Full run-2 measurement of ttHbb at 13 TeV

DESY ATLAS Common Group Meeting

Filip Nechanský, Thorsten Kuhl, Timothée Theveneaux-Pelzer

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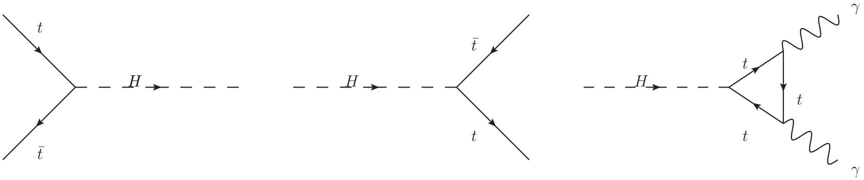
HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

Introduction

- In the Standard Model (SM) the Higgs coupling proportional to mass of the fermion, top the heaviest = the strongest coupling
- Three ways to study such coupling: Higgs production, Higgs decay and loops ...

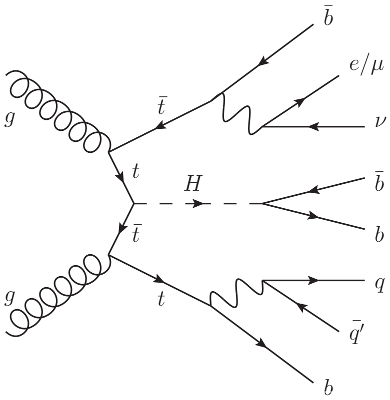


... top too heavy to be a decay product of Higgs, loop only indirect measurements (other contributors to such loop)

- Production ($t\bar{t}H$) the only feasible way to directly measure the top-Higgs coupling
- Spring 2018 CMS observation of the $t\bar{t}H$ process (Phys. Rev. Lett. 120, 231801 (2018)) ... ... ATLAS was not far behind (Phys. Lett. B 784 (2018) 173)

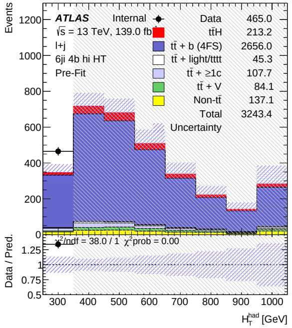
The $t\bar{t}Hb\bar{b}$ analysis at 13 TeV

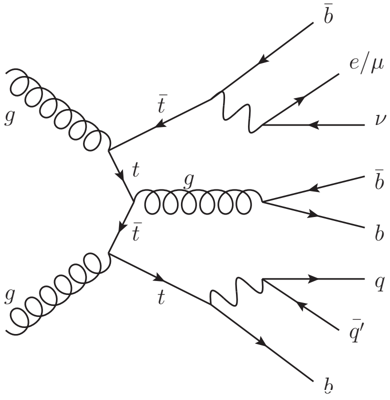
- $t\bar{t}H$ - many decay channels, showing only $t\bar{t}H(H \to b\bar{b})$
- $t\bar{t}Hb\bar{b}$ - possible to reconstruct the $t\bar{t}H$ kinematics, difficult due to combinatorics $\implies$ use of MVA
- ttHbb currently studied in four channels:
  - **Dilepton**
  - **Single lepton resolved**
  - Single lepton boosted
  - All-hadronic
- Will focus on single lepton resolved channel (6 jets, 1 lepton and 4 b-jets) and dilepton channel (4 jets, 2 leptons and 4 b-jets)
- Main difficulty: modelling of the dominant background



Dominant background

- Non-reducible background from the $t\bar{t}b\bar{b}$ (gluon to $b\bar{b}$ pair)
- B-tagging not perfect, contribution from $t\bar{t}$+jets in general
- Dividing $t\bar{t}$ based on the flavour of additional jets:
  - $t\bar{t}+\geq$ 1b - at least one additional b-hadron
  - $t\bar{t}+\geq$ 1c - no add. b-hadron, at least one add. c-hadron
  - $t\bar{t}$+light - the rest





Multivariate techniques

- There is a large number of MVAs used in the analysis, here only those relevant to the talk
- More detailed example of MVA usage in the analysis in the next talk by José :)

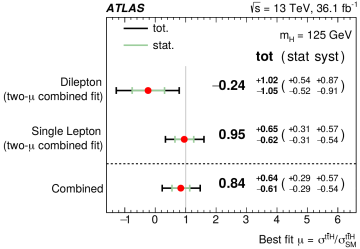
Reconstruction BDT

- BDT used to reconstruct event kinematics (e.g. Higgs p_{T}) from reconstructed objects (jets/b-jets/leptons)

Classification BDT

- Takes output from the other MVAs to make a single discriminant between the signal and background
- Used as a fit variable in the signal region

Paper results (Phys. Rev. D 97 (2018) 072016)



- 2015+2016 data only
- Single lepton (resolved+boosted) and dilepton channel
- 1.4 σ observed significance, 1.6 σ expected
- Systematically limited in both channels

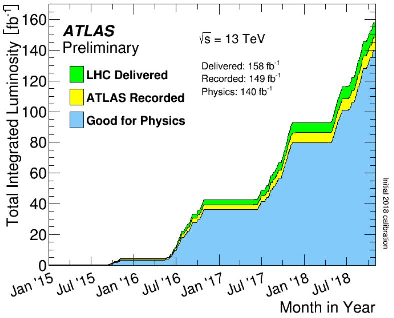
Dominant systematic uncertainties (combined):

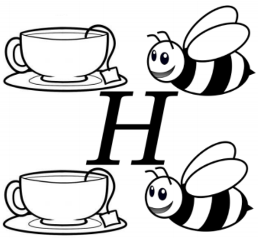
Uncertainty source	$\Delta\mu$	
$t\bar{t} + \geq 1b$ modeling	+0.46	−0.46
Background-model stat. unc.	+0.29	−0.31
b-tagging efficiency and mis-tag rates	+0.16	−0.16
Jet energy scale and resolution	+0.14	−0.14
$t\bar{t}H$ modeling	+0.22	−0.05
Total systematic uncertainty	+0.57	−0.54
Total uncertainty	+0.64	−0.61

- $t\bar{t}+\geq$ 1b modelling
- Low Monte Carlo (MC) statistics (influences the modelling unc. as well)
- b-tagging and jet calibration uncertainties

$t\bar{t}Hb\bar{b}$ analysis with full run-2 dataset [Glance]

- $\approx 4\times$ the data statistic w.r.t. previous paper
- Improved MC statistics





- New improved reconstruction software
- New recommendations and calibrations
  - New b-tagging
  - New jet calibration

Fit regions

- Jet multiplicity not well modelled - regions divided based on number of jets
- Also divided based on the b-tagging:
  - **4b (3b) tight:** at least 4 (3) b-jets @ 60% efficiency
  - **4b (3b) loose:** at least 4 (3) b-jets @ 70% efficiency (veto on tight)

Single lepton resolved regions

All regions are fitted as a function of the Classification BDT

- [=5j, 4b loose], [=5j, 4b tight], [$\geq 6j$, 4b loose], [$\geq 6j$, 4b tight]

Dilepton regions

Regions with a single bin:

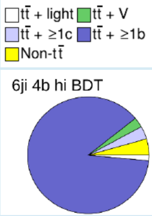
- [=3j, 3b tight], [≥4j, 3b loose], [≥4j, 3b tight]

Regions fitted as a function of the Classification BDT:

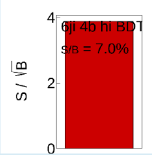
- [≥4j, 4b loose], [≥4j, 4b tight]

[$\geq 6j$, 4b tight]

Bkg composition:



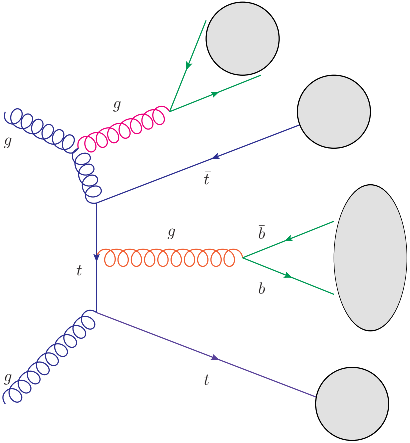
S/B and S/$\sqrt{B}$:



Modelling of tt+b (dominant background)

Two possible predictions of the tt+≥1b considered:

- ttbar 5 flavour scheme (5FS): additional massless b quarks come from parton shower
- ttbb 4 flavour scheme (4FS): 2 massive b-quarks in the matrix element (NLO)



ttbb 4FS samples

ttbb 4FS: better agreement with data then 5FS

- **Powheg+Py8 ttbb** (current nominal)
- Sherpa ttbb (only currently available alternative generator)
- Variations of var3c(α_s^{ISR}), μ_R/μ_F, α_s^{FSR} (ISR/FSR)

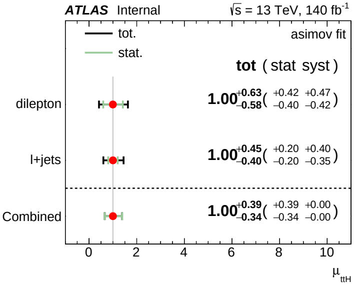
ttbar inclusive 5FS samples

Used to estimate additional unc. on the 4FS:

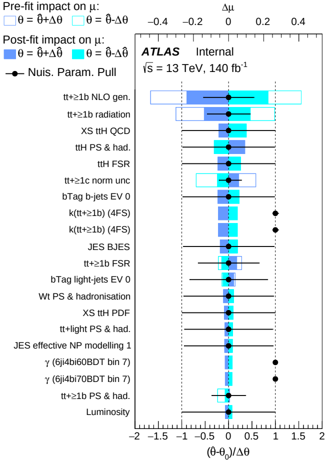
- Powheg+Py8 (reference sample)
- **aMC@NLO+Py8** (NLO matching systematic)
- Powheg+Her7 (PS&had. systematic)

ASIMOV fit

- Fit of MC to pseudodata build based of the same MC
- Done to show impact of systematics and expected sensitivity
- Parameter of interest ttH: normalization $\mu_{ttH} = \sigma^{measured} / \sigma^{SM}$
- ttb - free floating normalization $k(tt + b)$
- Expected significance around 3
- Dominant systematic NLO Gen Matching (aMC vs PP8)

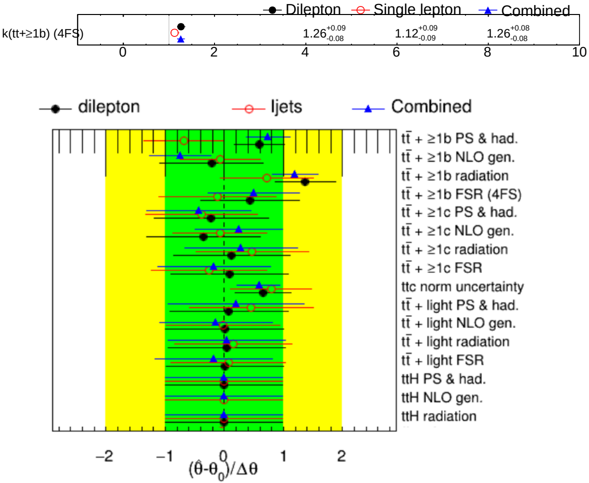


Ranking of the impact on the POI:

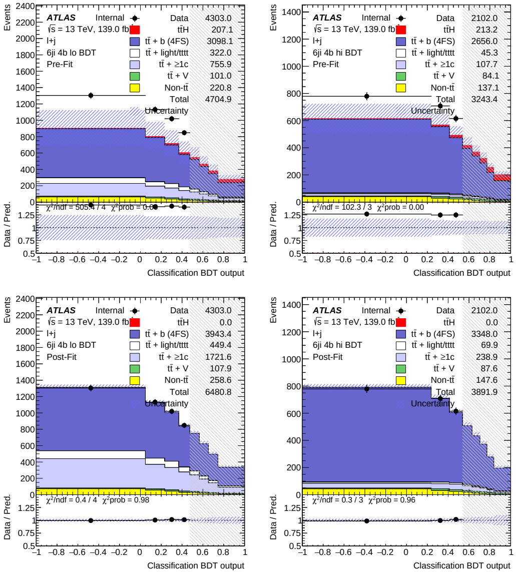


Background only fit to data in unblinded BDT bins

- Blinding of all bins with S/B> 5%
- To estimate background modelling fit all unblinded bins (without the signal sample)
- Difference in ttb normalization and ttb PS due to strong anti-correlation in l+jets only
- Is being investigated
- Otherwise comparable pulls



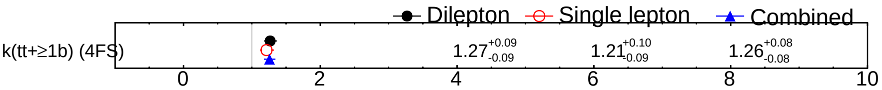
Pre- and post-fit plots (l+jets)



- Showing [$\geq 6j$, 4b loose], [$\geq 6j$, 4b tight] regions
- Significant reduction in the uncertainties
- Good post-fit agreement

"Realistic" asimov fit: Channel comparison and combination (WiP)

- Procedure:
  1. Take NP pulls from Data background only fit
  2. Create ASIMOV data based on these shifts
  3. Perform ASIMOV fit to the "realistic" asimov dataset

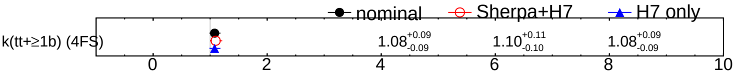


- Comparable performance between channels
- Medium significance: classical asimov 3.01, "realistic" 2.71, only 10% difference

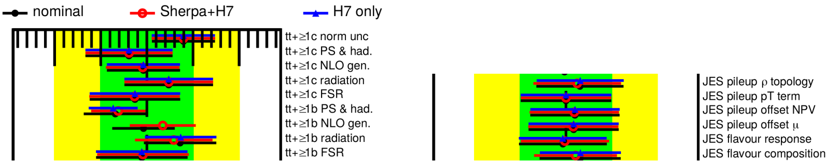
Alternative modelling studies

aMC seems to be NOT favoured by data $\Longrightarrow$ drop it? Switch to Sherpa 4FS?

Example: aMC+H7 vs Sherpa+Herwig7 vs Sherpa only



- Comparable performance of different models in data BONLY fits
- Vastly different sensitivity!
- aMC is never pulled, only constrained...



Expected significance

- aMC+H7: 3.17
- SH+H7: 4.26
- H7 only: 4.28

(slightly older results)

CP odd analysis (will be published separately)

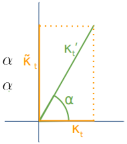
Last update [Emanuel Gouveia, Ana Luísa Carvalho, Nicolas Scharmberg]

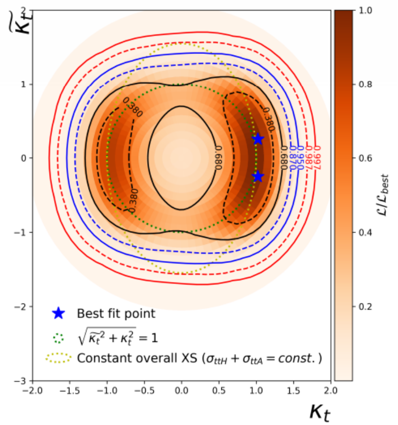
- In Standard Model $t\bar{t}H$ coupling is CP even, BSM allows for CP odd or mixed coupling

$$\mathcal{L}_{tth} = y_t \bar{\psi}_t \kappa_t' (\cos\alpha + i\gamma_5 \sin\alpha)\psi_t h \qquad \sigma = \kappa_t'^2 (\cos^2\alpha\,\sigma_{even} + \sin^2\alpha\,\sigma_{odd})$$

$$\mathcal{L}_{tth} = y_t \bar{\psi}_t (\kappa_t + i\gamma_5 \tilde{\kappa}_t)\psi_t h \qquad \sigma = \kappa_t^2 \sigma_{even} + \tilde{\kappa}_t^2 \sigma_{odd}$$

$$\kappa_t \equiv \kappa_t' \cos\alpha$$
$$\tilde{\kappa}_t \equiv \kappa_t' \sin\alpha$$





- Many discriminating variables, requires Higgs/top reconstruction
  ... but we do that anyway
- Fitting in inclusive 4b@70% regions, further divided by Class. BDT from nominal analysis
- CP-BDT trained to better distinguish between odd/even

Summary

- Observation of ttH last year!
- ttHbb one of the "smaller" channels, challenging background
- Use of multivariate algorithms to separate signal from background
- Using Pow+Py8 ttbb 4FS sample as nominal sample for dominant background
- tt+jets modelling still leading systematics - optimizing still in progress!
- EB created, first meeting being scheduled
- CP-odd BSM analysis developed in parallel

... and there is more (see backup)

- Single lepton boosted channel
- All hadronic analysis
- Simplified template cross-section interpretation (STXS) in Higgs p_{T}

Backup slides

tt+HF categorisation [Timothée]

- tt+jets process subdivided at truth level depending on origin of the additional jets
- First match **not-from-top** hadrons to particle-level jets:

Particle-level jet p_T	>15 GeV
Particle-level jet $\|\eta\|$	<2.5
Hadron p_T	>5 GeV
Jet-Hadron matching	ΔR <0.4

- Then, count the number of jets matched to not-from-top HF hadrons:

process	# jets	w/ # hadrons
$t\bar{t}+\geq 1b$	≥ 1	$\geq 1b$
$t\bar{t}+b(MPI/FSR)$	all b-jets from MPI/FSR	
$t\bar{t}+b$	$=1$	$=1b$
$t\bar{t}+bb$	$=2$	$=1b$
$t\bar{t}+B$	$=1$	$\geq 2b$ ($\geq$1b with p_T threshold)
$t\bar{t}+\geq 3b$	other $t\bar{t}+\geq 1b$ events	
$t\bar{t}+\geq 1c$	≥ 1	$\geq 1c$
$t\bar{t}+\text{light}$	other tt+jets events	

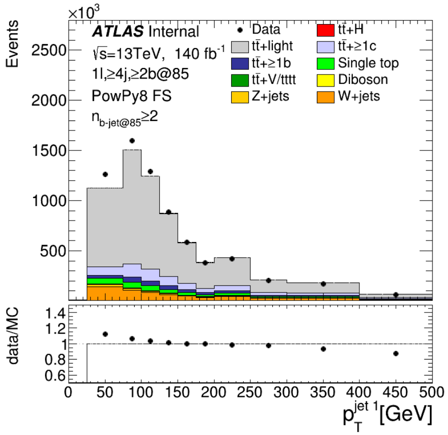
- For 4FS samples there is for technical reasons no mpi/fsr classification
  $\Longrightarrow$ is mpi/fsr significant in 5FS? Will answer later ...

Monte Carlo - filtered samples

Full run 2 plot:

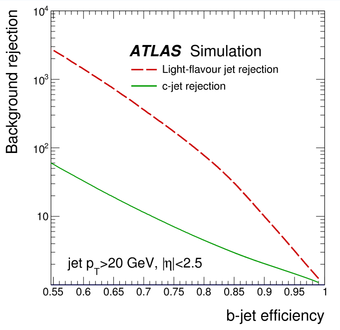
- Solution to MC stat problem - cannot just request super large samples, we need to be more clever
- We are mostly limited by tt+b but in pure sample its contribution is rather small

$\Longrightarrow$ Filter the tt+b during generation.
$\Longrightarrow$ Get lots of stats where it matters!
$\Longrightarrow$????
$\Longrightarrow$ Profit!

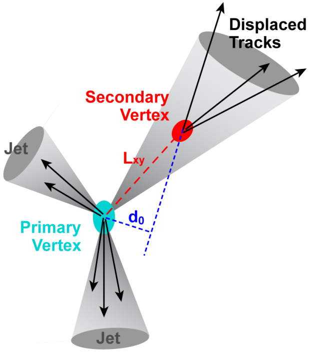


Interlude - b-tagging

- *b*-quarks hadronize to b-hadrons with relatively large lifetime
- Identification using e.g. secondary vertex (few mm from PV)
- MV2c10 algorithm exploits all available information to discriminate between b-jets, c-jets and light-jets



- 4 b-tagging working points
- Based on signal efficiency: 60%,70%,77%,85%
- Either inclusive or in bins (60-70%,70-77%, etc)
- Trade-off between efficiency and background rejection



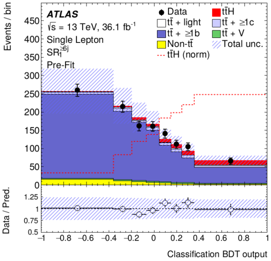
Maximum likelihood fit ...

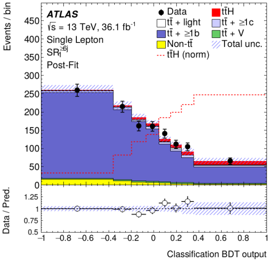
... is a topic for an entire lecture, but in a nutshell:

- Our models always have a Parameters of Interest (POI) and Nuisance Parameters (NP)
  - Example of POI - normalization of signal, in our case: $\mu_{ttH} = \sigma^{measured}/\sigma^{SM}$
  - Nuisance parameters would be e.g. normalizations of the tt+b and tt+c subcomponents
  - In most cases all systematics are a nuisance ...
- Maximizing likelihood to obtain best estimation of all the parameters
- Can lead to a shift in the central value (so-called pull)
  and in change of the uncertainty (constrain) of POIs and NPs!
- Basically we can use data to constrain systematic uncertainties

- Profile likelihood fit done in all regions together
- Done in TRExFitter fitting tool (former TtHFitter, used to be ttH specific)
- Build upon RooStats, all is done using convenient config file (though little bit of a black box)
- Useful when managing large number of systematics/samples/regions

Example of pre- and post-fit plots (here for the tightest region with 6 jets and 4 b-jets at 60% WP):

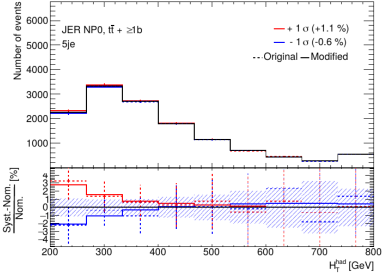




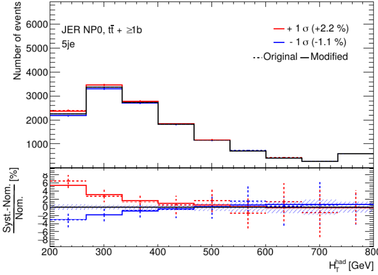
TREx creates all the plots for you!

Older plot for one of the systematics:

non-filtered:



filtered:

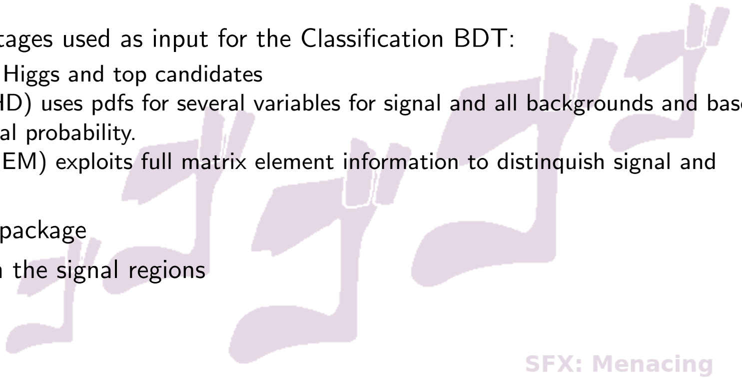


Here statistical uncertainty significantly reduced
X two times larger syst. uncertainty for filterered!

Multivariate techniques

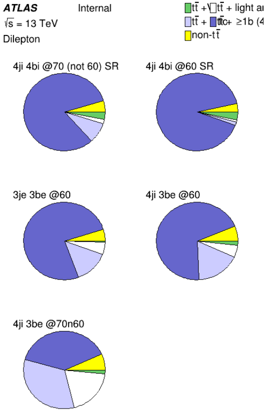
... not gonna pretend I understand half of these

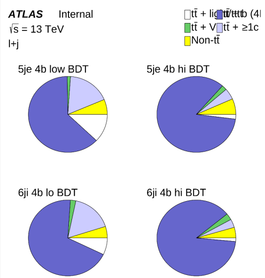
- Classification Boosted Decision Tree (BDT) used to further discriminate between signal and background
- There are three independent stages used as input for the Classification BDT:
  - Reconstruction BDT builds Higgs and top candidates
  - Likelihood Discriminant (LHD) uses pdfs for several variables for signal and all backgrounds and based on them tries to assign signal probability.
  - Matrix Element Method (MEM) exploits full matrix element information to distinquish signal and background
- BDT done in the TMVA root package
- Output variable used for fits in the signal regions

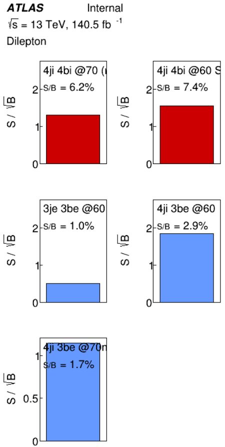


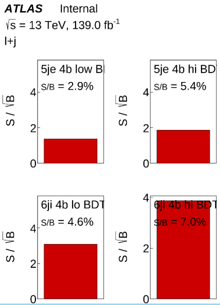
Regions composition

- Most regions dominated by ttb subcomponent
- One "looser" region in dilepton to better control ttc sub-component



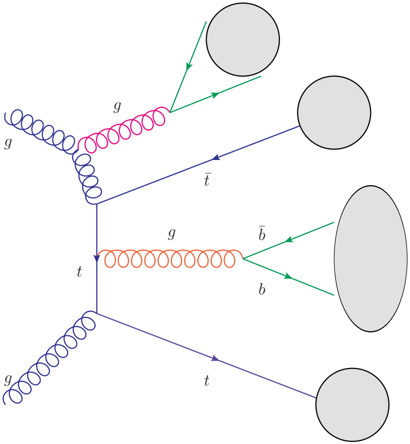






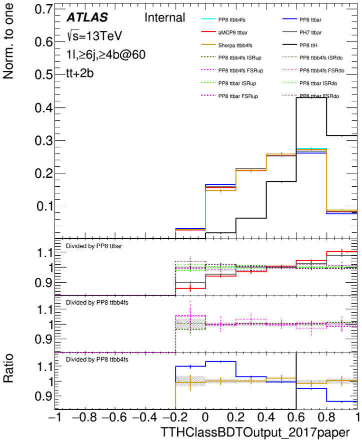
Event generation

… compressed into one slide



- Matrix Element (ME) - the hard scattering process, generated with certain precision (LO,NLO)
- Parton shower - emission of additional partons in QCD/EW
  - Initial state radiation (ISR) and Final state radiation (FSR)
  - Needs to be interfaced with radiation in the Matrix Element to remove overlap (matching)
- Fragmentation produces additional partons to create colorless objects which then hadronize

ttb modelling: L+jets signal regions, dR_{bb}^{avg}, tt+2b



- Normalized to one, component with two b-jets (+ttH incl.)
- Generally small differences, PP8 5FS and 4FS two "extremes"
- 4FS samples more signal-like compared to other samples

Modelling of other samples

ttc

- ME NLO Matching (aMC@NLO)
- Parton Shower (H7)
- ISR/FSR (internal weights)
- **100% norm. unc.**

ttlight

- ME NLO Matching (aMC@NLO)
- Parton Shower (H7)
- ISR/FSR (internal weights)
- 6% norm. unc.

ttH

- ME NLO Matching (aMC)
- **Parton Shower (H7)**
- **ISR/FSR (int. weights)**
- **YR4 XS unc. (QCD/PDF)**

$t\bar{t}$ modelling and associated uncertainties

Nominal

- Before: Pow+Py8.210 (5F)
- Now: Pow+Py8.230 (5F)

NLO matching

- Before: Sherpa 2.2.1 (5F), diff. order in pQCD and matching, also different PS&hadronisation
- Now: aMC@NLO+Py8.230 (5F)

PS and hadronization

- Before: Pow+Hw7.01
- Now: Pow+Hw7.04

ISR/FSR

- Before: Pow+Py8.210 var3c(α_s^{ISR}), μ_R/μ_F, hdamp
- Now: Pow+Py8.230 var3c(α_s^{ISR}), μ_R/μ_F, α_s^{FSR}

Boosted Selection

JG|U

selections / variable	Boosted
# small jets	≥ 4
# b-tagged 85% jets	≥ 3
	Higgs candidate: 1 reclustered jet
reco p_T[GeV]	300
mass[GeV]	[100-140)
R=0.4 subjets b-tagged 85%	==2
P(true Higgs)	$\geq$ 0.6
	Hadronic Top candidate: - (no special cut)
	Leptonic Top: - (no special cut)

- First, searching for ***Higgs candidate***:
  if $\exists > 1 \xrightarrow{choose}$ that with mass closest to Higgs mass
- Then, searching for ***HadrTop cand*** (for reconstruction see Backup)
- Finally, searching for ***Leptonic Top*** (for reconstruction see Backup)
- ▶ **Higgs**, **Hadronic Top** and **Leptonic Top** jets don't overlap

Modelling of other samples

ttc

- ME NLO Matching (aMC@NLO)
- Parton Shower (H7)
- ISR/FSR (internal weights)
- **100% norm. unc.**

ttlight

- ME NLO Matching (aMC)
- Parton Shower (H7)
- ISR/FSR (internal weights)
- 6% norm. unc.

ttH

- ME NLO Matching (aMC)
- **Parton Shower (H7)**
- **ISR/FSR (int. weights)**
- **YR4 XS unc. (QCD/PDF)**

Bosonic

W+jets

- 40% incl. XS unc.
- 40% HF XS unc.

Z+jets

- 35% XS unc. (3j,4j)

diboson

- 50% XS unc.

Single top

- ME NLO matching
- Parton shower
- 5% XS unc.

Other top

tW

- DS vs. DR

ttV

- YR4 CS unc. (PDF/QCD)

4-top

- 50% XS unc.

$t\bar{t}H$ coupling CP

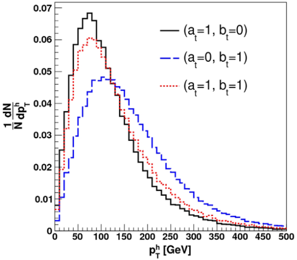
- In Standard Model $t\bar{t}H$ coupling is CP even, various BSM model allow for CP odd or mixed coupling
- Additional parameter α in the lagrangian:

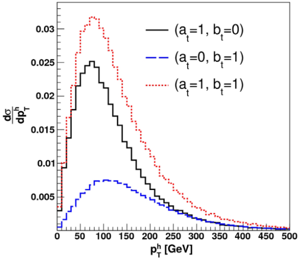
$$\mathcal{L}_{ht\bar{t}} = y_t \kappa \bar{t}(\cos\alpha + i\sin\alpha\gamma_5)th$$

cosα=0 ≡ pure CP-odd
cosα=1 ≡ pure CP-even

- Many discriminating variables, usually require Higgs/top reconstruction...
  ... but we do that anyway

BOUDJEMA *et al.* PHYSICAL REVIEW D **92,** 015019 (2015)





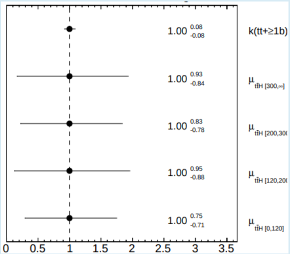
Is there anything beyond the Standard Model?

Additional aspects of the analysis

Last update[Peter Berta, Manuel Guth, Eftychia Tzovara]

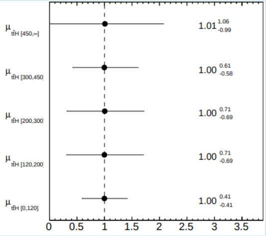
Simplified template cross-section (STXS)

- Studying Higgs XS in various Higgs p_{T} bins
- Allows for example BSM studies
- Using reconstructed p_{T}^{H} from our Reco BDT, divided in following bins: 0-120,120-200,200-300,300-450,450+ GeV
- L+jets resolved results:



Boosted single lepton channel

- Selection in nutshell (details in backup)
  - 4 jets, 3 b-jets@85%
  - Reconstructed Higgs (reclustered jet, p_{T} >300 GeV, 2 b-sub-jets)
  - One hadronic top candidate
  - One leptonic top candidate
- Improves sensitivity (extra p_{T} bin!):



All hadronic analysis (will be published separately)

Last update [Giovanni Bartolini]

- Newest addition between ttHbb channels
- Takes advantage of b-jet triggers

Trigger chain	Luminosity 2016	Luminosity 2017	Luminosity 2018
HLT_2j35_bmv2c2060_split_2j35_L14J15.0ETA25	24.6 fb^{-1}	–	–
HLT_2j15_gsc35_bmv2c1060_split_3j15_gsc35_boffperf_split	–	43.7 fb^{-1}	–
HLT_2j35_bmv2c1060_split_2j35_L14J15.0ETA25	–	–	58.5 fb^{-1}

- Large jet multiplicities! Regions with 6,7,8 and 9+ jets
- Significant background from QCD multijet backgrounds
- Used new class. BDT
- Statistical sensitivity comparable to dilepton

S/B and S/$\sqrt{B}$ in 2017