J. Pazzini
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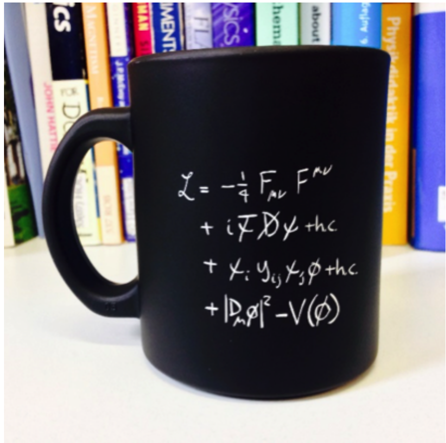
*On behalf of the **ATLAS** and **CMS** Collaborations*

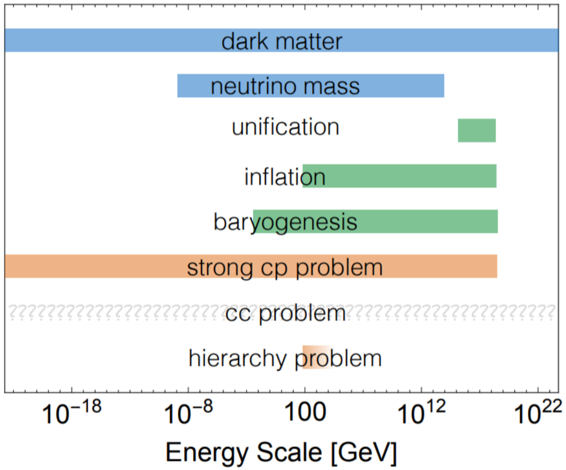
BSM Searches on diboson resonances, vector-like quarks, and heavy bosons with top in the final state

25th Rencontres du Vietnam - Windows on the Universe
5-11 Aug 2018

QUO VADIS?

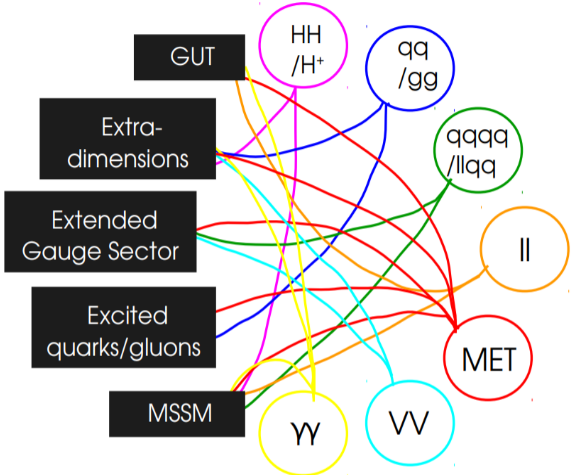
- The Standard Model is not the ultimate description of Nature… but it's still standing strong!
  - Precision measurements in the electroweak sector
  - Observation of very rare processes (e.g. Bs → μμ, …)
  - Higgs discovery and observation of most of its decay channels
  - …
- Some tantalizing hints of "chips" or "cracks" appeared here and there throughout the years
  - Yet, no evidence of something *new* have been observed so far
- We **know** something new must appear somewhere, but what's the scale?





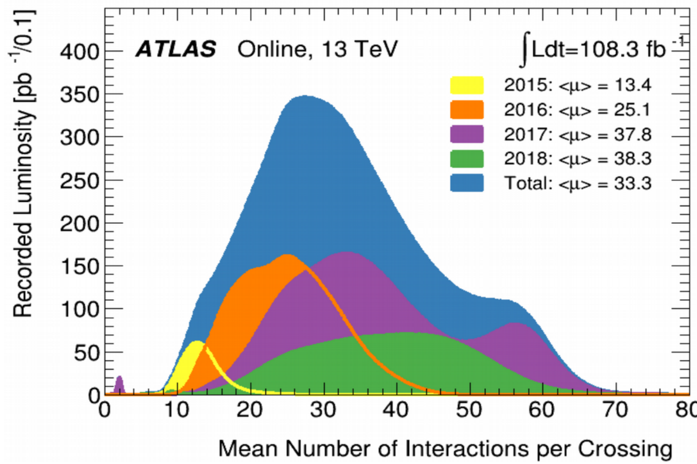
No easy answer

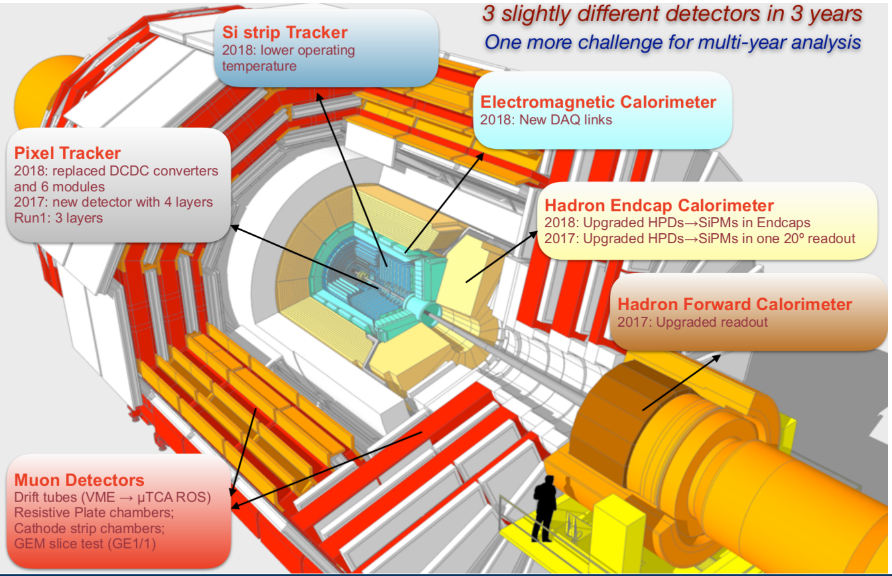
We have to dig further…

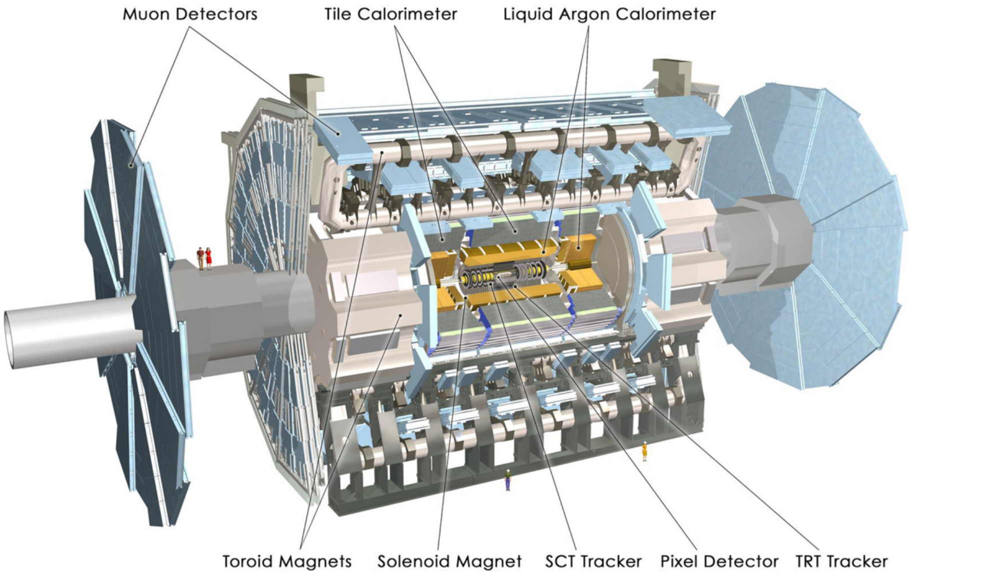


- LHC has been spoiling us with its outstanding performances
    - Aiming to 150/fb in Run2 @ 13 TeV

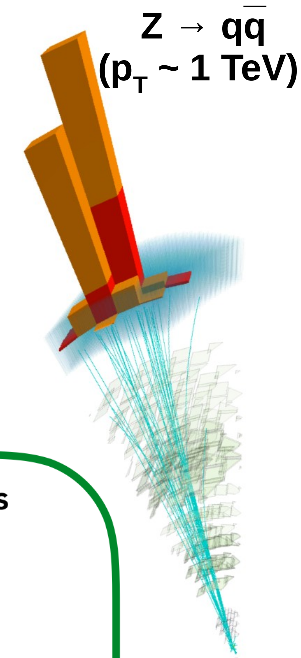
- With more data comes greater… challenges!
    - increased number of simultaneous interactions
      → pile-up mitigation techniques
      → improvements in tools & techniques is key for discovery







THIS TALK

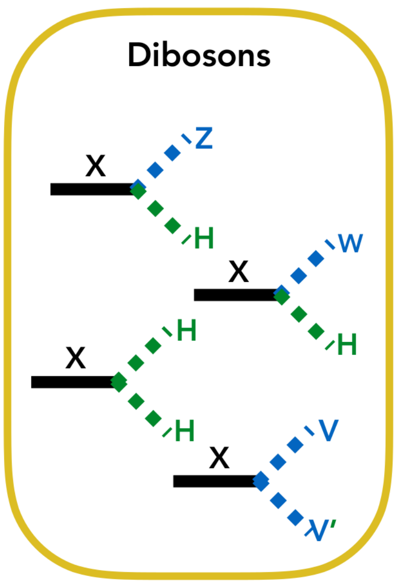


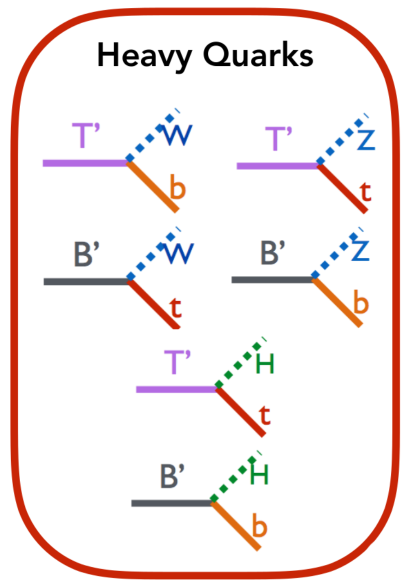
Focus on a *broad* (and quite varied) set of searches for new physics in unique topologies:

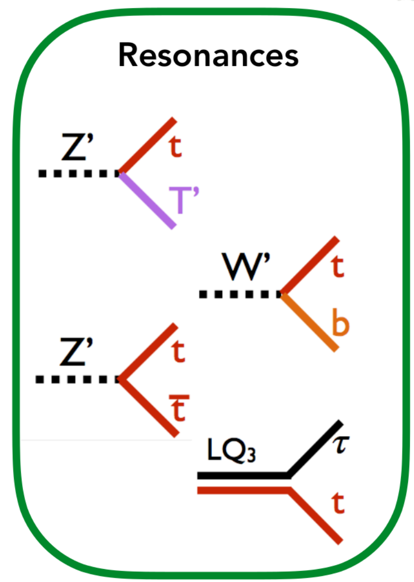
- 4th generation of quarks
- new resonance production
- decays to 3rd generation SM quarks or gauge bosons

With something in *common*:

- Typically massive particles producing highly Lorentz-boosted SM objects
  → reconstruction and identification of hadronic decays critical to most searches

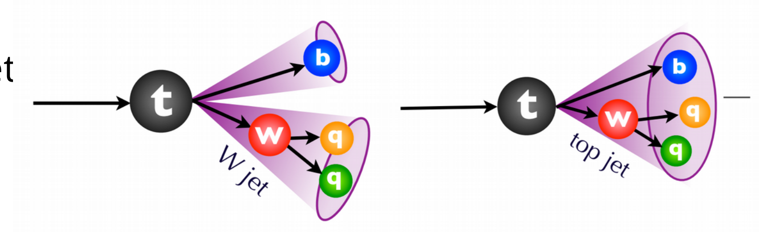






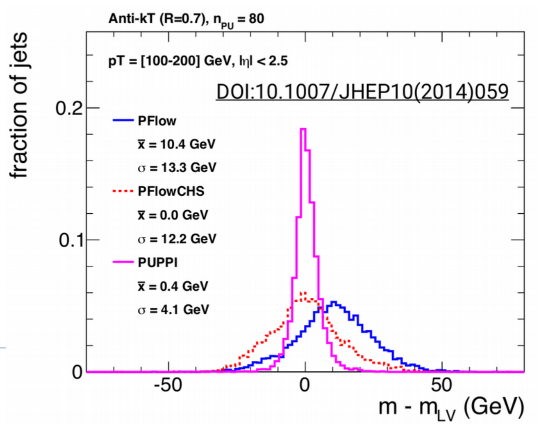
[J.Pilot]

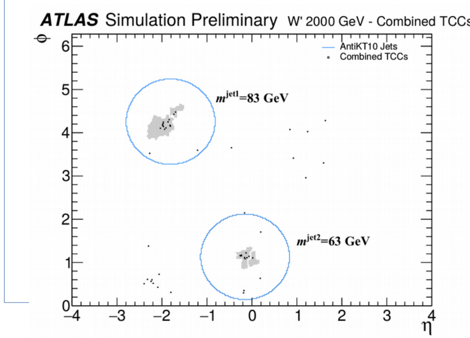
- Common issue in most of the analyses:
  how to tell a $W/Z \rightarrow q\bar{q}$ (or a $t \rightarrow q\bar{q}b$ / $H \rightarrow b\bar{b}$) from a QCD jet
  1. **Reconstruction**
  2. Grooming
  3. Tagging



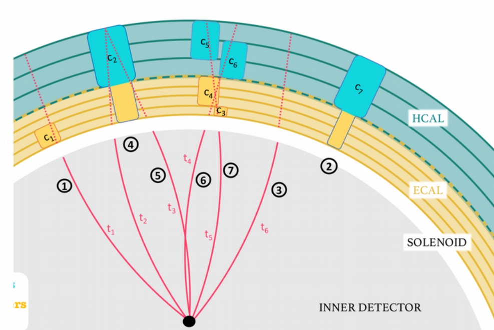
1. Use the best possible combination of detector information to reconstruct jets

CMS	ATLAS
• Use as starting objects CMS standard **particle-flow candidates** • Mitigate pileup with dedicated per-particle identification approach (**PUPPI**)	• Standard use of Calo information for jets • Recently introduced **Track-CaloCluster** objects as input to jet clustering ○ Angular information taken from track, energy from calorimeter

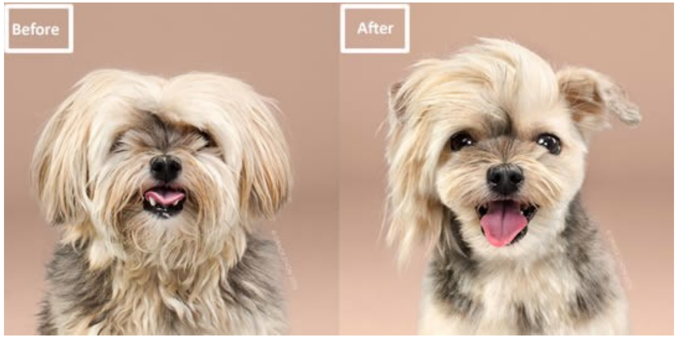




(c) Jets built from only combined TCCs



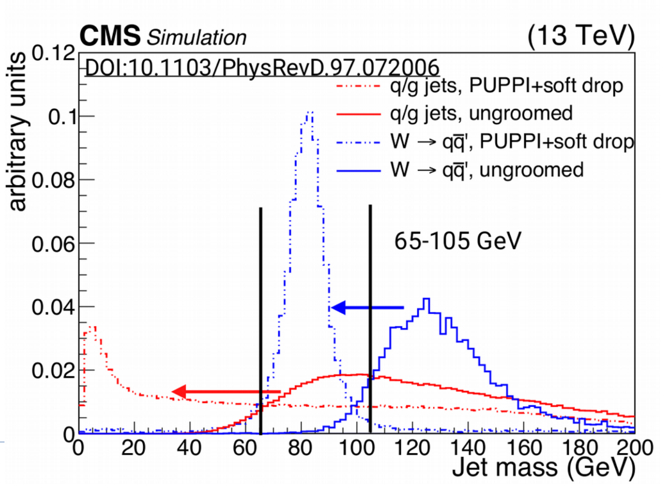
- Common issue in most of the analyses:
  how to tell a $W/Z \to q\bar{q}$ (or a $t \to q\bar{q}b$ / $H \to b\bar{b}$) from a QCD jet?
  1. Reconstruction
  2. **Grooming**
  3. Tagging



2. Removal of soft and large-angle radiation (recover mass)

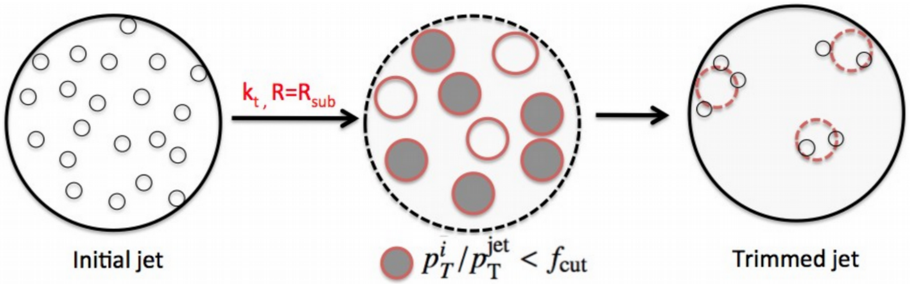
CMS

- **modified Mass Drop Tagger** (softdrop β=0, z=0.1)



ATLAS

- **Trimming** (remove any R=0.2 subjet with less than 5% of the jet p_T)

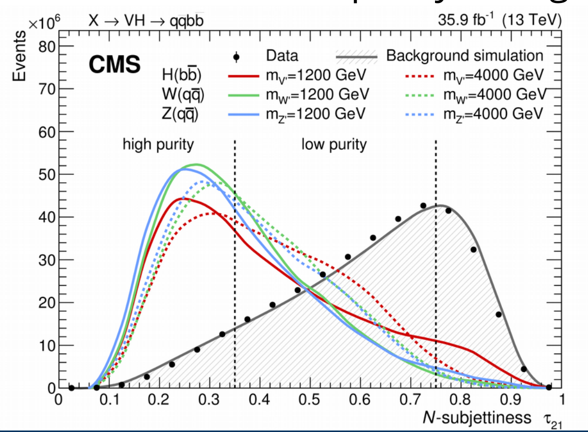


- Common issue in most of the analyses:
  how to tell a W/Z → $q\bar{q}$ (or a t → $q\bar{q}b$ / H → $b\bar{b}$) from a QCD jet?
  1. Reconstruction
  2. Grooming
  3. **Tagging**

3. Assign a tag to a jet based on its likelihood to be "signal" or QCD

CMS

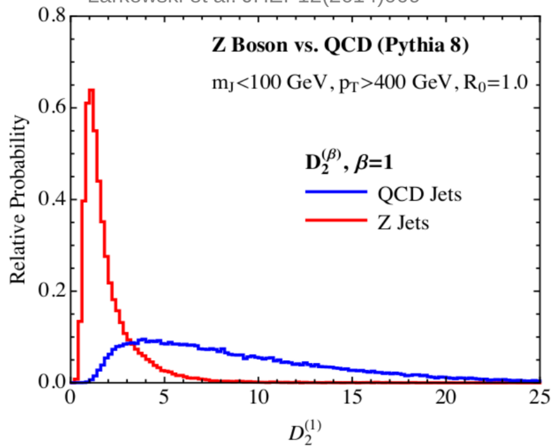
- Soft-drop mass
- N-subjettiness widely used to tag 2-prong W and 3-prong top jets from QCD
  - Often used to define "purity" categories



ATLAS

- Trimmed-jet mass
- 2-points energy density ratio (D_2) used as well as N-subjettiness

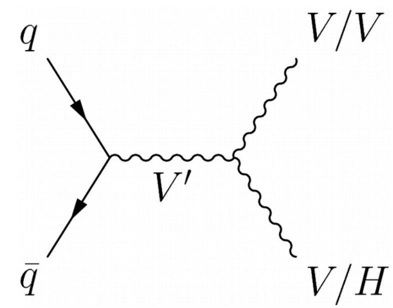
Larkowski et al. JHEP12(2014)009

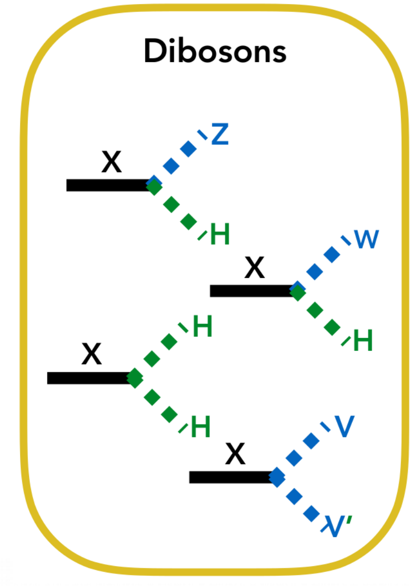


DIBOSON RESONANCES

New heavy resonances coupling to **vector (W/Z) and Higgs bosons** postulated in many BSM models:

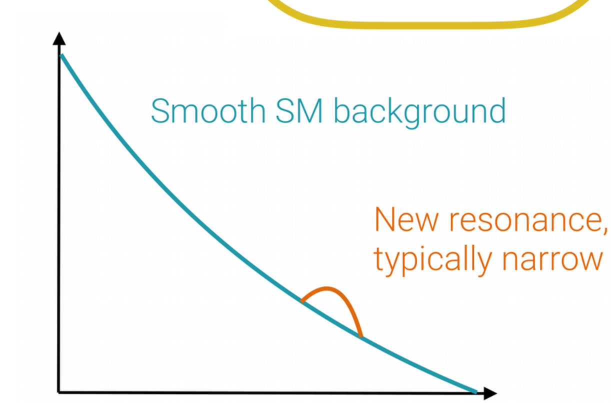
- extended gauge symmetry models
- theories with warped extra dimensions
- two Higgs doublet models
- little Higgs models
- composite Higgs models
- …





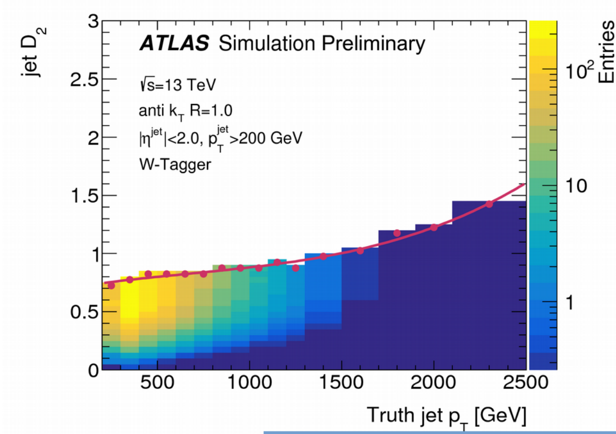
Several VV and VH final states to play with:
- **leptonic / semi-leptonic**
  → good mass resolution and powerful constraints on low-mass
- **fully hadronic**
  → large statistical power, strong large-mass results

Typical search strategy is to look for **bumps over falling background**
- different background expectation approaches available
  mostly based on data

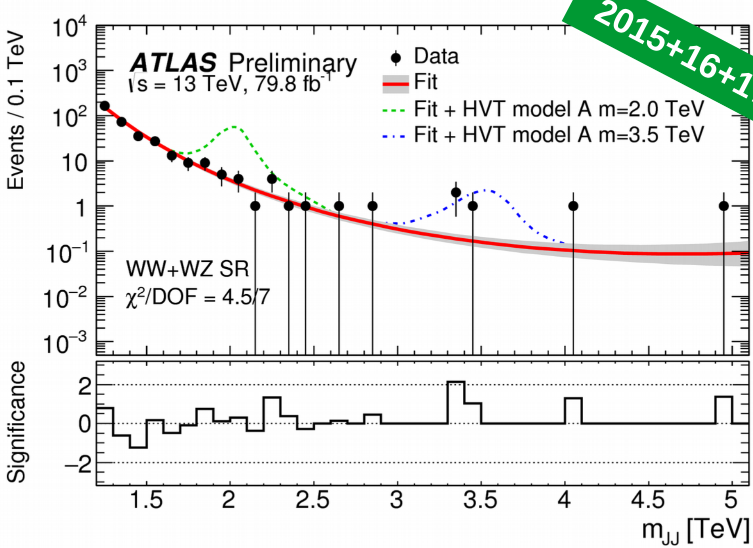


Fully hadronic final state accessible to all WW/WZ/ZZ decays almost exclusively **dominated by QCD** (>95%)

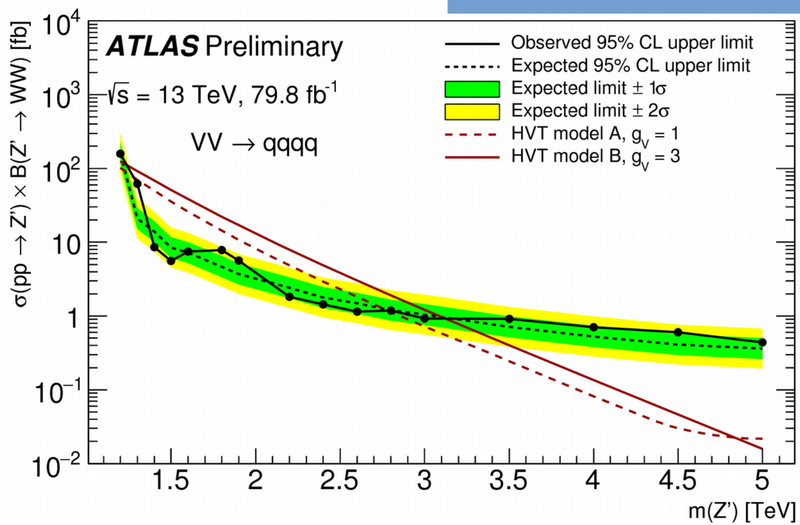
- 2 highly-energetic large radius jets, reconstructed with TCC
- Strongly affected by the tagging performance
  - D_2 and mass used to tag W/Z
  - Use of "dynamic" windows depending on jet p_T to optimize search
- Background is estimated by fitting m_{JJ} falling spectrum + validating in control region



ATLAS-CONF-2018-016



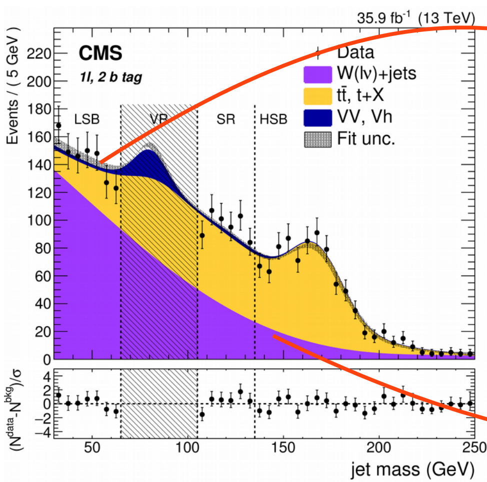
2015+16+17 DATA

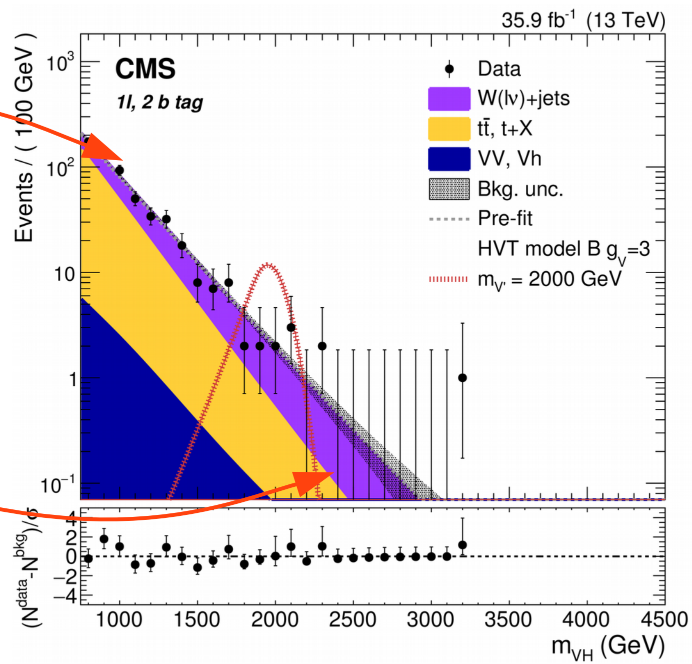


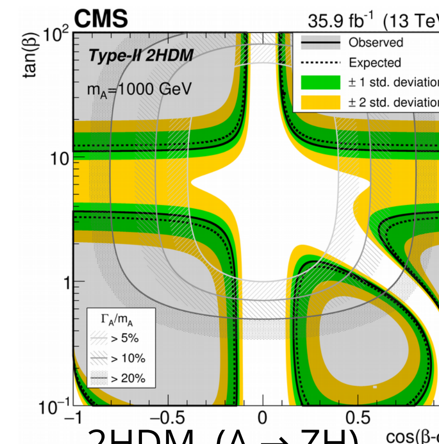
Combination of **H → bb** + **0/1/2 lepton(s)** Z/W final states

CMS-PAS-B2G-17-004

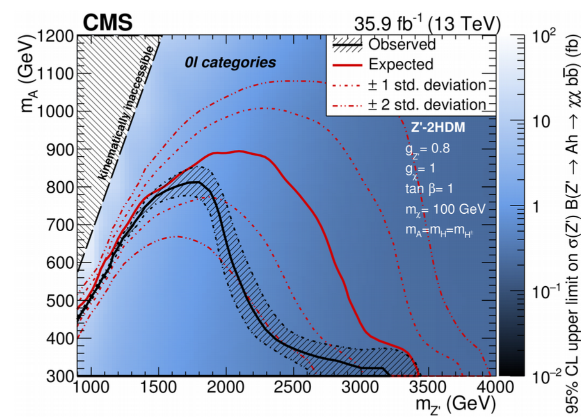
- **H → bb tagging** to discriminate against electroweak/tt background
- **V+jet** background estimated in **mass sidebands**
  + corrections from simulation to account for mJ-mVH correlation







2HDM (A → ZH)



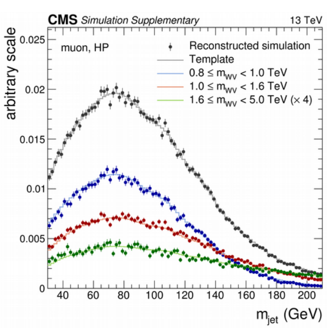
Dark-Matter

Search in **single lepton + large-radius jet** final state

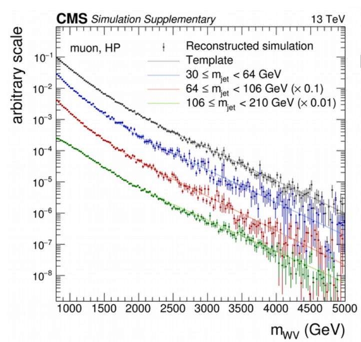
JHEP 05 (2018) 088

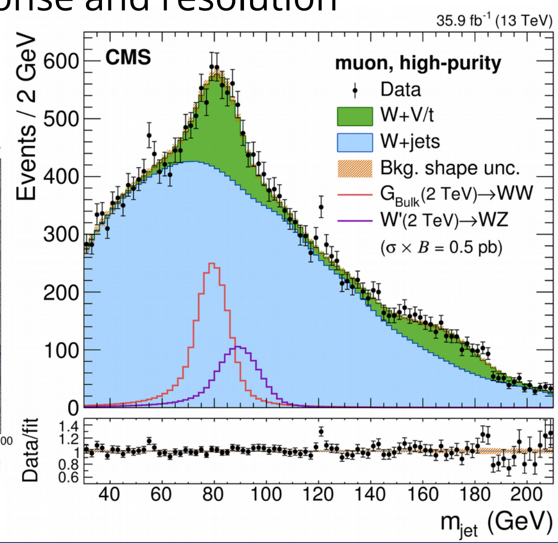
- Bkg. estimated fully based on data, as an extension of the “classic” bump-hunt approach
  - **Bump-hunt in 2-dimensional plane** of **m_J-m_{VW}**, where signal is expected to peak in both
  - Background not peaking in m_{VW} and divided into two classes
    - WV diboson production and tt → peaking in m_J
    - W+jet production → not peaking in m_J

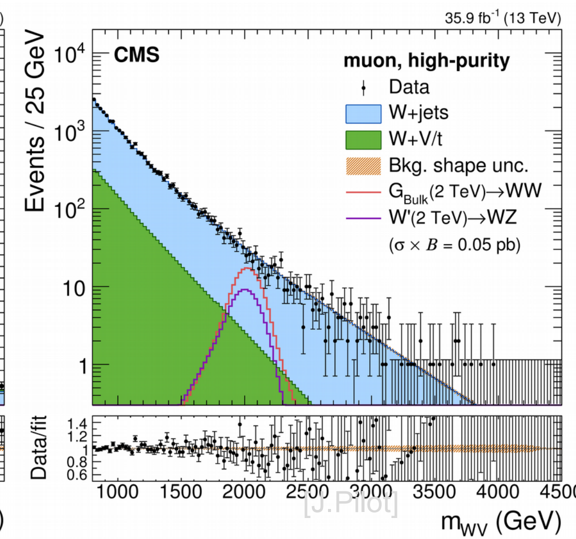
- Smooth 2D templates build with Kernel Estimator Approach: each generated event modeled with a dedicated Gaussian, smeared for response and resolution



x







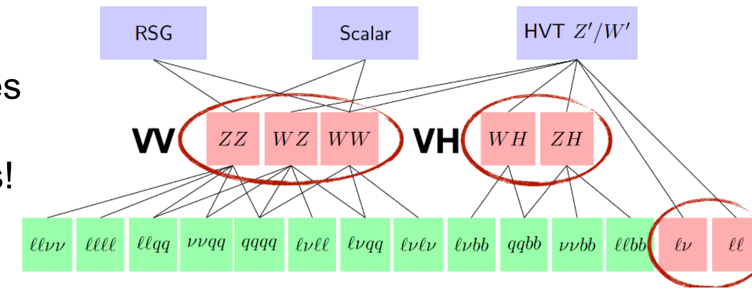
[J.Pilot]

Both collaborations are covering an impressive set of **complementary final states** in their diboson search programmes

Recently released results with the combination of 2015+16 diboson results from ATLAS

Wide interpretation of the results, with strong exclusion limits set:

- **Model-independent** limits on ZZ/WZ/WW/ZH/WH processes
- **Model-dependent** combination of **VV+VH**
- Grand-**combination** of X → VV/VH **with X → ll/lν** searches!



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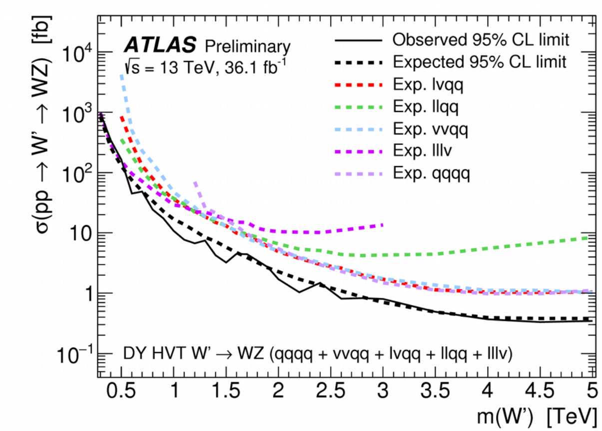
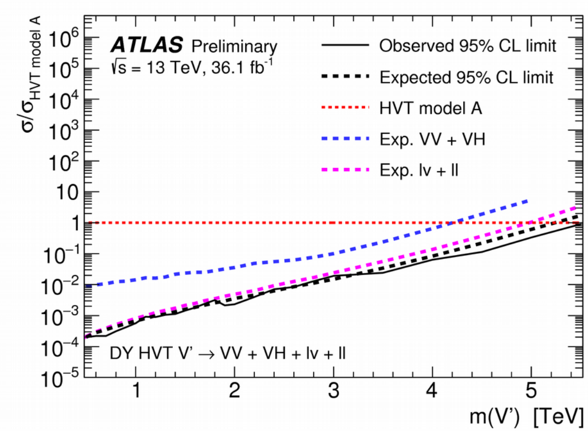
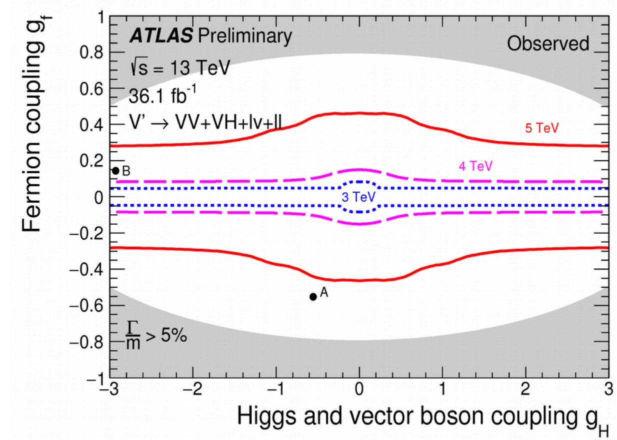






Fermionic objects (4th gen. “quarks”), **not chiral** (“vector-like”)

→ can appear as **singlets**

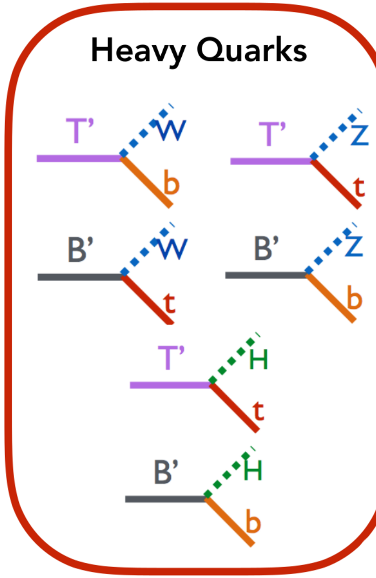
- **T , B**

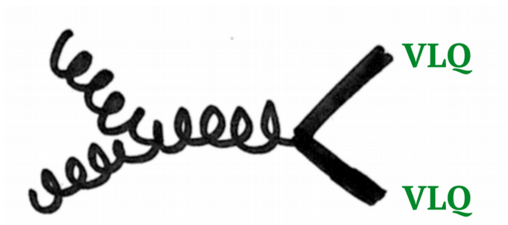
→ or **multiplets**

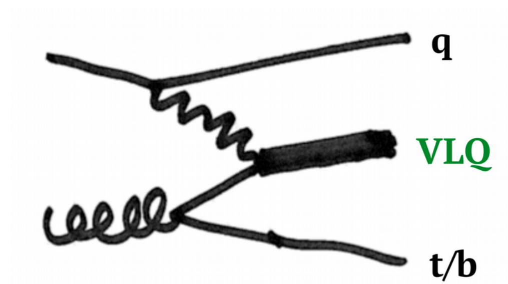
- **(X5/3, T) , (B, Y4/3) , (X, T, B) , (T, B, Y)**

→ Produced by QCD and Electroweak processes

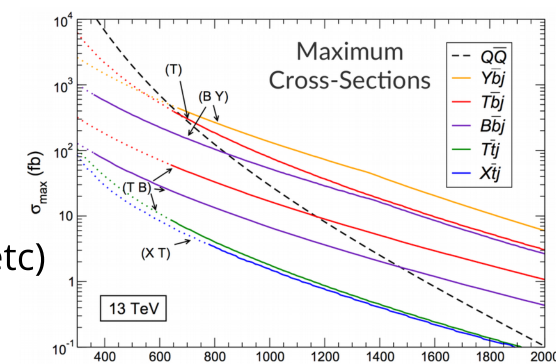
- **Pair production** → mostly model-independent + high cross-section
- **Single production** → coupling to SM quarks is also involved!







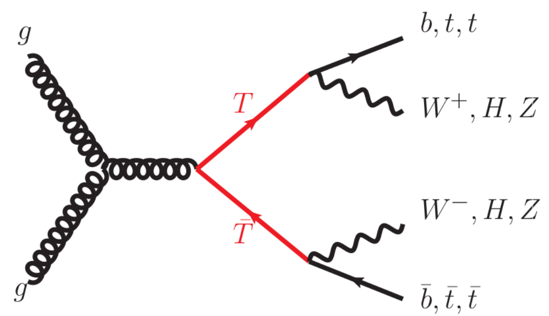
- Present in many extensions to the SM (little-Higgs, extra dimensions, etc)
- Good candidate for solving hierarchy problem, among others…

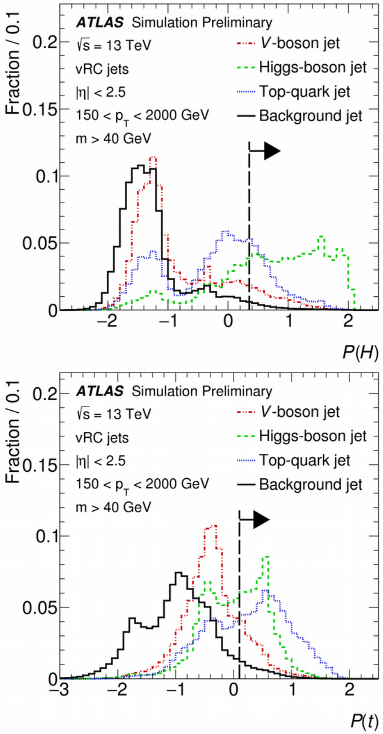


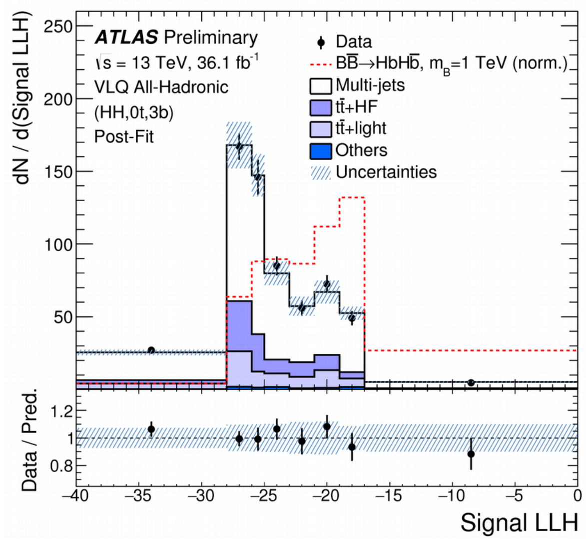
arXiv:1306.0572

Final state targeting all the hadronic decays of TT and BB

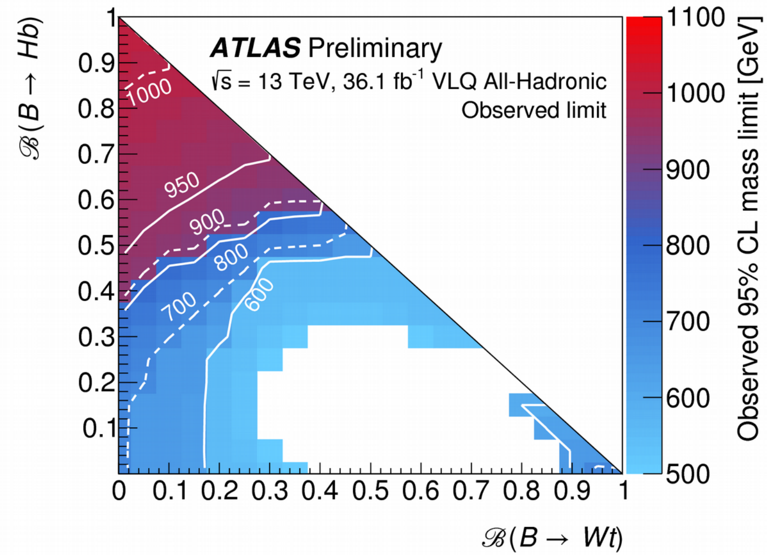
- Very interesting for **B → bH** – hard to probe in leptonic channels
- High multiplicity of small-radius jets (R=0.4)
  + *variable-radius reclustering technique → vRC jets*
- A multi-class DNN is used to tag vRC jets as W/Z, H, t
- Final discriminator based on the matrix element method







See talk by Erich Varnes (T2 parallel session)



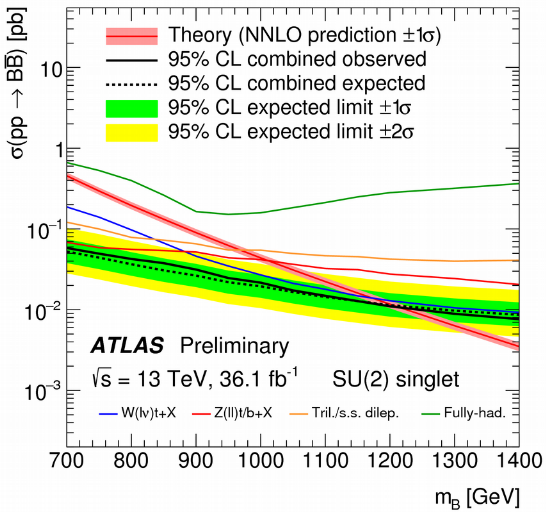
CERN-EP-2018-176

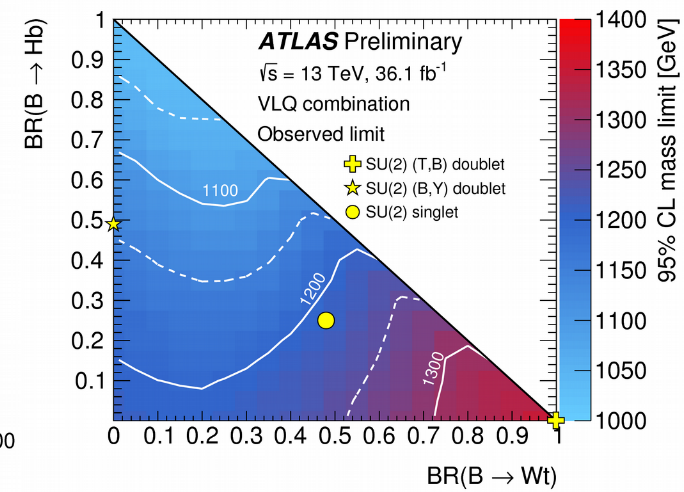
VECTOR-LIKE QUARKS – PAIR PRODUCTION COMBINATION

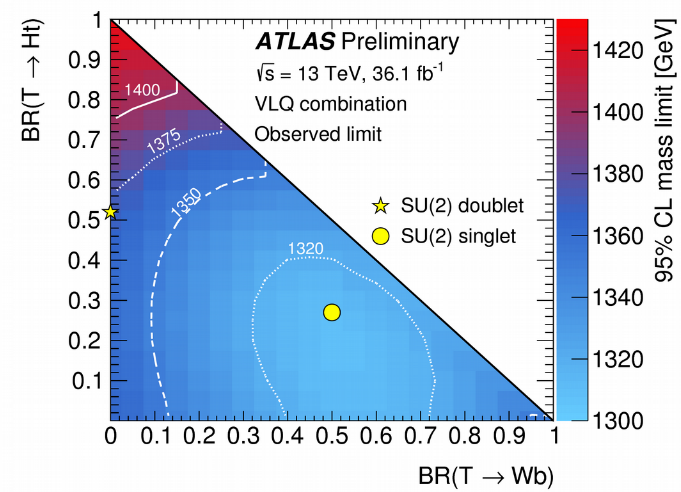
Recent **combination of all 13 TeV TT/BB** searches from ATLAS

- Powerful result as **model-independent** searches
- 0 / 1 / 2 / >2 lepton final states
- Significant extension of the results from single searches thanks to the complementarity of the final states

Analysis	$T\bar{T}$ decay	$B\bar{B}$ decay
$H(bb)t + X$	$HtH\bar{t}$	-
$W(\ell\nu)b + X$	$WbW\bar{b}$	-
$W(\ell\nu)t + X$	-	$WtW\bar{t}$
$Z(\nu\nu)t + X$	$ZtZ\bar{t}$	-
$Z(\ell\ell)t/b + X$	$ZtZ\bar{t}$	$ZbZ\bar{b}$
tril./s.s. dilepton	$HtH\bar{t}$	$WtW\bar{t}$
fully-hadronic	$HtH\bar{t}$	$HbH\bar{b}$



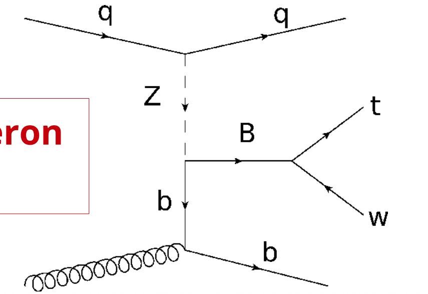




- Exclusions **for any considered branching ratio**:
  → m(T) < 1.31 TeV
  → m(B) < 1.03 TeV

See talk by Erich Varnes (T2 parallel session)

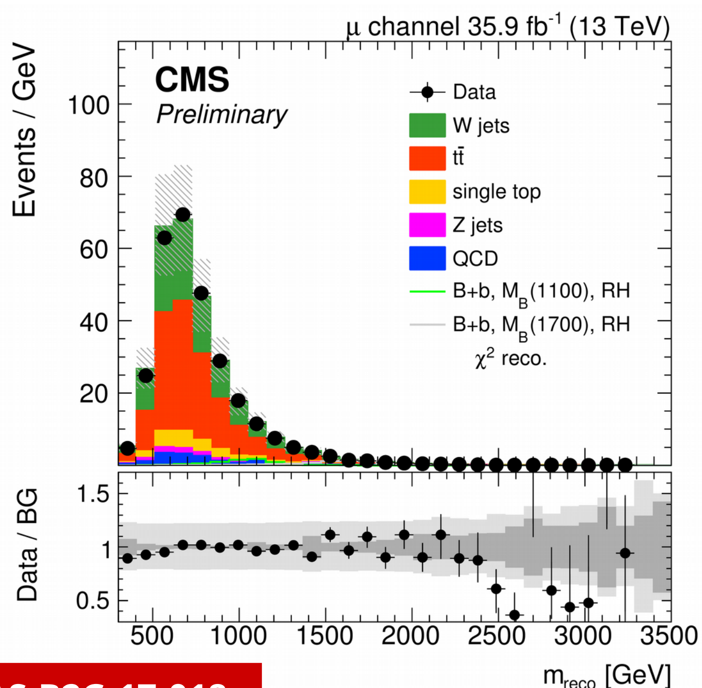
ATLAS-CONF-2018-032

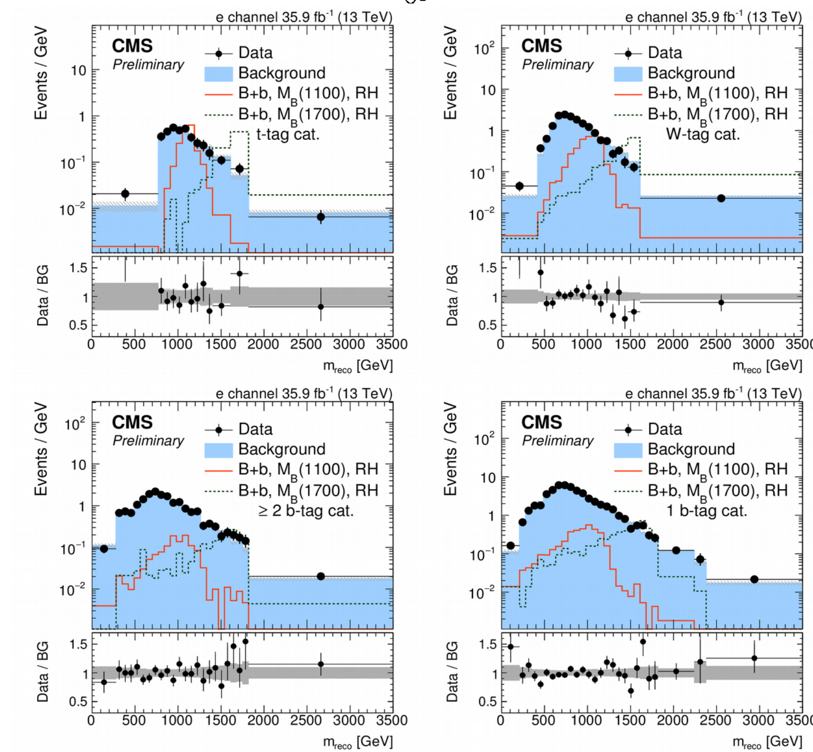


Single production of a **B (or $X^{5/3}$)** VLQ, probed in single-lepton final state

- Categorization based on the topology (boosted t / boosted W / non-boosted W,t) and b-jet multiplicity
- **Control region** with **no forward jets** used to extrapolate the background shape to signal region

See talk by Stephanie Beauceron (T2 parallel session)



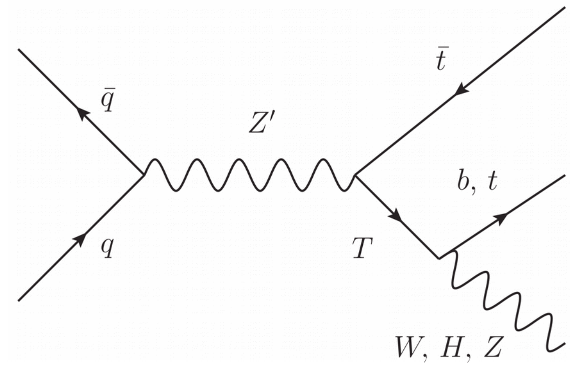


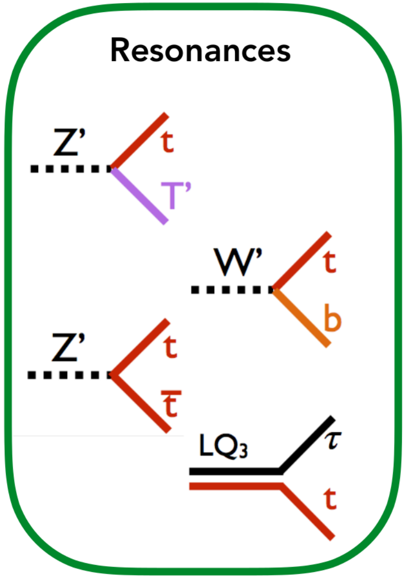
CMS-PAS-B2G-17-018

Resonances with top are a highly promising field for BSM searches:

- Top quark is in general a peculiar object in the SM:
  - **almost 1 Yukawa coupling** to the Higgs potential
  - top-quark loops provide the largest corrections to the Higgs field, and play a **major role in the hierarchy problem**
- Many BSM models involving new bosonic resonance feature enhanced coupling to third gen. quarks
- Models typically involving higgs compositeness allow decays of new heavy resonances in VLQs + t quarks

- Final states are generally very rich:
  - Searches for new resonances with top are **often** performed as **bump hunt in the resonance mass peak**
  - in **complex final states** precise reconstruction of the candidate is close to impossible → some proxy to **energy measured in the detector** (H_T, S_T) is also used.



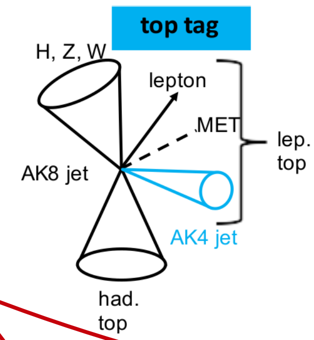


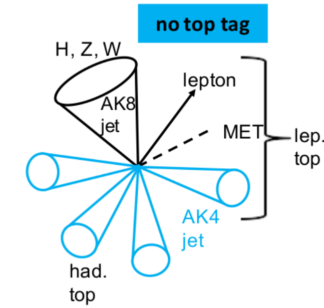
CMS-PAS-B2G-17-015

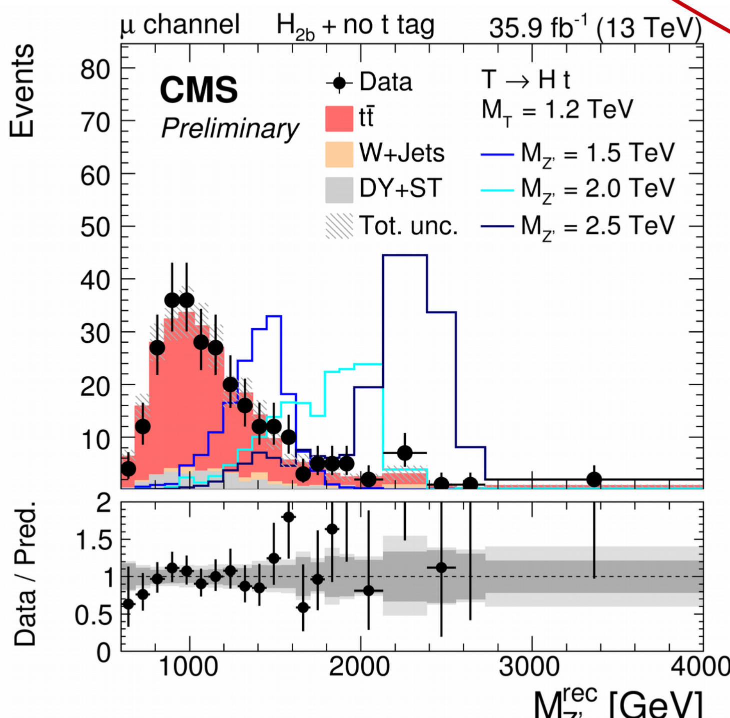
Search for **resonant production** of a VLQ **T** and a SM **t**

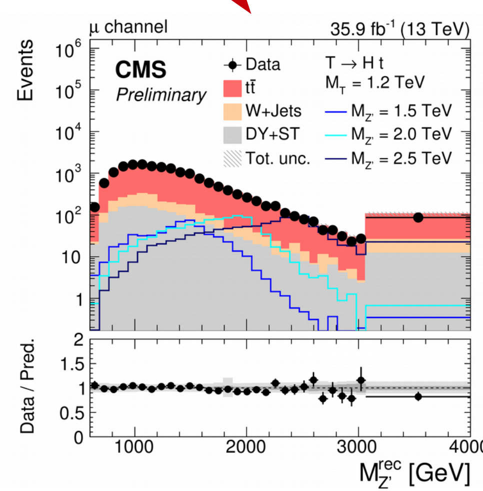
- Complex final state involving **t + Ht/Zt/Wb**
  → Multiple **boosted jet categories** are used to target all the final states

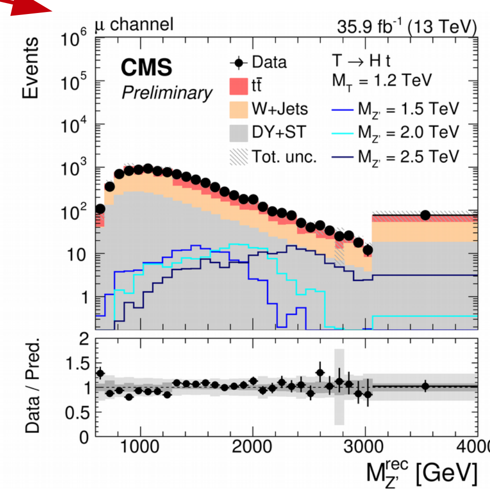
- Main backgrounds controlled in V/H mass sidebands
  - W+jet extracted from 0-b category
  - tt extracted from >=1 b category







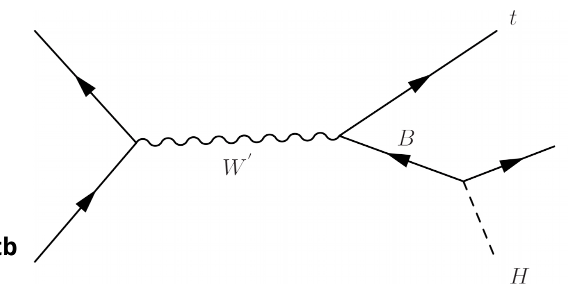


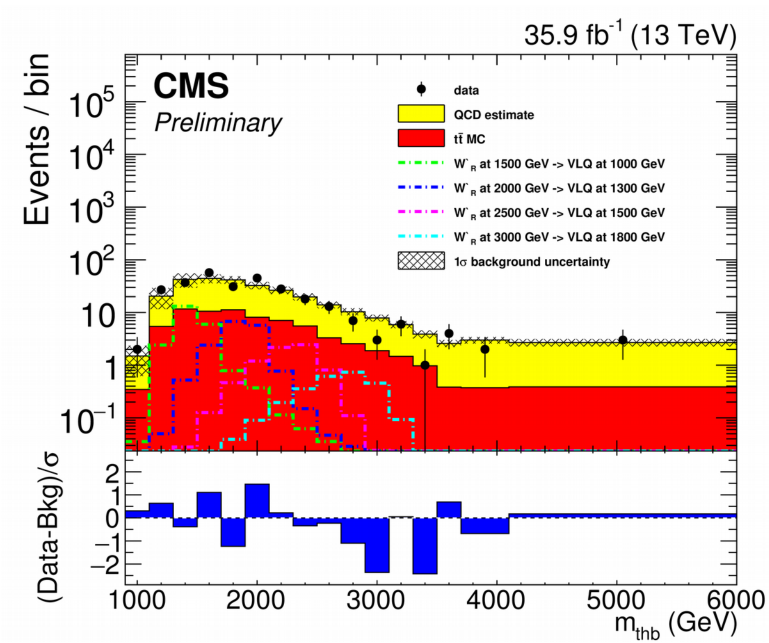


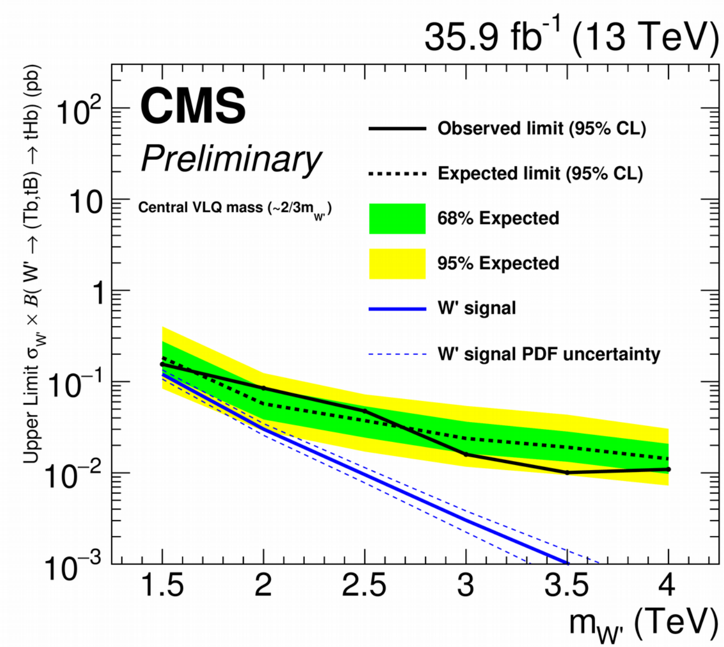
CMS-PAS-B2G-18-001

Recent search for resonant production of a **VLQ** and a **SM 3rd gen. quark**

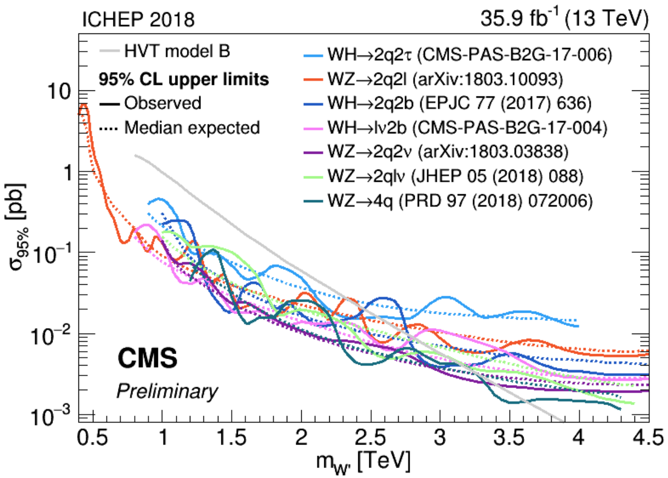
- Targeting the **T→Ht / B→Hb** decays → **fully boosted Htb final state**
- All-hadronic final state involving ~all taggers
  1. top-tagging
  2. Higgs-tagging
  3. b-tagging
- **QCD** background estimated in **anti-tagged control-regions**
- Final fit is performed on the fully reconstructed candidate mass $\mathbf{m_{Htb}}$
- Exclusion up to W' < 1.6 TeV under the 100% BR(Tb) assumption

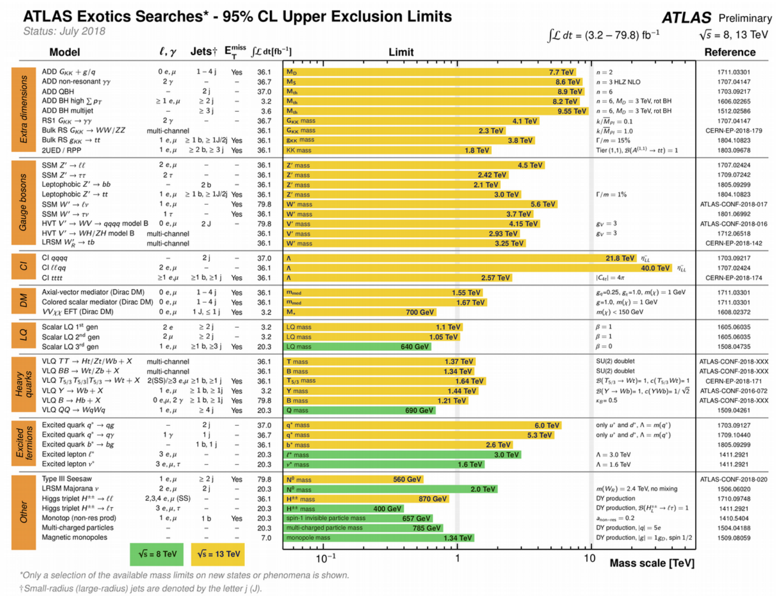






- The results on BSM searches presented here are only a **small fraction** of the physics production by CMS and ATLAS, and only covering a **limited slice** of the final states available and probed by the two collaboration!



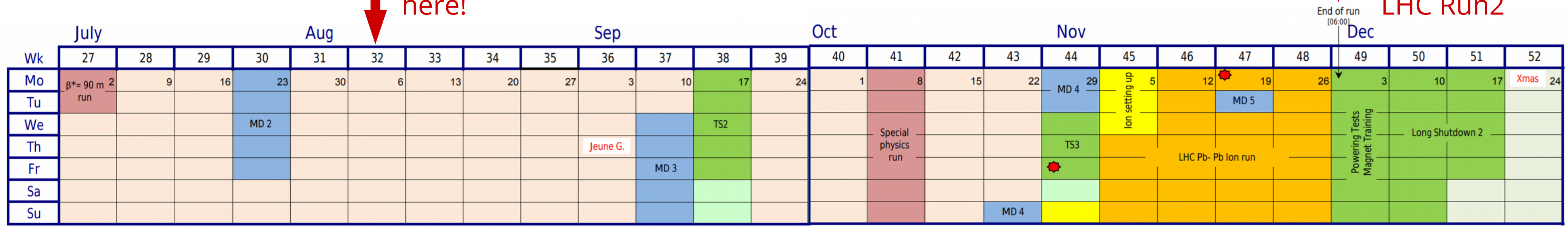


- The development of the **tools** and the theoretical understanding of the **tagging** of boosted final states is a **central** ingredient for achieving optimal results in this challenging final states

- The end of Run2 just a few months ahead of us
→ real turn-point in the LHC program, with an unprecedented dataset of p-p collisions of **~150/fb at 13 TeV**

We're here!

End of LHC Run2

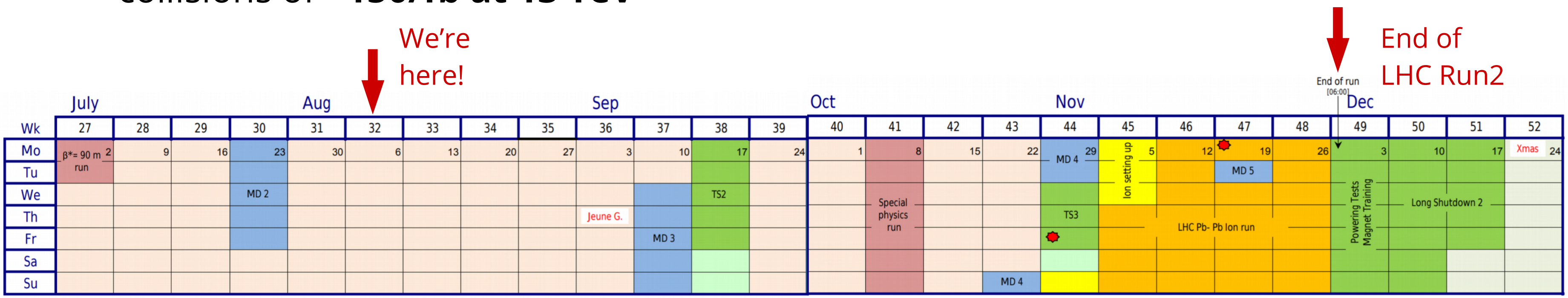


- Being prepared to get the most out of it is paramount!
→ Work in the CMS and ATLAS collaborations is already at full swing to be prepared to get the best results out of this impressive dataset, improving the tools, and optimizing the analysis strategies

- *So, more than ever so far…*

SUMMARY AND OUTLOOK

- The end of Run2 just a few months ahead of us
  → real turn-point in the LHC program, with an unprecedented dataset of p-p collisions of **~150/fb at 13 TeV**



- Being prepared to get the most out of it is paramount!
  → Work in the CMS and ATLAS collaborations is already at full swing to be prepared to get the best results out of this impressive dataset, improving the tools, and optimizing the analysis strategies

- *So, more than ever so far...*

STAY TUNED!

cảm ơn

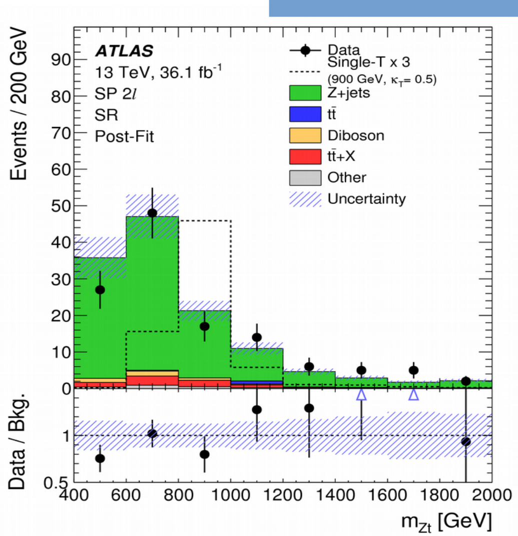
BACKUP

Pair production of a pair of BB or TT, in (OS and SS) leptonic final states

TT/BB → Zt/b + x (OS)

- Targeting the presence of at least one Z → ll decay.
- 4 signal regions to accept events in all possible final states
- Background from MC simulation, corrected by a simultaneous fit using dedicated CRs

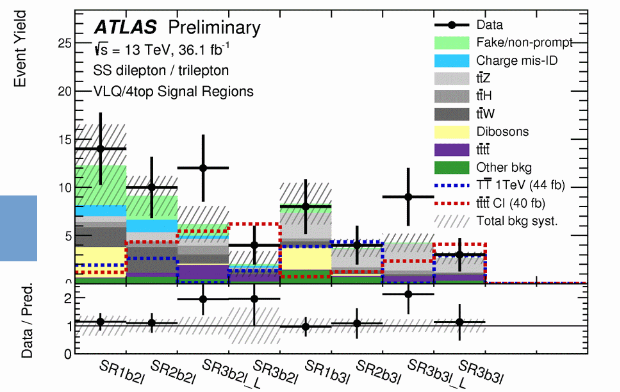
CERN-EP-2018-145



TT/BB → Wt/b + x (SS)

- Challenging topology targeting VLQ and other interesting signals (as 4 top production)
- 8 single-bin signal regions with selections on H_T, missing p_T, n. leptons and n. b-jets
- Data-driven Backgrounds:
  - Fake/non-prompt e/μ backgrounds estimated using a matrix method
  - Charge mis-ID backgrounds (for same-sign dilepton events) estimated via rate measured in data.

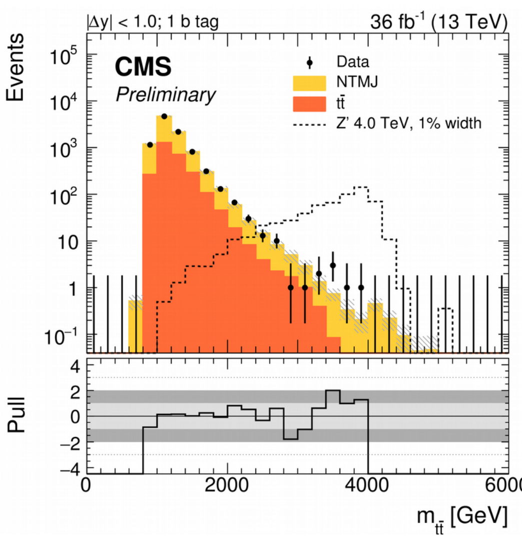
CERN-EP-2018-171

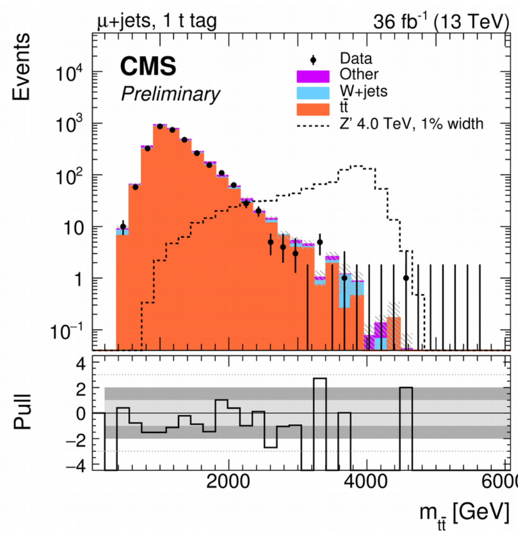


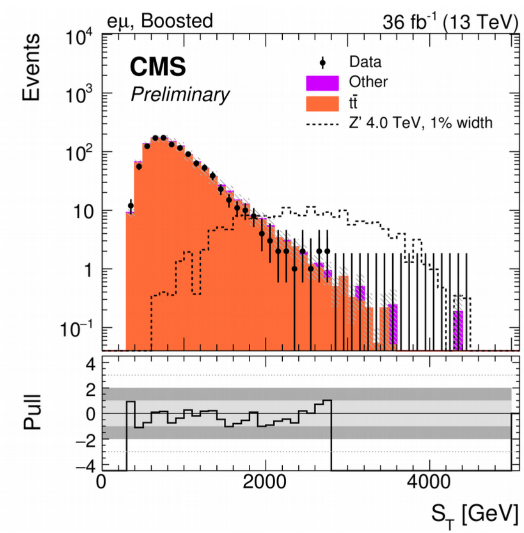
CMS-PAS-B2G-17-017

Model-independent search of **tt resonance in 0/1/2 lepton(s)** final states

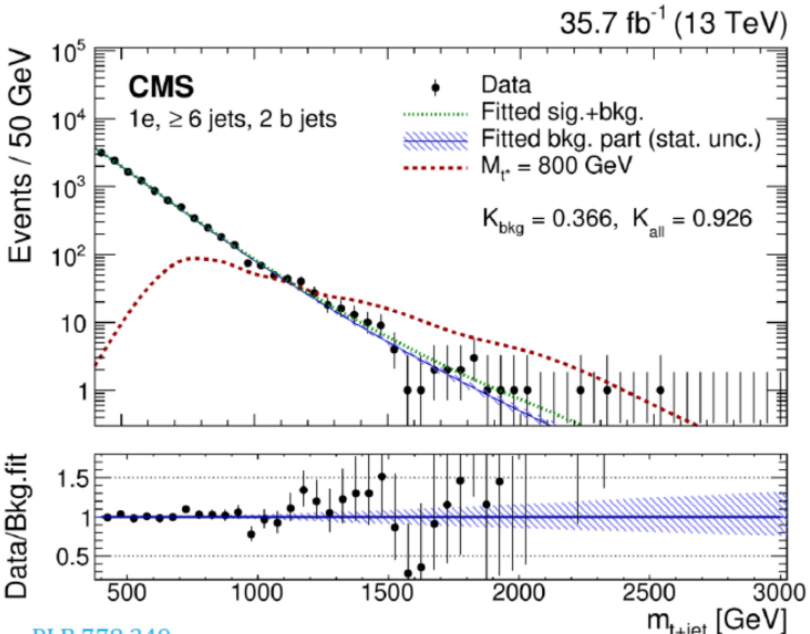
Fully-hadronic	Semi-leptonic	Di-leptonic
• 2 large-radius top-tagged jets • Jet rapidity and b-tag of subjets used to categorize • Non-top multijet bkg estimated with mistag rate evaluated inverting τ_3/τ_2 cut	• 2 jets: 0 or 1 top-tagged • 1 Loosely-isolated lepton • Large missing pT → final state reconstructed by X^2 • SM W+jet production suppressed with dedicated BDT	• 2 jets, at least one b-tag • 2 OS loosely-isolated leptons • Large missing pT → S_T used for signal extraction • Categorization by lepton-jet angular distance





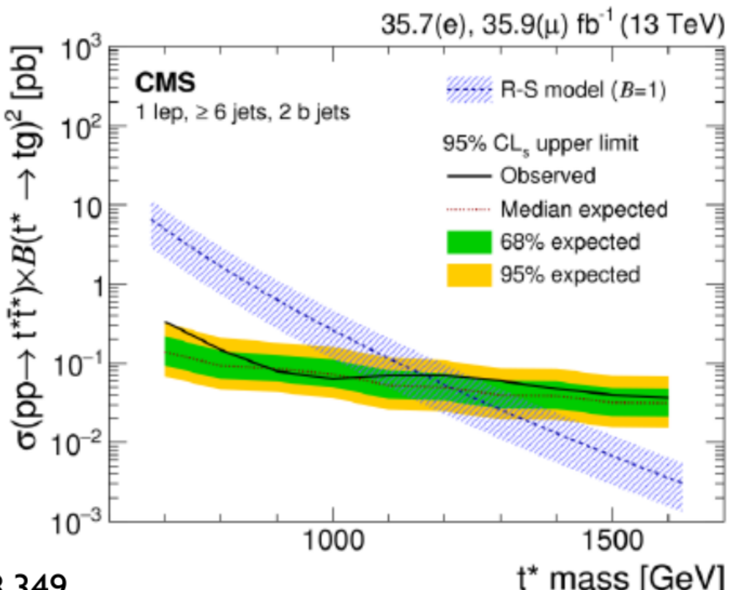


CMS: t* t* → tg tg, semi-leptonic $t\bar{t}$ + 2jets



PLB.778.349

- Composite quark models predict excited quarks with spin 3/2, lightest could be t*
- Large contributions from high-x parton-parton interactions
  - **1 TeV t* cross section in pb!**



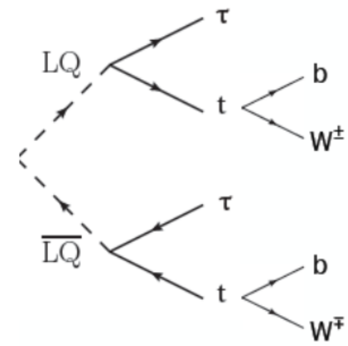
R-S t* > 1.2 TeV

CMS: PLB.778.349

PLB 778 349

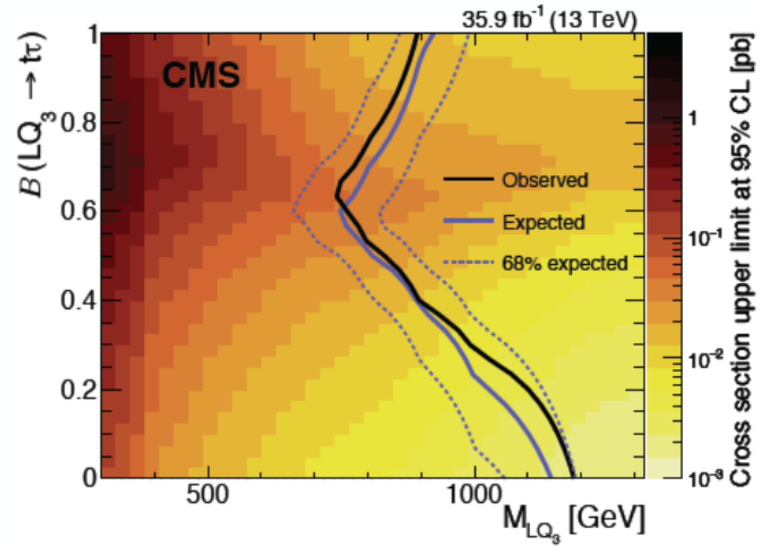
Leptoquarks: LQLQ→τt τt

CMS: Search for 3rd gen LQ pairs decaying to top+tau



- Fit to top pT or count events. Set limits assuming =1 or
- 3 categories:
  - OS e/μ + τ had + b-jet
  - SS e/μ + τ had + b-jet
  - e/μ + 2τ had

- Mass limit: 900 GeV for β=1
- Limits set in 2D mass v. BR plane

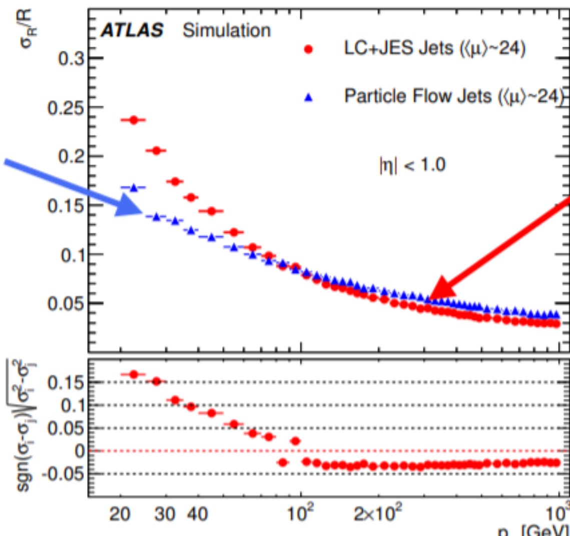


CMS-PAS-B2G-16-028

ATLAS Particle Flow

- Traditionally jet substructure based on calorimeter quantities only
  - Precise EM and HAD calorimeters
  - Tracking information used for calibration
  - Improvements from combined quantities $m_{comb} = w_c\, m_{calo} + w_t\, m_{TA}$
- Particle flow commissioned and studied in ATLAS [ATLAS, EPJ C 77, 466 (2017)]

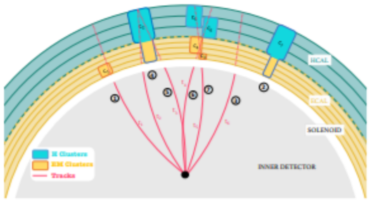
PF improves resolution
- low p_T tracks
- unambiguous track/cluster matching
- intrinsic pileup subtraction



CAL-only better
- tracking efficiency decreases for core of high p_T jet
- confusion term larger

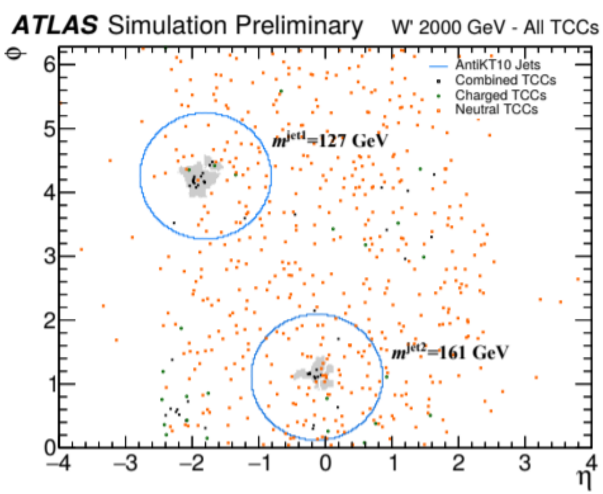
Note: angular resolutions always better with PF

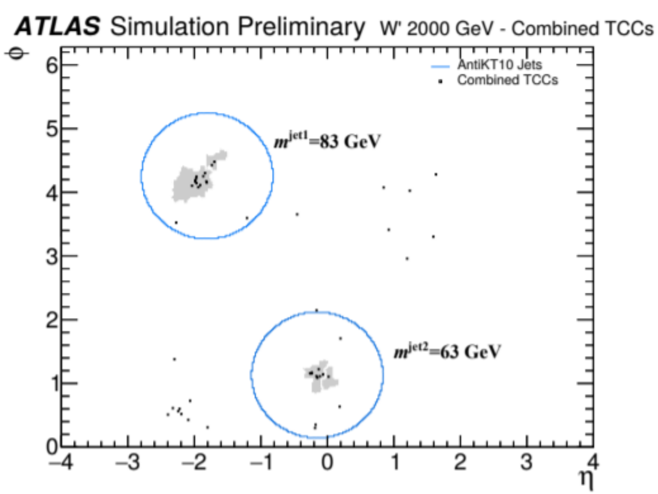
ATLAS TCC



- Track-CaloClusters [ATLAS, PHYS-PUB-2017-015]
  - Energy measurement: calorimeter
  - angular information: tracker

redistribute measured energy according to tracking information

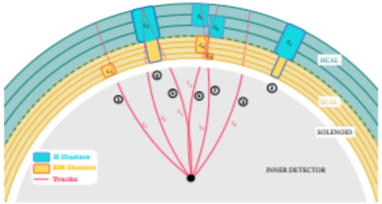




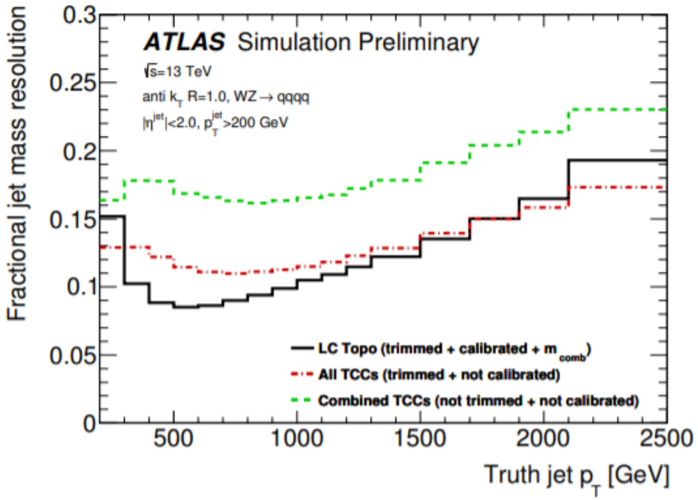
All TCCs: include neutrals, also from PU (→trimming)

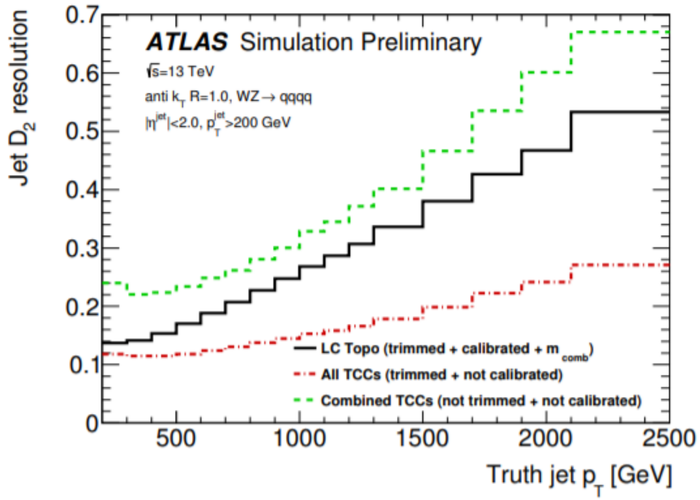
Combined TCCs only: not suceptible to PU, lose information

ATLAS TCC



- Track-CaloClusters [ATLAS, PHYS-PUB-2017-015]

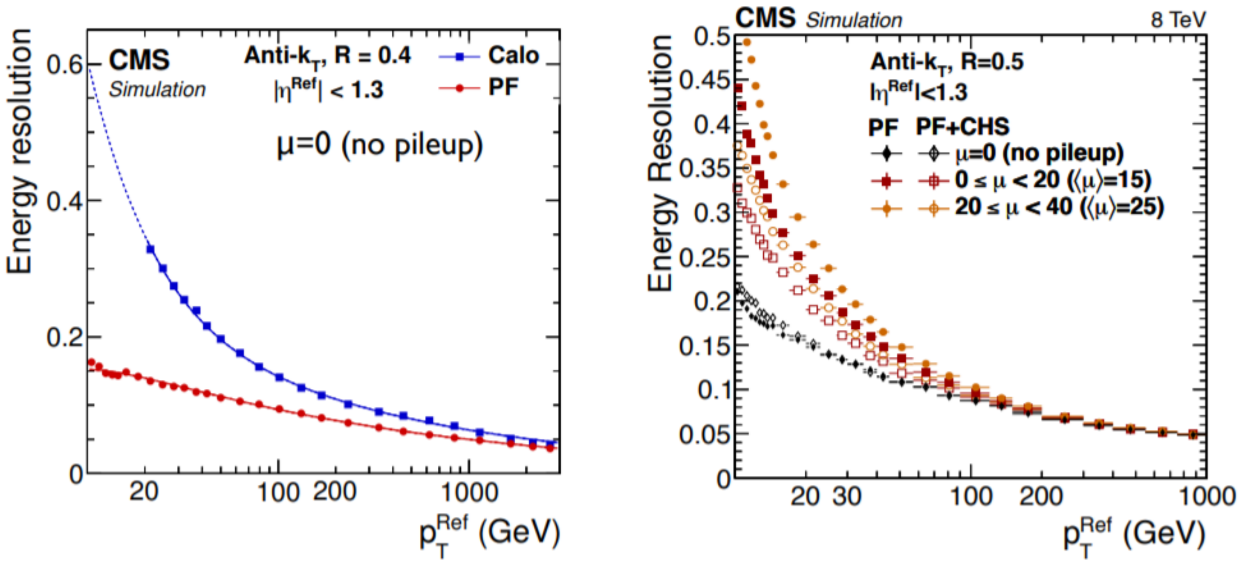




- All TCCs + trimming improves resolution of two-point correlations significantly, jet mass slightly worse
- Improved sensitivity in searches (e.g.VV all-had search) [ATLAS-CONF-2018-016]

CMS Particle Flow

- In use since the start of data taking, recent paper [CMS, JINST 12, P10003 (2017)]
  - Improvements w.r.t Calo-only over full p_T range, also with PU
  - Facilitates simple and robust way for PU mitigation (CHS)

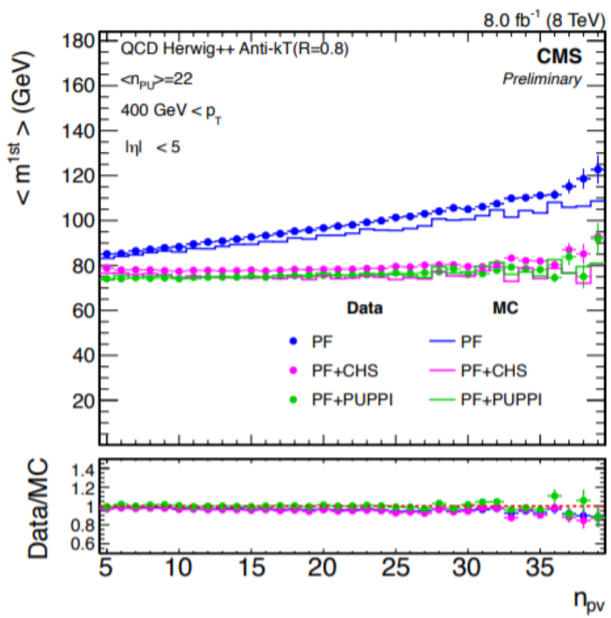


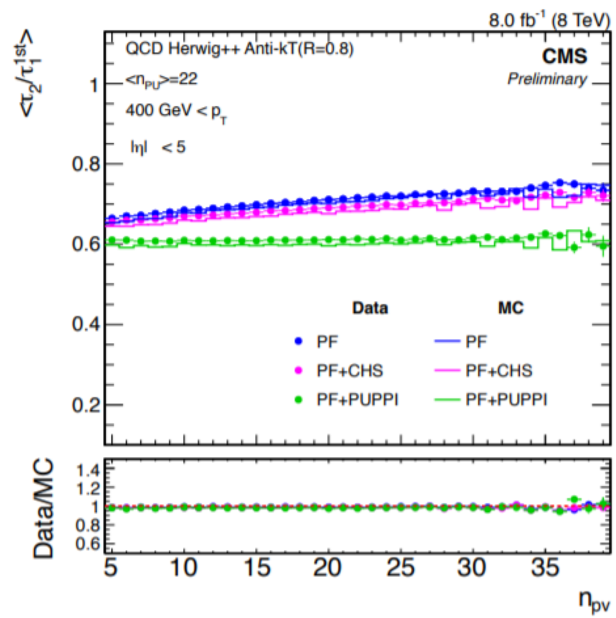
Incredibly powerful for jet substructure applications

CMS PU Mitigation

"Factorized approach" of PU mitigation and jet grooming

- either PF+CHS or PUPPI
- CHS shows stable and good performance, PUPPI helps esp. for angular variables [CMS, PAS-JME-14-001]

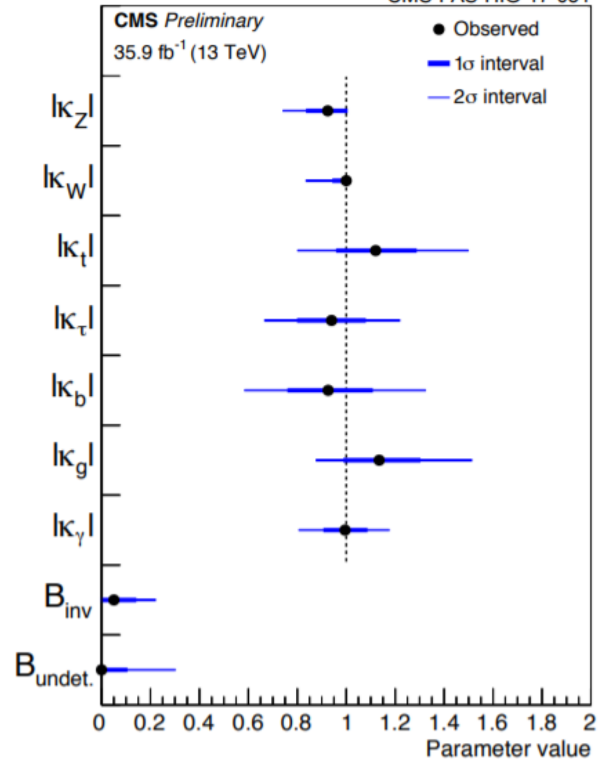




- Higgs boson cross section measurements strongly constrain a chiral 4th generation of quarks
  - Interact via Yukawa couplings; would cause deviation
  - We are still left with the hierarchy problem!

- **Vector-like quarks (VLQ)** escape these constraints and provide a feasible solution
  - Present in many extensions to the SM (little-Higgs, extra dimensions, e.g.)
  - Left- and right-handed components transform equally under SU(2) ('vector')
  - Can be produced with high rates at LHC energies!

CMS-PAS-HIG-17-031



- t/b partners denoted T/B (singlets)
  - Can also have exotic charges in doublets or triplets
    - ($X_{5/3}$ T), (B $Y_{4/3}$), (X T B), (T B Y)

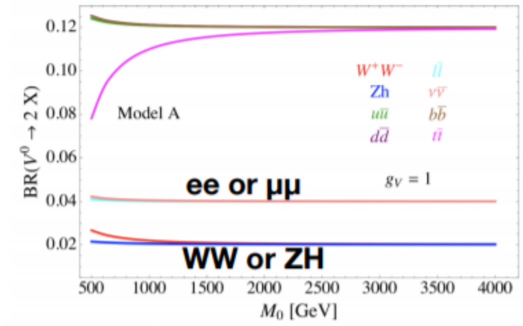
Models for interpretation

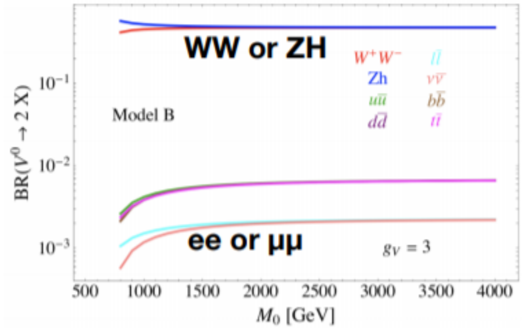
- **Heavy vector triplet** (HVT) model features triplet of colorless vector bosons V' (W'+, Z', W'-)

$$\mathcal{L}_W^{\mathrm{int}} = -g_q W_\mu^a \bar{q}_k \gamma^\mu \frac{\sigma_a}{2} q_k - g_\ell W_\mu^a \bar{\ell}_k \gamma^\mu \frac{\sigma_a}{2} \ell_k - g_H \left(W_\mu^a H^\dagger \frac{\sigma_a}{2} i D^\mu H + \mathrm{h.c.} \right)$$

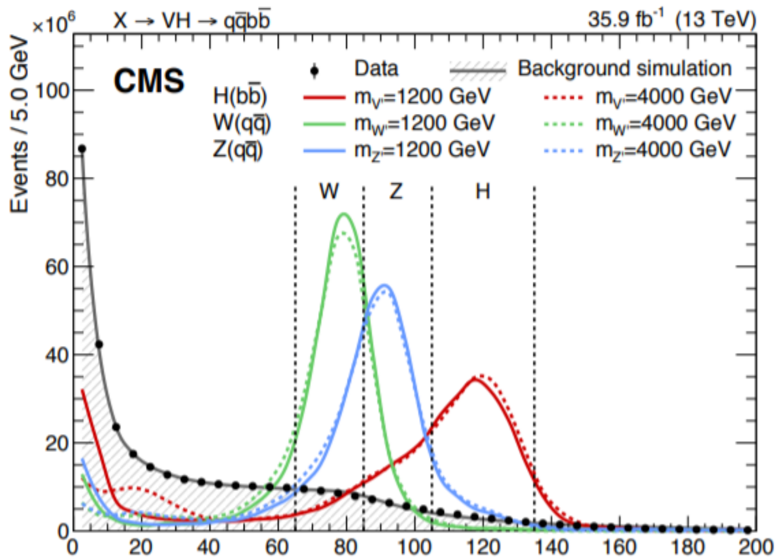
  - g_q and g_ℓ: Universal coupling strength of V' to quarks and leptons
  - g_H : Coupling strength of V' to Higgs field => to W and Z
- HVT model A
  - Weakly coupled (e.g. extended gauge symmetry): $g_H = -0.56$ and $g_f = g_q = g_\ell = -0.55$
- HVT model B
  - Strongly coupled (e.g. composite Higgs): $g_H = -2.9$ and $g_f = g_q = g_\ell = 0.14$
- HVT model C
  - VBF only: $g_H = 1$ and $g_f = g_q = g_\ell = 0$
- **Randall-Sundrum** warped extra dimensions "bulk" model
- Empirical **heavy scalar** model
  - Natural width negligible relative to experimental resolution

arXiv:1402.4431

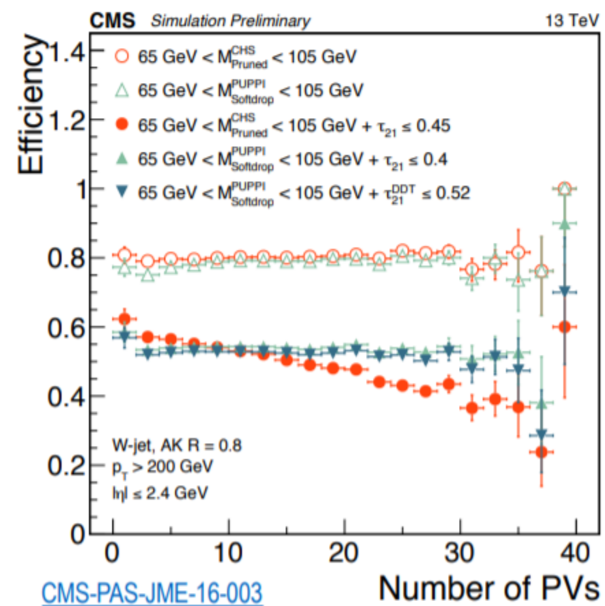




- Pileup subtraction based on **PileUp Per Particle Identification (PUPPI)**:
  - Rescale particle momenta according to compatibility with primary vertex.
  - Re-cluster the jet with modified constituents.
- Removal of soft and large-angle radiation via the **soft-drop algorithm**:
  - Infrared and collinear safe.
  - Soft-drop jet mass (with dedicated corrections) used in V/H jet tagging, in definitions of sidebands, or as 2nd dimension in fits.



Eur. Phys. J. C 77 (2017) 636



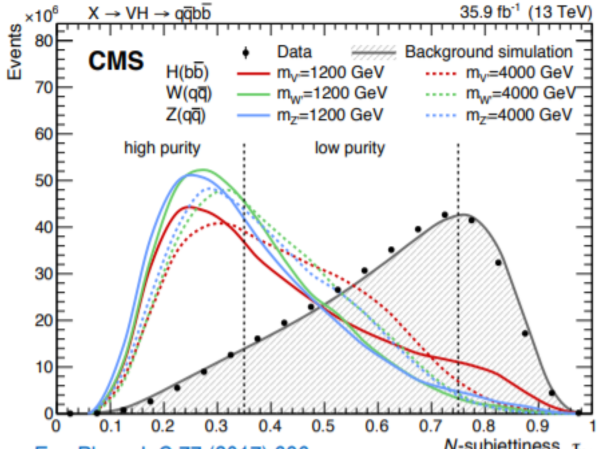
CMS-PAS-JME-16-003

- Quantifies to what extent energy flow is aligned with N directions:

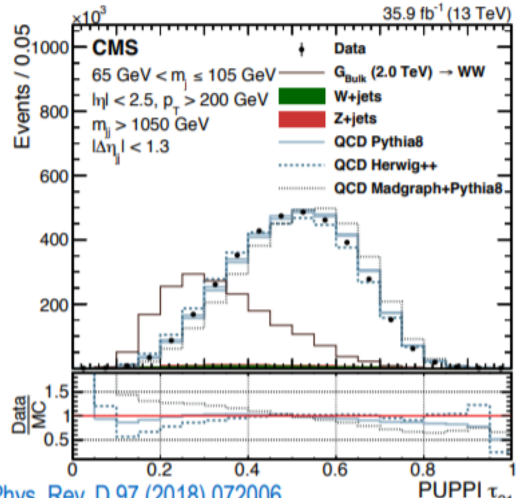
$$\tau_N = \frac{1}{d_0}\sum_k p_{\mathrm{T},k}\,\min(\Delta R_{1,k}, \Delta R_{2,k}, \ldots, \Delta R_{N,k})$$

- Consistent use of the ratio $\tau_{21} = \tau_2/\tau_1$ in all analyses.
  - Lower values for 2-prong W/Z→qq than for quark- or gluon-initiated jets.
  - Key variable, carefully validated in data.

- Used to define event categories:
  - Split into high/low purity (HP/LP), τ_{21} thresholds depend on analysis.
  - LP categories recover signal efficiency at very high mass.



Eur. Phys. J. C 77 (2017) 636



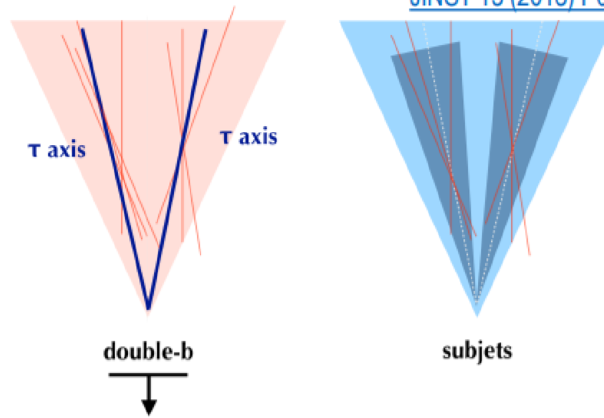
Phys. Rev. D 97 (2018) 072006

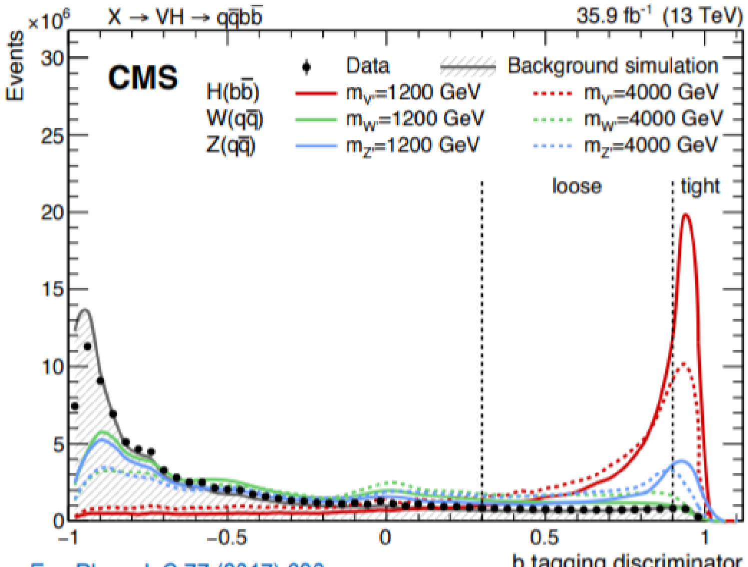
JINST 13 (2018) P05011

H→bb decays are tagged with 2 methods of similar performance:

- **Double-b tagger**, exploits the presence of 2 B hadrons in the fat jet.
  - Associates secondary vertices with the 2 directions of N-subjettiness axes.
  - Used in the VH→qqbb analysis (plot).
- Or apply the well-known **CSV tagger** to the two subjets.
  - Used in the VH→(2l/lν/2ν)bb analysis.

➔ Again define event categories (loose / tight).



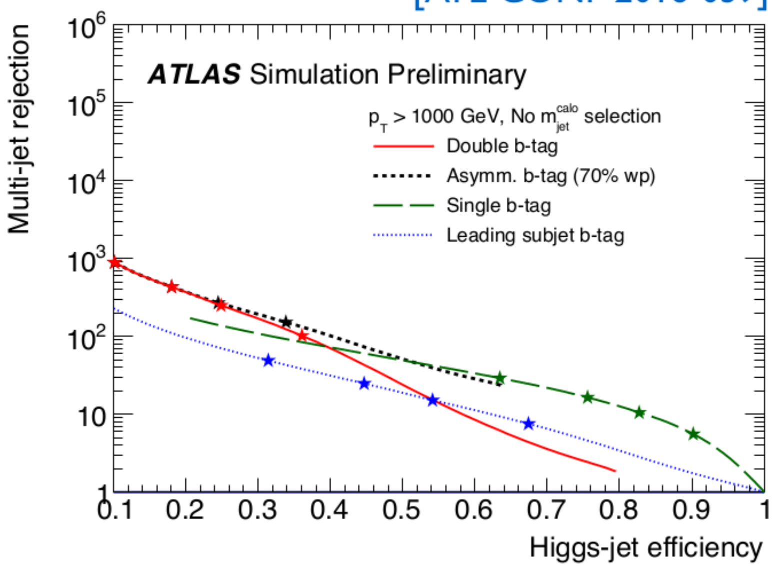


Eur. Phys. J. C 77 (2017) 636

Subjet b tagging (ATLAS)

Leading track jets with R=0.2 inside a large jet with R=1.0

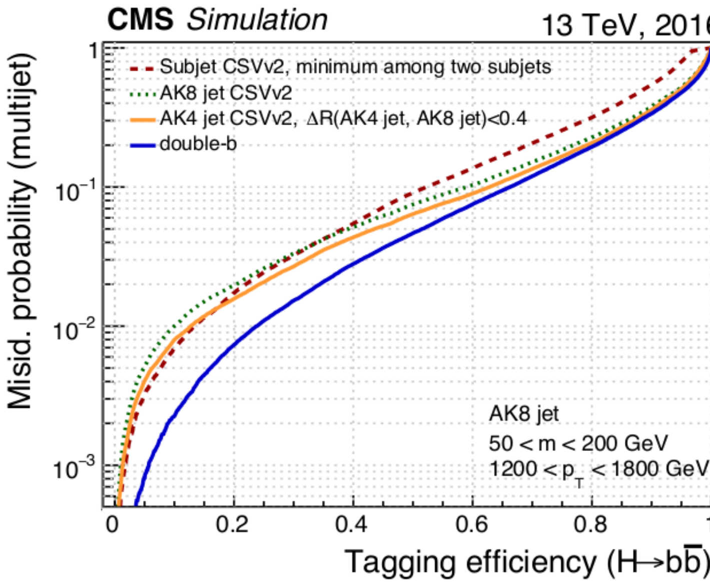
[ATL-CONF-2016-039]



Discrimination against boosted t→bW with double b-tag

Double-b tagger (CMS)

BDT based on track, SV, substructure inputs



[CMS, JINST 13 (2018) P05011]

Improvement at high p_T, discrimination against g→bb