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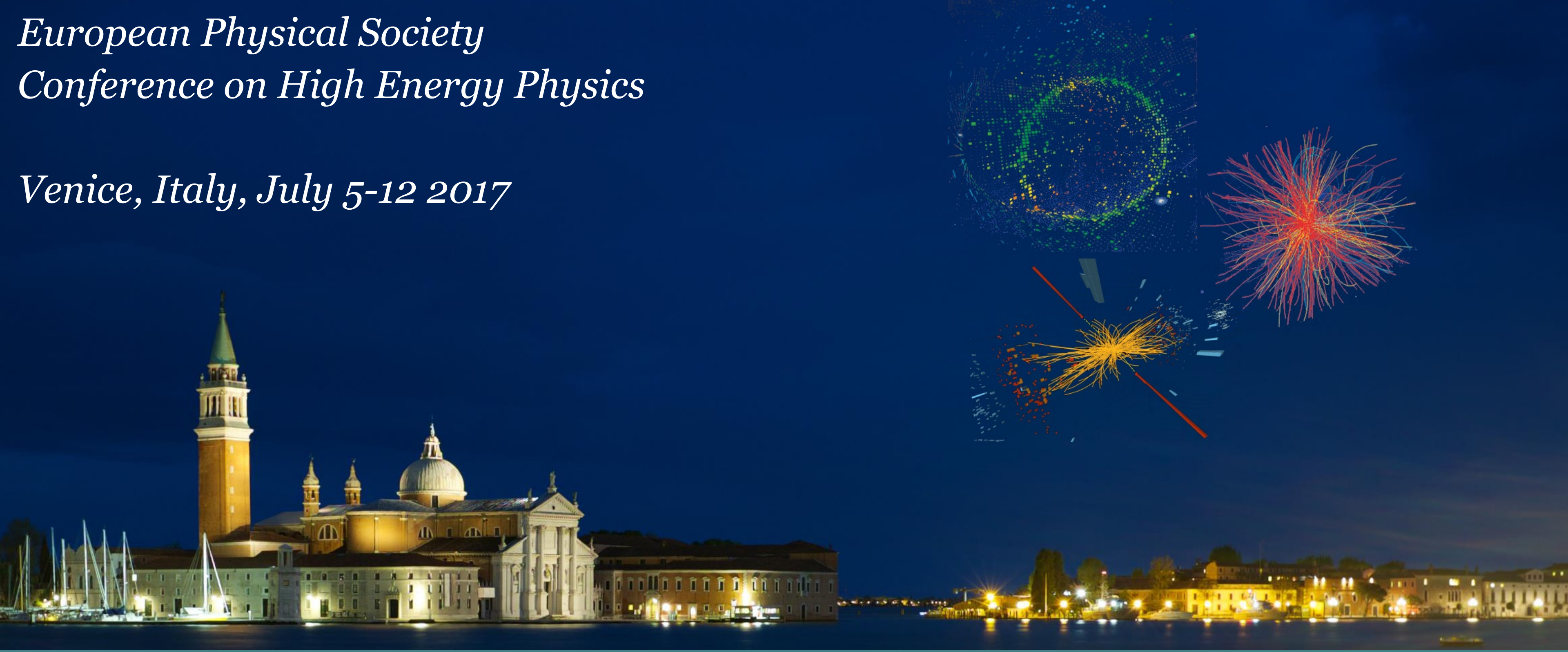

ATLAS Searches for VV/Vγ Resonances

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Introduction

- The Standard Model (SM) and the recently discovered Higgs boson address issues in our understanding of nature and provide a more solid basis on which to continue our exploration

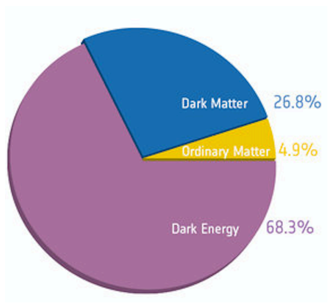
- A plethora of precision measurements and limit settings with data from the Large Hadron Collider (LHC) has shown no (significant) indication of new physics

- While the SM describes particle interactions for energy scales up to a few hundred GeV, a number of issues, such as the sensitivity of the Higgs mass to radiative corrections indicate either extreme fine-tuning or the presence of new physics

- **Where is the new physics?**

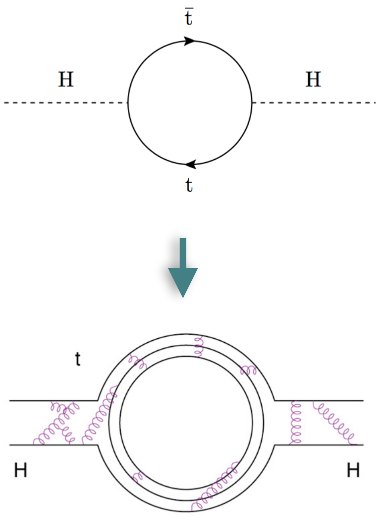
- Many theories attempt to provide answers:
  - Predict heavy resonances decaying to heavy quarks or bosons
    - This talk covers VV/Vγ, where V = W/Z

  - Many issues can be addressed:
    - The hierarchy problem
    - Can fundamental scalars exist in nature?
    - Do interactions unify at some high energy scale?
    - Where do fermion properties come from?
    - Dark matter and gravity can be incorporated

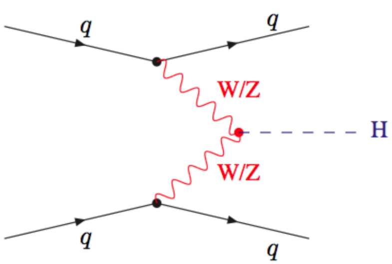


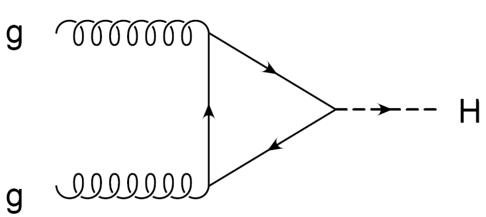
Composite Higgs Models

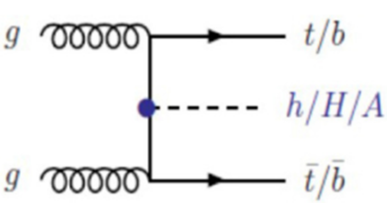
- Higgs is not an elementary particle but has structure
- Bound state of a new force that manifests itself at O(1) TeV scale
- Predicts resonances related to this new dynamics at O(1) TeV scale
- Stabilizes the mass and solves the hierarchy problem
- Dark matter can be incorporated naturally in composite Higgs models



- <u>Final states:</u> *neutral/charged, narrow or large width, produced via gluon-gluon fusion (ggF) or vector boson fusion (VBF)*







Heavy Vector Triplets (HVT)

- Could appear in composite Higgs models but also in weakly coupled theories

- A simplified phenomenological Lagrangian where only the relevant parameters that control the mass of the resonance and the interactions involved in its production and decay are retained

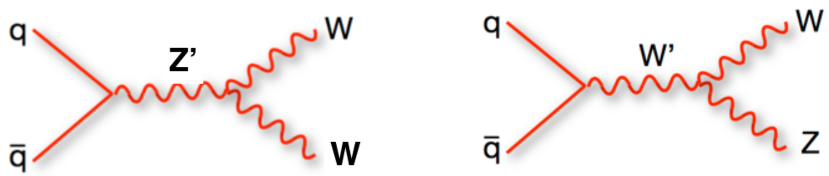
- Models according to the typical strength of vector boson interactions (g_V) and the dimensionless coefficients(c_i):
  - Model A: *weakly coupled vector resonances from extension of the gauge group, g_V~1, c_H~-g^2/g_V^2, c_F~1*
  - Model B: *produced in a strong scenario (composite Higgs models), $1 < g_V \leq 4\pi$, c_H~c_F~1*

- From an experimental perspective, models A and B represent different cross sections

- Final states: *neutral or charged*

- Narrow spin-1 resonances

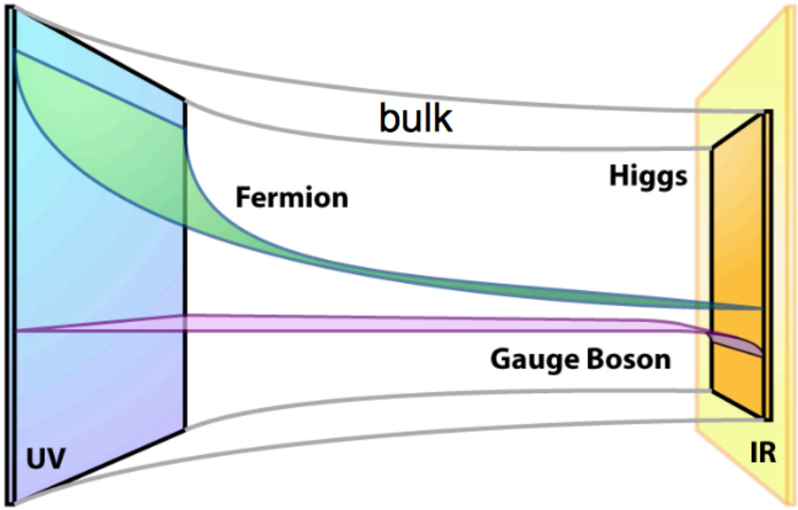
- $q\bar{q}$ or VBF production



HVT theory 10.1007/JHEP09(2014)060

Warped Extra Dimensions

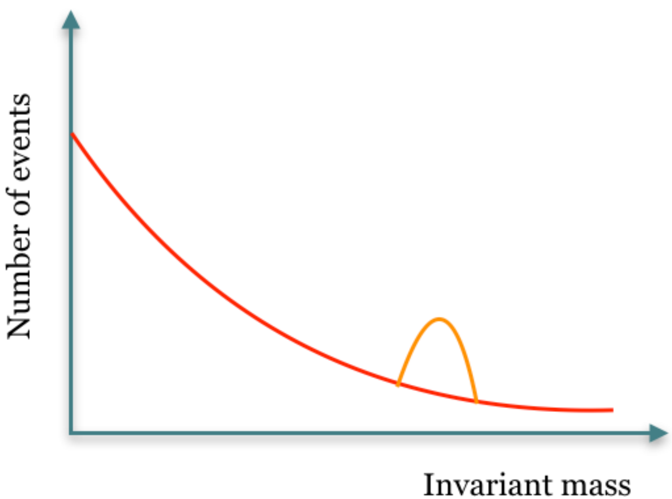
- The so called Randall-Sundrum (RS) models
  - Gravity propagates in a warped extra dimension
  - The SM fields are constrained to one brane
  - It provides a solution to the hierarchy problem
- Bulk graviton models allow SM particles into 5D-bulk
  - Overlap of 5D profiles at TeV-brane determine particle masses
- The most distinctive feature of this scenario is the existence of spin-2 Kaluza-Klein (KK) gravitons whose masses and couplings to the SM are set by the TeV scale
- Neutral final states
- ggF production is dominant
- Narrow width, depends on the $k/\bar{M}_{Pl}$ choice, where $\bar{M}_{Pl} = M_{Pl}/8\pi$ is the reduced Planck scale and k is the curvature scale of the extra dimension

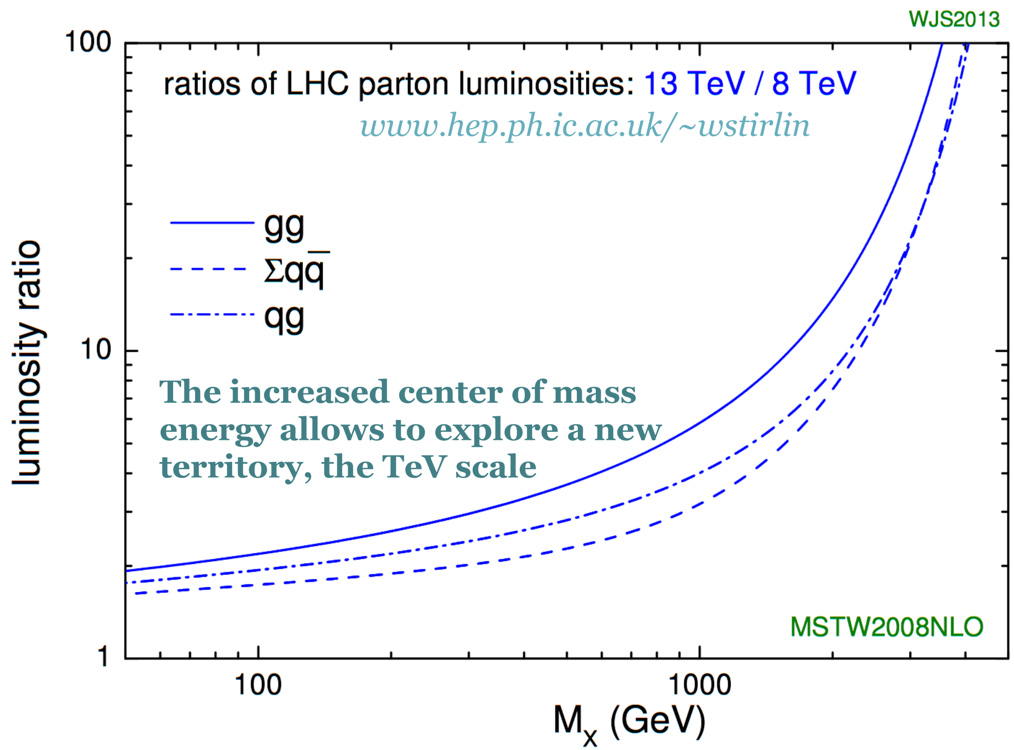


Graviton 10.1103/PhysRevD.76.036006

Di-Boson Searches

- Di-boson searches are highly motivated and have been proven fruitful in the past (Higgs discovery)
- Many theories predict di-boson resonances with different properties (charge, spin, width, production mechanism)
- <u>Simple methodology</u>: search for excesses above the background





Model independent searches are important!

V Decays & Channels To Be Covered

Leptonic decays (ll, lv, vv)

- *Small branching ratios:*
  - *BR(W→ lv) = 33.3%*
  - *BR(Z→ ll) = 10.2%*
  - *BR(Z→ vv) = 20.5%*
- *Cleaner final states through leptons reconstruction*
- *Perform better at low masses*

Hadronic (qq)

- *Large branching ratios:*
  - *BR(W→ qq) = 66.6%*
  - *BR(Z→ qq) = 69.2%*
- *Background estimation is trickier*
- *Reconstruction using anti-kt jets*
- *Perform better at high masses where SM backgrounds fall off*

Channel to be covered	References	Luminosity (fb^{-1})
$VV \rightarrow qqqq$	ATLAS-EXOT-2016-19	36.1
$WV \rightarrow l\nu qq$	ATLAS-CONF-2017-051	36.1
$ZV \rightarrow llqq/\nu\nu qq$	ATLAS-EXOT-2016-29	36.1
$Z\gamma \rightarrow ll\gamma/qq\gamma$	Phys.Lett. B764 (2017) 11-30	3.2

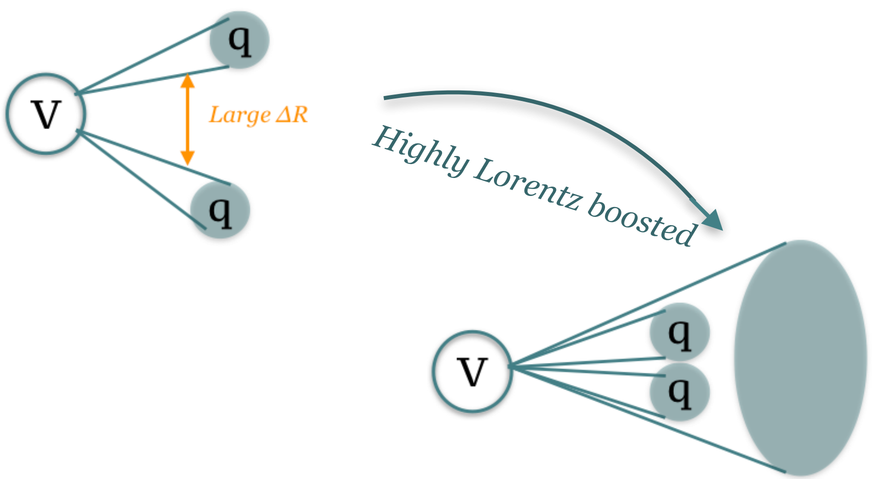
Hadronic V Decays

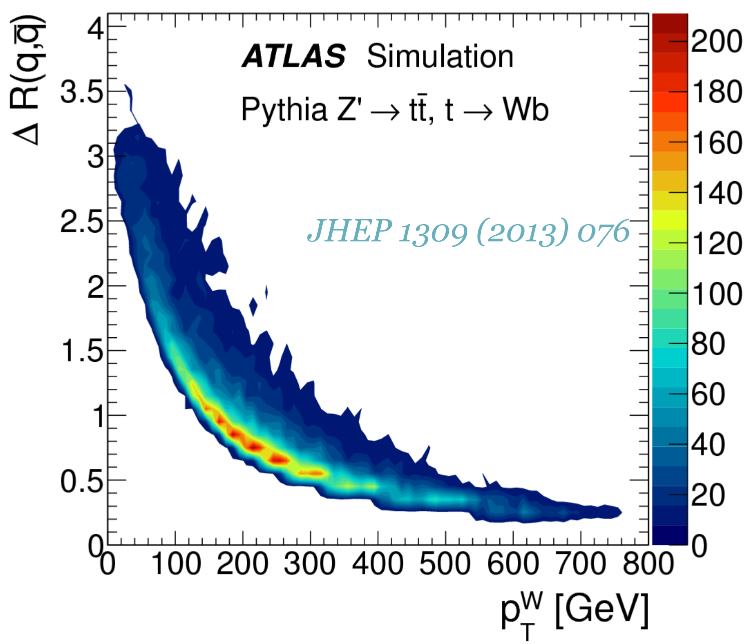
Final state decay products can be highly energetic if search particle is very massive

- *Angular separation*

$$\Delta R = \sqrt{(\Delta\varphi^2 + \Delta\eta^2)} \approx 2m/p_T$$

- *Resolved Regime: relatively low momentum, one small-R jet (distance parameter R = 0.4) is reconstructed for each quark*
- *Boosted Regime: relatively high momentum, boson is reconstructed as a large-R jet (R = 1.0), it is denoted as J*
- *Novel techniques have been developed for boosted objects identification*





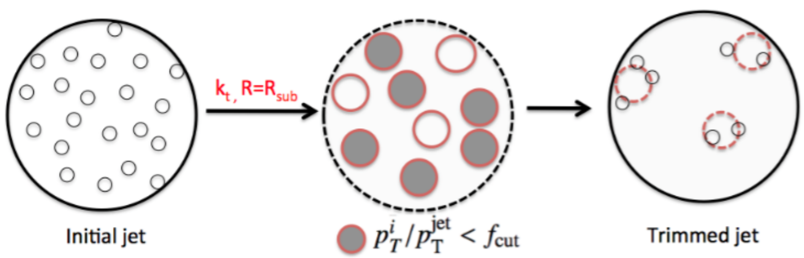
JHEP 1309 (2013) 076

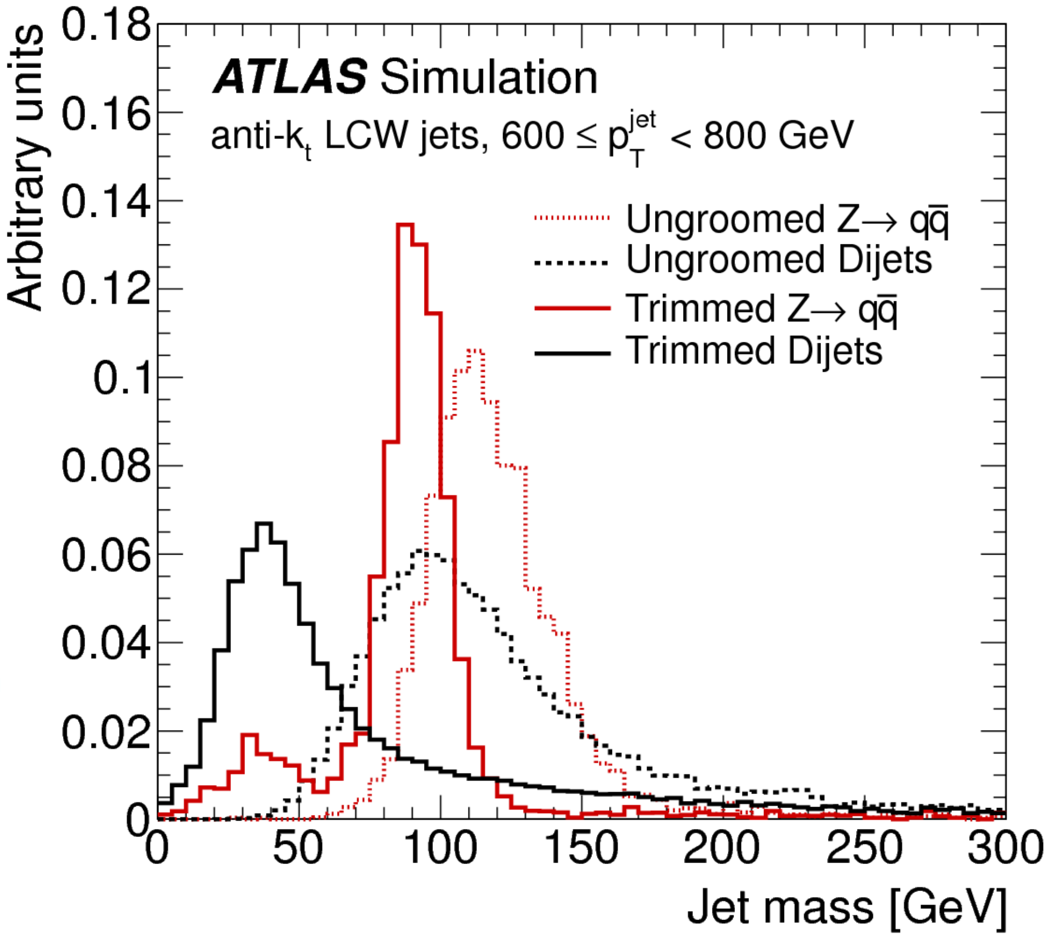
Towards Boosted Boson Tagging

Grooming technique (pile-up & soft QCD subtraction):

- **Trimming**
  - Remove constituents with $p_T^{constituent}/p_T^{jet} < 5\%$

- Possible due to the fine calorimeter granularity ~0.025 (EM) to 0.1 (HAD)





Large-R Jet Mass

Very energetic jets with prong structure have small angular separation between their constituents → the missing calorimeter information makes the mass resolution worse

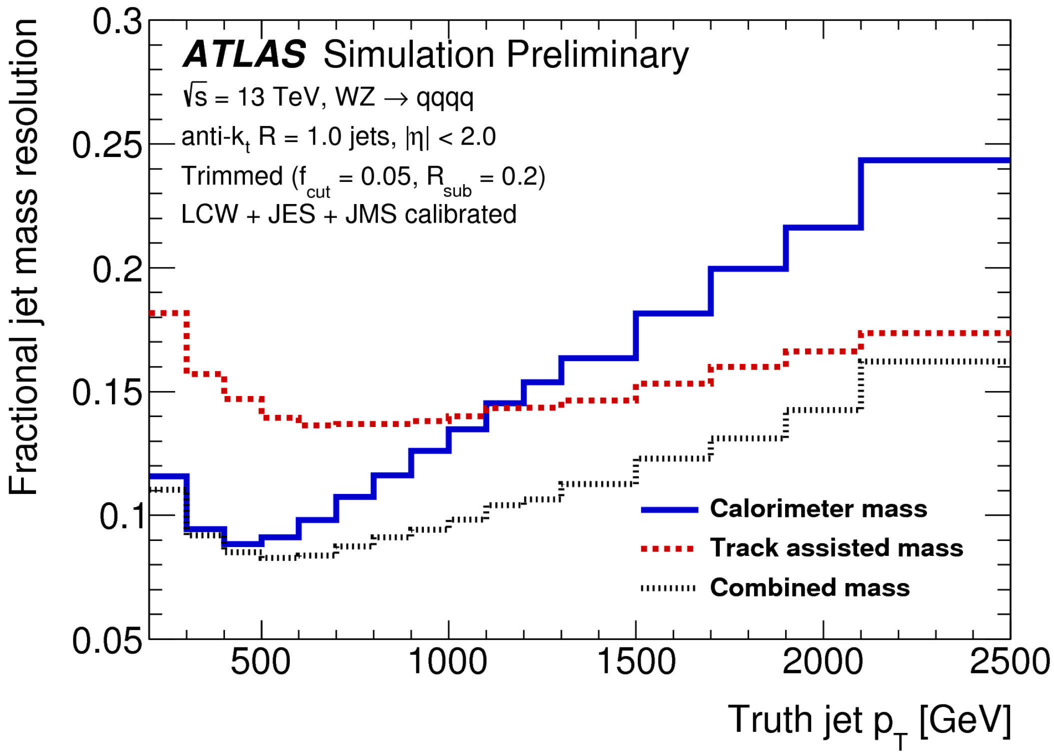
The tracker information can improve the mass resolution in the high p_T region

A combination of the calorimeter and track information is used:

$$m^{\text{comb}} = \frac{\sigma_{\text{calo}}^{-2} m^{\text{calo}} + \sigma_{\text{TA}}^{-2} m^{\text{TA}}}{\sigma_{\text{calo}}^{-2} + \sigma_{\text{TA}}^{-2}}$$

where

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



Substructure Variable

- Energy Correlation Functions (ECF)

$$E_{\mathrm{CF1}} = \sum_i p_{\mathrm{T},i}$$

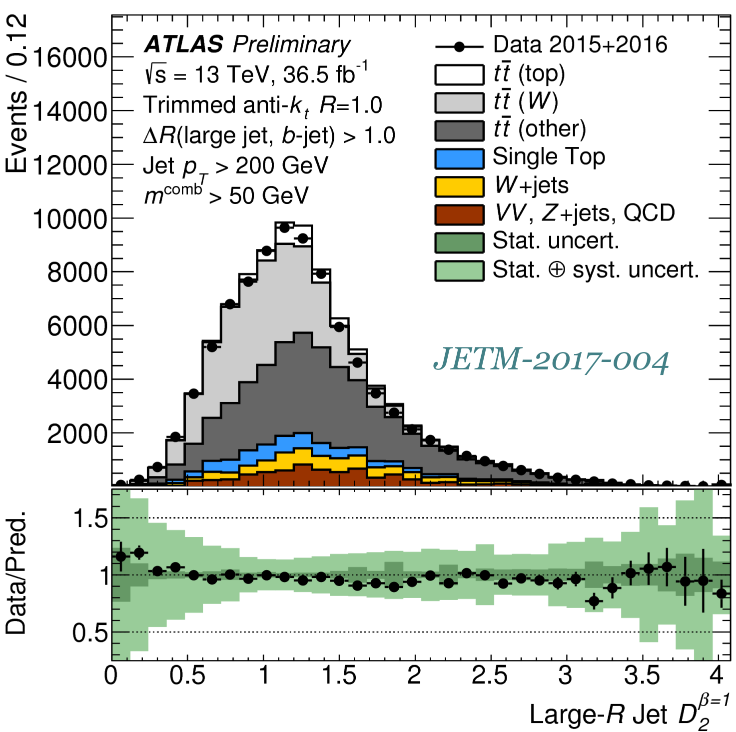
$$E_{\mathrm{CF2}} = \sum_{ij} p_{\mathrm{T},i} p_{\mathrm{T},j} \Delta R_{ij}$$

$$E_{\mathrm{CF3}} = \sum_{ijk} p_{\mathrm{T},i} p_{\mathrm{T},j} p_{\mathrm{T},k} \Delta R_{ij} \Delta R_{jk} \Delta R_{ki}$$

- Substructure Variable:

$$D_2^{\beta=1} = E_{\mathrm{CF3}} \left(\frac{E_{\mathrm{CF1}}}{E_{\mathrm{CF2}}} \right)^3$$

- *Different working points (w.p.): providing different signal efficiency, e.g. 50%, 80%*
- *Variable cuts: according to the jet p_T*



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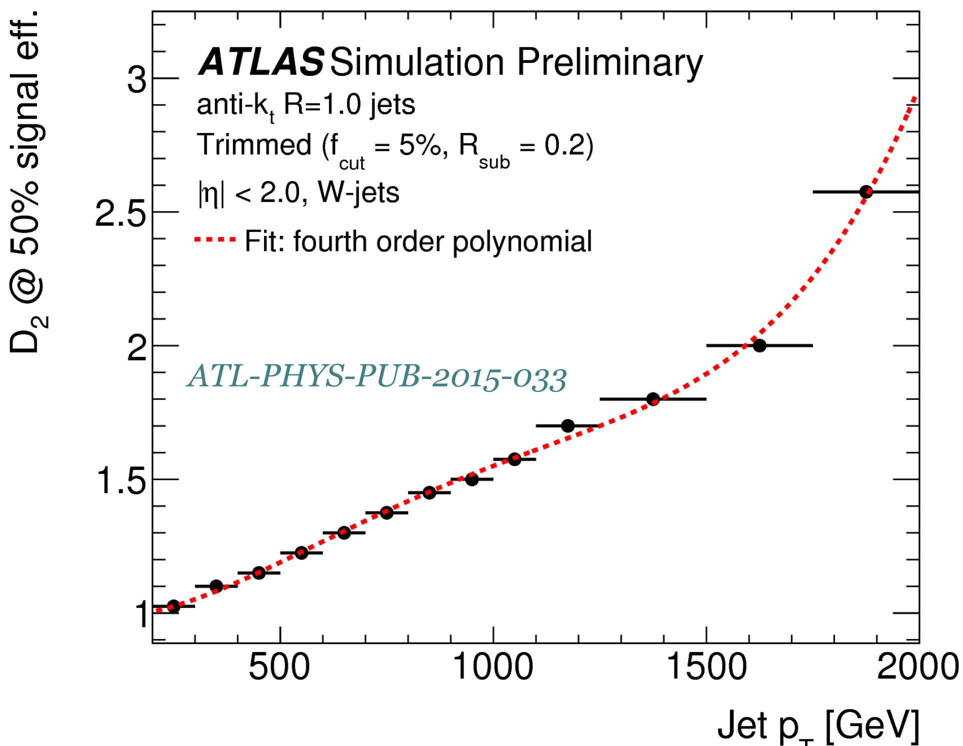
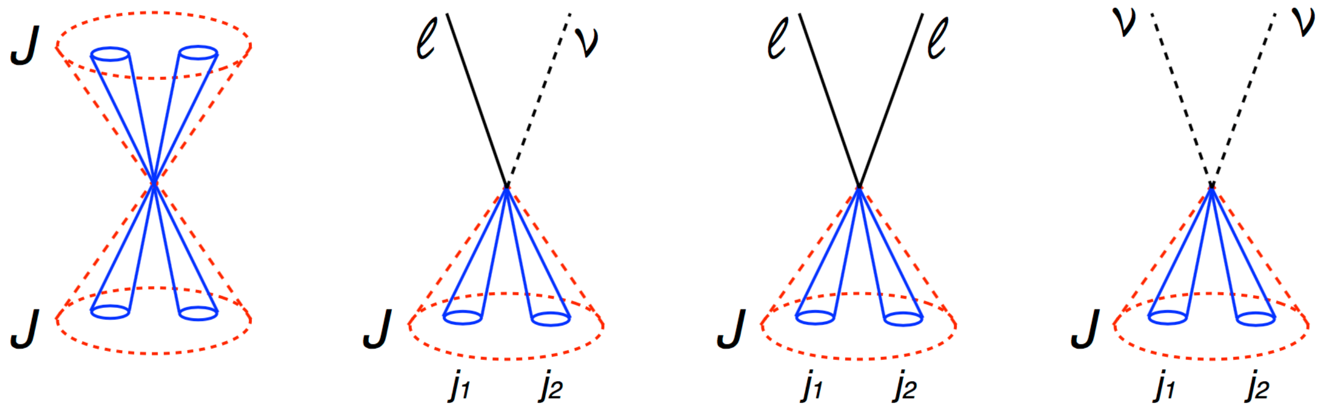


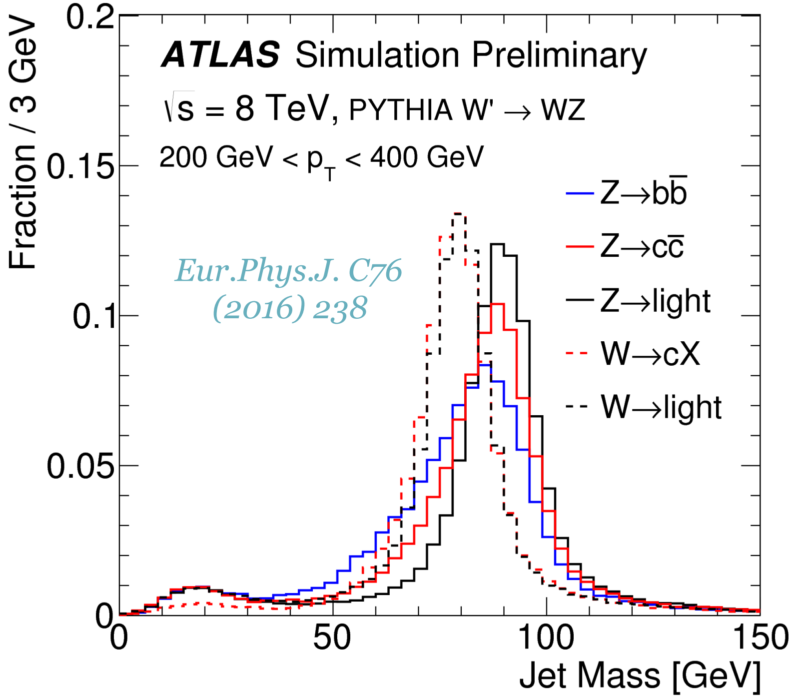
ATL-PHYS-PUB-2015-033

VV Boosted Searches



- *At least one hadronic V decay*
- *Hadronic W and Z signal regions partially overlap*
- *Different VV final states are orthogonal*
- *Final discriminant is the invariant VV mass*
  - *Exception: the ννqq channel uses the transverse mass because it is not possible to fully reconstruct the mass due to the presence of neutrinos*

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

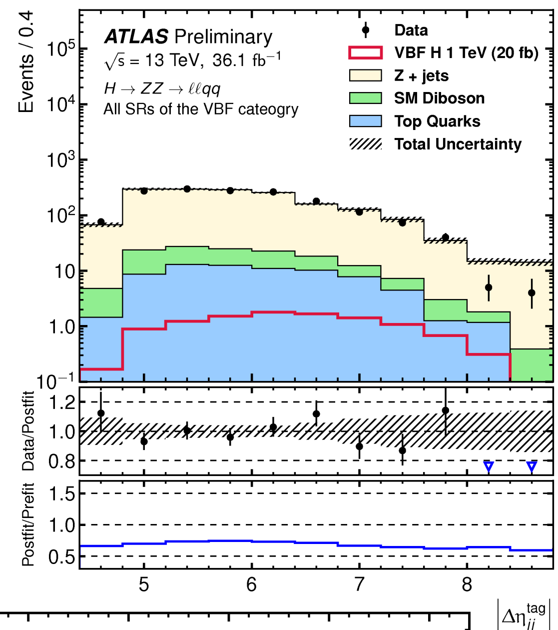


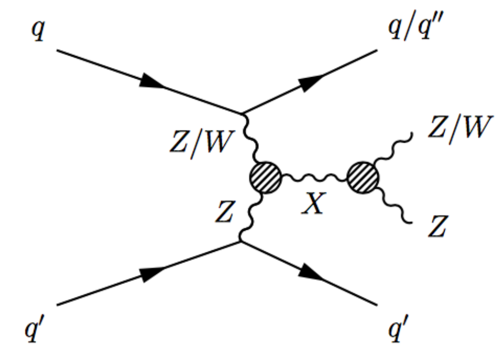
VV Semi-Leptonic Production Mechanism Categorization

<u>Categories</u>:
- *VBF (is prioritized)*
- *Drell-Yan (DY): qq or ggF production*

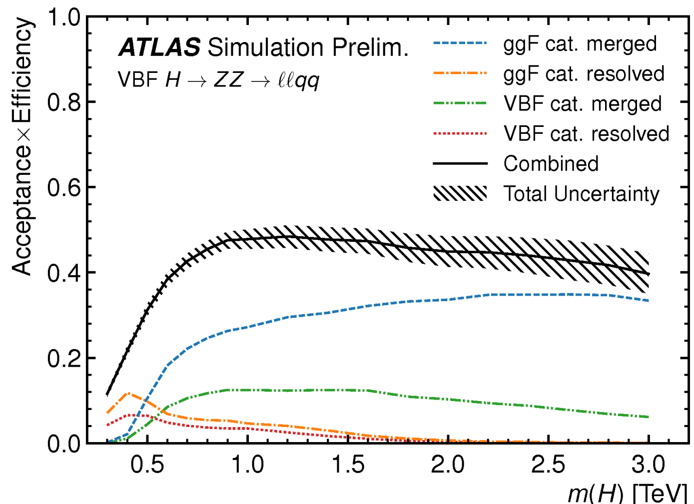
<u>VBF signature</u>:
- *Two quarks, i.e. small-R jets, are expected to be found in opposite pseudo-rapidity hemisphere*

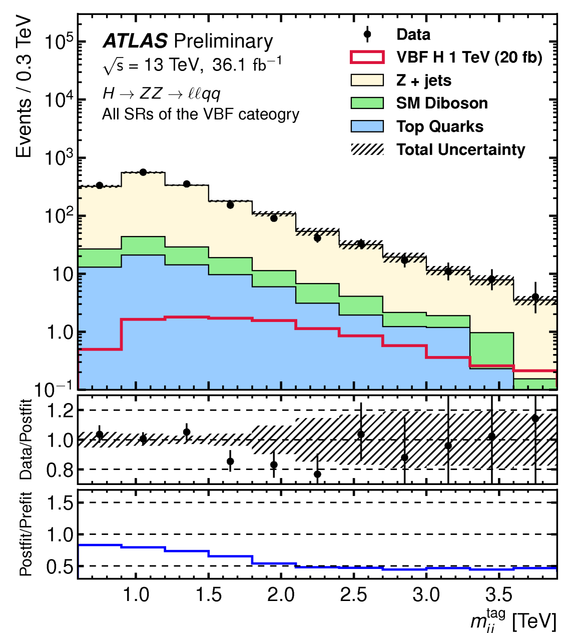
<u>DY production</u>:
- *Absence of VBF topology*



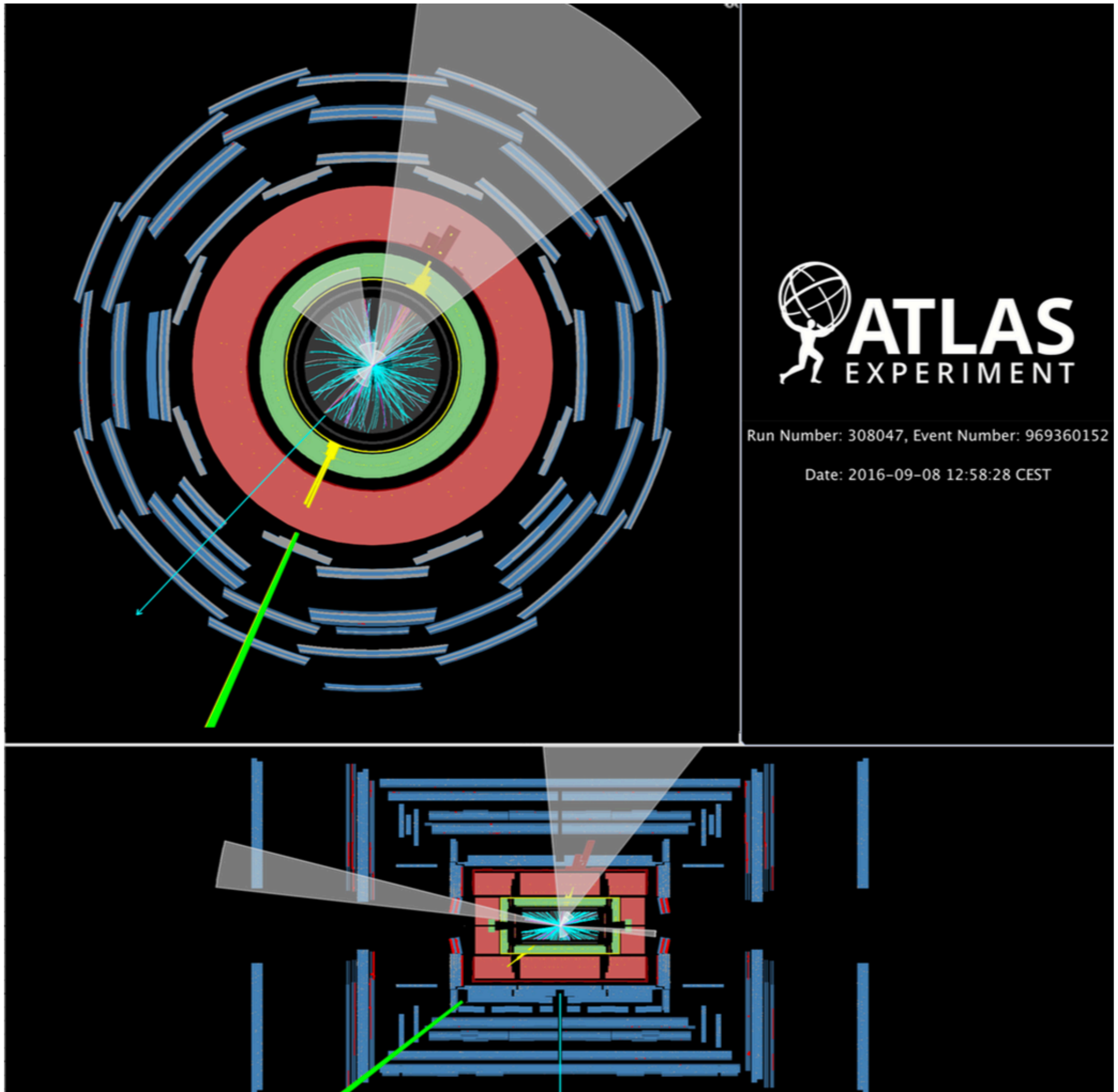


ZZ → llqq Example





VV Semi-Leptonic Production Mechanism Categorization



<u>Analysis</u>:
1. Search for production mechanism
2. Search for VV decays

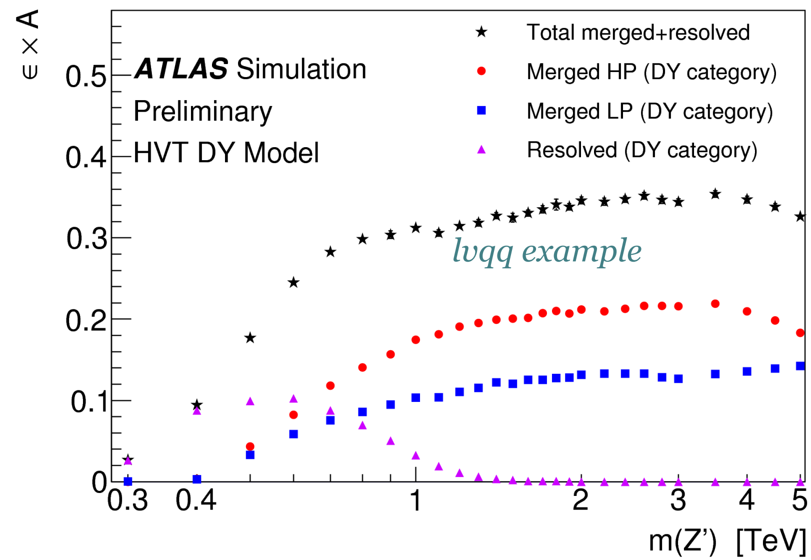
<u>VV → lvqq event display</u>:
- *Electron* p_T *= 777 GeV*
- E_T^{miss} *= 362 GeV*
- *Large-R jet:* m *= 81 GeV,* p_T *= 1118 GeV*

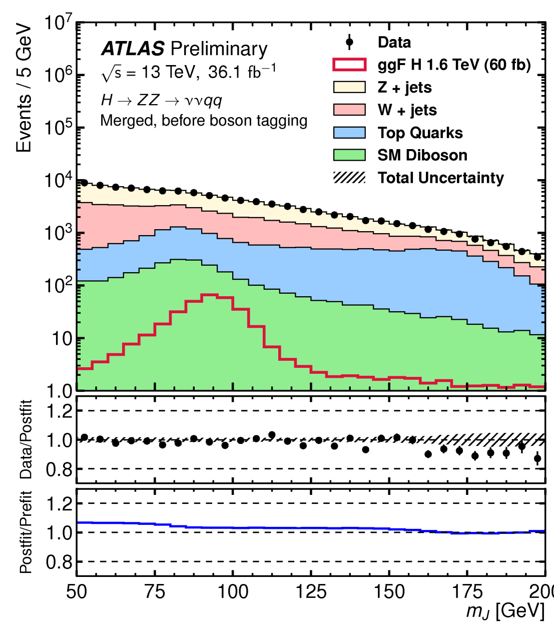
m(WV) = 2.759 TeV
VBF: $m_{tag}(jj)$ *= 812 GeV,* $\Delta\eta_{tag}(jj)$ *= 5.6*

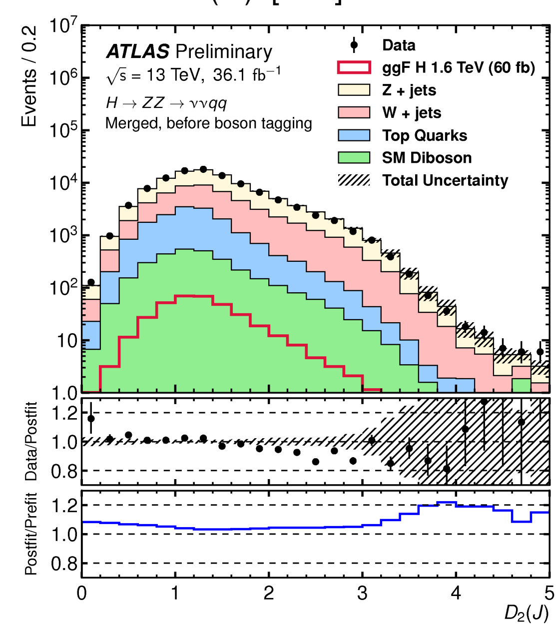
<u>Note:</u>
The two boson candidates are "balanced", each boson holds ~half of the energy

VV Semi-Leptonic Selection

- **Search for a leptonic V decays**:
  - $W \to l\nu$ or $Z \to ll$ or $Z \to \nu\nu$
- **Search for a hadronic V decay**:
  - <u>Merged analysis is prioritized</u>
    - Large-R jet: $p_T > 200$ GeV, $|\eta| < 2.0$
    - Mass and D_2 cuts:
      - 50% w.p.: *High Purity* (HP)
      - 80% w.p.: *Low Purity* (LP)
  - <u>Resolved analysis (if the event failed the merged selection)</u>
    - Two small-R jets
    - Invariant mass compatible with a V mass
    - Prioritizing $Z \to bb$ events increases the sensitivity

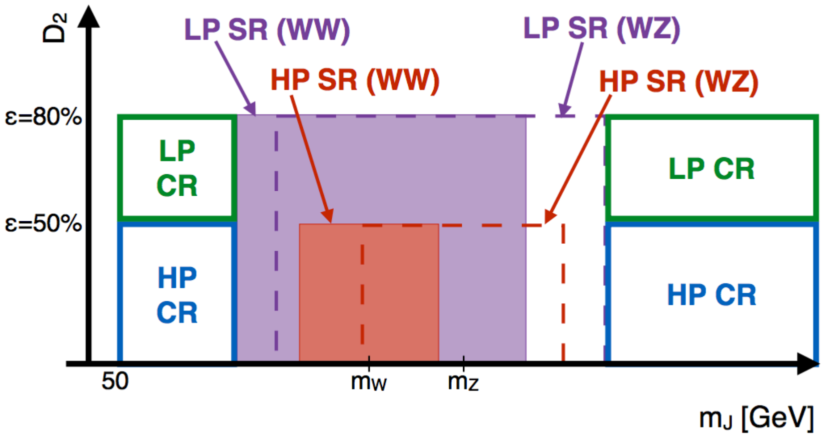






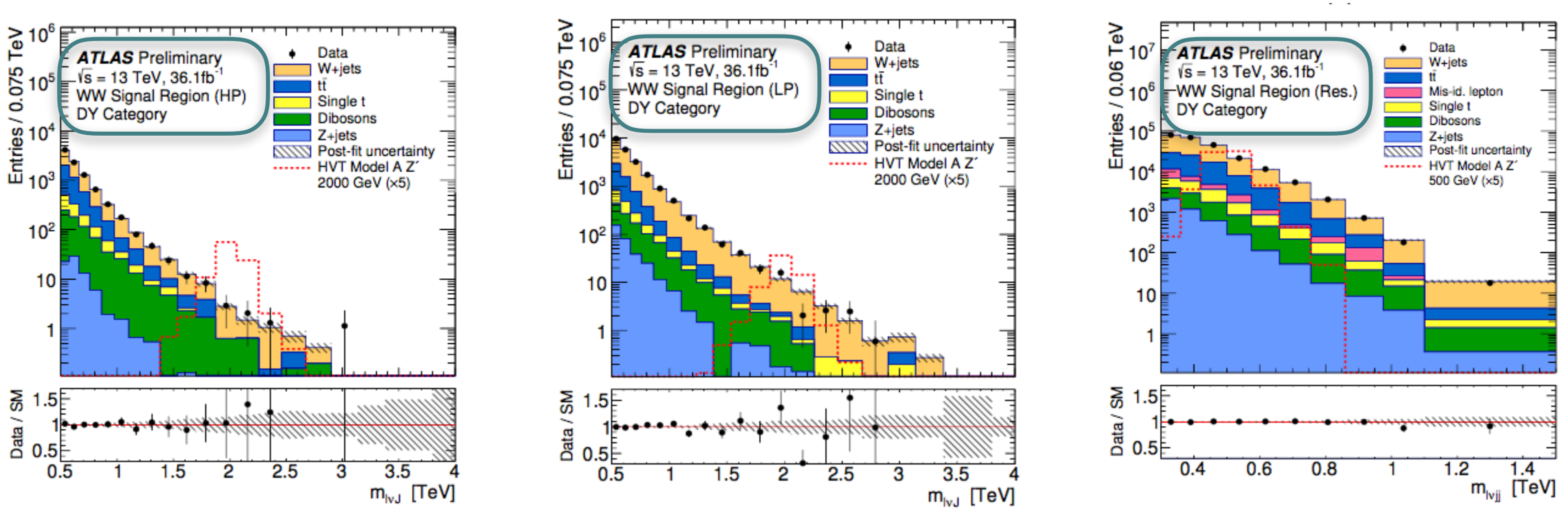
VV Semi-Leptonic Background Estimate

<u>Background composition</u>:
- V+jets
- ttbar
- Smaller contributions from SM dibosons, single top and QCD



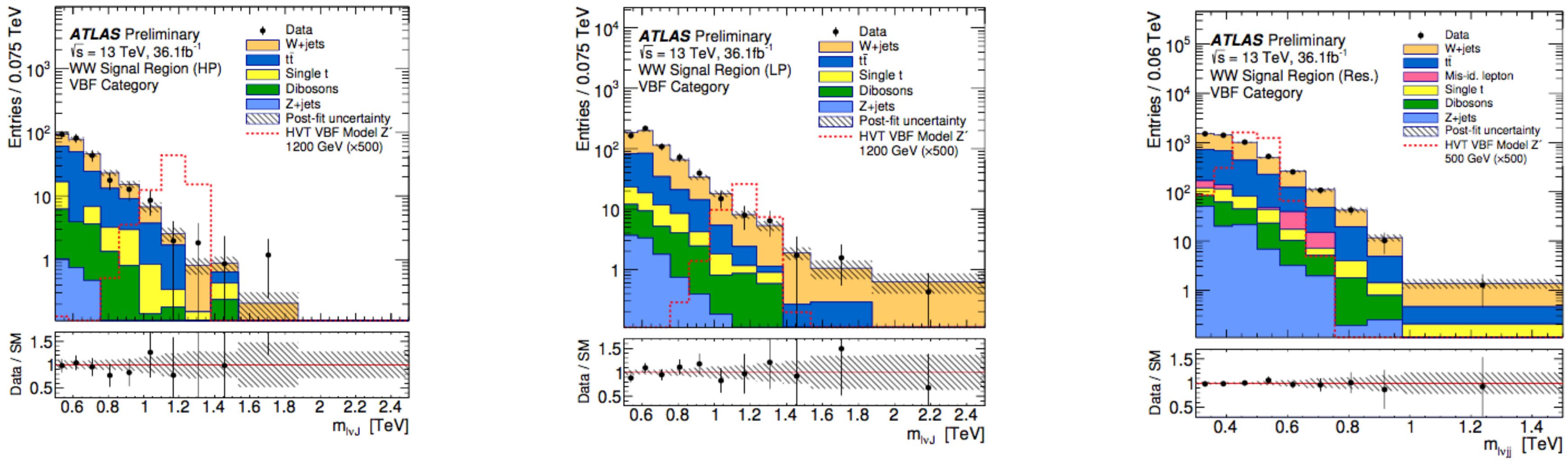
For each VV channel, set of signal and control regions are formed for:
- DY, VBF
- WW, WZ, ZZ, ZW
- HP, LP, Resolved (not for the vvqq)

WW → lvqq example (DY category)

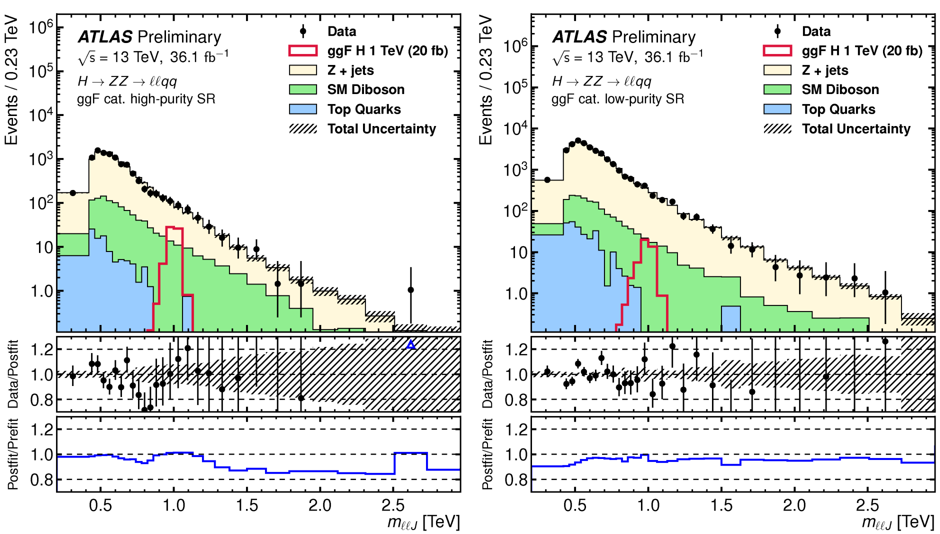


A Few … VV Semi-Leptonic Final Discriminants

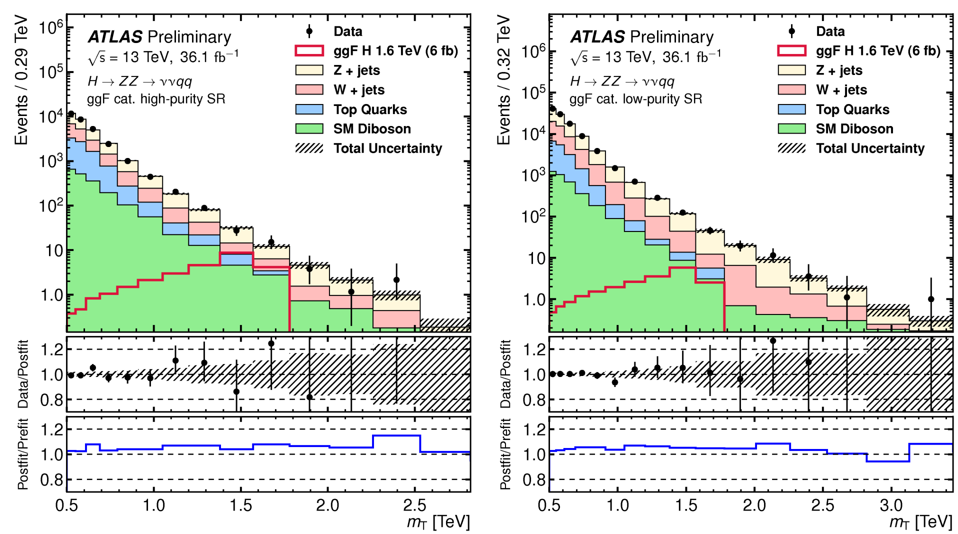
WZ → lvqq example (VBF category)



ZZ → llqq example (DY category)

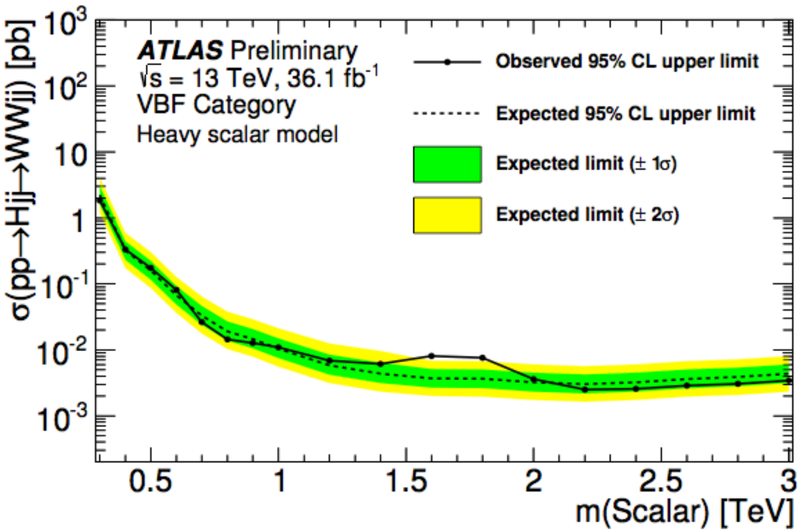


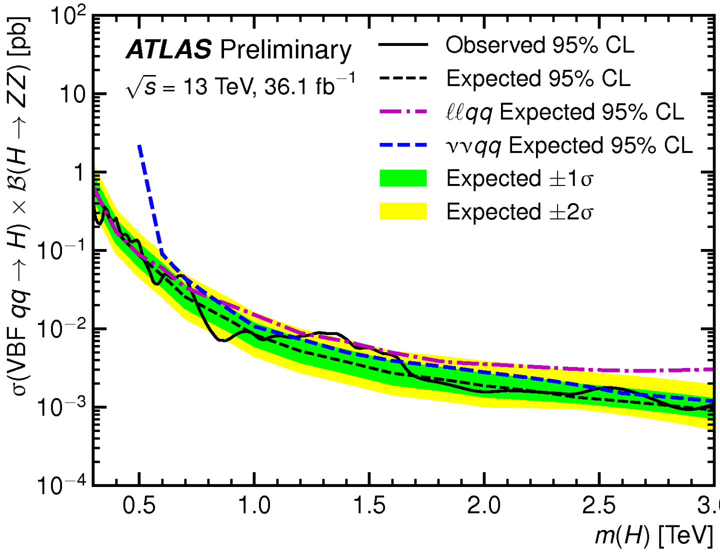
ZZ → vvqq example (DY category)

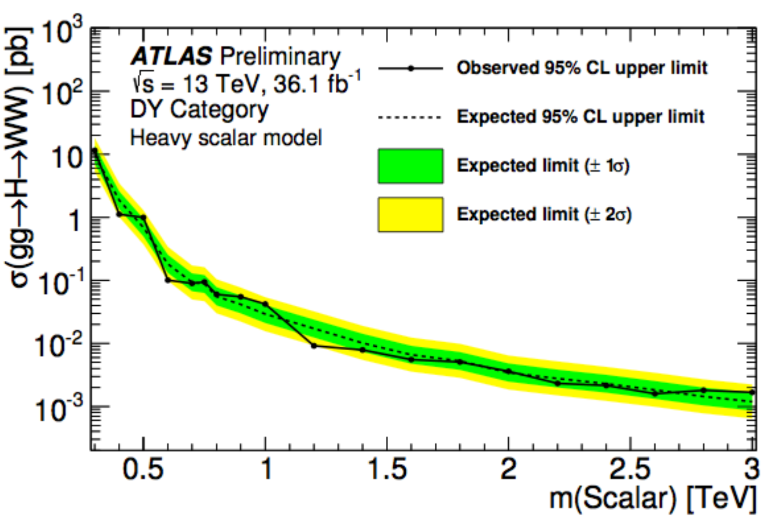


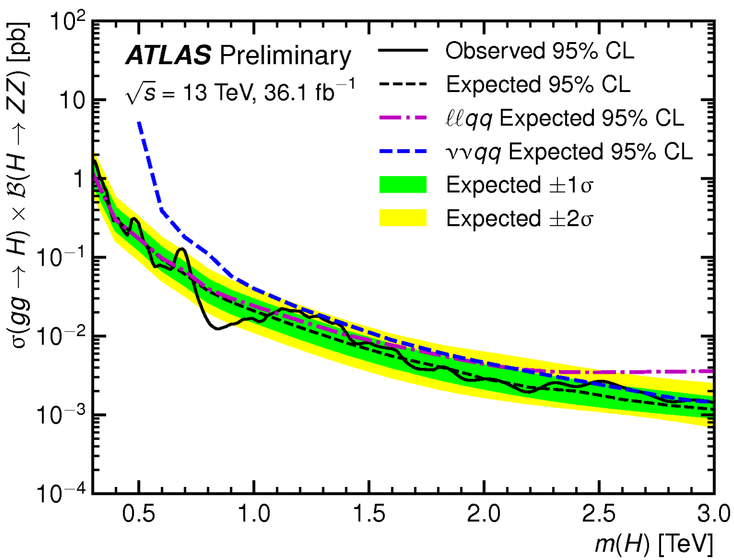
VV Semi-Leptonic Scalar Limits

VBF production





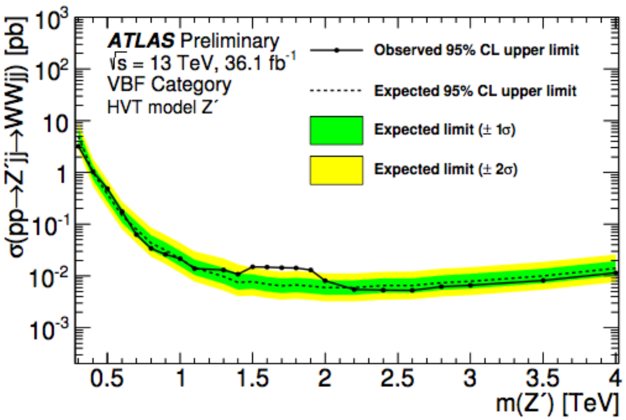


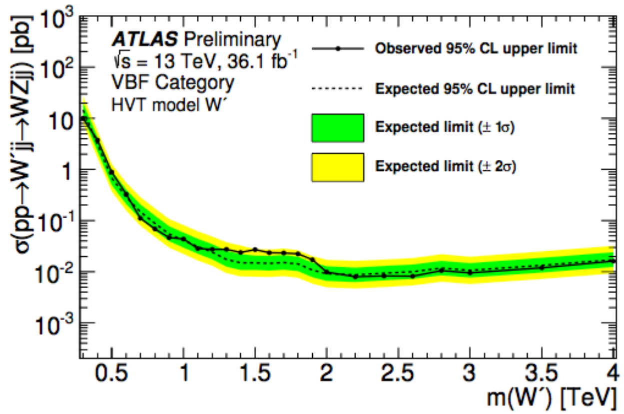


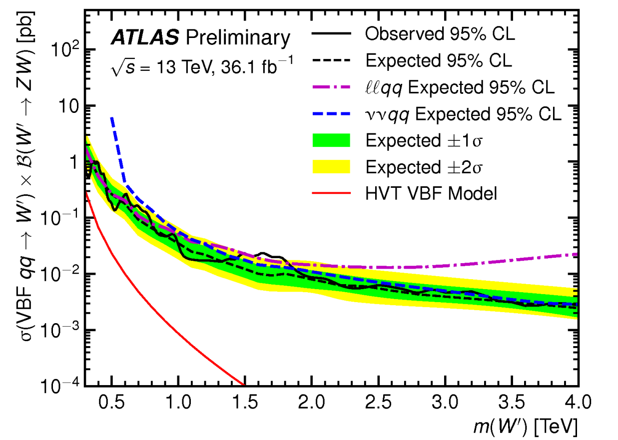
DY production

VV Semi-Leptonic HVT Limits

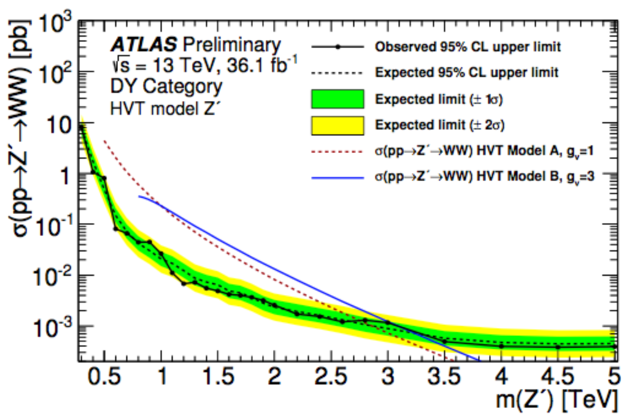
VBF production

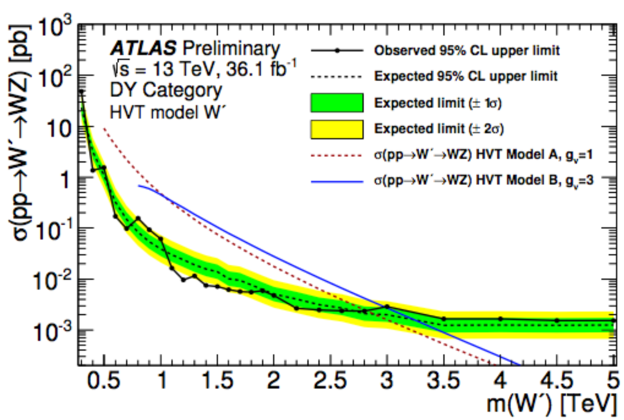


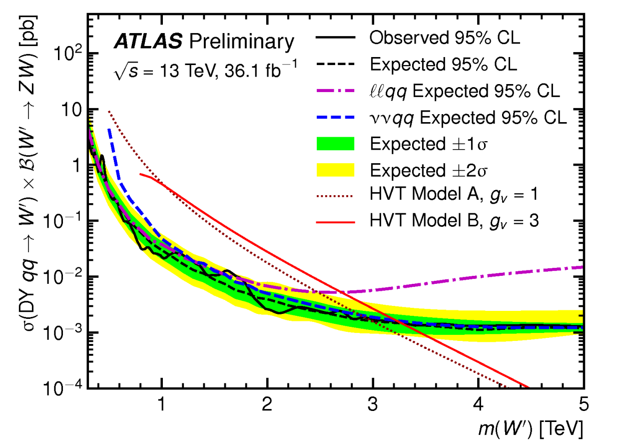




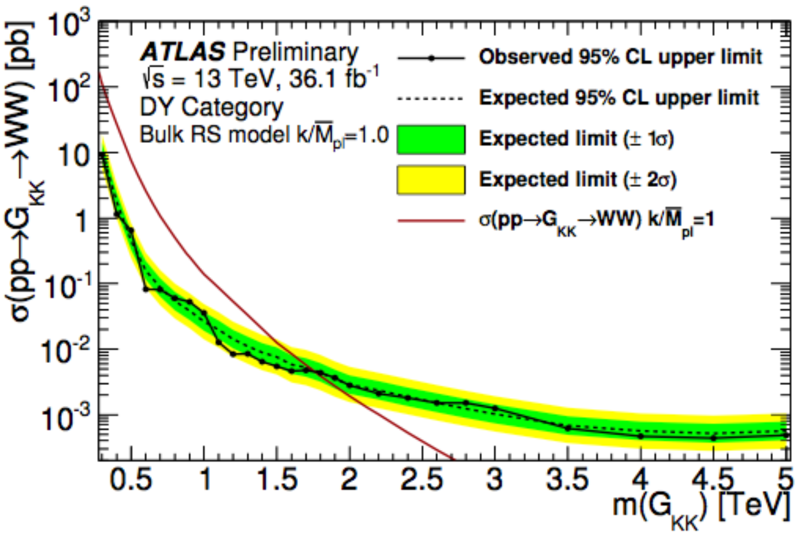
DY production

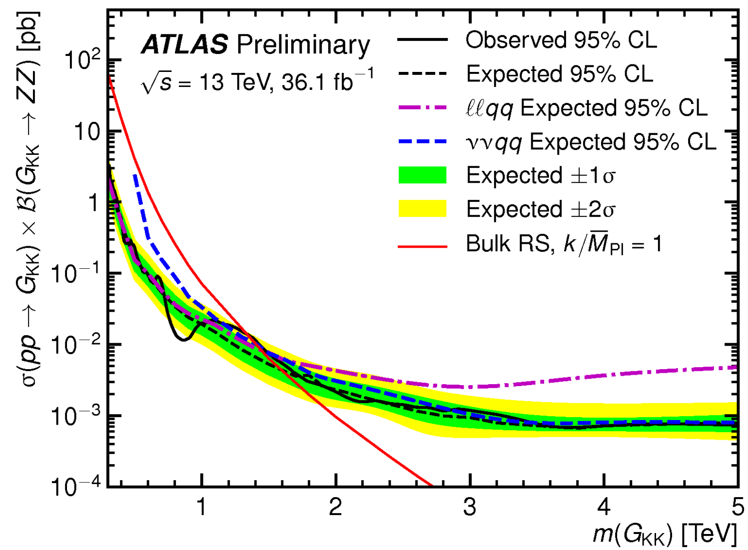






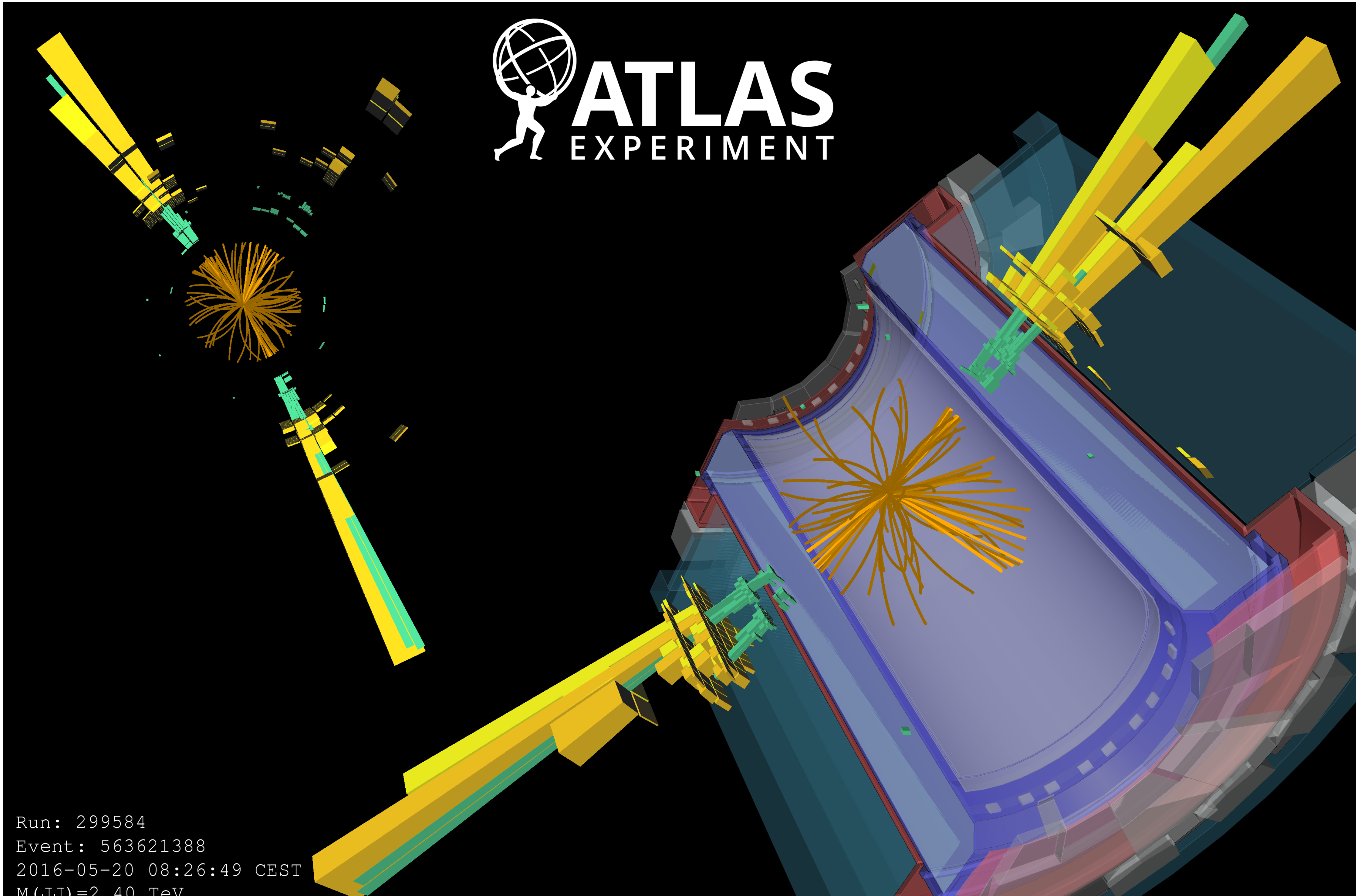
VV Semi-Leptonic Graviton Limits





ATLAS-CONF-2016-055

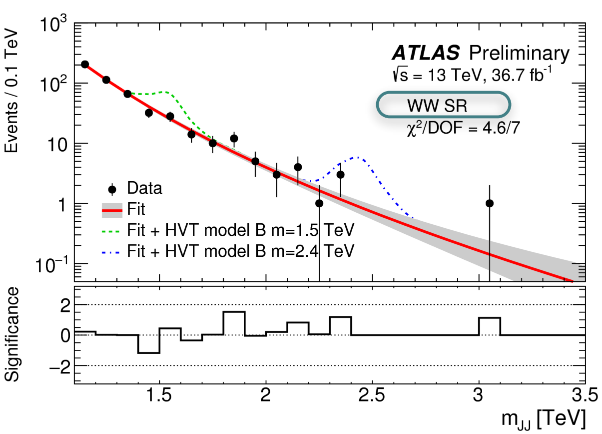
VV→ JJ

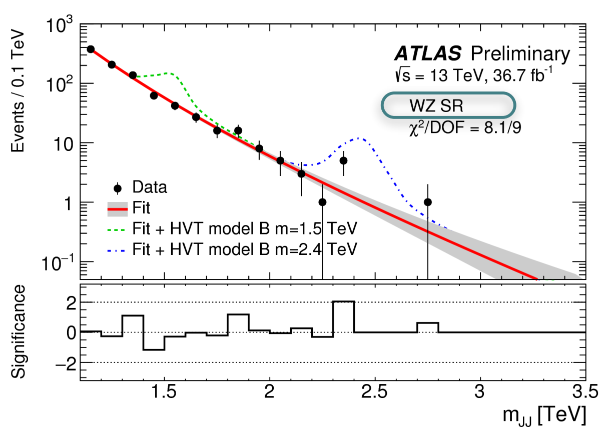


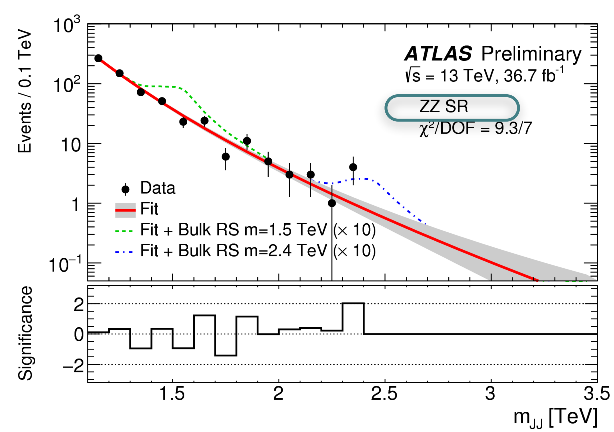
VV→ JJ Background Estimation

- Multijet background dominates
- High purity signal regions only
- It is modeled with: $dn/dx = p_1(1 - x)^{(p_2 - \xi p_3)} x^{-p_3}$

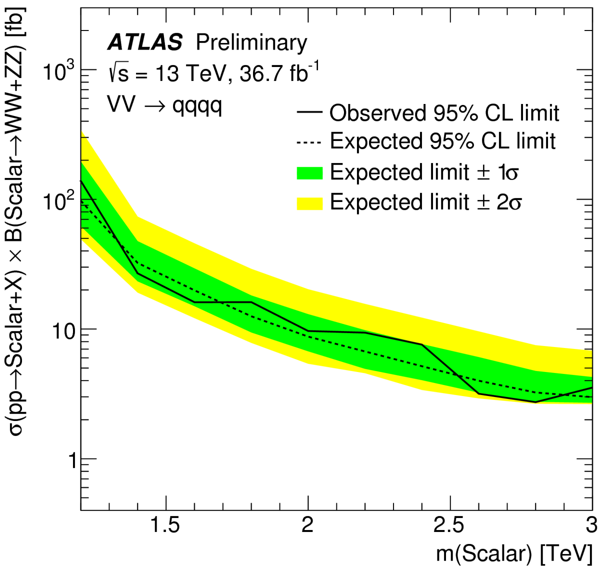
where $x = m_{JJ}/\sqrt{s}$, p_1 is a normalization factor, p_2 and p_3 are dimensionless shape parameters, ξ is a constant chosen to remove the correlation between p_2 and p_3 in the fit

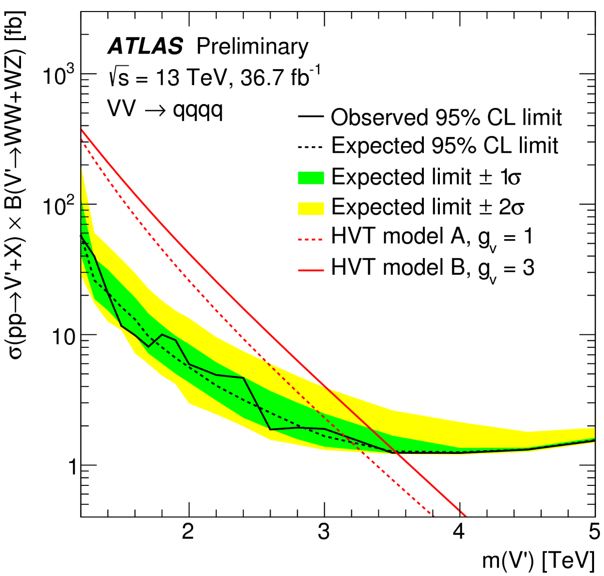


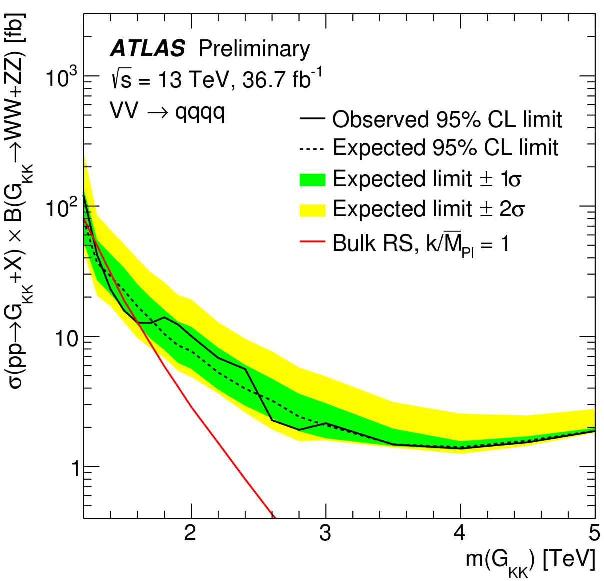




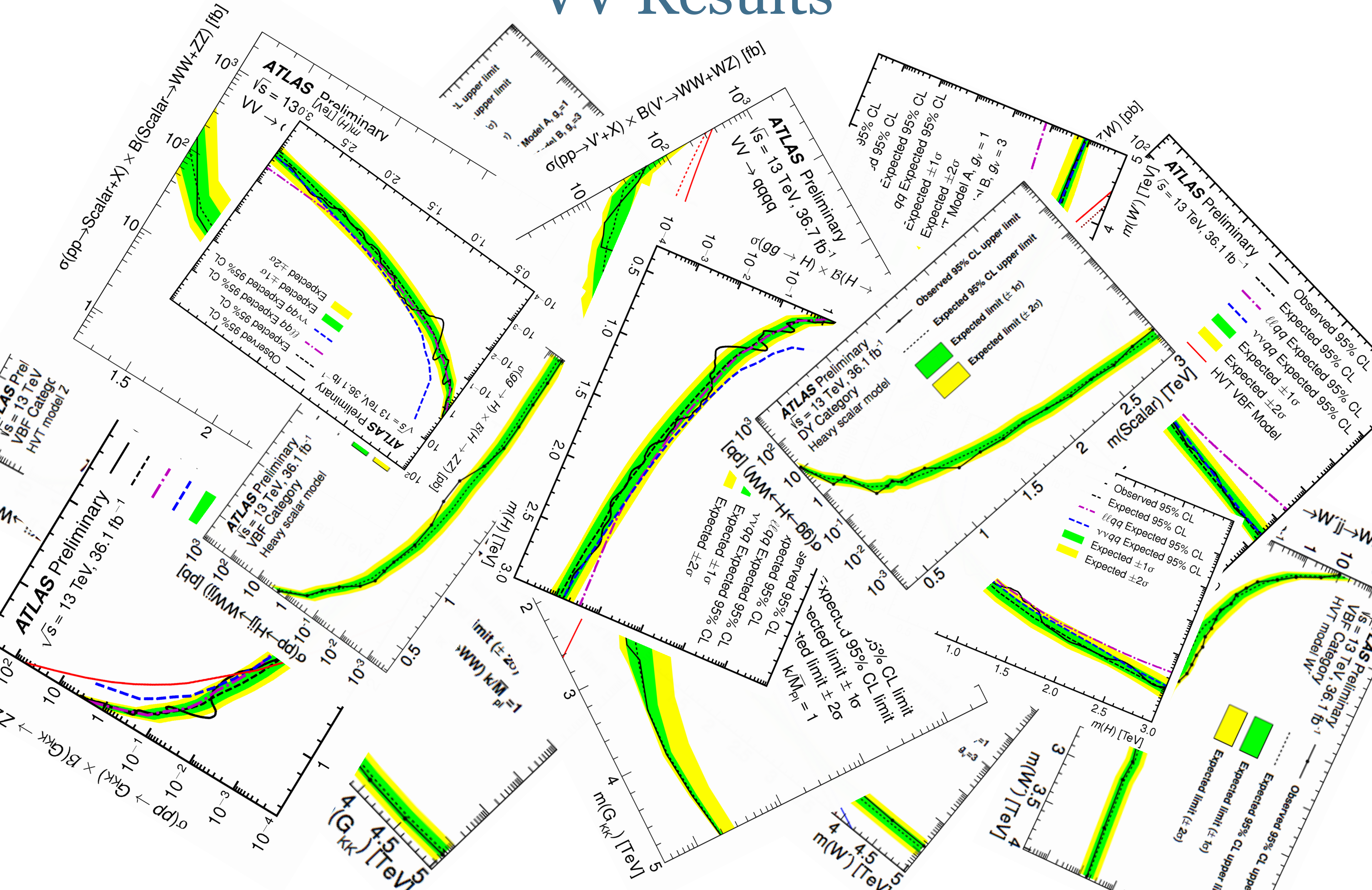
VV→ JJ Results



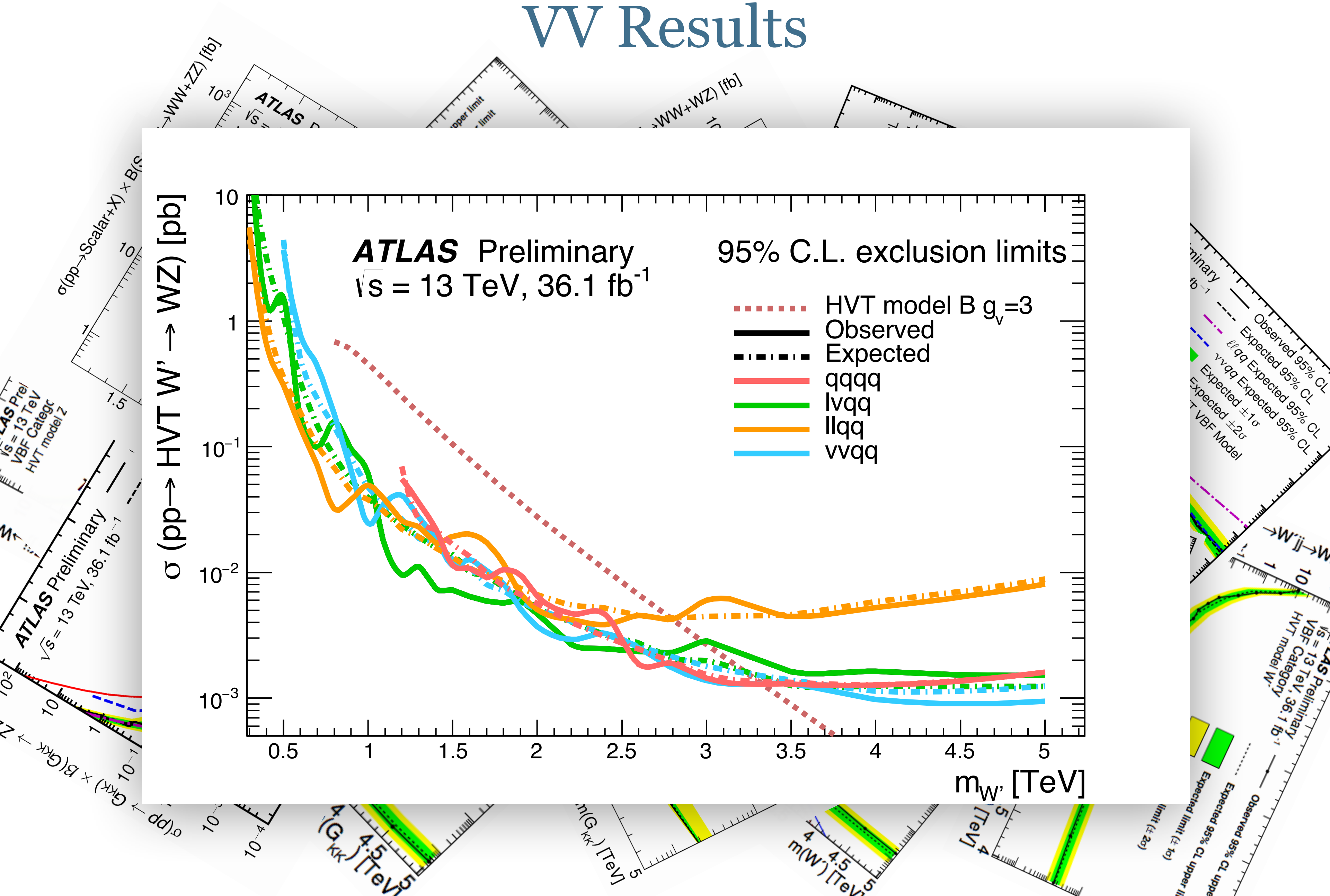




VV Results

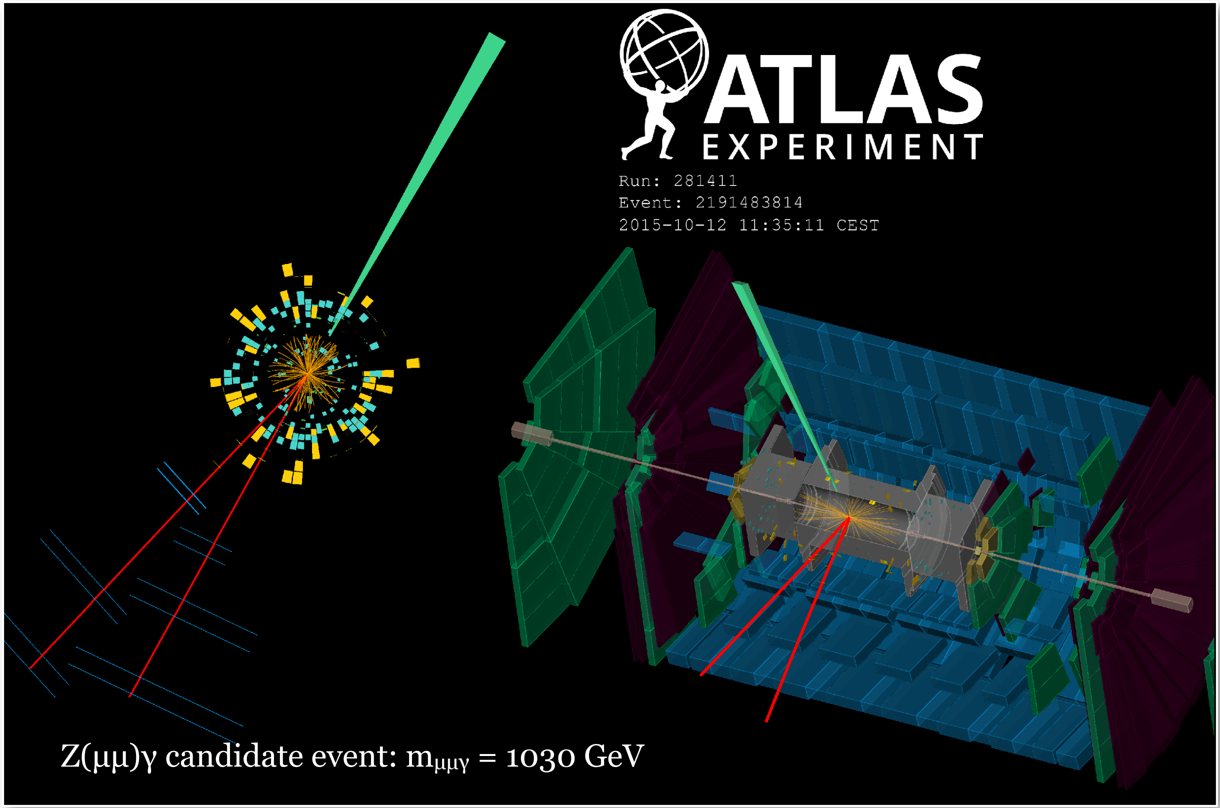


VV Results


ATLAS Preliminary
√s = 13 TeV, 36.1 fb⁻¹
95% C.L. exclusion limits
HVT model B g_v=3
Observed
Expected
qqqq
lvqq
llqq
vvqq
σ (pp→ HVT W' → WZ) [pb]
m_W' [TeV]

Phys.Lett. B764 (2017) 11-30

$X^0 \rightarrow Z\gamma$ Searches

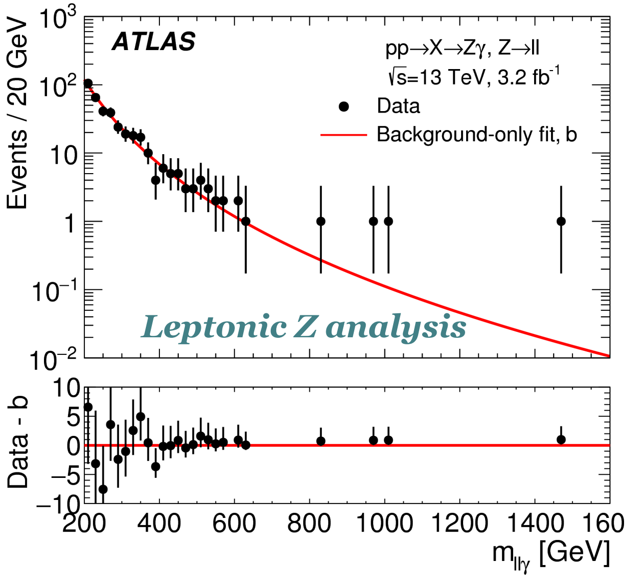


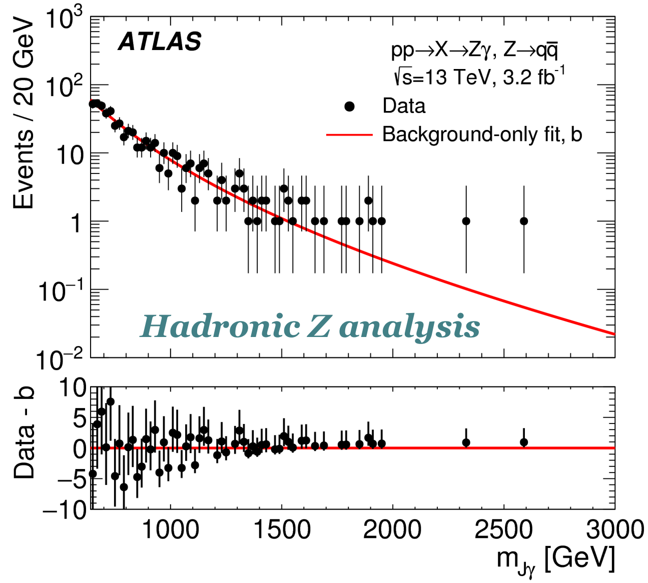
- $Z \rightarrow e^-e^+/\mu^-\mu^+/J$ and $p_T(\gamma) > 250$ GeV

- Main backgrounds:
  - Leptonic Z analysis: non-resonant Z+γ, Z+jet
  - Hadronic Z analysis: γ+jet, multijet, V+jet

Phys.Lett. B764 (2017) 11-30

X⁰→Zγ Searches



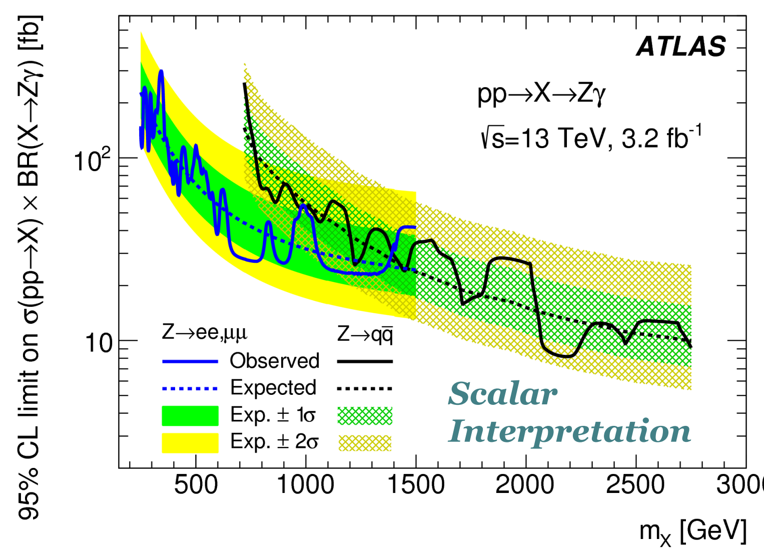


Results with 3.2 fb⁻¹ only!

The mass distribution is parametrized:

$$f_{\mathrm{bkg}}(m) = N(1-x^k)^{p_1+\xi p_2} x^{p_2}$$

N is a normalization factor, $x = m/\sqrt{s}$, $k = 1/3(1)$ for the leptonic (hadronic) analysis, $\xi = 0$ (10) in the leptonic (hadronic) analysis, p_1 and p_2 are dimensionless shape parameters

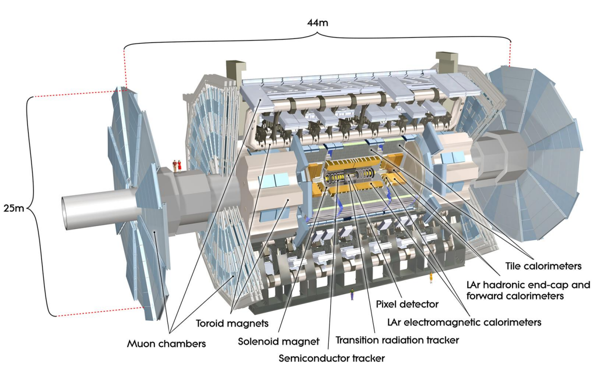


Summary

- Latest ATLAS Run II searches for VV/Vγ resonances presented
- Di-boson searches are motivated by multiple models and they are a direct way to explore the TeV scale
- These searches are experimentally challenging
- Boosted object tagging is an important key to probe high mass new physics and an active area of development
- No evidence for heavy resonance production at ATLAS … yet
- More data are being recorded now, stay tuned

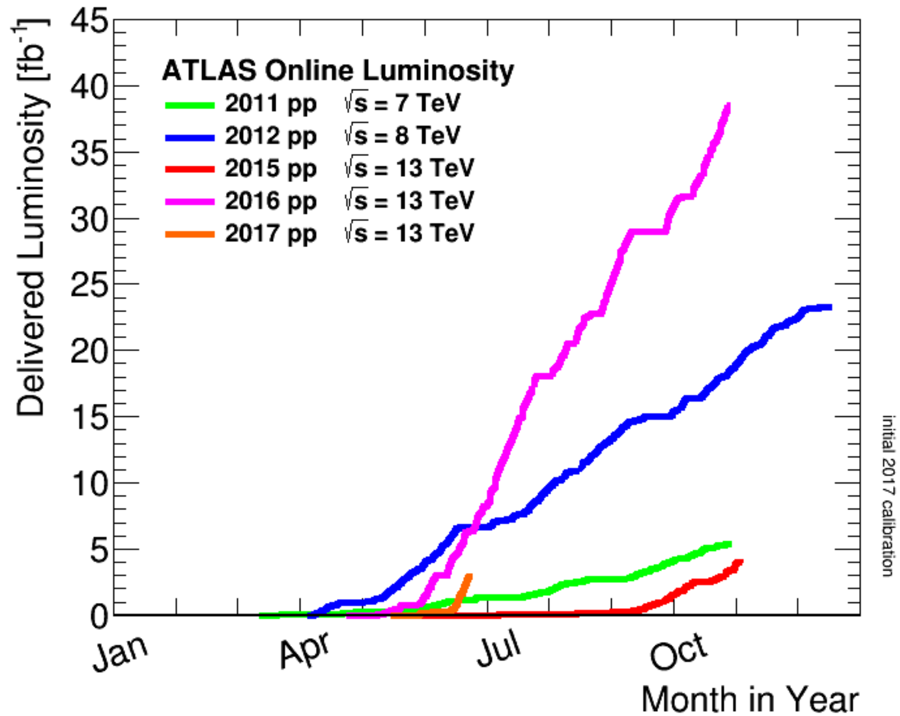
Thank you for your attention!

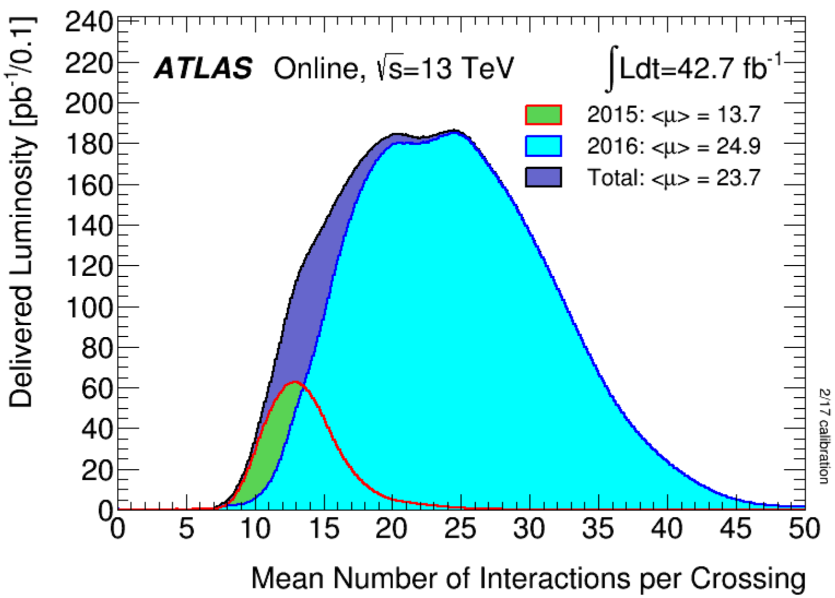
Back - up Slides

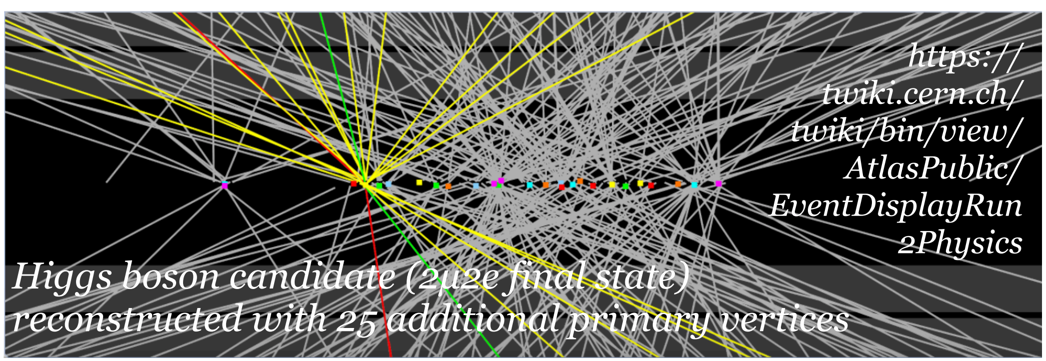


Luminosity

- Run II at $\sqrt{s}$ = 13 TeV started in 2015
- Recorded 3.2 fb^{-1} in 2015, 32.9 fb^{-1} in 2016
- Data taking efficiency > 92.4%
- 2017 data taking has started, ~45 fb^{-1} are expected this year



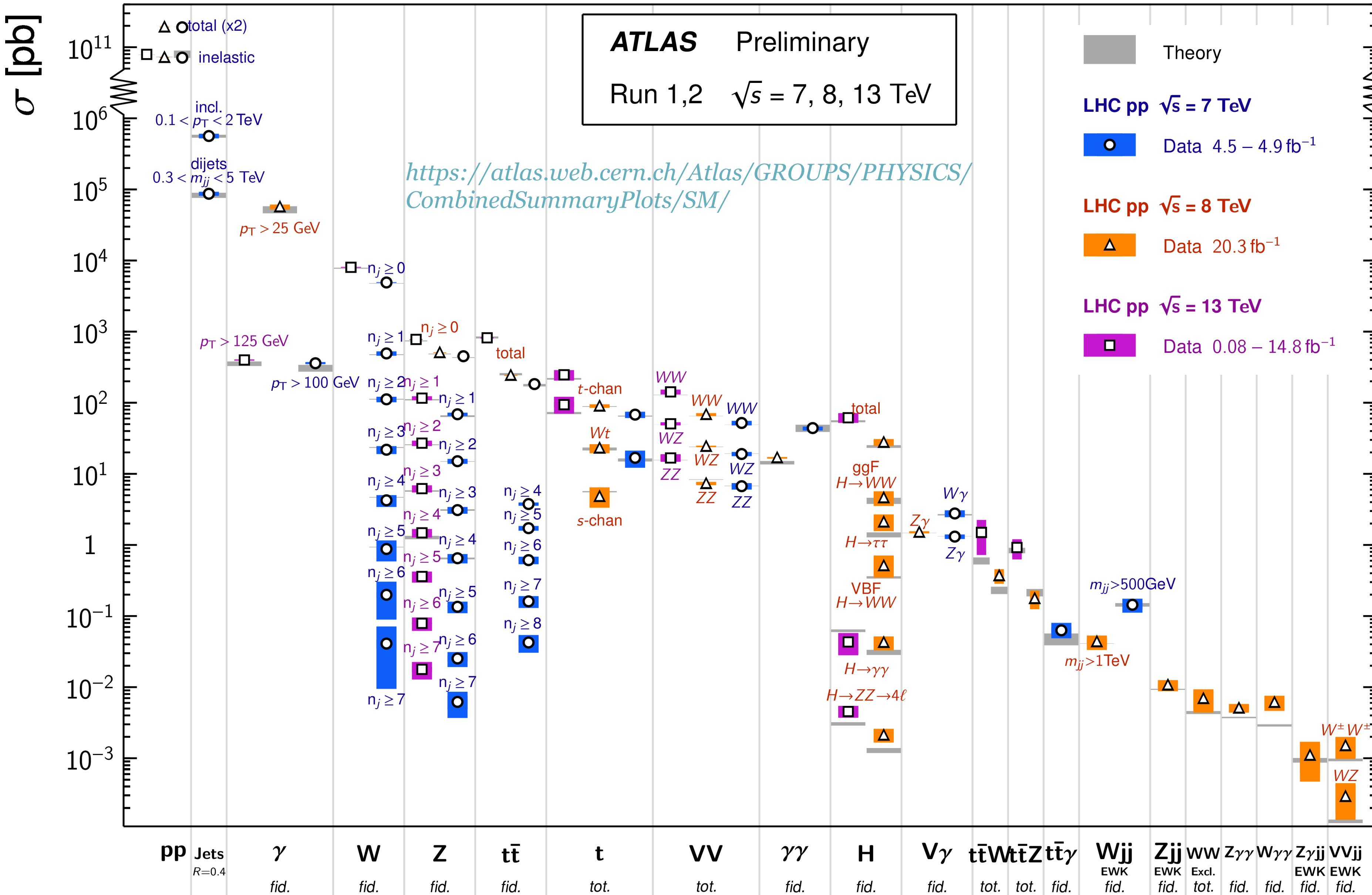




https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2

Standard Model Production Cross Section Measurements

Status: March 2017



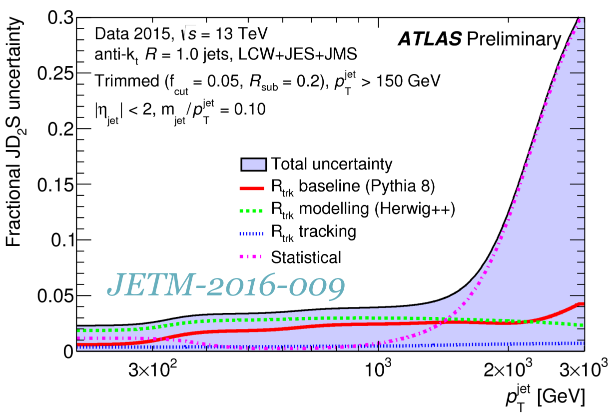
Large-R Jet Uncertainties

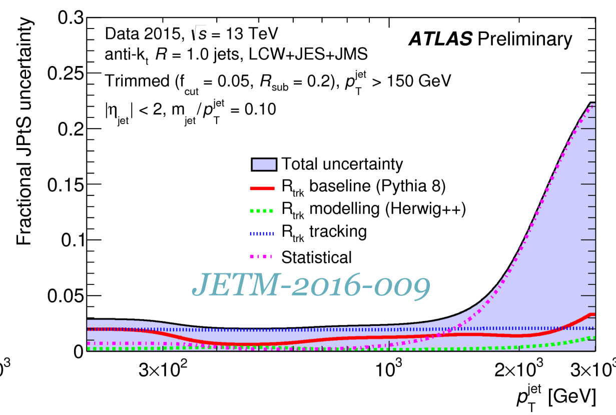
The relative uncertainty is determined using the ratio of calorimeter to track-jet quantities:

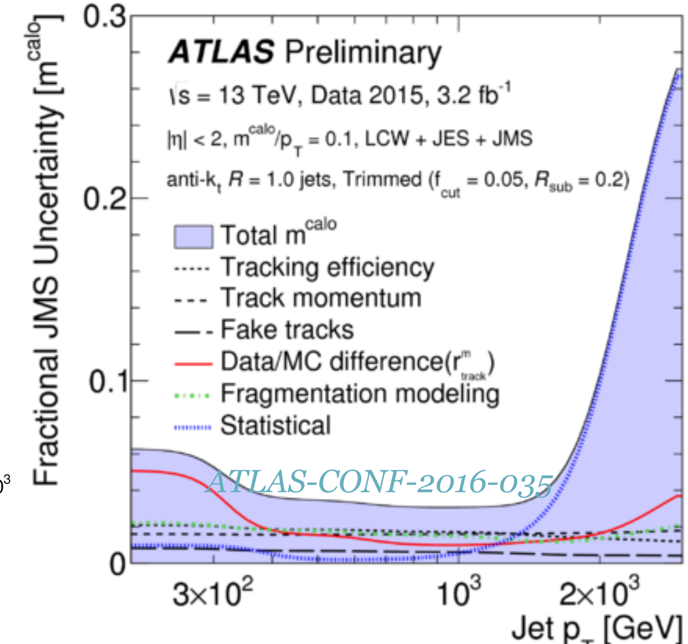
$$r^{p_{\mathrm{T}}}_{\text{track jet}} = \frac{p_{\mathrm{T}}^{\text{jet}}}{p_{\mathrm{T}}^{\text{track jet}}}, \qquad r^{m}_{\text{track jet}} = \frac{m^{\text{jet}}}{m^{\text{track jet}}}$$

Double ratios are constructed :
$$R^{p_{\mathrm{T}}}_{r\ \text{track jet}} = \frac{r^{p_{\mathrm{T}},\text{data}}_{\text{track jet}}}{r^{p_{\mathrm{T}},\text{MC}}_{\text{track jet}}}, \qquad R^{m}_{r\ \text{track jet}} = \frac{r^{m,\text{data}}_{\text{track jet}}}{r^{m,\text{MC}}_{\text{track jet}}}$$

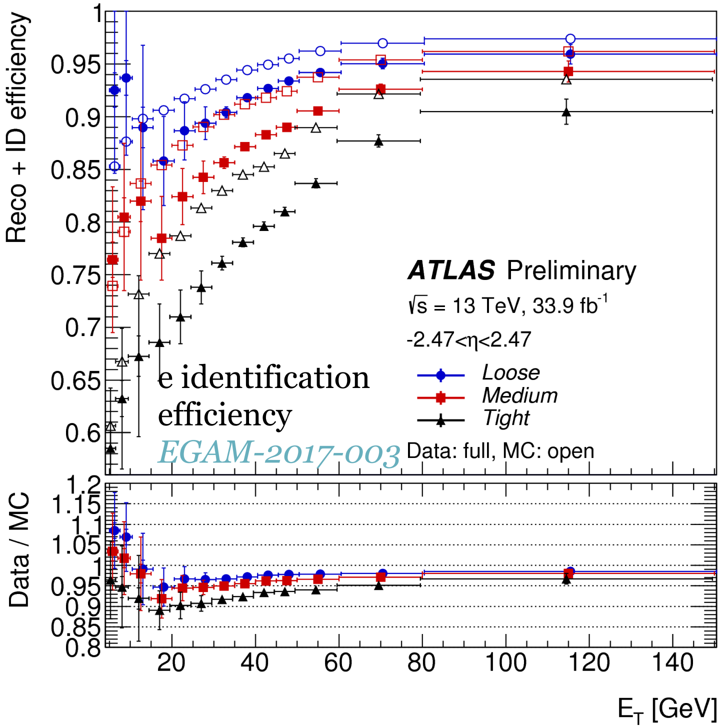
<u>Uncertainties</u>:
- **Baseline**: *difference between data and MC*
- **Modeling**: *difference between MC generators*
- **Tracking**: *related to track reconstruction efficiency, impact parameter resolution, track momentum calibration and reconstruction of fake tracks*





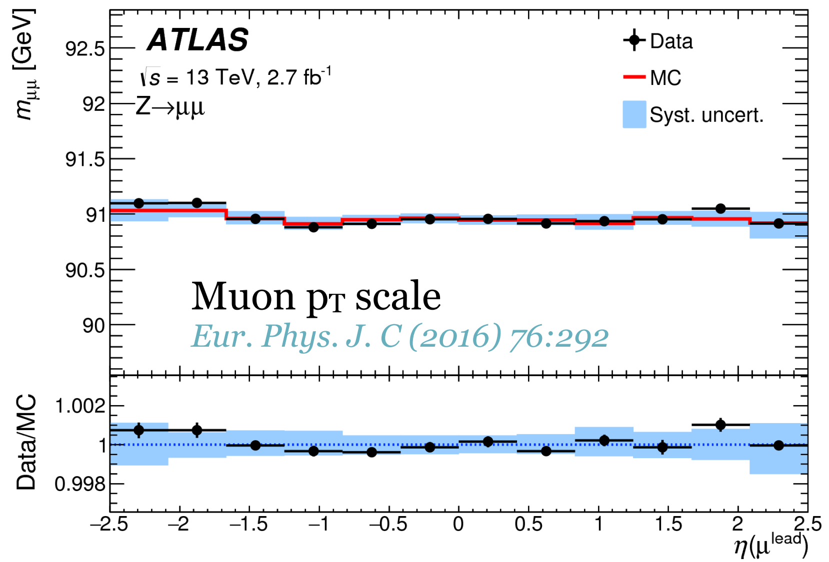


Performance @13 TeV



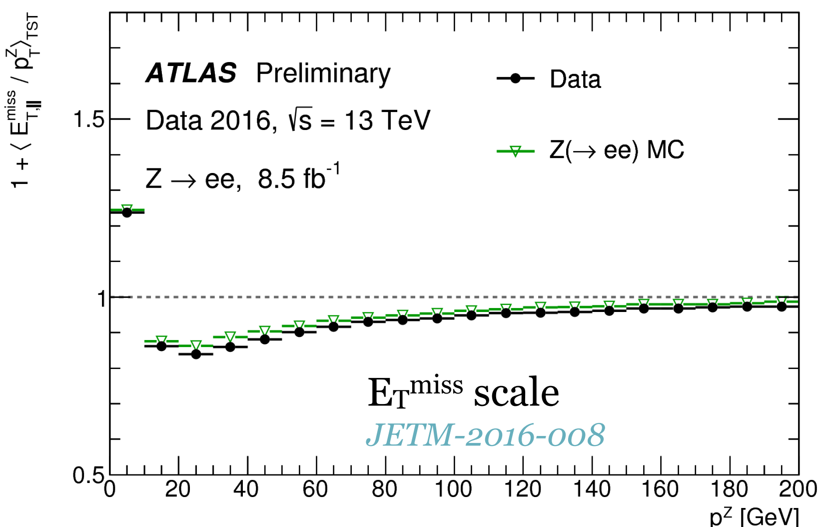
e identification efficiency

EGAM-2017-003



Muon p_T scale

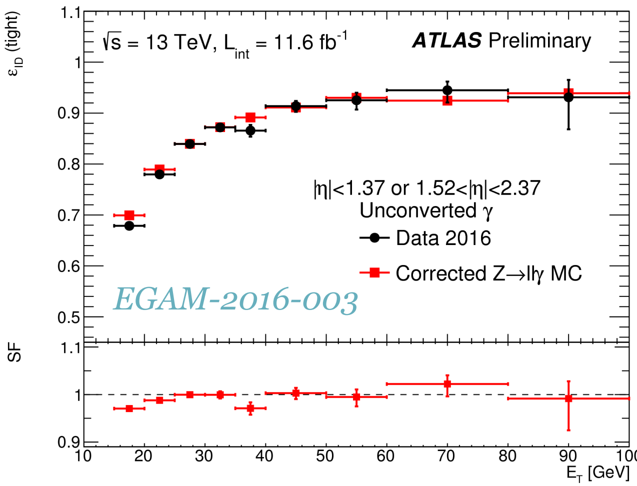
Eur. Phys. J. C (2016) 76:292

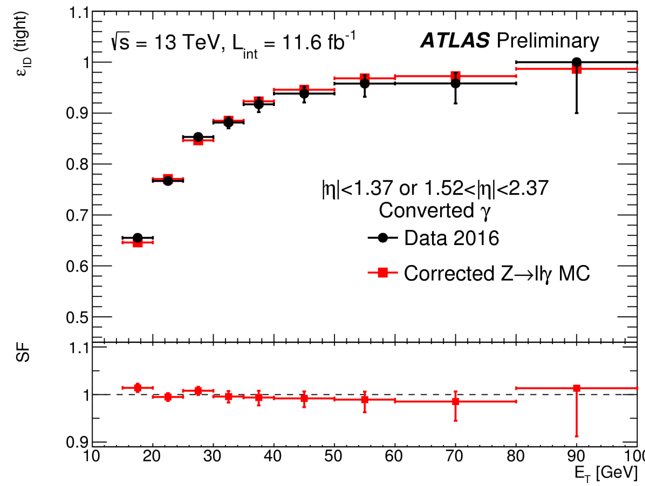


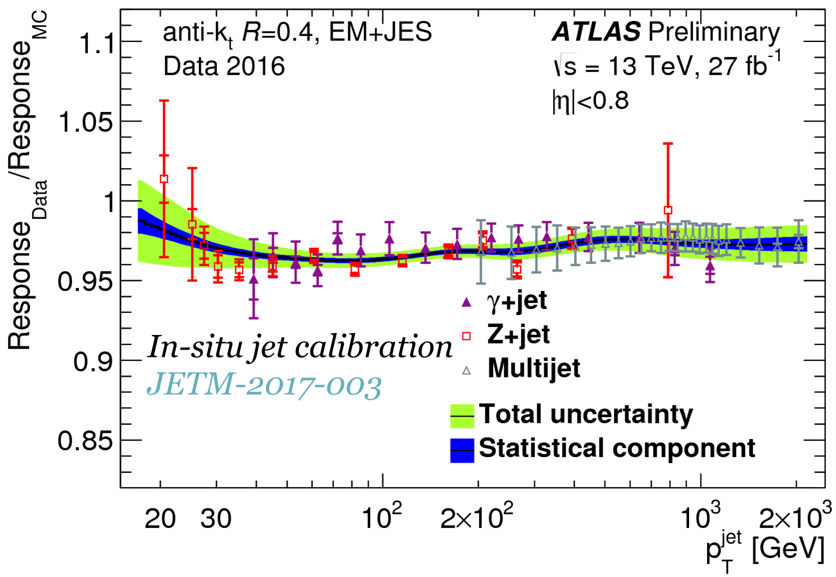
E_T^{miss} scale

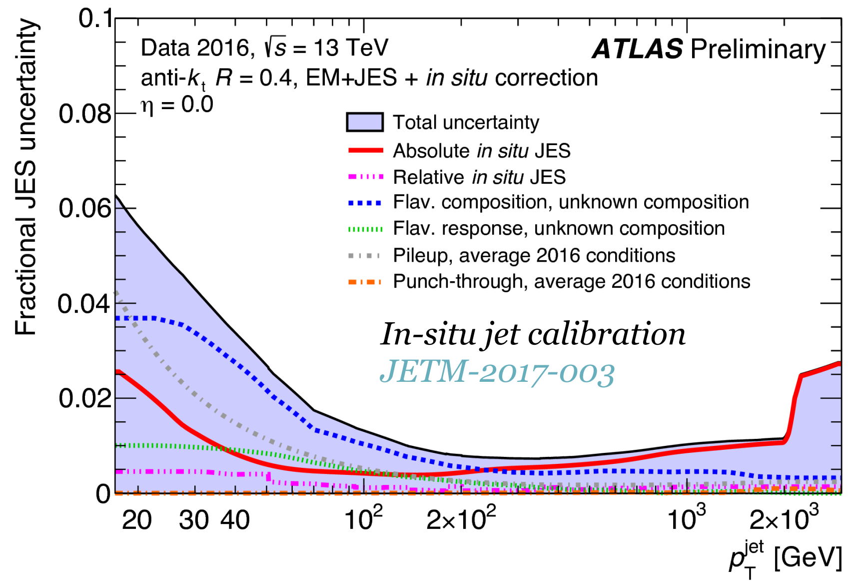
JETM-2016-008

Performance @13 TeV









Additional VV Plots