Latest SM results with the ATLAS detector (including SM-Higgs)

KEK Theory Meeting on Particle Physics and Phenomenology

14th February 2017, KEK, Tsukuba

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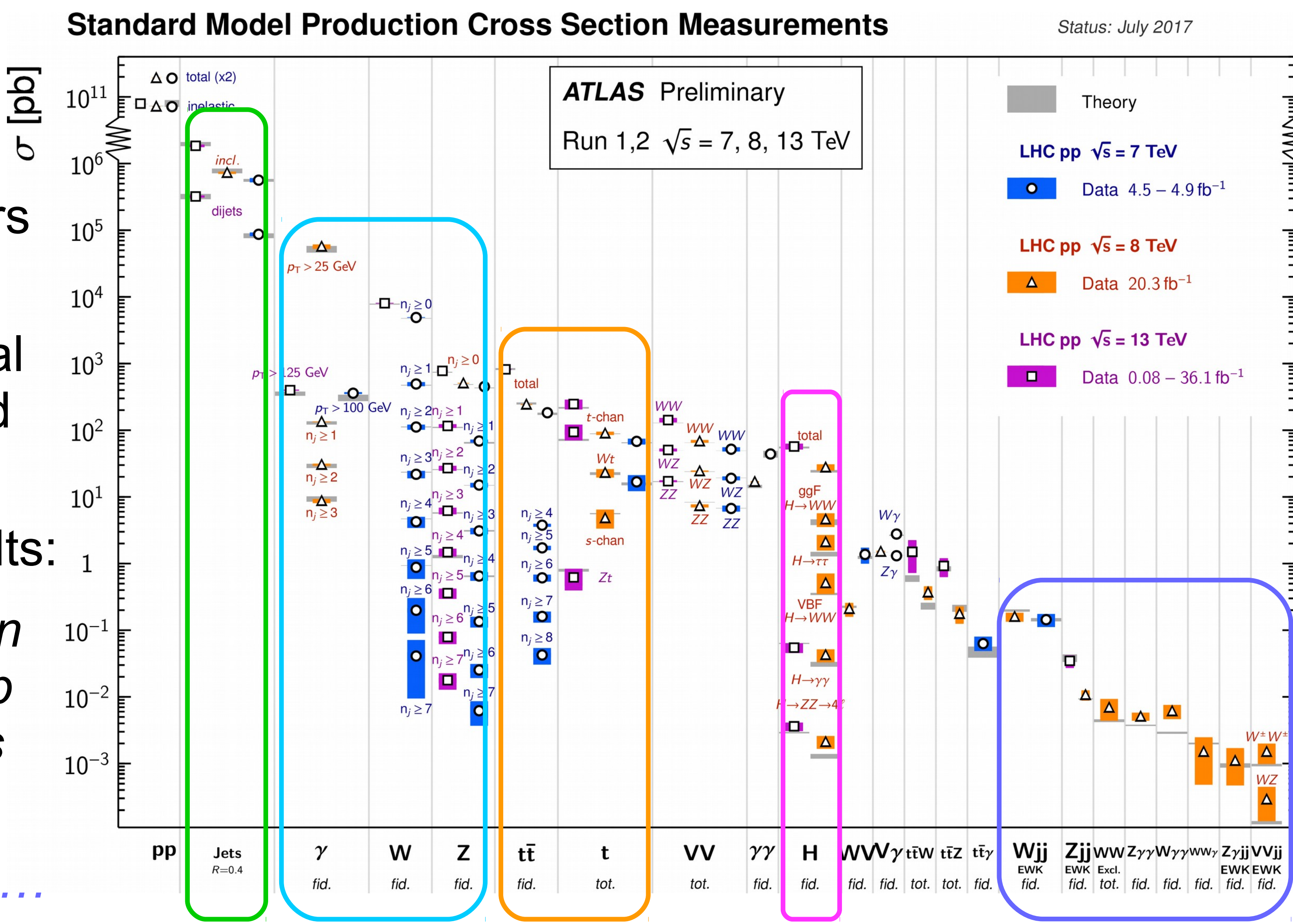
on behalf of ATLAS Collaboration

The Landscape of SM Measurements

- Cross section spans 10 orders of magnitude!
- Variety of signal final-states and backgrounds
- Wealth of results:

  >250 papers on SM, Higgs, Top measurements

Impossible to cover everything…



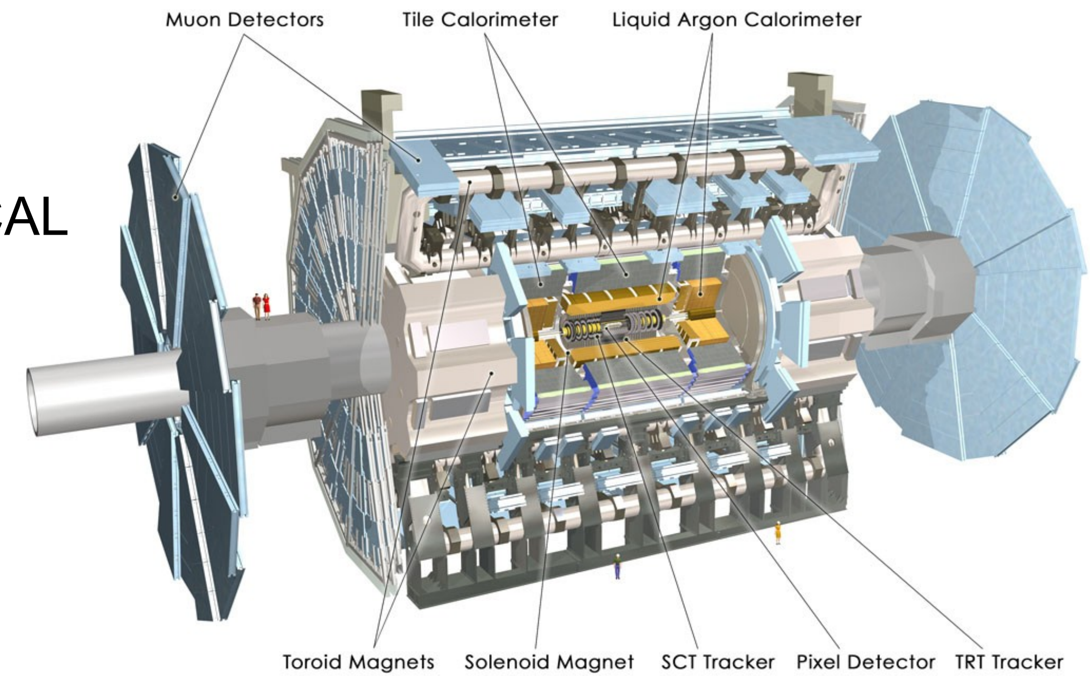
Presenting only a personal selection of recent ATLAS measurements

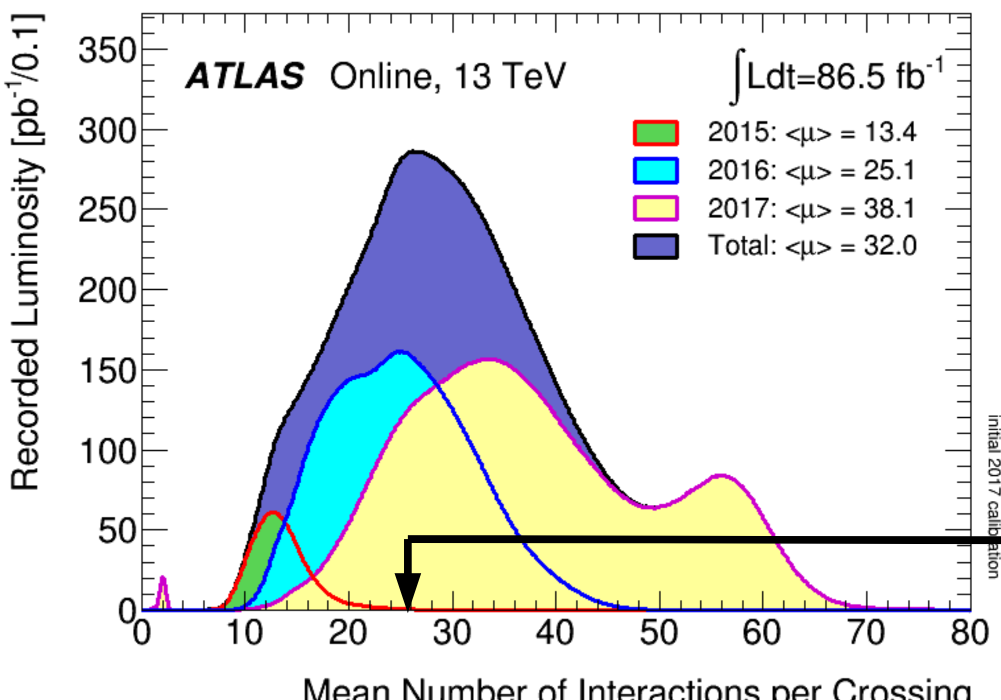
All details available at SM, Top, Higgs public-pages

ATLAS Experiment and Data Sets

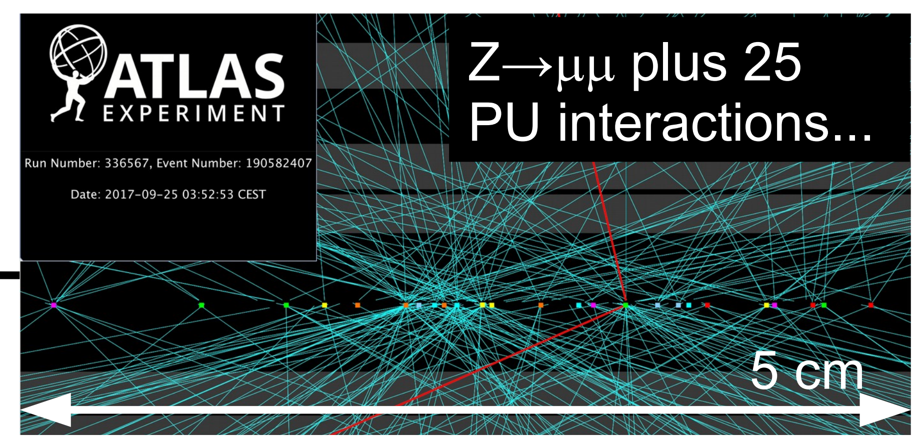
The ATLAS Experiment:

- Multipurpose detector based on:
  → Precise inner-tracker (2 T solenoid)
  → Longitudinally segmented ECAL/HCAL
  → Air-core muon-spectrometer
- **Run 1 data set:**
  - 7 TeV 4.7 fb^{-1}, 8 TeV 20.2 fb^{-1}
- **Run 2, 13 TeV data set :**
- *reached* ***>85 fb^{-1}!*** *(results up to 36 fb^{-1})*





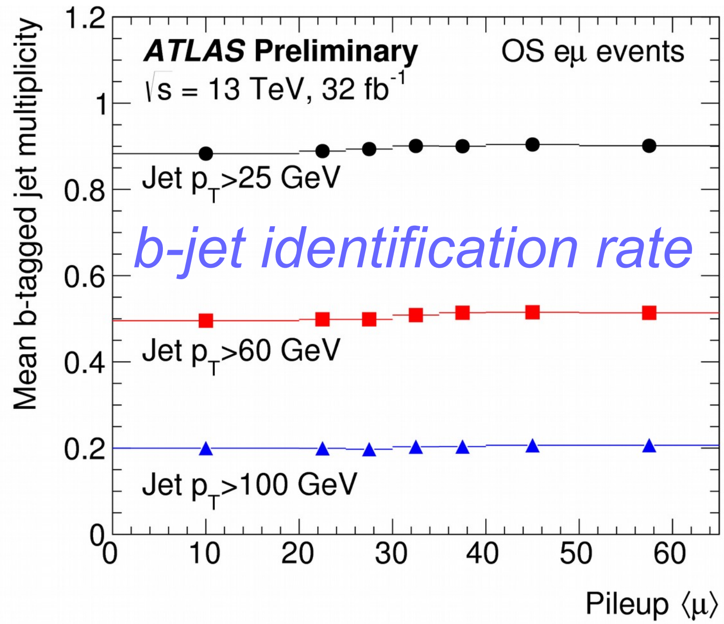
- *Luminosity at the cost of large pileup (PU)*
- *PU in 2018 can be > 60 → challenging!*

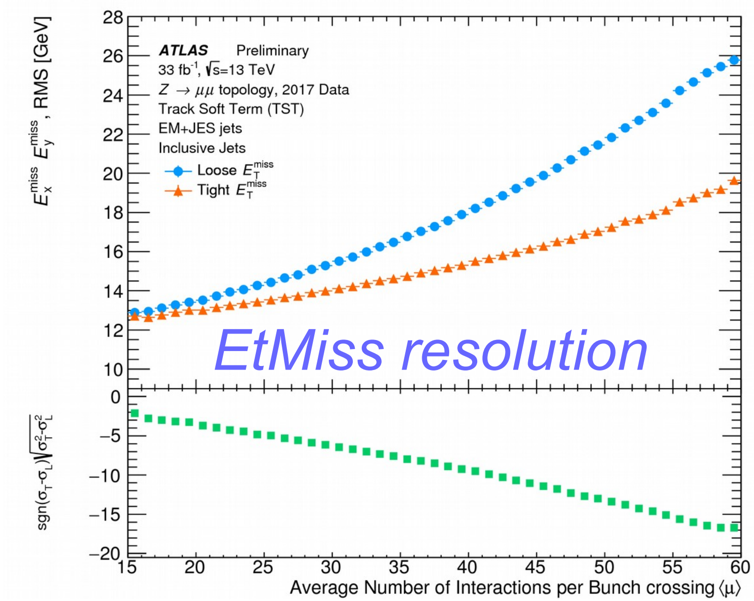


ATLAS Physics at High-Luminosity

ATLAS can deal with high-PU, although some performance may worsen. Two (of many) examples:

- Roughly constant lepton and *b*-jet identification efficiency vs PU
- But worst EtMiss resolution, important for W→lν identification and reconstruction



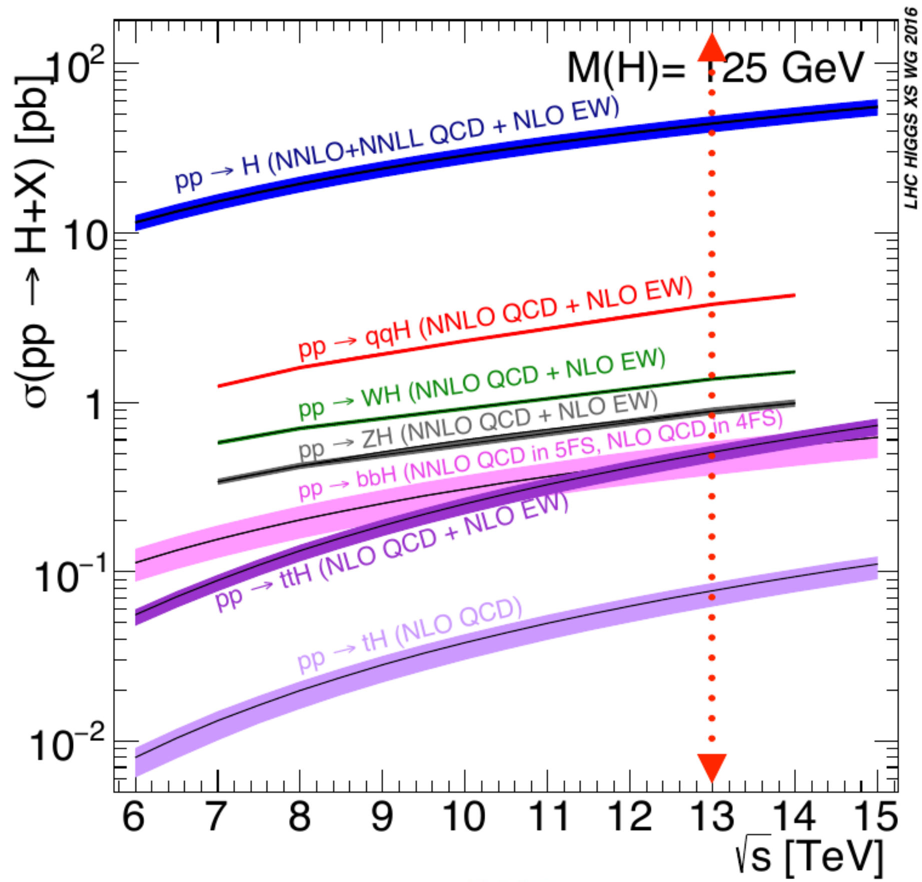


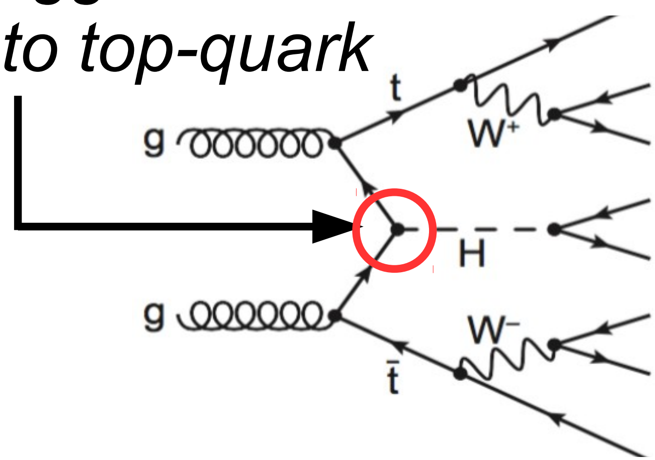
So, what will be in the next slides:

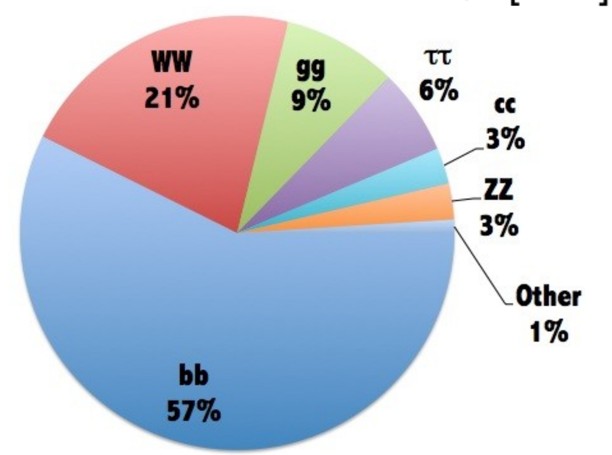
1) The achievements possible thanks to our large datasets
2) Current limitations and results that could help to improve them
3) Example of fundamental measurements where we reached maximum precision and how to maybe go beyond them

Search for Rare Processes: $t\bar{t}H$

- Large integrated luminosity allows to probe one of the rarest Higgs production modes: **$t\bar{t}H$**
- Cross-section ~0.5 pb @13TeV
- $O(10^{-2})$ Higgs gluon-fusion, and $O(10^{-3})$ inclusive $t\bar{t}$ production
- *Test of Higgs Yukawa coupling to top-quark*







- Wide variety of final states of top and Higgs → *can exploit many analysis channels*

$t\bar{t}H(b\bar{b})$ Search Channel

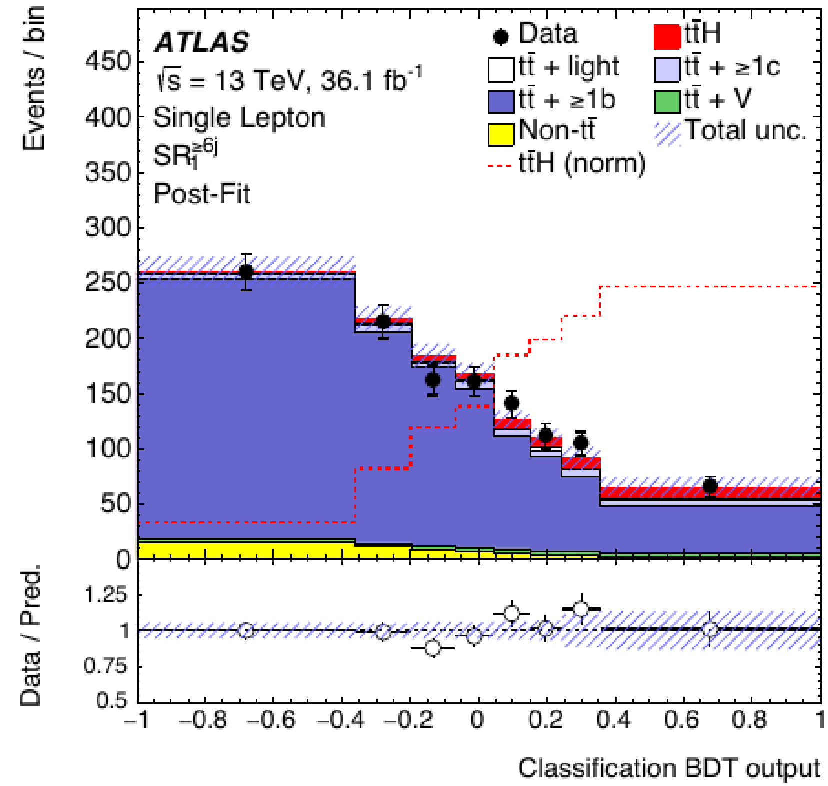
arXiv:1712.08895[hep-ex]
NEW!

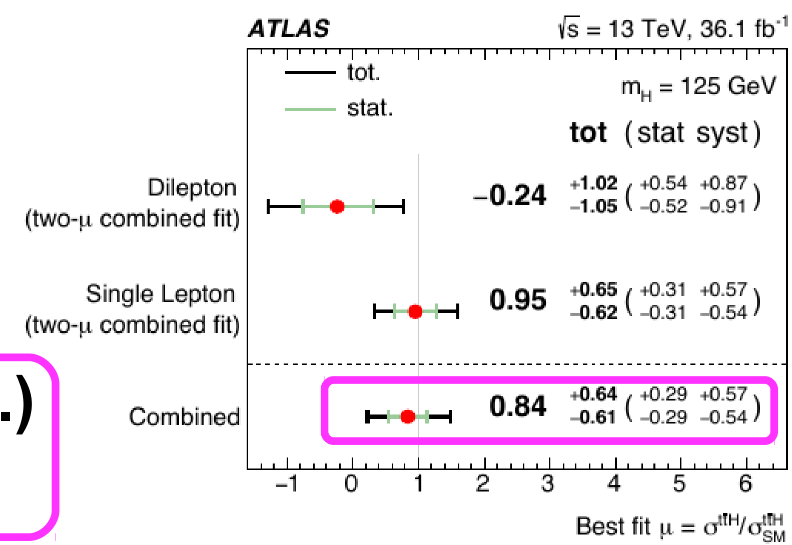
- Largest yield expected as BR($H \to b\bar{b}$)~57%
- Sub-catetories in jet-flavour and BDT to improve S/B, profile-likelihood to constraint systematic errors, etc.
- *But $t\bar{t}+b\bar{b}$ challenging to control and model:*

  Dominant uncertainty from 4 vs 5 Flavour-Number Scheme (FNS) $t\bar{t}+b\bar{b}$ predictions

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

- Nevertheless: **1.4σ (1.6σ) obs. (exp.)**
- Signal strength, μ,consisted with SM

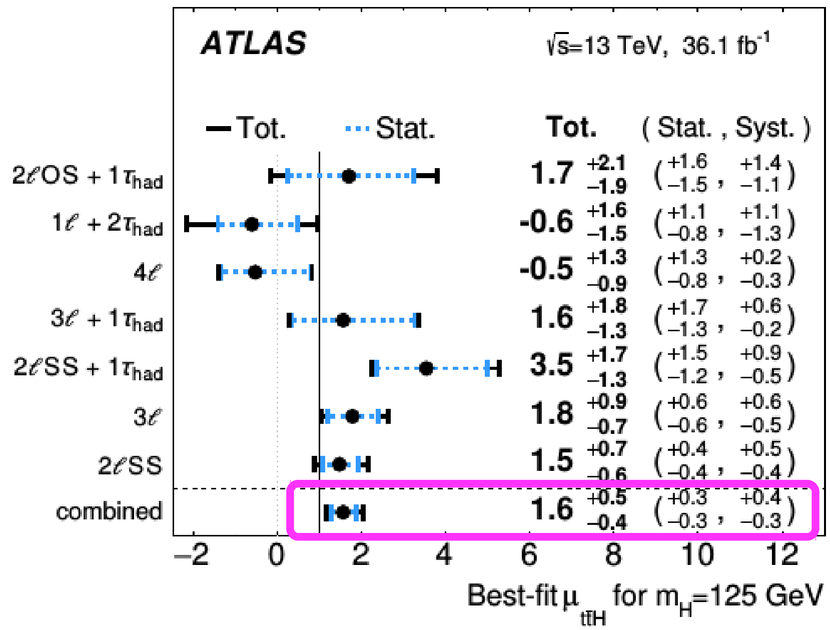


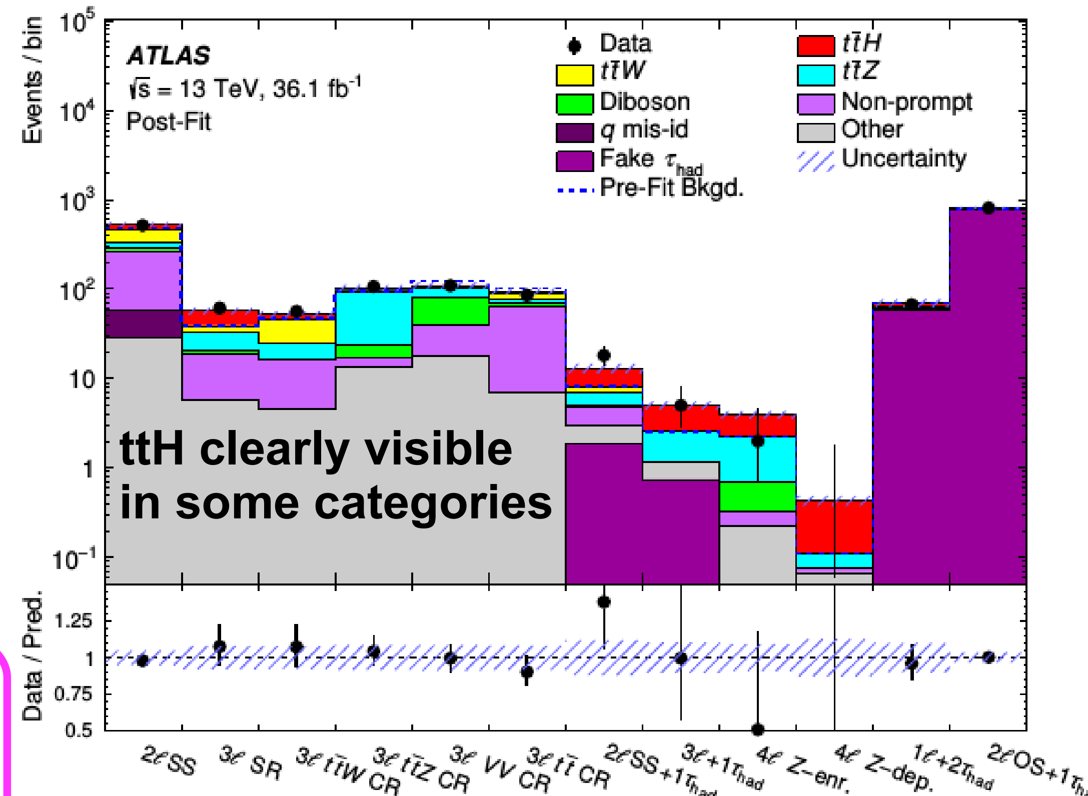


tt̄H Analysis in Multileptons

arXiv:1712.08891[hep-ex] ***NEW!***

- Using *all other* Higgs leptonic decay modes, WW, ZZ,ττ, divided in regions with different purity
- Strong suppression of most SM backgrounds in multi-lepton final states → *tt̄V production dominates purest categories*





ttH clearly visible in some categories

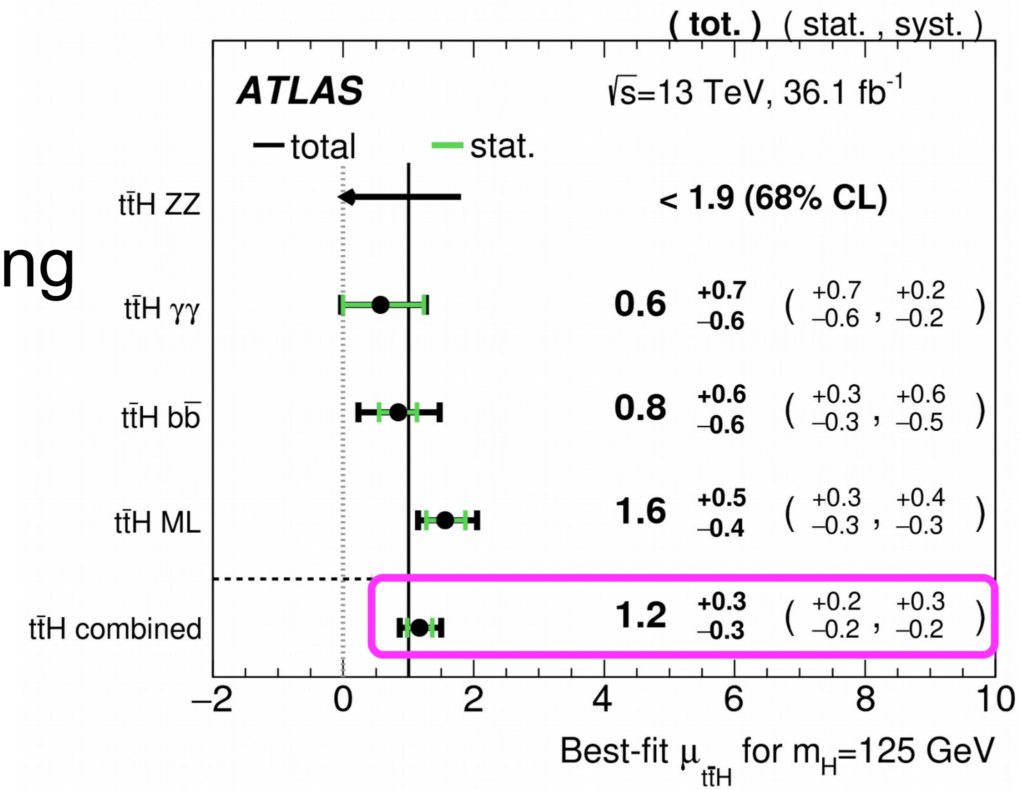
- **Evidence for ttH!**
  4.1σ (2.8σ) obs. (exp.)
- **Slight upward fluctuation of μ**

- Main systematics on μ coming from ***signal and bkg. predictions***

ATLAS $t\bar{t}H$ Combination

arXiv:1712.08891[hep-ex]
NEW!

- Combined analysis (including also $t\bar{t}H \rightarrow \gamma\gamma$) shows strong evidence of $t\bar{t}H$ production using 36 fb^{-1} of 13 TeV ATLAS data
- **4.2σ (3.8σ) obs. (exp.)**
- **μ consistent with SM**



Bring home lessons:

- Advanced analysis techniques (MVA, optimized categories, nuisance parameter profiling,etc.): *fundamental but not enough…*
- Precision $t\bar{t}H$ measurement limited by systematic uncertainties on signal and background predictions

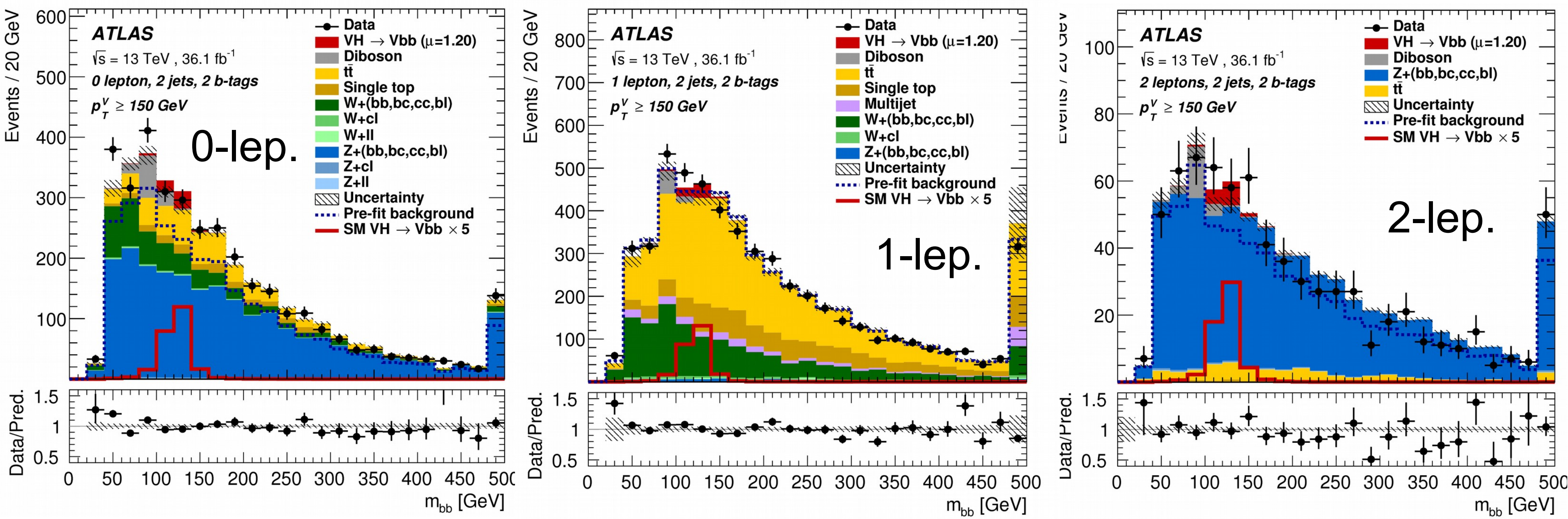
Crucial to reduce them if want to measure coupling to better than ~20% uncertainty, also with larger dataset

Higgs Coupling to b-Quark

JHEP 12 (2017) 024
from last Summer

$H \to b\bar{b}$ not only useful for $t\bar{t}H$ analysis…

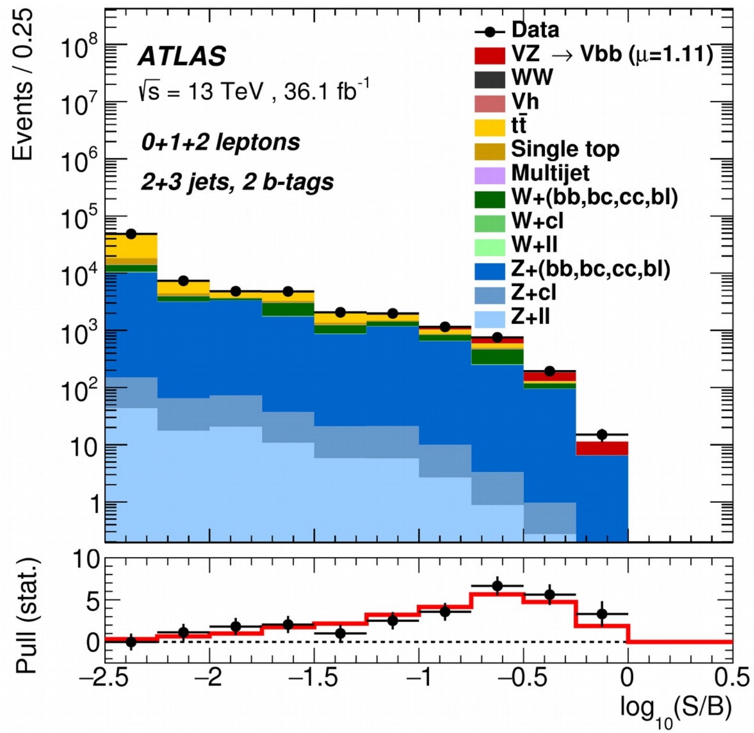
- Fundamental to test SM Higgs characteristics (Yukawa, total width, etc.)
- *Analysis challenging because of hadronic final state*
- Search relies on associate production with W, Z (V) decaying leptonically
- Classification for charged lepton multiplicity (0,1, 2), kinematic classification (e.g. Vp_T, n-jets), most of separation power from M_{bb}, use of MVA



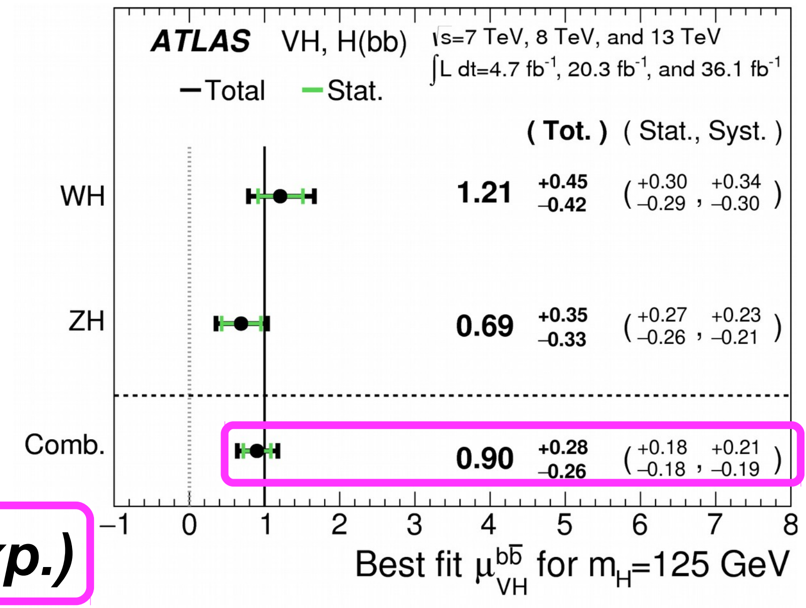
Background large and composite… precise modeling is fundamental

Evidence for $VH(b\bar{b})$

JHEP 12 (2017) 024
from last Summer

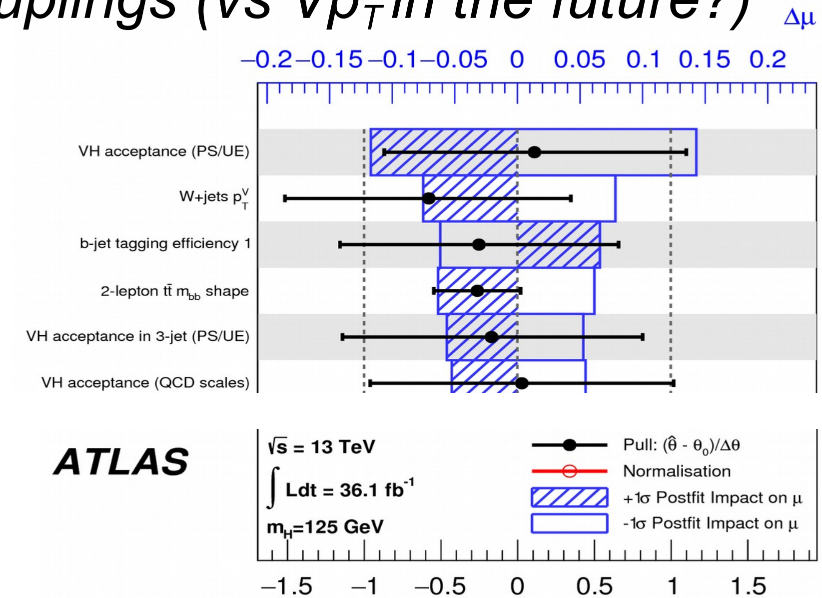


- Run 1 & Run 2 combined (Run 2 dominates)
- ***Evidence for VH production and $H \rightarrow b\bar{b}$ decay!***
- ***3.5σ obs. (4.0σ exp.)***
- **μ consistent with SM**
- *Test of VH couplings (vs Vp_T in the future?)*



Bring home lessons:

- Dominant uncertainties originate from signal and background modeling
- Situation even more complex than $t\bar{t}H$: V+HF modeling vs Vp_T, M_{bb} background shape, parton-shower, etc.

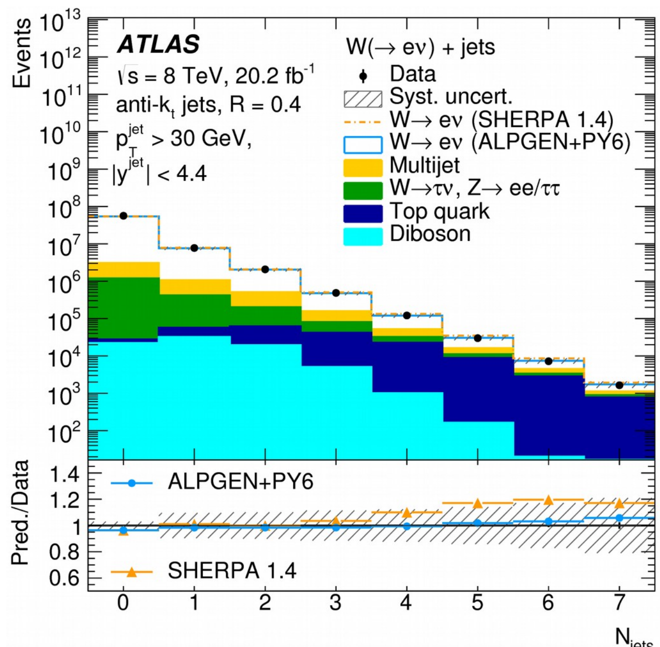


MC Modeling and QCD Measurements

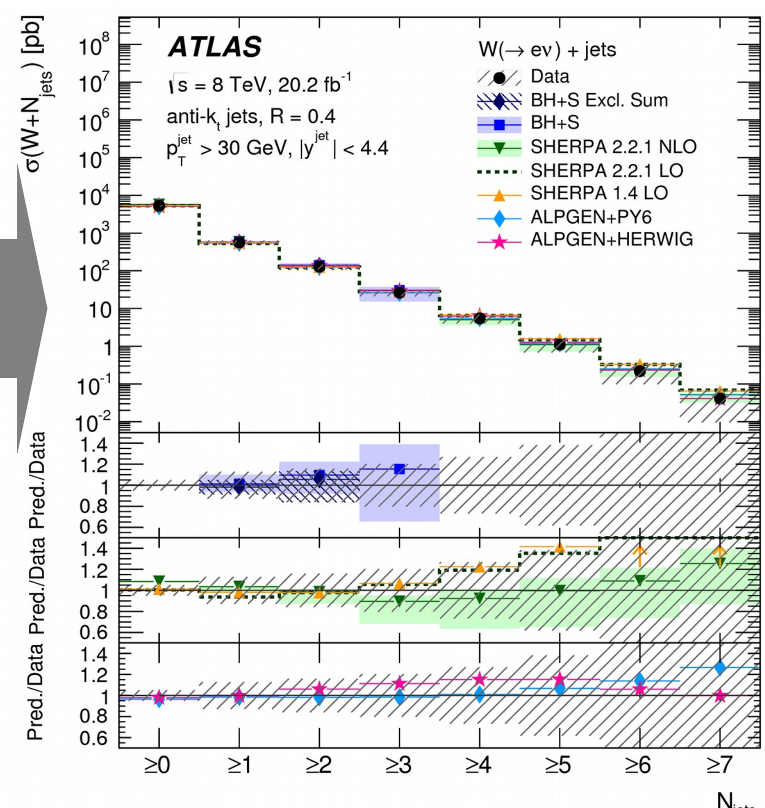
- As seen, reliable modeling of QCD-jets produced in association with top, W or Z bosons, is a key element of Higgs (and BSM) physics
- ***Dedicated measurements of differential cross sections are essential:***
  - *As test of perturbative QCD (pQCD)*
  - *As input for MC tuning/development*

Cross section measurement basics:

- Background subtracted yields corrected for detector resolution and efficiency using MC
- Scale by integrated luminosity to obtain cross section in fiducial volume
- Predictions are compared in the fiducial acceptance of the measurement



E.g: *N-jets in W→eν*



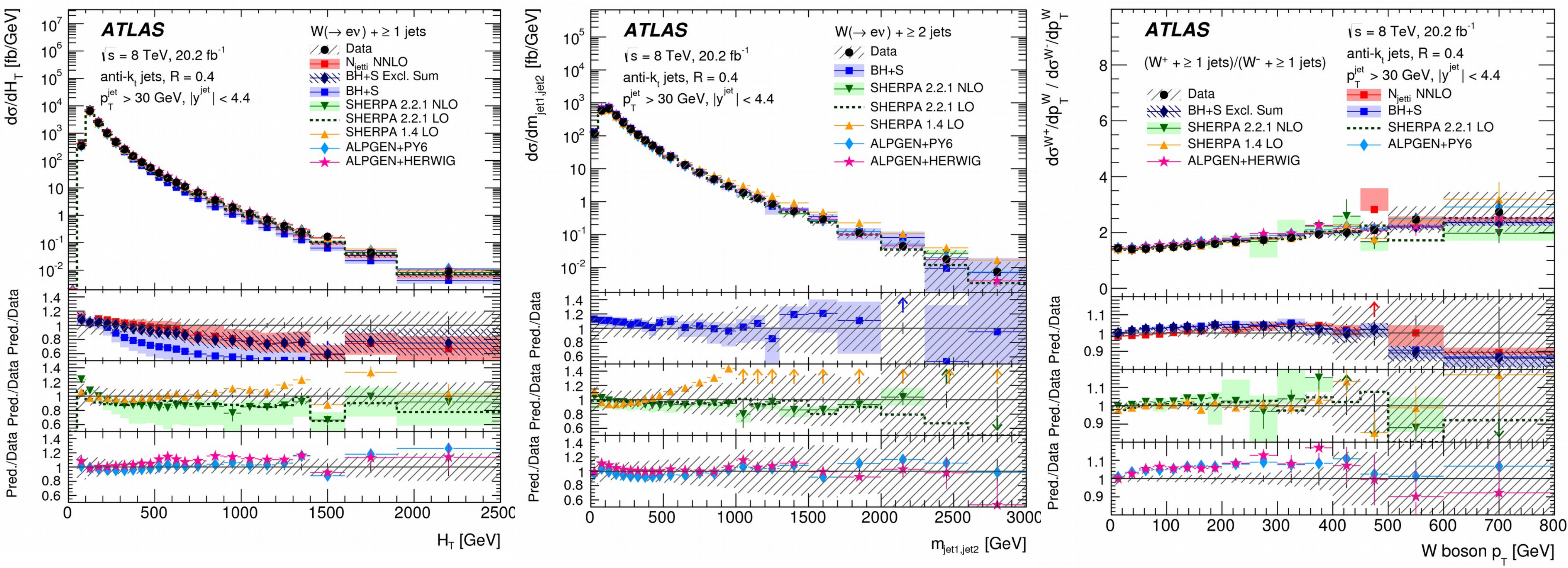
- Anti-k_T0.4 jets, p_T>30 GeV, $|Y_{jet}|$<4.4,

W plus Jets at 8 TeV

arXiv:1711.03296[hep-ex]
NEW!

W(→eν) + jets analysis on 8 TeV 20.2 fb^{-1} dataset:

- Large, well understood dataset probing up to a few TeV scale
- Includes analysis of W^+/W^- cross-section-ratio observables:
  → *Jet energy scale (JES) on other uncertainties mostly cancel*
- >50 unfolded W-boson and jet distributions, sensitive to MC modeling and PDFs
- Compared to wide set of predictions including NNLO



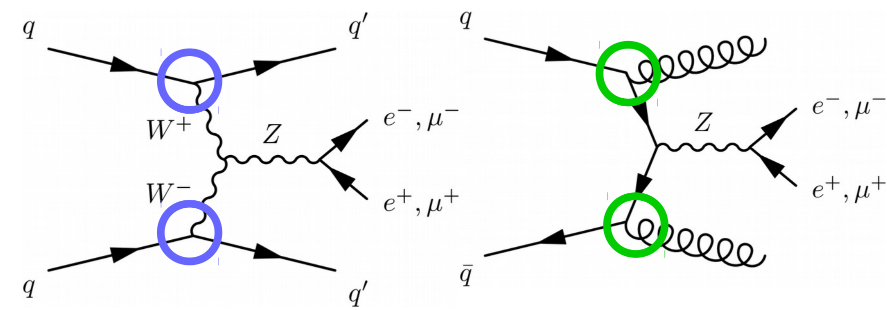
ALPGEN+PY6 and Sherpa 2.2 NLO (Run 2 ATLAS default) describe data well

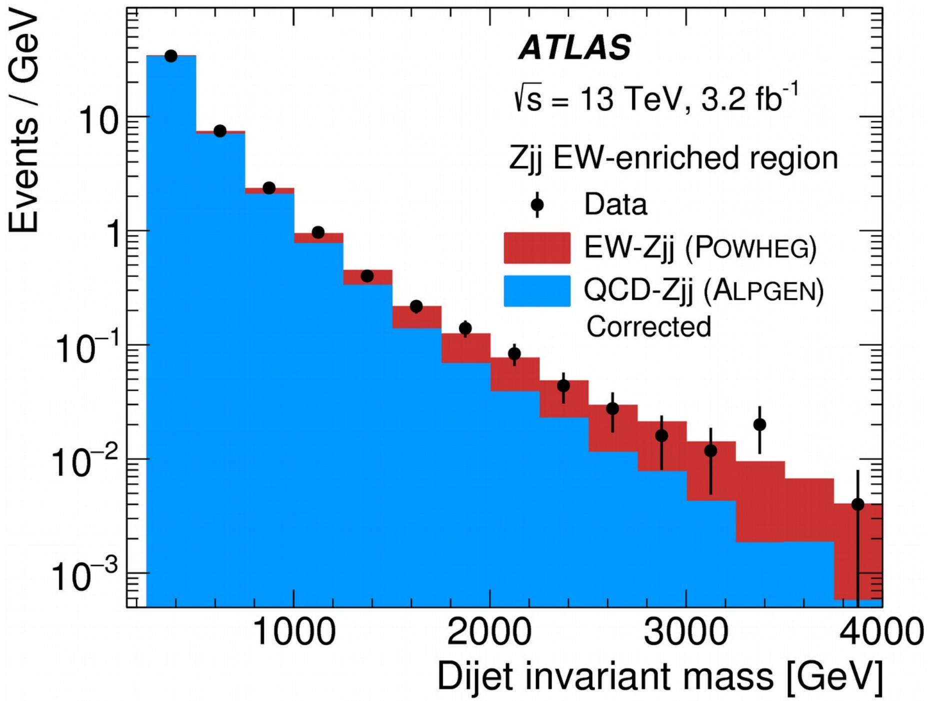
Z+Jets EWK Measurement

arXiv:1709.10264[hep-ex]
NEW!

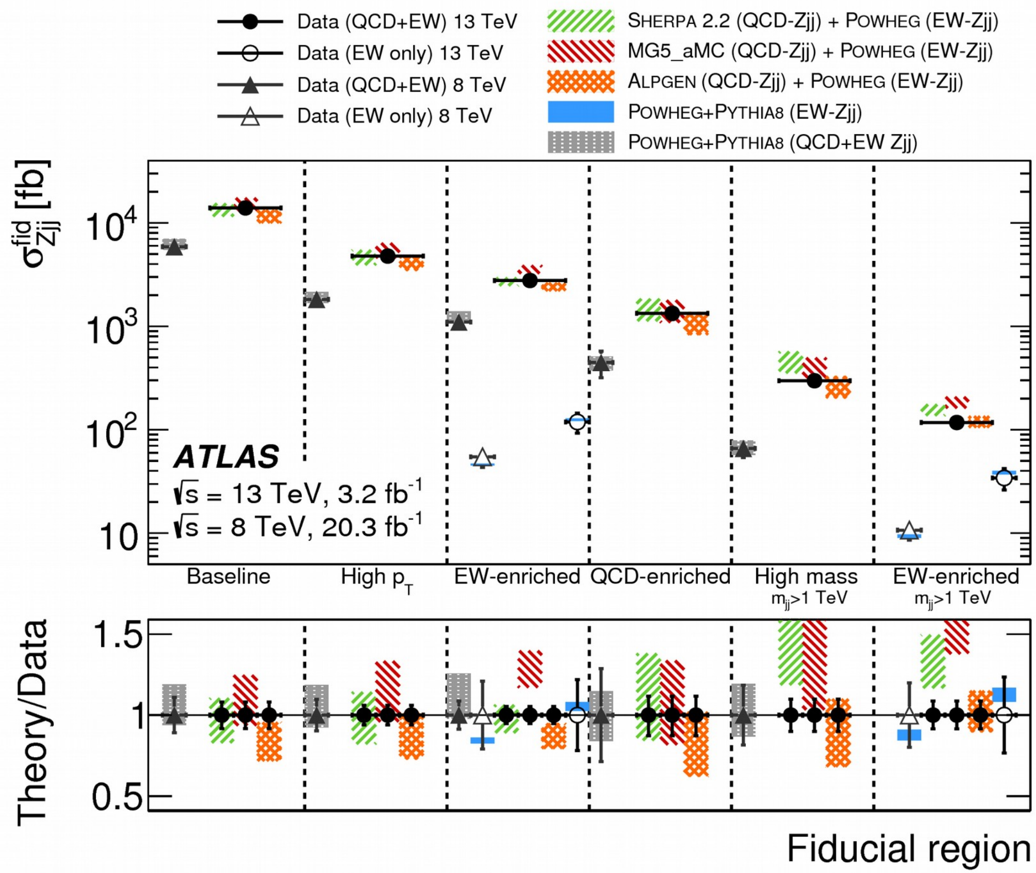
13 TeV collisions probe even better the TeV-scale:

- EWK and QCD V+jets production comparable
- Sensitivity to EWK component enhanced asking for forward jets, high-mass, no central jets cuts





- EWK Zjj fiducial measurement in regions with purity from ~ 5% to 26%

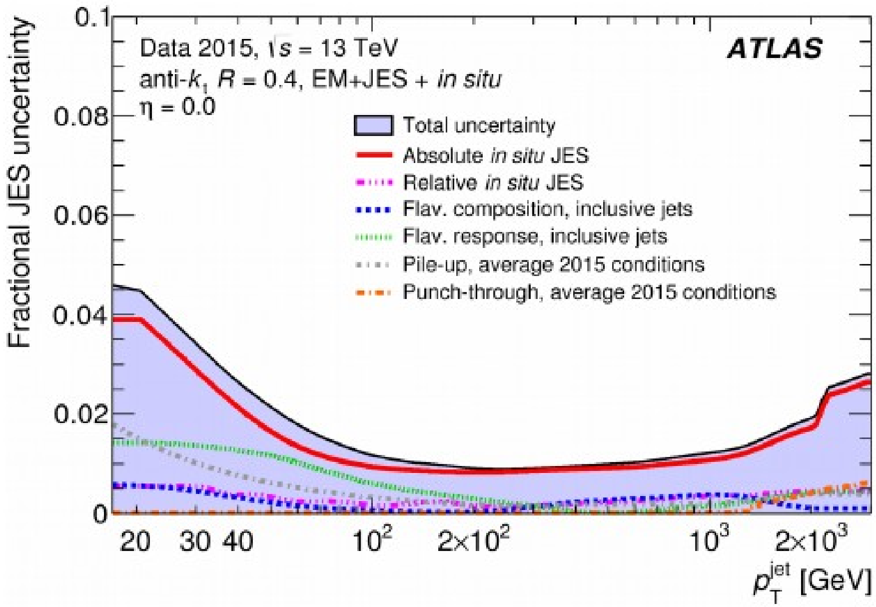


- Zjj QCD corrected to data using control-region with 1 central jet
- Compare Zjj EWK and QCD predictions:

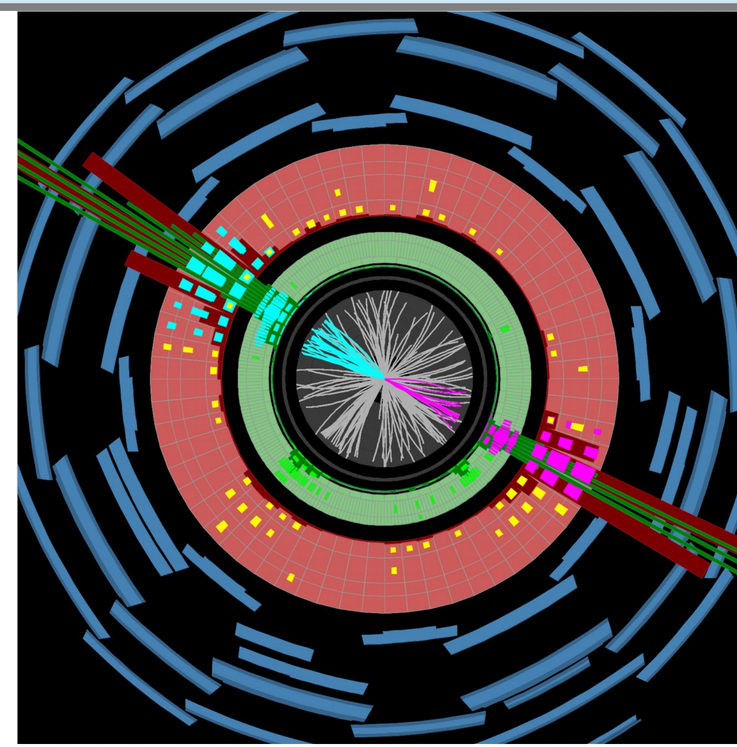
→ Powheg+Pythia8 fits well Zjj EWK data

Testing the SM at Multi-TeV Scale

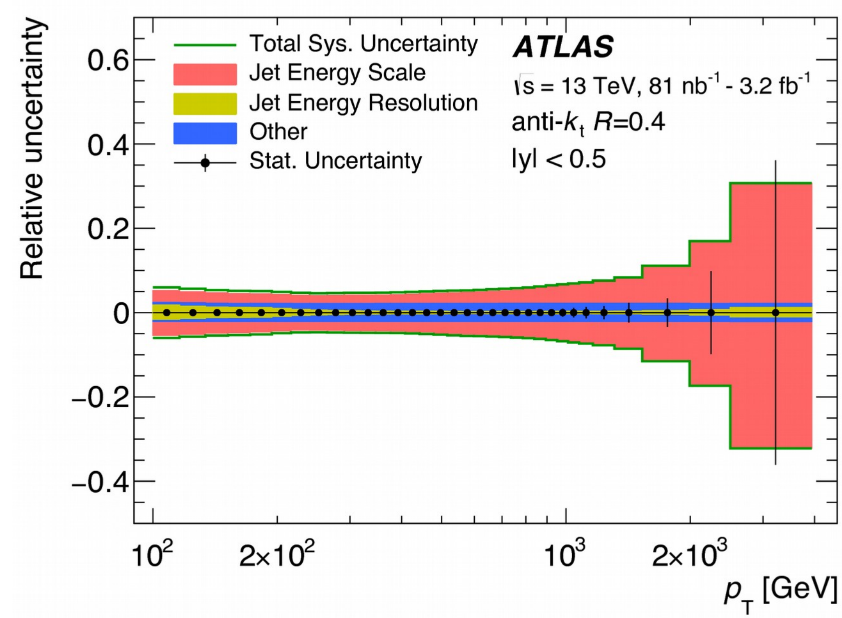
- *Di-jet production allows to probe even higher scales!*
- Experimental challenge for in-situ calibration of jet energy scale



- Keep track of uncertainties and correlations of across phase space
- Strong constraints on PDFs and qQCD from multi-differential measurements



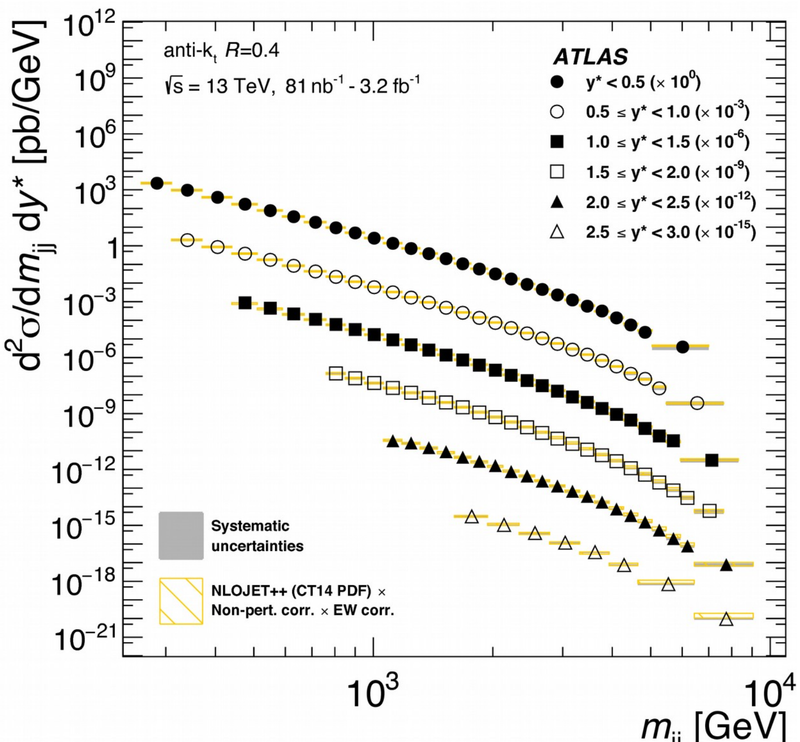
Mjj=9.3 TeV
$p_T(j_1)$=2.9 TeV, $p_T(j_2)$=2.9 TeV

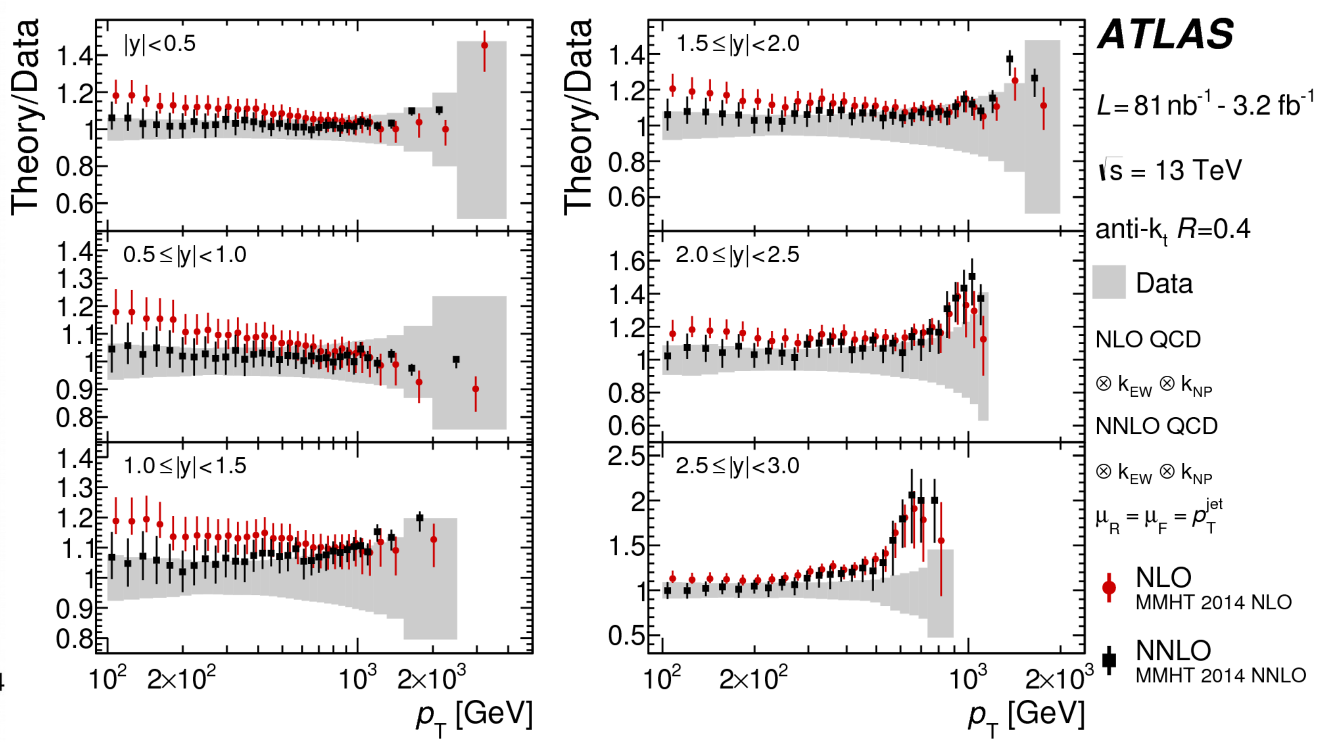


Di-jet Measurement at 13 TeV

arXiv:1711.02692[hep-ex]
NEW!

- Double differential measurement: $$\frac{d^2\sigma}{dp_T dy} = \frac{N_{jets}}{\mathcal{L}\Delta p_T \Delta y} \qquad \frac{d^2\sigma}{dm_{jj} dy^*} = \frac{N_{dijet}}{\mathcal{L}\Delta m_{jj} \Delta y^*}$$
- Jets with anti-k_T0.4, p_T>100 GeV, |Y|<3, and 3.2 fb^{-1} @13 TeV
- ***Reaches just below 10 TeV!*** (9.3 TeV actually)

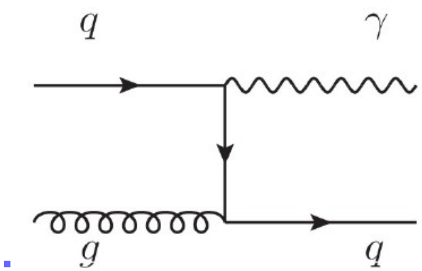


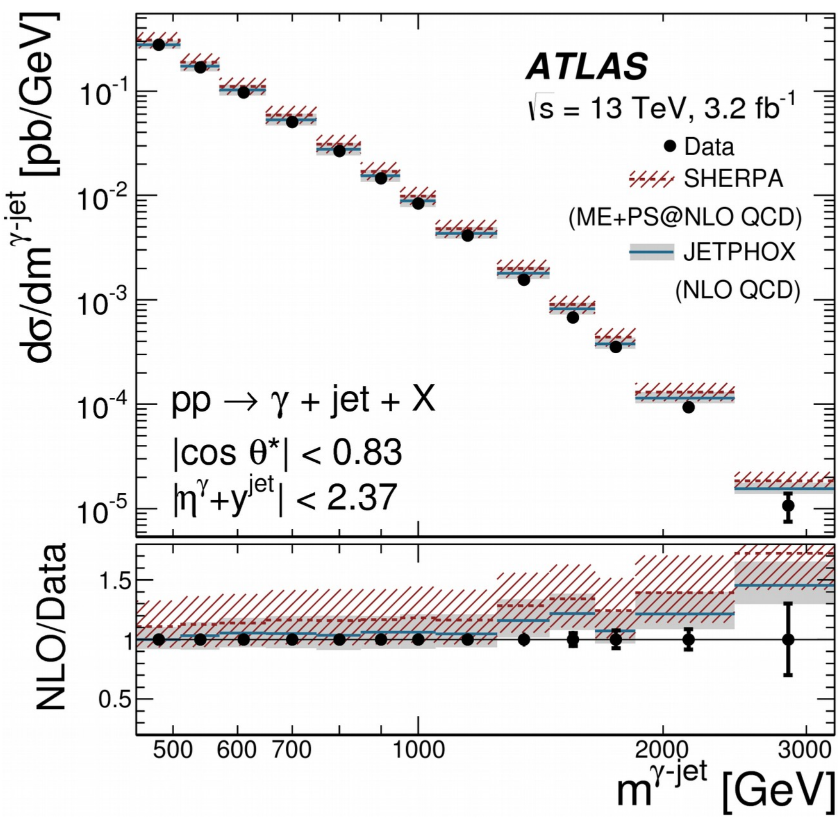


- Measurement corrected at particle level and compared to NLO and NNLO
- Highly sensitive to PDFs and choice of renormalization scale in predictions

Additional Probes of QCD: γ+jets

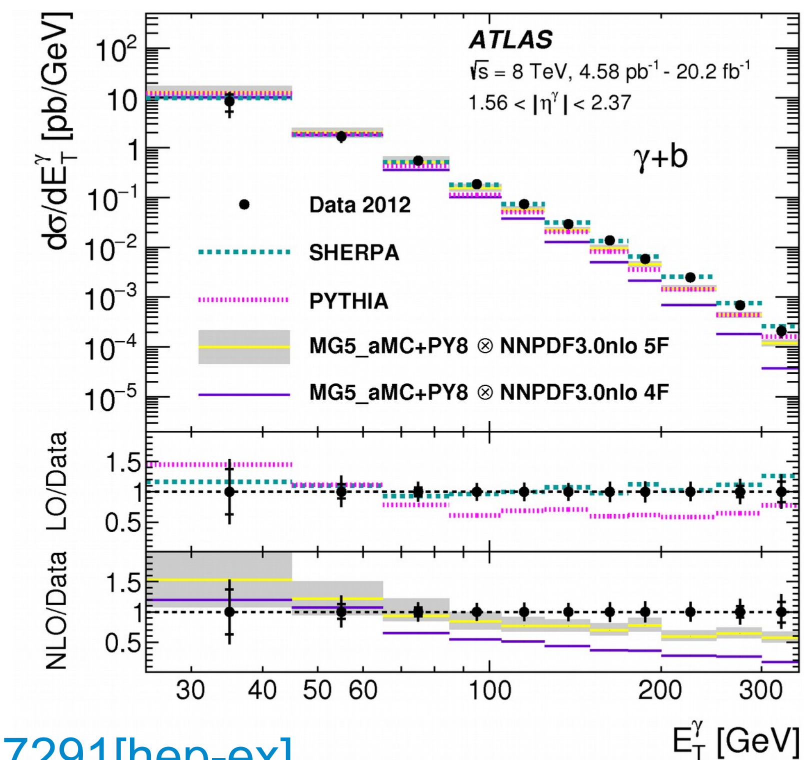
- Isolated photons + QCD jets abundantly produced
- Deep probe of proton structure, mainly gluon PDF





Cleaner signature allows:

- Reduced systematic uncertainties
- But also investigation of challenging final states → γ+HF (PLB 776(2018),295)

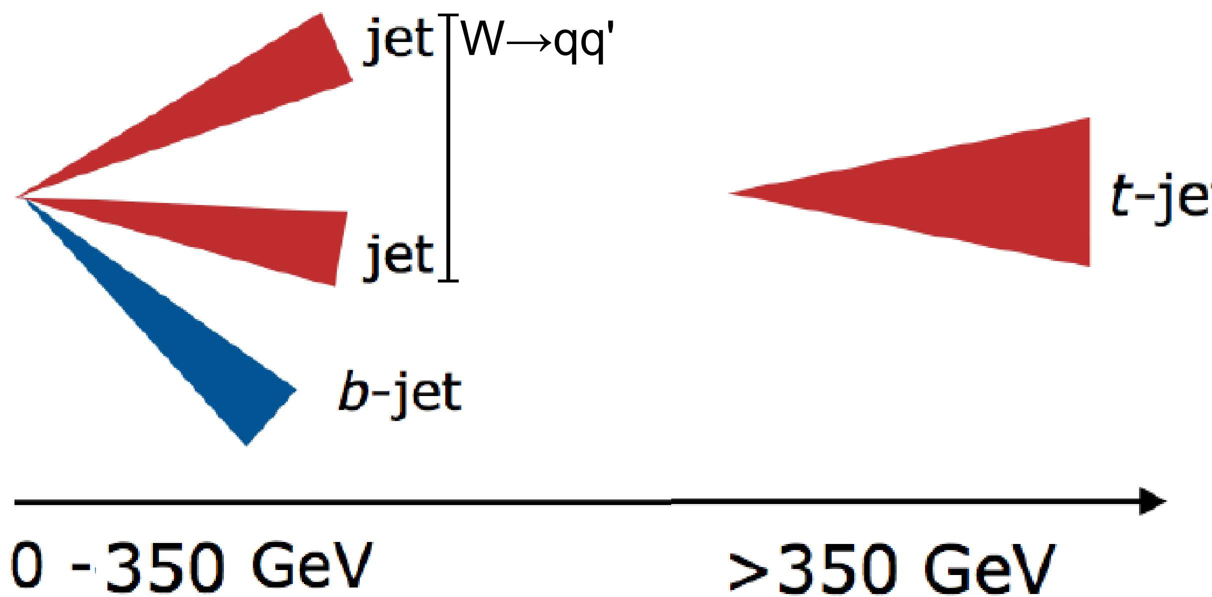


- Reaching up to ~3 TeV with measurement more precise than current predictions
- NLO particle-level predictions start to depart from data at high mass
- Also now available 3-γ cross section: arXiv:1712.07291[hep-ex]

Additional Probes of the SM: Top-quark

LHC sometimes called a "top-quark" factory:

- $t\bar{t}$ production cross section @13 TeV is ~800pb
- Analysis methods optimized for each energy range



- Boosted top reconstructed with large-R jets R=1.0 and jet sub-structure information (trimmed R_{sub}=0.2, f_{cut}=0.05)
- *Top-quark can be used to probe low and high scales*

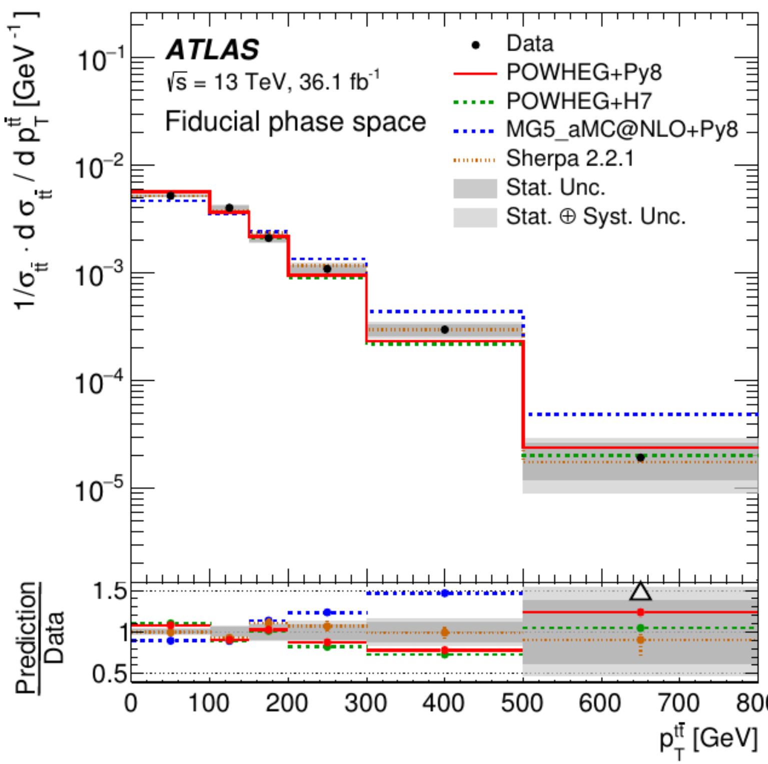
All-Hadronic Top Cross Section

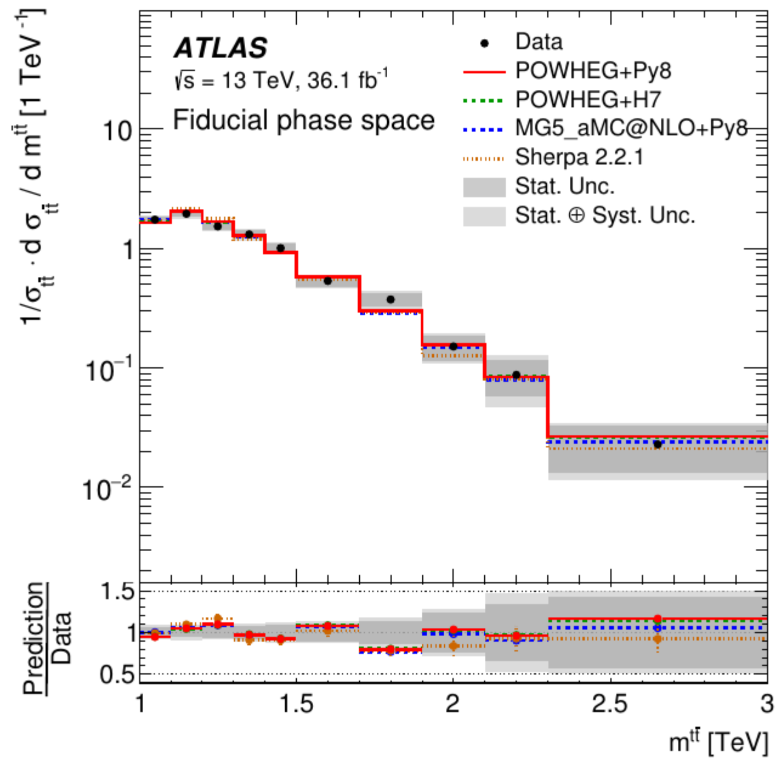
arXiv:1801.02052[hep-ex]
NEW!

- Majority of analyses use $t\bar{t}$ semi-leptonic or di-leptonic decays:

  → Allow precise measurement of inclusive/fiducial cross section, at 5% level in recent 8 TeV results (arXiv:1712.06857[hep-ex])

- *Now also available more challenging measurement in all-hadronic channel:*





Excellent agreement in $p_T(t\bar{t})$ from improved Powheg+Pythia8 tuning (now current ATLAS default)

- $t\bar{t}$ resonant searches limited by low stat and resolution at high-$m(t\bar{t})$…
- *All-hadronic boosted shows best high-p_T resolution up to date!*

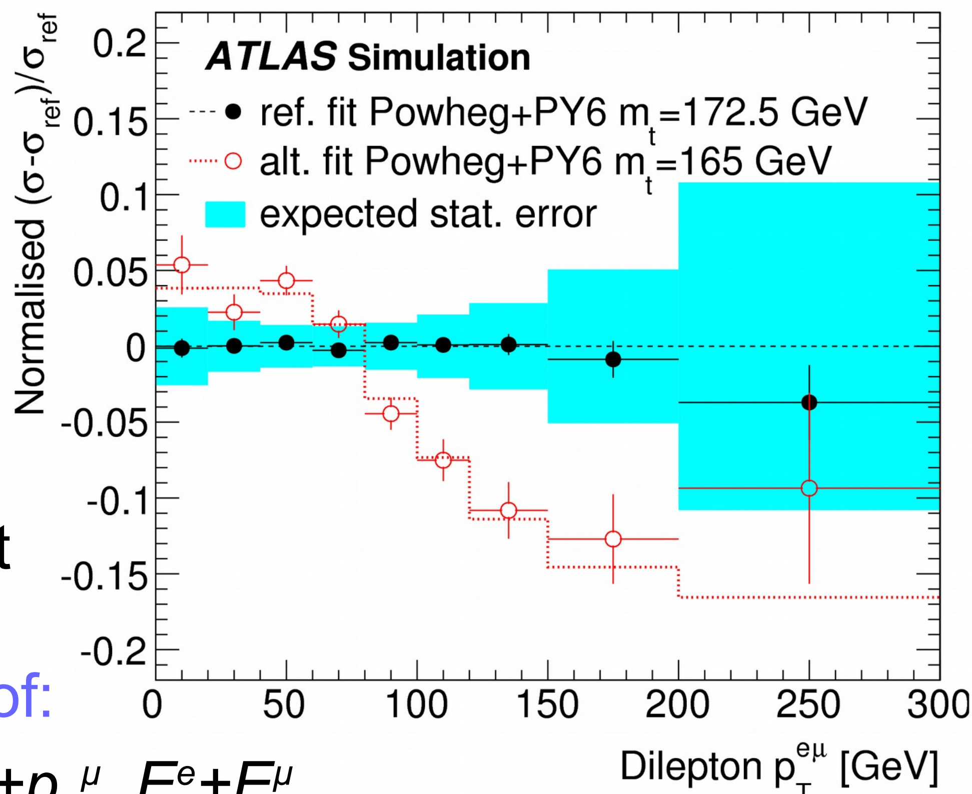
Top Cross-Section & Mass

EPJC 77(2017)804
from September

What else can be done with precision physics?

First example: $t\bar{t}$ cross section sensitive to top-quark pole-mass!

- Analysis of di-lepton channel @8TeV: less hadronic syst., well know data set



Mass extraction from combined analysis of:

- *m_t sensitive variables: p_T^l $p_T^{e\mu}$, $m^{e\mu}$, $p_T^e+p_T^\mu$, E^e+E^μ*
- *PDFs/QCD-scale sensitive variables: $|\eta^l|$, $|y^{e\mu}|$, $\Delta\varphi^{e\mu}$*

m_{top} = 173.2 ± 0.9 (stat) ± 0.8 (sys) ± 1.2 (theo)

- QCD-scale uncertainty from NLO MCFM predictions dominates error and is constrained by fit in data
- *Improvement from NNLO predictions? Rely on larger statistics?*

ATLAS W-mass Measurement

EPJC 78 (2018) 110
just published!

An other prototype of analysis pushing to the limits theory and experiment

- Template-fit of p_T & m_T spectra together with DY production/decay decomposition:

Breit-Wigner — Parton-Shower

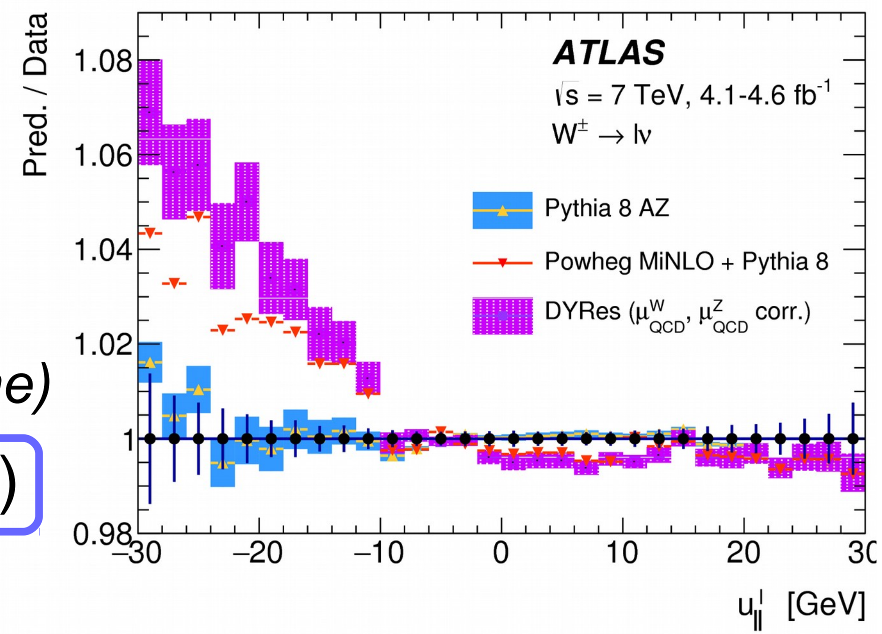
$$\frac{d\sigma}{dp_1\,dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T,y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[(1+\cos^2\theta)+\sum_{i=0}^{7}A_i(p_T,y)P_i(\cos\theta,\phi)\right]$$

NNLO pQCD (reweight to measurements)

- Extreme care in calibration and bkg estimate
- Ancillary measurements (Vp_T, A_i, PDFs, etc.) used to pin-down modeling uncertainties
- Investigation of several option for Wp_T description→ finally relying on *Pythia8 (AZ Tune)*

m_W = 80370 ± 19 MeV (0.02% precision!)

- *QCD-related unertainties dominate!*



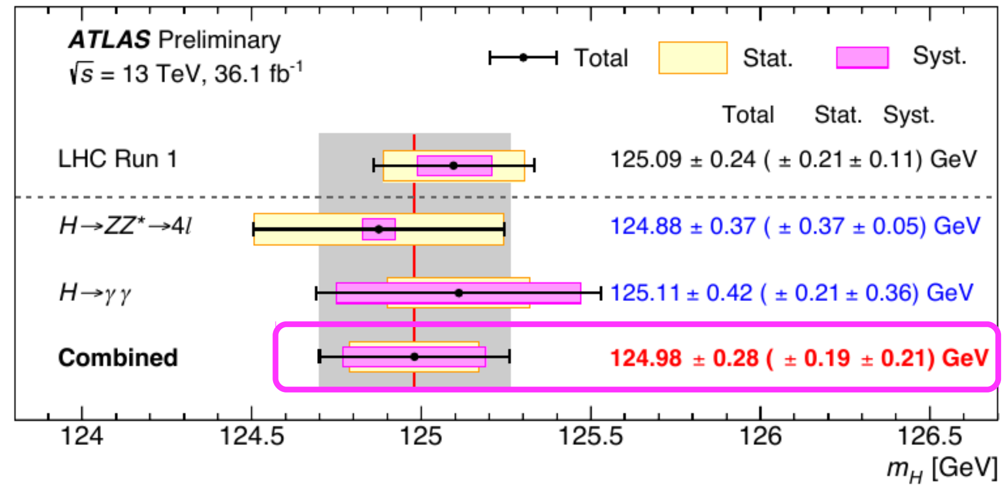
Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

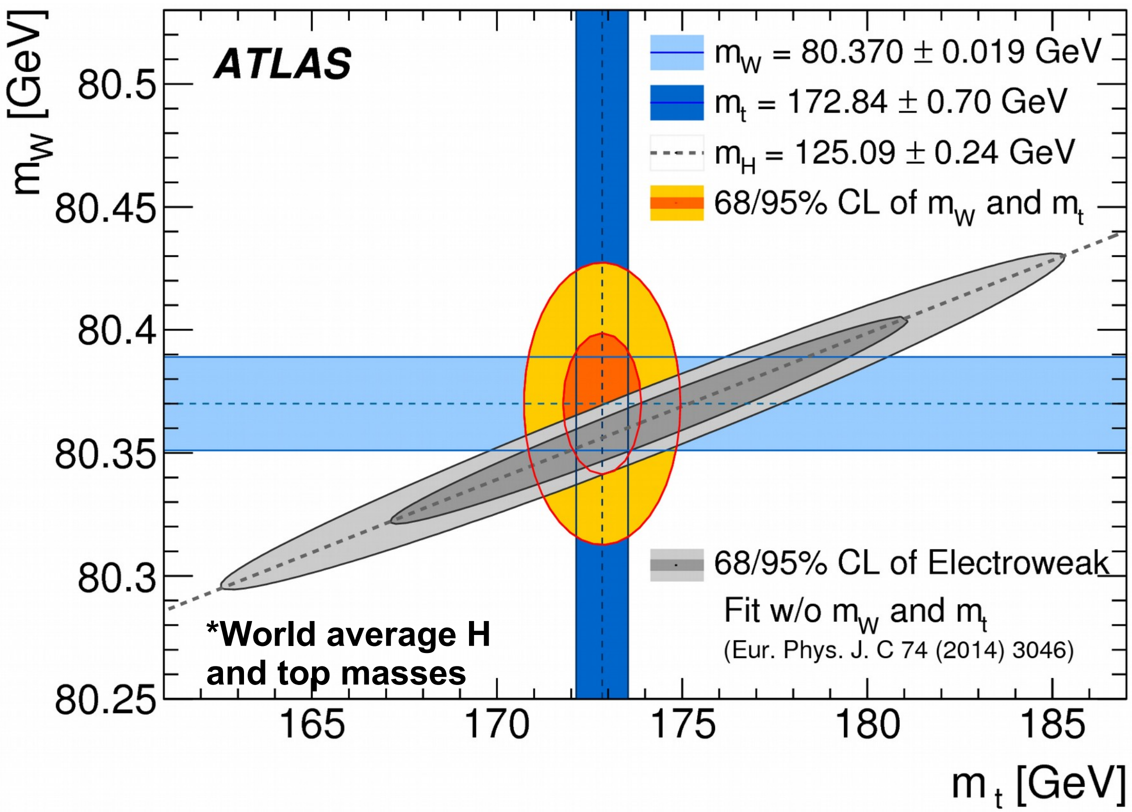
Adding the Higgs to the Picture

ATLAS-CONF-2017-047
from last Summer

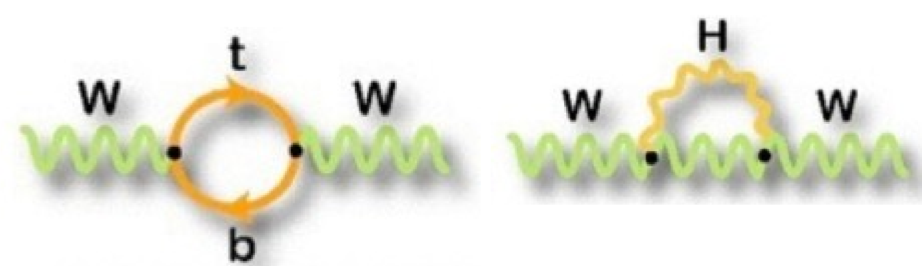
High resolution in m_H measurement:

- $H \to \gamma\gamma$ and $H \to ZZ^* \to 4L$
- Tiny experimental uncertainty from lepton & photon calibrations
- *Already reached Run 1 precision!*





- m_W, m_t, m_H are related in SM:



- Probing BSM though loop corrections → *consistent with SM*
- Current measurements reaching experimental and theoretical systematic uncertainty limits

Drell-Yan 3D Analysis

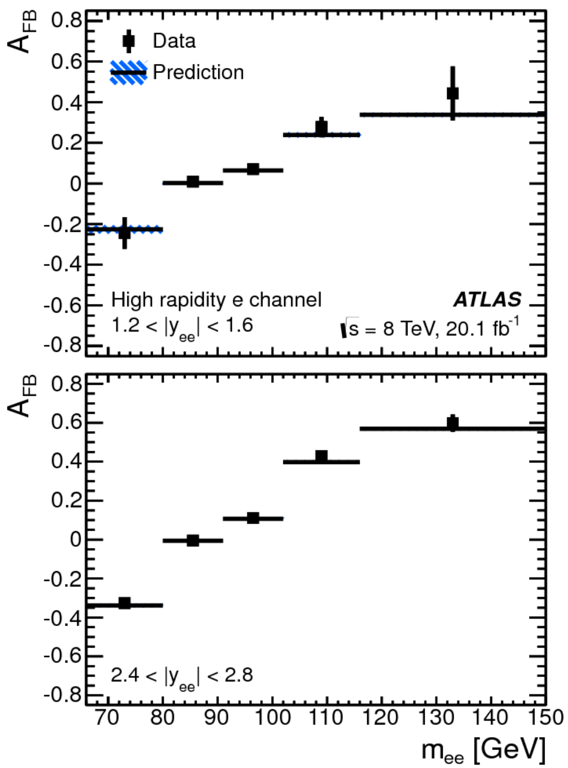
arXiv:1710.05167[hep-ex]
NEW!

One last example (and recent result) of precision measurement exploiting both large statistics data set and with sensitivity to a fundamental SM parameter

3-Dim. DY analysis @8 TeV:

- DY fully described by 5 variables → *using 3 of them!*

$$\frac{d^3\sigma}{dm_{\ell\ell}dy_{\ell\ell}d\cos\theta^*}$$



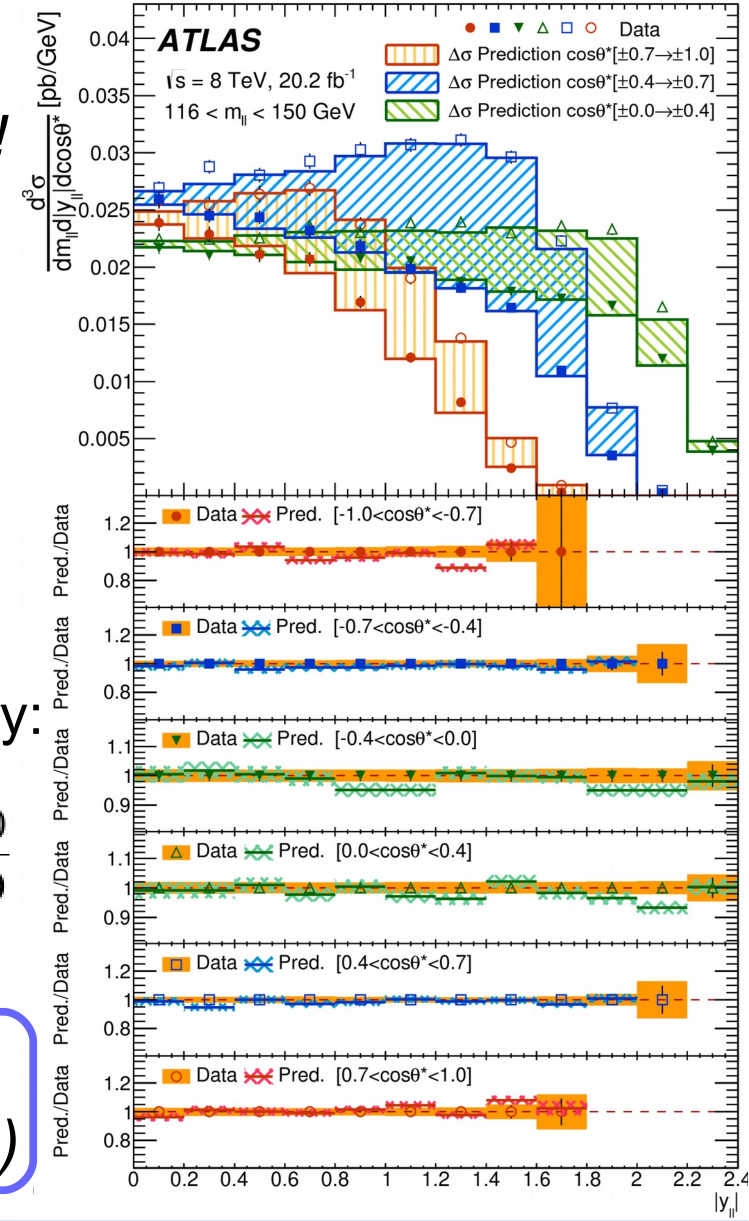
Strong off-peak A_{FB}

- M_{ll}, $|Y_{ll}|$ maximizes sensitivity to PDFs
- cosθ* (in Collins-Sopper frame) allows to define forward-backward asymmetry:

$$A_{FB} = \frac{d^3\sigma(\cos\theta^* > 0) - d^3\sigma(\cos\theta^* < 0)}{d^3\sigma(\cos\theta^* > 0) + d^3\sigma(\cos\theta^* < 0)}$$

Sensitive to sin θ_w !

(but no measurement yet...)



Conclusions

SM is (still now), at the basis of every interaction at the LHC

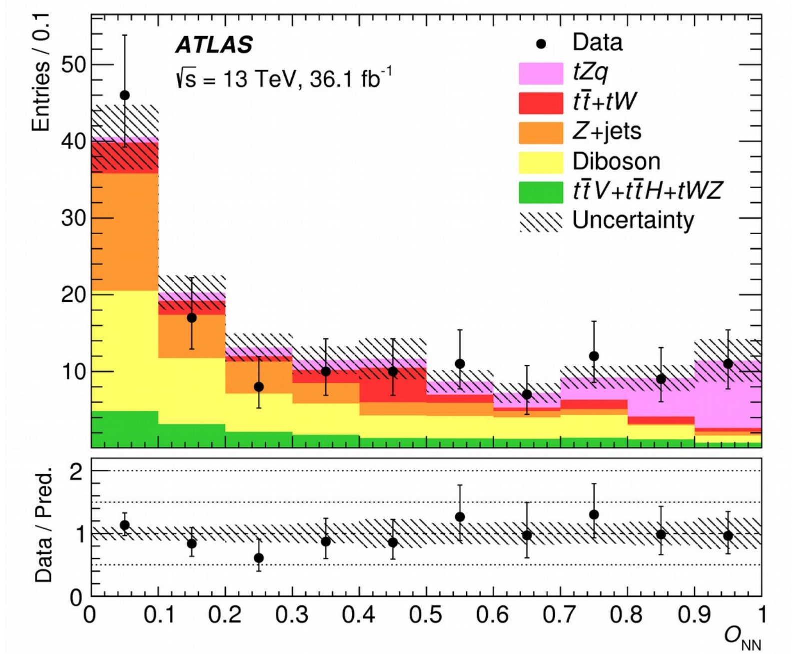
- Large 13 TeV dataset showed evidence of rare (and difficult to probe) Higgs production and decay modes:
  → *Direct test of Yukawa coupling to 3rd family quarks!*
- Modeling of QCD and SM backgrounds posing a limit for the precise measurement also when much larger dataset will be soon analyzed!
- Direct measurement of V+jets, di-jet and top-quarks are fundamental to stress-test MC generators and predictions with high accuracy and in unexplored regimes
- Precision analysis of SM processes are probing fundamental constants of Nature
- *Experimental & theoretical uncertainties have similar contribution!*

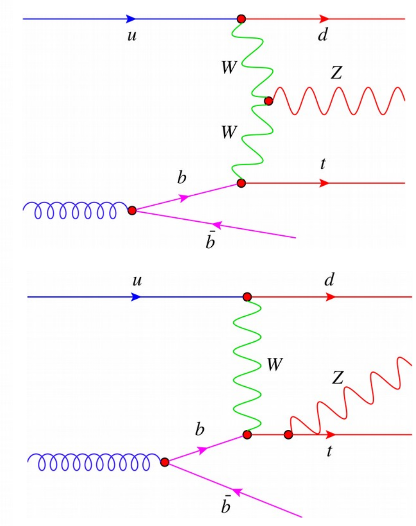
Backup

Other Recent Measurements

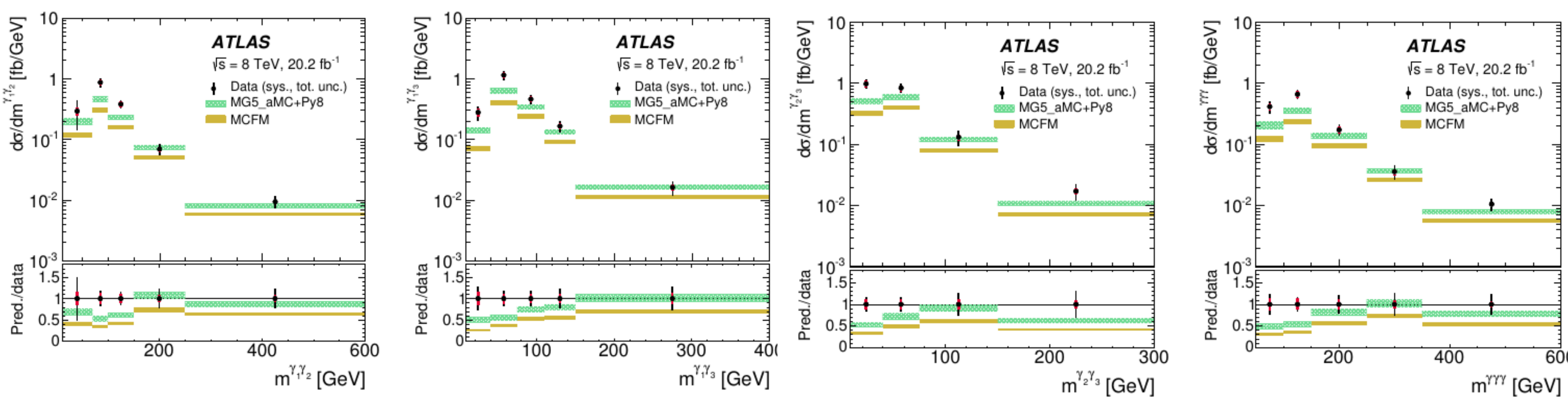
- Evidence for tZq @13 TeV: arXiv:1710.03659[hep-ex]
- 4.2σ obs. (5.4σ exp)
- Cross section:

  600±170(stat.)±140(syst.) fb





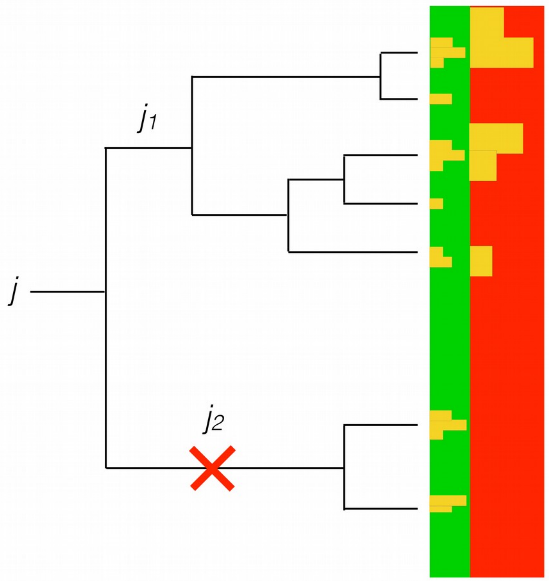
- Tri-photon cross section: arXiv:1712.07291[hep-ex]

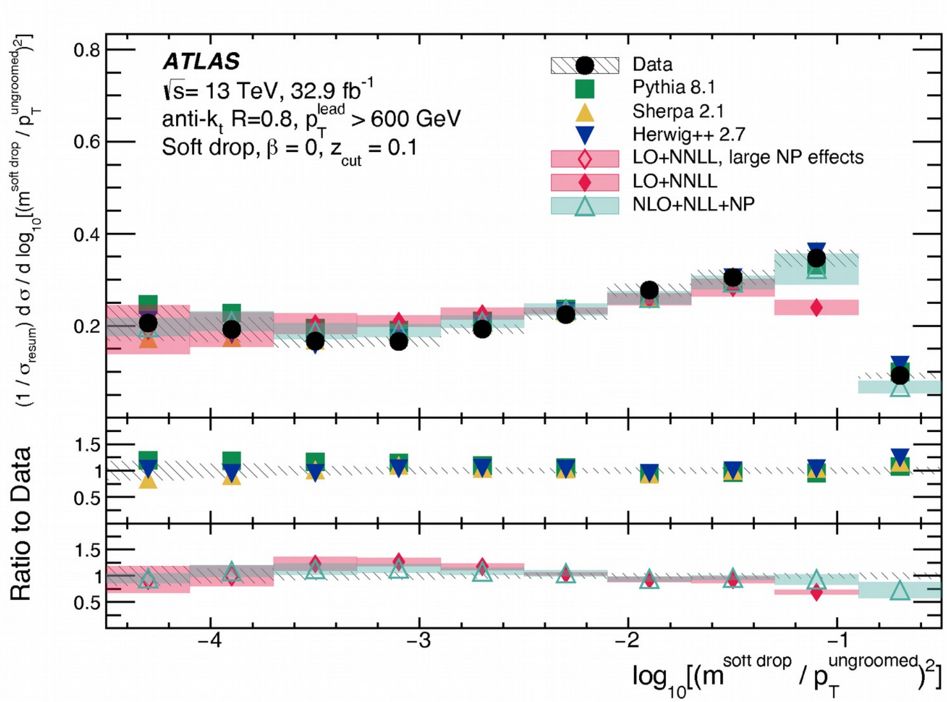


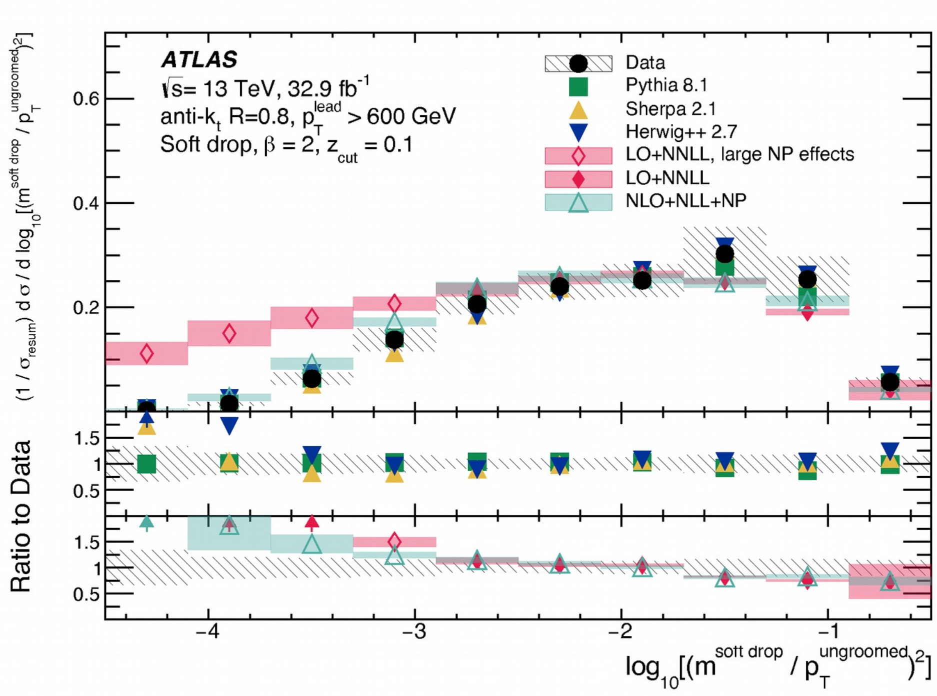
arXiv:1711.08341[hep-ex]

Soft-Drop Jet Mass Measurement

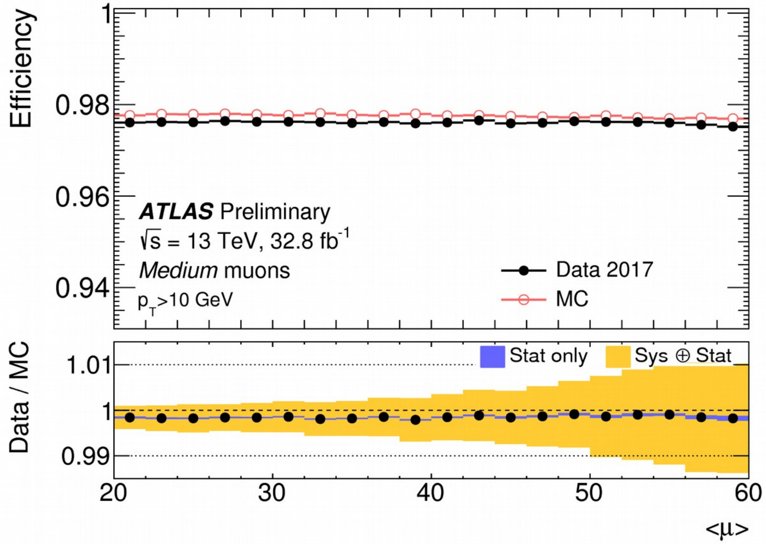
$$\frac{\min(p_{T,j_1}, p_{T,j_2})}{p_{T,j_1} + p_{T,j_2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R} \right)^{\beta}$$

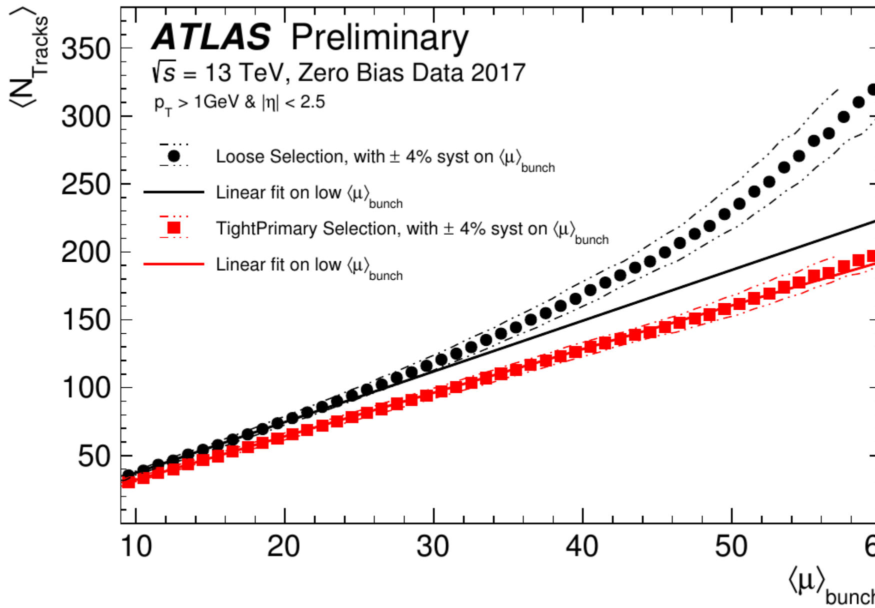


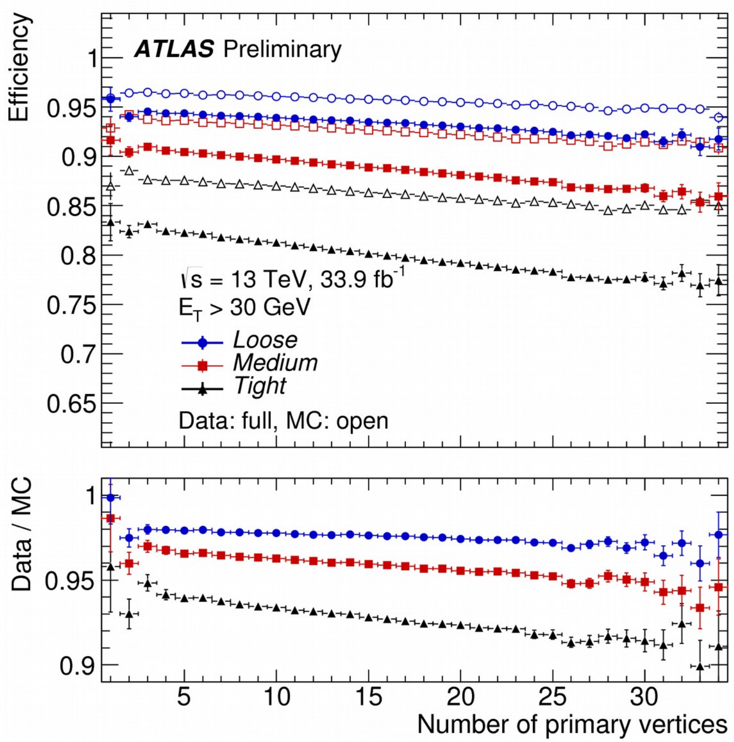


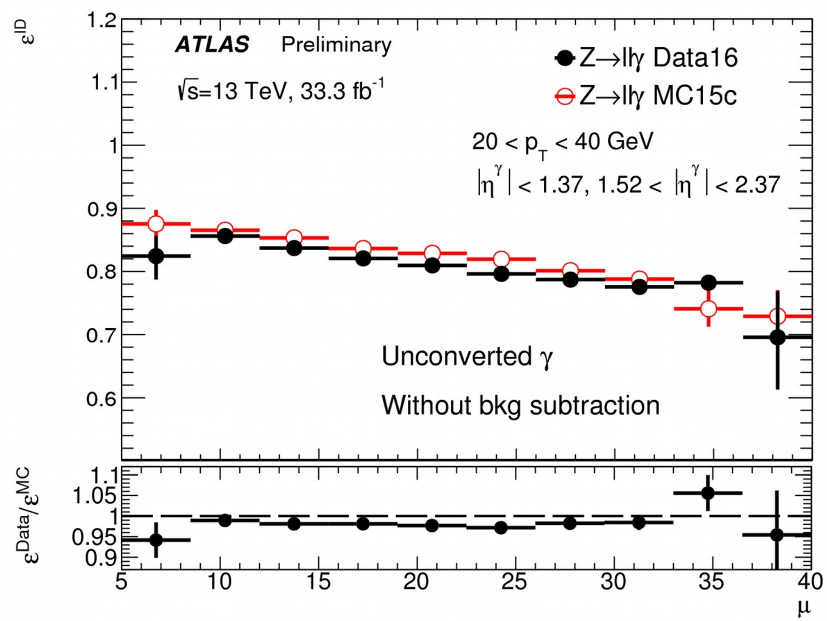


Physics Object Performance vs <μ>

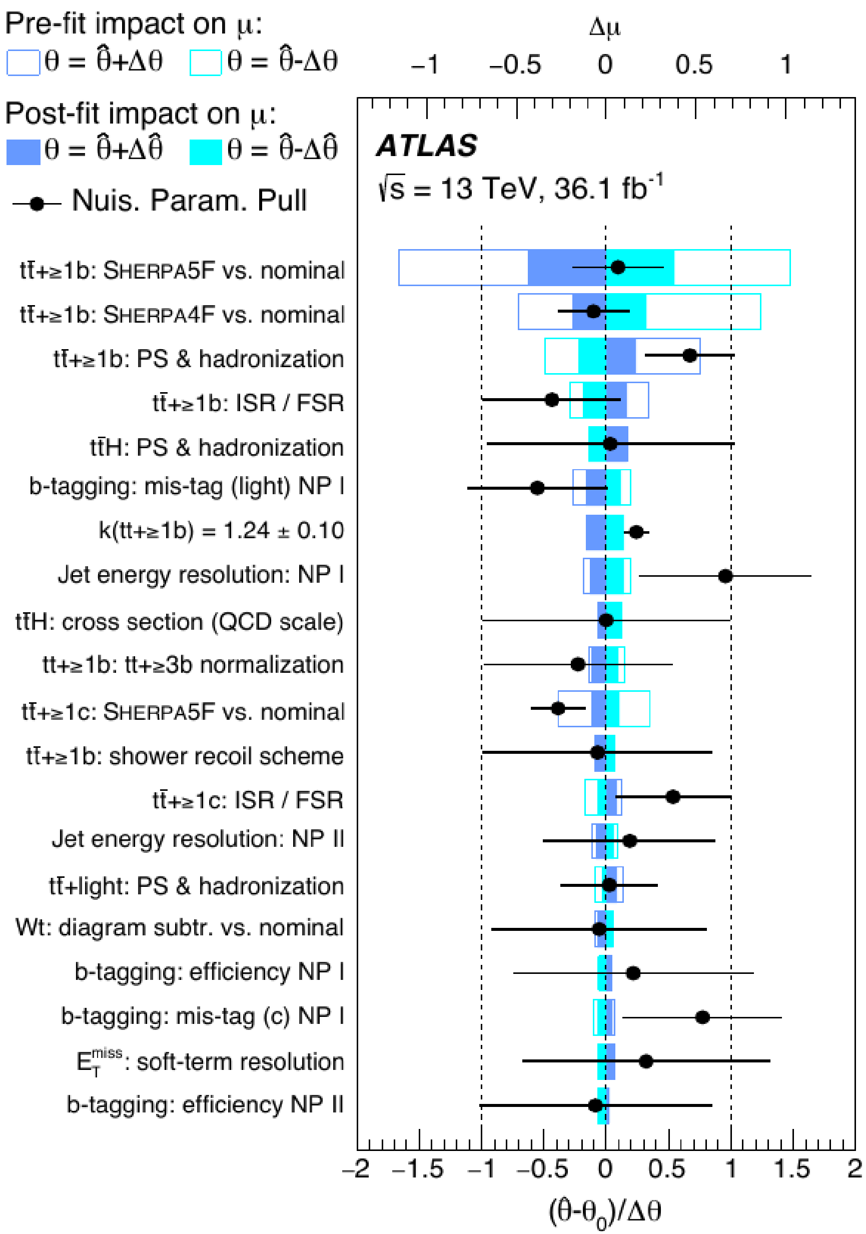




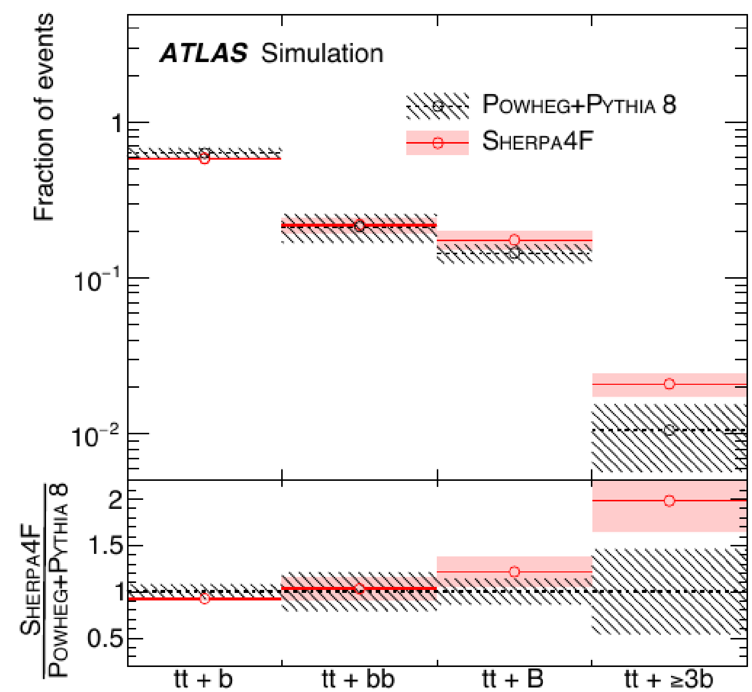




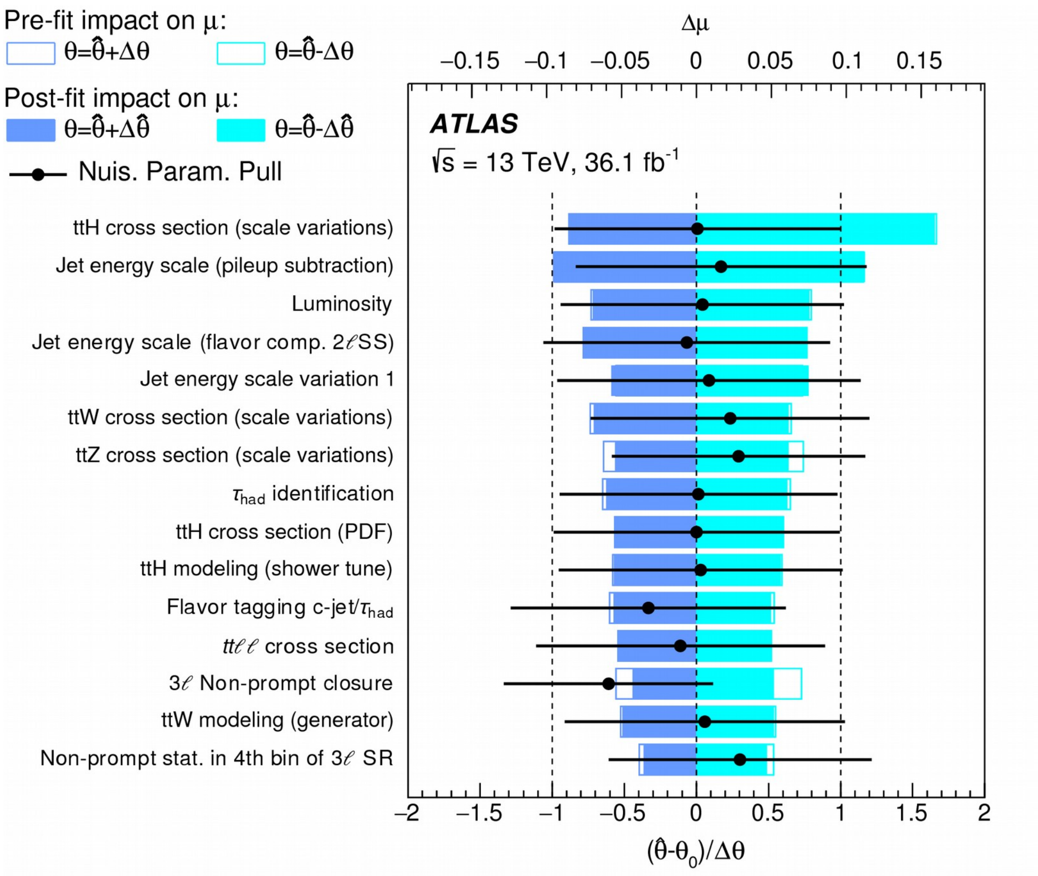
ttH(bb) Details

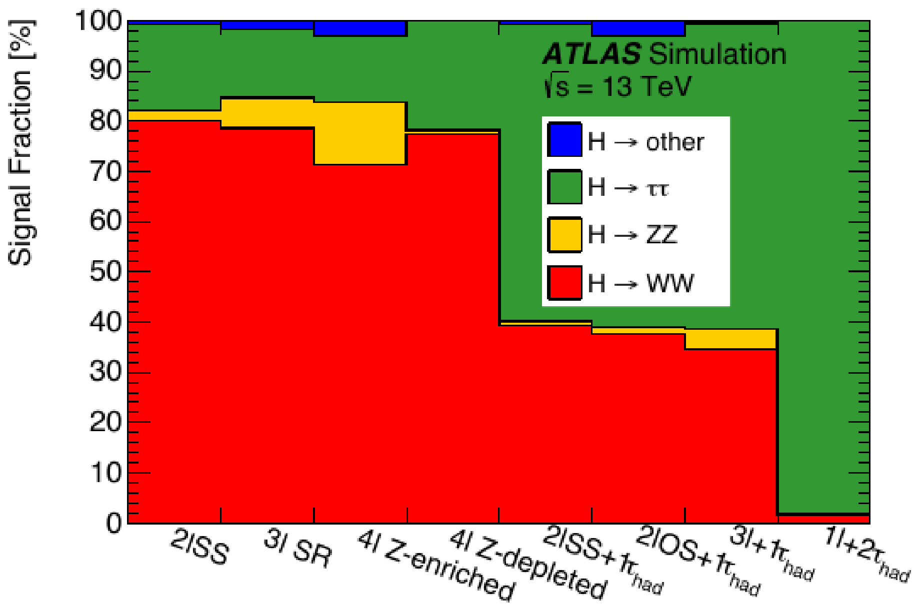


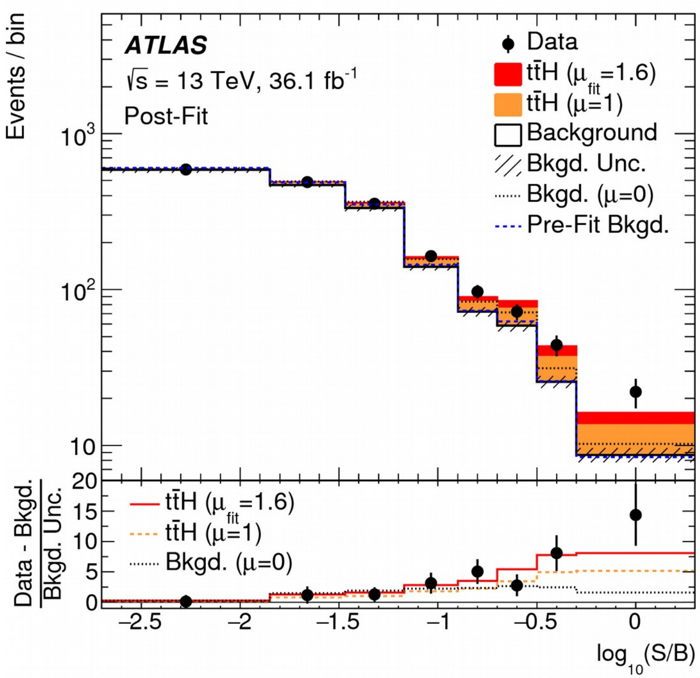
<table>
<tr><th colspan="2">1-lepton</th><th>2-leptons</th></tr>
<tr><td colspan="3">Single un-prescaled e/μ trigger</td></tr>
<tr><td colspan="2">= 1 e or μ p_T>27 GeV
≥ 5 jets with p_T>25 GeV</td><td rowspan="3">= 2 opposite sign e or μ
≥ 3 jets with p_T>25 GeV
≥ 2 jets tagged as b at 77% WP
Z mass window veto |M_{ll}-91|<8 GeV
= 0 hadronic τ (veto)</td></tr>
<tr><td>Resolved (low p_T)</td><td>Boosted (high p_T)</td></tr>
<tr><td>≥ 2 jets tagged as b at 60% WP or
≥ 3 jets tagged as b at 77% WP
< 2 hadronic τ (veto)</td><td>≥ 2 LRJ
≥ 1 jet outside of LRJ tagged as b at 85%
1 boosted H→bb candidate
1 boosted Top candidate</td></tr>
</table>



ttH multilepton details

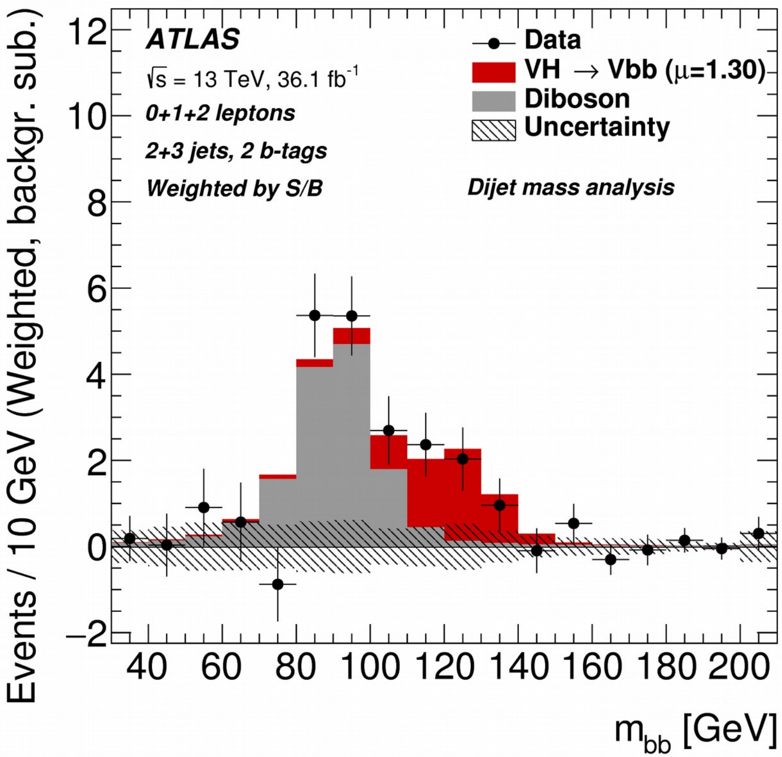


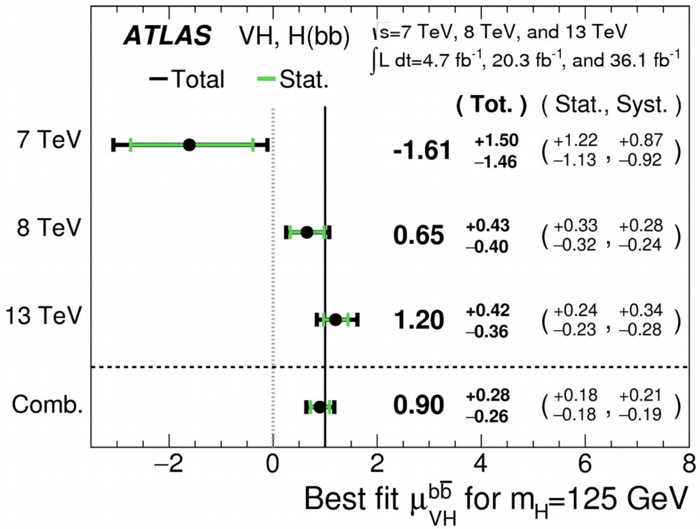


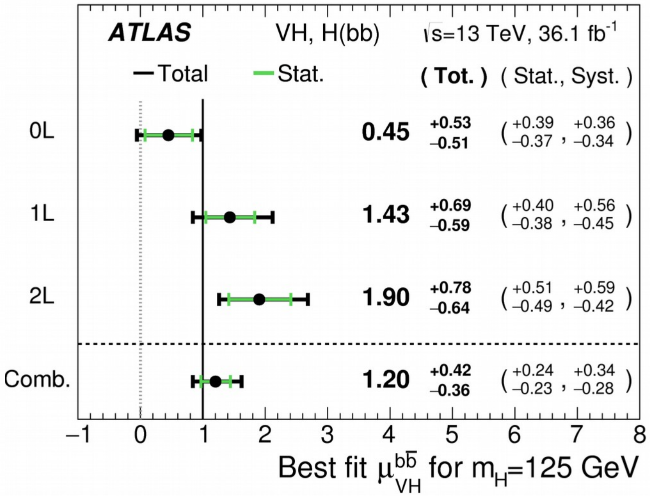


VH(bb) details

Source of uncertainty		σ_μ
Total		0.39
Statistical		0.24
Systematic		0.31
Experimental uncertainties		
Jets		0.03
$E_{\mathrm{T}}^{\mathrm{miss}}$		0.03
Leptons		0.01
b-tagging	b-jets	0.09
	c-jets	0.04
	light jets	0.04
	extrapolation	0.01
Pile-up		0.01
Luminosity		0.04
Theoretical and modelling uncertainties		
Signal		0.17
Floating normalisations		0.07
Z + jets		0.07
W + jets		0.07
$t\bar{t}$		0.07
Single top quark		0.08
Diboson		0.02
Multijet		0.02
MC statistical		0.13







More about Cross Sections

$$\sigma^{tot} = \frac{\sigma^{fid}}{A} = \frac{N-B}{\mathcal{L}\cdot A\cdot C}$$

A: signal acceptance in fiducial phase space $\Rightarrow$ depends on theoretical predictions

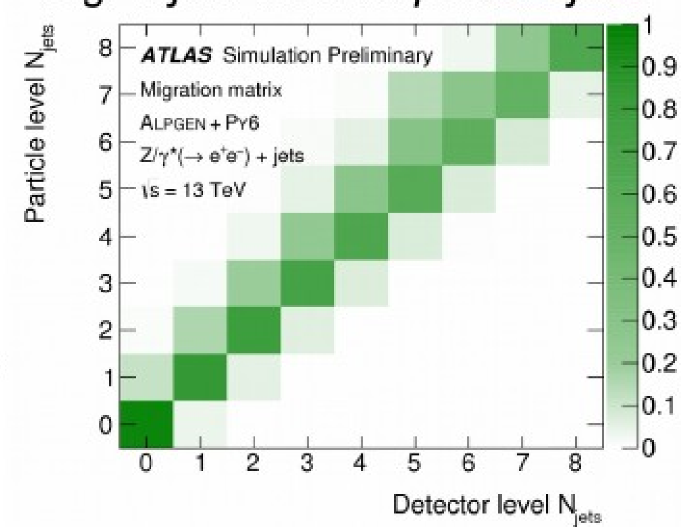
C: experimental acceptance correction $\Rightarrow$ depends on identification/reconstruction algorithms

$N - B$: background subtracted data candidates $\Rightarrow$ depends on selection/background estimate

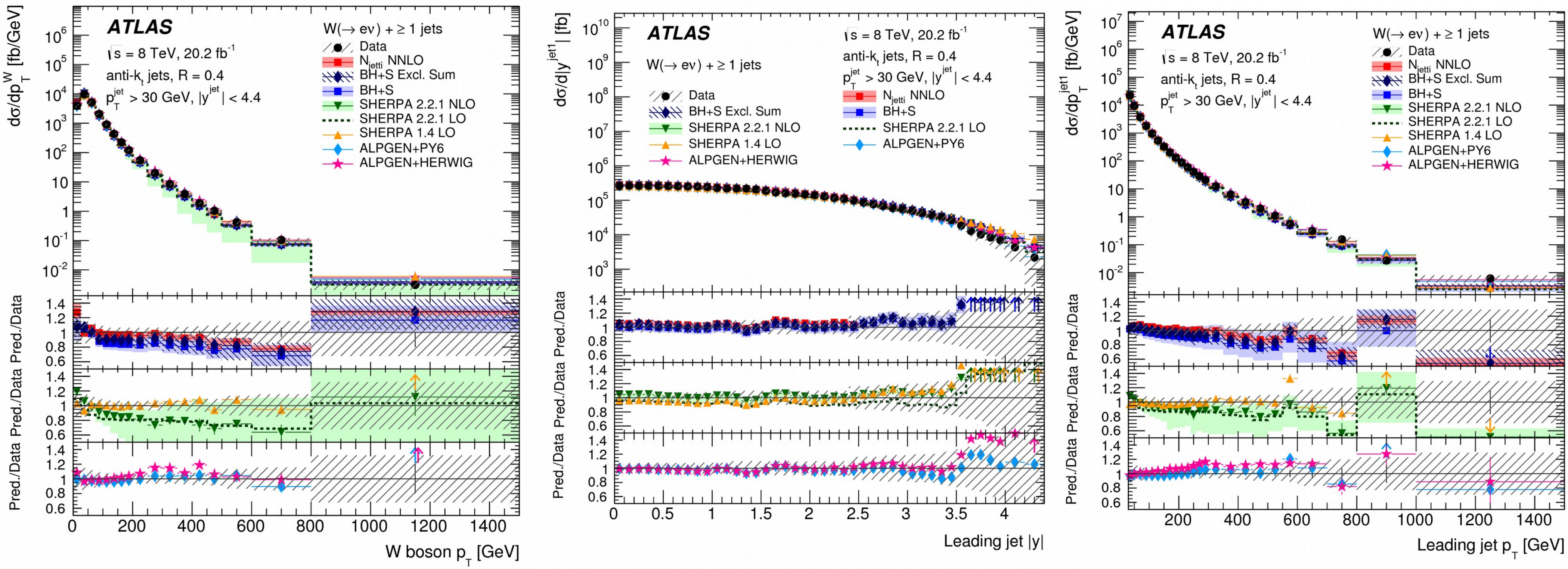
$\mathcal{L}$: integrated luminosity $\Rightarrow$ dependents on LHC and on luminosity measurement precision

- Define fiducial volume of the measurement in phase space similar to experimental acceptance
- Use signal MC to remove *detector* effects (efficiencies, resolution, scales) on background subtracted data
- Compare unfolded data to available MC simulations or to fixed-order calculations (after correction for non-perturbative effects as fragmentation, underling event, etc.)

E.g. n-jets reco-vs-particle jets:



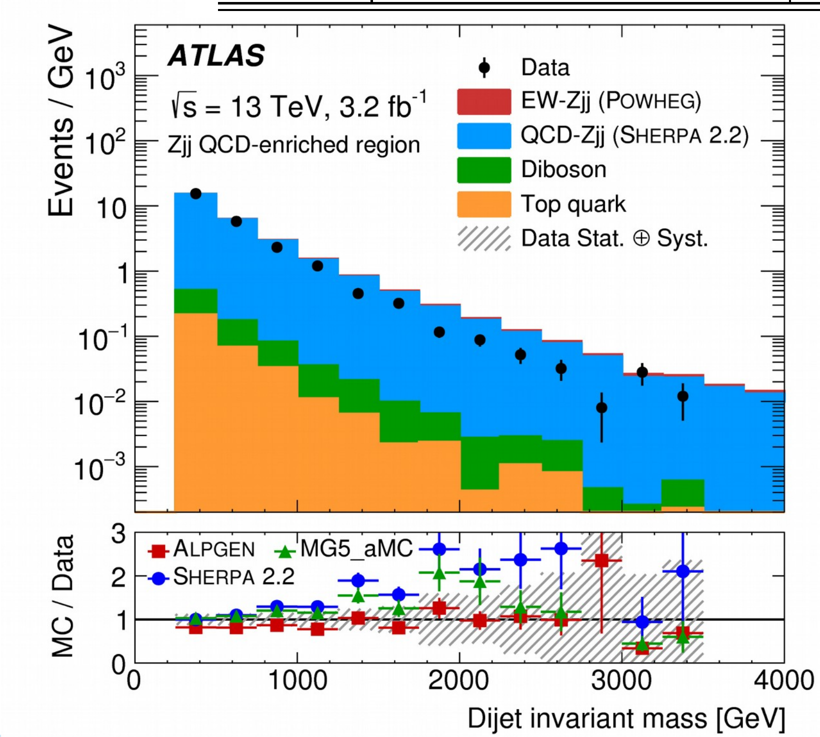
W+jets 8 TeV: Details

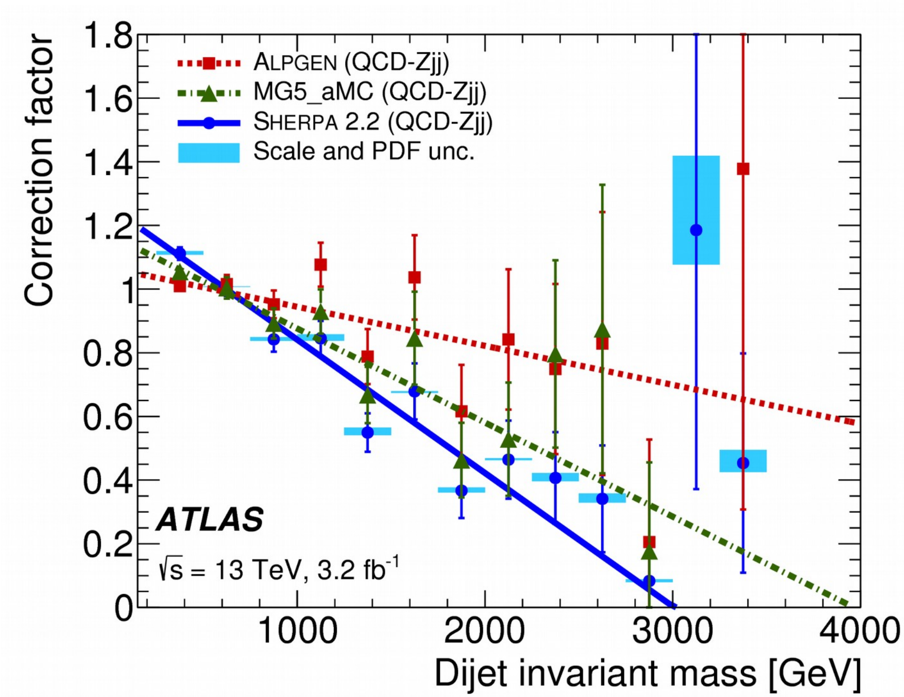


Type of Prediction	MCs & Calculations “label”	Usage & Notes
multi-partons (Np) LO ME+PS	Sherpa 1.X (up to Np = 4)	Wide usage in ATLAS Run I analyses
	Madgraph5 (up to Np = 4)	Wide usage in CMS Run I analyses
	ALPGEN (up to Np = 5)	Run I (and Run II) “workhorse”
multi-parton (Np) NLO and LO ME+PS	Madgraph5 aMC@NLO (NLO up to Np = 2)	“Standard” in many Run II CMS analyses
	Sherpa 2.X (NLO up to Np = 2)	“Standard” in many Run II ATLAS analyses
	Powheg (NLO Np = 1)	Tested in Run I by CMS
Fixed order NLO calculation	BlackHat + Sherpa (NLO up to Np = 5)	Tested in Run I, II (both ATLAS and CMS)

Zjj EWK Details

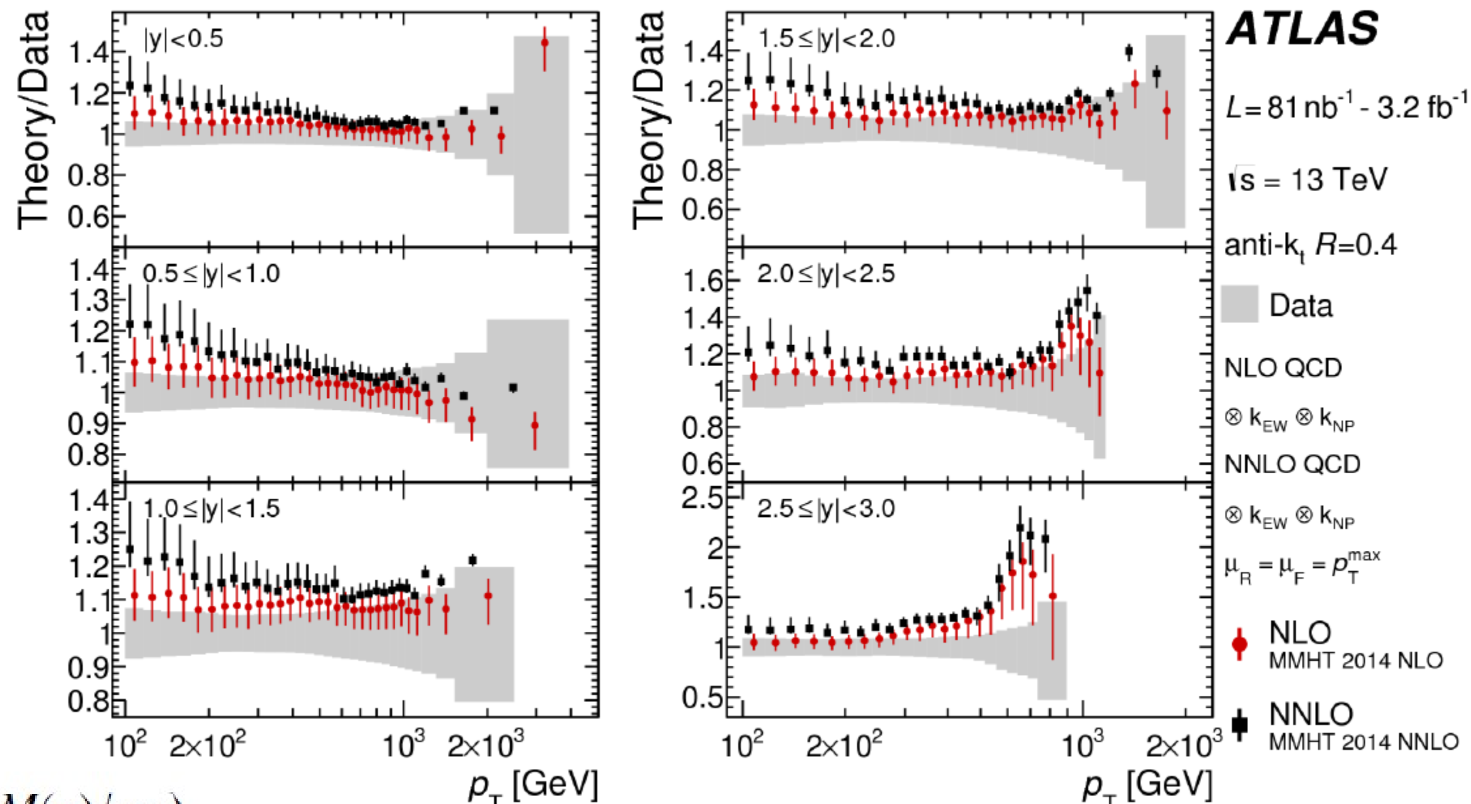
Object	Fiducial region: Baseline	High-mass	High-p_T	EW-enriched	EW-enriched, $m_{jj} > 1$ TeV	QCD-enriched
Leptons	$\lvert\eta\rvert < 2.47$, $p_T > 25$ GeV, $\Delta R_{j,\ell} > 0.4$					
Dilepton pair	$81 < m_{\ell\ell} < 101$ GeV					
	—			$p_T^{\ell\ell} > 20$ GeV		
Jets	$\lvert y\rvert < 4.4$					
	$p_T^{j_1} > 55$ GeV		$p_T^{j_1} > 85$ GeV	$p_T^{j_1} > 55$ GeV		
	$p_T^{j_2} > 45$ GeV		$p_T^{j_2} > 75$ GeV	$p_T^{j_2} > 45$ GeV		
Dijet system	—	$m_{jj} > 1$ TeV	—	$m_{jj} > 250$ GeV	$m_{jj} > 1$ TeV	$m_{jj} > 250$ GeV
Interval jets	—			$N_{\text{jet }(p_T>25\text{ GeV})}^{\text{interval}} = 0$		$N_{\text{jet }(p_T>25\text{ GeV})}^{\text{interval}} \geq 1$
Zjj system	—			$p_T^{\text{balance}} < 0.15$		$p_T^{\text{balance},3} < 0.15$





Di-jet 13 TeV Details

- Better NLO agreement for scale = p_T^{max}



$$f_1(p_T, y) = C(p_T, y) \cdot c_1 / \log(M(y)/p_T)$$
$$f_2(p_T, y) = C(p_T, y) \cdot c_2 \cdot y^2 / \log(M(y)/p_T)$$
$$f_3(p_T, y) = C(p_T, y) \cdot c_3$$
$$f_4(p_T, y) = C(p_T, y) \cdot c_4 \cdot y^2$$
$$f_5(p_T, y) = C(p_T, y) \cdot c_5 \cdot \log(15 p_T / M(y))$$
$$f_6(p_T, y) = C(p_T, y) \cdot c_6 \cdot y^2 \cdot \log(15 p_T / M(y))$$
$$M(y) = \sqrt{s} \cdot exp(-y)$$

- Test of realistic syst correlation assumptions, also for theory systematics
- 6 sub-components smooth in p_T – Y

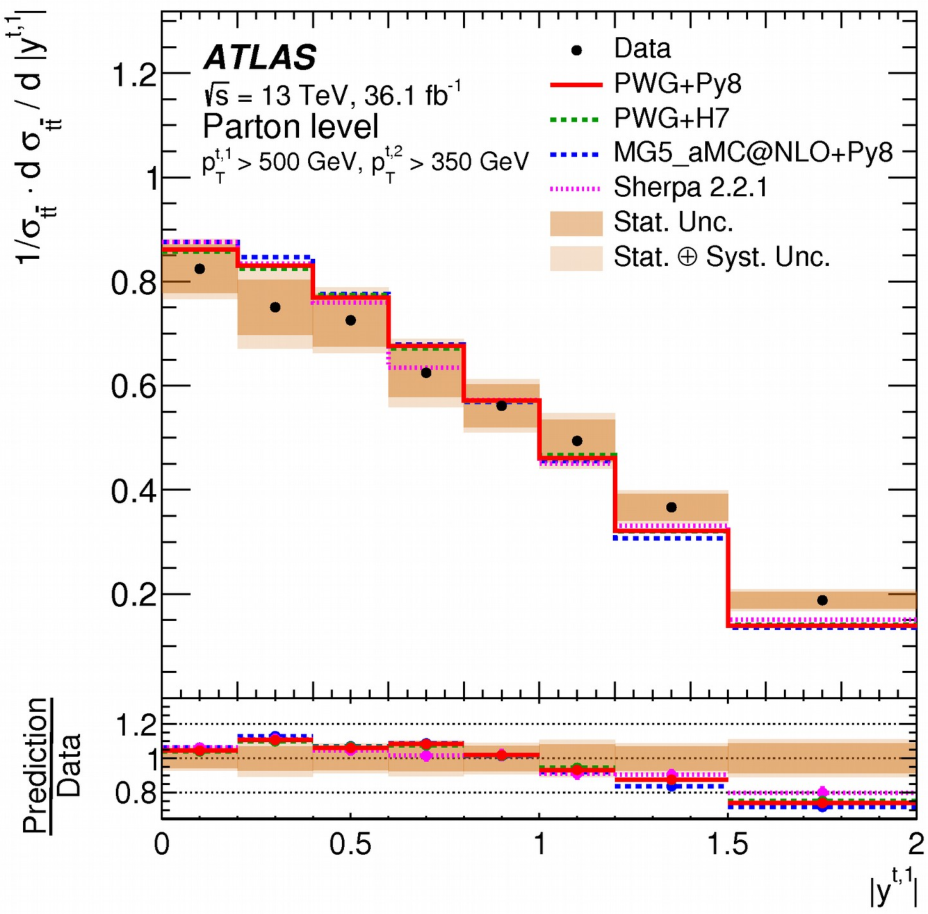
Based on:

Phys. Rev. D81 (2010) 035018

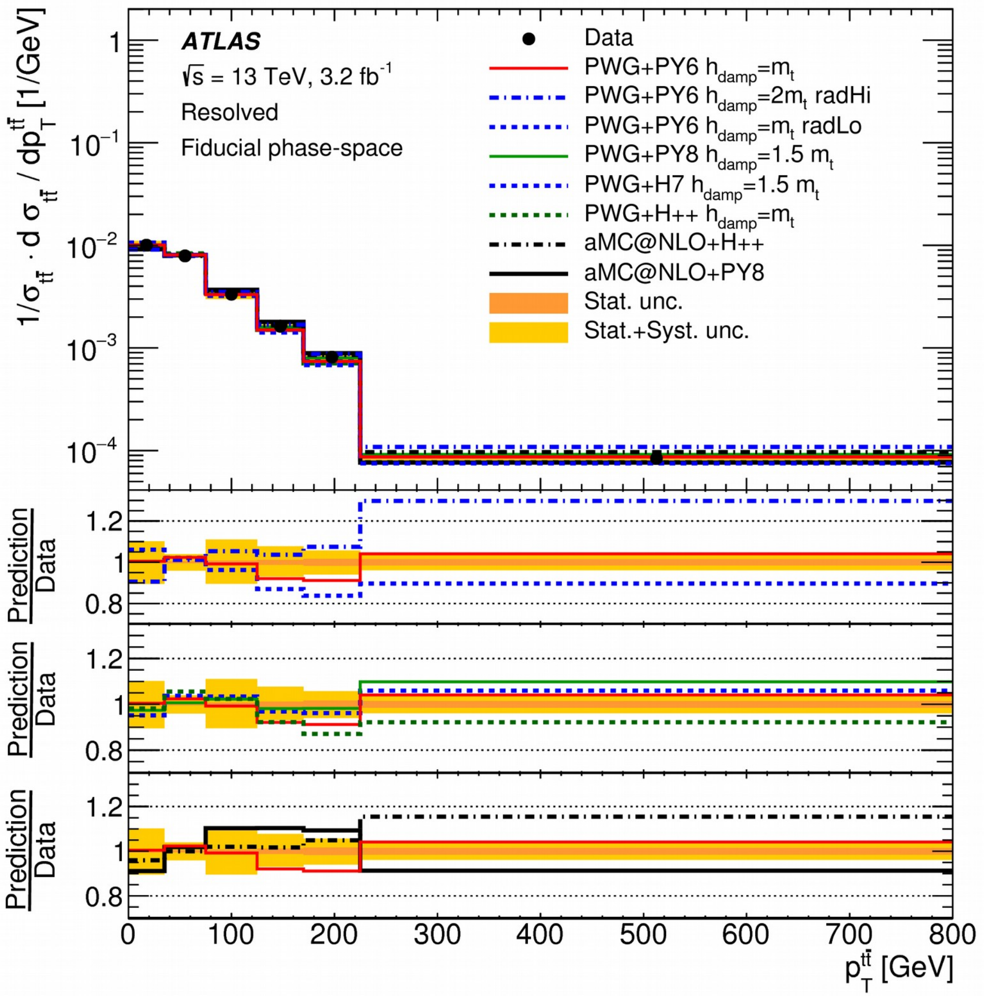
arXiv:0907.5052 [hep-ph]

Top Modeling Details

- All-hadronic



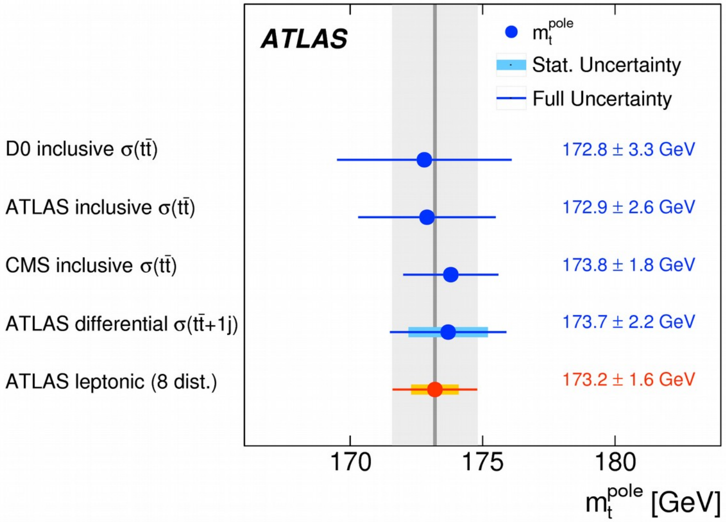
- lepton+jets measurement: arXiv:708.00727[hep-ex]



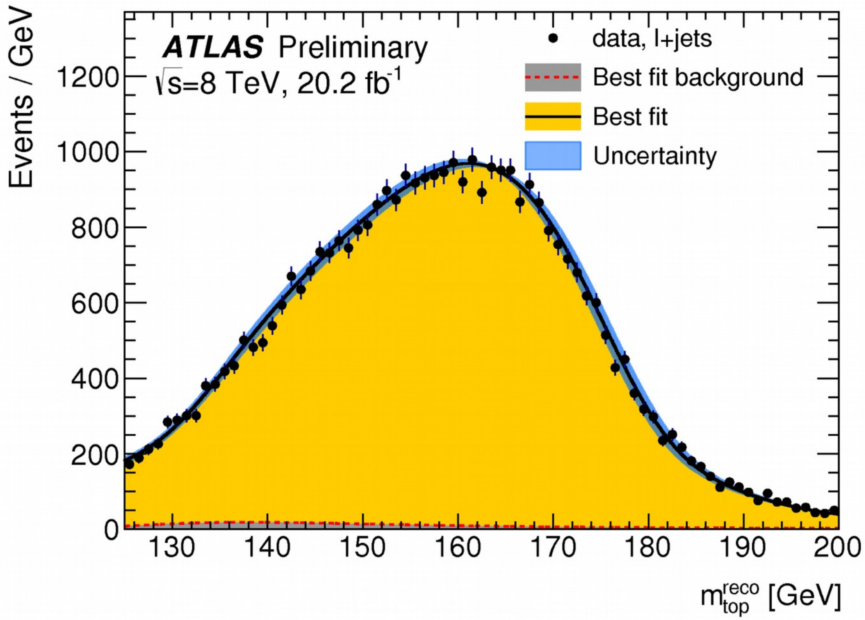
Top Mass

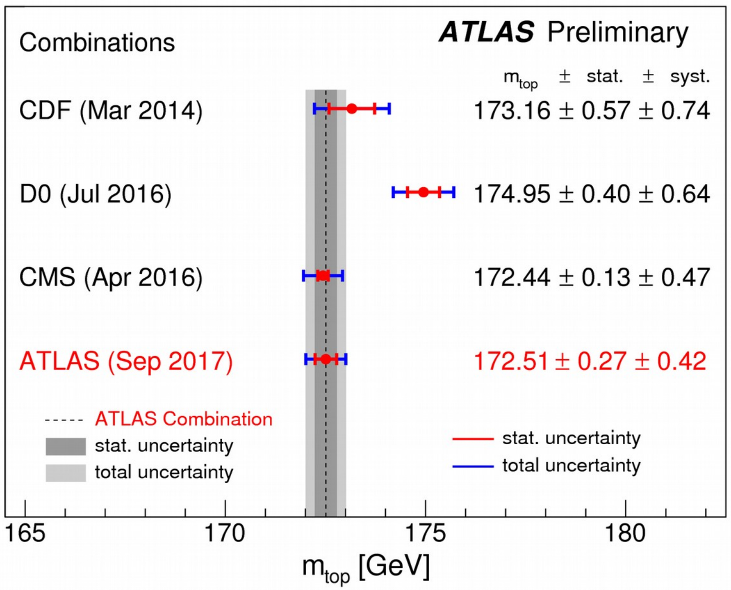
- Di-leptonic cross section Top-pole extraction & systematics:

	p_T^ℓ	$p_T^{e\mu}$	$m^{e\mu}$	$p_T^e + p_T^\mu$	$E^e + E^\mu$
χ^2/N_{dof}	9/8	5/7	11/10	11/6	8/8
m_t^{pole} [GeV]	$169.7^{+2.9}_{-2.7}$	175.1 ± 1.9	$174.5^{+5.1}_{-5.3}$	170.3 ± 2.1	$168.5^{+3.2}_{-3.3}$
Data statistics	± 2.0	± 1.4	$^{+3.8}_{-4.0}$	± 1.4	± 2.3
Expt. systematic	$^{+2.5}_{-2.3}$	± 0.9	$^{+2.9}_{-3.3}$	$^{+1.5}_{-1.6}$	± 2.0
PDF uncertainty	± 0.5	± 0.1	± 1.1	± 0.5	± 1.4
QCD scales	± 1.1	$^{+0.7}_{-0.8}$	± 2.6	$^{+0.4}_{-0.5}$	± 0.7



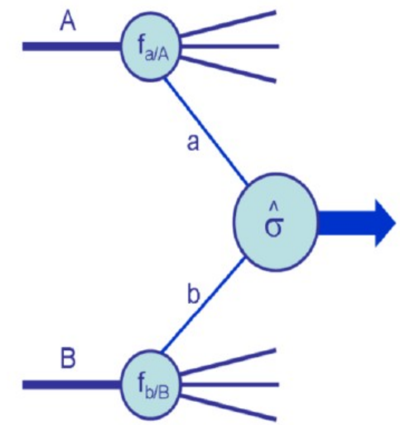
- Most precise ATLAS measurement in l+jets and combination: ATLAS-CONF-2017-071





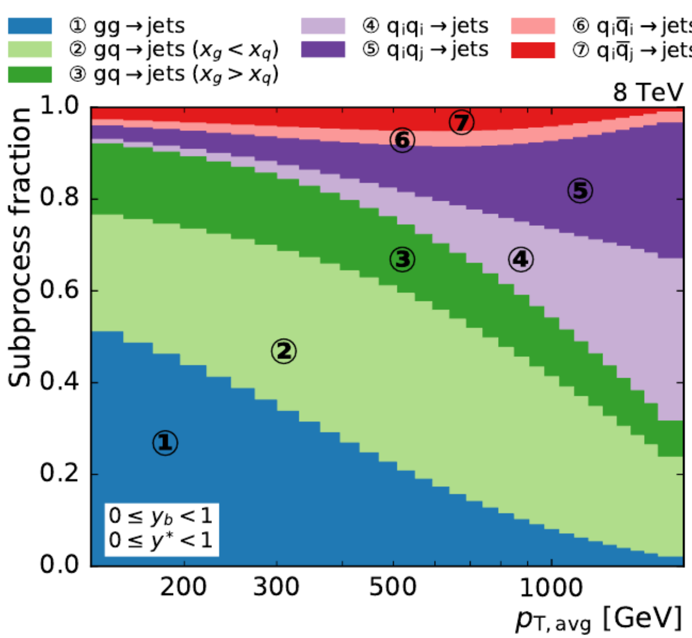
Sensitivity to PDFs

- LHC probe of the hard scattering (running of α_s), factorization theorem:

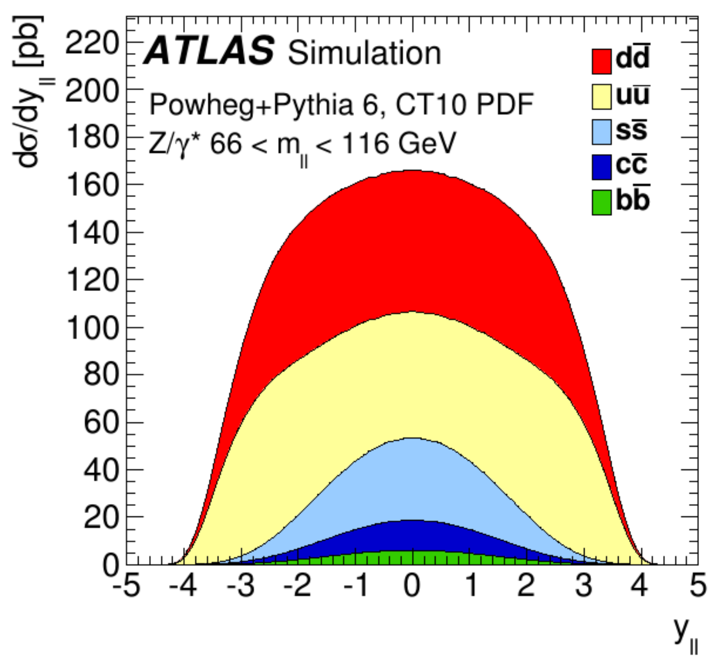


$$\sigma(P_1,P_2)=\sum_{i,j}\int dx_1\,dx_2 f_i(x_1,\mu_F)f_j(x_2,\mu_F)\hat{\sigma}_{ij}(p_1,p_2,\alpha_S(\mu_R),Q^2,\mu_R\mu_F)$$

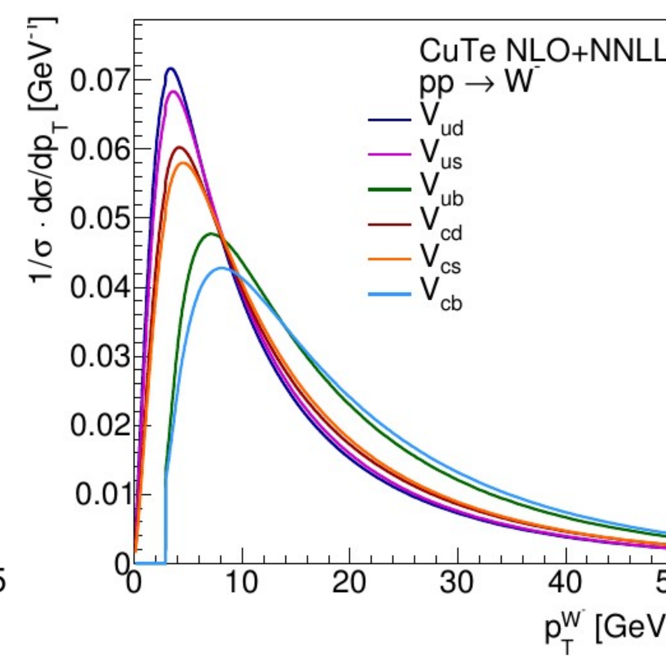
- Different processes can probe contribution form all partons



di-jet: kinematic dependent fraction of involved partons

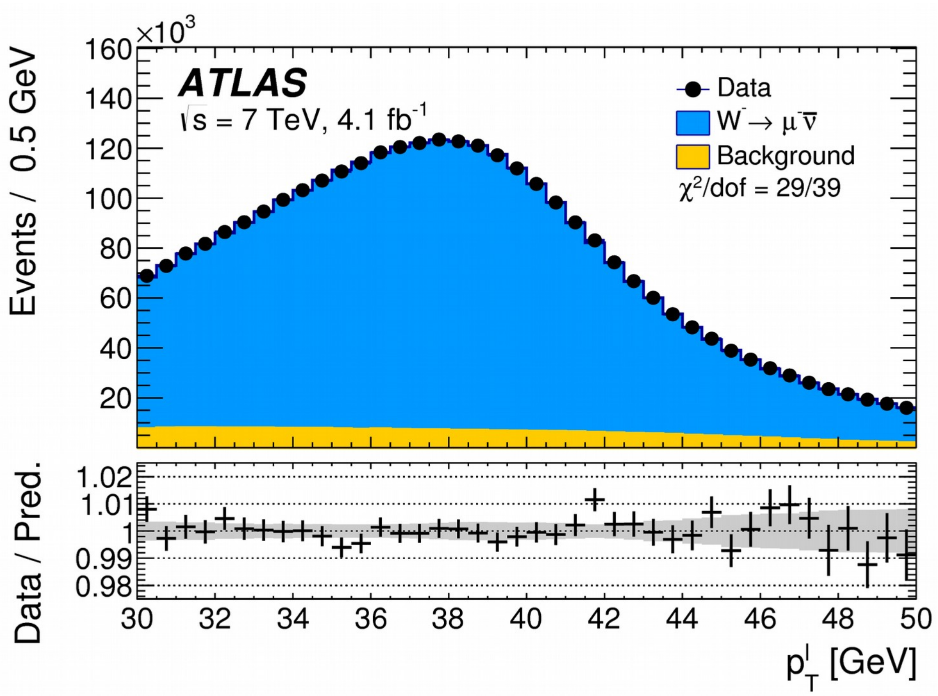


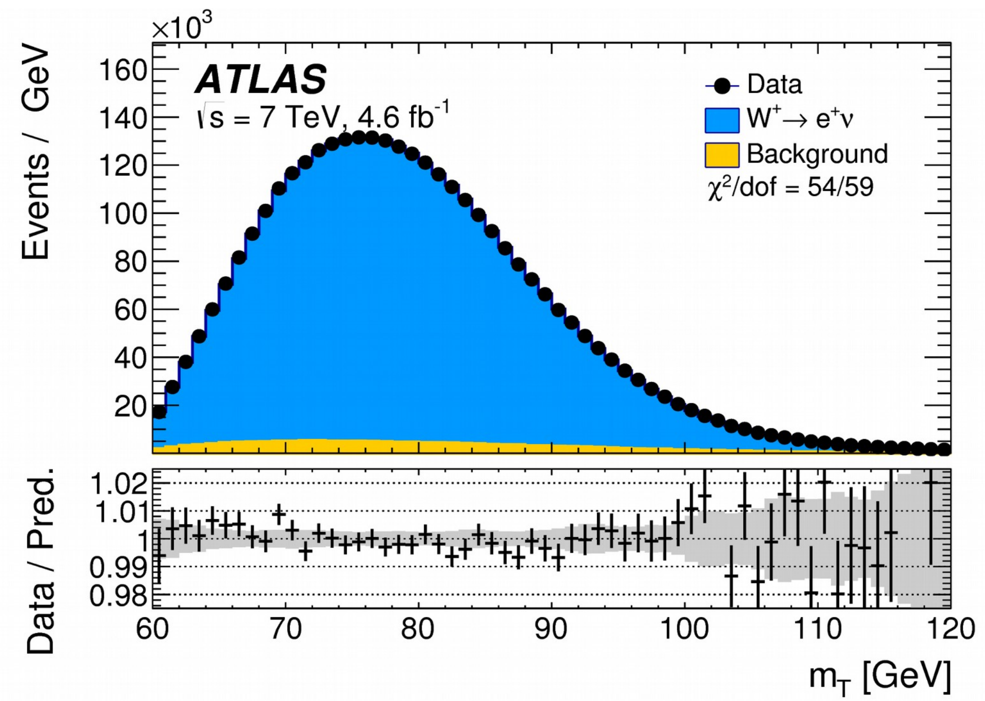
Y(Z) dependence vs quark flavor

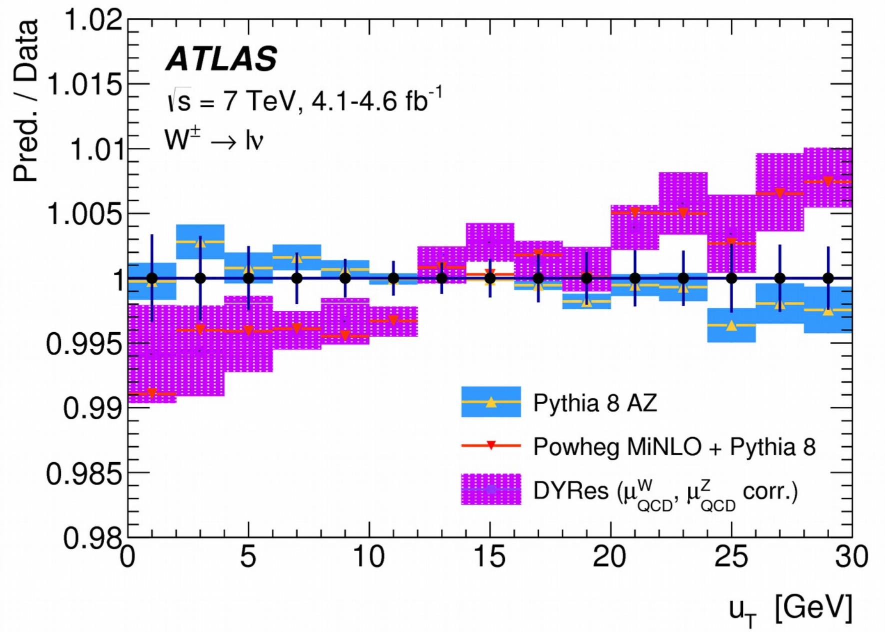


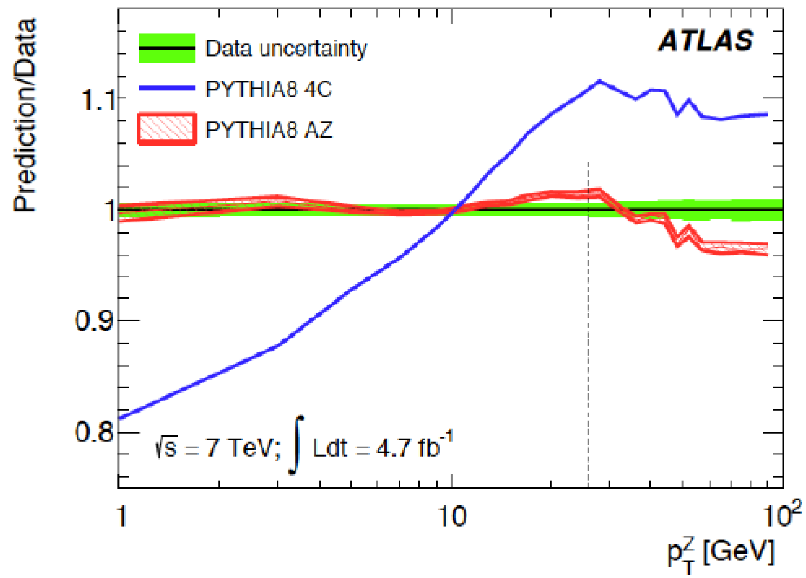
HF-quark couplings vs W-p_T

W-mass Details

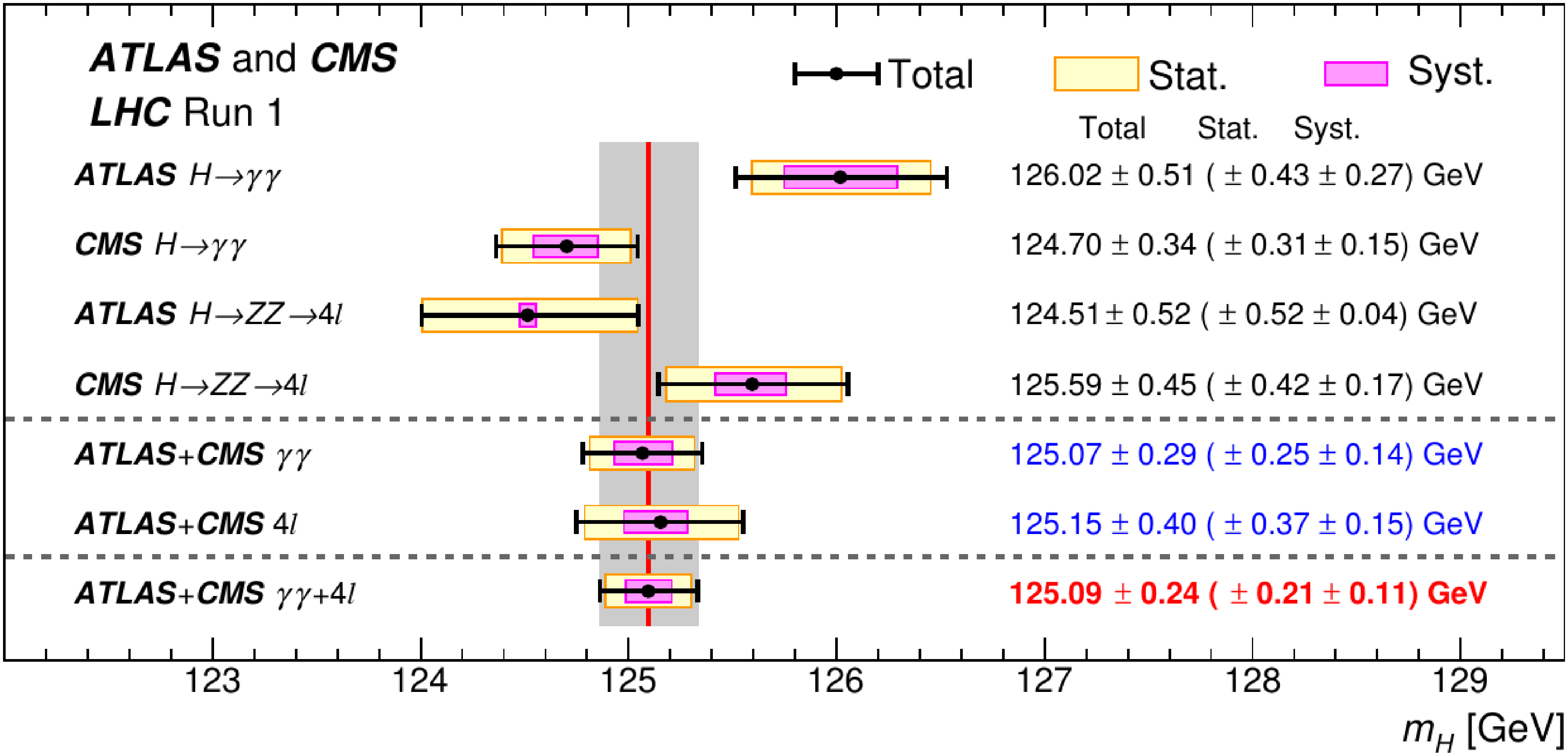






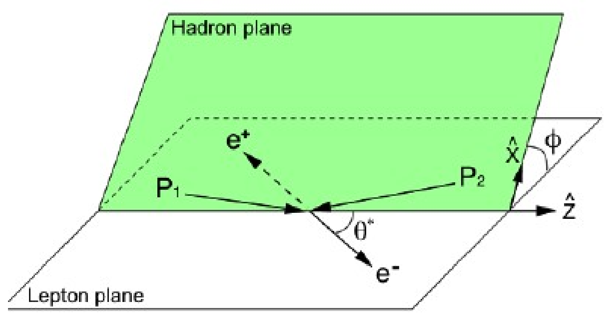


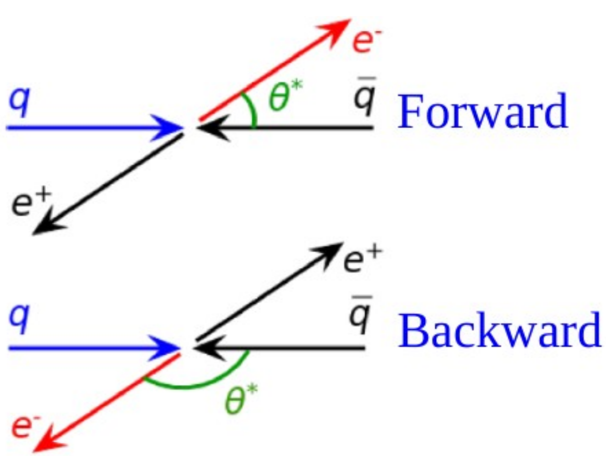
Run 1 Higgs Mass

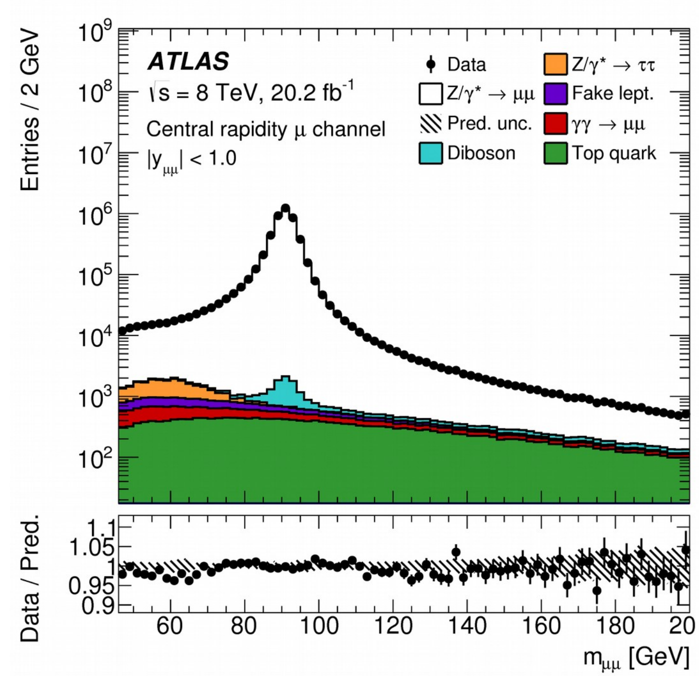


Z3D Details

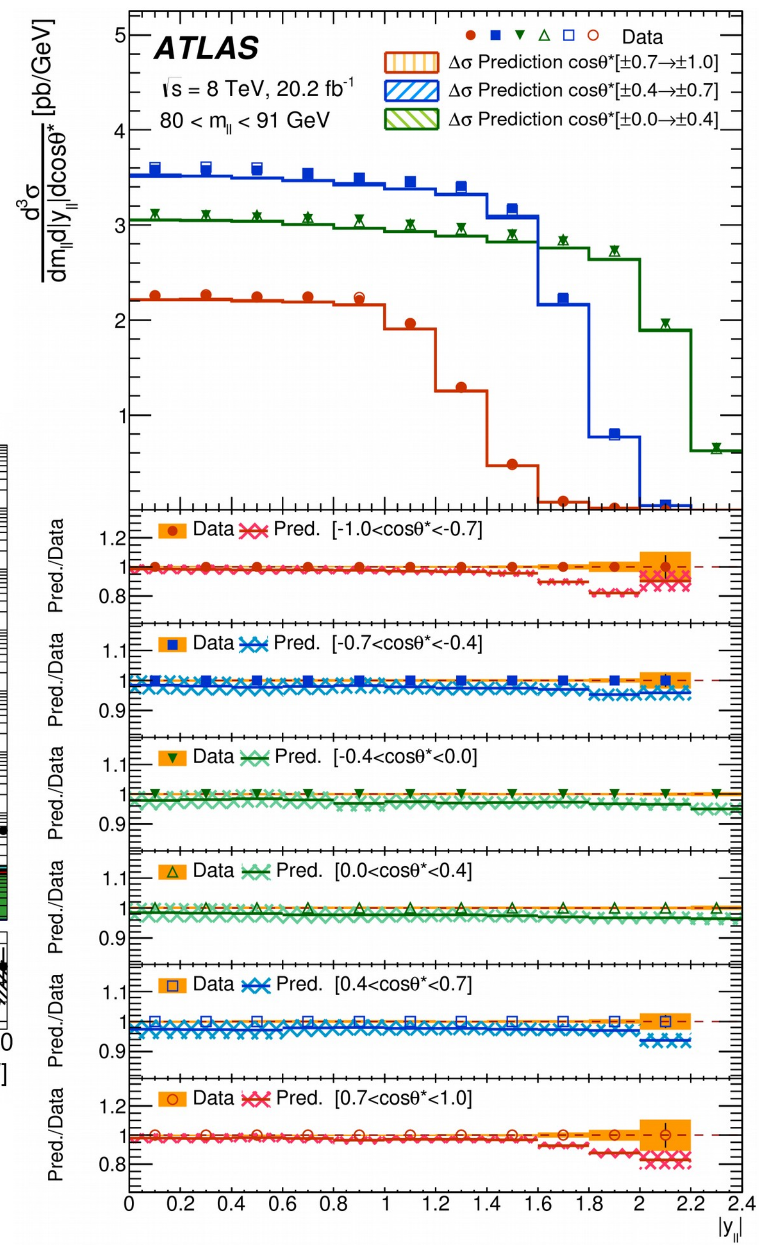
- Collin-sopper frame: decay angle measured from an axis symmetric with respect to the two incoming partons
- avoids potential ambiguity in the case that one or both partons have non-zero transverse momentum in the lab frame.







Less asymmetry on peak



Weinberg Angle

$$\sin^2\theta_W = \frac{g'^2}{g^2+g'^2} = 1 - \frac{M_W^2}{M_Z^2}$$

$$\sin^2\theta_{\text{eff}}^{\ell} \equiv \frac{1}{4}\left(1 - \frac{v_\ell}{a_\ell}\right)$$