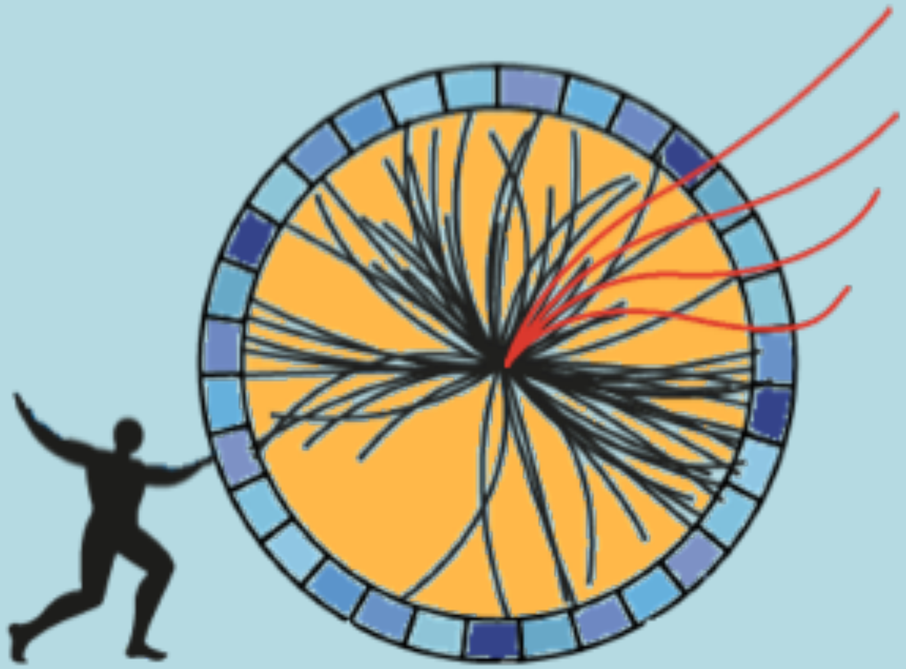

Highlights on Standard Model measurements from ATLAS and CMS experiments at the LHC

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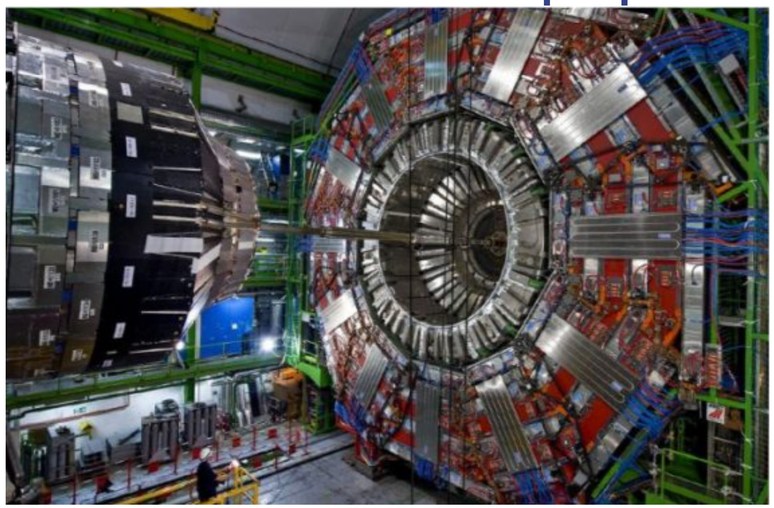
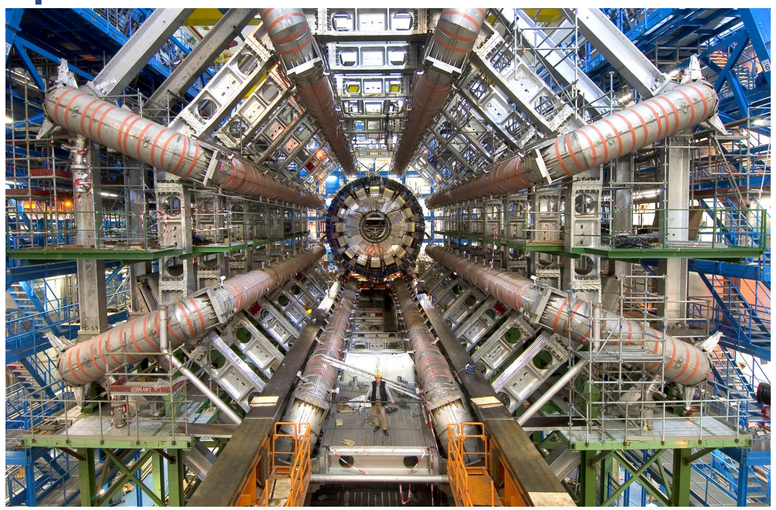
13 September 2021

CMS and ATLAS at the LHC

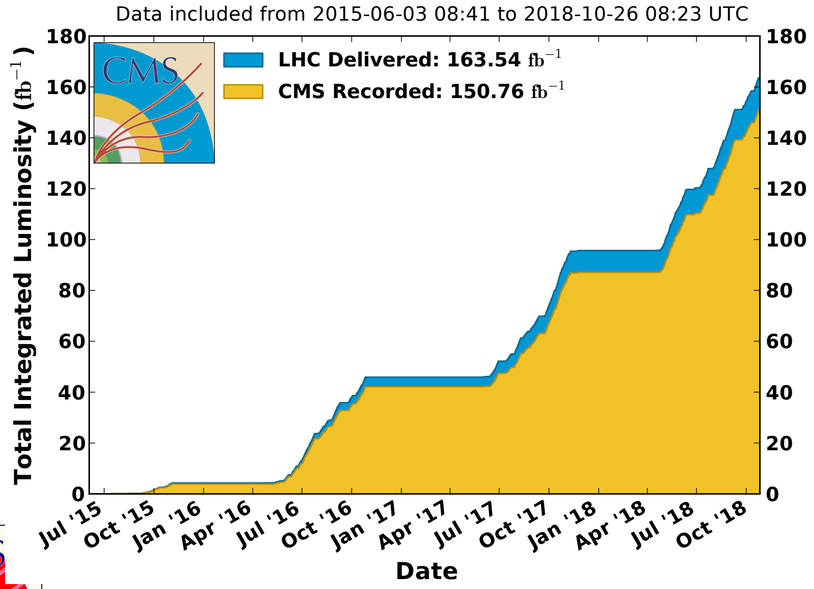
CMS and ATLAS multipurpose experiments at the LHC





LHC ran at √s = 13 TeV from 2015-2018 in pp and heavy ion collisions (Run 2)

Extremely successful Run 2
→dataset is a goldmine for physics



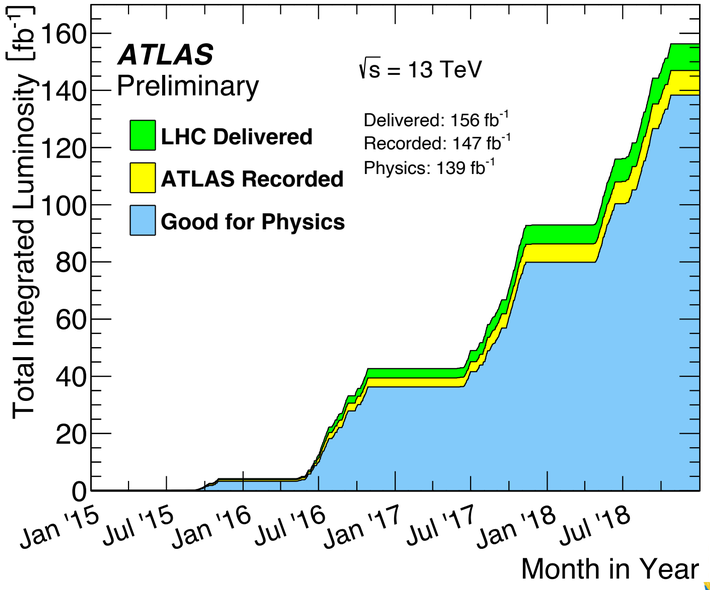
Luminosity:

- Recorded luminosity ~150 fb^{-1}
- **Good for physics luminosity ~140 fb^{-1}**

High pileup data: $\langle\mu\rangle$ ~34

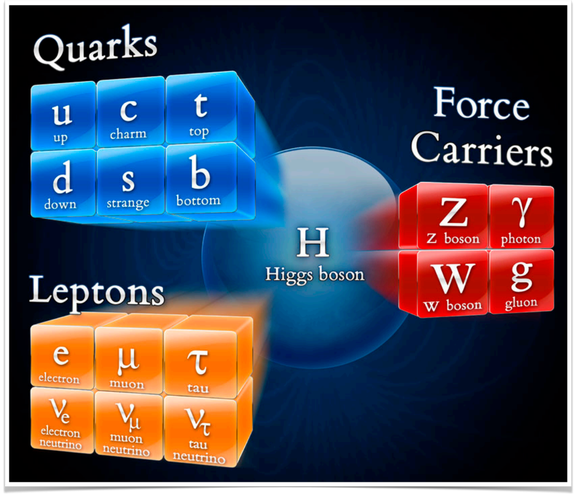
Precise calibration of physics objects:

- lepton efficiencies <1% *e*, ~0.1% μ
- Jet Energy Scale ~1-3% for p_T>30 GeV



Why Standard Model Physics?

- **Standard Model** (SM): **extremely predictive theory successfully verified by experiments** for about 50 years
- After the Higgs boson discovery, SM measurements has two main goals:
  - **validate SM** in new energy regime and **improve precision** of SM parameters
  - **test SM for new physics contributions** (indirect search) and **provide information about SM processes to tune MC** (background to direct new physics searches)



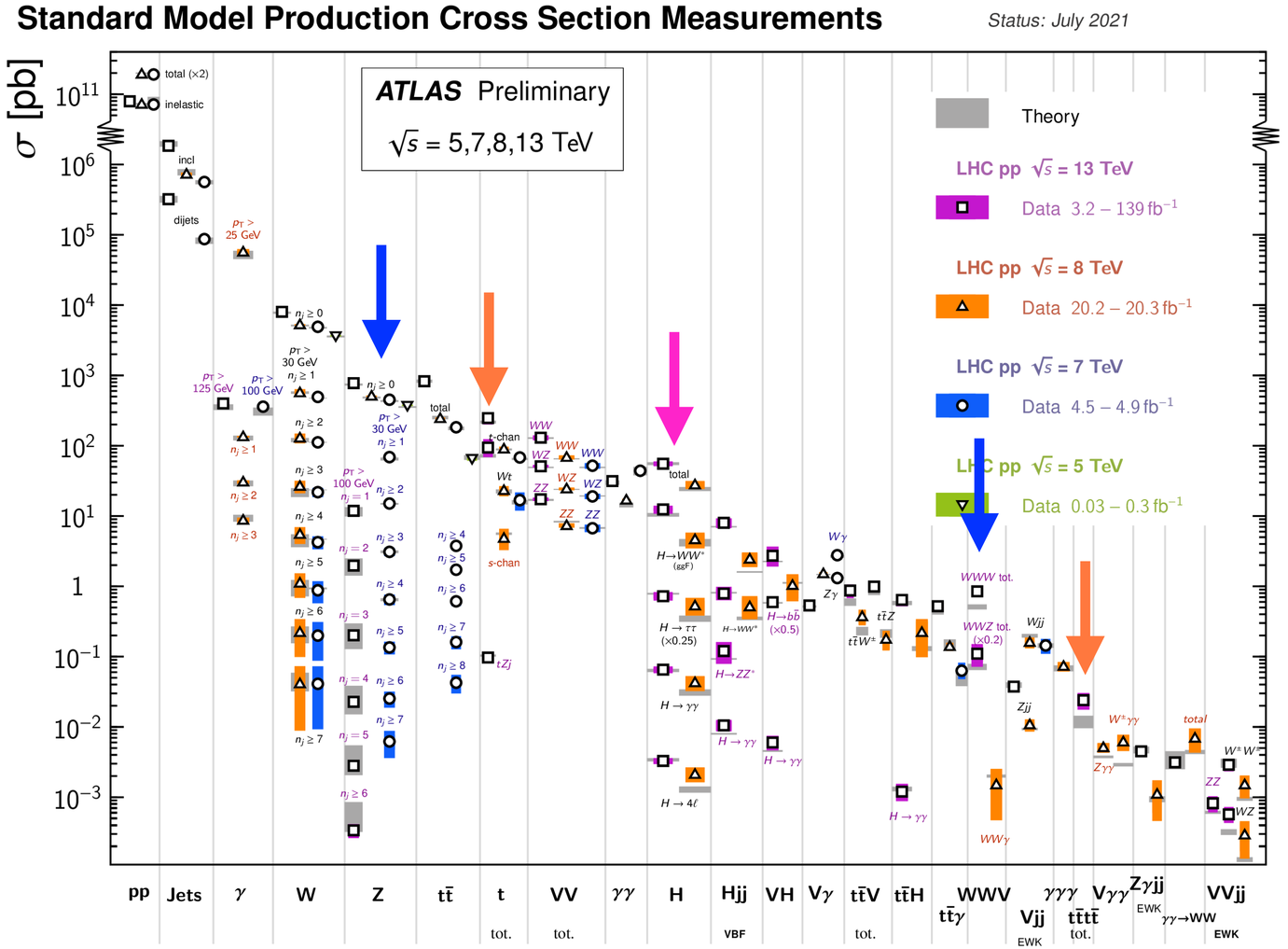
This talk: results on Standard Model physics by CMS and ATLAS focusing on

- ➤ **High precision measurements**
- ➤ **Rare processes**
- ➤ **SM as probe for new physics**

A selection of measurements is presented. Links with complete list of public results: **CMS** **ATLAS**

Results on SM physics by CMS and ATLAS

- Wide variety of measurements of (differential) **production processes,** spanning **14 orders of magnitude**
- **Check theory calculations** → deviations may indicate new physics, EFT interpretation

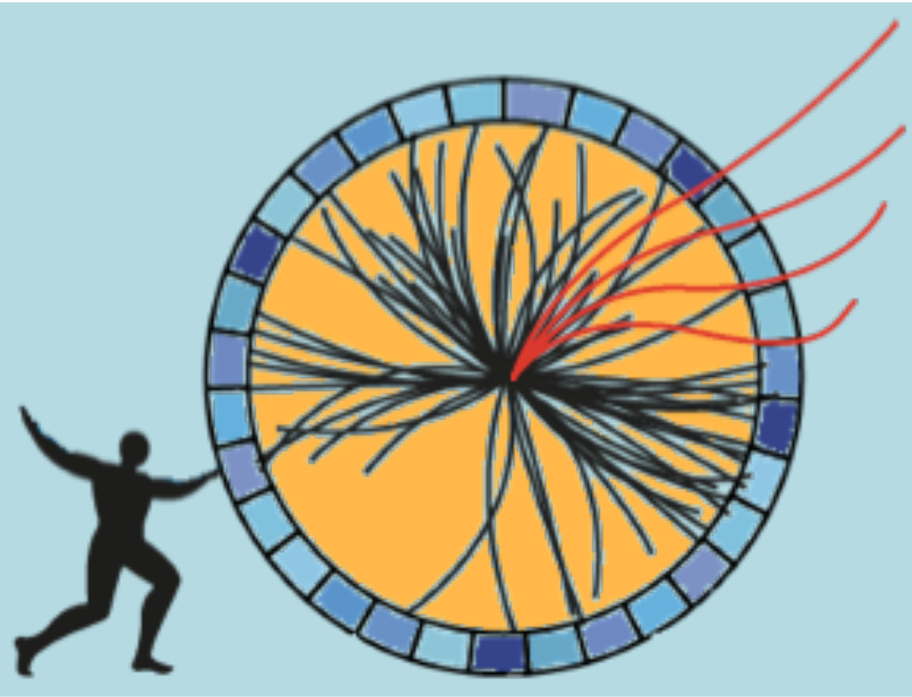


- **W/Z**, ɣ, jets, **di(tri)-boson production**, precision measurements of EWK parameters, soft QCD

- **Top-quark** physics, **top-pairs** production

- **Higgs boson** and **HH** (non resonant) productions, Higgs properties

*More **QCD-related measurements** in F.Giuli & V.Mariani's talk.*



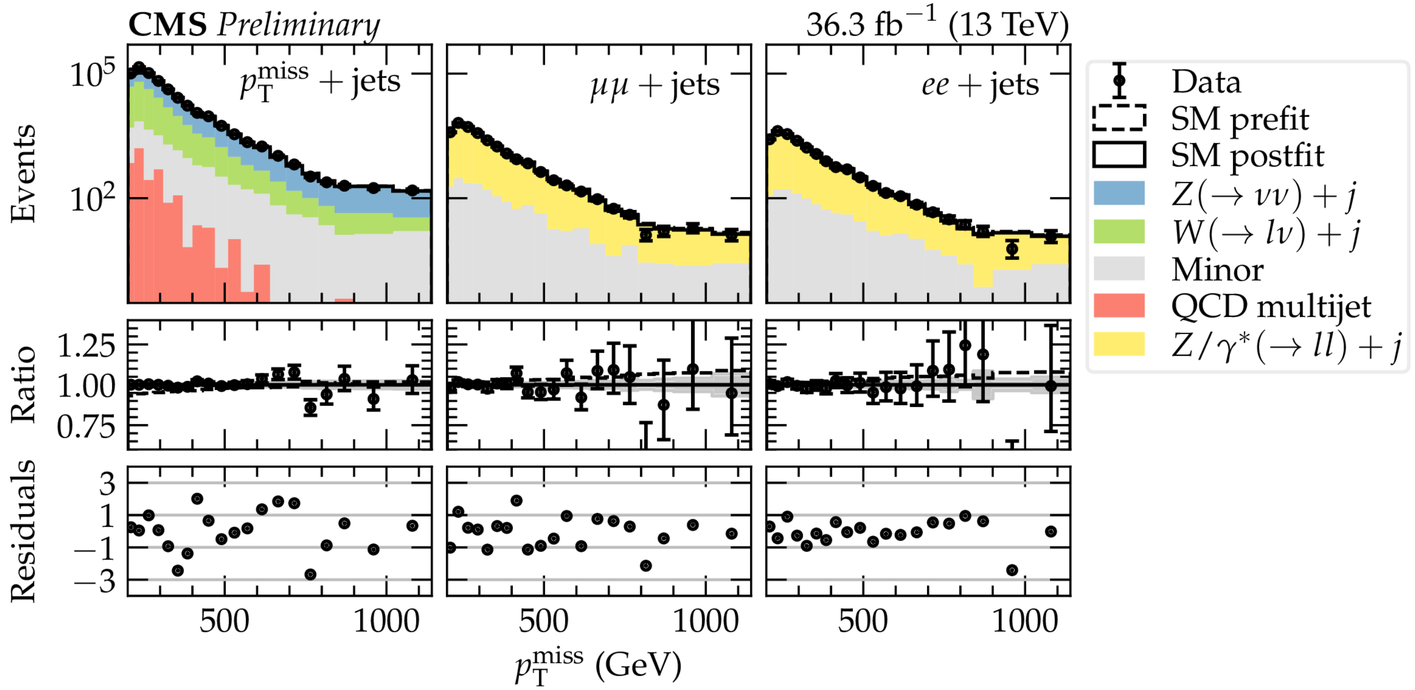
High precision measurements

Measurement of Z invisible width (Γ_{inv})

13 TeV, $\mathscr{L}$ = 138 fb^{-1} CMS

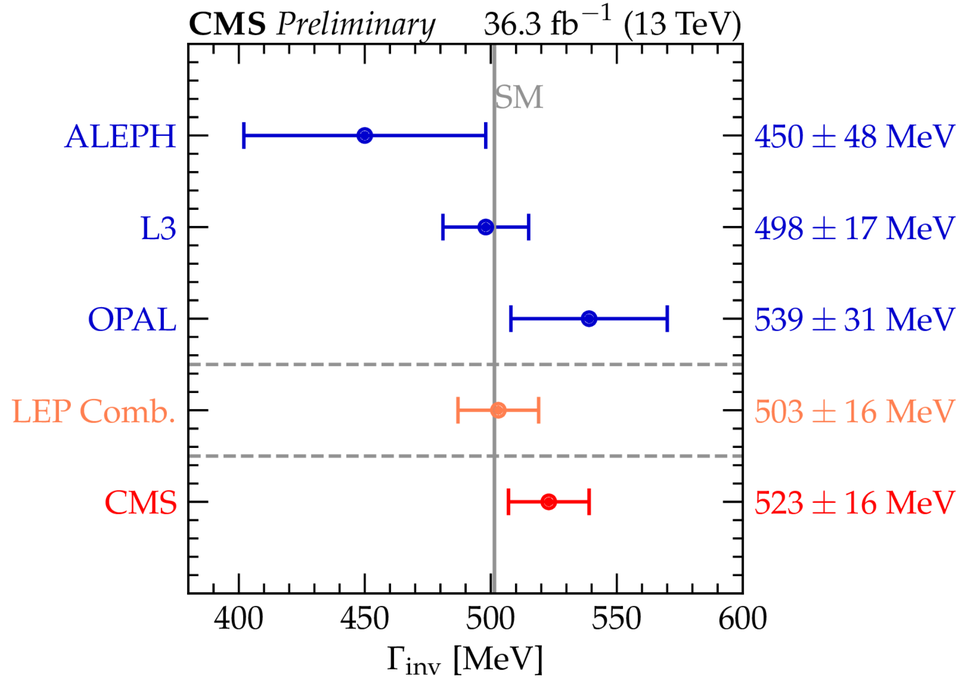
CMS-PAS-SMP-18-014

- **Goal:** measure $$R = \frac{\sigma(Z+jets)\cdot BR(Z\to\nu\nu)}{\sigma(Z+jets)\cdot BR(Z\to ll)} = \frac{\Gamma(Z\to\nu\nu)}{\Gamma(Z\to ll)}$$ and convert into Γ_{inv}
- Simultaneous fit to data regions with Z→$\nu\nu$ and Z→$\ell\ell$ decays
- Z→$\nu\nu$ events selected in the p_T^{miss}>200 GeV region



- Major background from W+jets and QCD, estimated using data-driven
- Contribution from γ^*→$\ell\ell$ and Z/γ^* interference is evaluated

Γ_{inv} = 523 ± 3 (stat.) ± 16 (syst.) MeV



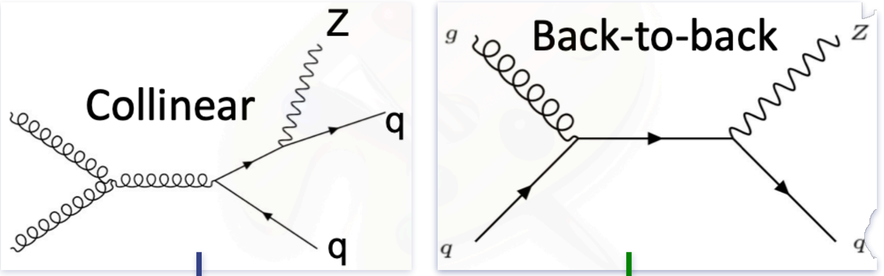
- **First Γ_{inv} measurement at hadron colliders!**
- **Single most precise direct measurement of Γ_{inv}, competitive with LEP combination**

Z+jets at high p_T production

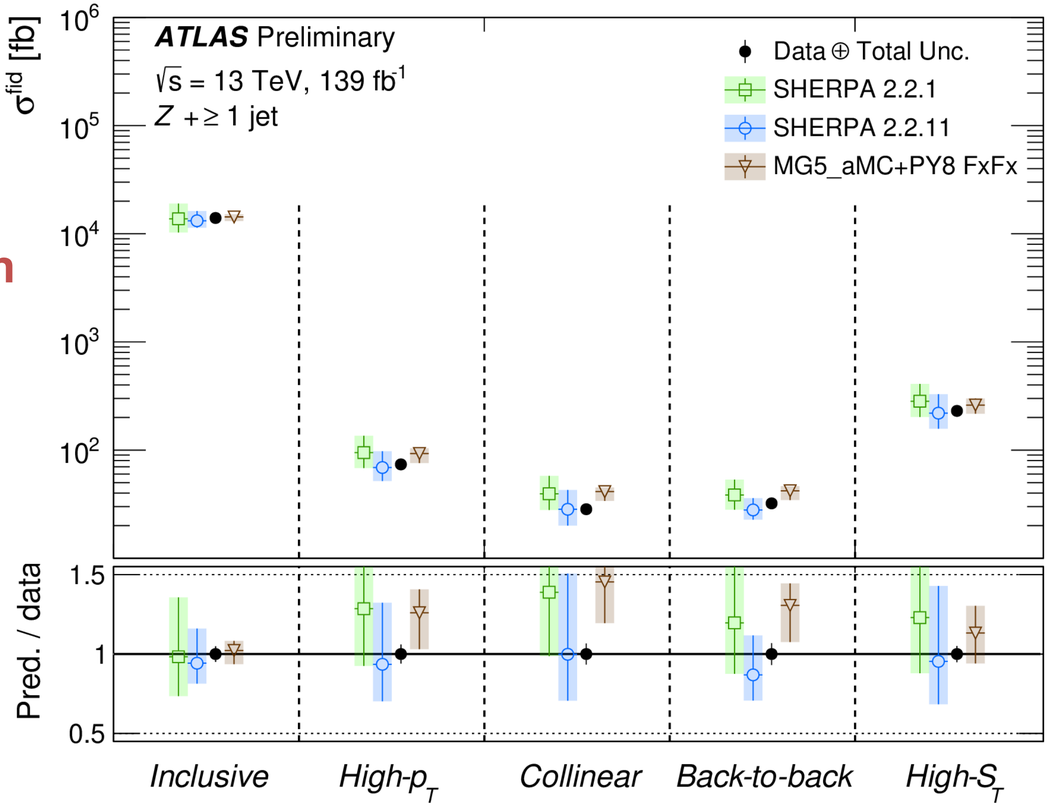
13 TeV, $\mathscr{L}$ = 139 fb^{-1} ATLAS

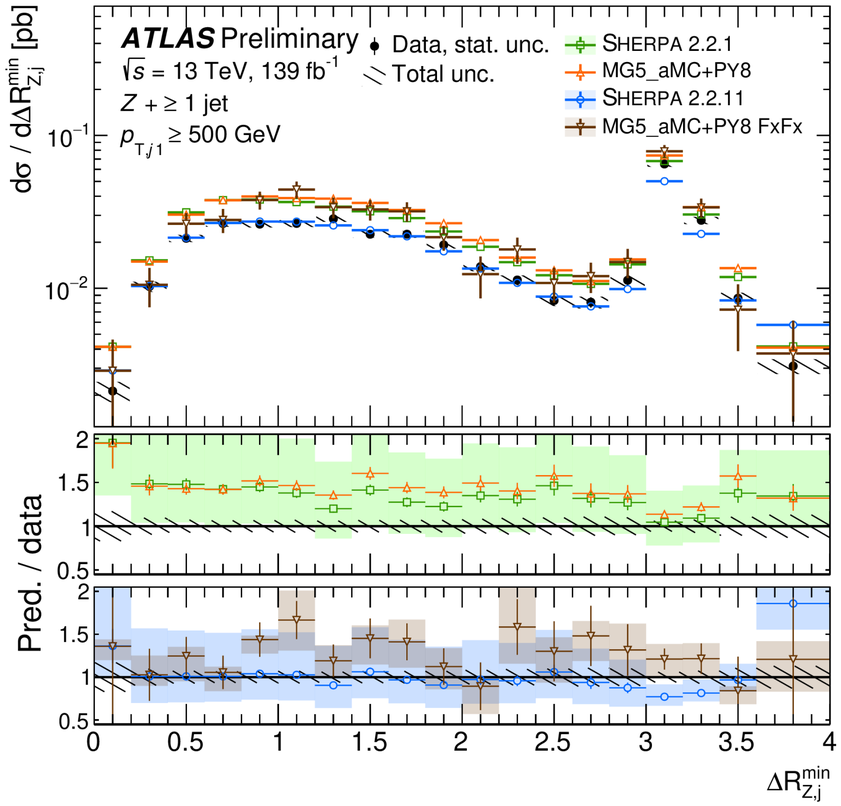
ATLAS-CONF-2021-033

- Z(→ee, $\mu\mu$) + jets with p_T>100 GeV
- Probing for real **Z emission as FSR from a quark**
- Measure cross section in more extreme phase space: **collinear** and **back-to-back** jet emission, **high p_T** or **high sum p_T**
- HT sensitive to pQCD and high jet multiplicities



- **Sherpa 2.2.11 and MG5_aMC+Py8 FxFx: improved modelling in collinear and high-pT regions**
- Prediction **uncertainties** dominated by **QCD scale**





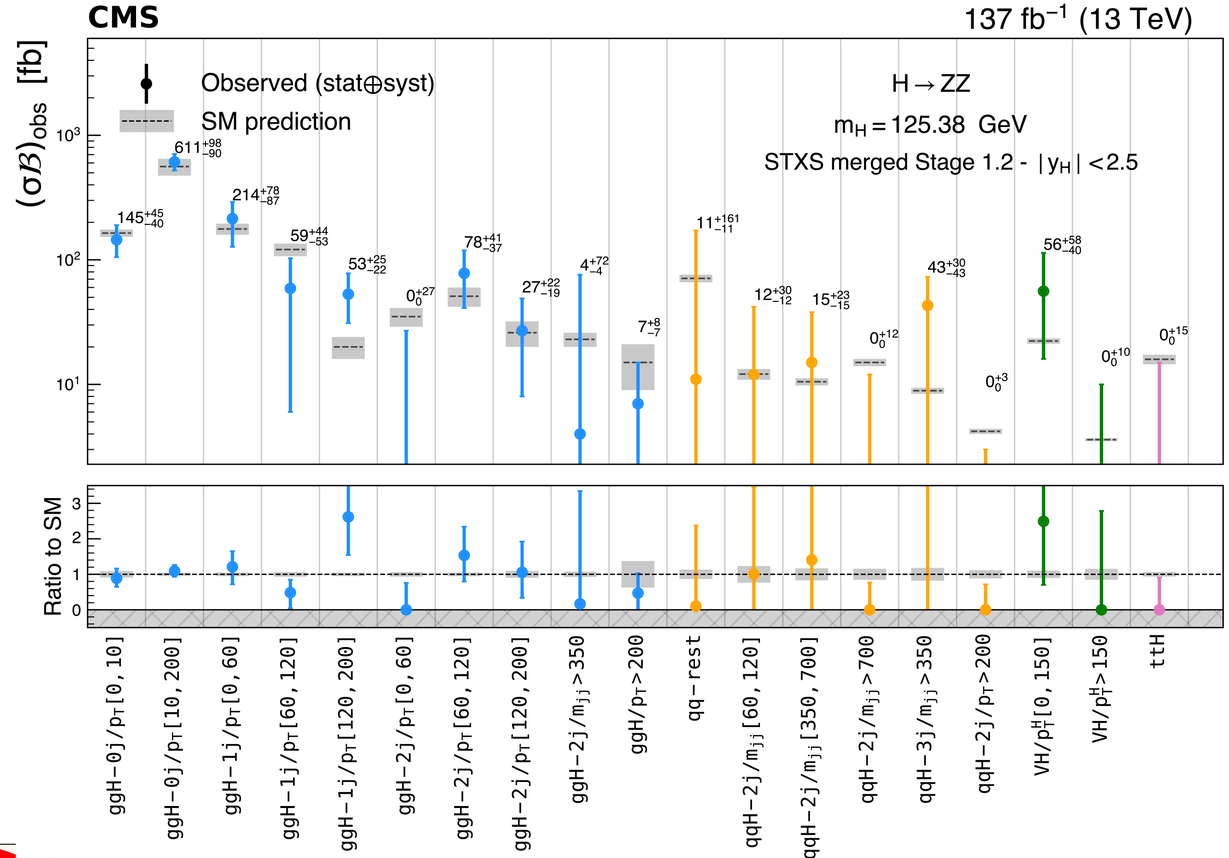
H→4ℓ Production

13 TeV, $\mathscr{L}$ = 138 fb^{-1} **CMS** — Eur. Phys. J. C 81 (2021) 488

$\mathscr{L}$ = 139 fb^{-1} **ATLAS** — Eur. Phys. J. C 80 (2020) 942, Eur. Phys. J. C 80 (2020) 957

- ***Golden channel:*** **fully reconstruct decay kinematics ⇛ low BR but very clean final state**
- **NEW:** Full Run 2 statistics, improvements in lepton reconstruction and better understanding of main ZZ* bkg

➡ Measurements of main production modes in different kinematic regions in the STXS framework

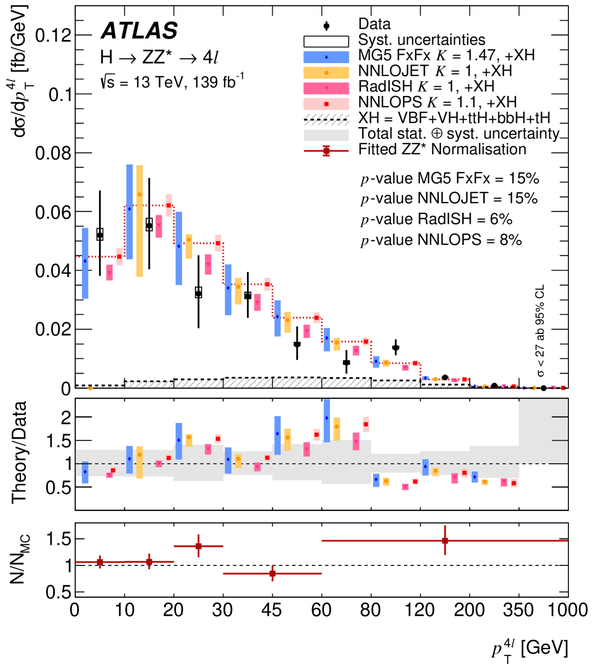


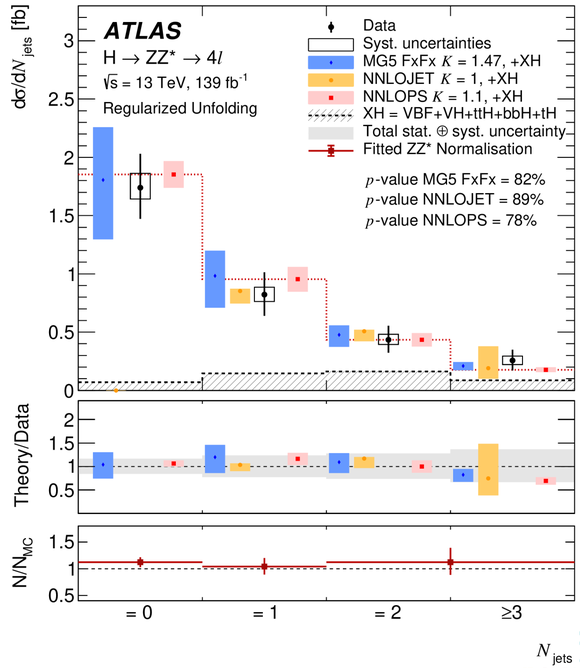
➡ Fiducial inclusive cross sections

CMS: $\sigma = 2.84^{+0.34}_{-0.31}$ fb (SM: 2.84 ± 0.15 fb)

ATLAS: $\sigma = 3.28 \pm 0.32$ fb (SM: 3.41 ± 0.18 fb)

➡ Differential measurements





H→ττ production

13 TeV, $\mathscr{L}$ = 138 fb^{-1} **CMS** $\mathscr{L}$ = 139 fb^{-1} **ATLAS**

CMS-HIG-20-015 **ATLAS-CONF-2021-044**

- **Higgs coupling to third generation of fermions: BR(H→ττ) ~6%, largest among all leptonic decays**
- **4 final states:** $\tau_{had}\tau_{had}$, $e\tau_{had}$, $\mu\tau_{had}$, $e\mu$ ➠ **very challenging** due to the high number of neutrinos

- Main Z→ττ background estimated with Z→ℓℓ data events with simulation-based corrections to kinematics

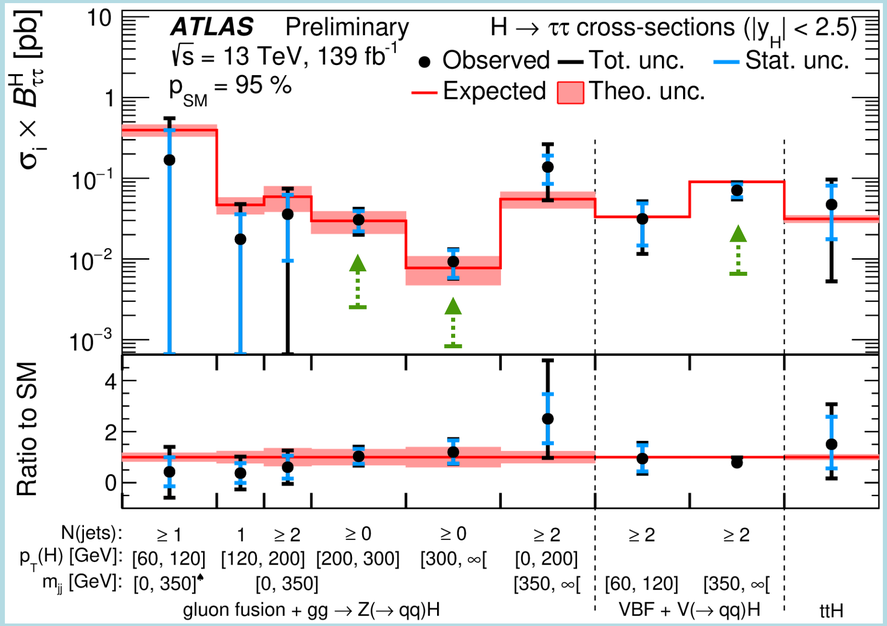
✳**Inclusive $\sigma_{(pp\to H\to\tau\tau)}$ for $|y_H|<2.5$**

$\sigma_{(pp\to H\to\tau\tau)}$ = **2.90 ± 0.21(stat)$^{+0.37}_{-0.32}$ (syst) pb**

SM: σ= 3.15 ± 0.09 pb

✳**Measurements in 9 STXS kinematic regions**

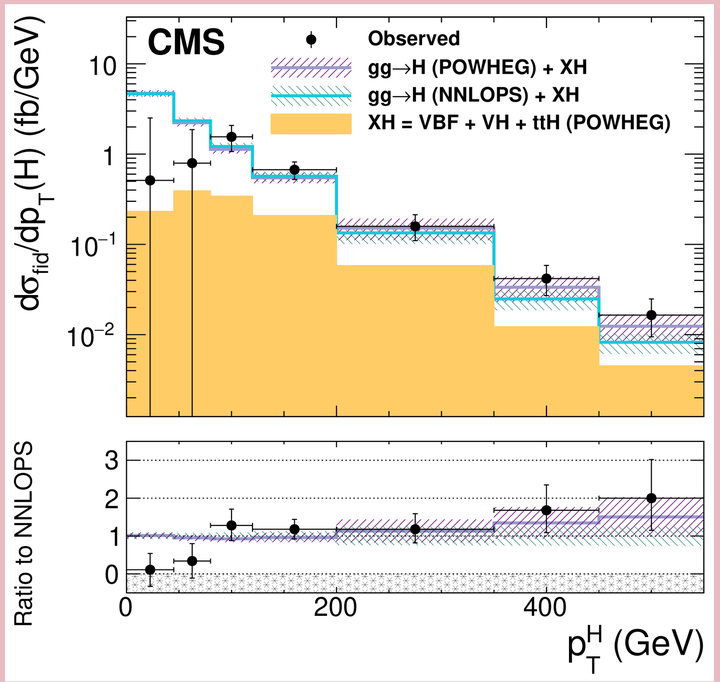
- ➠ Target the **four main Higgs production modes**
- ➠ Uncertainties dominated by signal modelling



✳**Differential $\sigma_{(pp\to H\to\tau\tau)}$ vs p_T^H, N_{jets} and p_T^H**

in fiducial volume defined by kinematics of visible τ decays

- ➠ **Good sensitivity at high p_T and for VBF topology**
- ➠ **Results in agreement with SM predictions**

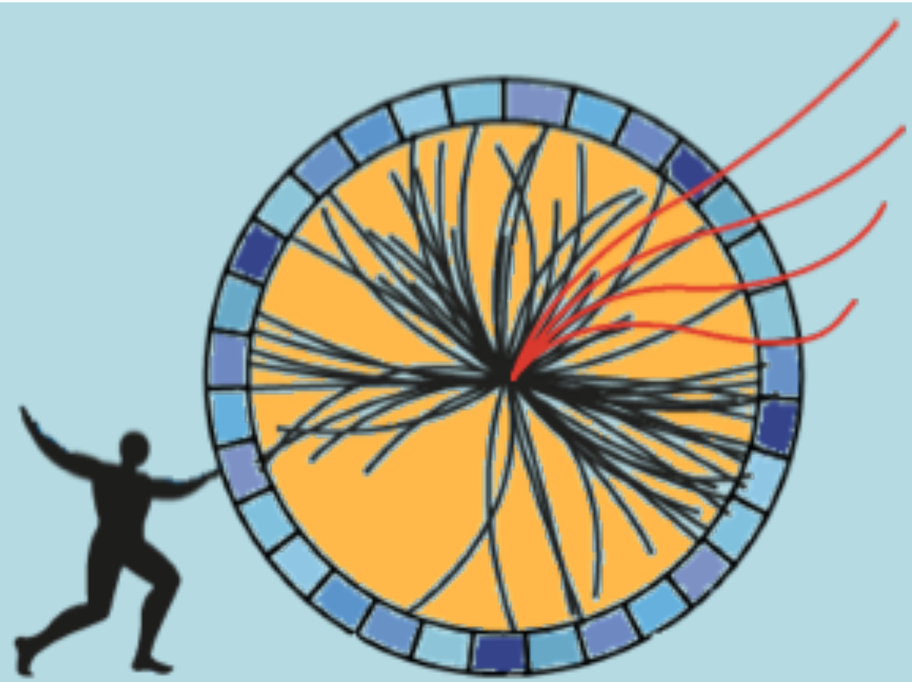


✳**Fiducial Inclusive $\sigma_{(pp\to H\to\tau\tau)}$**

by summing N_{jets} bins

$\sigma_{(pp\to H\to\tau\tau)}$ = **426 ± 102 fb**

SM: $\sigma_{(pp\to H\to\tau\tau)}$ = 408 ± 27 fb



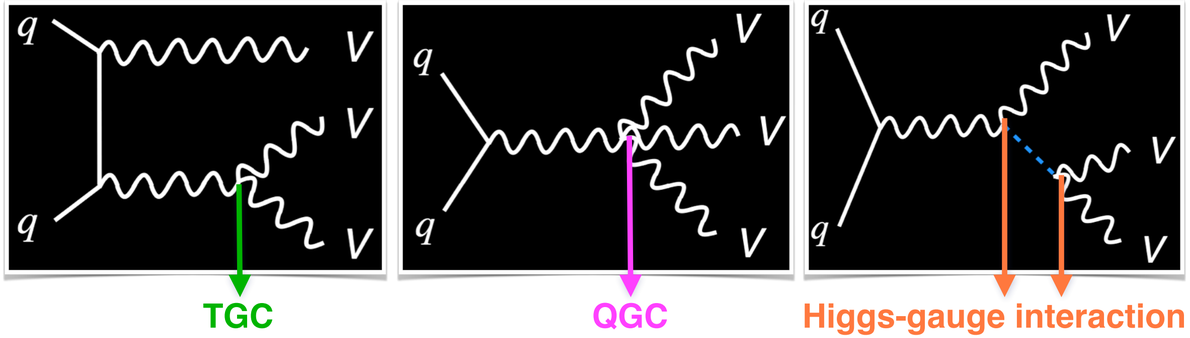
Rare processes

Observation of VVV production

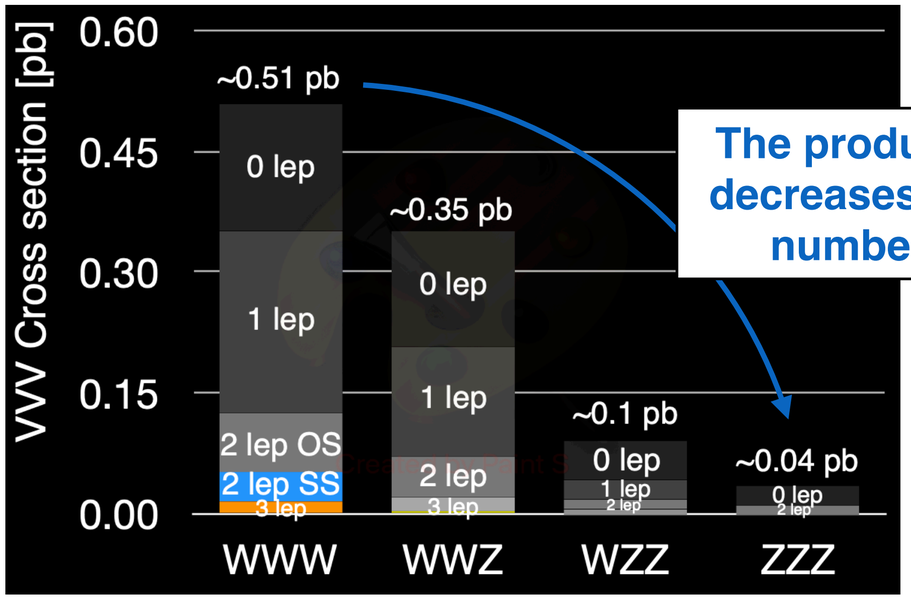
13 TeV, $\mathscr{L}$ = 138 fb^{-1} CMS

Phys. Rev. Lett. 125 (2020) 151802

- **Rare process providing direct investigation to W/Z self-interactions** → triple/quadratic gauge couplings (**TGC**, **QGC**)

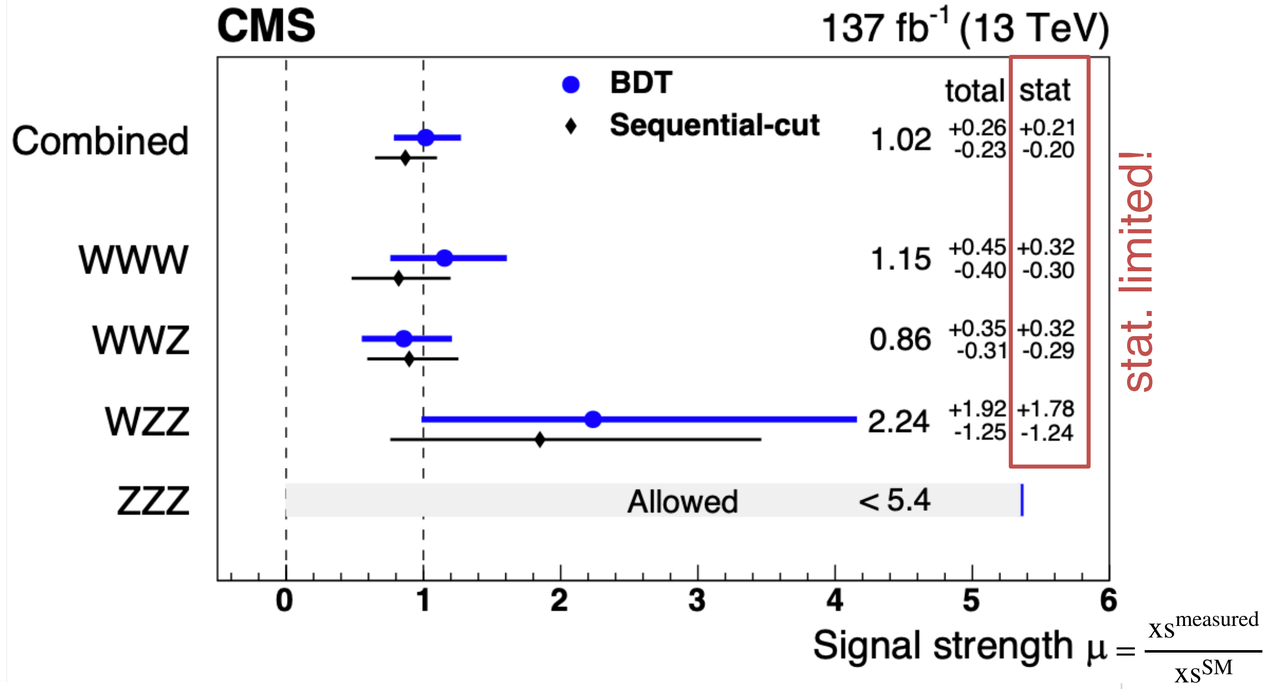


- Measure of the combined production of four VVV modes: **WWW, WWZ, WZZ, ZZZ**



The production xs decreases with the number of Z!

- Exploiting fully leptonic final states
- Different signal regions (SR) according to the number of leptons and the lepton flavour

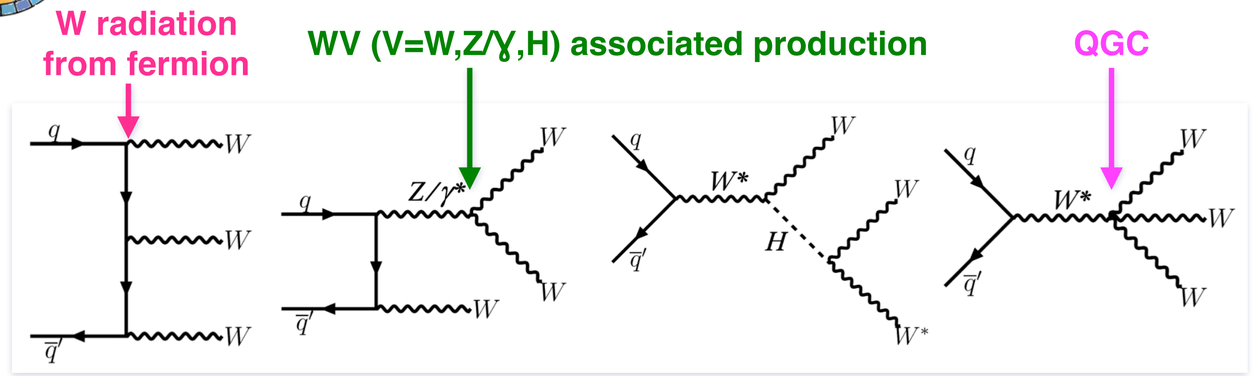


- ➡ **Observation of the combined production of three massive gauge boson!**
- ➡ Cross section (xs) compatible with SM

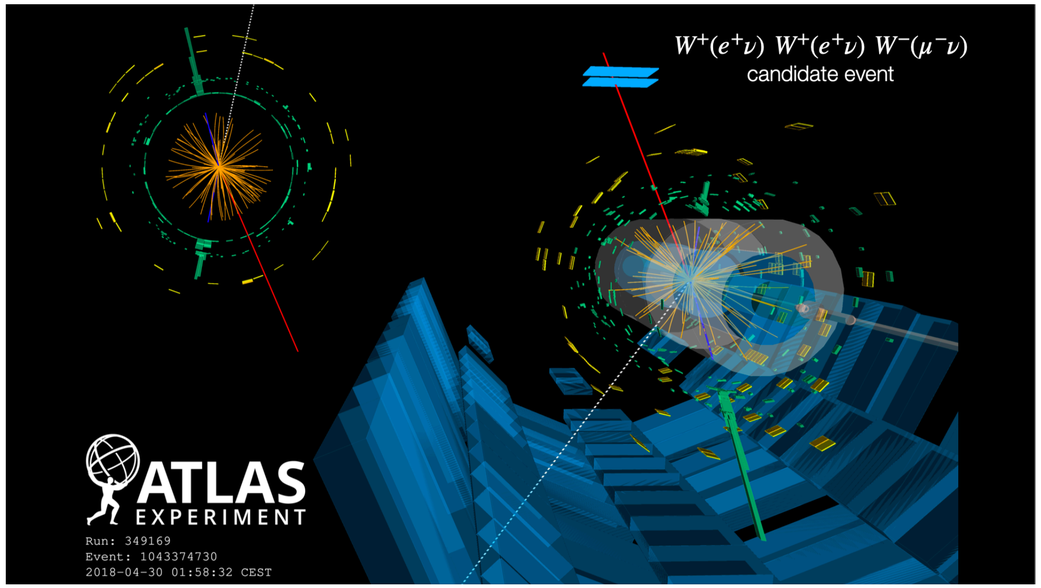
Observation of WWW production

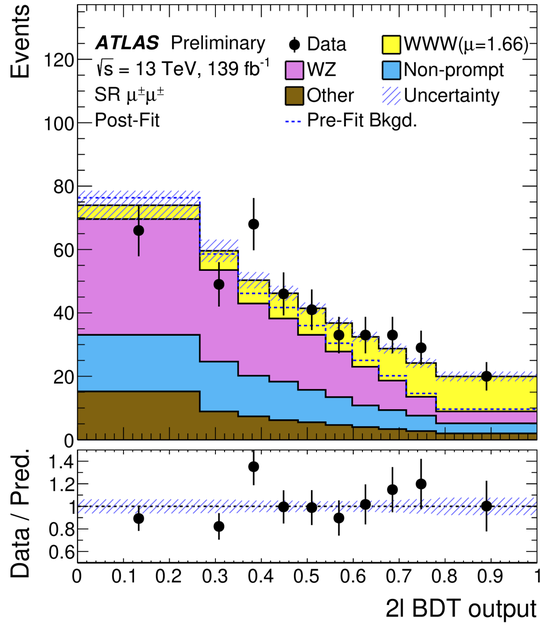
13 TeV, $\mathscr{L}$ = 139 fb^{-1} ATLAS

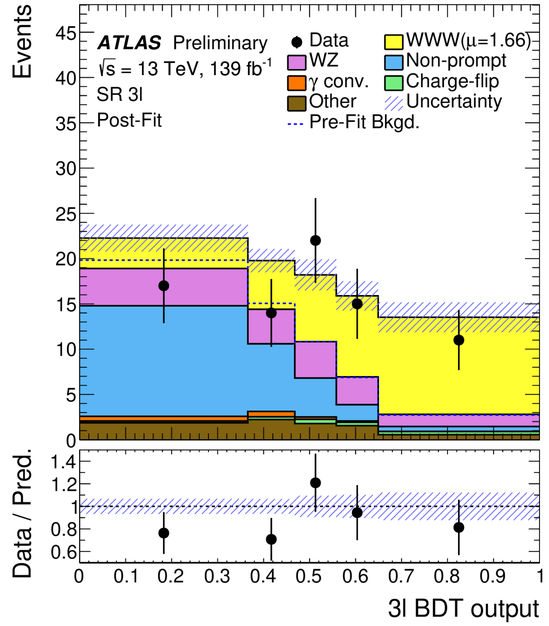
ATLAS-CONF-2021-039



- Channels: $W^{\pm}W^{\pm}W^{\mp} \rightarrow \ell^{\pm}\nu\ell^{\pm}\nu qq'$ with ℓ=e, μ
  $\rightarrow \ell^{\pm}\nu\ell^{\pm}\nu\ell^{\mp}\nu$
- Main background:
  $WZ \rightarrow \ell\nu\ell\ell$ estimated with control regions
- Signal extracted with BDTs for both channels







➡ **First WWW observation** with significance:
8.2σ obs. (5.4σ exp.), μ = 1.66 ± 0.28.

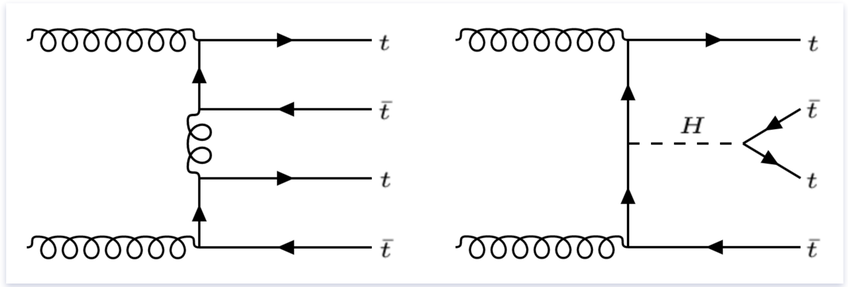
σ(pp→ W±W±W∓) = 850 ± 100 (stat.) ± 80 (syst) fb

4 top production

13 TeV, $\mathscr{L}$ = 139 fb^{-1} ATLAS

arXiv:2106.11683

- **Rare process** (σ_{SM}=12.0±2.4 fb) **sensitive to top coupling** with the Higgs (Yukawa), with BSM particles and with leptons in the EFT framework



- BR(t→Wb)~1: different signatures based on W decay
  - 13% **2LSS or ≥3L**
    Eur. Phys. J. C 80 (2020) 1085
  - 57% **1L or 2LOS**

σ_{tttt}^{1L2LOS} = 26 ± 8 (stat)$^{+15}_{-13}$ (syst) fb

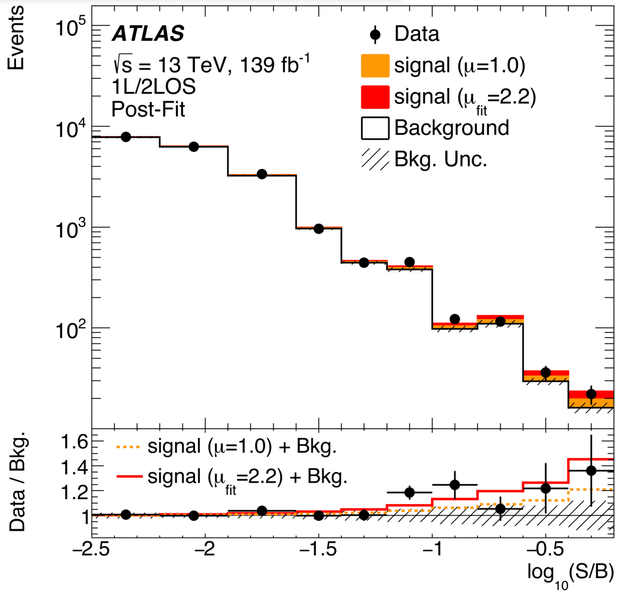
combined

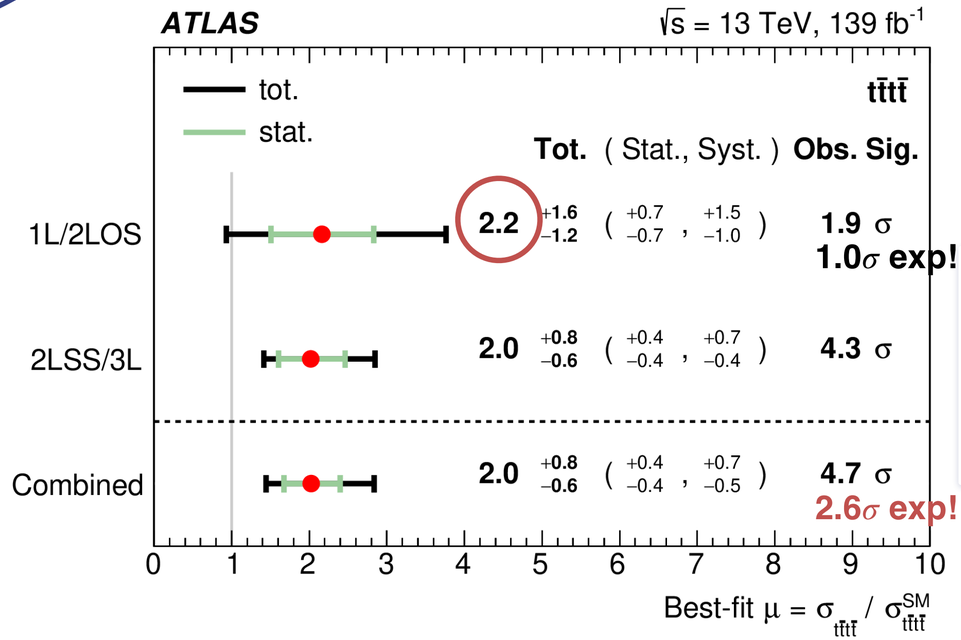
$\mu_{tttt}^{comb.}$ = 2.0 ± 0.4 (stat)$^{+0.7}_{-0.5}$ (syst)

$\sigma_{tttt}^{comb.}$ = 24 ± 4 (stat)$^{+5}_{-4}$ (syst) fb

- Categorise events on number of (b-)jets
- **Largest background from ttbar+(b-)jets**
- Build BDT in signal region (SR) to discriminate S/B
- **Fit in 21 regions (SR/CRs) to extract signal strength μ**

- Consistent with SM predictions
- **Dominant uncertainties** from **signal and tt+(b-)jets modelling and normalisation**





- compatible with SM (<2σ) → to explore in Run 3

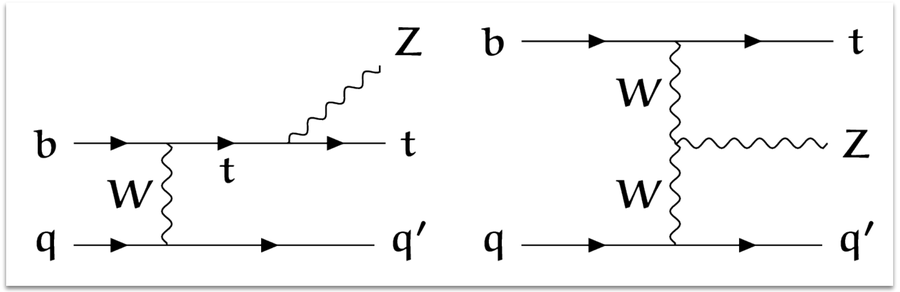
EWK tZq production

13 TeV, $\mathscr{L}$ = 138 fb^{-1} CMS

CMS-PAS-TOP-20-010

✦ **Rare process sensitive to ttZ, WWZ coupling, top polarisation, proton PDFs**

- ✦ **3ℓ +≥ 2 jets (≥1 b-jet) selection**
- ✦ data-driven **non-prompt lepton background**
- ✦ **NN and BDTs to discriminate S/B**



✳**Top spin asymmetry**

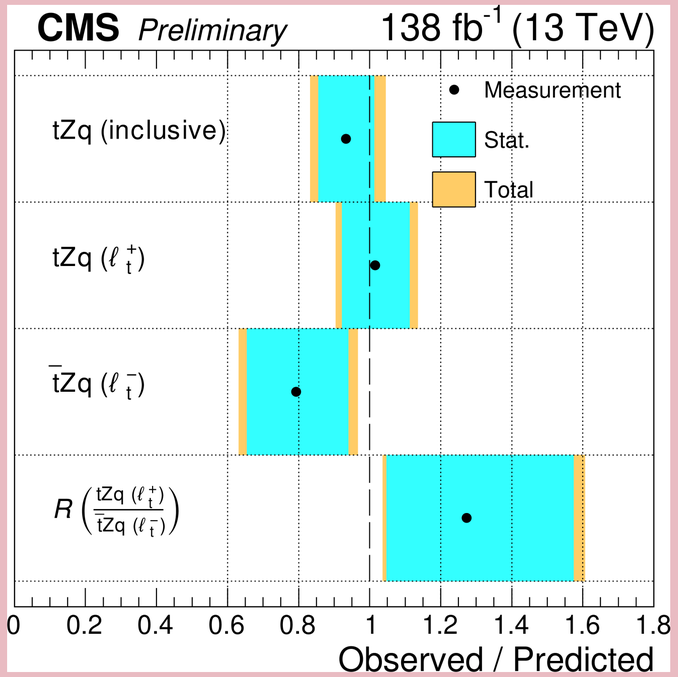
A = 0.58$^{+0.15}_{-0.16}$ (stat) ± 0.06 (syst) fb

➡ Polarisation angle fit at parton level

➡ Compatible with 4/5FNS predictions

✳**Inclusive σ_{tZq}**

σ_{tZq} = 87.9$^{+7.5}_{-7.3}$ (stat) $^{+7.3}_{-6.0}$ (syst) fb



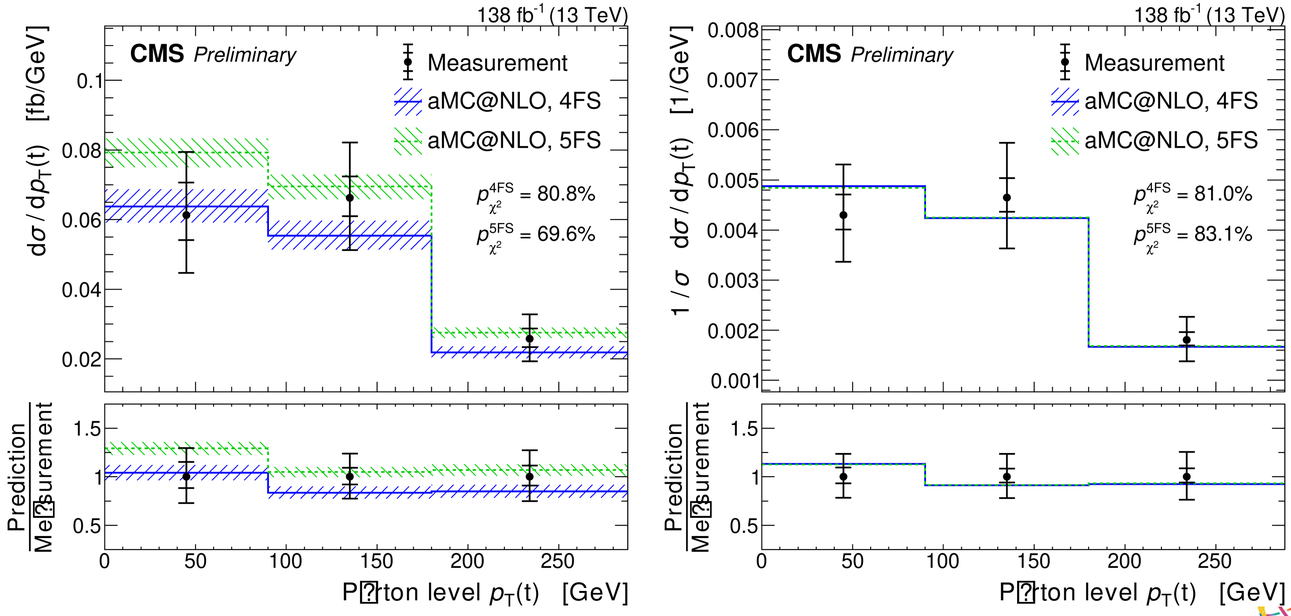
tot unc. 11%!

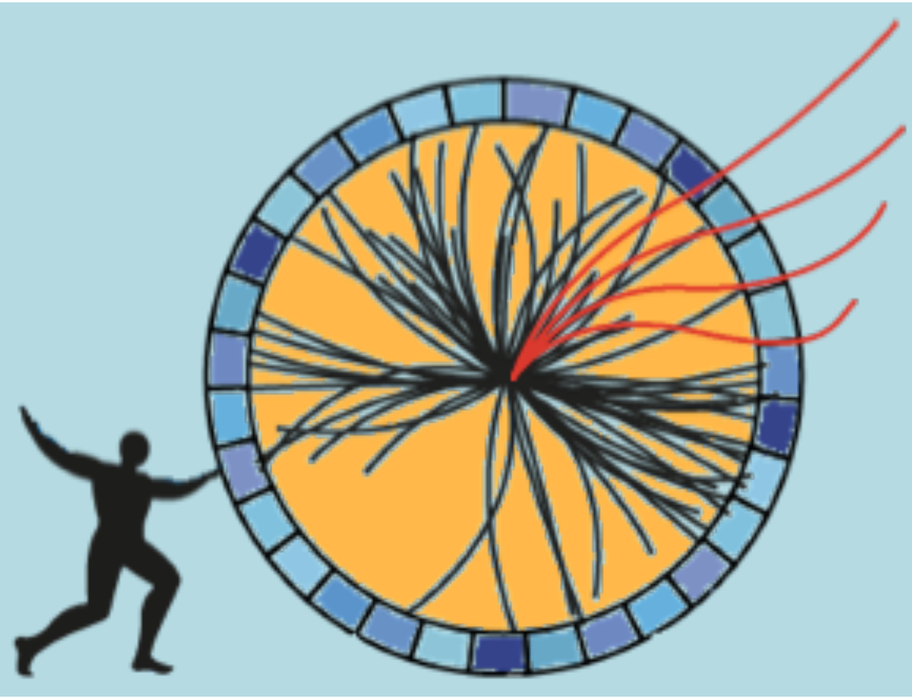
➡ **~30% more precise than previous meas.**
- larger dataset, larger fiducial space, MVA, constrain non-prompt lepton background

➡ **Measure partial tZq and t̄Zq σ and ratio R**

✳**First parton and particle differential σ_{tZq} measurements!**

➡ **Good agreement** between data and **4/5FNS** prediction





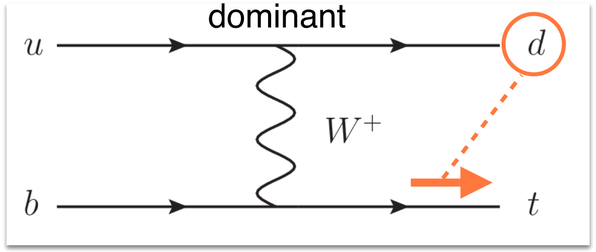
SM as probe for new physics

Single top polarisation (t-channel)

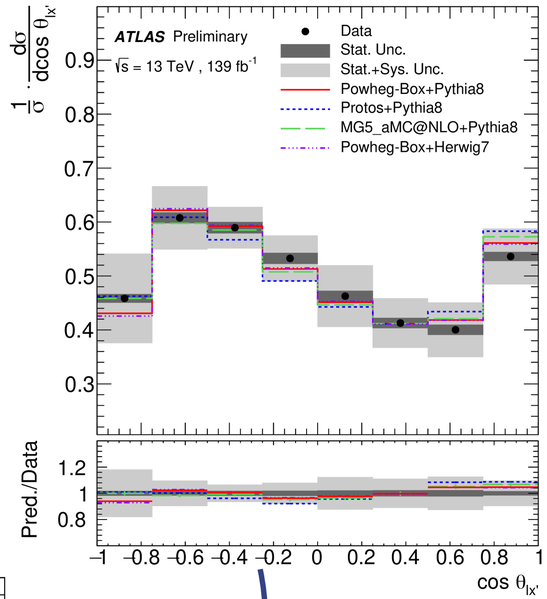
13 TeV, $\mathscr{L}$ = 139 fb^{-1} ATLAS

ATLAS-CONF-2021-027

- **t-channel dominant** single top production **at the LHC**:
  - exchange of W between b-quark and incoming light quark



- **V-A structure of tWb vertex:** top spin aligned along d-quark
- **z axis: outgoing spectator quark**

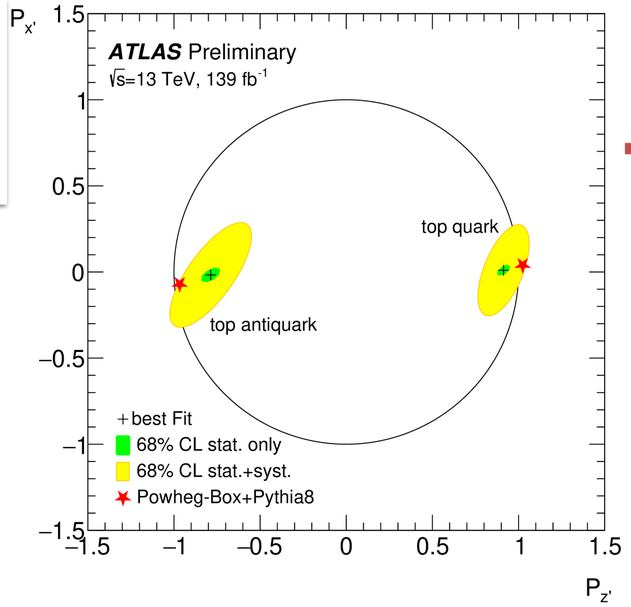


- Reconstruct **t→ℓνb** decay
  - the angular distribution of the charged lepton in the top rest frame gives information on the top polarisation

➡ **First measurement of polarisation vector in 3D!**

$\vec{P}$ top:
P_x = 0.01 ± 0.18
P_y = -0.029 ± 0.027
P_z = 0.91± 0.10

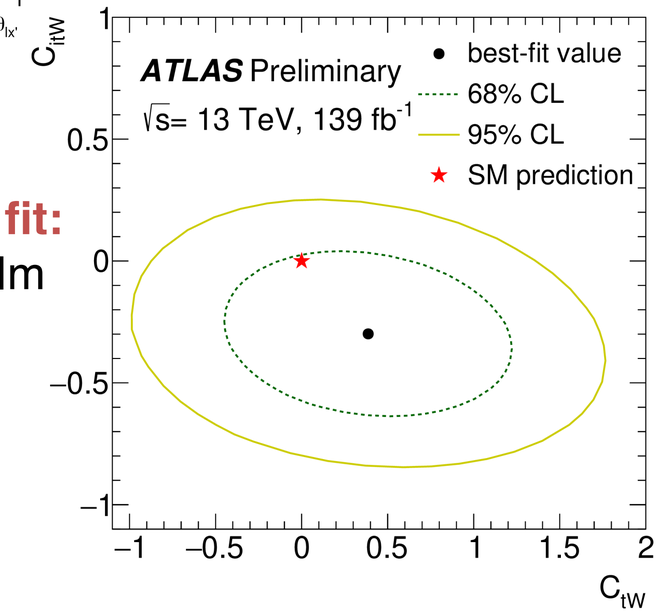
$\vec{P}$ antitop:
P_x = -0.02 ± 0.20
P_y = -0.007 ± 0.051
P_z = -0.79 ± 0.16



➡ Systematic dominated, in agreement with SM: **high polarisation of top** (antitop) **along** (against) **the spectator quark direction**

➡ **dσtt/dcosϑ measurement→ EFT fit:** constrains on Re and Im part of $\mathcal{O}_{tW}$

-0.7 < C_{tW} < 1.5
-0.7 < C_{itW} < 0.2

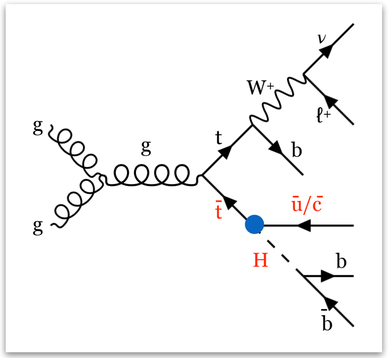


Search for t→H(→bb)q FCNC interactions

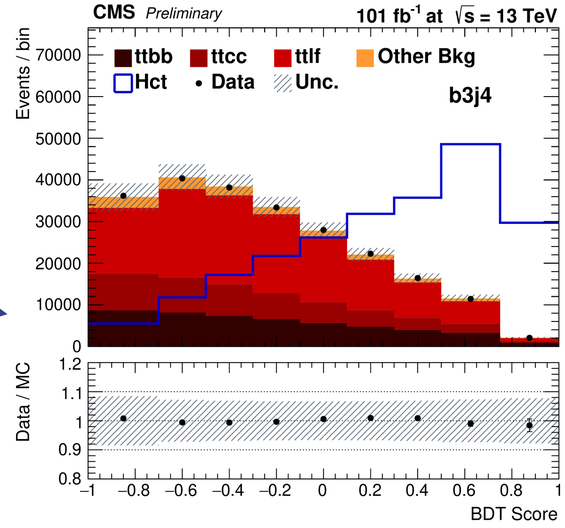
13 TeV, $\mathscr{L}$ = 138 fb^{-1} CMS

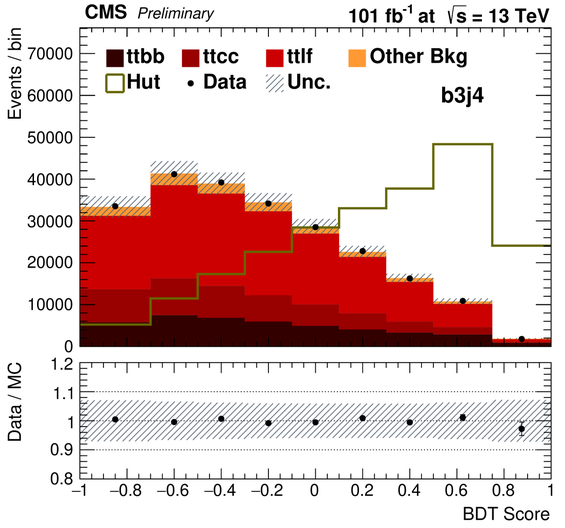
CMS-PAS-TOP-19-002

✦ t→Hq (q=u,c) FCNC decays suppressed in SM → clear sign of BSM physics!



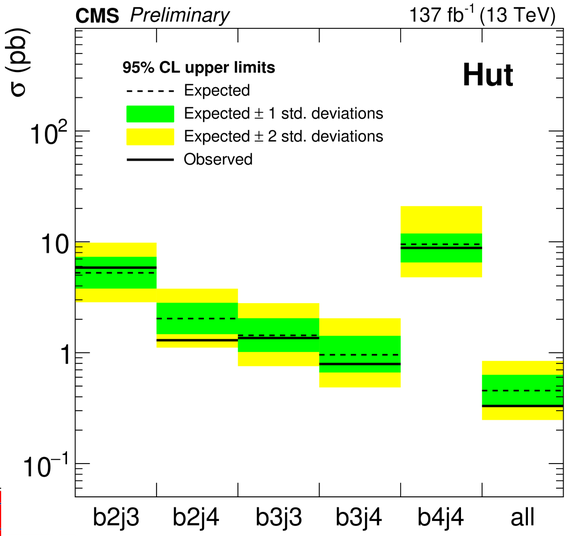
- ✦ H→bb decay mode
- ✦ 1ℓ+≥3 jets (2 b-jets) selection
- ✦ **5 SRs** based on (b-)jets multiplicity
  - ✦ DNN to assign jets to partons
- ✦ BDTs to discriminate S/B

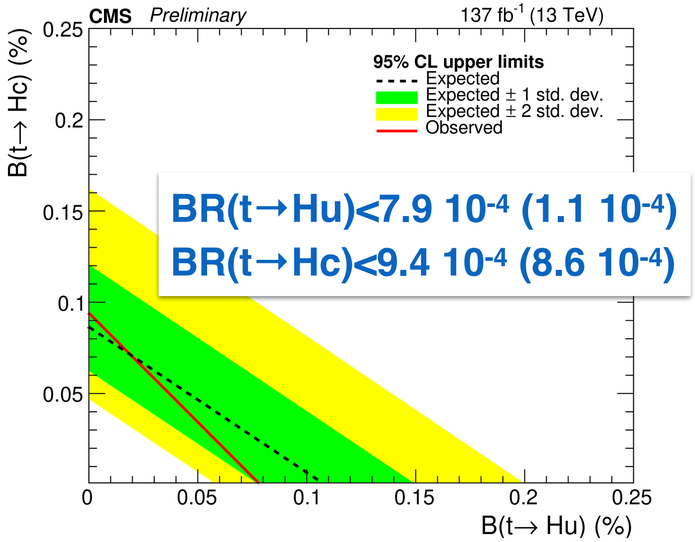




➡ no excess wrt SM bkg expectations
→95% CL limits are set on the xs, couplings and BR

➡ the b3j4 category has the highest sensitivity

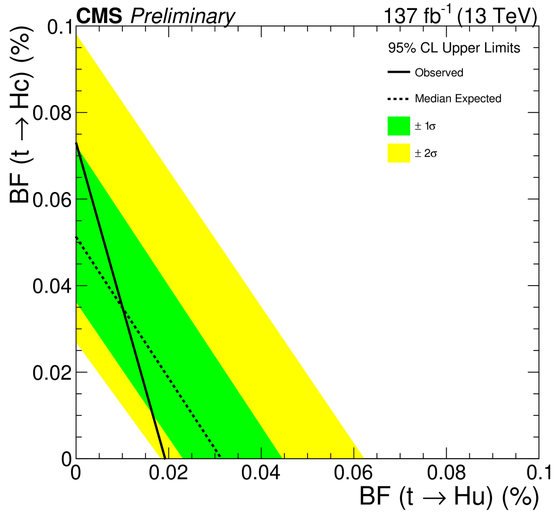


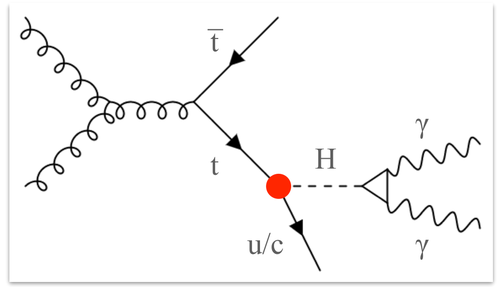


BR(t→Hu)<7.9 10^{-4} (1.1 10^{-4})
BR(t→Hc)<9.4 10^{-4} (8.6 10^{-4})

✦ Previous analysis with H→$\gamma\gamma$ decay mode

CMS-PAS-TOP-20-007





BR(t→Hu)<1.9 10^{-4} (3.1 10^{-4})
BR(t→Hc)<7.3 10^{-4} (5.1 10^{-4})

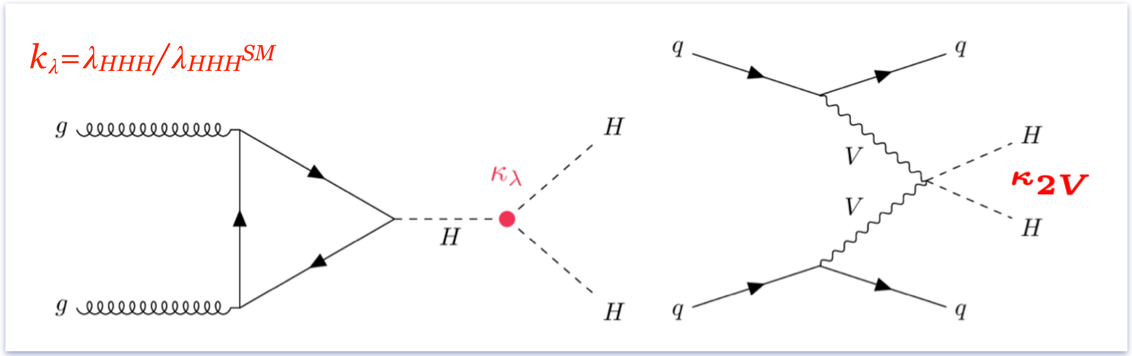
Search for HH→4b

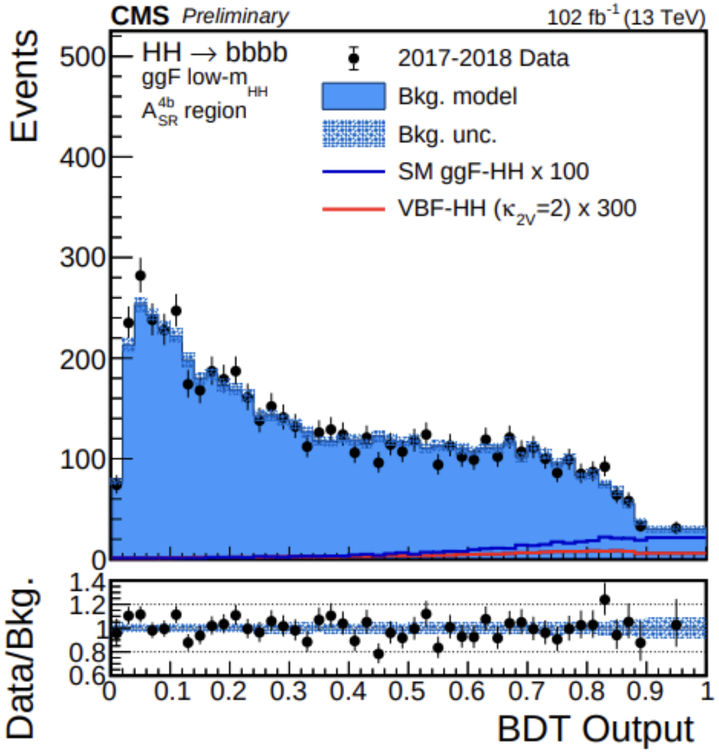
13 TeV, $\mathscr{L}$ = 138 fb^{-1} CMS

CMS-PAS-HIG-20-005

✦ **Directly study the Higgs boson self coupling with largest BR = 34%**

- **HH produced mainly via ggHH at the LHC**
  - tiny cross section: $\sigma(pp\to HH)^{SM}$ = 31.05 fb
- With full Run 2, **possible to target also VBFHH** production mode → sensitive to VVHH coupling





- **Large multijet background from QCD and ttbar** estimated with *data-driven* method
- BDT for S/B separation

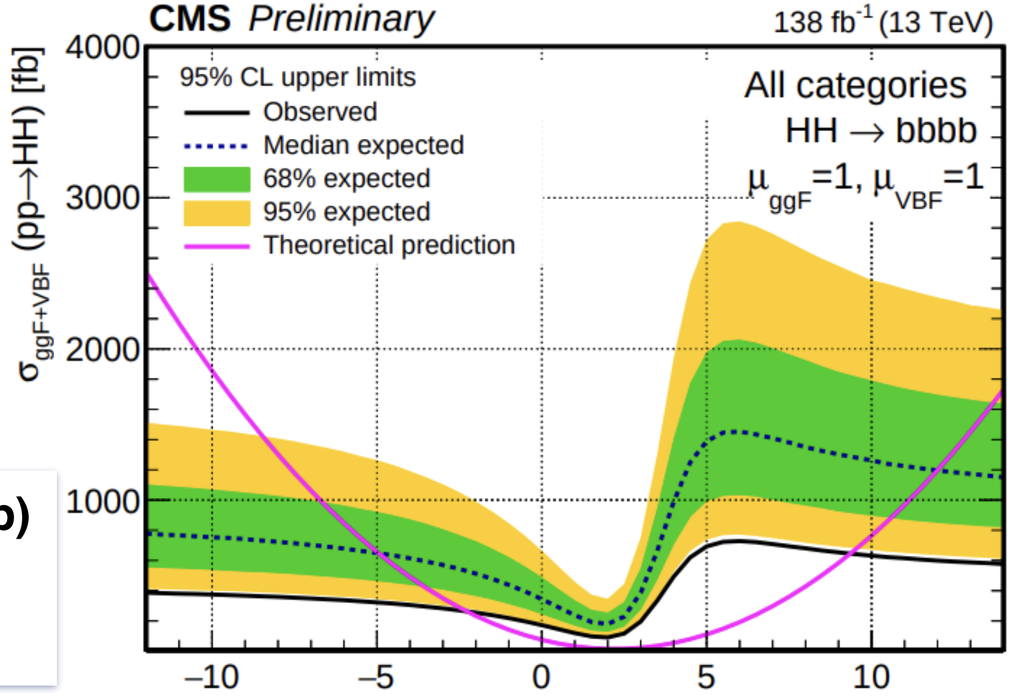
➡ No signal excess found!

➡ **Very promising limits at 95% CL:**

$\sigma(pp\to HH\to 4b)$ **< 3.6 (7.3) x SM obs (exp)**

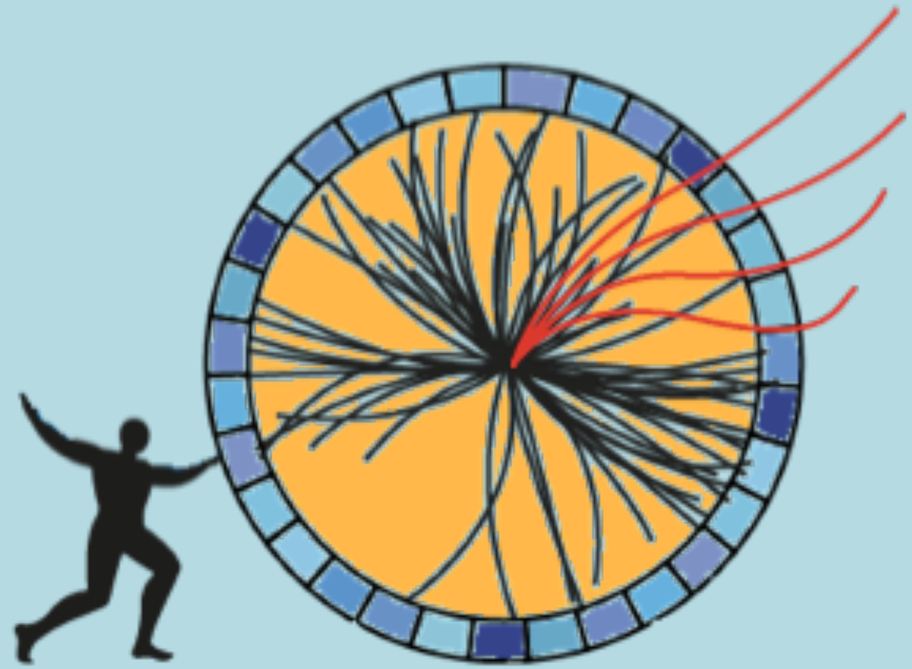
-2.3 < k_λ < 9.4 (-5.0 < k_λ < 12.0)

-0.1 < k_{2V} < 2.2 (-0.4 < k_{2V} < 2.5)



Conclusions

- **Vibrant atmosphere towards Run 3 of LHC for SM measurements**
  - Precision measurements allow stringent test of theory predictions
  - necessary to reduce experimental and theoretical uncertainties to enhance the sensitivity
  - Rare processes will benefit from the statistical increase
  - Interesting interpretations in BSM scenarios



Backup slides

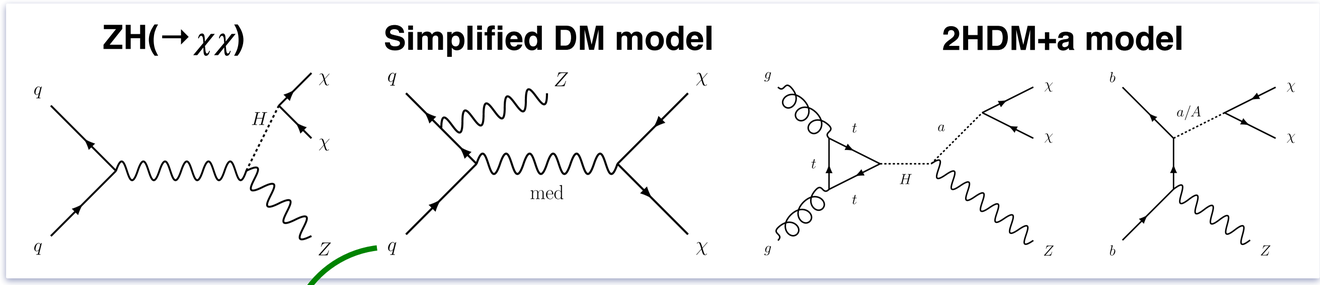
Search for ZH(→invisible)

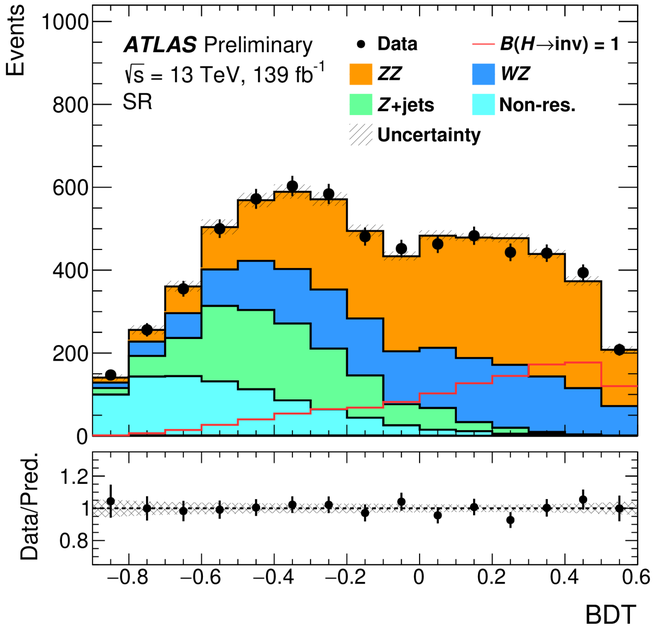
13 TeV, $\mathscr{L}$ = 139 fb^{-1} ATLAS

ATLAS-CONF-2021-029

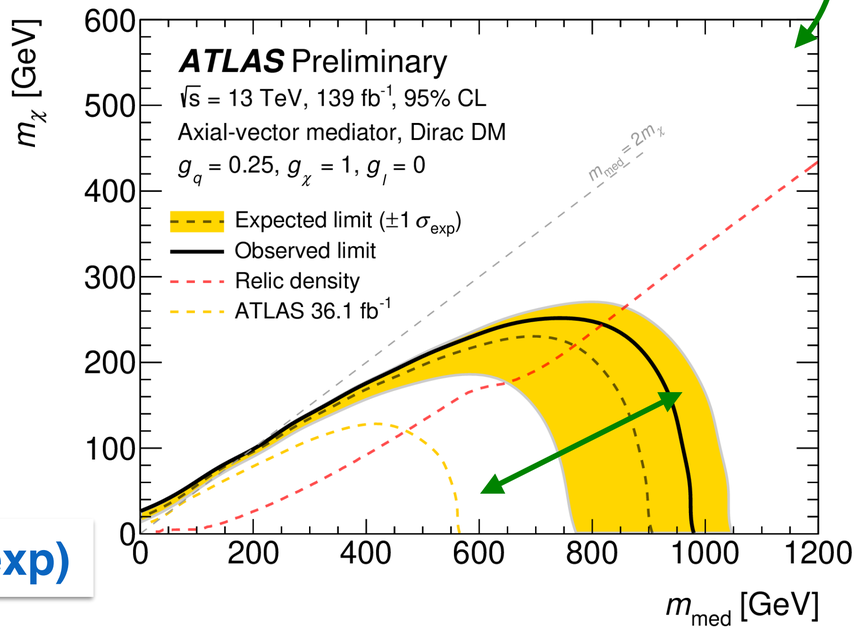
- **Since DM particles are expected to be massive, can H boson couple with DM (χ)?**

- Experimental signature: **Z(→$\ell\ell$)+ETmiss**
- **Sensitive to: SM ZH(→$\nu\nu$) and DM processes**
- Main background from ZZ→$\ell\ell$+ETmiss in 3/4ℓ CRs
- BDT for S/B separation





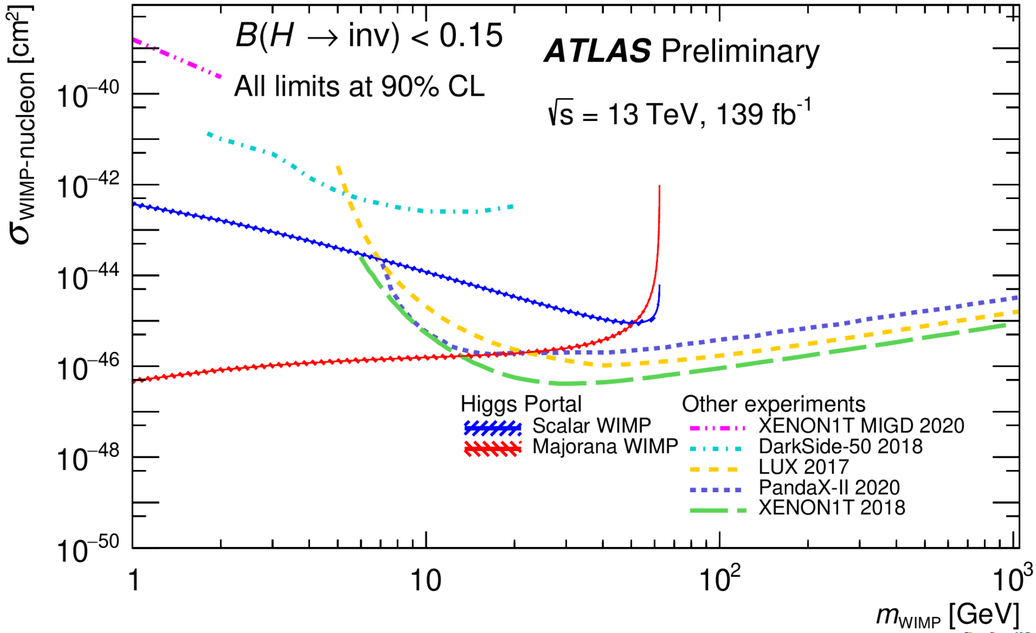
➡ **Improved exclusion limits** on Simplified DM and 2HDM+a models



➡ **Interpretation: limit on WIMP-nucleon scattering**

Higgs portal scenario: **DM from Higgs decays** assumed to be **scalar or Majorana fermion**

➡ Complementary to direct DM searches



➡ **Upper limit at 95% CL:**

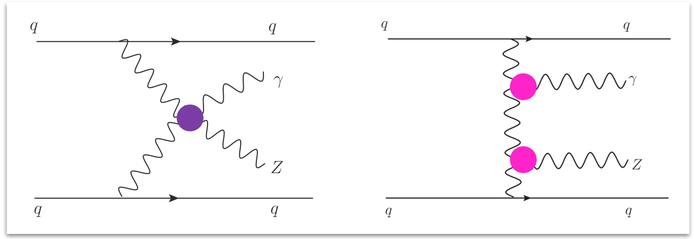
BR(H→inv) < 18% obs (18% exp)

EW $Z\gamma$ + 2 jets production

13 TeV, $\mathscr{L}$ = 139 fb^{-1} ATLAS

ATLAS-CONF-2021-038 | CERN-EP-2021-137

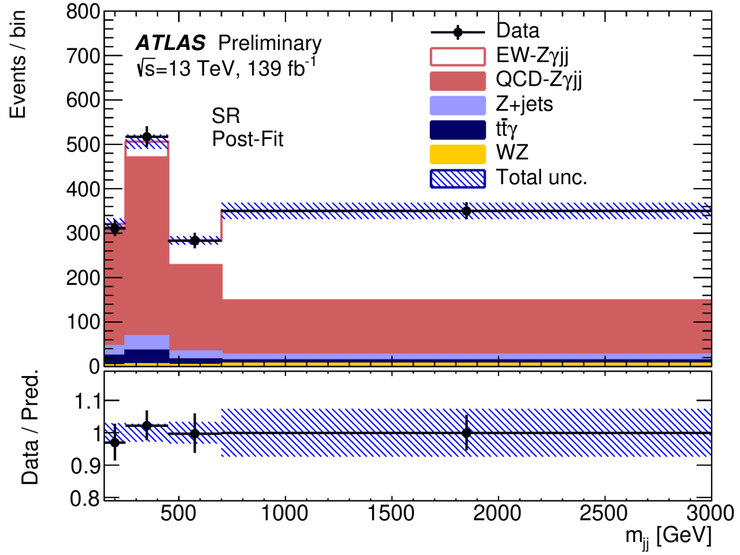
- Test of EW symmetry: sensitive to vector boson self-interactions and cubic-quartic couplings



- **Events characterised by large m_{jj} mass and y_{jj} gap**
- Main background from QCD $Z\gamma jj$

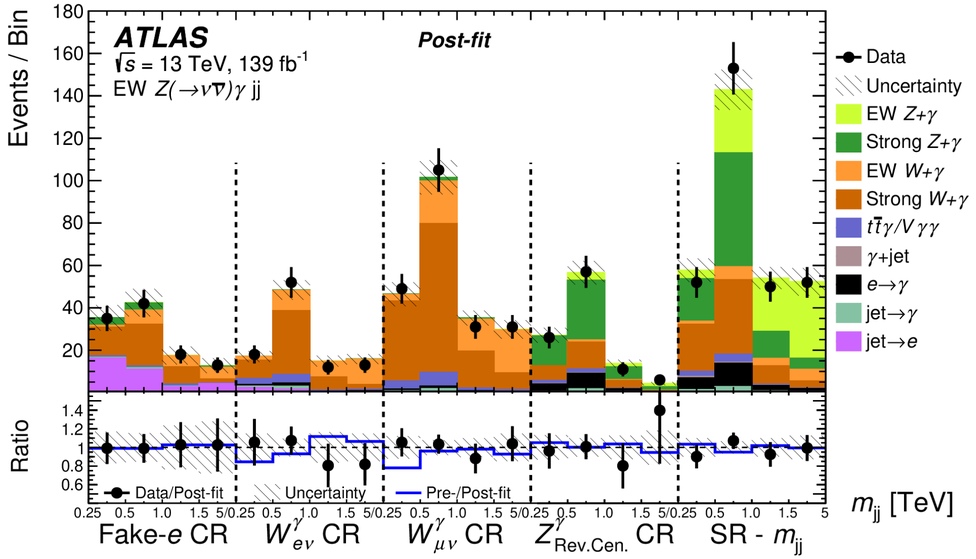
$Z(\rightarrow \ell\ell)\gamma jj$

- **Target VBF topology + $Z(\rightarrow \ell\ell)$ + γ**
- **➡ Observation of the EW $Z\gamma jj$ with ~10σ obs.**
- **➡ Fiducial cross section** $\sigma^{EW}_{Z(\rightarrow \ell\ell)\gamma jj}$ = 4.49 ± 0.58 fb



$Z(\rightarrow \nu\nu)\gamma jj$

- **Target VBF topology + E_T^{miss}**
- **➡ First observation of the EW $Z(\rightarrow \nu\nu)\gamma jj$ with 5.2σ obs**
- **➡ Fiducial cross section** $\sigma^{EW}_{Z(\rightarrow \nu\nu)\gamma jj}$ = 1.31 ± 0.29 fb



Lepton Flavour Universality (LFU)

13 TeV, $\mathscr{L}$ = 139 fb^{-1}

ATLAS

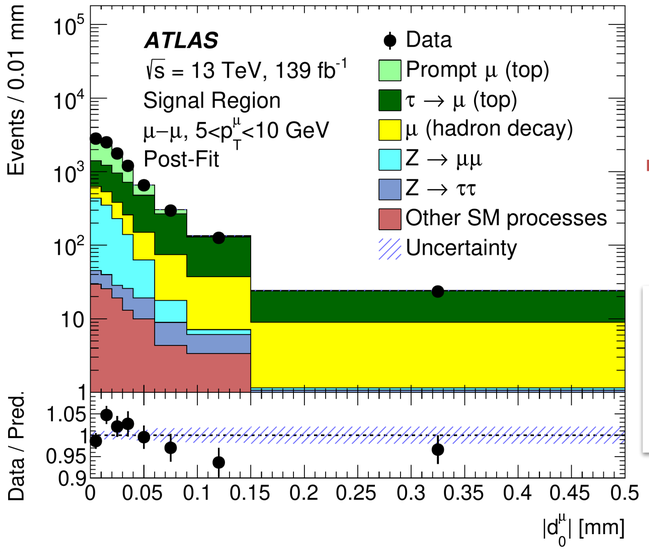
Nat. Phys. (2021)

- **First LHC test of LFU in W boson decays in ttbar dileptonic processes**

$$R(\tau/\mu) = BR(W \to \tau\nu_\tau)/BR(W \to \mu\nu_\mu)$$

Clear deviation of the experimental results from SM in rare B-decays:
BR($B^+ \to K^+\mu\mu$)/BR($B^+ \to K^+ee$) deviates 3.1σ from SM (LHCb)
BR($B^0 \to D^*\tau\nu$)/BR($B^0 \to D^*\mu\nu$) deviates 3.4σ from SM (LHCb+Belle+Babar)

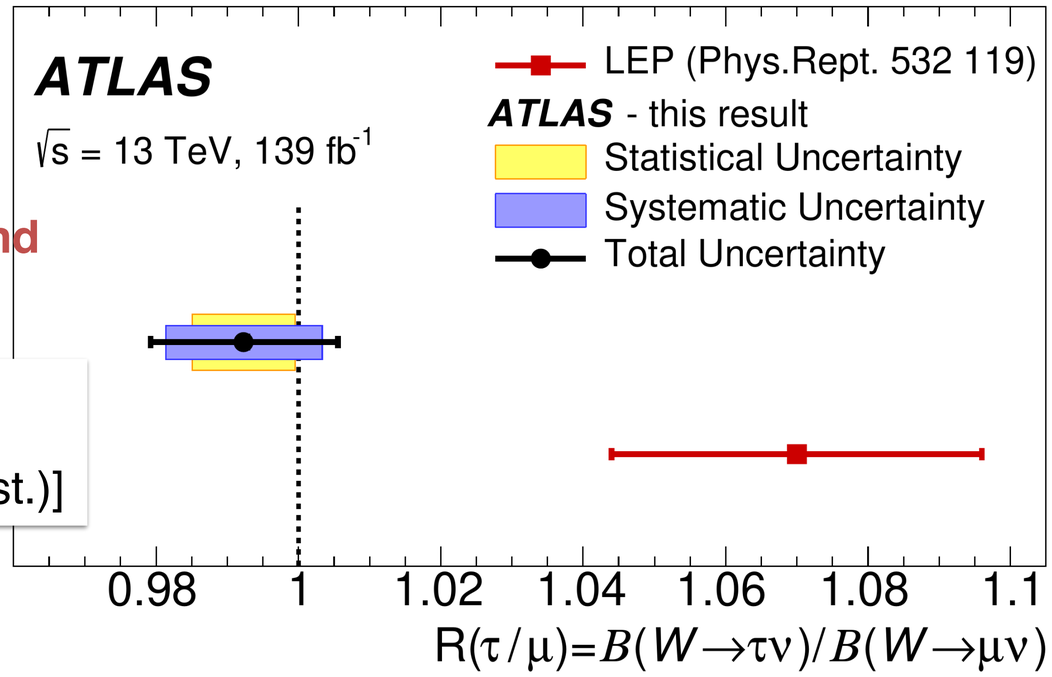
- **previous result from LEP had a deviation of 2.7σ from SM**
- Information of the τ lifetime (through d_0^μ) is used to distinguish events in the R(τ/μ)
- $Z \to \mu\mu$ events to calibrate d_0^μ
- Z+jets and μ not from W background estimated with data-driven



➡ **R(τ/μ) in good agreement with SM and most precise measurement to date**

$$R(\tau/\mu) = 0.992 \pm 0.013$$
$$[\pm 0.007(\text{stat.}) \pm 0.011\ (\text{syst.})]$$

Main uncertainties: d_0^μ calibration, signal modelling and muon isolation



H→4ℓ Production

13 TeV, $\mathscr{L}$ = 138 fb^{-1} CMS | $\mathscr{L}$ = 139 fb^{-1} ATLAS

Eur. Phys. J. C 81 (2021) 488 | Eur. Phys. J. C 80 (2020) 942, Eur. Phys. J. C 80 (2020) 957

- **Fiducial inclusive cross sections are measured in different fiducial volumes by ATLAS and CMS**

CMS: $\sigma = 2.84^{+0.34}_{-0.31}$ fb (SM: 2.84 ± 0.15 fb)

ATLAS: σ = 3.28 ± 0.32 fb (SM: 3.41 ± 0.18 fb)

Requirements for the H → 4ℓ fiducial phase space

Lepton kinematics and isolation	
Leading lepton p_T	$p_T > 20$ GeV
Next-to-leading lepton p_T	$p_T > 10$ GeV
Additional electrons (muons) p_T	$p_T > 7(5)$ GeV
Pseudorapidity of electrons (muons)	$\|\eta\| < 2.5$ (2.4)
Sum of scalar p_T of all stable particles within $\Delta R < 0.3$ from lepton	$< 0.35 p_T$
Event topology	
Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above	
Inv. mass of the Z_1 candidate	$40 < m_{Z_1} < 120$ GeV
Inv. mass of the Z_2 candidate	$12 < m_{Z_2} < 120$ GeV
Distance between selected four leptons	$\Delta R(\ell_i, \ell_j) > 0.02$ for any $i \neq j$
Inv. mass of any opposite sign lepton pair	$m_{\ell^+\ell^-} > 4$ GeV
Inv. mass of the selected four leptons	$105 < m_{4\ell} < 140$ GeV

Table 3: List of event selection requirements which define the fiducial phase space for the cross-section measurement. SFOC lepton pairs are same-flavour opposite-charge lepton pairs.

Leptons and jets	
Leptons	$p_T > 5$ GeV, $\|\eta\| < 2.7$
Jets	$p_T > 30$ GeV, $\|y\| < 4.4$
Lepton selection and pairing	
Lepton kinematics	$p_T > 20, 15, 10$ GeV
Leading pair (m_{12})	SFOC lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Subleading pair (m_{34})	remaining SFOC lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Event selection (at most one quadruplet per event)	
Mass requirements	50 GeV$< m_{12} <$ 106 GeV and 12 GeV$< m_{34} <$ 115 GeV
Lepton separation	$\Delta R(\ell_i, \ell_j) > 0.1$
Lepton/Jet separation	$\Delta R(\ell_i, \text{jet}) > 0.1$
J/ψ veto	$m(\ell_i, \ell_j) > 5$ GeV for all SFOC lepton pairs
Mass window	105 GeV$< m_{4\ell} <$ 160 GeV
If extra lepton with $p_T > 12$ GeV	Quadruplet with largest matrix element value

High-p_T Higgs production

13 TeV, $\mathscr{L}$ = 138 fb^{-1} CMS JHEP 12 (2020) 085

$\mathscr{L}$ = 136 fb^{-1} ATLAS ATLAS-CONF-2021-010

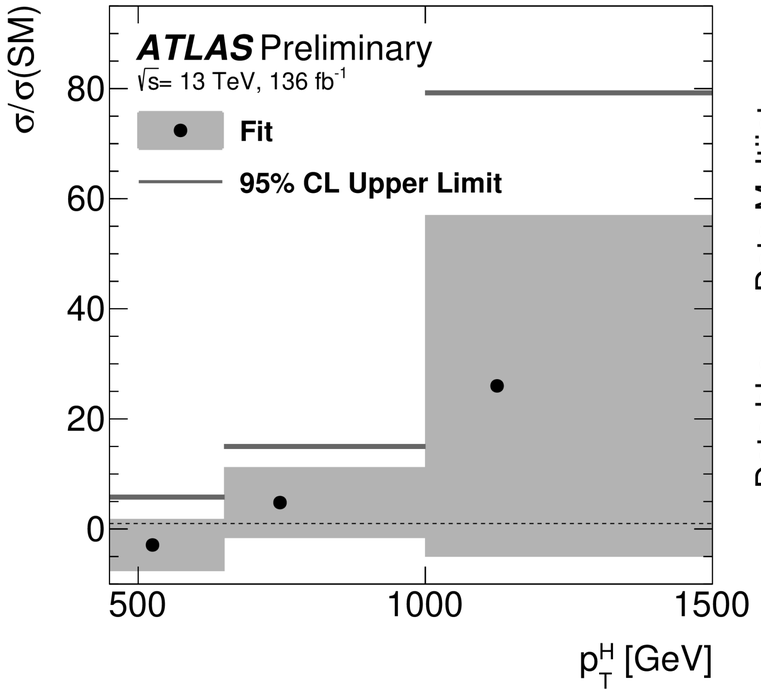
- **Study extreme region of phase space in most abundant Higgs decay**
- H→bb candidate reconstructed from **single large-R jet** and identified by the experimental signature of **2 b-jets**
- **Large background**: multijet parametrised using a VR, V+jets and ttbar from CRs
- Analysis method validated with Z→bb events

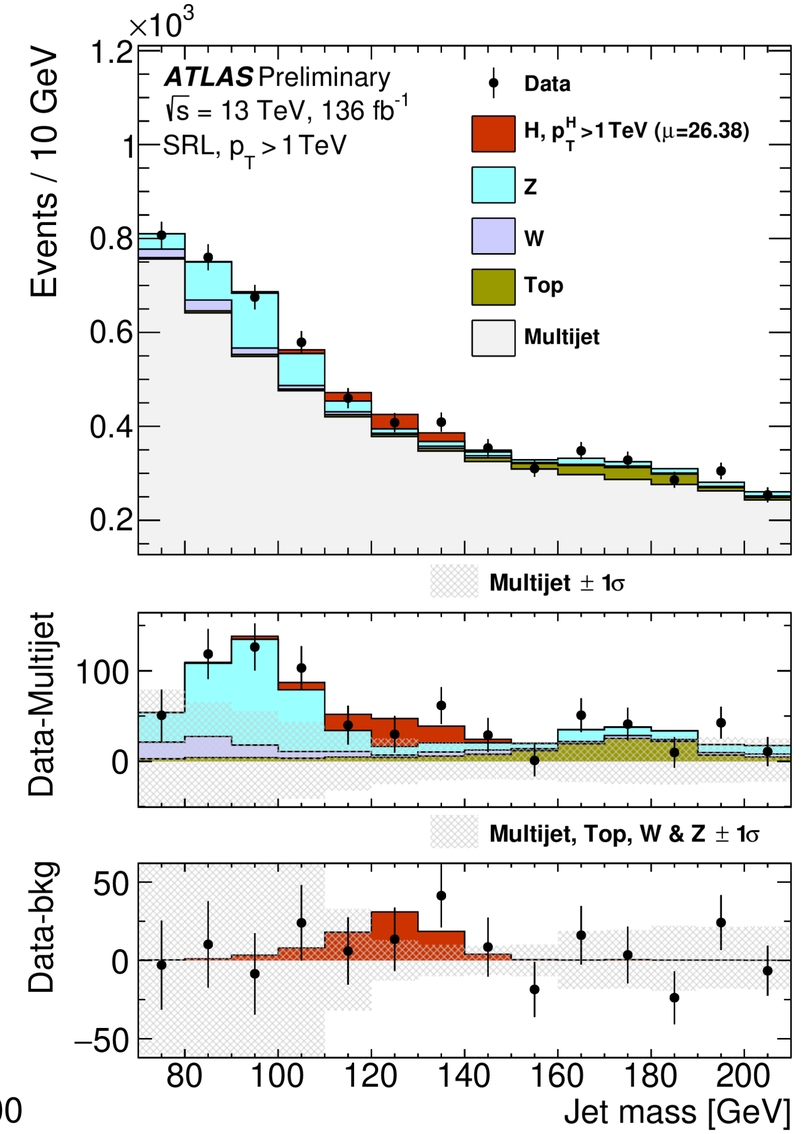
➡ Inclusive σ**(H→bb) for** p_T^H>450 GeV:

σ(H→bb) = 13 ± 57(stat) ± 22(syst) ± 3(theo) fb

➡ Differential σ(H→bb) measured in several p_T^H bins: 300-450 GeV, 450-650 GeV, >650 GeV, > 1 TeV

Limit at 95% CL on fiducial cross section for p_T>1 TeV: 10.3 fb





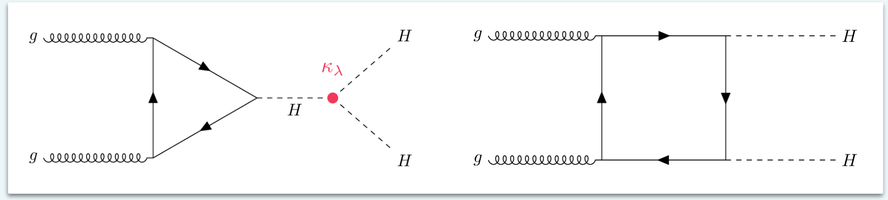
Search for HH→bb$\gamma\gamma$

13 TeV, $\mathscr{L}$ = 139 fb^{-1}

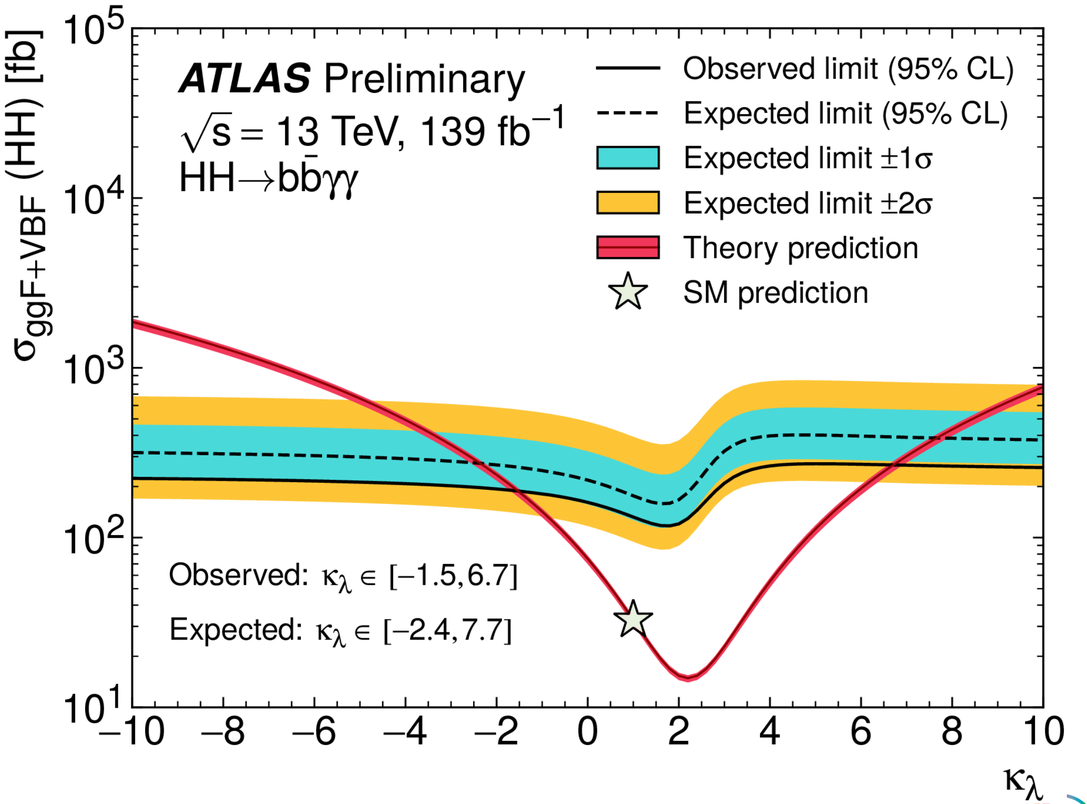
ATLAS

ATLAS-CONF-2021-016

- **Di-Higgs production sensitive to H self-coupling**
- Destructive interference with "box" diagram reduces cross section ($\sigma_{HH} \sim 30$ fb)
- Higgs trilinear coupling scaled by $k_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$ (k_λ=1 in SM)



- **pp→HH→bb$\gamma\gamma$ one of the most sensitive channel**
- **Very rare process (BR~0.26%) but cleaner final state**
  - combing high HH→bb BR and low HH→$\gamma\gamma$ BR with clean signature
- Events are categorised by $m_{bb\gamma\gamma}$ and a multivariate discriminant
  - **Low and high $m_{bb\gamma\gamma}$ regions are sensitive to large and small k_λ**
- Signal and background parametrised in $\mathbf{m_{\gamma\gamma}}$
  - main background from bb$\gamma\gamma$



➡ **Upper limits at 95% CL on non-resonant HH:**

σ(pp→HH→bb$\gamma\gamma$) < 4.1 (5.5) x SM obs. (exp.)

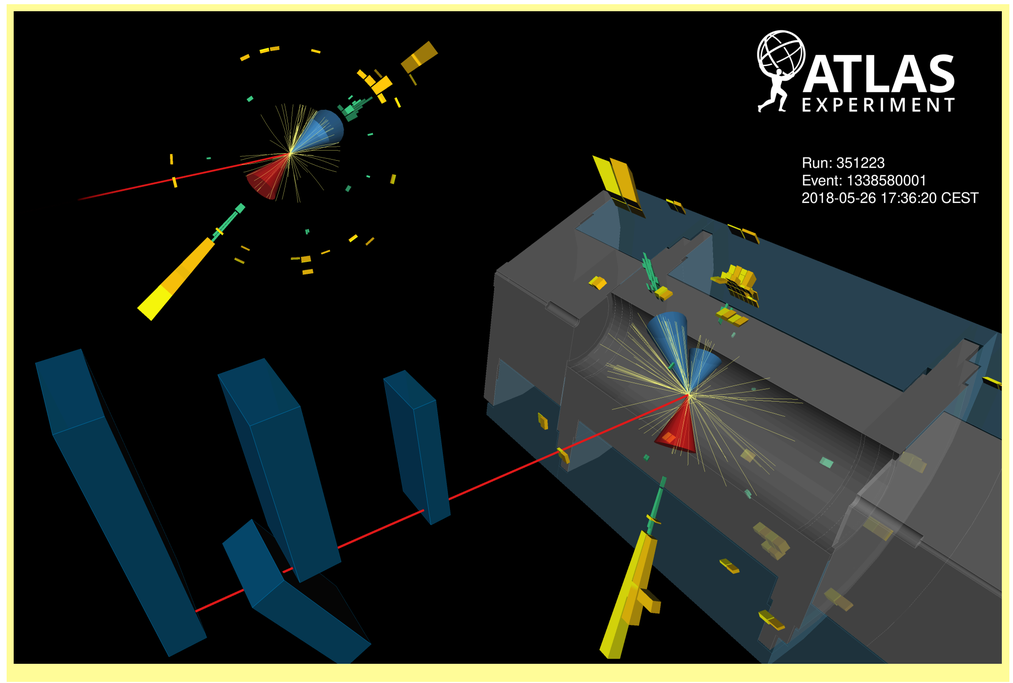
-1.5 (-2.4) < k_λ < 6.7 (7.7) obs. (exp.)

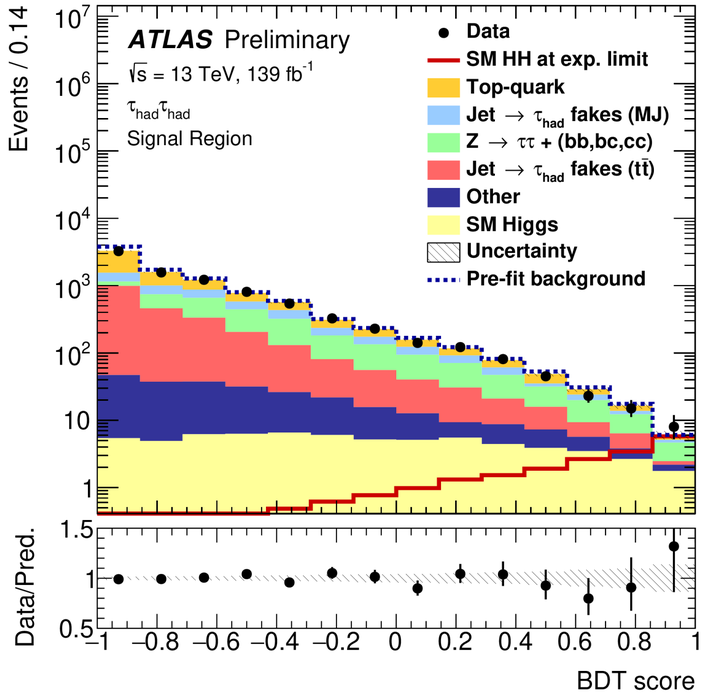
factor of 5 improvement over 36 fb^{-1} analysis

Search for HH→bb$\tau\tau$

- **One of the most sensitive HH search signatures: BR~7.3% and not too large background**

- Analysing $\tau_{had}\tau_{had}$ **and** $\tau_{had}\tau_{lep}$ **decay channels** with significantly improved τ_{had} efficiencies
- Variety of sizeable background: ttbar, V+jets, VV, multijet, single Higgs, fake τ estimated from MC and data
- **Signal extracted from fit on multivariate discriminants**





➡ Upper limits at 95% CL:

$\sigma(pp \to HH \to bb\tau\tau) < 4.7\ (3.9)$ x SM obs. (exp.)

factor of 4 improvement over 36 fb^{-1} analysis

HH combination and prospects

13 TeV CMS ATLAS

Combination with 36 fb^{-1}

- **ATLAS:** 6 channels combined, leading channel **HH→bb$\tau\tau$**
- **CMS:** 4 channels, leading channel **HH→bb$\gamma\gamma$**
- **reached limit: ~10xSM**

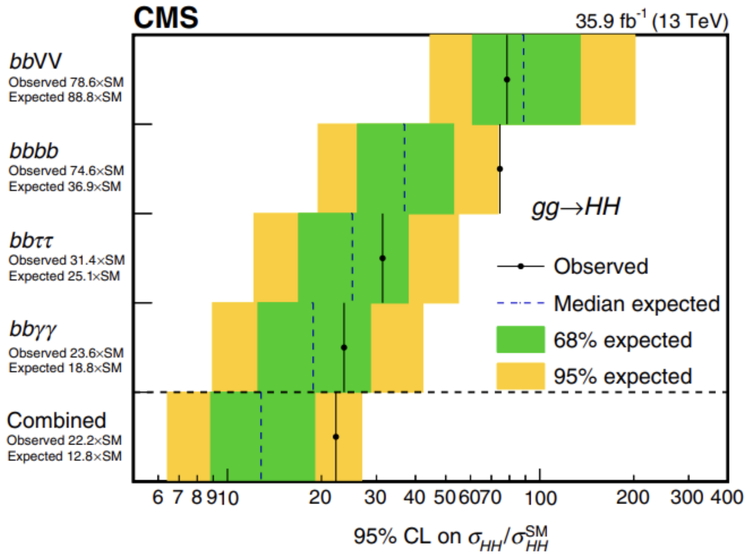
Full Run 2 combination:

- not available yet
- **full Run 2 results very promising, even more than HL-LHC extrapolation!**

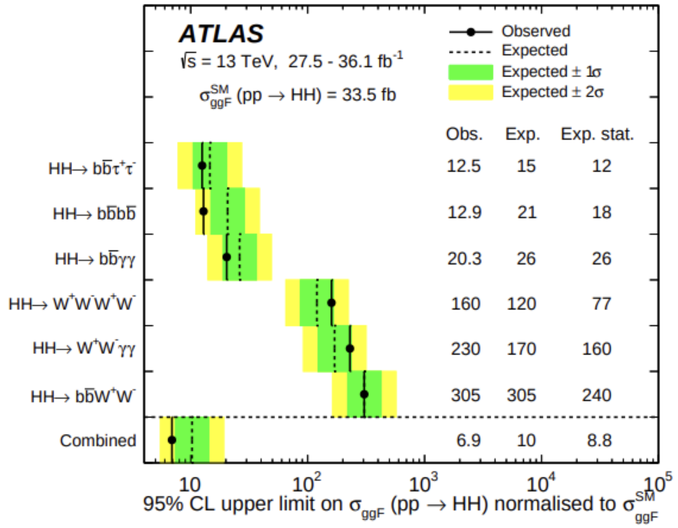
HL-LHC extrapolation:

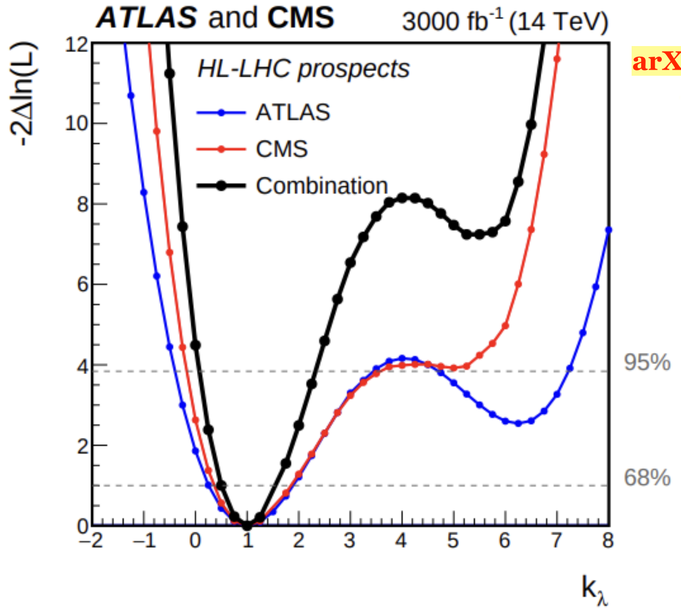
- based on 2016 results
- single experiment and ATLAS+CMS extrapolation
- **evidence expected, but no observation**

Phys.Rev.Lett. 122 (2019) 121803



Phys.Lett.B 800 (2020) 135103





arXiv:1902.00134

	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		Combined	
	4.5		4.0	

HH combination and prospects