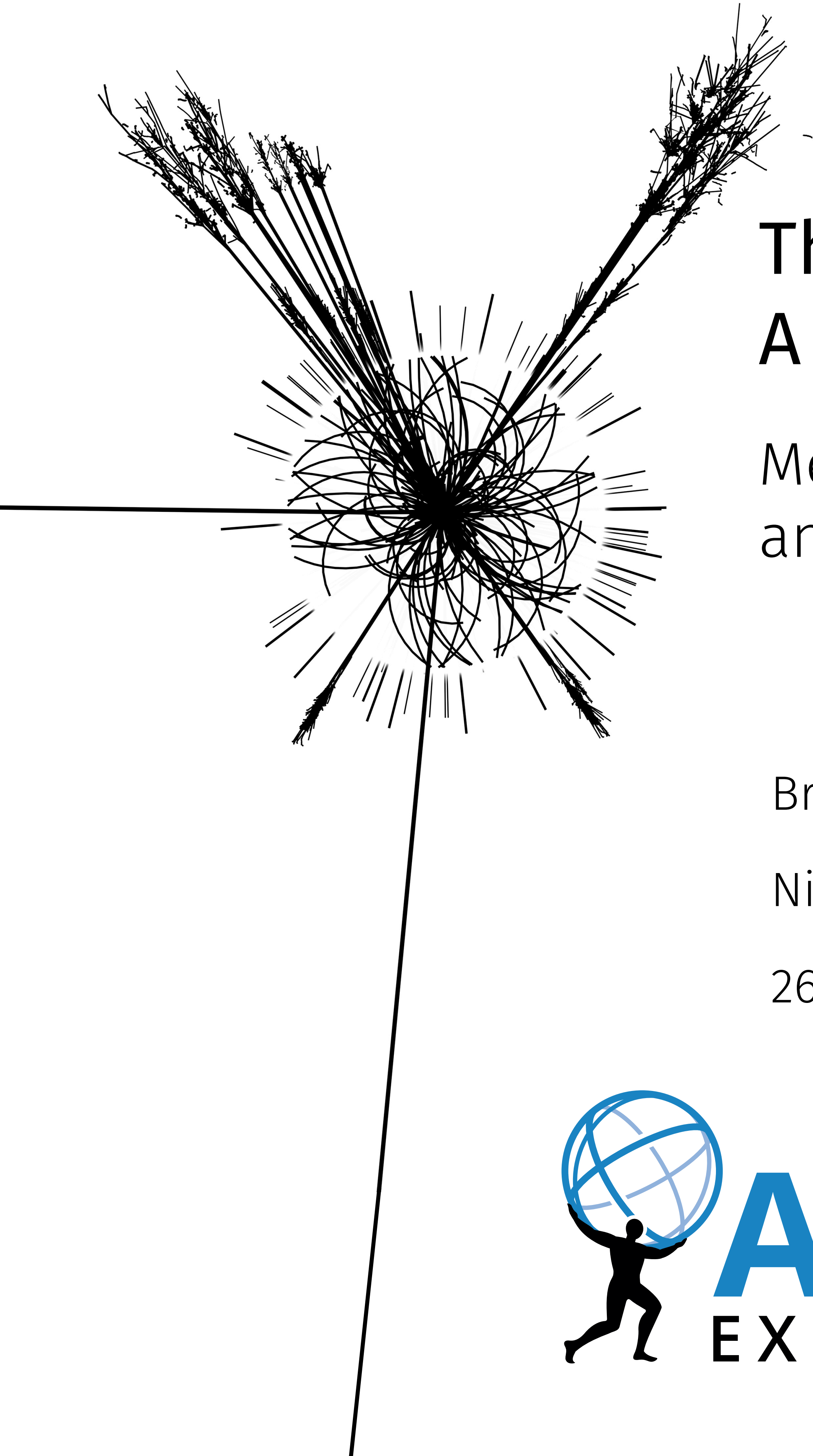


The Beauty and the Boost: A Higgs boson tale

Measuring boosted VH, H—>bb with ATLAS and interpreting the results using SMEFT

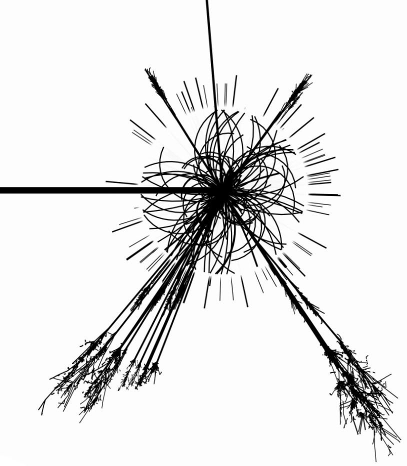
ATLAS-CONF-2020-007

Brian Moser

Nikhef colloquium and Theory Meets Experiment WS

26/06/2020

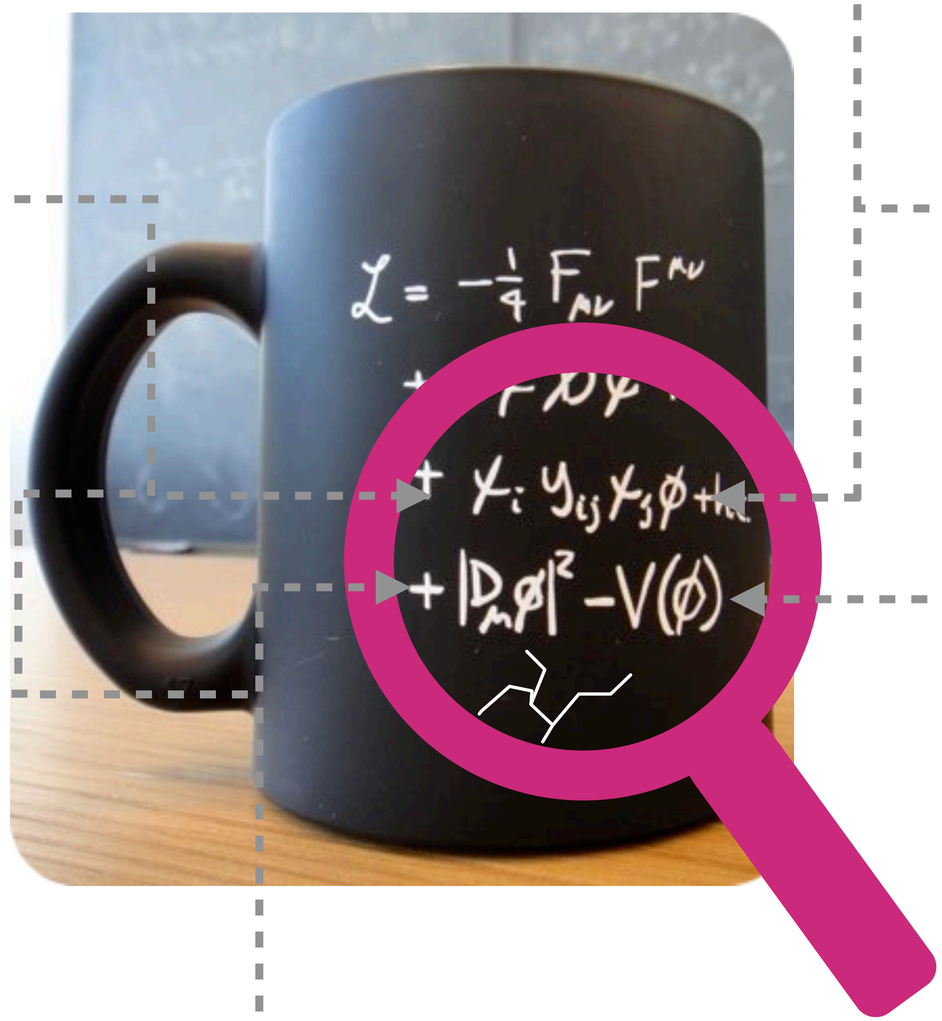
Searching for cracks in a mug



Higgs couplings to 3rd gen. fermions with 20% precision

2nd generation?

1st generation?



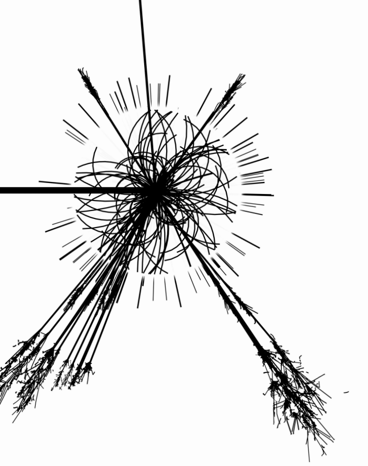
CP-nature of the couplings?

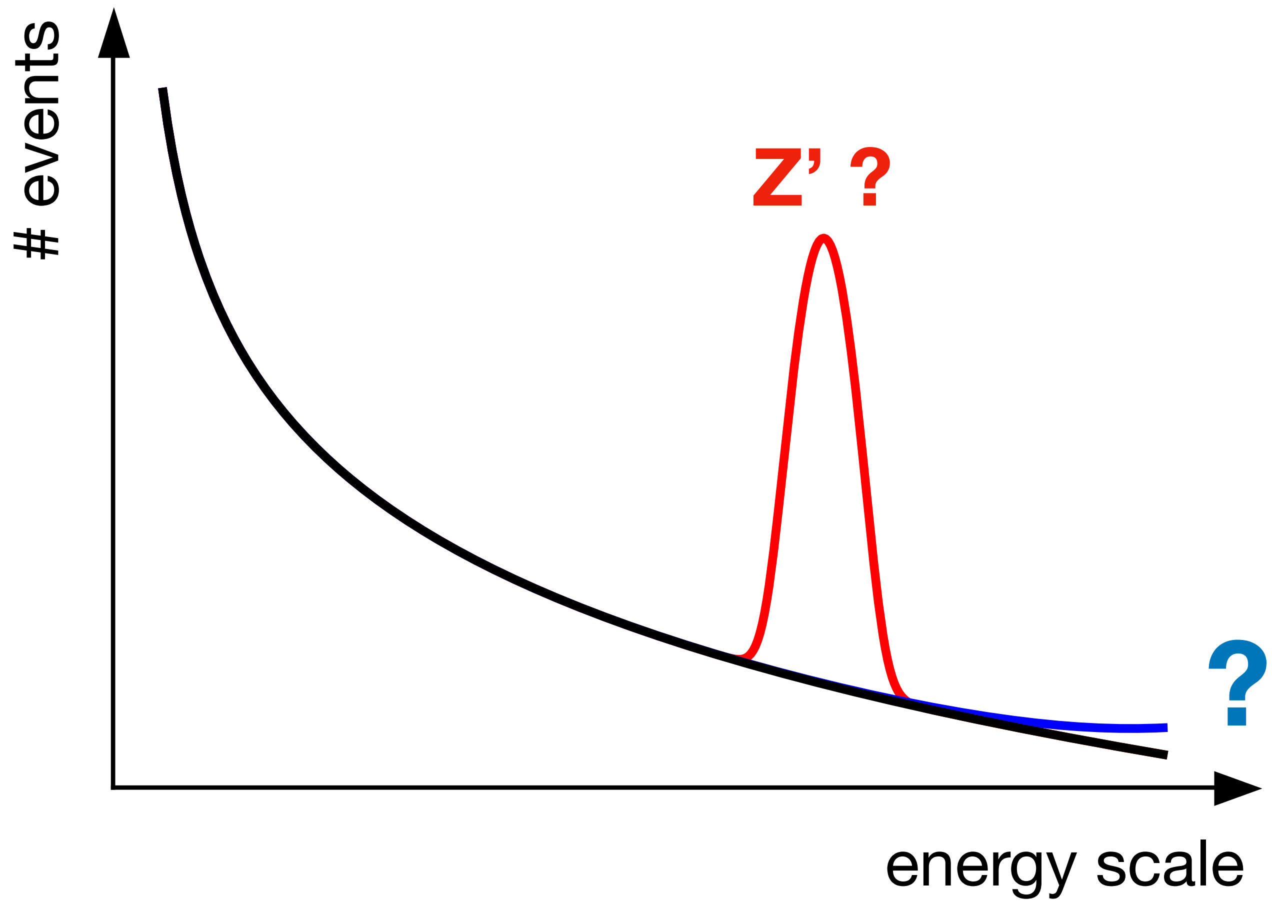
Higgs potential?

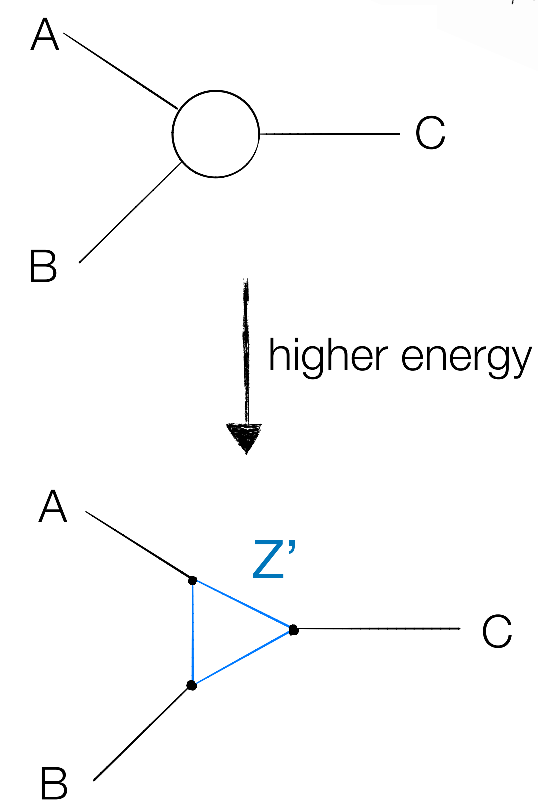
Higgs couplings to (heavy) vector bosons with 10% precision

It's not a bottomless mug, but there's **room for cracks everywhere**!

At which energy does the mug burst?



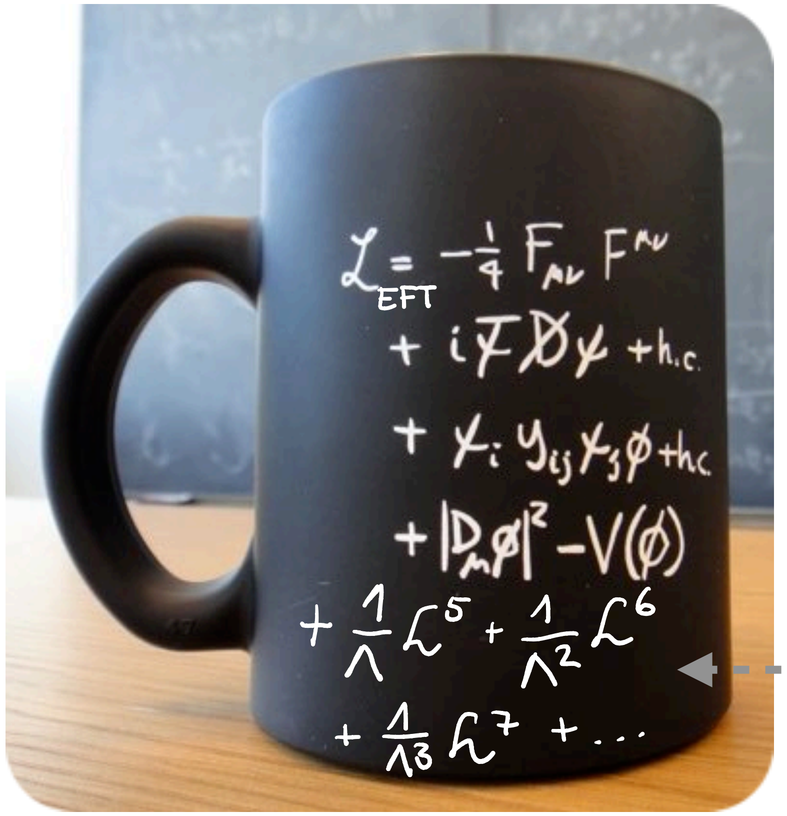




So far no clear sign of new physics within the LHC's energy reach

We can use precision measurements to reveal small cracks that would burst the mug only at energy scales beyond LHC reach

The space of all possible cracks



Expand the SM Lagrangian in E/Λ ← Scale of New Physics

$$\mathcal{L}_6 = \sum_i c_i \; \mathcal{O}_i^{(\text{dim}=6)}$$

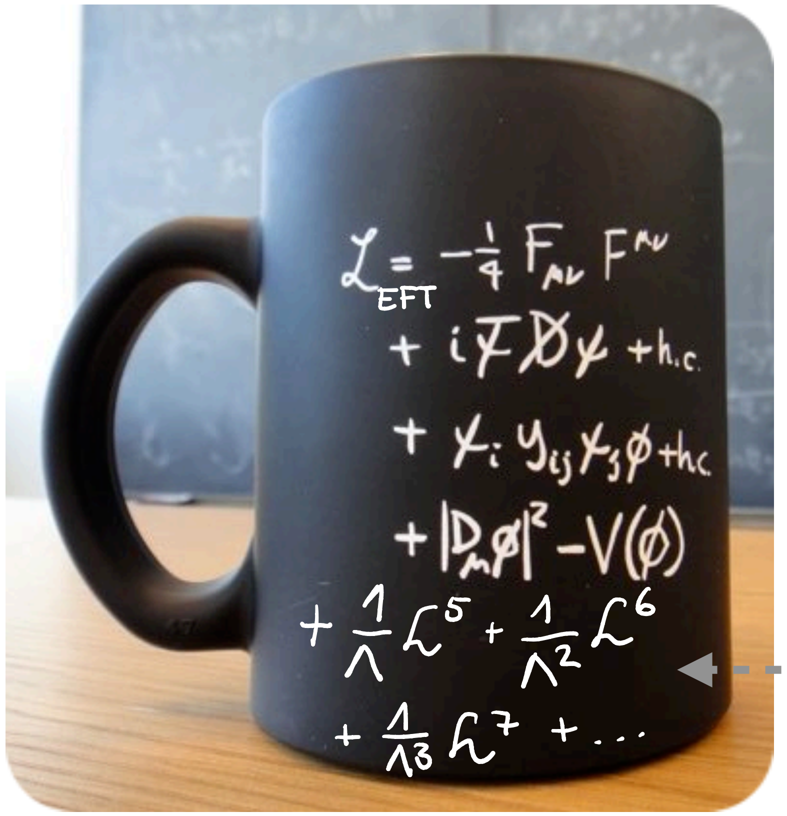
Wilson coefficients
Free parameters to be constrained from

All operators that fulfill SM symmetries

Treating the SM as Effective Field Theory allows to **systematically classify all possible cracks**

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \dots$$

The space of all possible cracks



Expand the SM Lagrangian in E/Λ ← Scale of New Physics

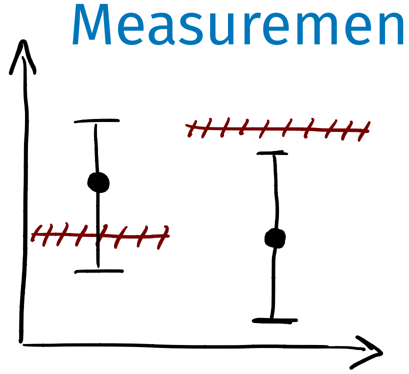
$$\mathcal{L}_6 = \sum_i c_i \; \mathcal{O}_i^{(\mathrm{dim}=6)}$$

Wilson coefficients
Free parameters to be constrained from

All operators that fulfill SM symmetries

Treating the SM as Effective Field Theory allows to **systematically classify all possible cracks**

Measurements

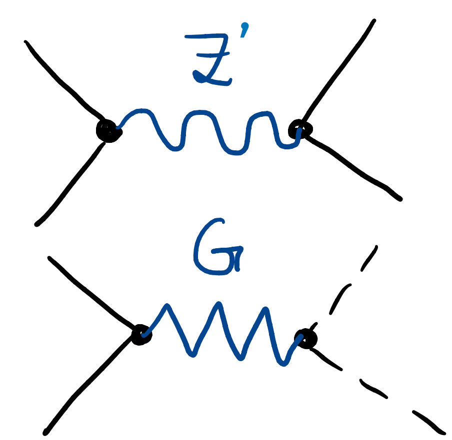


EFT interpretations

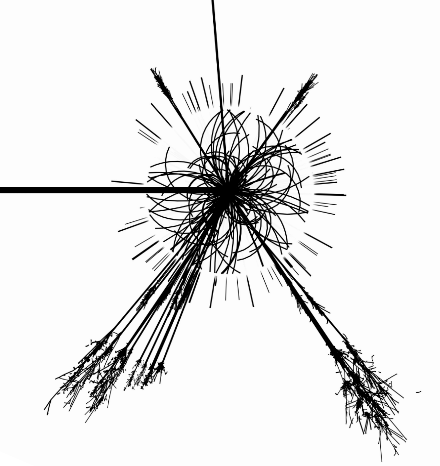
Limits

$$\mathcal{L}_6 = \sum_i c_i \; \mathcal{O}_i^{(\mathrm{dim}=6)}$$

UV complete models

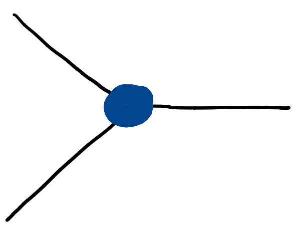


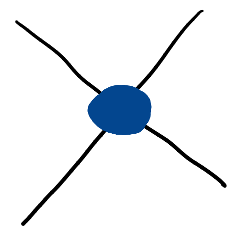
Sensitivity is not always equal to precision



EFT: Modification of existing vertices + addition of (new) effective vertices

Precision vs. **Energy**





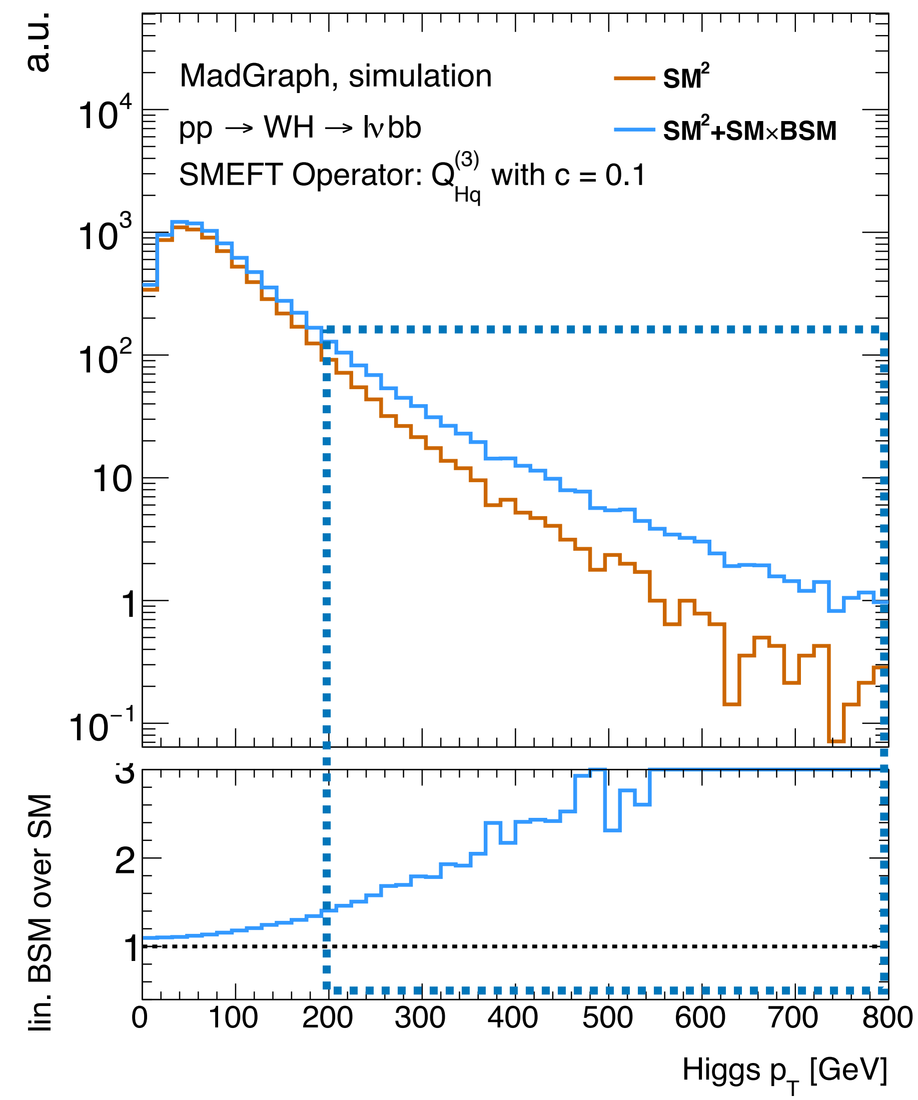
this talk

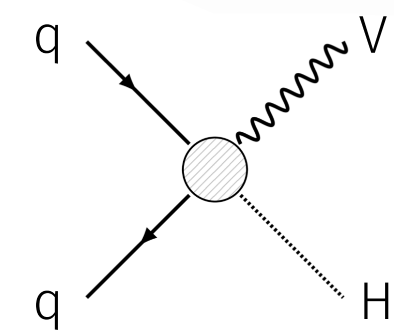
tight constraints already,
e.g. from LEP

$$\delta O \sim \left(\frac{v}{\Lambda}\right)^2 \sim 6\% \left(\frac{\text{TeV}}{\Lambda}\right)^2$$

$$\delta O_Q \sim \left(\frac{Q}{\Lambda}\right)^2$$

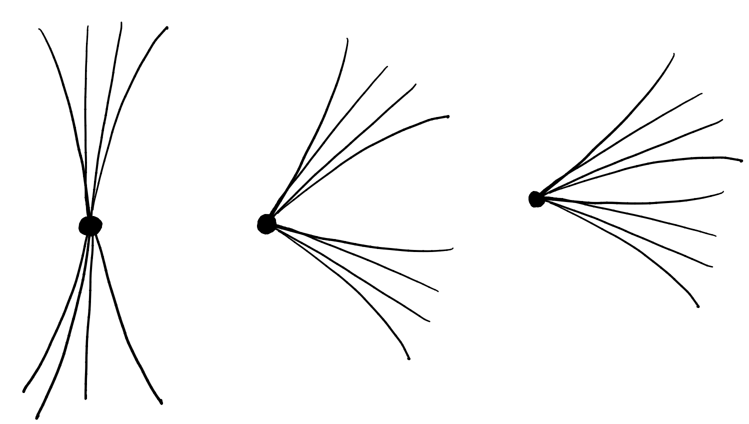
$$0.3\% \ @ \ 100\,\text{GeV} \quad \sim \quad 30\% \ @ \ 1\,\text{TeV}$$





High energy is interesting

but introduces experimental problems



By the end of this talk you will know...

... how to observe VH, H→bb with the ATLAS detector

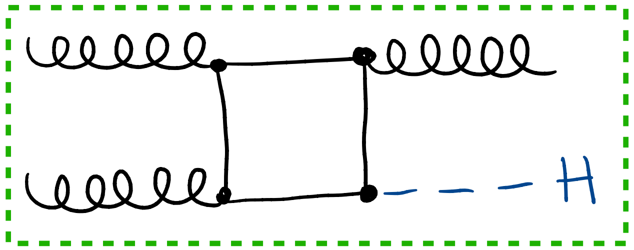
... why the method that enabled the observation ultimately fails at high energies

... how to overcome these obstacles to provide the first measurement at high Higgs p_T

... how to interpret the results within the framework of SMEFT

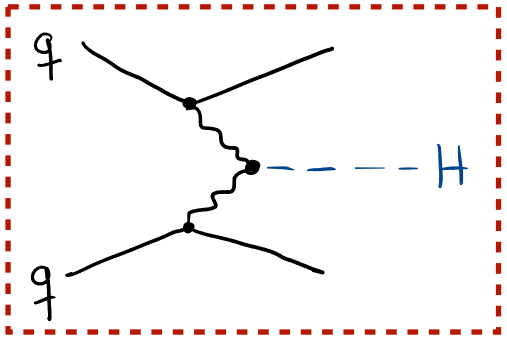
How to reach high momentum Higgs bosons?

- Focus on H → bb decay as it has the largest BR of ~ 58%
- Which production channel?



Gluon-Gluon Fusion:

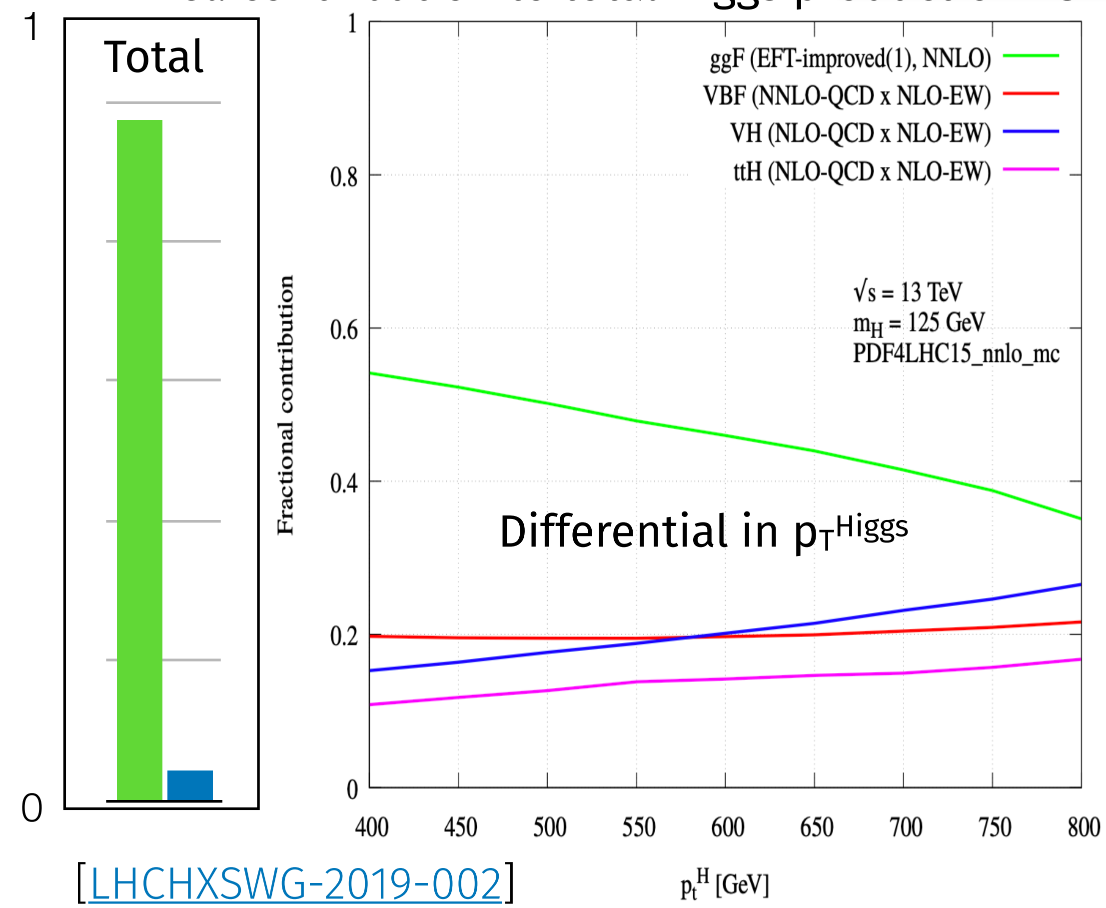
- Huge cross-section
- Huge multi-jet background
- Triggering on high p_T jets possible



Vector Boson Fusion:

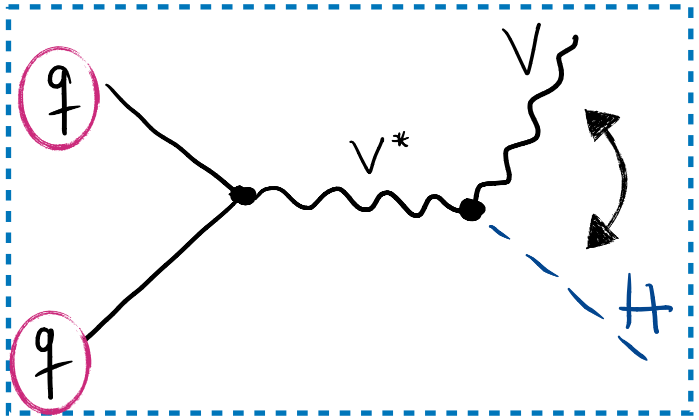
- Large cross-section
- Large multi-jet background
- Fully hadronic final state

rel. contribution to total Higgs production XS



[LHCHXSWG-2019-002]

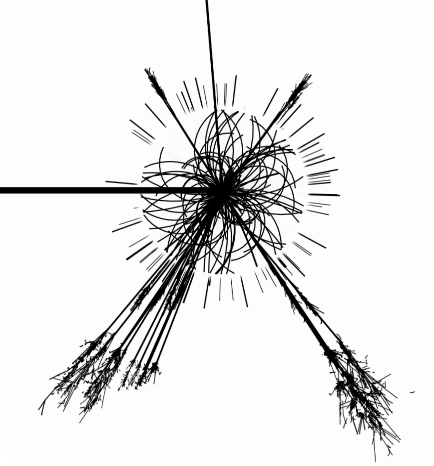
this talk

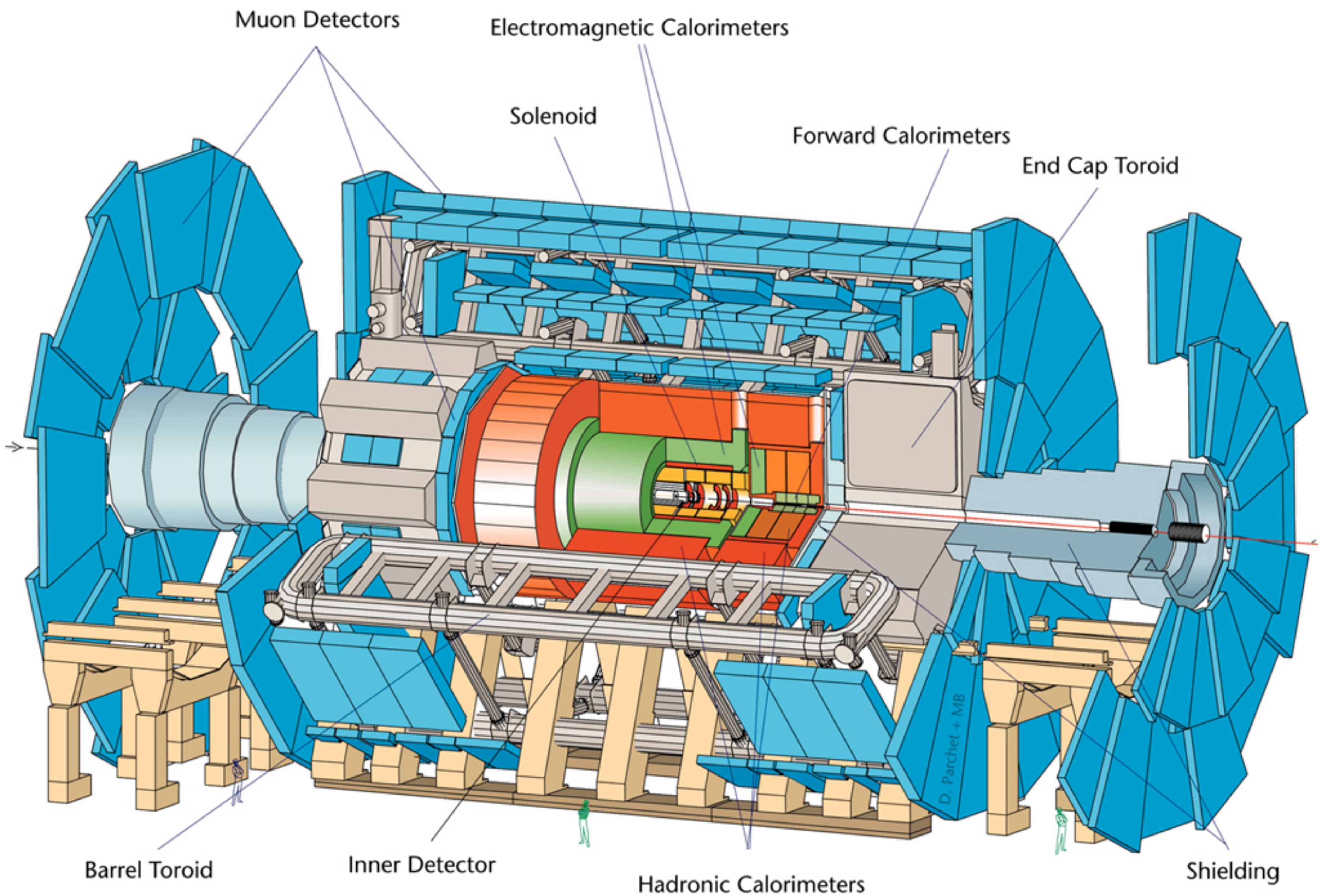


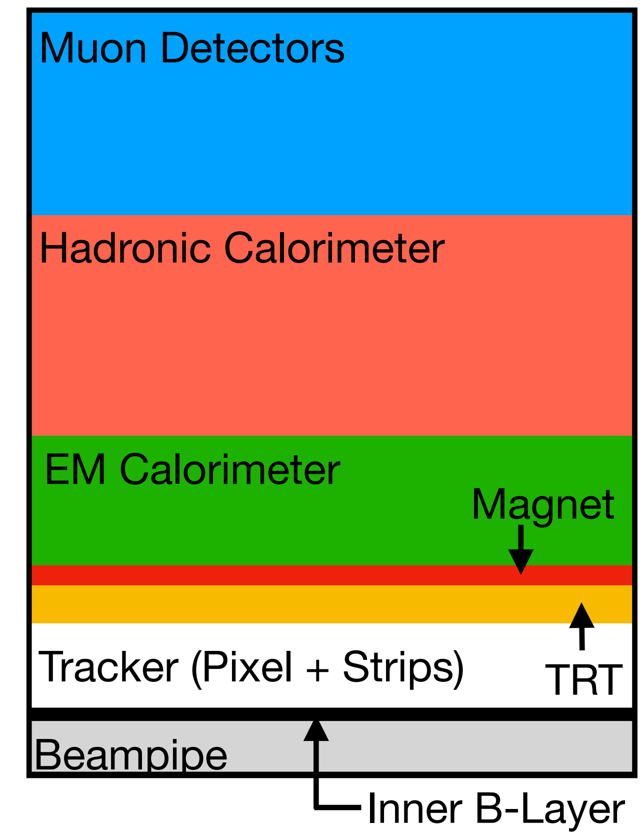
Higgs Strahlung (**VH**):

- Leptonic V decays to trigger and improve S/B
- Main search channel
- $p_T^H > 0$ at LO already, only limited by PDF suppression
- Harder p_T^H spectrum than Σ bkgs

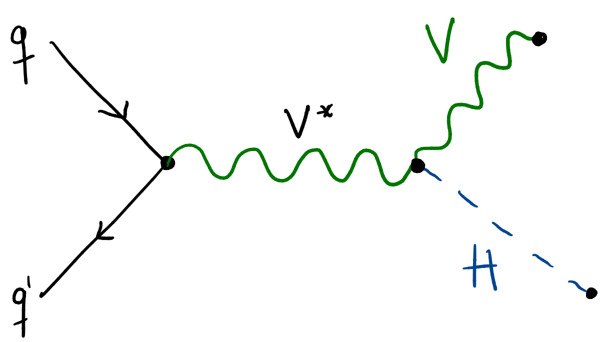
The ATLAS detector



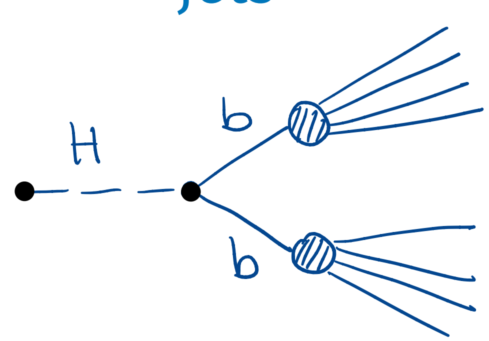




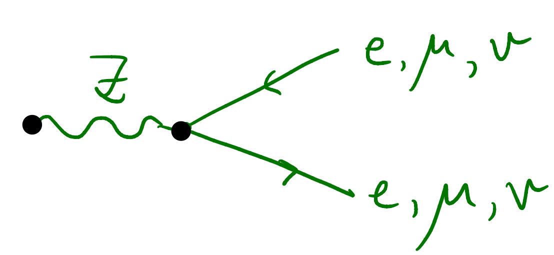
Signal signatures:

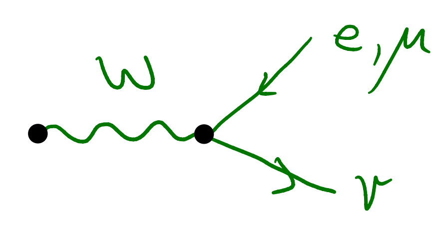


jets

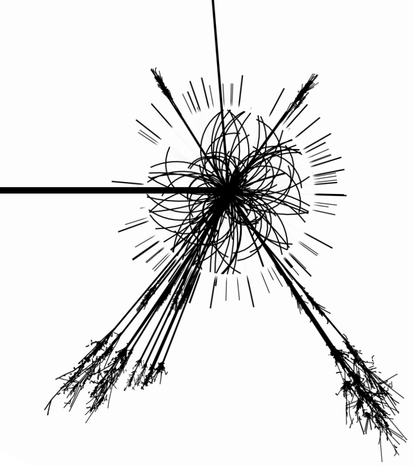


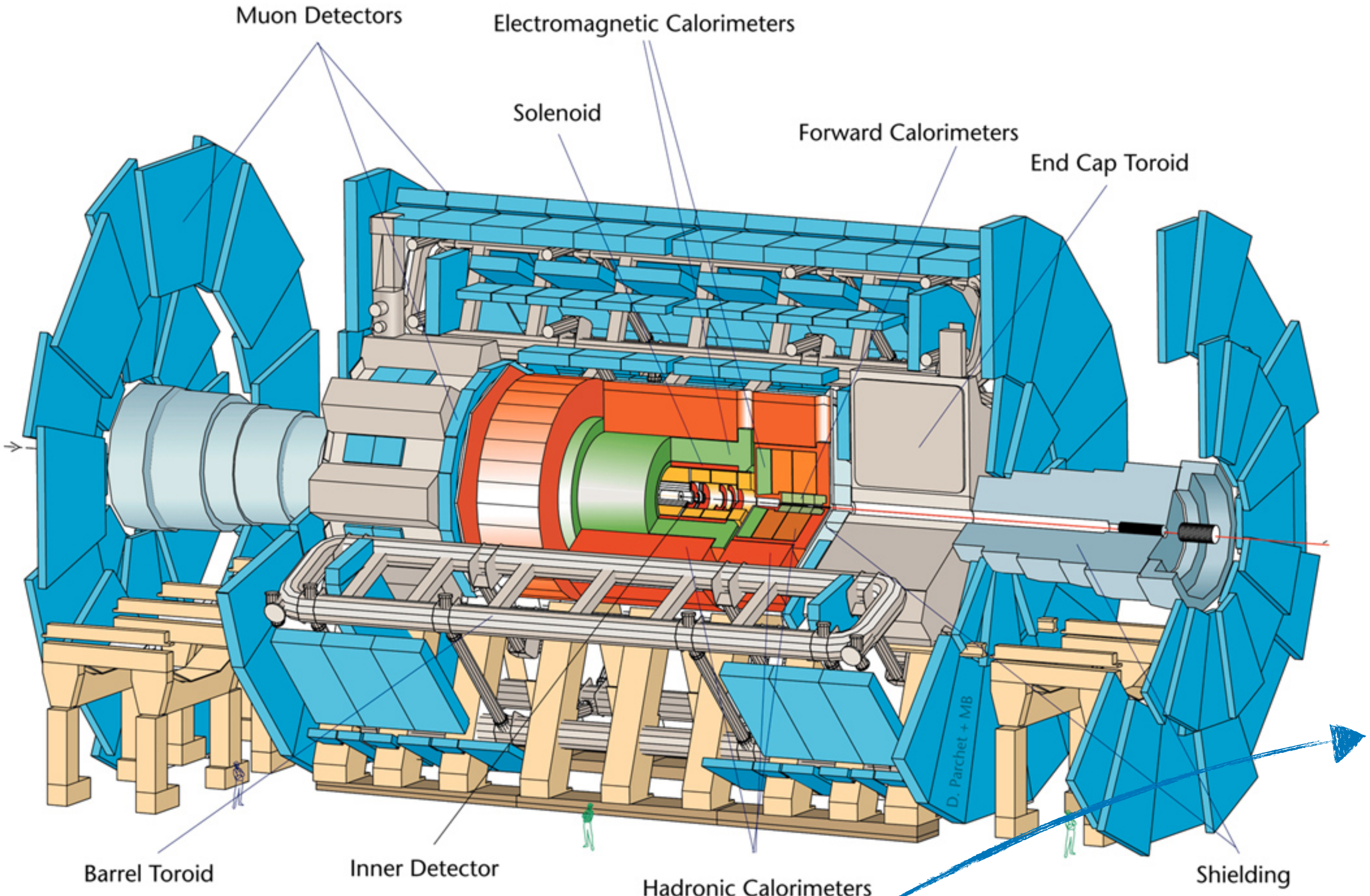
electrons, muons, neutrinos

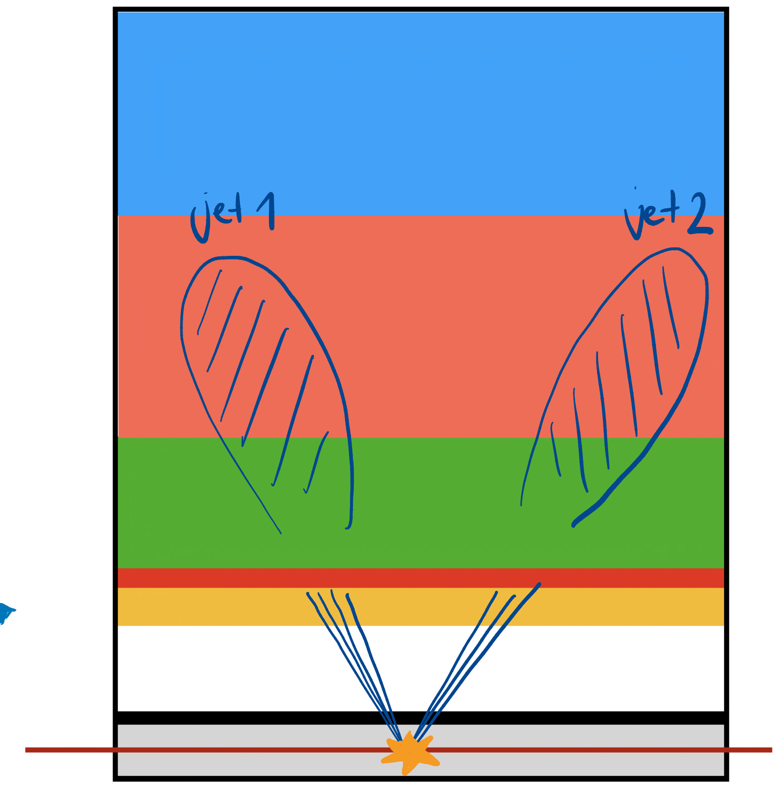




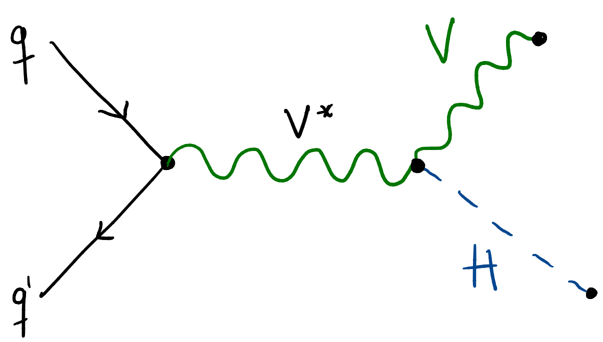
The ATLAS detector

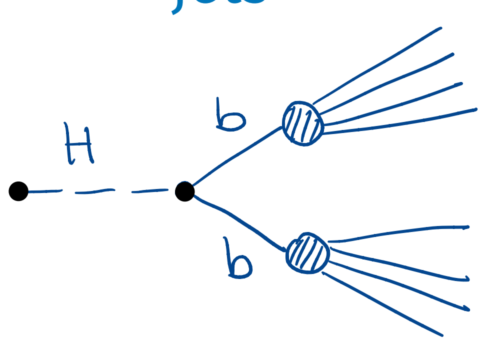




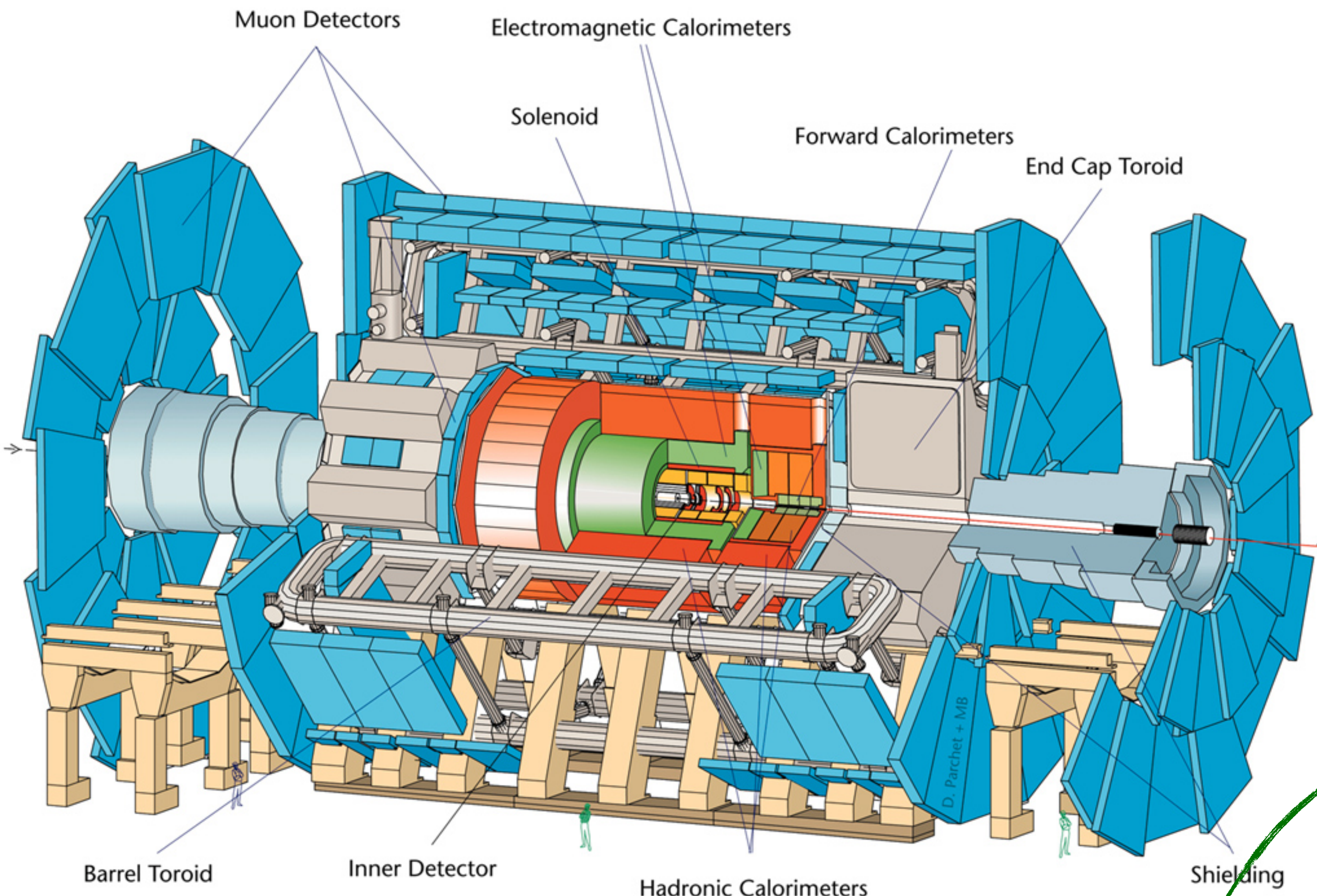


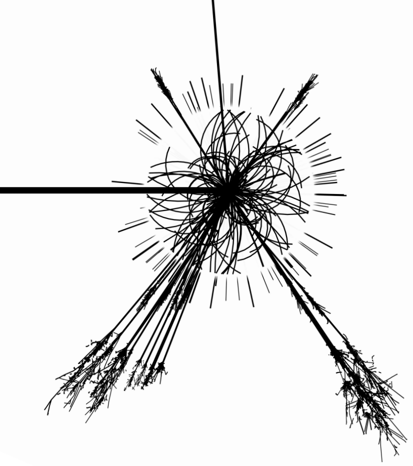
Signal signatures: jets electrons, muons, neutrinos

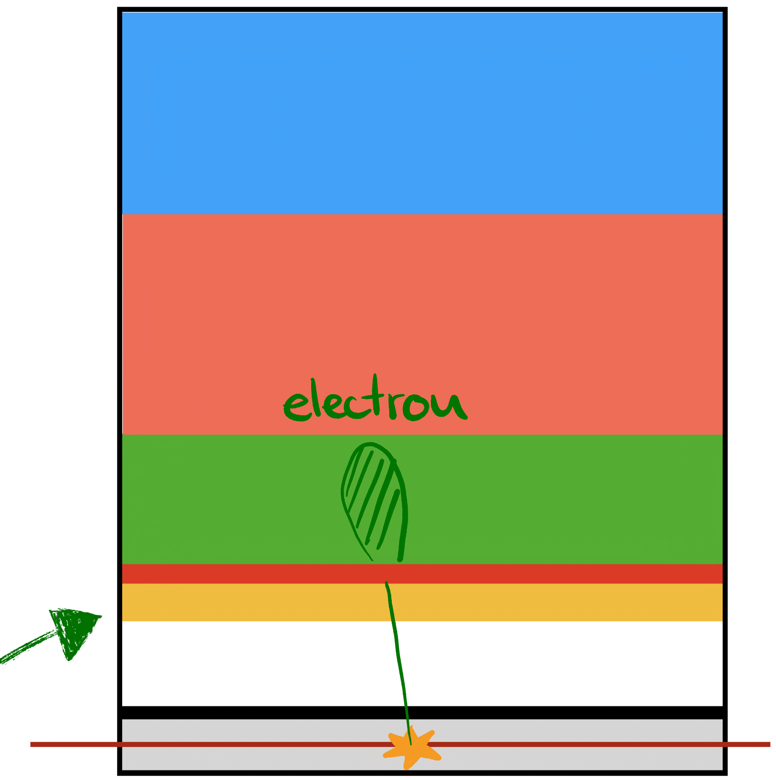




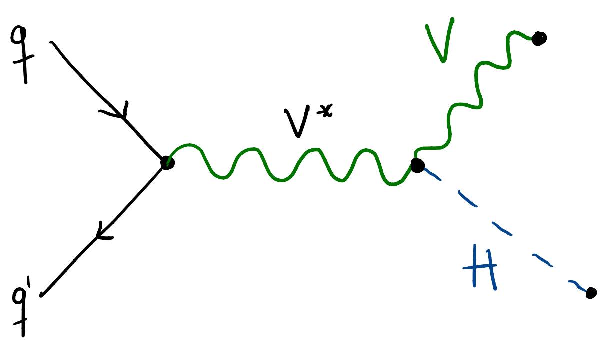
The ATLAS detector





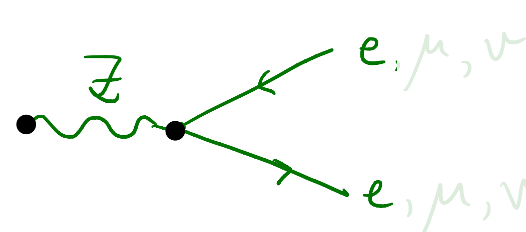


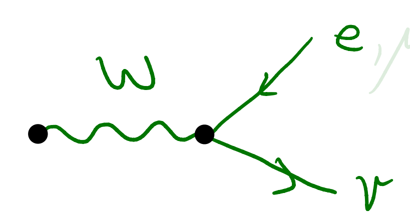
Signal signatures:



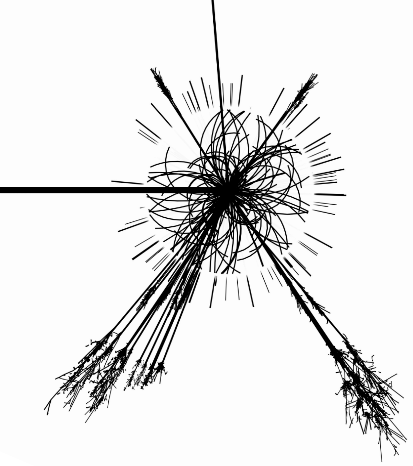
jets

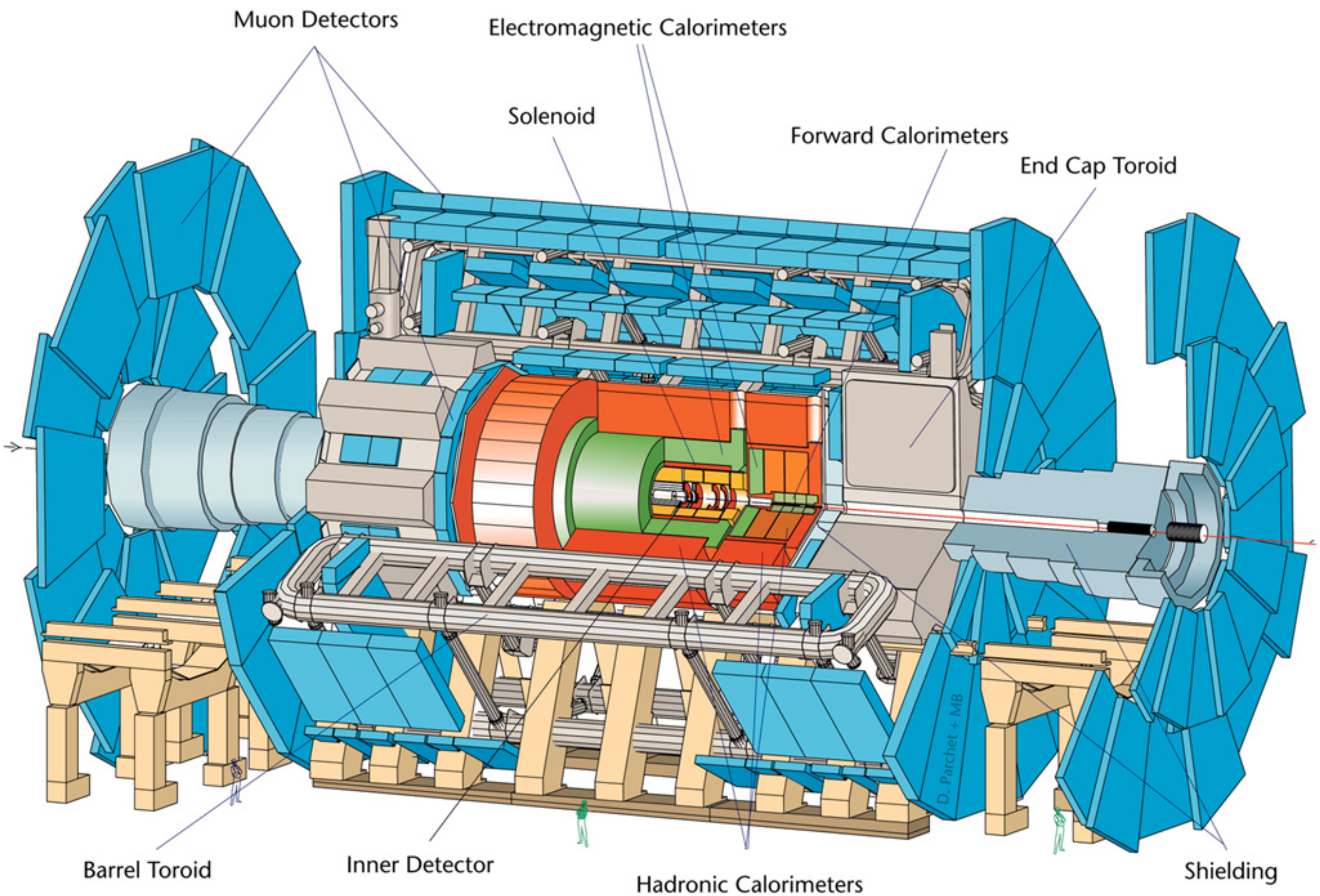
electrons, muons, neutrinos

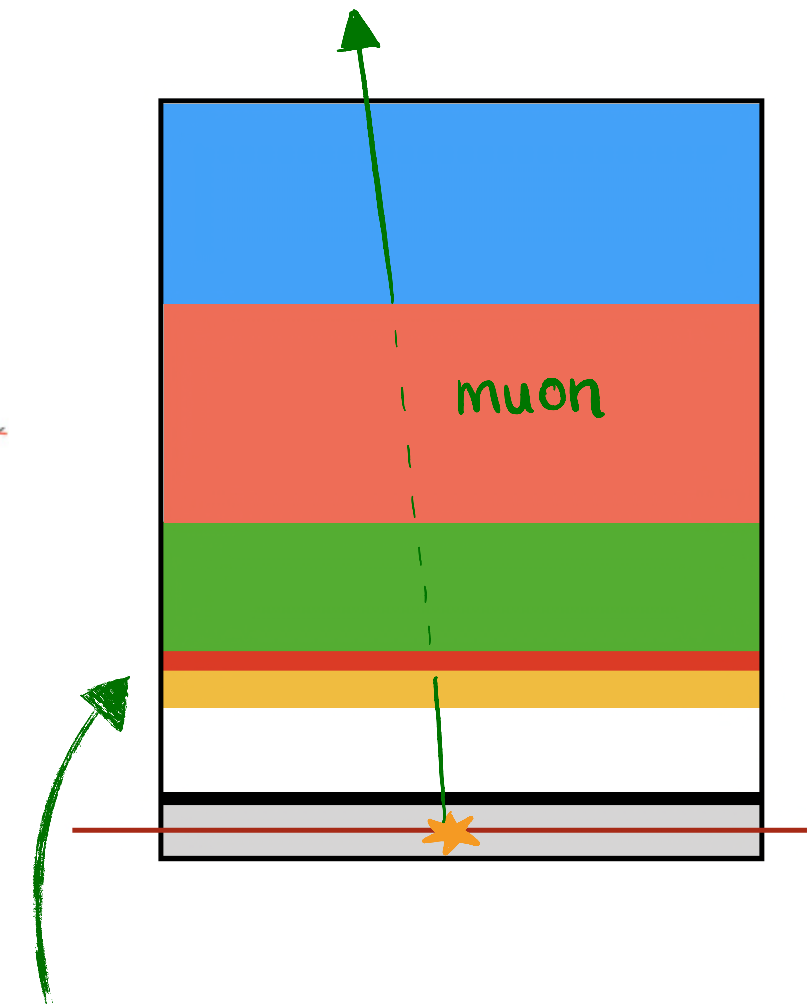




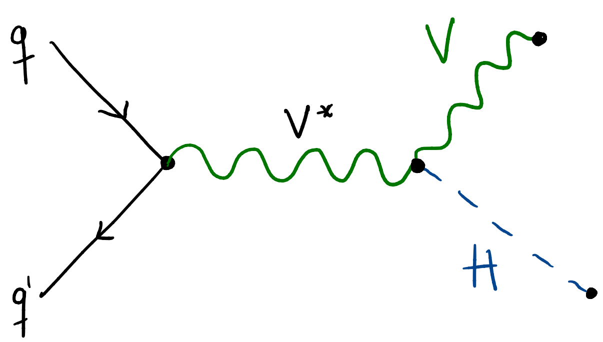
The ATLAS detector

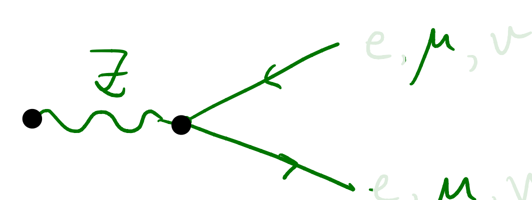


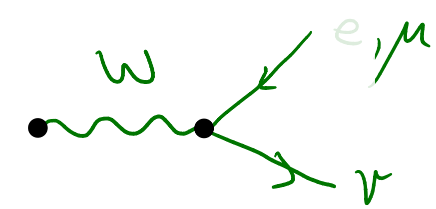




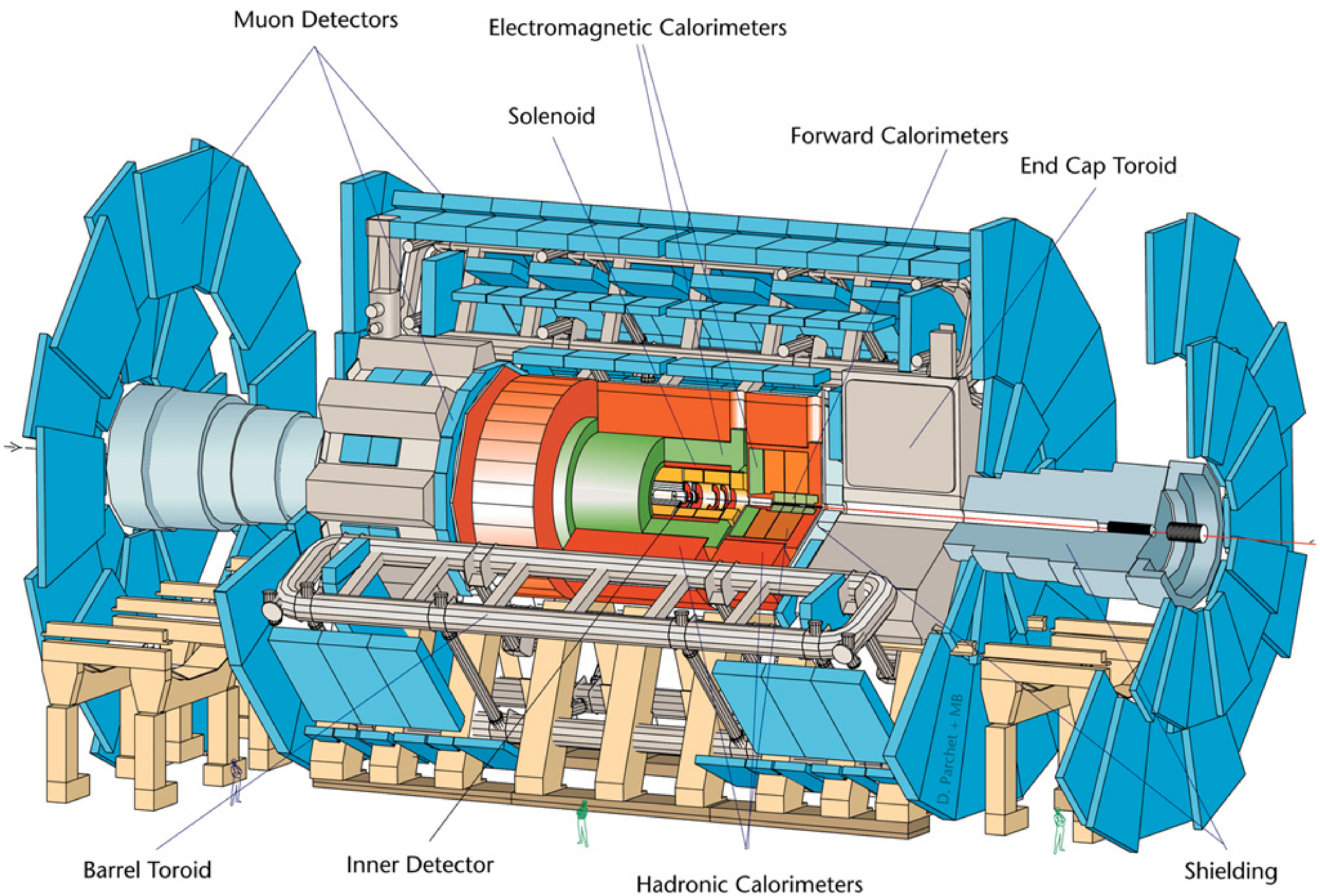
Signal signatures: jets electrons, **muons,** neutrinos

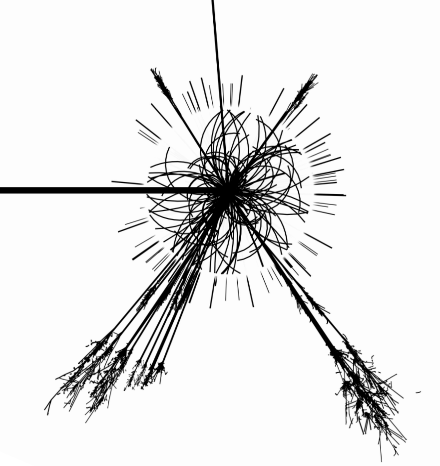


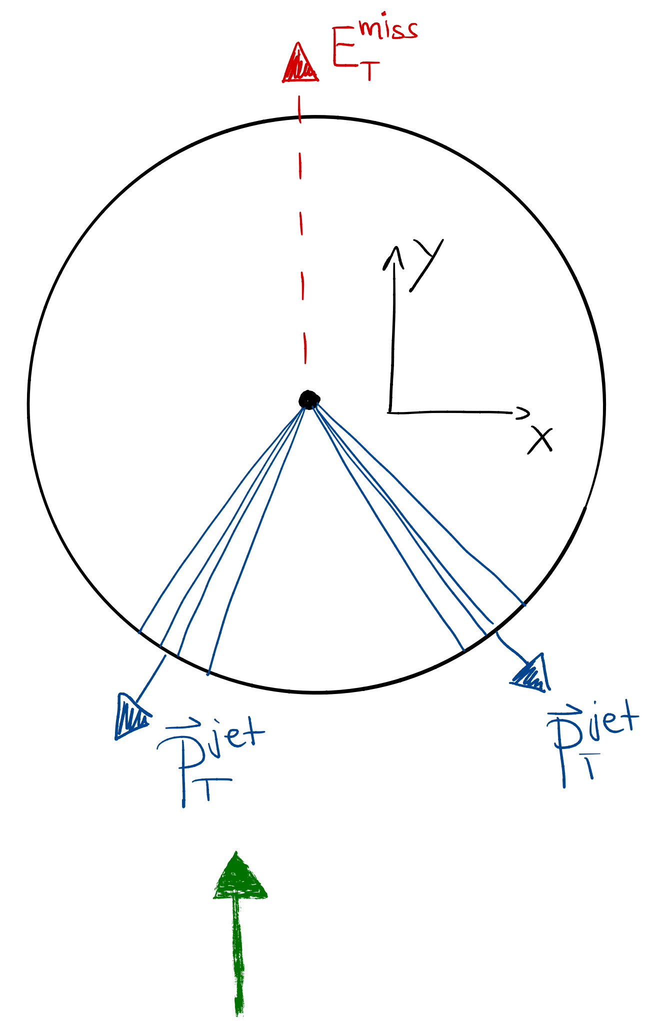




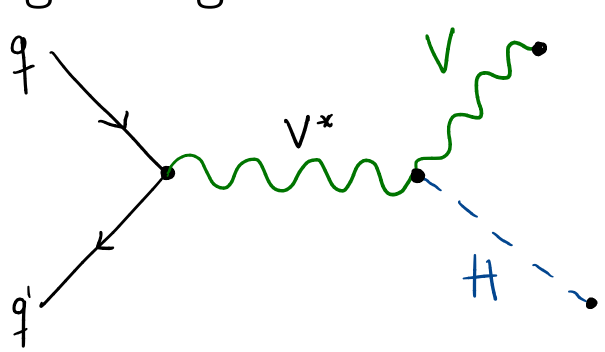
The ATLAS detector

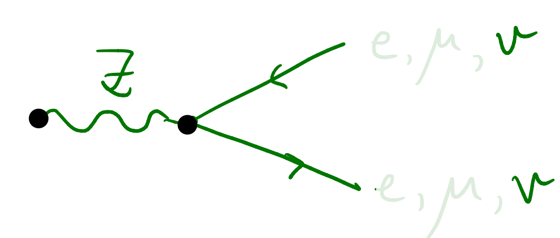


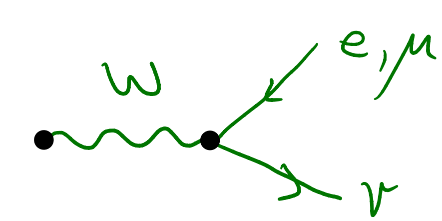




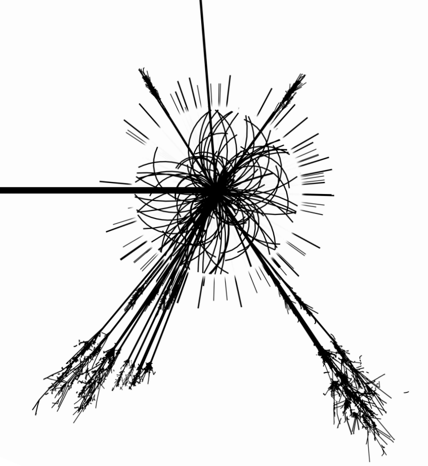
Signal signatures: jets electrons, muons, **neutrinos**



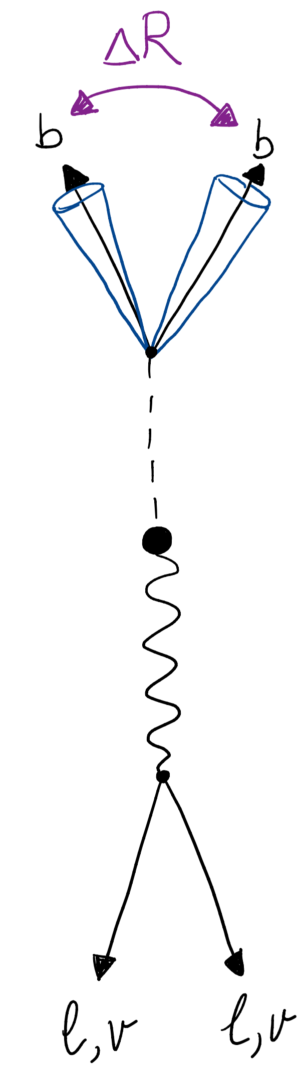


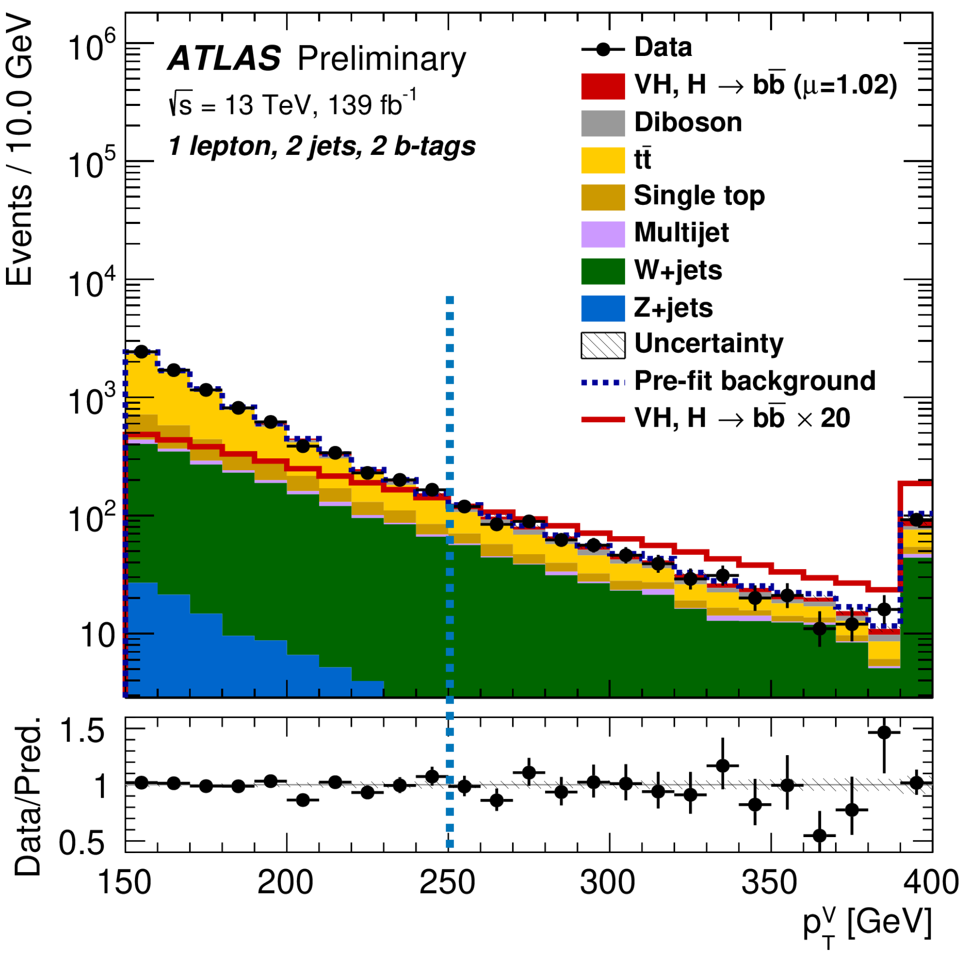


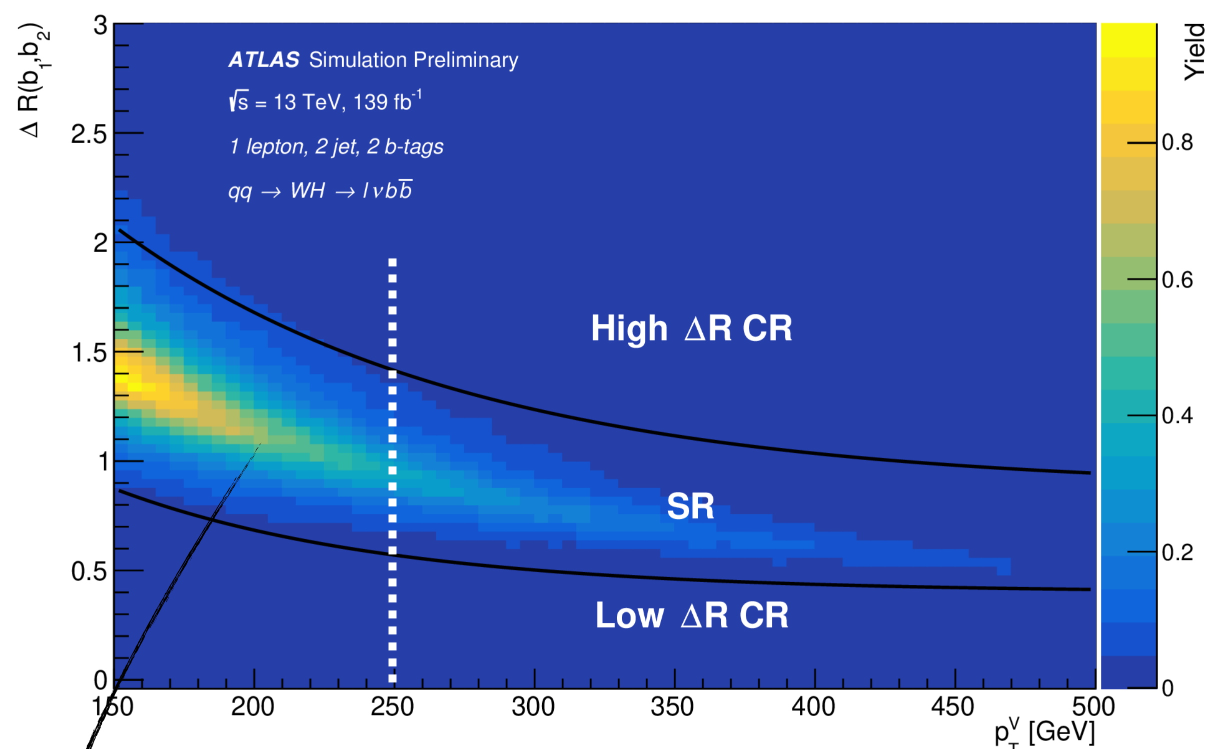
The „low p_T“ VHbb analysis in a nutshell (1/2)



- Trying to individually reconstruct the two b-jets from the Higgs decay
- Categorize in regions of p_T^V (signal harder than sum of all bkgs)
  (75-150 GeV) 150-250 GeV >250 GeV
- Use jet angular separation $\Delta R(b_1, b_2)$ to define signal and control regions







- High ΔR CR: enriched in tt background
- Low ΔR CR: enriched in V+bb

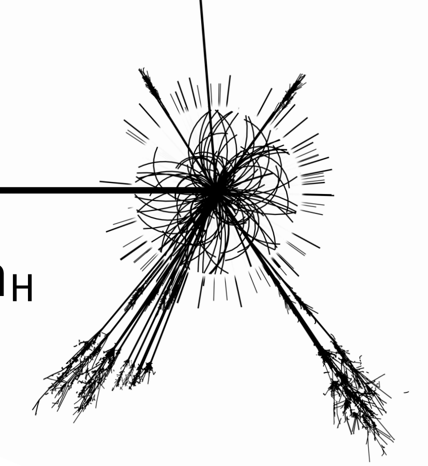
[additional split in jet multiplicity]

contains > 80-90% of the signal

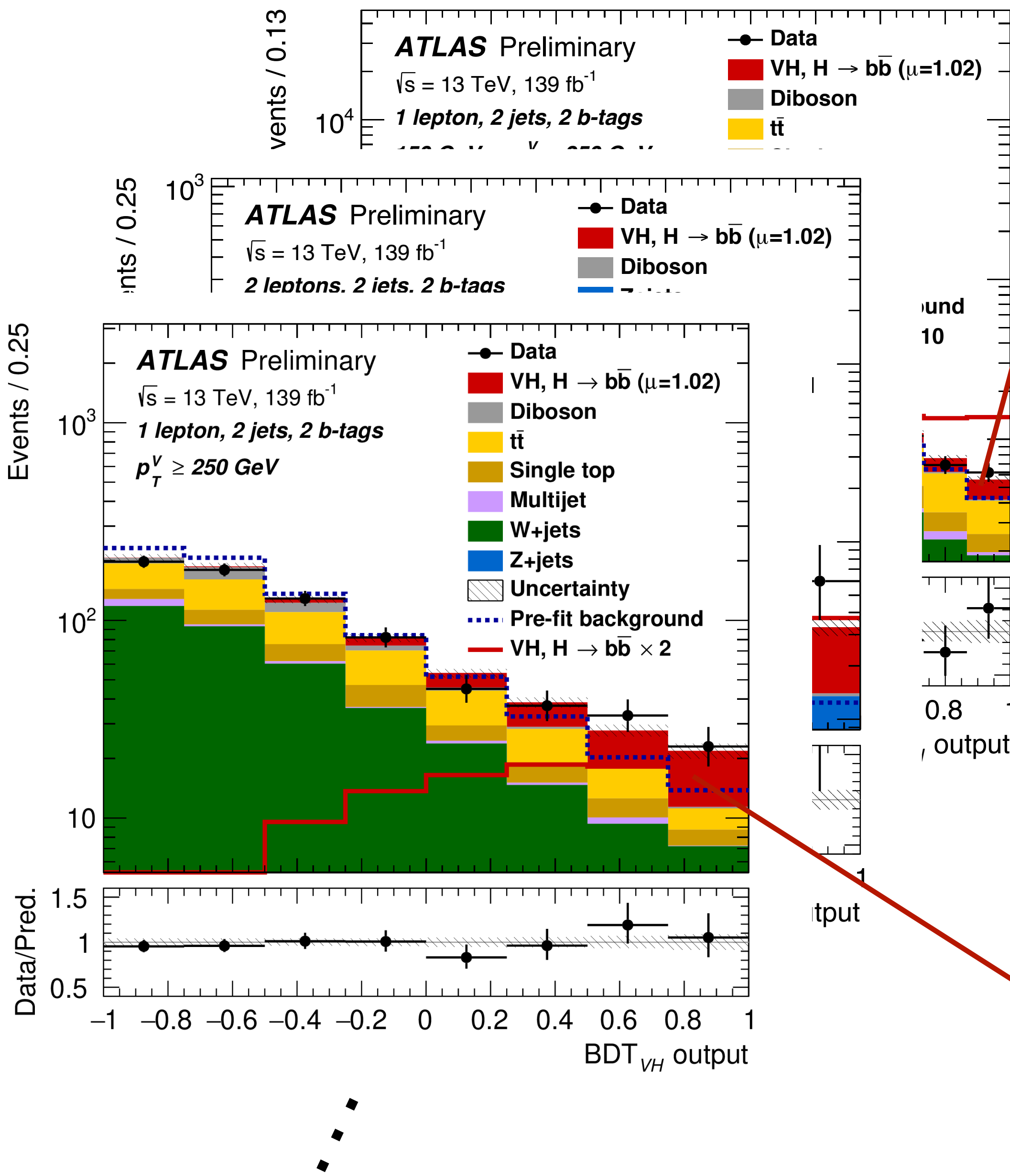
Signal moves to lower ΔR with higher p_T^V

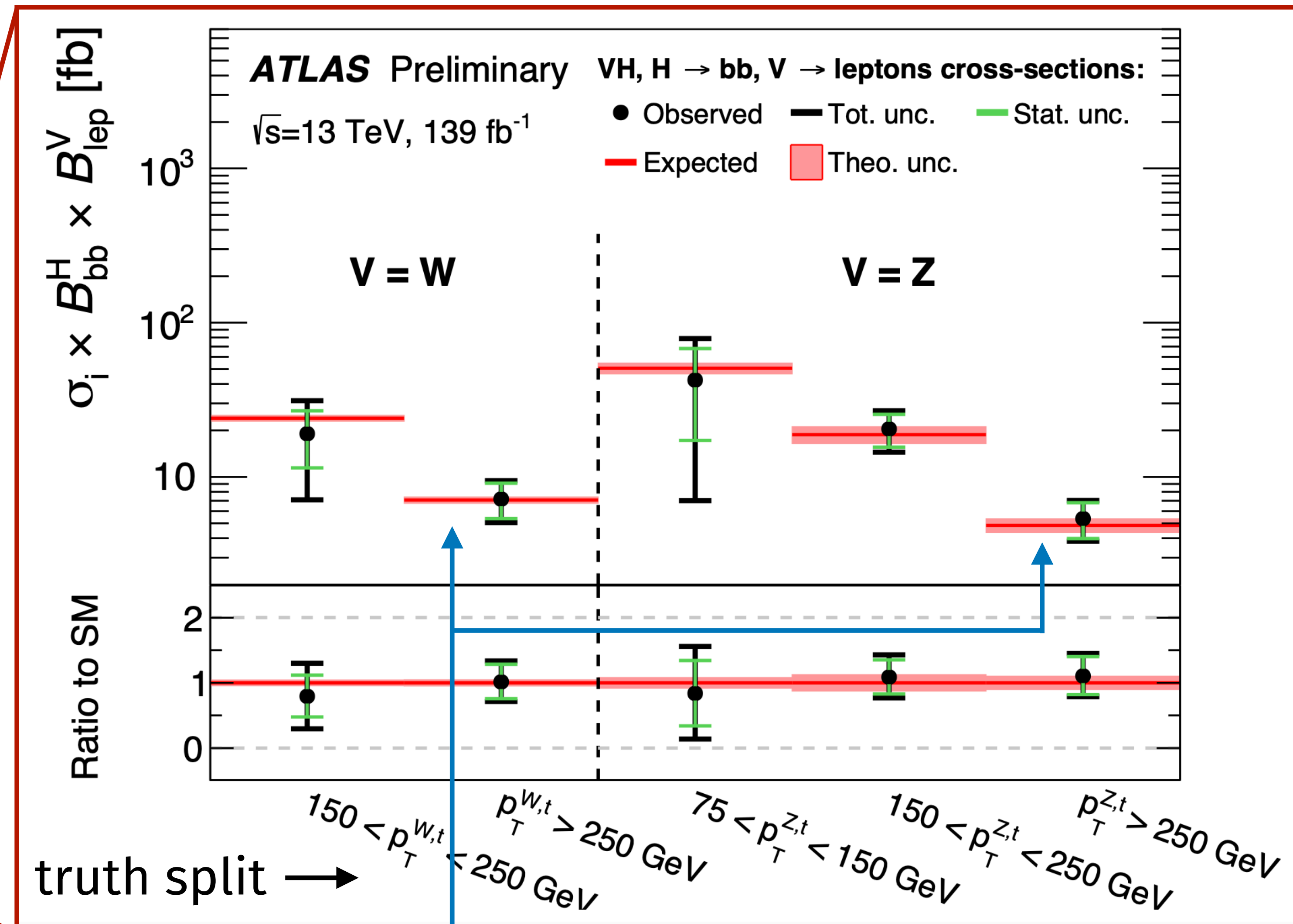
[ATLAS-CONF-2020-006]

The „low p_T“ VHbb analysis in a nutshell (2/2)



- **Invariant di-jet mass** has best separation between signal and bkg. ⟶ **peak at ~ m_H**
  [combined in a BDT with O(10) other variables (event kinematics + b-tagging)]
- The BDT score is fit simultaneously in each region to extract the signal





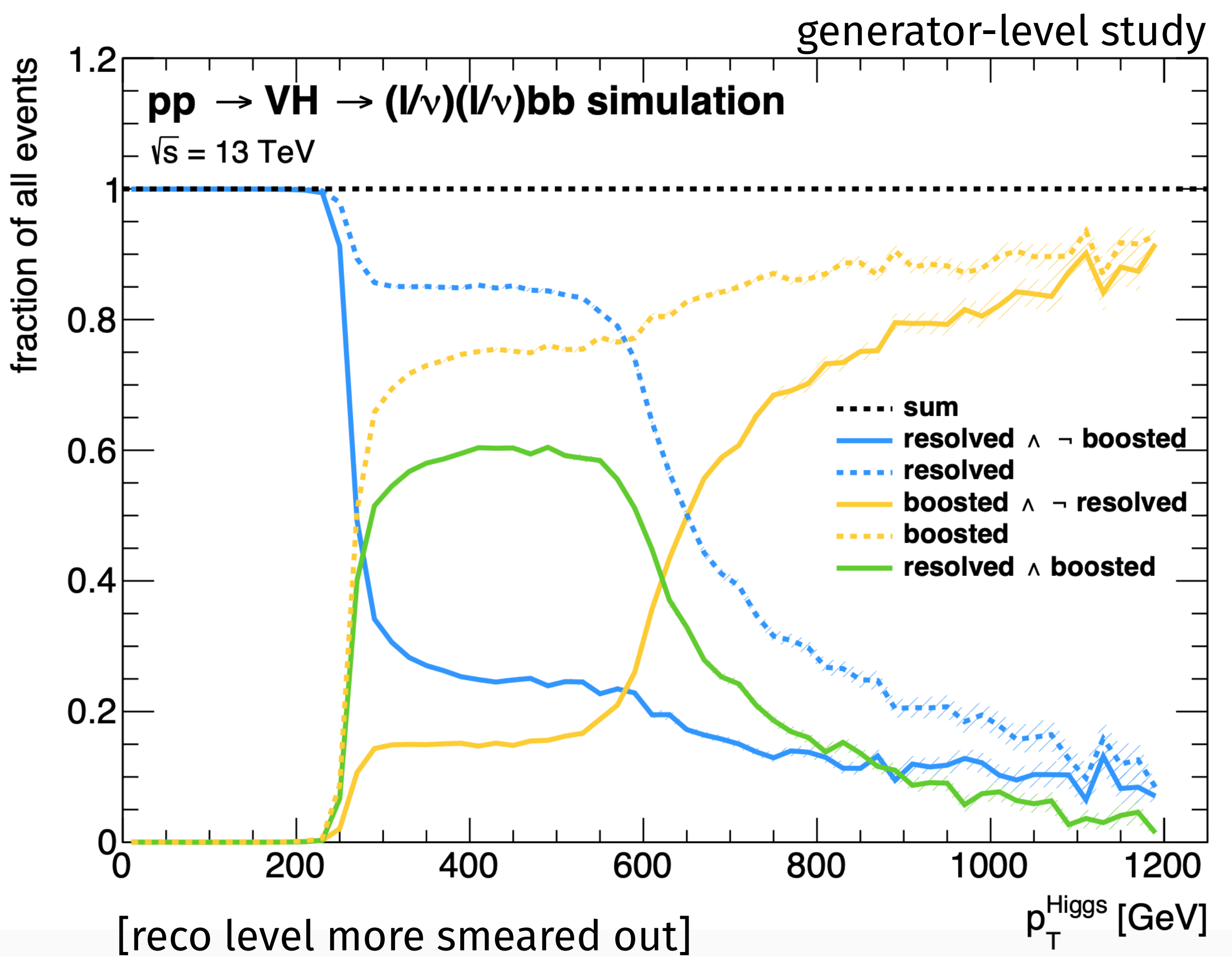
What is happening in the regime beyond?

[ATLAS-CONF-2020-006]

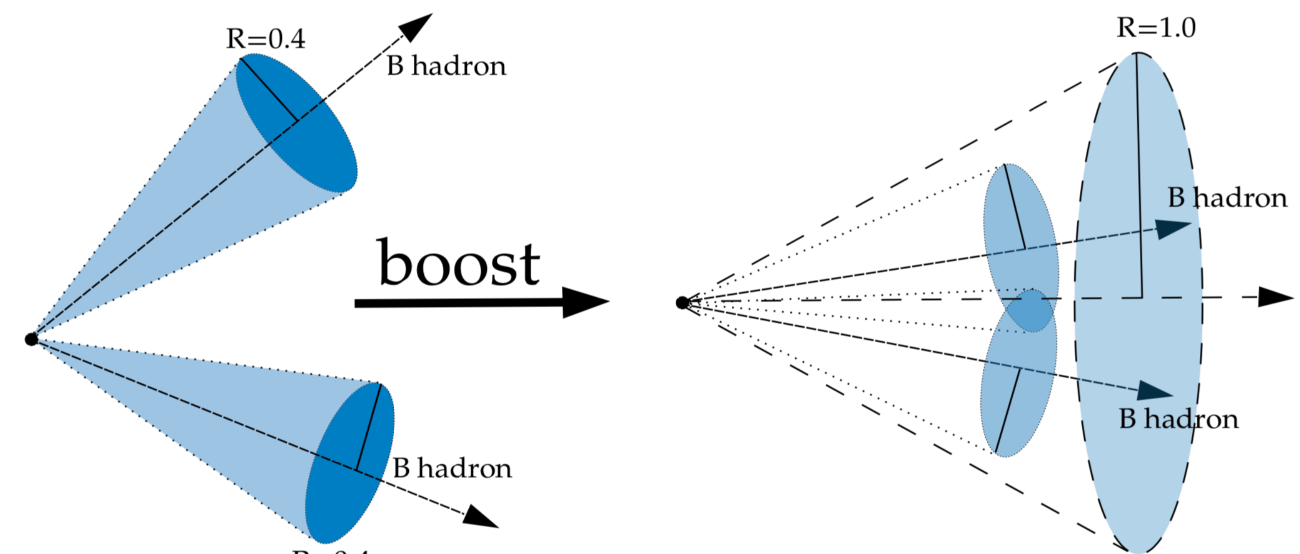
p_T limitations and the need for new techniques

- H→bb is a simple 1→2 decay: In LO defined by m^{Higgs} and p_T^{Higgs}
- Rule of thumb: $\Delta R(b_1, b_2) \sim \frac{2m^{\text{Higgs}}}{p_T^{\text{Higgs}}}$
- Reconstructing the Higgs system with **two anti-k_T (R=0.4) jets** gets less efficient at p_T^{Higgs} ~ 550 GeV

→ **New paradigm:** Reconstruct the Higgs decay by using a single anti-k_T (R=1.0) jet



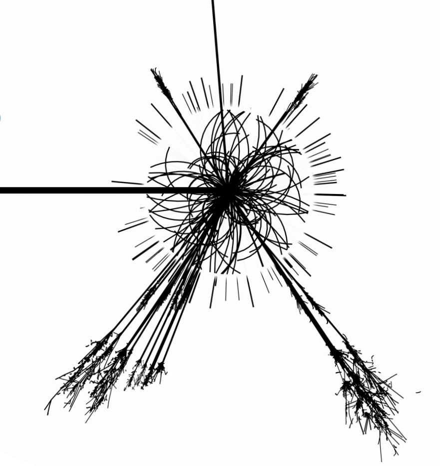
[reco level more smeared out]



The event is reconstructable:

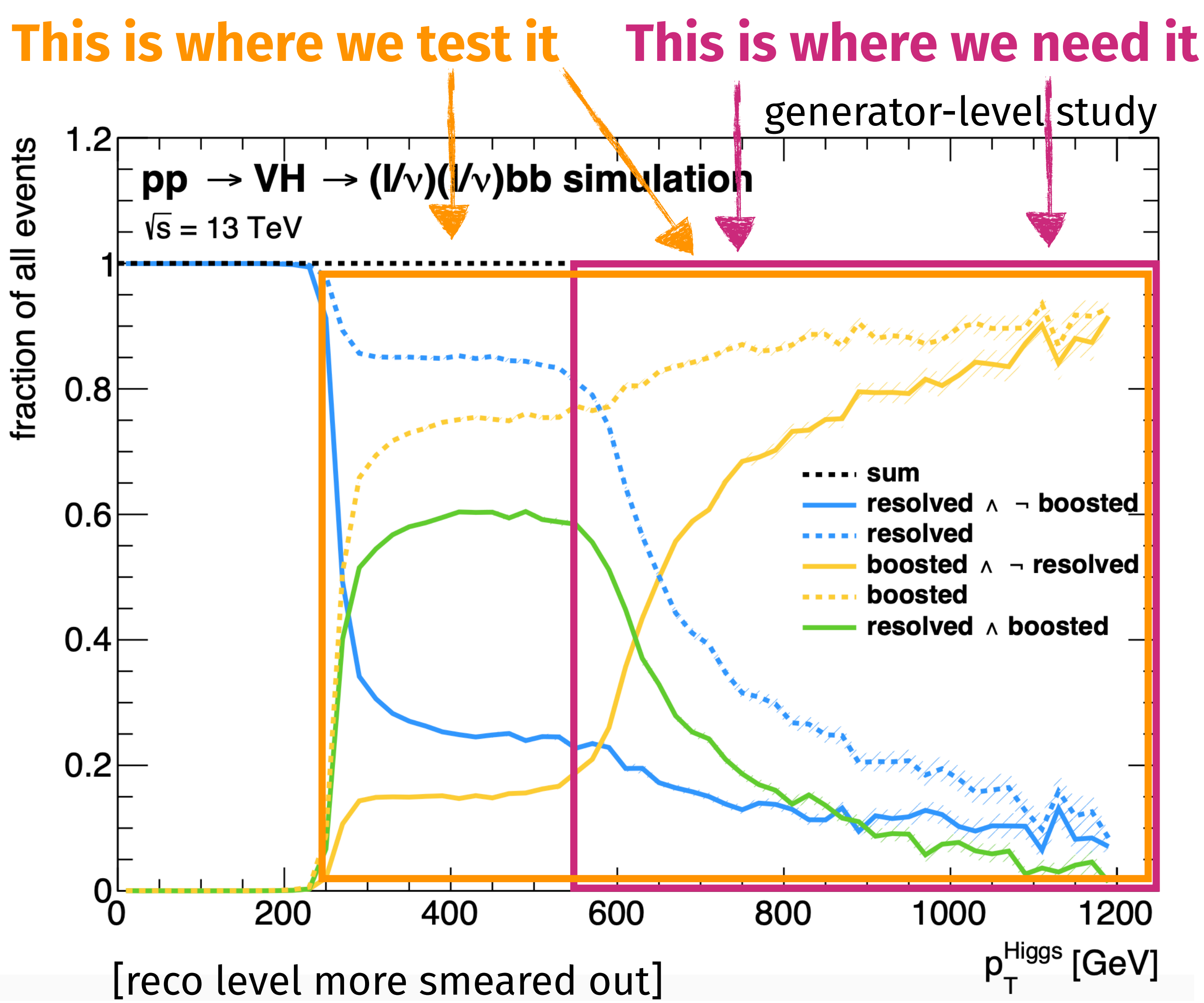
- resolved and not boosted
- both resolved and boosted
- boosted and not resolved

p_T limitations and the need for new techniques



- H→bb is a simple 1→2 decay: In LO defined by m^{Higgs} and p_T^{Higgs}
- Rule of thumb: $\Delta R(b_1, b_2) \sim \frac{2m^{\text{Higgs}}}{p_T^{\text{Higgs}}}$
- Reconstructing the Higgs system with **two anti-k_T (R=0.4) jets** gets less efficient at p_T^{Higgs} ~ 550 GeV

⟶ **New paradigm:** Reconstruct the Higgs decay by using a single anti-k_T (R=1.0) jet

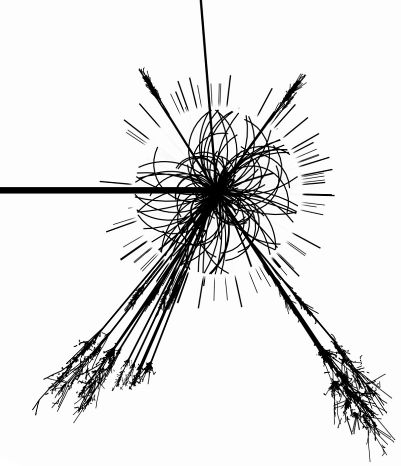


- Robust analysis, proof of principle:
  „we can do a Higgs measurement using boosted techniques"
- Do not remove the overlap with resolved VHbb analysis

The event is reconstructable:

- resolved and not boosted
- both resolved and boosted
- boosted and not resolved

From first ideas to the first measurement



Jet substructure as a new Higgs search channel at the LHC

2008

Jonathan M. Butterworth, Adam R. Davison
Department of Physics & Astronomy, University College London.

Mathieu Rubin, Gavin P. Salam
LPTHE; UPMC Univ. Paris 6; Univ. Denis Diderot; CNRS UMR 7589; Paris, France.

It is widely considered that, for Higgs boson searches at the Large Hadron Collider, WH and ZH production where the Higgs boson decays to $b\bar{b}$ are poor search channels due to large backgrounds. We show that at high transverse momenta, employing state-of-the-art jet reconstruction and decomposition techniques, these processes can be recovered as promising search channels for the standard model Higgs boson around 120 GeV in mass.

ATLAS PUBLIC NOTE

August 19, 2009

2009

ATLAS Sensitivity to the Standard Model Higgs in the HW and HZ Channels at High Transverse Momenta

Boosted Higgs $\to b\bar{b}$ in vector-boson associated production at 14 TeV

2015

Jonathan M. Butterworth, Inês Ochoa, Tim Scanlon
Department of Physics and Astronomy, University College London,
Gower St., London, WC1E 6BT, UK

[ATLAS-CONF-2020-007]

ATLAS CONF Note

ATLAS-CONF-2020-007

11th April 2020

Measurement of the associated production of a Higgs boson decaying to b quarks with a vector boson at high transverse momentum in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

The ATLAS Collaboration

The associated production of a Higgs boson with a W or Z boson decaying to leptons and where the Higgs boson decays to a $b\bar{b}$ pair is measured in the high vector boson transverse momentum regime, above 250 GeV, with the ATLAS detector. The analysed data, corresponding to an integrated luminosity of 139 fb^{-1}, were collected in proton–proton collisions at the Large Hadron Collider between 2015 and 2018 at a centre-of-mass energy of $\sqrt{s}$ = 13 TeV. The measured signal strength, defined as the ratio of the measured signal yield to that predicted by the Standard Model, is $0.72^{+0.39}_{-0.36}$ corresponding to an observed (expected) significance of 2.1 (2.7) standard deviations. Fiducial cross-sections are measured in two ranges of gauge boson transverse momentum, 250 – 400 GeV and above 400 GeV, according to region definitions of the simplified template cross-section framework.

ATLAS-CONF-2020-007
11 April 2020

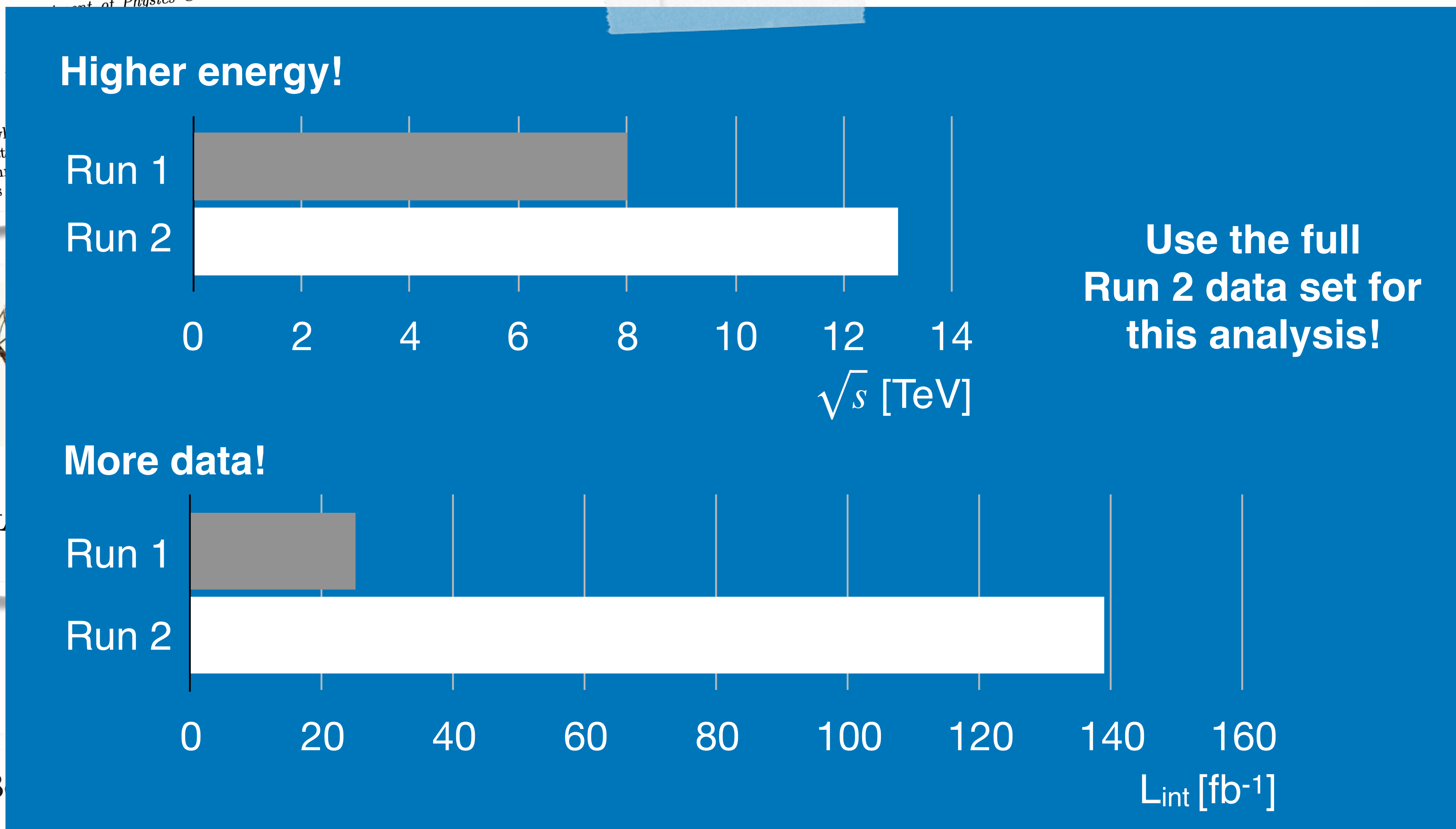
From first ideas to the first measurement

Jet substructure as a new Higgs search channel at the LHC

Jonathan M. Butterworth, Adam R. Davison
Department of Physics & Astronomy, University College London.

2008

With the increasing LHC data set…



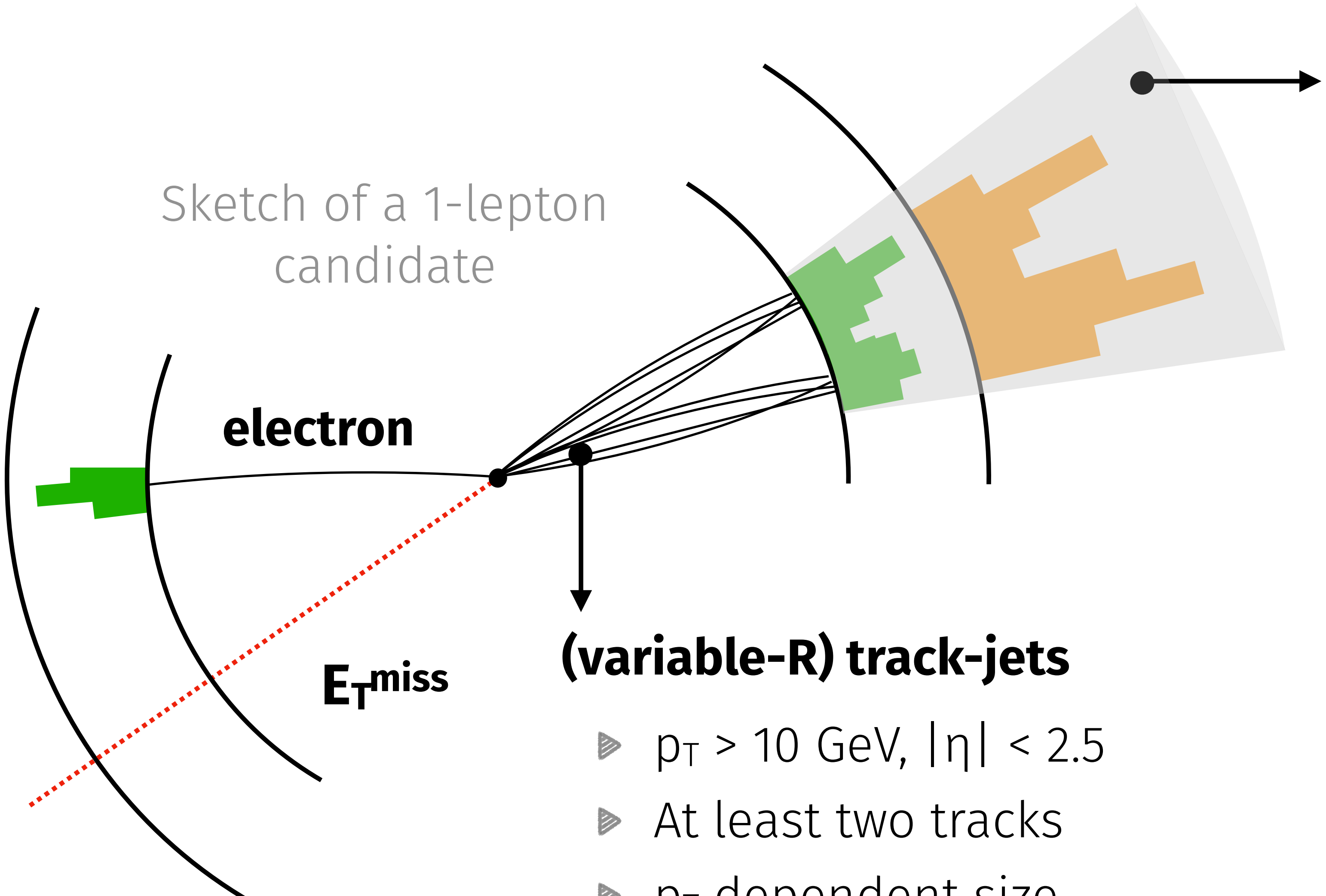
Jonathan M. Butterworth, Inês Ochoa, Tim Scanlon
Department of Physics and Astronomy, University College London,
Gower St., London, WC1E 6BT, UK

…these topologies finally start to become accessible

The targeted event topology: an overview

- Categorize according to the charged lepton multiplicity in the final state:
  $Z \to \nu\nu$: 0-lepton $W \to \ell\nu$: 1-lepton $Z \to \ell\ell$: 2-lepton $(\ell \in \{e, \mu\})$
- Boosted Higgs candidate selection chosen commonly between all three channels
  - Higgs candidate: leading (highest p_T) large-R (R=1.0) calorimeter jet in the event
  - b-tagging done on the two leading variable-R track-jets ghost-associated to it

Sketch of a 1-lepton candidate



large-R (calorimeter) jet

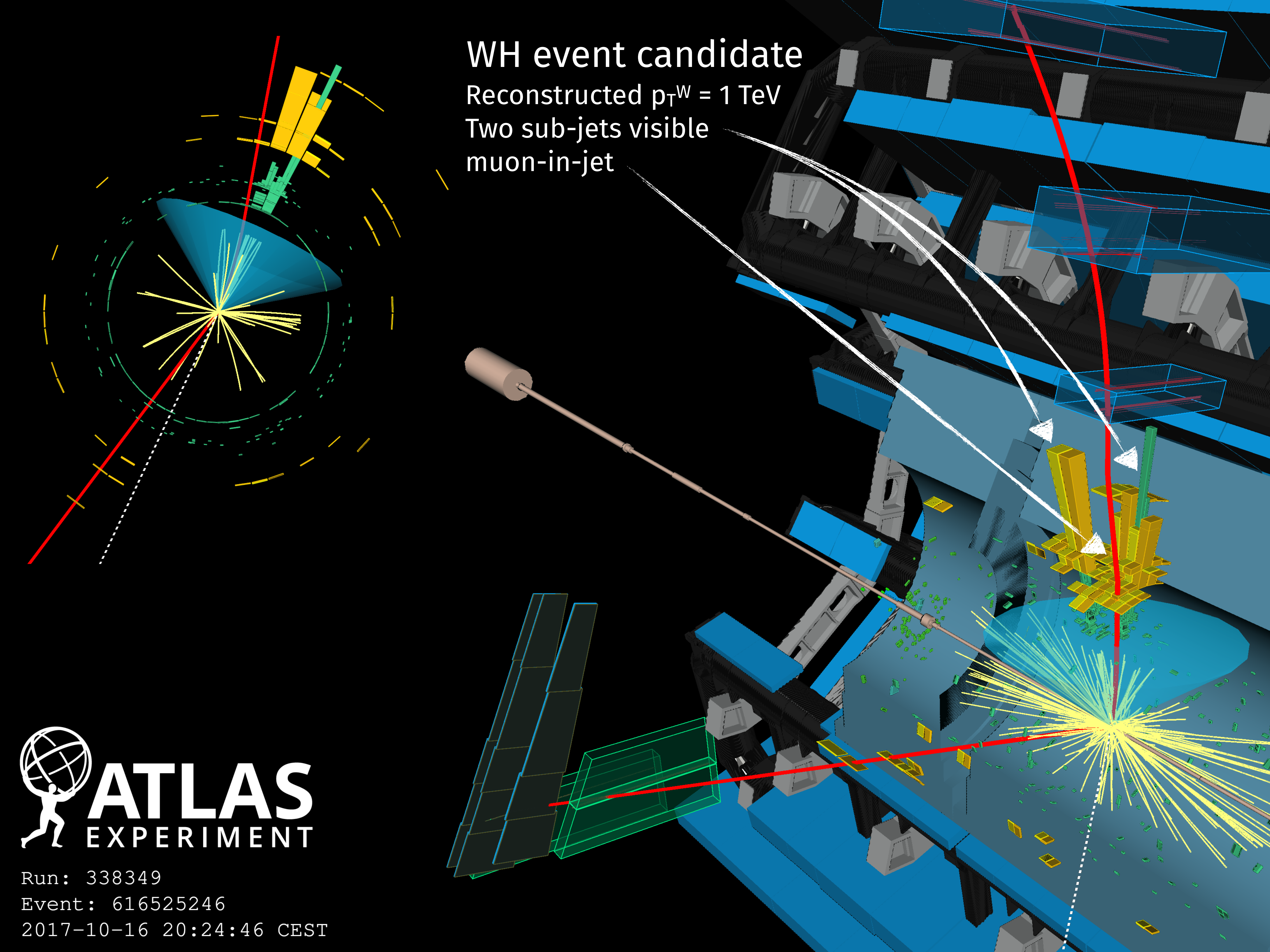
- p_T > 250 GeV, $|\eta|$ < 2.0 (central)
- **m_J is final discriminant**
- Dedicated energy corrections

(variable-R) track-jets

- p_T > 10 GeV, $|\eta|$ < 2.5
- At least two tracks
- p_T dependent size

Require 2 b-tags using a 70% single-tag WP

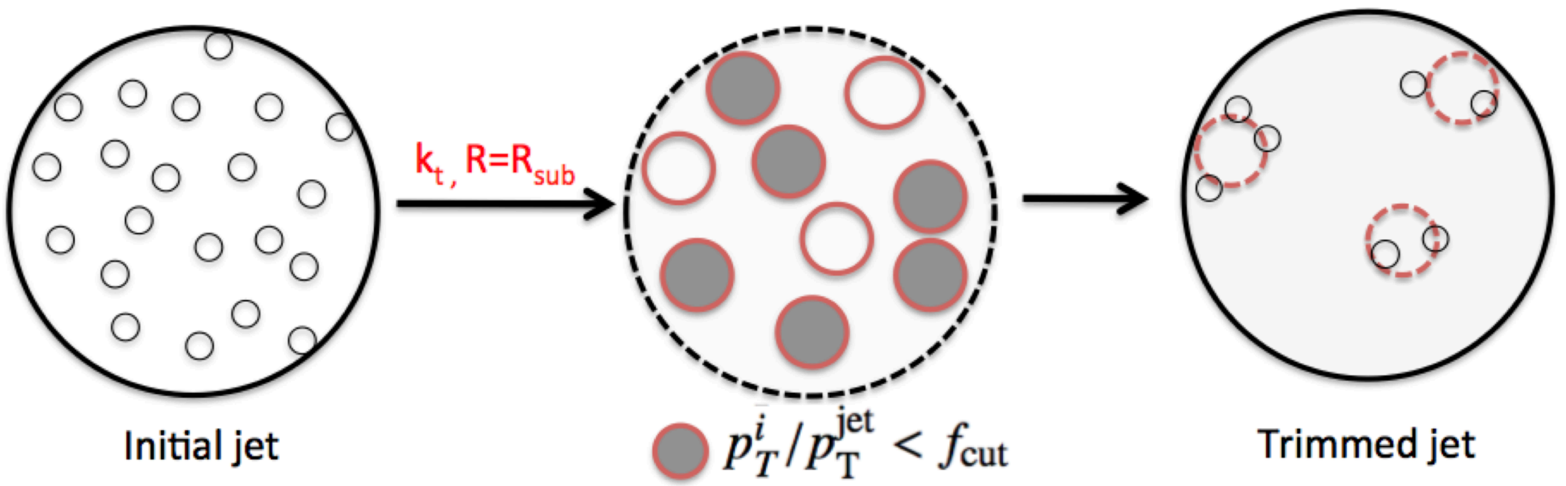
+ small-R (R=0.4) calo jets for event categorization (later)


WH event candidate
Reconstructed p_T^W = 1 TeV
Two sub-jets visible
muon-in-jet
ATLAS
EXPERIMENT
Run: 338349
Event: 616525246
2017-10-16 20:24:46 CEST

How to handle large-R jets

Jet Inputs → Clustering → **Grooming** → Calibration

Trimming used as grooming procedure: [CERN-PH-EP-2013-069]

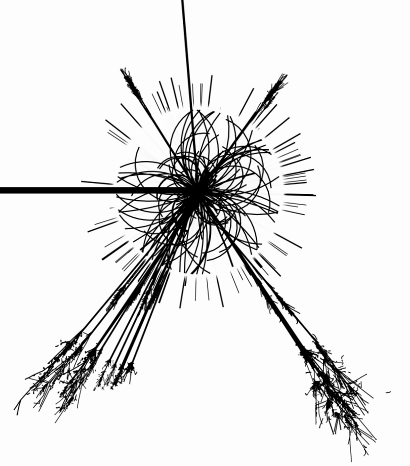


Large Jet = Contamination from pile-up, initial state radiation, multiple parton interactions

These are often much softer than outgoing patrons and their radiation

1. Create k_t sub-jets of size R = 0.2 from the large-R jet constituents
2. Remove them if their p_T fraction is less than 5% of the large-R jet

Improving the large-R jet mass resolution



- Use the **combined mass*** (weighted sum of calorimeter and tracker mass)

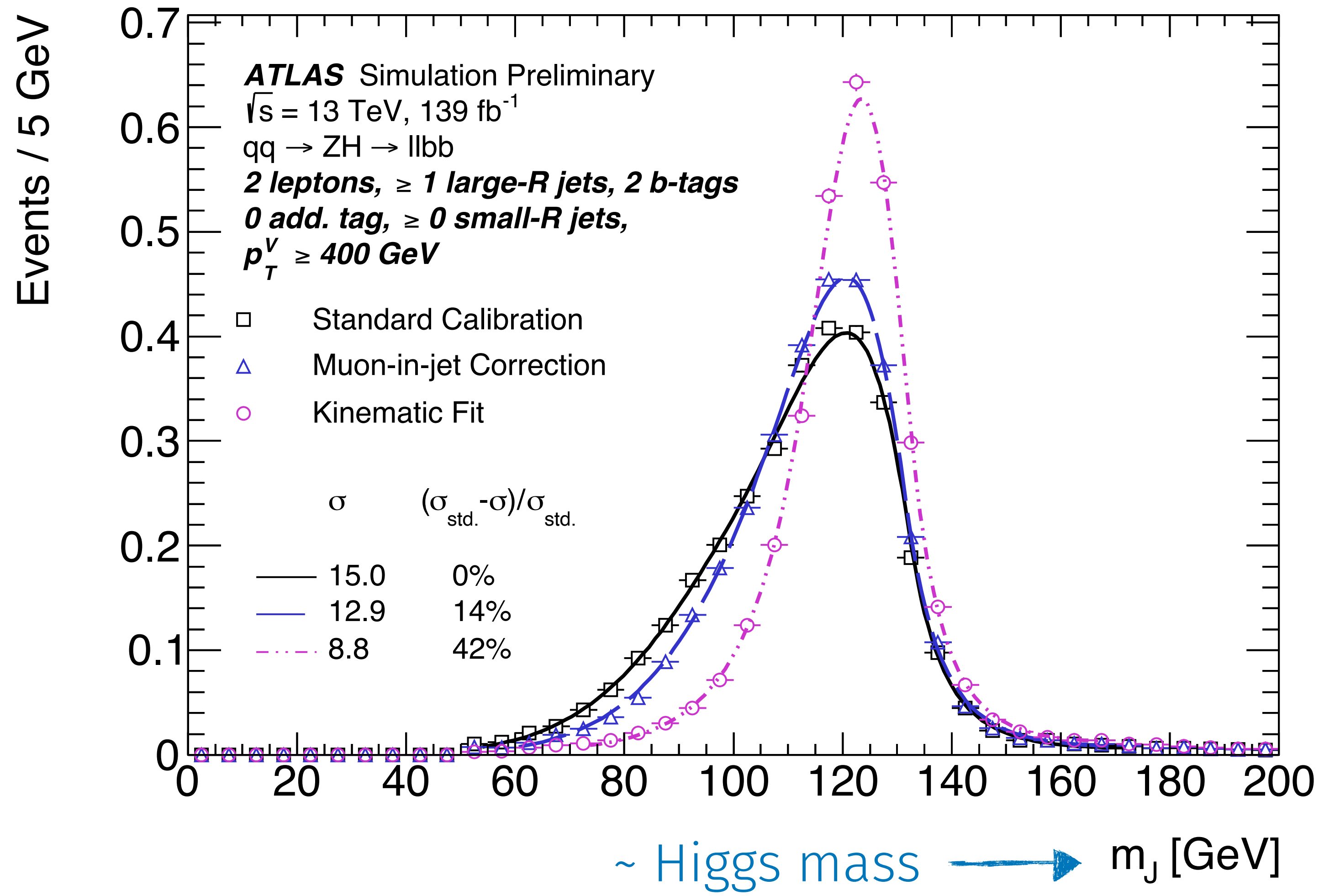
$$m_{\text{comb}} = w_{\text{calo}} \times m_{\text{calo}} + w_{\text{TA}} \times m_{\text{tracker}} \frac{p_T^{\text{calo}}}{p_T^{\text{tracker}}}$$

- Mass resolution: ~ 15%

Improving the resolution:

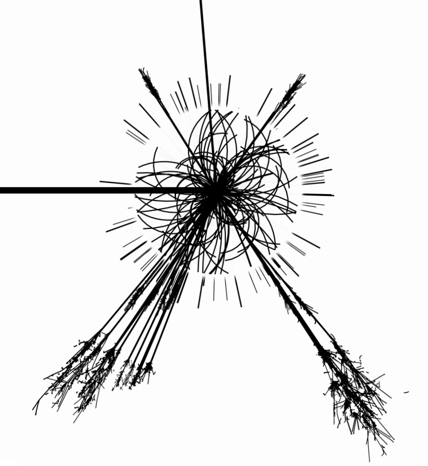
1. Muon-in-jet correction
   correcting for muons created in heavy hadron decays that exit the calorimeter
   → 6%-14% improvement w.r.t. m_{comb}

2. Kinematic Fit in 2-lepton channel
   exploiting the kinematic balance of the di-lepton system (1% resolution) with the jet system
   → 30%-40% improvement w.r.t. m_{comb}



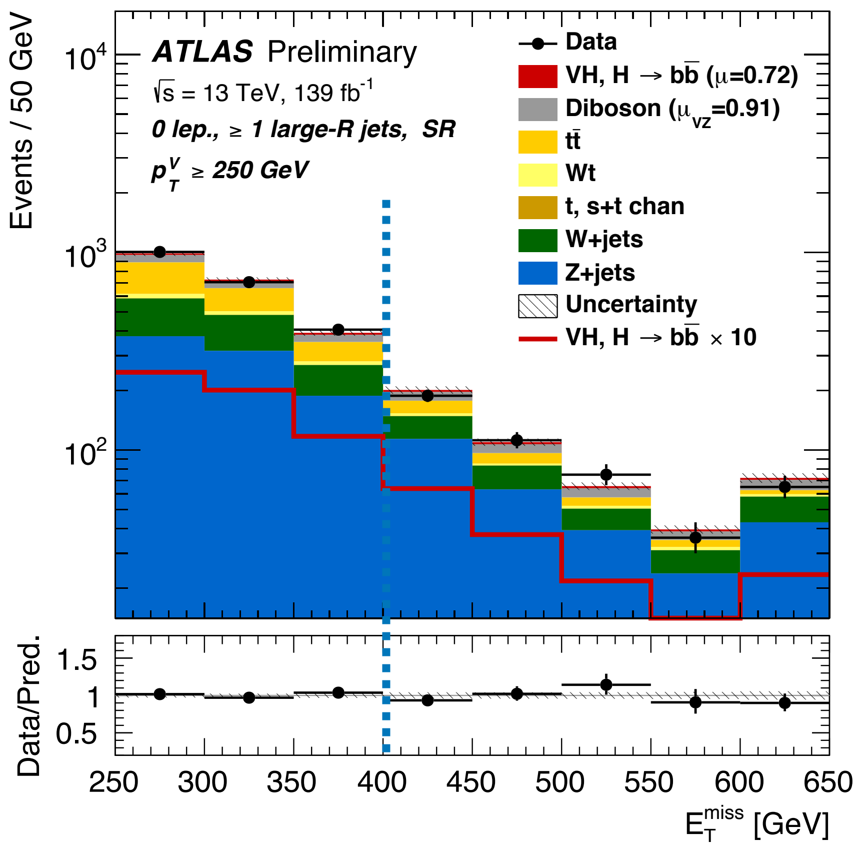
* outperforms pure calorimeter mass jet from p_T ~ 500 GeV upwards, see [ATLAS-CONF-2016-035]

Binning in vector boson p_T

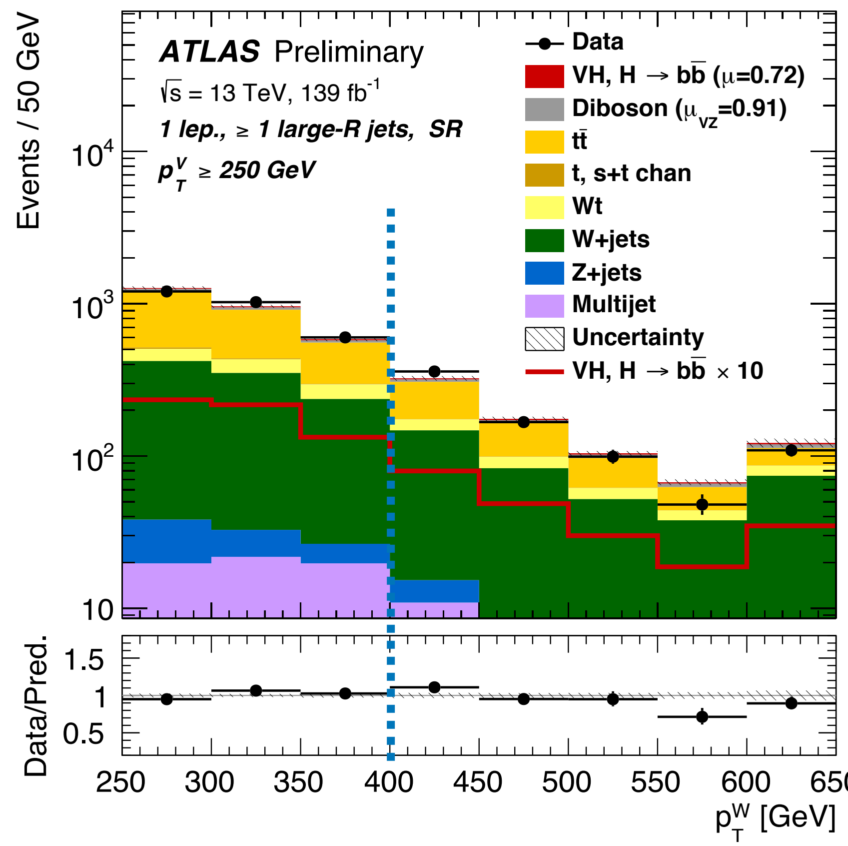


- Since $p_T^H \sim p_T^V$, require at least p_T^V = 250 GeV
- 2 regions exploited: **[250, 400[GeV and [400, ∞[GeV**

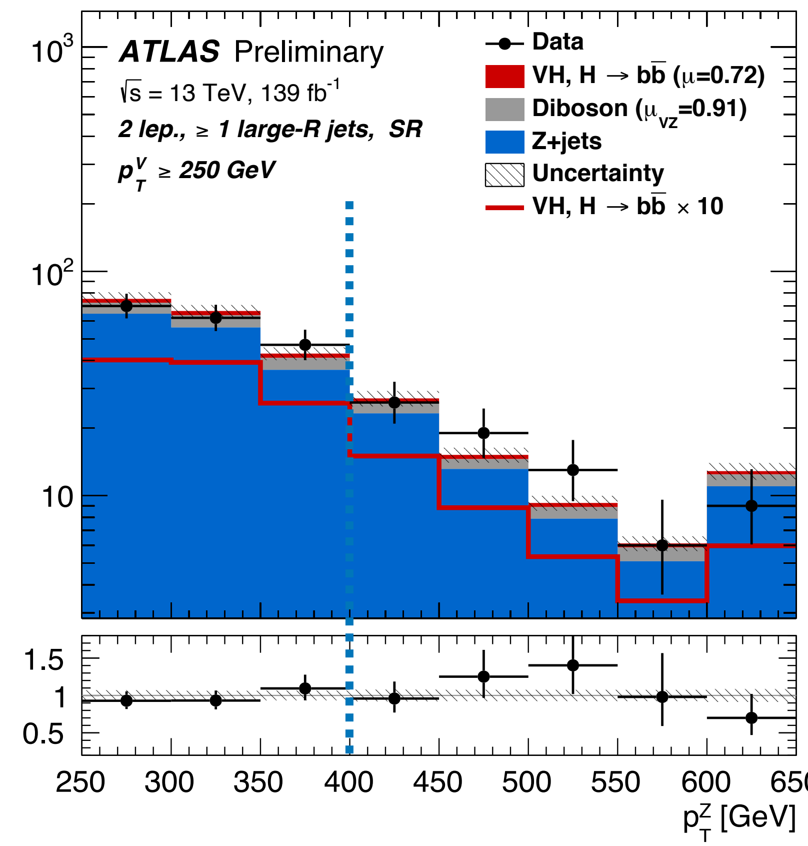
0-lepton



1-lepton



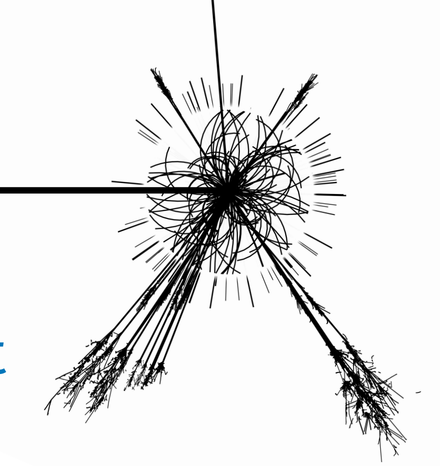
2-lepton



Main backgrounds:

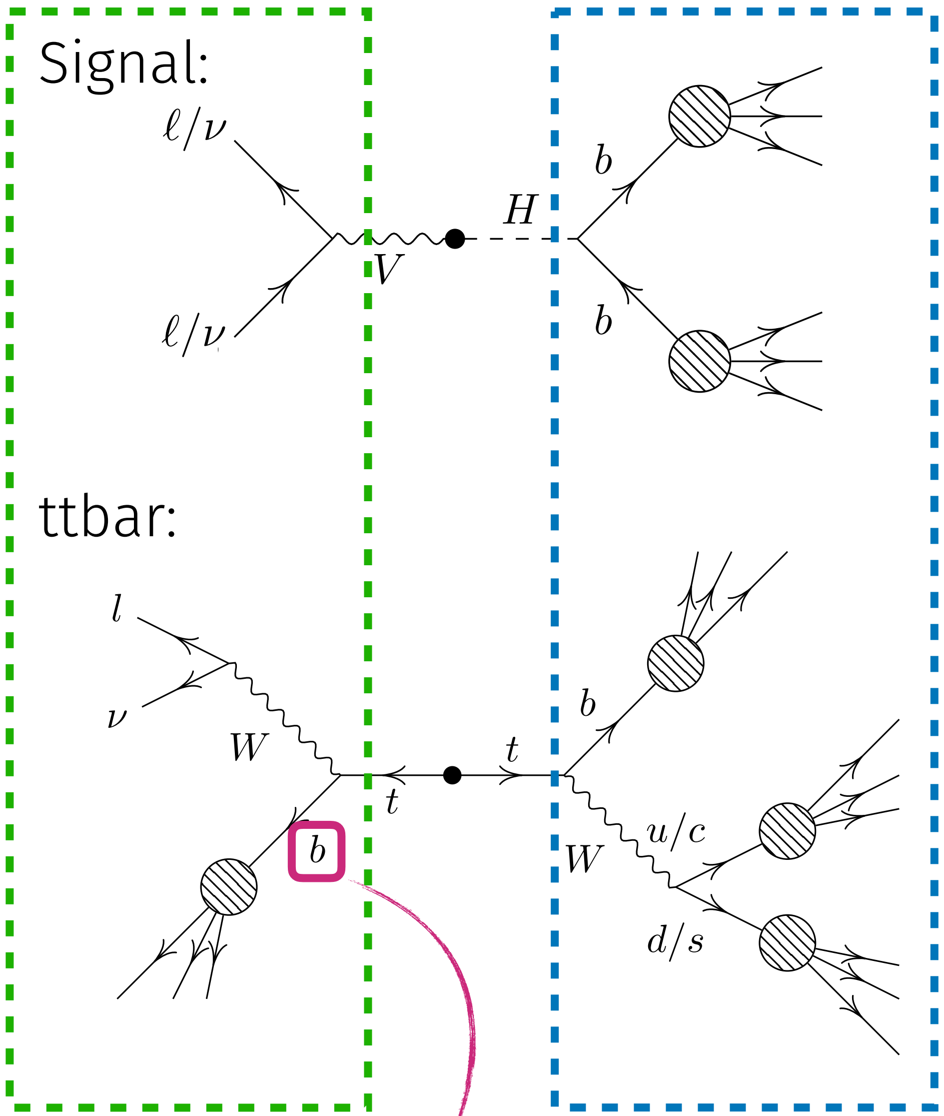
- 0-lepton: **ttbar**, **W+jets**, **Z+jets**
- 2-lepton: **Z+jets**, **diboson**
- 1-lepton: **ttbar**, **W+jets**, **single top**

Signal- and Control Regions (SRs + CRs)



The signal region:

- In LO, **no add. b-jet** outside the large-R jet
- Veto on additional b-tags



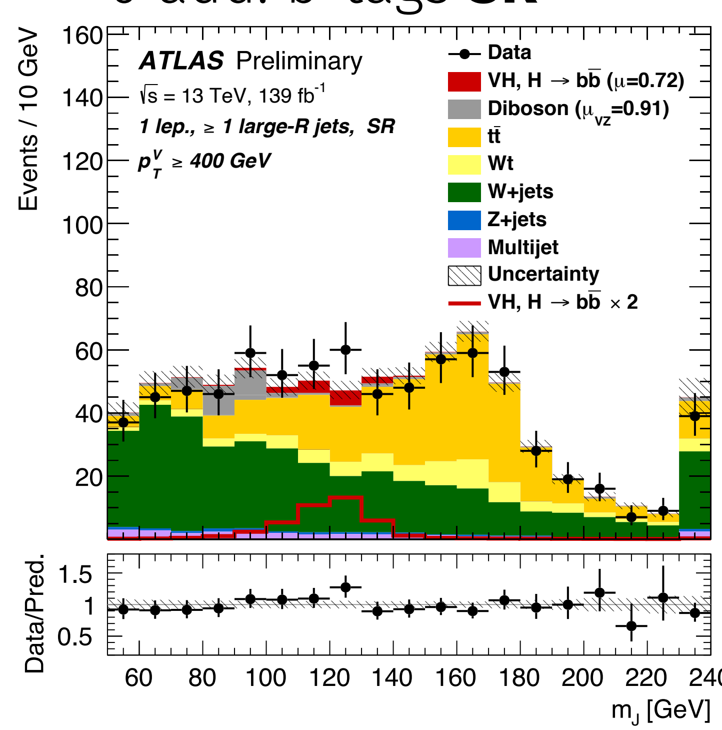
(different levels of containment)

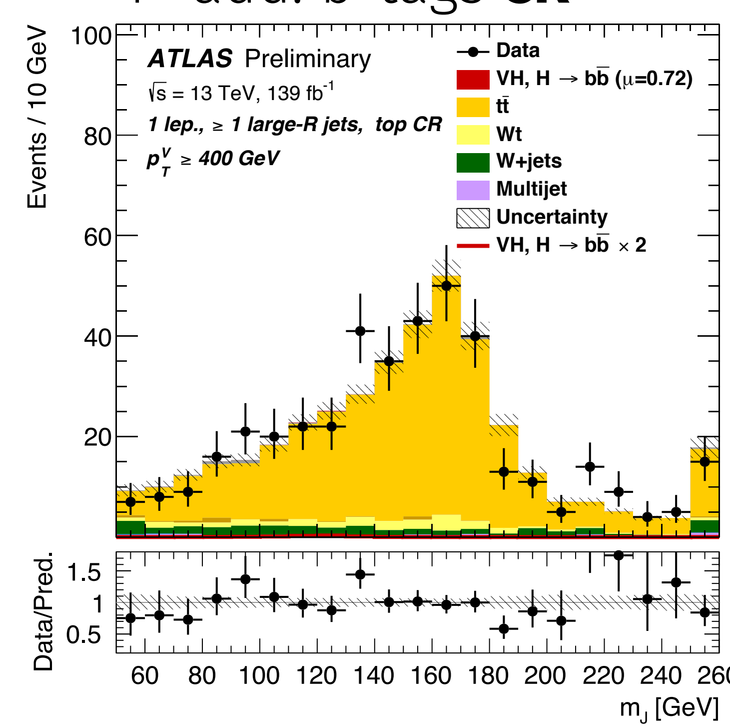
additional b

The ttbar control region:

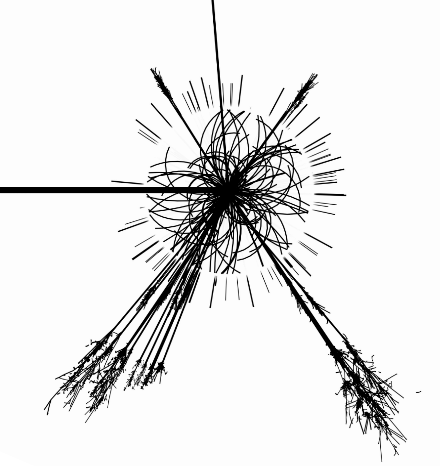
- Higgs candidate most-likely built from boosted (had.) top
- b-jet from the lept. top-quark decay still somewhere
- Obtain a ttbar CR in 0L and 1L by requiring additional b-tags outside the large-R jet

0 add. b-tags **SR** → 1+ add. b-tags **CR**

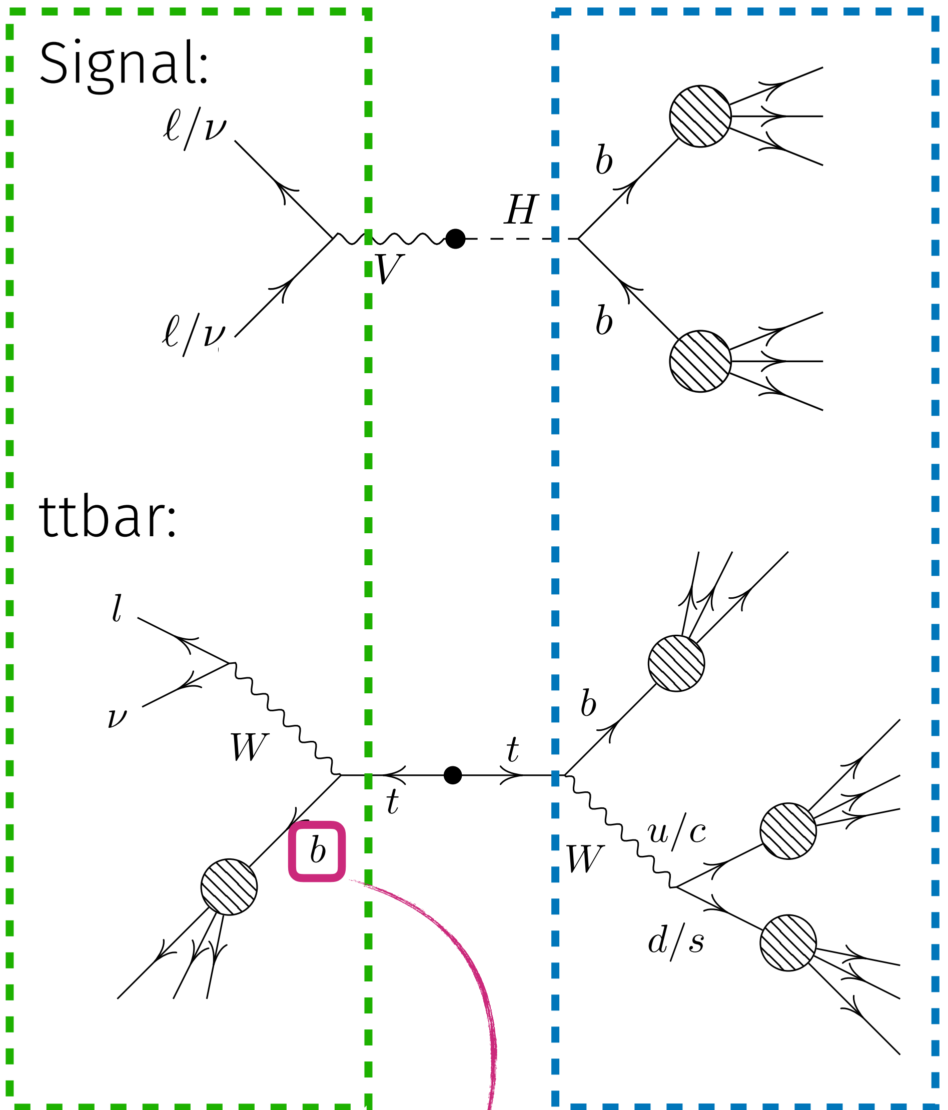




High purity (HP) and low purity (LP) SRs



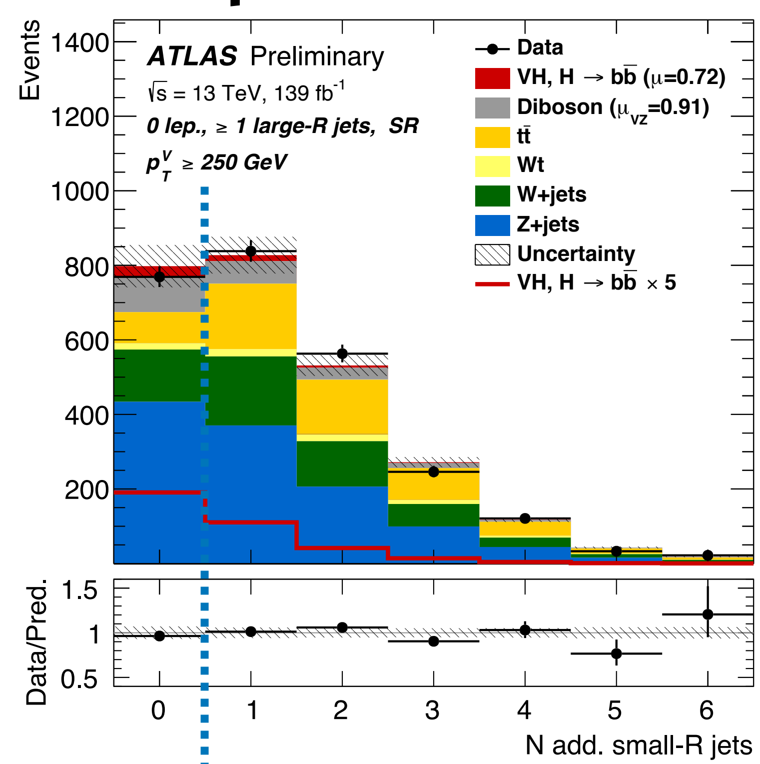
- In the 0-lepton and 1-lepton channels the signal region is further split into a high purity and low purity SR



un-identified b (and/or additional radiation)

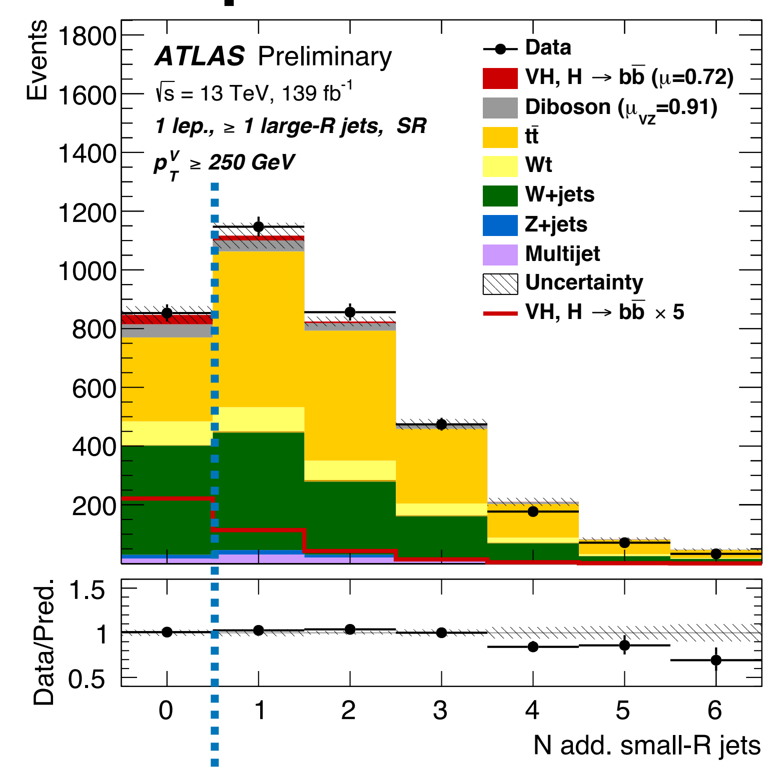
(different levels of containment)

0-lepton



HP SR ⟷ LP SR

1-lepton



HP SR ⟷ LP SR

Split according to small-R (calo) jet multiplicity:

- high: 0 small-R jets outside of the leading large-R jet
- low: ≧ 1 small-R jet outside of the leading large-R jet

To summarize: the analysis regions and the fit

- 10 signal regions
- 4 control regions

} 14 regions distributed over 3 lepton channels

Channel	Categories					
	$250 < p_T^V < 400$ GeV			$p_T^V > 400$ 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	≥ 1add. small-R jets		0 add. small-R jets	≥ 1add. small-R jets	
0-lepton	SR	SR	CR	SR	SR	CR
1-lepton	SR	SR	CR	SR	SR	CR
2-lepton	SR			SR		

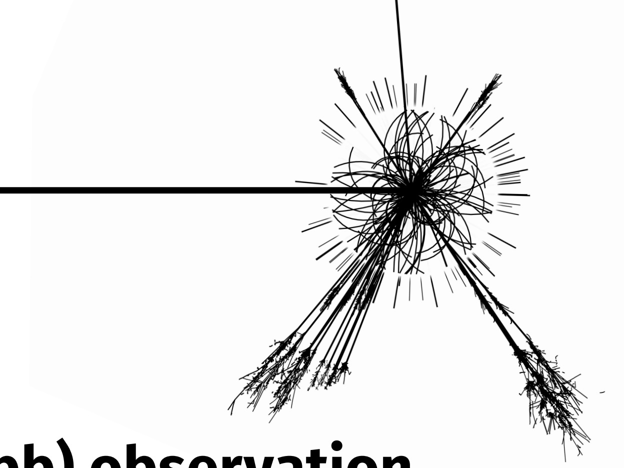
- Perform a **binned profile likelihood fit** in m_{comb} to the 14 regions to **extract the signal strengths** μ_{VH} **and** μ_{VZ} **simultaneously**

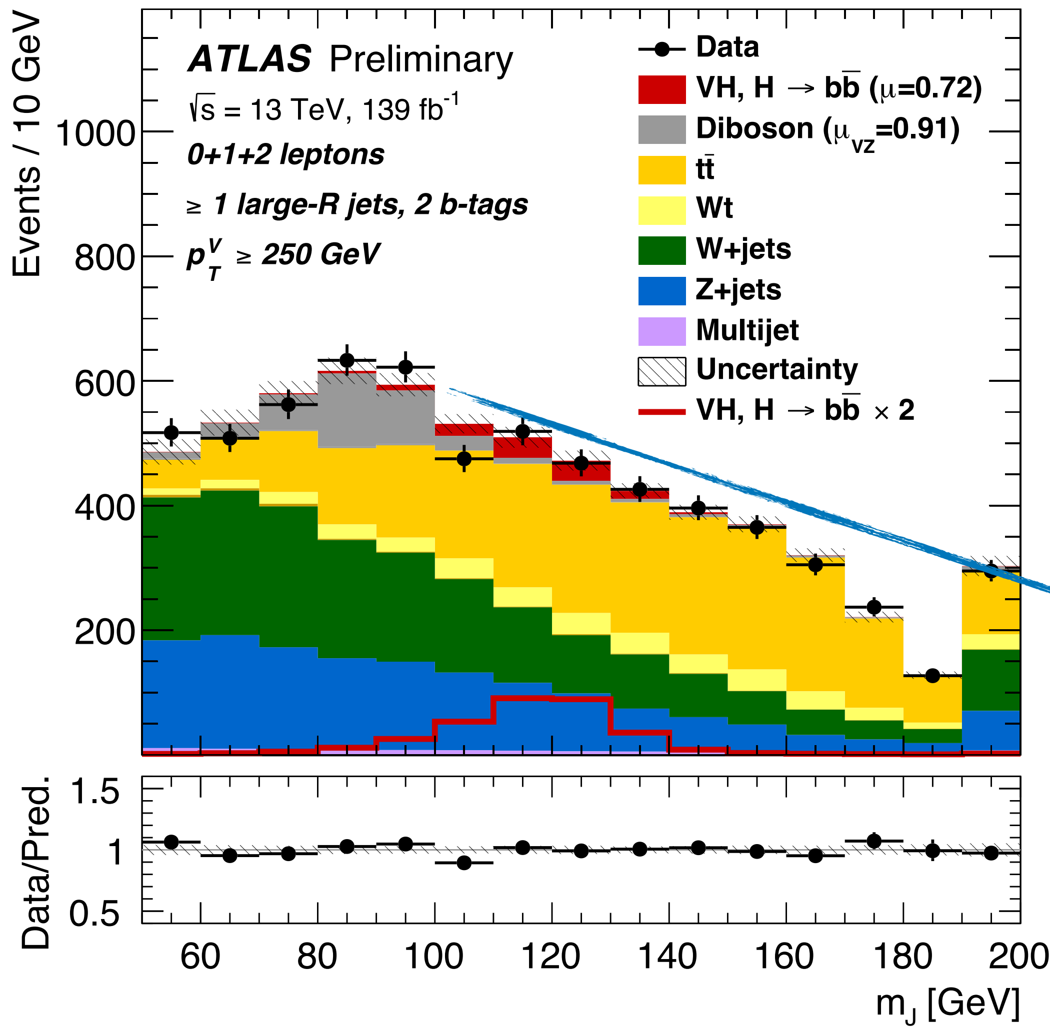
Fit setup and systematics:

- Normalizations of „V+heavy flavor“ and „ttbar" left unconstrained in the fit
- Systematic uncertainties included as nuisance parameters:
  - Experimental: **large-R jet JMS/JMR**, JES/JER; small-R jets, MET, leptons, b-tagging, …
  - Modelling: Acceptance, containment and flavor uncertainties, sub-dom. norms, …
  - MC statistics

Results

- VH signal: Observed (expected) significance: **Z = 2.1 (2.7) [σ]**
- VZ signal: Observed (expected) significance: **Z = 5.2 (5.7) [σ]** ⟵ **Boosted V(lep.)Z(bb) observation**





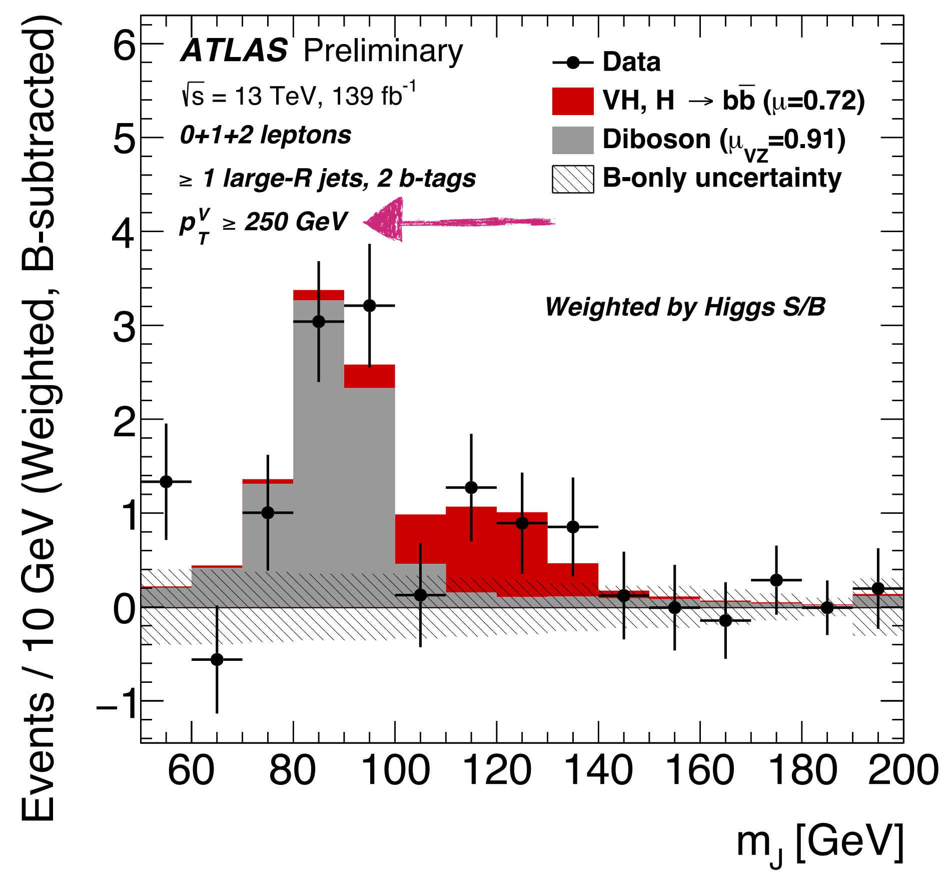
VH signal strength:

$$\mu_{VH}^{bb} = 0.72^{+0.39}_{-0.36} = 0.72^{+0.29}_{-0.28}(\text{stat.})^{+0.26}_{-0.22}(\text{syst.})$$

VZ signal strength:

$$\mu_{VZ}^{bb} = 0.91^{+0.29}_{-0.23} = 0.91 \pm 0.15(\text{stat.})^{+0.25}_{-0.17}(\text{syst.})$$

weighting regions by Higgs S/B before adding them; bkg subtracted



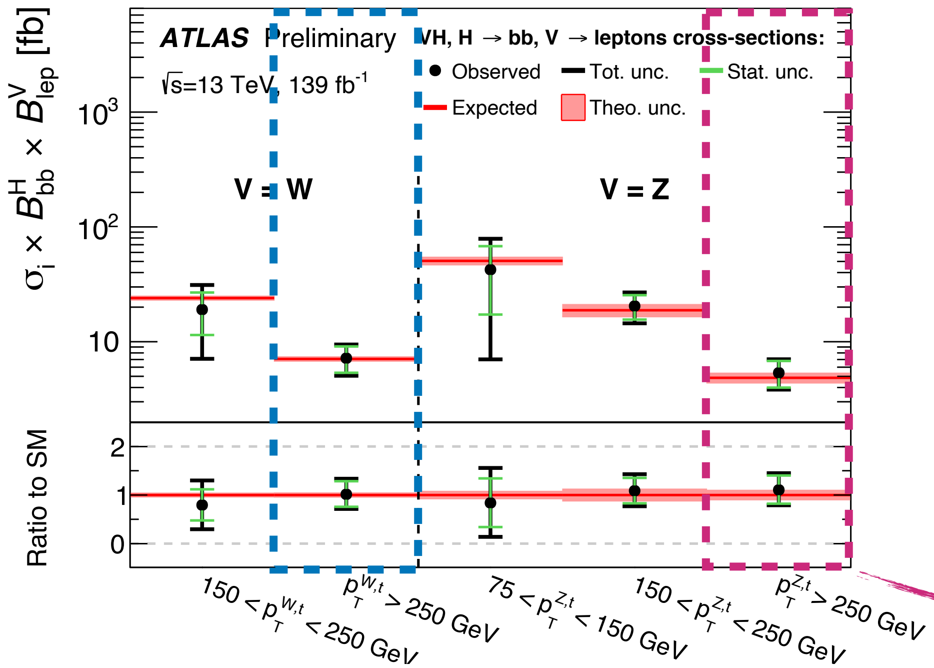
Challenges:

1. Data statistics
2. Large-R jet mass scale + resolution
3. Background modelling

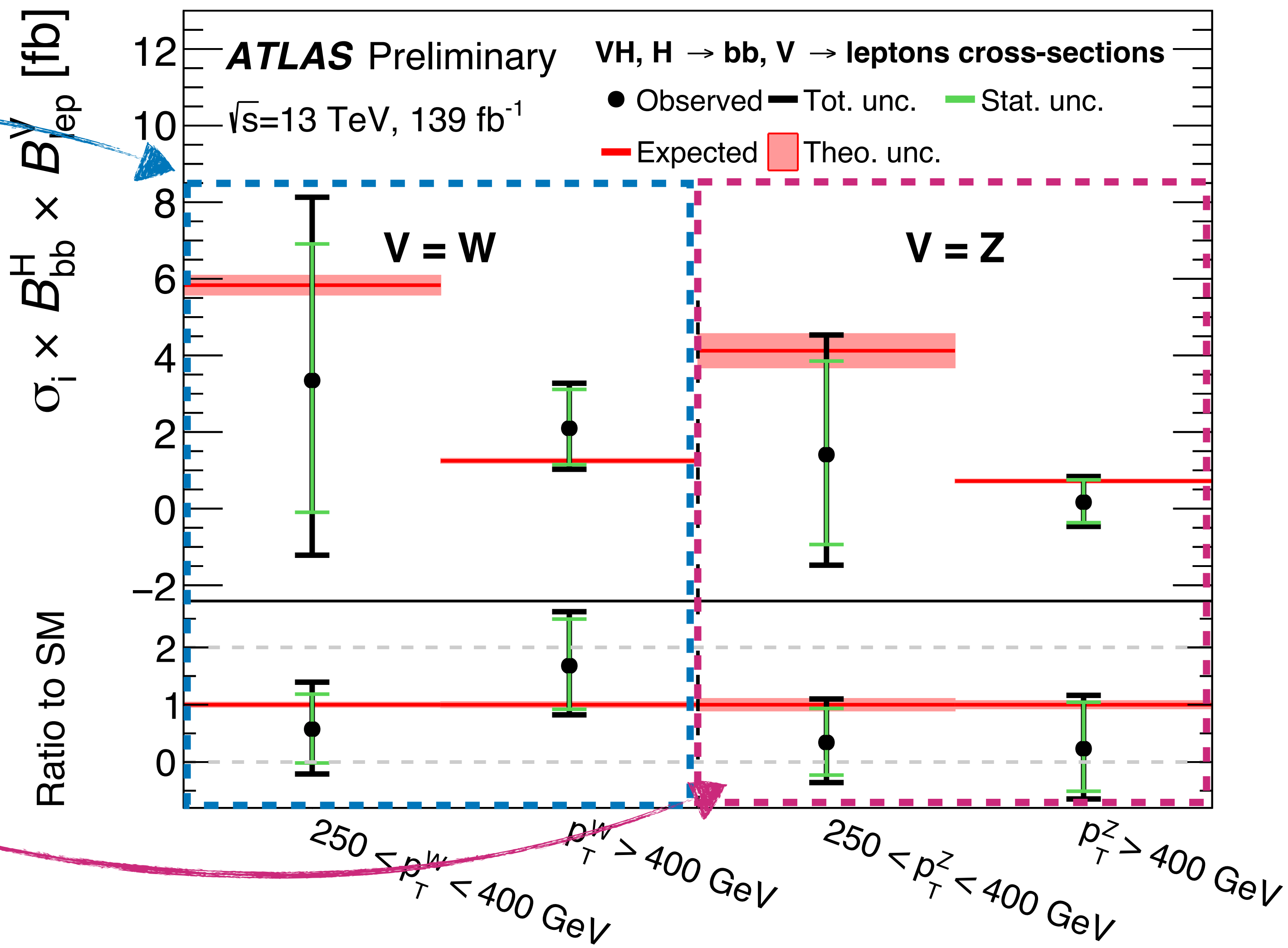
Increasing granularity in p_T^V ($\sim p_T^H$)

- First explicit measurement of Higgsstrahlung σ x BR for p_T^V (truth) > 400 GeV !

[ATLAS-CONF-2020-006]



„Low p_T" analysis



Boosted analysis

Interpreting the result using SMEFT

Taylor expansion in E/Λ:

more and more suppressed [Λ^4]

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \dots$$

Violate lepton #
Majorana masses
Large suppression
scale from ν oscillations

Violate lepton #
Some violate barion #

Wilson coefficients (free parameters)

$$\mathcal{L}_6 = \sum_i c_i \, \mathcal{O}_i^{(\mathrm{dim}=6)}$$

2499 operators and coeff.s

Warsaw basis

(flavor) symmetries

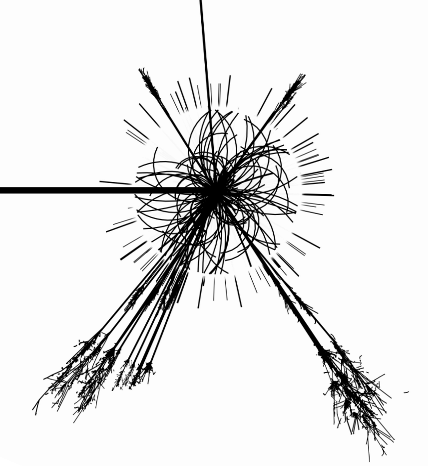
leading order only

13 operators affect VH prod.

a few more the decay

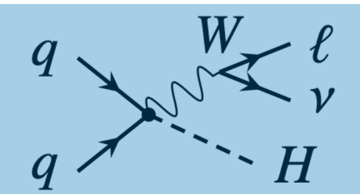
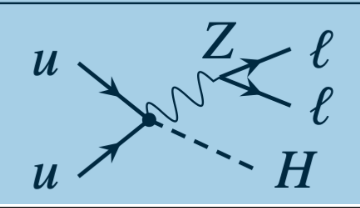
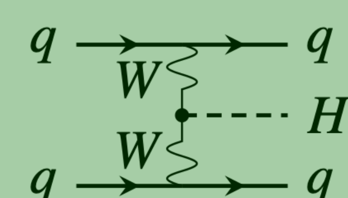
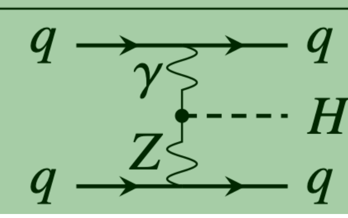
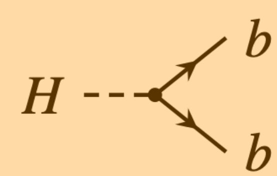
→ Cross-section parametrization → Limit extraction

How do the operators look like?



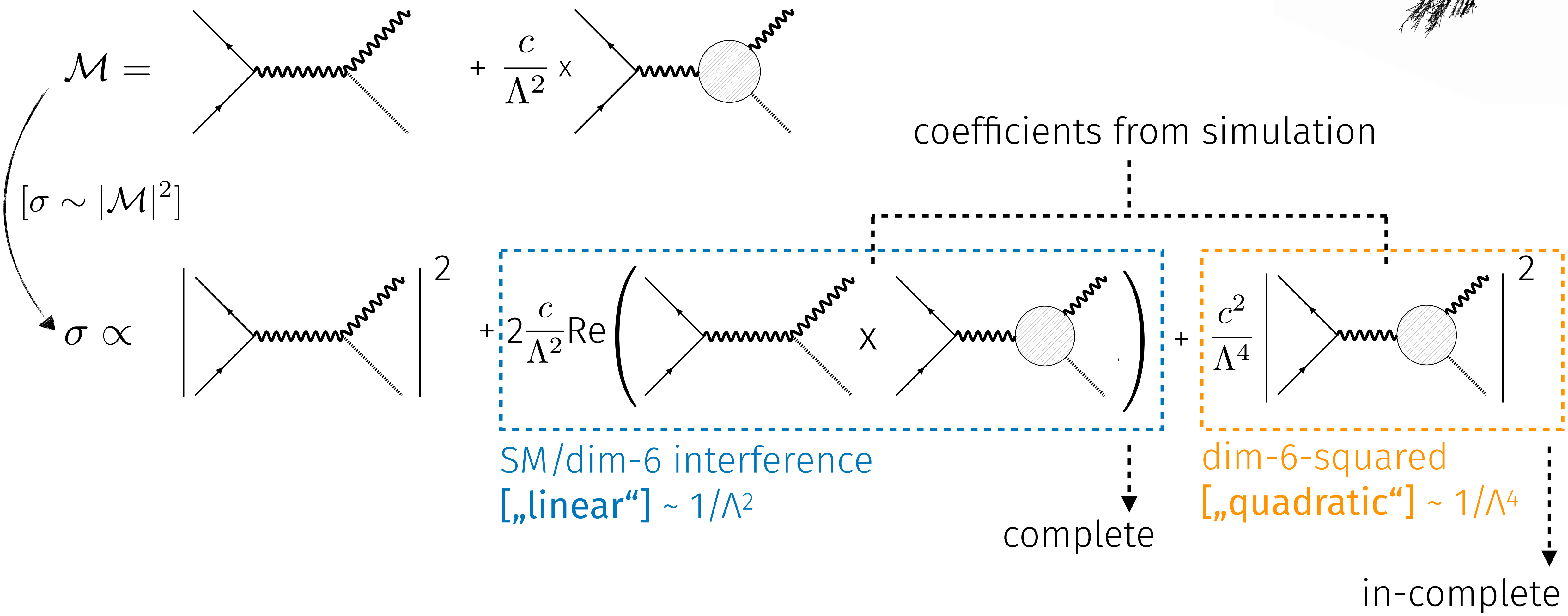
- Focus on **CP-even operators** as p_T^V shows no discrimination to CP-odd effects
- Looking closer at a selection of 5 operators:

Decreasing sensitivity ↓

c_{Hq3}	$(i\Phi^\dagger \overleftrightarrow{D}^I_\mu \Phi)(\bar{q}\sigma^I\gamma^\mu q)$		Four-point interactions qqZH qqWH	VH production
c_{Hu}	$(i\Phi^\dagger \overleftrightarrow{D}^I_\mu \Phi)(\bar{u}\gamma^\mu u)$			
c_{HW}	$\Phi^\dagger\Phi W^I_{\mu\nu}W^{I\mu\nu}$		Modifications to HWW HZZ	
c_{HWB}	$\Phi^\dagger\Phi W^I_{\mu\nu}B^{I\mu\nu}$			
$\lvert c_{dH}\rvert$	$(\Phi^\dagger\Phi)(\bar{q}d\Phi)$		Modifications to Hbb (specific to Hbb analyses)	H decay

[Table courtesy of Saskia Falke, here]

Parametrizing the signal cross-section

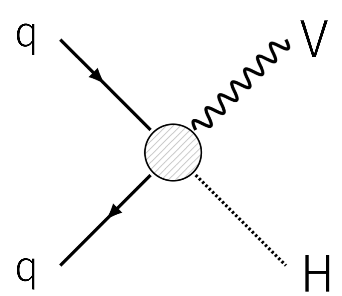


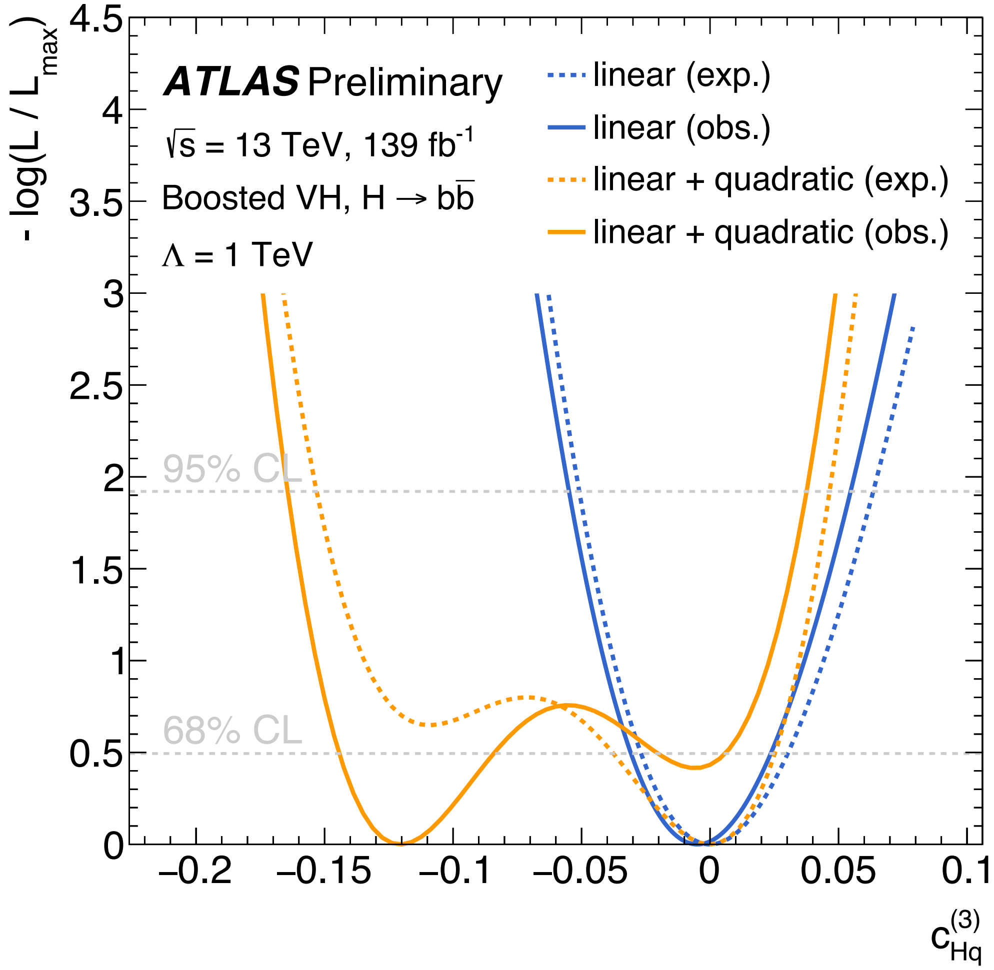
Re-parametrizing the Likelihood: $\mathcal{L}(\text{data}|\mu, \theta) \rightarrow \mathcal{L}(\text{data}|c_i, \theta)$

$$\left[\mu = \frac{\sigma_{VH} \times \text{BR}(H \rightarrow bb)}{[\sigma_{VH} \times \text{BR}(H \rightarrow bb)]_{\text{SM}}} = \frac{\sigma_{VH}}{\sigma_{VH}^{\text{SM}}} \times \frac{\frac{\Gamma(H \rightarrow bb)}{[\Gamma(H \rightarrow bb)]_{\text{SM}}}}{\frac{\Gamma(H)}{[\Gamma(H)]_{\text{SM}}}} \right]$$

Familiarizing with the results

- Fitting only 1 coefficient at a time (fixing all others to 0)





$$1 + \alpha_i \, c_i + \beta_{ij} \, c_i c_j$$

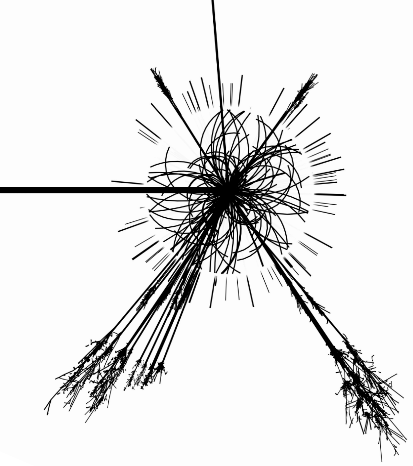
$$1 + A_i^{bb} \, c_i + B_{ij}^{bb} \, c_i c_j$$

$$\mu = \frac{\sigma_{VH} \times \mathrm{BR}(H \to bb)}{[\sigma_{VH} \times \mathrm{BR}(H \to bb)]_{\mathrm{SM}}} = \frac{\sigma_{VH}}{\sigma_{VH}^{\mathrm{SM}}} \times \frac{\frac{\Gamma(H \to bb)}{[\Gamma(H \to bb)]_{\mathrm{SM}}}}{\frac{\Gamma(H)}{[\Gamma(H)]_{\mathrm{SM}}}}$$

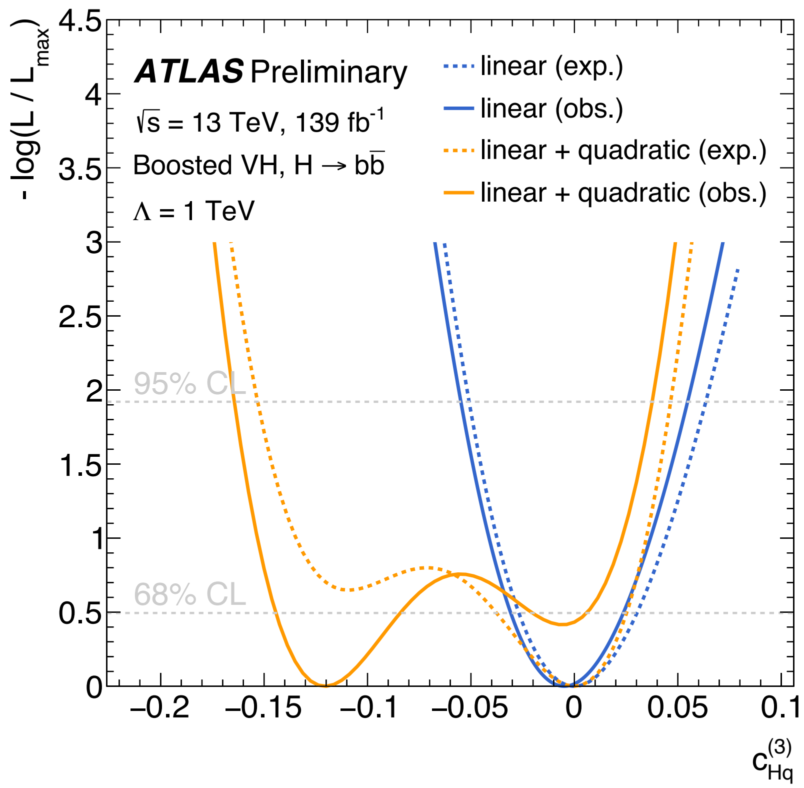
$$1 + A_i \, c_i + B_{ij} \, c_i c_j$$

Including quadratic terms significantly changes the limits

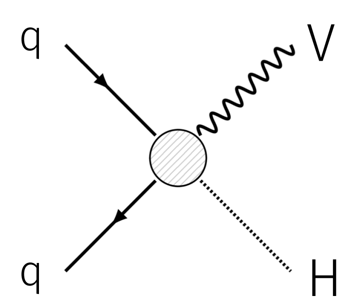
1D + 2D likelihood scans

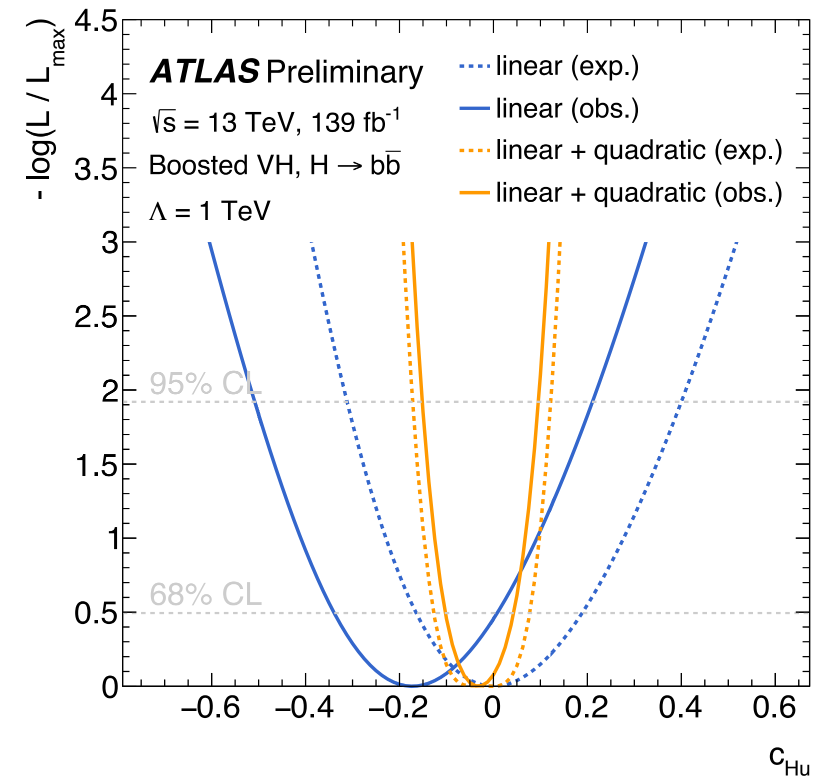


- Fitting only 1 or 2 coefficients at a time (fixing all others to 0)

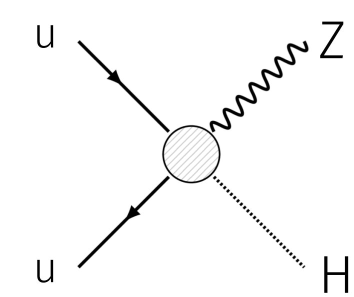


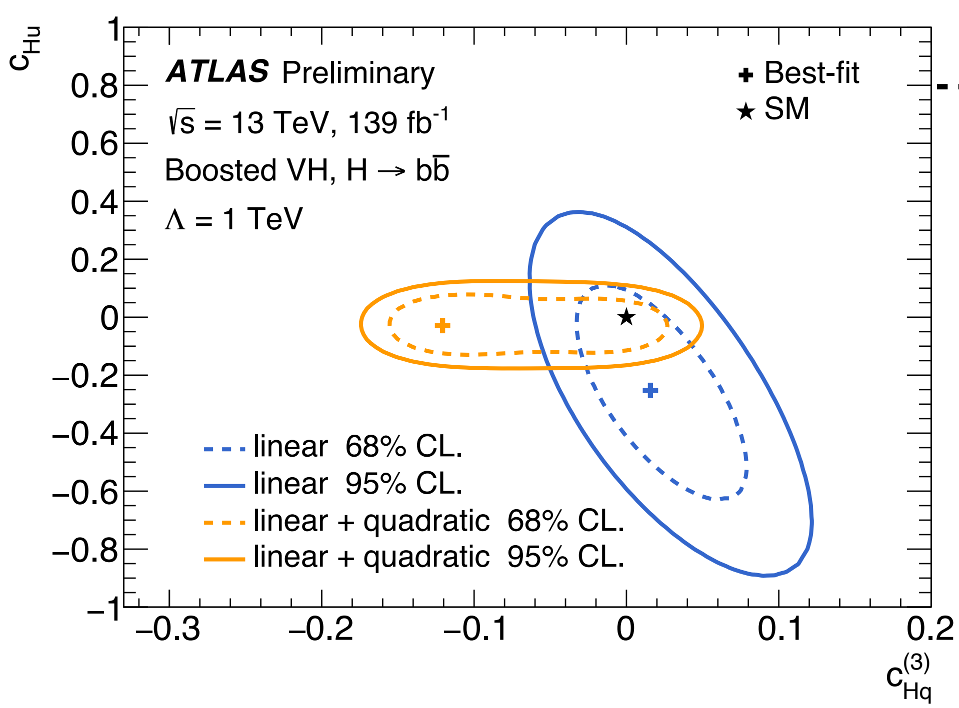
Lin. + quad. **weaker** constraint w.r.t. linear only



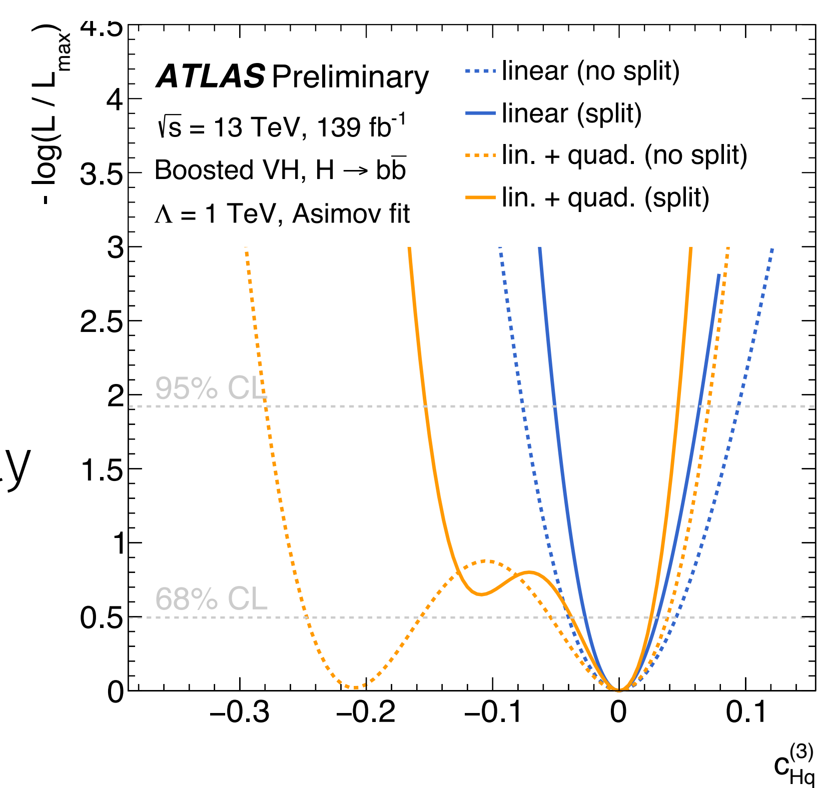


Lin. + quad. **stronger** constraint w.r.t. linear only





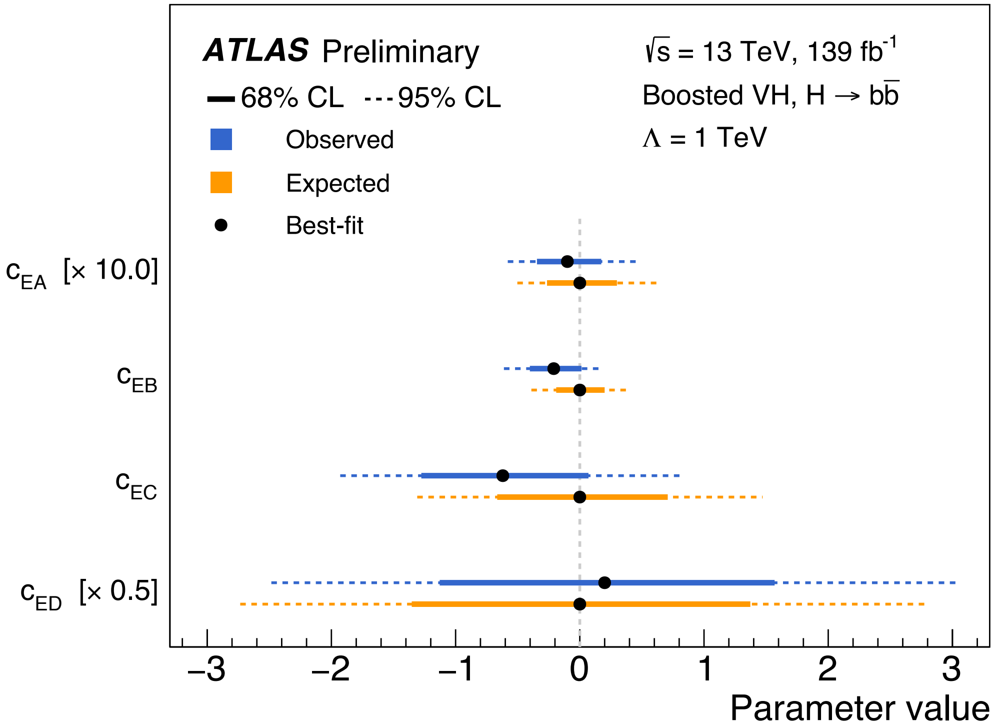
Lin. + quad. **different corr.** w.r.t. linear only



Additional split **improves** limits up to a **factor 2**

Eigenvectors

- Measuring 4 p_T^V bins ⟶ **impossible to constrain 13+ Wilson coefficients at the same time**
- Perform a Principal Component Analysis to find the most sensitive directions [removing decay degeneracy by parametrizing the BR as one coefficient]
- Using linear coefficients only



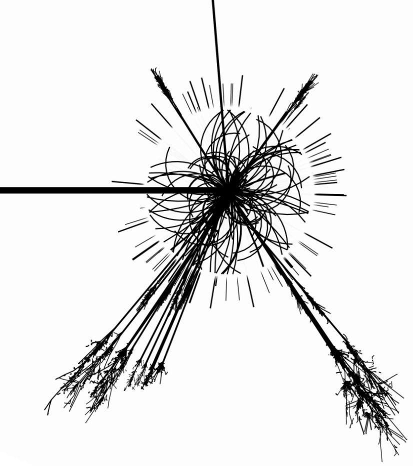
Coefficient	Eigenvalue	Eigenvector combination
c_{EA}	1500.0	$0.99 \cdot c_{Hq}^{(3)} + 0.11 \cdot c_{Hu}$
c_{EB}	26.9	$0.82 \cdot c_{Hu} + 0.49 \cdot c_{Hq}^{(1)} + 0.24 \cdot c_{Hd} - 0.13 \cdot c_{Hq}^{(3)}$
c_{EC}	2.2	$0.67 \cdot \mathcal{I}_{BR} + 0.66 \cdot c_{HW} + 0.18 \cdot c_{Hq}^{(1)} - 0.16 \cdot c_{Hl}^{(3)} + 0.14 \cdot c_{HWB} + 0.12 \cdot c_{ll}^{(1)}$
c_{ED}	0.1	$0.70 \cdot c_{Hq}^{(1)} + 0.52 \cdot c_{HWB} + 0.27 \cdot c_{Hu} - 0.27 \cdot c_{HW} - 0.24 \cdot c_{Hd} + 0.13 \cdot c_{HB}$

[coefficients less than 0.1 removed]

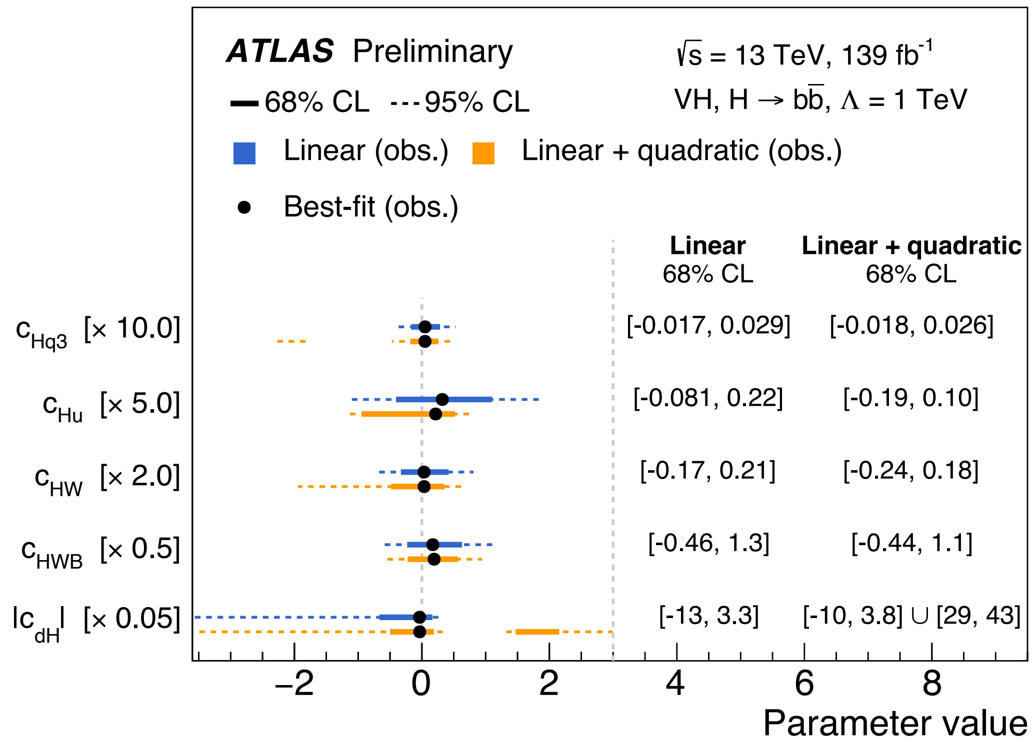
Mostly sensitive to p_T dependent effects

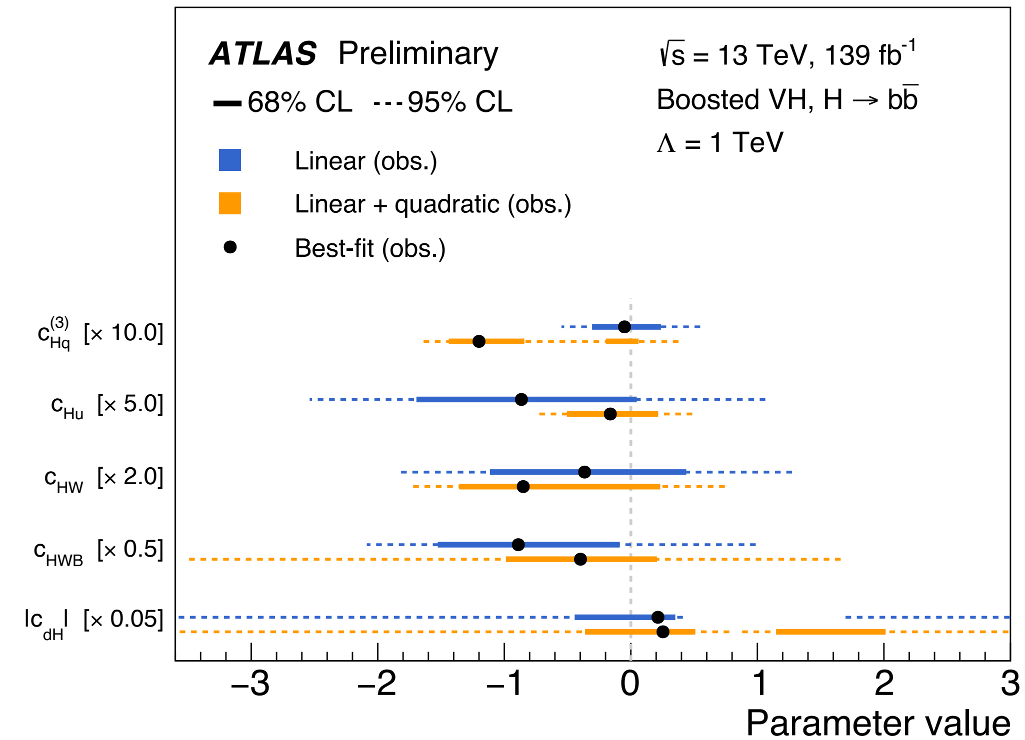
New basis that is orthogonal on data and therefore can be fit simultaneously

Putting it in perspective



„Low p_T“ VH(bb)	Boosted VH(bb)
$\sigma_\mu = 0.17$	$\sigma_\mu = 0.38$





Boosted analysis is competitive with much less statistics ⟶ **high p_T is key**

Going as differential as possible is the future

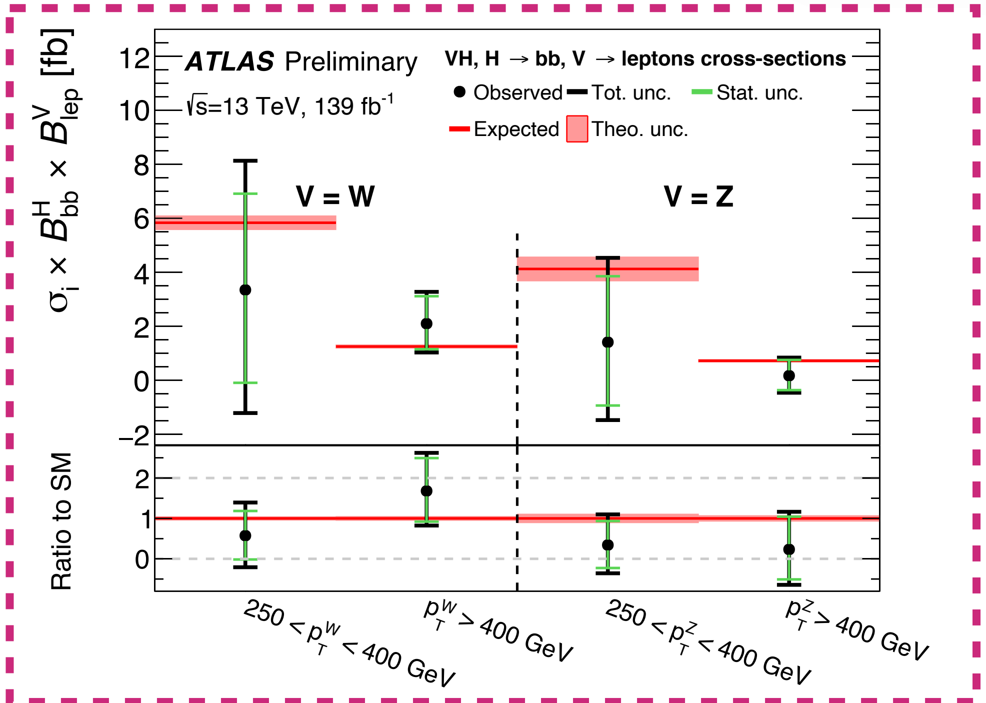
- Higher luminosity and large branching fraction ⟶ we can go to the extremes
- Shapes are not affected by unbeatable systematics such as luminosity determination

Conclusion

- Measurement of high-energetic VH production using **boosted jet techniques**

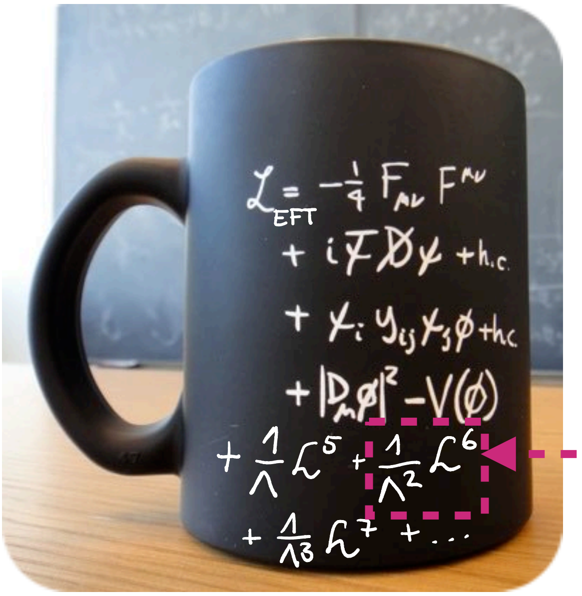
  We're pushing the boundaries towards ultra high Higgs p_T!
  ⟶ First direct measurement for p_T^V > 400 GeV
  ⟶ Boosted V(lep.)Z(bb) observation

  Boosted is **the** path to exploit the full energy reach of the LHC in a data rich future



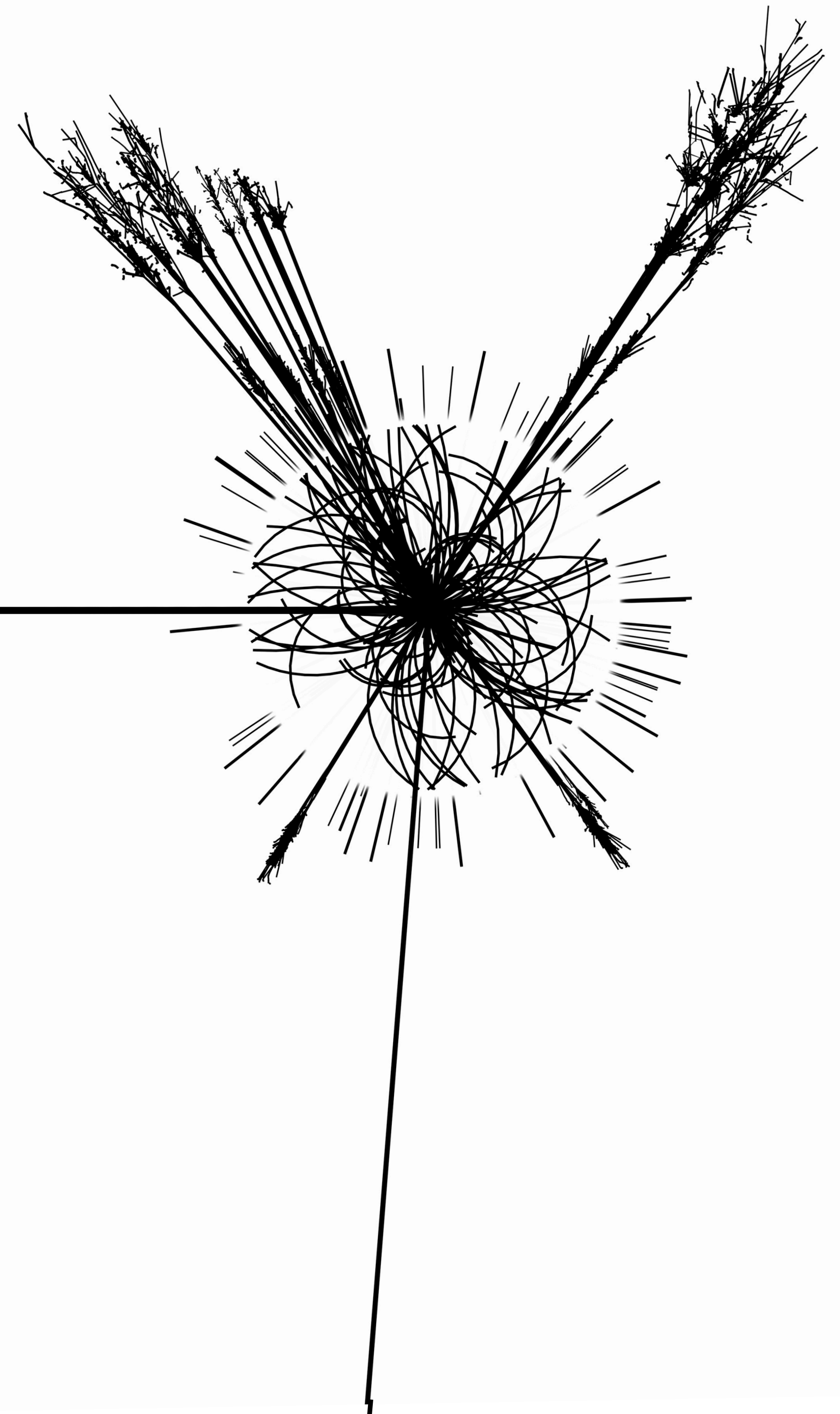
- Interpretation of the results using the SMEFT framework

  Going differential at high p_T^V increases the limits greatly



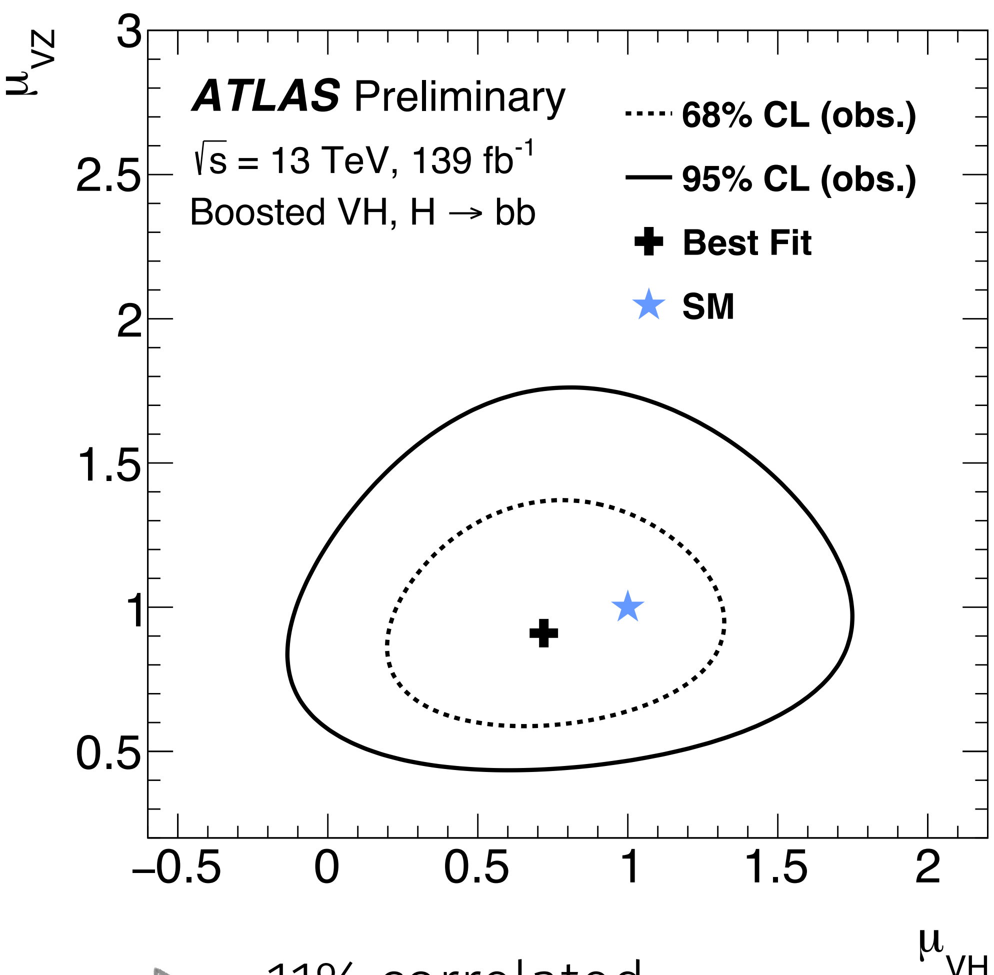
Let's discuss!

Backup.

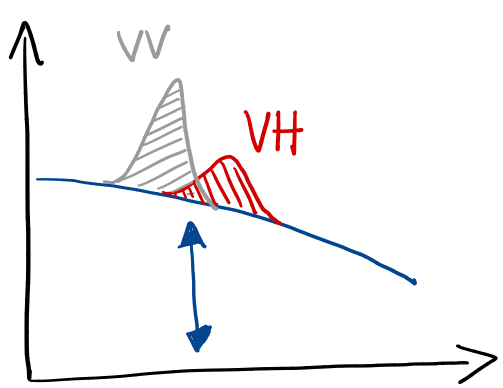


Small correlations and where to find them

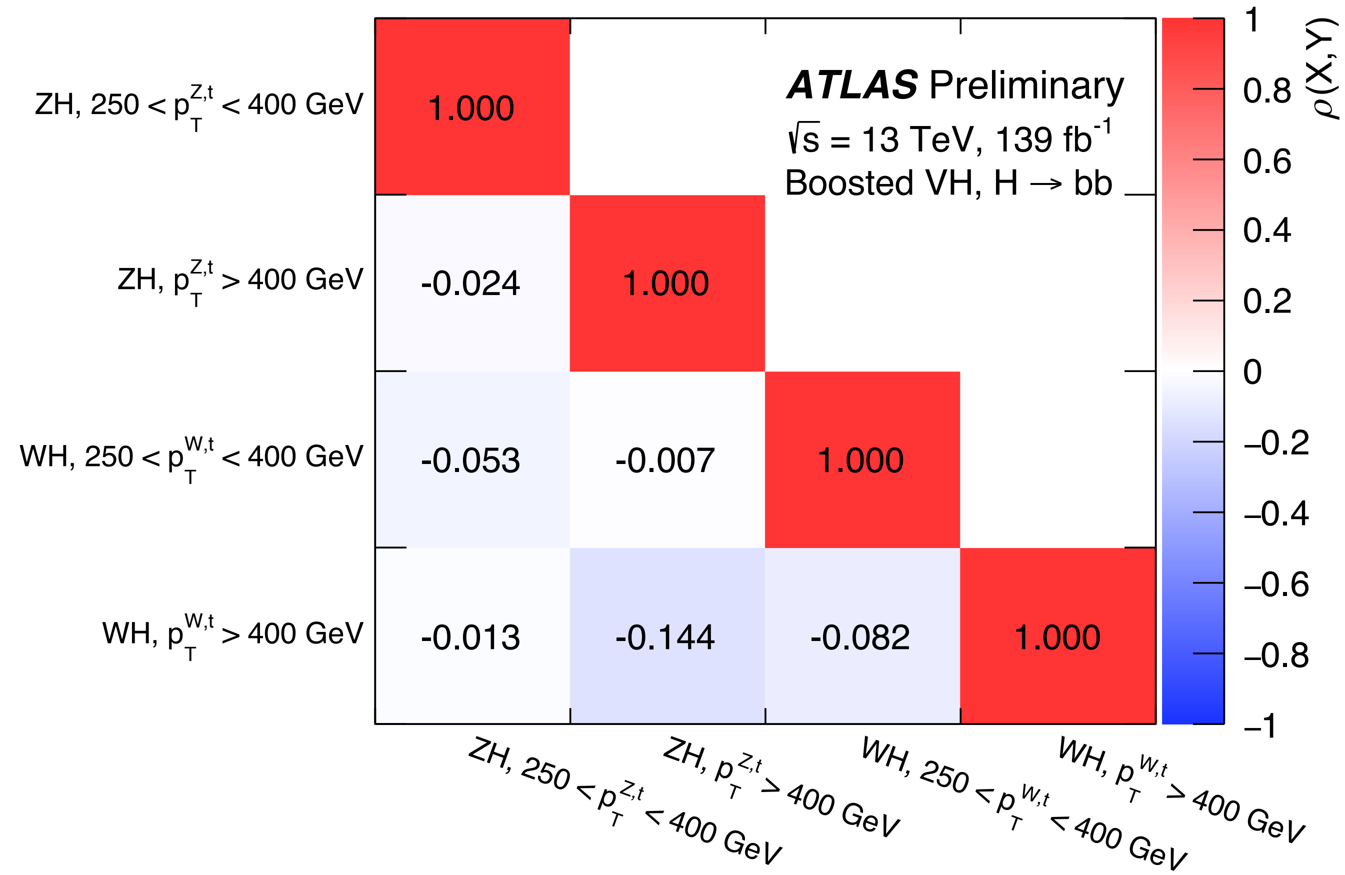
Higgs-Diboson correlation



- ~ 11% correlated

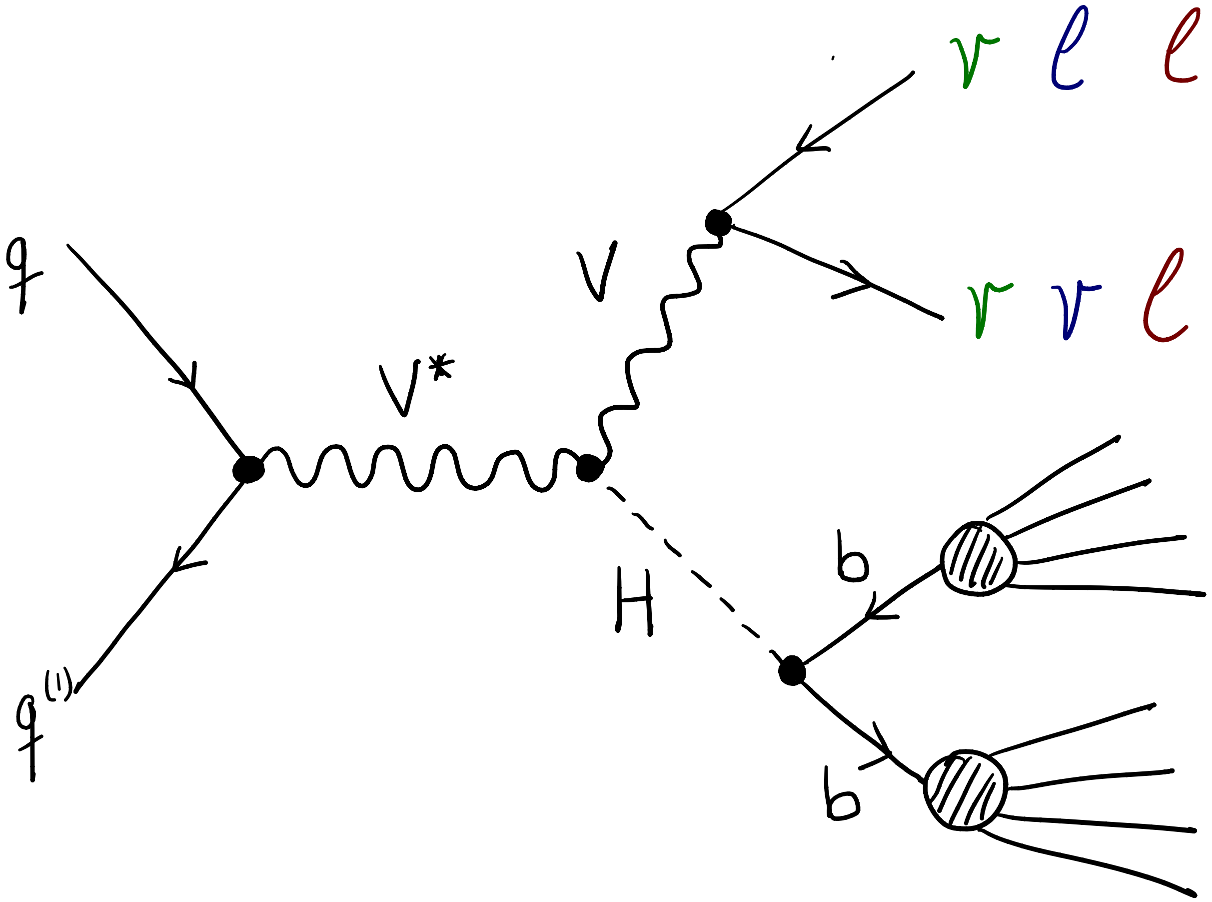


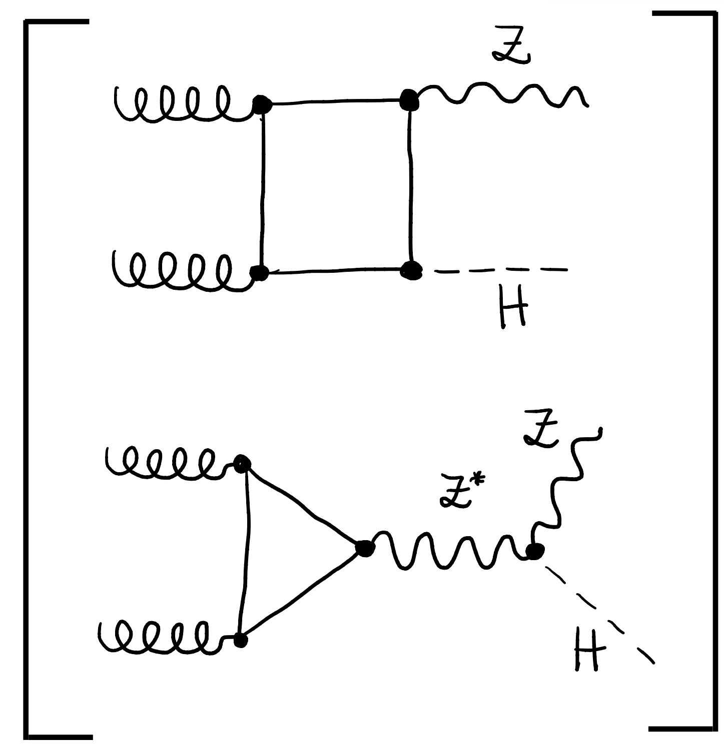
WH-ZH correlation



- Roughly diagonal
- WH contamination in 0-lepton channel from W→ τν (had. τ) decays

What are we looking for?





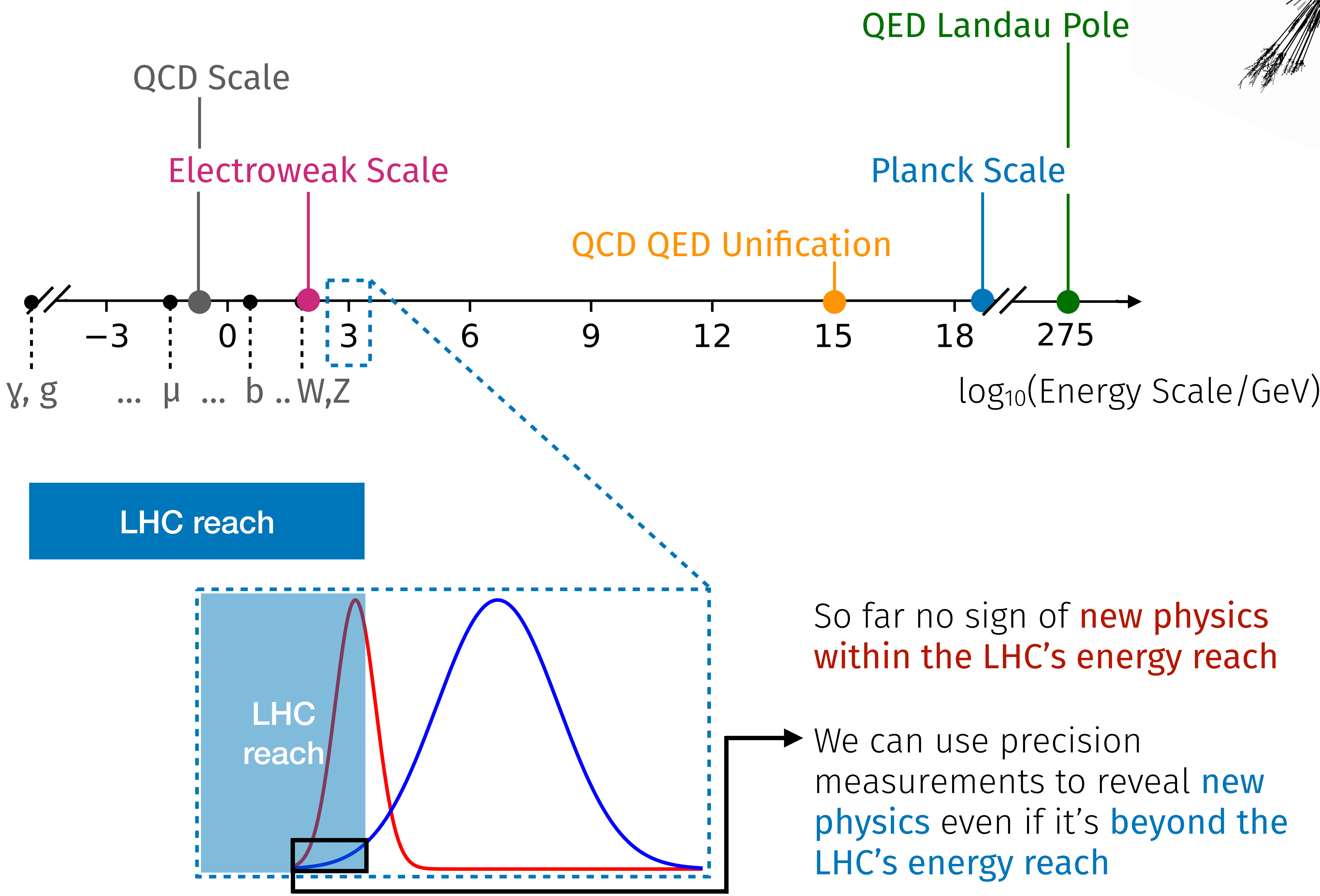
H → bb decay:

- 2 jets, both containing B-hadrons

Leptonic V decays:

- Z → νν: missing transverse momentum [0-lepton]
- W → ℓν: {e, μ} and missing transverse momentum [1-lepton]
- Z → ℓℓ: ee or μμ [2-lepton]

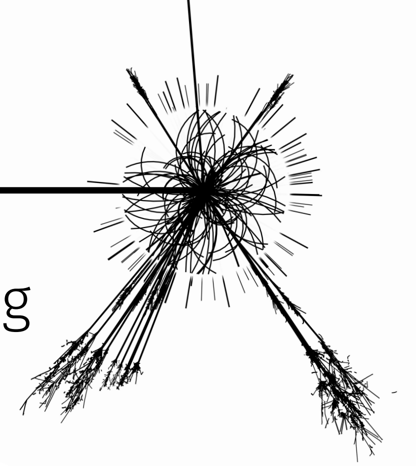
Where does the mug burst?



So far no sign of **new physics within the LHC's energy reach**

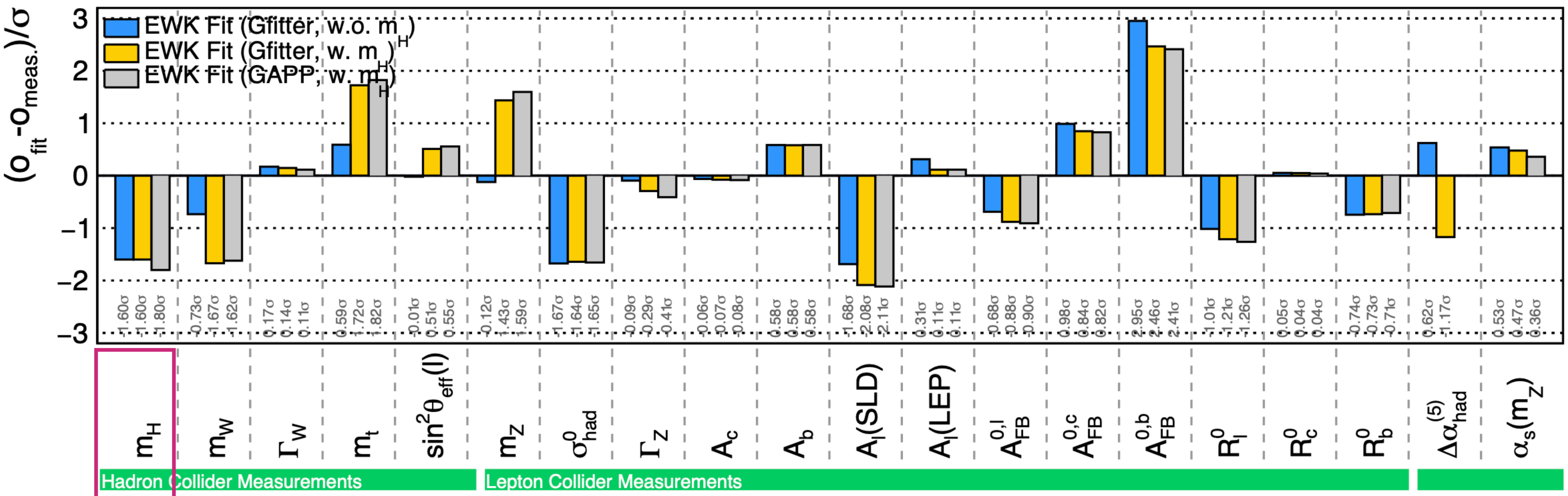
We can use precision measurements to reveal **new physics** even if it's **beyond the LHC's energy reach**

Where to look for new physics (at colliders)?



- Testing the self-consistency of the Standard Model yields some tensions but nothing above the statistical significant threshold

[arXiv:1902.05142]

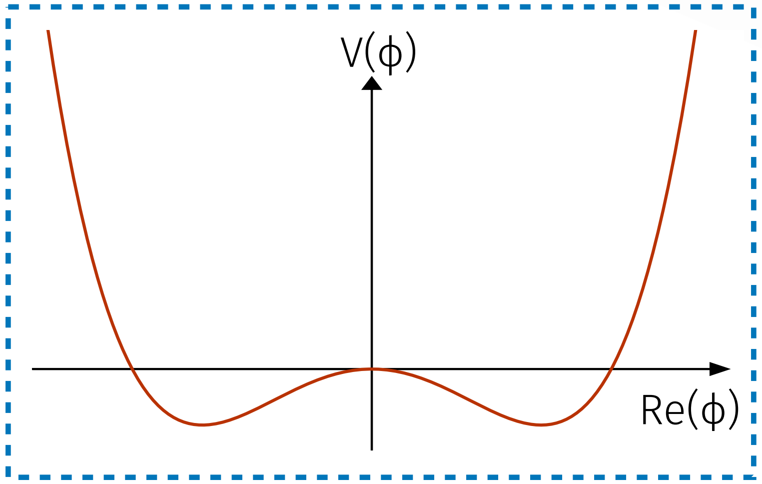


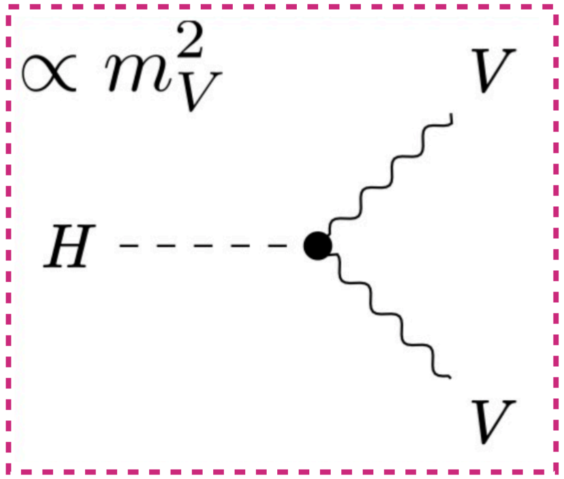
Pragmatic approach:

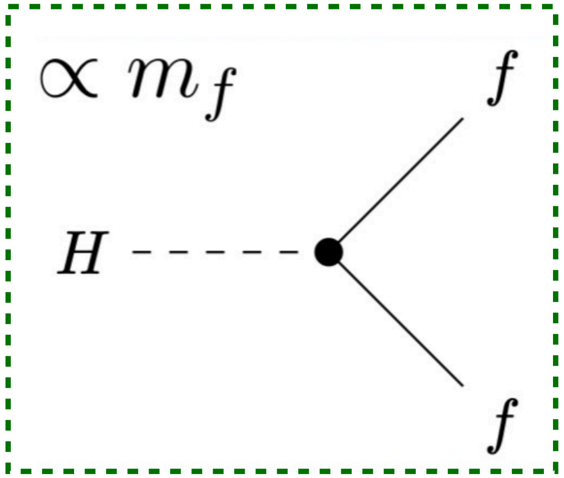
- This is the newest part of the SM, we have direct evidence of it since 2012
- What do we really know about it?
- Is there room for BSM physics?

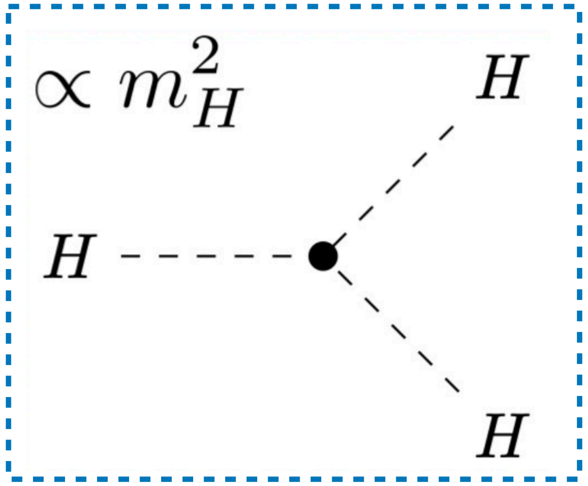
Deciphering the Higgs sector

$$\mathcal{L}_{\mathrm{SM}} = -\frac{1}{4}F^a_{\mu\nu}F_a^{\mu\nu} + i\bar{\psi}\not{D}\psi + |D_\mu\phi|^2 - \mu^2(\phi^\dagger\phi) - \lambda(\phi^\dagger\phi)^2 + y_{ij}\psi_i\phi\psi_j + \mathrm{h.c.}$$

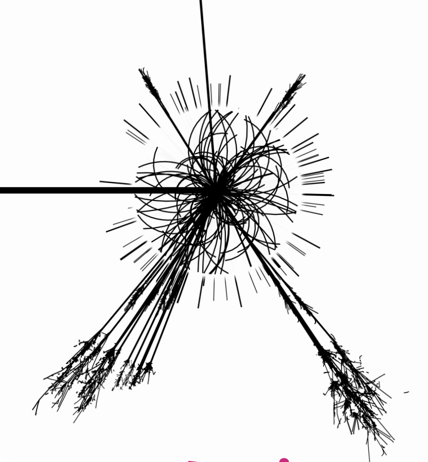








Deciphering the Higgs sector

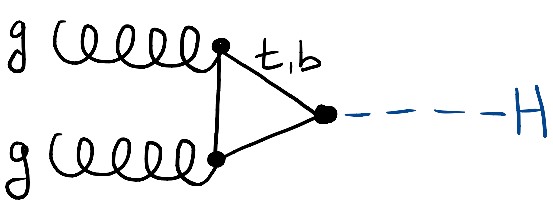


- Using the allowed couplings, the main production modes and decay channels are:

[arXiv:1610.07922]

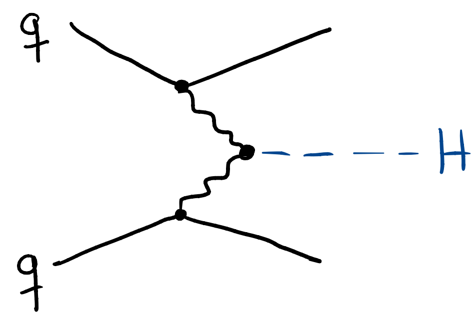
production

gluon-gluon fusion [ggF]



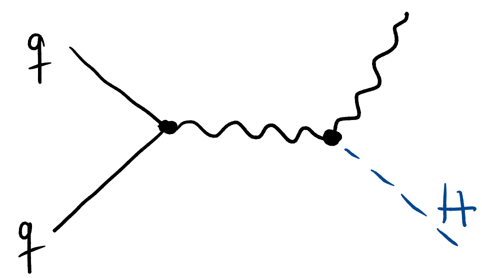
48.7 pb

vector-boson fusion [VBF]



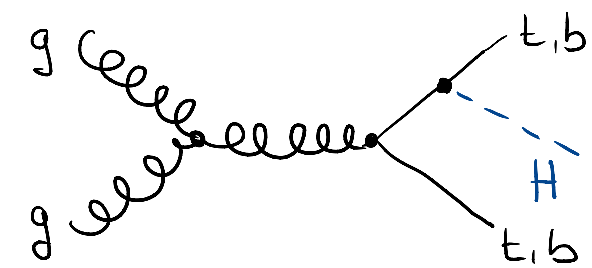
3.77 pb

Higgs-Strahlung [VH]



2.25 pb

t-/b-assoc. prod. [ttH/bbH]



0.51 pb (each)

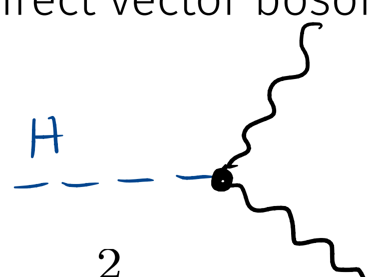
inclusive cross-section

Run 2 yield: **6.7 million** | **520 000** | **310 000** | **71 000 (each)**

✘ [narrow width]

decay

direct vector boson

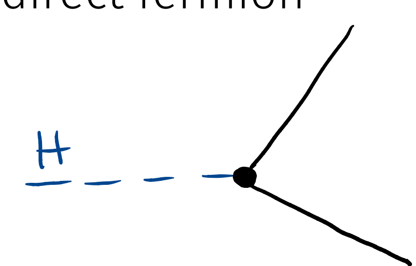


WW*

ZZ*

$\propto m_V^2$

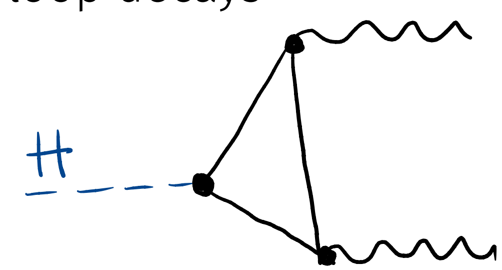
direct fermion



$\propto m_f$

u	c	
d	s	b
e	μ	τ

loop decays

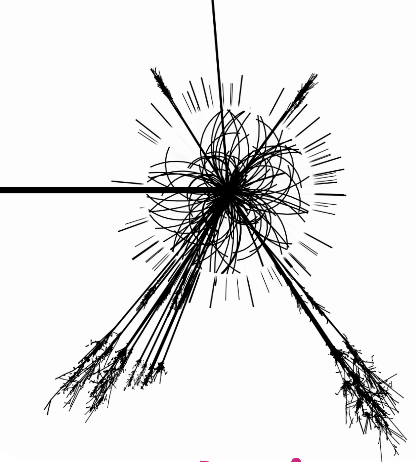


γγ

gg

Zγ

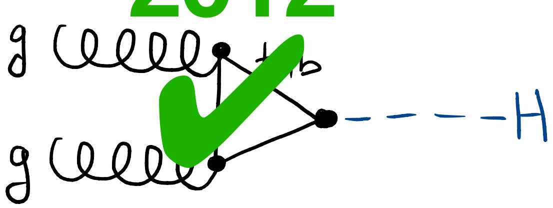
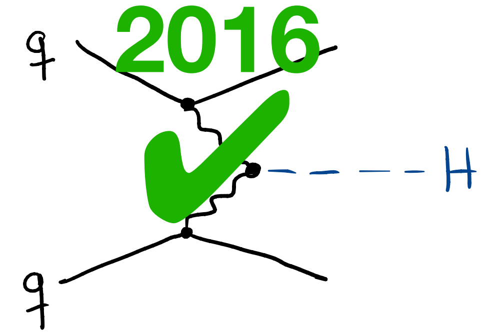
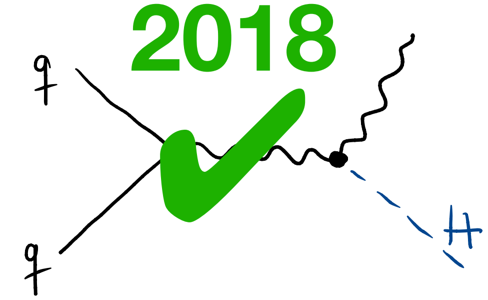
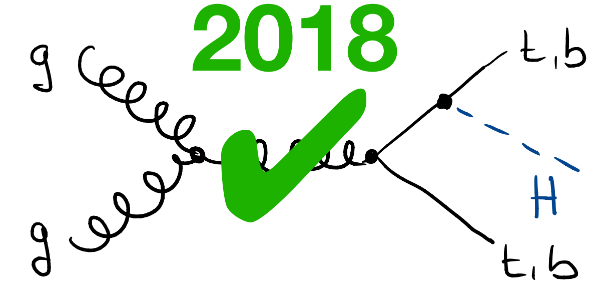
Deciphering the Higgs sector



- Using the allowed couplings, the main production modes and decay channels are:

[arXiv:1610.07922]

production

gluon-gluon fusion [ggF]	vector-boson fusion [VBF]	Higgs-Strahlung [VH]	t-/b-assoc. prod. [ttH/bbH]
2012 ✔	**2016** ✔	**2018** ✔	**2018** ✔
			
48.7 pb	3.77 pb	2.25 pb	0.51 pb (each)

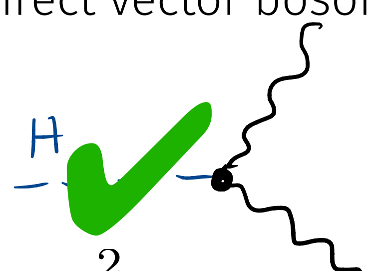
◀ inclusive cross-section

Run 2 yield:	**6.7 million**	**520 000**	**310 000**	**71 000 (each)**

✘ [narrow width]

decay

direct vector boson

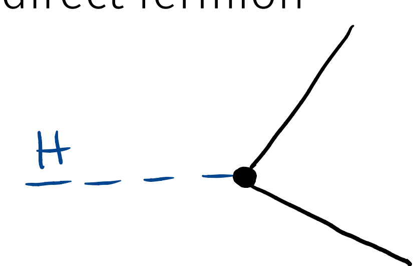


2014 ✔ WW^*

2014 ✔ ZZ*

$\propto m_V^2$

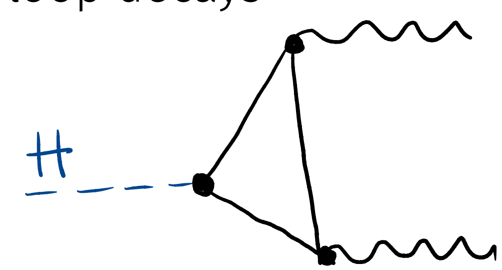
direct fermion



$\propto m_f$

u	c	
d	s	b ✔ **2018**
e	μ	τ ✔ **2016**

loop decays



2014 γγ ✔

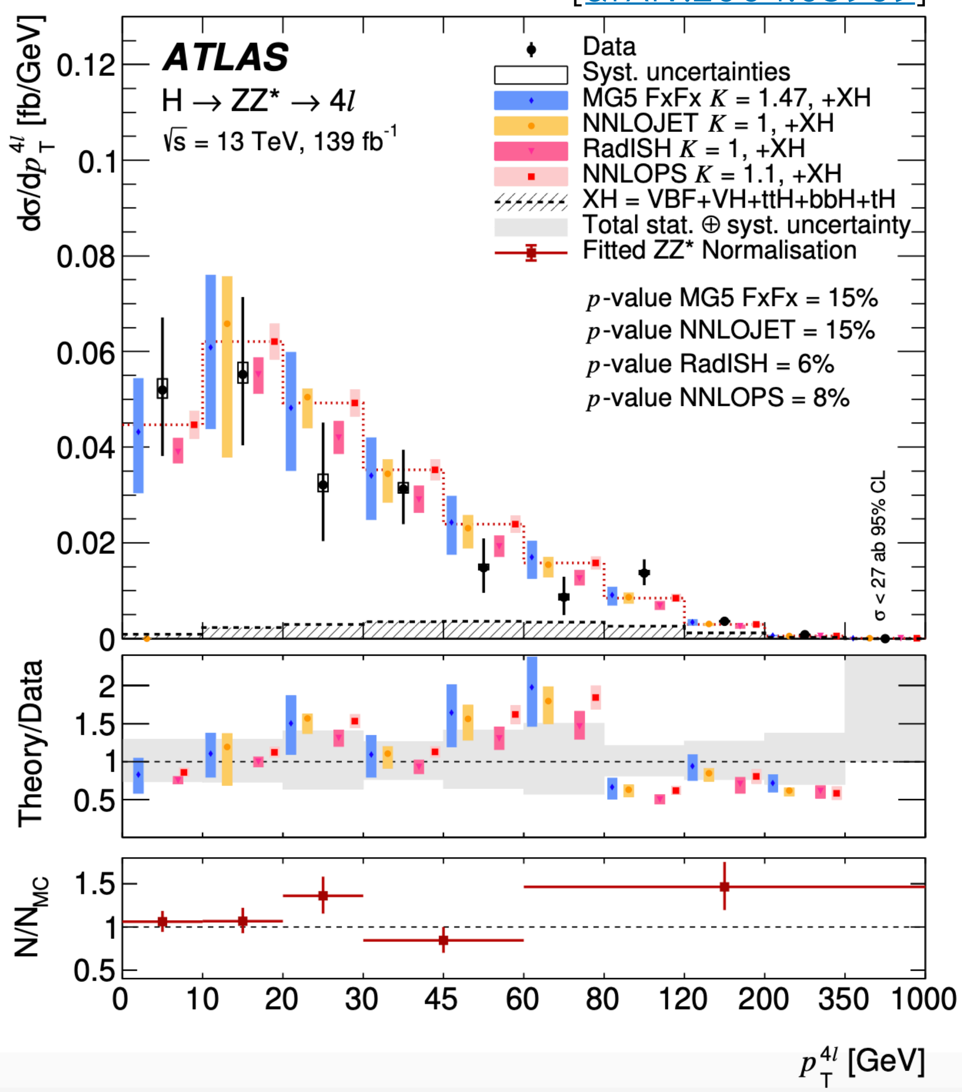
gg

Zγ

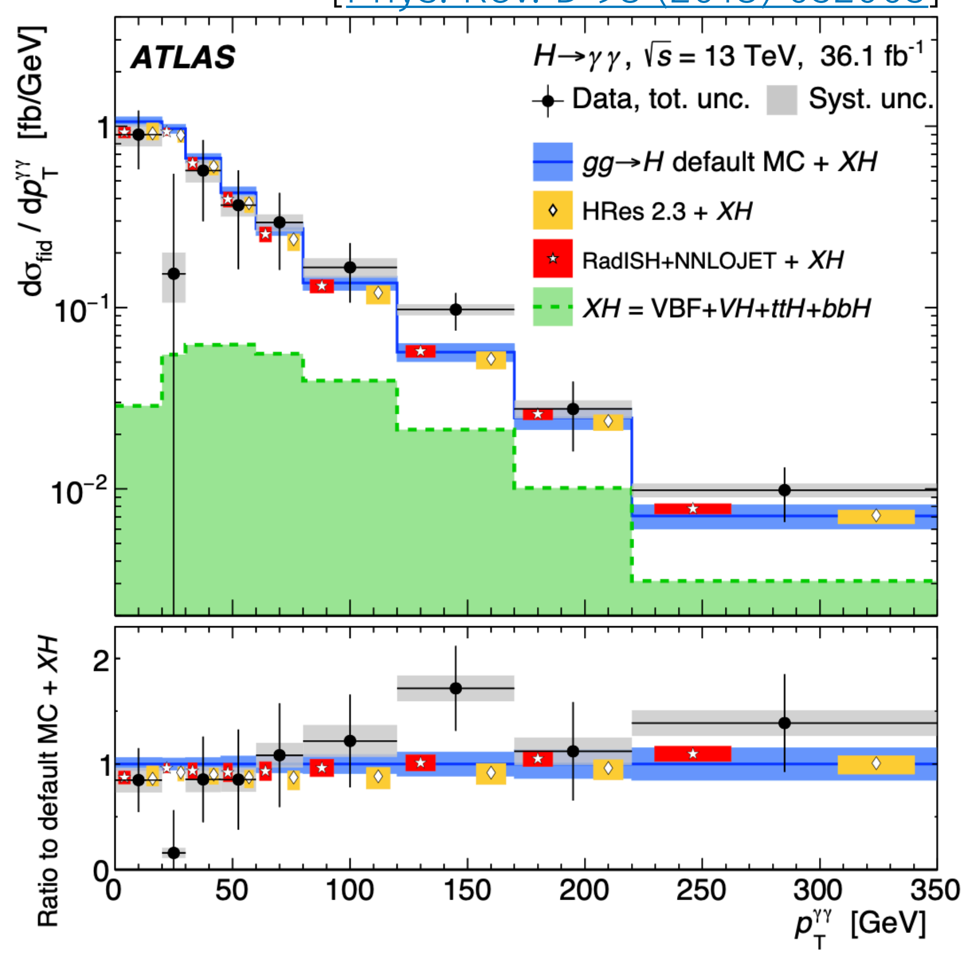
What do we know beyond signal strengths?

- Slowly going beyond inclusive quantities …

[arXiv:2004.03969]



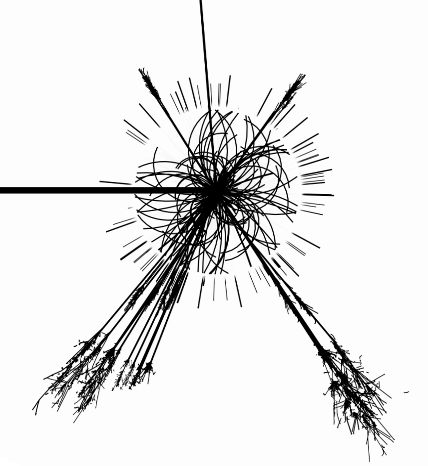
[Phys. Rev. D 98 (2018) 052005]

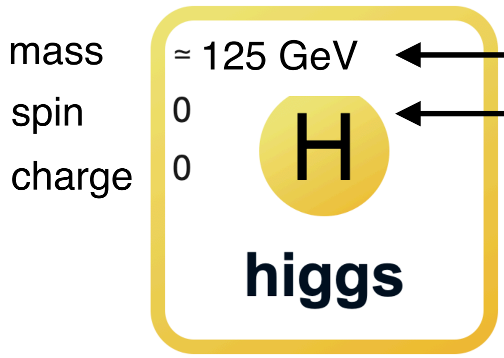


„Higgs boson“ transverse momentum

… but quite limited in energy reach with the golden channels

Puzzles in the Higgs sector





The (bare) Higgs mass is sensitive to higher mass scales

The Higgs boson is the only fundamental scalar particle

$+|D_\mu\phi|^2$ Are the structure/values of the couplings with the vector bosons as predicted by the SM? ⟶ Within ~ 10% precision, yes

$+y_{ij}\psi_i\phi\psi_j + \text{h.c.}$ Are the structure/values of the couplings with the fermions as predicted by the SM? ⟶ Within ~ 20% precision, yes for b and t

Does the Higgs boson also couple to second/first generation fermions?

$-\mu^2(\phi^\dagger\phi) - \lambda(\phi^\dagger\phi)^2$ Is there a deeper reason for the shape of the Higgs potential?

What is the exact shape?

How stable is the electroweak vacuum?

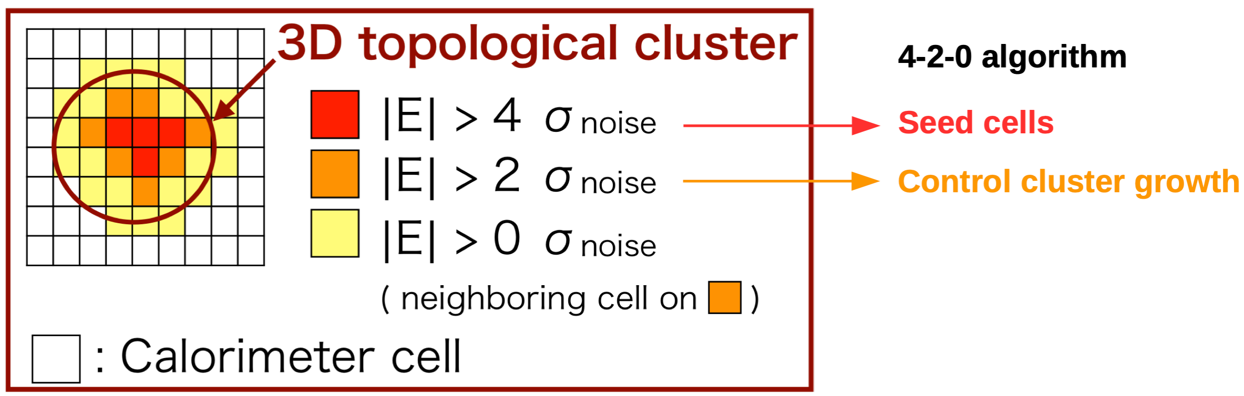
Is there only one Higgs boson?

\+ ...

Boosted VHbb from bottom-up: Large-R jets (1)

Jet Inputs → Clustering → Grooming → Calibration

1. Use 3-dim. topological calorimeter clusters as inputs using Local Cell Weighting



[CERN-PH-EP-2015-304]

use the cluster's properties to assign a probability to be originated from an EM or HAD interaction

apply a weight to each cell

$$E_{\text{clus}}^{\text{LCW}} = \sum_{i \in \text{cluster}} w_{\text{cell},i}^{\text{LCW}} \; E_{\text{cell},i}^{\text{EM}}$$

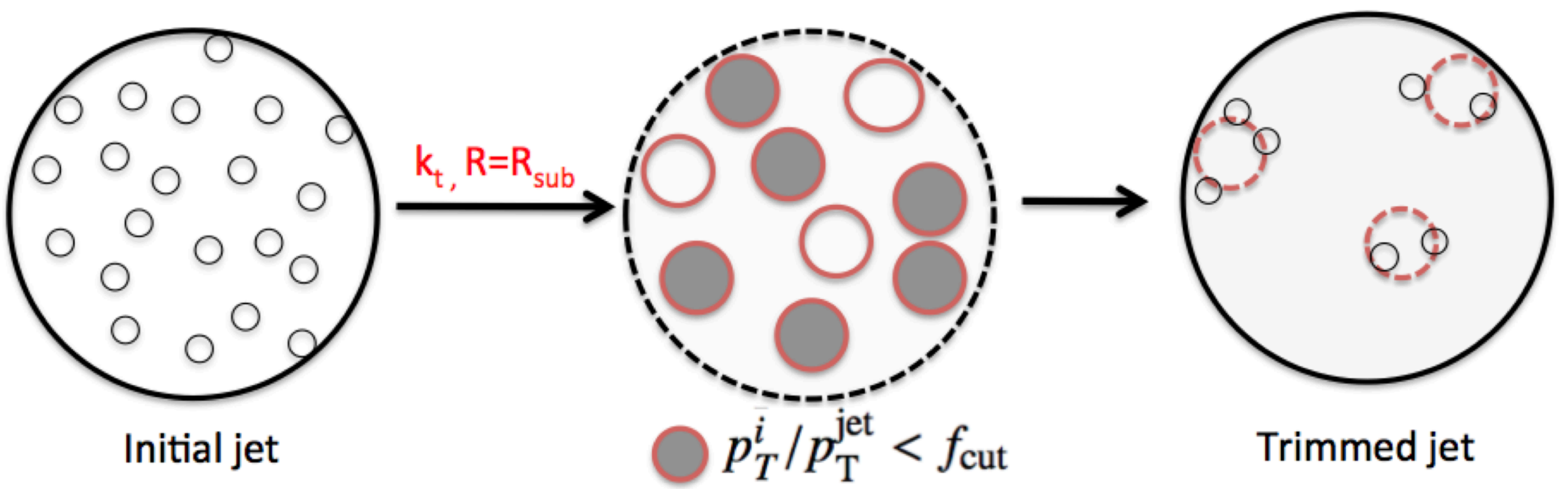
apply pile-up suppression

2. Cluster using anti-kt with R=1.0

Boosted VHbb from bottom-up: Large-R jets (2)

Jet Inputs → Clustering → **Grooming** → Calibration

Trimming used as grooming procedure: [CERN-PH-EP-2013-069]



- Contamination from pile-up, initial state radiation, multiple parton interactions often much softer than outgoing patrons and their FSR

1. Create k_t sub-jets of size R = 0.2 from the large-R jet constituents
2. Remove them if their p_T fraction is less than 5% of the large-R jet

Boosted VHbb from bottom-up: Large-R jets (3)

Jet Inputs → Clustering → Grooming → Calibration

Jet Inputs	Clustering	Grooming
LCTopo	anti-kt R = 1.0	trimmed R_{sub} = 0.2 f = 5%

Optimized for performance on boosted W bosons in Run 1
[e.g. to minimize the QCD-jet rejection and pile-up dependence of <m_{Jet}>]

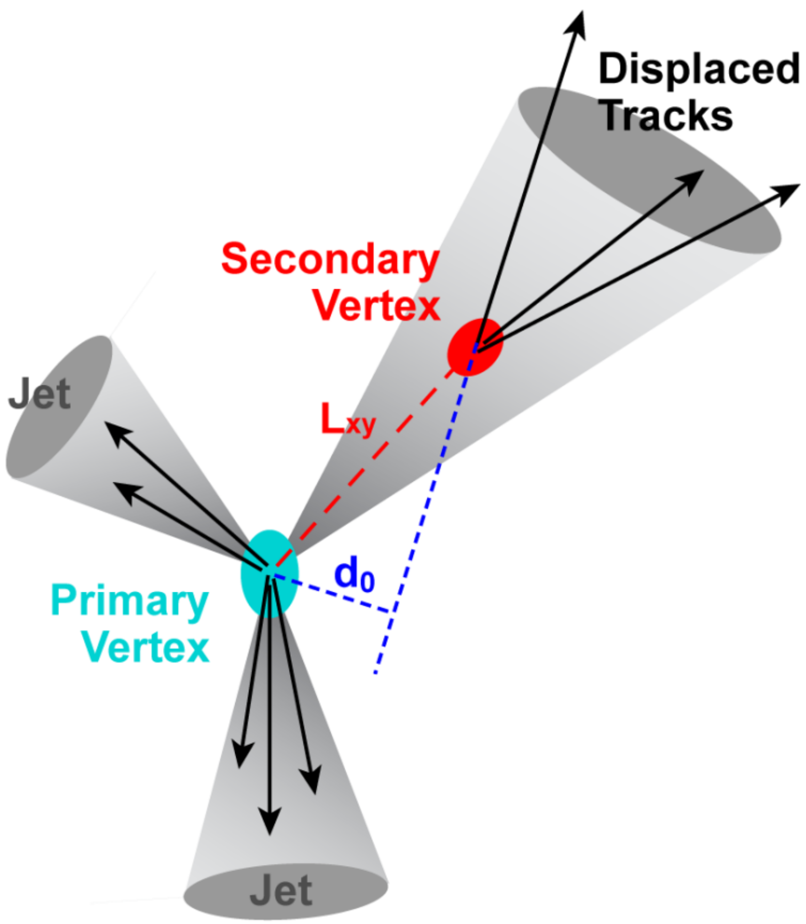
[CERN-PH-EP-2015-204]

These choices are currently under re-optimization with promising improvements

[ATL-PHYS-PUB-2019-027]

Boosted VHbb from bottom-up: b-tagging

- Identifying (sub-) jets originating from B-hadrons (b-tagging) crucial for this analysis
- Making use of physics properties of B-hadrons:



B-hadron carries most of the initial b-quark energy (~80%)

High mass of B-hadrons of ~ 5 GeV

High decay multiplicity (~ 5 charged particles)

CKM suppressed lifetime τ ~ 1.5 ps (cτ ~ 450 μm)

20% semi-leptonic decays with muons

Weak decays mostly into C-hadrons

3 classes of algorithms:

Impact parameter based | Secondary Vertex Finder | Decay Chain Fitter

→ **MVA combining all information (trained on simulation, calibrated on data)**

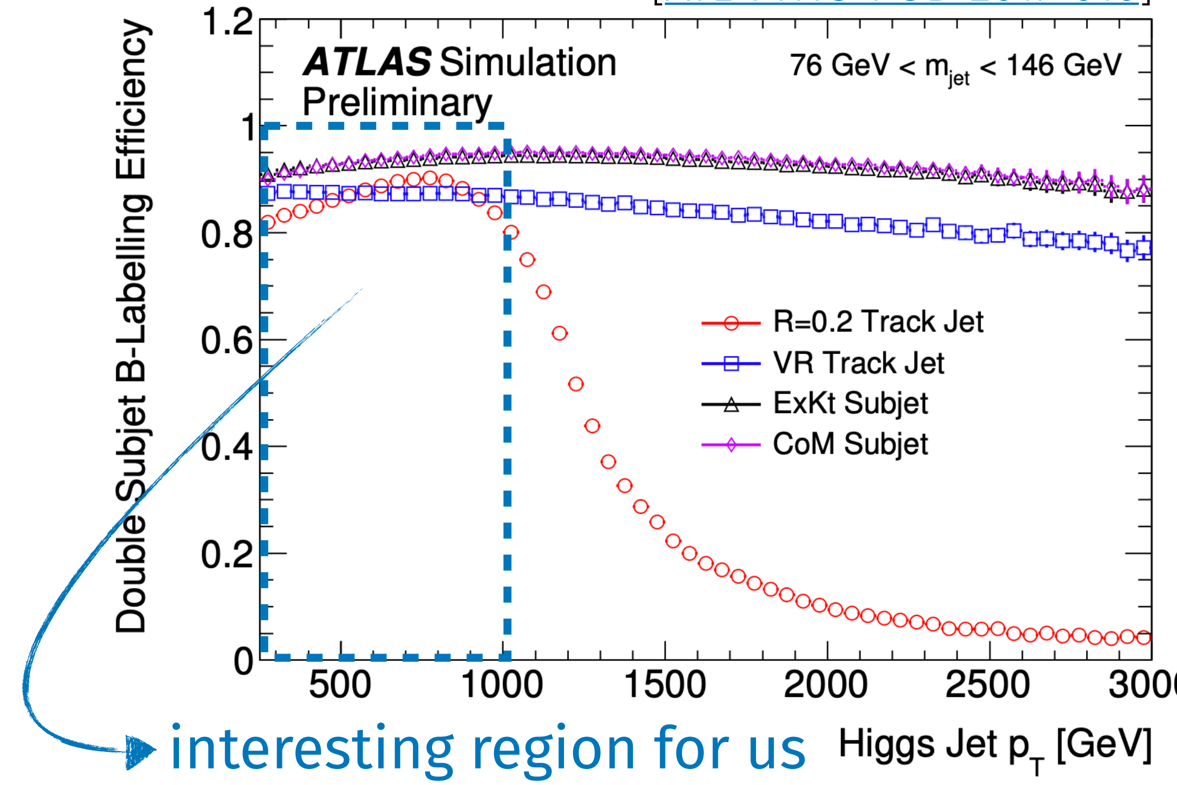
Higgs candidate tagging on VR track-jets

- Use the leading two VR track-jets that are ghost-associated to the leading large-R jet for (single) b-tagging

Pros of track-jets:
- High granularity
  ⟶ tiny R possible
- Pile-up insensitive
- Independent of large-R jet (no grooming, indep. calib.)

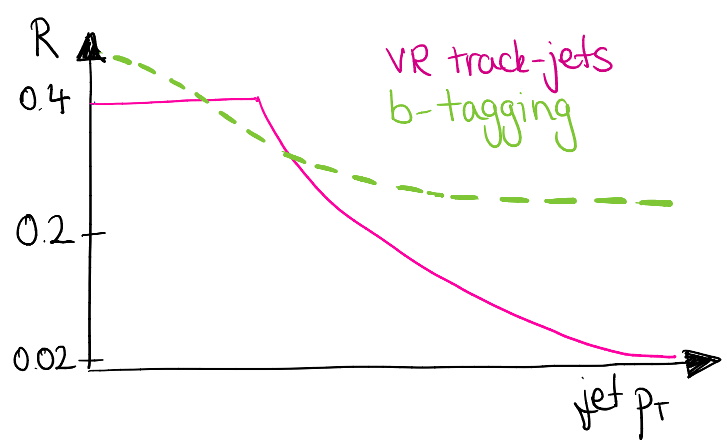
Cons of track-jets:
- Missing neutrals

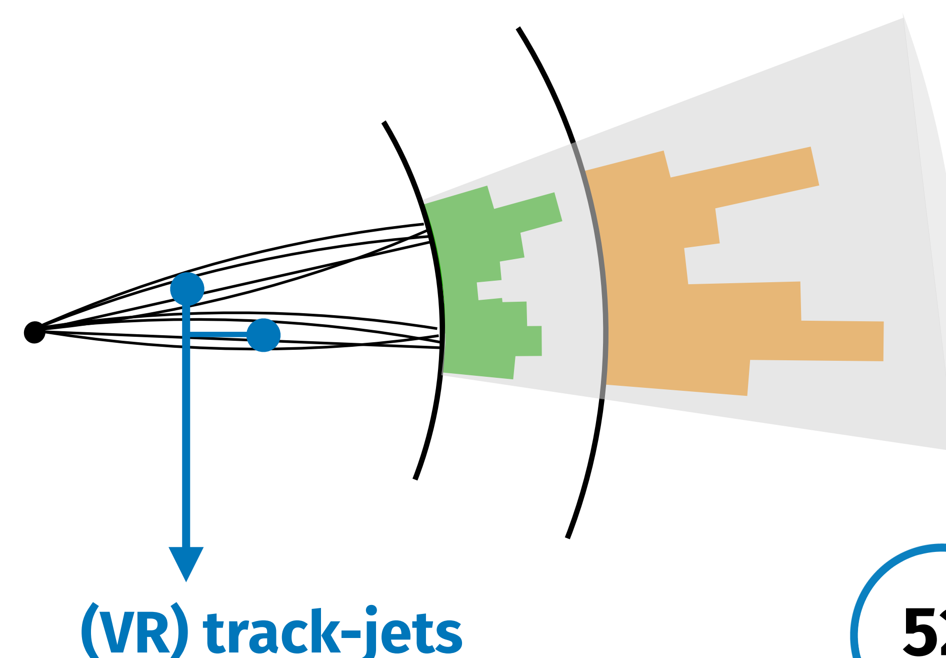
[ATL-PHYS-PUB-2017-010]



Variable-R:

$$R_{\text{eff.}} = \frac{30\ \text{GeV}}{p_T}$$



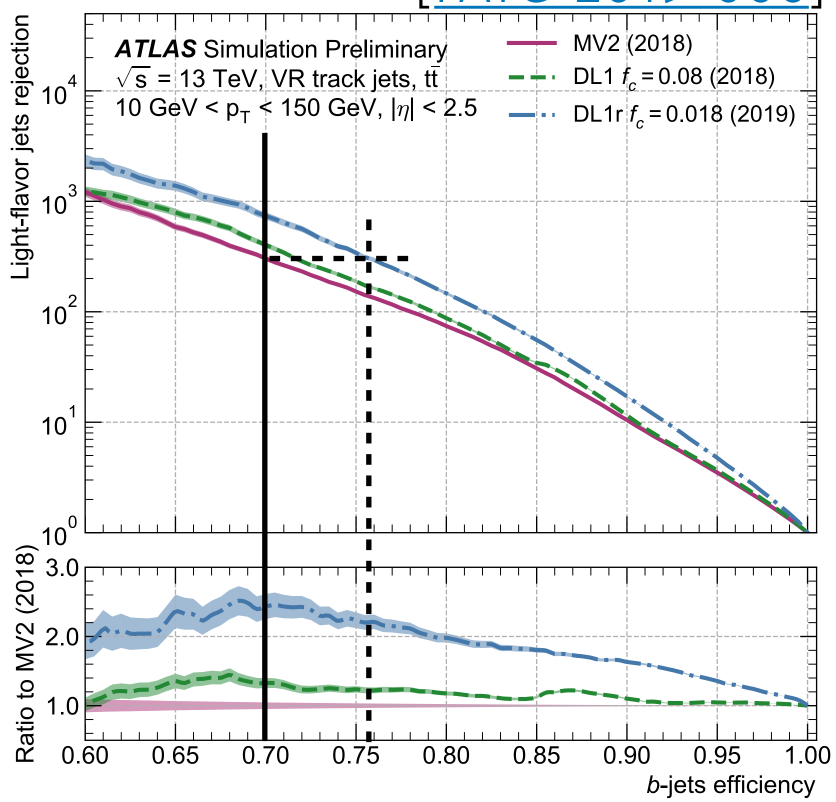


- MV2c10 algorithm used at 70% single-tag efficiency
  - light-jet rejection: 304
  - c-jet rejection: 9

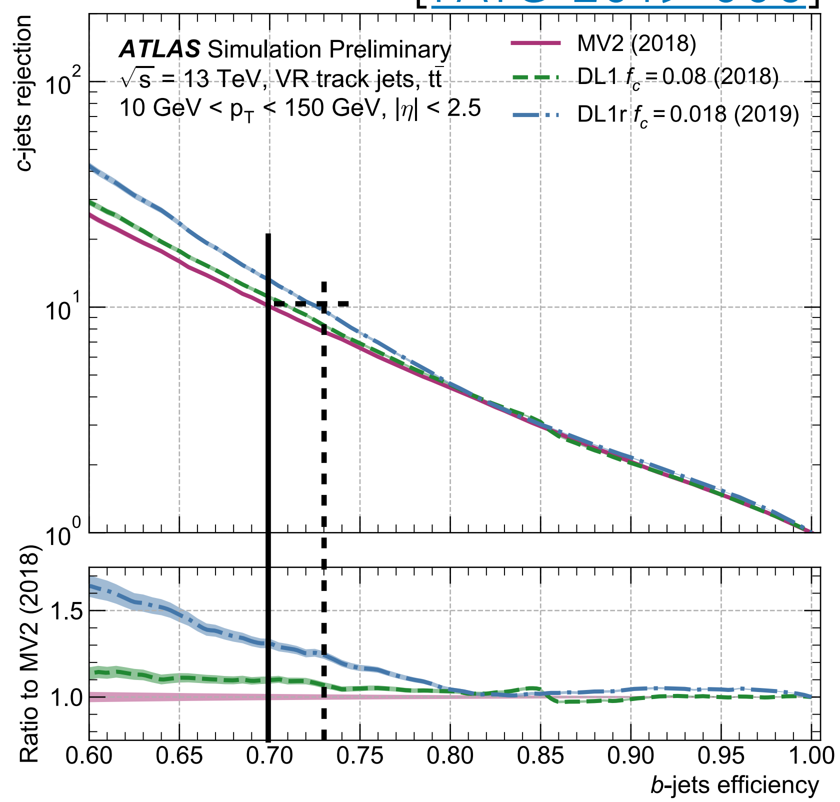
Potential improvements

- Lots of refinements with promising potential ready to be tested

[FATG-2019-006]



[FATG-2019-006]



Single b-tagging algorithm improvements

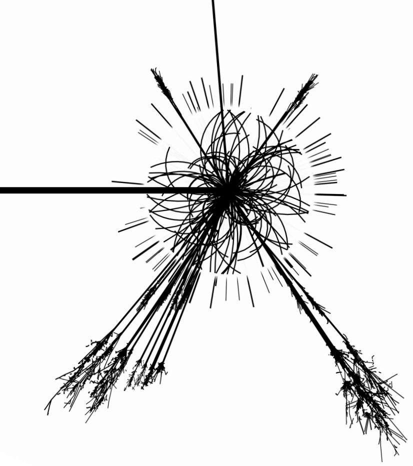
Revisiting the jet inputs, clustering algorithms, grooming procedures, ... [ATL-PHYS-PUB-2019-027]

together with refinements on the analysis itself!

The used generators

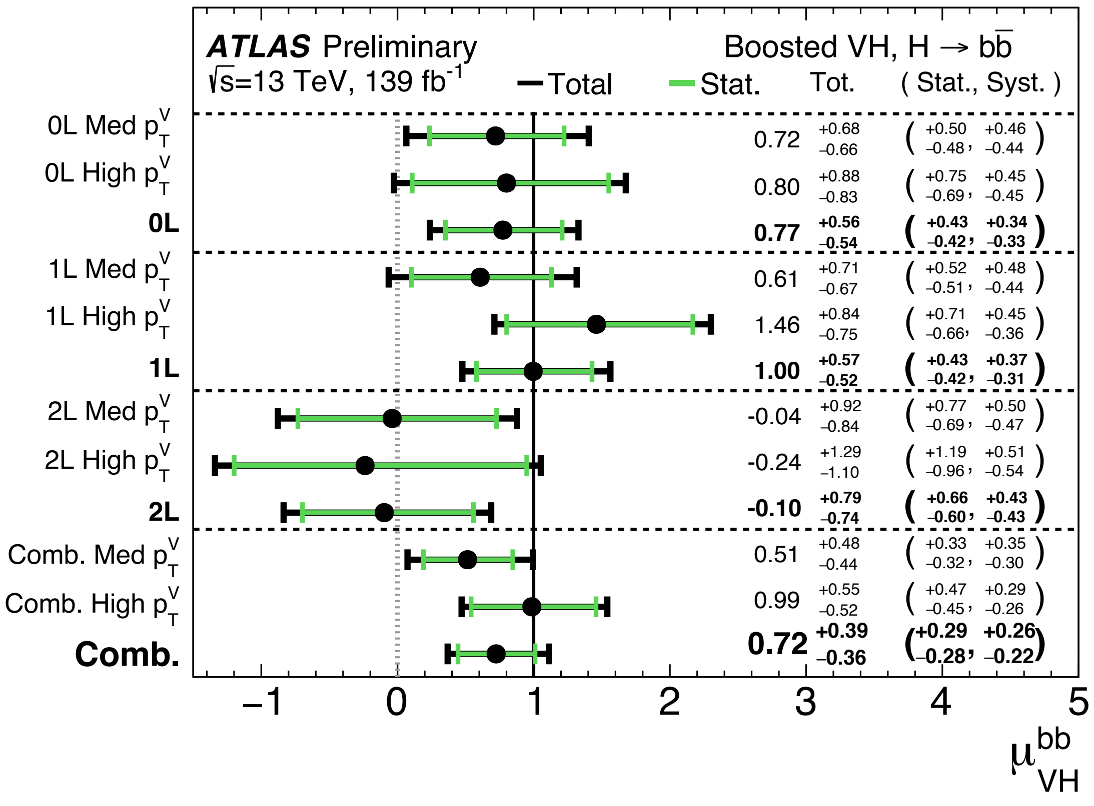
Process	ME generator	ME PDF	PS and Hadronisation	UE model tune	Cross-section order
Signal ($m_H = 125$ GeV and $b\bar{b}$ branching fraction set to 58%)					
$qq \to WH \to \ell\nu b\bar{b}$	POWHEG-BOX v2 + GOSAM + MINLO	NNPDF3.0NLO$^{(\star)}$	PYTHIA 8.212	AZNLO	NNLO(QCD)+ NLO(EW)
$qq \to ZH \to \nu\nu b\bar{b}/\ell\ell b\bar{b}$	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
Top quark ($m_t = 172.5$ GeV)					
$t\bar{t}$	POWHEG-BOX v2	NNPDF3.0NLO	PYTHIA 8.230	A14	NNLO+NNLL
s-channel	POWHEG-BOX v2	NNPDF3.0NLO	PYTHIA 8.230	A14	NLO
t-channel	POWHEG-BOX v2	NNPDF3.0NLO	PYTHIA 8.230	A14	NLO
Wt	POWHEG-BOX v2	NNPDF3.0NLO	PYTHIA 8.230	A14	Approximate NNLO
Vector boson + jets					
$W \to \ell\nu$	SHERPA 2.2.1	NNPDF3.0NNLO	SHERPA 2.2.1	Default	NNLO
$Z/\gamma^* \to \ell\ell$	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

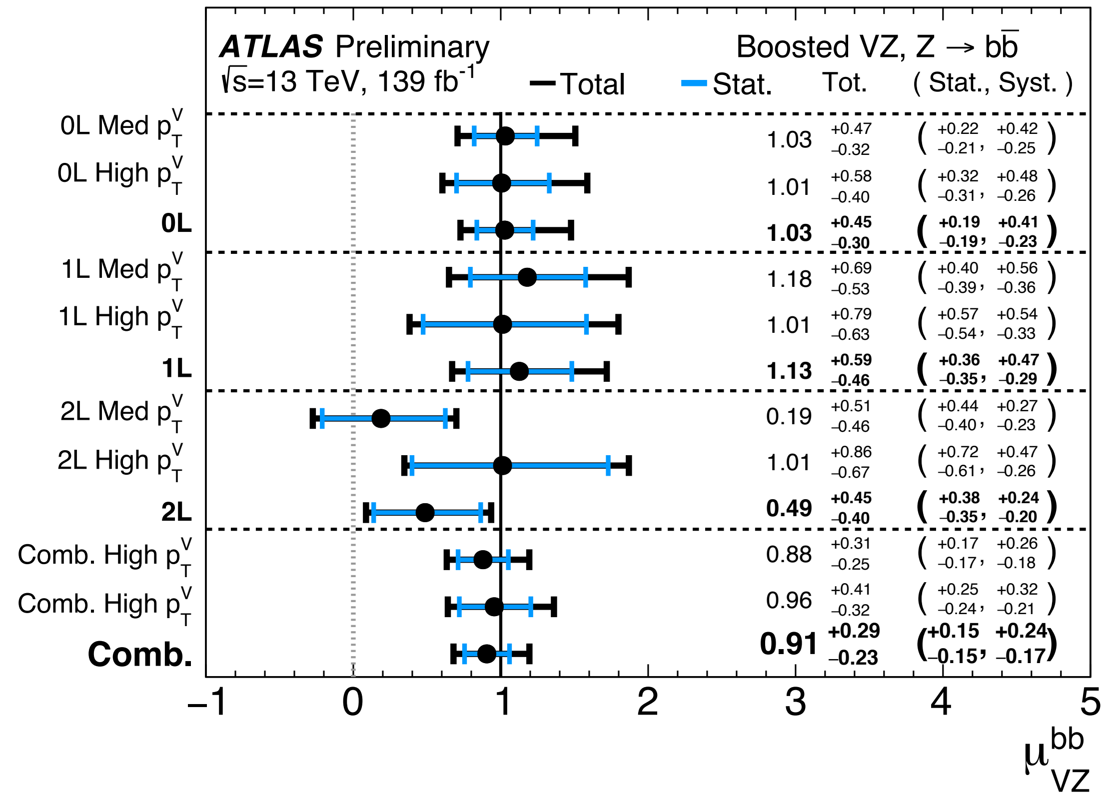
The event selection



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

Compatibility tests





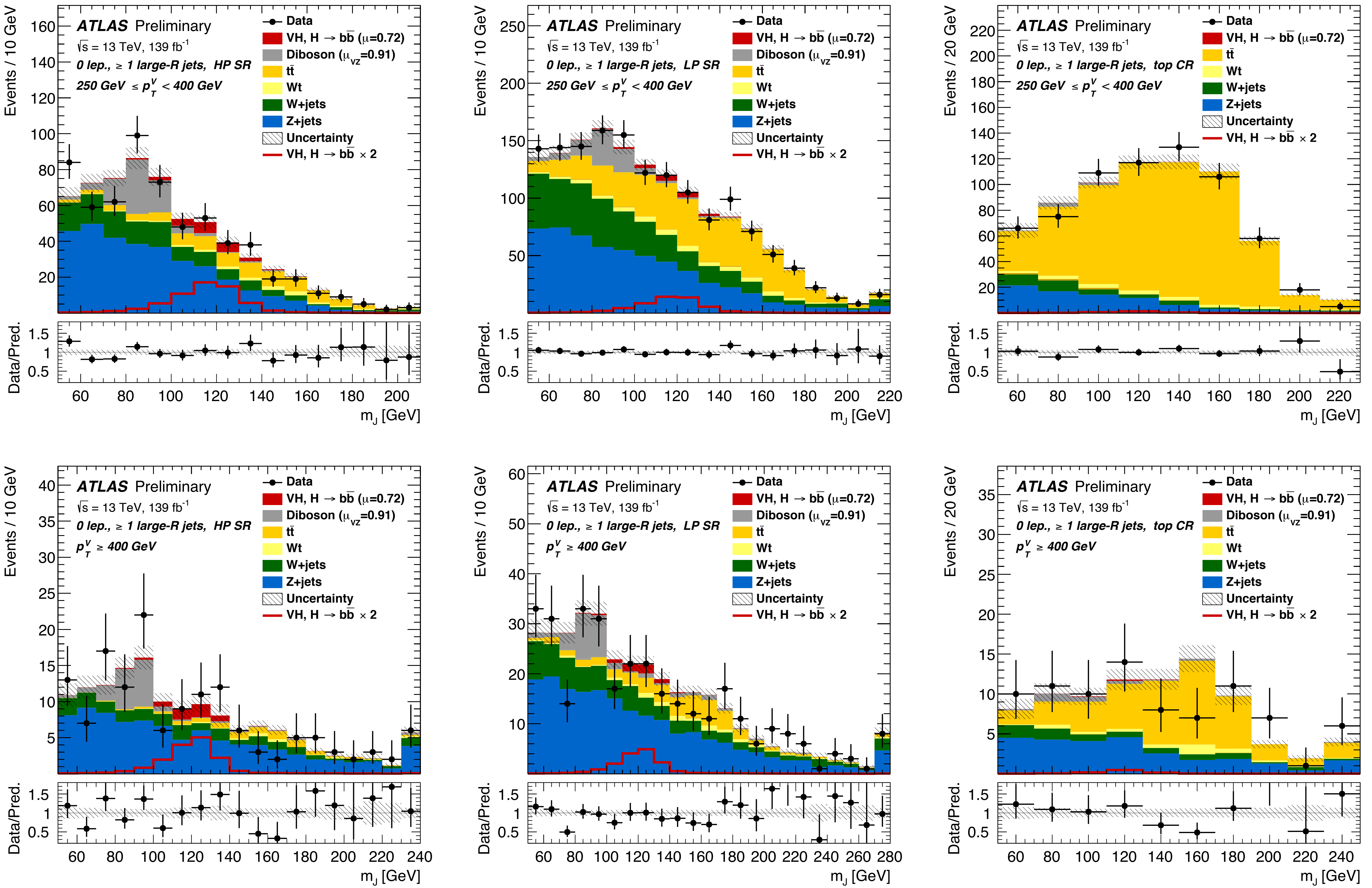
Measured STXS cross-sections

Measurement region ($\lvert y_H \rvert < 2.5, H \to b\bar{b}$)	SM prediction [fb]	Result [fb]	Stat. unc. [fb]	Syst. unc. [fb]
$W \to \ell\nu;\ p_T^W \in [250, 400[\,\mathrm{GeV}$	5.83 ± 0.26	$3.3\ ^{+4.8}_{-4.6}$	$^{+3.6}_{-3.4}$	$^{+3.2}_{-3.0}$
$W \to \ell\nu;\ p_T^W \in [400, \infty[\,\mathrm{GeV}$	1.25 ± 0.06	$2.1\ ^{+1.2}_{-1.1}$	$^{+1.0}_{-0.9}$	$^{+0.6}_{-0.5}$
$Z \to \ell\ell, \nu\nu;\ p_T^Z \in [250, 400[\,\mathrm{GeV}$	4.12 ± 0.45	$1.4\ ^{+3.1}_{-2.9}$	$^{+2.4}_{-2.3}$	$^{+1.9}_{-1.7}$
$Z \to \ell\ell, \nu\nu;\ p_T^Z \in [400, \infty[\,\mathrm{GeV}$	0.72 ± 0.05	$0.2\ ^{+0.7}_{-0.6}$	$^{+0.6}_{-0.5}$	$^{+0.3}_{-0.3}$

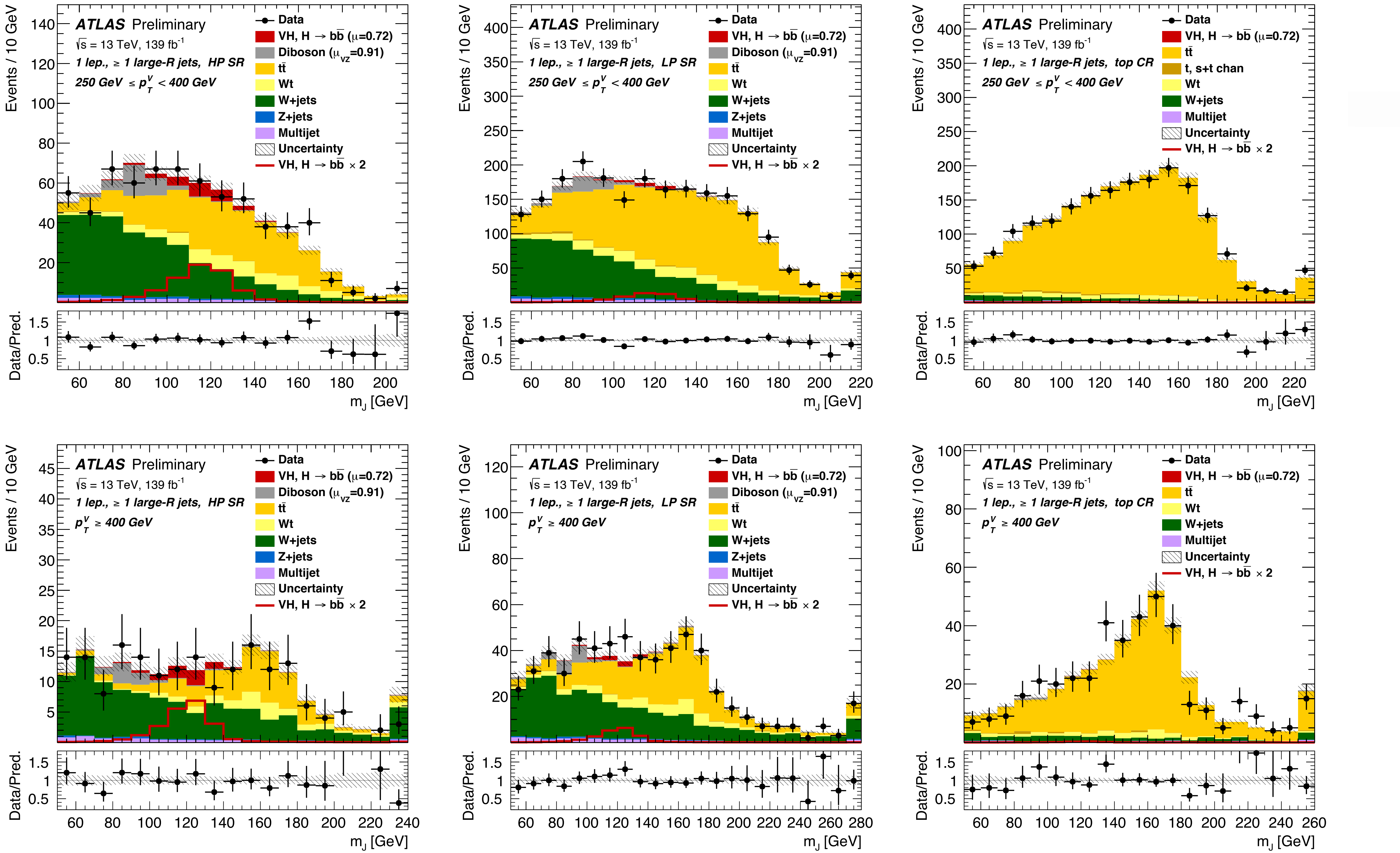
Uncertainty breakdown

Source of uncertainty		Avg. impact
Total		0.372
Statistical		0.283
Systematic		0.240
Experimental uncertainties		
small-R jets		0.038
large-R jets		0.133
E_T^{miss}		0.007
Leptons		0.010
b-tagging	b-jets	0.016
	c-jets	0.011
	light-flavour jets	0.008
	extrapolation	0.004
Pile-up		0.001
Luminosity		0.013
Theoretical and modelling uncertainties		
Signal		0.038
Backgrounds		0.100
$\hookrightarrow$ Z + jets		0.048
$\hookrightarrow$ W + jets		0.058
$\hookrightarrow$ $t\bar{t}$		0.035
$\hookrightarrow$ Single top quark		0.027
$\hookrightarrow$ Diboson		0.032
$\hookrightarrow$ Multijet		0.009
MC statistical		0.092

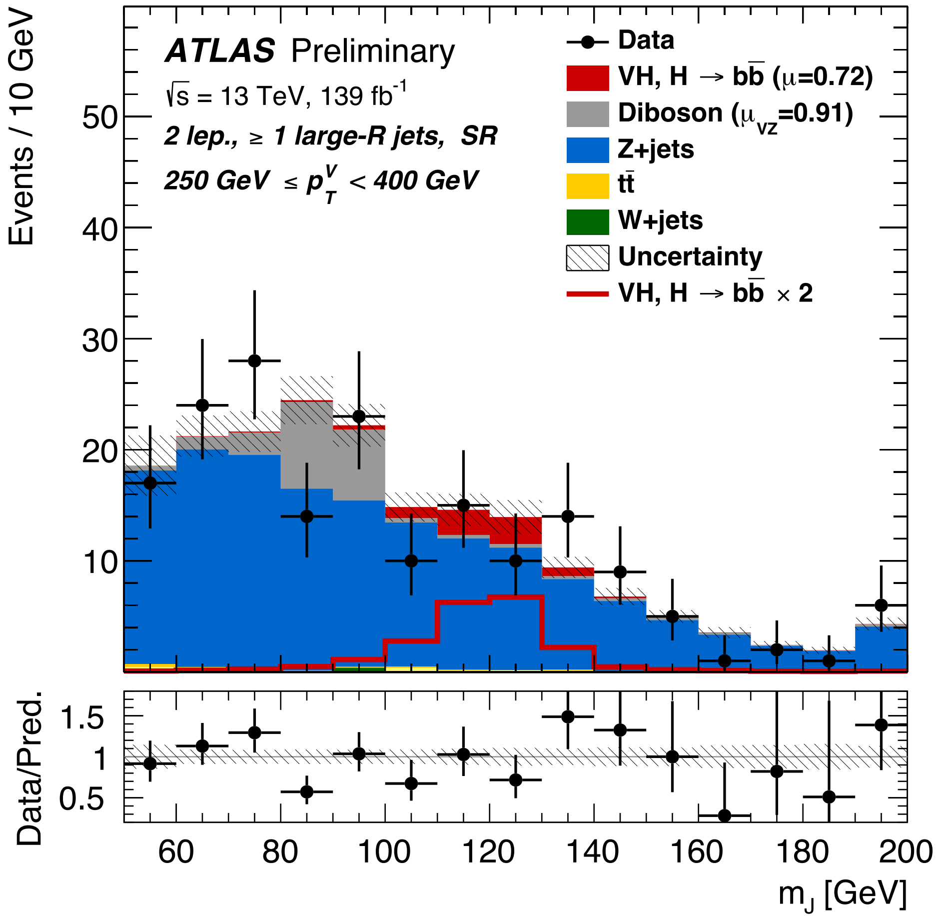
Post-fit plots: 0-lepton

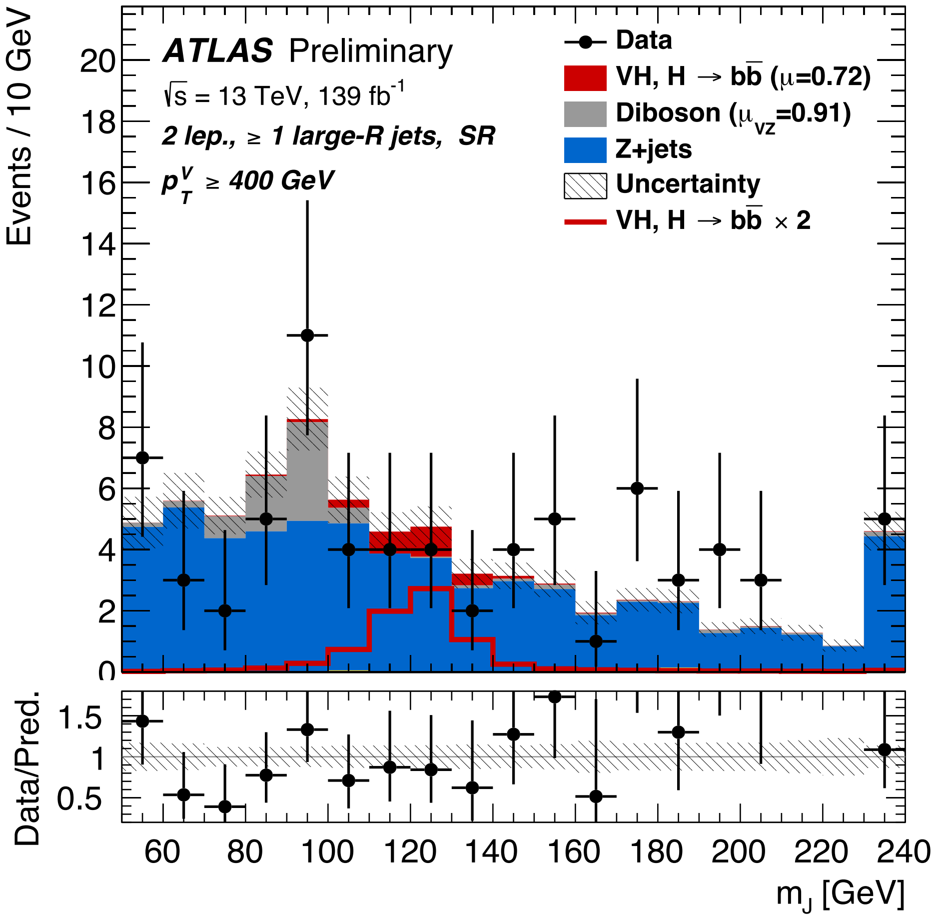


Post-fit plots: 1-lepton



Post-fit plots: 2-lepton





EFT Limits Comparison

[arXiv:1803.03252]

Coefficient	Z-pole + m_W	WW at LEP2	Higgs Run1	Higgs Run2	LHC WW high-p_T
$\bar{C}_{dH}$	×	×	36	64	×
$\bar{C}_{eH}$	×	×	49.6	50.4	×
$\bar{C}_{G}$	×	×	2.3	97.7	×
$\bar{C}_{HB}$	×	×	19	81	×
$\bar{C}_{H\Box}$	×	×	19.7	80.3	0.01
$\bar{C}_{Hd}$	99.88	×	0.04	0.07	×
$\bar{C}_{HD}$	99.92	0.06	×	×	×
$\bar{C}_{He}$	99.99	0.01	×	×	×
$\bar{C}_{HG}$	×	×	34	66	0.02
$\bar{C}^{(1)}_{H\ell}$	99.97	0.03	×	×	×
$\bar{C}^{(3)}_{H\ell}$	99.56	0.41	×	×	0.01
$\bar{C}^{(1)}_{Hq}$	99.98	×	0.01	0.01	×
$\bar{C}^{(3)}_{Hq}$	98.6	0.96	0.19	0.23	0.07
$\bar{C}_{Hu}$	99.5	×	0.2	0.3	0.04
$\bar{C}_{HW}$	×	×	18	82	×
$\bar{C}_{HWB}$	57.9	0.02	8.2	33.9	×
$\bar{C}_{\ell\ell}$	99.66	0.32	×	0.01	0.01
$\bar{C}_{uG}$	×	×	7.8	92.2	×
$\bar{C}_{uH}$	×	×	9.5	90.5	×
$\bar{C}_{W}$	×	96.2	×	×	3.8

Table 5: *Impact of different sets of measurements on the fit to individual Wilson coefficients in the Warsaw basis as measured by the Fisher information contained in a given dataset for each coefficient. A cross indicates no (current) sensitivity.*