Beyond inclusive resonances: hadronic final states

LHCP 2021

7/6/2021

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for the CMS and ATLAS collaborations

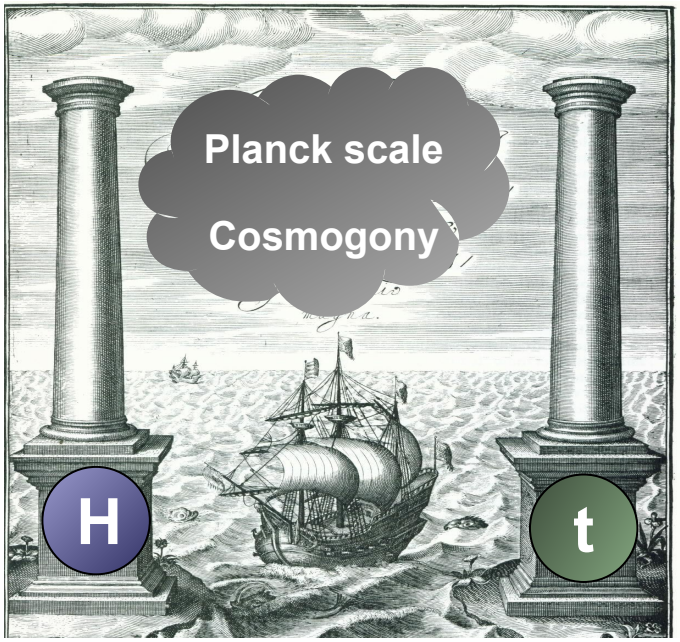
Particle physics after the Higgs: Nec plus ultra?

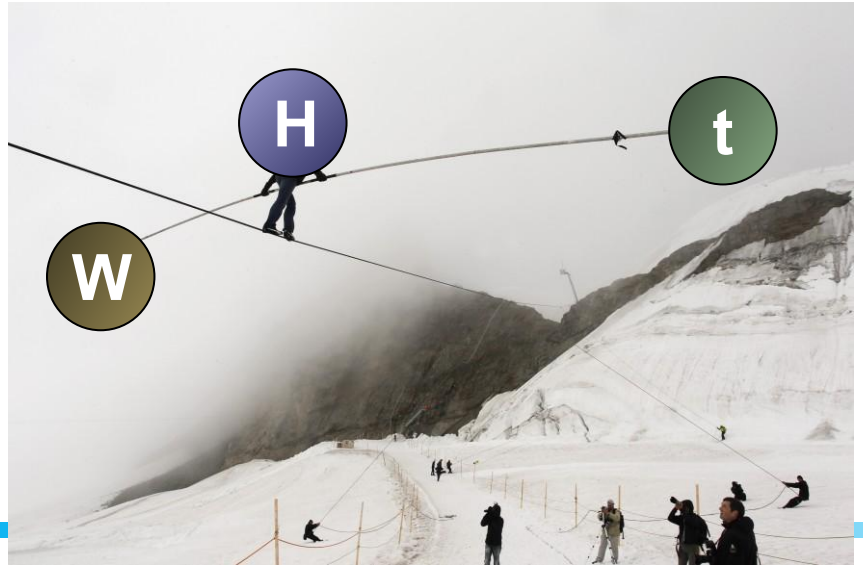
Going beyond and missing pieces:

→ **Inclusion of gravity**

→ **Dark matter, dark energy**

→ **Matter-antimatter asymmetry**





The SM's "effective theory" vibe:

→ **Origin of EWK symmetry breaking**

→ **Why does the higgs stay so light**

→ **So many "free" parameters!**

Why search through hadronic final states?

LHC collisions: a "hadron-heavy" environment by default!

→ Hadronic **BSM signatures can be challenging** to reconstruct:
- complex composite physics objects
- combinatorics self-background

→ **Significant QCD background** all new physics hadronic signatures

But this also means: this might be the **place where new physics is still eluding us!**

- Unexplored final states with **high multiplicity** of hadronic objects
- Unusual peak structures : **"broad" peaks** w or w/o **heavy SM interference**
- Unconventional signatures with **ad hoc** physics objects

In this talk

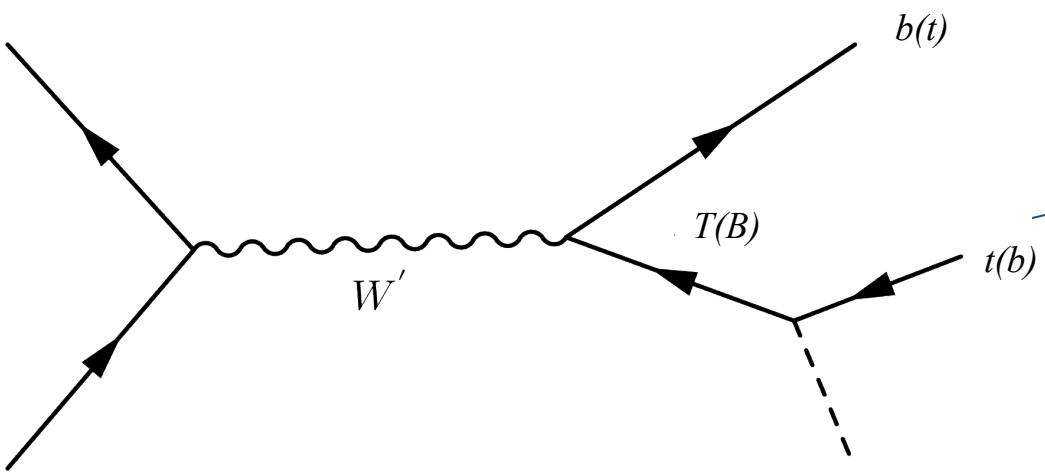
Analysis	Reference
Search for W' decaying to a vector-like quark and a top or bottom quark in the all-jets final state	CMS-PAS-B2G-20-002
Search for charged Higgs bosons decaying into a top quark and a bottom quark at √s=13 TeV with the ATLAS detector	ATLAS HDBS-2018-51 arXiv:2102.10076
Search for heavy particles in the b-tagged di-jet mass distribution with additional b-tagged jets in proton-proton collisions at s√=13 TeV with the ATLAS experiment	ATLAS-CONF-2021-019
Search for W' bosons decaying to a top and a bottom quark at √s = 13 TeV in the hadronic final state	CMS B2G-20-005 arXiv:2104.04831
Search for Higgs boson pair production in the two bottom quarks plus two photons final state in pp collisions at s√=13 TeV	ATLAS-CONF-2021-016

Note: impossible here to encompass all interesting hadronic analyses! Links to specific topics **during the talk** and **in the backup** → for more results, see also the ATLAS EXO/HDBS and CMS EXO/B2G public pages!

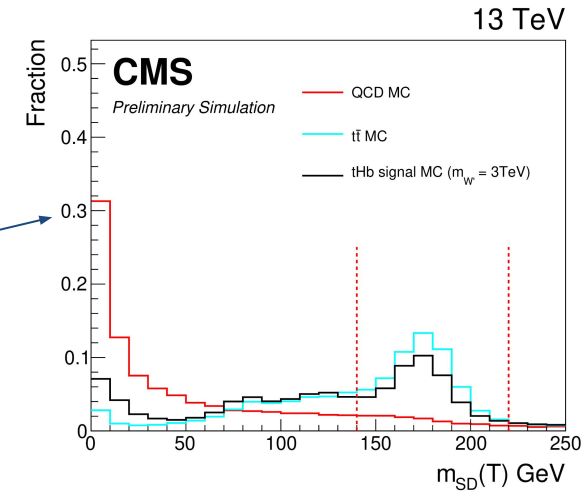
High-multiplicity of jets: W' → tH(Z)b

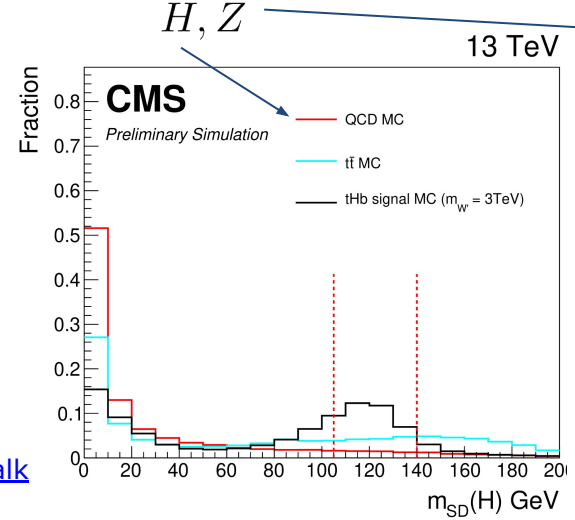
CMS-PAS-B2G-20-002

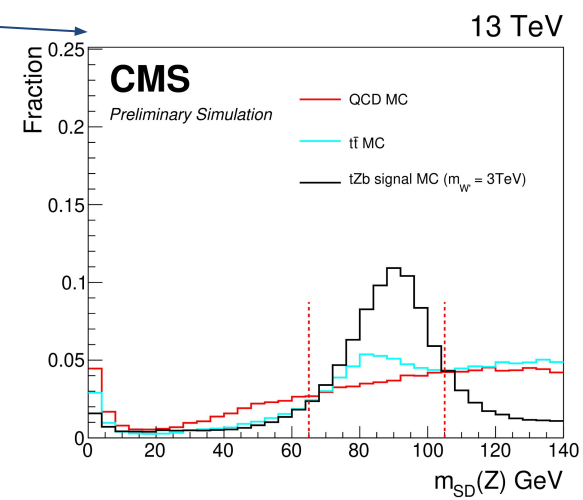
- Composite scenarios that foresee the presence of new resonances AND vector like quarks, with **privileged decays to VLQ**



1 top







Each particle ⇔ 1 Anti-kt jet

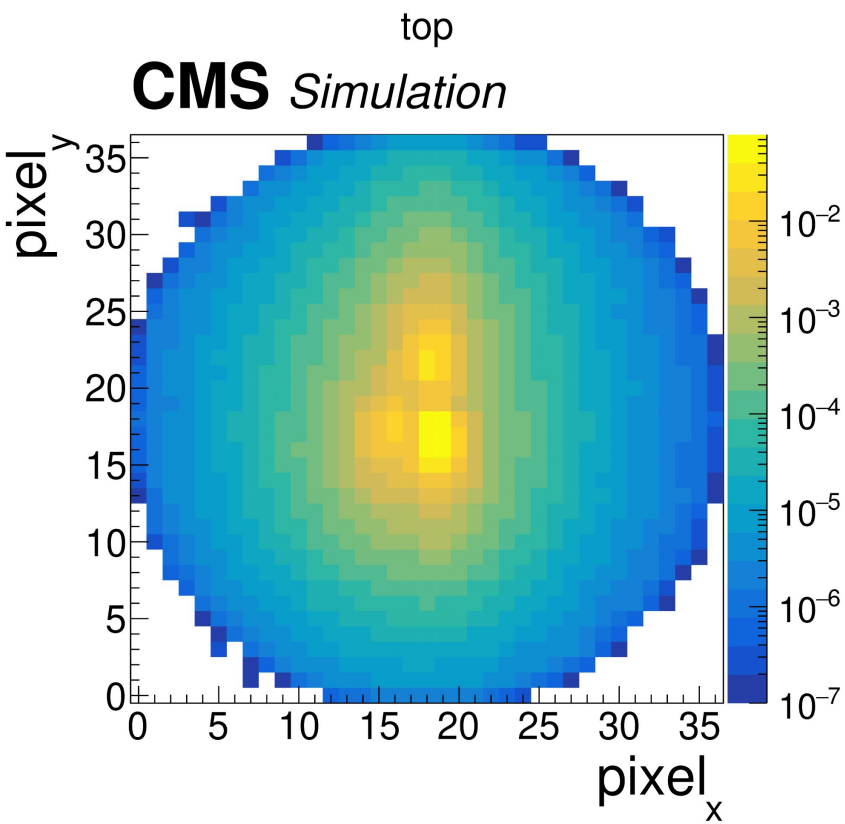
- b-jets with R=0.4

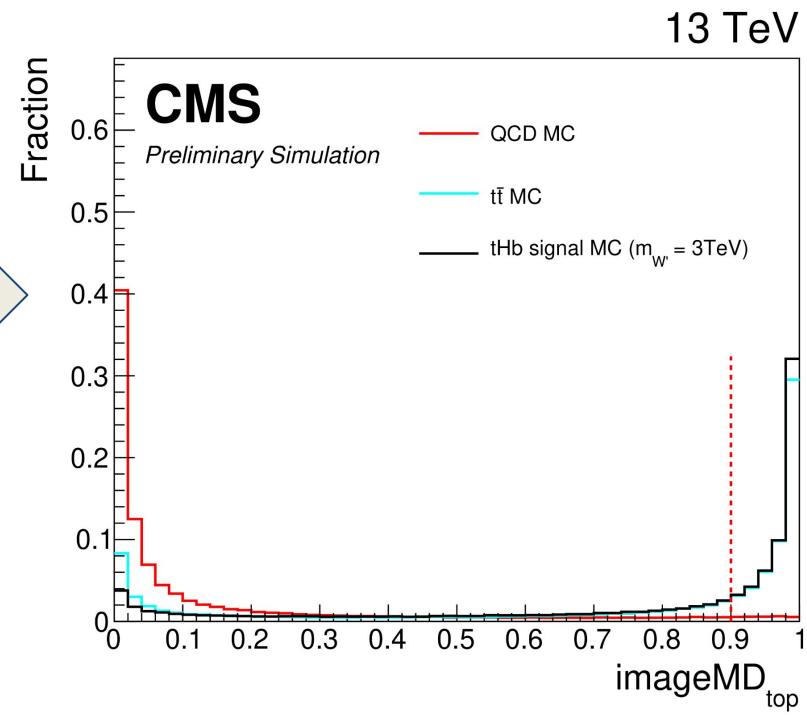
- top / H / Z jets with R=0.8
→ **Soft drop** mass used as discriminant

For top-quark related final states, see also Junpei's talk
For VLQ-related final states, see also Timothy's talk

W' → tH(Z)b: new top tagging techniques

- Image top tagger: jet information to create a "pixelated" image → **DNN training**
- Decorrelated from top quark mass: can **make use of jet mass as discriminating variable**





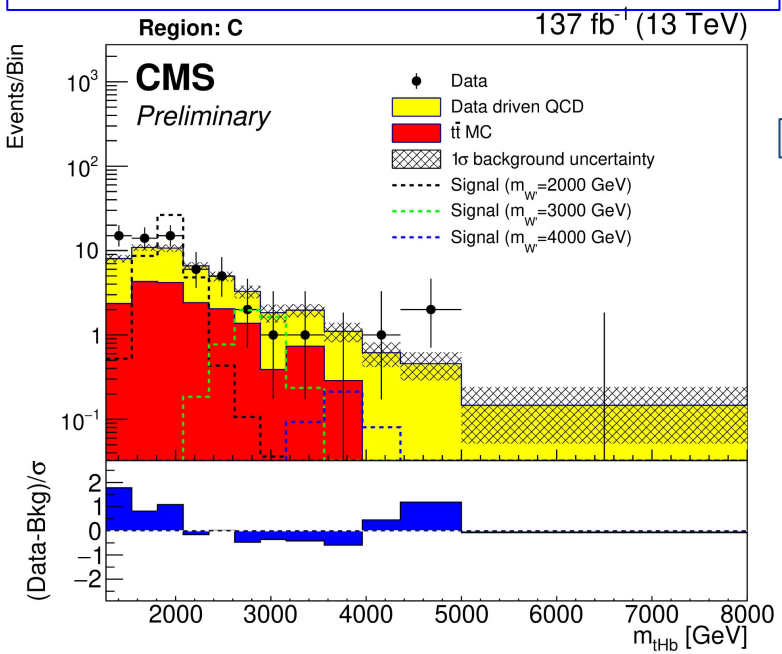
→ Scale factor measured on data

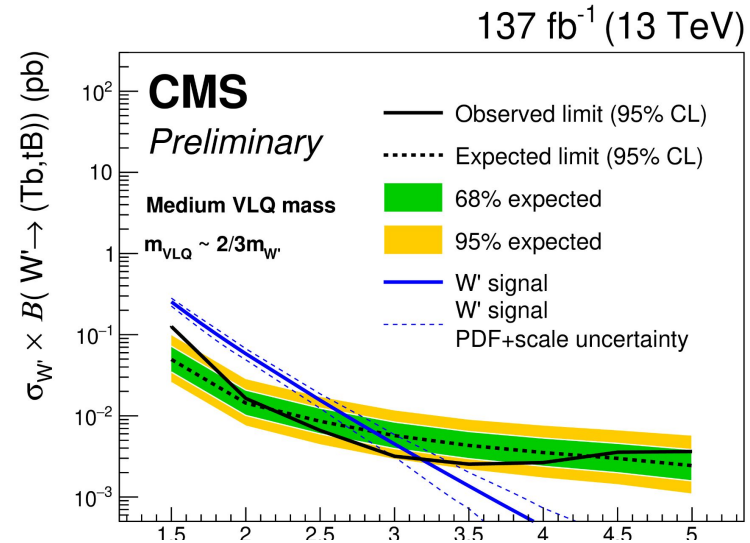
See also *JINST 15 (2020) P06005* and this *talk by Yotam*

W' → tHb: results

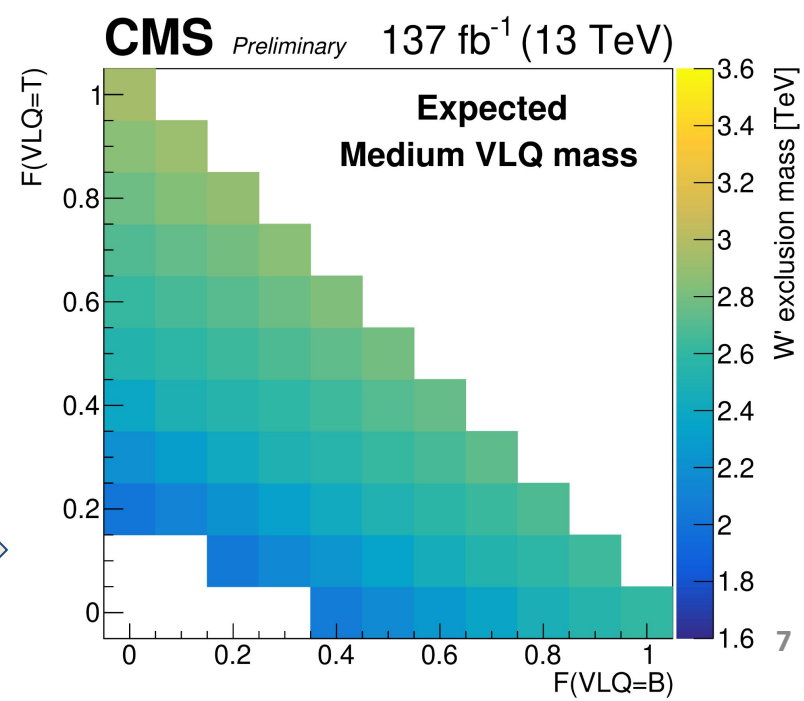
- Multiple control regions defined for the background estimation based on taggers requirements
- Fit to the 3-jet mass

For mT' ~ ½ mW' and BR(B=0)
⇒ mW' > 3.2 TeV



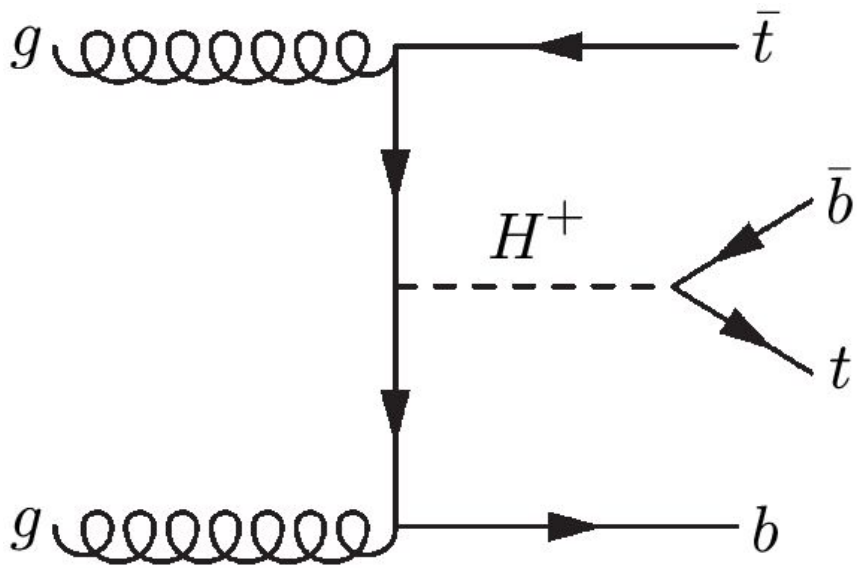


Releasing the BR:
limit as function of the BR(T)/BR(B)



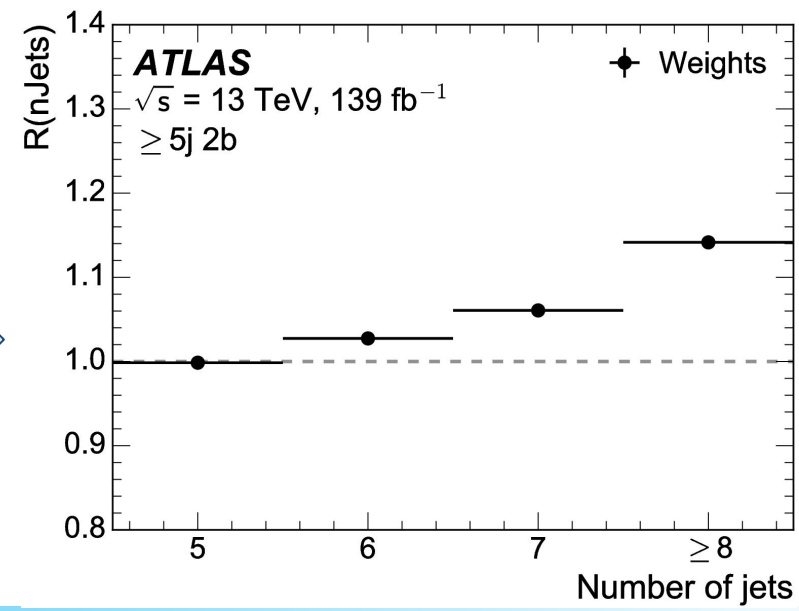
High-multiplicity of jets: $tH^+b \rightarrow tbtb$

- Charged Higgs boson produced in association with **third generation quarks**



- 1 lepton from top quark decays
- **High jet multiplicity**, up to 4 b-jets
- H+ mass ranging from 0.2 to ~2 TeV

- Number of jets in ttbar simulation **reweighted to data**
- Followed by **HT reweighting**

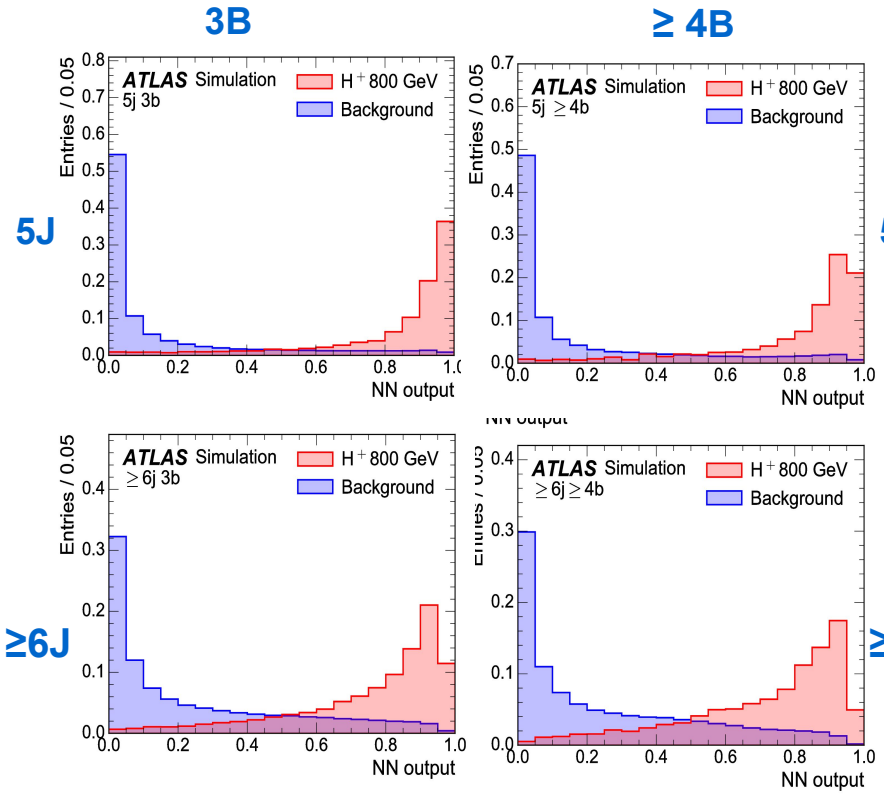


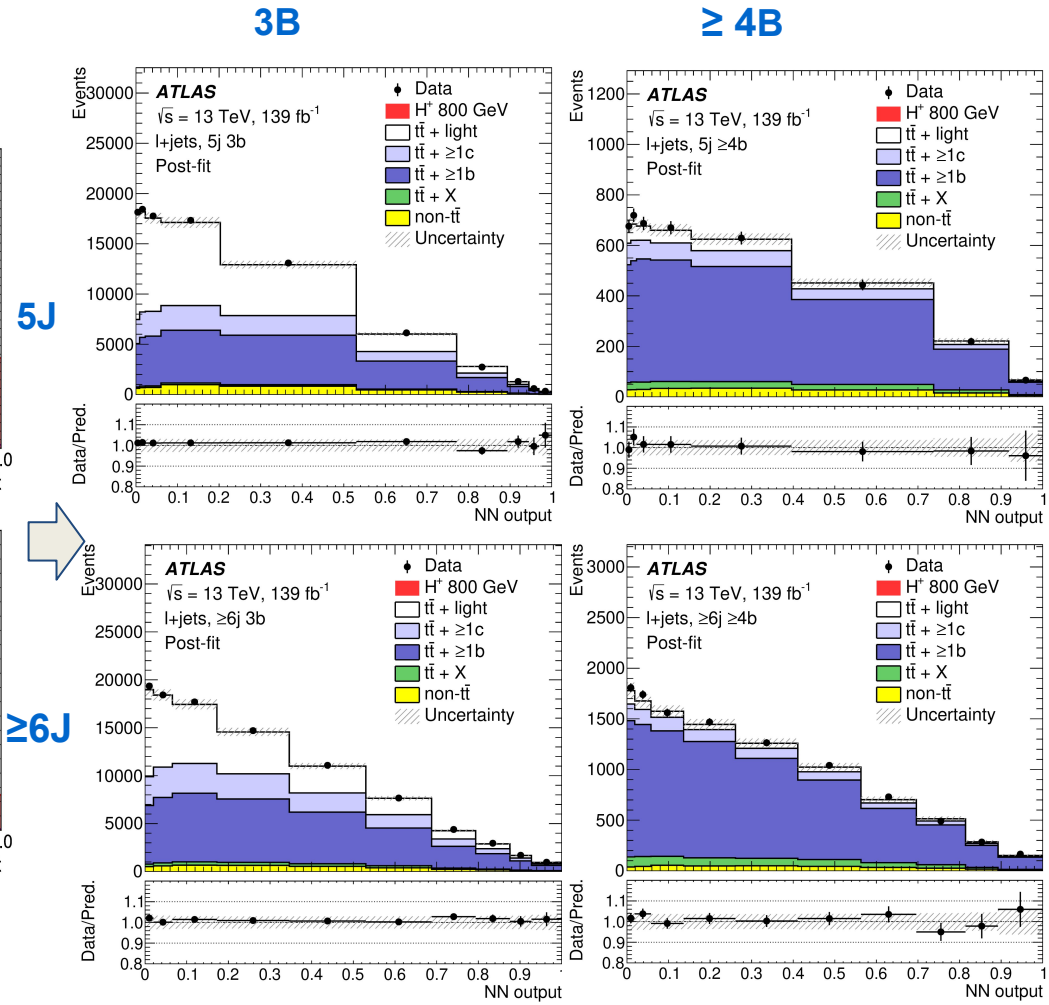
ATLAS HDBS-2018-51
arXiv:2102.10076

For BSM Higgs searches, see also Junquan 's talk

Multiple jet regions

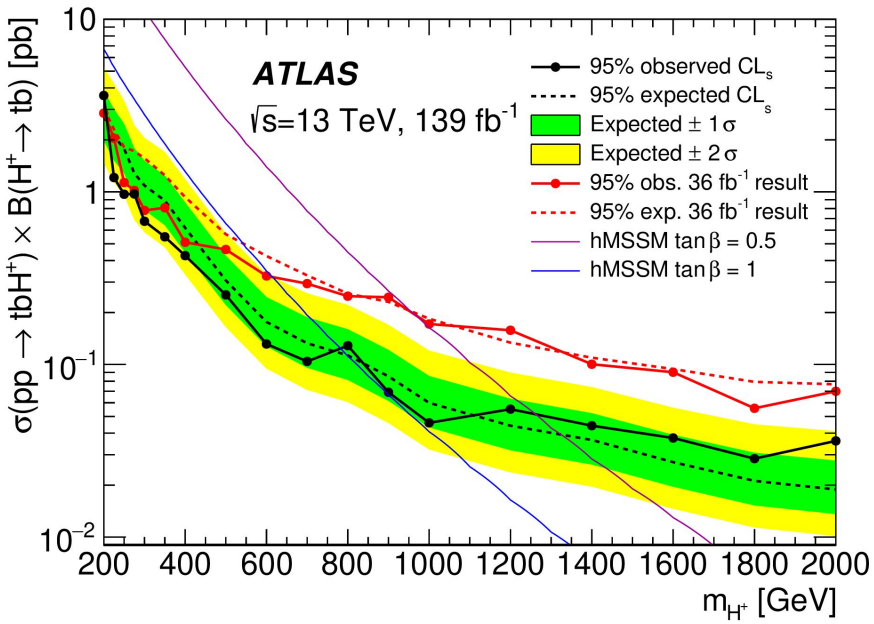
- Defining regions with 5, ≥ 6 jets, vs 3, ≥ 4 b-tagged jets
- One NN per region trained vs backgrounds

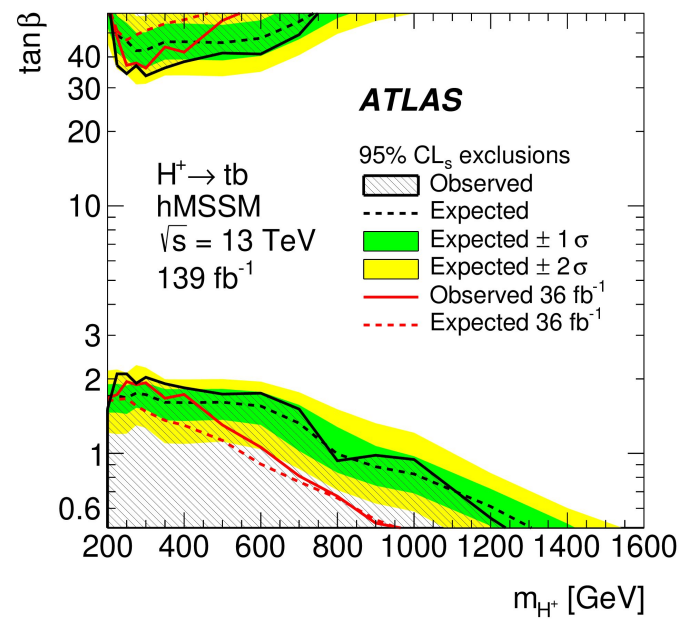




$tH^+b \rightarrow tbtb$ results

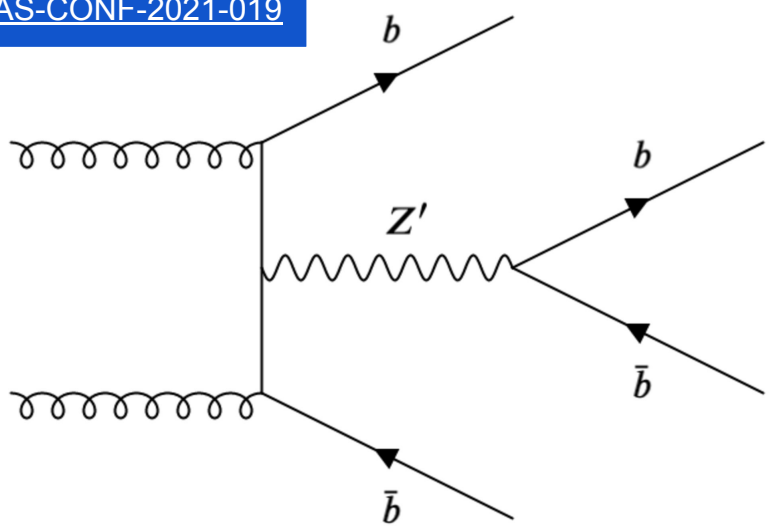
- Simultaneous fit to all **NN outputs** in the different regions
- Results as cross section "model independent" and interpreted in several models, **e.g.MSSM**

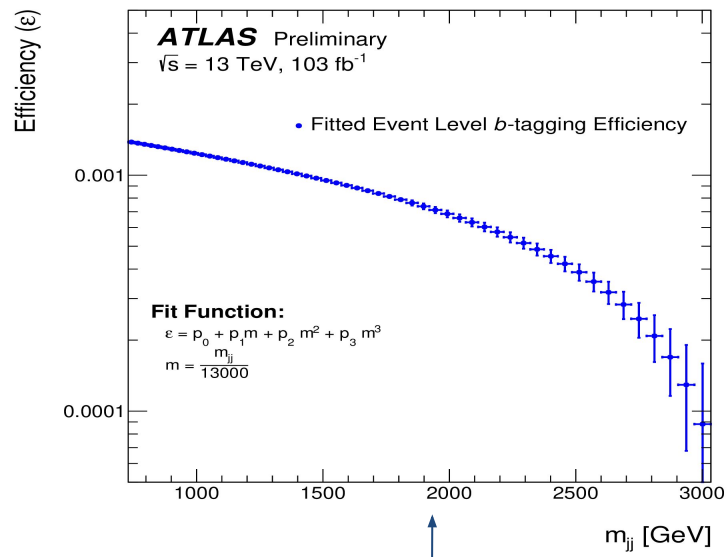




High b-jet multiplicity: Z'+bb production

ATLAS-CONF-2021-019





- **4 narrow (R=0.4) b-jet:**
  - multiple b-jet identification - or "tagging"
  - large QCD background
  - difficult to model with simulation

- **Modelling of background**
  - generating a pseudo-data sample based on untagged events x tagging efficiency
  - using a functional decomposition approach to get the m_{jj} spectrum

Probability of a pre-selected event passing b-tagging : used to generate pseudo-data for QCD model building

- **New tri-jet trigger**
  - asymmetric threshold, implemented from 2017 onwards
  - at least 250 / 250 / 120 GeV required on the jets' transverse energy

For heavy mediator searches, see also Claudio's talk

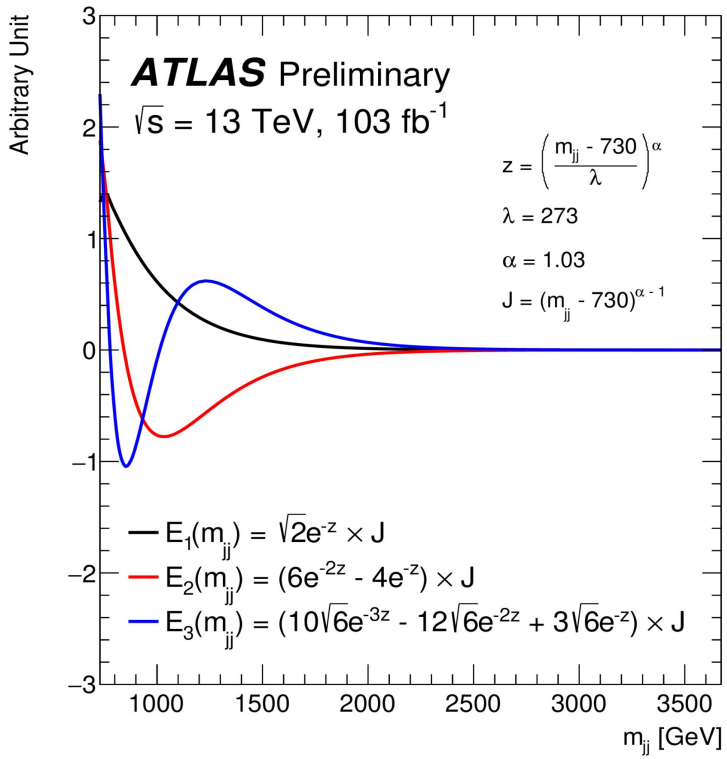
Multi-b-jet background estimate

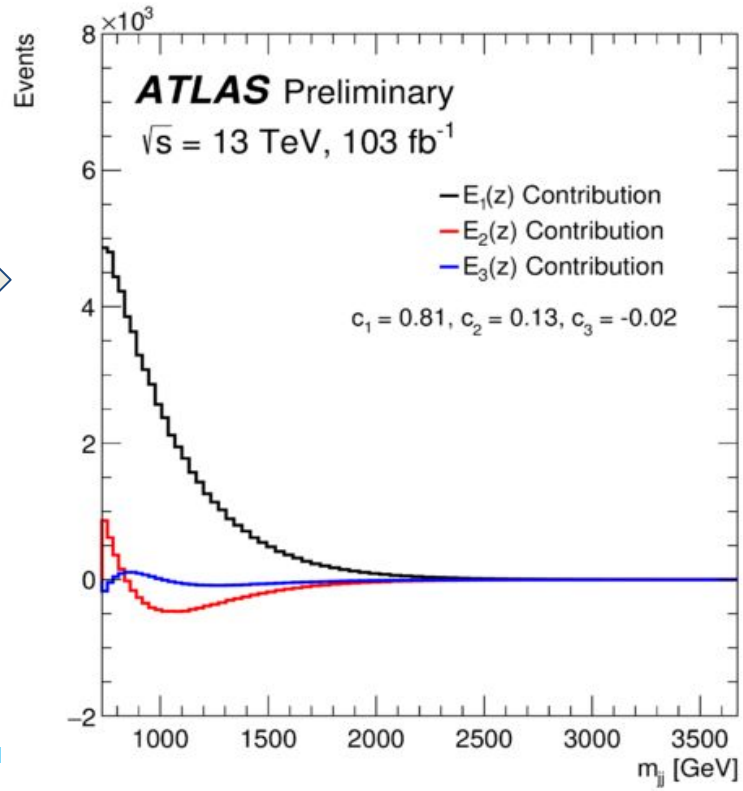
1) Transform the fit variable with a **power law**

$$z \equiv \left(\frac{m_{jj} - m_{jj}^{0}}{\lambda} \right)^{\alpha}$$

2) Spectrum in terms of momenta in a basis of exponential functions

$$\Omega(z) = \sum_{n=1}^{N} c_n E_n(z),$$

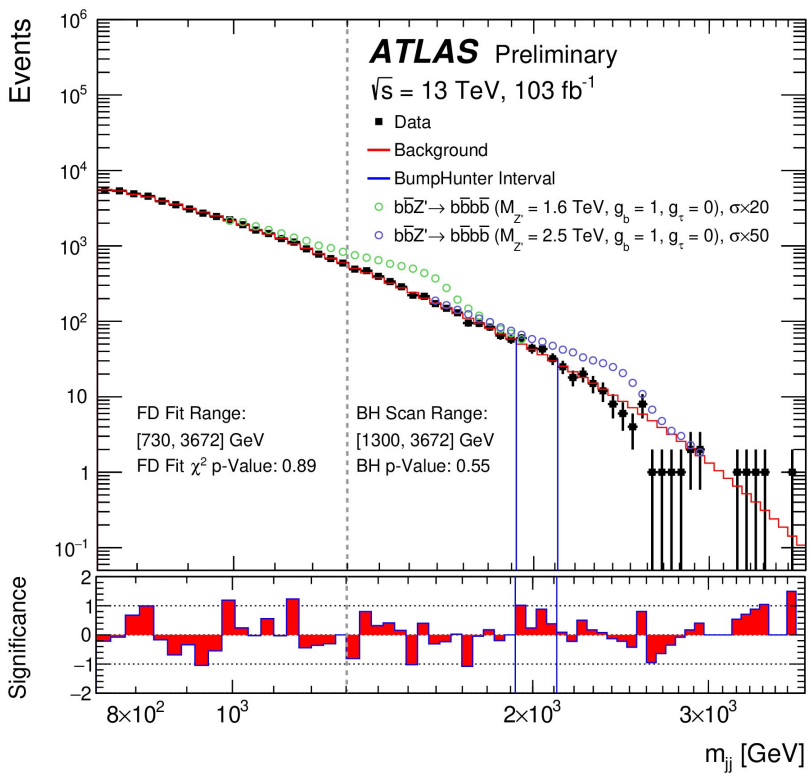


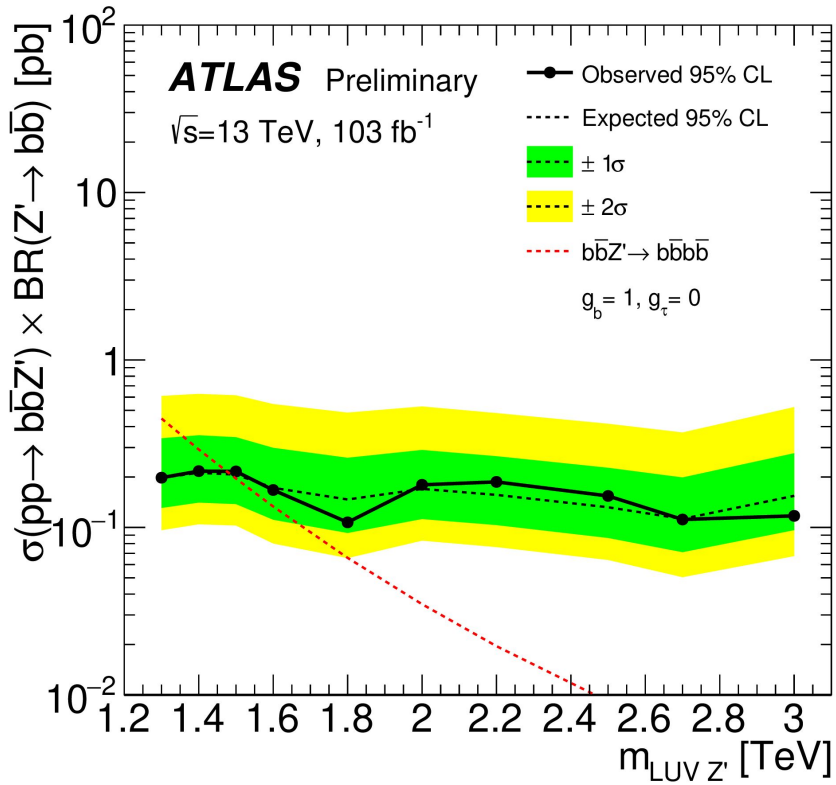


Multi-b-jet fit results

3) Search for the best N, α, and λ , limiting the number of moments to 4 to avoid overfitting - validated on the pseudo-datasets

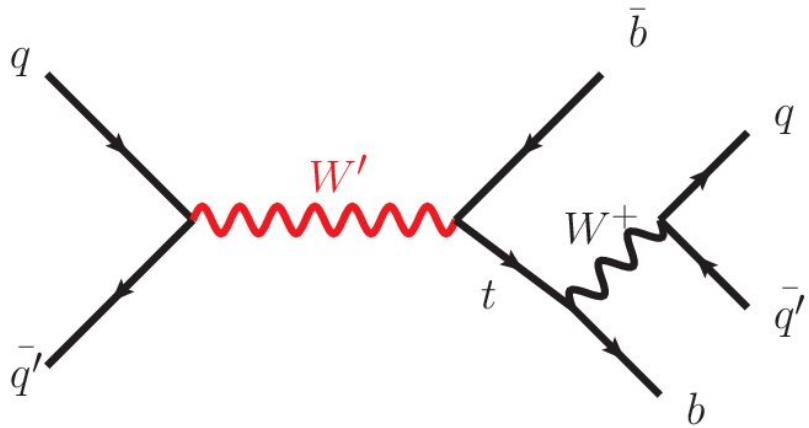
Interpreted in terms of a **Lepton Universality Violating** Z': coupling preferentially to third generation of fermions

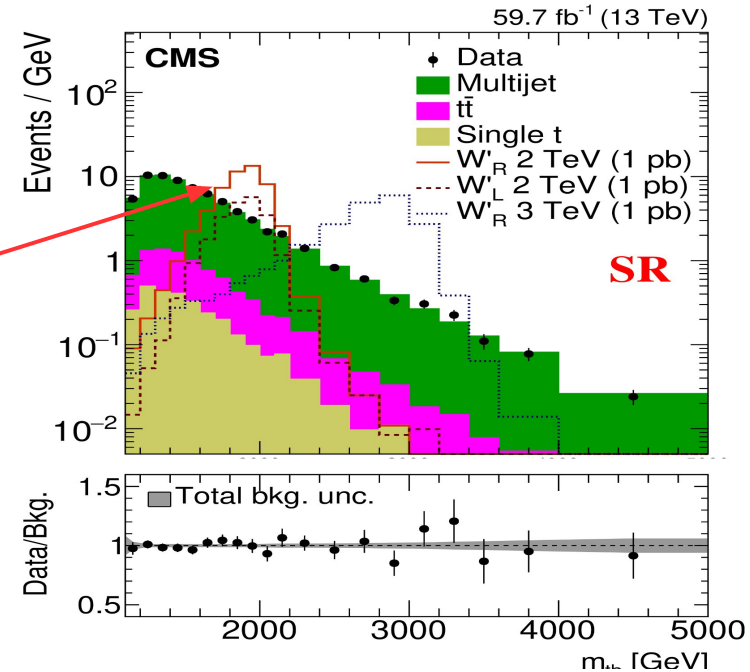




Heavy particles: W' → tb with SM interference

CMS B2G-20-005
arXiv:2104.04831



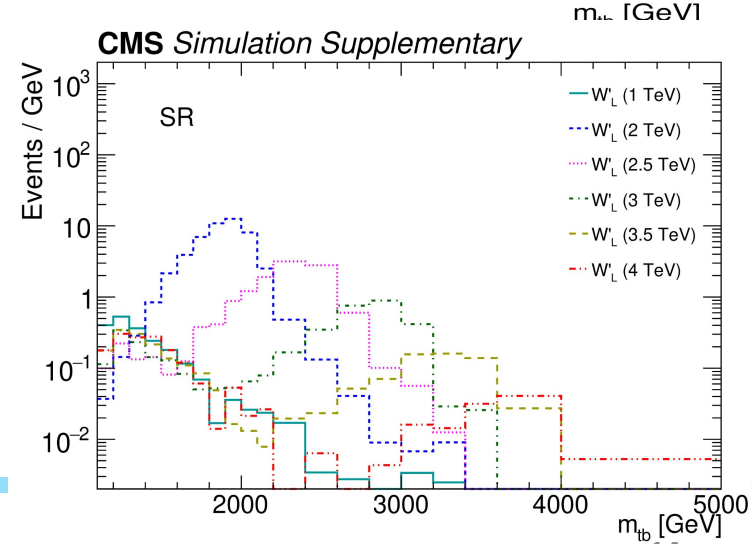


- A top quark and a b-quark reconstructed as:
  - 1 Large radius jet
  - 1 Narrow radius jet

- Identified via Deep NN algorithms

Main background:
multijet QCD, extracted from control regions

Signal can make **interference with SM s-channel**
→ shape includes non-resonant slope



For heavy mediator searches, see also Claudio's talk

Right vs Left-handed W' results:

- **Right-handed**:

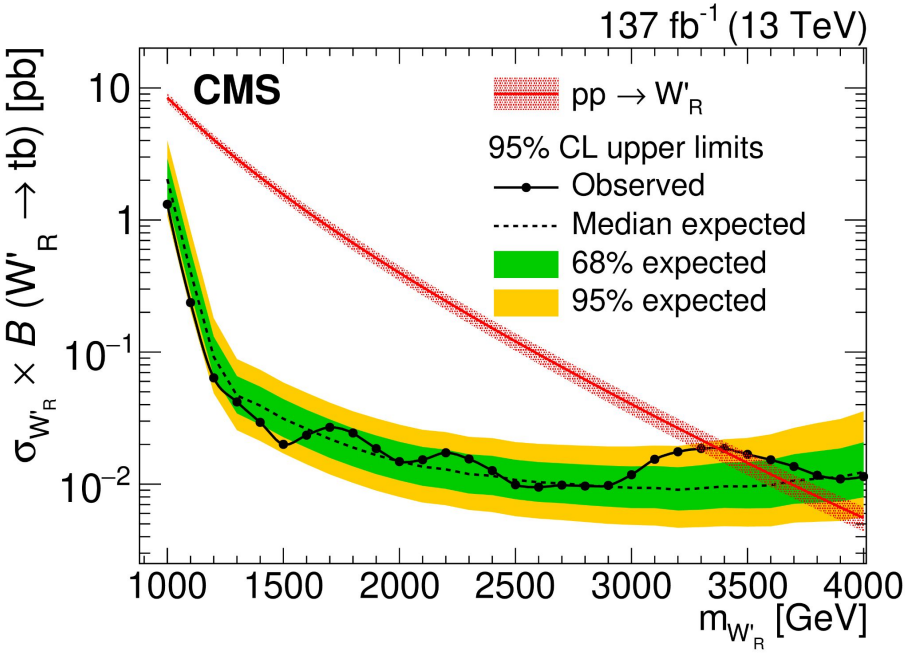
→ No SM interference

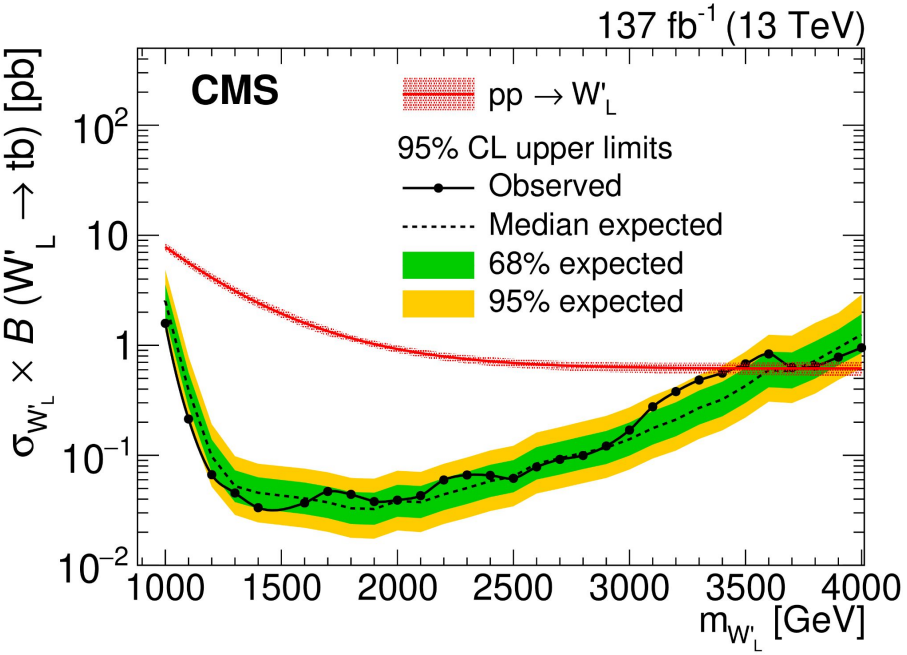
→ **Limits set at 3.4 TeV**

- **Left-handed**:

→ SM interference changes the scenario

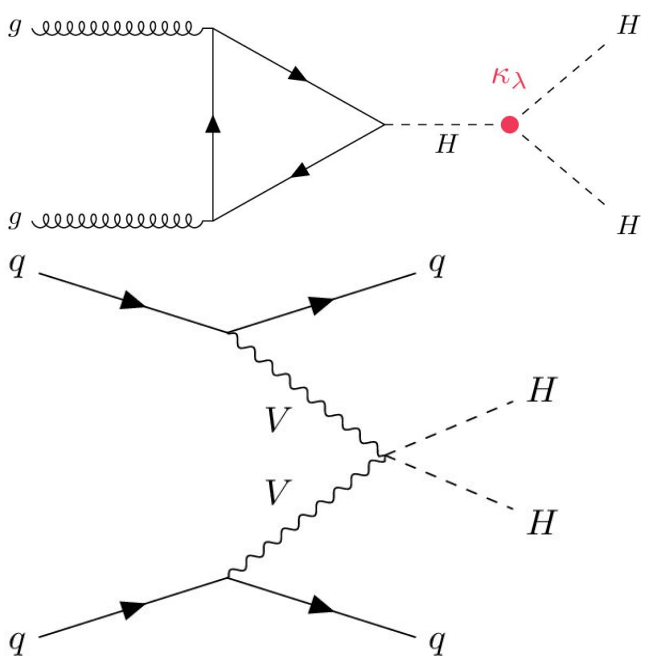
→ Still **driven by the presence** (or lack) of a resonant **peak**

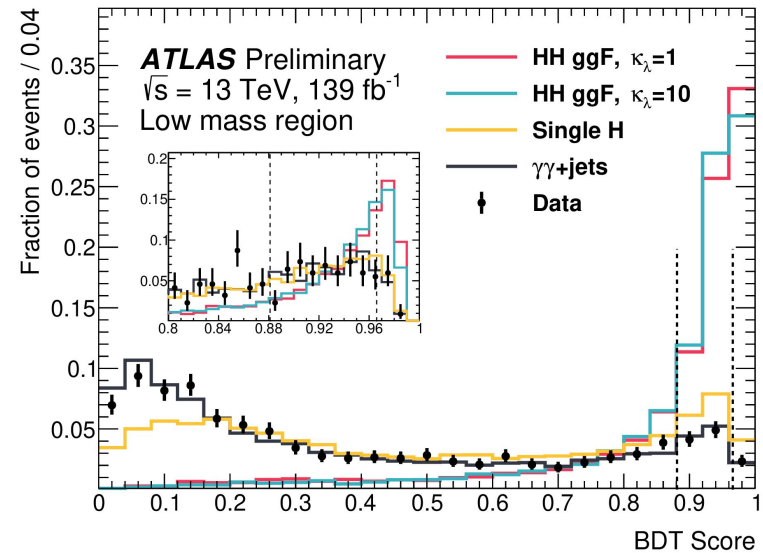


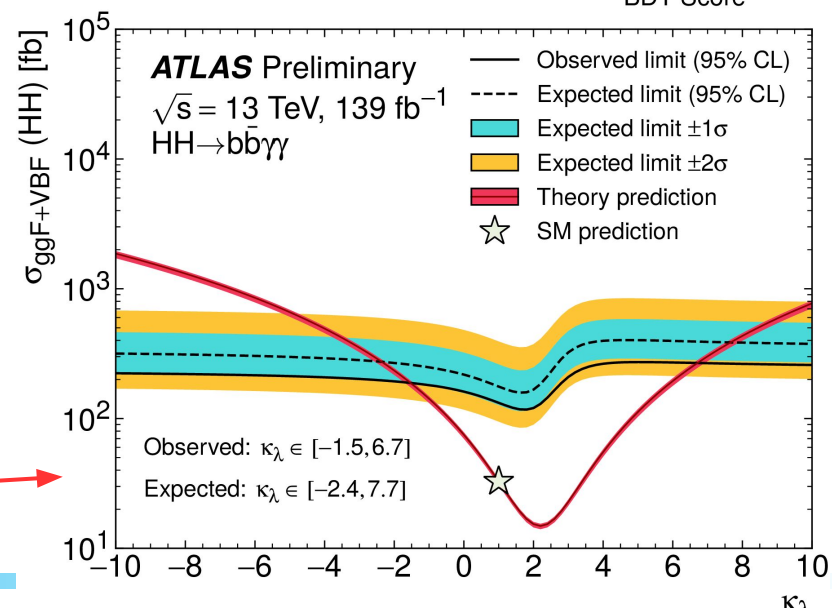


Nonresonant final states: HH → bb$\gamma\gamma$

ATLAS-CONF-2021-016







- Multiple possible models share similar signatures:
  - **Resonant [See next talk!]** or **Non resonant**
  - **VBF** or **Non-VBF**
- **BDT score** against backgrounds
- **di-photon mass** fit to extract the signal component

→ Limits in terms of trilinear coupling $k\lambda$
→ $k\lambda = \lambda_{HHH}/\lambda_{HHH,SM}$ in the range **[-1.5, 6.7]**

For di-higgs and dibosons, see also Antonis's talk
For higgs EFT, see also talks from Laura and Juan
For BSM Higgs searches, see also Junguan 's talk

Overview

- Varied phenomenology of hadronic final states studied at ATLAS and CMS
- We didn't even touch other like dark matter and SUSY searches or long-lived particles
- Both **model dependent** and **model independent analyses** are being considered
- **No significant deviation** from Standard Model was found
- These searches have proven to be **a forge for new ideas** for directions to search for and cutting edge technologies to investigate → especially bringing them into about Run 3 of LHC!

Thanks!

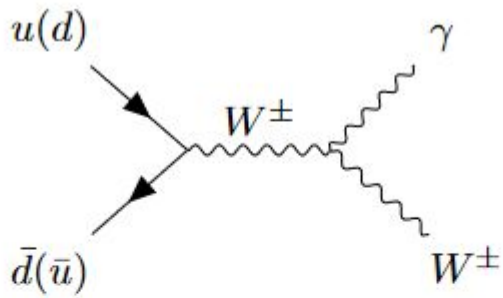
Backup

Other related talks and sessions

- For di-higgs and dibosons, see also Antonis's talk
- For BSM Higgs searches, see also Junquan 's talk
- For higgs EFT searches, see also talks from Laura and Juan
- For heavy mediator searches, see also Claudio's talk
- For top-quark related final states, see also Junpei's talk
- For VLQ-related final states, see also Timothy's talk
- Check out also dedicated sessions for Dark Matter and SUSY searches
- Fork long-lived particles searches, see also the dedicated session

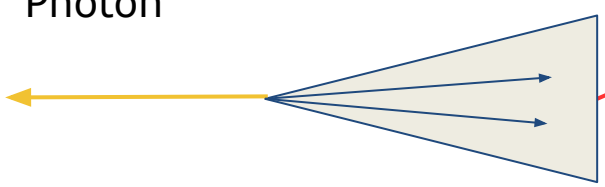
New final states: hadrons + photon

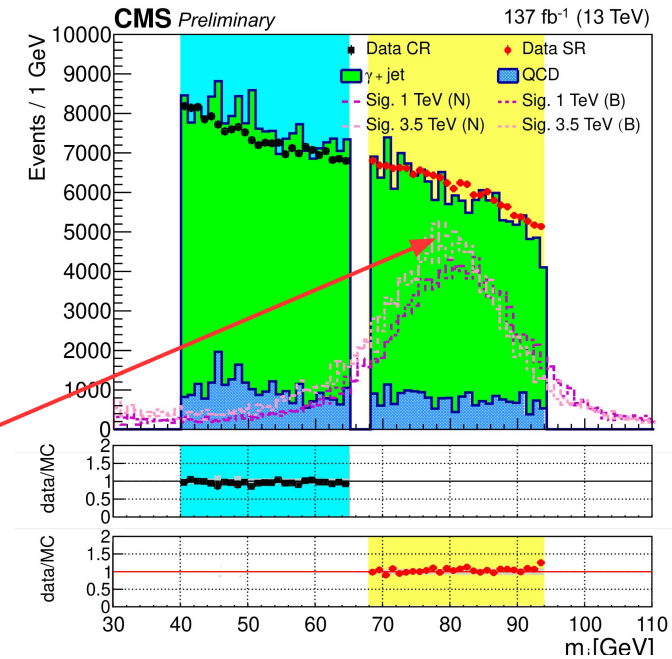
CMS-PAS-EXO-20-001

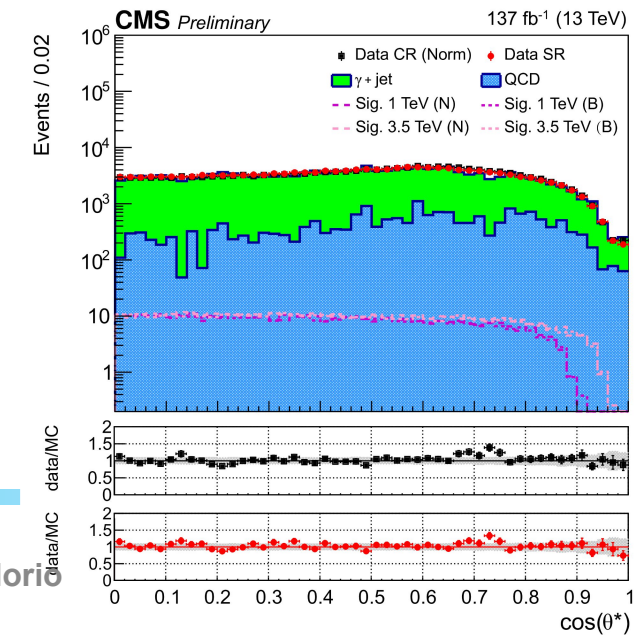


W boson → hadrons

Photon







- Production of exotic final state :
  - 1 Large radius jet J consistent with W/Z
  - 1 Photon recoiling against it

- Using soft drop mass

Selection variables:

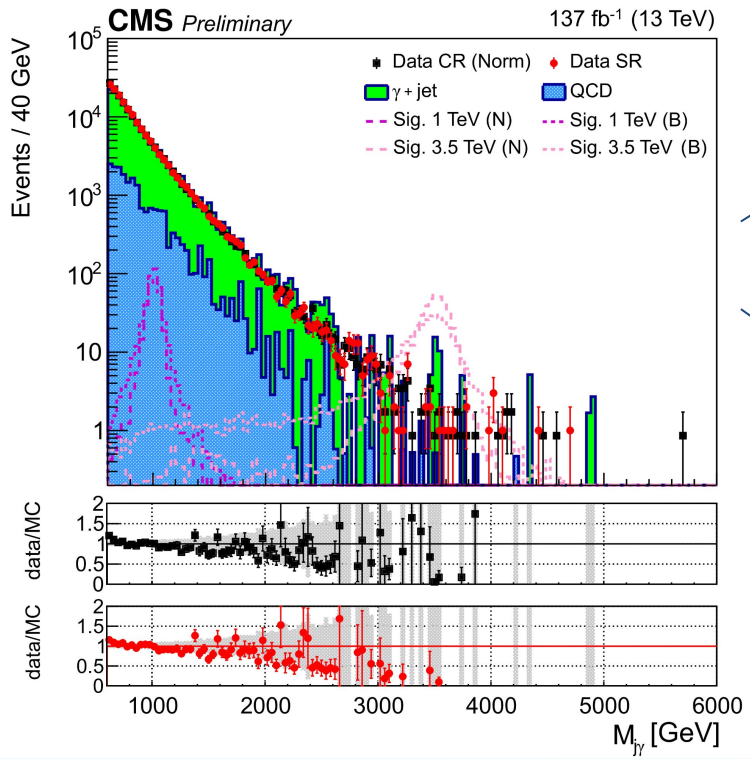
- Include spin sensitive variables like cos θ*:
  → polar angle in the $J\gamma$ system

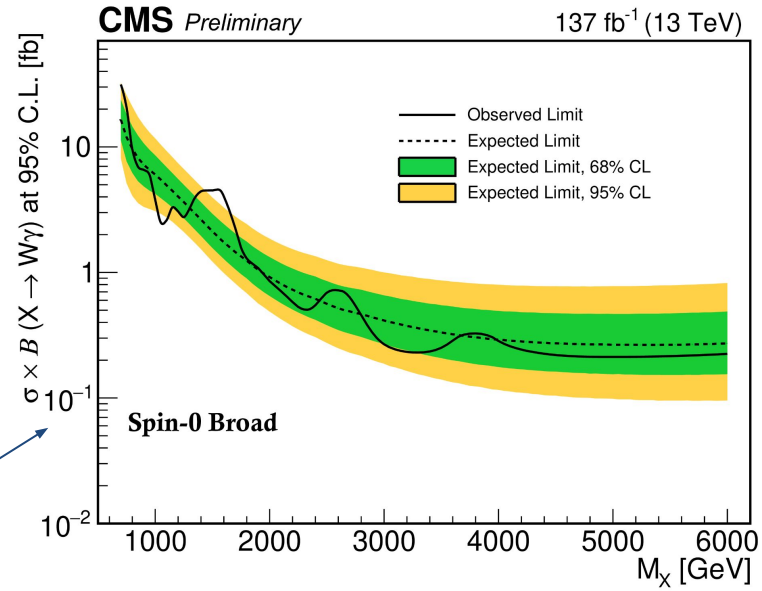
New final states: hadrons + photon

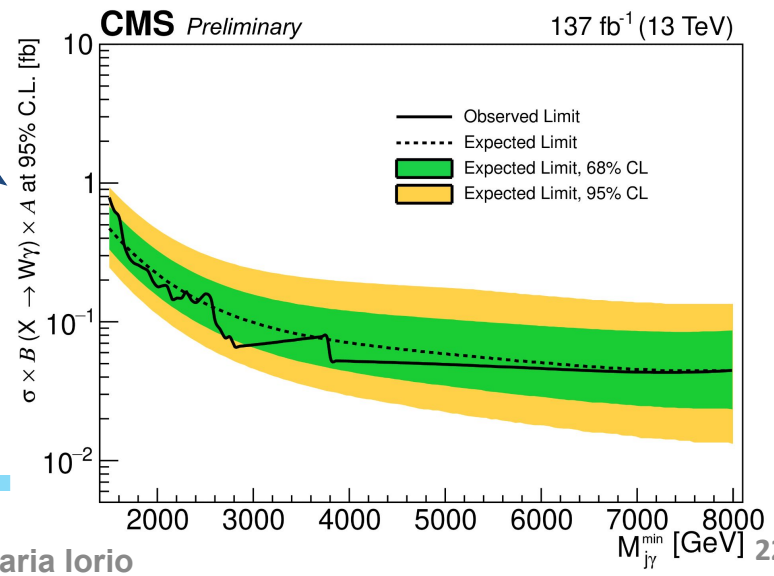
- mass scan:

→ **Model dependent**: fitting the mass peak

→ **Model-independent**:
event counting in the mass range



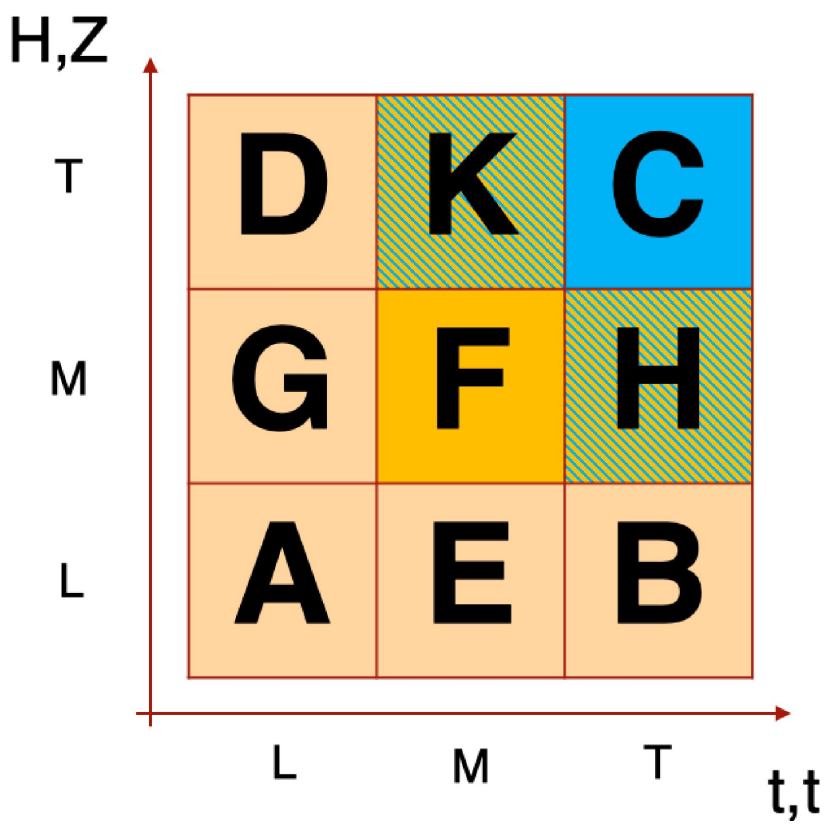




CMS-PAS-B2G-20-002

W' → tH(Z)b: control regions

- **Higgs/Z** double b-tagger **vs** **top quark image tagger** : different working points used



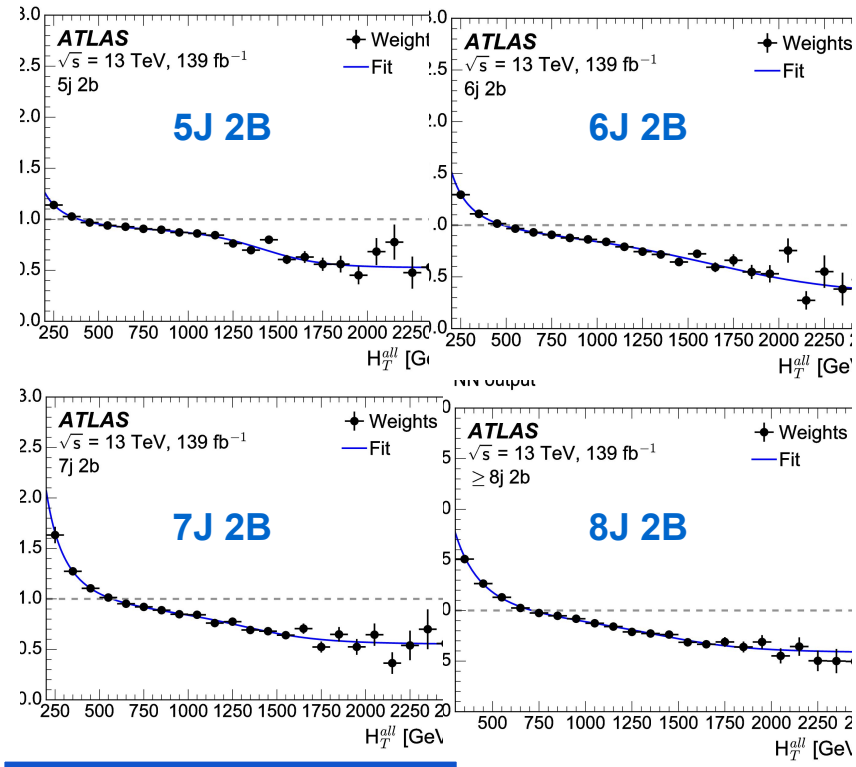
- Signal region is **region C** ;
- Scale factors from **regions A → B and applied onto region D**
- Validation regions:

$$TF(p_T,\eta) \equiv (B_{data} - B_{t\bar{t}})/(A_{data} - A_{t\bar{t}}),$$
$$TF_v(p_T,\eta) \equiv (E_{data} - E_{t\bar{t}})/(A_{data} - A_{t\bar{t}}),$$
$$C_{qcd} \simeq (D_{data} - D_{t\bar{t}}) \times TF(p_T,\eta),$$
$$H_{qcd} \simeq (G_{data} - G_{t\bar{t}}) \times TF(p_T,\eta),$$
$$K_{qcd} \simeq (D_{data} - D_{t\bar{t}}) \times TF_v(p_T,\eta),$$
$$F_{qcd} \simeq (G_{data} - G_{t\bar{t}}) \times TF_v(p_T,\eta).$$

Multiple jet regions

- Reweighting the **HT distribution**
- Separately per each jet bin

→ Difference reduces to an overall yield effect



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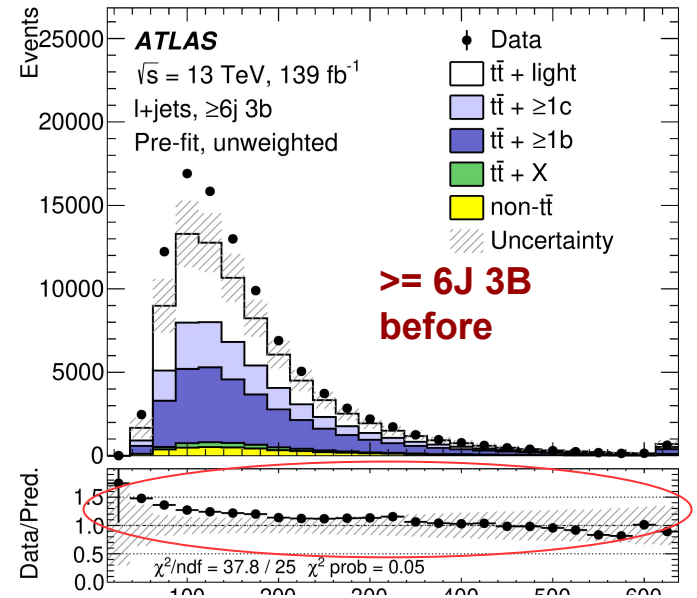

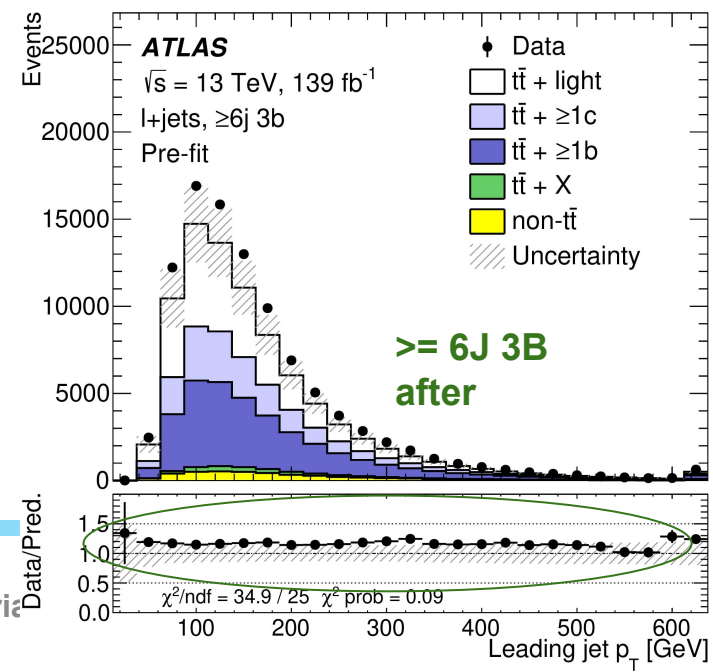

CMS B2G-20-005
arXiv:2104.04831

W' → tb control regions

Jet	Variable	SR	VR	CR1	CR2
t	m_{SD}	$\in [105, 210]$ GeV	$\in [105, 210]$ GeV	<105 GeV	<105 GeV
t	t tagging	pass	fail	pass	fail
b	b tagging	pass	pass	pass	pass

Jet	Variable	SR′	VR′	CR1′	CR2′
t	m_{SD}	$\in [105, 210]$ GeV	$\in [105, 210]$ GeV	<105 GeV	<105 GeV
t	t tagging	pass	fail	pass	fail
b	b tagging	fail	fail	fail	fail

- Get transfer function from fitting control regions

$$R^1_{p/f}(m_{tb}) = \frac{CR1}{CR1'},$$
$$R^2_{p/f}(m_{tb}) = \frac{CR2}{CR2'}.$$

- Ratios fitted with bifurcating function

$$\text{Multijet background in SR} = f^1_{p/f}(m_{tb})\ SR';$$
$$\text{Multijet background in VR} = f^2_{p/f}(m_{tb})\ VR'.$$

Validation done in **VR** and **simulation**

→ Additional corrections given by the difference between Data-Driven and MonteCarlo prediction from QCD

Multi-b-jet fit

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$$\Omega(z) = \sum_{n=1}^{N} c_n E_n(z),$$

- First three terms :

$$E_1(z) = \sqrt{2}e^{-z},$$
$$E_2(z) = 6e^{-2z} - 4e^{-z},$$
$$E_3(z) = 10\sqrt{6}e^{-3z} - 12\sqrt{6}e^{-2z} + 3\sqrt{6}e^{-z}.$$

- Search for the best N, α, and λ minimizing

$$\mathcal{L} = D_{\mathrm{KL}}(\tilde{\mathbf{f}} \parallel \tilde{\mathbf{c}}) + D_{\mathrm{KL}}(\tilde{\mathbf{c}} \parallel \tilde{\mathbf{p}}),$$

- Where those are the Kullback-Lieber divergencies

$$D_{KL}(f \,||c\,) = \int f(x)\, log\frac{f(x)}{c(x)}dx$$

For M events with N terms:

$$D_{\mathrm{KL}}(\tilde{\mathbf{c}} \parallel \tilde{\mathbf{p}}) \approx \frac{N}{2}(\ln M - \ln N - 1),$$