Searches for Diboson Resonances in ATLAS

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Diboson resonances - Theoretical motivation

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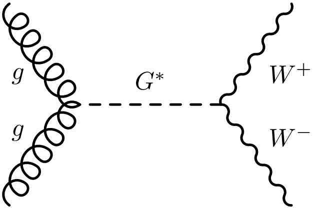
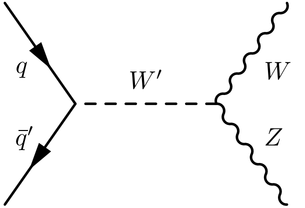
- Many extensions of the SM predict the existence of diboson resonances
    - Grand Unified Theories
    - Warped extra dimensions
    - Technicolor





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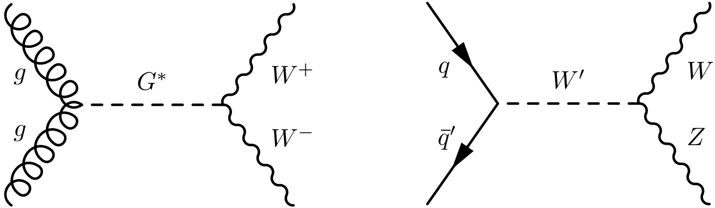
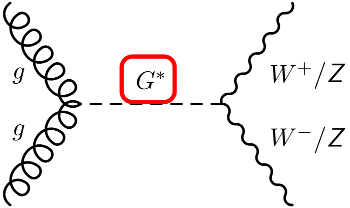


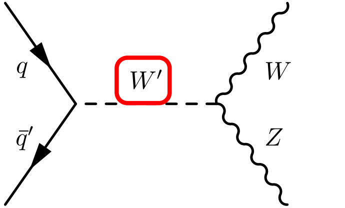
- Three different **benchmark** models studied in ATLAS
  1. Bulk Randall-Sundrum model
  2. Extended gauge model (EGM)
  3. Heavy Vector Triple (HVT)

Benchmark models

1. **Bulk Randall-Sundrum model**
   - Model of warped extra dimensions
   - Spin-2 Kaluza-Klein graviton (G*)
   - $G^* \to WW, ZZ$
   - BR(G* $\to WW$) $\approx$ 20%
     BR(G* $\to ZZ$) $\approx$ 10%
   - $\sigma(G^* \to ZZ) = 0.25$ fb ($m_{G^*} = 2$ TeV)



2. **Heavy Vector Triplet**
   - Simplified phenomenological Lagrangian
   - Spin-1 gauge bosons (W', Z')
   - $W' \to WZ$ and $Z' \to WW$
   - BR(W' $\to$ WZ) $\approx$ 2%
   - $\sigma(W' \to WZ) = 7.5$ fb ($m_{W'} = 2$ TeV)

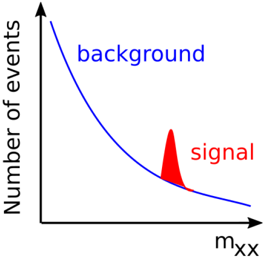


3. **Heavy Higgs**
   - Spin-0 H boson, narrow width approx.
   - $H \to WW/ZZ$
   - ggF and VBF production for $H \to ZZ$

How to find new physics - the easy way!

General idea

- Search for new particle Z $\rightarrow$ XX or XY
- Reconstruct invariant mass $m_{\mathrm{XX/XY}}$
- Search for narrow resonance on top of background



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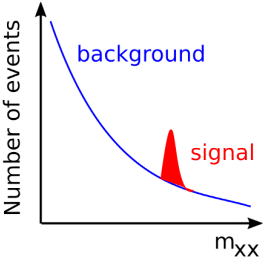
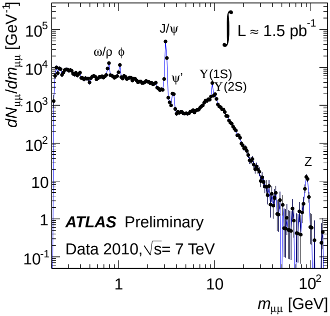
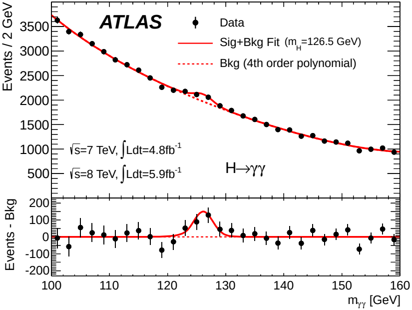
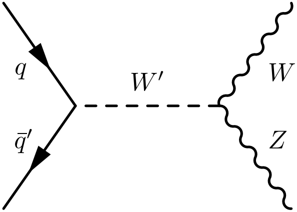


The past: (re)discovery of SM particles





What about the diboson resonances?



- **Hadronic** decay of vector bosons
  - Large branching ratio:

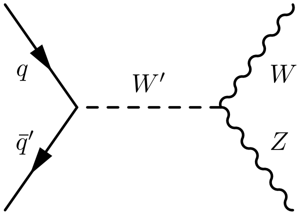
    $\mathrm{BR}(W \to qq) \approx 3 \times \mathrm{BR}(W \to \ell\nu)$

    $\mathrm{BR}(Z \to qq) \approx 10 \times \mathrm{BR}(Z \to \ell\ell)$
  - No MET
  - large dijet background

- **Leptonic** final state
  - Clean signature and low background
  - Small branching ratio

- **Semi-leptonic** decay channel:
  - "Golden channel"
  - Good compromise between fully hadronic and fully leptonic final state

What about the diboson resonances?



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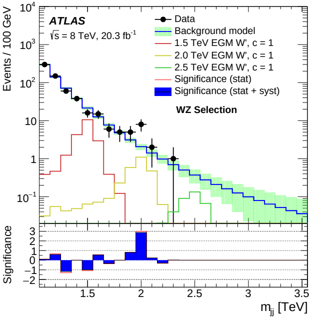
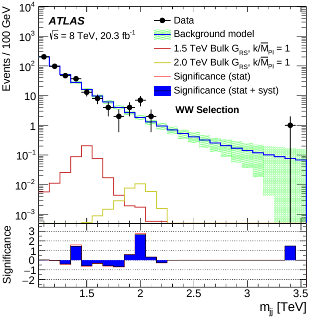
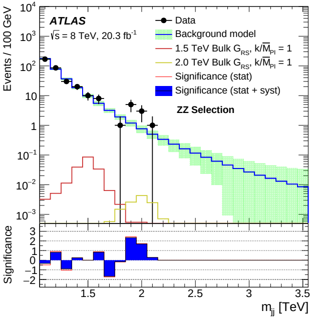
WZ



WW



ZZ



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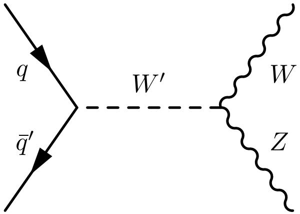

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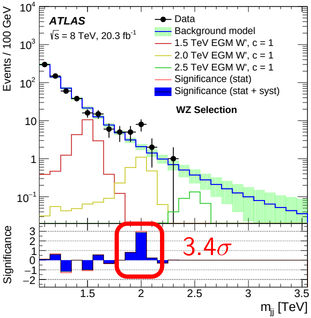
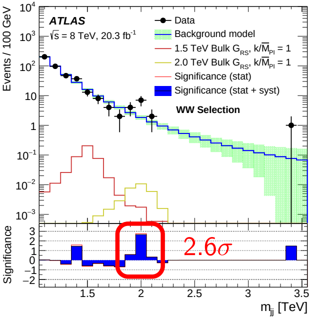
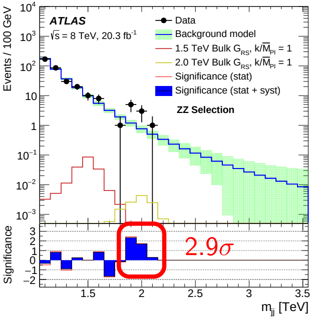
WZ



WW

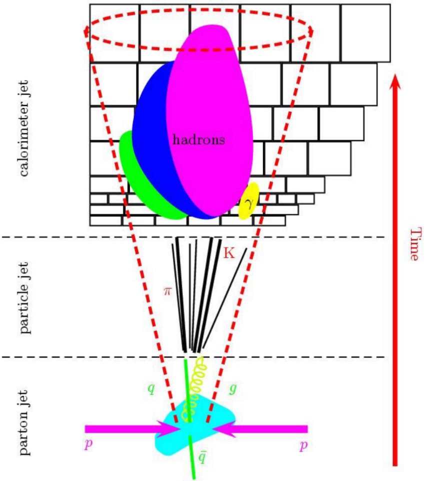


ZZ



Challenges of final states with hadronic decays

1. **How can we measure the hadronically decaying vector bosons?**
   - Cannot measure quarks directly in the detector
     → reconstruct as jet



Challenges of final states with hadronic decays

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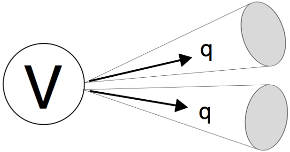
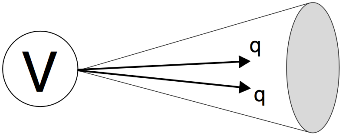
2. **How do we handle the high transverse momentum?**





Low p_{T} vector bosons

- Decay products well separated
- Two **small-R** jets ($R \approx 0.4$)

High p_{T} vector bosons

- Decay products are collimated
- One **large-R** jet ($R \approx 1.0$)

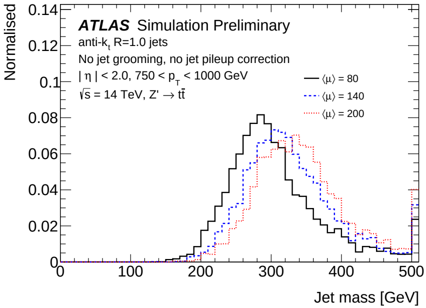
Rule of thumb

Angular separation of decay products:

$$\Delta R \approx \frac{2m^W}{p_{\mathrm{T}}^W}$$

Challenges of final states with hadronic decays

1. How can we measure the hadronically decaying vector bosons?
   - Cannot measure quarks directly in the detector
     $\rightarrow$ reconstruct as jet
2. How do we handle the high transverse momentum?
3. **How can we handle the high pile-up?**



- large-R jet containing $t \rightarrow bq\bar{q}$
- Jet mass depends on pile-up
- Jet mass diminishes with $\langle \mu \rangle$

Grooming techniques

- Remove soft gluon radiation and pile-up effects
- Improve jet mass resolution

Challenges of final states with hadronic decays

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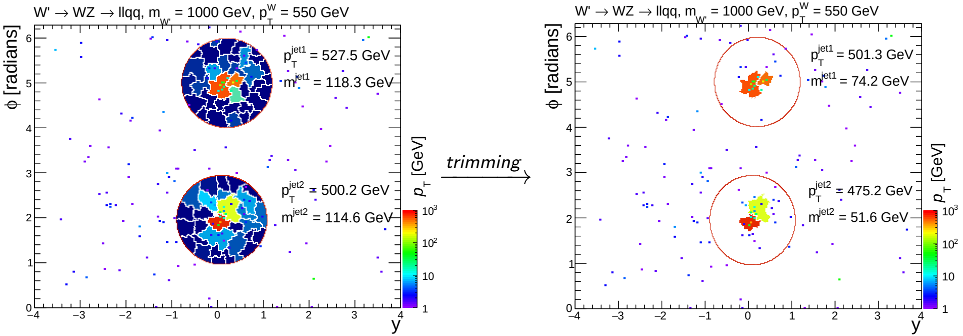
2. How do we handle the high transverse momentum?

3. **How can we handle the high pile-up?**



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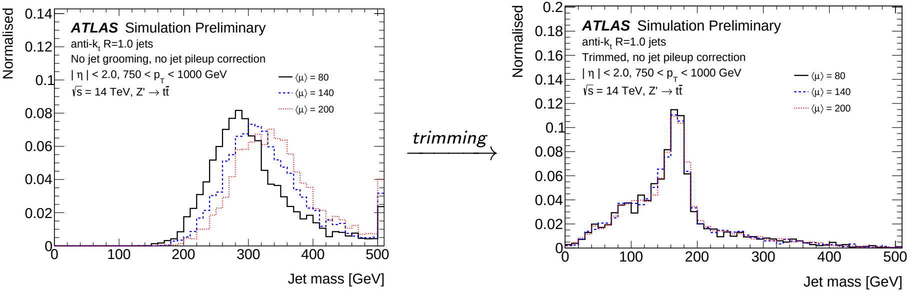
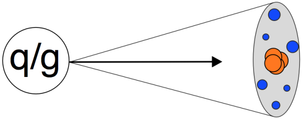


Challenges of final states with hadronic decays

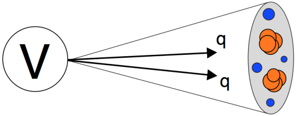
1. How can we measure the hadronically decaying vector bosons?
   - Cannot measure quarks directly in the detector
     $\rightarrow$ reconstruct as jet
2. How do we handle the high transverse momentum?
3. How can we handle the high pile-up?
4. **How can we suppress the enormous QCD dijet background?**
   - $\sigma_{\text{dijet}} \gg \sigma_{\text{BSM}} \rightarrow$ **use internal structure of large-R jet**

Quark/gluon jet



- One region with high energy density
- Mass from wide-angle radiation

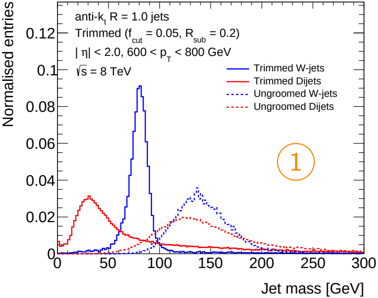
W/Z jet

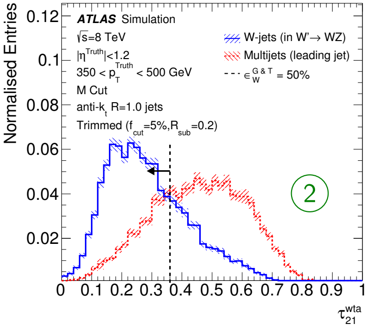


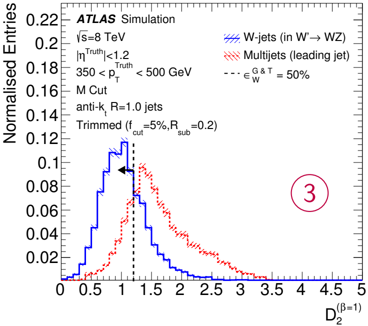
- Two regions with high energy density
- $m_{\text{jet}} \approx m_{W/Z}$
- Balanced subjet p_{T}

Jet mass + substructure variables

1. Jet mass
   - QCD jets originate from ≈ massless q/g
2. N-subjettiness τ_N
   - Is the jet composed out of N subjets?
3. Energy correlation variables C_2, D_2
   - Similar idea to τ_N but does not require subjets



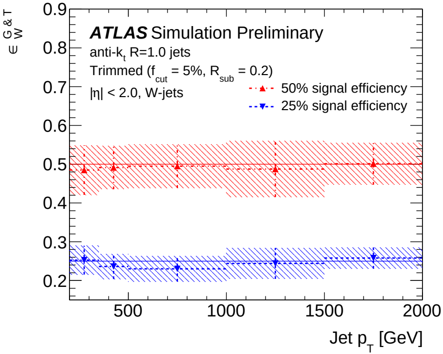




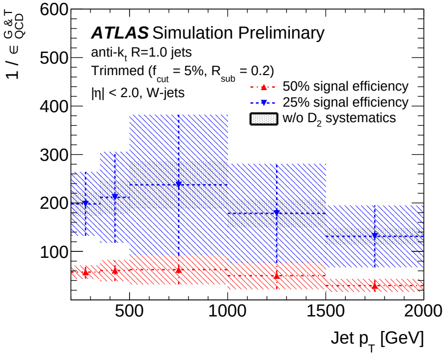
Signal efficiency and background rejection

- Derived two working points: $\varepsilon_{\text{sig}} = 25\%, \ 50\%$
- Tagger based on trimmed jets + mass + D_2 criteria
- Error bands show statistical + systematic uncertainties
- For 50% signal efficiency: **bkg rejection of 60 or bkg eff. of 1.6%**
- Tagger has been updated for Moriond using combined mass (more details later)

signal efficiency



background rejection



Diboson analyses in a nutshell

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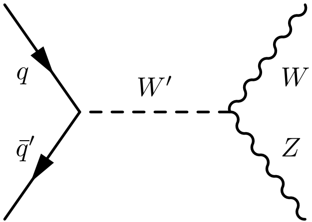

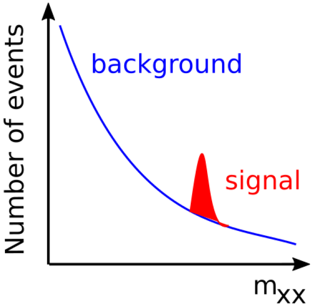

- Search for resonant structure in m_{WW}, m_{ZZ}, m_{WZ}
- Analysis performed with 13.2-15.5 fb^{-1} of 13 TeV *pp* collisions (ICHEP)
- Covering today:
  - WV $\rightarrow \ell\nu qq$ ATLAS-CONF-2016-062
  - ZZ/ZW $\rightarrow \ell\ell qq$, $\nu\nu qq$ ATLAS-CONF-2016-082
  - VV $\rightarrow$ JJ ATLAS-CONF-2016-055

$WV \to \ell\nu qq$ - Overview

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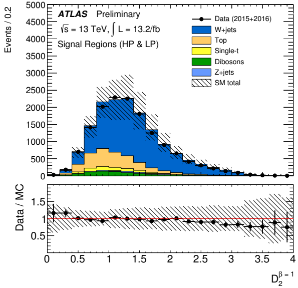
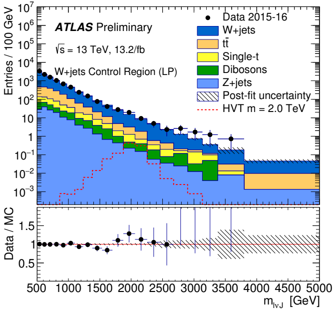
Event selection (only merged analysis for ICHEP)

- One lepton
- ≥ 1 large-R jet
- $E_{\mathrm{T}}^{\mathrm{miss}} > 200$ GeV
- $p_{\mathrm{T}}(J)/m_{\ell\nu J} > 0.4$, $p_{\mathrm{T}}(\ell\nu)/m_{\ell\nu J} > 0.4$
- Reject events close-by small-R b-tagged jet
- High purity and low purity SR based on D_2





Background estimation

- Shape estimated from MC
- Normalisation for W+jets and $t\bar{t}$ taken from CR
- $t\bar{t}$ CR: require close-by b-tagged jet
- W+jets CR: invert mass window
- Simultaneous fit to CR + SR

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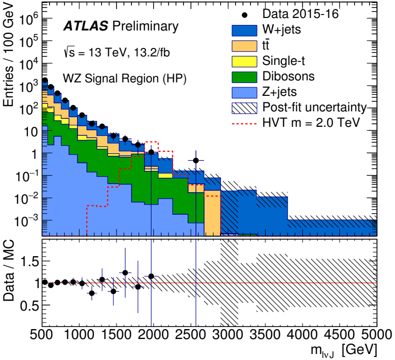
Dominating systematic uncertainties

- Scale and resolution uncertainties for D_2
- Energy and mass scale uncertainties for large-R jet
- Modelling of background shape
- About 10-20% effect on signal strength

Results

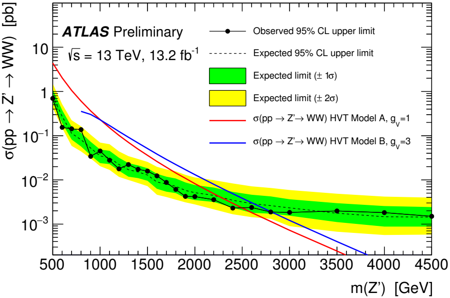


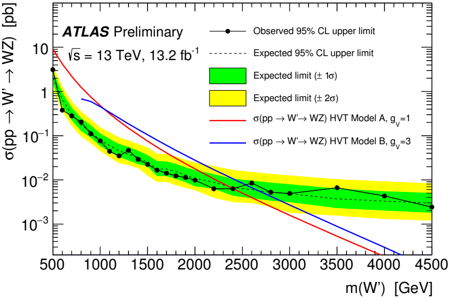
	WZ signal region	W+jets control region	$t\bar{t}$ control region
High-purity category			
W+jets	1810 ± 92	3050 ± 120	194 ± 28
$t\bar{t}$	830 ± 87	1130 ± 82	2300 ± 100
Single-t	160 ± 23	221 ± 26	312 ± 38
Z+jets	18.1 ± 5.1	50.7 ± 8.4	11.5 ± 2.6
Dibosons	165 ± 43	68 ± 18	19.8 ± 5.5
Total SM	2990 ± 70	4520 ± 97	3510 ± 94
Data	2972 ± 55	4534 ± 67	3509 ± 59
Low-purity category			
W+jets	4003 ± 130	7250 ± 196	670 ± 85
$t\bar{t}$	670 ± 72	1505 ± 120	3150 ± 125
Single-t	153 ± 21	284 ± 33	409 ± 46
Z+jets	54.1 ± 4.0	126 ± 12	16.7 ± 3.3
Dibosons	155 ± 40	135 ± 34	19.2 ± 6.1
Total SM	5035 ± 100	9300 ± 180	4260 ± 95
Data	5059 ± 71	9276 ± 96	4270 ± 65

No significant deviations observed from SM prediction

WV $\rightarrow \ell\nu qq$ - Limits

- 95% CL upper limits on cross-section times BR
- Exclude W' with $m_{W'} < 2400$ (2540) GeV for HVT Model A (B)
- Exclude Z' with $m_{Z'} < 2500$ (2810) GeV for HVT Model A (B)
- Improvement of more than one TeV with respect to previous analysis

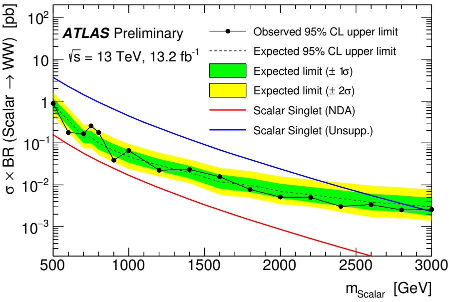


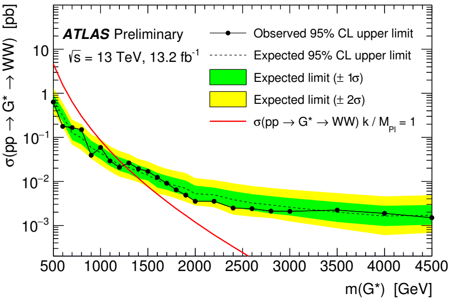


- Model A: similary to extended gauge model
- Model B: coupling to fermions is suppressed

WV $\rightarrow \ell\nu qq$ - Limits II

- 95% CL upper limits on cross-section times BR
- Exclude RS Graviton with masses below 1240 GeV
- Improvement of approximately 200 GeV with respect to previous analysis





$ZV \to \ell\ell qq$ - Overview

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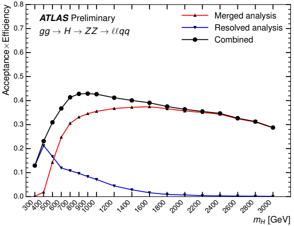
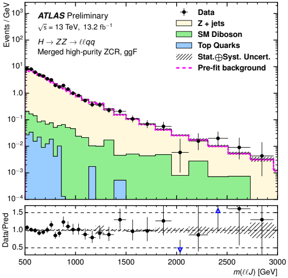
- Consider both merged and resolved regime
- First study of VBF production in Higgs doublet model (tag two additional jets)

Event selection

- Two isolated leptons
- $m_{\ell\ell}$ compatible with Z-boson mass
- merged: $\min(p_{\mathrm{T}}(J), p_{\mathrm{T}}(\ell\ell))/m_{\ell\ell J} > 0.3$ (0.35)
- resolved: b-tag categories for H search
- High purity and low purity SR based on D_2





Background estimation

- Shape estimated from MC
- Z+jets and $t\bar{t}$ norm. estimated in CR
- $t\bar{t}$ CR: diff. flavour leptons, 2 b-tagged jets
- Z+jets CR: invert mass window
- Simultaneous fit to CR + SR

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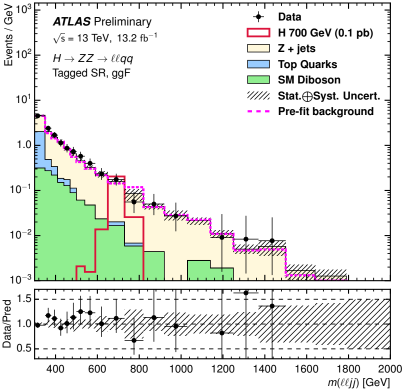
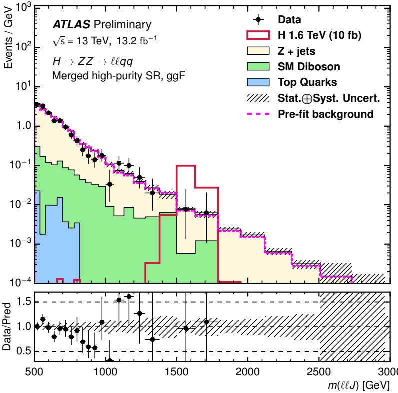
Dominating systematic uncertainties

- Jet energy scale and resolution uncertainties
- Scale and resolution uncertainties for D_2
- Z+jets modelling

Results

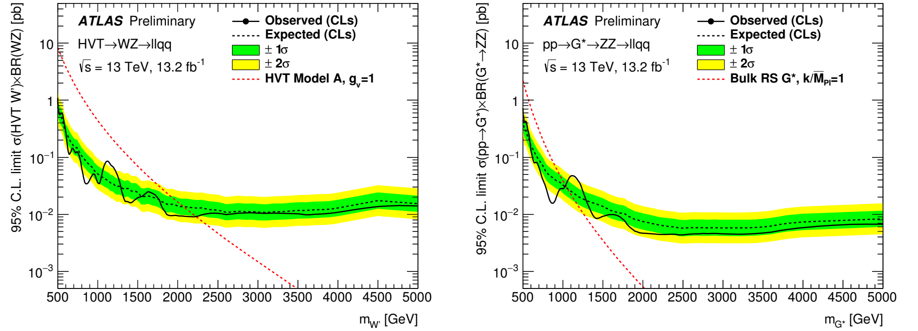




No significant deviations observed from SM prediction

ZV $\to \ell\ell qq$ - Limits

- 95% CL upper limits on cross-section times BR
- Exclude RS Graviton with masses below 1035 GeV ($\sim$ 200 GeV improvement)
- Exclude W' with $m_{W'} < 2225$ GeV ($\sim$ 800 GeV improvement)



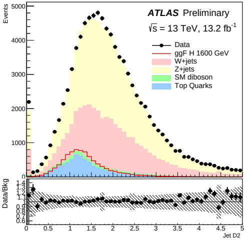
$ZV \to \nu\nu qq$ - Overview

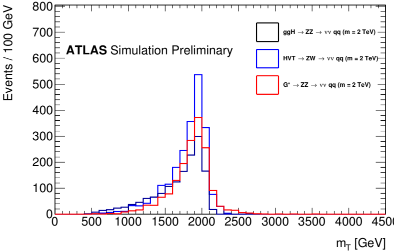
Observable: transverse mass:

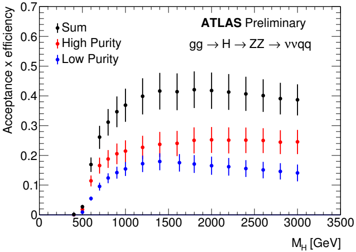
$$m_{\mathrm{T}} = \sqrt{(E_{\mathrm{T,J}} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\vec{p}_{\mathrm{T,J}} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}})^2}, \text{ with } E_{\mathrm{T,J}} = \sqrt{m_{\mathrm{J}}^2 + p_{\mathrm{T,J}}^2}$$

Event selection

- Lepton veto
- $E_{\mathrm{T}}^{\mathrm{miss}} > 250$ GeV
- $\Delta\Phi(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, \vec{E}_{\mathrm{T}}^{\mathrm{miss}}) < 1$
- High purity and low purity SR based on D_2





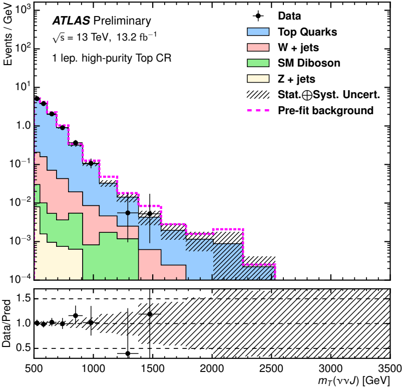


Dominating systematic uncertainties

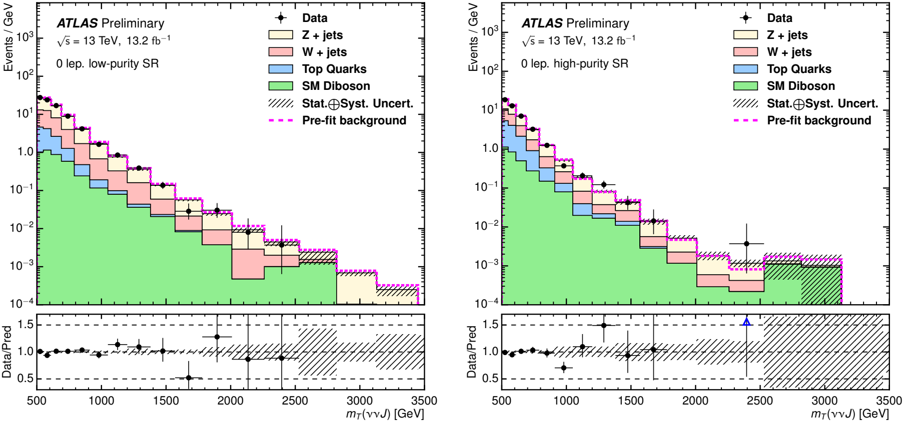
- Jet energy scale and resolution uncertainties
- Scale and resolution uncertainties for D_2

Background estimation

- Z+jets, W+jets and $t\bar{t}$ CR to determine normalisation in SR
- Z+jets estimated from $Z \rightarrow \mu\mu$ + J (with m_J outside of Z-boson window)
- CR use new definition of $E_{\mathrm{T}}^{\mathrm{miss}}$ removing muon contribution
- Build transverse mass with new $E_{\mathrm{T}}^{\mathrm{miss}}$ definition
- Two SR and 6 CR are used in fit



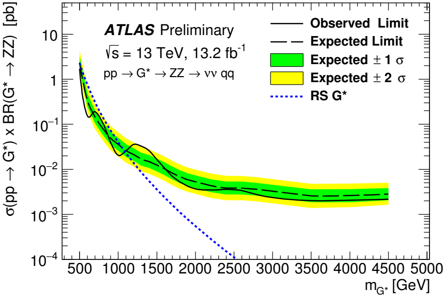
ZV $\rightarrow \nu\nu qq$ - Results

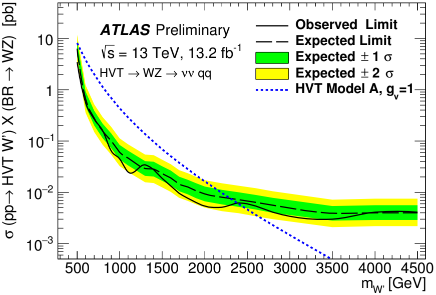


No significant deviations observed from SM prediction

ZV $\rightarrow \nu\nu qq$ - Limits

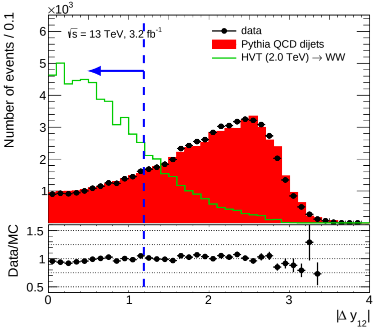
- 95% CL upper limits on cross-section times BR
- Exclude RS Graviton with masses below 1100 GeV ($\sim$ 200 GeV improvement)
- Exclude W' with $m_{W'} < 2400$ GeV ($\sim$ 700 GeV improvement)

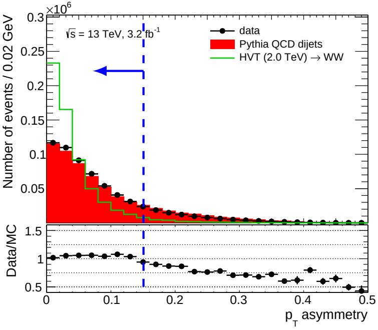




VV→JJ - Overview

- Require two large-R boson-tagged jets → addition n_{trk} cut
- Dominating background: QCD dijet production
- Rapidity difference $|y_1 - y_2|$ (reject t-channel QCD production)
- p_{T} asymmetry $|(p_{\mathrm{T}_1} - p_{\mathrm{T}_2})|/(p_{\mathrm{T}_1} + p_{\mathrm{T}_2})$ (quality criteria)
- Overlap between WW, WZ, ZZ selection due to chosen mass window





Number of ghost-associated tracks

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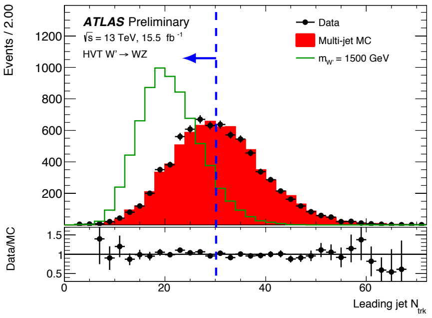
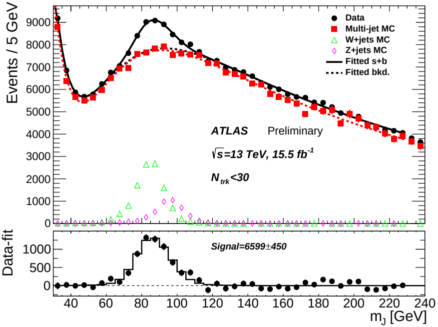
- n_{trk}: number of ghost-associated tracks to ungroomed jets
- Gluons produce more particles during fragmentation
- Measure efficiency in V+jets events in data



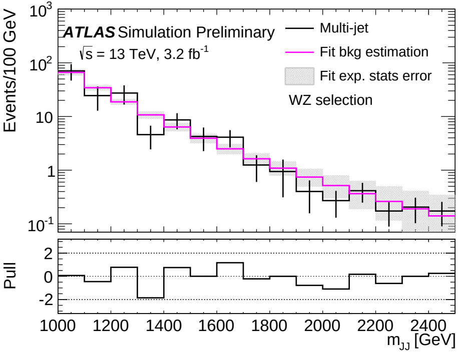


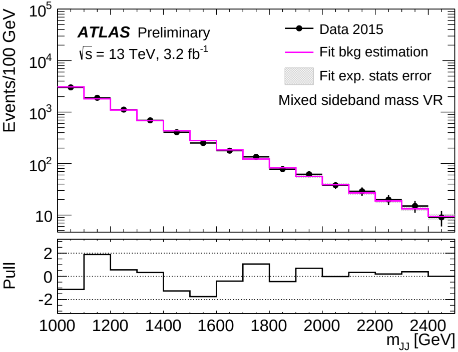
Background Parameterisation

- m_{JJ} bkg distribution assumed to be smoothly falling, characterised by:

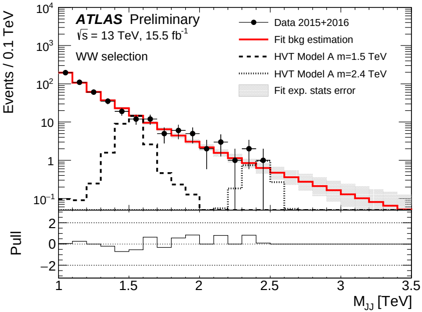
$$\frac{\mathrm{d}n}{\mathrm{d}x} = p_1(1-x)^{p_2+\xi p_3}x^{p_3}, \quad x = m_{jj}/\sqrt{s}$$

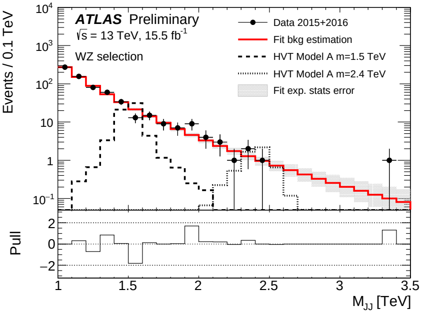
- p_1: normalisation, p_2, p_3 dimensionless shape parameters, ξ constant
- Binned maximum-likelihood fit performed to data to estimate background





Results


ATLAS Preliminary
√s = 13 TeV, 15.5 fb-1
WW selection
Data 2015+2016
Fit bkg estimation
HVT Model A m=1.5 TeV
HVT Model A m=2.4 TeV
Fit exp. stats error
Events / 0.1 TeV
Pull
M_JJ [TeV]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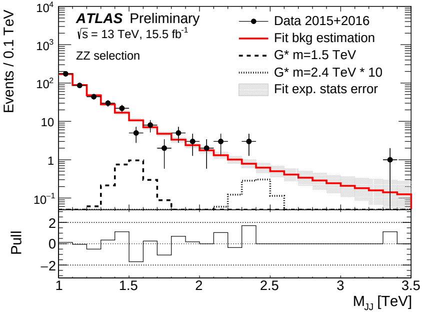
ATLAS Preliminary
√s = 13 TeV, 15.5 fb-1
ZZ selection
Data 2015+2016
Fit bkg estimation
G* m=1.5 TeV
G* m=2.4 TeV * 10
Fit exp. stats error
Events / 0.1 TeV
Pull
M_JJ [TeV]

Statistical interpretation

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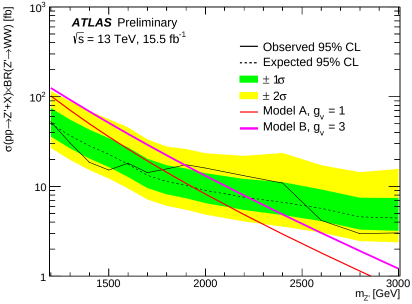
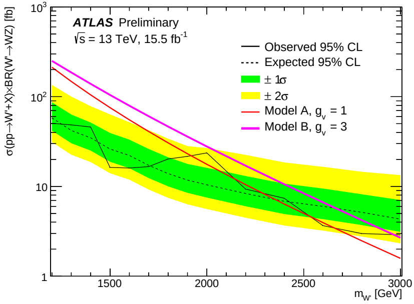
$Z' \to WW$



$1.2 < m_{Z'} < 1.8$
$(1.2 < m_{Z'} < 1.9)$
excluded for $g_V = 1$ $(g_V = 3)$

$W' \to WZ$

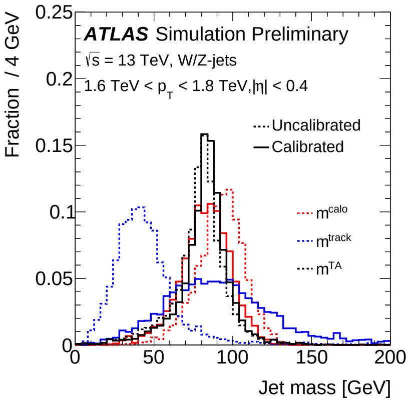


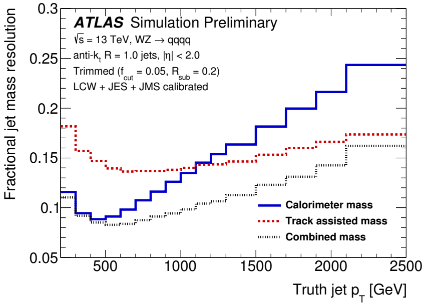
$1.2 < m_{W'} < 1.9$
$(1.2 < m_{W'} < 3.0)$
excluded for $g_V = 1$ $(g_V = 3)$

Towards W vs Z discrimination

- **Drawback** of the analyses: cannot discriminate between W and Z boson due to overlapping mass windows
- Overlapping due to degradation of mass resolution at high p_{T} → use tracks

$$m^{\mathrm{comb}} = \frac{\sigma_{\mathrm{calo}}^{-2}}{\sigma_{\mathrm{calo}}^{-2} + \sigma_{\mathrm{TA}}^{-2}} \times m_{\mathrm{calo}} + \frac{\sigma_{\mathrm{TA}}^{-2}}{\sigma_{\mathrm{calo}}^{-2} + \sigma_{\mathrm{TA}}^{-2}} \times m_{\mathrm{TA}}, \quad m^{\mathrm{TA}} = \frac{p_{\mathrm{T}}^{\mathrm{reco}}}{p_{\mathrm{T}}^{\mathrm{trk}}} \times m_{\mathrm{trk}}$$



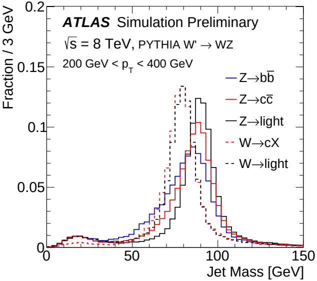


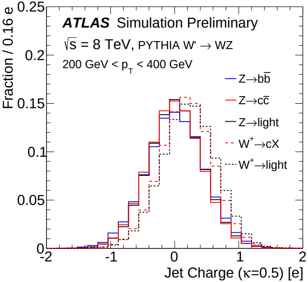
W vs. Z discrimination

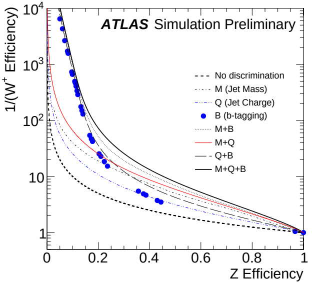
- Track-assisted mass improves discrimination but need more
- Three dimensional likelihood ratio
- Jet mass, jet charge and *b*-tagging discriminant
- Jet charge:

$$Q = \frac{1}{p_{\mathrm{T,J}}^{\kappa}} \sum_{i \epsilon \mathrm{Tracks}} q_i \times (p_{\mathrm{T}}^{i})^{\kappa}$$

- $\varepsilon_Z = 90\%,\ 50\%,\ 10\% \rightarrow 1/\varepsilon_W = 1.7,\ 8.3,\ 1000$







Jet uncertainty improvement

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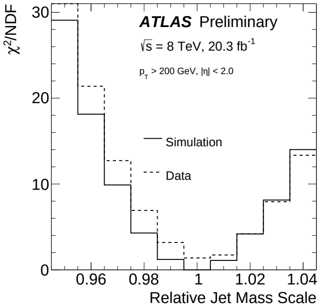
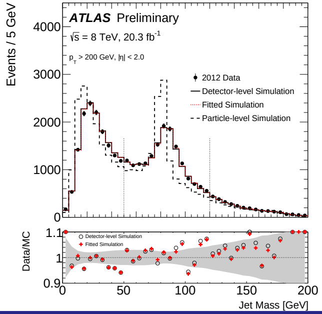
- Currently the searches are dominated by large-R jet uncertainties
- Uncertainties are derived using track-jet double ratio
  (probe calorimeter measurement with that from **track-jets**)
- Improve jet energy unc. significantly using γ or small-R jets as reference
- Improve jet mass scale unc. by using W boson resonance peak in $t\bar{t}$ events

Forward folding method (ATLAS-CONF-2016-035)

- Avoids finding functional form for response function
- Shift and stretch mass resolution function to best match the data





Improving tagging techniques

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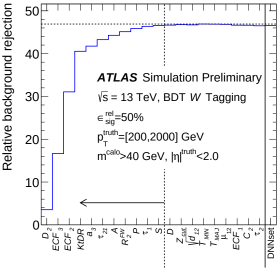
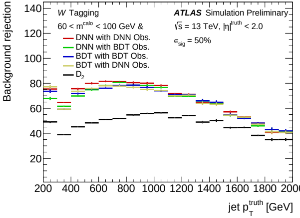
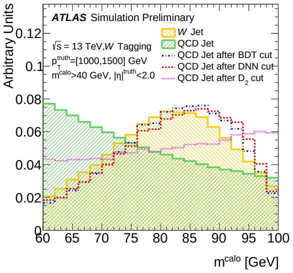
How can we improve the performance of our boson taggers???

- Constituent-level pile-up suppression techniques
- Variable-radius jets (ATL-PHYS-PUB-2016-013)
- Optimise tagging algorithm for different polarisations
- Flat background rejection?
- Multivariate analyses ...
  - New ATLAS publication ATL-PHYS-PUB-2017-004
  - W and top tagging studied using BDT and DNN







Summary

- The diboson final state provides a direct key to new physics beyond the SM
  $\rightarrow$ small excess observed in 8 TeV data
- For high resonance masses, the decay products of the W/Z bosons are boosted
  $\rightarrow$ need **novel** and **innovative** reco techniques for hadronic decay
- No significant deviation from background expectation observed at 13 TeV
  $\rightarrow$ set upper limits on cross-section $\times$ BR for benchmark models
- Analyses will be updated for EPS/LHCP using full 2015+2016 dataset
- **Challenge** of analyses: substructure techniques at very high-p_{T}

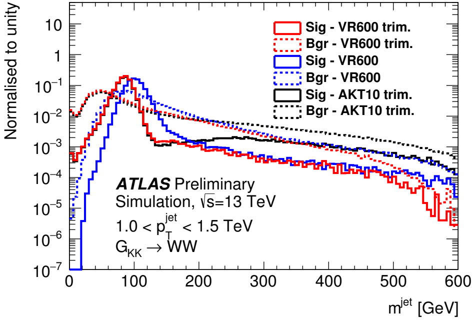
Backup

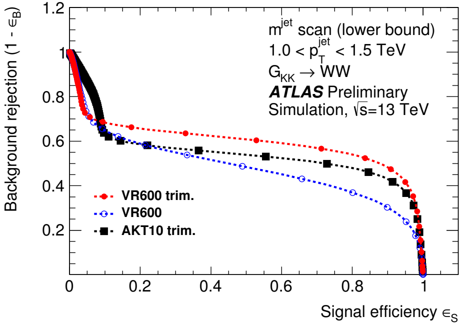
Outlook - Variable-R jets

- Use variable jet radius size:

$$R_0 \rightarrow R_{\text{eff}} = \frac{\rho}{p_{\text{T,i}}}$$

- Still need additional pile-up suppression techniques
- VR + trimming outperforms trimming at high p_{T}



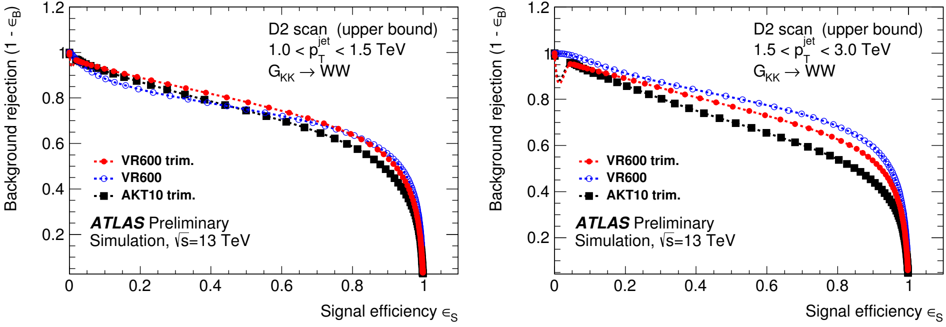


Outlook - Variable-R jets - II

- Use variable jet radius size:

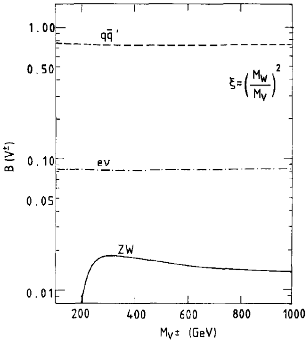
$$R_0 \to R_{\rm eff} = \frac{\rho}{p_{\rm T,i}}$$

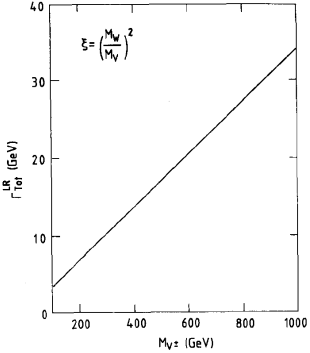
- Still need additional pile-up suppression techniques
- VR + trimming outperforms trimming at high $p_{\rm T}$



Extended Gauge Model

- Does not solve shortcomings of the Standard Model
- Predicts existence of heavier spin-one vector bosons W' and Z'
- Coupling of W' to fermions as in the SM
- $W'WZ$ coupling suppressed by $c \cdot (m_W^2/m_{W'}^2)$
- Width of W' increases linearly with its mass ($\approx$3.5%)





Heavy Vector Triplet

- Simplified phenomenological Lagrangian as diboson resonance searches only sensitive to parameters that retain mass and coupling strength
- Allows to describe a large class of models
- Coupling of vector triplet to fermions: $(g^2/g_V^2) \cdot c_{\mathrm{F}},\ c_{\mathrm{F}} \approx 1$
- Coupling to vector bosons and Higgs boson: $g_V c_{\mathrm{H}}$
- Model A: $g_V = 1$, Model B: $g_V = 3$
- BR($W' \to WZ,\ Z' \to WW \approx 2\%$)
- Width of new spin-one particles: 2.5% of mass

Bulk Randall-Sundrum model

- Provides solution to hierarchy problem and results in unification of coupling constants
- four-dimensional spacetime is embedded in larger dimensional bulk with one single warped extra dimension
- SM gauge bosons and fermions are allowed to propagate in additional dimension (as opposed to previous model)
- Higgs field is contained in TeV brane, gravitation localised at Planck brane
- SM particles propagating through bulk $\rightarrow$ Kaluza-Klein excitations
- spin-2 KK graviton close to TeV scale with decays mostly to top, Higgs, WW and ZZ
- Width: approx. 6% of resonance mass
- $\text{BR}(G^* \rightarrow WW) \approx 18\%$ and $\text{BR}(G^* \rightarrow ZZ) \approx 9.5\%$

Scalar Higgs

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- Higgs boson at high mass in the narrow width approximation
- Higgs width is about 4 MeV, much less than experimental resolution
- WW results interpreted in CP-even scalar singlet model:
  - Naive dimensional analysis: $c_3 = 1/(4\pi)^2$, $c_H = 0.9$
  - Unsuppressed: $c_3 = 1/8\pi$, $c_H = 0.4$
- c_3 determines production cross-section and decay width to gluons
- Unsuppressed: BR $(H \to WW) = 59\%$ - 73%

What are jets?

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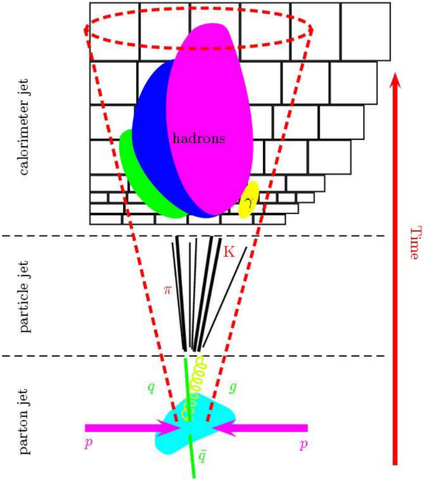
- Confinement of the strong force → quarks/gluons **not directly measured**
- Measure particles produced in the showering and hadronization
- Jets are collimated bunches of energetic particle
- Jets are not directly mappable to individual partons
  - finite calorimeter resolution, gaps, cracks, dead material ...



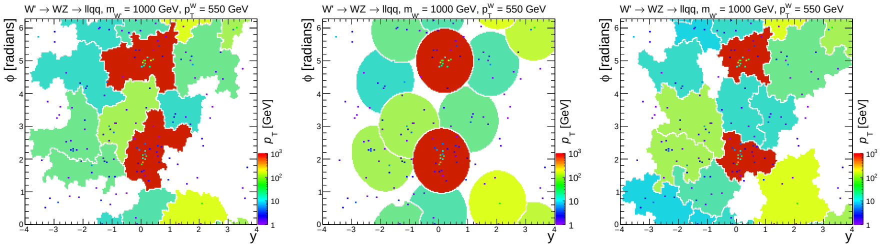
Sequential jet recombination algorithms

Used to cluster objects into a jet based on their angular separation

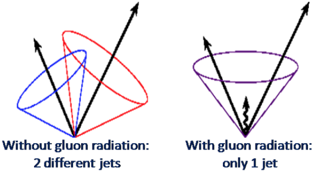
$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2} \quad (R : \text{jet radius})$$

- p = 1: k_t
- p = -1: anti-k_t: clusters most energetic particles first
- p = 0: C/A : based on angular separation

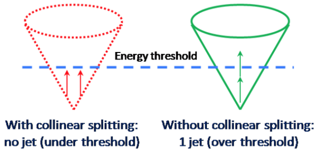
There is no *correct* jet def., but require **infrared and collinear safety**



Infrared safety



Collinear safety



Infrared safety

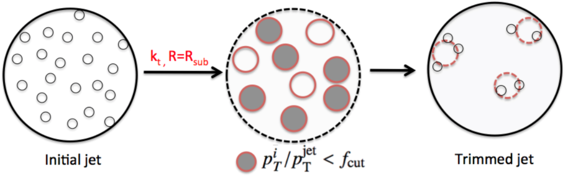
- Result of jet algorithm does not change with additional soft radiation

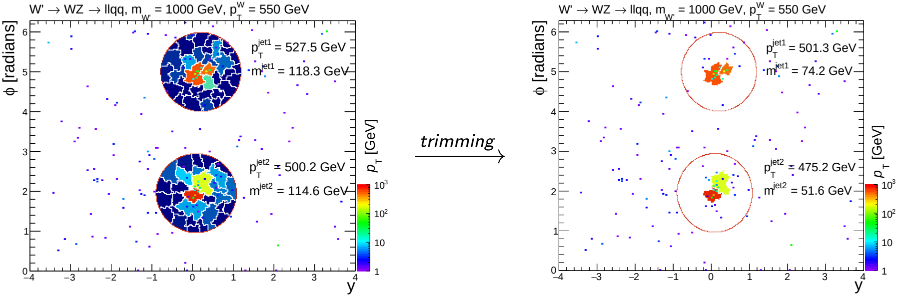
Collinear safety

- Hard particle that are splitting in two soft particles give nearly the same result

Jet grooming in a nutshell

1. **Trimming**
   - Removes subjet (size R_{sub}) if: $p_T^i / p_T^{\text{jet}} < f_{\text{cut}}$





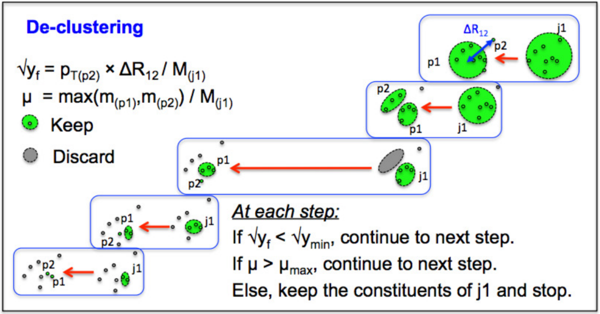
Jet grooming in a nutshell

1 Trimming

- Removes subjet (size $\mathrm{R_{sub}}$) if: $p_{\mathrm{T}}^{i}/p_{\mathrm{T}}^{\mathrm{jet}} < f_{\mathrm{cut}}$

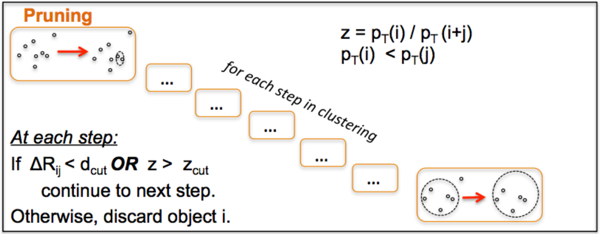
2 Mass drop/filtering

- Splitting: require symmetric splitting $\sqrt{y_{\mathrm{f}}} = \frac{\min(p_{\mathrm{T1}}, p_{\mathrm{T2}})}{m_{12}} \times \Delta R_{12}$
- Filtering: remove soft radiation by keeping only N hardest subjets



Jet grooming in a nutshell

1. **Trimming**
   - Removes subjet (size $\mathrm{R_{sub}}$) if: $p_{\mathrm{T}}^{i}/p_{\mathrm{T}}^{\mathrm{jet}} < f_{\mathrm{cut}}$
2. **Mass drop/filtering**
   - Splitting: require symmetric splitting $\sqrt{y_{\mathrm{f}}} = \frac{\min(p_{\mathrm{T}1}, p_{\mathrm{T}2})}{m_{12}} \times \Delta R_{12}$
   - Filtering: remove soft radiation by keeping only N hardest subjets
3. **Pruning**
   - For each step in reclustering, remove softer constituent from jet if
     - wide-angled: $\mathrm{R_{12} > R_{cut} \cdot 2m/p_T}$ or
     - soft: $\frac{\min(\mathrm{p_{T,1}, p_{T,2}})}{\mathrm{p_{T,1} + p_{T,2}}} < Z_{cut}$

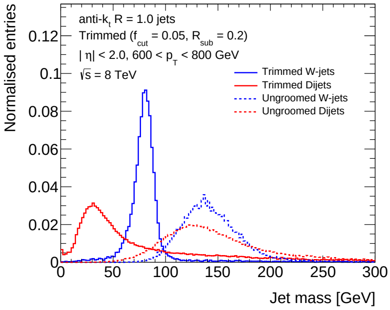


Jet mass

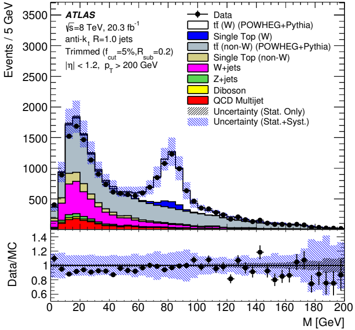
- Calculated from the constituents of the jet, e.g. topo-clusters, tracks

$$m^2 = \left(\sum_i E_i\right)^2 - \left(\sum_i \vec{p}_i\right)^2$$

Simulation



$t\bar{t} \rightarrow$ lep+jets events in data



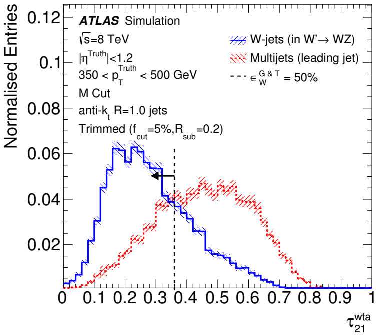
N-subjettiness

- Describes how likely it is that a jet is composed out of N subjets:

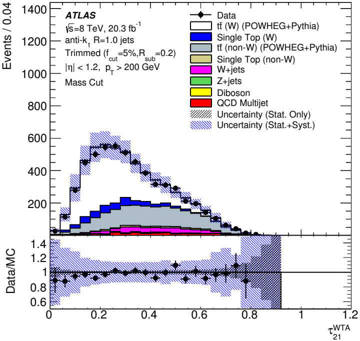
$$\tau_N = \frac{\sum_k p_{\mathrm{T,k}}(\min(\Delta R_{1,k}, R_{2,k}, ..., R_{N,k}))^\beta}{\sum_k p_{\mathrm{T}}(R_0)^\beta}$$

- Powerful discrimination using the ratio: τ_2/τ_1

Simulation



$t\bar{t} \to$ lep+jets events in data



Energy correlation variables

Energy correlation C_2 and D_2

$$C_2^{\beta} = \frac{E_{CF}1(\beta)}{E_{CF}2(\beta)} \times \frac{E_{CF}3(\beta)}{E_{CF}2(\beta)}$$

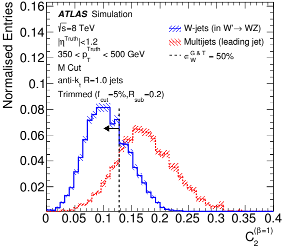
$$D_2^{\beta} = \frac{E_{CF}^3 1(\beta)}{E_{CF}^3 2(\beta)} \times E_{CF}3(\beta)$$

N-point energy correlation function

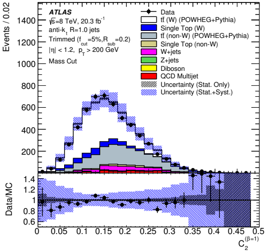
$$E_{CF}1(\beta) = \sum_{i \in J} p_{\mathrm{T}_i}, \qquad E_{CF}2(\beta) = \sum_{i<j \in J} p_{\mathrm{T}_i} p_{\mathrm{T}_j} \left(\Delta R_{ij}\right)^{\beta},$$

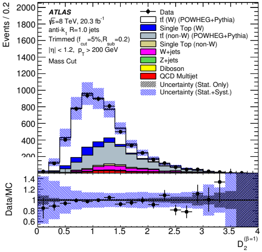
$$E_{CF}3(\beta) = \sum_{i<j<k \in J} p_{\mathrm{T}_i} p_{\mathrm{T}_j} p_{\mathrm{T}_k} \left(\Delta R_{ij} \Delta R_{ik} \Delta R_{jk}\right)^{\beta},$$

Simulation



$t\bar{t} \to$ lep+jets events in data





Track-jet double ratio method - Intro

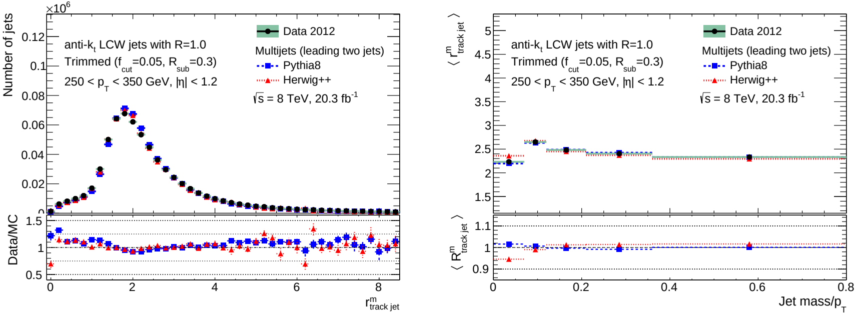
- Jet mass measurement in calorimeter probed with **track-jets as reference**
- Track-jets are well measured and independent of calorimeter and pile-up
- Ratio of calorimeter and track jet mass:

$$r^{m,\mathrm{data/MC}}_{\mathrm{track\ jet}} = \frac{m^{\mathrm{data/MC}}_{\mathrm{jet}}}{m^{\mathrm{data/MC}}_{\mathrm{track\ jet}}}$$

- Allows for separation between physics and detector effects (if new physics affects both calorimeter and ID)
- If detector effects are well modelled in simulation, the ratios in data and MC should be in decent agreement:

$$R^{m}_{\mathrm{track\ jet}} = \frac{r^{m,\mathrm{data}}_{\mathrm{track\ jet}}}{r^{m,\mathrm{MC}}_{\mathrm{track\ jet}}}$$

Jet mass scale uncertainty determination



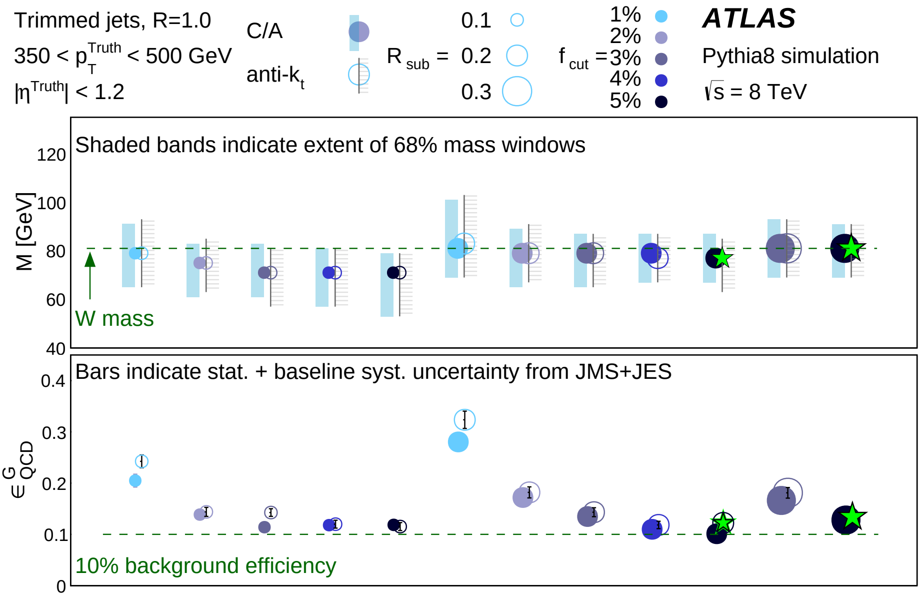
Left:

- $r^{m,\mathrm{data/MC}}_{\mathrm{track\ jet}} < 1$ due to trimming procedure $\rightarrow$ track-based grooming
- $r^{m,\mathrm{data/MC}}_{\mathrm{track\ jet}} \approx 2$ due to soft particles (bent by magnetic field

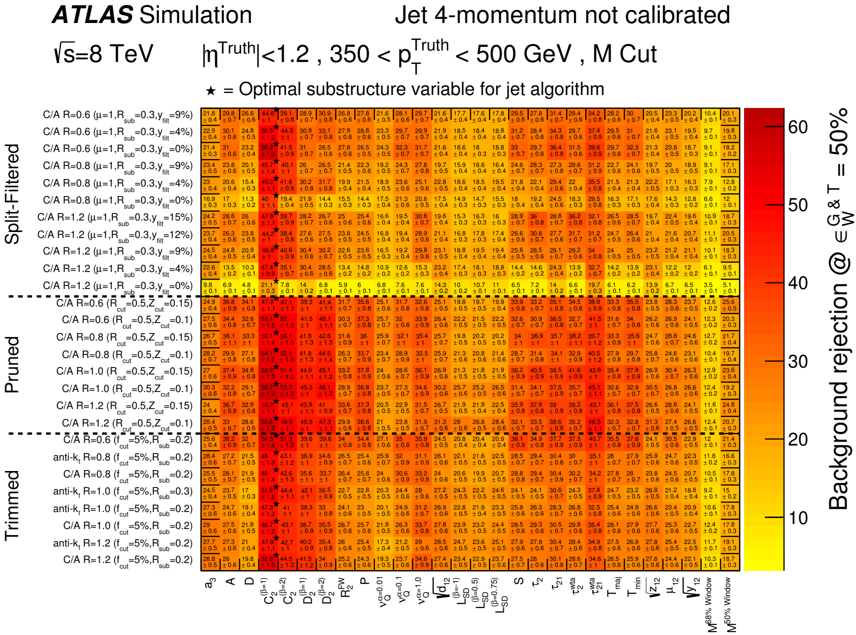
Right:

- Mean of $r^{m,\mathrm{data/MC}}_{\mathrm{track\ jet}}$ used to estimate uncertainties (less fluctuations))
- Uncertainties derived in η, p_{T} and m/p_{T} bins
- m/p_{T}: mass dependent uncertainties (but independent of the actual scale)

How to find the "best" groomer



How to find the "best" tagger



Boosted boson tagging in Run-2

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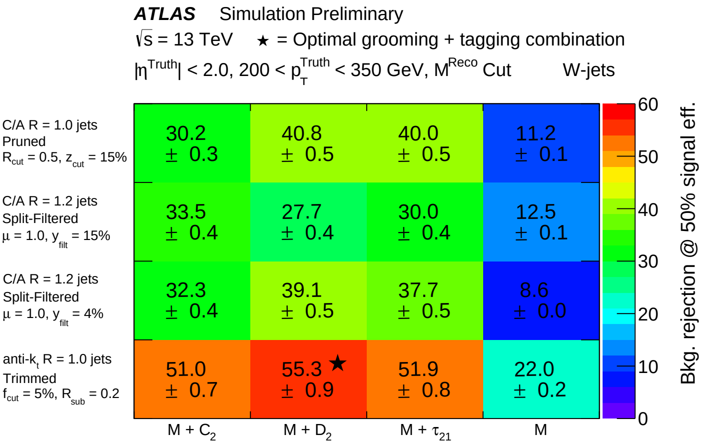
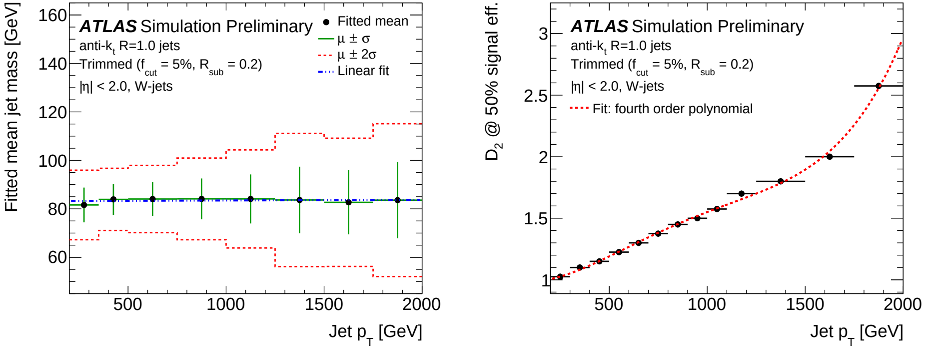
- **Aim:**
  - Provide *W* and **Z** boson tagging algorithm (50% signal efficiency)
  - Derive dedicated jet energy/mass calibration + systematic uncertainties
- Studies heavily based on 8 TeV effort



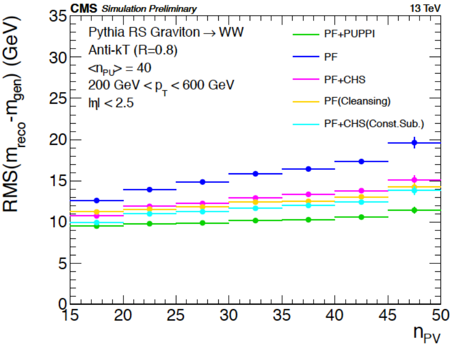
Boson identification criteria

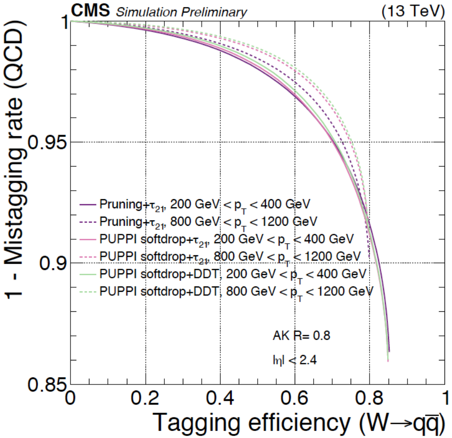
- 15 GeV window around mean is chosen → signal efficiency ≈ 55-80%
- Smooth criteria on $D_2^{\beta=1}$ → **flat** signal efficiency of 50%



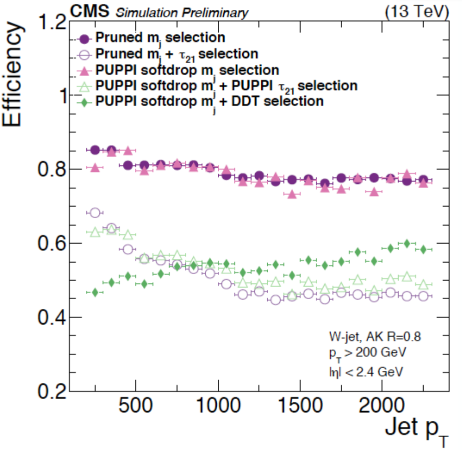
Boson tagging in CMS

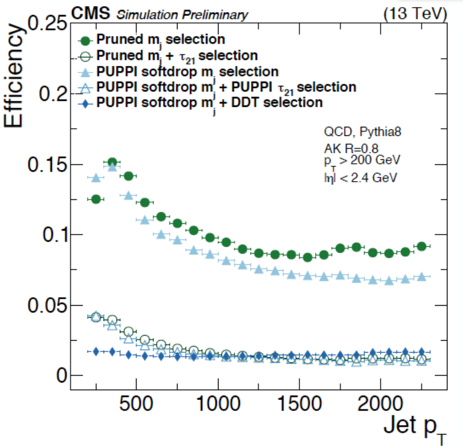
- Considered three different W-tagger algorithms (anti-k_t $R = 0.8$)
  1. pruning + τ_{21} (à la Run-I)
  2. soft drop + τ_{21} (PUPPI)
  3. soft drop + DDT (mass and p_{T} independent version of τ_{21}) (PUPPI)



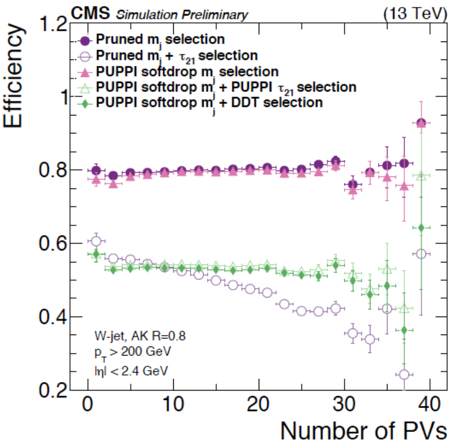


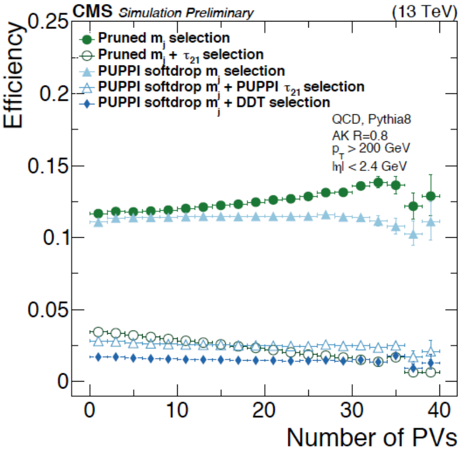
Boson tagging in CMS - p_{T} dependence





Boson tagging in CMS - N_{PV} dependence





Soft-drop

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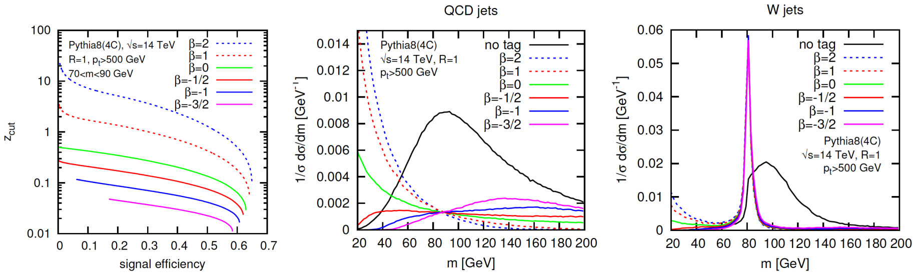
- Preferred by theory community

Algorithm:

1. Recluster constituents of large-R jet j (e.g. anti-k_t) with C/A algorithm
2. Undo the last stage of C/A clustering and label the two subjets $j1$ and $j2$
3. If the subjets pass the soft-drop condition:

$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{cut} \left(\frac{\Delta R_{12}}{R_0} \right)^{\beta}$$

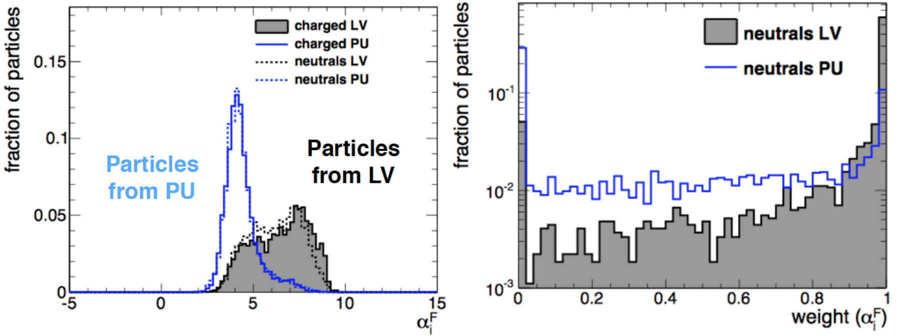
the jet j is considered as final jet. Otherwise define j to be equal to the subjet with larger p_T and iterate the procedure



- **Charge Hadron Subtraction (CHS)**:
  removes charged particles associated with pileup vertices
- **PileUp Per Particle Identification (PUPPI)**:
  Define variable α for each particle-flow particle i using close-by particles j:

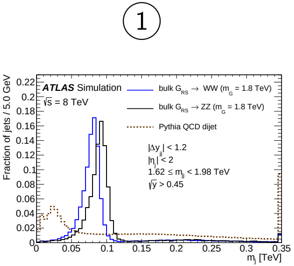
$$\alpha_i = \sum_j \frac{p_{\mathrm{T}}^j}{\Delta R_{ij}} \theta(R_{\mathrm{min}} < \Delta R_{ij} < R_0)$$

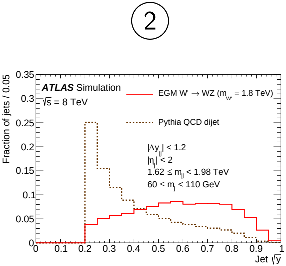
Transform α into weight that is used during the reconstruction algorithm

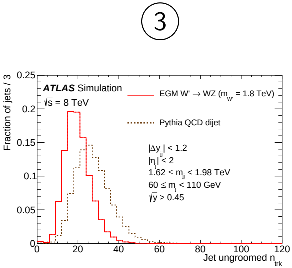


Boson tagging requirements in Run-I analysis

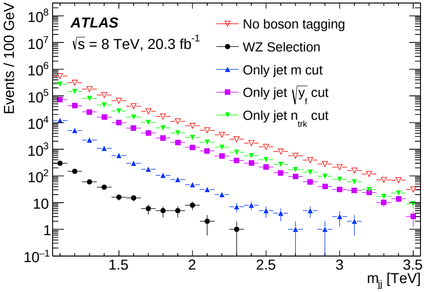
- **Jet reconstruction:**
  C/A $R = 1.2$ jets groomed with the BDRS (split-filtering) algorithm
- **Boson tagging:**
  1. the large-R jet mass m_J (13 GeV mass window around boson mass)
  2. y_f as tagging variable: $\sqrt{y_f} = \frac{\min(p_{T1}, p_{T2})}{m_{12}} \times \Delta R_{12}$, $\sqrt{y_f} > 0.45$
     - QCD dijet events have unbalanced subjet momenta compared to signal jets due to soft gluon radiation
  3. Number of charged-particle tracks associated to the ungroomed jet:
     - $n_{\mathrm{trk}} < 30$: expect QCD jet to be composed of more hadrons

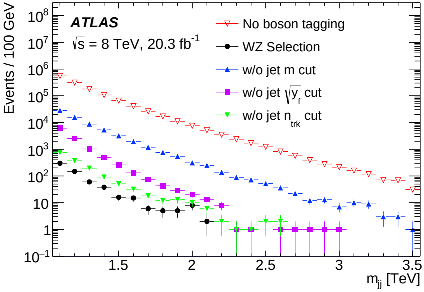






Shaping of background of tagging criteria





- Left: Comparison of no tagging criterion and only one boson tagging requirement applied to each jet
- Right: The effect of applying all tagging requirements except one is displayed.

Cross-check - Detector Effect?

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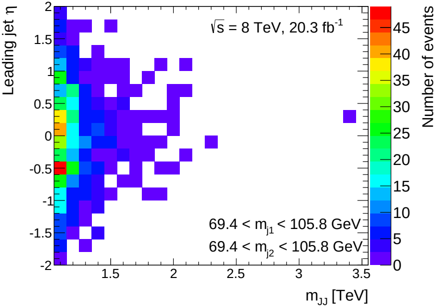
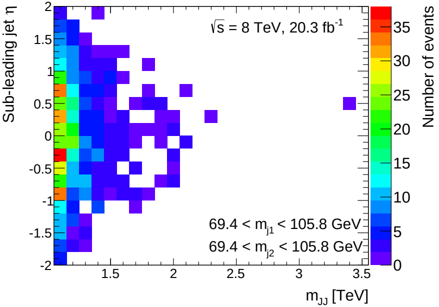
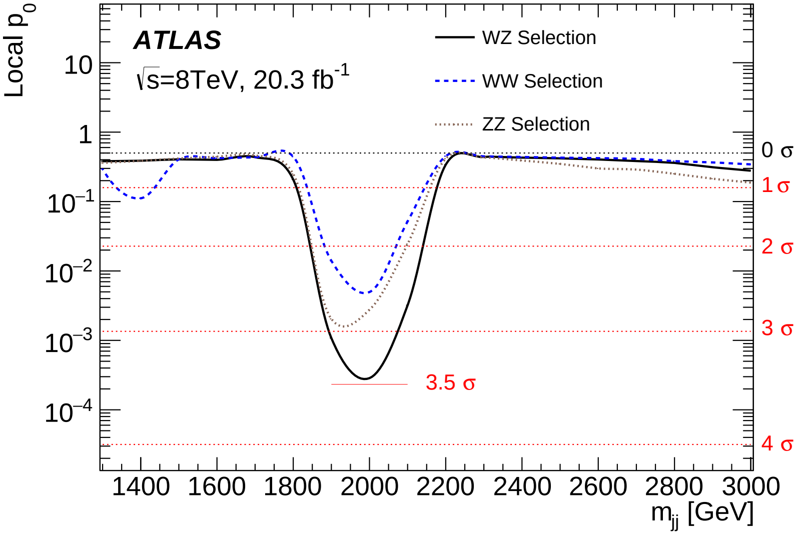




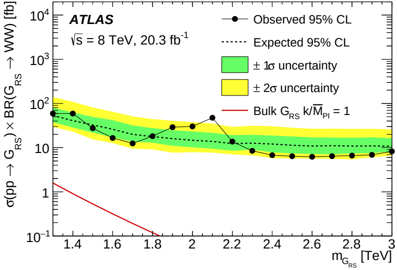
- η vs m_{JJ} for the leading jet (left) and subleading jet (right)

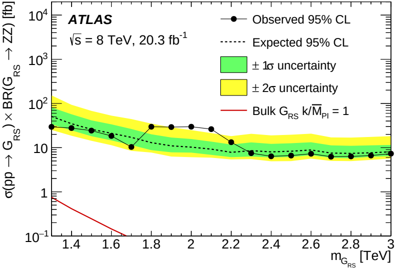
Local p_0 value

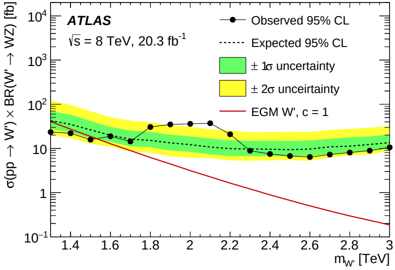


Limits on benchmark models

- $\sigma \times \mathrm{BR}$ for gravitons with chosen model parameters too low to be excluded
- Exclude $1300 < \mathrm{M}(W') < 1500$ GeV

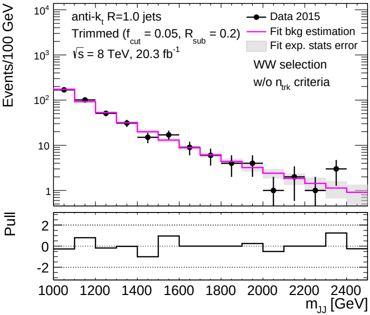


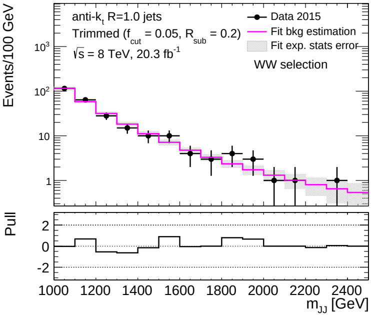




Run-II tagger on Run-I data

- *WW* selection
- Trimmed anti-k_t $R = 1.0$ jets with criteria on mass and $D_2^{\beta=1}$
- Dedicated 8 TeV jet energy and mass calibration





Run-II tagger on Run-I data

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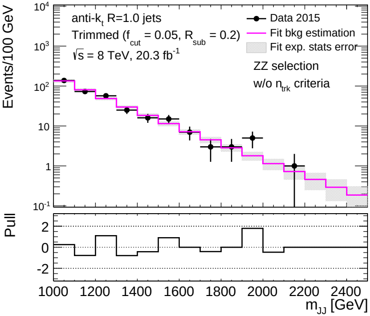
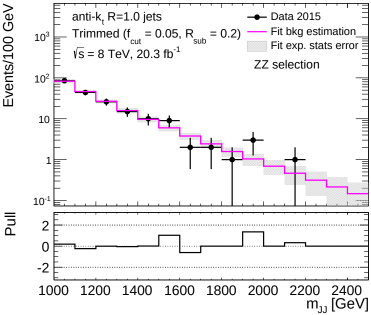
- ZZ selection
- Trimmed anti-k_t $R = 1.0$ jets with criteria on mass and $D_2^{\beta=1}$
- Dedicated 8 TeV jet energy and mass calibration





Run-II tagger on Run-I data

- *WZ* selection
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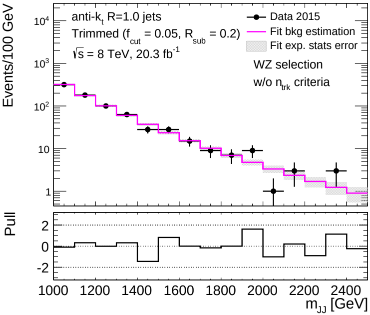
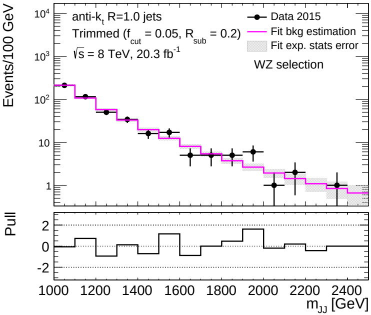
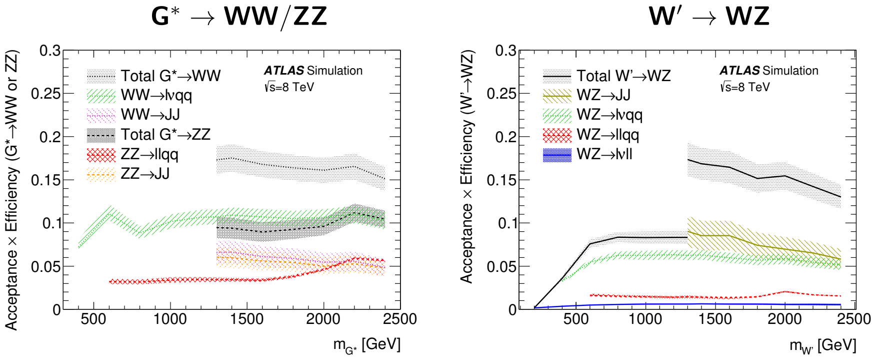




Combination overview

- Consider **four different channels**: $\ell\nu\ell'\ell'$, $\ell\ell qq$, $\ell\nu qq$ and $qqqq$
- Statistical independent analyses due to **orthogonal event selection**
- Correlations of systematic uncertainties in the different channels considered in statistical interpretation
- Optimisation of analysis sensitivity using **different signal regions**
  - $\ell\nu\ell'\ell'$: low-p_{T} resolved, high-p_{T} resolved
  - $\ell\ell qq$, $\ell\nu qq$: low-p_{T} resolved, high-p_{T} resolved, high-p_{T} merged
- Resolved analyses: hadronic W/Z decay reconstructed with two $R = 0.4$ jets
- MC-based background estimation but control regions in data to correct normalisation and shape

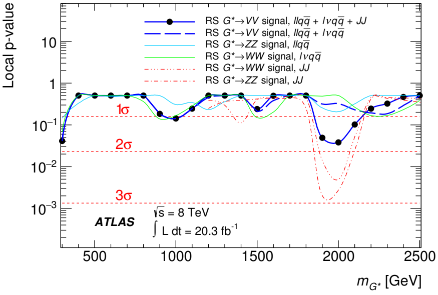
Acceptance × Efficiency



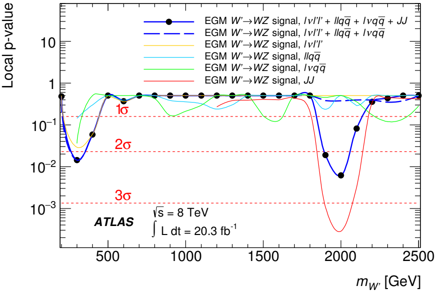
- Highest acceptance × efficiency
  - $G^* \to WW$: $\ell\nu qq$
  - $G^* \to ZZ$: qqqq (except for very high masses)
  - $W' \to WZ$: $\ell\nu qq$ ($m_{JJ} < 1.3$ TeV) and qqqq ($m_{JJ} > 1.3$ TeV)

p_0 values

Graviton



EGM



- Largest deviations observed for the $W' \to WZ \to JJ$ analysis at $m_{W'} = 2.0$ TeV with 3.4σ
- Other channels do not observe any deviations at $m_{W'} = 2.0$ $\to$ significance decreases to 2.5σ

CMS diboson resonance searches - I

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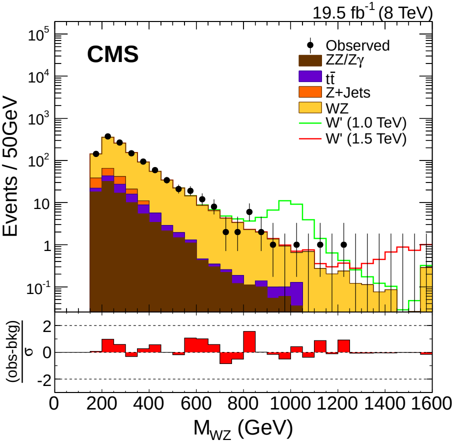
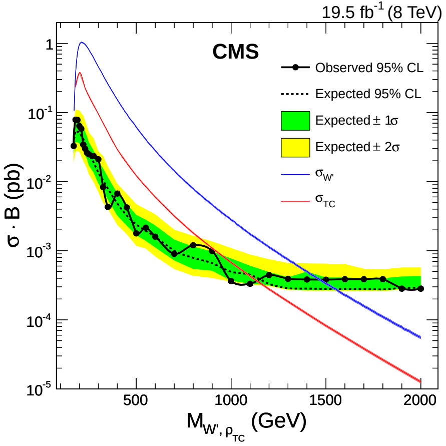
W′ → WZ → $\ell\nu\ell'\ell'$

- Excluded EGM W' with $m_{W'} < 1.47$ TeV (ATLAS: $m_{W'} < 1.52$ TeV)

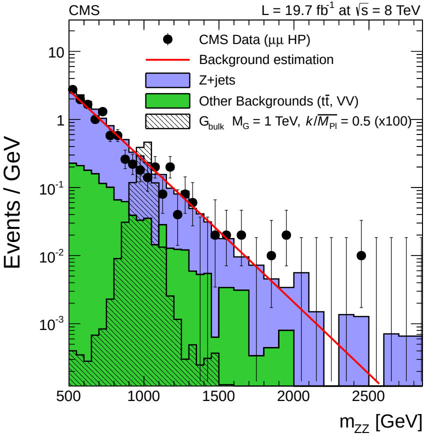


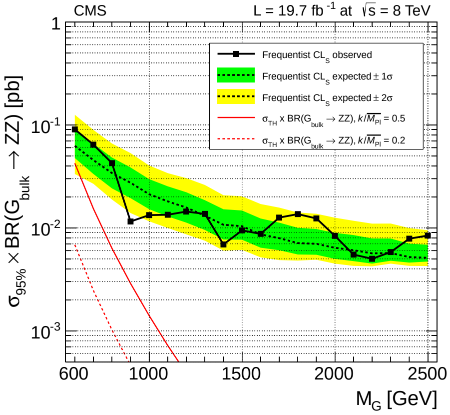


CMS diboson resonance searches - II

$\ell\nu\mathbf{qq} + \ell\ell\mathbf{qq}$

- Interpreted only in terms of two bulk graviton models with $k/\bar{M}_{\rm Pl} = 0.5,\ 0.2$
- Set upper limits on the cross-section times branching ratio

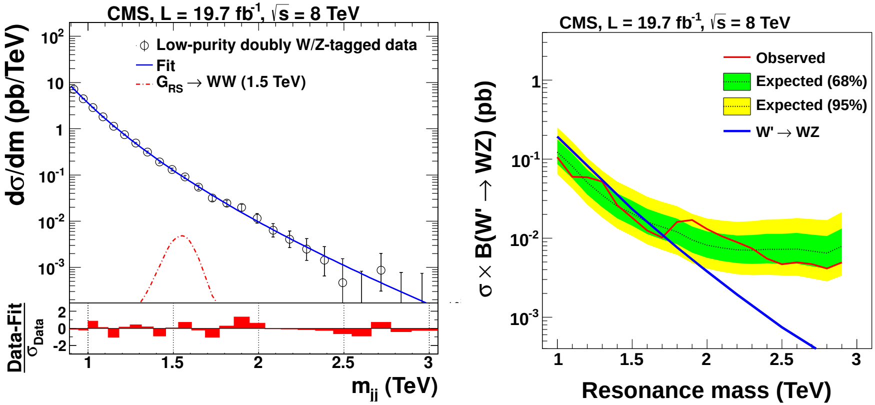




CMS diboson resonance searches - III

qqqq

- C/A $R = 0.8$ pruned jets with mass (70-100 GeV) + τ_{21}
- Interpreted in terms of EGM model + RS and bulk graviton model
- Exclude $G_{RS} \rightarrow WW$ with masses below 1.2 TeV ($k/\bar{M}_{\mathrm{Pl}} = 0.1$)
- Exclude EGM W' with $m_{W'} < 1.7$ TeV (ATLAS: $1.3 < m_{W'} < 1.5$ TeV)



n_{trk} efficiency measurement - Introduction

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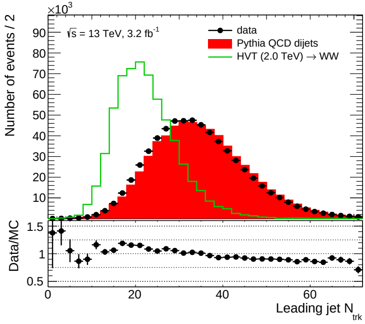
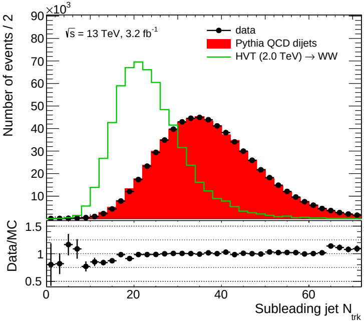
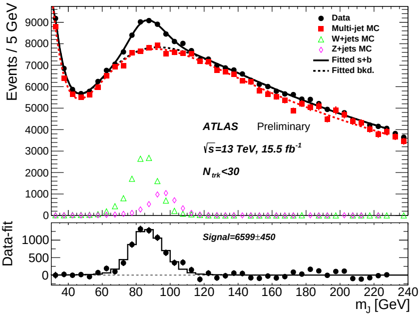
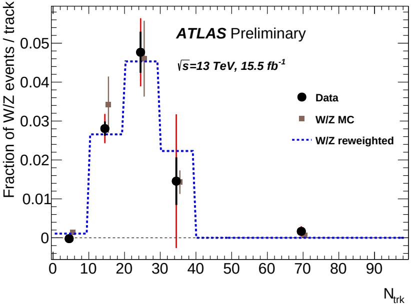




- Improved modelling with respect to Run-I due to special PYTHIA8 tunes
- Measure efficiency in V+jets events in data
- **V + jet selection**: $500 < p_{\mathrm{T}}^{\mathrm{lead}} < 700$ GeV, $D_2^{\beta=1}$ criteria

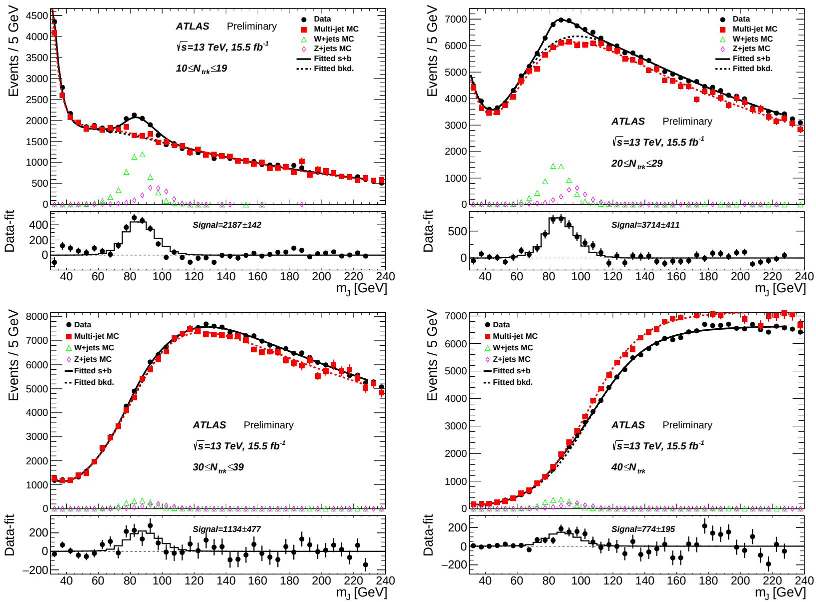
n_{trk} efficiency measurement





- QCD dijet background: exponential + sigmoid turn-on
- W/Z: double Gaussian, shape parameters from $W' \to WZ \to qqqq$
- Template fit to derive scale factor: SF = 1.07
- Lower efficiency for $n_{\mathrm{trk}} < 30$ selection of 6% in data compared to MC

n_{trk} efficiency measurement



Flavour composition of background

- Background consists of qq, qg and gg
- MC studies: 9.4% qq, 41.7% gg and 48.8% qg
- 36% of background events have quark-initiated leading jet
- Smooth boson tagging efficiencies observed for both quark and gluon jets

Spurious signal - Run-II

- Uncertainties arising from the possibility of the fitting function to fake a signal
- Estimate uncertainties by fitting m_{JJ} distribution in validation regions in data and considering sig+bkg fits

1. Generate spectrum with 5-parameter function and fit with sig + bkg (2-parameter function)
   - Compare extracted signal to statistical uncertainty of sample
   - Tested different W' masses
2. Spectra with different quark/gluon composition
   - Does a different flavour composition create signal in m_{JJ} spectrum
3. $S + B$ fit to spectrum from 2-parameter function $\rightarrow N_S/\sigma_S$

Did we miss something with the new tagger?

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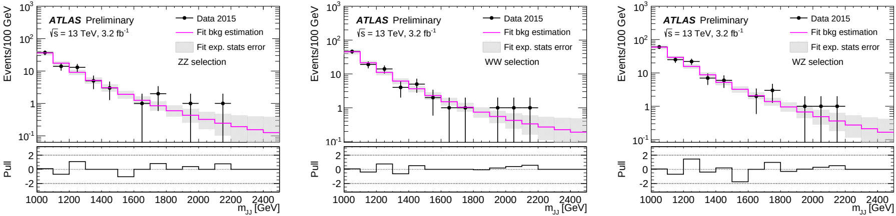
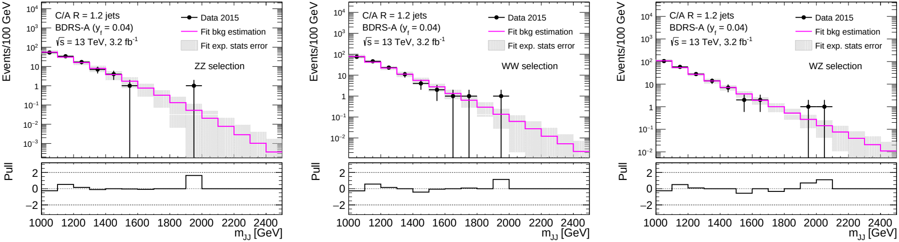
Run-II tagger



Run-I tagger



Nothing significant observed with neither Run-I nor Run-II tagger

- Analysis performed in fully hadronic and $\ell\nu qq$ final state
- $\sqrt{s} = 13$ TeV, $\mathcal{L} = 2.6\ \mathrm{fb}^{-1}$

W/Z identification

- Anti-k_t $R = 0.8$ soft-drop jets
- Mass window + $\tau_{21} < 0.75$
- $65 < m_W < 85$ GeV, $85 < m_Z < 105$ GeV

Event selection

- Define two different purity categories based on the τ_{21} variable

- No significant deviation observed
- Results interpreted with respect to HVT B model