Top quark couplings: challenging the SM

IHEP seminar, Beijing, August 2017

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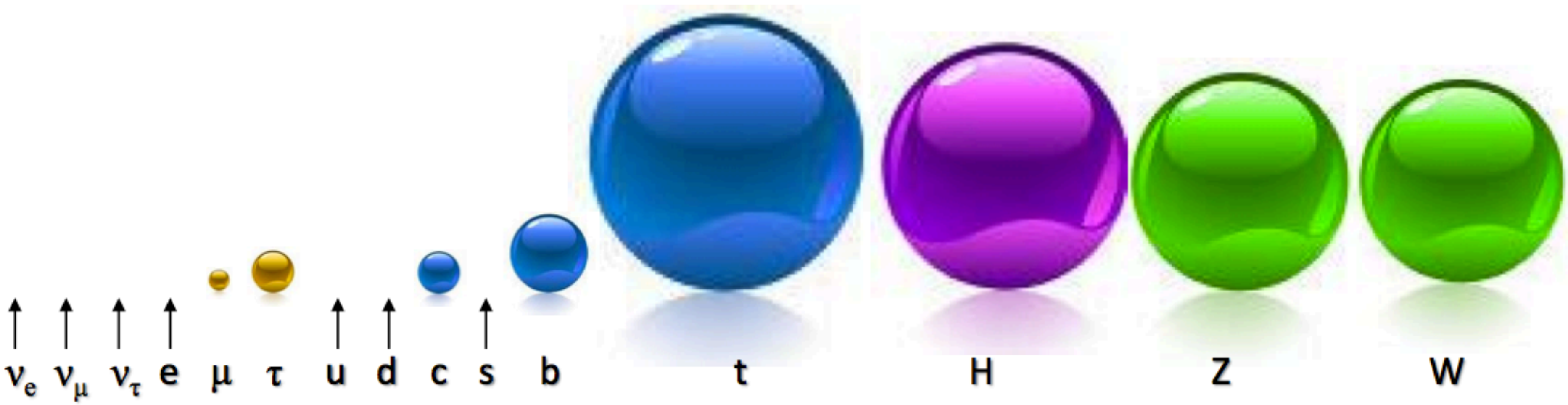


- Top quark in the Standard Model →
  - The road to the top quark
  - From discovery (at Tevatron) to a top quark factory (LHC)
  - Top quark physics at hadron colliders

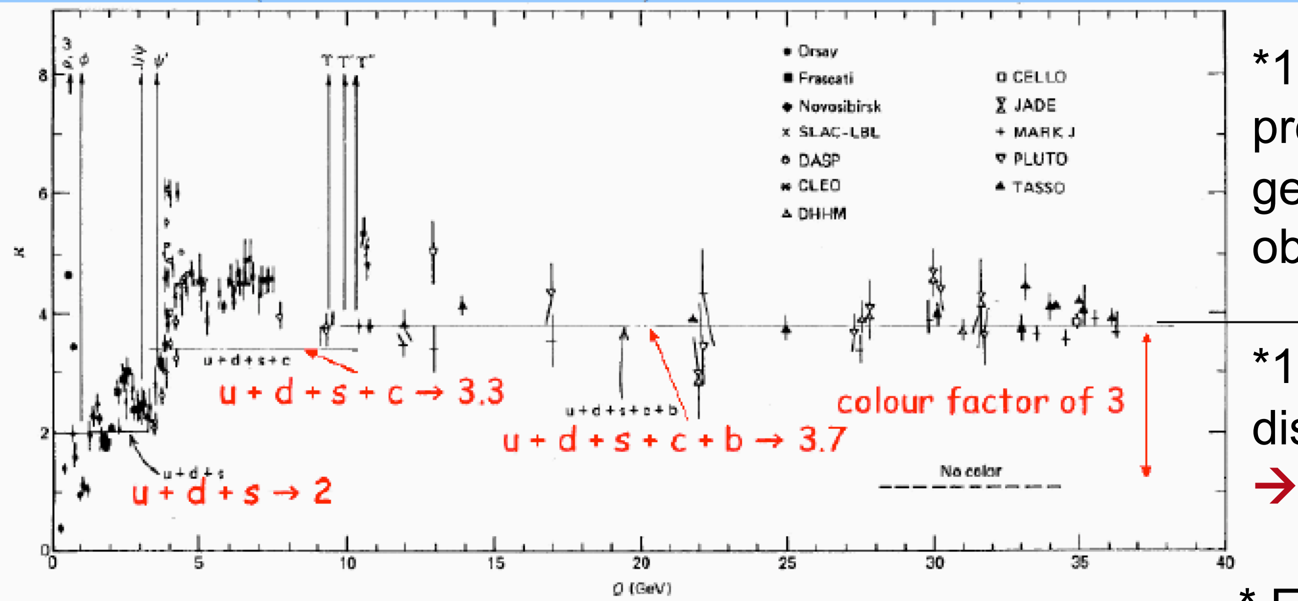
- Completes the 3rd family structure of SM
- Electric charge = 2/3|e|
- Spin = 1/2, Isospin (T_3) = +1/2
- Mass ~173.34 ± 0.76 GeV
- Fast decay: τ ~$4 \cdot 10^{-25}$ s, Γ = 1.32 GeV
- Dominant decay to $t \rightarrow Wb$:
  $|V_{tb}| > 0.999$ ➔ BR($t \rightarrow Wb$) ~100%
  BR($t \rightarrow Ws$) ≤0.18%
  BR($t \rightarrow Wd$) ≤0.02%

- Top quark couplings to other Standard Model fields (g, γ, W, Z, and H) through gauge and Yukawa interactions

- Searches for flavour changing neutral currents (FCNC)

- Outlook

$$R = \frac{\sigma(e^+ + e^- \rightarrow hadrons)}{\sigma(e^+ + e^- \rightarrow \mu^+ + \mu^-)} = \frac{3\sum(quark\,charge)^2}{1^2}$$



*1973: M. Kobayashi and T. Maskawa predicted the existence of a third generation of quarks to explain observed *CP* violations in kaon decay.

*1977: bottom quark (5th quark) was discovered by the E288 exp. at Fermilab
→ 6th quark expected !!

* Early eighties, the SPS at CERN discovered the *W* and the Z boson, it was again felt that the top quark discovery was imminent.

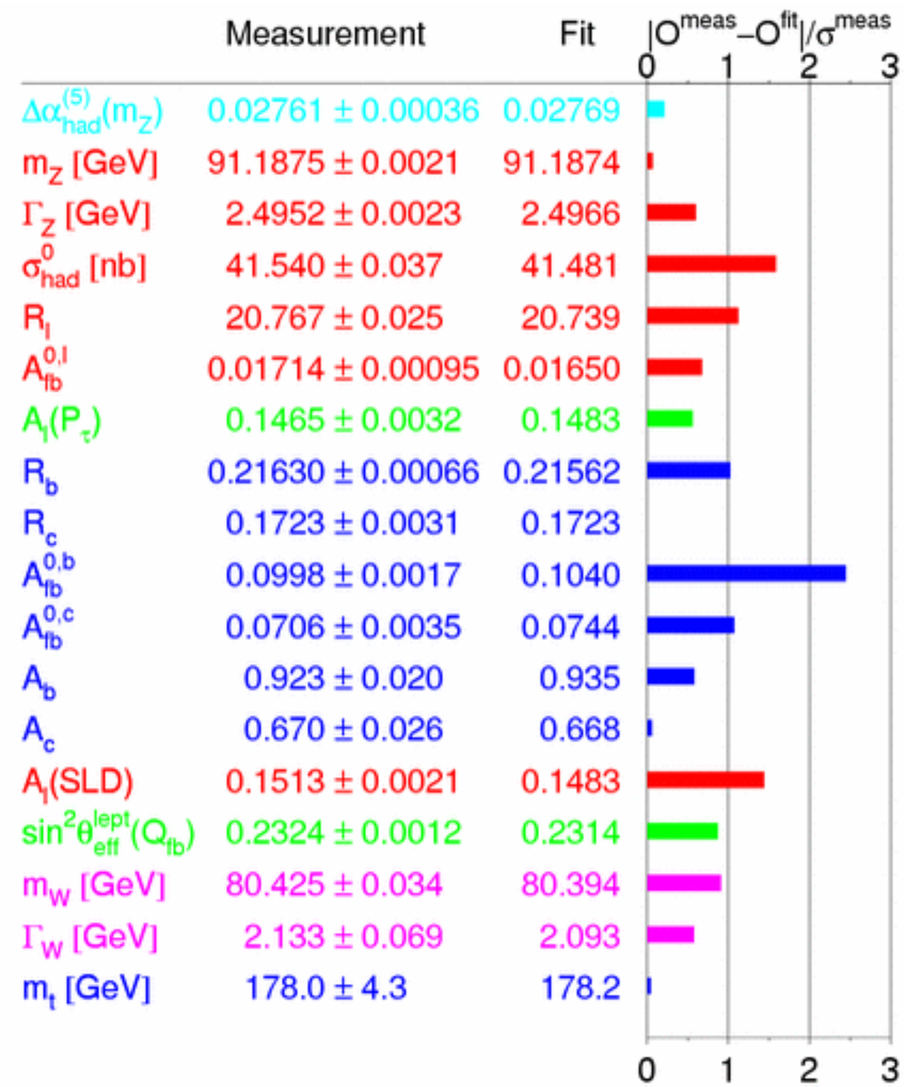
* Direct search in e^+e^- and p^+p^- colliders, increasing limits on the top mass.

- **Direct searches:**

Year	Collider	Particles	Limit on m_t
1979-84	PETRA (DESY)	e^+e^-	> 23.3 GeV/c^2
1987-90	TRISTAN (KEK)	e^+e^-	> 30.2 GeV/c^2
1989-90	SLC (SLAC), LEP (CERN)	e^+e^-	> 45.8 GeV/c^2
1984	SppS (CERN)	$p\bar{p}$	> 45.0 GeV/c^2
1990	SppS (CERN)	$p\bar{p}$	> 69 GeV/c^2
1991	TEVATRON (FNAL)	$p\bar{p}$	> 77 GeV/c^2
1992	TEVATRON (FNAL)	$p\bar{p}$	> 91 GeV/c^2
1994	TEVATRON (FNAL)	$p\bar{p}$	> 131 GeV/c^2
1995	TEVATRON (FNAL)	$p\bar{p}$	$= 174 \pm 10^{+13}_{-12}$ GeV/c^2
			$= 199^{+19}_{-21} \pm 22$ GeV/c^2

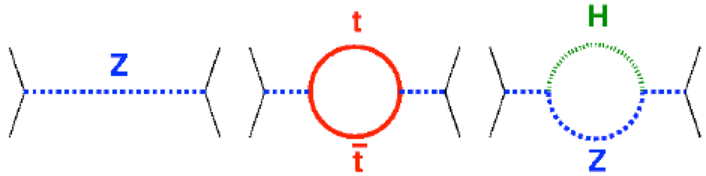
Top quark mass prediction from EW measurements

- **Indirect searches:** ~1990– indirect estimate of quark mass from precision EWK measurements (LEP)



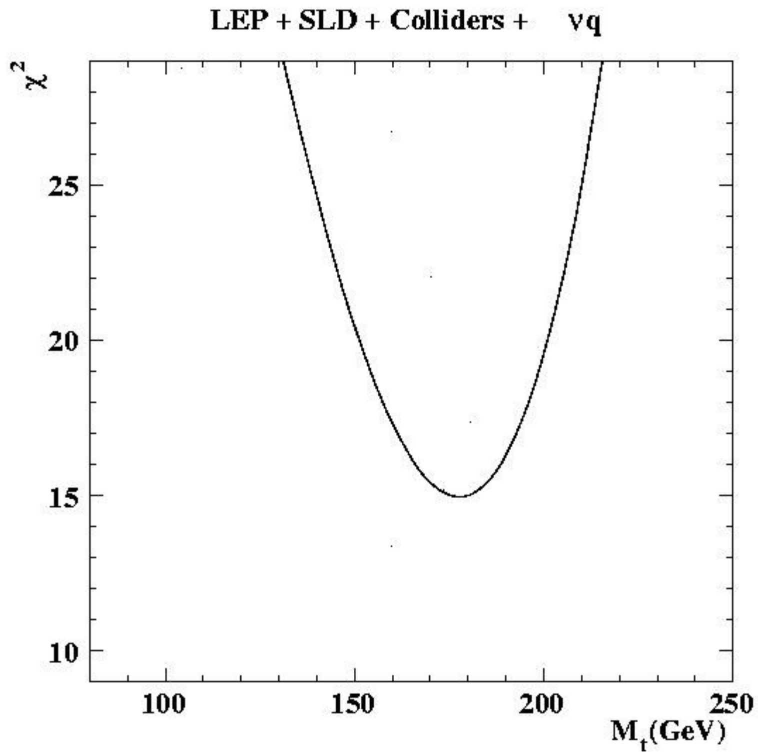
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	0.02769
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4966
σ_{had}^0 [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01650
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1483
R_b	0.21630 ± 0.00066	0.21562
R_c	0.1723 ± 0.0031	0.1723
$A_{fb}^{0,b}$	0.0998 ± 0.0017	0.1040
$A_{fb}^{0,c}$	0.0706 ± 0.0035	0.0744
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.026	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1483
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.394
Γ_W [GeV]	2.133 ± 0.069	2.093
m_t [GeV]	178.0 ± 4.3	178.2

precision measurement ⇔ correction
⇨ top quark mass prediction

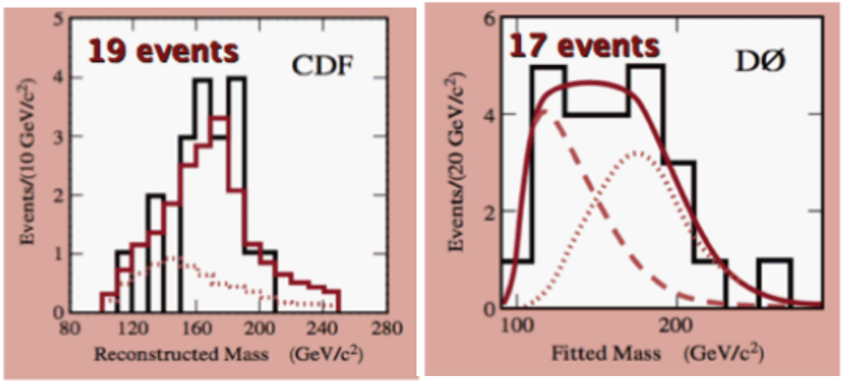


$$M_Z^2 = M_Z^{2\ \text{0.order}} / (1 - \Delta)$$

$$\Delta \approx \ldots\ m_t^2\ \ldots + \ldots \ln m_h\ \ldots$$



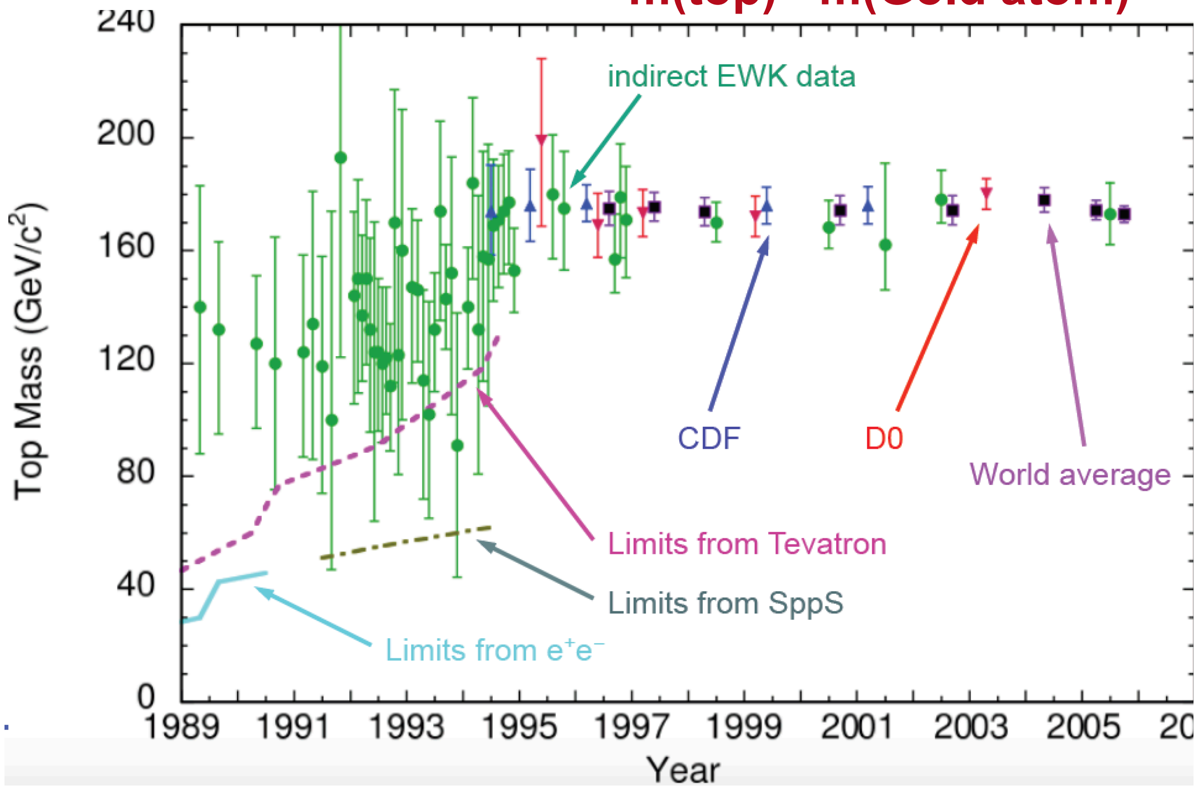
Discovered the top quark exactly where it was expected...



Top quark discovery in 1995 by CDF and D0 at Tevatron (Fermilab)

F. Abe *et al*. (CDF collaboration), PRL 74:2626-2631 (1995)
S. Abachi *et al*. (D0 collaboration),PRL 74:2632-2637 (1995)

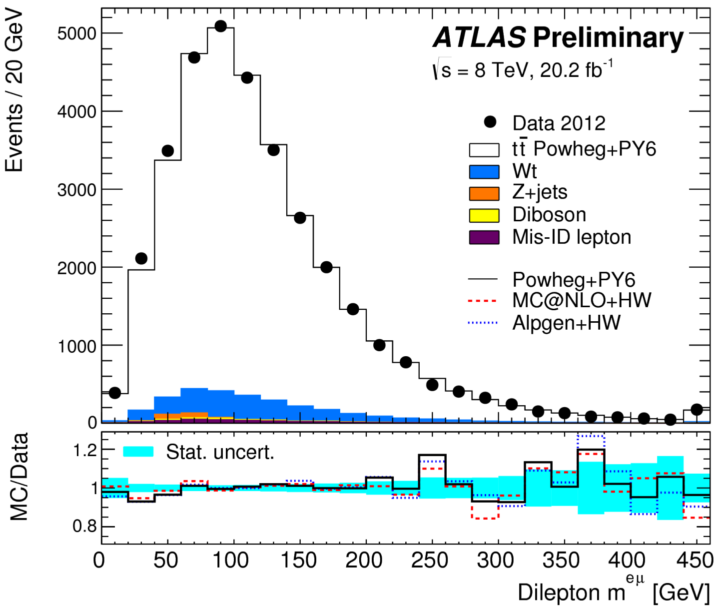
m(top)~ m(Gold atom)



From discovery to precision with LHC top quark factory !

Situation today:
LHC is a top quark factory!
→ Millions of events
→ Many precision measurements possible!

At peak instantaneous luminosity,
~2-5 top pairs/sec, and
~1-2 single top/sec
are produced in ATLAS !!



pp collider

- Run I:

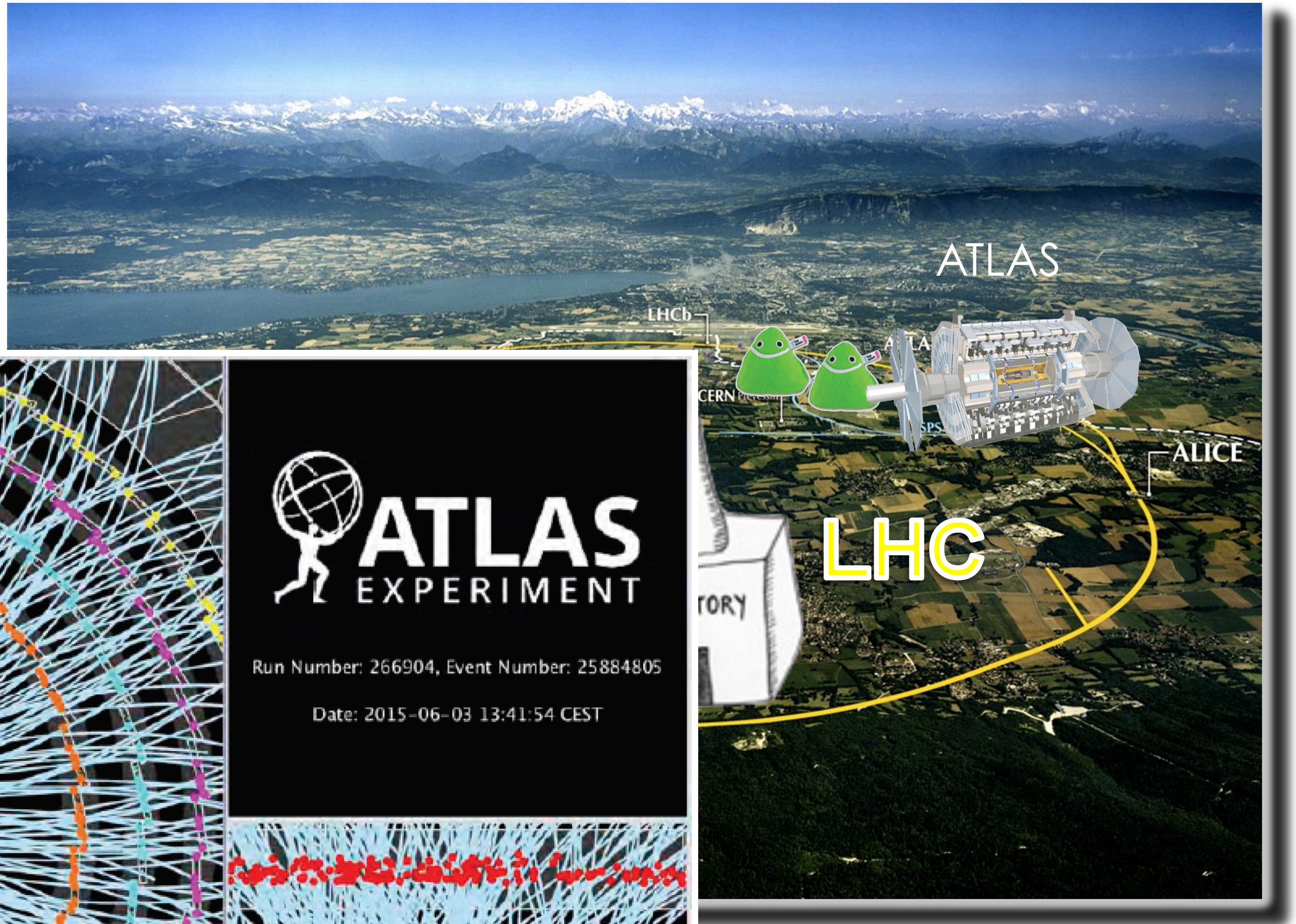
2010: $\sqrt{s}$=7 TeV, L≈45 pb^{-1}
2011: $\sqrt{s}$=7 TeV, 5 fb^{-1}
2012: $\sqrt{s}$=8 TeV, 20 fb^{-1}

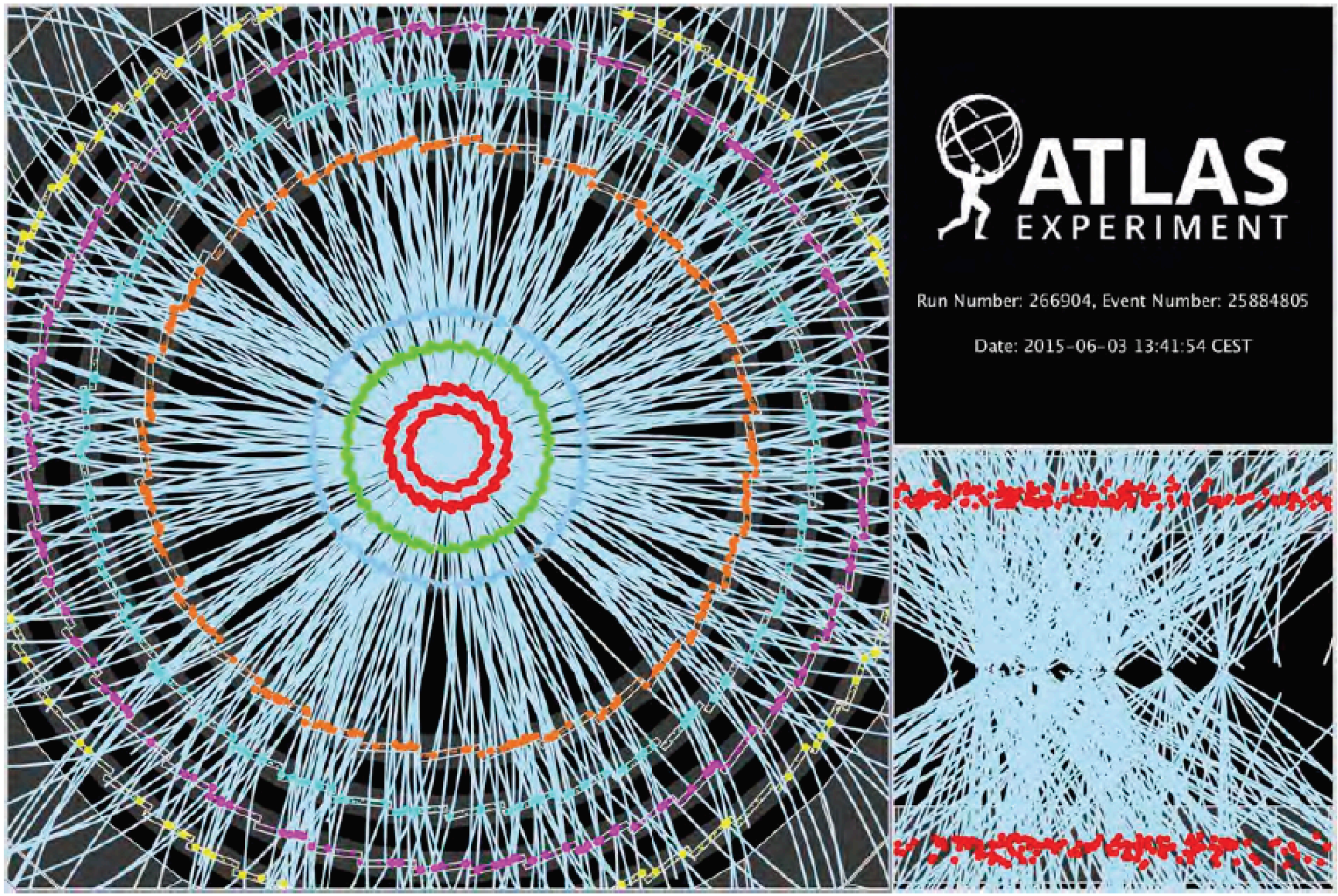
- Run II:

2015-16: $\sqrt{s}$=13 TeV, 36 fb^{-1}
2017: $\sqrt{s}$=13 TeV, 18 fb^{-1}
Expected end 2018: 150 fb^{-1}

From discovery to precision with LHC top quark factory !

Multiple interactions per event
→ High pile-up

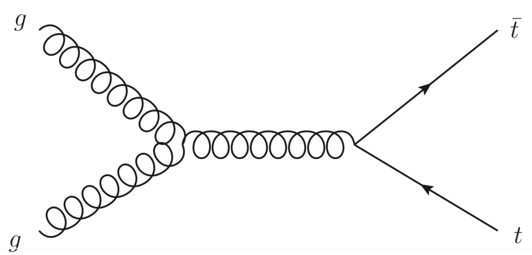


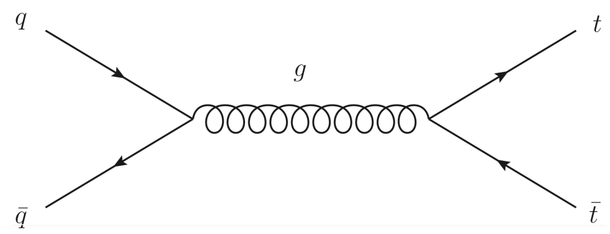


- Run II:

2015-16: √s=13 TeV, 36 fb^{-1}
2017: √s=13 TeV, 18 fb^{-1}
Expected end 2018: 150 fb^{-1}

Top pair production (strong interaction)





gluon fusion **quark-antiquark annihilation**

Czakon *et al.*, PRL 110 252004 (2013)

σ_{7TeV} (pb)	$172^{+4.4}_{-5.8}{}^{+4.7}_{-48}$
σ_{8TeV} (pb)	$245^{+6.2}_{-8.4}{}^{+6.2}_{-6.4}$
σ_{13TeV} (pb)	$831^{+19}_{-29}{}^{+35}_{-35}$

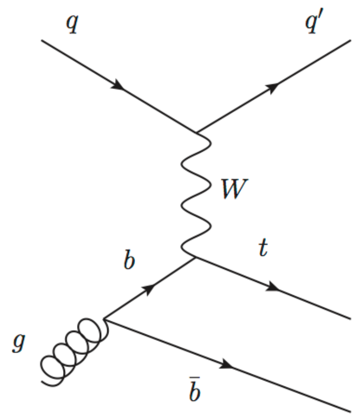
Long standing theoretical effort

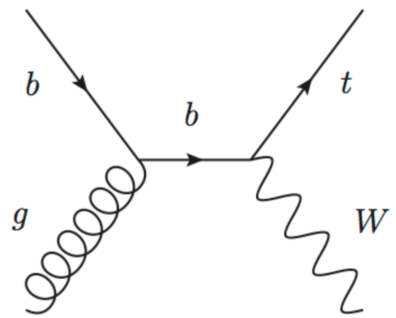
@ NNLO + NNLL
m_{top} = 172.5 GeV

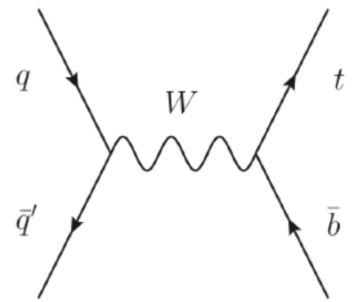
Single top production (electroweak interaction)

@ NLO + NNLL
m_{top} = 172.5 GeV

t-channel **Wt** **s-channel**



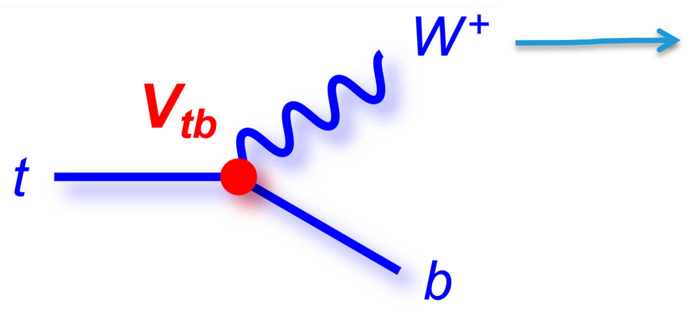


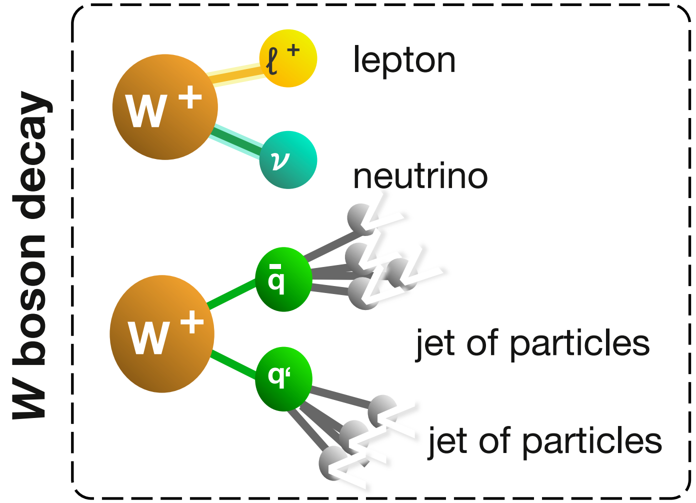


	t-chan	Wt chan	s-chan
σ_{7TeV} (pb)	64.6±2.4	15.7±1.1	4.6±0.2
σ_{8TeV} (pb)	87.8±3.4	22.4±1.5	5.6±0.2
σ_{13TeV}	221^{+5}_{-2}±3	72.6±1.1±1.8	11.29±0.18±0.26

JHEP 0910 (2009) 042
Kidonakis, PRD 83, 091503 (2011)
Kidonakis, PRD 82, 054018 (2010)
Kidonakis, PRD 81, 054028 (2010)

* Since $m_{top} > m_W + m_b \rightarrow$ decays predominantly into a *b* quark and a *W* boson





Different sub-channels depending on *W* decay

*Full-hadronic (4 jets being 2 of them from *b*-quarks)

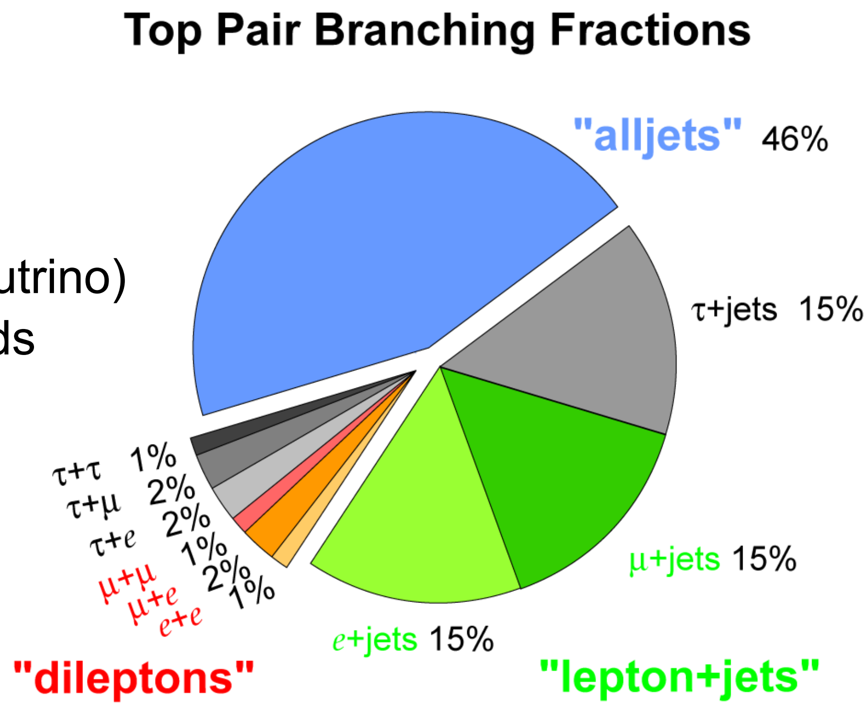
High branching ratio, large backgrounds (QCD)

* Single-lepton (1 lepton, 4 jets being 2 *b*-jets and 1 neutrino)

Reasonable branching ratio, moderate backgrounds

* Di-lepton (2 leptons, 2 *b*-jets and 2 neutrinos)

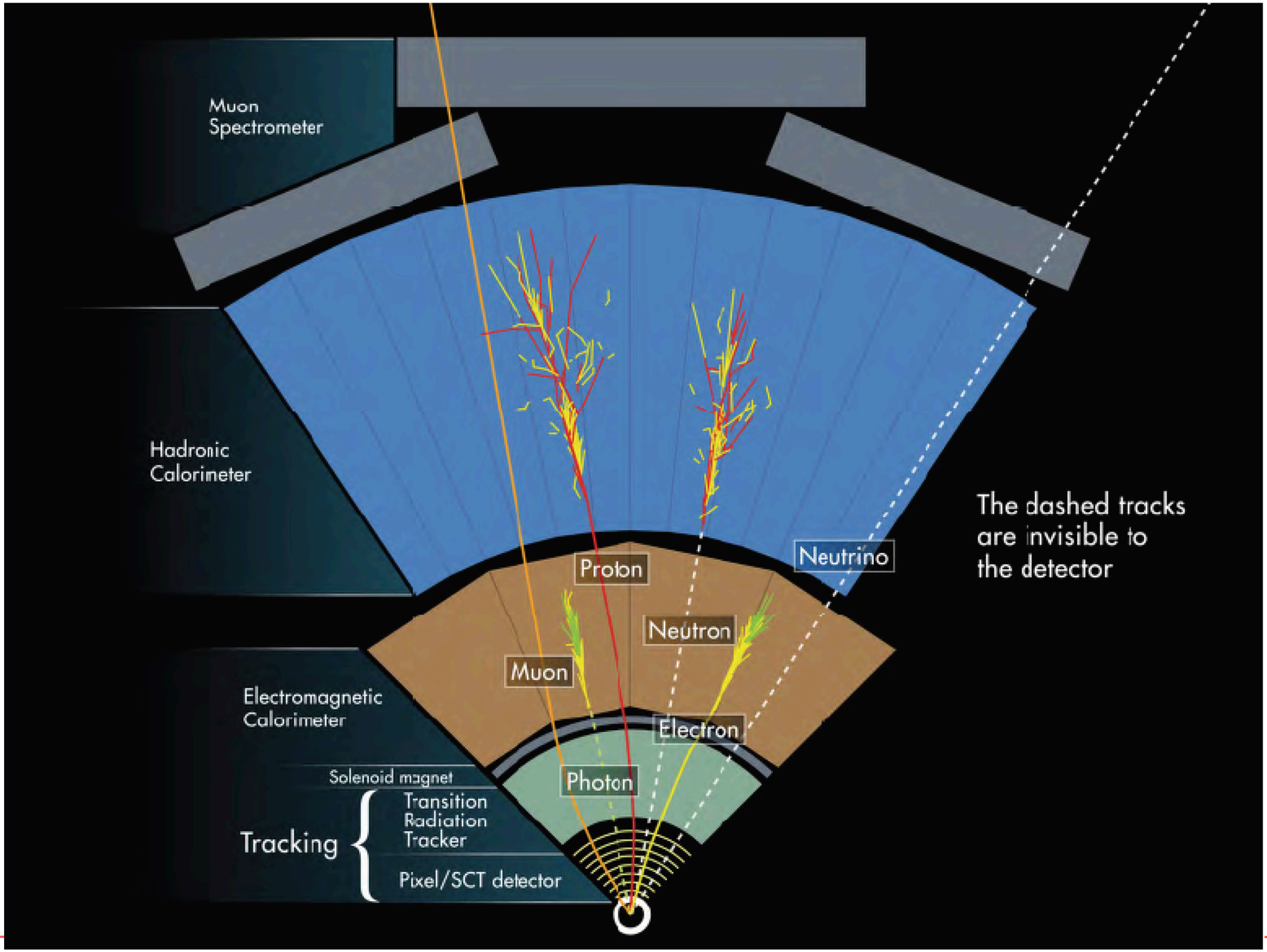
Low branching ratio, small backgrounds

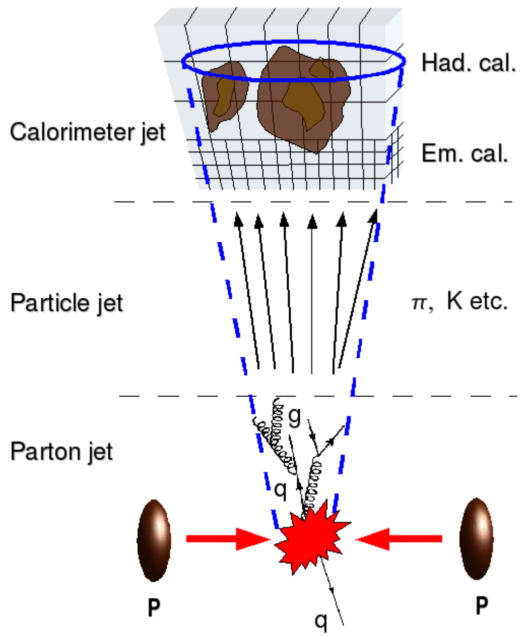


Final state objects reconstructed in LHC experiments

The reconstruction of top quark events (i.e. all its final state objects: electrons, muons, jets, E_T^{miss} and *b*-tagging) requires information from all the ATLAS or CMS subdetectors

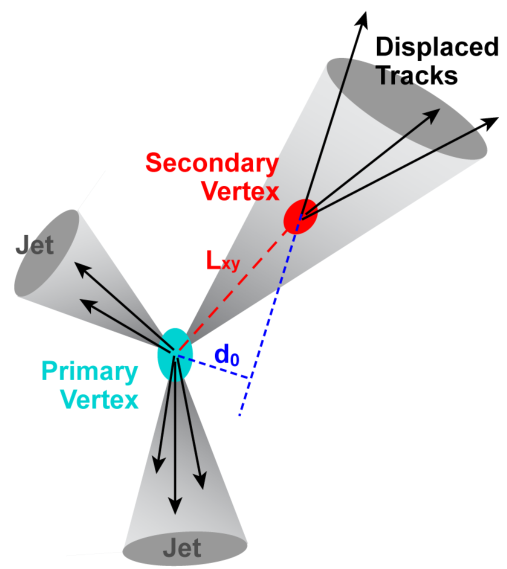
➔ A proper/precise understanding of the detector is required.

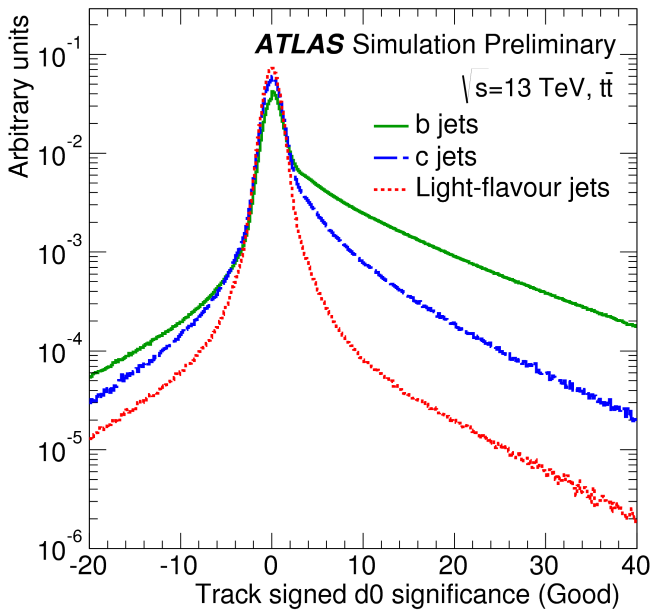


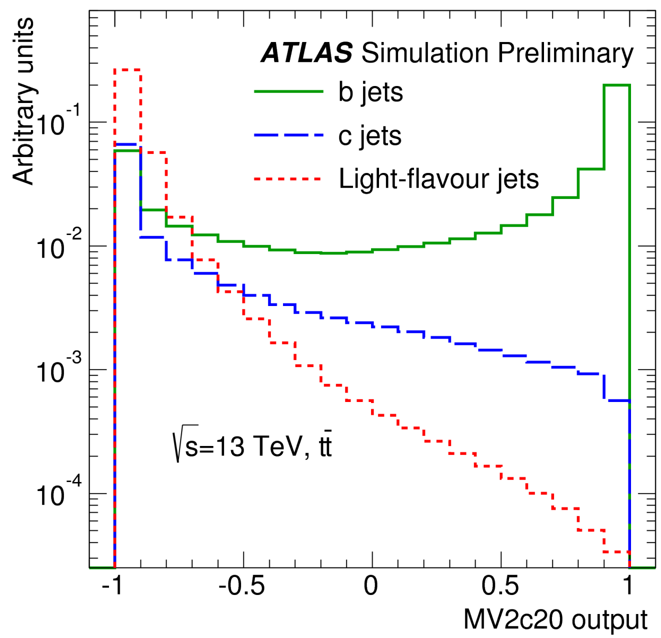


• Jets are reconstructed using the information of the calorimeters. **Precise** (and **in-situ) calibrations** of the energy scale of inclusive jets (**JES**) and the relative b-to-light-jet energy scale (**bJES**) are vital.

At least 2 jets originated from *b*-quarks in all *tt*+*X* events
→ **b- (and c-) tagging: very important tool(s) to increase *tt* purity**
• *B*-hadrons live long enough to create a secondary vertex,
i.e. travels few mm before it decays
• Neural Network (e.g. MV1, MV2) combines properties of displaced tracks (which cross the jet axis) and displaced vertices



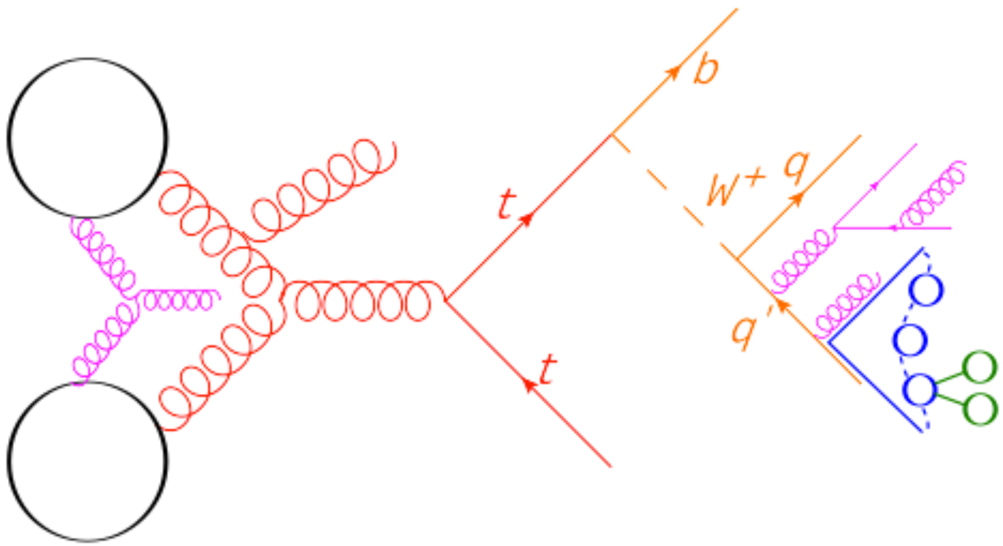




Analysis challenges: physics modelling uncertainties

- Monte Carlo generators used at LHC include multi-leg or fixed NLO+PS predictions for signal and main background processes.

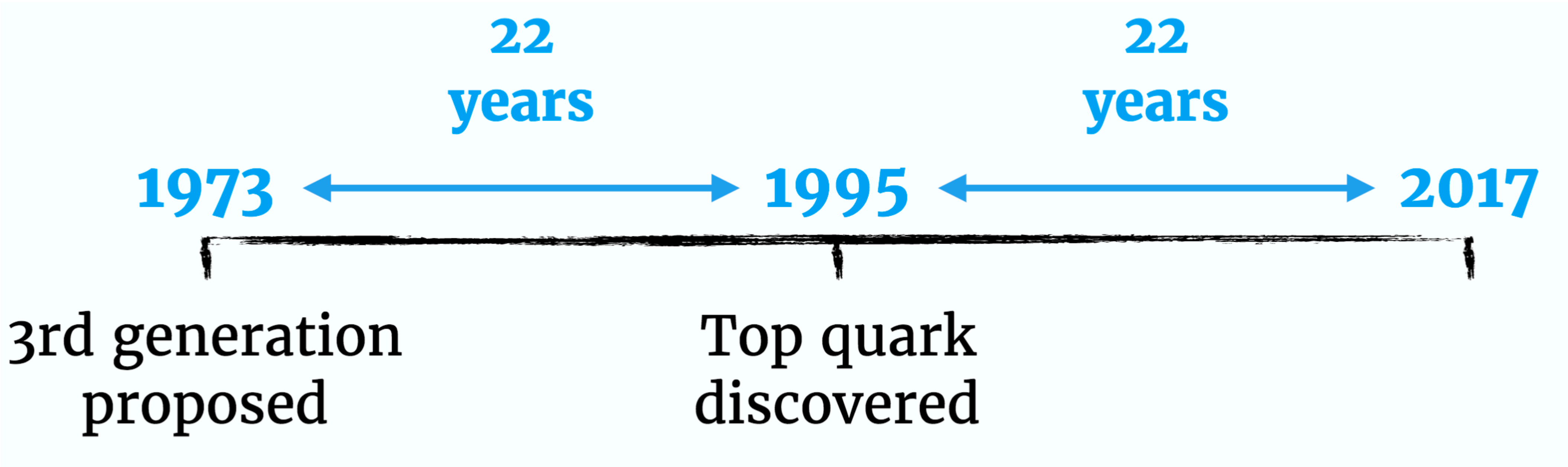
- Signal modelling uncertainties (e.g. radiation, parton shower & hadronisation models, PDF, colour reconnection) are typically important/dominant.



- Proton PDF
- Hard process
- Resonance decays
- Parton shower, MPI
- Hadronization
- Hadron decays

Two important strategies:

- Perform measurements that allow constraining these modelling uncertainties from data
  - differential measurements
- Reduce generator dependency on measurements by providing results at particle level in a fiducial region experimentally accessible


22
years
22
years
1973
1995
2017
3rd generation
proposed
Top quark
discovered

22 years | 22 years

1973 ⟷ 1995 ⟷ 2017

3rd generation proposed | Top quark discovered | ?

Important things happen every 22 years

Why do we still care about the top quark ?

The top quark is the **heaviest fundamental particle**, leading to unique properties from both the theoretical and experimental sides:

- only place to study the properties of a bare quark
  - short lifetime ➔ decays before hadronising ➔ properties studied through its decay products

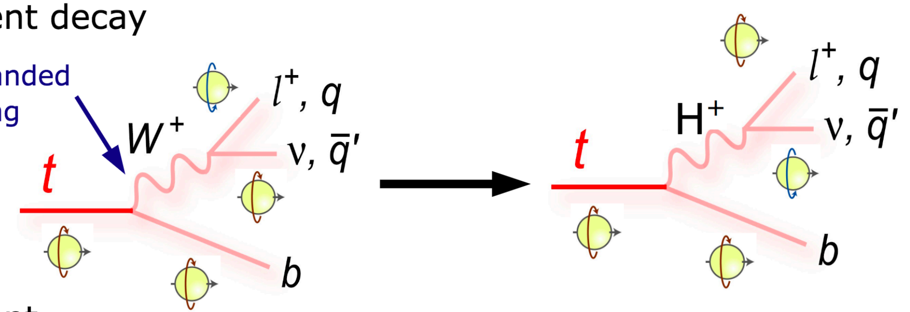
$1/m_t <$	$1/\Gamma_t <$	$1/\Lambda <$	m_t/Λ^2
Production time<	Lifetime <	Hadronization time <	Spin decorrelation time

- sensitive to new physics in production and decay
- Yukawa coupling almost unity
- can play an important role in the observations related to the electroweak symmetry breaking
- first place a new particle could be observed
  - ➔ particularly if new particle couples to mass

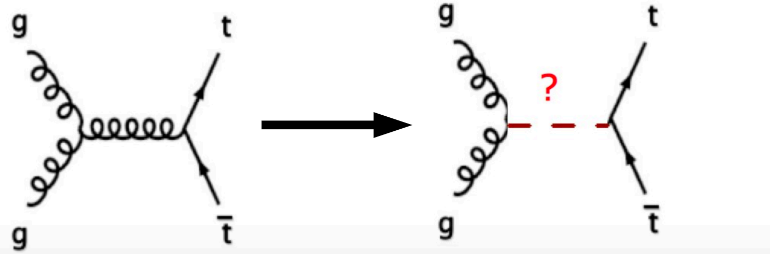
Deviation of the measured top quark properties from the SM predictions would be a signal of new physics.

Measured spin correlation can change

- Due to different decay



- Due to different production



Top quark couples to other SM fields through its **gauge and Yukawa interactions.**
t→*Wb* coupling measured already at the Tevatron.
High statistics at the LHC: *tt*+bosons (γ, *Z*, *W* and *H*) becomes available!!

* Observation of *tt*+γ/*Z*/*W* processes by both ATLAS and CMS with LHC Run1 data.
* Not yet for *tt*+*H* process but getting close… (Run1 LHC Higgs combination: 4.4 σ)

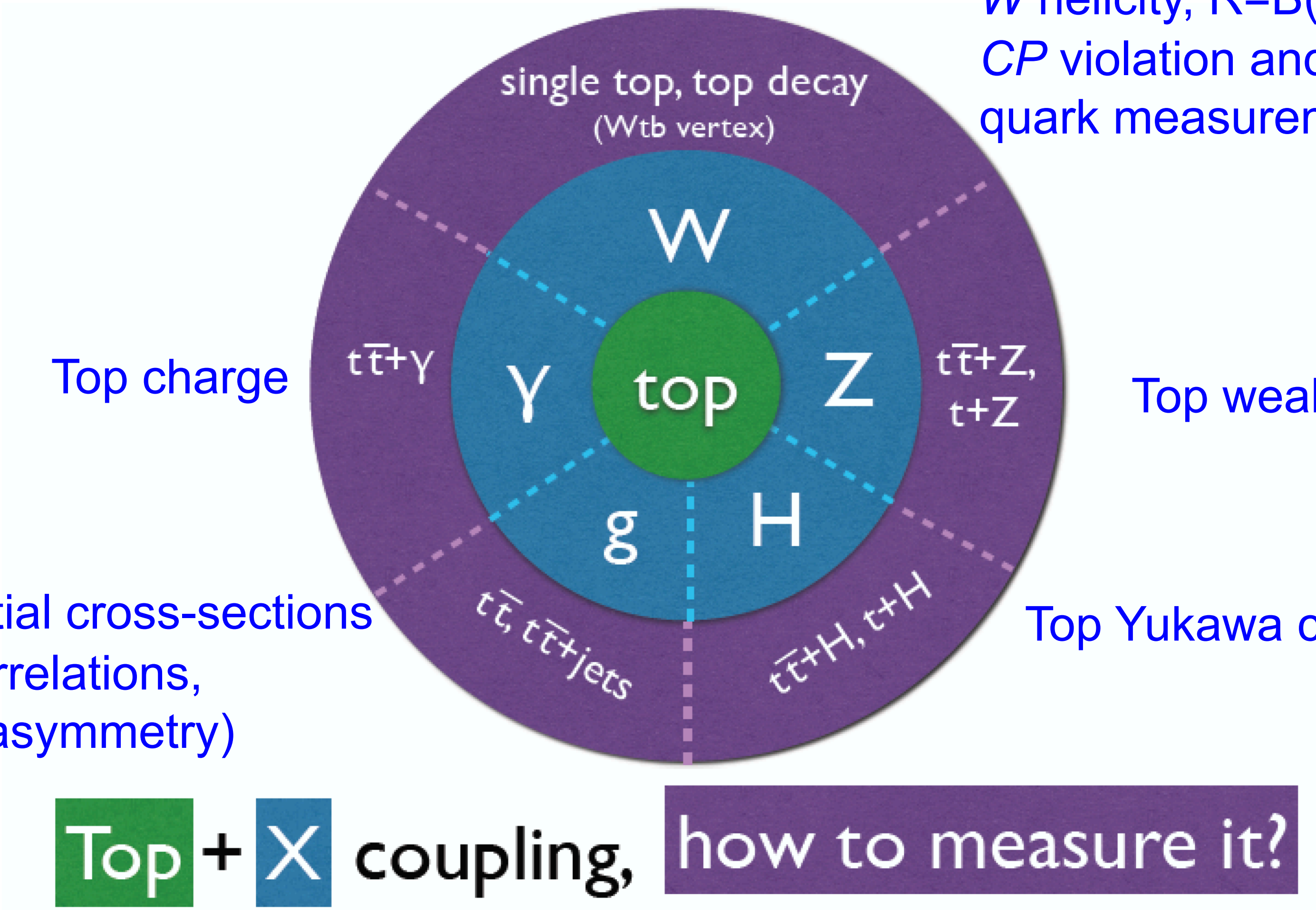
W helicity, R=B(*t*→*Wb*)/B(*t*→*Wq*), *CP* violation and different single top quark measurements

Top charge

Top weak isospin

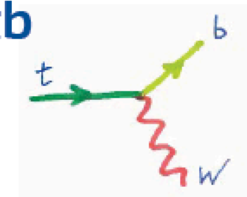
Top Yukawa coupling

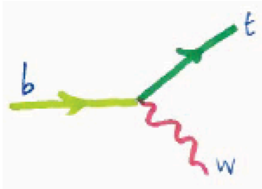
Differential cross-sections (spin correlations, charge asymmetry)

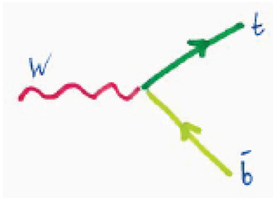


Flavour changing charged current

- **Wtb**

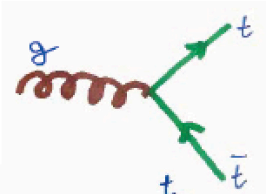


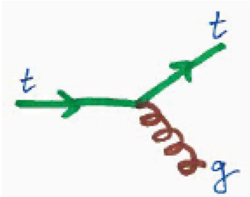




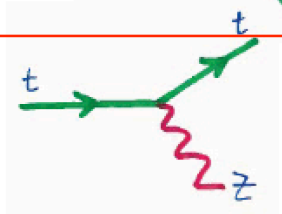
Flavour conserving neutral current

- **tgt**

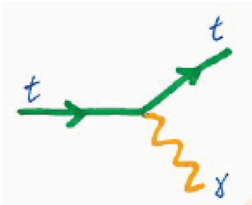




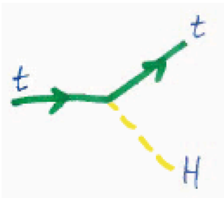
- **tZt**



- **tγt**

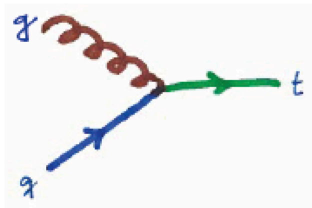


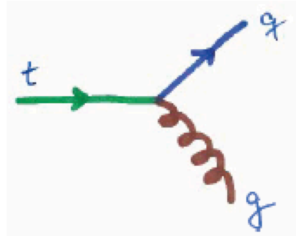
- **tHt**

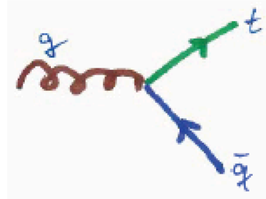


… and neutral current

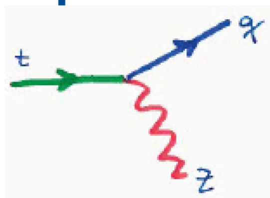
- **tgq**

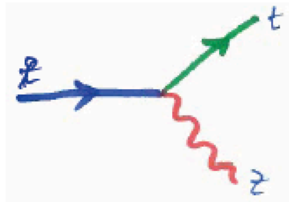




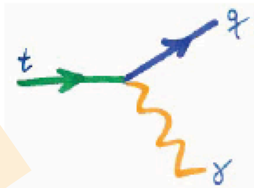


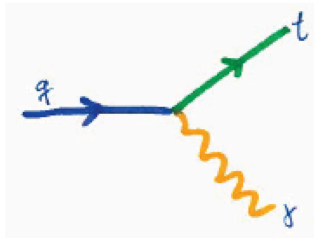
- **tZq**



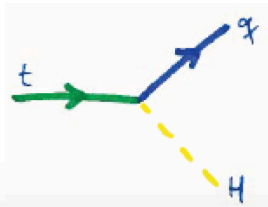


- **tγq**



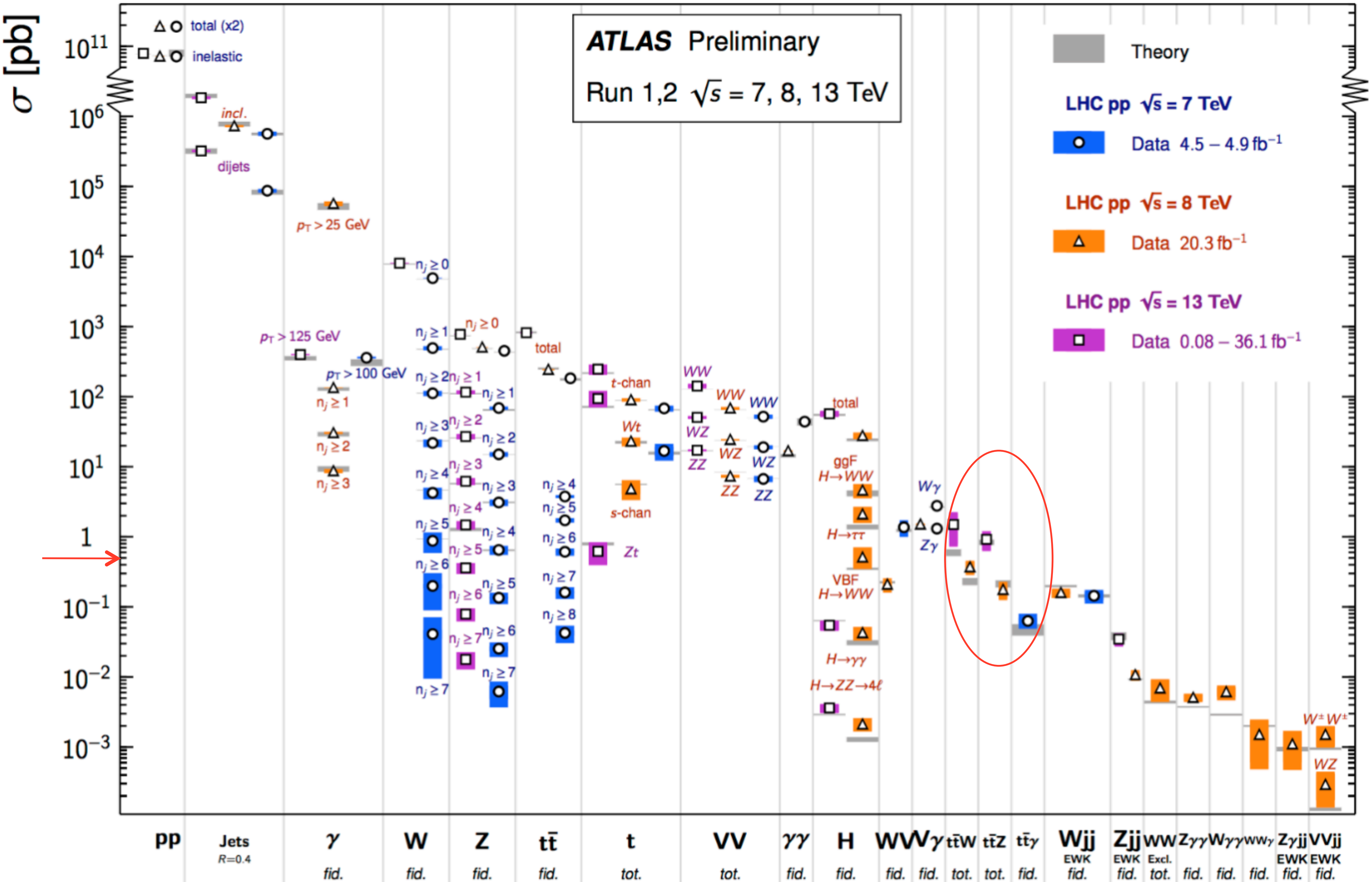


- **tHq**



One of the highlights of LHC RunII ☺,
but very challenging for both
experimental and theoretical sides.

Searching for the tiniest signals



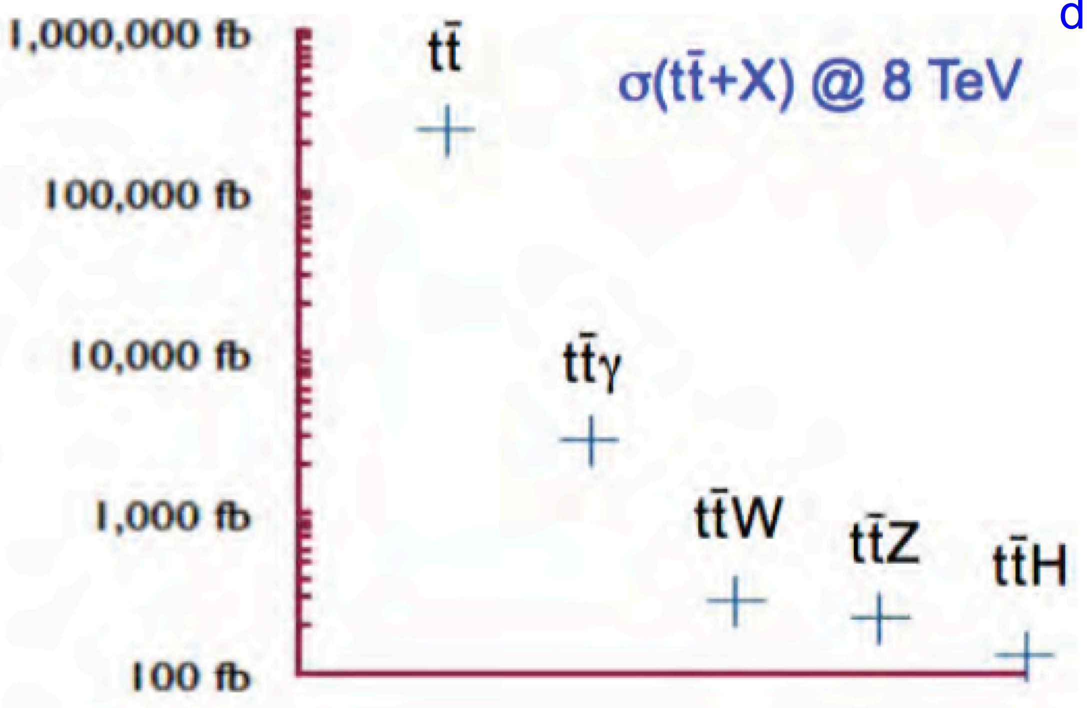
Searching for the tiniest signals: very challenging

Virtues:

Many possible final states to consider!

Challenges:

- low production cross section
- a priori many handles against backgrounds with large theoretical uncertainties!



→ Most of these analyses entering regime of results being systematically limited !!

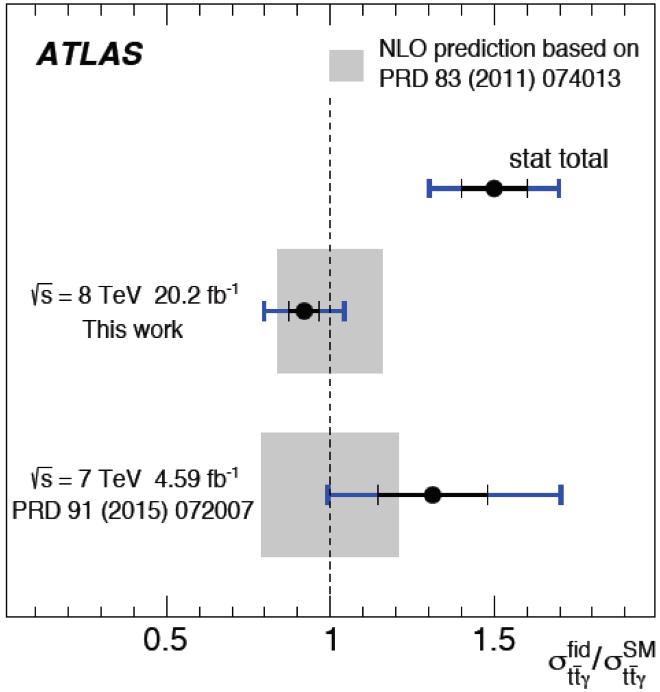
→ Recent developments in theory community:

- NLO QCD+EW corrections to *tt+H/Z/W*
  - Also NLO+NNLO for *tt+Z*
- NLO QCD corrections to *t+H*
- off-shell effects in *tt+H* production
- beyond NLO QCD: soft resummation

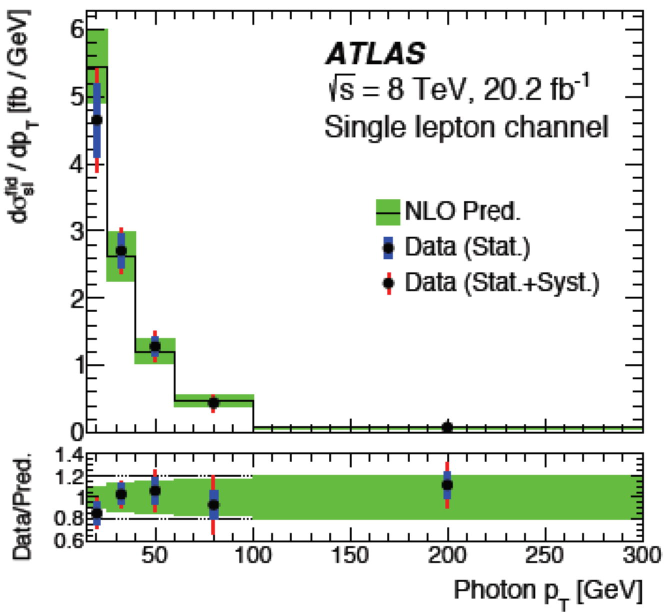
→ Implementation of latest theoretical developments is crucial to reduce uncertainties.

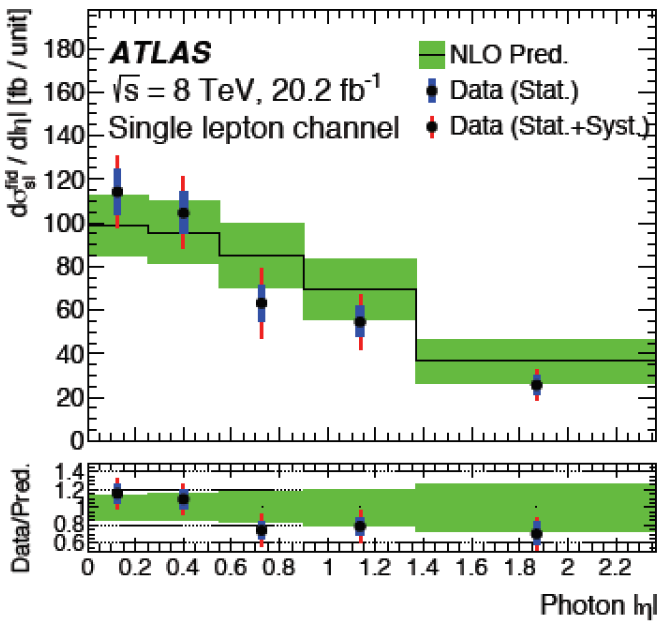
σ (pb)	8 TeV	13 TeV	13 / 8
tt+Z	0.206	0.839 (±12%)	3.7
tt+W	0.232	0.601 (±13%)	2.4
tt+H	0.129	0.5085 (±13%)	3.9
tt	~250	~830	3.3

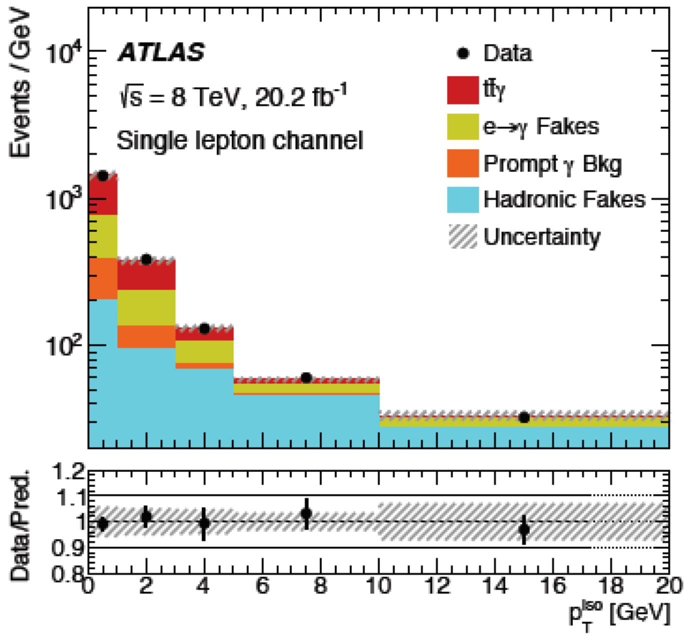
- **First observation (5.3 σ) with 7 TeV data**
  - measurement performed in a fiducial region within the ATLAS acceptance (as $p_T^{\gamma} > 20$ GeV)
  - template fit to track isolation distribution of photons
  - non-prompt photon contributions: data-driven estimates
  - systematics limited, dominant sources: jet energy scale, photon, signal modelling, b-tagging



- **First differential measurements with 8 TeV data** in photon p_T and $|\eta|$ arXiv:1706.0304
  - fiducial cross-section: rel. unc. 13% (~ theoretical pred.)

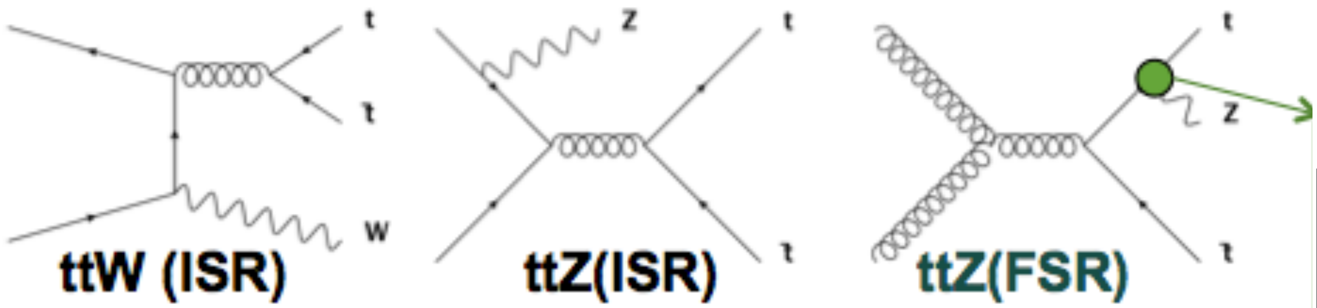






tt+W and *tt+Z* are rare processes - could be modified by new physics

→ Important irreducible background for *tt+H*(multilep), new physics (VLQ, SUSY, etc)



$$\gamma^{\mu}(C_V^{SM} - \gamma_5 C_A^{SM})$$

$$C_V^{SM} = T^3 - 2Q_t sin^2(\theta_W)$$

$$C_A^{SM} = T^3$$

Direct measurement of top quark weak isospin in ttZ production via FSR.

Many experimental signatures:

tt+Z	*tt*→ dilepton	*tt*→ l+jets	*tt*→ all-had.
Z→*ll*	4l + 2j(2b)	3l + 4j(2b)	2l (OS) + 6j(2b)
Z→$\nu\nu$, *Z*→*jj*	2l (OS) + ≥2j(≥2b)	1l + ≥4j(≥2b)	0l + ≥6j(≥2b)

Z decay modes:
BR(Z→ *ee*/$\mu\mu/\tau\tau$): 0.10
BR(Z→ $\nu\nu$): 0.20
BR(Z→ *jj*): 0.70

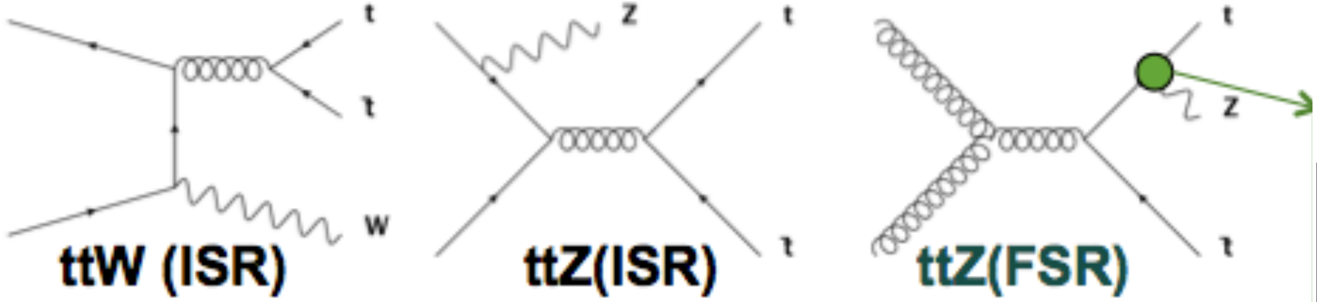
tt+W	*tt*→ dilepton	*tt*→ l+jets	*tt*→ all-had.
W→*l*ν	3l + 2j(2b)	2l (OS or SS) + 4j(2b)	1l + 6j(2b)
W→*jj*	2l (OS) + ≥2j(≥2b)	1l + ≥4j(≥2b)	0l + ≥6j(≥2b)

Experimental analyses focus on 2l OS or SS, 3l and 4l channels with *e* and/or μ.
→ MANY MORE TO BE EXPLORED !!!

Top coupling to vector bosons: *tt+Z/W*

tt+W and *tt+Z* are rare processes - could be modified by new physics

→ Important irreducible background for *tt+H*(multilep), new physics (VLQ, SUSY, etc)



$$\gamma^\mu(C_V^{SM} - \gamma_5 C_A^{SM})$$

$$C_V^{SM} = T^3 - 2Q_t sin^2(\theta_W)$$

$$C_A^{SM} = T^3$$

Direct measurement of top quark weak isospin in ttZ production via FSR.

Only the most sensitive channels explored in latest ATLAS results (3.2fb^{-1}, 2015 data):

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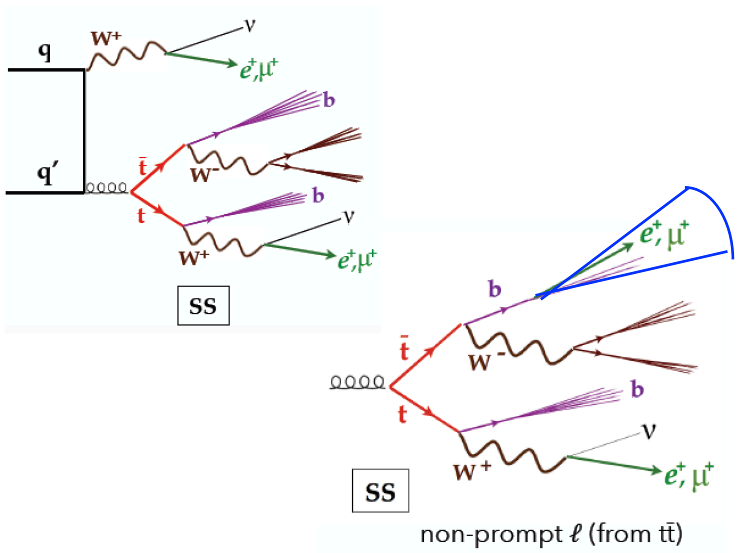
Process	$t\bar{t}$ decay	Boson decay	Channel
$t\bar{t}W^\pm$	$(\mu^\pm\nu b)(q\bar{q}b)$	$\mu^\pm\nu$	SS dimuon
	$(\ell^\pm\nu b)(\ell^\mp\nu b)$	$\ell^\pm\nu$	Trilepton
$t\bar{t}Z$	$(\ell^\pm\nu b)(q\bar{q}b)$	$\ell^+\ell^-$	Trilepton
	$(\ell^\pm\nu b)(\ell^\mp\nu b)$	$\ell^+\ell^-$	Tetralepton

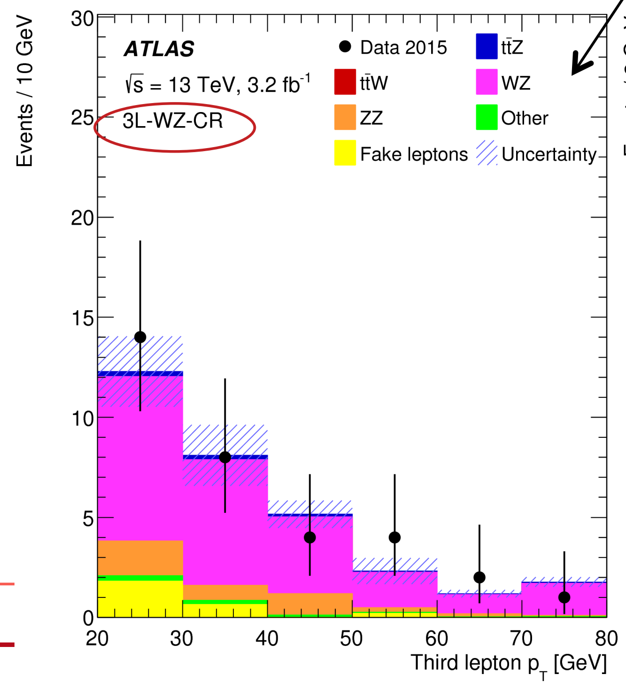
Top coupling to vector bosons: *tt+Z/W*

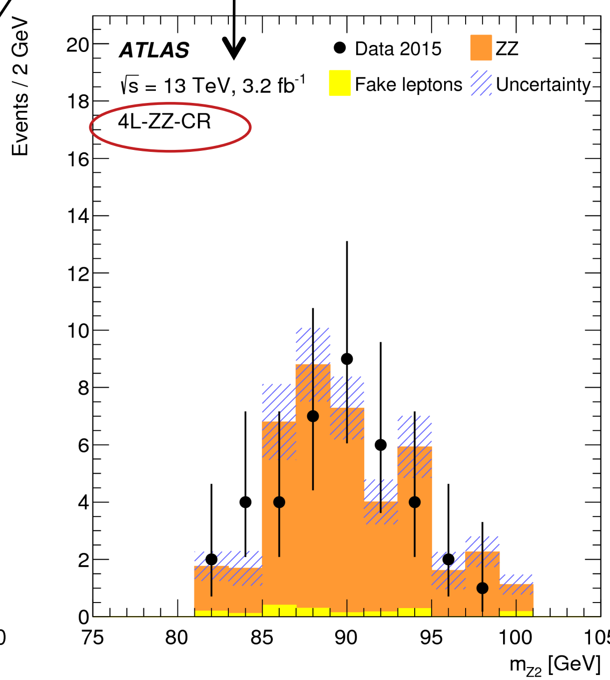
Sample statistics, S/B ratio and dominant backgrounds vary across different channels

→ for each of them, several SRs (lepton flavour/charge, nJets, nBjets) and CRs (*WZ*, *ZZ*)

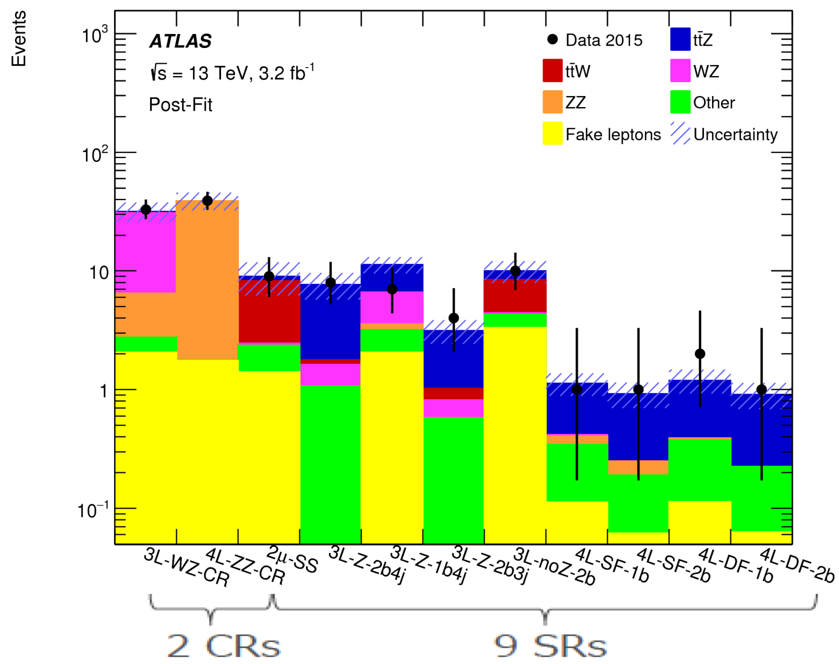
Channel	Sub-channels	Characteristics	Main cuts	Main background
SS dilepton	$\mu\mu$	targets *tt+W*	≥2 b-tags, $E_{T,miss}$	fake leptons (from *tt* events) derived from matrix method (DD) in control sample with 2l OS+SS and looser lepton requirements
Trilepton	*tt+Z*(*W*) enriched	small sample size, good S/B	≥1 b-tag Z mass (veto)	leptonic decay *WZ* (fake leptons) One *WZ* CR is included in the fit; another is defined for validation
Tetralepton	tt→ same (diff.) flavour	very small sample size, excellent S/B	1-2 OSSF pairs	leptonic decay *ZZ* (rare SM) One *ZZ* CR is included in the fit;



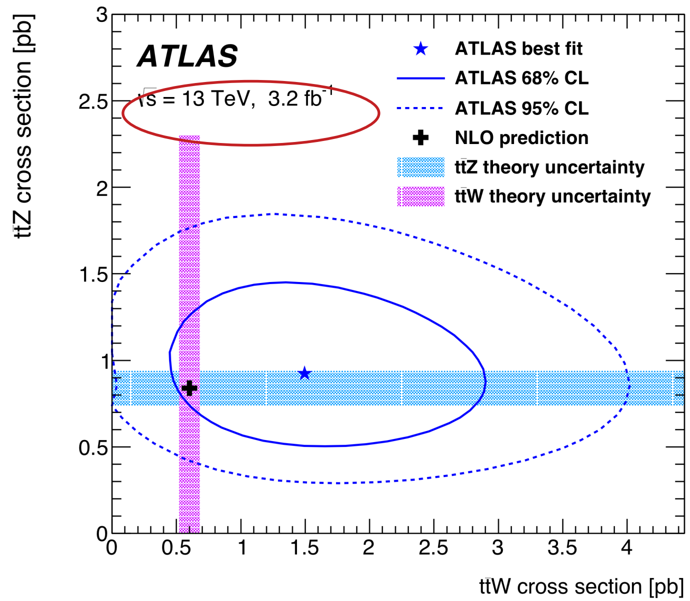




Top coupling to vector bosons: *tt+Z/W*



→ Cross-sections obtained from combined profile likelihood fit to signal and control regions



Δσ/σ (%), Significance	*tt+Z*	*tt+W*
ATLAS 2012	32%, 4.2σ	26%, 5.0σ
CMS 2012	27%, 6.4σ	31%, 4.8σ
ATLAS 2015	32%, 3.9σ (31% stat.)	only $\mu\mu$ 53%, 2.2σ (48% stat.)
CMS 2015+2016	14%, 9.9σ (stat ~syst. unc.)	15%, 5.5σ (stat ~syst. unc.)

Uncertainty	$\sigma_{t\bar{t}Z}$	$\sigma_{t\bar{t}W}$
Luminosity	2.6%	3.1%
Reconstructed objects	8.3%	9.3%
Backgrounds from simulation	5.3%	3.1%
Fake leptons and charge misID	3.0%	18.7%
Signal modelling	2.3%	4.2%
Total systematic	11%	22%
Statistical	31%	48%
Total	32%	53%

Analysis ongoing with 2015+2016 data (36 fb^{-1}), STAY TUNED !
Better fake & charge mis-id. suppression (MVA techniques), also improvements on detectors systematics !

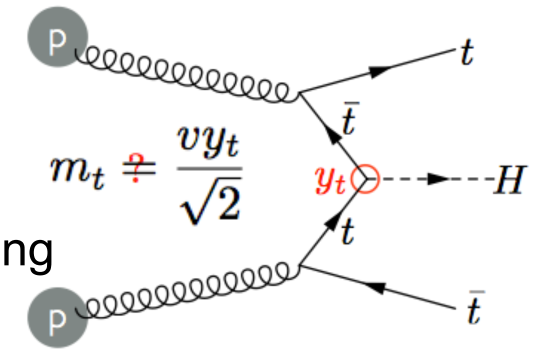
Search for *tt+H* process

One of the highlights of Run II physics program

Top coupling to Higgs boson: *tt+H*

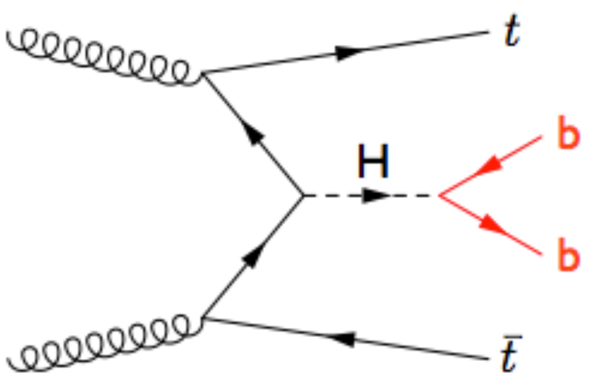
- Higgs boson discovery in July 2012
- In the SM, fermion masses are proportional to Higgs fermion Yukawa couplings → Important to test this prediction
- *tt+H* production provides **direct sensitivity** to top-Higgs Yukawa coupling
- **Indirect constraints** to this coupling extracted from channels involving the *ggH* and *H*$\gamma\gamma$ vertices (assumes no new particles in loops)

$$m_t \stackrel{?}{=} \frac{v y_t}{\sqrt{2}}$$



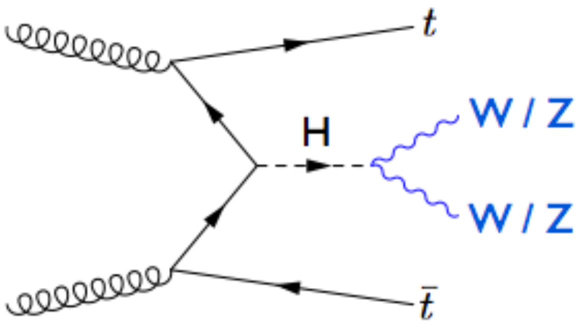
tt+H (H→ bb)

- Largest BR (58%)
- Final state with multiple *b*-quarks (challenge to reconstruct Higgs)
- Large background from *tt*+jets



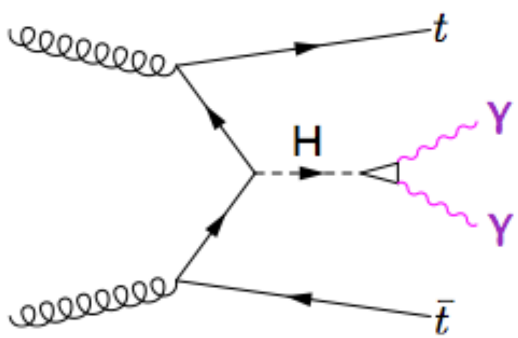
tt+H (H→ WW/ZZ/ττ)

- Significant BR (30%)
- Leptonic decays of *W*, *Z* and taus can give distinct multilepton signatures (but difficult to reconstruct the Higgs)
- Main background from tt+W/Z and non-prompt leptons



tt+H (H→ $\gamma\gamma$)

- Small BR (0.2%)
- Higgs boson can be reconstructed as a narrow peak
- Backgrounds from *tt*+γ and QCD multi-γ/jet final states



ATLAS $t\bar{t}+H$ search channels

Higgs decay channel	Run I (20.3 fb^{-1} / 24.8 fb^{-1}) 8 TeV / 7+8 TeV	Run II (13.2 fb^{-1} / 36.1 fb^{-1}) 13 TeV
H→bb *tt* single & di-leptonic *tt* full-hadronic	Eur. Phys. J. C (2015) 75:349 JHEP 05 (2016)160	ATLAS-CONF-2016-080 ---------
Multileptons **(*H→WW**, ττ, *ZZ**)**	Phys.Lett. B 749 (2015) 519	ATLAS-CONF-2016-058
***H→ZZ*→*4l (l=e,μ)**	Phys. Rev. D 91 012006 (2015) (within ggH category)	ATLAS-CONF-2017-043
H→γγ	Phys. Lett. B 740 (2015) 222	ATLAS-CONF-2017-045
ATLAS *tt+H* combination	JHEP 05 (2016) 160	ATLAS-CONF-2016-068 (bbar, multileptons, γγ) ATLAS-CONF-2017-047 (ZZ*→4l, γγ)

- LHC Run I Higgs combination:
  ***tt+H* significance of 4.4 σ (2.0 σ expected)**
  Excess in both ATLAS and CMS from multilepton ch.

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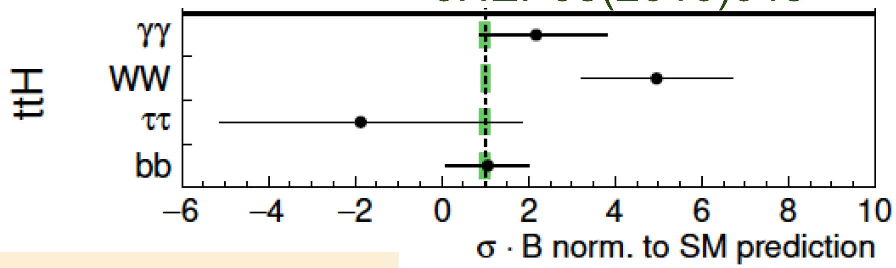
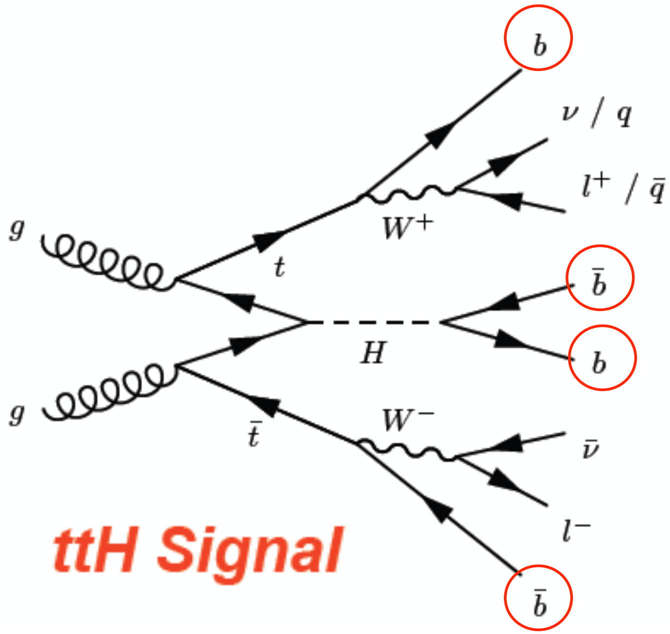


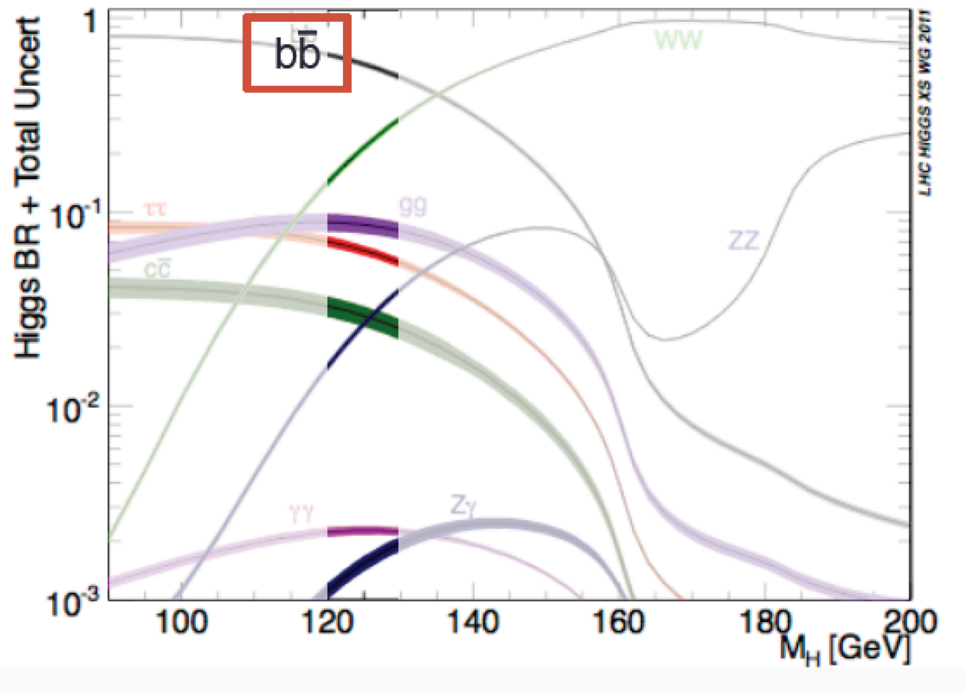
In the rest, I will focus on Run II analysis methods and preliminary results.

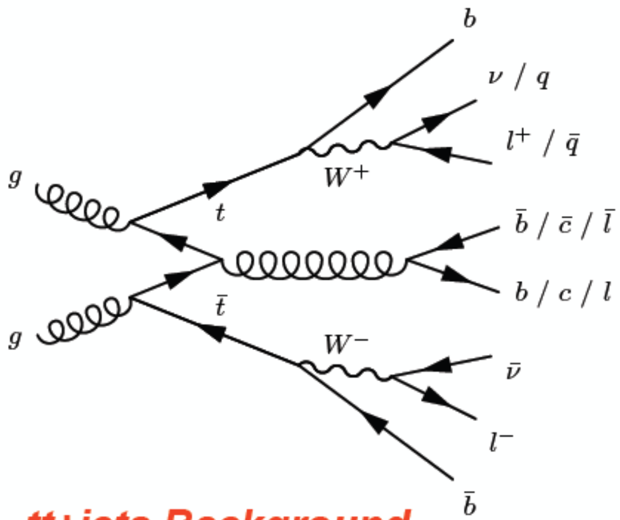
Search for *tt+H(H→bb)*

ATLAS-CONF-2016-080



ttH Signal



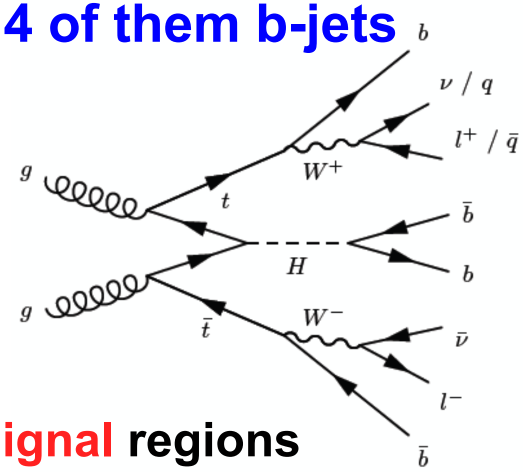


tt+jets Background

H→bb **channel has largest branching ratio (58%), and offers sensitivity to Higgs-Bottom Yukawa coupling.**

In analysed dataset (13.2 fb^{-1}), about 4k *tt+H*(*bb*) signal events have been produced with 1000k *tt*+jets background.

tt+H (H→bb) signal produces 1 or 2 leptons and 6 or 4 jets, 4 of them b-jets

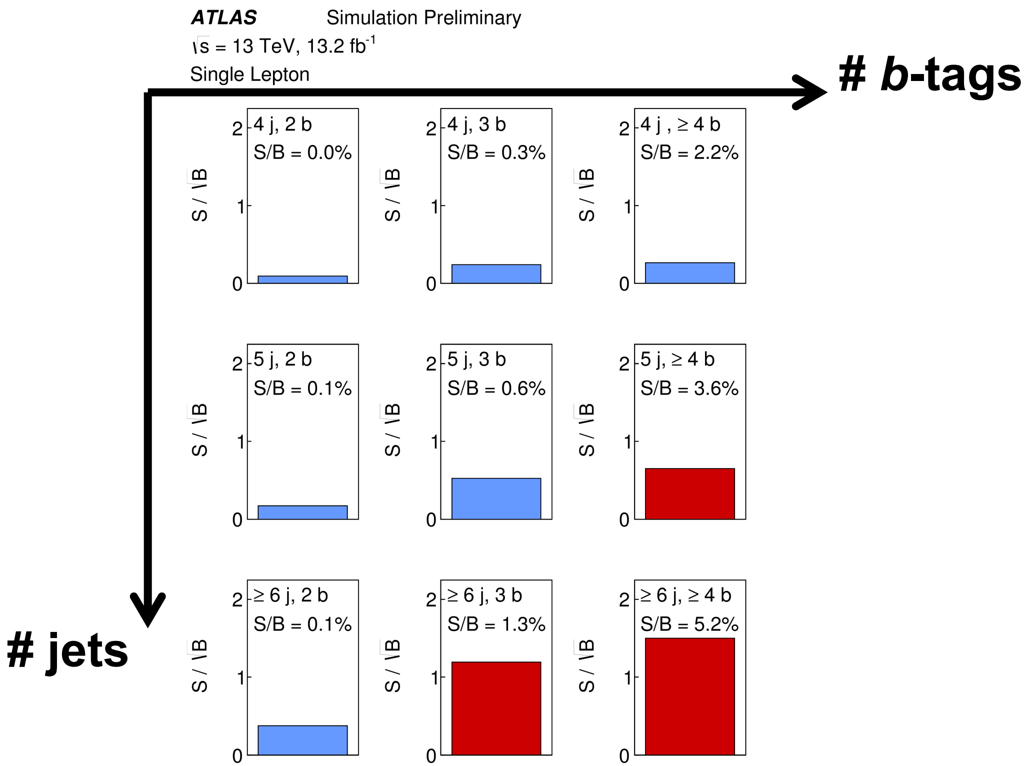


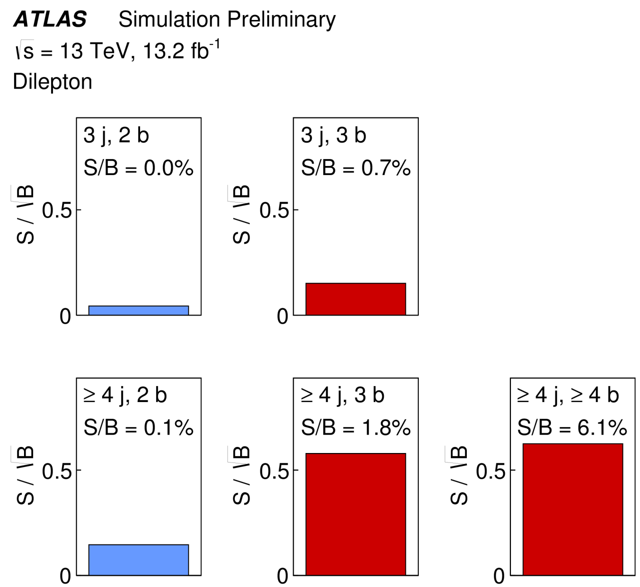
Single lepton:
- exactly 1 charged leptons (e/μ)
- ≥ 4 jets being ≥ 2 *b*-tagged

Dilepton:
- exactly 2 charged leptons (e/μ) with OS (m_{ll} > 15 GeV, *Z* veto)
- ≥ 3 jets being ≥ 2 *b*-tagged

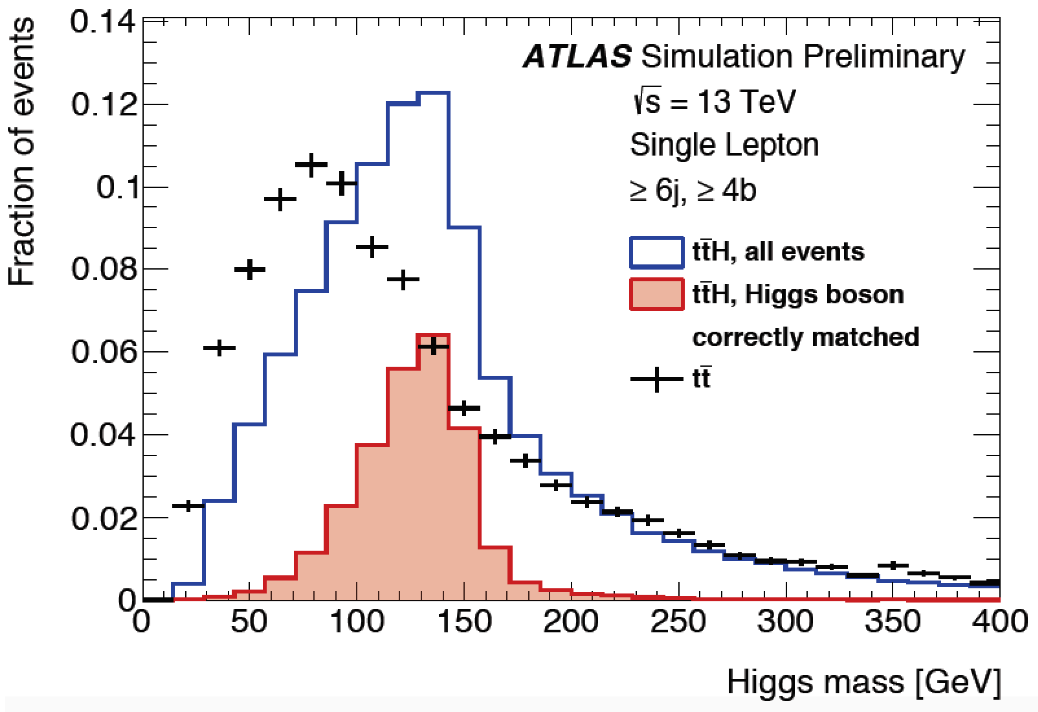
Analysis strategy

- Categorize events according to the # jets and *b*-jets → **control and signal regions**
- Simultaneous profiled likelihood fit including all regions





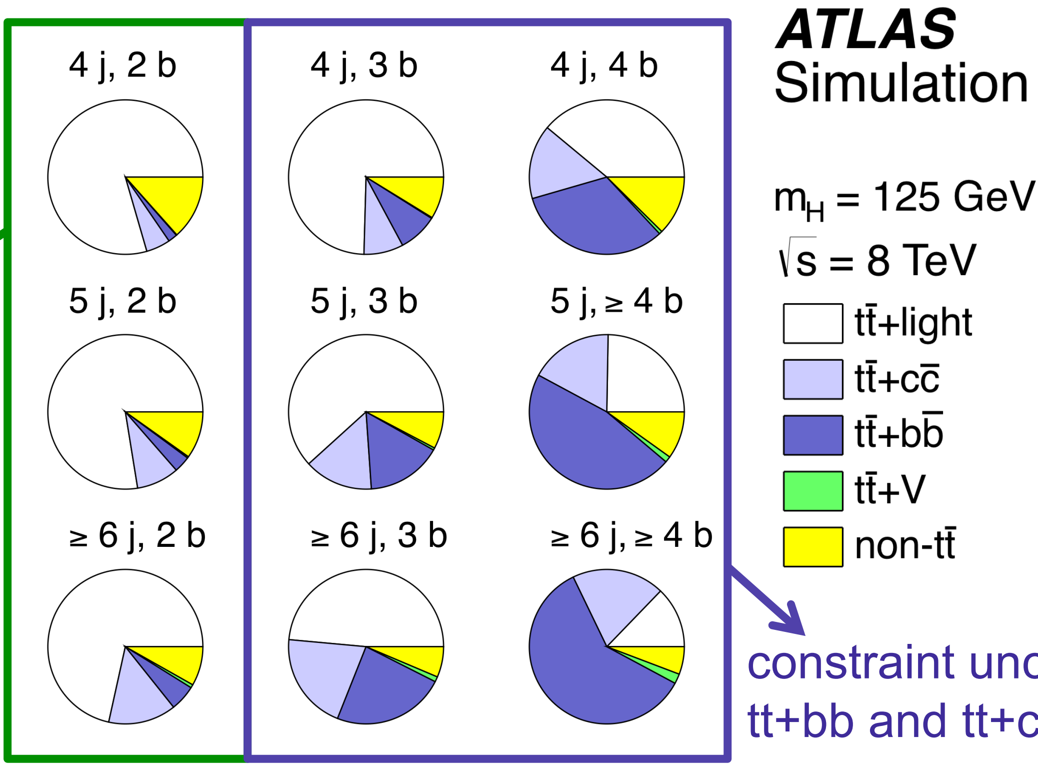
- Discriminant variables:
  - **control regions**: scalar sum of p_T for all jets (and the leptons) in single (di)-lepton channel
  - **signal regions**: build **multivariate discriminant** (two-stage multivariate technique)
    1. Match observed jets to Higgs and top quarks (BDTreco)
    2. Classify event as more signal-or-bkg. like (Classification BDT or NN output)
       - using topological variables from tt and Higgs decay



L+jets	2 b-tag	2 b-tag	4 b-tag
4 jet	HT_{had}	HT_{had}	HT_{had}
5 jet	HT_{had}	HT_{had}	BDT (NN)
6 jet	HT_{had}	BDT (NN)	BDT (NN)

Dilepton	2 b-tag	3 b-tag	4 b-tag
3 jet	HT_{all}	NN **(BDT)**	
4 jet	HT_{all}	BDT (NN)	BDT (NN)

Background composition
Single lepton



high statistics, constraint on overall tt+jets normalisation and modelling

constraint uncertainties on tt+bb and tt+cc normalisations

- Very challenging final state affected by large systematics:
  tt+jets, *tt*+heavy flavour modelling, *b*-tagging, JES
- Analysis relies on a profiled likelihood fit, in order to constrain in-situ the leading systematics
  - signal-depleted regions play a key role constraining syst. unc.

$$L(\mu,\theta) = L_{Pois}(\mu,\theta) \cdot \boxed{\prod_p \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{\theta_p^2}{2}\right)} \cdot \boxed{\prod_{i,j} \frac{1}{\sqrt{2\pi}\sigma_{\gamma,ij}} \exp\left(-\frac{(\gamma_{ij}-1)^2}{2\sigma_{\gamma,ij}^2}\right)}$$

penalty terms or priors: inputs from subsidiary measurements (**nuisance parameters**)

statistical uncertainty of MC

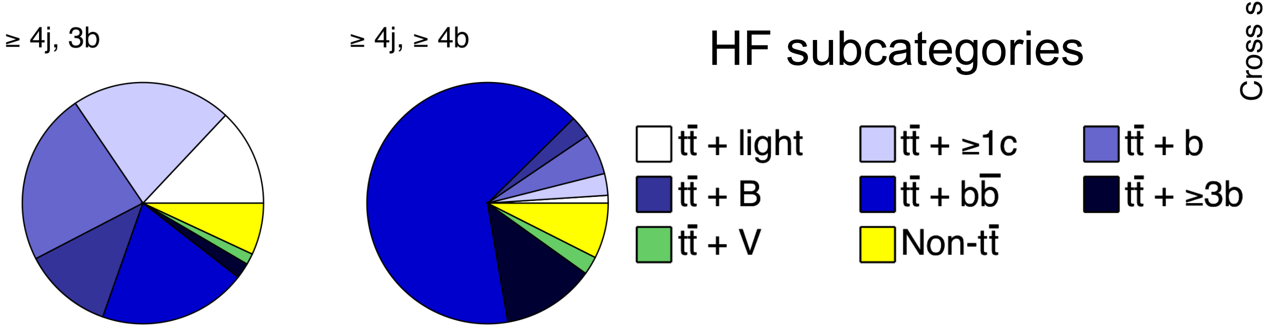
tt+jets (heavy flavour) modelling: critical piece

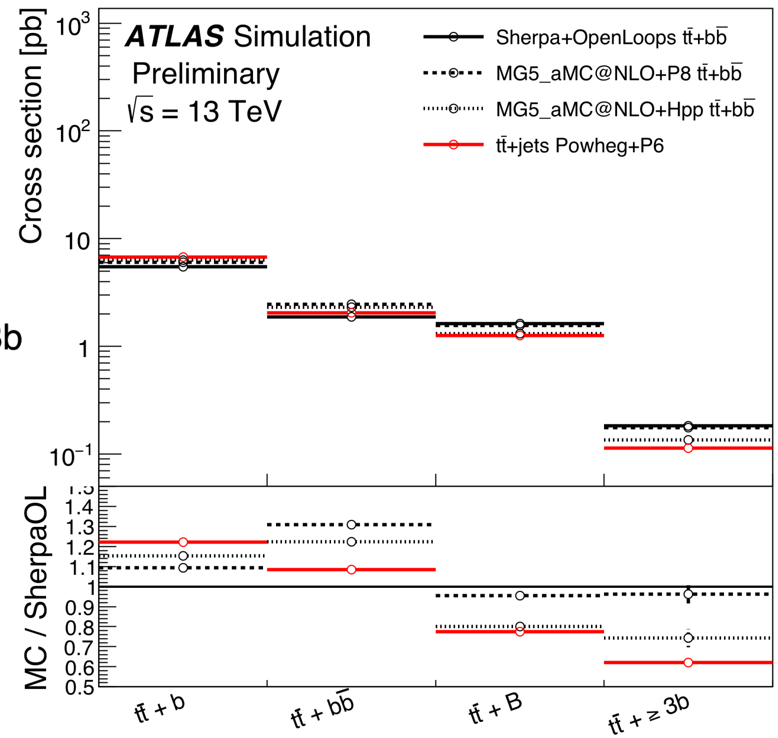
* *tt*+jets is the largest background, with sizeable syst. that have a large impact on the sensitivity
  → more heavy flavour (HF) dominating towards SRs
* Estimating *tt*+jets critical part of analysis: use Powheg+Pythia6 NLO+PS simulation,
  with top and *tt* p_T spectra corrected to NNLO calculation
* Classify events into: *tt*+light, *tt*+≥1c and *tt*+≥1b jets

***tt* + ≥1 b-jet:** pure parton shower in Powheg+Pythia (5-flavour scheme)

- large uncertainty on prediction (both normalization and kinematics)
- corrected to 4-flavour scheme NLO QCD *tt+bb* calculation with Sherpa+OpenLoops

1st) relative contributions of diff. categories of *tt*+HF





resolved "tt+Xb" unresolved g→bb "tt+XB"

tt+jets (heavy flavour) modelling: critical piece

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- large uncertainty on prediction (both normalization and kinematics)
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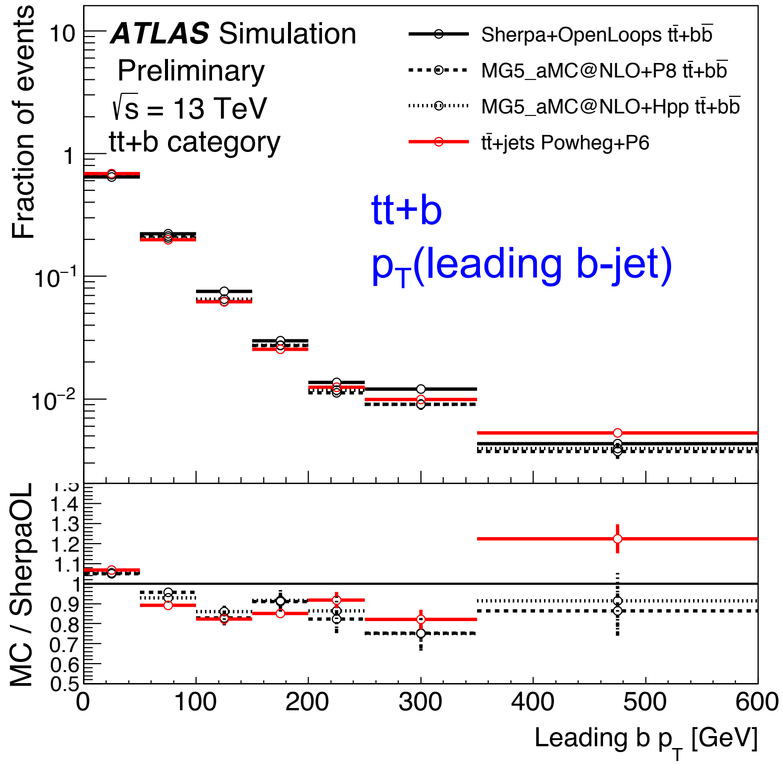
1st) relative contributions of diff. categories of *tt*+HF
2nd) compare kinematic dist. → re-weight events to match kinematics of Sherpa 4F NLO

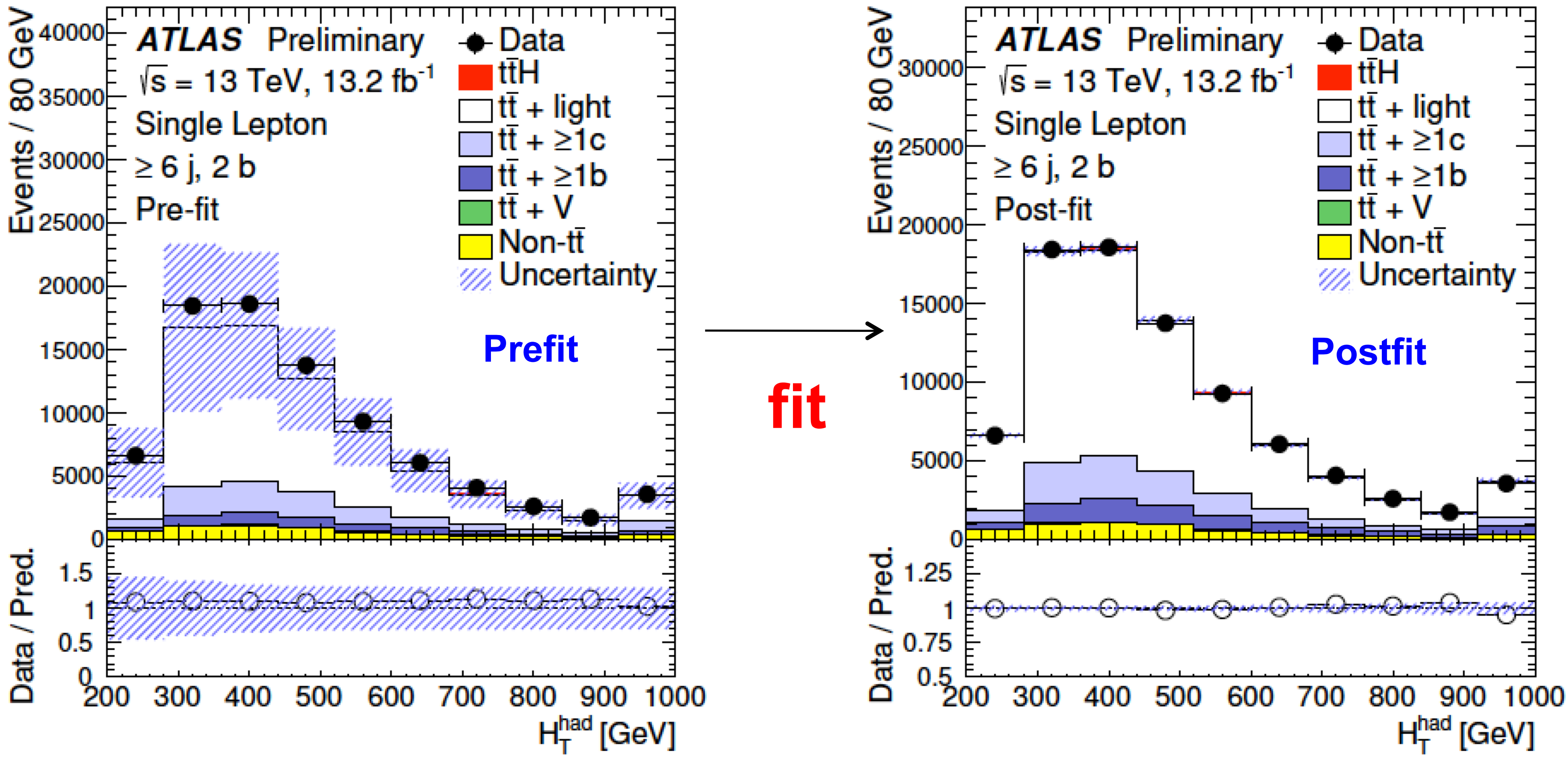


- Normalization of **tt + ≥1b and tt + ≥1c jets** backgrounds taken as **free parameters in the fit**
[Run I: NP with 50% prior → down ~20% in the fit]

- Many sources of uncertainty considered, including choice of hard process MC generator, parton shower and hadronisation model, initial/final state radiation.

Profiling uncertainties: signal-depleted region (H_T)

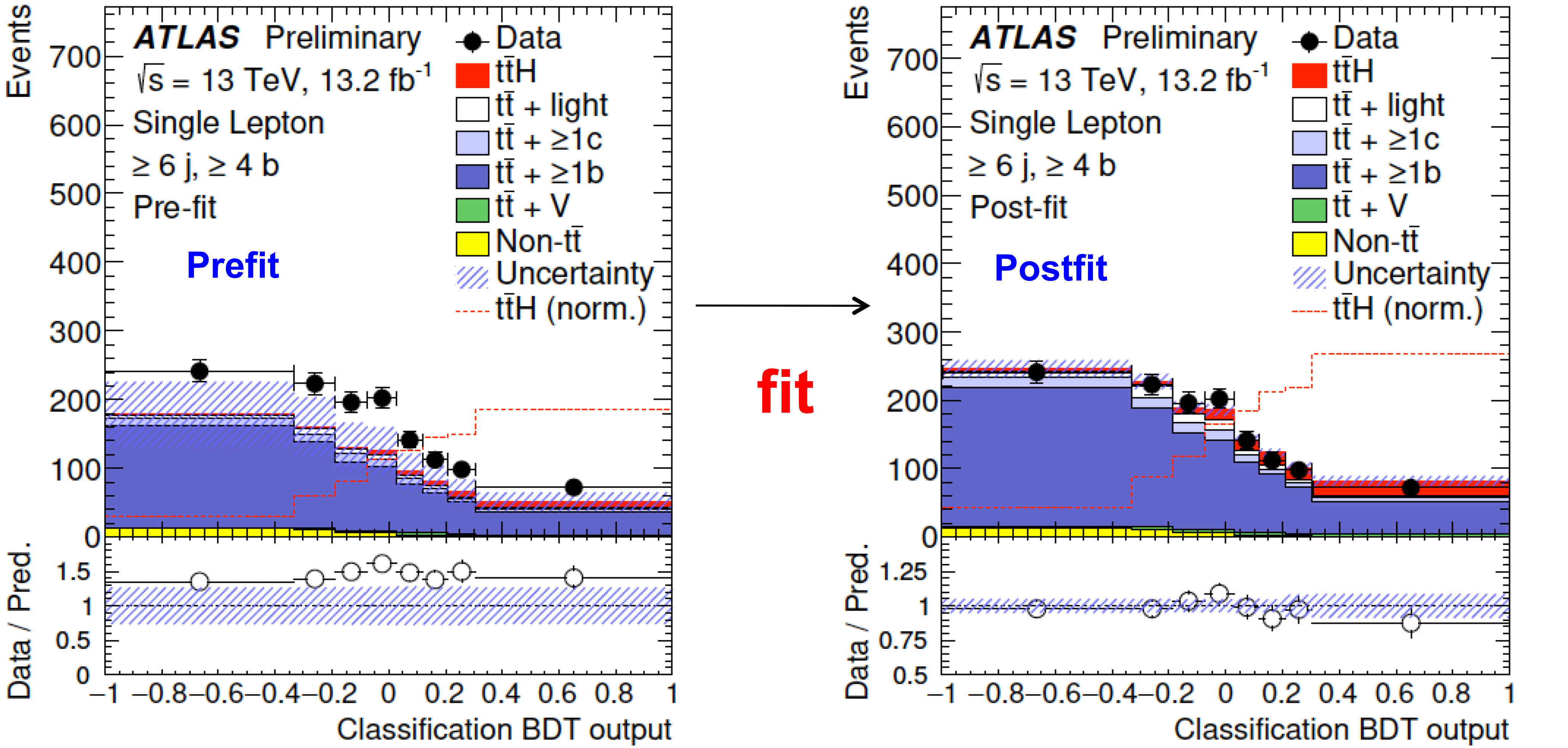
Single lepton, ≥6 jets =2 b-jets



- Observed mis-modelling (slopes) in CRs (dominated by *$t\bar{t}$*+light) for H_T and jet multiplicity: data has softer H_T and harder N_{jets} dist. (top/*$t\bar{t}$* p_T mismodelling, observed in other analysis)

Profiling uncertainties: signal-enriched region (BDT)

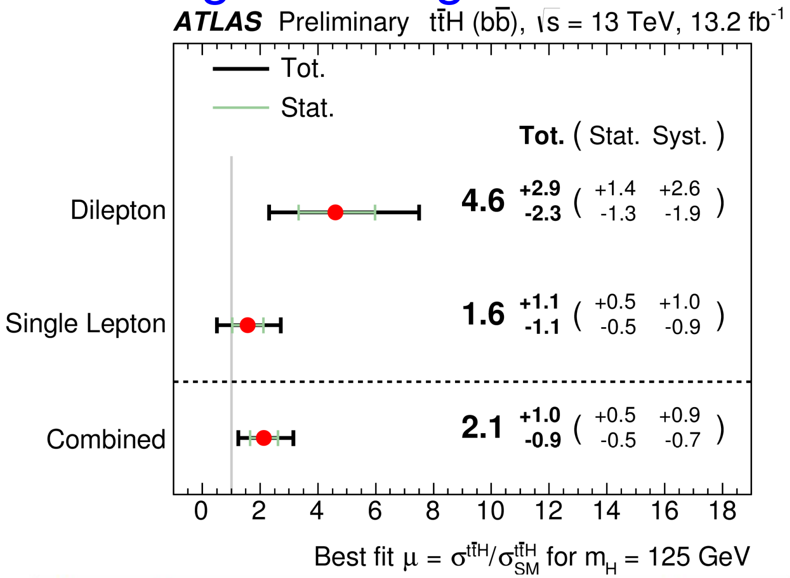
Single lepton, ≥6 jets ≥4 b-jets



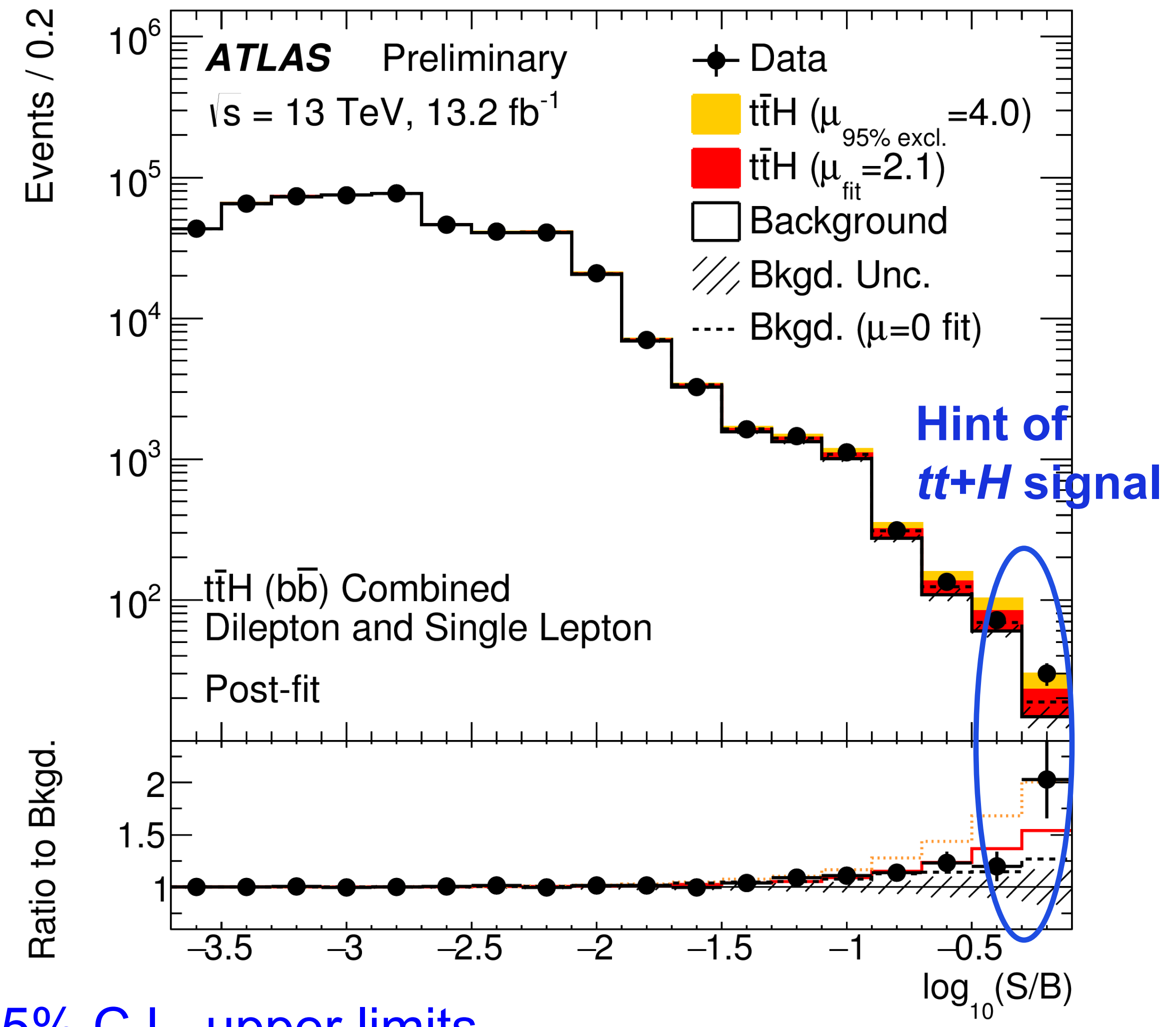
- The observed data/MC discrepancy is higher in regions dominated by *tt*+HF.
- Large uncertainties in predictions for *tt*+≥1b (and *tt*+≥1c) normalisation

→ norm. factors are free-floating parameters in the fit: $\mathbf{k_b=1.33^{+0.18}_{-0.17}}$ $\mathbf{k_c=1.31^{+0.53}_{-0.40}}$

tt+H signal strength



Uncertainty source	$\Delta\mu$	
$t\bar{t}+\geq 1b$ modelling	+0.53	−0.53
Jet flavour tagging	+0.26	−0.26
$t\bar{t}H$ modelling	+0.32	−0.20
Background model statistics	+0.25	−0.25
$t\bar{t}+\geq 1c$ modelling	+0.24	−0.23
Jet energy scale and resolution	+0.19	−0.19
$t\bar{t}$+light modelling	+0.19	−0.18
Other background modelling	+0.18	−0.18
Jet-vertex association, pileup modelling	+0.12	−0.12
Luminosity	+0.12	−0.12
$t\bar{t}Z$ modelling	+0.06	−0.06
Light lepton (e,μ) ID, isolation, trigger	+0.05	−0.05
Total systematic uncertainty	+0.90	−0.75
$t\bar{t}+\geq 1b$ normalisation	+0.34	−0.34
$t\bar{t}+\geq 1c$ normalisation	+0.14	−0.14
Statistical uncertainty	+0.49	−0.49
Total uncertainty	+1.02	−0.89



95% C.L. upper limits

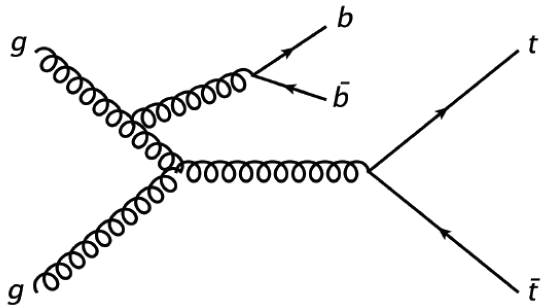
	Observed	Expected ($\mu = 0$) Median	$+/-1\sigma$	$+/-2\sigma$	Expected ($\mu = 1$)
Dilepton	10.1	5.3	[3.8, 7.9]	[2.8, 12.6]	6.0
Single lepton	3.6	2.2	[1.6, 3.2]	[1.2, 4.7]	2.9
Combined	4.0	1.9	[1.4, 2.8]	[1.0, 4.2]	2.7

A difficult and controversial task: *tt*+HF modelling

NLO QCD bring new questions on modelling

- *tt*+*bb* pure QCD process, very complicated and poorly understood: involves several scales and massive quarks
  - ➢ challenging for the MC generator community
  - ➢ implementation of latest theoretical developments crucial
- studies ongoing in both experiments in close collaboration with theorists (LHCHiggs WG)
  - NLO 4F scheme *tt*+*bb* predictions (with massive *b*-quarks in ME) with novel generators
  - comparisons with inclusive 5F scheme *tt*+jets
  - how to merge 4F and 5F samples?
  - heavy flavour classification

Two possible schemes for NLO calculations:



→ **5FS scheme**: (m_b = 0, N_f in proton PDF = 5)
x divergencies at m_{bb} ~0 GeV, must set a cut-off for calculation
✓ inclusive calculations for all *tt*+jets contributions (b-quark treated as others)

→ **4FS scheme**: (m_b != 0, N_f = 4)
✓ full description of gluon splitting (calculations up to m_{bb} ~0 GeV)
✓ NLO accuracy for any observable (EW corrections might be significant → not implemented in MC generators)
x need additional step to combine with inclusive *tt*+jets samples

NLO QCD bring new questions on modelling

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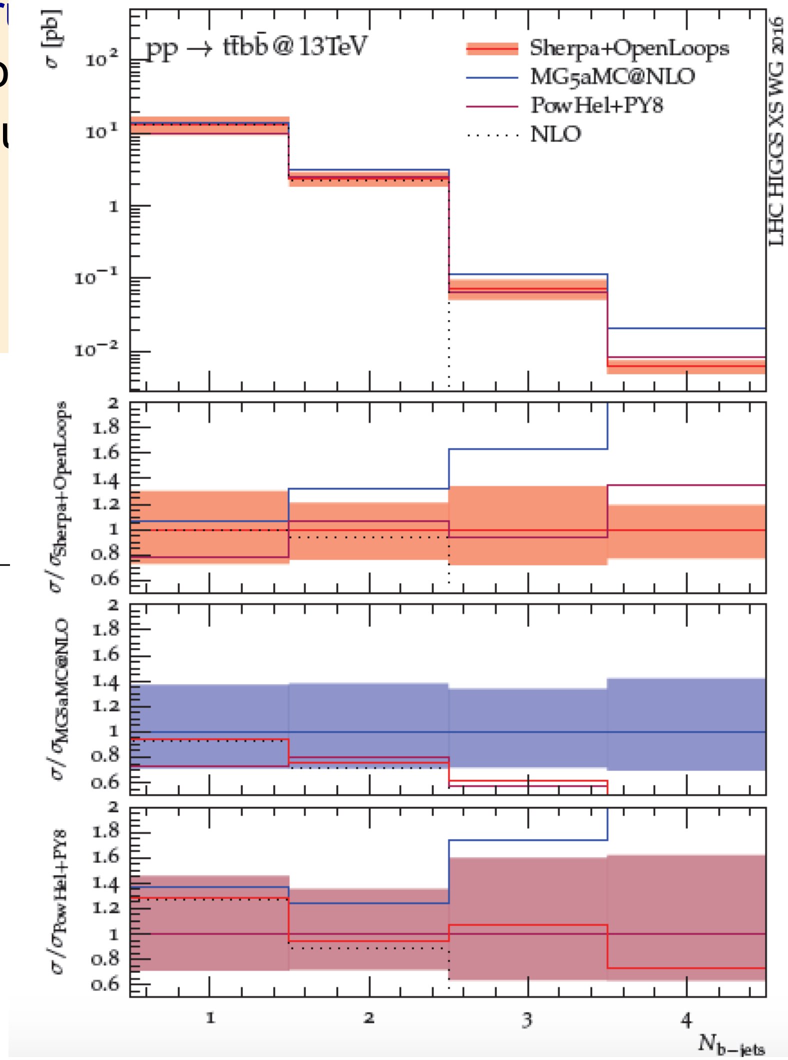
  - how to merge 4F and 5F samples?
  - heavy flavour classification

additional b-jets (inclusive)



Different NLO+PS methods, showers, and m_b treatments

Tool	Matching	Shower	m_b [GeV]	gencuts
SHERPA2.1+OPENLOOPS	SMC@NLO	Sherpa 2.1	4.75 (4F)	no
MG5_AMC@NLO	MC@NLO	Pythia 8.2	4.75 (4F)	no
POWHEL	Powheg	Pythia 8.2	0 (5F)	$p_{T,b} > 4.75\,\mathrm{GeV}$, $\frac{m_{bb}}{2} > 4.75\,\mathrm{GeV}$

- differences of ≥40% for tt+≥2b cross section
- further studies on some of the settings ongoing e.g. strong sensitivity to resummation scale (shower starting scale) in MG5_aMC@NLO

A difficult and controversial task: *tt*+HF modelling

NLO QCD bring new questions on modelling

- *tt+bb* pure QCD process, very complicated and poorly understood: involves several scales and massive quarks
  - ➢ challenging for the MC generator community
  - ➢ implementation of latest theoretical developments crucial
- studies ongoing in both experiments in close collaboration with theorists (LHCHiggs WG)
  - NLO 4F scheme *tt+bb* predictions (with massive *b*-quarks in ME) with novel generators
  - comparisons with inclusive 5F scheme *tt*+jets
  - <u>how to merge 4F and 5F samples?</u>
  - heavy flavour classification

Approach proposed in the LHCHiggs Yellow Report 4

* NLOPS 4F *tt+bb* sample

- can be applied in full phase space (no generation cuts)
- inclusive description of *tt*+≥1*b*-quarks
- includes *gb*→*ttb* contributions also in the 5F scheme

* Inclusive 5F *tt*+jets sample

- needs to be restricted to *tt*+0 *b*-quarks to avoid double counting (veto events containing *b*-quarks not arising from showered top decays or MPI or UE)

→ Ongoing discussions on possible implementations

A difficult and controversial task: *tt*+HF modelling

NLO QCD bring new questions on modelling

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  - how to merge 4F and 5F samples?
  - heavy flavour classification

Subcategories

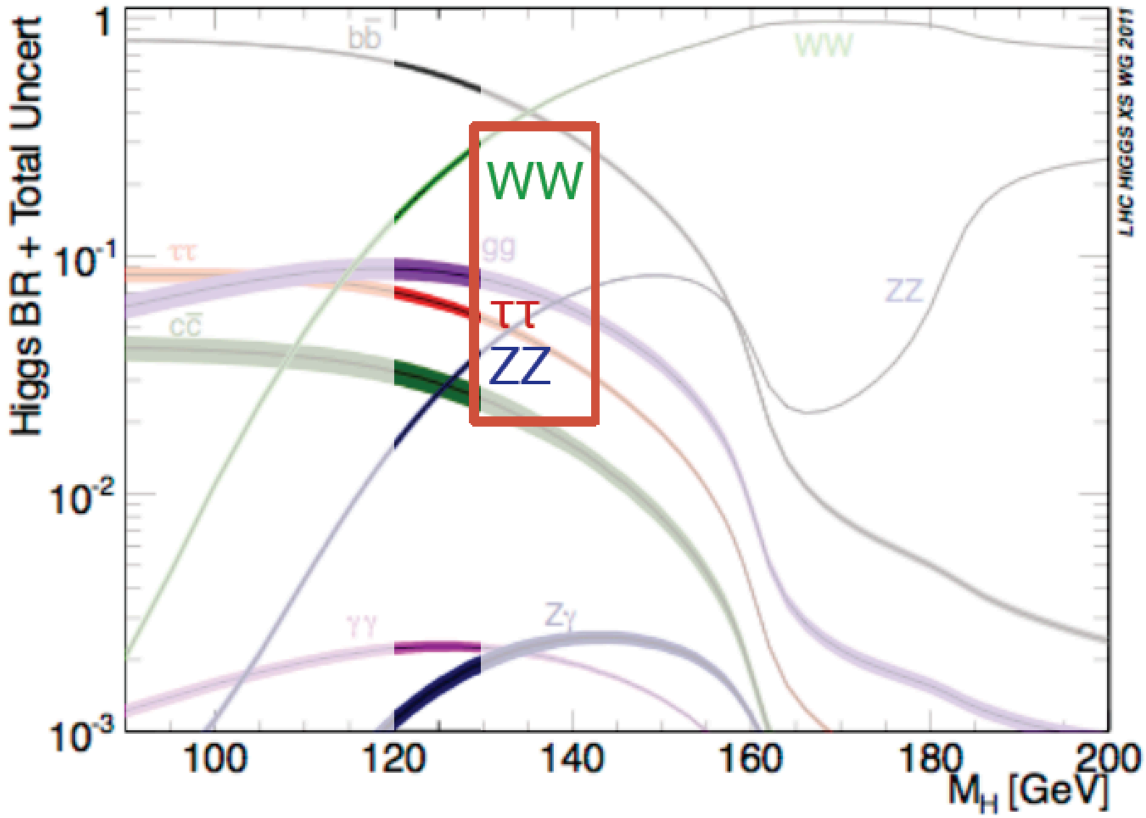
- **"tt+b"**: 1 extra particle jet in the event which is matched to exactly 1 HF hadron
- **"tt+bb"**: 2 particle jets, each of them matched to exactly 1 HF hadron
- **"tt+B/2b"** (ATLAS/CMS): 1 particle jet which is matched to a bb pair (g→bb splitting), i.e to >1 hadron

Cuts	ATLAS *	CMS
Reco-level jets	(all events are classified)	≥ two jets with p_T > 30 GeV
Particle level jets	15 GeV	20 GeV
Hadrons	5 GeV, no p_T^{hadron}/p_T^{jet} cut	No cuts
Particle-hadron matching	dR<0.3	Ghost matching

* From ongoing studies, the relative differences among generators in tt+jets fractions seem stable against these cuts

Search for *tt+H(H→multilepton)*

ATLAS-CONF-2016-058



***tt+H→*multileptons channel has clean final states, and has a priori better modelled irreducible background (*tt+W* and *tt+Z*).**

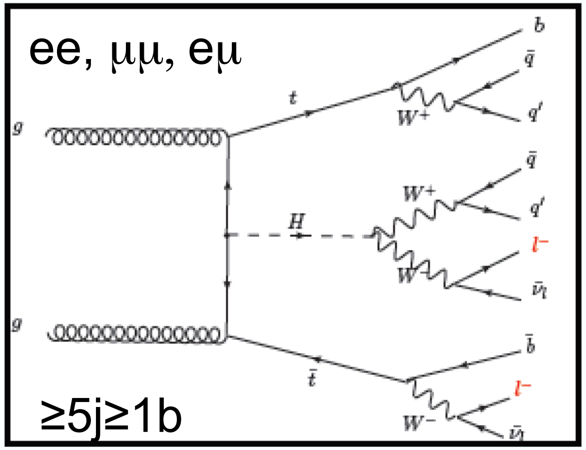
Search for *tt+H* (*H*→multilepton)

- Sensitive to H→WW, ττ, ZZ
- Consider 4 final states (6 categories) with multiple e/μ/τ_{had}

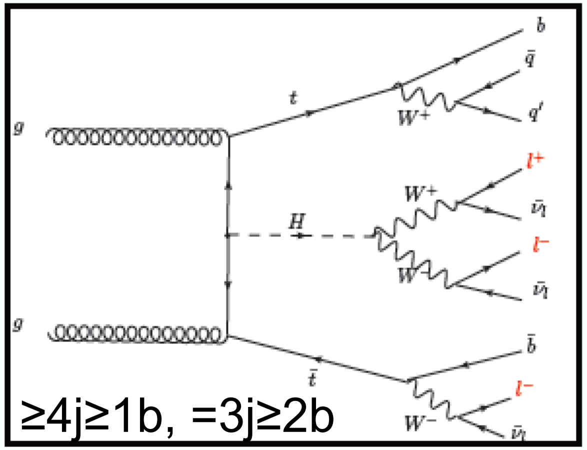
→ only combinations that can not originate from ttbar

Category	Higgs boson decay mode WW^*	$\tau\tau$	ZZ^*	Other
$2\ell 0\tau_{had}$	77%	17%	3%	3%
$2\ell 1\tau_{had}$	46%	51%	2%	1%
3ℓ	74%	20%	4%	2%
4ℓ	72%	18%	9%	2%

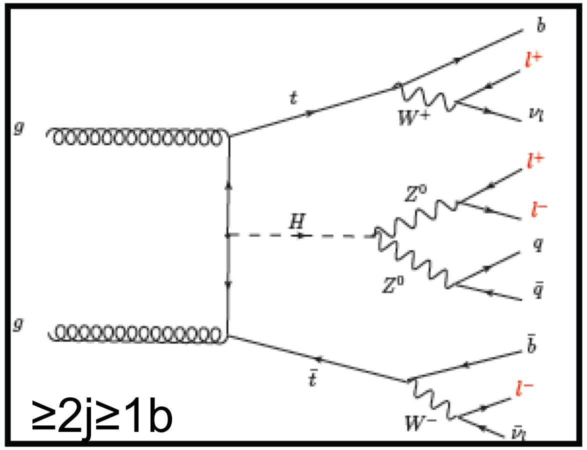
2 SS leptons (e/μ), no τ_{had}



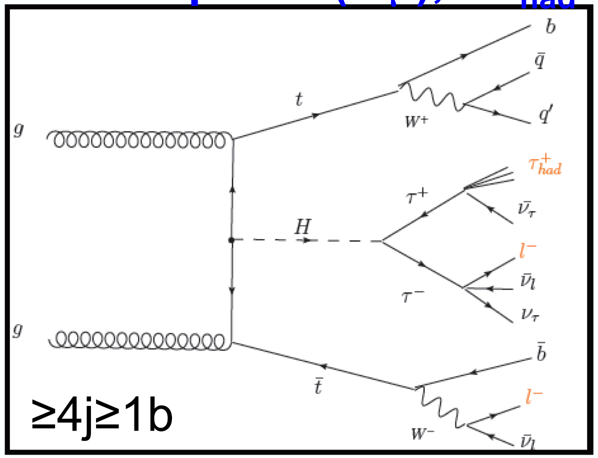
3 leptons (e/μ), |sum(Q)|=1



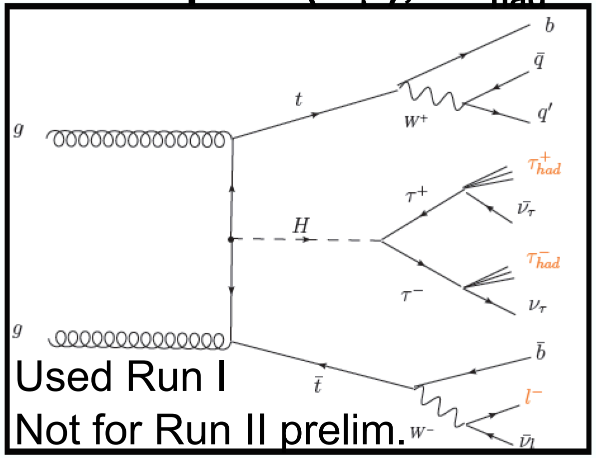
4 leptons (e/μ)



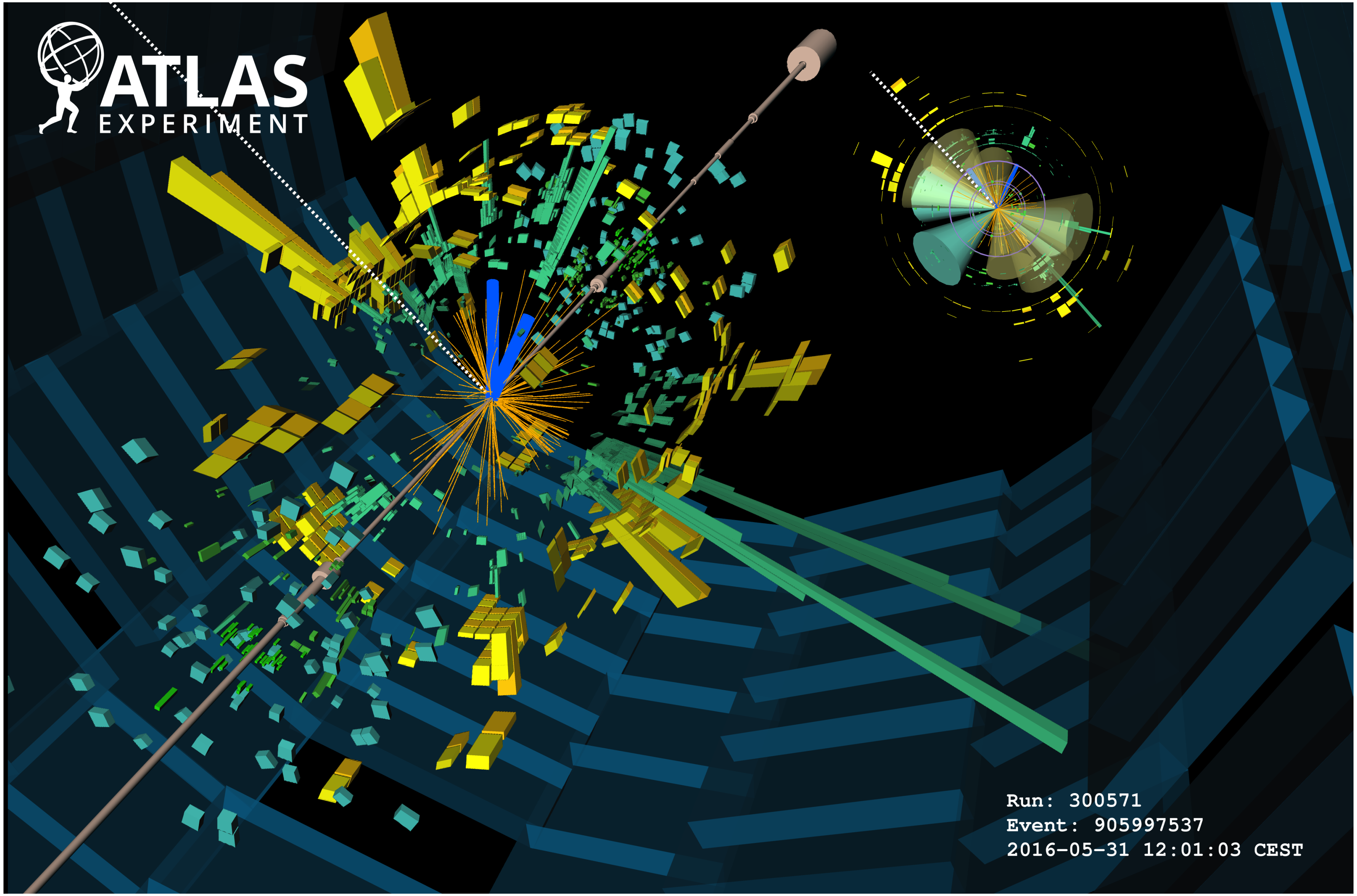
2 SS leptons (e/μ), 1 τ_{had}



1 lepton (e/μ), 2 τ_{had}



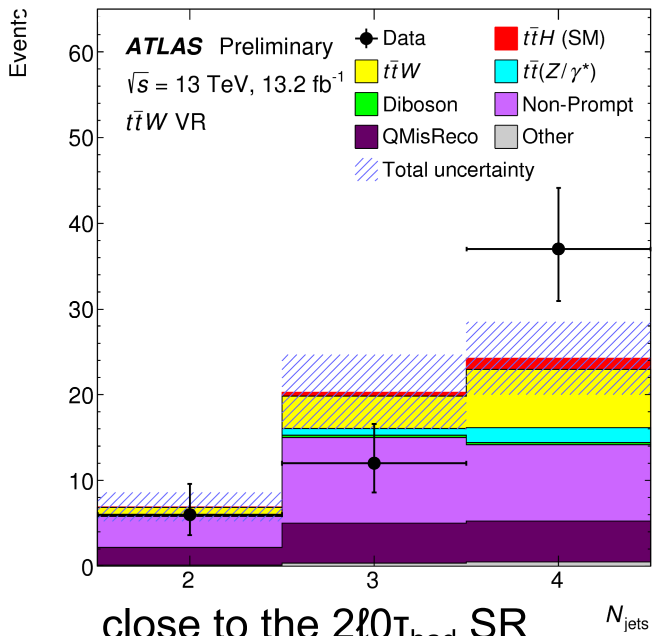
A candidate ee event in 2ℓ0τhad category



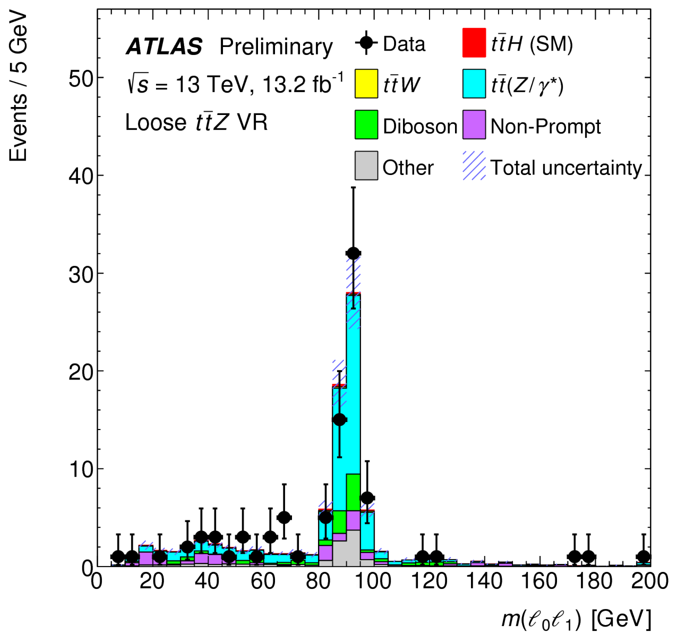
- Two selected electrons.
- Energy deposits in the electromagnetic (LAr) and hadronic (tile) calorimeters.
- Azure cones are the three b-tagged jets and the yellow cones are the six non-b-tagged jets.

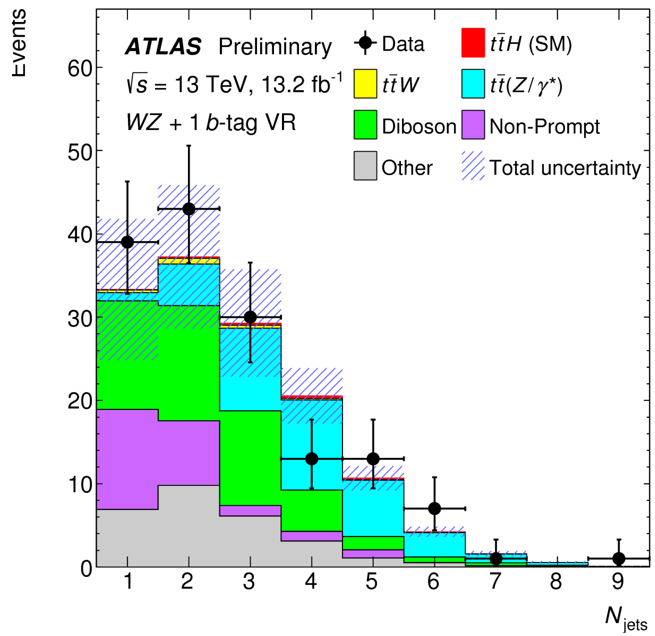
Analysis strategy and background estimates

- Low rates, but high purity S/B >0.2
- Cut-and-count analysis in 6 categories: 2ℓ0τhad (ee,eμ,μμ), 2ℓ1τhad, 3ℓ and 4ℓ
- Simultaneous fit in 6 bins
- Backgrounds:
  - **Reducible bkgs.** (data-driven techniques)
    - non-prompt light leptons → estimated from data control region
    - electron charge misidentification → estimate from *Z*+jets OS+SS events
    - hadronic tau misreconstruction → simulation scaled by data/MC normalisation
  - **Irreducible bkgs.** estimated from simulation, checked in validation regions
    - *tt*+*W*, *tt*+*Z* and diboson (*VV*) → estimated from simulation

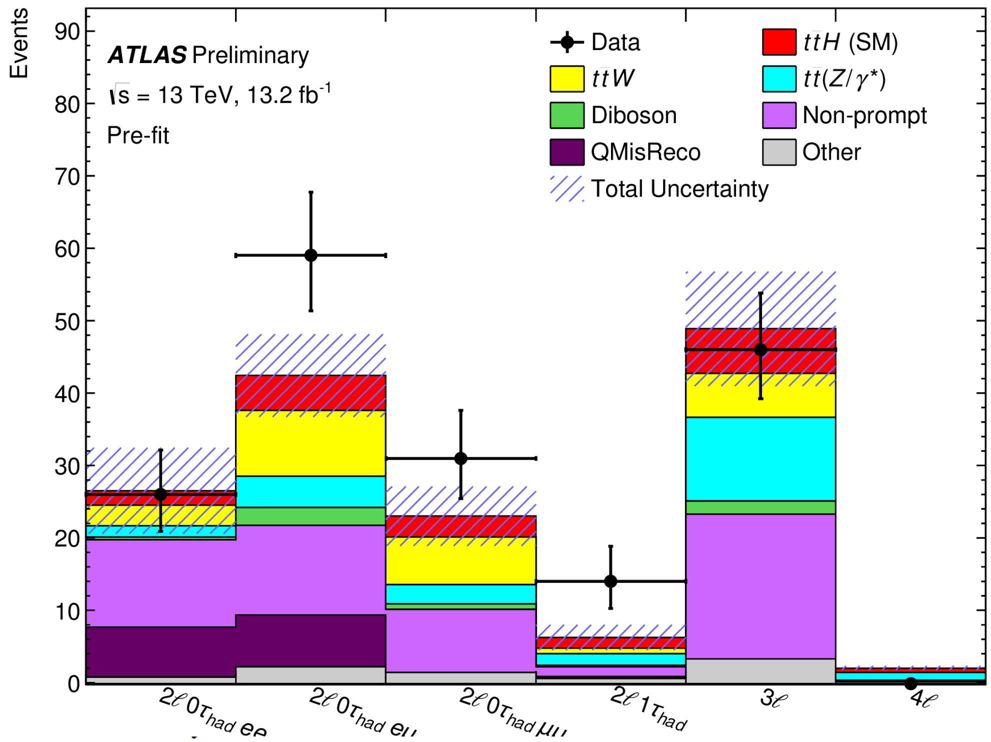


close to the 2ℓ0τ_{had} SR
but with low jet multiplicity



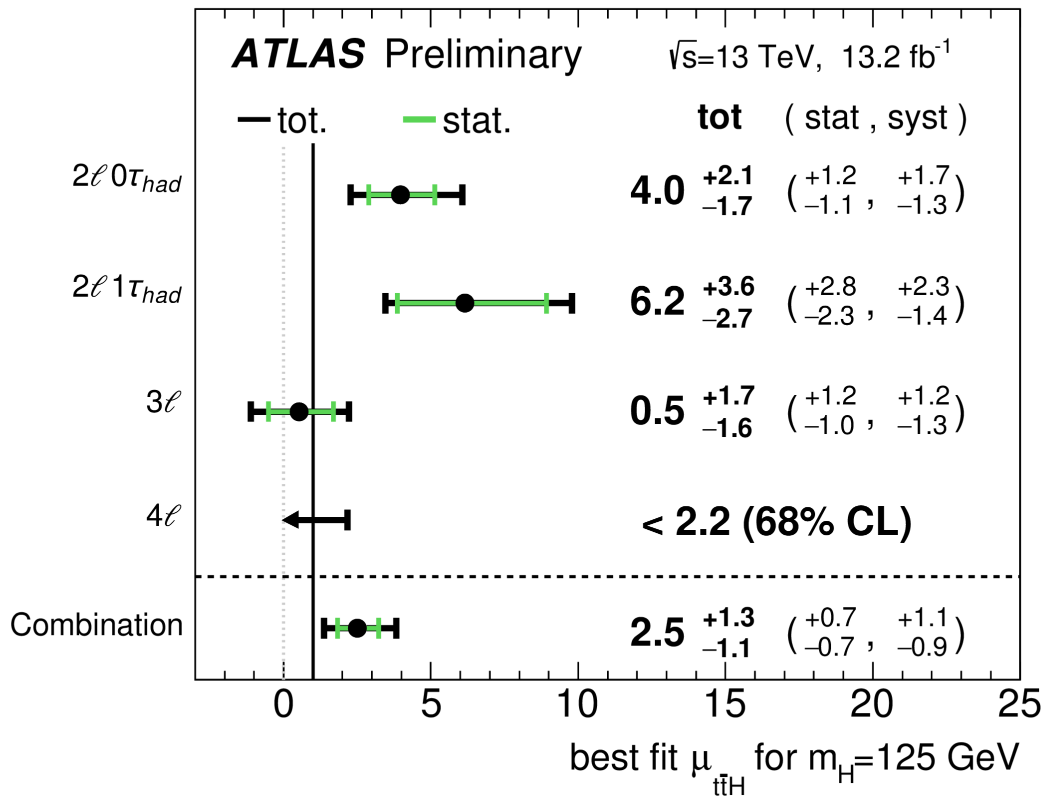


Prefit predictions and observed data events



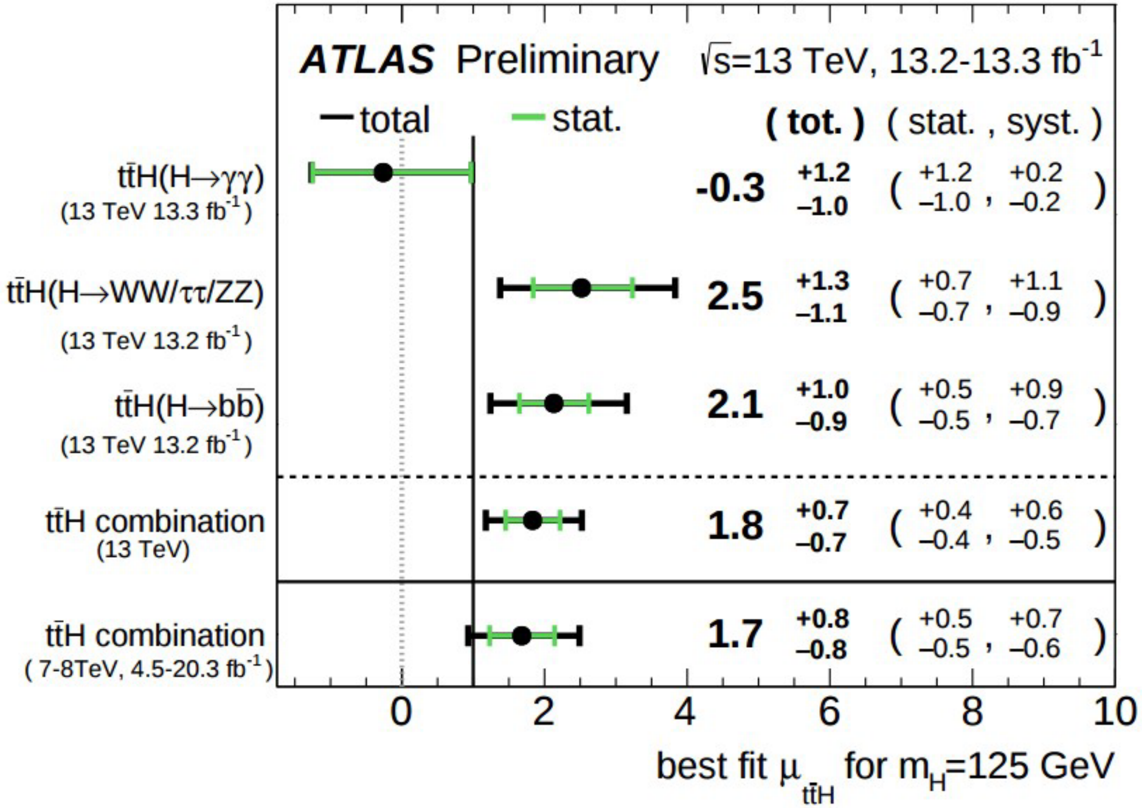
Uncertainty Source	$\Delta\mu$	
Non-prompt leptons and charge misreconstruction	+0.56	−0.64
Jet-vertex association, pileup modeling	+0.48	−0.36
$t\bar{t}W$ modeling	+0.29	−0.31
$t\bar{t}H$ modeling	+0.31	−0.15
Jet energy scale and resolution	+0.22	−0.18
$t\bar{t}Z$ modeling	+0.19	−0.19
Luminosity	+0.19	−0.15
Diboson modeling	+0.15	−0.14
Jet flavor tagging	+0.15	−0.12
Light lepton (e, μ) and τ_{had} ID, isolation, trigger	+0.12	−0.10
Other background modeling	+0.11	−0.11
Total systematic uncertainty	+1.1	−0.9

Best fit values of the *tt+H* signal strength

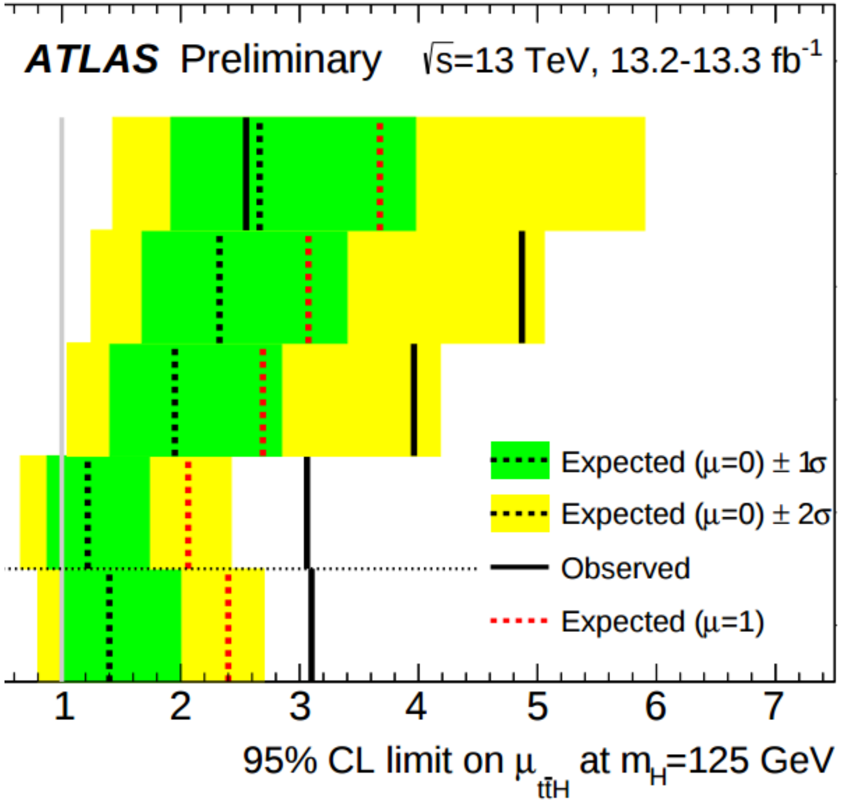


- Statistical unc. ~ systematics limited, main syst. from non-prompt and charge misID, jet-vertex fraction (due to pile-up, ~2.5% per jet)
- Slight excess, consistent with SM prediction

tt+H signal strength



tt+H cross section upper limits



Signal significance

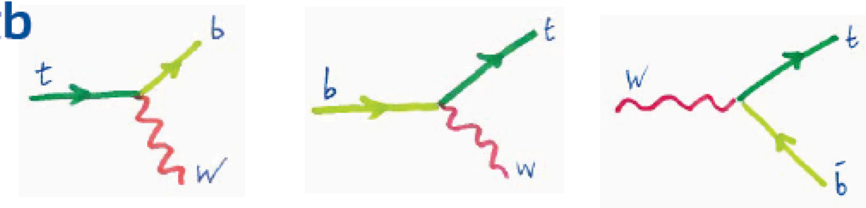
	Significance	
	Observed [σ]	Expected [σ]
$t\bar{t}H, H \to \gamma\gamma$	−0.2	0.9
$t\bar{t}H, H \to (WW, \tau\tau, ZZ)$	2.2	1.0
$t\bar{t}H, H \to b\bar{b}$	2.4	1.2
$t\bar{t}H$ combination	2.8	1.8

* Run I ATLAS sensitivity 2.3σ (1.5σ)
* Entering regime of results being systematically limited !!!!

Flavour changing neutral currents

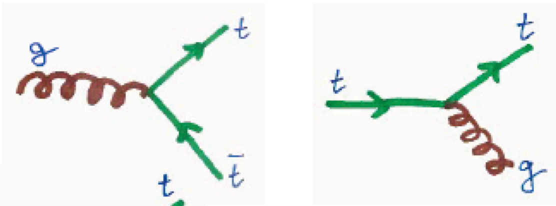
Flavour changing charged current

- **Wtb**

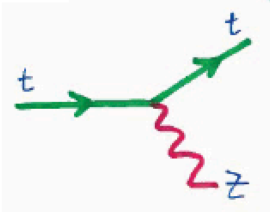


Flavour conserving neutral current

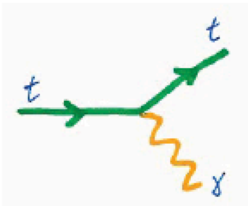
- **tgt**



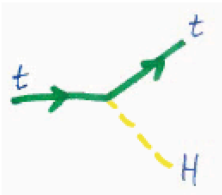
- **tZt**



- **tγt**

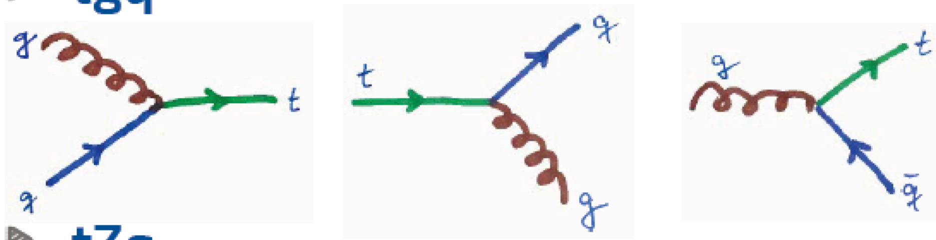


- **tHt**

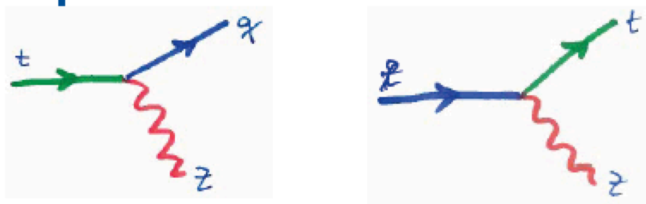


… and neutral current

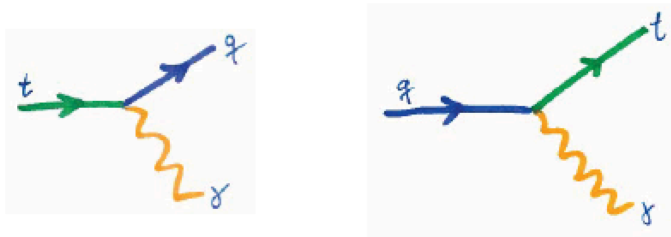
- **tgq**



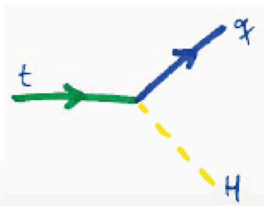
- **tZq**



- **tγq**

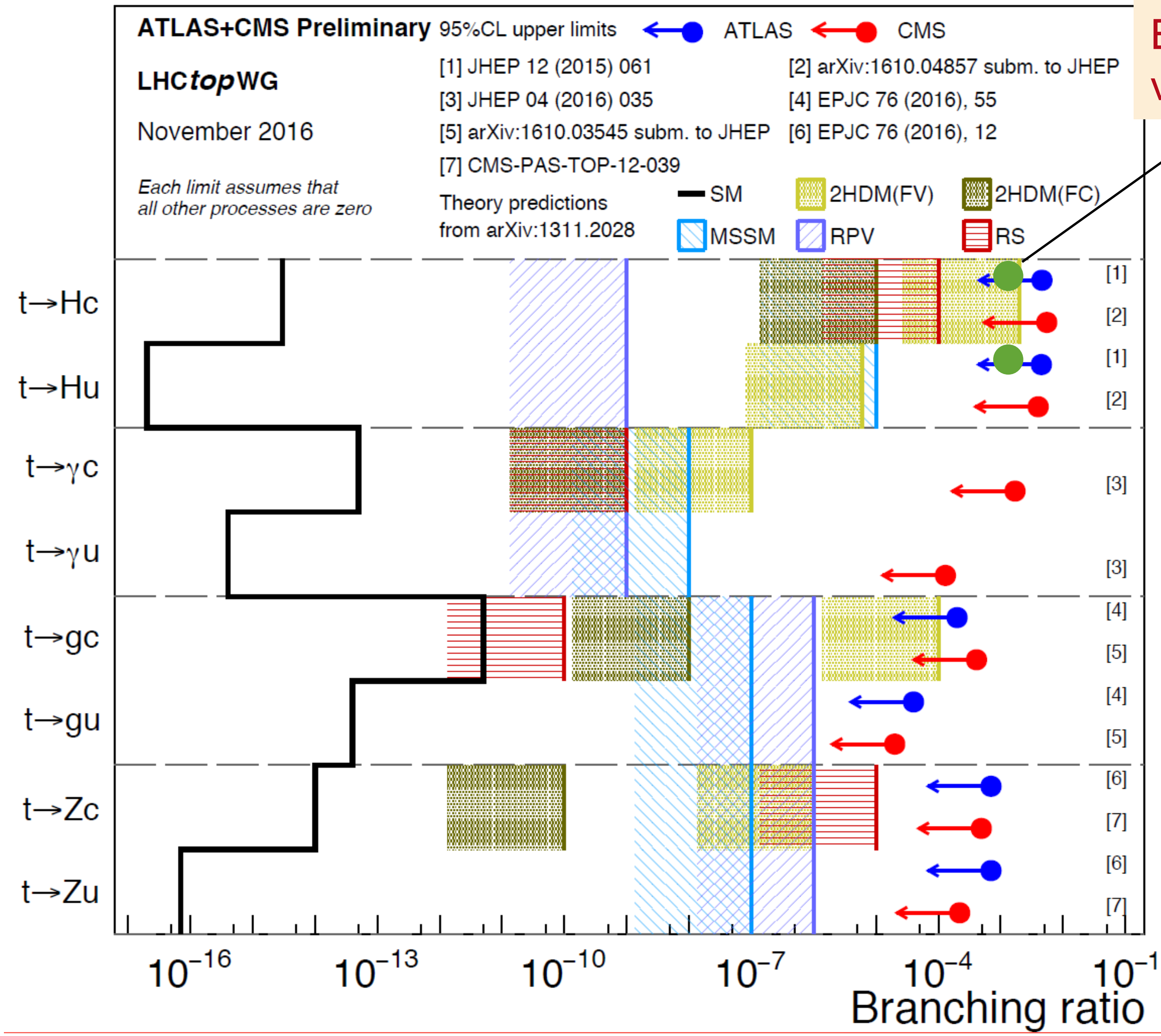


- **tHq**



→ Searches in decay ($t \to Xq$) and production ($pp \to tX$)

FCNC are forbidden in SM at tree level, strongly suppressed by GIM mechanism at higher orders
➔ Powerful probe for new physics BSM can enhance FCNC production.



Entering region sensitive to flavour violating Yukawa coupling in 2HDM

BR(10^{-4})	ATLAS 8 / 13 TeV	CMS (7+)8 TeV
$t \to Hc$	46 / 22(γγ)	40
$t \to Hu$	45 / 24(γγ)	55
$t \to \gamma c$	-	17
$t \to \gamma u$	-	1.3
$t \to gc$	2	4.1
$t \to gu$	0.4	0.2
$t \to Zc$	7	4.9
$t \to Zu$	7	2.2

FCNC $t \to H(\mathrm{all})q$, $t_{SM} \to bW$
JHEP12(2015)061
($\sqrt{s}$ = 8 TeV, 20.3 fb^{-1})

$H \to WW, \tau\tau, ZZ$
- multilepton final states
- reinterpretation of *tt+H* search

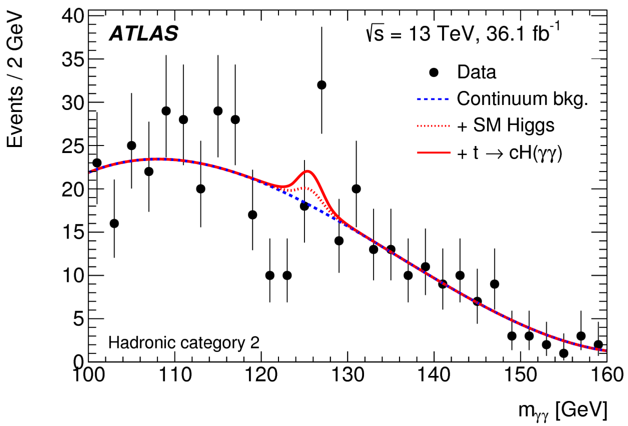
$H \to bb$
- dedicated analysis
- split events into several regions (nJets, nBjets)
- sophisticated MVA techniques

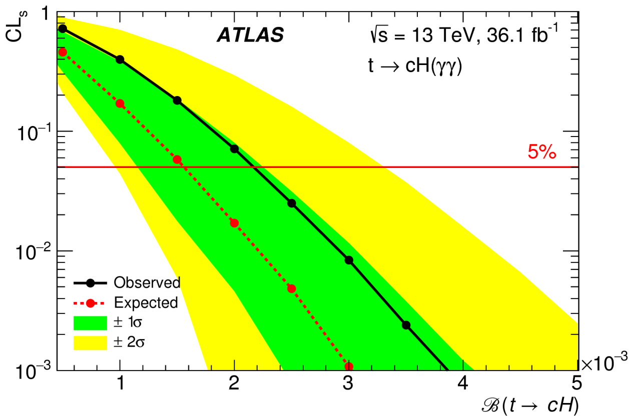
$H \to \gamma\gamma$
- limited by data statistcs

BR $t \to Hc$ < 4.6x10^{-3} @95% CL
BR $t \to Hu$ < 4.5x10^{-3} @95% CL

FCNC $t \to H(\gamma\gamma)q$, $t_{SM} \to bW$
arXiv:1707.01404
($\sqrt{s}$ = 13 TeV, 36.1 fb^{-1})

- Two modes for t_{SM}:
  - Hadronic: 2 photons, ≥4 jets, ≥1 b-tagged.
  - Leptonic: 2 photons, 1e or 1μ, ≥ 2 jets.
- Cuts on m(t_{FCNC}) and m(t_{SM})
- For each of mode, two categories: passing full selection / failing only t_{SM} mass criterion
- 4-channels combined: **BR $t \to H(\gamma\gamma)c$ < 2.2x10^{-3} @95% CL**
  BR $t \to H(\gamma\gamma)u$ < 2.4x10^{-3} @95% CL





- Compatibility of channels: 2.3σ
- Statistics limited. Dominant systematic uncertainties: JES, ME generator and radiation modelling

Outlook

- Precise measurements of the top quark couplings may provide insights on the underlying mechanism for EWSB and whether or not the top quark plays a role in it.

- The program of measurements for *tt+X* production at the LHC is well underway:

- ***tt+Z/W***: statistics limited (with full 2016 dataset statistical unc. ~ systematics unc.)
  - also **differential measurement and EFT interpretation**

- ***tt+H***: main decay modes being explored (*H*→*bb*, *WW*, $\tau\tau$, *ZZ* and $\gamma\gamma$)
  - entering regime of results being systematically limited (bkg. and signal modelling)
    → one of the main focus of the experiments in collaboration with theorists
  - expected ***tt+H* evidence with full 2016 dataset !! STAY TUNED ☺**

Unprecedented & unique dataset NOW available: ideal for new physics searches!

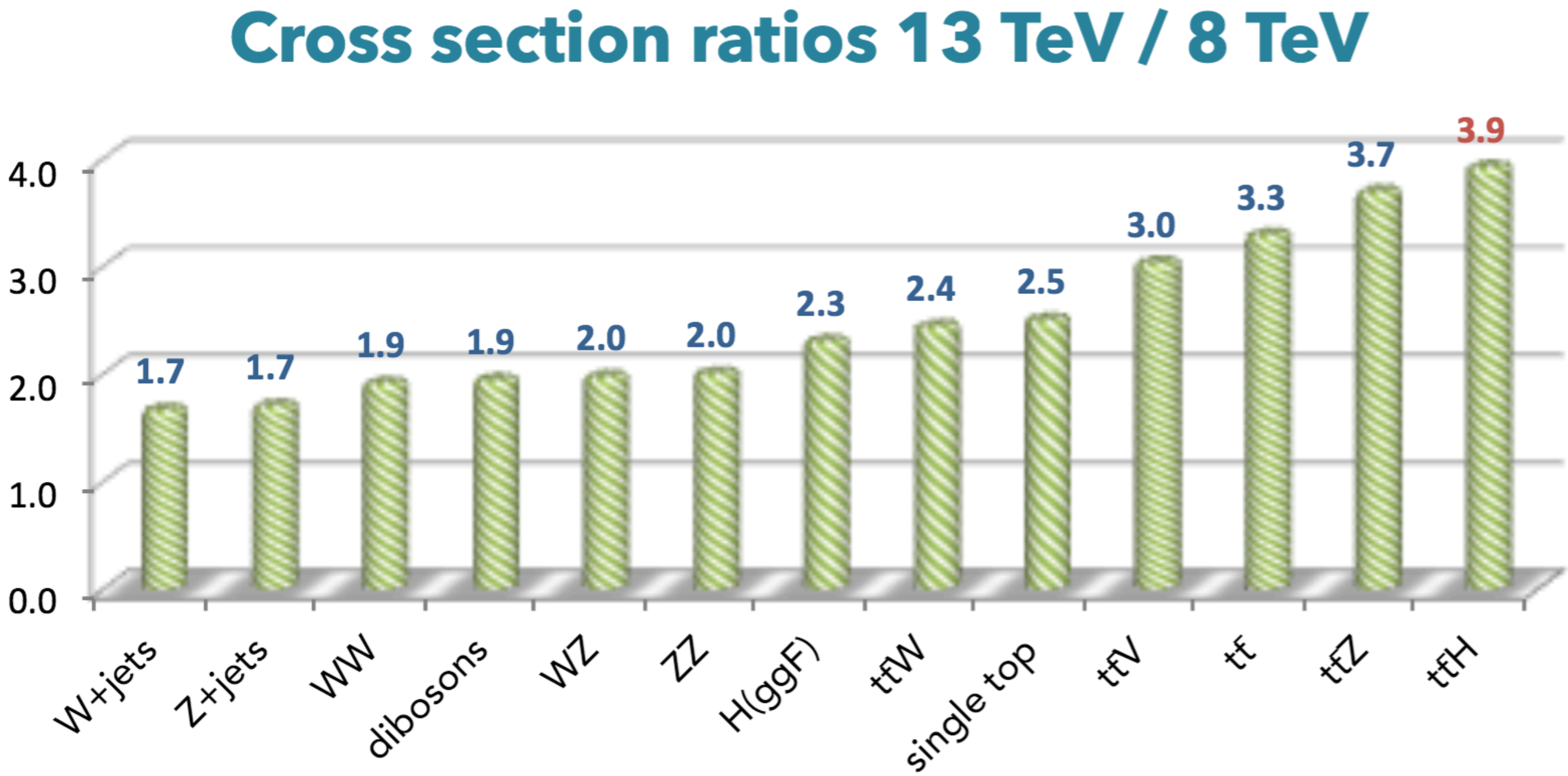
Several new projects:
* Exploit boosted regime
* *t+H* production
* For a given Y_t, σ(***tt+H***)/σ(***tt+Z***) can be predicted theoretically with a much better precision !
* Angular distributions to study ***CP* violation**

THANKS FOR YOUR ATTENTION

BACK-UP

Increase in the cross sections

Increase of expected cross section in Run 2 → more tt+X events in Run2 !!!!!



Simultaneous binned profile likelihood fit *L*(μ,θ) to all analysis regions (S+B hypothesis)

$$\boxed{L(\mu,\theta) = L_{Pois}(\mu,\theta) \cdot \prod_p \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{\theta_p^2}{2}\right)}$$

$$L_{Pois}(\mu) = \prod_j^{reg} \prod_i^{bins(j)} \frac{(\mu s_{ij} + b_{ij})^{n_{ij}}}{n_{ij}!} \exp\left(-(\mu s_{ij} + b_{ij})\right) \quad \text{with} \quad \mu = \frac{\sigma_{t\bar{t}V}}{\sigma_{t\bar{t}V}^{SM}}$$

- parameter of interest: signal strength **μ_{tt+H}**
- nuisance parameters **θ_p**: systematic uncertainties
- include CRs to constrain main irred. backgrounds
(floating normalisation factors correlated across ch.)

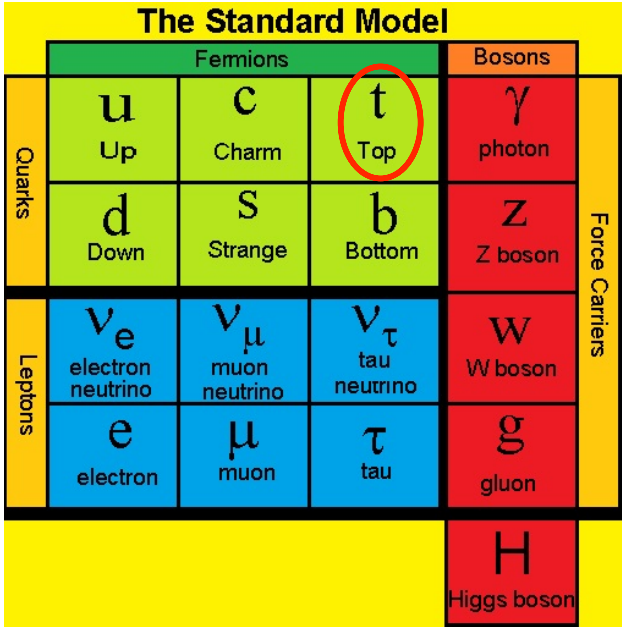
Measurements made using profile likelihood ratio test statistic **$\Lambda(\vec{\alpha})$**
* conditional / unconditional likelihoods

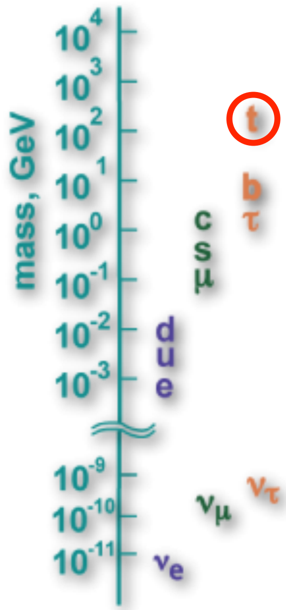
$$\Lambda(\vec{\alpha}) = \frac{L(\vec{\alpha}, \hat{\hat{\vec{\theta}}}(\vec{\alpha}))}{L(\hat{\vec{\alpha}}, \hat{\vec{\theta}})}$$

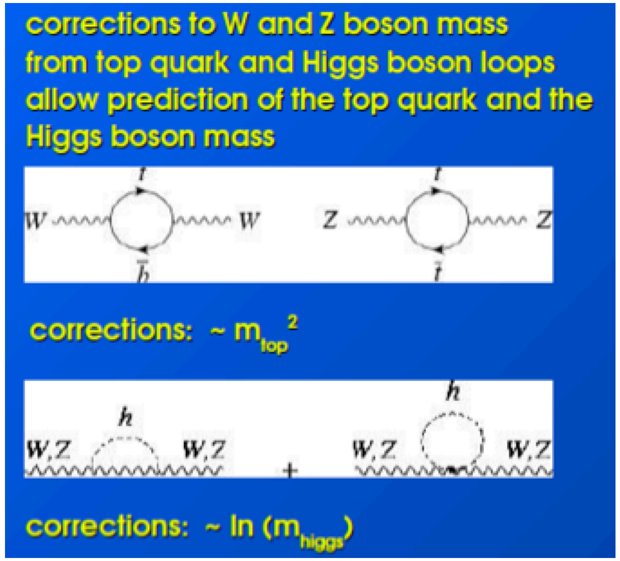
Parameter(s) of interest

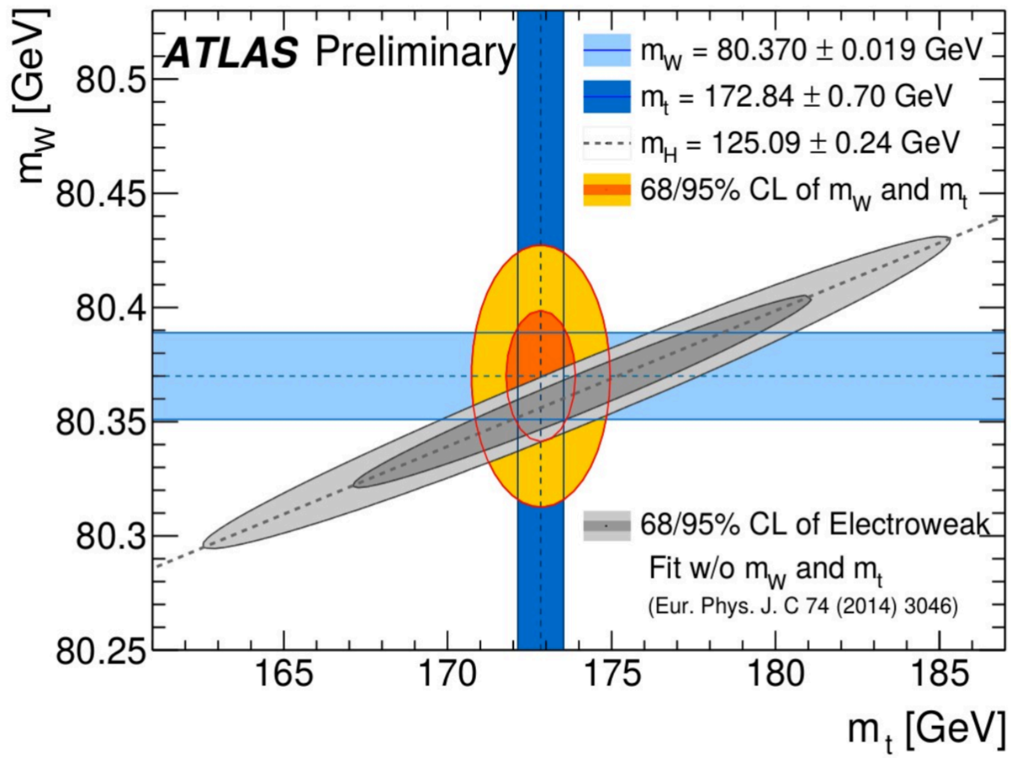
Nuisance parameter modelling uncertainties

The top quark in the Standard Model









- Completes the 3rd family structure of SM
- Electric charge = 2/3|e|
- Spin = 1/2, Isospin (T_3) = +1/2
- Mass ~173.34 ± 0.76 GeV
- Fast decay: $\tau \sim 4\cdot 10^{-25}$ s, Γ = 1.32 GeV
- Dominant decay to $t \rightarrow Wb$:
  - $|V_{tb}| > 0.999$ ➔ BR($t \rightarrow Wb$) ~100%
  - BR($t \rightarrow Ws$) ≤0.18%
  - BR($t \rightarrow Wd$) ≤0.02%

HF definition and treatment of uncertainties

Reconstructed *tt*+jets events are classified into several categories and subcategories, based on the flavour of additional jets (at particle level) and number of hadrons in each of them.

* Only additional particle level jets above a p_T threshold are considered in the classification

* Jets flavour (b, c or light) is determined via a ghost or dR matching to hadrons.

- For b and c jets, kinematics cuts on the leading hadron to which they are matched being studied.
- No p_T ratio p_T^{hadron}/p_T^{jet} cut is considered (so far) in the HF classification.

Cuts	ATLAS *	CMS
Reco-level jets	(all events are classified)	≥ two jets with p_T > 30 GeV
Particle level jets	15 GeV	20 GeV
Hadrons	5 GeV, no p_T^{hadron}/p_T^{jet} cut	No cuts
Particle-hadron matching	dR<0.3	Ghost matching

* From ongoing studies, the relative differences among generators in tt+jets fractions seem stable against these cuts

Subcategories

- **"tt+b"**: 1 extra particle jet in the event which is matched to exactly 1 HF hadron
- **"tt+bb"**: 2 particle jets, each of them matched to exactly 1 HF hadron
- **"tt+B/2b"** (ATLAS/CMS): 1 particle jet which is matched to a bb pair (g→bb splitting), i.e to >1 hadron

Treatment of uncertainties

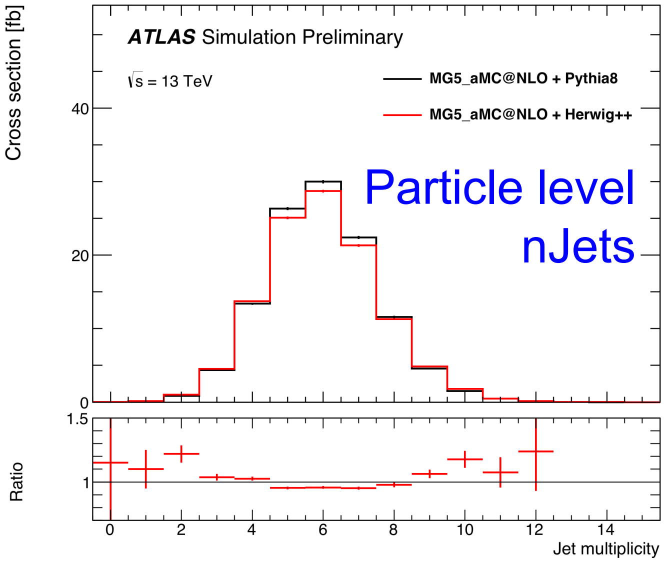
ATLAS: reweighting of kinematics for each subcategory in 5F sample to 4F predictions

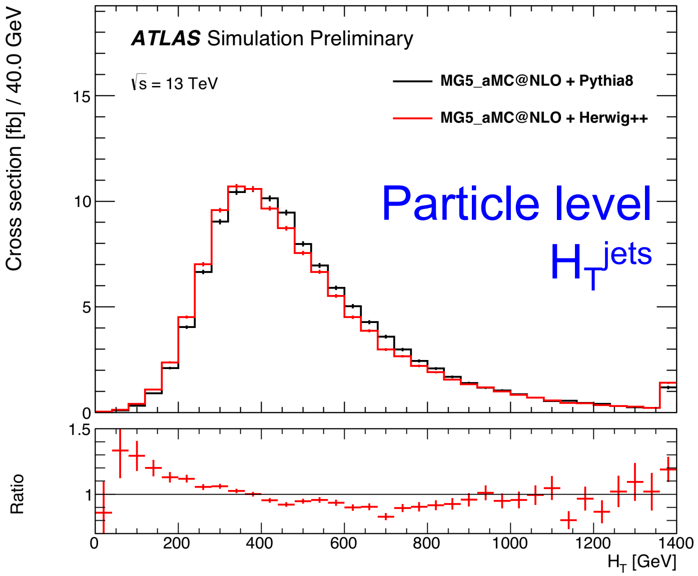
→ treating uncertainties as fully correlated among subcategories

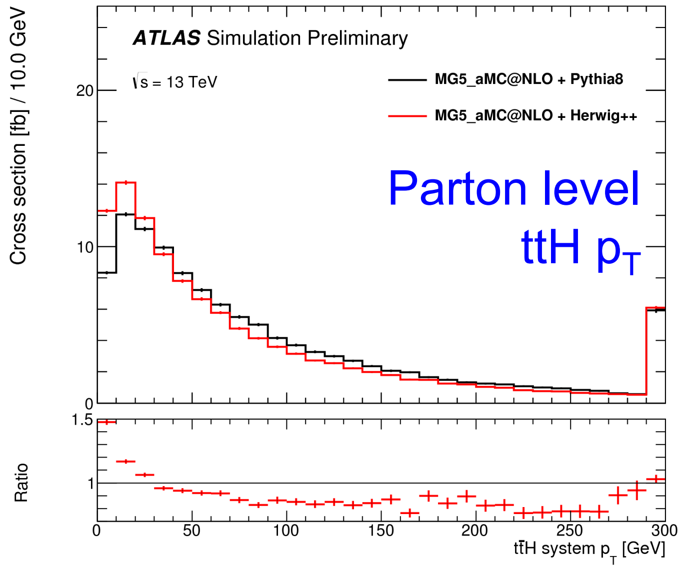
CMS: shapes from 5F predictions → treating uncertainties as fully uncorrelated.

ATL-PHYS-PUB-2016-005

tt+H (*tt*→lep+jets, *H*→*bb*), Parton shower and hadronisation





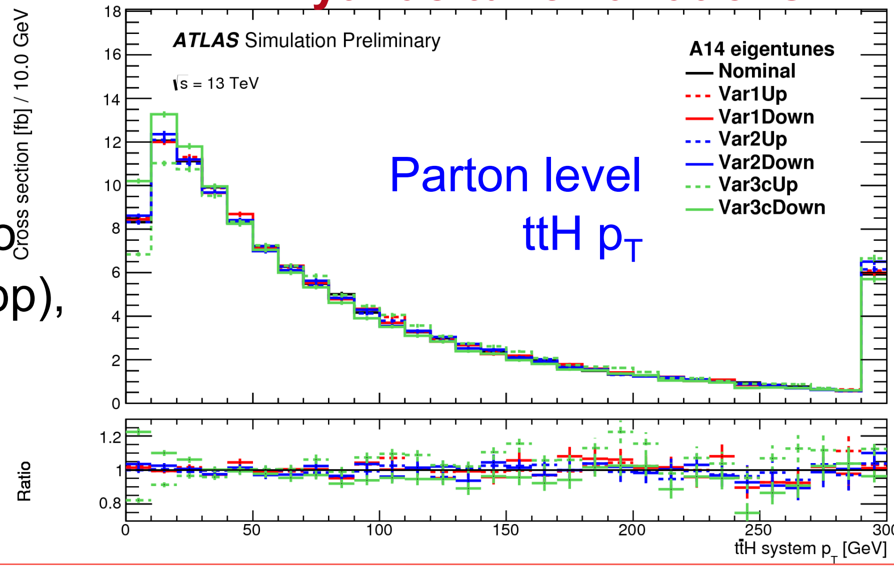


* MG5_aMC@NLO+Pythia8 prediction: slightly more events with six jets (number of expected jets for the selected channel *tt+H* with *tt*→lep+jets, *H*→*bb*). In addition, jets transverse momenta is harder.

* Visible effects in low region of *tt+H* p_T spectrum due to different showering and hadronisation model (Py8/HWpp), larger than A14 Var3c (ISR) variations.

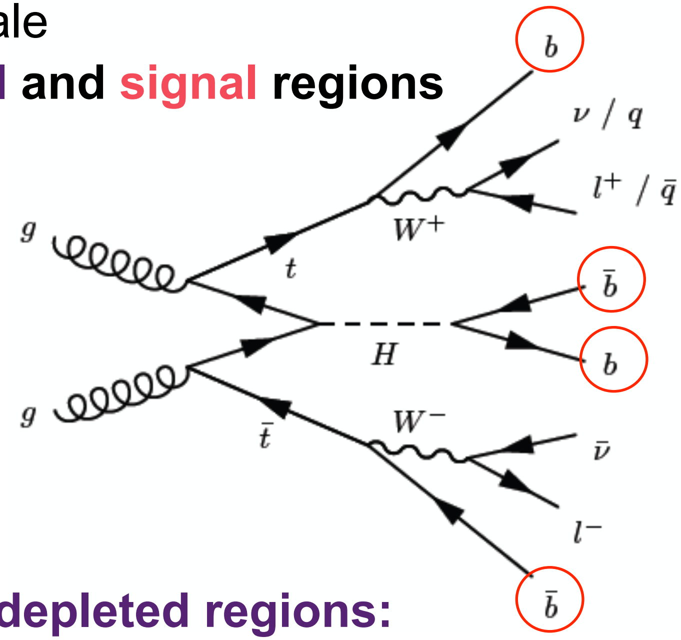
* Scale choice: main effect from μ_R, cross-section varies 9%, shape effect <1%

A14 Pythia8 tune variations



ttH (H→bb) signal produces 1 or 2 leptons and 6 or 4 jets, 4 of them _b_-jets

- Very challenging final state affected by large systematics:
  tt+jets, tt+heavy flavour modelling, *b*-tagging, jet energy scale
- Categorize events according to the # jets and b-jets → **control** and **signal regions**
- Build **multivariate discriminant** in signal-enriched regions



b-jets

jets

Single lepton

	2 *b*-tags	3 *b*-tags	$\geq$ 4 *b*-tags
4 jets	H_T^{had}	H_T^{had}	H_T^{had}
5 jets	H_T^{had}	NN	NN
$\geq$ 6 jets	H_T^{had}	NN	NN

Dilepton

	2 *b*-tags	3 *b*-tags	$\geq$ 4 *b*-tags
2 jets	H_T		
3 jets	H_T	NN	
$\geq$ 4 jets	H_T	NN	NN

- **Signal-depleted regions:**
  use H_T^{had}= sum p_T of jets for single lepton
  H_T= sum p_T of jets and leptons for dilepton
- **Region with 5 jets and 3 *b*-jets:**
  use neural networks (NN) trained to separate tt+bb/cc from tt+light jets
- **Signal-rich regions:**
  use MVA trained to separate ttH for tt+jets in each region

Systematic uncertainties

Systematic uncertainty	Type	Components
Luminosity	N	1
Reconstructed Objects		
Electron trigger+reco+ID+isolation	SN	5
Electron energy scale+resolution	SN	2
Muon trigger+reco+ID+isolation	SN	6
Muon momentum scale+resolution	SN	3
Pileup reweighting	SN	1
Jet vertex Tagger	SN	1
Jet energy scale	SN	18
Jet energy resolution	SN	1
Missing transverse momentum	SN	3
b-tagging efficiency	SN	5
c-tagging efficiency	SN	4
Light-jet tagging efficiency	SN	14
High-p_T tagging	SN	2
Background and Signal Model		
$t\bar{t}$ cross section	N	1
$t\bar{t}$+HF: normalisation	N	2
$t\bar{t}+\geq 1b$: NLO Shape	SN	10
$t\bar{t}+\geq 1c$: NLO Shape	SN	1
$t\bar{t}$ modelling: residual Radiation	SN	3
$t\bar{t}$ modelling: residual NLO generator	SN	3
$t\bar{t}$ modelling: residual parton shower+hadronisation	SN	3
$t\bar{t}$ NNLO reweighting	SN	4
W+jets normalisation	N	6
Z+jets normalisation	N	6
Single top cross section	N	2
Single top model	SN	2
Diboson normalisation	N	1
Fakes normalization	SN	7
$t\bar{t}V$ cross section	N	4
$t\bar{t}V$ model	SN	XXXX
$t\bar{t}H$ cross section	N	2
$t\bar{t}H$ branching ratios	N	4
$t\bar{t}H$ model	SN	XXX

Many systematic uncertainties, both theoretical and experimental.

- **Luminosity**
- **Physics objects**
  - leptons (ID, trigger, isolation)
  - jets: pile-up,JVT, JES, JER
  - MET
  - b-tagging
- **Background model**
  - tt+jets
  - small backgrounds

    → single lepton:

    • W+jets:
    overall 30% unc. decorrelated across N(jets)
    additional W+HF 30% unc. decorrelated across N(b-tags)
    •Z+jets XS systematic unc. 45%.
    •Fakes: 50% norm. unc. per N(b-tags) and lepton flavour

    → dilepton:

    • Z+jets: overall 30% unc. decorrelated across N(jets)
    additional Z+HF 30% unc. decorrelated across N(b-tags)
    •Fakes: overall 50% norm. unc.
- **Signal model**

tt+H(bb): summary of tt+jets modelling uncertainties

Systematic source	How evaluated	$t\bar{t}$ categories
$t\bar{t}$ cross-section	$\pm 6\%$	All, correlated
NLO generator (*residual*)	Powheg-Box + Herwig++ vs. MG5_aMC + Herwig++	All, uncorrelated
Radiation (*residual*)	Variations of μ_{R}, μ_{F}, and *hdamp*	All, uncorrelated
PS & hadronisation (*residual*)	Powheg-Box + Pythia 6 vs. Powheg-Box + Herwig++	All, uncorrelated
NNLO top & $t\bar{t}$ p_{T}	Maximum variation from any NLO prediction	$t\bar{t}+\geq 1c$, $t\bar{t}$ +light, uncorr.
$t\bar{t}+b\bar{b}$ NLO generator *reweighting*	SherpaOL vs. MG5_aMC + Pythia8	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ PS & hadronis. *reweighting*	MG5_aMC + Pythia8 vs. MG5_aMC + Herwig++	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ renorm. scale *reweighting*	Up or down a by factor of two	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ resumm. scale *reweighting*	Vary μ_{Q} from $H_{\mathrm{T}}/2$ to μ_{CMMPS}	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ global scales *reweighting*	Set μ_{Q}, μ_{R}, and μ_{F} to μ_{CMMPS}	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ shower recoil *reweighting*	Alternative model scheme	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ PDF *reweighting*	CT10 vs. MSTW or NNPDF	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ MPI	Up or down by 50%	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ FSR	Radiation variation samples	$t\bar{t}+\geq 1b$
$t\bar{t}+c\bar{c}$ ME calculation	MG5_aMC + Herwig++ inclusive vs. ME prediction	$t\bar{t}+\geq 1c$

Expected signal and post-fit background yields

Channel	Region	$t\bar{t}H$ (S)	Bkgd (B)	$tHjb + WtH$	S/B	$\mathrm{N_{Data}}$
$H \to \gamma\gamma$	all-hadronic	1.58	8.27	0.10	0.19	9
	leptonic	1.16	2.42	0.10	0.48	2
$H \to (WW, \tau\tau, ZZ)$	2ℓSS ee	1.99 ± 0.51	22.2 ± 3.4	0.10 ± 0.03	0.09	26
	2ℓSS $e\mu$	4.82 ± 0.95	38.5 ± 5.1	0.26 ± 0.07	0.13	59
	2ℓSS $\mu\mu$	2.85 ± 0.58	21.2 ± 3.8	0.15 ± 0.04	0.13	31
	2ℓSS $+\tau_{\mathrm{had}}$	1.43 ± 0.31	5.7 ± 1.7	0.11 ± 0.03	0.25	14
	3ℓ	6.2 ± 1.1	38.9 ± 5.3	0.30 ± 0.08	0.16	46
	4ℓ	0.59 ± 0.10	1.42 ± 0.24	0.014 ± 0.006	0.42	0
$H \to b\bar{b}$	ℓ+jets ($\geq$ 6j,3bj)	119 ± 16	11250 ± 240	6.2 ± 1.5	0.011	11561
	ℓ+jets (5j,$\geq$ 4bj)	11.8 ± 2.6	429 ± 28	0.91 ± 0.14	0.028	418
	ℓ+jets ($\geq$ 6j,$\geq$ 4bj)	44.9 ± 9.4	1191 ± 55	2.10 ± 0.50	0.038	1285
	dilepton ($\geq$ 4j,3bj)	20.6 ± 4.2	1423 ± 45	0.71 ± 0.20	0.014	1467
	dilepton ($\geq$ 4j,$\geq$ 4bj)	6.6 ± 2.0	133 ± 12	0.171 ± 0.053	0.050	154

Contribution of each Higgs decay mode in SRs

Channel	Region	WW	$\tau\tau$	ZZ	$b\bar{b}$	$\gamma\gamma$
$H \to \gamma\gamma$	all-hadronic	–	–	–	–	100%
	leptonic	–	–	–	–	100%
$H \to (WW, \tau\tau, ZZ)$	2ℓSS ee	76%	17%	2%	4%	–
	2ℓSS $e\mu$	77%	17%	3%	3%	–
	2ℓSS $\mu\mu$	79%	17%	3%	1%	–
	2ℓSS $+\tau_{\text{had}}$	46%	51%	2%	1%	–
	3ℓ	74%	20%	4%	1%	–
	4ℓ	72%	18%	9%	–	–
$H \to b\bar{b}$	ℓ+jets ($\geq$ 6j,3bj)	5%	1%	1%	90%	–
	ℓ+jets (5j,$\geq$ 4bj)	–	–	–	99%	–
	ℓ+jets ($\geq$ 6j,$\geq$ 4bj)	1%	–	1%	97%	–
	dilepton ($\geq$ 4j,3bj)	6%	1%	1%	90%	–
	dilepton ($\geq$ 4j,$\geq$ 4bj)	–	–	–	98%	–

Standard model deviations are described by higher dimensional operators:

$$\mathcal{L}_{SM}^{(6)} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \dots$$

Interference SM-BSM | Pure BSM term

$$\sigma = \sigma_{SM} + \sum_i \frac{C_i}{(\Lambda/1\mathrm{TeV})^2}\sigma_i^{(1)} + \sum_{i\leq j}\frac{C_i C_j}{(\Lambda/1\mathrm{TeV})^4}\sigma_{ij}^{(2)}$$

Dimension 6 operators relevant for top quark physics.

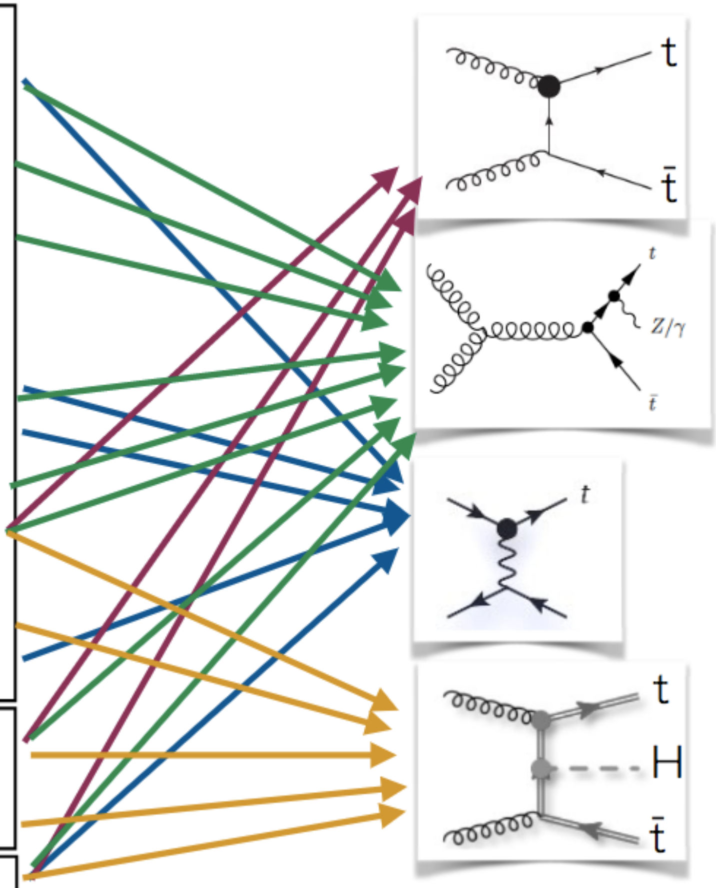
modify vector and axial coupling of top to EW gauge bosons

O_{tB}, O_{tW}: EW dipole operator
O_{tG}: chromomagnetic dipole operator

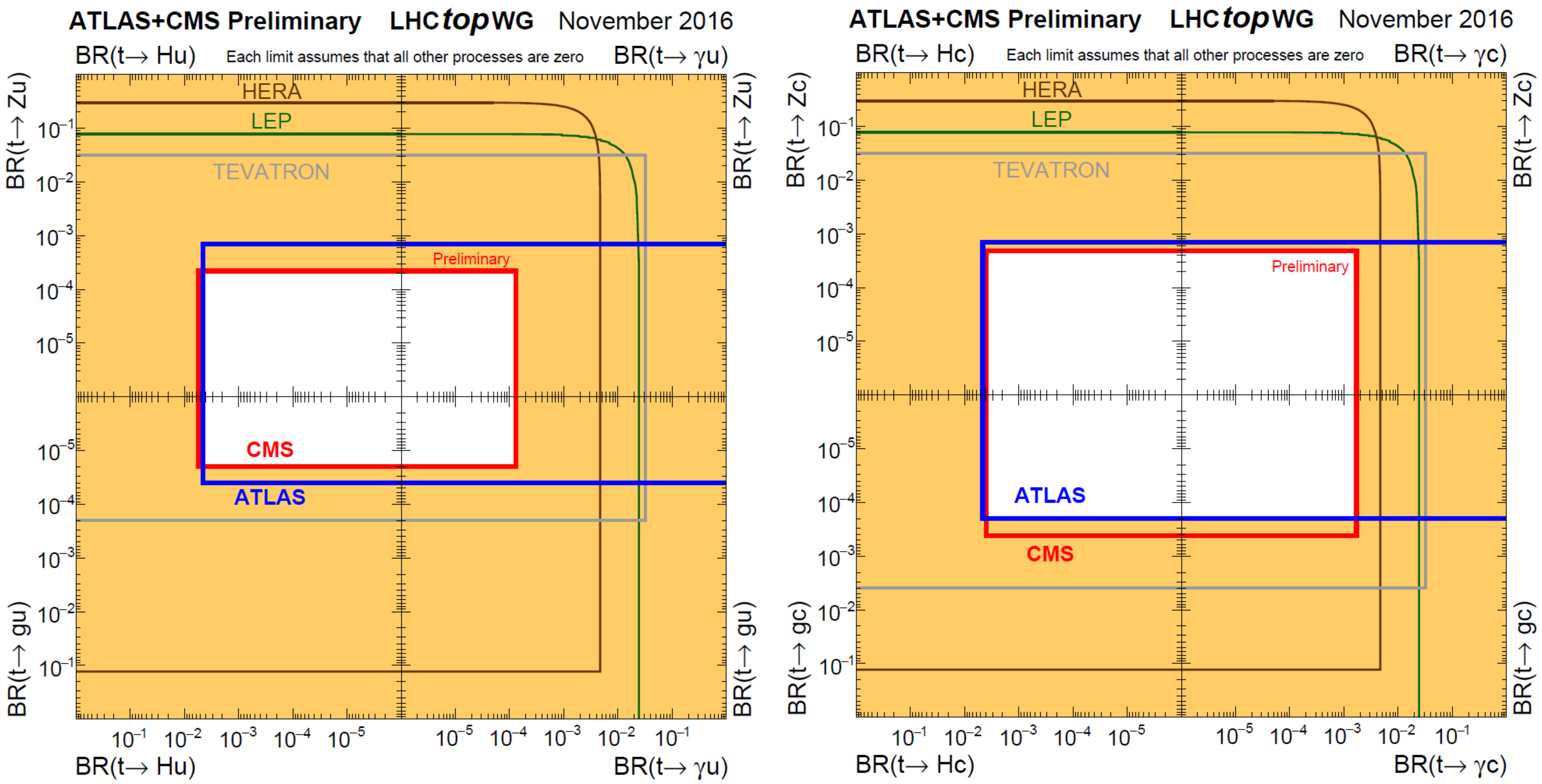
$$O_{\varphi Q}^{(3)} = i\tfrac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)\left(\bar{Q}\gamma^\mu \tau^I Q\right)$$
$$O_{\varphi Q}^{(1)} = i\tfrac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{Q}\gamma^\mu Q\right)$$
$$O_{\varphi t} = i\tfrac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{t}\gamma^\mu t\right)$$
$$O_{\varphi b} = i\tfrac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{b}\gamma^\mu b\right)$$
$$O_{tW} = y_t g_w(\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}$$
$$O_{bW} = y_b g_w(\bar{Q}\sigma^{\mu\nu}\tau^I b)\varphi W^I_{\mu\nu}$$
$$O_{tB} = y_t g_Y(\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu}$$
$$O_{tG} = y_t g_s(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}$$
$$O_{t\varphi} = (\varphi^\dagger\varphi)(\bar{Q}t\tilde{\varphi})$$
$$O_{\varphi tb} = i(\varphi^\dagger D_\mu \varphi)(\bar{t}\gamma^\mu b)$$

$$O_G = g_s f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$$
$$O_{\varphi G} = g_s^2\left(\varphi^\dagger\varphi\right) G^A_{\mu\nu}G^{A\mu\nu}$$

4-fermion ops



Run I LHC top FCNC searches



FCNC QCD Lagrangian: anom. coupl.

Run I LHC FCNC results are expressed in the framework of anomalous couplings:

$$\begin{aligned}
\mathcal{L}_{FCNC} = \sum_{q=u,c} \Bigg[& \frac{\sqrt{2}}{2} g_s \frac{\kappa_{gqt}}{\Lambda} \cdot \bar{t}\sigma^{\mu\nu}\left(f^L_{gq}P_L + f^R_{gq}P_R\right) q \boxed{G^a_{\mu\nu}} && \text{tensor} \\
+ & \frac{\sqrt{2}}{2} e \frac{\kappa_{\gamma qt}}{\Lambda} \cdot \bar{t}\sigma^{\mu\nu}\left(f^L_{\gamma q}P_L + f^R_{\gamma q}P_R\right) q \boxed{A_{\mu\nu}} && \text{tensor} \\
+ & \frac{1}{\sqrt{2}} \eta_{hqt} \cdot \bar{t}\left(f^L_{hq}P_L + f^R_{hq}P_R\right) q \boxed{H} && \text{scalar} \\
+ & \frac{\sqrt{2}}{4} \frac{g}{\cos\theta_W} \frac{\kappa_{zqt}}{\Lambda} \cdot \bar{t}\sigma^{\mu\nu}\left(f^L_{zq}P_L + f^R_{zq}P_R\right) q \boxed{Z_{\mu\nu}} && \text{tensor} \\
+ & \frac{1}{4} \frac{g}{\cos\theta_W} \zeta_{zqt} \cdot \bar{t}\gamma^{\mu}\left(\tilde{f}^L_{zq}P_L + \tilde{f}^R_{zq}P_R\right) q \boxed{Z_{\mu}} \Bigg] + h.c && \text{vector}
\end{aligned}$$

Top decay	κ_{gqt}/Λ	$\kappa_{\gamma qt}/\Lambda$	κ_{zqt}/Λ	ζ_{zqt}	η_{hqt}
t→g q	X				
t→γ q		X			
t→Z q			X	x NLO	
t→h q					X

Single top	κ_{gqt}/Λ	$\kappa_{\gamma qt}/\Lambda$	κ_{zqt}/Λ	ζ_{zqt}	η_{hqt}
p p → t (g)	X				
p p → t γ	X	X			
p p → t Z	X		X	X	
p p → t h	X				X

X: considered
X: usually neglected

Assumptions

Example of conventions

$$\sqrt{\left|f^L_{xq}\right|^2 + \left|f^R_{xq}\right|^2} = 1 \qquad \frac{\kappa_{xqt}}{\Lambda},\ \zeta_{xqt},\ \text{and}\ \eta_{xqt} > 0$$

$$\sqrt{\left|\tilde{f}^L_{xq}\right|^2 + \left|\tilde{f}^R_{xq}\right|^2} = 1$$

Simplifications

f^R_{xq} =0 & f^L_{xq}=1

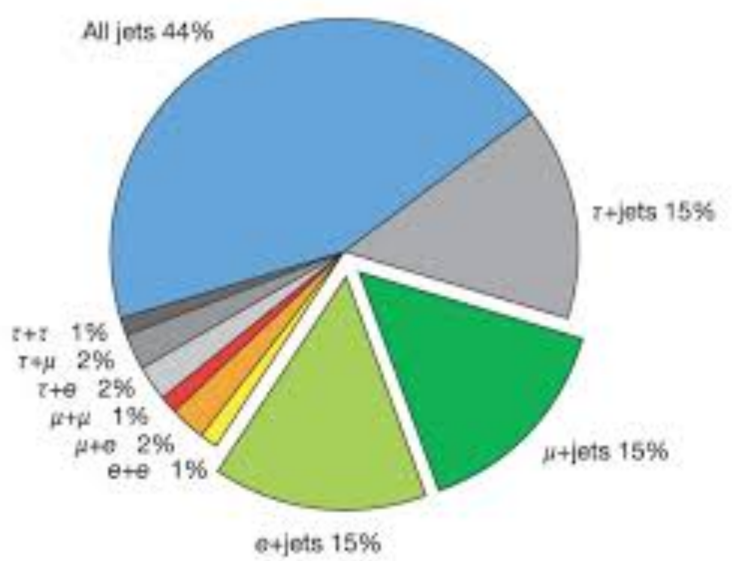
f^R_{xq} =1 & f^L_{xq}=0

- Depending on decay mode of *t* or *tt* and *Z/H*: from 0 to 5 light (e/μ) leptons (+X jets + Y b-jets)

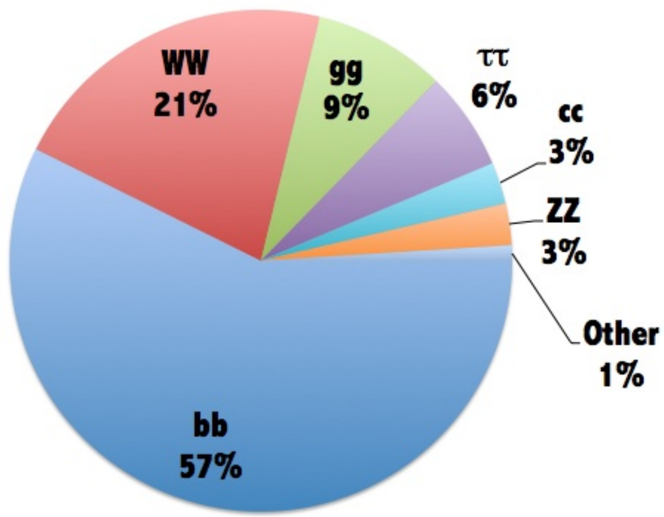
Z boson decays:

hadronic	leptonic: visible	leptonic: invisible
$Z^\circ \to q\bar{q}$	$Z^\circ \to e^+e^-$	$Z^\circ \to \nu\bar{\nu}$
	$Z^\circ \to \mu^+\mu^-$	
	$Z^\circ \to \tau^+\tau^-$	

Top quark pairs decays:



Higgs boson decays:



→ Several unexplored signatures !!