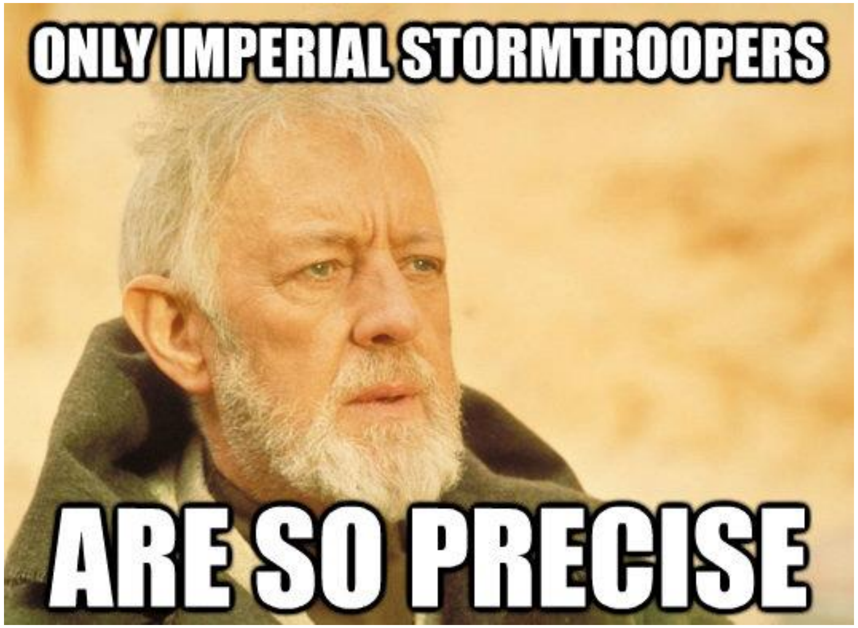
Treatment of theory uncertainties for Higgs measurements and searches at ATLAS



Thomas CALVET on behalf of the ATLAS Collaboration
Stony Brook University

Higgs Couplings
October 01st, 2019

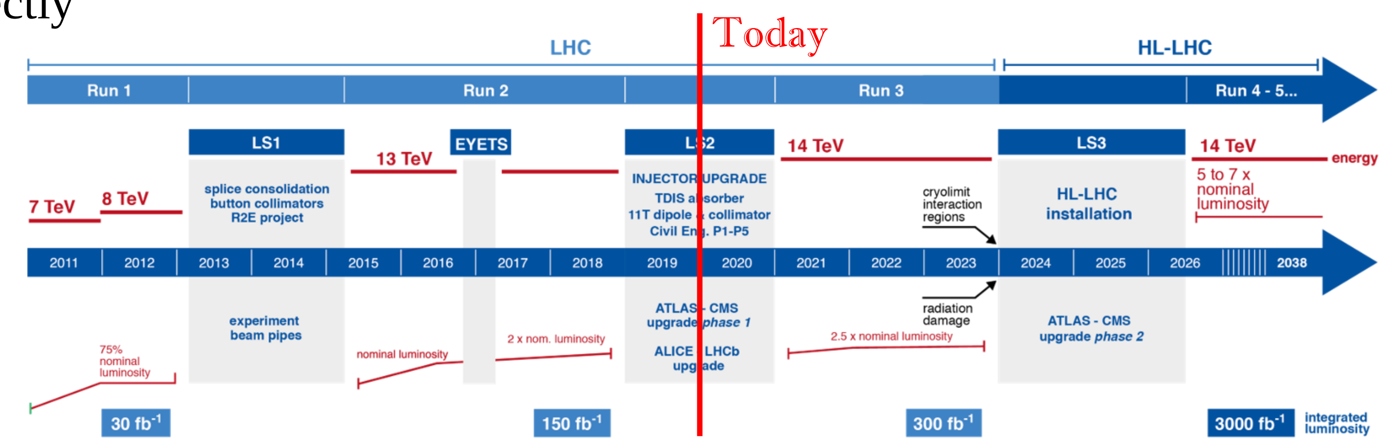
The Importance Of Systematic Uncertainties

- Higgs boson production at LHC is rare
  - Required time to accumulate data, first for the discovery
- New era for Higgs studies:
  - Most analysis turning "systematically limited"
  - "worst" case: 4 times more data is enough to reach point where more data does not help directly

Status for inclusive cross-section

Higgs channel	$H\to\gamma\gamma$ 139 fb^{-1}	$H\to 4l$ 139 fb^{-1}	$H\to\tau\tau$ 36.1 fb^{-1}	$H\to bb$ VH 80 fb^{-1}	$H\to bb$ VBF 30.6 fb^{-1}	ttH $H\to bb$ 36.1 fb^{-1}	ttH ML 36.1 fb^{-1}
Stat limited		✓			✓		=
Syst limited	✓		✓	✓		✓	=
Ratio $\frac{Syst}{Stat}$	**1.2**	**0.5**	**~ 1.4**	**~ 1.3**	**~ 0.4**	**~ 2.0**	**~ 1**

- Only 1/23 of the LHC data collected so far



Systematic uncertainty reduction, key for precision measurements

The Importance Of Theory Uncertainties

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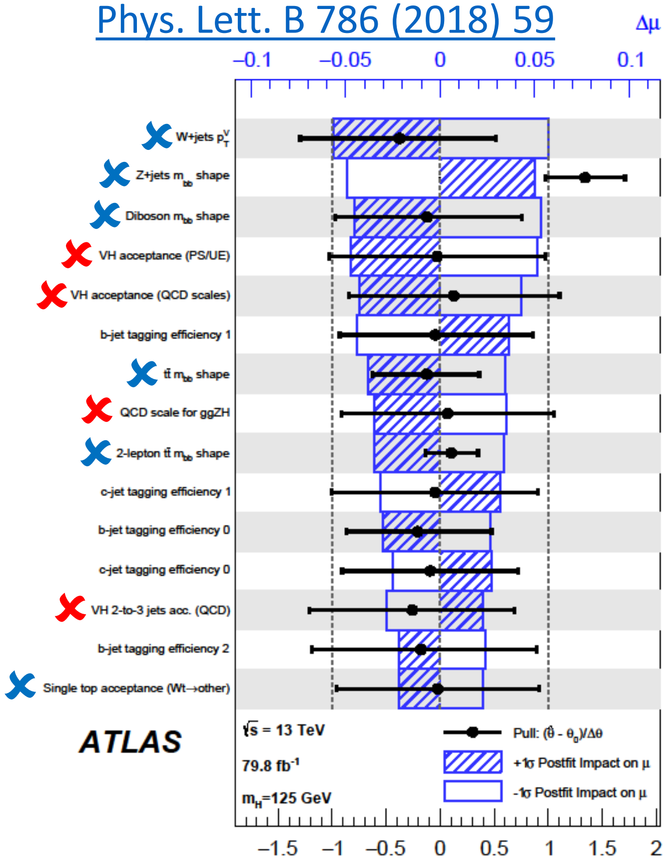


Signal and Background theory uncertainties are the main sources

arXiv:1906.02025

Upper limit percentage variation	NR	Spin-0 1 TeV	Spin-0 3 TeV	Spin-2 $k/\overline{M}_{Pl} = 1$ 1 TeV	Spin-2 $k/\overline{M}_{Pl} = 1$ 3 TeV	Spin-2 $k/\overline{M}_{Pl} = 2$ 1 TeV	Spin-2 $k/\overline{M}_{Pl} = 2$ 3 TeV
Simulation statistics	3%	1%	-	2%	-	1%	-
Background modelling	5%	7%	9%	11%	15%	16%	21%
Signal theory	1%	-	-	-	1%	-	-
Tau	2%	-	-	-	-	1%	-
Jet	-	1%	2%	2%	3%	5%	4%
b-tagging	1%	2%	-	3%	-	4%	-
All	13%	12%	11%	19%	18%	29%	25%

Main (ranked by impact on μ) uncertainties in VH with Higgs to bb:

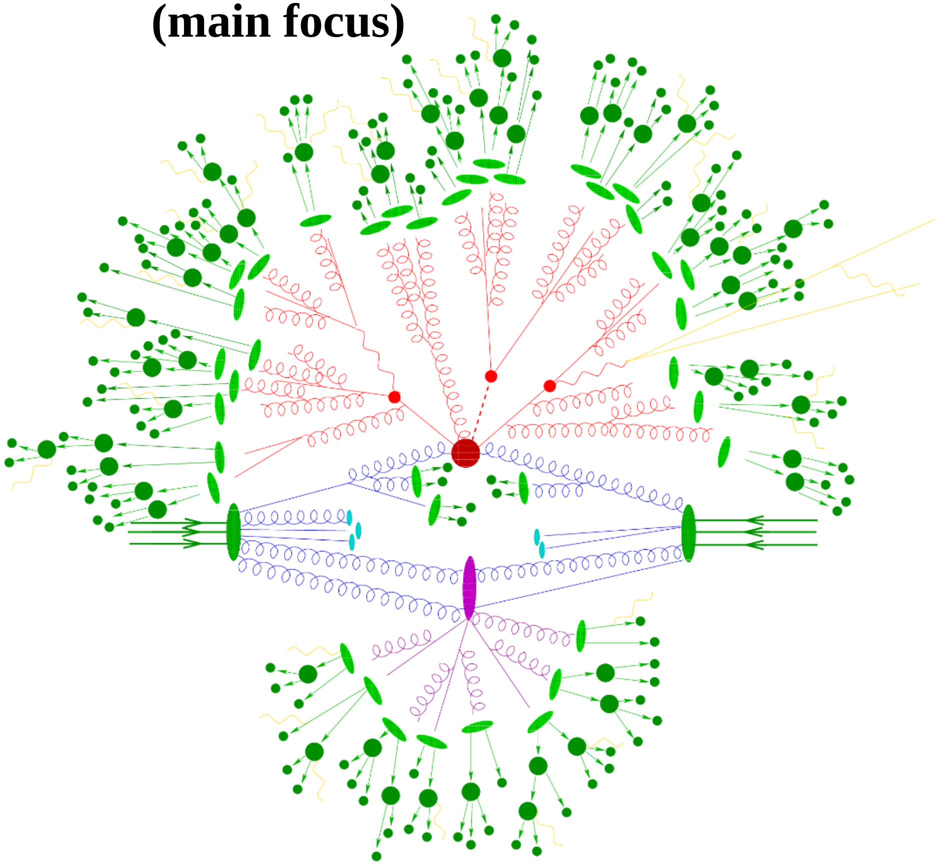
signal (×) and background (×) modelling

Theory uncertainties => largest impact on HH cross-section limit (after data stat)

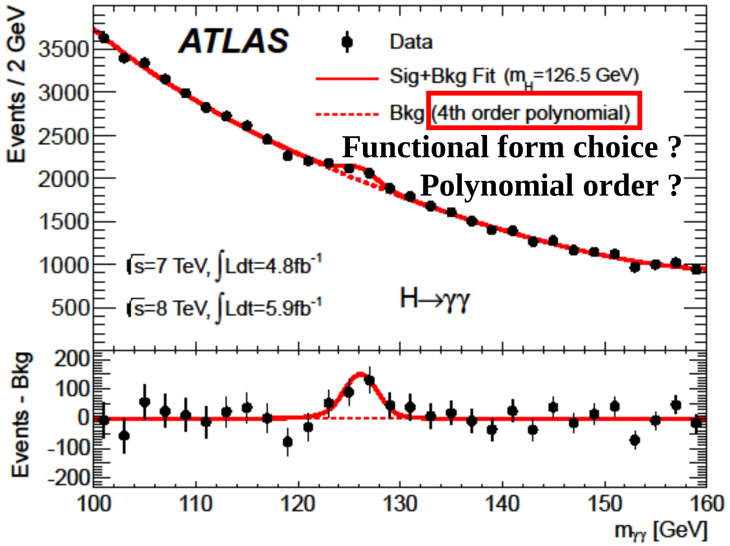
Three Background Estimation Methods

- Theory/Modelling uncertainty definition depends on analysis strategy for each process

1) Monte-Carlo based prediction (main focus)



2) Functional form fit to data
=> Backup <=



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3) Fully data driven estimate

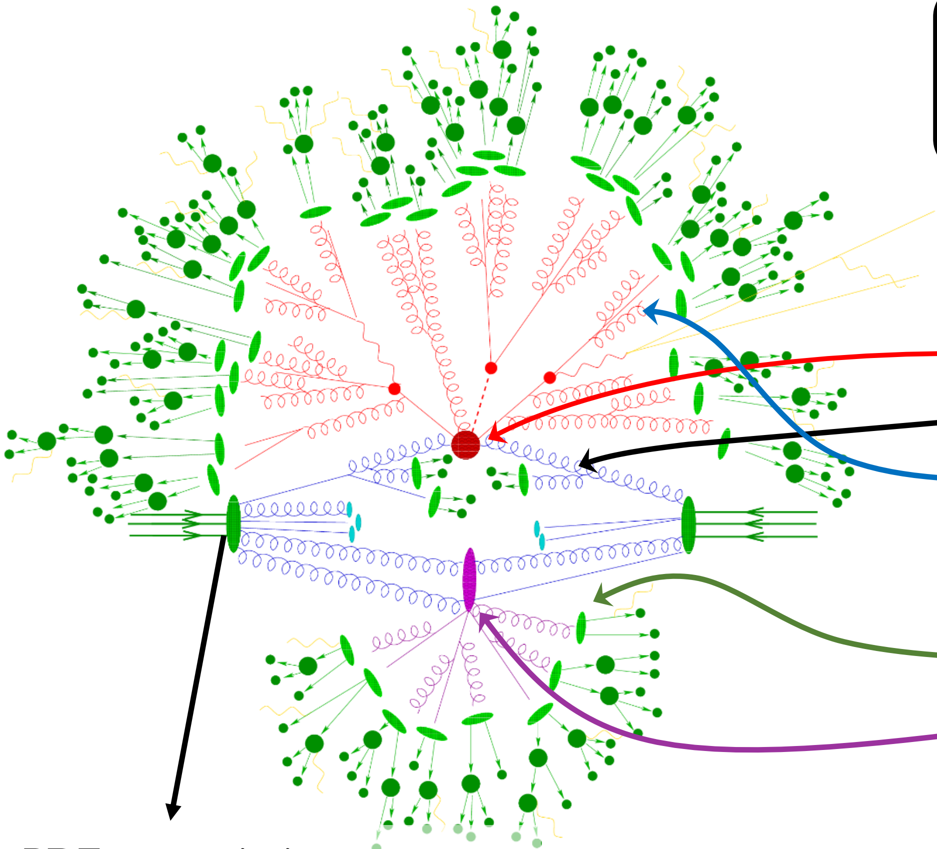
- Binned templates from data in control-regions
- Uncertainty = data-stat

=> Not covered <=

Theory uncertainties: concept

Theory/Modelling Uncertainties For MC Predictions

Theoretical point of view



Theory uncertainties
cover various physical processes

- Perturbative QCD effects:
  - ➢ Matrix Element or Hard Scattering
  - ➢ Initial State Radiation (ISR)
  - ➢ Final State Radiation (FSR)
- Non-perturbative QCD:
  - ➢ Hadronization and hadronic decays
  - ➢ Underlying Events (UE) and Multiple-Parton Interaction (MPI)

PDF uncertainties
Not covered
See Maria's and James' talks

Input For The Estimation Of The Uncertainty

- Perturbative QCD effects:
  - ➢ Matrix Element or Hard Scattering
  - ➢ Initial State Radiation (ISR)
  - ➢ Final State Radiation (FSR)
- Non-perturbative QCD:
  - ➢ Hadronization and hadronic decays
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- Various inputs available to estimate theory uncertainties:
  - ➢ Renormalization μ_R and factorization μ_F scales (×)
  - ➢ Shower tunes and hdamp (×)
  - ➢ "2-point comparisons": difference between 2 generators (×)

Clear decomposition does not necessarily exist !

- Impact on ttH system p_T of:

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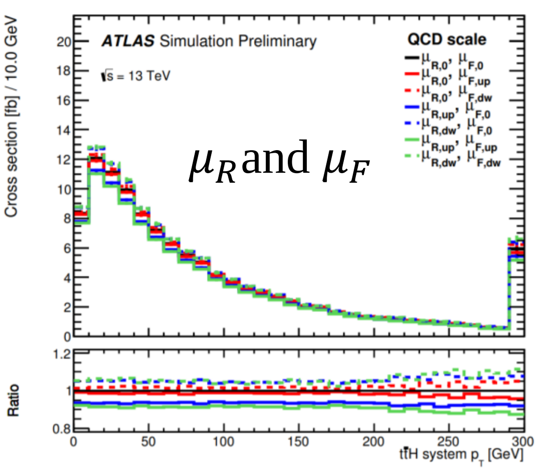
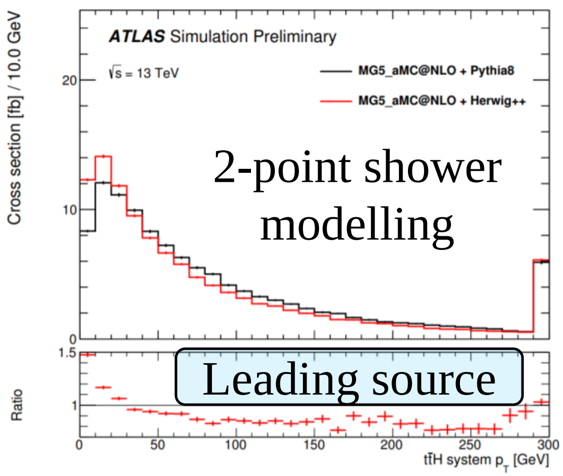
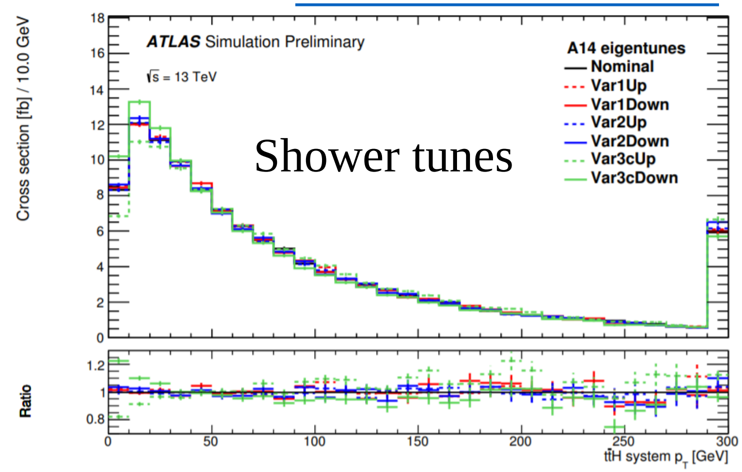






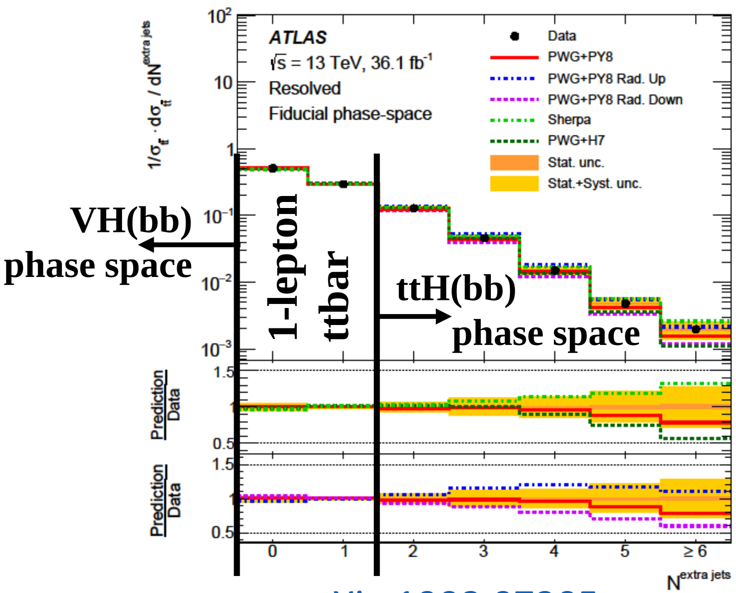
More on Parton-Shower ? See James' and Keith's talks

A Few Doors Ahead

- Perturbative QCD effects:
  - ➢ Matrix Element or Hard Scattering
  - ➢ Initial State Radiation (ISR)
  - ➢ Final State Radiation (FSR)
- Non-perturbative QCD:
  - ➢ Hadronization and hadronic decays
  - ➢ Underlying Events (UE) and Multiple-Parton Interaction (MPI)

- Ideal case: decompose uncertainty across all physical effects
  - ➢ Reduce impact of single uncertainties

- Make use of the increasing availability of data:



arXiv:1908.07305

2-point uncertainties for Higgs signal:
- ➢ H→γγ, 4l differential well established
- ➢ ttH and H→bb differential starting

Can start constraining Higgs models ?

2-point uncertainties for Higgs backgrounds:
- ➢ Models tuned in process phase-space
- ➢ More data => phase-space closer to Higgs ?

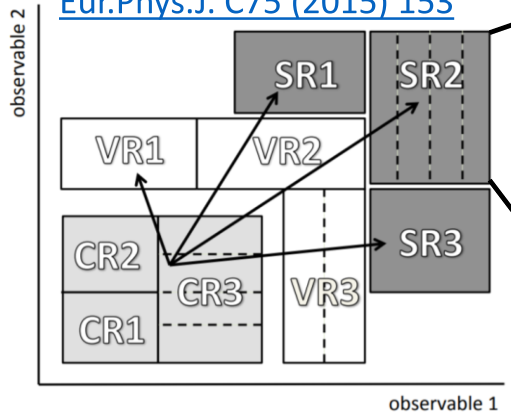
Theory uncertainties: parametrization

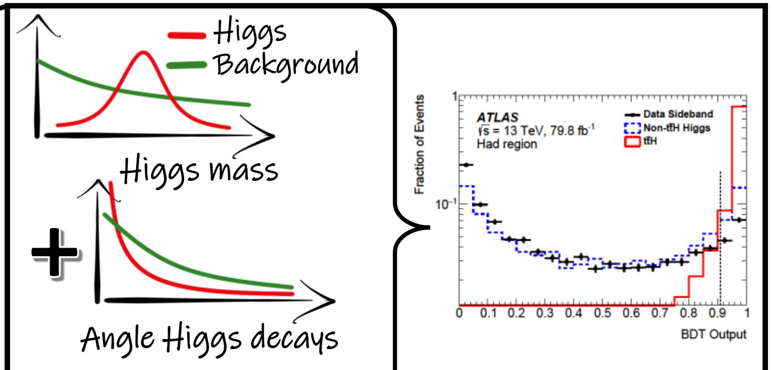
Theory Uncertainties Effects On The Analysis

Analysis point of view

σ(process)

Eur.Phys.J. C75 (2015) 153





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Uncertainty on **cross-section**

Uncertainty on **acceptance** in and across categories

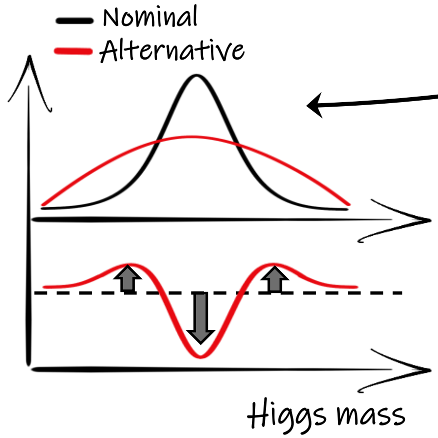
In most cases: uncertainty on p.d.f "**shapes**" in categories
Often: involve combination with machine-learning

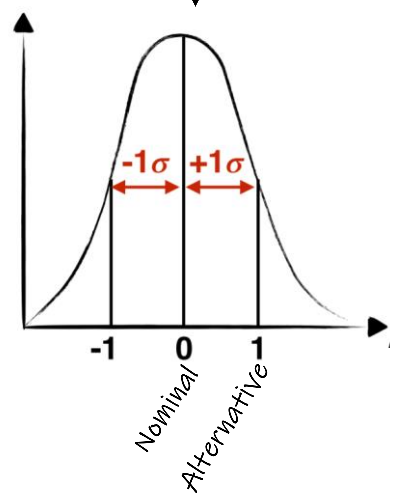
Theory uncertainties cover unknowns in a multi (large)-dimensional phase-space

Theory Uncertainties Effects On The Analysis

- Distributions in all control and signal regions fitted simultaneously
  - Binned Likelihood Fit

$$\mathcal{L}(\mu,\vec{\theta}) = \prod_{i \in bins} \text{Poiss}\left(N^i_{data} \mid \mu \cdot N^i_{sig}(\vec{\theta}) + N^i_{bkg}(\vec{\theta})\right) \prod_{\theta \in \vec{\theta}} PDF(\theta)$$





Theory uncertainties = Nuisance Parameters:
- Distribution smoothly drifted from nominal to alternative prediction
- Post-fit uncertainty from Likelihood profiling
  - Can be reduced by data in control regions

Assume Gaussian penalty:
- 0 = nominal model
- 1σ = alternative generator
- Sort of arbitrary choice favoring nominal model

Background Theoretical Uncertainties

- Covering multi-aspects => require several independent uncertainties:
  - Decompose => reduce impact of single uncertainties, avoid large "over-constraints"
- Implementation analysis dependent

A snapshot

Origin based decomposition:

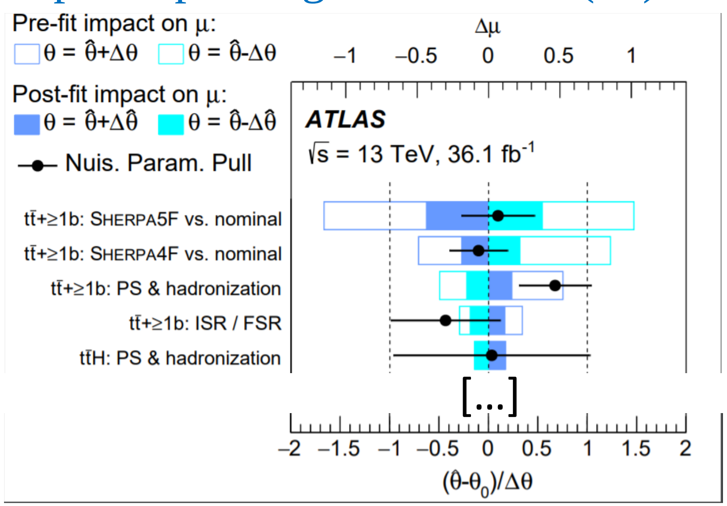
- Generator / PartonShower / Radiation
- Generator or PartonShower + Scales
- …

Observable based decomposition:

- Isolating effects along 'analysis' observables then treated uncorrelated
- In general max available variation in observable spectrum

Example: top backgrounds in ttH(bb)

Phys. Rev. D 97 (2018) 072016



Example: Higgs mass and $p_T(V)$ in VH(bb)

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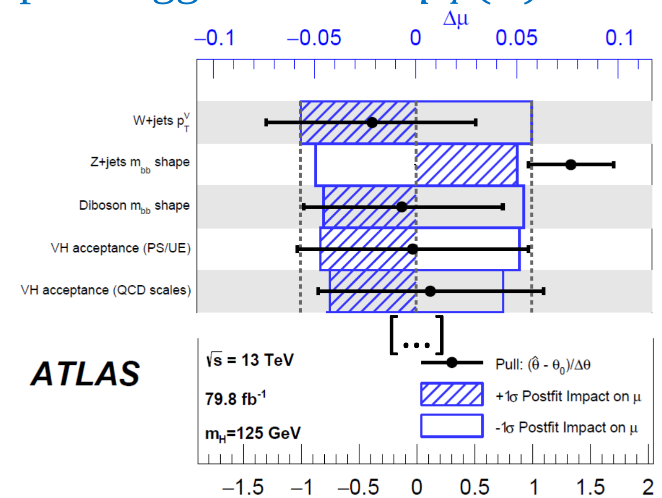

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A snapshot

Origin based decomposition:
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- Generato
- …

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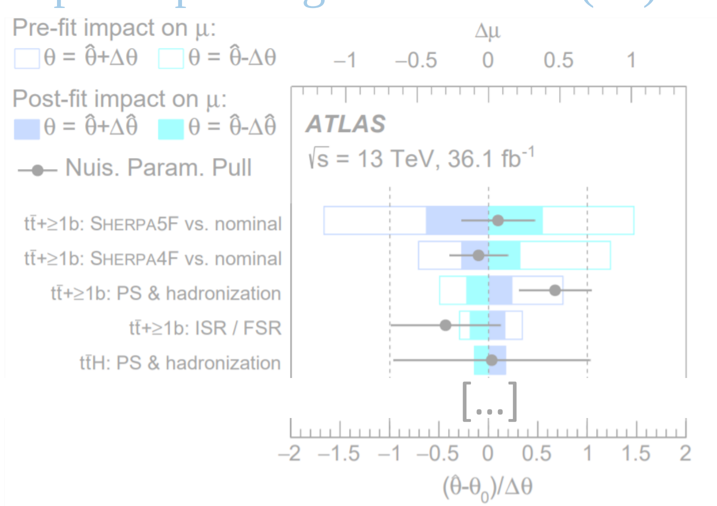
- Isolating effects along 'analysis' observables

riation in

Strong reduction of the uncertainty (usually in CR) transported to the signal region

Example: top backgrounds in ttH(bb)

Phys. Rev. D 97 (2018) 072016



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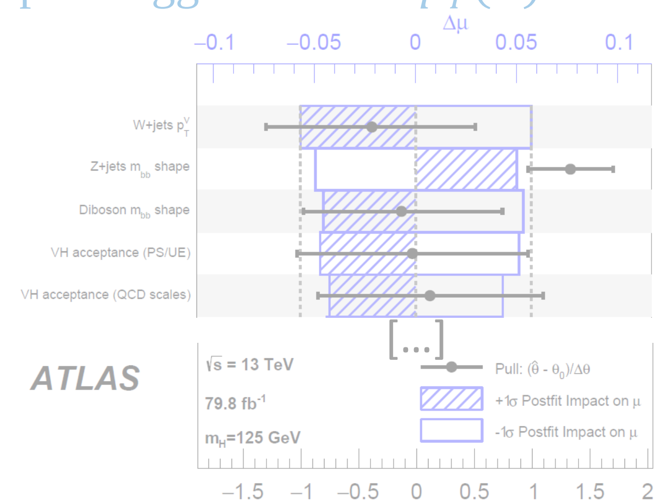

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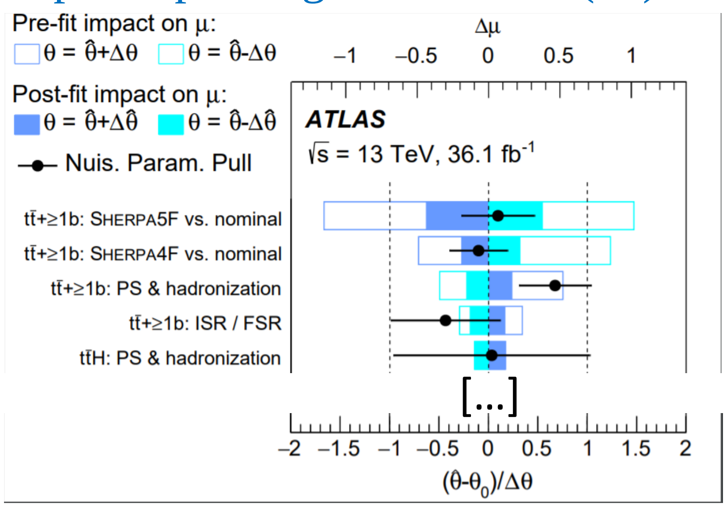

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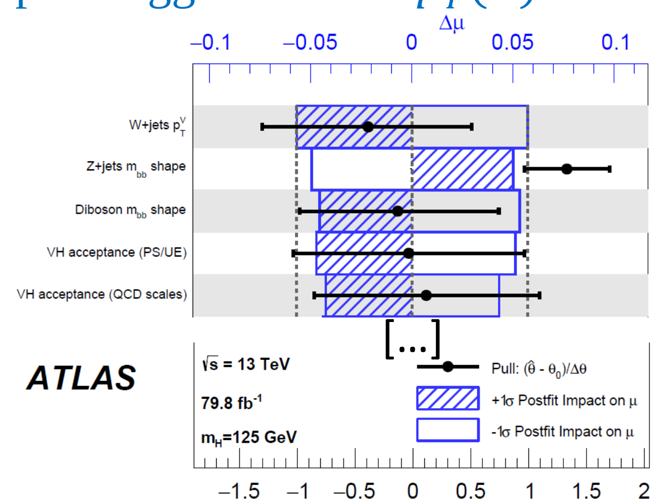

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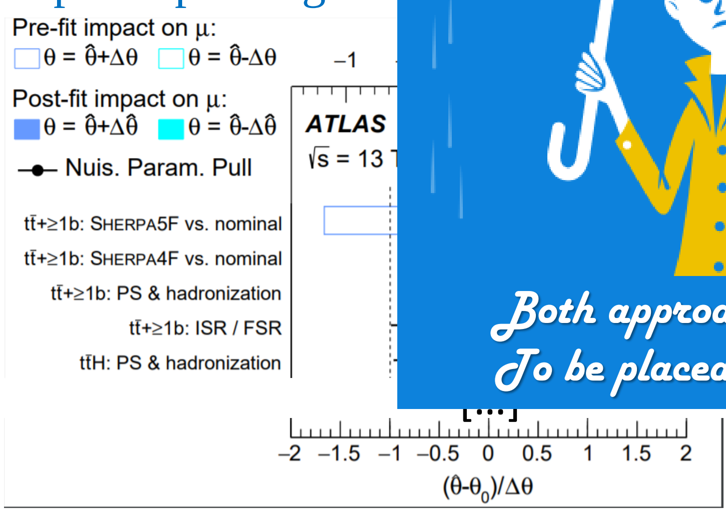
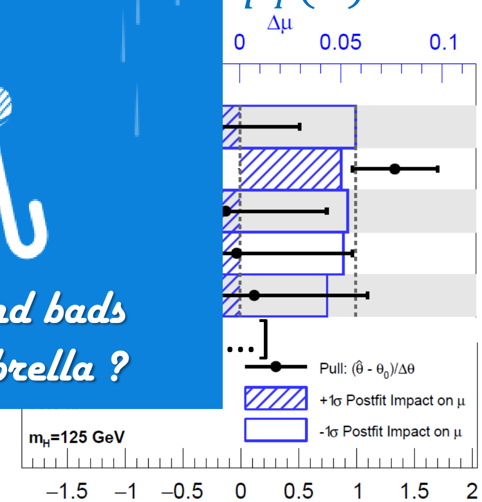
Example: top backgrou



Phys. Rev. D 97 (2018) 072016

$p_T(V)$ in VH(bb)



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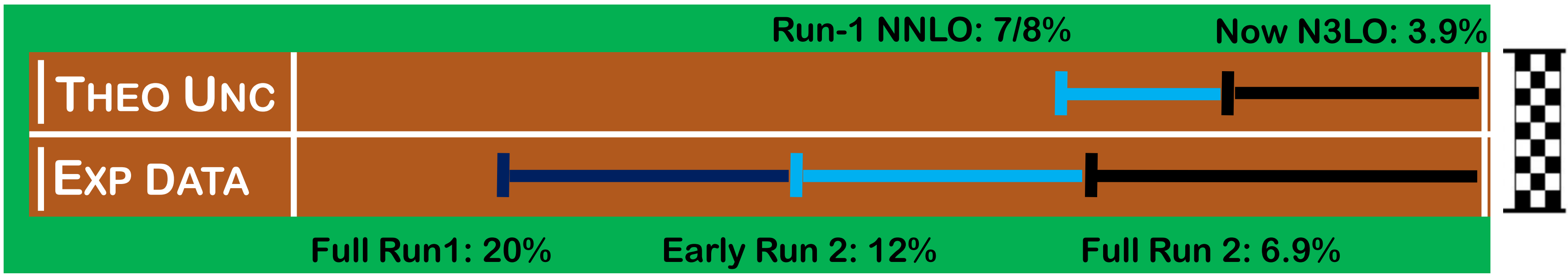
Signal Theory Uncertainties

- Higgs signal cross-section uncertainties generally from scale variations
- Example ggH cross-section uncertainty VS impact of data stat on H→γγ:

Up to now



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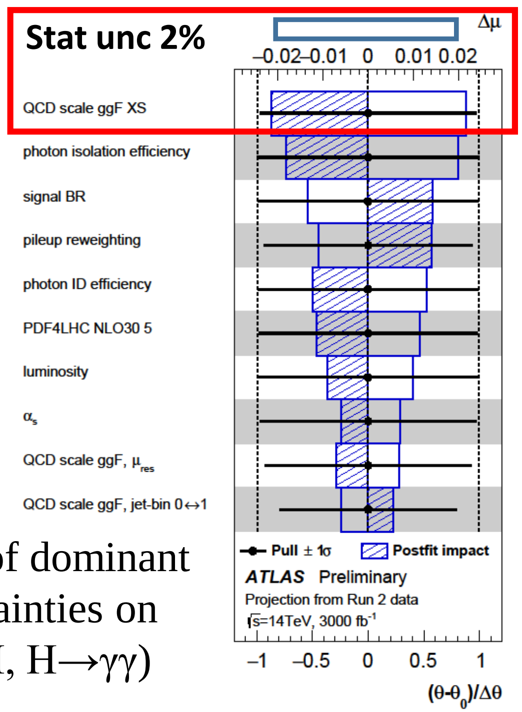


Impact of dominant uncertainties on μ(ggH, H→γγ)

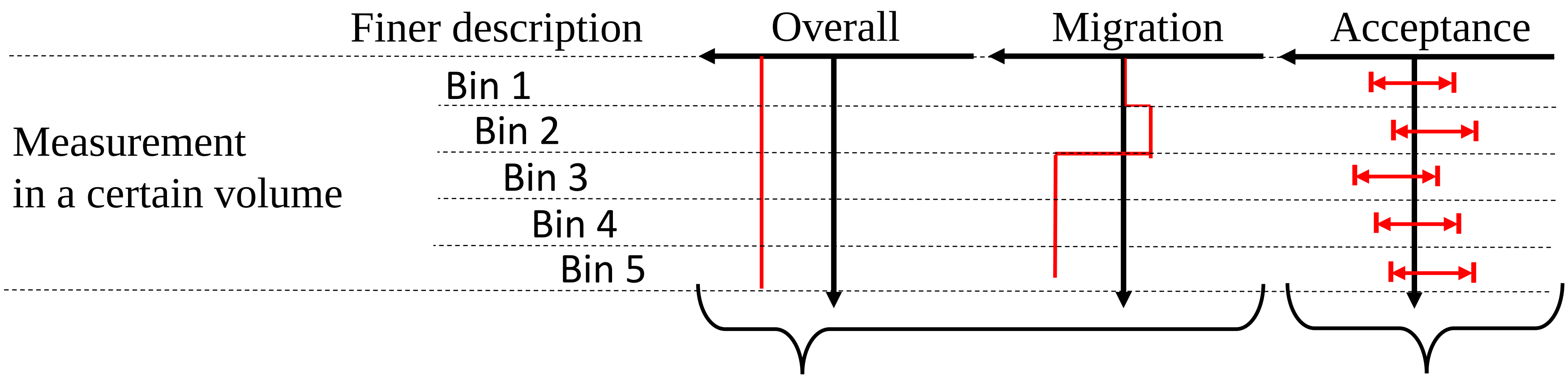
In H→γγ

Impact of σ(ggH) uncertainty and of data-stat closing up

They will equalize at HL-LHC

Signal Theory Uncertainties

- Signal uncertainties reduced with "fiducial" or Simplified Template Cross-Section:



Impact of μ_R and μ_F on prediction decomposed:

- Keep only "migrations" with null total impact

Variation of acceptance changing shower model or tunes

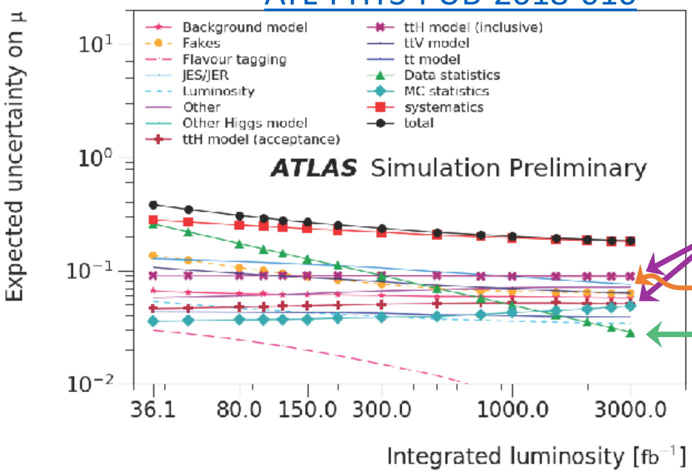
Measurement region ($\lvert y_H \rvert < 2.5$, $H \to b\bar{b}$)	SM prediction [fb]	Result [fb]	Stat. unc. [fb]	Syst. unc. [fb] Th. sig.	Th. bkg.	Exp.
3-POI scheme						
$W \to \ell\nu$; $p_T^V > 150$ GeV	31.1 ± 1.4	35 ± 14	± 9	± 2	± 9	± 4
$Z \to \ell\ell, \nu\nu$; $75 < p_T^V < 150$ GeV	50.6 ± 4.1	81 ± 45	± 35	± 10	± 21	± 19
$Z \to \ell\ell, \nu\nu$; $p_T^V > 150$ GeV	23.7 ± 3.0	28.4 ± 8.1	± 6.4	± 2.4	± 3.6	± 2.3

Removed (SM prediction uncertainty) — Kept (Th. sig.)

Illustration from VH(bb) STXS [JHEP 05 (2019) 141]

Conclusions

ATL-PHYS-PUB-2018-010



- Theory uncertainties are in phase to become main limitation

ttH theory uncertainties

Data-driven background and experimental uncertainties

Data-stat

- Many probes on the market:
  - Scale variations, Monte-Carlo generator choice, Parton-Shower model/tune, …
  - Better disentangle physical stages => better understanding of the uncertainty
  - Differential measurements still stat limited; approaching constraints soon ?
- Better uncertainty decomposition: reduced single systematic uncertainty impact
  - Cover several shapes and acceptances
  - Signal theory uncertainties reduced with fiducial/STXS
    - But important for interpretation
  - Origin or/and observable based decomposition ?
    - Avoid propagation of constrain between different physics

Thank you for your attention

Backup

Theory/Modelling In Parametric Fits To Data

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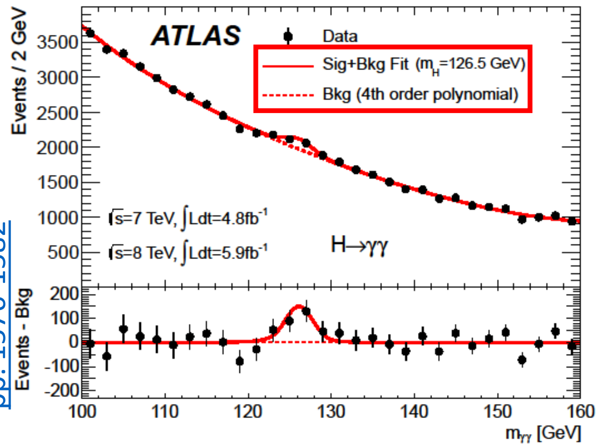
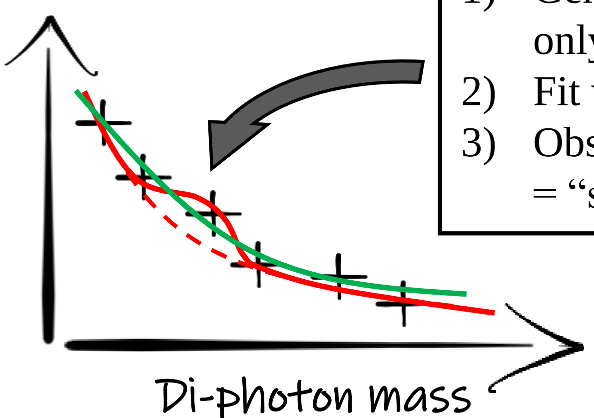


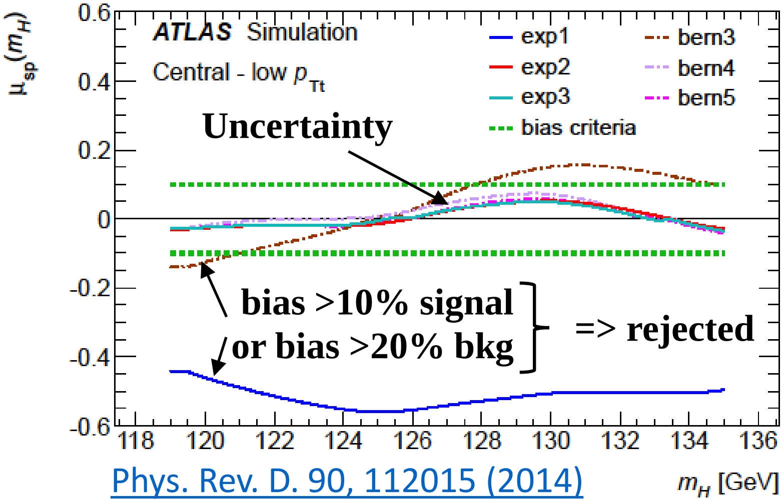
Large uncertainties on choice of parametric function

Source	Uncertainty (%)
Statistics	6.9
Signal extraction syst.	7.9
Photon energy scale & resolution	4.6
Background modelling (spurious signal)	6.4
Correction factor	2.6
Pile-up modelling	2.0
Photon identification efficiency	1.2
Photon isolation efficiency	1.1
Trigger efficiency	0.5
Theoretical modelling	0.5
Photon energy scale & resolution	0.1
Luminosity	1.7
Total	11.0

- H→γγ signal: impact of photon reconstruction on width and position
- H→γγ backgrounds: uncertainty on signal = potential bias from function choice
  - Spurious signal test



1) Generate background only MC (+)
2) Fit with S+B functions
3) Observed signal yields = "spurious signal"



Phys. Rev. D. 90, 112015 (2014)

Additional references

- Status table p2
  - $H\rightarrow\gamma\gamma$ full run 2: ATLAS-CONF-2019-029
  - $H\rightarrow 4l$ full run 2: ATLAS-CONF-2019-025
  - $H\rightarrow\tau\tau$ 36.1 fb^{-1}: Phys. Rev. D 99 (2019) 072001

- Racing p14 $H\rightarrow\gamma\gamma$:
  - Run 1: Phys. Rev. D. 90, 112015 (2014)
  - Early Run 2: Phys. Rev. D 98 (2018) 052005
  - Full Run 2 (see above)