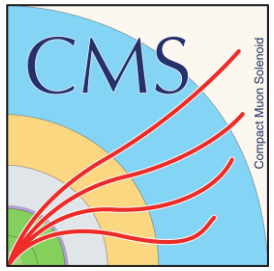
Single boson (W, Z, H) cross-section measurements

Maximilian Goblirsch-Kolb (CERN),
on behalf of the ATLAS and CMS collaborations

QCD@LHC 2024, Freiburg
10th October, 2024

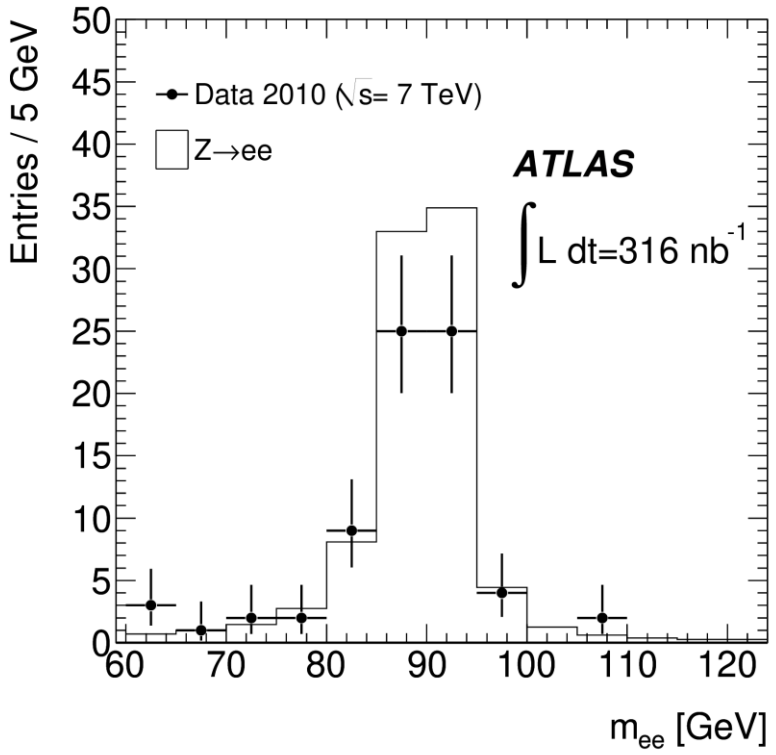


Introduction

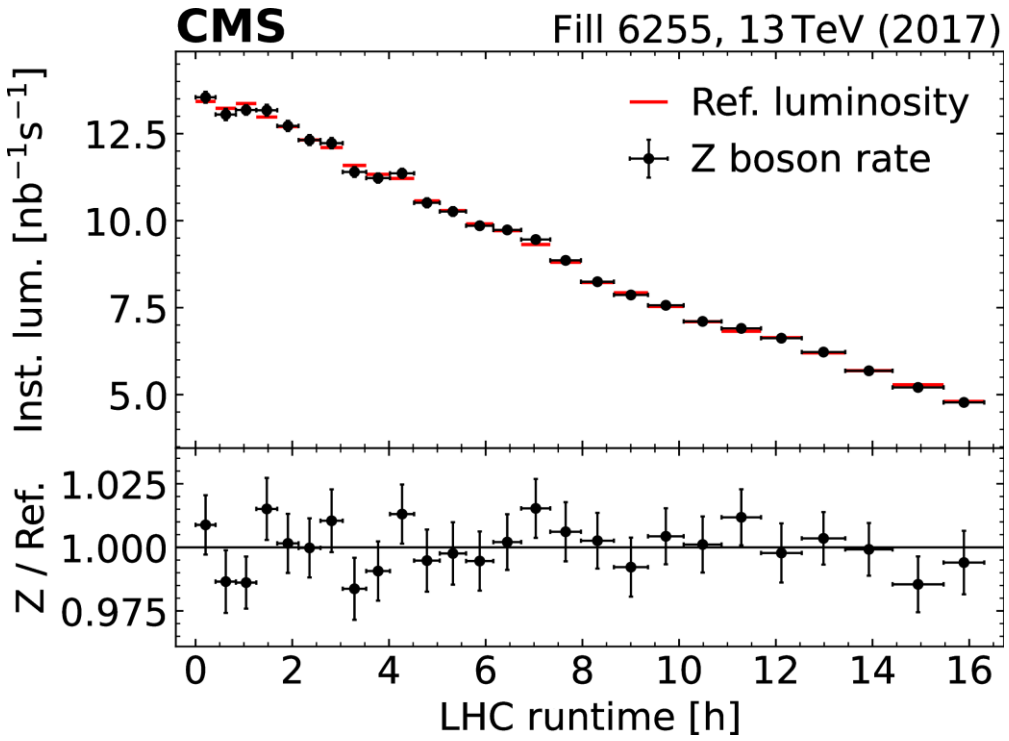
Single **gauge** boson (W,Z) production: **Standard candle** for SM physics at hadron colliders

- Important **calibration tool**
- **Background** to measurements and searches
- Probe of **QCD** in initial state, **proton substructure**

JHEP 12 (2010) 060



Eur. Phys. J. C 84 (2024) 26

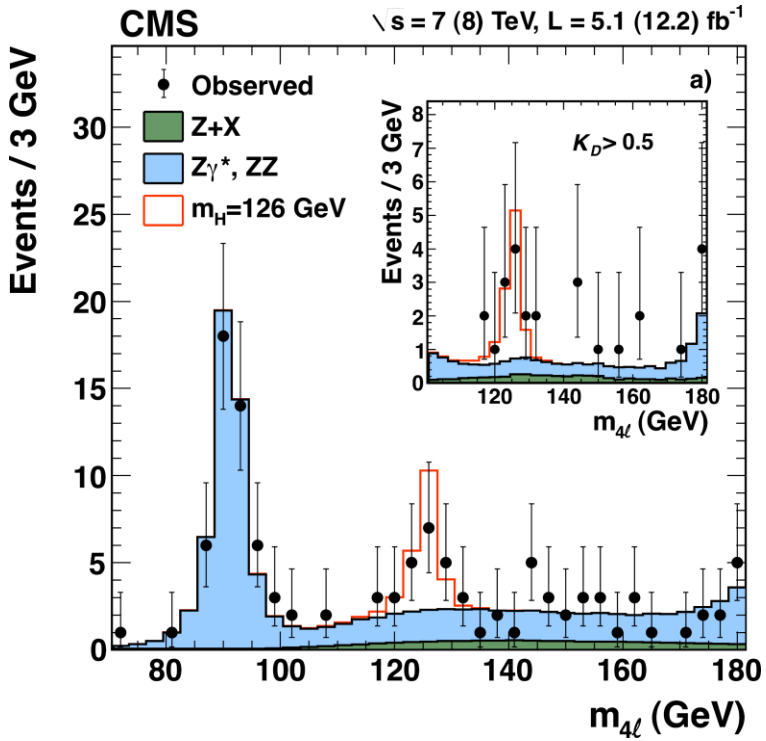


Introduction

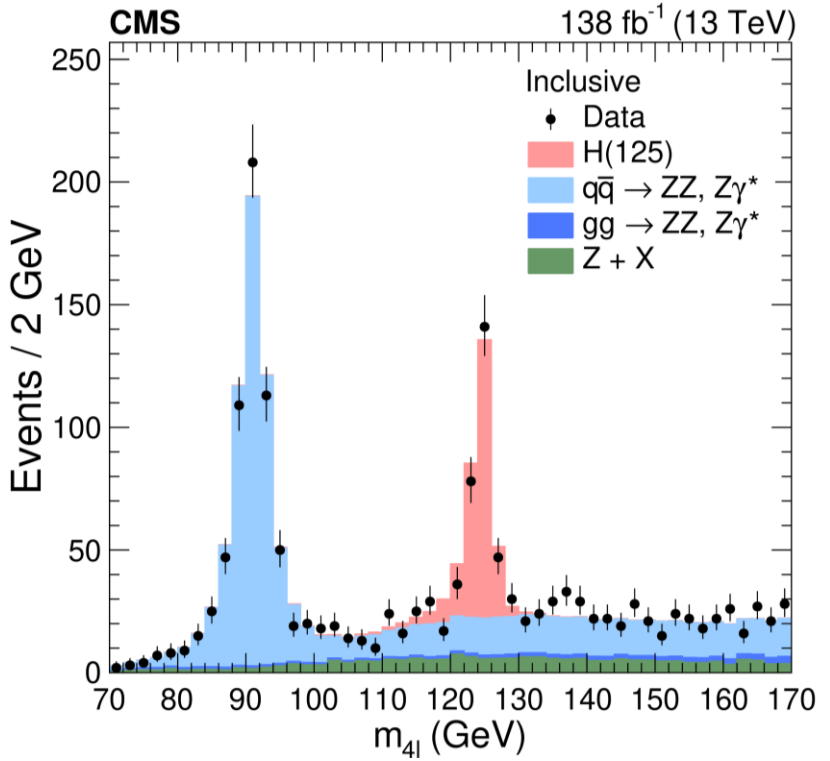
Single **Higgs** boson production: Evolved from searches to **precision physics**

- Exploration of the **Yukawa** sector
- Test of **electroweak** symmetry breaking
- Indirect sensitivity to **BSM** physics
- **Background** to Higgs pair searches

Phys. Rev. Lett. 110 (2013) 081803



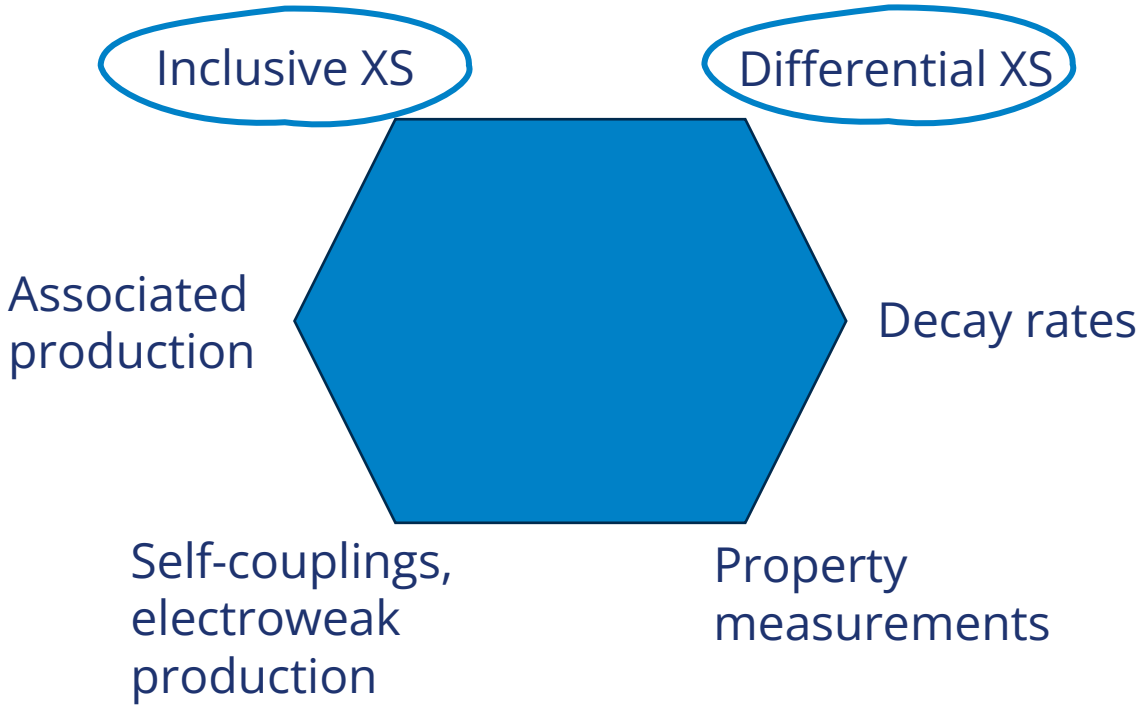
CERN-EP-2024-210 (submitted to Phys. Rev. D)



Introduction

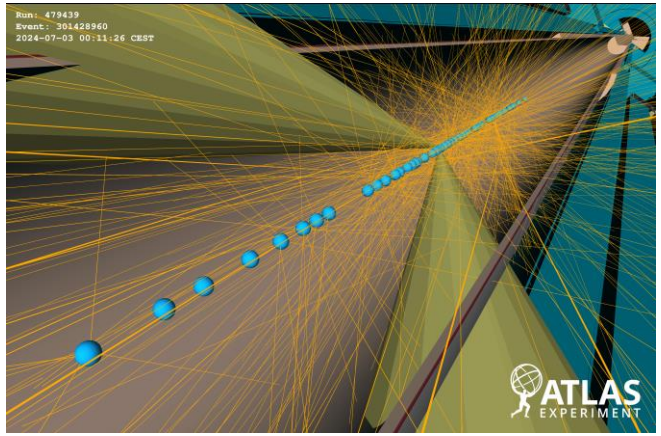
Both: Wide suite of measurements at LHC experiments

Here: Focus on **cross-section** measurements



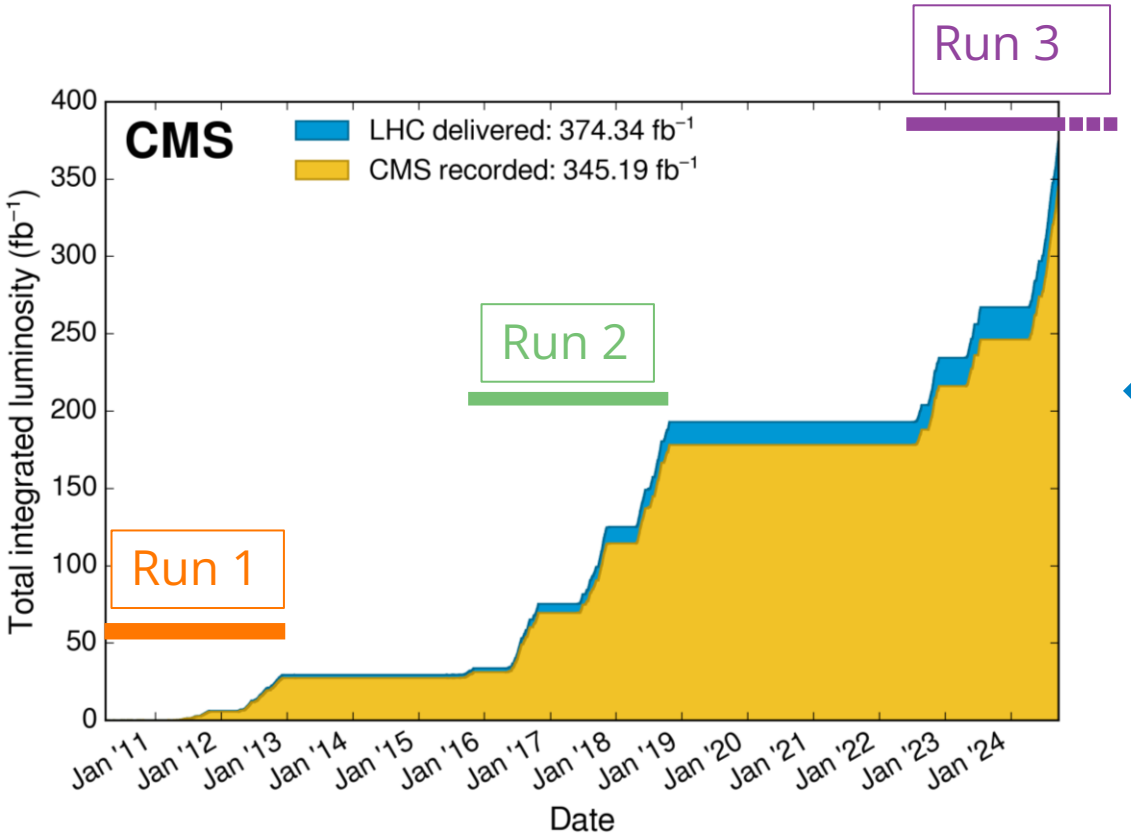
An evolving experimental landscape

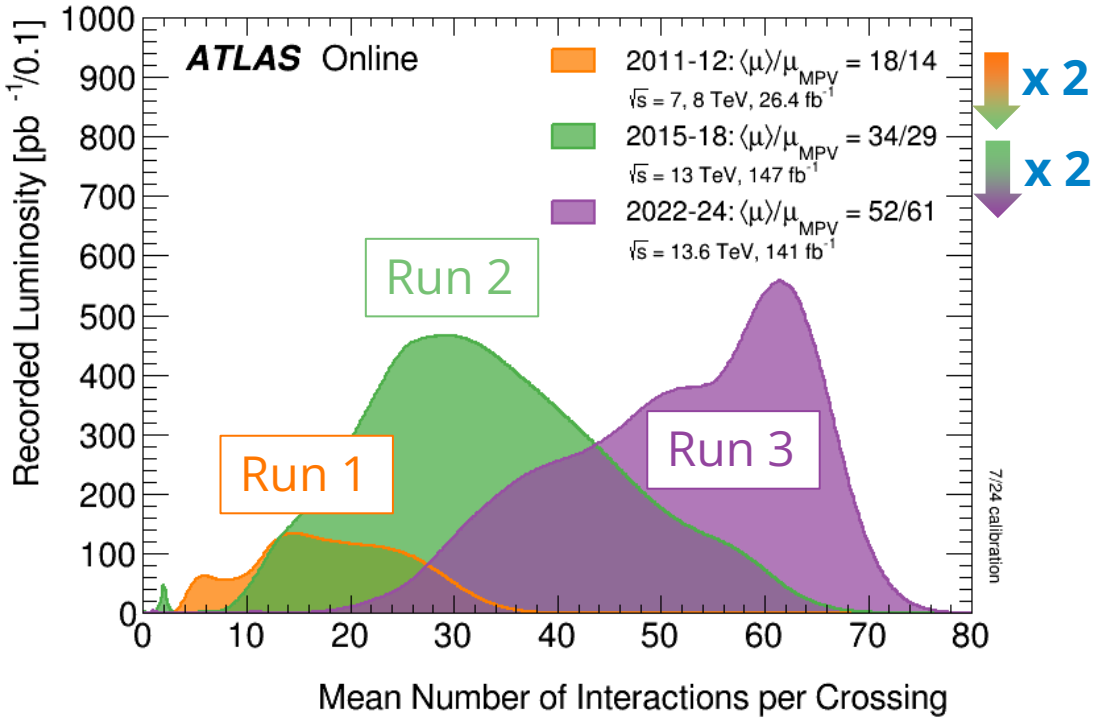
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/EventDisplayRun3Collisions



LHC collecting data **more and more rapidly**

- At a price: Increasing **pileup** (μ) – up to **60** in Run 3
- Busy events **challenge** precision measurements
  - Partially overcome by improved reconstruction and calibration
  - Run-1 and early Run-2 datasets still relevant for precision physics





Higgs boson production

Large-scale Higgs combinations

Nature 607 (2022) 60-68
Nature 607 (2022) 52

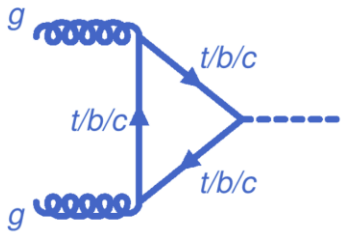
Higgs production and decay via a range of processes

- Most frequent modes not most easily accessible

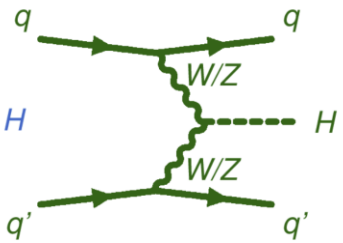
→ trade-off between precision and abundance

- Different couplings involved

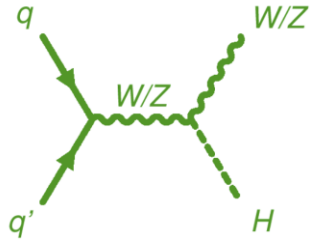
Combine many production / decay modes



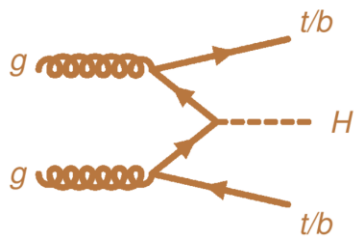
ggH



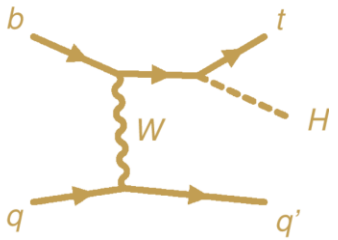
VBF



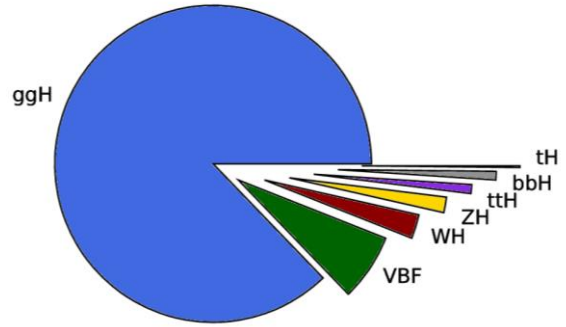
VH



ttH / bbH



tH



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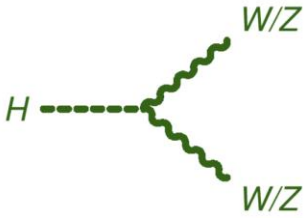
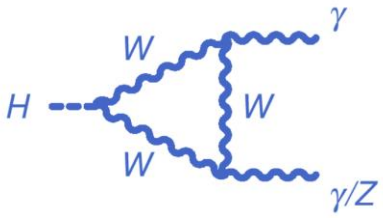
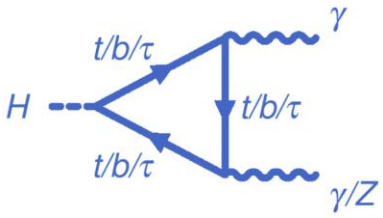
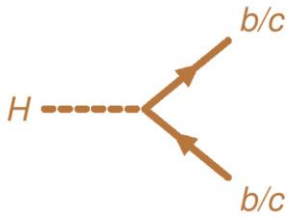


WW/ZZ

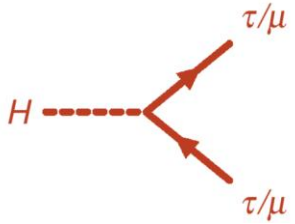




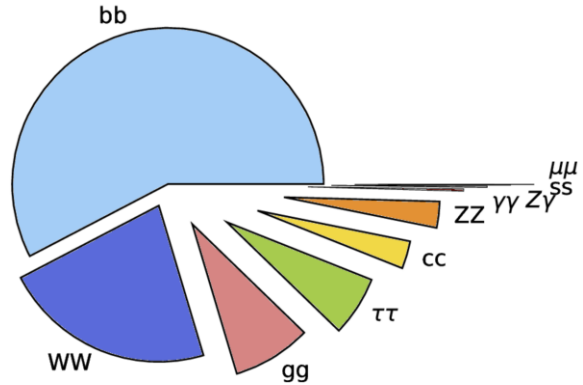
Zγ / γγ



bb / cc



ττ / μμ



Large-scale Higgs combinations

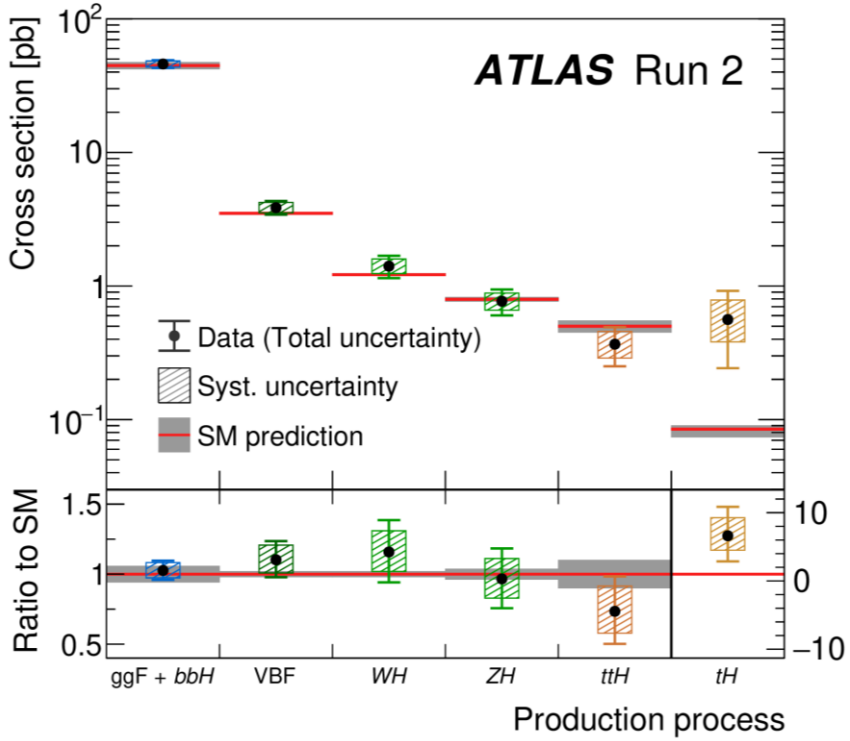
Nature 607 (2022) 60-68
Nature 607 (2022) 52

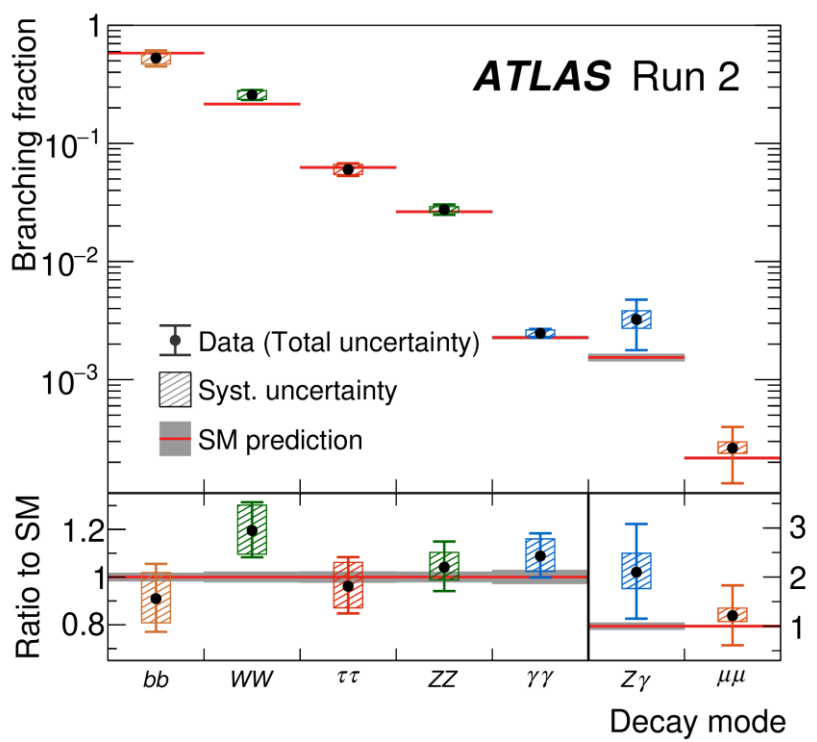
Large-scale combination: 2022 (10-year discovery anniversary)

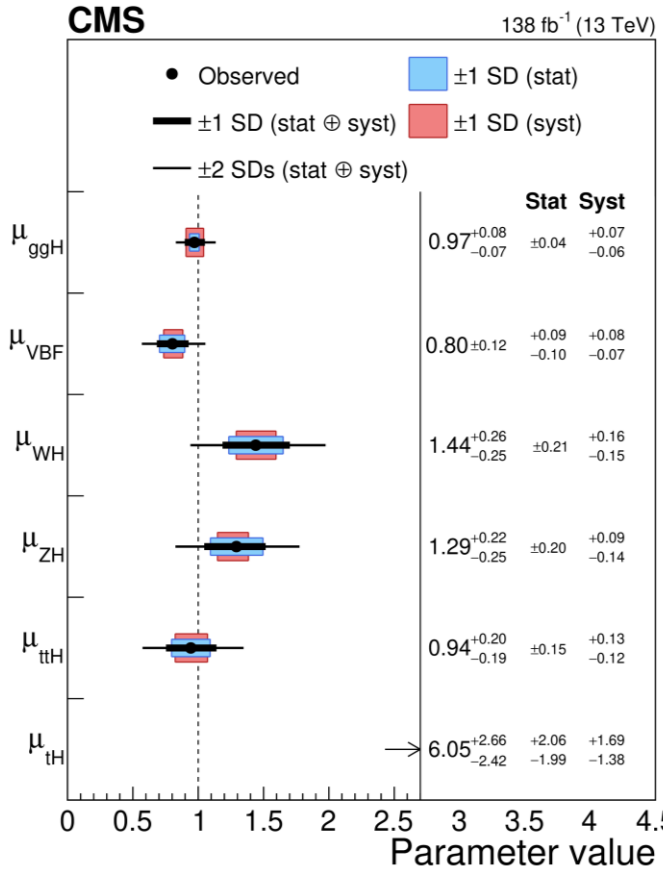
All major **production modes** experimentally established by 2022

- Inclusive production cross-sections becoming systematically limited

→ Achieve further gains through more and more sophisticated measurements







Large-scale Higgs combinations

Nature 607 (2022) 60-68
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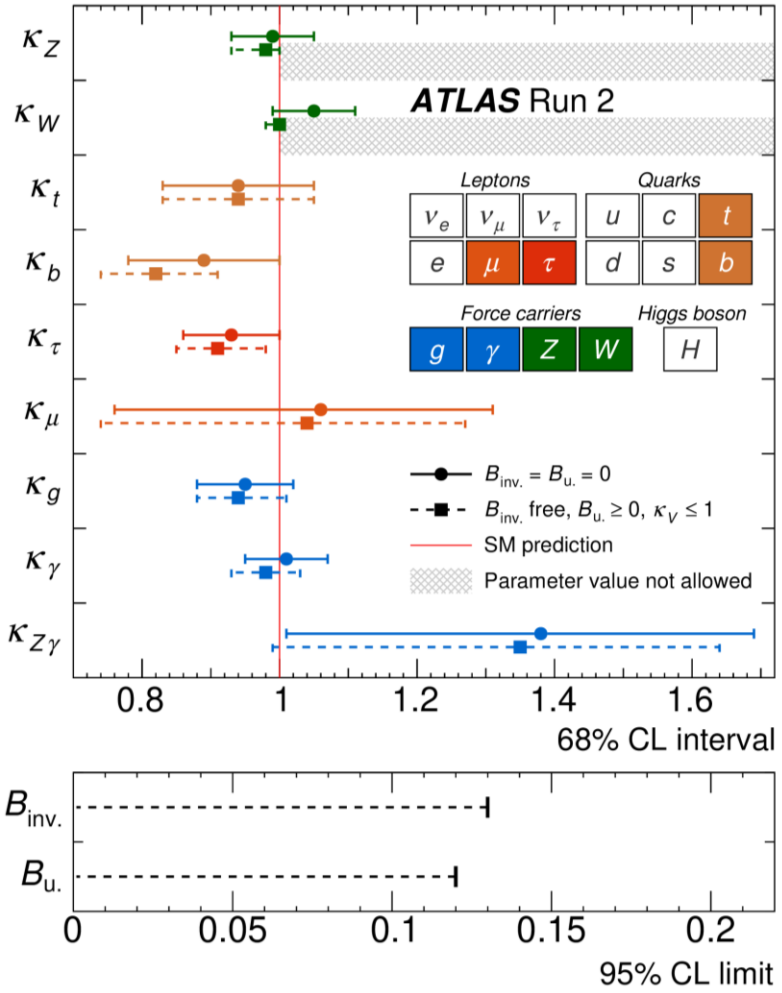
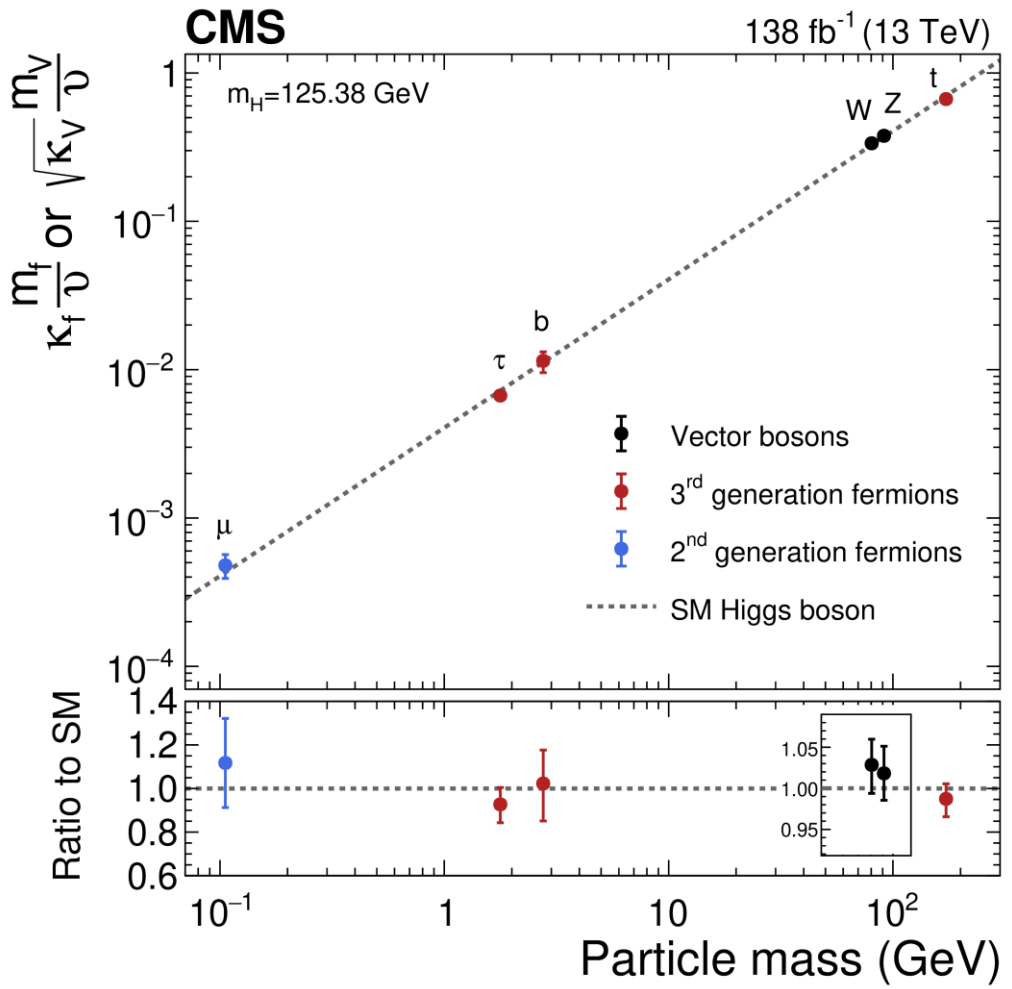
Interpretation of results as **global** statements about the Higgs boson

- Parametrisation of cross-sections in terms of **coupling modifiers (κ)**





Large-scale Higgs combinations

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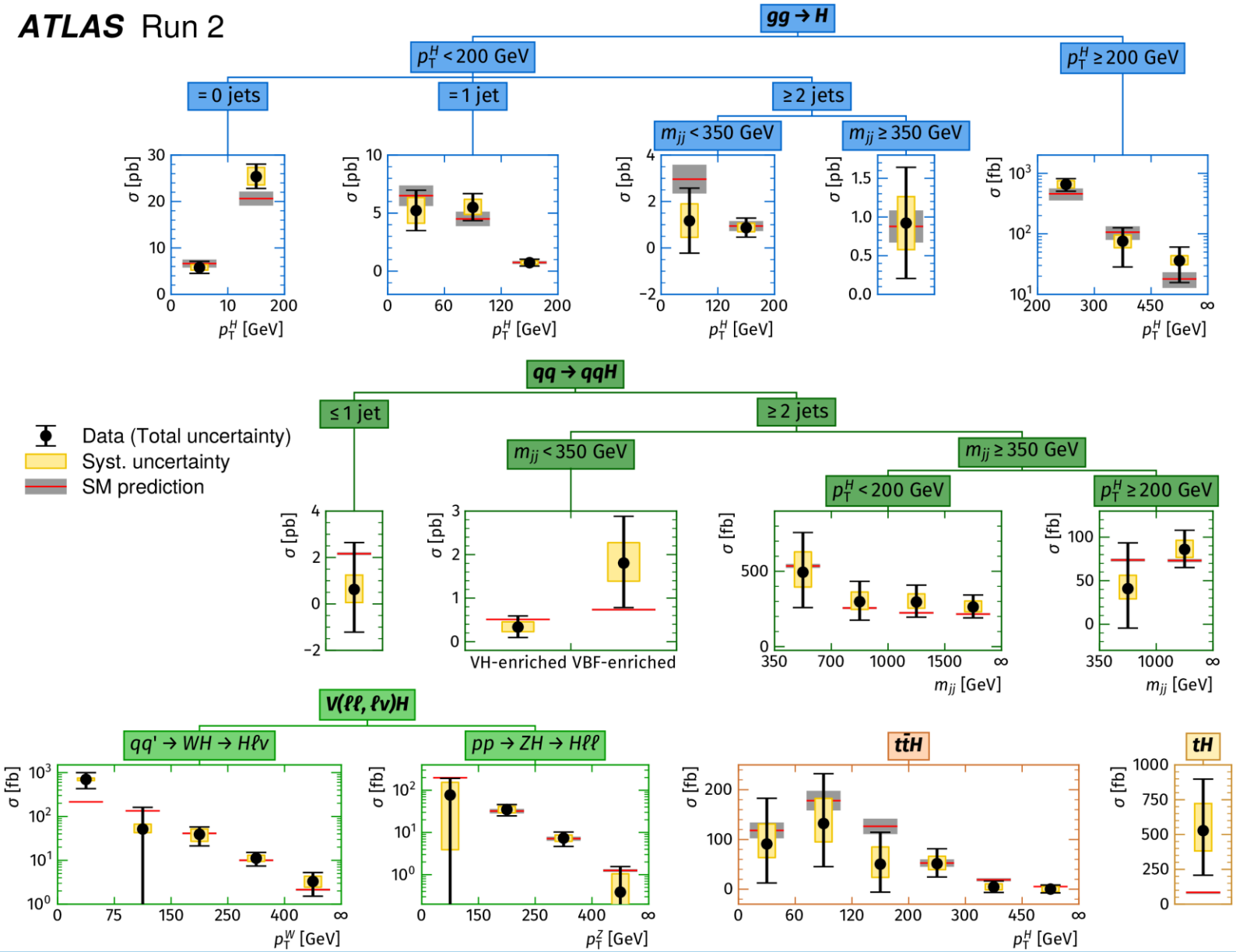
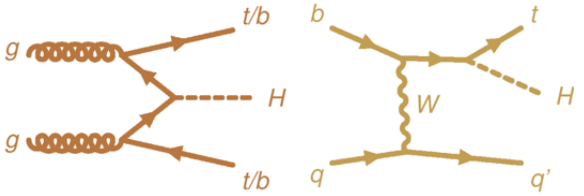
- Quasi-differential analysis of production via **simplified template cross-sections** (STXS)
- **Differential** production cross-sections



H-top couplings in bb final states

CERN-EP-2024-179 (submitted to JHEP)
CERN-EP-2024-194 (submitted to EPJC)



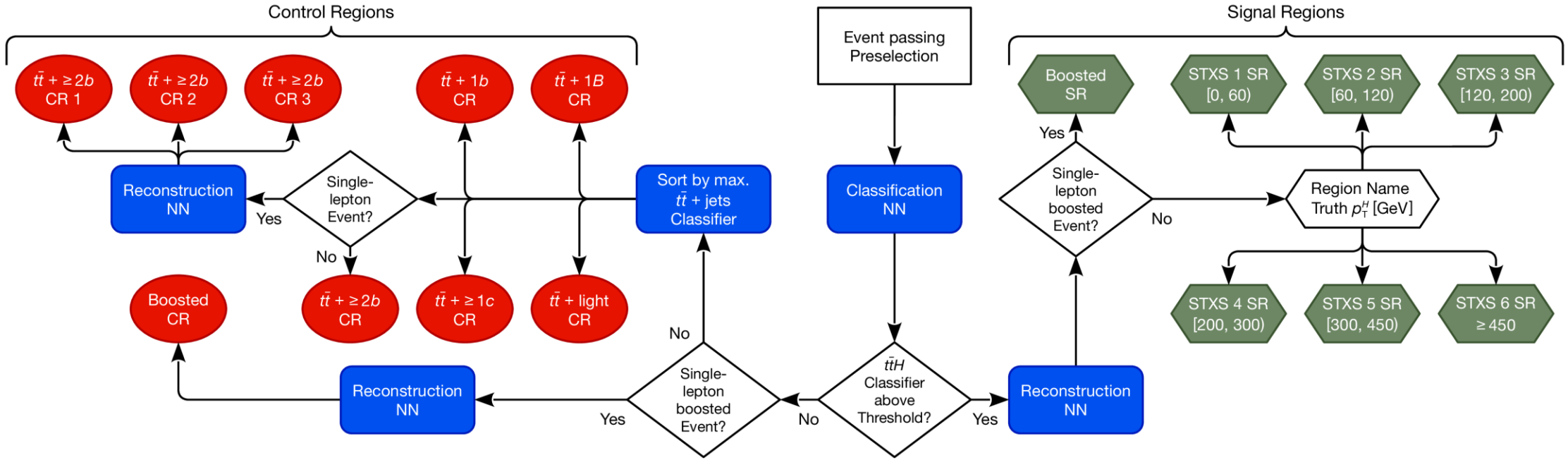
H-top coupling: kinematically inaccessible in decay

→ target via loop effects and rare **ttH production mode**

Major **challenge**: tt+jets (esp. ttbb) background – efforts to **improve modelling**

- Dedicated simulation of tt+bb process and normalization / correction in dedicated control regions

Use of multivariate **multiclass ML classifiers** to separate processes and isolate signal

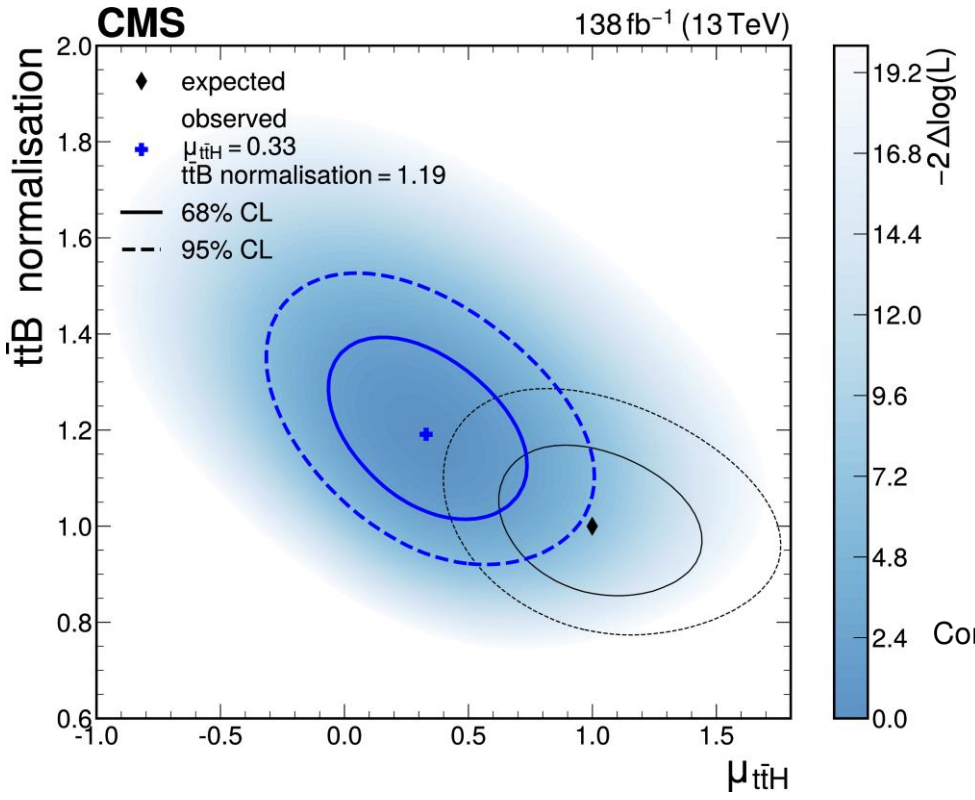


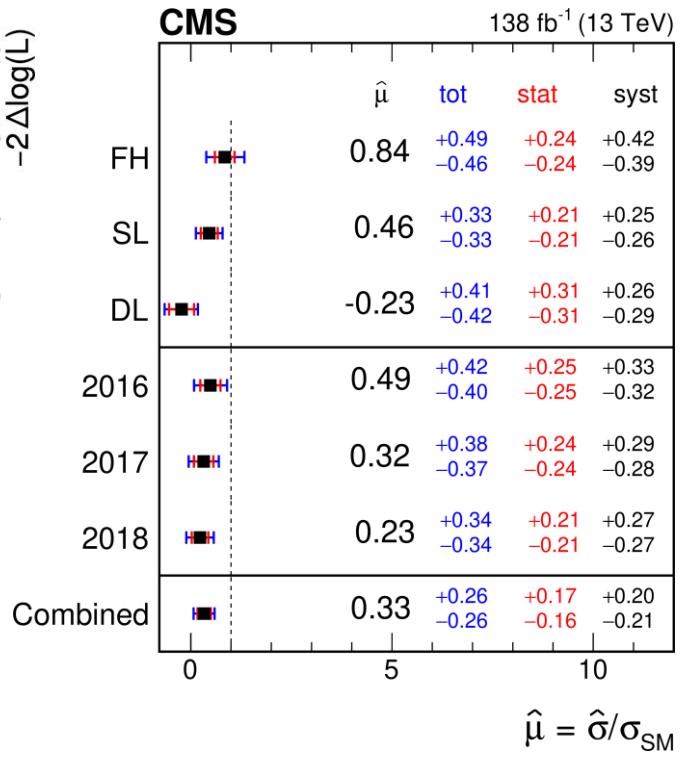
H-top couplings in bb final states

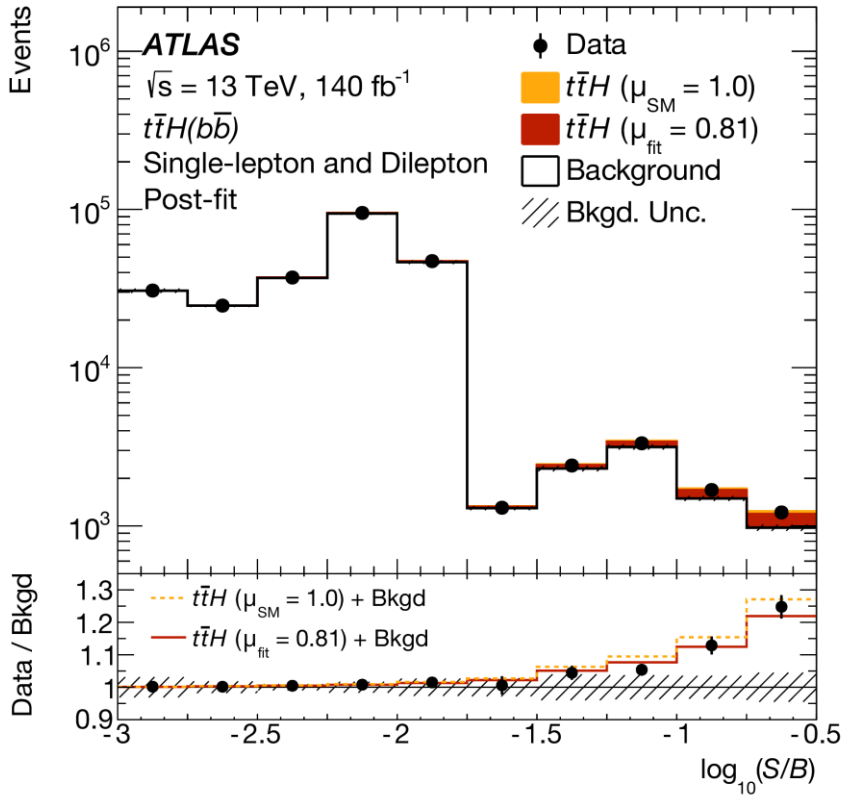
CERN-EP-2024-179 (submitted to JHEP)
CERN-EP-2024-194 (submitted to EPJC)

Analysis improvements drive sensitivity to 4σ (CMS) / 5σ (ATLAS) level

- Example: Signal acceptance in ATLAS increased by factor 3
- ATLAS: Observation close to SM prediction
- CMS: 2.4σ compatibility with SM, fit larger ttbb normalisation (1.2) than ATLAS







H-top couplings in bb final states

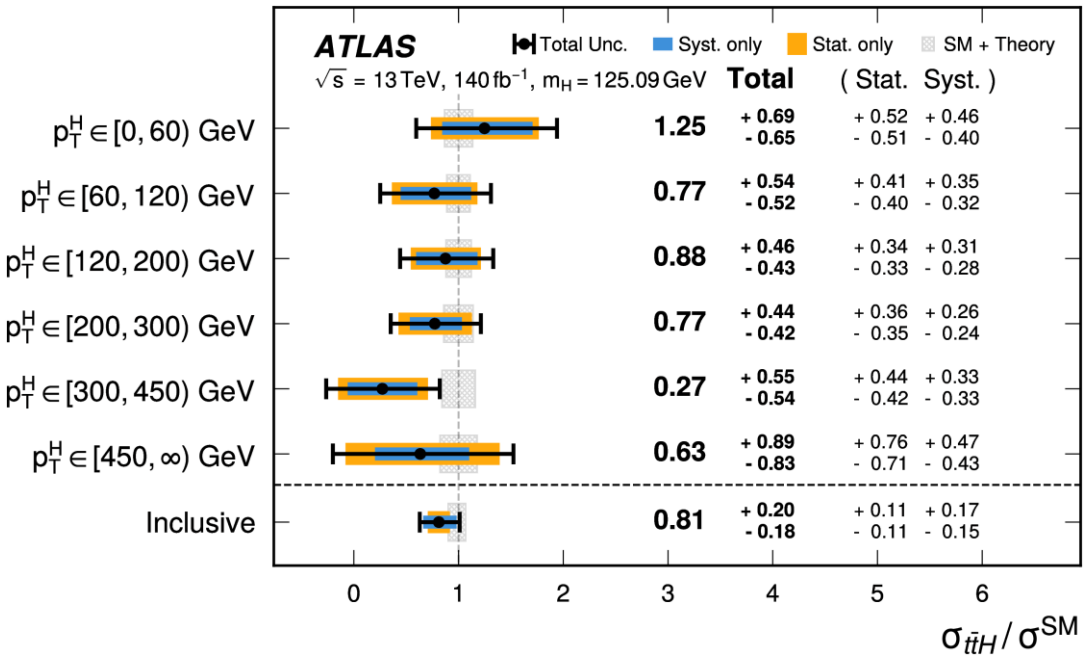
CERN-EP-2024-179 (submitted to JHEP)
CERN-EP-2024-194 (submitted to EPJC)

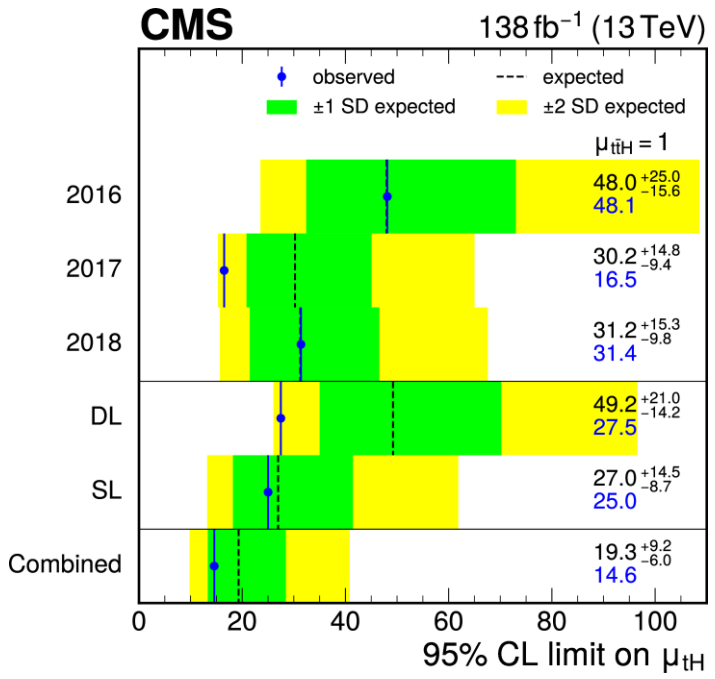
Additional extraction of **simplified template cross-sections**

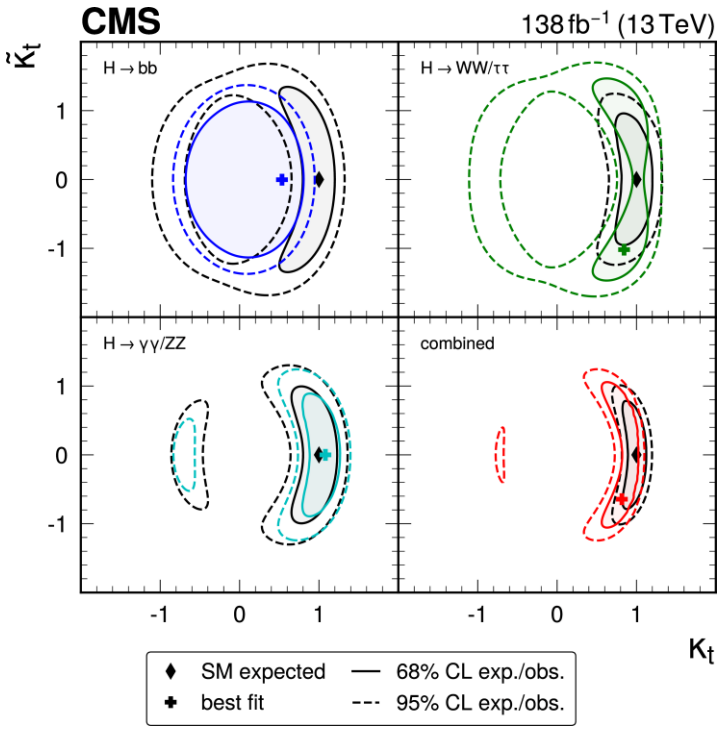
- For ttH process: differential cross-section in Higgs p_T

CMS: Search for **tH** production and constraints on **CP-odd** admixture in t-H coupling

- Improve sensitivity through combination with other decay modes







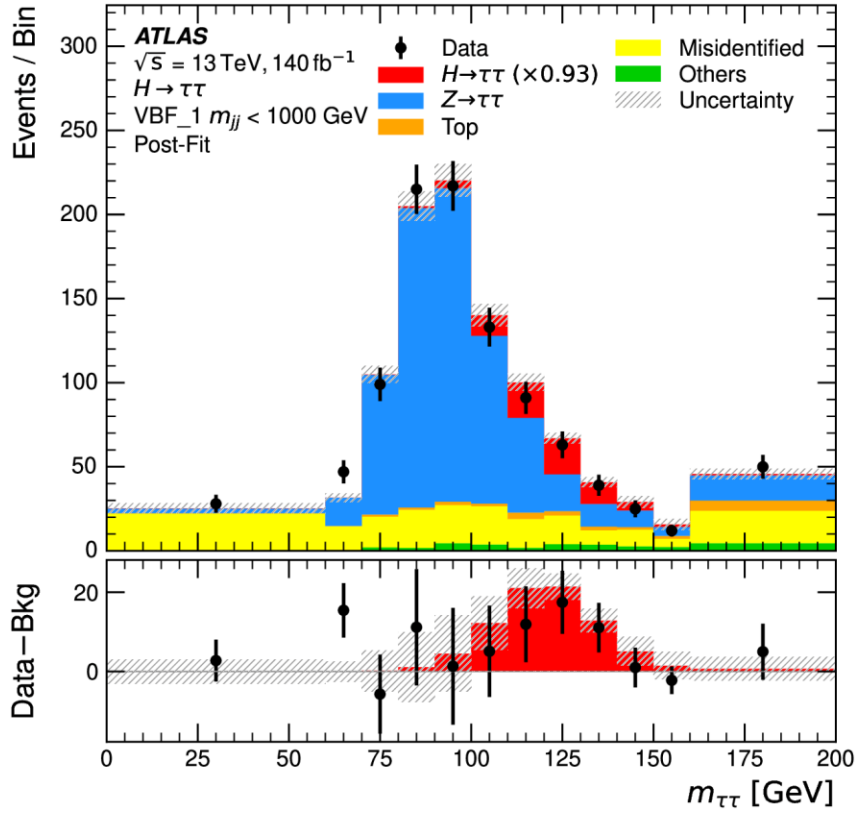
Differential H→ττ

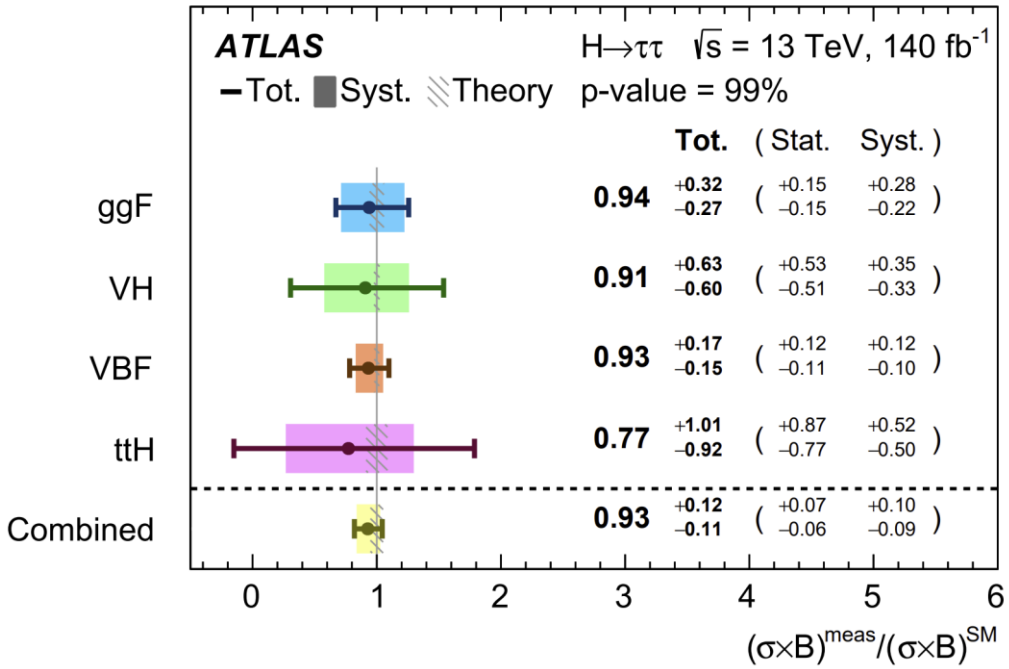
CERN-EP-2024-198 (submitted to JHEP)

H→ττ decays: Excellent probe for VBF production

ATLAS measurement: Extract **differential cross-sections** in VBF-dominated phase-space and **simplified template cross-sections**

- Include categories for VH and boosted ggF to enhance STXS reach
- Z→ττ background constrained to data using simplified Z→ll embedding technique



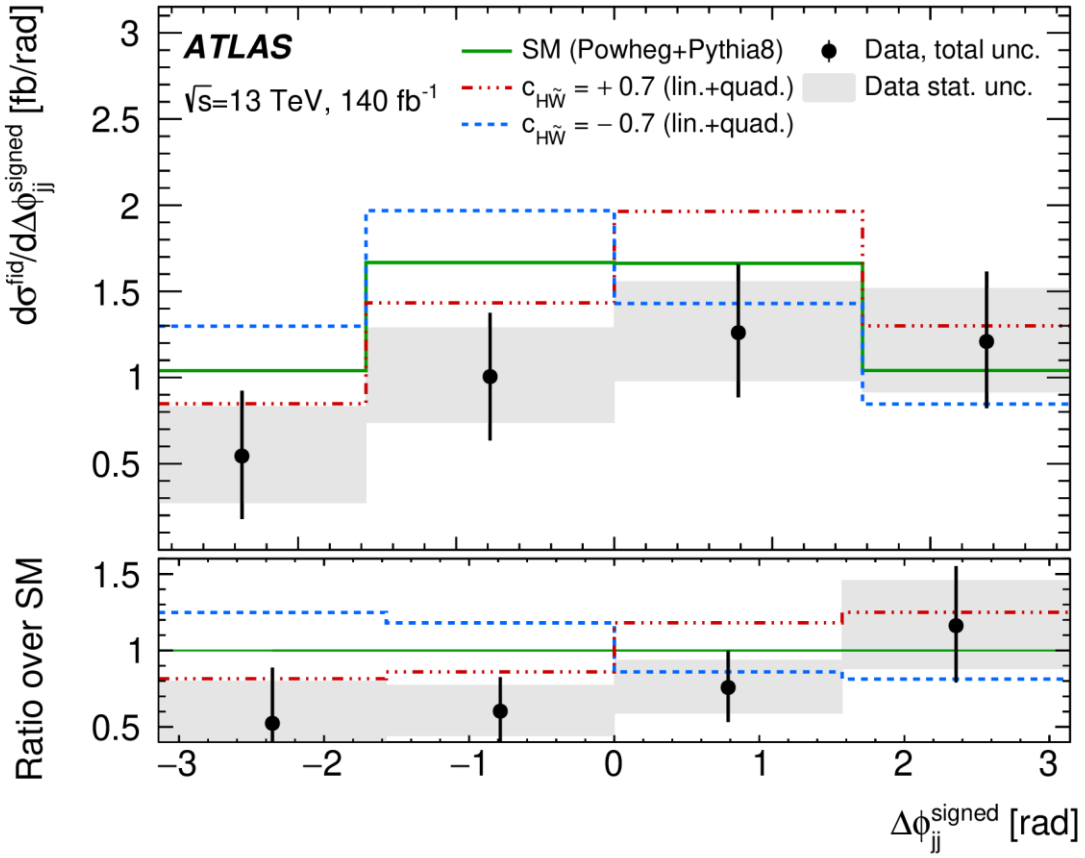


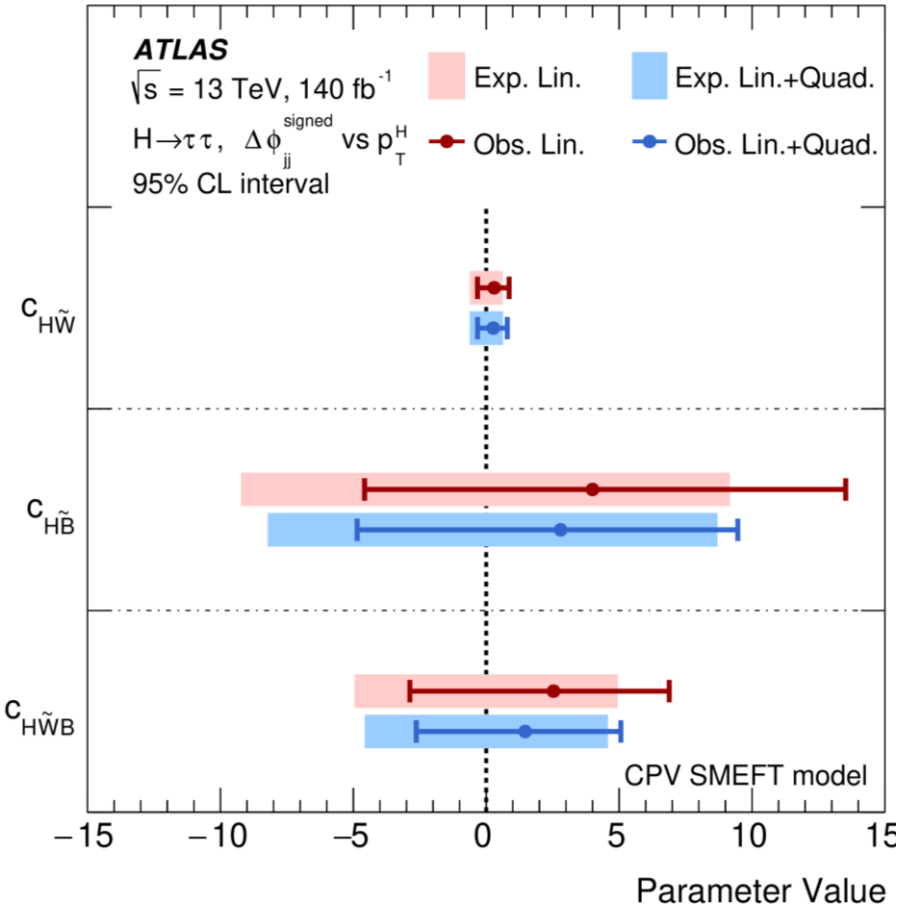
Differential H→ττ

CERN-EP-2024-198 (submitted to JHEP)

Successful extraction of differential cross-sections

- including **CP-sensitive observables**: Search for CP-violation in HVV coupling

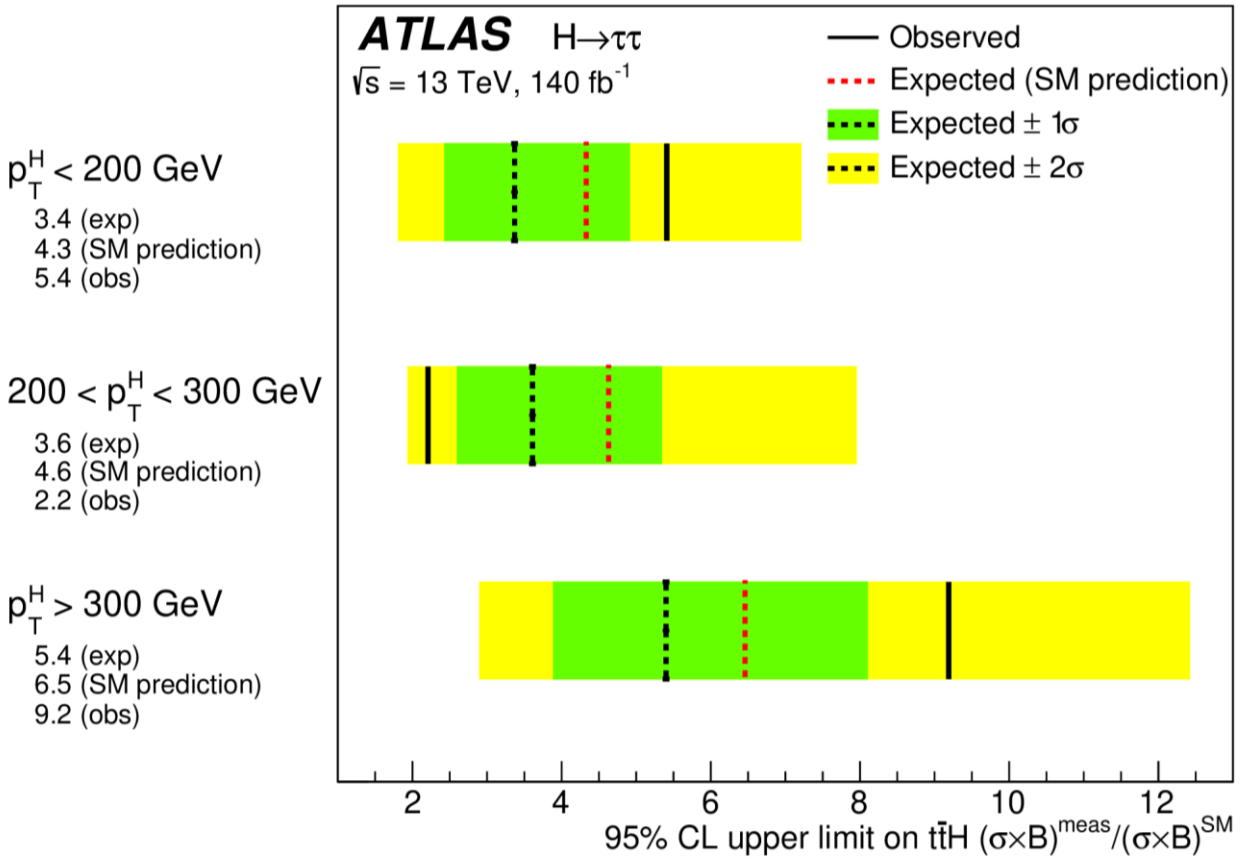


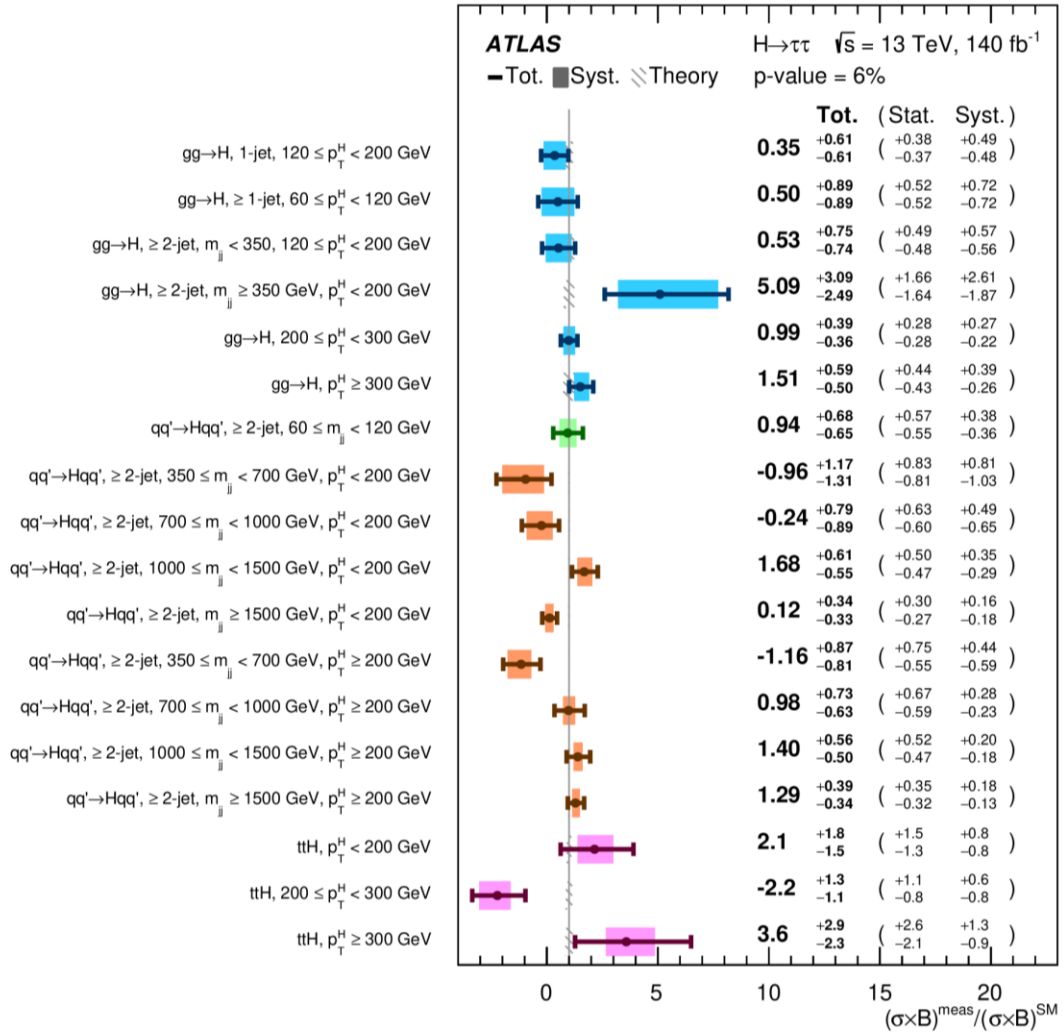


Differential H→ττ

CERN-EP-2024-198 (submitted to JHEP)

- Measure wide range of STXS bins – excellent precision especially at high pT
- Using dedicated multi-class BDT: Limits on ttH production



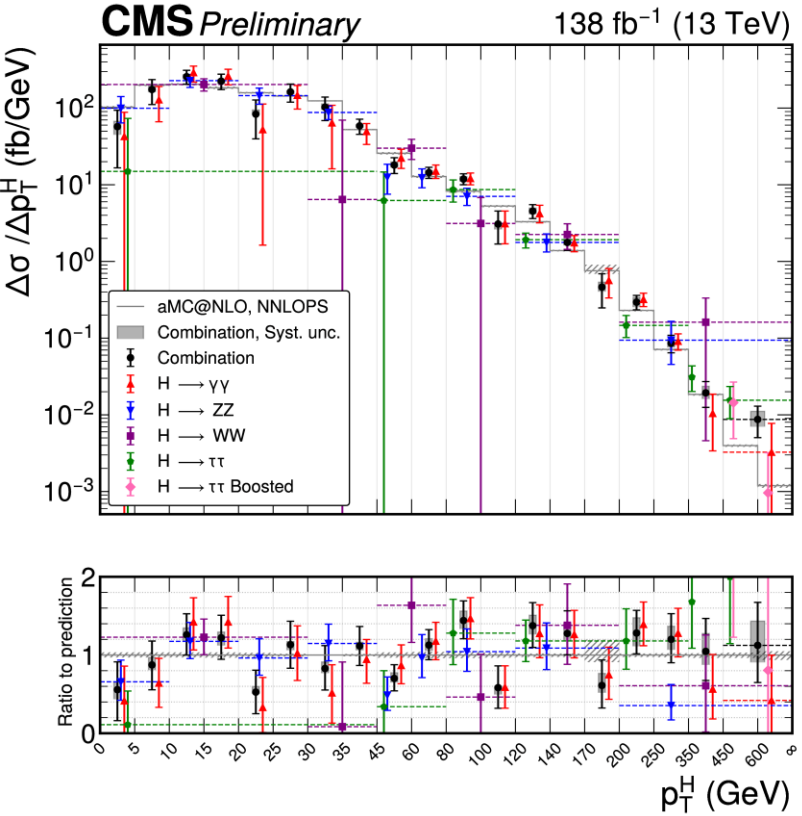


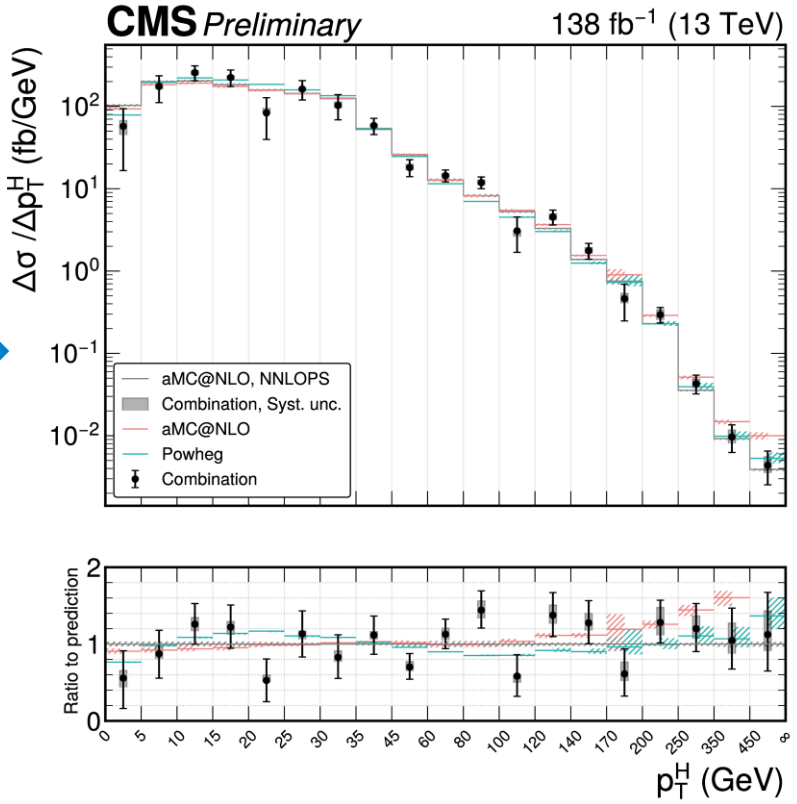
Combination of H differential measurements

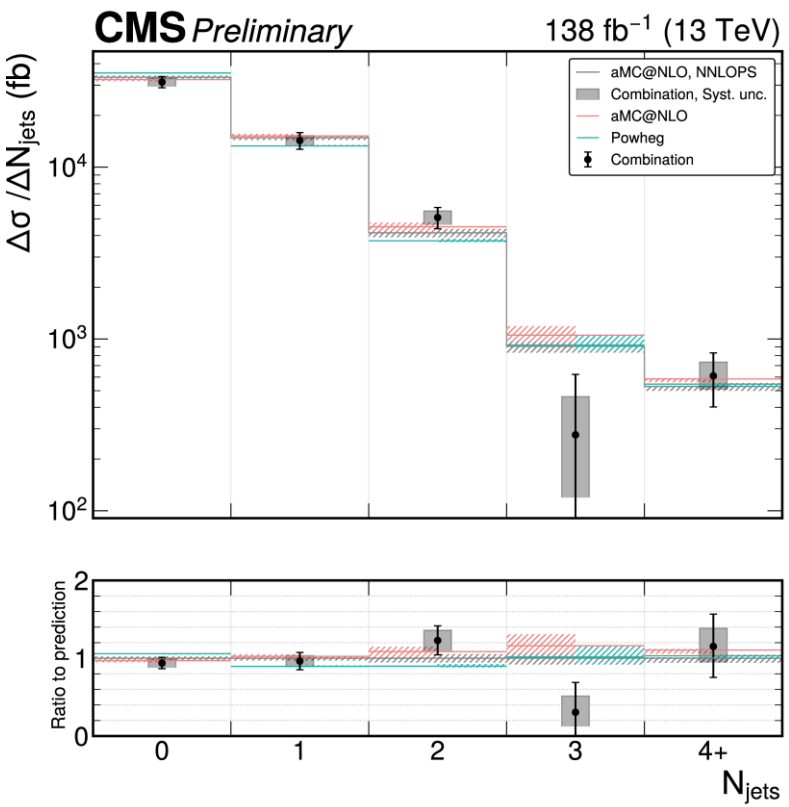
CMS-PAS-HIG-23-013

CMS: **Combination of differential measurements** in γγ, ZZ, WW and ττ final states

- Combined fit to detector-level distributions in all final states
- Resulting precise spectra: Interpret in coupling modifier and effective field theory frameworks







Combination of differential measurements

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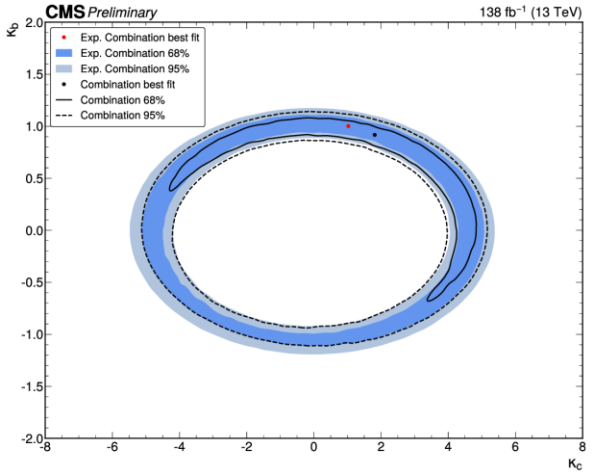
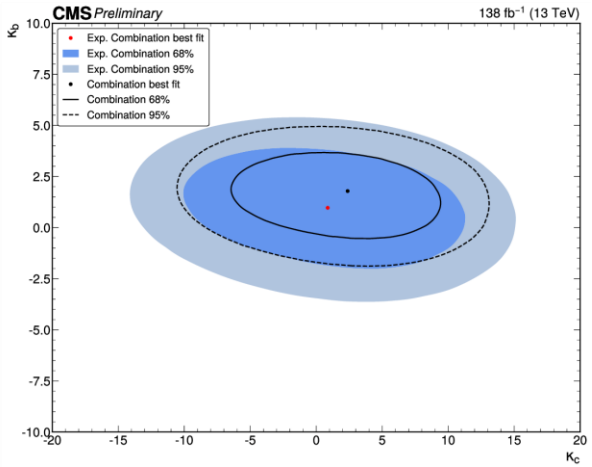
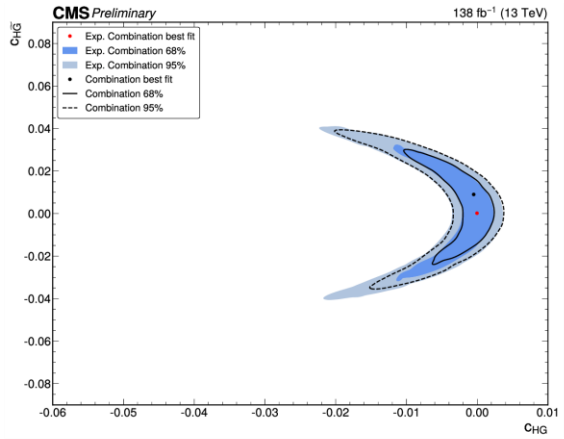
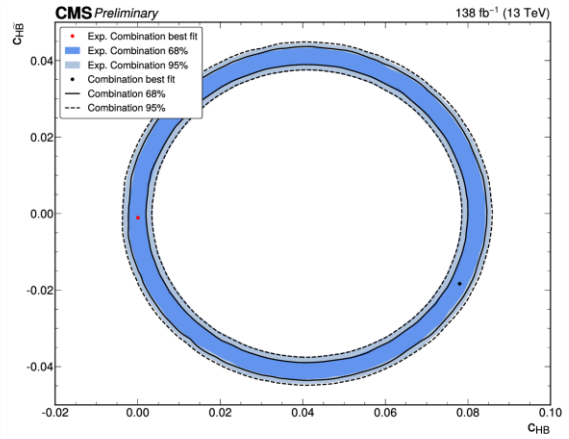
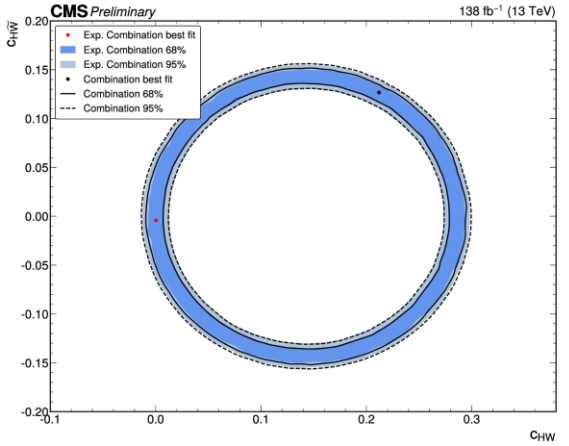
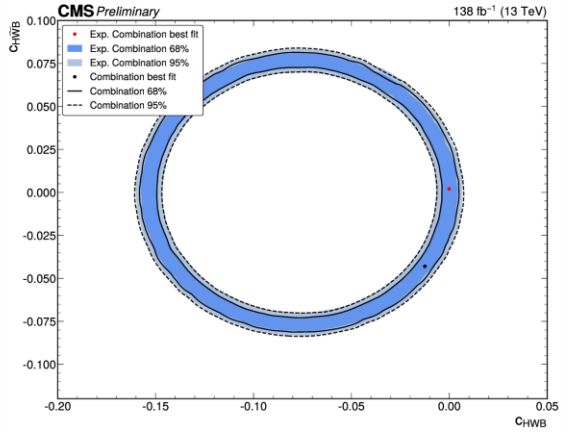












W/Z gauge boson production

Precision W-/Z-boson pT measurements

CERN-EP-2024-134 (submitted to JHEP)
CERN-EP-2024-080 (submitted to EPJC)

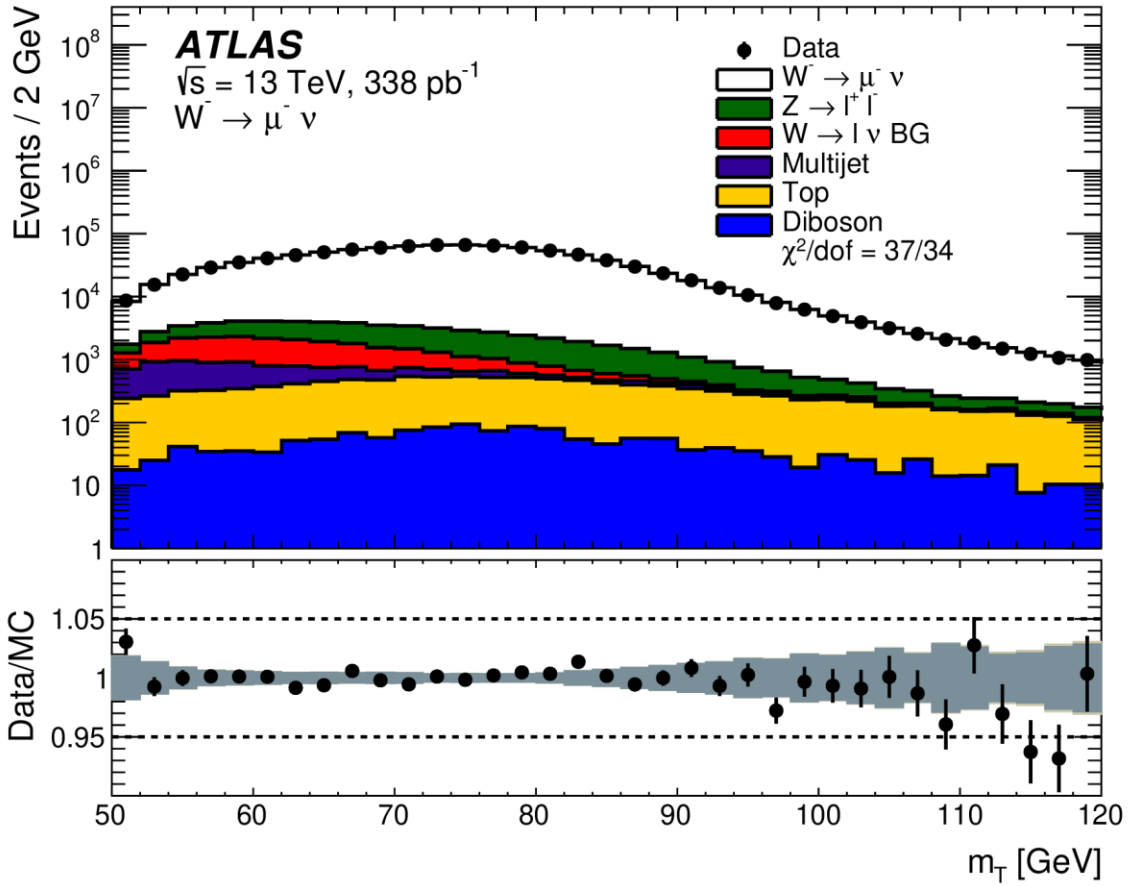
Also see Talk by Florencia (Monday)

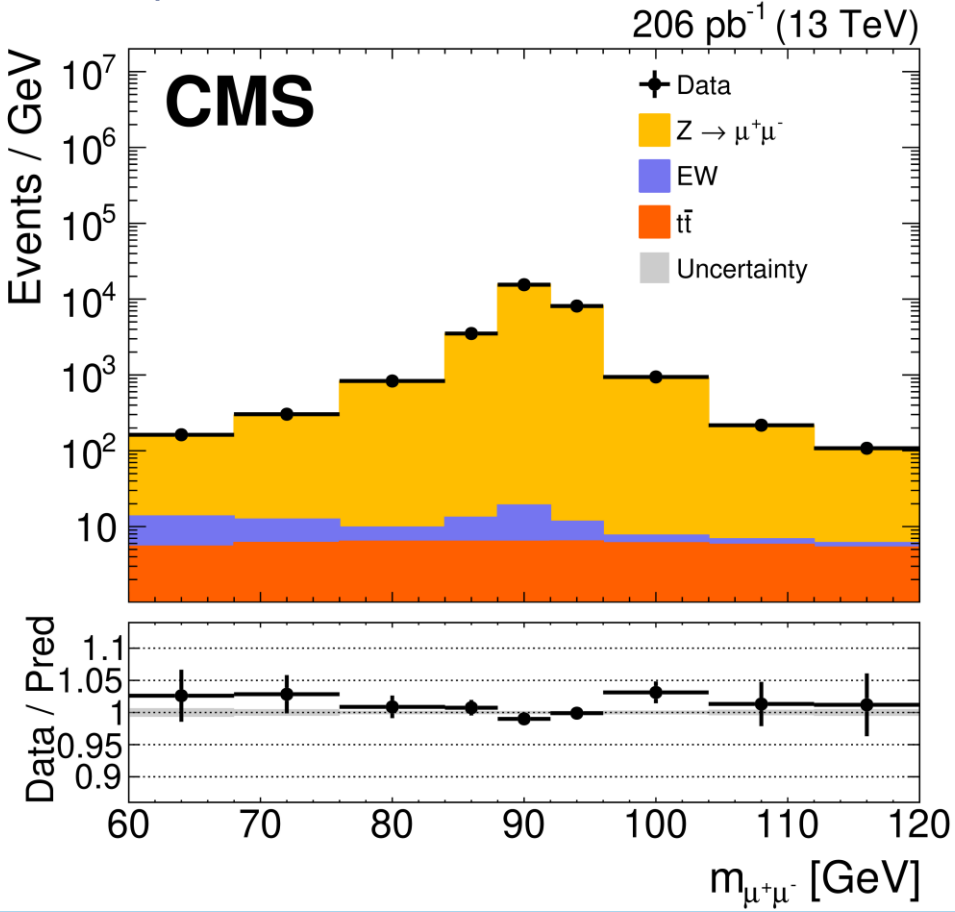
Inclusive W/Z production: **Systematically** limited

- One limitation: Pileup activity – impact on E_T^{Miss} resolution, hadronic recoil and lepton isolation

→ **Special runs** in 2017 at 5.02 and 13 TeV with <μ>~2-3, collecting 0.2-0.3 fb^{-1}

- Used for **precision measurements** by ATLAS and CMS (e.g. W mass)



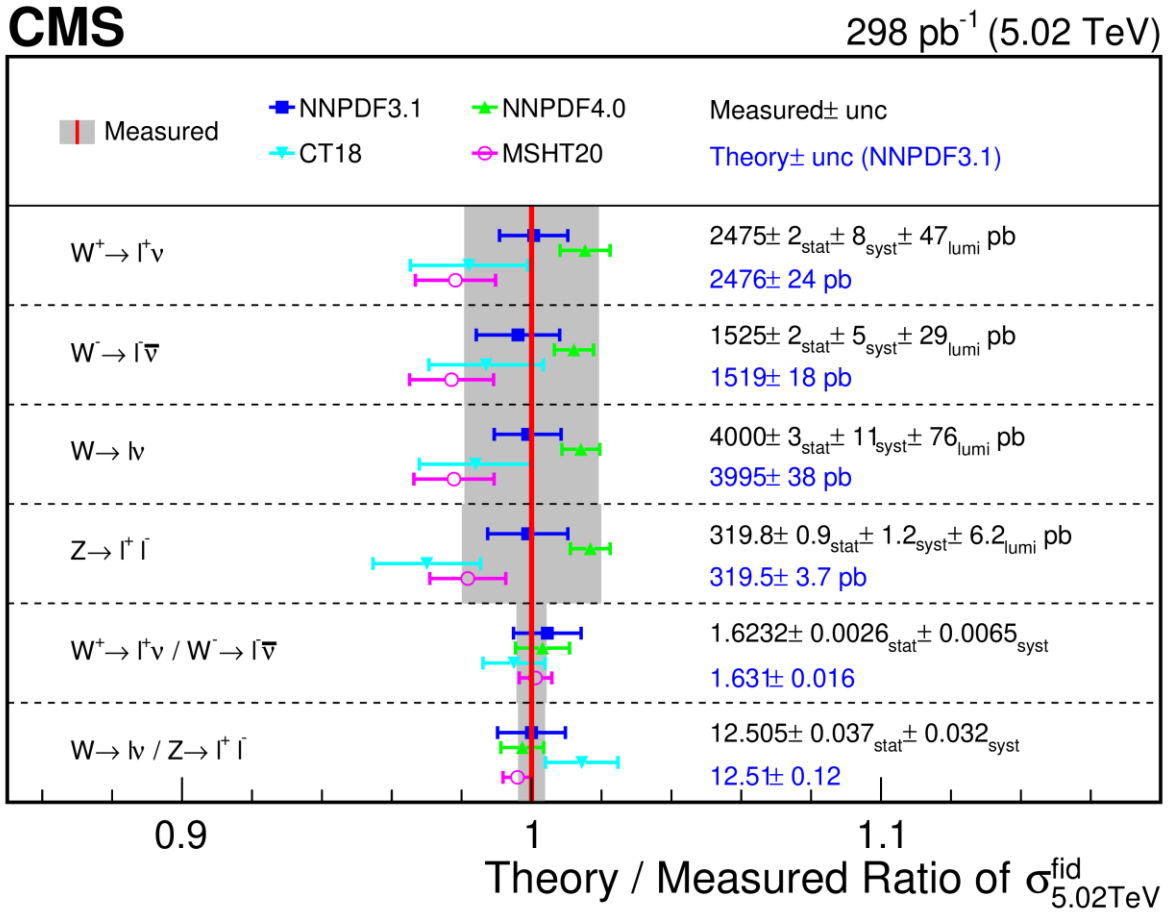


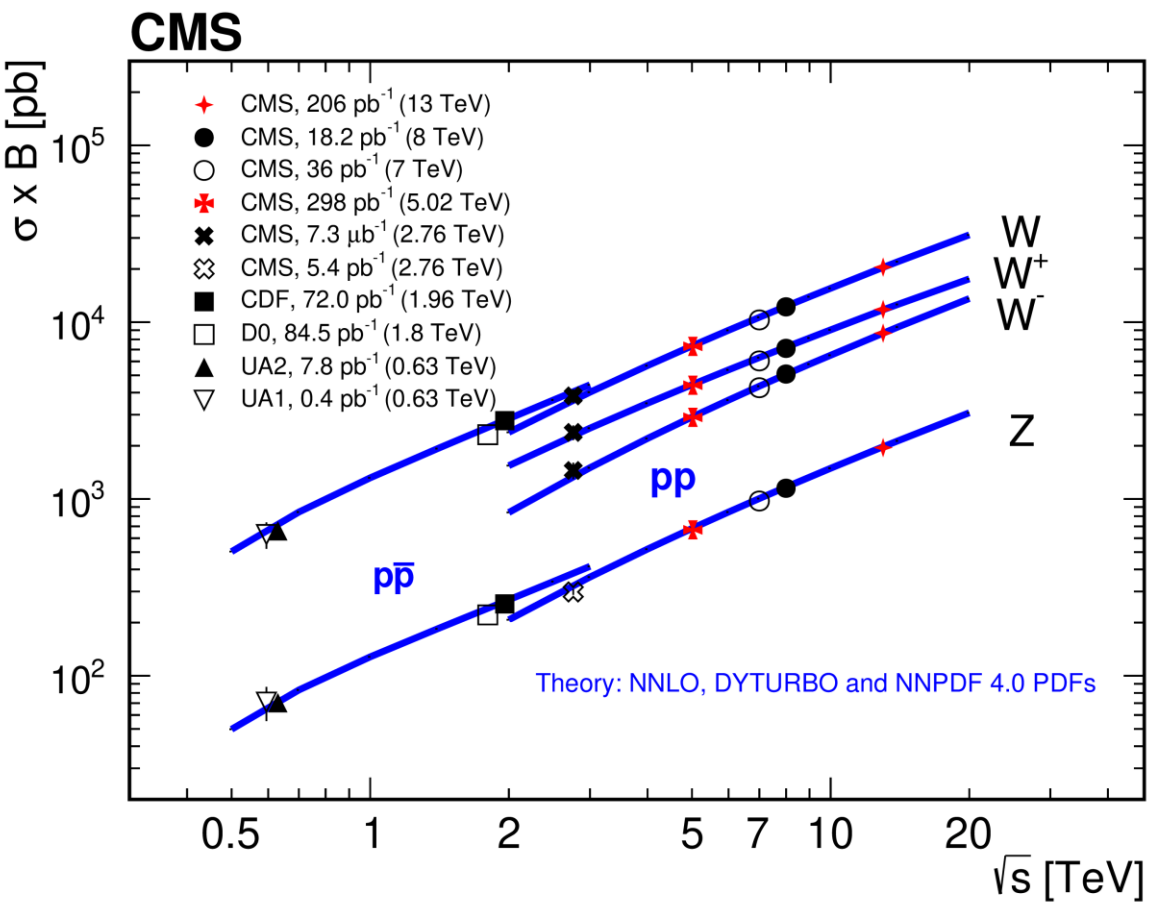
Precision W-/Z-boson pT measurements

CERN-EP-2024-134 (submitted to JHEP)
CERN-EP-2024-080 (submitted to EPJC)

Both experiments: Inclusive fiducial and total cross-sections and ratios

- Ratios: Cancellation of uncertainties, esp. luminosity





Precision W-/Z-boson pT measurements

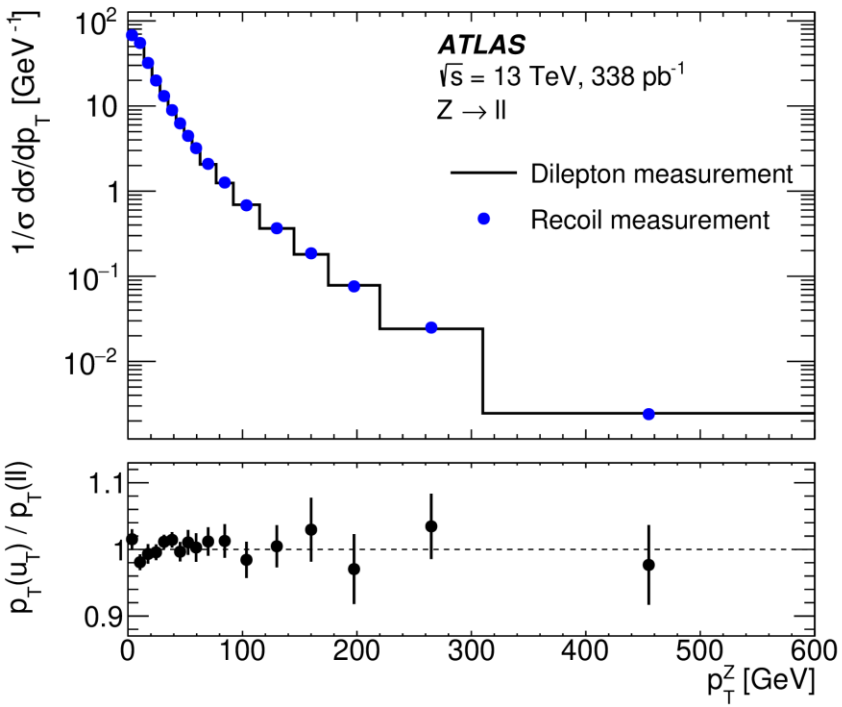
[CERN-EP-2024-134 (submitted to JHEP)](#)
[CERN-EP-2024-080 (submitted to EPJC)](#)

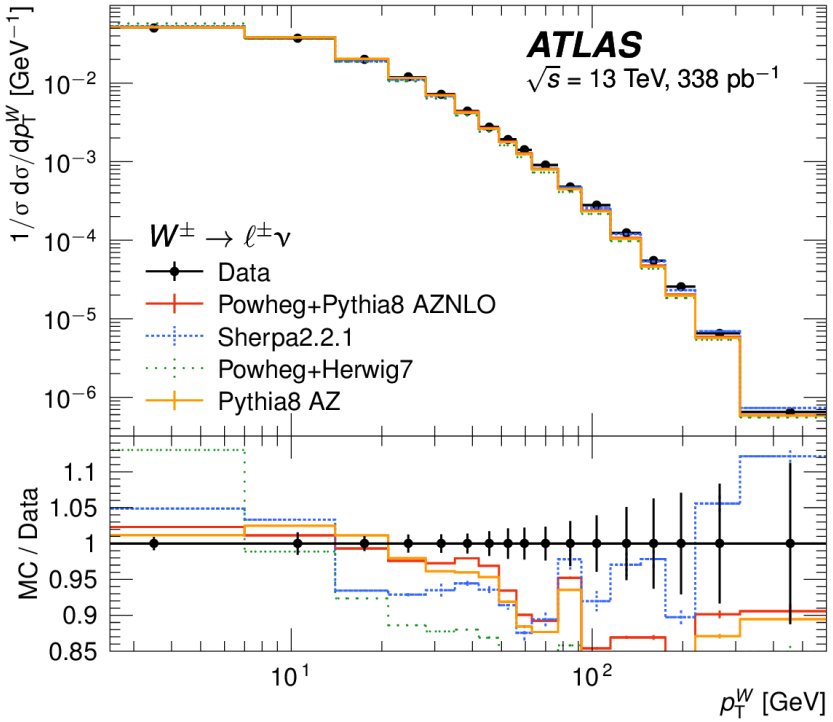
ATLAS: Calibrate hadronic recoil using Z to measure **differential cross-sections** in $\mathbf{p_{T,V}}$

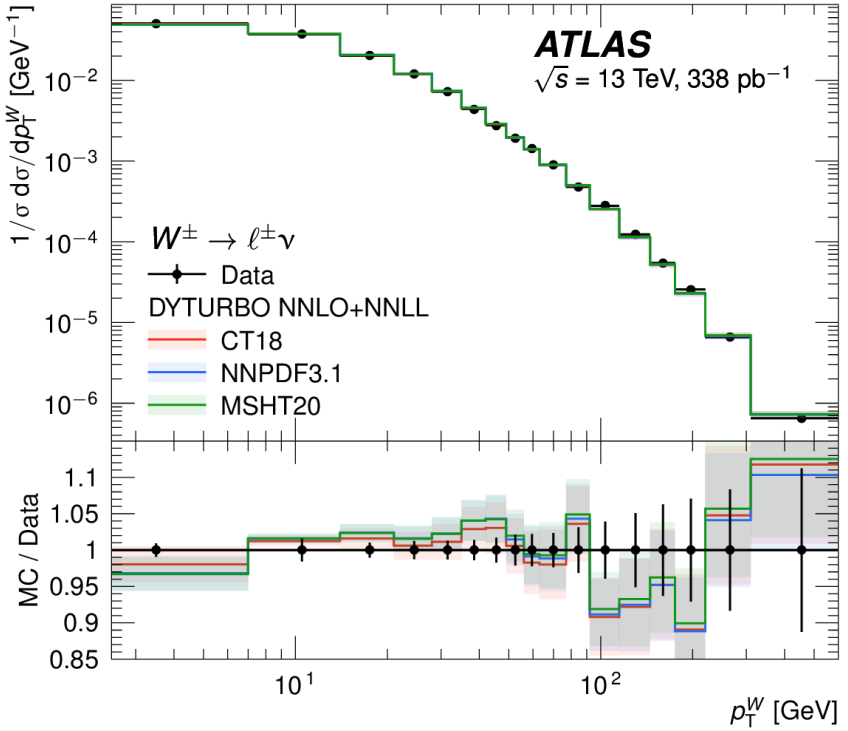
- Able to test modelling and compare parton shower MC to analytical resummation

→ Important ingredient for W mass measurement

- Validation of AZNLO tune used for 7 TeV measurement
- Small impact of PDFs on data/prediction agreement







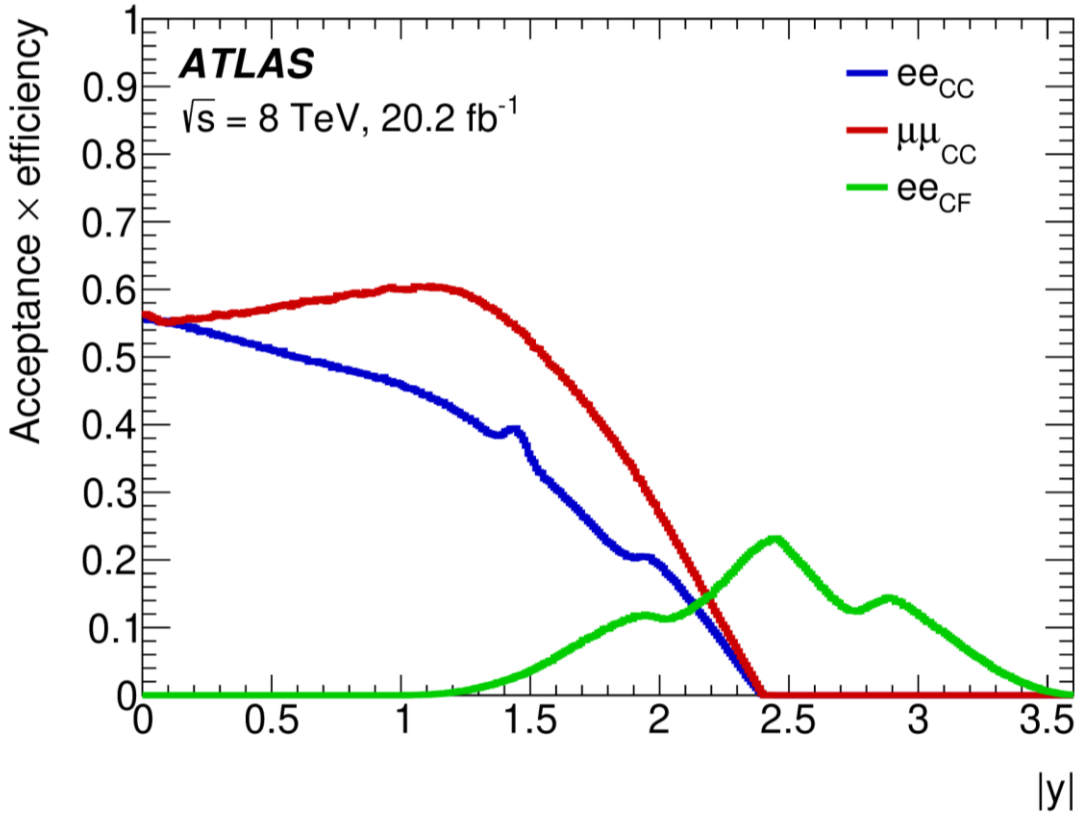
Double-differential Z

Eur. Phys. J. C 84 (2024) 315

Also see Talk by Florencia (Monday)

Exploit **factorization** of Z cross-section

- Extract double-differential (p_T,y) cross-sections for **full phase-space**
  - Fit **templates** representing detector-folded polynomials
- Use of **forward electrons** for high-rapidity region



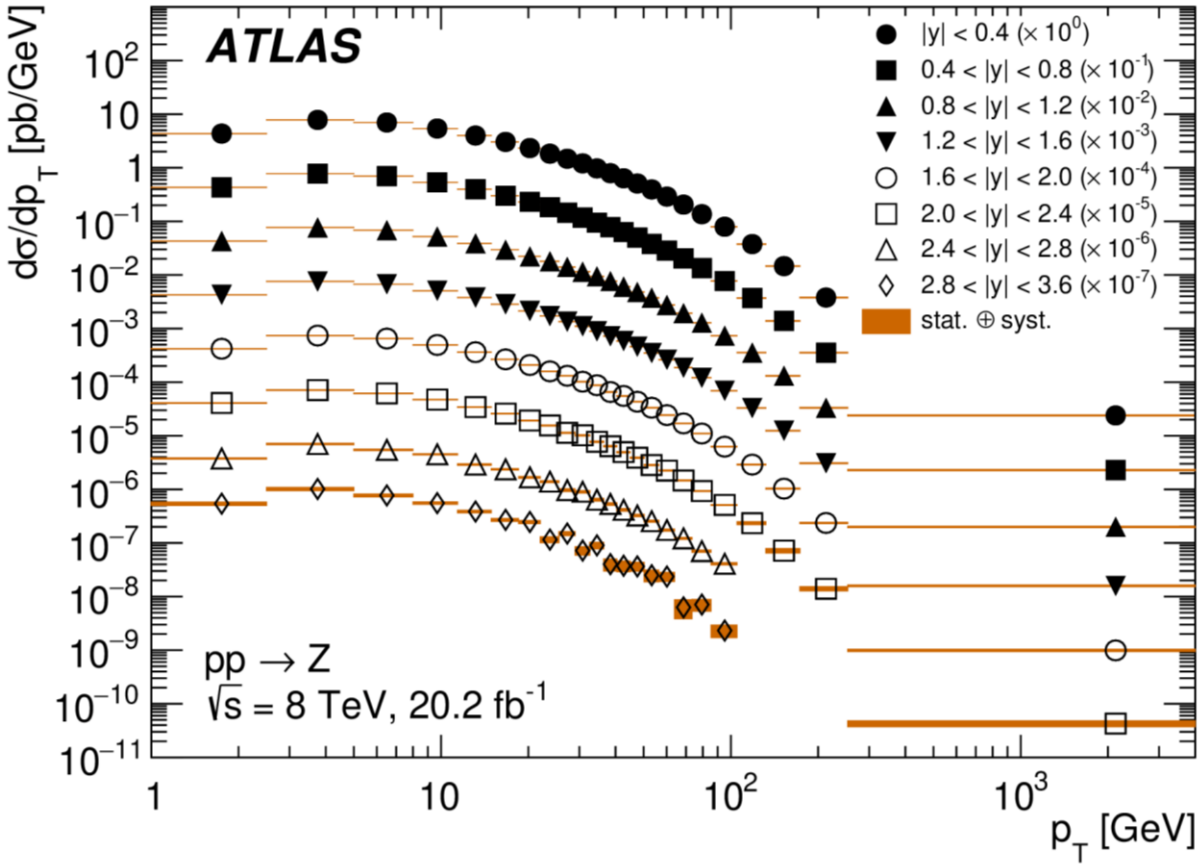
$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T}}\,\mathrm{d}y\,\mathrm{d}m\,\mathrm{d}\cos\theta\,\mathrm{d}\phi} = \frac{3}{16\pi}\frac{\mathrm{d}\sigma^{U+L}}{\mathrm{d}p_{\mathrm{T}}\,\mathrm{d}y\,\mathrm{d}m}$$
$$\Big\{(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi$$
$$+\frac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta$$
$$+A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\Big\}.$$

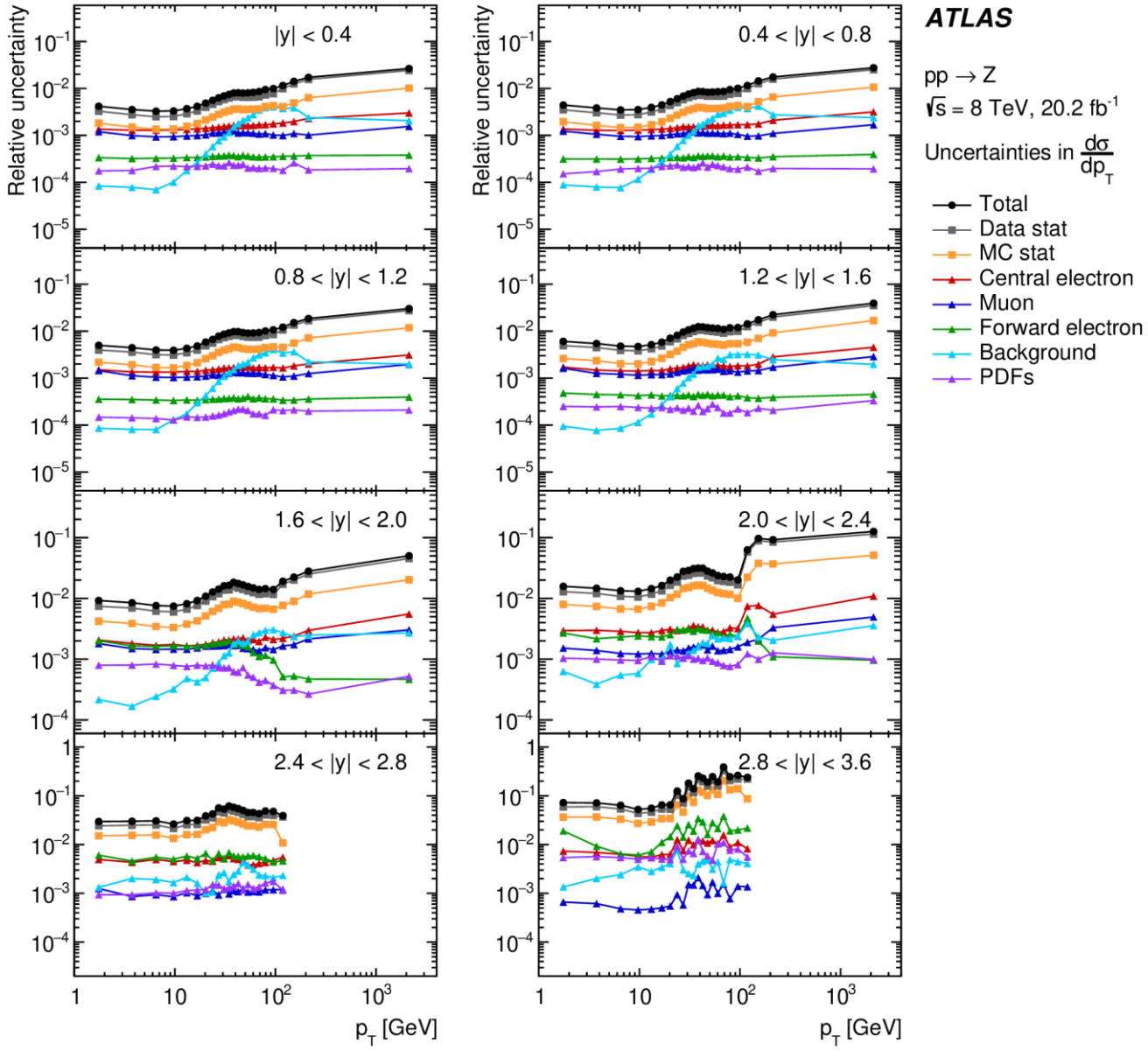
Double-differential Z

Eur. Phys. J. C 84 (2024) 315

Extract double-differential (p_T,y) cross-sections for **full phase-space**

- 352 bins
- Percent to permille-level precision

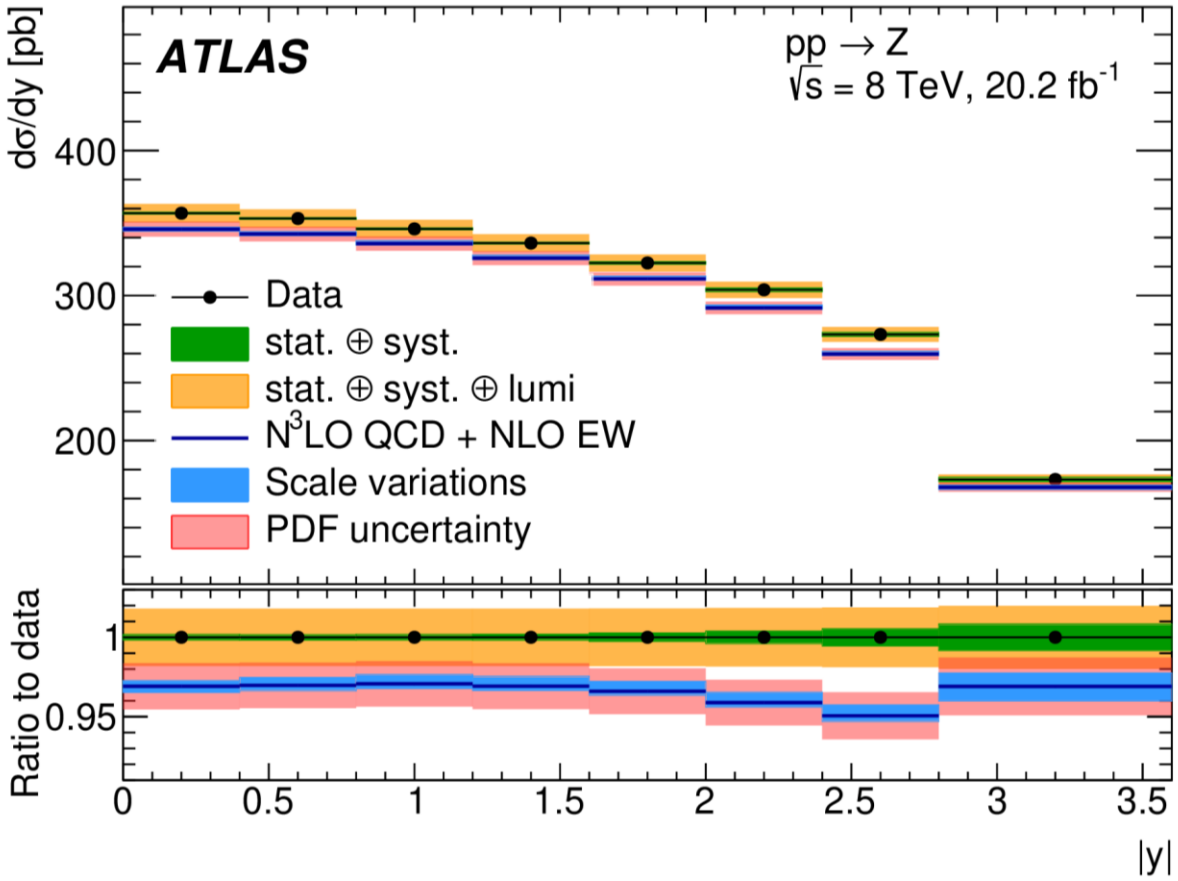


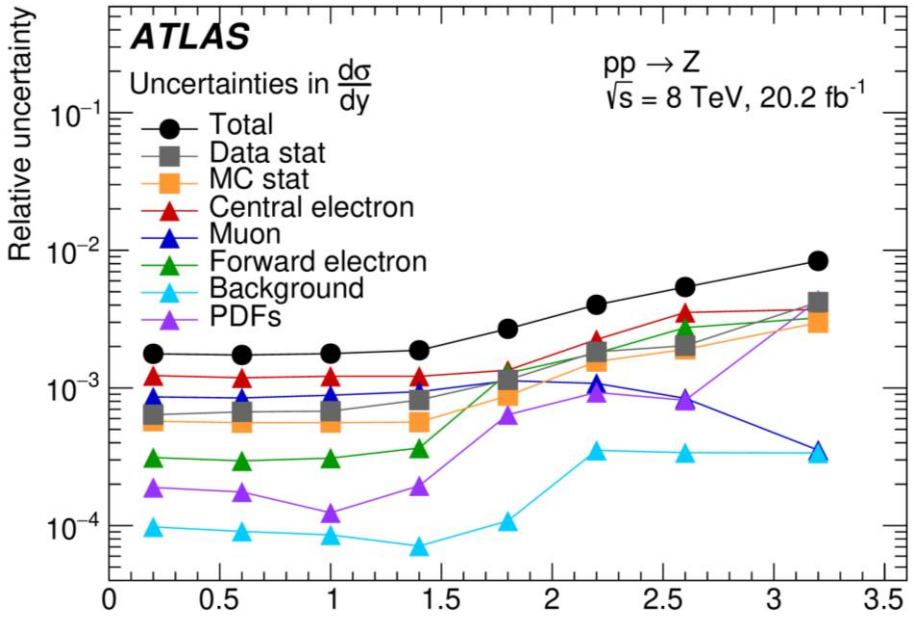


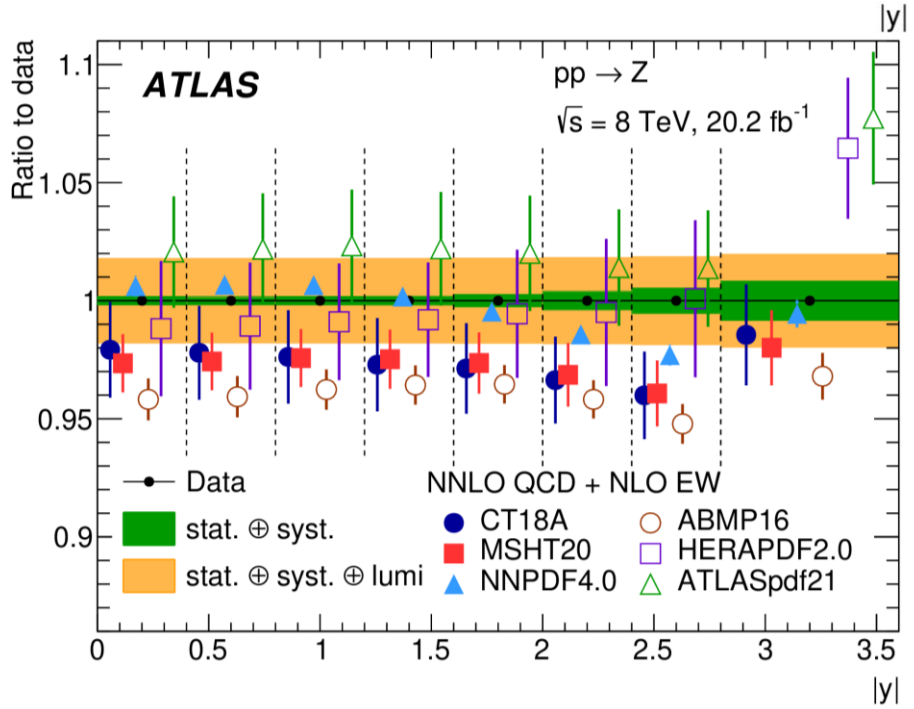
Double-differential Z

Eur. Phys. J. C 84 (2024) 315

- Integrate into single-differential and inclusive absolute cross-sections
- Enables precise and unambiguous PDF interpretation
  - with QCD scale uncertainties now smaller than PDF ones



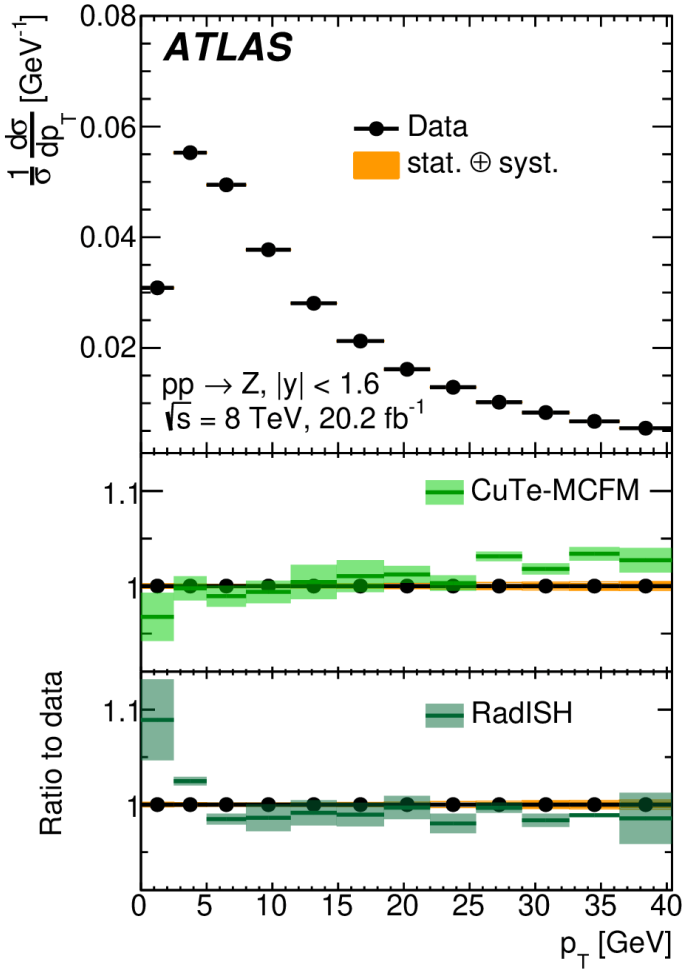


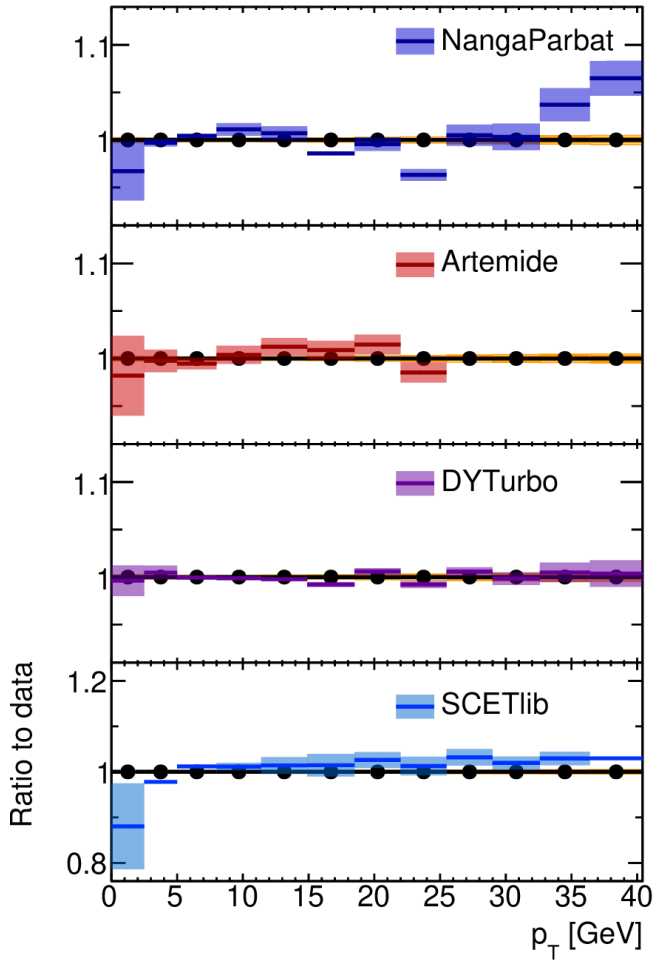


Double-differential Z

Eur. Phys. J. C 84 (2024) 315

- Integrate into single-differential and inclusive absolute cross-sections
- Precision allows to challenge state-of-the-art calculation





→ Allows α_S determination – not covered here, but see talks by Valentina and Oleg on Monday

A look at Run 3

First Run 3 results

Eur. Phys. J. C 84 (2024) 78

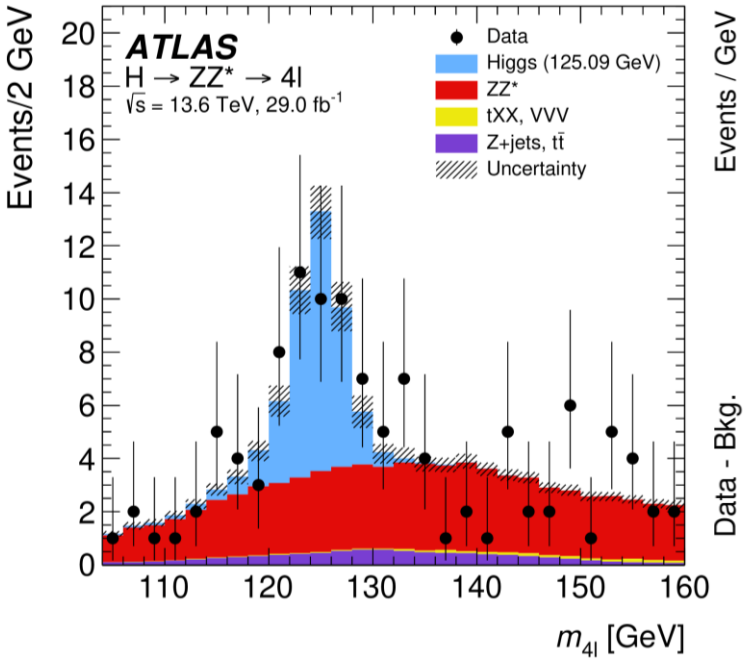
LHC Run 3 in full swing – first single-boson production results!

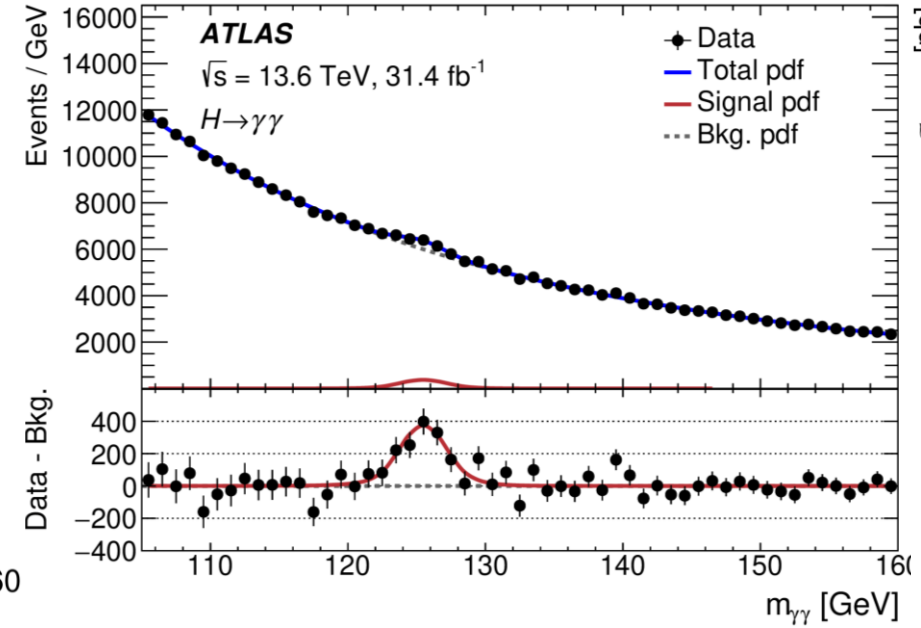
- Early stage, still less data than Run 2 – main purpose to **establish measurements** under new conditions

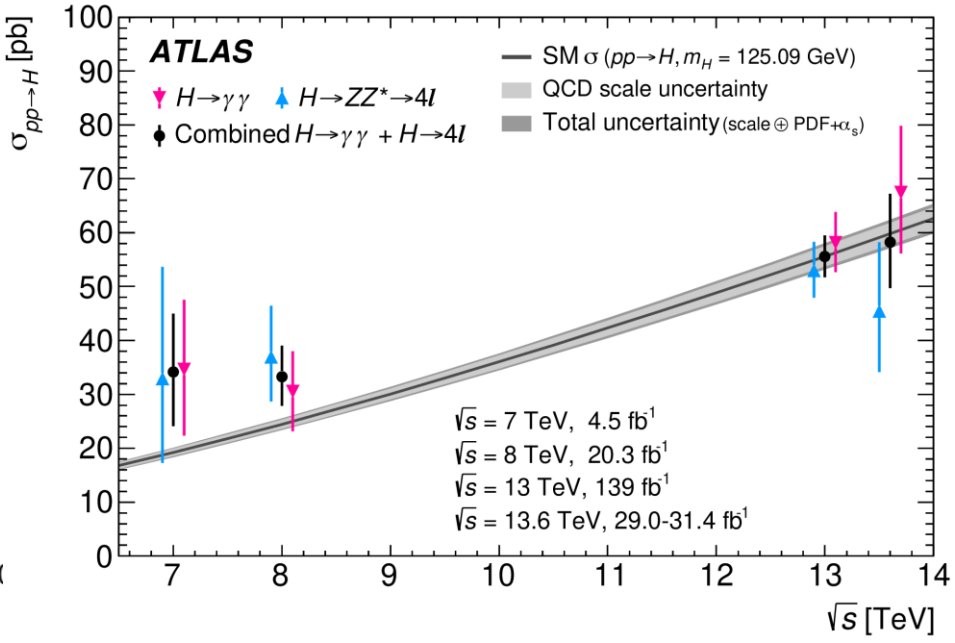
→ First steps towards eventually surpassing Runs 1/2

ATLAS: Inclusive fiducial H cross-section in H4l and yy final states

→ Higgs as **standard candle** 10 years after discovery





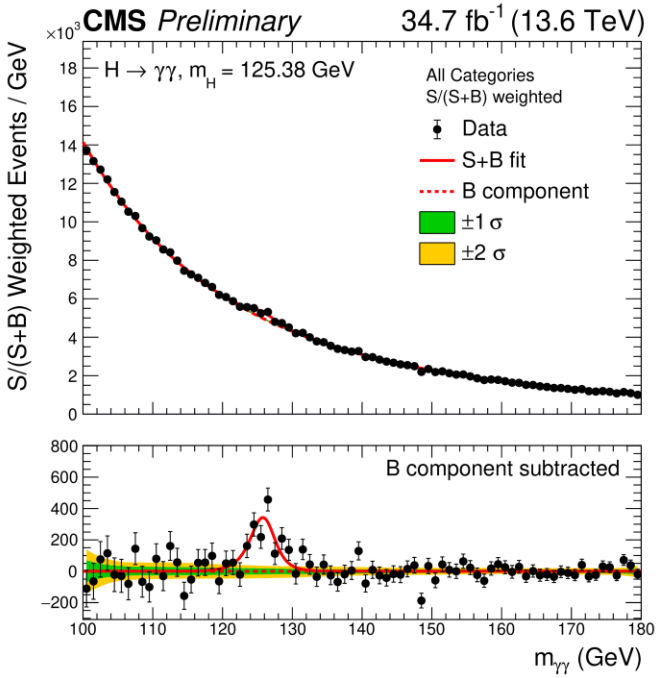


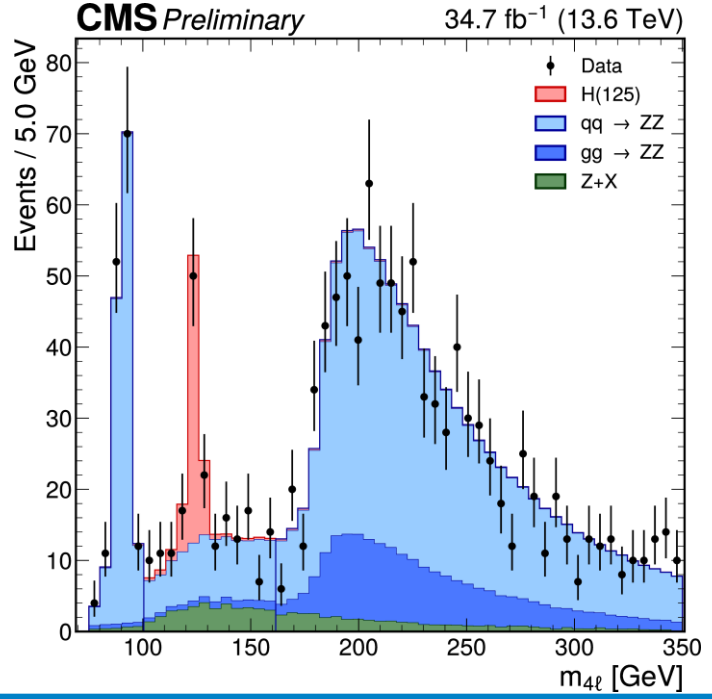
First Run 3 results

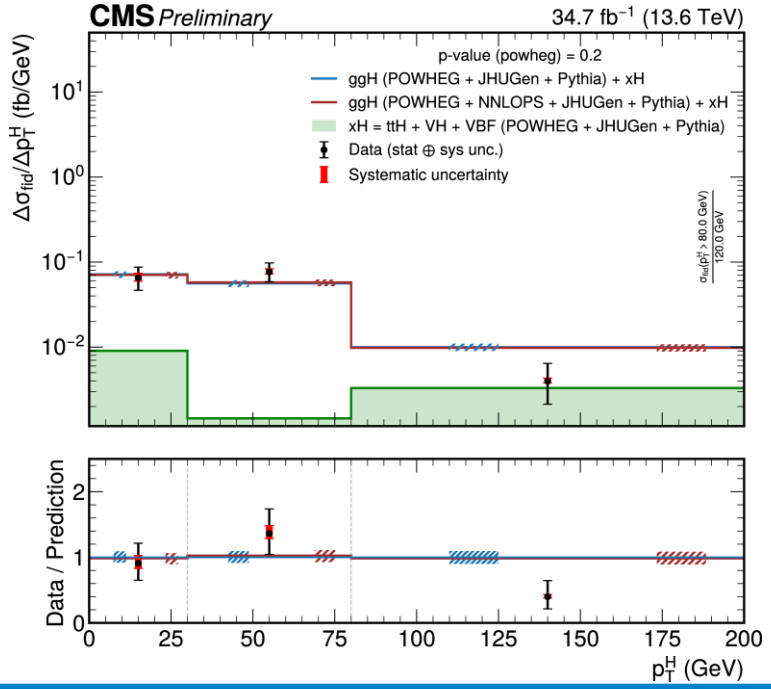
[CMS-PAS-HIG-24-013](#)
[CMS-PAS-HIG-23-014](#)

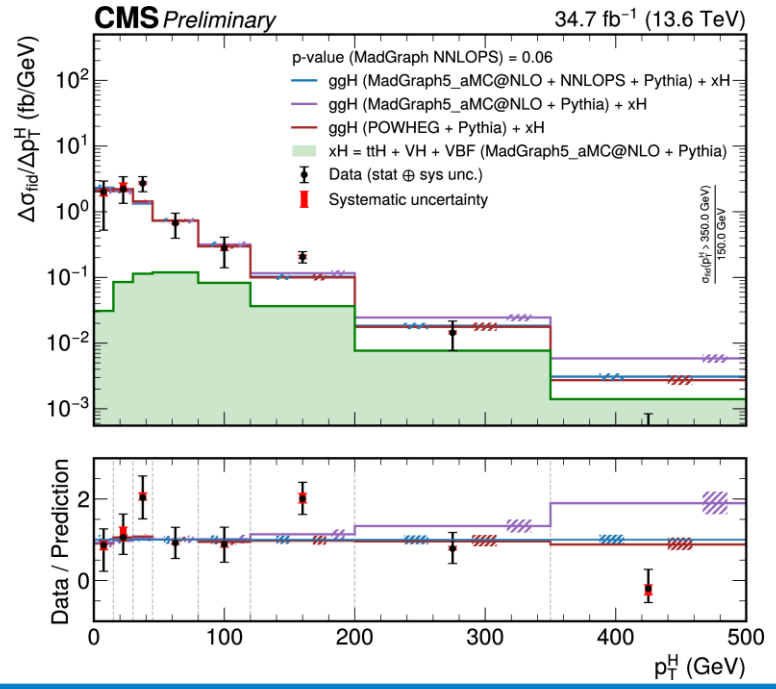
CMS: First **differential Higgs cross-sections** with 2022 data

- Our favourite scalar is re-established in both general-purpose detectors!







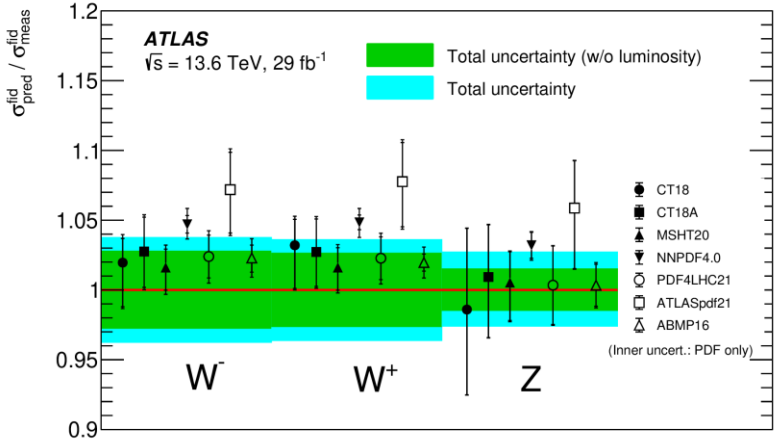


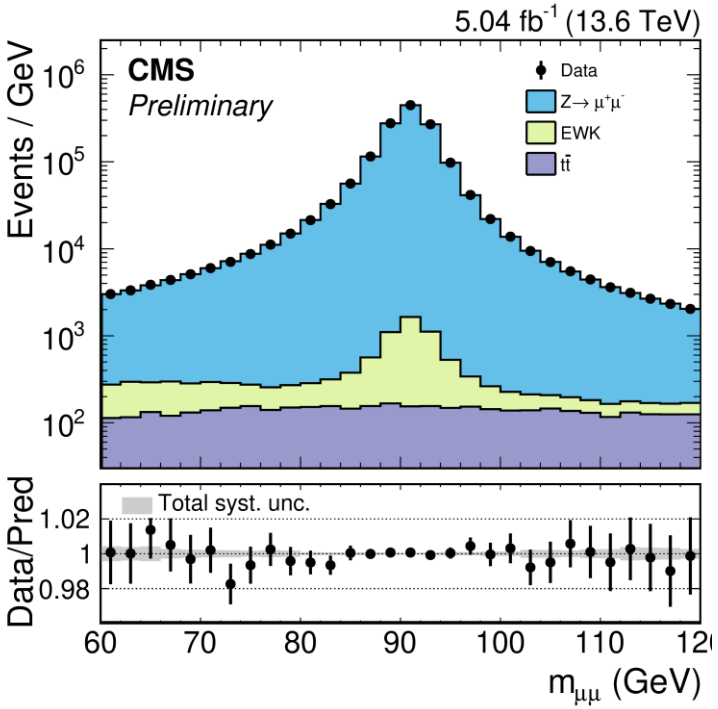
First Run 3 results

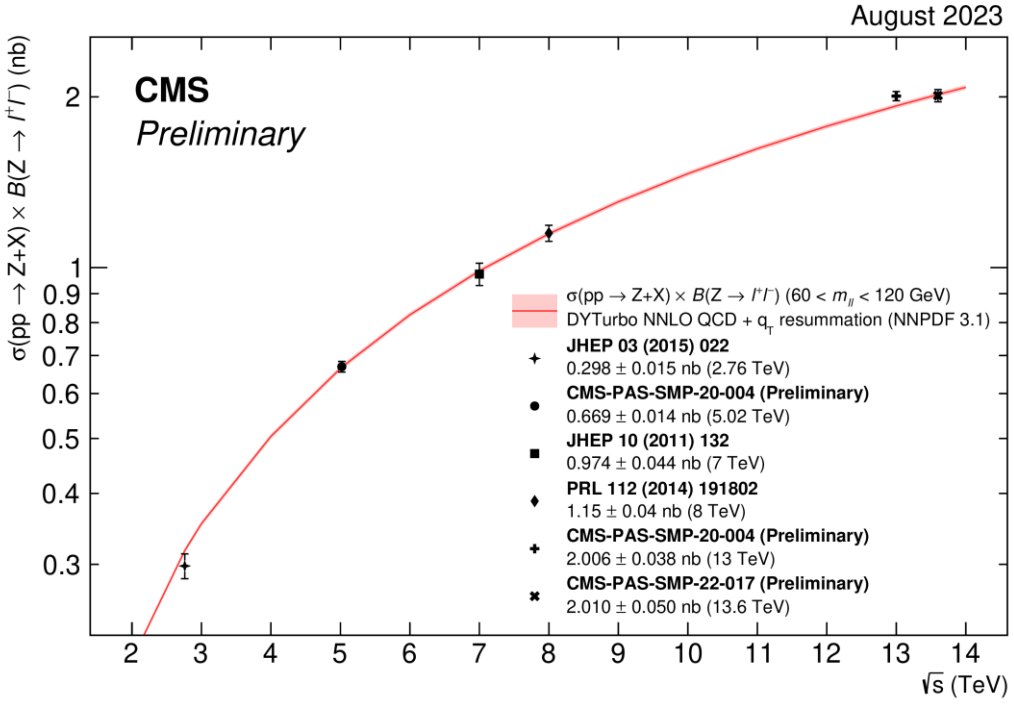
CMS-PAS-SMP-22-017
Phys. Lett. B 854 (2024) 138725

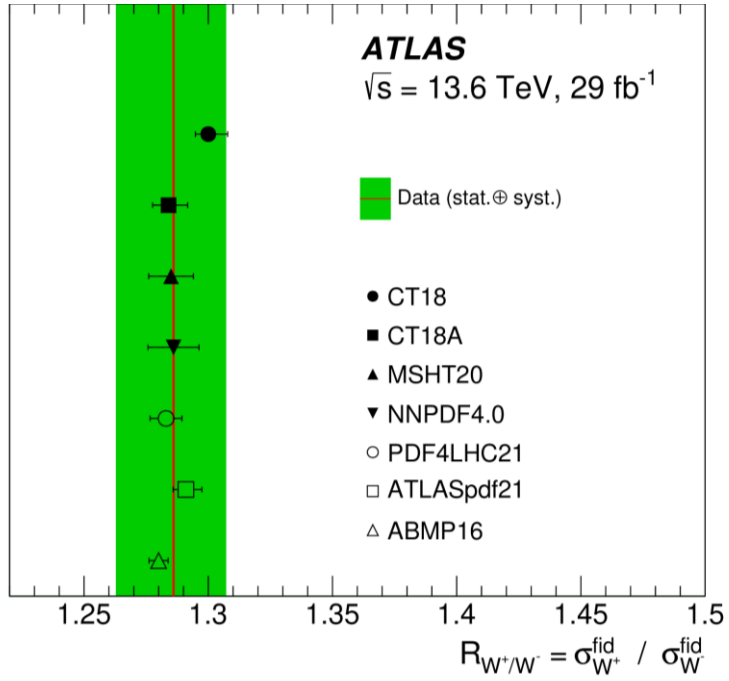
CMS: Established **Z cross-section** on early 2022 data soon after

Followed by **ATLAS** – fiducial W,Z cross-sections and ratios to top production









Summary

Single boson production measurements: **Workhorse of the SM and Higgs physics programme**

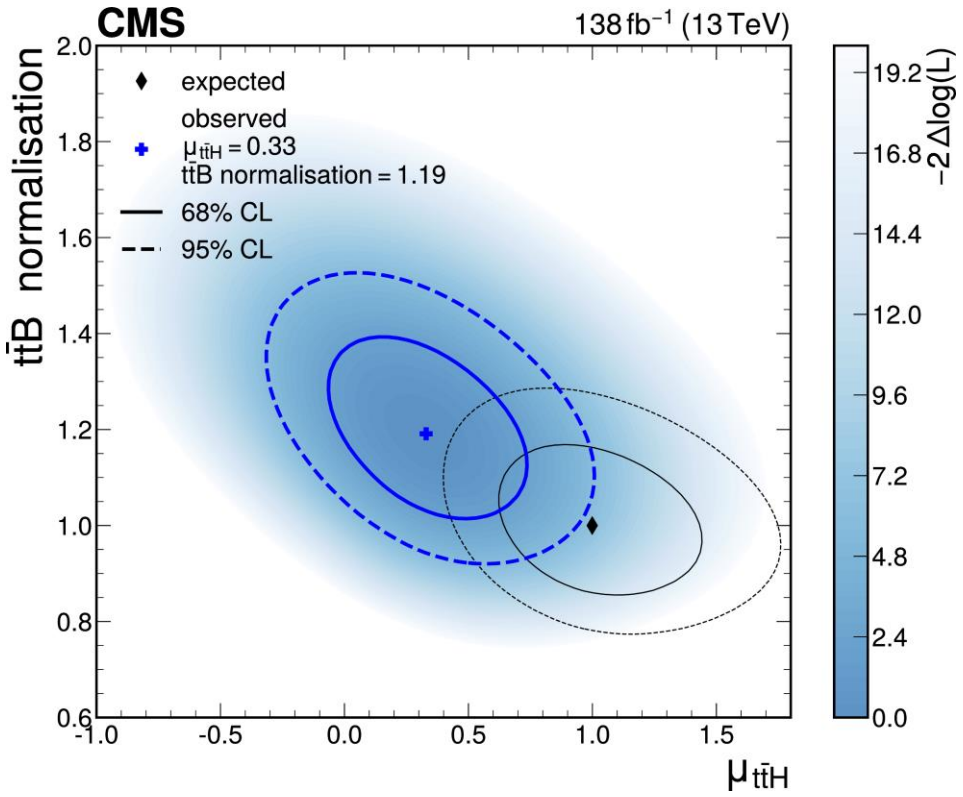
- Sub-percent level precision for gauge bosons, percent-level for Higgs
- Even 6 years after the end of Run 2, a lot of progress being made
  - And even still benefiting from 8 TeV Run 1 data!
- Gaining sensitivity through more and more sophisticated techniques
  - W/Z largely systematically limited, statistical errors still relevant in Higgs (channel-dependent)

Meanwhile, **Run 3 is ramping up**

- Dataset exceeding Run 2
- Single-boson cross-sections among very first physics results
- Demonstration of rapid understanding of early data
- Establishing the foundations for **further improvements in the future**

Backup

ttH->bb



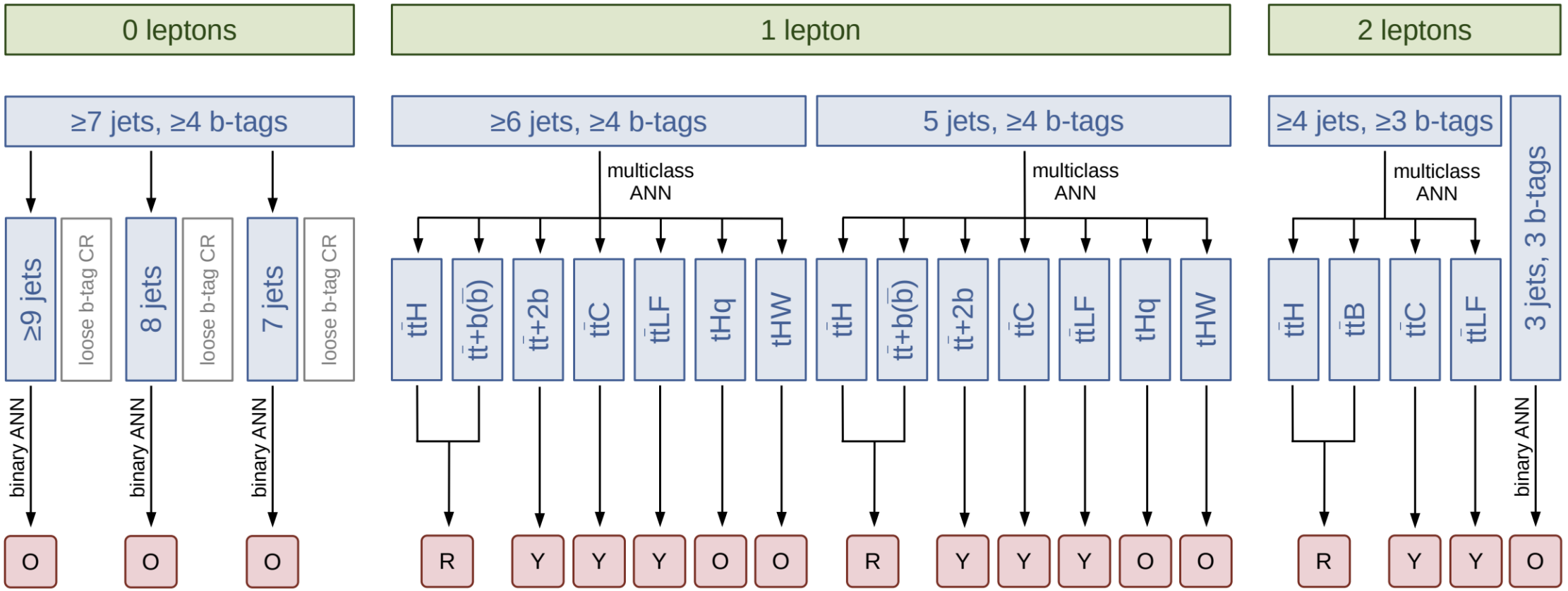
ATLAS results for background norm.:

Normalisation factor	$t\bar{t}$ + light	$t\bar{t}$ + ≥ 1c	$t\bar{t}$ + 1b	$t\bar{t}$ + 1B	$t\bar{t}$ + ≥ 2b
Single-lepton	$0.78^{+0.08}_{-0.08}$	$1.51^{+0.19}_{-0.18}$	$1.06^{+0.10}_{-0.10}$	$1.15^{+0.15}_{-0.14}$	$0.94^{+0.08}_{-0.08}$
Dilepton	$0.88^{+0.11}_{-0.10}$	$1.36^{+0.10}_{-0.10}$	$1.24^{+0.09}_{-0.09}$		

two b in one jet

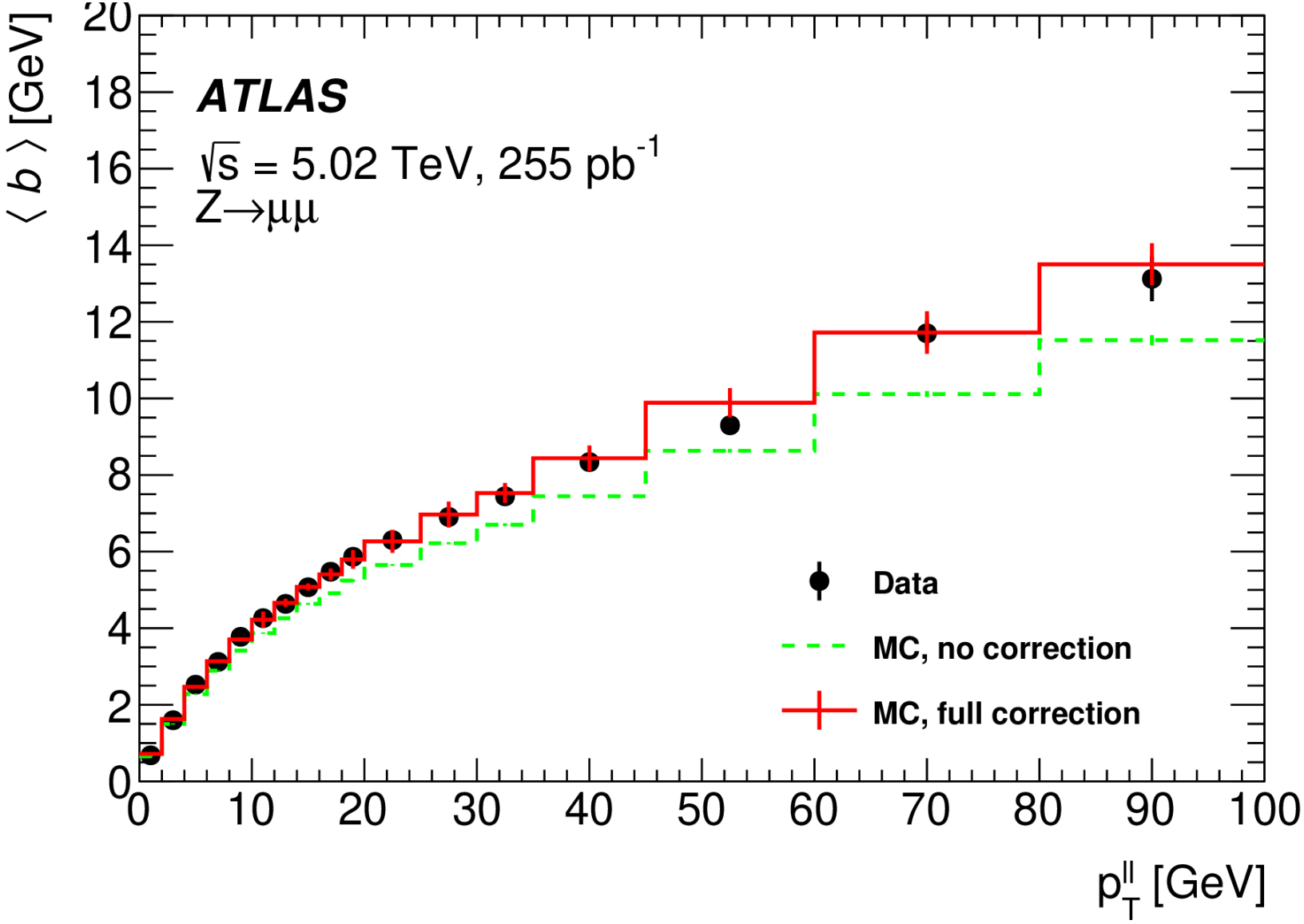
two separate jets

ttH->bb

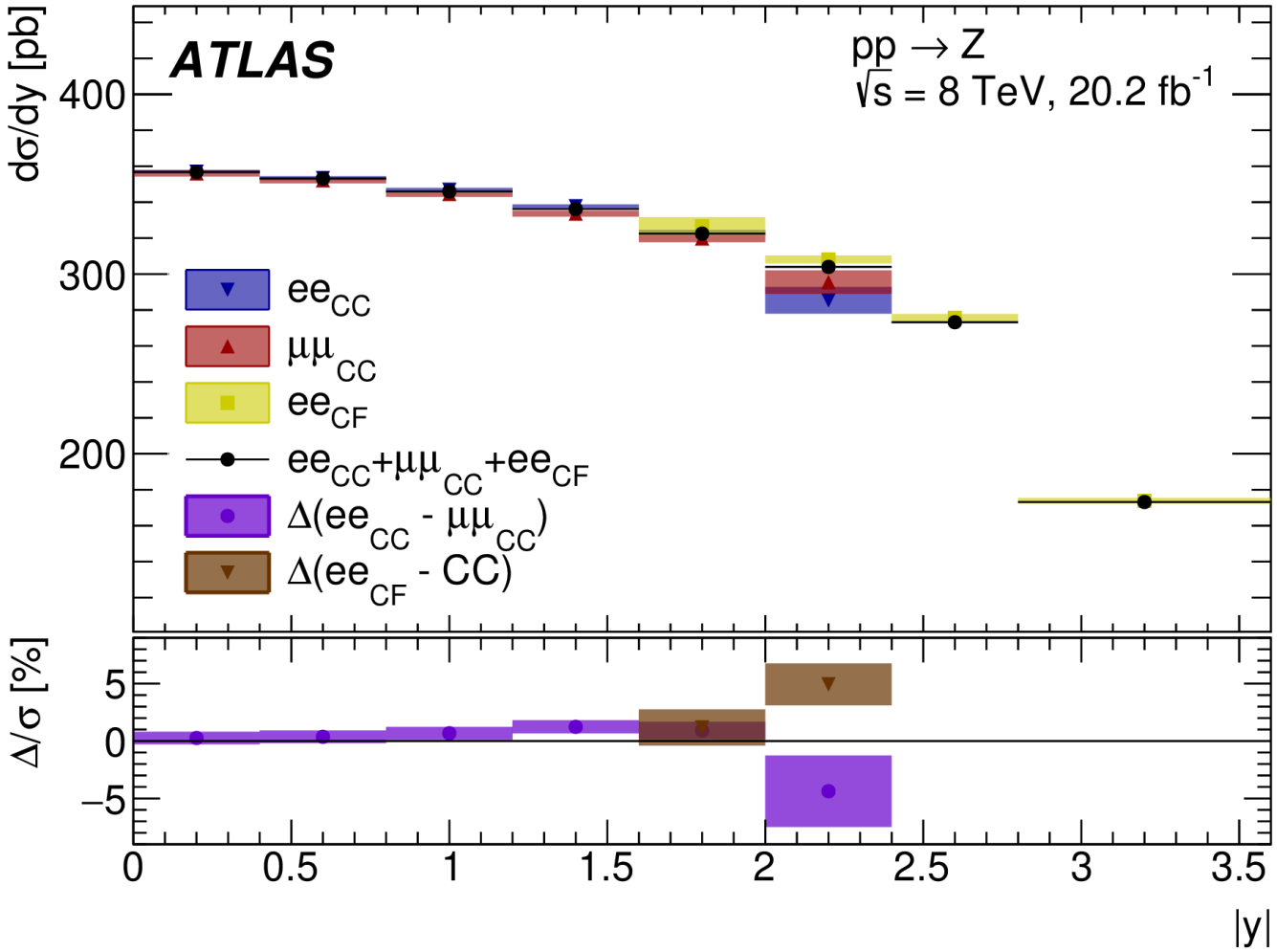


Distribution in template fit, event yield (Y), ANN output (O), likelihood ratio of ANN outputs (R)

Precision W/Z-boson measurements at low μ



Double-differential Z



First Run 3 results

Phys. Lett. B 854 (2024) 138725