Recent experimental precision measurements at CMS

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On behalf of **CMS Collaborations**

EuroTechPostdoc2 Programme
Excellence in Science and Technology

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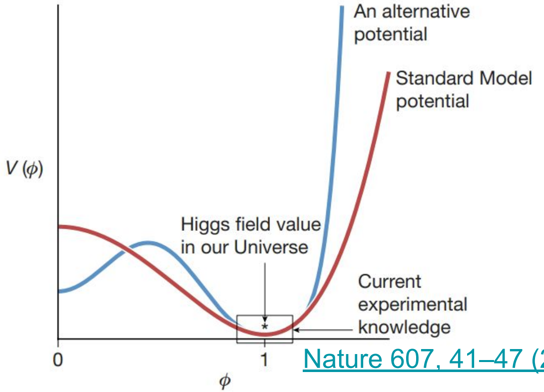
CMS

Motivation for precision measurements

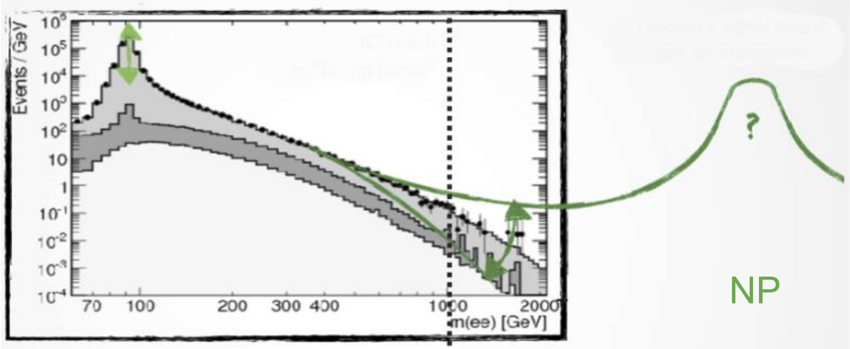
Precision measurements → pivotal role in **refining** the **SM**

Test self-consistency of the SM
- look for tensions in direct or indirect measurements
- deviations could arise from new physics

→ contribute to shaping a more comprehensive model of the origin of matter and cosmology
→ understanding features that affect the early universe and its eventual fate
(e.g. shape of the BEH vacuum potential and the EW vacuum stability)



Nature 607, 41–47 (2022)

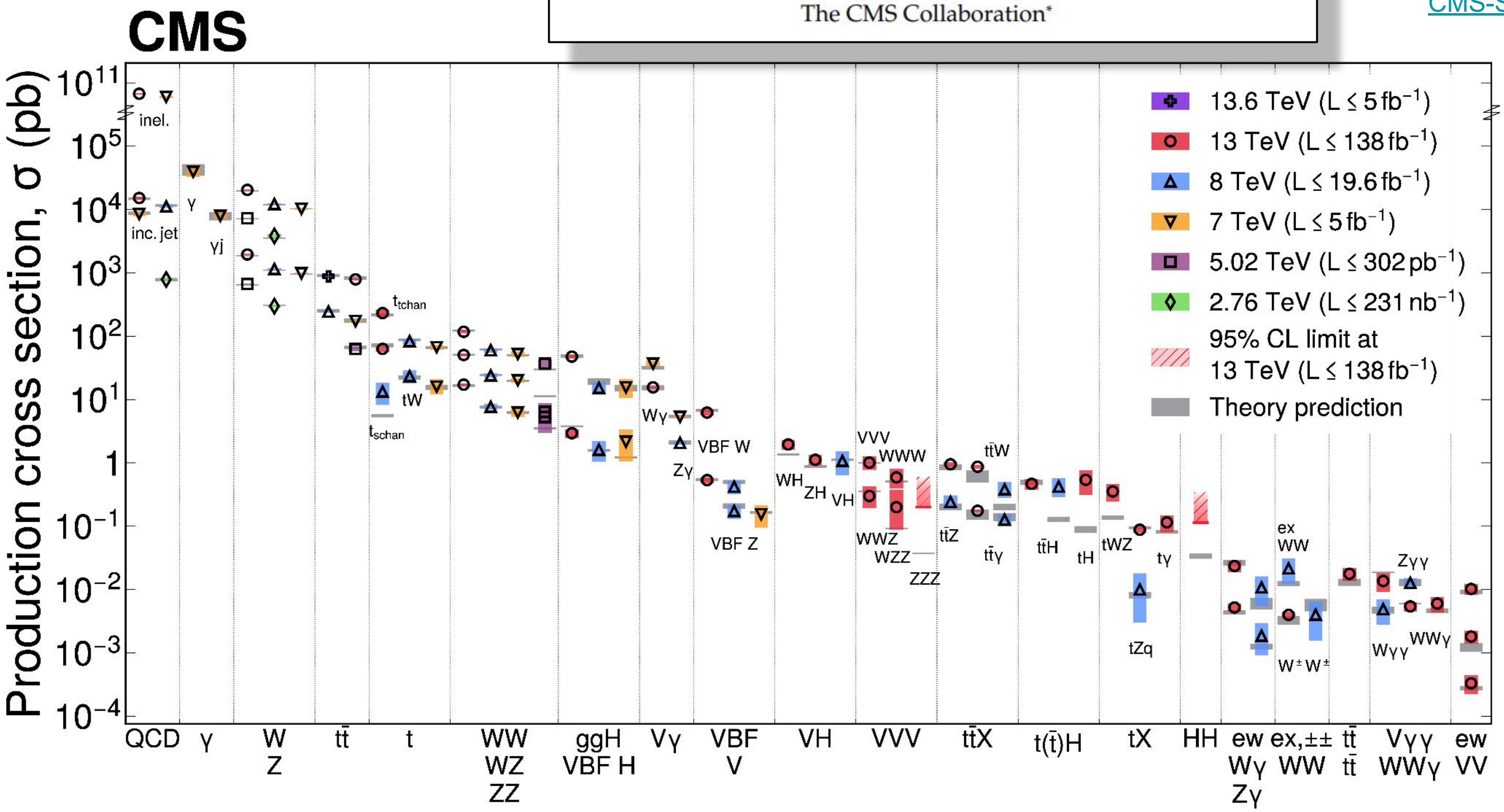


Cross-section summary

Stairway to discovery: a report on the CMS programme of cross section measurements from millibarns to femtobarns

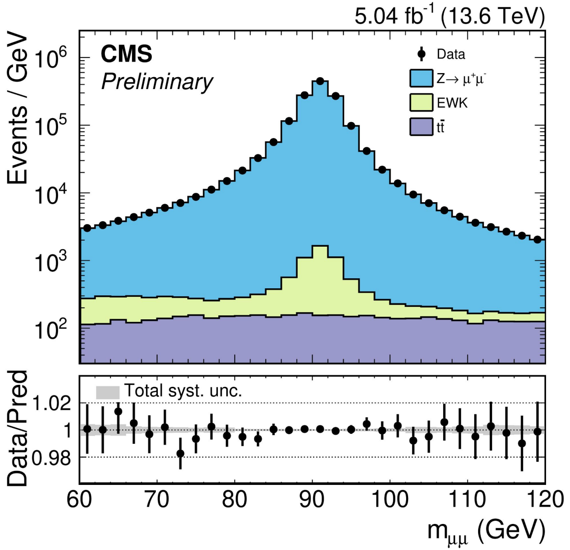
The CMS Collaboration*

CMS-SMP-23-004



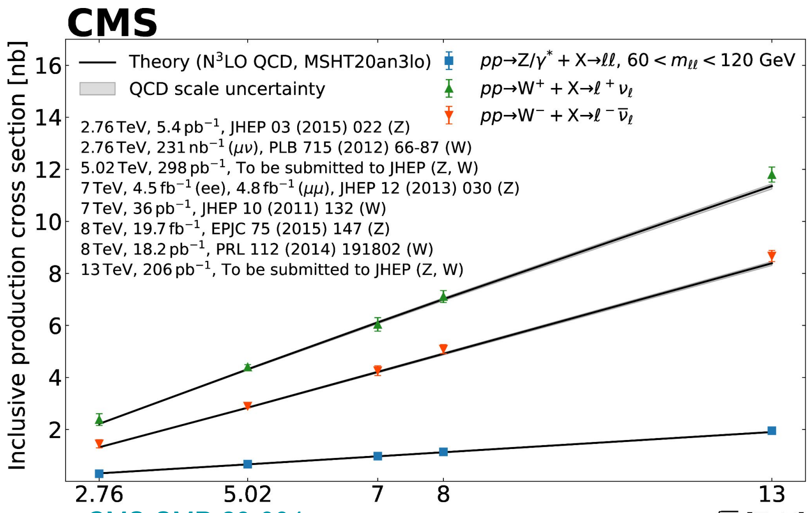
Z and W cross-section

CMS-PAS-SMP-22-017



Z cross-section @13.6 TeV, $Z\to\mu\mu$
fundamental measurement and crucial validation for Run3 data

$$(\sigma_{\text{fid}}\mathcal{B})_{\text{measured}} = (0.7635 \pm 0.0004(\text{stat}) \pm 0.0069(\text{syst}) \pm 0.0176(\text{lumi}))\,\text{nb},$$
$$(\sigma_{\text{fid}}\mathcal{B})_{\text{predicted}} = (0.7666 \pm 0.0065(\text{PDF})^{+0.0021}_{-0.0045}(\text{scale}))\,\text{nb},$$



CMS-SMP-23-004

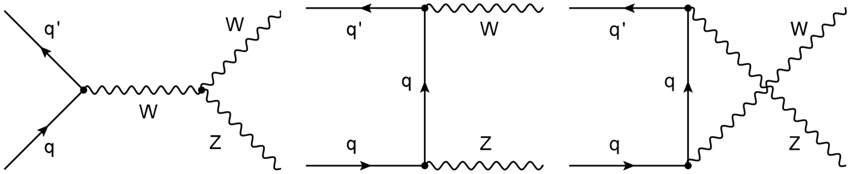
Evolution of Z and W production **cross-section** (leptonic decays)

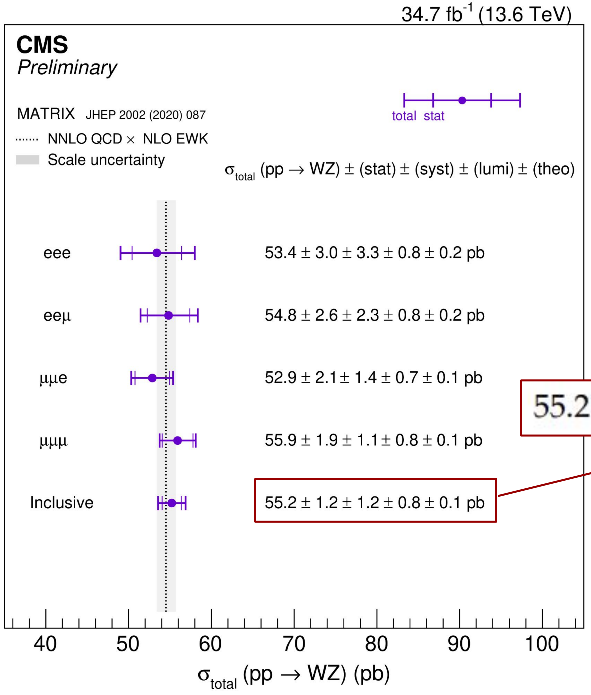
→ comparison with N3LO in QCD predictions (with MSHT20aN3LO PDF set)

→ precise (~2% precision) comparison between theory predictions and experimental measurements

Multiboson production: WZ

WZ cross-section @13.6 TeV in leptonic final states
→ very clean final state (85% S/B purity after selection)

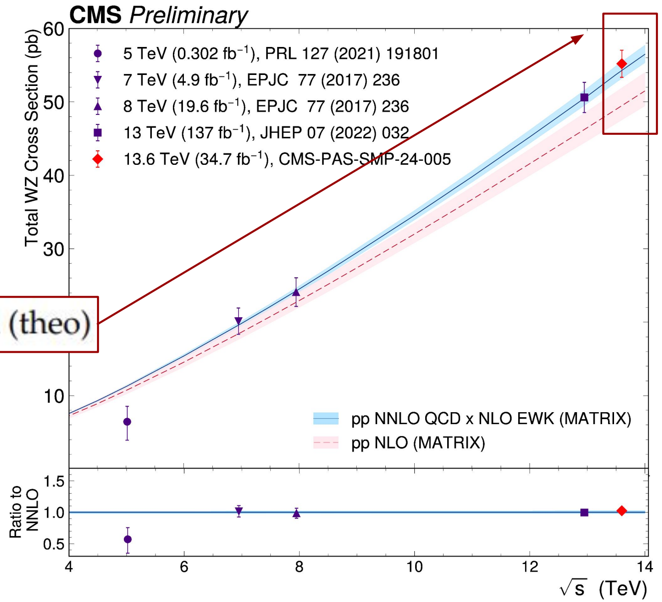




Results in good agreement with NNLO QCD x NLO EW predictions (MATRIX):

$$54.7^{+1.2}_{-1.1}\,(\text{scale})$$

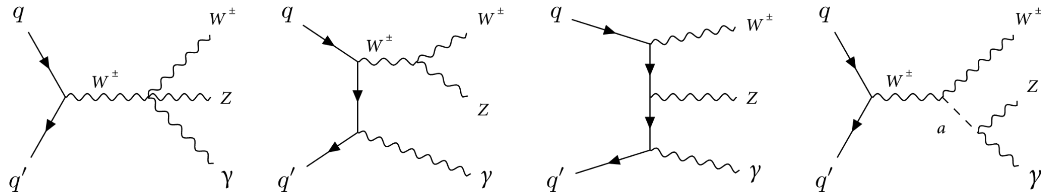
$$55.2 \pm 1.2\,(\text{stat}) \pm 1.2\,(\text{syst}) \pm 0.8\,(\text{lumi}) \pm 0.1\,(\text{theo})$$



3.3% relative uncertainty (inclusive)
→ competitive with Run2

CMS-PAS-SMP-24-005

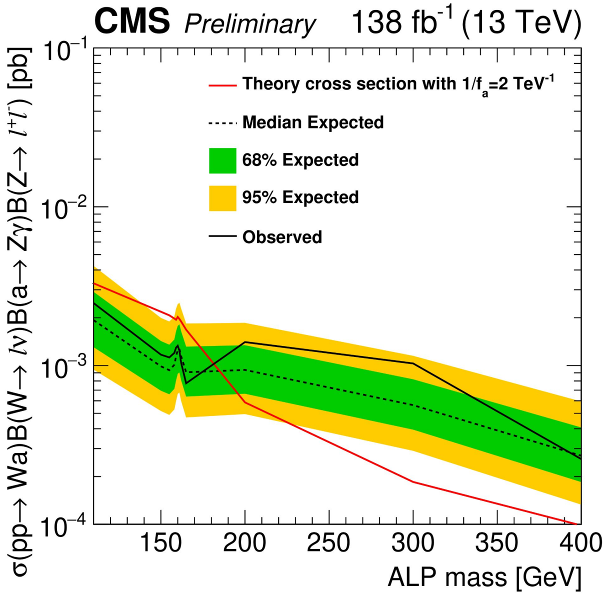
Multiboson production: WZγ



WZγ cross-section @13 TeV
in leptonic final states

$$\sigma_{\text{obs.}} = 5.48 \pm 0.57\ (\text{syst.}) \pm 0.10\ (\text{theo.}) \pm 0.95\ (\text{stat.})$$

→ **constraints** on **new physics** both
direct (search for ALP)
and indirect (limits on aQGC)



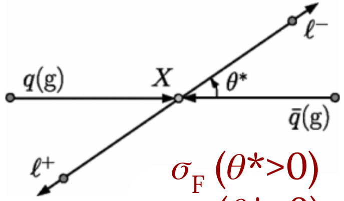
Operators	Observed limits [TeV $^{-4}$]	Expected limits [TeV $^{-4}$]	Unitarity bound [TeV]
$F_{T,0}/\Lambda^4$	[-2.60, 2.60]	[-2.52, 2.52]	1.32
$F_{T,1}/\Lambda^4$	[-3.28, 3.24]	[-3.18, 3.14]	1.48
$F_{T,2}/\Lambda^4$	[-7.15, 7.05]	[-6.95, 6.85]	1.35
$F_{T,5}/\Lambda^4$	[-2.54, 2.56]	[-2.46, 2.50]	1.55
$F_{T,6}/\Lambda^4$	[-3.18, 3.22]	[-3.08, 3.14]	1.61
$F_{T,7}/\Lambda^4$	[-6.85, 7.05]	[-6.65, 6.85]	1.71

CMS-PAS-SMP-22-018

EW mixing angle: $\sin^2\theta^\ell_{eff}$

Fundamental EW parameter
Important measurement to **test the SM**

$$\sin^2\theta^\ell_{eff} = k^\ell\,(1 - m^2_W/m^2_Z)$$

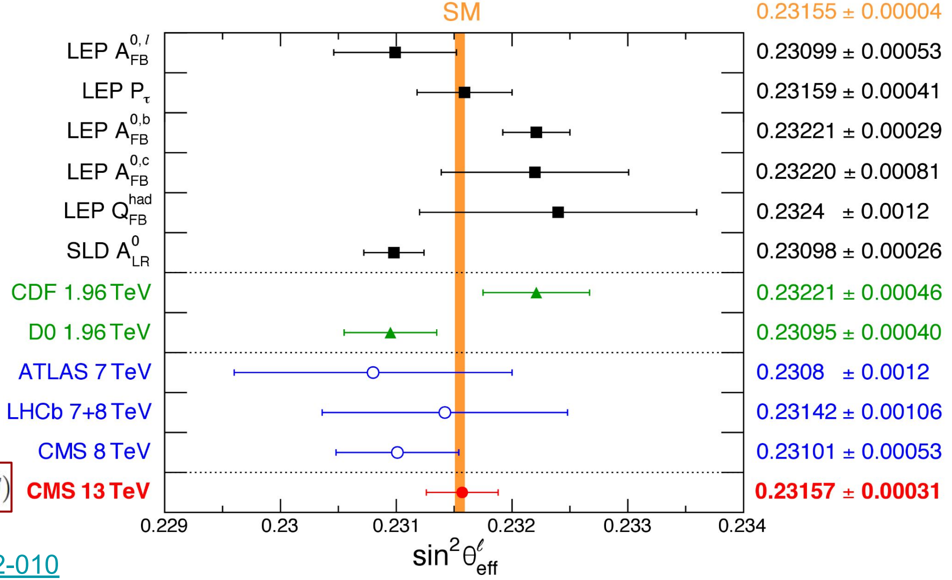


σ_F $(\theta^*>0)$
σ_B $(\theta^*<0)$

$$A_{FB} = \sigma_F - \sigma_F \,/\, \sigma_F + \sigma_F$$
$$A_{FB} = 3/8\, A_4$$

Recent result @13 TeV, measured via **$Z/\gamma^*\to ll$**

- from **forward-backward angular asymmetry** A_{FB} (same as Run 1)
  → cancellation of detector acceptance and efficiencies syst. unc.
- fit **A_4 coefficient** while unfolding diff distributions
  → smaller theory and PDF unc., useful for future combination



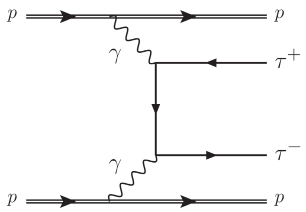
Most precise measurement at hadron colliders, precision comparable to LEP

$$\sin^2\theta^\ell_{eff} = 0.23157 \pm 0.00010(\text{stat}) \pm 0.00015(\text{syst}) \pm 0.00009(\text{theo}) \pm 0.00027(\text{PDF})$$

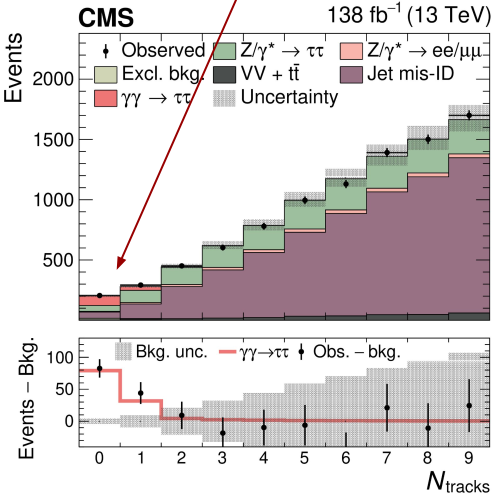
CMS-SMP-22-010

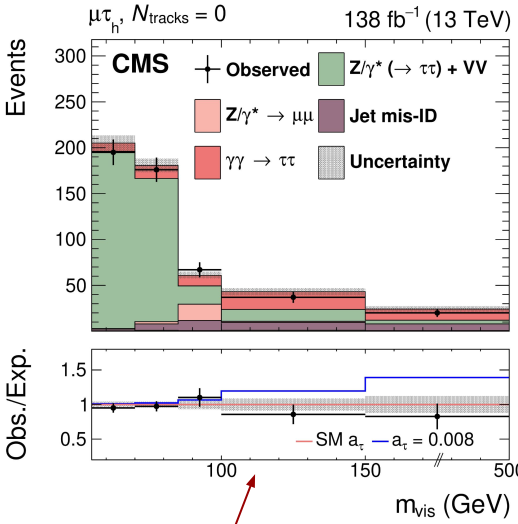
$\gamma\gamma \rightarrow \tau\tau$ and τ g-2

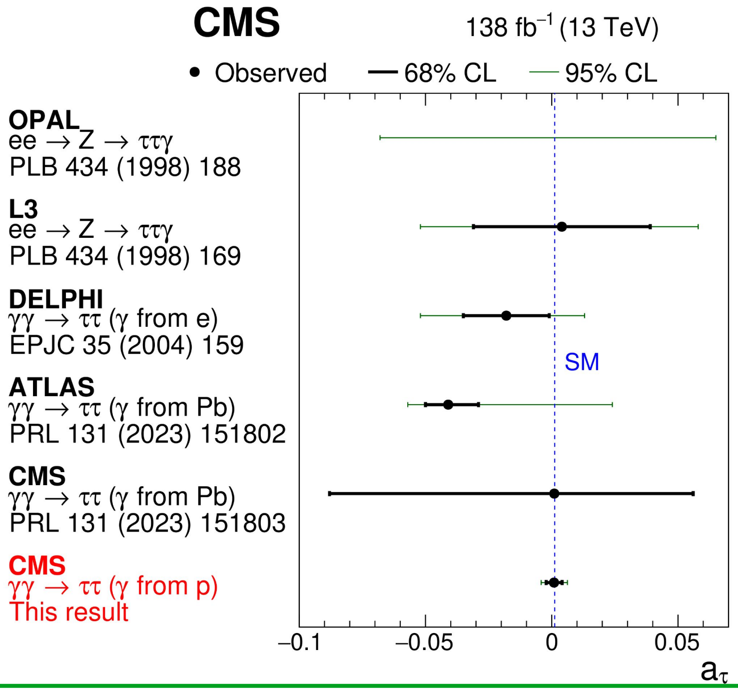
CMS-SMP-23-005



First **observation** of $\boldsymbol{\gamma\gamma \rightarrow \tau\tau}$ in pp collisions
→ 5.3σ observed







Constraints on $\boldsymbol{a_\tau}$ from m_{vis} distribution

$$a_\tau = 0.0009^{+0.0016}_{-0.0015}\,(\text{syst})^{+0.0028}_{-0.0027}\,(\text{stat})$$

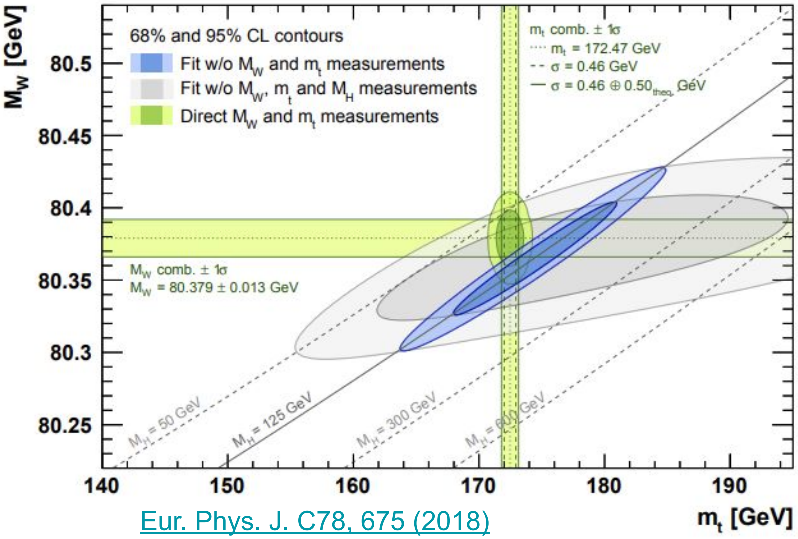
Top quark

Deep connection to both EW and QCD sectors

Large $\mathbf{m_t}$ → Yukawa coupling ~ unity → key **parameter for vacuum stability**

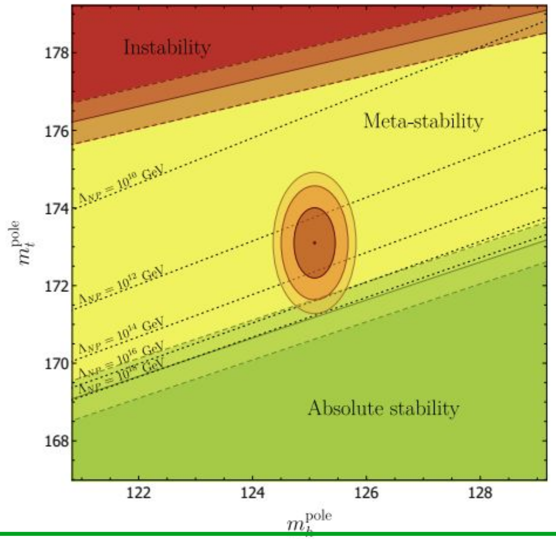
Excellent setting to **test pQCD predictions** (cross-section, α_S..)

Production and decay **sensitive to new physics** (anomalous couplings, CP violation, spin correlation..)



Eur. Phys. J. C78, 675 (2018)

Phys. Rev. D 97, 056006 (2018)



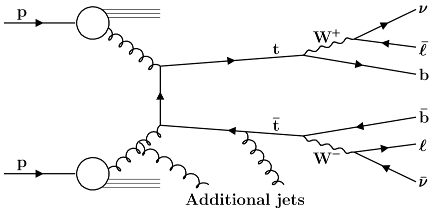
top quark pair production

CMS-TOP-20-006

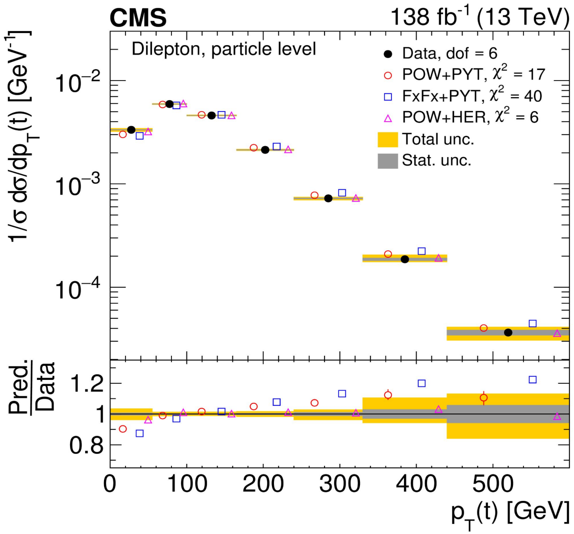
$t\bar{t}$ cross-section **@13 TeV**, ll+jets events

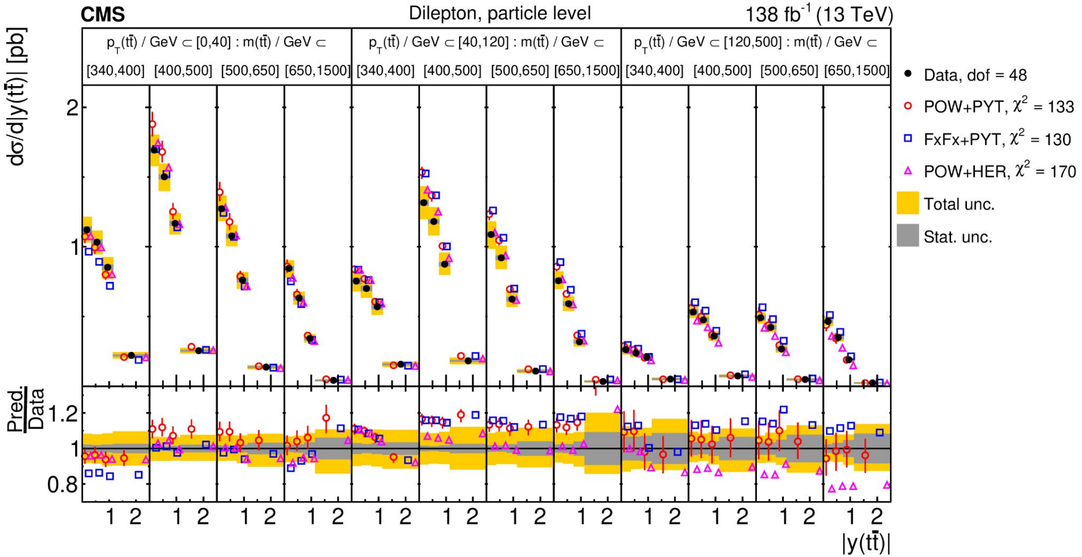
→ complete set of **differential** results

- production and decay observables
- single, double, triple differential
- particle and parton level (for comparison to pQCD computations)



→ 1D distribution reasonably well described
→ 2D/3D often not well described by any generator

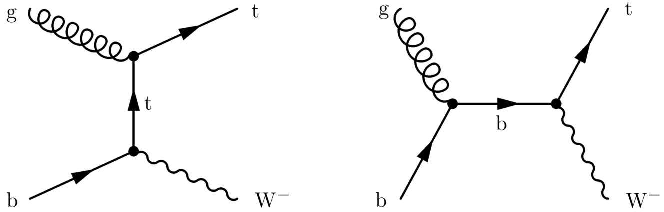


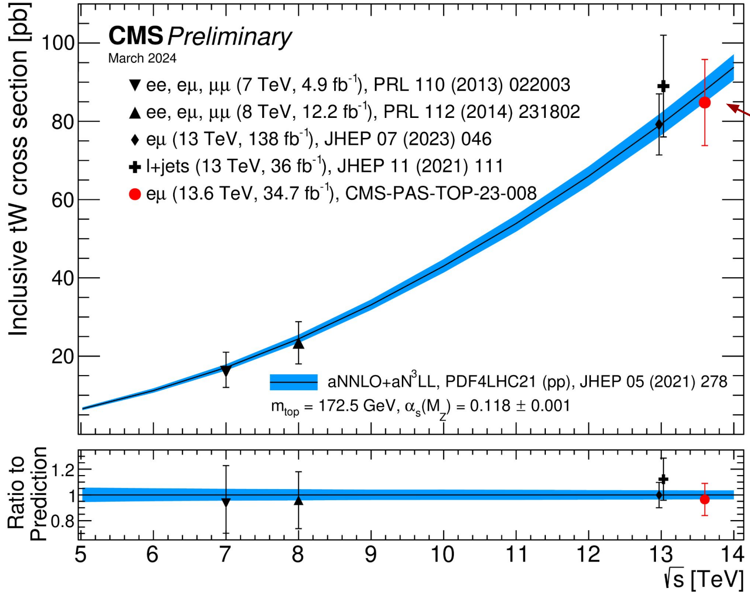


tW production

Single-top +W cross-section @13.6 TeV, in eμ channel

- sensitivity to $\mathbf{V_{tb}}$ and **b-PDF**
- tW @NLO interferes with $t\bar{t}$
- large $t\bar{t}$ background → ML to separate tW from $t\bar{t}$





$$\sigma_{\mathrm{tW}} = 84.1 \pm 2.1\,(\mathrm{stat})\,^{+9.8}_{-10.2}\,(\mathrm{syst}) \pm 3.3\,(\mathrm{lumi})\,\mathrm{pb}$$

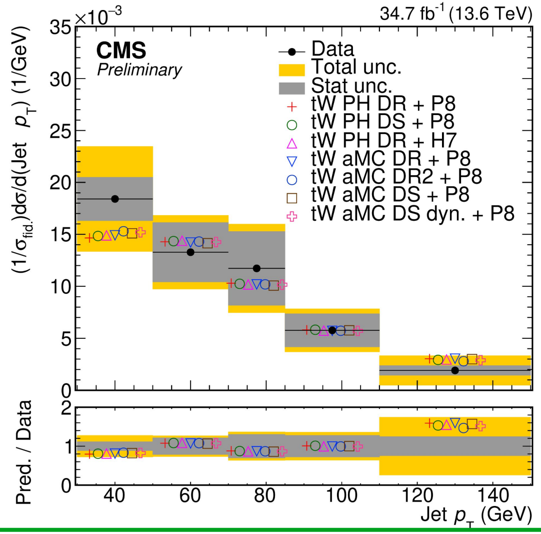
~13% precision

main syst: JES, b-tag, bkg

Differential results

→ comparison to different methods to treat **tW/$\mathbf{t\bar{t}}$ interference**

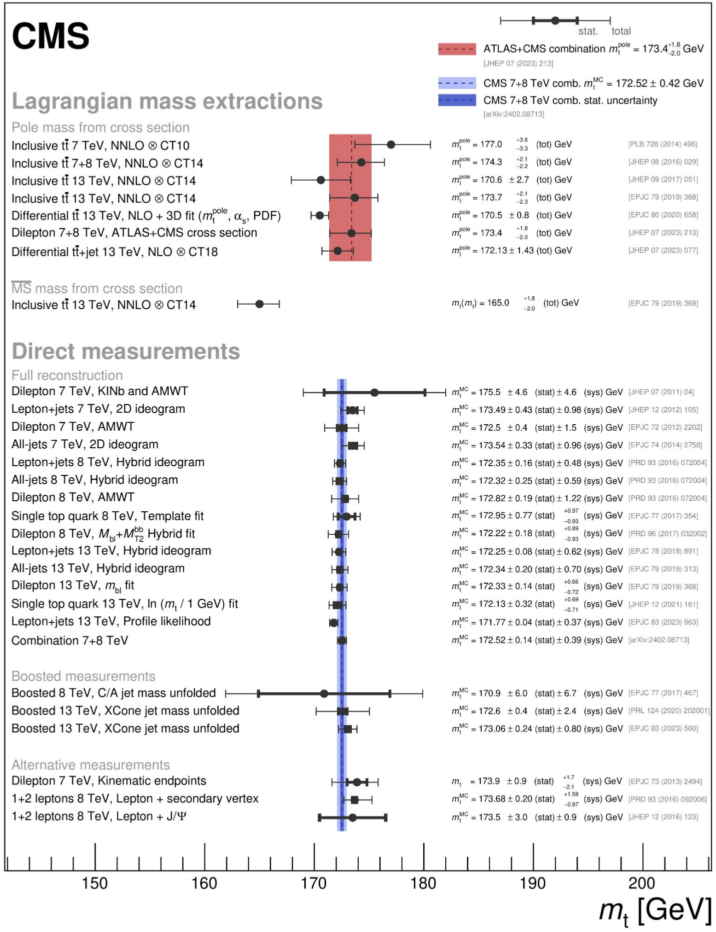
→ small effects in fid region



CMS-PAS-TOP-23-008

Top quark mass

[CMS-TOP-23-003](CMS-TOP-23-003)



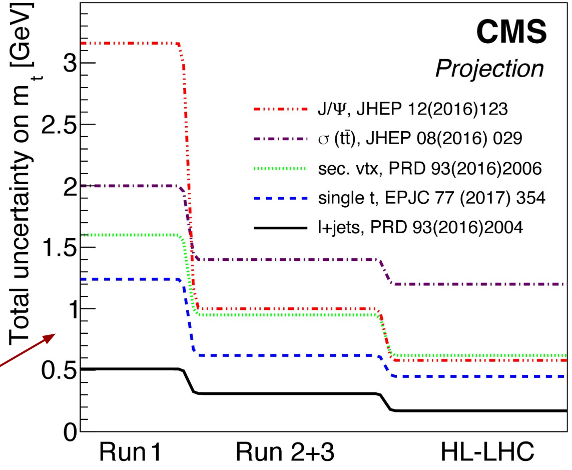
Improvements to the measurement **over the past years**: better calibrations, alternative techniques, improved theoretical modelling

Indirect measurement, from cross-section
→ ~1% precision

Direct measurement, from top quark decays
→ better precision

Most precise result to date from ATLAS+CMS comb:
m_t=172.52 ± 0.33 GeV

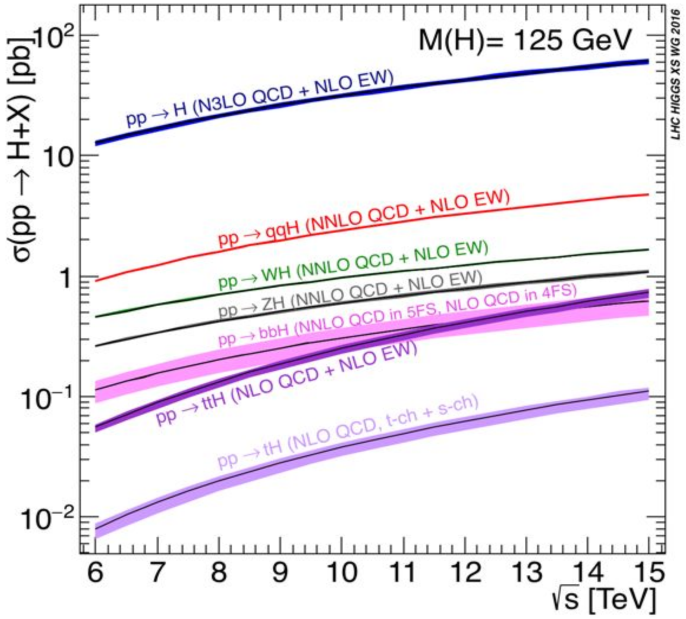
Projection for total uncertainty on m_t for different techniques

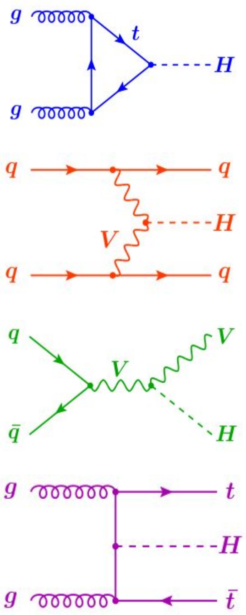


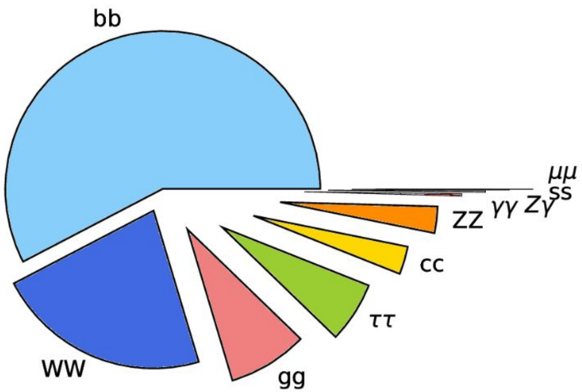
Higgs boson

Over 10 years after the Higgs boson discovery
→ Many new measurements possible, new channels accessible
→ H properties studied with **precision**

- main production processes and decay channels established
- measurement more differential
- search for decays to second generation
- search for HH







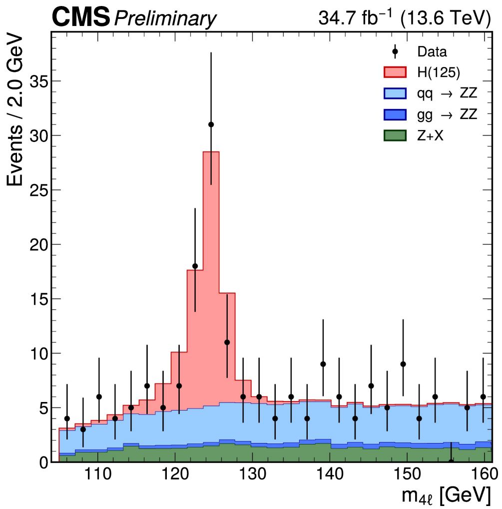
Nature 607 (2022) 60-68

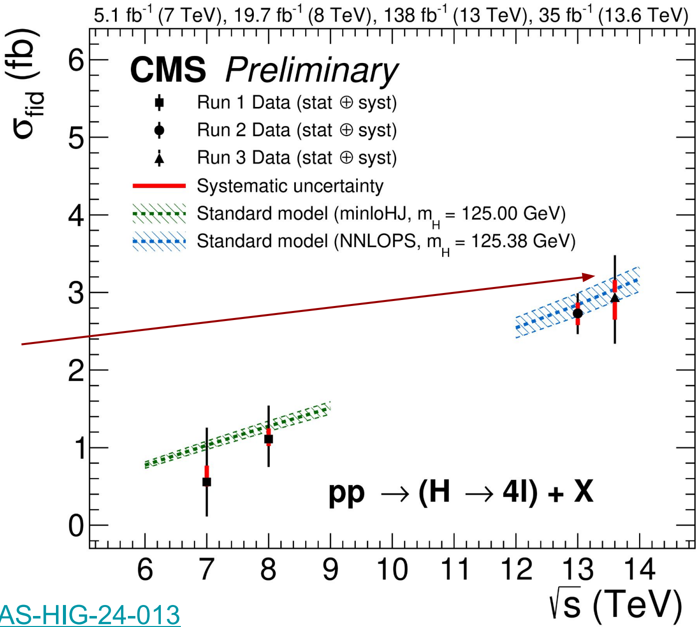
H production cross-section

H fiducial cross-section **@13.6 TeV**, in 4l and $\gamma\gamma$ final states
→ crucial validation for Run3 data and objects (e, μ, γ) performance

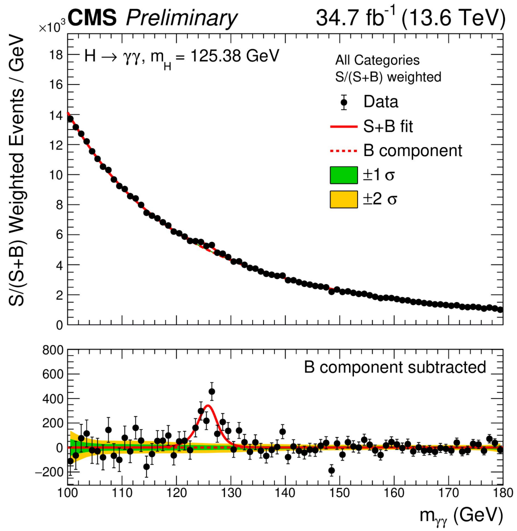
measurements still statistically dominated

Syst dominated by
→ photon scale/resolution ($\gamma\gamma$)
→ electron efficiency (4l)





CMS-PAS-HIG-24-013



CMS-PAS-HIG-23-014

Cross-section for production/decay mode

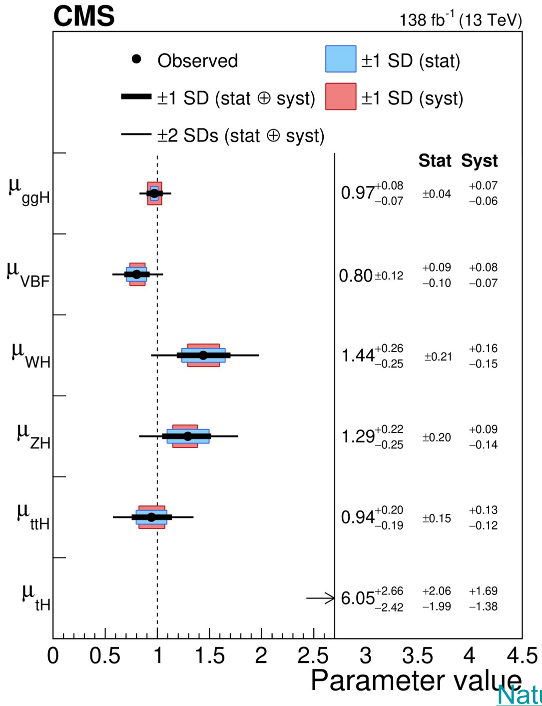
Signal strength: ratio of the measured cross-section and the SM expectation

By production mode, **assuming SM BR**

~10% precision

~20% precision

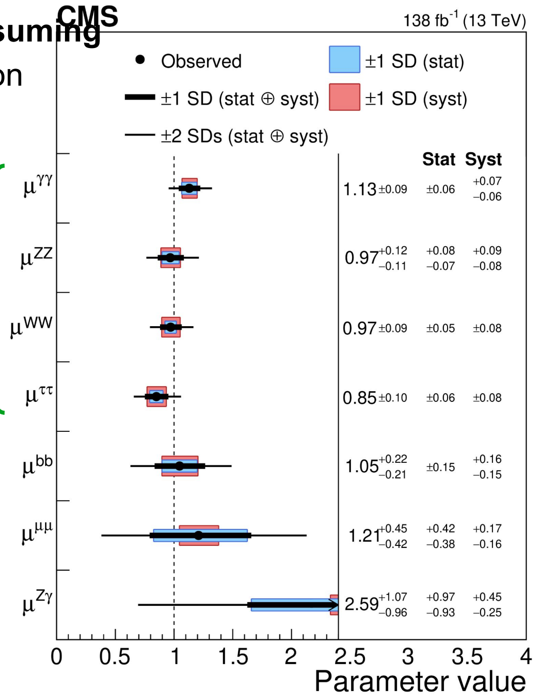
All main prod. modes observed with significance ⩾ 5σ
→ tH production not yet observed



Per decay channel, **assuming SM** values for production **cross-section**

~10% precision

Rare decays ($Z\gamma$, $\mu\mu$) not observed yet, all others observed with significance ⩾ 5σ



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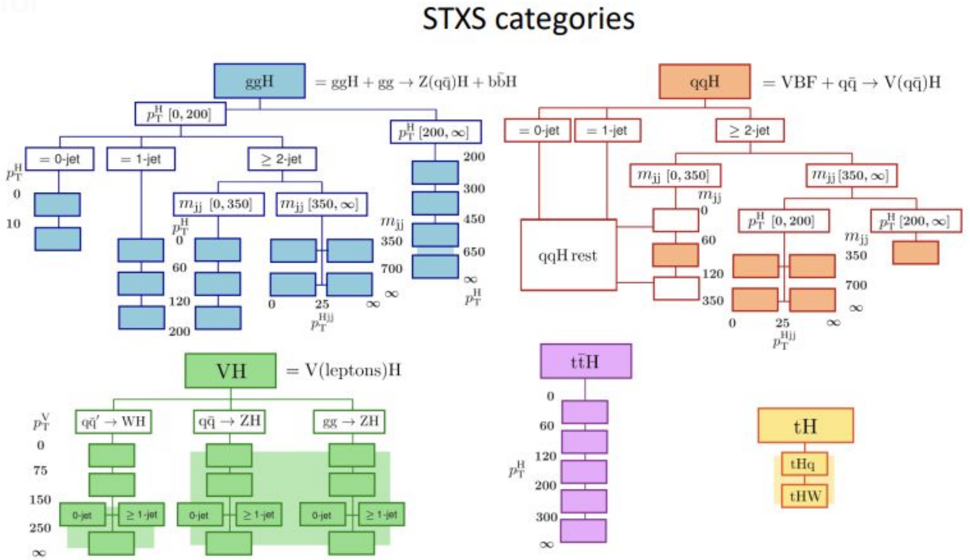
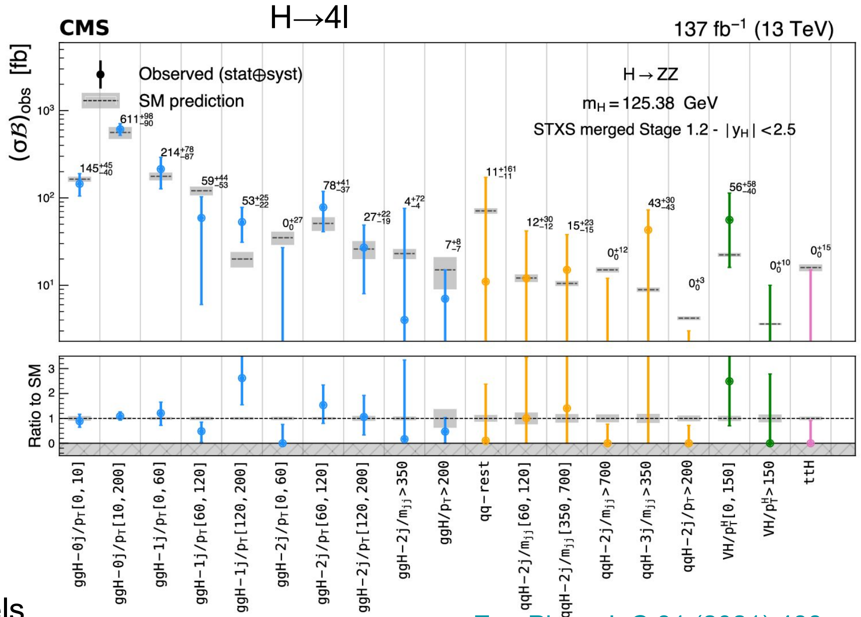
Simplified Template Cross-Sections

More data available → probe the Higgs kinematics in a **more model independent way**

STXS: categorize events in simplified kinematic regions
→ maximize sensitivity to isolate BSM effects while reducing theory dependence

STXS Stage 1.2 : splitting based on number of jets and kinematic selections (p_T^H)





More public results available for other channels

[Eur. Phys. J. C 81 (2021) 488](#)

Differential fiducial cross-sections

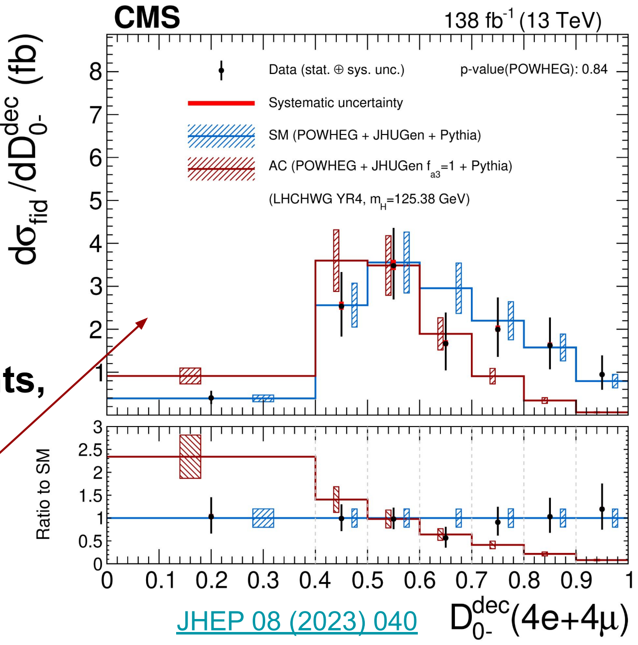
key to Higgs boson properties characterization (production and decay)
→ test SM predictions for full spectra of variable of interest
→ measured in fiducial phase space → largely **model independent**

H→ττ channel great handle for **large jet multiplicity region**

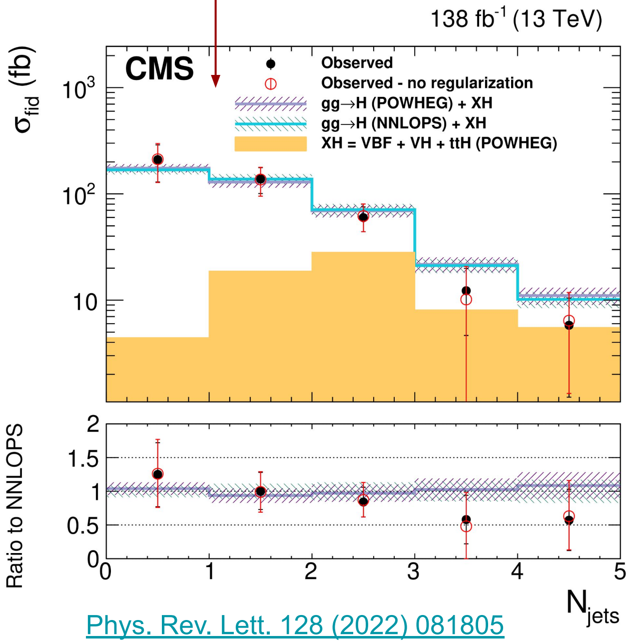
Full Run 2 results from CMS in different decay channels

Consistent with SM, meas. still **stat. limited**

In **H→ZZ*→4l** ME **discriminants,** sensitive to **HVV anomalous couplings**
→ D_{0-}^{dec} sensitive to possible CP-violation effects



JHEP 08 (2023) 040



Phys. Rev. Lett. 128 (2022) 081805

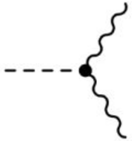
Anomalous couplings

Couplings modifiers per interaction vertex

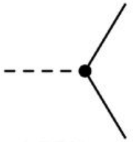
does not cover all effects

H confirmed to be spin 0, and consistent with CP++ since run 1
→ pure CP-odd state excluded ≠ CP-even state → active studies
→ **compatible** with **SM** for now

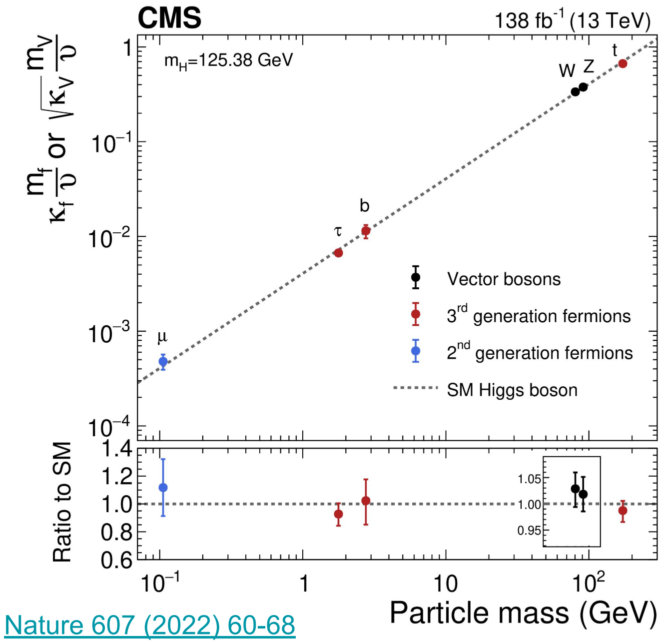
Cross-check of linear behaviour of vector bosons and Yukawa couplings



$$g_V = 2\frac{m_V^2}{v}$$



$$g_F = \sqrt{2}\frac{m_f}{v}$$



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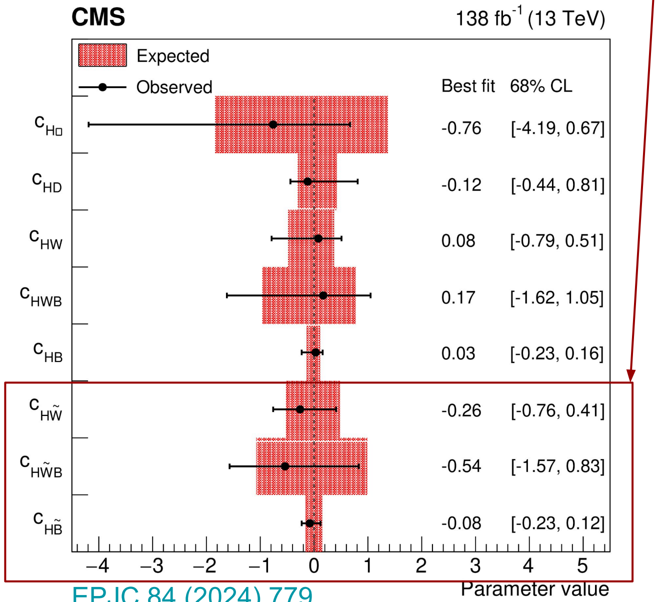
Constraints on CP-even and CP-odd Wilson coeff in H→WW→2l2ν



EPJC 84 (2024) 779

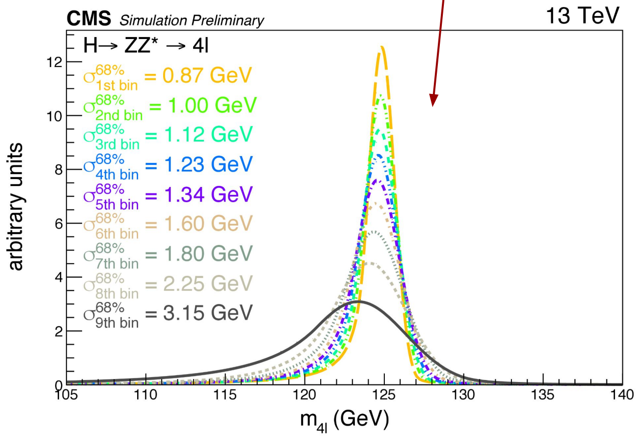
Higgs boson mass

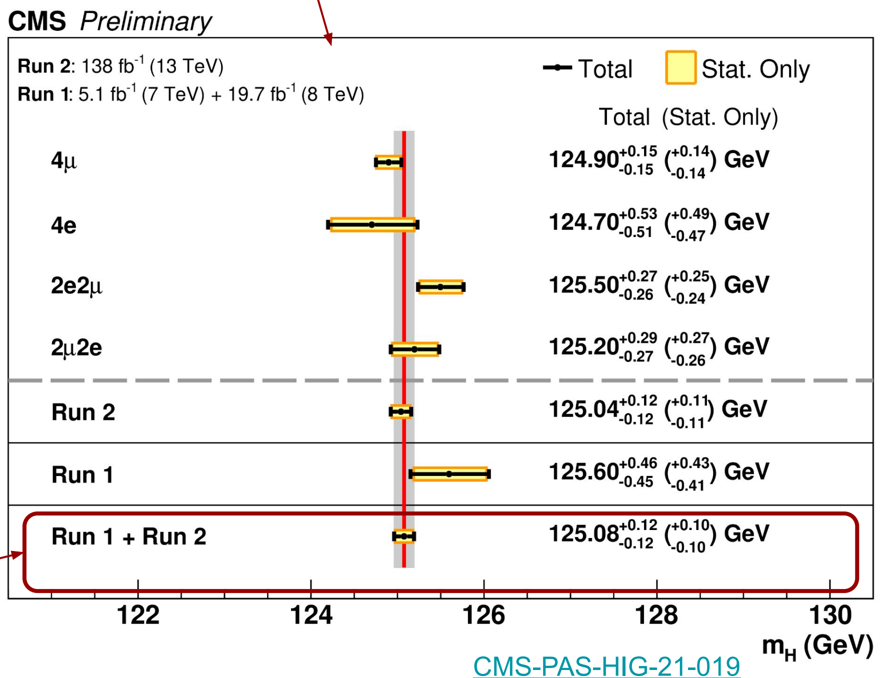
Measurement in decay channels with **good resolution**: $H\to\gamma\gamma$ and $H\to ZZ^*\to 4l$

In $H\to 4l$

2D fit over $\mathbf{m_{4l}}$ and **kinematic discriminant**

→ 9 mass resolution categories





Most precise single-channel measurement (0.1% precision)

CMS-PAS-HIG-21-019

Higgs boson width

SM H width (4.1 MeV) → inferred from **off-shell/on-shell cross-section ratio** in **pp→H→ZZ** (4l+2l2ν)

$$\frac{\sigma_{offshell}}{\sigma_{onshell}} \propto \Gamma_H$$

Off-shell region (m_{4l}^{reco} > 200 GeV) studied in H→ZZ→4l and H→ZZ→2l2ν

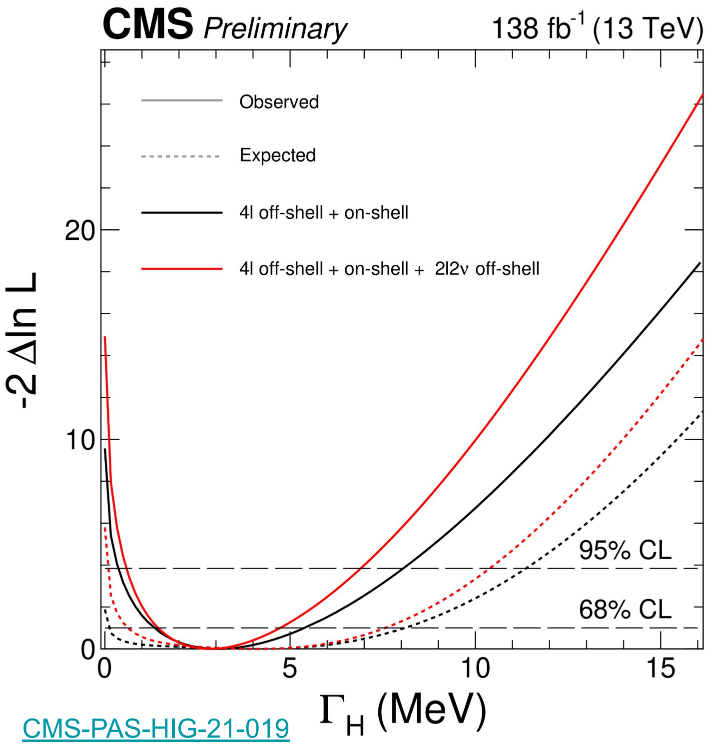
\+ **combination** with **on-shell** H→ZZ→4l

$$\Gamma_H = 2.9^{+2.3}_{-1.7}\,\mathrm{MeV}$$

In agreement with SM predictions

In addition:

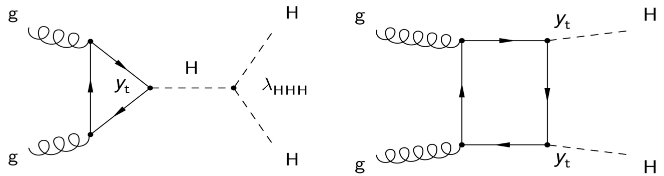
- **direct constraint** on Γ_H: <330 MeV @95% CL
- zero **off-shell** H **production** hp excluded at 3.9σ



CMS-PAS-HIG-21-019

HH production

HH production → directly study Higgs boson **self-coupling** and Higgs **potential**



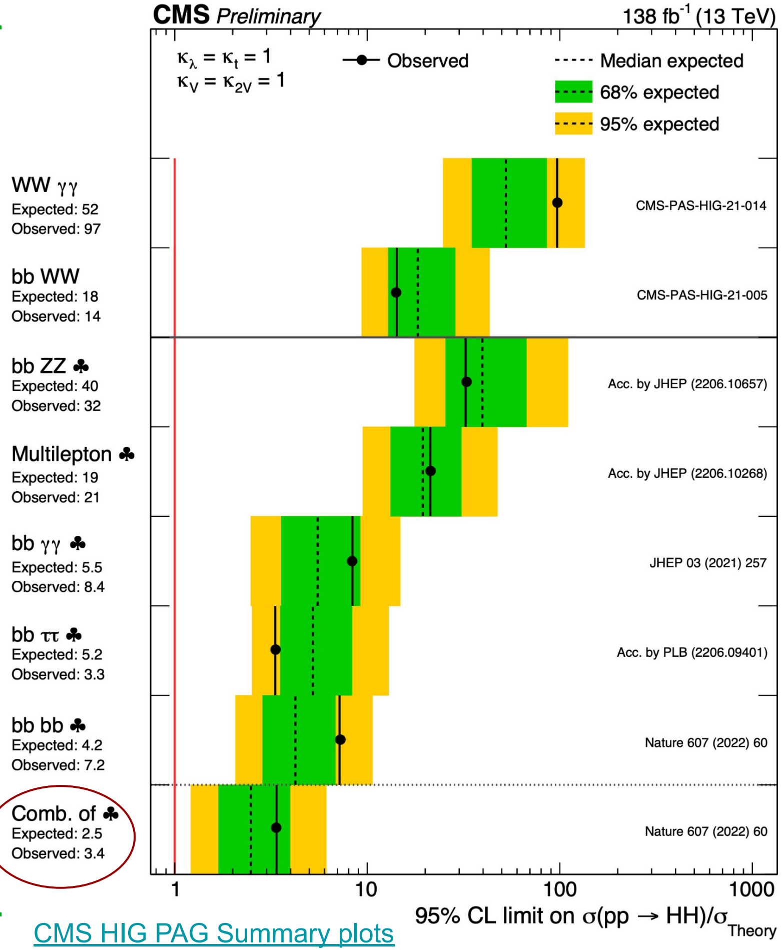
destructive interference in SM → tiny cross-section (31.05 fb) → Experimentally challenging

Many **improvements** over past years
→ promising results!

σ(HH) < **3.4** (2.5) σ_{SM}

-1.24 (-2.28) < $\boldsymbol{k_\lambda}$ < **6.49** (7.94)

0.67 (0.61) < $\boldsymbol{k_{2V}}$ < **1.38** (1.42)



CMS HIG PAG Summary plots

Conclusion and prospects

Selection of recent precision measurements at CMS presented
Many other results available, not covered by this talk!

The LHC has proved to be more than capable as a precision physics machine

Comprehensive characterization of the SM
→ measurements becoming more precise and more differential
→ probe more extreme regions of phase space

Overall **good agreement** with SM predictions

Much more to be learned about the SM with Run3 and HL-LHC data!