Search for new physics: Diboson resonance searches in ATLAS Run-2

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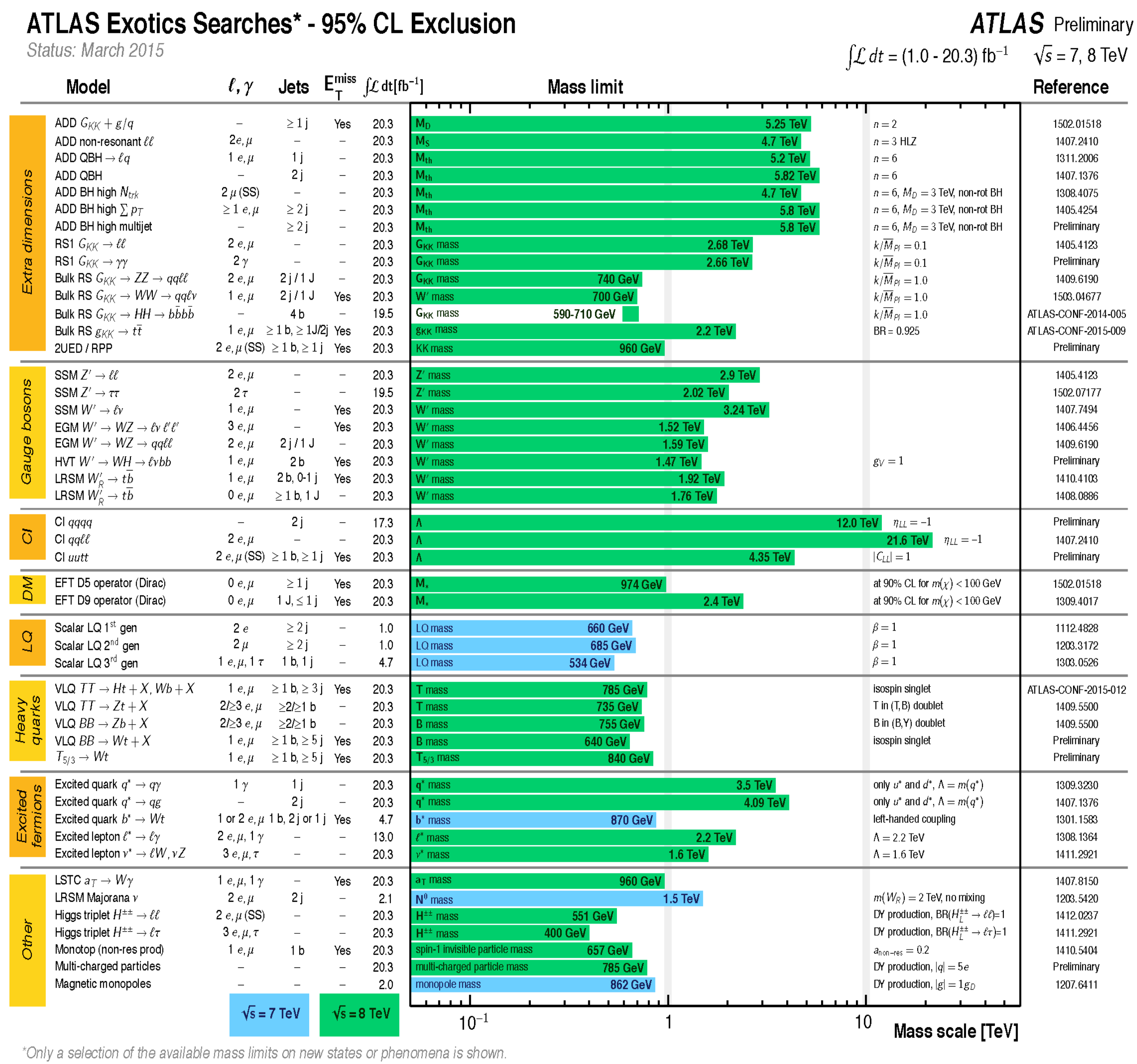
Outline

- Motivation
- Reconstruction techniques for high mass resonances
- Recent Run-2 searches results
  - VV resonances
  - VH resonances
  - Vγ resonances
- Conclusions

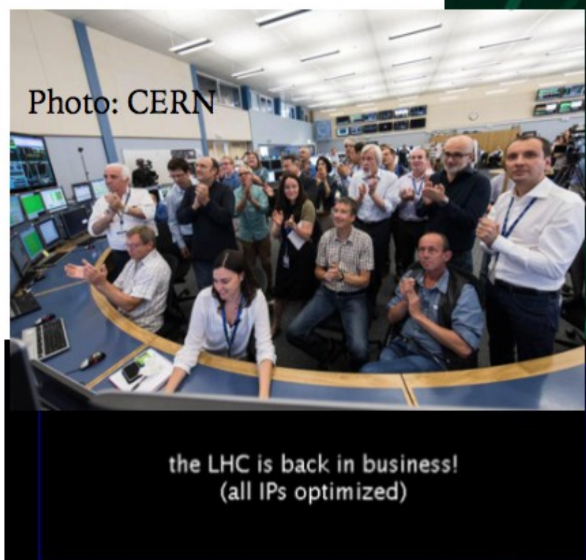
Lessons from Run-1

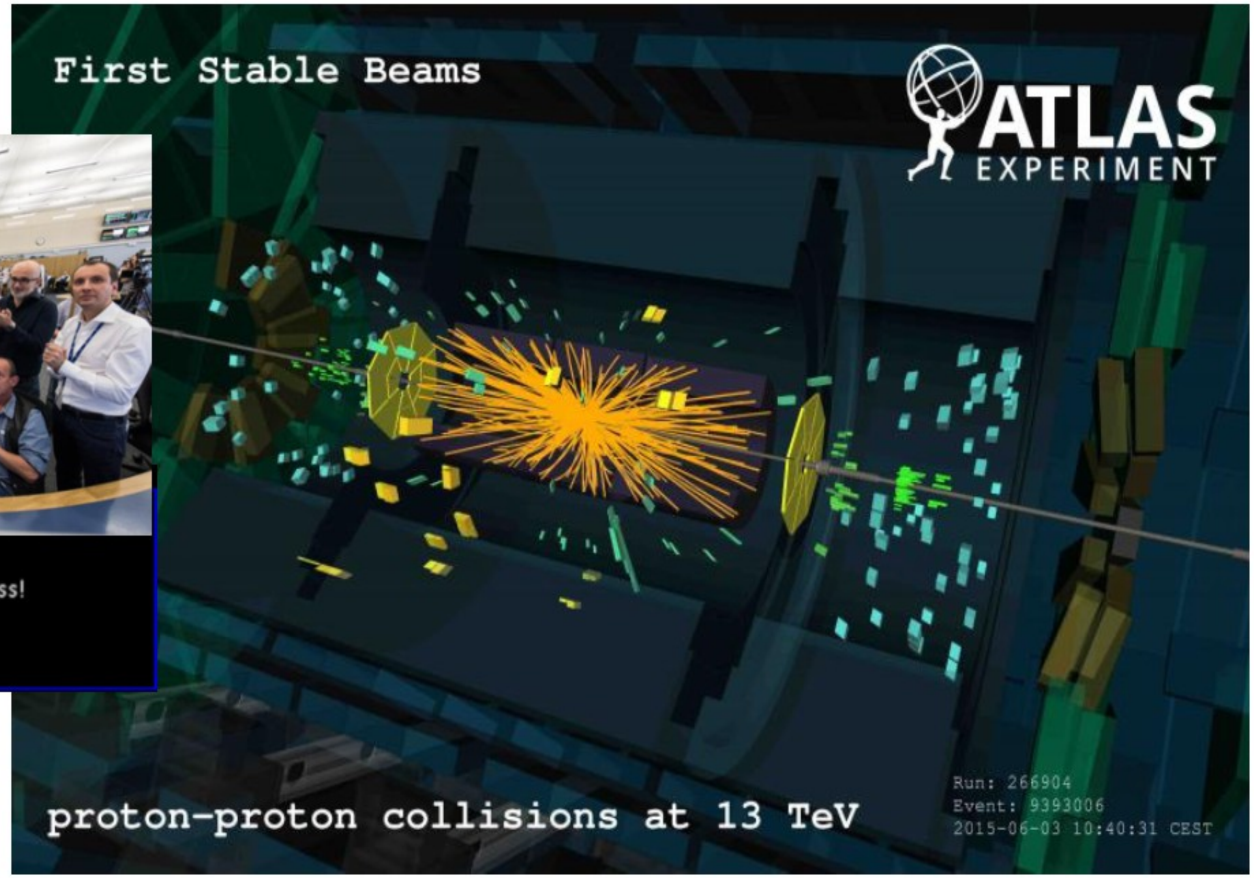
- Detectors performed very well in challenging LHC environment
- A Higgs boson was discovered with less luminosity and half the energy
- Remeasuring the Standard Model (SM)
- Nothing beyond the SM yet (not significant ones at least)



LHC Run-2 started in 2015

LHC proton-proton collisions restarted in June 2015 at **13 TeV**



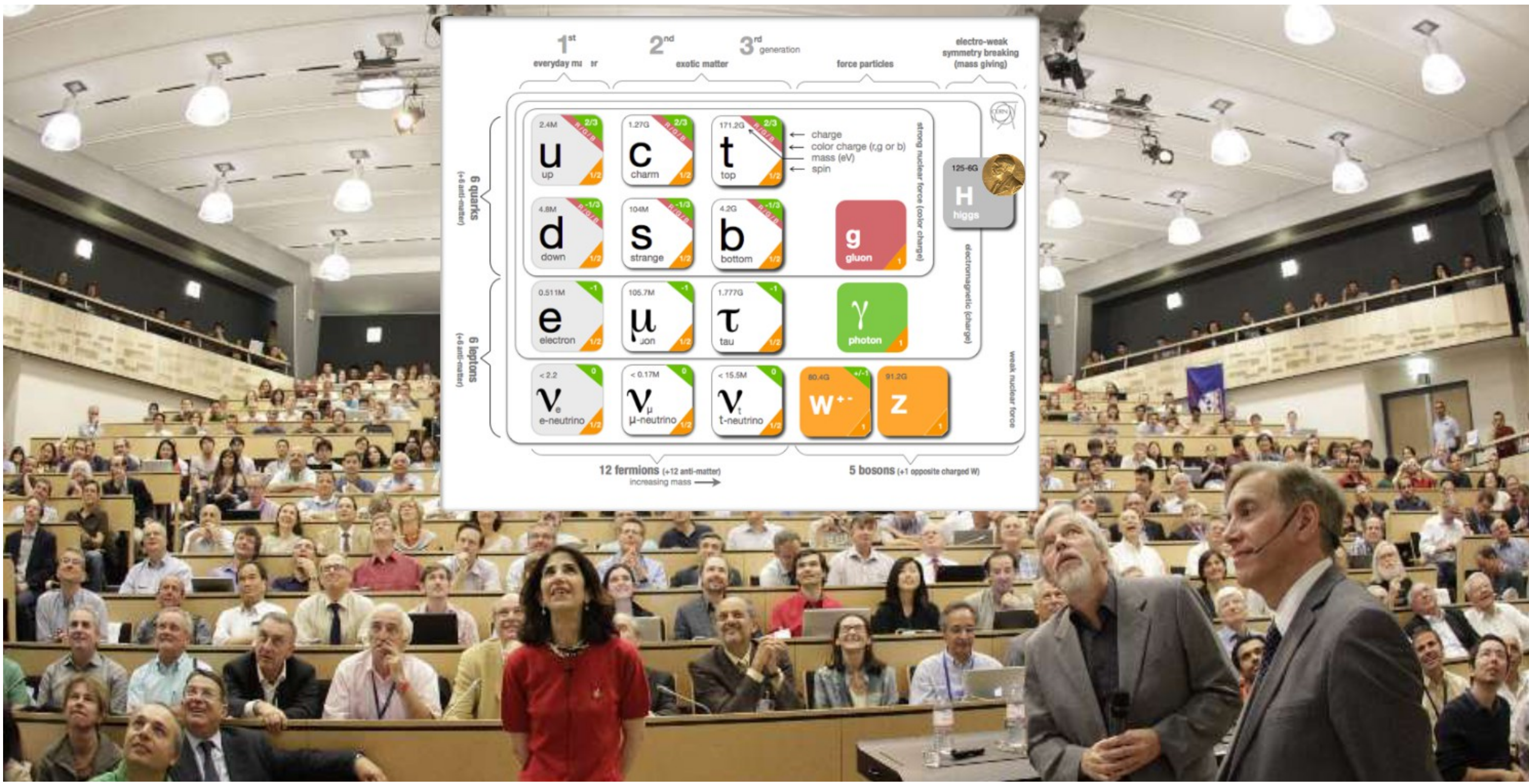


Thanks to the LHC team!

- ATLAS program for Run-2?
  - Is this boson the Higgs boson?
  - Increase precision in SM measurements
  - **Push searches BSM further**

Discovery of the Higgs boson

Guided by ***clues*** from the SM of particle physics



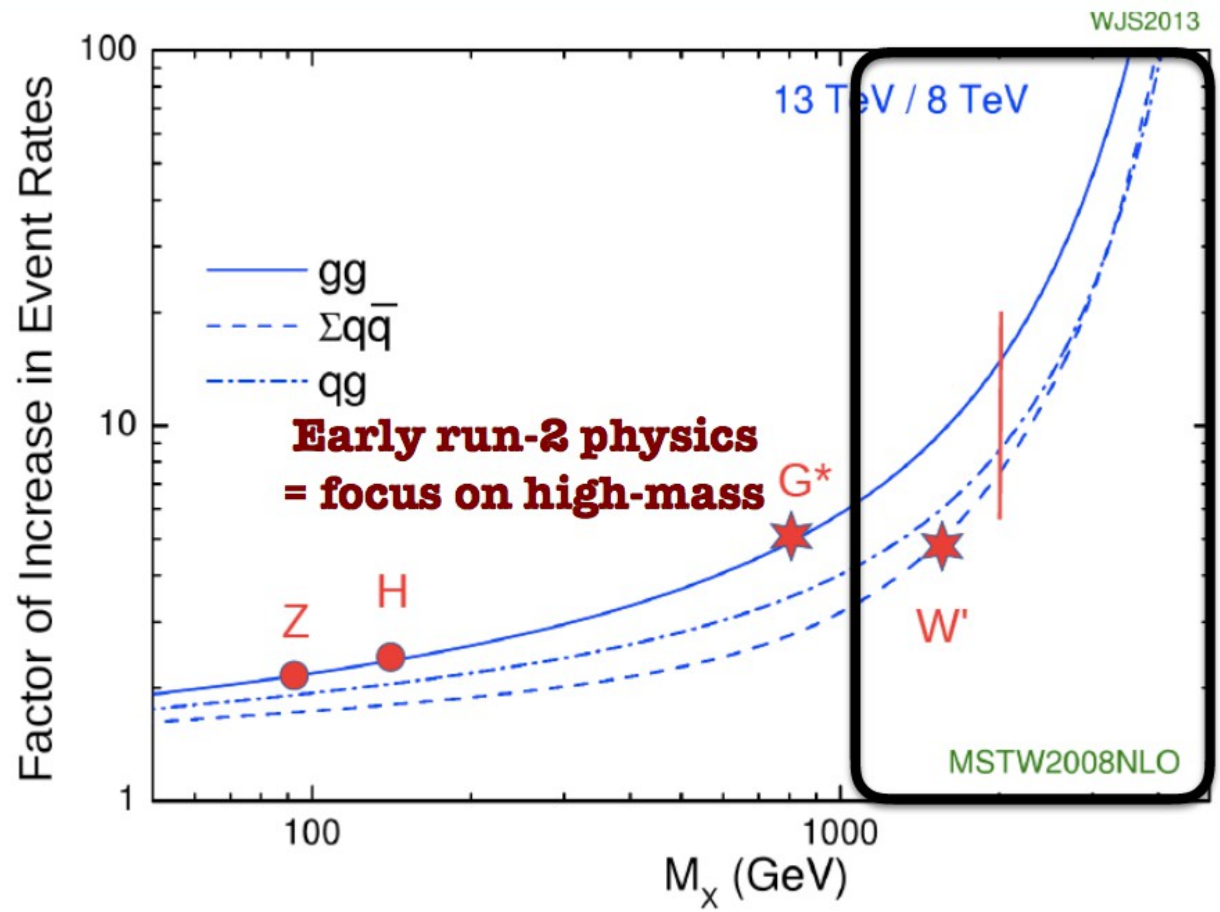
Where to look for new physics in Run-2?

- Everywhere starting with high masses

- Increase of energy → Increase of reach for new phenomena

- Example: production rate of a W' with a mass of 2 TeV increased by 5x times from Run-1 to Run-2
  - You already can see where this is going...

- High mass searches are challenging!
  - Usually require revisiting our object reconstruction and analysis techniques



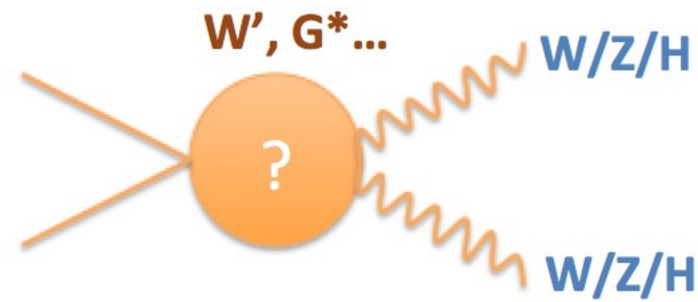
High mass diboson searches are well motivated

- Interactions with pairs of electro-weak bosons are a **fundamental element in electroweak symmetry breaking**

- These interaction played a key role in the **Higgs boson discovery in Run-1**

- The high mass is **particularly sensitive** to a wide range of **BSM physics models**

- **Diboson searches important in general**

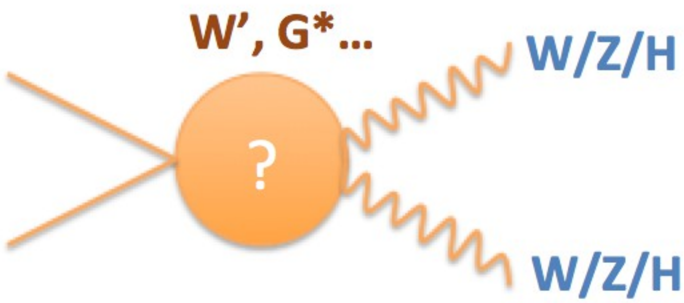


- ✔ Clear signature in detector
- ✔ Known properties and decay kinematics

High mass diboson searches are well motivated

- **Several theories predict the existence of new heavy resonance coupling to W/Z/Higgs**
  - Extra dimensions, compositness, GUT

- Resonance benchmarks you will hear about in this talk
  - Spin 0 **Higgs-like scalar** singlet
  - Spin-1 **HVT** (simplified Lagrangian)
    - *Model A:* Stronger constraints from leptonic searches
    - *Model B:* Enhanced couplings to dibosons
  - Spin-2 **Randram Sundrum graviton (RGS)**

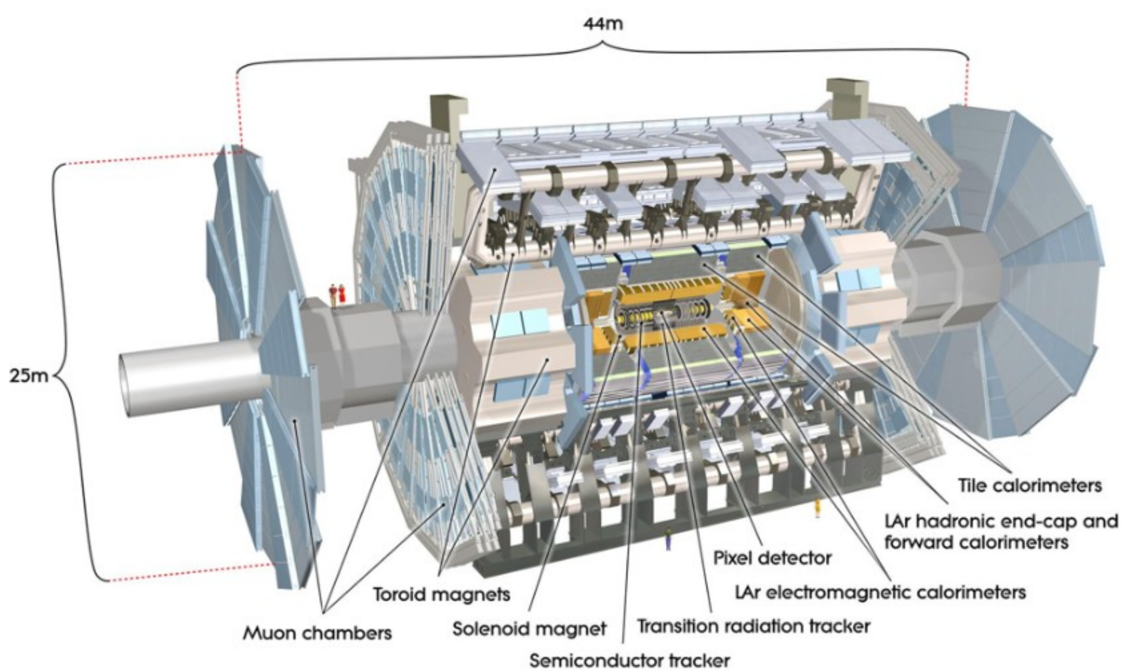


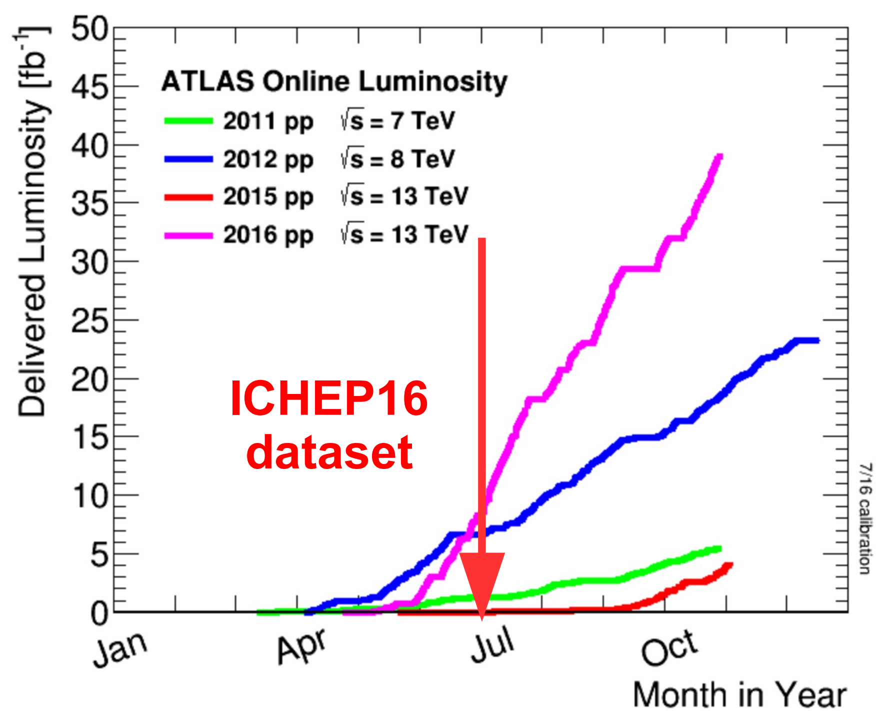
- Clear signature in detector
- Known properties and decay kinematics

	WW	WZ	ZZ	VH
HVT	Z'	W'		Z'/W'
Gravi	RSG		RSG	
Scalar	Scalar		Scalar	

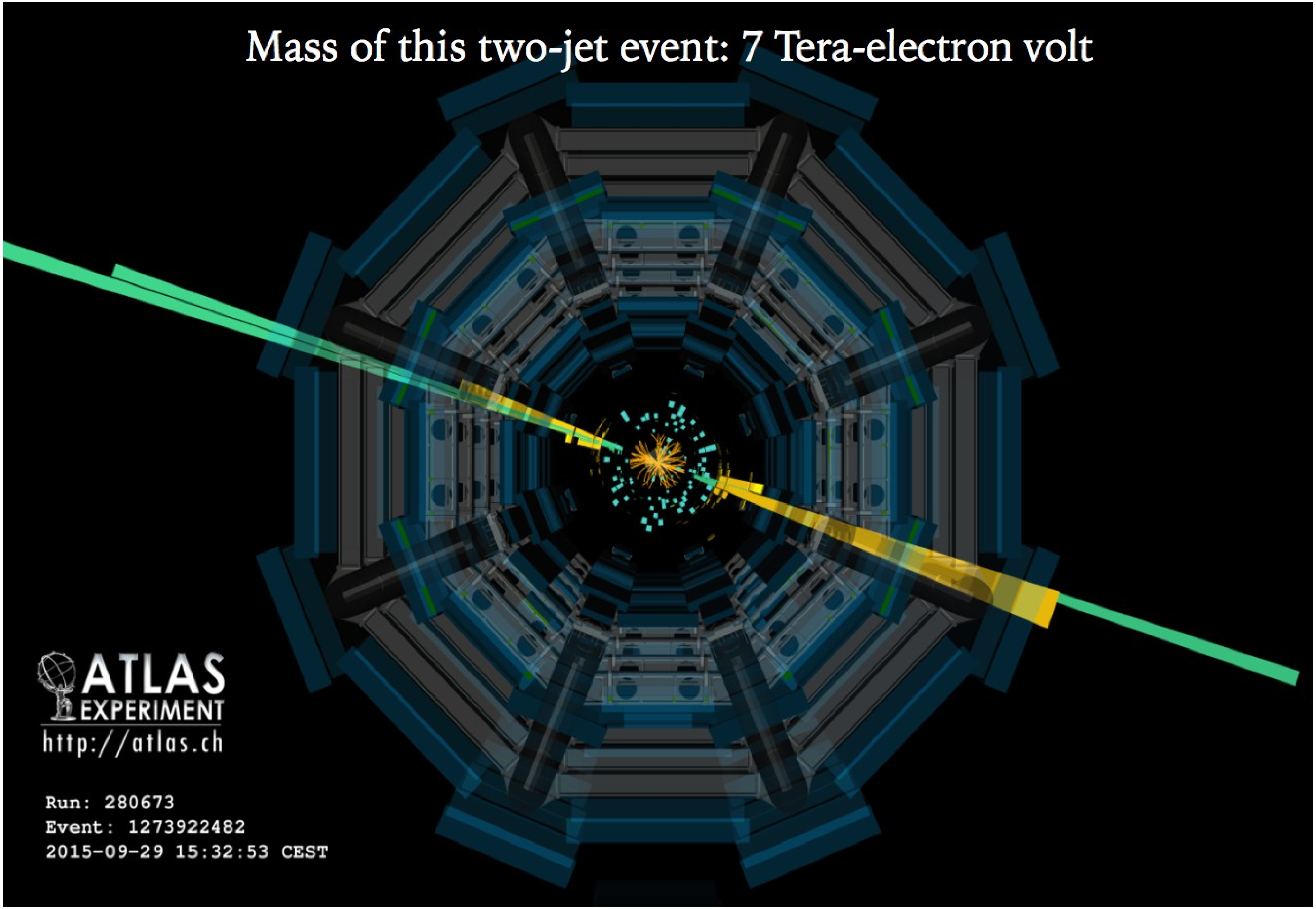
LHC Run-2 started in 2015

- Up to the summer 2016 **~15/fb of 25 ns data good for physics**
- Data quality efficiency ~**92%**
- Smooth running and excellent trigger performance!
  - >96% working channels (pixels, cells, …) in each sub-detector



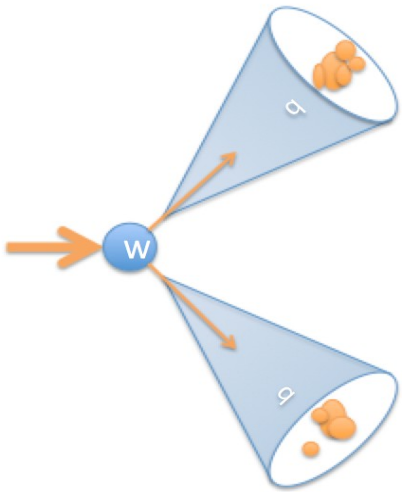


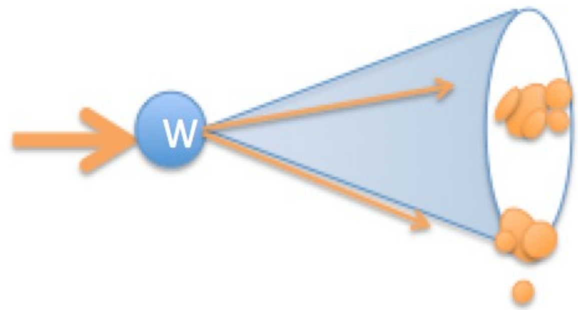
Reconstructing boosted bosons
Traditional jet algorithms



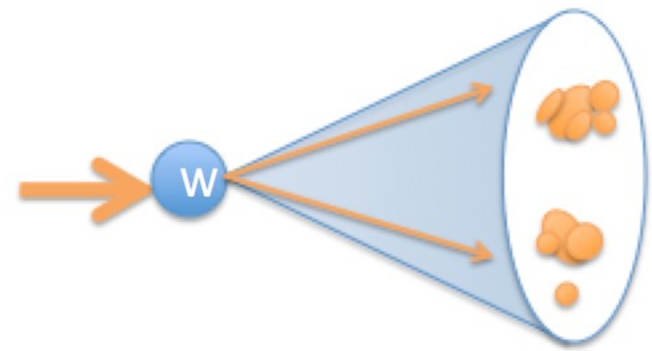
Reconstructing boosted bosons

Resolved regime	**Merged regime**





Standard algorithms
Small-R jets (default R~0.4)



"New" algorithms
Large-R jets

- In the boosted regime the decay products are collimated in the direction of the initial particle

- Rule of thumb for angular separation of decay products

$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} \approx \frac{2m}{p_{\mathrm{T}}}$$

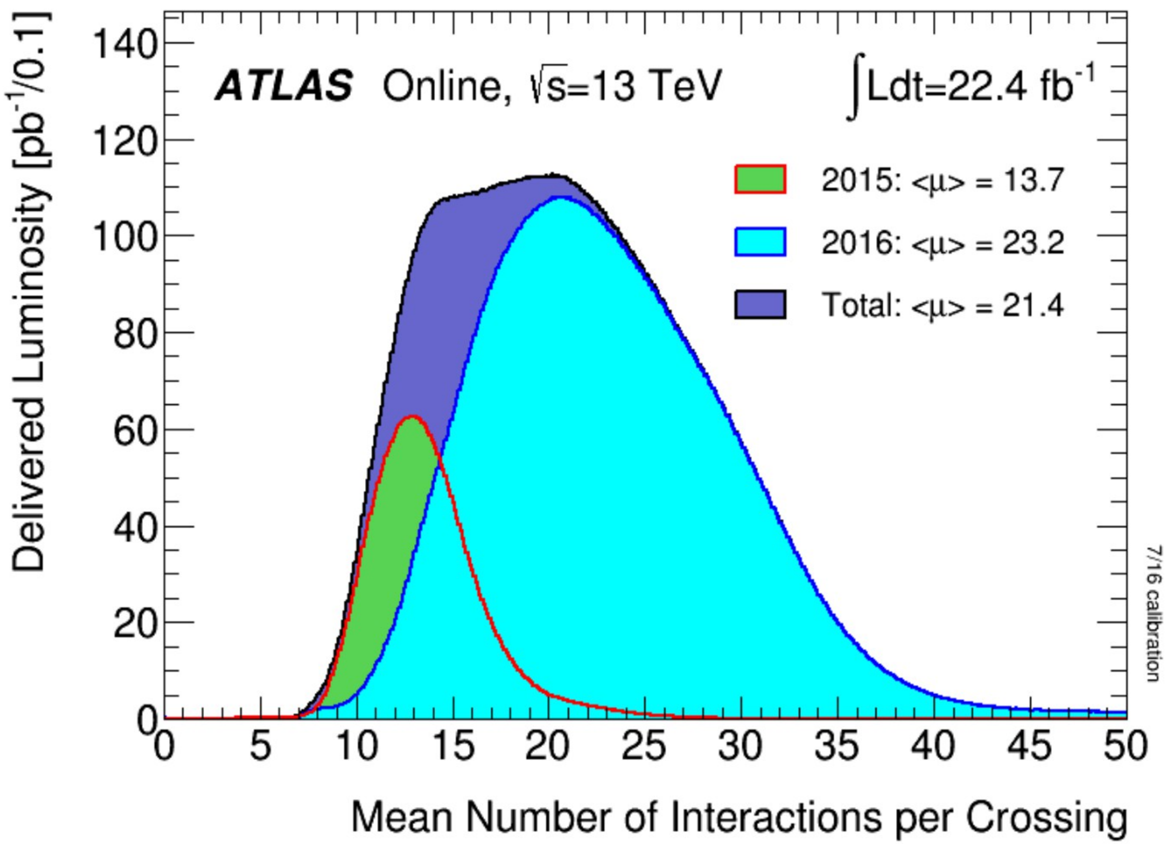
A *W* boson with p_T~200 GeV, ΔR=0.8

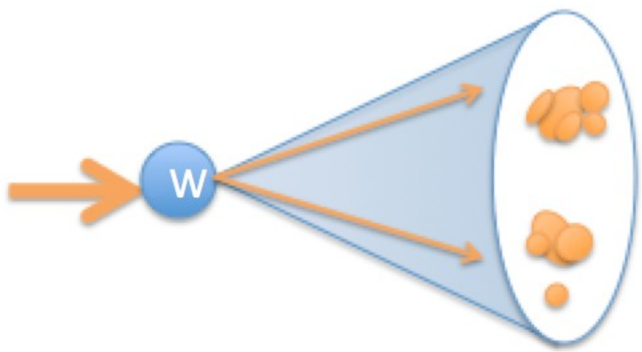
- From a practical point of view this means:

  - Hadronic decay products merge into a single jet
  - Leptons close to (or even) inside jets
    - (need to modify lepton isolation criteria)
  - At very high p_T the calorimeter granularity is a limitation

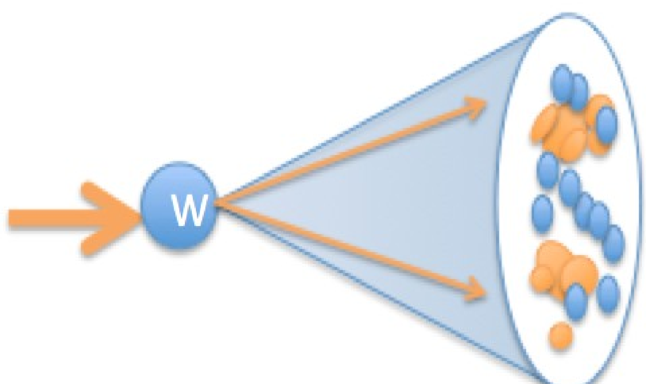
Reconstructing boosted bosons

Pile-up conditions make this task more challenging





Without pile-up



With pile-up

BooBo/top tagging: what do we need?

Fat jets

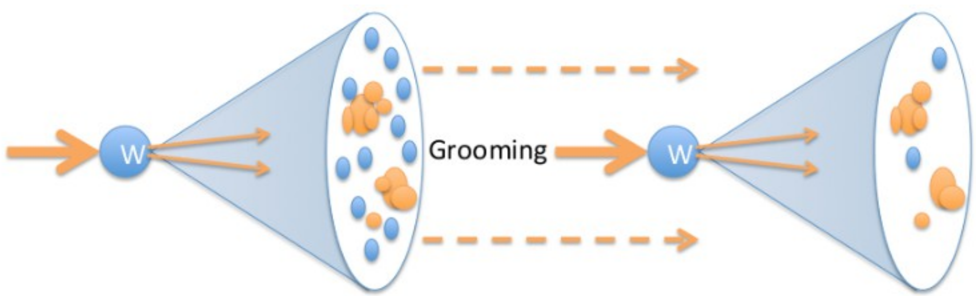
Large distance parameter to pick up all radiation from original decay

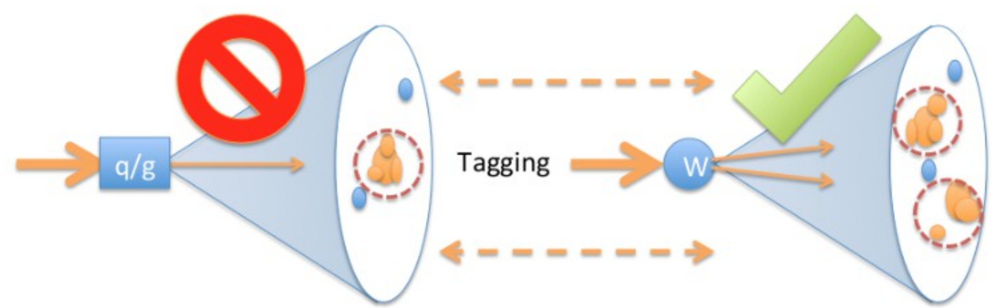
Grooming

- Remove soft comp. PU+UE
- Increase separation between signal and background
- Improve resolution of the signal mass peak

Tagger: substructure

Observables to characterize the underlying jet substructure, i.e. jet mass, momentum balance between subjets, track multiplicity



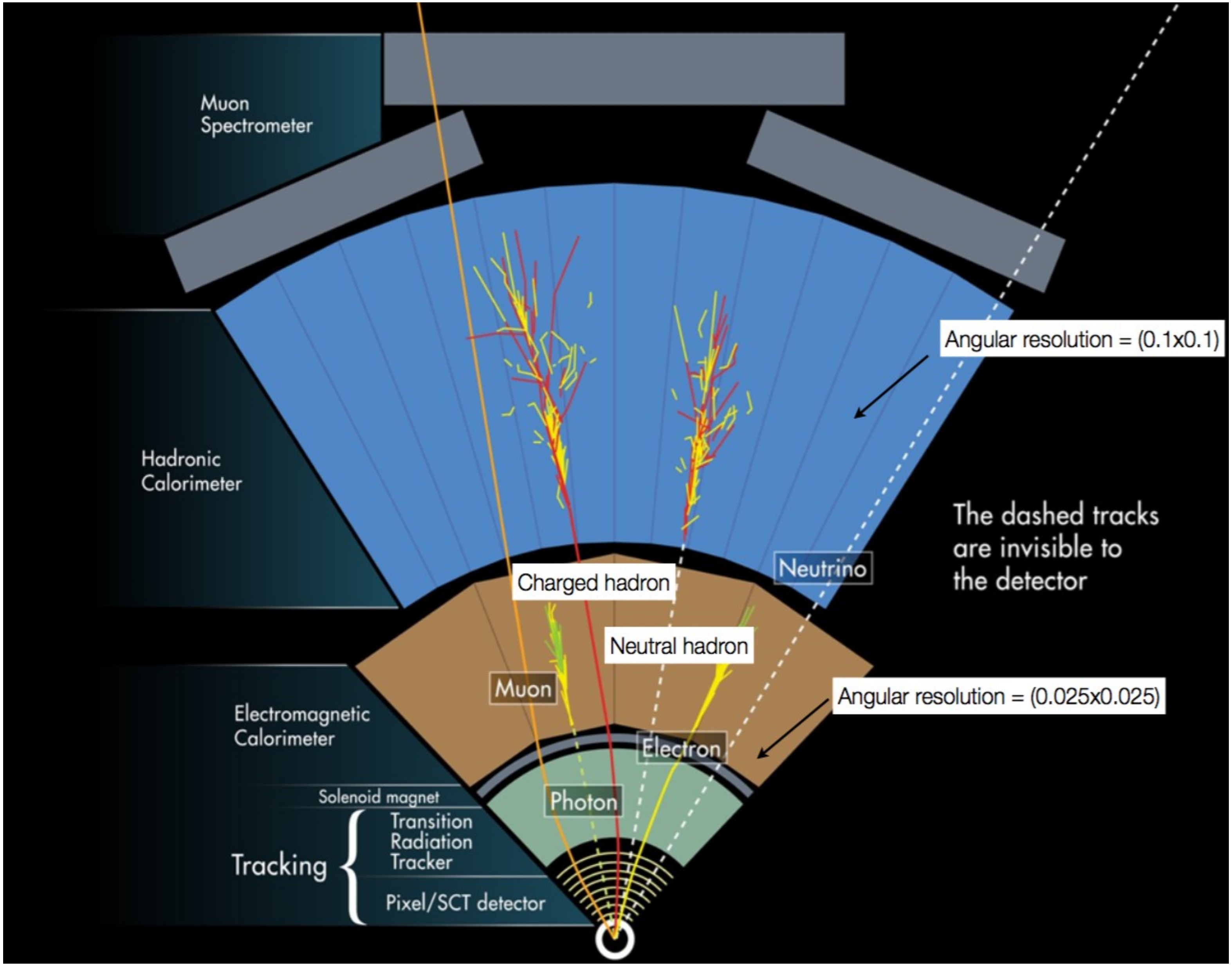


B-tagging

- H→bb, Z→bb
- For obvious reasons
- Standard algorithms not adapted for dense environments

Cartoons by A. Martyniuk

ATLAS calorimetry



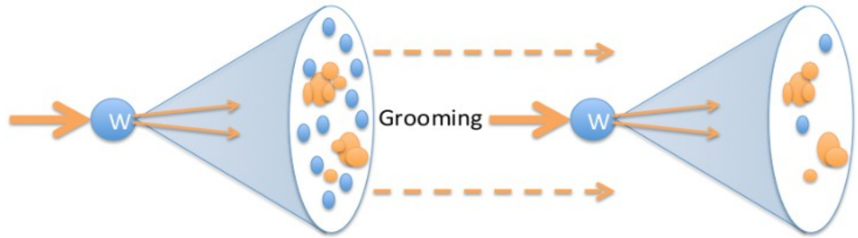
Good resolution to pick apart the large-R jets and look at its substructure

Grooming techniques

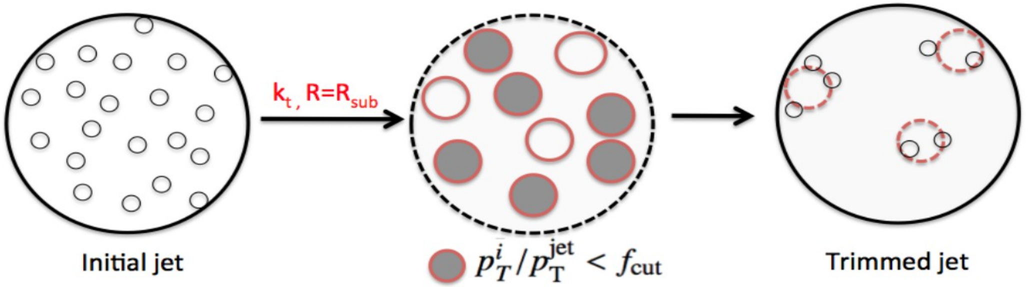
Grooming

Remove soft comp. PU+UE

- Trimming [arXiv:0912.1342]
- Filtering [arXiv:0802.2470]
- Pruning [arXiv:0903.5081]
- Soft-drop [arXiv:1402.2657]



arXiv:1306.4945



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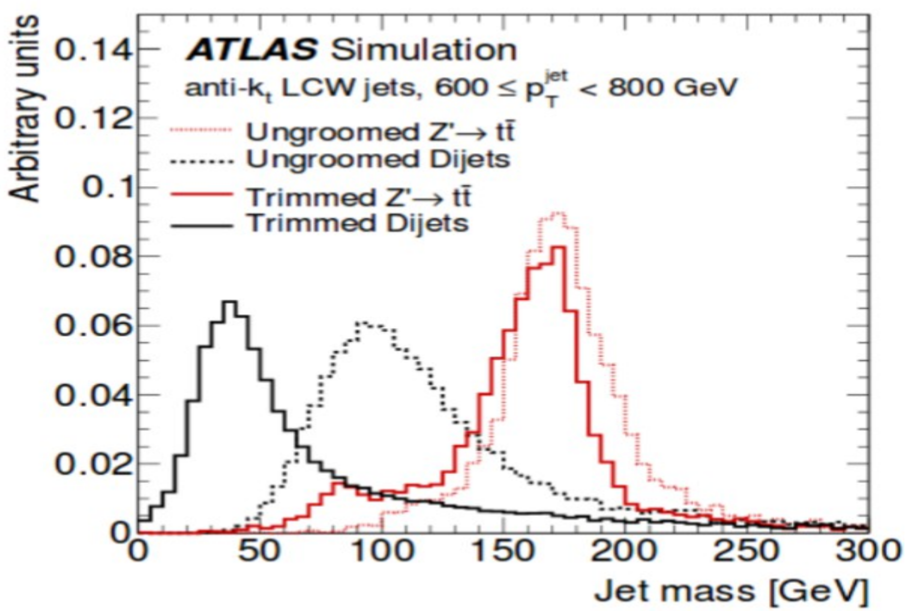

Trimming:

- Reclustering of constituents of large-R jet into small-R jets of size R_{sub}
- Remove subjet *i* if $p_T^i < f_{cut} \times p_T^{jet}$
- **Default ATLAs groomer (stable against PU)**

Jet variables for tagging

Again…can not cover all! Some of them strongly linear correlated

Mass

- Deduced from 4-momentum sum of all jet constituents
- Expected to be small for QCD jets, but closer to the boson/top mass for signal jets

N-subjettiness (*JHEP 03 (2011) 015*)

- Measure of how N or less "subjet"-like a large-R is

Energy correlation variables (*JHEP 1306 (2013) 108*)

- Energy correlations functions (ECFs) construct a complete representation of the jet by combining the p_T and angular separation of all jet constituents (ECF1), all pairs of jet constituents (ECF2) and triplets (ECF3)

- Ratios of these are powerful in rejecting jets from multi jet processes

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

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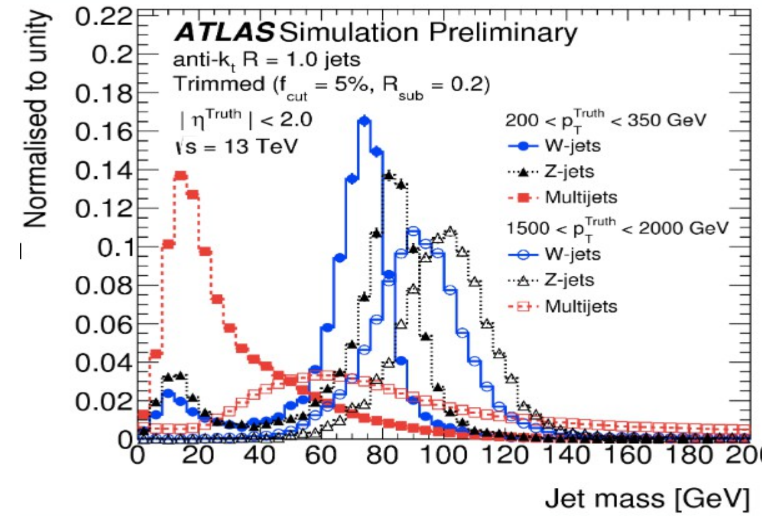
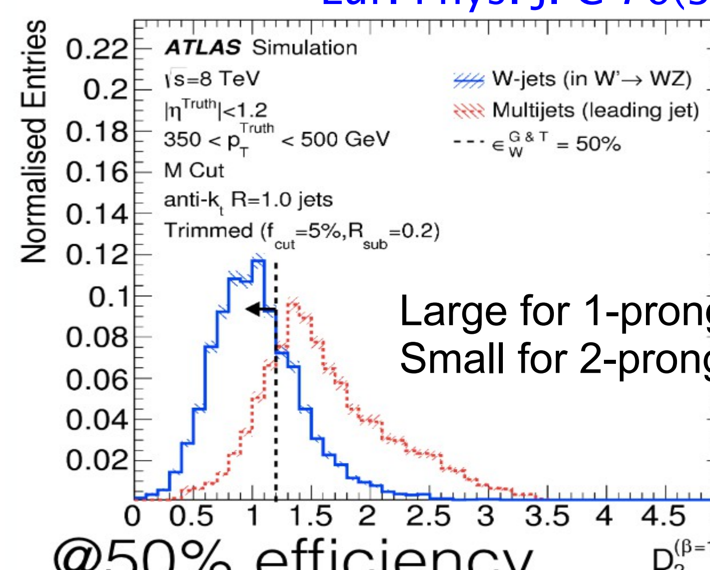


Eur. Phys. J. C 76(3)



Large for 1-prong jet
Small for 2-prong jet

@50% efficiency

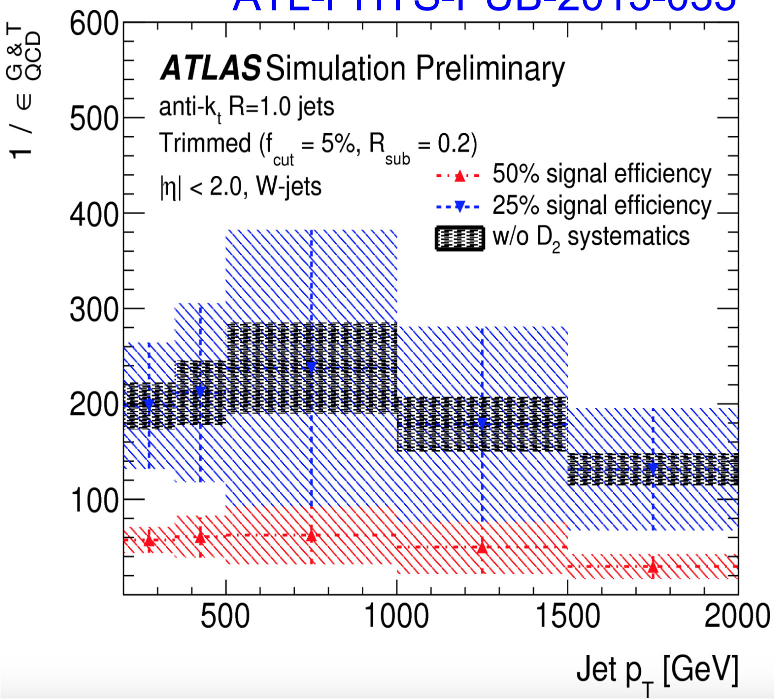
W/Z boson tagging for early Run-2

- **Huge optimization effort** at the end of Run-1: arXiv:1510.05821
- 4 sets of algorithms studied for Run-2, of which this is the most performant:

Mass and energy calibrated anti-kt jets with R = 1.0
Trimmed with fcut = 5% and Rsub = 0.2
Dynamic mass window cut (68%) + p_T dependent D2 cut for jets gives the best rejection (~90%) at 50% signal efficiency

- Uncertainties derived by comparing the measured calorimeter jet energy and mass to the same quantities measured by the tracker in both data and MC, using a double ratio method

ATL-PHYS-PUB-2015-033



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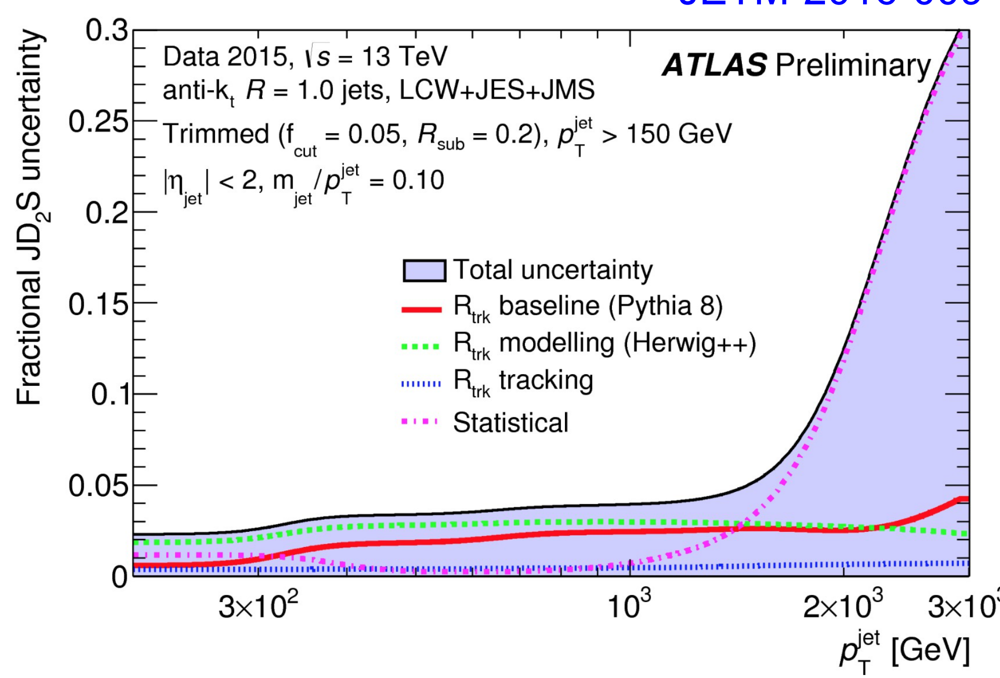
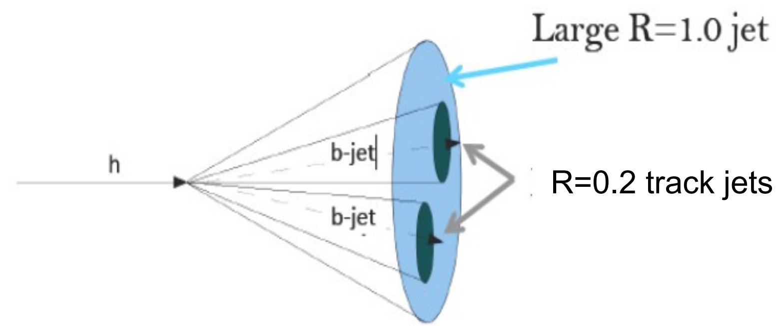


H→bb boson tagging for early Run-2

- **Tag small-radius** (R=0.2) jets made of tracks:
  - Match tracks directly to PV → pileup insensitive
  - Smaller radius jets for close-by b-tagging
  - Better resolution w.r.t. b-hadron direction than calo



Mass and energy calibrated anti-kt jets with R = 1.0
Trimmed with fcut = 5% and Rsub = 0.2
Mass window cut + track-jet b-tagging (MV2c20 70% wp) + p_T dependent D2 cut (optional)

- Uncertainties driven by b-tagging (calibrated in 2015 data using ttbar events)

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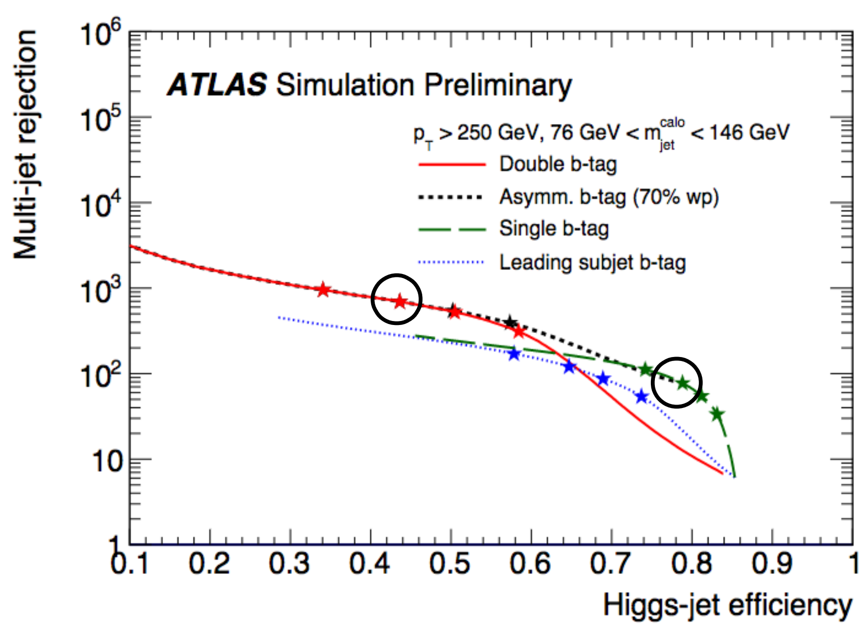

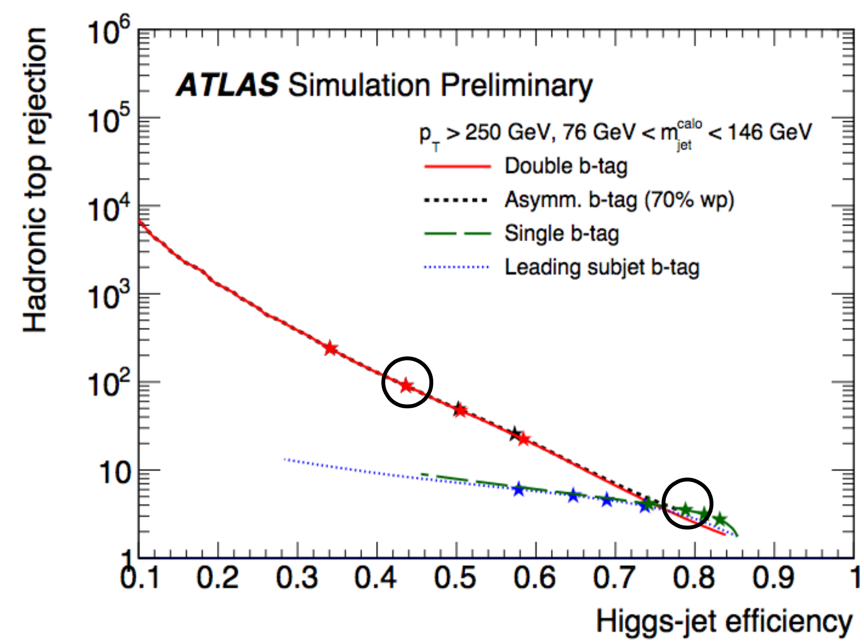

Boosted boson tagging at work

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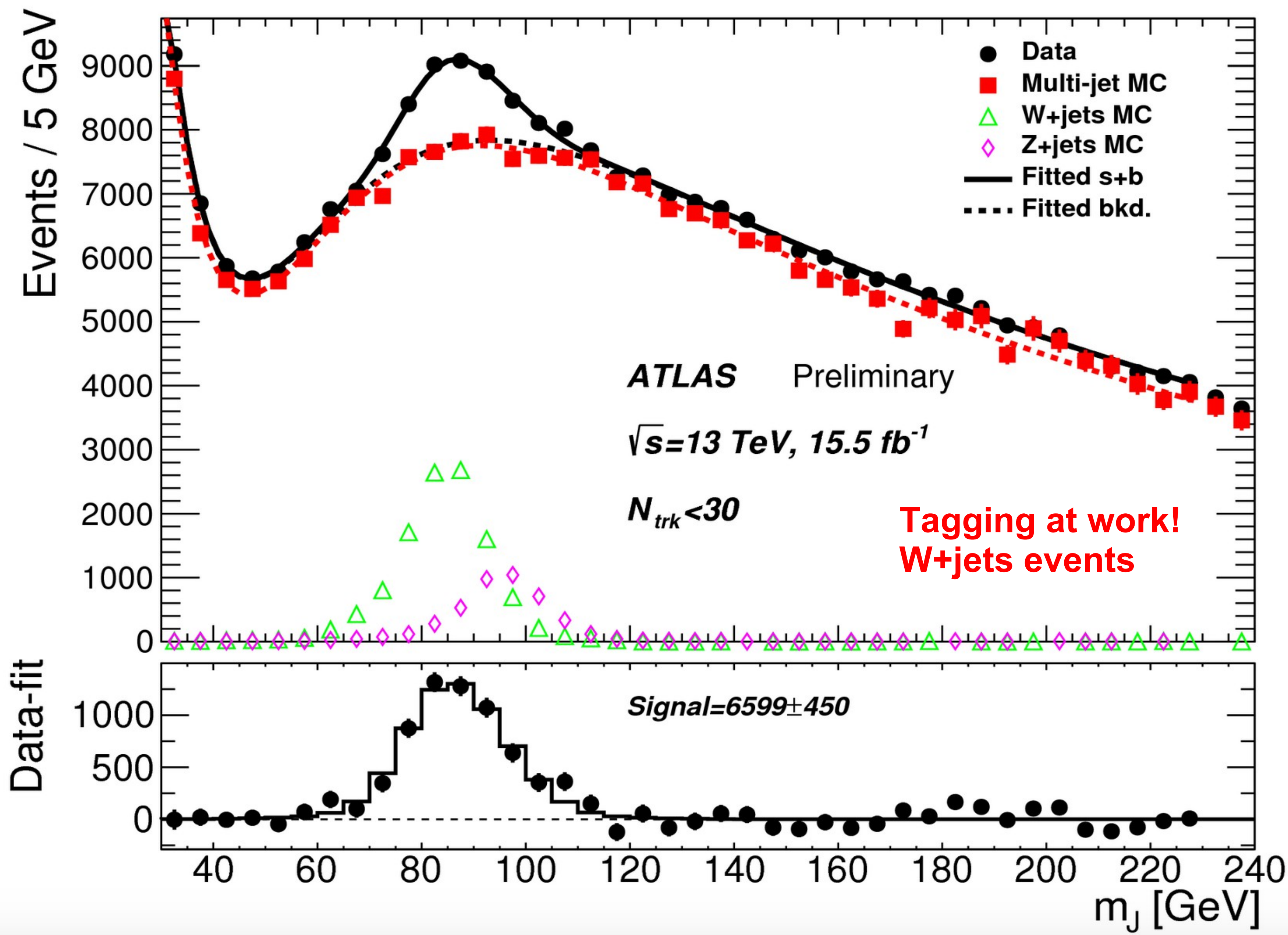
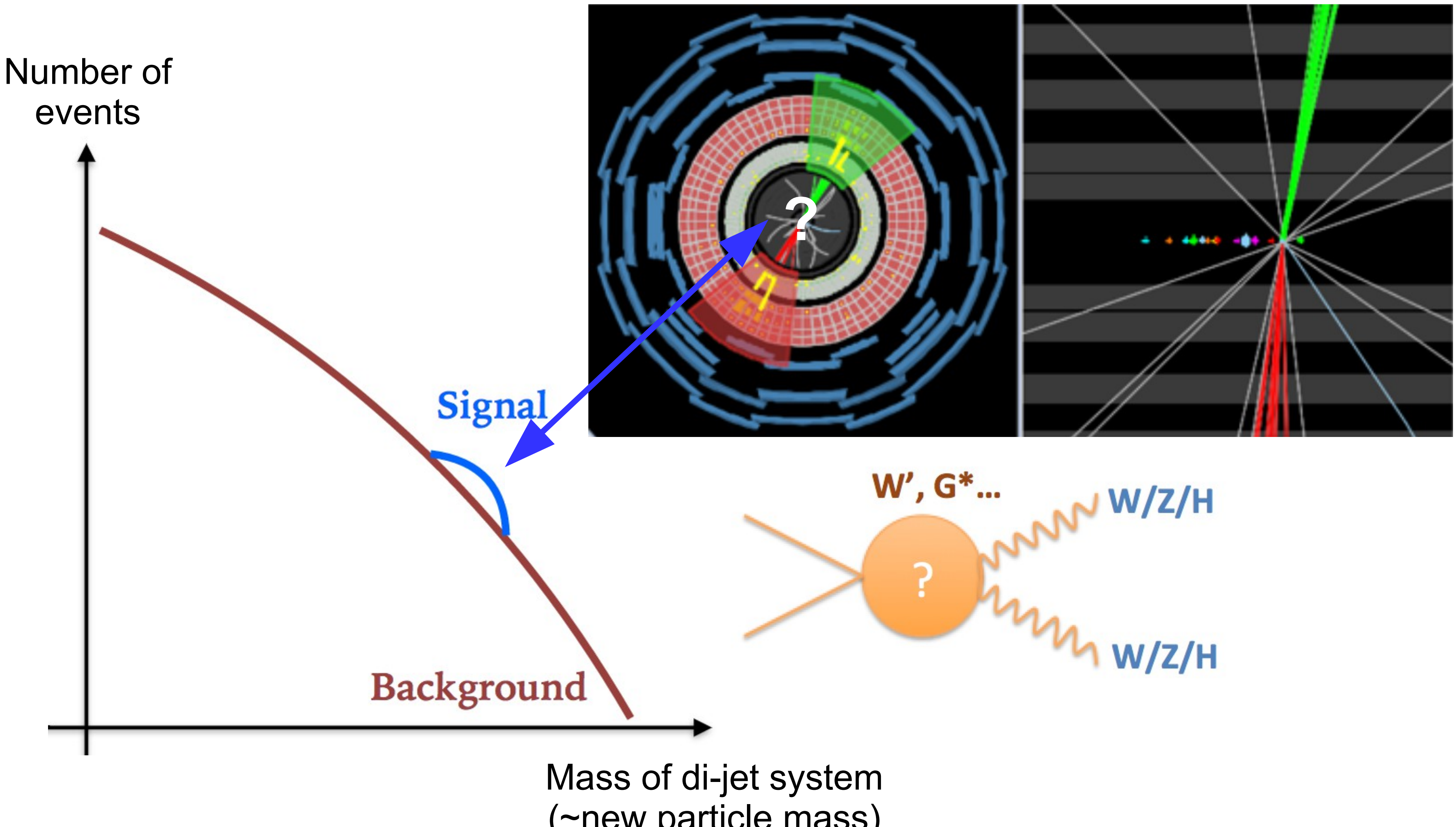


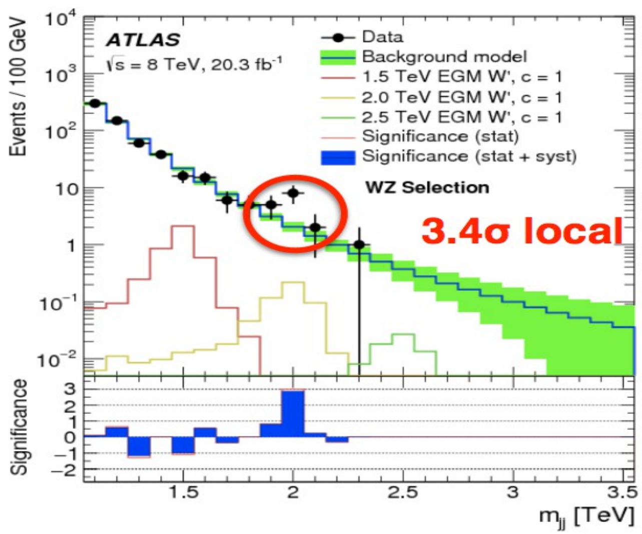
How would new resonances manifest themselves?

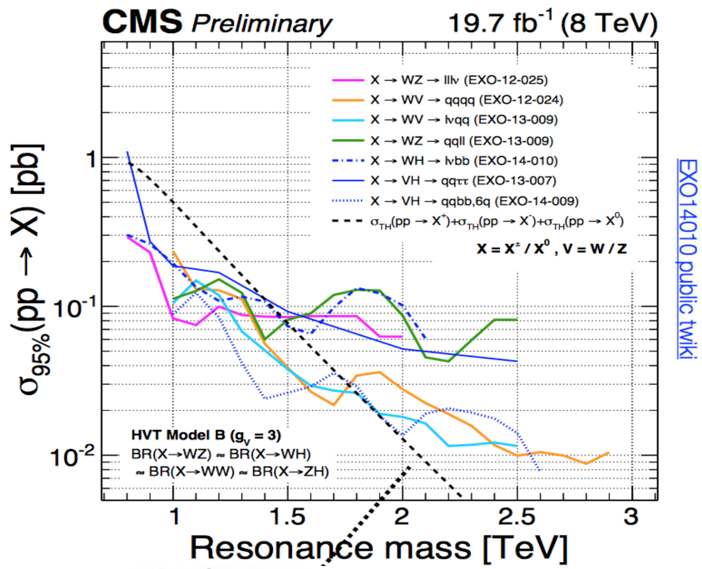
New particles: resonant excess (bump) over Standard Model background

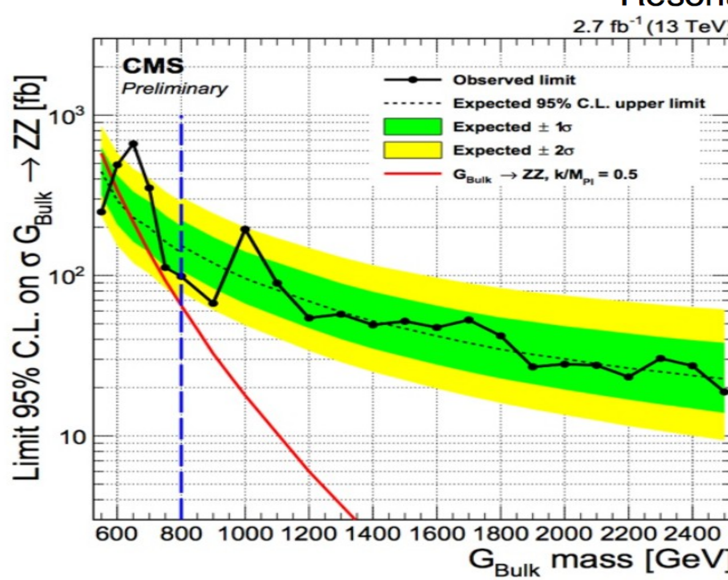


Some extra from Run-1: an analysis you might remember

- Fully hadronic channel observed a 3σ local excess with the Run-1 dataset arXiv:1506.00962v2
  - Not seen by other channels in ATLAS (arXiv:1512.05099)
- CMS observed smaller deviations around 1.9 TeV (EXOT14010) and at 650 GeV ()

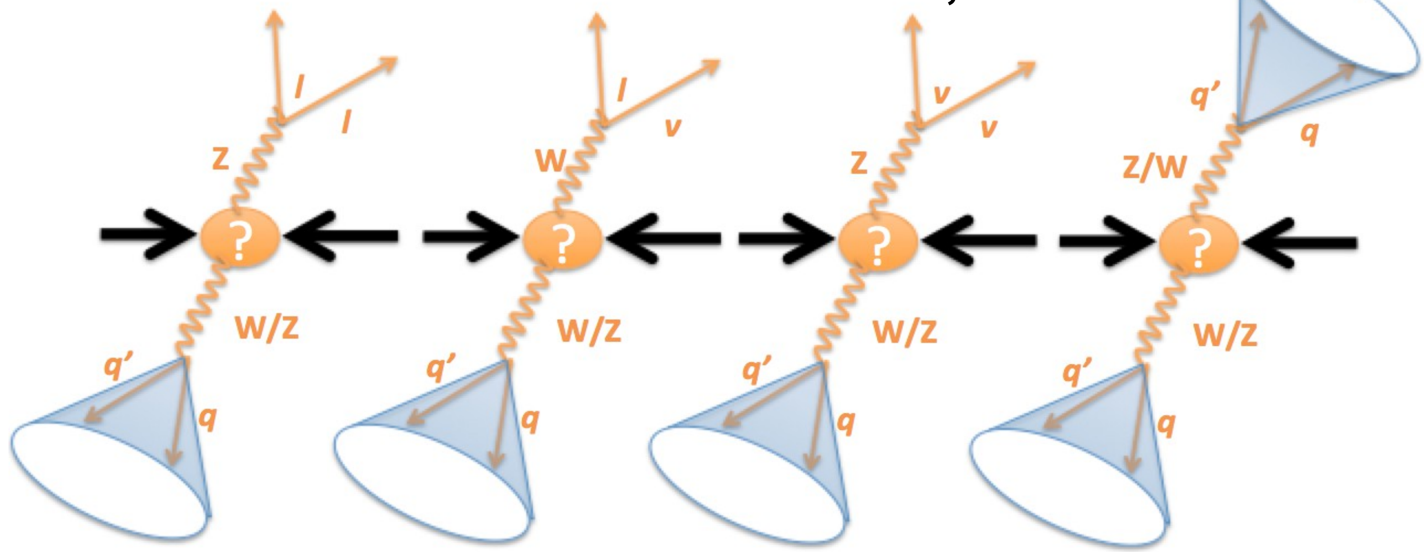






Quick review of the results

VV searches with V=Z,W



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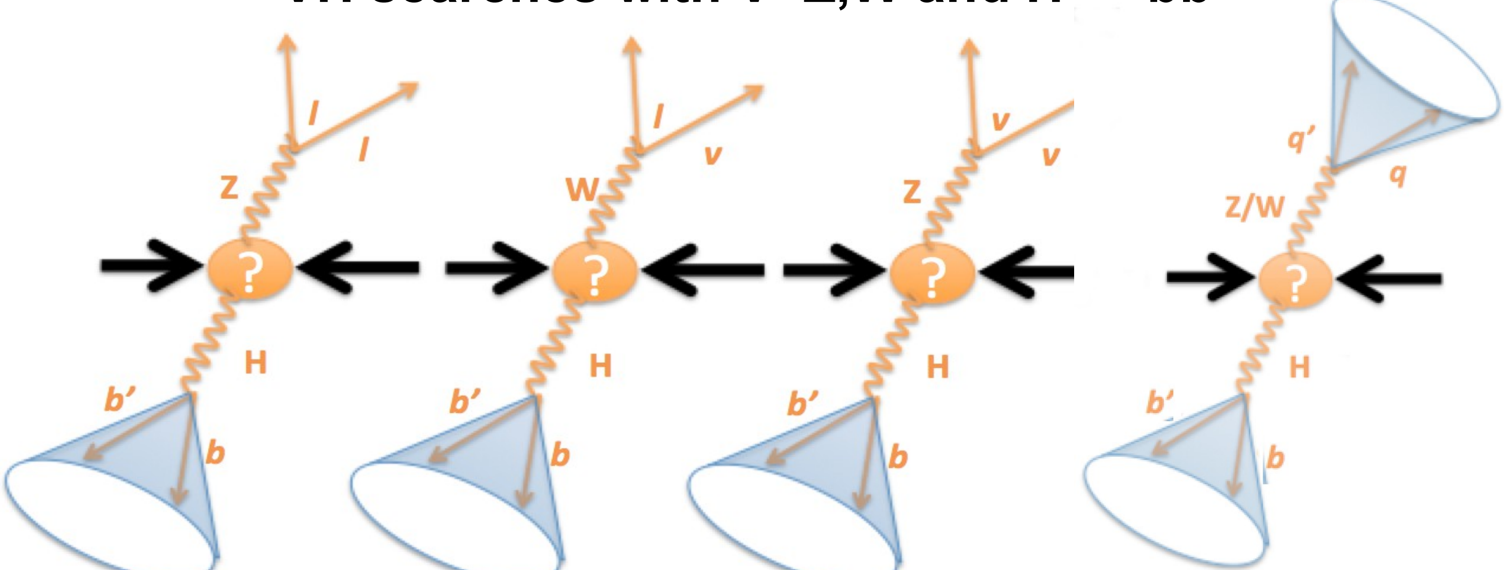
VH searches with V=Z,W and H → bb



Physics Letters B 765(2017) 32-52

ATLAS-CONF- 2016-083

Analysis strategy

Get the objects:

- Identify particles
- Calibrate them if needed

↓

Built distributions of interesting variables

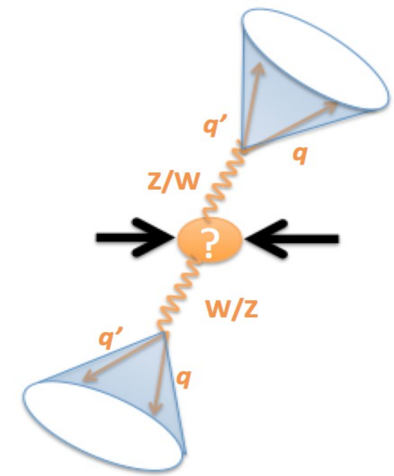
↓

Search phase:
Compare data and background
Do you see any deviation?

No → Limit setting phase:
Constrain new physics models

Yes →

VV → qqqq: Selection



- **Entirely dominated by multijet background**
- **Two highest p_T jets (>450/200 GeV)** boson tagged
  - + Cut on number of tracks associated to the jet
  - 70% bkg rejection, 30% loss in signal
- $|y_1-y_2|<1.2$, p_T asymmetry <0.15
- Veto on leptons and E_T^{miss}
- 3 partially overlapping signal regions WW,WZ, ZZ

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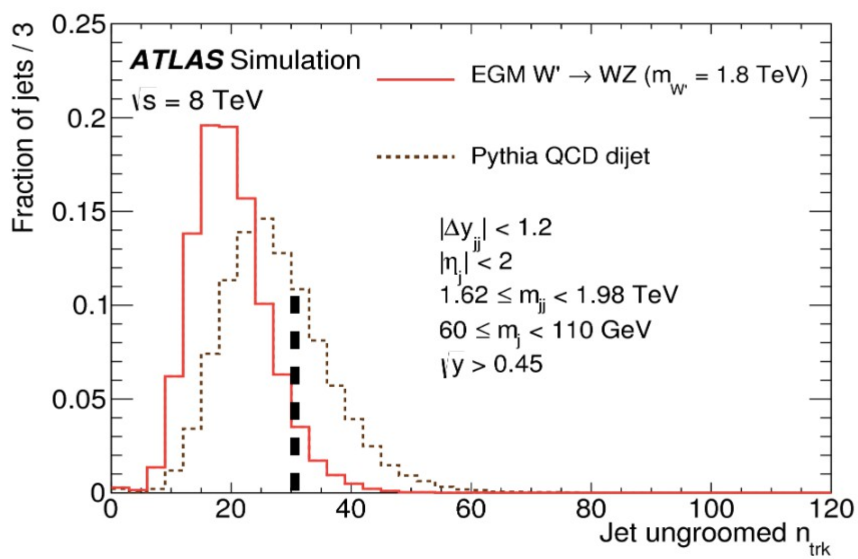
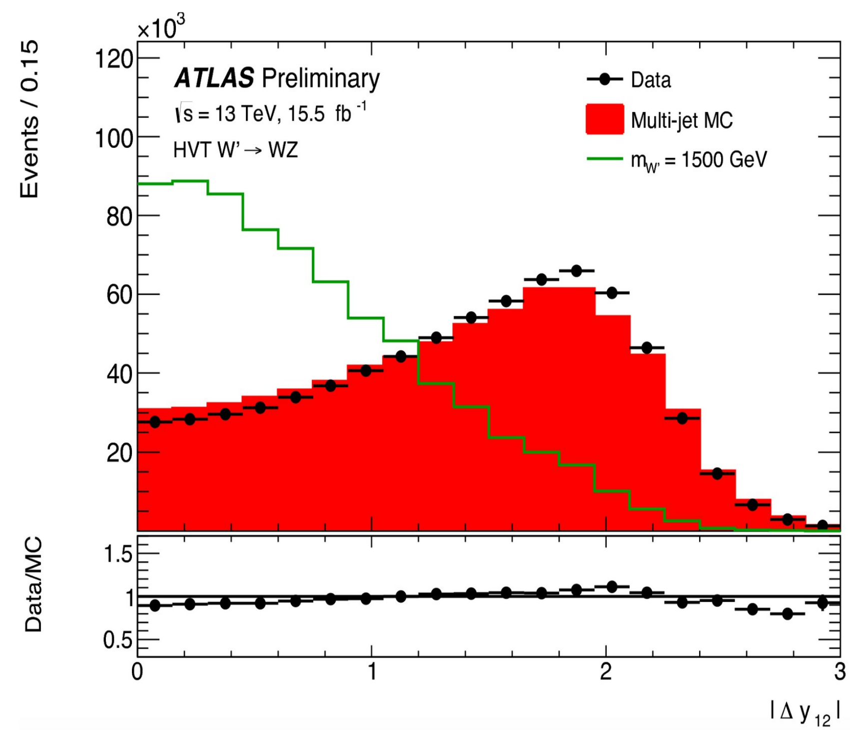




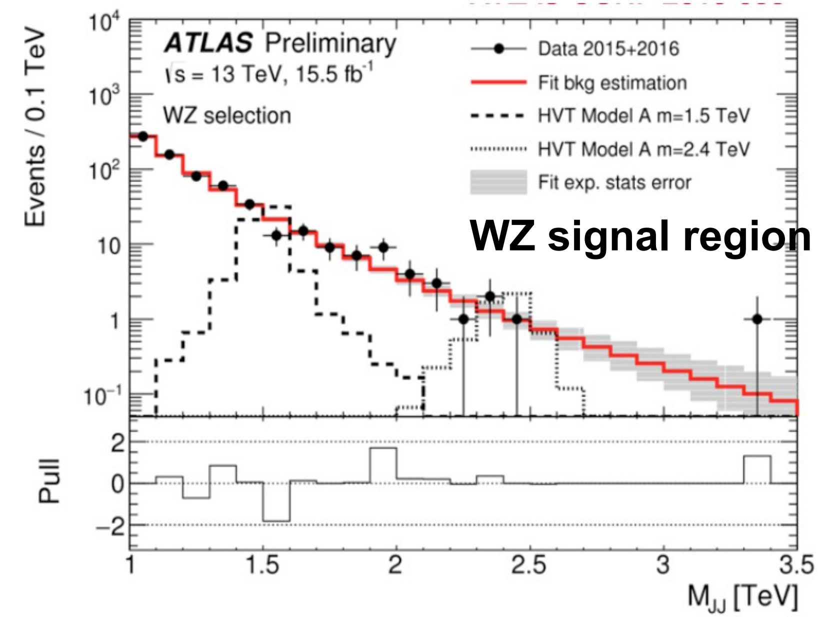
VV → qqqq: Background and signal regions

ATLAS-CONF-2016-055

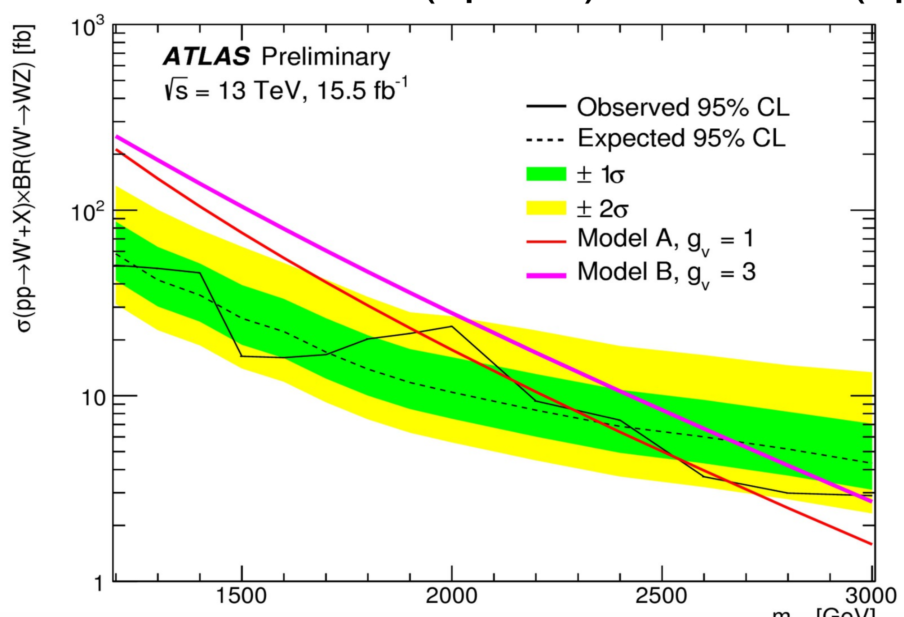
- Background estimated from fit to the data
  - Validation on simulation and checked against data in mass sidebands control regions

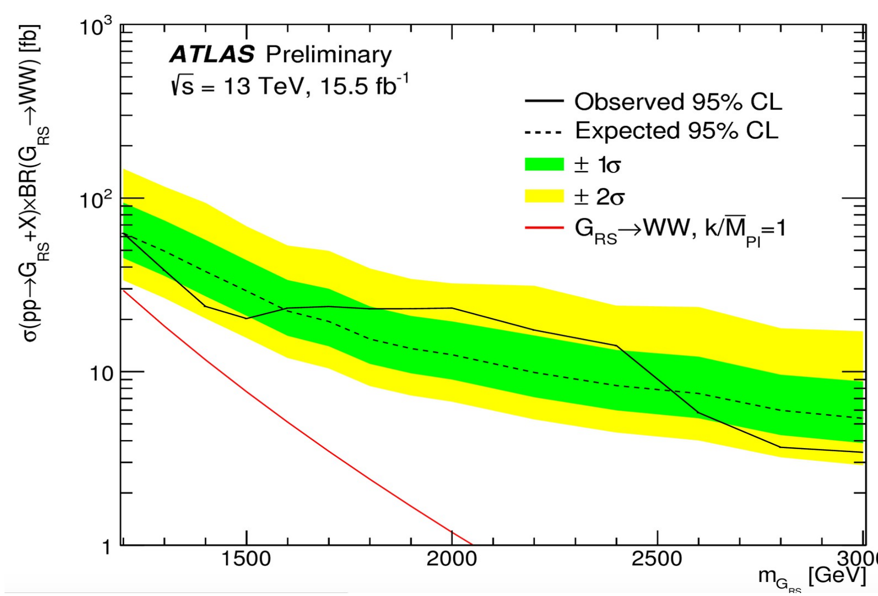
$$\frac{dn}{dx} = p_1(1-x)^{p_2+\xi p_3} x^{p_3}, \quad x = \frac{m_{jj}}{13TeV}$$

- No significant deviation found in the WW/WZ/ZZ signal regions
- Larger systematic uncertainties from jets

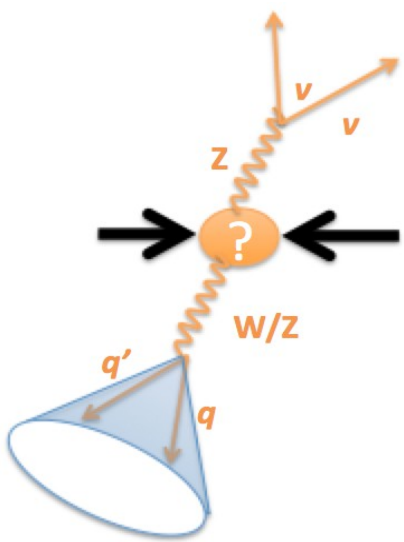


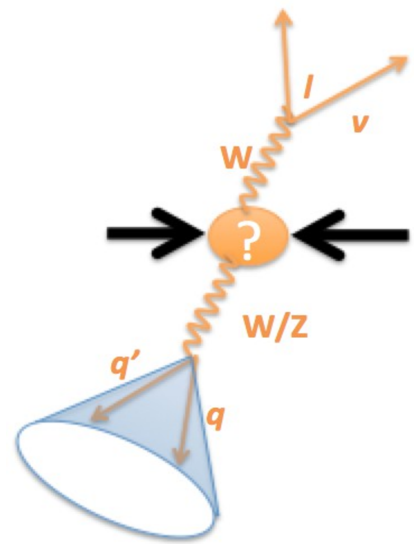
- Limits set on HVT (spin-1) and RSG (spin-2)

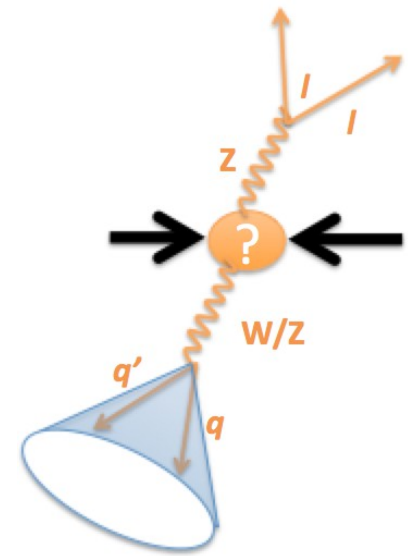




VV → llqq/lvqq/vvqq: Selection







High E_T^{miss}

- Boosted regime
- Dataset 13 TeV 13.2/fb
- Main background: V+jets, ttbar

1 lepton + E_T^{miss}

- Boosted regime
- Dataset 13 TeV 13.2/fb
- Main background: W+jets, ttbar

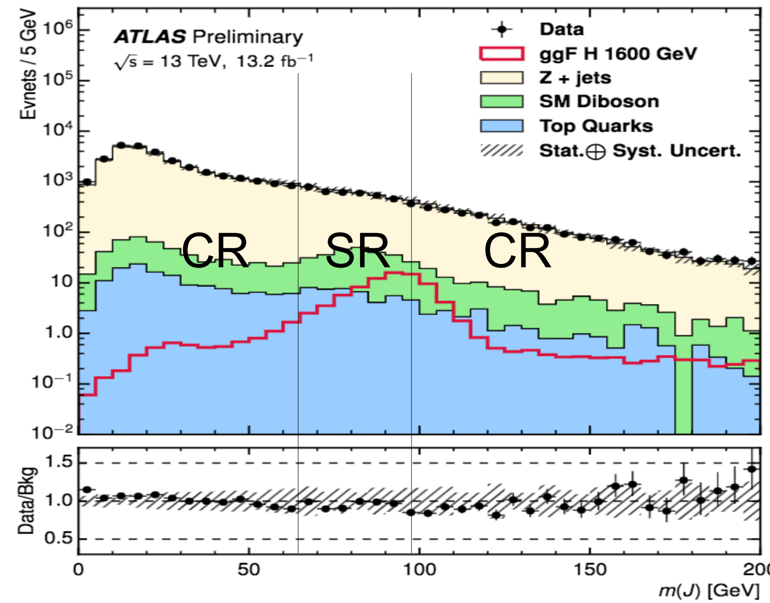
2 leptons and $m_{ll} \sim M_Z$

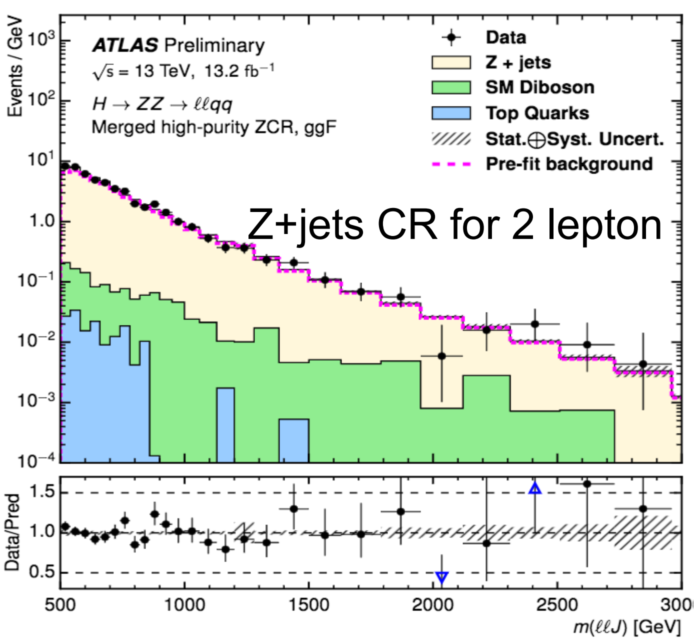
- boosted & resolved + VBF production
- Dataset 13 TeV 13.2/fb
- Main background: Z+jets

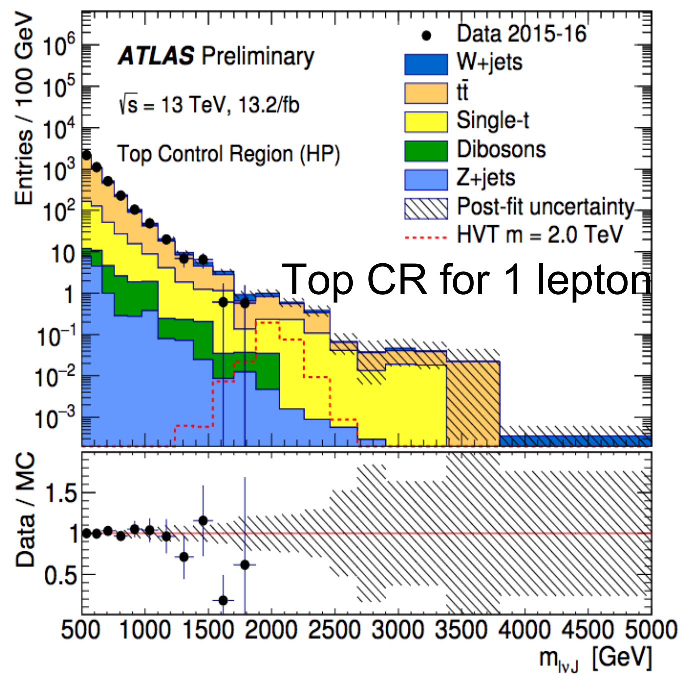
- **In boosted regime two signal regions defined**
  - **High purity with a** large-R boson tagged jet
  - Low purity with inverse D_2 cut applied to gain sensitivity at high masses

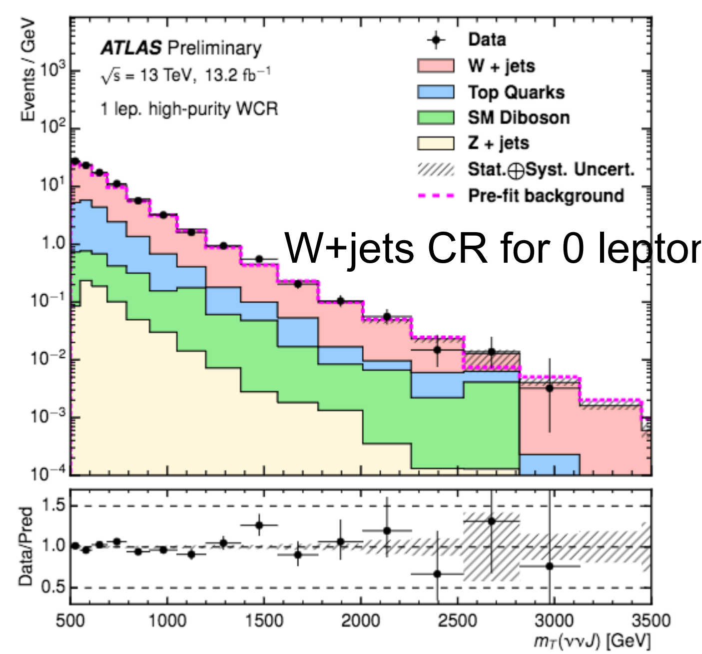
VV → llqq/lvqq/vvqq: Backgrounds

- Backgrounds are estimated using Monte Carlo simulation and checked in control regions defined using:
  - The jet mass sidebands for W/Z+jets
  - By asking additional number of b-jets in the event for ttbar
- Control regions are included in the final fit to better constrain the normalisation





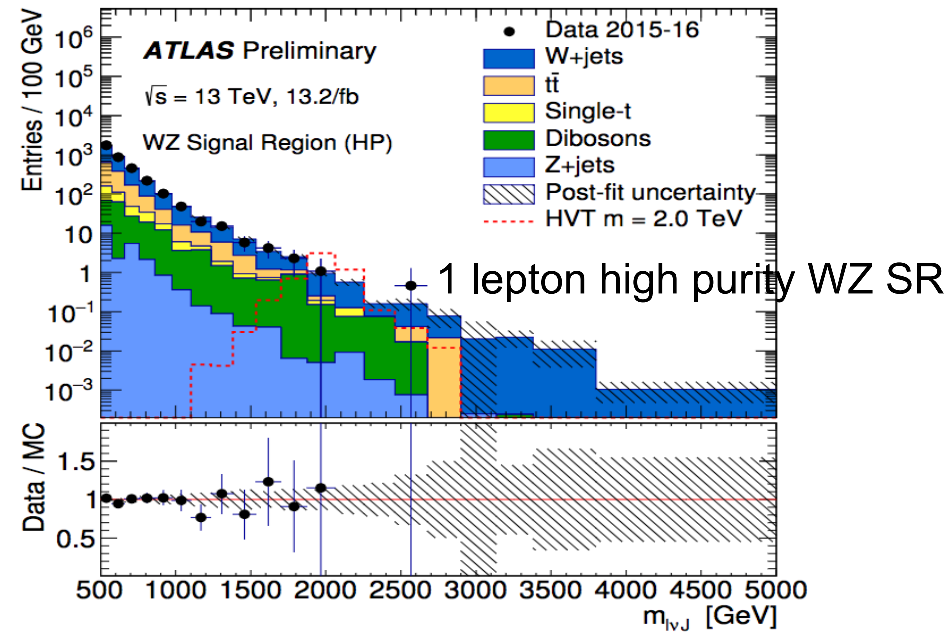


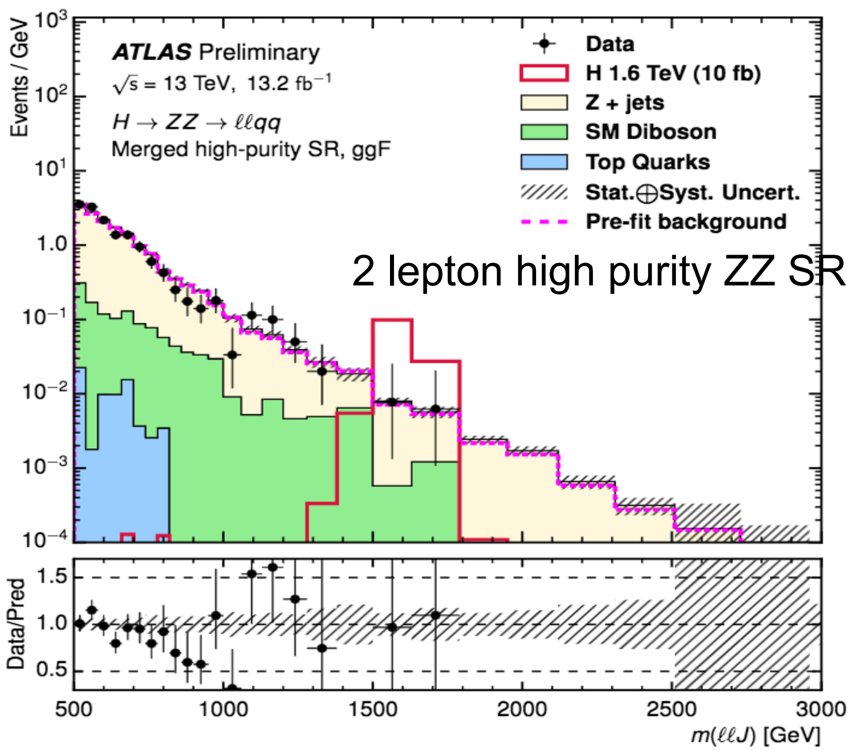


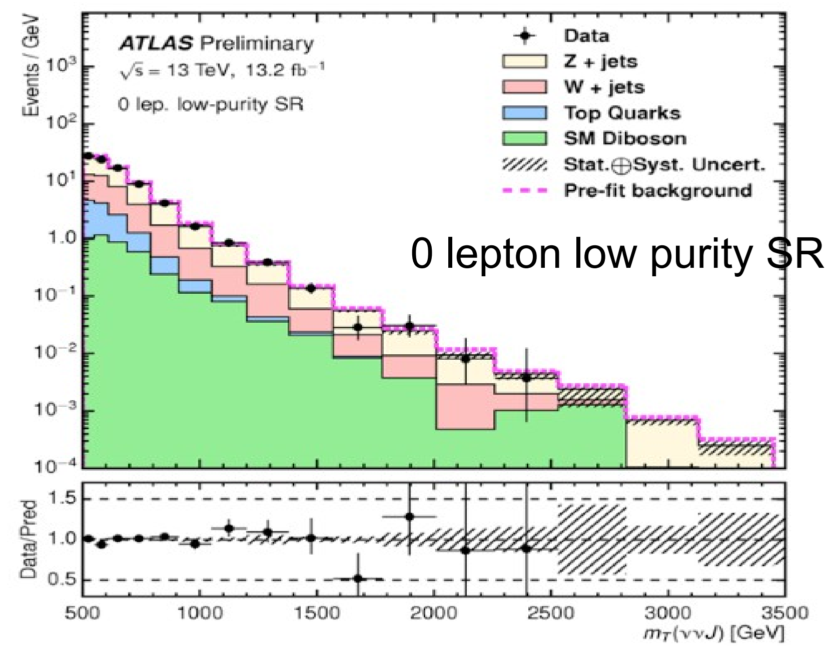
VV → llqq/lνqq/ννqq: Signal regions

- Use m_{VV} ($m_{T,VV}$ for the ννqq channel) as a discriminant
- Larger systematic uncertainties are jet and background modelling related

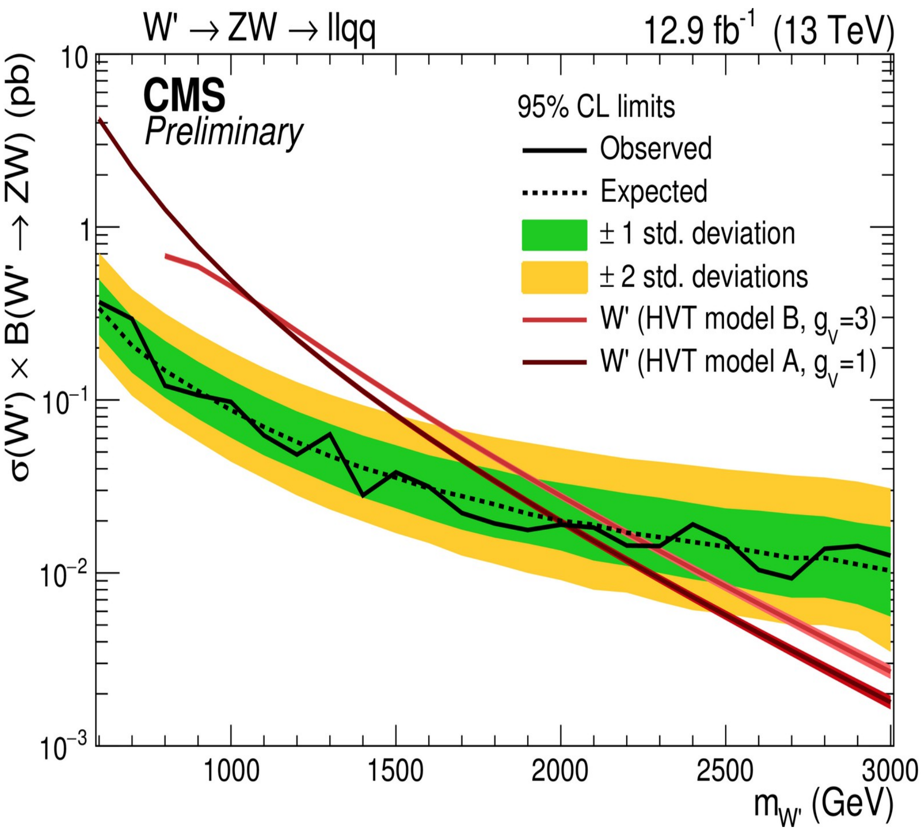
- No significant deviation observed
- Limits set on HVT (spin-1), RSG (spin-2) and Heavy Higgs (spin-0)

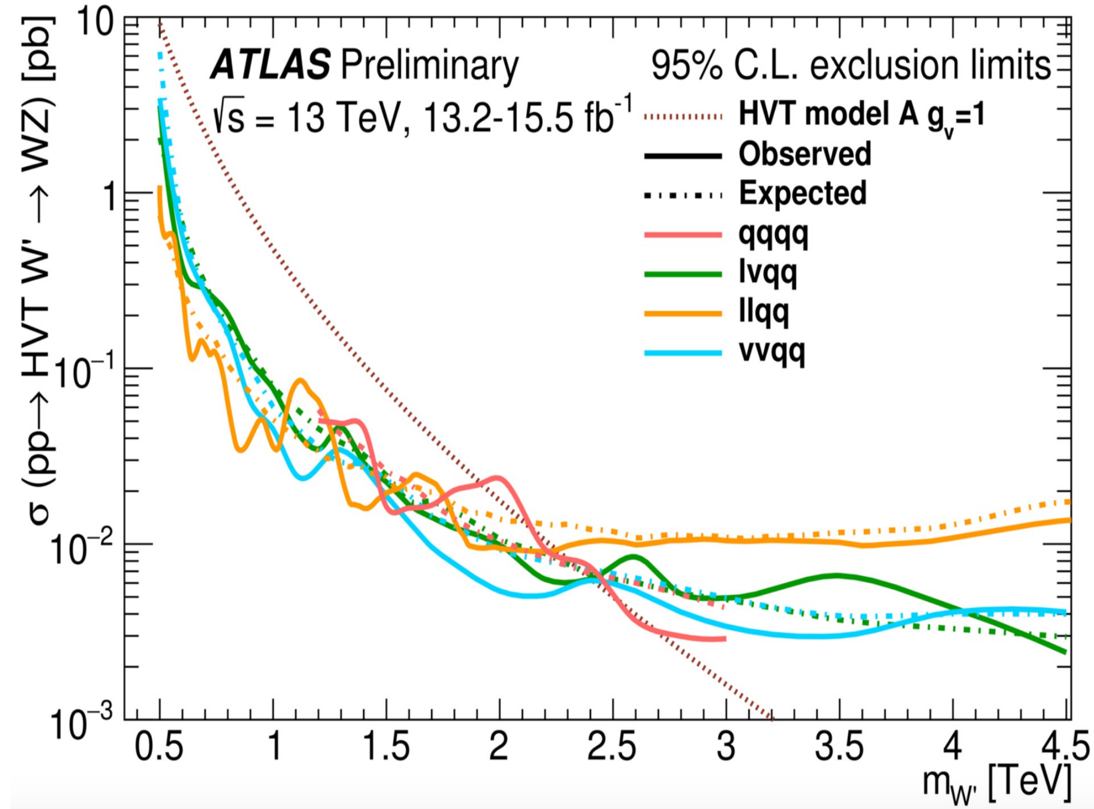






VV resonances searches: A bit of perspective





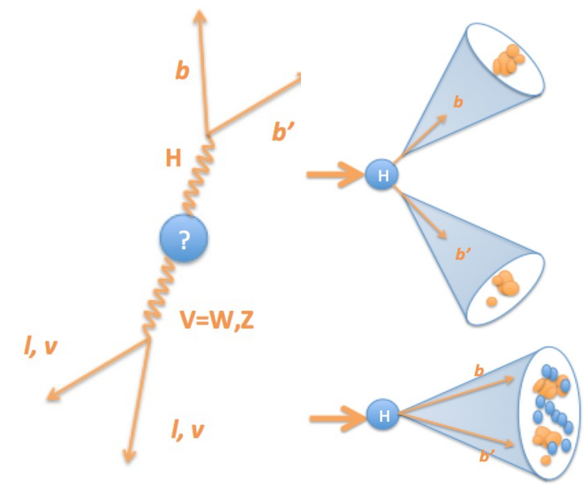
Deviation at 650 GeV in the llqq channel not present when adding more data (B2G-16-022)

Here we can see which channel is more sensitive and where for the ATLAS searches

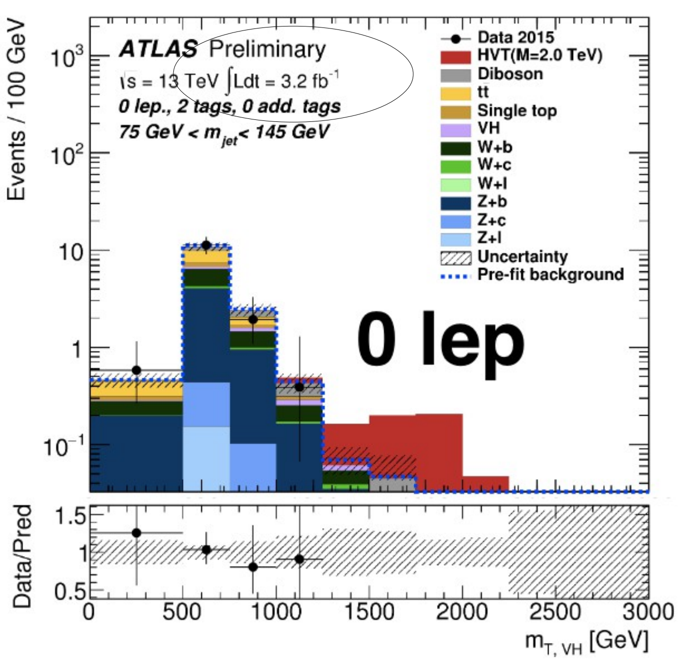
Current ATLAS Run-2 results highly disfavor the Run-1 2 TeV excess at its observed signal strength

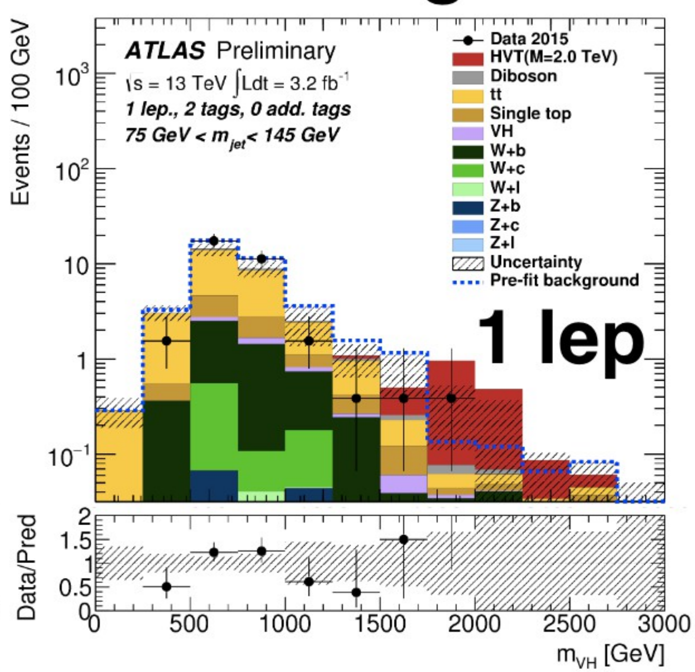
VH → llbb/lvbb/vvbb: Selection and backgrounds

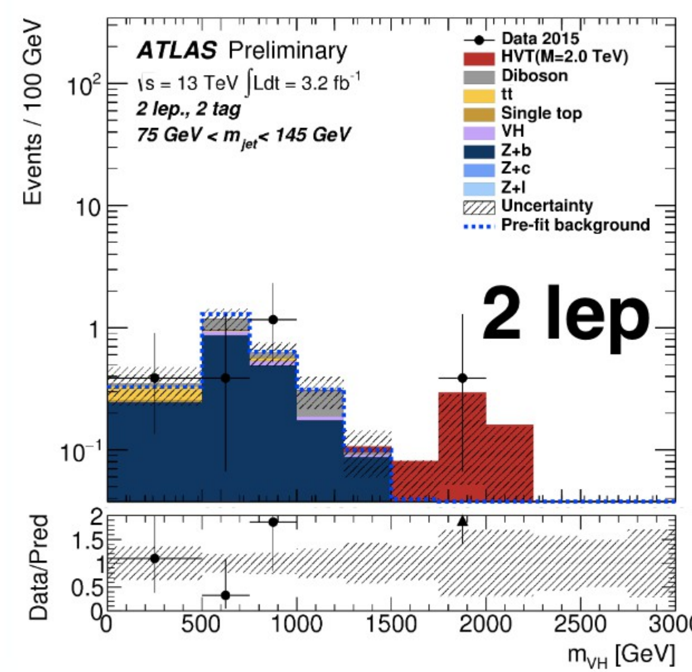
- Similar selection to the un-tagged (VV) analyses on leptonic side
- Use H → bb boosted tagger on the hadronic side
  - 1 and 2 b-tag categories
- Main backgrounds
  - Top and W/Z+heavy flavour
  - Estimated with simulation and checked in control regions
- No excess over the SM background



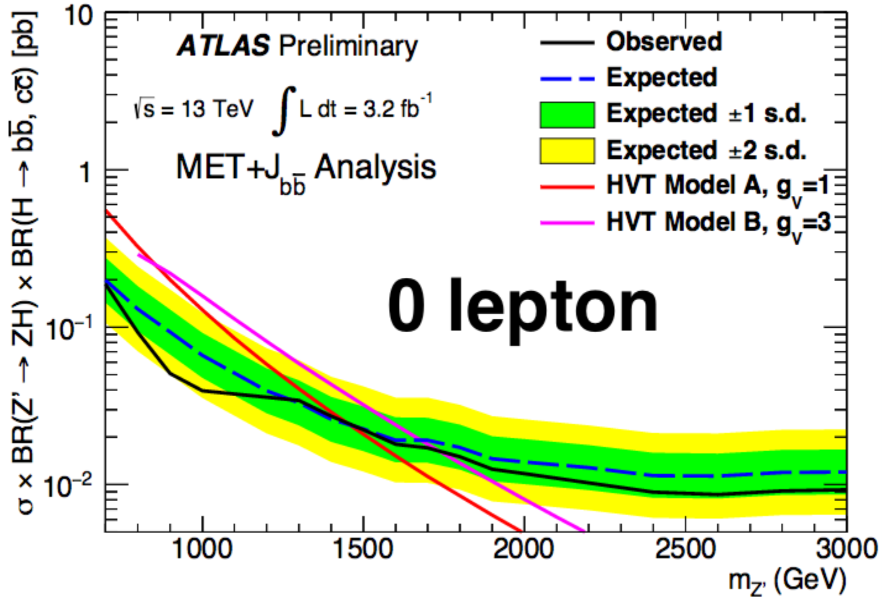
2-tag



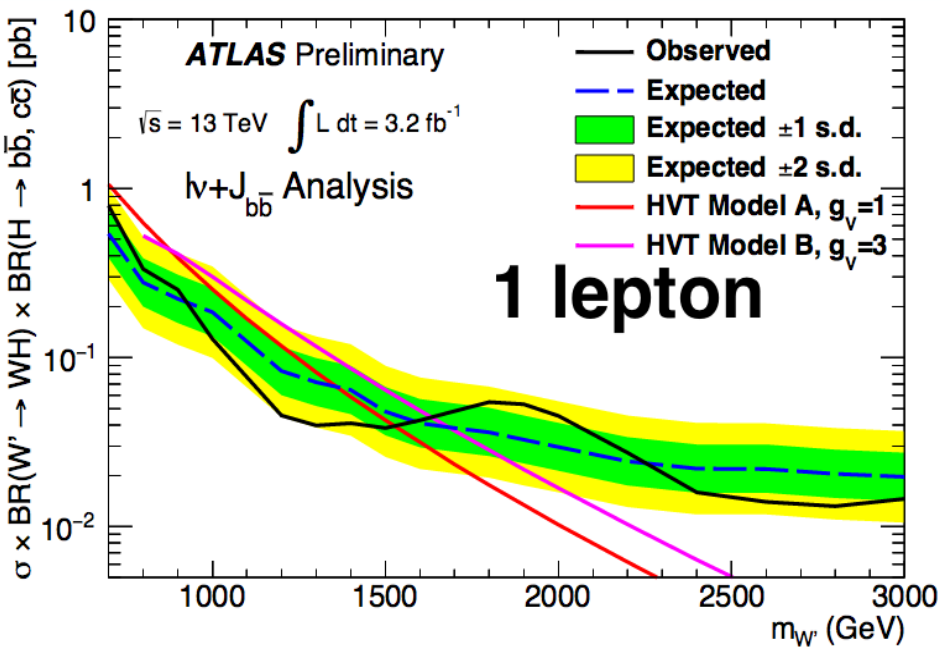


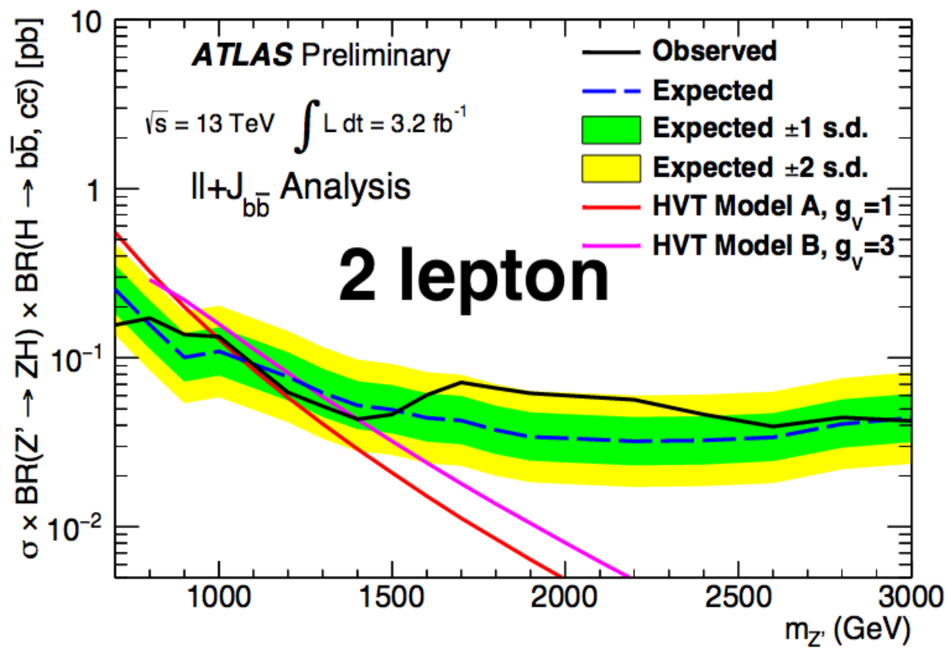


VH → llbb/lvbb/vvbb: Limits results

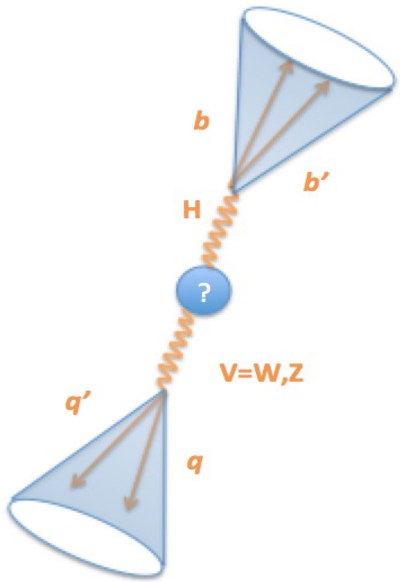


Set Limits for HVT: model A and model B

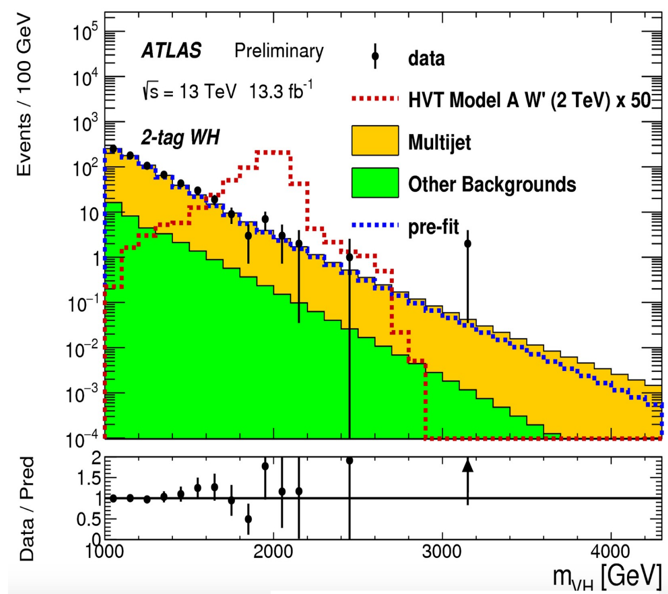


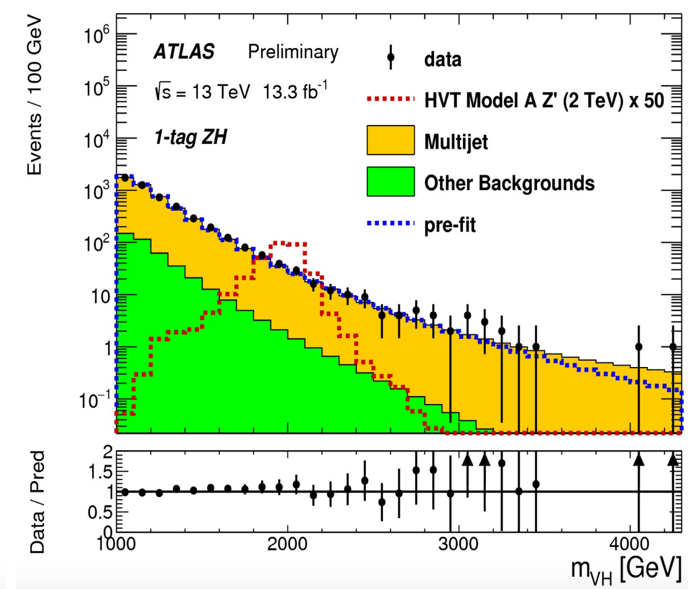


Search for VH, V→ qq and H→b$\bar{b}$

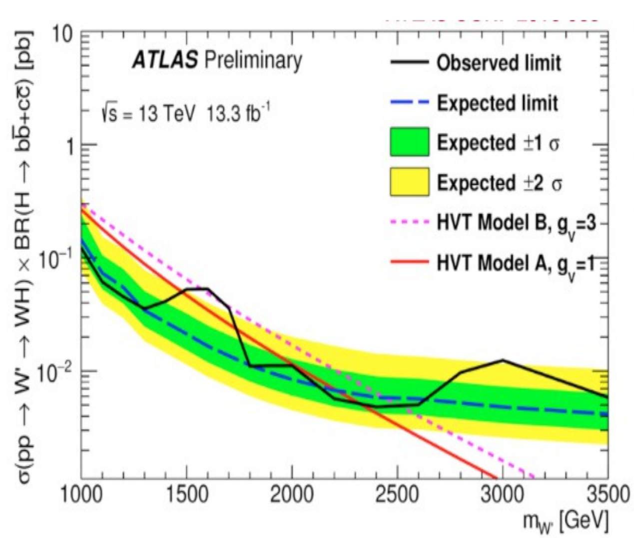


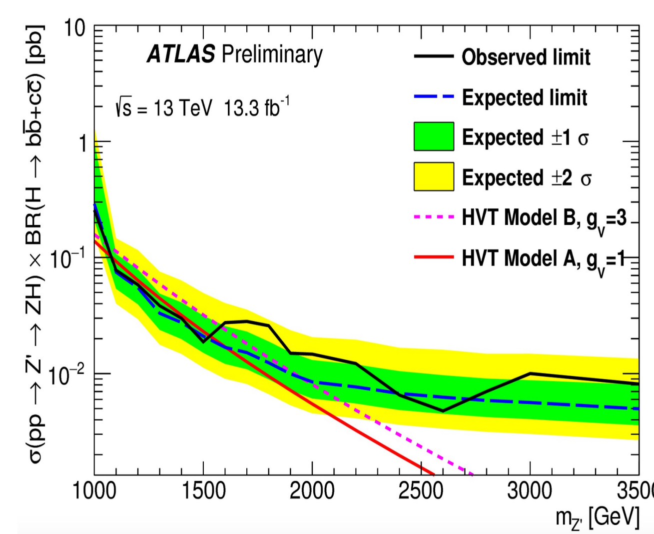
ATLAS-CONF-2016-083





- Complementary to semi-leptonic VH searches at high masses
- Main backgrounds: multijet and t$\bar{t}$
- ATLAS results with 13 TeV 3.2/fb
- No significant deviation found
  - Largest deviation at 3 TeV reported by ATLAS (2.5σ global significance)





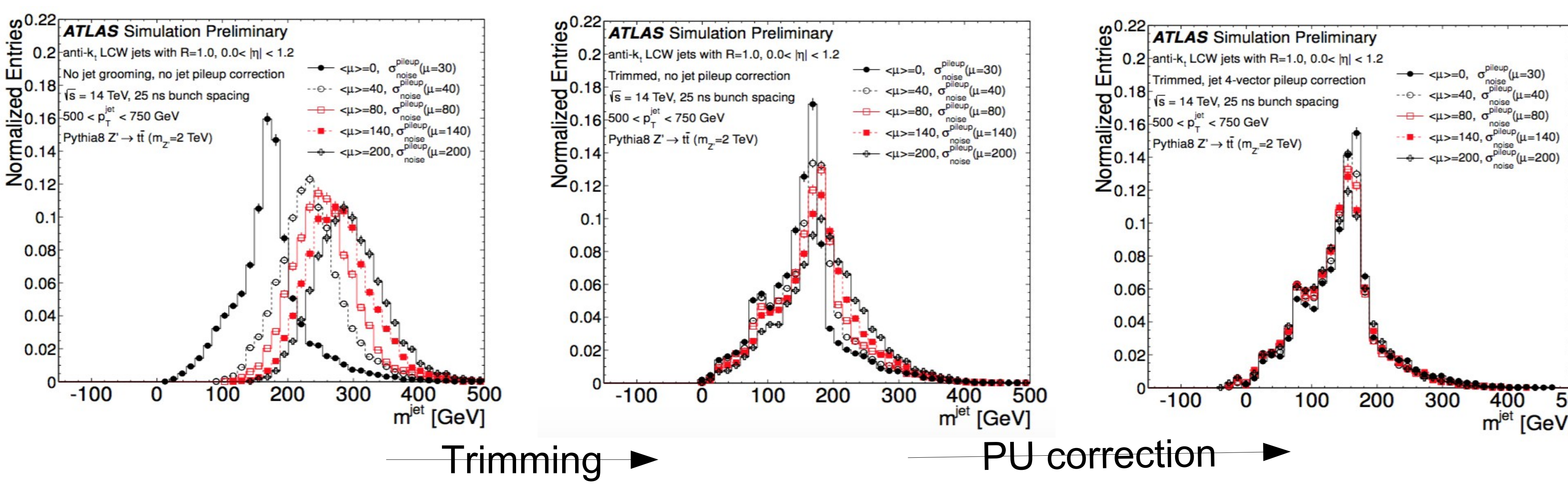
Extra thoughts for the future: the challenges we still face

- Excellent performance of ATLAS! Our searches look into many different final states/phase space

- **Modeling** of complex observables by Monte Carlo simulation is essential
  - Measurements of jet mass and other jet shapes need to be fed back to simulation

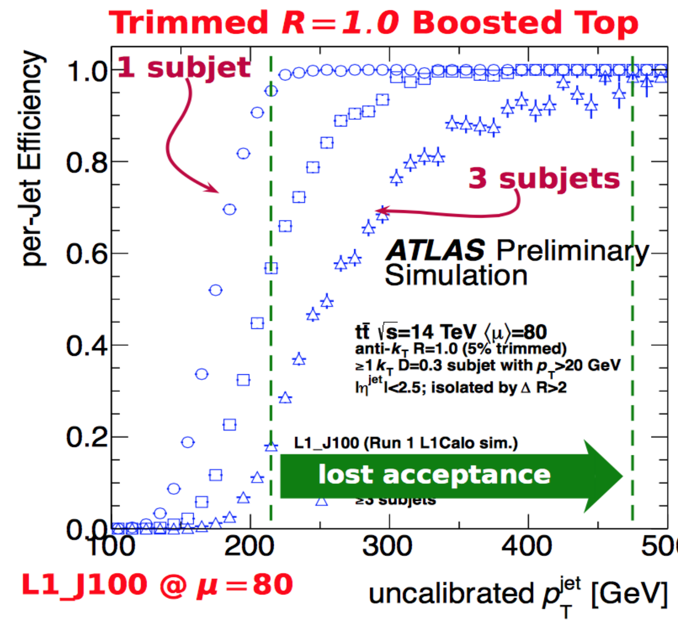
- We have many tools to **mitigate PU**, but the increases we face in Run-2 and beyond will be challenging

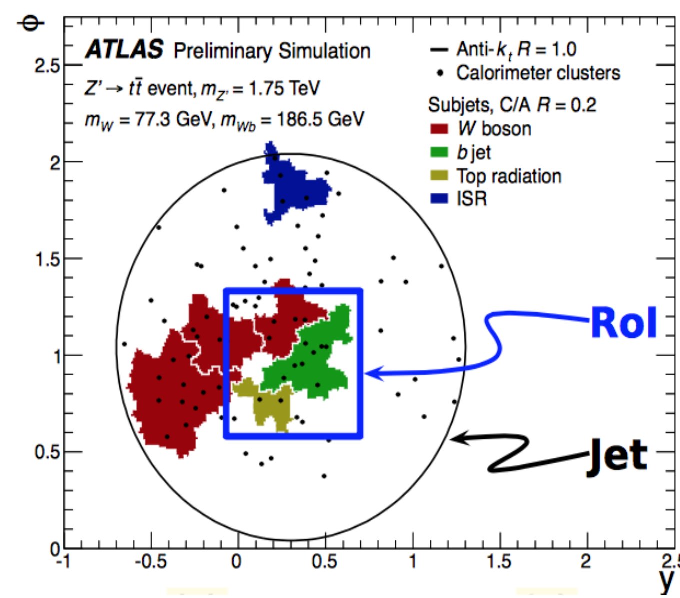
- Going to **even higher p_T** → very very collimated decay products... Limited calorimeter granularity



Looking into the future
ATLAS Run-3 boosted objects trigger development

- Hadronic decays of high p_T bosons and fermions is a vital part of the ATLAS physics program
  - Isolated lepton triggers inefficient for some analyses → use jet triggers (e.g. VV → qqqq)
- Many techniques to suppress PU and to identify substructure in jets are implementable in the ATLAS High Level Trigger (HLT)
  - Large-R acceptance in HLT depends on the L1 requirements
  - But adding these in the level-1 hardware-based trigger is more complicated
- **ATLAS** is planning **major detector updates in Run-3, like Level-1 trigger (calorimeter) system**
  - Including the Global Feature Extractor (**gFEX**)
  - Institutions: BNL, UChicago, Indiana, Pittsburgh, Oregon and Stockholm

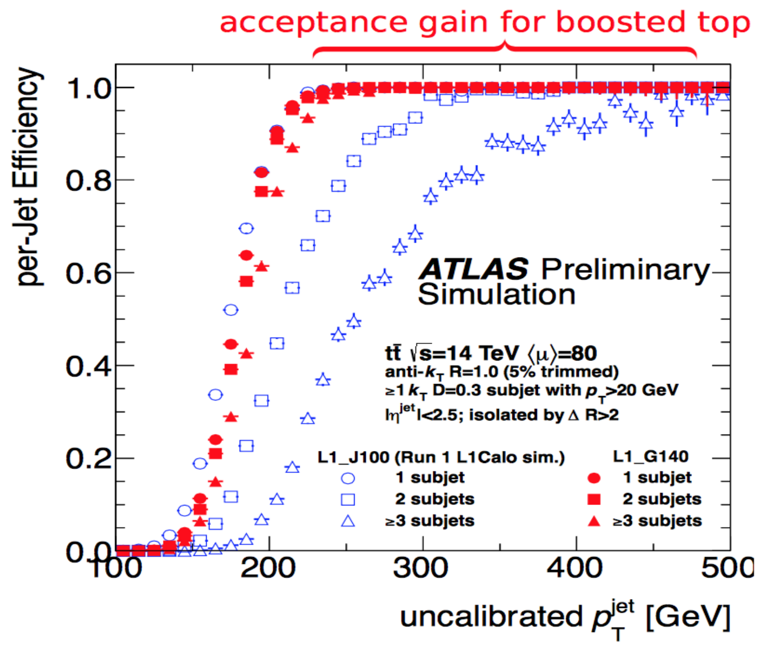


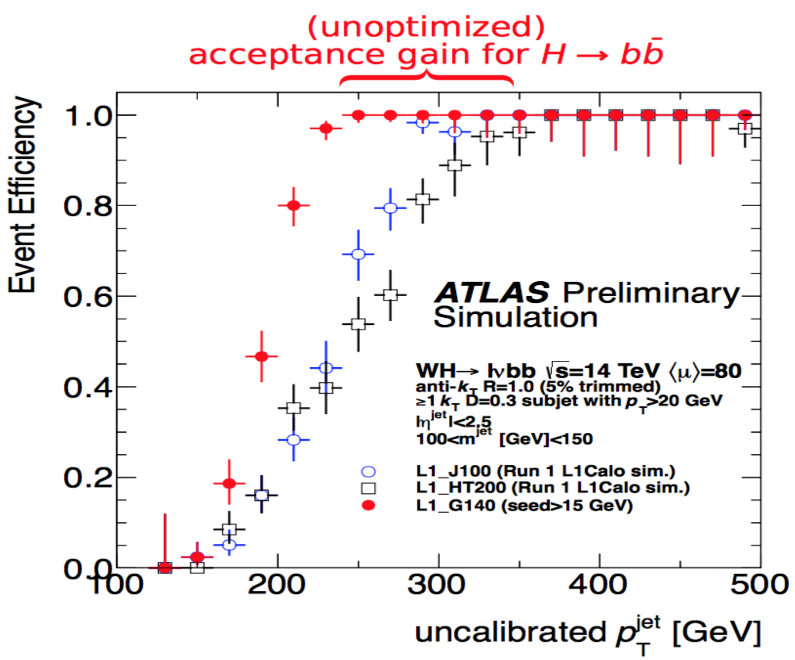


Nice overview in M. Begel's talk at BOOST15

Global Feature EXtractor (gFEX)

- **gFEX** is a single board that will have access to the information from the whole calorimeter!
- Will **identify events with large-radius jets**
  - Improving acceptance for boosted objects
  - Jet-level pile-up substraction
  - Substructure variables could be used
- Will calculate global event variables:
  - E_T^{miss}, centrality
- Implemented in a highly parallelized structure (3 large Xilinx Ultrascale FPGAs and Zync System-On-Chip)
- Prototype is available. Initial **LAr calorimeter-L1Calo link speed communication tests very successful!**





Summarizing

- Search for **heavy resonances** is **one of the most direct ways to find new physics** at TeV scale

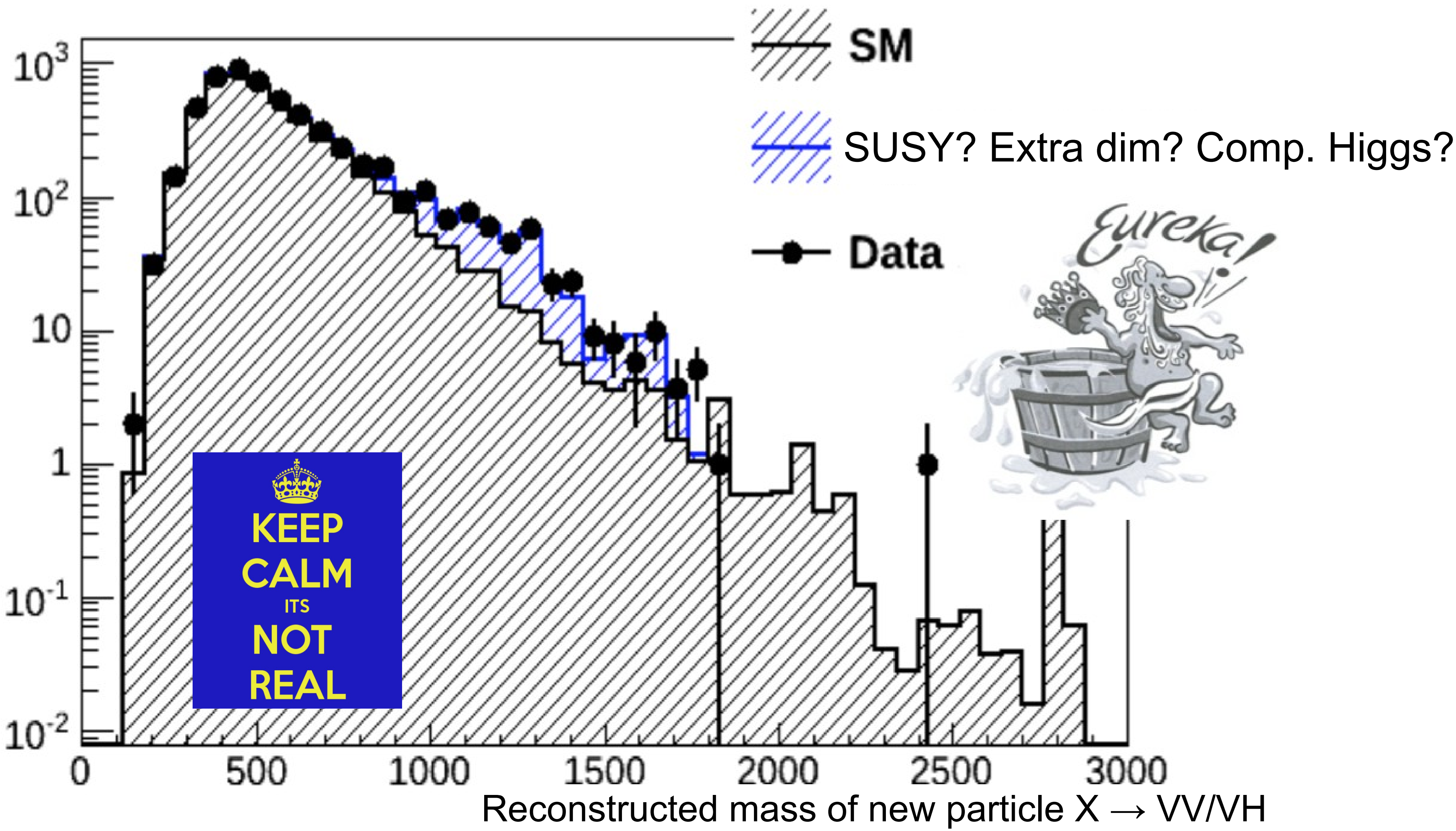
- Many Run-2 searches are now using these boosted techniques and many more are coming. **Wealth of physics encoded inside jets!**
  - A **very active field**
  - Important to build confidence in these tools through its use in more SM measurements
  - **Main challenges**: pile-up, detector granularity and simulation modeling

- **No significant excess** observed so far but only a third of the data collected in 2016 has been analyzed so far

- Thinking ahead: gFEX will increase trigger rejection to present acceptance in Run-3

Thanks for your attention!

Will diboson final states show us new physics in Run-2?



BACKUP

ATLAS improvements in Run-2

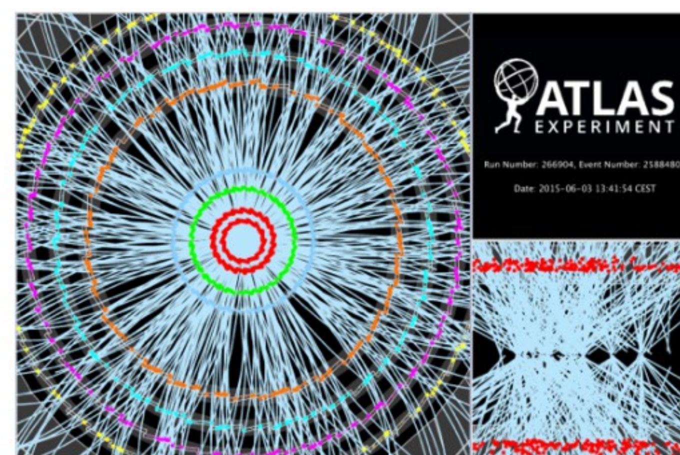
- **Insertable b-layer (IBL)** in place
- Upcoming trigger improvements:
  - **Fast TracK trigger (FTK)**
  - L1 topological trigger
- Software improvements:
  - New data format for analysis
  - Online (trigger) and offline jet reconstruction are ~the same

Insertable b-layer insertion (2014)

Trigger and data acquisition:

- First step: **fast hardware selection**
  - Run-1 data taking rate: 75 kHz
  - Run-2 data taking rate: 100 kHz
- Second step: **computer farm**
  - Run-1 data taking rate: 400 Hz
  - Run-2 data taking rate: 1000 Hz

From C. Doglioni

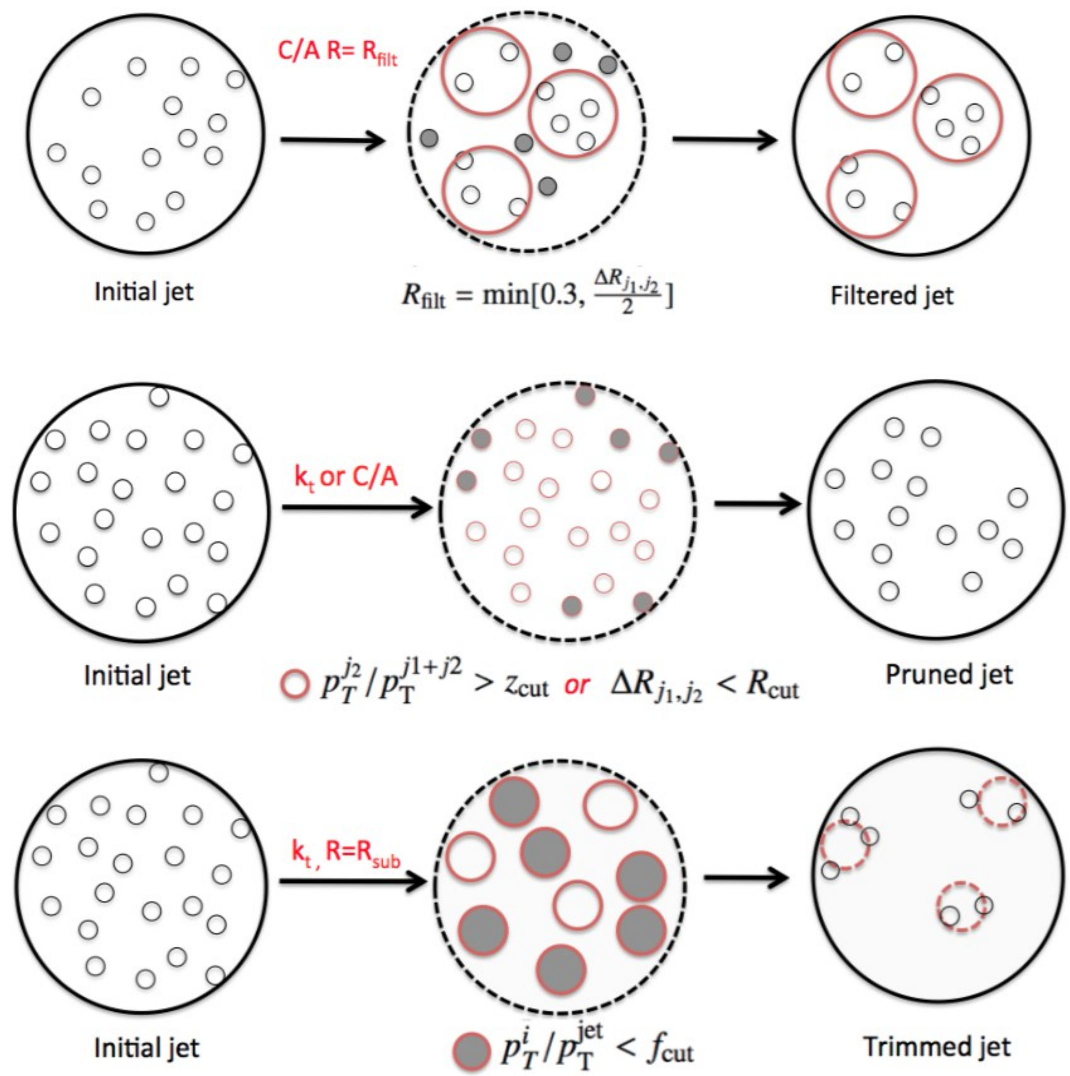


IBL takes first proton-proton data

Grooming techniques

Can not cover all tools…but these 3 are widely used

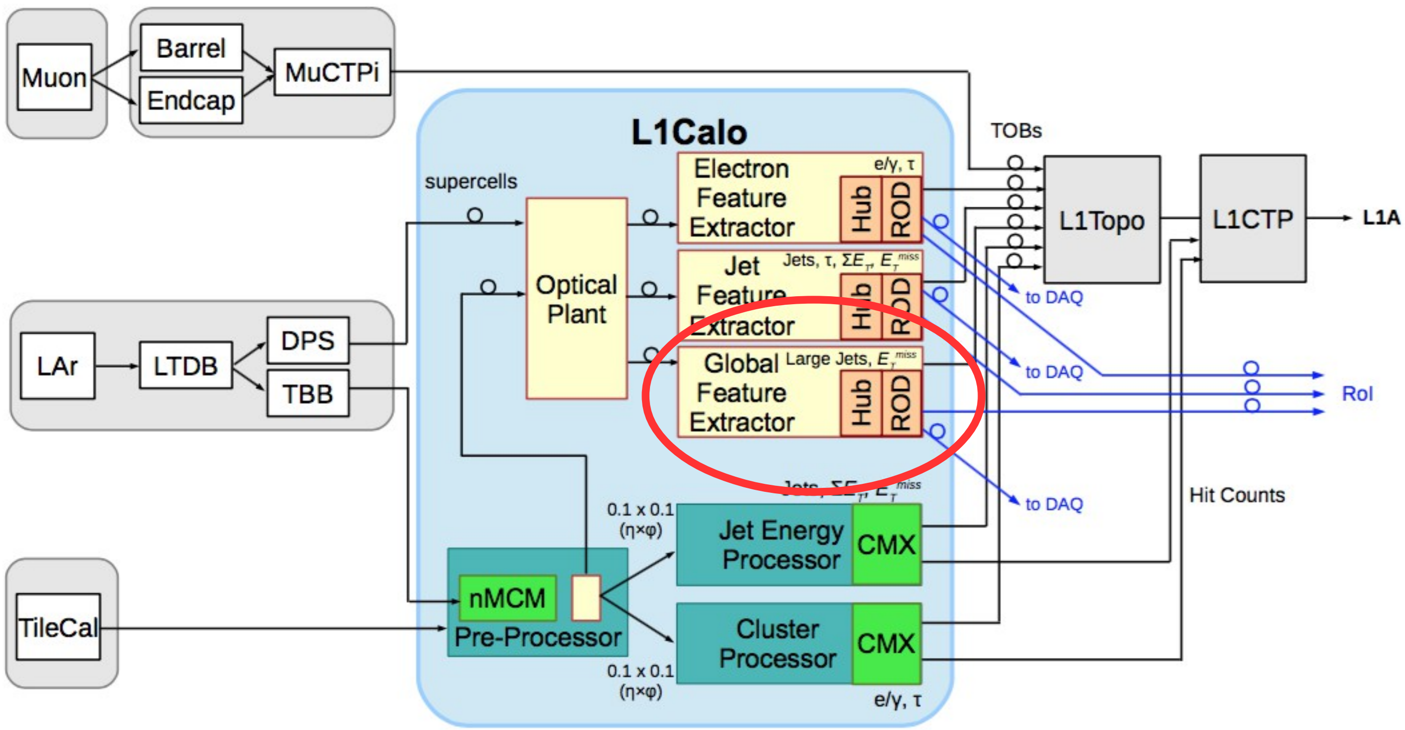
- **Split-filtering:** http://arxiv.org/abs/0802.2470
  - Decluster and discard soft junk
  - Requiring symmetric splitting
  - Repeat until find hard structure
  - Small-radius jet reclustering, keeping only the three highest p_T subjets
- **Pruning:** http://arxiv.org/abs/0912.0033
  - Constituents of large-R jet are reclustered with either C/A or k_t algorithm
  - In each clustering step, large angle and soft clusterings are removed
- **Trimming**: http://arxiv.org/abs/0912.1342
  - Reclustering of constituents of large-R jet into small-R jets of size R_{sub}
  - Remove subjet *i* if $p_T^i < f_{cut} \times p_T^{jet}$
  - **Default ATLAs groomer (stable against PU)**



arXiv:1306.4945

global Feature Extraction (gFEX)
The big picture

A new level 1 calorimeter trigger system for Run 3 (~2020)



- Entire **calorimeter in one single board**:
  - Jet substructure in Run 3 and beyond: fat jet reconstruction and jet-level pile-up corrections
  - Global event variables, e.g: E_T^{miss} and centrality

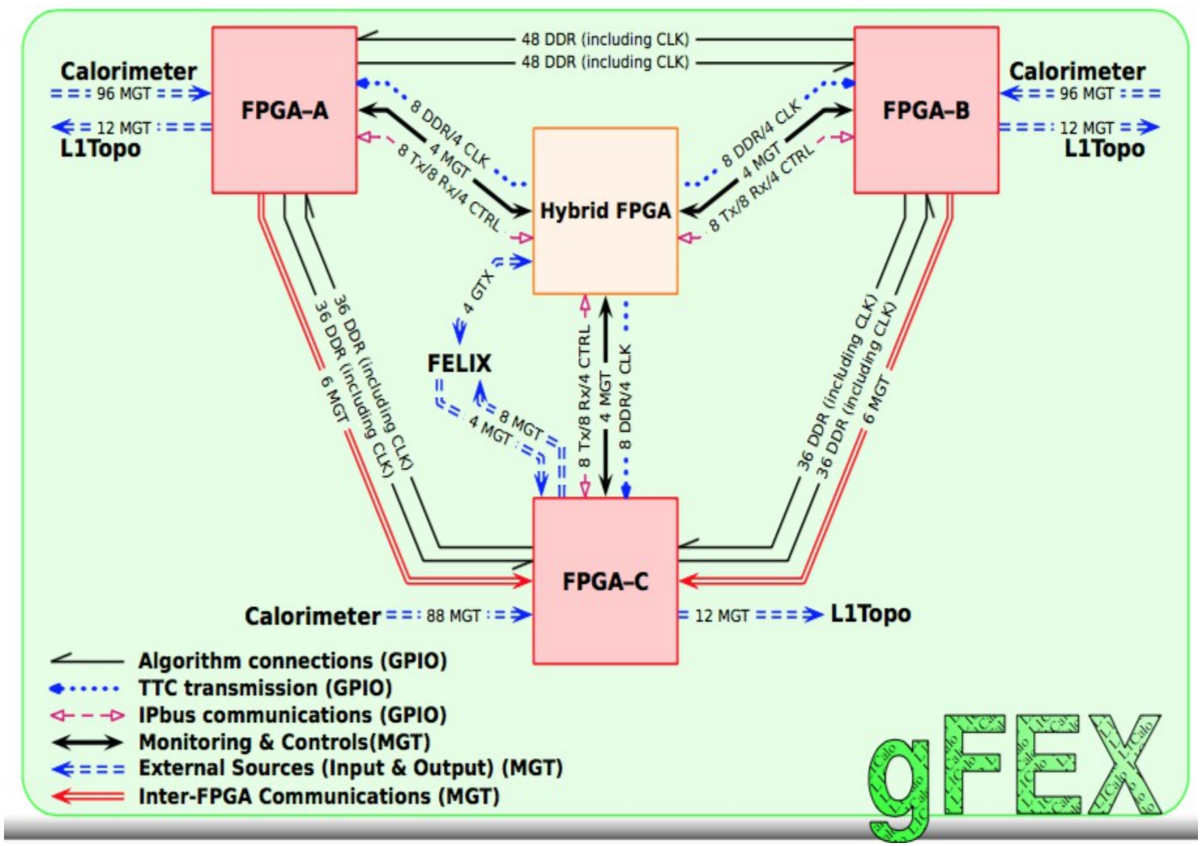
- Physics algorithms run within 5 bunch crossings (125 ns), not including data input/output

More on algorithms in Walter's talk!

global Feature Extraction (gFEX)
The big picture

A new level 1 calorimeter trigger system for Run 3 (~2020)

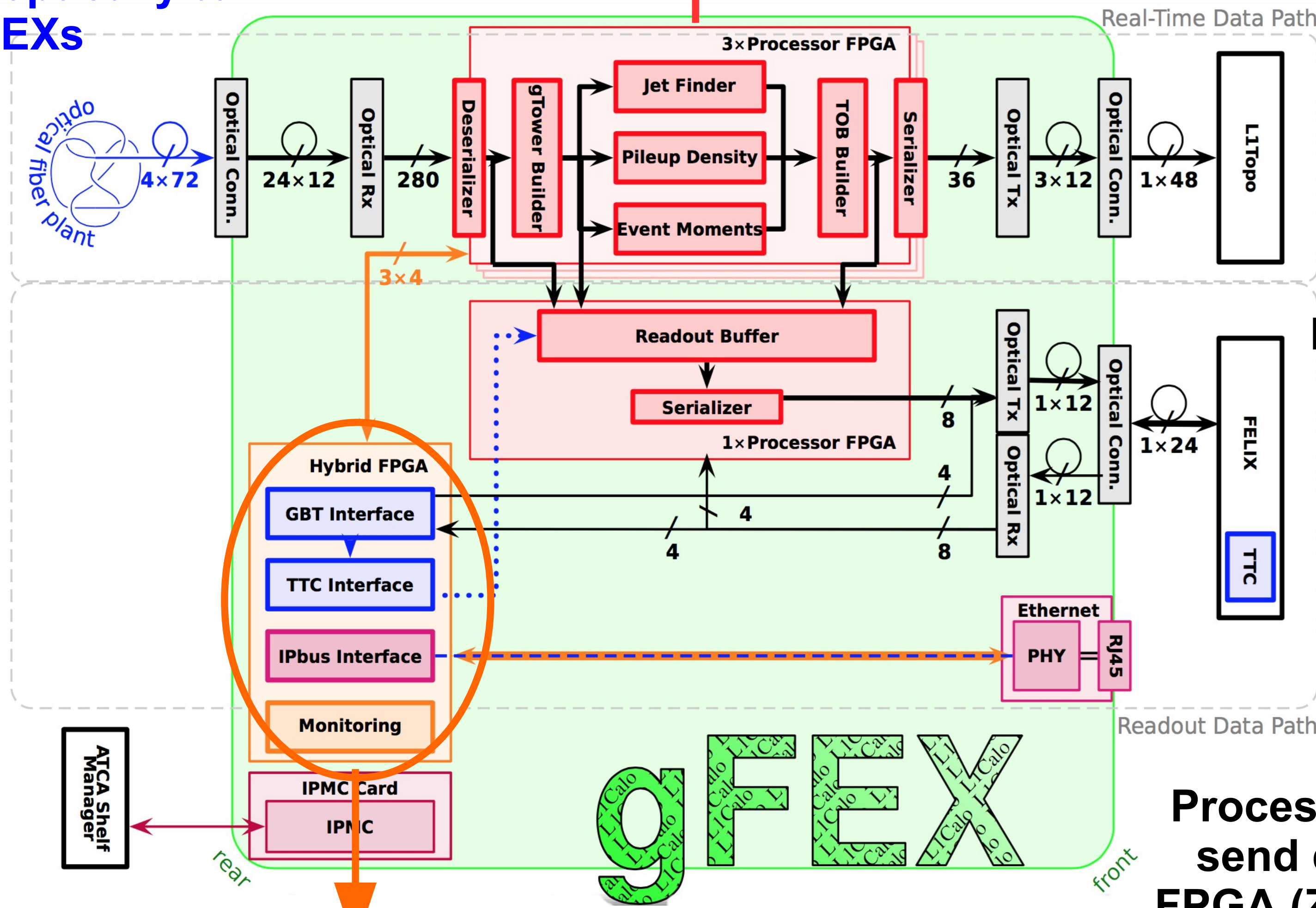
- One single module with several FPGAs for data processing
  - Inter-communication to avoid environments
- Hybrid FPGA (FPGA+CPU system-on-ship or Zynq) for control and monitoring
  - Process the event data from processor FPGAs
  - Algorithms to quickly detect calorimeter issues
  - Emulate the feature identification algorithms
  - Histograms interesting quantities



Zynq in gFEX

Data processing: algorithms run on FPGAs

Digitized signals transmitted optically to the FEXs



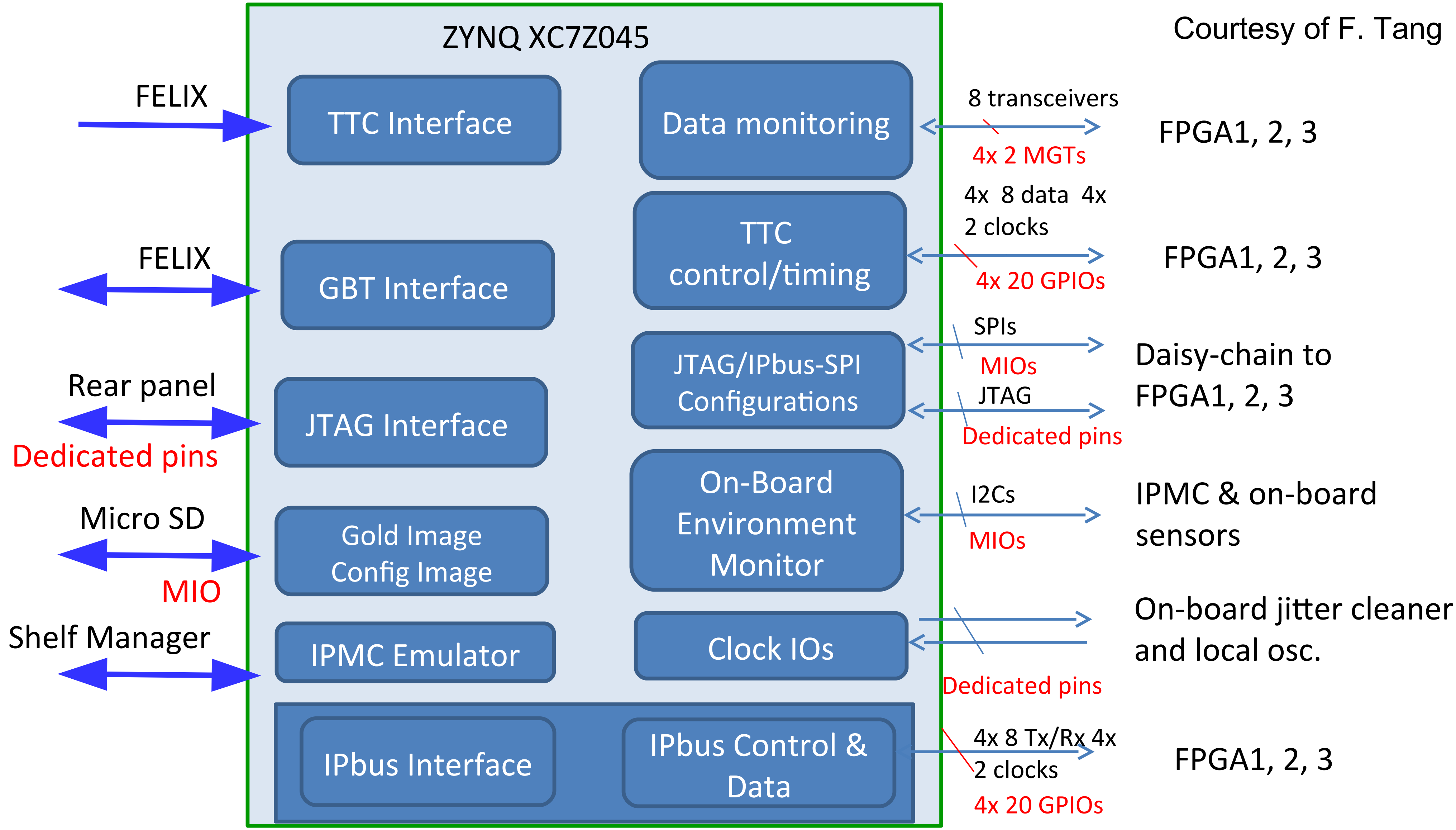
Data on the prototype can be transmitted via FELIX

Processor FPGAs can send data to Hybrid FPGA (Zynq) for further analysis upon request or predefined error condition

Zynq provides configuration, slow control, monitoring and playback for gFEX

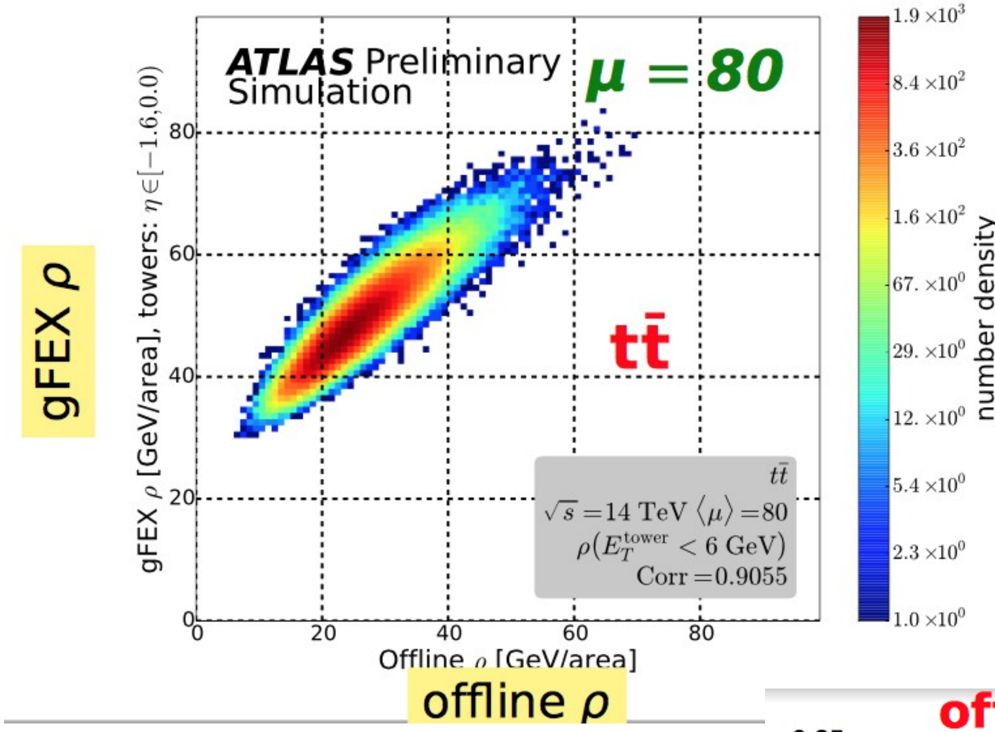
Zynq functionality/features in gFEX
Control and monitoring

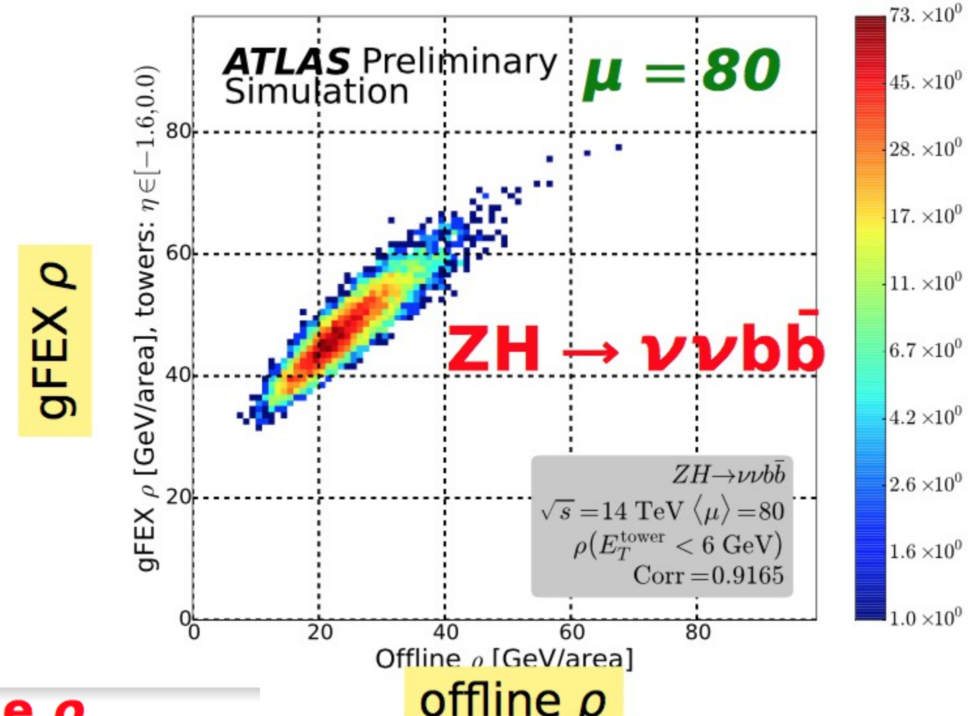
Courtesy of F. Tang

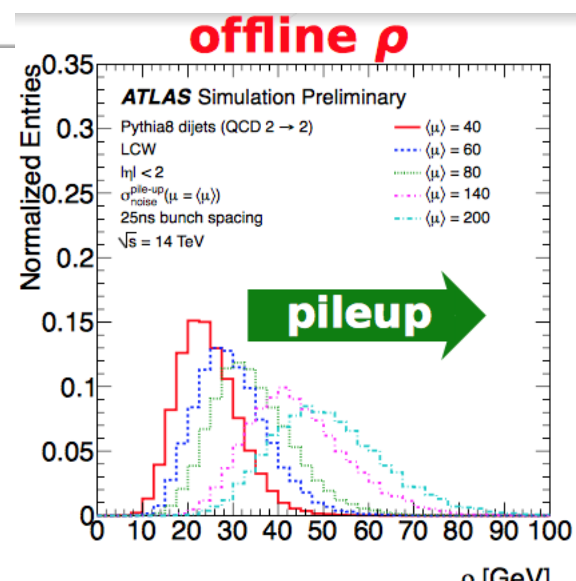


Disclaimer: GPIO and MGT counts out of date

gFEX: area based PU subtraction







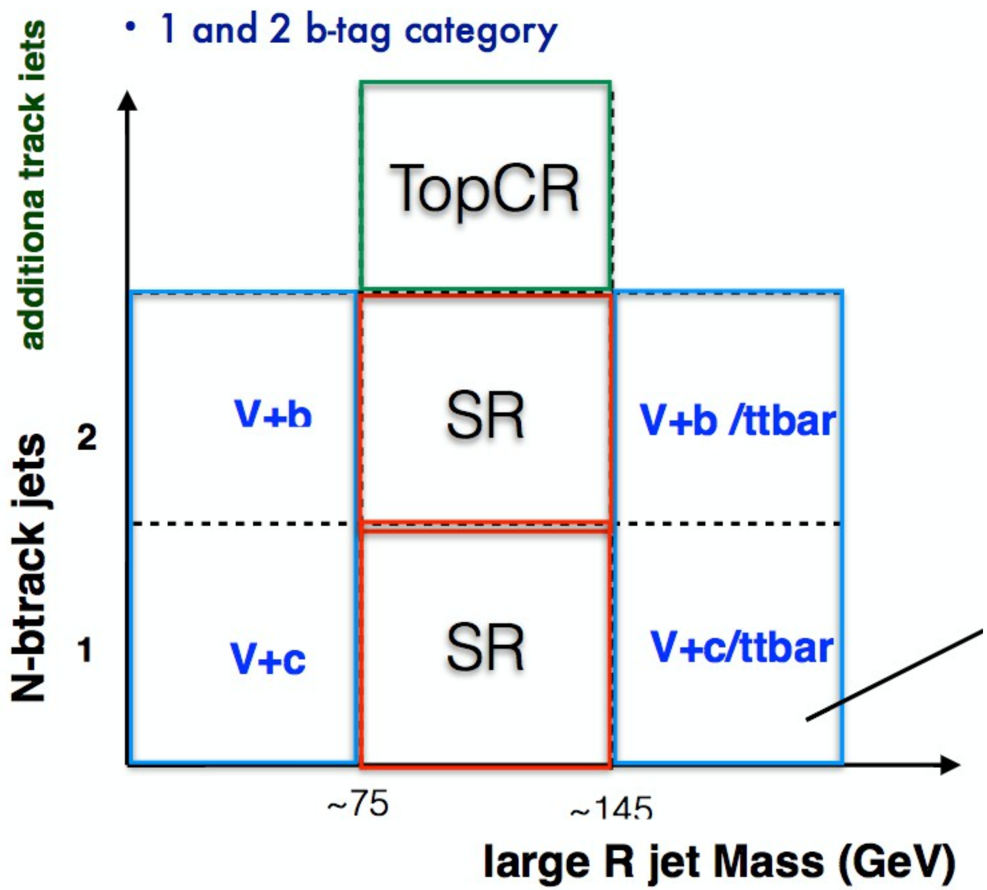
gFEX ρ = measure truncated mean (towers with E_T < 6 GeV) separately on each FPGA

Global Feature EXtractor (gFEX)

Successful Link Speed Test @CERN

Unfortunately not all the people that worked hard in the project are in this picture (taken during LAr-gFEX test)

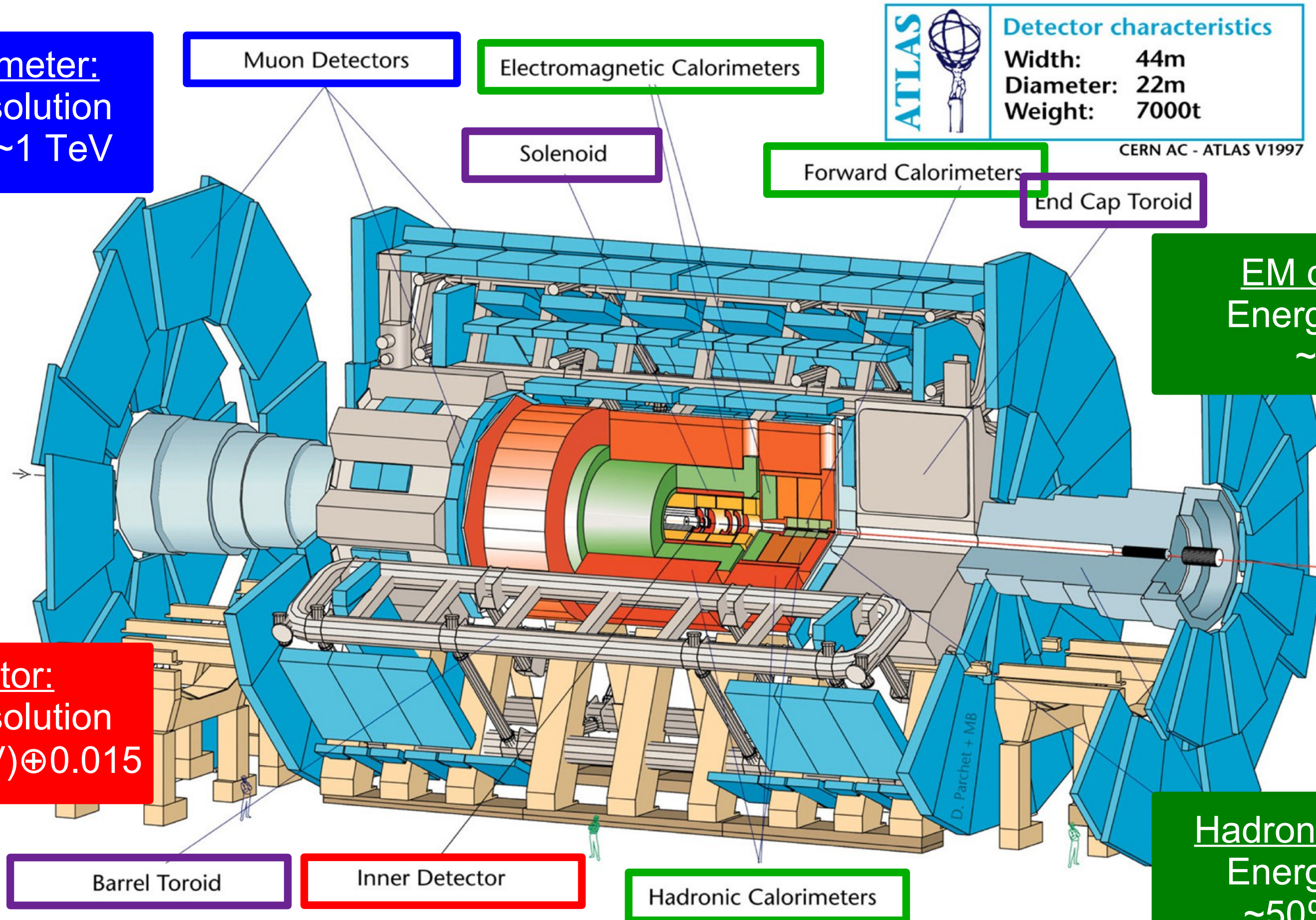
VH → llbb/lvbb/vvbb: backgrounds



ATLAS (A Toroidal LHC ApparatuS)

- ATLAS consists of a series of concentric sub-detectors around the interaction point
- Divided into 4 major parts: **the inner detector, the calorimeters, the muon spectrometer and the magnet systems**

Muon spectrometer:
Momentum resolution
<10% up to $E_\mu \sim 1$ TeV



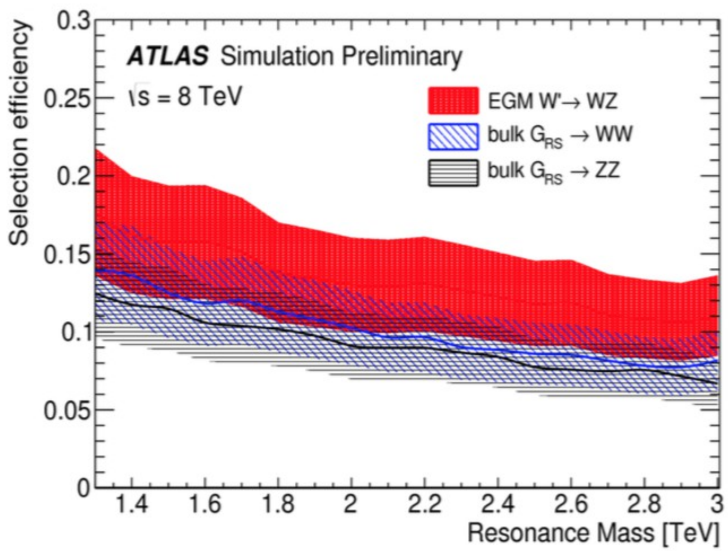
EM calorimeter:
Energy resolution
$\sim 10\%/\sqrt{E}$

Inner detector:
Momentum resolution
$\sim 3.8\times10^{-4}\, p_T(\mathrm{GeV}) \oplus 0.015$

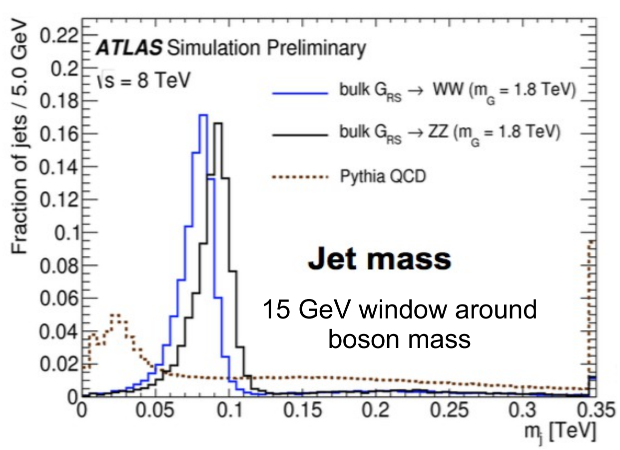
Hadronic calorimeter:
Energy resolution
$\sim 50\%/\sqrt{E} \oplus 0.03$

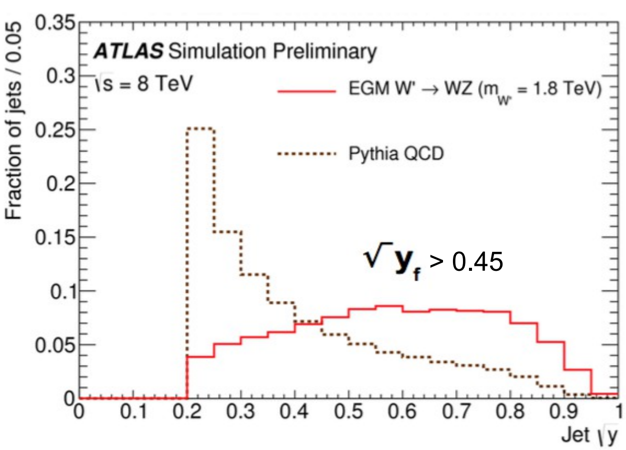
Search for new diboson resonances in ATLAS: Run-1 Event selection

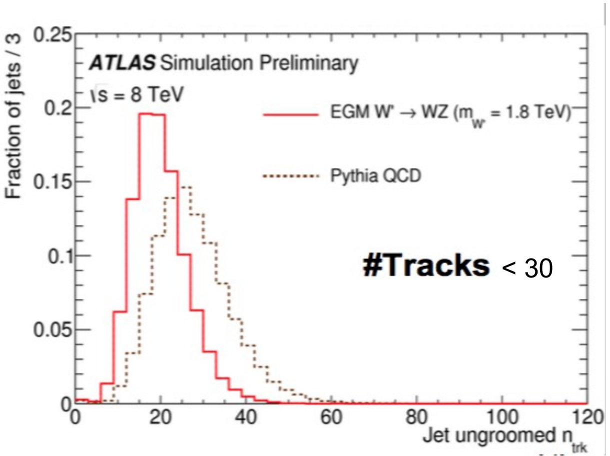
1. **Trigger selection:** EF_j360_a10tcem (lowest unprescaled jet trigger for 2012)
2. **Quality:**
   - GRL
   - DQ checks from data preparation: coreFlags, LArError, TileError, TileTripReader
   - Bad/ugly jets
   - BCH_CORR_CELL cleaning
3. **Lepton/MET veto:** orthogonal with other diboson searches
4. **Jets:**
   - **2 jets filtered with BDRS-A**
   - **Mass of dijet-system** is required to be **above 1.05 TeV**[1], in order to avoid region with trigger inefficiency
   - **Rapidity gap between the two leading jets** $|\Delta y_{12}| < 1.2$, to reject QCD t-channel dijet production
   - p_{T} **asymmetry,** $A < 0.15$, between two leading jets, to select balanced events
   - $|\eta < 2.0|$ to ensure good overlap with the inner detector
   - **Boson tagging criteria applied**



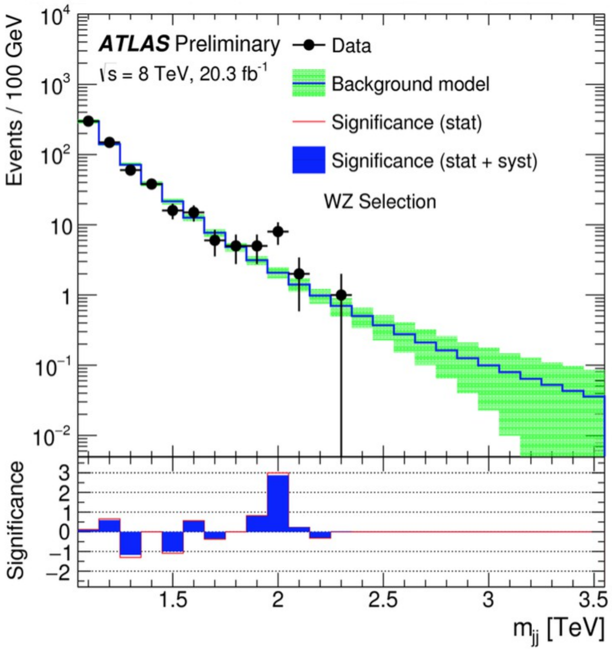
WW, WZ, ZZ partially overlapping selections

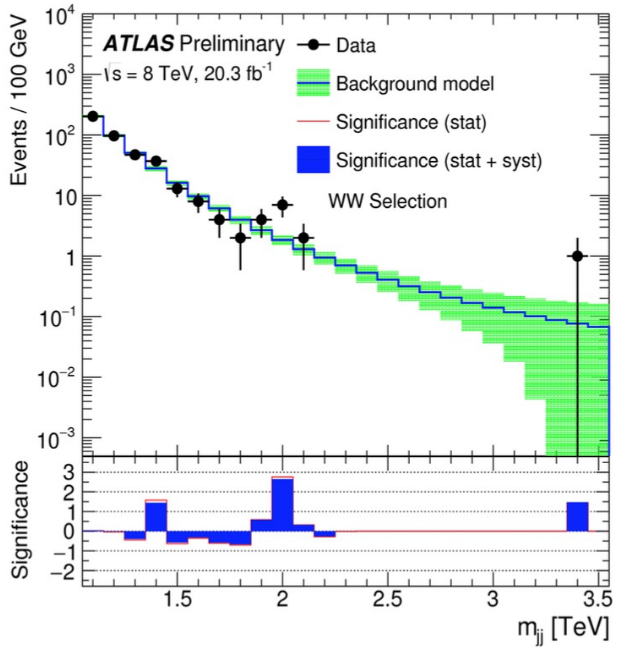


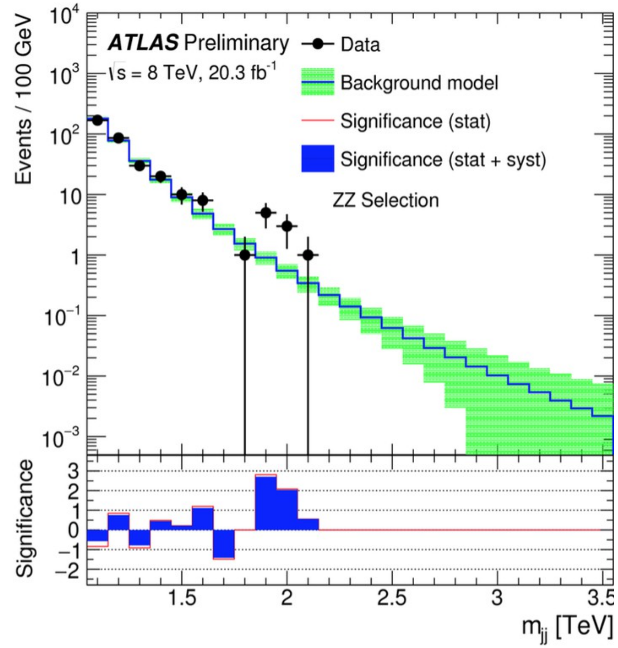


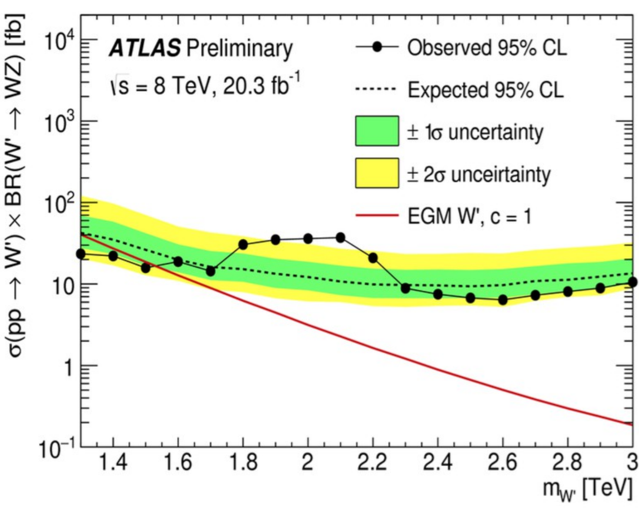


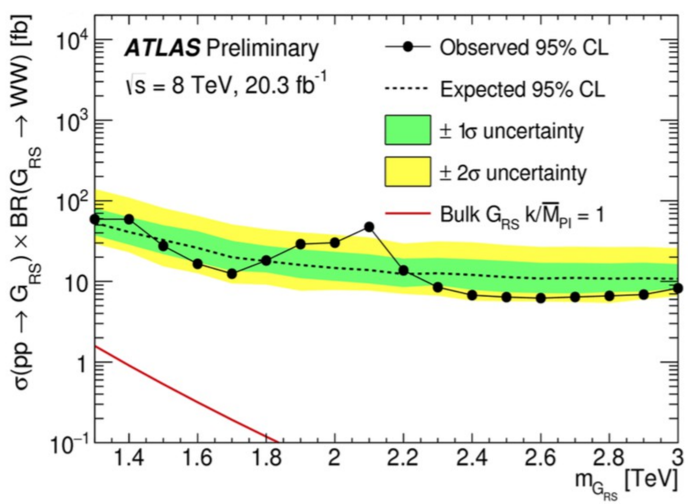
Full hadronic diboson Run-1 results

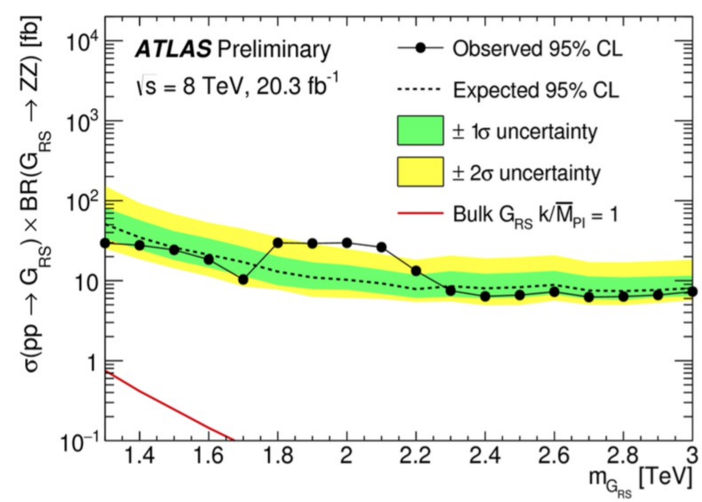




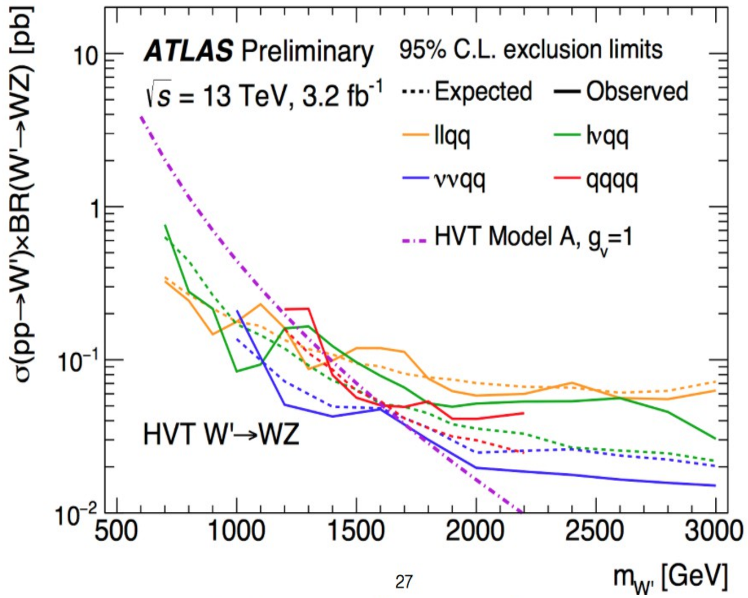




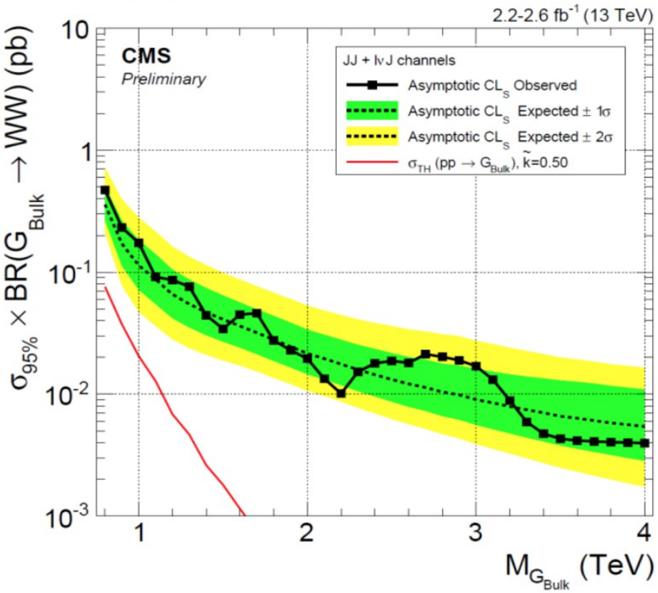




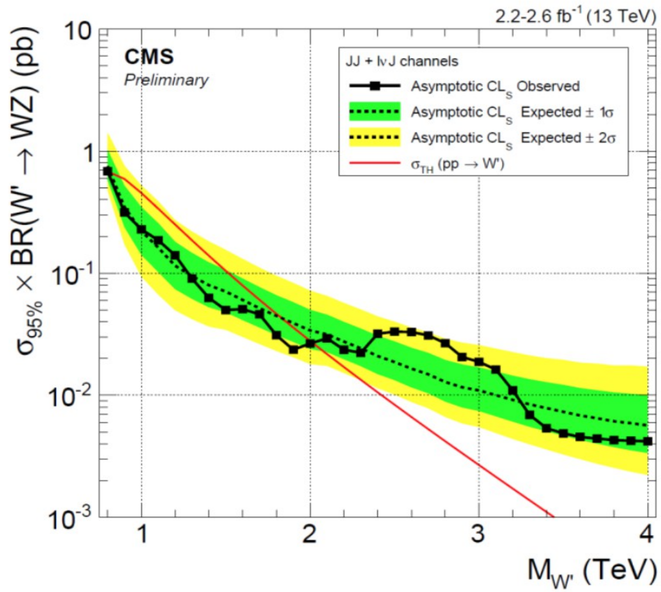
Diboson Run-2 results: ATLAS and CMS



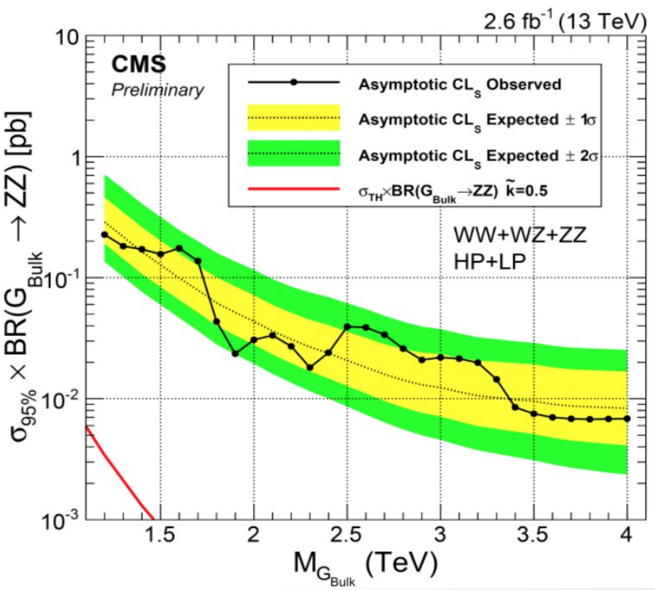
G_{Bulk}→WW (lνJ+JJ)



W'→WZ (lνJ+JJ)



G_{Bulk}→ZZ (JJ)



Information about benchmarks used in the 13 TeV analyses

Table 1: The resonance width (Γ) and the product of cross-section times branching ratio (BR) for diboson final states, for different values of the mass pole m of the resonances predicted by the CP-even scalar model ($\Lambda = 1$ TeV, $c_H = 0.9, c_3 = 1/16\pi^2$), by model B of the HVT parameterisation ($g_V = 3$), and by the graviton model ($k/\bar{M}_{Pl} = 1$).

	Scalar			HVT W' and Z'			G^*		
		WW	ZZ		WW	WZ		WW	ZZ
m [TeV]	Γ [GeV]	$\sigma \times$ BR [fb]	$\sigma \times$ BR [fb]	Γ [GeV]	$\sigma \times$ BR [fb]	$\sigma \times$ BR [fb]	Γ [GeV]	$\sigma \times$ BR [fb]	$\sigma \times$ BR [fb]
0.8	4.2	730	359	32	682	354	46	301	155
1.6	33	7.8	3.9	51	79.3	38.5	96	4.4	2.2
2.4	111	0.32	0.16	74	10.5	4.87	148	0.28	0.14

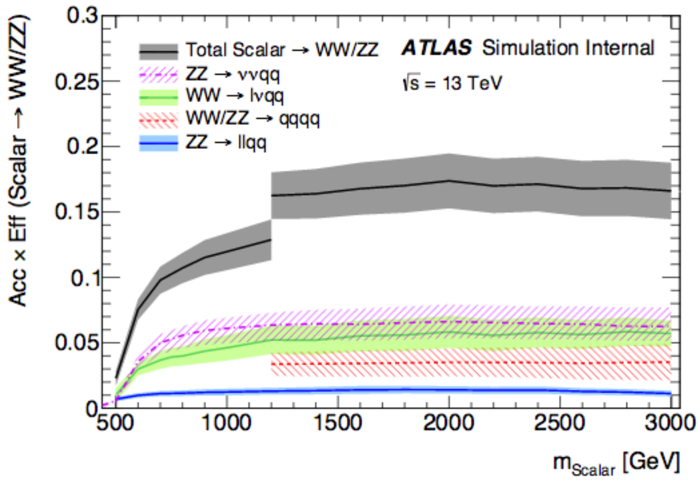
Table 2: Generators and PDFs used in the simulation of the various background processes.

Process	PDF	Generator
W/Z + jets	CT10	SHERPA 2.1.1
$t\bar{t}$	CT10	POWHEG-BOX v2+PYTHIA 6.428
Single top (Wt, s−channel)	CT10	POWHEG-BOX v2+PYTHIA 6.428
Single top (t−channel)	CT10	POWHEG-BOX v1+PYTHIA 6.428
Diboson (WW, WZ, ZZ)	CT10	SHERPA 2.1.1
Dijet	NNPDF23LO	PYTHIA 8.186

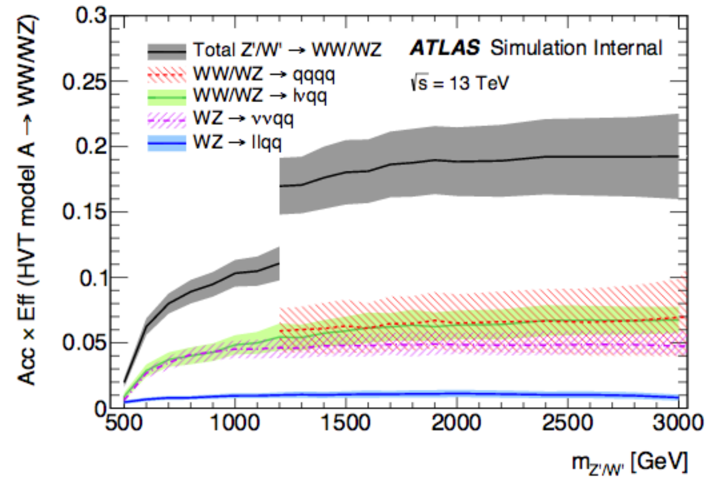
Table 4: Channels, signal regions and mass ranges where the channels contribute to the search.

Channel	Signal region	Scalar mass range [TeV]	HVT W' and Z' mass range [TeV]	G^* mass range [TeV]
$qqqq$	$WW + ZZ$ selection	1.2–3.0	–	1.2–3.0
	$WW + WZ$ selection	–	1.2–3.0	–
$\nu\nu qq$	WZ selection	–	0.5–3.0	–
	ZZ selection	0.5–3.0	–	0.5–3.0
$\ell\nu qq$	$WW + WZ$ selection	–	0.5–3.0	–
	WW selection	0.5–3.0	–	0.5–3.0
$\ell\ell qq$	WZ selection	–	0.5–3.0	–
	ZZ selection	0.5–3.0	–	0.5–3.0

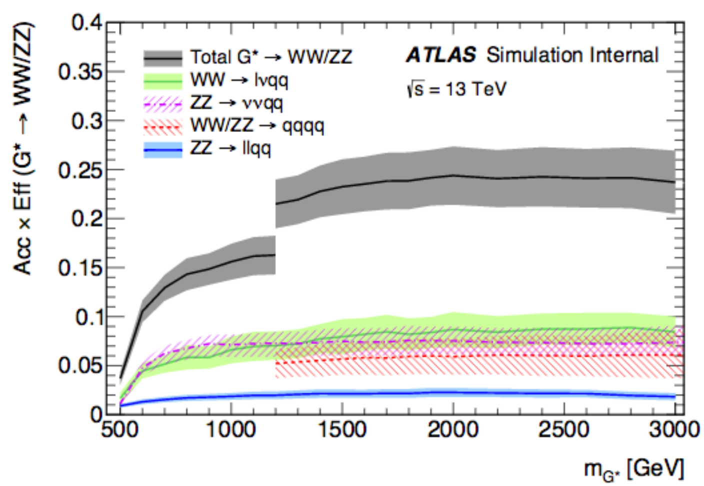
Information about benchmarks used in the 13 TeV analyses



(a)



(b)

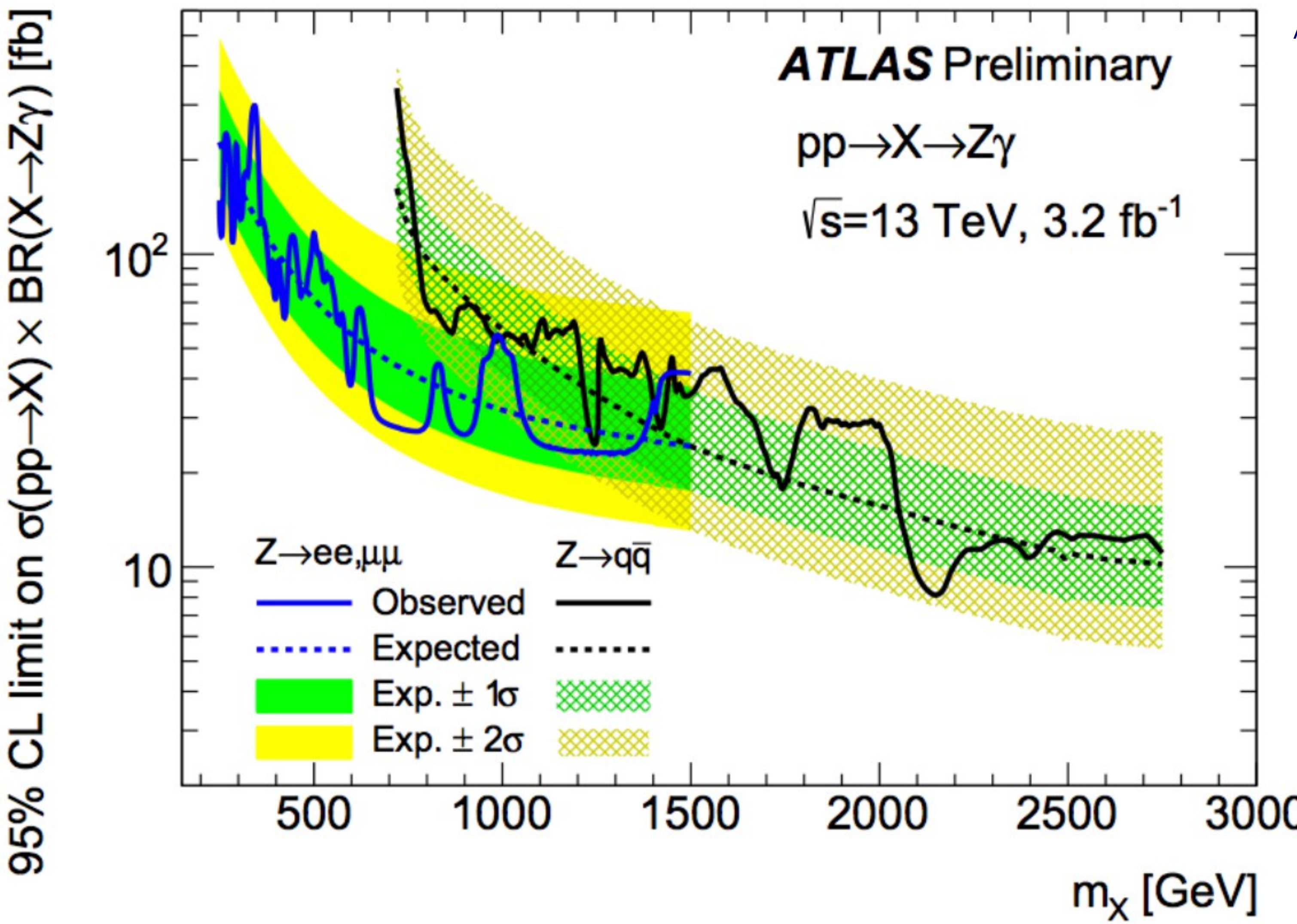


(c)

Figure 1: Signal acceptance times efficiency for the different analyses contributing to the searches for (a) a scalar decaying to WW and ZZ, (b) HVT decaying to WW and WZ and (c) bulk RS gravitons decaying to WW and ZZ. The branching ratio of the new resonance to diboson is included in the denominator of the calculation. The error bands represent statistical and systematic uncertainties.

Other intriguing results... diphotons at 750 GeV

- Limits set on σ(pp→X)*BR(X→Zγ) assuming scalar X produced in gluon fusion
- Observed limits between 295 fb for m_X = 340 GeV and 7.5 fb for m_X = 2.15 TeV



ATLAS-CONF-2016-010

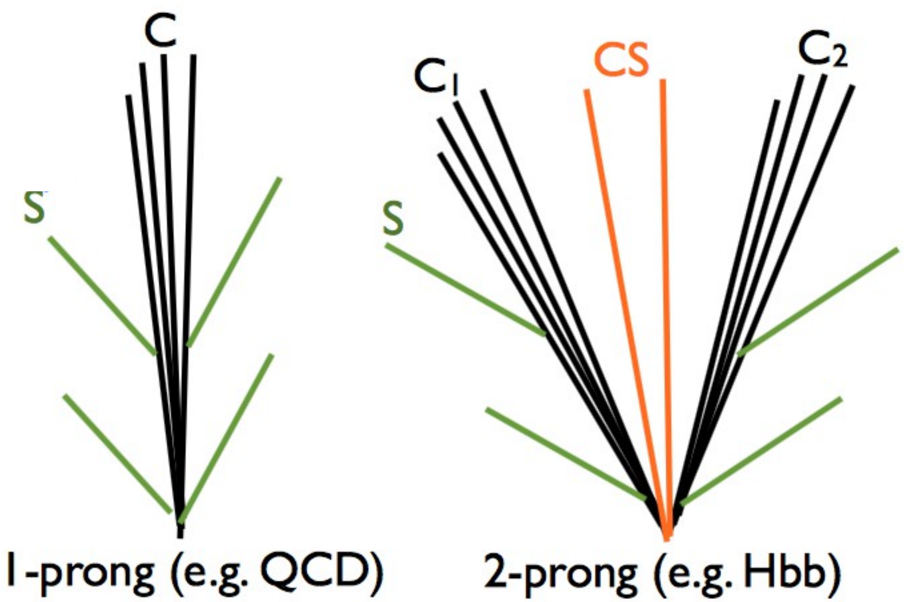
D2 definition

$$e_2^{(\beta)} = \frac{1}{p_{TJ}^2} \sum_{1 \le i < j \le n_J} p_{Ti} p_{Tj} R_{ij}^{\beta} \,,$$

$$e_3^{(\beta)} = \frac{1}{p_{TJ}^3} \sum_{1 \le i < j < k \le n_J} p_{Ti} p_{Tj} p_{Tk} R_{ij}^{\beta} R_{ik}^{\beta} R_{jk}^{\beta} \,,$$

$$D_2^{(\beta)} = \frac{e_3^{(\beta)}}{(e_2^{(\beta)})^3}$$

Larkoski et al,arXiV:1409.6298



D_2: large for 1-prong jet (e.g. QCD bkg.)

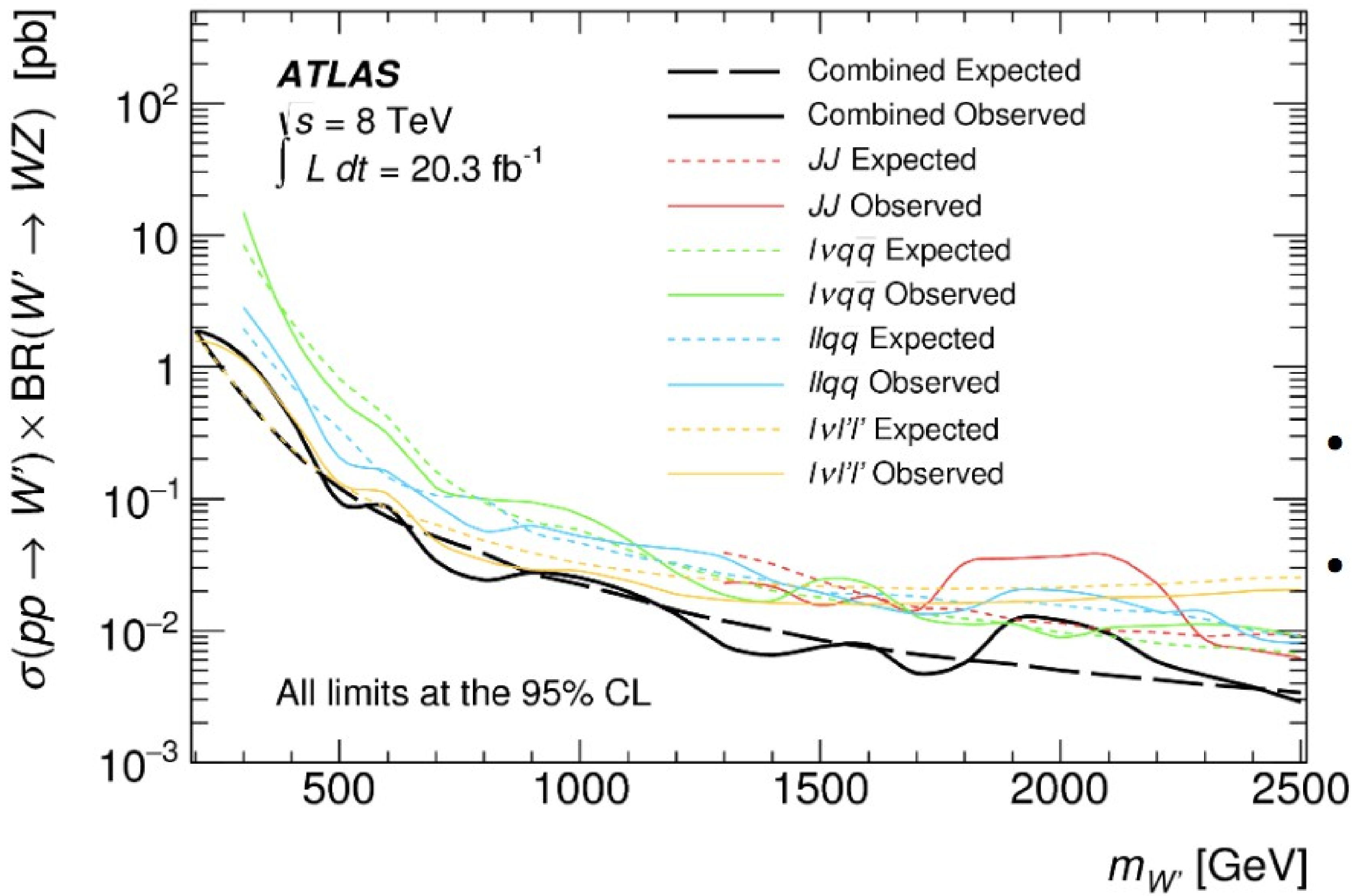
$$(e_2)^3 \lesssim e_3 \lesssim (e_2)^2$$

small for 2-prong jet (Higgs signal)

$$0 < e_3 \ll (e_2)^3$$

Plots from R. Jacobs

Some extra from Run-1: an analysis you might remember



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W/Z boson tagging for early Run-2

JETM-2016-009