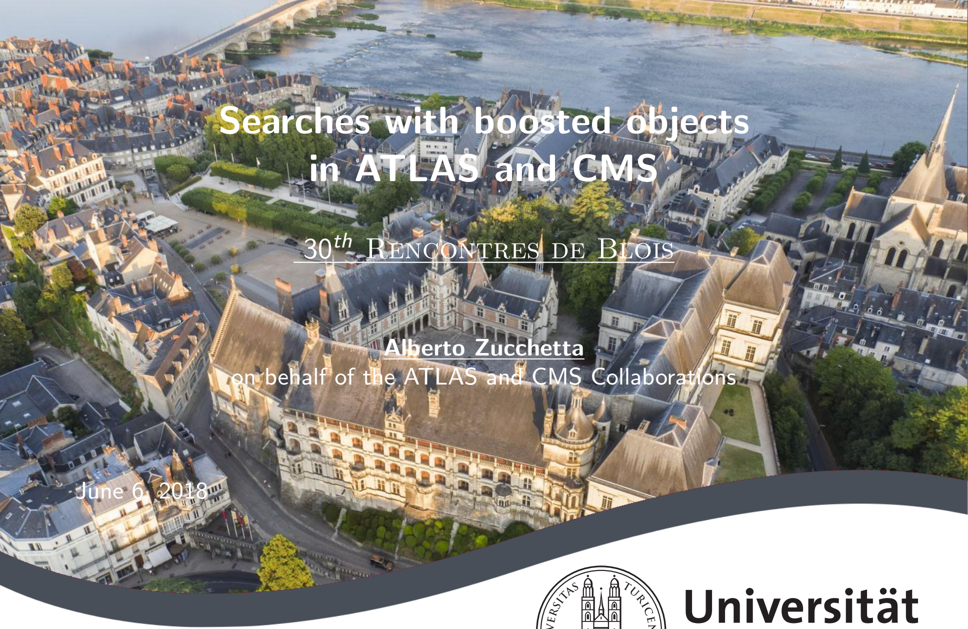


Searches with boosted objects in ATLAS and CMS

30th Rencontres de Blois

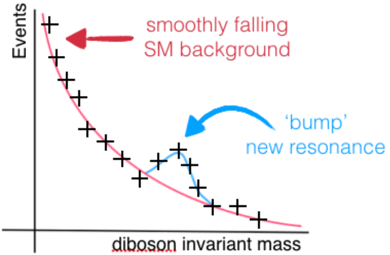
Alberto Zucchetta
on behalf of the ATLAS and CMS Collaborations

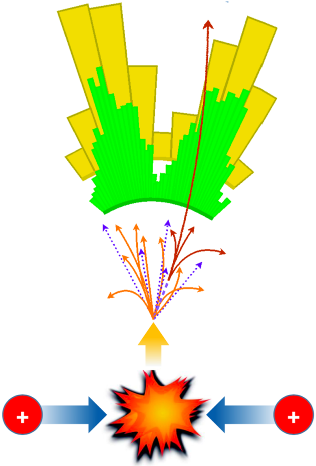
June 6, 2018

Universität Zürich[UZH]

Introduction

- Hadronic colliders (LHC) intrinsecally favored for heavy resonances discovery
- Reconstruction of final-state particles in the detector $\rightarrow$ look for bumps in the invariant mass spectrum
  - $X \rightarrow t\bar{t}$
  - VV, VH, HH
  - γV, γH
  - $W' \rightarrow tb$
  - Vector-like quarks
  - Light $Z' \rightarrow q\bar{q}$



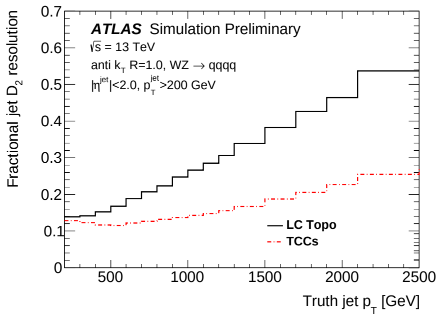


- Large resonance mass implies large Lorentz boost of the decay products
- **Boosted object reconstruction** (W, Z, H, t) is crucial for these searches

Substructure reconstruction

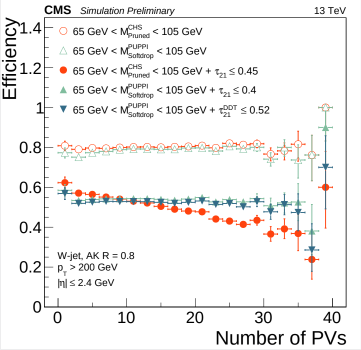
ATLAS

- Novel technique (**TrackCaloCluster**) that combines tracking and calorimeter information [1]
  - Energy measurement from calo
  - Spatial information from tracker
- major improvemets (factor ~ 2) in jet substructure resolution
- **Trimming** [2] for the jet mass



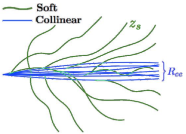
CMS

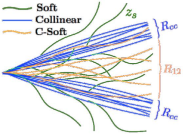
- Based on Particle-Flow candidates (track+calo) [3]
- Successfully moved to **Soft drop** [4] in 2016: **PUPPI** [5]
  - stability vs pileup
  - good m_j resolution ($\approx 10\%$)

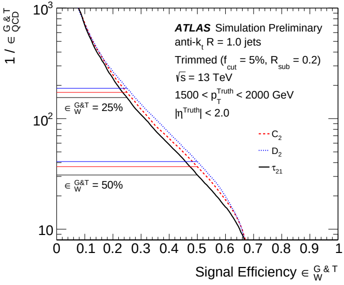


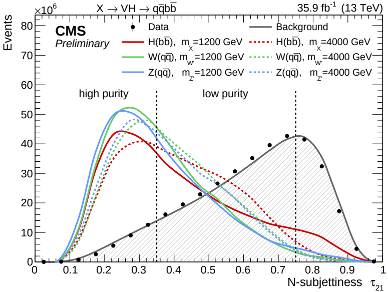
Vector boson tagging

- ATLAS: **Energy Corr. Functions** (D_2) + n_{trk} [6]
- CMS: **N-subjettiness** (τ_{21}) + PUPPI [7] (also ATLAS in JHEP03(2018)042)
- Measure how consistent is the jet with the 2 vs 1 sub-jets hypotheses
- Scale factors and uncertainties derived from $W \to q\bar{q}$ in $t\bar{t}$ sample
- Working points and categorization according to purity





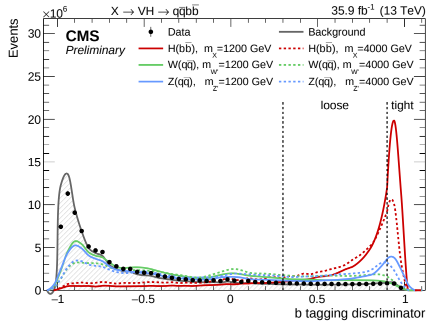




H and t reconstruction and identification

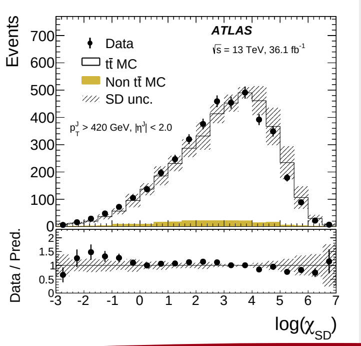
Higgs boson tagging ($H \to b\bar{b}$)

- Subjet b-tagging (ATLAS, CMS)
  - split jet to two subjets
  - apply b-tagging algorithms to both subjets independently
- Dedicated algorithms [5] (CMS)
  - exploit b-tagging to identify **two** b-quarks within the same jet
  - use soft lepton (e, μ), tracking and vertexing information



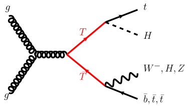
Top quark tagging

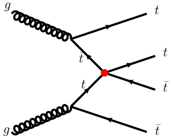
- Decompose large-cone jets (0.8, 1.0, 1.2, 1.5) in subjets as proxy for partons
- Calculate probability of shower developments compatible to expected configuration [6] (ATLAS)
- Apply subjet b-tagging, cut on τ_{32} and mass (CMS)



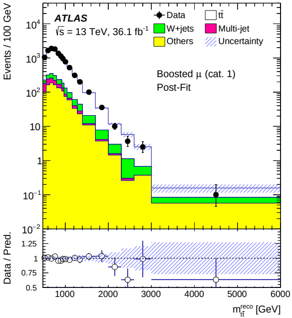
$t\bar{t}$ resonances

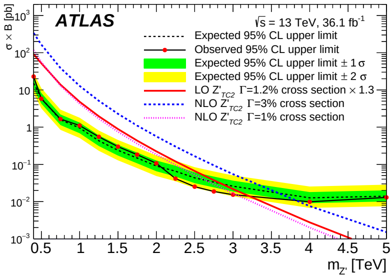
ATLAS [EXOT-2015-04]





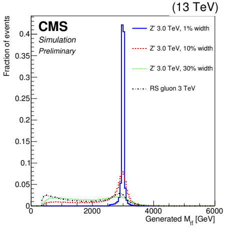
- Look for resonant $t\bar{t}$ production
- Theoretical models: Z', G_{KK}, g_{KK}
- Semileptonic decay:
  - ℓ + MET + b-jet + large-cone hadronic top jet
  - alternatively, fully resolved reconstruction (4 jets)
- Data-driven estimation of the multijet and W+jets background, $t\bar{t}$ from MC
- Constrain dark matter with a Z' mediator (see also Oleg's talk) [7], [8]



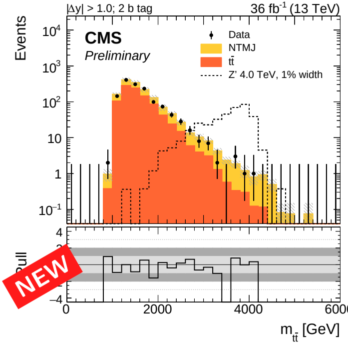


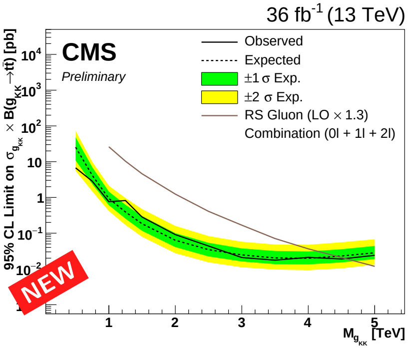
$t\bar{t}$ resonances

CMS [B2G-17-017]



- NEW CMS search for resonant $t\bar{t}$ also in non-narrow signals
- Combination of 0ℓ, 1ℓ, 2ℓ final states
- Boosted top quark reconstruction (m_j, τ_{32}, b-tag)
- Data-driven multijet estimation (0ℓ), DBT to suppress W+jets (1ℓ)
- Narrow Z' excluded up to **3.8 TeV**

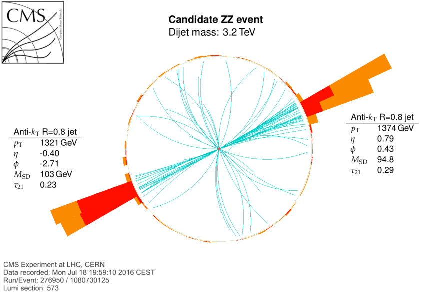




Diboson: all-hadronic final states

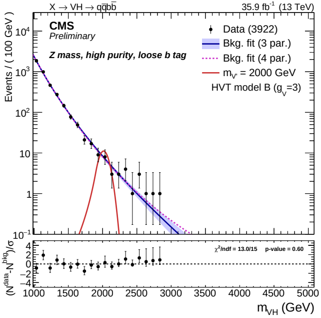
ATLAS [PLB777(2017)91, PLB774(2017)494], CMS [PRD97(2018)072006, EPJC77(2017)636]

- ✓ Large ($W, Z \to q\bar{q}$, $H \to b\bar{b}$) branching fraction
- **X** Overwhelming QCD background (difficult prediction)



- At least 2 large-cone jets, back-to-back topology
- Requires **trigger efficiency** ~ 1
- Extensive bias studies

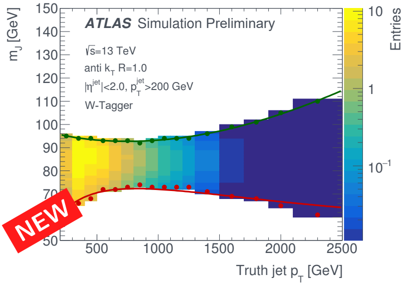
- Background estimation: "bump-hunt" fit with power law functions directly to data
- Number of parameters (2-5) determined with F-test
- b-tagged final states: use anti-tag for bkg pred.

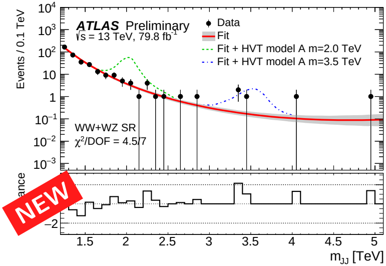


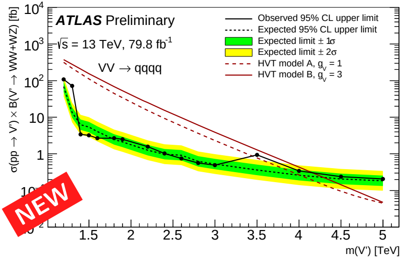
Diboson: all-hadronic final states

ATLAS [CONF-2018-016]

- New $X \to VV$ result from ATLAS based on 2015+2016+2017 data
- W/Z tagging based on **TTC** mass + $\mathbf{D_2}$ ECF variable (sliding cuts)
- CRs mimick SR to test background modeling functions
- Heavy V' excluded up to 4.15 TeV
- Bulk G excluded up to 2.3 TeV ($k/\bar{M}_{pl} = 1$)







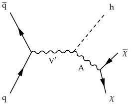
Diboson: semileptonic final states

ATLAS [JHEP03(2018)042, JHEP03(2018)009, JHEP03(2018)174], CMS B2G-17-005, B2G-17-013, JHEP03(2018)003]

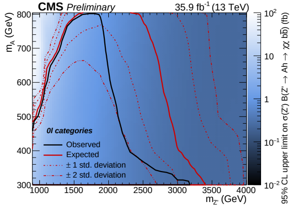
✓ Clean final state, more reliable background simulation

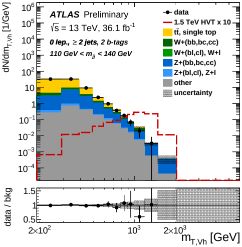
X Small branching fraction

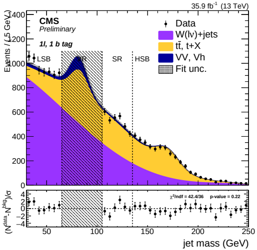
- Experimental challenges:
  - $Z \to \nu\nu$: use transverse mass m_T
  - $W \to \ell\nu$: very high p_T lepton reconstruction
  - $Z \to \ell\ell$: high-efficiency dilepton identification, isolation (CMS)
- Different strategies depending on background:
  - MC and fit bkg templates in SR and SB (ATLAS)
  - Take main background from m_j sidebands (CMS)

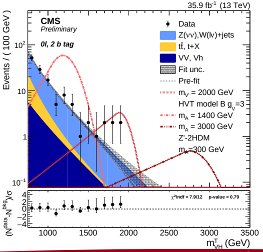


Mono-Higgs signature: most stringent limits on Z'-2HDM DM models





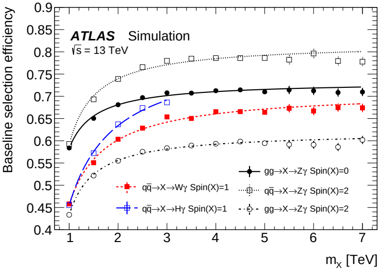


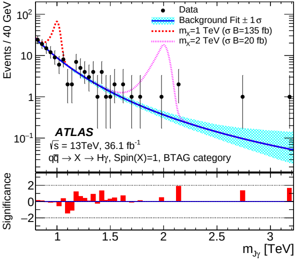


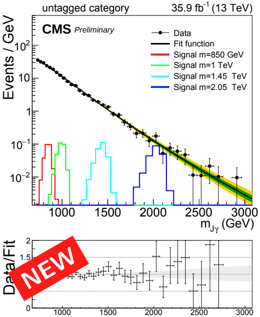
Diboson: $\gamma + H$ final state

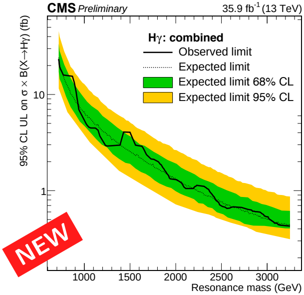
ATLAS [arXiv:1805.01908], CMS [EXO-17-019]

- ATLAS and CMS (**NEW**) analysis for $X \to \gamma W$, γZ, γH
- b-tagging, jet mass to tag the boosted $H \to b\bar{b}$
- Non b-tagged categories (ATLAS D_2) to recover $V \to q\bar{q}$ efficiency
- Multijet background estimated from direct fit to data



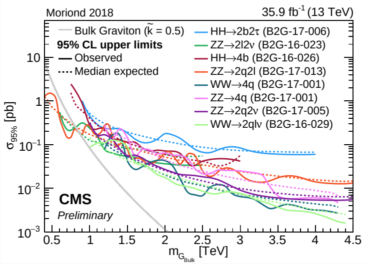




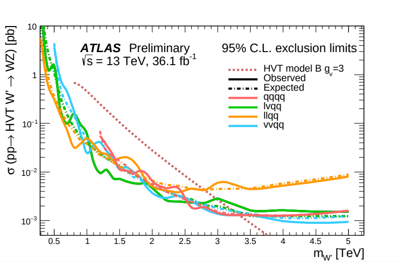


- No statistically significant excess observed
- Comparable sensitivity between the two experiments
- Limited by luminosity, at least at large resonance mass
- Sensitivity dominated by all-hadronic channels, and final states with $Z \to \nu\nu$ and $W \to \ell\nu$

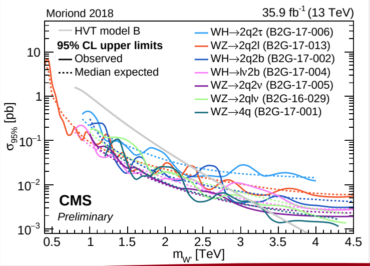
CMS Bulk Graviton



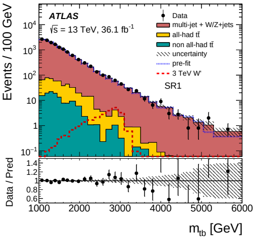
ATLAS W' (HVT model B)

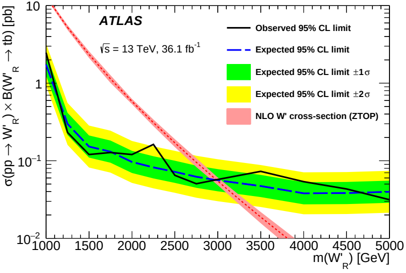


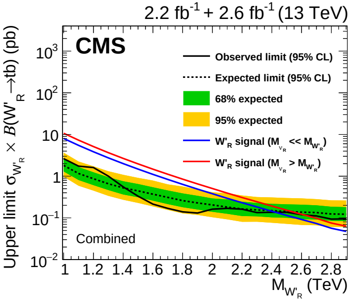
CMS W' (HVT model B)



- All-hadronic final state: a boosted top and a b quark
- Semi-leptonic (only CMS): ℓ+MET+2 b
- Background: EWK from MC, data-driven for multijet
  - b-tagging probability for CMS, ABCDEF-method for ATLAS
- No excess, limits up to 3.0 TeV for W'_R

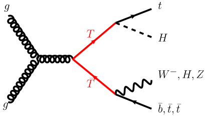




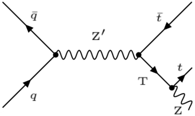


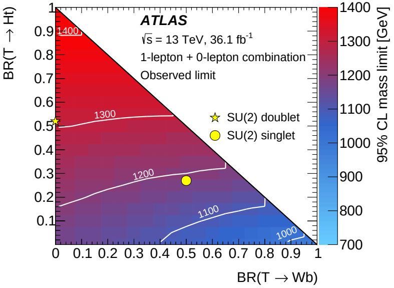
Vector-like quarks (T, B)

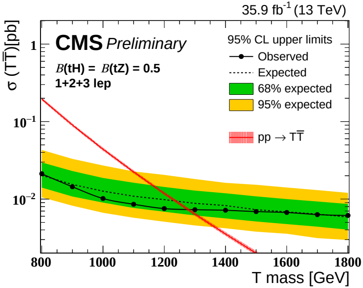
ATLAS [EXOT-2016-13], CMS [B2G-17-011, B2G-17-009, B2G-17-007]



- Up-type vector-like quarks (T) may decay to tZ or tH
- Also singly-produced T from $Z' \to tT$
- Down-type $B \to bH(bb)$
- Boosted $t \to Wb \to qqb$, $H \to bb$
- Lepton + MET final state + jet (7+) + b-tag jet (4+)
- Also, same-sign lepton category (CMS)
- Simultaneous fit on all categories





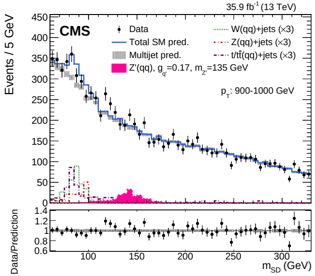


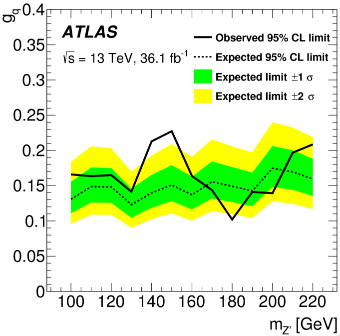
see also Tobias' talk

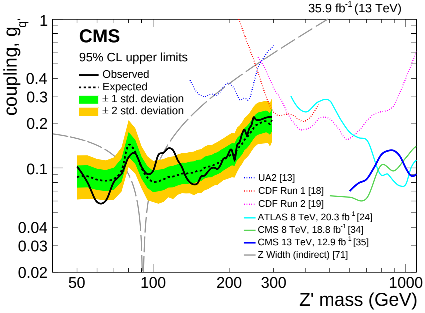
Light boosted $Z' \to q\bar{q}$

ATLAS [EXOT-2017-01], CMS [JHEP01(2018)097]

- If Z' is light enough ($m_{Z'} \gtrsim 300$ GeV) it may be produced with large boost
- Final state consists in a large-cone jet + ISR (q, g, γ)
- Challenge: cutting on jet substructure (τ_{21}) sculpts the jet mass
- Solution: use τ_{21}^{DDT} tagger to decorrelate m_j and τ_{21}

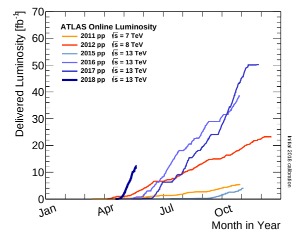






Concluding remarks

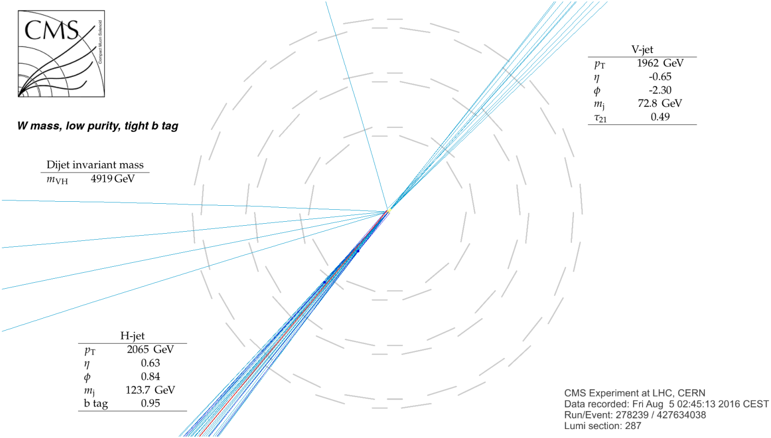
- Impressive and continuous flow of analyses on 2016 data, new results with **2017 data**!
- No convincing excess neither in ATLAS nor CMS
- Many new ideas on the table, can improve by 30 $\sim$ 50% the reach of our searches
  - machine learning, n-dimensional fits, ...
  - improved detectors and reco techniques
- 2018 data taking proceeding smoothly



Future considerations

- What if we are missing something? What if the resonance has moderate mass ($\sim$ 1 TeV), but large width?
  - a broad Z' would contribute to explain the lepton flavor anomalies
- Need adequate background prediction methods
- Heavy resonance searches $\leftrightarrow$ precision SM differential measurements
- Do we need more exotic models? $X \rightarrow VY \rightarrow VVV$

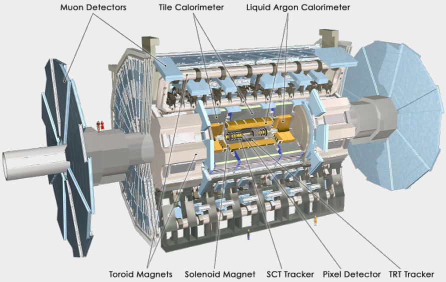
Thank you!


CMS
W mass, low purity, tight b tag
Dijet invariant mass
m_{VH} 4919 GeV
V-jet
p_{T} 1962 GeV
η -0.65
ϕ -2.30
m_{j} 72.8 GeV
τ_{21} 0.49
H-jet
p_{T} 2065 GeV
η 0.63
ϕ 0.84
m_{j} 123.7 GeV
b tag 0.95
CMS Experiment at LHC, CERN
Data recorded: Fri Aug 5 02:45:13 2016 CEST
Run/Event: 278239 / 427634038
Lumi section: 287

Backup slides

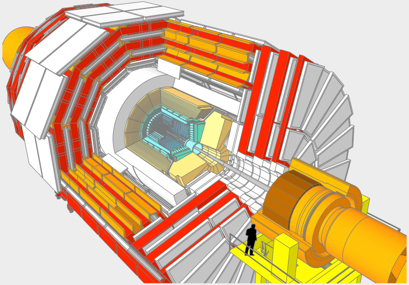
ATLAS and CMS

ATLAS



- 2 Tesla solenoid + barred and endcap toroid
- Silicon detector (new pixel IBL) and Transition Radiation Tracker (TRT)
- Em. calorimeter (PB+Lar, $\sigma(E)/E \sim 10\%/\sqrt{E} + 0.007$)
- Had. calorimeter (Iron Tile+scint., Cu+Lar HEC, $\sigma(E)/E \sim 50\%/\sqrt{E} + 0.03$)
- Muon Chambers (Drift Tubes)

CMS

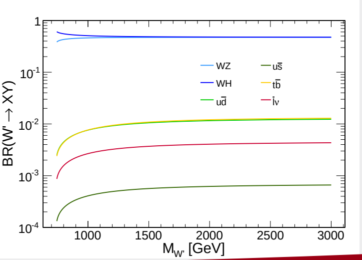


- 4 Tesla solenoid + return yoke
- Huge silicon detector (pixel and strips)
- Em. calorimeter (PbWO4 crystals, $\sigma(E)/E \sim 3\%/\sqrt{E} + 0.003$)
- Had. calorimeter (Brass+scint., $\sigma(E)/E \sim 100\%/\sqrt{E} + 0.05$)
- Muon Chambers (DT, RPC, CSC, $\sigma(p_T)/p_T \sim 1\%@50GeV,\ 10\%@100GeV$)

Theoretical motivations

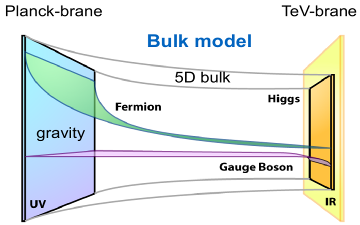
Heavy Vector Triplet (HVT)

- Heavy Z', W' predicted by several models: Little Higgs, composite Higgs, Minimal Walking Technicolor
- Described by a simplified Lagrangian in the HVT framework [1] [2]
- 3 new BSM vector fields V^+, V^-, V^0
- Two possible scenarios:
  - couplings to fermions dominating (**Model A**)
  - coupling to fermions suppressed w.r.t. to SM bosons (**Model B**):



Warped Extra Dimension (WED)

- WED models as possible solution to the hierarchy problem



- Radion (spin-0) and Graviton (spin-2)
- Radion scale Λ_R depends on Planck scale, Warp factor $k/\bar{M}_{Pl} \sim$ TeV
- May have similar coupling strength to SM fermions and gauge boson
- Production through DY and gluon-fusion, decay to WW, ZZ, HH

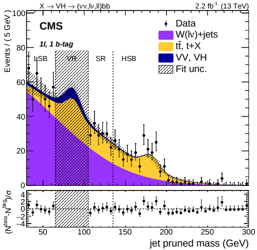
Analysis strategy (α-method)

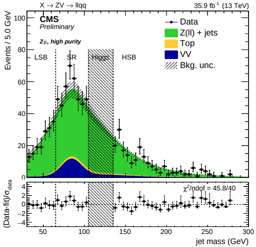
Get background **normalization** in SR from m_j sidebands:

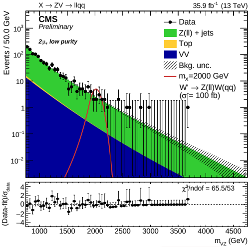
- Build background model:
  $F(m_j) = n^{Vjets} \cdot F^{Vjets}(m_j) + n^{Top} \cdot F^{Top}(m_j) + n^{VV} \cdot F^{VV}(m_j)$
- **Fit** normalization and shape of the main background to data **in jet mass SB**
- Secondary backgrounds normalization and shape fixed in the fit

Get background **shape** in m_{VH}:

- Main bkg SB → SR transfer factor from MC: $\alpha(m_{VH}) = \frac{N_{SR}^{MC,bkg}(m_{VH})}{N_{SB}^{MC,bkg}(m_{VH})}$
- Main bkg prediction in SR: $N_{SR}^{pred}(m_{VH}) = N_{SB}^{data}(m_{VH}) \times \alpha(m_{VH})$



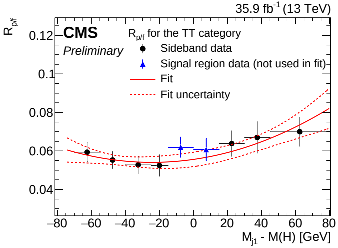


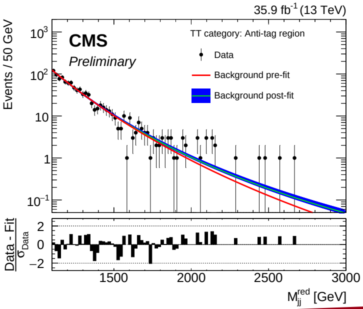


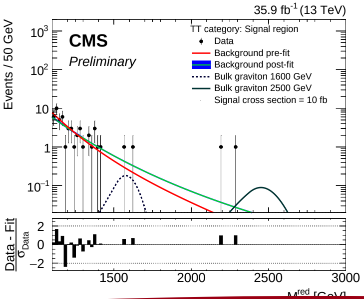
- Search for resonant di-Higgs in all-hadronic (4b) final states (CMS)

Alphabet method

- Extension of the ABCD method to multiple regions
- Normalization from mass sidebands
- Shape from simultaneous fit to "tag" and "anti-tagged" $H \to b\bar{b}$ events





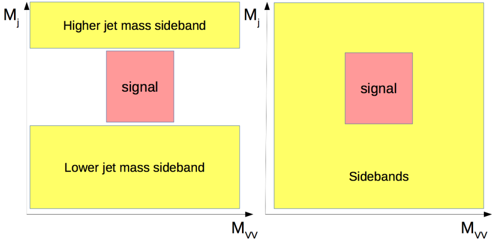


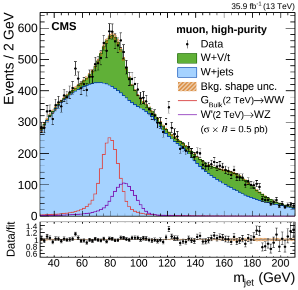
Diboson: N-dimensional fits

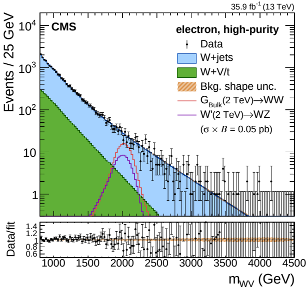
CMS WV semileptonic [B2G-16-029]

2D fit

- 1D method (alpha): mass sidebands aided bump hunt
- 2D method (fit): 2D bump hunt in the $[m_j, m_{VV}]$ plane
- exploit correlations between m_j and m_{VV}
- larger statistics and full line-shape information form jet mass
- correlations from data

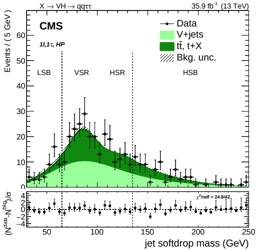


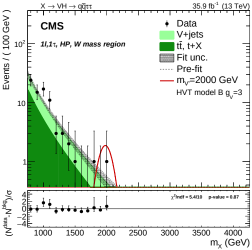


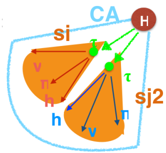


- Novel CMS search for $V \to qq$, $H \to \tau\tau$ ($\tau_h\tau_h$, $\tau_\mu\tau_h$, $\tau_e\tau_h$)
- Background estimated with tranfer function from m_j sidebands

Final state	Signal searched
$qq\tau\tau$	$W' \to WH$ $Z' \to ZH$ $R, G \to HH$
$\ell\nu\tau\tau$	$W' \to WH$
$\ell\ell\tau\tau$	$Z' \to ZH$

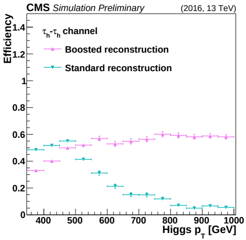






Boosted τ reconstruction (CMS-DP-2016-038)

- CA8 jets split in two subjets
- subjets provided as seeds to the HPS τ_h reconstruction algorithm
- τ_h: MVA isolation, τ_μ: τ_h subtraction



Combination of the diboson searches

CMS-PAS-B2G-16-007

- Combination between 2015 $\sqrt{s} = 13$ TeV and 2012 $\sqrt{s} = 8$ TeV searches
- Favored by orthogonality between analyses, and common techniques
- Stringent limits on HVT model B: $m_{V'} < 2.4$ TeV
- Not sensitive enough to exclude Bulk Graviton
- 2016 searches already more sensitive than combination