Probing the top and Higgs sectors

using multiℓepton and multibjets events

with the ATLAS EXPERIMENT

Photograph: ATLAS Collaboration

Tamara Vázquez Schröder

CERN

Experimental Particle and Astro-Particle Physics Seminar

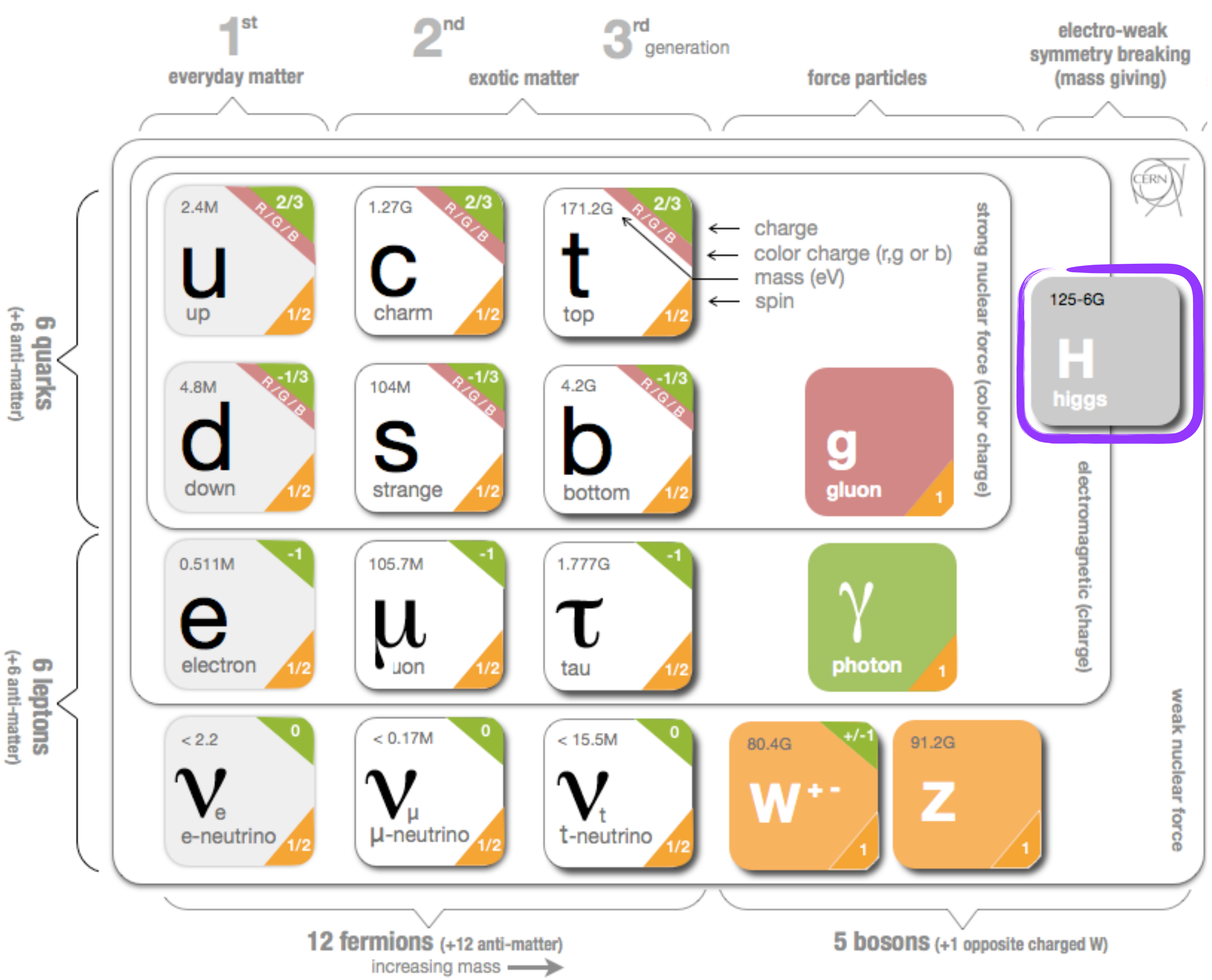
Zürich - 12 April 2021

Why particle colliders?

- To understand the fundamental description of Nature

Why particle colliders?

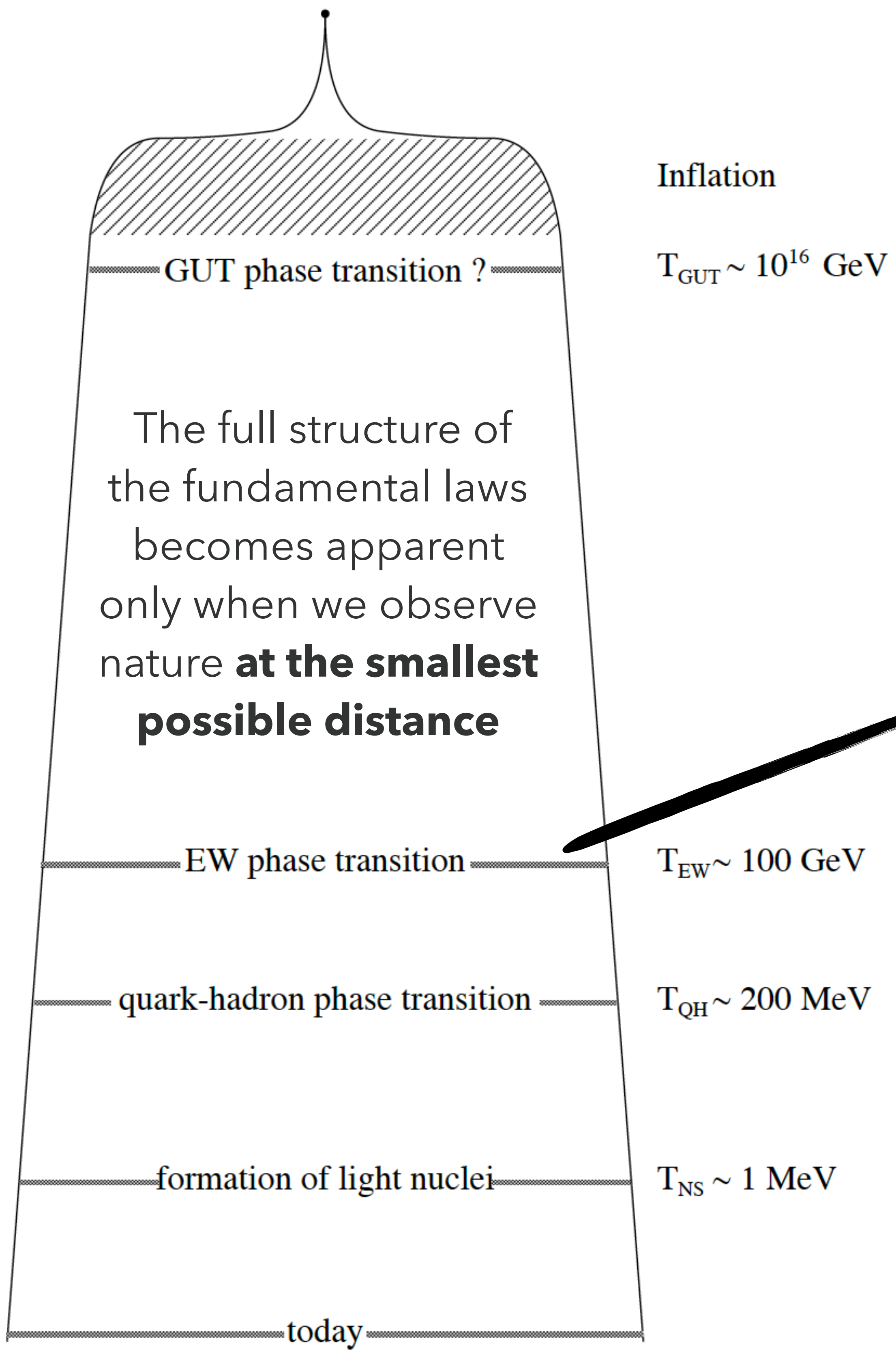
- To understand the fundamental description of Nature
- Best Model so far: The Standard Model of Particle Physics



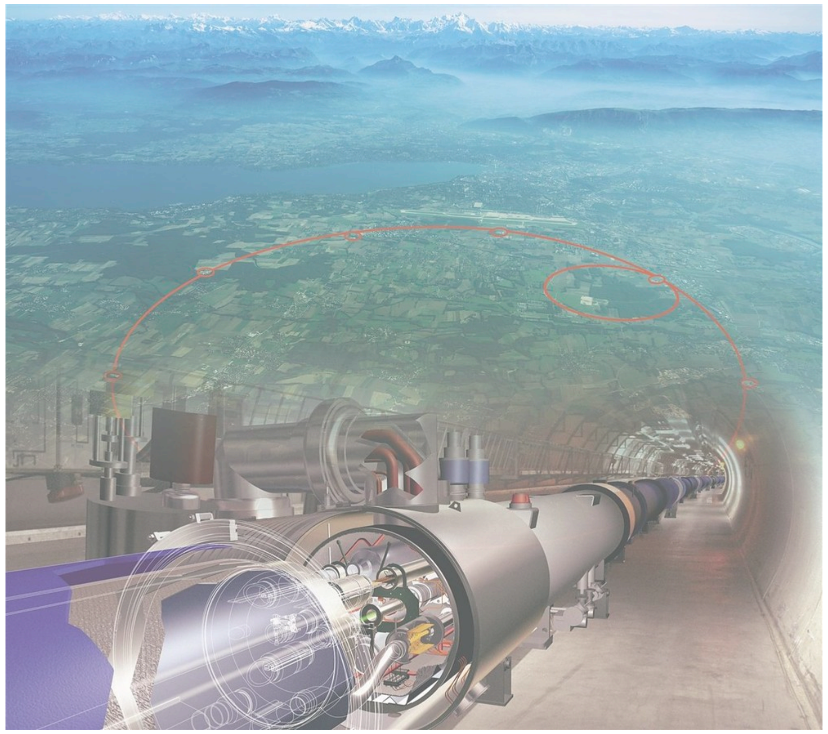
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c. + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

- **Higgs** field: added to the SM to generate the mass of EW bosons and fermions

Starting from the beginning

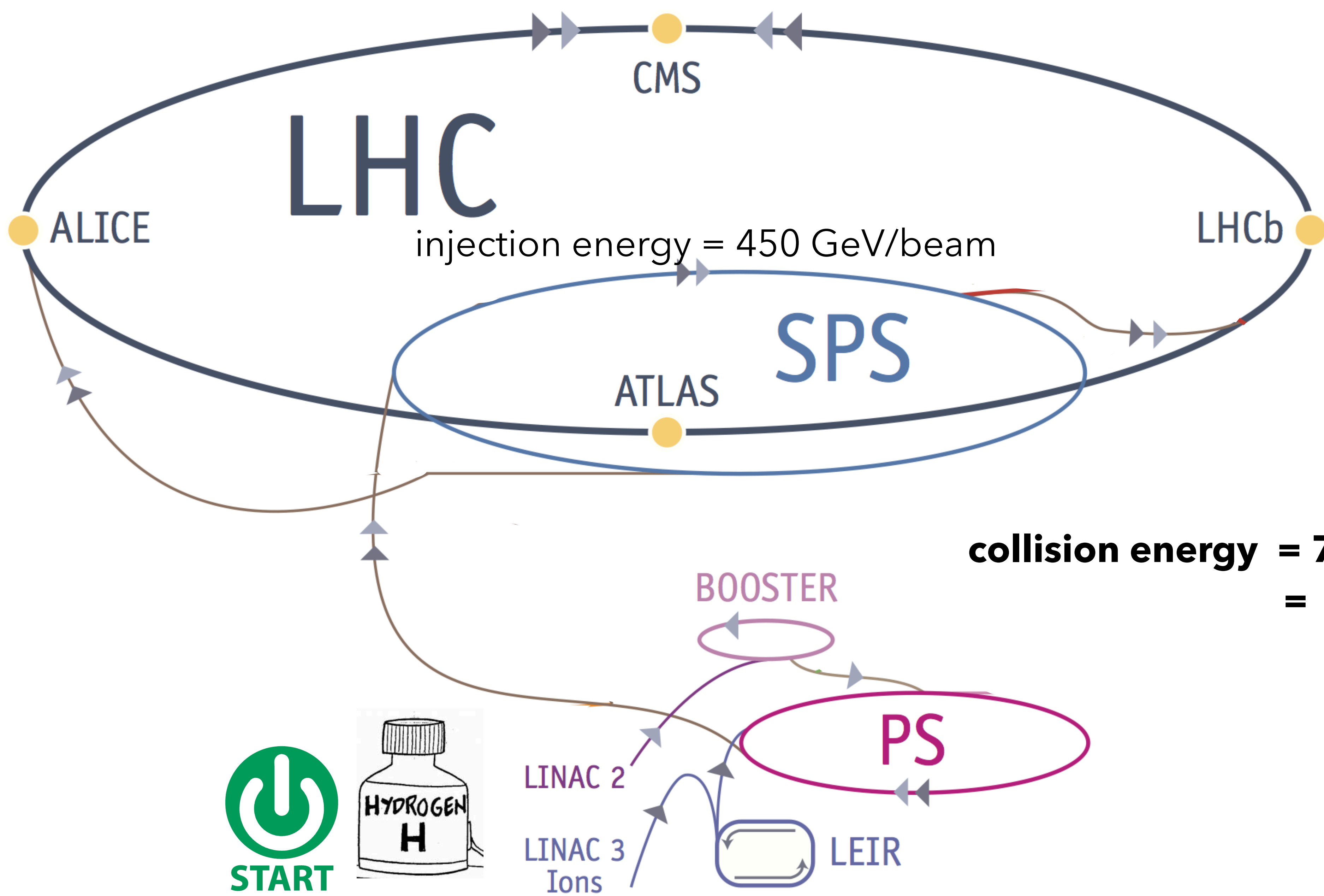


The full structure of the fundamental laws becomes apparent only when we observe nature **at the smallest possible distance**



With particle accelerators and colliders we have managed to "access" the particles present up to 10^{-12} s after the Big Bang

The Large Hadron Collider (LHC)

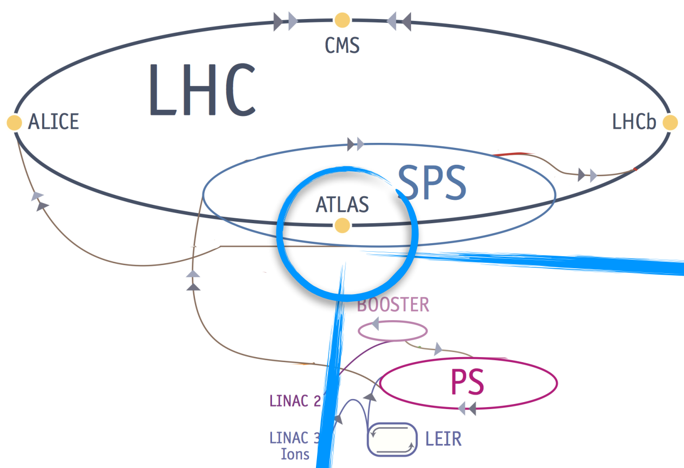


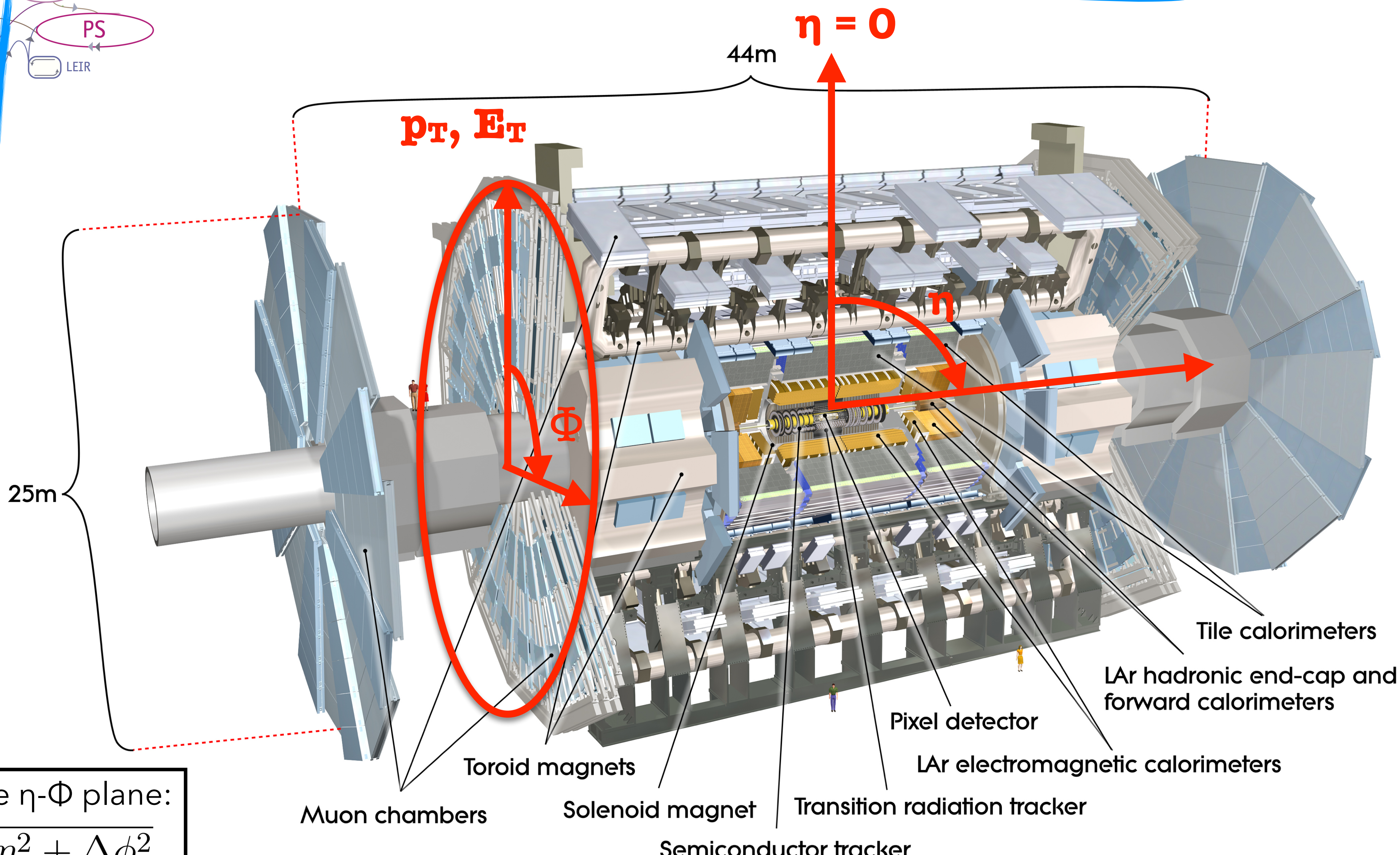
collision energy = 7/8 TeV (Run1)
= 13 TeV (Run2)

The CERN accelerator complex & the collider

The ATLAS experiment

Giant and sophisticated
multipurpose particle detector:
tracking detector + calorimeter + muon spectrometer

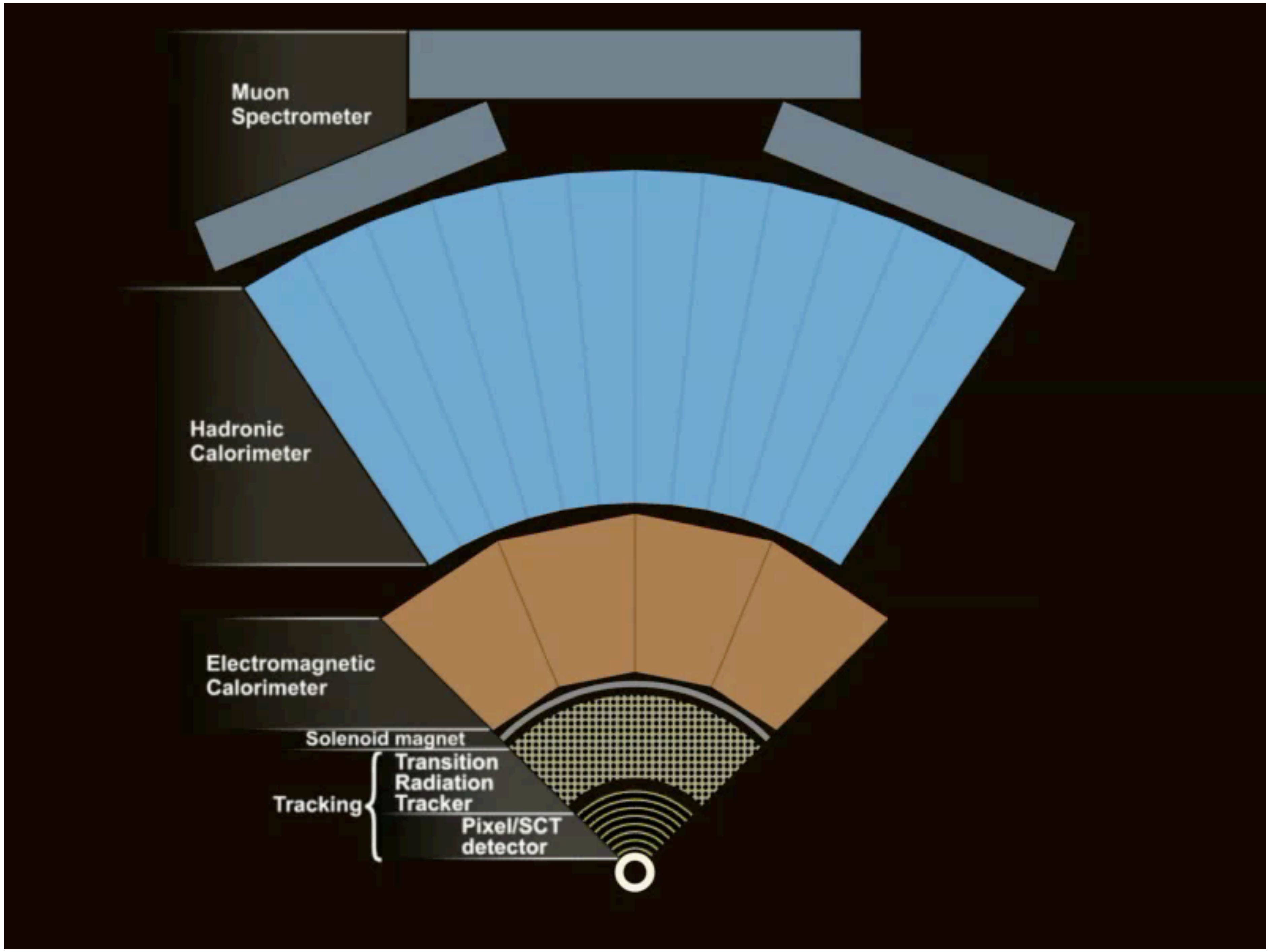




distance in the η-Φ plane:

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

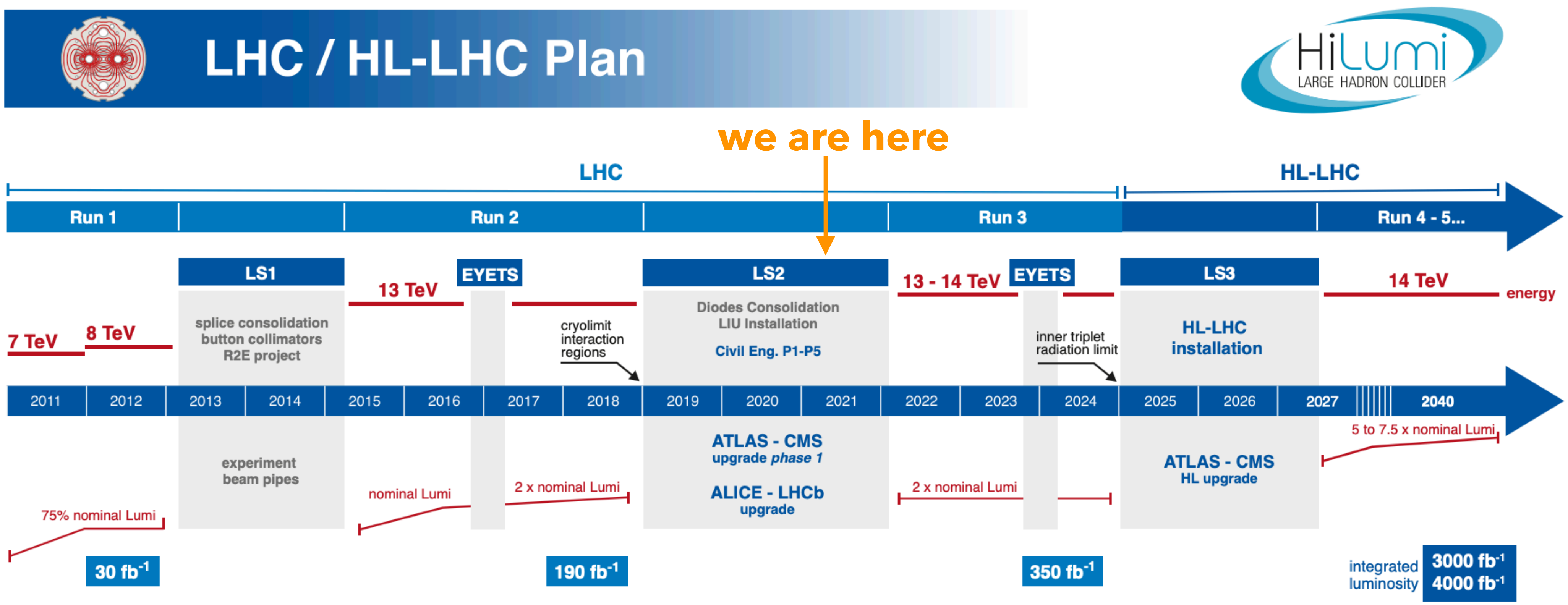
Particle identification

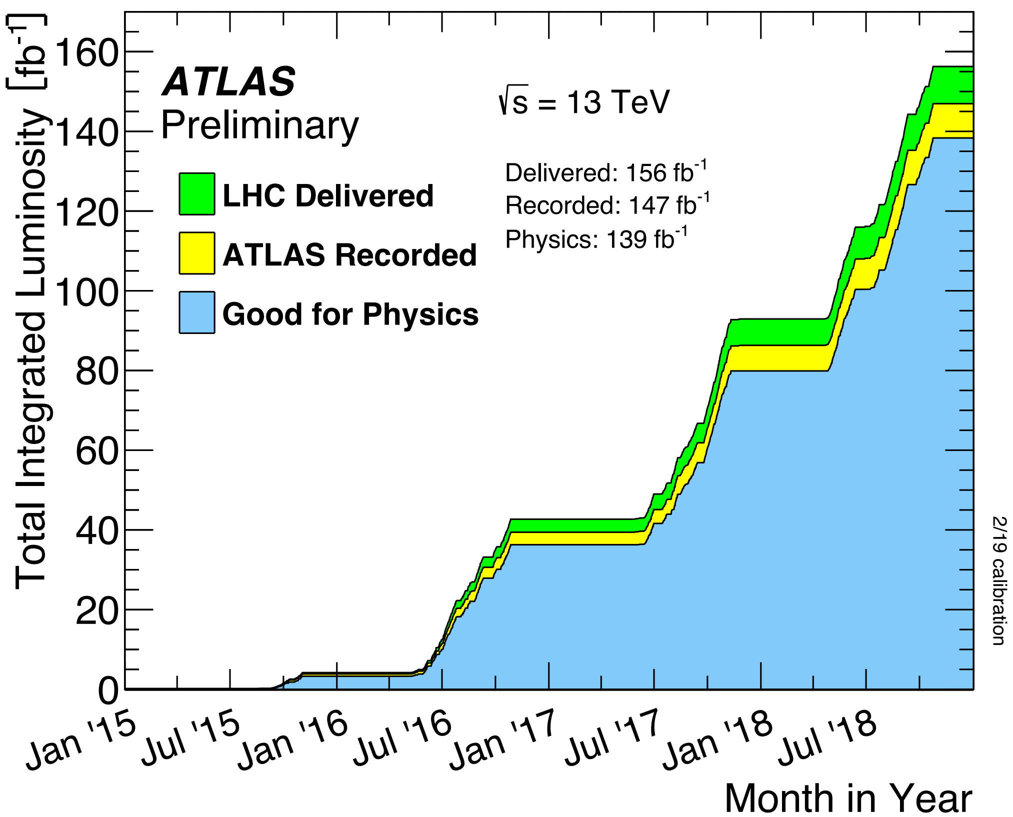


ATLAS Experiment © 2014 CERN http://www.atlas.ch/multimedia/#how-atlas-detects-particles

- Each layer, different interaction with particles, different targets
- Energy, momentum, measurements

The LHC plan





- Luminosity allows us to observe low cross section processes
  - The interesting ones!

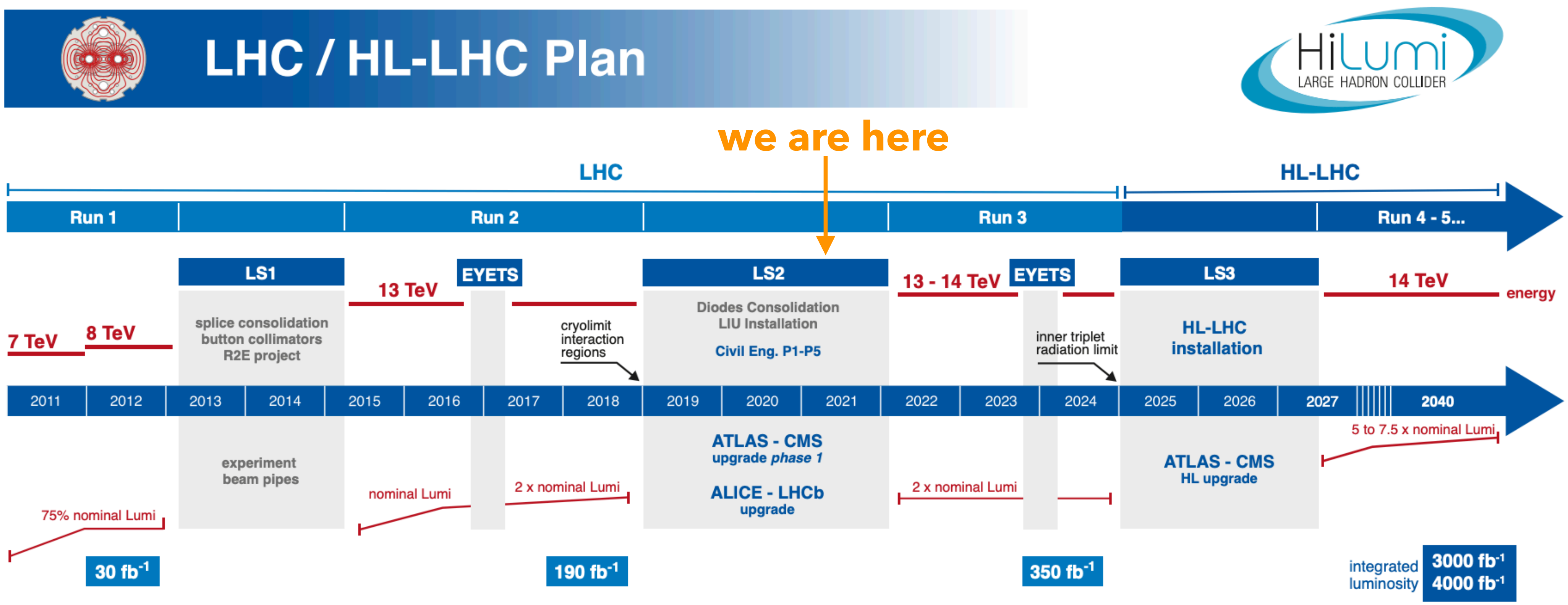
N^{obs}_{events} = **cross section** x **efficiency** x **$\int L\, dt$**

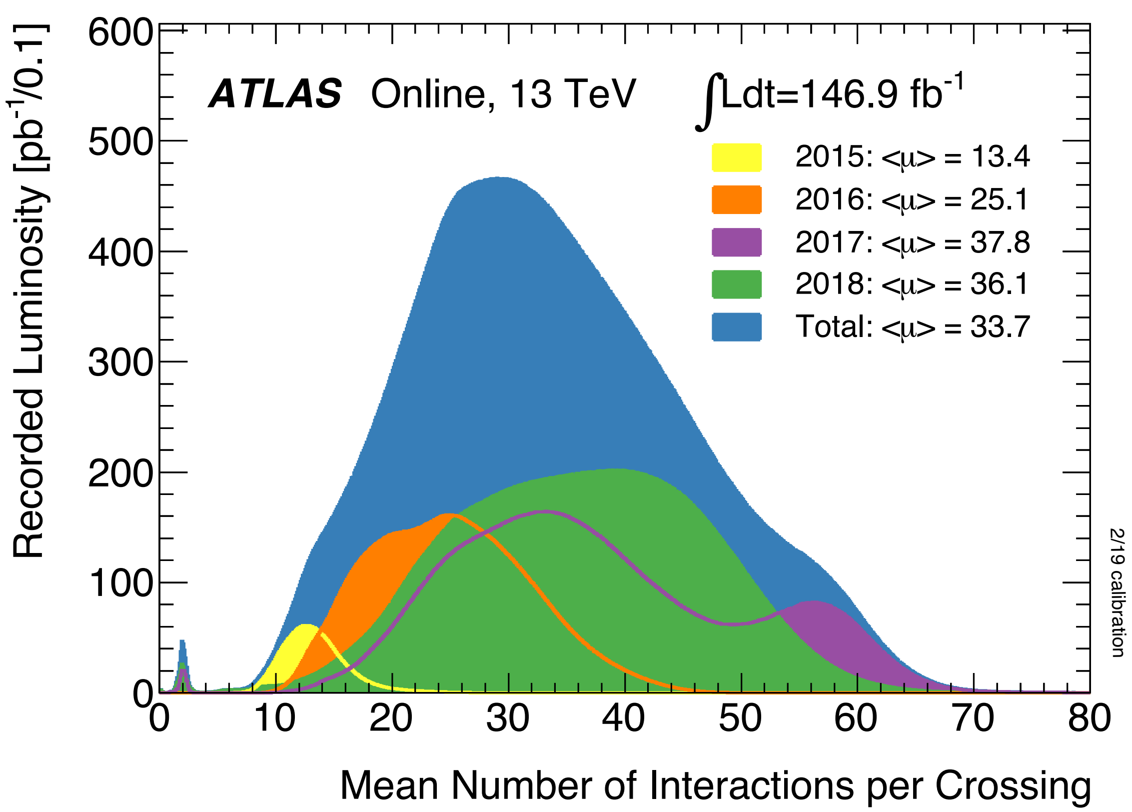
given by Nature

optimised by experimentalists

integrated luminosity delivered by LHC

The LHC plan





- But high luminosity comes with a challenge: **Pile up (additional interactions occurring in the same bunch crossing as the collision of interest)**
  - Controlling trigger rates at high interaction per bunch crossing
  - Online and offline reconstruction performance maintained even at the highest pile-up

The Higgs boson

- The primary goal of the LHC is to discover the **mechanism of electroweak symmetry breaking**
- The Higgs mechanism predicts the observation of a spin-0 particle: the Higgs boson
  - While the Yukawa couplings are defined with respect to the Higgs field, they equally determine the strength of the coupling to the Higgs boson

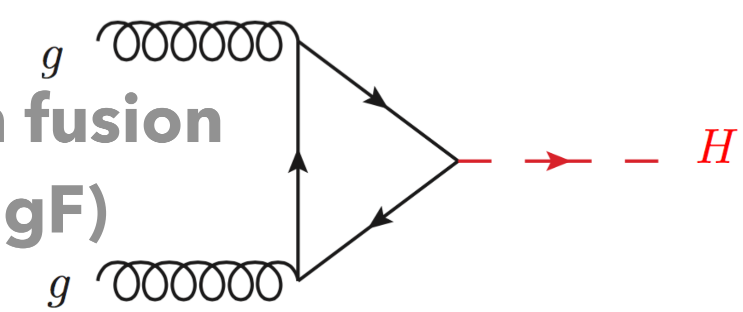
$$V(\phi) = \mu^2_{<0}|\phi|^2 + \lambda|\phi|^4 + Y^{ij}\psi^i_L\psi^j_R\phi$$

- The SM predicts all its properties, **except for its mass**
- Higgs boson discovered in 2012, already a standard candle of Standard Model!

The Higgs boson: production

- At the LHC, the Higgs boson is dominantly produced via gluon fusion

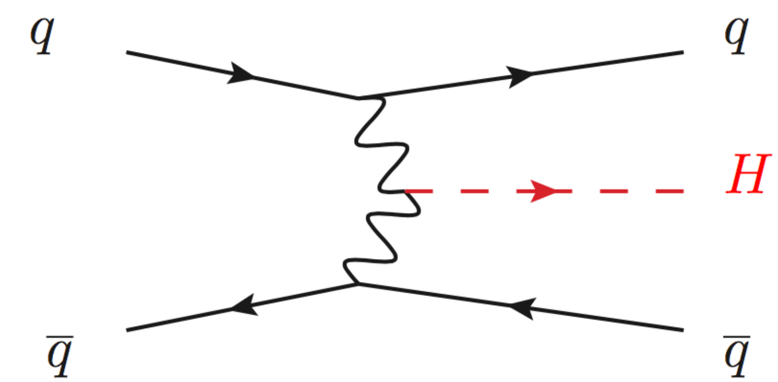
gluon fusion (ggF)



$\sigma_{H,ggF}$ ~ 49 pb at 13 TeV

6.9M events in Run-2

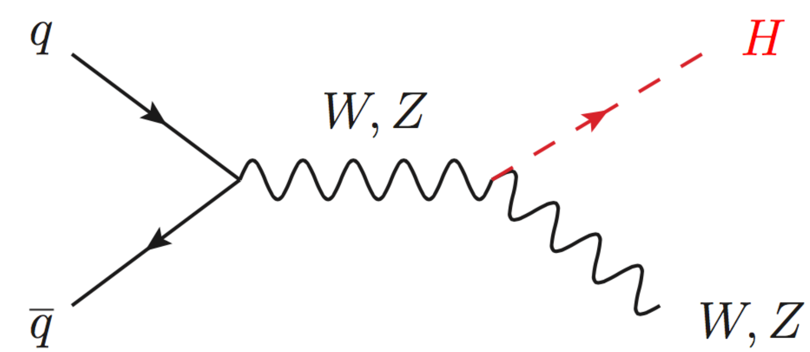
vector boson fusion (VBF)



σ_{VBF} ~ 3.8 pb

0.5M events in Run-2

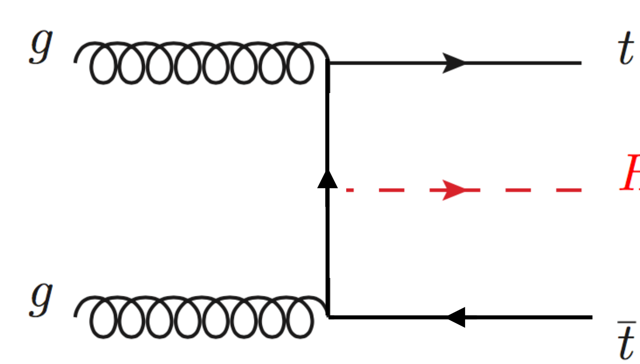
W, Z associated production (VH)



$\sigma_{W/ZH}$ ~ 1.4-0.9 pb

200-130k events in Run-2

top associated production (tt̄H)



σ_{ttH} ~ 0.5 pb

70k events in Run-2

The Higgs boson: decay

- The Higgs decays with preference to the heaviest particles allowed

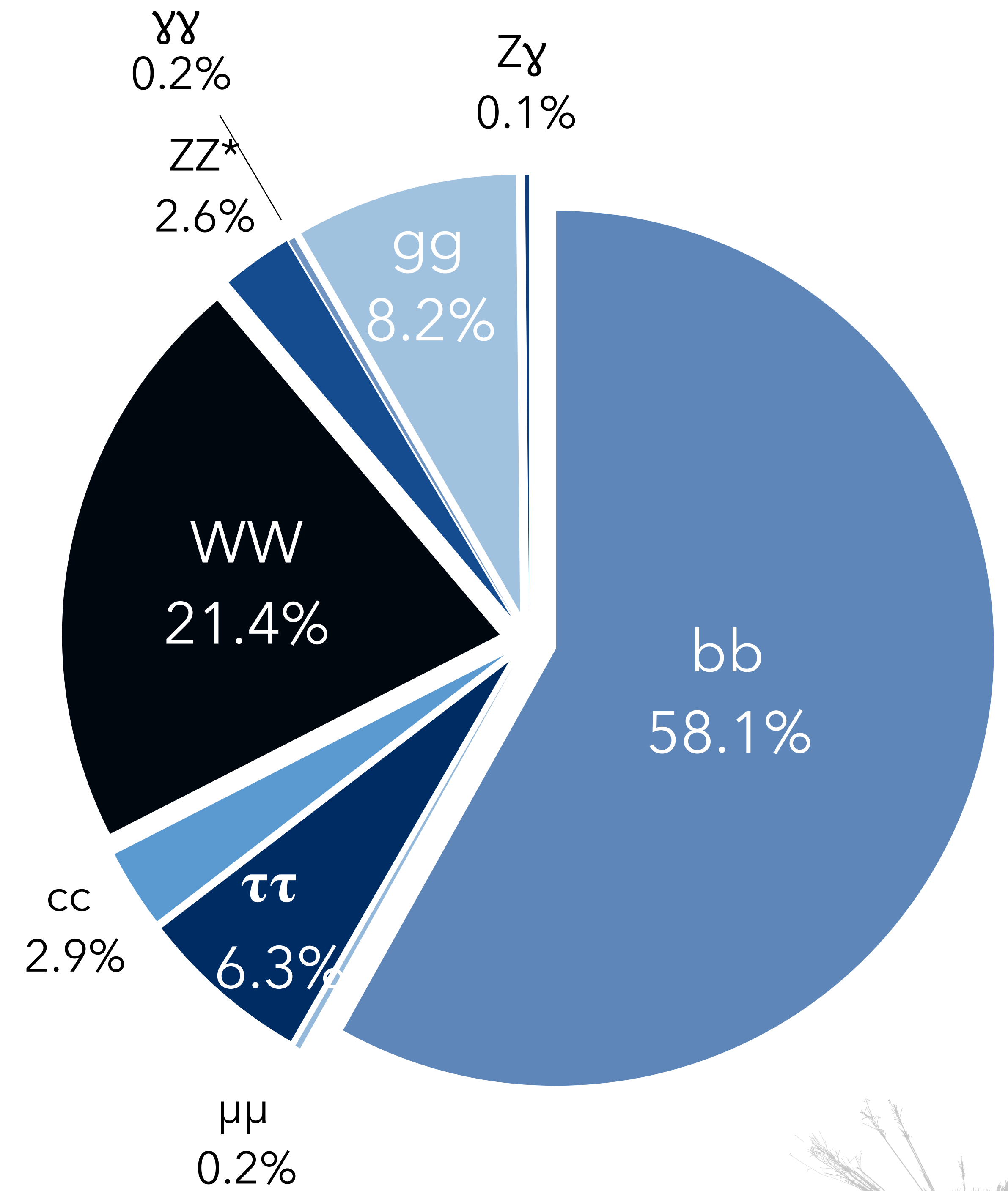
W and Z boson mass originates from the spontaneously symmetry breaking

Fermion masses originates from the Yukawa coupling to the Higgs boson

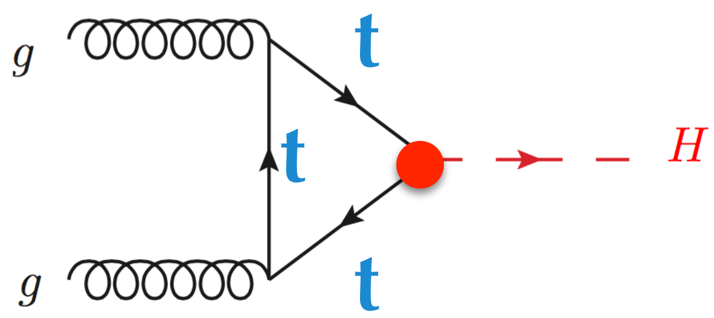
$$g_f = \sqrt{2}\frac{m_f}{v}$$

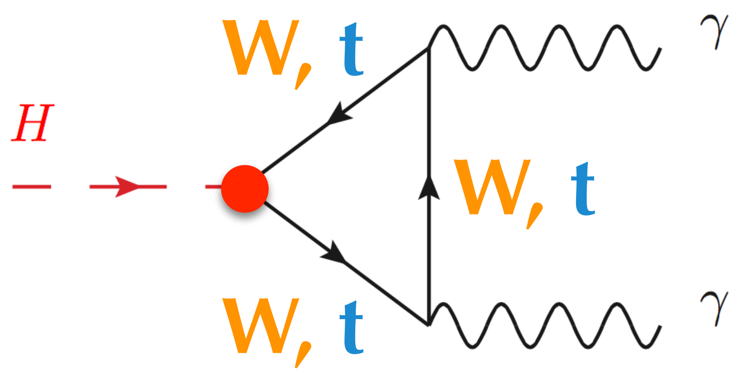
- The Higgs does not couple directly to photons and gluons, but only via "loops" of heavy particles (e.g.: top, W-boson)

- Though $b\bar{b}$ decays are the most dominant, they are very **difficult to reconstruct and have broad mass resolution**
  - contrary to γγ and ZZ(➜4ℓ)



Top & Higgs

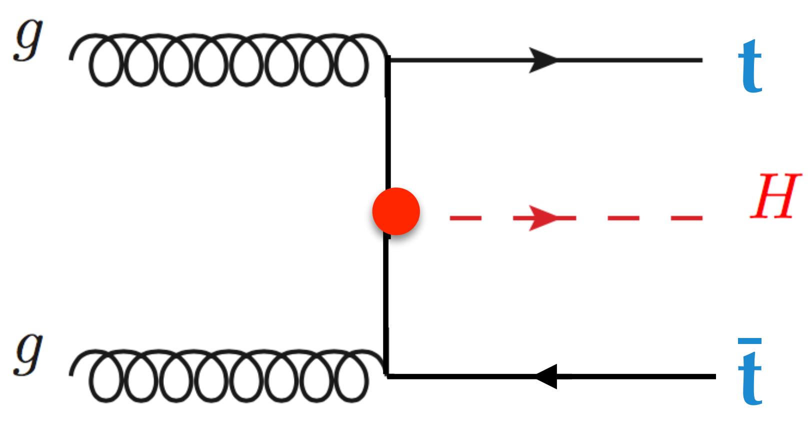


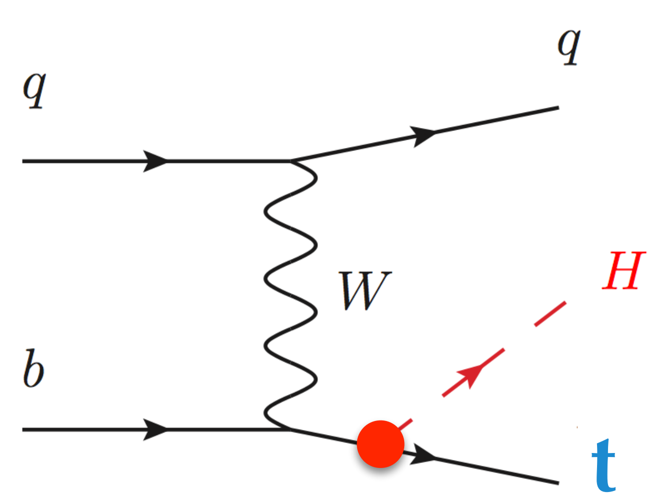


indirect top Yukawa coupling (y_{top}) constraints from gluon fusion production and γγ decay…

… assuming no additional heavy particles which could couple to the Higgs boson!

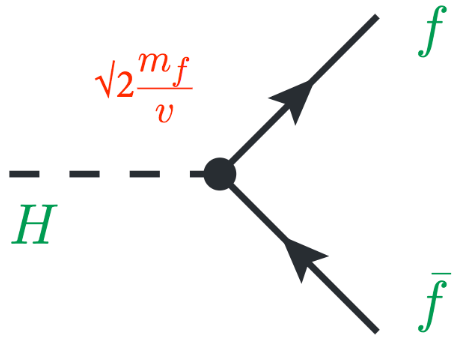
direct top Yukawa coupling measurement only possible at the LHC via $t\bar{t}H$ and tH





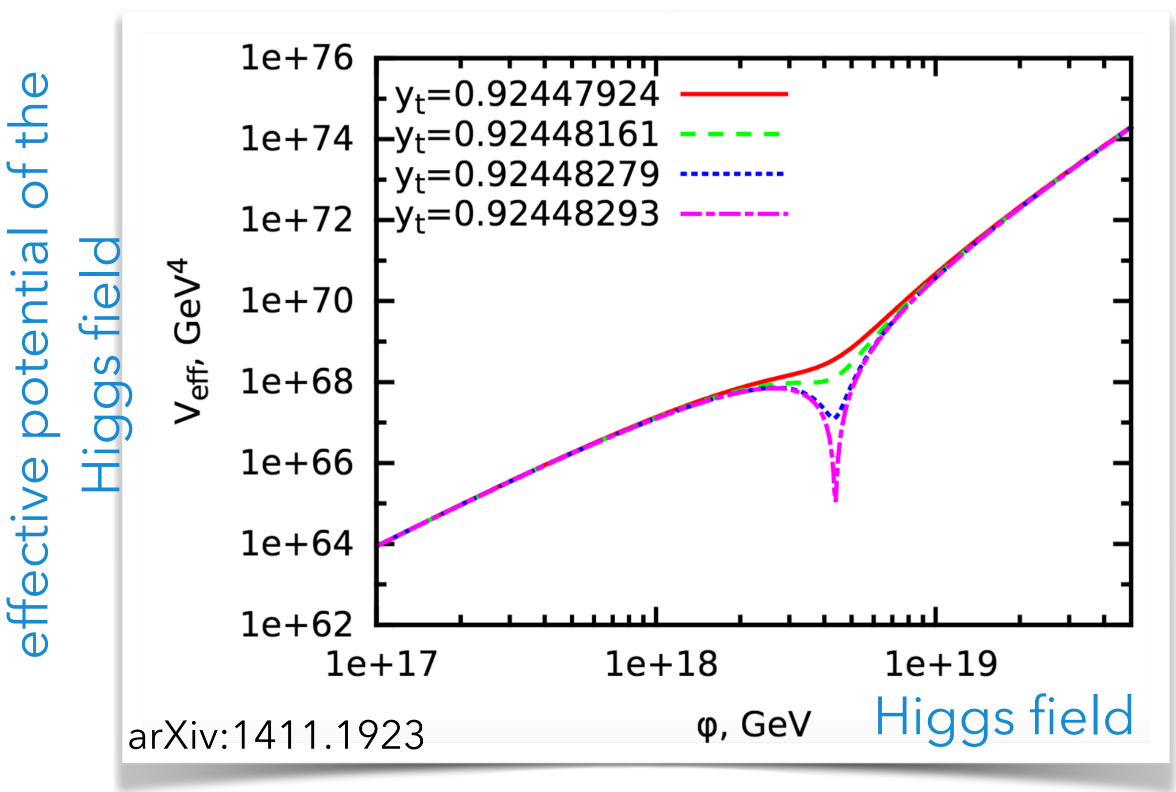
y_{top} … why should we care?

Top quark is the heaviest fermion in the SM ➜ Largest Yukawa coupling

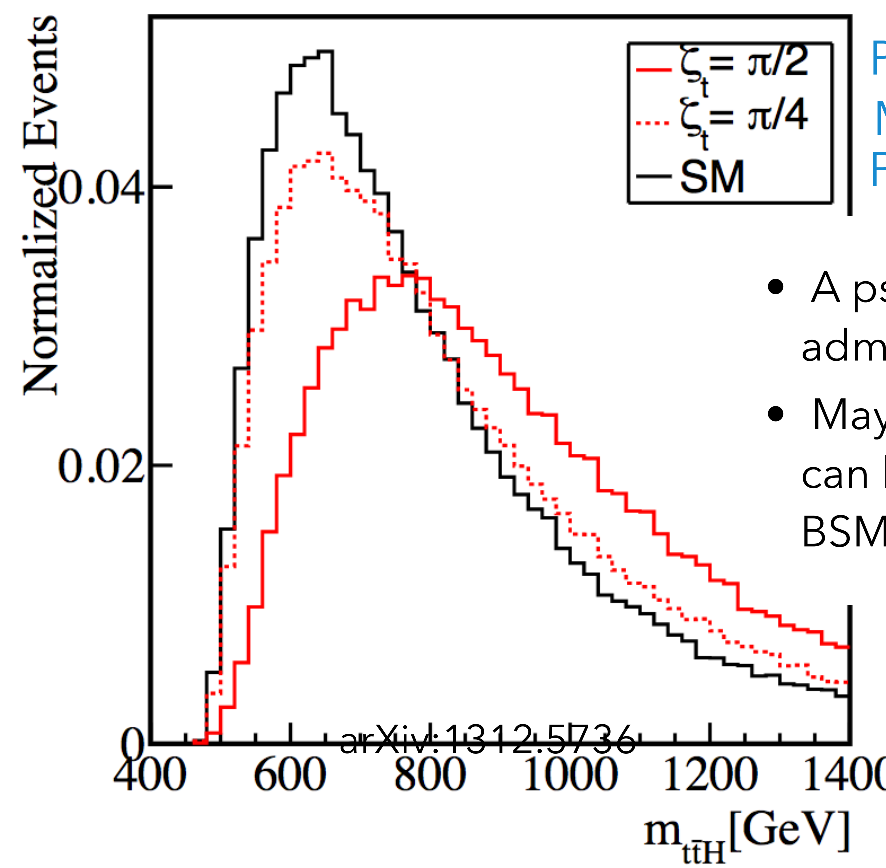


- The only fermion with predicted Yukawa coupling ~ 1
- Does this point to a special role in electroweak symmetry breaking or beyond the SM physics?
- Top quark Yukawa coupling is relevant for the stability of the Higgs potential and the required energy scale for new physics

Is the Universe stable or only metastable?



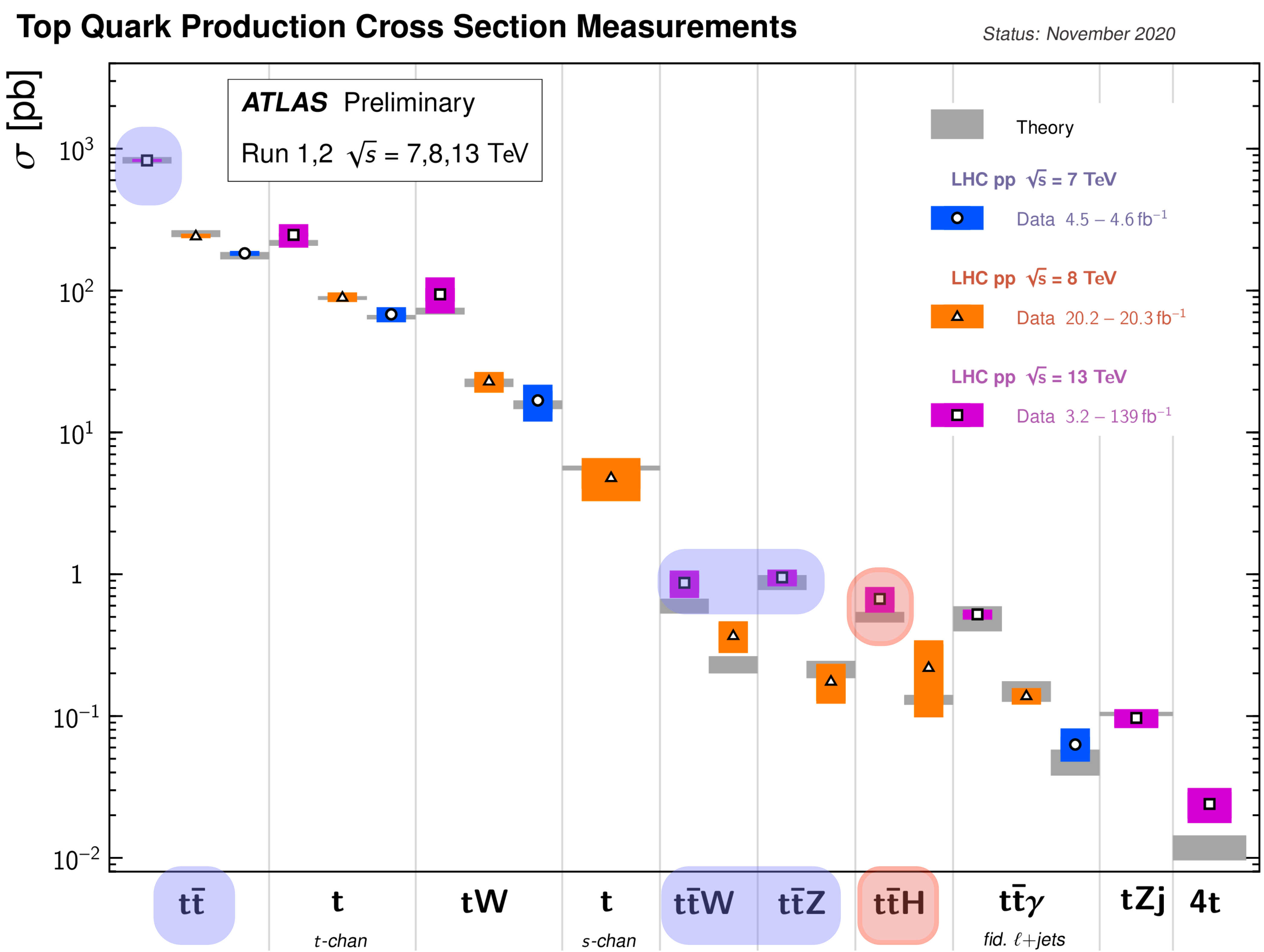
What is the CP nature of the Higgs boson?



Pure pseudo scalar
Maximally CP violating
Pure scalar

- A pseudoscalar admixture is still allowed
- Maybe $t\bar{t}H$ production can help disentangle the BSM component

$t\bar{t}H$: one of the tiniest rates!



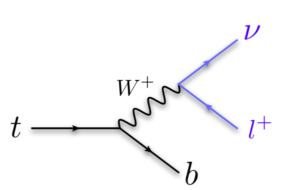
ATL-PHYS-PUB-2020-029

Where to look for tt̄H production?

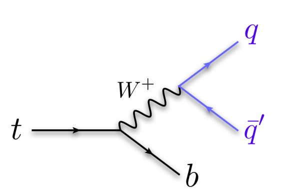
- tt̄H production (~500 fb @ 13TeV) is:
  - **two orders** of magnitude smaller than ggF Higgs production
  - **three orders** of magnitude smaller than tt̄ production

- Look for tt̄H in final states with distinctive signatures and features
  - Combination of top quark x Higgs boson decay modes

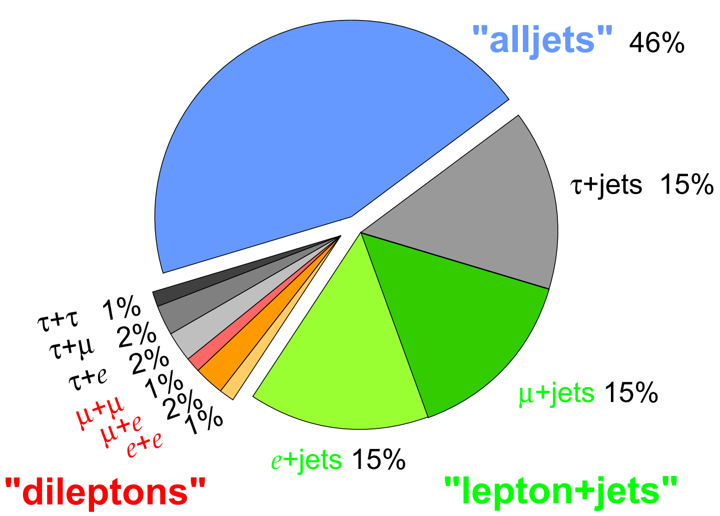
leptonic decay



hadronic decay

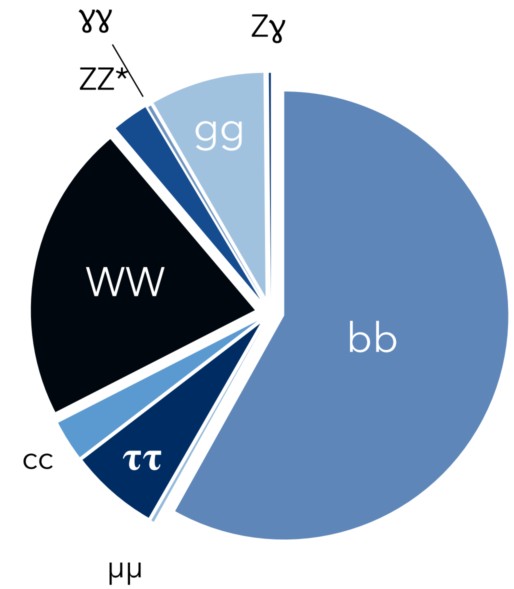


Top Pair Branching Fractions



x

Higgs Branching Fractions



= …

tt̄H analysis channels

ttH (H➔bb)

ttH (H➔WW, ττ, ZZ) ‘multilepton’

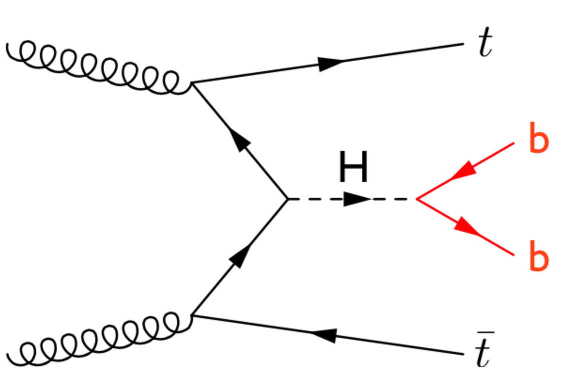
ttH (H➔γγ, ZZ(➔4ℓ))

Low signal/background (need MVA) → **Clear peak** (clean bump hunt)

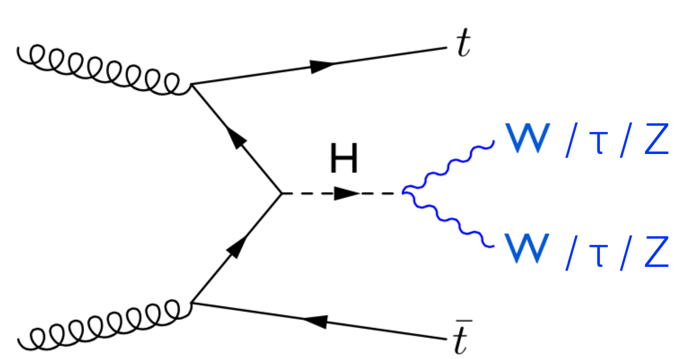
Large branching ratio (yields) ← **Small branching ratio**

Complex background modelling → **Simpler background**

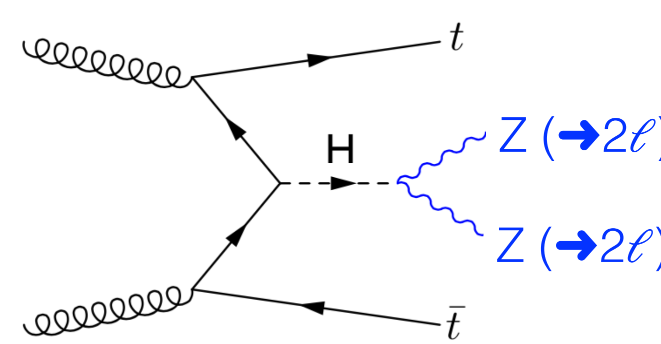
- large irreducible tt̄+jets (HF) background
- final states with **multiple b-jets**

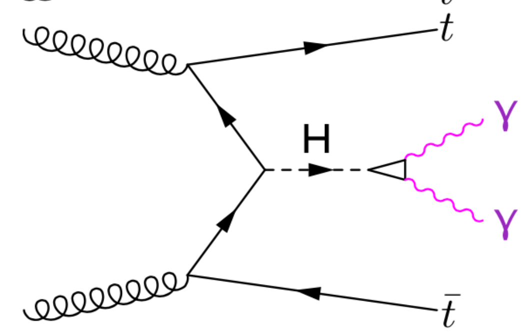


- leptonic decays of W / Z bosons and tau decays can give distinct **multilepton** signatures
- main background from tt̄Z/W and non-prompt leptons



- **resonant** channels





motivation ← **challenge**

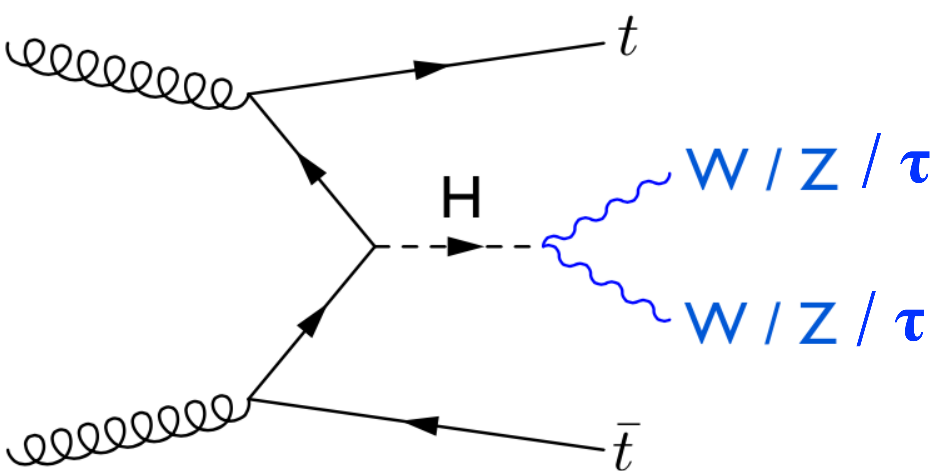
$t\bar{t}H$ state of the art Run 2

- 2015-2016 [~36 fb^{-1}]
- 2015-2017 [~80 fb^{-1}]
- 2015-2018 [~140 fb^{-1}]

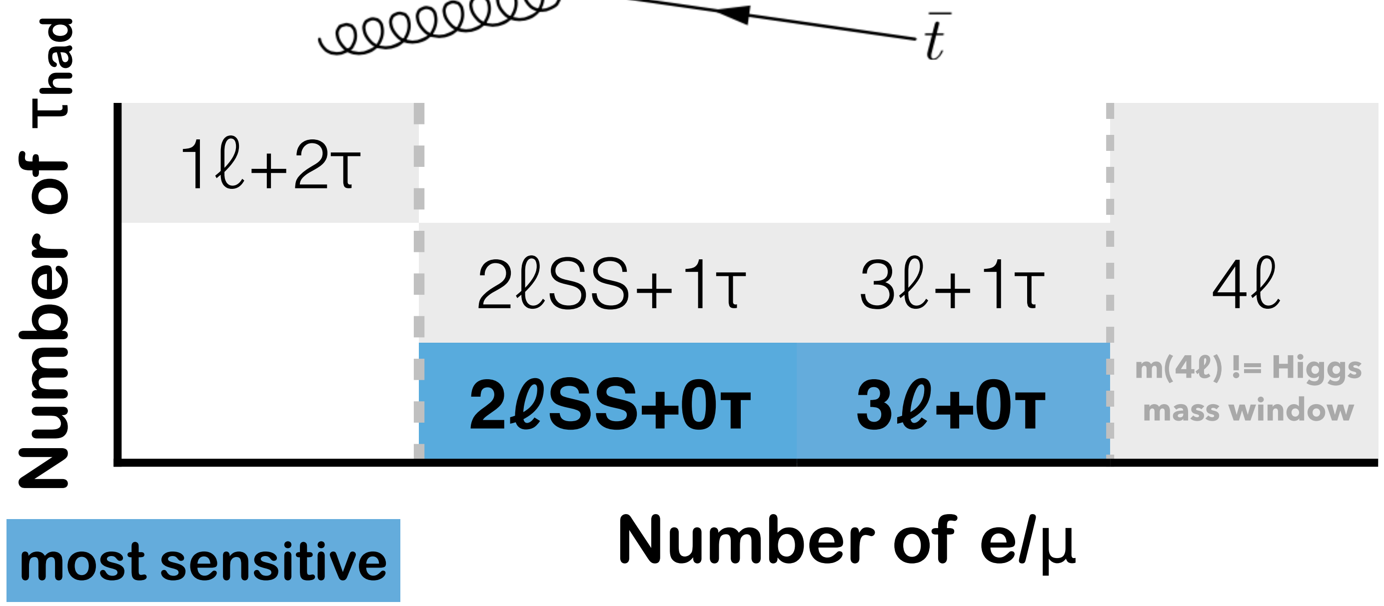
	ATLAS EXPERIMENT	CMS
ttH multilepton (H→WW/ττ/ZZ)	ATLAS-CONF-2019-045 $\mu_{ttH} = 0.58\,^{+0.26}_{-0.25}$	NEW arXiv:2011.03652 $\mu_{ttH} = 0.92 \pm 0.19\,(\text{stat})\,^{+0.17}_{-0.13}\,(\text{syst})$
ttH(bb)	NEW ATLAS-CONF-2020-058 $\mu_{ttH} = 0.43\,^{+0.36}_{-0.33}$	CMS-PAS-HIG-18-030 $\mu_{ttH} = 1.15\,^{+0.15}_{-0.15}\,(\text{stat})\,^{+0.28}_{-0.25}\,(\text{syst})$
ttH(ZZ→4ℓ)	Eur. Phys. J. C 80 (2020) 957 (+STXS) $\mu_{ttH} = 1.7\,^{+1.7}_{-1.2} \pm 0.2 \pm 0.2$	NEW arXiv:2103.04956 (+STXS) $\mu_{ttH} = 0.13\,^{+0.92}_{-0.13}\,(\text{stat})\,^{+0.11}_{-0.00}\,(\text{syst})$
ttH(γγ) Observation!	ATLAS-CONF-2020-026 (+ STXS) $\mu_{ttH+tH} = 0.92\,^{+0.27}_{-0.24}$ **4.7 (5.0) σ** obs (exp) PRL 125 (2020) 061802 (+CP) $\mu_{ttH} = 1.43\,^{+0.33}_{-0.31}\,(\text{stat})\,^{+0.21}_{-0.15}\,(\text{syst})$ **5.2 (4.4) σ** obs (exp)	NEW arXiv:2103.06956 (+STXS) $\mu_{ttH} = 1.35\,^{+0.34}_{-0.28}$ PRL 125 (2020) 061801 (+CP) $\mu_{ttH} = 1.38\,^{+0.36}_{-0.29}$ **6.6 (4.7) σ** obs (exp)
Combination	Phys. Lett. B 784 (2018) 173 (80/fb + 36.1/fb ➜ **Observation**)	Phys. Rev. Lett. 120 (2018) 231801 ➜ **Observation**

tt̄H(multiℓ): analysis strategy

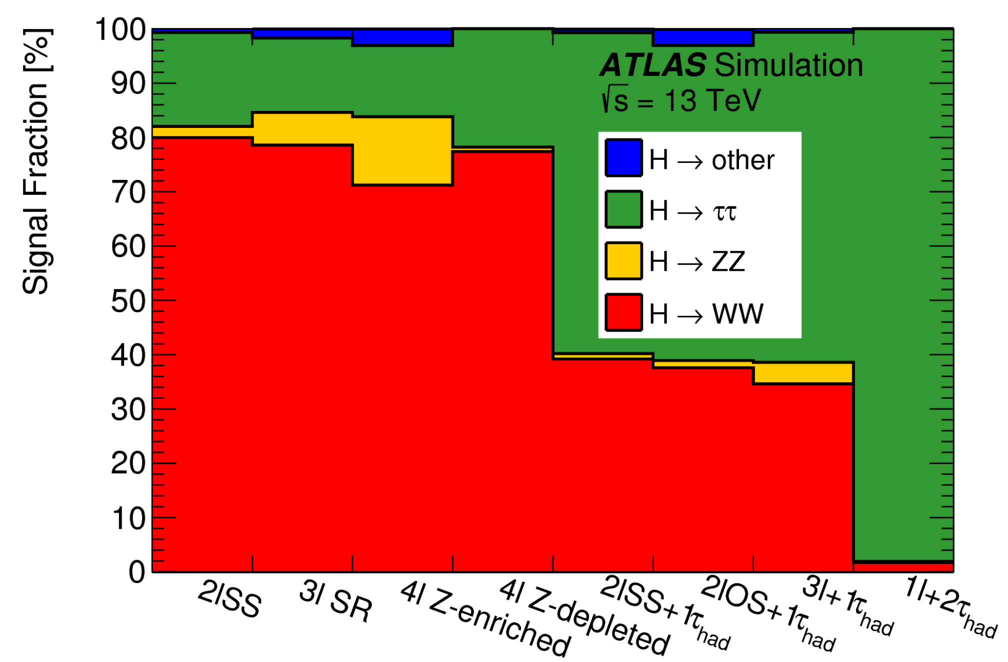
- **Target**: tt̄H with
  - H→WW/ZZ/ττ→≥1ℓ ➜ "multilepton" final state
  - tt̄→(ℓ+jets, dilepton)



- **High multiplicity** final state
- **Rare in SM:** same-sign 2ℓ, 3ℓ, 4ℓ



- Split in categories based on **number of e/μ** and **number of τ**



Results from ATLAS-CONF-2019-045

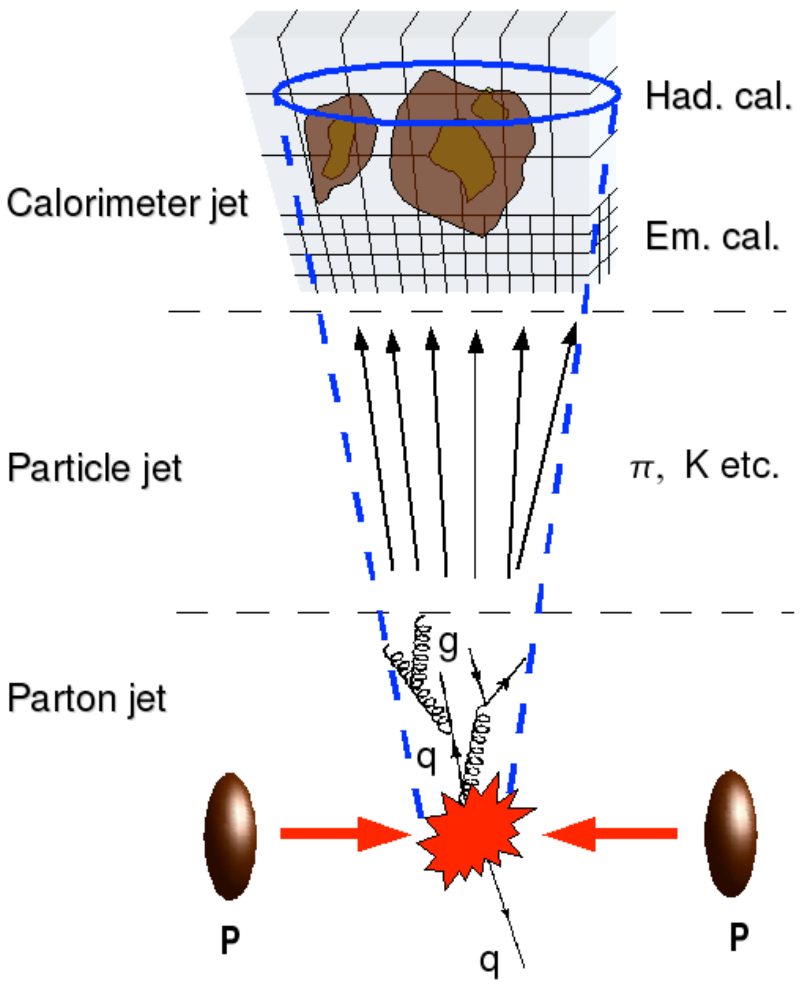
Experimental signatures

What to look for in the events?

- (≥ 2, 4, 6) **jets**!

jets are a consequence of the strong force

originate from b/c-quarks (heavy-flavour jets) or light quarks (light jets)



≥ 2 jets required in all channels

Experimental signatures

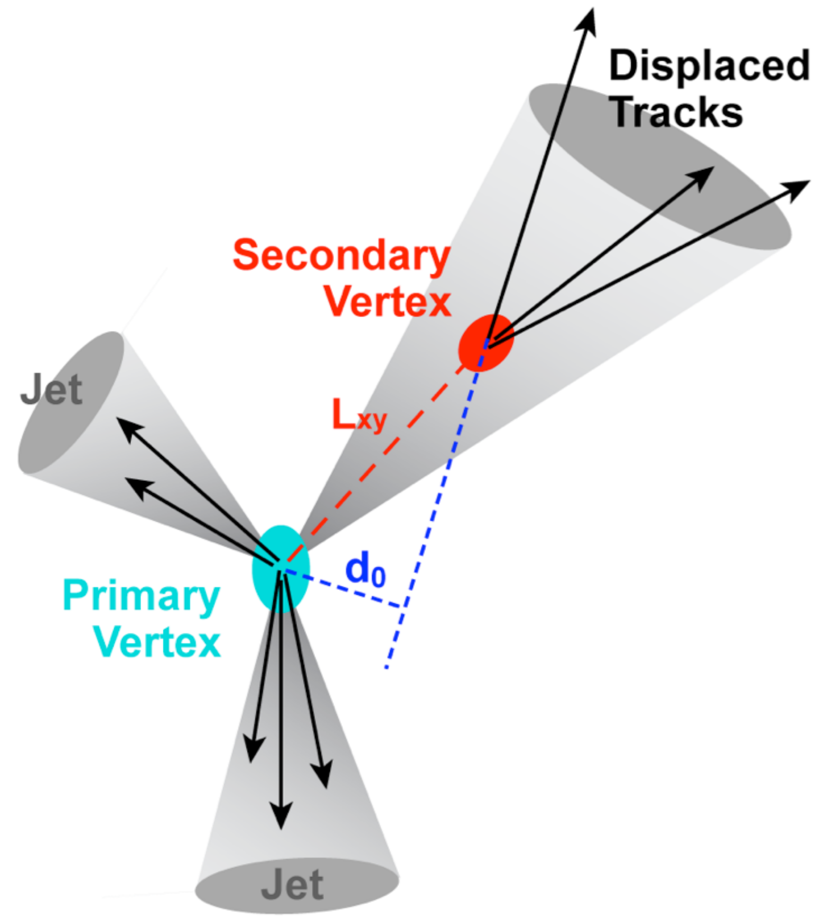
What to look for in the events?

- (≥ 2, 4, 6) **jets**!
- ≥ 2 jets originating from b-quarks (**bjets**)

≥ 1 b-jet required in all channels

b-quarks live long enough (~ps) to create a secondary vertex at the decay

finding these jets from b-quarks is known as *b-tagging*



Experimental signatures

What to look for in the events?

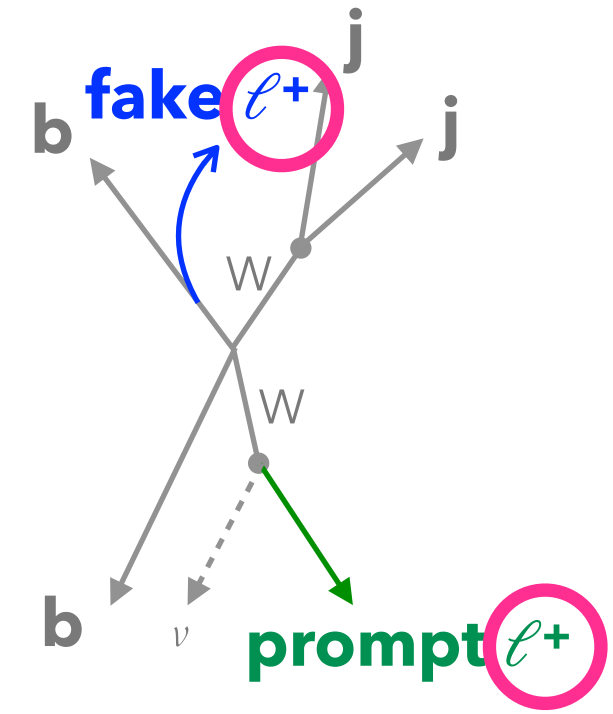
- (≥ 2, 4, 6) **jets**!
- ≥ 2 jets originating from b-quarks (**bjets**)
- **charged light leptons (electrons or muons)**

require events triggered by 2 light leptons

very important to have **well isolated** leptons

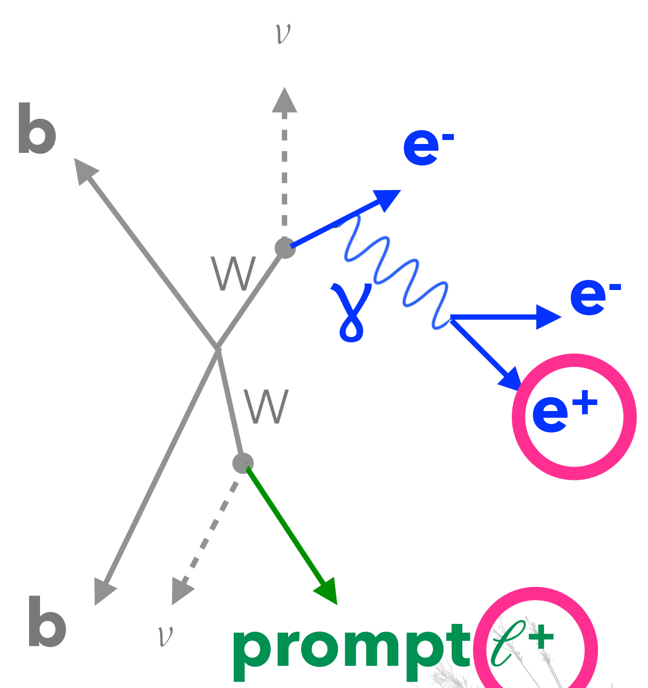
- **multivariate lepton isolation** to reject non-prompt leptons based on:
  - lepton and overlapping track jets properties
  - lepton track/calorimeter isolation variables

  ➜ Factor $\mathcal{O}(20)$ **rejection for leptons originating from b-hadrons**



- **multivariate lepton identification** to **reject misidentified charge electrons**

  ➜ Factor $\mathcal{O}(17)$ background rejection for a 95% signal efficiency

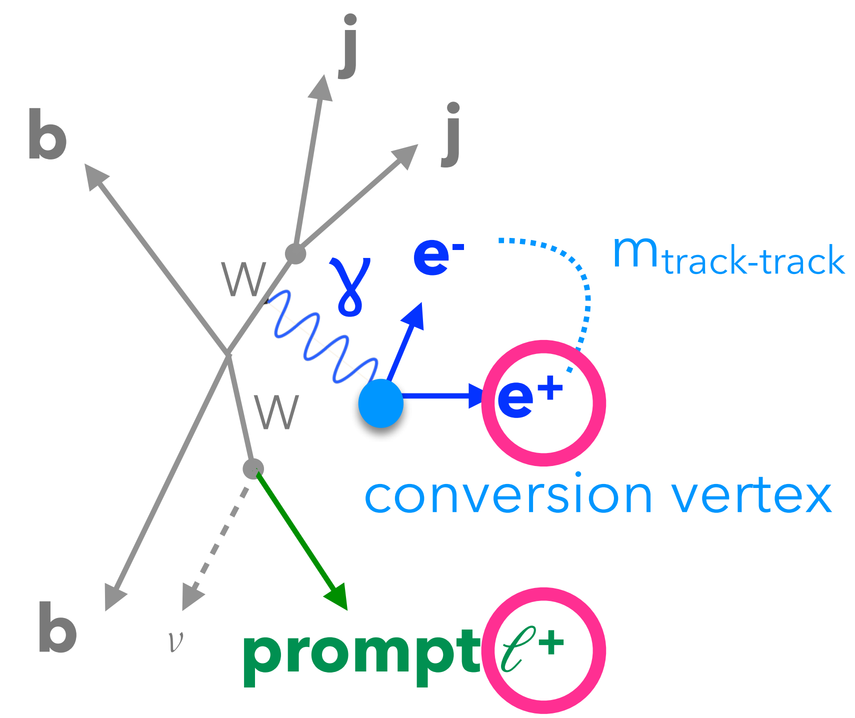


Experimental signatures

- material and internal electron **conversion** (CO) candidates further suppressed with track invariant masses and conversion radius

What to look for in the events?

- (≥ 2, 4, 6) **jets**!
- ≥ 2 jets originating from b-quarks (**bjets**)
- charged light leptons (**electrons** or muons)



	electron CO selection	CO radius	$m_{track-track}$
γ	**(1) material CO**	> 20 mm	< 100 MeV (wrt. CV)
γ*	**(2) internal CO**	**not (1)**	< 100 MeV (wrt. PV)
	(3) very tight	**not (1) and not (2)**	

(beam pipe @ 24 mm)

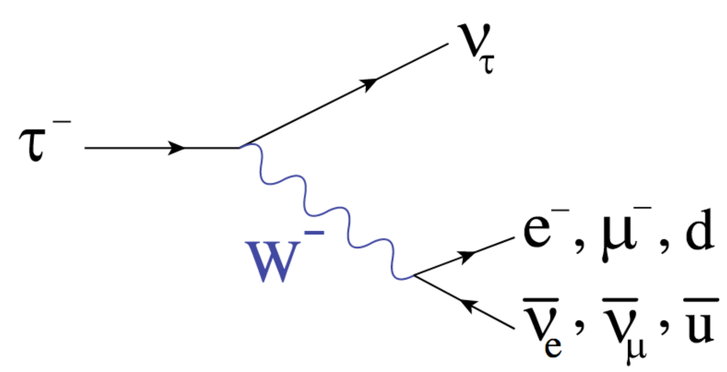
require events triggered by 2 light leptons

Experimental signatures

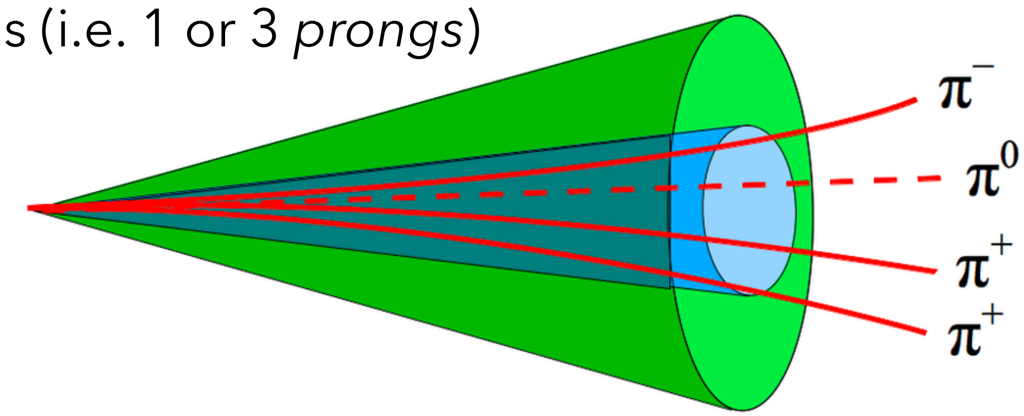
What to look for in the events?

- (≥ 2, 4, 6) **jets**!
- ≥ 2 jets originating from b-quarks (**bjets**)
- **charged light leptons (electrons or muons)**
- **hadronically decaying taus**

taus can decay into light leptons (e, μ) with BR ~ 35% or quarks with BR ~ 65%



to increase statistics, select hadronically decaying taus: can contain 1 or 3 charged pions (i.e. 1 or 3 *prongs*)



multivariate analysis discriminants to reject jets and electrons faking a tau

overlap removal wrt. muons and b-jets

$t\bar{t}H$(multiℓ): analysis strategy

Object definition

What to look for in the events?

- (≥ 2, 4, 6) **jets**!
- ≥ 2 jets originating from b-quarks (**bjets**)
- **charged light leptons (electrons or muons)**
- **hadronically decaying taus**
- **neutrinos** (missing transverse energy)

Event selection: MVA strategy

Signal extraction and background constrain: fit and/or categorise on **BDTs (boosted decision tree)** that discriminate signal against the main background processes [except in 2ℓSS+1τ and 3ℓ+1τ]

- **2ℓSS0τ**: a combination of 2 BDTs ($t\bar{t}H$ vs. $t\bar{t}V$, $t\bar{t}H$ vs. fakes/$t\bar{t}$) in a **2D space**
- **3ℓ0τ**: a **multi-dimensional BDT** ($t\bar{t}H$ vs. $t\bar{t}W$ vs. fakes/$t\bar{t}$ vs. $t\bar{t}Z$ vs. VV)
- **4ℓ (Z-enriched)**: $t\bar{t}H$ vs. $t\bar{t}Z$
- **1ℓ+2τ**: $t\bar{t}H$ vs. $t\bar{t}$ (with fake τ)

Estimating backgrounds in multi-ℓ

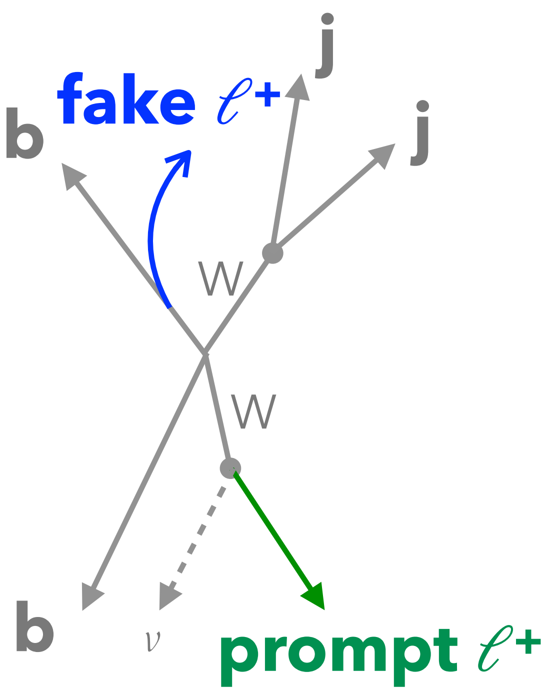
Reduce background:
- multi-variate lepton isolation
- conversions

Estimate fakes background
in regions close to the signal region

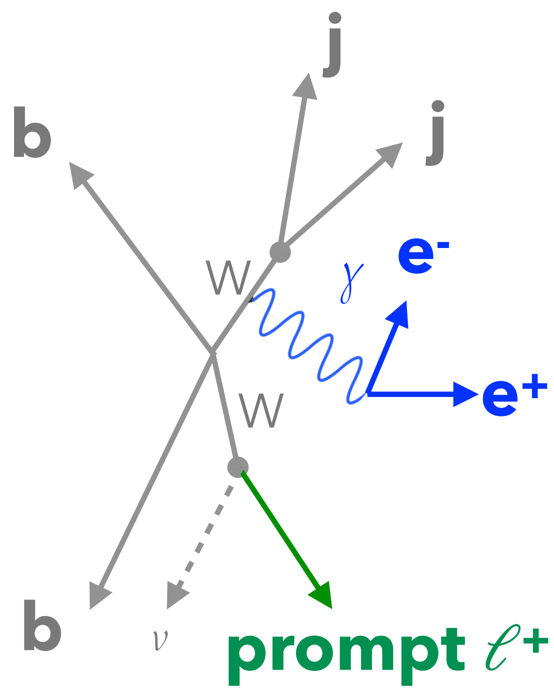
Fakes estimated in:
2-3 jets
≥ 1 b-jet
2ℓSS

"Fakes" composition very **diverse** and with **different kinematic** behaviour

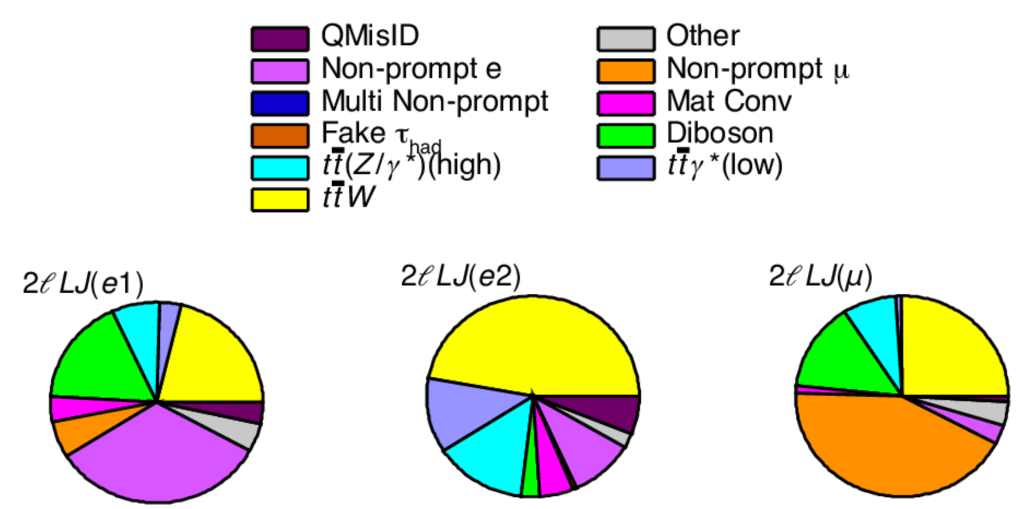
Large contribution from other irreducible backgrounds, such as **$t\bar{t}W$**, with a long history of excess above the SM expectation!



Semileptonic b-decay



Photon conversions



Estimating backgrounds in multi-ℓ

Reduce background:
- multi-variate lepton isolation
- conversions

Estimate fakes background
in regions close to the signal region

Fakes estimated in:
2-3 jets
≥ 1 b-jet
2ℓSS

"Fakes" composition very **diverse** and with **different kinematic** behaviour

Large contribution from other irreducible backgrounds, such as **$t\bar{t}W$**, with a long history of excess above the SM expectation!

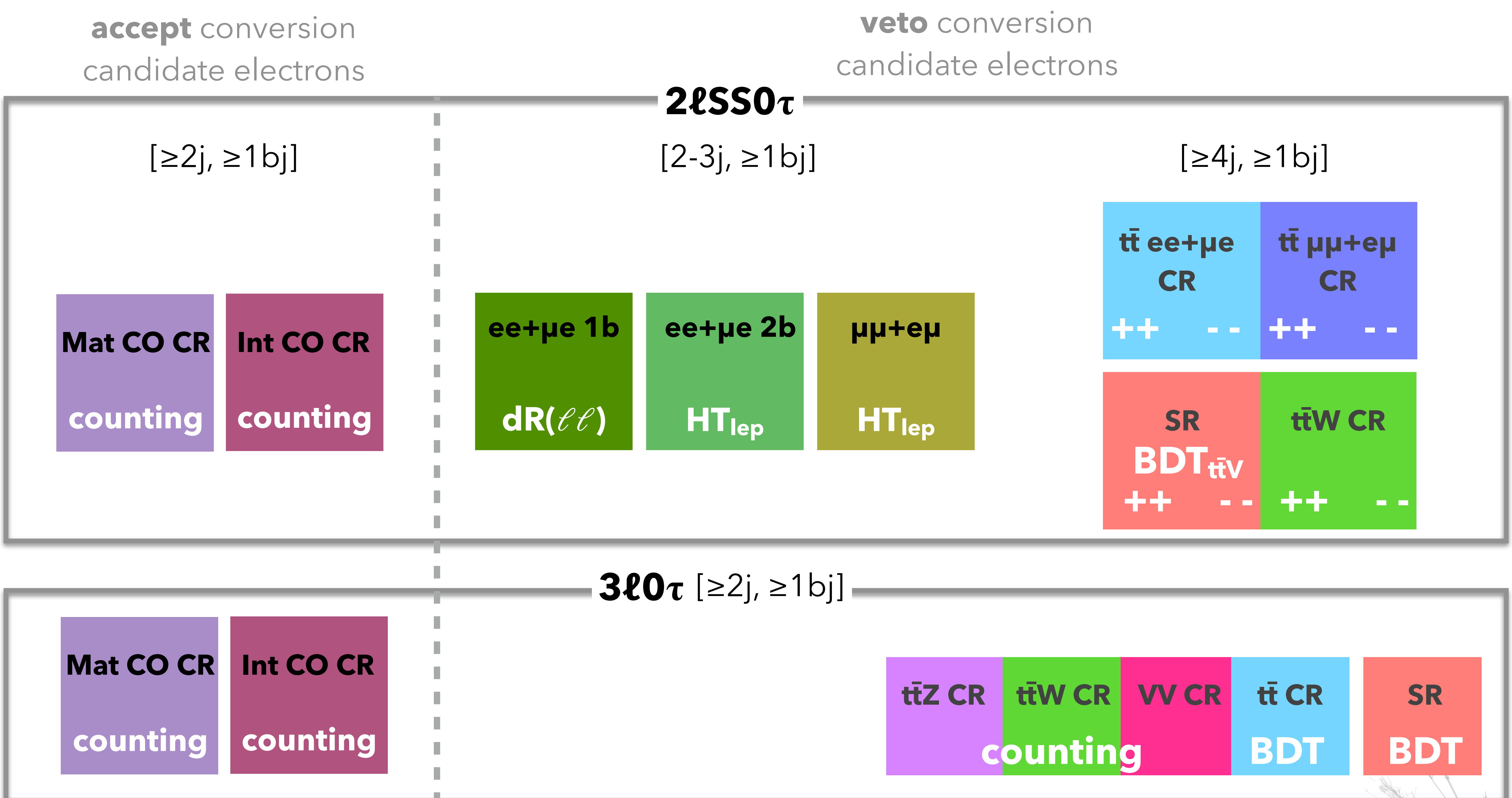
What to do?

Estimate fakes background
~~in regions close to the signal region~~
in QCD-enriched region, ensuring similar composition of fakes

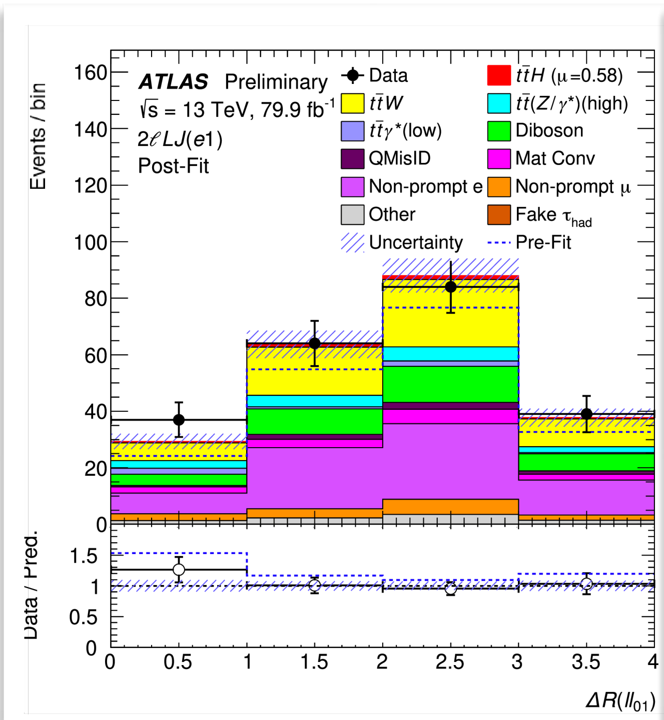
"Template fit": Estimate fakes and $t\bar{t}W$ normalisation in **simultaneous fit** to data together with $t\bar{t}H$ signal:
- rely on MC simulation for shapes
- create control regions (CRs) enriched in each background type

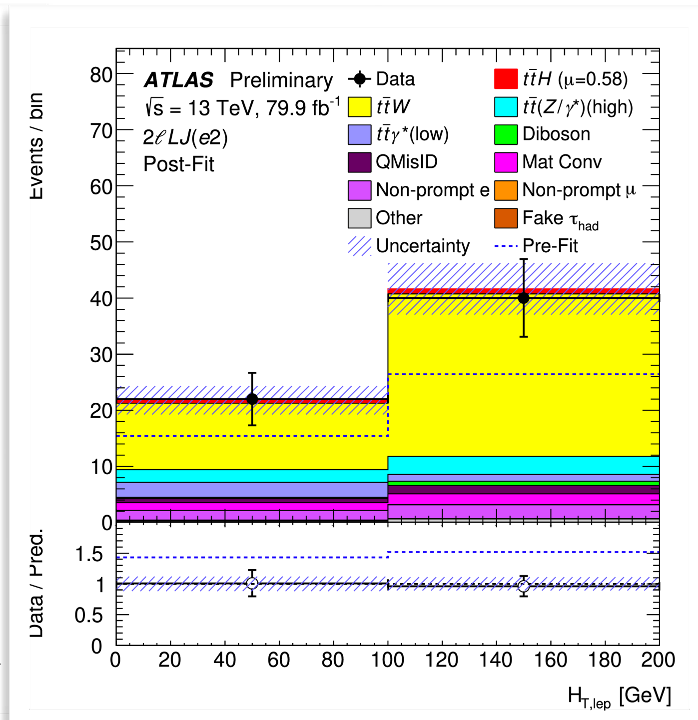
$t\bar{t}H$(multiℓ): Template Fit Categories

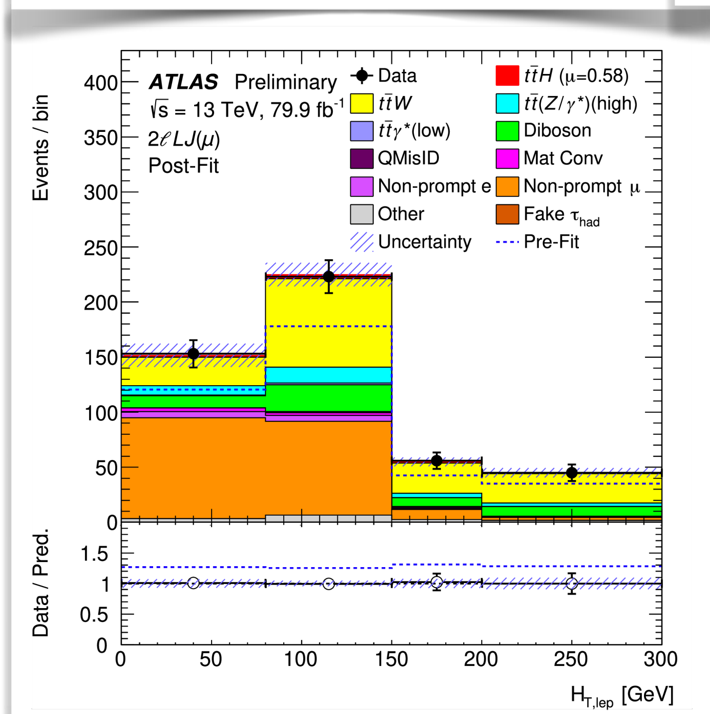
Categories based on *n*D **BDT space or** other kinematic variables, **b-jet multiplicity**, **lepton charge**, and/or **lepton flavour**

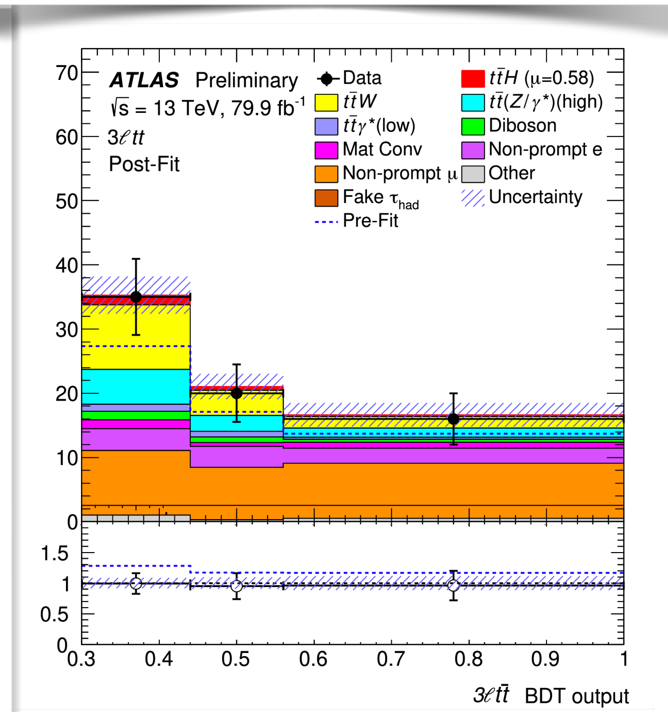


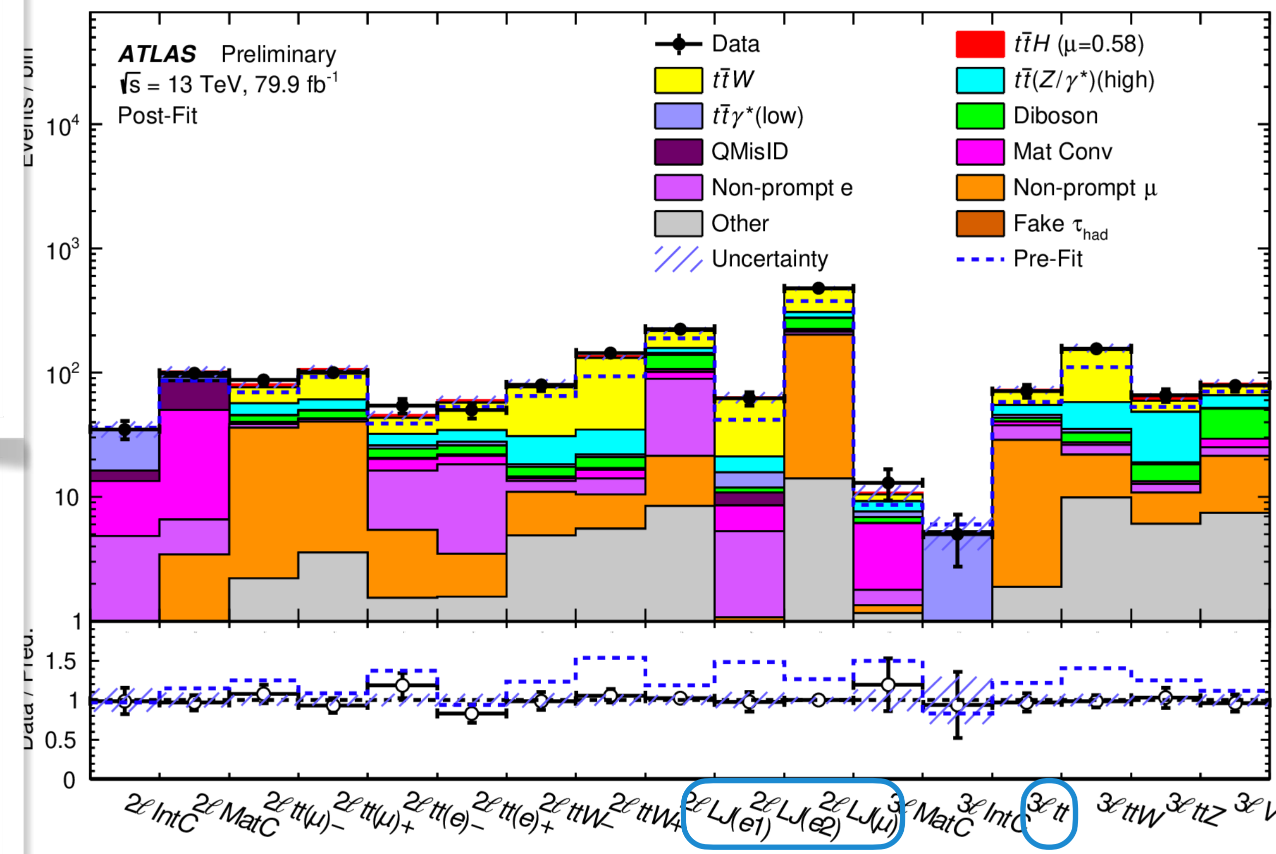
tt̄H(multiℓ): control regions





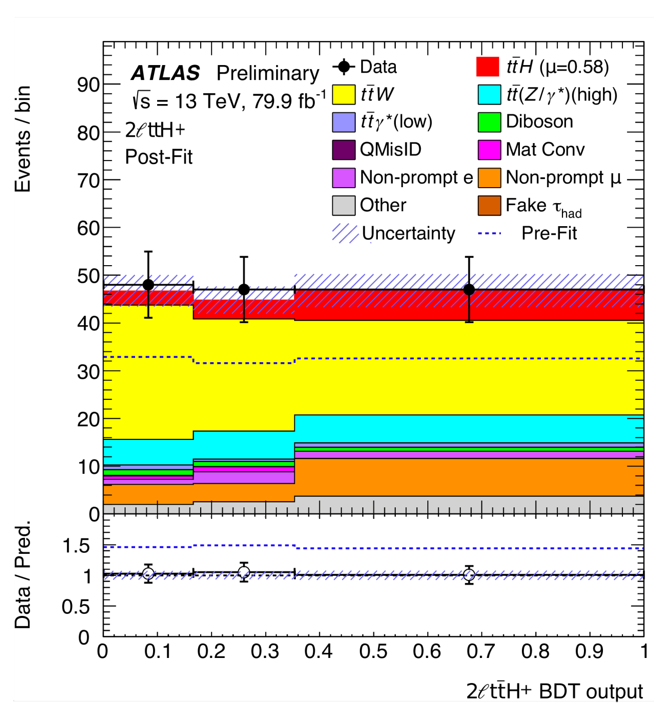


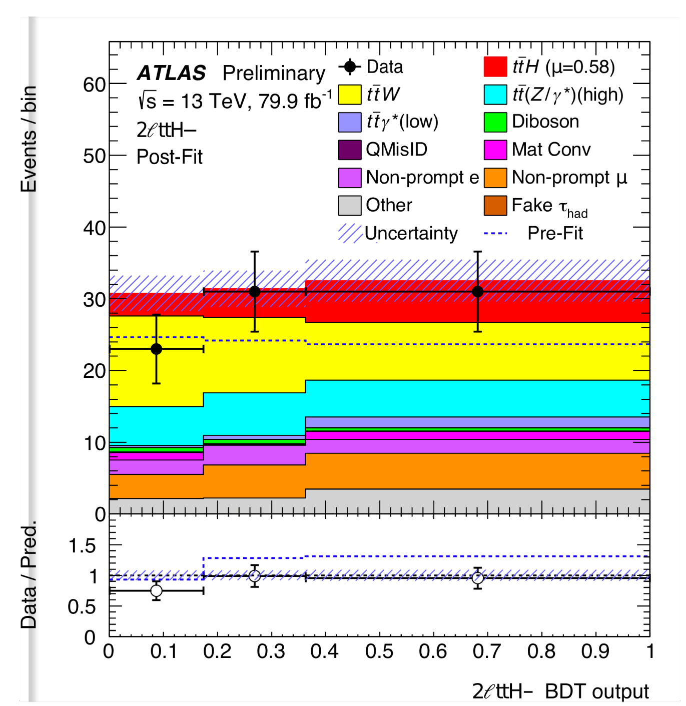


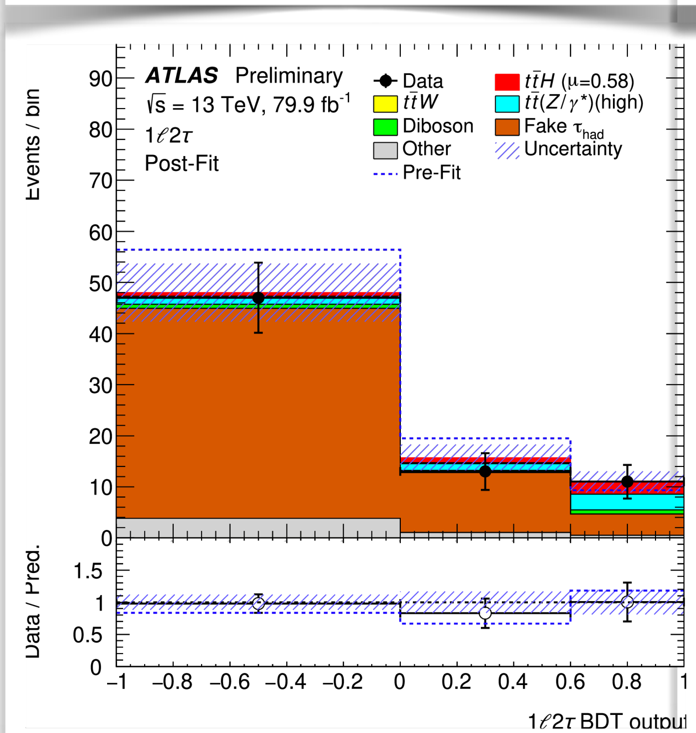


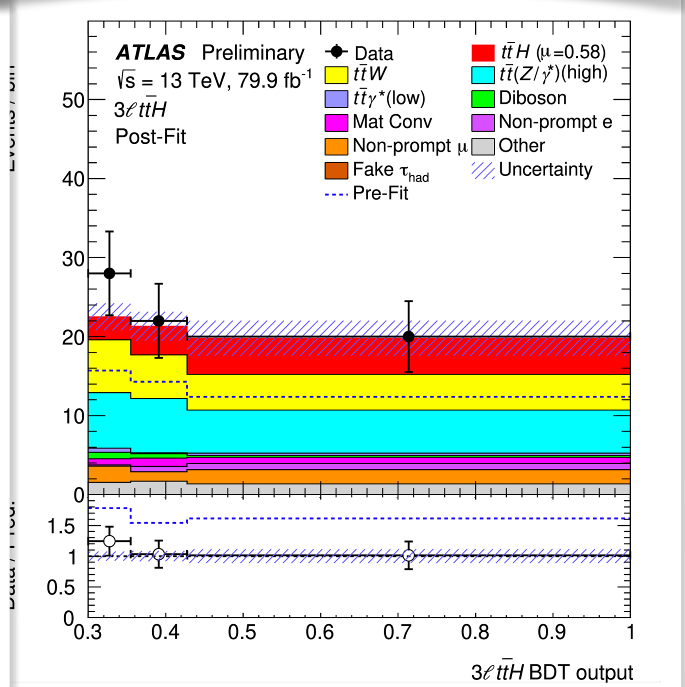
Kinematic variables / BDT discriminant fitted in these regions

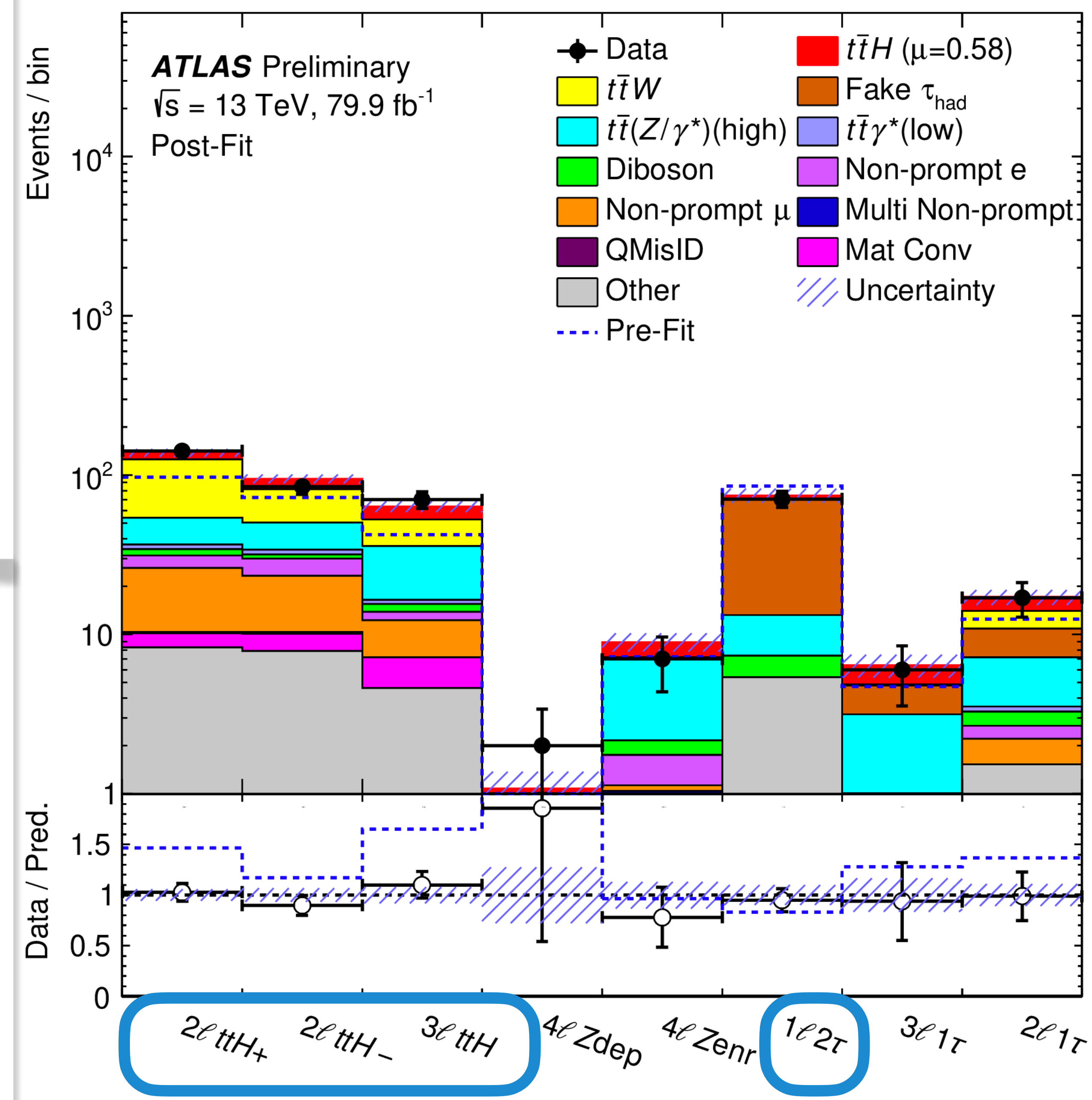
tt̄H(multiℓ): signal regions











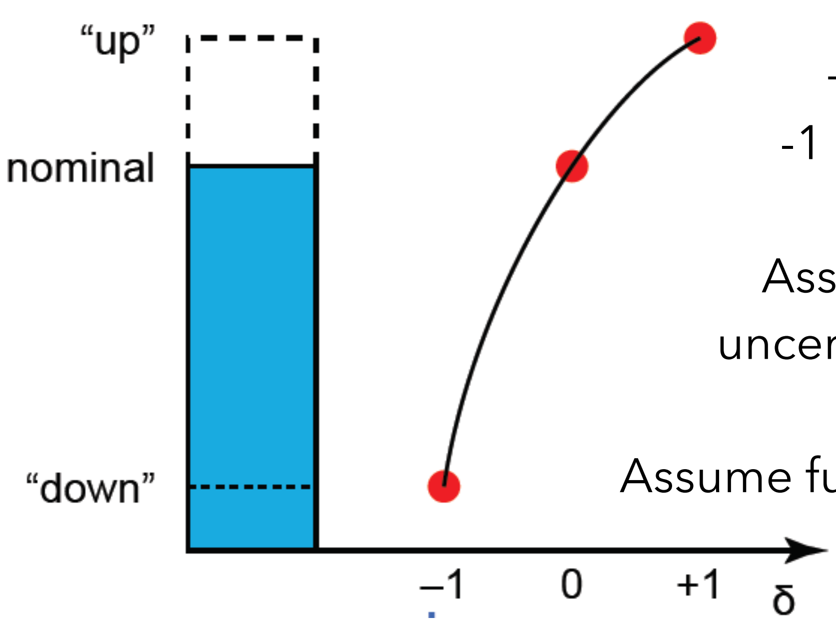
☞ BDT discriminant fitted in these regions

Profile likelihood fit

- Binned profile likelihood fit

$$L(\boldsymbol{n}, \boldsymbol{\theta}^0 | \mu_{\text{sig}}, \boldsymbol{b}, \boldsymbol{\theta}) = P_{\text{SR}} \times P_{\text{CR}} \times C_{\text{syst}}$$
$$= P(n_S | \lambda_S(\mu_{\text{sig}}, \mathbf{NF}, \mathbf{b}, \boldsymbol{\theta}) \times \prod_{i \in \text{CR}} P(n_i | \lambda_i(\mu_{\text{sig}}, \mathbf{NF}, \mathbf{b}, \boldsymbol{\theta}) \times C_{\text{syst}}(\boldsymbol{\theta}^0, \boldsymbol{\theta})$$

- **Parameter of interest**: signal strength $\mu_{t\bar{t}H} = \frac{\sigma_{t\bar{t}H}}{\sigma^{SM}_{t\bar{t}H}}$
- **Normalisation factors** of backgrounds: $\text{NF}_{t\bar{t}W}$, $\text{NF}_{\text{HF-e}}$, …
- **Systematic uncertainties** included in the fit as nuisance parameters θ
  - Need sufficiently flexible model of signal and background!



Given:
+1σ, nominal, and
-1 σ of each systematic

Assume interpolation of
uncertainty between [-1,1] σ

Assume full correlation between bins

Constrain uncertainty in control region, propagate this knowledge to signal region

- Find best values for μ, NF and θ from minimising the -log L

$t\bar{t}H$(multiℓ): systematic uncertainties (I)

Systematic uncertainty	Components
Luminosity (N)	1
Pileup modelling	1
Physics objects	
Electron	8
Muon	11
Tau	7
Jet energy scale and resolution	28
Jet vertex fraction	1
Jet flavour tagging	17
$E_{\mathrm{T}}^{\mathrm{miss}}$	3
Total (Experimental)	77
Data-driven background estimates	
Non-prompt light-lepton estimates (3ℓ, $3\ell 1\tau_{\mathrm{had}}$)	1
Fake τ_{had} estimates	6
Electron charge misassignment	2
Total (Data-driven reducible background)	9
Template fit uncertainties	
Material conversions	1
Internal conversions	1
HF non-prompt leptons	18
LF non-prompt leptons	2
Total (Template fit)	22

Systematic uncertainty	Components
$t\bar{t}H$ modelling	
Renormalisation and factorisation scales	3
Parton shower and hadronisation model	1
Higgs boson branching ratio	4
Shower tune	1
PDF	32
$t\bar{t}W$ modelling	
Radiation	1
Generator	1
PDF	32
Extrapolation	4
$t\bar{t}(Z/\gamma^*)$ (high mass) modelling	
Cross section (N)	2
Generator	1
Renormalisation and factorisation scales	3
Shower tune	1
$t\bar{t}$ modelling	
Radiation	1
WZ modelling	
HF composition (N)	3
Shower tune	1
Other background modelling	
Cross section (N)	22
Total (Signal and background modelling)	120
Total (Overall)	218

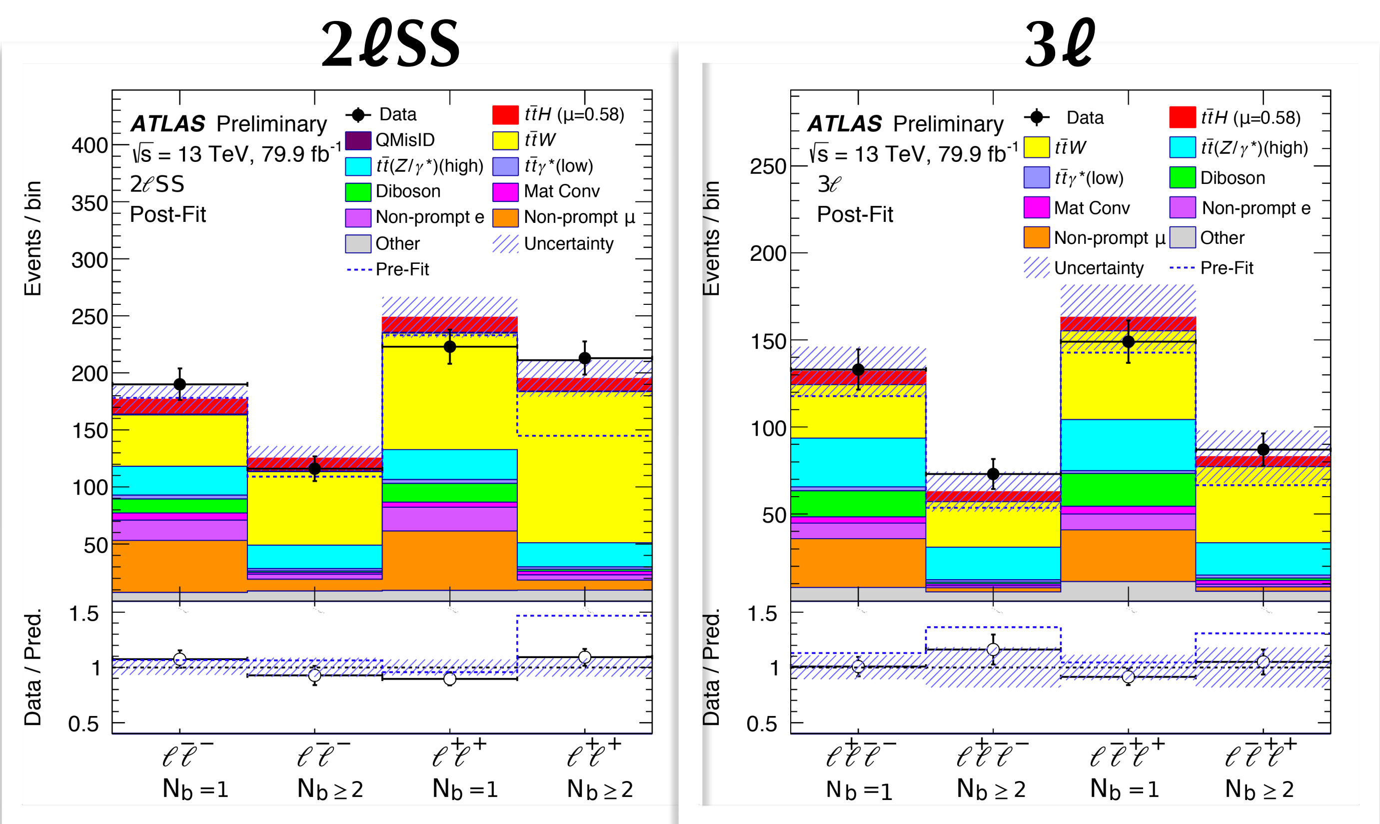
One parameter of interest: μ($t\bar{t}H$)

218 nuisance parameters

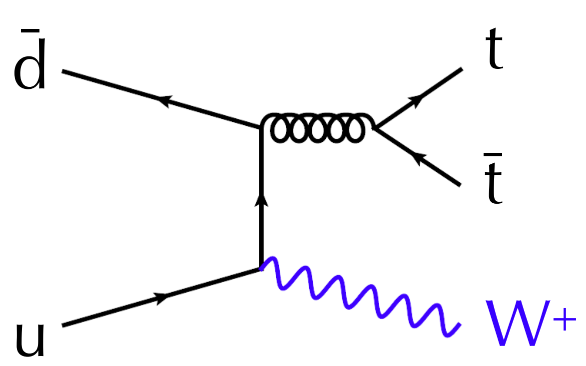
Seven normalisation factors:

- Non-prompt e
- $t\bar{t}\gamma^*$(low)
- $t\bar{t}W$ **(x3) !**
- Non-prompt μ
- Mat Conv

$t\bar{t}H(\text{multi}\ell)$: systematic uncertainties (II)



Additional uncertainties to cover data/MC disagreements as a function of the b-jet multiplicity and ℓ charge for $t\bar{t}W$



<u>Note</u>: a charge asymmetry **is expected** in the $t\bar{t}W$ production at pp colliders, but **not correlated** to the b-jet multiplicity!

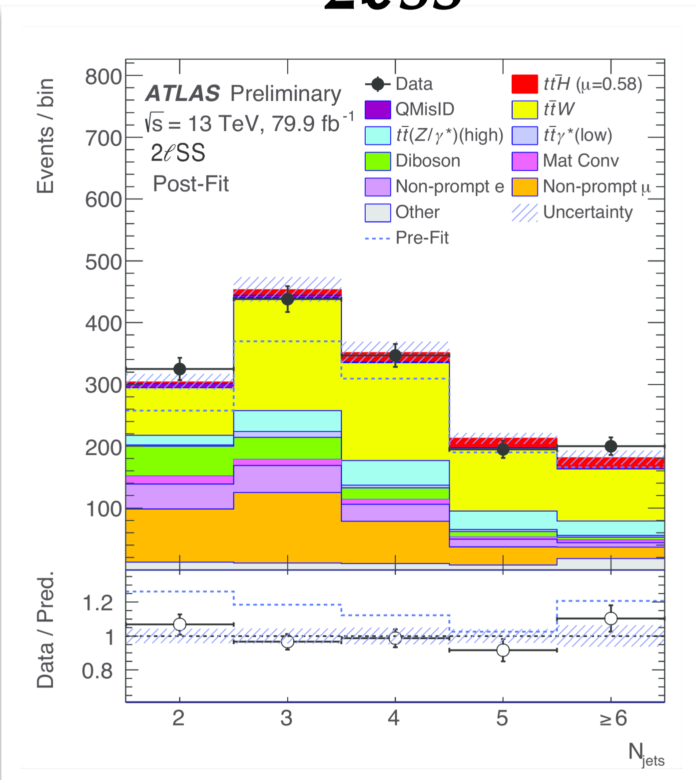
Systematic uncertainty	Components
$t\bar{t}H$ modelling	
Renormalisation and factorisation scales	3
Parton shower and hadronisation model	1
Higgs boson branching ratio	4
Shower tune	1
PDF	32
$t\bar{t}W$ modelling	
Radiation	1
Generator	1
PDF	32
Extrapolation	4
$t\bar{t}(Z/\gamma^*)$ (high mass) modelling	
Cross section (N)	2
Generator	1
Renormalisation and factorisation scales	3
Shower tune	1
$t\bar{t}$ modelling	
Radiation	1
WZ modelling	
HF composition (N)	3
Shower tune	1
Other background modelling	
Cross section (N)	22
Total (Signal and background modelling)	120
Total (Overall)	218

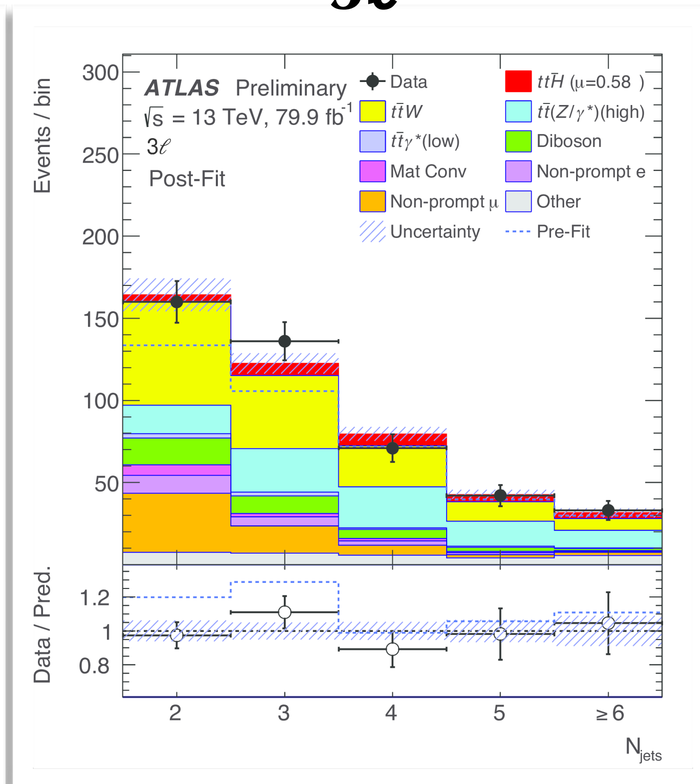
Seven normalisation factors:

- Non-prompt e
- $t\bar{t}\gamma^*$(low)
- $t\bar{t}W$ **(x3) !**
- Non-prompt μ
- Mat Conv

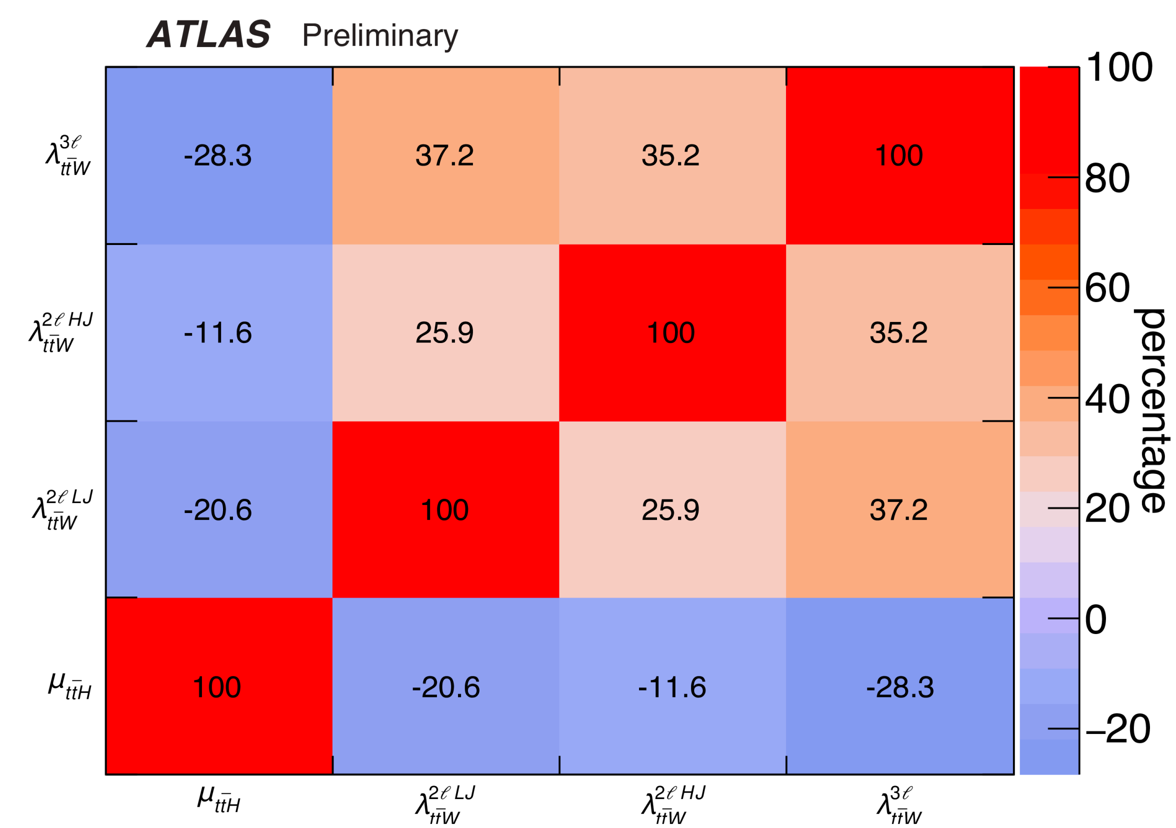
$t\bar{t}H$(multiℓ): systematic uncertainties (III)

2ℓSS | **3ℓ**





NF ($t\bar{t}W$) 2ℓ low NJet | NF ($t\bar{t}W$) 2ℓ high NJet | NF ($t\bar{t}W$) 3ℓ



Decorrelated normalisation factors for region where $t\bar{t}W$ has lost ≥1j from signal region

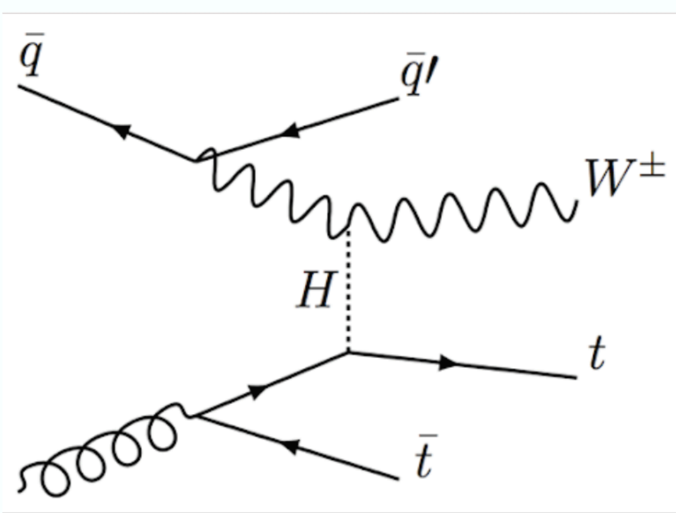
Decorrelated normalisation factors between 2ℓ and 3ℓ due to different kinematic behaviours

Seven normalisation factors:

- Non-prompt e
- $t\bar{t}\gamma^*$(low)
- $t\bar{t}W$ **(x3) !**
- Non-prompt μ
- Mat Conv

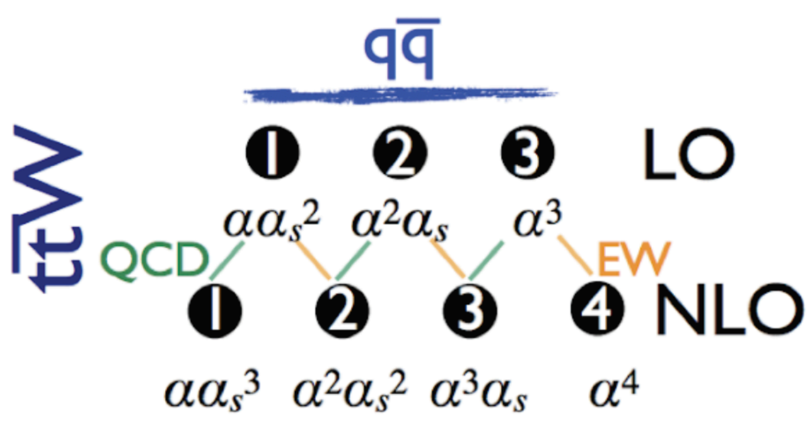
tt̄W: higher order QCD and EW corrections

- A normalisation factor of **1.2** applied on top of the YR4 cross section for tt̄W
- Origin of the correction factor:
  - Factor **1.11** to account for missing QCD corrections in higher order XS
    - ttW+0j@NLO ➜ tt̄W+0,**1j**@NLO
    - estimated using dedicated samples generated with Sherpa 2.2.1 using the MEPS@NLO prescription, and cross-checked with the NLO generator MadGraph5_aMC@NLO 2.2.1 using the FxFx prescription
  - Factor **1.09** to account for missing EW corrections
    - [1711.02116] shows "subleading" NLO EWK corrections, not included in YR4 XS, can be large
    - primarily because of the large **NLO3 term** driven by the tt̄W+1-jet diagrams with a Higgs boson exchanged in the t-channel

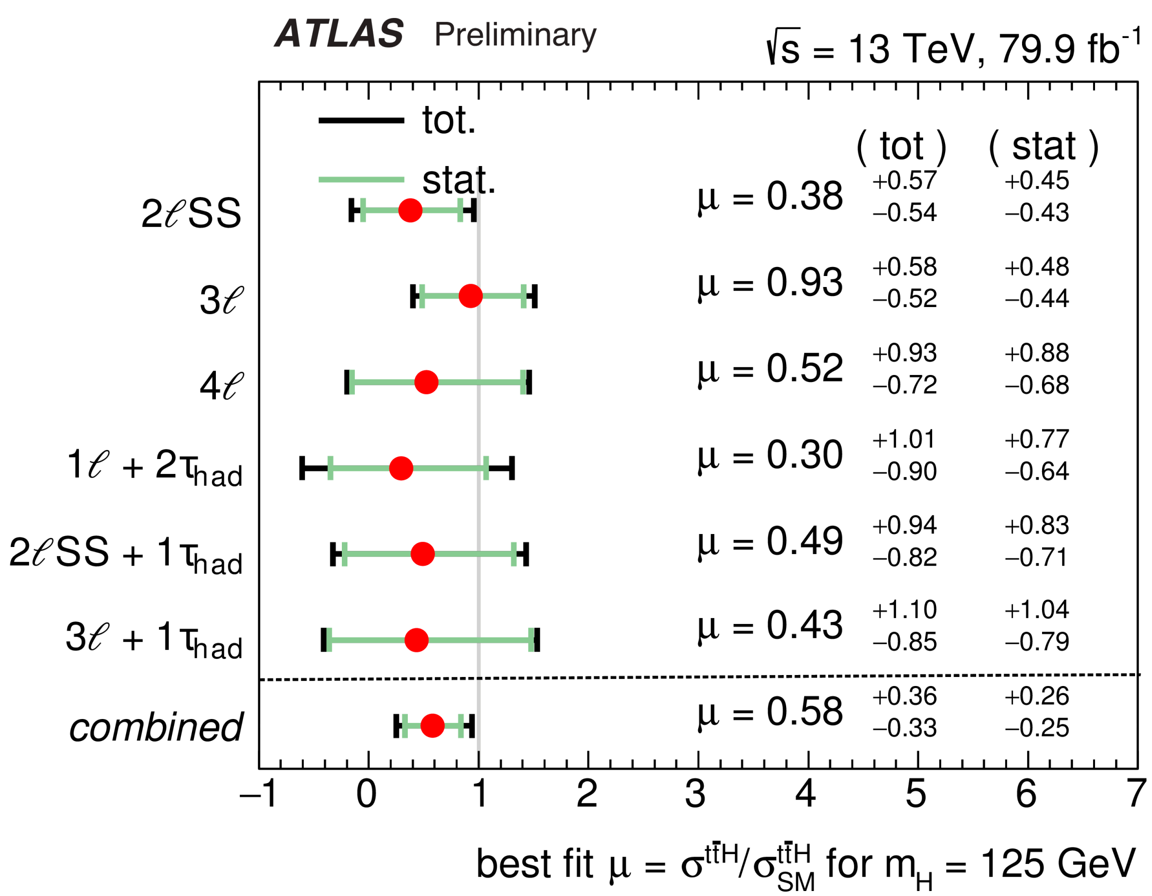


13 TeV

$\delta[\%]$	$\mu = H_T/2$
LO_2	-
LO_3	0.9
NLO_1	50.0 (25.7)
NLO_2	−4.2 (−4.6)
NLO_3	12.2 (9.1)
NLO_4	0.04 (−0.02)



$t\bar{t}H$(multiℓ): fit results (I)

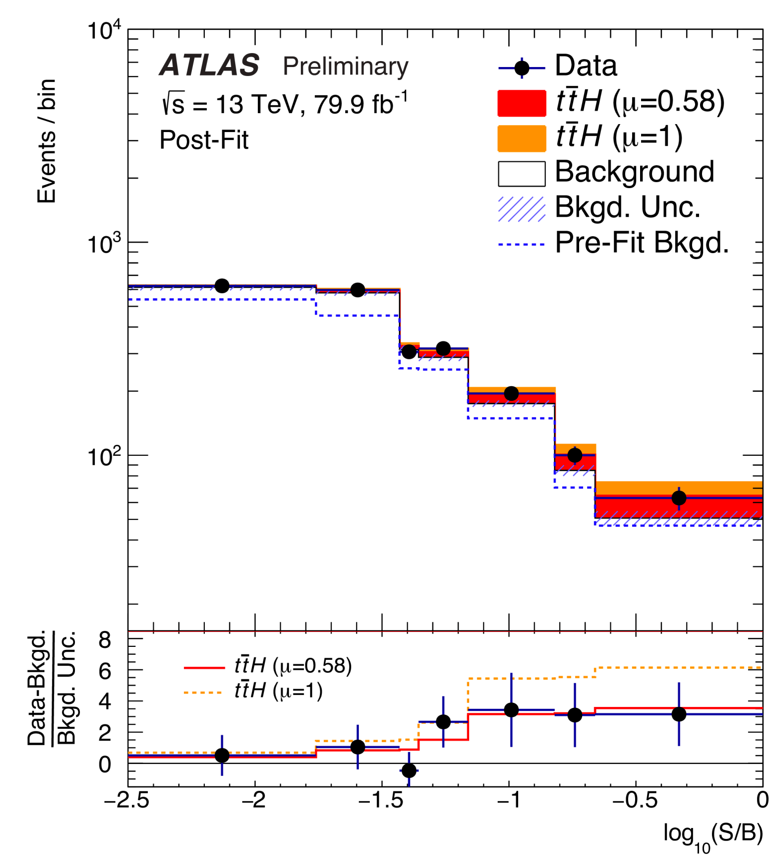


	Main result	Alternative fit
$\mu_{t\bar{t}H}$	**0.58 $^{+0.36}_{-0.33}$**	**0.70 $^{+0.36}_{-0.33}$**
NF($t\bar{t}W$)	1.56 $^{+0.30}_{-0.28}$ **(2ℓ LNJ)**	*1.39 $^{+0.17}_{-0.16}$*
	1.26 $^{+0.19}_{-0.18}$ **(2ℓ HNJ)**	*≡ 1.67 $^{+0.20}_{-0.19}$*
	1.68 $^{+0.30}_{-0.28}$ **(3ℓ)**	*(wrt. YR4 $t\bar{t}W$ XS)*

- Cross-section extrapolated to the inclusive phase space:

$$\hat{\sigma}(t\bar{t}H) = 294^{+132}_{-127}\ (\text{stat.})^{+94}_{-74}\ (\text{exp.})^{+73}_{-56}\ (\text{bkg. th.})^{+41}_{-39}\ (\text{sig. th.})\ \text{fb}$$

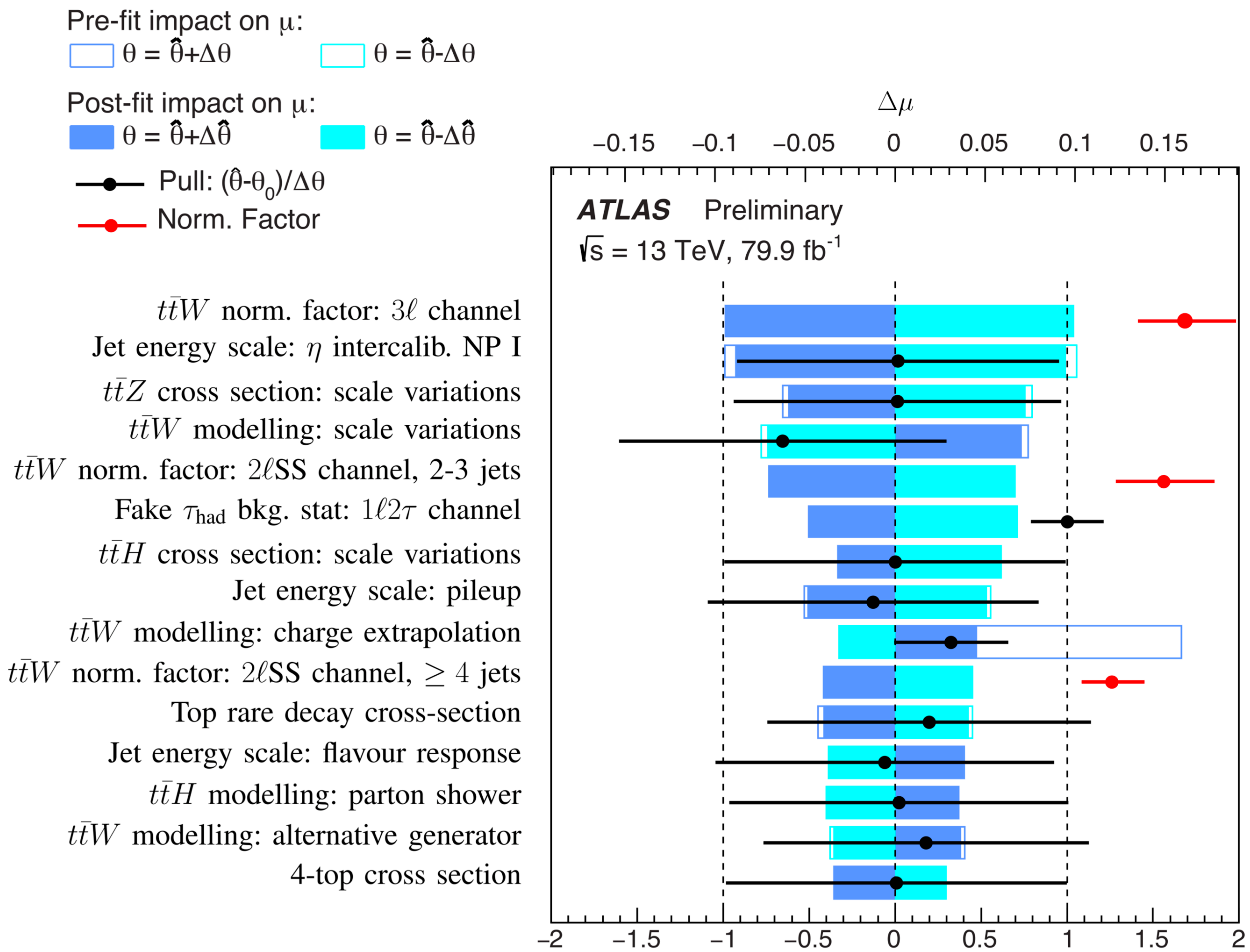
- Observed (expected) significance with respect to background-only hypothesis = **1.8 (3.1) σ**
- Compatibility between main and alternative fit = **0.59 σ**
- Consistent with the SM



$t\bar{t}H$(multiℓ): fit results (II)

- **Largest (grouped) impact on μ($t\bar{t}H$)**:
  - Jet energy scale and resolution still plays a major role
  - The largest modelling systematic uncertainties come from $t\bar{t}W$ and $t\bar{t}\ell\ell$ modelling
  - Fakes impact is reducing its size with more statistics!
- **No major constraints or pulls** of nuisance parameters
  - Exception: pull from $t\bar{t}W$ scale variation and constraint from $t\bar{t}W$ charge extrapolation uncertainties

Uncertainty source	$\Delta\hat{\mu}$	
Jet energy scale and resolution	$+0.13$	-0.13
$t\bar{t}(Z/\gamma^*)$ (high mass) modelling	$+0.09$	-0.09
$t\bar{t}W$ modelling (radiation, generator, PDF)	$+0.08$	-0.08
Fake τ_{had} background estimate	$+0.07$	-0.07
$t\bar{t}W$ modelling (extrapolation)	$+0.05$	-0.05
$t\bar{t}H$ cross section	$+0.05$	-0.05
Simulation sample size	$+0.05$	-0.05
$t\bar{t}H$ modelling	$+0.04$	-0.04
Other background modelling	$+0.04$	-0.04
Jet flavour tagging and τ_{had} identification	$+0.04$	-0.04
Other experimental uncertainties	$+0.03$	-0.03
Luminosity	$+0.03$	-0.03
Diboson modelling	$+0.01$	-0.01
$t\bar{t}\gamma^*$ (low mass) modelling	$+0.01$	-0.01
Charge misassignment	$+0.01$	-0.01
Template fit (non-prompt leptons)	$+0.01$	-0.01
Total systematic uncertainty	$+0.25$	-0.22
Intrinsic statistical uncertainty	$+0.23$	-0.22
$t\bar{t}W$ normalisation factors	$+0.10$	-0.10
Non-prompt leptons normalisation factors (HF, material conversions)	$+0.05$	-0.05
Total statistical uncertainty	$+0.26$	-0.25
Total uncertainty	$+0.36$	-0.33

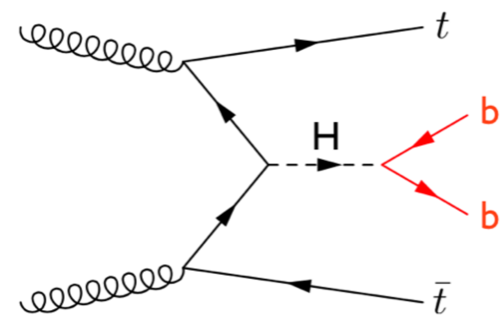


$t\bar{t}H(b\bar{b})$: analysis strategy

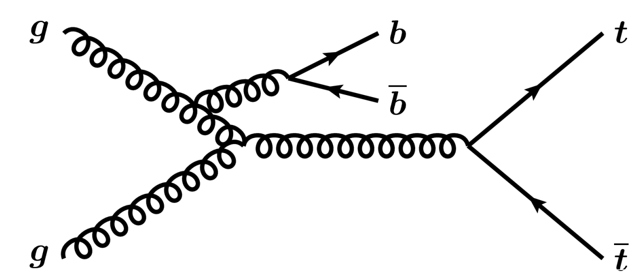
- **Biggest challenge**: good modelling of the $t\bar{t}$+HF (≥1b, ≥1c) background
  - $t\bar{t}$+≥1b: $t\bar{t}b\bar{b}$ PowhegBoxRes+Pythia8: @NLO 4-flavour scheme
  - $t\bar{t}$+≥1c and $t\bar{t}$+light: $t\bar{t}$ @NLO 5-flavour scheme sample

NEW

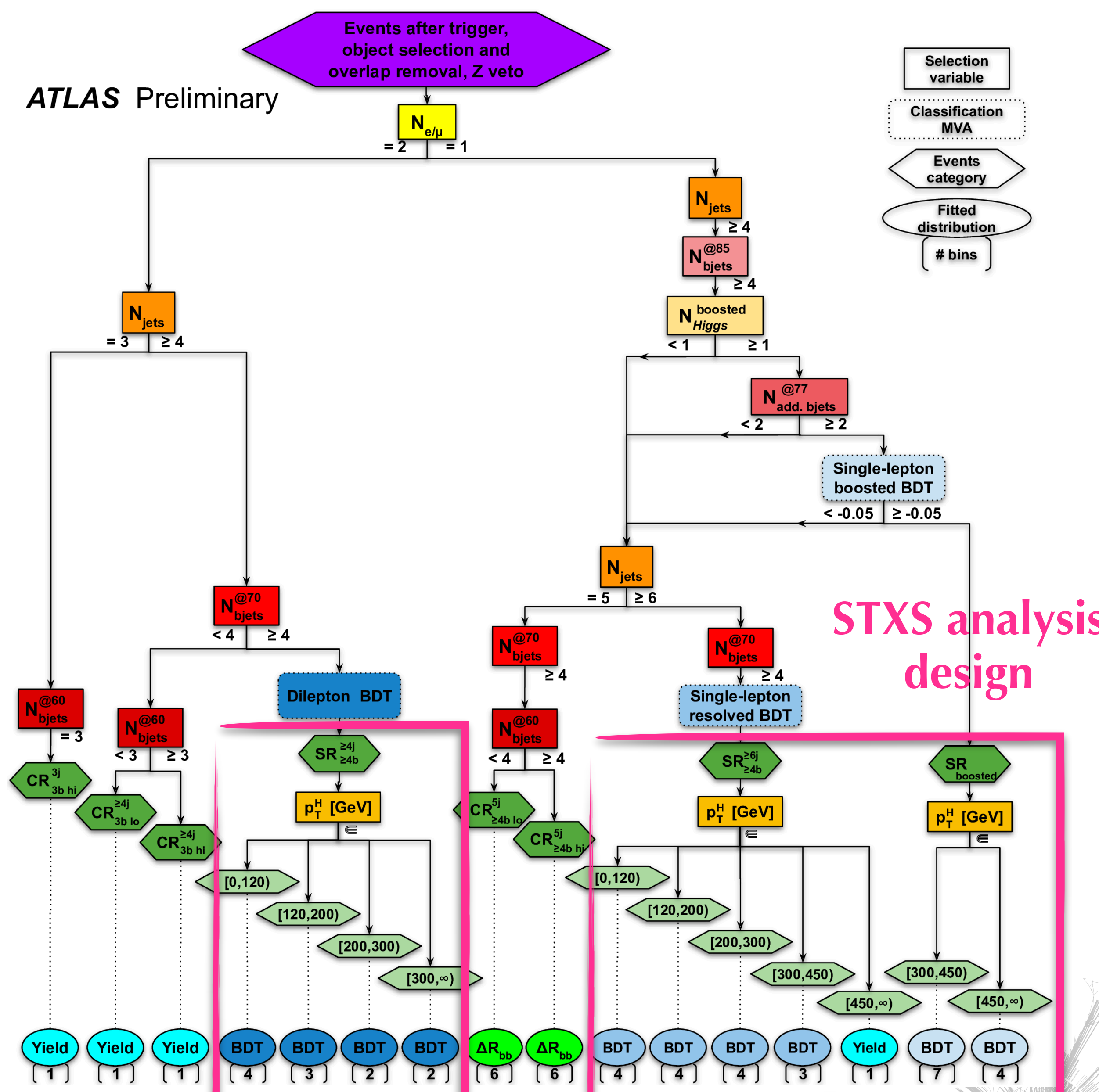
signal (ttH)



ttbb

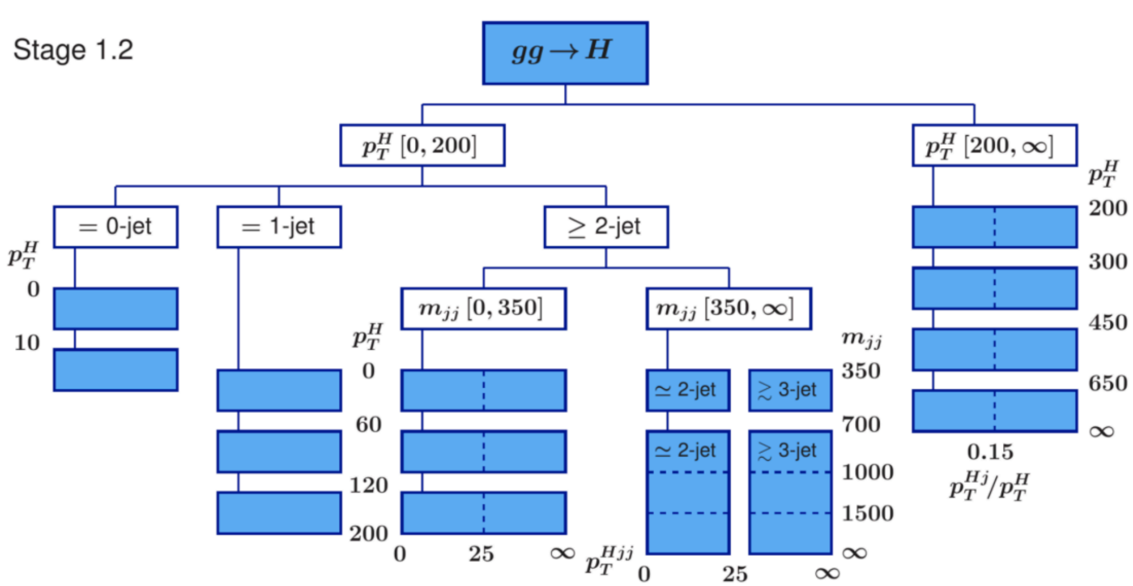


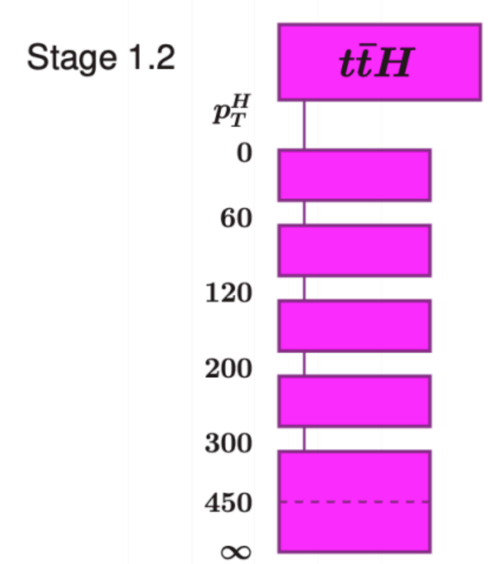
- **Channel categorisation** based on
  - Number of ℓ (1 or 2 opposite-sign)
  - Number of jets
  - Requirements on the b-tagging discriminant (based on 4 calibrated working points: 60, 70, 77, and 85% b-tagging efficiencies)
  - Resolved or boosted, for single lepton channel
  - Reconstructed p_T^{Higgs} categories



Simplified Template Cross Section (STXS)

- Measure **production modes** separately, categorising each into bins of key (truth) quantities (p_T^H , Njets, m_{jj}, ...)
  - Chosen as most sensitive variables to theory predictions / signal sensitivity / new physics
  - Different stages (e.g. stage 0, stage 1, stage 1.2) with varying degrees of granularity
  - Decay mode agnostic: well-suited for combinations
- **How to design an STXS analysis?**
  - How are events categorised?
    - Reconstructed quantities as proxy for truth quantities or multivariate classifier
  - How many / which bins to target?
    - Driven by analysis sensitivity

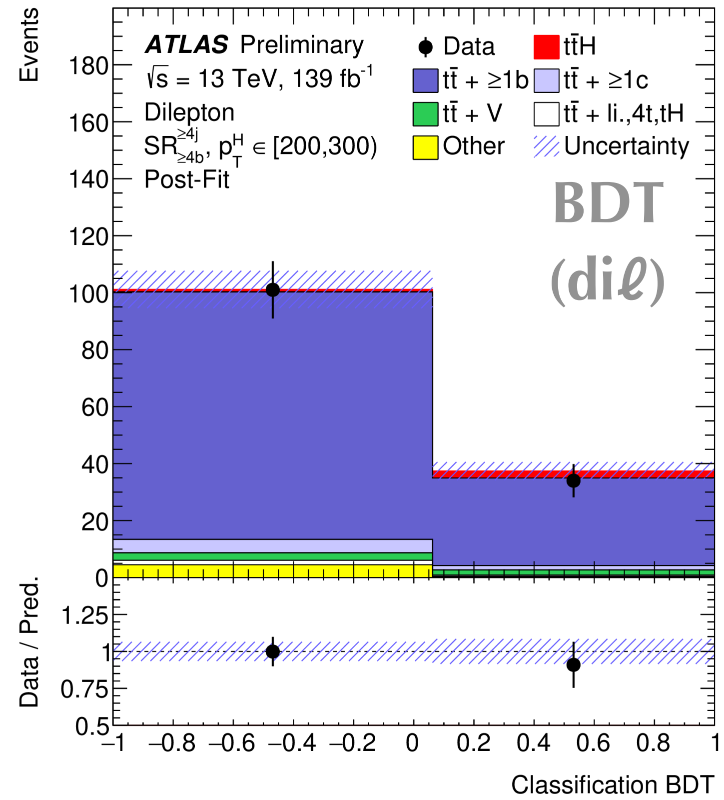


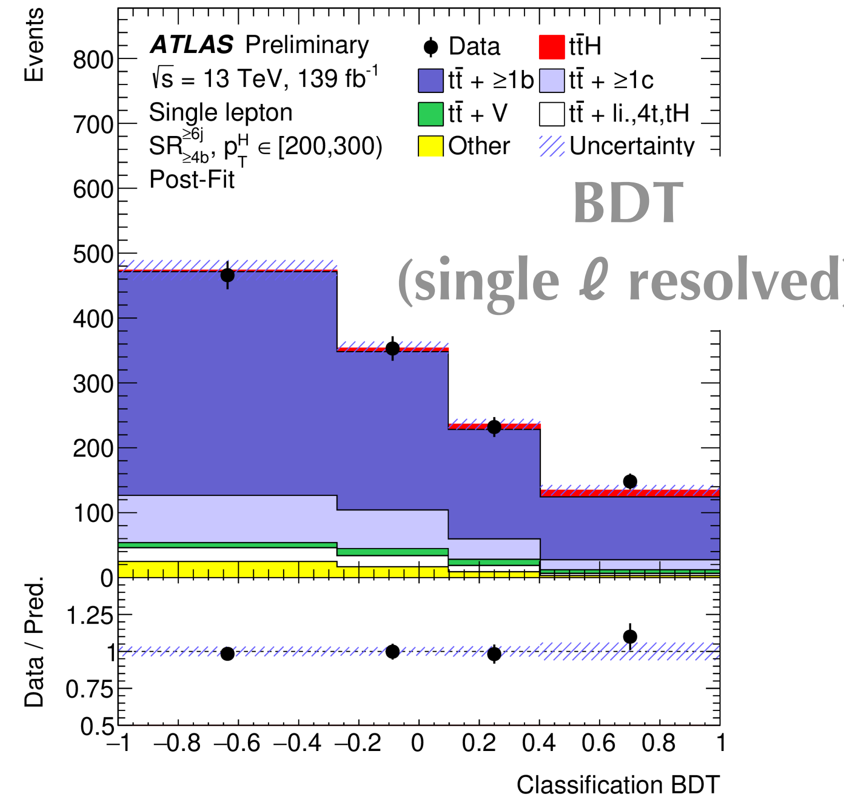


David Shope, Higgs STXS, Moriond'21

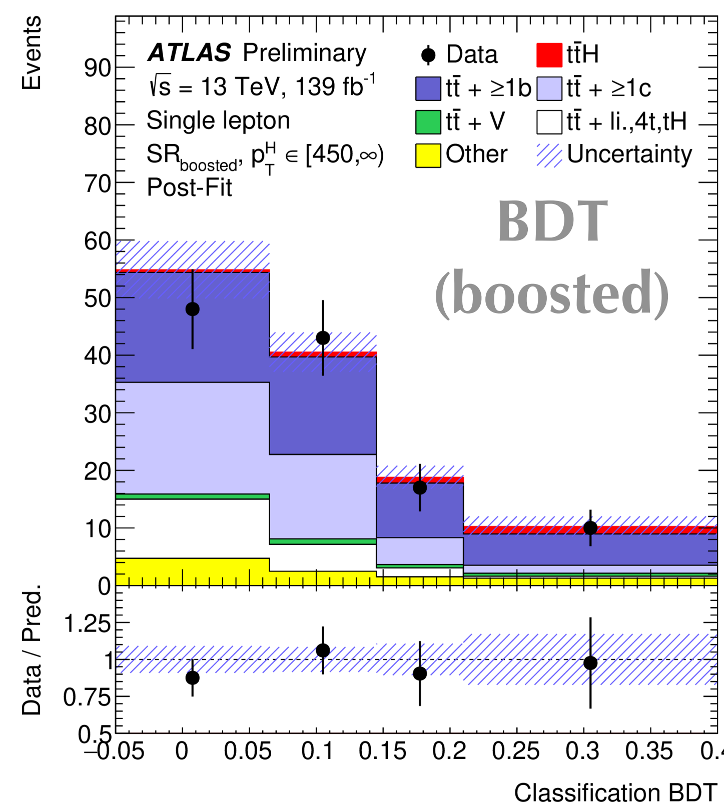
$t\bar{t}H(b\bar{b})$: MVA discriminants

- **MVA analysis** needed to discriminate signal from the overwhelming background
  - Input variables of **classification BDT**: kinematic variables, reconstruction BDTs (resolved - provides reco variables such as $\mathbf{p_T^H}$ or m_{bb}), likelihood, and **discrete** btagging discriminants



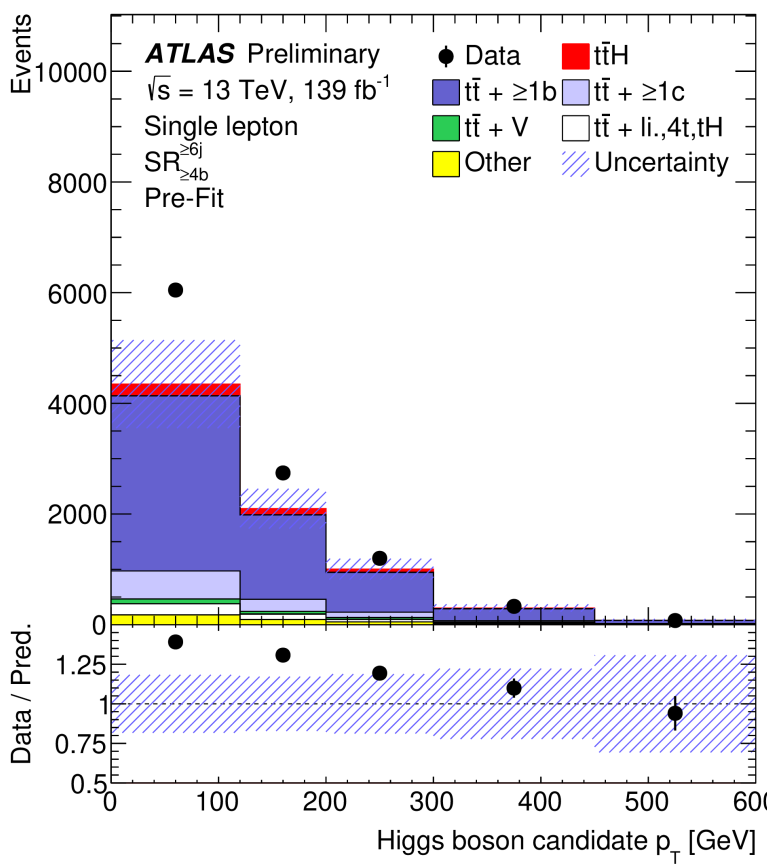


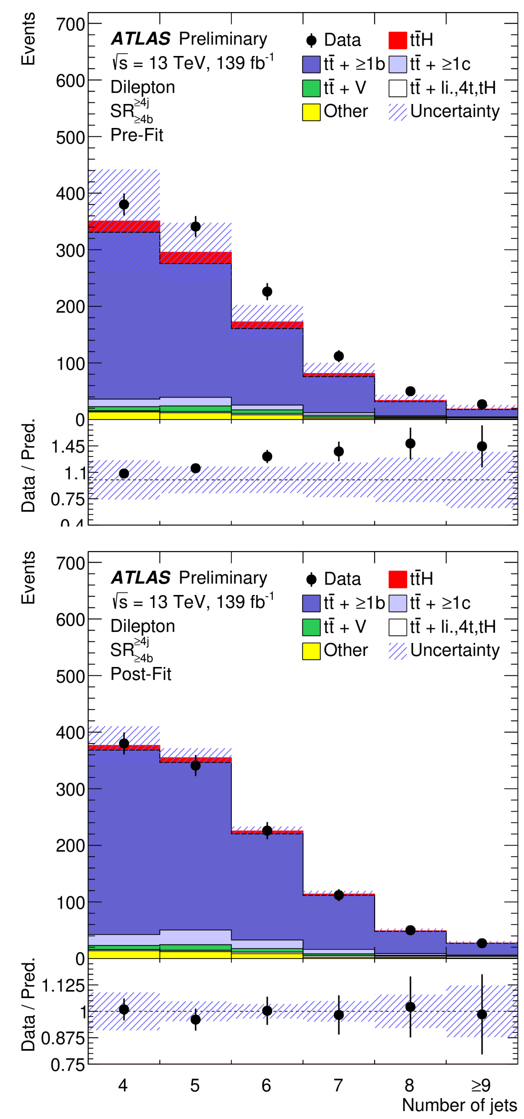
- **Boosted category**
  - RC jet: small-R jets reclustered with anti-k_t algorithm with radius 1.0
  - **DNN**: probability that an RC jet originates from Higgs [P(H)], top [P(top)] or multijet production [P(multijet)]
  - Event w/ boosted Higgs candidate:
    - P(H) > P(top) and P(H) > P(multijet)

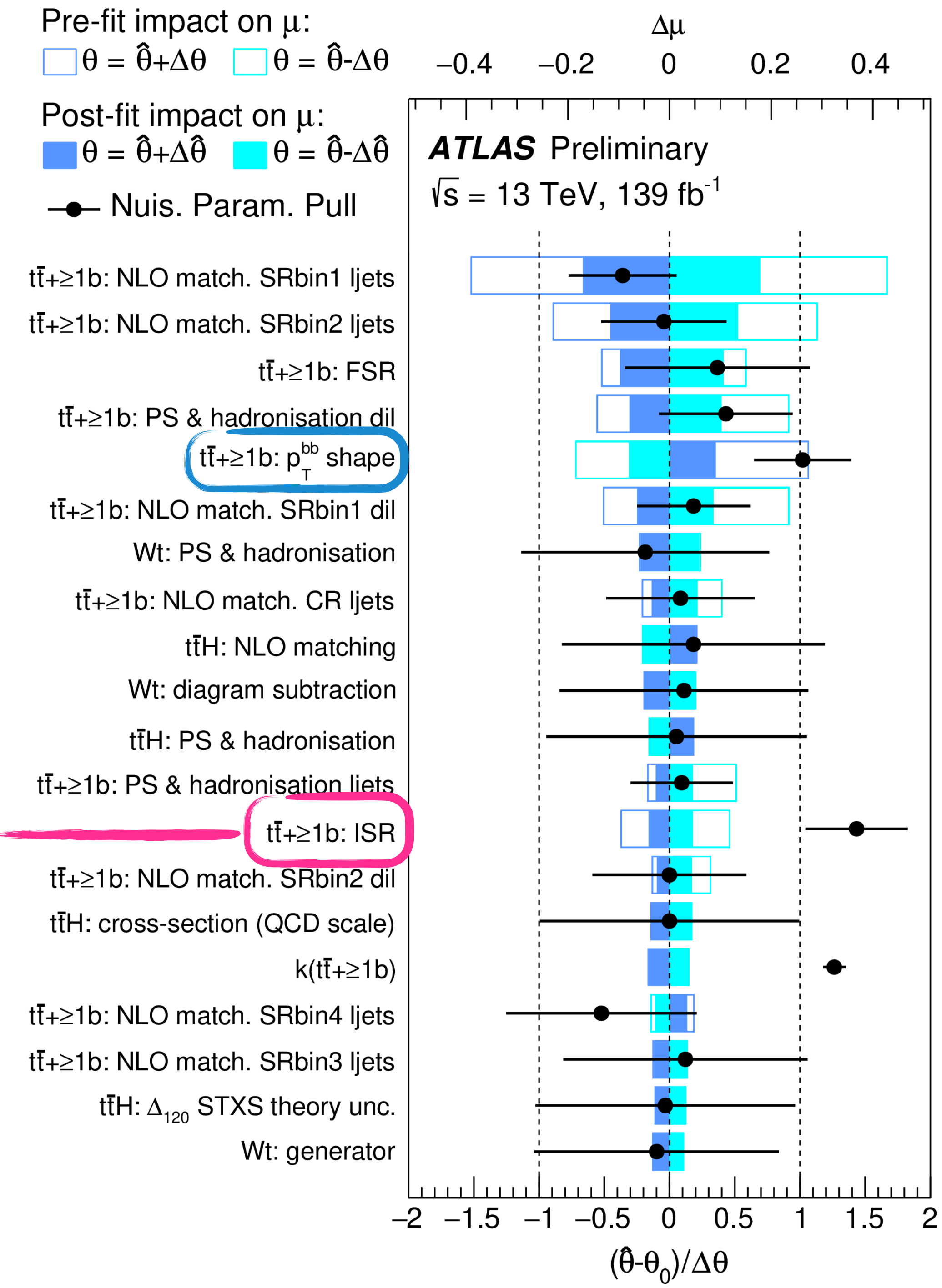


$t\bar{t}H(b\bar{b})$: modelling uncertainties

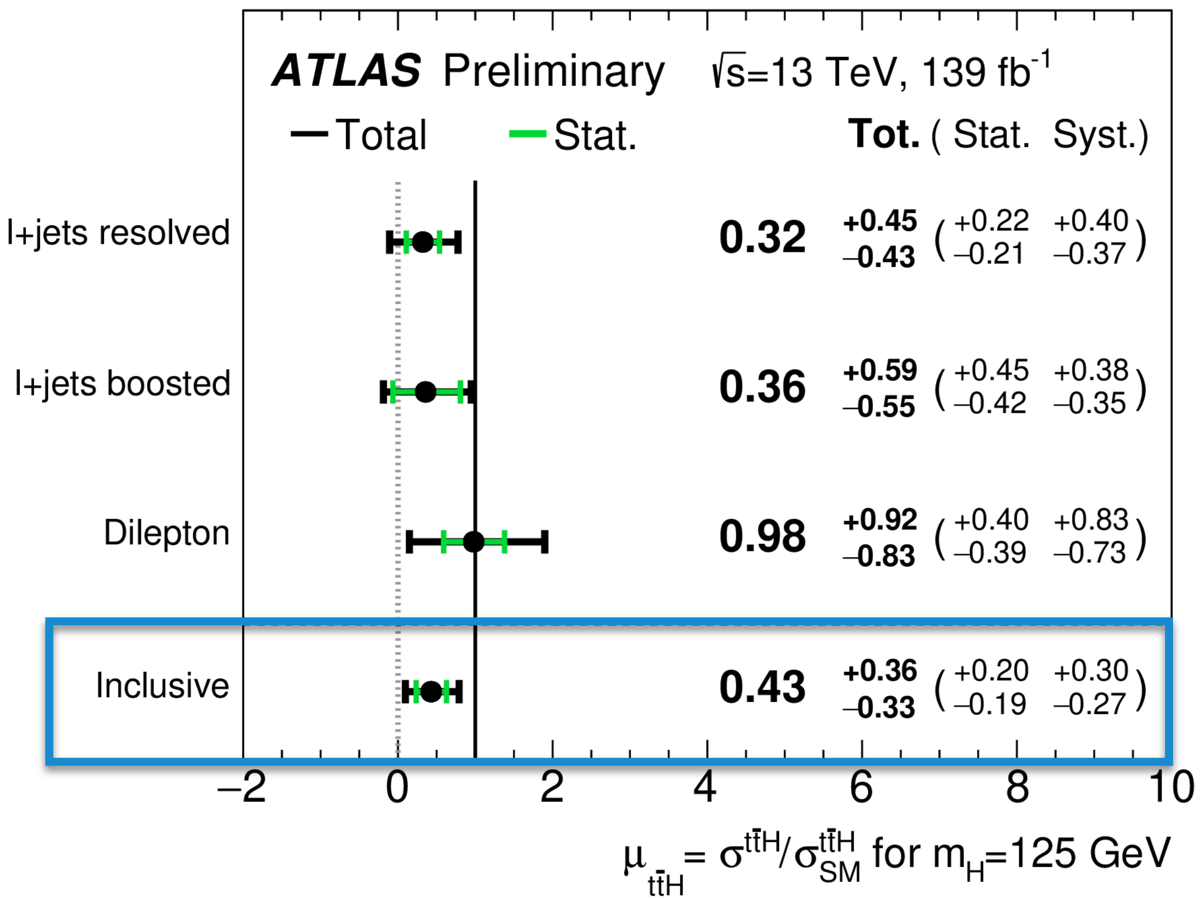
- Generator: `Powheg+Pythia8` vs `aMC@NLO+Pythia8` (5FS)
- Parton shower: `Powheg+Pythia8` vs `Powheg+Herwig7`
- **ISR (+scale)**, FSR, $t\bar{t}$+1b vs $t\bar{t}$+≥2b fraction uncertainties
- **p_T^{bb} shape uncertainty (ad-hoc)**
- **Free-floating** normalisation $t\bar{t}$+≥1b
- Nuisance parameter (100% prior) $t\bar{t}$+≥1c normalisation

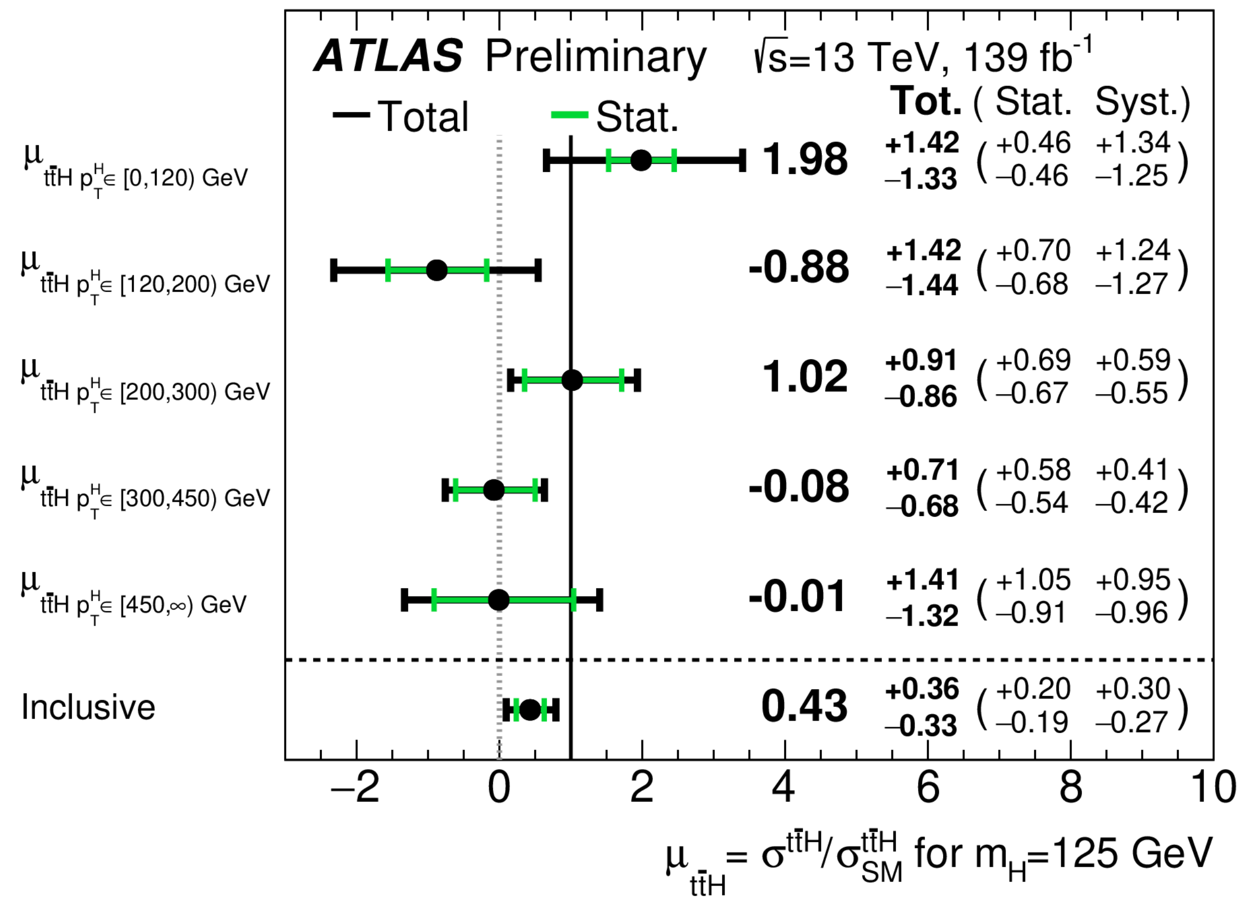






$t\bar{t}H(b\bar{b})$: results

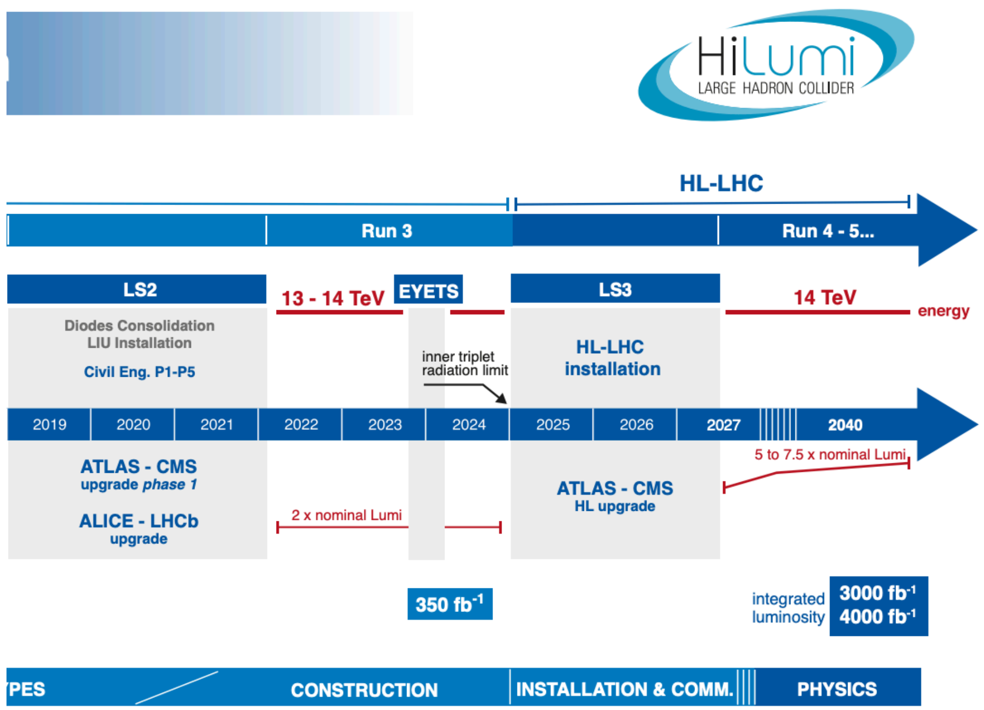




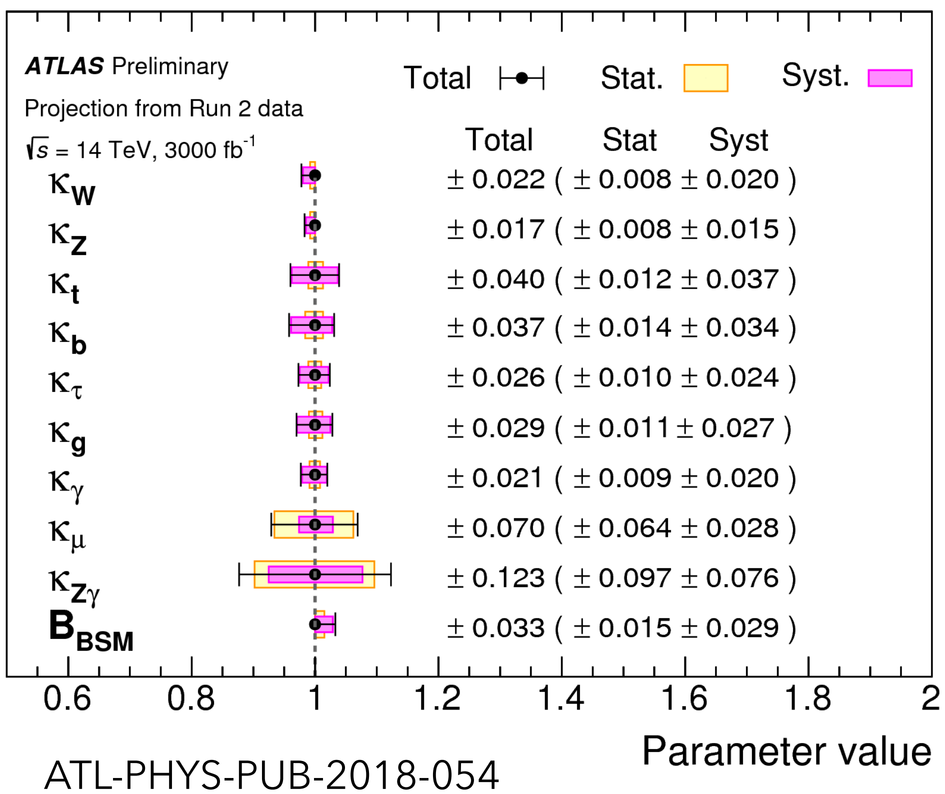
- **$NF(t\bar{t}+\geq 1b) = 1.26 \pm 0.09$**
- **Dominated by systematic** uncertainties
- Most relevant uncertainties from $t\bar{t}+\geq 1b$ background modelling ($\Delta\mu/\mu$ = 60%)
- Significance w.r.t background-only hypothesis: **1.3 (3.0σ)**
- **First $t\bar{t}H(bb)$ STXS measurement**
  - Complements $t\bar{t}H(\gamma\gamma)$ STXS measurements **at high p_T^H**

The future @ the LHC

- **Analyse full Run-2 dataset!**
- **Preparing for Run 3**: 13➜14 TeV (?), double luminosity
- **HL-LHC**: 10x more luminosity, explore less accessible processes such as di-Higgs (self-coupling of Higgs boson)



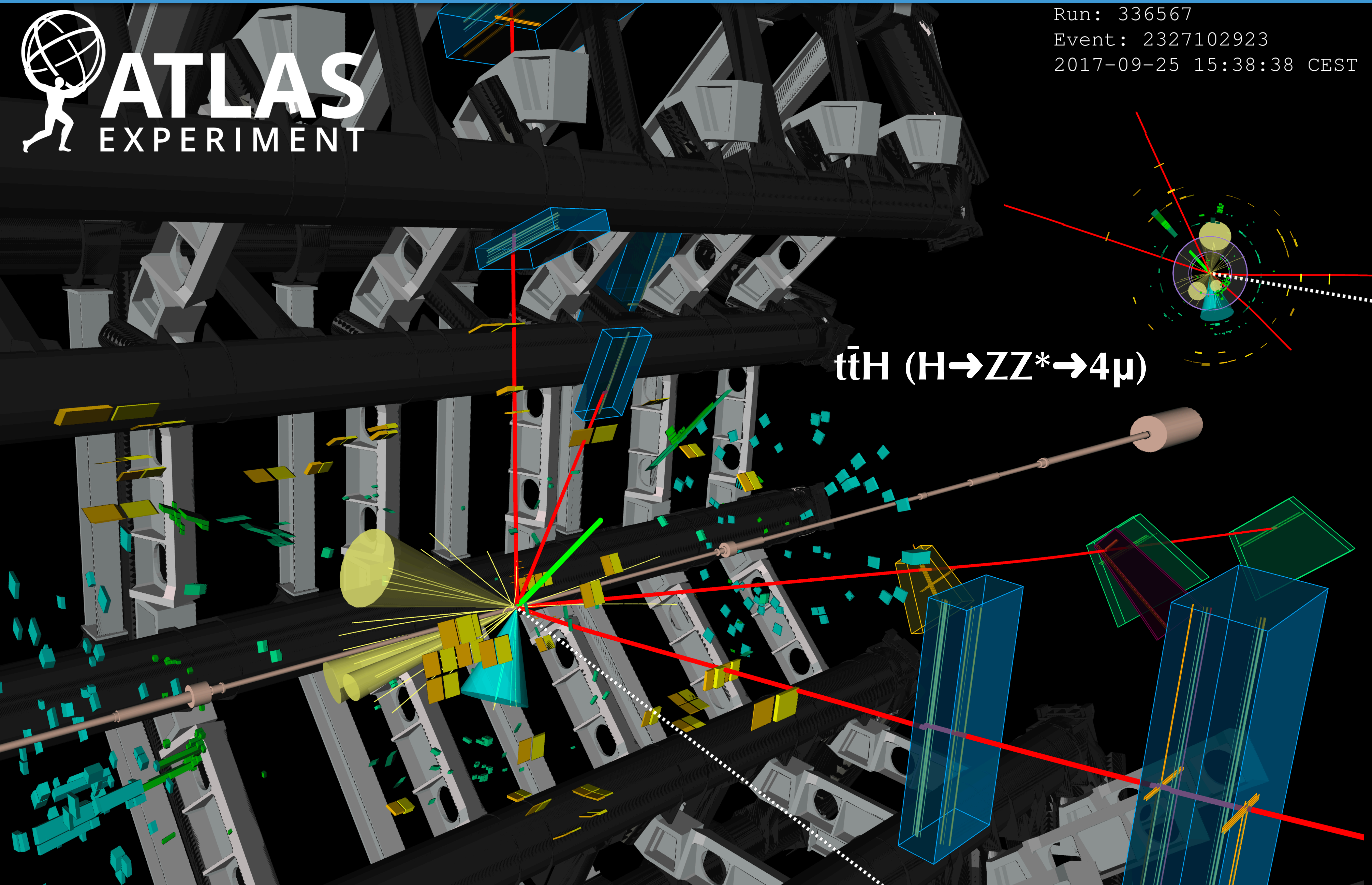
LHC/ HL-LHC Plan (last update January 2021)



ATL-PHYS-PUB-2018-054

- Expect to measure the top Yukawa coupling (modifier) κ_t at **4% level** at the end of HL-LHC
  - **Systematics-limited!**

Stay tuned for upcoming results!



Thanks for your attention!

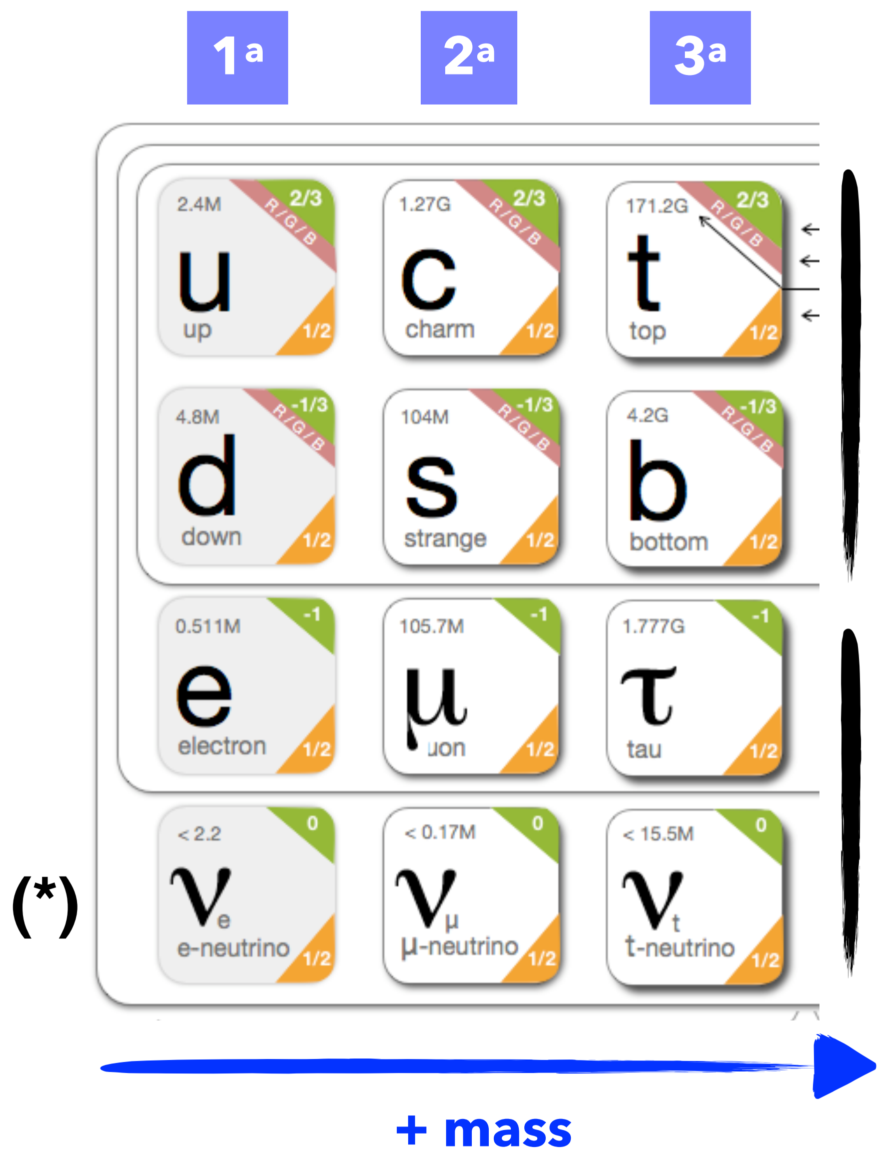
Back-up slides

Why particle colliders?

- To understand the fundamental description of Nature
- Best Model so far: The Standard Model of Particle Physics

Fermions: spin 1/2

generation



6 quarks

+ 6 anti-quarks

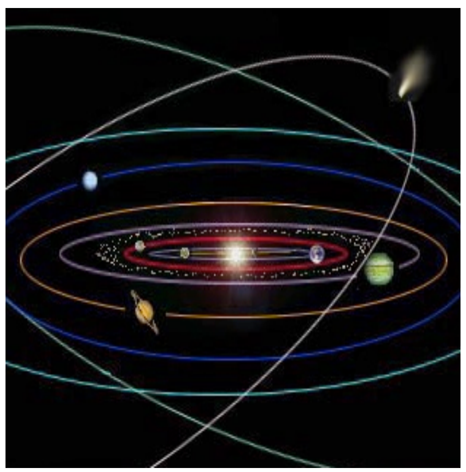
6 leptons

+ 6 anti-leptons

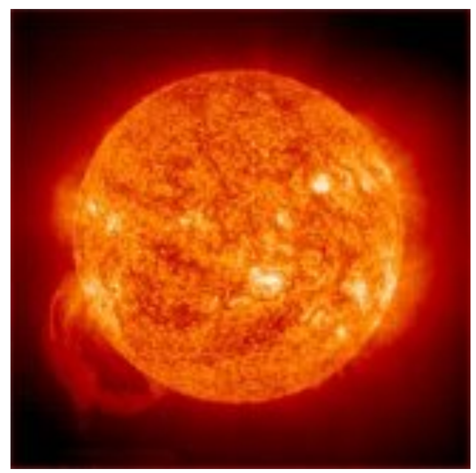
(*) <u>Disclaimer</u>: Still open questions from the neutrino sector (do not know yet if neutrinos are Dirac or Majorana particles, neutrinos mass hierarchy not yet established, …)
➜ Likely requires SM extension

Why particle colliders?

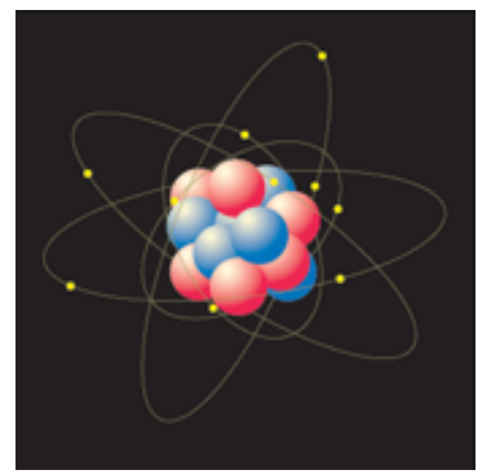
- To understand the fundamental description of Nature
- Best Model so far: The Standard Model of Particle Physics



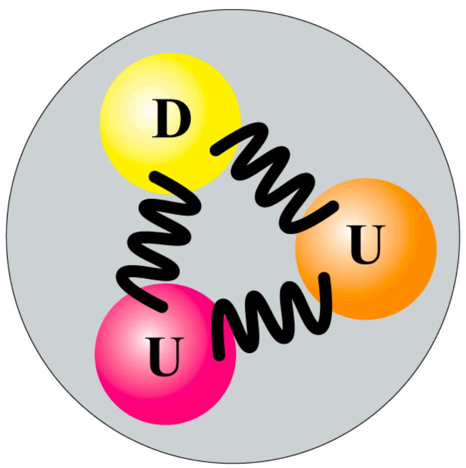
Gravity
Magnitude~10^{-38}



Weak
Magnitude~10^{-11}



Electromagnetic
Magnitude=1



Strong
Magnitude~100

Associated to a force carrier

Bosons: spin 1

ATLAS · CMS comparison: strategy

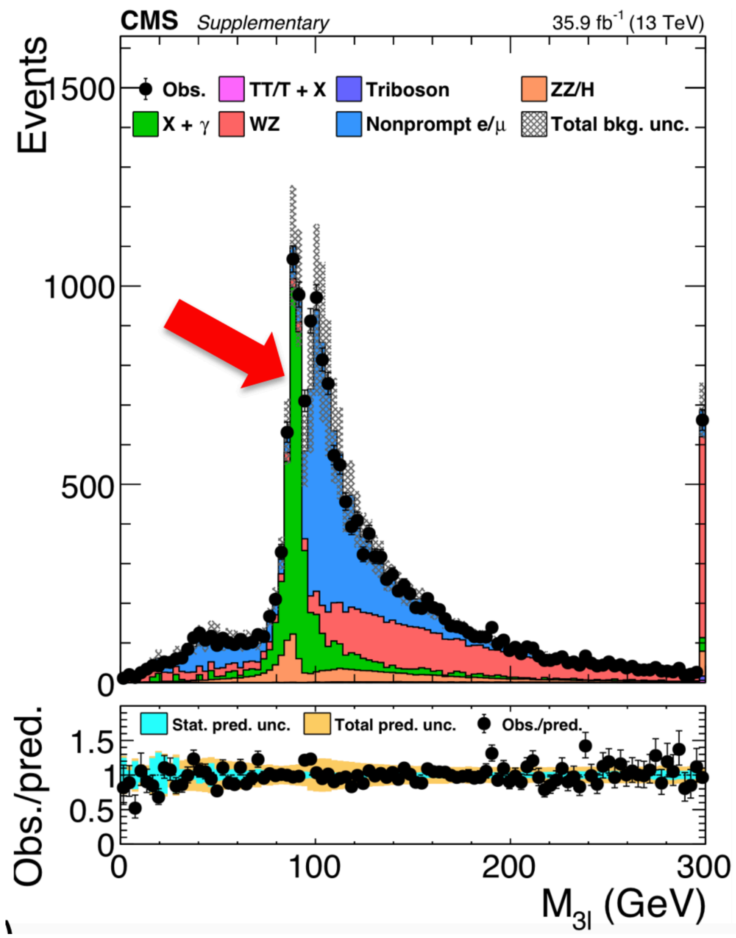
- **Similar** analysis strategy:
  - lepton-based BDT isolation suppressing background with ℓ from semi-leptonic b-decays
  - general categorisation: based on number of e/μ and τhad
  - SR optimisation: based on BDTs against main backgrounds
  - simultaneously measure normalisation of tt̄W in the fit
    - CMS has dedicated CRs for tt̄W, tt̄Z (on-shell), and diboson backgrounds

- **Different** techniques to estimate fakes:
  - CMS estimates fakes from data in a QCD control regions with relaxed object ID

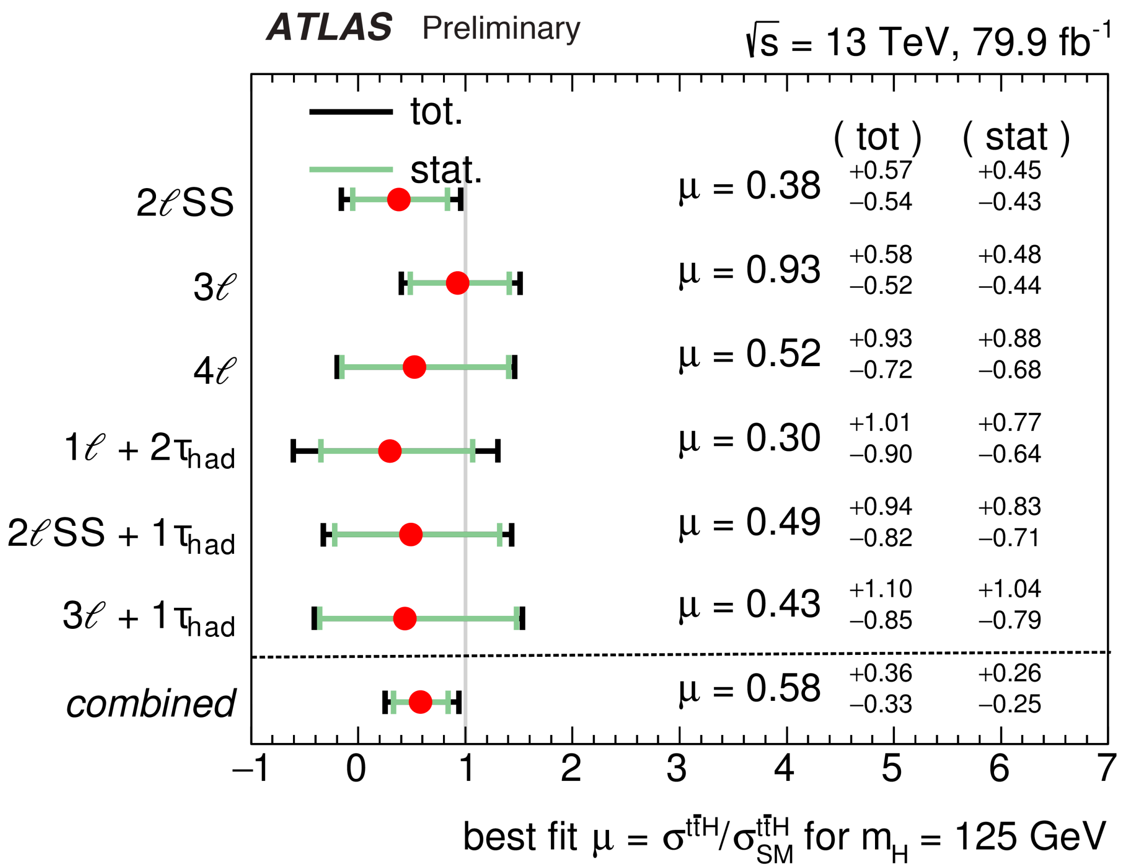
    ➜ Contamination from other processes (<10%) subtracted [tt̄W contamination is marginal]

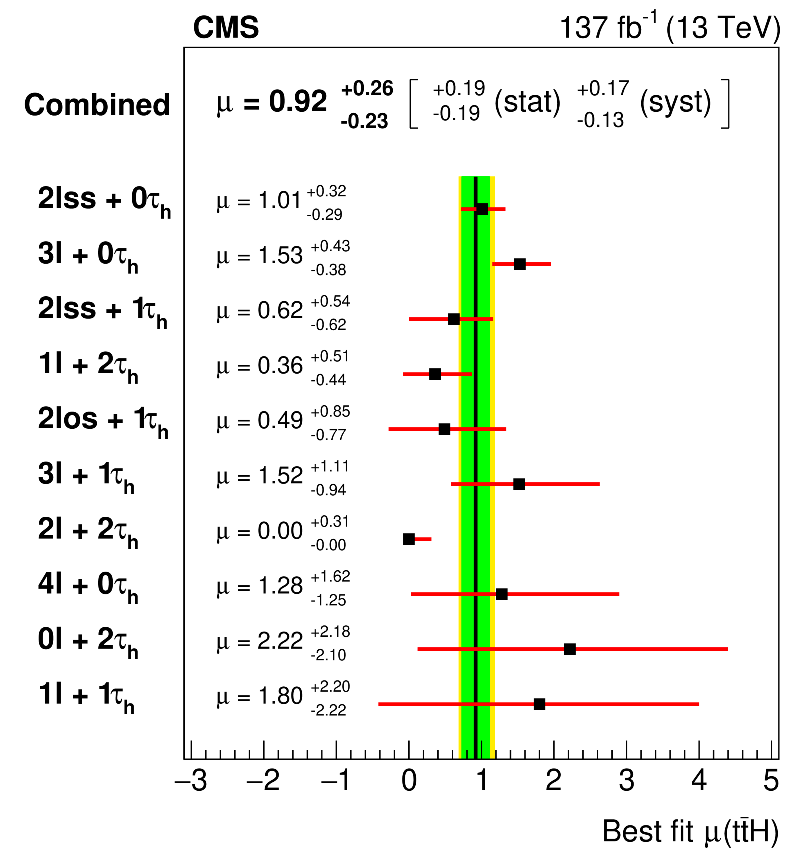
    ➜ electron from conversions **very well modelled by MC** in CMS

    ➜ loose lepton definition tuned to control potential flavour dependence of the fake rate (only light and heavy-flavour non-prompt leptons)



ATLAS · CMS comparison: results





- Combined $\mu_{t\bar{t}H}$ measured with **2015, 2016, 2017 and 2018** dataset:

	Main result (ATLAS)	Alternative fit	CMS
$\mu_{t\bar{t}H}$	**0.58 $^{+0.36}_{-0.33}$**	**0.70 $^{+0.36}_{-0.33}$**	**0.92 $^{+0.26}_{-0.23}$**
NF($t\bar{t}W$) (to compare with CMS take ~1.1xATLAS)	1.56 $^{+0.30}_{-0.28}$ **(2ℓ LNJ)** 1.26 $^{+0.19}_{-0.18}$ **(2ℓ HNJ)** 1.68 $^{+0.30}_{-0.28}$ **(3ℓ)**	1.39 $^{+0.17}_{-0.16}$ *[SM ref: 727 fb]*	1.43 ±0.21 *[SM ref: 650 fb]*
NF($t\bar{t}Z$)	-		1.03 ±0.14

Significance with respect to background-only hypothesis = **1.8 (3.1σ)** and **4.7σ (5.2σ)** obs (exp)

Compatibility between main and alternative fit = 0.59 σ

$t\bar{t}W$ measured consistently higher than SM in both experiments!

$t\bar{t}H$ (multiℓ): object definition

- Several "Loose" and "Tight" lepton definitions to optimise the event selection in each multilepton channel

	e				μ		
	L	L*	T	T*	L	L*	T/T*
Identification	Loose		Tight		Loose		Medium
Isolation	No	Yes			No	Yes	
Non-prompt lepton veto	No		Yes		No		Yes
Charge misidentification veto	No		Yes		N/A		
Material/internal conversion veto	No			Yes	N/A		
Lepton $\|\eta\|$	< 2.47			< 2	< 2.5		
$\|d_0\|/\sigma_{d_0}$	< 5				< 3		
$\|z_0 \sin\theta\|$	< 0.5 mm						

L = Loose
L* = + Loose isolated

T = Tight (PLI isolated + QMisID MVA veto)
T* = + QMisID MVA veto (el only)

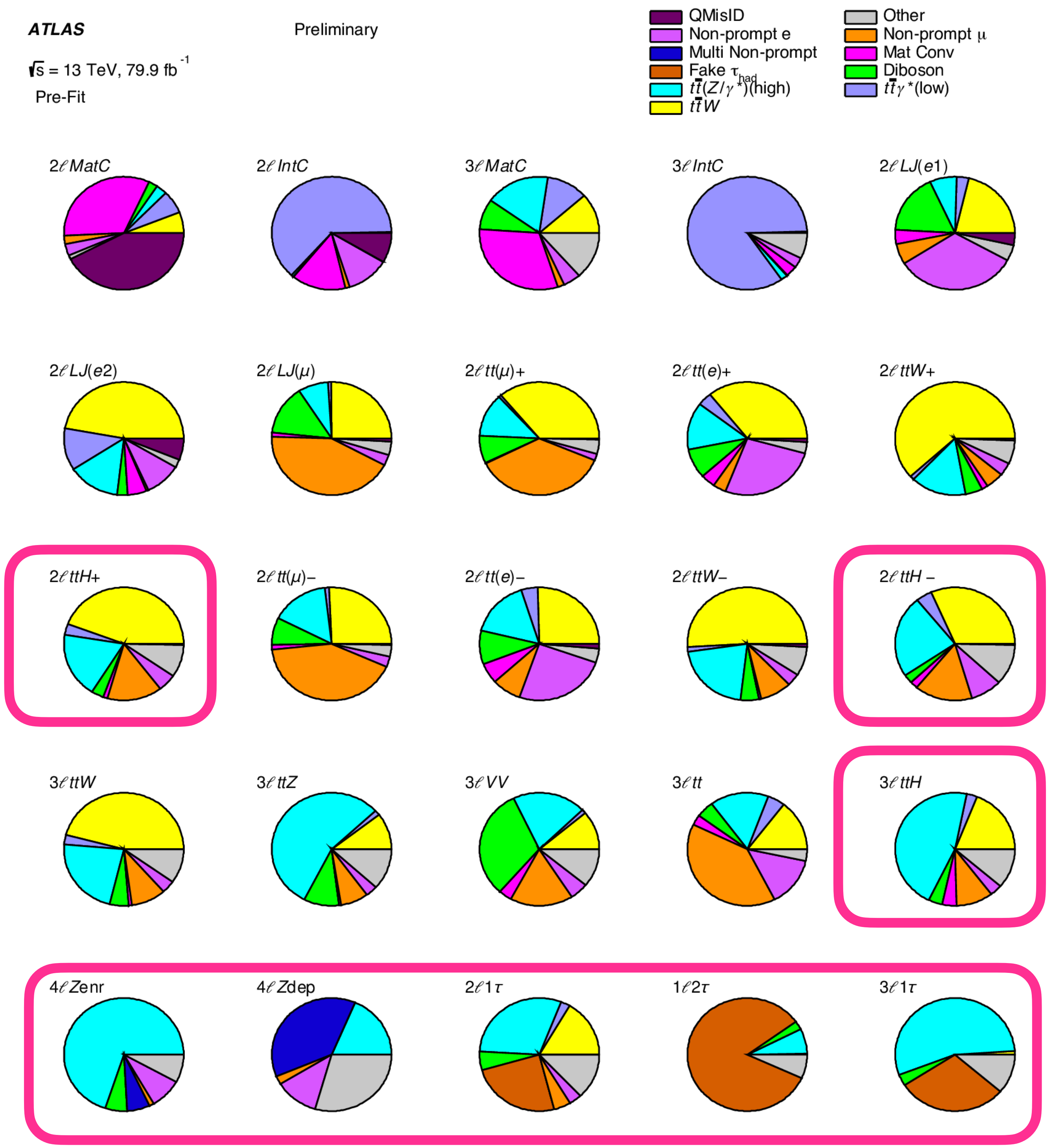
τ_{had}
Medium BDT ID to reject jets (1M, 1T in 1ℓ+2τ)
$p_T > 25$ GeV
BDT to reject el faking τ
τ-μ overlap removal
b-jet veto
τ_{had} vertex is PV

Jets $p_T > 25$ GeV
BJets MV2c10 70% WP

$t\bar{t}H$ (multiℓ): event selection

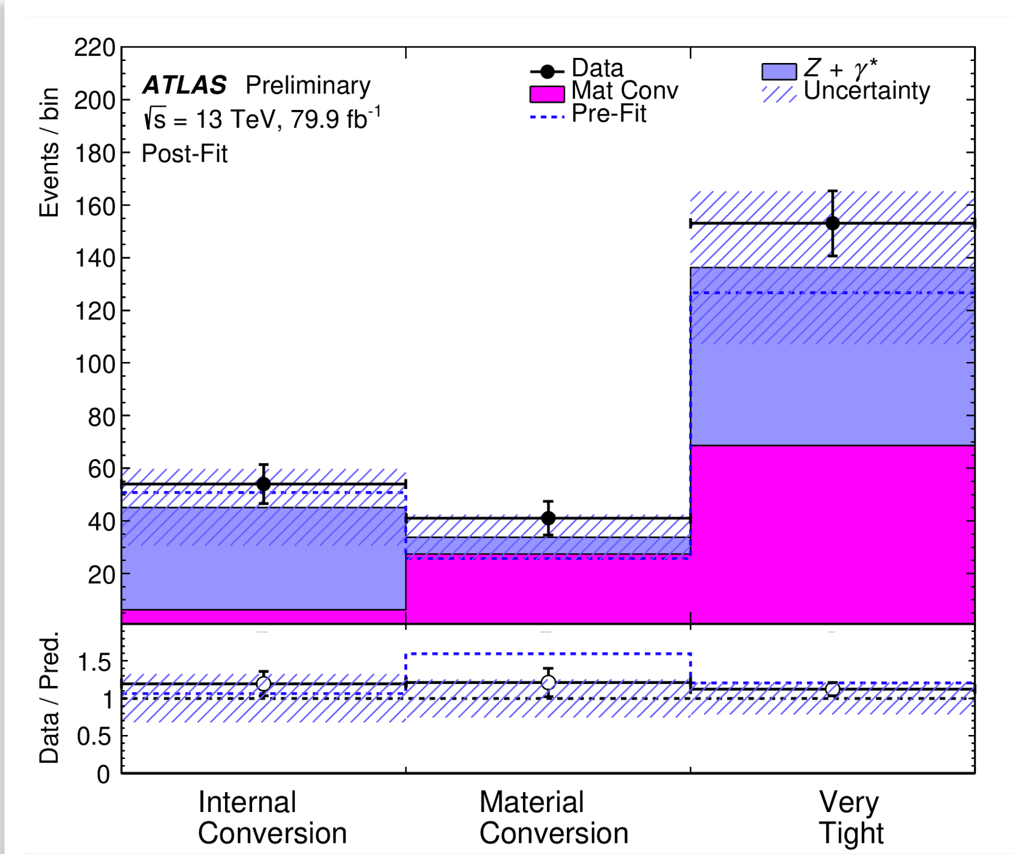
Channel	Selection criteria
Common	$N_{\text{jets}} \geq 2$ and $N_{b\text{-jets}} \geq 1$
2ℓSS	Two same-charge (SS) very tight (T*) leptons, $p_{\text{T}} > 20$ GeV No τ_{had} candidates $m(\ell^+\ell^-) > 12$ GeV for all SF pairs **13 categories**: enriched with $t\bar{t}H$, $t\bar{t}W$, $t\bar{t}$, mat. conv, int. conv., split by lepton flavour, charge, jet and b-jet multiplicity
3ℓ	Three loose (L) leptons with $p_{\text{T}} > 10$ GeV; sum of light-lepton charges $= \pm 1$ Two SS very tight (T*) leptons, $p_{\text{T}} > 15$ GeV One OS (w.r.t the SS pair) loose-isolated (L*) lepton, $p_{\text{T}} > 10$ GeV No τ_{had} candidates $m(\ell^+\ell^-) > 12$ GeV and $\|m(\ell^+\ell^-) - 91.2 \text{ GeV}\| > 10$ GeV for all SFOS pairs $\|m(3\ell) - 91.2 \text{ GeV}\| > 10$ GeV **7 categories**: enriched with $t\bar{t}H$, $t\bar{t}W$, $t\bar{t}Z$, VV, $t\bar{t}$, mat. conv, int. conv
4ℓ	Four loose-isolated (L*) leptons; sum of light lepton charges $= 0$ $m(\ell^+\ell^-) > 12$ GeV and $\|m(\ell^+\ell^-) - 91.2 \text{ GeV}\| > 10$ GeV for all SFOS pairs $m(4\ell) < 115$ GeV or $m(4\ell) > 130$ GeV **2 categories**: Zenr (Z-enriched;1 or 2 SFOS pairs) or Zdep (Z-depleted; 0 SFOS pairs)
$1\ell 2\tau_{\text{had}}$	One tight (T) lepton, $p_{\text{T}} > 27$ GeV Two OS τ_{had} candidates At least one tight τ_{had} candidate $N_{\text{jets}} \geq 3$
2ℓSS$1\tau_{\text{had}}$	2ℓSS selection, except: One medium τ_{had} candidate $N_{\text{jets}} \geq 4$
$3\ell 1\tau_{\text{had}}$	3ℓ selection, except: One medium τ_{had} candidate, of opposite charge to the total charge of the light leptons Two SS tight (T) leptons

tt̄H (multiℓ): Background composition



- Plus validation regions for internal & material electrons conversions

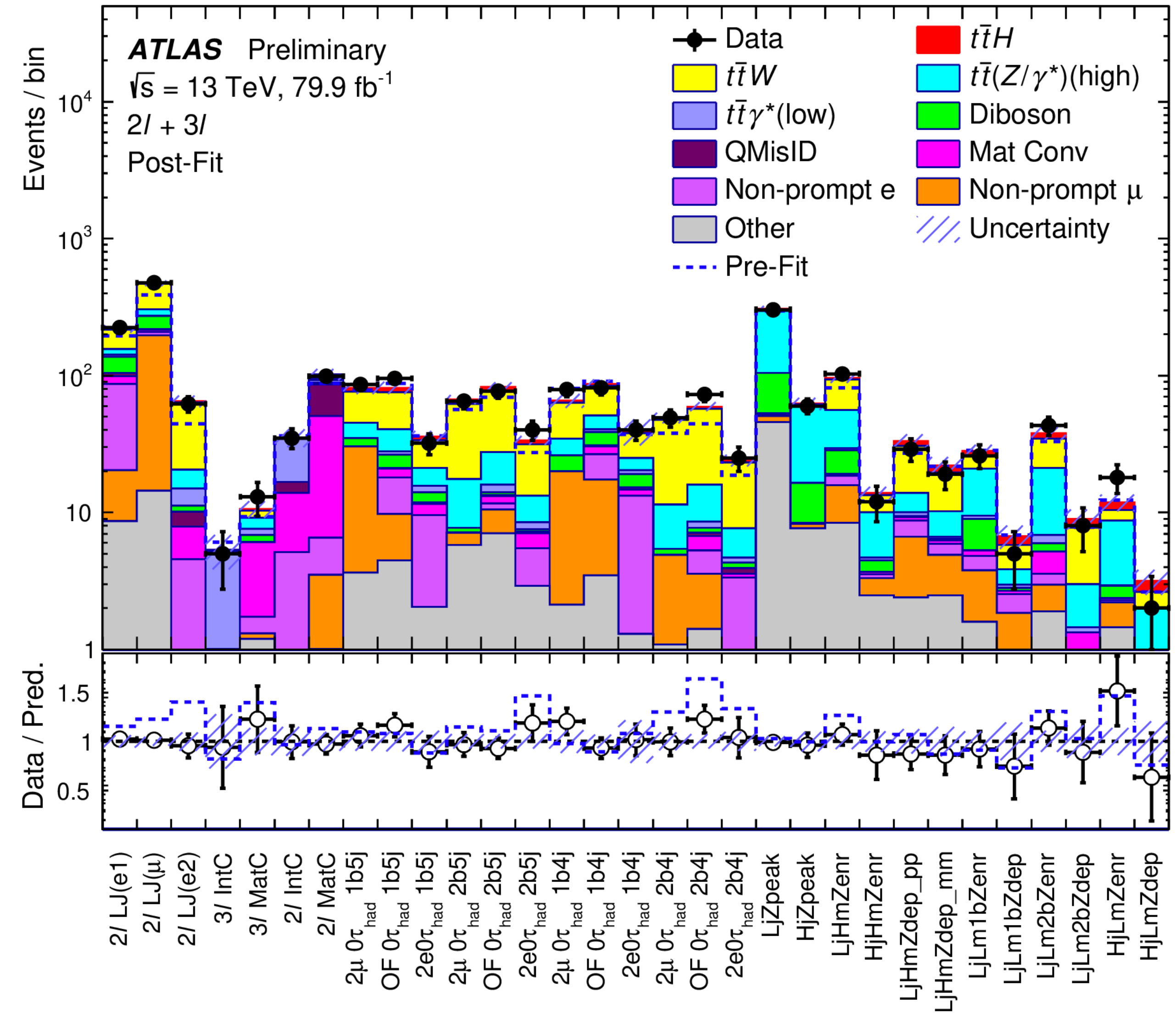
3ℓ selection: Z→μ⁺μ⁻γ*(→e⁺e⁻)



$t\bar{t}H$ (multiℓ): Cut&Count analysis

Channel	Selection criteria	
Common	$N_{\text{jets}} \geq 2$ and $N_{b\text{-jets}} \geq 1$	
2ℓSS	Two SS very tight (T*) leptons, $p_T > 20$ GeV	
	No τ_{had} candidates	
	$m(\ell_0\ell_1) > 12$ GeV	
	12 categories based on the following criteria:	
	· Number of jets: $N_{\text{jets}} = 4$ or $N_{\text{jets}} > 4$	
	· Number of b-tagged jets: $N_{b\text{-jets}} = 1$ or $N_{b\text{-jets}} > 1$	
	· Flavour of SS leptons: ee, $\mu\mu$ or opposite flavour (OF)	
3ℓ	Three light (L) leptons with $p_T > 10$ GeV; sum of light-lepton charges = ±1	
	Two SS very tight (T*) leptons, $p_T > 15$ GeV	
	One OS (w.r.t the SS pair) loose-isolated (L*) lepton, $p_T > 10$ GeV	
	No τ_{had} candidates	
	$m(\ell^+\ell^-) > 12$ GeV for all SFOS pairs	
	$\lvert m(3\ell) - 91.2 \text{ GeV}\rvert > 10$ GeV	
	12 categories based on the following criteria:	
	LjZPeak	$3 \leq N_{\text{jets}} \leq 5$; 1 SFOS pair, $m(\ell^+\ell^-) \in Z_{\text{win}}$
	HjZPeak	$N_{\text{jets}} \geq 6$; 1 SFOS pair, $m(\ell^+\ell^-) \in Z_{\text{win}}$
	LjHmZenr	$3 \leq N_{\text{jets}} \leq 5$; $m(\ell_0\ell_1) > 70$ GeV; 1 SFOS pair, $m(\ell^+\ell^-) \notin Z_{\text{win}}$
	HjHmZenr	$N_{\text{jets}} \geq 6$; $m(\ell_0\ell_1) > 70$ GeV; 1 SFOS pair, $m(\ell^+\ell^-) \notin Z_{\text{win}}$
	LjHmZdep_pp	$3 \leq N_{\text{jets}} \leq 5$; $m(\ell_0\ell_1) > 70$ GeV; 0 SFOS pair; ℓ_1 and ℓ_2 positively charged
	LjHmZdep_mm	$3 \leq N_{\text{jets}} \leq 5$; $m(\ell_0\ell_1) > 70$ GeV; 0 SFOS pair; ℓ_1 and ℓ_2 negatively charged
	LjLm1bZenr	$3 \leq N_{\text{jets}} \leq 5$; $N_{b\text{-jets}} = 1$; $m(\ell_0\ell_1) < 70$ GeV; 1 SFOS pair, $m(\ell^+\ell^-) \notin Z_{\text{win}}$
	LjLm1bZdep	$3 \leq N_{\text{jets}} \leq 5$; $N_{b\text{-jets}} = 1$; $m(\ell_0\ell_1) < 70$ GeV; 0 SFOS pair
	LjLm2bZenr	$3 \leq N_{\text{jets}} \leq 5$; $N_{b\text{-jets}} \geq 2$; $m(\ell_0\ell_1) < 70$ GeV; 1 SFOS pair, $m(\ell^+\ell^-) \notin Z_{\text{win}}$
	LjLm2bZdep	$3 \leq N_{\text{jets}} \leq 5$; $N_{b\text{-jets}} \geq 2$; $m(\ell_0\ell_1) < 70$ GeV; 0 SFOS pair
	HjLmZenr	$N_{\text{jets}} \geq 6$; $m(\ell_0\ell_1) < 70$ GeV; 1 SFOS pair, $m(\ell^+\ell^-) \notin Z_{\text{win}}$
	HjLmZdep	$N_{\text{jets}} \geq 6$; $m(\ell_0\ell_1) < 70$ GeV; 0 SFOS pair

$Z_{\text{win}} = [M_Z \pm 10 \text{ GeV}]$, where M_Z denotes the Z-boson pole mass.



$$\hat{\mu} = 0.67^{+0.44}_{-0.41} \text{ and } \hat{\mu} = 0.43^{+0.66}_{-0.65} \text{ for the } 2\ell\text{SS and } 3\ell \text{ categories}$$

(nominal) (Cut&Count)

$t\bar{t}H$ (multiℓ): other checks

- Cross-check across years

2015+2016	2017
$\hat{\mu} = 0.68^{+0.50}_{-0.45}$	$\hat{\mu} = 0.52^{+0.45}_{-0.40}$

$t\bar{t}W$ NF also found to be high in both datasets

- Comparison wrt. 36/fb $t\bar{t}H$ publication [Phys. Rev. D 97 (2018) 072003]

current fit model + $t\bar{t}W$ fixed to SM and no extrapolation uncertainties ➜ μ consistent with previous result

- Comparison wrt. 36/fb $t\bar{t}W$ publication [Phys. Rev. D 99 (2019) 072009]

comparable results wrt. $\hat{\lambda}_{t\bar{t}W} = 1.19 \pm 0.26$

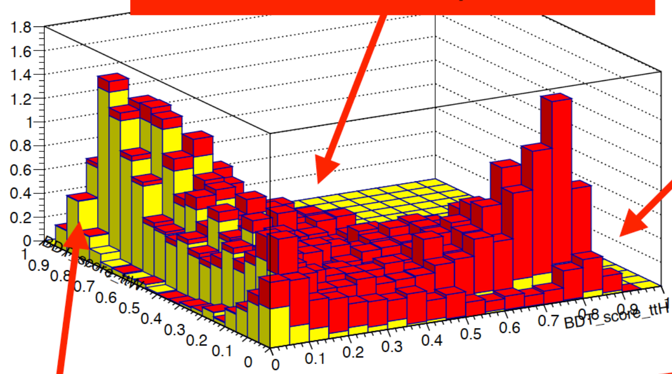
(expressed wrt. 1.2x YR4)

$t\bar{t}H$ (multiℓ): multinomial classification

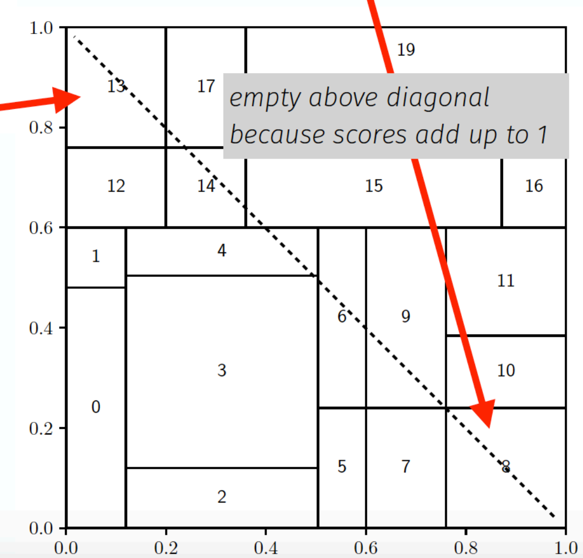
- Explore multinomial classifiers to simultaneously define signal and control regions
  - Processes are separated in the space of a multiD observable
  - Define CRs and VRs with a topology similar to the SR

"Rest" (not ttW, not ttH)

ttH like



ttW like

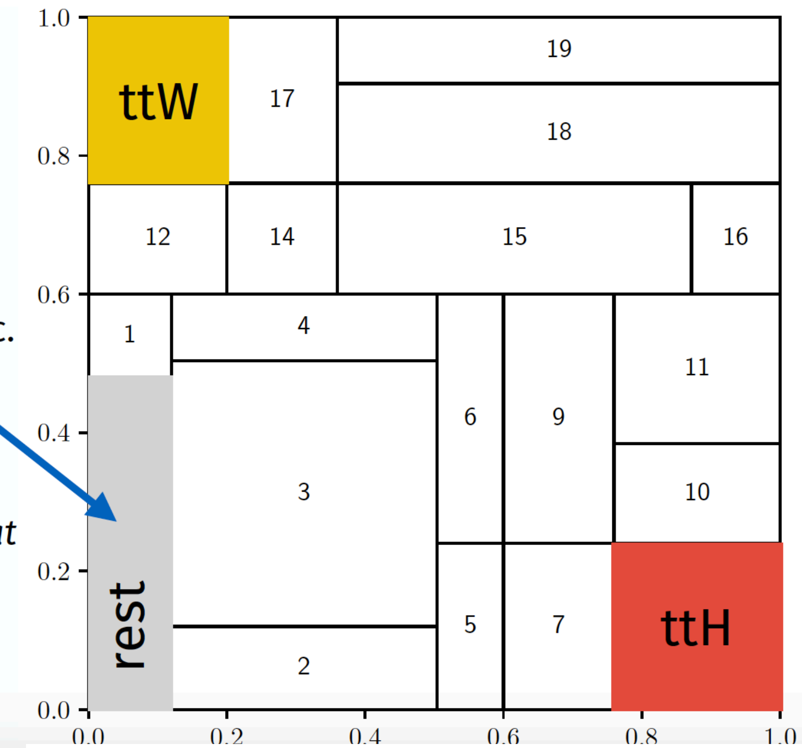


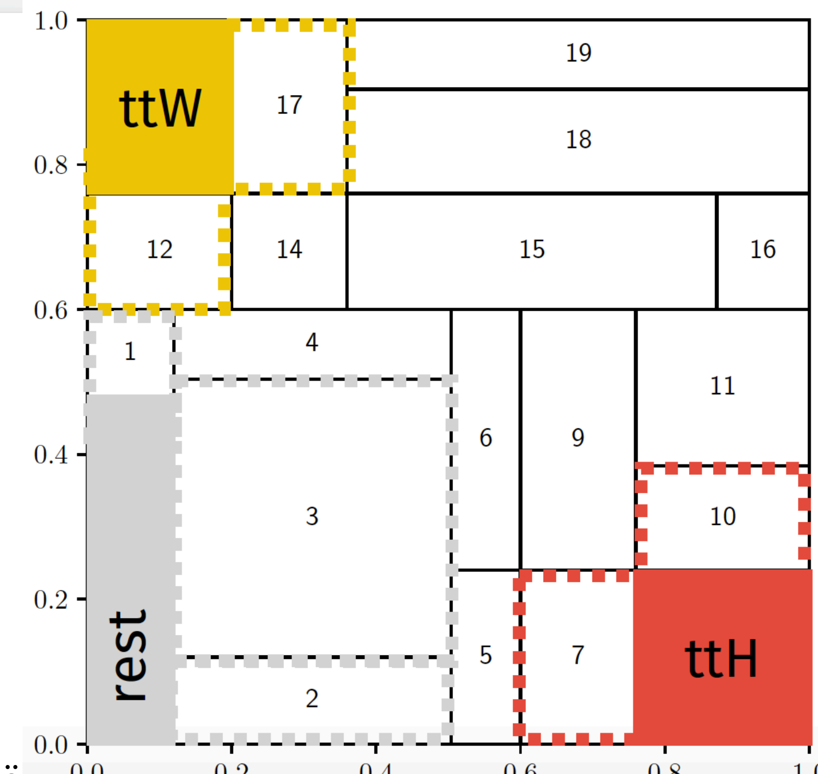
empty above diagonal because scores add up to 1

- Approximate the n-dimensional space of the BDT output scores by bins of variable size
- In practice, start with 1 large bin and split it according to the density

"rare" processes, etc.

Rest groups bins that do not contribute to ttH and ttW and speeds up the algorithm





- Clustering: add a single neighbouring bin to the seed and compute analytically the significance again; add the cell giving the largest improvement

Monte Carlo simulation (multilepton)

Process	Generator	ME order	Parton shower	PDF	Tune
$t\bar{t}H$	POWHEG-BOX [23,24]	NLO	PYTHIA 8	NNPDF3.0 NLO [25]/ NNPDF2.3 LO [48]	A14
	(POWHEG-BOX)	(NLO)	(HERWIG7)	(NNPDF3.0 NLO/ MMHT2014 LO [49])	(H7-UE-MMHT)
$tHqb$	MG5_AMC	LO	PYTHIA 8	CT10 [50]	A14
tHW	MG5_AMC	NLO	HERWIG++	CT10/ CTEQ6L1 [51,52]	UE-EE-5
$t\bar{t}W$	SHERPA 2.2.1	MEPS@NLO	SHERPA	NNPDF3.0 NNLO	SHERPA default
	(MG5_AMC)	(NLO)	(PYTHIA 8)	(NNPDF3.0 NLO/ NNPDF2.3 LO)	(A14)
$t\bar{t}(Z/\gamma^*)$	MG5_AMC	NLO	PYTHIA 8	NNPDF3.0 NLO/ NNPDF2.3 LO	A14
	(SHERPA 2.2.0)	(LO multileg)	(SHERPA)	(NNPDF3.0 NLO)	(SHERPA default)
$t\bar{t} \to W^+bW^-\bar{b}l^+l^-$	MG5_AMC	LO	PYTHIA 8	NNPDF3.0 LO	A14
tZ	MG5_AMC	LO	PYTHIA 6	CTEQ6L1	Perugia2012
tWZ	MG5_AMC	NLO	PYTHIA 8	NNPDF2.3 LO	A14
$t\bar{t}t$, $t\bar{t}t\bar{t}$	MG5_AMC	LO	PYTHIA 8	NNPDF2.3 LO	A14
$t\bar{t}W^+W^-$	MG5_AMC	LO	PYTHIA 8	NNPDF2.3 LO	A14
$t\bar{t}$	POWHEG-BOX	NLO	PYTHIA 8	NNPDF3.0 NLO/ NNPDF2.3 LO	A14
Single top (t-, Wt-, s-channel)	POWHEG-BOX [53,54]	NLO	PYTHIA 8	NNPDF3.0 NLO/ NNPDF2.3 LO	Perugia2012
VV, $qqVV$, VVV	SHERPA 2.2.2	MEPS@NLO	SHERPA	NNPDF3.0 NNLO	SHERPA default
$Z \to l^+l^-$	SHERPA 2.2.1	MEPS@NLO	SHERPA	NNPDF3.0 NLO	SHERPA default

Monte Carlo simulation (bb)

Process	ME generator	ME PDF	PS	Normalisation
Higgs boson				
$t\bar{t}H$	PowhegBox v2	NNPDF3.0NLO	Pythia8.230	NLO+NLO (EW) [19]
	PowhegBox v2	NNPDF3.0NLO	Herwig7.04	NLO+NLO (EW) [19]
	MadGraph5_aMC@NLO v2.6.0	NNPDF3.0NLO	Pythia8.230	NLO+NLO (EW) [19]
$tHjb$	MadGraph5_aMC@NLO v2.6.2	NNPDF3.0NLOnf4	Pythia8.230	–
tWH	MadGraph5_aMC@NLO v2.6.2 [DR]	NNPDF3.0NLO	Pythia8.235	–
$t\bar{t}$ and single-top				
$t\bar{t}$	PowhegBox v2	NNPDF3.0NLO	Pythia8.230	NNLO+NNLL [45,46,47,48,49,50,51]
	PowhegBox v2	NNPDF3.0NLO	Herwig7.04	NNLO+NNLL [45,46,47,48,49,50,51]
	MadGraph5_aMC@NLO v2.6.0	NNPDF3.0NLO	Pythia8.230	NNLO+NNLL [45,46,47,48,49,50,51]
$t\bar{t}+b\bar{b}$	PowhegBoxRes	NNPDF3.0NLOnf4	Pythia8.230	–
	Sherpa v2.2.1	NNPDF3.0NNLOnf4	Sherpa	–
tW	PowhegBox v2 [DR]	NNPDF3.0NLO	Pythia8.230	NLO+NNLL [52,53]
	PowhegBox v2 [DS]	NNPDF3.0NLO	Pythia8.230	NLO+NNLL [52,53]
	PowhegBox v2 [DR]	NNPDF3.0NLO	Herwig7.04	NLO+NNLL [52,53]
	MadGraph5_aMC@NLO v2.6.2 [DR]	CT10NLO	Pythia8.230	NLO+NNLL [52,53]
t-channel	PowhegBox v2	NNPDF3.0NLOnf4	Pythia8.230	NLO [54,55]
	PowhegBox v2	NNPDF3.0NLOnf4	Herwig7.04	NLO [54,55]
	MadGraph5_aMC@NLO v2.6.2	NNPDF3.0NLOnf4	Pythia8.230	NLO [54,55]
s-channel	PowhegBox v2	NNPDF3.0NLO	Pythia8.230	NLO [54,55]
	PowhegBox v2	NNPDF3.0NLO	Herwig7.04	NLO [54,55]
	MadGraph5_aMC@NLO v2.6.2	NNPDF3.0NLO	Pythia8.230	NLO [54,55]
Other				
W+jets	Sherpa v2.2.1 (NLO [2j], LO [4j])	NNPDF3.0NNLO	Sherpa	NNLO [56]
Z+jets	Sherpa v2.2.1 (NLO [2j], LO [4j])	NNPDF3.0NNLO	Sherpa	NNLO [56]
VV (had.)	Sherpa v2.2.1	NNPDF3.0NNLO	Sherpa	–
VV (lep.)	Sherpa v2.2.2	NNPDF3.0NNLO	Sherpa	–
VV (lep.) + jj	Sherpa v2.2.2 (LO [EW])	NNPDF3.0NNLO	Sherpa	–
$t\bar{t}W$	MadGraph5_aMC@NLO v2.3.3	NNPDF3.0NLO	Pythia8.210	NLO+NLO (EW) [19]
	Sherpa v2.0.0 (LO [2j])	NNPDF3.0NNLO	Sherpa	NLO+NLO (EW) [19]
$t\bar{t}\ell\ell$	MadGraph5_aMC@NLO v2.3.3	NNPDF3.0NLO	Pythia8.210	NLO+NLO (EW) [19]
	Sherpa v2.0.0 (LO [1j])	NNPDF3.0NNLO	Sherpa	NLO+NLO (EW) [19]
$t\bar{t}Z$ $(qq,\nu\nu)$	MadGraph5_aMC@NLO v2.3.3	NNPDF3.0NLO	Pythia8.210	NLO+NLO (EW) [19]
	Sherpa v2.0.0 (LO [2j])	NNPDF3.0NNLO	Sherpa	NLO+NLO (EW) [19]
$t\bar{t}t\bar{t}$	MadGraph5_aMC@NLO v2.3.3	NNPDF3.1NLO	Pythia8.230	NLO+NLO (EW) [57]
tZq	MadGraph5_aMC@NLO v2.3.3 (LO)	CTEQ6L1	Pythia8.212	–
tWZ	MadGraph5_aMC@NLO v2.3.3 [DR]	NNPDF3.0NLO	Pythia8.230	–

$t\bar{t}H(bb)$: uncertainties

Uncertainty source	Description		Components
$t\bar{t}$ cross-section	$\pm 6\%$		$t\bar{t}$ + light
$t\bar{t} + \geq 1b$ normalisation	Free-floating		$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 1c$ normalisation	$\pm 100\%$		$t\bar{t} + \geq 1c$
NLO matching	MadGraph5_aMC@NLO+Pythia8 vs. PowhegBox+Pythia8		All
PS & hadronisation	PowhegBox+Herwig7 vs. PowhegBox+Pythia8		All
ISR	Varying α_S^{ISR} (PS), μ_{R}&μ_{F} (ME)	in PowhegBoxRes+Pythia8	$t\bar{t} + \geq 1b$
		in PowhegBox+Pythia8	$t\bar{t} + \geq 1c$, $t\bar{t}$ + light
FSR	Varying α_S^{FSR} (PS)	in PowhegBoxRes+Pythia8	$t\bar{t} + \geq 1b$
		in PowhegBox+Pythia8	$t\bar{t} + \geq 1c$, $t\bar{t}$ + light
$t\bar{t} + \geq 1b$ fractions	PowhegBox+Herwig7 vs. PowhegBox+Pythia8		$t\bar{t} + 1b/1B$, $t\bar{t} + \geq 2b$
p_{T}^{bb} shape	Shape mismodelling measured from data		$t\bar{t} + \geq 1b$

Uncertainty source	$\Delta\mu$	
$t\bar{t} + \geq 1b$ modelling	$+0.25$	-0.24
$t\bar{t}H$ modelling	$+0.14$	-0.06
tW modelling	$+0.08$	-0.08
b-tagging efficiency and mis-tag rates	$+0.05$	-0.05
Background-model statistical uncertainty	$+0.05$	-0.05
Jet energy scale and resolution	$+0.03$	-0.03
$t\bar{t} + \geq 1c$ modelling	$+0.03$	-0.03
$t\bar{t}$ + light modelling	$+0.02$	-0.02
Luminosity	$+0.01$	-0.00
Other sources	$+0.03$	-0.03
Total systematic uncertainty	$+0.30$	-0.27
$t\bar{t} + \geq 1b$ normalisation	$+0.03$	-0.05
Total statistical uncertainty	$+0.20$	-0.19
Total uncertainty	$+0.36$	-0.33

$t\bar{t}H(bb)$: input variables BDT (I)

dilepton

Variable	Definition	$SR_1^{\geq 4j}$	$SR_2^{\geq 4j}$	$SR_3^{\geq 4j}$
General kinematic variables				
m_{bb}^{min}	Minimum invariant mass of a b-tagged jet pair	✓	✓	-
m_{bb}^{max}	Maximum invariant mass of a b-tagged jet pair	-	-	✓
$m_{bb}^{min\ \Delta R}$	Invariant mass of the b-tagged jet pair with minimum ΔR	✓	-	✓
$m_{jj}^{max\ p_T}$	Invariant mass of the jet pair with maximum p_T	✓	-	-
$m_{bb}^{max\ p_T}$	Invariant mass of the b-tagged jet pair with maximum p_T	✓	-	✓
$\Delta\eta_{bb}^{avg}$	Average $\Delta\eta$ for all b-tagged jet pairs	✓	✓	✓
$\Delta\eta_{\ell,j}^{max}$	Maximum $\Delta\eta$ between a jet and a lepton	-	✓	✓
$\Delta R_{bb}^{max\ p_T}$	ΔR between the b-tagged jet pair with maximum p_T	-	✓	✓
$N_{bb}^{Higgs\ 30}$	Number of b-tagged jet pairs with invariant mass within 30 GeV of the Higgs-boson mass	✓	✓	-
$n_{jets}^{p_T>40}$	Number of jets with $p_T > 40$ GeV	-	✓	✓
$\text{Aplanarity}_{b\text{-jet}}$	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the momentum tensor [100] built with all b-tagged jets	-	✓	-
H_T^{all}	Scalar sum of p_T of all jets and leptons	-	-	✓
Variables from reconstruction BDT				
BDT output	Output of the reconstruction BDT	✓**	✓**	✓
m_{bb}^{Higgs}	Higgs candidate mass	✓	-	✓
$\Delta R_{H,t\bar{t}}$	ΔR between Higgs candidate and $t\bar{t}$ candidate system	✓*	-	-
$\Delta R_{H,\ell}^{min}$	Minimum ΔR between Higgs candidate and lepton	✓	✓	✓
$\Delta R_{H,b}^{min}$	Minimum ΔR between Higgs candidate and b-jet from top	✓	✓	-
$\Delta R_{H,b}^{max}$	Maximum ΔR between Higgs candidate and b-jet from top	-	✓	-
ΔR_{bb}^{Higgs}	ΔR between the two jets matched to the Higgs candidate	-	✓	-
Variables from b-tagging				
$w_{b\text{-tag}}^{Higgs}$	Sum of b-tagging discriminants of jets from best Higgs candidate from the reconstruction BDT	-	✓	-

$t\bar{t}H(bb)$: input variables BDT (II)

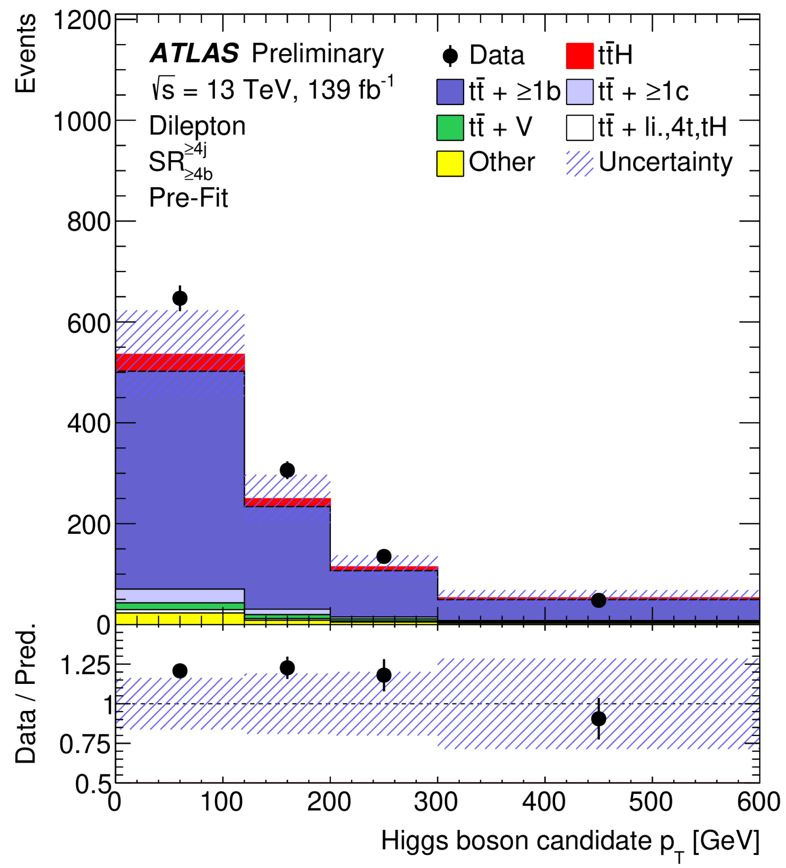
single lepton (resolved)

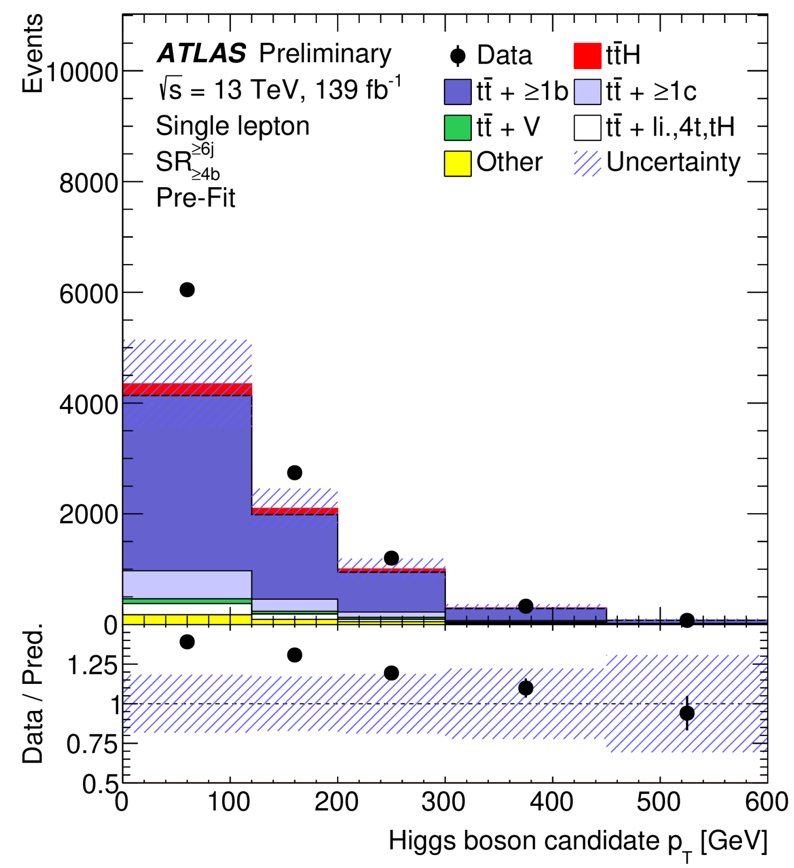
Variable	Definition	$SR^{\geq 6j}_{1,2,3}$	$SR^{5j}_{1,2}$
General kinematic variables			
ΔR^{avg}_{bb}	Average ΔR for all b-tagged jet pairs	✓	✓
$\Delta R^{max\ p_T}_{bb}$	ΔR between the two b-tagged jets with the largest vector sum p_T	✓	–
$\Delta\eta^{max}_{jj}$	Maximum $\Delta\eta$ between any two jets	✓	✓
$m^{min\ \Delta R}_{bb}$	Mass of the combination of two b-tagged jets with the smallest ΔR	✓	–
$m^{min\ \Delta R}_{jj}$	Mass of the combination of any two jets with the smallest ΔR	–	✓
$N^{Higgs\ 30}_{bb}$	Number of b-tagged jet pairs with invariant mass within 30 GeV of the Higgs-boson mass	✓	✓
H^{had}_T	Scalar sum of jet p_T	–	✓
$\Delta R^{min}_{\ell,bb}$	ΔR between the lepton and the combination of the two b-tagged jets with the smallest ΔR	–	✓
Aplanarity	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the momentum tensor [100] built with all jets	✓	✓
H_1	Second Fox–Wolfram moment computed using all jets and the lepton	✓	✓
Variables from reconstruction BDT			
BDT output	Output of the reconstruction BDT	✓*	✓*
m^{Higgs}_{bb}	Higgs candidate mass	✓	✓
$m_{H,b_{lep\ top}}$	Mass of Higgs candidate and b-jet from leptonic top candidate	✓	–
ΔR^{Higgs}_{bb}	ΔR between b-jets from the Higgs candidate	✓	✓
$\Delta R_{H,t\bar{t}}$	ΔR between Higgs candidate and $t\bar{t}$ candidate system	✓*	✓*
$\Delta R_{H,lep\ top}$	ΔR between Higgs candidate and leptonic top candidate	✓	–
$\Delta R_{H,b_{had\ top}}$	ΔR between Higgs candidate and b-jet from hadronic top candidate	–	✓*
Variables from likelihood and matrix element method calculations			
LHD	Likelihood discriminant	✓	✓
MEM_{D1}	Matrix element discriminant (in $SR^{\geq 6j}_1$ only)	✓	
Variables from b-tagging (not in $SR^{\geq 6j}_1$)			
$w^{Higgs}_{b\text{-tag}}$	Sum of b-tagging discriminants of jets from best Higgs candidate from the reconstruction BDT	✓	✓
B^3_{jet}	3rd largest jet b-tagging discriminant	✓	✓
B^4_{jet}	4th largest jet b-tagging discriminant	✓	✓
B^5_{jet}	5th largest jet b-tagging discriminant	✓	✓

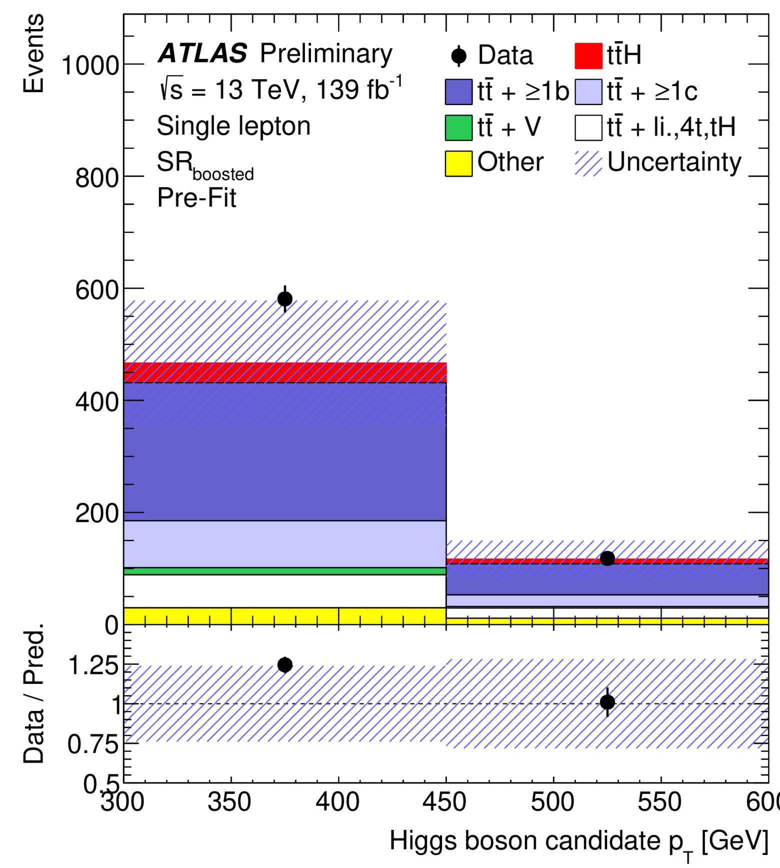
single lepton (boosted)

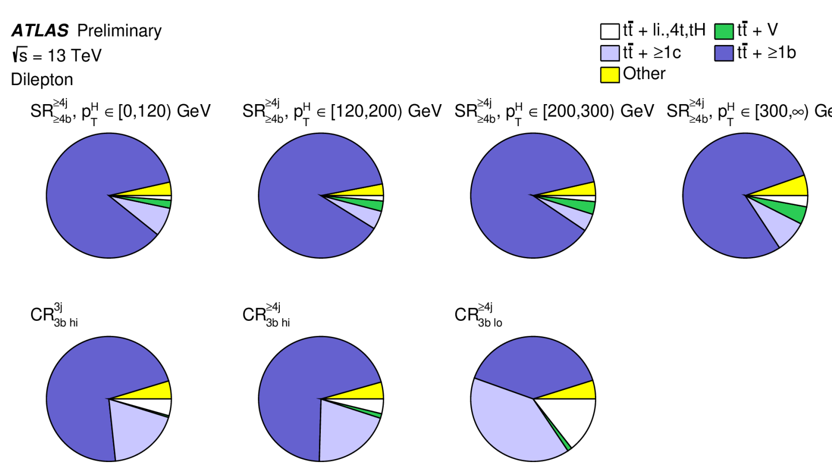
Variable	Definition
Variables from jet reclustering	
$\Delta R_{H,t}$	ΔR between the Higgs-boson and top-quark candidates
$\Delta R_{t,b^{add}}$	ΔR between the top-quark candidate and additional b-jet
$\Delta R_{H,b^{add}}$	ΔR between the Higgs-boson candidate and additional b-jet
$\Delta R_{H,\ell}$	ΔR between the Higgs-boson candidate and lepton
$m_{Higgs\ candidate}$	Higgs-boson candidate mass
$\sqrt{d_{12}}$	Top-quark candidate first splitting scale [101]
Variables from b-tagging	
$w_{b\text{-tag}}$	Sum of b-tagging discriminants of all b-jets
$w^{add}_{b\text{-tag}}/w_{b\text{-tag}}$	Ratio of sum of b-tagging discriminants of additional b-jets to all b-jets

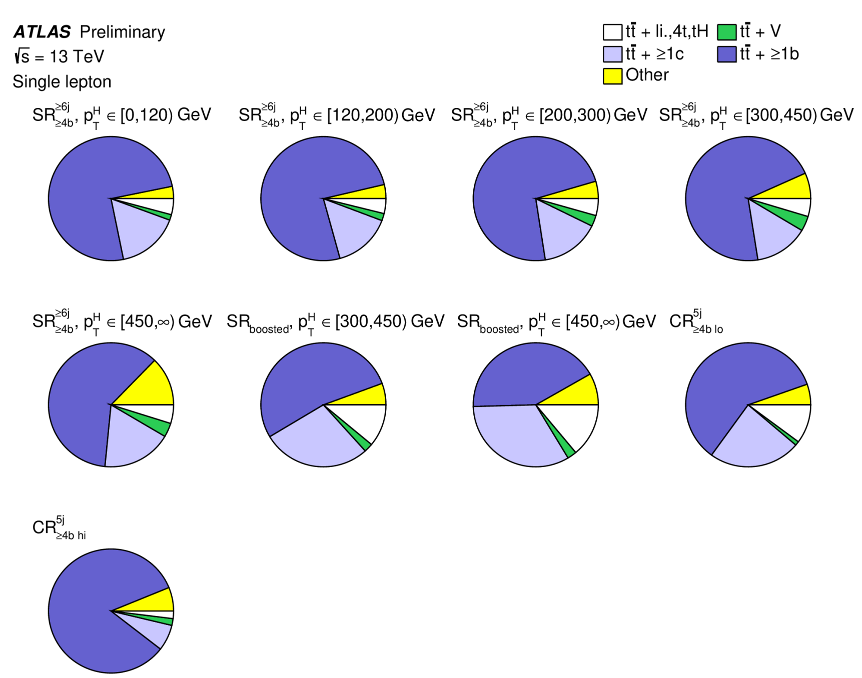
$t\bar{t}H(bb)$: background and p_T^H





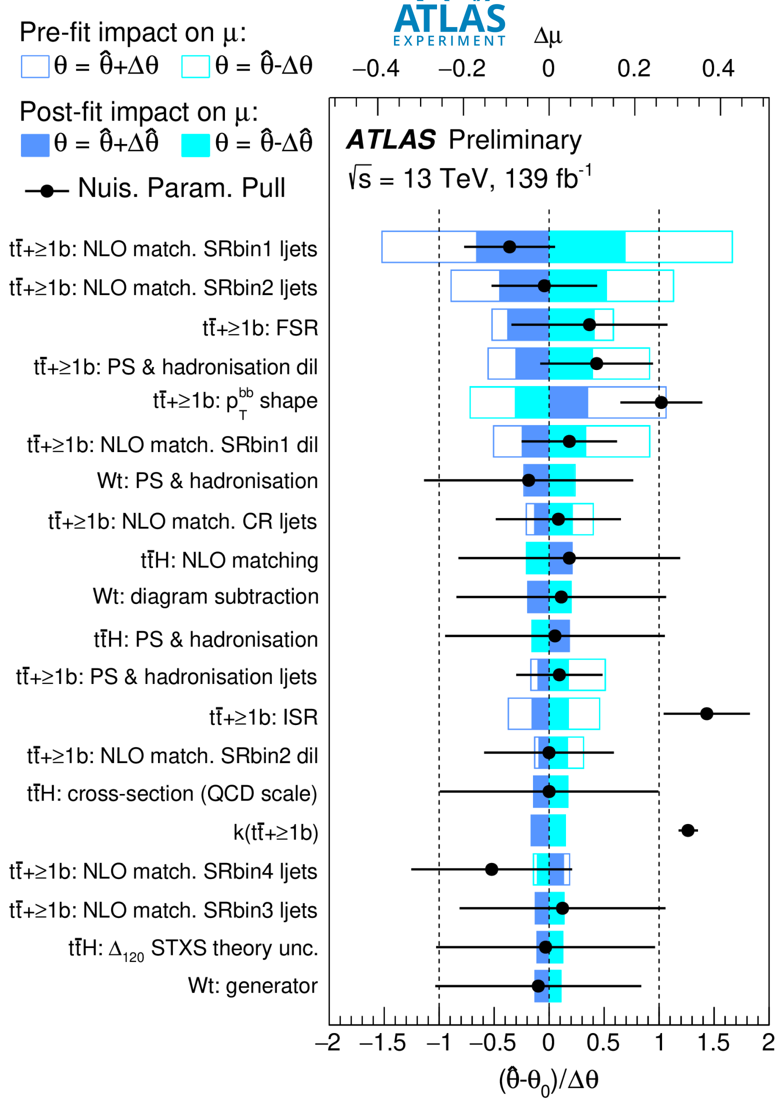




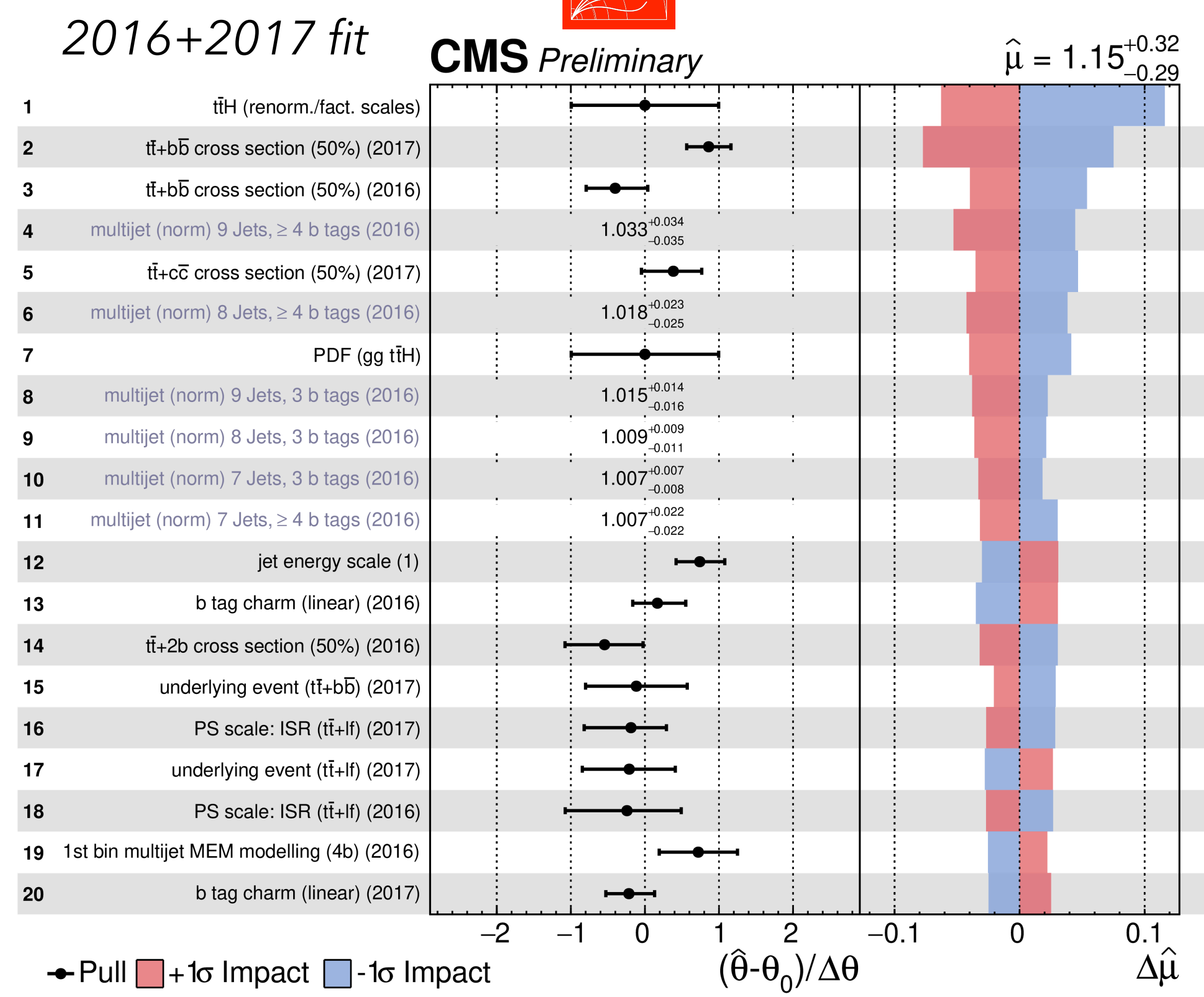


$t\bar{t}H(b\bar{b})$: modelling uncertainties

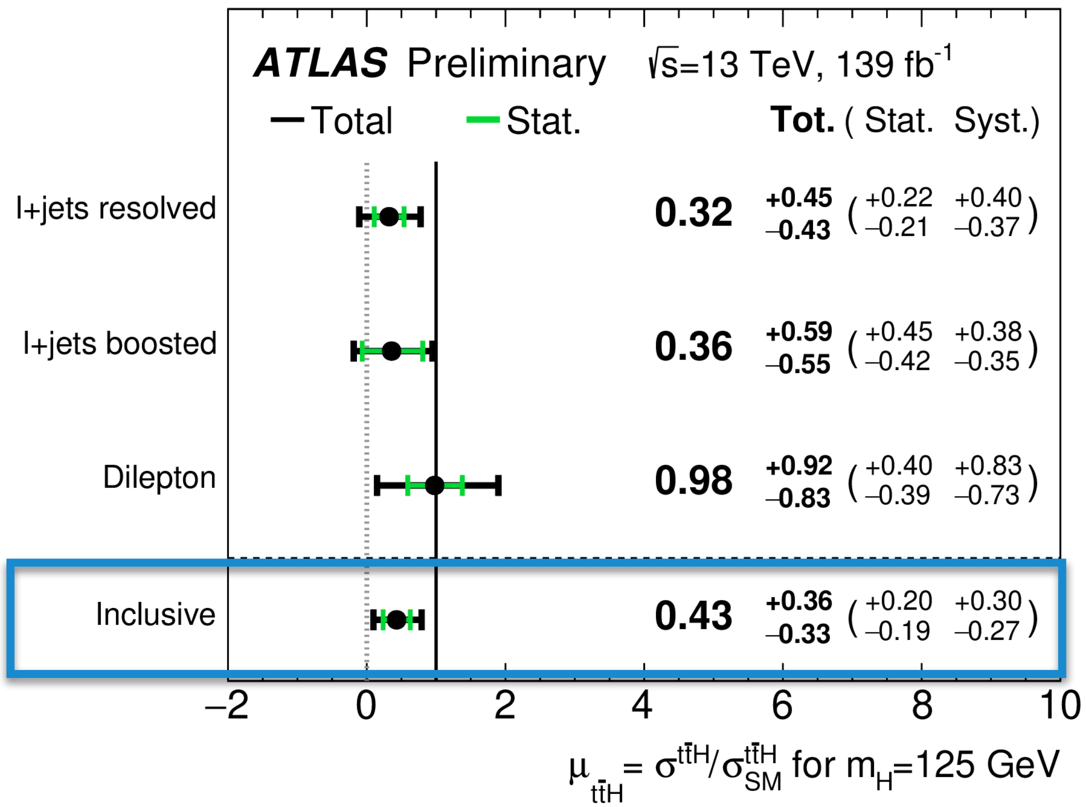
- Generator: Powheg+Pythia8 vs aMC@NLO+Pythia8 (5FS)
- Parton shower: Powheg+Pythia8 vs Powheg+Herwig7
- ISR (+scale), FSR, $t\bar{t}$+1b vs $t\bar{t}$+≥2b fraction uncertainties
- **p_T^{bb} shape uncertainty (ad-hoc)**
- **Free-floating** normalisation $t\bar{t}$+≥1b
- Nuisance parameter (100% prior) $t\bar{t}$+≥1c normalisation

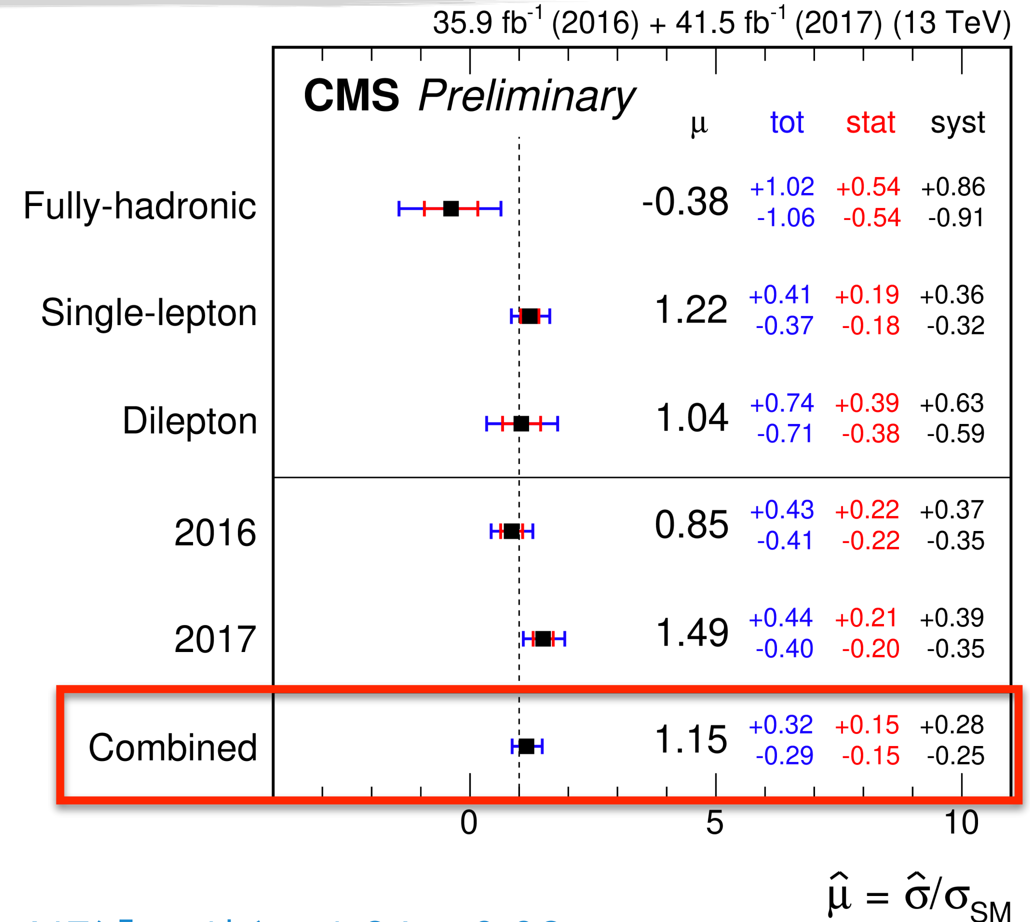


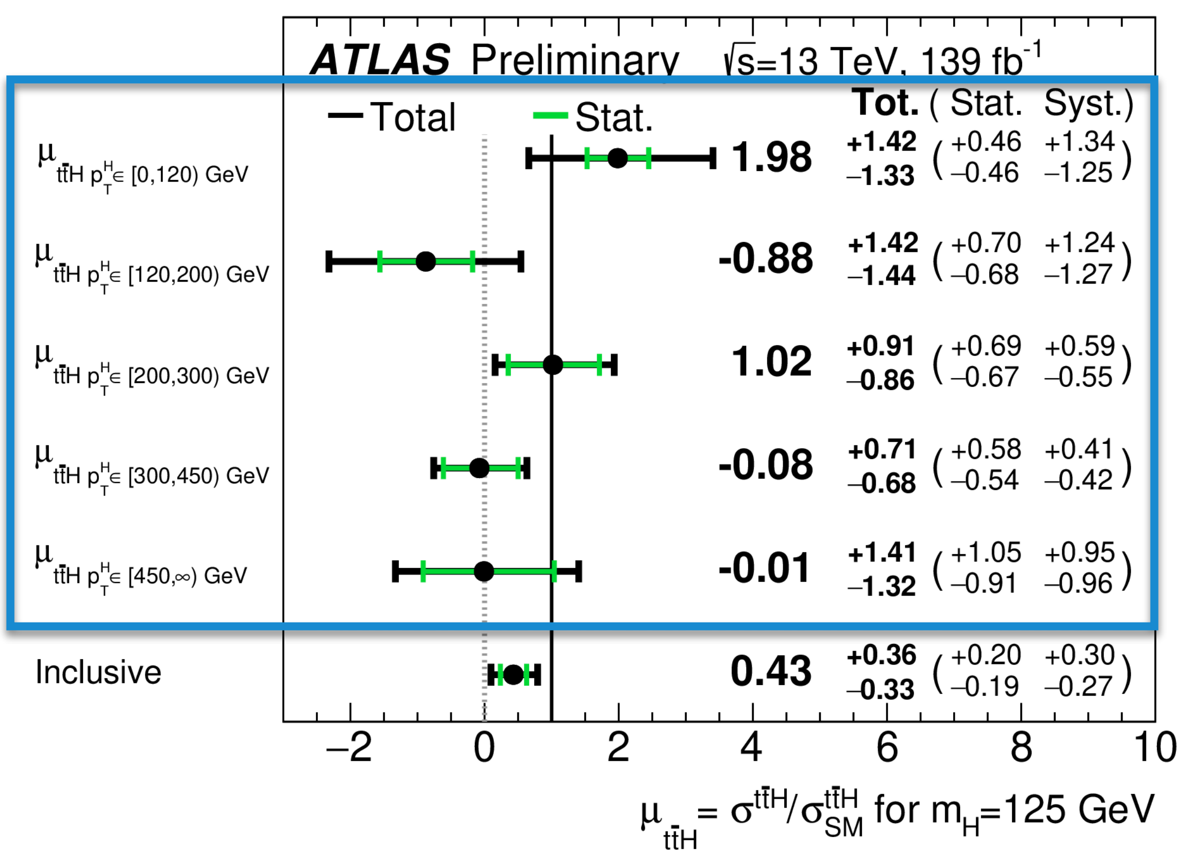
- Parton shower: ISR/FSR
- $t\bar{t}$ underlying event
- $t\bar{t}$ hdamp
- Scale variations
- **Nuisance parameters** for normalisation of tt+bb, tt+2b, tt+b, and $t\bar{t}$+≥1c (50% prior) and **decorrelated** between years



$t\bar{t}H(b\bar{b})$: results



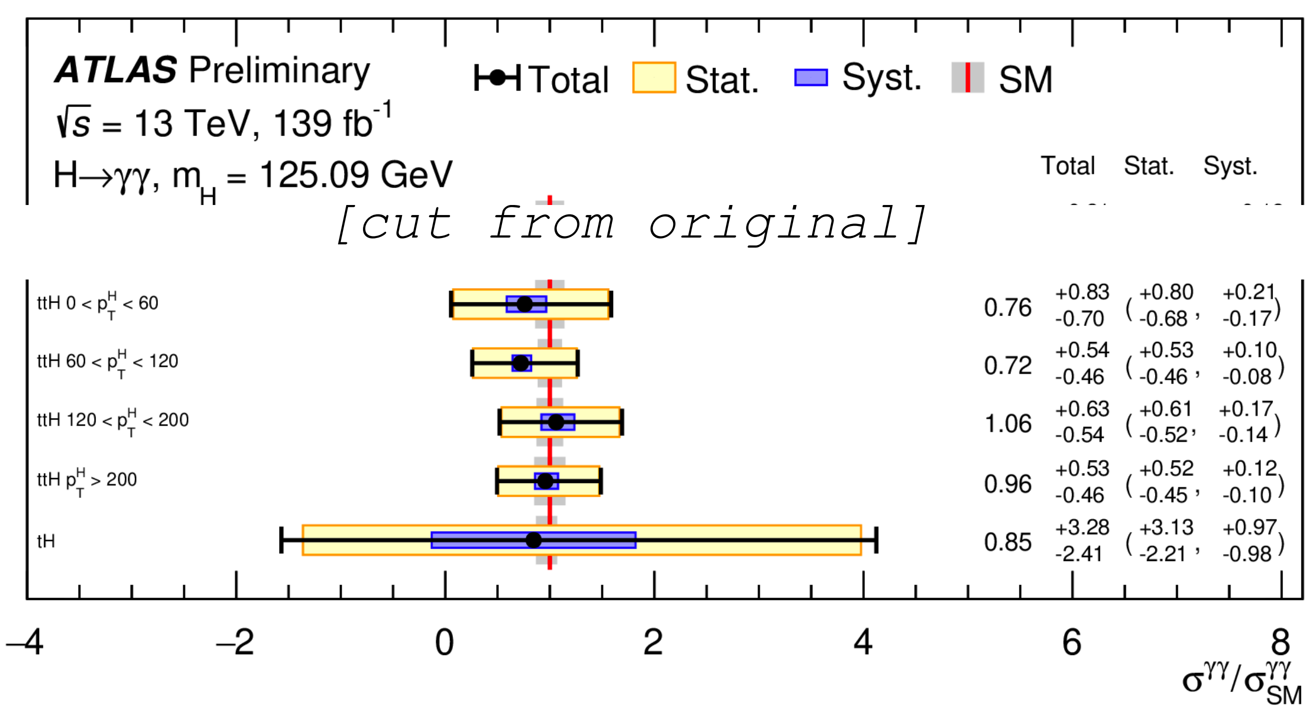




- NF($t\bar{t}+\geq 1b$) = 1.26 ± 0.09
- **Dominated by systematic** uncertainties
- Most relevant uncertainties related to $t\bar{t}+\geq 1b$ background modelling ($\Delta\mu/\mu$ = 60% and 15%)
- Significance w.r.t background-only hypothesis: **1.3 (3.0σ)** and **3.9σ (3.5σ)** obs (exp)
  - **Evidence** for $t\bar{t}H$ in H➔bb channel
- **First $t\bar{t}H(bb)$ STXS measurement**
  - Complements $t\bar{t}H(\gamma\gamma)$ STXS measurements **at high p_T^H**

tt̄H(H→γγ): STXS

- First channel to perform tt̄H measurement differentially
- Leptonic (tt̄H & tH) and hadronic channels (tt̄H & tH)
- Mixture of **multiclass BDT** (STXS signal vs other signals) and **binary BDTs** (STXS signal vs background)
- Mixture of **Top DNN** (tt̄H vs tH) and **BDT** (STXS signal vs non-Higgs SM background), and final classification based on **reco $p_T(\gamma\gamma)$**



- Dominated by stat uncertainty but overall compatible with SM predictions