Effects of parton shower and underlying event modelling in Higgs measurements and searches

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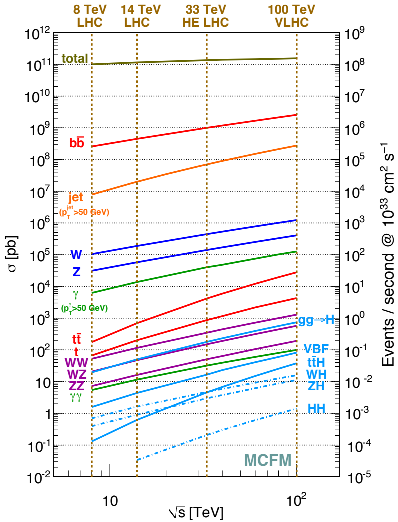
on behalf of the ATLAS Collaboration

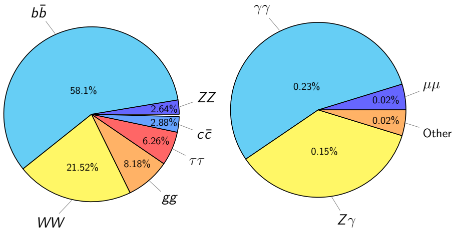
Shandong University

August 27th, 2018

Higgs boson @ ATLAS



MCFM program



Higgs Yellow Report 4

> 4.7 million of Higgs boson produced (4.7+20.3+79.8 fb^{-1}).

> 2.7 million decaying to $b\bar{b}$.

2012 Discovery of the Higgs boson with $m \sim 125$ GeV.

2013 Observations of $H \to WW$, $H \to ZZ$ and $H \to \gamma\gamma$ decay.

2016 Observation of $H \to \tau\tau$.

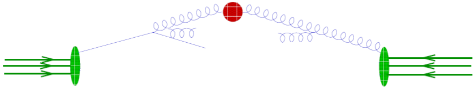
2017 Evidence of $H \to b\bar{b}$ decay.

2018 Observation of $H \to b\bar{b}$ decay.

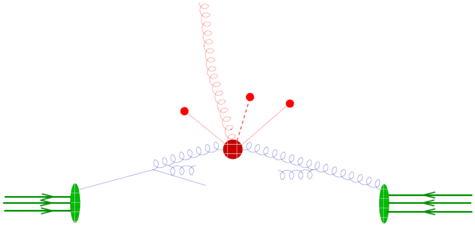
- Why did it take so much time to get here?
  Answer: QCD@LHC.
  - Particularly, parton shower and underlying event.

- Protons with structure.

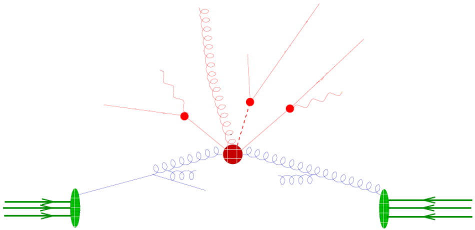
- Protons with structure.
- Two partons interacting.



- Protons with structure.
- Two partons interacting.
- Parton shower: initial state radiation.



- Protons with structure.
- Two partons interacting.
- Parton shower: initial state radiation.
- Production of Higgs boson + $t\bar{t}$ + gluon.



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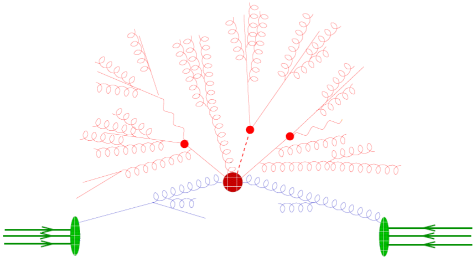

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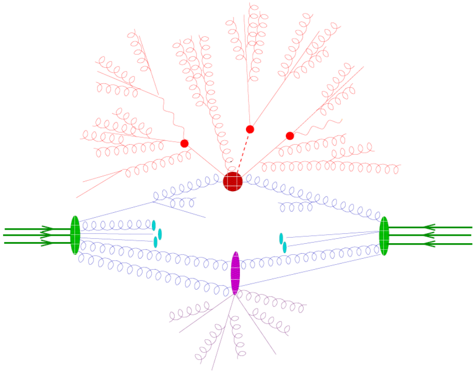
- Parton shower: final state radiation.



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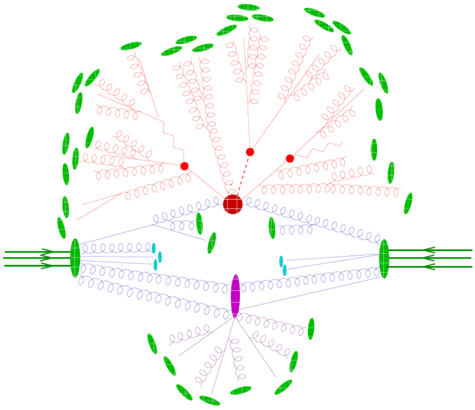
- Parton shower: final state radiation.
- Underlying event: proton remnants.



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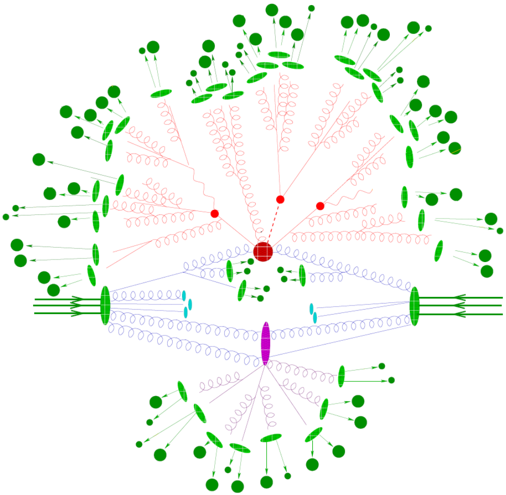
- Hadronization.



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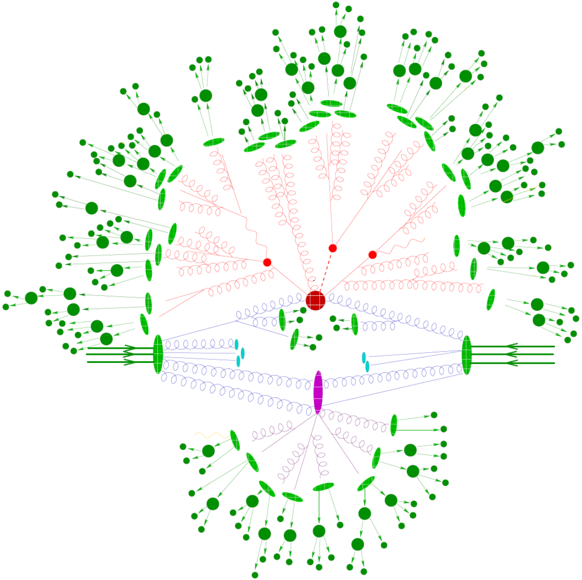
 adapted from SLAC-PUB 16160



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- Hadronization.
- Hadron production.
- Unstable hadron decays.

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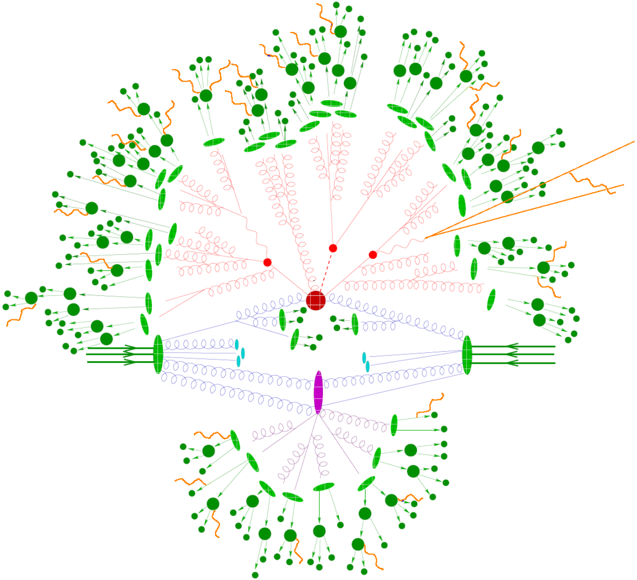

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- Hadronization.
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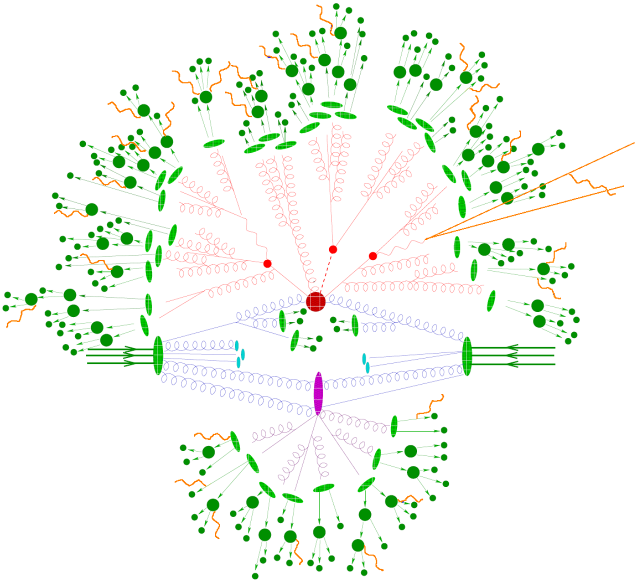
- Unstable hadron decays.
- Electroweak.



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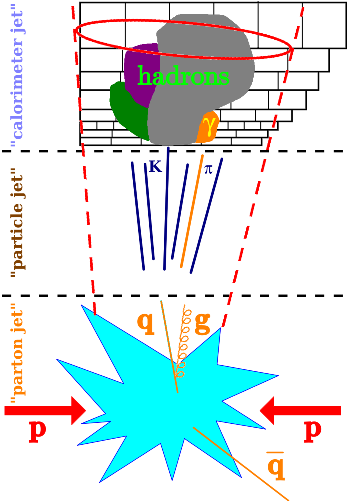
Jet reconstruction

Adapted from T. Gleisberg slides



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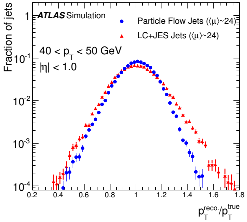

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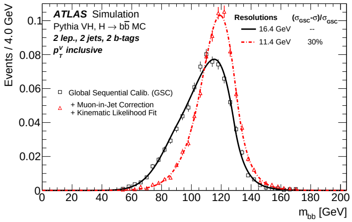

- Jets are our windows into outgoing quarks and gluons.
- Objective: calorimeter reconstructed jet $p_{\mathrm{T}} \equiv$ particle/parton level jet p_{T}.
- Effect propagated directly to invariant mass distribution: $m_{b\bar{b}}$.
- Affecting low mass/response tail:
  - final state radiation.
  - muon inside the jet.
- Affecting high mass/response tail:
  - initial state radiation.
  - underlying event.
  - pileup.

Evaluation of systematic uncertainty on PS and UE

- Usually evaluated by:
  - comparing two/three different MC parton shower generators.
    - caveat: changing also Hadronization and PDF.
  - tunning the parameter in order to remove these effects.
    - see backup.
- Uncertainty evaluated on:
  - Acceptance (number of events).
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- Results coming up next from Higgs measurements and searches:
  - Threshold of the jet transverse momentum.
  - Simulated samples used for systematic estimation for signal (and background)
  - Impact of the systematic uncertainty on parton shower and underlying event.
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Outline

- quarks: top, bottom
- gauge bosons: W, Z, γ
- leptons: τ, μ
- di-Higgs search

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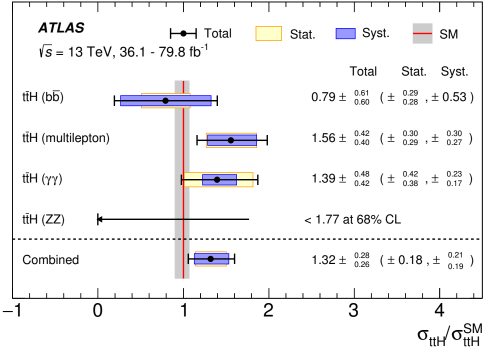
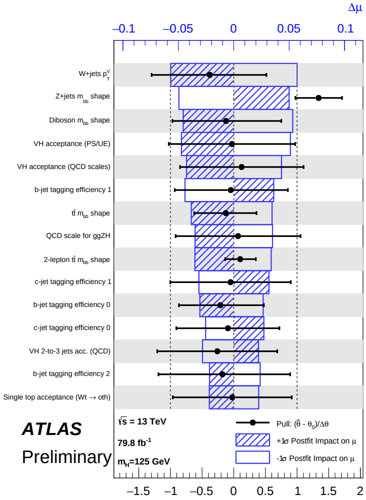


Uncertainty source	$\Delta\sigma_{t\bar{t}H}/\sigma_{t\bar{t}H}$ [%]
Theory uncertainties (modelling)	11.9
$t\bar{t}$ + heavy flavour	9.9
$t\bar{t}H$	6.0
Non-$t\bar{t}H$ Higgs boson production modes	1.5
Other background processes	2.2
Experimental uncertainties	9.3
Fake leptons	5.2
Jets, E_T^{miss}	4.9
Electrons, photons	3.2
Luminosity	3.0
τ-lepton	2.5
Flavour tagging	1.8
MC statistical uncertainties	4.4

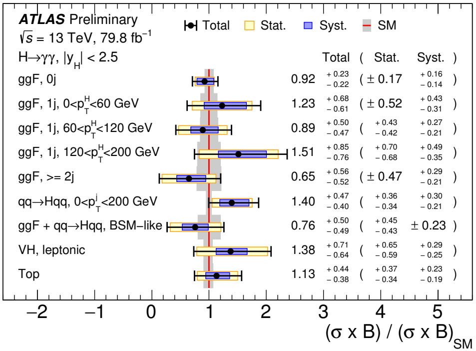
- Jet threshold: 25 GeV
- Uncertainty obtained from PYTHIA8 to HERWIG7 comparison:
  - $ttH(\gamma\gamma)$ PS modelling uncertainty values 8% in signal and 4% in background.
  - ttH(multilepton) PS uncertainty with about 10% uncertainty for both signal and background.
    - multilepton $\equiv H \to WW^*, H \to \tau\tau, H \to ZZ^*$ without $ZZ^* \to 4\ell$.
  - $ttH(b\bar{b})$ PS uncertainty with about 6% uncertainty for signal and 4 to 10% for background.



- Jet threshold: 20 GeV
- $\int L = 4.7, 20.3, 79.8\ \text{fb}^{-1}$ @ $\sqrt{s} = 7, 8, 13$ TeV, respectively.
- $\mu = 0.98 \pm 0.14(\text{stat.})^{+0.17}_{-0.16}(\text{syst.})$
- Analysis dominated by the VH production.
- VH signal:
  POWHEG v2 + MINLO + PYTHIA 8.212 + AZNLO tune vs POWHEG v2 + MINLO + HERWIG7 vs MADGRAPH5_AMC@NLO + PYTHIA 8.212
  - Acceptance from PS/UE variation for:

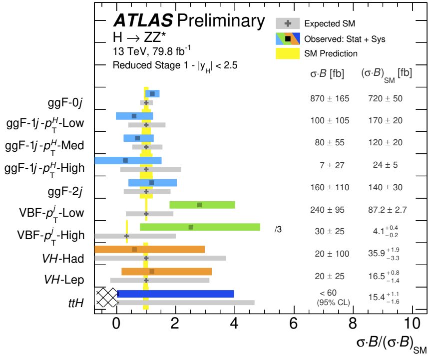
  $\geq$ 2 jets 10 to 14%
  3 jets 13%
  - Fourth largest impact on signal strength: 5%.
- Diboson background:
  SHERPA vs POWHEG+HERWIG++ vs POWHEG+PYTHIA8:
  - Acceptance from PS/UE variation for:

  $\geq$ 2 jets 5.6% (0-lep), 3.9% (1-lep) and 5.8% (2-lep)
  3 jets 7.3% (0-lep), 11% (1-lep) and 3.1% (2-lep)



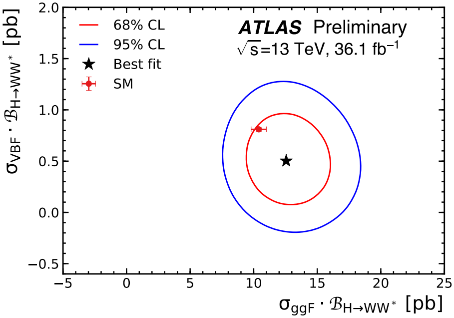
Source	Uncertainty (%)
Fit (stat.)	10
Fit (syst.)	8.3
Photon energy scale & resolution	4.0
Background modeling (spurious signal)	7.3
Correction factor	5.2
Photon isolation efficiency	4.6
Pileup	1.9
Photon ID efficiency	1.3
Trigger efficiency	0.7
Dalitz Decays	0.4
Theoretical modeling	$^{+0.3}_{-0.4}$
Diphoton vertex selection	0.1
Photon energy scale & resolution	0.1
Luminosity	2.0
Total	14

- Jet threshold: 25 GeV
- Underlying event and parton shower uncertainties obtained by changing the default showering with PYTHIA to HERWIG in signal samples and studying the effect.
  - Uncertainty assessed between 1% and 18%, depending on the signal region.
  - Impact of theoretical uncertainties (including UE/PS) on cross-section: about 0.4%.



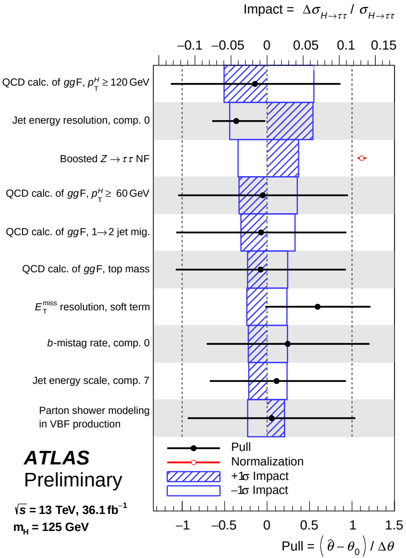
Measurement [-0.5ex]	Experimental uncertainties [%] Lum.	e, μ, pile-up	Jets, flavour tagging	Reducible backgr.	Theory uncertainties [%] ZZ^* backgr.	PDF	Signal QCD scale	Parton Shower	Composition
Fiducial cross section									
	2.8	4.3	< 0.1	0.3	1.6	0.6	0.5	0.4	0.1
Per decay channel fiducial cross sections									
4μ	2.8	3.9	< 0.1	0.3	1.6	0.6	0.4	0.6	0.2
$4e$	2.8	9.0	< 0.1	1.0	1.6	0.6	0.8	0.5	0.1
$2\mu 2e$	2.7	8.6	< 0.1	0.9	1.5	0.6	0.7	0.5	0.1
$2e2\mu$	2.8	3.6	< 0.1	0.4	1.8	0.6	0.7	0.5	0.2
Stage-0 production bin cross sections									
ggF	2.9	3.9	1.3	0.7	2.3	0.4	2.1	0.7	-
VBF	1.7	1.5	10.5	0.5	2.3	2.3	9.5	5.1	-
VH	2.0	1.7	7.8	1.8	5.6	2.1	14.9	3.1	-
ttH	2.5	1.9	3.9	1.5	1.9	0.3	8.8	9.6	-

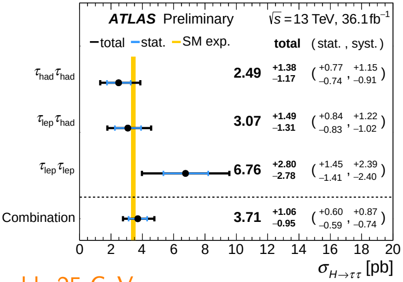
- Jet threshold: 30 GeV
- Underlying event and parton shower uncertainties obtained by changing the default showering:
  - ggF, VBF and VH: default Pythia8 vs Herwig++.
  - ttH: default Pythia8 vs Herwig7.
  - Including also changes in the AZNLO tune in Pythia8.
- Impact on cross-section ranging from 0.7% to 9.6% depending on production process.
- Impact on cross-section about 0.5% in all decay modes.



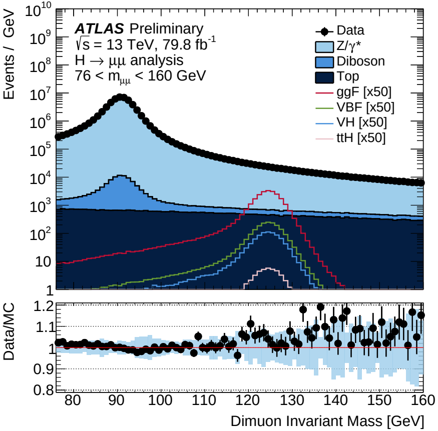
Source	$\frac{\Delta\sigma_{ggF}}{\sigma_{ggF}}$ [%]	$\frac{\Delta\sigma_{VBF}}{\sigma_{VBF}}$ [%]
Data statistics	±8	±46
CR statistics	±8	±9
MC statistics	±5	±23
Theoretical uncertainties	±8	±21
ggF signal	±5	±15
VBF signal	<1	±15
WW	±5	±12
Top-quark	±4	±4
Experimental uncertainties	±9	±8
b-tagging	±5	±6
Pile-up	±5	±2
Jet	±3	±4
Electron	±3	<1
Misidentified leptons	±5	±9
Luminosity	±2	±3
TOTAL	±17	±59

- Jet threshold: 20 GeV
- Underlying event and parton shower uncertainties obtained by changing the default showering:
  - ggF, VBF signal and $t\bar{t}$ background: default PYTHIA8 vs HERWIG7.
  - single top Wt background: default PYTHIA8 vs HERWIG++.
  - Diboson WW background: default SHERPA vs HERWIG++.
- Theoretical uncertainties (including PS/UE):
  - About 5% from ggF signal, Diboson and top backgrounds in ggF category.
  - Up to 15% in VBF category.

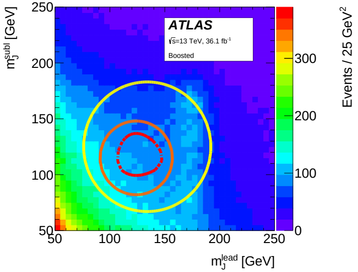




- Jet threshold: 25 GeV
- Underlying event and parton shower uncertainties obtained by changing the default showering:
  - ggF, VBF and VH signal: default PYTHIA8 vs HERWIG7.
  - V+jets background: default SHERPA vs PYTHIA8.
- Parton shower / underlying event uncertainty:
  - 2-26% for ggF production, depending on the category.
  - 2-18% for VBF production, depending on the category.
  - Maximum impact on signal strength: 2.5% (from VBF).



- Jet threshold: 25 GeV
- $\int L = 79.8\ \text{fb}^{-1}$ @ $\sqrt{s} = 13$ TeV
- Observed (expected) upper limit at 95% CL 2.1 (2.0) times SM expectation.
- Theoretical uncertainties (including PS/UE):
  - ggF category: 15% to 25%.
  - VBF category: about 5%.



Source	2015 Background	2015 Scalar	2015 SM HH	2015 G_{KK}	2016 Background	2016 Scalar	2016 SM HH	2016 G_{KK}
Luminosity	–	2.1	2.1	2.1	–	2.2	2.2	2.2
Jet energy	–	17	7.1	3.7	–	17	6.4	3.7
b-tagging	–	13	12	14	–	13	12	14
b-trigger	–	4.0	2.3	1.3	–	2.6	2.5	2.5
Theoretical	–	23	7.2	0.6	–	23	7.2	0.6
Multijet stat	4.2	–	–	–	1.5	–	–	–
Multijet syst	6.1	–	–	–	1.8	–	–	–
$t\bar{t}$ stat	2.1	–	–	–	0.8	–	–	–
$t\bar{t}$ syst	3.5	–	–	–	0.3	–	–	–
Total	7.5	31	16	15	1.8	31	16	15

Observed	-2σ	-1σ	Expected	$+1\sigma$	$+2\sigma$
13.0	11.1	14.9	20.7	30.0	43.5

- Jet threshold: 40 GeV.
- Two BSM signal samples:
  - Signal Gkk → HH:
    - MADGRAPH5_aMC@NLO + PYTHIA 8.186.
    - Maximum of 2.3σ observed @ m_{Gkk} = 280 GeV.
  - Signal gg → Scalar → HH.
    - MADGRAPH5_aMC@NLO + HERWIG++.
- Theoretical uncertainties (including PS/UE):
  - PS/UE evaluating interchanging HERWIG++ with PYTHIA 8.186:
  - *Gkk*: 0.6% ; Scalar: 23% ; HH SM: 7.2%
- The observed 95% CL upper limit on the non-resonant production is 13 times the SM prediction.

Summary

- Parton shower and underlying event affect all analysis, particularly those from Higgs, that contain jets (for either identification of veto).
- A summary was presented on the state of the art of several Higgs measurements and searches from the point of view of these uncertainties.
- The lower the threshold for the transverse momentum of the jets selected (identification or veto), the larger effects like the initial and final state radiation and the underlying event will impact the final result of the analysis.

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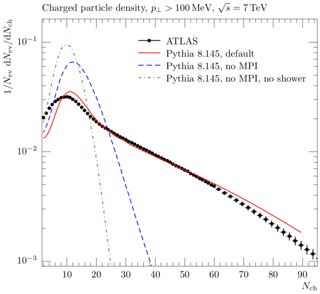
Thanks for the opportunity to present at this conference!

BACKUP: Effect on number of charged particles



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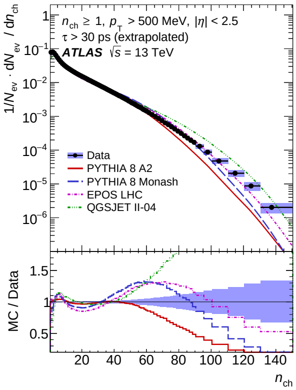

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PYTHIA8 time line:

- PYTHIA 8.145 ≡ November 2010
- A2 ≡ PYTHIA 8.185 ≡ March 2014
- Monash ≡ PYTHIA 8.186 ≡ July 2014
- PYTHIA 8.212 ≡ September 2015
- PYTHIA 8.235 ≡ March 2018
  - latest version.