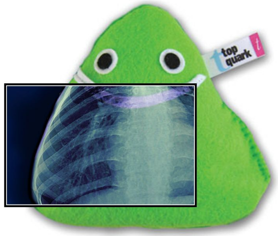
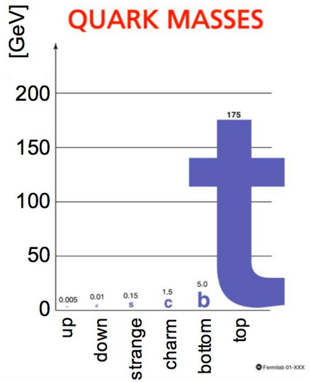
Top quark physics with the ATLAS detector



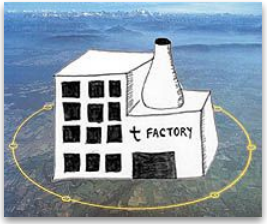
Michele Pinamonti
(INFN Trieste & University of Udine)
on behalf of the ATLAS Collaboration

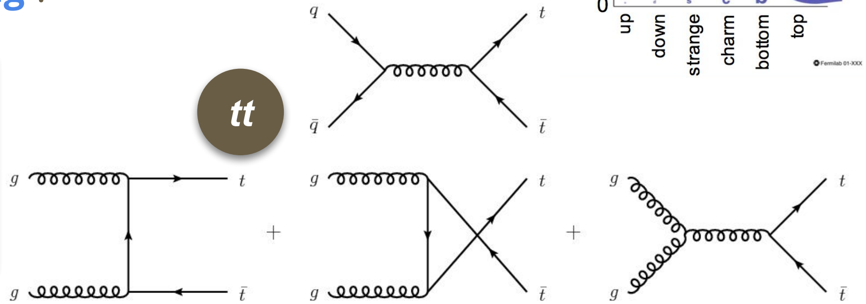
Interpreting the LHC Run 2 Data and Beyond
ICTP, Trieste (Italy)
May 27th 2019

The top quark

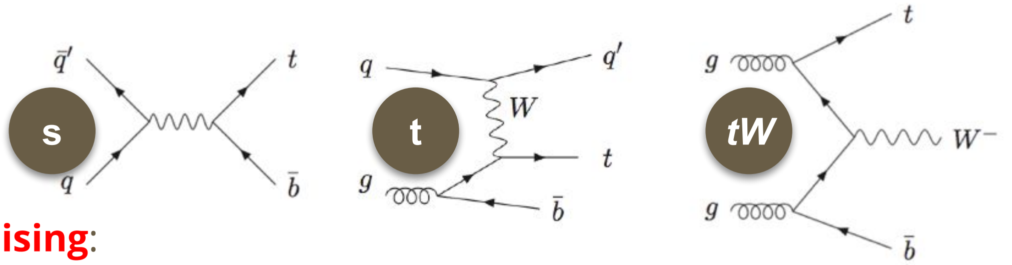


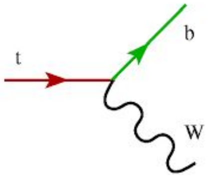
- **Heaviest** elementary particle:
  - same mass scale as *W*, *Z* and Higgs bosons
    - connection to **EW Symmetry Breaking** ?
  - Yukawa coupling $y_t \sim 1$





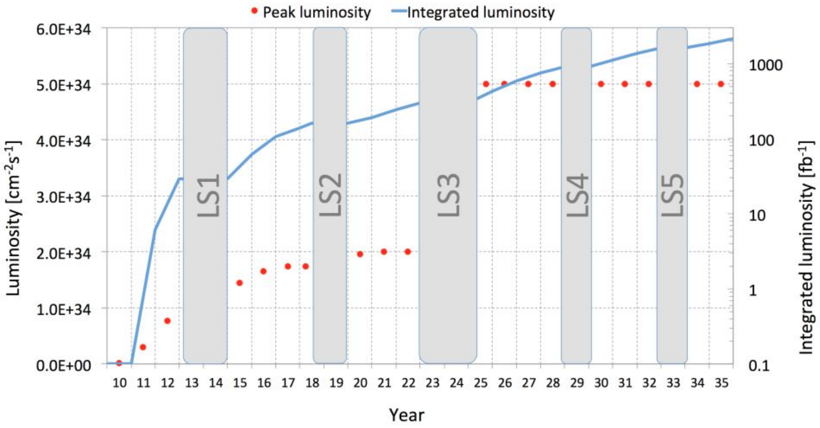
- **Copious production** at the LHC:
  - **strong** pair production: *tt*
  - EW **single production**:
    t-, s- and *Wt*-channels
  - **associated** production:
    tt+γ/W/Z/H, tt+bb, tt+tt…



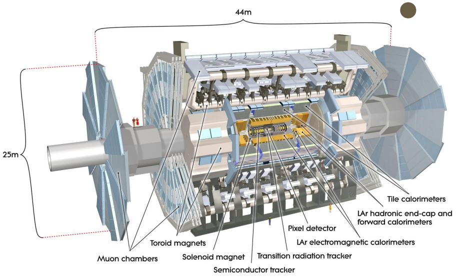


- **Decays before hadronising**:
  - ~ exclusively to *Wb*
    ⇒ clean **source** of *W* and *b*

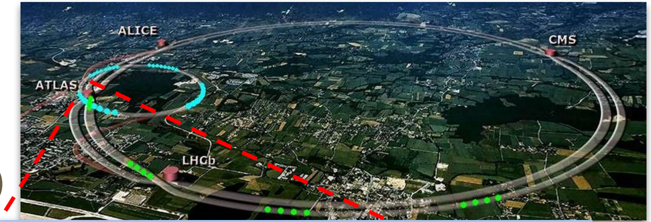
LHC and ATLAS

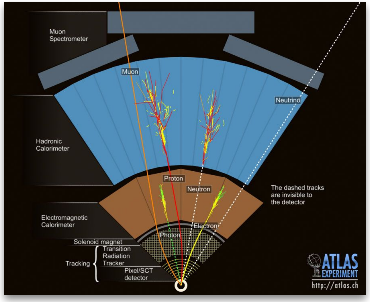


- **LHC**: 27 km - pp - CERN, Geneva (CH)
  - **Run 1:** $\sqrt{s}$ = 7 – 8 TeV, 2010 – 2012, 30 fb^{-1}
  - **Run 2:** $\sqrt{s}$ = 13 TeV, 2015 – 2018, 150 fb^{-1}
  - **Run 3:** $\sqrt{s}$ = 14 TeV, 2021 – 2023, ~150 fb^{-1}
  - **HL-LHC:** $\sqrt{s}$ = 14 TeV, 2026 – ?, ~3 ab^{-1}



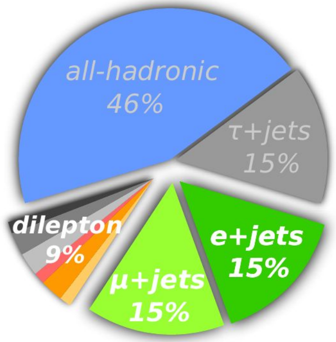
- **ATLAS**: one of the 2 ***general-purpose*** LHC detectors:
  - ~100 m, 40 tons, ~ 4 π coverage*
  - made of sub-detectors: (*: tracking |η| < 2.5)
    - **inner detector**
    - **calorimeters** (EM and Hadronic)
    - **muon spectrometer**
  - excellent measurement of:
    - **electrons**
    - **muons**
    - **photons**
    - **hadronic jets**

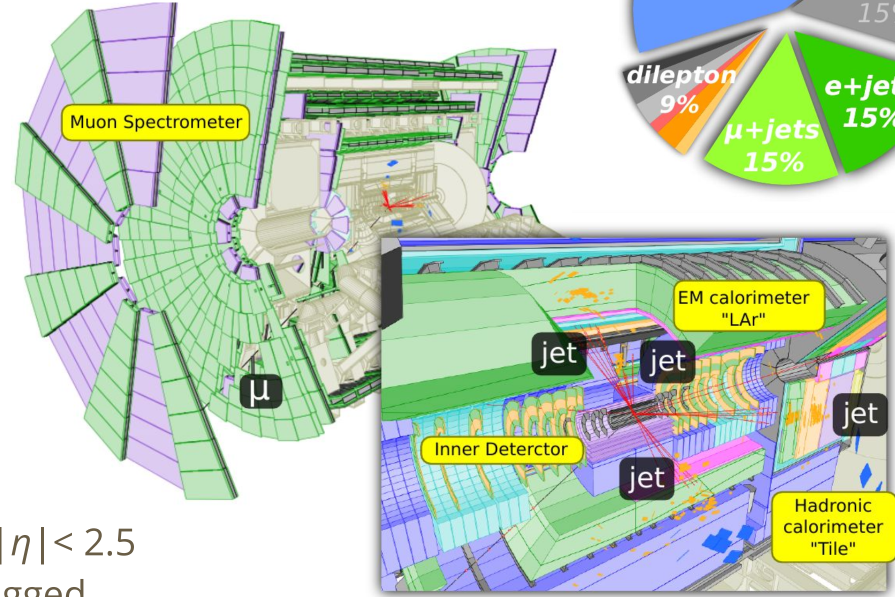




Top events and final states: experimental signatures

- $t \to Wb$, $W \to \ell\nu / qq'$
  ⇒ top events have **final states** with **leptons** (e, μ, τ), **missing energy**, ***b*-quark-jets**, **“light” jets**
  - ***e* and *μ*** identified and measured **precisely** in ATLAS
  - **jets** larger uncertainties (experimental & theoretical)
  - ***b*-jets** identified through *b*-tagging algorithms
    - *b*-tagging calibrated with top events!





- <u>**Typical selection requirements**</u>:
  - 0 – 2 e or μ (τ^{had} harder to identify), p_T > 25 GeV, $|\eta|$< 2.5
  - 2 – 6 jets, p_T > 25 GeV, $|\eta|$<2.5, ≥ 1 *b*-tagged
  - eventually minimum E_T^{miss}, $m_{\ell\ell}$ veto around *Z* mass (depending on channel)

  ⇒ excellent rejection of non-top events (background)

ATLAS Papers on Top Physics in the last year

Short Title	Journal reference	Date	√s (TeV)	L	Links
Measurement of the top-quark mass using ttbar+1jet events at 8 TeV NEW	Submitted to JHEP	06-MAY-19	8	20.3 fb^{-1}	Documents | 1905.02302 | Inspire Internal
Spin correlation measurement at 13 TeV	Submitted to EPJC	18-MAR-19	13	36 fb^{-1}	Documents | 1903.07570 | Inspire Internal
Measurement of the jet shapes at 13 TeV	Submitted to JHEP	07-MAR-19	13	36 fb^{-1}	Documents | 1903.02942 | Inspire Internal
ATLAS+CMS combination of Run 1 single top measurements and extraction of Vtb	Submitted to JHEP	18-FEB-19	8	20 fb^{-1}	Documents | 1902.07158 | Inspire Internal
Measurement of ttV in multilepton final states using 36.5fb-1 at 13 TeV	Phys. Rev. D 99 (2019) 072009	11-JAN-19	13	36 fb^{-1}	Documents | 1901.03584 | Inspire Internal
Search for flavor-changing neutral current t to Hq with H->b-bbar and tautau at 13 TeV	Submitted to JHEP	30-DEC-18	13	36 fb^{-1}	Documents | 1812.11568 | Inspire Internal
Measurement of the ttbar+gamma cross section at 13 TeV	Eur. Phys. J. C 79 (2019) 382	04-DEC-18	13	36 fb^{-1}	Documents | 1812.01697 | Inspire Internal
Measurement of the ttbb cross section at 13 TeV	JHEP 04 (2019) 046	29-NOV-18	13	36 fb^{-1}	Documents | 1811.12113 | Inspire HepData | Internal
4 top quark search with 1 or 2 leptons	Phys. Rev. D 99 (2019) 052009	06-NOV-18	13	36 fb^{-1}	Documents | 1811.02305 | Inspire Briefing | Internal
Measurement of the top quark mass in the lepton+jets channel at 8 TeV	Eur. Phys. J. C79 (2019) 290	03-OCT-18	8	20.2 fb^{-1}	Documents | 1810.01772 | Inspire Internal
Same-sign dilepton plus b-jet search	JHEP 12 (2018) 039	31-JUL-18	13	36.1 fb^{-1}	Documents | 1807.11883 | Inspire HepData | Internal
Quantum Interference Between Single and Doubly Resonant Top Quark Production	Phys. Rev. Lett. 121 (2018) 152002	12-JUN-18	13	36 fb^{-1}	Documents | 1806.04667 | Inspire Internal

- Will not just make a list of all ATLAS results:
  - some **new and fresh results** shown
  - few selected topics to trigger **discussion**

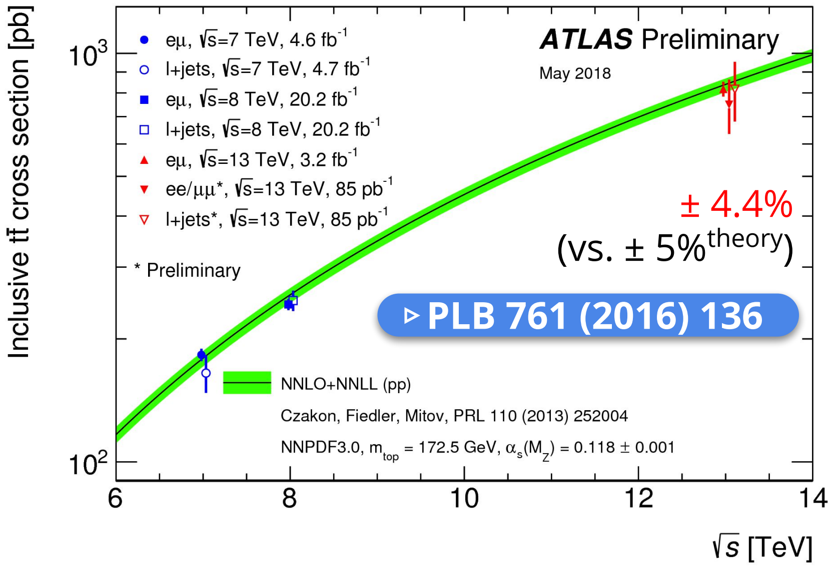
ATLAS EXPERIMENT — PUBLIC RESULTS

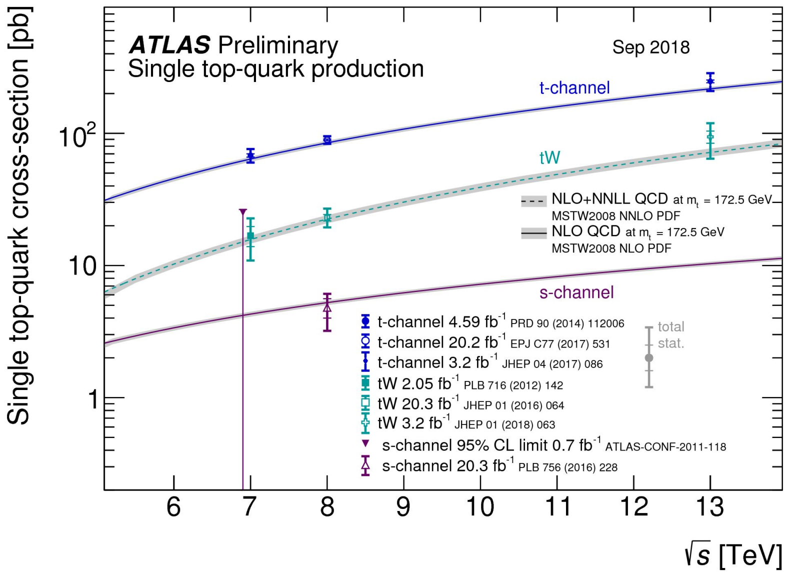
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

Top Quark Physics

Total cross-sections

- **Excellent agreement** between theory and experiments
- Experimental precision **challenging** best theory prediction uncertainties
- **Comparison** exp. vs theory can be used for:
  - **limits** on New Physics within EFT formalism
  - **indirect measurements** of α_s, m_t...



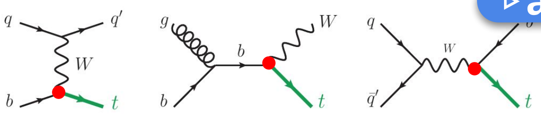


V_{tb} determination

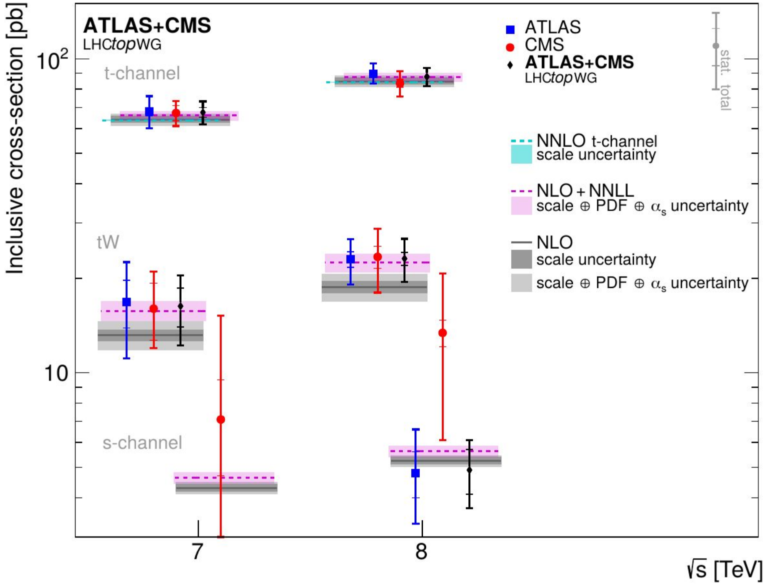
▹ arXiv:1902.07158

New!

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



- Indirect determination: $|V_{tb}| = 0.999105 \pm 0.000032$ Particle Data Group, Phys. Rev. D 98, 030001
- Use **single-top x-sec measurements** from LHC @7 and 8 TeV to extract "direct" measurement
- Combination of **ATLAS+CMS**, all channels used
- Largest **uncertainties** from **theory**



Combined $\|f_{LV}V_{tb}\|^2$	1.05	
Uncertainty category	Uncertainty	
	[%]	$\Delta\|f_{LV}V_{tb}\|^2$
Data statistical	1.8	0.02
Simulation statistical	0.9	0.01
Integrated luminosity	1.3	0.01
Theory modelling	4.5	0.05
Background normalisation	1.3	0.01
Jets	2.6	0.03
Detector modelling	1.6	0.02
Top-quark mass	0.7	0.01
Theoretical cross-section	4.3	0.04
Total syst. unc. (excl. lumi.)	7.1	0.07
Total syst. unc. (incl. lumi.)	7.2	0.08
Total uncertainty	7.4	0.08

$$|f_{LV}V_{tb}| = \sqrt{\frac{\sigma_{\mathrm{meas.}}}{\sigma_{\mathrm{theo.}}(V_{tb}=1)}}$$

Assumed:

$$|V_{td}|, |V_{ts}| \ll |V_{tb}|$$

- Tevatron combination from single top:

$$|f_{LV}V_{tb}| = 1.02^{+0.06}_{-0.05}$$

$$|f_{LV}V_{tb}|^2 = 1.05 \pm 0.02\ (\mathrm{stat.}) \pm 0.06\ (\mathrm{syst.}) \pm 0.01\ (\mathrm{lumi.}) \pm 0.04\ (\mathrm{theo.}) = \boxed{1.05 \pm 0.08}$$

$$\Rightarrow |f_{LV}V_{tb}| = 1.02 \pm 0.04\ (\mathrm{meas.}) \pm 0.02\ (\mathrm{theo.})$$

Differential cross-sections

- Going **beyond total** cross-sections, ATLAS measuring *tt* cross-section vs. many kinematic variables
  - unfolded to **parton-level**, in **total phase-space**
  - unfolded to **particle-level**, within certain **fiducial phase-space**
  - **normalised** distributions

- **Comparison with different theory predictions**:
  - **fixed order** calculations (parton-level, eg. NNLO-QCD+NLO-EW)
  - MC predictions (both parton and particle-level, various **NLO+PS**)

- **Why do we need them?**
  - powerful tests of QCD and EW predictions
  - useful to tune MC generators
  - used to extract measurements (PDFs, m_t...)

Some ATLAS analyses in Run1 and 2:

- tt 1 ℓ @8 TeV ▹ **Eur. Phys. J. C76 (2016) 538**
- tt 2 ℓ @8 TeV ▹ **Eur. Phys. J. C 77 (2017) 804**
- tt 1ℓ @13 TeV ▹ **JHEP 11 (2017) 191**
- tt 2ℓ @13 TeV ▹ **Eur. Phys. J. C77 (2017) 292**
- tt 0ℓ @13 TeV ▹ **Phys. Rev. D 98 (2018) 012003**
- Run 2 results still based on limited stat.

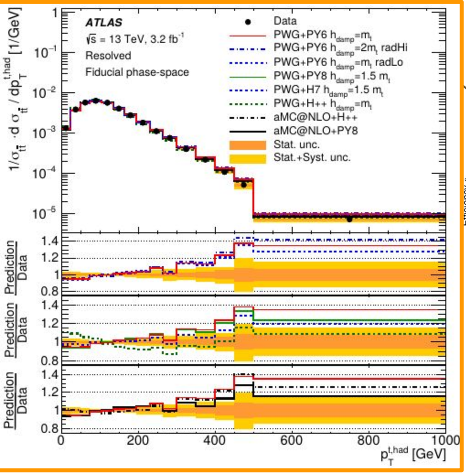
Differential cross-sections

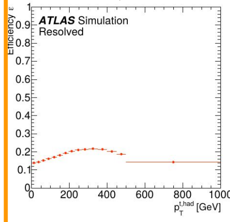
- Analysis setup:
  - typical *tt* selection cuts → low background
  - reconstruct tops from decay products,
    with simple algorithms easily reproducible by theorists (“pseudo-top” reconstruction)
  - **unfold*** background-subtracted data distributions to parton / particle level distributions

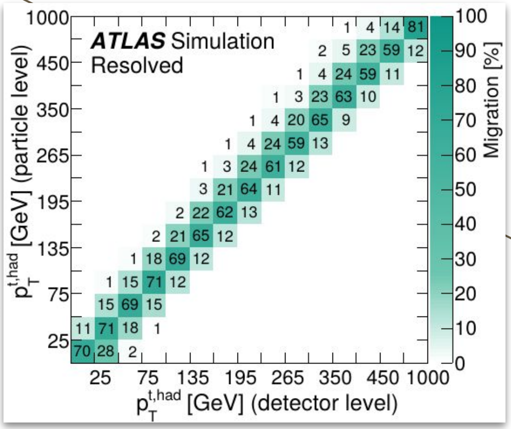
* **Iterative Bayesian Unfolding** used (D’Agostini et al. ▹ arXiv:1010.0632):
  - *regularised*, i.e. statistical fluctuation amplification reduced
  - ***unbiased*** result thanks to ***iterations***

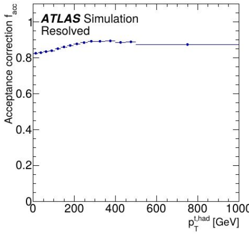
$$\frac{d\sigma^{\mathrm{fid}}}{dX^i} \equiv \frac{1}{\mathcal{L}\cdot\Delta X^i}\cdot f^i_{\mathrm{eff}}\cdot\sum_j \mathcal{M}^{-1}_{ij}\cdot f^j_{\mathrm{match}}\cdot f^j_{\mathrm{acc}}\cdot\left(N^j_{\mathrm{reco}} - N^j_{\mathrm{bg}}\right)$$

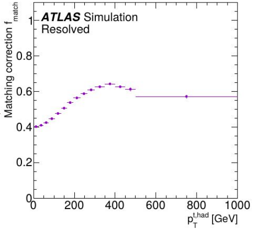
▹ JHEP 11 (2017) 191

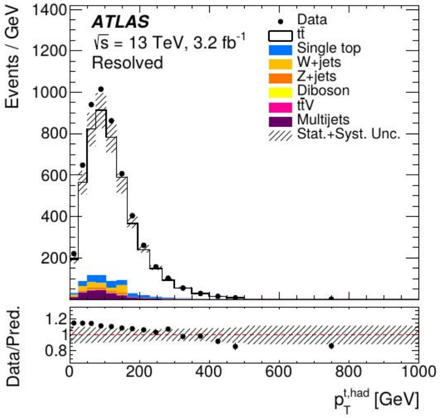






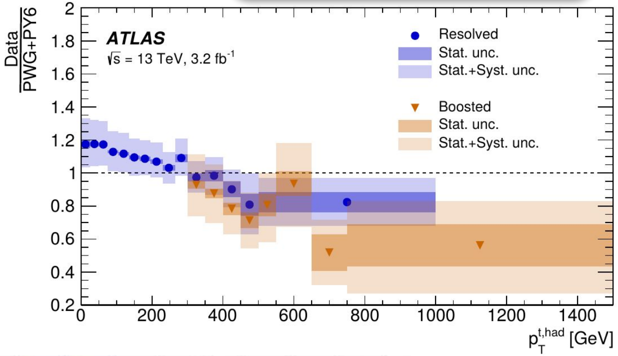






Highlights on differential x-sections

- Many distributions unfolded in Run 1:
  - parton and **particle-level**
  - comparison with fixed order calculations (**NNLO-QCD**) made agreement better
    - e.g. in top p_T: **NLO+PS predicting too soft spectra**
  - sensitivity to different **PDFs**

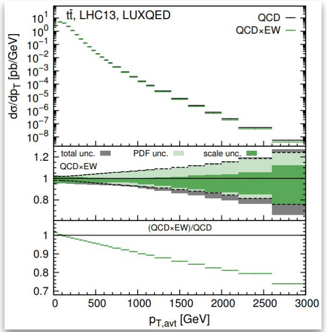


▹ JHEP 11 (2017) 191

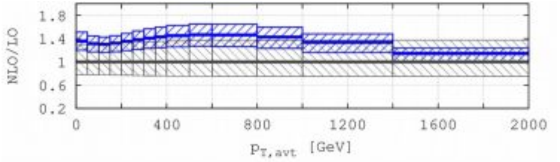
- **Run 2:**
  - still **limited number** of results (e.g. no parton level)
  - more energy ⇒ more statistics in **tail of distributions**
  - **“top-p_T issue”** larger than in Run 1:

    NNLO-QCD + NLO-EW predictions now available:

    Czakon, Mitov et al. ▹ JHEP (2017) 2017/10: 186



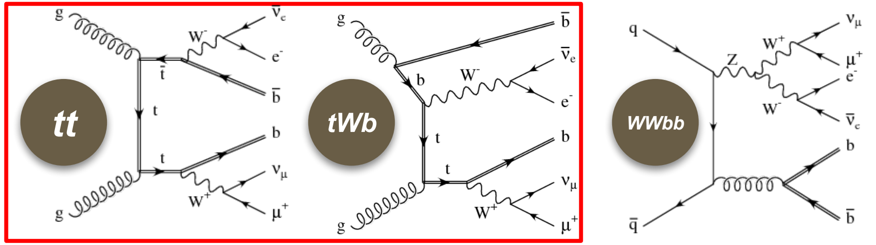
→ “in the right direction”, but need to wait for more results to declare issue as solved



tW / tt interference

New!

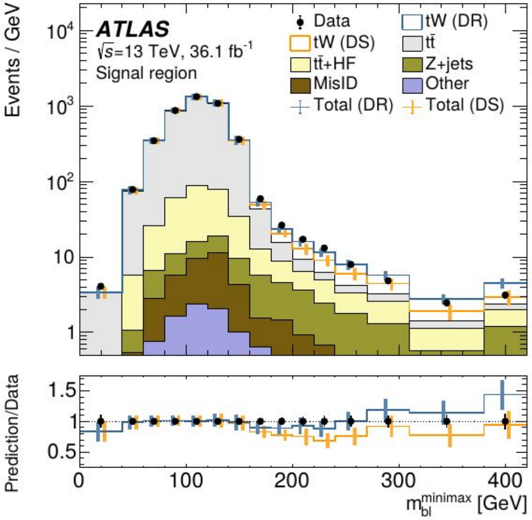
▹ Phys. Rev. Lett. 121 (2018) 152002

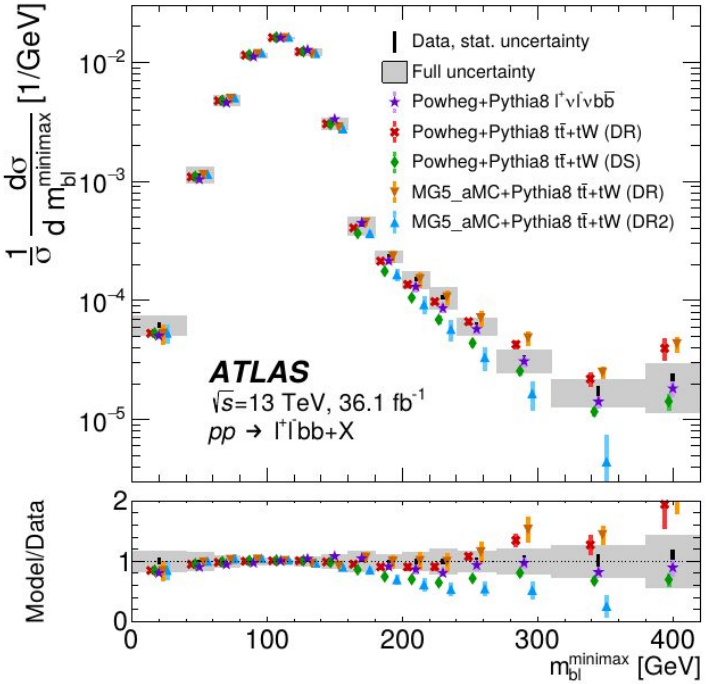


- Interesting recent measurement:
  - unfold a distribution sensitive to **interference** between ***tt* and *tW***

$$m_{b\ell}^{\text{minimax}} \equiv \min\{\max(m_{b_1\ell_1}, m_{b_2\ell_2}), \max(m_{b_1\ell_2}, m_{b_2\ell_1})\}$$

  - results from "***diagram subtraction***" and "***diagram removal***" schemes compared to data
  - unfolded data → **constraints** for future development of ***tt+tWb* process** (e.g. *all-inclusive* ***pp* → *WWbb***)

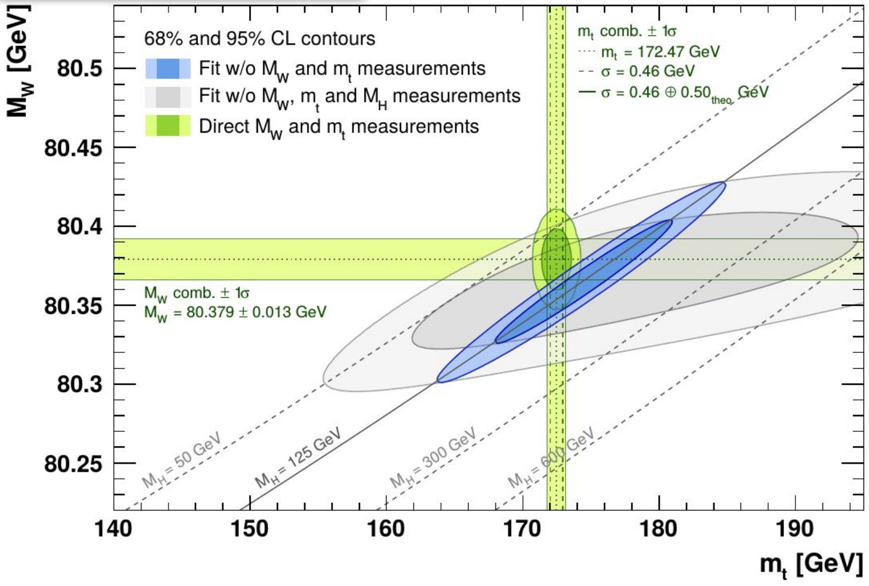




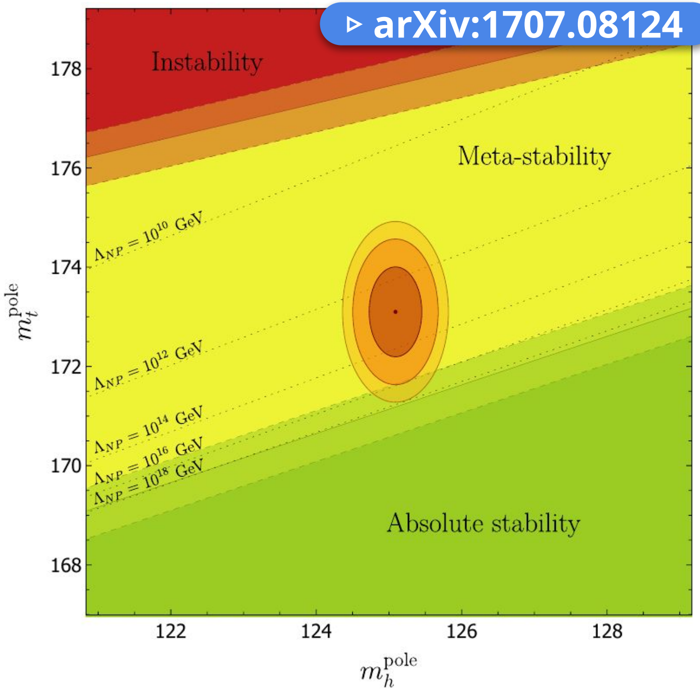
The Top Quark Mass

- $m_t + m_W + m_H$ measurements → over-constraints to SM fits
  - **direct measurements** can be compared to **indirect results** to probe validity of SM
  - m_t important to determine SM **vacuum stability**

▹ arXiv:1803.01853

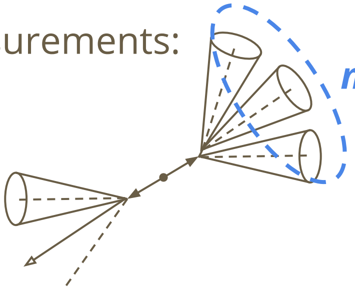


▹ arXiv:1707.08124



Methods to Measure the Top Mass

- **Direct** "m_t" measurements:



m_{top}^{reco} = *invariant mass of jets from top decay*

extraction from total or partial invariant mass of top decay products
⇒ **"Standard Method"**

  - data compared with MC simulation with different input values of m_t in MC
  - relying on jets, parton showers (LO), non-perturbative effects
    ⇒ measuring "m_t^{MC}"
    (still controversial arguments, see e.g. ▹ CERN-TH-2017-266)

- **Indirect** measurements of m_t from cross-sections (inclusive or differential)
  - in a well-defined renormalization scheme, e.g. m_t^{pole} (corresponding to definition of free particle mass)

$$\sigma^{theor.}(\alpha_s, \boxed{m_t}, \text{PDF}, \mu_F, \mu_R, \ldots) \text{ vs } \sigma^{meas.}$$

m_t = *parameter in the SM*

    - "O(1 GeV) difference" between m_t^{MC} and m_t^{pole}

Both types: precision measurements

⇩

presented measurements based on LHC Run1 *pp*-data

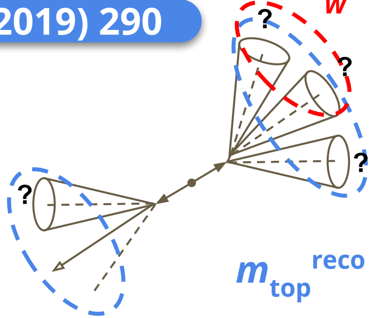
Direct m_t measurement, tt 1ℓ

▹ Eur. Phys. J. C79 (2019) 290

New!

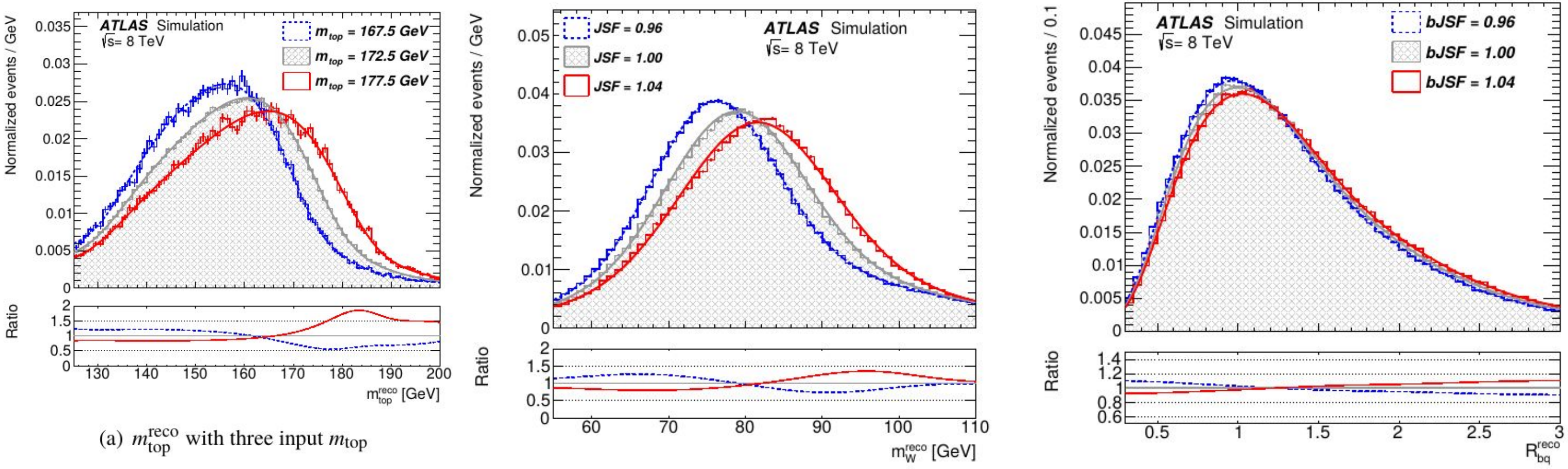
- **"3D" template method**:
  - simultaneous fit to **3 distributions**:
    - m_{top}^{reco}, m_W^{reco}, $R_{bq}^{reco} = \frac{p_T^{b_{had}} + p_T^{b_{lep}}}{p_T^{q_1} + p_T^{q_2}}$

    (q_1 and q_2 light jets assigned to W)
  - **3 free parameters** in the template fit:
    - m_t, JSF *, $bJSF$ * (*: (b-)Jet-energy-Scale-Factor)



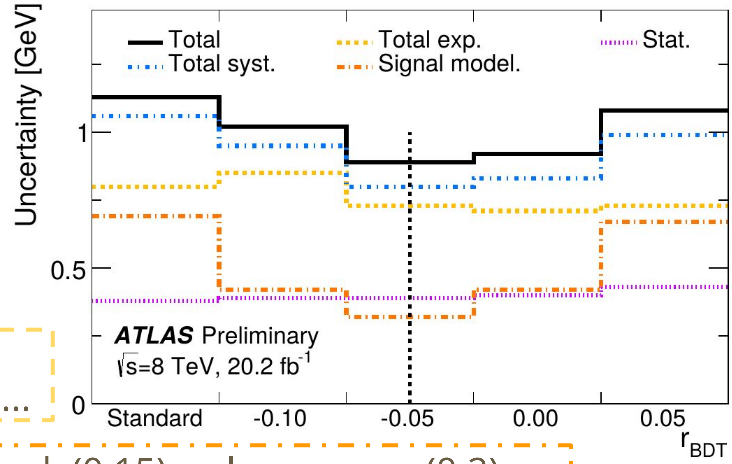
- **KLFitter*** to reconstruct tt system (for jet-parton assignment and m_{top}^{reco})

  *: kinematical likelihood fit in each event
- m_W^{reco} and R_{bq}^{reco} use chosen jet permutation, but with original jet 4-momenta (to retain the maximum sensitivity to JES and b-JES)



(a) m_{top}^{reco} with three input m_{top}

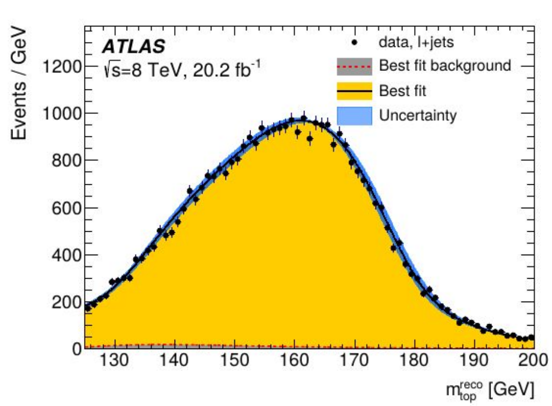
Direct m_t measurement, tt 1ℓ

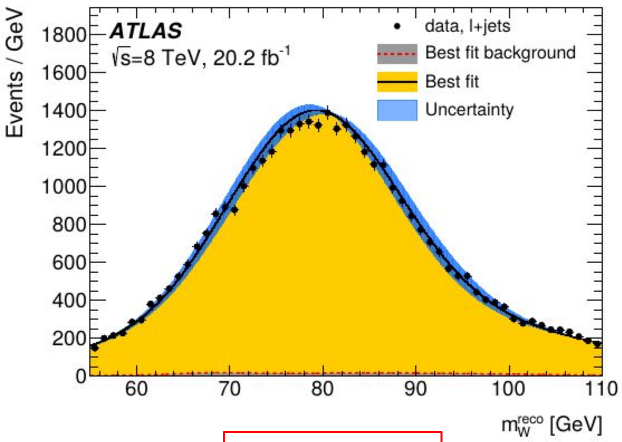


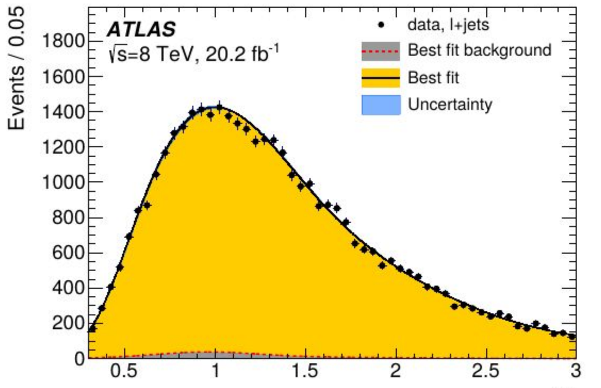
- **Optimization**:
  - cut on **BDT** built to remove **wrongly assigned events** ⇒ reduce systematics
  - BDT trained with 13 variables (best ones: KLFitter likelihood of best permutation and ΔR_{qq})

JES (0.54), *b*-JES, JER, *b*-tagging (0.38) ...

ME gen. (0.16), PS&had. (0.15), color reconn. (0.2) ...







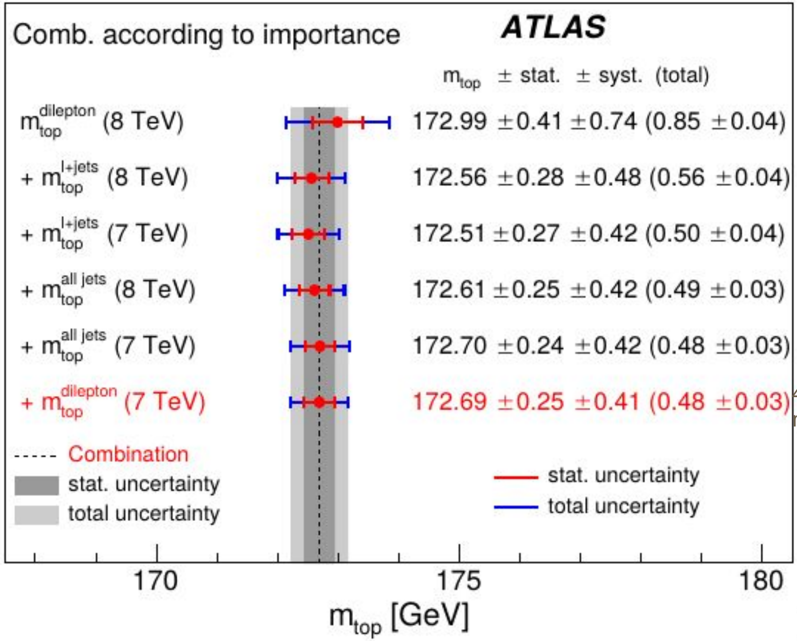
$$m_{\text{top}} = 172.08 \pm 0.39\,(\text{stat}) \pm 0.82\,(\text{syst})\ \text{GeV}$$ ± 0.91 GeV

$$\text{JSF} = 1.005 \pm 0.001\,(\text{stat})$$

$$\text{bJSF} = 1.008 \pm 0.005\,(\text{stat})$$

Direct m_t, combination

- 7 TeV + 8 TeV, ℓ+jets + dilepton:
  - **successive combination** from most sensitive to less sensitive



	dilep.@8TeV	ℓ+jets@8TeV	comb.@7+8TeV
Statistics	0.41	0.39	0.27
Method	0.05 ± 0.07	0.13 ± 0.11	0.06
Signal Monte Carlo generator	0.09 ± 0.15	0.16 ± 0.17	0.14
Hadronisation	0.22 ± 0.09	0.15 ± 0.10	0.07
Initial- and final-state QCD radiation	0.23 ± 0.07	0.08 ± 0.11	0.07
Underlying event	0.10 ± 0.14	0.08 ± 0.15	0.05
Colour reconnection	0.03 ± 0.14	0.19 ± 0.15	0.08
Parton distribution function	0.05 ± 0.00	0.09 ± 0.00	0.07
Background normalisation	0.03 ± 0.00	0.08 ± 0.00	0.03
W/Z+jets shape	0	0.11 ± 0.00	0.07
Fake leptons shape	0.07 ± 0.00	0	0.03
Jet energy scale	0.54 ± 0.04	0.54 ± 0.02	0.21
Relative b-to-light-jet energy scale	0.30 ± 0.01	0.03 ± 0.01	0.15
Jet energy resolution	0.09 ± 0.05	0.20 ± 0.04	0.10
Jet reconstruction efficiency	0.01 ± 0.00	0.02 ± 0.01	0.03
Jet vertex fraction	0.02 ± 0.00	0.09 ± 0.01	0.05
b-tagging	0.04 ± 0.02	0.38 ± 0.00	0.17
Leptons	0.14 ± 0.01	0.16 ± 0.01	0.09
E_T^{miss}	0.01 ± 0.01	0.05 ± 0.01	0.04
Pile-up	0.05 ± 0.01	0.15 ± 0.01	0.06
Total systematic uncertainty	0.74 ± 0.05	0.82 ± 0.06	0.42
Total	0.85 ± 0.05	0.91 ± 0.06	0.50

40% improvement w.r.t. most sensitive single channel

Correlations	m_{top}^{dil} (7 TeV)	m_{top}^{l+jets} (7 TeV)	m_{top}^{dil} (8 TeV)	m_{top}^{l+jets} (8 TeV)
m_{top}^{dil} (7 TeV)	1.00			
m_{top}^{l+jets} (7 TeV)	−0.07	1.00		
m_{top}^{dil} (8 TeV)	0.52	0.00	1.00	
m_{top}^{l+jets} (8 TeV)	0.06	−0.07	−0.19	1.00
BLUE weight (m_{top})	-	0.17	0.43	0.40

- Reduction of uncertainties thanks to **complementarity** and **anti-correlations**

Indirect m_t measurement from tt +jet

▹ arXiv:1905.02302

New!

- m_t^{pole} extractd from **normalized differential cross-section** of inverse of ***tt*+1j invariant mass**:

$$\mathcal{R}(m_t^{pole}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s}(m_t^{pole}, \rho_s).$$

$$\rho_s = \frac{2m_0^*}{\sqrt{s_{t\bar{t}+1\text{-jet}}}}$$

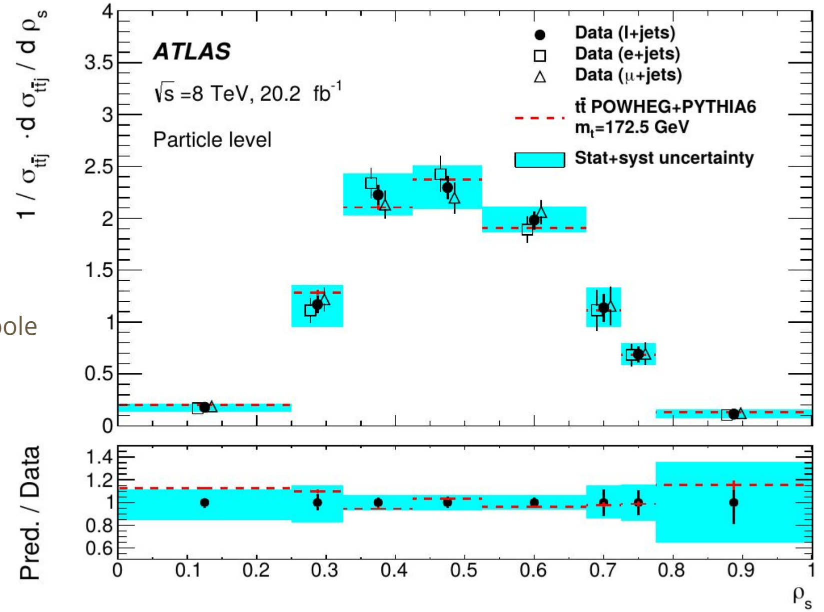
*: m_0 = 170 GeV

  - sensitive because amount of **gluon radiation depends on m_t**, with large effects in phase-space region near threshold
- **8 TeV data-set, *tt* ℓ+jets selection:**
  - ***tt* system reconstructed**, **additional** leading **jet** required p_T> 50 GeV
  - parton&particle-level **unfolded distribution** compared to NLO+PS *tt* +1jet calculation vs m_t^{pole}

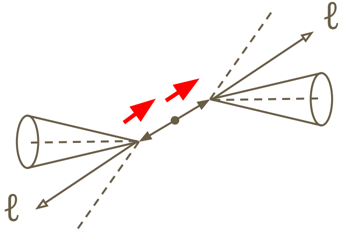
$$m_t^{pole} = 171.1 \pm 0.4\,(\text{stat}) \pm 0.9\,(\text{syst})\,^{+0.7}_{-0.3}\,(\text{theo})\text{ GeV} \qquad ^{+1.2}_{-1.1}\text{ GeV}$$

  - dominant systematic uncertainties:
    - JES and Theory (simulation & scales)
- Also value in running mass scheme derived:

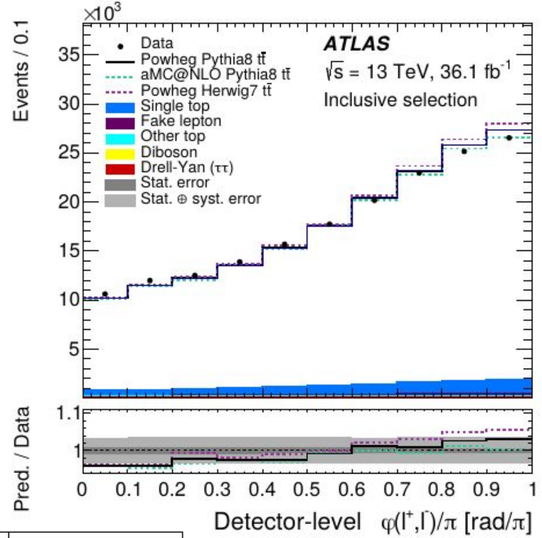
$$m_t(m_t) = 162.9 \pm 0.5\,(\text{stat}) \pm 1.0\,(\text{syst})\,^{+2.1}_{-1.2}\,(\text{theo})\text{ GeV}$$



$t\bar{t}$ Spin Correlation

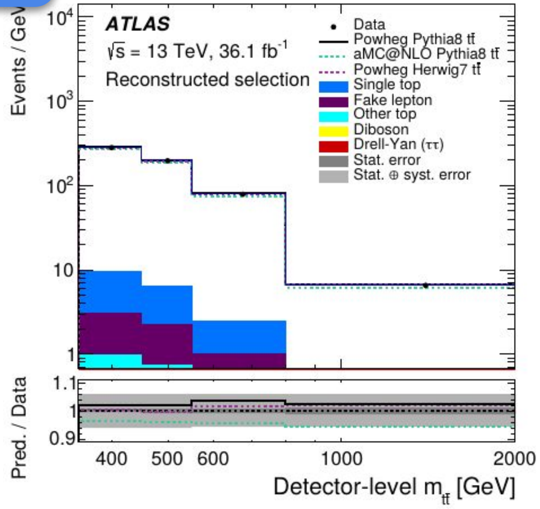


- **Spins of tops** in $t\bar{t}$ events predicted to be **correlated**
- Tops decay before hadronising ⇒ keep spin information
  - measurement of **angular distance between 2 leptons** in 2ℓ $t\bar{t}$ decay → sensitive to **spin correlation**



New!

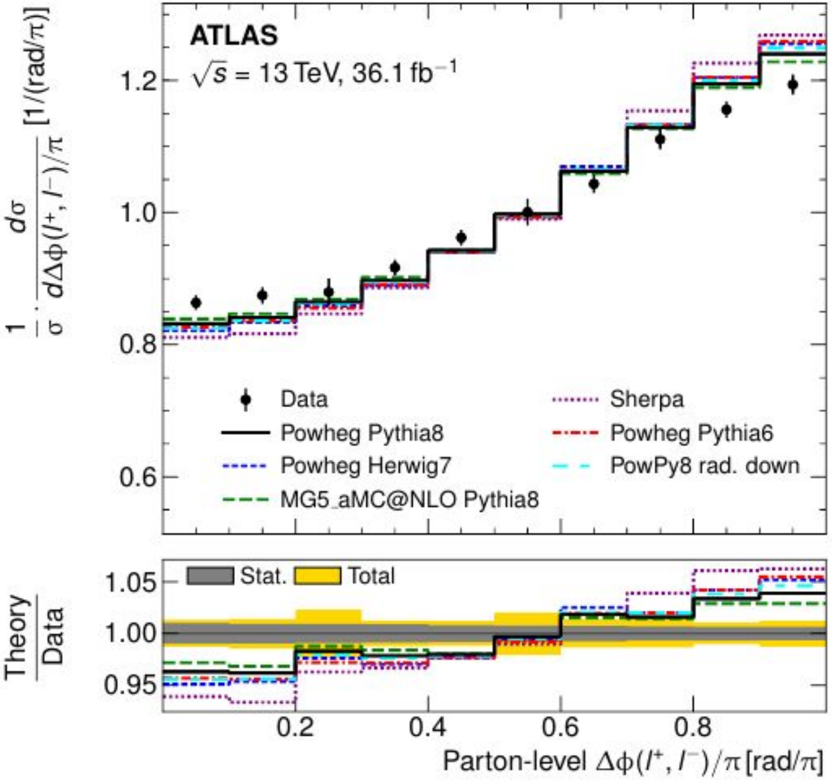
- **Run 2 ATLAS measurement:** ▹ arXiv:1905.02302
  - ***eμ* events** selected
  - ***$\Delta\varphi_{\ell\ell}$* and *$\Delta\eta_{\ell\ell}$*** distributions unfolded (*parton & particle level*) and compared to various predictions
  - also provided measurements **in bins of *$m_{t\bar{t}}$***
    - *$t\bar{t}$* system reconstructed with neutrino-weighting technique



$t\bar{t}$ Spin Correlation

- Unfolded data in some **tension** with MC predictions (NLO-QCD+PS)
  - **larger** spin correlation observed **in data**
  - **3.2 σ** significance

- Most **new physics** models (e.g. SUSY stop close to m_t) would ***reduce*** spin correlation
  - **discrepancy** in ***opposite direction***



Region	f_{SM} ± (stat.,syst.,theory)	Significance (excl. theory uncertainties)
Inclusive	$1.249 \pm 0.024 \pm 0.061 \pm 0.040$	3.2 (3.8)
$m_{t\bar{t}} < 450$ GeV	$1.12 \pm 0.04\ ^{+0.12}_{-0.13} \pm 0.02$	0.86 (0.87)
$450 \le m_{t\bar{t}} < 550$ GeV	$1.18 \pm 0.08\ ^{+0.13}_{-0.14} \pm 0.08$	1.0 (1.1)
$550 \le m_{t\bar{t}} < 800$ GeV	$1.65 \pm 0.19\ ^{+0.31}_{-0.41} \pm 0.22$	1.3 (1.4)
$m_{t\bar{t}} \ge 800$ GeV	$2.2 \pm 0.9\ ^{+2.5}_{-1.7} \pm 0.7$	0.58 (0.61)

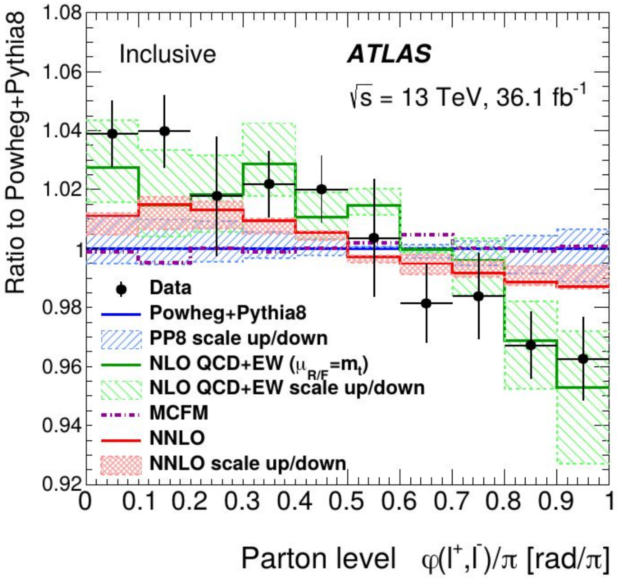
fraction of SM-like spin correlation

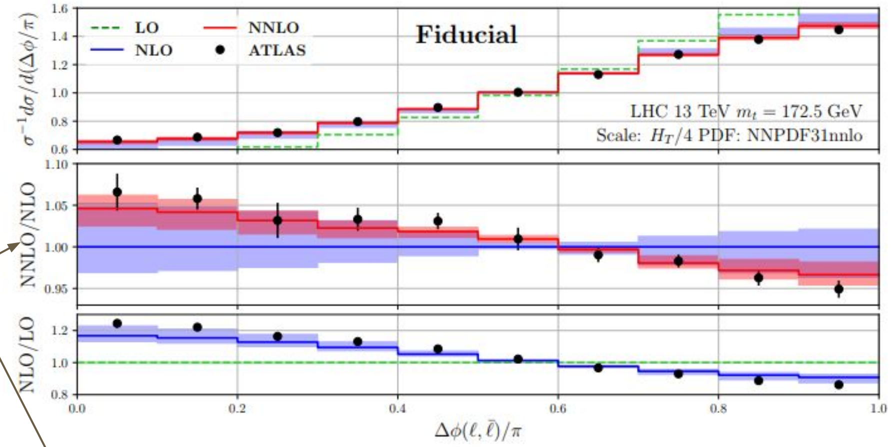
$$x_i = f_{SM} \cdot x_{spin,\,i} + (1 - f_{SM}) \cdot x_{nospin,\,i}$$

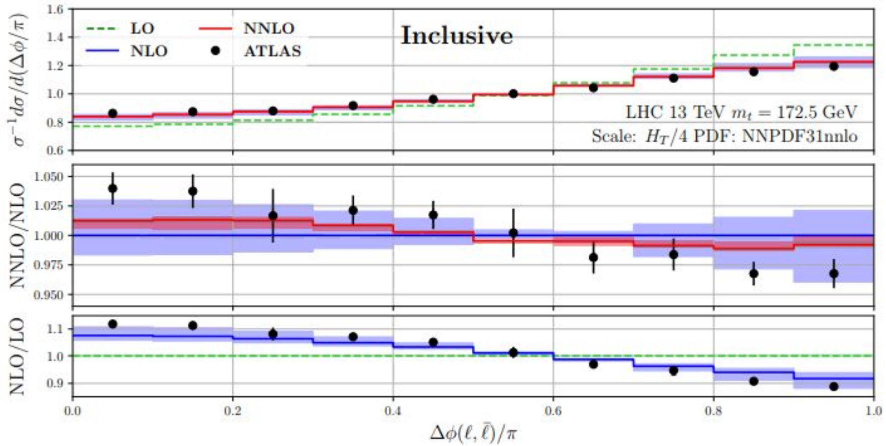
$t\bar{t}$ Spin Correlation

arXiv:1901.05407 [hep-ph]

- **Cross-checks:**
  - NWA and LO decay → not important
  - NNLO-QCD predictions in right direction
    - fiducial agreeing better than total
  - **NLO QCD+EW** (scale=m_t) **agrees** with data but ***large scale uncertainties***

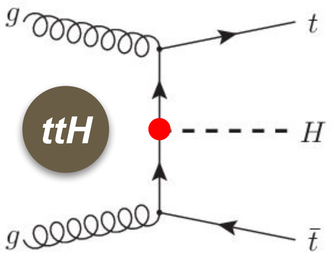


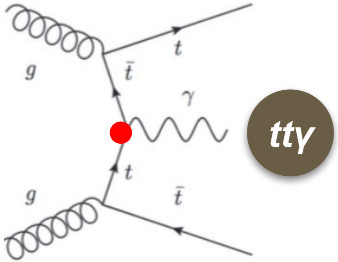


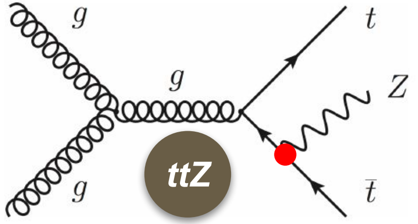


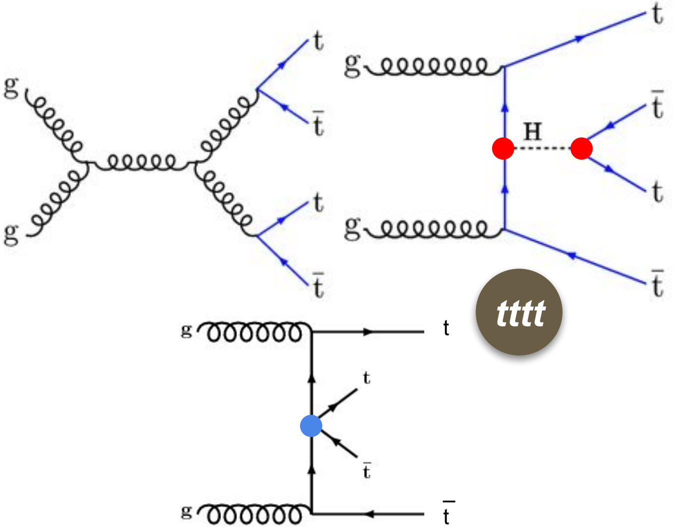
Associated production: *tt+X*

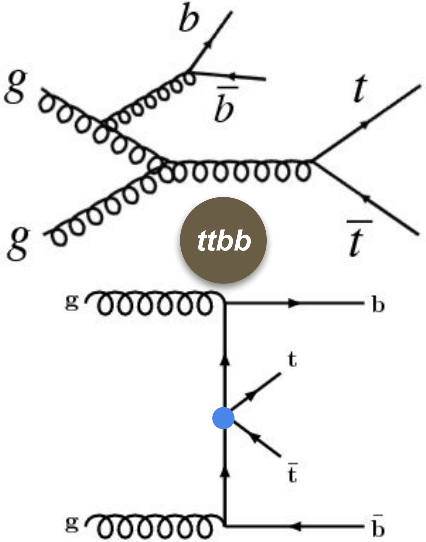
- **Rare** processes, interesting by themself
- A way to measure directly **top couplings**
  - *ttZ, ttH, ttγ* vertexes
  - new interactions like **4-fermion interactions** (e.g. *ttbb, tttt*)
- Important **background** processes for many new physics searches

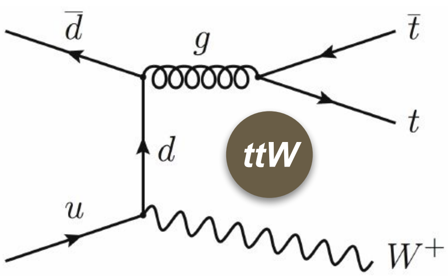










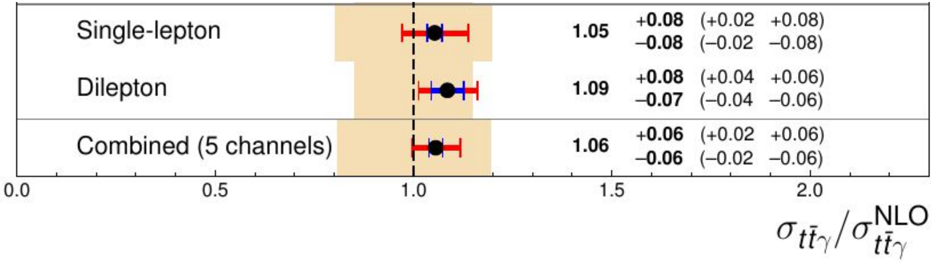


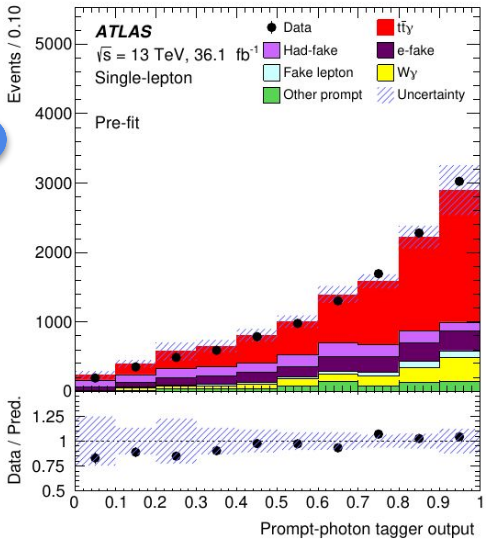
tt +photon

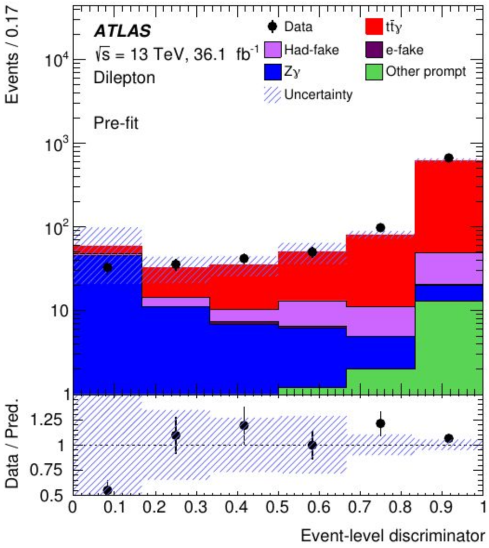
New!

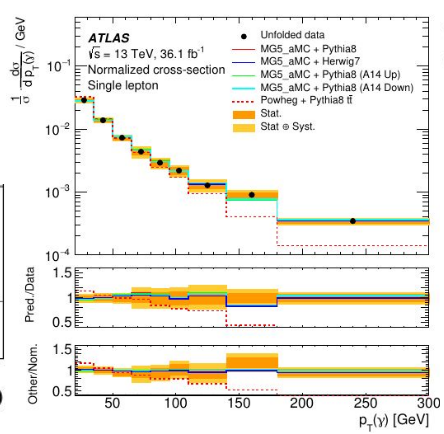
▹ Eur. Phys. J. C 79 (2019) 382

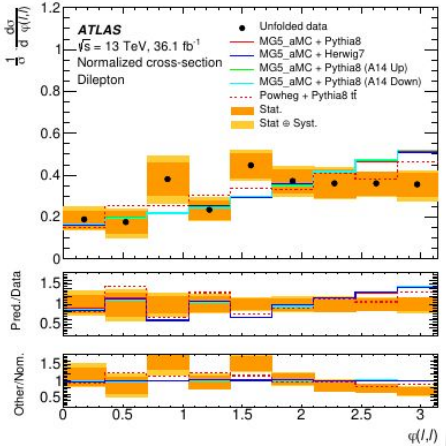
- *tt* 1ℓ and dilepton selections
  - plus **1 isolated γ** with $p_T > 20$ GeV
- ***Background*** mostly from **“fake” photons**
  - multi-variate **(MVA) discriminants** to discriminate vs. background
- **Fiducial** cross-section(s) from fit to event-level MVA distribution
- **Differential** cross-section also extracted, cutting on MVA
  - vs. $p_T(\gamma)$, $\eta(\gamma)$, $\Delta R(\ell,\gamma)$, $\Delta\eta(\ell\ell)$, $\Delta\varphi(\ell\ell)$



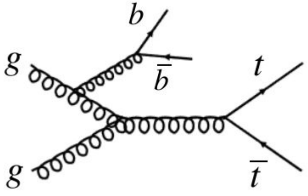








tt + bb

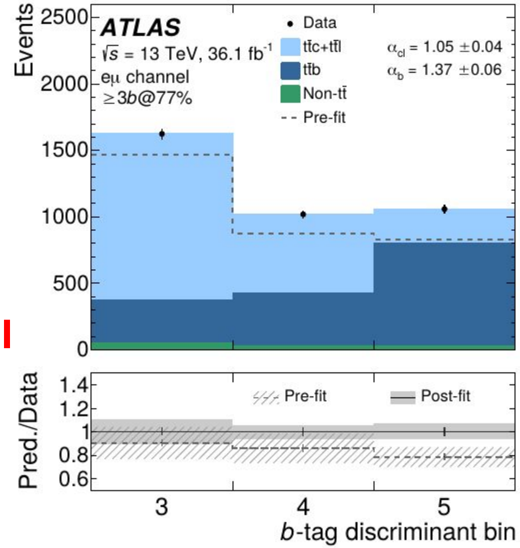


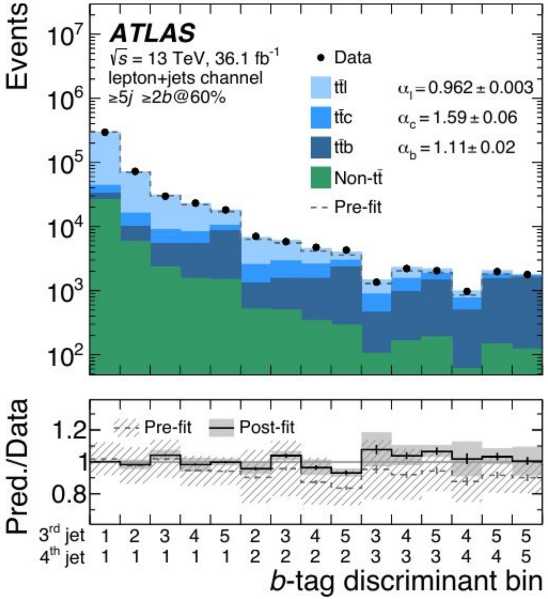
▹ JHEP 04 (2019) 046

New!

- *tt* plus **additional heavy flavour** jets:
  - suffers from **large theory uncertainties**
  - important **background** for processes like ***ttH (H → bb)***

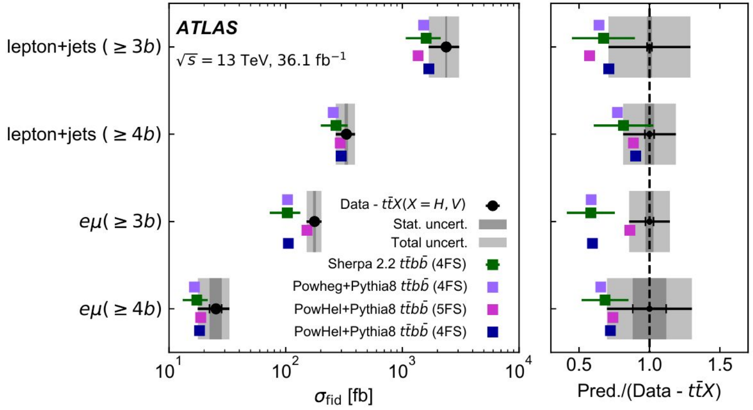
- **Analysis strategy & setup:**
  - 1ℓ and 2ℓ channels, ask for **≥ 3 *b*-tagged jets**
  - use **full information** from ***b*-tagging** algorithms to fit in data fractions of *tt*+*≥1b*, *tt*+*≥1c*, *tt*+light jets
  - **fiducial** *inclusive* and **differential** cross-sections extracted
  - **particle-level** definition of *b*-jets (no matching to partons)

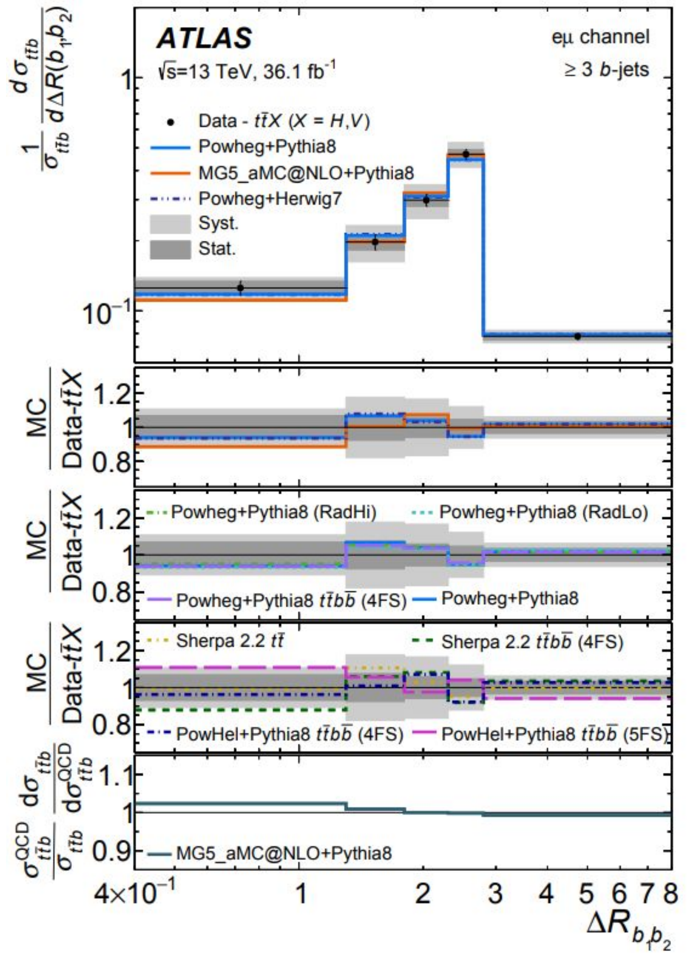




tt + bb

- Differential cross-section vs. **additional *b*-jet kinematics**
- Results compared with many **MC predictions**:
  - inclusive tt, dedicated *tt+bb*, multi-leg *tt*+jets NLO + PS
  - 5 FS, 4 FS
- Most MC ***underpredict*** *tt+bb* total yield
- Most MC setups describe **kinematics sufficiently good**
  - **systematic uncertainties** on unfolded data still large
- Unfolded data important for **future MC development**





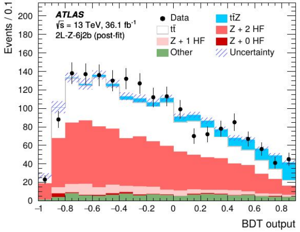
$t\bar{t}+W/Z$

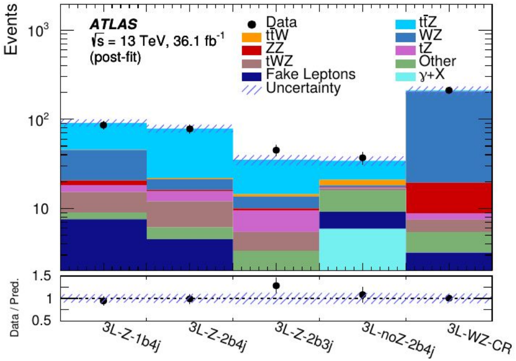
▹ Phys. Rev. D 99 (2019) 072009

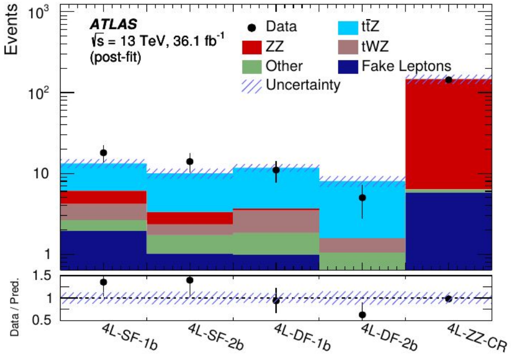
New!

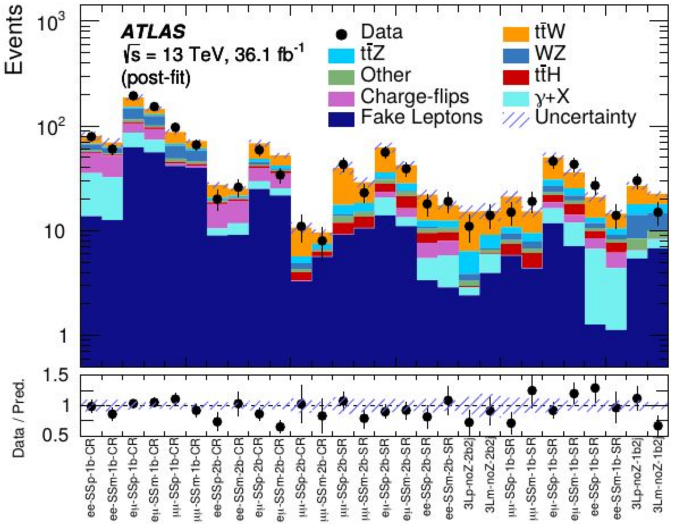
- ***ttZ*** → *tZ*-coupling, ***ttW*** → not linked to *tW*-coupling, but important background process
- *ttZ* and *ttW* share similar signature ⇒ common analysis, **simultaneous measurement**
- Targeting mostly **multi-leptonic final states**, i.e. *"at least two e/μ with same-sign charges"*
  - clean signature, small irreducible background
  - important to control **background** from **fake** and non-prompt leptons

Process	$t\bar{t}$ decay	Boson decay	Channel
$t\bar{t}W$	$(\ell^\pm \nu b)(q\bar{q}b)$	$\ell^\pm \nu$	SS dilepton
	$(\ell^\pm \nu b)(\ell^\mp \nu b)$	$\ell^\pm \nu$	Trilepton
$t\bar{t}Z$	$(q\bar{q}b)(q\bar{q}b)$	$\ell^+ \ell^-$	OS dilepton
	$(\ell^\pm \nu b)(q\bar{q}b)$	$\ell^+ \ell^-$	Trilepton
	$(\ell^\pm \nu b)(\ell^\mp \nu b)$	$\ell^+ \ell^-$	Tetralepton





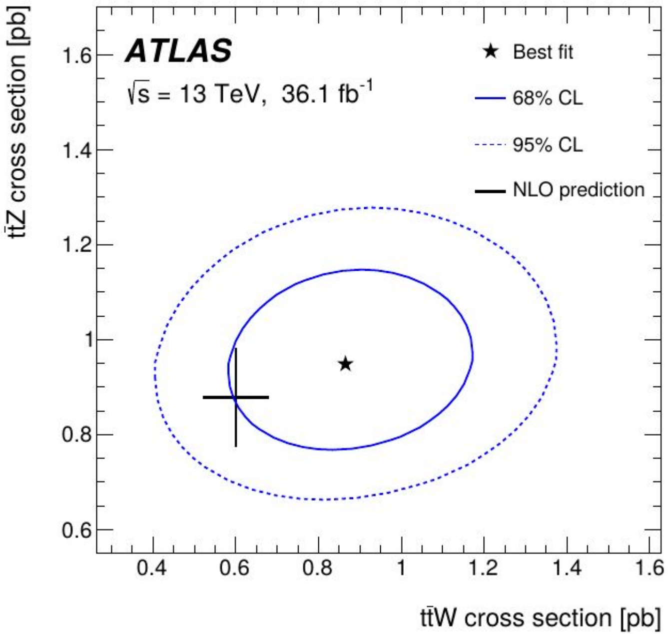




tt+W/Z

- **Results:**
  - *ttZ* cross-section **consistent** with SM at 10% accuracy
  - ***ttW* ~1 sigma larger** than SM prediction (*in line with Run 1 results*)

Fit configuration	$\mu_{t\bar{t}Z}$	$\mu_{t\bar{t}W}$
Combined	1.08 ± 0.14	1.44 ± 0.32
2ℓ-OS	0.73 ± 0.28	–
3ℓ $t\bar{t}Z$	1.08 ± 0.18	–
2ℓ-SS and 3ℓ $t\bar{t}W$	–	1.41 ± 0.33
4ℓ	1.21 ± 0.29	–

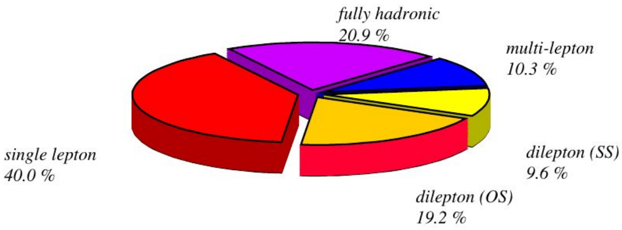


- **EFT interpretations**:

Coefficients	$C^{(3)}_{\phi Q}/\Lambda^2$	$C_{\phi t}/\Lambda^2$	C_{tB}/Λ^2	C_{tW}/Λ^2
Previous indirect constraints at 68% CL	[–4.7, 0.7]	[–0.1, 3.7]	[–0.5, 10]	[–1.6, 0.8]
Previous direct constraints at 95% CL	[–1.3, 1.3]	[–9.7, 8.3]	[–6.9, 4.6]	[–0.2, 0.7]
Expected limit at 68% CL	[–2.1, 1.9]	[–3.8, 2.7]	[–2.9, 3.0]	[–1.8, 1.9]
Expected limit at 95% CL	[–4.5, 3.6]	[–23, 4.9]	[–4.2, 4.3]	[–2.6, 2.6]
Observed limit at 68% CL	[–1.0, 2.7]	[–2.0, 3.5]	[–3.7, 3.5]	[–2.2, 2.1]
Observed limit at 95% CL	[–3.3, 4.2]	[–25, 5.5]	[–5.0, 5.0]	[–2.9, 2.9]
Expected limit at 68% CL (linear)	[–1.9, 2.0]	[–3.0, 3.2]	–	–
Expected limit at 95% CL (linear)	[–3.7, 4.0]	[–5.8, 6.3]	–	–
Observed limit at 68% CL (linear)	[–1.0, 2.9]	[–1.8, 4.4]	–	–
Observed limit at 95% CL (linear)	[–2.9, 4.9]	[–4.8, 7.5]	–	–

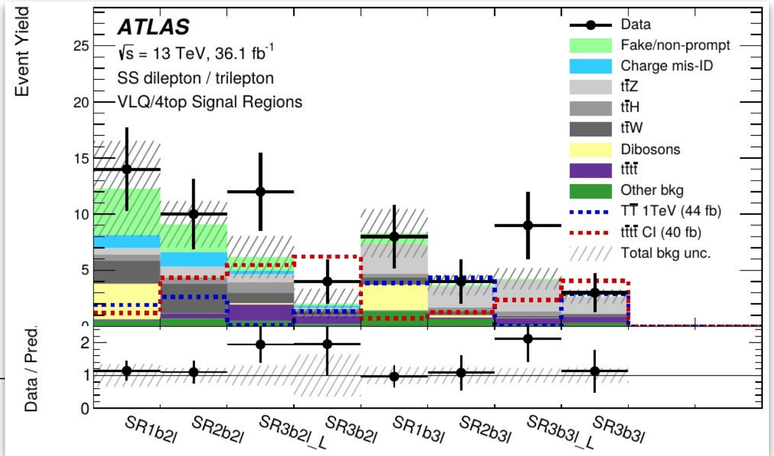
- Focusing on **differential cross-sections** (for *ttZ*) for ***future*** publications

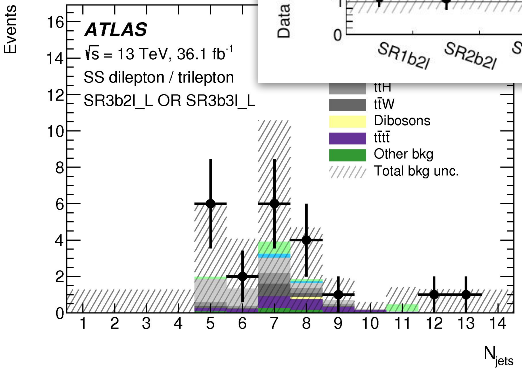
4-top



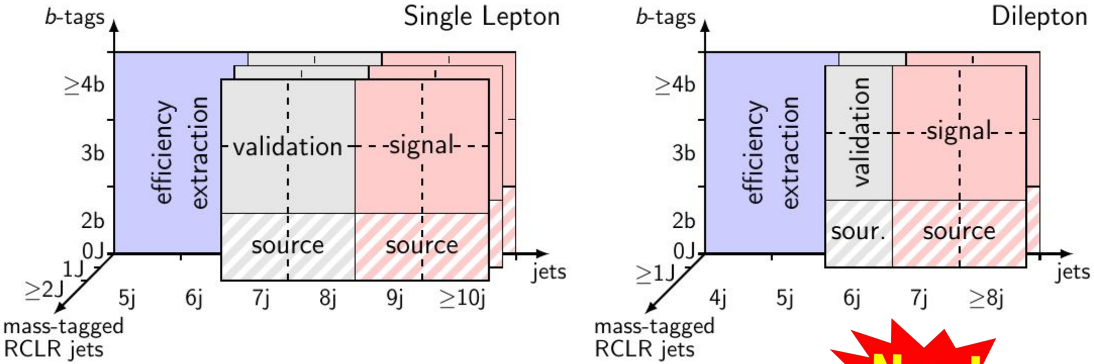
- *tttt* production:
  - one of the most **spectacular** processes predicted by SM @LHC, not observed yet
  - tiny cross-section: **~10 fb** @13 TeV (vs. ~800 pb *tt*)
- **2 separate analyses for 2 channels:**
  - multi-lepton, "*ttV*-like" ▹ **JHEP 12 (2018) 039**
  - 1ℓ / 2ℓ OS, "*tt*+jet-like"

- **Pure** but **low statistics**, similar to *ttW/Z*, with additional *b*-jet requirements
- Several signal regions defined to be sensitive to **different signal processes**
  - small **excess** (similar to Run 1)
  - ***not fully compatible*** with SM-like 4-top signal





4-top

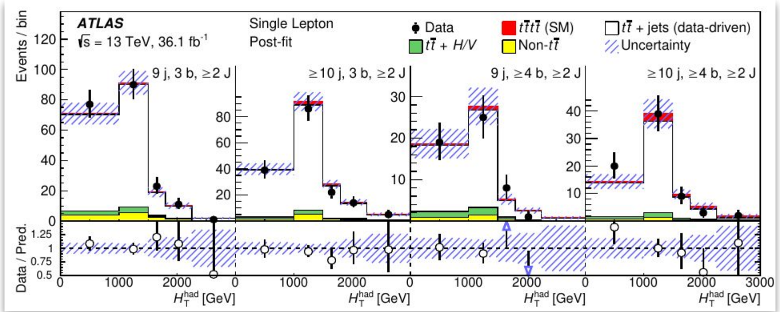


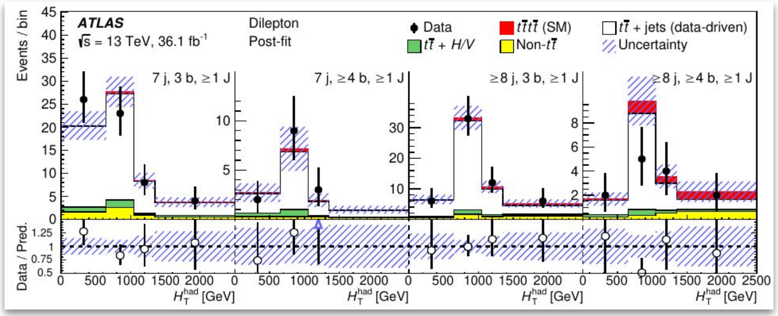
- **2 separate analyses for 2 channels**:
  - multi-lepton, "*ttV*-like"
  - 1ℓ / 2ℓ OS, "*tt*+jet-like"

▹ Phys. Rev. D 99 (2019) 052009

New!

- \> 50% of BR ⇒ "**large statistics**"
- Up to 10 jets and ≥ 4 *b*-tags required in final state, large-R jets to tag semi-boosted hadronic tops
- **Overwhelming background** from ***tt*+jets**, **estimated from data**, in CRs dominated by *tt*+jets:
  - effective ***b*-tagging probabilities** extracted at low jet multiplicities
  - and used to **weight data events** with 2-tags → *pseudo-data* sample for signal regions

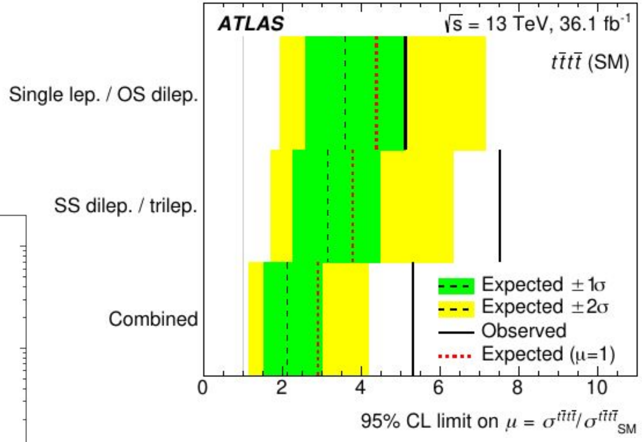


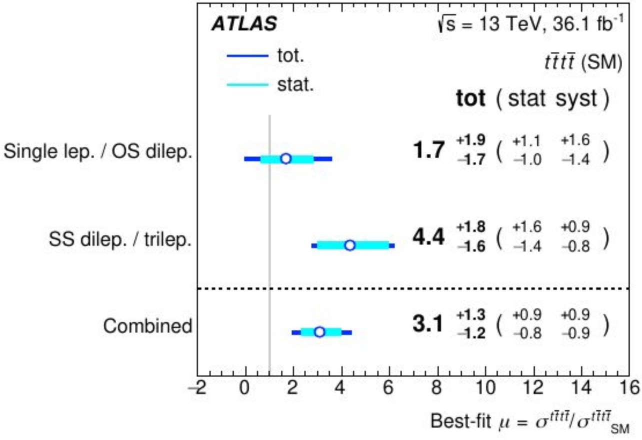


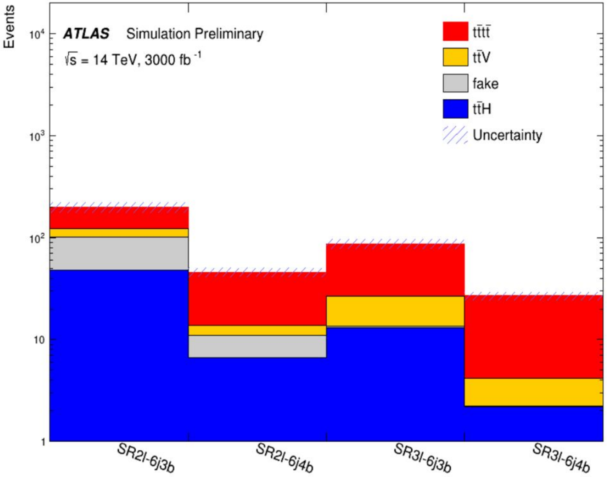
4-top

36 fb^{-1}	Exp sign.	Obs. sign.
SS-2L/3L	0.8	3.0
1L/OS-2L	0.6	1.0
Combination	1.0	2.8

- 2 channels **combined**:
  - **close to sensitivity to SM-4-top** production
  - excess in multi-lepton channel mitigate by "*tt*+jets" channel







- **Sensitivity study for HL-LHC** in multi-lepton channel:
  - **11% precision** expected with 3 ab^{-1}

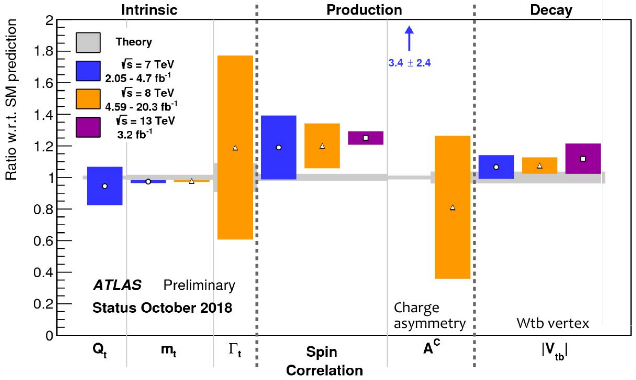
▹ ATL-PHYS-PUB-2018-047

New!

Summary

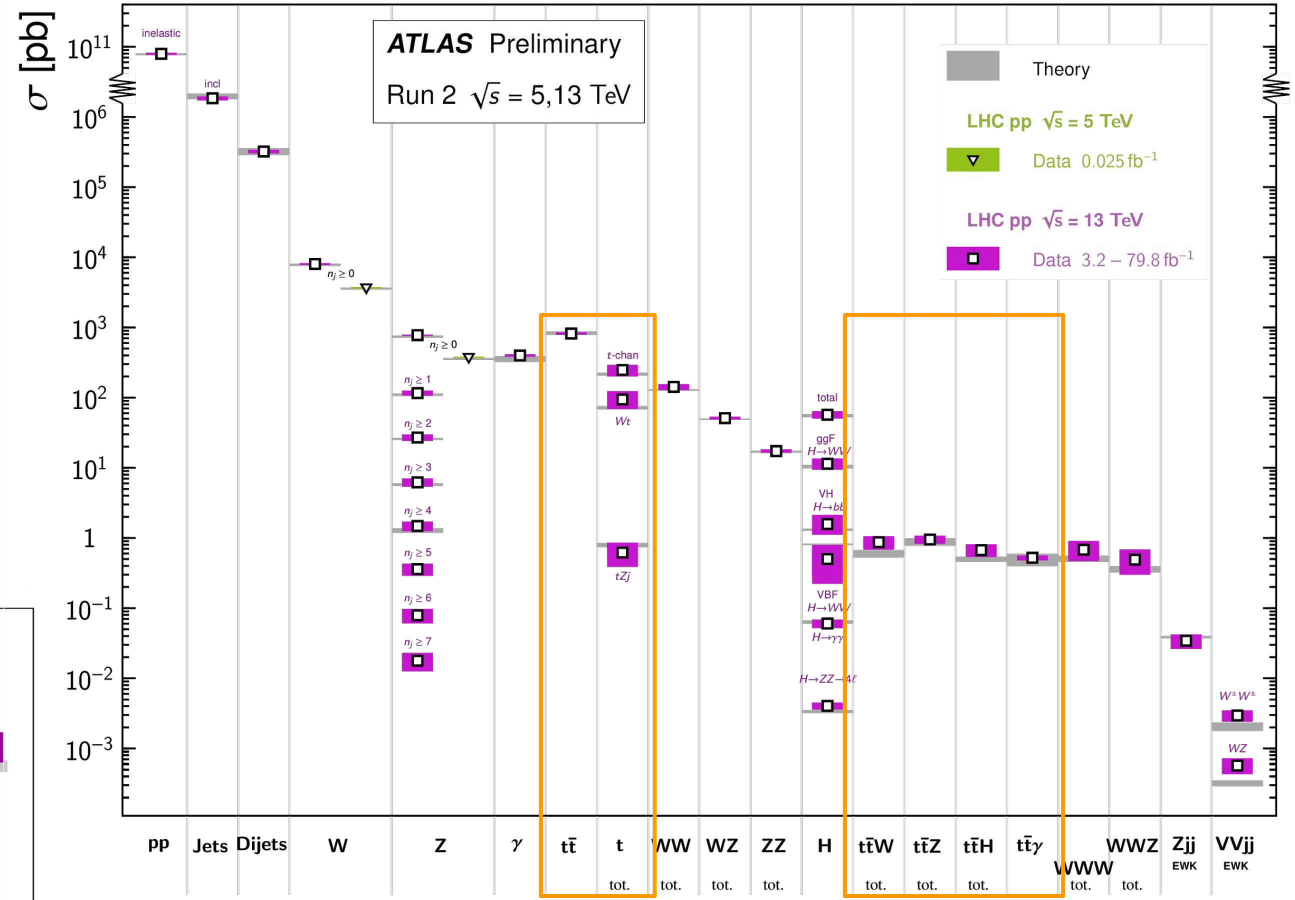
- **Rich Top Physics** experimental program ongoing in LHC Run 2
- Experimental **precision** challenging and helping theory predictions
- Many interesting Run 2 results **still to come**!

Top Property Measurements



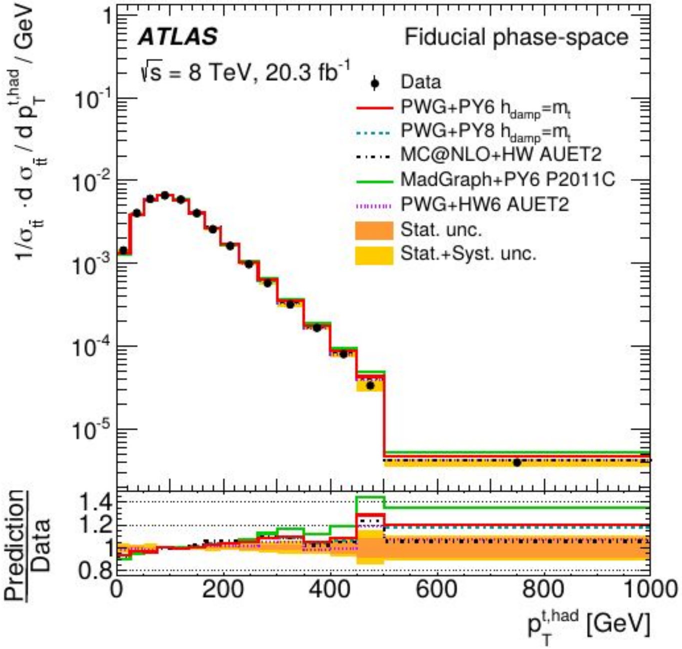
Standard Model Production Cross Section Measurements

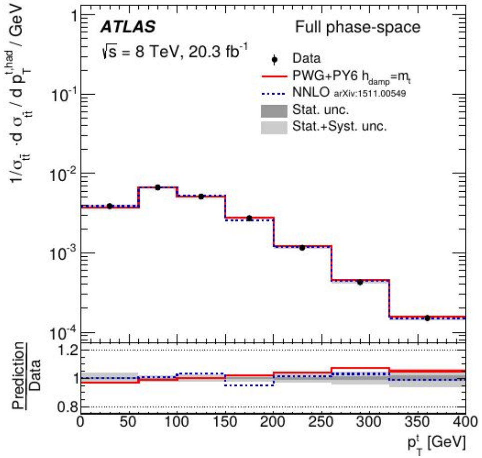
Status: March 2019



Backup

8 TeV differential





Differential cross-sections

- Unfolding:
  - extract differential cross-sections from signal event counts in bins of measured quantities

parton- / particle-level distributions in total / fiducial phase-space

detector-level distributions after event selection cuts

$$\frac{d\sigma^{\text{fid}}}{dX^i} \equiv \frac{1}{\mathcal{L}\cdot\Delta X^i}\cdot f^i_{\text{eff}}\cdot\sum_j \mathcal{M}^{-1}_{ij}\cdot f^j_{\text{match}}\cdot f^j_{\text{acc}}\cdot\left(N^j_{\text{reco}} - N^j_{\text{bg}}\right)$$