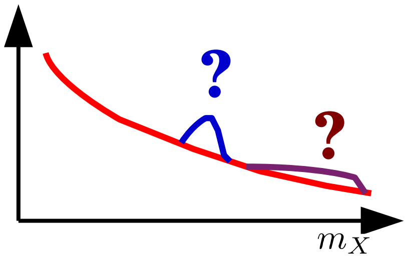
Search for high mass bosonic resonances with the ATLAS detector

SUSY 2017 Mumbai, India

Alexis Vallier (CNRS/IN2P3 LAPP)
On behalf of the ATLAS collaboration

High mass bosonic resonances

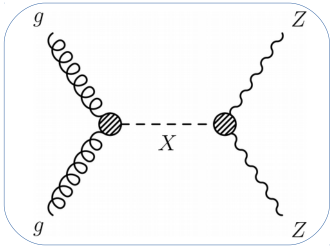


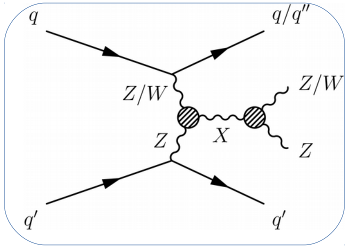
- **Variety of BSM theories predicts new particles decaying into vector boson pair**
  - Try to address hierarchy problem, naturalness, gravity, dark matter…
  - Spin-0: extended Higgs sector (e.g. 2HDM)
  - Spin-1: Heavy Vector Triplets (composite Higgs, weakly coupled theories)
  - Spin-2: Graviton in warped extra-dimension model or large extra-dimension scenario
- **Look for excess over smooth background in several experimental signatures**
  - Diphoton (X→γγ)
    - excellent mass resolution moderate background

    $m_{\gamma\gamma}$
  - Semi-leptonic (X→VV→llqq, ννqq, lνqq) [V=Z/W]
    - larger BR than fully leptonic
    - less background than fully hadronic

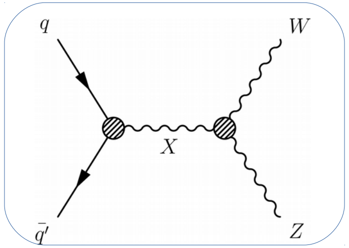
    m_{VJ}, m_{Vjj}, m_T
  - Leptonic (X→WW→eνμν)
    - clean signature

    m_T
- **Different production mode considered: ggF, qq annihilation, VBF**





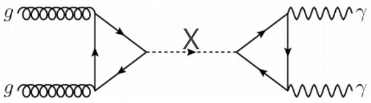
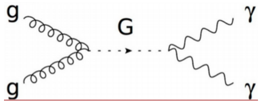
J = large-R jet
j = small-R jet



$\mathbf{X} \rightarrow \gamma\gamma$

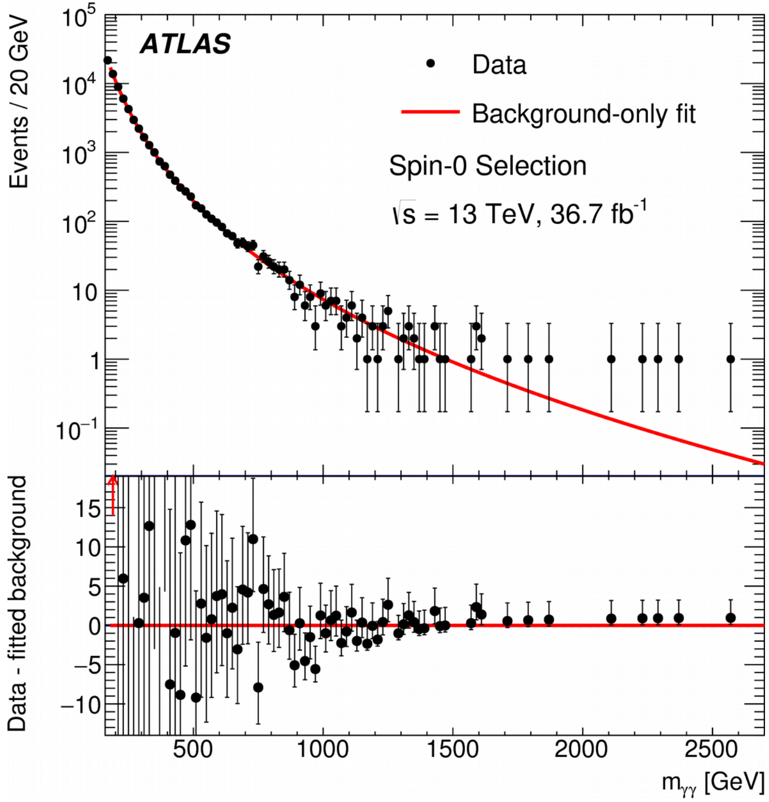
Phys.Lett. B775 (2017) 105-125

High mass diphoton search

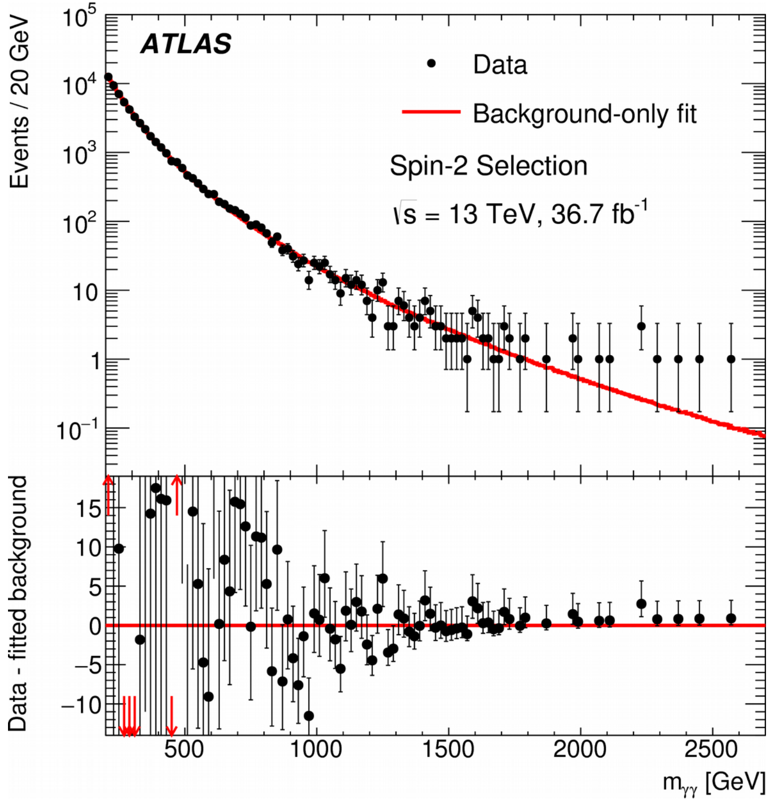
	Spin-0	Spin-2	
Model	Extended Higgs sector 	Randal-Sundrum graviton (RS) 	Arkani-Haed, Dimopoulos, Dvali graviton (ADD) *Non resonant*
Search Range	M_X = [0.2, 2.7] TeV Γ_X/m_x = [0, 10] %	m_{G*} = [0.5, 5] TeV $\kappa/\overline{M}_{Pl}$ = [0.01, 0.3] (dimensionless coupling)	m_S = [3.5, 8] TeV (UV cutoff scale)
Analysis Method	Search for localised excess with S+B fit		Cut and Count
Selection	$\lvert\eta\rvert$ < 2.37, 1.37-1.52 excluded , Tight photon ID E_T^{iso}<0.022 E_T + 2.45 GeV (ΔR=0.4) , p_T^{iso} < 0.05 E_T (ΔR=0.2)		
	$E_T^{\gamma1}$>0.4$m_{\gamma\gamma}$, $E_T^{\gamma2}$>0.3$m_{\gamma\gamma}$	E_T^{γ}> 55 GeV	
			$m_{\gamma\gamma}$>2240 GeV
Background Model	Function	MC prediction	

High mass diphoton search – Mass spectra

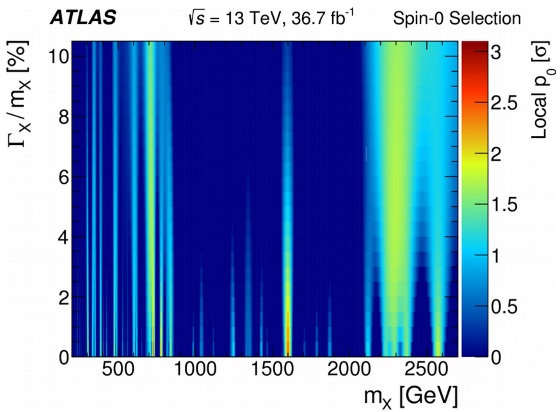
H→ γγ selection

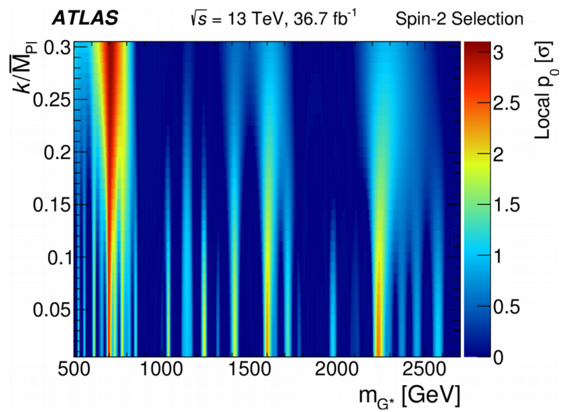


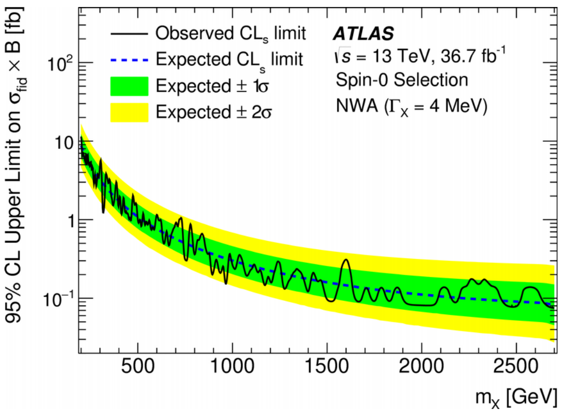
G→ γγ selection

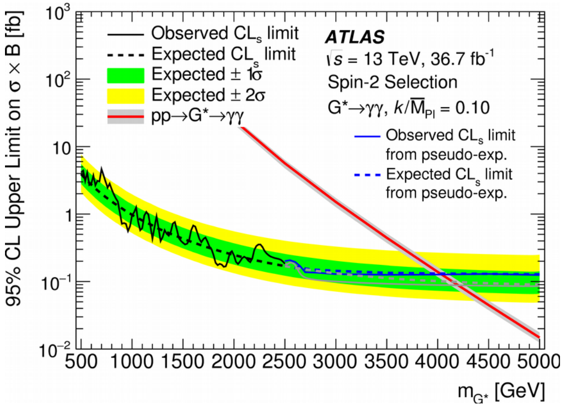


High mass diphoton search – Results









- **No excess found**
- **Largest deviation from B-only :**
  - Spin-0 : 2.6σ local at 730 GeV, Narrow width
  - Spin-2 : 3.0σ local at 708 GeV, $\kappa/\overline{M}_{Pl}$=0.3
  - Global signif. < 1
- **Limit on $\sigma_{fiducial}$ x BR(X→$\gamma\gamma$)**
  - 11.4 fb (200GeV) to 0.1 fb (2700 GeV)
- **Limit on σ x BR(G*→$\gamma\gamma$)**
  - 4.6 fb (500GeV) to 0.1 fb (5TeV)
  - $\kappa/\overline{M}_{Pl}$=0.1 RS model excluded up to 4.1 TeV
- **Limits on UV cutoff scale MS :**
  - 5.7– 8.6 TeV (depends on #extra dim. and formalism, see backup)

$X \to ZV \to llqq$ / $\nu\nu qq$ and $X \to WV \to l\nu qq$

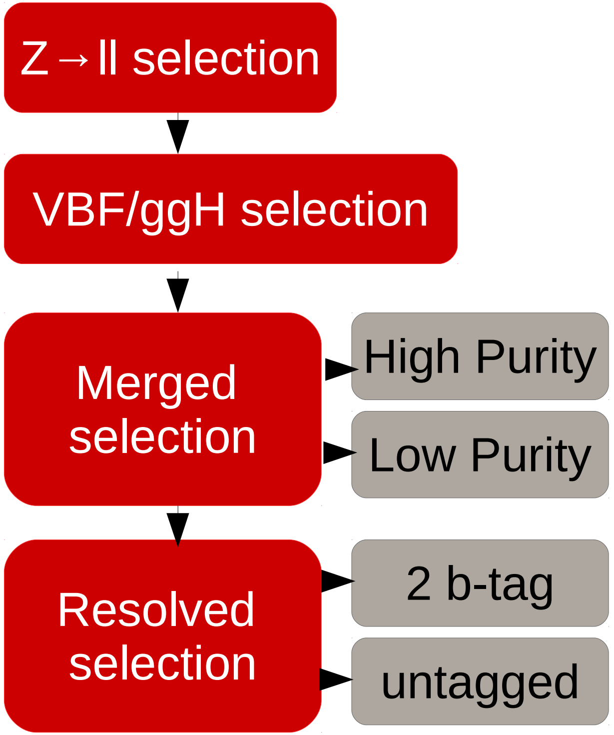
arXiv:1708.09638

arXiv:1710.07235

$X \to ZV \to llqq$ / $\nu\nu qq$ – Strategy

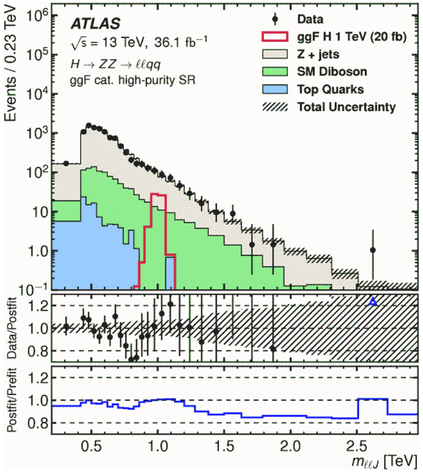
- **Z selection :**
  - ll : $p_T^{leading}$>28GeV, $p_T^{subleading}$>7GeV, mass compatible with Z boson
  - $\nu\nu$: E_T^{miss} > 250 GeV (only merged jets)
- **Maximise sensivity : ggF/VBF categories**
  - VBF = 2 jets in opposite hemisphere, $\Delta\eta^{tag}$>4.7, m_{jj}^{tag} >770 (630) GeV
    - Optimise sensitivity to VBF production for all signal masses
- **$V \to qq$ selection :**
  - Merged (J): large-R jet (R=1.0) → Boson tagger defines 2 working points
    - High and Low purity categories (50% and 80 % signal efficiency) [backup]
  - Resolved (jj): small-R jets (R=0.4) → 2 b-tag jets / <2 b-tag jets (only for ZZ ggF)
    - Z+jets background smaller heavy flavour content than $Z \to bb$
- **$ZV \to \nu\nu qq$: also cuts to reject multijet Background**
  - p_T^{miss}>50GeV, $\Delta\varphi(E_T^{miss}, p_T^{miss})$<1, min[$\Delta\varphi(E_T^{miss}$, small-R jet)]>0.4

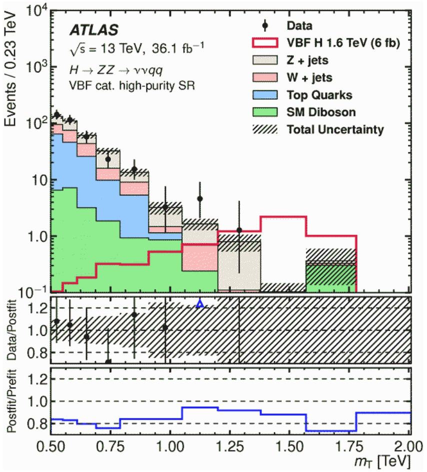
Look at ZV events with $V \to qq$, $Z \to e^+e^-$, $\mu^+\mu^-$ or $\nu\nu$

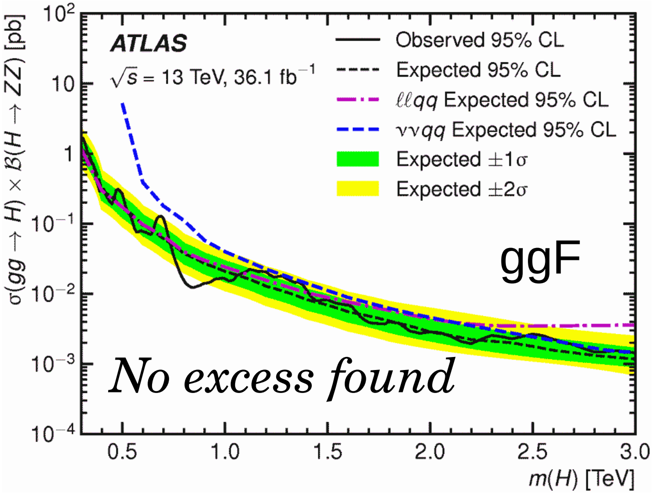


X → ZV → llqq / ννqq – Results

- **V+jets: shape from MC, normalised with data Control Region (CR)**
- **ttbar : shape from MC, normalised with data CR**
- **SM Diboson : fully from simulation**
- **Final combined fit run over signal region and CR**
  - Simultaneous likelihood fit on m_{lljj}, m_{llJ} and m_T
  - Background normalisation extracted together with the signal





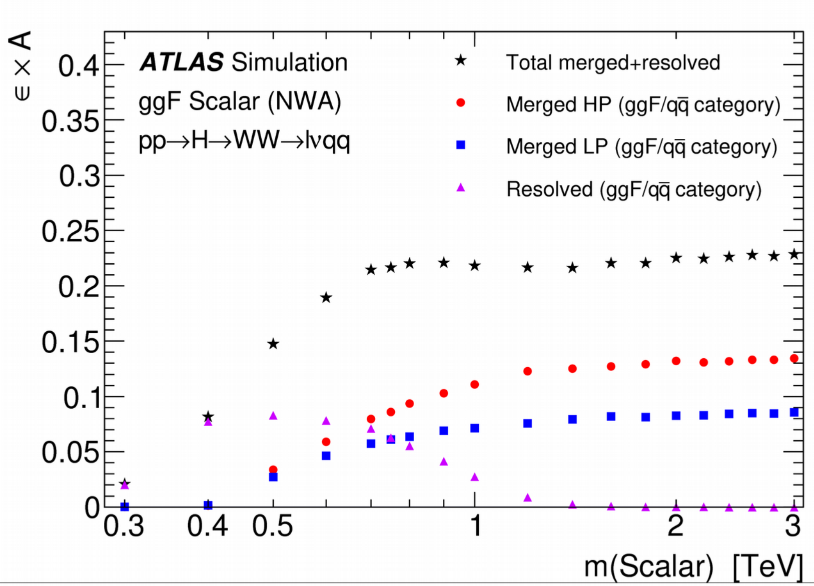


$$m_T = \sqrt{(E_{T,J} + E_T^{miss})^2 - (\vec{p}_{T,J} + \vec{E}_T^{miss})^2}$$

$$\text{with } E_{T,J} = \sqrt{m_J^2 + p_{T,J}^2}$$

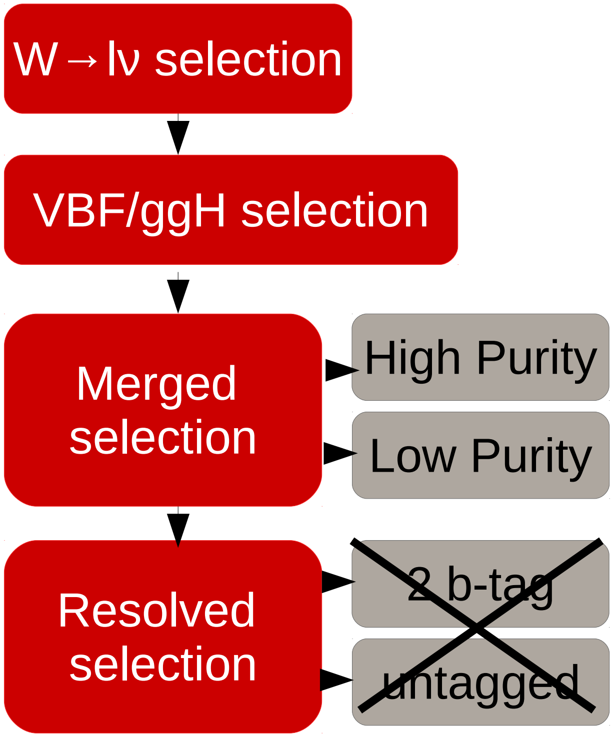
X → WV → lνqq – Strategy

- **Similar strategy to ZZ/ZW search, except :**
  - Small-R jet (jj) : b-tag info not considered
  - W mass constraint to obtain neutrino momentum



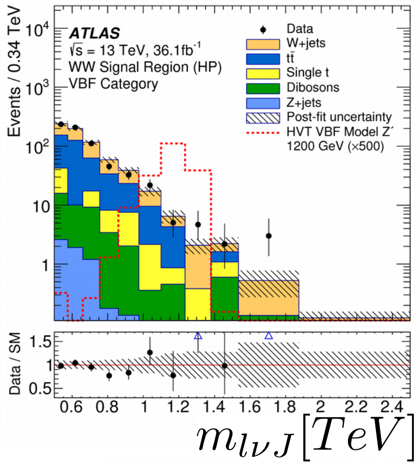
Merged (Resolved) optimal at high (low) mass

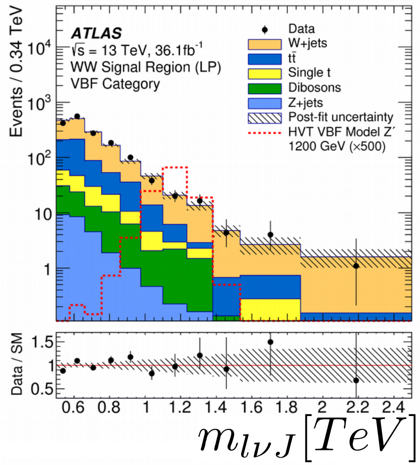
Look at WV events with V→$q\bar{q}$ / $q\bar{q}'$ and W → lν

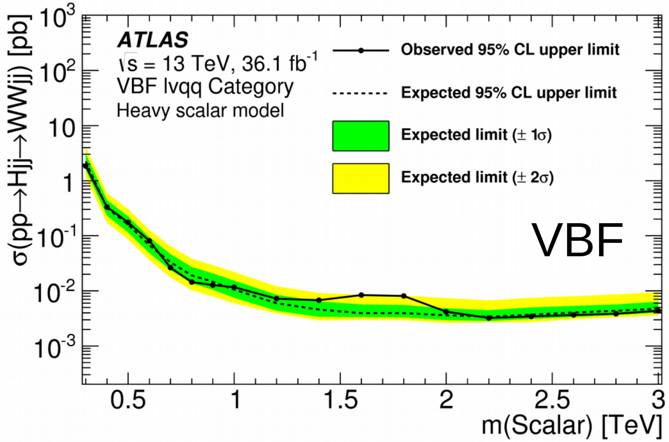


X → WV → lνqq – Results

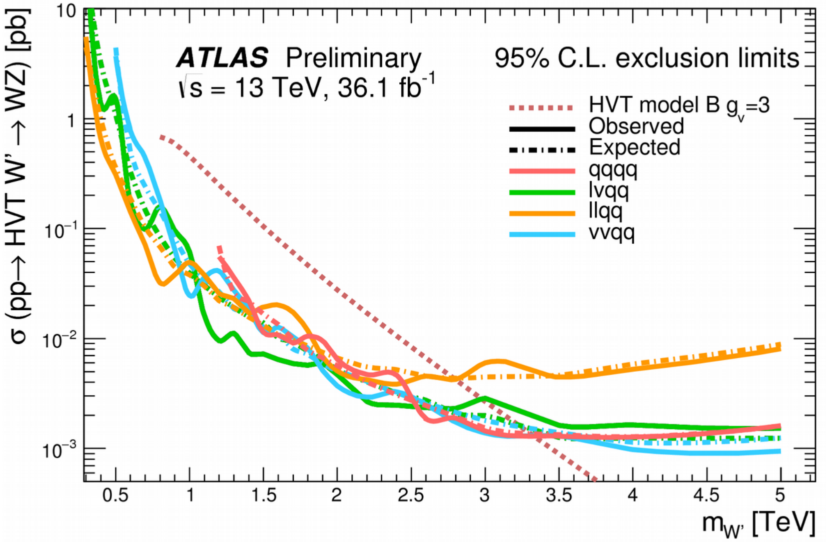
- **Dominant background sources**
  - W+jets (~60%) and ttbar (~30%)
  - Shape from MC, normalisation from data CR
- **Subdominant background**
  - Z+jets, single-top, SM diboson
  - Shape & normalisation from simulation
- **Final combined fit run over signal region and CR**
  - Background normalisation extracted with the signal
- **Data compatible with SM background**
- **Limits @ 95 % CL :**
  - $M_{Z'}$ > 2730 (3000) GeV for HVT model A (B)
  - $M_{W'}$ >2800 (2990) GeV for HVT model A (B)
  - M_G > 1750 GeV for RS signal of $\kappa/M_{\overline{Pl}}$=1.0 (ggF)







Semi-leptonic VV search – Summary



ggF/$q\bar{q}$ Category			
$m(W')$ = 2000 GeV		$m(Z')$ = 500 GeV	
Source	$\Delta\mu/\mu$ [%]	Source	$\Delta\mu/\mu$ [%]
MC statistical uncertainty	12	Large-R jets kinematics	17
W+jets: generator choice	8	MC statistical uncertainty	12
W+jets: scale	5	$t\bar{t}$: scale	11
SM diboson normalization	4	SM diboson cross section	10
Large-R jets mass resolution	4	W+jets: alternative generator	10
Large-R jets D_2 resolution	4	W+jets: scale	9
Total systematic uncertainty	20	Total systematic uncertainty	42
Statistical uncertainty	50	Statistical uncertainty	18

- **No significant excess found**
- **Semileptonic VV searches performant both at low and high mass**
- **At high mass Z→ll is less performant than Z→νν and W→lν**
  - Smaller branching ratio
  - Collimated leptons hard to resolve
- **Main systematic uncertainties :**
  - MC statistics
  - Large-R jet kinematics
  - Background modeling

  → *can all be improved*
- **At high mass statistics dominates**

$X \to WW \to e\nu\mu\nu$

arXiv:1710.01123

X → WW → eνμν – Strategy

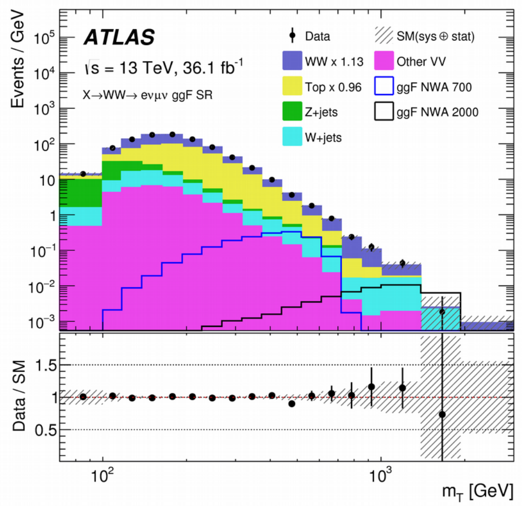
- **Search for neutral resonances in WW, that decay into eνμν**
  - Either directly or via τ decays (+additional ν) : 2 leptons + E_T^{miss}
- **Several Benchmark models :**
  - Spin-0 : Scalar (narrow and large width), 2HDM, Georgi-Machadeck
  - Spin-1 : Heavy Vector Triplet
  - Spin-2 : Bulk RS Graviton, Effective Lagrangian Model
- **Event categories : VBF 1jet, VBF 2jets, ggF**
- **Main background : WW (~43%) and top (~45%)**
  - Shape from MC, normalisation from simult. fit in signal region & CR
- **Discriminating variable :** $m_T = \sqrt{(E_T^{ll} + E_T^{miss})^2 - (\vec{p}_T^{ll} + \vec{E}_T^{miss})^2}$

  with $E_T^{ll} = \sqrt{m_{ll}^2 + {p_T^{ll}}^2}$

WW selection
2 leptons diff. charge & flav.

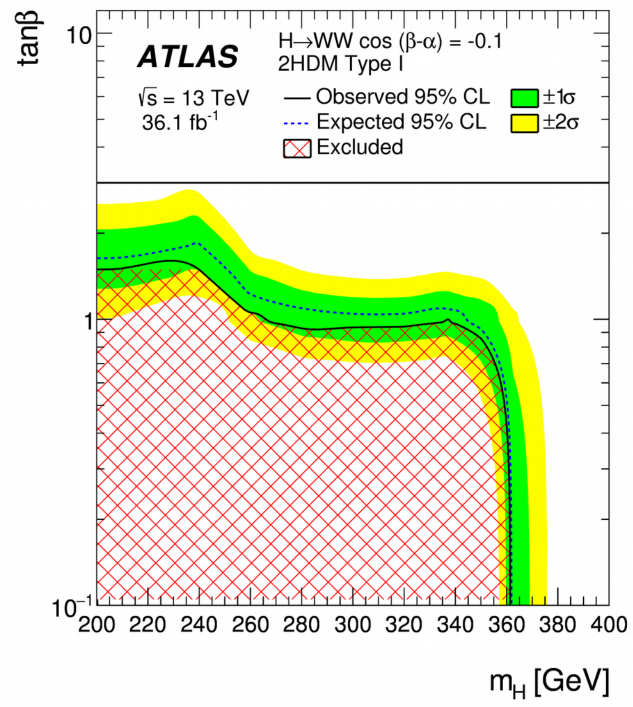
Top & Diboson veto
Extra lepton + b-tag veto

WW, top, V+jets rejection
$\Delta\eta_{ll}$, m_{ll}, p_T^l and m_T^W cuts



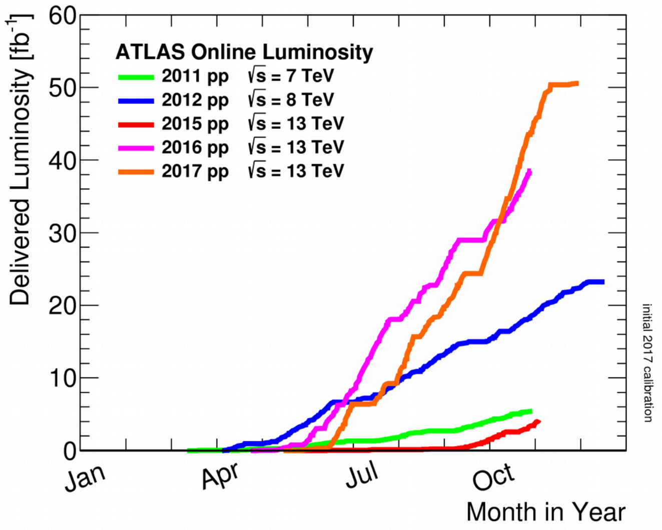
$X \to WW \to e\nu\mu\nu$ – Results

- **No excess found beyond the SM prediction in mass range 200 GeV to 5 TeV**
- **Limits set at 95 % CL :**
  - Higgs, NWA, ggF : 6.4 pb at 200 GeV – 0.008pb at 4 TeV
  - Higgs, NWA, VBF : 1.3 pb at 200 GeV – 0.006pb at 3 TeV
  - HVT model A : mX > 1.3 TeV
  - RS graviton : mG > 1.1 TeV (750 GeV) for $\kappa/\overline{M_{Pl}}$=1.0 (0.5)
- **Systematic uncertainty dominates**
  - p_T correction of leading lepton in top background
  - Scale variation for top background
  - Parton shower in WW simulation
  - Jet energy scale & resolution



Conclusion & Prospects

- **Latest ATLAS results on heavy diboson resonances search at $\sqrt{s}$ = 13 TeV with 2015+2016 dataset presented**
  - Motivated by several models and probe the TeV scale
  - Advanced analysis techniques to maximise the sensitivity
- **Similar Analyses not presented today :**
  - $X \to ZZ \to 4l$ / $ll\nu\nu$: ATLAS-CONF-2017-058
  - $X \to VV \to qqqq$: arXiv:1708.04445



No evidence of Beyond the Standard Model yet…

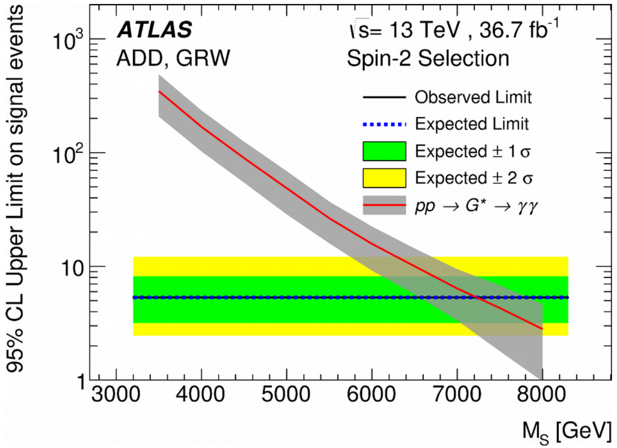
… But already a lot of new data to analyse !

Work on full Run-2 analysis has already started

BACKUP

$X \to \gamma\gamma$: Limits on ADD model

- **In signal region $m_{\gamma\gamma}$ > 2240 GeV**
  - Observed 4 events in data
  - Expect 4.3 ± 1.0
  - 95% CL upper limit on excess event: 5.4 (exp. & obs.)
  - Translated into lower limits on UV cutoff scale M_S



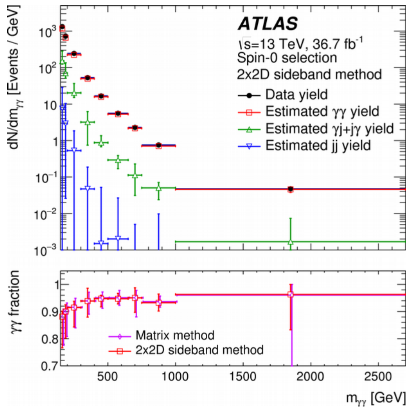
	ADD formalism Parameter	GRW	Hewett positive	HLZ $n=3$	HLZ $n=4$	HLZ $n=5$	HLZ $n=6$
Without K-factor	M_S observed limit [TeV]	6.8	6.1	8.1	6.8	6.1	5.7
With K-factor	M_S observed limit [TeV]	7.2	6.5	8.6	7.2	6.5	6.1

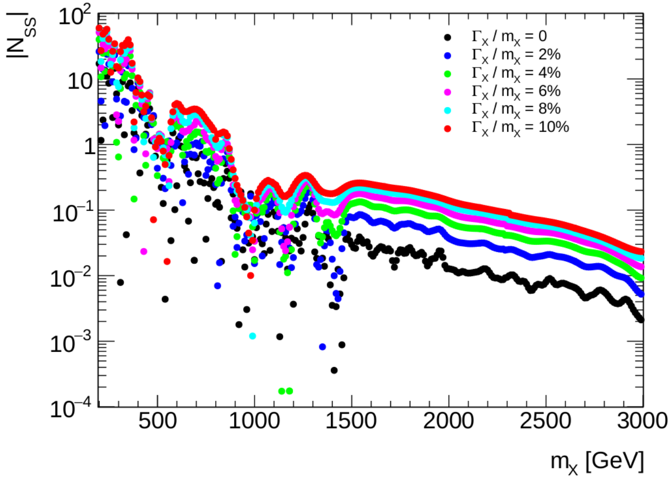
$X \rightarrow \gamma\gamma$: Background parametrisation – Spin-0

- **Spin-0 background model: function with 3 d.o.f.**

$$f(x; N, a, b) = N x^{-a}(1 - x^{\frac{1}{2}})^b, \; x = m_{\gamma\gamma}/\sqrt{s}$$

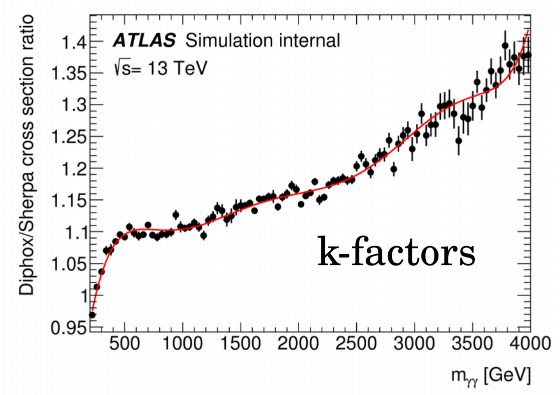
- **Validation with Spurious Signal method**
  - Build background template
    - Sherpa LO for $\gamma\gamma$ (91%)
    - Data-driven for γj, jγ and jj
  - Test function flexible enough to describe bkg
    - Measure signal bias in S+B fit (spurious signal)
    - Keep function with $|N_{SS}|^{max} < 50\% \, \Delta N_{signal}$
    - Parametrised N_{SS} used as nuisance parameter

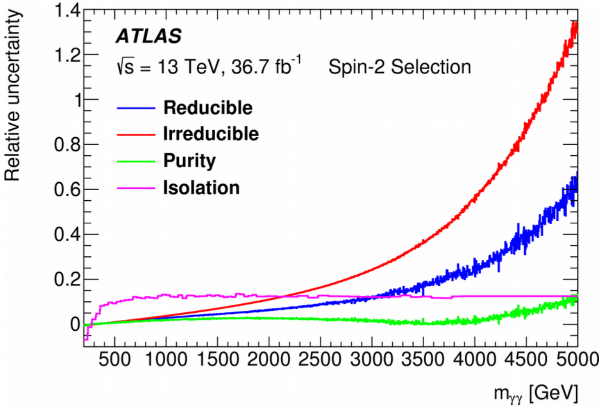


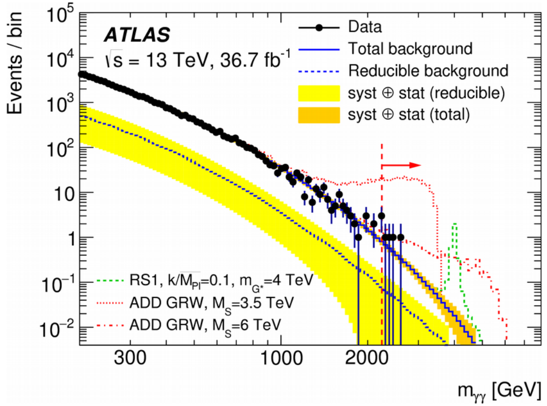


$X \rightarrow \gamma\gamma$: Background parametrisation – Spin-2

- **Spin-2 : template fit with $\gamma\gamma$ (MC) and γj, jγ and jj (data) components**
  - Sherpa $\gamma\gamma$ LO reweighted to DIPHOX NLO
  - Data driven estimate for γj, jγ and jj
- **Systematic uncertainties arises from uncertainty on shape and relative normalisation**



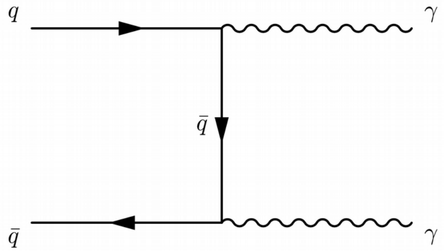




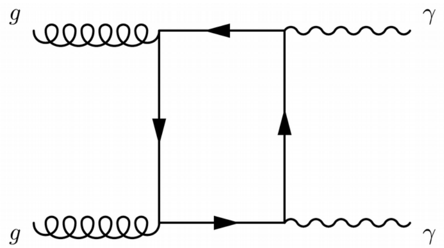
Diphoton Background topology

Irreducible

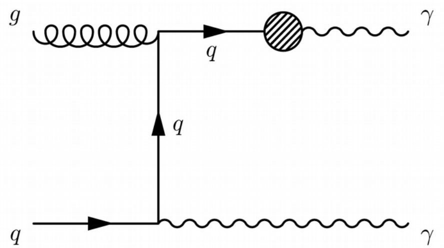
Born



Box

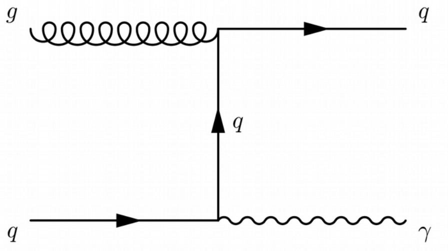


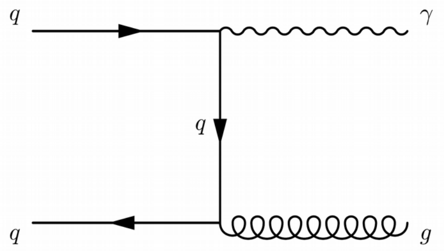
Parton fragmentation



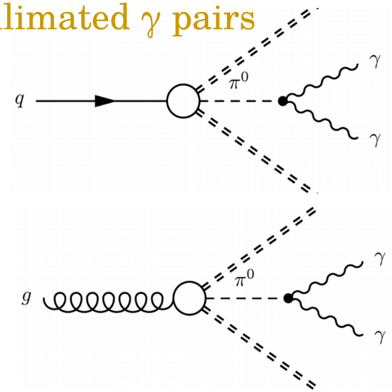
Reducible

jets in γj events





jj with π^0 decaying in collimated γ pairs



$X \to \gamma\gamma$ – Systematic Uncertainties

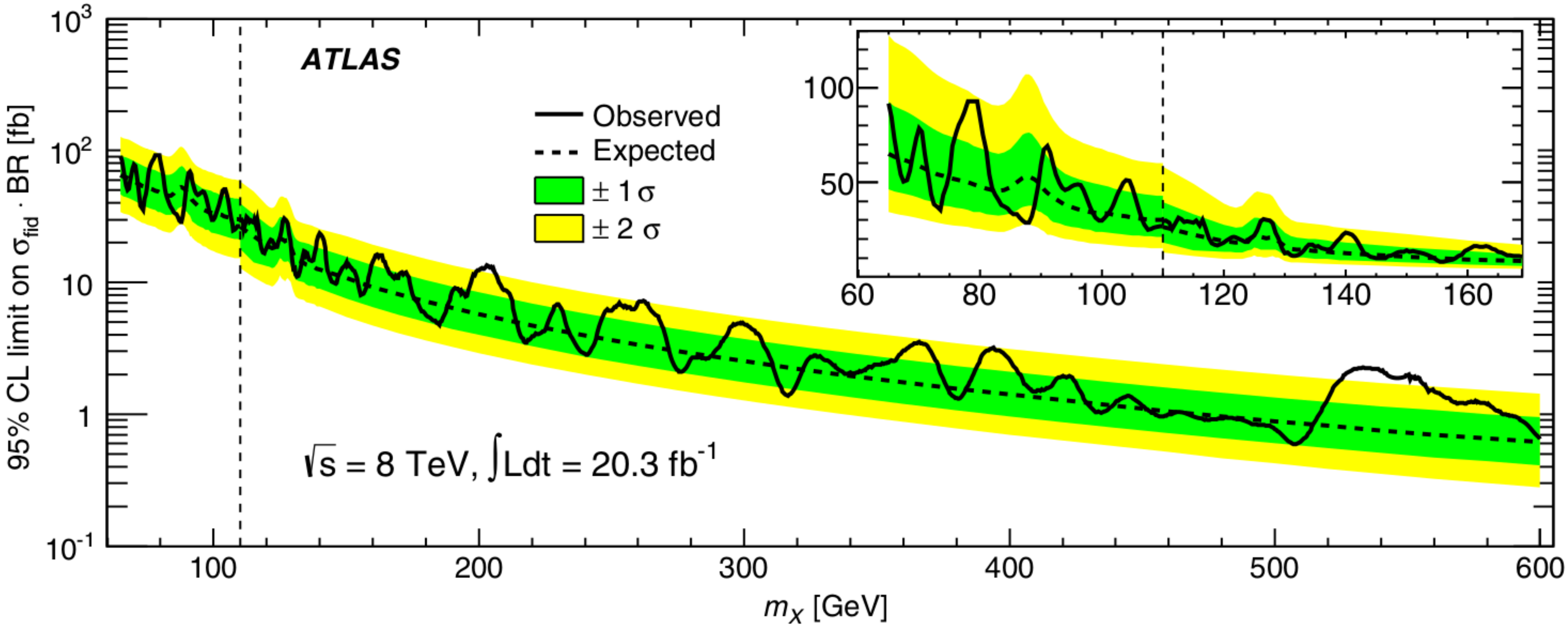
Uncertainty source	Spin-0 resonance [%]	Spin-2 resonance [%]	Spin-2 non-resonant [%]
Signal mass resolution	17–38	28–36	–
Signal photon identification efficiency	1.3–3.0	2.6–3.1	3.2
Signal photon isolation efficiency	1.1–1.3	1.2–1.4	1.4
Signal width dependence	2.8	2.9	–
Trigger efficiency	0.4	0.4	0.4
Luminosity		2.1 (2015), 3.4 (2016)	
Total uncertainty in signal yield	4.6–5.4	5.3–5.5	4.8

Uncertainty source	Spin-0 resonance	
Spurious signal [events]	Narrow width	74–0.006
	10% relative width	195–0.04

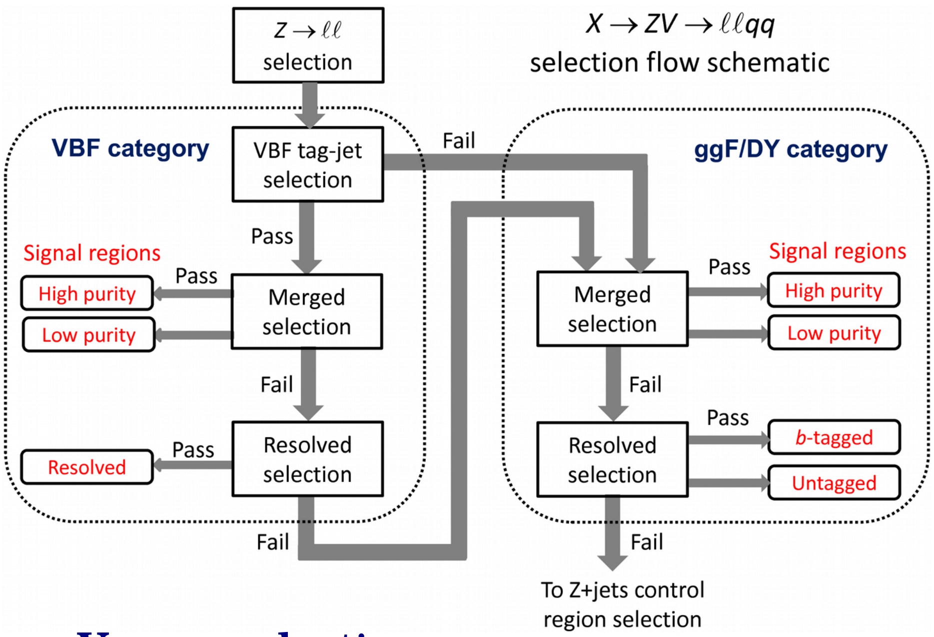
Uncertainty source	Spin-2 resonance [%]	Spin-2 non-resonant [%]
Scales and PDFs in DIPHOX computation	1–19	20
Shape of the reducible background	1–10	11
Relative normalization of reducible and irreducible backgrounds	1–2	2
Parton-level isolation requirement in DIPHOX	10–12	9
MC statistical uncertainty	< 1	
Total	10–25	25

ATLAS Run-1 diphoton results

PhysRevLett.113.171801



$X \rightarrow ZV \rightarrow llqq$ / $\nu\nu qq$ – Strategy



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- **Z selection :**
  - ll : $p_T^{leading}$>28GeV, $p_T^{subleading}$>7GeV, mass compatible with Z boson
  - $\nu\nu$: E_T^{miss} > 250 GeV ($\rightarrow$ only merged jets)

- **$V \rightarrow qq$ selection :**
  - Merged (J): large-R jet (R=1.0) $\rightarrow$ Boson tagger defines 2 working points
  - Resolved (jj): small-R jets (R=0.4) $\rightarrow$ 2 b-tag jets / <2 b-tag jets categories (only for ggF)

Boson Tagger

Fat Jet Reconstruction
Collect all radiations from collimated decay

Trimming
Mitigate effects of pile-up and soft radiation

Tagging
Determine the jet substructure Single parton or 2-body decay ?

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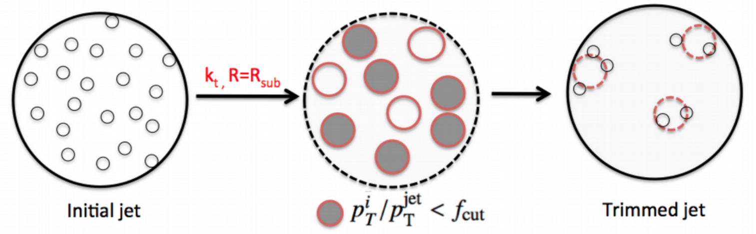
- **Large radius jet with antiK_T algorithm : R=1.0**



- **Reclustering of large-R jet into in small-R jet of R_{sub}=0.2**
- **Remove subjet if p_T^{subjet} < 5% p_T^{jet}**
- **Jet substructure variable D2 based on Energy Correlation Funtions (ECFs) :**

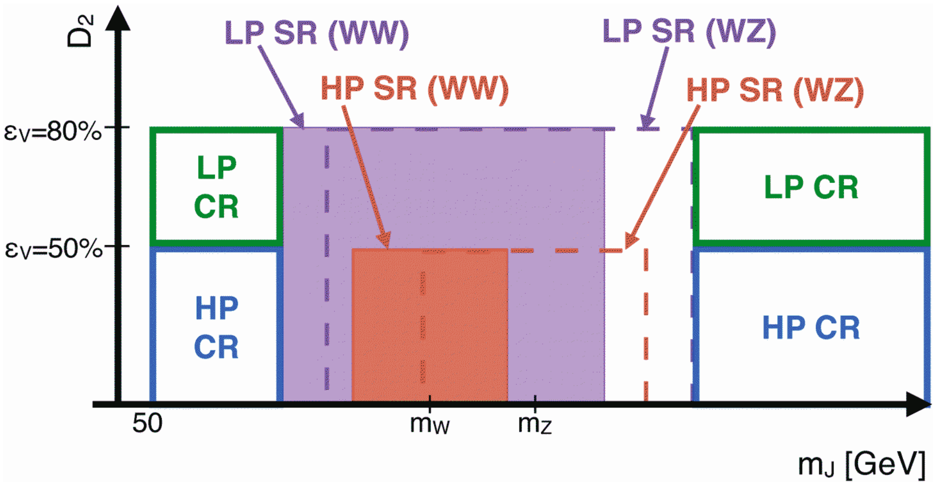
$$D_2 = E_{CF3}\left(\frac{E_{CF1}}{E_{CF2}}\right)^3$$

  - Combine p_T and ΔR separation of all jet constituent (ECF1), all pairs of jet constituents (ECF2), all triplets (ECF3)
- **Combined mass :**

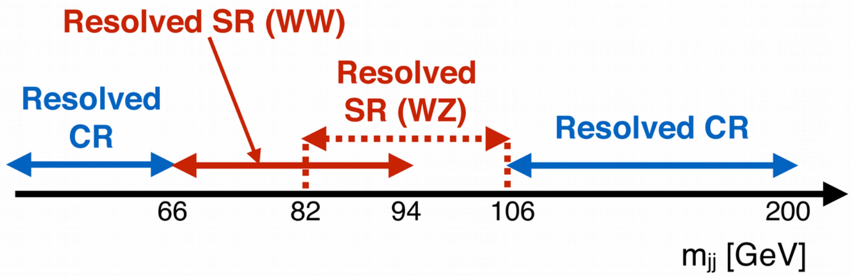
$$m_J = w_{calo} m_J^{calo} + w_{track}\left(m_J^{track}\frac{p_T^{calo}}{p_T^{track}}\right)$$

$X \to WV \to l\nu qq$ – Signal Regions

Merged jets



Resolved jets



$X \to WW \to e\nu\mu\nu$ – Model & Selection

Model	Resonance spin	Production mode		
		ggF	qqA	VBF
NWA	Spin-0	x		x
2HDM		x		x
LWA		x		x
GM				x
HVT	Spin-1		x	x
Bulk RS	Spin-2	x		
ELM				x

NWA = Scalar Narrow Width Approximation

2HDM = 2-Higgs-Doublet Models

GM= Georgi-Machacek (neutral member of fiveplet)

HVT = Heavy Vector Triplet

RS = Randall-Sundrum graviton

ELM= Effective Lagrangian Model (tensor)

SR_{ggF}	SR_{VBF1J}	SR_{VBF2J}
Common selections		
$N_{b\text{-tag}} = 0$ → top bkg $\lvert\Delta\eta_{\ell\ell}\rvert < 1.8$ $m_{\ell\ell} > 55\text{GeV}$ $p_{\text{T}}^{\ell,\text{lead}} > 45\text{GeV}$ → WW+top bkg $p_{\text{T}}^{\ell,\text{sublead}} > 30\text{GeV}$ → V+jets bkg veto if $p_{\text{T}}^{\ell,\text{other}} > 15\text{GeV}$ → diboson bkg $\max(m_{\text{T}}^{W}) > 50\text{GeV}$ → V+jets bkg		
ggF phase space	VBF1J phase space	VBF2J phase space
Inclusive in N_{jet} but excluding VBF1J and VBF2J phase space	$N_{\text{jet}} = 1$ and $\lvert\eta_j\rvert > 2.4$, $\min(\lvert\Delta\eta_{j\ell}\rvert) > 1.75$	$N_{\text{jet}} \geq 2$ and $m_{jj} > 500\text{GeV}$, $\lvert\Delta y_{jj}\rvert > 4$

$X \to ZZ \to 4l$ / $ll\nu\nu$