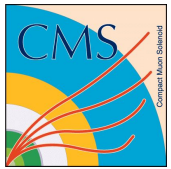
Standard Model, Top and Higgs physics at the LHC

Andy Buckley, University of Glasgow
for the LHC collaborations

IoP HEPP 2022, 4 April 2022



SM, top-quark, and Higgs physics

To state the obvious, this is a *huge* topic!
A ~20 min summary has to be selective: most focus on latest

Make sure all "characters" of this physics are represented:

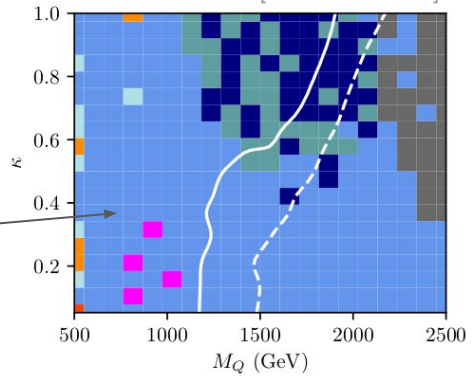
- "SM" is about understanding the complex dynamics of these fields. Just because it's known to exist doesn't mean we know how it behaves
- "SM" also isn't about SM! Testing agreement with models ⇒ understand & constrain BSM-search backgrounds, *and* test BSM generically

Spend ~equal time on each of QCD, EW, top, and Higgs

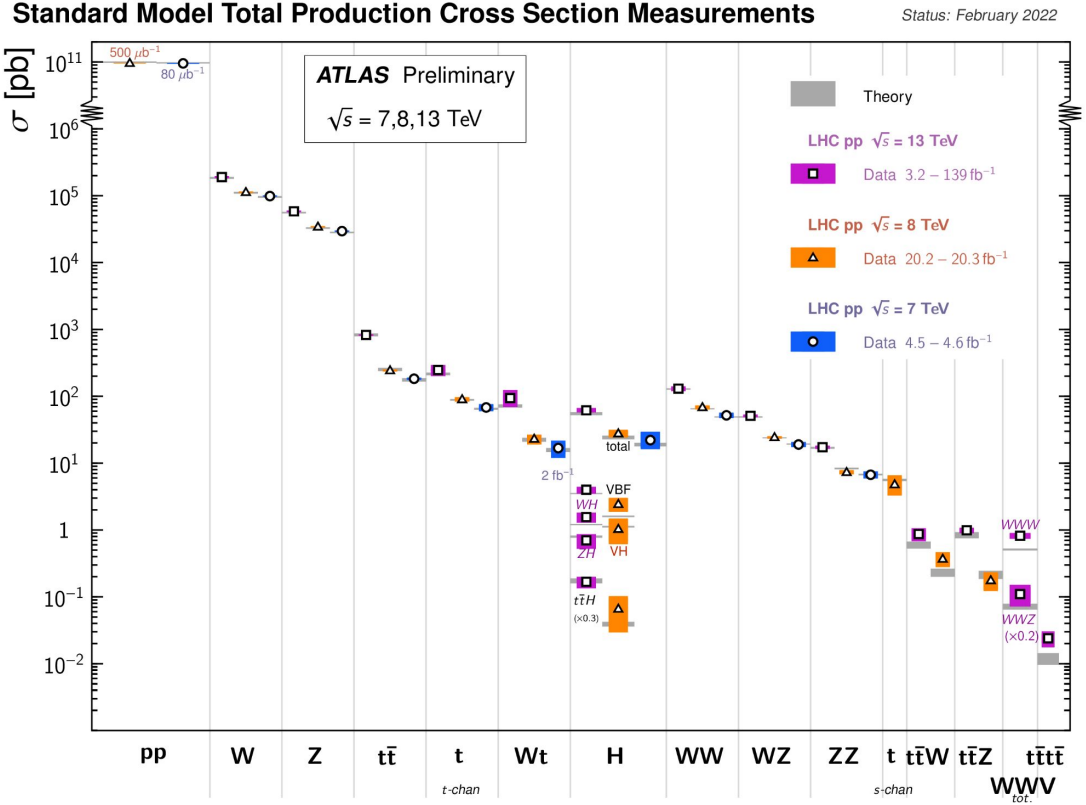
Good things: fiducial unfolding ~everywhere, and always-improving analysis preservation and re-use

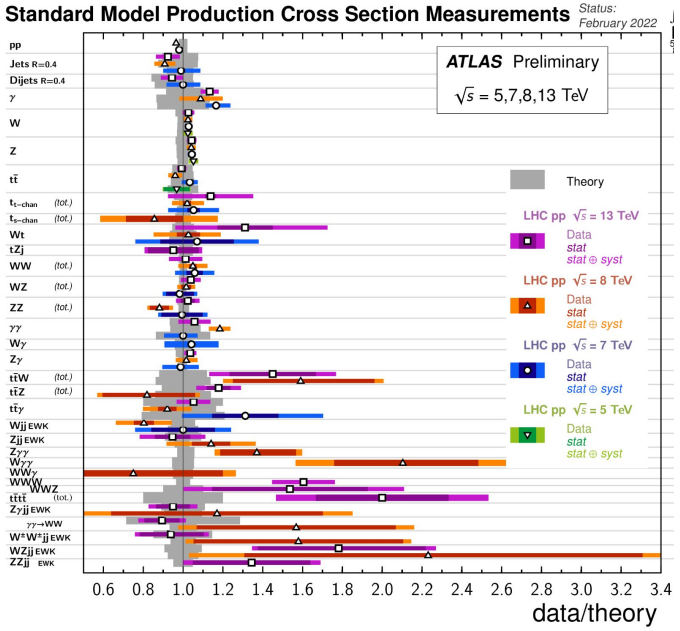
Huge thanks to Lepton-Photon & Moriond summary speakers!

[arXiv:2006.07172]

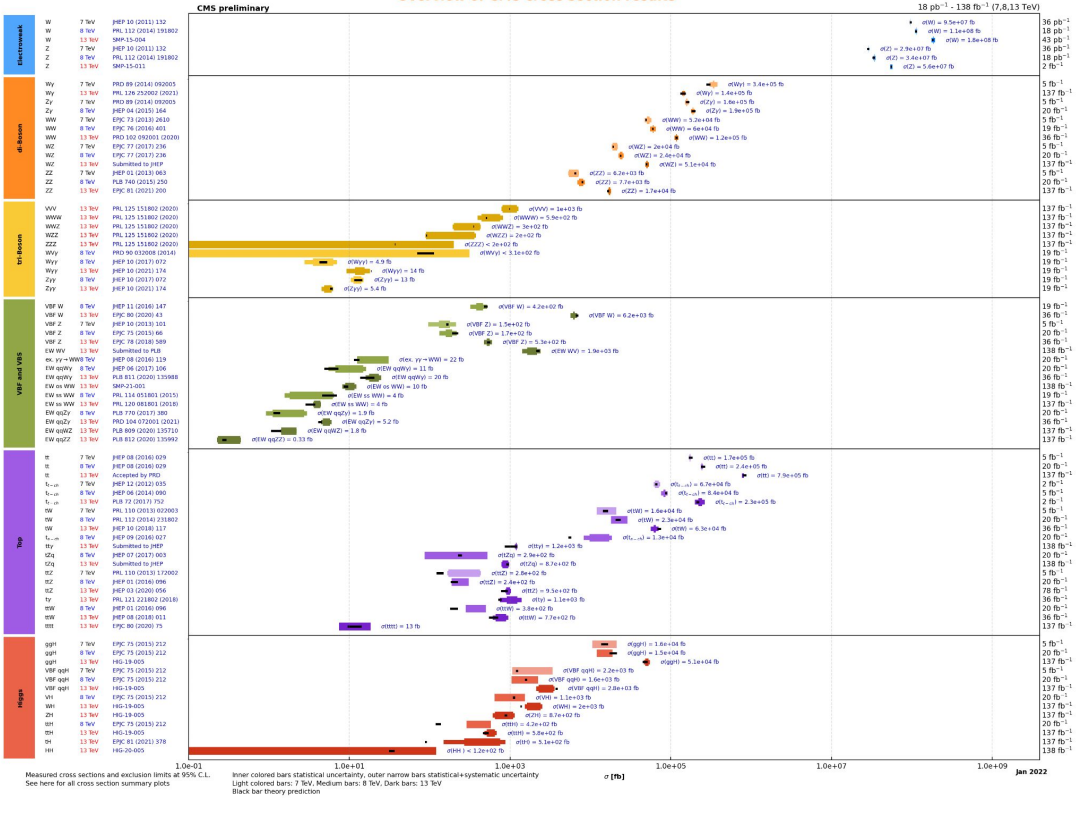


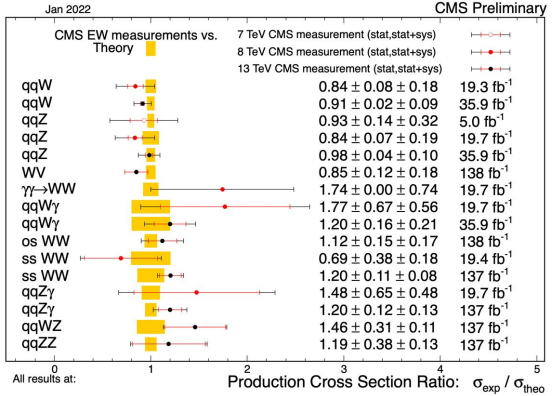
Summary (ATLAS)

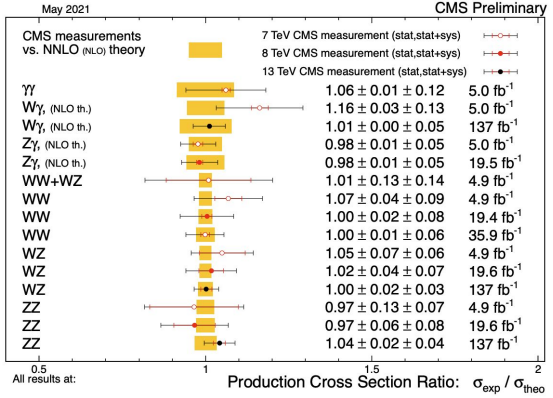




Summary (CMS)


Overview of CMS cross section results
CMS preliminary
Electroweak
di-Boson
tri-Boson
VBF and VBS
Top
Higgs
Measured cross sections and exclusion limits at 95% C.L.
See here for all cross section summary plots
Inner colored bars: statistical uncertainty, outer narrow bars: statistical+systematic uncertainty
Light colored bars: 7 TeV, Medium bars: 8 TeV, Dark bars: 13 TeV
Black bar theory prediction
σ [fb]
Jan 2022


Jan 2022
CMS Preliminary
CMS EW measurements vs. Theory
7 TeV CMS measurement (stat,stat+sys)
8 TeV CMS measurement (stat,stat+sys)
13 TeV CMS measurement (stat,stat+sys)
qqW 0.84 ± 0.08 ± 0.18 19.3 fb-1
qqW 0.91 ± 0.02 ± 0.09 35.9 fb-1
qqZ 0.93 ± 0.14 ± 0.32 5.0 fb-1
qqZ 0.84 ± 0.07 ± 0.19 19.7 fb-1
qqZ 0.98 ± 0.04 ± 0.10 35.9 fb-1
WV 0.85 ± 0.12 ± 0.18 138 fb-1
γγ→WW 1.74 ± 0.00 ± 0.74 19.7 fb-1
qqWγ 1.77 ± 0.67 ± 0.56 19.7 fb-1
qqWγ 1.20 ± 0.16 ± 0.21 35.9 fb-1
os WW 1.12 ± 0.15 ± 0.17 138 fb-1
ss WW 0.69 ± 0.38 ± 0.18 19.4 fb-1
ss WW 1.20 ± 0.11 ± 0.08 137 fb-1
qqZγ 1.48 ± 0.65 ± 0.48 19.7 fb-1
qqZγ 1.20 ± 0.12 ± 0.13 137 fb-1
qqWZ 1.46 ± 0.31 ± 0.11 137 fb-1
qqZZ 1.19 ± 0.38 ± 0.13 137 fb-1
All results at:
Production Cross Section Ratio: σexp / σtheo


May 2021
CMS Preliminary
CMS measurements vs. NNLO (NLO) theory
7 TeV CMS measurement (stat,stat+sys)
8 TeV CMS measurement (stat,stat+sys)
13 TeV CMS measurement (stat,stat+sys)
γγ 1.06 ± 0.01 ± 0.12 5.0 fb-1
Wγ, (NLO th.) 1.16 ± 0.03 ± 0.13 5.0 fb-1
Wγ, (NLO th.) 1.01 ± 0.00 ± 0.05 137 fb-1
Zγ, (NLO th.) 0.98 ± 0.01 ± 0.05 5.0 fb-1
Zγ, (NLO th.) 0.98 ± 0.01 ± 0.05 19.5 fb-1
WW+WZ 1.01 ± 0.13 ± 0.14 4.9 fb-1
WW 1.07 ± 0.04 ± 0.09 4.9 fb-1
WW 1.00 ± 0.02 ± 0.08 19.4 fb-1
WW 1.00 ± 0.01 ± 0.06 35.9 fb-1
WZ 1.05 ± 0.07 ± 0.06 4.9 fb-1
WZ 1.02 ± 0.04 ± 0.07 19.6 fb-1
WZ 1.00 ± 0.02 ± 0.03 137 fb-1
ZZ 0.97 ± 0.13 ± 0.07 4.9 fb-1
ZZ 0.97 ± 0.06 ± 0.08 19.6 fb-1
ZZ 1.04 ± 0.02 ± 0.04 137 fb-1
All results at:
Production Cross Section Ratio: σexp / σtheo

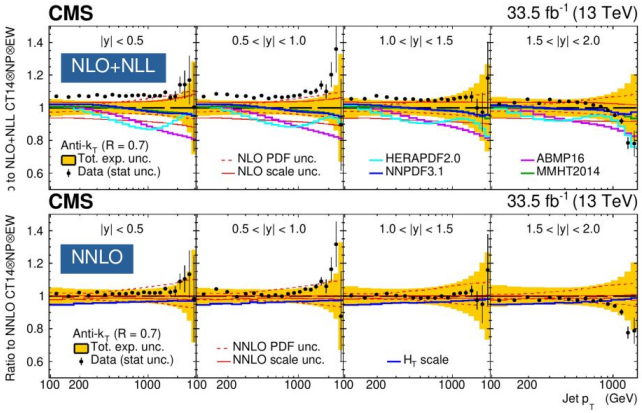
QCD

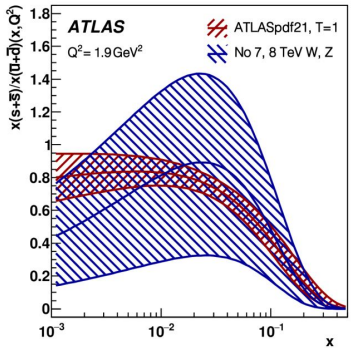
Jet-event spectra

(apologies, no time for inclusive QCD)

Inclusive jet distributions covered in great detail: e.g. recent CMS double-differential measurements of jet distributions [CMS-SMP-20-011,CMS-SMP-21-009]
→ gluon PDF, α_s, contact-interaction limits.

Plus ATLAS jet-data impact on PDF-fits

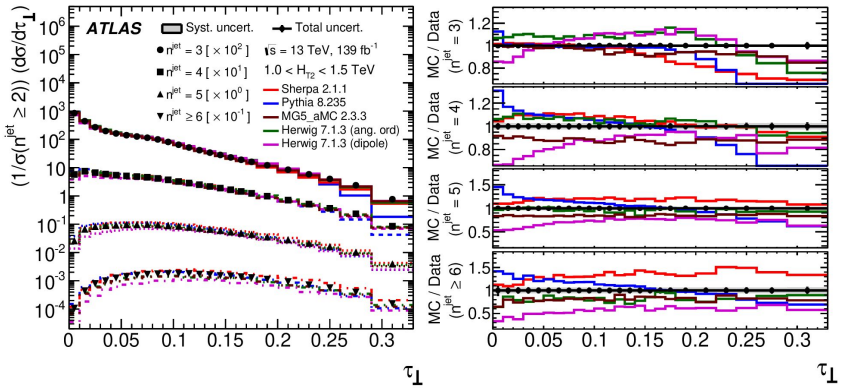




[arXiv:2112.11266 + EPJC]

Also more exclusive multijet measurements, breaking down into p_T's etc. of leading *N* jets, jet multiplicities, angular distributions: tests of pQCD methods [CMS-SMP-21-006]
and ATLAS 139/fb multijet event shapes [JHEP 01 (2021) 188]

All systematics-dominated

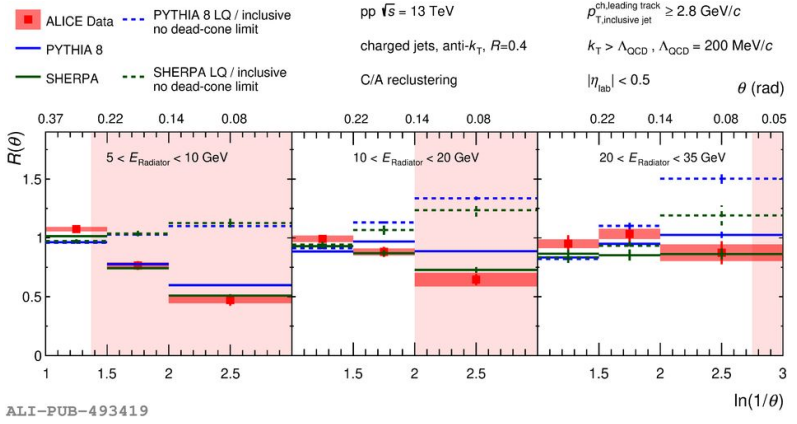


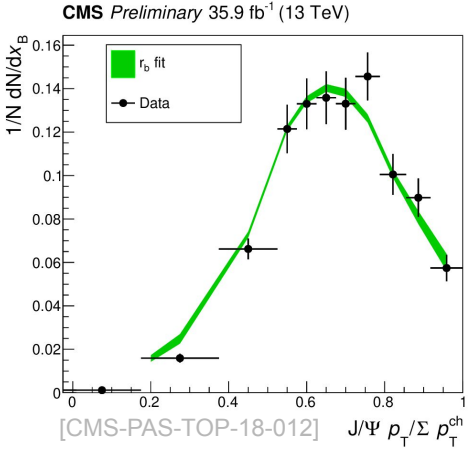
Jet structure

Emergence of structure in jets, particularly HF, is a relatively uncontrolled aspect of (semi-)pQCD

ALICE dead-cone measurement in pp: medium-enhancement of PS splittings [arXiv:2106.05713]

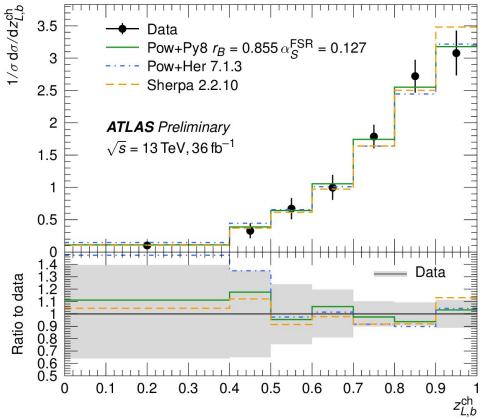
ATLAS+CMS jet fragmentation: light q/g; b in tt (D-mesons & track-jets): *plethora* of data for MC devel

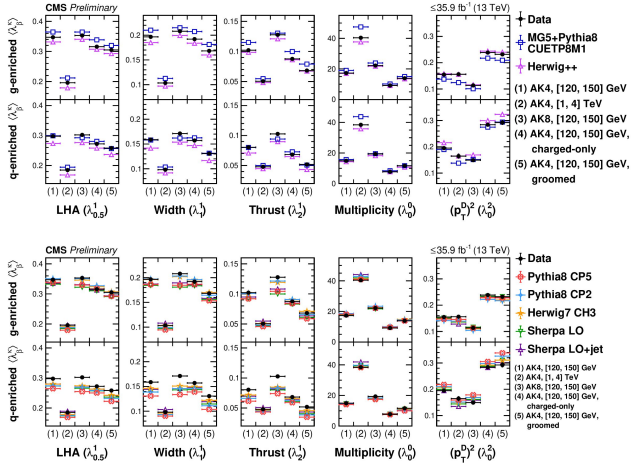




[CMS-PAS-TOP-18-012]

[ATLAS-CONF-2020-050]





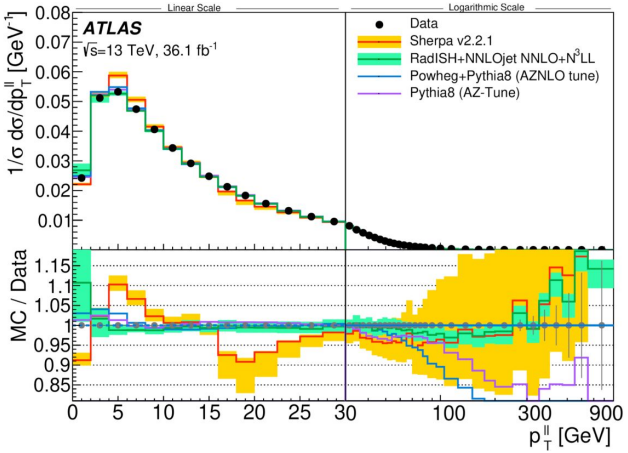
[CMS-PAS-SMP-20-010]

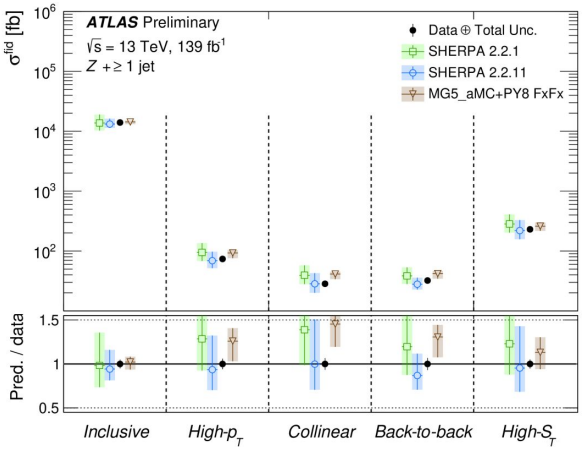
Jets + electroweak

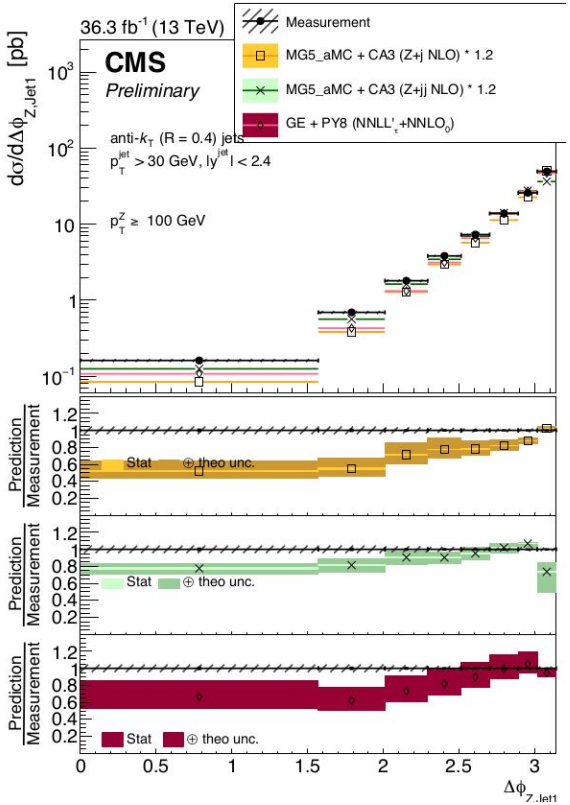
A key test for pQCD: natural Q^2 scale, clean measurements

Ideal for comparisons to higher-order calculations, input to HF PDFs. Also a key background for (particularly) leptophilic BSM

Differential kinematics of Z p_T, Z-jet dφ, and collinear real-Z radiation from jets [EPJC 80 (2020) 616, CMS-PAS-SMP-21-003, ATLAS-CONF-2021-033]







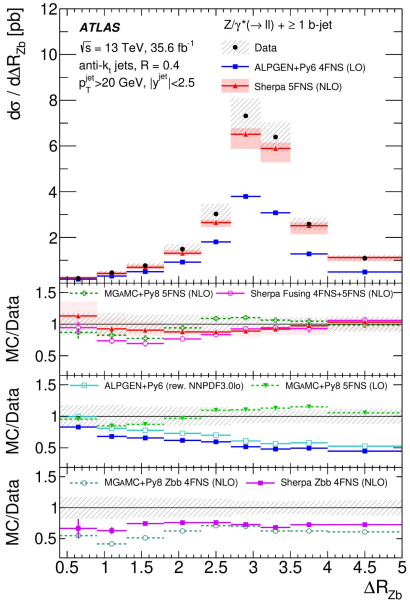
Weak-boson + HF jets (sorry, not enough space for γ+jet)

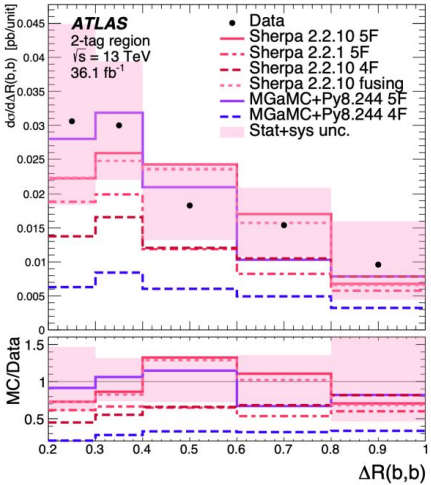
CMS W+c suggests ATLASPDF tension [EPJC 79 (2019) 269].

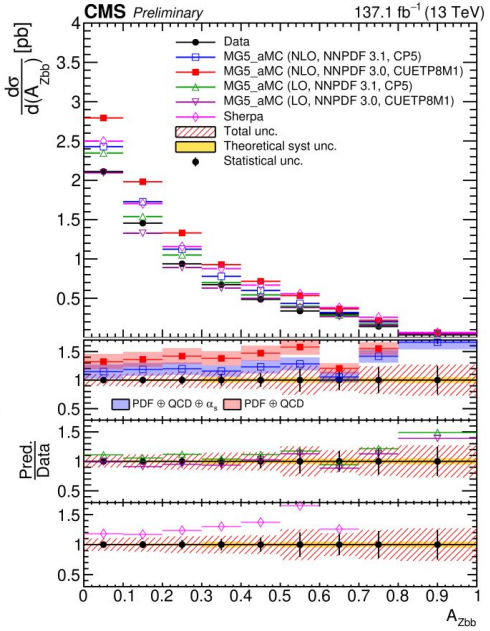
CMS Z+c/b: too much HF in NLO PDFs?
[JHEP 04 (2021) 109, CMS-PAS-SMP-20-015]

$$A_{ZBB} = \frac{\max\Delta R_{ZB} - \min\Delta R_{ZB}}{\max\Delta R_{ZB} + \min\Delta R_{ZB}}$$

CMS Z+bb angular asymmetry ⇒
[CMS-SMP-20-015 → PRD]







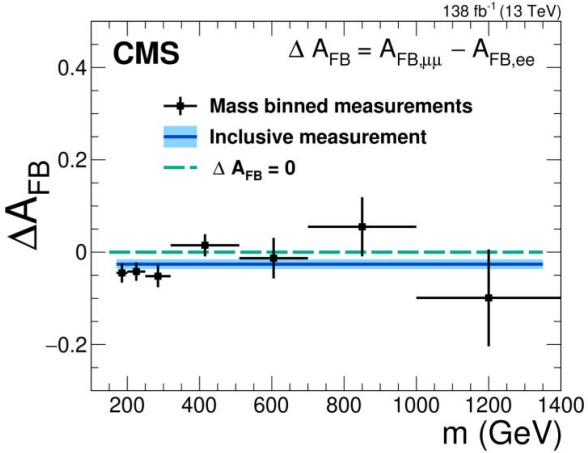
⇐ ATLAS Zb(b) resolved and boosted measurements
[JHEP 2020 44 (2020), preprint TBC]

Electroweak

Inclusive single-boson

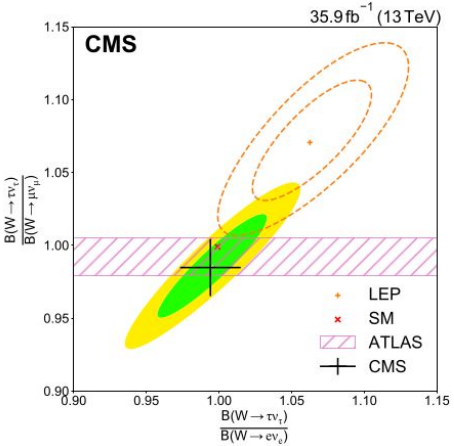
Inclusive or semi-inclusive single-boson events are a key means for precision EW coupling measurements

New CMS A_{FB}; template fit method, 138/fb, $m_{\ell\ell}$ > 170 GeV. Independent fits in 7 mass bins ⇒ constraint on extra Z' mass > 4.4 TeV. Inclusive 2.4σ discrepancy in LFU:



Lepton-flavour universality tests via W branching fractions; ATLAS and CMS consistent, no sign of LEP anomaly:

	CMS	LEP	ATLAS	LHCb	CDF	D0
$R_{\mu/e}$	1.009 ± 0.009	0.993 ± 0.019	1.003 ± 0.010	0.980 ± 0.012	0.991 ± 0.012	0.886 ± 0.121
$R_{\tau/e}$	0.994 ± 0.021	1.063 ± 0.027	—	—	—	—
$R_{\tau/\mu}$	0.985 ± 0.020	1.070 ± 0.026	0.992 ± 0.013	—	—	—
$R_{\tau/\ell}$	1.002 ± 0.019	1.066 ± 0.025	—	—	—	—



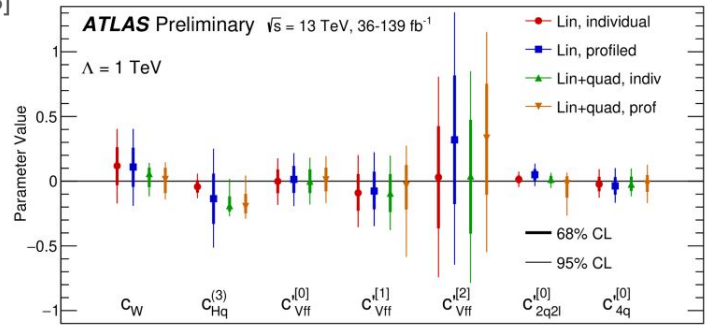
Multiboson results — ATLAS

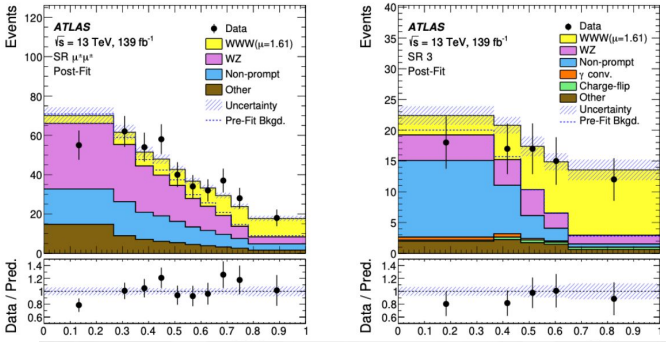
VV and VVV — direct sensitivity to BSM effects through directly or effectively modified EW couplings (aT/QGCs)

Observation of WWW, in 2 BDTs + binned LLR fit:
[arXiv:2201.13045]

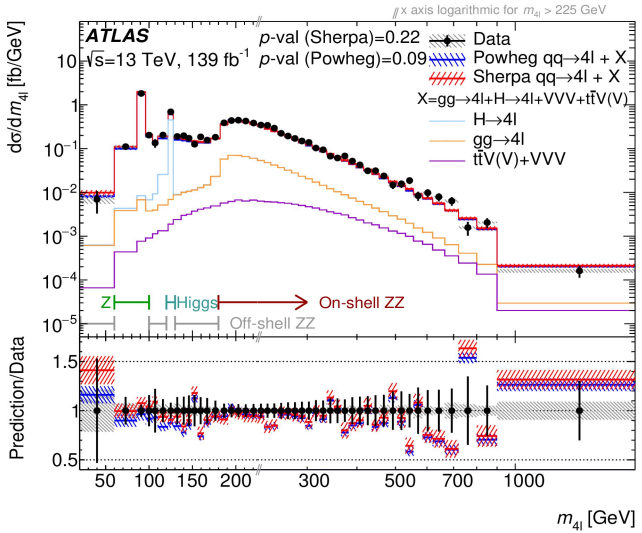
4ℓ [JHEP 07 (2021) 005] — model-indep fiducial $d\sigma/dm_{4\ell}$
+ angular dbns for polarisation models in $m_{4\ell}$ = 60-100 GeV

Combined 4ℓ, VV, Z+2j EFT interpretation in a linear-combination basis of fundamental EW operators:
[PRD 105 (2022) 052003]



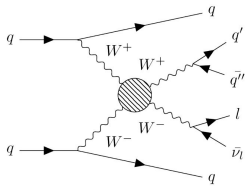


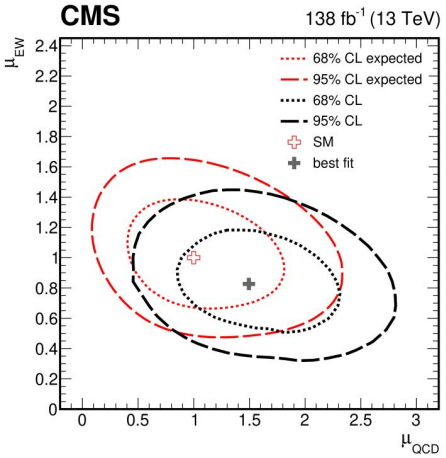
Fit	$\mu(WWW)$	Significance observed (expected)
Combined	**1.61 ± 0.25**	**8.0 (5.4) σ**



Multiboson results — CMS

Vector-boson fusion & scattering (1 or 2-boson weak production) key SM tests — connection to SM unitarity

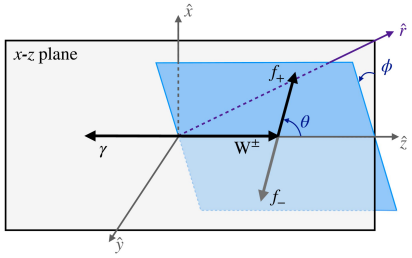


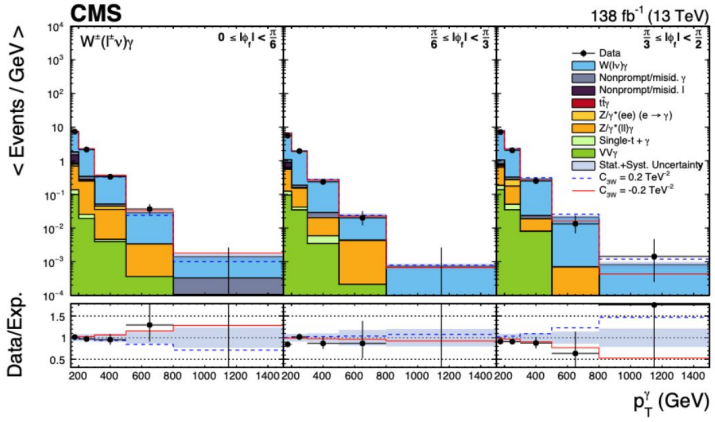


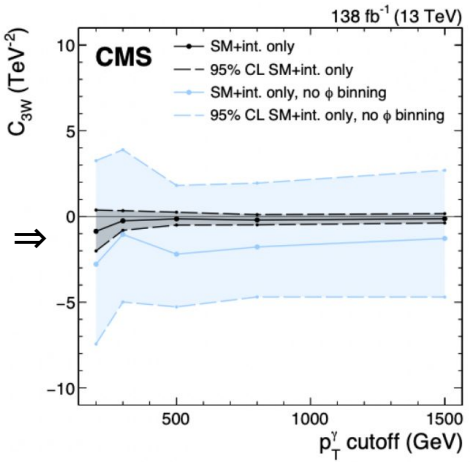
CMS evidence for WW/WZ ℓν qq VBS; 2 DNNs (resolved and boosted)
Assume μ_{QCD}= 1, μ_{EW}= 0.85 ± 0.22; or float both signal strengths:
[CMS-SMP-20-013]

Wγ differential cross-section measurements sensitive to WWV TGCs: indication of BSM effects. [Phys. Rev. D 105 (2022) 052003]

Increase in C_{3W} Wilson-coeff constraint by binning in φ_f angle:





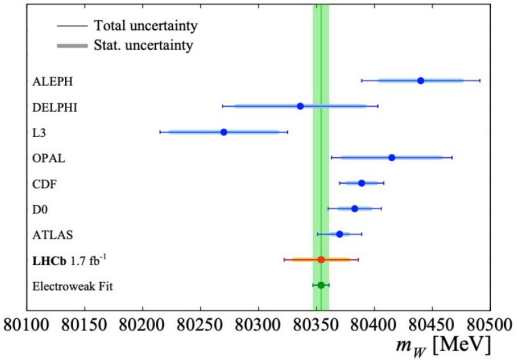


Forward bosons — LHCb

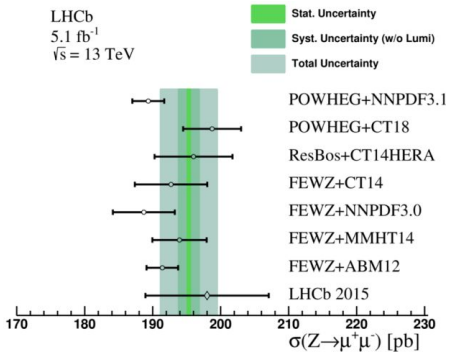
LHCb providing complementarity to GPDs: in W-mass measurement, PDF uncertainties anti-correlate
⇒ current analysis < 30% of R2, fit via templates…
and no MET requirement! [JHEP 01 (2022) 036]

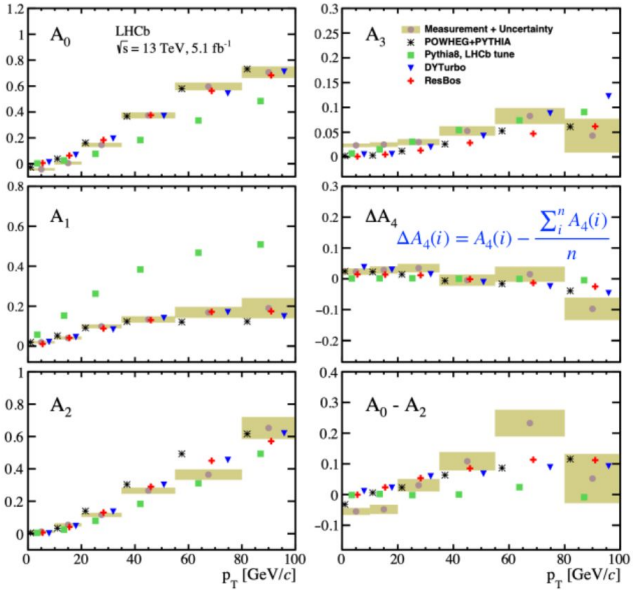
$$m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}\ \text{MeV}$$

Stat- and non-PDF theory dominated: eventually reduce PDF uncs in global fit (current Δm ~ 7 MeV)



Forward Z→ μμ: inclusive and double-diff cross-secs in y_Z and φ* vars; forward angular coeff analysis, A_n vs. p_T
[arXiv:2112.07458, arXiv:2203.01602]





Top quark

Top mass and properties

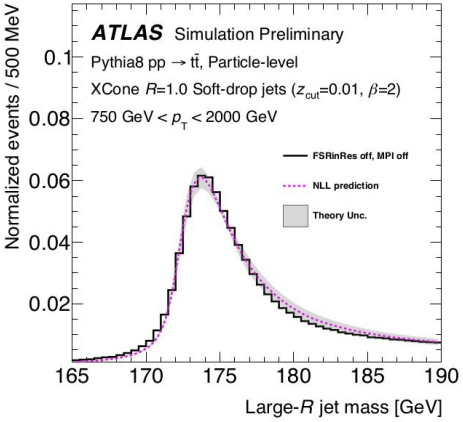
Familiar arguments: only fermion with y ~ 1, potential portal to BSM sensitivity, e.g. via FCNC searches and EFT fits

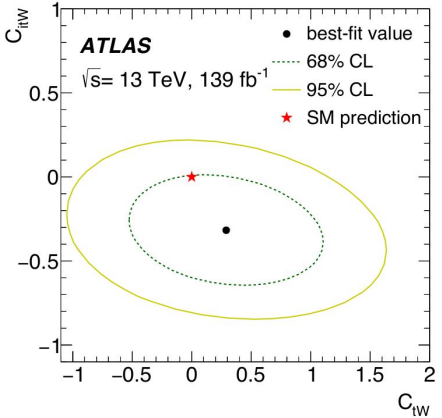
Distinction between direct, kinematically reconstructed “MC” mass and pole mass extracted via fixed-order fits to measured cross-sections. Mass average at ~173.3 ± 0.7 GeV.

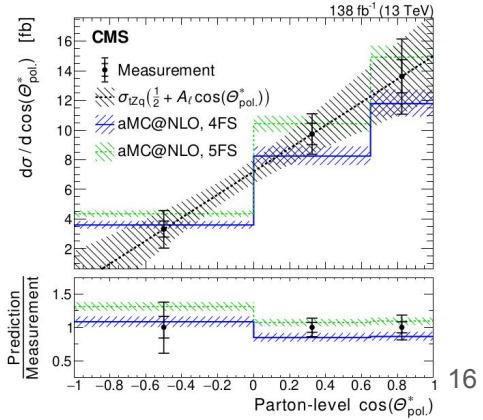
New measurements in single-top (CMS, [JHEP 12 (2021) 161]) and energy asymmetry (ATLAS, [arXiv:2110.05453]):
⇒ m_t = 172.13 ± 0.76 GeV — sub-% in single-t!

CMS pole-mass in dilepton tt, ± 1.37 GeV
[CMS-PAS-TOP-21-008]

Also, measurements of polarisation, spin asymmetry, more extraction of EFT-operator coeffs:







Top-pair cross-sections

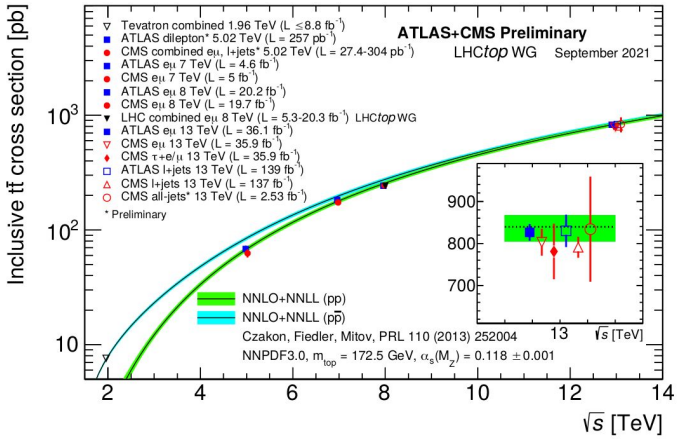
Central tt now at 13, 8, *and* 5 TeV — good agreement with NNLO+NNLL theory ⇒

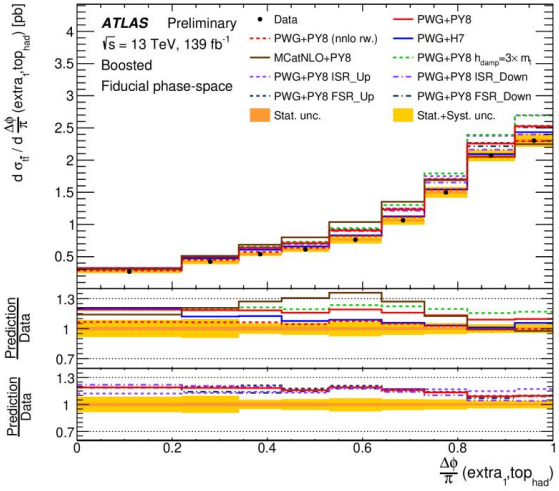
Forward dilepton tt by LHCb (2018) — jet tagging dominates syst uncertainties.

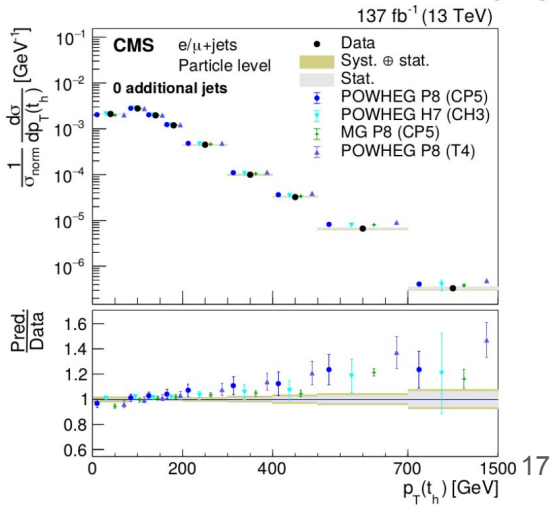
CMS combined boosted+resolved [Phys. Rev. D 104 (2021) 092013]

- $d\sigma/p_T(t_{had})$: longstanding disparity between theory and data: data softer, esp. in 0-jet selection.
- reduced uncertainties from combination of reco channels

ATLAS boosted tt — parton and fiducial dσ's, JES correction via m_t calibration. Fiducial -20% wrt predictions, but within systematics [arXiv:2202.12134]







Rare top channels

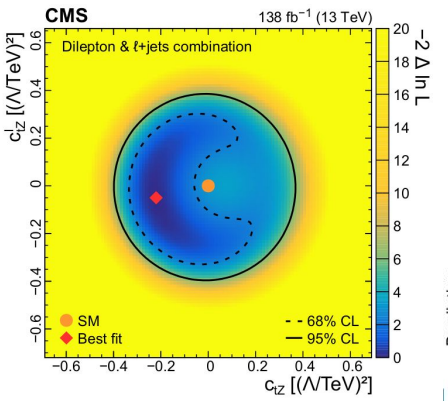
ttW and ttZ observed, both stat-limited, still need full Run 2 datasets (36+36/fb, 139+78/fb resp)

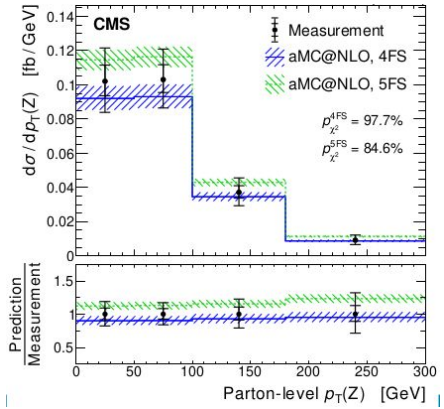
ttγ: measured by both, new CMS dilepton

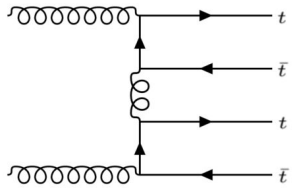
Weak production: tZq by ATLAS and CMS. [JHEP02 (2022) 107] NN classifier in event-selection: reproducible / re-use in BSM?

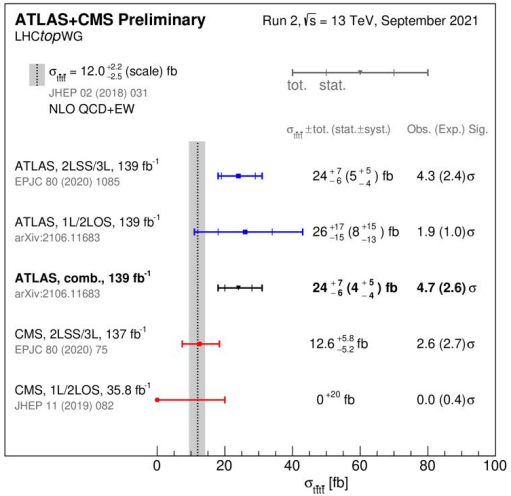
New t-chan single-top from CMS. tt and V+jet background rejection via BDT

tttt searches: σ ~ 12 fb, 70k tt event background for each tttt! Results from ATLAS and CMS: former close to 5σ (2 × μ_{exp}), latter ~3σ









Higgs

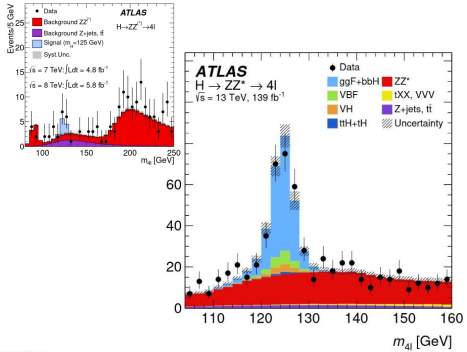
Higgs properties and interactions

10 years since the Higgs boson discovery
⇒ precise characterisation of its properties

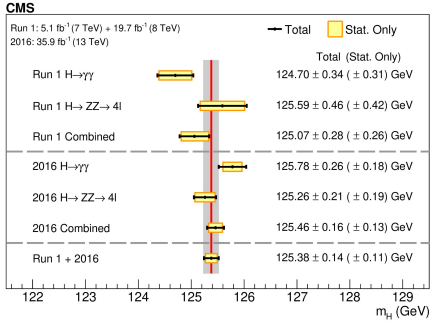
Mass important in combination with top mass as a constraint on vacuum meta-stability. Current average 125.25 ± 0.15 GeV

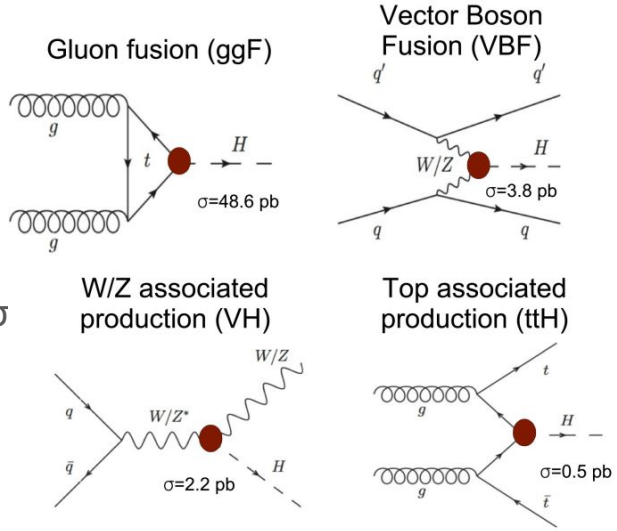
Consistency checks through combinations of different Higgs production and decay channels.

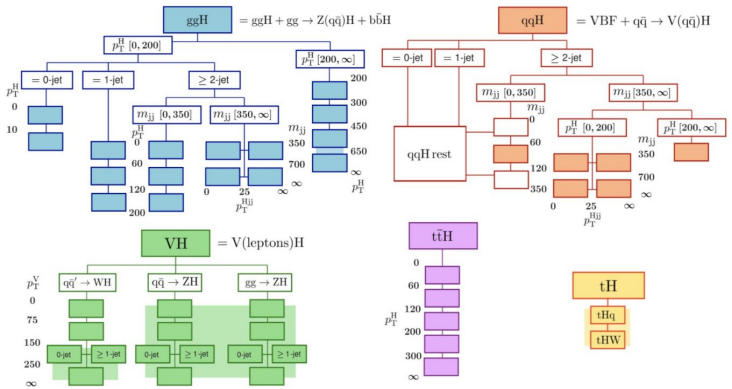
Extraction to “STXS” dσ grouped by prod mode; as stats increase, go full-differential/fiducial.



[CMS-HIG-19-004]





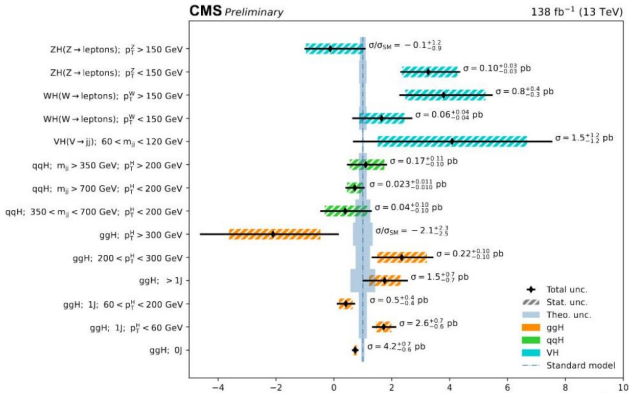


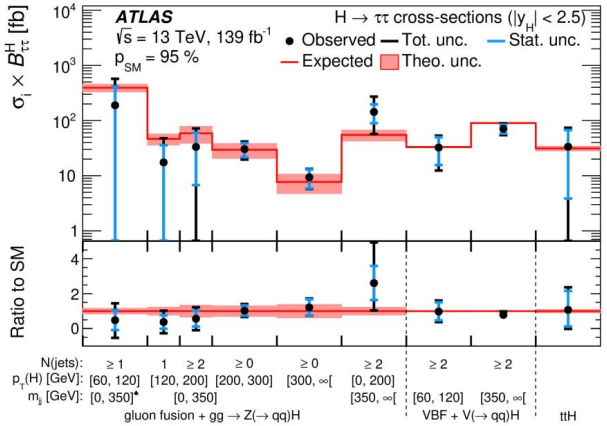
Higgs inclusive and STXS

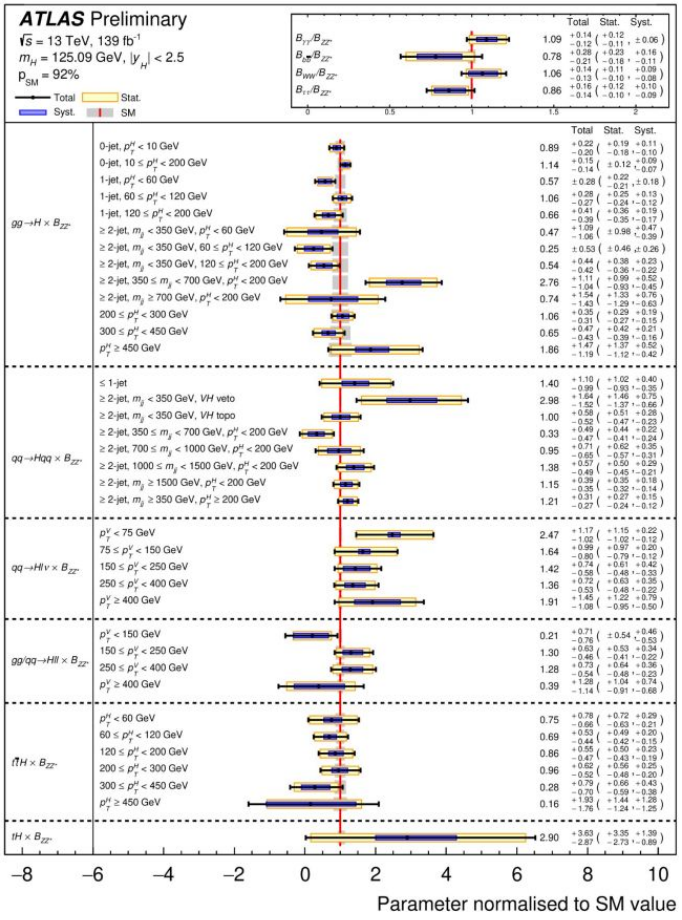
New CMS inclusive & STXS H→WW in ggF and VBF: ggF syst limited, more stat-limited for VBF+VH

ATLAS & CMS H→τ τ (both leptonic & hadronic). MVA-assisted.

⇒ STXS combination: still SM-consistent!



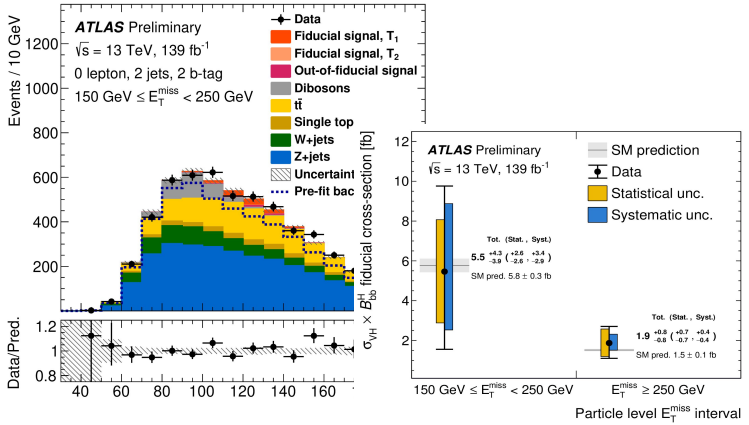




Higgs differential & fiducial

New ATLAS V(*vv*)H(bb) fiducial & differential measurements [ATLAS-CONF-2022-015] — 1,2-lepton channels as CRs.

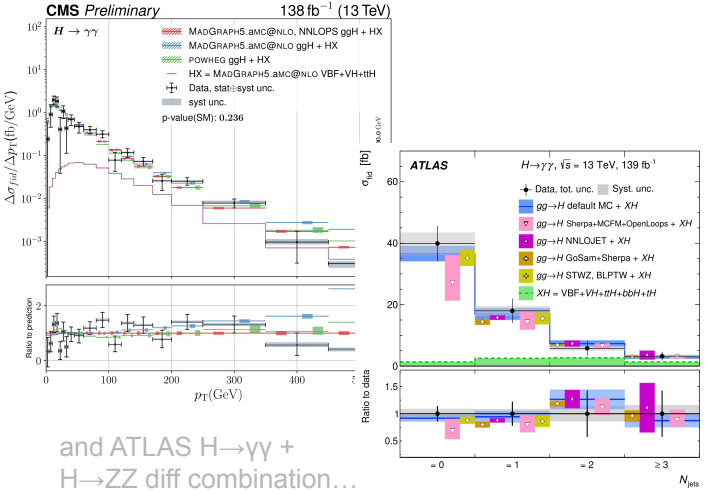
m_{bb} fit has less model-dependence than MVA methods. Unfolding in fit. Semi-differential: two $E_{T,miss}$ bins:



CMS [CMS-PAS-HIG-19-016] and ATLAS [arXiv:2202.00487] differential H→γγ; clean signature, full Run-2 stats. Fiducial cross-section 67 ± 6 fb extrapolated to 58 ± 6 pb: factor of 1000!

Differential cross-sections in p_T, y, $N_{(b)jets}$, m_{jj}, angles, … etc. Even double-differential! Tests of predictions and SM. Limits on b and c Yukawas via p_T spectrum; EFT interpretations

Run 3 stats will permit these differential Higgs measurements and interpretations with sensitivity to minor production modes



and ATLAS H→γγ + H→ZZ diff combination…

Higgs-fermion couplings

Fermion Yukawa couplings via both production and decay modes

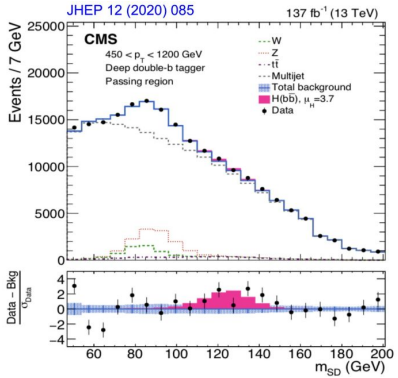
Prod: ttH & tH, most sensitive in H→γγ

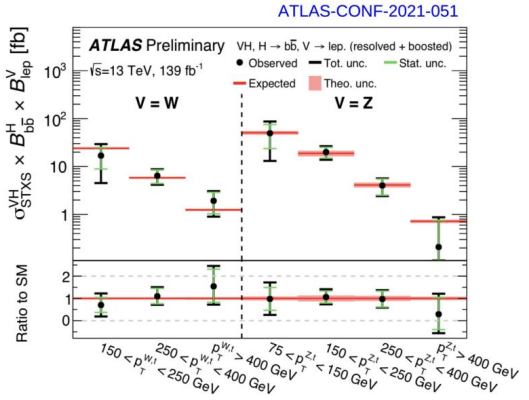
H→bb decay mode since 2018, use of boosted methods and p_T differential, σ ~ 2:

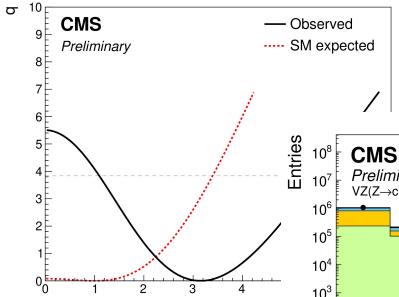
(H→τ τ from STXS shown earlier)

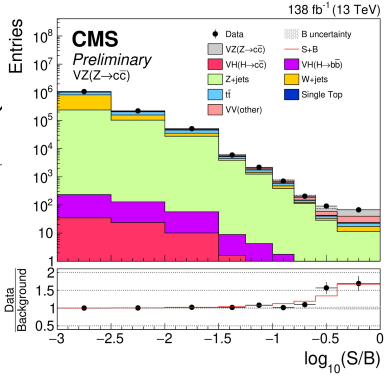
ATLAS & CMS H→cc searches:
CMS observes Z→cc at 5.7σ,
1.1 < κ < 5.5 ⇒ demonstrator for H→cc
[CMS-PAS-HIG-21-008]

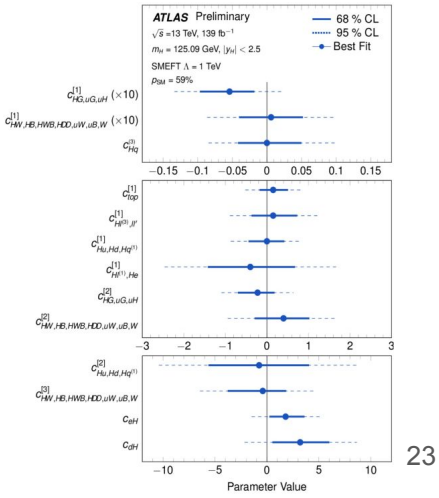
Combined fits in κ framework of coupling modification factors: looking very SM-consistent, up to ambiguities











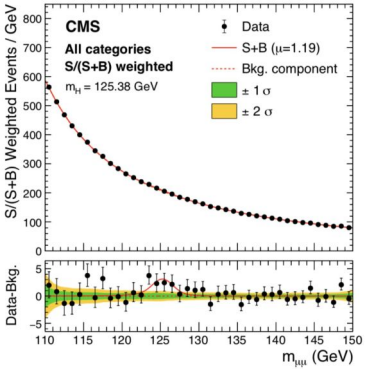
Rare Higgs channels and self-coupling

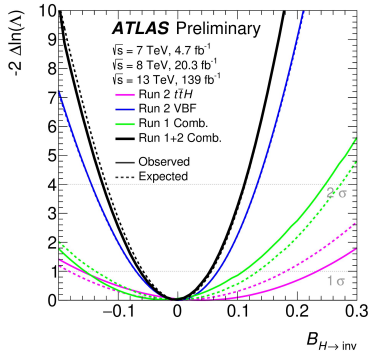
Lighter-fermion decay searches continue: μμ, ee, invisibles…

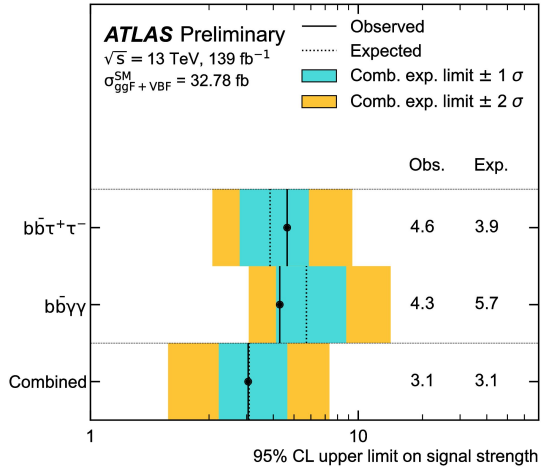
CMS evidence for H→μμ: 3.0σ vs 2.5 exp. Stat limited in all production modes, as expected [JHEP 01 (2021) 148]

Invisible decays [ATLAS-CONF-2020-052, arXiv:2201.11585]
- ATLAS VBF+MET, ttH+MET ⇒ BR < 11%
- CMS VBF+MET ⇒ BR < 18%

stat-limited, DM interpretations from fiducial MET measurement







… and HH! Self-coupling constrains the λ parameter. Check consistency of the Higgs potential between mass, VEV, HH.

Weak limits due to stat limitations: σ_{HH} ~ 30 fb, times BR and acceptance factors. Upper limits at ~3 times SM strength [ATLAS-CONF-2021-052, CMS-PAS-HIG-20-010]

Conclusion

Outlook

SM sectors being constrained from every angle by a multitude of increasingly precise measurements and sophisticated in-house interpretations.

Differential, fiducial, precision — mature phase of LHC.
A huge challenge for theory and MC / computing.

Excellent way to do science: say what you see, understand the detector, minimise extrapolations, maximise re-use.

BDT & DNN analyses useful for power, initial results; jury still out on how to incorporate into reproducible results

Analysis combination needs big strategy: done in focused domains, e.g. aT/QGCs & Higgs STXS, less for generic measurements. Few standalone “silver bullet” analyses

⇒ Analysis-preservation and statistical metadata are key considerations for making the most of Run-2 and 3 data