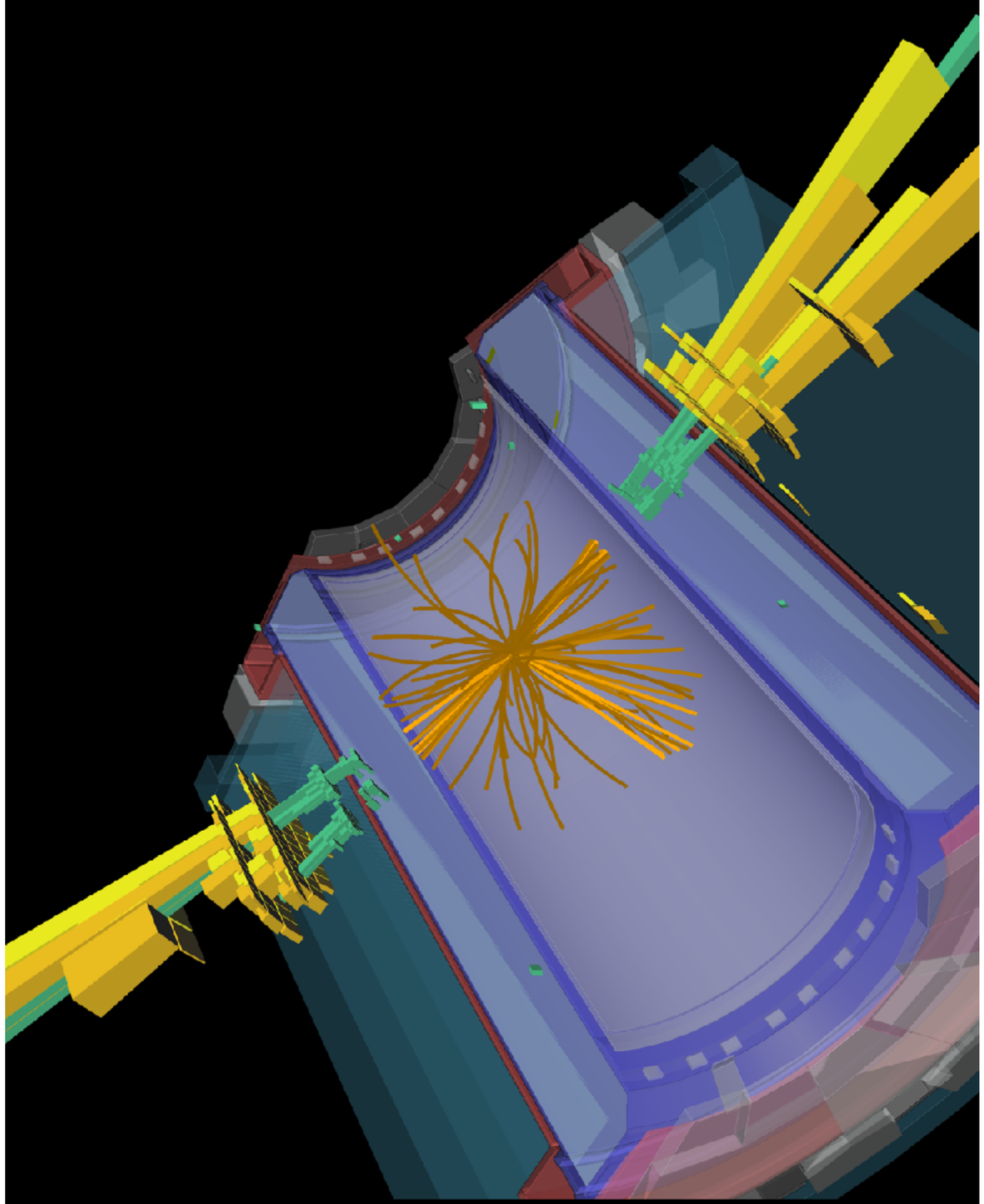
TRIUMF

ATLAS Searches using Jet Substructure Techniques

BOOST 2018

Francesco Guescini

on behalf of the ATLAS Collaboration



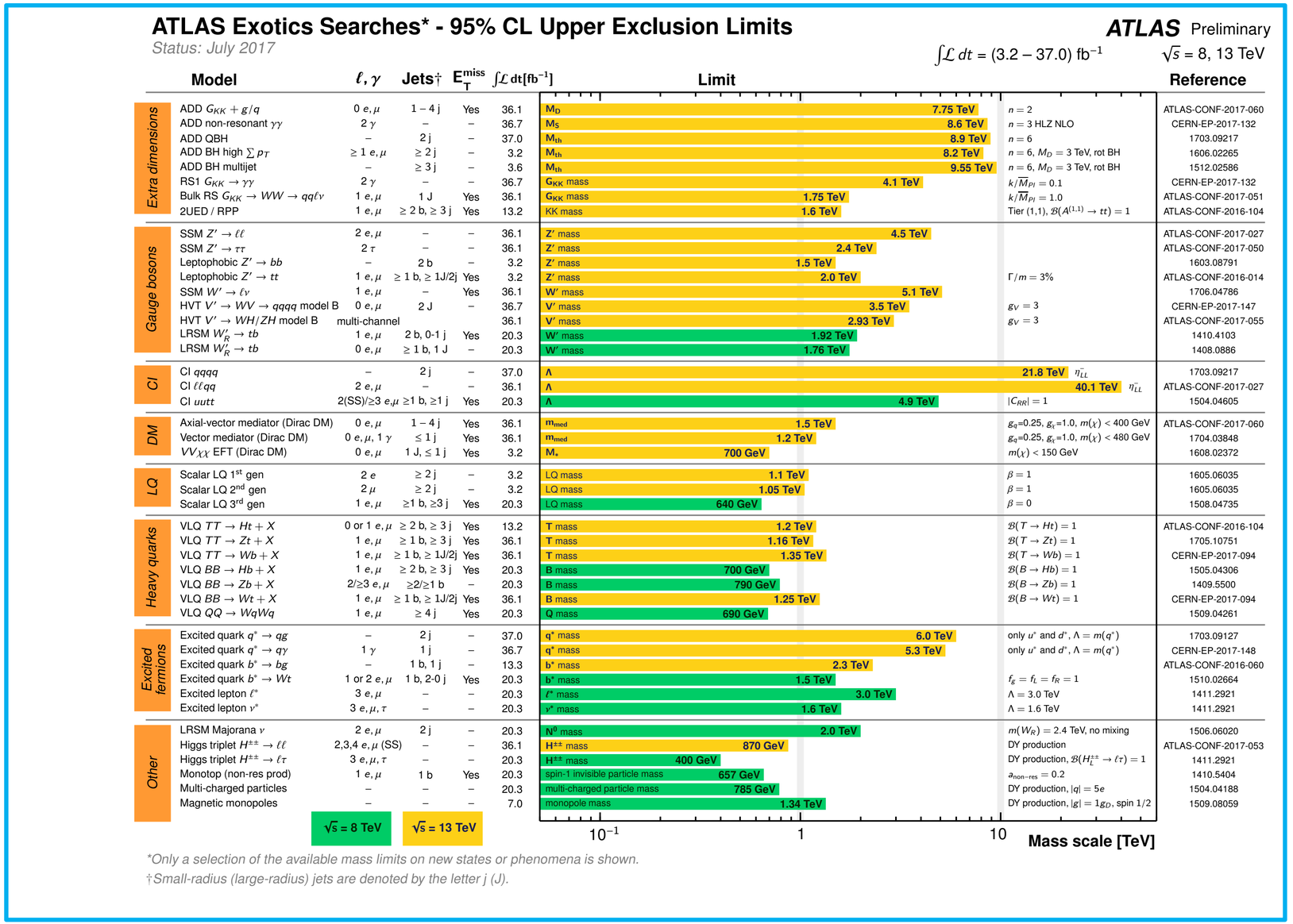
ATLAS EXPERIMENT

Discovery, accelerated

- the use of **Jet SubStructure** techniques has become common across all sorts of ATLAS analyses
- many analyses are performed in **resolved and boosted** regimes
  - facing **highly boosted** regimes

- this is an **overview** of ATLAS **exotic searches** using **JSS**
- **focus** on analyses that have significantly profited from using/ developing **new JSS methods**

- does this talk cover **all** ATLAS exotics searches using JSS?
  - no
- is it **biased**?
  - clearly



- **Wt+X** (1806.01762)
  - **Combined Mass** (ATLAS-CONF-2016-035)
- **boosted diboson** (ATLAS-CONF-2018-016)
  - **Track-CaloClusters** (ATL-PHYS-PUB-2017-015)
- **boosted dijet + ISR** (1801.08769)
  - **Design Decorrelated Tagger** (1603.00027)
- **W'→tb** (1801.07893)
  - **Shower Deconstruction** (ATLAS-CONF-2014-003, 1603.03127)
  - **Combined Mass** (ATLAS-CONF-2016-035)
- **mono-H→bb**
  - **VR track-jets**
- **all-hadronic VLQ** (EXOT-2017-14)
  - **VR reclustered jets**
  - **DNN** for V/H/top/background **tagging**

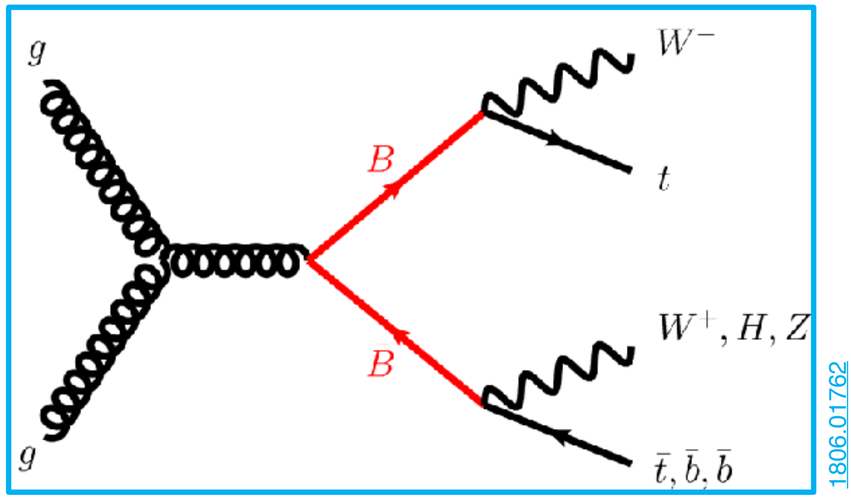
- where is **SUSY**?
  - no one knows but for ATLAS SUSY searches see talk by David Miller

Wt+X

- search for **pair** production of **Vector-Like B** quarks decaying to **Wt+X** in the **l+jets** final state
  - one B decays into **Wt**
  - the other B into **Wt, Hb or Zb**
- event **signature**: one lepton, MET, large-R jets and b-jets

- 2015-2016 data , 36.1 fb^{-1}

- **JSS** to reduce the background
  - using boosted objects reduces **combinatoric background**
- W boson tagging: D_2, combined jet mass



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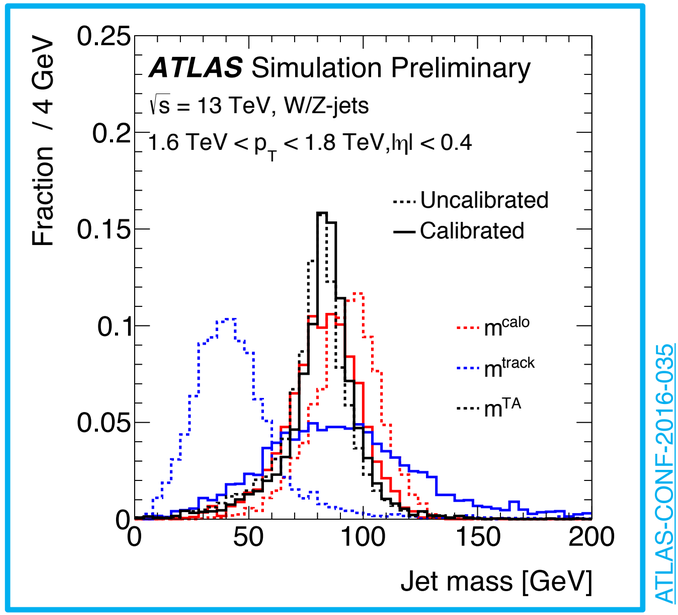
combined jet mass

- the reconstruction of **highly boosted jets** may hit the **calorimeter granularity limit**
  - **tracking** information may be used to **compensate**
- **track-assisted mass**:

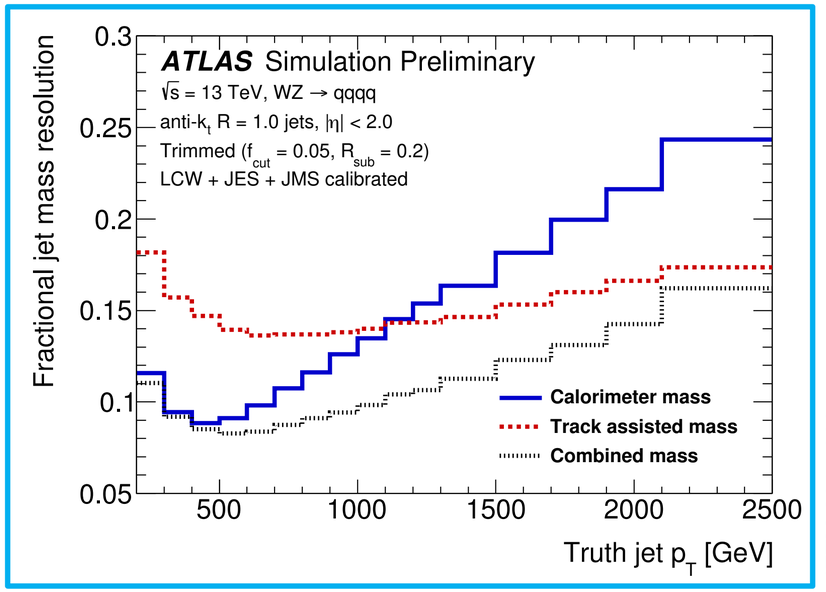
$$m_{TA} = \frac{p_T^{calo}}{p_T^{track}} \times m_{track}$$

- p_T^{calo}/p_T^{track} corrects for the **neutral particles contribution**

- improve jet mass resolution by linearly **combining m_{calo} and m_{TA}** using mass resolution as weight: **m_{comb}**
  - used in **Wt+X** analysis



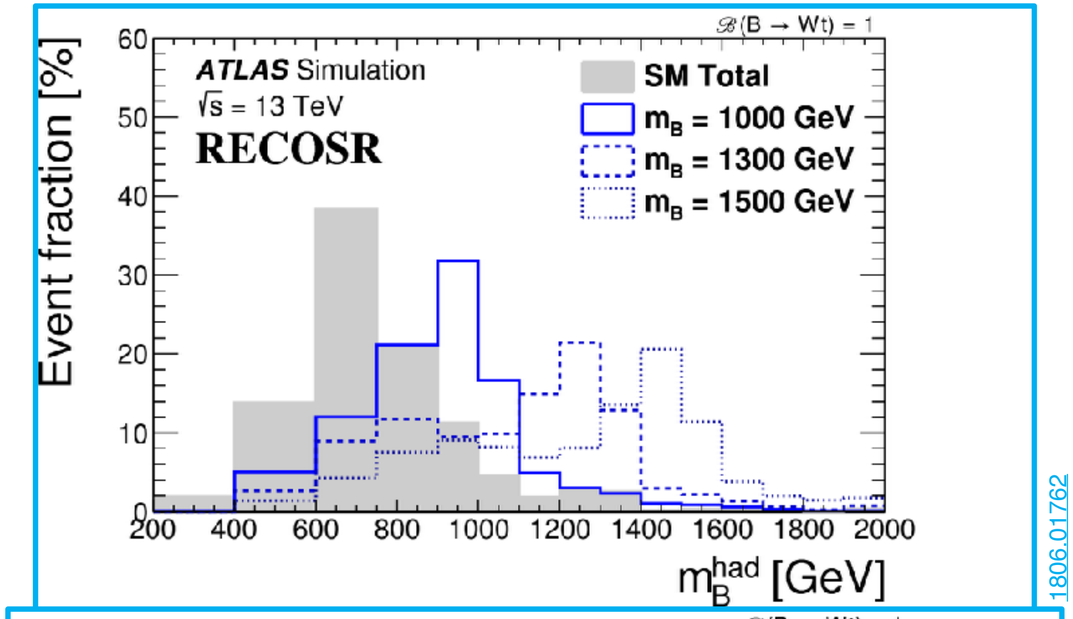
ATLAS-CONF-2016-035



JETM-2017-002

event selection [Wt+X]

- **trigger**: single muon or electron
- event **pre-selection**
  - exactly **1 lepton**
  - **≥4 jets**
  - **≥1 b-jet**
  - **≥1 large-R jet**, trimmed
  - **MET** > 60 GeV
- **2** mutually exclusive **Signal Regions**:
  - **RECOSR**: **reconstruct BB pair** (m_B^{had})
  - **BDTSR**: use **BDT** to discriminate
    - highest ranked variables: S_T and m_{J1}



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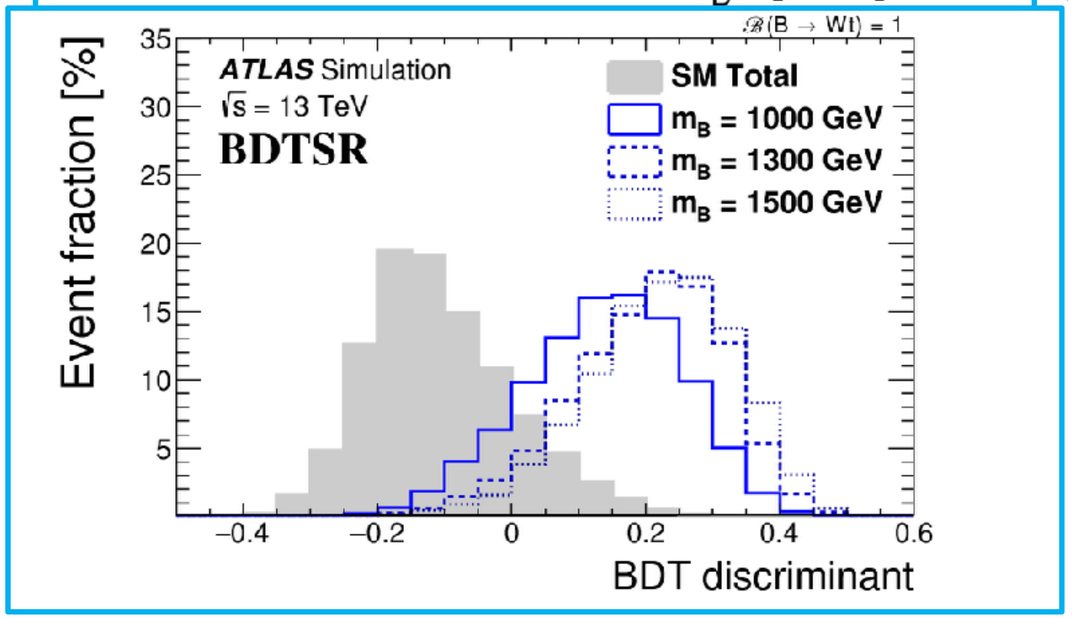

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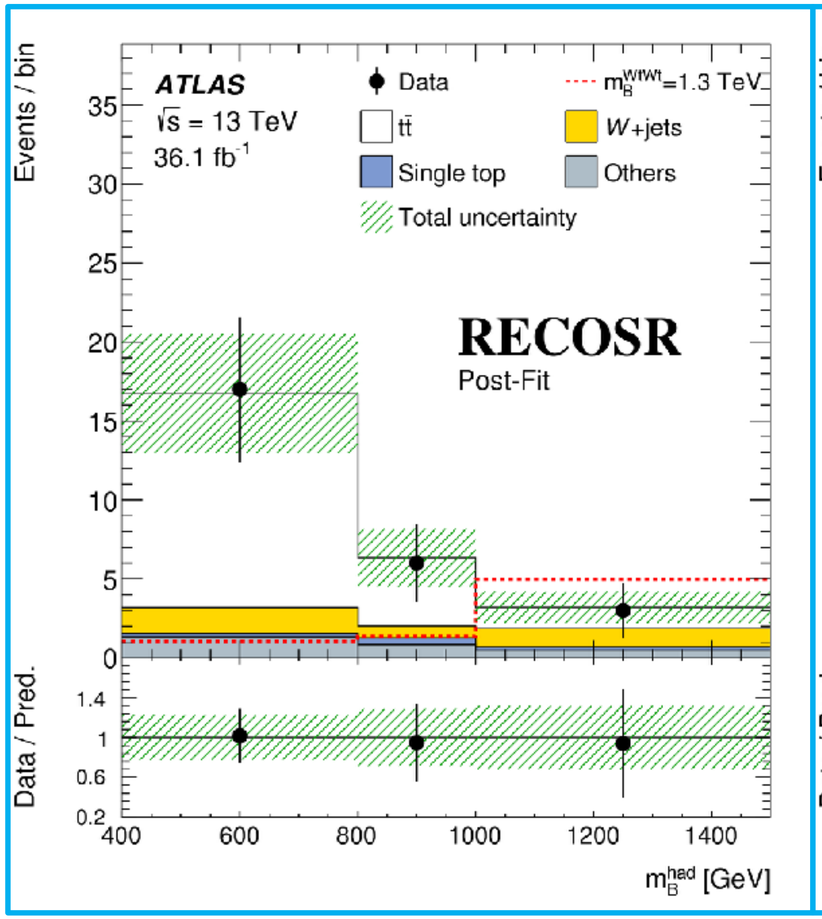
results [Wt+X]

- **RECOSR**: reconstruct BB system
  - ≥3 large-R jets
  - ≥1 W candidate
  - m_B^{had} used as final discriminator
- **BDTSR**
  - RECOSR **veto**
  - **BDT** discriminant

- **multi-jet background** evaluated from **Validation Region** and then scaled to SR using Matrix Method
- main sources of **systematic uncertainties**:
  - JES, JER, background modeling

- **simultaneous fit** of 2 SRs
- systematic uncertainties as **nuisance parameters**



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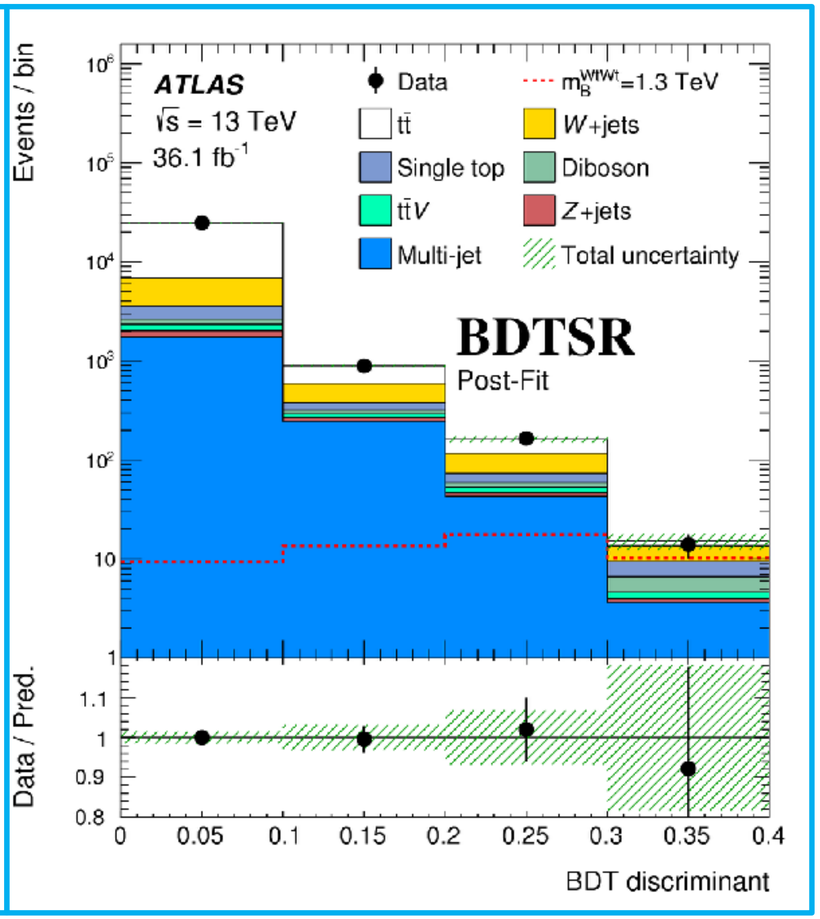

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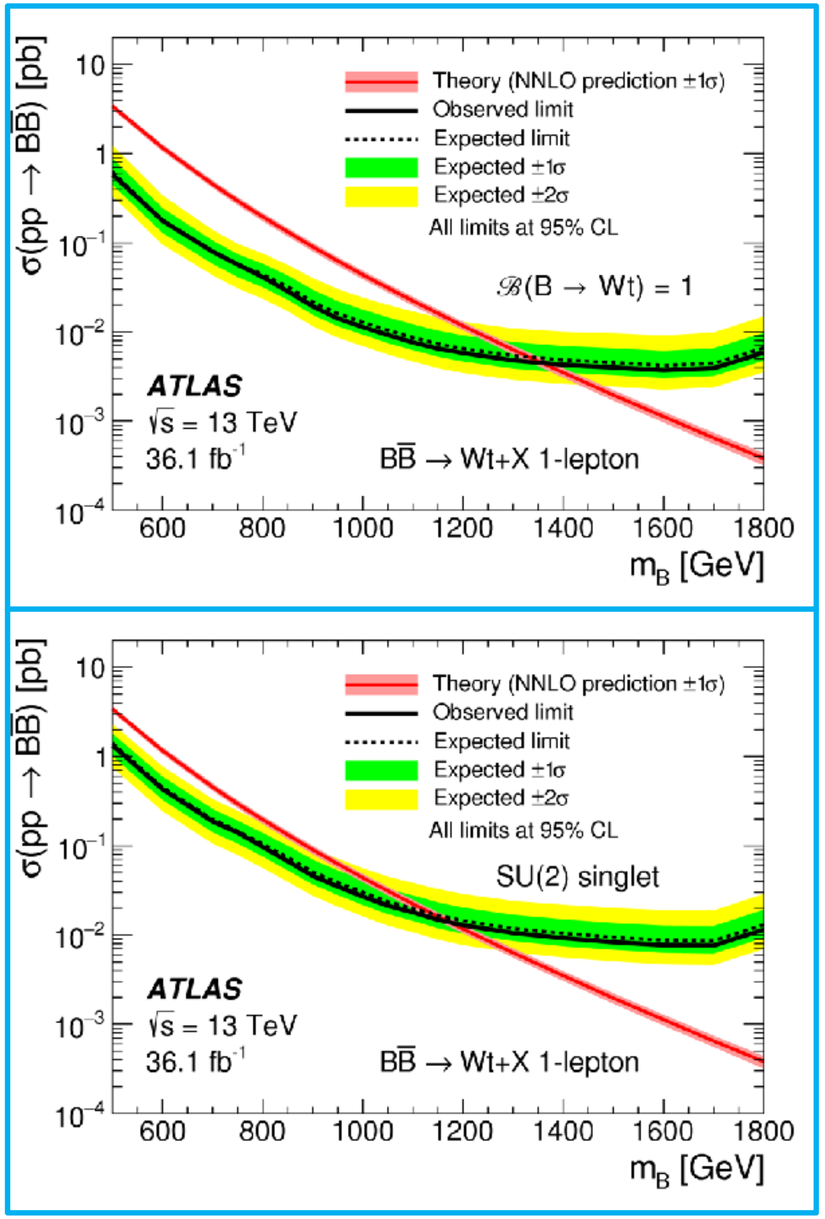
limits [Wt+X]

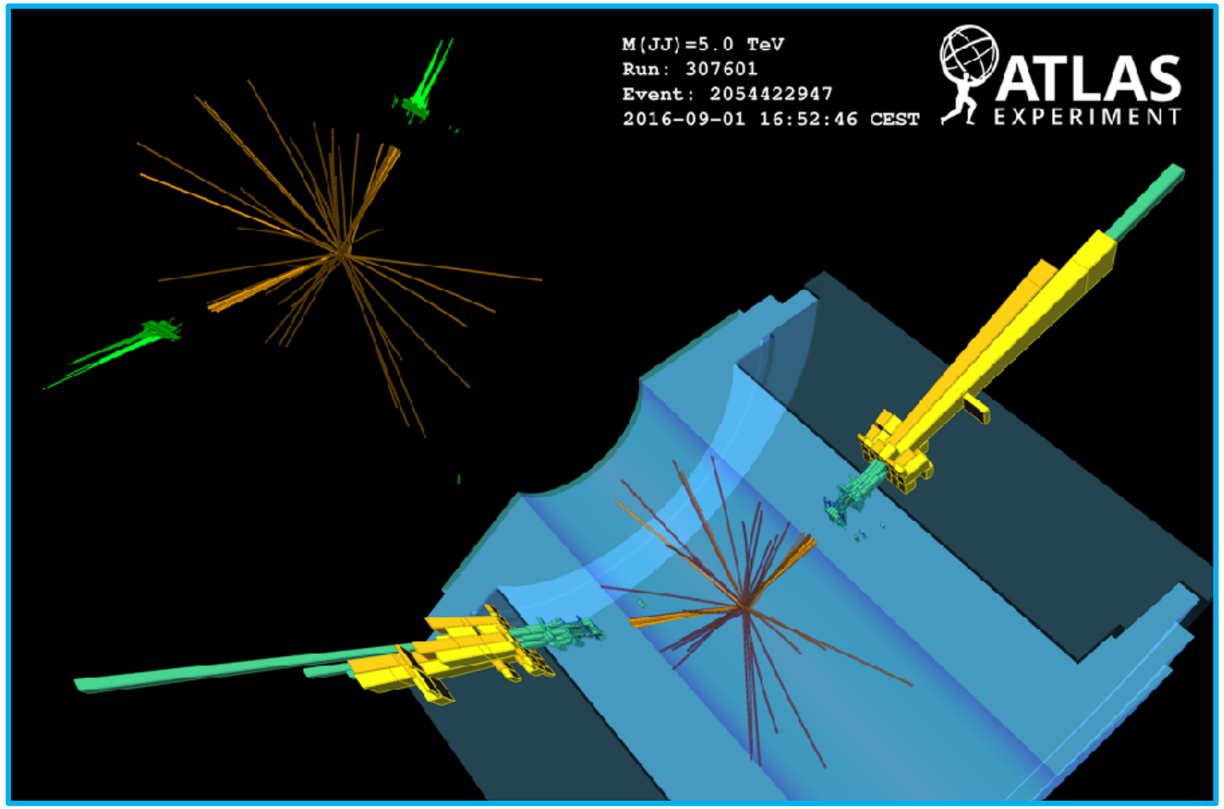
- 95% CL **limits** set with CL_s method
- B→Wt excluded up to **1350 GeV**
- B from SU(2) singlet excluded up to **1170 GeV**
- previous **limits** significantly **improved**
  - 1250 GeV for B(B→Wt) = 1
  - reinterpreted Wb+X analysis



VVJJ

boosted diboson [VVJJ]

- search for **diboson resonances** in **hadronic final states**
- **2015-2017** data, 79.8 fb^{-1}
- **main background** from multi-jets
  - **JSS** effective way of reducing background
- background extracted from **parametric function fit**
- single jet trigger
- lepton veto
- **Track-Calo Cluster** jets improve results in the **highly boosted** regime

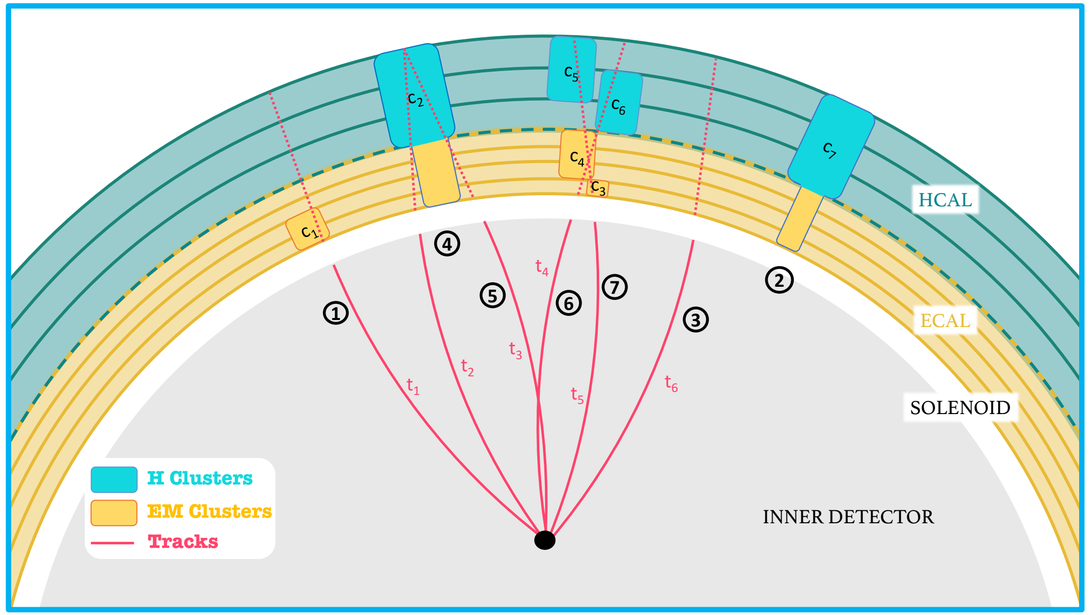


ATLAS-CONF-2018-016

Track-CaloClusters

- at **highly boosted** regimes, the **calorimeter angular resolution** is the **limiting** factor to access the jet substructure
- **tracks** have excellent angular resolution but **lack energy resolution**
- **combining tracking and calorimeter** information allows significant improvement in JSS at very high energies

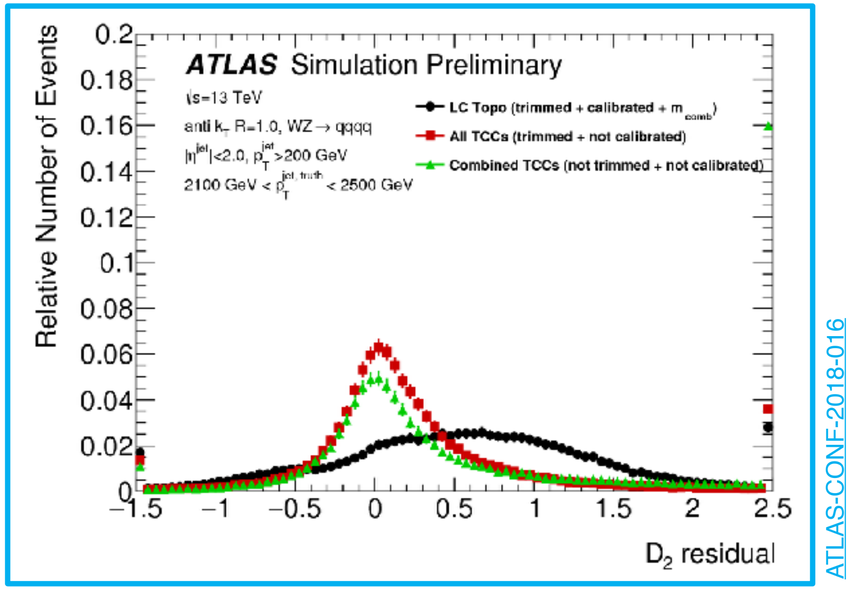
- **Track-Calo Clusters** as jet reconstruction **inputs**
- similar idea to particle-flow but ID and calo energies are **never compared**
- tracks **matched** to clusters: $\Delta R \lesssim \sigma_{cluster}$
- clusters can be **shared** among tracks



$$p_{\mu}^{TCC} = (p_T^c, \eta^t, \phi^t, m = 0)$$

TCC performance

- improved **angular resolution** of TCC jets reflected in $\mathbf{D_2^{\beta=1}}$
- $\mathbf{D_2}$ **resolution** for trimmed jets built from all TCCs is **half** of the traditional jets
  - outweigh slight degradation in jet mass resolution
  - combined non-trimmed TCC jets pay the longer tails in the distribution
- TCC jets are **robust against pile-up**



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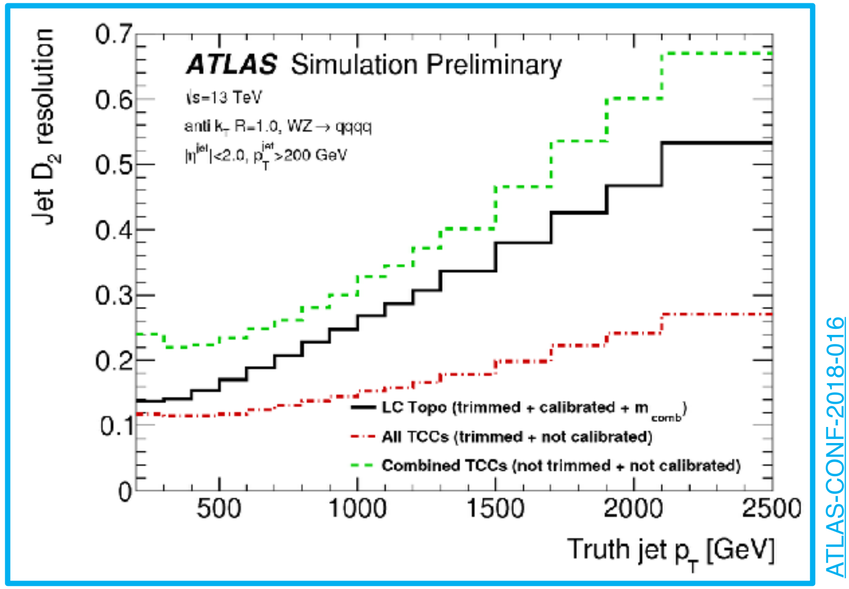


ATLAS-CONF-2018-016

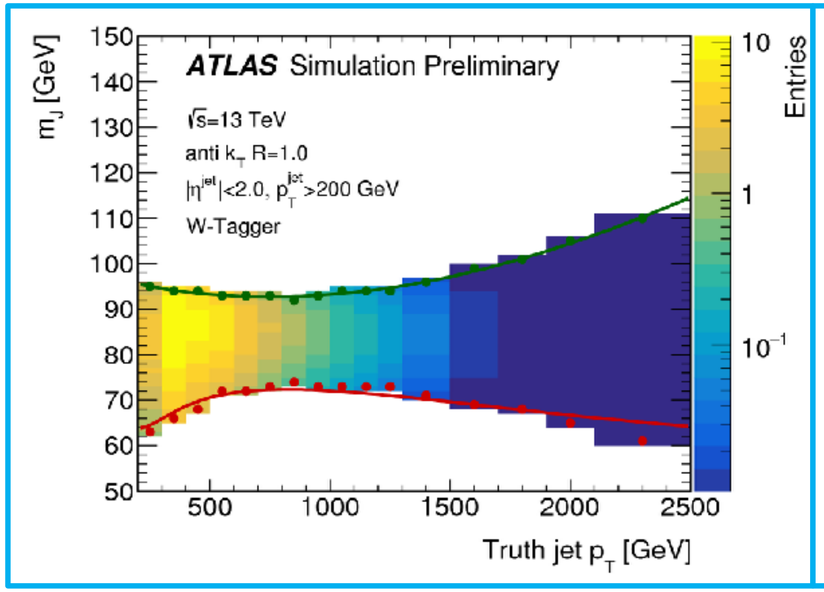
event selection [VVJJ]

- jets reconstructed from **combined and neutral TCCs**
  - trimmed
- ≥2 large-R jets
  - m_J > 50 GeV, m_{JJ} > 1.2 TeV
  - $|\Delta y_{JJ}| < 1.2$

- **boson tagging**
  - m_J and D_2
  - **parametrized** p_T dependent cut
  - smooth, **non-flat** efficiency

- dropped **track multiplicity cut** since introduction of TCC jets
  - used to remove multi-jet background from gluon-initiated jets
  - **negligible benefit** after new tagger

ATLAS-CONF-2018-016



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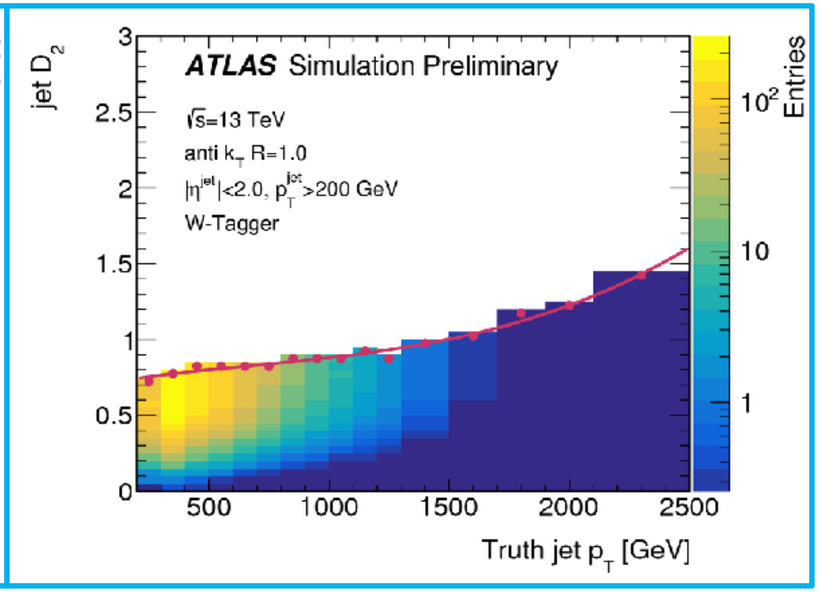

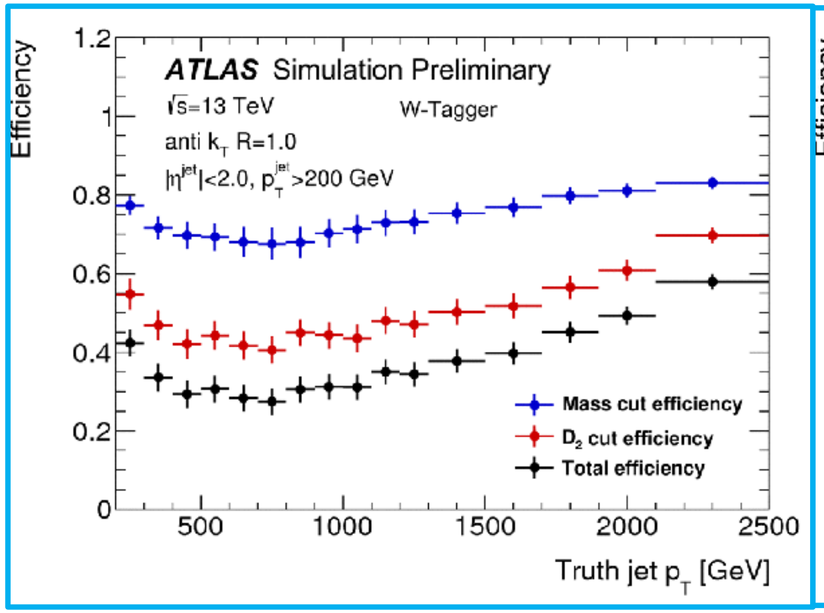

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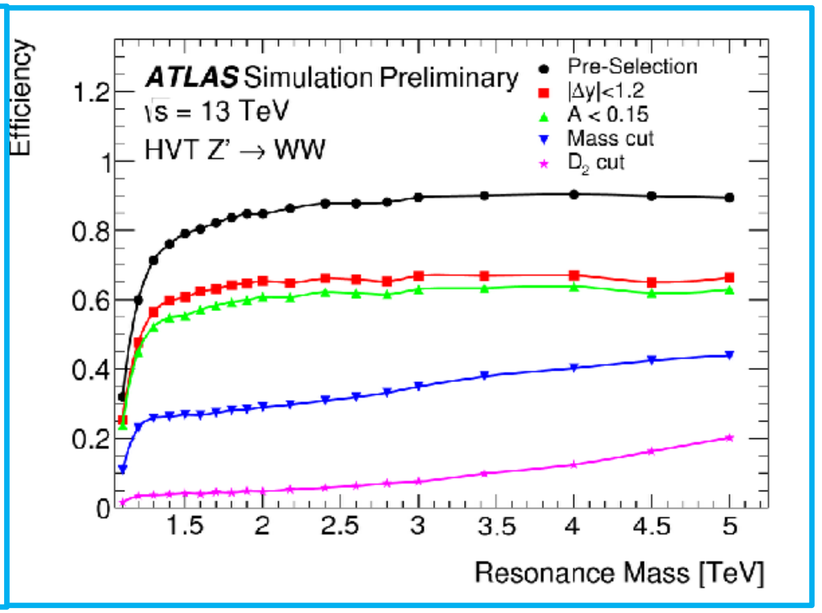


ATLAS-CONF-2018-016

background extraction [VVJJ]

- five non-exclusive **SRs**
  - WW, ZZ, WZ, WZ+WW, WW+ZZ

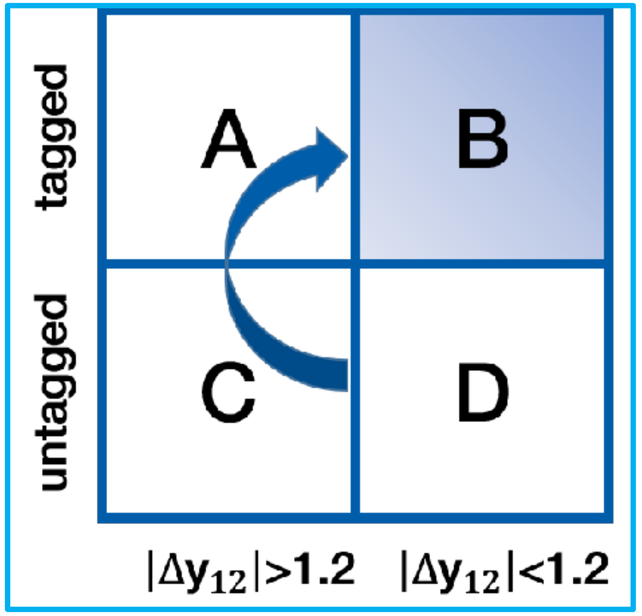
- parametric **background fit**

$$\frac{dn}{dx} = p_1(1-x)^{p_2-\xi p_3}x^{-p_3}$$

- fit tested in CR
  - ABCD method using transfer functions

- main sources of **systematic uncertainties**
  - background, boson tagging, jet calibration

- binned maximum-likelihood **fit**



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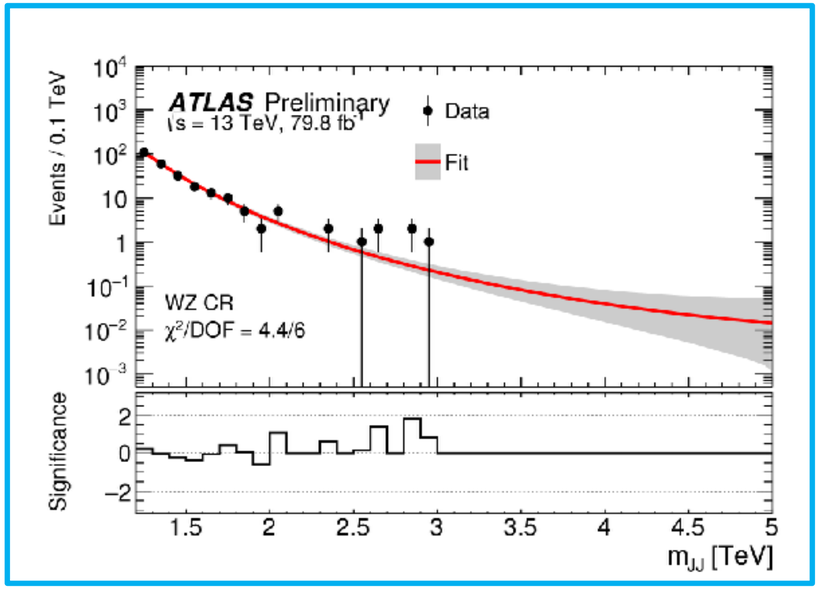


ATLAS-CONF-2018-016

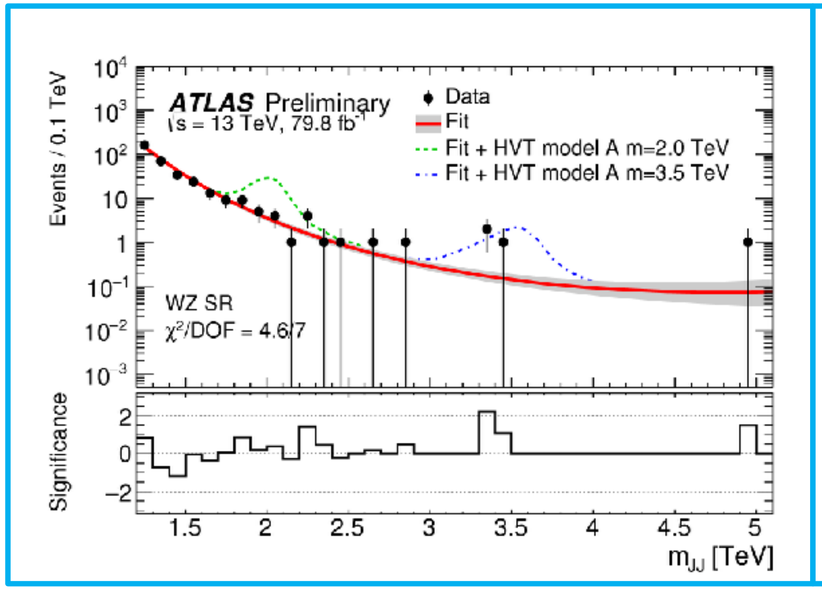
results [VVJJ]

- **most significant deviation** observed in HVT W'→WZ channel at **3.5 TeV**
  - local p-value significance is 1.8
- 95% CL limits set using CL_s method

- **HVT V'** models excluded in the ranges 1.20-3.40 TeV and 1.20-4.15 TeV
- **RS G_{KK}** excluded in the range 1.20-1.90 TeV and 2.10-2.30 TeV

- **significant improvement** over previous analysis iteration
  - largely due to **new analysis techniques**: TCC and tagger
  - 2-4 times larger than expected

ATLAS-CONF-2018-016



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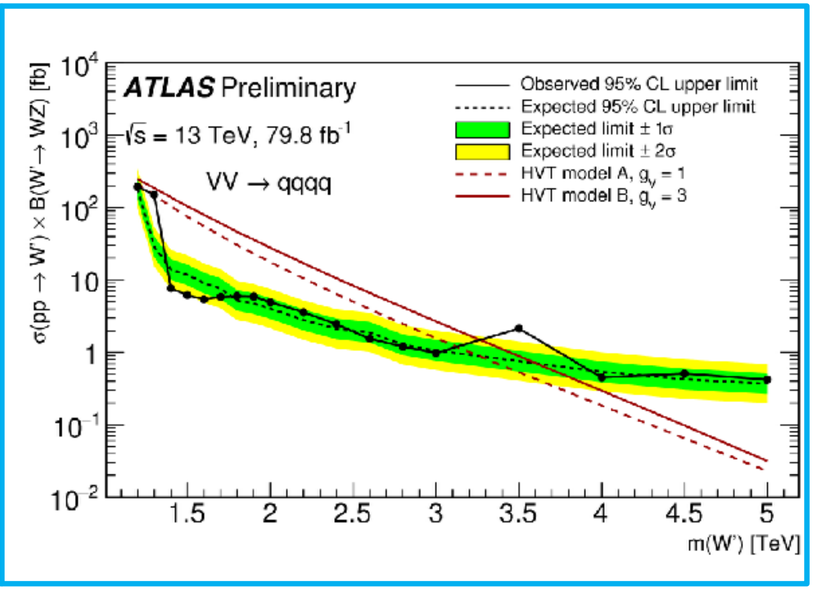
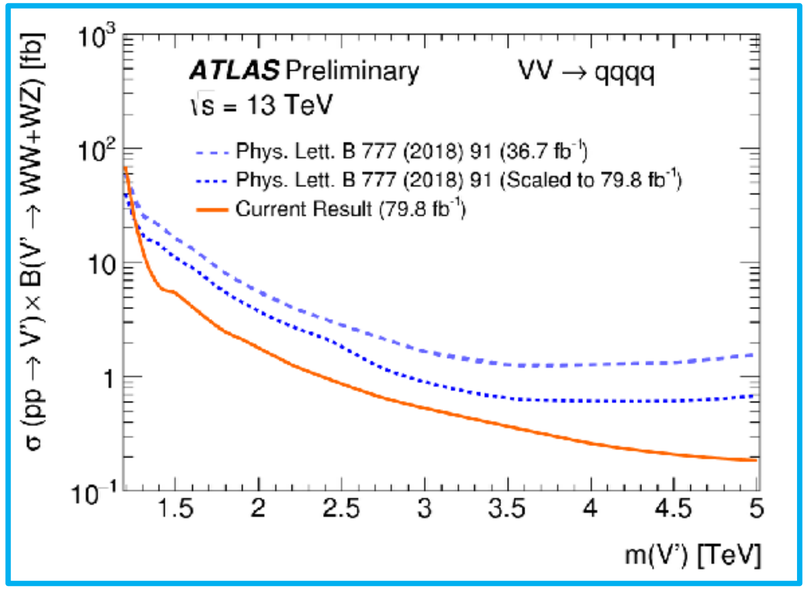




ATLAS-CONF-2018-016

boosted dijet + ISR

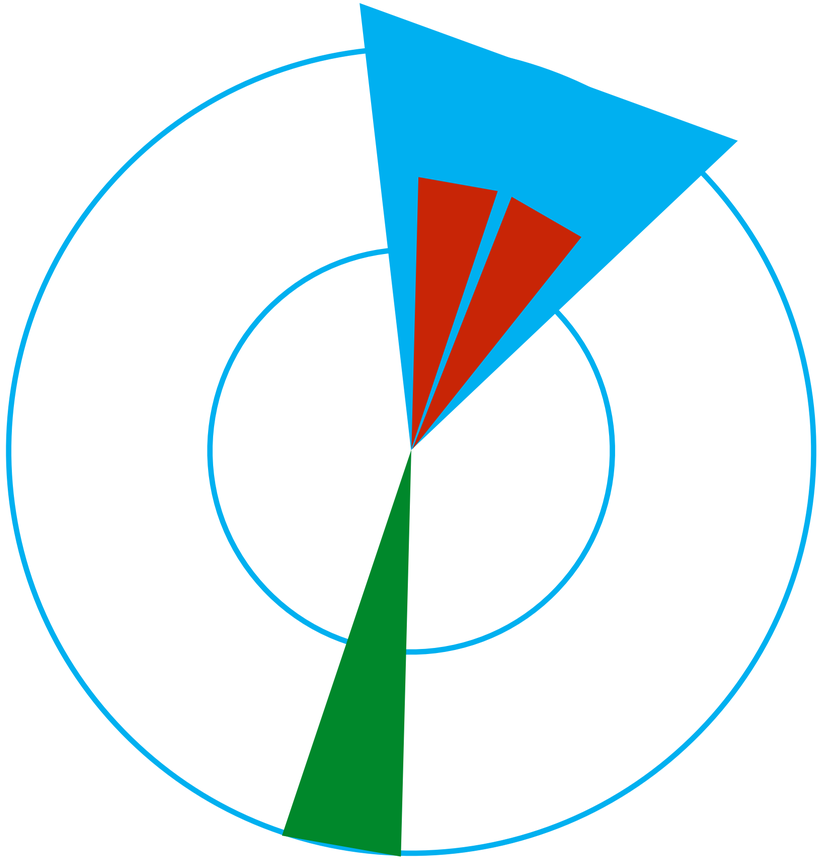
boosted-dijet + ISR

- search for **light resonances** decaying to **quark pairs** in association with a **high-pT photon or jet**

- dijet sensitivity overwhelmed by **background**
- **100 - 220 GeV** mass range
  - lower than **dijet TLA**

- 2015-2016 data, 36.1 fb^{-1}
- **trigger**
  - ≥1 photon or ≥1 jet

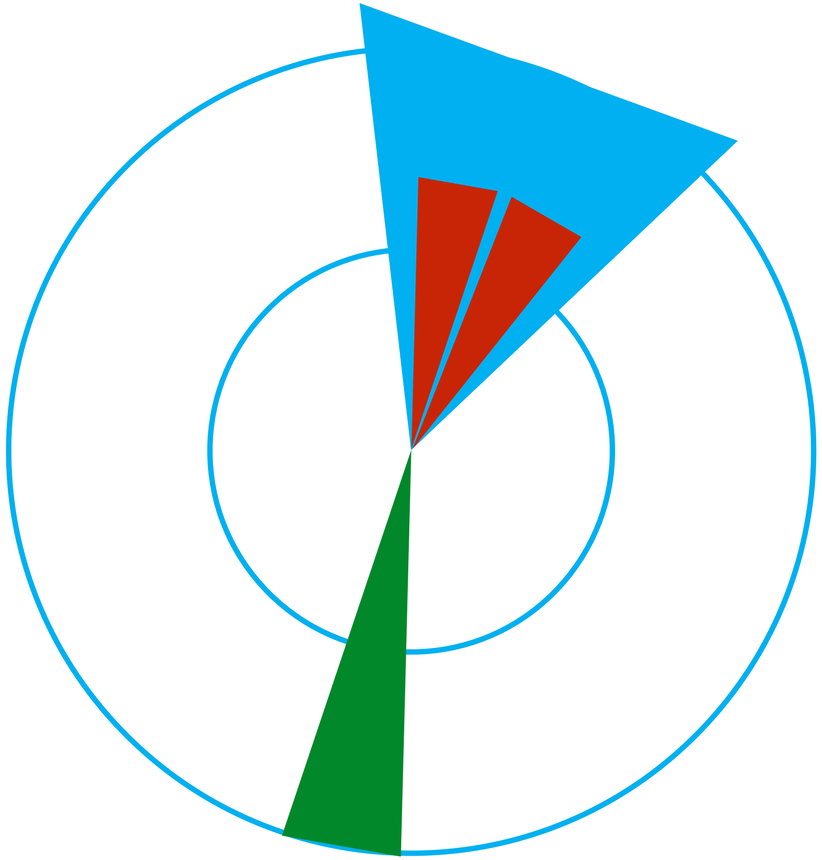
- dominant **backgrounds**
  - multi-jet
  - inclusive ɣ production
- **data-driven** background



event selection [J+ISR]

- **≥1 large-R jet**
  - trimmed
  - p_T > 450 GeV (jet) or 200 GeV (ɣ)
- **small-R jet**
  - p_T > 420 GeV
- **photon**
  - p_T > 155 GeV

- τ_{21} used to select boosted dijets
  - highly **correlated** to jet mass
  - **can't fit** dijet mass distribution
- use **Designed Decorrelated Tagger** instead

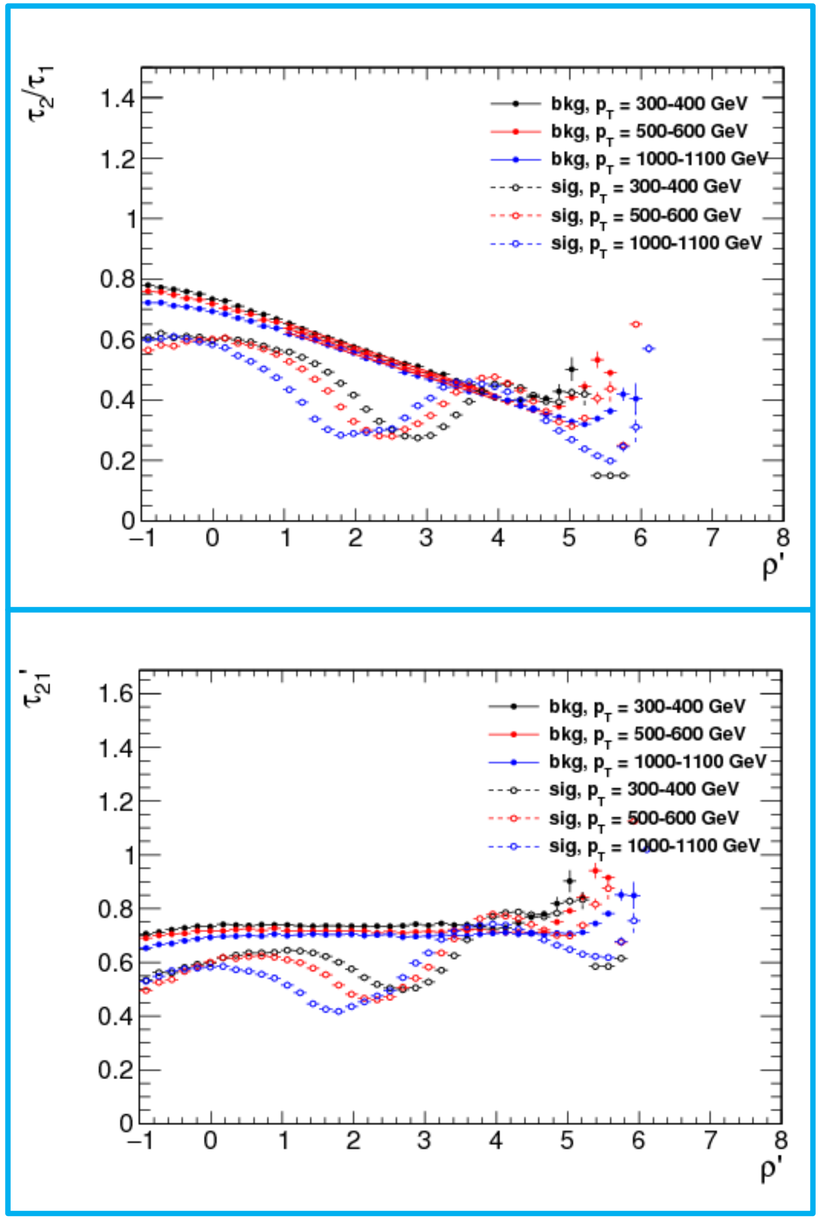


Designed Decorrelated Tagger

- allow **cutting on modified JSS variables** without affecting mass distributions
- τ'_{21} in an **empirical** solution
- DDT based on the **ρ scaling variable**
- implement correction to τ_{21} in region where behaviour is **linear**
- jet **mass** is observed **not to be sculpted** by new τ'_{21} definition
- τ'_{21} slightly **improves tagging efficiency** too

$$\rho = \log\left(\frac{m_J^2}{p_T^J \times \mu}\right)$$

$$\tau'_{21} = \frac{\tau_2}{\tau 1} - M \times \rho$$



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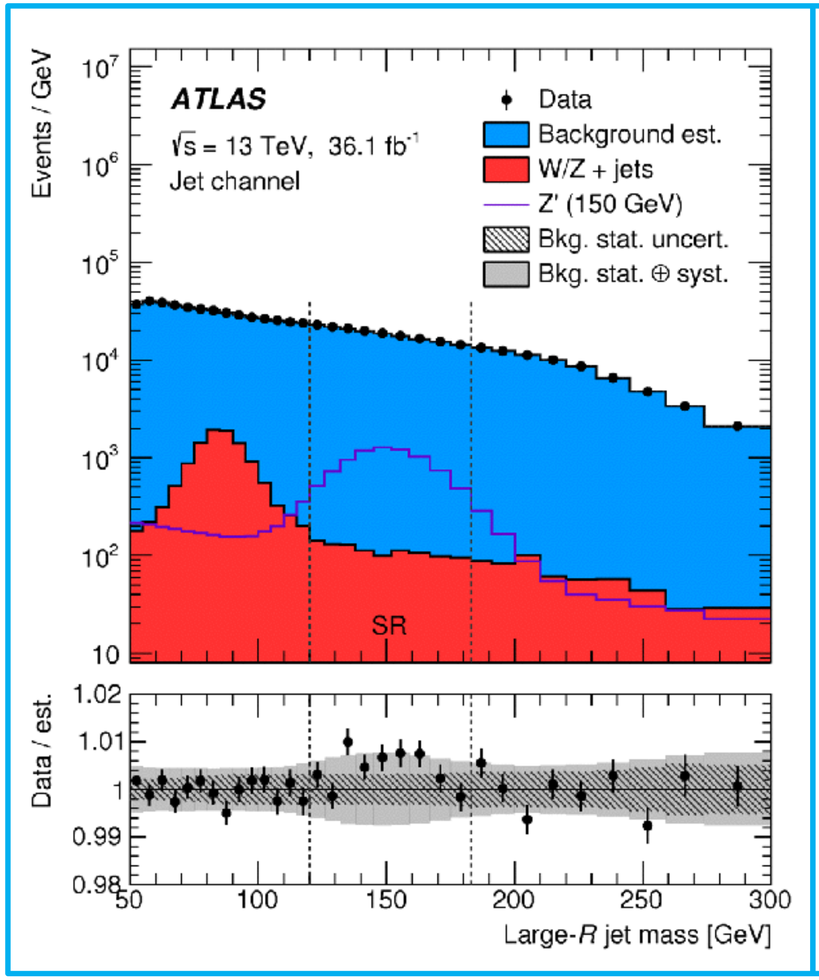
results [J+ISR]

- **Designed Decorrelated Tagger**
  - $\rho_{DDT} > 1.5$: linear behaviour
  - $\tau_{21}^{DDT} < 0.5$: suppress background
- **data-driven background**
  - estimated from CR
- main sources of **systematic uncertainties**
  - background, jet calibration, τ_{21}^{DDT} modelling
- **binned likelihood fit**
- **largest deviations**
  - ISR **jet** channel:150 GeV
    - 2.5 σ local, 1.1 σ global
  - ISR **photon** channel: 140 GeV
    - 2.2 σ local, 0.8 σ global



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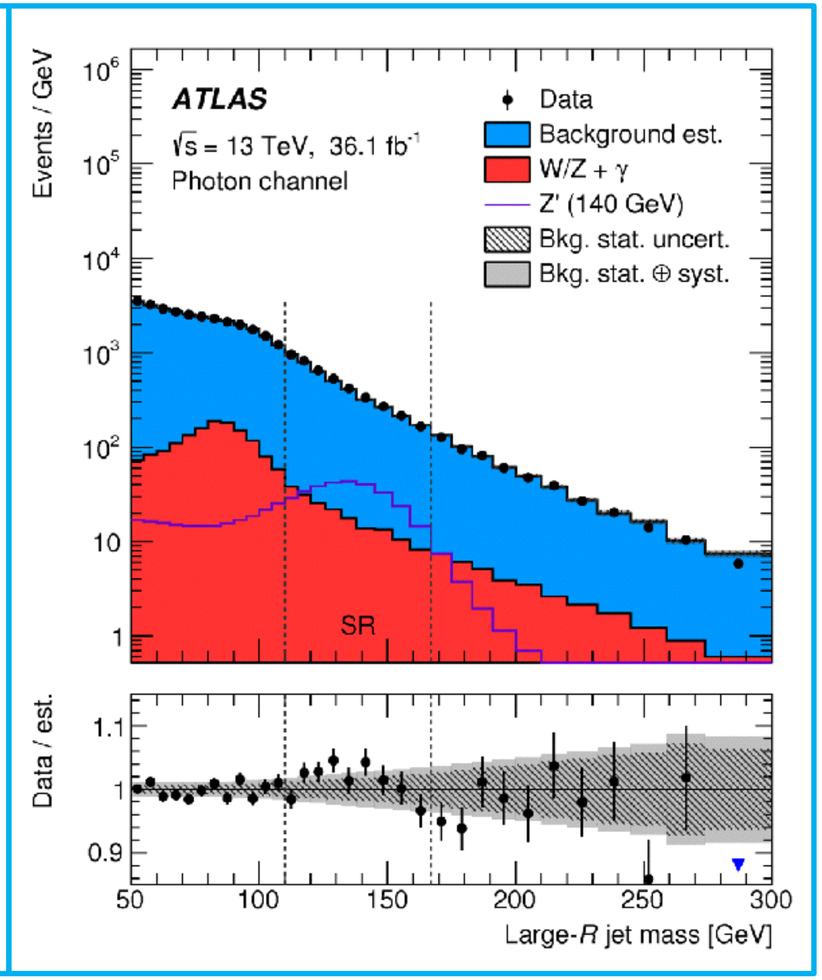

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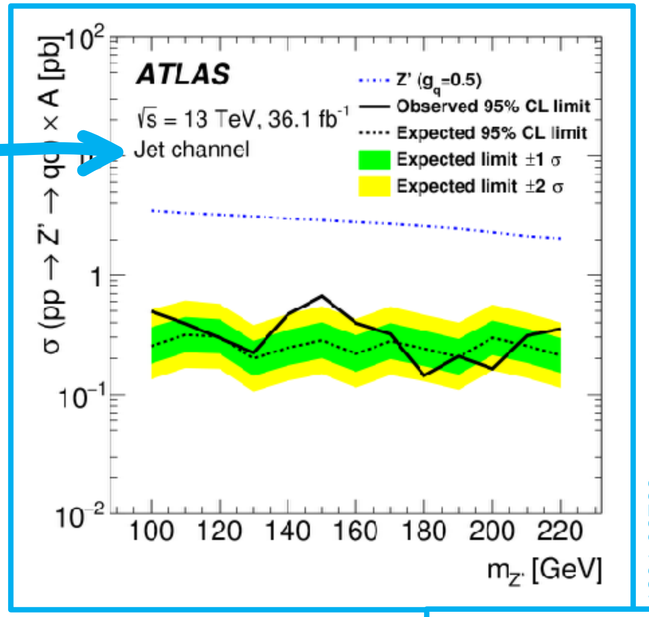
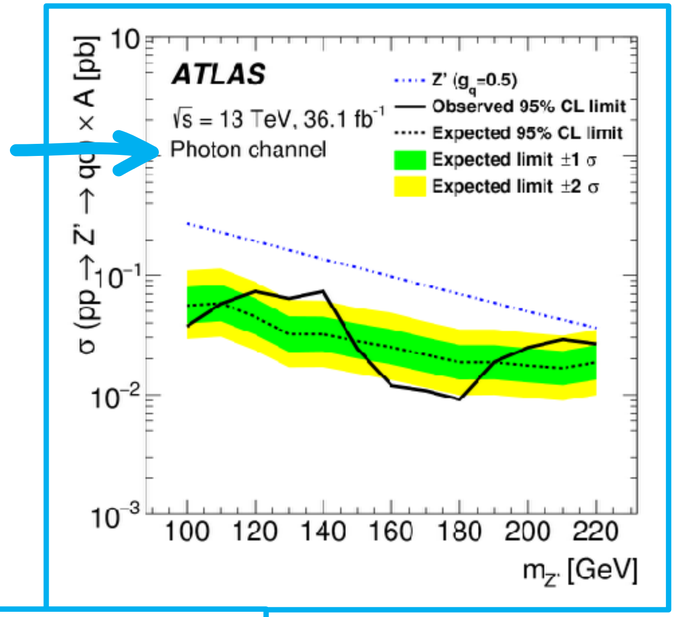
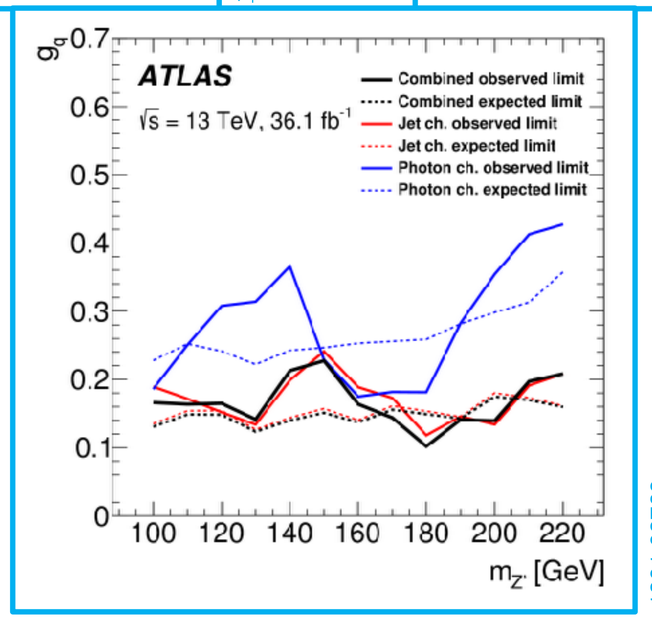
limits [J+ISR]

- limits set on **leptophobic Z'** with **CL_s** method
- lepthophobic Z' **excluded** over the **whole analysis range**
- **g_q coupling** limit ranging from 0.17 at 100 GeV to 0.21 at 220 GeV







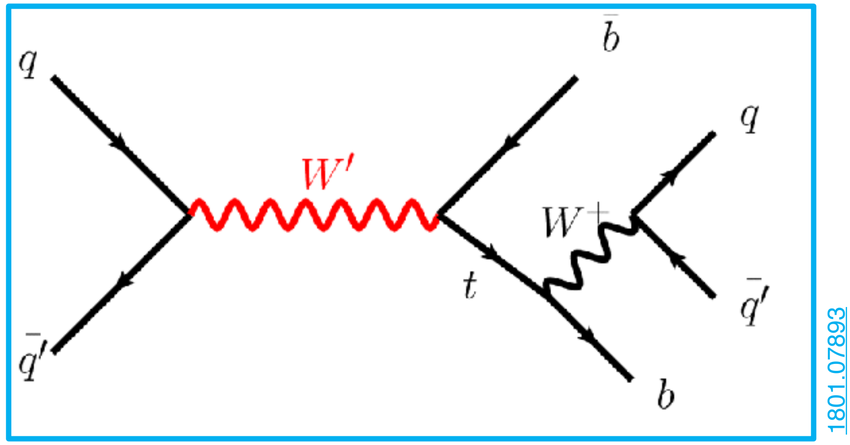
W’→tb

- search for **W’→tb** in the **hadronic final state**
- leptonic W’ analysis has no sensitivity to **right-handed W’**

- 2015-2016 data, 36.1 fb^{-1}

- **trigger**: single jet
- **electron** and **muon veto**
- **large-R jet**
- **top** candidate
  - mass from large-R jet and small-R jet combination
- **b-jet** candidate
  - $|\eta|<1.2$, $\Delta R_{\text{large-R jet}} > 2.0$

- **Shower Deconstruction** to tag boosted **top** jets



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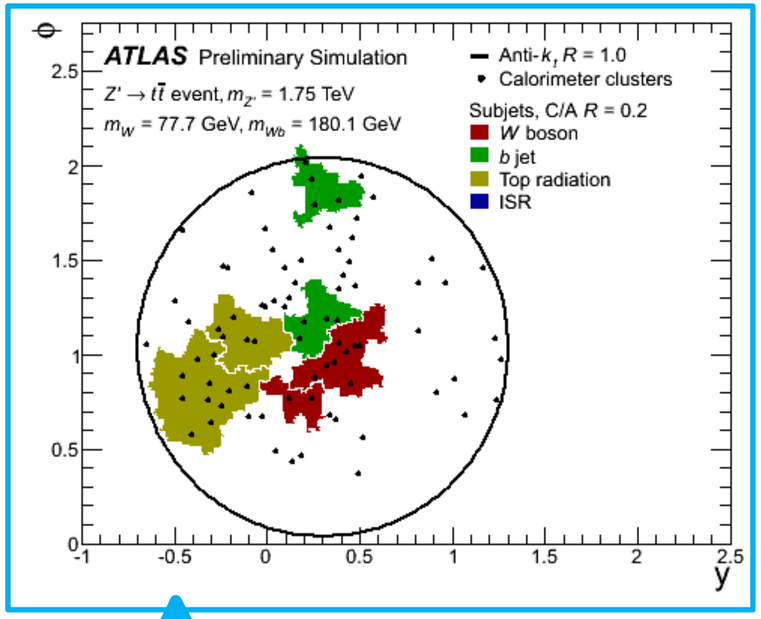
shower deconstruction

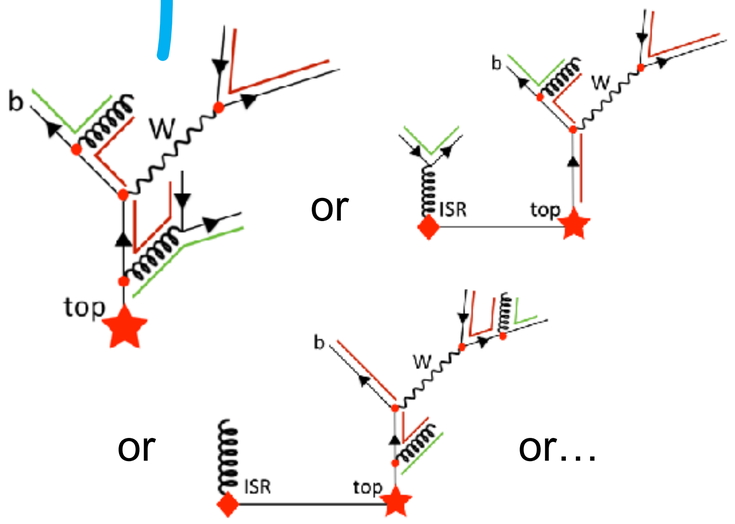
- **Shower Deconstruction** for top jet tagging
- **previous** W'→tb **analysis** iteration (8TeV) used cuts on: $\sqrt{d_{12}}$, τ_{32}, τ_{21}

- **likelihood weight** is computed for each possible **shower that can lead to** a **shower** like the one of the trimmed large-R jet
  - trimmed jet constituents taken as quark and gluon **proxies**

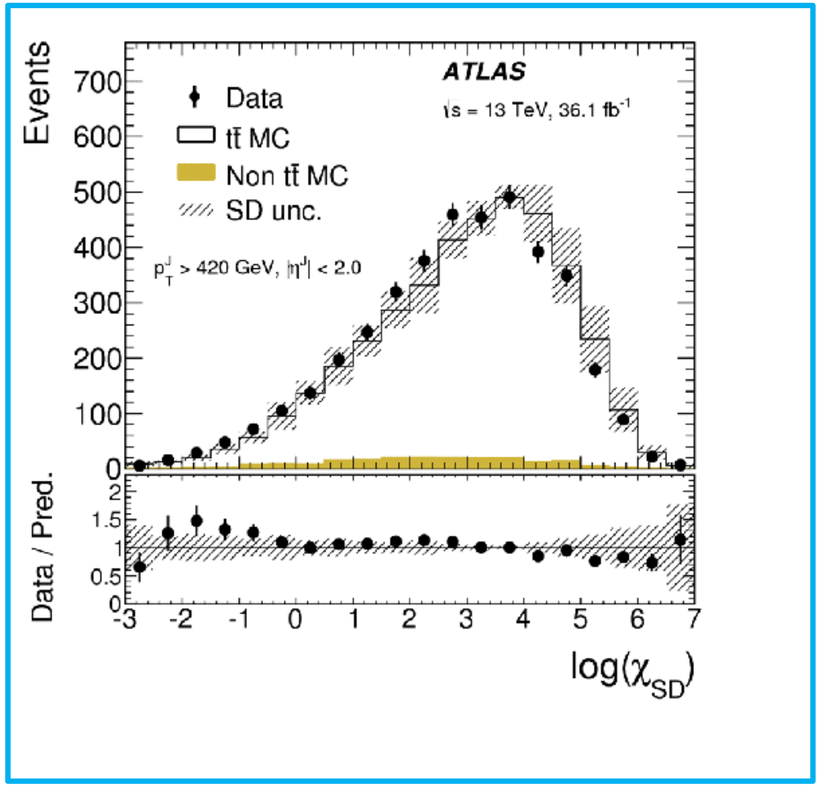
- additional **kinematic requirements**
  - ≥3 sub-jets
  - ≥2 sub-jets **combined W mass**
  - ≥3 sub-jets **combined top mass**



ATLAS-CONF-2014-003



$$\chi_{SD}(\{p_i^k\}) = \frac{\sum P(\{p_i^k\}\,|\,\text{top-quark jet})}{\sum P(\{p_i^k\}\,|\,\text{gluon/light-quark jet})}$$



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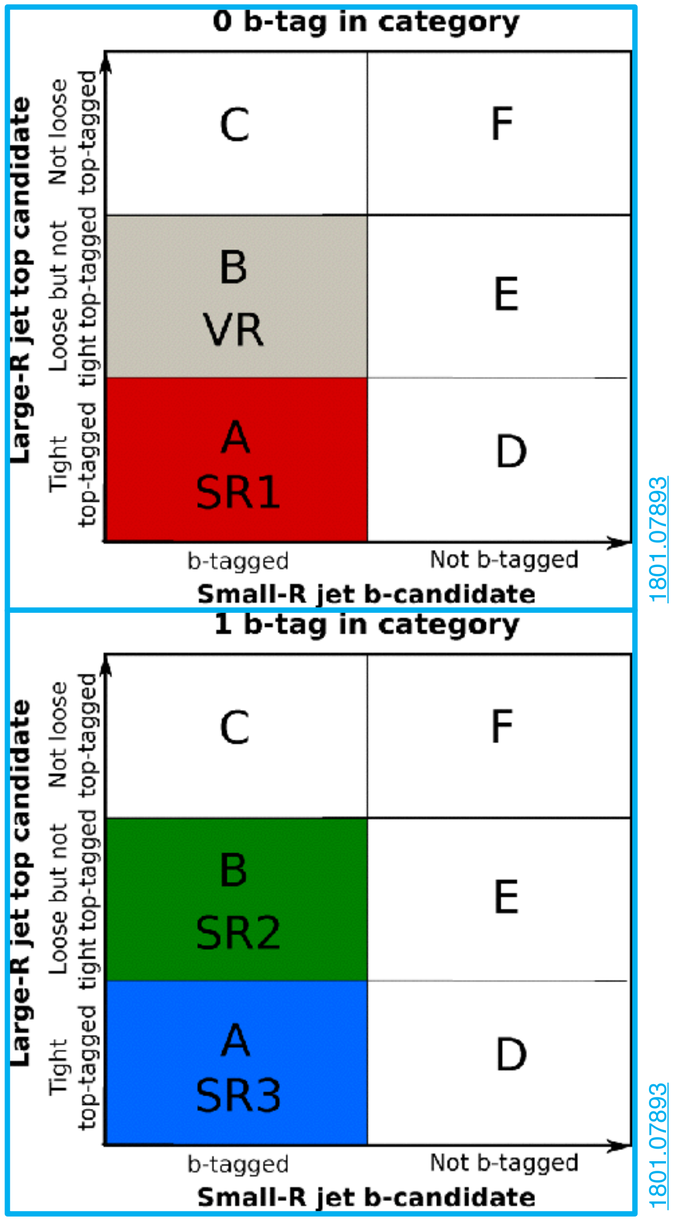
- **2 categories**
  - 0 and 1 **b-tag** jets **within the large-R jet** cone
    - 0 b-tag improves results at **large p_T**
- **6 regions** per b-tag category
  - based on top tagging quality and b-jets presence
- **3 SRs** and **1 VR**
- **data-driven** estimation of **multi-jet and V+jets background**



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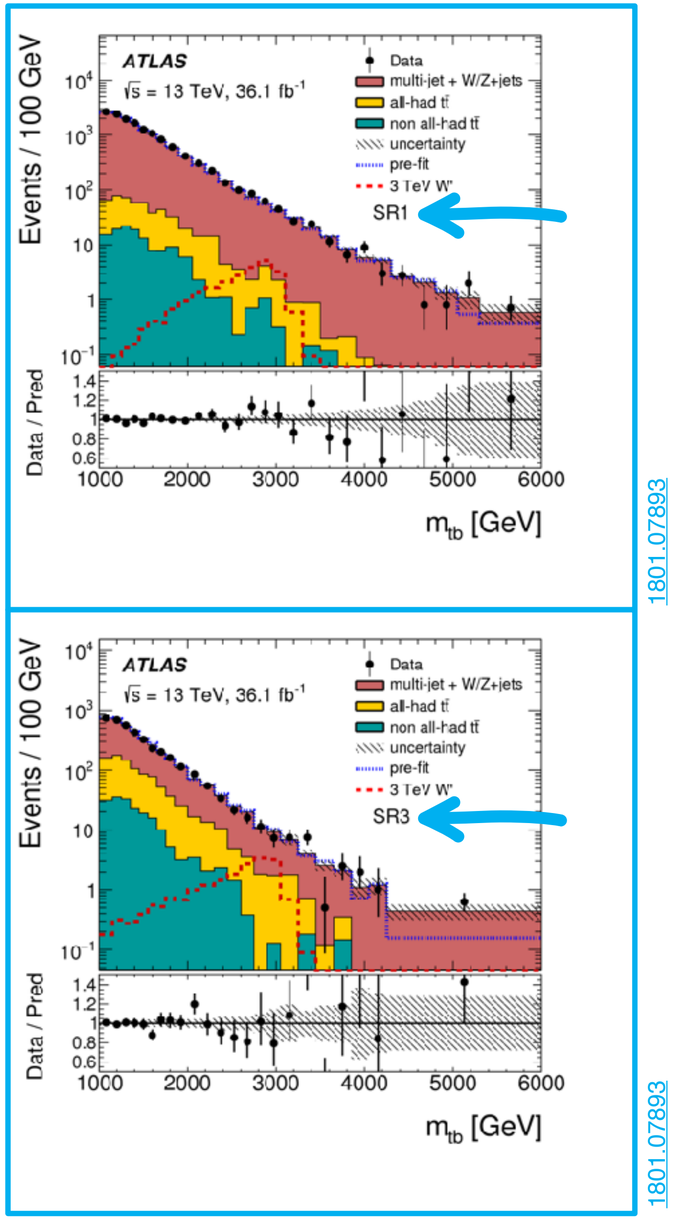
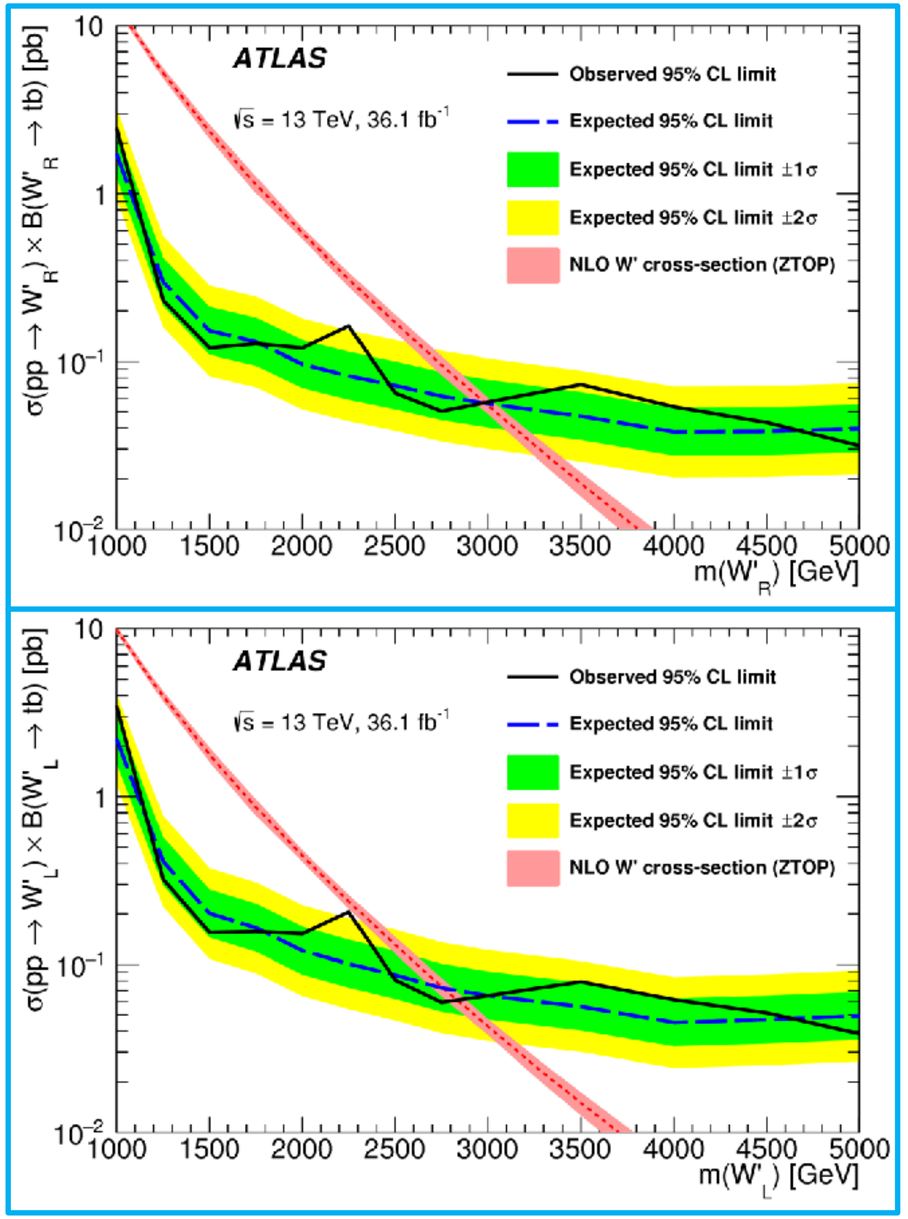
results [W'→tb]

- **simultaneous** binned maximum likelihood **m_{tb} fit** in 3 SRs
- main sources of **systematic uncertainties**
  - 2D sideband background method, flavour tagging
- systematic uncertainties as fit nuisance parameters
- **maximum excess** at 2.25 TeV with 2.0 σ local significance



limits [W'→tb]

- 95% CL limits set with CL_s method
- SSM **W'** excluded up to **3.0 TeV** (right-handed) and **2.9 TeV** (left-handed)
  - difference in cross-section

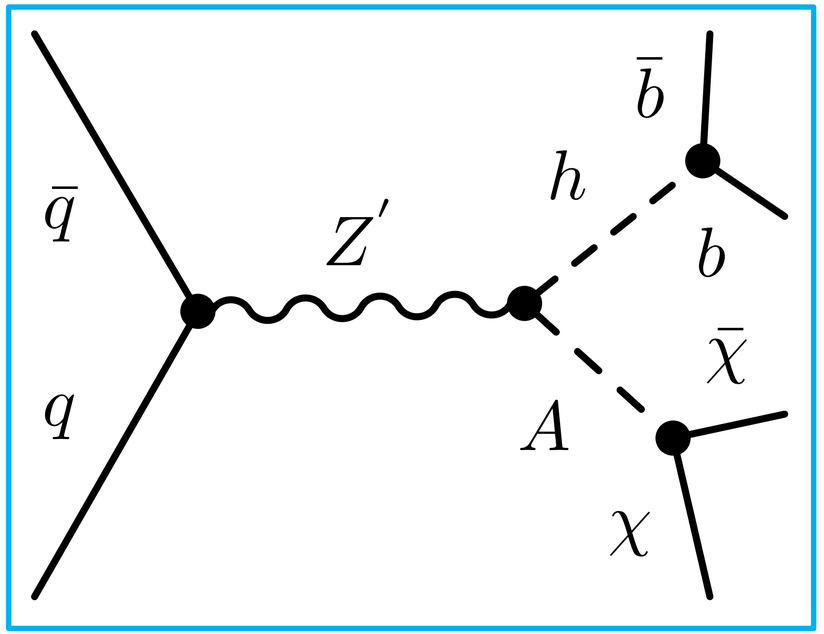


mono-H → bb

- search for **Dark Matter** produced **in association with H→bb**
  - MET + H(bb) **signature**
- **main backgrounds**: tt+jets, V+jets

- 2015-2017 data, **79.8 fb^{-1}**
- MET trigger
- **2 SRs**: **resolved** and **boosted**
  - 4 MET bins

- improvements
  - **Variable Radius track-jets** to improve double b-tagging performance in high boost regimes
  - **MET significance** built taken into account resolution of objects entering its calculation

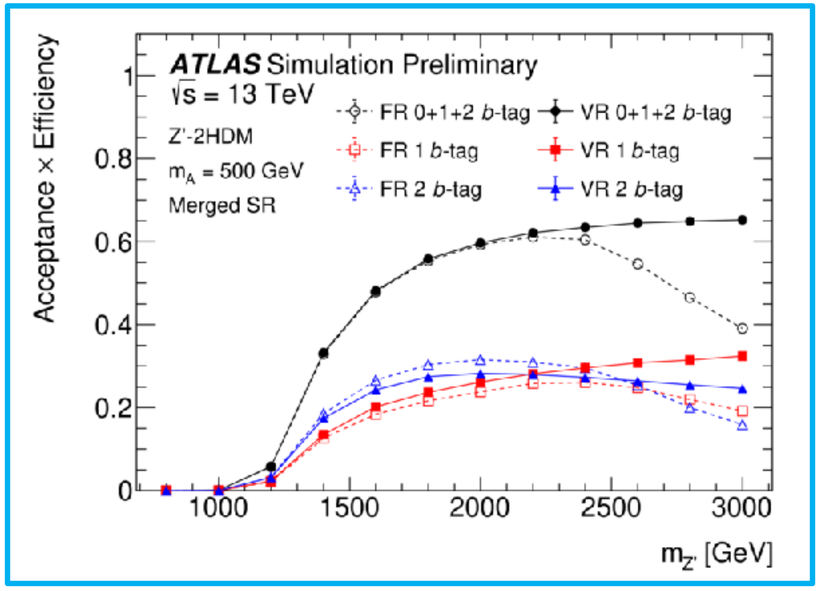


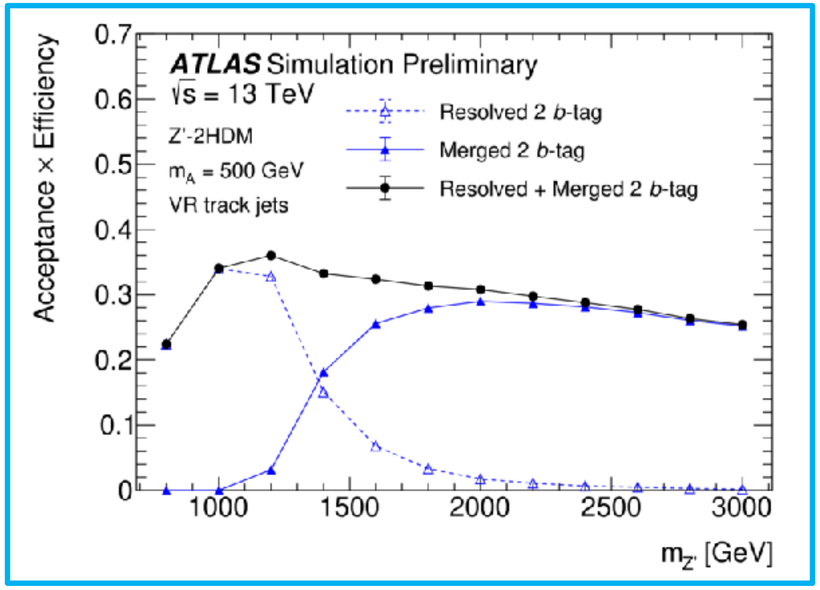
event selection [mono-H→bb]

- objects
  - **small-R jets**: |η|<4.5
  - **large-R jets**
    - trimmed
    - **combined jet mass**
    - b-tagging by **track-jet ghost matching**
  - **VR track-jets**
    - used for the **first time** in analysis
    - originally investigated for calo-jet top tagging
    - anti-k_t, R = 0.02-0.4, ρ = 30 GeV

$$R_{eff}(p_T) = \frac{\rho}{p_T}$$

    - **increased efficiency** $m_{Z'}$ > 2.5 TeV
    - **1.7-1.8 gain** at 3 TeV



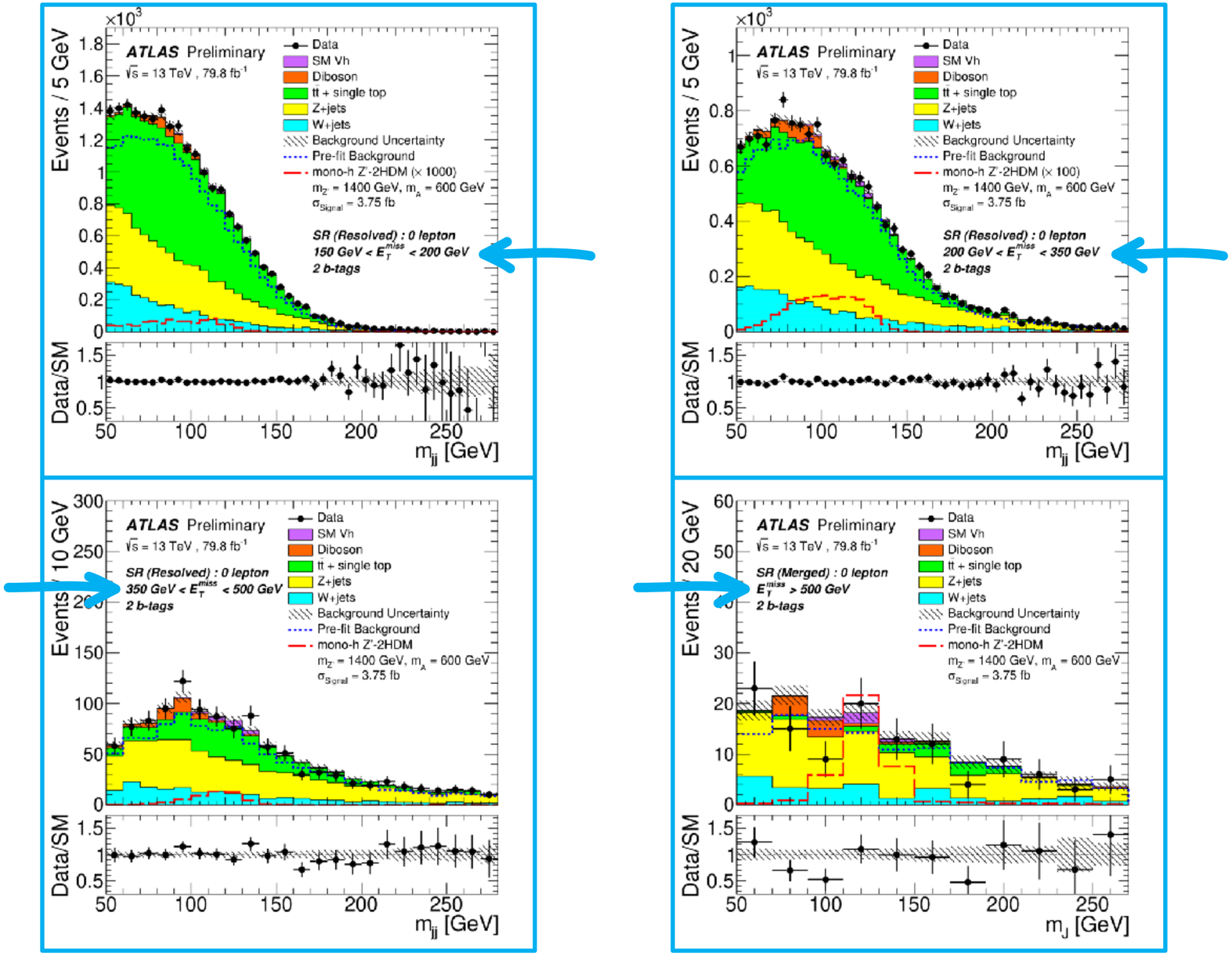


- objects
  - **MET** > 150 GeV
    - **significance** used to asses quality
    - computed from resolution of objects entering MET calculation
- **lepton veto**
  - leptons (1 or 2) used to define **CRs**
- **resolved**: MET = 150-500 GeV
  - exactly **2 b-jets**
- **merged**: MET > 500 GeV
  - **1 large-R jet** with **2 VR b-track-jets**
- **good complementarity** of two regimes

results [mono-H→bb]

- **4 MET bins**
  - **resolved**: 150-200 GeV, 200-350 GeV, 350-500 GeV
  - **merged**: >500 GeV
- **backgrounds**
  - Z+jets, W+jets and tt are dominant
  - multi-jet negligible in both SRs
- **systematic uncertainties**
  - b-tagging, luminosity, JES, JER, MC modeling and statistics

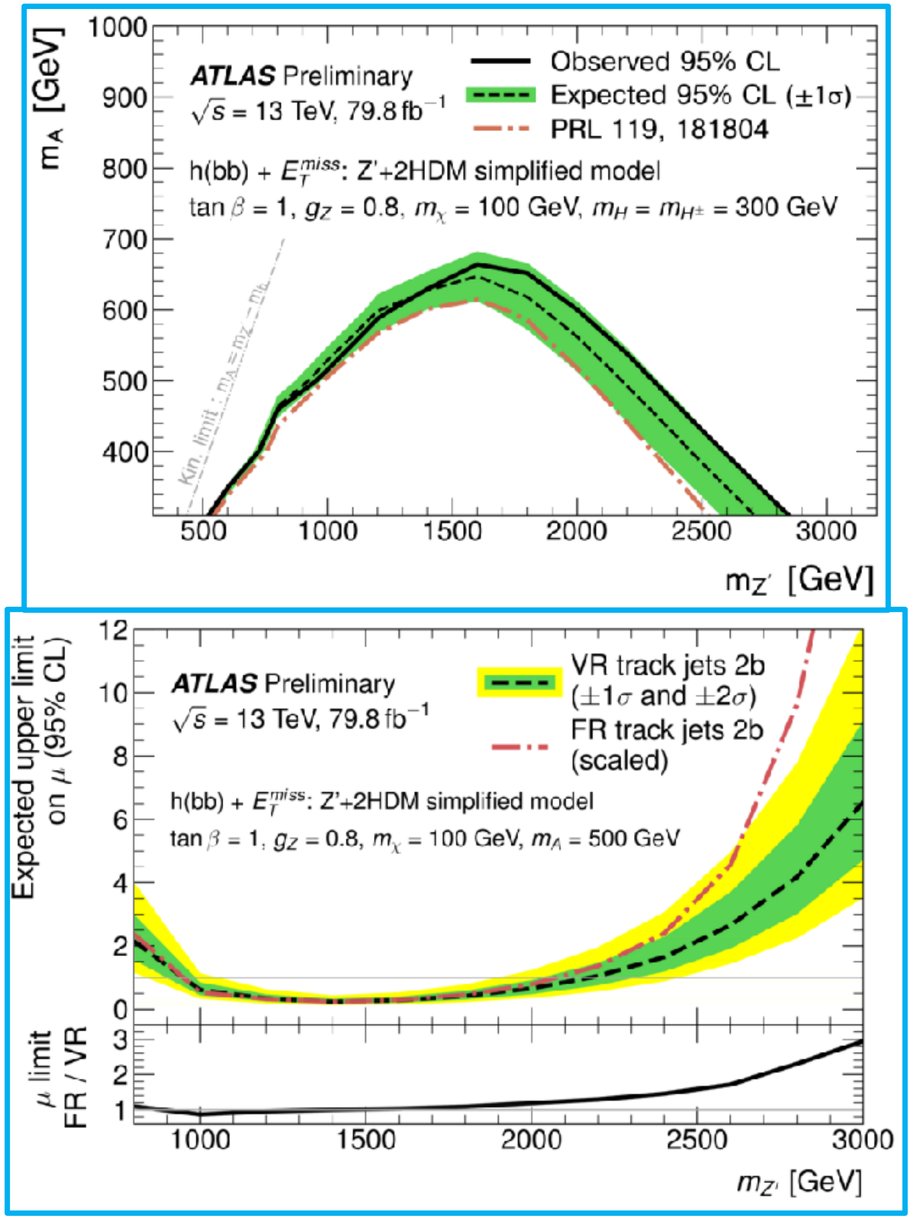
- **m_h** binned likelihood simultaneous **fit**
  - m_{jj} or m_J
  - systematics as nuisance parameters
- **no** significant **deviations** from SM



limits [mono-H→bb]

- limits set with **CL_s method**
- exclusion in the $m_{Z'}$ and m_A plane
- **Z'-2HDM** excluded up to 2.8 TeV for a 300 GeV A

- 3× **improvement** driven by **VR tracks-jets** in boosted region
  - compared to scaled previous results

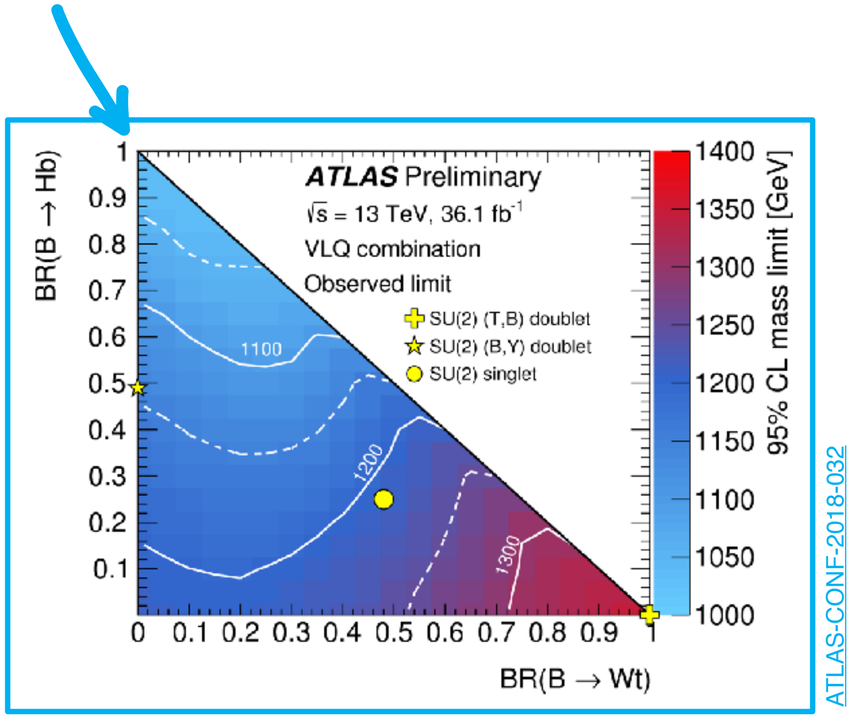


all-hadronic VLQ

- search for **pair production** of heavy **Vector-Like Quarks** that decay into **final states with jets** and **no leptons**
  - TT or BB
  - T → Wb, Ht, Zt or B → Wt, Hb, Zb
- **complementary** search to other VLQ leptonic searches
  - probe the **B → Hb channel**

- 2015-2016 data, 36.1 fb^{-1}

- **Variable Radius re-clustered small-R jets (vRC)**
  - **small-R** jets **re-clustered** using **anti-k_t** algorithm with **variable radius**
  - R_{eff} = **0.4-1.2**, ρ = 315 GeV
  - **trimming** applied on re-clustered jets



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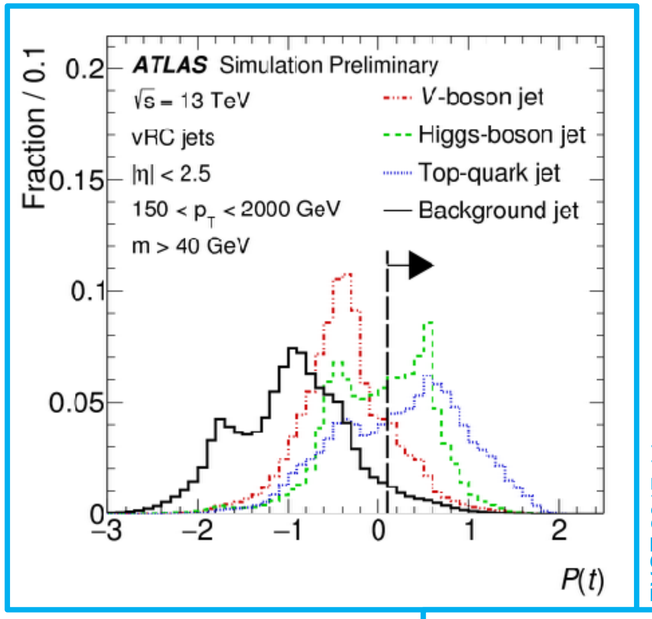
DNN jet tagging

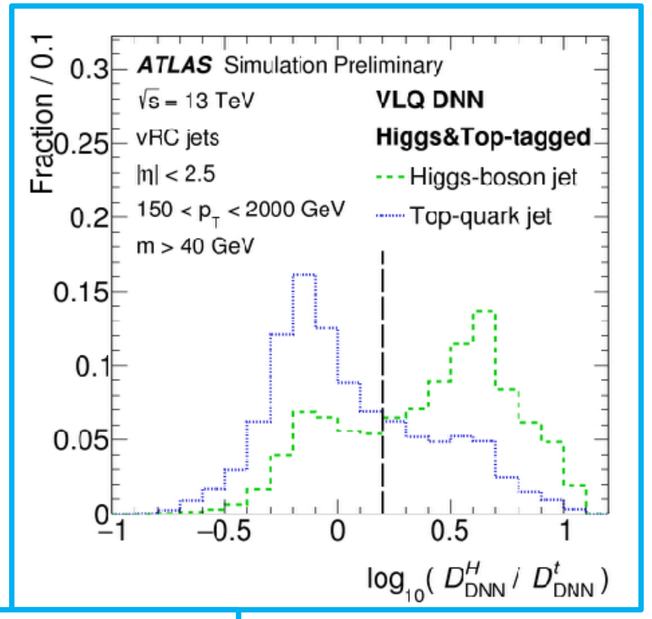
- vRC jets tagging
- multi-class: **W/Z, h, t or background**
- DNN **training** on jet mass, p_T, n constituent jets, four-momentum and b-tagging info
- four fully-connected **hidden layers**
- four-dimensional **output layer**
- **outputs combined** to build **discriminant**, e.g. for top:

$$P(t) = \log\left(\frac{D^{t}_{DNN}}{0.9 \cdot D^{background}_{DNN} + 0.05 \cdot D^{H}_{DNN} + 0.05 \cdot D^{V}_{DNN}}\right)$$

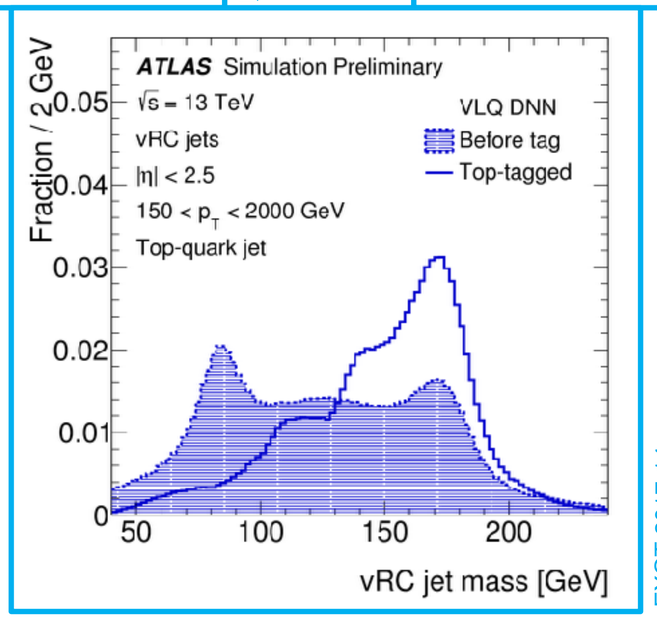
- additional discriminants built to **resolve multiple tagging**
- DNN tagger tends to select jets near the expected **object mass**



EXOT-2017-14



EXOT-2017-14



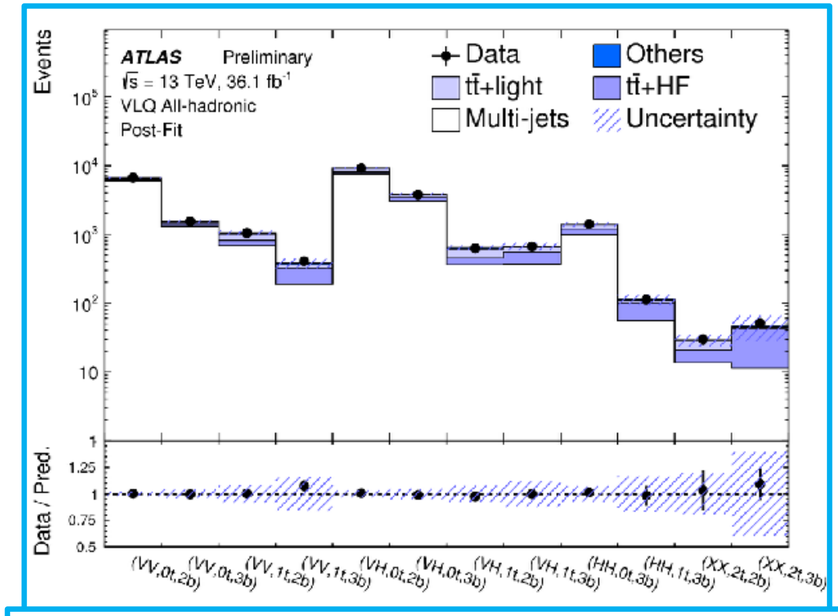
EXOT-2017-14

results [all-had VLQ]

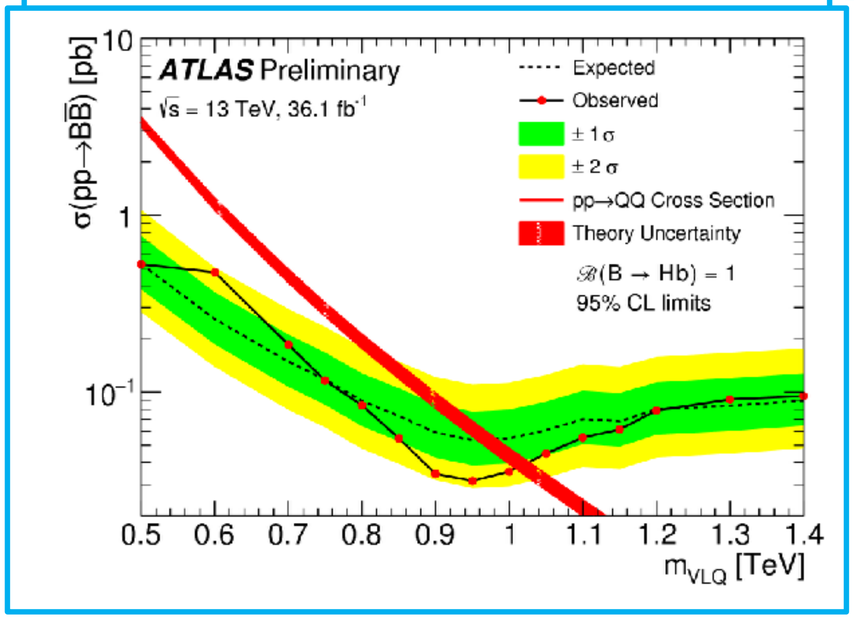
- H_T trigger, lepton veto, MET < 200 GeV
- **require** multiple small-R jets and b-jets
- **reject** events without V/H/t tagged vRC jets
  - **multi-jet background** suppression

- background extraction using ABCD method
- **12 SRs** defined based on: V/H, top and b-tags
  - 9 VRs
- signal probability using **matrix element**
- simultaneous binned likelihood **fit**

- **no significant excess**
- **limits** set using CL_s method
- B→hb excluded up to 1.10 TeV



EXOT-2017-14



EXOT-2017-14

conclusions

- **Wt+X**
  - **Combined Mass** improves mass resolution by combining track-jet and calo-jet information
- **boosted dibosons**
  - **Track-CaloClusters** improves the analysis sensitivity by a factor of 2-4 over projection from previous iteration ← **first time**
- **boosted dijet + ISR**
  - **Design Decorrelated Tagger** efficiently removes correlation between τ_{21} and jet mass
  - DDT allows jet tagging and background distribution fitting
- **W'→tb**
  - **Shower Deconstruction** used to tag top jets
  - use of **Combined Mass** for W and top
- **mono-H→bb**
  - **VR track-jets** to identify **two b-jets** within one large-R jet ← **first time**
- **all-hadronic VLQ**
  - **DNN** for V/H/top **tagging**
  - **VR reclustered jets** ← **first time**

- see talk by David Miller on ATLAS **SUSY** searches

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thank you
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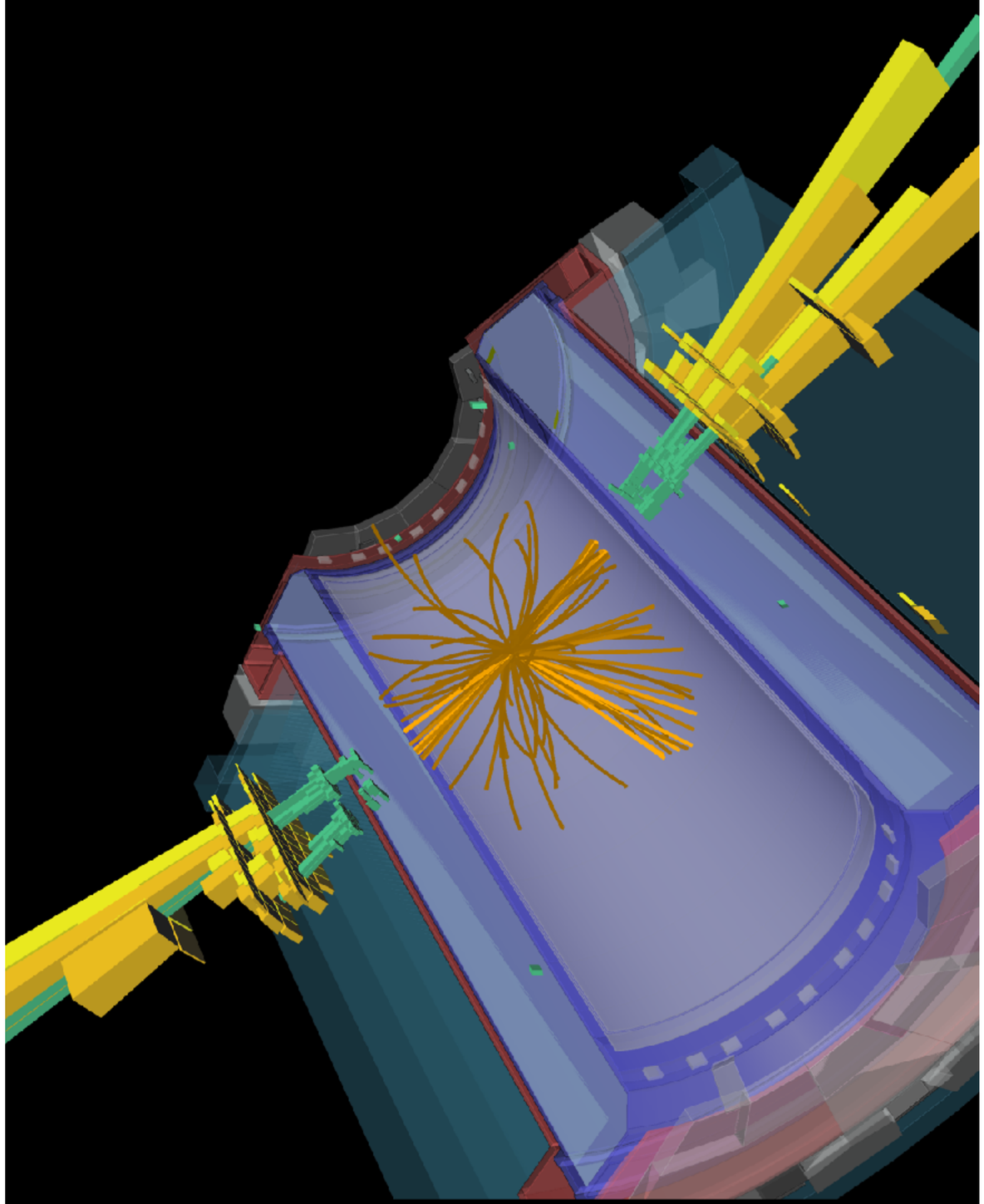

ATLAS EXPERIMENT

Discovery, accelerated