From searches to precision measurements (Part I)

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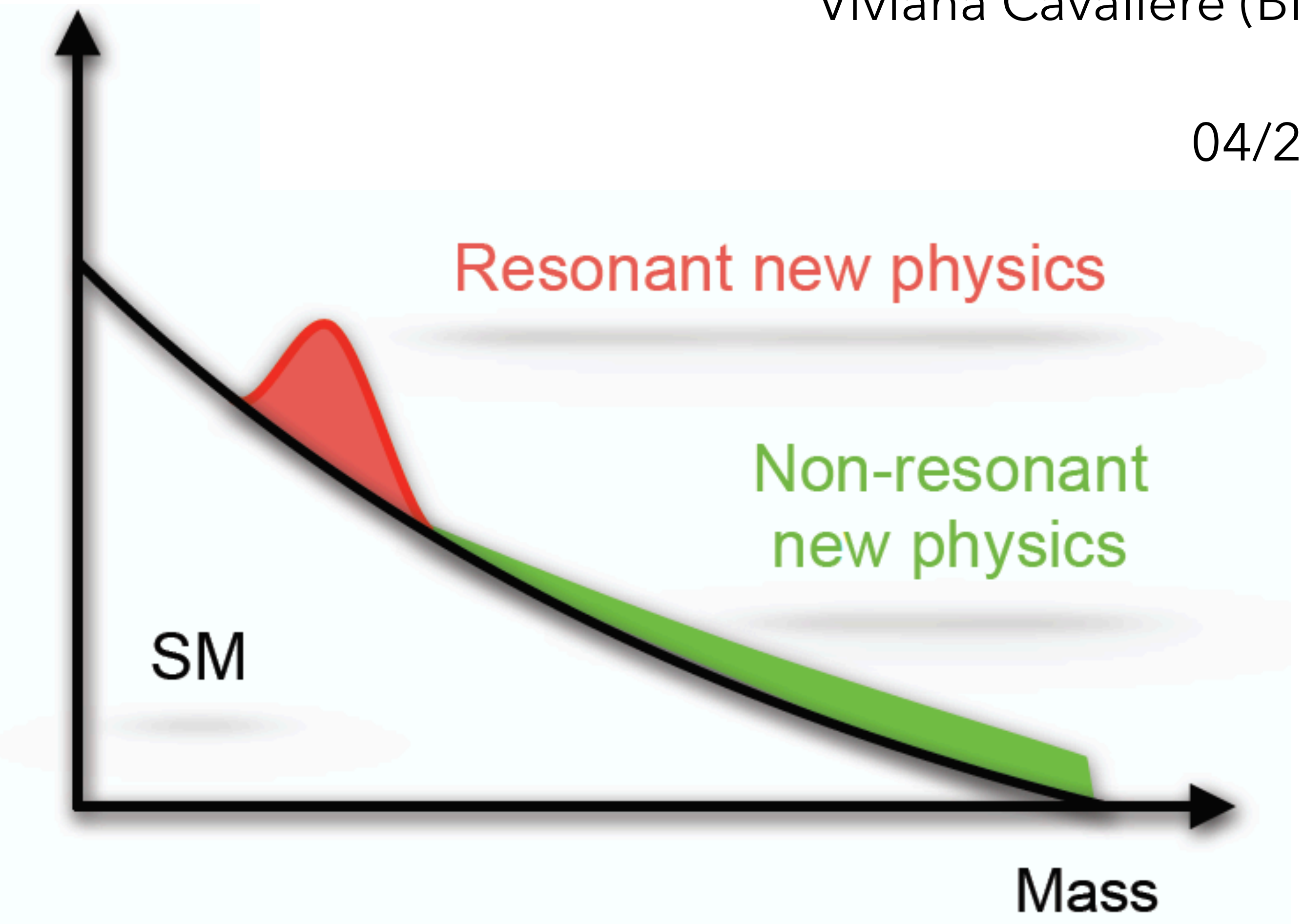
04/27/2021



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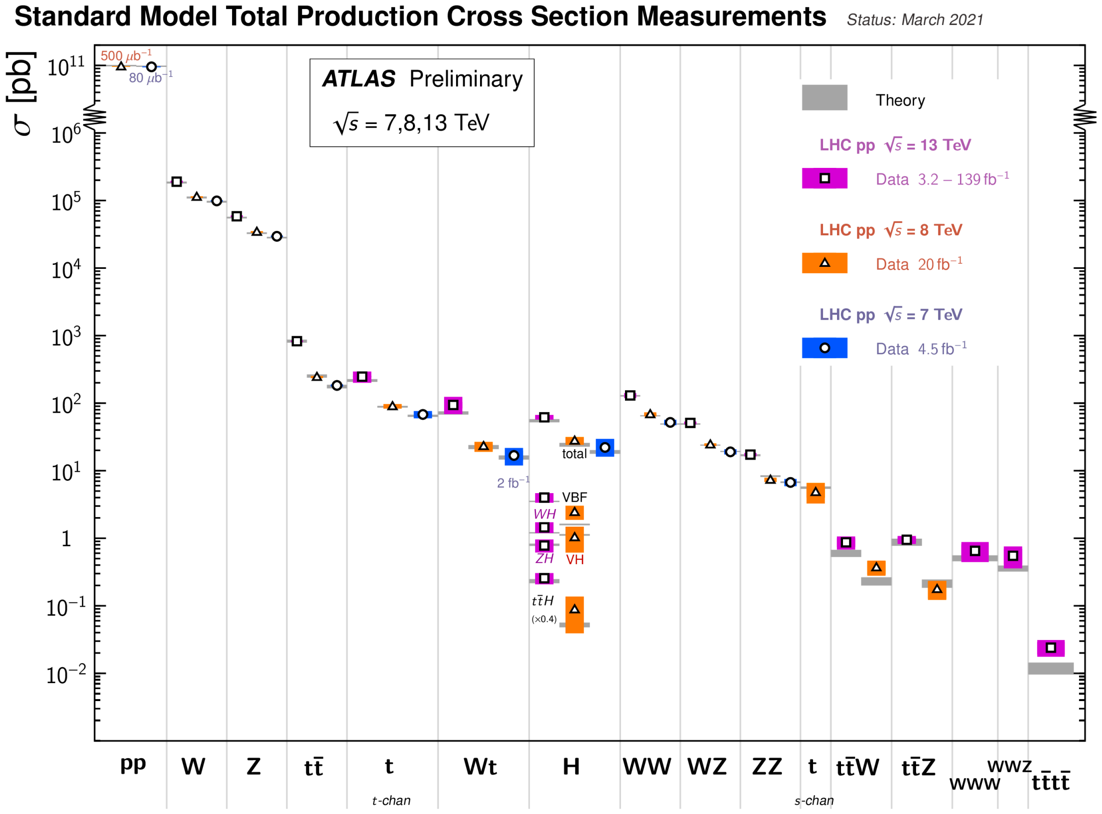
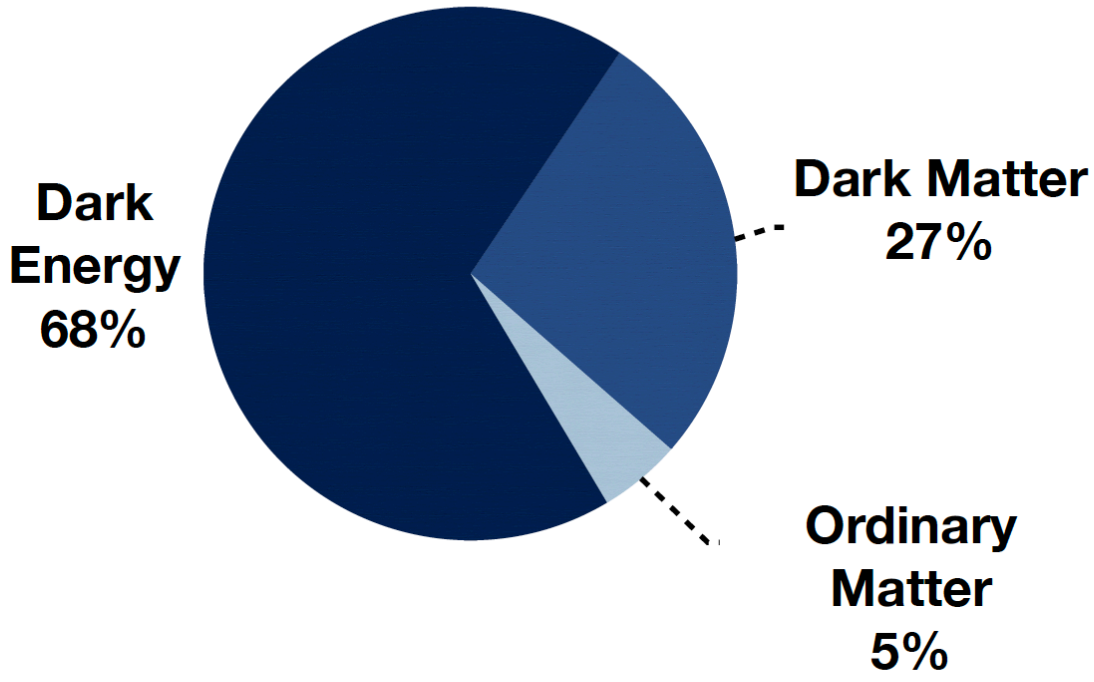
The Standard Model of Particle Physics

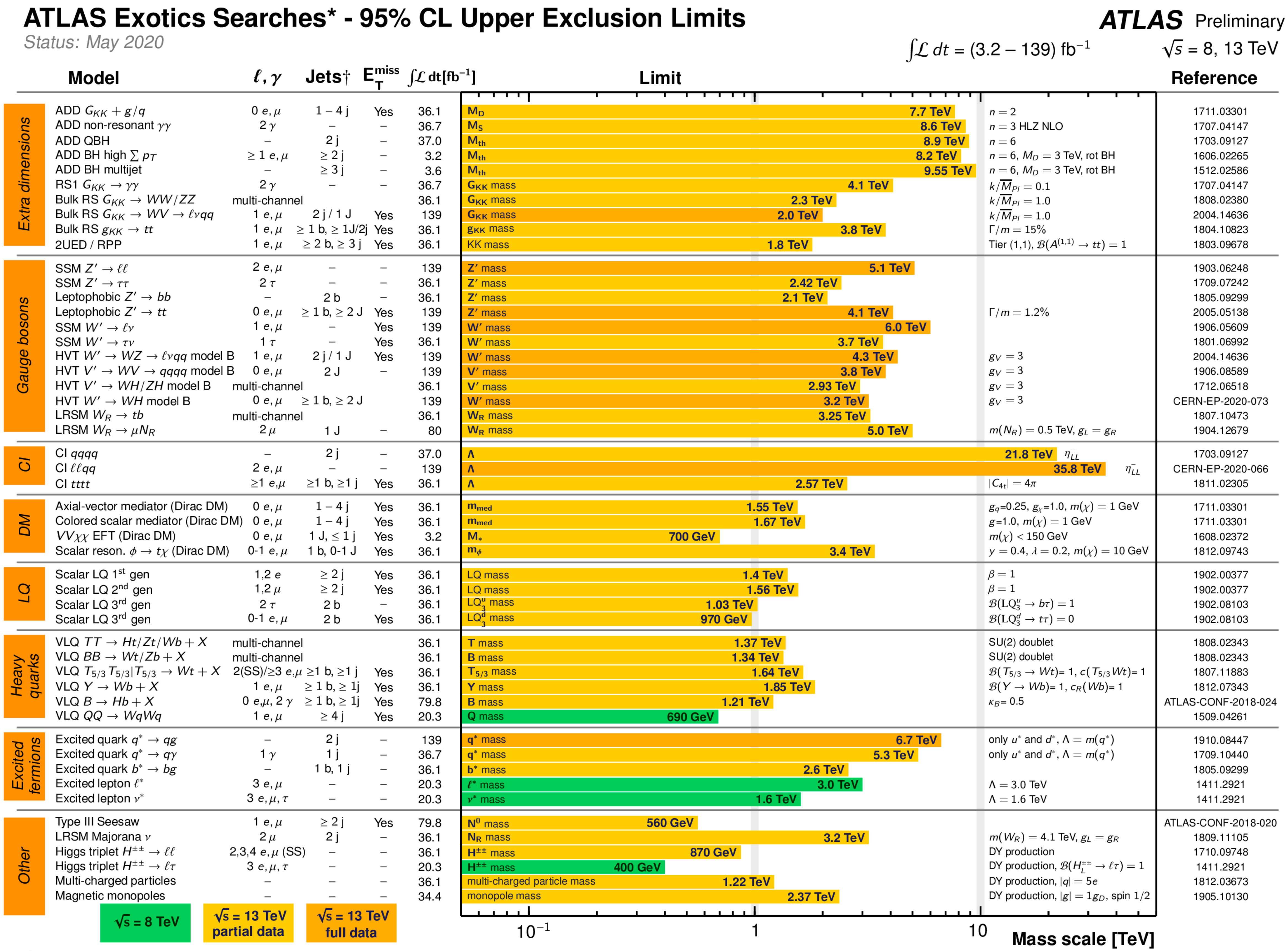
- The Standard Model of particle physics is a powerful theory that describes three of the four known fundamental forces in the universe and classifies all known elementary particles.
  - Higgs boson discovery in 2012 at the LHC
  - Wonderful agreement with experiments



- Even with such a successful description of Nature, a few, but major, pieces are missing in the puzzle:
  - Neutrino masses (and flavour oscillation) not predicted
  - Matter-antimatter imbalance
  - Unification of forces
  - No gravity
  - Missing dark matter/energy candidates
  - Hierarchy problem



But...



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2020

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 139)\ \text{fb}^{-1}$

$\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\text{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1 – 4 j	Yes	36.1	🟨 M_D 7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	🟨 M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	🟨 M_{th} 8.9 TeV	$n = 6$	1703.09127
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	🟨 M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	🟨 M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	36.7	🟨 G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	🟨 G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $G_{KK} \to WV \to \ell\nu qq$	1 e, μ	2 j / 1 J	Yes	139	🟧 G_{KK} mass 2.0 TeV	$k/\overline{M}_{Pl} = 1.0$	2004.14636
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	🟨 g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	36.1	🟨 KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	139	🟧 Z' mass 5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	🟨 Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	🟨 Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	0 e, μ	≥ 1 b, ≥ 2 J	Yes	139	🟧 Z' mass 4.1 TeV	$\Gamma/m = 1.2\%$	2005.05138
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	139	🟧 W' mass 6.0 TeV		1906.05609
	SSM $W' \to \tau\nu$	1 τ	–	Yes	36.1	🟨 W' mass 3.7 TeV		1801.06992
	HVT $W' \to WZ \to \ell\nu qq$ model B	1 e, μ	2 j / 1 J	Yes	139	🟧 W' mass 4.3 TeV	$g_V = 3$	2004.14636
	HVT $V' \to WV \to qqqq$ model B	0 e, μ	2 J	–	139	🟧 V' mass 3.8 TeV	$g_V = 3$	1906.08589
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	🟨 V' mass 2.93 TeV	$g_V = 3$	1712.06518
	HVT $W' \to WH$ model B	0 e, μ	≥ 1 b, ≥ 2 J		139	🟧 W' mass 3.2 TeV	$g_V = 3$	CERN-EP-2020-073
	LRSM $W_R \to tb$	multi-channel			36.1	🟨 W_R mass 3.25 TeV		1807.10473
	LRSM $W_R \to \mu N_R$	2 μ	1 J	–	80	🟨 W_R mass 5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	🟨 Λ 21.8 TeV η_{LL}^-		1703.09127
	CI $\ell\ell qq$	2 e, μ	–	–	139	🟧 Λ 35.8 TeV η_{LL}^-		CERN-EP-2020-066
	CI $tttt$	$\geq$1 e,μ	$\geq$1 b, $\geq$1 j	Yes	36.1	🟨 Λ 2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	1811.02305
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	🟨 m_{med} 1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	🟨 m_{med} 1.67 TeV	g=1.0, $m(\chi) = 1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	🟨 M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
	Scalar reson. $\phi \to t\chi$ (Dirac DM)	0-1 e, μ	1 b, 0-1 J	Yes	36.1	🟨 m_ϕ 3.4 TeV	$y = 0.4$, $\lambda = 0.2$, $m(\chi) = 10$ GeV	1812.09743
LQ	Scalar LQ 1st gen	1,2 e	≥ 2 j	Yes	36.1	🟨 LQ mass 1.4 TeV	$\beta = 1$	1902.00377
	Scalar LQ 2nd gen	1,2 μ	≥ 2 j	Yes	36.1	🟨 LQ mass 1.56 TeV	$\beta = 1$	1902.00377
	Scalar LQ 3rd gen	2 τ	2 b	–	36.1	🟨 LQ_3^u mass 1.03 TeV	$\mathcal{B}(\text{LQ}_3^u \to b\tau) = 1$	1902.08103
	Scalar LQ 3rd gen	0-1 e, μ	2 b	Yes	36.1	🟨 LQ_3^d mass 970 GeV	$\mathcal{B}(\text{LQ}_3^d \to t\tau) = 0$	1902.08103
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	🟨 T mass 1.37 TeV	SU(2) doublet	1808.02343
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	🟨 B mass 1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3}\lvert T_{5/3} \to Wt + X$	2(SS)/$\geq$3 e,μ	$\geq$1 b, $\geq$1 j	Yes	36.1	🟨 $T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $Y \to Wb + X$	1 e, μ	≥ 1 b, ≥ 1j	Yes	36.1	🟨 Y mass 1.85 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \to Hb + X$	0 e,μ, 2 γ	≥ 1 b, ≥ 1j	Yes	79.8	🟨 B mass 1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	🟩 Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	139	🟧 q^* mass 6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1910.08447
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	🟨 q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	🟨 b^* mass 2.6 TeV		1805.09299
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	🟩 ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	🟩 ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	1 e, μ	≥ 2 j	Yes	79.8	🟨 N^0 mass 560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	2 μ	2 j	–	36.1	🟨 N_R mass 3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	🟨 $H^{\pm\pm}$ mass 870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	🟩 $H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Multi-charged particles	–	–	–	36.1	🟨 multi-charged particle mass 1.22 TeV	DY production, $\lvert q\rvert = 5e$	1812.03673
	Magnetic monopoles	–	–	–	34.4	🟨 monopole mass 2.37 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1905.10130

🟩 $\sqrt{s}$ = 8 TeV

🟨 $\sqrt{s}$ = 13 TeV partial data

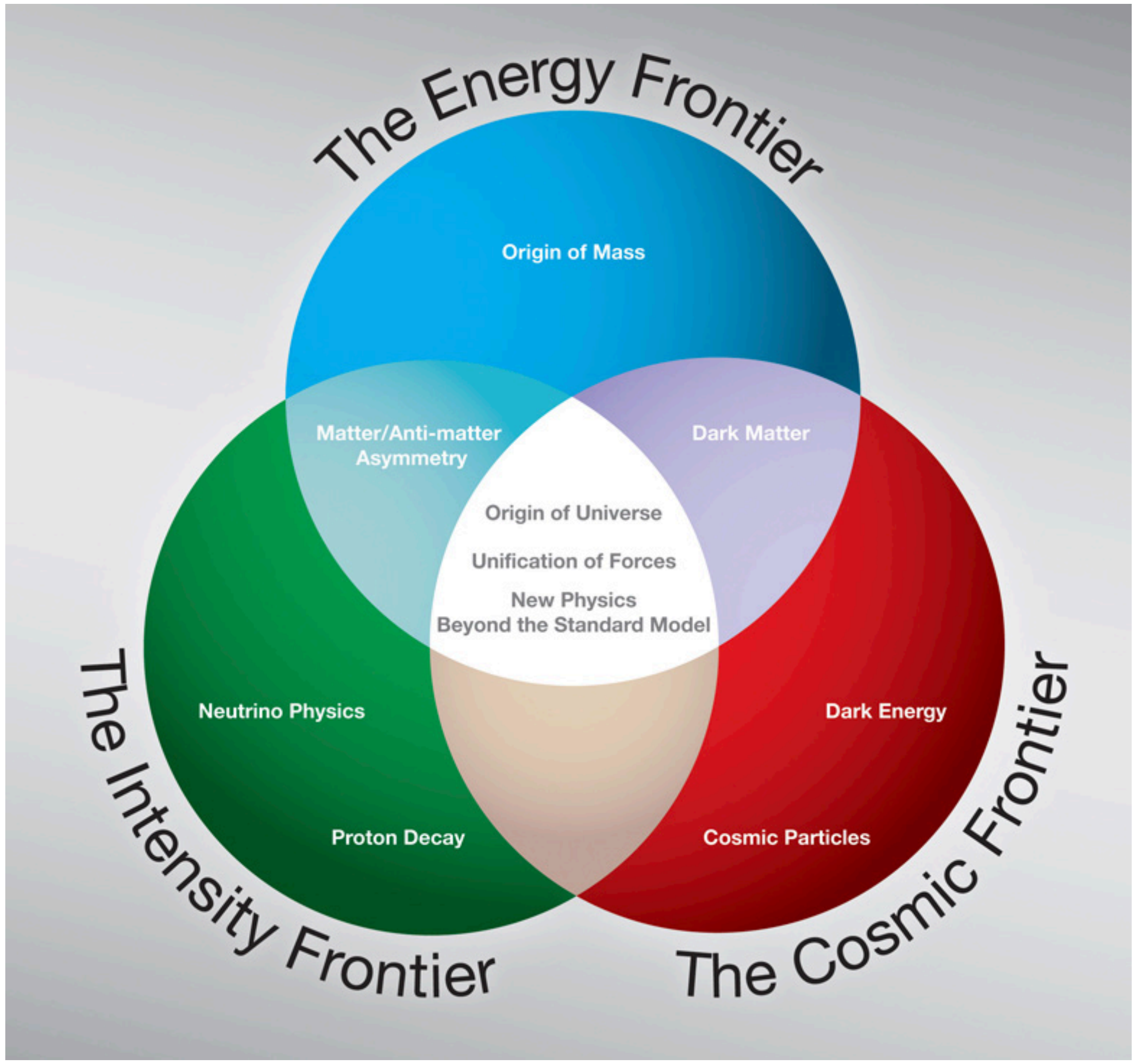
🟧 $\sqrt{s}$ = 13 TeV full data

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

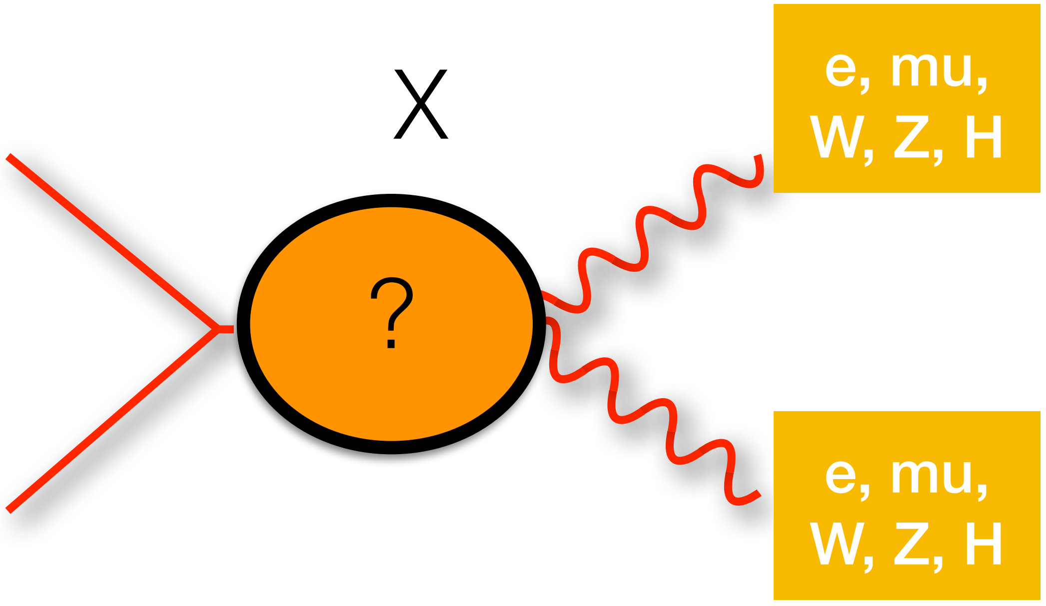
Where to look?

- LHC (and future colliders) offer a unique place where to look directly for new particles.
- **Direct BSM searches**
  - A plethora of kinematic regions and possible new resonances from heavy particles
- **Precision measurements of SM**
  - Each deviation could be an hint of new physics!
- Other focused experiments give alternative and fundamental opportunities!



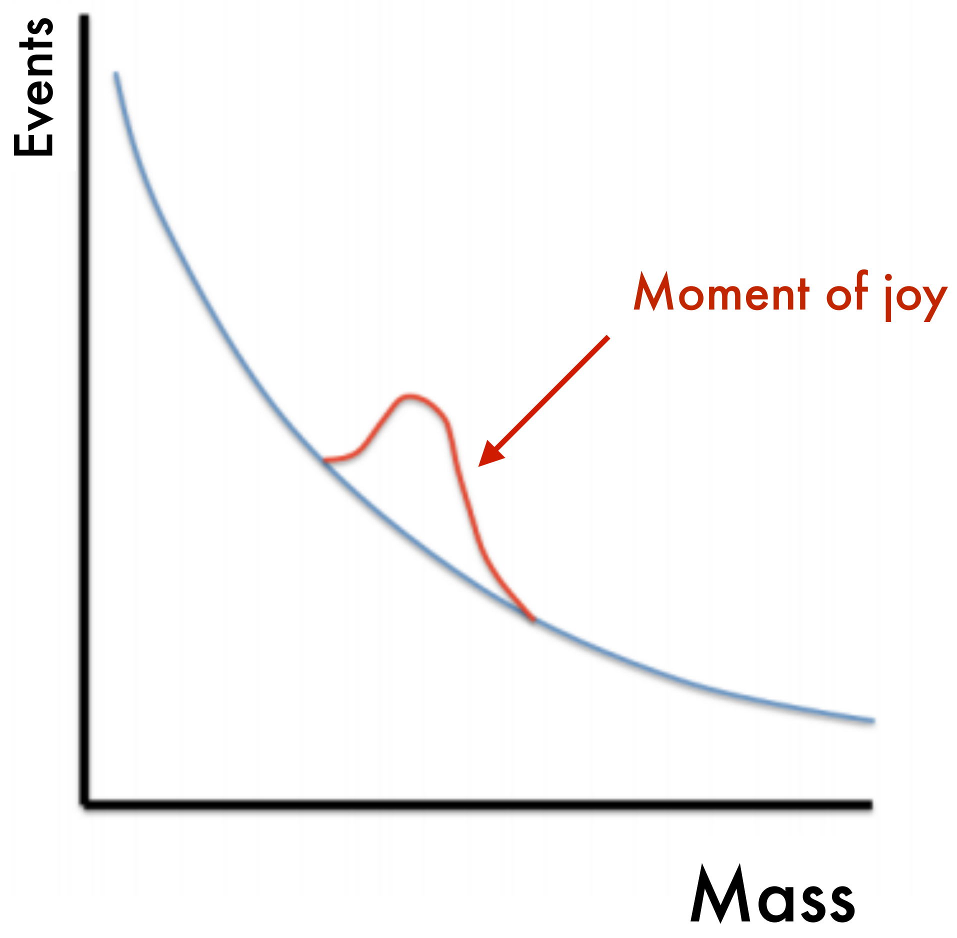
Resonance searches

- Many extension of the Standard Model predict new particles decaying into pair of SM particles (e.g. fermions, bosons, Higgs)
  - Composite models: X'—> W/Z +H
  - Extra dimensions : eg. Graviton—> HH
  - Supersymmetry models: new Higgses decaying to ZH



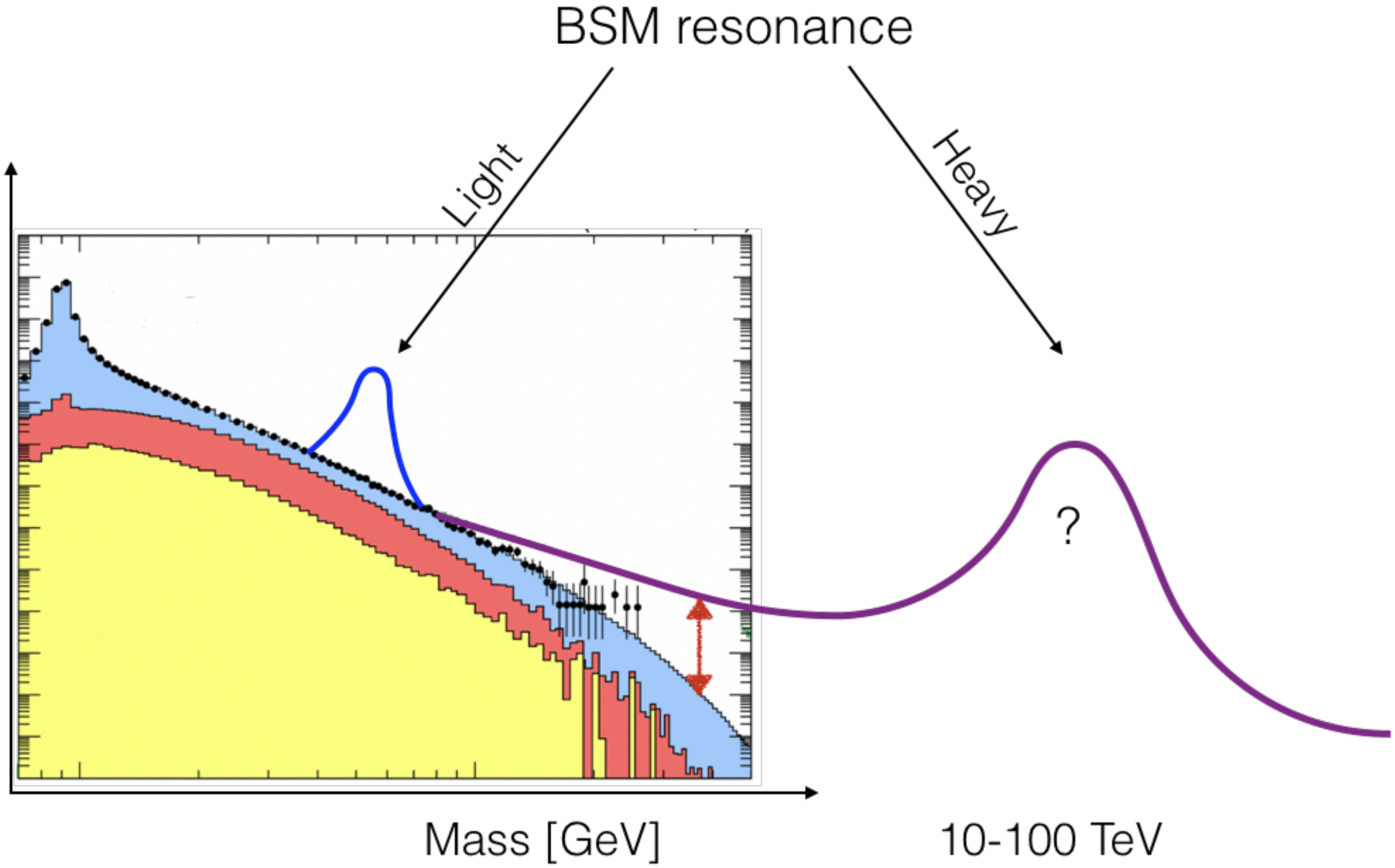
Searches for new resonances decaying into pairs of particles

- **Look for a peak on a smooth background**



What if?

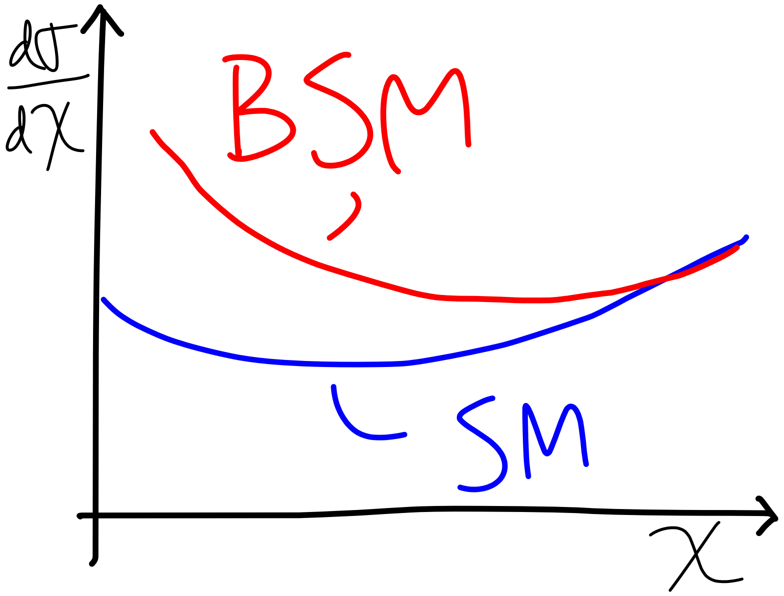
- While the presence of resonances is the most dramatic signal for new phenomena, they may be too heavy or broad to be clearly seen at the LHC.



- We can still look for this type of new phenomena in tails of distributions at the LHC

Resonance searches vs cross-section measurements

- At the LHC we can do more than searching for bumps !!
- Because of remarkable progresses in:
  - pdf determination
  - high-order calculations
  - precise MC generators
  - analysis techniques



- Precision is not bureaucratic certification of SM success ! Exciting tool to discover BSM indirectly. Same chance of success as direct search strategy used to have.

At the LHC now:

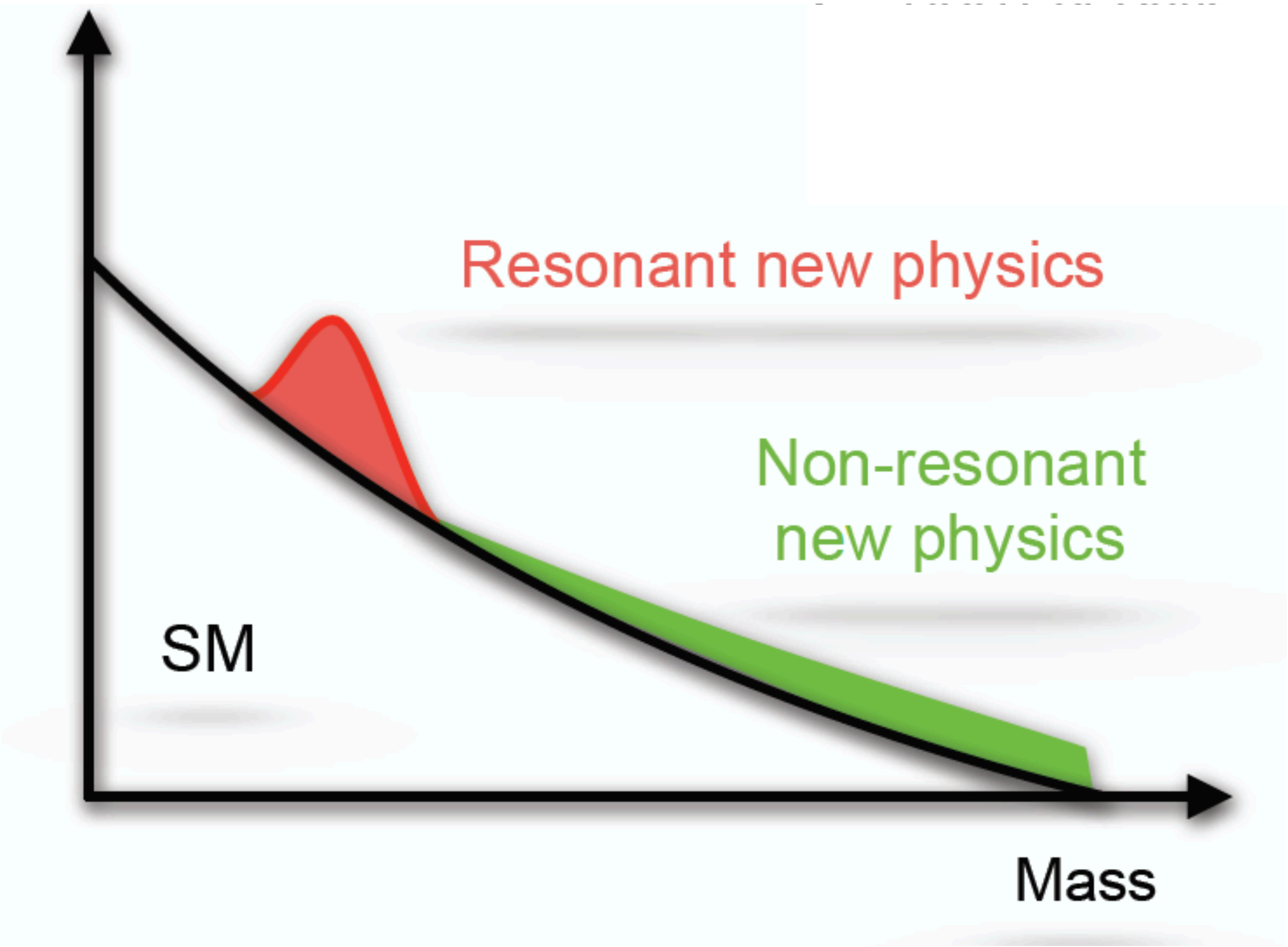
Measure SM parameters:
- Higgs Mass
- W boson mass
- ....

Search for New Physics:
- Directly
- Higgs coupling

Search for New Physics:

?

Indirect searches for New physics



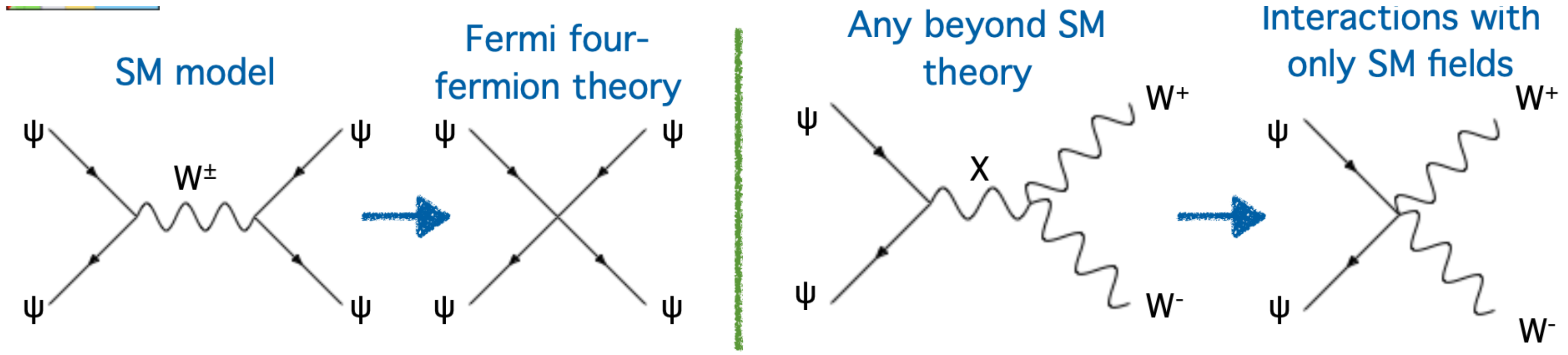
Analysis strategies

- Trying to look for a small enhancement rather than a bump
  - to get a better S/sqrt(B) more ML methods are often used
- Systematics become important even at high mass

Framework

- Non-resonant signals ==> which framework to use?
  - EFT? which flavor?

The EFT approach to New Physics



More on this in Haider's talk

- In absence of new particles, the SM can be considered as an effective low-energy theory.
- Any Beyond Standard Model physics can be thought of as modifications of the interactions containing only SM fields
- Assuming that the SM describes physics well in the energy range up to the scale Λ and new physics occurs only above that scale, the physics phenomena can be described by an effective Lagrangian

Classify the effect of any beyond SM model using operators with D > 4

$$\mathcal{L} = \mathcal{L}_4^{\mathrm{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \dots$$

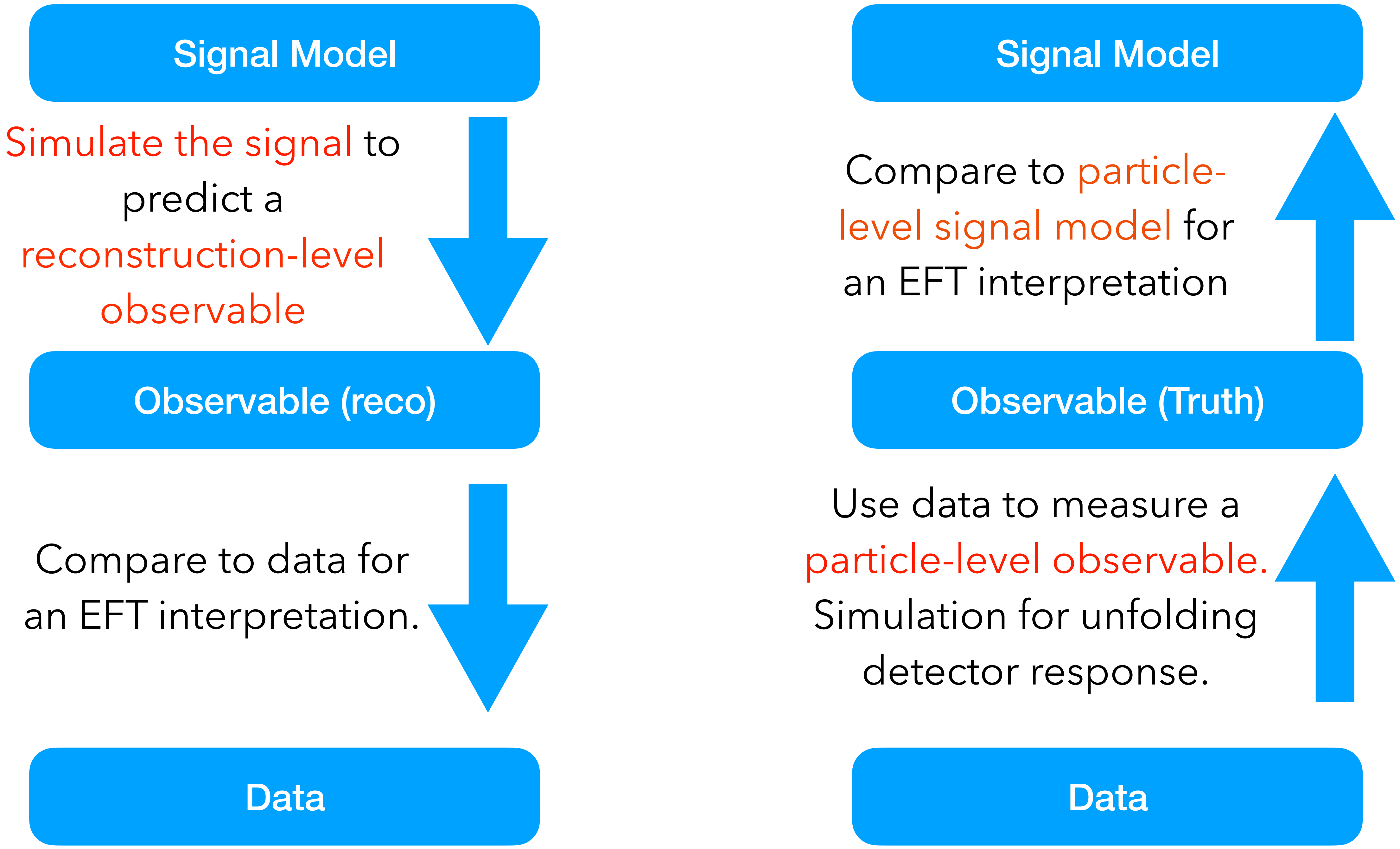
$$\frac{1}{\Lambda^2}\mathcal{L}_6 \to \left(\frac{E}{\Lambda}\right)^2 \qquad \frac{1}{\Lambda^4}\mathcal{L}_8 \to \left(\frac{E}{\Lambda}\right)^4$$

For large scales E/Λ « 1, only operators with lower mass dimension will matter.

$$\mathcal{L}^{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \boxed{\sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)}} + \sum_j \frac{c_j^{(8)}}{\Lambda^4}\mathcal{O}_j^{(8)} + \dots$$

$$c_i^{(D)} \simeq \frac{(\mathrm{coupling})^{n_i-2}}{(\mathrm{high\ mass\ scale})^{D-4}}$$

Approaches for an EFT interpretation



Top-Down

(most common for individual channels)

Signal Model

Simulate the signal to predict a reconstruction-level observable

Observable (reco)

Compare to data for an EFT interpretation.

Data

EFT interpretation

Similar to what we do in searches

Bottom-Up

(most common for combinations)

Signal Model

Compare to particle-level signal model for an EFT interpretation

Observable (Truth)

Use data to measure a particle-level observable. Simulation for unfolding detector response.

Data

Experimental outputs

1.single process cross section under SM assumptions

2. one (or more) observable differential distribution affected by multiple processes (typically with SM assumption of the rest of the kinematics)

3. **binned sub-process cross sections (SM assumptions in each bin) ==> STXS in Higgs ==> see Haider's talk**

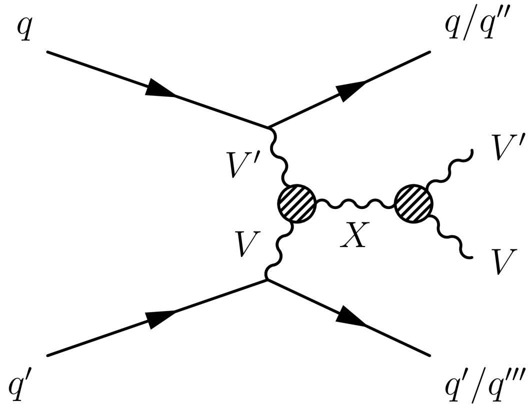
4. single-process cross-section per EFT operator
    - limited to a certain list of EFT operators
    - dedicated EFT measurements by experiments

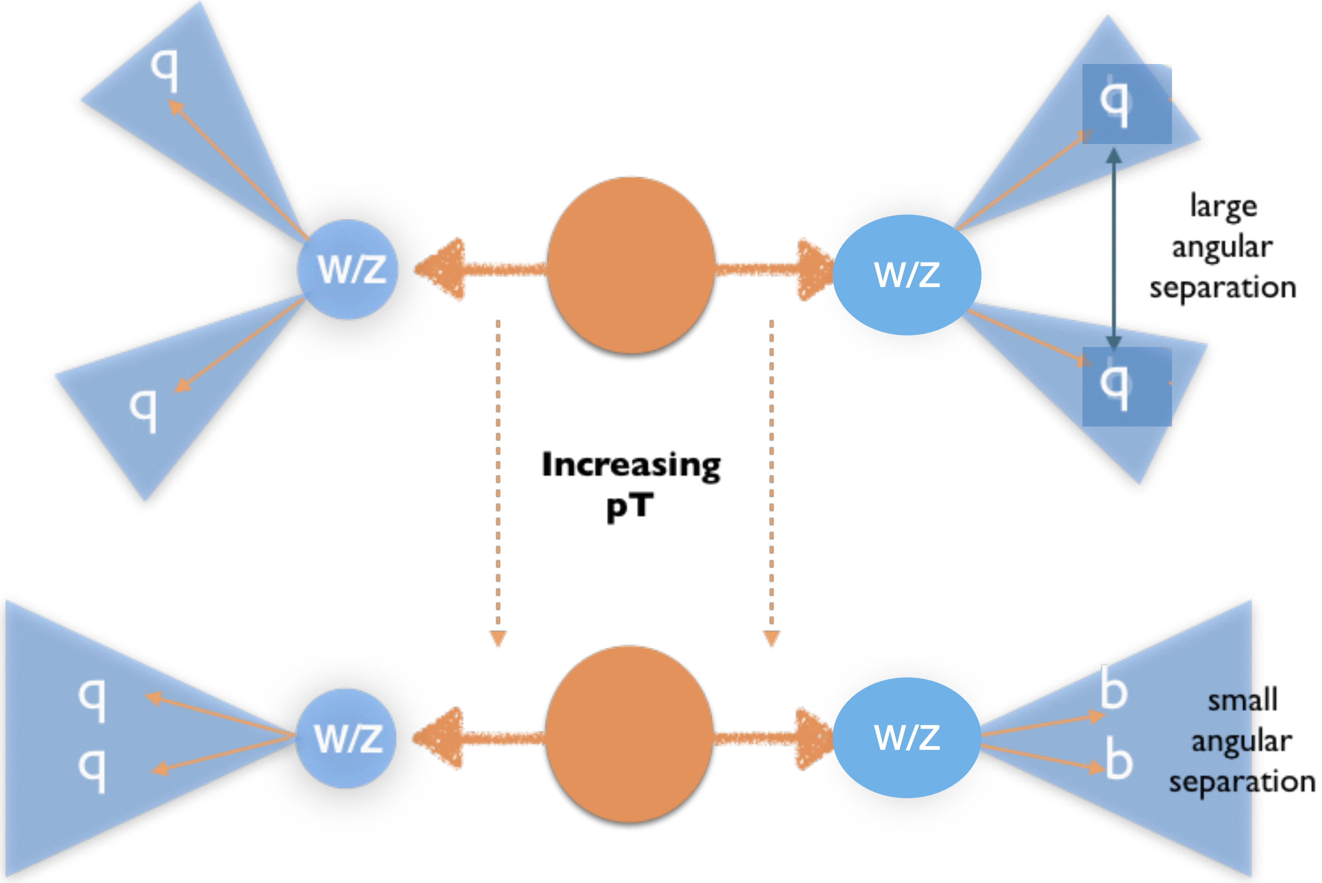
5.dedicated EFT operator extraction by experiments
    - pros: use full detector information, can be most optimal and correct
    - cons: limited to pre-defined list of operators, no alternative reinterpretation
    - questions: what information required to include in global fits?

- How do we move from searches to this? What are the differences?

Example 1: From VBF diboson analysis to VBS analysis

- Final state of VBF diboson analysis is the same as the one probed in **Vector Boson Scattering in the semileptonic final state**





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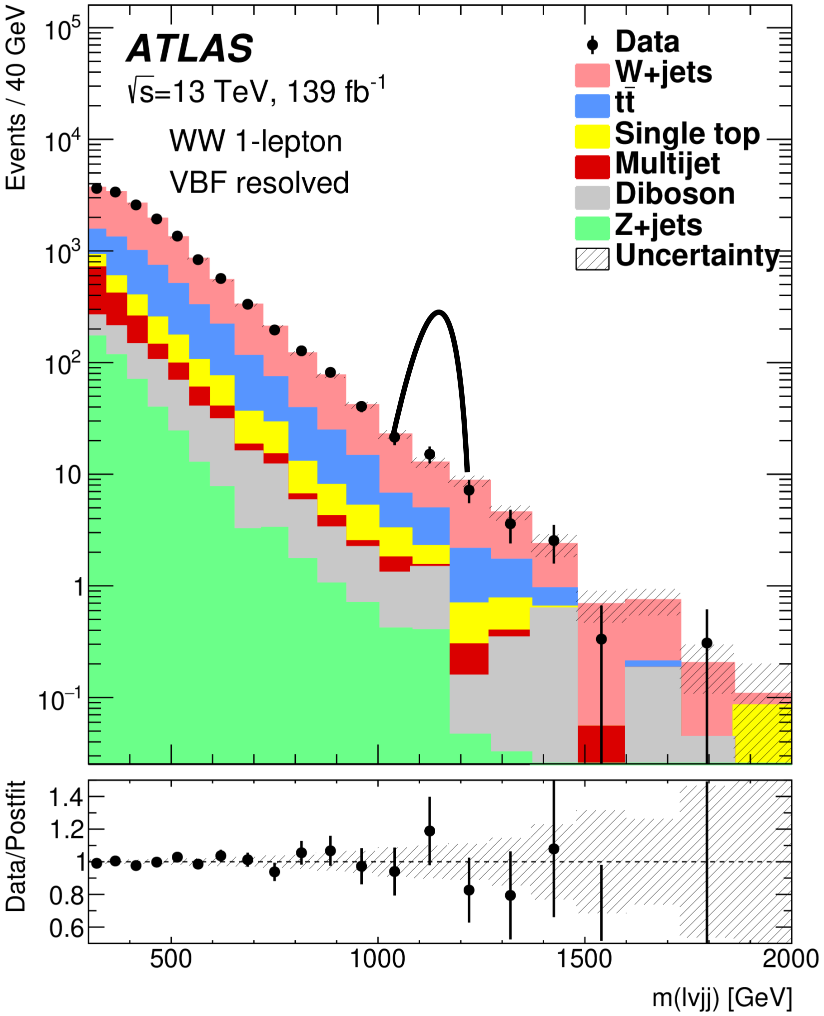

$m(G_{KK})$ = 600 GeV		$m(G_{KK})$ = 2 TeV	
Uncertainty source	$\Delta\mu/\mu$ [%]	Uncertainty source	$\Delta\mu/\mu$ [%]
Total	32	Total	39
Statistical	19	Statistical	33
Systematic	26	Systematic	21
MC statistics	13	Large-R jet	16
Large-R jet	12	MC statistics	7.0
Background normalisations	11	Small-R jet	3.3
W/Z+jets modelling	9.8	$t\bar{t}$ modelling	3.3
Small-R jet	8.0	Flavour tagging	3.0
Diboson modelling	6.3	W/Z+jets modelling	2.2
$t\bar{t}$ modelling	4.3	Background normalisations	2.1

Example 1: From VBF diboson analysis to VBS analysis

- Tagging jets: large pT, large Δη

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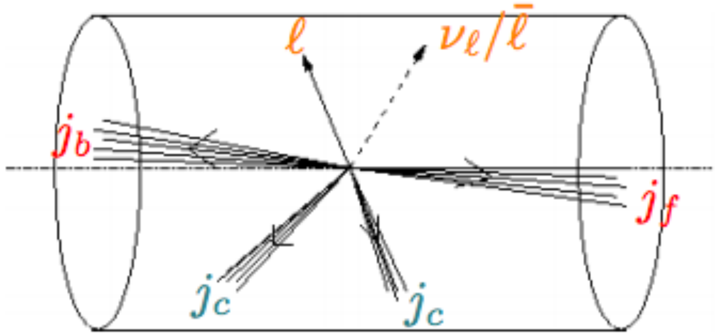
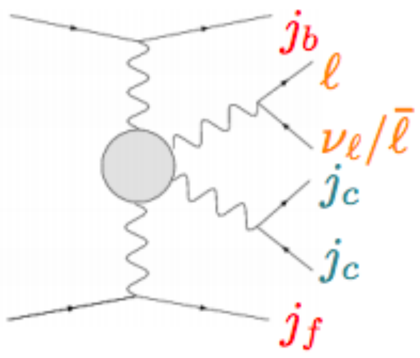
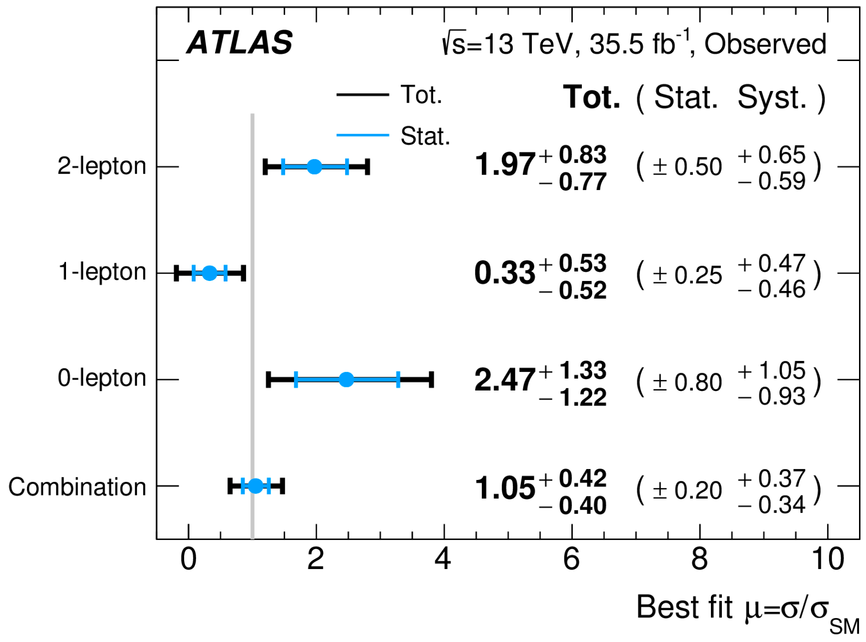
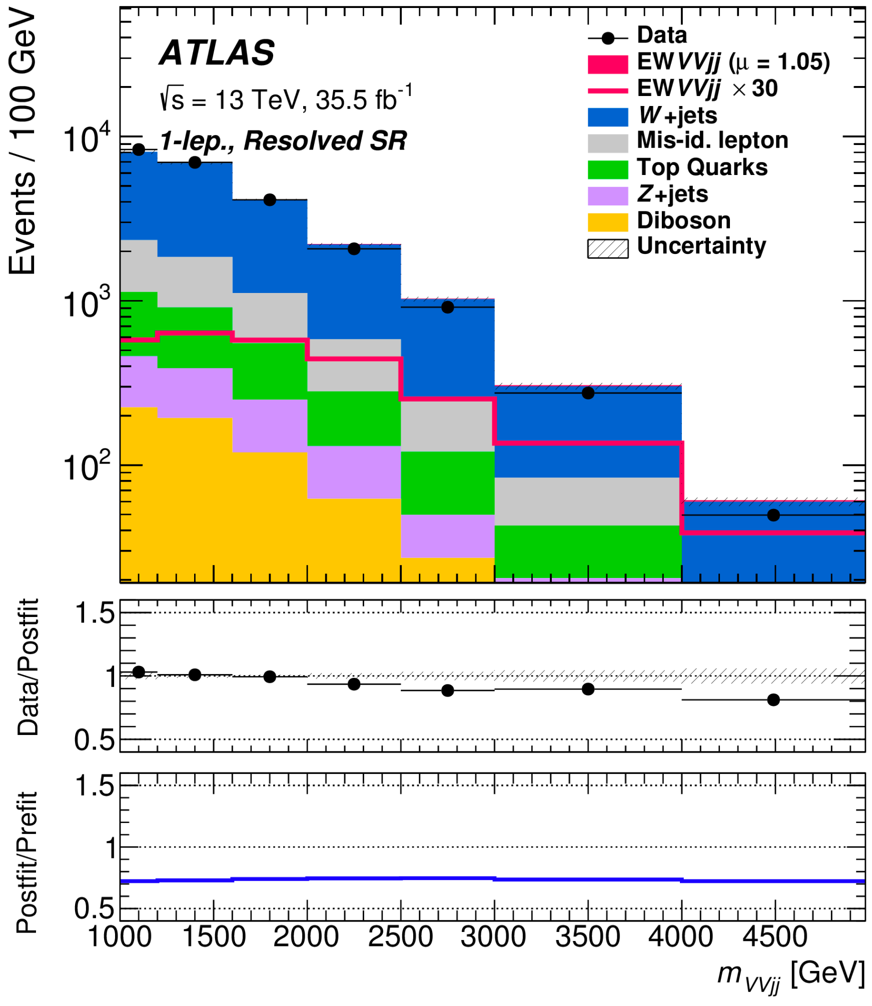
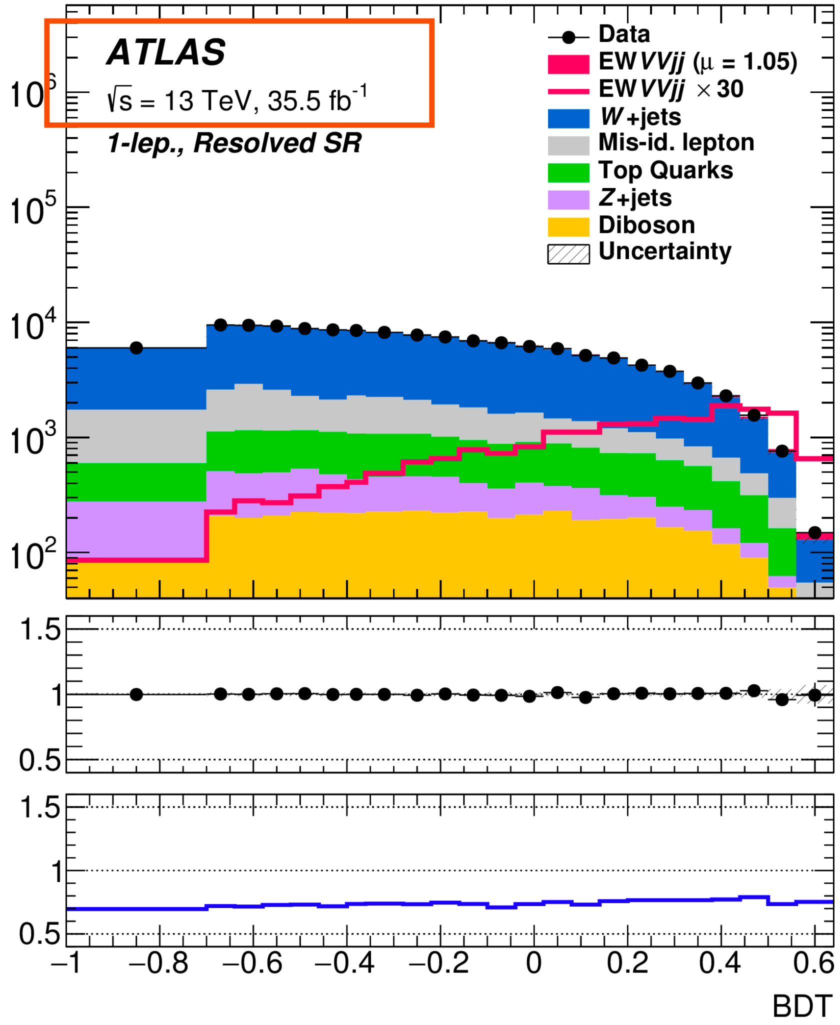
- The main experimental challenges are similar to those faced in the previous searches











Uncertainty source	σ_μ
Total uncertainty	0.41
Statistical	0.20
Systematic	0.35
Theoretical and modeling uncertainties	
Floating normalizations	0.09
$Z+$jets	0.13
$W+$jets	0.09
$t\bar{t}$	0.06
Diboson	0.09
Multijet	0.04
Signal	0.07
MC statistics	0.17
Experimental uncertainties	
Large-R jets	0.08
Small-R jets	0.06
Leptons	0.02
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.04
b-tagging	0.07
Pileup	0.04
Luminosity	0.03

Example 1: From VBF diboson analysis to VBS analysis

- Traces of heavy states from Beyond Standard Model Physics can be parameterized in terms of the Effective Field Theory (EFT) approach.
- ATLAS did not provide EFT limits but the corresponding CMS analysis did
- Limits on aQGCs are set via EFT approach. Dimension-8 operators that can modify VVjj production through aQGCs are considered; one at a time

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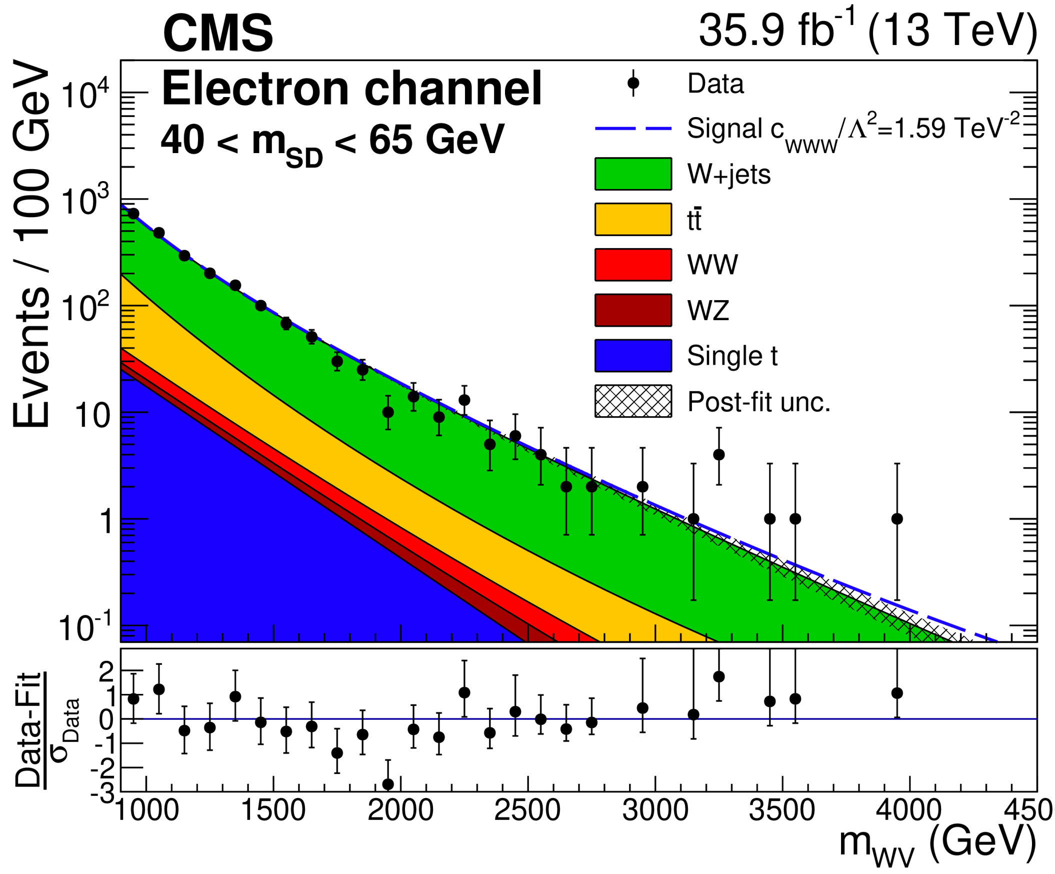
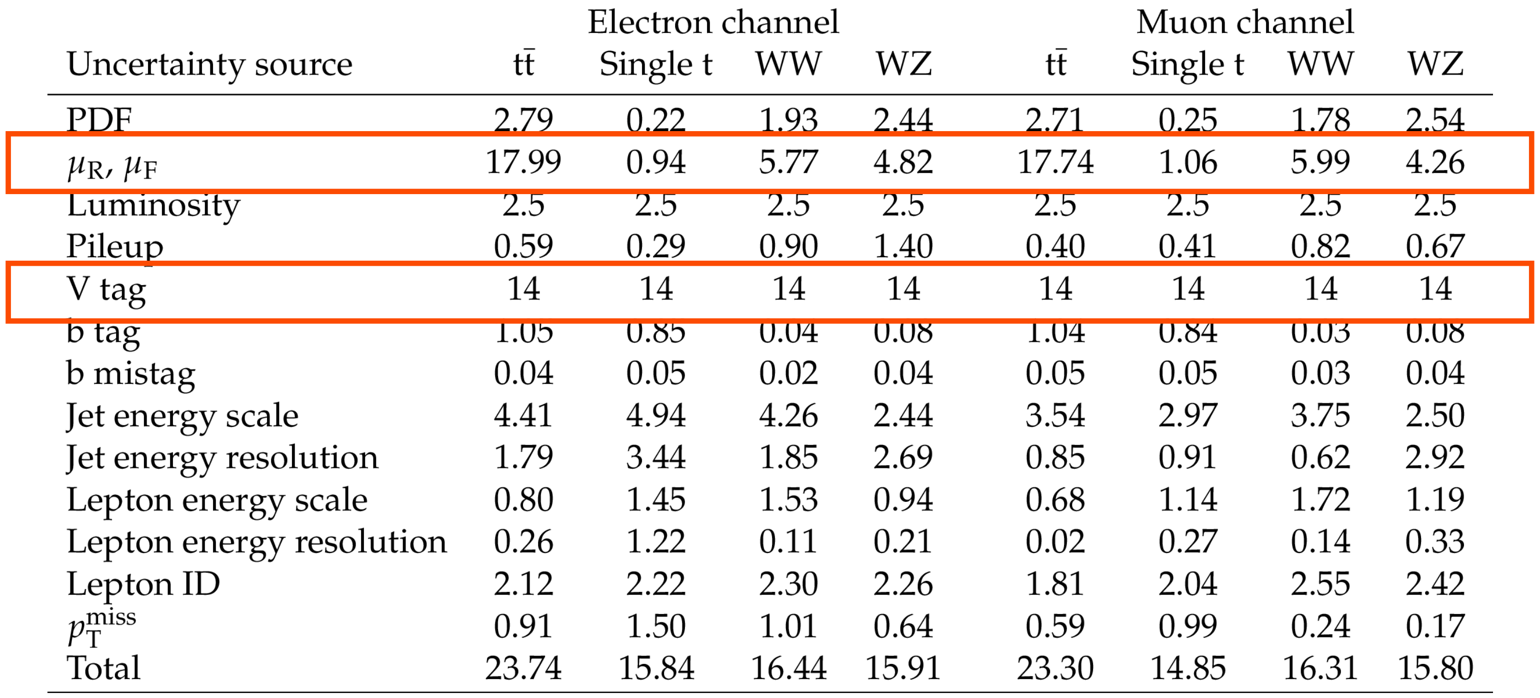
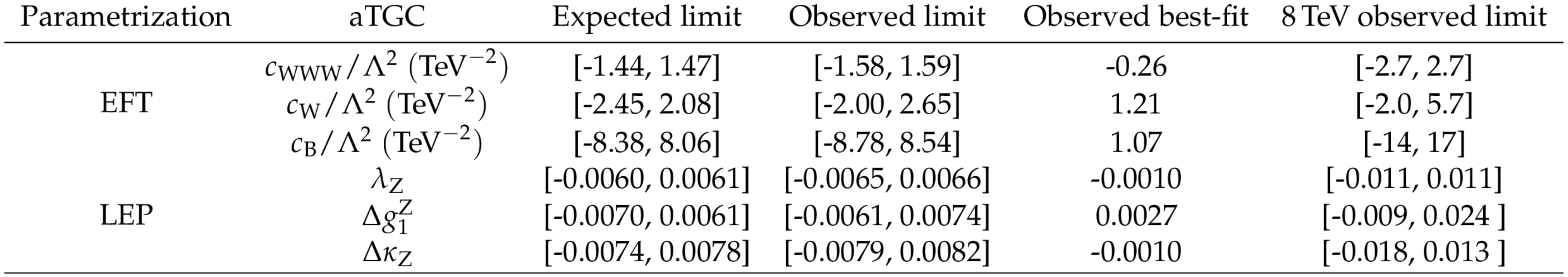




Uncertainty source	Electron channel tt̄	Single t	WW	WZ	Muon channel tt̄	Single t	WW	WZ
PDF	2.79	0.22	1.93	2.44	2.71	0.25	1.78	2.54
μ_R, μ_F	17.99	0.94	5.77	4.82	17.74	1.06	5.99	4.26
Luminosity	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Pileup	0.59	0.29	0.90	1.40	0.40	0.41	0.82	0.67
V tag	14	14	14	14	14	14	14	14
b tag	1.05	0.85	0.04	0.08	1.04	0.84	0.03	0.08
b mistag	0.04	0.05	0.02	0.04	0.05	0.05	0.03	0.04
Jet energy scale	4.41	4.94	4.26	2.44	3.54	2.97	3.75	2.50
Jet energy resolution	1.79	3.44	1.85	2.69	0.85	0.91	0.62	2.92
Lepton energy scale	0.80	1.45	1.53	0.94	0.68	1.14	1.72	1.19
Lepton energy resolution	0.26	1.22	0.11	0.21	0.02	0.27	0.14	0.33
Lepton ID	2.12	2.22	2.30	2.26	1.81	2.04	2.55	2.42
p_T^{miss}	0.91	1.50	1.01	0.64	0.59	0.99	0.24	0.17
Total	23.74	15.84	16.44	15.91	23.30	14.85	16.31	15.80



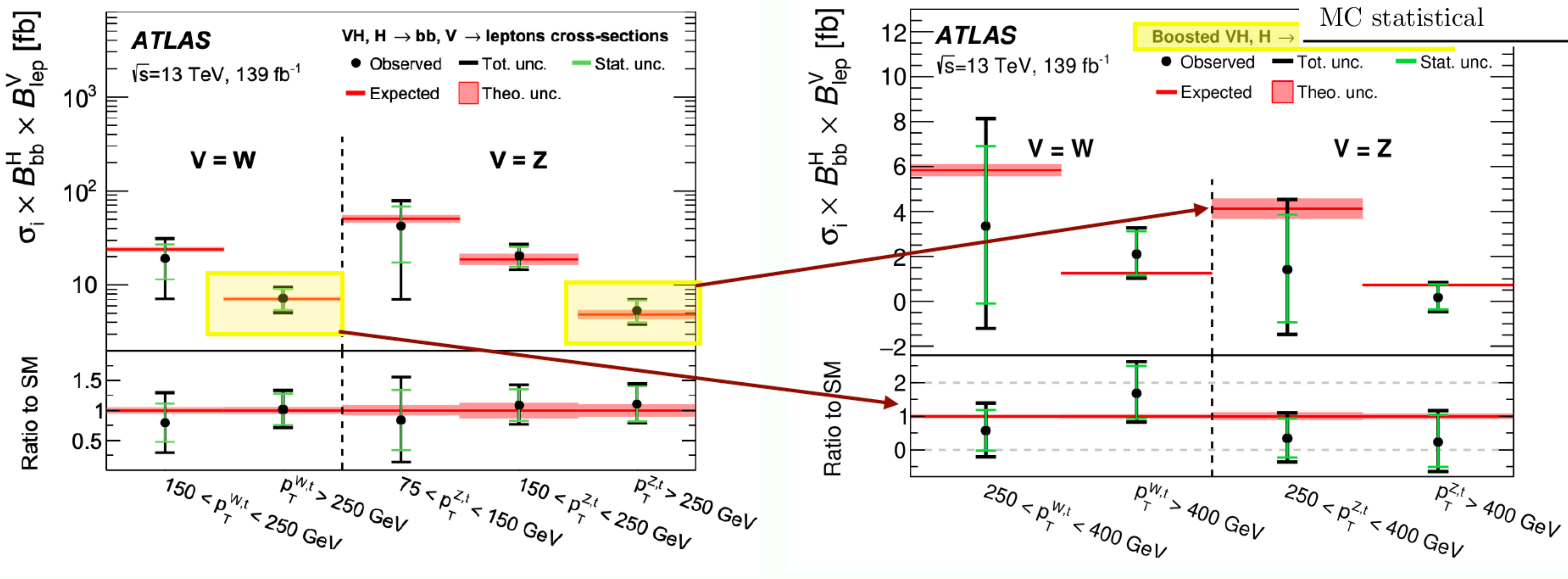
Parametrization	aTGC	Expected limit	Observed limit	Observed best-fit	8 TeV observed limit
EFT	c_{WWW}/Λ^2 (TeV^{-2})	[-1.44, 1.47]	[-1.58, 1.59]	-0.26	[-2.7, 2.7]
	c_W/Λ^2 (TeV^{-2})	[-2.45, 2.08]	[-2.00, 2.65]	1.21	[-2.0, 5.7]
	c_B/Λ^2 (TeV^{-2})	[-8.38, 8.06]	[-8.78, 8.54]	1.07	[-14, 17]
LEP	λ_Z	[-0.0060, 0.0061]	[-0.0065, 0.0066]	-0.0010	[-0.011, 0.011]
	Δg_1^Z	[-0.0070, 0.0061]	[-0.0061, 0.0074]	0.0027	[-0.009, 0.024]
	$\Delta\kappa_Z$	[-0.0074, 0.0078]	[-0.0079, 0.0082]	-0.0010	[-0.018, 0.013]

Other possibilities: VH boosted

Phys. Lett. B 816 (2021) 136204

- Boosted VH (semile-ptonic) also started as a resonance analysis
- Different approaches to reinterpret Higgs measurements searching for BSM effects using the EFT framework
  - In general, sensitivity to different types of operators from different kinematic distributions
  - STXS in the 3rd generation with V$H \to bb$ with Sensitivity to Higgs p_T above 300 GeV and m_{jj} above 700 GeV

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
↪ Z + jets		0.048
↪ W + jets		0.058
↪ $t\bar{t}$		0.035
↪ Single top quark		0.027
↪ Diboson		0.032
↪ Multijet		0.009
MC statistical		0.092



Other possibilities: VH boosted

arXiv:1908.06980

- Boosted VH (semile-ptonic) also started as a resonance analysis
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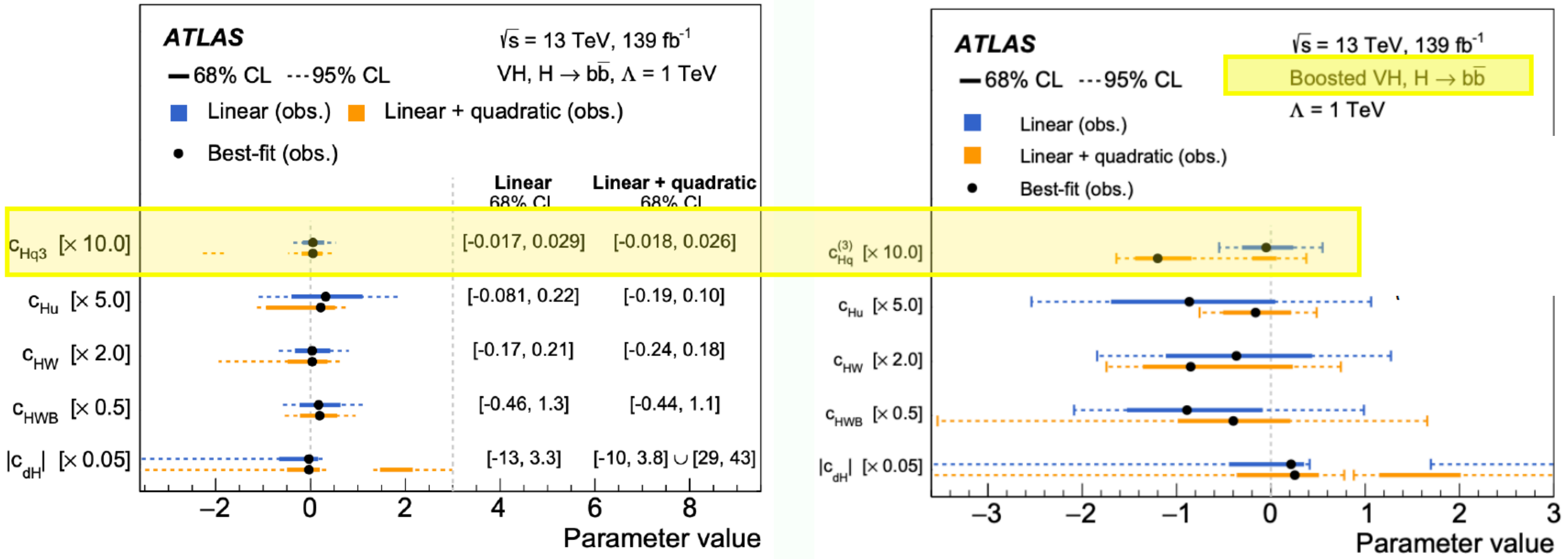
  - In general, sensitivity to different types of operators from different kinematic distributions
  - STXS in the 3rd generation with V$H \to bb$ with Sensitivity to Higgs pT above 300 GeV and mjj above 700 GeV

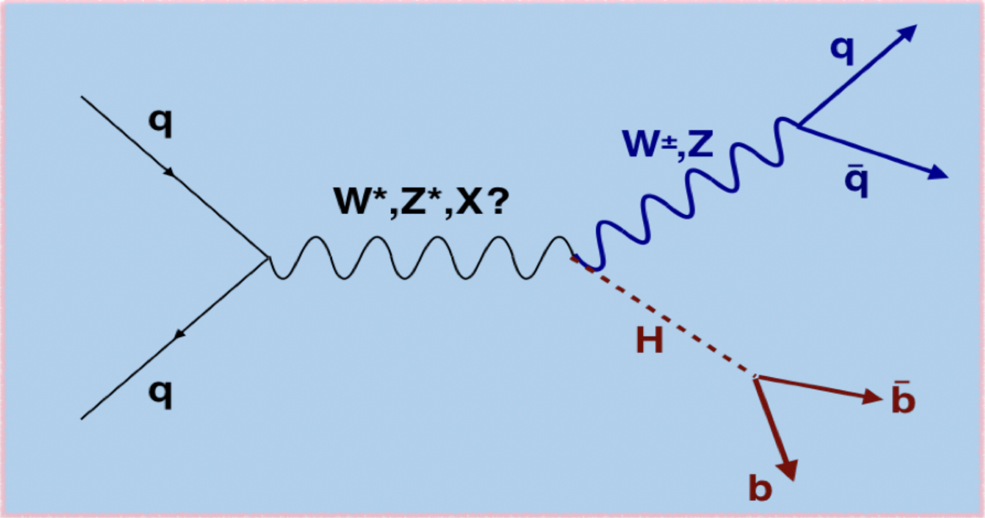
Wilson coefficient	Operator	Impacted vertex Production	 Decay
c_{HWB}	$O_{HWB} = H^\dagger \tau^I H W^I_{\mu\nu} B^{\mu\nu}$	HZZ	
c_{HW}	$O_{HW} = H^\dagger H W^I_{\mu\nu} W_I^{\mu\nu}$	HZZ, HWW	
c_{Hq3}	$O^{(3)}_{Hq} = (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$	$qqZH, qq'WH$	
c_{Hq1}	$O^{(1)}_{Hq} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$	$qqZH$	
c_{Hu}	$O_{Hu} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$	$qqZH$	
c_{Hd}	$O_{Hd} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$	$qqZH$	
c_{dH}	$O_{dH} = (H^\dagger H)(\bar{q} d H)$		Hbb



NOTE THE CHANGE ON THE X-AXIS

VH fully hadronic resonance analysis

- Basic Idea: Discriminate W/Z/H jets from quark/gluon background jets and hunt for ‘bumps’ on an otherwise smoothly falling mVH background.
- Primary Tools (H/W/Z Tagging):
    - Jet Mass
    - Jet Substructure (D2)
        - Select for W/Z two-pronged structure
    - Jet Ntrk
        - Reject gluon jets which have higher track multiplicity
    - B-tagging
        - Pick out H->bb decays.
        - Variable Radius (VR) Track Jets $H \rightarrow b\bar{b}$
    - Background Estimation:
        - Use low-purity selection of events with 0 b-tags to produce background estimations with high statistics for 1/2-tag SR channels.



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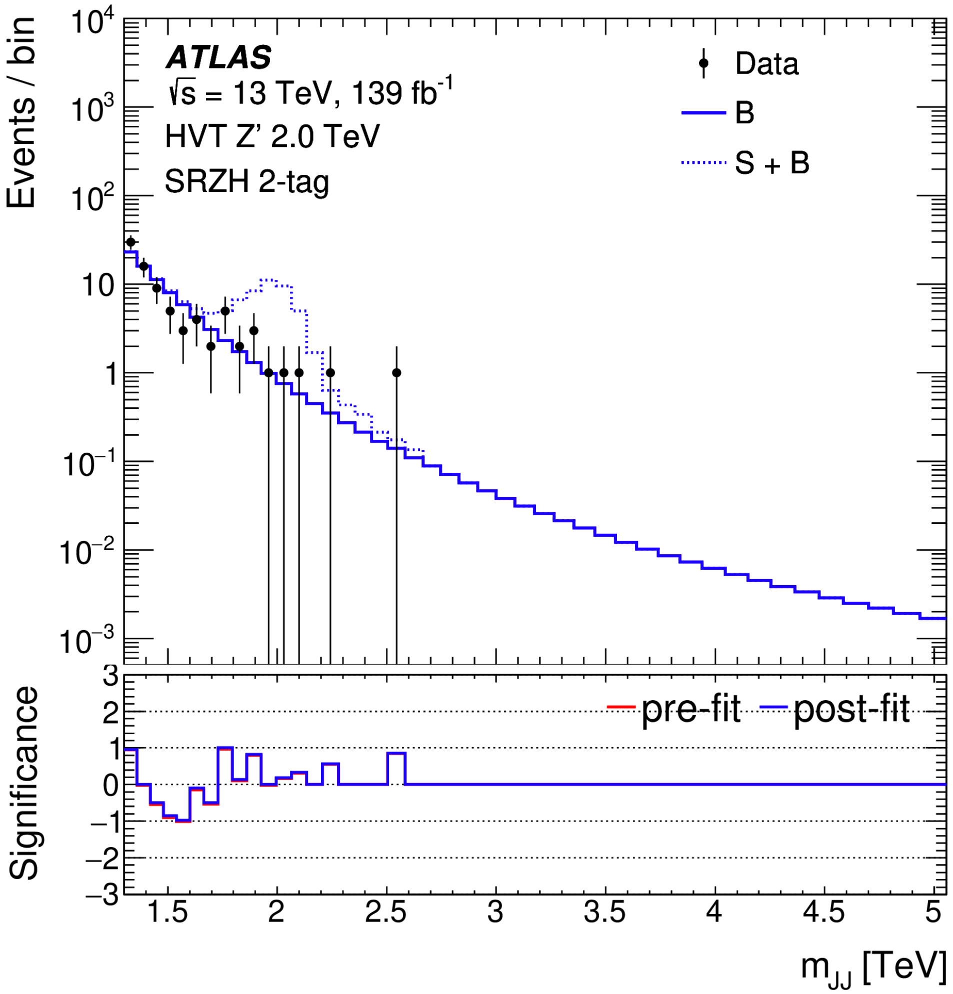
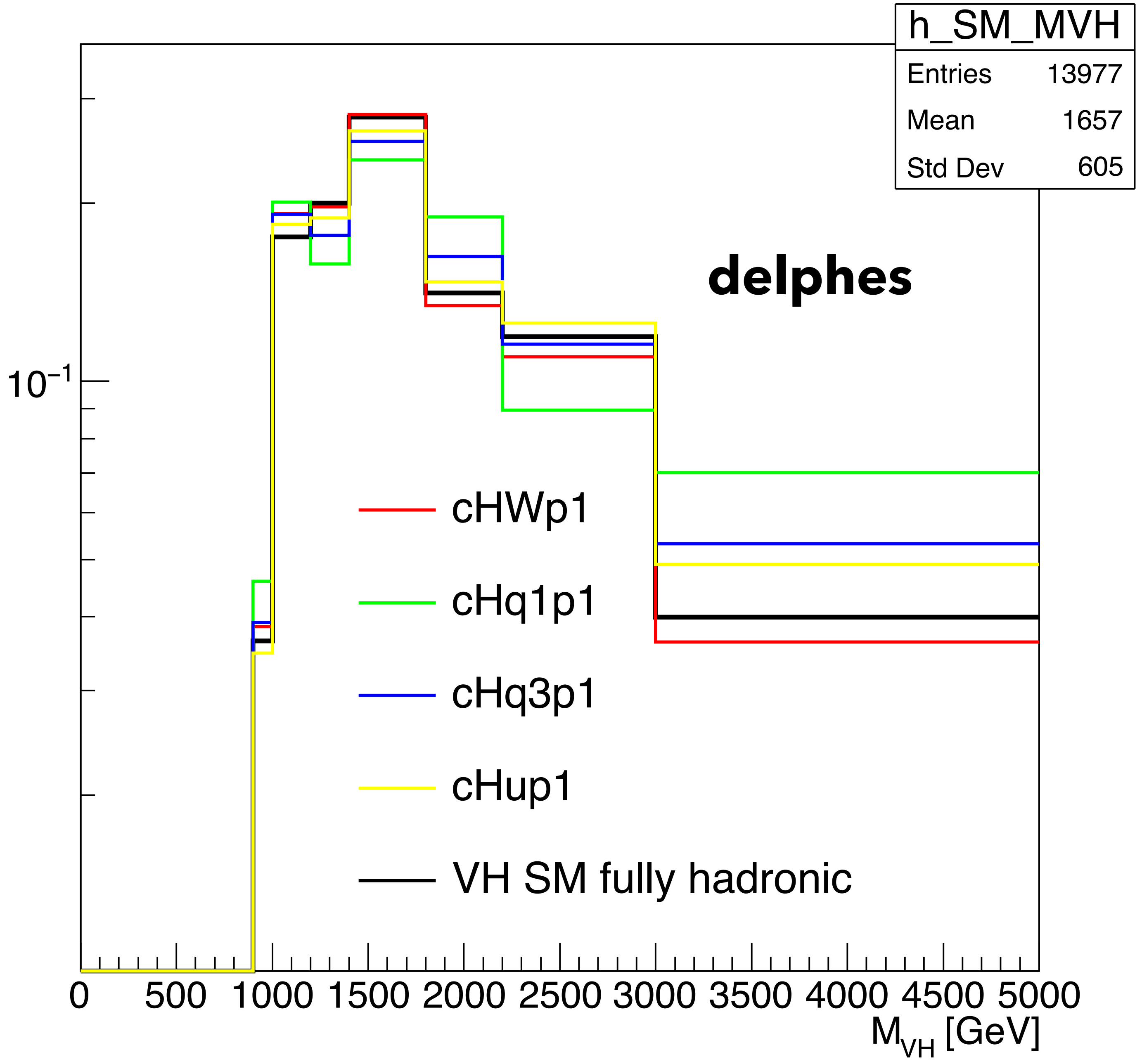
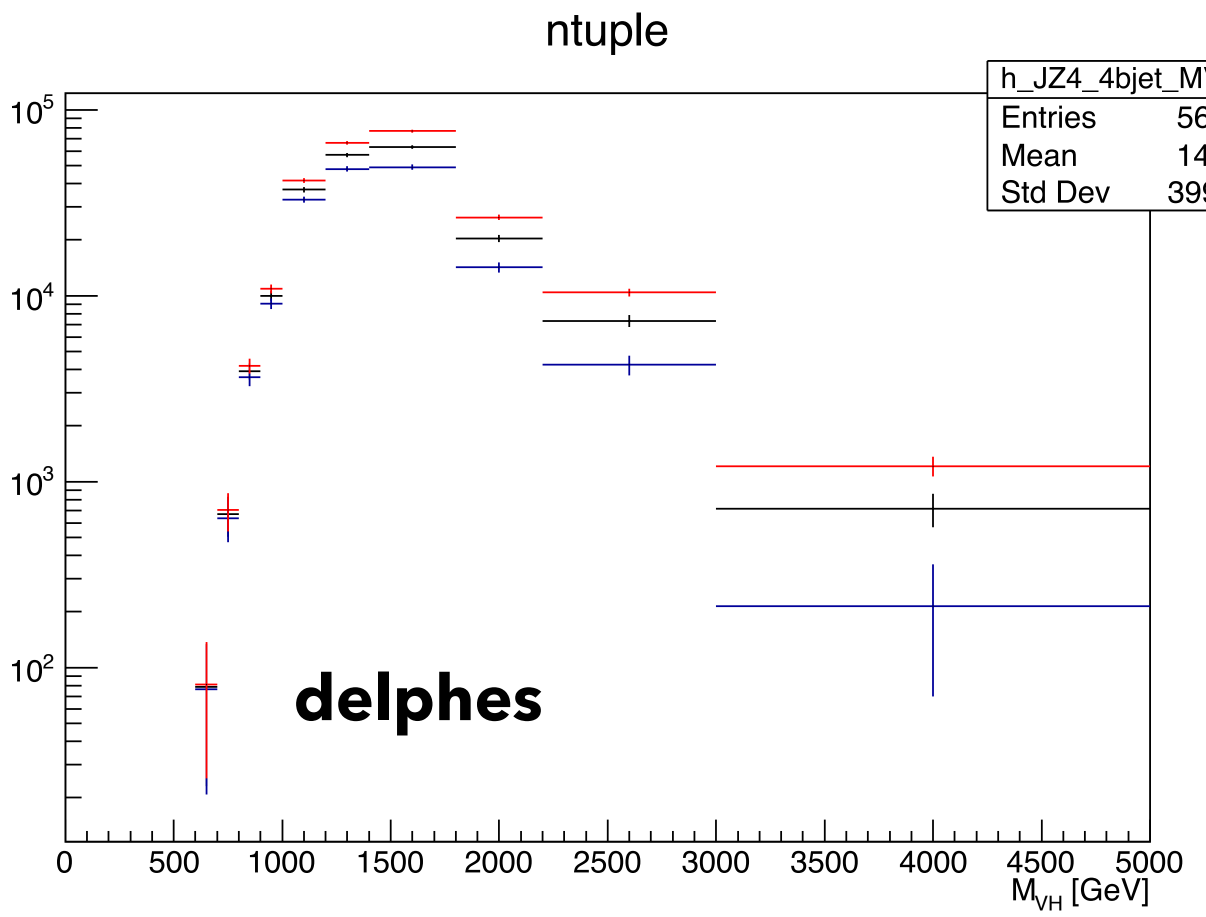


EFT search in VH resonance analysis

- Started looking at delphes to see if analysis looked promising in the fully hadronic final state
  - With no systematic limits on wilson coefficients are very good ==> comparable with semileptonic final states
- Need to be very careful about how to estimate the background and its uncertainty





+20% on the shape uncertainty

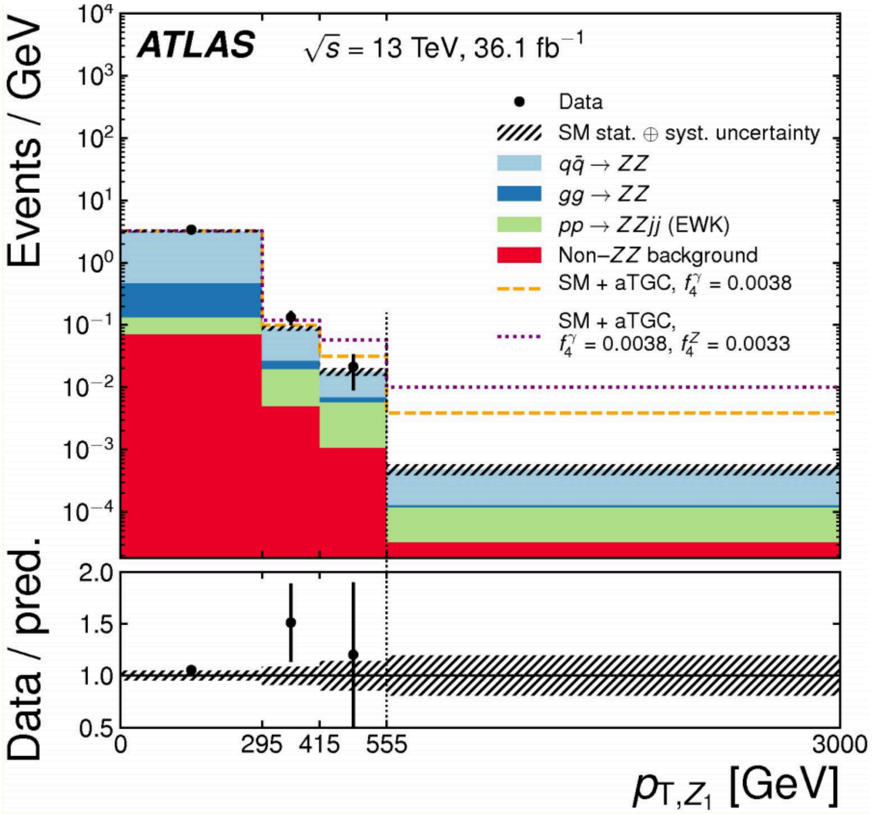
-20% on the shape uncertainty

Discussion points

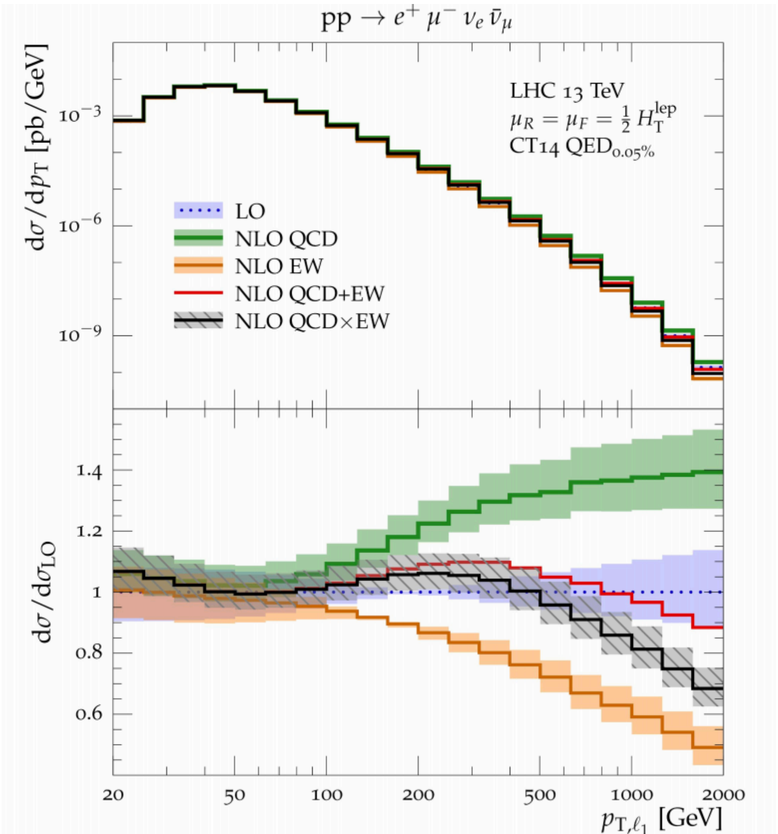
- Variables and binning:
  - What variables to measure (in case of unfolded distributions)
  - Which are the most sensitive to EFT parameters?
  - Often only most obvious variables, correlated with the centre-of-mass energy are used
  - Useful to receive feedback on other interesting distributions (angular variables, 2 D distributions)

Discussion points

- Tools? What is the best approach to interpolate between EFT !=0 points?
    - MC@NLO, aMC@NLO (reweighting, possibility to generate single terms), etc…
- Theory uncertainties on tails
- On the SM predictions :
    - Are EFT effects large where SM corrections are also large (large energy spread)?
- On the EFT predictions:
    - Higher order in the SM couplings
    - Higher order in Λ
    - Scale (running) and PDF uncertainties (PDF at LO/NLO/NNLO)
    - EFT contribution to background
    - Scaling the EFT contribution as the SM?

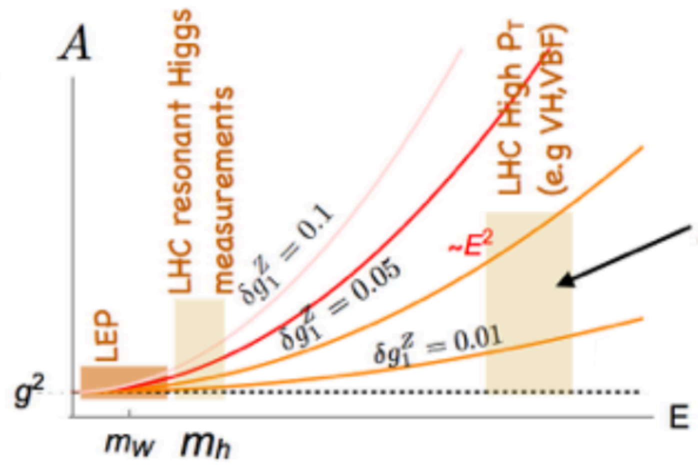


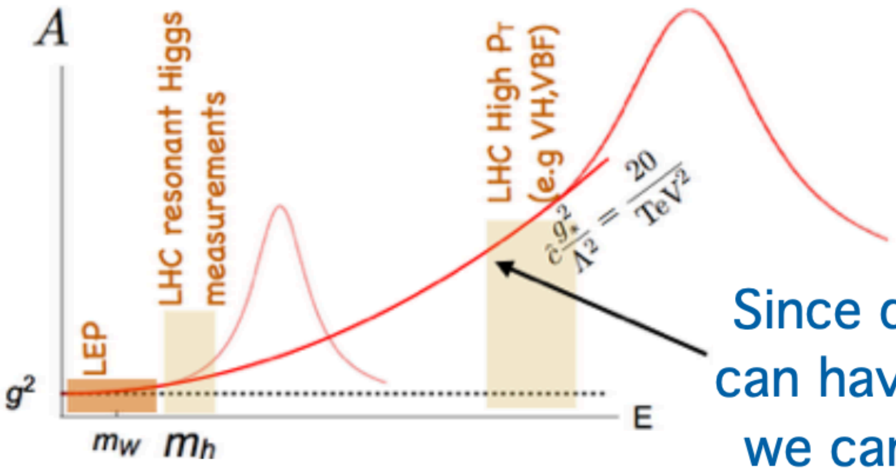
arXiv:1705.00598v1



EFT validity

- EFT amplitudes grow with MVV and this growth is unphysical above a certain scale Λ; this sets the limit of validity of EFT approach
- Clipping? removing EFT signals above a certain threshold on truth level
  - easiest to implement but not well studied
  - Above Λ , since the data is consistent with SM, we replace prediction of EFT amplitudes with SM in that region; this leads to conservative bounds on EFT Wilson coefficients
  - With this method we would loose most of the sensitivity



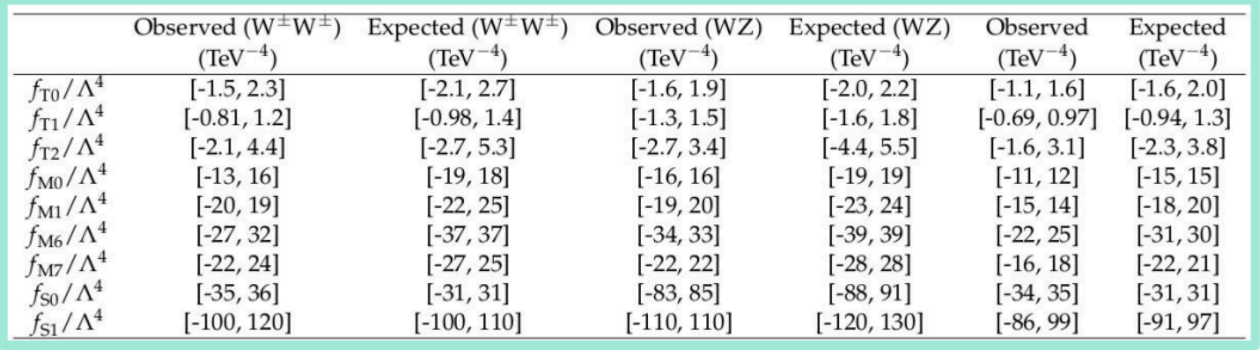


Since dibosons processes can have very high energy, we can easily go outside the validity region of the EFT approach.

From CMS:

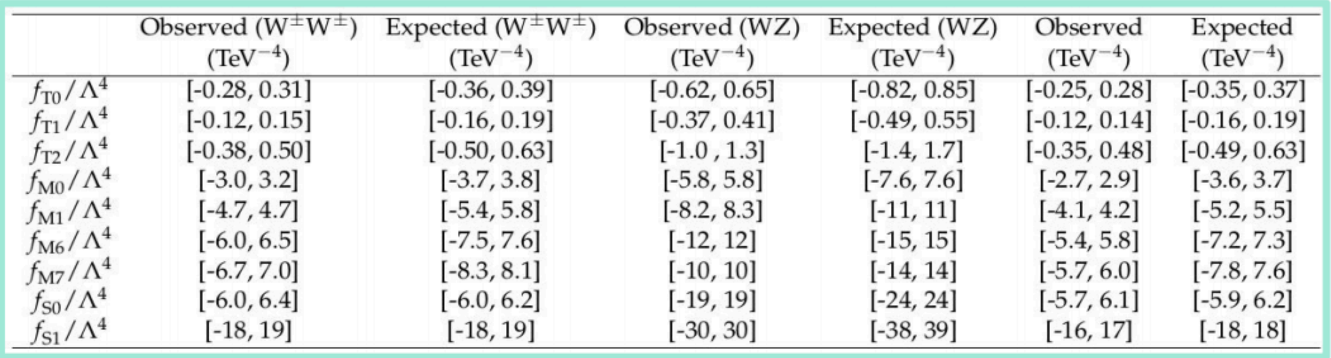
- For aqgc simulation, events violating unitarity (vary with operator values) are rejected ~ max 80% (WW) & max 50%(WZ). Data & SM processes are not affected.

$W^{\pm}W^{\pm}$ & WZ with considering unitarity bounds



	Observed ($W^{\pm}W^{\pm}$) (TeV^{-4})	Expected ($W^{\pm}W^{\pm}$) (TeV^{-4})	Observed (WZ) (TeV^{-4})	Expected (WZ) (TeV^{-4})	Observed (TeV^{-4})	Expected (TeV^{-4})
f_{T0}/Λ^4	[-1.5, 2.3]	[-2.1, 2.7]	[-1.6, 1.9]	[-2.0, 2.2]	[-1.1, 1.6]	[-1.6, 2.0]
f_{T1}/Λ^4	[-0.81, 1.2]	[-0.98, 1.4]	[-1.3, 1.5]	[-1.6, 1.8]	[-0.69, 0.97]	[-0.94, 1.3]
f_{T2}/Λ^4	[-2.1, 4.4]	[-2.7, 5.3]	[-2.7, 3.4]	[-4.4, 5.5]	[-1.6, 3.1]	[-2.3, 3.8]
f_{M0}/Λ^4	[-13, 16]	[-19, 18]	[-16, 16]	[-19, 19]	[-11, 12]	[-15, 15]
f_{M1}/Λ^4	[-20, 19]	[-22, 25]	[-19, 20]	[-23, 24]	[-15, 14]	[-18, 20]
f_{M6}/Λ^4	[-27, 32]	[-37, 37]	[-34, 33]	[-39, 39]	[-22, 25]	[-31, 30]
f_{M7}/Λ^4	[-22, 24]	[-27, 25]	[-22, 22]	[-28, 28]	[-16, 18]	[-22, 21]
f_{S0}/Λ^4	[-35, 36]	[-31, 31]	[-83, 85]	[-88, 91]	[-34, 35]	[-31, 31]
f_{S1}/Λ^4	[-100, 120]	[-100, 110]	[-110, 110]	[-120, 130]	[-86, 99]	[-91, 97]

$W^{\pm}W^{\pm}$ & WZ without considering unitarity bounds



	Observed ($W^{\pm}W^{\pm}$) (TeV^{-4})	Expected ($W^{\pm}W^{\pm}$) (TeV^{-4})	Observed (WZ) (TeV^{-4})	Expected (WZ) (TeV^{-4})	Observed (TeV^{-4})	Expected (TeV^{-4})
f_{T0}/Λ^4	[-0.28, 0.31]	[-0.36, 0.39]	[-0.62, 0.65]	[-0.82, 0.85]	[-0.25, 0.28]	[-0.35, 0.37]
f_{T1}/Λ^4	[-0.12, 0.15]	[-0.16, 0.19]	[-0.37, 0.41]	[-0.49, 0.55]	[-0.12, 0.14]	[-0.16, 0.19]
f_{T2}/Λ^4	[-0.38, 0.50]	[-0.50, 0.63]	[-1.0 , 1.3]	[-1.4, 1.7]	[-0.35, 0.48]	[-0.49, 0.63]
f_{M0}/Λ^4	[-3.0, 3.2]	[-3.7, 3.8]	[-5.8, 5.8]	[-7.6, 7.6]	[-2.7, 2.9]	[-3.6, 3.7]
f_{M1}/Λ^4	[-4.7, 4.7]	[-5.4, 5.8]	[-8.2, 8.3]	[-11, 11]	[-4.1, 4.2]	[-5.2, 5.5]
f_{M6}/Λ^4	[-6.0, 6.5]	[-7.5, 7.6]	[-12, 12]	[-15, 15]	[-5.4, 5.8]	[-7.2, 7.3]
f_{M7}/Λ^4	[-6.7, 7.0]	[-8.3, 8.1]	[-10, 10]	[-14, 14]	[-5.7, 6.0]	[-7.8, 7.6]
f_{S0}/Λ^4	[-6.0, 6.4]	[-6.0, 6.2]	[-19, 19]	[-24, 24]	[-5.7, 6.1]	[-5.9, 6.2]
f_{S1}/Λ^4	[-18, 19]	[-18, 19]	[-30, 30]	[-38, 39]	[-16, 17]	[-18, 18]

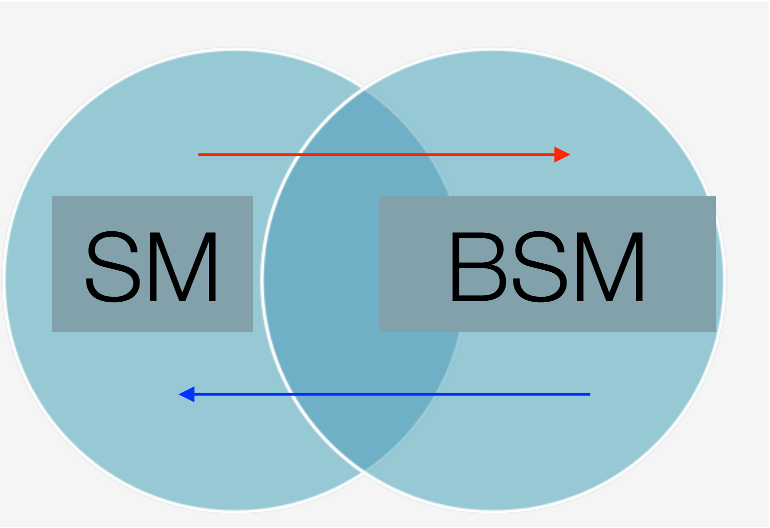
Analysis strategies and experimental outputs (I)

- Differential measurements and the best choice of observables for re-interpretation
  - pros: general-purpose information open for reinterpretation
  - cons: not necessarily optimal information, measured under SM assumption
  - questions: are SM assumption important?
- two approaches:
  - Fiducial differential measurements:
    - pros: matched to experimental phase-space ⇒ least model-dependent
    - cons: no separation of subprocesses; usually 1D or 2D, difficult to combine
  - Binned sub-process cross sections (e.g. STXS in Higgs)
    - pros: separated sub-processes; global binning based on multiple variables
    - cons: more model-dependence; coarser binning
  - questions: how to address “unfolding” uncertainties ? treatment of bkg ?

Analysis strategies and experimental outputs (II)

- Most of the analysis are limited by the MC modeling
  - Would it help to measure a simplified cross section in searches sidebands?

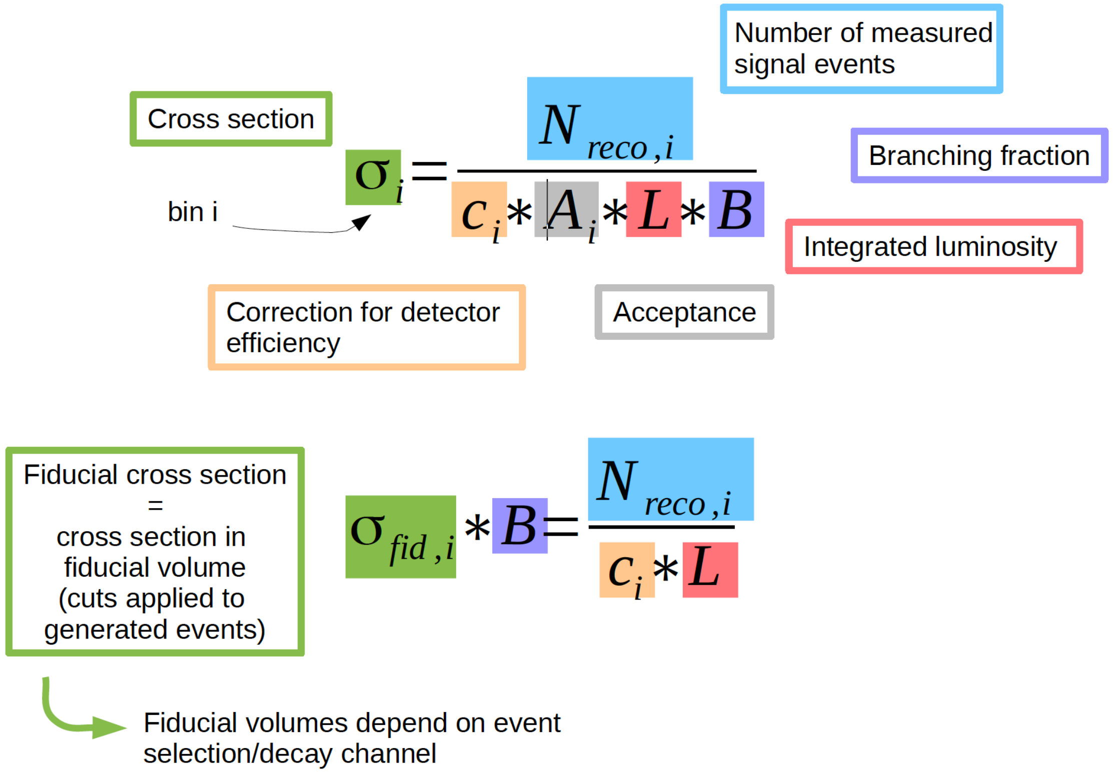
From BSM to SM:



- Precision Standard Model cross-sections are **usually (there are exceptions)** performed in phase-spaces which are not so sensitive to BSM physics (e.g. Z boson mass peak)
  - SM MC predictions in ‘exotic’ phase spaces are less well known
- → Exotic Cross Sections:
  - cross-section of final-state, rather than one particular process
  - Useful for theory community to reinterpret ATLAS results with their models ==> **Is this true?**
  - Particle-based fiducial cross-section measurements are good way to get Monte Carlo generators that describe our final state.
- Why not measure in extreme phase space of control region of particular searches ?
  - → Would allow to tune MC in new phase space corners e.g. Met+jets, MET+ttbar, ttbar+HF, W+HF, large multiplicity physics objects.

Exotic cross-section

- Standard Model fiducial cross section for a particular process
- Same basic formula for exotic cross section:
  - Treat multi-jet processes / fake leptons as background
  - Other SM processes are signal
- Updated definition of C to account for multiple SM processes, i
- not covered by existing SM analyses
- Could be measured inclusively or differentially
- Good agreement with SM + data in control plots would be demanded
- In addition to uncertainties detailed in original analysis would need to evaluate theoretical and modeling uncertainties on the cross section



Number of measured signal events

Cross section

Branching fraction

bin i

$$\sigma_i = \frac{N_{reco,i}}{c_i * A_i * L * B}$$

Integrated luminosity

Correction for detector efficiency

Acceptance

Fiducial cross section = cross section in fiducial volume (cuts applied to generated events)

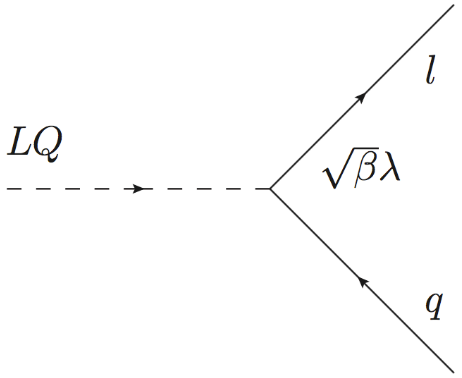
$$\sigma_{fid,i} * B = \frac{N_{reco,i}}{c_i * L}$$

Fiducial volumes depend on event selection/decay channel

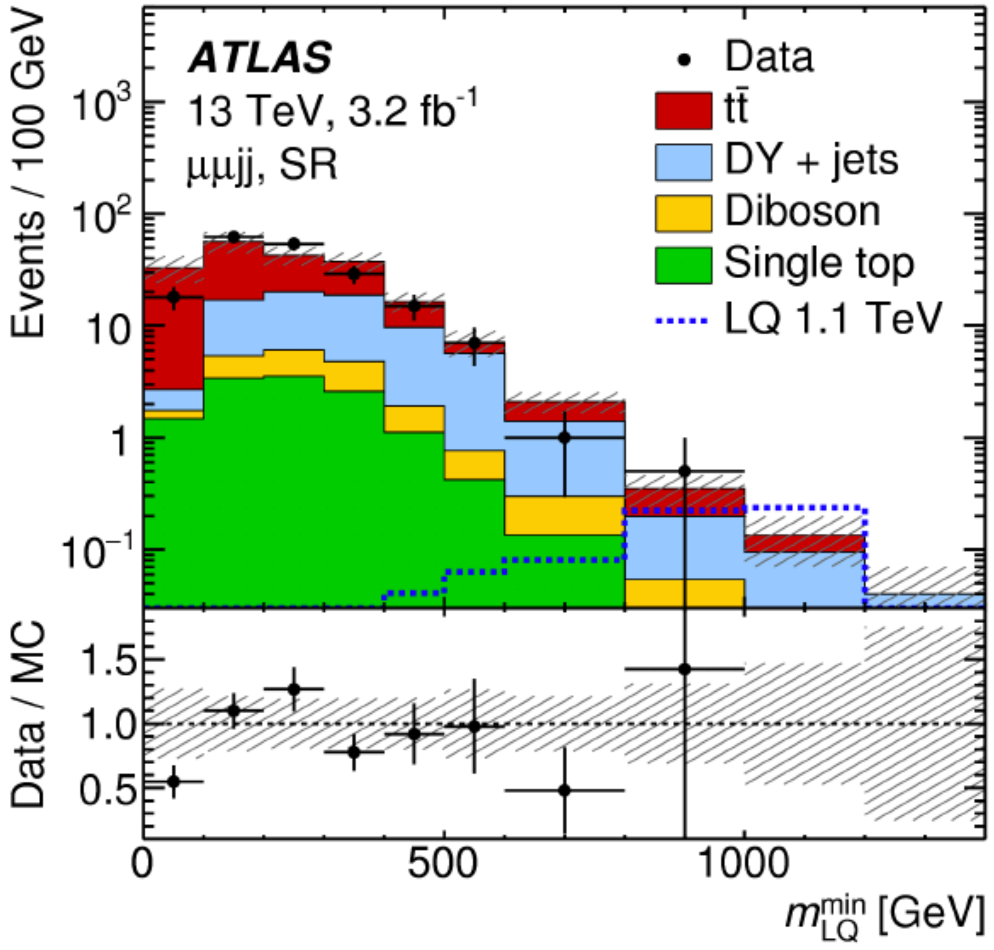
$$\boxed{\frac{1}{C} = \sum_{i}^{N} \frac{\sigma_i}{\sigma_{total}} \cdot \frac{1}{C_i}}$$

LeptoQuark analysis

- Pair-produced LeptoQuark analysis
- New J. Phys. 18 (2016) 093016 [paper]
- Final state of interest
- 2 leptons + 2 jets
- Unfold and extract cross section in CR:
  - Z CR where m_ll is compatible with the Z
  - tt bar CR

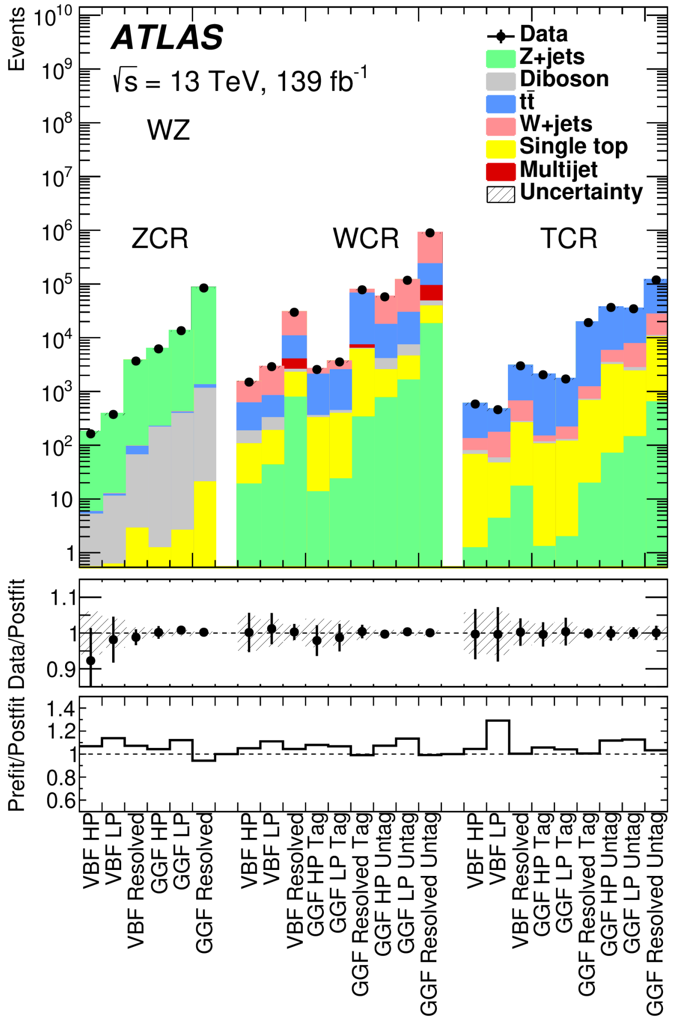


- Produce correction factor, C, using $t\bar{t}$ and Z→μμ MC (fiducial measurement)
  - inclusive: i.e. one value of C per MC
  - differential measurement would also be possible in the future
  - Include all systematics
    - MC theoretical uncertainties such as scale and PDF variations
- Theoretical cross section uncertainty important when adding C factors
- Other interesting final states are the DarkMatter ones:
  - Missing E_T + b
  - Missing E_T+bb

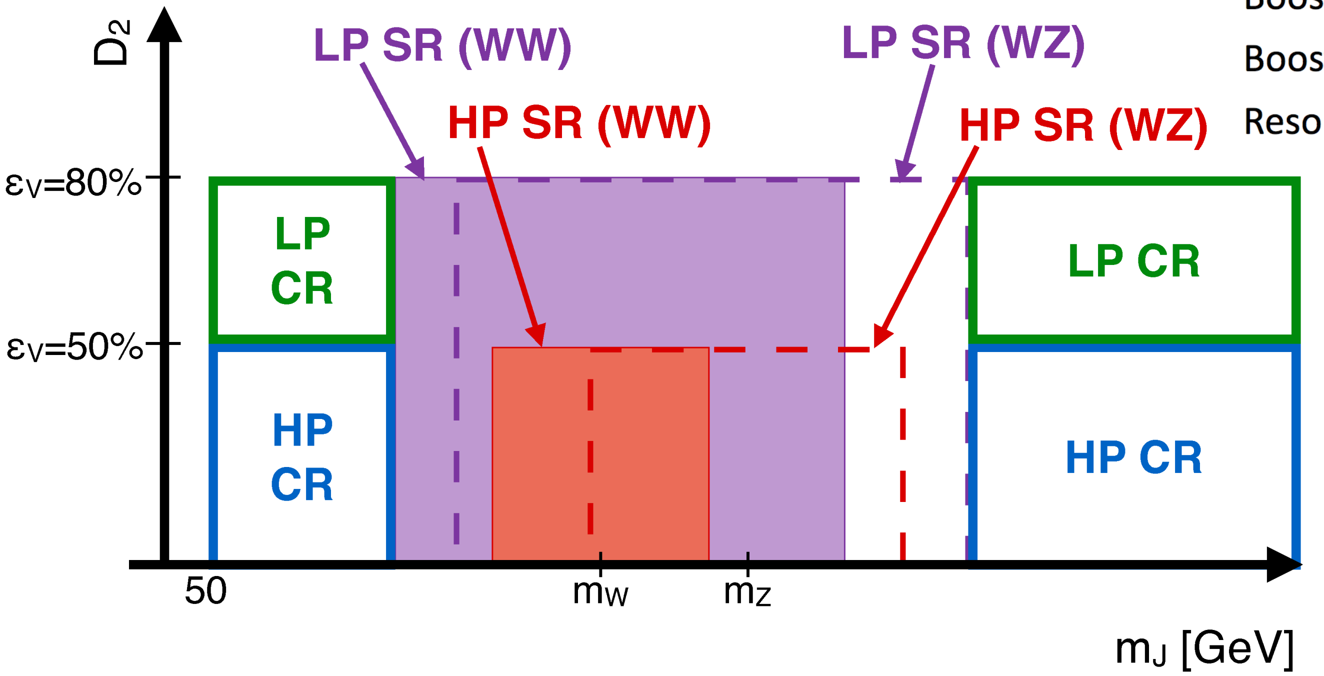


Other possibilities: control regions in diboson analysis

- Many diboson exotics analysis use control regions
- Defined as mJ sidebands
- Allows to really constrain W+jets and t tbar modeling and normalization systematics
    - Different phase spaces give different constraints: Resolved, Boosted and VBF



- W+jets normalization constrained to 3%
- Can this be turned into something more useful?



Boosted HP - fat jet D2 @50%

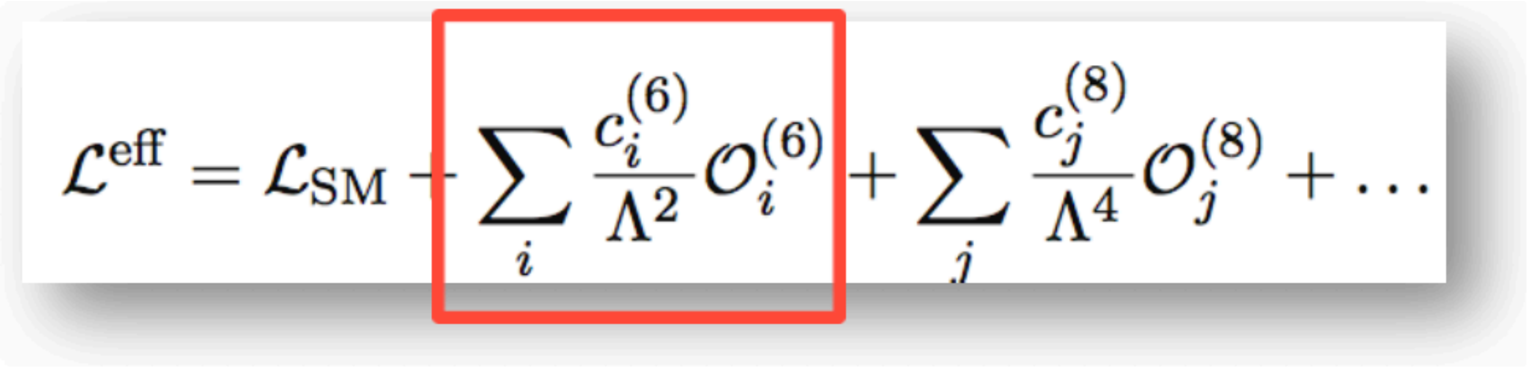
Boosted LP - fat jet D2 @80%

Resolved - two resolved jet

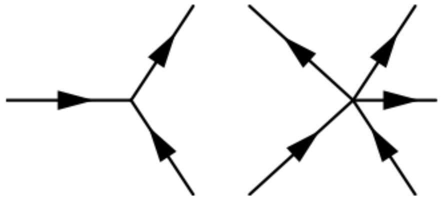
Summary of first part

- Naturalness and Dark Matter point to new physics in reach of the LHC
  - Higher energy, more luminosity
  - Goal: discover new physics if it is in our data (only 5% of the overall project luminosity analyzed)
- At the LHC we can do more than searching for bumps !!
- Start looking at tails!
  - This needs some thoughts both on the framework side and on the analysis strategies
  - More on the STXS from Haider!

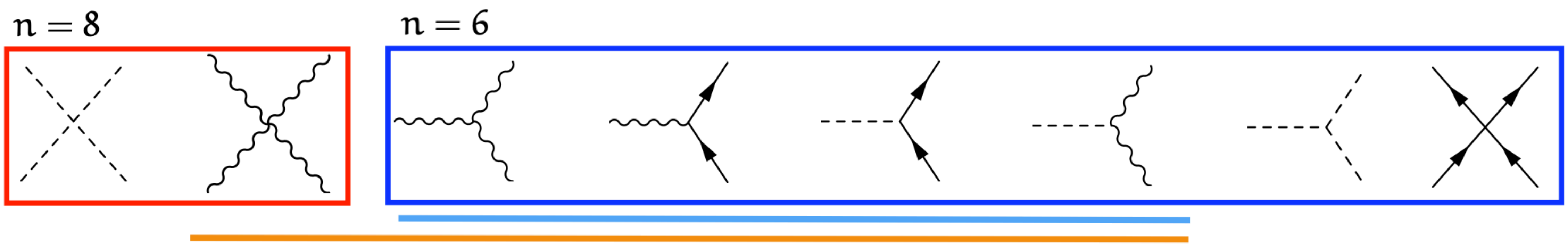
EFT on VV, VVjj



$$\mathcal{L}^{\text{eff}} = \mathcal{L}_{\text{SM}} + \boxed{\sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)}} + \sum_j \frac{c_j^{(8)}}{\Lambda^4}\mathcal{O}_j^{(8)} + \dots$$

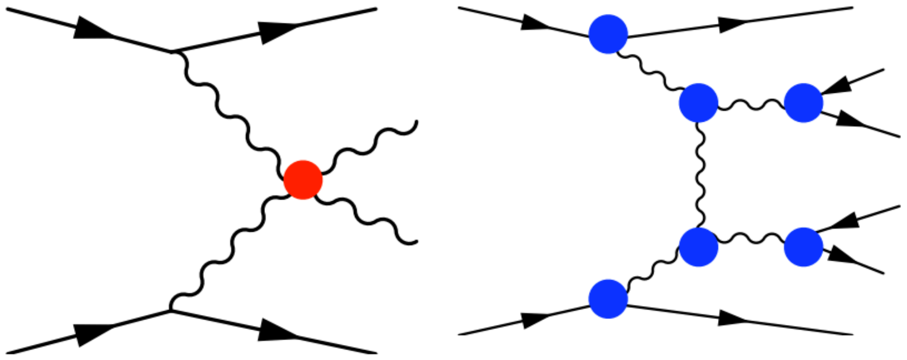


n=5,7 : violate
lepton number



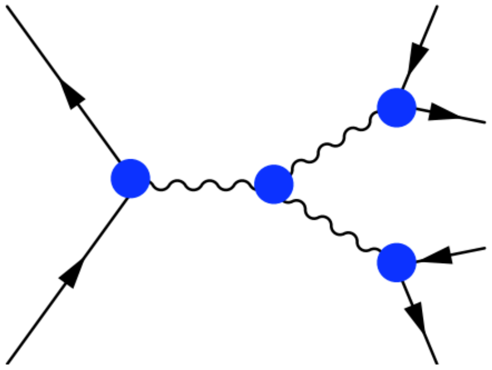
VVjj

- **Semi-lep**
- Full-lep
- (Full-had)



VV

- **Semi-lep**
- Full-lep
- Full-had



Operators

Gauge Fields

1 : X^3	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$\boxed{Q_W}$	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

Higgs Fields

2 : H^6	
Q_H	$(H^\dagger H)^3$

3 : $H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D^\mu H\right)^* \left(H^\dagger D_\mu H\right)$

5 : $\psi^2 H^3 +$ h.c.	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

Gauge & Higgs Fields

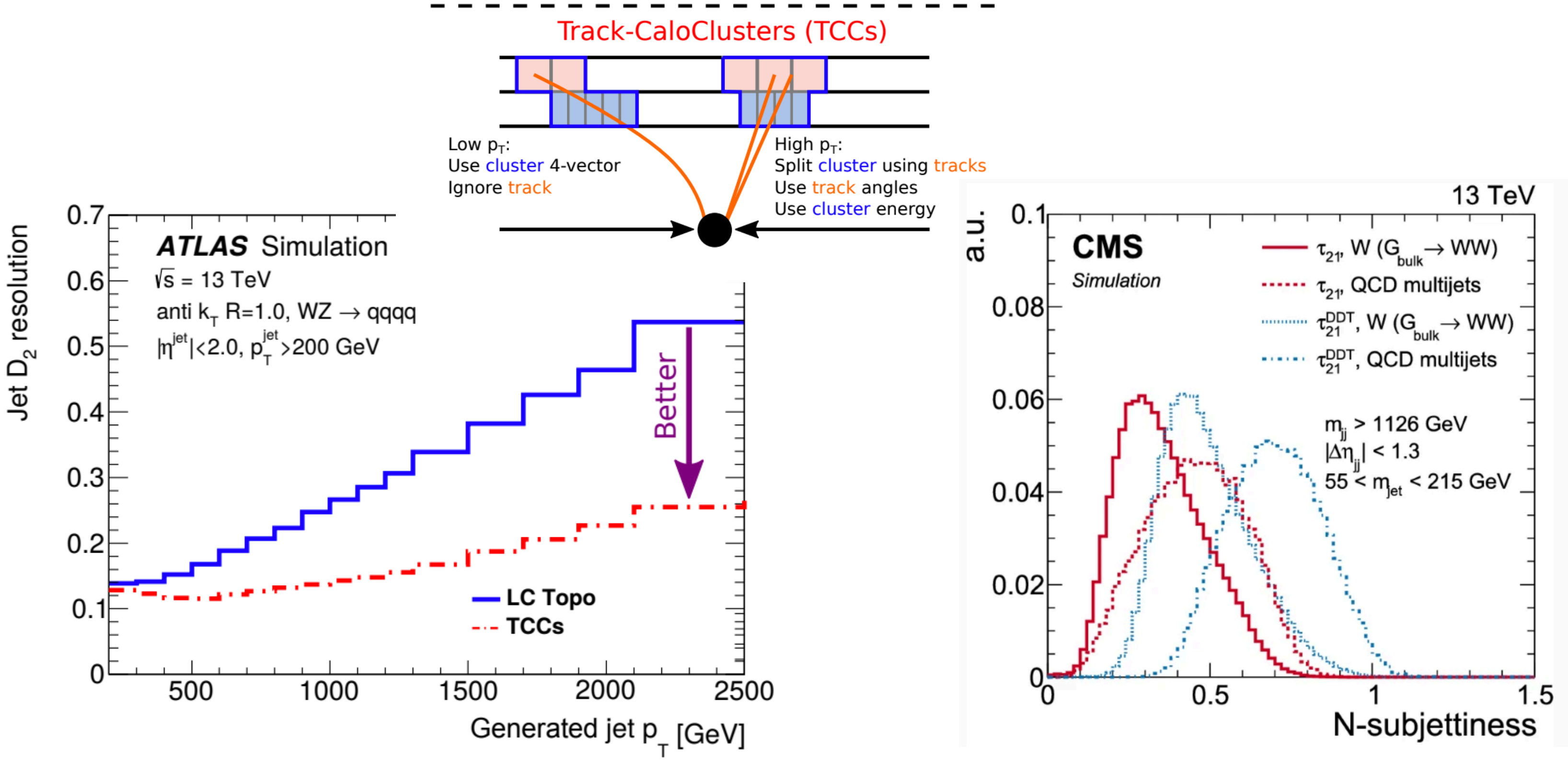
4 : $X^2 H^2$	
Q_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$
$\boxed{Q_{HW}}$	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$

fermion

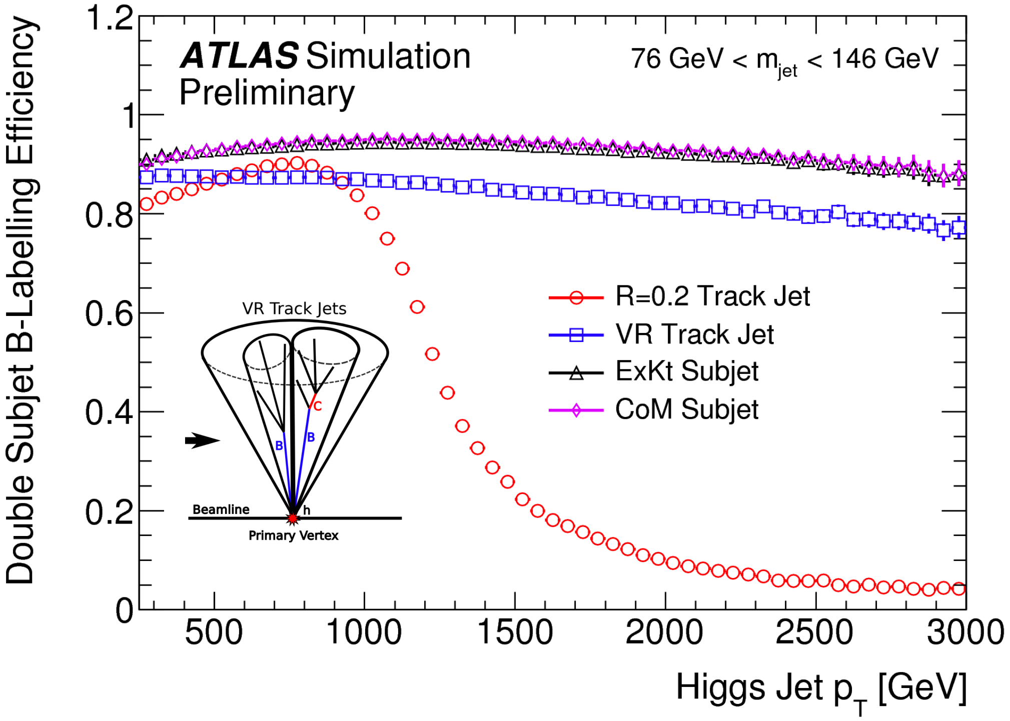
6 : $\psi^2 X H +$ h.c.	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I H W^I_{\mu\nu}$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \widetilde{H}\, G^A_{\mu\nu}$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \widetilde{H}\, W^I_{\mu\nu}$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G^A_{\mu\nu}$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I H\, W^I_{\mu\nu}$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

7 : $\psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$\boxed{Q_{Hq}^{(1)}}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

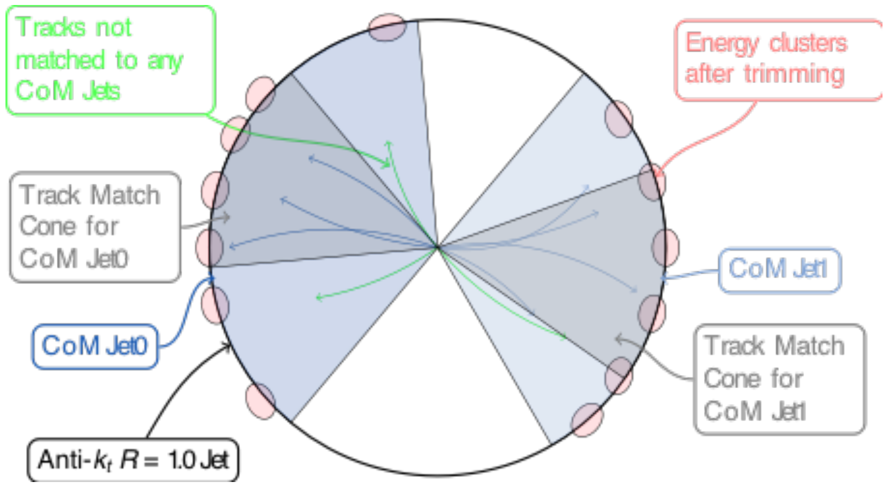
Object performance



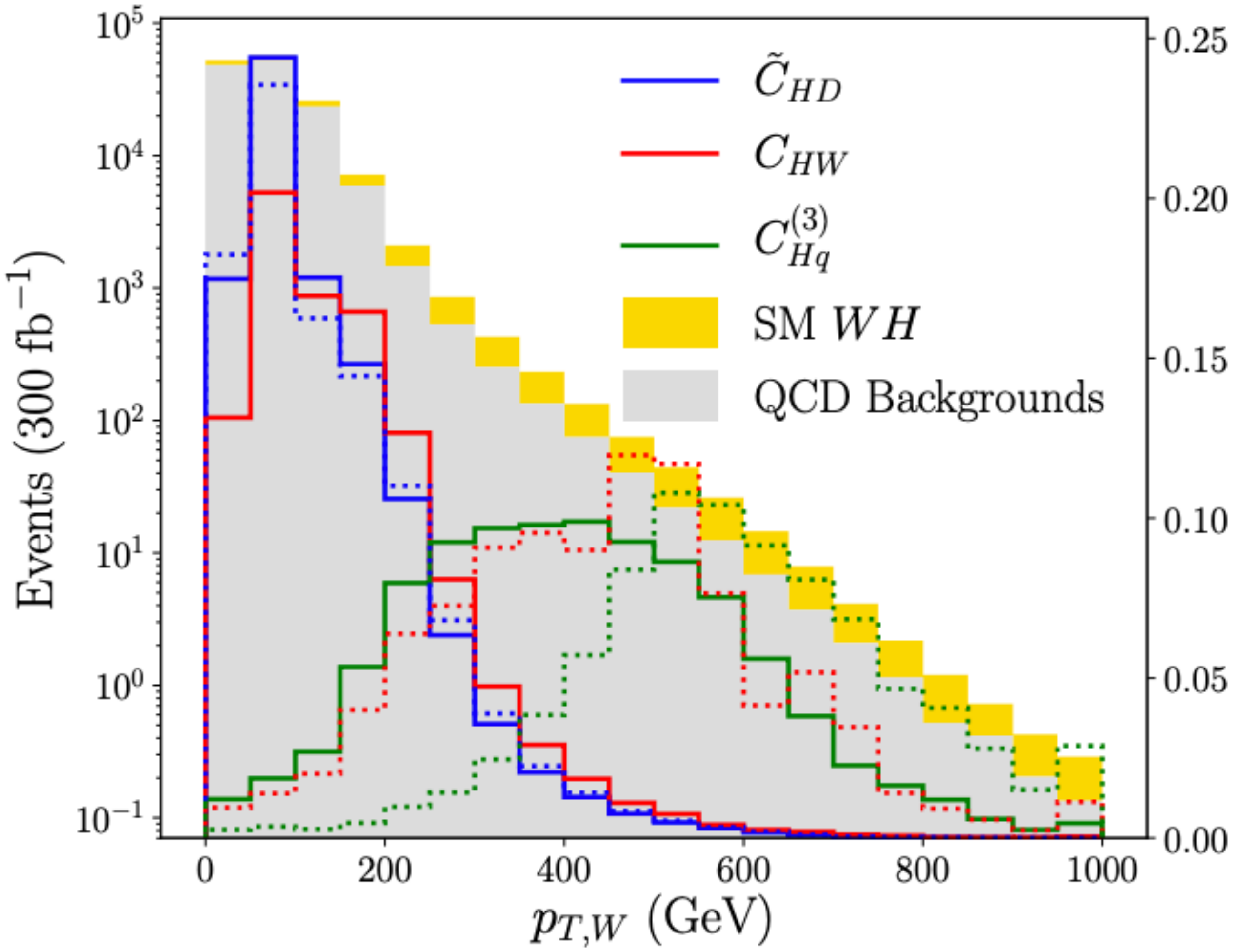
- CMS: PFlow jets with N-subjettiness
- ATLAS: new TCC jets to combine calorimeter info with superior angular resolution of trackers. ATL-PHYS-PUB-2017-010



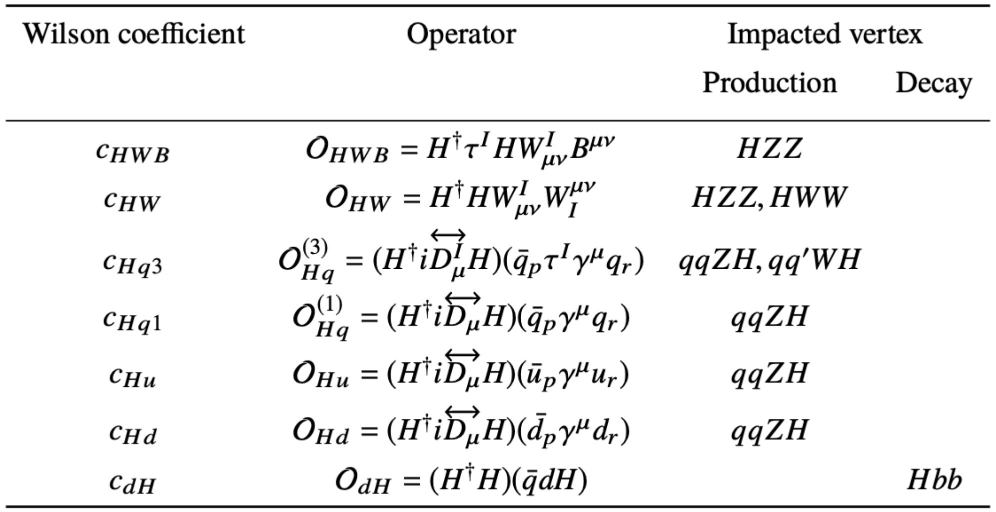
- H → bb tagging in ATLAS matched pairs of b-tagged R = 0.2 track jets to R = 1.0 jets
    - Breaks down at high pT as b-hadron decays overlap → **switch to variable-radius (VR) jets**
        - or CenterOfMass jets: Boost to Higgs frame to reconstruct two subjets
- **CMS: DeepCSV algorithm** ==> deep neural network applied to small or large R jets by providing information on tracks and secondary vertices associated with the jet input.



VH operators



arXiv:2008.02508



Wilson coefficient	Operator	Impacted vertex	
		Production	Decay
c_{HWB}	$\mathcal{O}_{HWB} = H^\dagger \tau^I H W^I_{\mu\nu} B^{\mu\nu}$	HZZ	
c_{HW}	$\mathcal{O}_{HW} = H^\dagger H W^I_{\mu\nu} W_I^{\mu\nu}$	HZZ, HWW	
c_{Hq3}	$\mathcal{O}^{(3)}_{Hq} = (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$	$qqZH, qq'WH$	
c_{Hq1}	$\mathcal{O}^{(1)}_{Hq} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$	$qqZH$	
c_{Hu}	$\mathcal{O}_{Hu} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$	$qqZH$	
c_{Hd}	$\mathcal{O}_{Hd} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$	$qqZH$	
c_{dH}	$\mathcal{O}_{dH} = (H^\dagger H)(\bar{q} d H)$		Hbb

- CHq(3) probes the high ptW/H bin
- The other operators grow more slowly with s that does CHq(3) but we should still expect an improvement when adding a high pT bin.
- Note that this paper uses the linearized approach, i.e. only the term linear in the EFT coefficient is included
- if you square the amplitude (which generates pieces quadratic in the eft coefficient) you get a larger effect

From searches to precision measurements

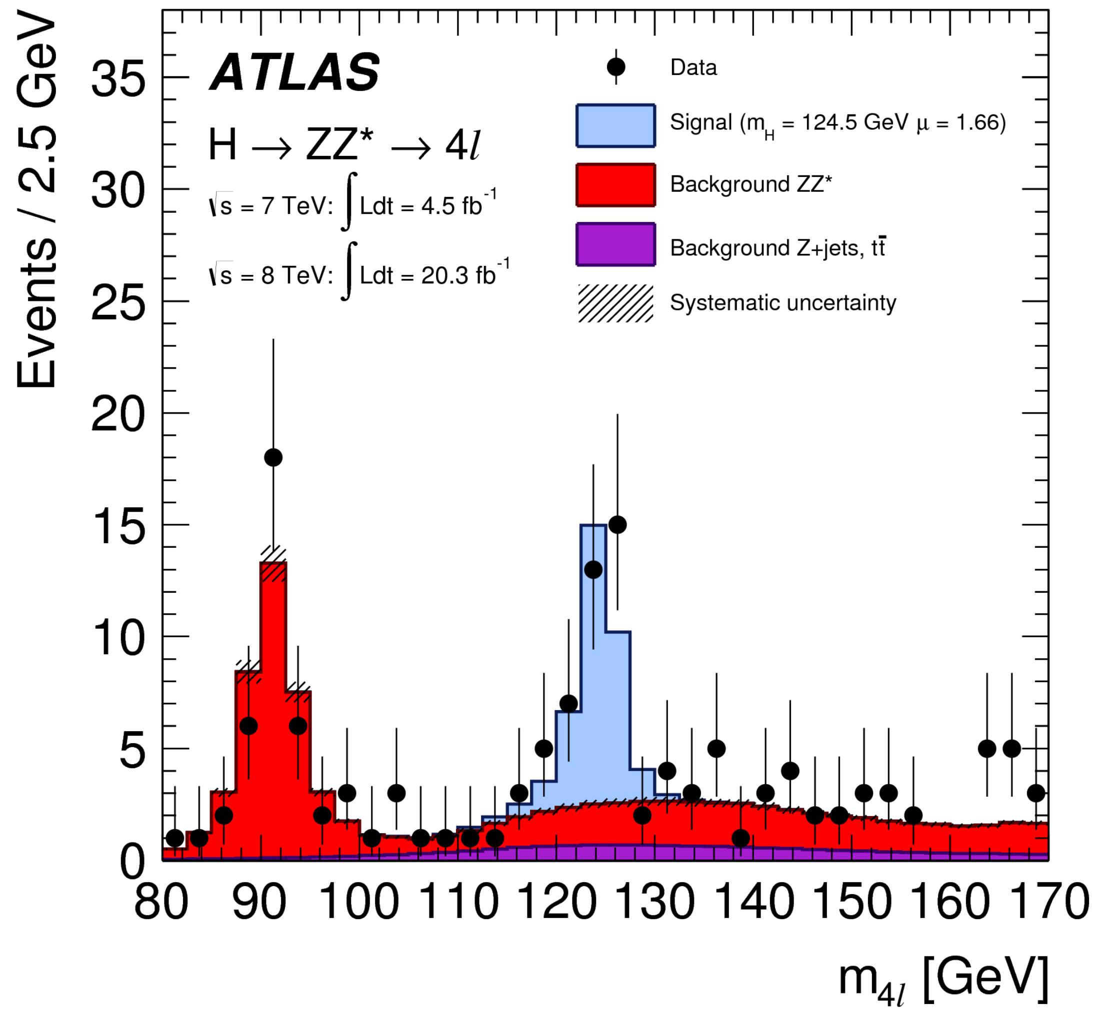
EFT limits using Higgs measurements

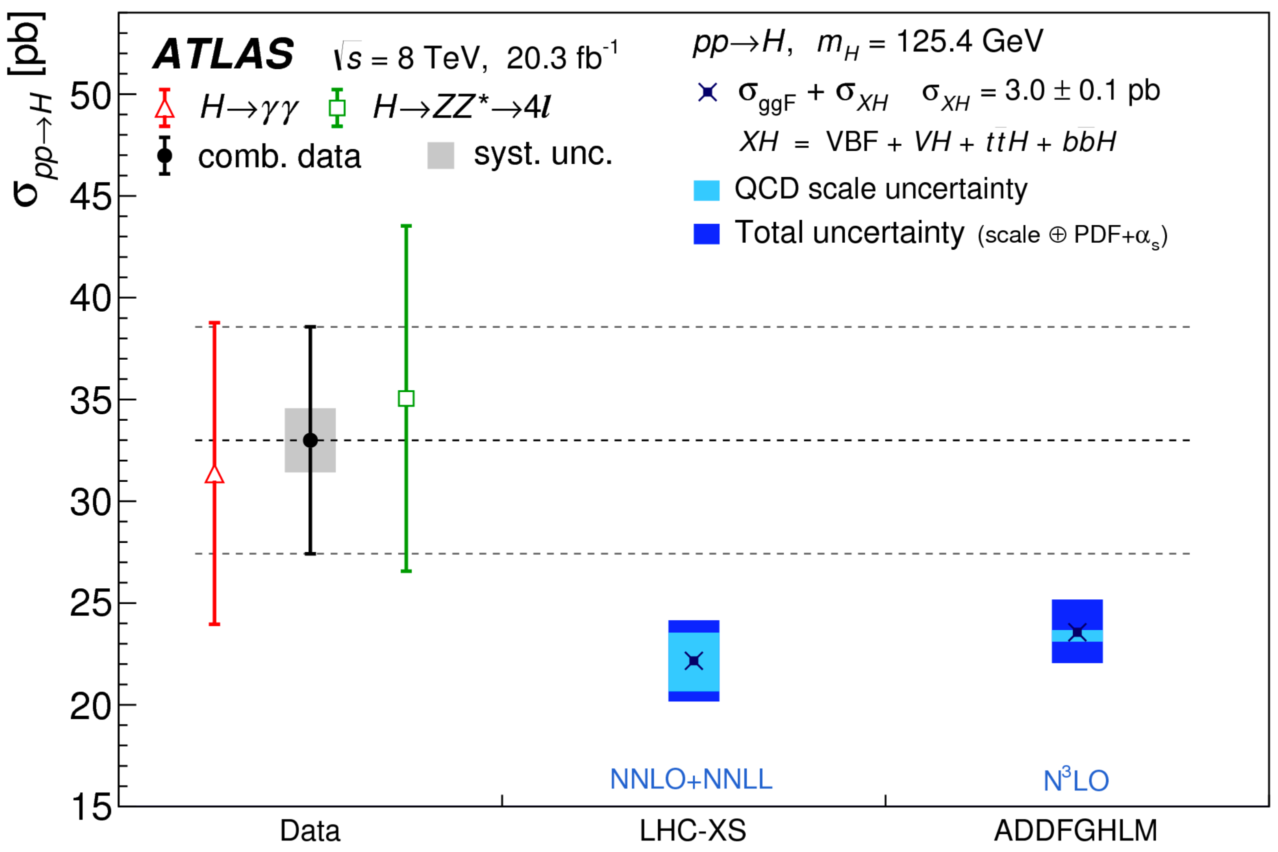
Viviana & Haider
April 27th, 2021
KITP

BROOKHAVEN
NATIONAL LABORATORY

Higgs boson & discovery

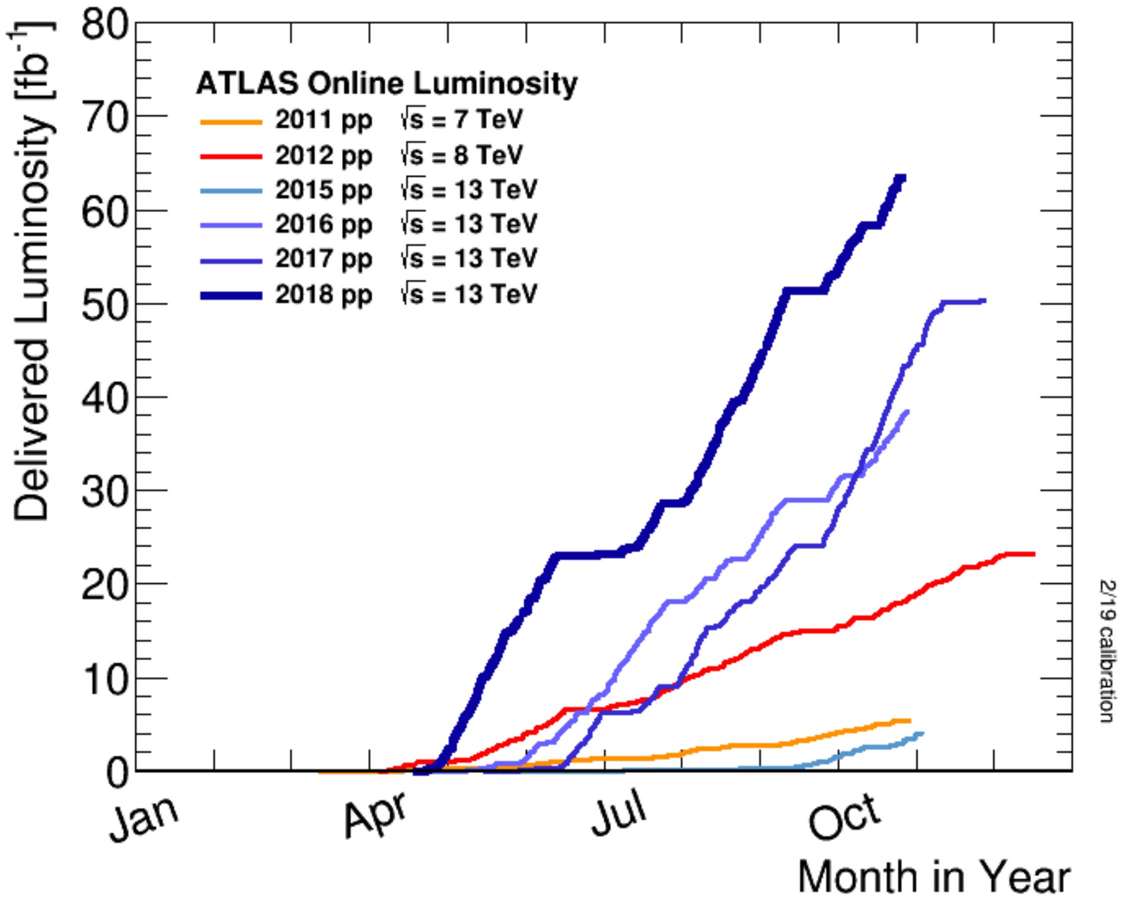
- In 2012, **discovery** of a new particle by the ATLAS and CMS collaborations
- Initial studies showed the particle was **consistent** with the SM Higgs
- A new sector to understand and probe for new physics
  - Results were mostly of inclusive properties + statistically limited
- Some early data/MC differences, but no conclusive evidence



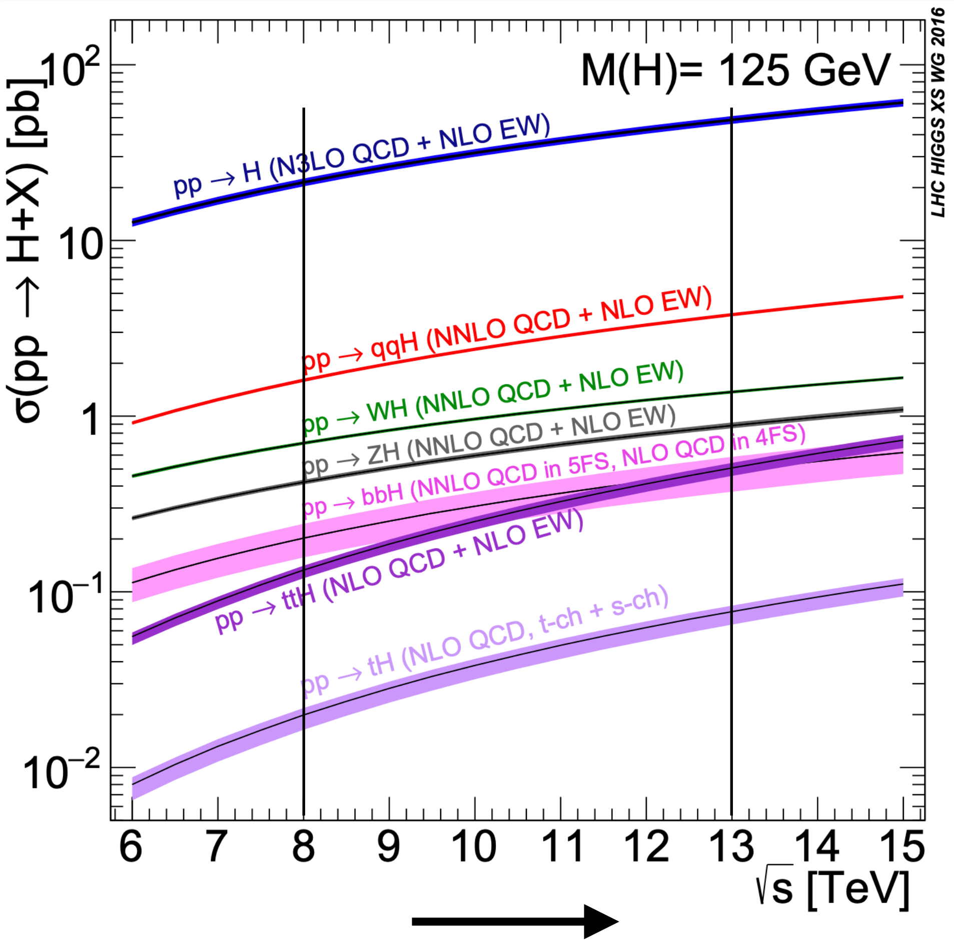


Focus of Run 2

- LHC delivered an unprecedented amount of data between 2015-2018
  - Collision energy changed to 13 TeV ~ 2.3x increase in the Higgs production XS
- Coupled with:
  - Better understanding of the detector → eg. Improved reconstruction
  - Advanced analysis techniques → eg. Machine learning
  - Improved theoretical predictions → eg. N3LO for ggF
- Precision measurements of the Higgs boson!
  - Inclusive/ggF Higgs XS ~ 7% precision, others at O(10%)



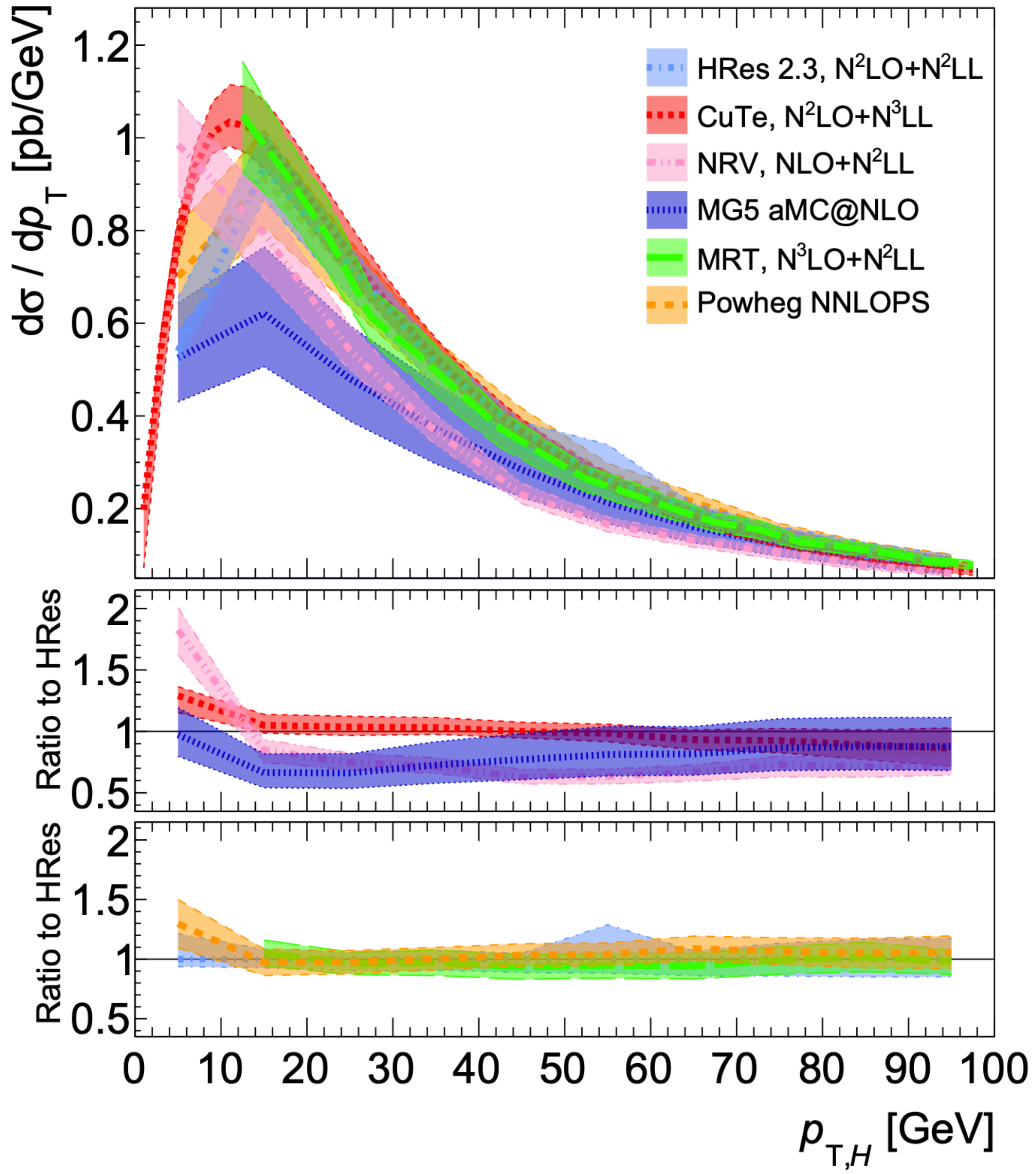
ATLA collected ~ 140/fb of data



~2.3x increase in Higgs XS

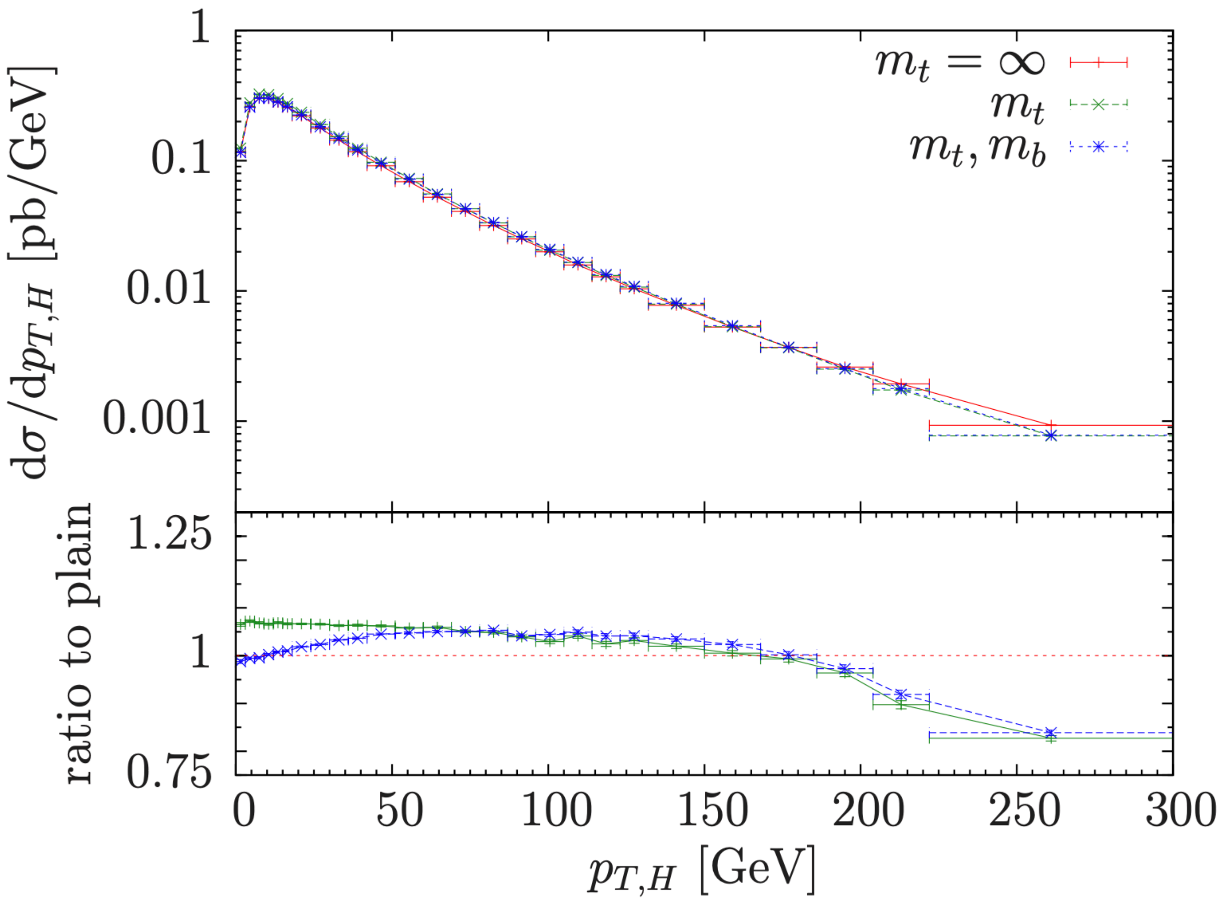
What can we do with it?

- Measure the fundamental parameters as well as possible
- Feedback to improve our theoretical predictions
  - Previously acceptable approximations not good enough with increased experimental precision



Predictions of Higgs pT

Yellow report 4

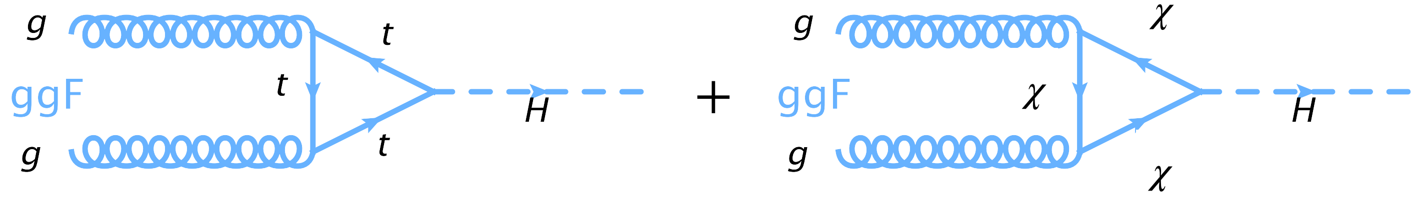


Effect of the quark mass

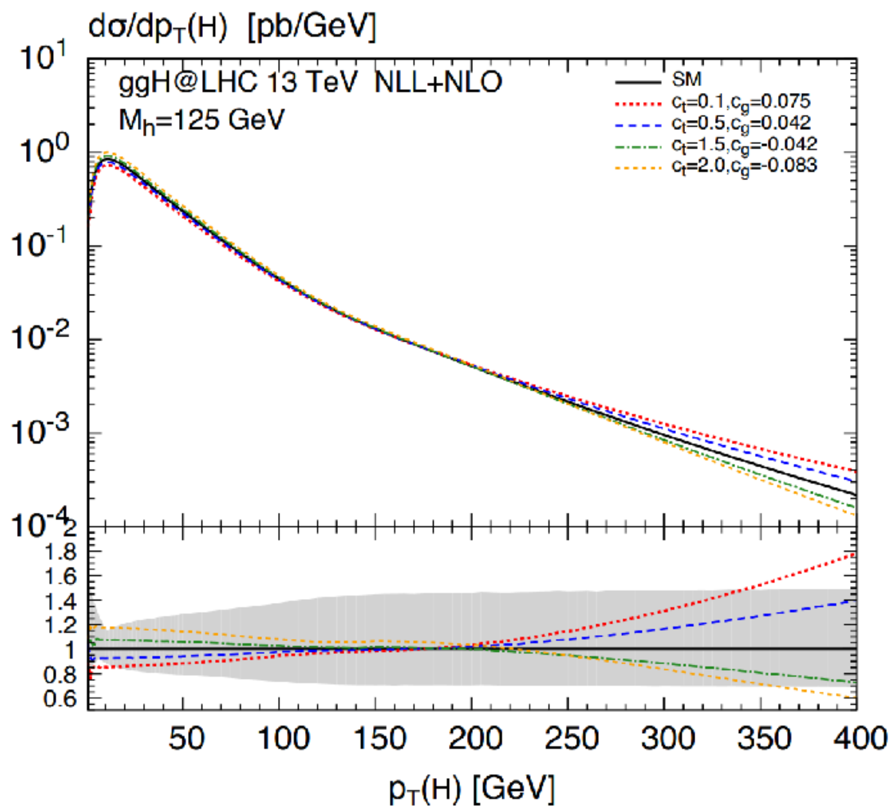
1501.04637

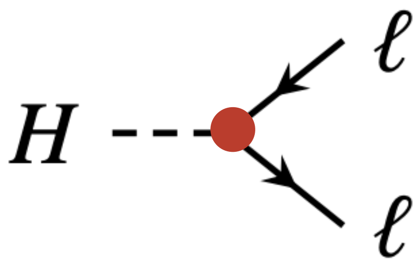
What can we do with it?

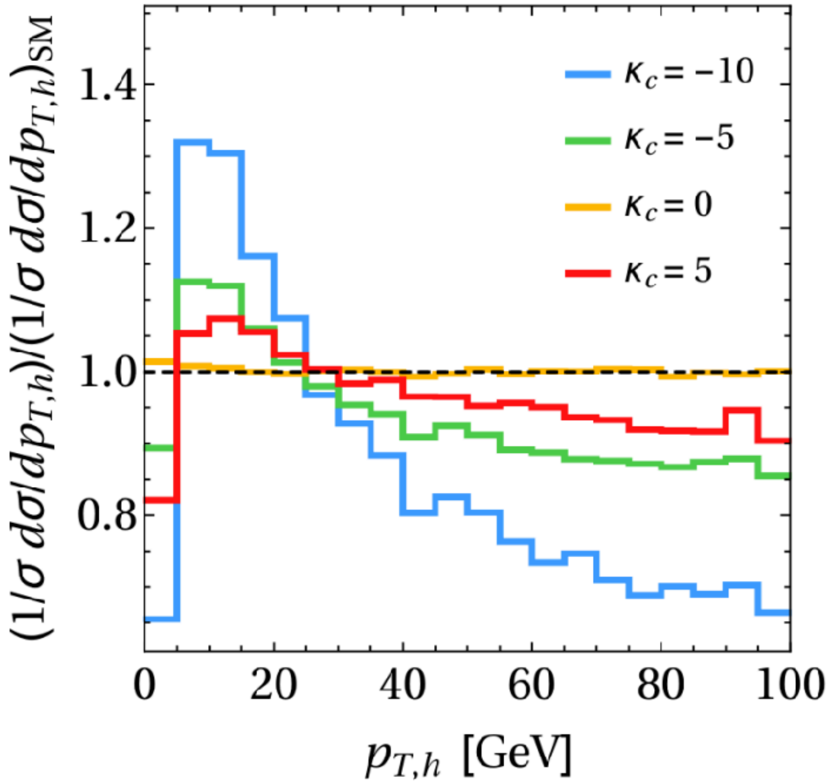
- But hints of new physics might lie in the same places



New heavy particles coupling to Higgs



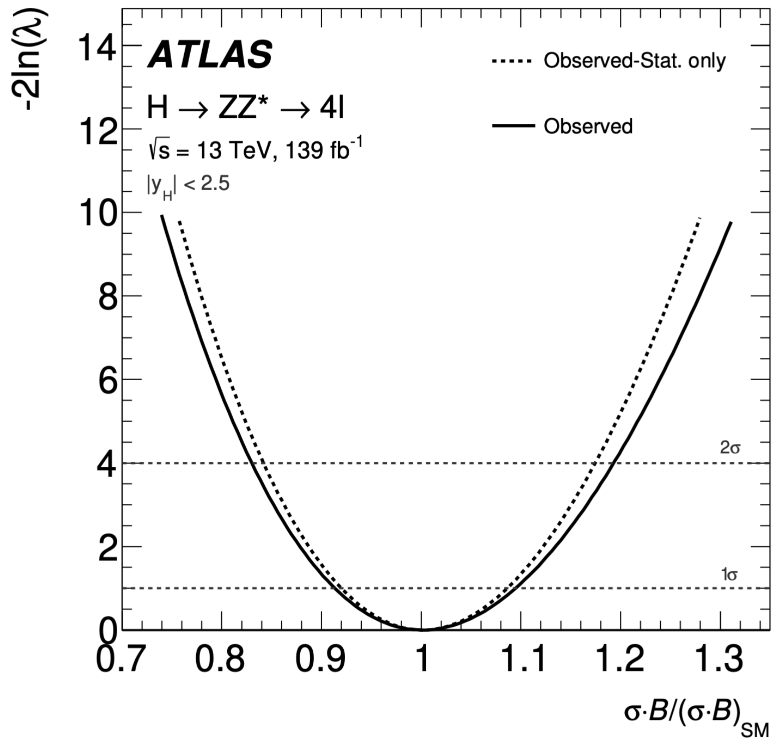


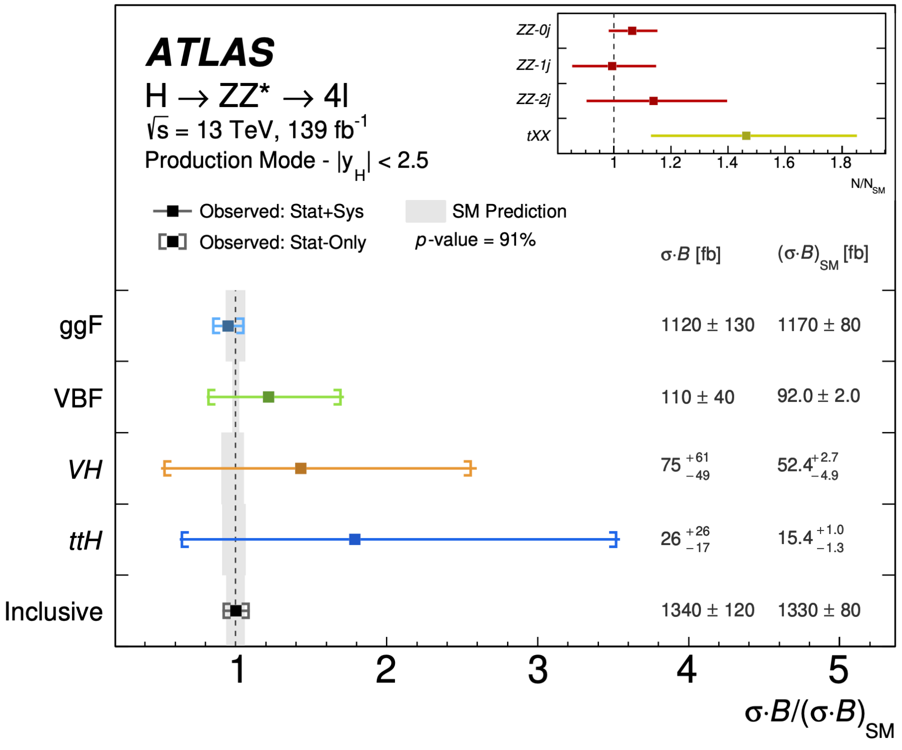


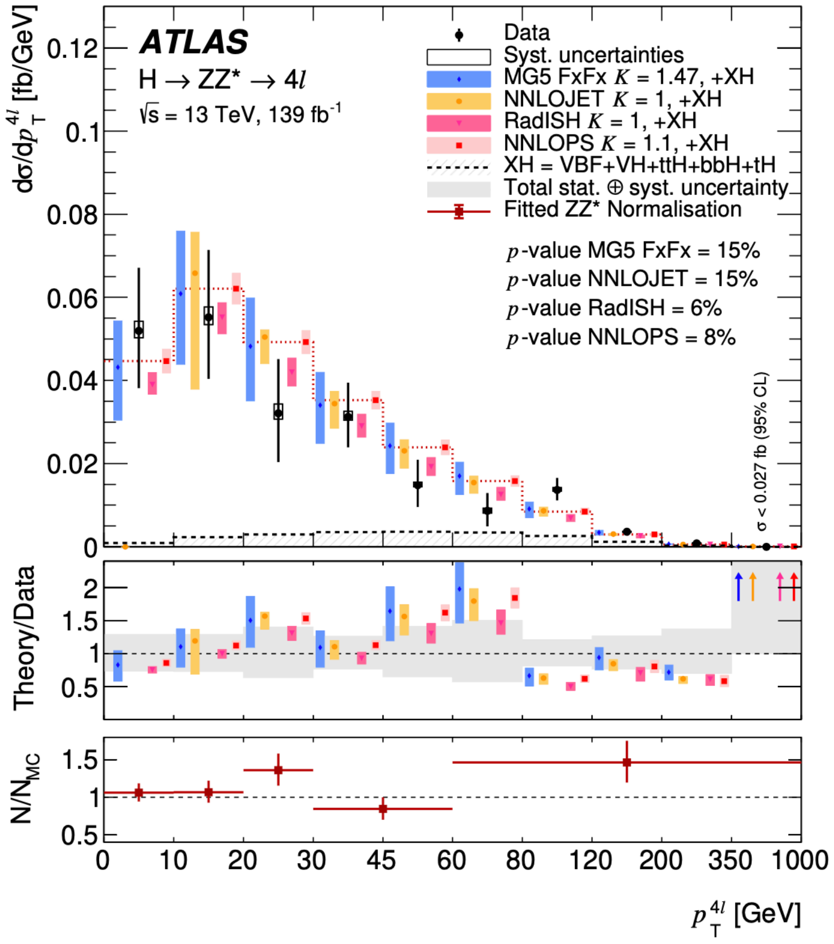
Modification of the light quark coupling

1606.09253

What measurements can we do?







Inclusive XS

Best precision

but no sensitivity to any new physics that leaves the overall XS unchanged

Production XS

New channels available

with more data,
but level of granularity still can cause tail effects to washout

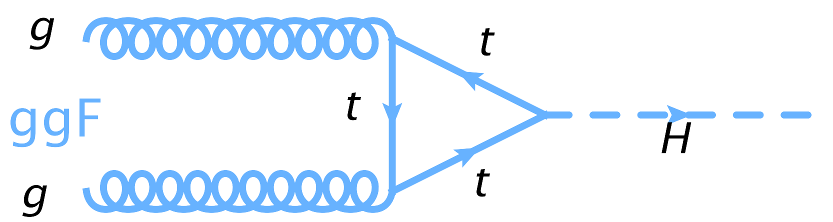
Differential XS

Least dependant on SM & more bins

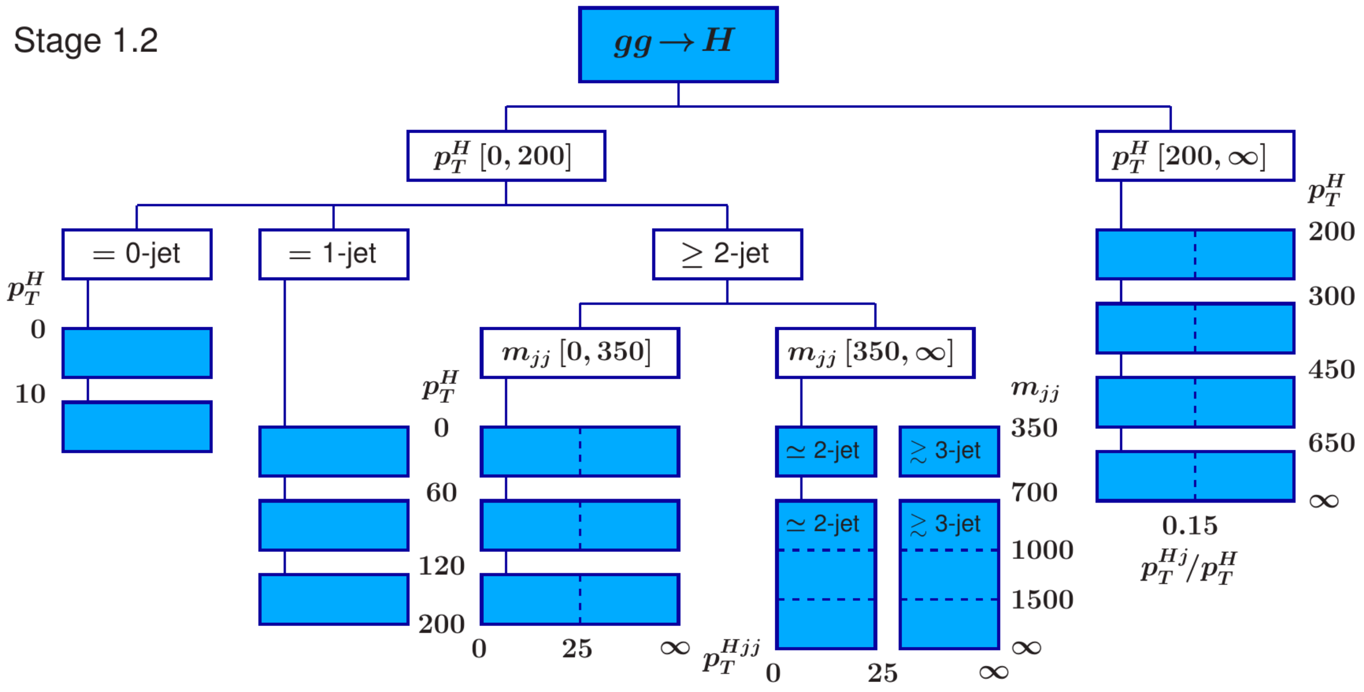
but hard to combine and limited to few variables

Simplified Template XS (STXS)

- With larger dataset, opportunity to make new measurements
- Combine the best parts of production modes and differential XS - STXS measurements
- Motivations for STXS:
  - Factorize out phase spaces that are difficult to compute theoretically
  - Target regions where new physics is most likely to show up
  - Simplify combination between measurements in various decay channels
  - Limit model dependancy to only one STXS bin - relationship between bins are free from SM assumption



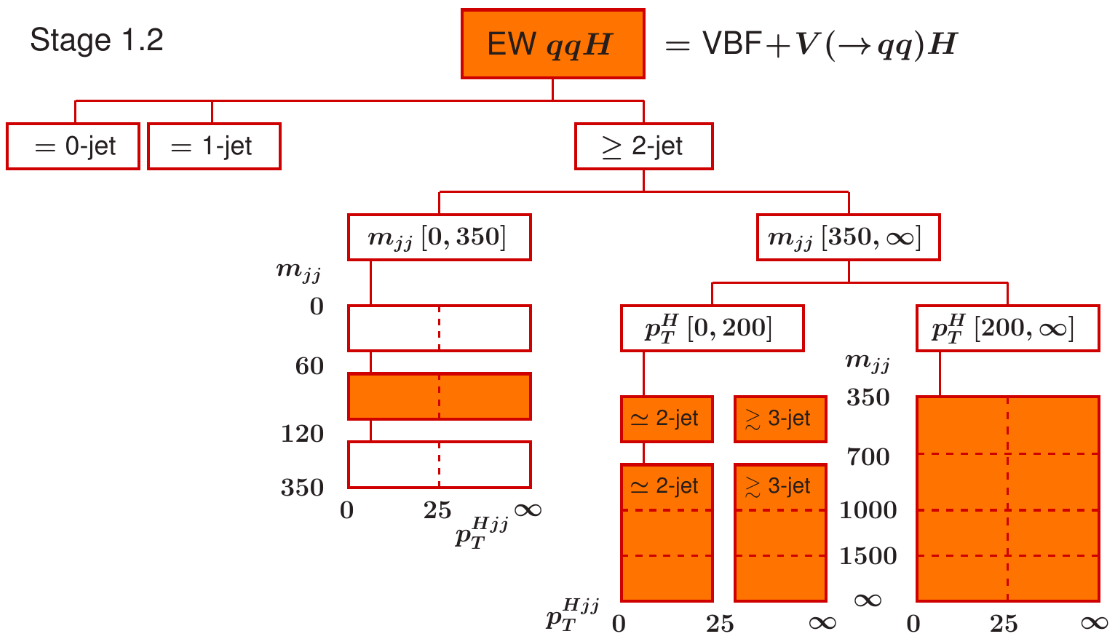
Simplified Template Cross-Section

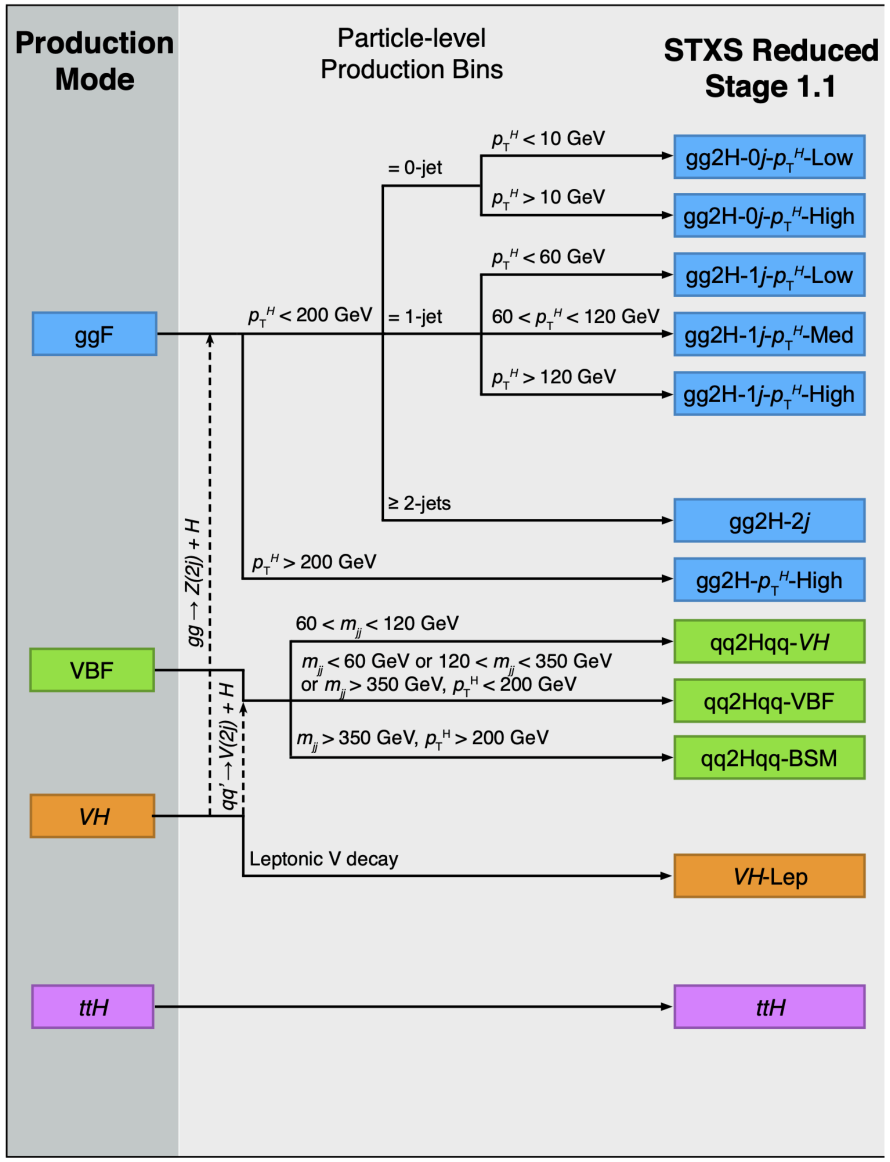


STXS merging

- Scheme is designed with 300/fb of data and sensitivity for all channels in mind
  - Typically merge bins that one analysis can't measure - with the intention of undoing this when combining other channels in future

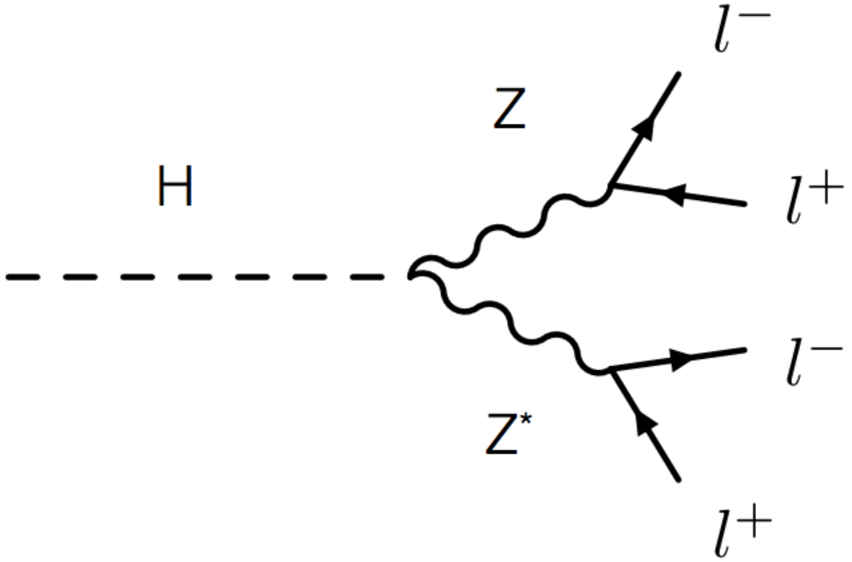
Example of bin merging for ATLAS H → ZZ → 4l analysis

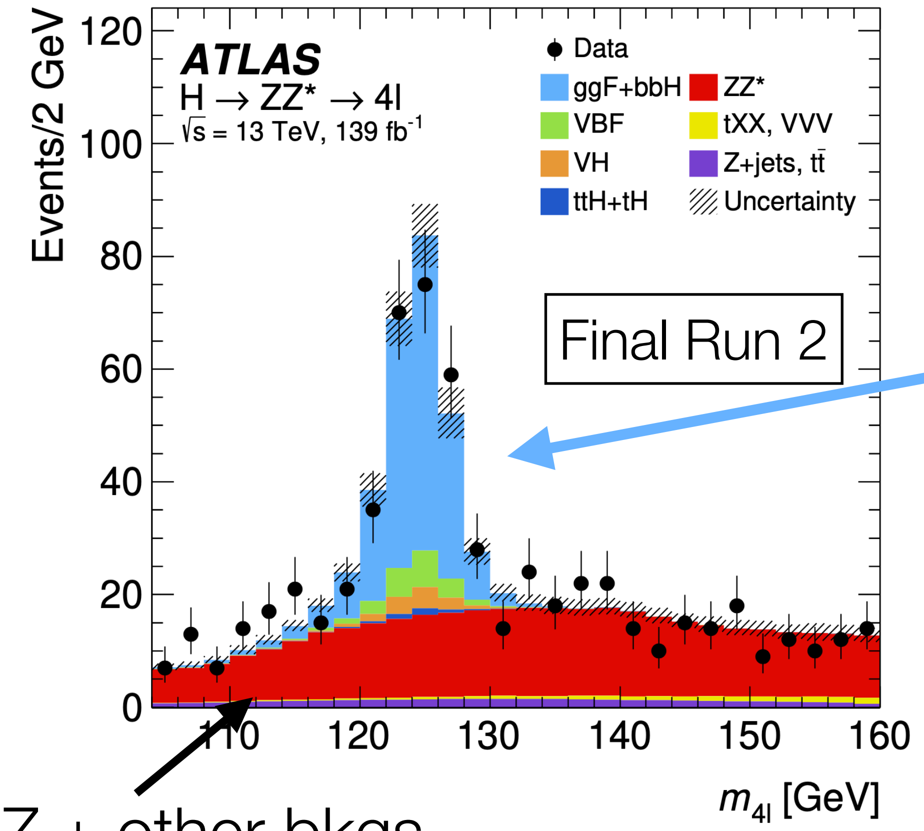




Higgs - Why H → ZZ → 4l?

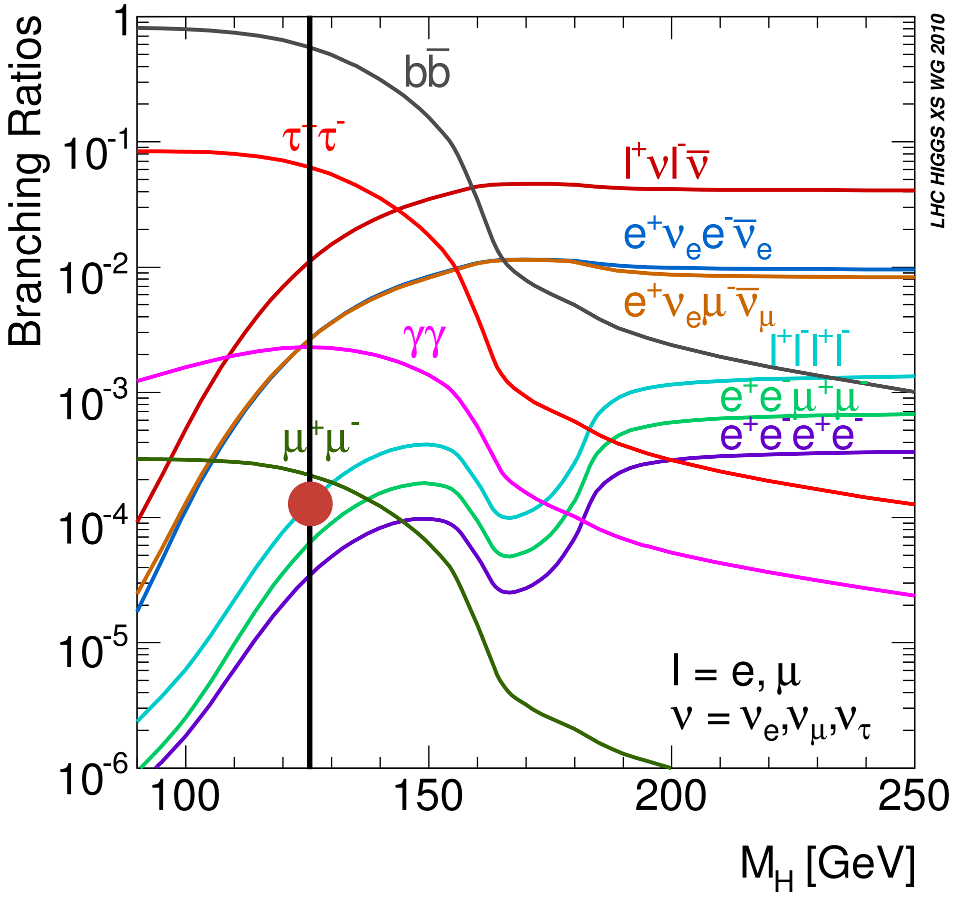
- H4l: ‘The Golden Channel’
  - Fully leptonic final state → Precise measurement
  - Fully reconstructable → Resolution ~ O(2GeV)
- The cost: low statistics
  - Branching ratio is small H→4l ~ O(0.01%)
- Saving Grace:
  - Very small backgrounds → S/B ~ 2.4





Higgs

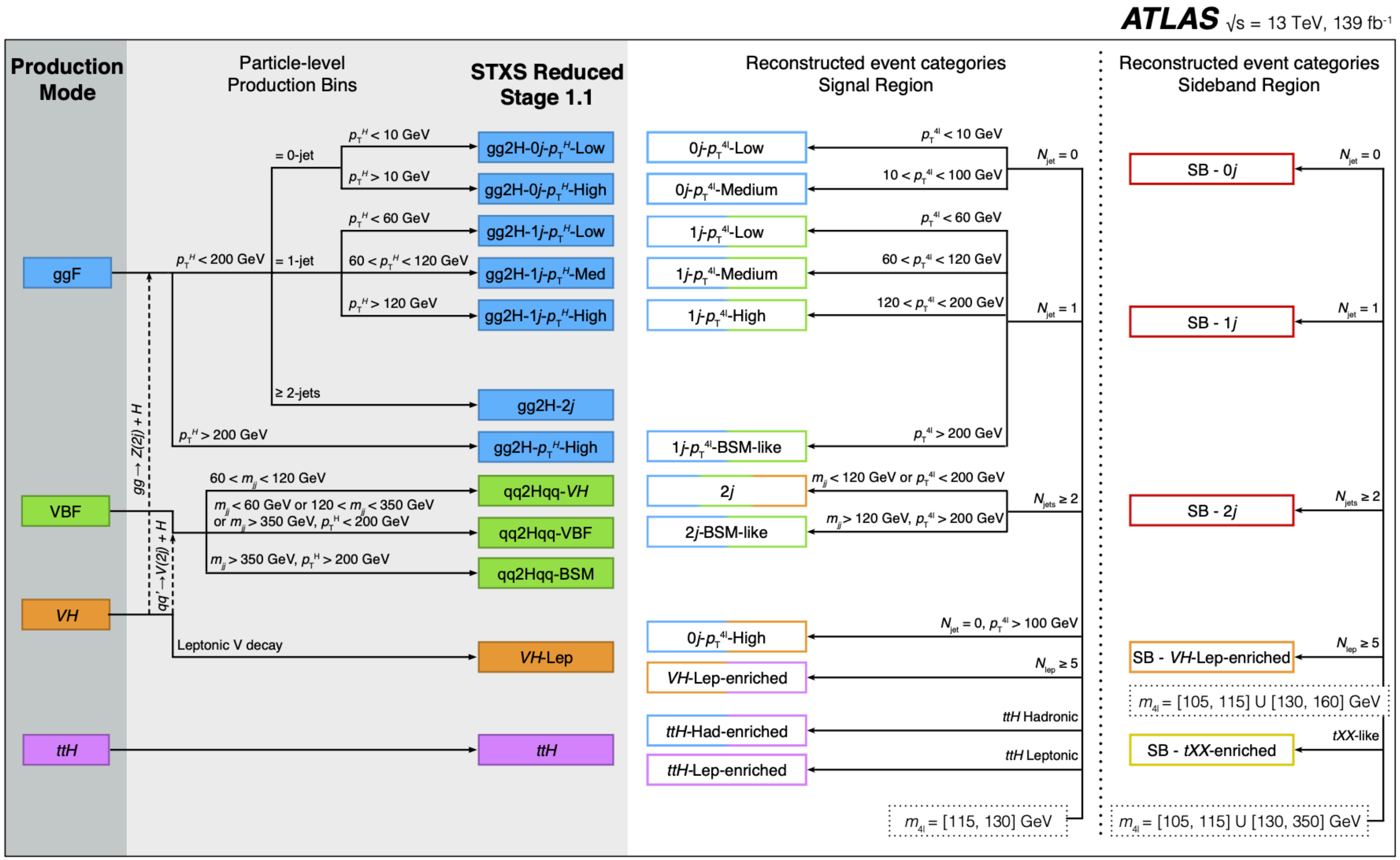
ZZ + other bkgs



arXiv:2004.03447

H4l Analysis

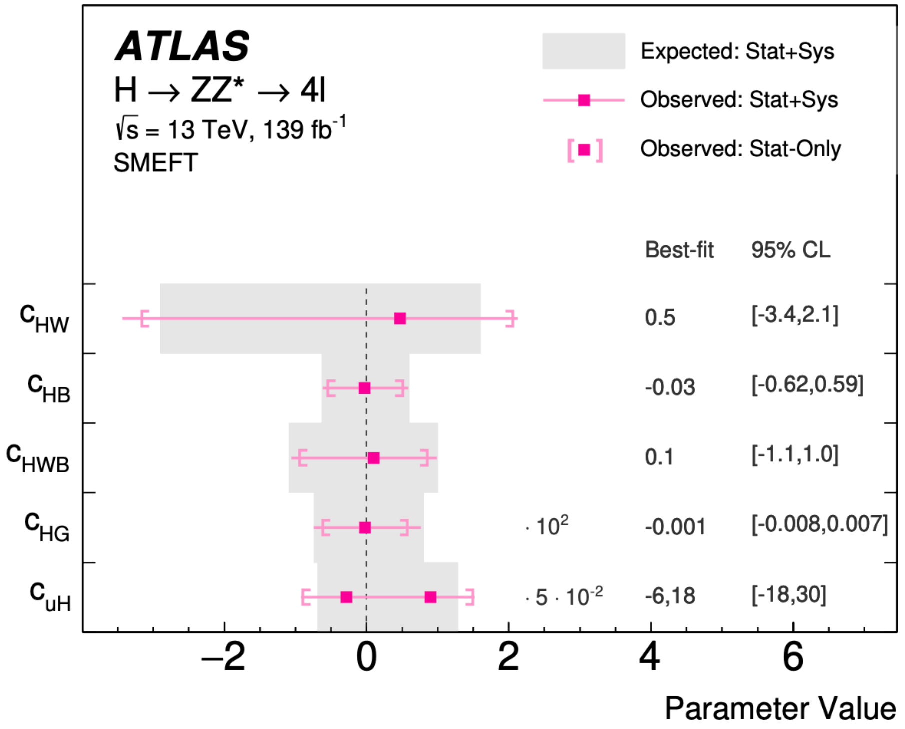
- Usual optimization of cuts, background estimations, statistical modelling
- Extension to STXS amounts to just categorizing the events and measuring XS



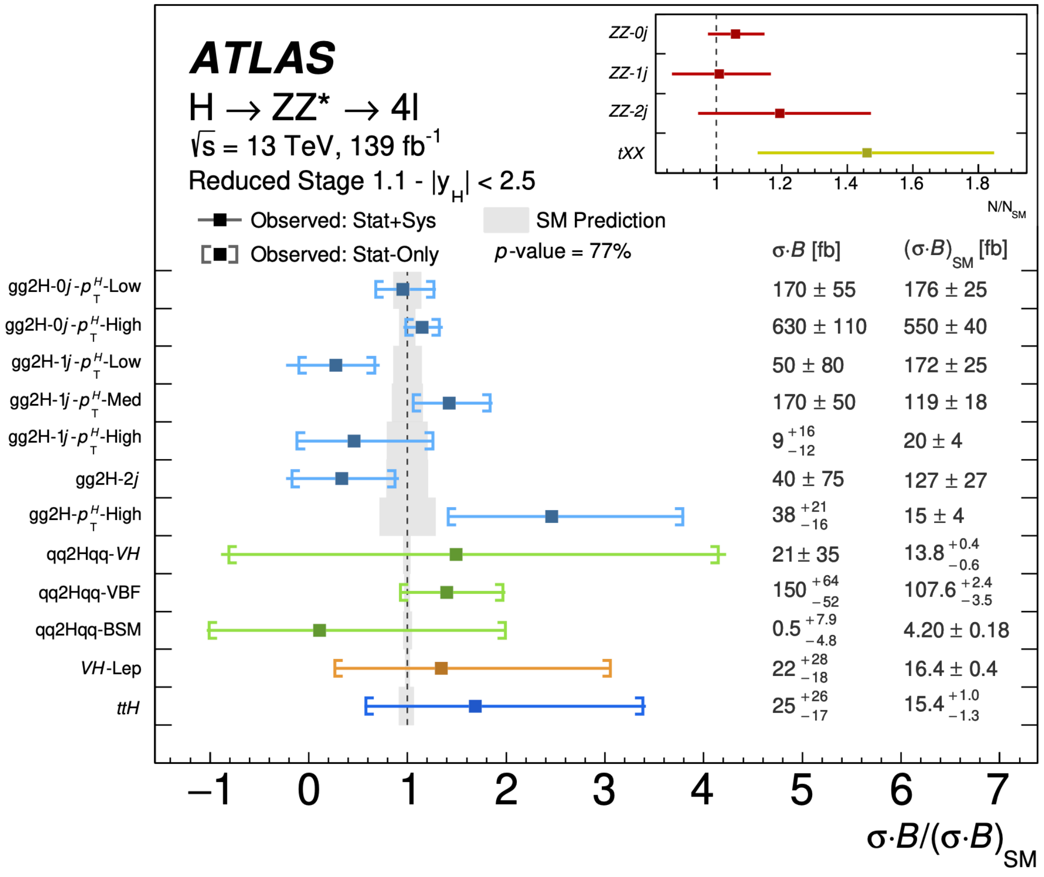
Mirror STXS bins on the analysis side

H4l Results

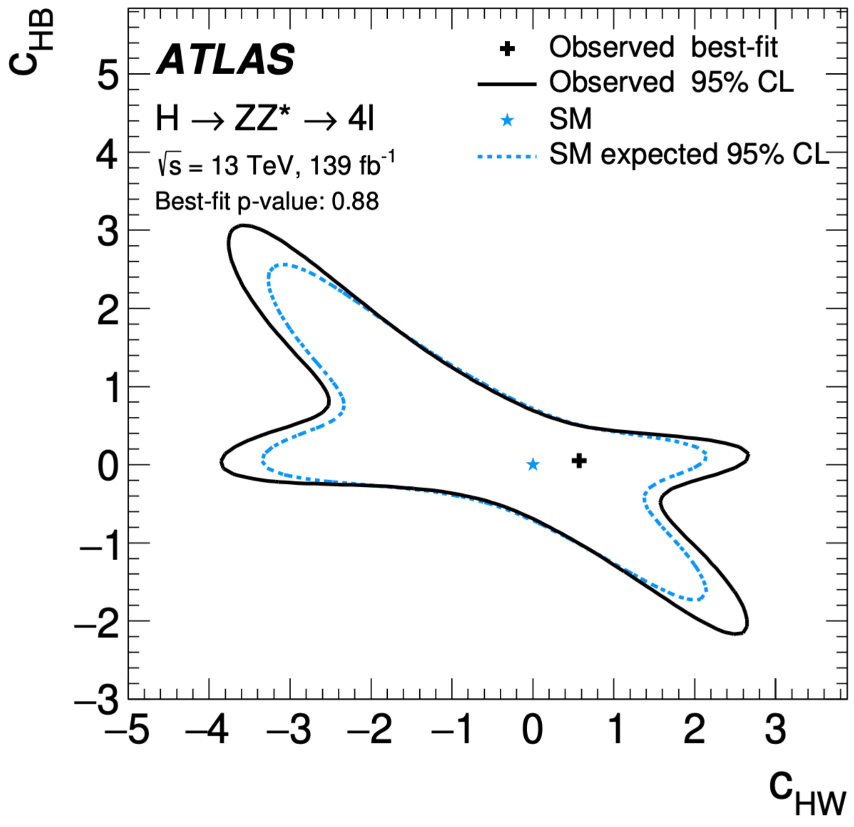
- Extract nominal STXS results
  - Interpret them in the SMEFT formalism in Warsaw basis
  - Limit to dimension 6 operators that this analysis is sensitive to
- Deconstruct what went into making this in the upcoming slides



STXS results



EFT interpretation



Designing the analysis

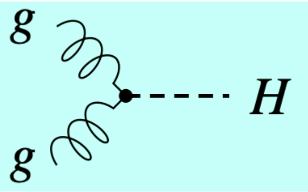
- In H → ZZ → 4l decay, sensitivity comes from both the decay and the production
  - **Goal for EFT interp:** Measure each production mode as precisely as possible, while still targeting the most sensitive BSM like phase space

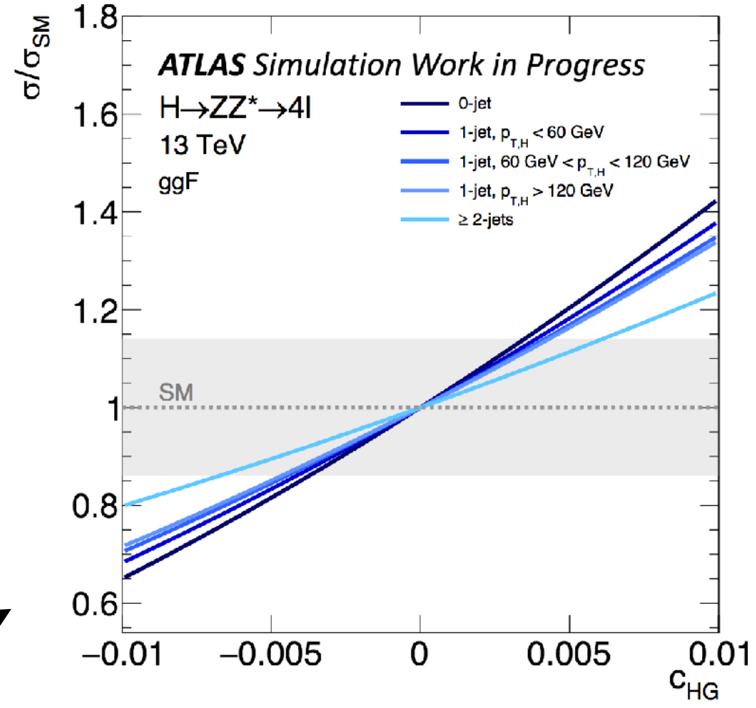
Different effects EFT operators have on H4l

Higgs - gluon vertex

c_{HG}

$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$





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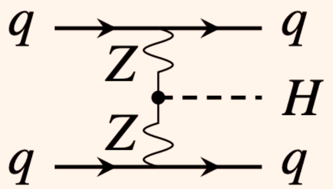
Higgs - EW boson

c_{HB}

$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$



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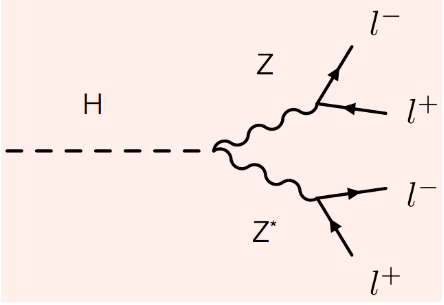
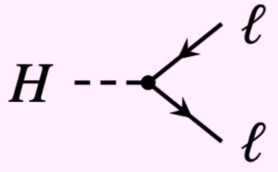


……

Most others

c_{eH}

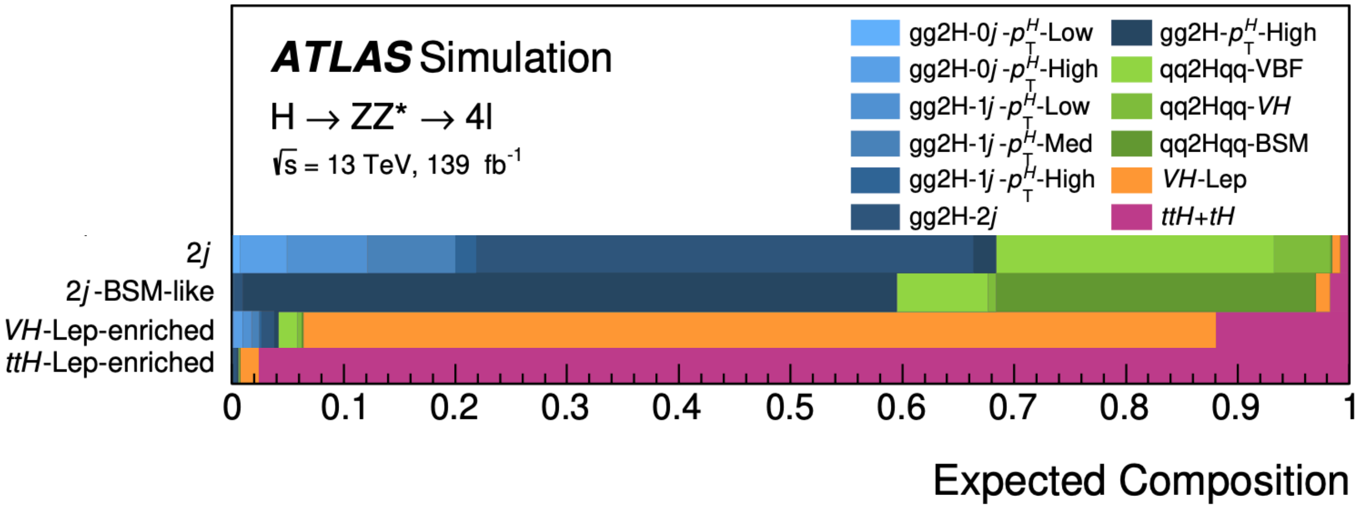
$(H^\dagger H)(\bar{l}_p e_r H)$



Only affect through changing the total Higgs width
Not considered

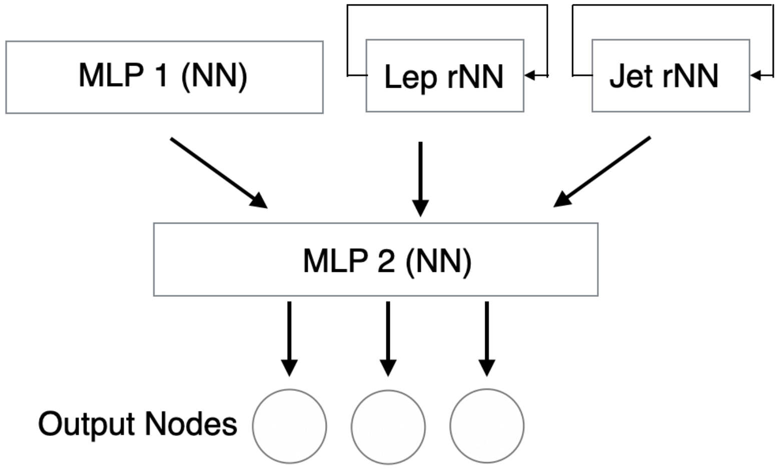
ML - 2jet example

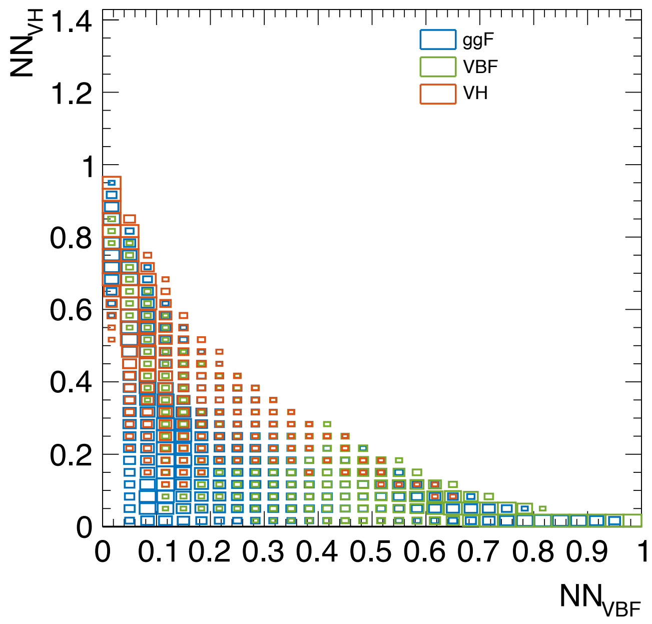
- H+2jet topology is particularly sensitive to many EFT operators
  - Various topologies contribute - Have to optimize for all of them, ML techniques



- Use reconstructed Higgs and jet kinematics to make a multi-dimensional rNN classifier
  - Limited by having no ME level generators for H+3j at NLO & theory prediction large uncertainties
  - Can't rely on parton showers either

General NN structure


MLP 1 (NN)
Lep rNN
Jet rNN
MLP 2 (NN)
Output Nodes



EFT interpretation: Parametrization

- After measuring STXS, we need to convert them into EFT limits
  - **Parametrize** all the ingredients

$$\longrightarrow \quad \sigma * \mathrm{BR}_{4l} = \sigma * \frac{\Gamma_{4l}}{\Gamma_{\mathrm{Total}}}$$

- Actual impact of operators on the XS can have a linear (interference) or a quadratic term (Pure BSM)
  - With current sensitivity, cannot **ignore the quadratic term** and need to include both

$$\sigma \propto |\mathcal{M}_{\mathrm{SMEFT}}|^2 = \left|\mathcal{M}_{\mathrm{SM}} + \sum_i \frac{C_i}{\Lambda^2}\mathcal{M}_i\right|^2 = |\mathcal{M}_{\mathrm{SM}}|^2 + \sum_i 2Re\left(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_i\right)\frac{C_i}{\Lambda^2} + \sum_{ij} 2Re\left(\mathcal{M}^*_i\mathcal{M}_j\right)\frac{C_iC_j}{\Lambda^4},$$

$$\downarrow$$

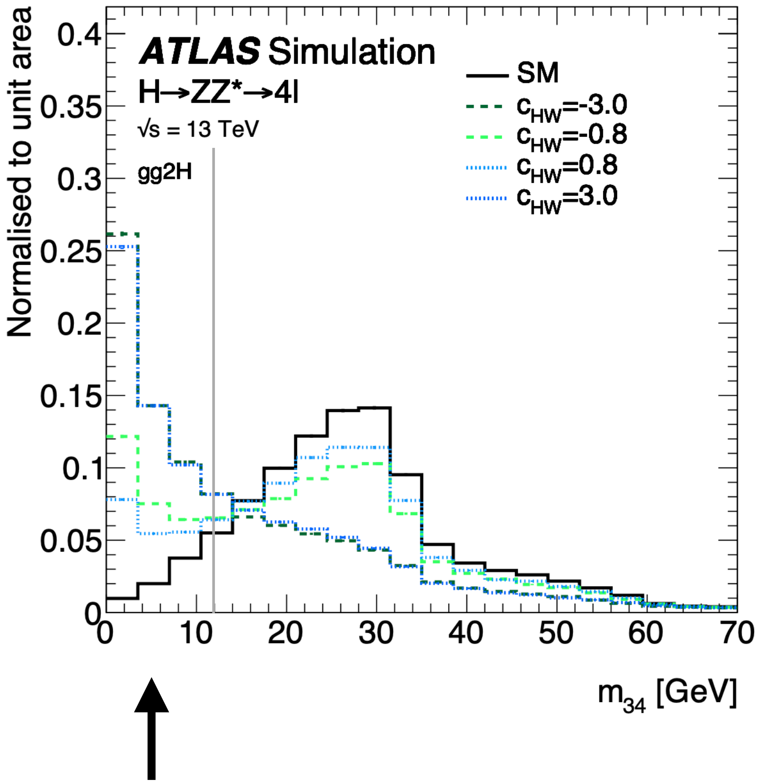
$$\frac{\sigma^p(\vec{c})}{\sigma^p_{\mathrm{SM}}} = 1 + \boxed{\sum_i A^p_i c_i} + \boxed{\sum_{ij} B^p_{ij} c_i c_j,} \qquad + \qquad \mathcal{B}^{4\ell}(\vec{c}) = \frac{\Gamma^{4\ell}(\vec{c})}{\Gamma^{\mathrm{tot}}(\vec{c})} = \mathcal{B}^{4\ell}_{\mathrm{SM}} \cdot \frac{1 + \boxed{\sum_i A^{4\ell}_i c_i} + \boxed{\sum_{ij} B^{4\ell}_{ij} c_i c_j}}{1 + \sum_f \left(\boxed{\sum_i A^f_i c_i} + \boxed{\sum_{ij} B^f_{ij} c_i c_j}\right)},$$

- **Caveat:** EFT predictions are not at the same precision as SM ones - SM ggF is N3LO, while EFT is NLO
  - Parametrize the ratio of BSM XS/SM XS within an EFT model and multiply with the best known SM
- This makes calculating theory uncertainty **difficult** - How do we mix NLO errors on the ratio with N3LO errors on SM prediction?
  - **Currently, assume the ratio uncertainties cancel out, but that is most likely not true as EFT operators will introduce new terms in the calculations**

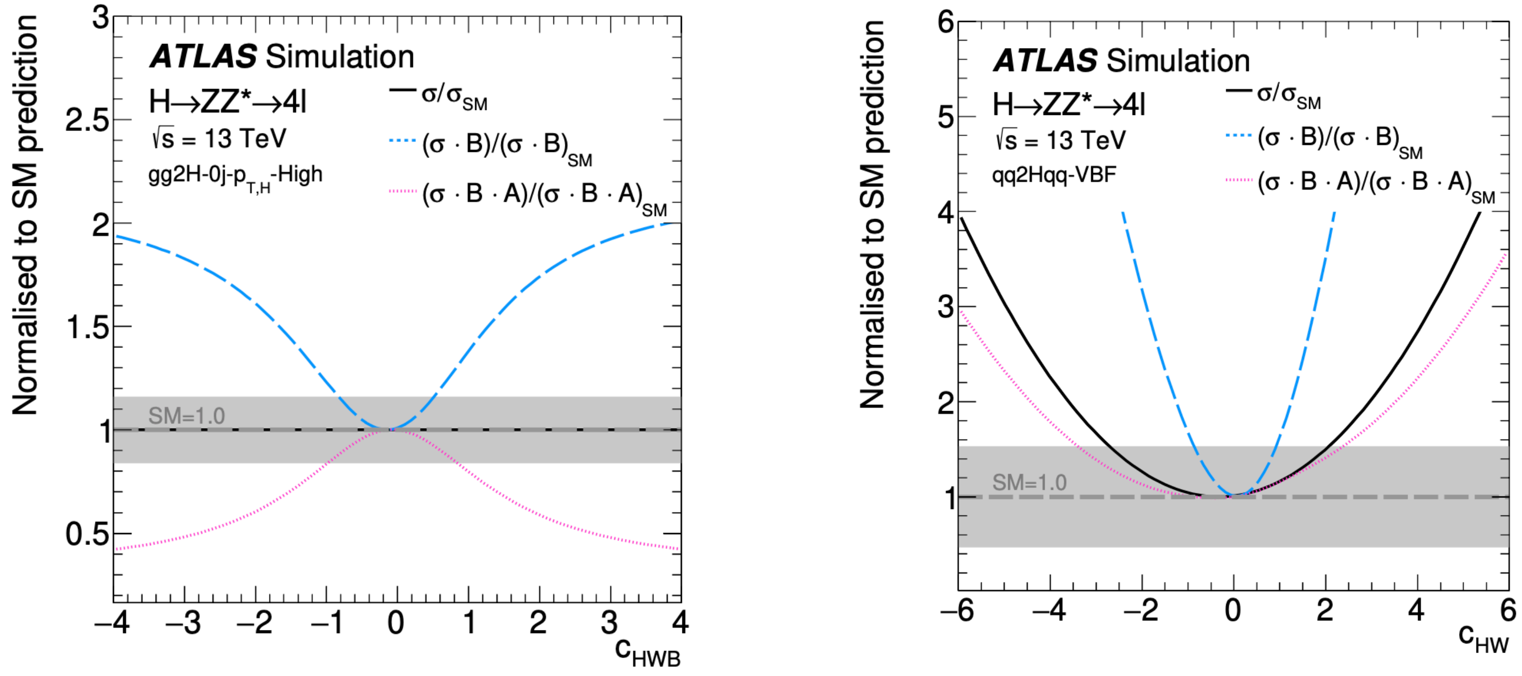
Acceptance effects

- Extrapolate results into full phase space using fiducial acceptance -
  Estimated using a SM MC
  - Typically, BSM physics doesn't change this too much and results are ~ valid
- But for H4l, these effects are large for many operators
  - Modelled these using a Lorentzian function -
    Is there a better theoretically motivated parametrization?

$$\sigma * \mathrm{BR}_{4l} = \frac{N}{A_{SM} * \epsilon * \mathcal{L}}$$



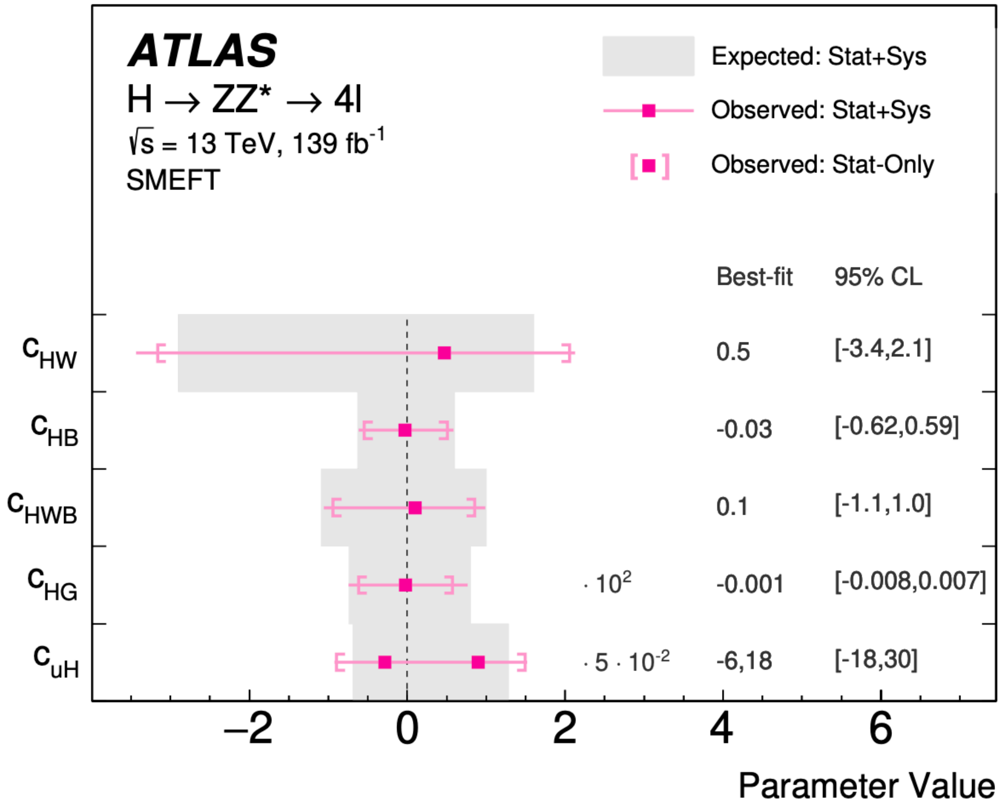
This part not measured due to detector acceptance + reconstruction efficiency

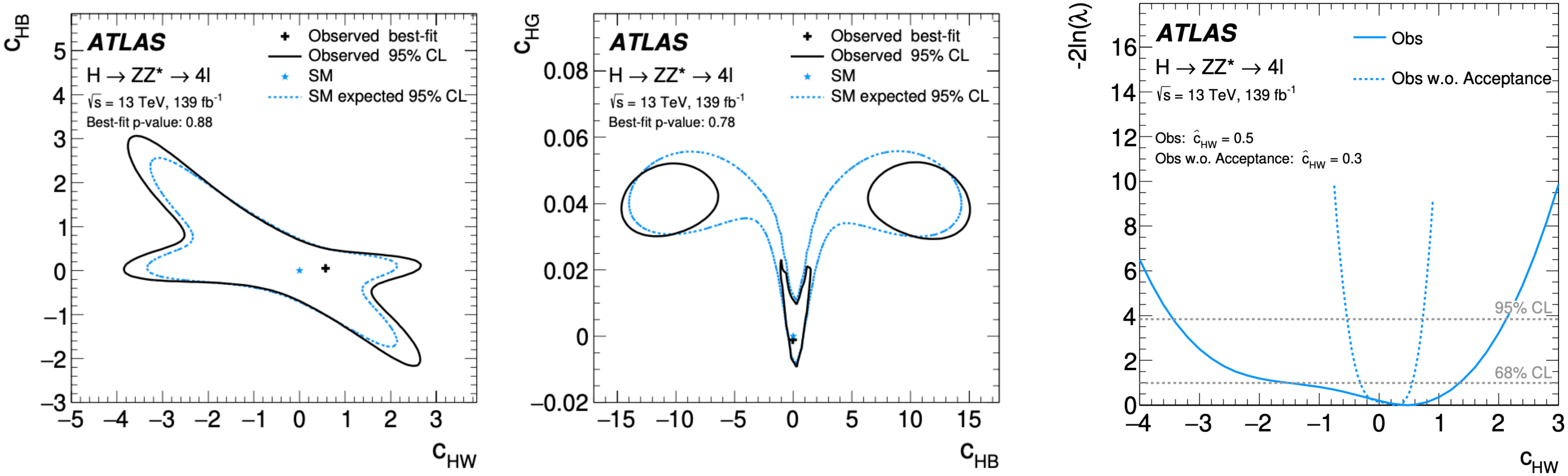


Impact of acceptance can drastically change the sensitivity

Results again!

- Interpreting the measurement into limits on EFT operators
  - Many assumptions and simplifications - Areas to improve
- There are still things to account for that can change the picture
  - Acceptance effects taken into account for the first time in an interpretation



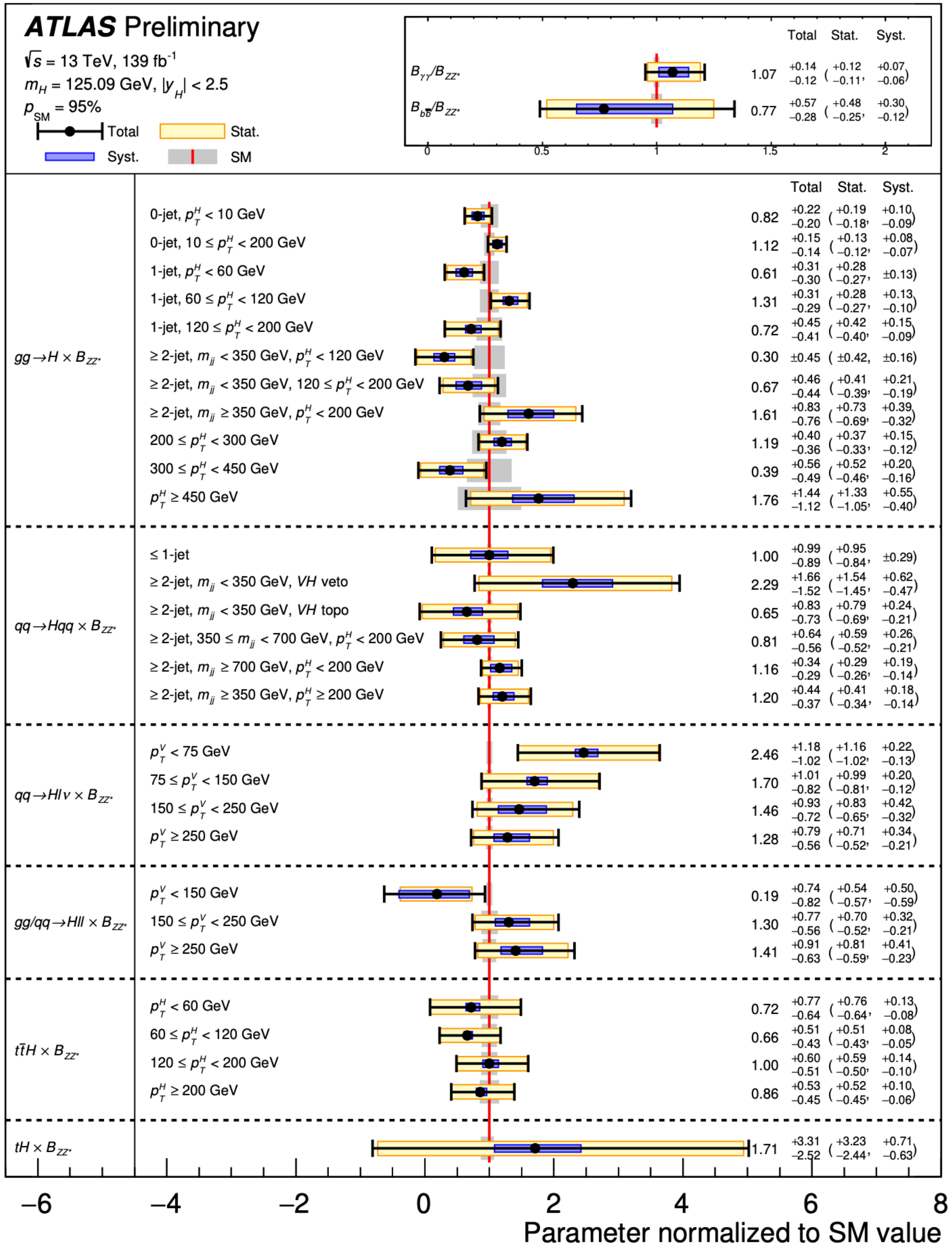


Impact of acceptance corrections

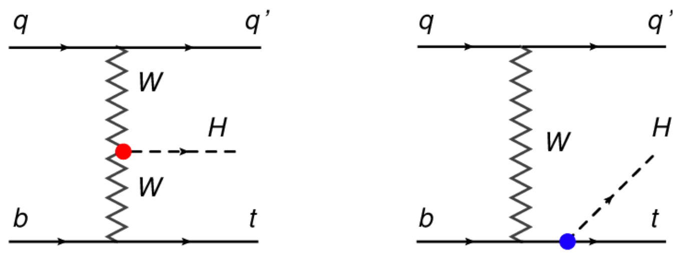
ATLAS-CONF-2020-053

Combined Results

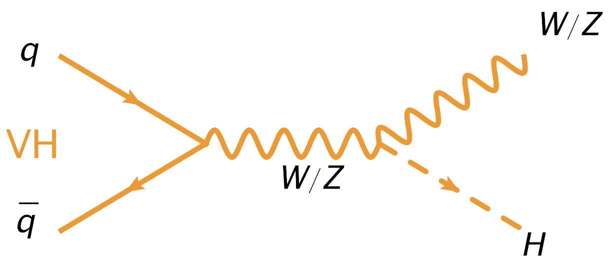
- One analysis limits how far we can go and what we can measure
- Combine channels with various sensitivities
  - Finer STXS bin possible
- More information to constrain even more EFT operators



- Even a first limit on single top associated production

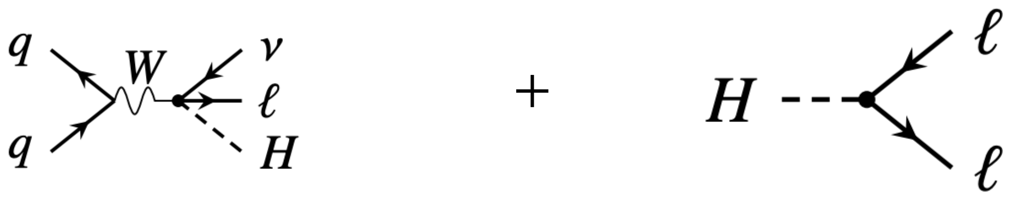


Increased sensitivity



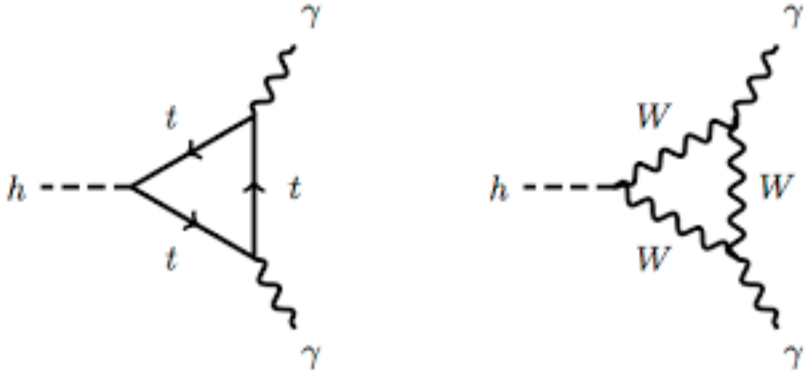
- The latest combined STXS results in H → ZZ → 4l, VH → bb & H → yy
- VH → bb targets the largest BR final state in the vector associate production
  - Provides the best SM to this production & decay
- New class of operators can be probed :

$c^{(3)}_{Hl}$ $\quad$ $(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$



- H4l has some sensitivity to these - but washed due to correlation + limited stats

- H → yy - better statistical precision on VBF and high pT regime
- Indirect constraints on Higgs-top and Higgs-W coupling through the decay loop
  - Can resolve the sign on the Higgs-top coupling through interference effects



Parametrization

- Similar ideas as before - parametrize XS/BR and Acceptance

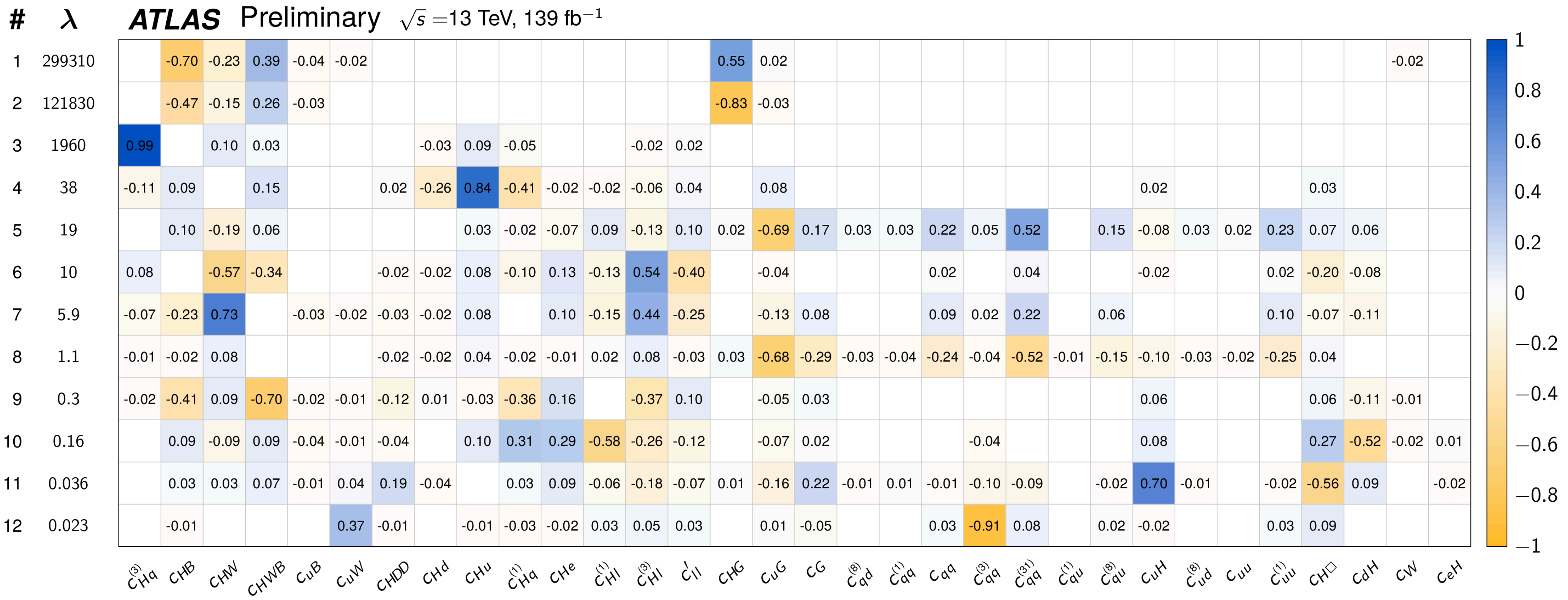
$$(\sigma\times B)^{i,H\to X}_{\text{SM}+\Lambda^{-4}} = (\sigma\times B)^{i,H\to X}_{\text{SM,((N)N)LO}} \left(1+\sum_j A_j^{\sigma_i} c_j + \sum_{jk} B_{jk}^{\sigma_i} c_j c_k\right)\left(\frac{1+\sum_j A_j^{\Gamma^{H\to X}} c_j + \sum_{jk} B_{jk}^{\Gamma^{H\to X}} c_j c_k}{1+\sum_j A_j^{\Gamma^{H}} c_j + \sum_{jk} B_{jk}^{\Gamma^{H}} c_j c_k}\right)$$

- Both linear only and linear + quadratic parameterizations are consider
- Quadratic terms are suppressed by Λ^{-4}
  - Dimension 8 operators enter at the same power
  - But without MC or predictions for d8 operators, cannot take into account and effects are fully ignored

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i}^{N_{d6}} \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_{j}^{N_{d8}} \frac{b_j}{\Lambda^4}\mathcal{O}_j^{(8)} + \ldots,$$

Flat Directions

- However, considering all the various operators leads to **flat directions**
  - Limit the number of operators? Or one-at-a-time
- Can do better by finding a Eigen rotation and holding the flat direction constant



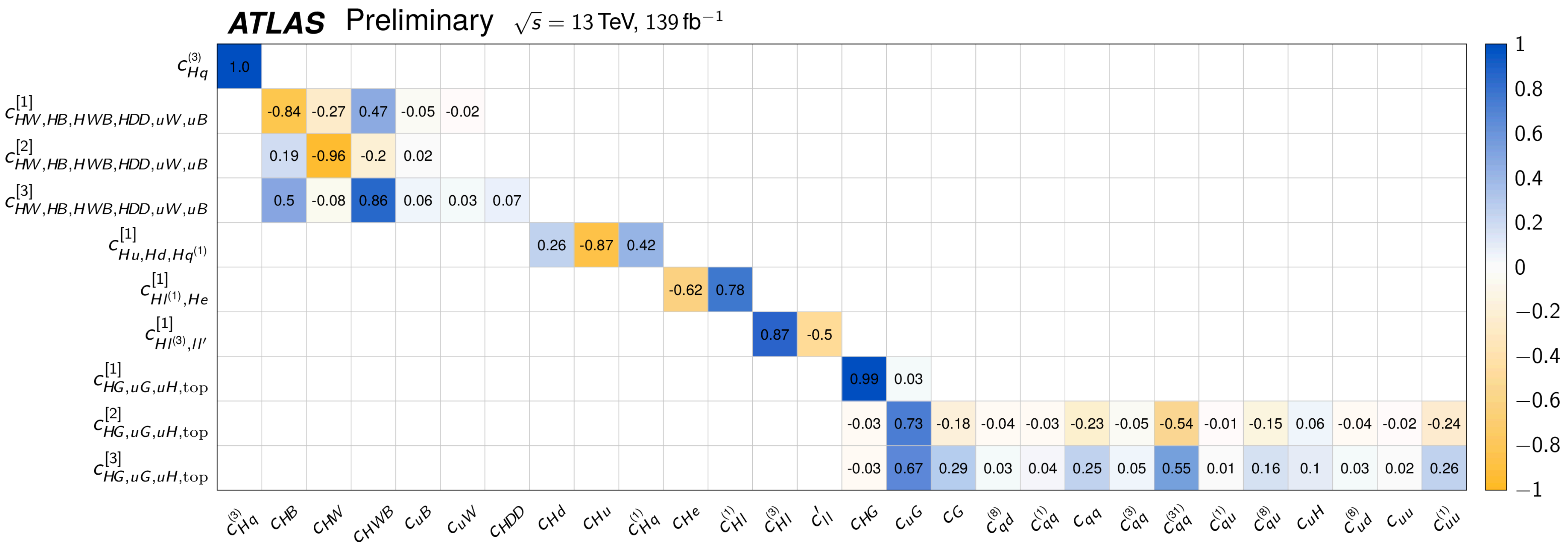
#	λ	$c_{Hq}^{(3)}$	c_{HB}	c_{HW}	c_{HWB}	c_{uB}	c_{uW}	c_{HDD}	c_{Hd}	c_{Hu}	$c_{Hq}^{(1)}$	c_{He}	$c_{Hl}^{(1)}$	$c_{Hl}^{(3)}$	c'_{ll}	c_{HG}	c_{uG}	c_{G}	$c_{qd}^{(8)}$	$c_{qq}^{(1)}$	c_{qq}	$c_{qq}^{(3)}$	$c_{qq}^{(31)}$	$c_{qu}^{(1)}$	$c_{qu}^{(8)}$	c_{uH}	$c_{ud}^{(8)}$	c_{uu}	$c_{uu}^{(1)}$	$c_{H\Box}$	c_{dH}	c_{W}	c_{eH}
1	299310		-0.70	-0.23	0.39	-0.04	-0.02									0.55	0.02															-0.02	
2	121830		-0.47	-0.15	0.26	-0.03										-0.83	-0.03																
3	1960	0.99		0.10	0.03				-0.03	0.09	-0.05			-0.02	0.02																		
4	38	-0.11	0.09		0.15			0.02	-0.26	0.84	-0.41	-0.02	-0.02	-0.06	0.04		0.08									0.02				0.03			
5	19		0.10	-0.19	0.06					0.03	-0.02	-0.07	0.09	-0.13	0.10	0.02	-0.69	0.17	0.03	0.03	0.22	0.05	0.52		0.15	-0.08	0.03	0.02	0.23	0.07	0.06		
6	10	0.08		-0.57	-0.34			-0.02	-0.02	0.08	-0.10	0.13	-0.13	0.54	-0.40		-0.04				0.02		0.04			-0.02			0.02	-0.20	-0.08		
7	5.9	-0.07	-0.23	0.73		-0.03	-0.02	-0.03	-0.02	0.08		0.10	-0.15	0.44	-0.25		-0.13	0.08			0.09	0.02	0.22		0.06				0.10	-0.07	-0.11		
8	1.1	-0.01	-0.02	0.08				-0.02	-0.02	0.04	-0.02	-0.01	0.02	0.08	-0.03	0.03	-0.68	-0.29	-0.03	-0.04	-0.24	-0.04	-0.52	-0.01	-0.15	-0.10	-0.03	-0.02	-0.25	0.04			
9	0.3	-0.02	-0.41	0.09	-0.70	-0.02	-0.01	-0.12	0.01	-0.03	-0.36	0.16		-0.37	0.10		-0.05	0.03								0.06				0.06	-0.11	-0.01	
10	0.16		0.09	-0.09	0.09	-0.04	-0.01	-0.04		0.10	0.31	0.29	-0.58	-0.26	-0.12		-0.07	0.02				-0.04				0.08				0.27	-0.52	-0.02	0.01
11	0.036		0.03	0.03	0.07	-0.01	0.04	0.19	-0.04		0.03	0.09	-0.06	-0.18	-0.07	0.01	-0.16	0.22	-0.01	0.01	-0.01	-0.10	-0.09		-0.02	0.70	-0.01		-0.02	-0.56	0.09		-0.02
12	0.023		-0.01				0.37	-0.01		-0.01	-0.03	-0.02	0.03	0.05	0.03		0.01	-0.05			0.03	-0.91	0.08		0.02	-0.02			0.03	0.09			

- Use a mixture of experimental sensitivity and theoretical information to **create various subspaces**
  - cHW, cHB and cHWB are primarily constrained by Hγγ and match well the predicted direction from the analytical calculation for H→ γγ decay width
  - Various Higgs - lepton operators derive sensitivity from Hbb, but analysis is not setup for measure these and hence are very correlated

Eigen-direction

- Final subspaces of operators considered:

$$
\begin{aligned}
\{c_i\} \;=\;& \{c^{(3)}_{Hq}\}\times \\
& \{c_{HG}, c_{uG}, c_{uH}, c^{(1)}_{qq}, c_{qq}, c^{(3)}_{qq}, c^{(31)}_{qq}, c_{uu}, c^{(1)}_{uu}, c^{(8)}_{ud}, c^{(1)}_{qu}, c^{(8)}_{qu}, c^{(8)}_{qd}, c_G\}\times \\
& \{c_{HW}, c_{HB}, c_{HWB}, c_{HDD}, c_{uW}, c_{uB},\}\times \\
& \{c^{(1)}_{Hl}, c_{He}\}\times \\
& \{c^{(3)}_{Hl}, c'_{ll}\}\times \\
& \{c_{Hu}, c_{Hd}, c^{(1)}_{Hq}\}.
\end{aligned}
$$



	$c^{(3)}_{Hq}$	c_{HB}	c_{HW}	c_{HWB}	c_{uB}	c_{uW}	c_{HDD}	c_{Hd}	c_{Hu}	$c^{(1)}_{Hq}$	c_{He}	$c^{(1)}_{Hl}$	$c^{(3)}_{Hl}$	c'_{ll}
$c^{(3)}_{Hq}$	1.0													
$c^{[1]}_{HW,HB,HWB,HDD,uW,uB}$		-0.84	-0.27	0.47	-0.05	-0.02								
$c^{[2]}_{HW,HB,HWB,HDD,uW,uB}$		0.19	-0.96	-0.2	0.02									
$c^{[3]}_{HW,HB,HWB,HDD,uW,uB}$		0.5	-0.08	0.86	0.06	0.03	0.07							
$c^{[1]}_{Hu,Hd,Hq^{(1)}}$								0.26	-0.87	0.42				
$c^{[1]}_{Hl^{(1)},He}$											-0.62	0.78		
$c^{[1]}_{Hl^{(3)},ll'}$													0.87	-0.5
$c^{[1]}_{HG,uG,uH,\mathrm{top}}$														
$c^{[2]}_{HG,uG,uH,\mathrm{top}}$														
$c^{[3]}_{HG,uG,uH,\mathrm{top}}$														

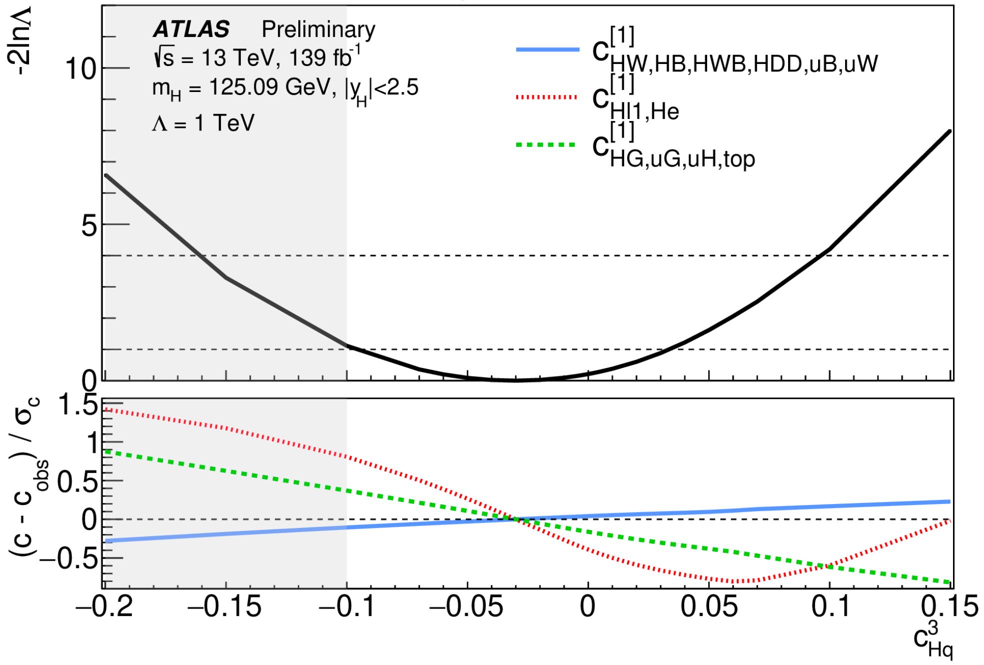
	c_{HG}	c_{uG}	c_G	$c^{(8)}_{qd}$	$c^{(1)}_{qq}$	c_{qq}	$c^{(3)}_{qq}$	$c^{(31)}_{qq}$	$c^{(1)}_{qu}$	$c^{(8)}_{qu}$	c_{uH}	$c^{(8)}_{ud}$	c_{uu}	$c^{(1)}_{uu}$
$c^{(3)}_{Hq}$														
$c^{[1]}_{HW,HB,HWB,HDD,uW,uB}$														
$c^{[2]}_{HW,HB,HWB,HDD,uW,uB}$														
$c^{[3]}_{HW,HB,HWB,HDD,uW,uB}$														
$c^{[1]}_{Hu,Hd,Hq^{(1)}}$														
$c^{[1]}_{Hl^{(1)},He}$														
$c^{[1]}_{Hl^{(3)},ll'}$														
$c^{[1]}_{HG,uG,uH,\mathrm{top}}$	0.99	0.03												
$c^{[2]}_{HG,uG,uH,\mathrm{top}}$	-0.03	0.73	-0.18	-0.04	-0.03	-0.23	-0.05	-0.54	-0.01	-0.15	0.06	-0.04	-0.02	-0.24
$c^{[3]}_{HG,uG,uH,\mathrm{top}}$	-0.03	0.67	0.29	0.03	0.04	0.25	0.05	0.55	0.01	0.16	0.1	0.03	0.02	0.26

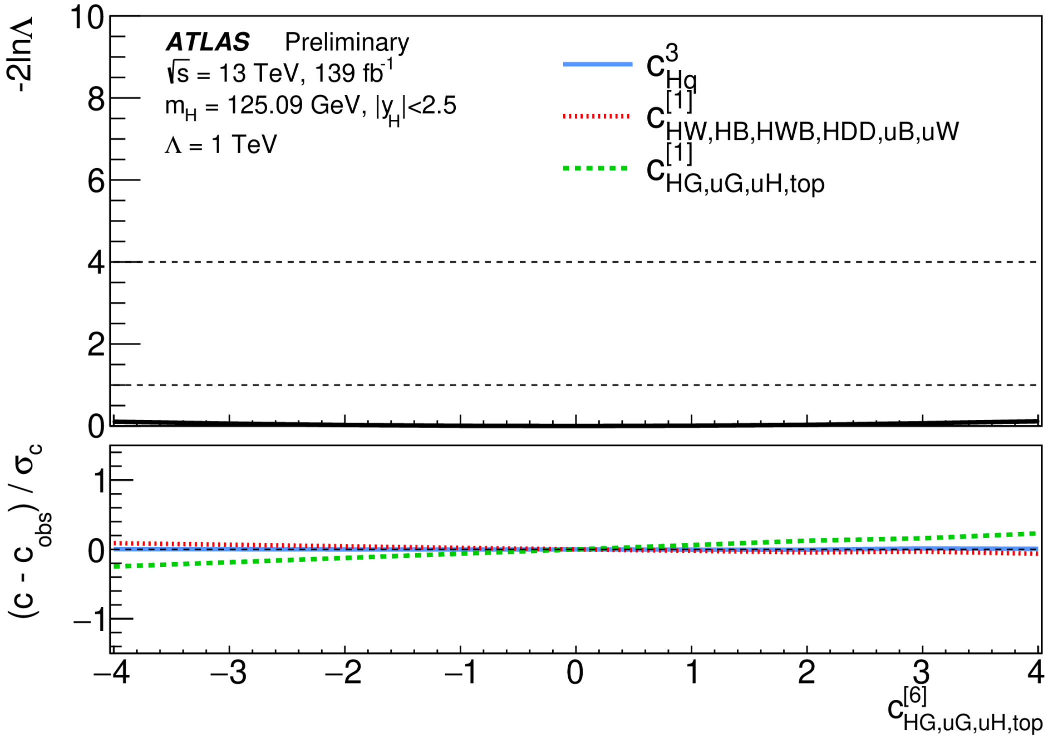
- Approximately half of eigenvectors are held constant

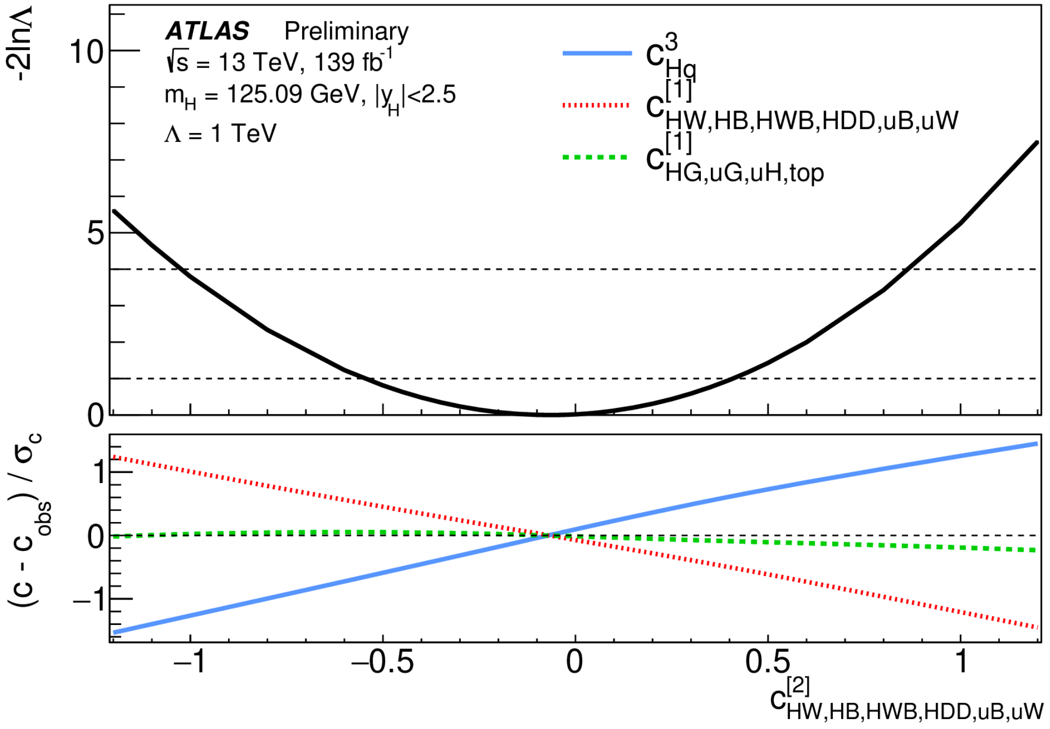
Sensitivity for eigenvector combinations

- Examples of various combinations and their sensitivity & correlations
- Acceptance effect still play a significant role
  - Manifest as non-linear correlations between parameters

Non-linear correlations due to acceptance corrections





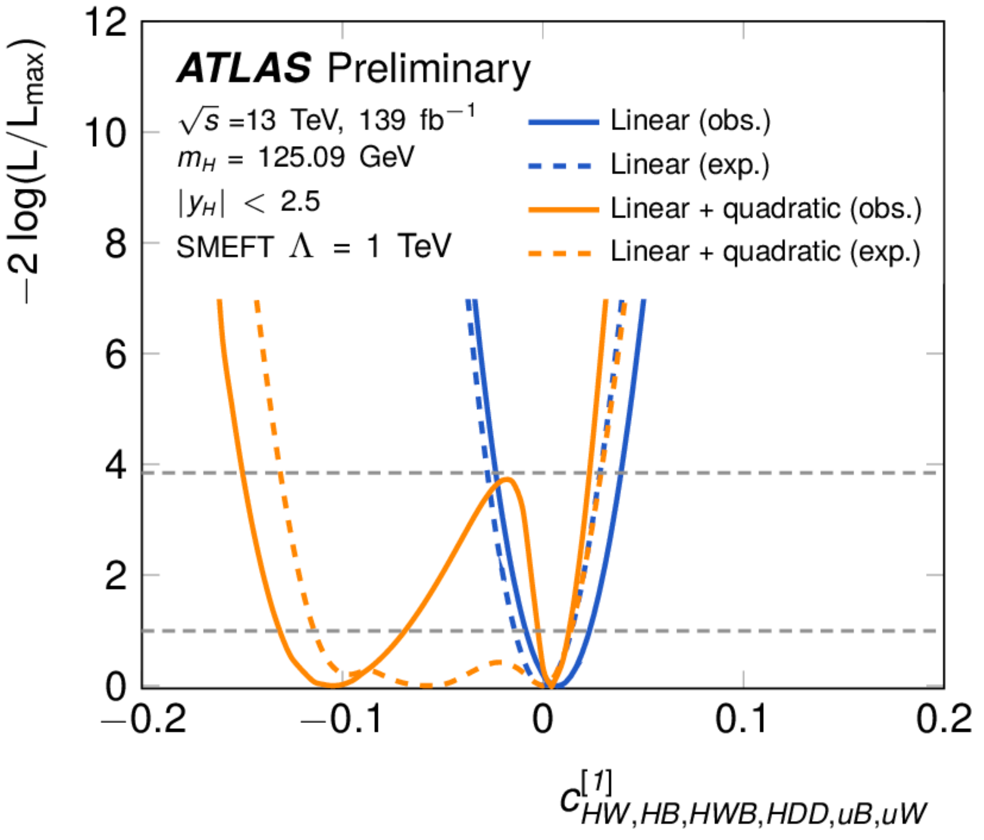


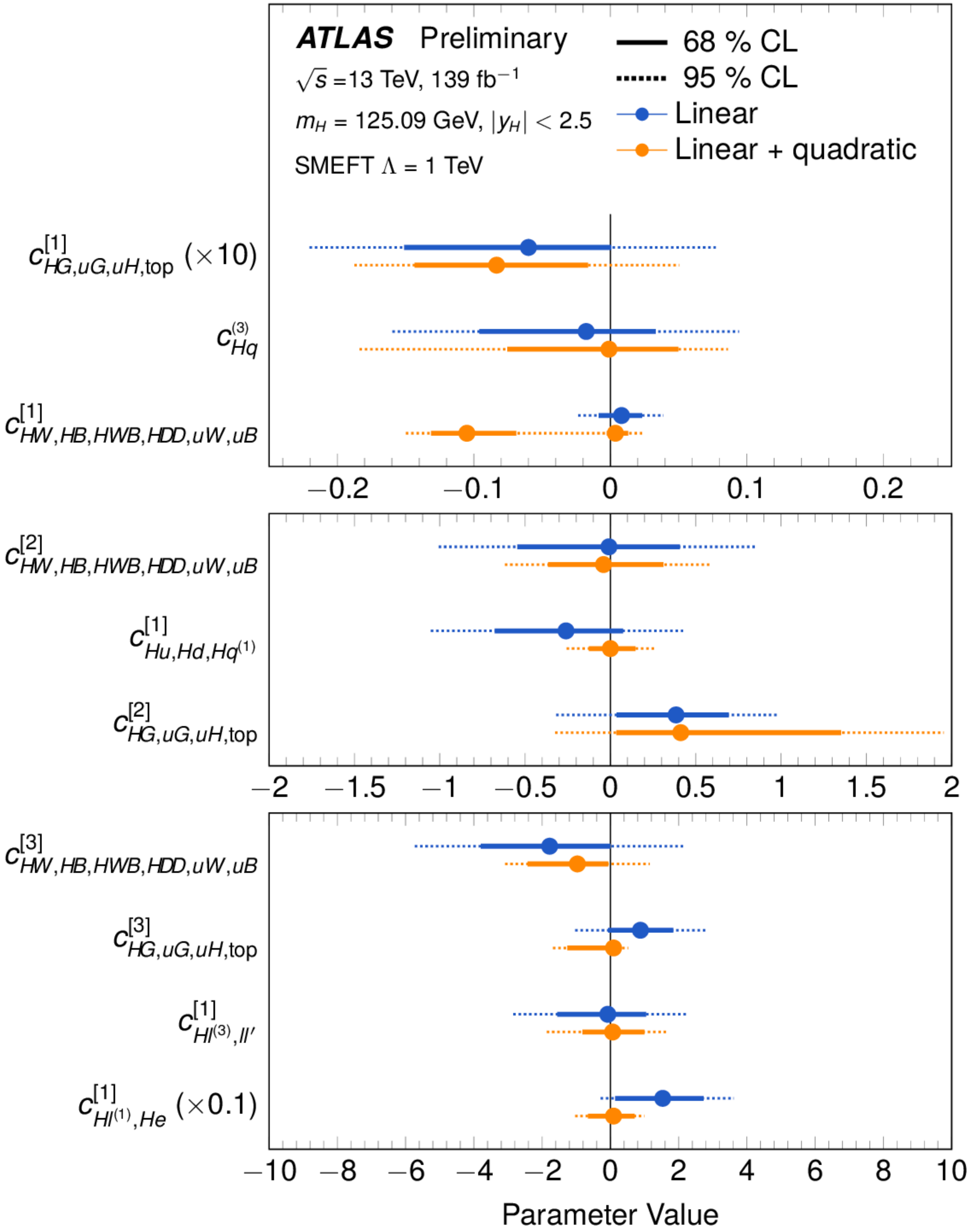
Flat direction

Sensitive direction

Results

- Linear only and linear+quadratic can have very different results





Conclusions

- Tried to deconstruct and peel back some of the considerations that go in interpretations from an experimental perspective

- Many areas where we can benefit from increased collaboration with experts:
  - Want to push ML → Need to improve MC accuracy
  - Many correlated effects in EFT models - Ex acceptance effects
    - Closer collaborations with theory community
    - Know the models the best + STXS is independent of analysis choice
    - Can there be theoretical parametrization for various model? Or theory motivated operator combinations? Or better treatment of acceptances
  - Tons of results from experimental community - How best can they be provided to be useful to a wider audience?

- This is just the beginning of the Higgs measurement era - Many full Run 2 results to come, and another LHC data run at the horizon
  - Exciting times ahead!