Search for new physics using diboson topologies: from the direct to the indirect quest

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Habilitation à diriger de recherches
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Jury members:

Maria Teresa DOVA, Universidad Nacional de La Plata
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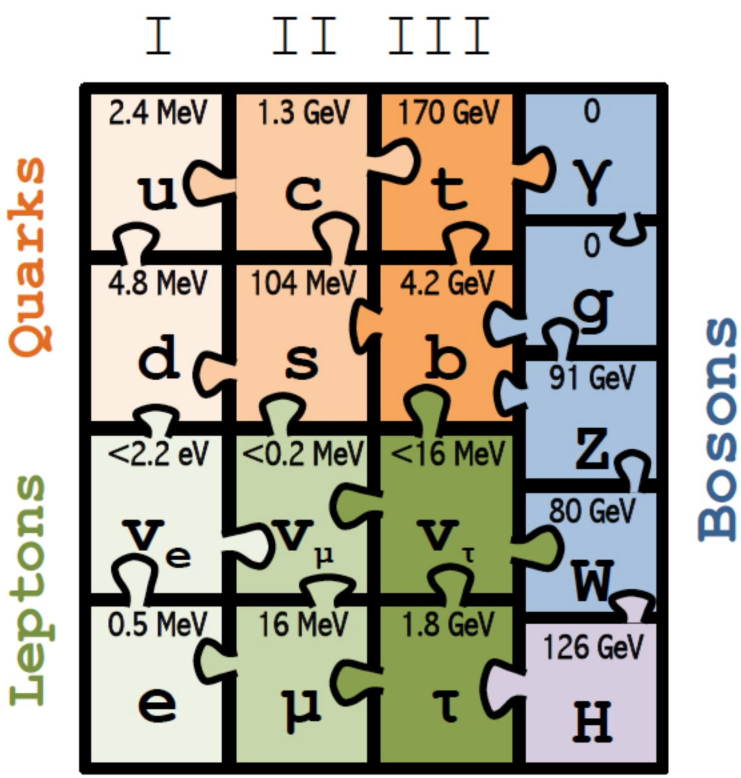
The Standard Model

An experimental success

The Standard Model (SM) is a huge success from the experimental point of view



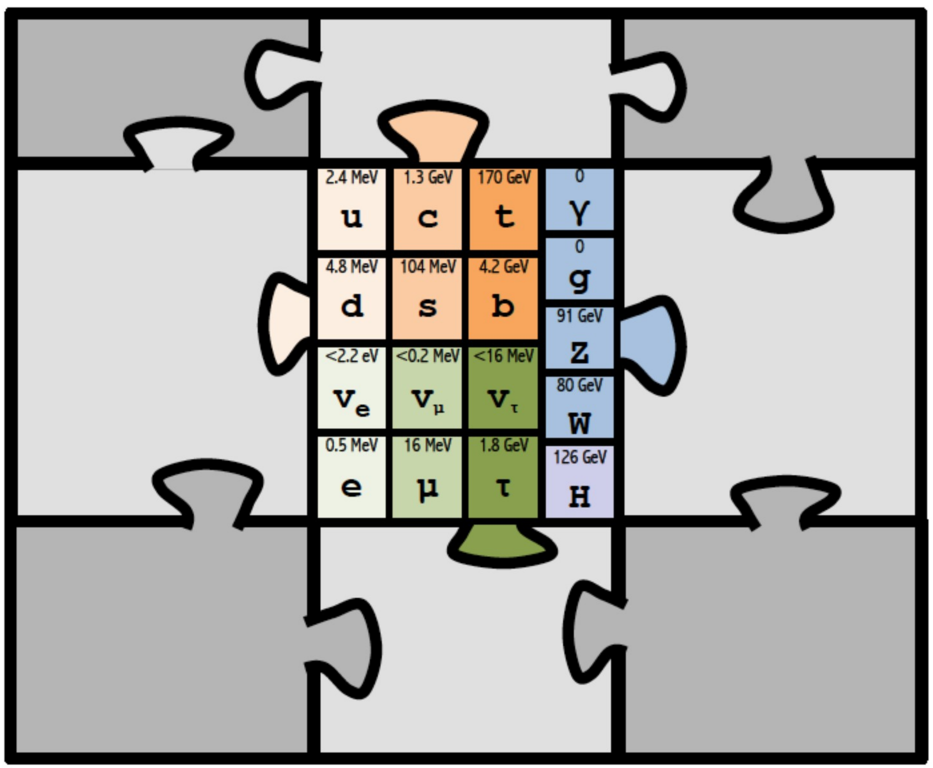
$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
& + i \bar{\psi} \not{D} \psi \\
& + \psi_i y_{ij} \psi_j \phi + h.c. \\
& + |D_\mu \phi|^2 - V(\phi)
\end{aligned}
$$

July 4th 2012: "Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC"

- The particle content of the SM is complete
- With the measurement of the Higgs mass, no more unmeasured parameters

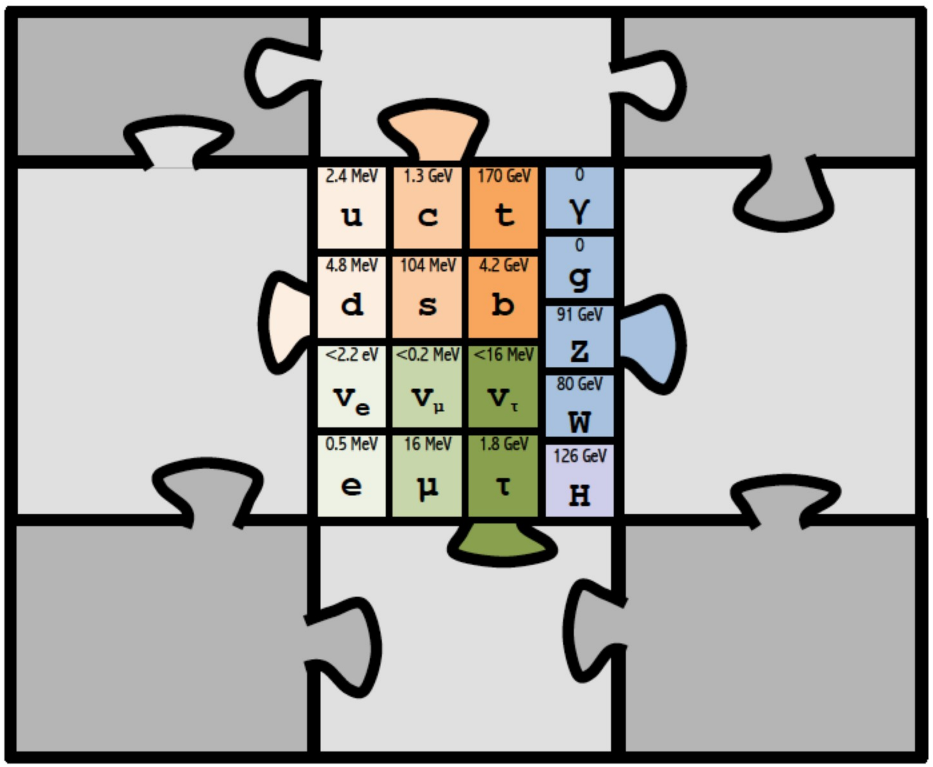
The Standard Model

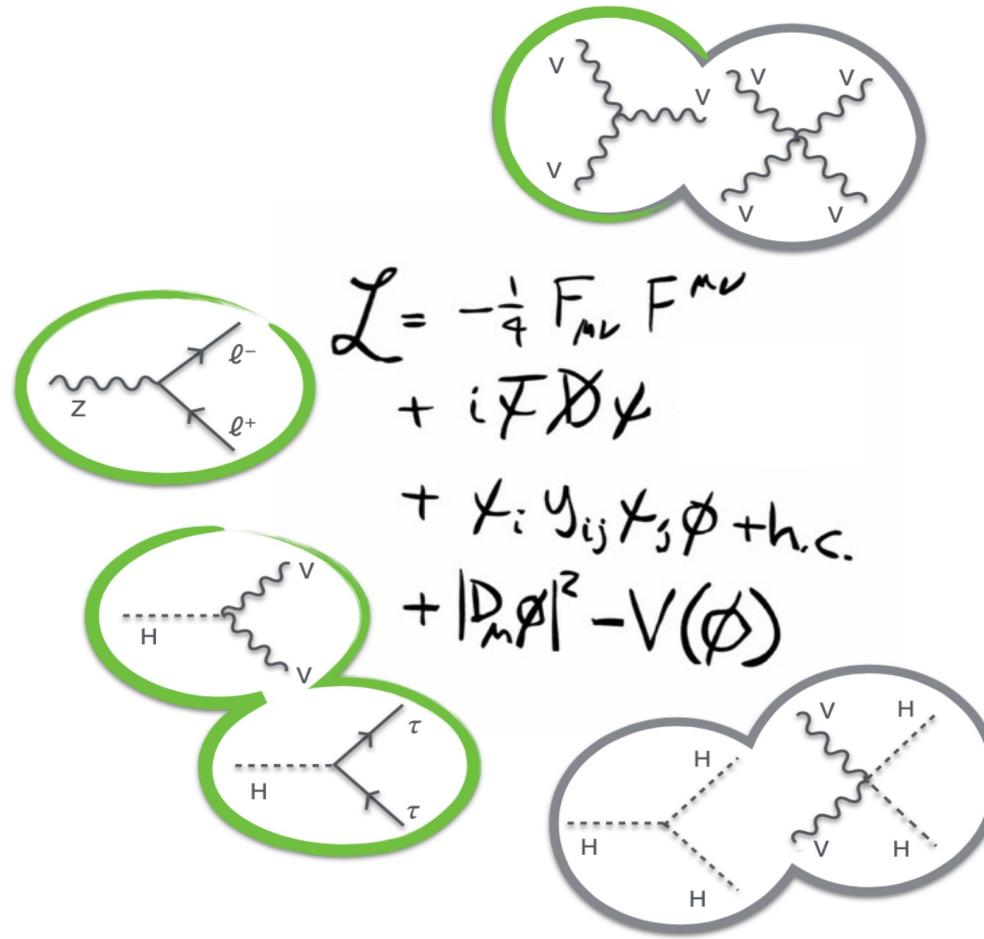
One piece of the universe puzzle?



- But it does not accommodate everything we need to know about nature:
  - Dark matter
  - Dark energy
  - Neutrino oscillation
  - Matter-antimatter asymmetry
  - Fermion mass hierarchy
  - Gravity
  - ...
- There must be something more!
- Our work as scientists is to search for that something and understand what we have
- Lots of work to do!

The Standard Model
One piece of the universe puzzle?





- Could new physics be hidden in the Electroweak Symmetry Breaking (EWSB) sector?
  - Study the dynamics of the scalar sector of the SM as a whole, considering both the Higgs boson and the Nambu-Goldstone states could shed light on this question

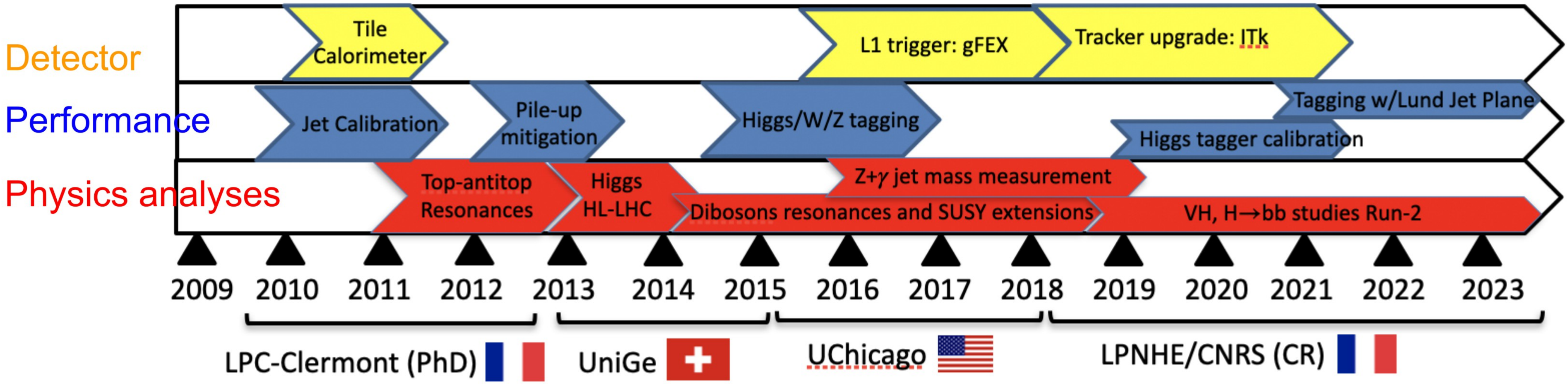
- **Diboson states could serve as swiss army knife in our quest for new physics**!

Before moving forward: my academic path

- **Bachelor in physics**, ULA, Venezuela (2003-2008)

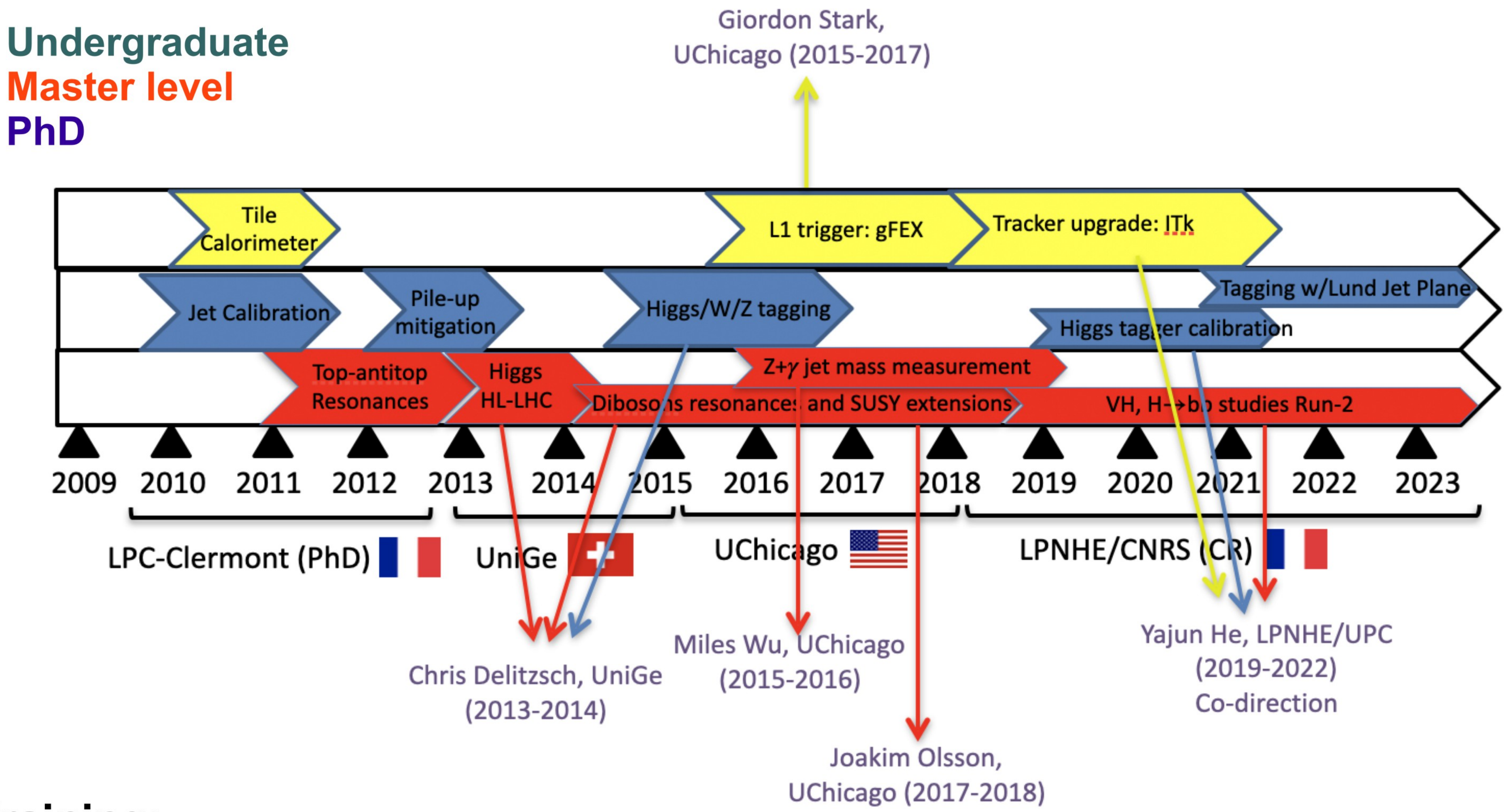
- HEP Latinamerican-European Network (HELEN) fellowship, LPNHE, Paris (2008-2009)
  - **B-physics phenomenology**

- **Doctoral, postdoctoral & staff experience:**



- **Teaching:**
  - Postdoctoral teaching assistant at Université de Genève
  - LA-CoNGA physics (Latin American alliance for Capacity buildING in Advanced physics) and CEVALE2VE
- **Students supervision:** 5 PhD (1 co-direction), 3 master students, 6 undergrads

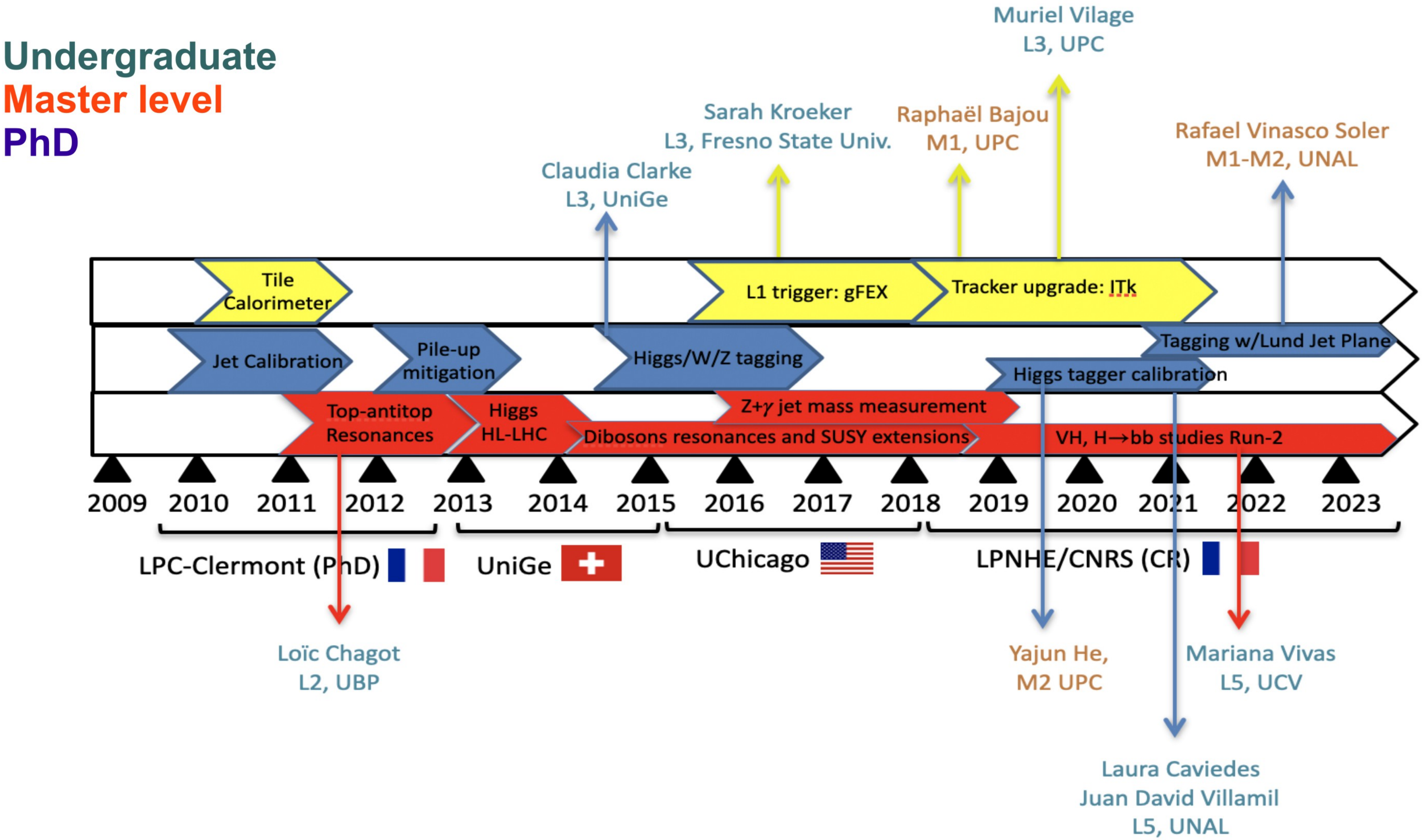
Student supervision and training



Training:

- Echanges de pratiques entre encadrants de doctorants. Association Bernard Gregory (ABG). France. April 2020
- Management d'un projet doctoral. Institut de formation doctorale, UPMC-Sorbonne Universités. 2019
- Conseil collectif d'encadrants. Sorbonne Université. 2019

Student supervision and training

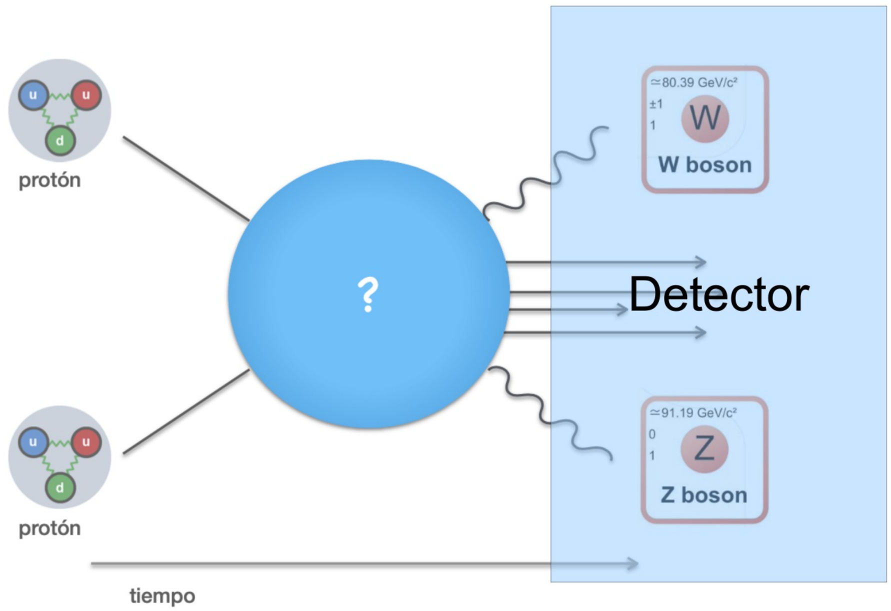


In this talk:
Direct participation

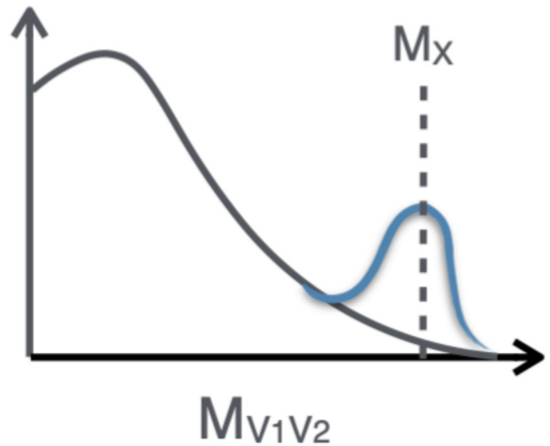
How to search for new physics with dibosons?

1. Produce and reconstruct diboson pairs

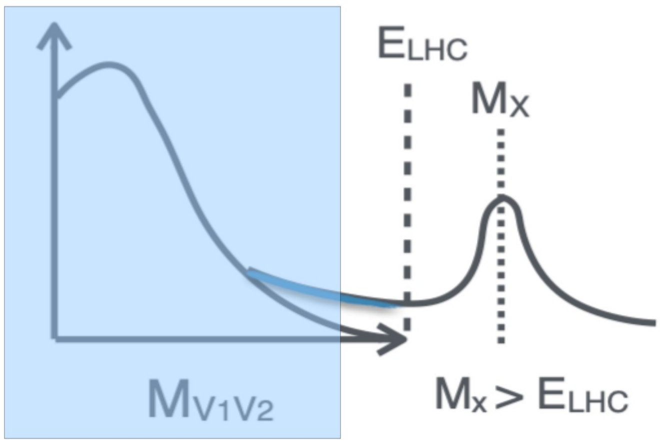
2. Compare with the SM predictions

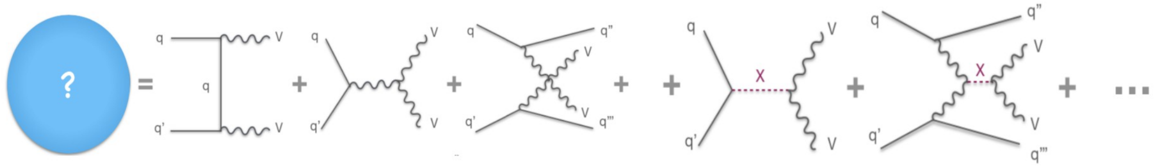


Direct searches: new resonances



Indirect searches: beyond LHC reach can still leave measurable fingerprints





Adapted from J. Manjarrés
LA-CoNGA physics seminar 2021

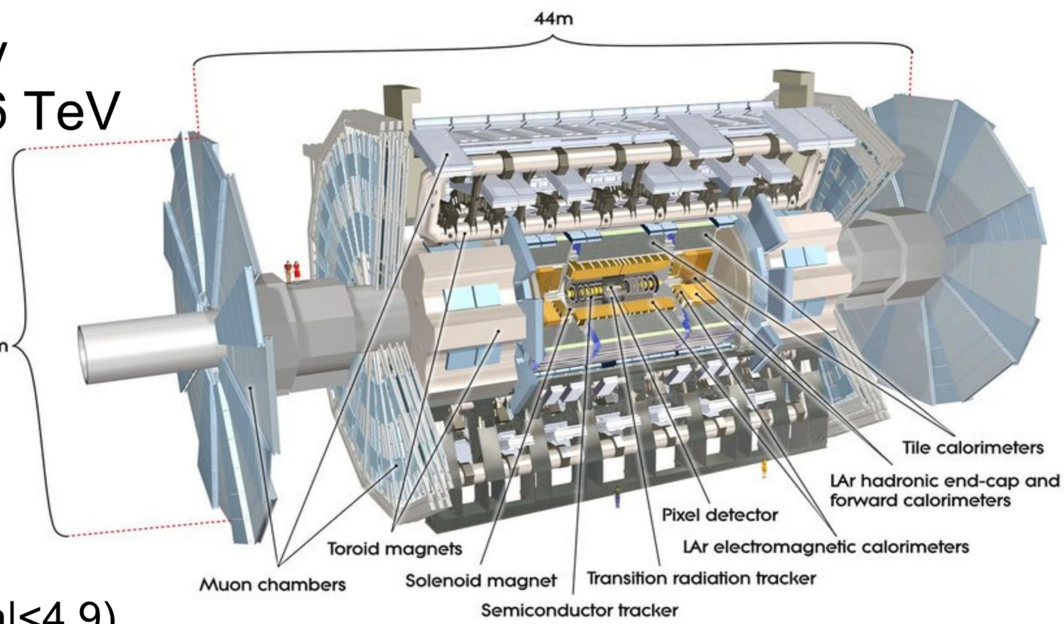
Our tools

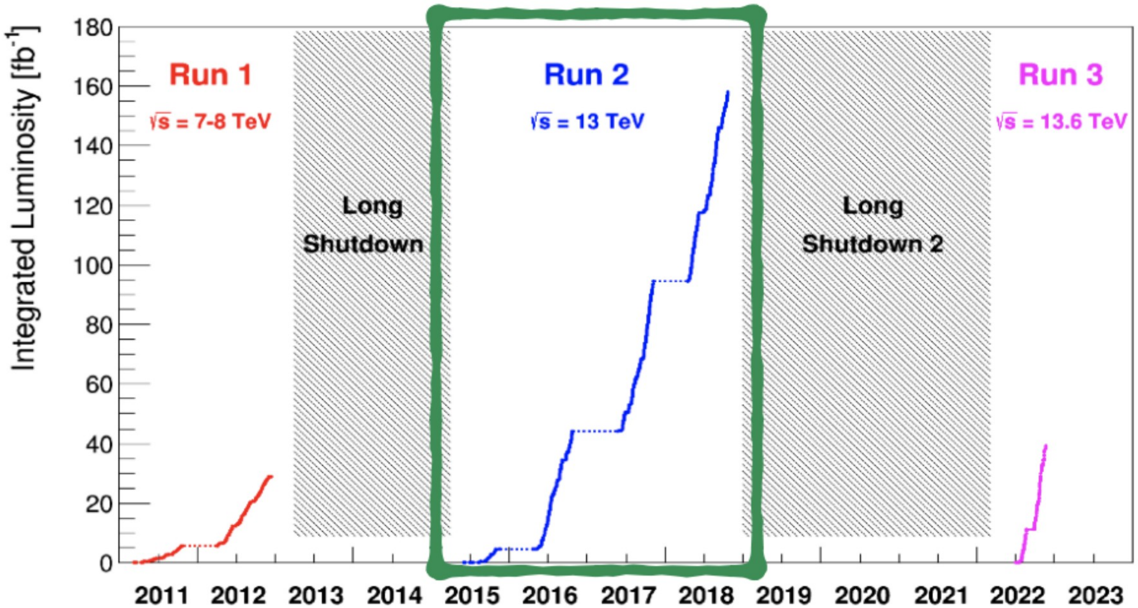
The LHC and ATLAS

- A proton-proton collider of 27 Km circumference situated at CERN. Currently running at a center-of-mass energy of 13.6 TeV since 2022

- **Fantastic machines with capabilities beyond design**

- ATLAS is a non-specialized detector:
  - Excellent vertex and tracking systems (|η|<2.5)
  - Large coverage for muon detection
  - Excellent calorimetry with extended coverage (|η|<4.9)



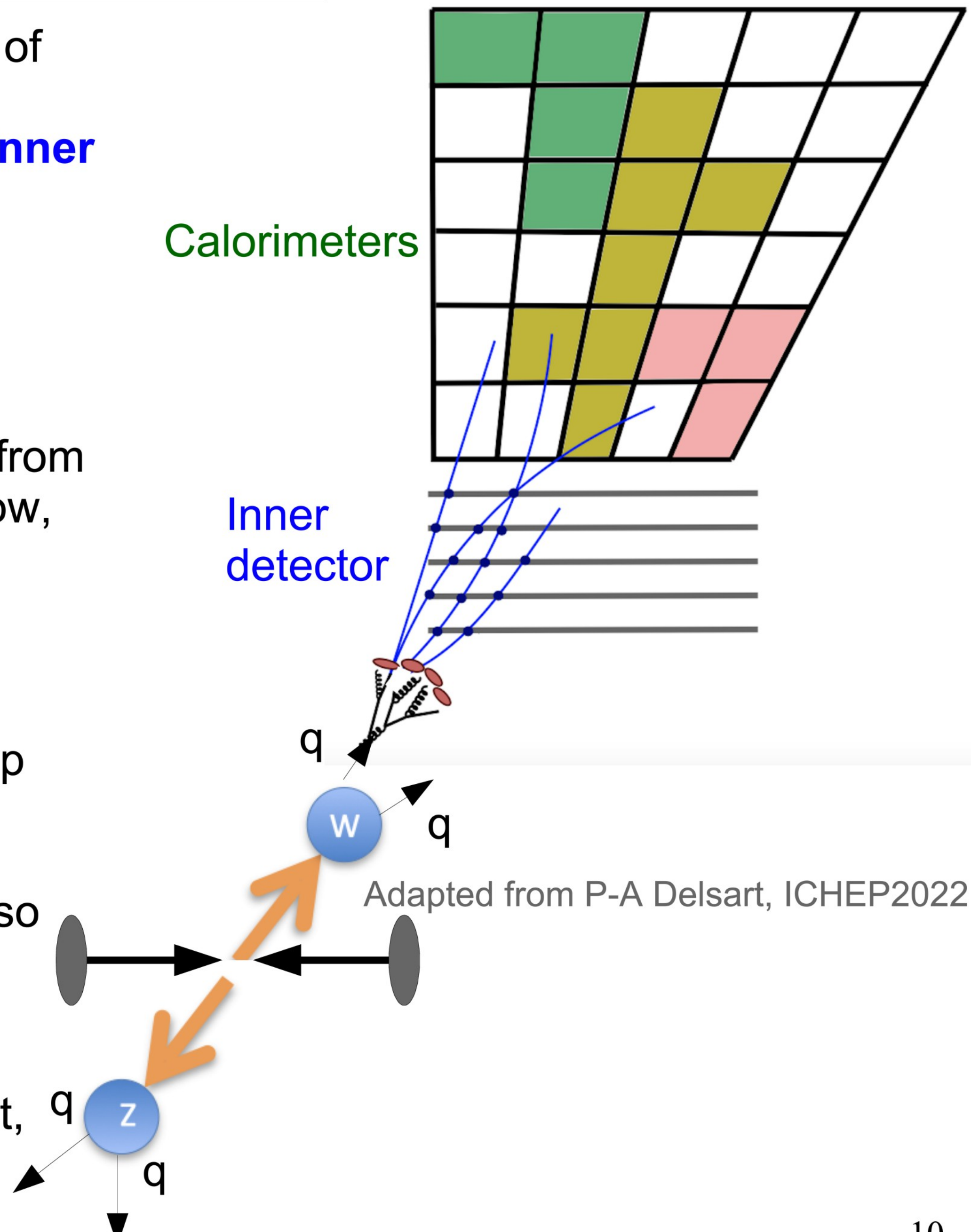


ATLAS pp Run-2: July 2015 – October 2018										
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.5	99.9	99.7	99.6	99.7	99.8	99.6	100	100	99.8	98.8
Good for physics: 95.6% (139 fb^{-1})										

Reconstructing boosted bosons: focus on hadronic decays

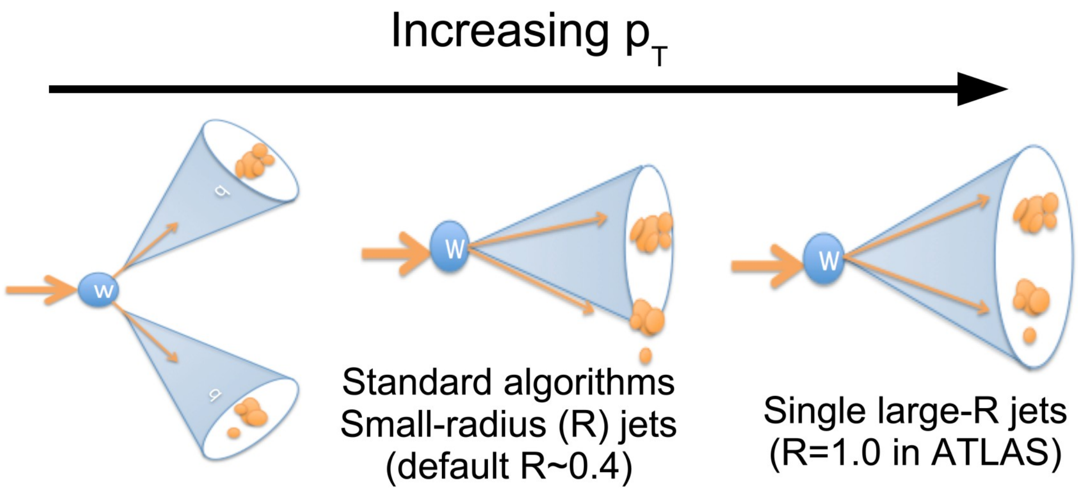
- **Jets:** quarks/gluons hadronize in collimated set of hadrons
- Charge hadrons reconstructed as tracks in the **Inner Detector**. All hadrons are then absorbed (and measured) in the **Calorimeters**

- **Steps in jet building:**
  - **Inputs/constituents:** jets are reconstructed from 4-vectors inputs representing the hadronic flow, such as tracks, calorimeter clusters, truth particles
  - **Reconstruction:** group constituents with a proper jet algorithm. Apply "grooming" (pile-up mitigation)
  - **Calibration:** to correct the jet energy (and also the mass in some cases) scale
  - **Tagging:** studying its substructure we can identify which particle is at the origin of the jet, e.g. is a quark or a gluon? Or rather a vector boson? Is it a Higgs or a top quark?



Adapted from P-A Delsart, ICHEP2022

Reconstructing boosted bosons: focus on hadronic decays

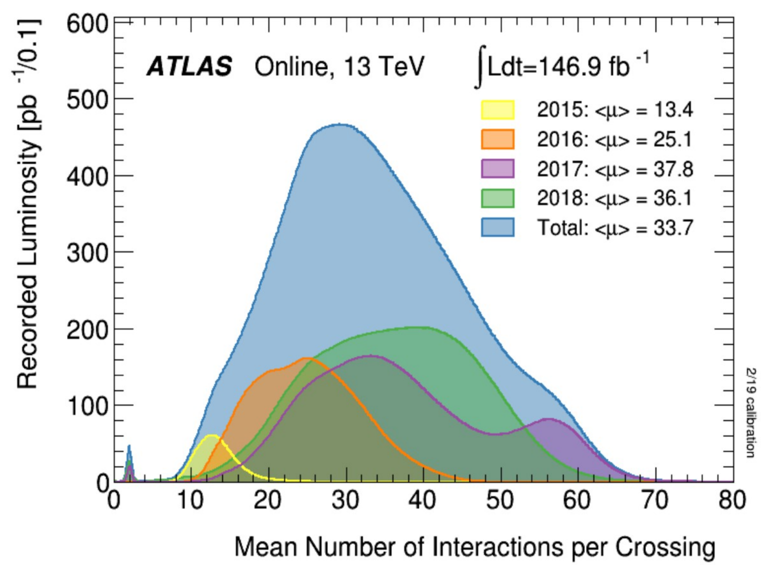


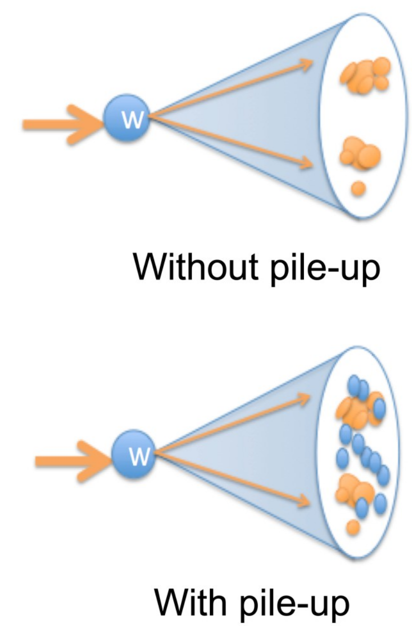
- Rule of thumb for angular separation of decay products

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

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** (ΔηxΔφ=0.025$*\pi$/128 for EM and ΔηxΔφ=0.1-0.2x0.1 for hadronic)
  - Additional proton-proton interactions (**pile-up) are a big challenge**





Reconstructing boosted bosons: focus on hadronic decays

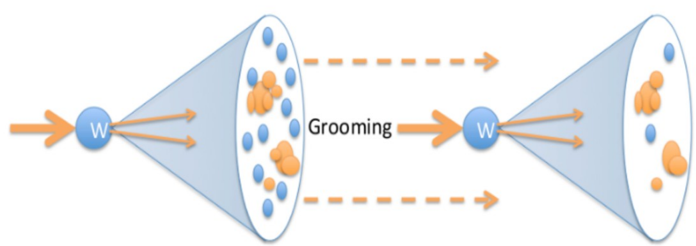
Large-R jets

Large distance parameter to pick up all radiation from original decay

- Became a very active field around 2010
- Large number of grooming algorithms and substructure variables
- **Few ATLAS analyses used these techniques at the end of Run-1, e.g. diboson resonance searches**

Grooming

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

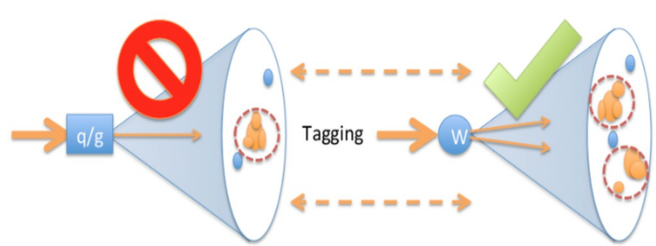


Some used algorithms:

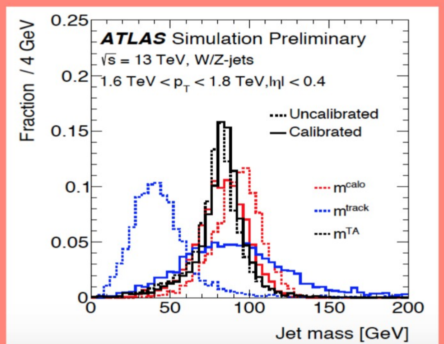
- Trimming [arXiv:0912.1342]
- Filtering [arXiv:0802.2470]
- Pruning [arXiv:0903.5081]
- Soft-drop [arXiv:1402.2657]

Tagger: substructure

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

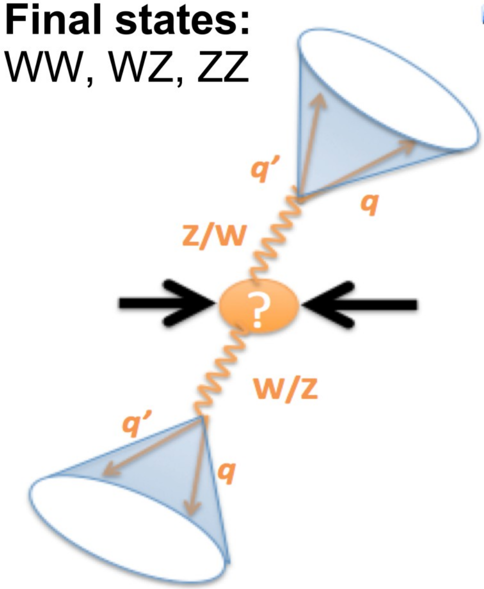


An example:



Run-1: Full hadronic diboson resonance search
Analysis in a nutshell

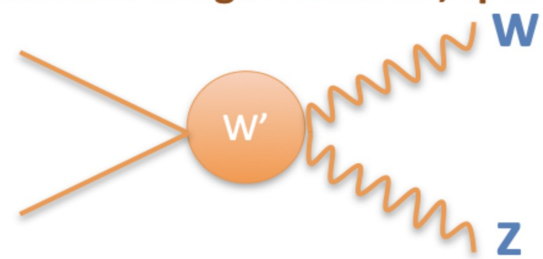
Final states:
WW, WZ, ZZ



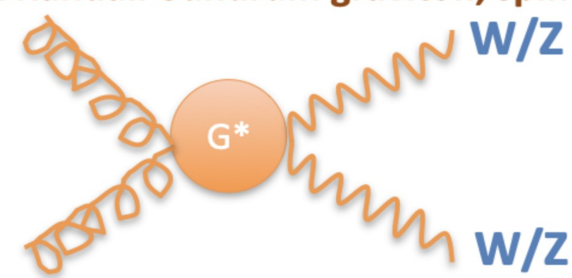
- **Strategy:**
  - Benchmark models are used as a guide when designing the search
  - Looking only for hadronic decays due to large BR
  - Narrow resonance is assumed which will show up only as a deviation in a small number of bins
  - Assume a smoothly, steeply falling background, and dijet mass spectrum is fitted

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

Extended Gauge Model W', spin-1

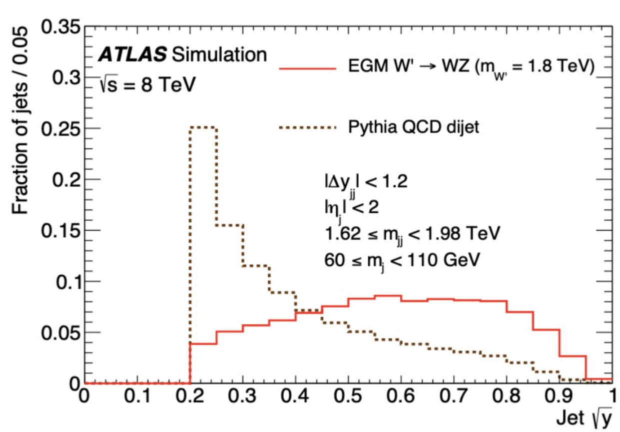


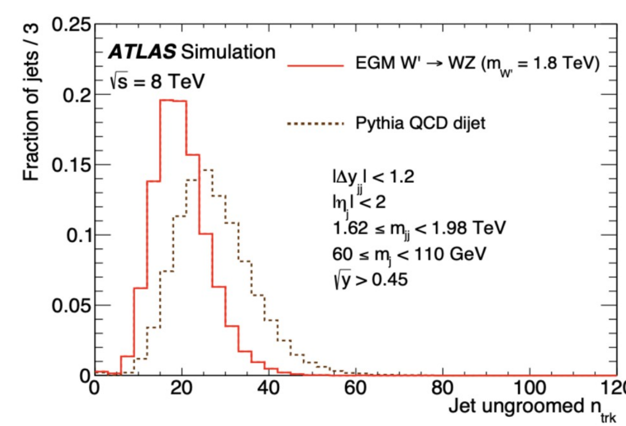
KK Randall-Sundrum graviton, spin-2



- **Selection:**
  - Two large-R jets C/A algorithm, R=1.2 and split-filtering algorithm grooming
  - Boson tagged jets, cuts on
    - Subjet momentum balance
    - Track multiplicity
    - Jet mass

JHEP 12 (2015) 55





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Run-1: Full hadronic diboson resonance search
Many cross-checks performed

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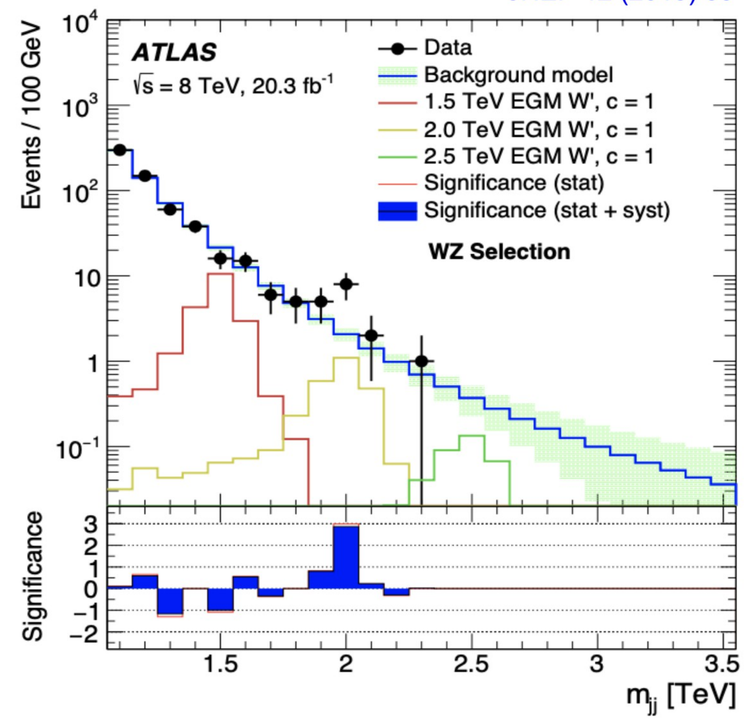

- **An excess was observed**
  - Largest in “WZ” 3.4σ local (2.5σ global)
  - 49% of events shared for “WZ” and “WW”, 43% shared between “WZ” and “ZZ”
- Many cross checks were performed at the time:
  - Events not in a particular region of the detector
  - No dependence on data taking conditions
  - N-1 plots for boosted boson tagging... etc
  - *The choice of jet reconstruction algorithm could not be studied, at the time no other algorithm was optimized and calibrated*

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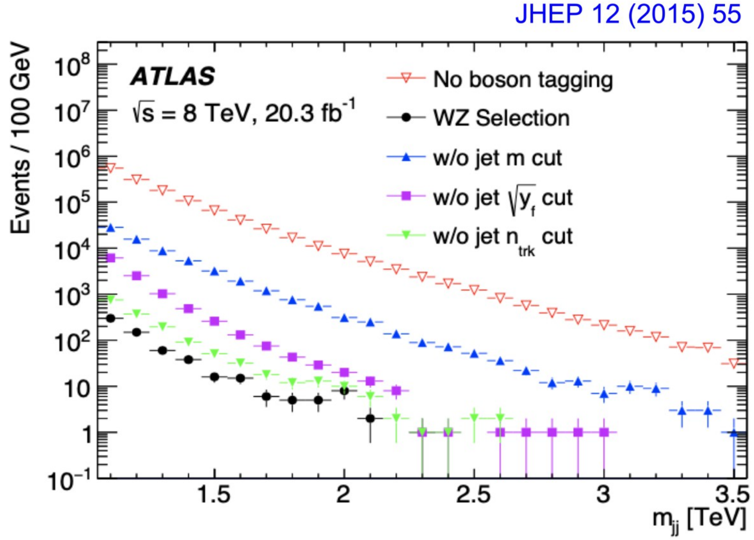

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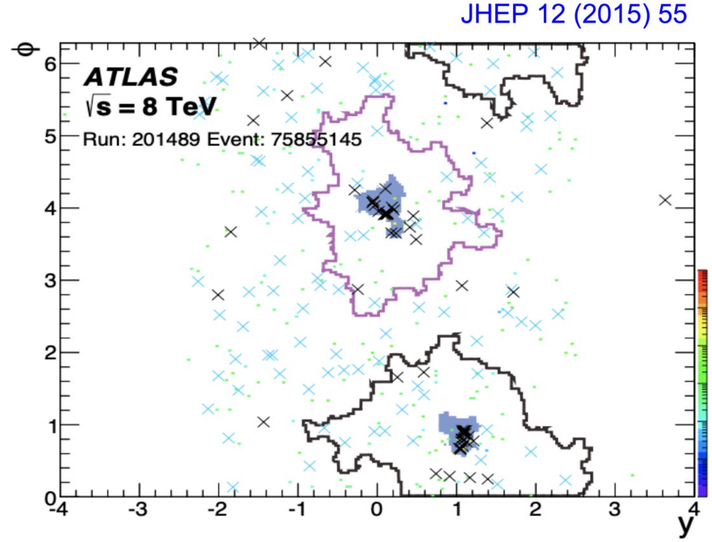
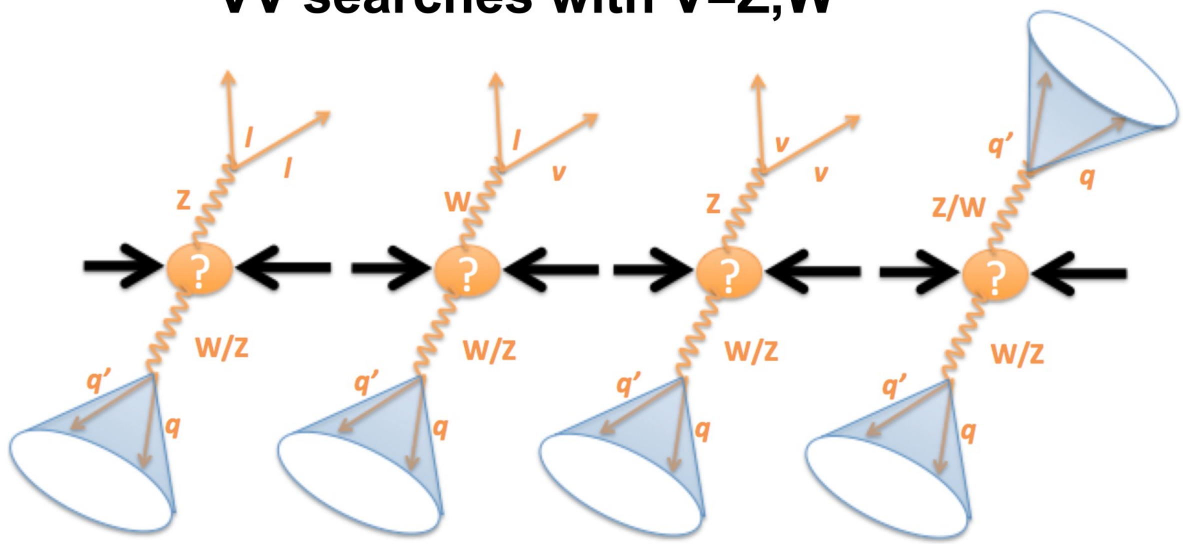


Run-1: Full hadronic diboson resonance search
A bit of perspective

- What was being observed in other diboson analyses in ATLAS and on the other side of the ring at CMS at the end of Run-1?

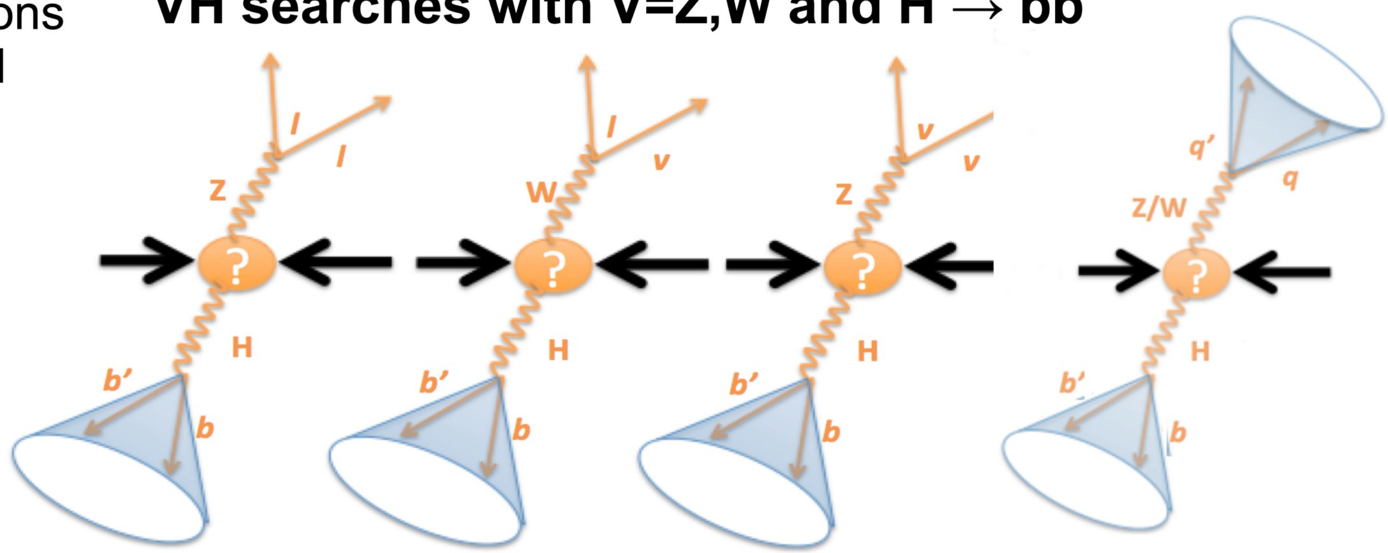
VV searches with V=Z,W



Complementarity:

- Leptonic modes covering low p_T
- Exploiting different S/B across regions and background composition

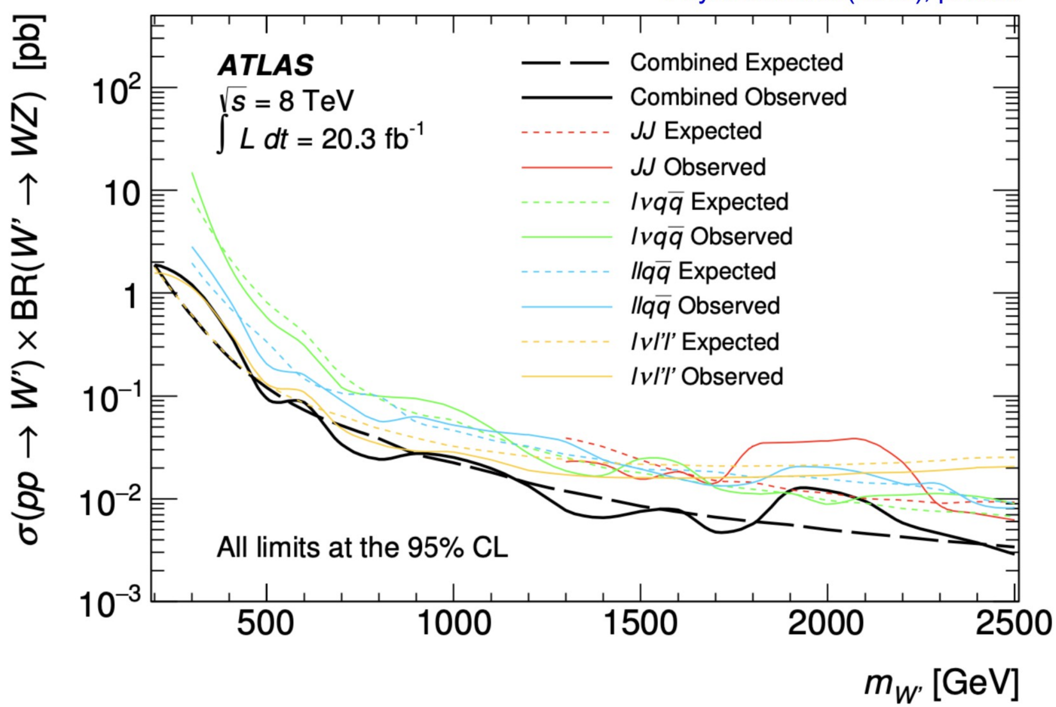
VH searches with V=Z,W and H → bb

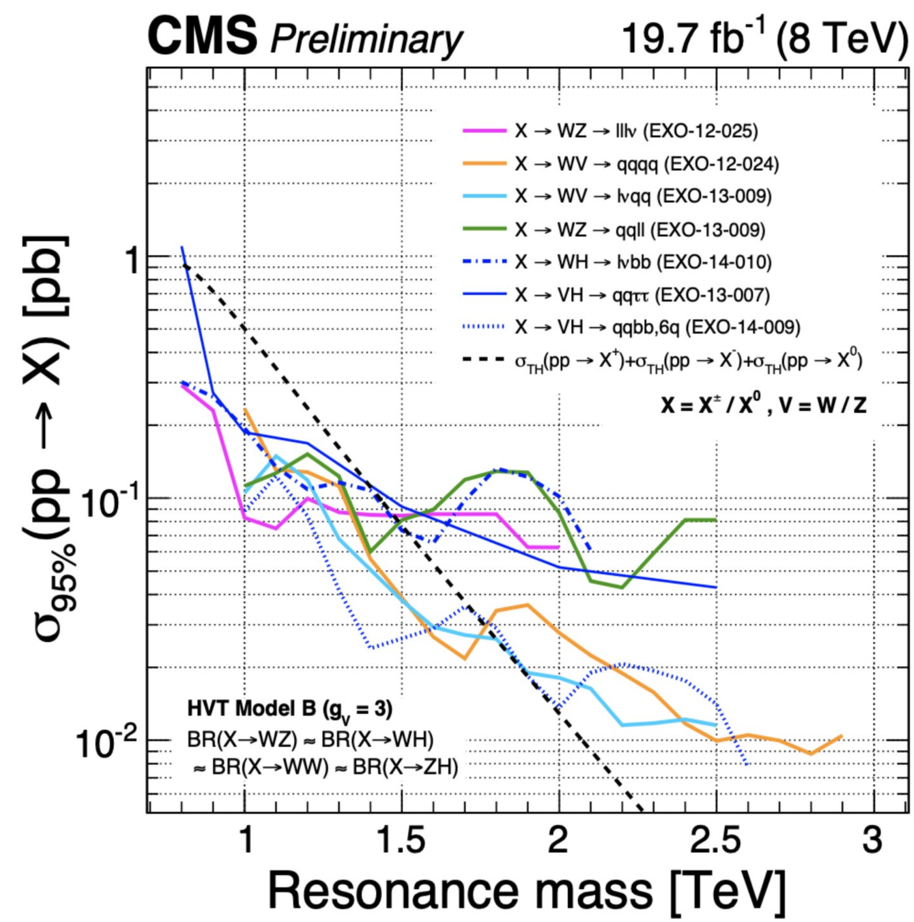


Run-1: Full hadronic diboson resonance search
A bit of perspective

- What was being observed in other diboson analyses in ATLAS and on the other side of the ring at CMS at the end of Run-1?

Phys.Lett.B755(2016), p. 285.





- **CMS:** small excesses observed in some channels, around 1.8-1.9 TeV
  - Analysis different from ATLAS: different jets, boson tagger τ21, etc
- **ATLAS:** Not seen in other more sensitive channels

Run-1: Full hadronic diboson resonance search
A bit of perspective

- ***Some interest generated in the community, high expectations for Run-2***

arXiv > hep-ph > arXiv:1512.04357

High Energy Physics – Phenomenology

[Submitted on 14 Dec 2015]

The Diboson Excess: Experimental Situation and Classification of Explanations; A Les Houches Pre-Proceeding

Regular Article - Theoretical Physics | Open Access | Published: 18 May 2016

A model for the LHC diboson excess

Manuel Buen-Abad, Andrew G. Cohen & Martin Schmaltz

Journal of High Energy Physics **2016**, Article number: 111 (2016) | Cite this article

arXiv > hep-ph > arXiv:1511.08921

High Energy Physics – Phenomenology

[Submitted on 28 Nov 2015 (v1), last revised 8 Jun 2016 (this version, v3)]

ATLAS Diboson Excess from Stueckelberg Mechanism

arXiv > hep-ph > arXiv:1705.07885

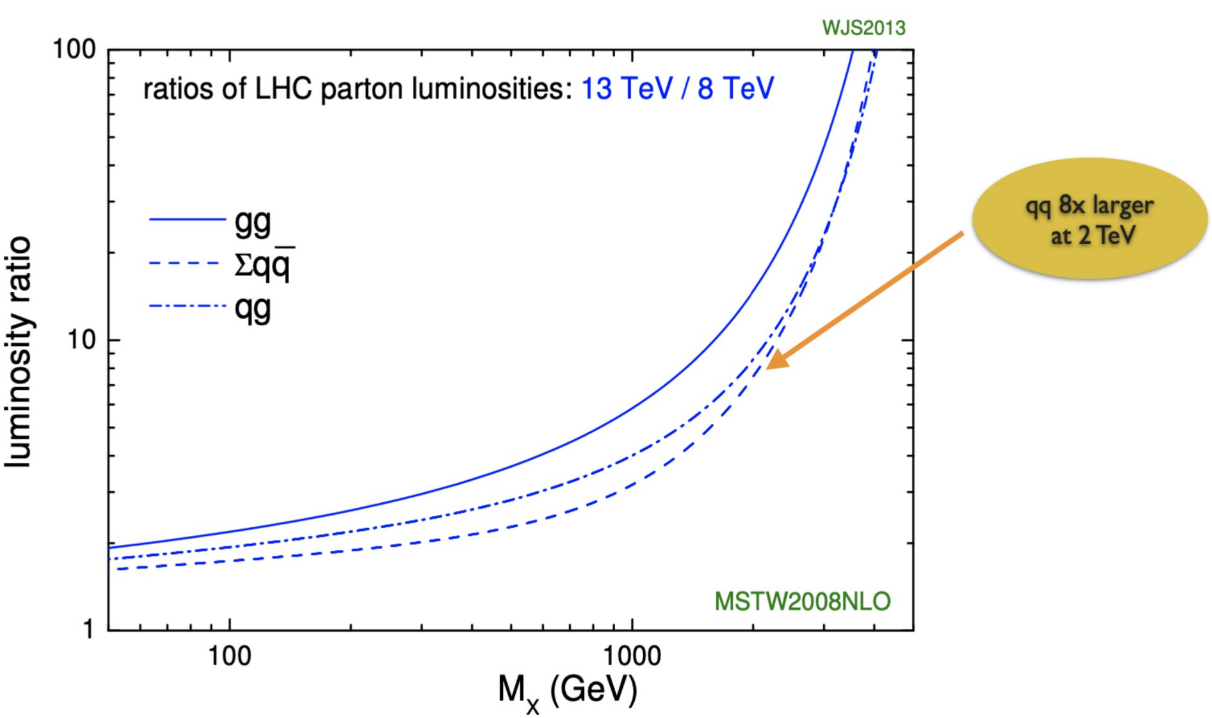
High Energy Physics – Phenomenology

[Submitted on 22 May 2017 (v1), last revised 8 Oct 2017 (this version, v2)]

Stealth multiboson signals

J. A. Aguilar-Saavedra

We introduce the `stealth bosons' S, light boosted particles with a decay $S \to AA \to q\bar{q}q\bar{q}$ into two daughter bosons A,



Run-2 was coming:

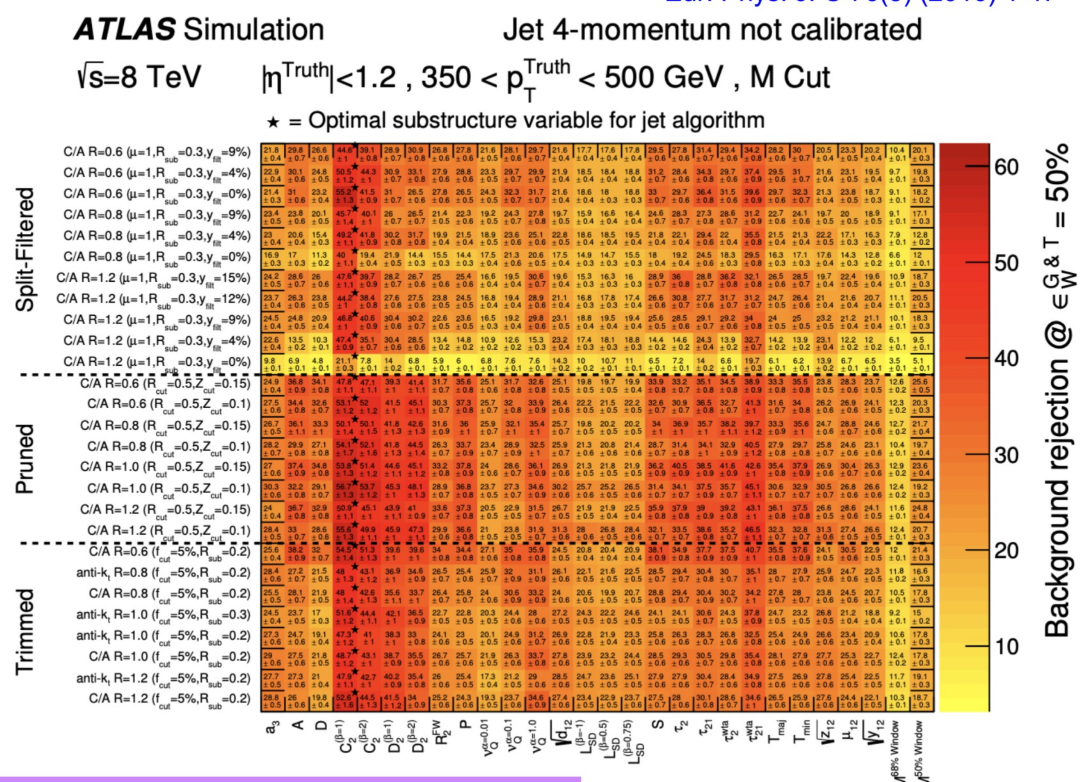
- Increase of energy → Increase of reach for new phenomena
- Larger parton distribution functions at 13 TeV than at 8 TeV
- Required revisiting our object reconstruction and analysis techniques

Run-1: W/Z tagger optimization effort
While waiting for Run-2 data…

- ATLAS performed a broad study of different grooming techniques for boson-tagging in Run-1
  - **More than 500 configurations jet reconstruction and grooming tested**

- The optimization of a tagger was based on:
  - Sensible JMS (i.e., tagged jet mass close to the W/Z/top mass),
  - A narrow jet mass response with an approximate Gaussian lineshape
  - Stability with respect to pileup and jet p_T
  - Good background rejection at a given signal efficiency

Eur. Phys. J. C 76(3) (2016) 1-47



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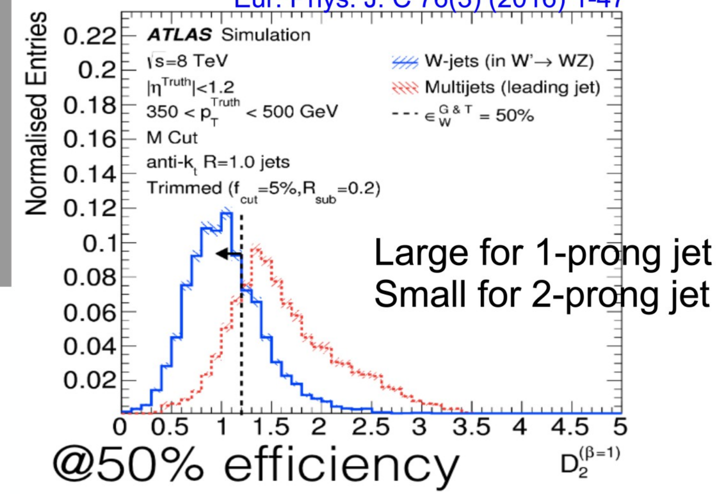
Early Run-2: W/Z tagger optimisation effort
Based on Run-1 results

- 4 sets of algorithms studied for Run-2, of which this is the most performant:

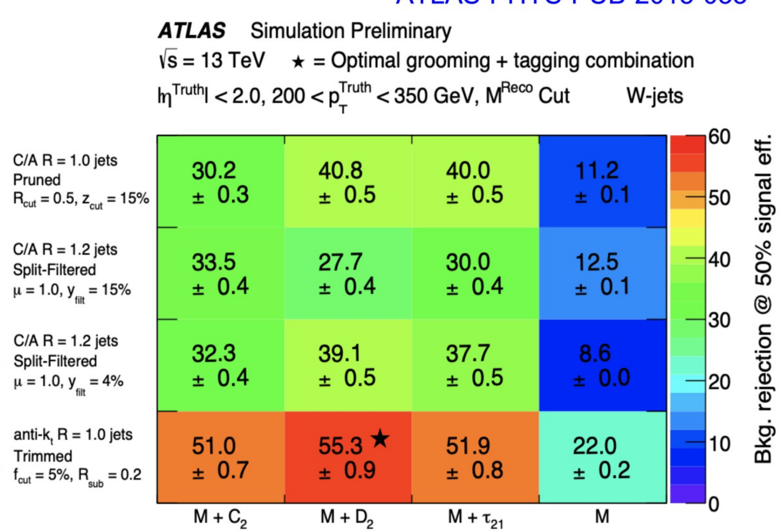
Anti-kt jets with R = 1.0
Trimmed with fcut = 5% and Rsub = 0.2
Dynamic mass window cut (68%)
+ p_T dependent D2 (energy correlation ratios) cut for jets
gives the best rejection (~90%) at 50% signal efficiency

- Assuming the signal is indeed dibosons, this new tagger results in larger bkg rejection wrt Run-1 tagger

Eur. Phys. J. C 76(3) (2016) 1-47



ATLAS-PHYS-PUB-2015-033



Jet collection for Run-1 full hadronic analysis

Jet collection chosen for early Run-2 analyses

Warning: the tagging variables used are not exactly the same

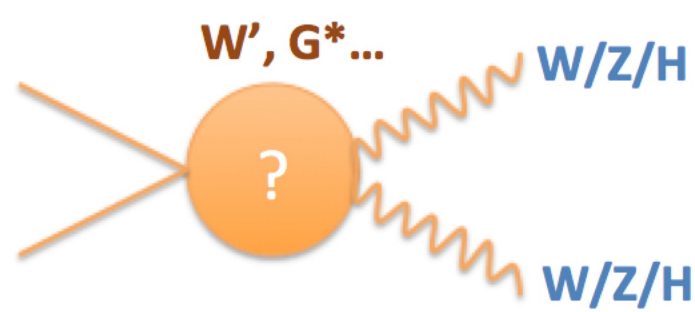
- Uncertainties derived by comparing the measured calorimeter jet energy and mass to the same quantities measured by the tracker in both data and MC, using a double ratio method

Early Run-2: Full hadronic diboson resonance search
Changes and improvements

- **Main changes wrt the Run-1 analysis:**
  - A **new way of tagging boosted W/Z bosons** to account for the higher boost and changes in the pile-up conditions
  - A **new jet mass definition** combining tracking and calorimeter information → better mass resolution
  - **New theoretical/interpretation models**

	Run-1	Run-2
Jet algorithm	C/A $R = 1.2$	anti-k_t $R = 1.0$
Jet grooming	Split-Filtering:	Trimming:
	$R_{sub} = 0.3$, $y_{cut} = 0.04$, $\mu = 100\%$	$f_{cut} = 5\%$, $R_{sub} = 0.2$
Jet tagging	Mass window ± 13 GeV	Mass window ± 15 GeV
	$\sqrt{y_{12}} \geq 0.45$	D_2 p_T-dependent cut
	$n_{trk} < 30$	$n_{trk} < 30$

- **Resonance benchmarks** you will hear about in this section of the talk
  - **Spin 0:** 2HDM, additional **Higgs-like scalar** singlet
  - **Spin-1:** Heavy Vector Triplets or **HVT** (simplified Lagrangian)
    - *Model A:* Stronger constraints from leptonic searches
    - *Model B:* Enhanced couplings to dibosons
  - **Spin-2: Randram Sundrum G* (RGS)**
  - *In all signal samples, **the bosons are longitudinally polarized** (preferred by the tagger developed)*



Model \ Decay mode	WW	WZ	ZZ	WH	ZH	$\ell\nu$	$\ell\ell$
HVT	Z'	W'		W'	Z'	W'	Z'
Bulk RS	G_{RS}		G_{RS}				
Scalar	Scalar		Scalar				

Early Run-2: Full hadronic diboson resonance search
Changes and improvements

- I will present the **strategy and results for the analysis using 36/fb of data**
  - A very early version of the analysis using 3.2/fb was performed but was not sensitive enough to exclude the excess of events observed at $m_{JJ} \sim 2$ TeV

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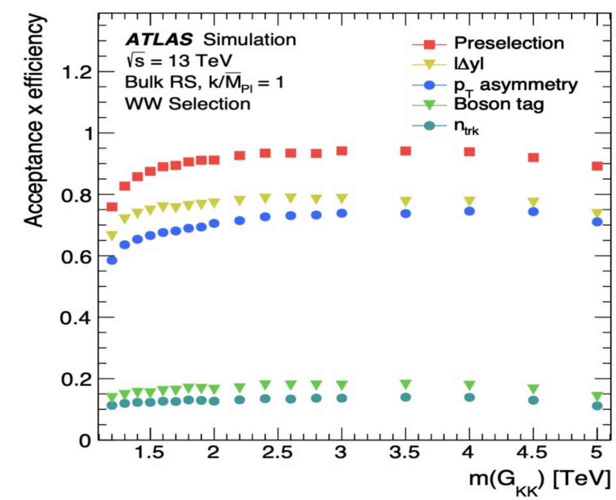
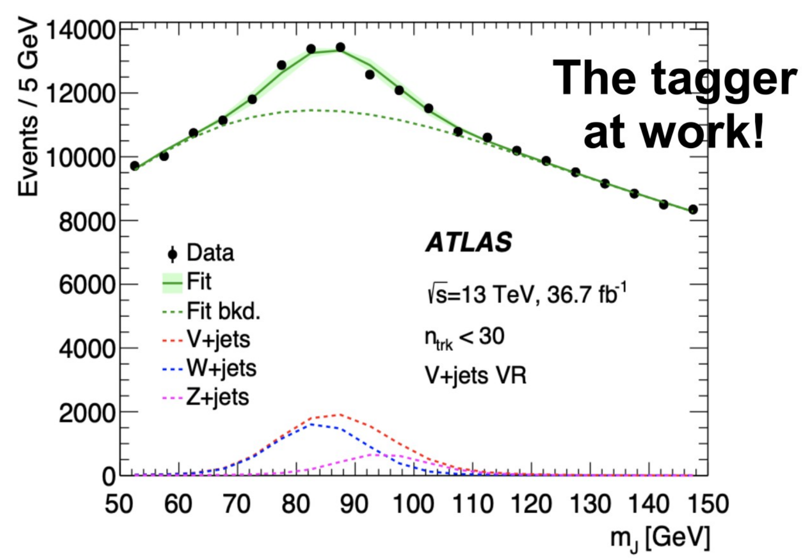
Phys. Lett. B 777 (2017) 91

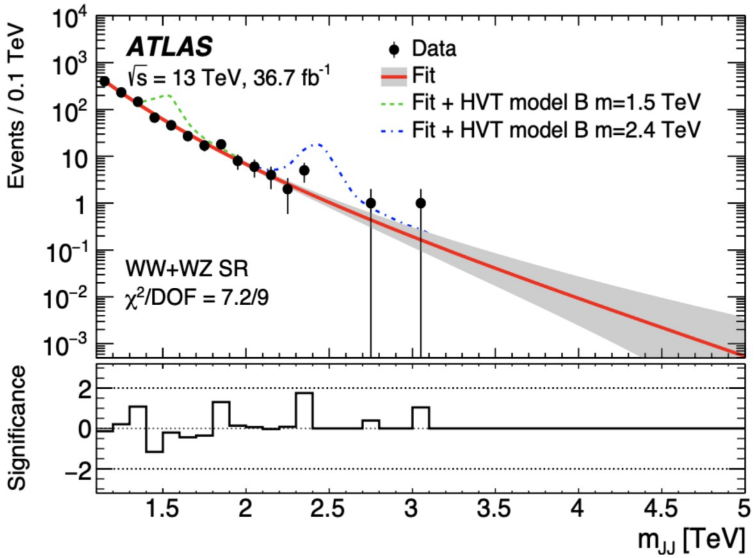


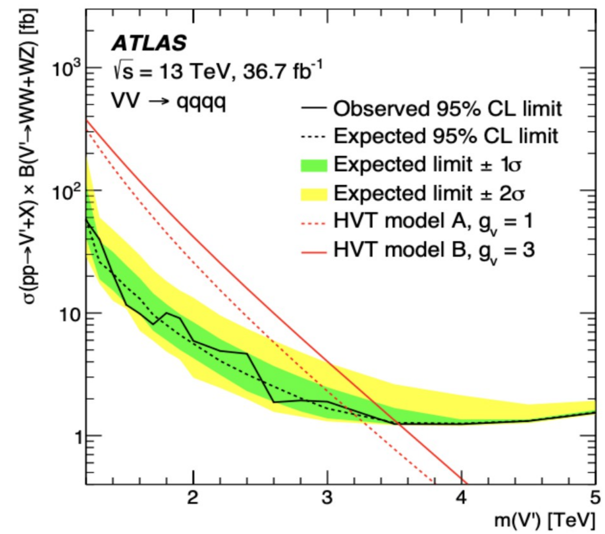
- How to model the QCD multijet background is the main challenge of this analysis
  - In additional to the boson tagger, **2 additional cuts are applied to reduce the overwhelming QCD/multijet background**
    - Rapidity difference between boson candidates, $|y_1-y_2|<1.2$
    - p_T asymmetry <0.15
  - **Mass sidebands validation regions** are used to test the validity of the parametric shape used
- Tagger at work:
  - A V+jet validation region is defined to assign an uncertainty on the tagger efficiency



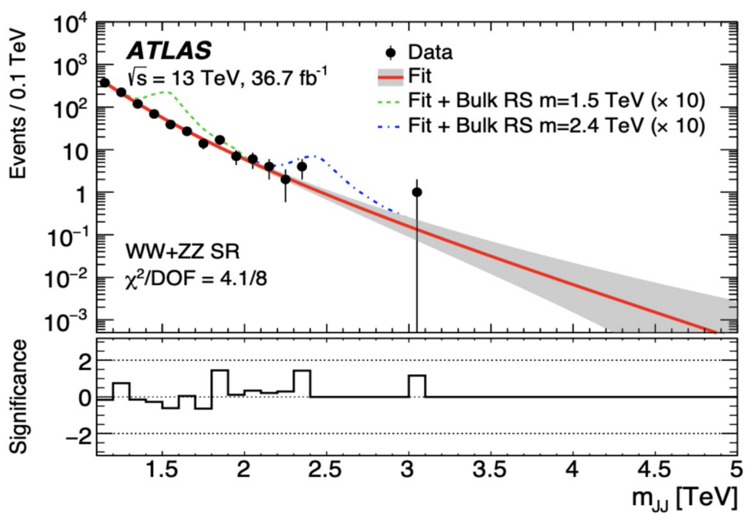
Early Run-2: Full hadronic diboson resonance search
Tell me what happened with the excess!

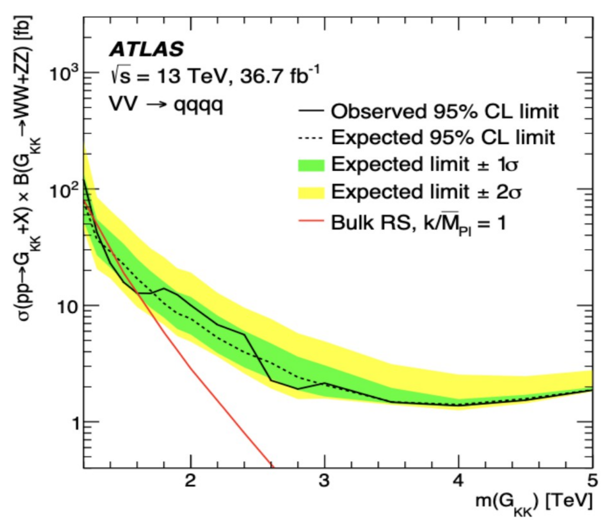
Spin 1, HVT





Spin 2, RS Graviton





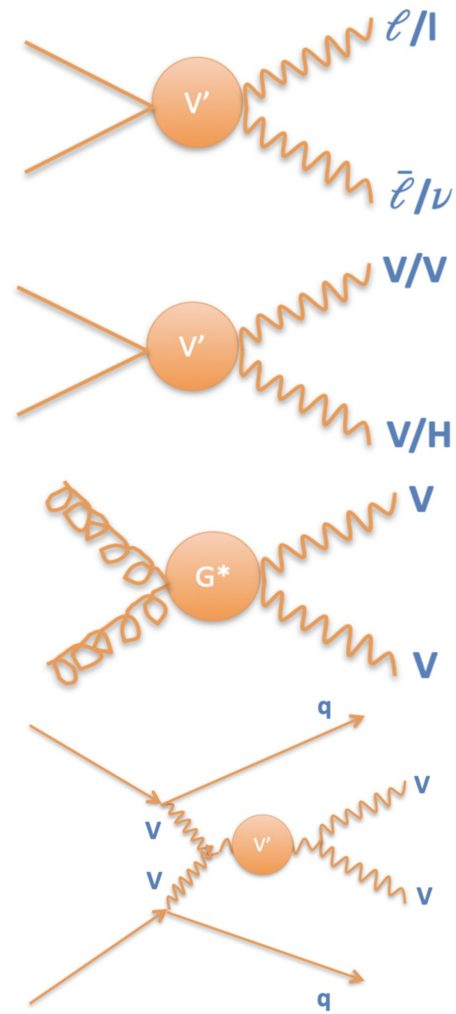
- **Excess of events observed at m_{JJ}~ 2 TeV in the Run-1 analysis excluded**
- The dominant sources of uncertainty are related large-R jet energy and mass calibrations
- Can the limits be pushed further? → **Next: exploring combinations**

Early Run-2: Combining VV, VH and dilepton resonances

- Two production modes studied: **Drell-Yann and Vector Boson Fusion**
- Exploiting **different S/B across regions**
- **Different background composition** is the key to constrain background normalisation through different control regions
- **Orthogonality** between the different channels was a guiding criteria when defining the event selection

Phys. Rev. D 98, 052008 (2018)

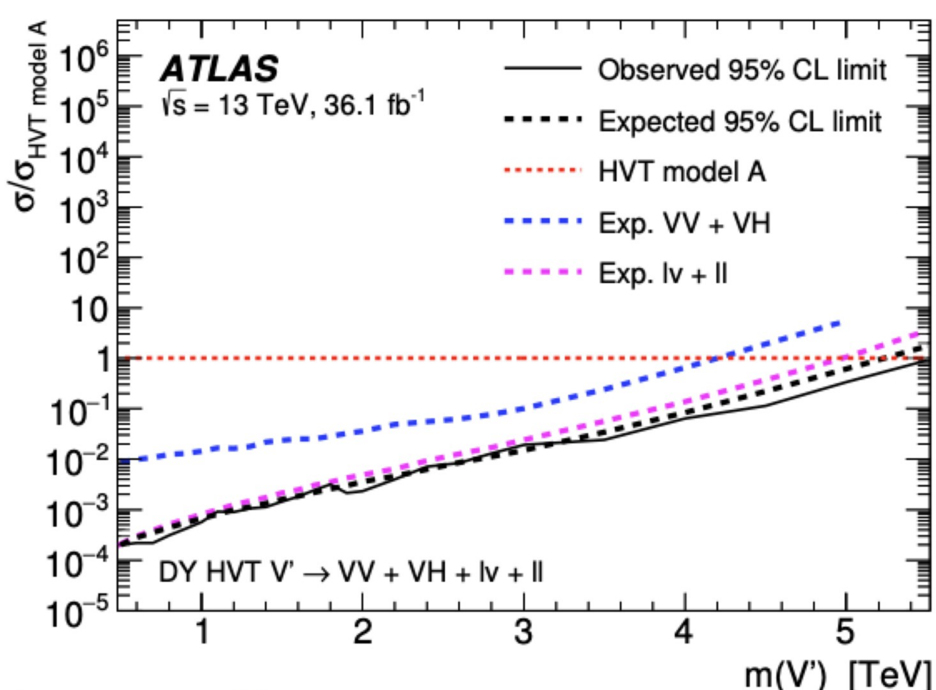
Channel	Diboson state	Selection: Leptons	Selection: E_T^{miss}	Selection: Jets	Selection: b-tags	VBF cat.
$qqqq$	$WW/WZ/ZZ$	0	veto	2J	–	–
$\nu\nu qq$	WZ/ZZ	0	yes	1J	–	yes
$\ell\nu qq$	WW/WZ	$1e, 1\mu$	yes	2j, 1J	–	yes
$\ell\ell qq$	WZ/ZZ	$2e, 2\mu$	–	2j, 1J	–	yes
$\ell\ell\nu\nu$	ZZ	$2e, 2\mu$	yes	–	0	yes
$\ell\nu\ell\nu$	WW	$1e{+}1\mu$	yes	–	0	yes
$\ell\nu\ell\ell$	WZ	$3e, 2e{+}1\mu, 1e{+}2\mu, 3\mu$	yes	–	0	yes
$\ell\ell\ell\ell$	ZZ	$4e, 2e{+}2\mu, 4\mu$	–	–	–	yes
$qqbb$	WH/ZH	0	veto	2J	1, 2	–
$\nu\nu bb$	ZH	0	yes	2j, 1J	1, 2	–
$\ell\nu bb$	WH	$1e, 1\mu$	yes	2j, 1J	1, 2	–
$\ell\ell bb$	ZH	$2e, 2\mu$	veto	2j, 1J	1, 2	–
$\ell\nu$	–	$1e, 1\mu$	yes	–	–	–
$\ell\ell$	–	$2e, 2\mu$	–	–	–	–

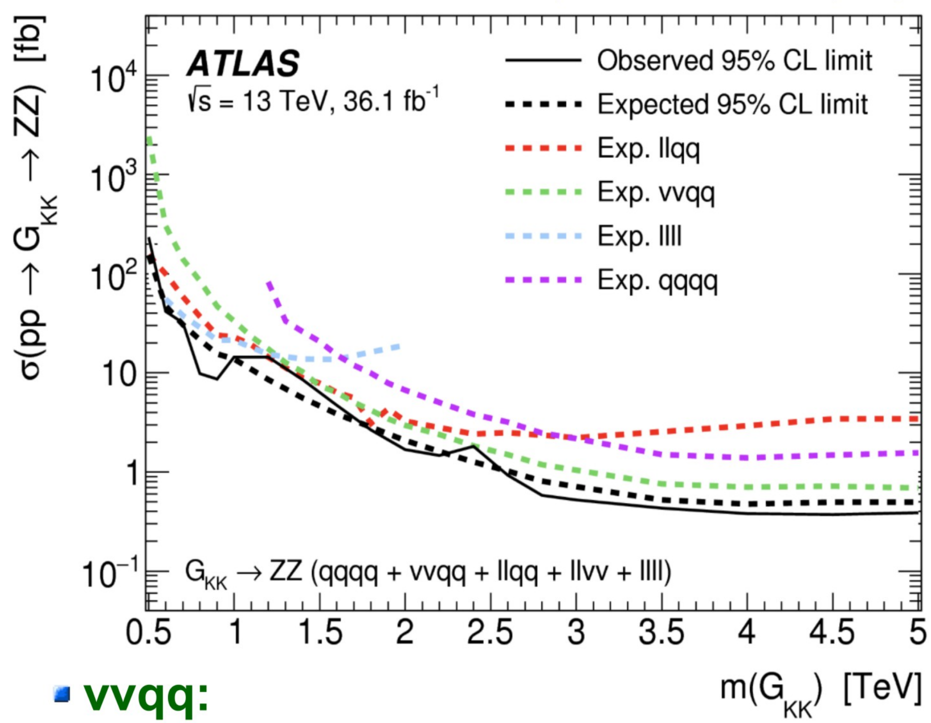


Early Run-2: Combining VV, VH and dilepton resonances

- One-dimensional upper limits on the cross section times branching fraction
- Their combination extend the reach beyond that of the individual search

Phys. Rev. D 98, 052008 (2018)





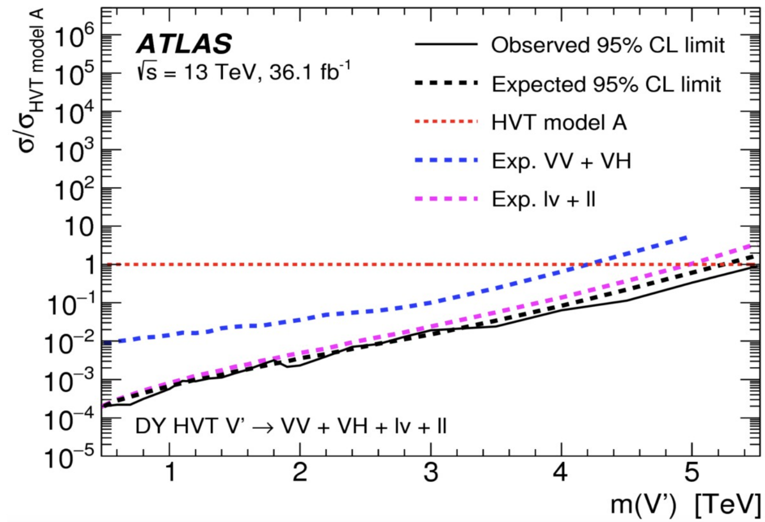
- **llqq and llll:**
  - Low mass region → good resolution
  - High mass region → statistically limited
- **lνqq:**
  - Good sensitivity in wide mass region
- **ννqq:**
  - Low mass region → bad mass resolution
  - High mass region → high statistics
- **qqqq:**
  - Low mass → QCD background
  - High mass → Jet related uncertainties

* Two-dimensional limits on the coupling strengths in the context of the HVT model also set!

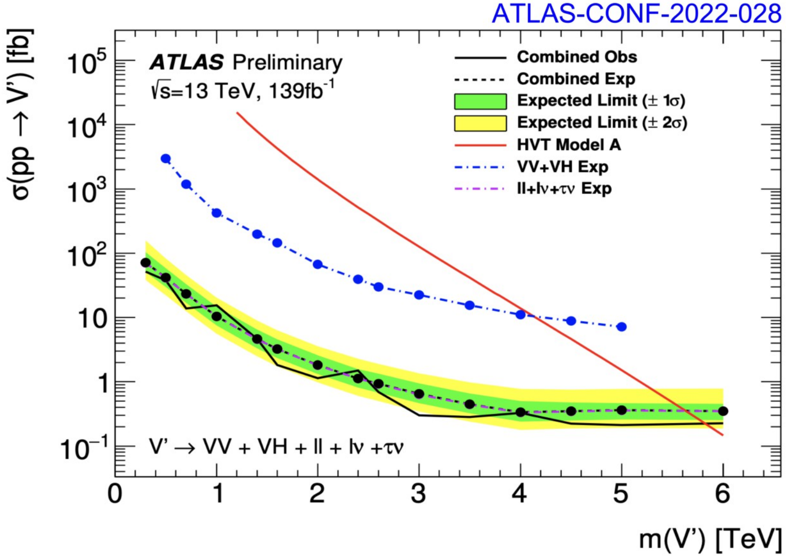
Diboson resonance searches today

- Diboson resonance searches **continue to be a great candle for the new physics** quest
- Although **no significant excess** has been observed to date, **limits have improved** in the last years:
  - Full Run-2 dataset
  - New jet collections using tracking and calorimeter information
  - ...
- Still a few **corners to exploit** in the near future!

Phys. Rev. D 98, 052008 (2018)



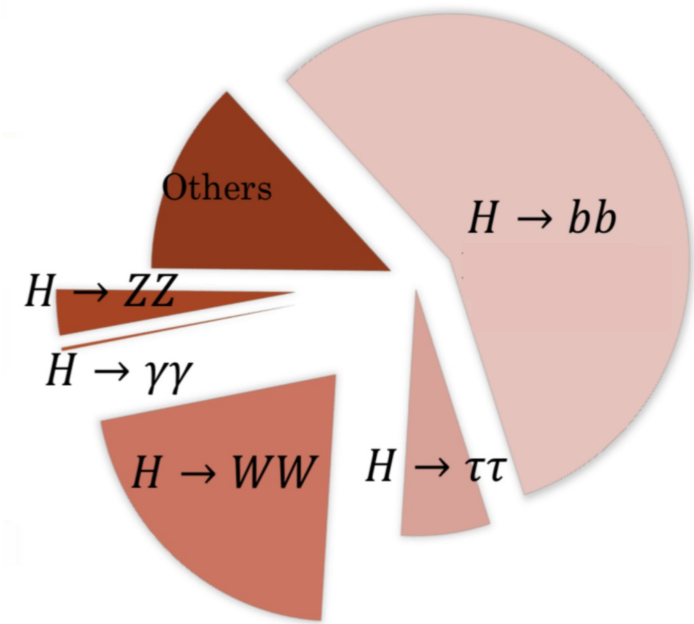
ATLAS-CONF-2022-028



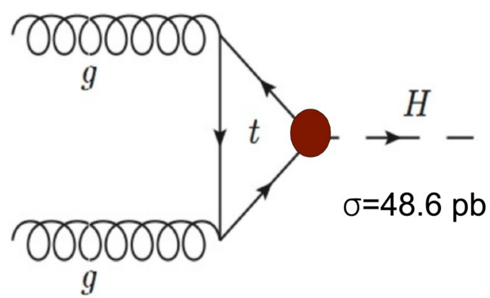
- **Personally, it was time to explore new ways to look for new physics (*the indirect way*)** and contribute to the understanding of the EWSB mechanism

LHC is a Higgs factory

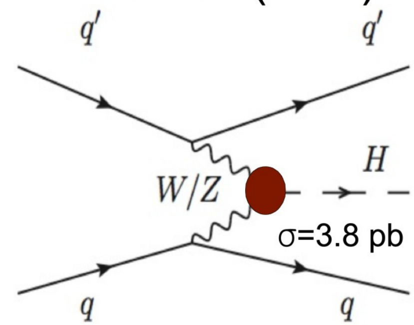
- **Different coupling strengths can be probed through a wide variety of decays and production modes**
- **7M Higgs boson** produced by LHC during **Run-2**!
- LHC experiments are making the most of this dataset!



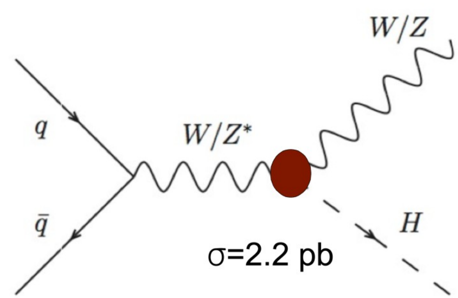
Gluon fusion (ggF)



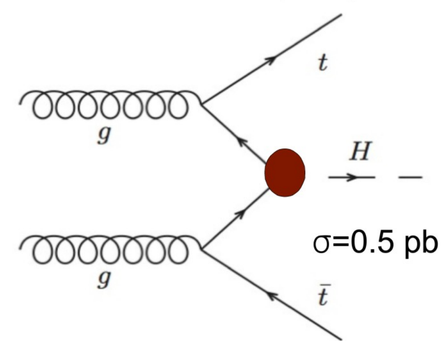
Vector Boson Fusion (VBF)



W/Z associated production (VH)



Top associated production (ttH)

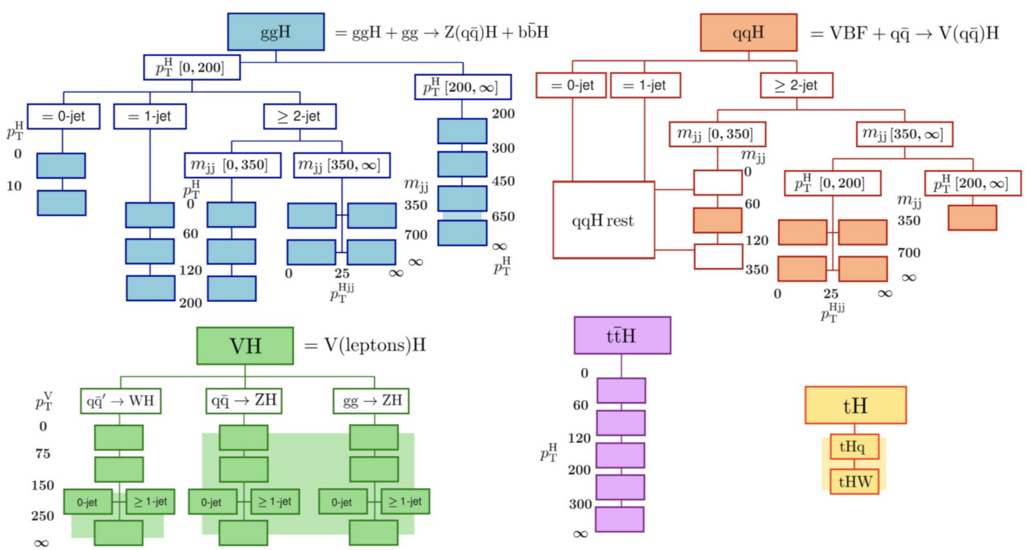


Toward the end of Run-2: status

- **Major progress** in the understanding of the Higgs mechanism **after the Higgs discovery** on the ZZ, WW and γγ channels in 2012
  - Observation of H→ττ using 2016 data
  - Observation of H→bb decay in 2018
  - Observation of ttH production combining different decay modes
  - Evidence of H→μμ decay

Analyses at different stages:

- **Precision** (e.g. γγ, WW, ZZ)
- **Most recently observed** and entering the precision era (e.g. bb, ττ)
- **Searches** (e.g. cc, μμ, ee, Zγ, di-Higgs)

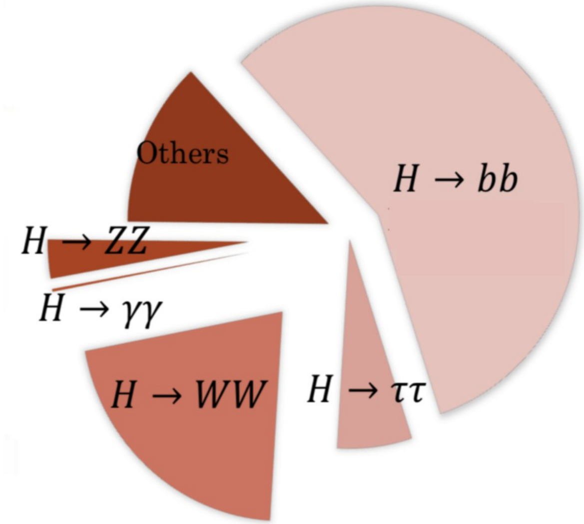


STXS regions defined per production mode, optimized for sensitivity while reducing theory dependence

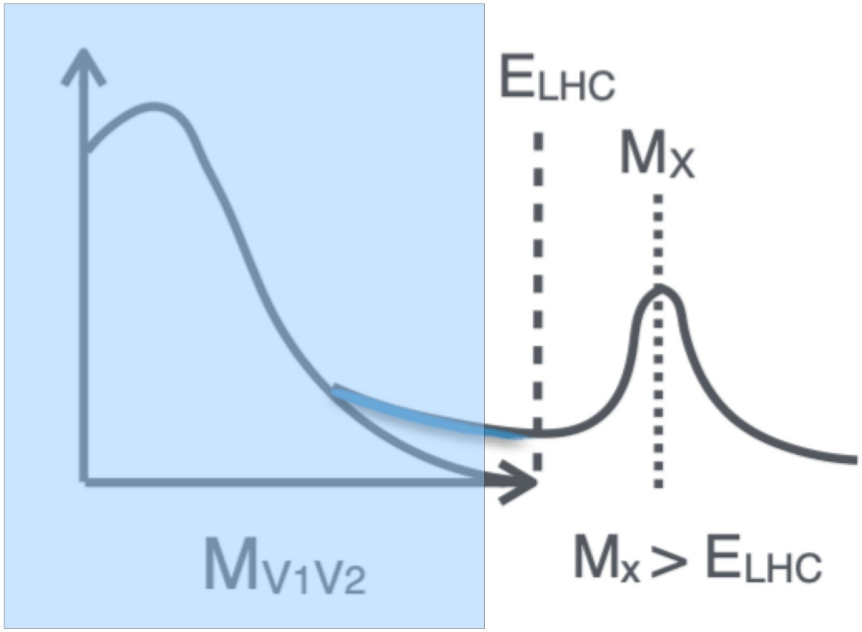
Analyses trying to provide more granular information on the Higgs:

- **Inclusive measurements:**
  - Cross sections (σ)
  - Signal strengths ($\mu = \sigma.BR/\sigma.BR_{SM}$)
  - Coupling strength scale factor relative to SM (κ framework, κ = 1 for SM)
- **Differential measurements**
- **Or semi-differential:** Simplified Template Cross Section (STXS) framework

H→ bb: motivation and challenges



- **H→bb: an interesting challenge** matching some of my previous experience
- **Pros:**
  - Largest BR (~0.58), H→bb controls the Higgs total width and therefore BRs of all other decays
  - Direct probe of the b-quark Yukawa coupling
  - Enhanced sensitivity to BSM physics at high p_T
- **Challenges:**
  - Poor kinematic resolution
  - QCD background overwhelms the signal by 7 orders of magnitude
  - **VH production mode:**
    - Use leptons to reduce QCD bkg
    - Dibosons one more time!

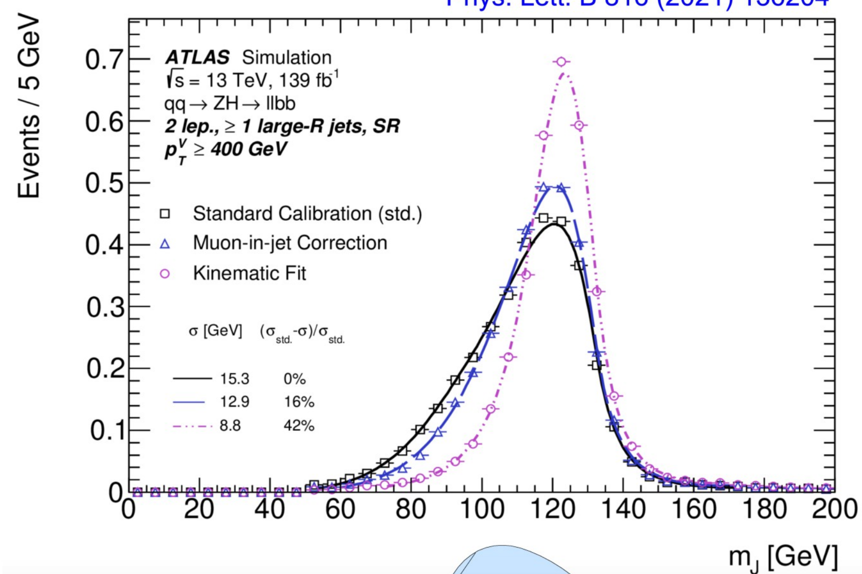


Joined the first ATLAS VH, H→bb using boosted boson techniques ~mid 2018

Boosted Higgs bosons

- A **R=1.0 trimmed jet from calorimeter inputs to gather all decays**
  - Additional muon and kinematic corrections used to improve mass resolution
- **p_T-dependent variable-radius jets build from tracks are used as proxy for the b-quaks**
  - b-tagging: Combines track- and vertex-based physics taggers into high-level discriminants with multivariate classifiers (MV2c10 used in the analyses presented today)

Phys. Lett. B 816 (2021) 136204



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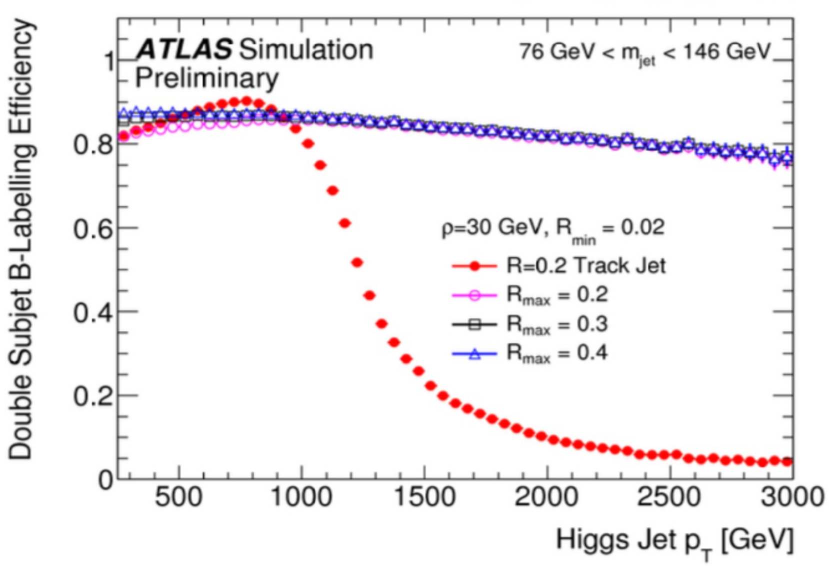
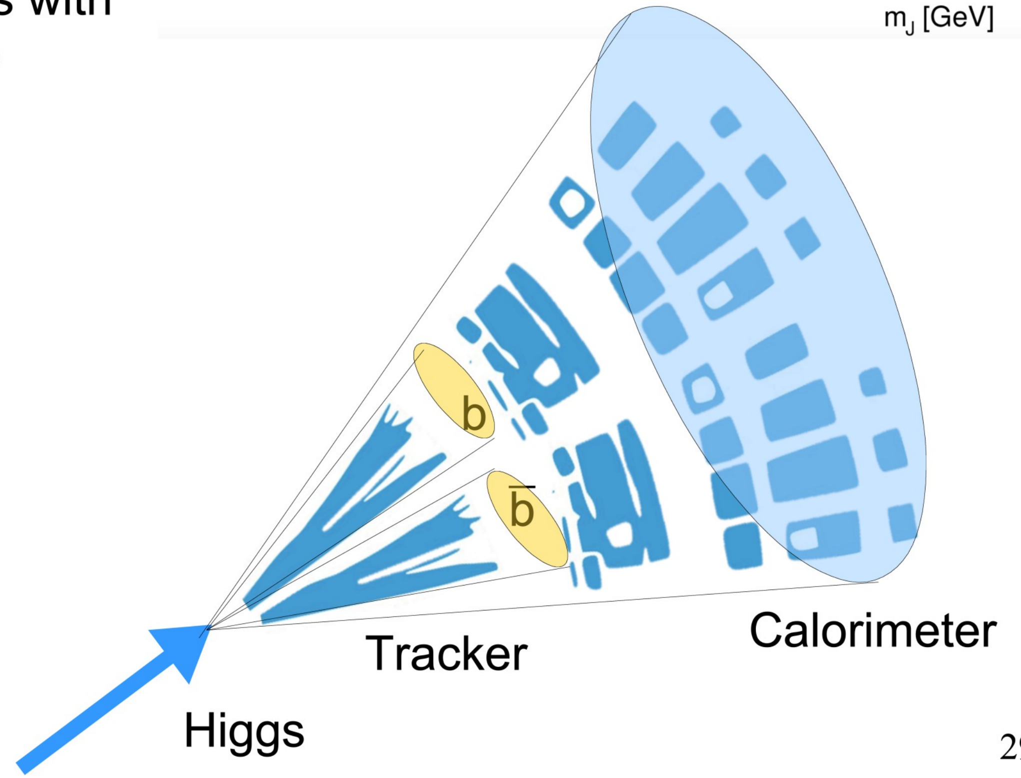
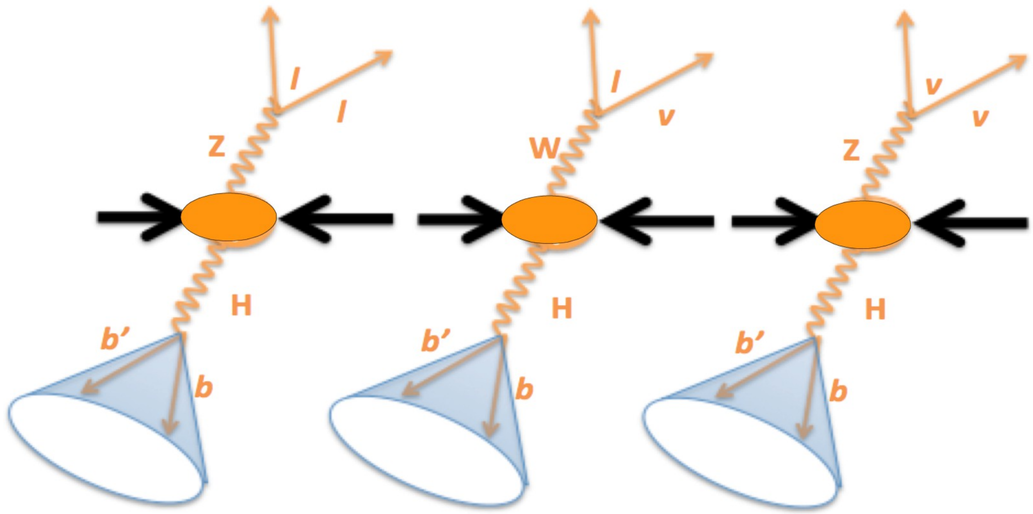




VH, H→bb: event selection and categorization



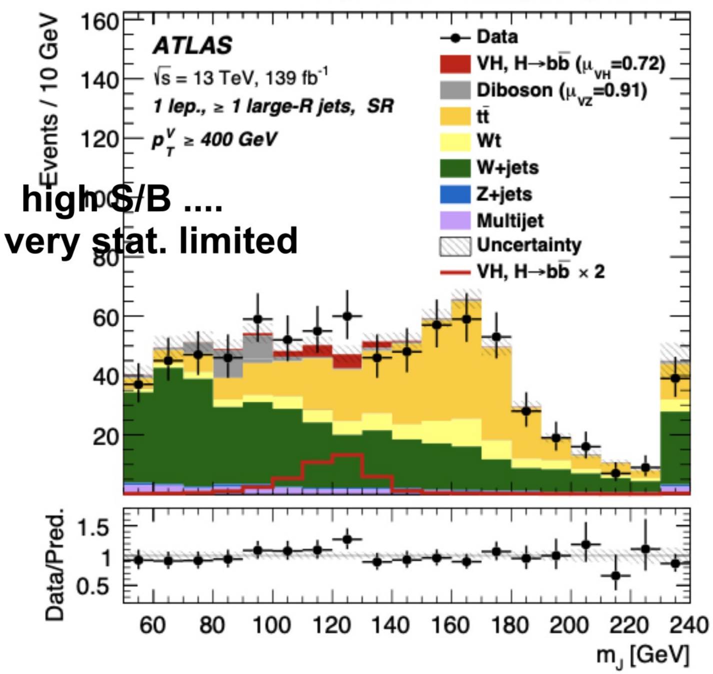
2 leptons (ee/μμ) and $m_{ll} \sim M_Z$	1 lepton (e/μ) + E_t^{miss} (>50 GeV)	High E_t^{miss}>250 GeV
• V p_T = MET • Lepton p_T imbalance<0.8 • Main background: Z(ll)+jets, ttbar	• V p_T = p_T(l, MET) • $\lvert\Delta y(V, H_{cand})\rvert < 1.4$ • Main background: W (lv)+jets, ttbar	• V p_T = p_T(l,l) • Optimised to remove bkg from jet energy mismeasurements • Main background: Z(vv)+jets, ZZ

- **Discriminant variable: the large-R jet mass**
- **Backgrounds treatment**:
  - Z+jets and W+jets, $t\bar{t}$ and single top are constrained by control regions
  - Diboson (WZ, ZZ): final state similar to VH when Z → bb, used to validate the analysis
  - Multijets: suppressed in 0 and 2-leptons and evaluated data-driven method in 1-lepton

VH, H→bb: backgrounds

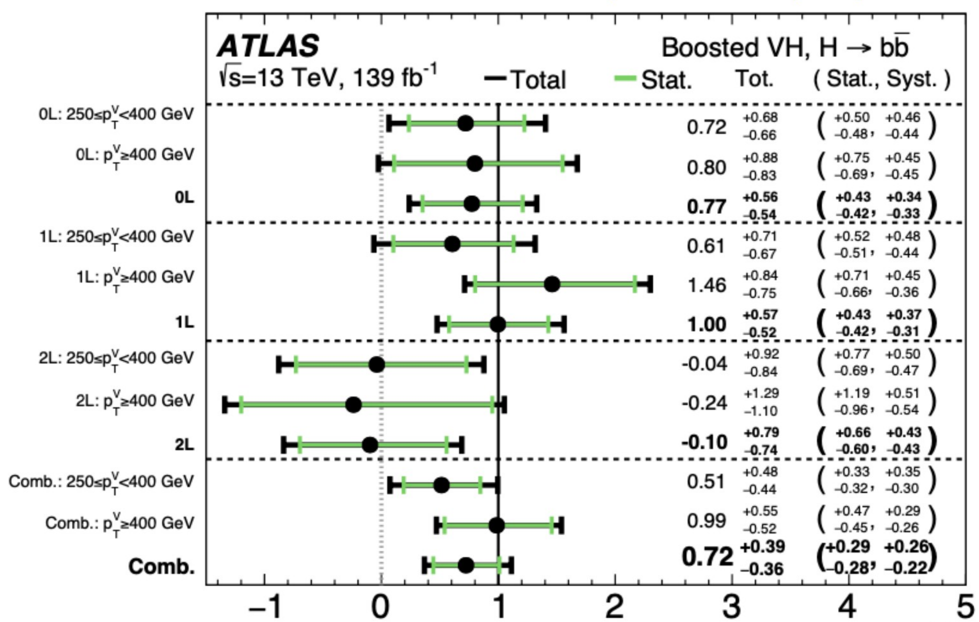
- **Categorize events is key:**
  - **Exploiting different S/B across regions and background composition**
  - Based on #leptons, #additional b-tagged track-jets, p_T^V (250-400 GeV, >400 GeV): 10 signal regions and 4 control regions
  - **Selecting 6-16% of the signal**

Phys. Lett. B 816 (2021) 136204



high S/B ....
but very stat. limited

Phys. Lett. B 816 (2021) 136204



Signal strength: $\mu = \frac{(\sigma \cdot BR)_{\text{observed}}}{(\sigma \cdot BR)_{\text{expected}}}$ Data / Standard Model

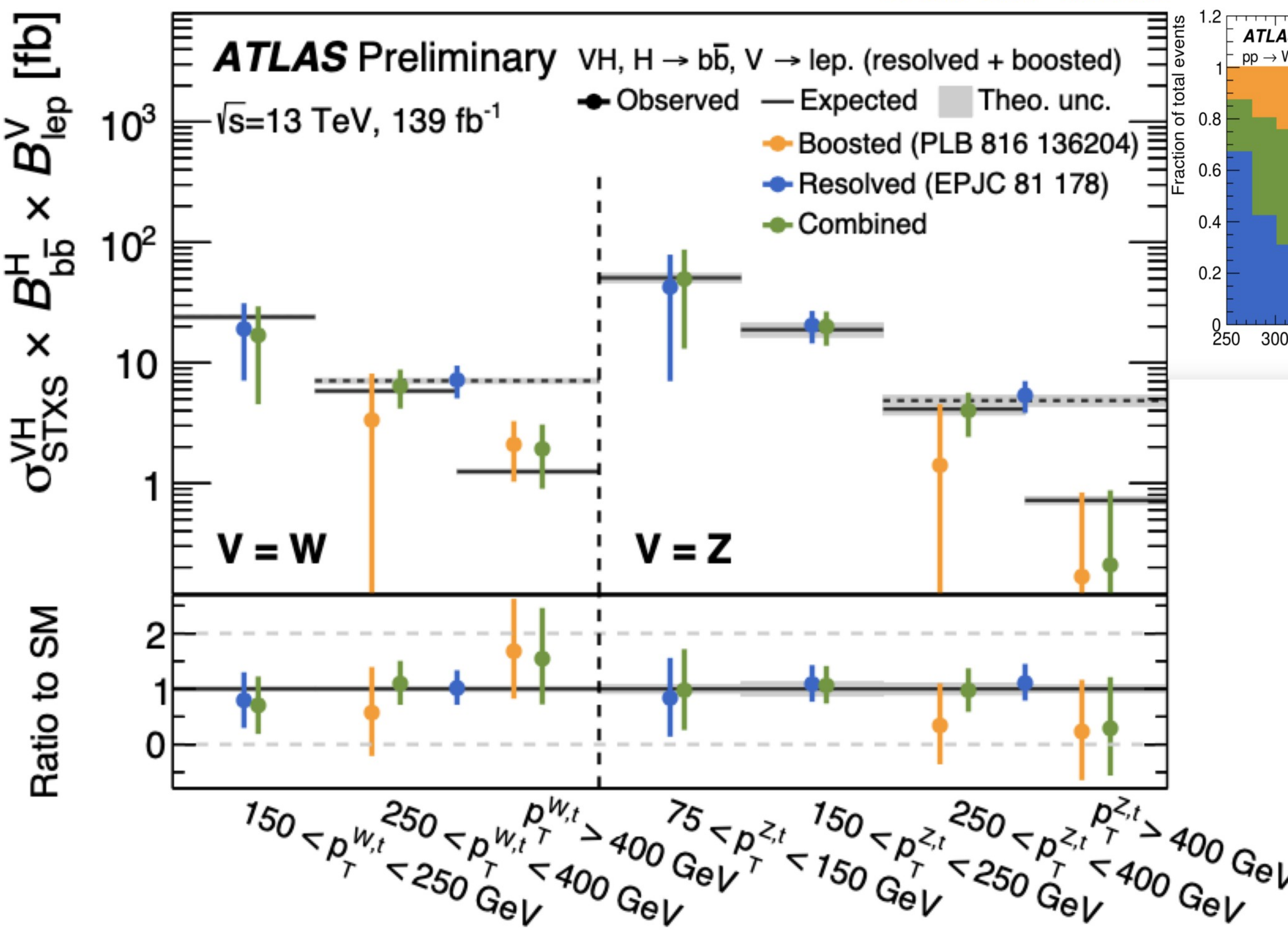
- **Main uncertainties**:
  - Large-R jet calibration in particular mass resolution and bkg modelling

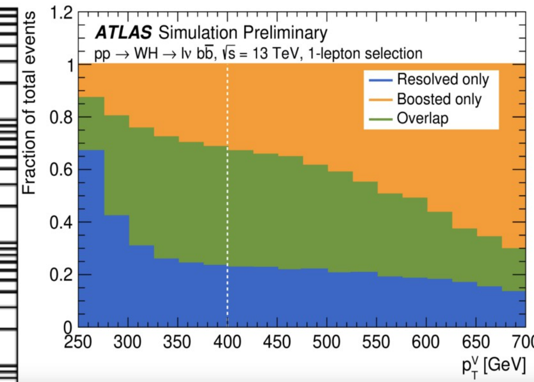
- Obs. (exp.) significance of **2.1(2.7)σ for VH** and 5.4(5.7)σ for VZ

- **Measured signal strength compatible with SM predictions**

VH, H→bb: going differential

ATLAS-CONF-2021-051



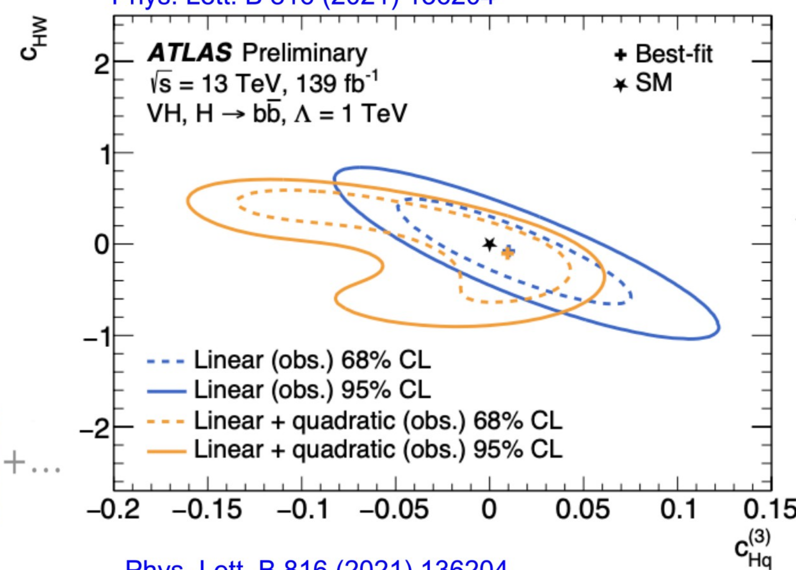


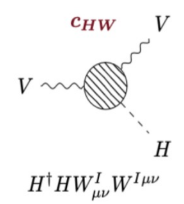
- This analysis represented the **first STXS VH, H→bb measurement of p_T^V > 400 GeV**
- **Combination with resolved analysis:**
  - Uncertainties ranging from 30% to 100%
  - Most bins dominated by statistical uncertainty

VH, H→bb: couplings

- Couplings are a **powerful test of nature of Higgs** : SM, or subtly different?
- Interpretations **evolving from coupling strength to full coupling structure** (EFT)

Phys. Lett. B 816 (2021) 136204



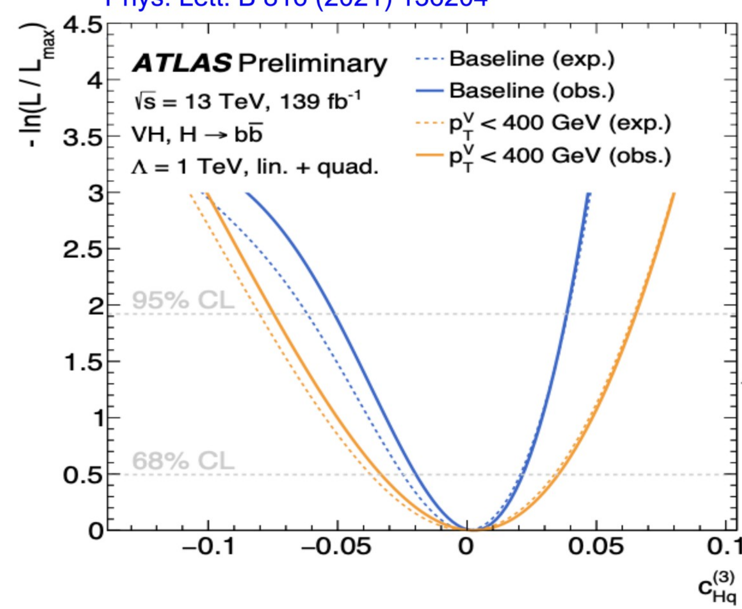


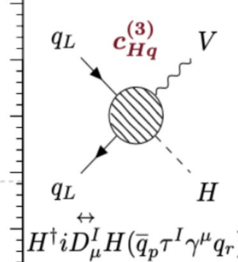
- **EFT framework:**
  - One Wilson coefficient c_i introduced per BSM coupling
  - Measured in combination of multiple final states, targeting CP-even operators
  - **SM-like → c_i = 0**

$$\mathscr{L}_{\mathrm{SMEFT}} = \mathscr{L}_{\mathrm{SM}} + \sum_i \frac{c_i^{(5)}}{\Lambda_i}\mathcal{O}_i^{(5)} + \boxed{\sum_i \frac{c_i^{(6)}}{\Lambda_i^2}\mathcal{O}_i^{(6)}} + \dots$$

- **Notes:**
  - Effects of operators differ *depending on the bin*: **capability to simultaneously constrain different operators** (important in global EFT fits)
  - Energy-dependent operators have stronger effect at high V pT : **high pT bins**, while less precise, **have competitive sensitivity**

Phys. Lett. B 816 (2021) 136204

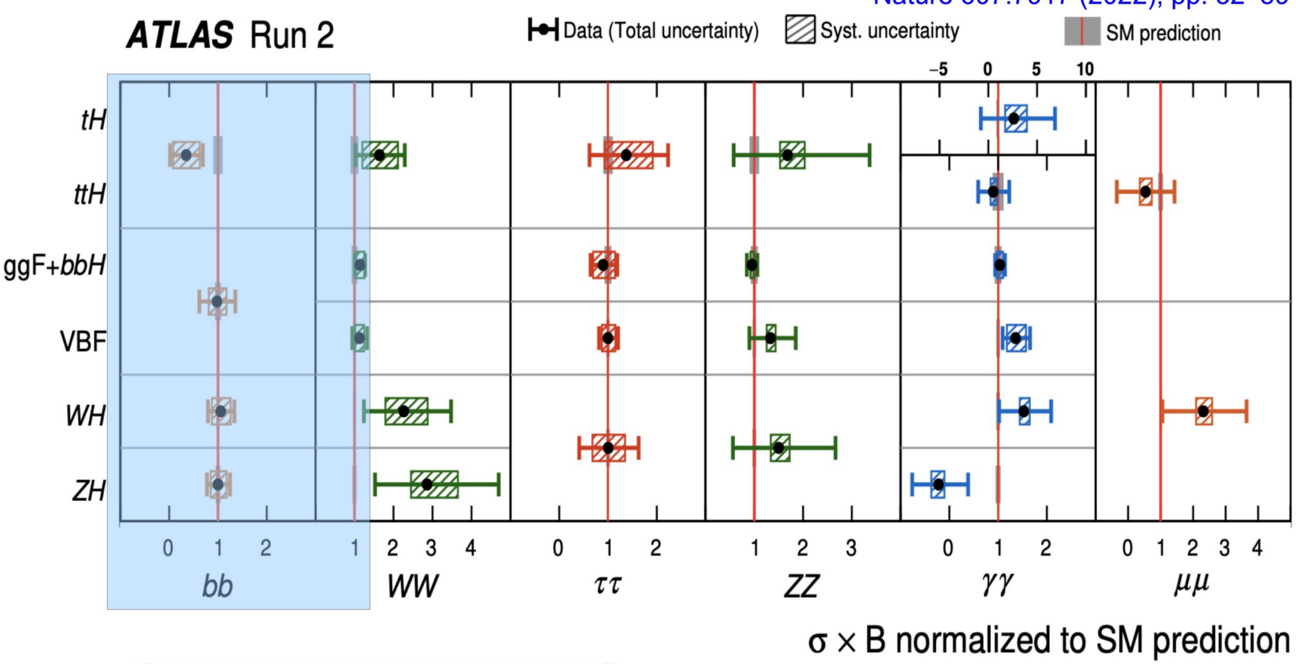




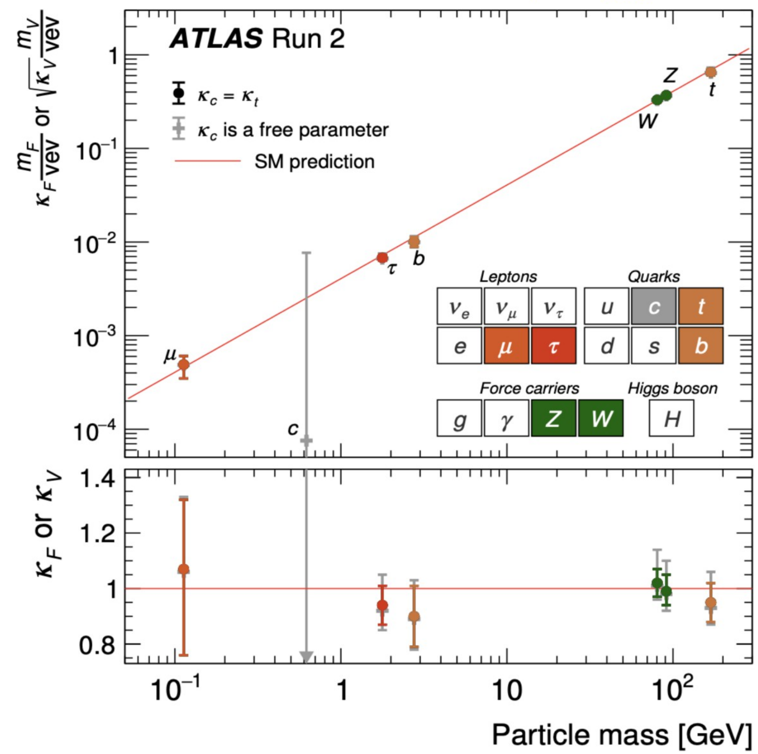
SM Higgs global context

- Latest global ATLAS Higgs combination. The most complete snapshot of Higgs boson measurements
  - The VH, H→bb result dominates both the **Hbb** and **VH** precision landscape
- CMS and ATLAS have made big progress in the understanding of the Higgs sector since its discovery
  - **More analyses and combinations in progress using full Run-2 statistics, while preparing Run-3 analyses as well**

Nature 607.7917 (2022), pp. 52–59



Nature 607.7917 (2022), pp. 52–59

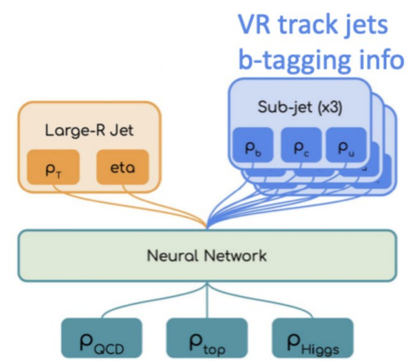


μ_{bb} = 0.91± 0.14

p_{SM}= 72%

Preparing legacy Run-2 boosted H→bb analysis (1/2)

- Continuous improvement in b-tagging performance over years: clear advantage from **modern neural network architectures**
  - Wrt double MV2c10 tagger used in the semileptonic VH analysis, the **new Neural Network-based X→bb tagger increases the QCD (top) rejection at 60% efficiency by 1.4 (2.0) for jets with p_T > 500 GeV**



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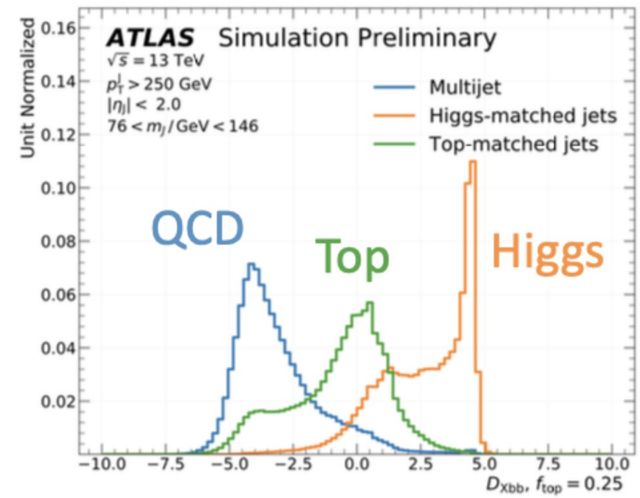

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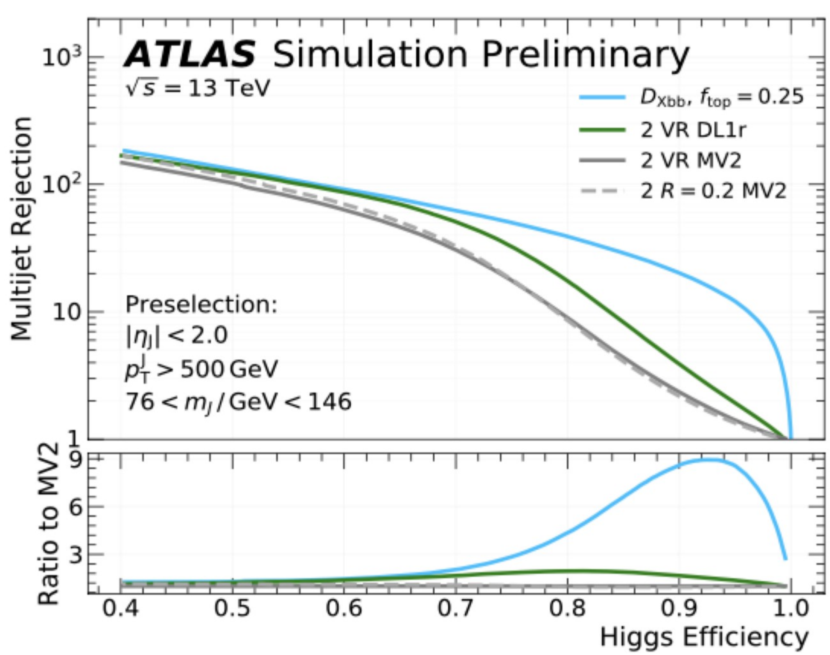
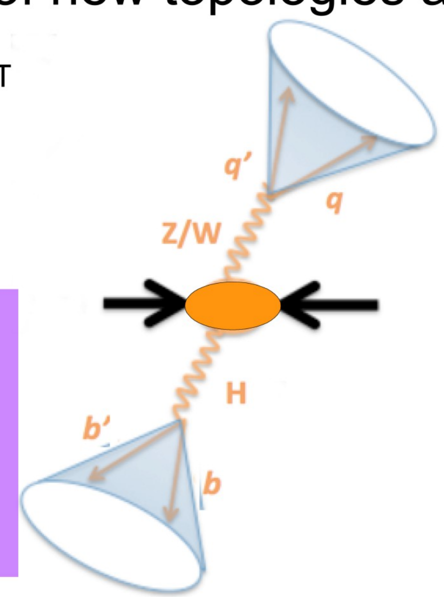


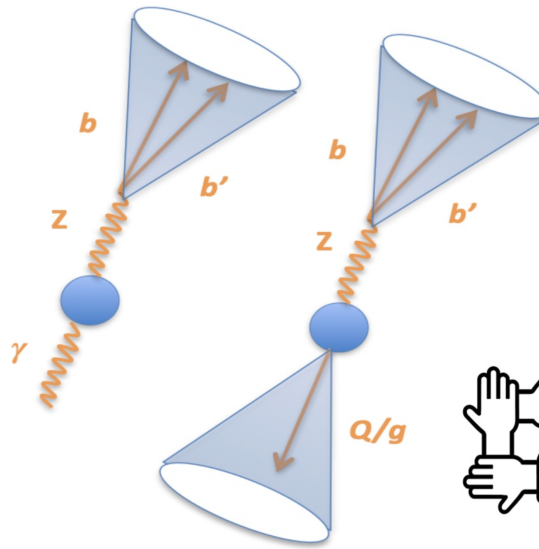
- Potential to improve the VH analysis, even allowing exploration of new topologies also accessing the high p_T

Yajun He's thesis @LPNHE, Université Paris Cité. Analysis in internal review

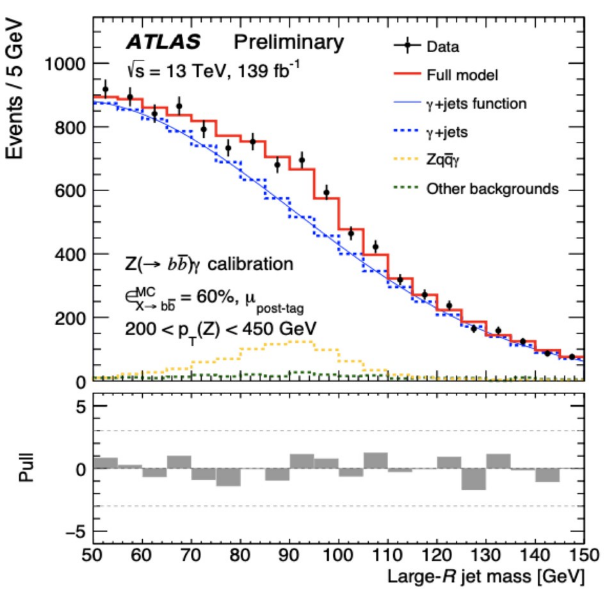


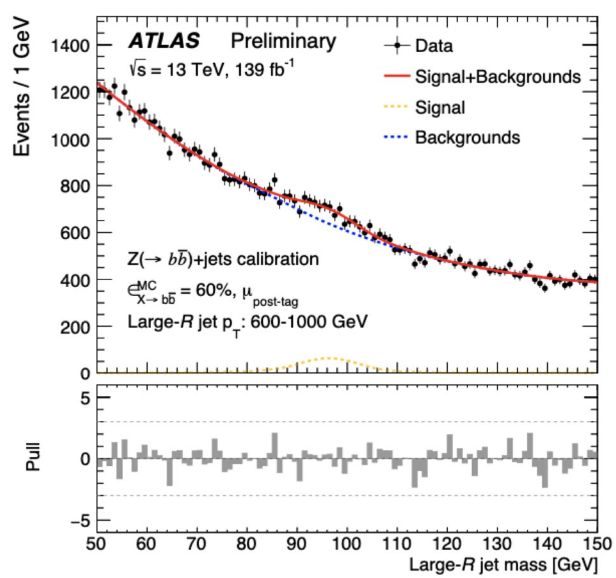
Preparing legacy Run-2 boosted H→bb analysis (1/2)

- Contributed to the **signal calibration of this new tagger** (correct difference in efficiency in data and MC), using:
  - **Z(bb)+γ**: based on a measurement of the fiducial and differential jet mass x-sections for Z(bb)+γ (Miles Wu's thesis @University of Chicago, Phys. Lett. B 812 (2020) 135991)
  - **Z(bb)+jets**: explored for the first time in ATLAS in Yajun He's thesis @LPNHE, Université Paris Cité, ATL-PHYS-PUB-2021-035



- **Main challenges:**
  - Large backgrounds, difficult to model
  - Functional form used to model the background
  - Pre-tagged information boostrapped from Z(→ ll) events





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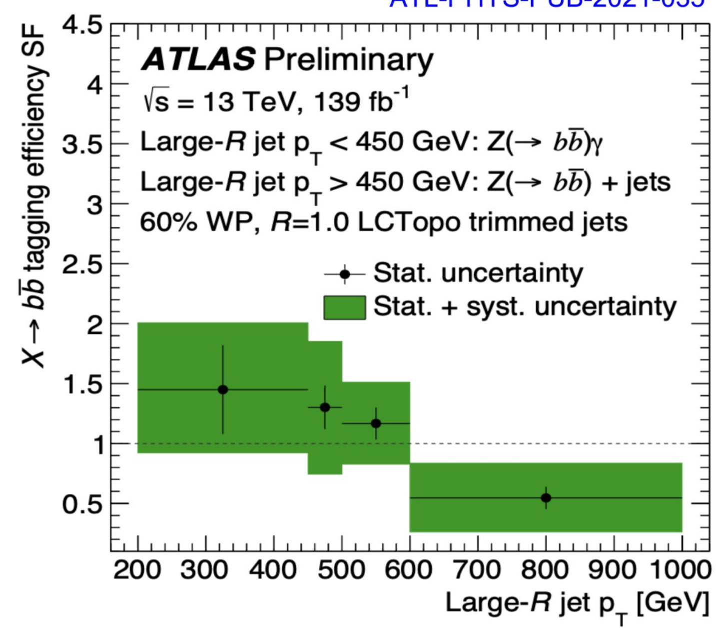
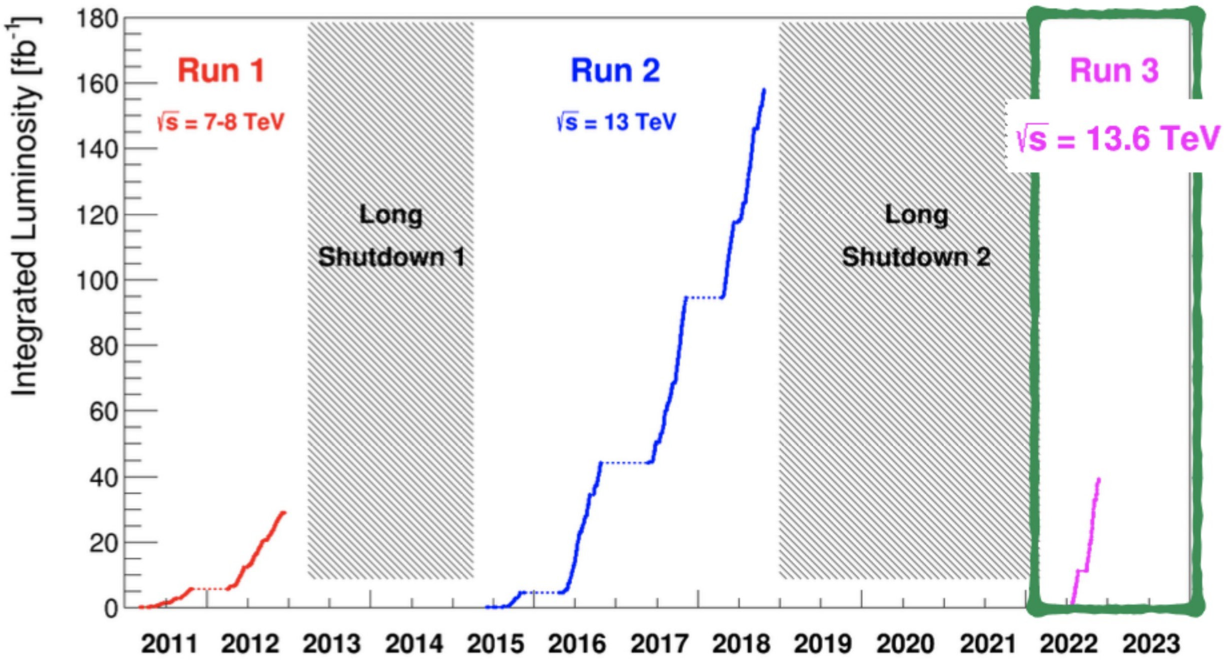


Outlook: troy horses
More data

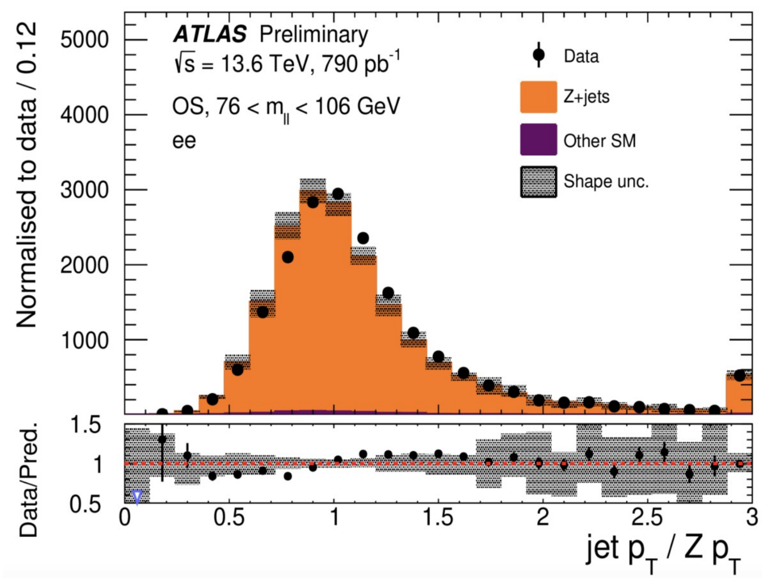


- **Run 3** could reach up to 250 fb^{-1} **tripling the available data** w.r.t. Run 2
- And **HL-LHC** should be following (**~x10 data**)

JETM-2022-007

E.g. extrapolation performed from VH, H → bb results obtained with the 2015-2017 80/fb datasets show an improvement μ precision by a factor 2.5-3 (arXiv: 1902.00134)

- For now we are all doing our best to better understand the new data that is being collected

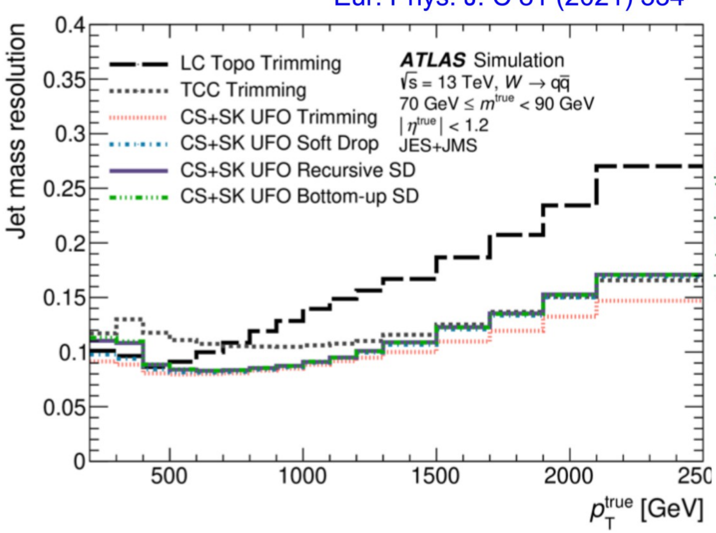


Outlook: troy horses
Improved reconstruction techniques

- **Continuous improvements object reconstruction techniques,**
  - E.g. current state of the art for jet reconstruction is the use of **Unified Flow Objects (UFO):** good angular resolution of tracker and good energy resolution from calorimeter

- In particular for **cutting-edge machine learning** and artificial intelligence algorithms
  - Improved b-tagging algorithms
  - Constituents-based boosted particle taggers

Eur. Phys. J. C 81 (2021) 334



UFO currently being commissioned as baseline for large-radius jets

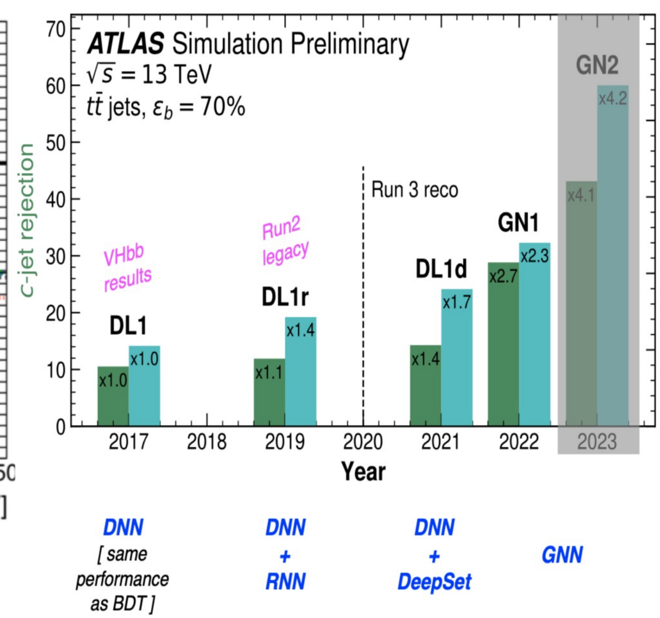
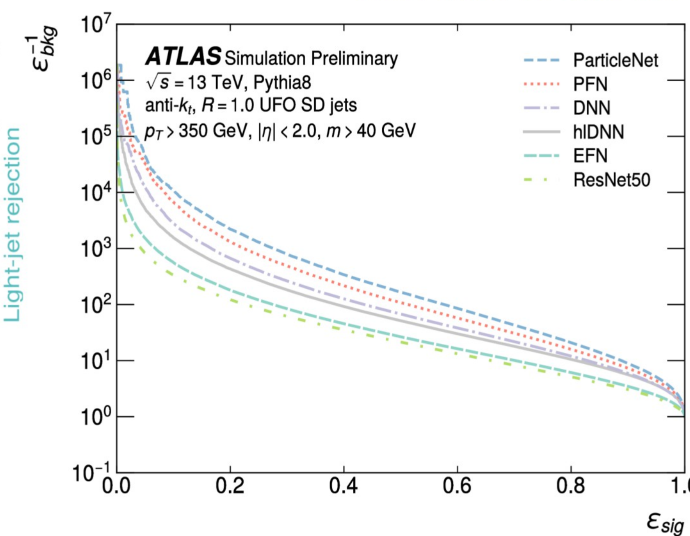


Image adapted from V. Dao

ATL-PHYS-PUB-2022-039

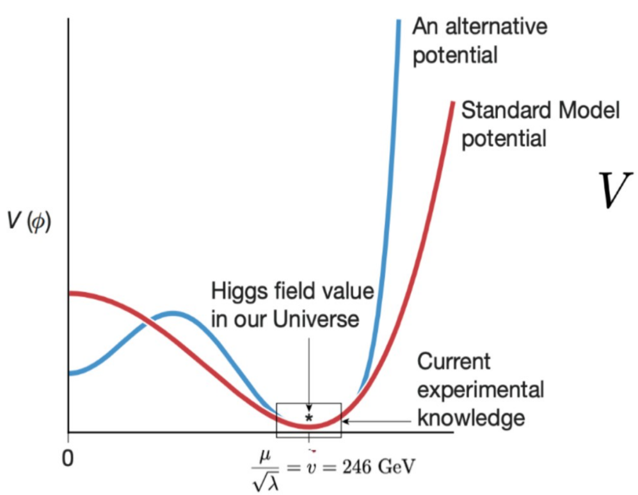


3 of the constituent-based taggers (ParticleNet, PFN, DNN) surpass the performance of the high-level-quantity-based tagger (hlDNN) for top-jets

Outlook: troy horses
New physics analysis strategies

- The BEH mechanism implies the existence of a Higgs boson self-interaction, HHH, and its interactions with vector bosons, VVH and VVHH

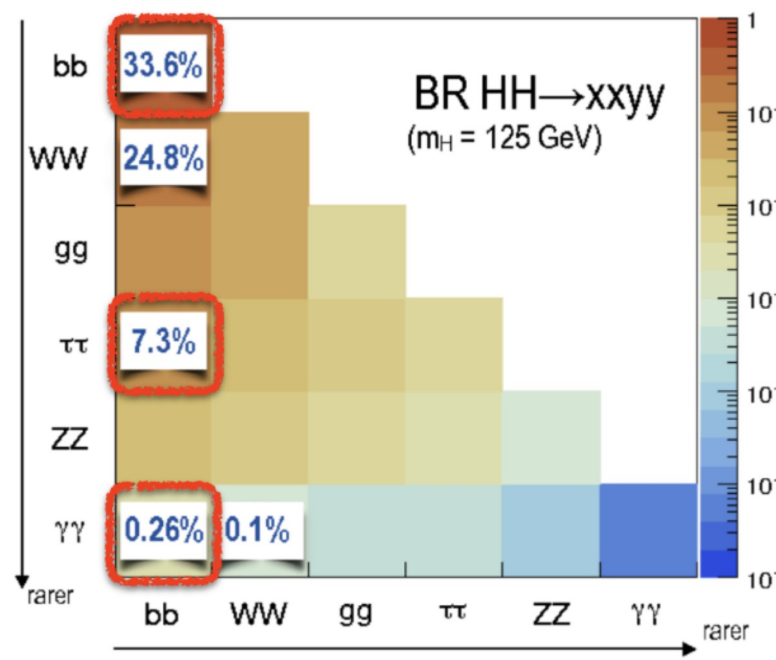
- An improved understanding of the EWSB sector can be achieved in 2 ways:
  - Improve the precision of the current measurements, e.g. VH (HVV interactions)
  - Access other interactions through gluon fusion di-Higgs and VBF di-Higgs measurements



$$V = V_0 + \frac{1}{2} m_H^2 h^2 + \boxed{\frac{m_H^2}{2v^2} v h^3} + \ldots$$

Higgs boson mass: *know to 0.2%*

Higgs boson self interaction



Outlook: troy horses
Detector upgrades

- Several upgrades planned to the ATLAS detector in order to cope with high luminosity conditions
  - Higher event rate
  - More pile- up events
  - Higher radiation doses and fluences

- One of then is the Inner Tracker (ITk) upgrade, an all silicon detector composed of pixels and strips

- French interest focuses on the pixels:
  - In particular those in the outer barrel (OB)
  - ~ 9500 pixel modules
  - Commitment from French institutions: production of O(1000) quad modules for the OB
  - Paris cluster focused on module assembly and testing
  - From 2018 to 2021 I had the opportunity to contribute to this effort

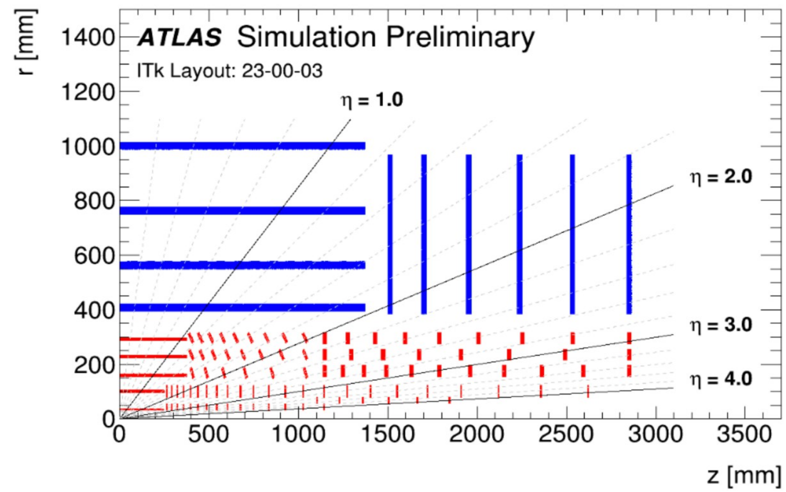
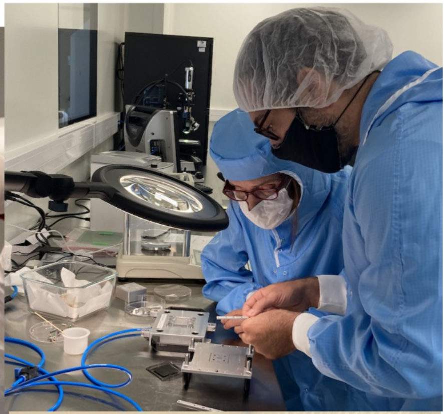
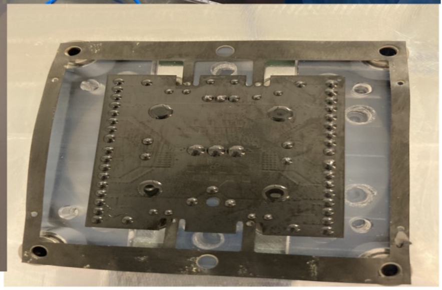
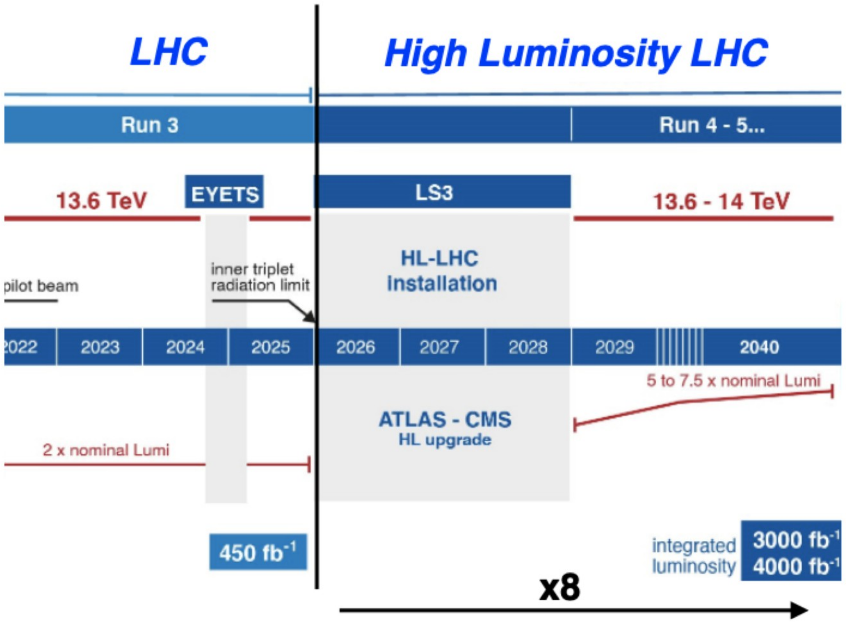


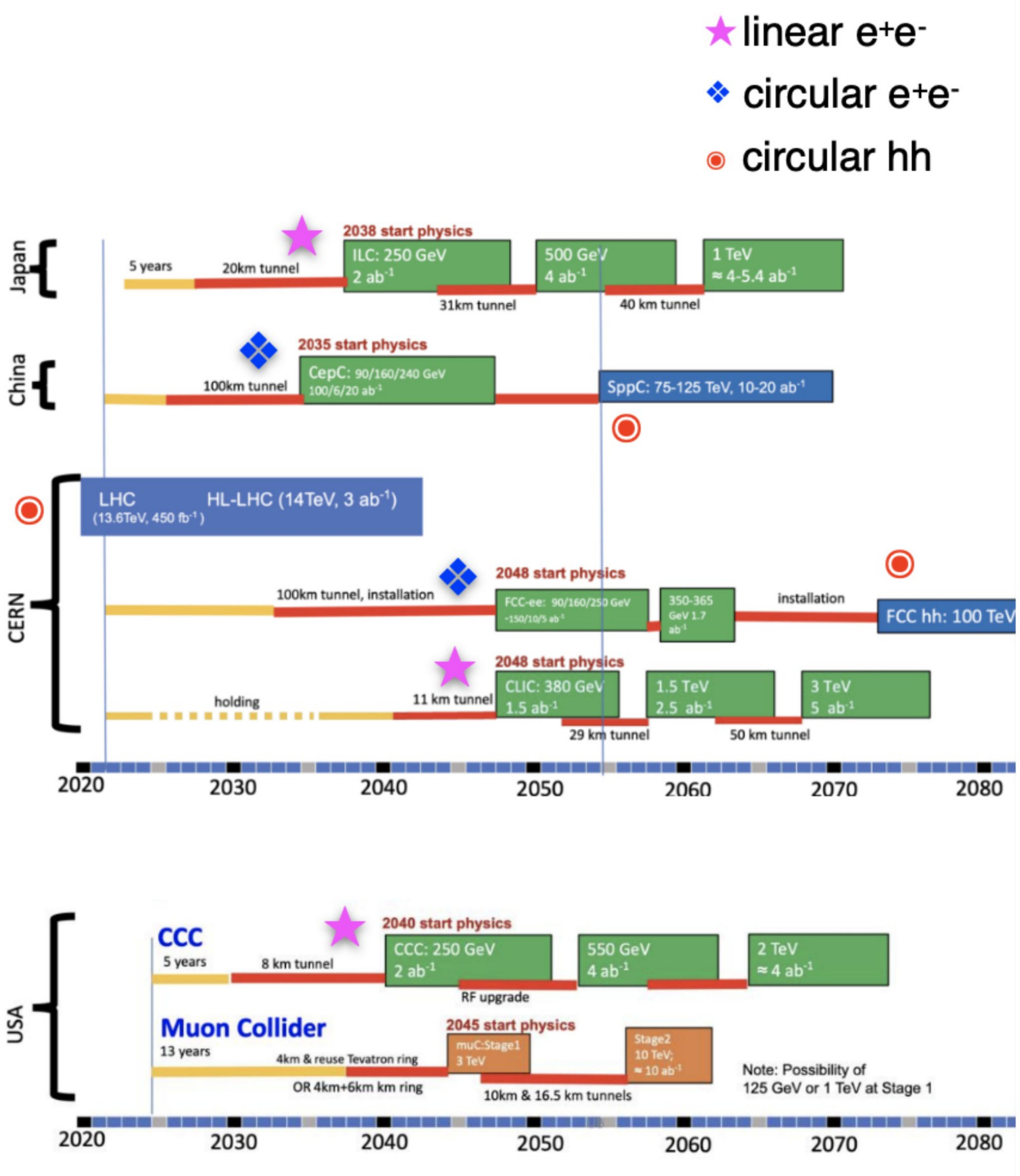
FIGURE 5.2: A schematic representation of the new internal detector proposed for the HL-LHC as a function of the distance to the interaction point along the beam axis (distance z) and the radius in transverse plane (distance





Outlook: troy horses
Further ahead





And an amazing team of people


The third run of the Large Hadron Collider has successfully started


Start of run2 physics at the Large Hadron Collider (LHC) --- ATLAS Control Room


Part of the LPNHE ATLAS team (2021)


ATLAS Hadronic Calibration Workshop, Cambridge 2022


Part of the VVJJ team (2015)

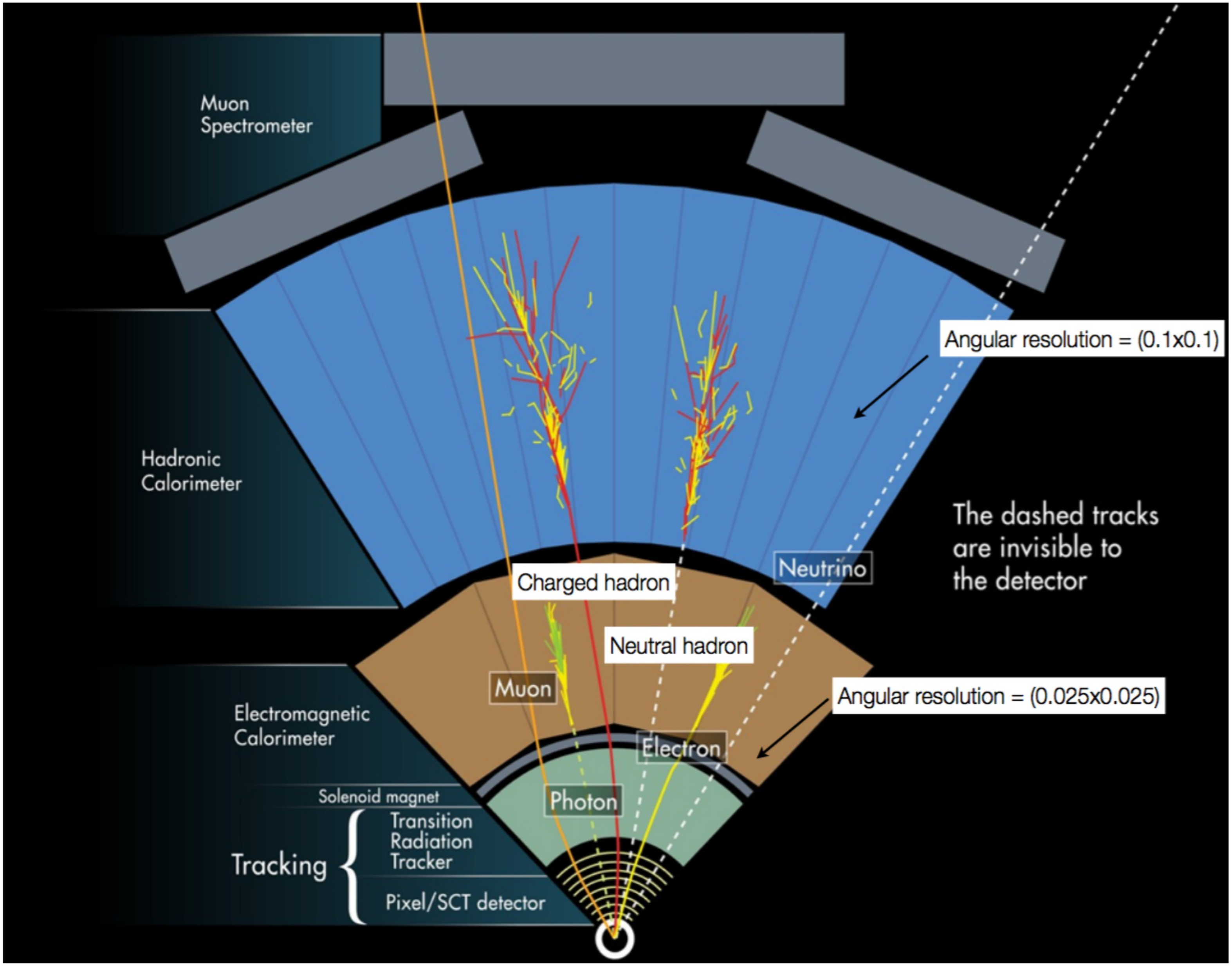

Part of the Diboson-Lepton team (2017)


ATLAS Hadronic Calibration Workshop, Corfu 2016

Thanks Gracias Merci

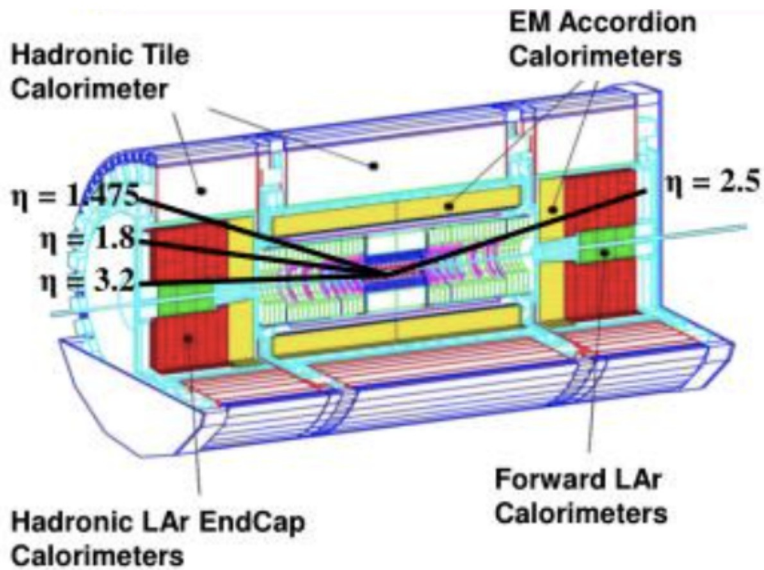
BACKUP

ATLAS calorimetry and tracking



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

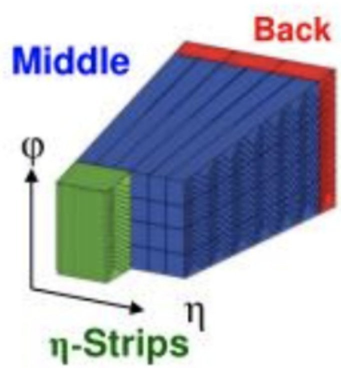
ATLAS Calorimeters



Calorimeter :

- Electromagnetic : (in $|\eta|<3.2$)
  $\sigma_E/E = 10\%/\sqrt{E(GeV)} \oplus 0.245/E(GeV) \oplus 0.7\%$
  (low luminosity)

Layer	Granularity ($\Delta\eta \times \Delta\varphi$)
Pre-sampler	0.025 x 0.1
Strips	0.003 x 0.1
Middle	0.025 x 0.025
Back	0.05 x 0.025



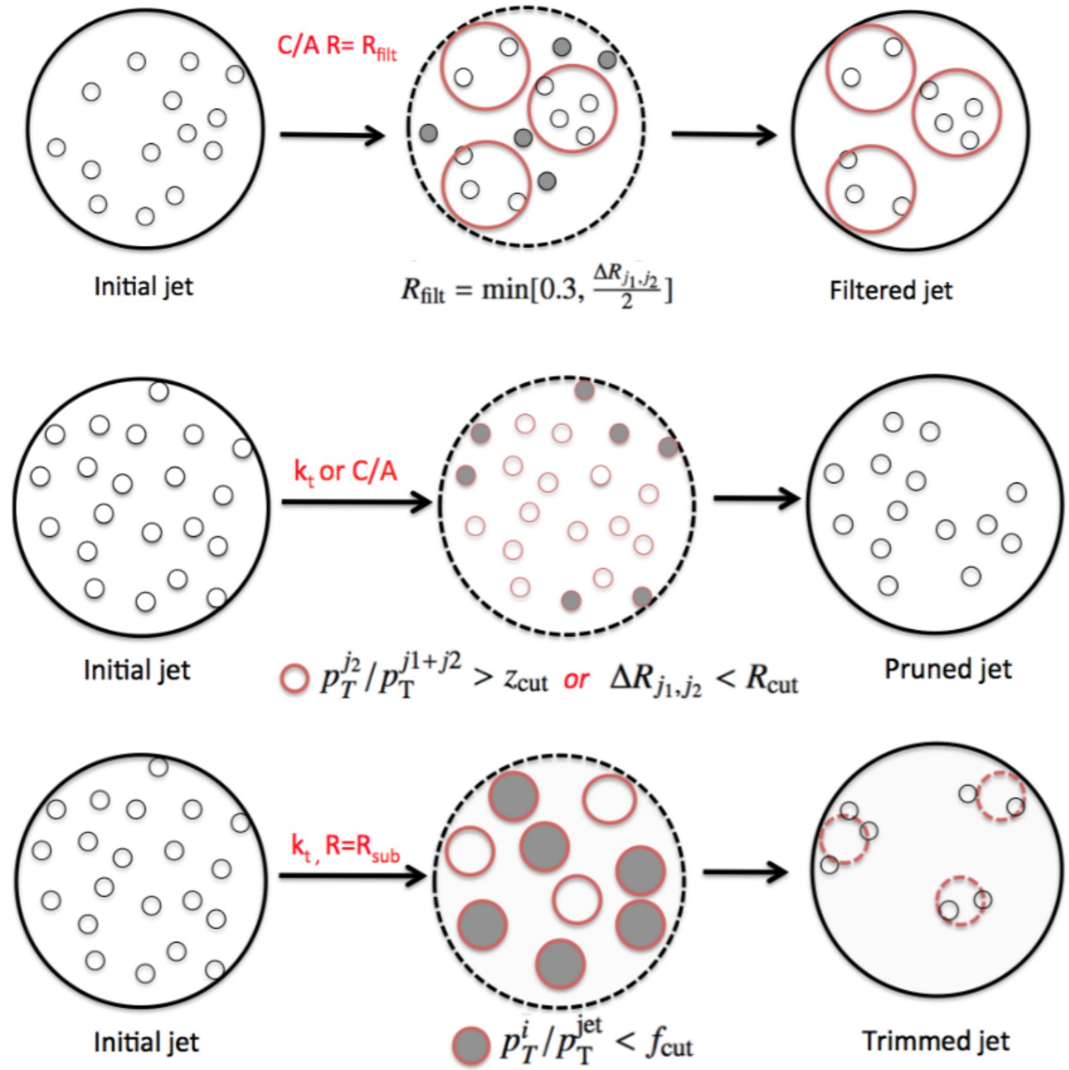
- Hadronic : (in $|\eta|<3$)
  $\sigma_E/E = 50\%/\sqrt{E(GeV)} \oplus 3.0\ \%$

Layer	Granularity ($\Delta\eta \times \Delta\varphi$)
Tile0	0.1 x 0.1
Tile1	0.1 x 0.1
Tile2	0.2 x 0.1

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

D2 definition

- **Energy correlation variables**
  - 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

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

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

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

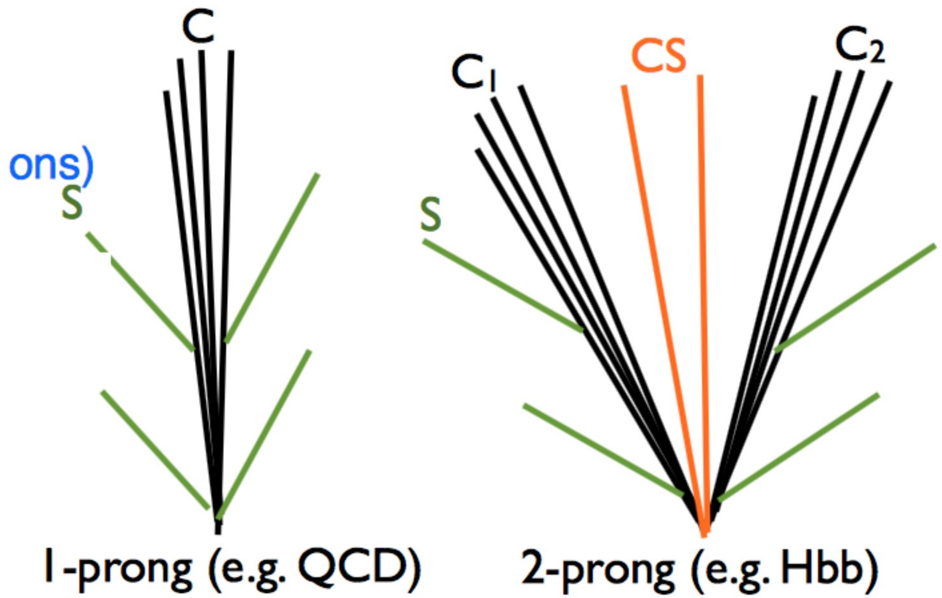
Larkoski et al,arXiV:1409.6298

D2: 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

Track assisted mass

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

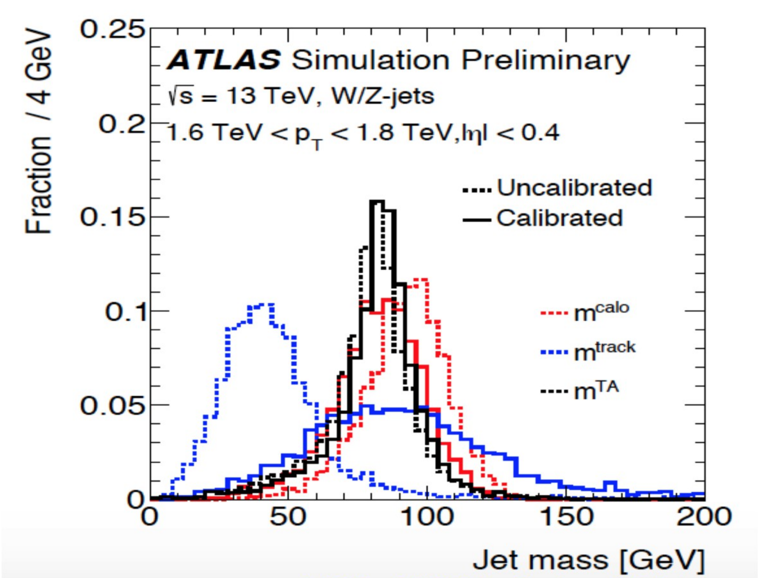
Track-assisted Mass

- Combined information from calorimeter and tracker → Improved mass resolution, especially at high p_T due to the relatively coarse calorimeter angular resolution

- Expected to be small for QCD jets, but closer to the boson mass for signal jets

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

ATLAS-CONF-2016-035



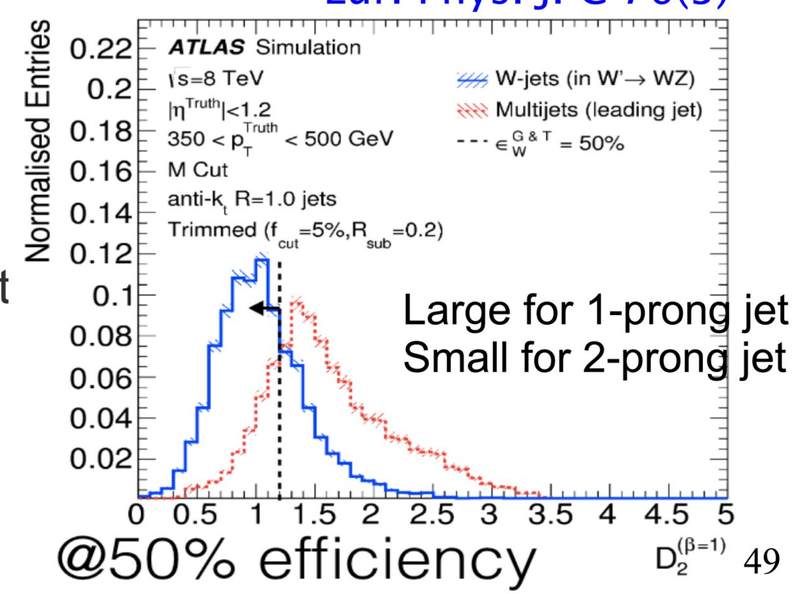
Energy correlation variables (*JHEP 05 (2016) 117*)

- 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

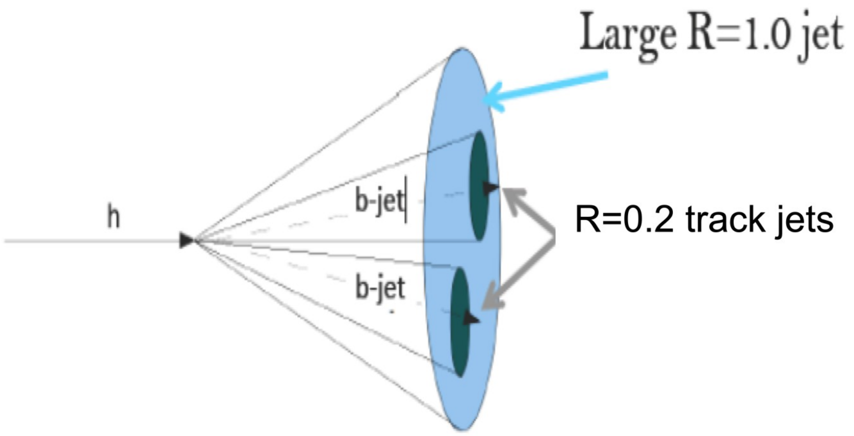
$$D_2^{\beta=1} = E_{\text{CF3}} \left(\frac{E_{\text{CF1}}}{E_{\text{CF2}}} \right)^3$$

Eur. Phys. J. C 76(3)

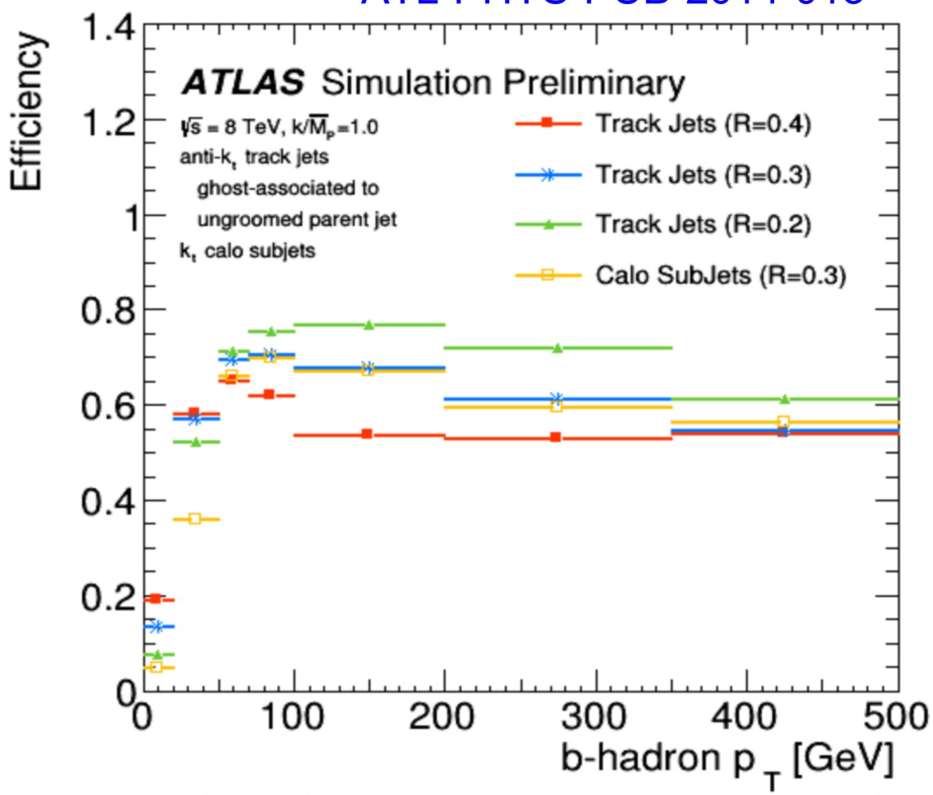


+ b-tagging for H→bb and Z→bb

- **In addition we 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
- They are associated to the large-R jet!



ATL-PHYS-PUB-2014-013



Old plot/old perf. but you can get the idea! Latest performance plots ATLAS-CONF-2016-039

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 ($k/\bar{M}_{\rm Pl} = 1$).

	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

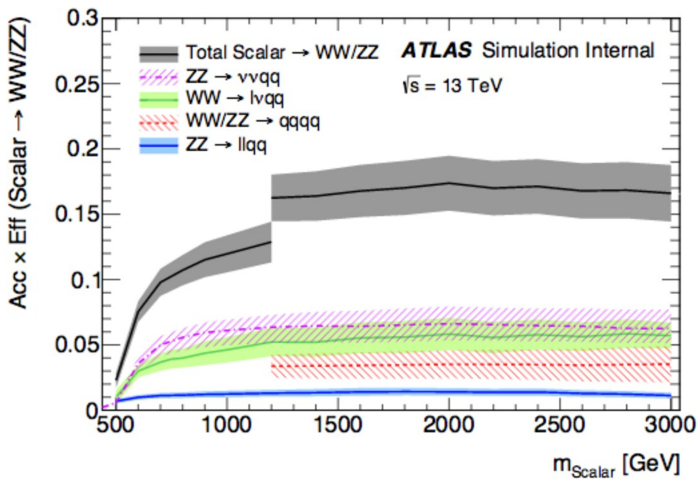
Table 2: Generators and PDFs used in the simulation of the various background processes.

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

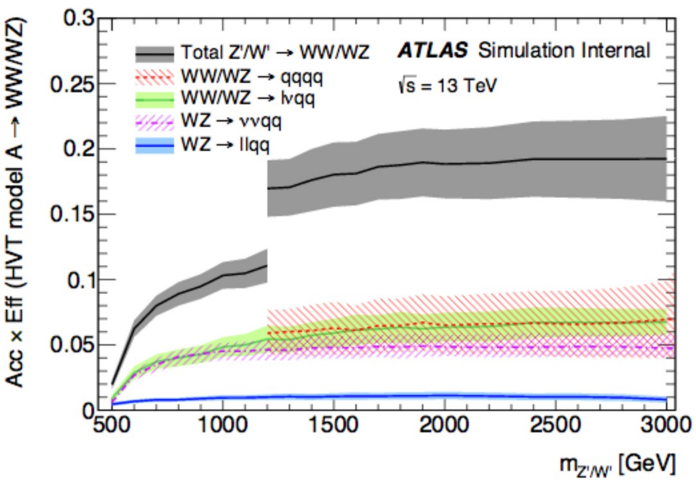
Table 4: Channels, signal regions and mass ranges where the channels contribute to the search.

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

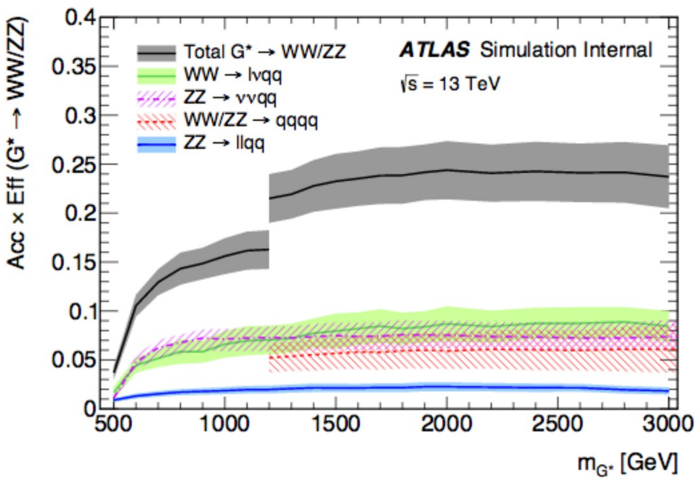
Information about benchmarks used in the 13 TeV analyses



(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.

VVJJ: Run-1 and Run-2 taggers

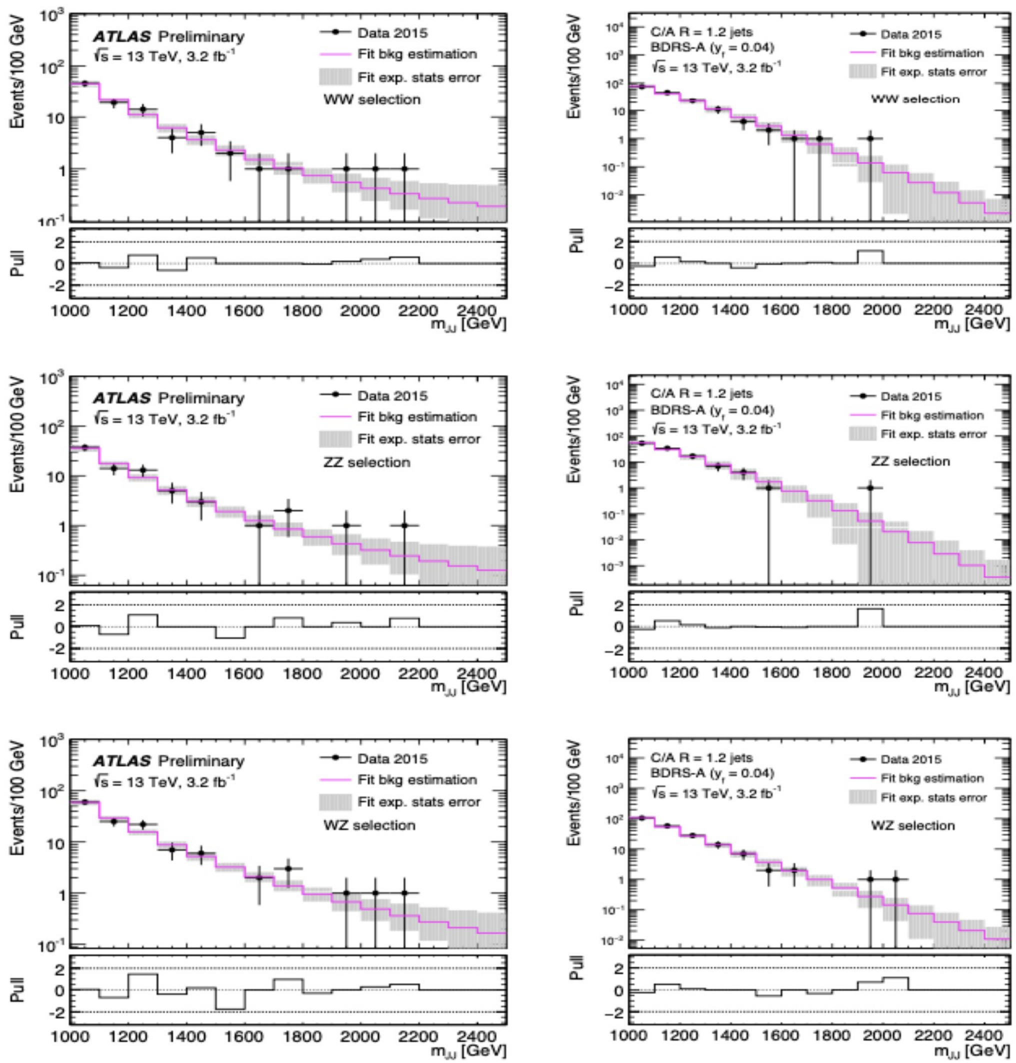


FIGURE 3.1: Background-only fit to the invariant dijet mass (m_{JJ}) distribution in 3.2/fb $\sqrt{s} = 13$ TeV data for boson-tagged jets in the three different signal regions: (top) WW, (middle) ZZ, (bottom) WZ using the Run-1 (left) and Run-2 (right) boosted boson tagger [104, 170].

Taggers and polarisation

- The polarisation affects the angular separation and momentum sharing between the decay products in the W → qq decay and thus affects the boson-tagging efficiency
- In the case of quark-initiated production, A × ε is similar for longitudinally and transversely polarised W bosons, as the reduction in kinematic acceptance (differences on the jet |η| of the two leading jets and their rapidity separation) is approximately compensated by an increase in boson-tagging efficiency

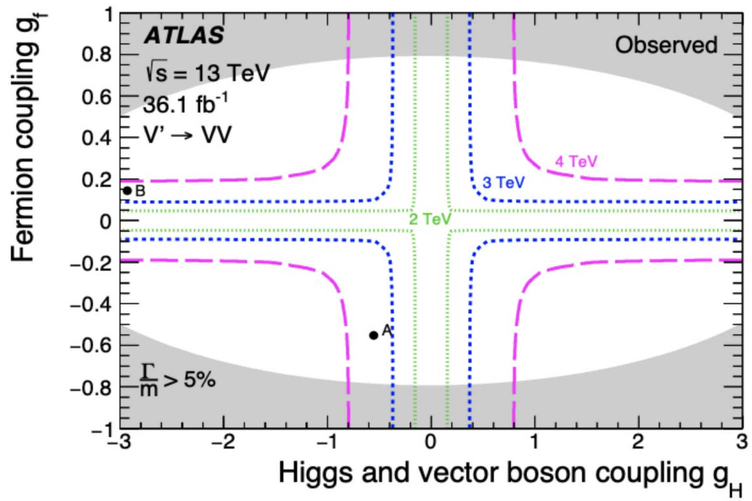
Phys. Lett. B 777 (2017) 91

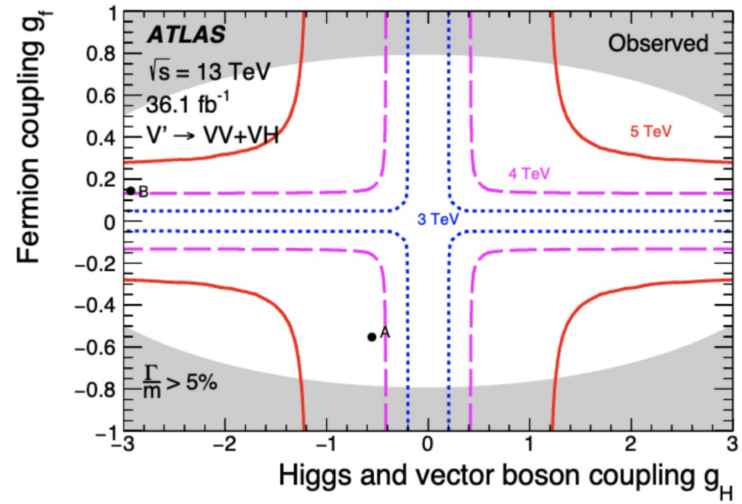
Model / process	Acceptance × efficiency	
	$m = 2$ TeV	$m = 3$ TeV
Heavy scalar	7.3%	7.2%
HVT model A, $g_V = 1$	13.8%	13.9%
Bulk RS, $k/\overline{M}_{\mathrm{Pl}} = 1$	12.7%	13.6%
$gg \to G_{\mathrm{KK}} \to WW$ (longitudinally polarised W)	12.3%	13.4%
$gg \to G_{\mathrm{KK}} \to WW$ (transversally polarised W)	1.8%	1.9%
$q\bar{q} \to G_{\mathrm{KK}} \to WW$ (longitudinally polarised W)	5.4%	5.4%
$q\bar{q} \to G_{\mathrm{KK}} \to WW$ (transversally polarised W)	5.2%	5.8%

Early Run-2: Combining VV, VH and dilepton resonances

- Two-dimensional limits on the coupling strengths of heavy resonances to SM particles in the context of the HVT model

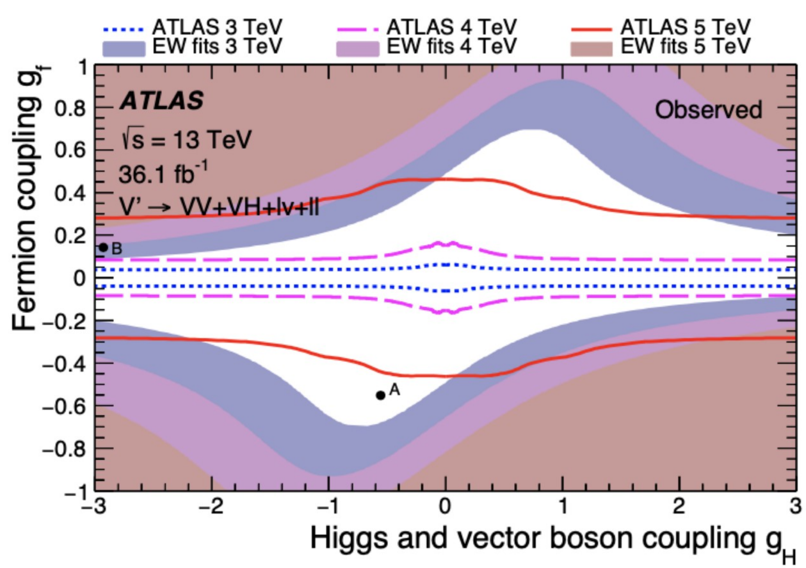
Phys. Rev. D 98, 052008 (2018)





$$(g_f = g_\ell = g_q)$$

- VV/VH constraint are better at large couplings for g_f and g_H, but become weak as the couplings approach zero

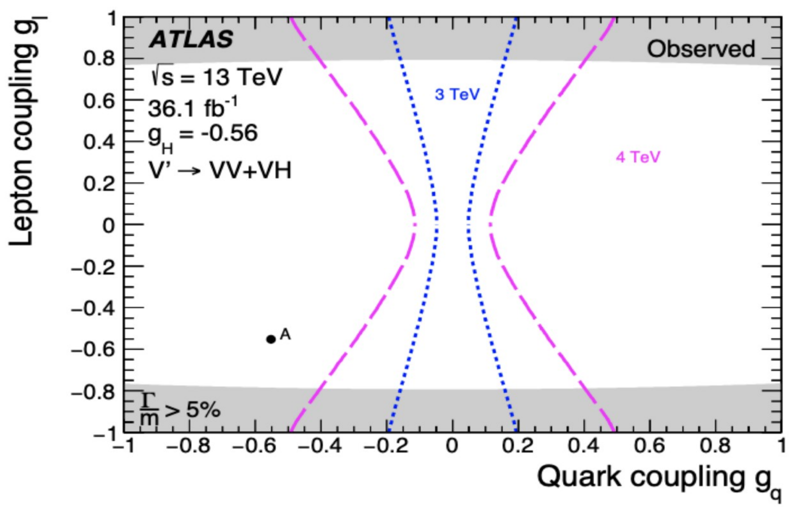


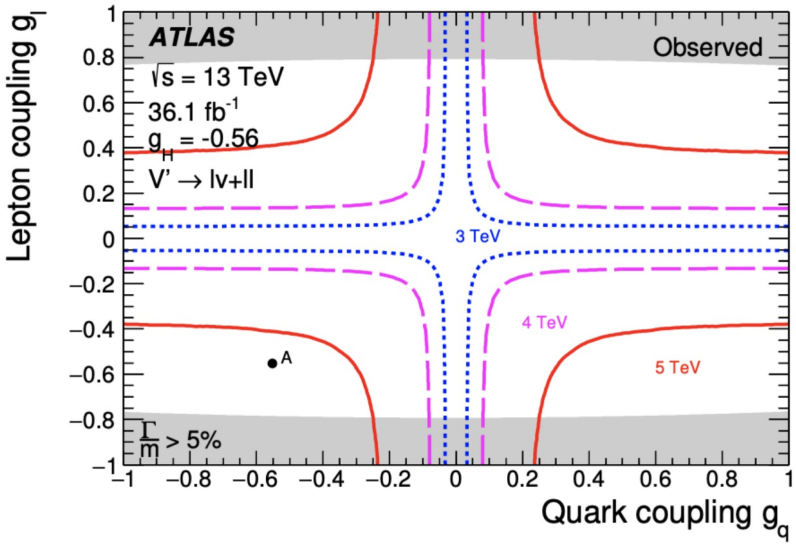
- Improved limits from the best precision EW measurements at the time, except at low $|g_q|$

- Constrains were set also on the $\{g_l, g_q\}$ plane (see backup)

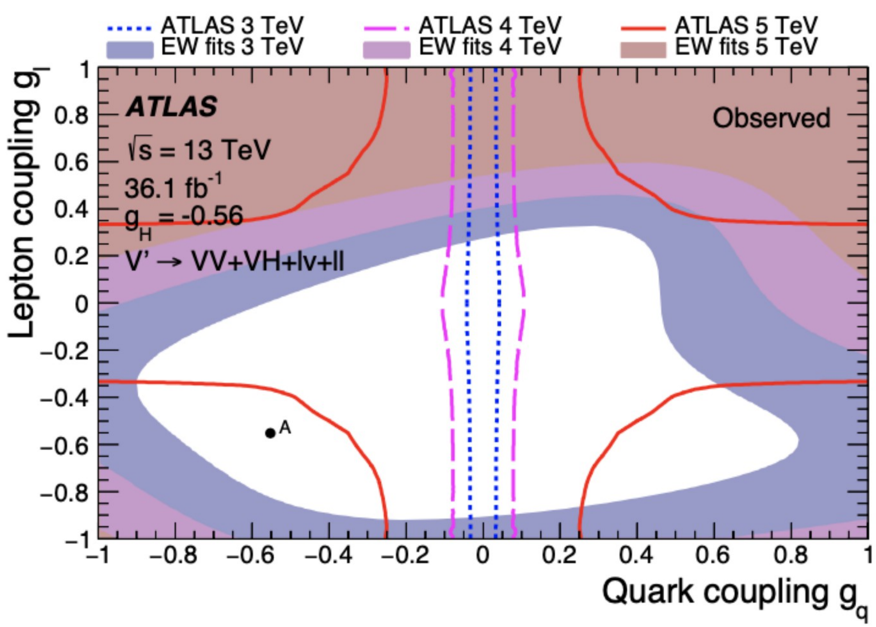
Early Run-2: Combining VV, VH and dilepton resonances

- Two-dimensional limits on the coupling strengths of heavy resonances to SM particles in the context of the HVT model





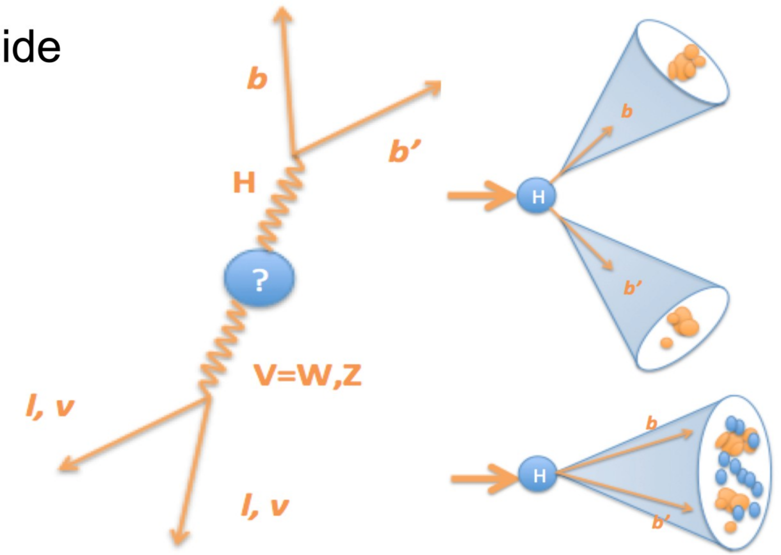
- VV/VH constraint is worst at large gl as the bosonic branching fraction decrease while the leptonic one increases in that region

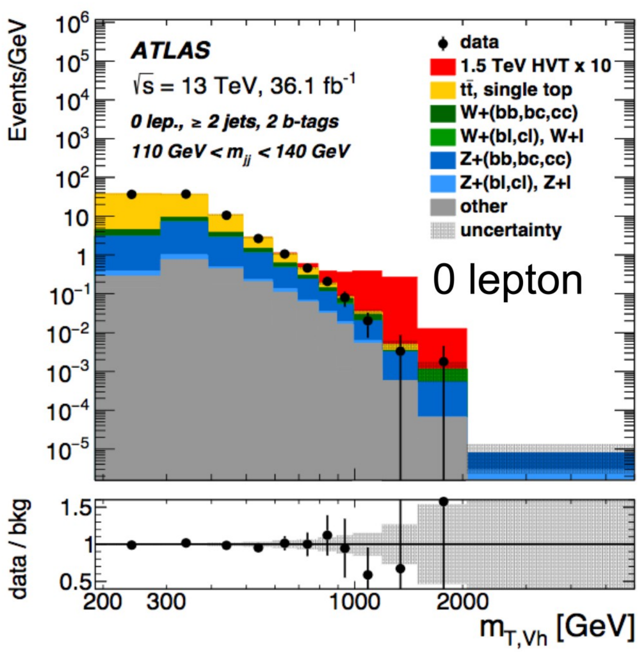


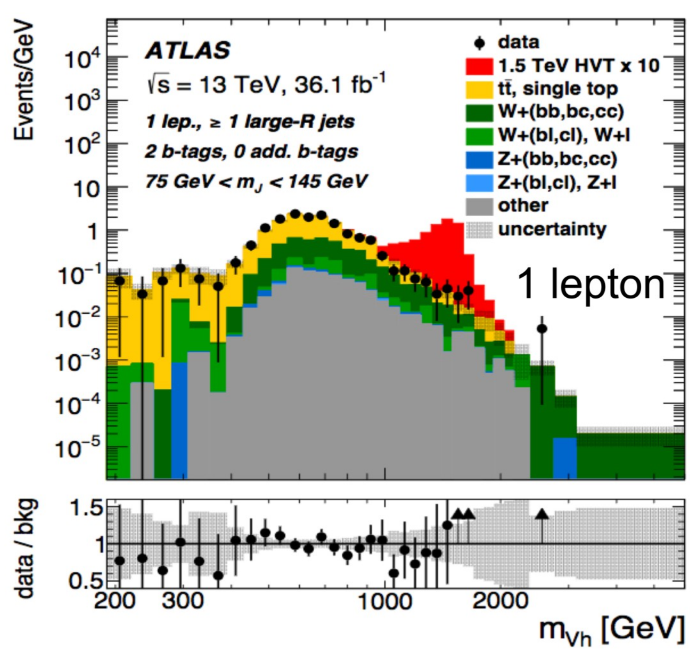
- GH =0 or gH =−0.56,where the latter takes the value predicted in the HVT model A benchmark

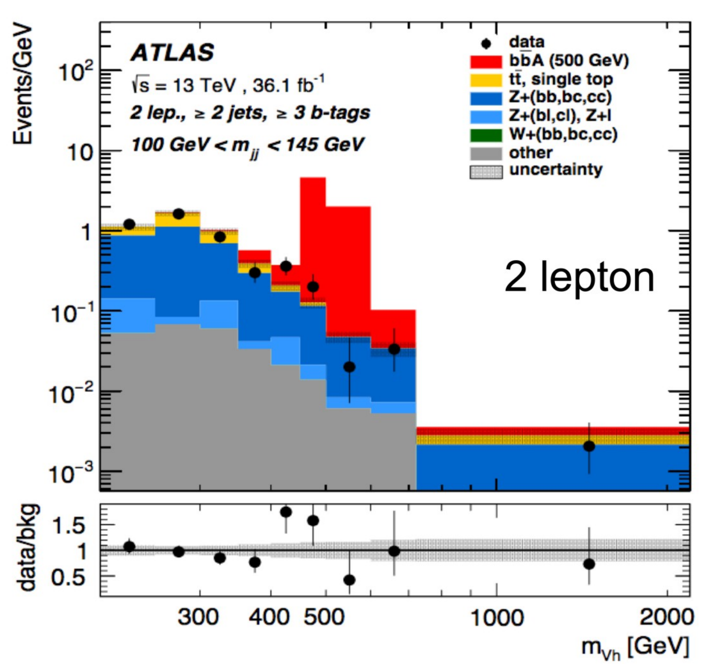
VH → llbb/lvbb/vvbb: Selection and backgrounds

- **Selection:** similar 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
- **Models:** HVT, 2HDM
- **Main uncertainties:** jet related and b-tagging

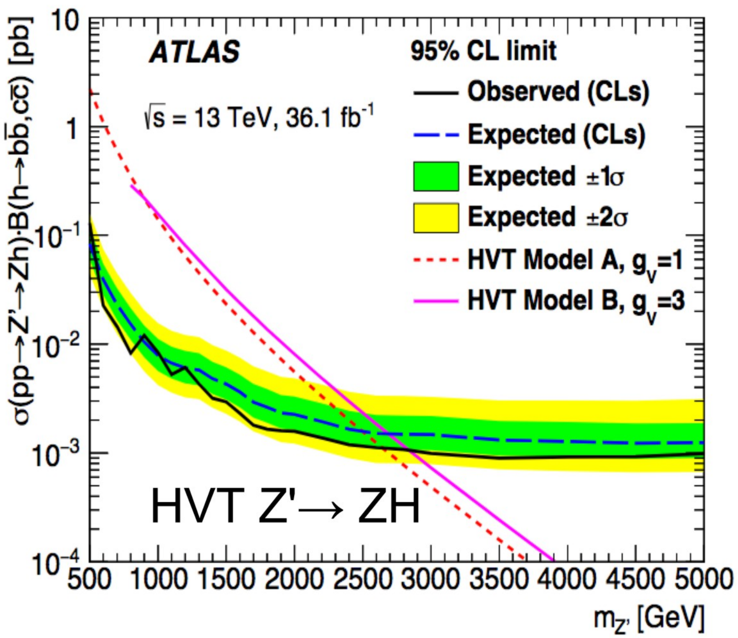


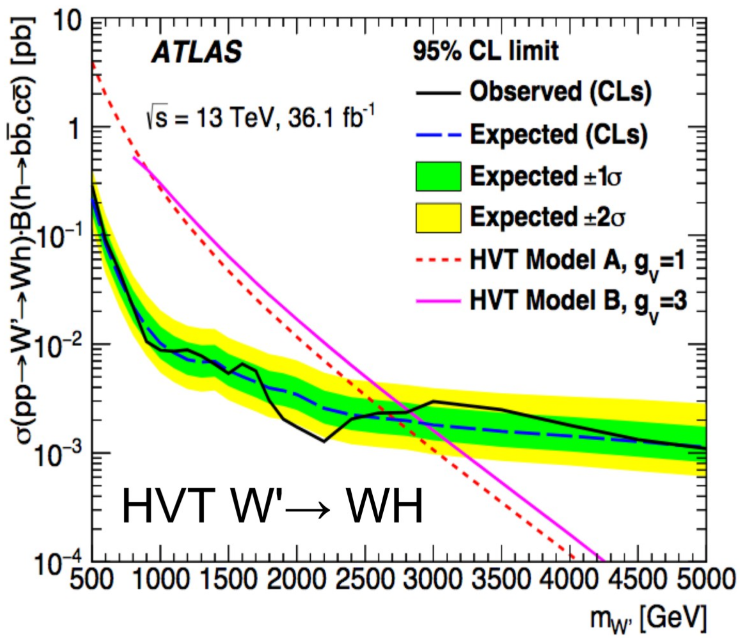


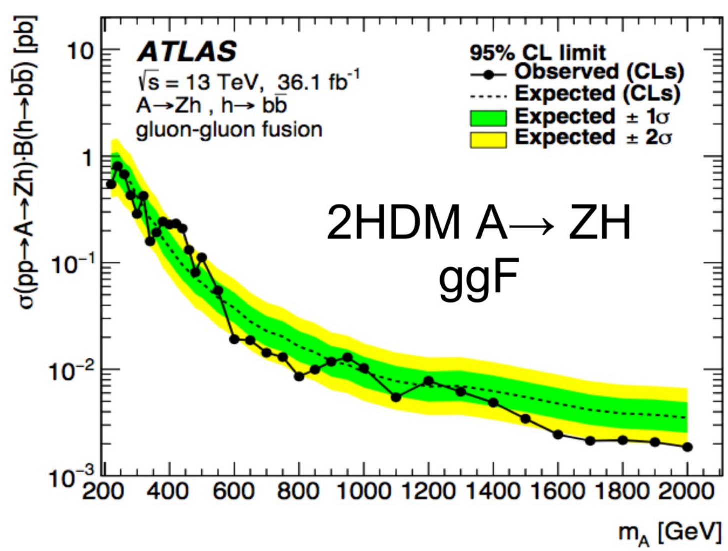




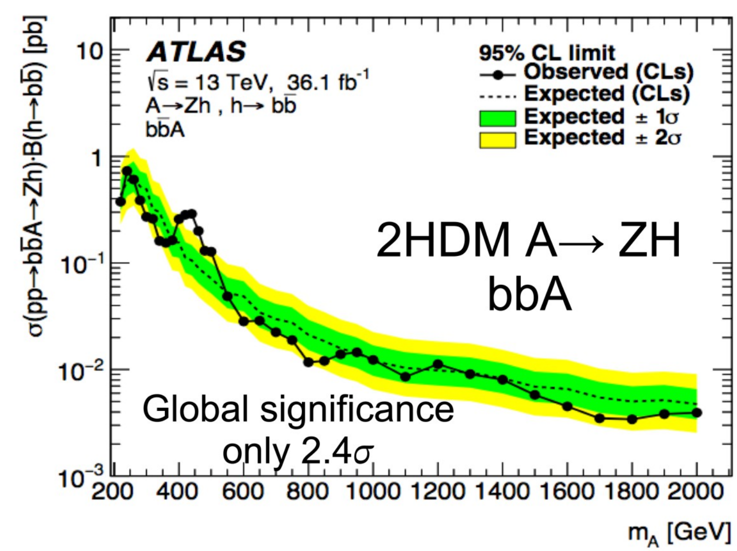
VH → llbb/lνbb/ννbb: Limits results





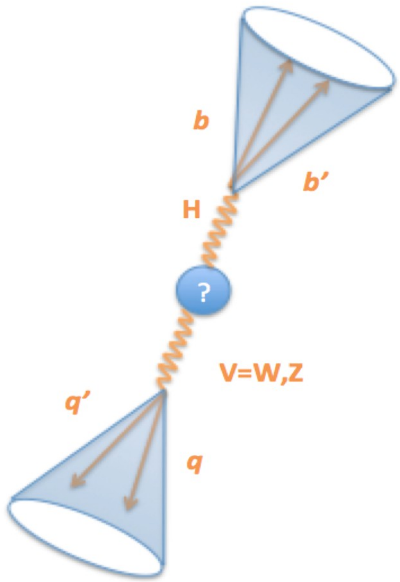


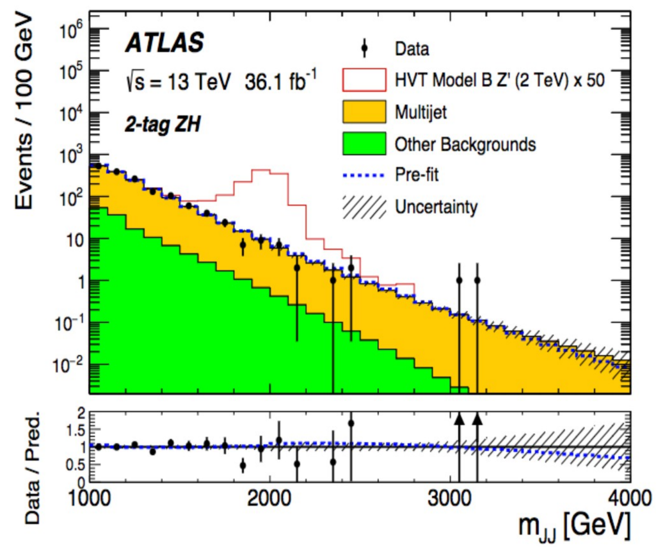
(a) Pure gluon–gluon fusion production

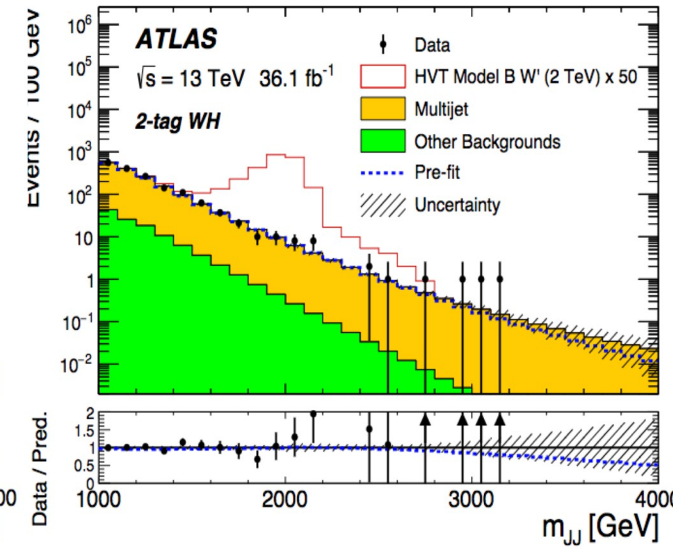


(b) Pure b-quark associated production

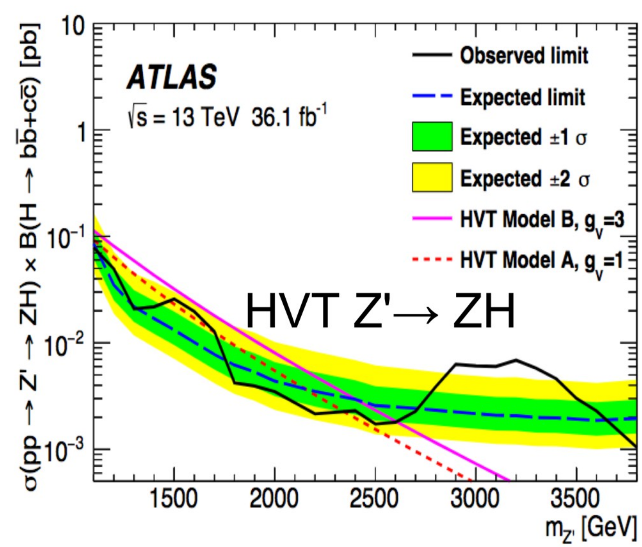
Search for VH, V→ qq and H→$b\bar{b}$

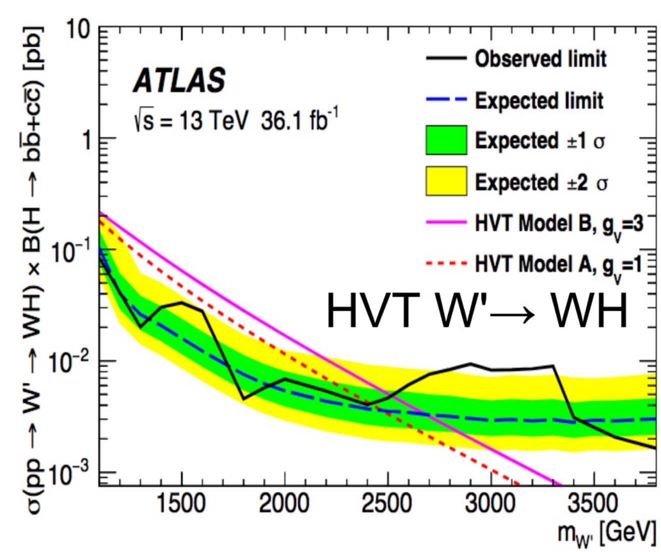






- Complementary to semi-leptonic VH searches at high masses
- Main backgrounds: data driven multijet QCD and $t\bar{t}$
- Only boosted regime
- No significant deviation found
  - Largest deviation at 3 TeV (2.1σ global significance)

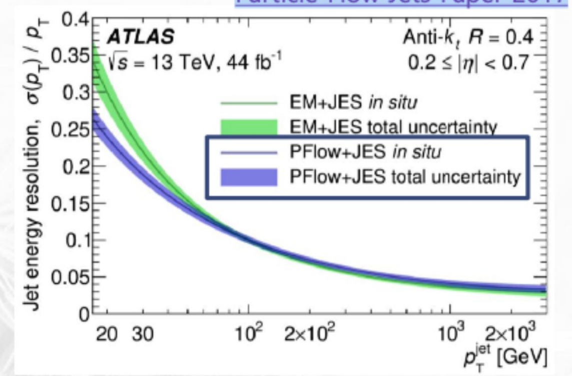




Particle Flow

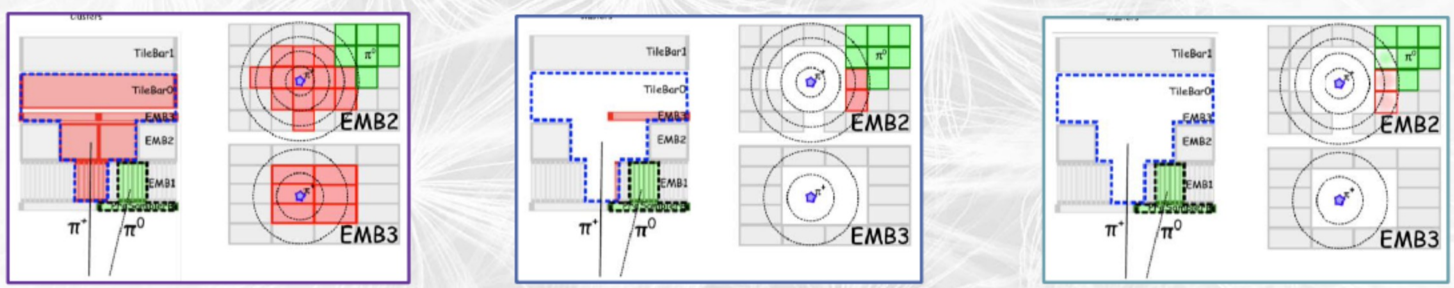
Particle Flow Jets

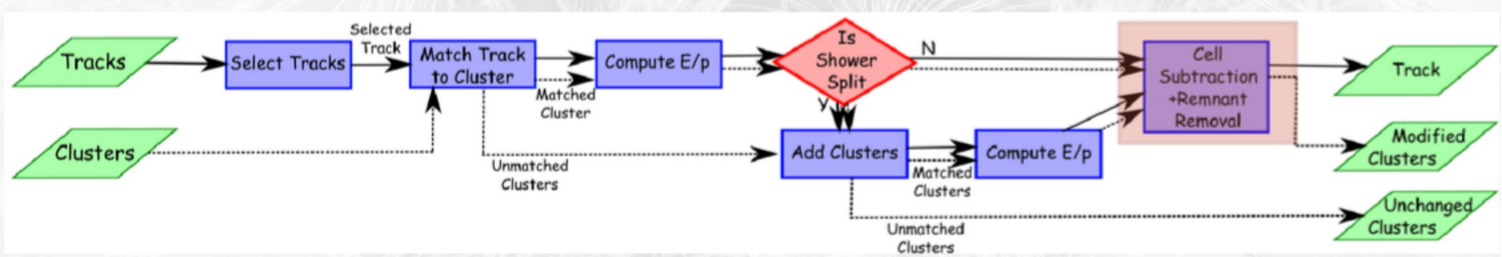
Particle Flow Jets Paper 2017



Combine Calo+Tracks w/o double counting

- Associate Tracks with ≥ 1 Topoclusters
- Subtract calo energy deposits matching a track.
- Remove PU tracks at the end using Charged Hadron Subtraction (CHS)
- Better performance/resolution at low p_T

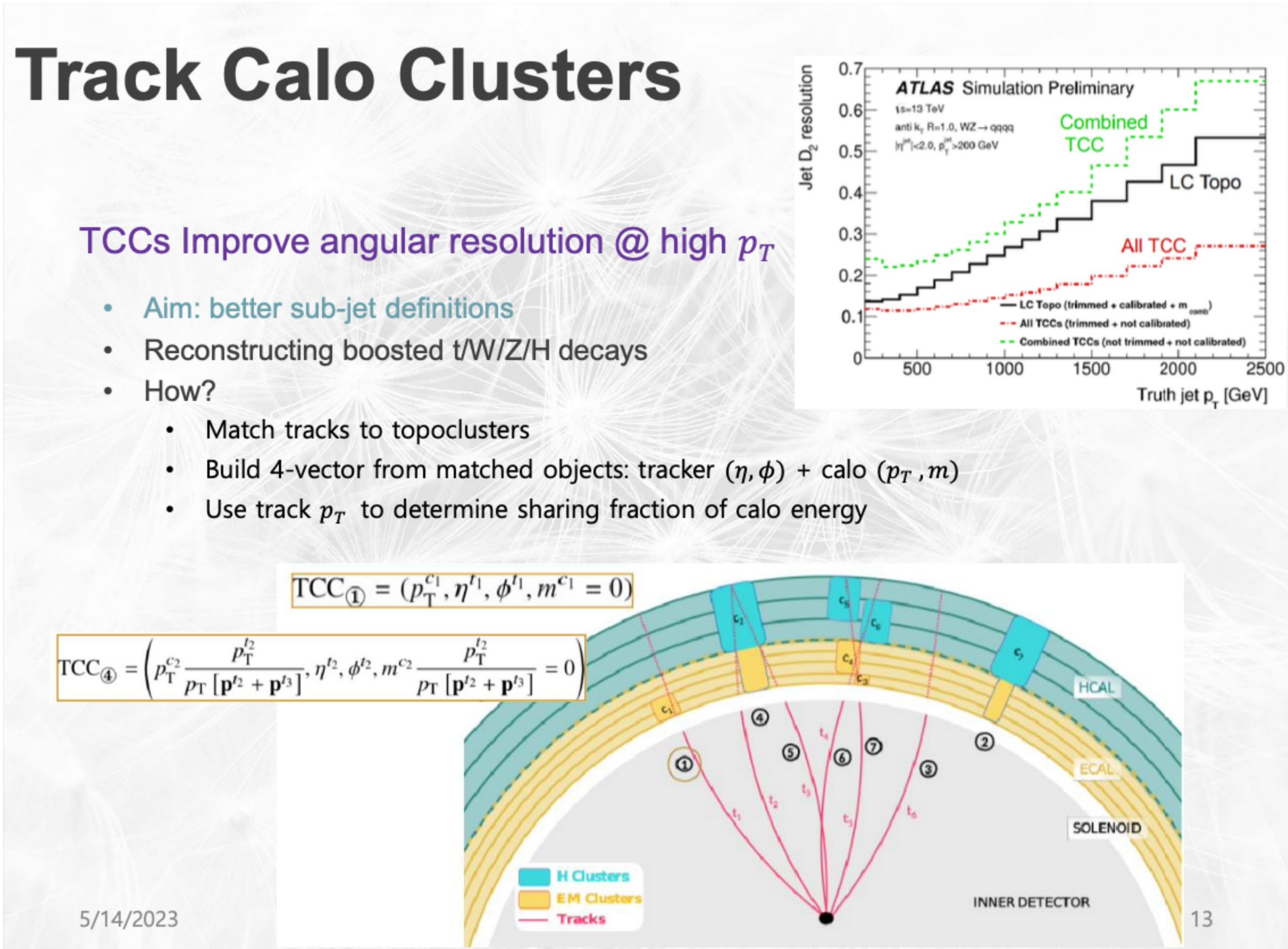




5/14/2023 Holly Pacey, University of Oxford 12

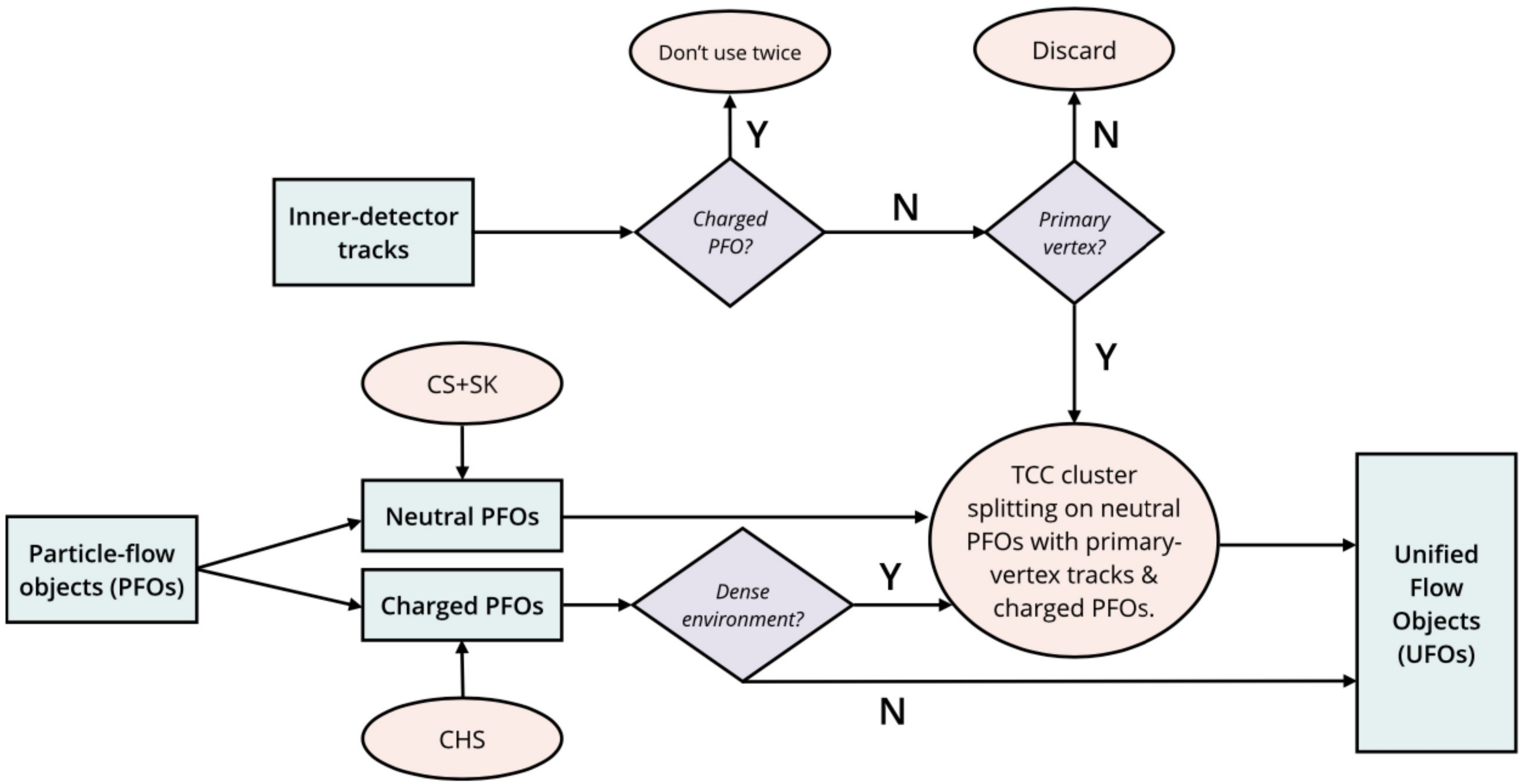
Particle Flow (PFlow) algorithm: tracks with good momentum resolution extrapolated to calorimeter, cell-by-cell subtraction of their deposited energy. At high p_T tracks are ignored

Track-Calo Clusters



Track-calo cluster (TCC) algorithm: effectively uses tracks to split up large clusters at high p_T, get energy from clusters but angles from tracks. At low p_T clusters-only are used

Unified Flow Objects (UFO)



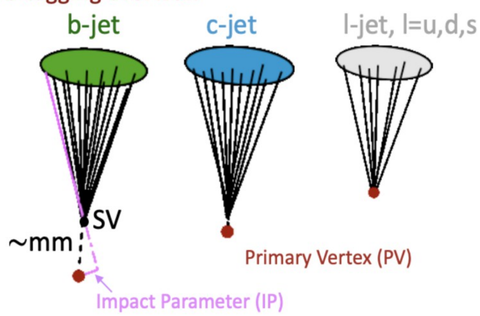
Eur. Phys. J. C 81, 334 (2021)

Current state of the art is combination of TCC and PFlow

Unified Flow Objects (UFO): good angular resolution of tracker and good energy resolution from calorimeter

Small-R jets or VR track jets

b-tagging overview



- Small-R jets: R=0.4
- **VR track jets:** $R \rightarrow R_{eff}(p_T) = \frac{\rho}{p_T}$, $\rho = 30$ GeV
  $R_{max} = 0.4, R_{min} = 0.02$

Inputs: Hadronic jets / Tracks / Primary vertex → **Low level**: IP based algorithms / SV finding algorithm / Multi-vertex finding algorithm ↓ **High level**: Boosted Decision Tree algorithm (MV2) / Neural Network algorithm (DL1/DL1r) → **Output**: b-tagging discriminant

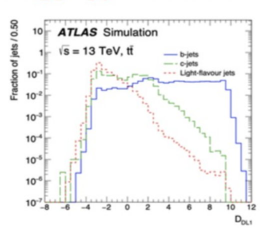
b-jets

- Measurable Secondary Vertex (SV).
- High decay product multiplicity.

The b-tagging info is necessary to identify H→bb

Small-R jets or VR track jets

b-tagging performance and calibration



Choose cuts on the discriminant from high level algorithms

b-tagging efficiency: $\epsilon_b = \frac{N_b^{tagged}}{N_b^{total}}$

c, l-jet mistag rate: $\epsilon_{c,l} = \frac{N_{c,l}^{tagged}}{N_{c,l}^{total}}$

- Taggers developed/measured using specific (nominal) Monte-Carlo (MC) simulations
  - May have a different performance from MCs used in physic analyses. → MC-to-MC scale factors $\frac{\epsilon_{alt.\ MC}}{\epsilon_{nom.\ MC}}$
  - Not able to fully describe data. → Data-to-MC scale factors $\frac{\epsilon_{data}}{\epsilon_{nom.\ MC}}$

    b-jet tagging efficiency/calibrations measured using 2L $t\bar{t}$
    c-jet mis-tag rate/calibrations measured using 1L $t\bar{t}$
    l-jet mis-tag rate/calibrations measured using Z+jets event

Boosted VH, H→bb categories

Channel	Categories					
	$250 < p_T^V < 400$ GeV			$p_T^V \geq 400$ GeV		
	0 add. b-track-jets		≥ 1 add. b-track-jets	0 add. b-track-jets		≥ 1 add. b-track-jets
	0 add. small-R jets	≥ 1 add. small-R jets		0 add. small-R jets	≥ 1 add. small-R jets	
0-lepton	HP SR	LP SR	CR	HP SR	LP SR	CR
1-lepton	HP SR	LP SR	CR	HP SR	LP SR	CR
2-lepton	SR			SR		

Table 2: Event selection requirements for the boosted $VH, H \to b\bar{b}$ analysis channels and sub-channels.

Selection	0 lepton channel	1 lepton channel		2 leptons channel	
		e sub-channel	μ sub-channel	e sub-channel	μ sub-channel
Trigger	E_T^{miss}	Single electron	E_T^{miss}	Single electron	E_T^{miss}
Leptons	0 *baseline* leptons	1 *signal* lepton		2 *baseline* leptons among which	
		$p_T > 27$ GeV	$p_T > 25$ GeV	≥ 1 *signal* lepton, $p_T > 27$ GeV	
		no second *baseline* lepton		both leptons of the same flavour	
				-	opposite sign muons
E_T^{miss}	> 250 GeV	> 50 GeV	-	-	
p_T^V	$p_T^V > 250$ GeV				
Large-R jets	at least one large-R jet, $p_T > 250$ GeV, $\|\eta\| < 2.0$				
Track-jets	at least two track-jets, $p_T > 10$ GeV, $\|\eta\| < 2.5$, matched to the leading large-R jet				
b-tagged jets	leading two track-jets matched to the leading large-R must be b-tagged (MV2c10, 70%)				
m_J	> 50 GeV				
$\min[\Delta\phi(\boldsymbol{E}_T^{miss}, \text{small-}R \text{ jets})]$	$> 30°$	-			
$\Delta\phi(\boldsymbol{E}_T^{miss}, H_{cand})$	$> 120°$	-			
$\Delta\phi\ (\boldsymbol{E}_T^{miss}, \boldsymbol{E}_{T,\,trk}^{miss})$	$< 90°$	-			
$\Delta y(V, H_{cand})$	-	$\|\Delta y(V, H_{cand})\| < 1.4$			
$m_{\ell\ell}$	-			66 GeV$< m_{\ell\ell} <$ 116 GeV	
Lepton p_T imbalance	-			$(p_T^{\ell_1} - p_T^{\ell_2})/p_T^Z < 0.8$	

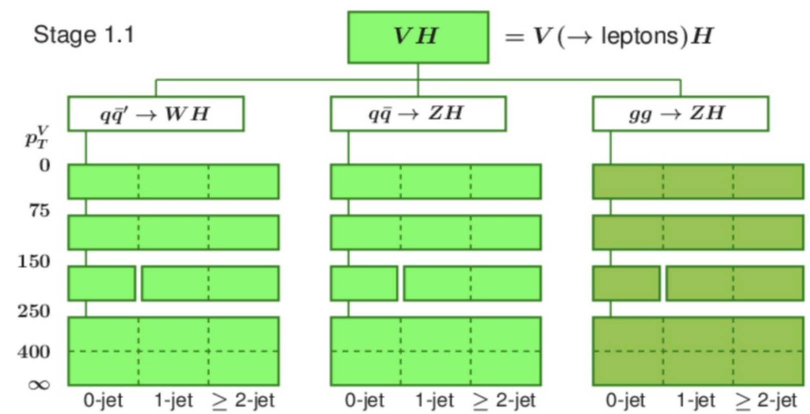
Boosted VH, H→bb samples

Process	ME generator	ME PDF	PS and Hadronisation	UE model tune	Cross-section order
Signal (m_H = 125 GeV and $b\bar{b}$ branching fraction set to 58%)					
$qq \to WH \to \ell\nu b\bar{b}$	Powheg-Box v2 [41] + GoSam [43] + MiNLO [44, 45]	NNPDF3.0NLO$^{(\star)}$ [37]	Pythia 8.212 [42]	AZNLO [30]	NNLO(QCD)+ NLO(EW) [46–52]
$qq \to ZH \to \nu\nu b\bar{b}/\ell\ell b\bar{b}$	Powheg-Box v2 + GoSam + MiNLO	NNPDF3.0NLO$^{(\star)}$	Pythia 8.212	AZNLO	NNLO(QCD)$^{(\dagger)}$+ NLO(EW)
$gg \to ZH \to \nu\nu b\bar{b}/\ell\ell b\bar{b}$	Powheg-Box v2	NNPDF3.0NLO$^{(\star)}$	Pythia 8.212	AZNLO	NLO+ NLL [53–57]
Top quark (m_t = 172.5 GeV)					
$t\bar{t}$	Powheg-Box v2 [41, 58]	NNPDF3.0NLO	Pythia 8.230	A14 [31]	NNLO+NNLL [59]
s-channel	Powheg-Box v2 [41, 60]	NNPDF3.0NLO	Pythia 8.230	A14	NLO [61]
t-channel	Powheg-Box v2 [41, 60]	NNPDF3.0NLO	Pythia 8.230	A14	NLO [62]
Wt	Powheg-Box v2 [41, 63]	NNPDF3.0NLO	Pythia 8.230	A14	Approximate NNLO [64]
Vector boson + jets					
$W \to \ell\nu$	Sherpa 2.2.1 [32–35]	NNPDF3.0NNLO	Sherpa 2.2.1 [65, 66]	Default	NNLO [67]
$Z/\gamma^* \to \ell\ell$	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NNLO
$Z \to \nu\nu$	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NNLO
Diboson					
$qq \to WW$	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NLO
$qq \to WZ$	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NLO
$qq \to ZZ$	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NLO
$gg \to VV$	Sherpa 2.2.2	NNPDF3.0NNLO	Sherpa 2.2.2	Default	NLO

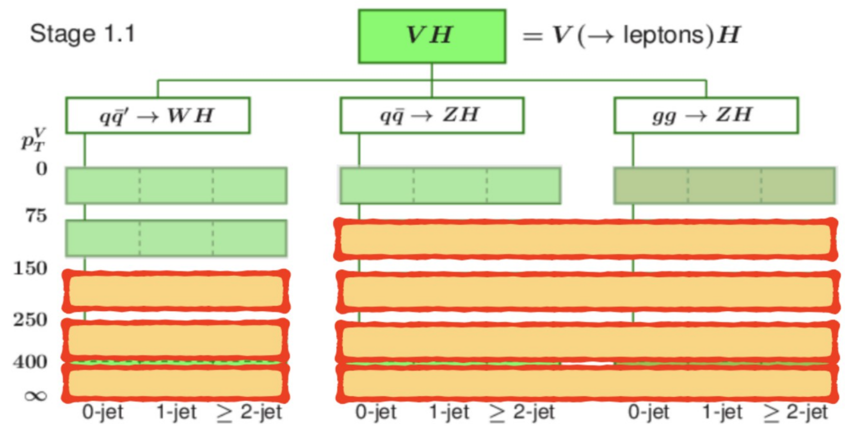
Boosted VH, H→bb: STXS

- ***Simplified template cross section:***
  - *truth template defined only with global VH kinematics (W VS Z, V p_T)*
  - *no dependance on Higgs decay: allow combination across decay modes*
  - one step closer to a proper fiducial / differential cross section measurements …

- ***What theorists would like us to measure***



- ***What we can measure in VHbb*** *exploiting analysis categorisation:*
  - extract signal strength in analysis regions
  - correct from truth-recon migrations



Taken from V. Dao

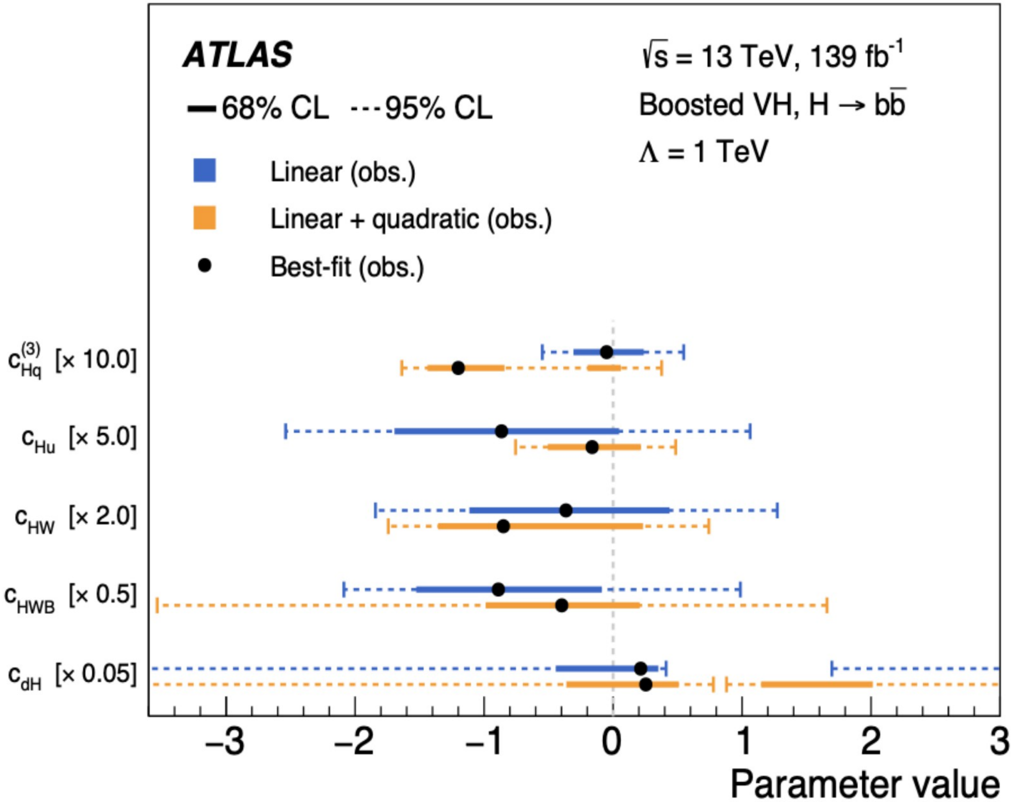
Boosted VH, H→bb: EFT

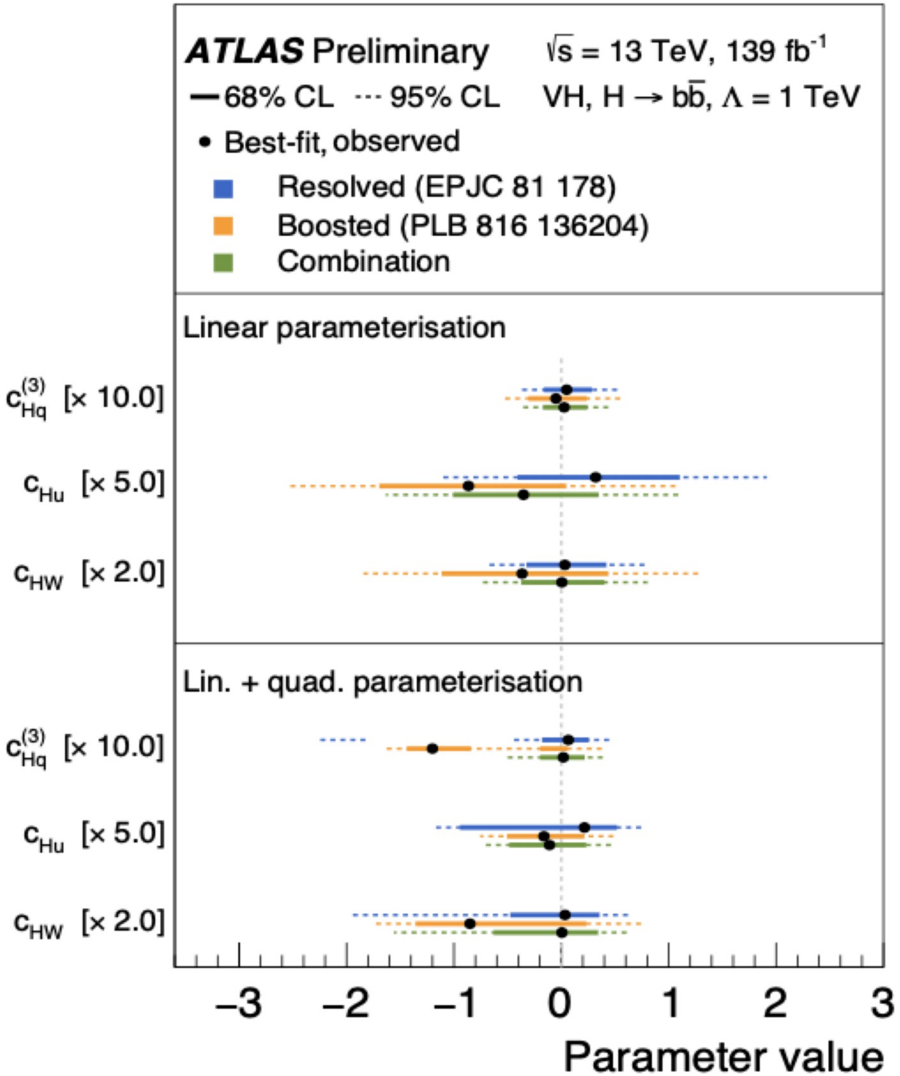
Coefficient	Operator
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
c_{HDD}	$(H^\dagger D^\mu H)^*(H^\dagger D_\mu H)$
c_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$
c_{HW}	$H^\dagger H W^I_{\mu\nu} W^{I\mu\nu}$
c_{HB}	$H^\dagger H B_{\mu\nu} B^{\mu\nu}$
c_{HWB}	$H^\dagger \tau^I H W^I_{\mu\nu} B^{\mu\nu}$
$c^{(1)}_{Hl}$	$H^\dagger i \overleftrightarrow{D}_\mu H(\bar{l}_p \gamma^\mu l_r)$
$c^{(3)}_{Hl}$	$H^\dagger i \overleftrightarrow{D}^I_\mu H(\bar{l}_p \tau^I \gamma^\mu l_r)$
$c^{(1)}_{He}$	$H^\dagger i \overleftrightarrow{D}_\mu H(\bar{e}_p \gamma^\mu e_r)$
$c^{(1)}_{Hq}$	$H^\dagger i \overleftrightarrow{D}_\mu H(\bar{q}_p \gamma^\mu q_r)$
$c^{(3)}_{Hq}$	$H^\dagger i \overleftrightarrow{D}^I_\mu H(\bar{q}_p \tau^I \gamma^\mu q_r)$
c_{Hu}	$H^\dagger i \overleftrightarrow{D}_\mu H(\bar{u}_p \gamma^\mu u_r)$
c_{Hd}	$H^\dagger i \overleftrightarrow{D}_\mu H(\bar{d}_p \gamma^\mu d_r)$
c'_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$

in addition to the operator which affects the H→bb decay

- The scale of new physics Λ is a free parameter set to 1 TeV
- Dimension d = 6 operators is used, taking into account only the lepton- and baryon-number-conserving ones
- Only considers the CP-even terms respecting a U(3)5 flavour symmetry
- Takes into account the linear terms originating from the interference between SM and non-SM amplitudes as well as the quadratic ones from the squared non-SM amplitudes. The former are of order 1/Λ2 and the latter of order 1/Λ4
- Given that the current parameterisation takes neither next-to-leading-order effects nor the interference between SM and dimension-8 operators into account, the 1/Λ4 terms are incomplete
- The impact of the Wilson coefficients on the experimental analysis acceptance is not accounted for in this study. It was, however, verified that the impact was less than 20% of the SMEFT parameterization in the kinematic range considered in this study
- Due to the limited number of STXS bins, not all Wilson coefficients can be measured simultaneously

Boosted VH, H→bb: EFT





H→bb: full snapshot

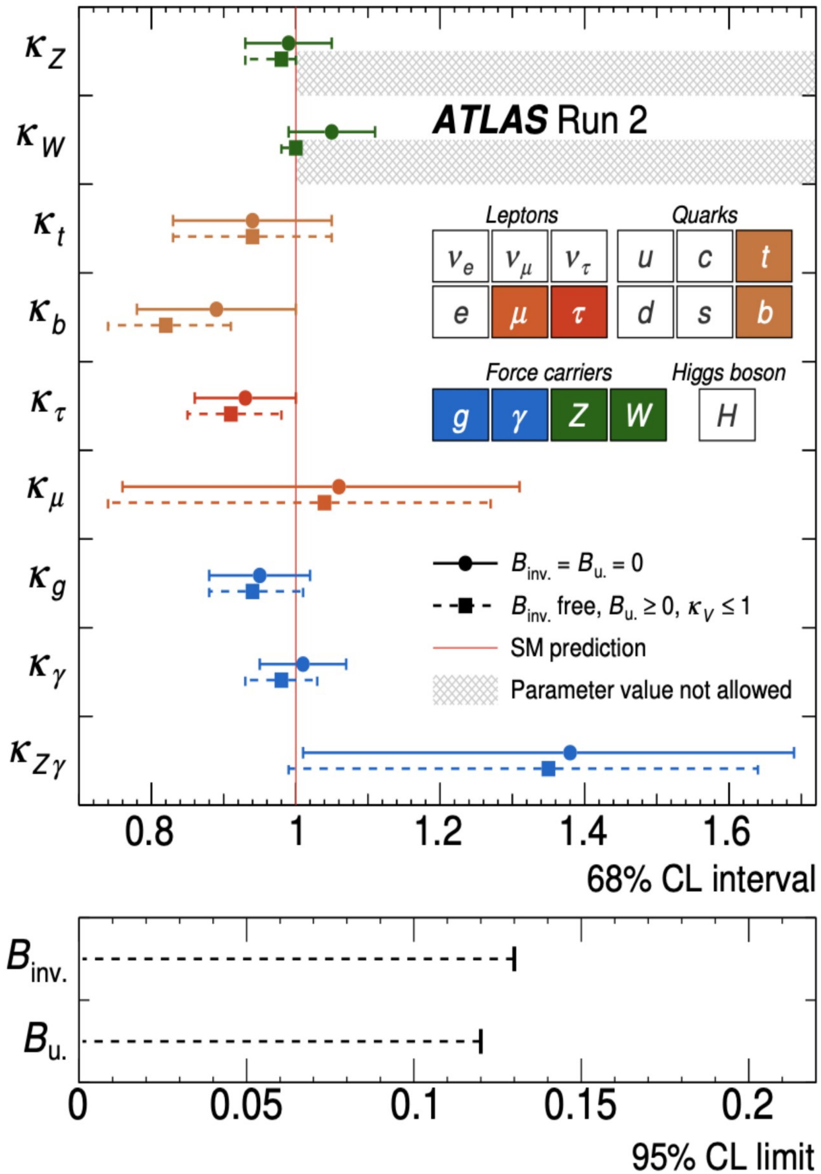
process	experiment	lumi (fb^{-1})	exp. sig.	obs. sig.	signal strength
VH	ATLAS	140	6.7 s.d.	6.7 s.d.	1.02 ± 0.18
	CMS (**)	138	5.2 s.d.	3.3 s.d.	0.58 ± 0.18
VBF	ATLAS	126	3.0 s.d.	3.0 s.d.	0.99 ± 0.34
	CMS (**)	91	2.9 s.d.	2.5 s.d.	0.92 ± 0.42
ttH	ATLAS	140	2.7 s.d.	1.0 s.d.	0.35 ± 0.35
	CMS (**)	80	3.5 s.d.	3.9 s.d.	1.15 ± 0.31
ggH	ATLAS	136	—	—	0.8 ± 3.2
	CMS	137	—	—	3.7 ± 1.5
COMB	ATLAS	-	7.7 s.d.	7.0 s.d.	0.91 ± 0.14
	CMS (*)	-	—	—	1.05 ± 0.22

(*): ttH result only from 2016, no VBF

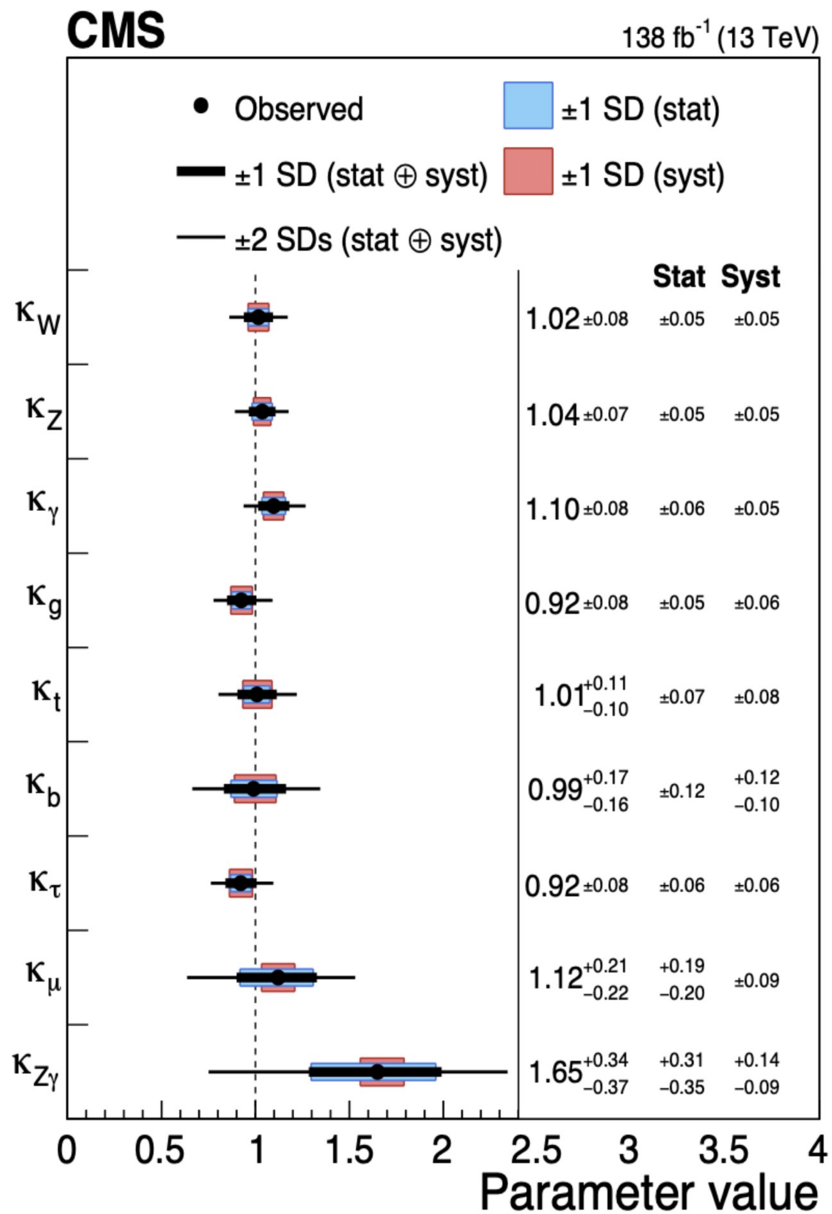
(**): prelim

SM Higgs global context

Nature 607.7917 (2022), pp. 52–59



Nature 607 (2022) 60



Xbb calibration

Methodology

- Why calibration?
  - Simulation VS data.
- Why $Z \to b\bar{b}$ events?
  - $Z \to b\bar{b}$ similar to $H \to b\bar{b}$ topology.
  - Enriched statistics at high p_T.
- p_T-dependent calibration:
  - 200-450 GeV — $Z\gamma$
  - 450-500 GeV
  - 500-600 GeV — $Z + \text{jets}$
  - 600-1000 GeV
- Data collected during 2015-2018, 139 fb^{-1}.

- How to do it? → scale factor (SF)

$$\mathrm{SF} = \frac{\epsilon^{\text{data}}}{\epsilon^{\text{MC}}} = \frac{\frac{N^{\text{data}}_{\text{passed}}}{N^{\text{data}}_{\text{total}}}}{\frac{N^{\text{MC}}_{\text{passed}}}{N^{\text{MC}}_{\text{total}}}} = \frac{\frac{N^{\text{data}}_{\text{passed}}}{N^{\text{MC}}_{\text{passed}}}}{\frac{N^{\text{data}}_{\text{total}}}{N^{\text{MC}}_{\text{total}}}} = \frac{\mu^{post-tag}}{\mu^{pre-tag}}$$

- $\mu^{post-tag}$: Fit the large-R jet mass distribution.
- $\mu^{pre-tag}$: Measured from the $Z \to l^+l^-$ channel.

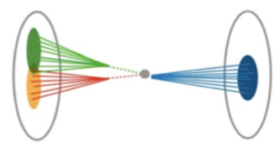
$$N^{\text{data}}_{Z\to bb} = N^{\text{MC}}_{Z\to bb} \cdot \mu^{pre-tag} = N^{\text{MC}}_{Z\to bb} \cdot \frac{N^{\text{data}}_{ll} - N^{\text{MC}}_{\text{bkg},ll}}{N^{\text{MC}}_{Z\to ll}}$$

From Yajun He's thesis defense 2022

Xbb calibration

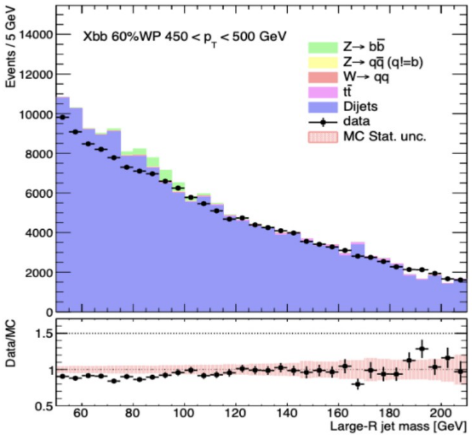
Measurement of $\mu^{post-tag}$

Event Selection



- Single large-R jet triggers used.
- Leading p_T large-R jet.
- $p_T^1 > 450$ GeV and $m_1 > 50$ GeV.
- $|\eta| < 2.0$.
- At least two associated VR track jets.
- Passing the $X \to b\bar{b}$ tagger at the 60% efficiency WP.

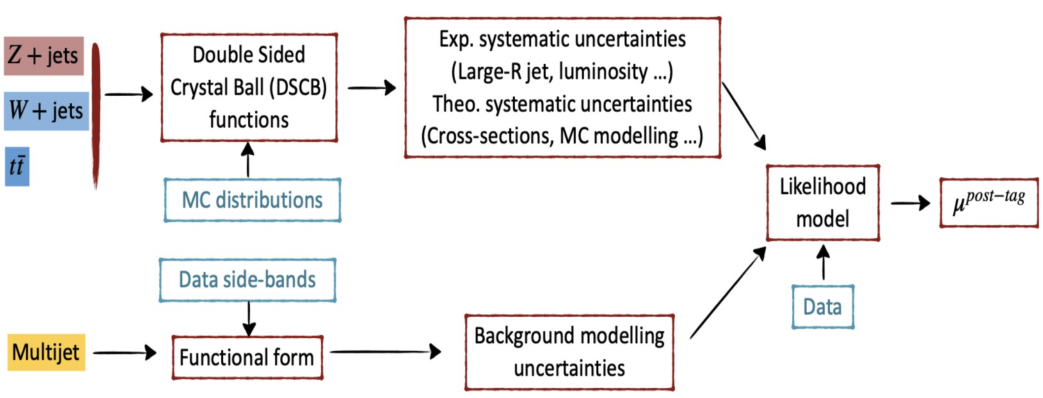
- Subleading p_T large-R jet.
- $p_T^2 > 200$ GeV.
- $|\eta| < 2.0$.
- $\frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}} < 0.15$.
- $|\Delta y_{1,2}| < 1.2$.



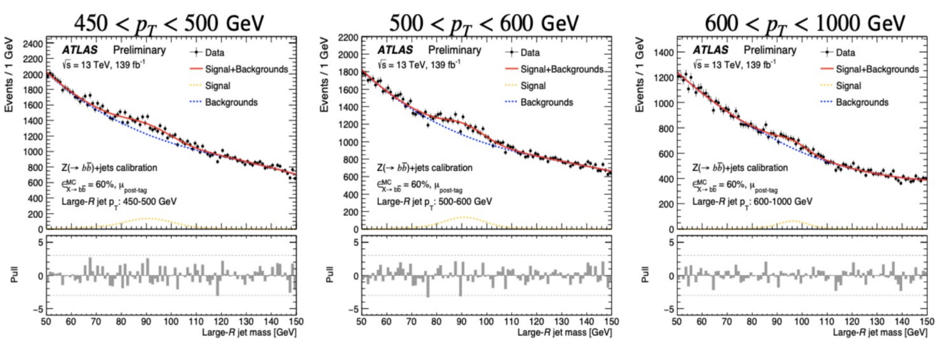
The dijets simulation can not be trusted. A data-driven method is used to model dijets.

18

- **Unbinned** fit the large-R jet mass distribution from 50-150 GeV for three p_T bins separately.



Results



- Good agreement between data and the fit model.
- Leading systematic uncertainties from jet mass resolution.

From Yajun He's thesis defense 2022

Xbb calibration

Measurement of $\mu^{pre-tag}$

Event Selection

- How to avoid bias?
  - Same simulation setups.
  - Similar energy scale between the leptonic and hadronic channel for $p_T^Z < 1\ TeV$.

- Lepton triggers used.
- Two same flavour leptons with $p_T > 27(5)$ GeV for $\mu(e)$.
- $(p_T^{l_1} - p_T^{l_2})/p_T^{ll} < 0.8$.
- $66 < m^{ll} < 116\ GeV$.
- $p_T^{ll} > 450\ GeV$.
- $p_T^{ll} > p_T^{\text{lead. jet}}$.

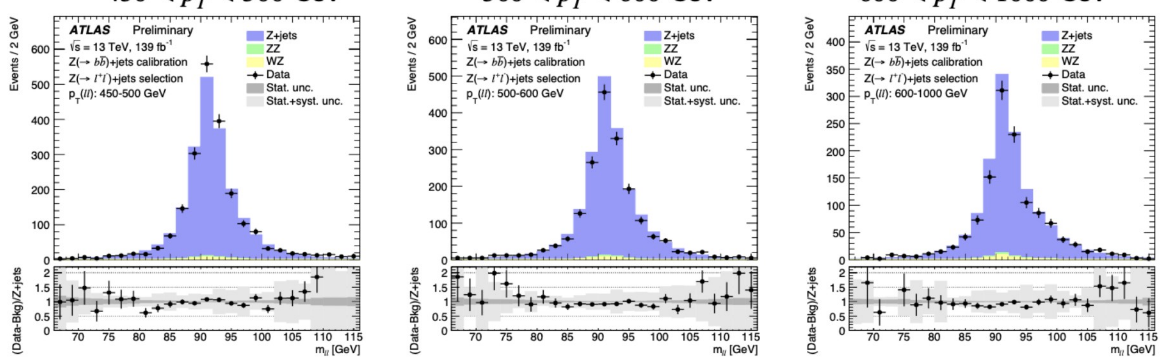
- Leading p_T large-R jet
- $p_T > 200\ GeV$
- $|\eta| < 2.0$

- $\dfrac{p_T^{ll} - p_T^{\text{lead. jet}}}{p_T^{ll} + p_T^{\text{lead. jet}}} < 0.15,$
- $|\Delta y_{ll,lead.j}| < 1.2.$

Measurement of $\mu^{pre-tag}$

Results

$450 < p_T < 500$ GeV $\quad$ $500 < p_T < 600$ GeV $\quad$ $600 < p_T < 1000$ GeV



- Good agreement between data and MC.
- **Simple counting method** to derive $\mu^{pre-tag}$.

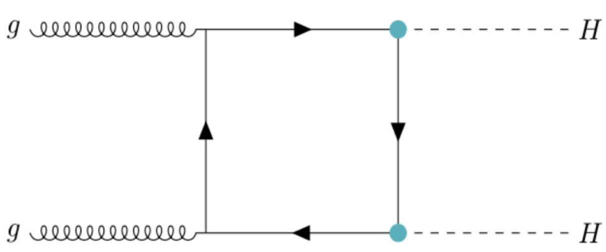
$$\mu^{pre-tag} = \frac{N_{ll}^{\text{data}} - N_{\text{bkg},ll}^{\text{MC}}}{N_{Z\to ll}^{\text{MC}}}$$

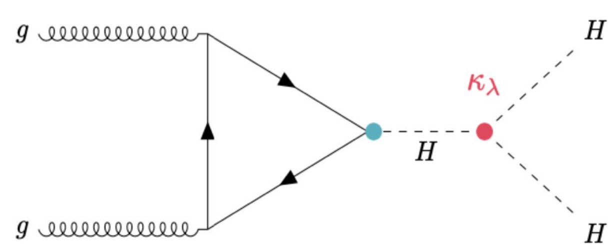
From Yajun He's thesis defense 2022

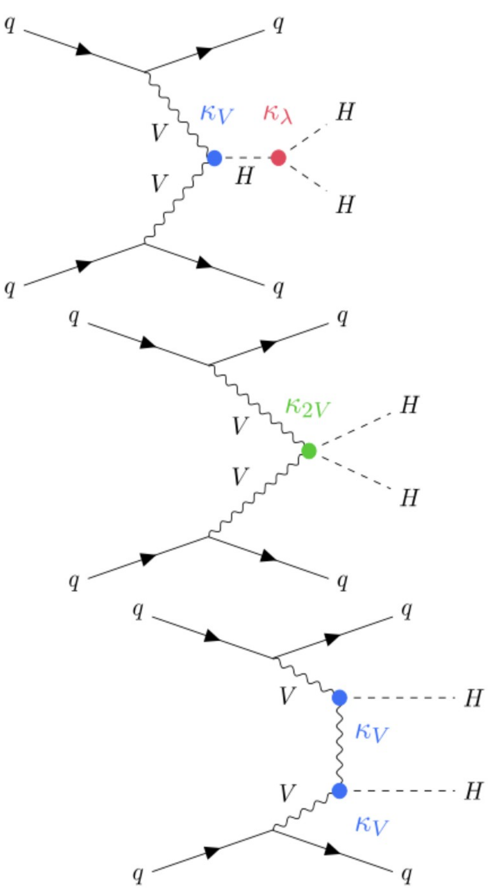
di-Higgs

- Di-Higgs production is ***unique direct probe*** *for Higgs self-interaction*

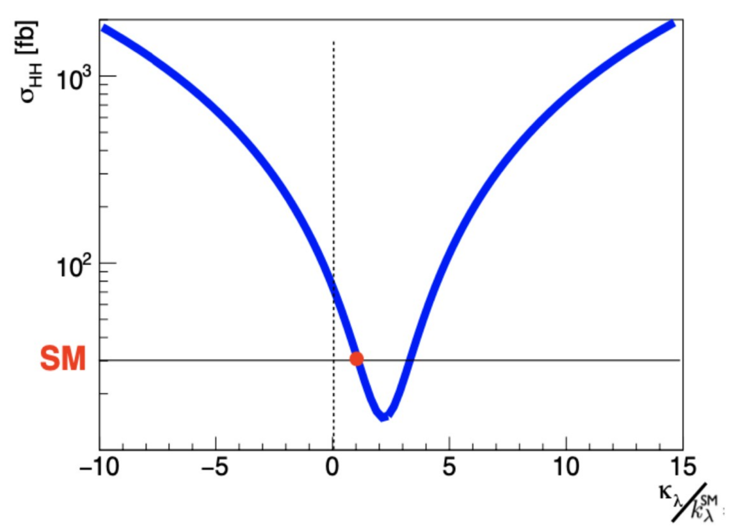
$$k_\lambda^{SM} = \frac{m_h^2}{2v^2}$$





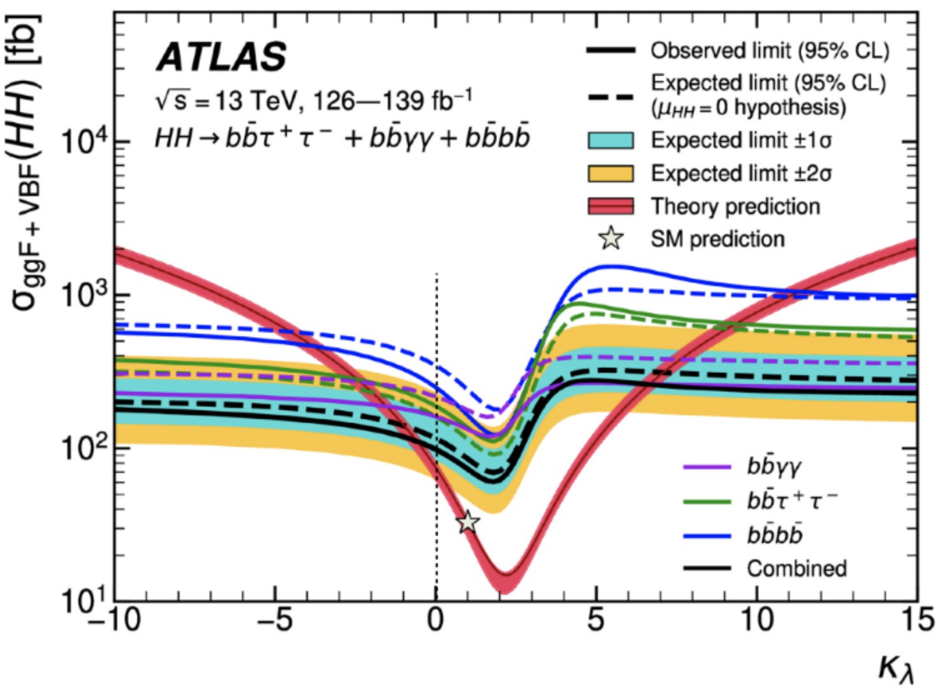


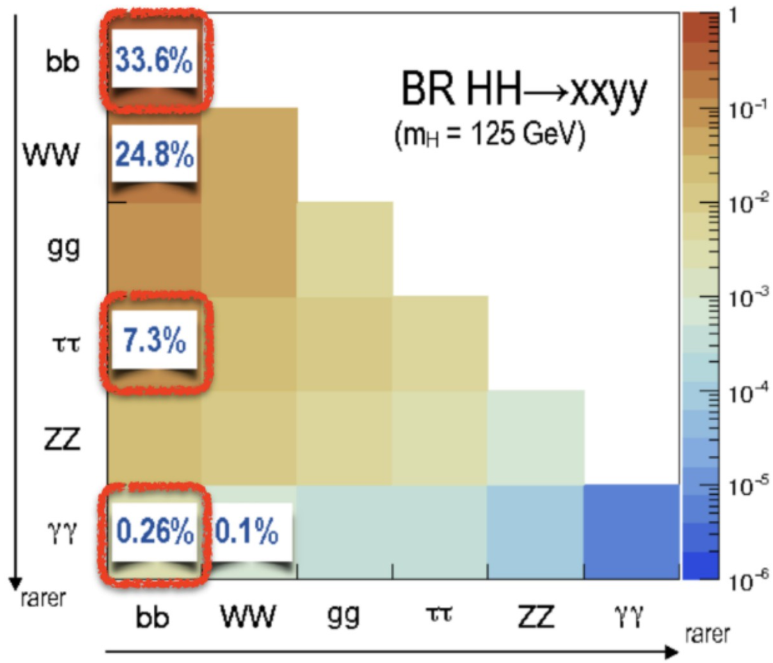
- *Negative interference of two diagrams:*
  - *SM cross section = 30 fb*
  - ***1000 smaller than single Higgs cross section***
  - ***strong dependence on*** κ_λ*: x 2.3 larger XS if no self interaction*
  - *signal kinematics strongly depends on* κ_λ



di-Higgs

- *Most sensitive channels all require* ***at least one Higgs boson to decay into bb***





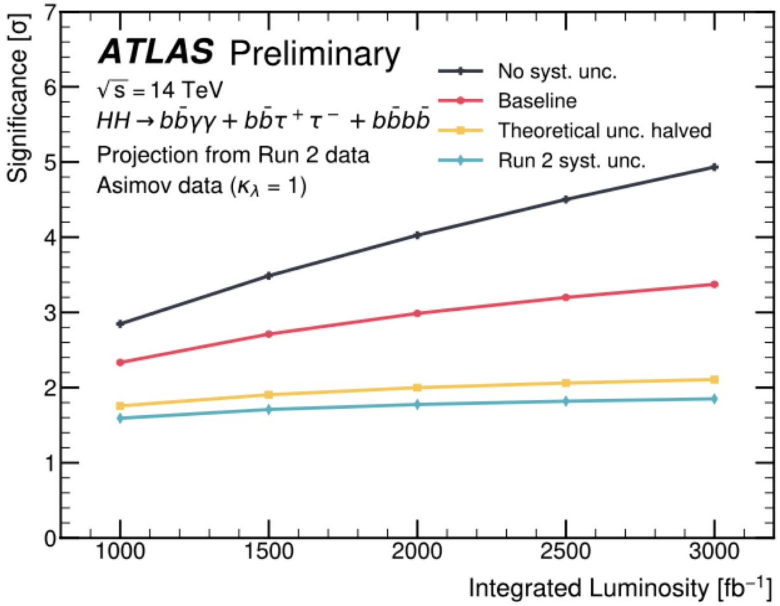
- *Full Run 2 results:*

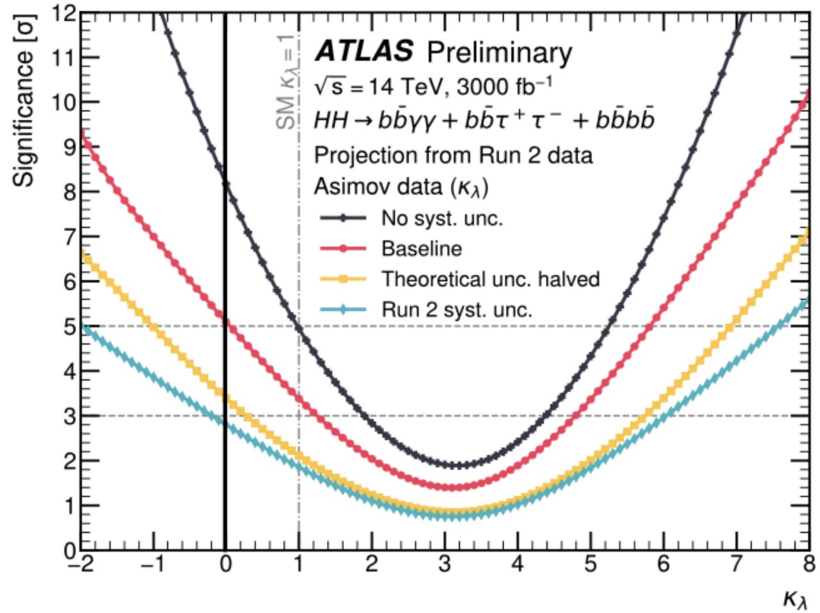
κ_λ=1 : σ/σ_{SM} < 2.4 *(2.9)* **@ 95% CL obs.** *(exp)*

-0.6 < κ_λ < 6.6 @ 95% CL

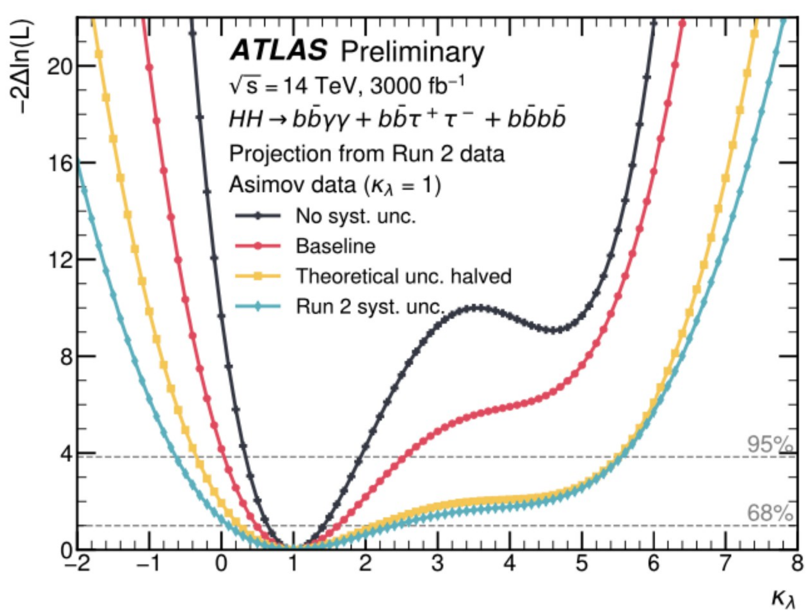
HH production is one of the main physics goals of LHC

Di-Higgs projections





Predictions suggest we will find first direct evidence of Di-Higgs production by both ATLAS and CMS during HL-LHC operations, with less than 3000 fb-1



Analysis strategy

Get the objects:
- Identify particles
- Calibrate them if needed

↓

Built distributions of interesting variables

↓

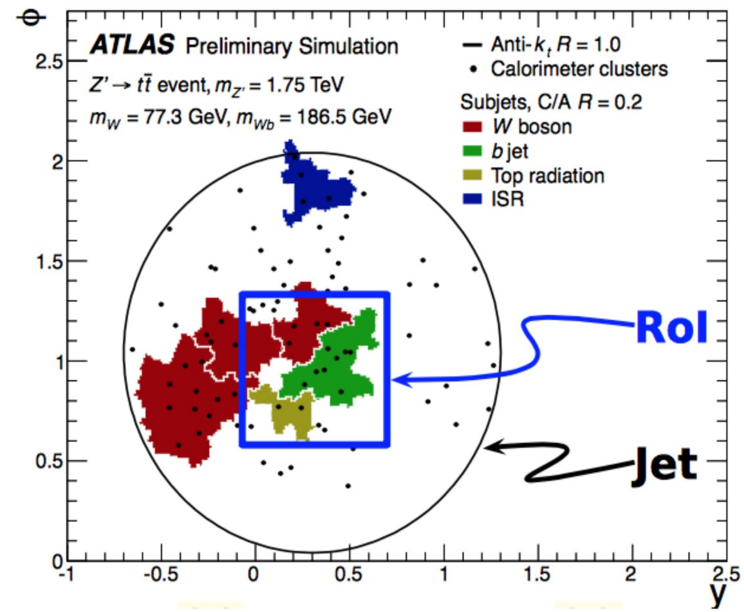
Search phase:
Compare data and background
Do you see any deviation?

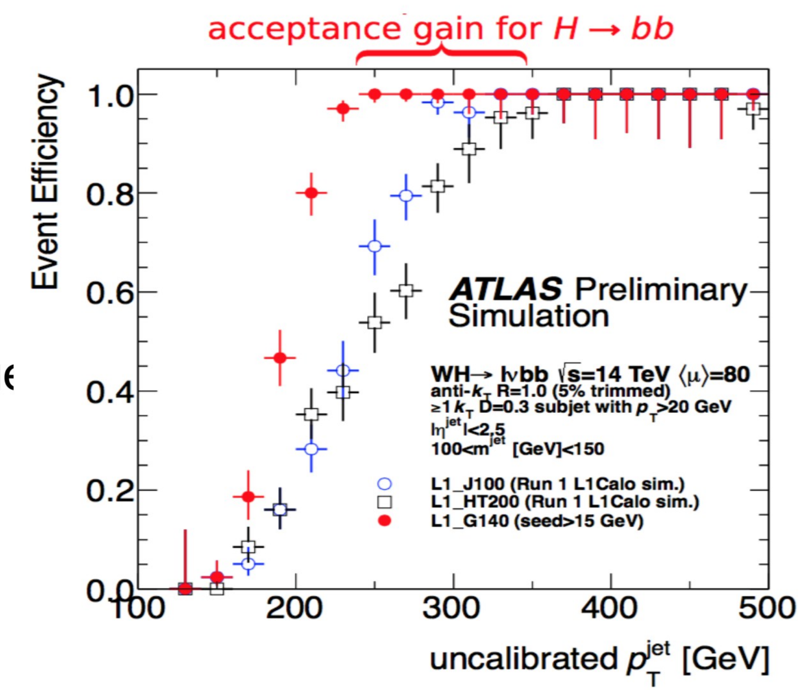
No → Limit setting phase:
Constrain new physics models

Yes →

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

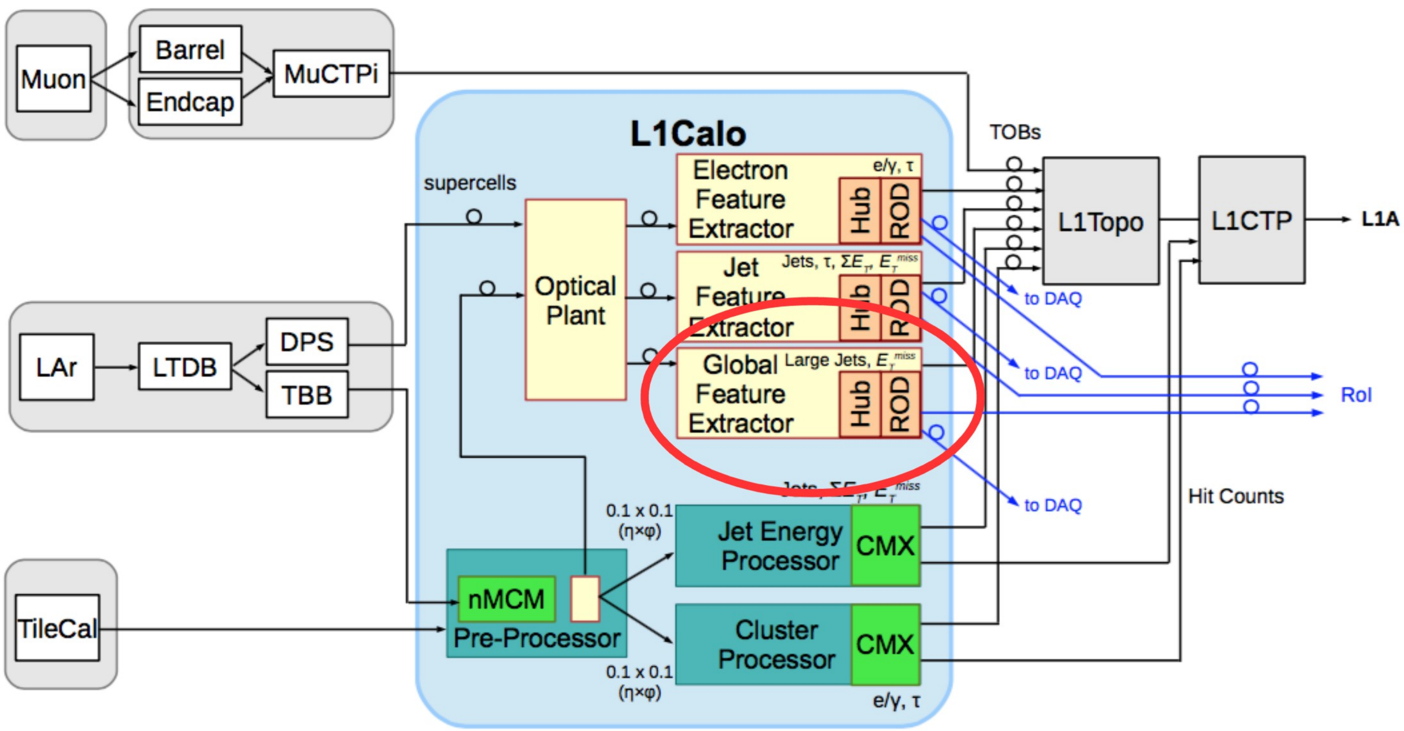
- Hadronic decays of high p_T bosons and fermions is a vital part of the ATLAS physics program
- **ATLAS** is planning **major detector updates in Run-3, like Level-1 trigger (calorimeter) system**
- **gFEX** is a single board that will have access to the information from the whole calorimeter!
- Will **identify events with large-radius jets**
  - Improving acceptance for boosted objects
  - Jet-level pile-up substraction
- Will calculate also global event variables like missing transverse energy
- Implemented in a highly parallelized structure (3 large Xilinx Ultrascale FPGAs and Zync System-On-Chip)





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

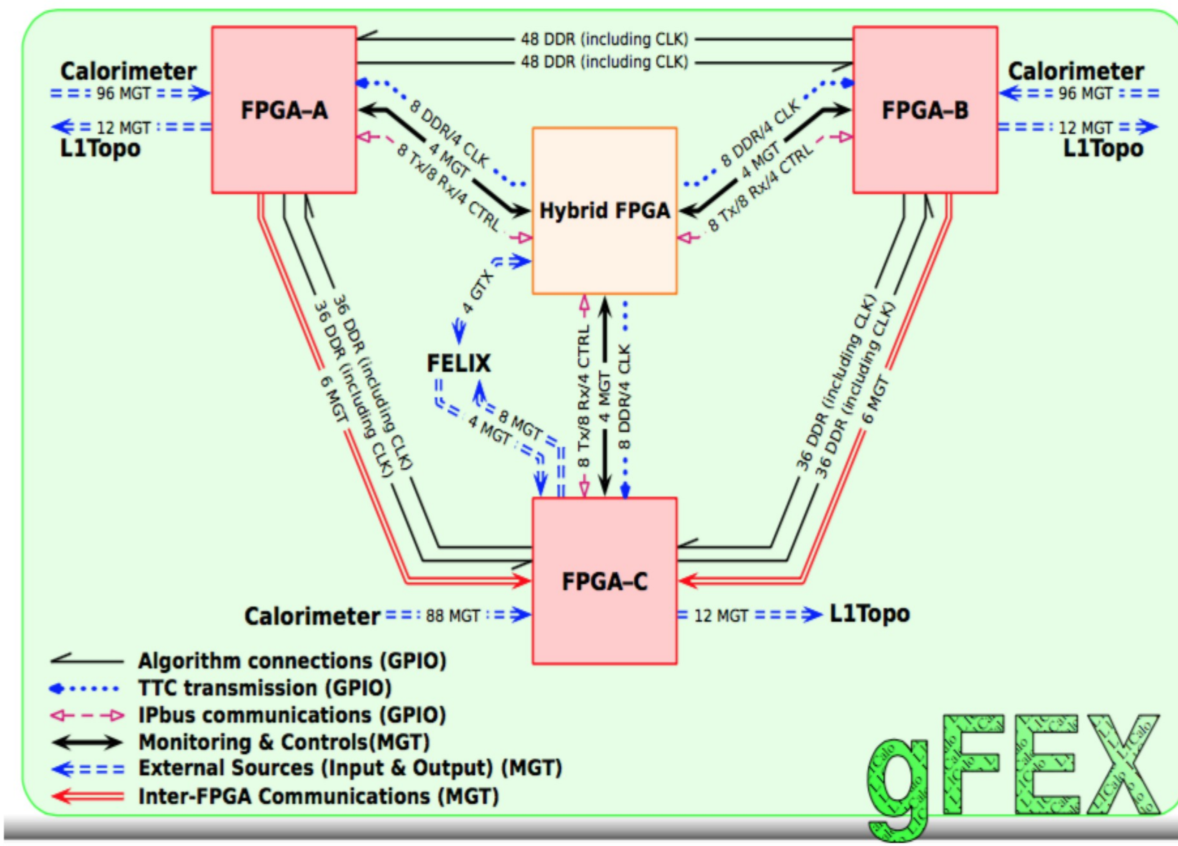
- Physics algorithms run within 5 bunch crossings (125 ns), not including data input/output

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)

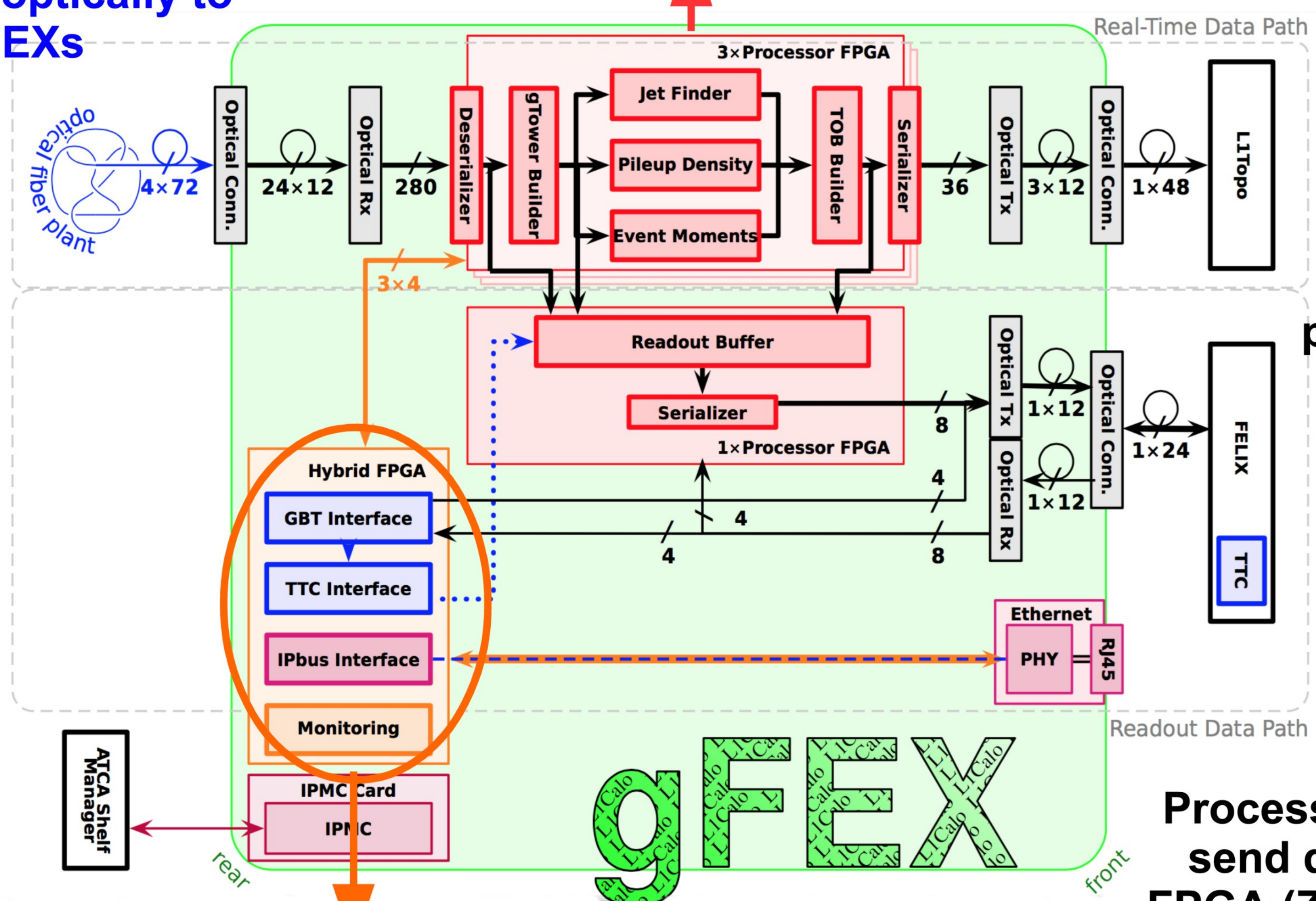
- One single module with several FPGAs for data processing
    - Inter-communication to avoid environments
- Hybrid FPGA (FPGA+CPU system-on-ship or Zynq) for control and monitoring
    - Process the event data from processor FPGAs
    - Algorithms to quickly detect calorimeter issues
    - Emulate the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



Zynq in gFEX

Data processing: algorithms run on FPGAs

Digitized signals transmitted optically to the FEXs

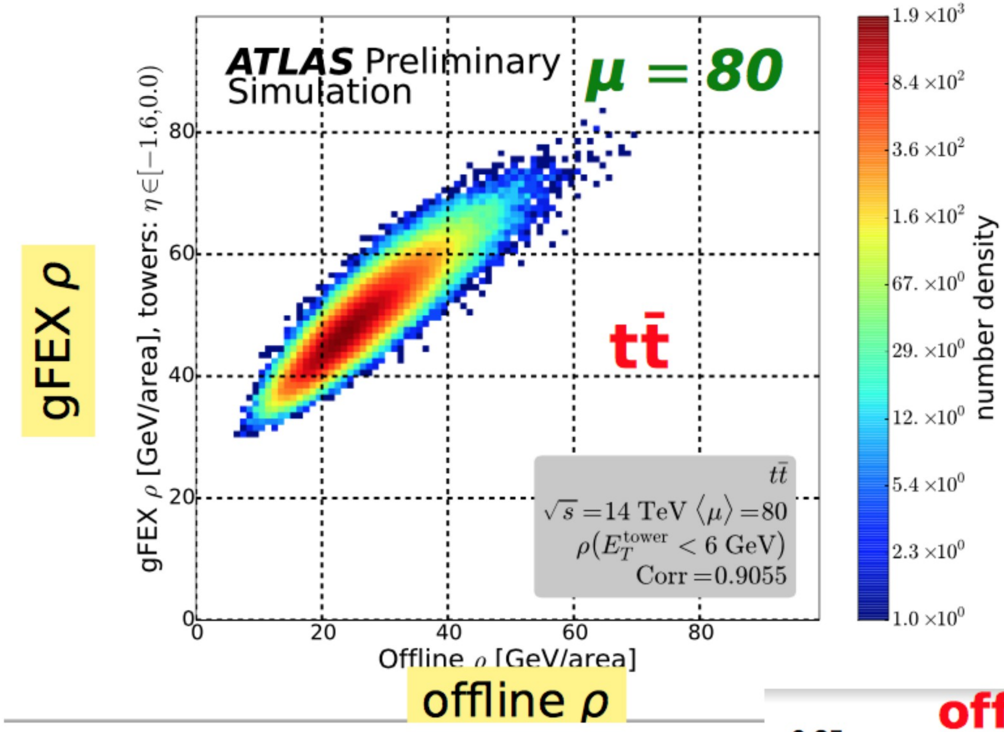


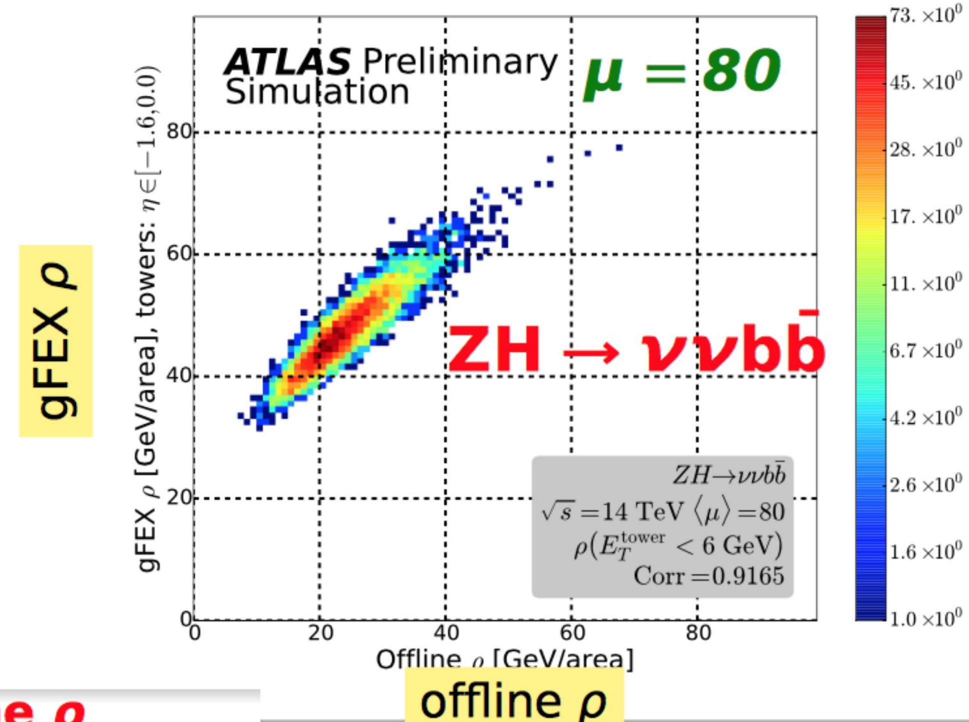
Data on the prototype can be transmitted via FELIX

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

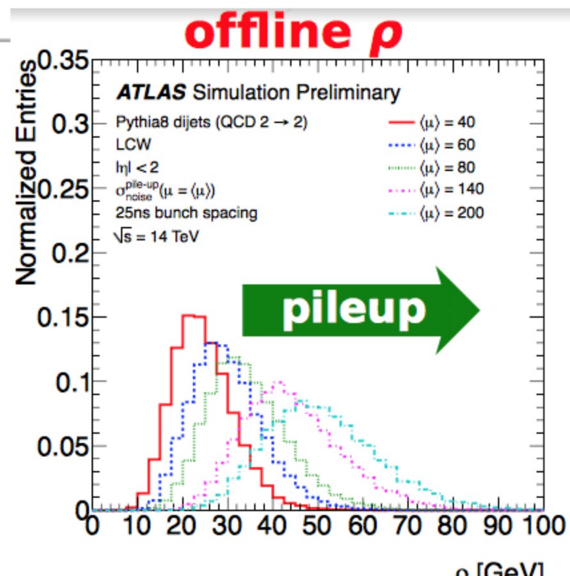
Processor FPGAs can send data to Hybrid FPGA (Zynq) for further analysis upon request or predefined error condition

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)