Search for low and high mass mediators in ATLAS and CMS with dijet and dilepton events

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LHCP2022: 10th Annual Large Hadron Collider Physics Conference, 16-21 May 2022, Virtual (Taiwan)

Outline

- Brief Introduction and Motivation

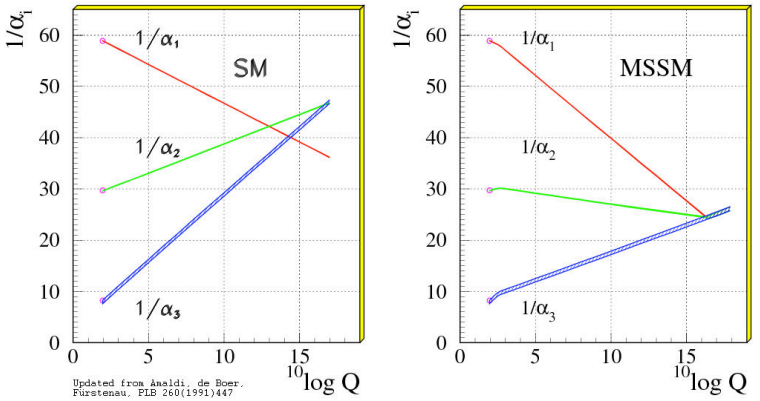
- Hunting for New Mediators@LHC :
  - Decaying to jets
  - Decaying to leptons

  ***(selected recent Run II** results will be shown):*

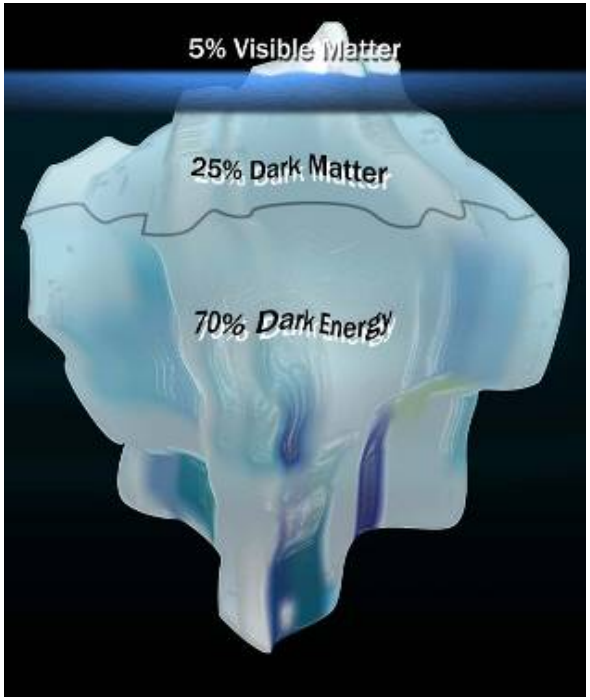
- Summary - Outlook

Introduction : SM is incomplete

- **Hierarchy Problem :** *Why is $M_{Pl}/M_{EW} \sim 10^{15}$.*
- **Unification of Gauge couplings** *: Why are gauge couplings so different, are they unified at a higher scale? Are there more forces in nature?*



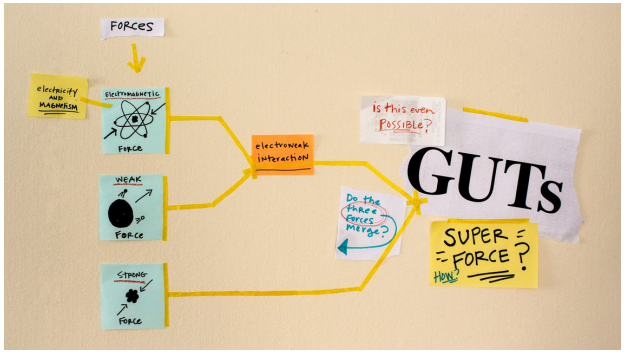
- **Origin of generations :** *Why do quarks and leptons come in three generations? Are they elementary particles?*
- **Gravity :** *SM describes three of the four fundamental interactions at the quantum level (microscopically) but gravity is only treated classically.*



- **Dark matter :** *What is 25% of the Universe made off, and how does it interact with ordinary matter?*
- **Neutrino masses :** *What is the origin of neutrino masses?*
- ***CP Violation :*** *What is the origin?*

New Mediators from a variety of BSM Models

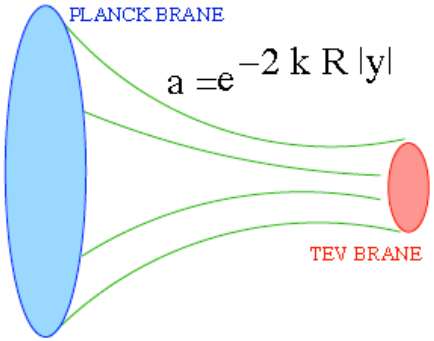
Grand Unified Theories



Extended gauge group models

SU(3) x SU(2) x U(1)

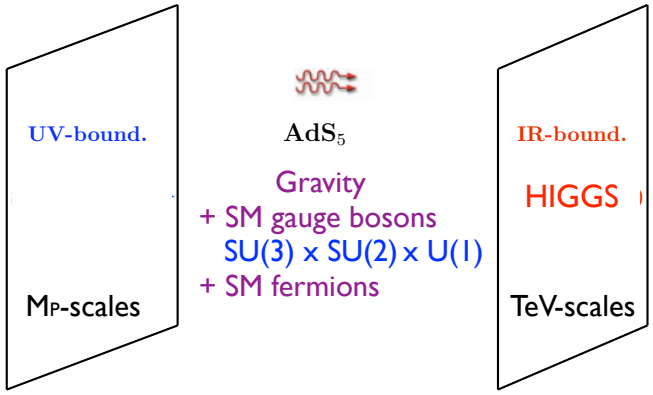
$W' \rightarrow q\bar{q}\,, Z' \rightarrow q\bar{q}\ (\bar{l}l)$



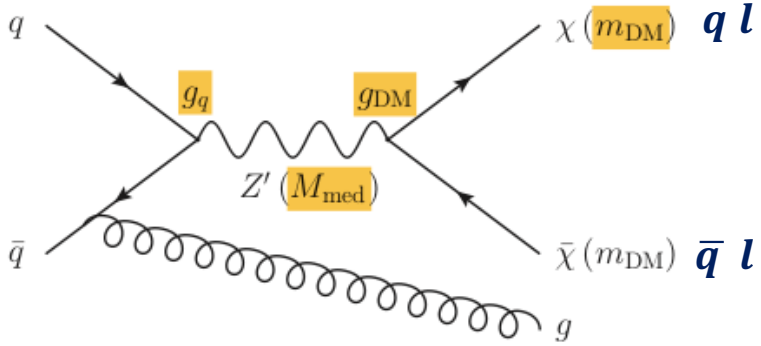
Randall-Sundrum **Graviton G**

$q\bar{q}, gg \rightarrow G \rightarrow q\bar{q}, gg$

Vector-like quarks in Little/Composite Higgs Models to solve the Hierarchy Problem

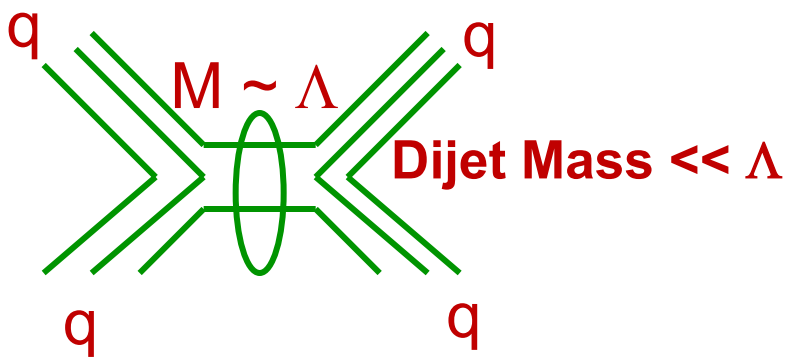


Dark Matter Mediators Leptophilic or leptophobic



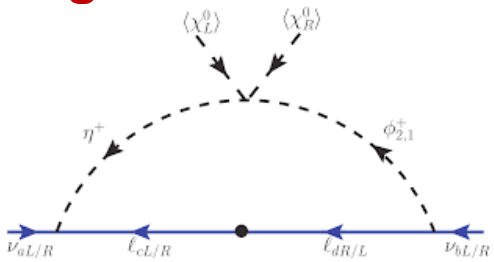
New Mediators from a variety of BSM Models

Quark Compositeness



Excited quarks $qg \rightarrow q^* \rightarrow qg$

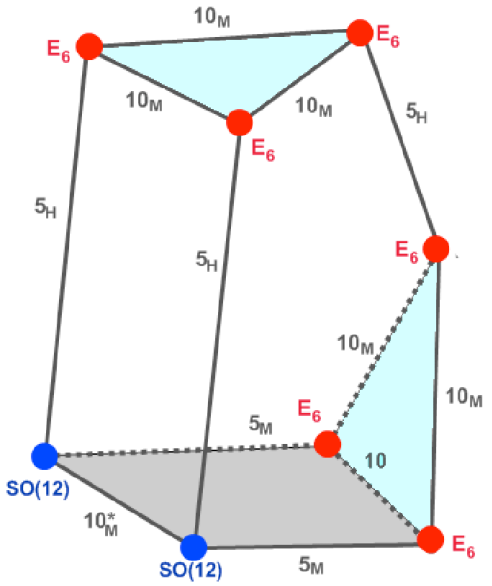
Left-Right extensions of the SM explaining the smallness of ν masses



$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

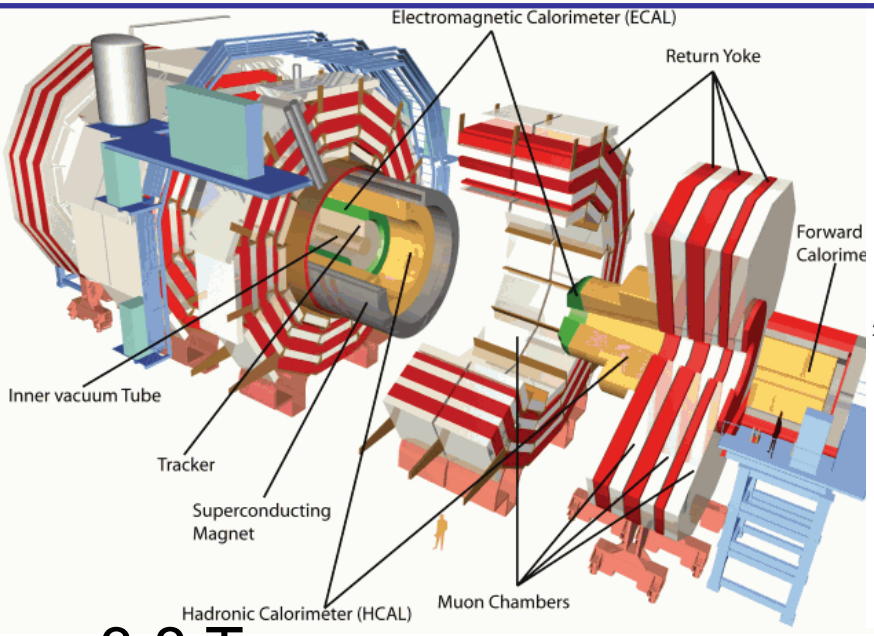
Doubly charged Higgs $H^{++/--} \rightarrow l^+ l^-$

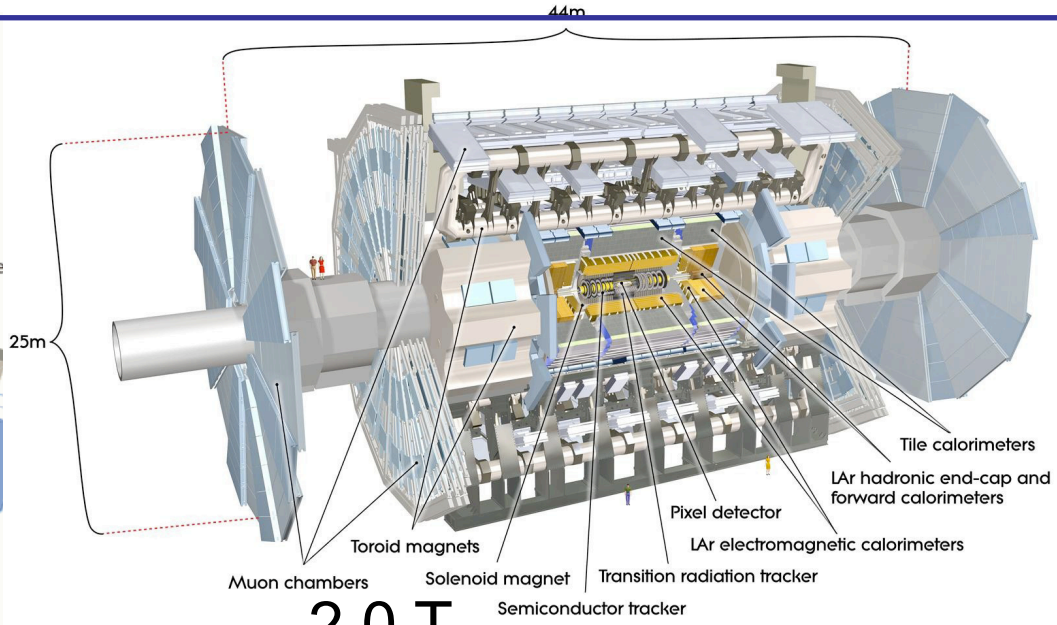
Scalar diquarks in renormalizable BSM theories



E6 GUT models contain
Scalar diquarks $qq \rightarrow D \rightarrow qq$

ATLAS and CMS Experiments





3.8 T

Pixels

$\sigma(p_T)/p_T \sim 1.5 \cdot 10^{-4} p_T(\text{GeV}) \oplus 0.005$

Electromagnetic Calorimeter

$\sigma(E)/E \approx 2.9\%/\sqrt{E(\text{GeV})} \oplus 0.5\% \oplus 0.13\text{GeV}/E$

Hadronic Calorimeter

$\sigma(E)/E \approx 120\%/\sqrt{E(\text{GeV})} \oplus 6.9\%$

Muons

$\sigma(p_T)/p_T \approx 1\%$ for low pT muons

$\sigma(p_T)/p_T \approx 5\%$ for 1 TeV muons

2.0 T

Pixels,Si strips & Straw tubes

$\sigma(p_T)/p_T \sim 3.8 \cdot 10^{-4} p_T(\text{GeV}) \oplus 0.015$

Electromagnetic Calorimeter

$\sigma(E)/E \approx 10\%/\sqrt{E(\text{GeV})} \oplus 0.7\% \oplus 0.2\text{GeV}/E$

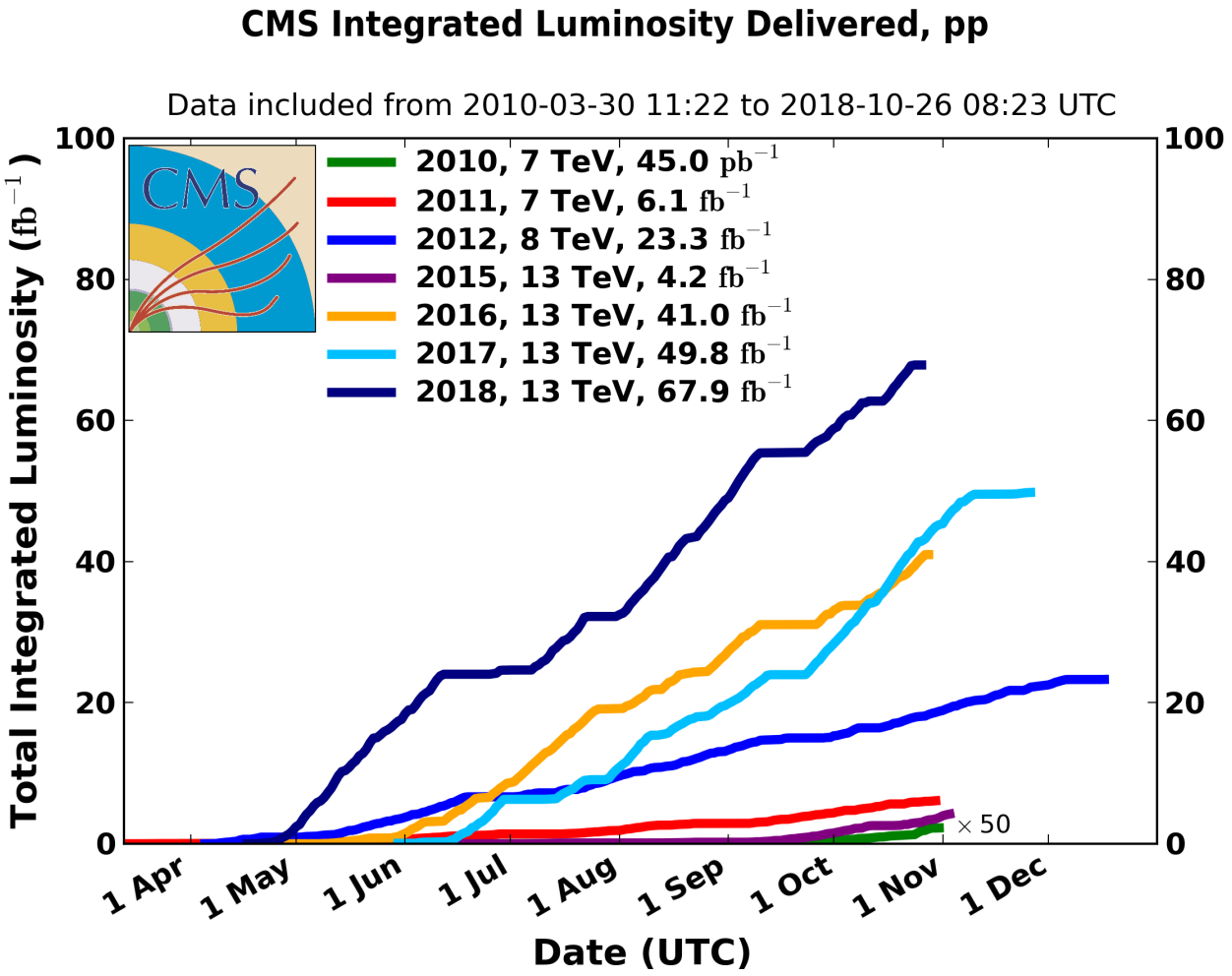
Hadronic Calorimeter

$\sigma(E)/E \approx 60\text{-}100\%/\sqrt{E(\text{GeV})} \oplus 3\%$

Muons

$\sigma(p_T)/p_T < 10\%$ up to 1 TeV muons

The LHC Accelerator



LHC Accelerator had so far a superb performance.
Expecting the same in Run III

Mediators Decaying to Leptons

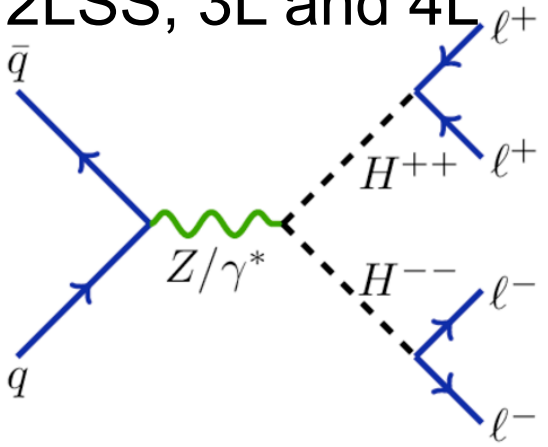
Dilepton Search for doubly charged Higgses

- **Main Experimental Signature :**
  - **≥2 leptons (2LSS,3L,4L)** satisfying **quality selection criteria.**
  - **Control (CR), Validation (VR), Signal regions (SR) defined. CR, VR and SRs** determined using the **invariant mass** of the **two same-charge** leptons with the **highest pT** .
- **Main backgrounds:**
  - **SM Diboson production estimated from simulation,** and events with **fake leptons** coming mostly from **V+jets/gamma production estimated from data.**

ATLAS EXOT-2022-010

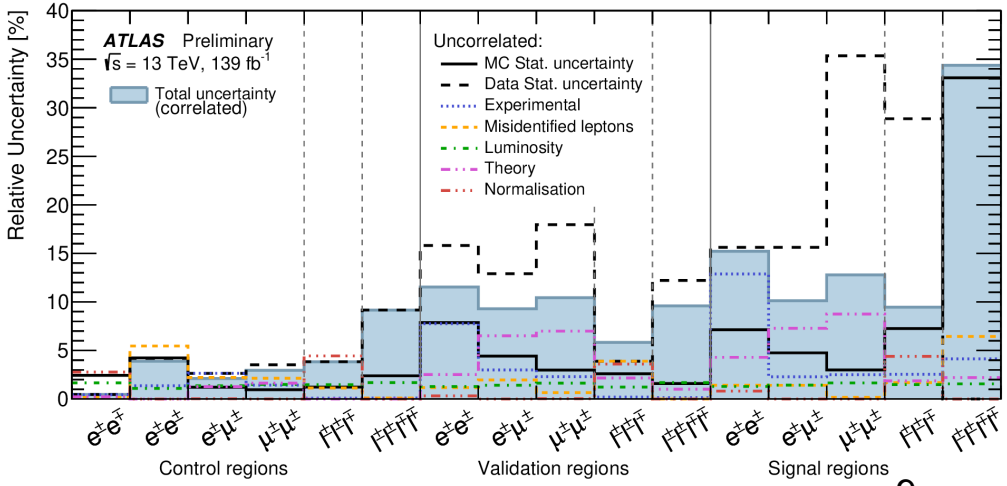
Final State

2LSS, 3L and 4L



- **Signal Model:**
  - **Left-right symmetric (LRS) models** based on $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ symmetry, **where doubly charged Higgs bosons composes the $SU(2)_{L,R}$ gauge boson triplet.**

Uncertainties

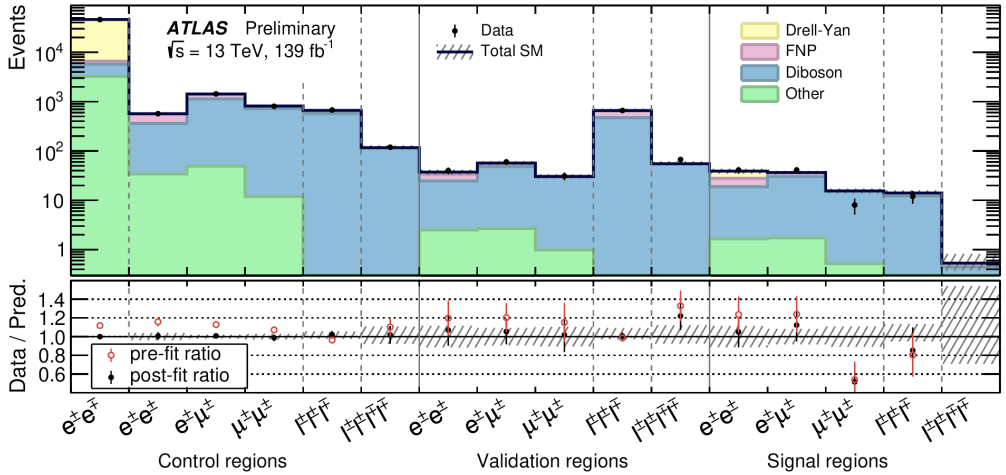


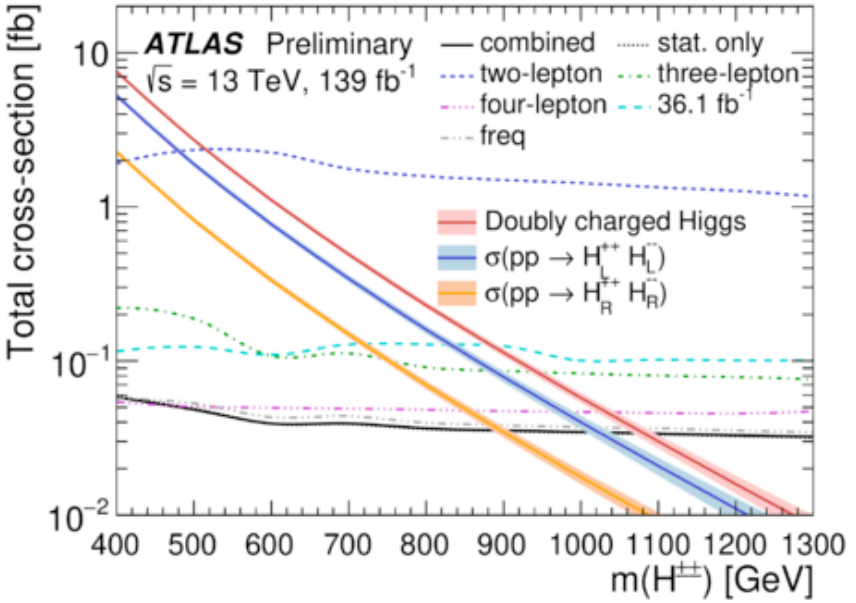
Results and Interpretations

ATLAS EXOT-2022-010

- Maximum likelihood fit in the dilepton mass performed **in the three SRs**
  - **Signal (simulation)** and **background** (simulation and data-driven) **templates** utilized, and **systematics** encoded as **nuisance parameters.**
  - **Profile likelihood ratio** is the **test statistic** for **limit estimation.**

Event Yields





- **Reach extended by 300 GeV with respect to the previous** results:
  - **Lepton flavour violation (LFV)** decays **allowed** connecting **high energy searches** at LHC with **low energy neutrinoless double beta decay ones.**
  - The **search is broad** and the results can **be interpreted** in **several BSM scenarios.**

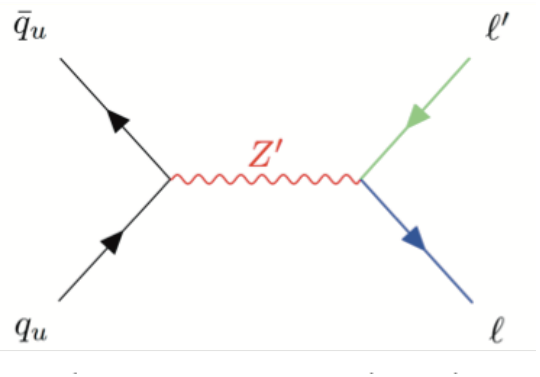
Dilepton Search for LFV Z'

- **Main Experimental Signature :**
  - **≥1 prompt, isolated light lepton** (electron or muon) and **≥1 prompt, isolated τ_h .**

- **Main backgrounds:**
  - **ttbar, diboson, Z, Wγ**. Estimated from **simulation** and with **data-driven methods** for the **multijet** and **W+jets** ones.

CMS-EXO-2019-014

Final State



- **Signal Model:**
  - Addition of **an extra U(1)** gauge symmetry provides a **massive Z' with LFV eμ, eτ, and μτ final states.**

Observable

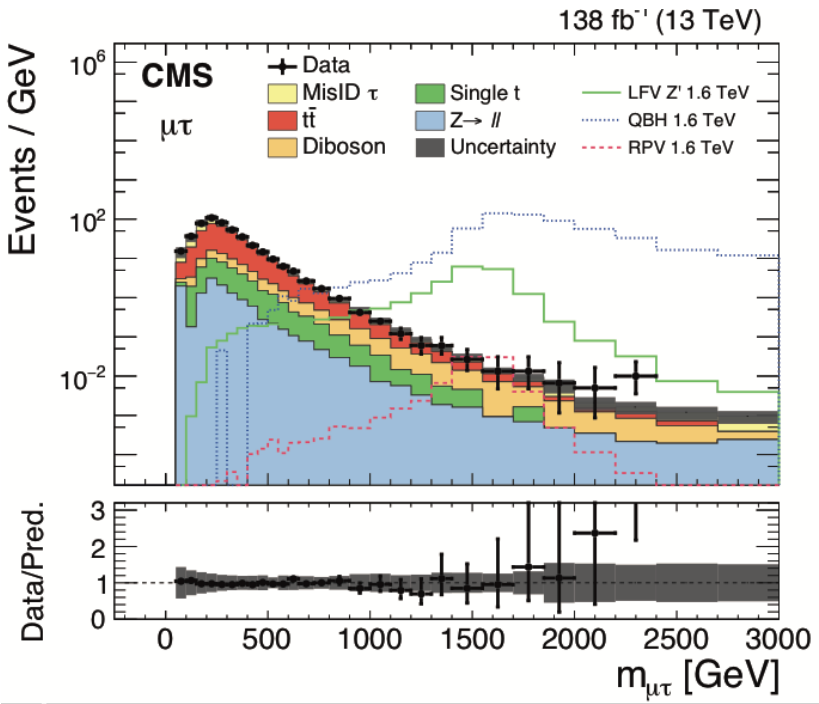
$$x_\tau^{\text{vis}} = p_{\text{T}}^{\text{vis}} / \left(p_{\text{T}}^{\text{vis}} + p_{\text{T, coll}}^{\text{miss}}\right)$$

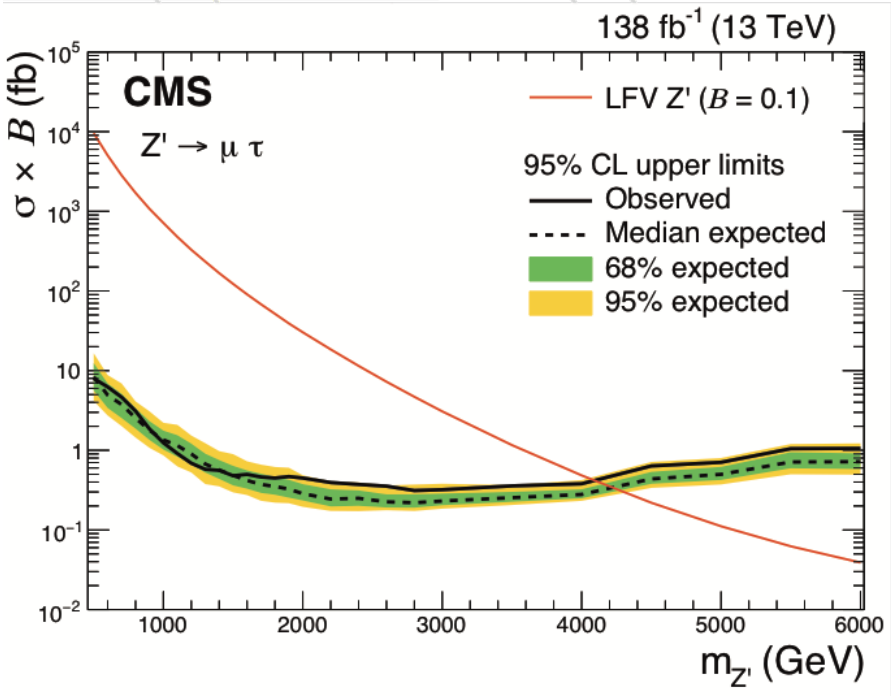
$$m_{\text{coll}} = m_{\text{vis}} / \sqrt{x_\tau^{\text{vis}}}$$

Results and Interpretations

- **Bayesian binned-likelihood utilized,** with a **uniform positive prior probability density** for the signal cross section. **Nuisance parameters** modeled **via log-normal** distributions for **normalization and via "template morphing" for shape**. A **Markov Chain MC metho**d is used for the integration.

CMS-EXO-19-014



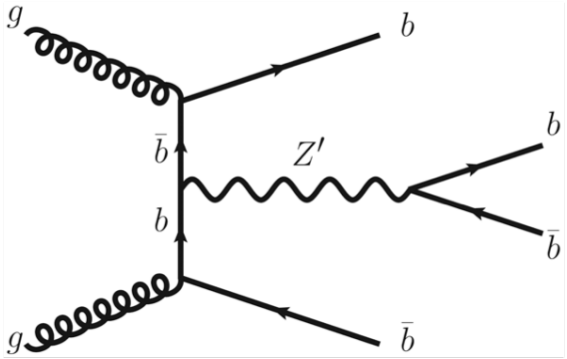


- These are the **first results** of a **high-mass lepton flavor violation search** using the full Run II dataset. All results of this search are currently **the most stringent limits from any collider experiment.**

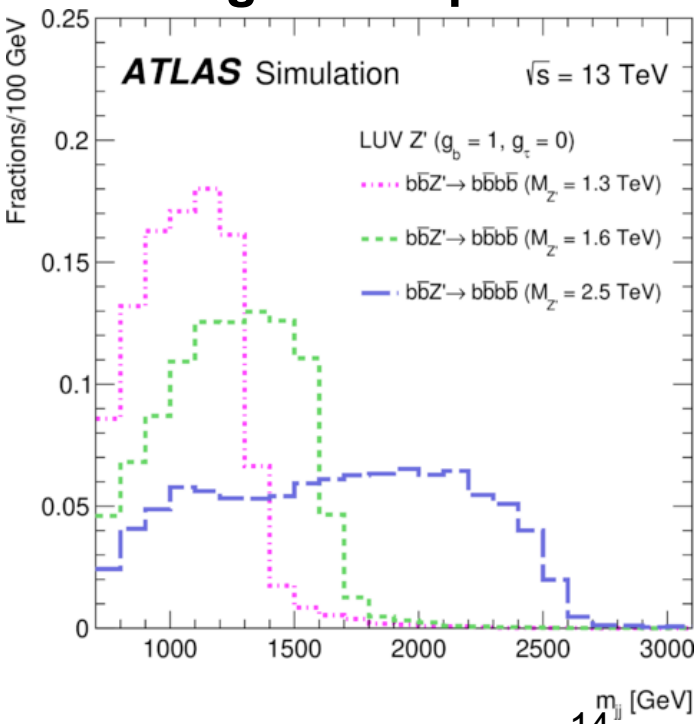
Mediators Decaying to Jets

Di-b-jet Search

- **Data-sets :** PHYSICAL REVIEW D 105, 012001 (2022) **Final State**
  - **New trijet trigger** deployed in 2017, **extending search by 100 GeV.**
- **Main Experimental Signature :**
  - **Four-jet final state**, the two **leading jets** are **b-tagged** and either the third or the fourth one as well **to reduce QCD backgrounds.**
  - Deep ANN used for b-tagging **improving performance at high pT**.
- **Main backgrounds:**
  - **QCD estimated in a data-driven way** using functional decomposition with truncated series.
- **Signal Model:**
  - **Lepton Universality Violating Z'** exclusively **coupled** to the **3rd generation** SM fermions.

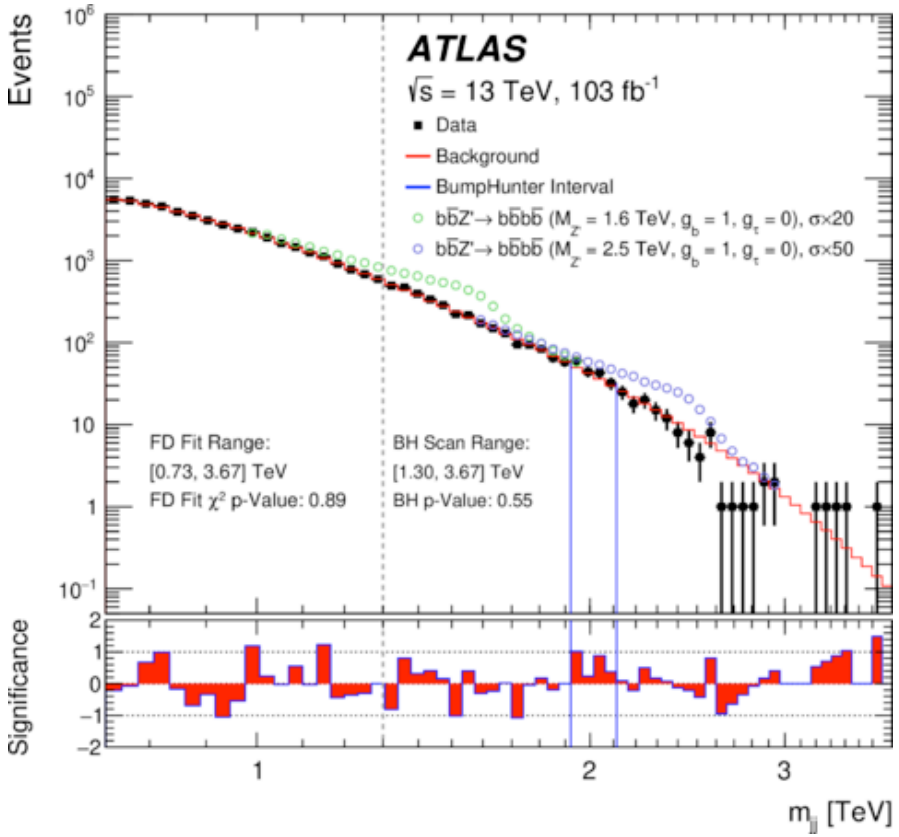


Signal Shapes

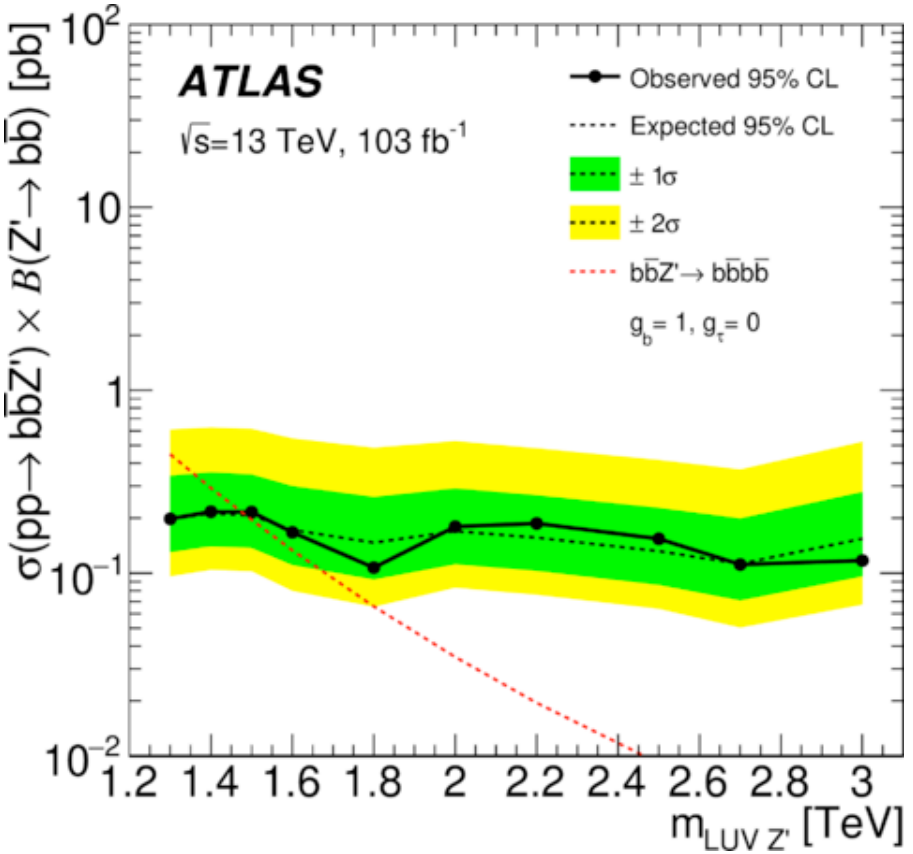


Results & Interpretations

- Maximum likelihood fit performed
  - **Signal (simulation)** and **background (data-driven prediction) templates** utilized, and **systematics** encoded as **nuisance parameters.**
  - **Profile likelihood ratio** is the **test statistic** for **limit estimation.**



ATLAS EXOT-2018-09



- This **model,** which can **address b-physics "anomalies"** is compared with **data** for **the first time.**

Di-b-jet Search

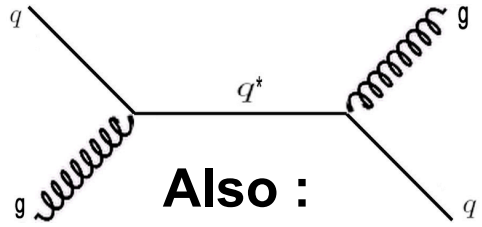
CMS-EXO-20-008

- **Main Experimental Signature :**
  - Two **large-radius (wide) resolved jets,** with **at least one b-tagged. Three Signal Regions, 1 b-tagged jet, 2 b-tagged jets, 1 jet containing a muon** for **Z', ≥1 b-tagged jet for q***

- **Main backgrounds**
  - **Multijet QCD production** estimated with a **data-driven approach, using a parametric functional form.**

- **Signal Model:**
  - **Sequential Standard Model generalized with a Heavy vector triplet** (HVT) **Z', Compositeness** with scale **Λ equal** to the **resonance mass, generic resonances & model independent limits.**

Final States

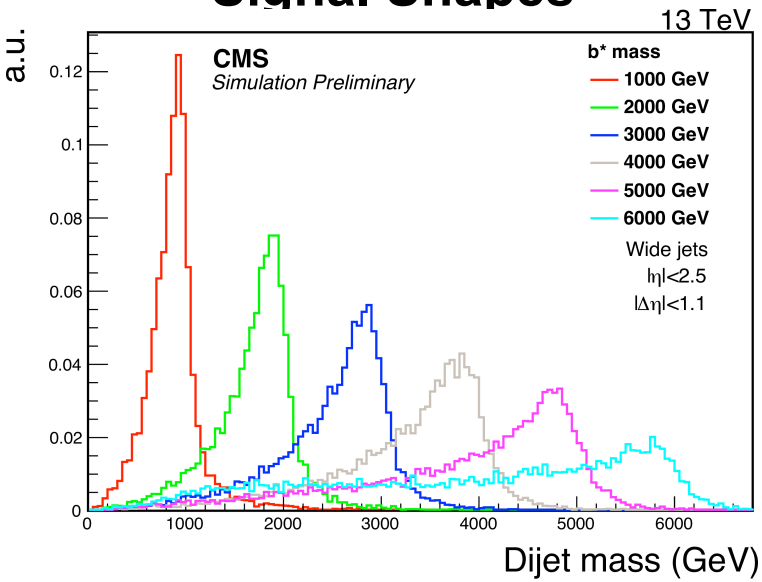


Also :

$$q\bar{q} \rightarrow b^{*}\bar{b}(b\bar{b}^{*}) \rightarrow b\bar{b}g$$

$$\mathbf{Z'} \rightarrow b\bar{b}$$

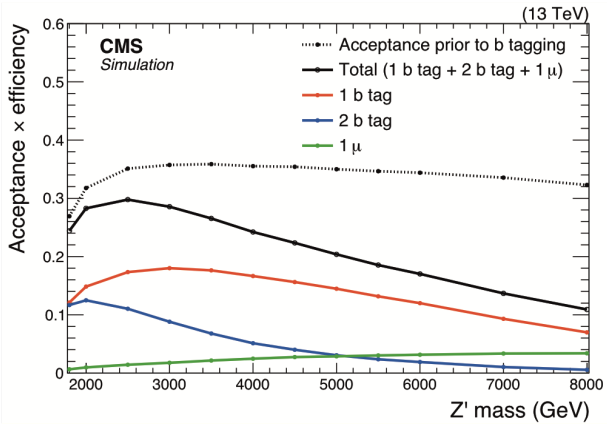
Signal Shapes

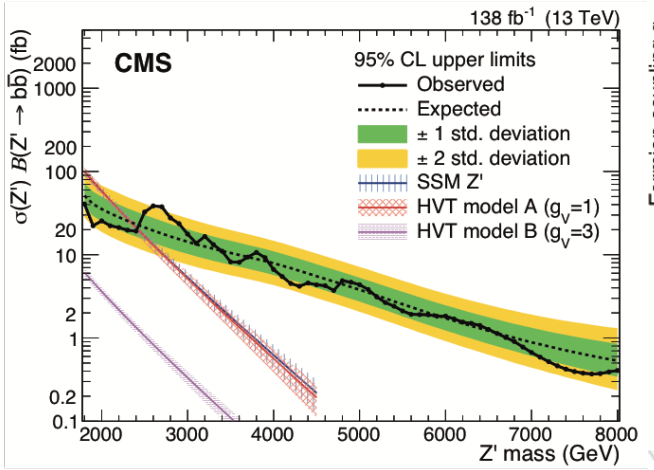


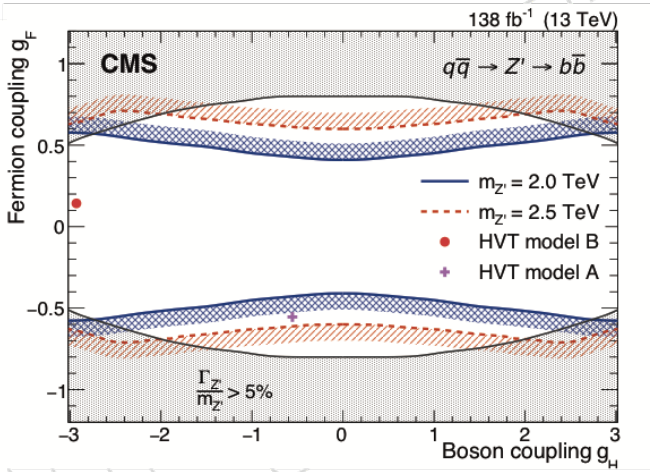
Results and Interpretations

- Maximum likelihood fit in the dijet mass performed **in the SRs**
  - **Signal (simulation)** and **background (data-driven prediction) templates** utilized, and **systematics** encoded as **nuisance parameters.**
  - **Profile likelihood ratio** is the **test statistic** for **limit estimation.**

CMS-EXO-20-008







- **New HVT model explored**, Z' masses between 1.8 and 2.4 TeV at 95% CL are excluded, coupling limits of the HVT boson to SM bosons and fermions are provided.
- Excited **b quarks with mass from 1.8 to 4.0 TeV are** excluded at 95% CL. **This is the most stringent exclusion of excited b quarks to date.**

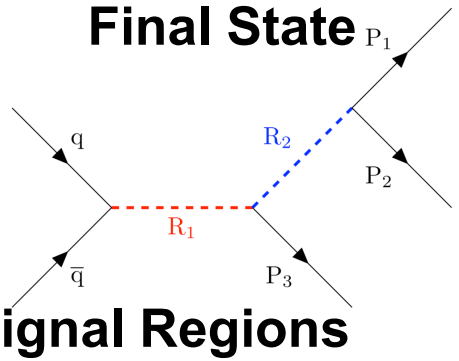
Di-tri-jet Search

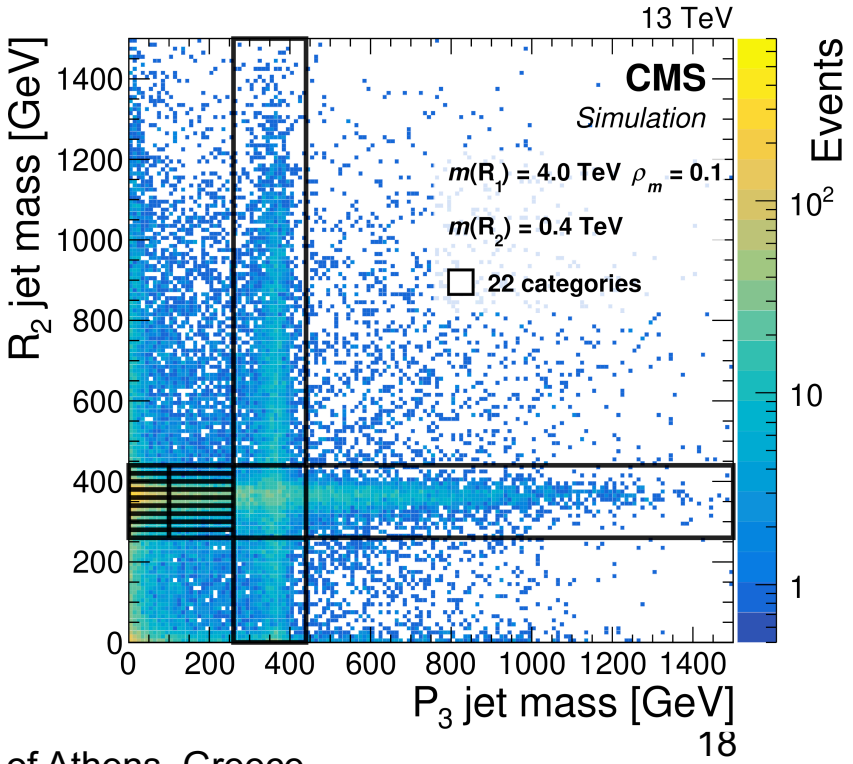
- **Main Experimental Signature :**
  - Two **large-radius (wide) resolved jets considered to encapsulate P_3 and R_2. P_1,P_2,P_3 are gluons**
  - **Several Signal Regions (SRs)** defined, 22 in total, in the $m(R_2)/m(P_3)$ plane.

- **Main backgrounds:**
  - **Multijet QCD production** estimated with a **data-driven approach, using a parametric functional form.**

- **Signal Model:**
  - **Kaluza-Klein Graviton (R_1) decaying** to a **Radion (R_2)** and a **gluon (P_3),** but search is **generic** and largely **model independent.**

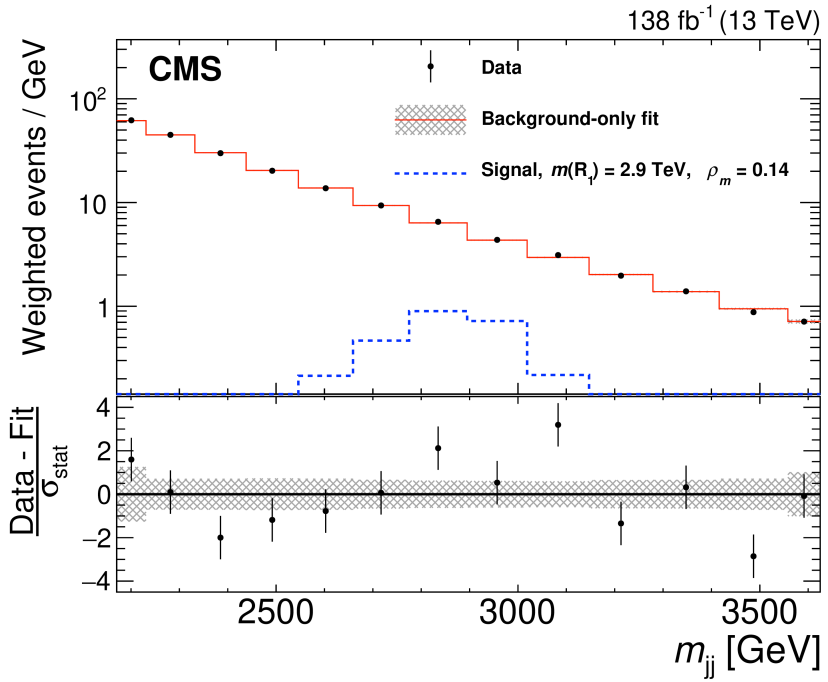
CMS-EXO-20-007



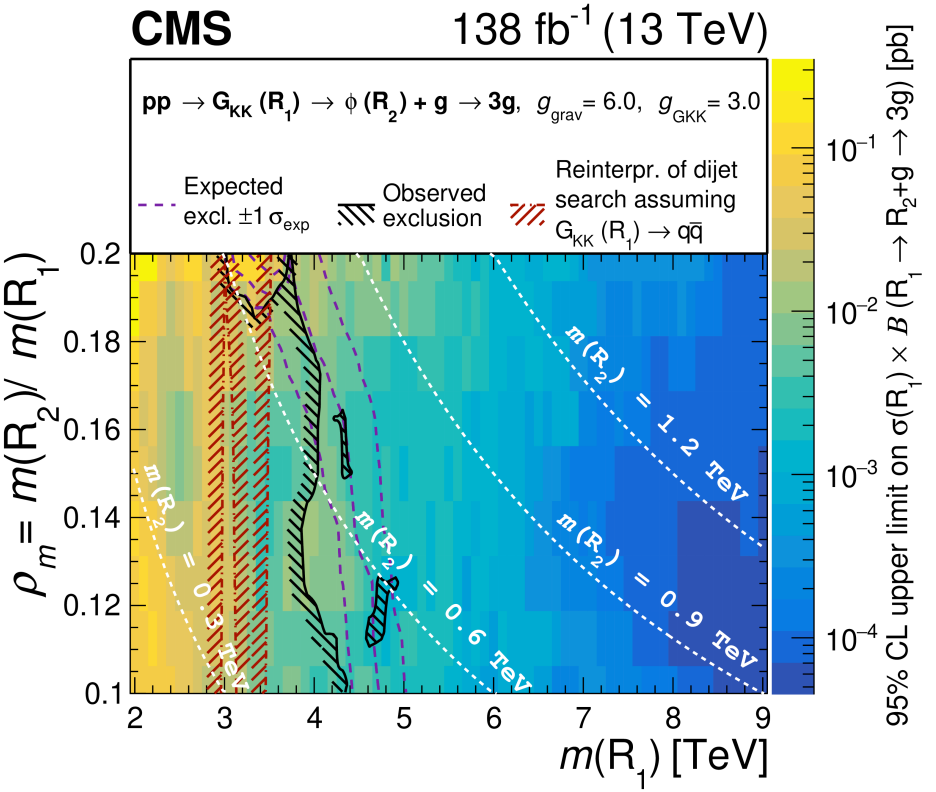


Results and Interpretations

- Maximum likelihood fit in the dijet mass performed **in the SRs**
  - **Signal (simulation)** and **background (data-driven prediction) templates** utilized, and **systematics** encoded as **nuisance parameters.**
  - **Profile likelihood ratio** is the **test statistic** for **limit estimation.**



CMS-EXO-20-007



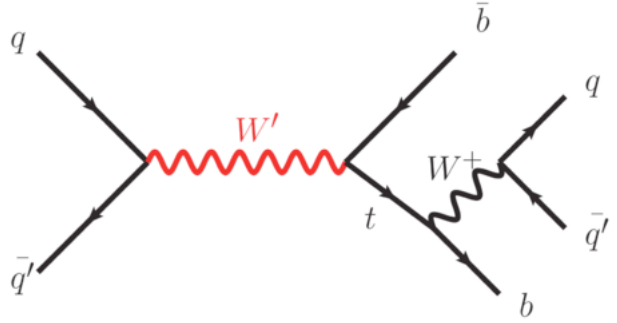
- This is the **first dedicated search** for **resonances decaying into three final state** partons **at the LHC** in events **with a boosted resonance.**

Di-tb-jet Search for W'

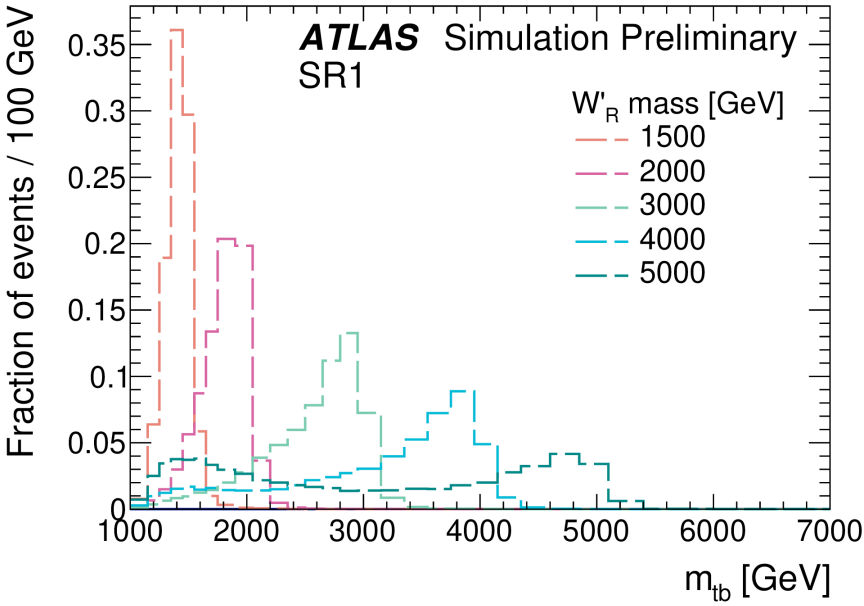
- **Main Experimental Signature :**
  - One **large-radius (large-R)** jet while to capture the **top-quark** and one a **small-radius (small-R)** jet to capture the b **quark, no leptons.**
  - **Dedicated, optimized DNN top-tagger** and a DNN b-tagger used.
  - Several **Signal (SR), Control (CR)** and **Template (TR)** Regions utilized. **CRs** used for **background normalization**, **TRs** for **background shape** estimation.

ATLAS EXOT-2021-043

Final State



Signal Shapes



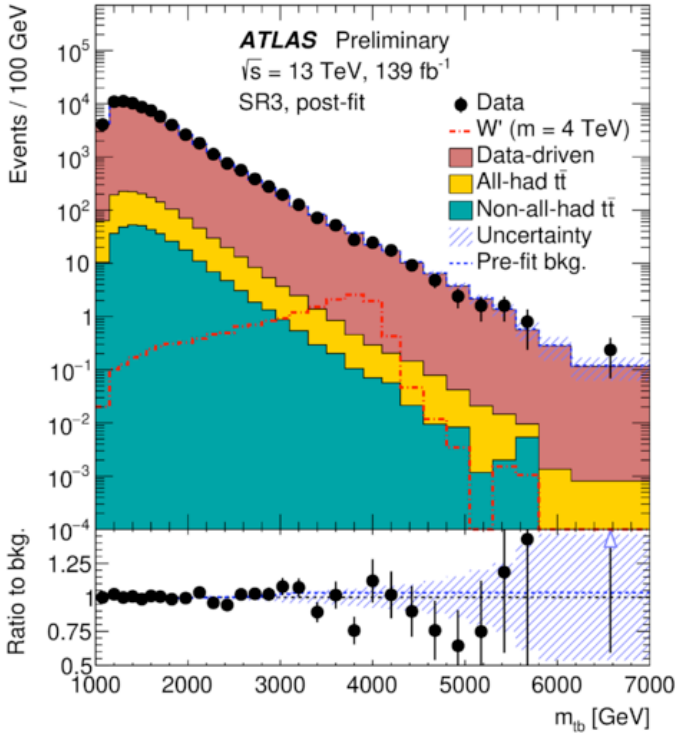
- **Main backgrounds:**
  - **Multijet QCD production** estimated with a **data-driven** approach and **ttbar** estimated from **simulation.**

- **Signal Model:**
  - **Sequential Standard Model with a W' "a replica" of W but with higher mass and right-handed chirality.**

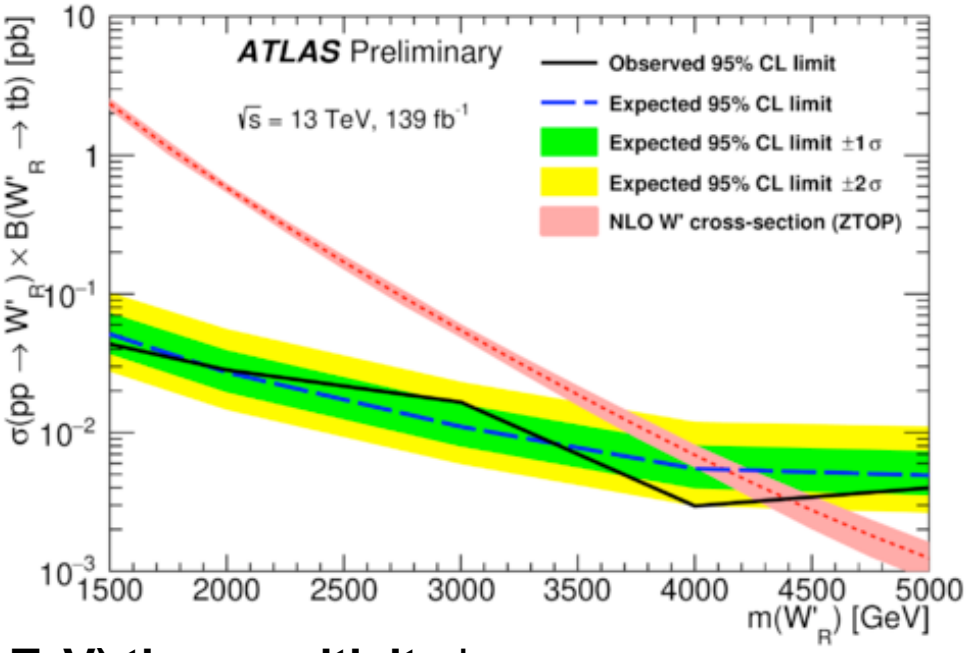
Results and Interpretations

- Maximum likelihood fit in the dijet mass performed **in the three SRs**
  - **Signal (simulation)** and **background (data-driven prediction) templates** utilized, and **systematics** encoded as **nuisance parameters.**
  - **Profile likelihood ratio** is the **test statistic** for **limit estimation.**

ATLAS EXOT-2021-043



Main uncertainties are the statistical ones on the SR and the TRs.



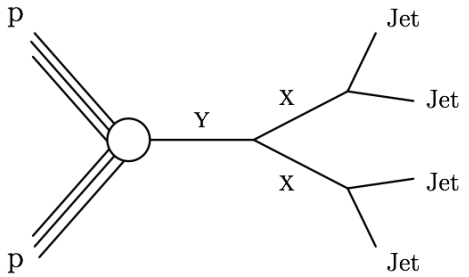
- Results **significantly extend (by ~ 1 TeV) the sensitivity** by :
  - **Improved top-tagging techniques.**
  - a **data-driven multijet background estimate reducing the uncertainty in the background modeling.**

Paired Dijet Search

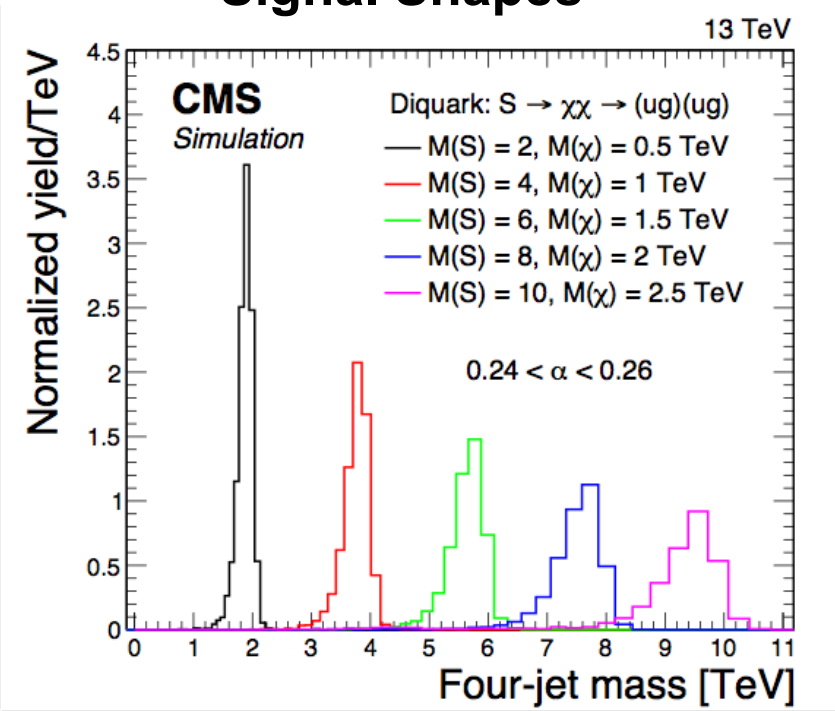
CMS-EXO-21-010

- **Main Experimental Signature :**
  - **Four resolved AK4CHS jets** paired **to same mass resonances.**
- **Main backgrounds**
  - **Multijet QCD production** estimated with a **data-driven approach, using several a parametric functional forms.**
- **Signal Model:**
  - **Diquarks model decaying** to **pairs of vector-like quarks,** which in-turn **decay** to a **quark and a gluon. Search largely model independent.**

Final States

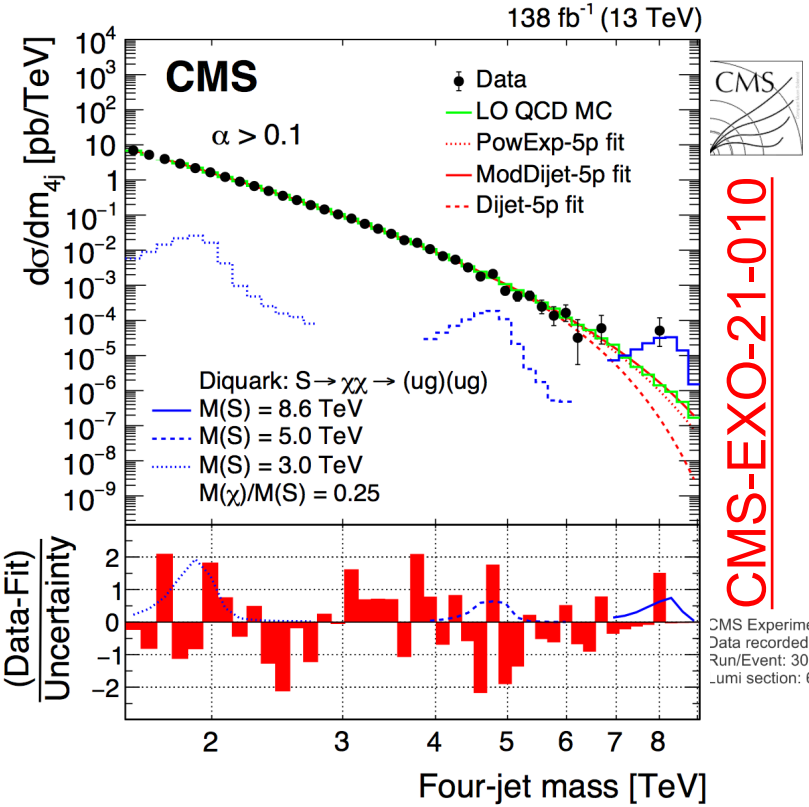


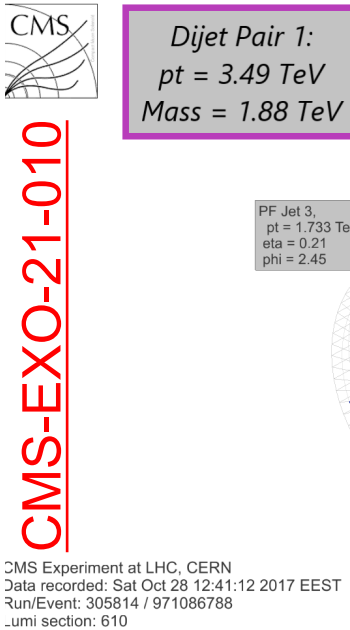
Signal Shapes



Results and Interpretations

- Maximum likelihood fit in the dijet mass performed **in the SRs**
  - **Signal (simulation)** and **background (data-driven prediction) templates** utilized, and **systematics** encoded as **nuisance parameters.**
  - **Profile likelihood ratio** is the **test statistic** for **limit estimation.**





- This is the **first dedicated search** for **resonant production of paired dijet resonances at high mass.** There is an **intriguing excess 1.6 σ global (3.9 σ local)** to **follow up** on **Run III**

Summary and Outlook

- Many **powerful new and novel** results **with the full Run II datasets.**
- **Reach** on analyses with **additional data** improved **beyond luminosity scaling. More results in the pipeline in the near future.**
- However, with **140 fb^{-1}** of the anticipated **400 fb^{-1} for RunII and Run III** and **3000 fb^{-1} (HL-LHC) we have just started hunting for new Mediators.**
- Anticipating additional data, we work on **improving our detectors, trigger, reconstruction, tagging and analysis methods in order to significantly extend** the discovery reach for **new physics, and hope/prepare for a discovery in Run III.**

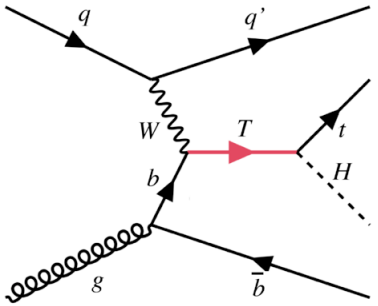
Thank you!

Di-fat-jet Search for Vector-like quarks

ATLAS EXOT-2019-07

- **Main Experimental Signature :**
  - **≥2 large-R jets** with pT>350 GeV, $|\eta|$ < 2.0 with **a mass between [100, 225] GeV, no leptons.**
  - The Signal Region (SR) has one **Higgs-boson tagged jet** with **≥2 b-tags** and **one top-quark-tagged jet** with **≥1 b-tag.**
  - Several Validation Regions (VR), QCD regions, and ttbar Normalization Regions.

Final State



- **Main backgrounds:**
  - ttbar, multijet QCD production. **Data-driven estimation from dedicated regions,** and with an **ABCD-like methodology.**

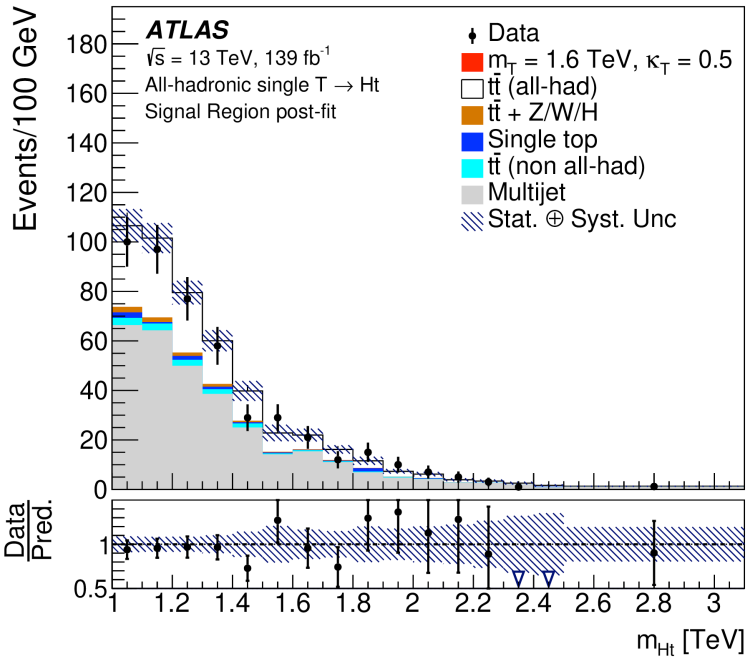
- **Signal Model:**
  - **Little Higgs/Composite Higgs models, predicting vector-like quarks.**

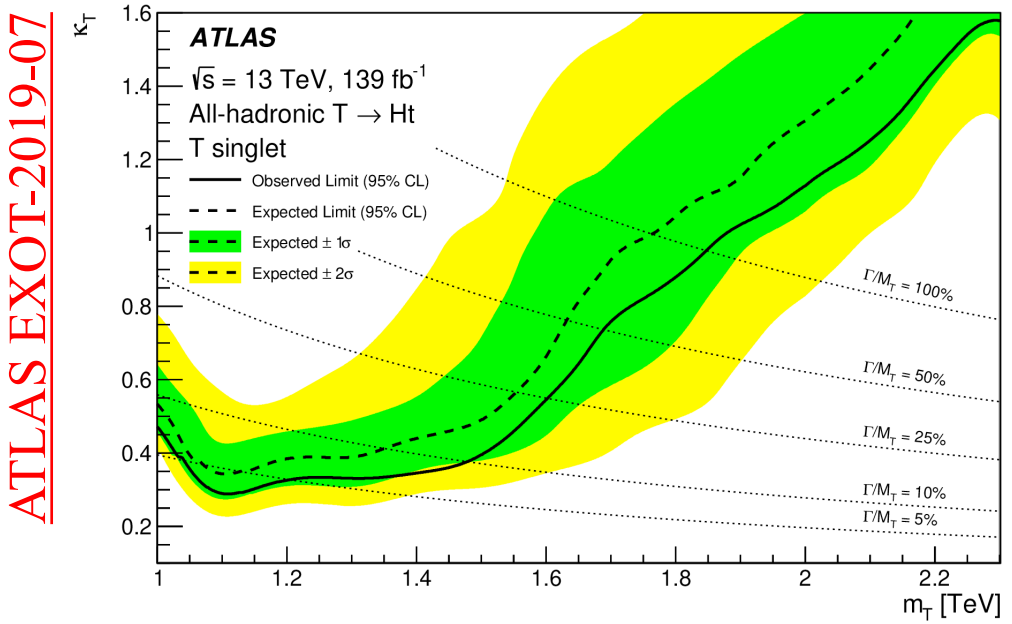
Event Categories

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									

Results & Interpretations

- Maximum likelihood fit in the dijet mass performed **in the SR and the NR**
  - **Signal (simulation)** and **background (data-driven prediction) templates** utilized, and **systematics** encoded as **nuisance parameters.**
  - **Profile likelihood ratio** is the **test statistic** for **limit estimation.**

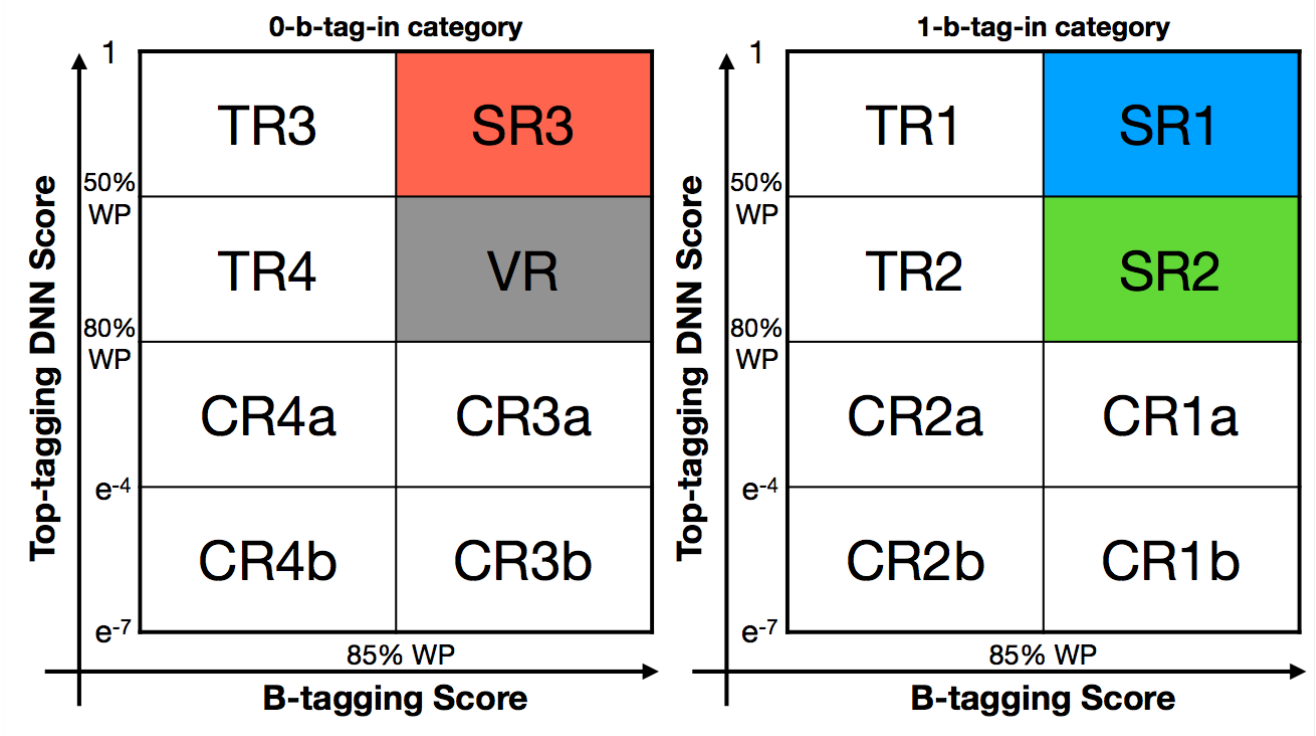




- Results **significantly extend the sensitivity** by :
  - **tagging techniques** with **greater background rejection,**
  - a **data-driven multijet background estimate reducing the uncertainty in the background modeling.**

Di-tb-jet Search for W'

ATLAS EXOT-2021-043



$$N^{\text{data-driven-background}}_{\text{SR1,SR2}}(i) = R^{1}_{\text{corr}}(i) \times \left(N^{\text{obs}}_{\text{TR1,TR2}}(i) - N^{t\bar{t}}_{\text{TR1,TR2}}(i)\right) \times \frac{N^{\text{obs}}_{\text{CR1a}}(i)}{N^{\text{obs}}_{\text{CR2a}}(i)}$$

$$R^{1}_{\text{corr}}(i) = \frac{N^{\text{obs}}_{\text{CR1a}}(i) \times N^{\text{obs}}_{\text{CR2b}}(i)}{N^{\text{obs}}_{\text{CR2a}}(i) \times N^{\text{obs}}_{\text{CR1b}}(i)}$$

$$N^{\text{data-driven-background}}_{\text{SR3,VR}}(i) = R^{0}_{\text{corr}}(i) \times \left(N^{\text{obs}}_{\text{TR3,TR4}}(i) - N^{t\bar{t}}_{\text{TR3,TR4}}(i)\right) \times \frac{N^{\text{obs}}_{\text{CR3a}}(i)}{N^{\text{obs}}_{\text{CR4a}}(i)}.$$

$$R^{0}_{\text{corr}}(i) = \frac{N^{\text{obs}}_{\text{CR3a}}(i) \times N^{\text{obs}}_{\text{CR4b}}(i)}{N^{\text{obs}}_{\text{CR4a}}(i) \times N^{\text{obs}}_{\text{CR3b}}(i)},$$

Paired Dijet Search

CMS-EXO-21-010