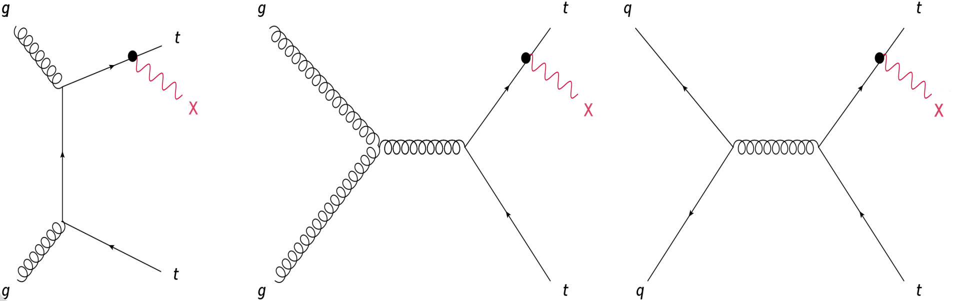
Measurements and perspectives for $t\bar{t}$+X physics

ATLAS-CMS Monte Carlo Generators Workshop

Marco A. Harrendorf on behalf of the ATLAS and CMS collaboration | January 12th, 2016

INSTITUT FÜR EXPERIMENTELLE KERNPHYSIK (IEKP)



Contributions

This talk is based on the work of the ATLAS and CMS collaboration and on contributions by the following persons among others:

Andrew Brinkerhoff, James Ferrando, Andrea Giammanco, Dominic Hirschbühl, Andrea Helen Knue, Maria Moreno Llacer, Benedikt Maier, Fabrizio Margaroli, Josh McFayden, Andre Mendes, Ben Nachman, Monica D'Onofrio, Darren Puigh, Korbinian Schweiger, Markus Cristinziani, Martijn Mulders, Matthias Danninger, Pietro Govoni, Luca Perrozzi, Guillelmo Retuerto, Tamara Vazquez Schröder, Ulrich Husemann, . . .

Thanks to all of them and all persons I have forgotten to mention!

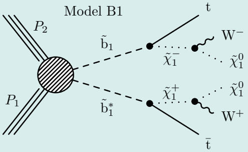
Motivation to study $t\bar{t}$+X processes

Impact on many SM measurements

- Precise measurement of top quark properties.
- Many SM analyses have $t\bar{t}$+X backgrounds.

$t\bar{t}$+X final-state contributions by possible BSM models

- Many BSM models could contain $t\bar{t}$+X final-states.
  Example: Bottom-squark pair production, taken from arXiv:1311.6736v2.



- BSM models could also enhance the production of SM $t\bar{t}$+X final-states through new couplings.
  Example: Dimension-six operators contributing to $t\bar{t}Z$ production.

Search for $t\bar{t}H$ signal

Motivation

- After the discovery of a Higgs-boson in Run 1 the focus in Run 2 lies on its full characterization.
- Precise knowledge of the Top-Higgs-Yukawa coupling is essential, and the $t\bar{t}H$ process allows a model-independent measurement of it.
- Due to its large mass the top-quark has the strongest coupling to the Higgs-boson among all known SM particles.

Experimental challenges

- Small signal cross section compared to other Higgs production modes.
- Tiny signal cross section compared to $t\bar{t}$+jets background and suffering especially from irreducible $t\bar{t}+b\bar{b}$ background process.

Searches for $t\bar{t}$H, H→bb signal in Run 1

ATLAS: Search for $t\bar{t}$H, H→bb

- Combining both matrix element method (MEM) and neural networks (NN).
- arXiv:1503.05066 / Eur. Phys. J. C (2015) 75:349

CMS: Search for $t\bar{t}$H, H→bb with BDT

- Using boosted decision tree (BDT) method for discrimination of signal and bkg.
- arXiv:1408.1682 / JHEP 09 (2014) 087

CMS: Search for ttH, H→bb with MEM

- Using matrix element method (MEM) for full event interpretation.
- arXiv:1502.02485 / Eur. Phys. J. C 75 (2015) 251

Note: Other Higgs decay modes and further information

- Further $t\bar{t}$H analyses using other less dominant Higgs decay modes ($t\bar{t}$H, H→leptons and $t\bar{t}$H, H→$\gamma\gamma$) are also publicly available, links can be found in backup.
- Detailed summary talk about $t\bar{t}$H, H→bb analyses given by Darren Puigh at TOP15.

Modelling of the $t\bar{t}H$ process

MC samples for the $t\bar{t}H$, H→bb Run 1 analyses

Process	ATLAS	CMS
$t\bar{t}H$	PowHel+Pythia8	Pythia6
$t\bar{t}$+jets	POWHEG-BoxV2+Pythia6 MadGraph5+Pythia6 Sherpa+OpenLoops	MadGraph5+Pythia6
$t\bar{t}W$	MadGraph5+Pythia6	MadGraph5+Pythia6
$t\bar{t}Z$	MadGraph5+Pythia6	MadGraph5+Pythia6
Single top	POWHEG-BoxV2+Pythia6	POWHEG-BoxV1+Pythia6
DY+jets	Alpgen+Pythia6	MadGraph5+Pythia6
W+jets	Alpgen+Pythia6	MadGraph5+Pythia6
ZZ+jets	Alpgen+Herwig6	MadGraph5+Pythia6 (BDT) / Pythia6 (MEM)
WW+jets	Alpgen+Herwig6	MadGraph5+Pythia6 (BDT) / Pythia6 (MEM)
WZ+jets	Alpgen+Herwig6	MadGraph5+Pythia6 (BDT) / Pythia6 (MEM)

- Mostly LO event generators are used.
- Choice of event generator is quite different between the analyses.

Modelling of the $t\bar{t}H$ process

Normalization of the MC samples for the $t\bar{t}H$, H$\rightarrow$bb Run 1 analyses

Process	ATLAS	CMS
$t\bar{t}H$	NLO	NLO
$t\bar{t}$+jets	NNLO	NNLO
$t\bar{t}W$	NLO	NLO
$t\bar{t}Z$	NLO	NLO
Single top	NNLO	NNLO (BDT) / no norm. (MEM)
DY+jets	NNLO	NNLO
W+jets	NNLO	NNLO
ZZ+jets	NLO	NLO
WW+jets	NLO	NLO
WZ+jets	NLO	NLO

- Note: Some of the samples are additionally reweighted to match NLO computations.
- Scale factors between LO and (N)NLO are often large (e.g. roughly 1.07-1.31 for $t\bar{t}H$, strongly depending on PDF).
  $\Rightarrow$Use of NLO event generators is strongly encouraged – if possible – in the future.

Modelling of the $t\bar{t}H$ process

Importance of MC-related uncertainties

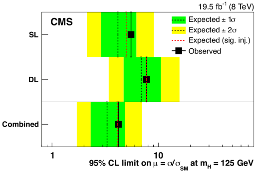
Source	Rate uncertainty	Shape	Process		
			$t\bar{t}H$	$t\bar{t}$+jets	Others
Experimental uncertainties					
Integrated luminosity	2.6%	No	✓	✓	✓
Trigger and lepton identification	2–4%	No	✓	✓	✓
JES	4–13%	Yes	✓	✓	✓
JER	0.5–2%	Yes	✓	✓	✓
b tagging	2–17%	Yes	✓	✓	✓
Theoretical uncertainties					
Top p_T modelling	3–8%	Yes		✓	
μ_R/μ_F variations	2–25%	Yes		✓	
$t\bar{t}+b\bar{b}$ normalisation	50%	No		✓	
$t\bar{t}$+b normalisation	50%	No		✓	
$t\bar{t}+c\bar{c}$ normalisation	50%	No		✓	
Signal cross section	7%	No	✓		
Background cross sections	2–20%	No		✓	✓
PDF	3–9%	No	✓	✓	✓
Statistical uncertainty (bin-by-bin)	4–30%	Yes	✓	✓	✓

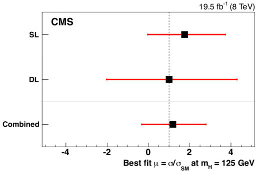
- Note: Systematic uncertainties of the CMS MEM $t\bar{t}H$, H$\rightarrow$bb analysis are stated. Similar uncertainties are occuring in the other analyses.
- Theoretical uncertainties are dominant in comparison to experimental uncertainties and could limit the significance of upcoming analyses.
  $\Rightarrow$Reduction of theoretical uncertainties by making use of more advanced MC event generators seems essential in Run 2 and thereafter.

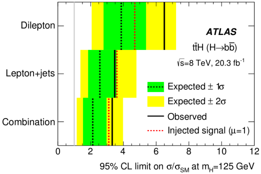
$t\bar{t}H$, H$\rightarrow$bb Run 1 results

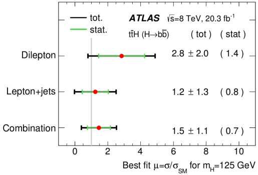
Combined observed and expected limits and best-fit value

Analysis	Comb. obs. limit μ	Comb. exp. limit μ	Best-fit value $\hat{\mu}$
ATLAS	3.4	2.2	1.5 ± 1.1
CMS (BDT)	4.1	3.5	0.7 ± 1.9
CMS (MEM)	4.2	3.3	$1.2^{+1.6}_{-1.5}$









Outlook: Run 2 searches for $t\bar{t}H$ signal

ATLAS: Upcoming public note

- The ATLAS Note ATL-COM-PHYS-2015-1510 about "Modelling of the $t\bar{t}H$ and $t\bar{t}V$ (V = W, Z) processes for $\sqrt{s} = 13$ TeV ATLAS analyses" is in the final steps of publication.

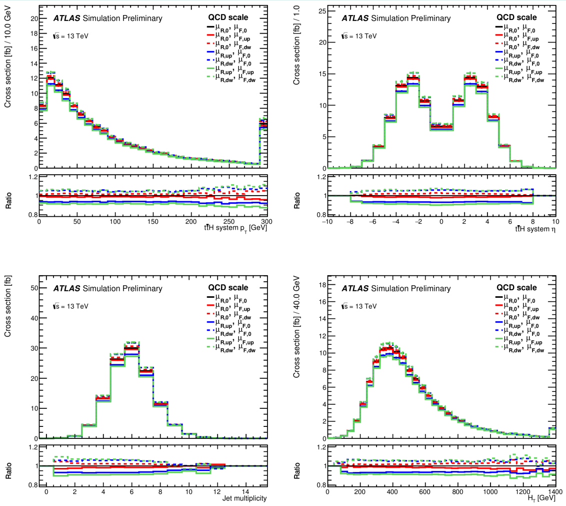
Applying NLO event generation using MG5aMC(NLO)

- At present two kind of $t\bar{t}H$ samples are available: Samples produced with MG5aMC(NLO)+Pythia8 and MG5aMC(NLO)+Herwig++.

$t\bar{t}H$, $\sqrt{s}$=13 TeV, m$_H$= 125 GeV, m$_t$= 172.5 GeV		
ME gen.	MadGraph5_aMC@NLO v2.2.1 + MadSpin	MadGraph5_aMC@NLO v2.3.2 + MadSpin
PS/UE gen.	Herwig++ v2.7.1	Pythia 8 v8.210
Ren./Fac. scale	$H_T/2$	$H_T/2$
ME & PS/UE PDF	CT10nlo & CTEQ6L1	NNPDF3.0nlo & NNPDF2.3lo
Tune	UE-EE-5	A14
Cross-section [pb]	0.447 ± 0.007	0.457 ± 0.001

Outlook: Run 2 searches for tt̄H signal

ATLAS: tt̄H, H→bb ME scale variation studies using reweighting



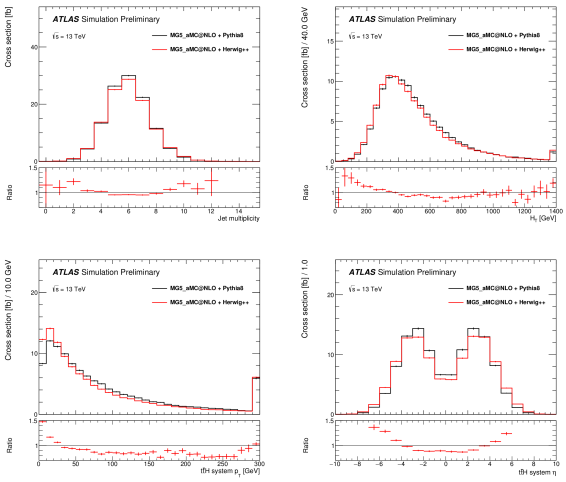
Outlook: Run 2 searches for $t\bar{t}H$ signal

ATLAS: $t\bar{t}H$, H→bb ME scale variation studies using reweighting

- Note: Discussing it further on the corresponding CMS slide later on, showing also some PDF variation by reweighting which is also used by both experiments.
- Note on reweighting: Use of the multiple weights functionality instead of producing individual samples with the ME event generator. Functionality has been checked by closure tests done in both experiments.
- Scale choice has no significant influence on the shape.
- Change of the acceptance is close to 9% when both μ_R and μ_F are varied simultaneously in the same direction.

Outlook: Run 2 searches for $t\bar{t}H$ signal

ATLAS: $t\bar{t}H$, H→bb GPMC event generator comparison



Outlook: Run 2 searches for $t\bar{t}$H signal

ATLAS: $t\bar{t}$H, H→bb GPMC event generator comparison

- Pythia8: Slightly more events with six jets.
- Pythia8: Harder transverse momenta H_T.
- Pythia8: More central pseudo-rapidity η.
- In the lower $t\bar{t}$H p_T region a difference close to 50% between the two GPMC event generators is observed.

Outlook: Run 2 searches for $t\bar{t}H$ signal

CMS: Applying NLO event generation

- Started to test and validate NLO $t\bar{t}H$ samples since MG5aMC(NLO) version 2.0.0.beta3 (November 2013), observing major improvements (speed, FxFx merging, ...) over time.
  $\Rightarrow$Decided to use MG5aMC(NLO) for $t\bar{t}H$ samples by default in Run 2.
- Challenge: Large fraction of events with negative event weight reduce drastically statistical power.
  - $t\bar{t}H$+0jets (No FxFx merging): 25 % of events having negative weight.
  - $t\bar{t}H$+0/1jets (add. FxFx merging): 34 % of events having negative weight.
  - $t\bar{t}H$+0jets(POWHEG-BoxV2): Less than 0.1 % of events having negative weight.

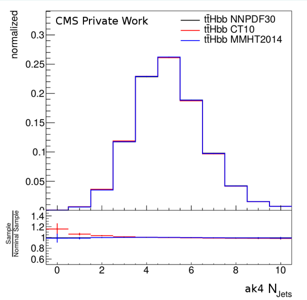
$\Rightarrow$Reconsidered choice of default event generator for $t\bar{t}H$ samples.

Outlook: Run 2 searches for $t\bar{t}H$ signal

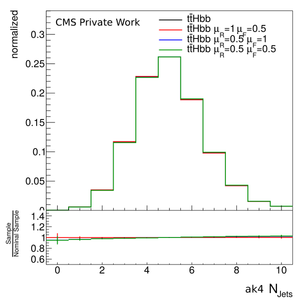
CMS: Using reweighting techniques for PDF and scale variations

- Changing PDF by reweighting has small effect on jet multiplicity but this depends a lot on the observable.
- Scale variation in the hard subprocess by reweighting has only small influence on the sample shape, while scale variation in parton shower has large impact on shape.
- Challenge: Scale variation in parton shower still must be done in single runs.

$t\bar{t}H$, H→bb PDF variation



$t\bar{t}H$, H→bb ME Scale variation



$t\bar{t}+b\bar{b}$ physics process

Overview

- Major background for $t\bar{t}H$ ($H \rightarrow bb$) and other signals.
- Test of NLO QCD predictions.
- Could be used to constrain $g \rightarrow bb$ fragmentation.

Challenges

- Generation of exclusive $t\bar{t}+b\bar{b}$ samples with massive b-quarks or divergence associated with gluon splitting into massless b-quarks.
- Categorization of $t\bar{t}$+HF events differs between analyses and experiments.

Run 1 analyses

- ATLAS: Dilepton and Lepton+Jets at $\sqrt{s} = 8$ TeV arxiV:1508.06868.
- CMS: Dilepton at $\sqrt{s} = 8$ TeV arXiv:1510.03072.
- CMS: Lepton+Jets at $\sqrt{s} = 8$ TeV CMS-TOP-13-016.
- CMS: Measurement of the $t\bar{t}+b\bar{b}/ttjj$ ratio at $\sqrt{s} = 8$ TeV PLB 746 (2015) 132.

$t\bar{t}$+$b\bar{b}$ physics process

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Common comparison studies of ATLAS+CMS+Theory

- A taskforce was put in place by the LHCHXSWG consisting of ATLAS, CMS, and theory members with the following goals:
  - Study and validate the generation of $t\bar{t}$+$b\bar{b}$ samples.
  - Precisely define a framework for consistent comparison of different MC simulations.
  - Omit some layers of MC simulations to get more transparent picture of QCD mechanism of $t\bar{t}$+b-jet production.
  - Simulations done under the guidance of MC authors.
  - Relevant runcards, Rivet analysis, and results will be public.
  - Results will also serve as benchmarks for validation of future $t\bar{t}$+HF simulations in ATLAS and CMS.
- Up to now the MG5aMC, PowHel, Pythia8, and Sherpa+OpenLoops event generators are considered.
- Already first parton-level results were discussed in internal meeting in December, more studies will be done and presented soon.

Modelling of $t\bar{t}$+$b\bar{b}$ process

ATLAS Run 1 approach

- Making use of inclusive $t\bar{t}$+jets sample produced with:
  - MadGraph5+Pythia6.
  - Powheg-BoxV1+Pythia6.
  - Sherpa+OpenLoops.

CMS Run 1 approach

- Making use of inclusive $t\bar{t}$+jets sample produced with MadGraph5+Pythia6.

Modelling of $t\bar{t}$+$b\bar{b}$ process

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ATLAS Run 2 approach

- Additionally to inclusive tt+jets samples Sherpa+OpenLoops $t\bar{t}$+$b\bar{b}$ samples were generated and are studied.
  $\Rightarrow$Sherpa+OpenLoops $t\bar{t}$+$b\bar{b}$ samples will maybe used in the future.

CMS Run 2 approach

- First approach: Produced a dedicated NLO $t\bar{t}$+$b\bar{b}$ 4FS sample using MG5aMC(NLO)+Pythia8 besides inclusive LO and NLO $t\bar{t}$+jets 5FS samples.
- Challenge: Combination of NLO $t\bar{t}$+$b\bar{b}$ 4FS sample with inclusive NLO $t\bar{t}$+jets sample.
  $\Rightarrow$Thought about producing a NLO $t\bar{t}$+$b\bar{b}$ 5FS sample by filtering inclusive NLO $t\bar{t}$+jets sample.
- New approach: Producing large inclusive NLO samples filtered by dilepton and semilepton final-state.

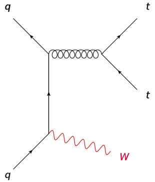
$t\bar{t}V$ physics processes

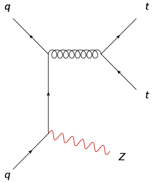
$t\bar{t}Z$ and $t\bar{t}W$: Important background and signal processes

- $t\bar{t}Z$ and $t\bar{t}W$ are important (irreducible) background processes for the $t\bar{t}H$ process. Between $t\bar{t}H$ and $t\bar{t}Z$, especially, is a close analogy which could be studied further in the long run (arXiv: 1507.08169).
- Enhancement of $t\bar{t}V$ cross sections in some new physics models without change in Higgs or top production.

$t\bar{t}W$: Associated production of a top-quark pair and a W-boson

- Only ISR subprocesses which are similar to the $t\bar{t}Z$ ISR processes.

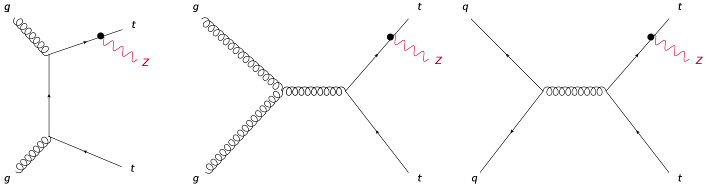




$t\bar{t}V$ physics processes

$t\bar{t}Z$: Associated production of a top-quark pair and a Z-boson

- FSR subprocesses: Measure of the weak isospin of the top-quark.
- Cross section sensitive to anomalous top-quark-Z-boson couplings.



$t\bar{t}V$ Run 1 measurements

Documentation of Run 1 measurements

- ATLAS collaboration: JHEP 11 (2015) 172 / arXiv:1509.05276.
- CMS collaboration: CMS-TOP-14-021 / arXiv:1510.01131.

Combination of Run 1 measurements

- In progress.
- More detailed status talk given by Tamara Schröder.
- Todays focus is on modelling the $t\bar{t}V$ processes using various MC event generators.

Modelling of $t\bar{t}V$ processes

Signal samples

- ATLAS and CMS: $t\bar{t}V$ signal samples are generated using MadGraph5+Pythia6.

$t\bar{t}Z$ signal cross section

- ATLAS and CMS: Same $t\bar{t}Z$ cross section obtained by using PowHel (arxiv 1208.2665).
- CMS: Makes use of the $t\bar{t}Z$ on-shell cross section of 206 fb.
- ATLAS: Includes the off-shell $t\bar{t}\gamma^{*}\rightarrow ll$ production, resulting in a $t\bar{t}Z$ cross section of 215 fb.
  An invariant mass of at least 5 GeV is required for any opposite-sign, same-flavour pair of leptons appearing in the matrix element.

Modelling of $t\bar{t}V$ processes

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$t\bar{t}W$ signal cross section

- ATLAS: $t\bar{t}W$ cross section of 232 fb, obtained with MCFM (arxiv 1204.5678).
- CMS: $t\bar{t}W$ cross section of 203 fb, obtained with PowHel (arxiv 1208.2665).
- Difference in the choice of the scales:
  - $\mu = mt$ (MCFM)
  - $\mu = m_t + \frac{mw}{2}$ (PowHel)

Outlook: $t\bar{t}W$ NLO QCD calculation

- Difference in $t\bar{t}W$ NLO cross section does not change the result, just different signal strength (not quoted in ATLAS).
- ATLAS will most likely adopt PowHel with the scale choice of CMS.

$t\bar{t}V$ Run 1 results

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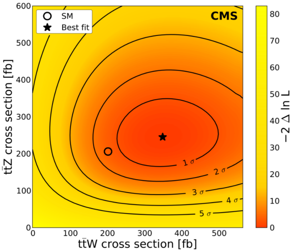
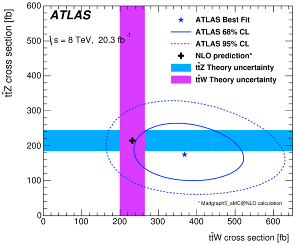
ATLAS results

- $\sigma(t\bar{t}W) = 369^{+86}_{-79}\,(\text{stat.}) \pm 44\,(\text{syst.})$ fb $= 369^{+100}_{-91}$ fb
- $\sigma(t\bar{t}Z) = 176^{+52}_{-48}\,(\text{stat.}) \pm 24\,(\text{syst.})$ fb $= 176^{+58}_{-52}$ fb

CMS results

- $\sigma(t\bar{t}W)$ $= 350^{+150}_{-123}$ fb
- $\sigma(t\bar{t}Z)$ $= 245^{+104}_{-80}$ fb





Outlook: Run 2 searches for $t\bar{t}V$ signal

ATLAS: Studying LO multileg and NLO event generation

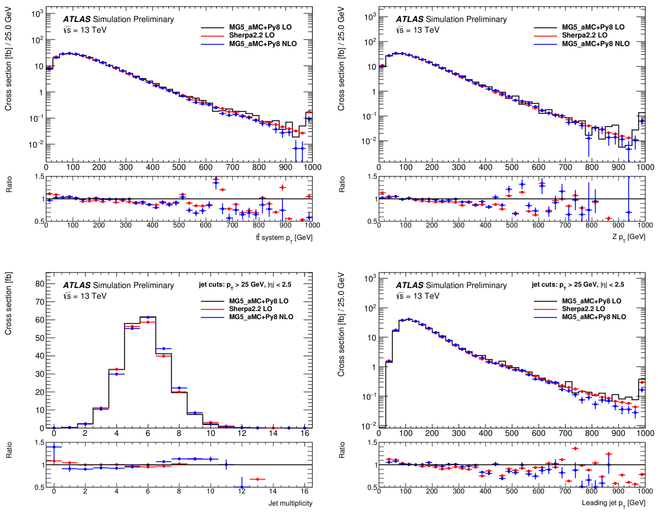
- ATLAS is studying the following event generators for Run 2 for now:
  - MG5aMC(LO)+Pythia8 together with the CKKW-L merging scheme.
  - Sherpa together with the ME+PS@LO prescription.
  - MG5aMC(NLO)+Pythia8.

Description Generator	Order	Process	Xsec [pb]	NLO xsec [pb]	Norm. factor
MG5_aMC+Py8	LO	$t\bar{t}W^{\pm} + 0,1,2j$	0.4534	0.5662	1.25
Sherpa	LO	$t\bar{t}W^{\pm} + 0,1,2j$	0.5773	0.5662	0.98
MG5_aMC+Py8	NLO	$t\bar{t}W^{\pm}$	0.5414	0.5662	1.05
MG5_aMC+Py8	LO	$t\bar{t}Z\rightarrow \nu\nu, qq + 0,1,2j$	0.5128	0.6831	1.33
Sherpa	LO	$t\bar{t}Z\rightarrow \nu\nu, qq + 0,1,2j$	0.6881	0.6831	0.99
MG5_aMC+Py8	NLO	$t\bar{t}Z\rightarrow \nu\nu, qq$	0.5384	0.6831	1.27
MG5_aMC+Py8	LO	$t\bar{t}+\ell^+\ell^- + 0,1j$	0.0817	0.1107*	1.35
Sherpa	LO	$t\bar{t}+\ell^+\ell^- + 0,1j$	0.1131	0.1107*	0.98
MG5_aMC+Py8	NLO	$t\bar{t}+\ell^+\ell^-$	0.1107	0.1107*	–

- All NLO cross section values were taken from arXiv:1405.0301 / JHEP 07 (2014) 079, except those marked *. For those the NLO MG5aMC(NLO) result was used including the full Z/$\gamma*\rightarrow$leptons contributions.

Outlook: Run 2 searches for $t\bar{t}V$ signal

ATLAS: $t\bar{t}Z$, $Z \rightarrow qq$ MC event generator comparison



Outlook: Run 2 searches for $t\bar{t}V$ signal

ATLAS: $t\bar{t}Z$, $Z \rightarrow qq$ MC event generator comparison

- MG5aMC(NLO)+Pythia8: Slightly higher p_T(tt) and p_T(Z), also reflected in the leading and sub-leading jet p_T spectra.
- Very good agreement in the number of jets distribution between the two LO-multileg samples.
- MG5aMC(NLO)+Pythia8: Systematically higher jet multiplicity.

Outlook: Run 2 searches for $t\bar{t}V$ signal

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ATLAS and CMS: Scale choice for Run 2 production

- ATLAS is using a common scale of $\mu = \frac{H_T}{2}$.
- CMS will most likely use the Run 1 scale $\mu = m_t + \frac{m_W}{2}$.

CMS: Studying LO multileg and NLO event generation

- CMS is studying / considering the following event generators to produce $t\bar{t}W$ and $t\bar{t}Z$ samples for Run 2 up to now:
  - MG5aMC(LO)+Pythia8 together with the MLM merging scheme.
  - MG5aMC(LO)+Pythia8 together with the CKKW-L merging scheme.
  - MG5aMC(NLO)+Pythia8 (together with the FxFx merging scheme).
- Unfortunately, no public results are available yet.

Short comments on $t\bar{t}+\gamma\gamma$

ATLAS

- ATLAS used more or less MadGraph5+Pythia6 in Run 1 for the production of $t\bar{t}+\gamma\gamma$.
- More studies are on-going to understand the production of $t\bar{t}+\gamma\gamma$ in Run 2.

CMS

- CMS used Pythia6 for the $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV analyses including $t\bar{t}+\gamma\gamma$.
- For the Run 2 all the theory tools needed to produce $t\bar{t}+\gamma$, $t\bar{t}+\gamma\gamma$, and $t+\gamma\gamma$ are available. Still some input by the MC authors on how to remove the overlap between photons coming from the hard scatter (simulated by the MG5aMC for instance), and photon emerging as radiation by Pythia8 would be useful.

Conclusion

Conclusion of Run 1

- In Run 1 many different event generators were used.
  - ATLAS: Use of NLO event generators more common.
  - CMS: Often tending to MadGraph5 and Pythia6 for sample production.
- In almost all cases the produced samples were scaled to NLO or even NNLO QCD calculations later.
- Theoretical uncertainties are becoming dominant.
  $\Rightarrow$For upcoming precision analysis of $t\bar{t}$+X processes in Run 2 reduction of theoretical uncertainties seems indispensable.

Conclusion for Run 2

- ATLAS will produce even more NLO event samples.
- CMS tends to use NLO ME event generators and Pythia8 as a GPMC event generator by default.

Outlook

Dramatic increase of expected $t\bar{t}$+X cross sections in Run 2

$\sigma(t\bar{t}+X)$	$\sqrt{s} = 8$ TeV	$\sqrt{s} = 13$ TeV	Ratio $\frac{\sigma(13\text{ TeV})}{\sigma(8\text{ TeV})}$
$\sigma(t\bar{t}$, NNLO)	≈ 248 pb	≈ 816 pb	≈ 3.29
$\sigma(t\bar{t}H$, NLO)	≈ 129 fb	≈ 509 fb	≈ 3.95
$\sigma(t\bar{t}W$, NLO)	≈ 203 fb	≈ 566 fb	≈ 2.79
$\sigma(t\bar{t}Z$, NLO)	≈ 206 fb	≈ 760 fb	≈ 3.69

- Larger cross section increase for $t\bar{t}H$ than other SM processes from $\sqrt{s} = 8$ TeV to $\sqrt{s} = 13$ TeV.
- LHC plans to deliver a luminosity of 100 fb^{-1} in Run 2.
- Expecting a lot more $t\bar{t}$+X events in Run 2.
  $\Rightarrow$ Entering the era of precision studies of $t\bar{t}$+X processes.

Outlook

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Putting new (NLO) event generators into full operation

- In Run 1 mostly traditional (LO) event generators were used to model the $t\bar{t}$+X processes together with NLO QCD calculations for the $t\bar{t}$+X cross sections.
- Between end of Run 1 and also up to now major progress in the event generator field has been made thanks to our theory colleagues.
- The consistent use of more advanced (NLO) event generators in Run 2 is almost certain for many of the $t\bar{t}$+X processes.
- Many studies of the new advanced event generators have been conducted already and many more will be done in the near future. Unfortunately, not many results are official until Moriond 2016 and the summer conferences.
- Stay tuned and let's express our gratitude to the theory community for these great advances!

ttH backup slides

Object selection in different ttH analyses

Object selection

	ATLAS ttH Hbb	CMS ttH Hbb BDT	CMS ttH Hbb MEM	CMS tHq Hbb
Muons or Electrons	$p_T > 25$ (15) GeV $\|\eta\| < 2.5$ id, isolation	$p_T > 30/20$ (10) GeV $\|\eta\| < 2.1$ or 2.5 id, isolation	$p_T > 30/20$ (20) GeV $\|\eta\| < 2.1$ or 2.5 id, isolation	$p_T > 26$ or 30 GeV $\|\eta\| < 2.1$ or 2.5 id, isolation
Jets	$p_T > 25$ GeV $\|\eta\| < 2.5$ Anti-k_T, R=0.4 JVF > 0.5	$p_T > 30$ GeV $\|\eta\| < 2.4$ Anti-k_T, R=0.5 PU / noise id	$p_T > 30$ GeV $\|\eta\| < 2.4$ Anti-k_T, R=0.5 PU / noise id	$p_T > 30$ GeV $\|\eta\| < 2.4$ Anti-k_T, R=0.5 PU / noise id
B-tag	B-eff = 70% Mis-tag = 1% Charm = 20%	B-eff = 70% Mis-tag = 2% Charm = 20%	B-eff = 70% Mis-tag = 2% Charm = 20%	B-eff = 50% Mis-tag = 0.4% Charm = 7%

Further searches for $t\bar{t}H$ signal in Run 1

ATLAS: Search for $t\bar{t}H$, H$\rightarrow$leptons

- Search for $t\bar{t}H$, H$\rightarrow$WW*, $t\bar{t}H$, H$\rightarrow\tau\tau$, and $t\bar{t}H$, H$\rightarrow$ZZ* final-state.
- arXiv:1506.05988 / Physics Letters B 749 (2015) 519-541

ATLAS: Search for $t\bar{t}H$, H$\rightarrow$photons

- Search for $t\bar{t}H$, H$\rightarrow\gamma\gamma$ final-state.
- arXiv:1409.3122 / Physics Letters B 740 (2015) 222-242

CMS: Search for $t\bar{t}H$, H$\rightarrow$hadrons, leptons, and photons with BDT

- Using boosted decision tree method to discriminate between signal and background.
- arXiv:1408.1682 / JHEP 09 (2014) 087

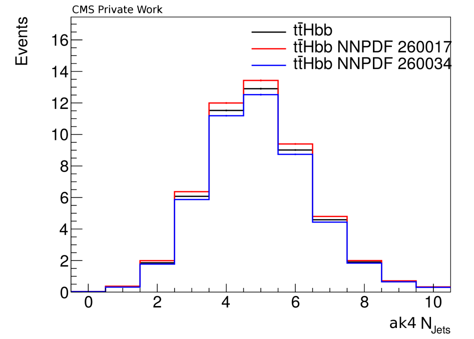
CMS: Search for ttH with NN

- Neural networks (NN) are applied to study mainly $t\bar{t}H$, H$\rightarrow$bb using only 2011 and 2012 data.
- arXiv:1303.0763 / JHEP 05 (2013) 145

Outlook: Run 2 searches for $t\bar{t}H$ signal

CMS: Using reweighting techniques for PDF variations – Envelope around nominal PDF

- Shown below is the nominal NNPDF3.0 and the two sub-PDFs with the largest deviations from the nominal PDF.
- To determine these two sub-PDFs, the deviation from the nominal PDF was calculated bin-by-bin and normalized to the bin content of the nominal PDF.



tt+bb backup slides

ttV backup slides

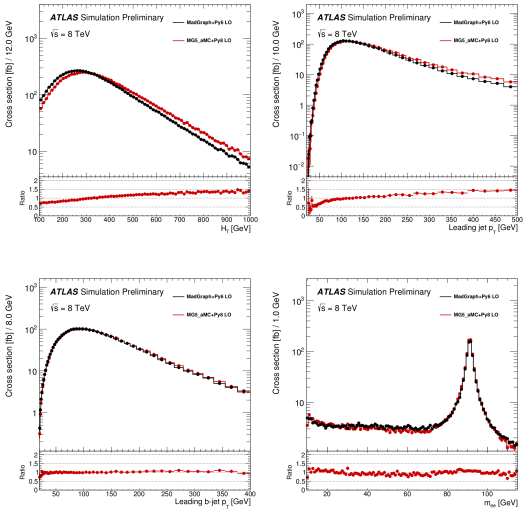
Outlook: Run 2 searches for $t\bar{t}V$ signal

ATLAS: Comparing with Run 1 event generator setup

- As a validation the LO $t\bar{t}$+leptons MG5aMC(LO)+Pythia8 sample was compared to the Run 1 LO MG5aMC(LO)+Pythia6 sample.
- Differences expected due to
  - Pythia6 vs. Pythia8 GPMC event generator,
  - MLM vs. CKKW-L merging scheme.
- In general good agreement but discrepancies between the jet-based kinematic variables.

Outlook: Run 2 searches for $t\bar{t}V$ signal

ATLAS: Comparing with Run 1 event generator setup



Outlook: Run 2 searches for $t\bar{t}V$ signal

ATLAS: Comparing with Run 1 event generator setup – Rivet analysis setup

- E_T miss of at least 30 GeV with leptonically decaying W-boson candidates required.
- The opposite-sign lepton-pair having an invariant mass closest to the PDG mass of Z-boson is selected as the Z-boson candidate.
- A minimum cut of 10 GeV is applied to the invariant mass of the dilepton system.
- All jets are required to have a minimum p_T of 25 GeV and a $|\eta| < 2.5$, while all leptons are required to have a minimum p_T of 10 GeV.
- The event must have at least two light-jets and two b-jets.

Outlook: Run 2 searches for $t\bar{t}V$ signal

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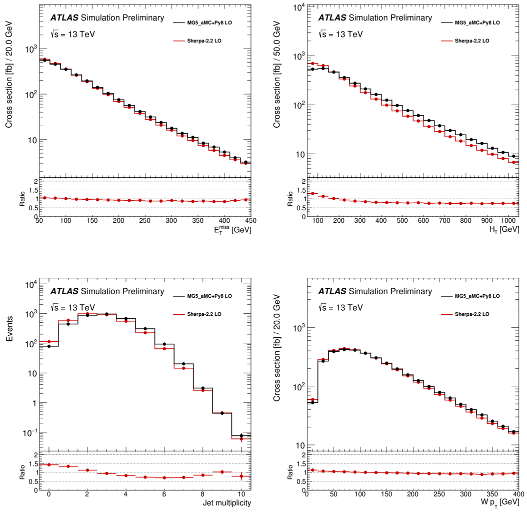
ATLAS: $t\bar{t}Z$, $Z \rightarrow qq$ MC event generator comparison – Rivet analysis setup

- Events are required to have a semi-leptonic decay of the top-quark pair and the Z-boson decay hadronically at parton level.
  $\Rightarrow$Events are expected to have six jets.
- Selected jets are required to have $p_T > 25$ GeV and $|\eta| < 2.5$.

Outlook: Run 2 searches for $t\bar{t}V$ signal

ATLAS: $t\bar{t}W$ MC event generator comparison



Outlook: Run 2 searches for $t\bar{t}V$ signal

ATLAS: $t\bar{t}W$ MC event generator comparison

- The MG5aMC(NLO)+Pythia8 NLO sample is not yet available.
- No selection is applied so all decay products of the top-quark pair and W-boson are included.
- Small discrepancy in the shape of the jet multiplicty and at low H_T, but otherwise the agreement is very good between the two LO-multileg generator setups.