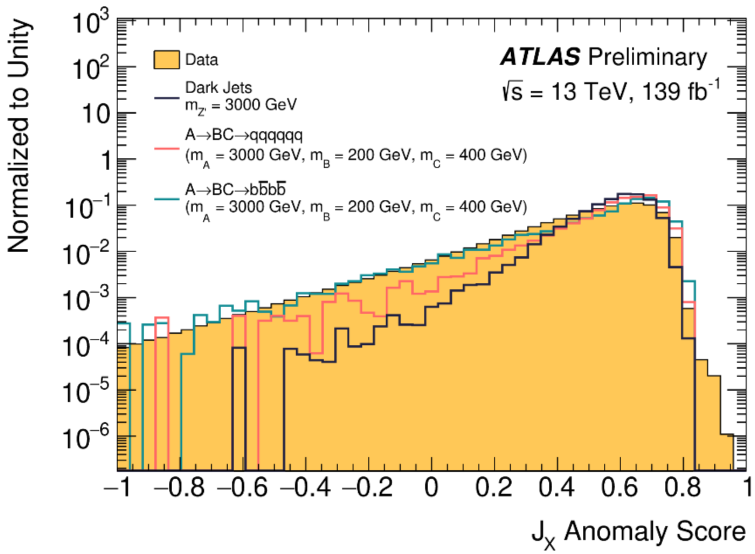


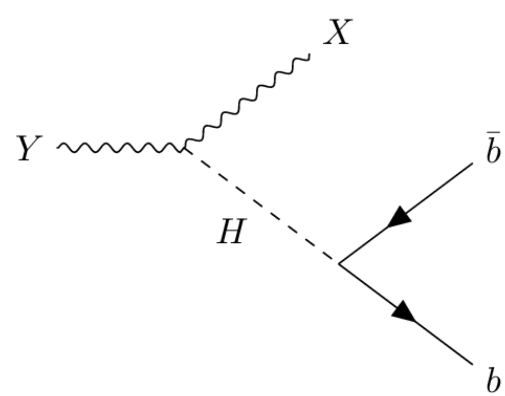


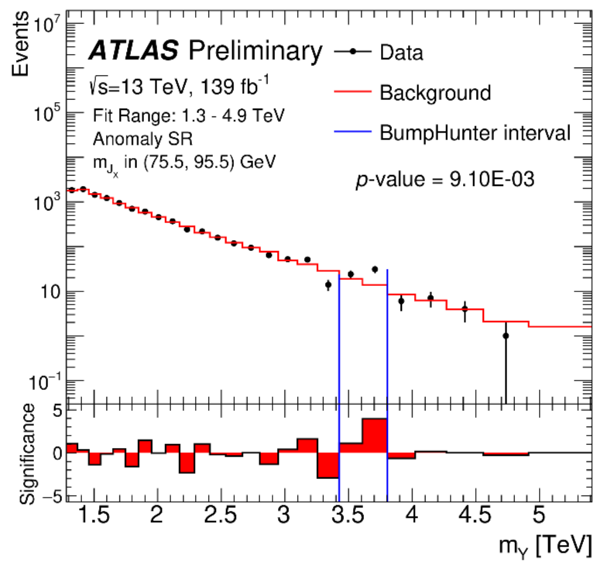
Y → XH w/ Anomaly Detection



- Anomaly score from variational recurrent NN
  - Trained on wide, high-p_T jets from data: constituent four-vectors & jet substructure variables
- Largest excess: m_Y = 3.6 TeV, 1.47σ global







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