Electroweak and Higgs

experiments

a selection of results

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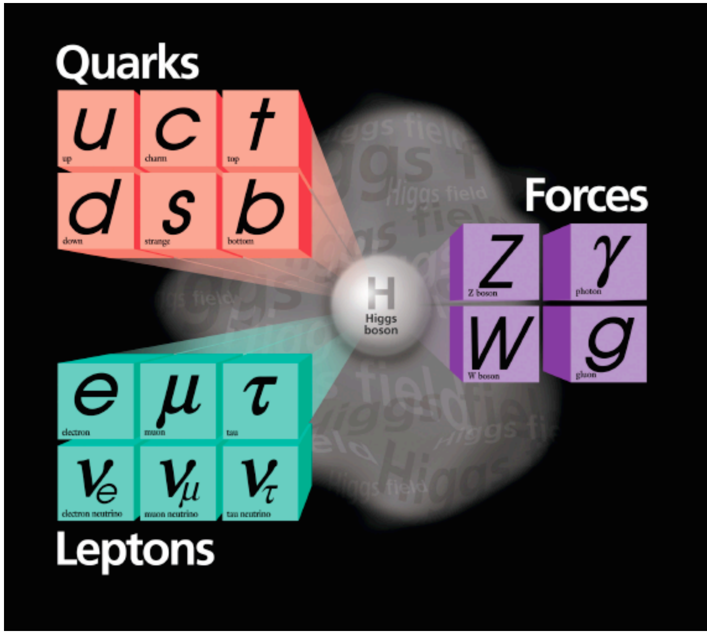
Bari - June 3st, 2019

Outline

LHC results after the end of Run2 @ $\sqrt{s}$ = 13 TeV

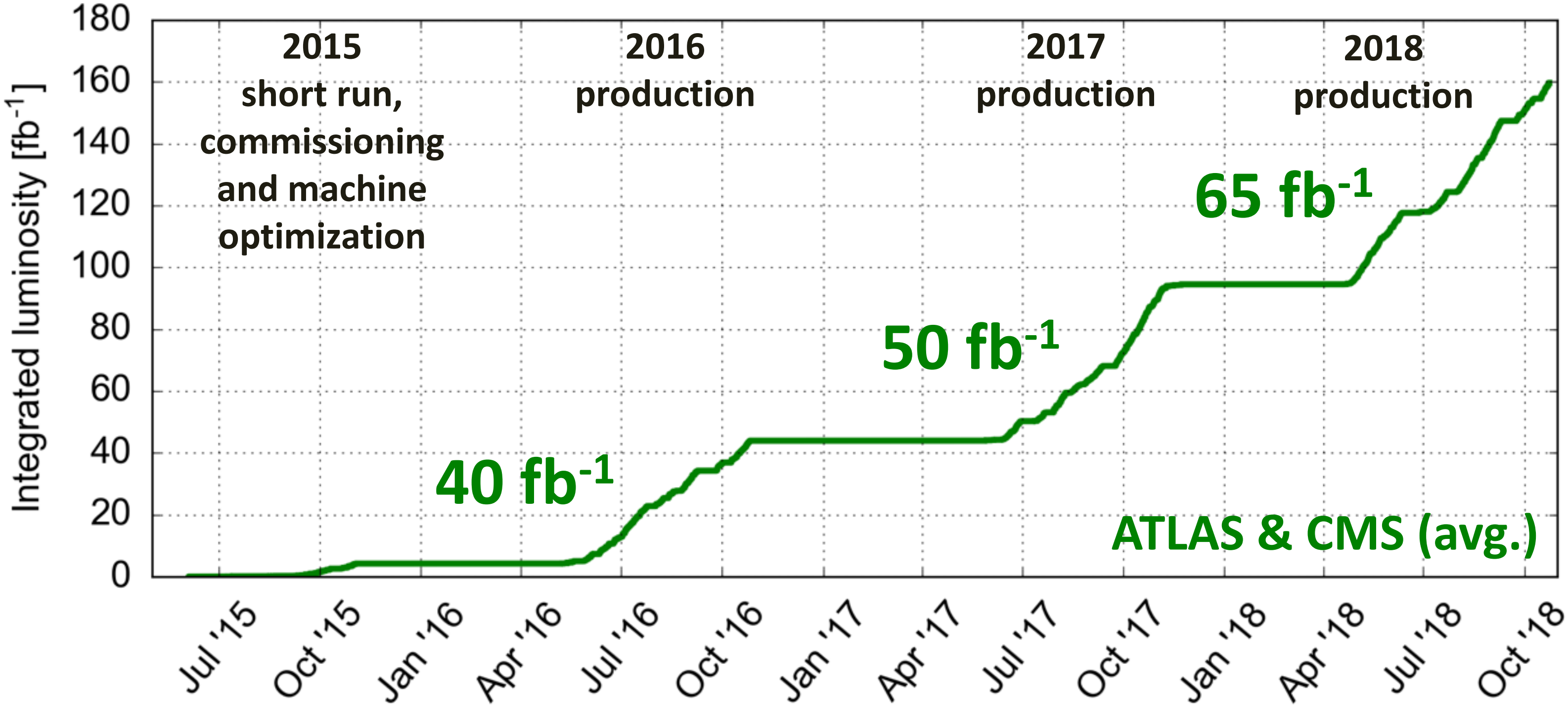
- ✓ LHC and experiments: ATLAS and CMS
- ✓ Electroweak measurements
- ✓ Higgs physics
- ✓ Future prospects



Conclusions and outlook for Run3 and HL-LHC

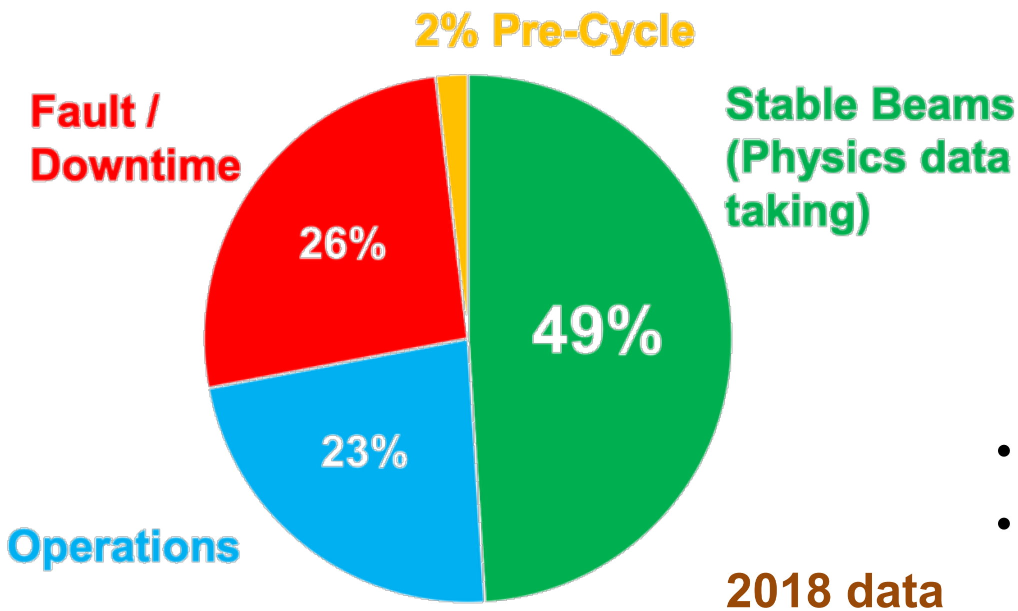
LHC @ 13 TeV

- **In Run 2 (2015-18) the LHC set important milestones:**
  - Demonstrated reliable operation with **6.5 TeV beams**
  - Exploited **25 ns** bunch spacing to operate with **>2500 bunches**
  - Reached **design luminosity** $\mathcal{L}_{IP1/5} = 10^{34}$ cm^{-2}s^{-1} … **and doubled it!**
  - Delivered **160 fb^{-1} to ATLAS and CMS, 6.7 fb^{-1} to LHCb** and **33 pb^{-1} to ALICE**



total 160 fb^{-1}

LHC operations @ 13 TeV



Efficiency similar to CERN LEP (1990-2000) in spite of more complex machine, larger stored beam energy, etc.

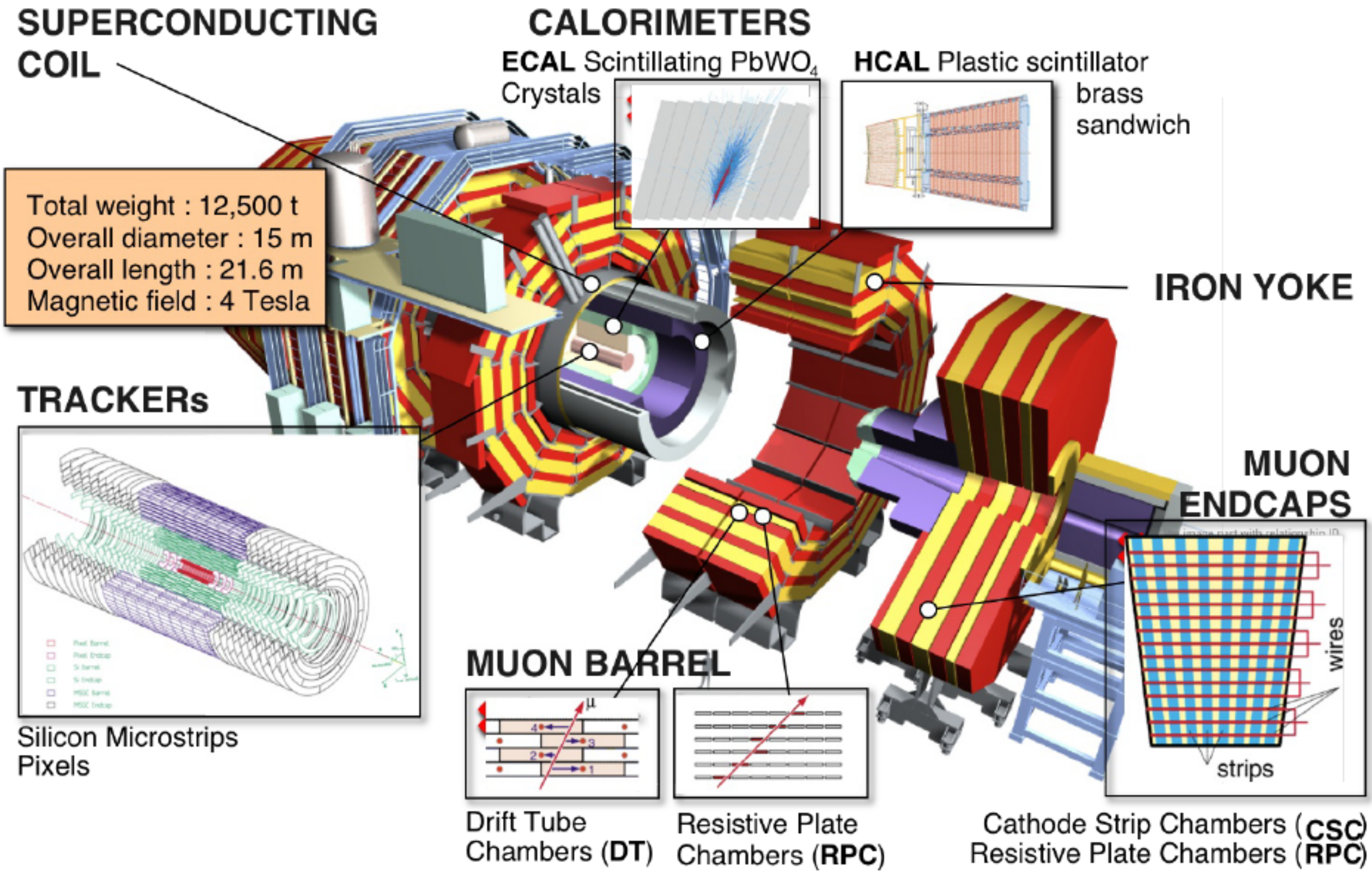
- **Robust machine configuration**
- Efficient and optimized **operational procedures and tools**

→ **Exploited to push the luminosity**

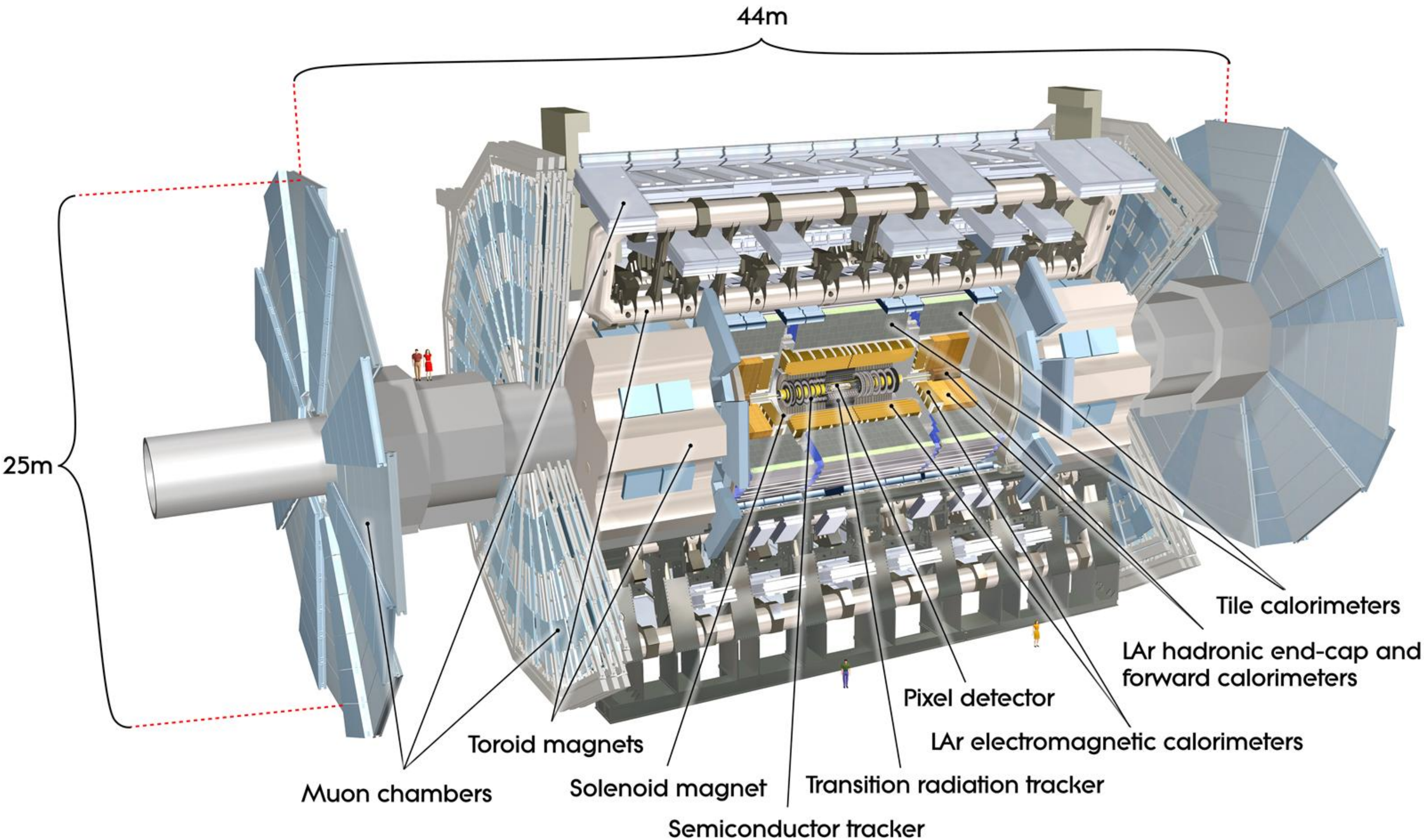
- Stronger focusing at the interaction points: **β* down to 30 cm** (design was 55 cm)
- Usage of **high-brightness beams** from the injectors (BCMS)
- Operational usage **luminosity leveling** (separation, crossing angle and β* - down to 25 cm!)

→ **Luminosity leveling** in ATLAS and CMS routinely used in operation during 2018

Sketch of the CMS detector



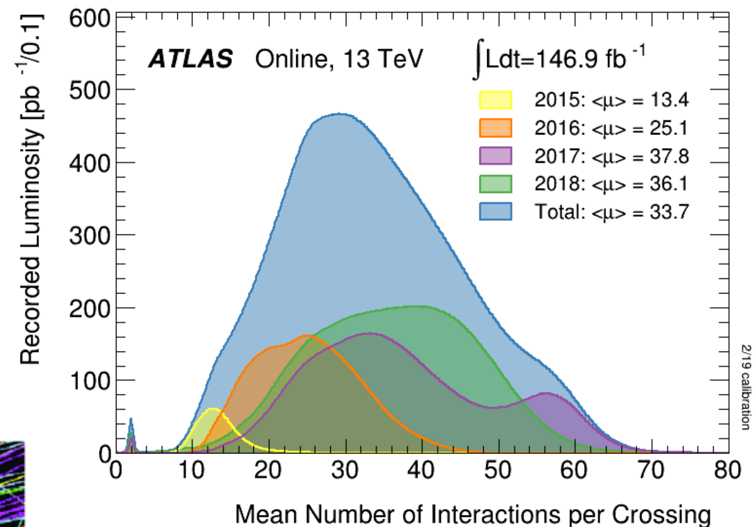
Sketch of the ATLAS detector



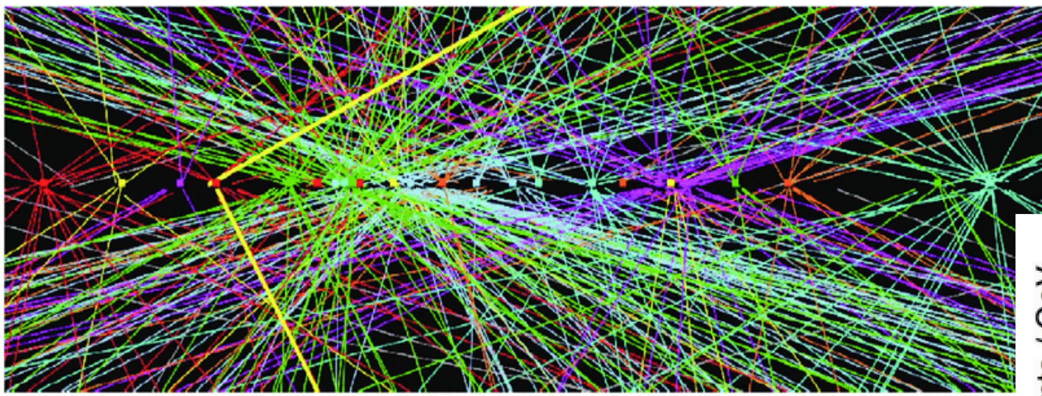
Pile-up - trigger

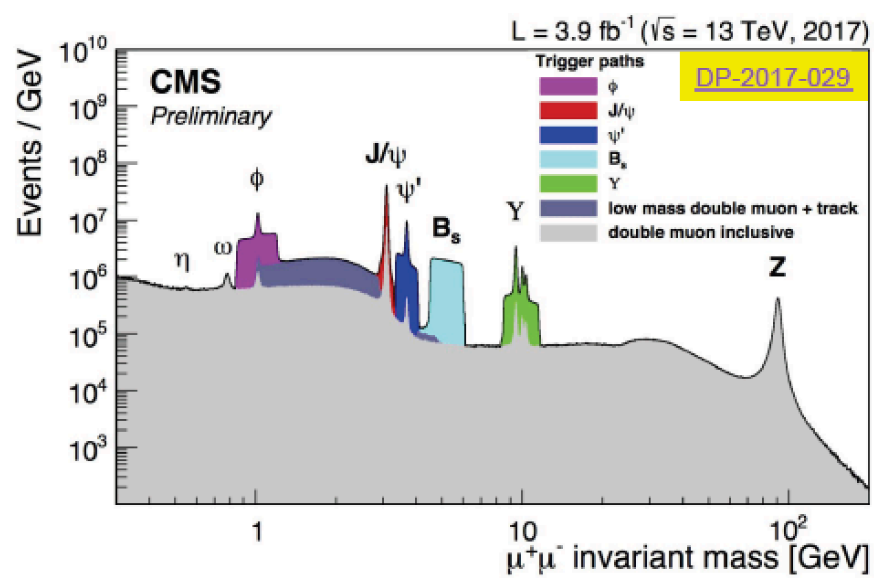
- Total inelastic pp cross section ~80 mb
- Multiple events overlap with the main hard interaction and several vertices are reconstructed in the detectors
- Maximum pileup of ~60 events until now

PU distribution in Run 2



Run 1 event with ~20 pileup vertices





- Mitigation measures adopted to reduce the effect of PU on the measurement of the main interaction

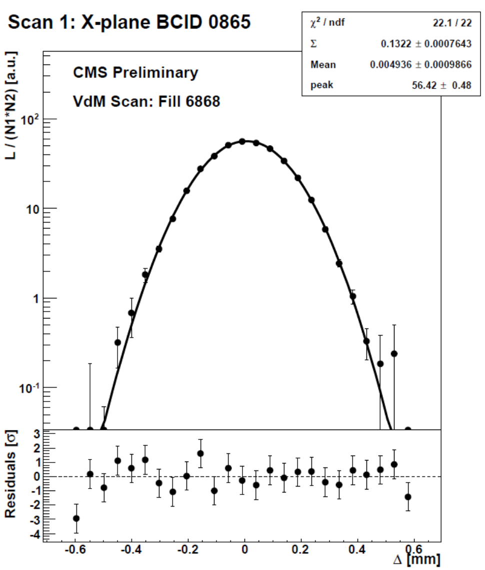
Luminosity measurement

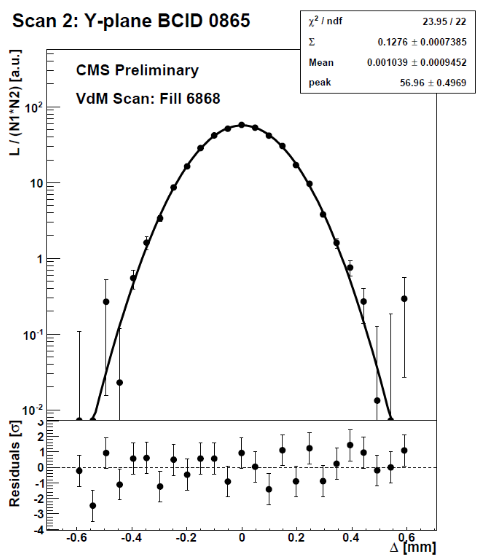
- The luminosity enters all cross section measurements and its uncertainty is in some cases the dominant uncertainty
- ATLAS and CMS relies on different detectors
- Calibration of luminometers is carried out with VdM scans
- Beams are separated by the LHC in known steps

$$N_{events} = \sigma \int \mathcal{L}\, dt$$

CMS-PAS-LUM-18-002

2018 data taking



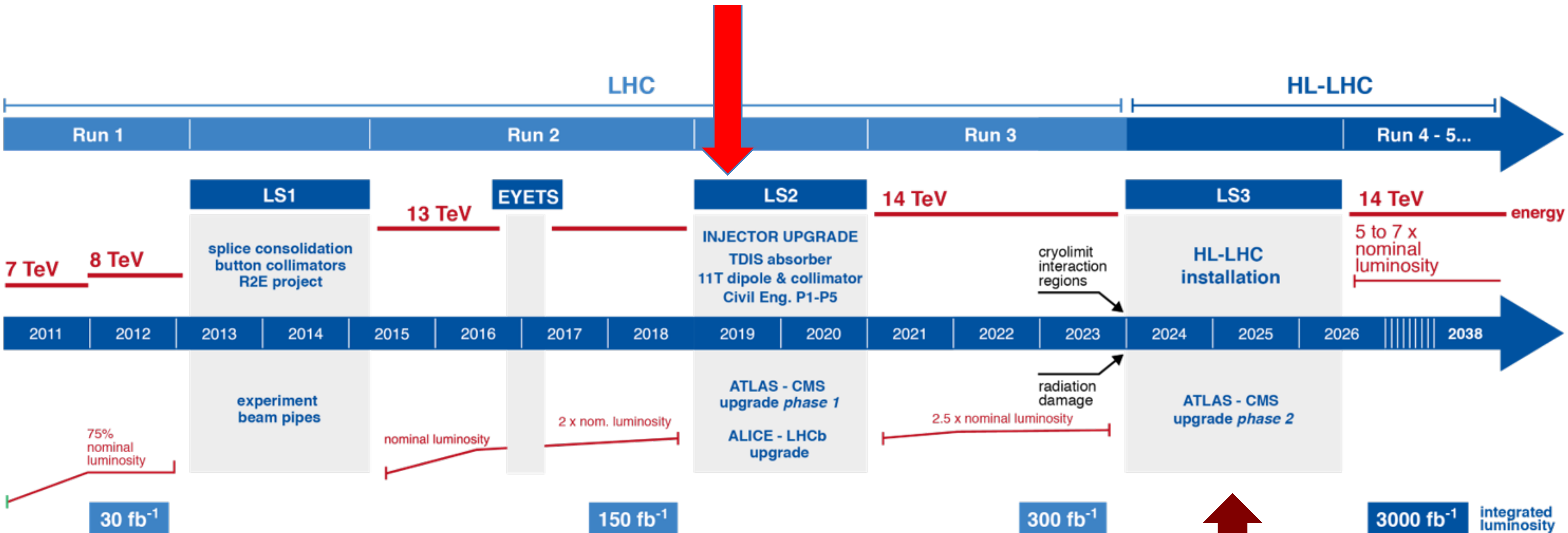


	Systematic	Correction (%)	Uncertainty (%)
Normalization	Length scale	−0.8	0.2
	Orbit drift	0.2	0.1
	x-y nonfactorization	0.0	2.0
	Beam-beam deflection	1.5	0.2
	Dynamic-β^*	−0.5	
	Beam current calibration	2.3	0.2
	Ghosts and satellites	0.4	0.1
	Scan to scan variation	—	0.3
	Bunch to bunch variation	—	0.1
	Cross-detector consistency	—	0.5
	Background subtraction	0 to 0.8	0.1
Integration	Afterglow (HFOC)	0 to 4	$0.1 \oplus 0.4$
	Cross-detector stability	—	0.6
	Linearity	—	1.1
	CMS deadtime	—	<0.1
	Total		2.5

- Normalization: uncertainties from luminosity calibration in the VdM scan procedure: 2.1%
- Integration: uncertainties from the detector operations
- **Total uncertainty for 2018: 2.5%**

LHC+HL-LHC schedule

We are here



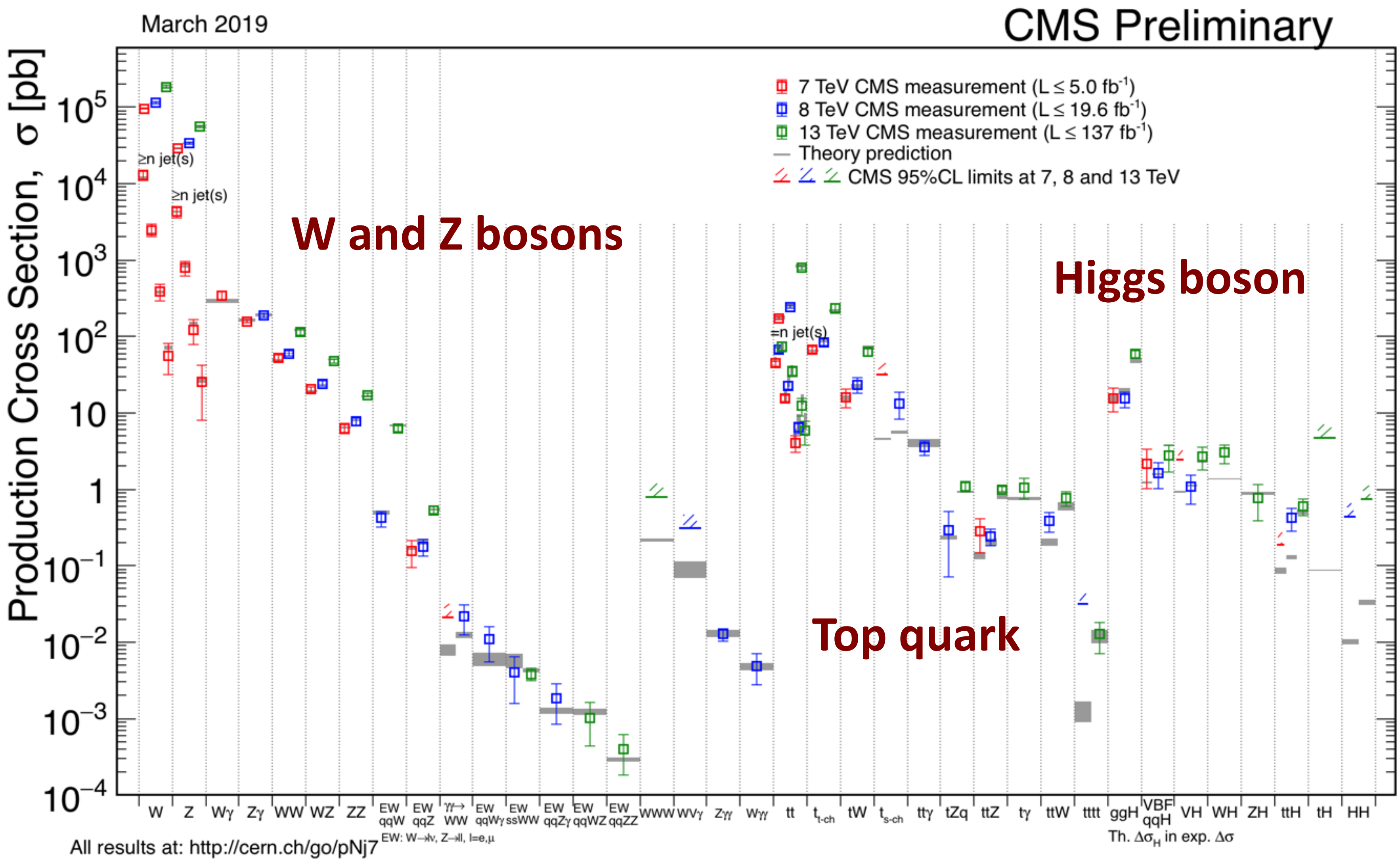
PU 55-60

PU 140-200

Approximately 5% of the total integrated luminosity collected until now

Important detector upgrades in view of HL-LHC

Cross section of SM processes

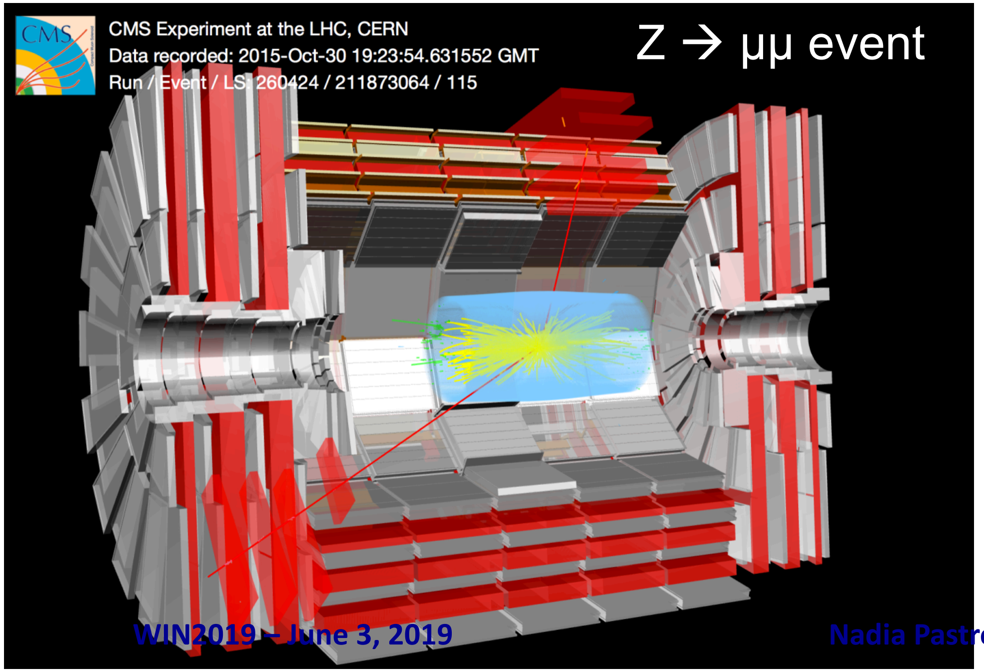


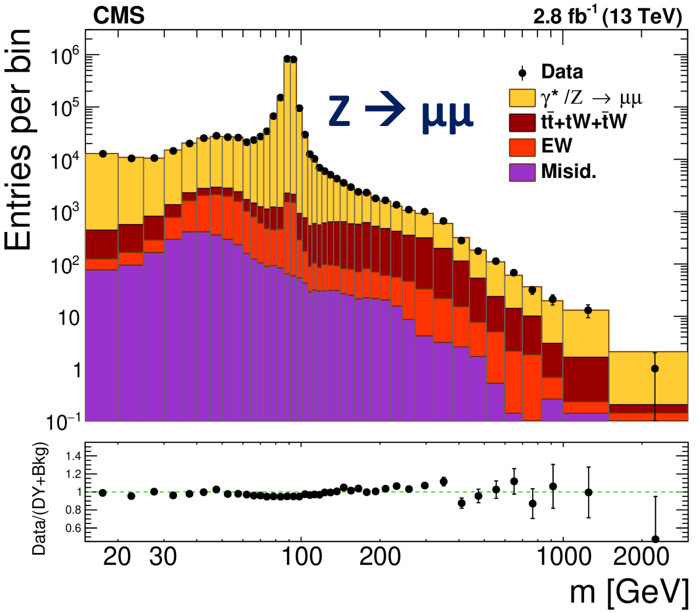
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined

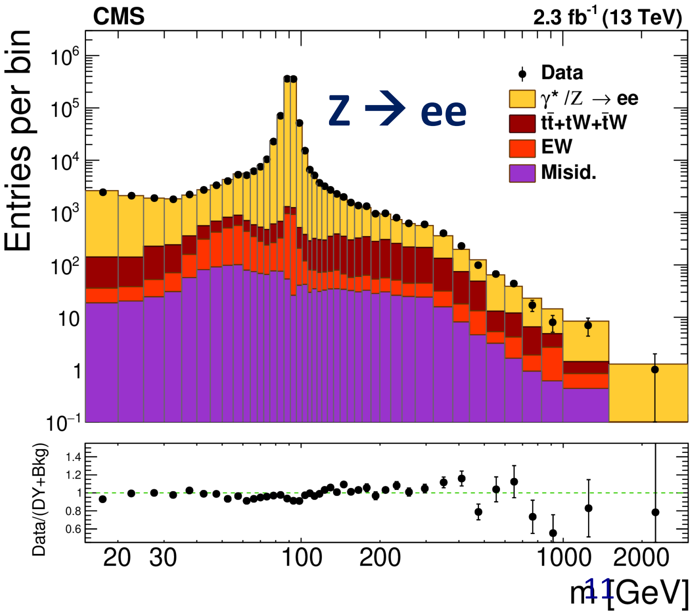
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2019-010/

Electroweak measurements

- Precision EW measurements at the LHC:
  - M_W,
  - Differential W and Z (+jets) cross sections and asymmetries and $\sin^2\vartheta_W$
  - Di-, tri-boson production and anomalous couplings
- All measurements are mainly based on Z and W production and their leptonic decays to ℓ where ℓ =e,μ
  - $Z \rightarrow \ell\ell$
  - $W \rightarrow \ell\nu$





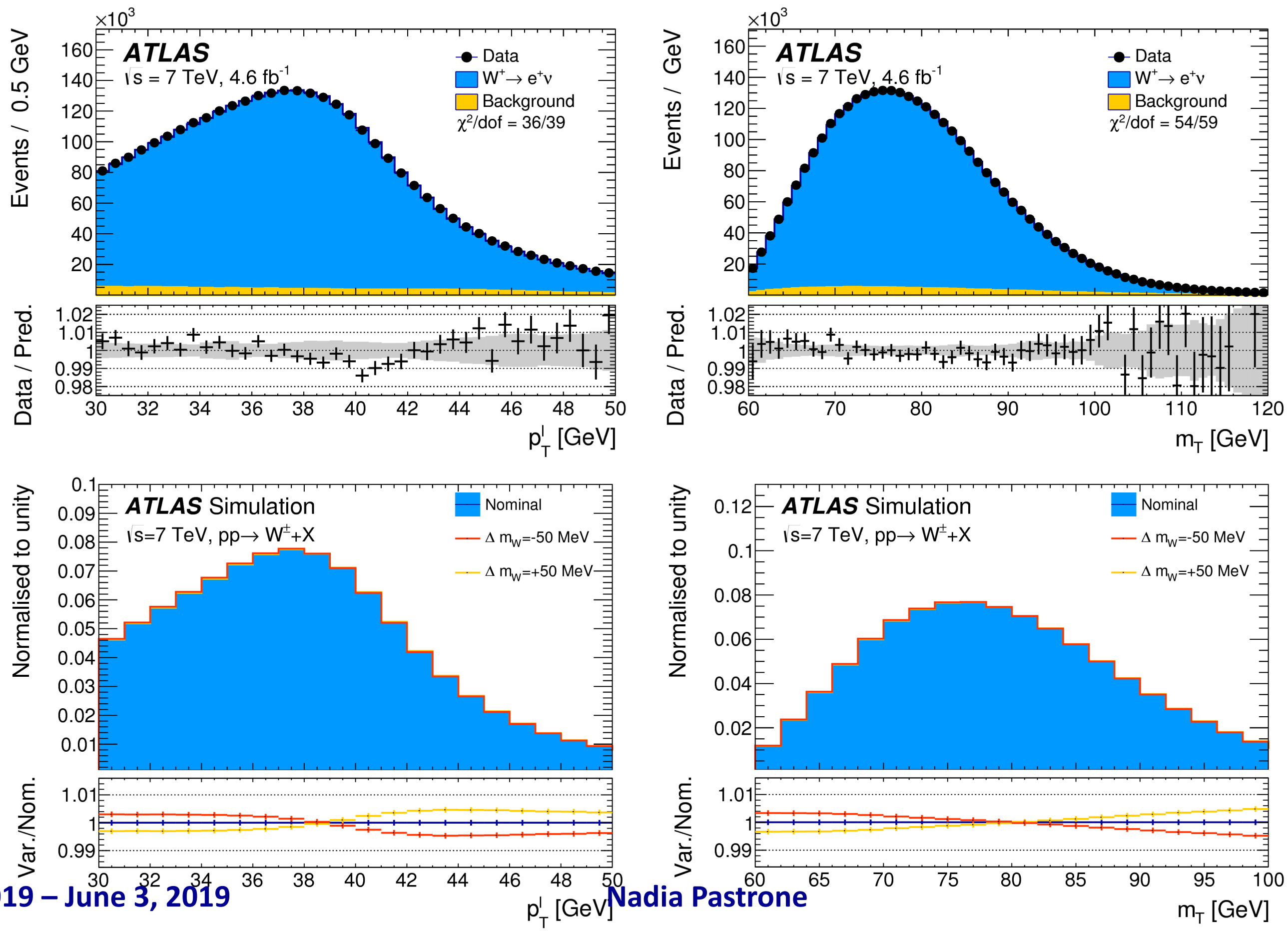


W mass

[EPJC 78 (2018) 110](https://doi.org/10.1140/epjc/s10052-017-5475-4)

pp collisions
139±2 fb^{-1} @ $\sqrt{s}$ = 13 TeV

- Need very good control of detector performance
- Understanding of theoretical modelling and related measurements e.g. p_{tW}
- Template fits are performed to the lepton p_t and transverse mass distributions



W mass

EPJC 78 (2018) 110

pp collisions
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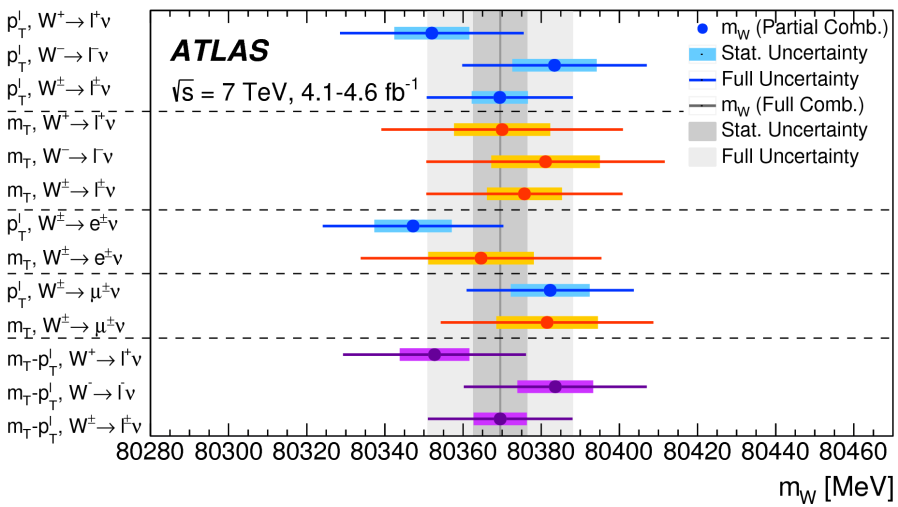
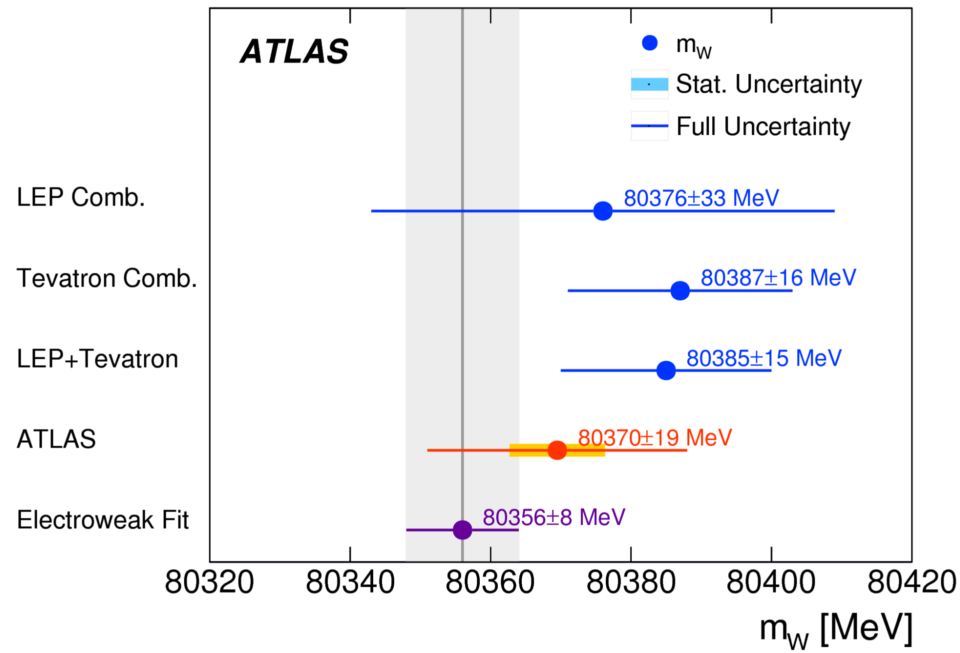


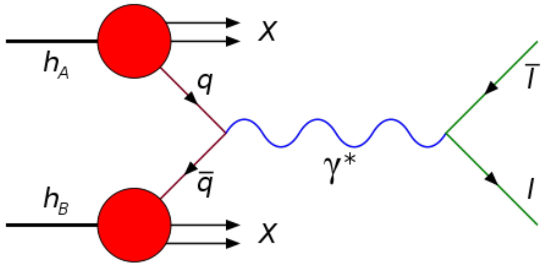


$$m_W = 80370 \pm 19 \text{ MeV} = 80370 \pm 7 \text{ (stat.)} \pm 11 \text{ (exp. syst.)} \pm 14 \text{ (mod. syst.) MeV}$$

$\sin^2\vartheta_W$ measurement

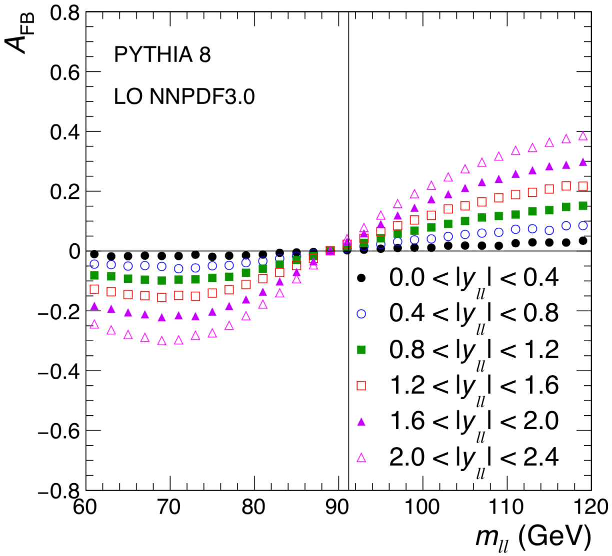
- Forward-backward (FB) asymmetry in Drell Yan process using Z → μμ and Z → ee @ 8 TeV:

$$A_{\rm FB} = \frac{\sigma_{\rm F} - \sigma_{\rm B}}{\sigma_{\rm F} + \sigma_{\rm B}}$$



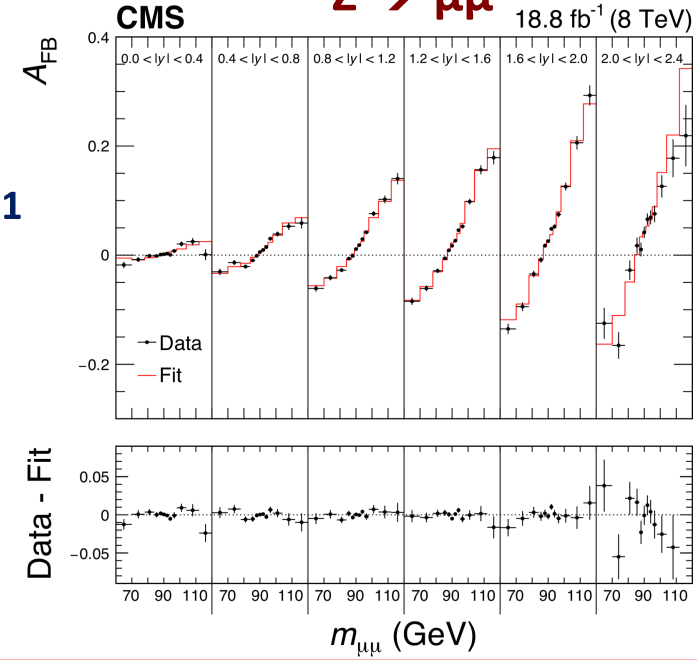
➔ FB asymmetry related to interference of vector and axial currents and sensitive to $\sin^2\vartheta_W$ though the axial and vector components of the lepton couplings

Diluted A_{FB} at different rapidity Y



EPJC 78 (2018) 701

Z → μμ



$\sin^2\vartheta_{eff}$ = 0.23101 ± 0.00053 (0.00036 (stat) ± 0.00018 (syst) ± 0.00016 (th) ± 0.00031 (PDF)

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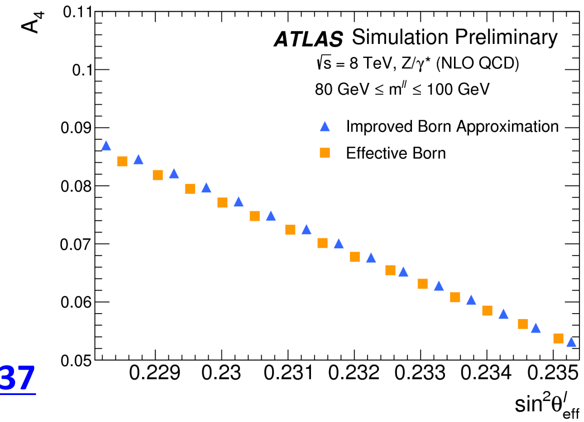
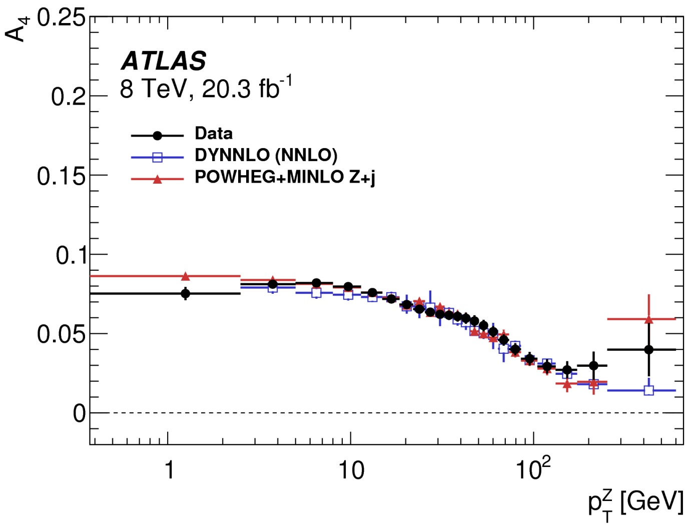
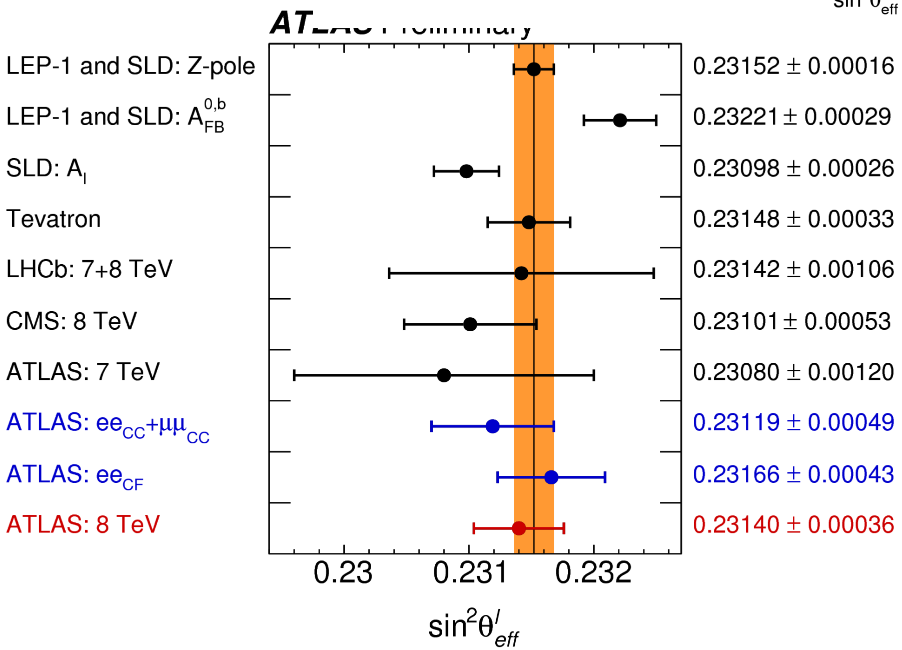
$\sin^2\vartheta_W$ measurement

- ATLAS measures all the Z boson decay angular coefficients, A_0 to A_7 with $Z \rightarrow \mu\mu$ and Z->ee (both central and one central, one forward)
- A_4 originates from the Z axial and vector currents and is sensitive to $\sin^2\vartheta_W$





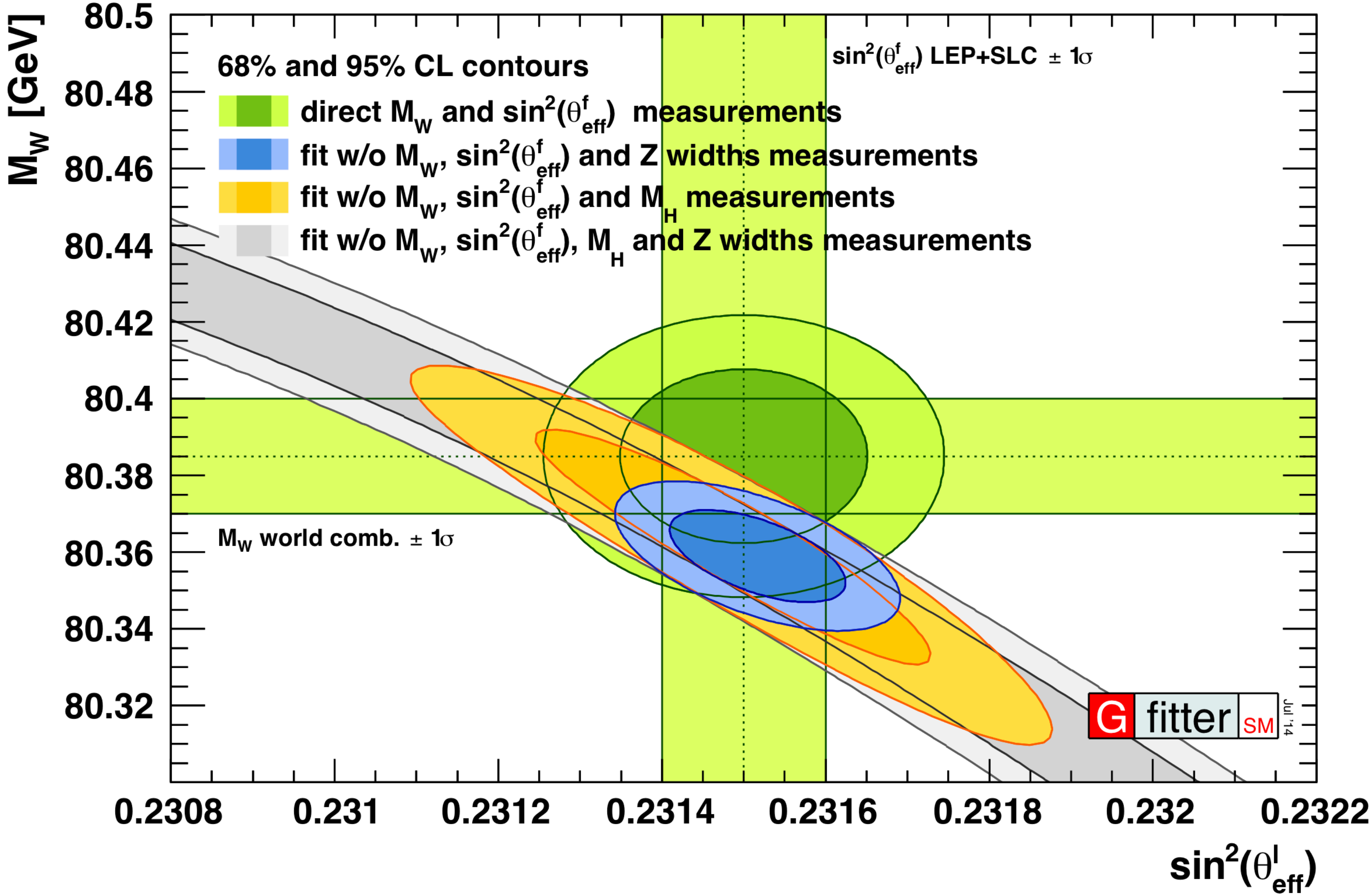
ATLAS-CONF-2018-037



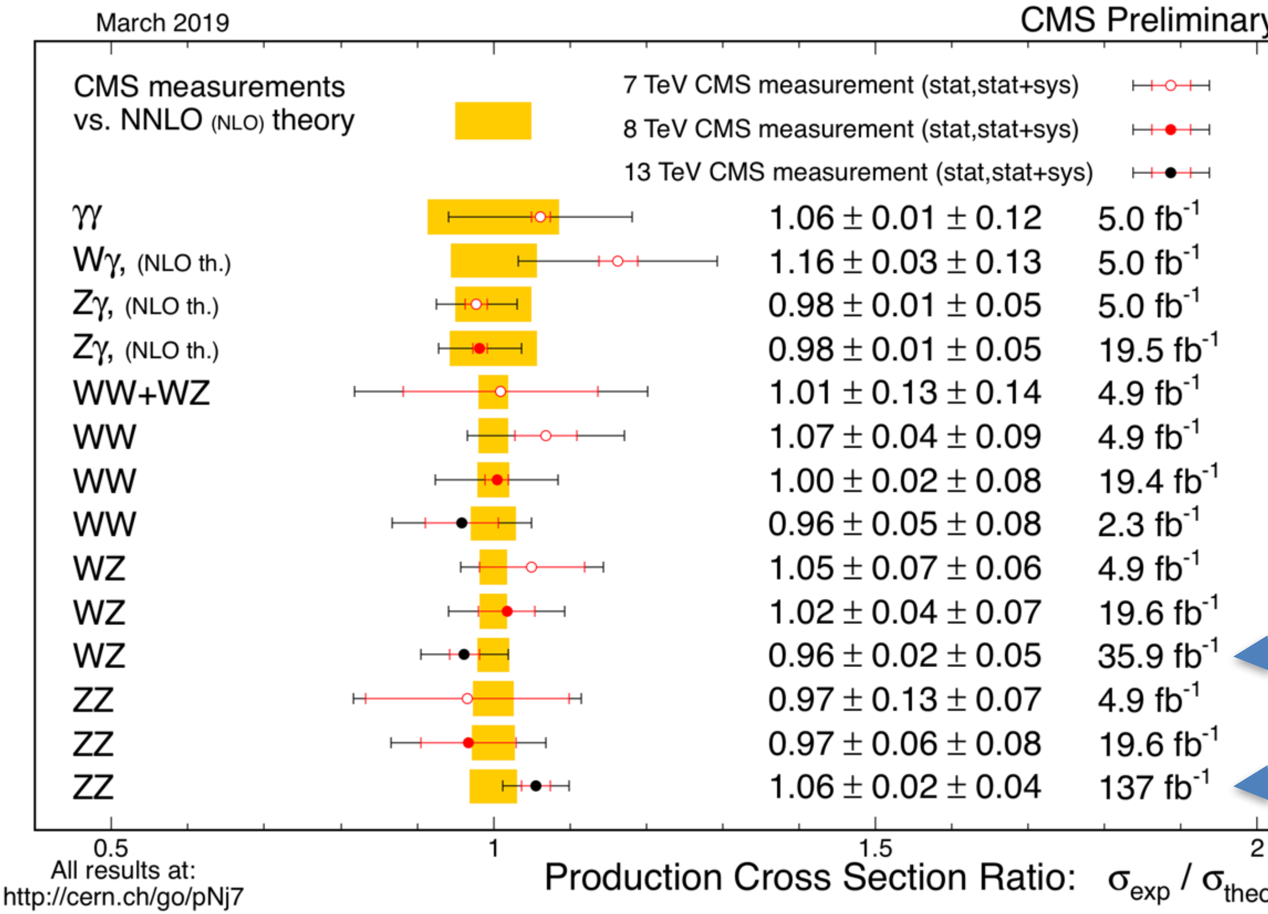
Expect to reach a precision of ~0.00015 or better at HL-LHC

$$\sin^2\vartheta_W = 0.23140 \pm 0.00021\ (\text{stat.}) \pm 0.00024\ (\text{PDF}) \pm 0.00016\ (\text{syst.})$$

M_W vs $\sin^2\vartheta_{eff}^{lept}$



Di-boson: cross section ratio to theory



- Dedicated analysis to reduce systematics
- High precision differential measurements

Higher statistical power @ 13 TeV ➔ no longer a limitation

Theory predictions updated to latest NNLO calculations

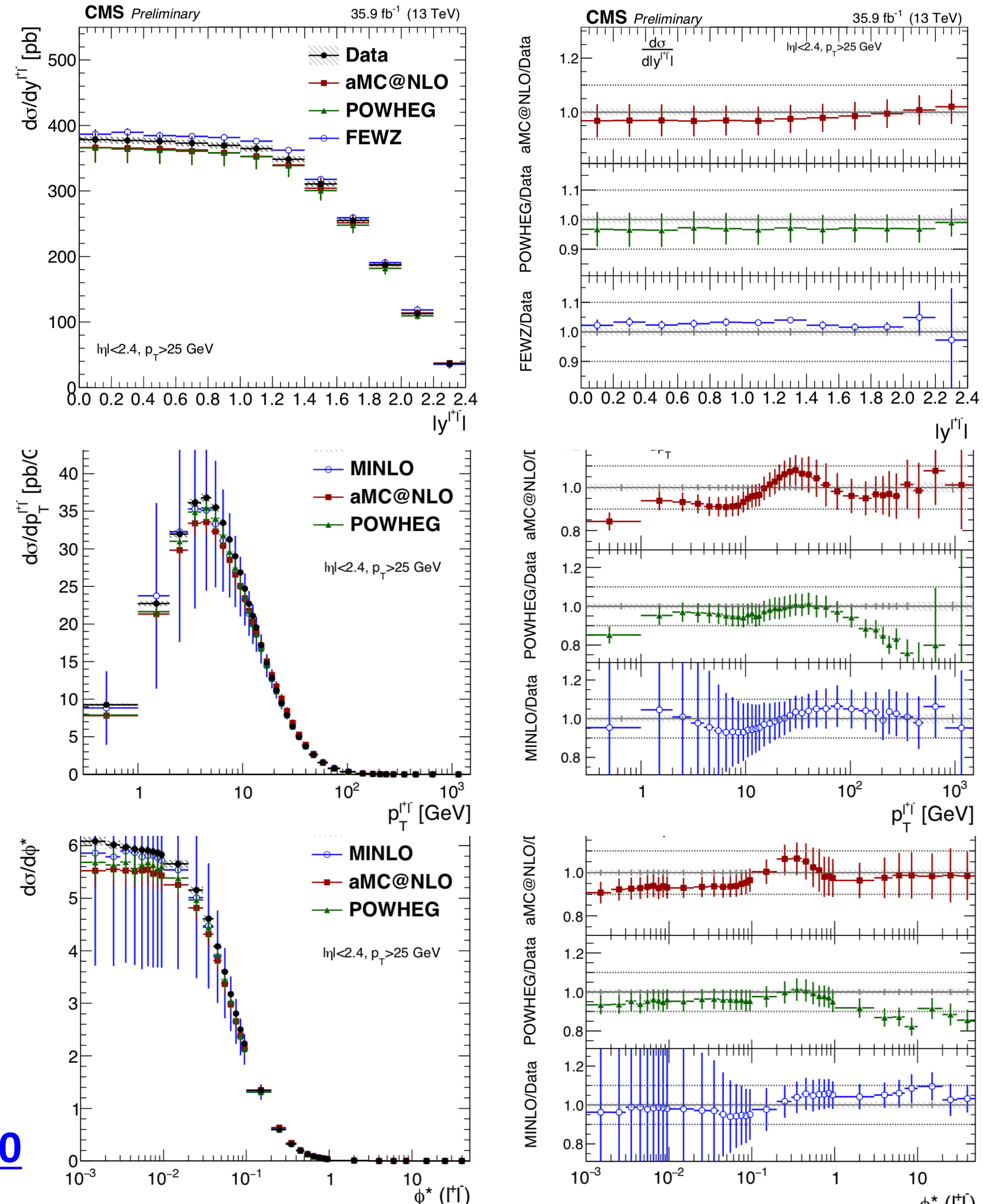
Z differential measurements

- Differential distributions of Z production with 2016 data
- Y, pT and ϕ^* of the l^+l^- system
- Compared with several MC generators
  - MINLO
  - aMC@NLO
  - POWHEG
  - FEWZ

$$\phi^* = \tan\left(\frac{\pi - \Delta\phi}{2}\right)\sin(\theta^*_\eta)$$

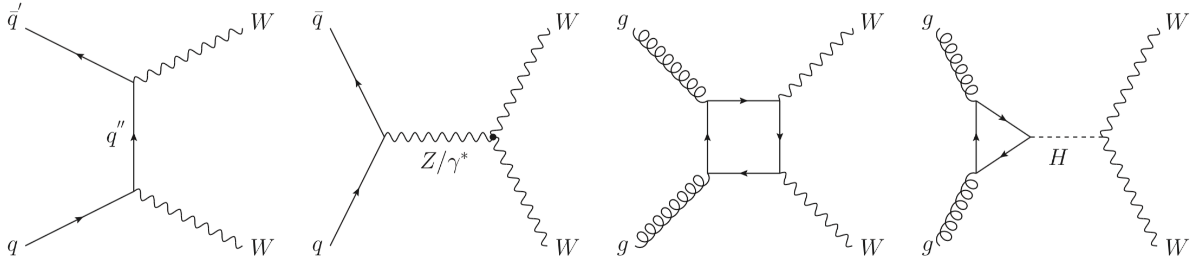
$$\cos(\theta^*_\eta) = \tanh\left(\frac{\eta^- - \eta^+}{2}\right),$$

CMS-PAS-SMP-17-010



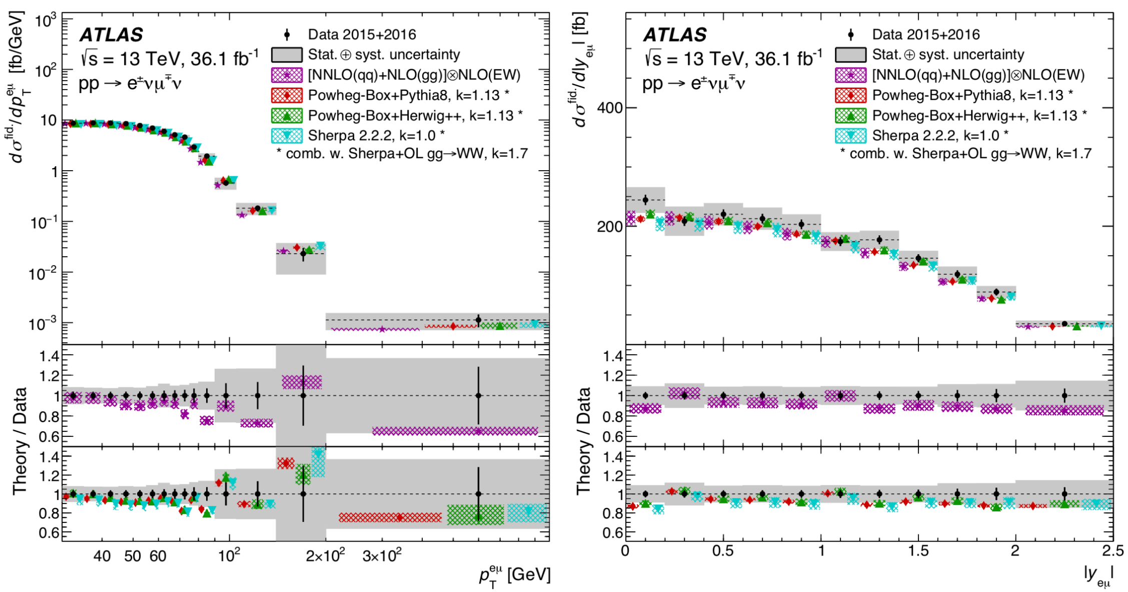
Diboson differential measurements

- From single bosons to di-bosons using WW → μνeν events:



arXiv:1905.04242

- Measure fiducial and differentia cross sections



Anomalous couplings related to dim 6 operators in EFT approach
arXiv:1205.4231

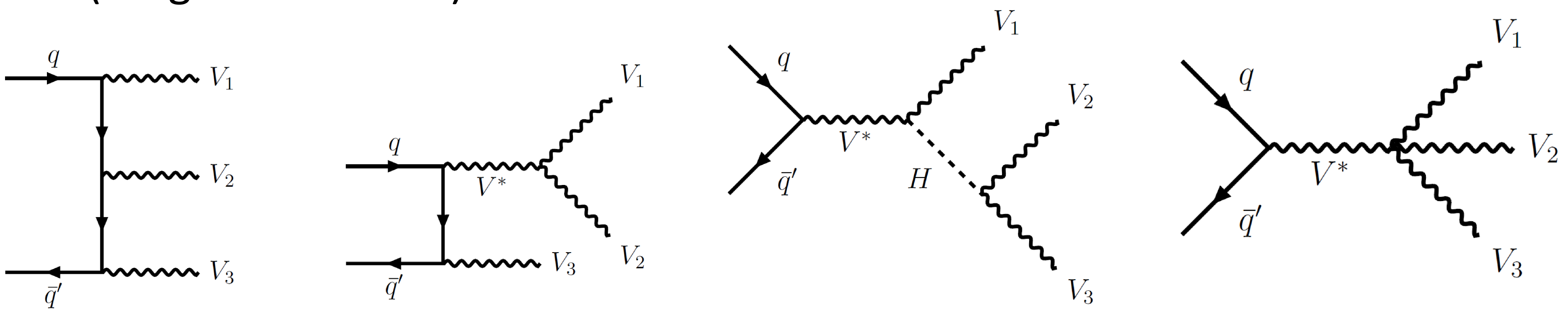
Parameter	Observed 95% CL [TeV^{-2}]
c_{WWW}/Λ^2	[−3.4 , 3.3]
c_W/Λ^2	[−7.4 , 4.1]
c_B/Λ^2	[−21 , 18]
$c_{\tilde{W}WW}/\Lambda^2$	[−1.6 , 1.6]
$c_{\tilde{W}}/\Lambda^2$	[−76 , 76]

All measurements in agreement with SM ➔ limits on anomalous couplings derived

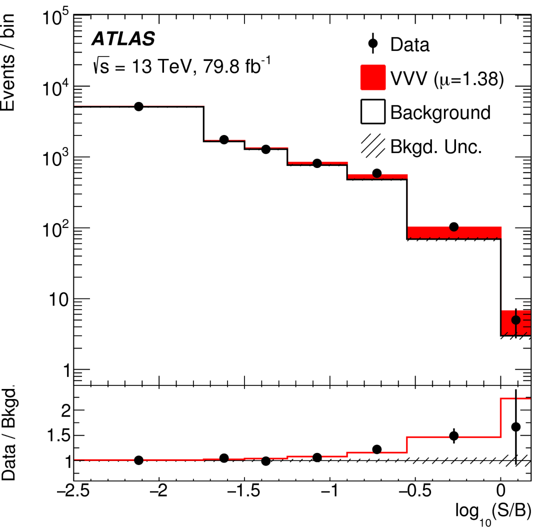
... and tri-bosons

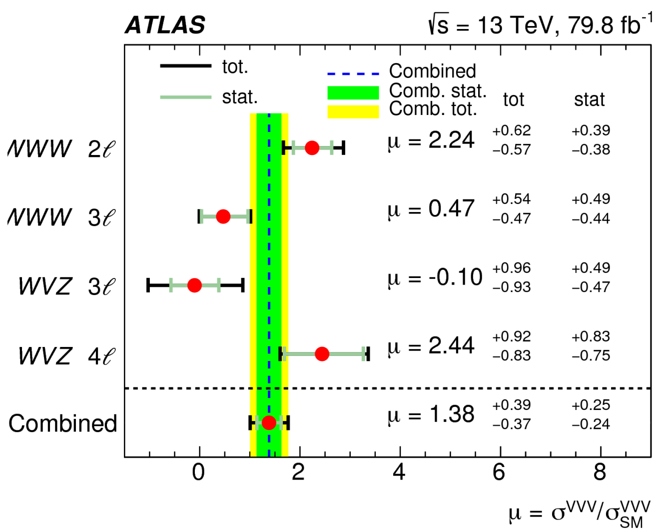
arXiv:1903.10415

- ATLAS, using 80 fb^{-1} (2015-2017) sees evidence of triboson production WWW, WWZ (4 sigma observed)



- Search in several decay channels: WWW, WWZ, WZZ with leptons





Decay channel	Significance	
	Observed	Expected
WWW combined	3.3σ	2.4σ
$WWW \to \ell\nu\ell\nu qq$	4.3σ	1.7σ
$WWW \to \ell\nu\ell\nu\ell\nu$	1.0σ	2.0σ
WVZ combined	2.9σ	2.0σ
$WVZ \to \ell\nu qq\ell\ell$	–	1.0σ
$WVZ \to \ell\nu\ell\nu\ell\ell/qq\ell\ell\ell\ell$	3.5σ	1.8σ
VVV combined	4.0σ	3.1σ

Top physics

- Heaviest quark
- Very short lifetime, no top hadrons
- Top mass Yukawa coupling order 1,

large effect in the global electroweak fits

- LHC is a top factory: @ 13 TeV CM energy, ~800 pb

➔ 40M tt pairs produced per experiment in 2018

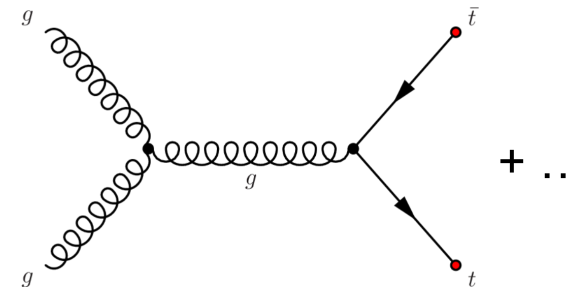
- Top decays almost always
- into a real W and a b quark
- According to W decay:
  leptonic, semileptonic
  and fully hadronic
- Very clean signature

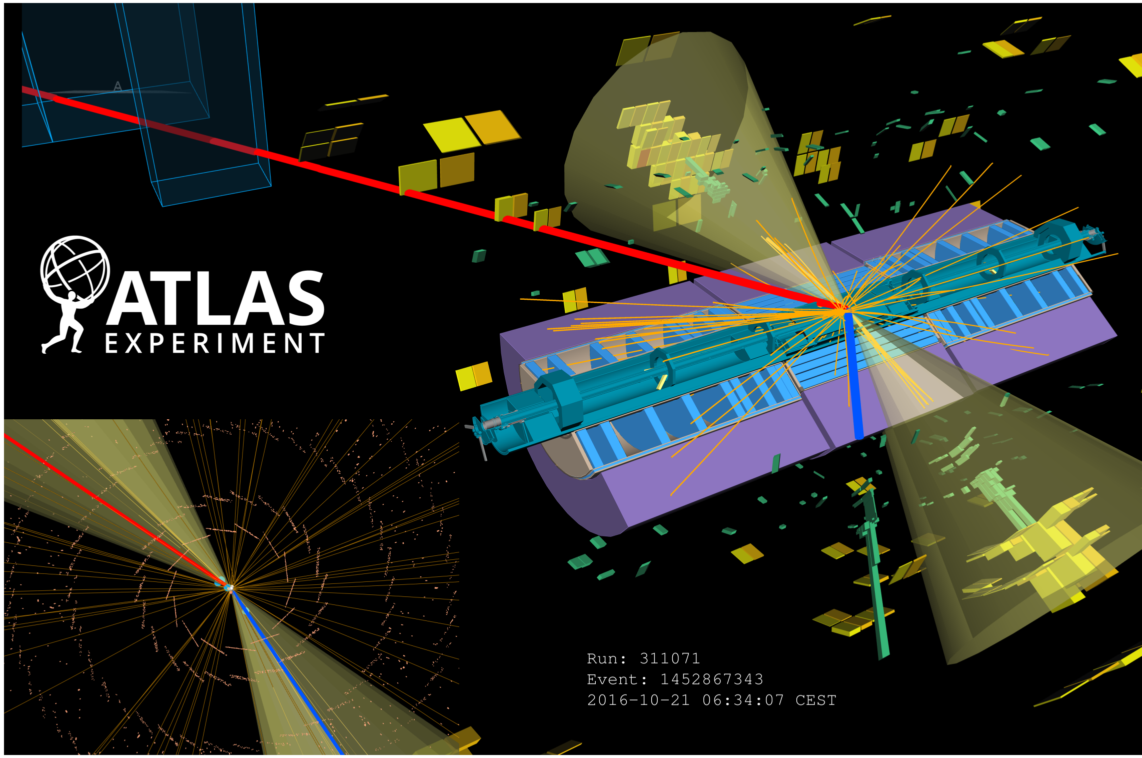
for leptonic and semi-leptonic decays,

leptons plus b-tagged jets

   – **b-tagging important**

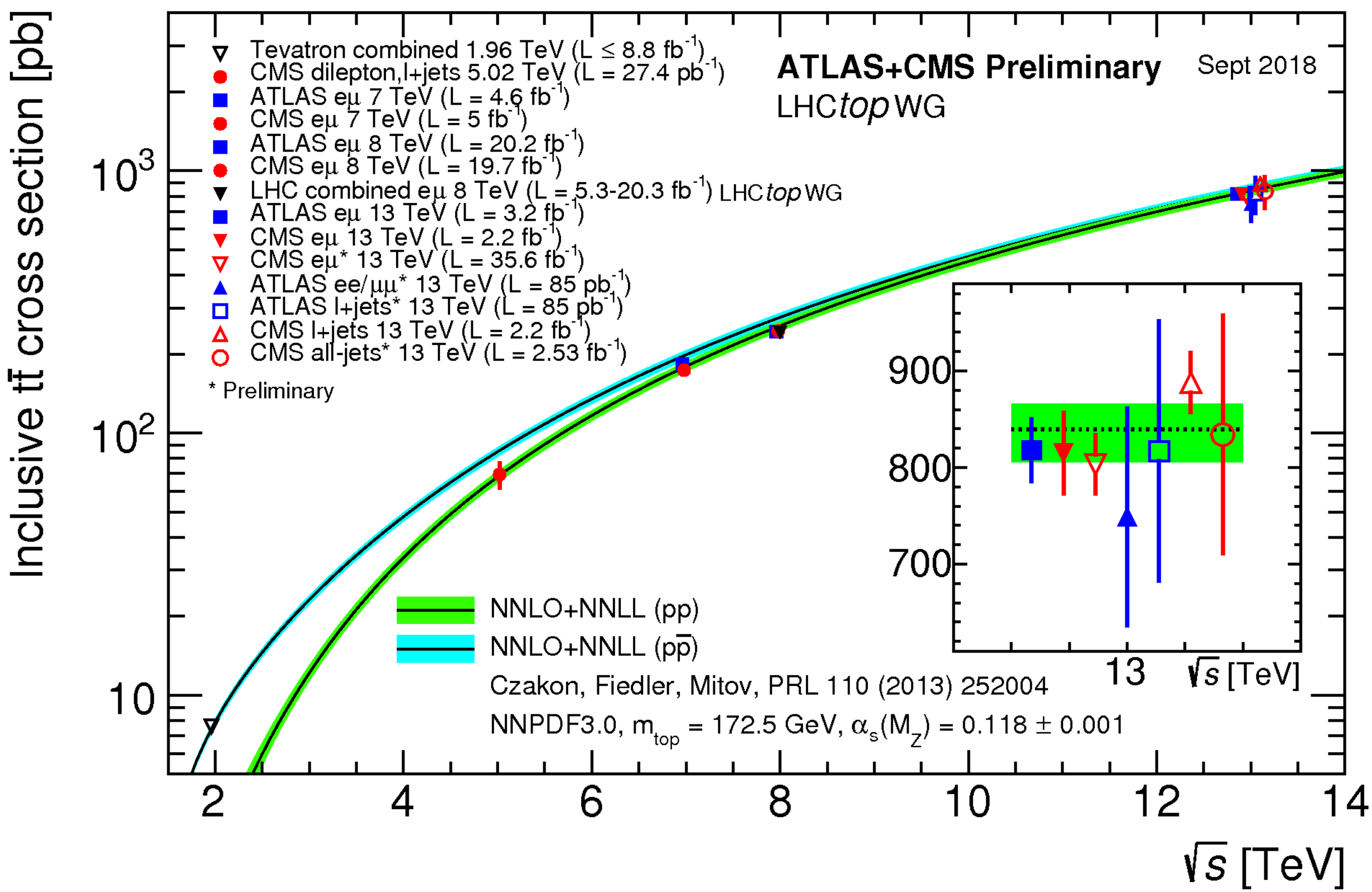
@ LHC tt is mainly produced through gg fusion:





top-pair production cross-section

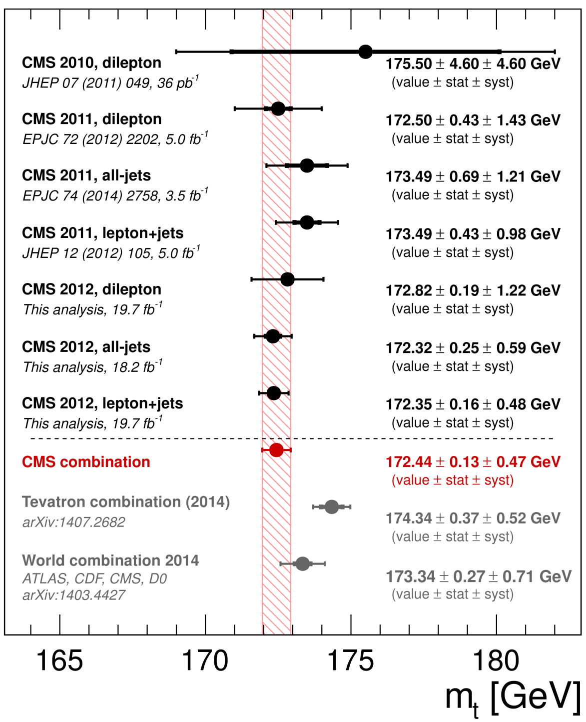
LHC + Tevatron measurements



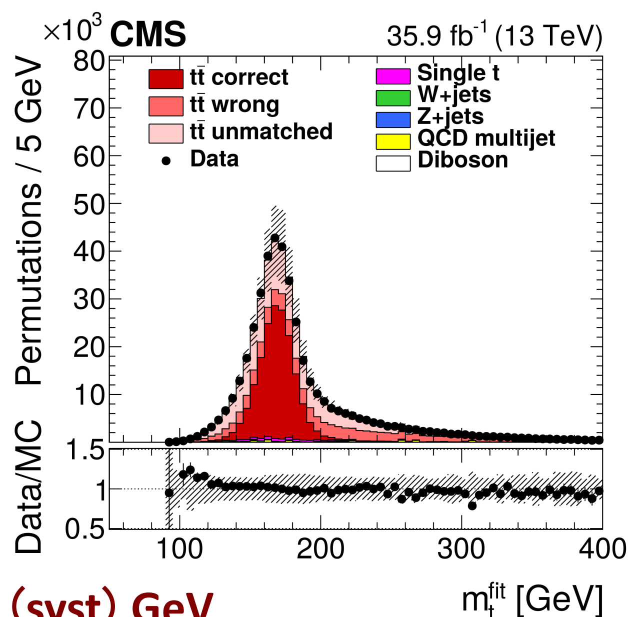
Direct top mass measurement

- Direct mass measurements (MC mass)
  - Recostruction of top decays in fully leptonic, semileptonic and fully hadronic channels

CMS Run 1 results [PRD 93 (2016) 072004]



- CMS measurement at 13 TeV
- Largest systematic uncertainties
  - Color reconnection models (more models than in Run 1)
  - Flavour jet energy response



EPJC 78 (2018) 891

EPJC 79 (2019) 313

M_{top} = 172.25 ± 0.08 (stat+JSF) ± 0.62 (syst) GeV

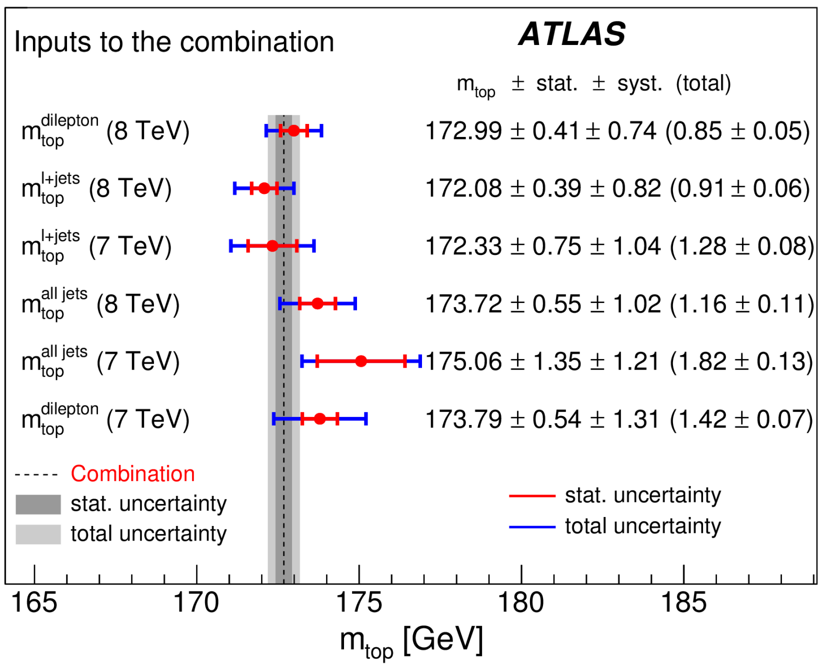
Dominated by semileptonic channel

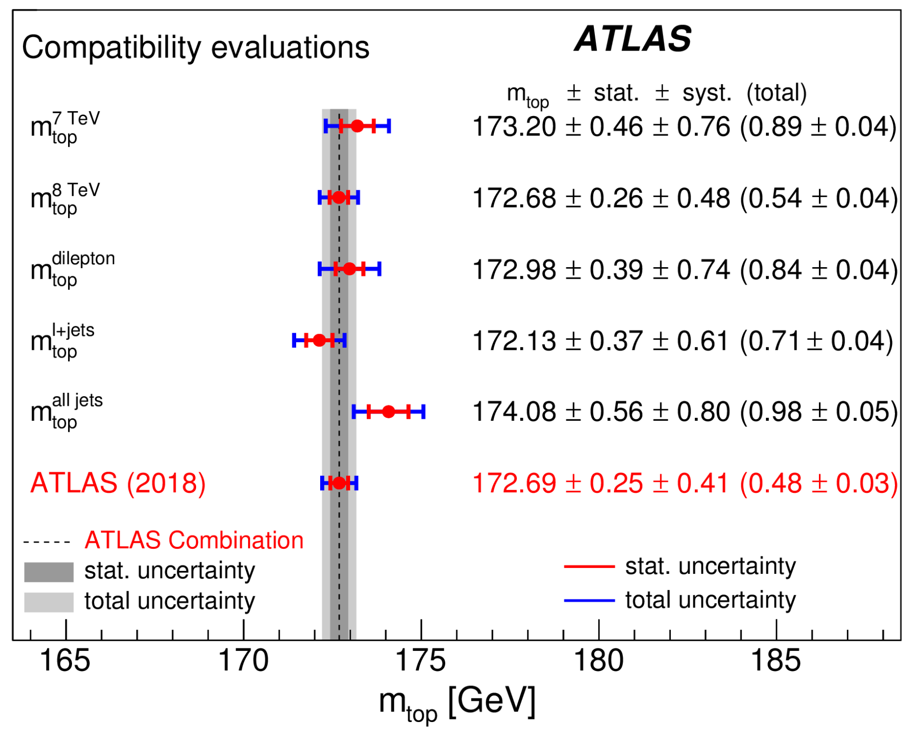
Direct top mass measurement

- Direct mass measurements (MC mass)
  - Recostruction of top decays in fully leptonic, semileptonic and fully hadronic channels

Recent ATLAS combination of all direct measurements in Run 1

EPJC 79 (2019) 290



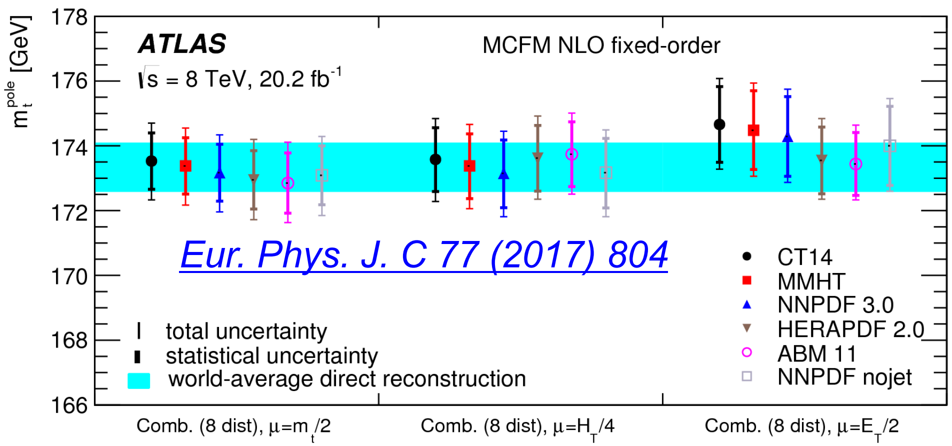


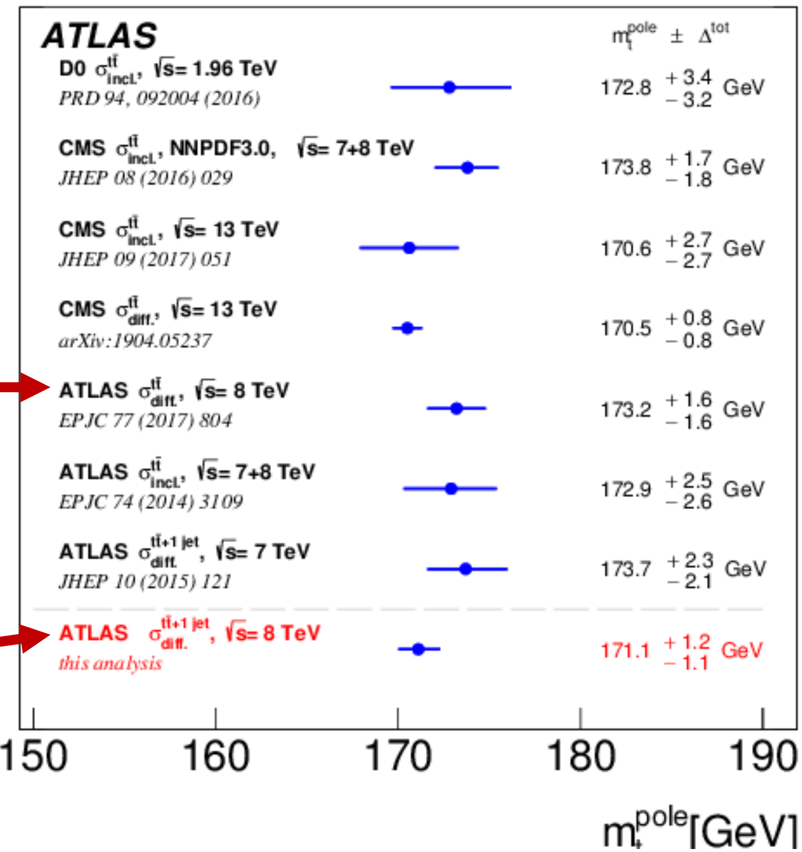
Top pole mass measurement

Direct mass measurements can be interpreted as pole mass measurement (pole of propagator)

- MC mass relation with pole mass still under study, difference due to non perturbative effects estimated to be ~0.5-1 GeV
- Using the tt production cross section, inclusive and differential, the pole mass and running mass in the MS bar scheme can be determined

From lepton and dilepton differential distributions





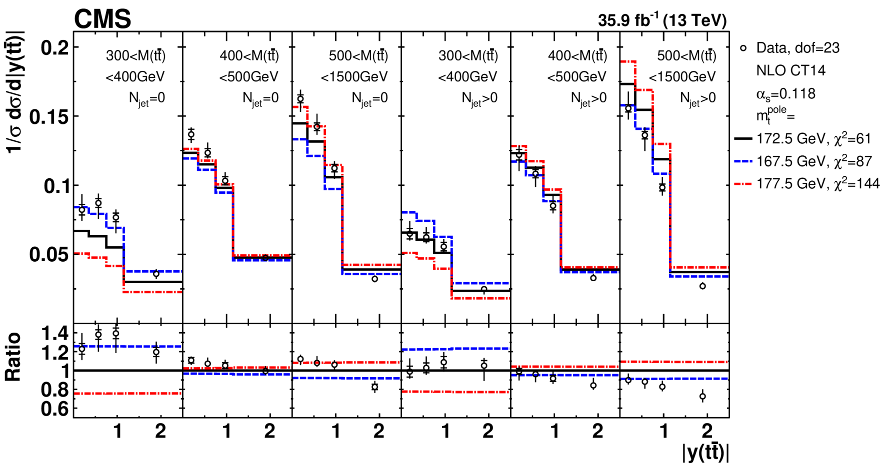
ATLAS tt+1 jet arXiv:1905.02302

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

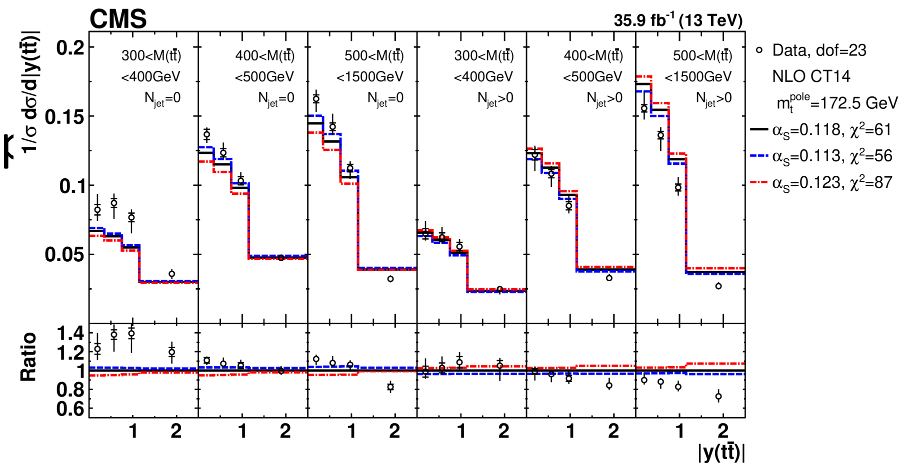
Running mass $m_t(m_t) = 162.9 \pm 0.5\,(\text{stat}) \pm 1.0\,(\text{syst})\ ^{+2.1}_{-1.2}\,(\text{theo})$ GeV

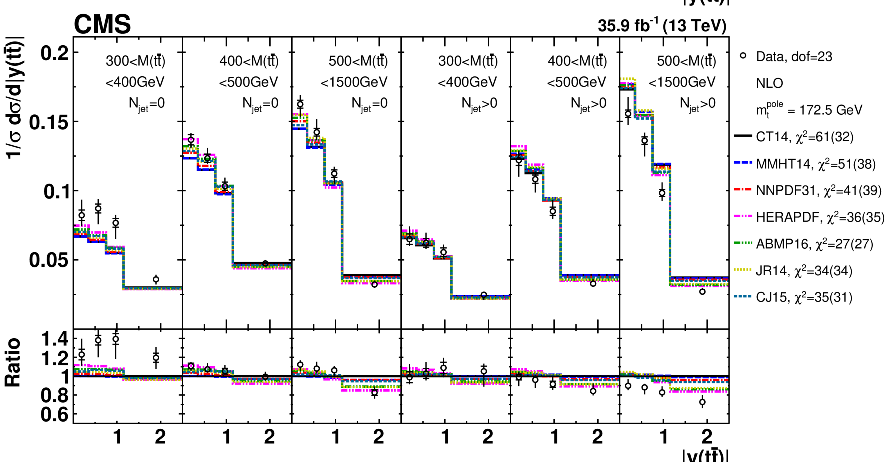
Consistent results between direct and indirect measurements

tt differential measurements and mass

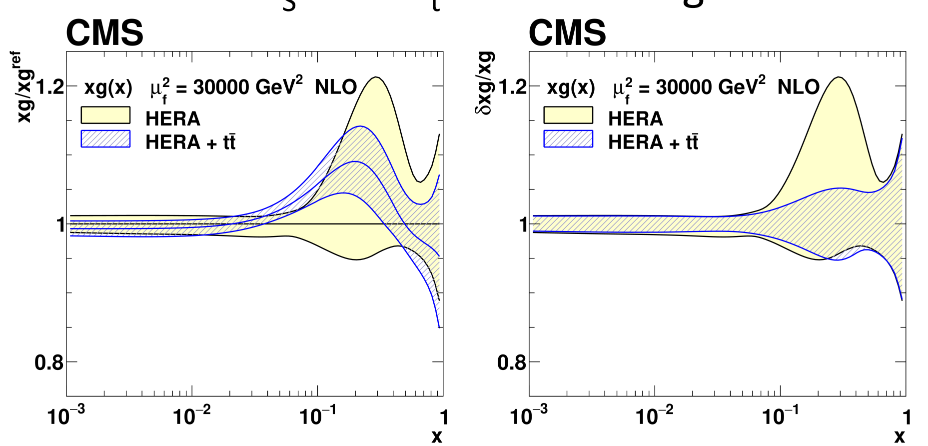


trip





- Extracted α_S and m_t^{pole} and also gluon PDF

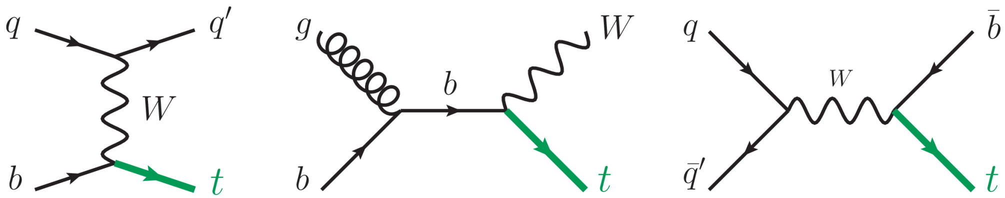


[arXiv:1904.05237](https://arxiv.org/abs/1904.05237)

$$\alpha_S(m_Z) = 0.1135 \pm 0.0016(\text{fit})^{+0.0002}_{-0.0004}(\text{model})^{+0.0008}_{-0.0001}(\text{param})^{+0.0011}_{-0.0005}(\text{scale}) = 0.1135^{+0.0021}_{-0.0017}(\text{total})$$

$$m_t^{\text{pole}} = 170.5 \pm 0.7(\text{fit}) \pm 0.1(\text{model})^{+0.0}_{-0.1}(\text{param}) \pm 0.3(\text{scale})\ \text{GeV} = 170.5 \pm 0.8(\text{total})\ \text{GeV}$$

Single top production also measured

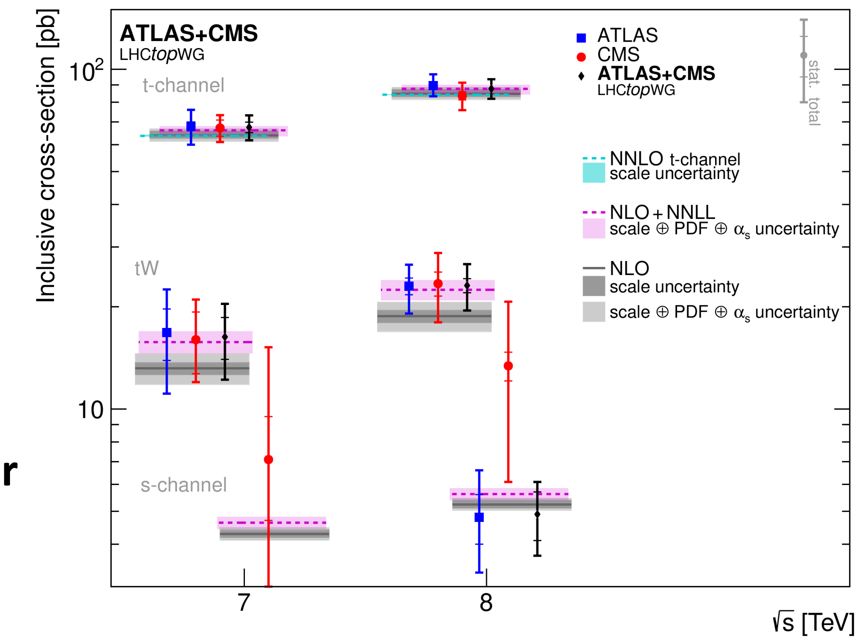


t-channel (dominant) | *tW* production | *s*-channel (very small)

JHEP 05 (2019) 088

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

f_{LV}: left handed form factor = 1 in the SM



Directly sensitive to Vtb:

ATLAS + CMS 7 and 8 TeV combined

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

CMS 13 TeV tW: $63.1 \pm 1.8\,(\text{stat}) \pm 6.4\,(\text{syst}) \pm 2.1\,(\text{lumi})\,\text{pb}$ [JHEP 10 (2018) 117]

CMS 13 TeV t-channel

Top quark $136 \pm 1\,(\text{stat}) \pm 22\,(\text{syst})\,\text{pb}$

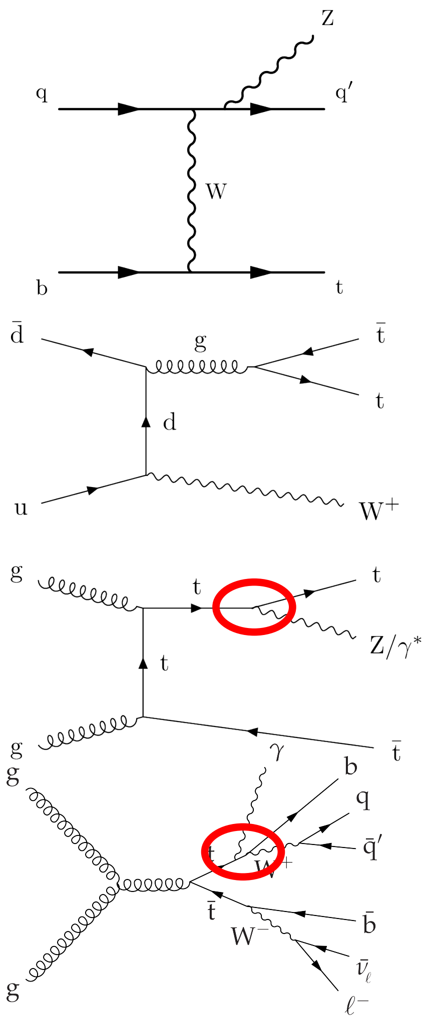
Top antiquark $82 \pm 1\,(\text{stat}) \pm 14\,(\text{syst})\,\text{pb}$ [arXiv:1812.10514]

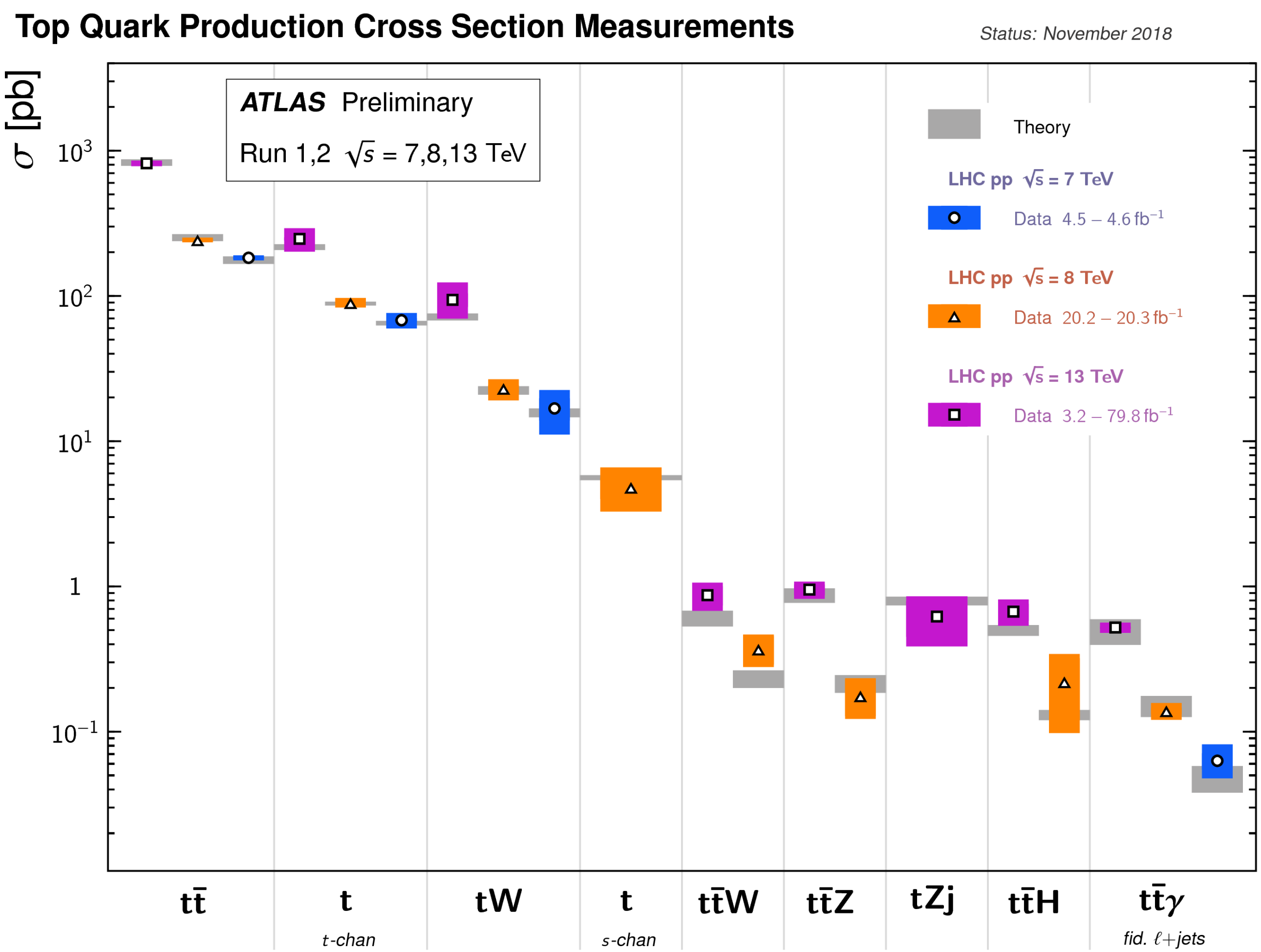
Ratio (PDF) $1.66 \pm 0.02\,(\text{stat}) \pm 0.05\,(\text{syst})$

ttV measurements

Several tV and ttV measurements carried out by ATLAS and CMS

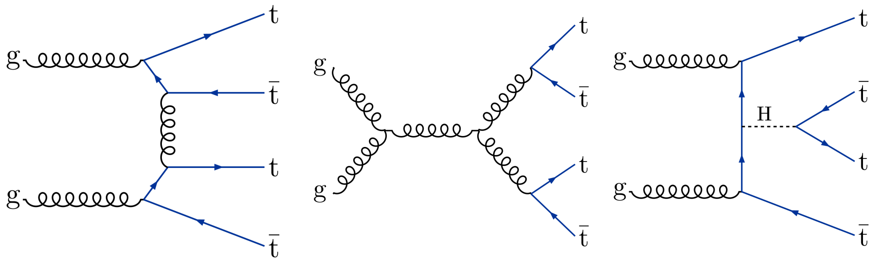
Very important to probe couplings of the top with photon and Z boson



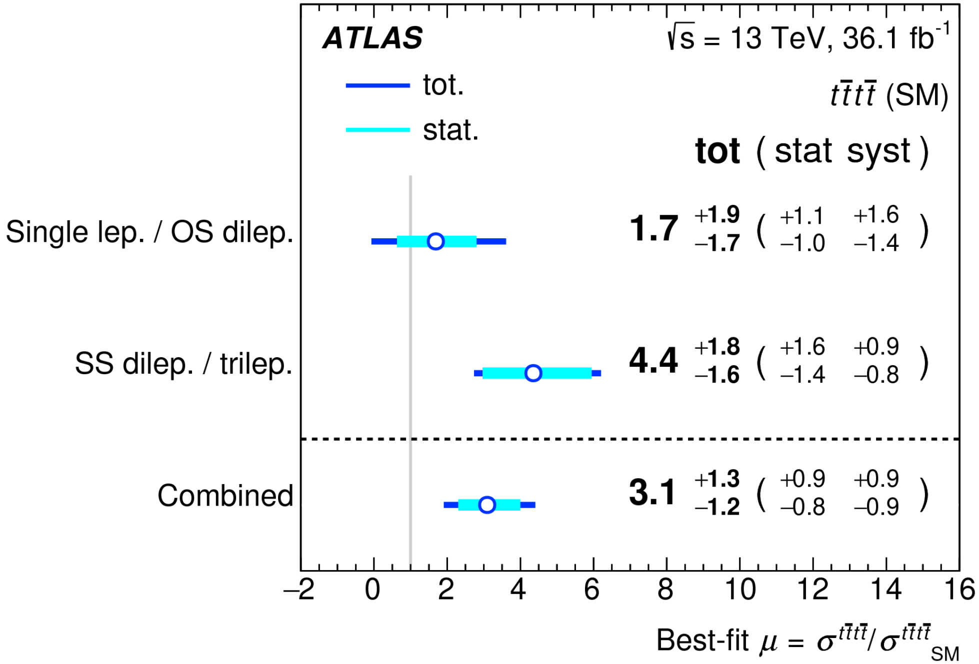


Four top production (tttt)

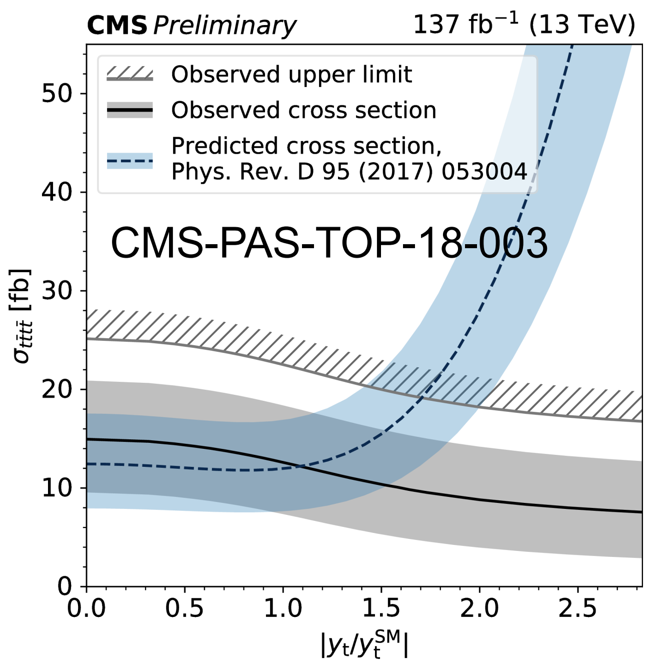
- Spectacular process with 4 top quarks in the final state
- Searches in single lepton, double lepton same and opposite sign, triple lepton



ATLAS PRD 99, 052009 (2019)



Full Run 2 dataset used



- ATLAS: significance 2.8 σ (1.0 σ expected)
- CMS: same sign dileptons and three leptons, significance 2.6 σ (2.7 σ expected)

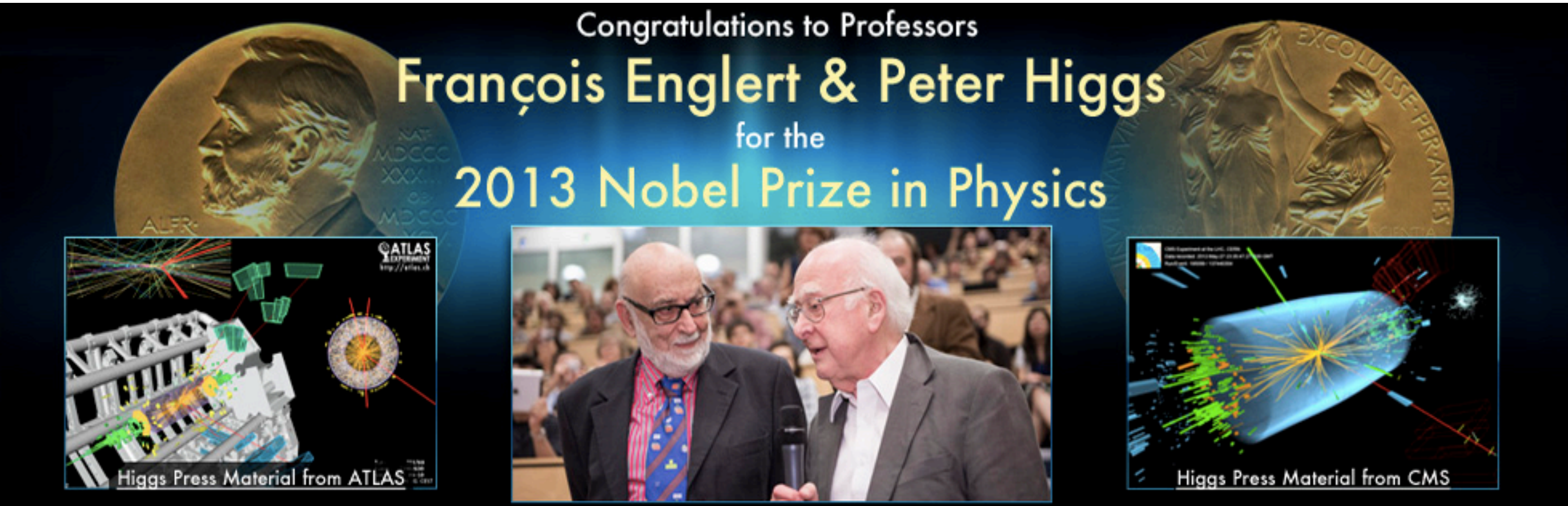
Higgs boson discovery

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2013 to

François Englert
Université Libre de Bruxelles, Brussels, Belgium

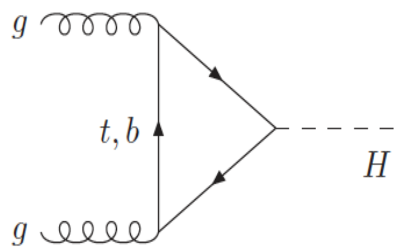
Peter W. Higgs
University of Edinburgh, UK

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

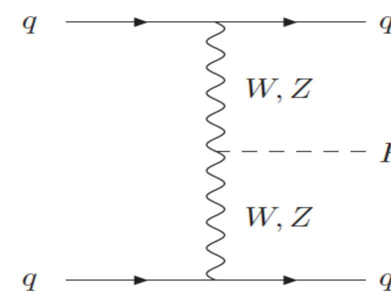


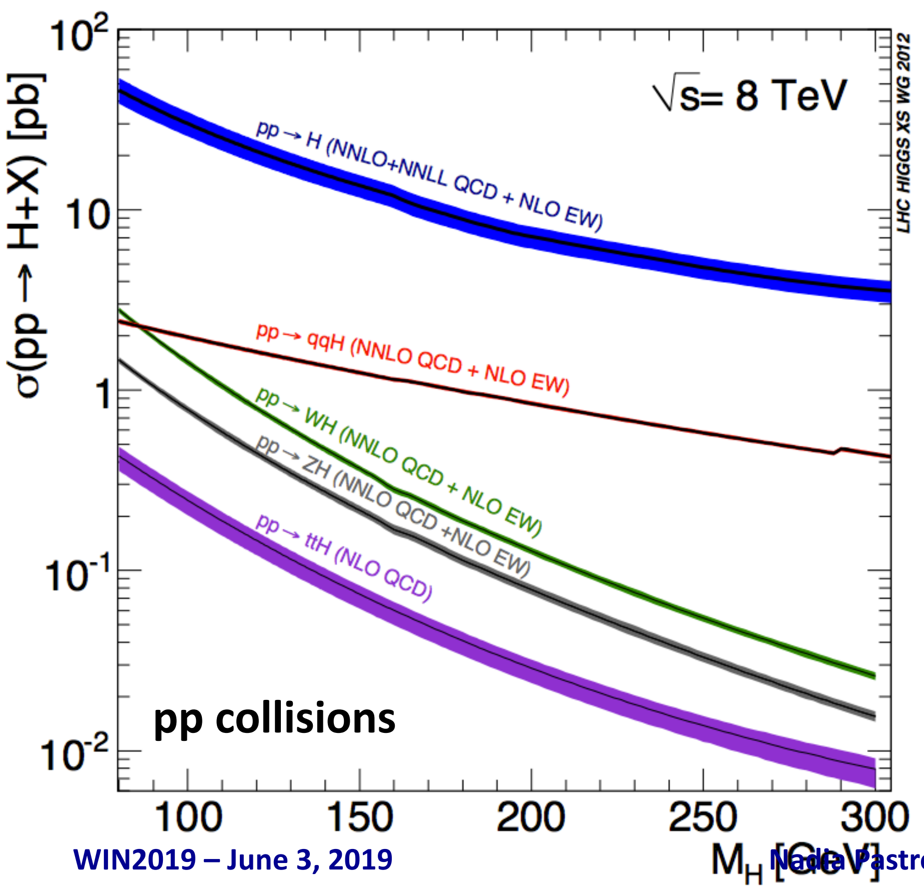
Main Higgs production processes

ggH

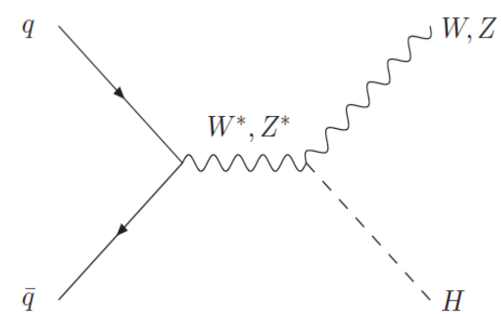


VBF

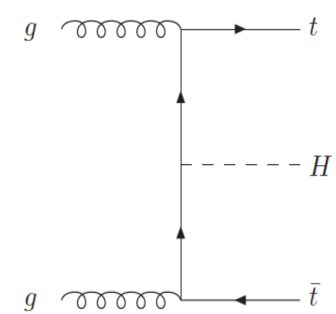




VH

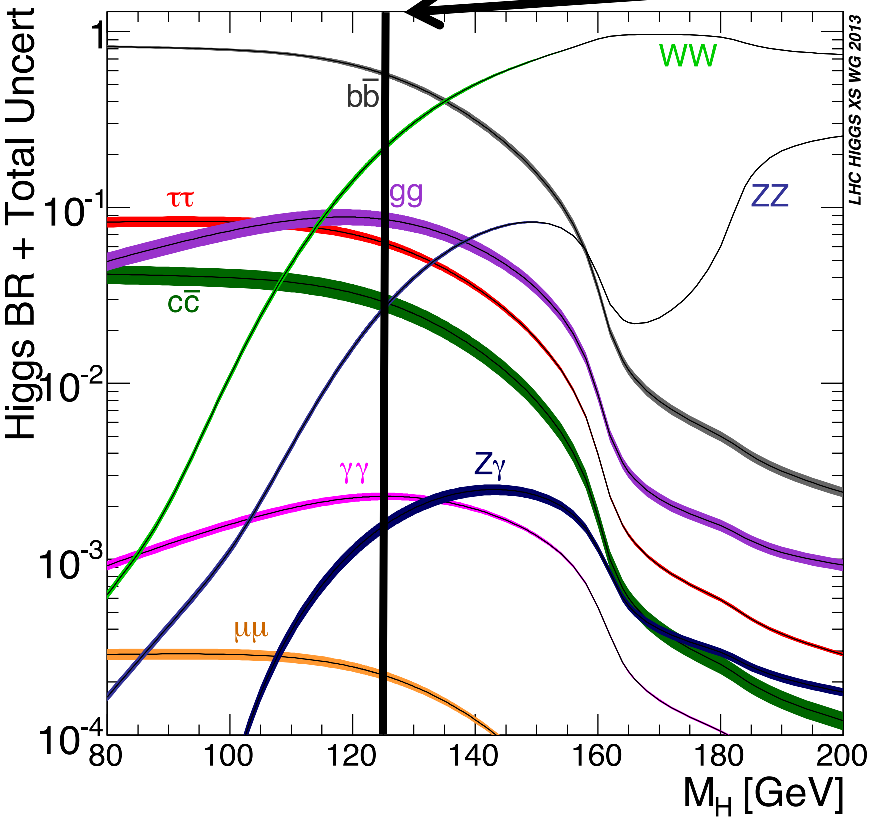


ttH



SM Higgs boson decays

m_H=125.09 GeV

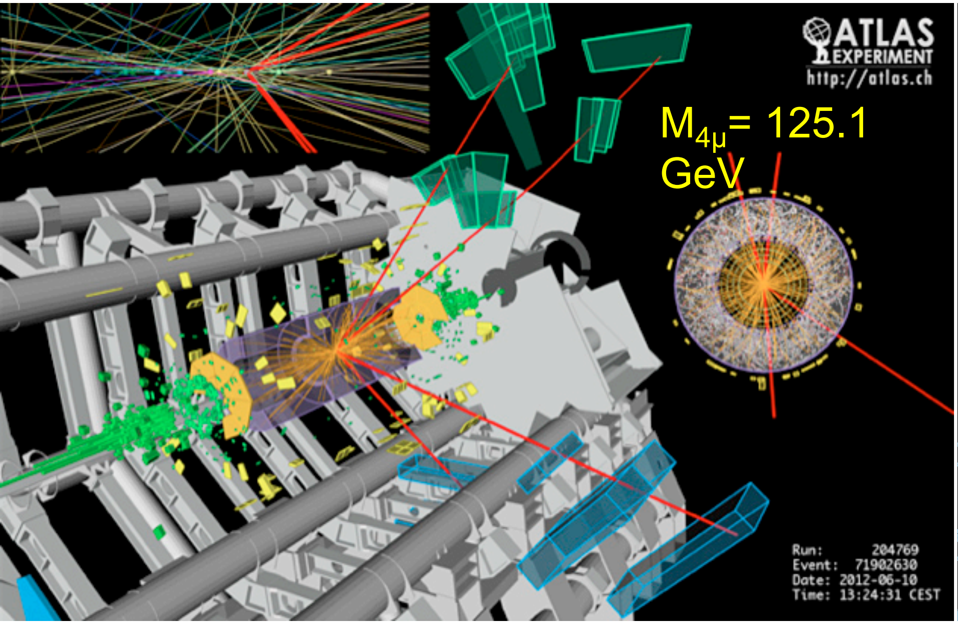


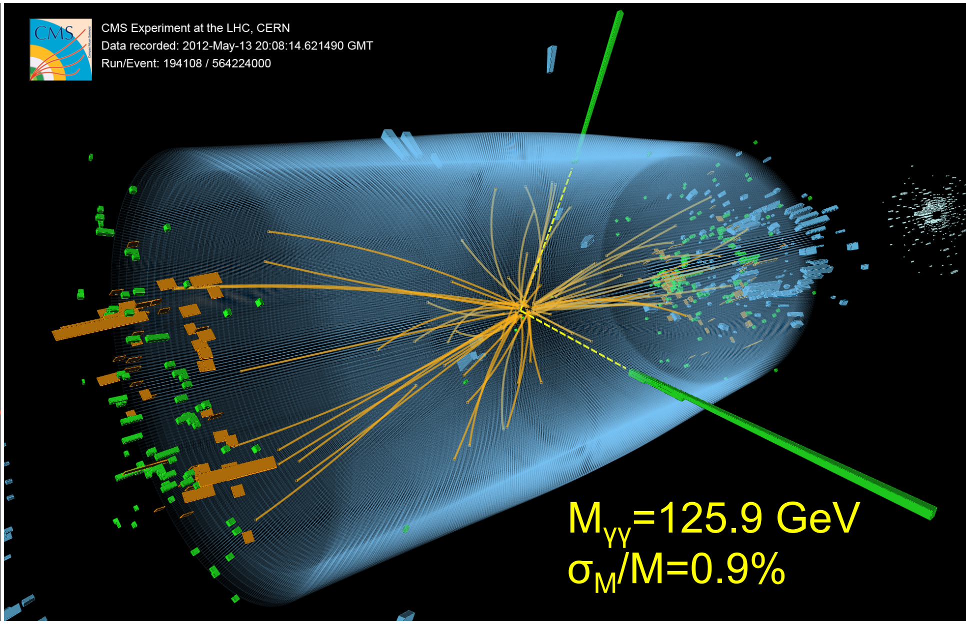
Decay channel	Branching ratio [%]
$H \to b\bar{b}$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to c\bar{c}$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

expected Higgs boson's natural width: 4 MeV << experimental resolution

Higgs boson mass measurement

- ✓ SM cross sections and decay BRs depend on the mass
- ✓ The mass is measured using high resolution channels:
  - **H→ZZ→4l – small systematic uncertainties compared to current statistical ones**
  - **H→γγ – more important systematic uncertainties and effect of interference**





Run 1, ATLAS and CMS combined
M_H = 125.09 ± 0.24 [± 0.21 (stat) ± 0.11(syst)] GeV

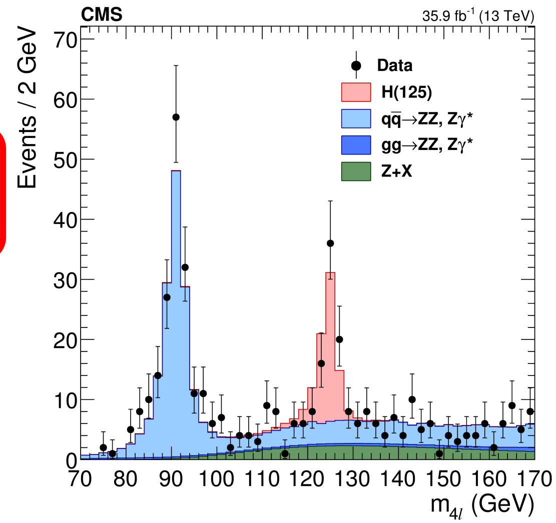
Still used as common reference measurement

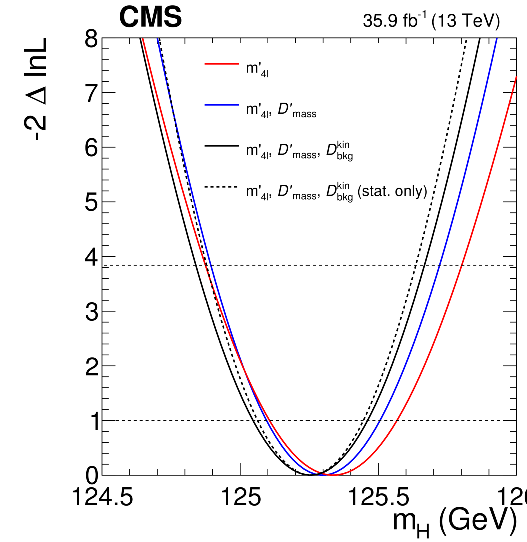
Mass measurement @ 13 TeV

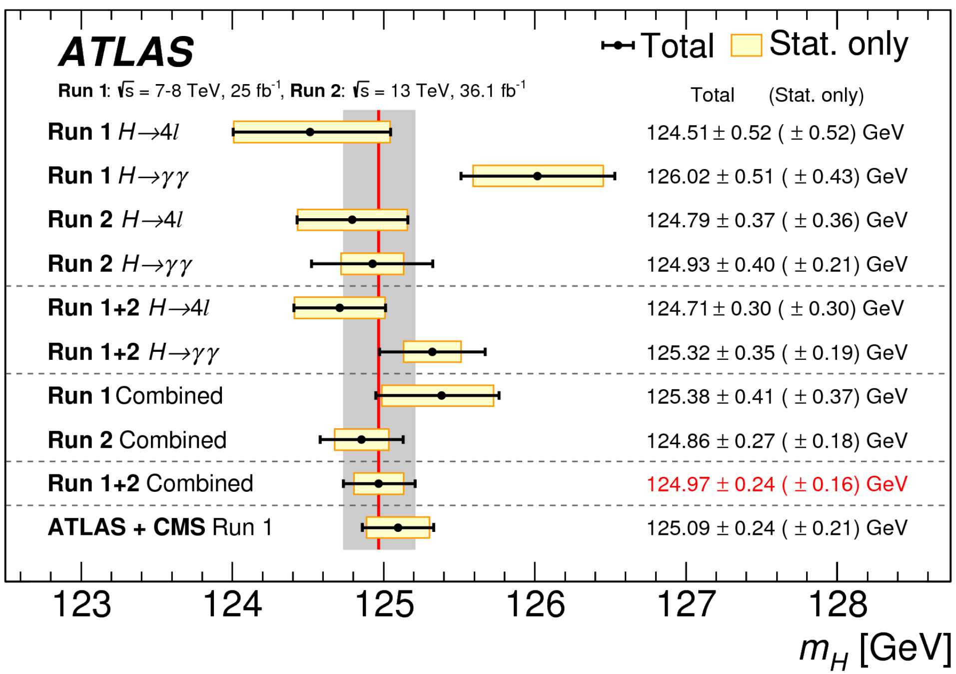
4 lepton channel, using 3D fit with Z1 mass constrained to the Z mass, mass, mass resolution and a BG discriminant

$\boldsymbol{m_H}$ **= 125.26 ± 0.21 GeV**
= 125.26 ± 0.20 (stat) ± 0.08 (syst)

[JHEP 11 (2017) 047]







ATLAS in Run 2 combination paper:
Phys. Lett. B 784 (2018) 345

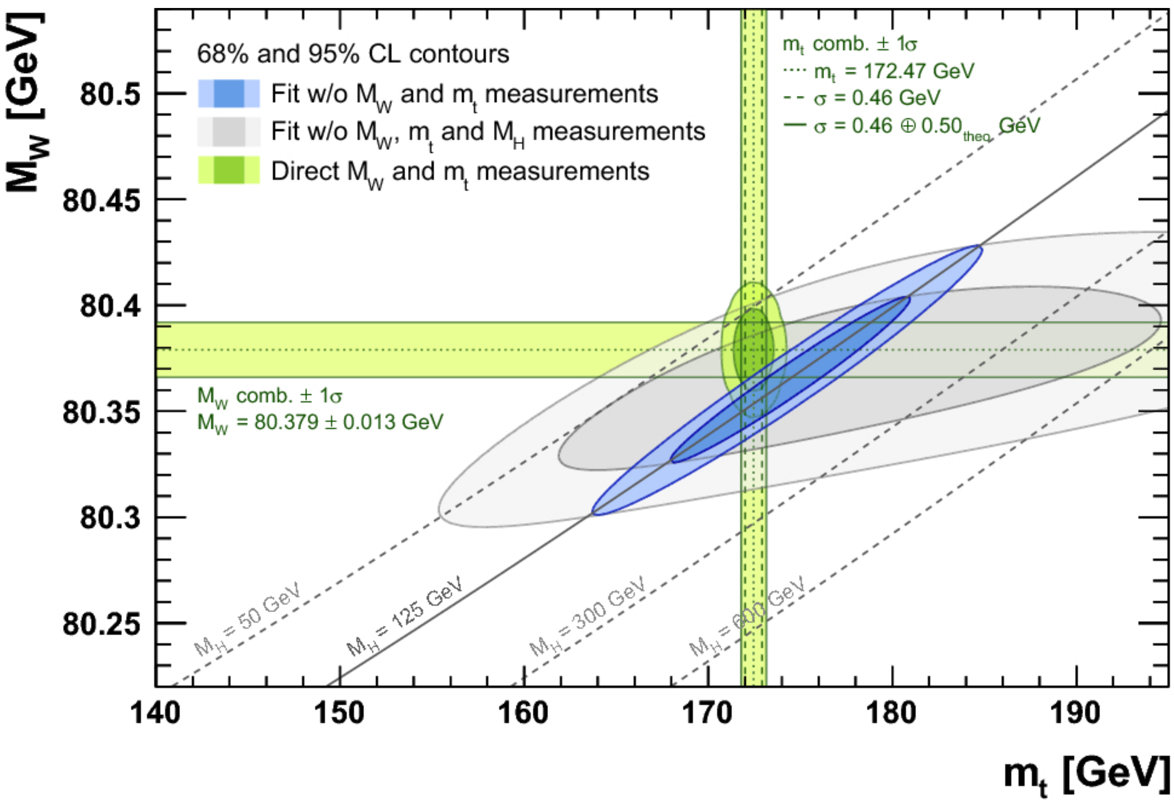
$\boldsymbol{m_H}$ **= 125.26 ± 0.24 GeV**

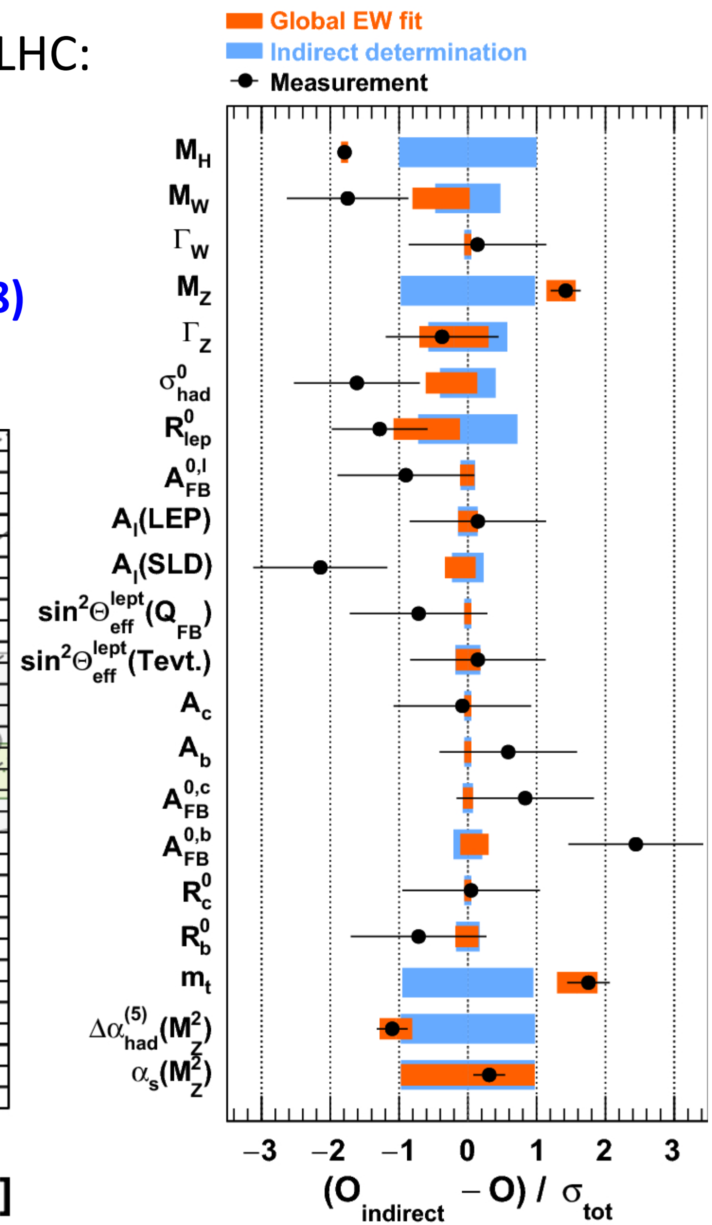
Here, interference in H→γγ neglected

SM fits to all EW precision measurements

- Fundamental parameters of SM measured at the LHC:
  - M_W, M_t, M_H, $\sin^2\vartheta_W$
- Used in SM fits to all EW precision measurements

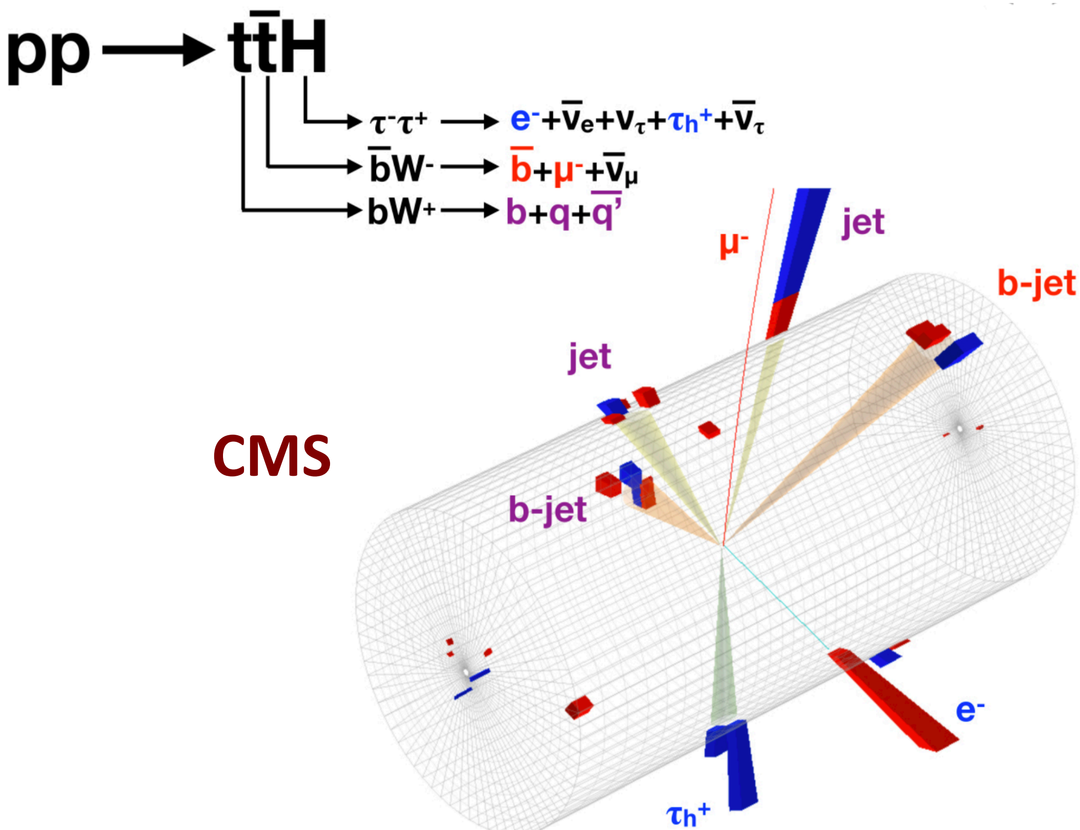
Gfitter EPJC 78, 675 (2018)





2018: observation of ttH

- Several channels are combined:
  - H→γγ, H →ZZ →4l: cleanest channel
  - Multilepton (H→WW, ZZ, ττ): simultaneous fit of ttH, ttW and ttZ (important BG)
  - H→bb: : tt+HF background is constrained from data

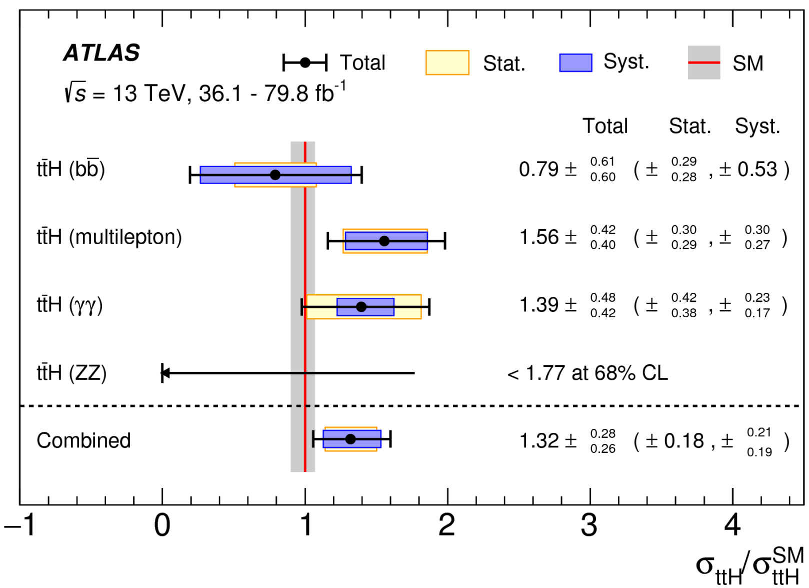


ttH results

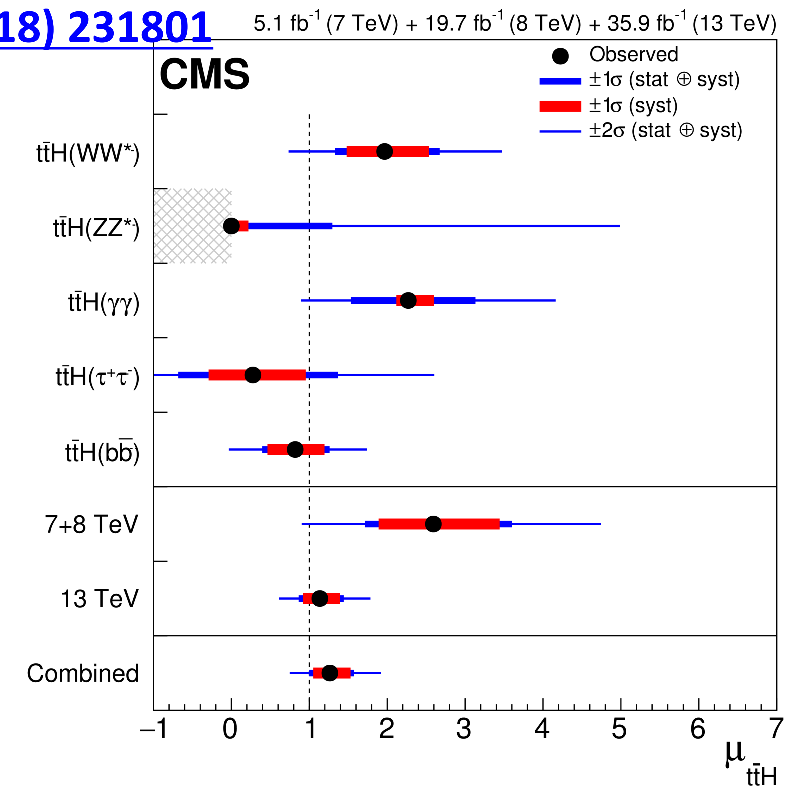
ATLAS significance

PLB 784 (2018) 173

Analysis	Integrated luminosity [fb^{-1}]	$t\bar{t}H$ cross section [fb]	Obs. sign.	Exp. sign.
$H \to \gamma\gamma$	79.8	$710\ ^{+210}_{-190}$ (stat.) $^{+120}_{-90}$ (syst.)	4.1σ	3.7σ
$H \to$ multilepton	36.1	790 ± 150 (stat.) $^{+150}_{-140}$ (syst.)	4.1σ	2.8σ
$H \to b\bar{b}$	36.1	$400\ ^{+150}_{-140}$ (stat.) $\pm$ 270 (syst.)	1.4σ	1.6σ
$H \to ZZ^* \to 4\ell$	79.8	<900 (68% CL)	0σ	1.2σ
Combined (13 TeV)	36.1–79.8	670 ± 90 (stat.) $^{+110}_{-100}$ (syst.)	5.8σ	4.9σ
Combined (7, 8, 13 TeV)	4.5, 20.3, 36.1–79.8	–	6.3σ	5.1σ



PRL 120 (2018) 231801

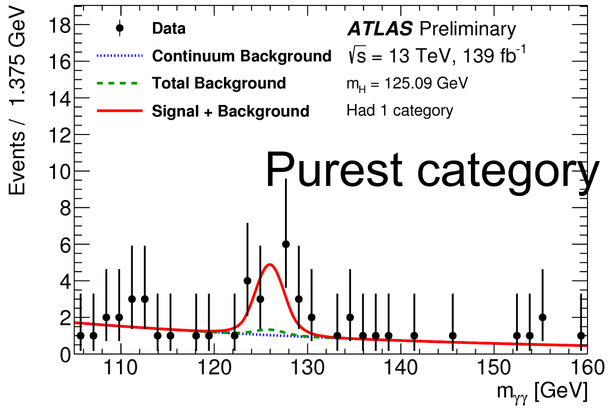


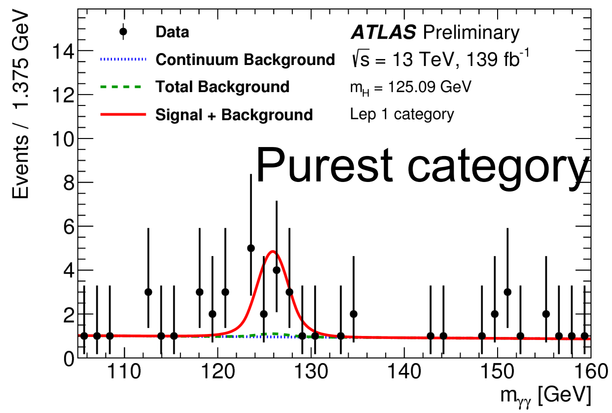
CMS significance: 5.2 σ (exp. 4.2 σ)

ttH, H→γγ with full Run 2 data

>=1 lepton
e or mu + 1 btagged jet

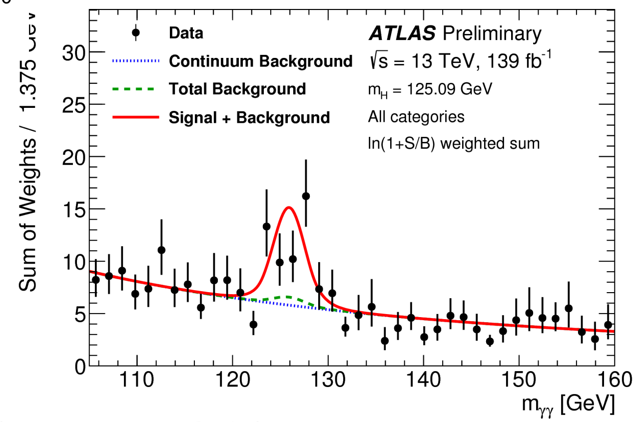
Fully hadronic
No e nor mu + 1 btagged jet + 2 jets





Continuous BG
+ small BG for other
Higgs production modes

Weighted sum of all categories



Category	$t\bar{t}H$ Signal	non-$t\bar{t}H$ Higgs	Continuum Background	Total (Expected)	Data
$t\bar{t}H$ "Lep" Category 1	7.9 ± 1.5	0.42 ± 0.12	4.6 ± 0.9	12.9 ± 1.8	15
$t\bar{t}H$ "Lep" Category 2	3.9 ± 0.6	0.43 ± 0.15	7.5 ± 1.2	11.8 ± 1.3	11
$t\bar{t}H$ "Lep" Category 3	1.45 ± 0.24	0.49 ± 0.19	7.5 ± 1.2	9.5 ± 1.2	6
$t\bar{t}H$ "Had" Category 1	6.9 ± 1.6	0.8 ± 0.5	4.5 ± 0.9	12.2 ± 1.9	15
$t\bar{t}H$ "Had" Category 2	5.6 ± 1.0	1.1 ± 0.8	16.5 ± 1.7	23.2 ± 2.3	31
$t\bar{t}H$ "Had" Category 3	7.7 ± 1.3	3.1 ± 2.2	56.0 ± 3.0	67 ± 4	82
$t\bar{t}H$ "Had" Category 4	4.9 ± 0.8	5 ± 4	101 ± 4	111 ± 6	105

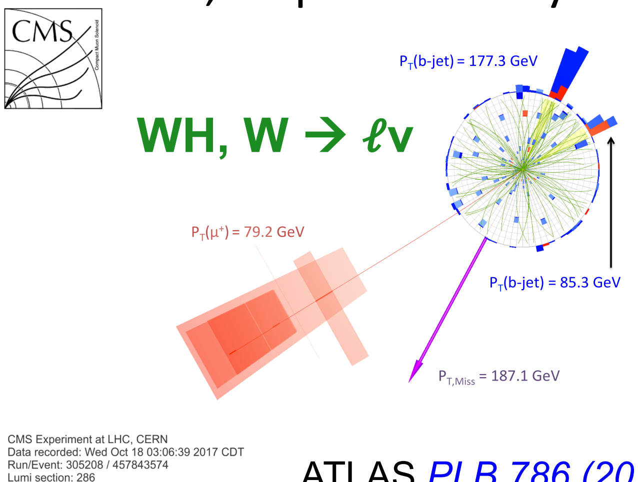
$$\sigma_{t\bar{t}H} \times B_{\gamma\gamma} = 1.59^{+0.43}_{-0.39}\ \text{fb} = 1.59^{+0.38}_{-0.36}\ (\text{stat.})\ ^{+0.15}_{-0.12}\ (\text{exp.})\ ^{+0.15}_{-0.11}\ (\text{theo.})\ \text{fb}$$

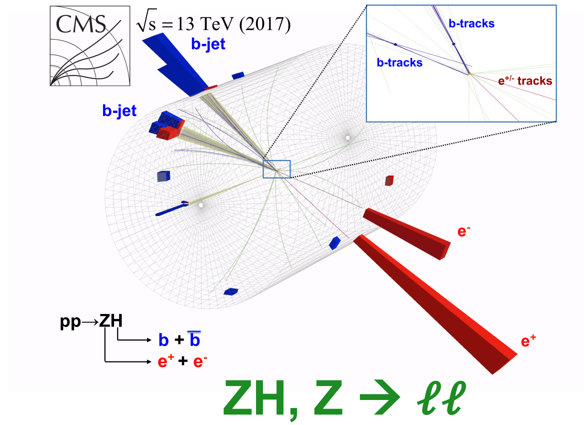
$$\mu_{t\bar{t}H} = 1.38\ ^{+0.41}_{-0.36} = 1.38\ ^{+0.33}_{-0.31}\ (\text{stat.})\ ^{+0.13}_{-0.11}\ (\text{exp.})\ ^{+0.22}_{-0.14}\ (\text{theo.})$$

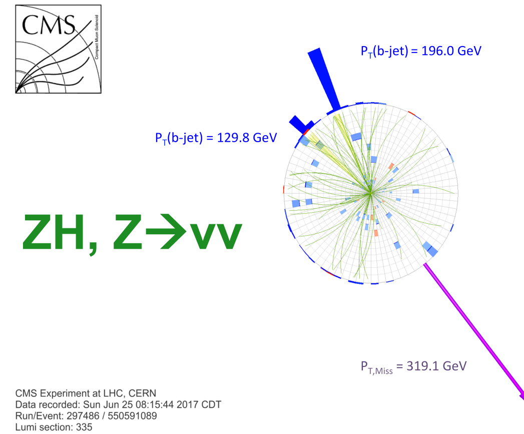
Significance 4.9 σ (expected 4.2 σ)

2018: observation of H → bb

- Production process with highest sensitivity: VH, H → bb
- All W,Z leptonic decays exploited

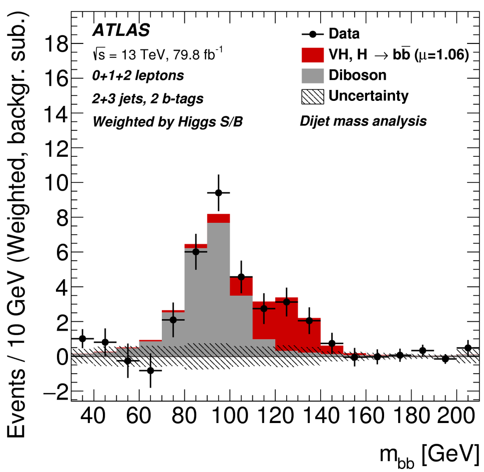


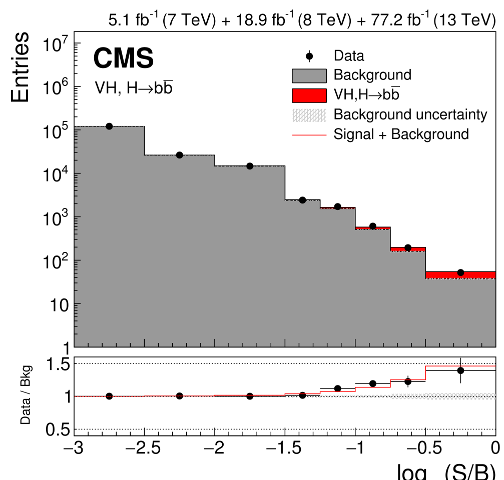


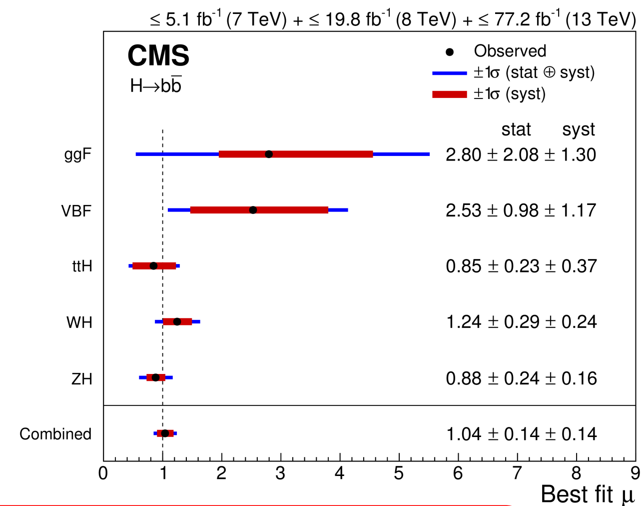


ATLAS [PLB 786 (2018) 59]

PRL 121 (2018) 121801







Run 1 + Run 2 data:

ATLAS significance 5.4 σ (expected 5.5 σ)
CMS significance 5.6 σ (expected 5.5 σ)

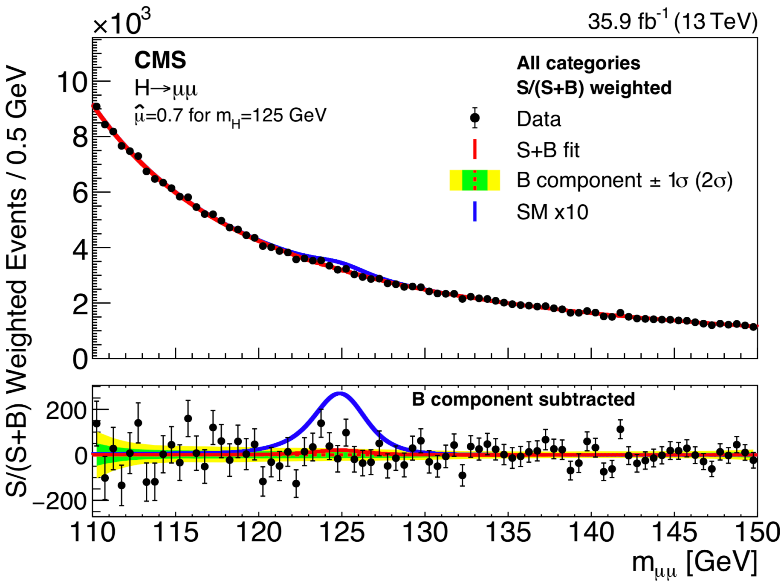
Higgs coupling to 2nd generation fermions

- No conclusive results yet, first channel with sensitivity reaching SM prediction $H \rightarrow \mu\mu$
- Excellent mass resolution, which matters a lot for this channel
  - ATLAS 2.4-3.3 GeV
  - CMS 1.2-3.3 GeV

2015-2017 data

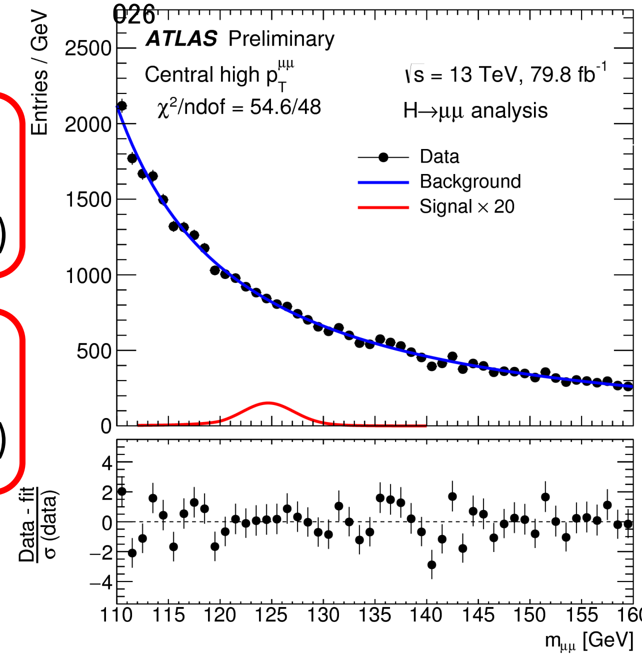
PRL 122 (2019) 021801

ATLAS-CONF-2018-026



CMS:
μ = 1.0
Signif. 0.9 σ (exp. 1.0 σ)

ATLAS:
μ = 0.1
Signif. 0.0 σ (exp. 0.9 σ)



- several categories to improve the sensitivity mainly based on mass resolution and addressing the VBF signature
- Both results are dominated by statistics, expected to keep improving with $1/\sqrt{\int L}$
- ATLAS and CMS currently have similar sensitivity but different data sets
- If coupling is SM like, CMS, with current analysis extended to full Run 2 data expects to start setting a lower limit on the Higgs coupling to muons: $\mu = 1.0 \pm 0.5$
- Analysis improvements could further improve the sensitivity

Combination of all channels

- All main channels have been measured/combined in each experiment
- Measurements and compatibility tests are carried out:
  - Fits of signal strengths μ – σ, BR relative to SM and their ratios, including new STXS measurements
  - Fits in the κ-framework - coupling modifiers and their ratios
- All of them assume a SM-like Higgs boson Spin Parity 0^+ and with a narrow width such that production and decay are decoupled

$$\sigma_i \cdot \mathrm{BR}^f = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_{\mathrm{H}}}$$

- At the LHC we can only measure σxBR need further assumptions to extract σ, BR or couplings independently
- Spin parity and width compatibility tests are also carried out and no deviations from SM have been found

Decay/Production	ggF	VBF	WH	ZH	ttH
$H\to\gamma\gamma$	■	■	■	■	■
$H\to ZZ$	■	■	■	■	■
$H\to WW$	■	■	■	■	■
$H\to\tau\tau$	■	■	■	■	■
$H\to bb$	■	■	■	■	■
$H\to\mu\mu$	■	■			

Channel measured	■

Signal strengths μ

Results @ 13 TeV
ATLAS-CONF-2019-005
CMS: arXiv:1809.10733

- μ is the so called signal strength (μ=1 in the SM)

$$\mu_i = \frac{\sigma_i}{\sigma_i^{\mathrm{SM}}} \quad \text{and} \quad \mu^f = \frac{\mathrm{BR}^f}{\mathrm{BR}^f_{\mathrm{SM}}}. \qquad \mu_i^f \equiv \frac{\sigma_i \cdot \mathrm{BR}^f}{(\sigma_i \cdot \mathrm{BR}^f)_{\mathrm{SM}}} = \mu_i \times \mu^f$$

- Most constrained parameterization: one single signal strength μ

ATLAS + CMS at Run 1 (7+8 TeV)

$$\mu = 1.09^{+0.11}_{-0.10} \qquad = 1.09^{+0.07}_{-0.07}\,(\text{stat})\,{}^{+0.04}_{-0.04}\,(\text{expt})\,{}^{+0.03}_{-0.03}\,(\text{thbgd})^{+0.07}_{-0.06}\,(\text{thsig})$$

ATLAS 13 TeV

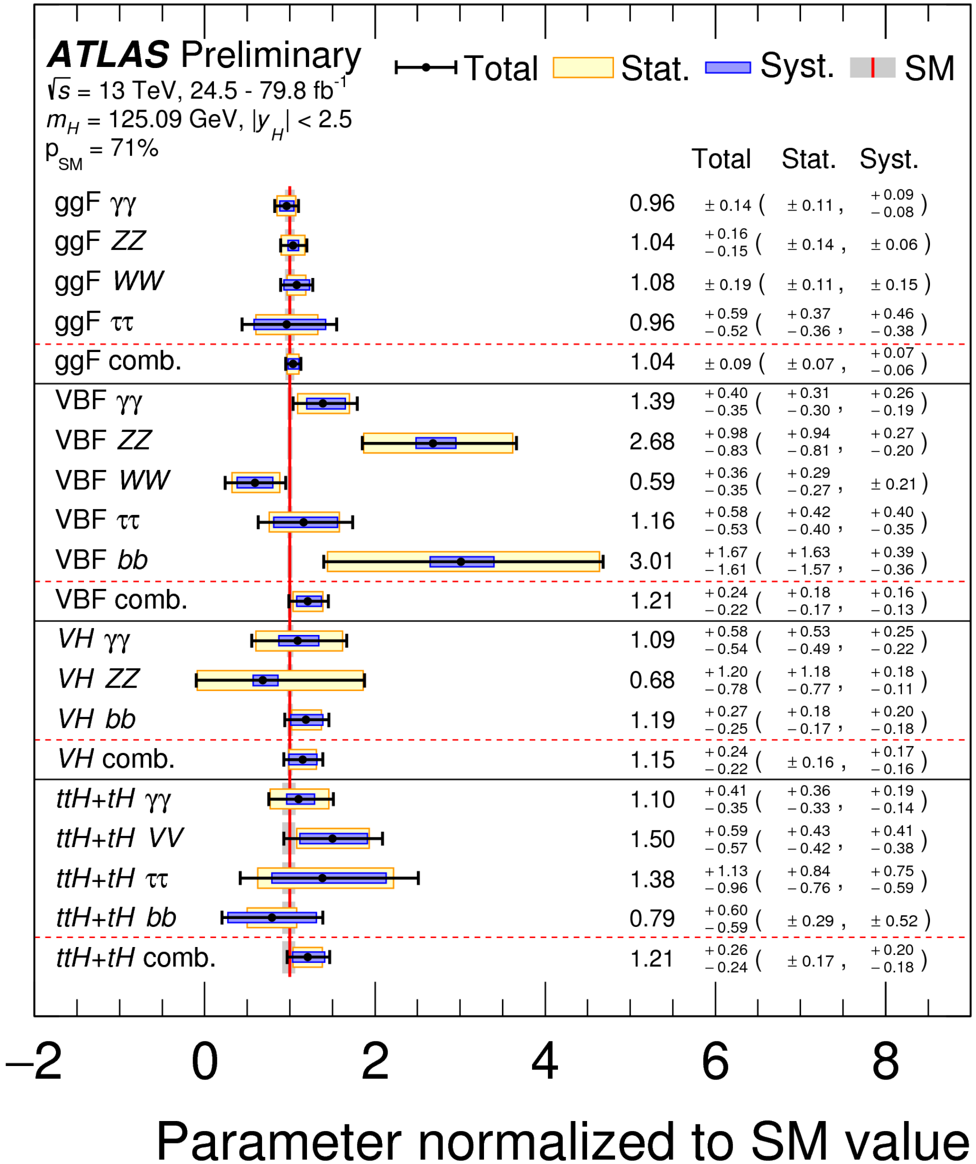
$$\mu = 1.11^{+0.09}_{-0.08} = 1.11 \pm 0.05\,(\text{stat.})\,{}^{+0.05}_{-0.04}\,(\text{exp.})\,{}^{+0.05}_{-0.04}\,(\text{sig. th.}) \pm 0.03\,(\text{bkg. th.})$$

CMS 13 TeV

$$\mu = 1.17 \pm 0.10 = 1.17 \pm 0.06\,(\text{stat})\,{}^{+0.06}_{-0.05}\,(\text{sig theo}) \pm 0.06\,(\text{other syst})$$

- Statistical, experimental systematic and theoretical uncertainties comparable
- For all other measurement, except μ_{ggF}, statistical uncertainties are dominant

Signal strengths μ

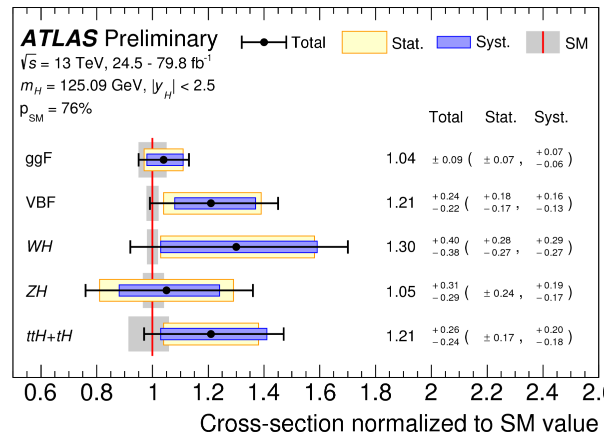


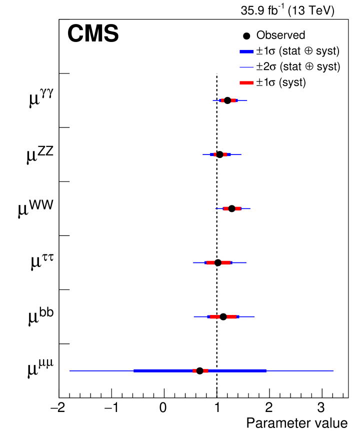
σ x BR measured

Results @ 13 TeV
ATLAS-CONF-2019-005
CMS: arXiv:1809.10733

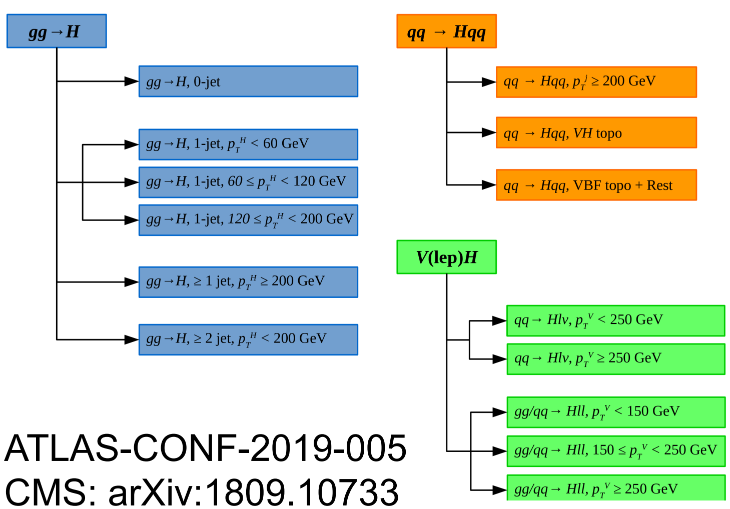
Signal strength μ: production, decay

- Production σ measured, fixing SM BRs
- BR measured, fixing SM σ

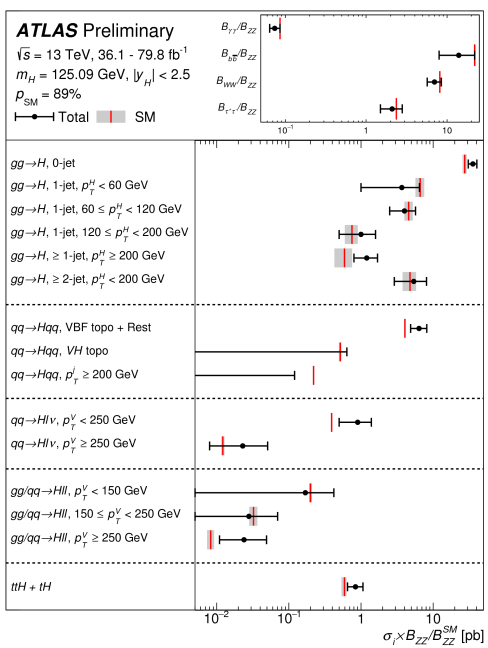


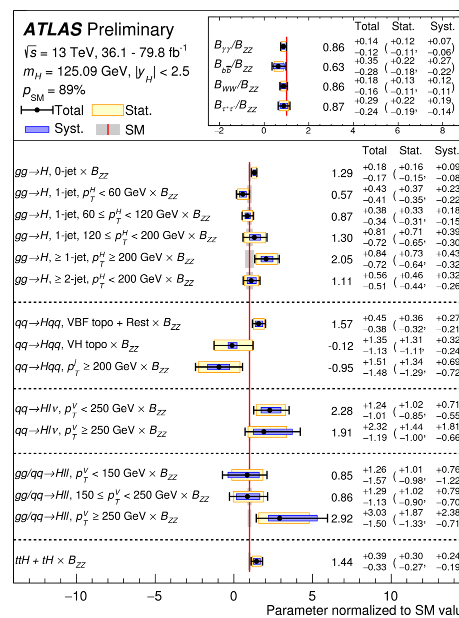


- Simplified Template Cross Sections (STXS) in specific phase space in each production mode.
- Limit model dependency, measure regions of phase space sensitive to BSM effects, and allow phase space dependent interpretations, such as EFTs



ATLAS-CONF-2019-005
CMS: arXiv:1809.10733





All signal strengths and STXS in different channels are consistent with 1 (SM)

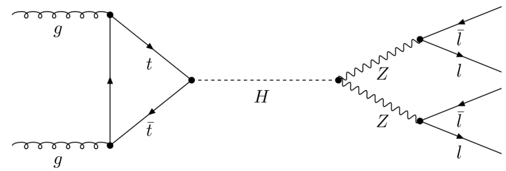
Higgs Couplings: κ-framework

- In the k-framework the Higgs boson couplings are scaled by coupling modifiers κ
- The definition is such that:

$$\kappa_j^2 = \sigma_j/\sigma_j^{SM} \quad \text{or} \quad \kappa_j^2 = \Gamma^j/\Gamma^j_{SM}$$

$$\kappa_H^2 = \sum_j \mathrm{BR}^j_{SM}\kappa_j^2 \qquad \Gamma_H = \frac{\kappa_H^2 \cdot \Gamma_H^{SM}}{1-\mathrm{BR}_{BSM}}$$

- With BR_{BSM} the BR of invisible + undetected decays
  - Undetected decays can be non SM decays or come from different BRs of known but not measured decays: cc, gg, …

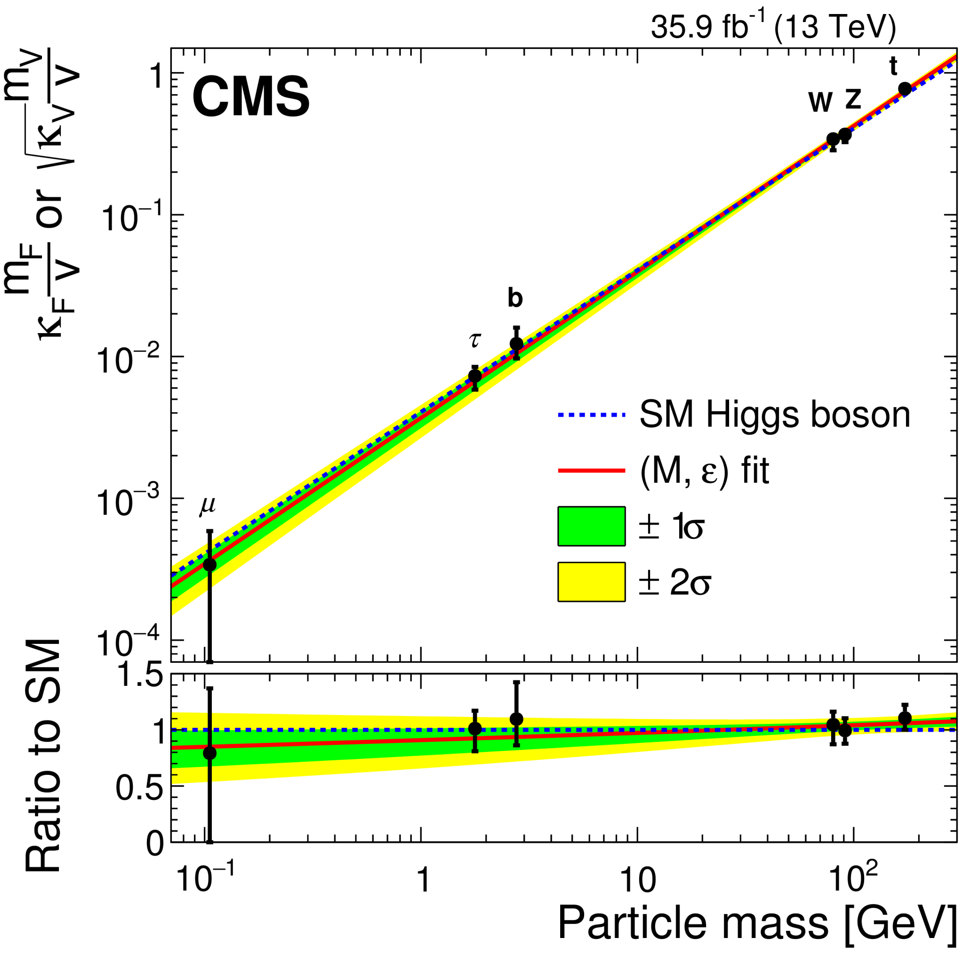


	Loops	Interference	Effective scaling factor	Resolved scaling factor
Production				
$\sigma(\mathrm{ggH})$	✓	g-t	κ_g^2	$1.04\kappa_t^2 + 0.002\kappa_b^2 - 0.038\kappa_t\kappa_b$
$\sigma(\mathrm{VBF})$	—	—		$0.73\kappa_W^2 + 0.27\kappa_Z^2$
$\sigma(\mathrm{WH})$	—	—		κ_W^2
$\sigma(\mathrm{qq/qg} \to \mathrm{ZH})$	—	—		κ_Z^2
$\sigma(\mathrm{gg} \to \mathrm{ZH})$	✓	Z-t		$2.46\kappa_Z^2 + 0.47\kappa_t^2 - 1.94\kappa_Z\kappa_t$
$\sigma(\mathrm{ttH})$	—	—		κ_t^2
$\sigma(\mathrm{gb} \to \mathrm{WtH})$	—	W-t		$2.91\kappa_t^2 + 2.31\kappa_W^2 - 4.22\kappa_t\kappa_W$
$\sigma(\mathrm{qb} \to \mathrm{tHq})$	—	W-t		$2.63\kappa_t^2 + 3.58\kappa_W^2 - 5.21\kappa_t\kappa_W$
$\sigma(\mathrm{bbH})$	—	—		κ_b^2
Partial decay width				
Γ^{ZZ}	—	—		κ_Z^2
Γ^{WW}	—	—		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	W-t	κ_γ^2	$1.59\kappa_W^2 + 0.07\kappa_t^2 - 0.67\kappa_W\kappa_t$
$\Gamma^{\tau\tau}$	—	—		κ_τ^2
Γ^{bb}	—	—		κ_b^2
$\Gamma^{\mu\mu}$	—	—		κ_μ^2
Total width for $\mathcal{B}_{BSM} = 0$				
Γ_H	✓	—	κ_H^2	$0.58\kappa_b^2 + 0.22\kappa_W^2 + 0.08\kappa_g^2 + 0.06\kappa_\tau^2 + 0.026\kappa_Z^2 + 0.029\kappa_c^2 + 0.0023\kappa_\gamma^2 + 0.0015\kappa_{Z\gamma}^2 + 0.00025\kappa_s^2 + 0.00022\kappa_\mu^2$

If New Physics is lower than $m_H/2$, BR_{BSM} could be affected
If above $m_H/2$, effective couplings of the loops would be modified

Higgs boson couplings

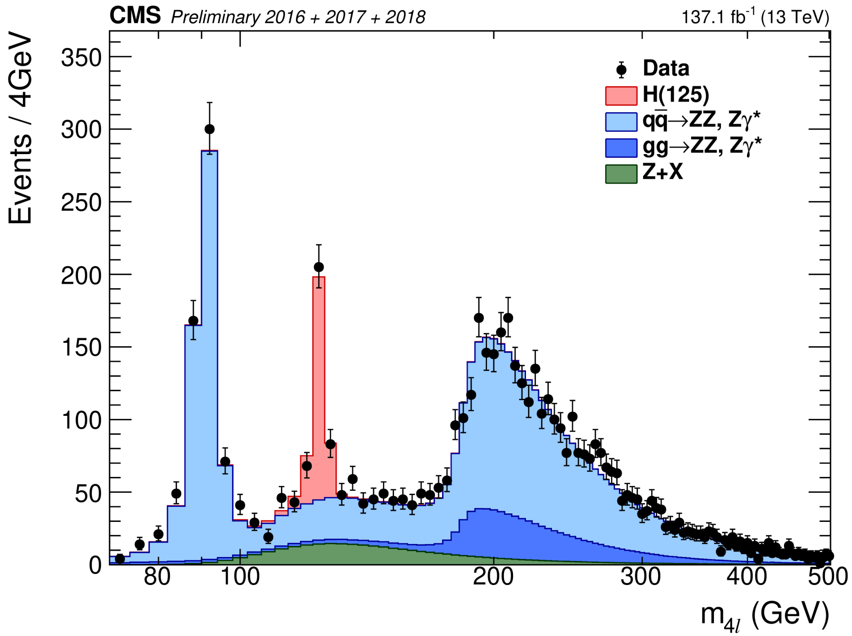
- No BSM in the loops, loops as in SM only depend on couplings
- Fitting the 5 main tree level coupling modifiers + κ_μ and resolving all the loops
- Within current precision Higgs couplings scale with particle masses

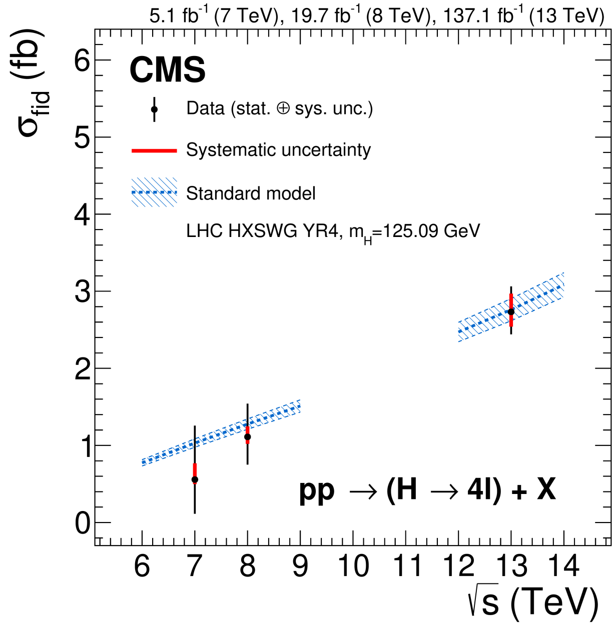


ATLAS-CONF-2019-005
CMS: arXiv:1809.10733

CMS H → ZZ → 4l, full Run 2 datasets

CMS-PAS-HIG-19-001





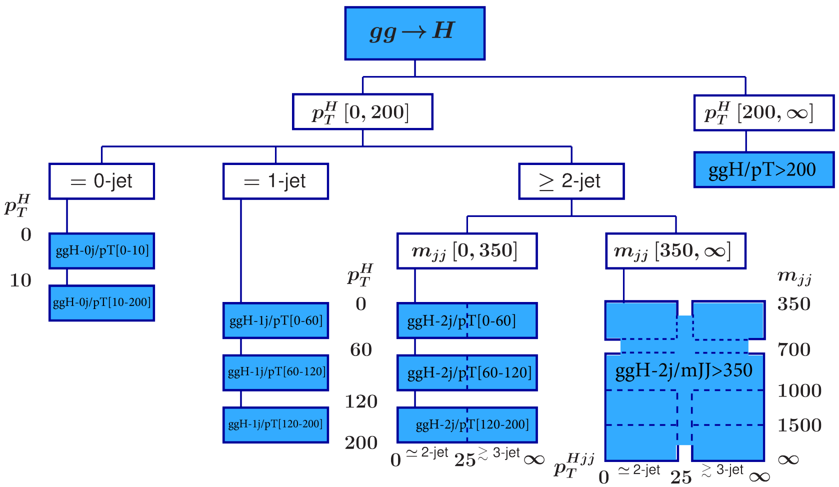
- Various measurements have been carried out, including fiducial and differential cross sections

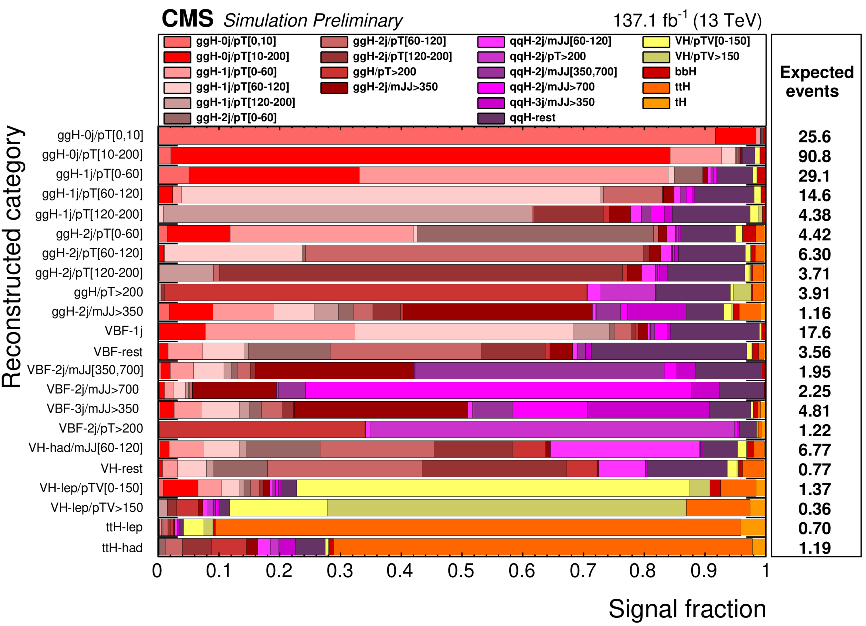
	Expected	Observed
$\mu_{\text{inclusive}}$	$1.00^{+0.08}_{-0.08}(\text{stat.})^{+0.09}_{-0.07}(\text{syst.})$	$0.94^{+0.07}_{-0.07}(\text{stat.})^{+0.08}_{-0.07}(\text{syst.})$
μ_{ggH}	$1.00^{+0.10}_{-0.10}(\text{stat.})^{+0.09}_{-0.07}(\text{syst.})$	$0.97^{+0.09}_{-0.09}(\text{stat.})^{+0.09}_{-0.07}(\text{syst.})$
μ_{VBF}	$1.00^{+0.54}_{-0.45}(\text{stat.})^{+0.27}_{-0.14}(\text{syst.})$	$0.64^{+0.45}_{-0.36}(\text{stat.})^{+0.16}_{-0.09}(\text{syst.})$
μ_{VH}	$1.00^{+0.91}_{-0.72}(\text{stat.})^{+0.29}_{-0.16}(\text{syst.})$	$1.15^{+0.89}_{-0.72}(\text{stat.})^{+0.26}_{-0.16}(\text{syst.})$
$\mu_{\text{t\bar{t}H,tH}}$	$1.00^{+1.16}_{-0.73}(\text{stat.})^{+0.19}_{-0.04}(\text{syst.})$	$0.13^{+0.92}_{-0.13}(\text{stat.})^{+0.11}_{-0.00}(\text{syst.})$

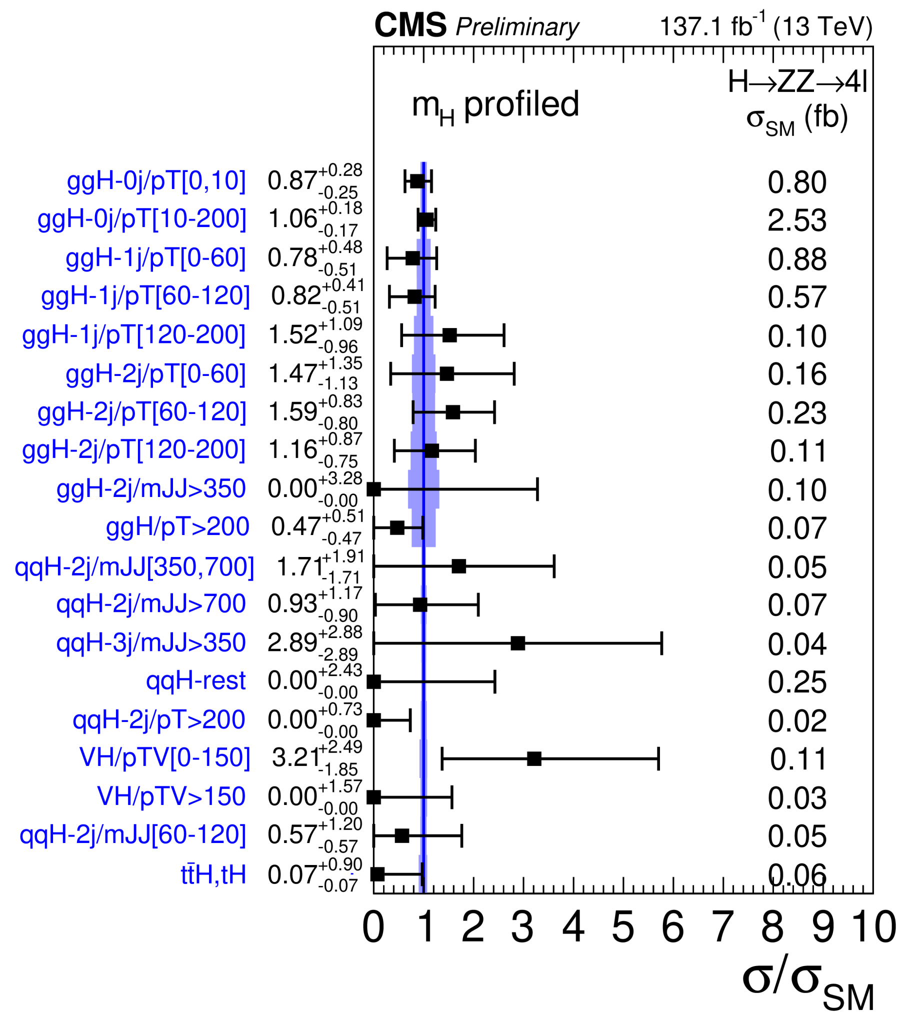
CMS H->ZZ->4l, full Run 2 statistics

- **More granural STXS measurements are also performed**

[CMS-PAS-HIG-19-001]







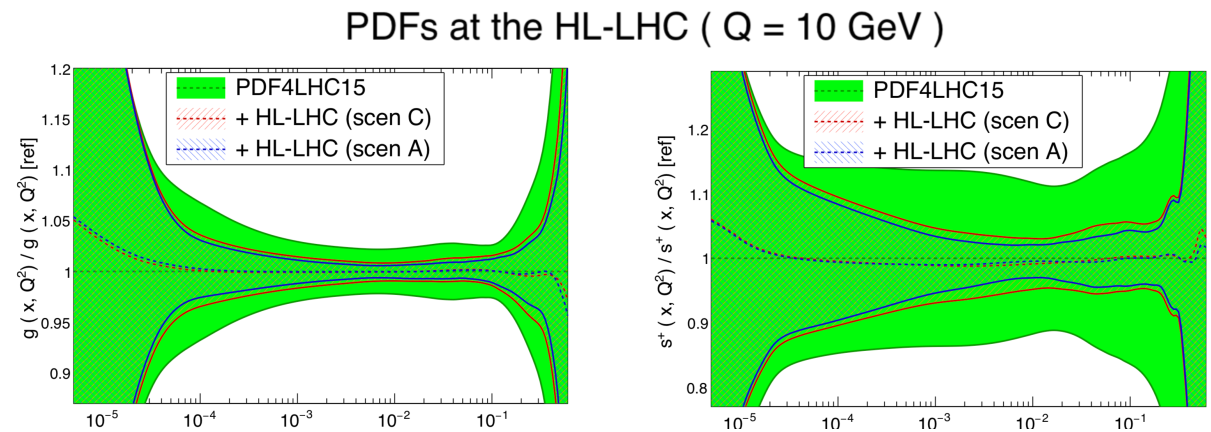
- **All measurements again in agreement with SM**

Electroweak: future prospects

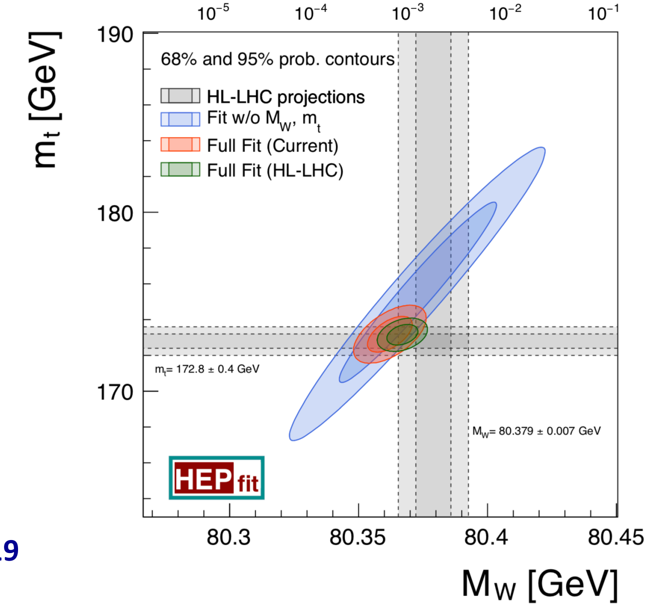
- ATLAS and CMS are working to complete the full Run 2 analyses in all channels
- Once published, as for Run 1, Run 2 results may be combined
- Run 3 and later at HL-LHC will allow an increase in precision

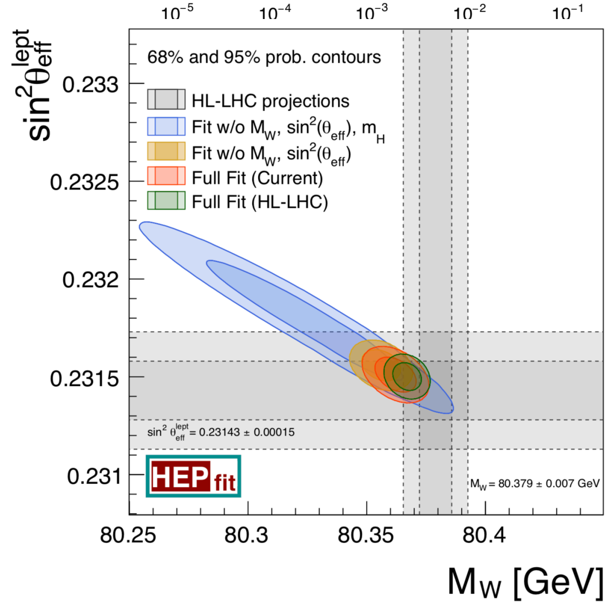
arXiv:1902.04070

PDF improvements



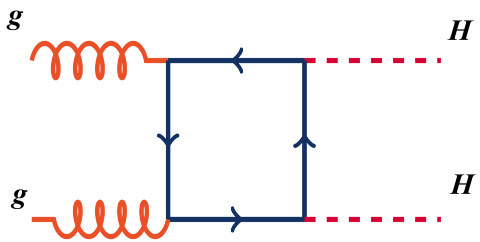
Improvements in the measurement of precision EW observables:
Δm_W ~10 MeV
$\Delta \sin^2\vartheta_W$ ~0.00015

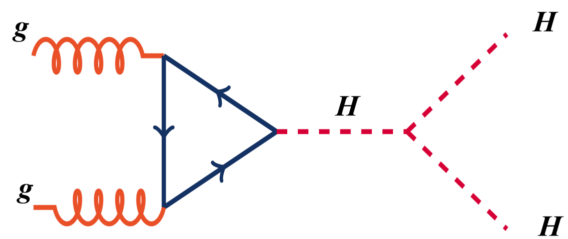




Higgs: future prospects

PRL 122 (2019) 121803

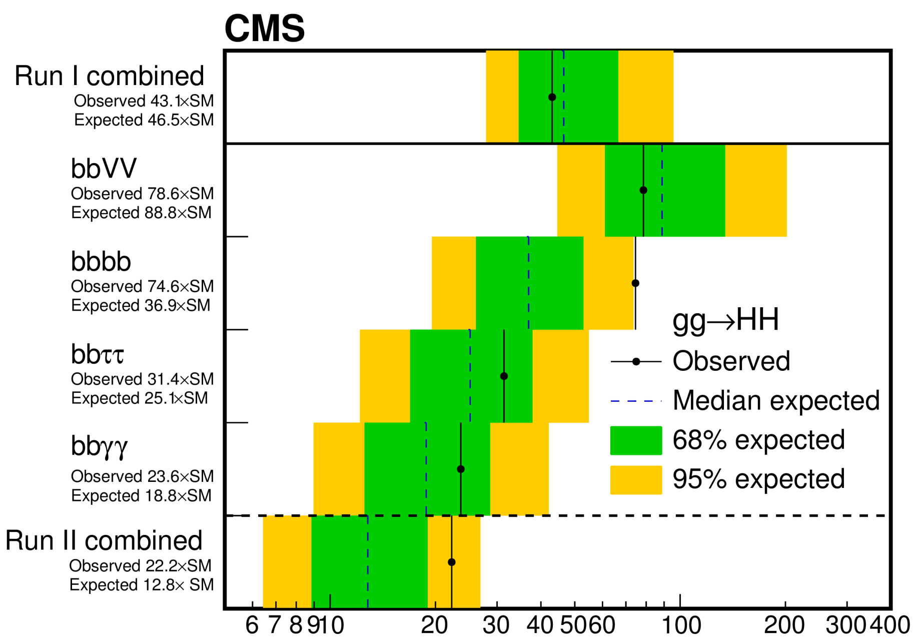




pp collisions 2016
35.9 fb^{-1} @ $\sqrt{s}$ = 13 TeV

combined results from four final states: bbγγ, bbττ, bbbb, and bbVV

V = W or Z boson



Quite far from SM sensitivity O(10x)

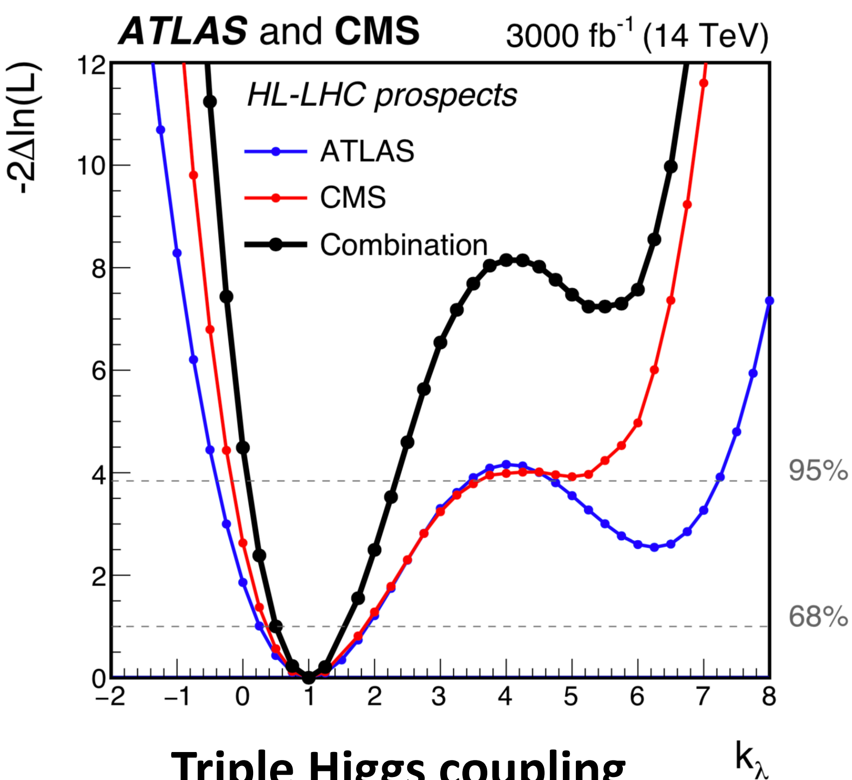
No evidence for a signal is observed in a search for **narrow resonances** → HH performed in the **mass range 250-3000 GeV**

Higgs: future prospects

arXiv:1902.00134

With 3000 fb^{-1}/experiment current projections indicate a combined 4.0 σ sensitivity to double Higgs production

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	



Triple Higgs coupling

Conclusions

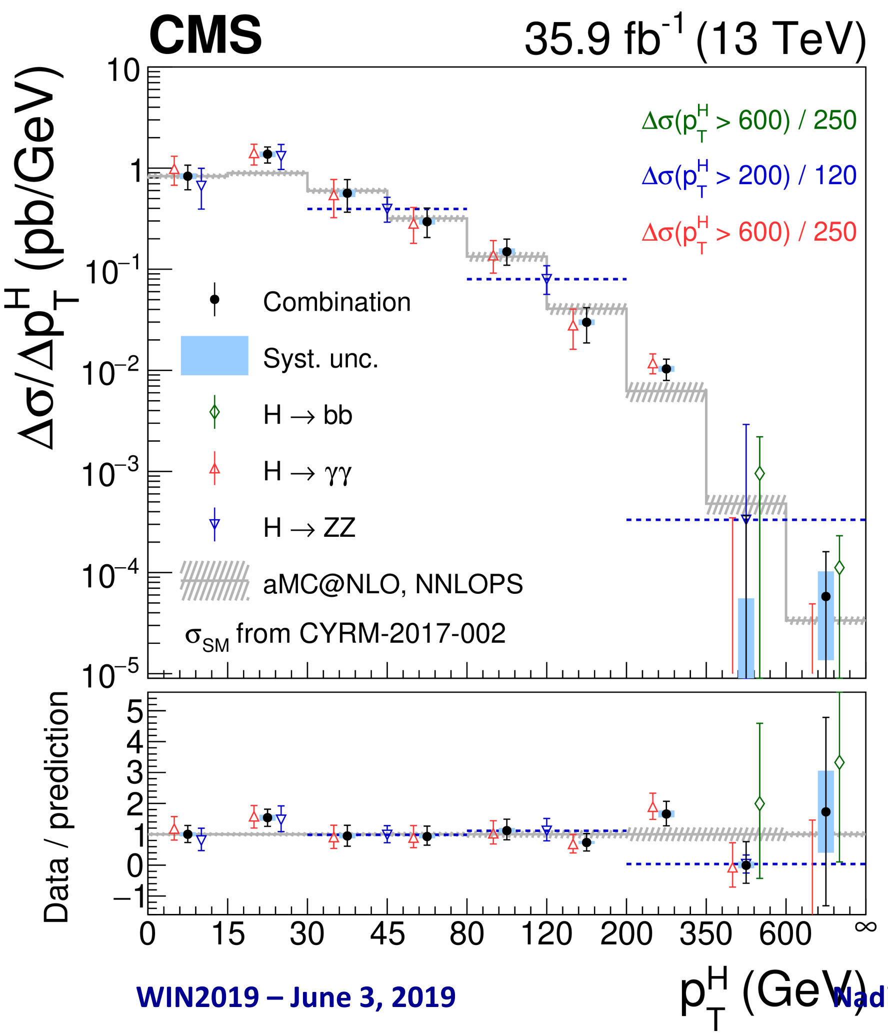
- Outstanding results from the LHC experiments thanks to the LHC team and the excellent performance of the collider
- Achieved crucial improvements on the knowledge of electroweak interactions, top physics and of the Higgs boson:
  - Precise measurements of EW interactions
  - Higgs discovery and related measurements
- Only ~ 5% of the expected total data have been collected until now
- ATLAS and CMS will continue to collect and analyze the data and upgrade the detectors in view of High Lumi LHC
- Improved measurements may further confirm the validity of the SM or indicate deviations which could be hints of new physics

extras

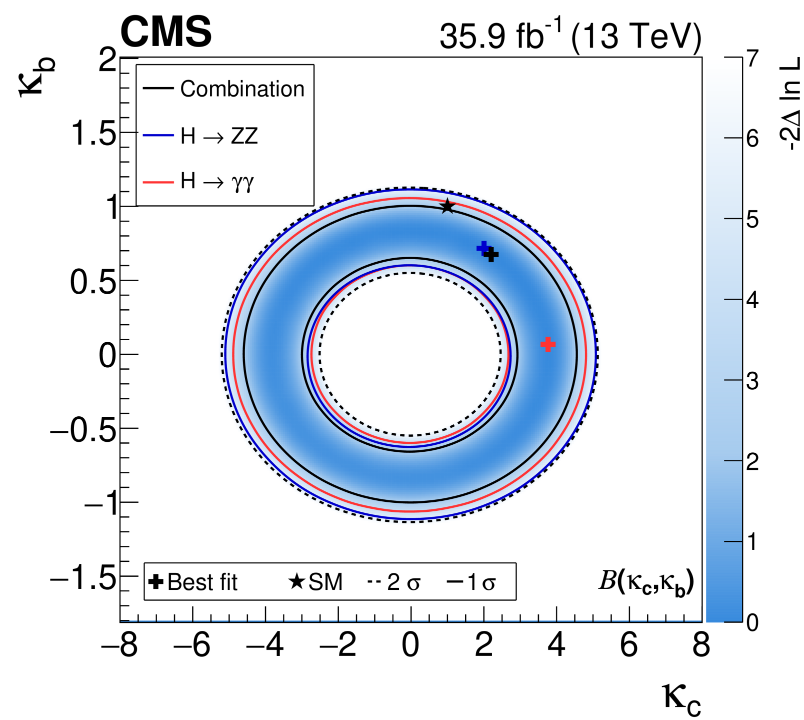
Differential measurements

arXiv:1812.06504

- Differential measurements mainly carried out in H→γγ and H→ZZ->4l channels
- To verify QCD modelling and accessing Higgs couplings and spin parity properties

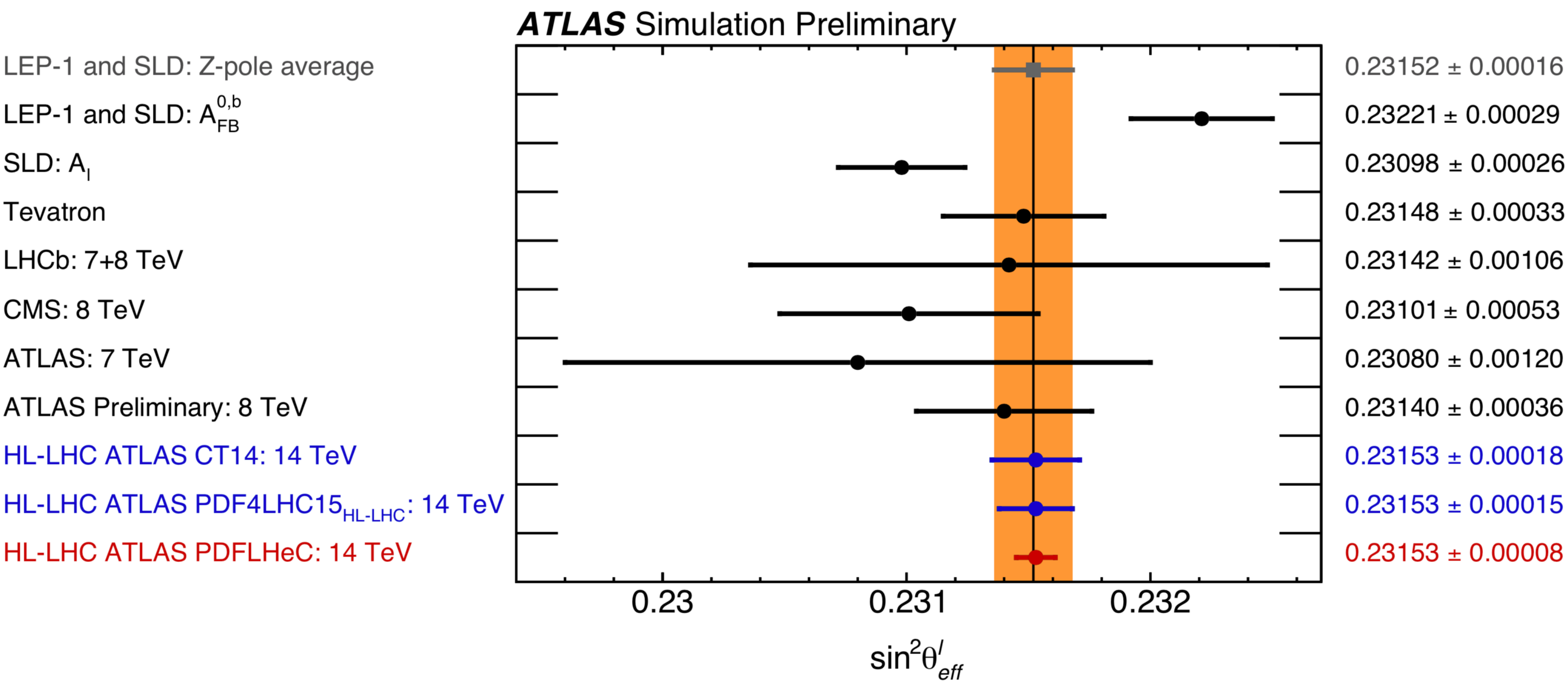


- No deviations from predictions observed
- Constrains on $\kappa_c, \kappa_b, \kappa_t$ and dimension-6 operators in the EFT approach can be derived



$\sin^2\vartheta_W$ with projections

ATL-PHYS-PUB-2018-037



Measurement of $\sin^2\vartheta_W$

- $\sin^2\vartheta_W$ provides an indirect measurement of W mass

$$\sin^2\theta_{\mathrm{W}} = 1 - M_{\mathrm{W}}^2/M_{\mathrm{Z}}^2$$

- Z decays are sensitive to the axial and vector lepton couplings,

at tree level:
$$v_{\mathrm{f}} = T_3^{\mathrm{f}} - 2Q_{\mathrm{f}}\sin^2\theta_{\mathrm{W}},$$
$$a_{\mathrm{f}} = T_3^{\mathrm{f}},$$

and allow the measurement of $\sin^2\vartheta_{eff}^{lept}$

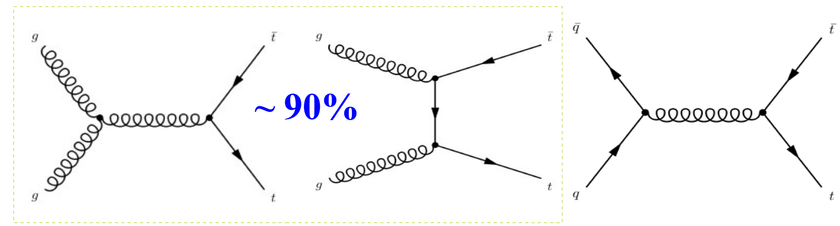
$$v_{\mathrm{f}}/a_{\mathrm{f}} = 1 - 4|Q_{\mathrm{f}}|\sin^2\theta_{\mathrm{eff}}^{\mathrm{f}} \qquad \sin^2\theta_{\mathrm{eff}}^{\mathrm{f}} = \kappa_{\mathrm{f}}\sin^2\theta_{\mathrm{W}}$$

Enhanced Born Approximation (EBA

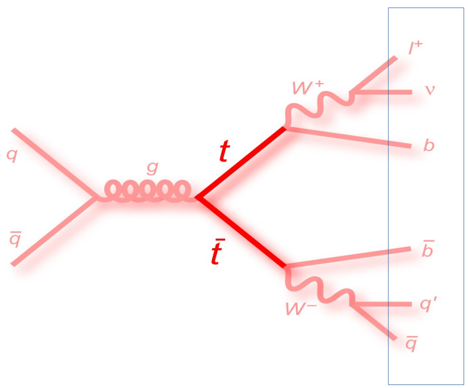
- Will help to disentangle LEP/SLD tension (3.2σ)
  - $\sin^2\vartheta_{eff}$ from A_{FB}^{0b} (LEP) = 0.23221 ± 0.00029
  - $\sin^2\vartheta_{eff}$ from A_l(SLD) → 0.23098 ± 0.00026

Top pair production and decay

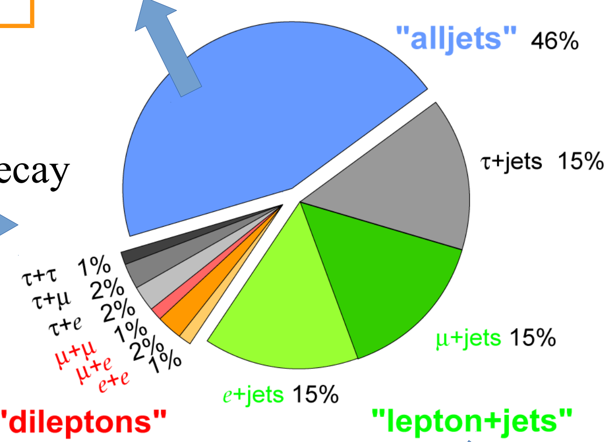
E_{COM}^{LHC}	σ_{tt} (m_t = 172.5 GeV)[1]
7 TeV	$177.31^{+10.1}_{-10.8}$
8 TeV	$252.89^{+13.3}_{-14.5}$
13 TeV	$831.76^{+40.2}_{-45.6}$



- high rate, large background
- Used with more data



Based on W decay



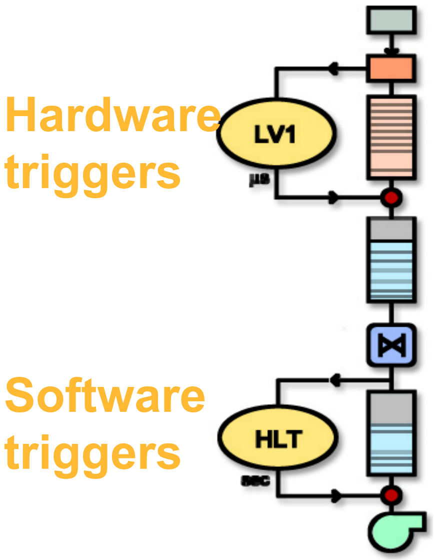
- Low rate but clean
- Early measurement

- Moderate rate, moderate background
- Early differential measurement

[1]https://twiki.cern.ch/twiki/bin/view/LHCPhysics/TtbarNNLO

Trigger and Data Acquisition

- The trigger system must be able to take in real time the decision of which collisions must be saved
- 2-level trigger systems



40 MHz
- Design input: 40 MHz

100 KHz
- Level1 output 100 KHz

O(1) kHz
- High Level Trigger output O(1) kHz (saved for physics analysis)

- The HLT has access to the full event information

$t\bar{t}H$ production with H→γγ

ATLAS-CONF-2019-004

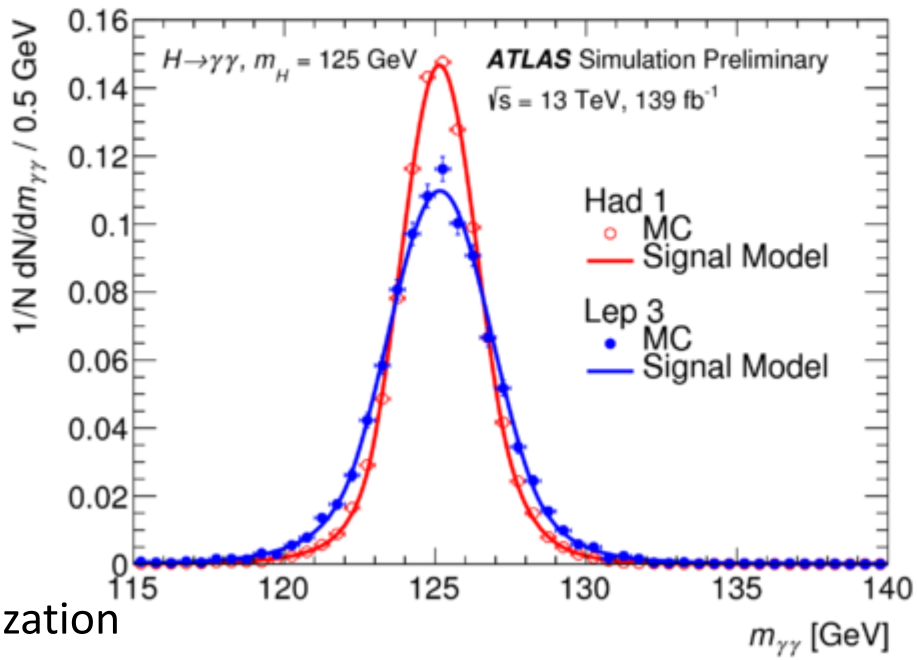
pp collisions
139±2 fb^{-1} @ $\sqrt{s}$ = 13 TeV

- updated photon identification and jet calibration
- <PU> = 23 (2015-16) up to 37 (2017-18)
- data-driven background estimations
- simultaneous fit in seven signal-enriched event categories

$\boldsymbol{\sigma\,(t\bar{t}H) \times B_{\gamma\gamma} = 1.59^{+0.43}_{-0.39}}$ **fb**

in agreement with SM prediction

significance of 4.9 (4.2 expt) σ



Powheg generator – PDF 4LHC15

+ Pythia8 (A14 set) parton showering/hadronization