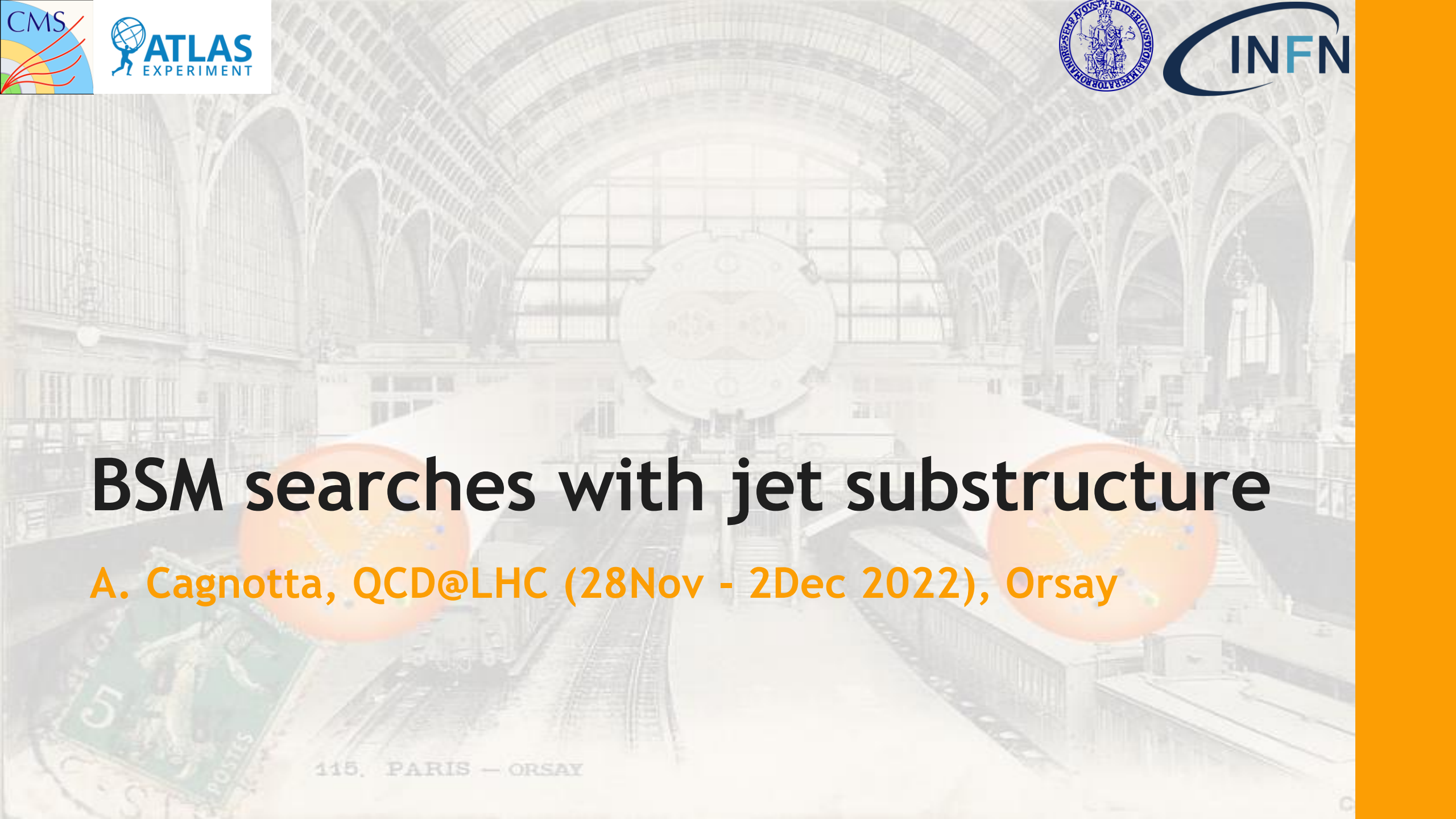


BSM searches with jet substructure

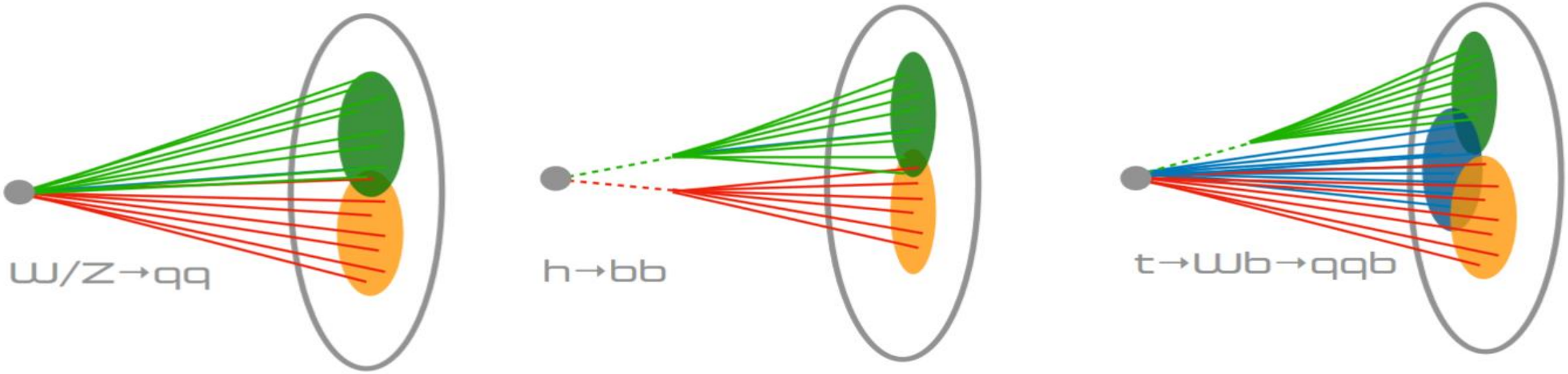
A. Cagnotta, QCD@LHC (28Nov - 2Dec 2022), Orsay

Contents

- **Introduction** to Jet substructure
- **Jet tagging** algorithms
- Many **searches** considered - more found at **CMS** (B2G, EXO, SUS) and **Atlas** (SUSY, EXOT, HDBS) public pages:
  - $W_{KK} \rightarrow WR \rightarrow WWW$ PRL 129 (2022) 021802 
  - $X \rightarrow YH \rightarrow b\bar{b}b\bar{b}$ Accepted by Phys. Lett. B 
  - $Y \rightarrow XH \rightarrow q\bar{q}b\bar{b}$ ATLAS-CONF-2022-045 
  - **Nonresonant Higgs pair production** Accepted by Phys. Rev. Lett. 
  - **Stop production** Phys. Rev. D 104 (2021) 052001 
  - **Electroweakino pair production** Phys. Rev. D 104 (2021) 112010 
  - **Vector-Like Quark T** Phys. Rev. D 105 (2022) 092012 
  - **Energetic jets+ missing momentum** JHEP 11 (2021) 153 

Introduction

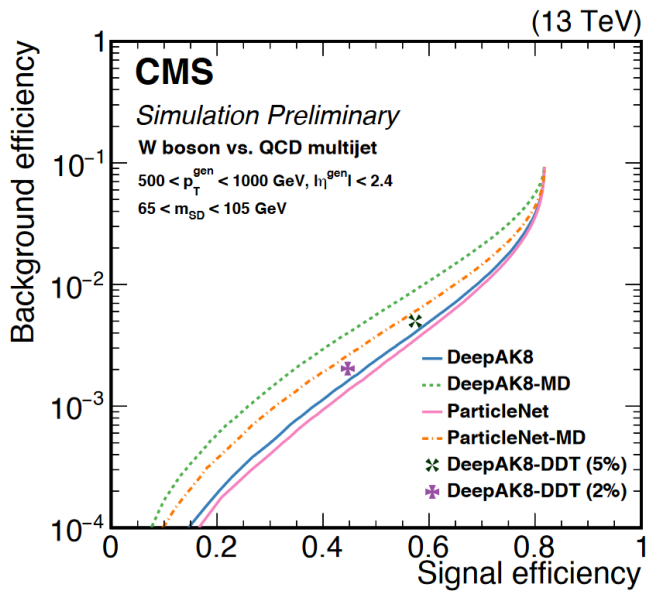
- **New Physics searches**: rare final states **or** high-centre-of-mass energy $\sqrt{s}$
- Decays to heavy SM objects, **H/W/Z/Top**: high $\sqrt{s}$ → large Lorentz boost
- **Large BR** in hadronic decays → **large background** (multijet) → **Jet tagging**



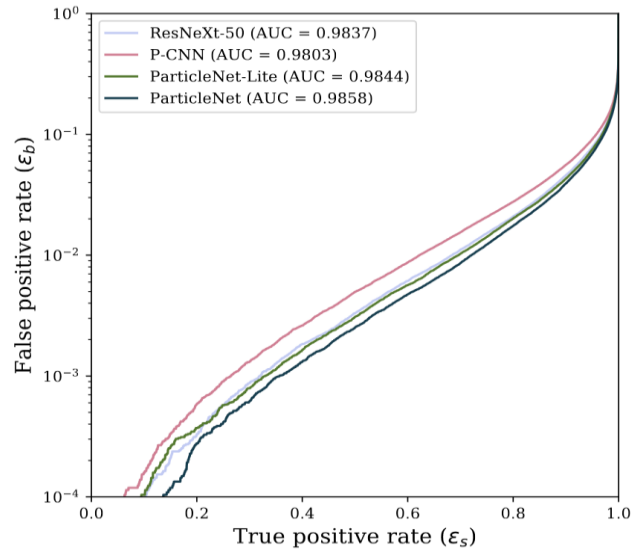
Jet algorithms overview

See also F.Carnevali

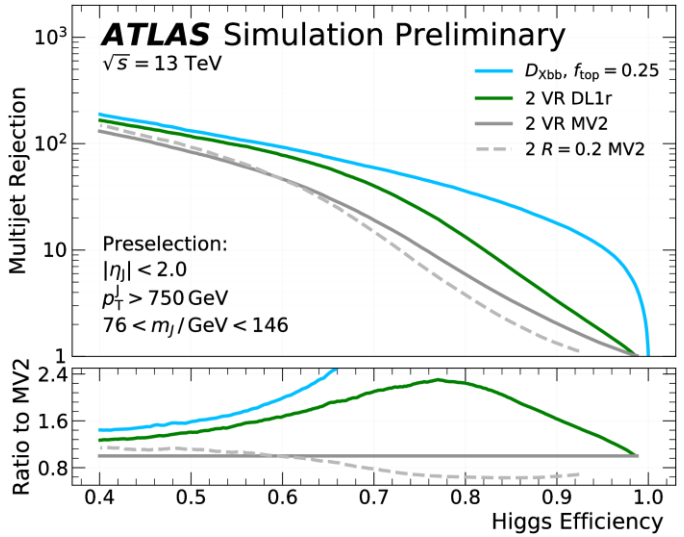
- DeepAk8, based on CNN for Ak8 classification in Top/H/Z/W/QCD



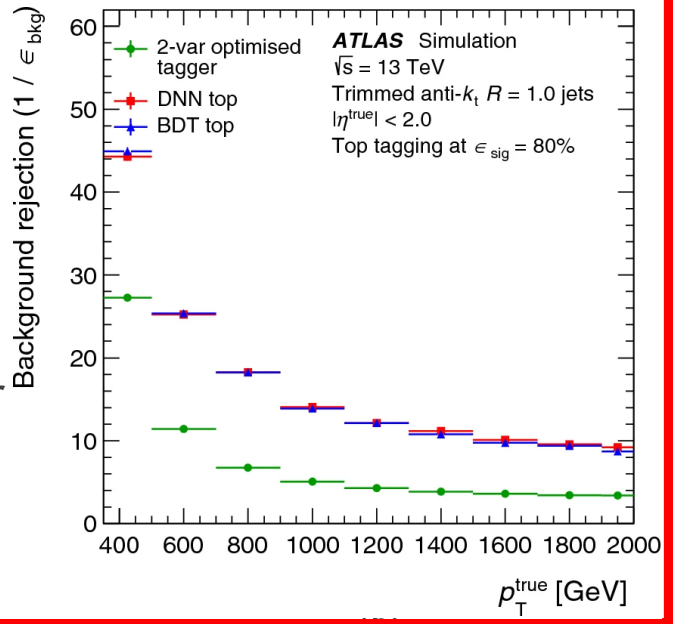
- ParticleNet, based on GNN, treats a Jet like a "particle cloud"



- Xbb tagger, combines flavor discriminants from up to three subjects using a feed-forward neural network



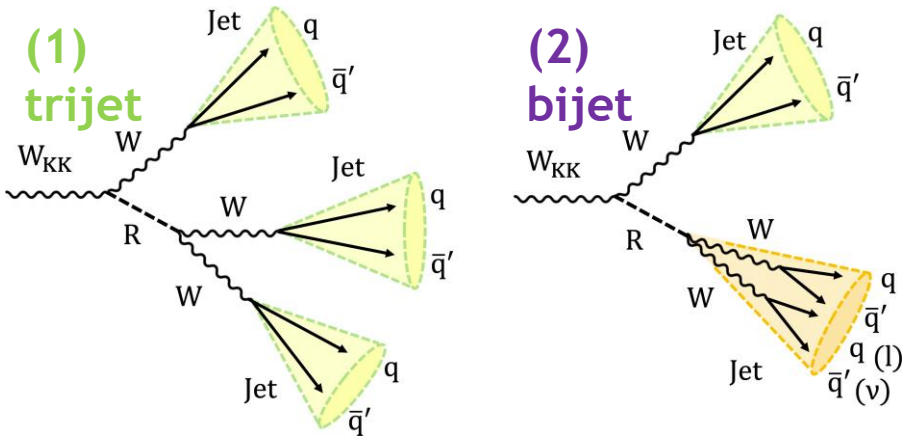
- W/top tagger, combinations of substructure observables as a multivariate tagger using BDTs or DNNs



$W_{KK} \rightarrow WR \rightarrow WWW$

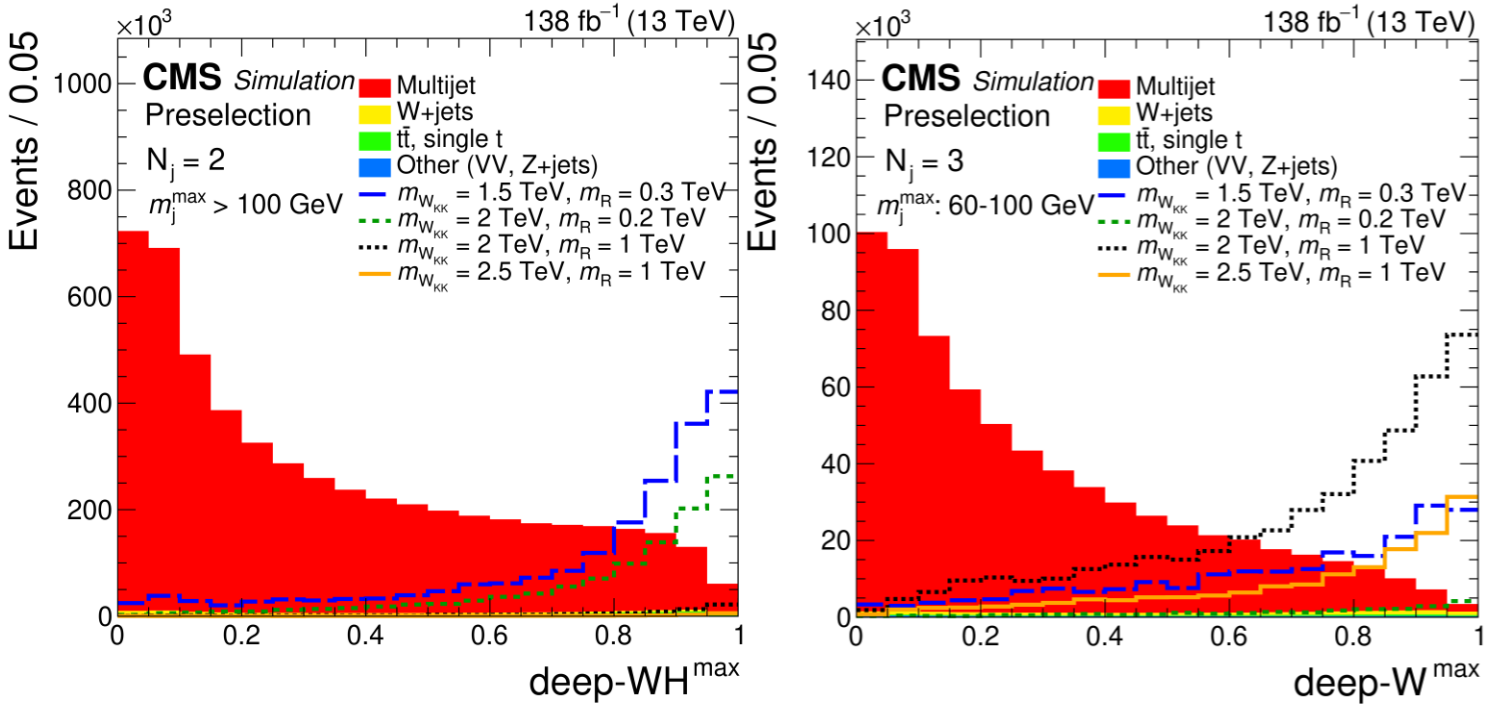
PRD 106 (2022) 012002

- **triboson final state** → 2step cascade
- $m_R/m_{W_{KK}}$ → R in 2jets (1), R in 1jet (2)
- **Tagger redefinition**, to account for W→qq and H→4q
- **MD version** necessary
- raw score(r.s) DeepAk8-MD



$$\text{deep-W} = \frac{\text{raw score}(W \rightarrow qq)}{\text{raw score}(W \rightarrow qq) + \text{raw score}(QCD)'}$$

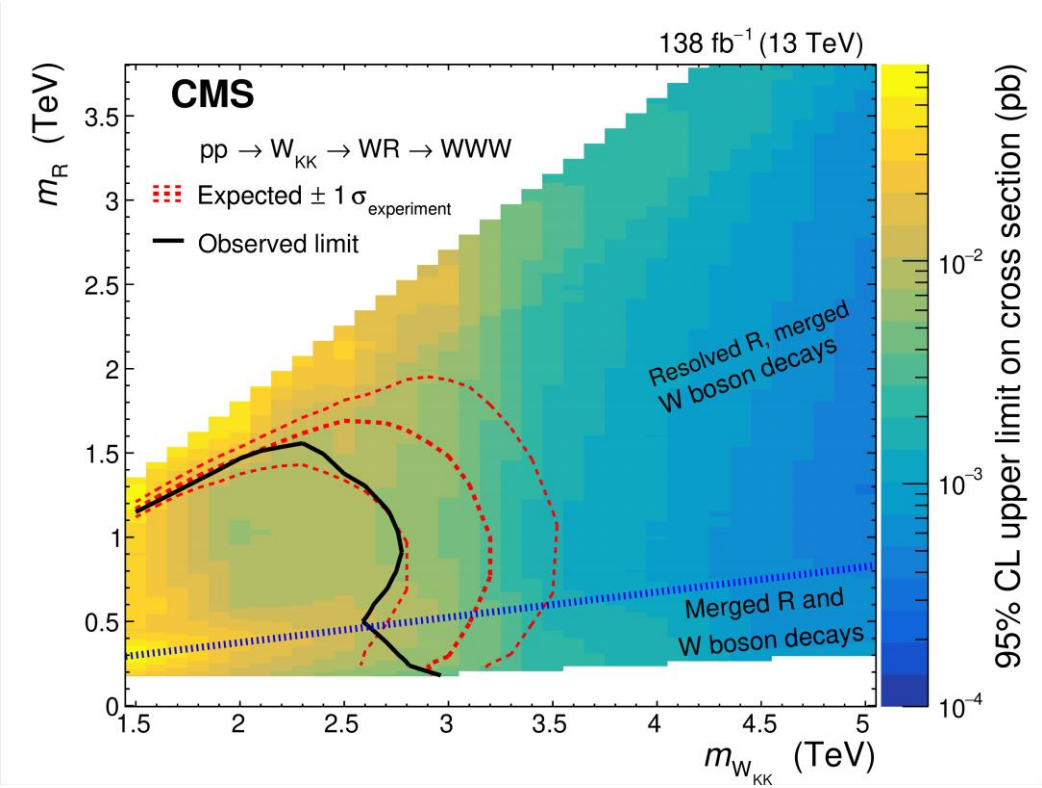
$$\text{deep-WH} = \frac{\text{r.s.}(W \rightarrow qq) + \text{r.s.}(H \rightarrow 4q)}{\text{r.s.}(W \rightarrow qq) + \text{r.s.}(H \rightarrow 4q) + \text{r.s.}(QCD)'}$$

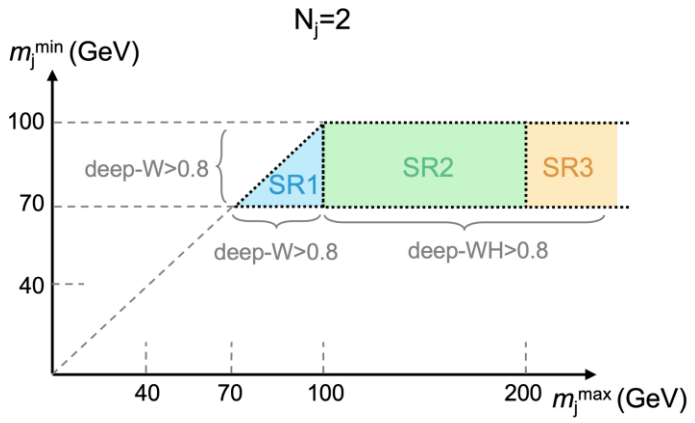


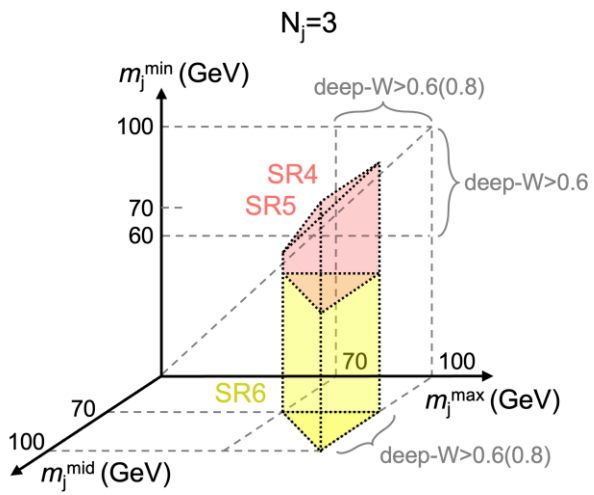
$W_{KK} \rightarrow WR \rightarrow WWW$

PRD 106 (2022) 012002

- 6 SRs defined on jet mass and deep tag score
- QCD estimated on CRs defined inverting the jet-tagging request





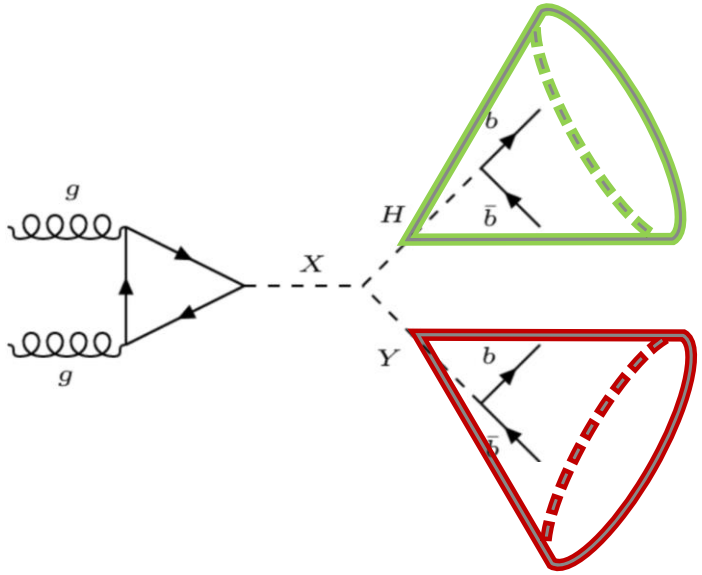


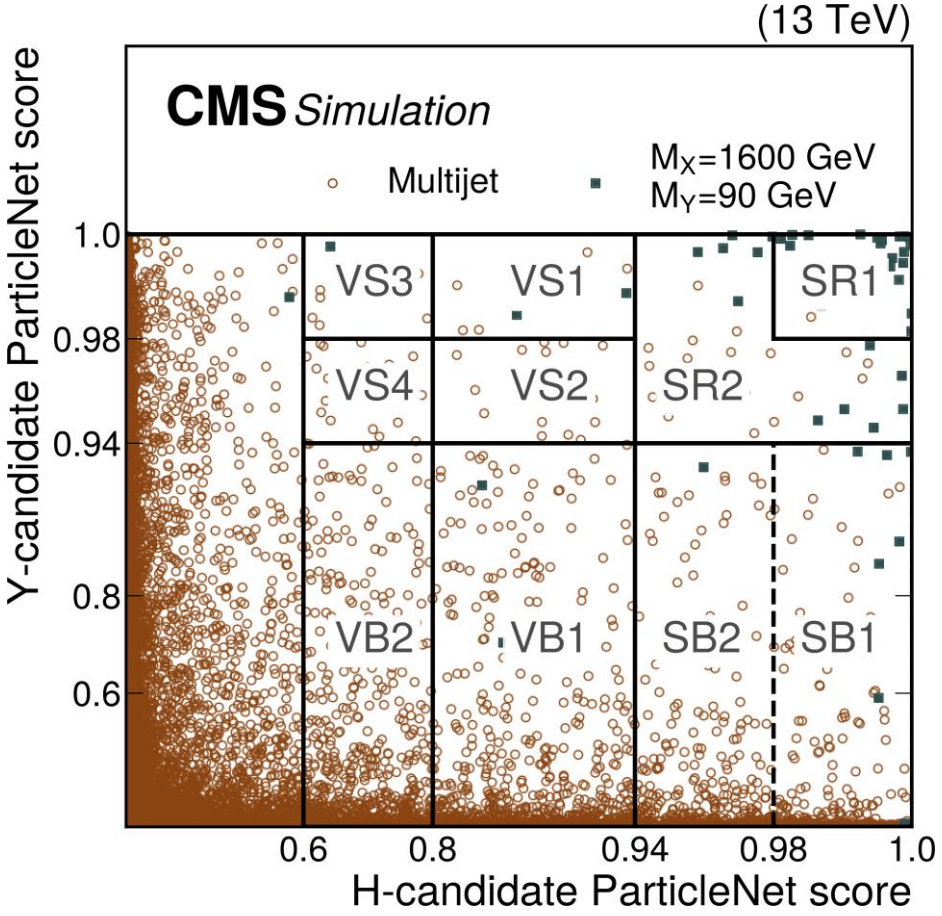
- 95% CL upper limit on cross-section process is derived
- Excluded up to m_W 2.5 TeV

$X \to YH \to b\bar{b}b\bar{b}$

Accepted by Phys. Lett. B

- Heavy resonance X to light scalar Y and SM Higgs
- Mass range, $m_X \gg m_Y, m_H$
- final state: 4b quarks reconstructed in 2 large-R (bb) jets



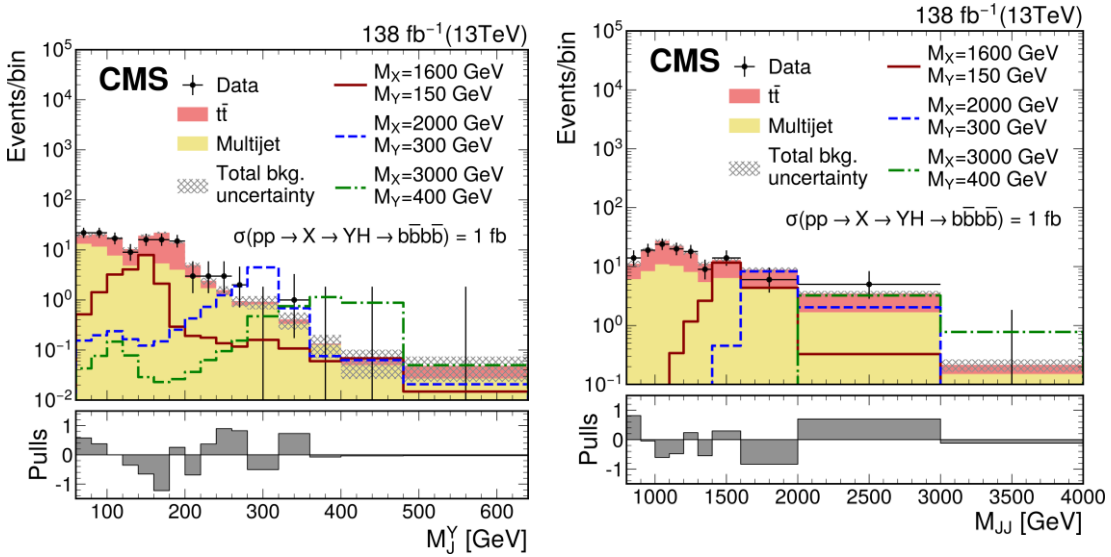


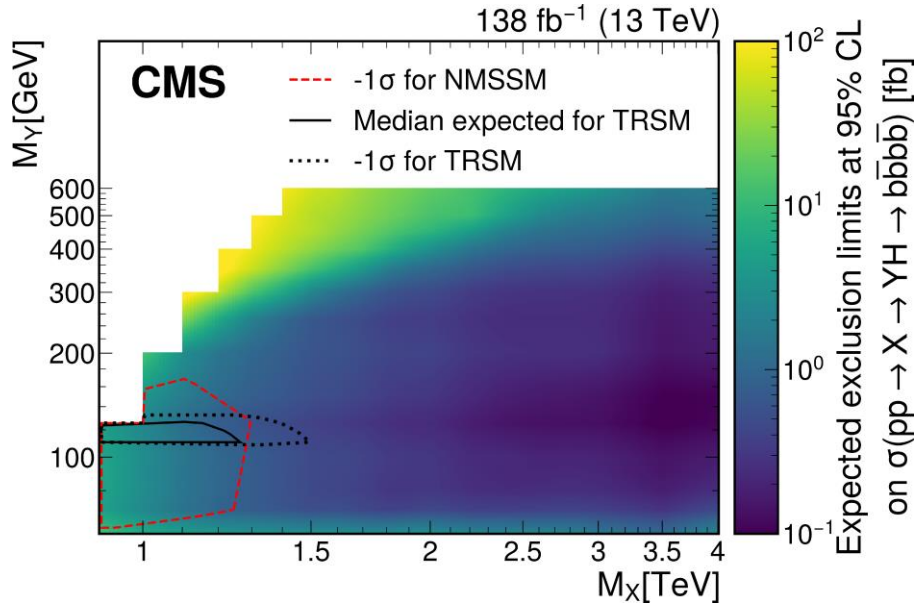
- 2 Signal regions defined: Tight (SR1), Loose (SR2)
- 2 corresponding Sideband regions(SB) for background estimation
- 6 validation regions to validate background estimation method

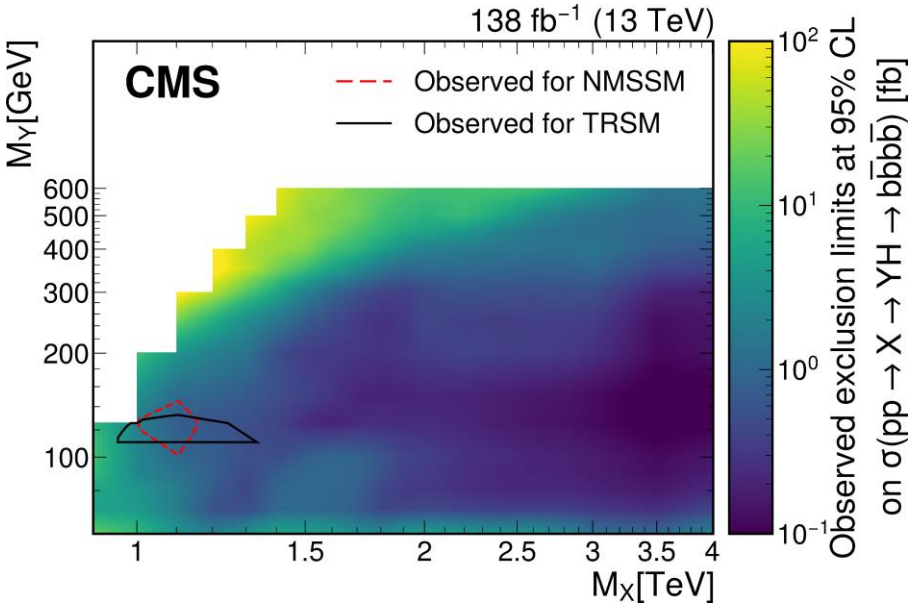
$X \to YH \to b\bar{b}b\bar{b}$

Accepted by Phys. Lett. B

- Fit of M_J^Y, M_{JJ} in SRs, SBs and M_J^t
  - No excess above the SM prediction observed
  - Model-independent limits on $\sigma\mathcal{B}$
  - TRSM observed exclusion area:
    $0.95 < M_X < 1.33\ TeV\ \&\ 110 < M_Y < 132 GeV$







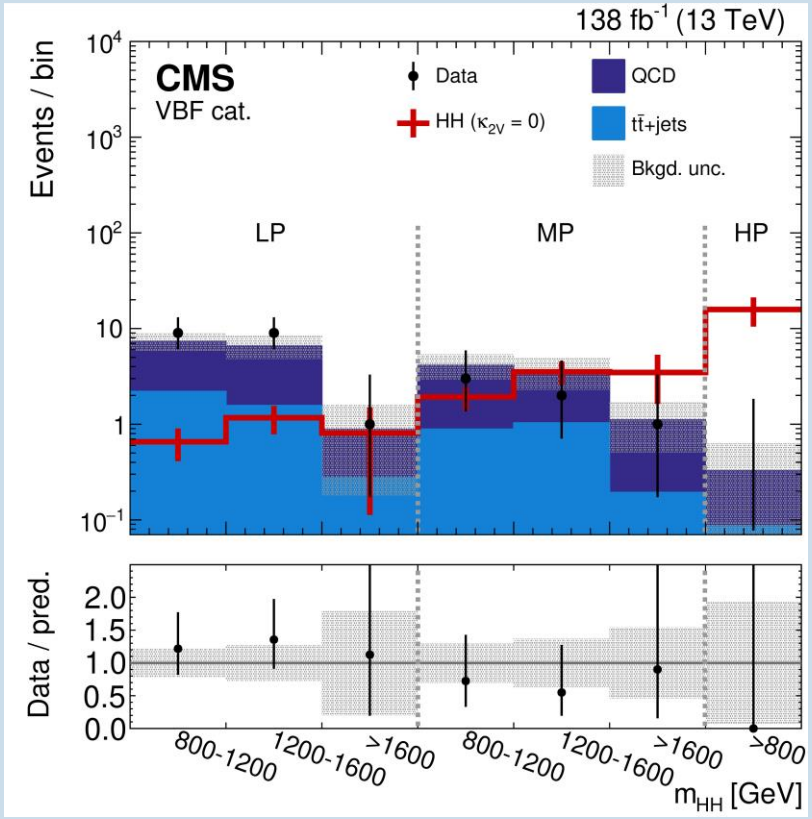
Nonresonant Higgs pair production

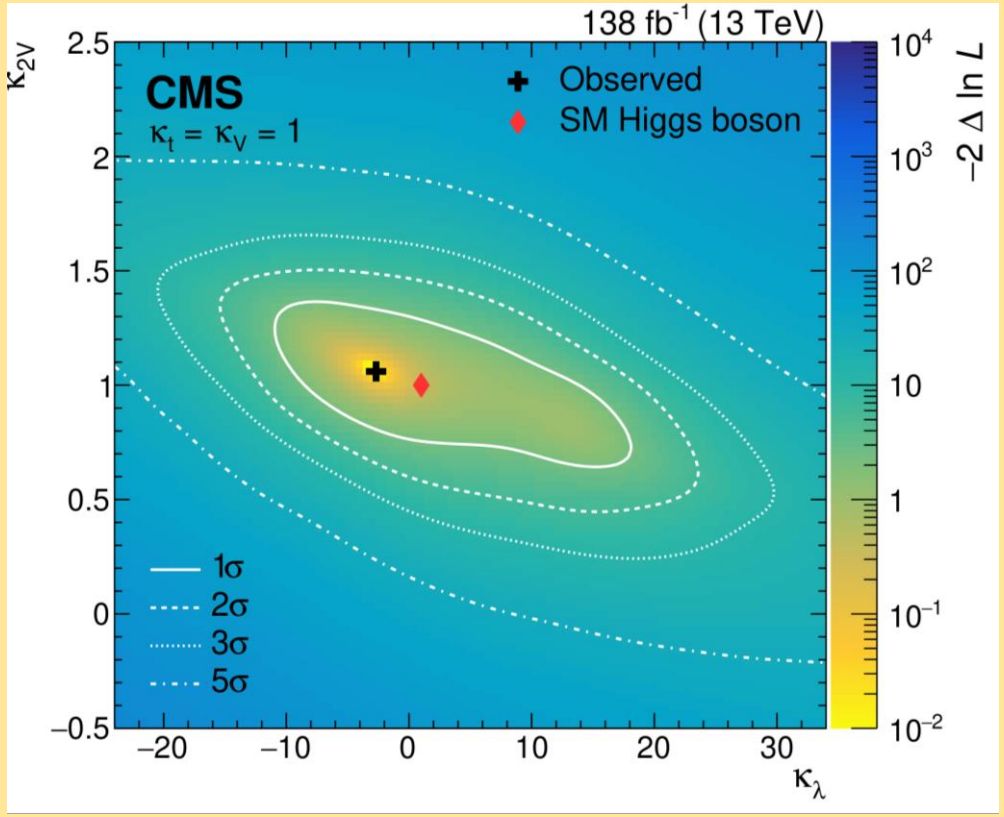
Accepted by Phys. Rev. Lett.

- Nonresonant Higgs boson (H) pair production via **ggF** and **VBF** in the **four-bottom-quark final state** reconstructed via 2 largeR jets (+ 2 additional smallR jets for VBF)

- Based on the discriminant ($D_{b\bar{b}}$) 3 regions are defined:
  - **High Purity** (**HP**), tight cut on both jets ($\epsilon_s = 60\%,\ BKG_r = 0.3\%$)
  - **Medium Purity** (**MP**), medium cut on both jets ($\epsilon_s = 80\%,\ BKG_r = 1\%$)
  - **Low Purity** (**LP**), loose cut on both jets ($\epsilon_s = 90\%,\ BKG_r = 2\%$)

Among the first to use the **ParticleNet HbbVsQCD** discr.





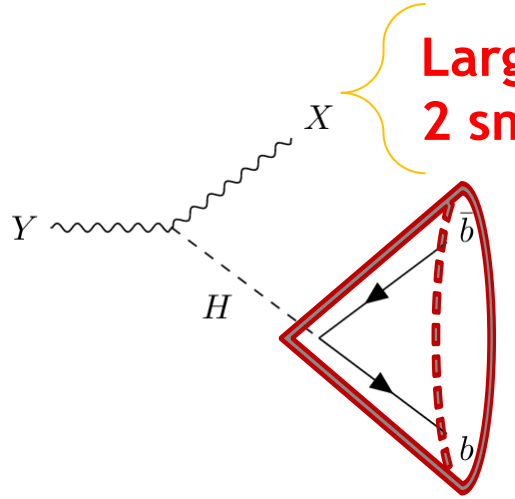
- **95% CL upper limits** translated on **parameters κ_λ and κ_{2V}**
- **Excluding $\kappa_{2V} = 0$** for the first time, with a significance of **6.3σ**

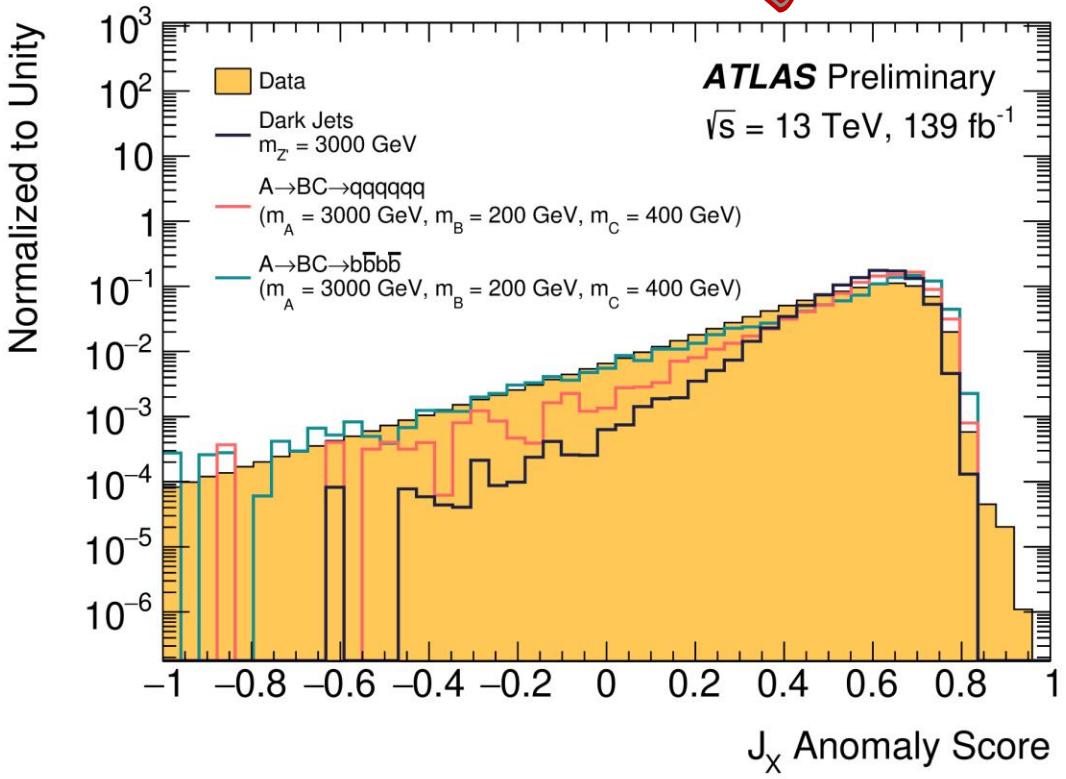
$Y \rightarrow XH \rightarrow q\bar{q}b\bar{b}$

ATLAS-CONF-2022-045

- Search for narrow-width heavy resonance Y decaying into SM Higgs(→bb) and a new X particle
- Model-independent search & HVT model used as benchmark for $Y \rightarrow XH \rightarrow q\bar{q}b\bar{b}$
- **Higgs candidate** tagged with a η reweighted version of Xbb tagger
- **X candidate :**
  1. Discovery Region based on jet-level anomaly score (from a Variation Auto Encoder (VAE) Recurrent Neural Network (RNN))
  2. Exclusion Regions for two-prongs jets $X \rightarrow q\bar{q}$ for merged and resolved regimes

First Atlas result for model independent search using an anomaly detection jet method (fully unsupervised)



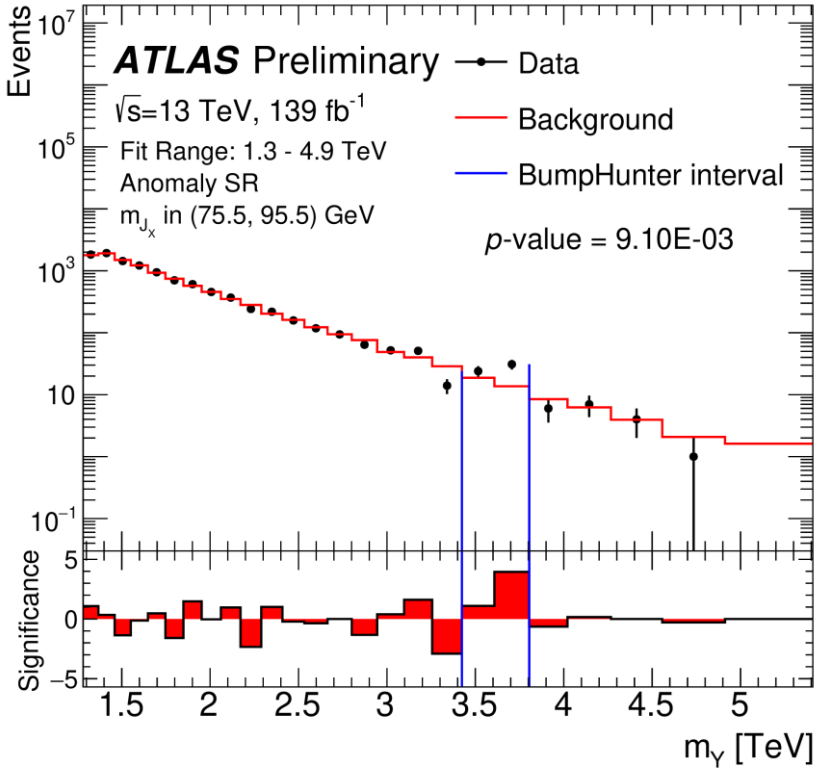


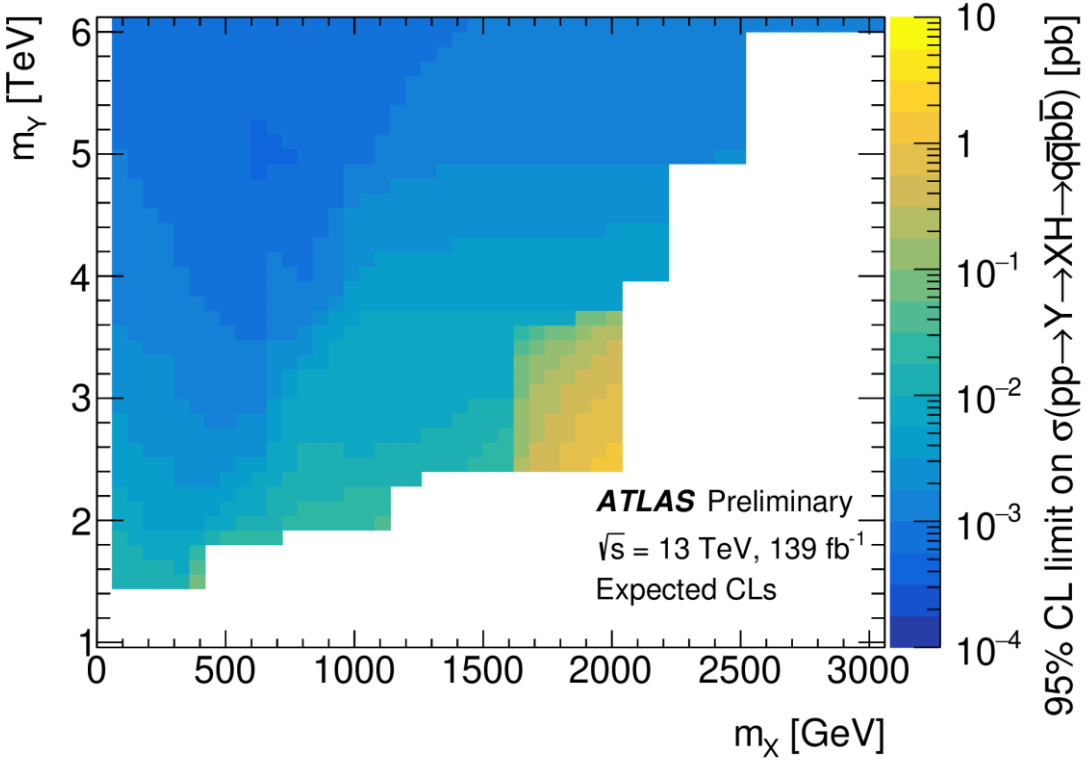
$Y \rightarrow XH \rightarrow q\bar{q}b\bar{b}$

ATLAS-CONF-2022-045

Good compatibility with the SM background with the largest deviation in $[75.5, 95.5]\ GeV$ of M_X mass range correspondent to a global significance of 1.47σ

2dimension 95% CLs limits on the cross-section of the **HVT process** in the $\{M_Y, M_X\}$ **plane**



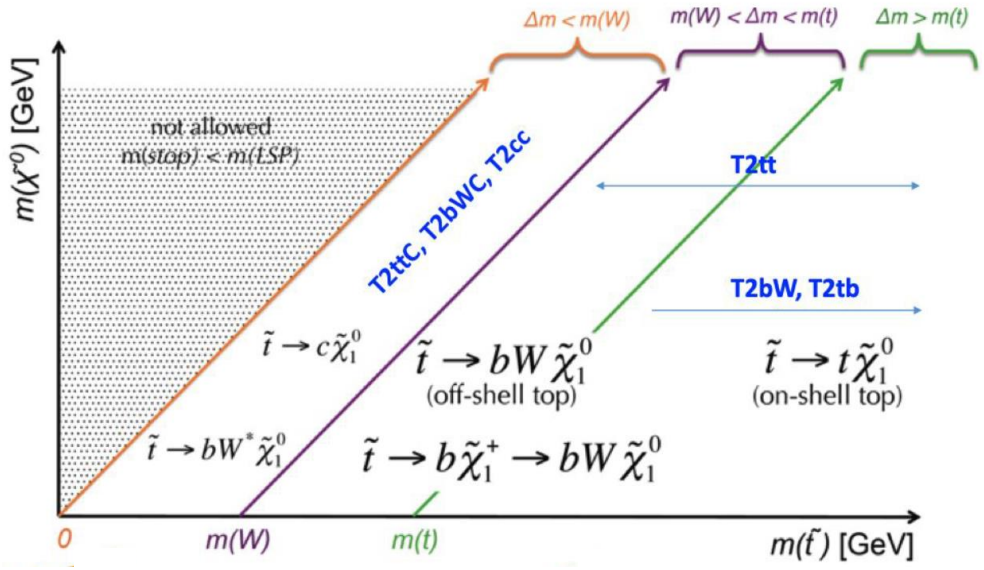


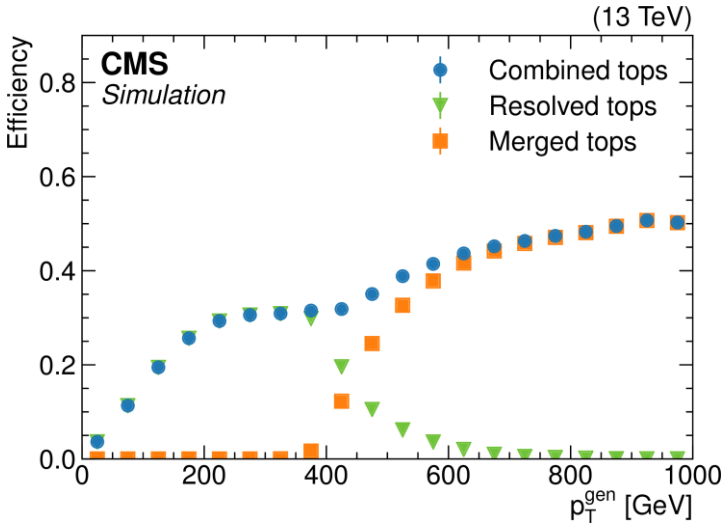
Stop production

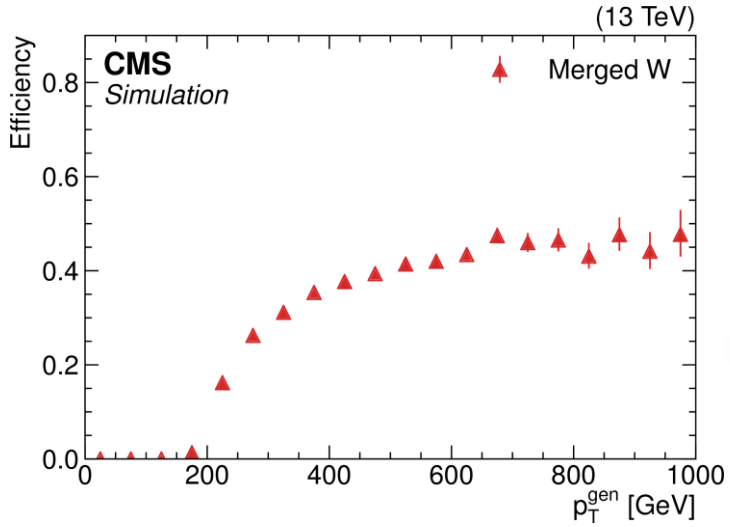
Phys. Rev. D 104 (2021) 052001

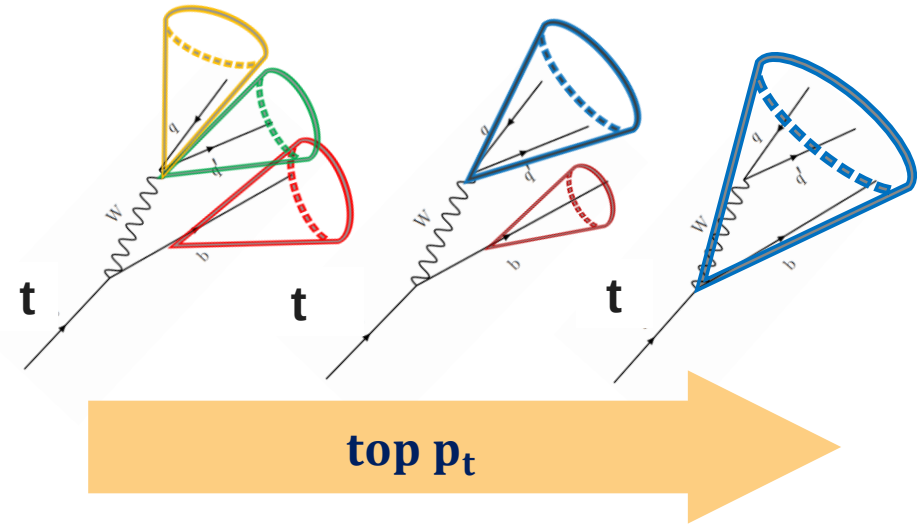
- top squark production interpreted in R-parity conserving SUSY models → novel top quark/W boson tagging algorithm

- New top reconstruction approach:
  - merged top/W : deepAk8, covers high-p_t large-R jet
  - resolved top : low-p_t using combinations of small-R jets





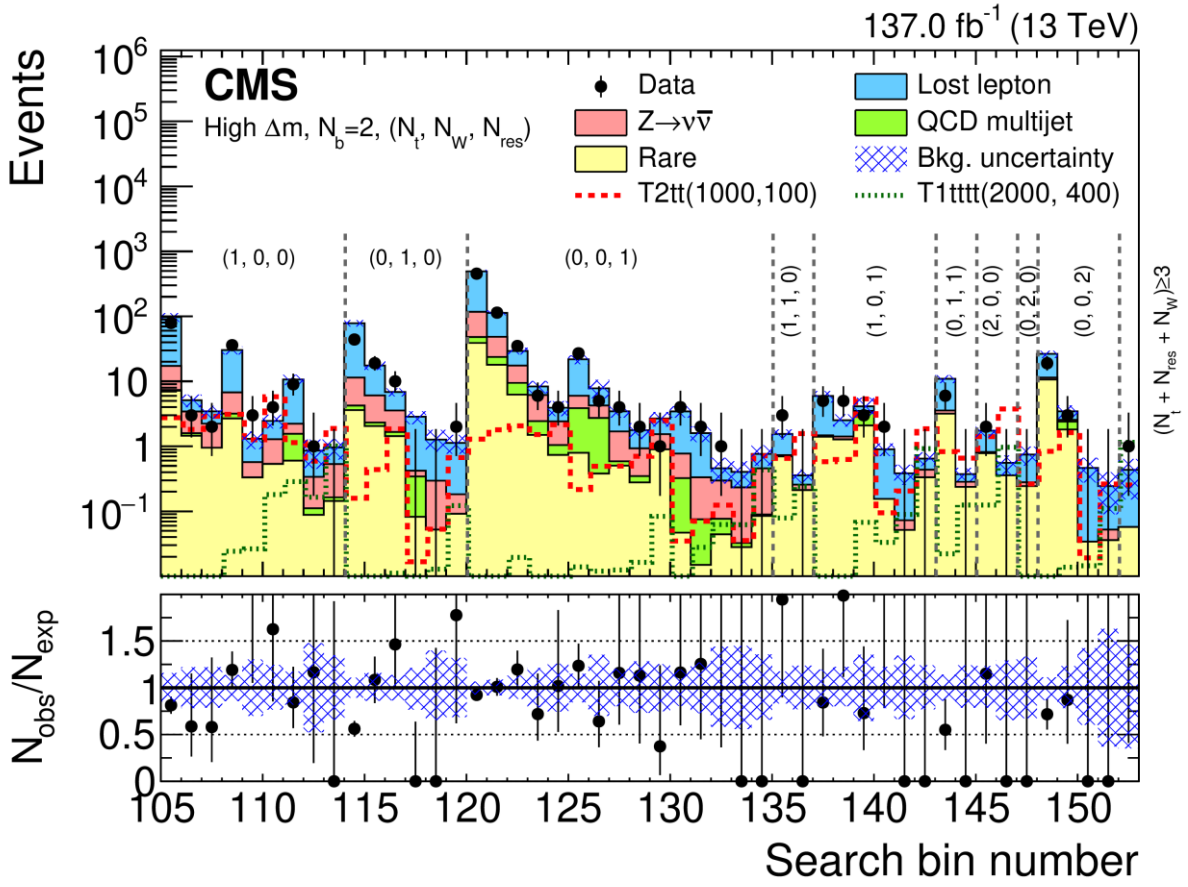


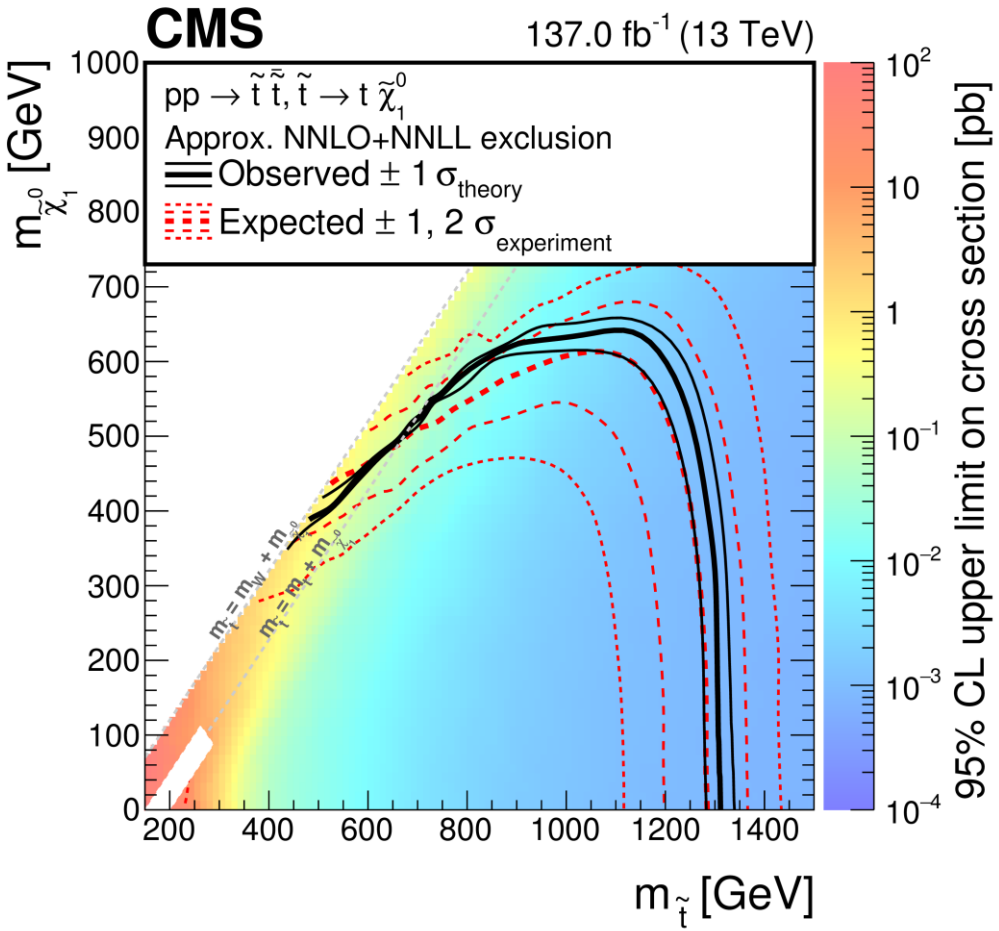


Stop production

Phys. Rev. D 104 (2021) 052001

- 183 search bins for low Δm region and high Δm region (bottom left with $N_b = 2$)
- No significant excess of events is observed relative to the expectation from the SM
- Exclusion limits for the models of stop pair production in the plane $\{m_{\tilde{t}}, m_{\widetilde{\chi}_1^0}\}$

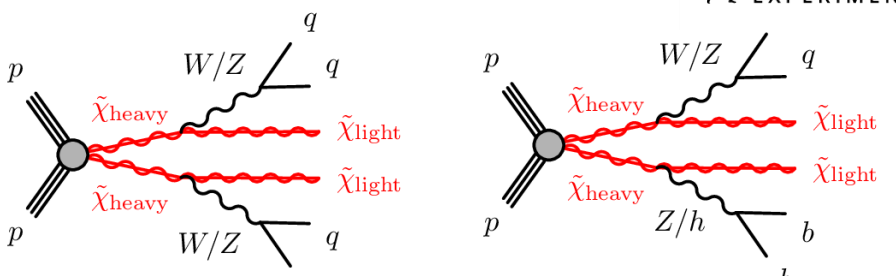


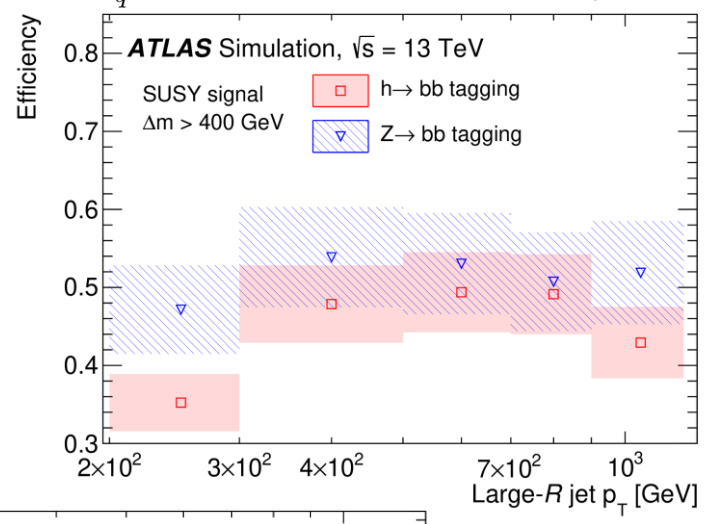


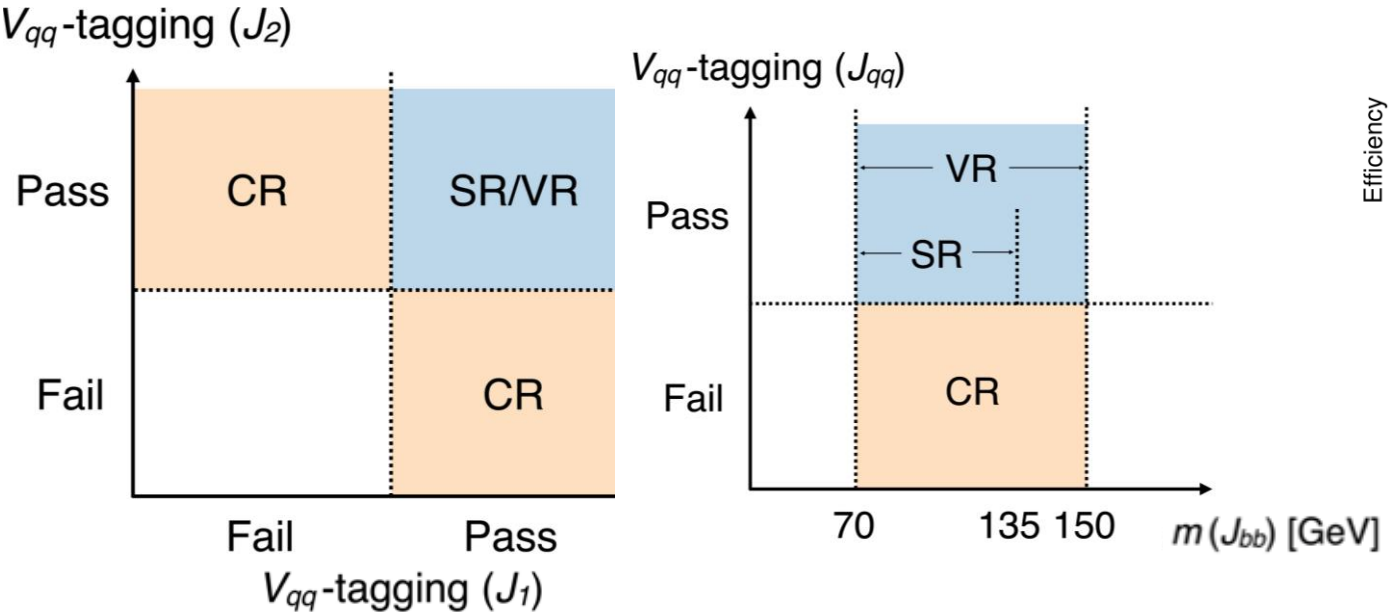
Electroweakino pair production

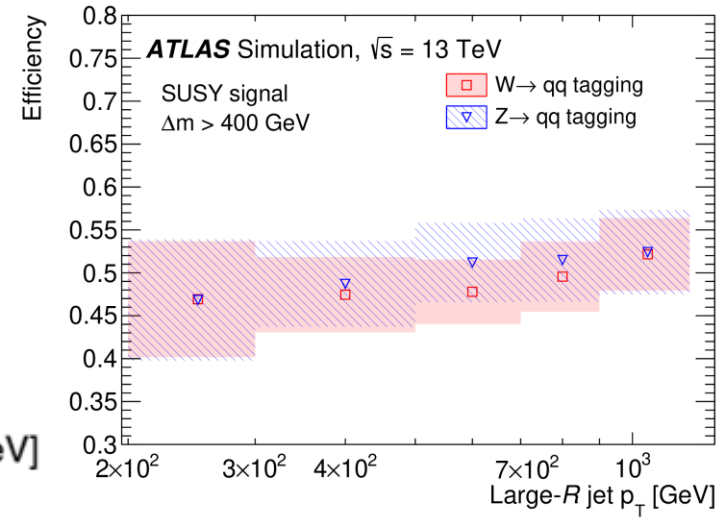
Phys. Rev. D 104 (2021) 112010

- Final states consisting of E_T^{miss} and 2 boosted heavy SM bosons (W, Z, or H)
- Two types of SRs are defined based on largeR jets tagging (V→qq and/or Z/H→bb): 4Q(VV), 2B2Q(V+Z/H)
- For each tagger the MV2c10 b-tagging algorithm has been used to estimate the b-multiplicity into the jet









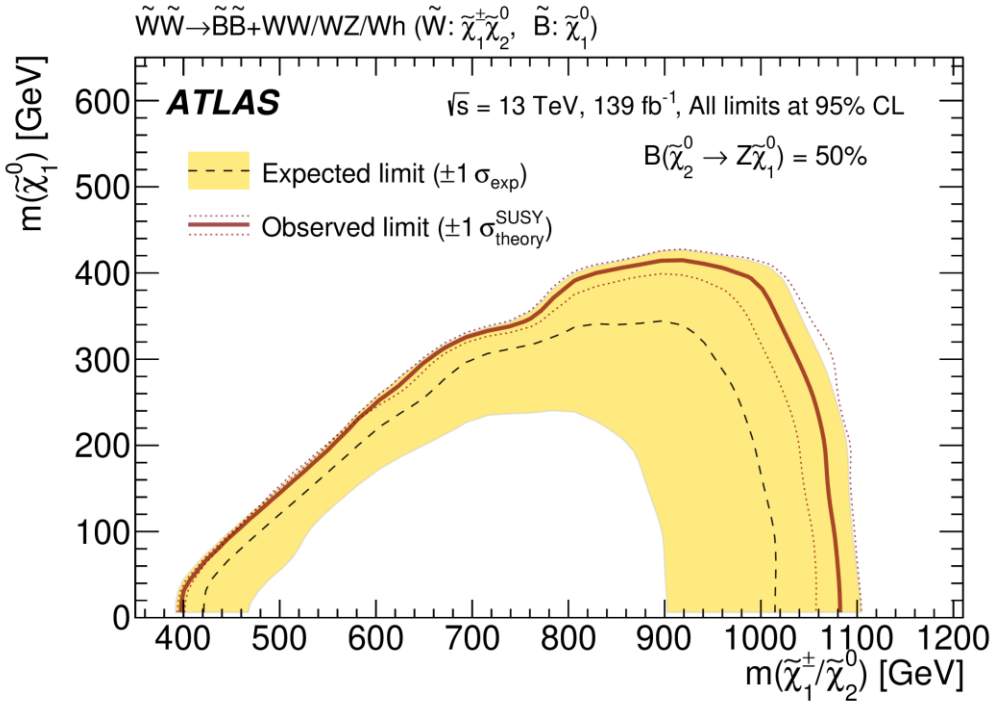
Electroweakino pair production

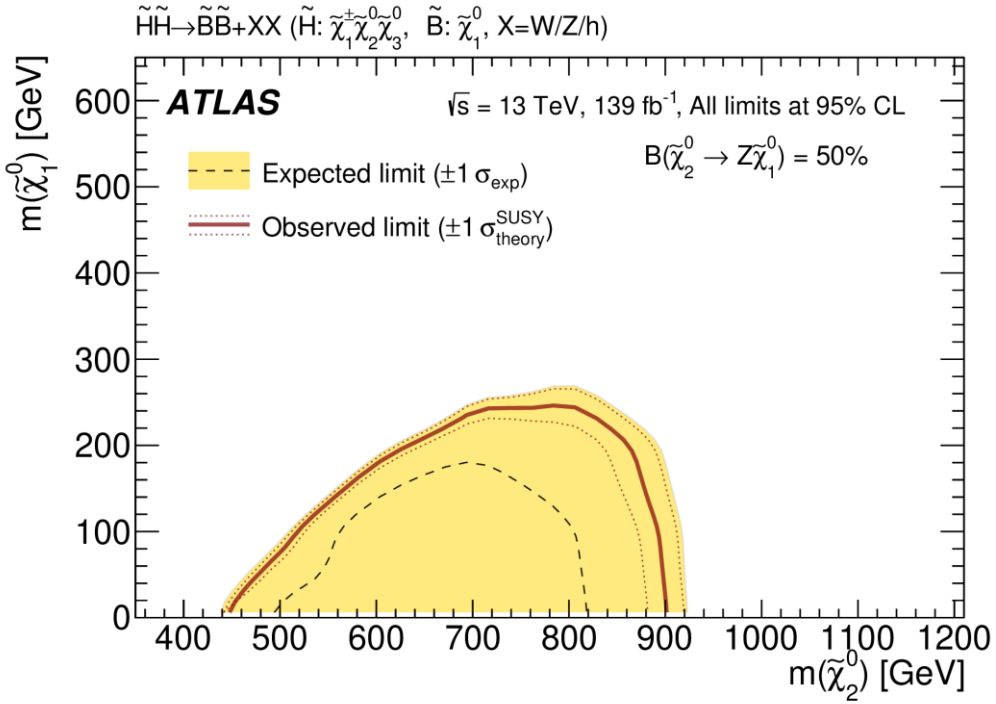
Phys. Rev. D 104 (2021) 112010

- No excess over the SM background prediction is observed, and 95% CL exclusion limits are set for signal models in various R-parity-conserving scenarios.

- The plots shown :
  - wino pair production with direct decays into a bino LSP or higgsino (left),
    $400 < m_{\widetilde{W}} < 1060\ GeV$ $(m_{LSP} < 400\ GeV\ \&\ \Delta m > 400\ GeV)$
  - higgsino pair production with direct decays into a bino LSP or wino (right),
    $450 < m_{\widetilde{H}} < 900\ GeV$ $(m_{LSP} < 240\ GeV\ \&\ \Delta m > 450\ GeV)$

Similar analysis is going to be published for CMS
Accepted by Phys. Lett. B

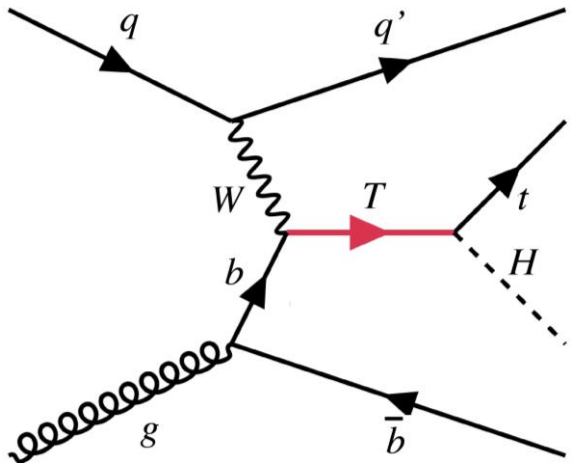




Vector-like quark T

Phys. Rev. D 105 (2022) 092012

- Search for single production of VLQ T decaying into t+H both of which decay hadronically



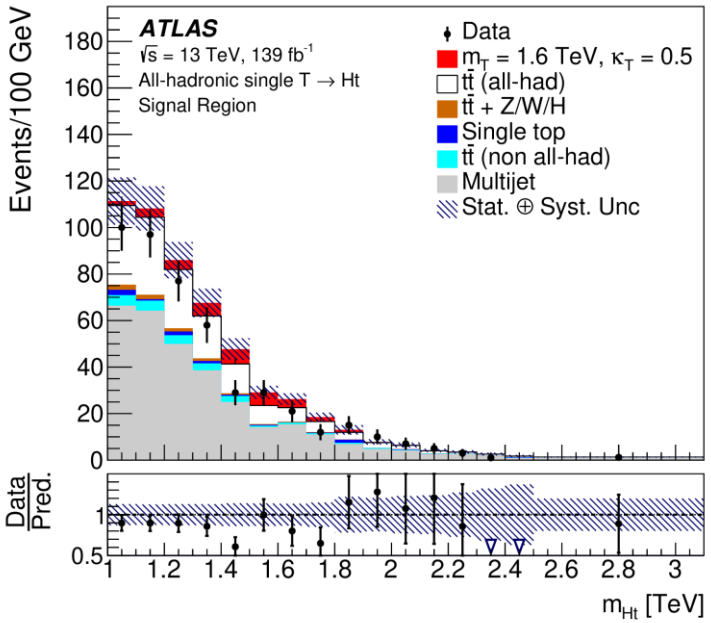
- The final states is composed by 2 large-R jets :
  - Higgs tagged:
    $100 < m_{jet} < 140\ GeV$, upper bound on τ_{21} according to p_T
  - Top tagged :
    $140 < m_{jet} < 225\ GeV$, top-tagger
  - b-tagged:
    DL1 tagger (b-multiplicity of large-R jet)
- Regions definition based on 9x9 matrix
- Background estimation:
  - QCD multijet → from data using ABCD method
  - $t\bar{t}$ constrained to data in 2 top-tag region

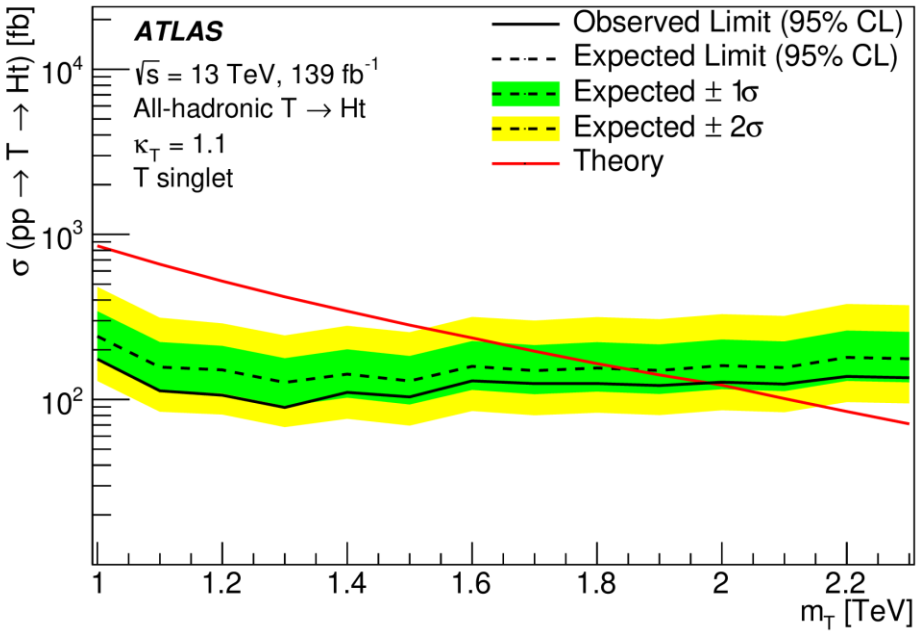
Second-leading large-R jet tagging state \ Leading large-R jet tagging state	0t 0H 0b	0t 1H 0b	1t 0H 0b	0t 0H 1b	0t 1H 1b	1t 0H 1b	0t 0H ≥2b	0t 1H ≥2b	1t 0H ≥2b
1t 0H ≥2b				VR8		NR		SR	NR
0t 1H ≥2b			VR6			SR			SR
0t 0H ≥2b									
1t 0H 1b						NR		SR	NR
0t 1H 1b						VR1			
0t 0H 1b						VR2			VR7
1t 0H 0b						VR3		VR5	
0t 1H 0b						VR4			
0t 0H 0b									

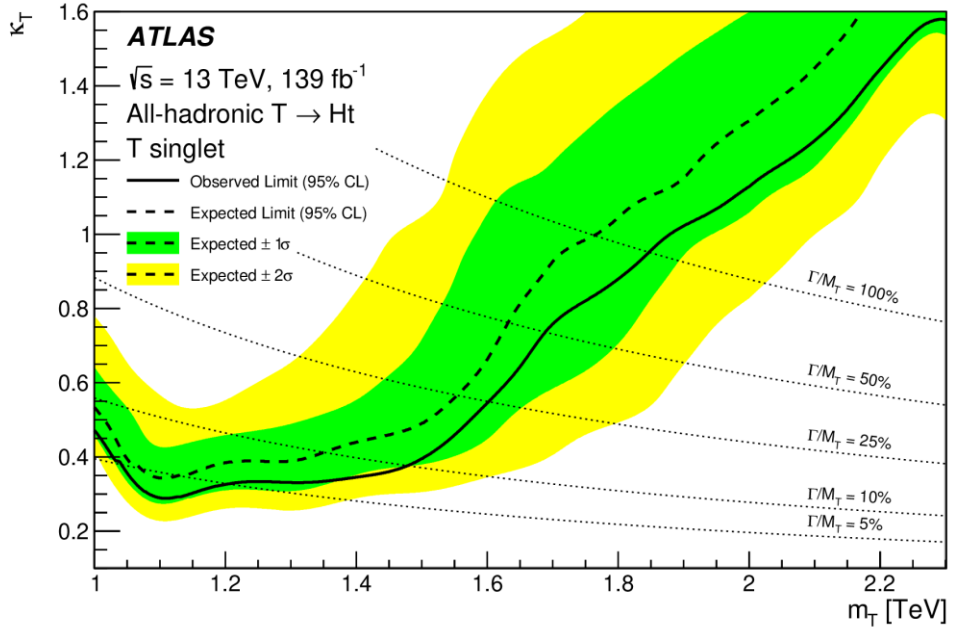
Vector-like quark T

Phys. Rev. D 105 (2022) 092012

- Improved the sensitivity by using tagging techniques → signal-to-background improvement of a factor 3 (wrt previous search)
- No evidence of new T
- The result set limits as function of the coupling to SM particles and T mass



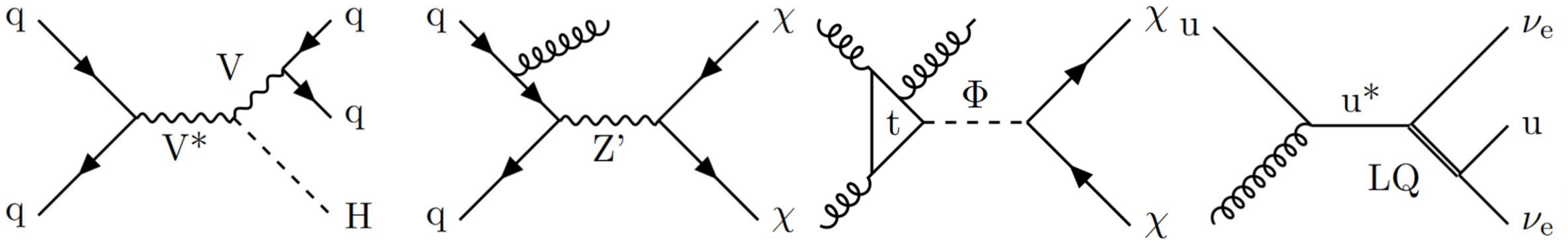




Energetic jets+ missing momentum

JHEP 11 (2021) 153

- Search for new particles that decays invisibly + energetic jets
- 3 SRs mutually exclusive (high p_T^{miss}) based on highest p_T largeR jet:
  - **monoV**, $65 < m_{jet} < 120\ GeV$ + V-tag based on **deepAk8**
    - Low-purity V-tag
    - High-purity V-tag
  - **monojet**, events that fail monoV selection
- 5 CRs defined for each SR enriched with the main backgrounds:
  - dielectron(dimuon), enriched in $Z \to \nu\nu$
  - single-electron(muon), enriched in $W \to \ell\nu$
  - $\gamma + jets$

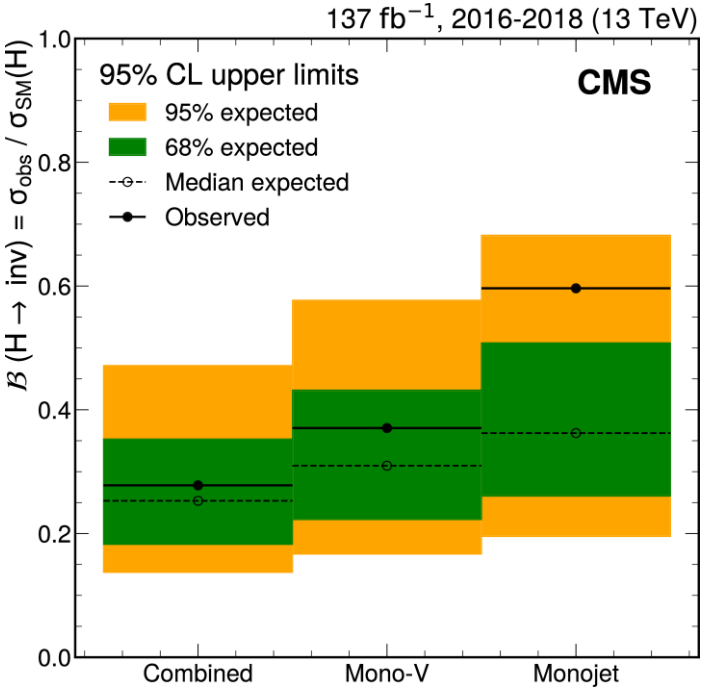


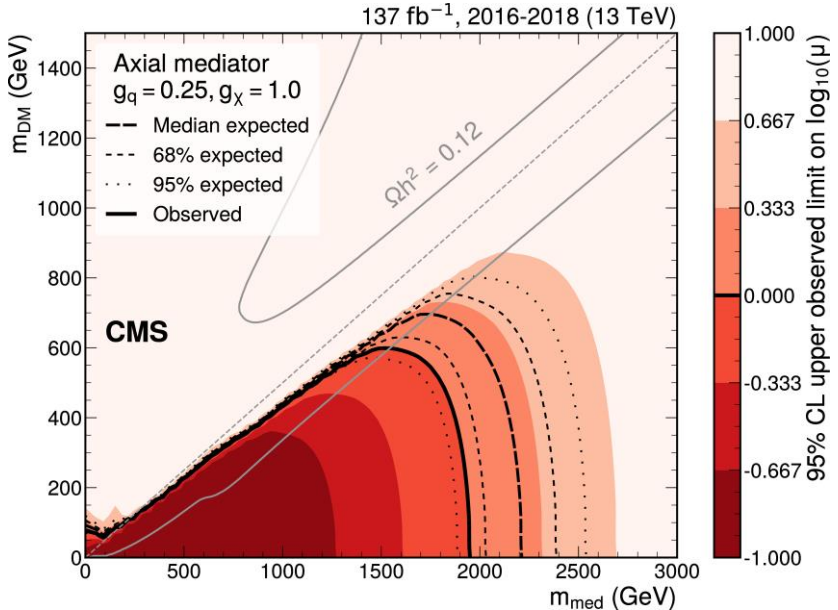
Energetic jets+ missing momentum

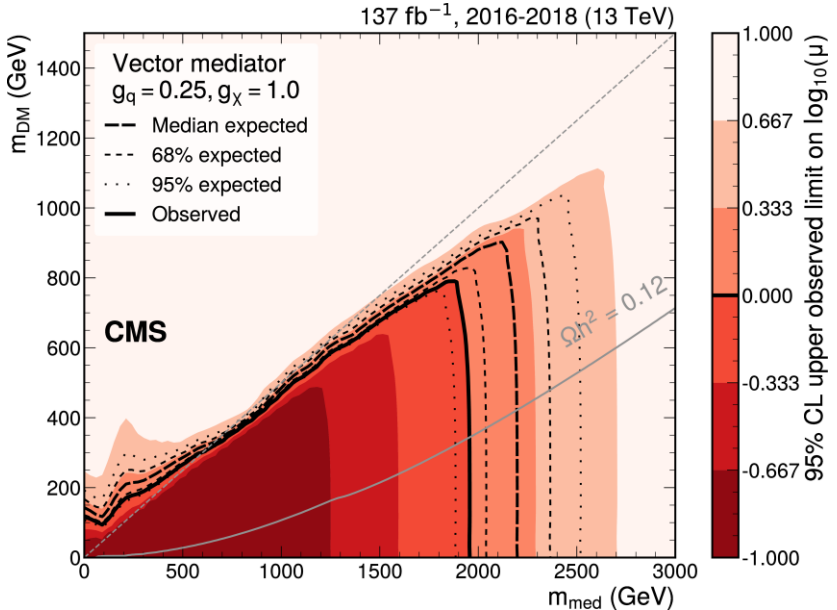
JHEP 11 (2021) 153

- Results interpretation
  - Higgs portal, a limit on the BR of Higgs in invisible
  - Simplified DM models, exclusion limit in the $\{m_{med}, m_{DM}\}$ plane

- The result is also interpreted in the context of extra-dimensions scenarios and for a LQ decays

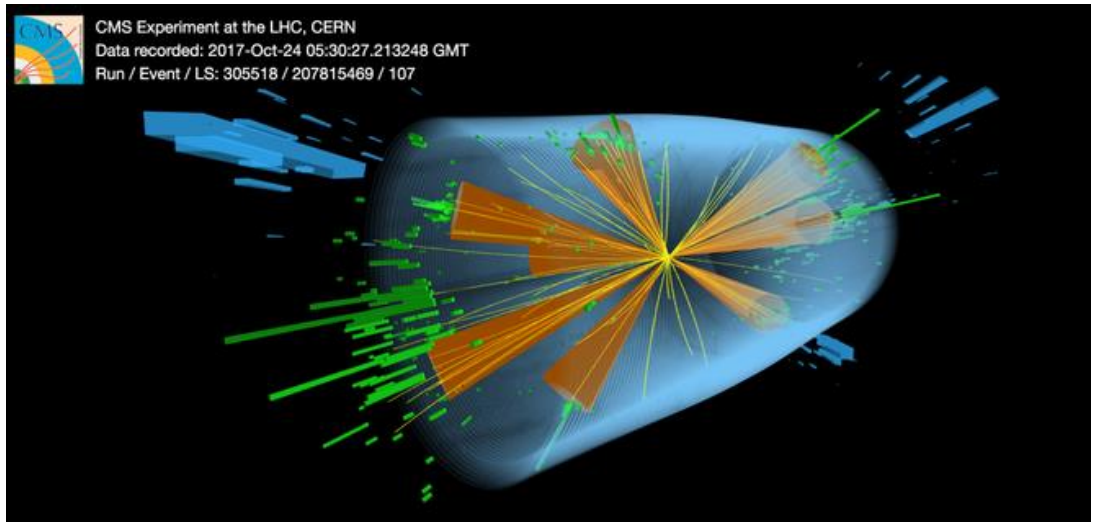


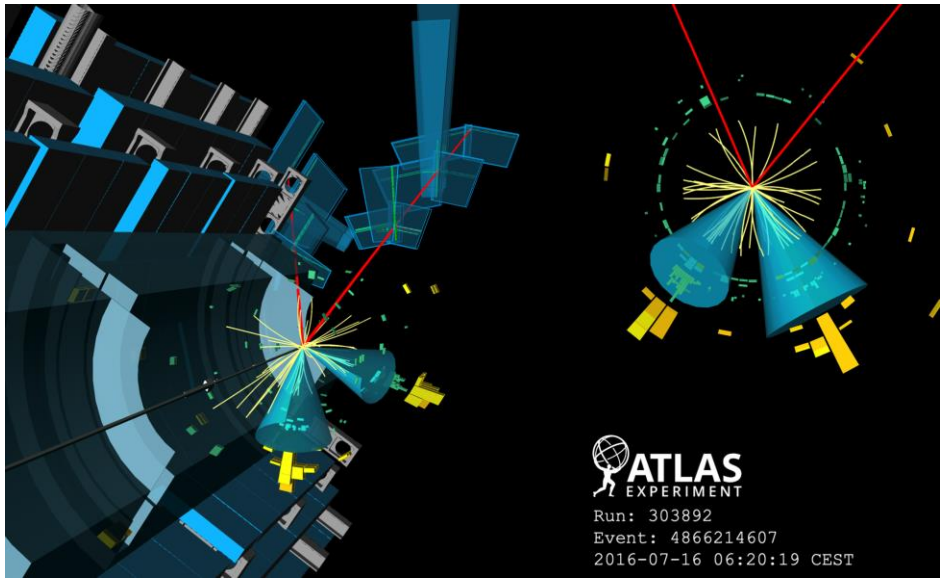




Conclusion

- The ML approach has led to an incredible improvement of the jet tagging techniques
- Many searches have been developed making use of state-of-the-art algorithms
- Looking forward to Run 3 for further improvements on jet-tagging and new exciting results!





Thank you