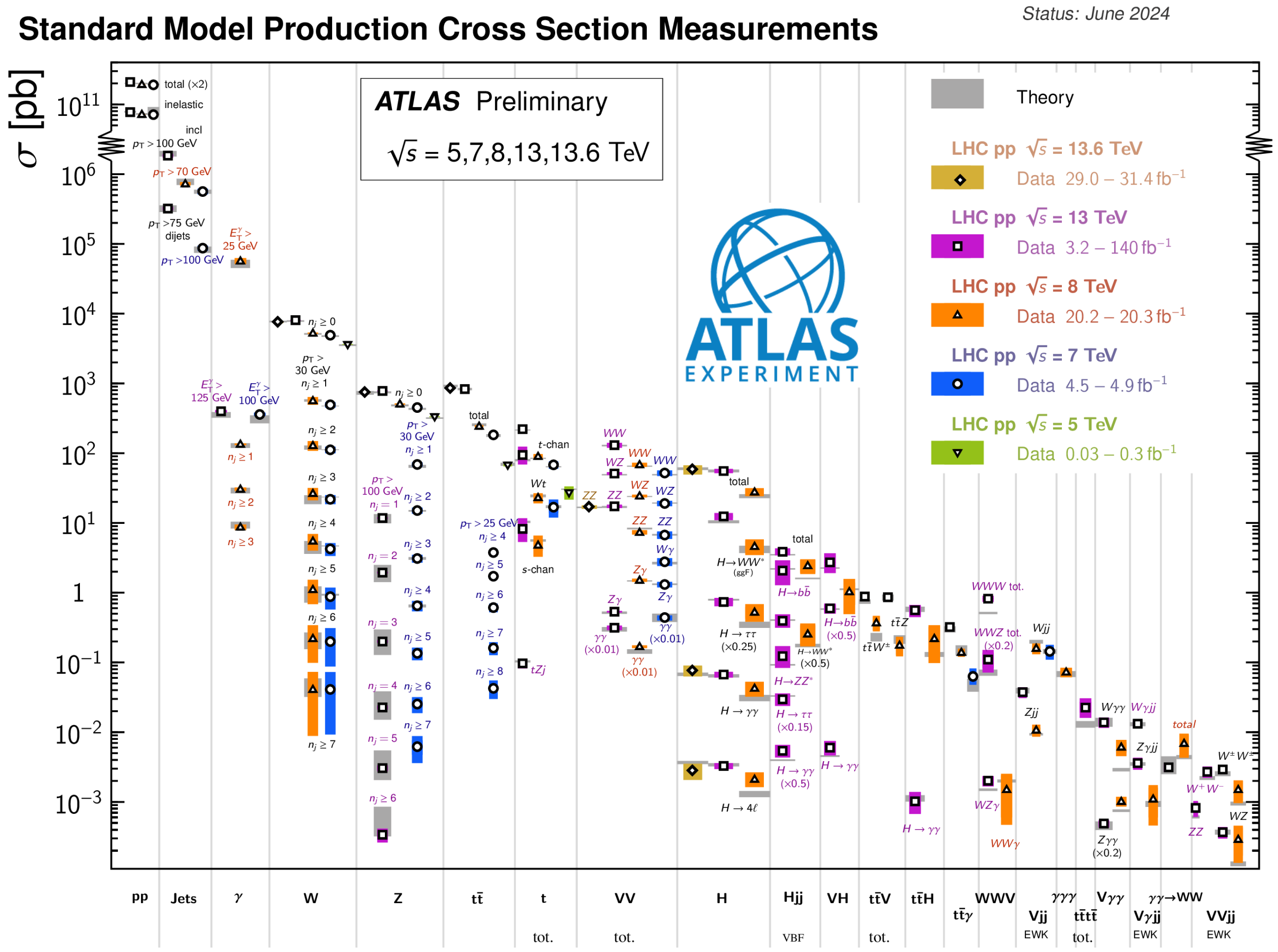
Experimental status of SM and Higgs physics

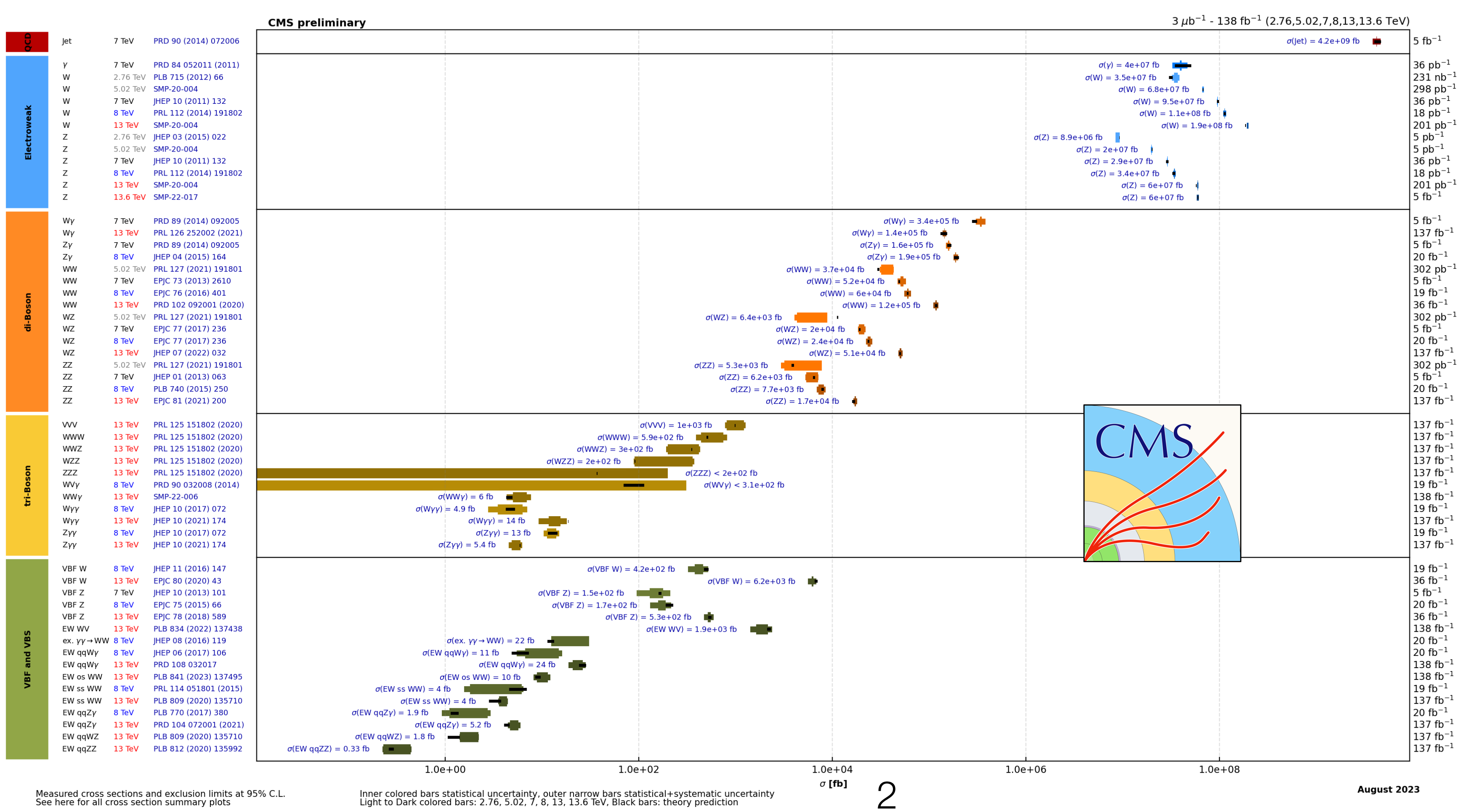
Lidia Dell'Asta
(Università degli Studi di Milano & INFN)
on behalf of the ATLAS & CMS Collaborations

Overview

- Status of the LHC data taking
- Summary of status and recent results from
  - electroweak physics
  - Higgs boson physics
  - top quark physics



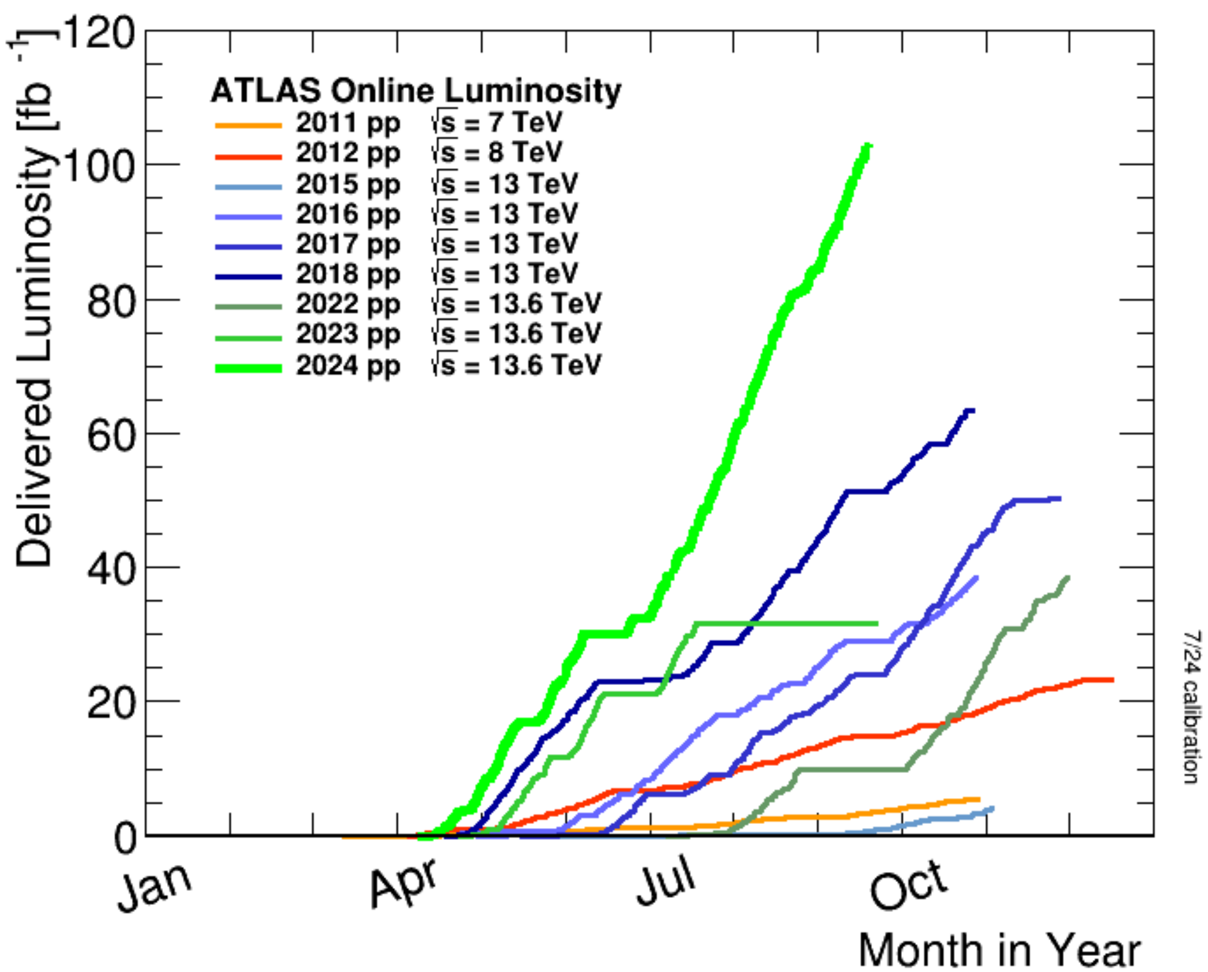
Overview of CMS cross section results

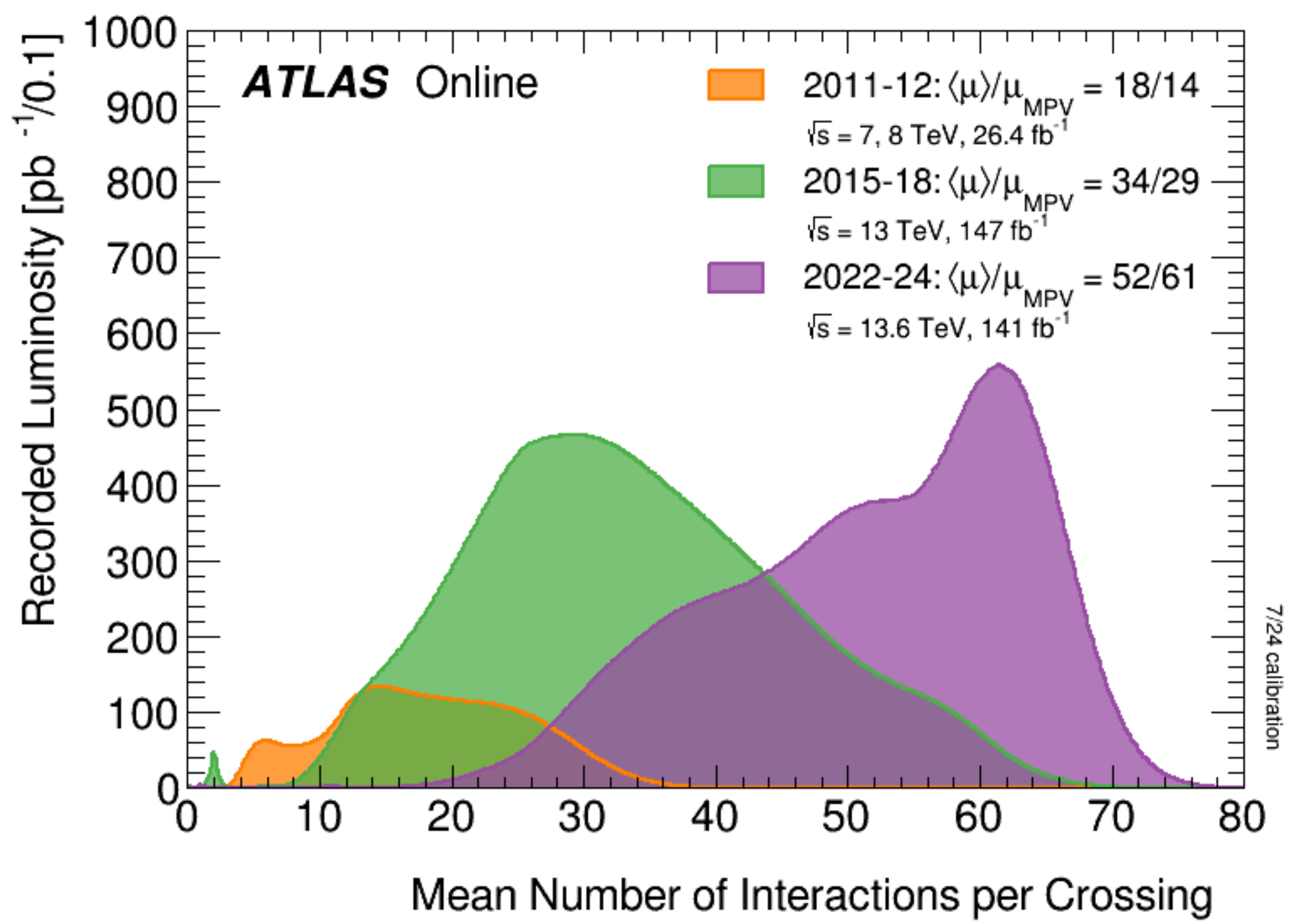


LHC data

- Impressive performance of the LHC
  - Huge amount of data available for measurements
  - Increasingly challenging dataset, with higher pile-up
- Expected by the end of Run3: 300 fb^{-1}

	$\sqrt{s}$	Integrated Luminosity
Run1	7 TeV 8 TeV	4.5 fb^{-1} 20 fb^{-1}
Run2	5.02 TeV 13 TeV	~250/300 pb^{-1} 140 fb^{-1}
Run3	13.6 TeV	~160 fb^{-1} (so far)

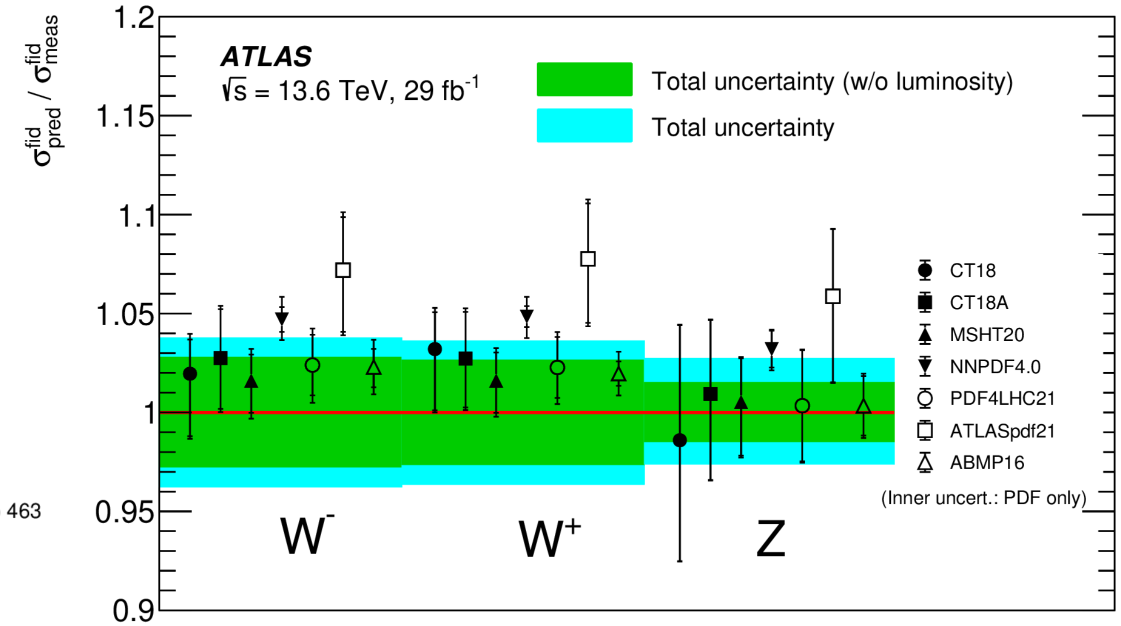




Electroweak physics

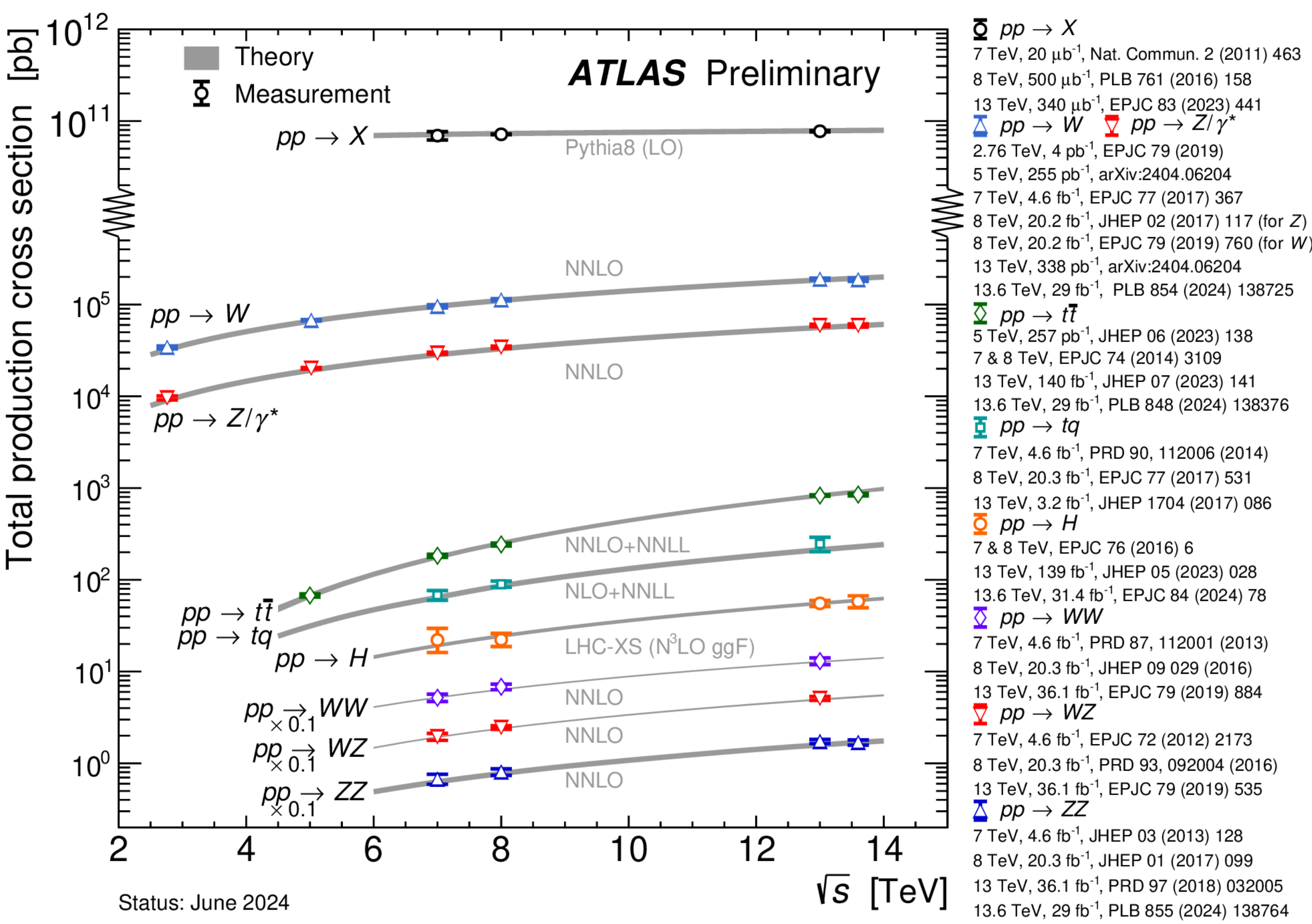
Electroweak physics

- LHC data allows to test electroweak theory by
  - performing precise measurements of single **W** and **Z bosons**
  - investigating higher energy regime with **multi-bosons** production

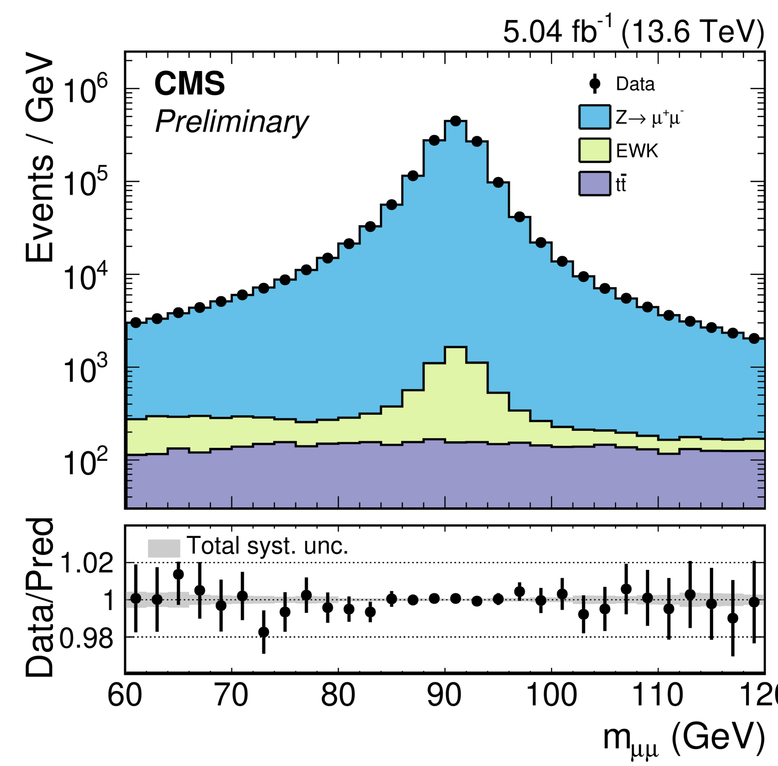


W and Z production at 13.6 TeV

[PLB 854 (2024) 138725]



[ATL-PHYS-PUB-2024-011]

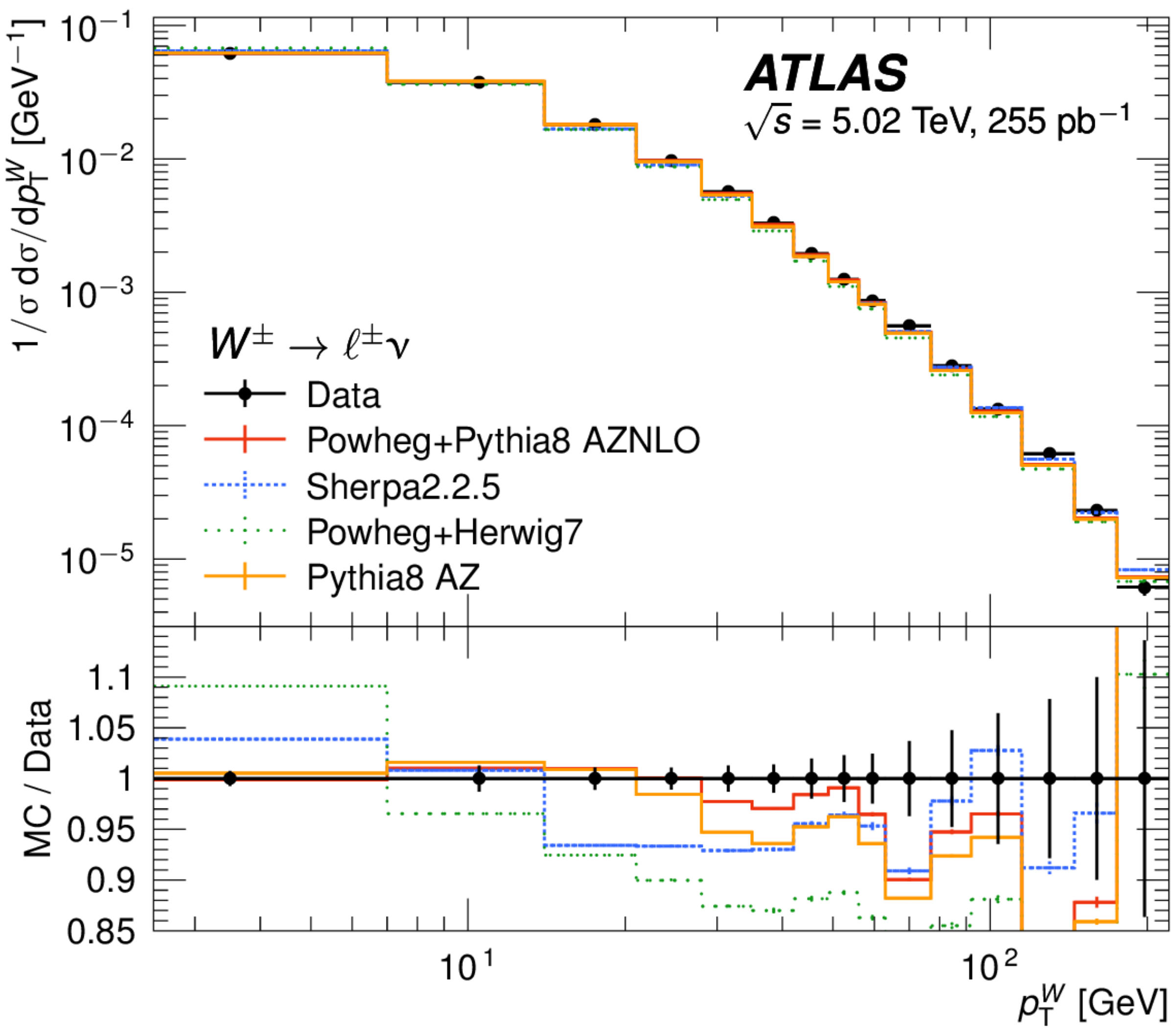


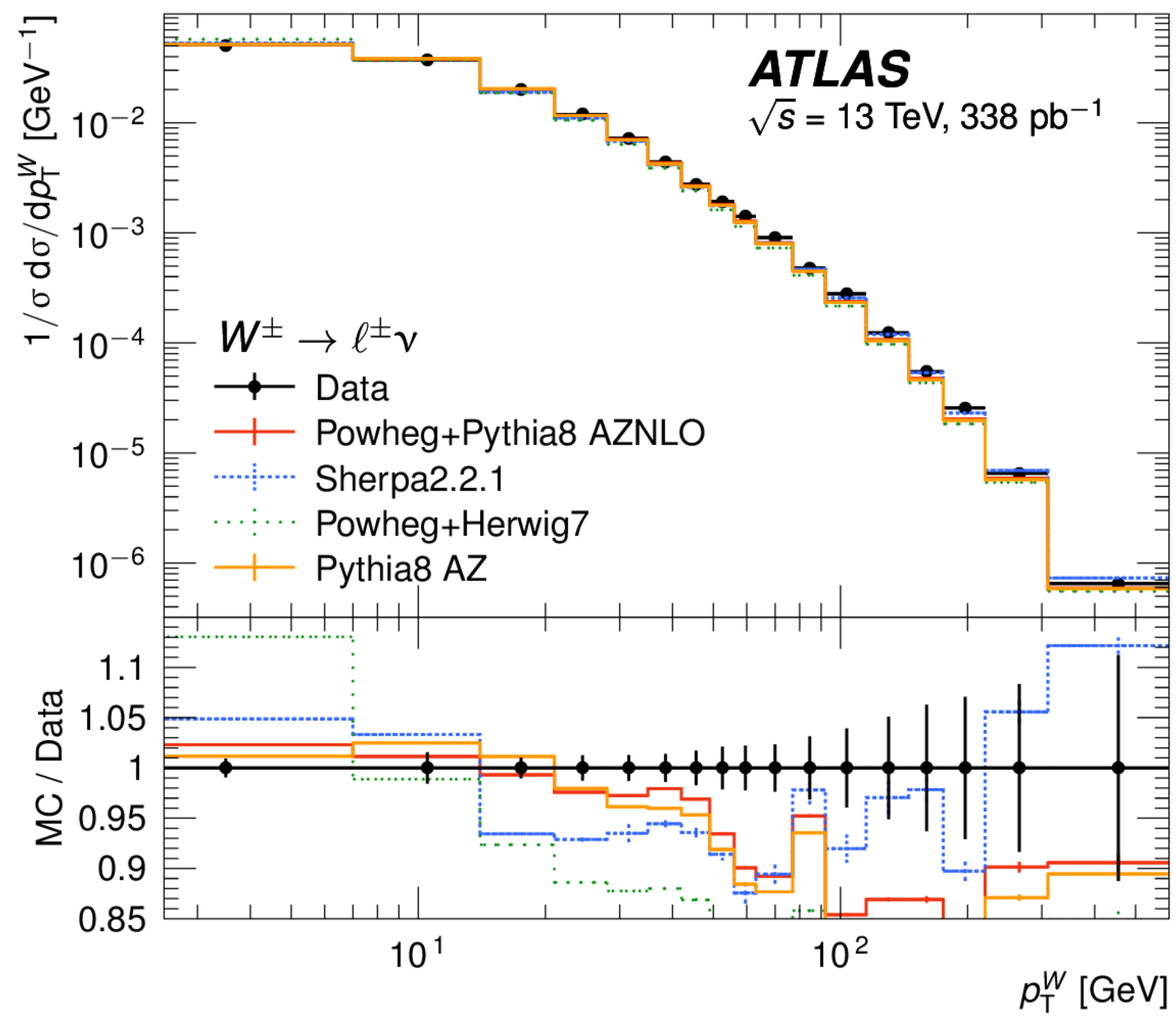
Z production at 13.6 TeV

[CMS-PAS-SMP-22-017]

W and Z boson transverse momenta

- Measurements of the $\mathbf{p_T}$ of **W** and Z bosons
  - Using pp data at 5.02 and 13 TeV
  - Direct measurement of $p_T(W)$ can improve future measurements of W mass





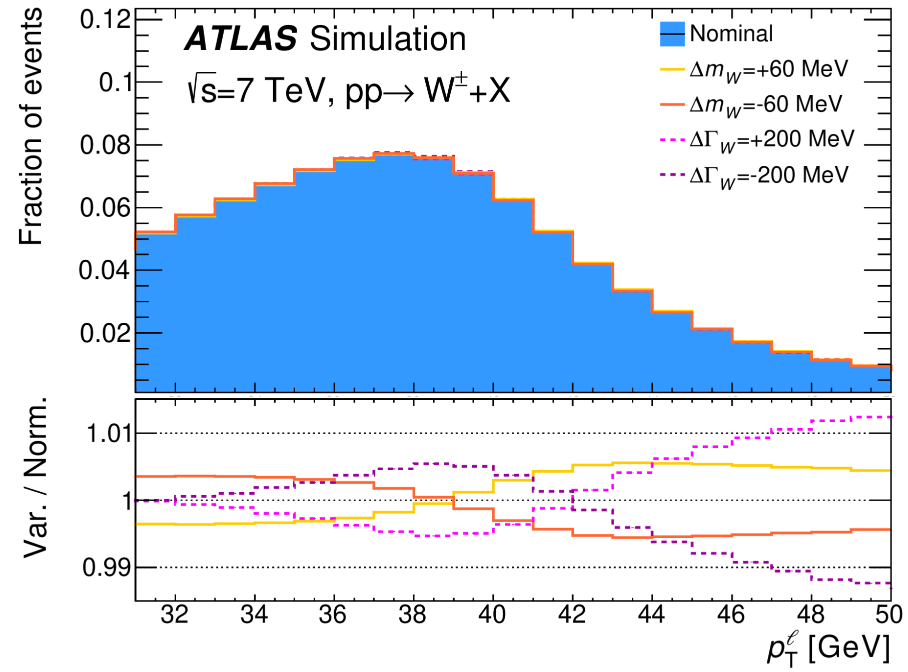
arxiv:2404.06204

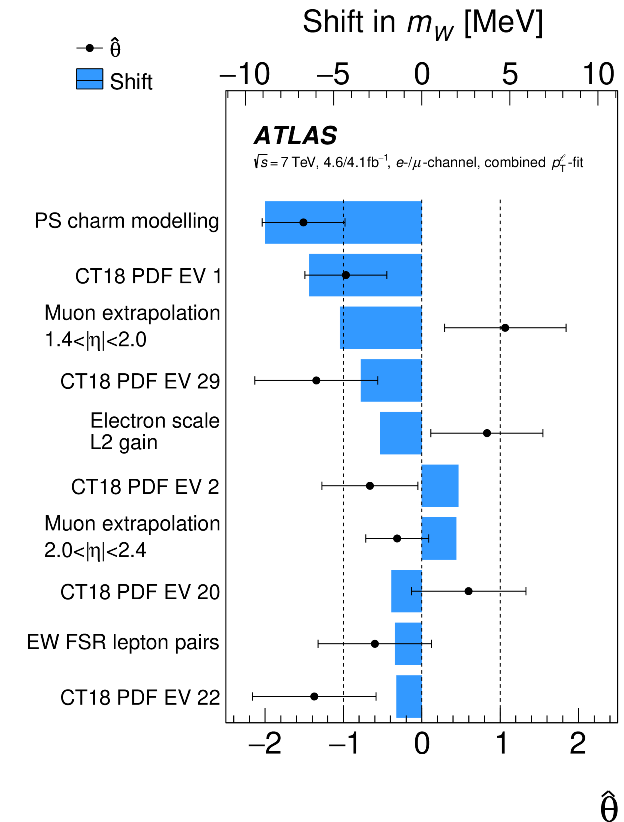
W boson mass and width

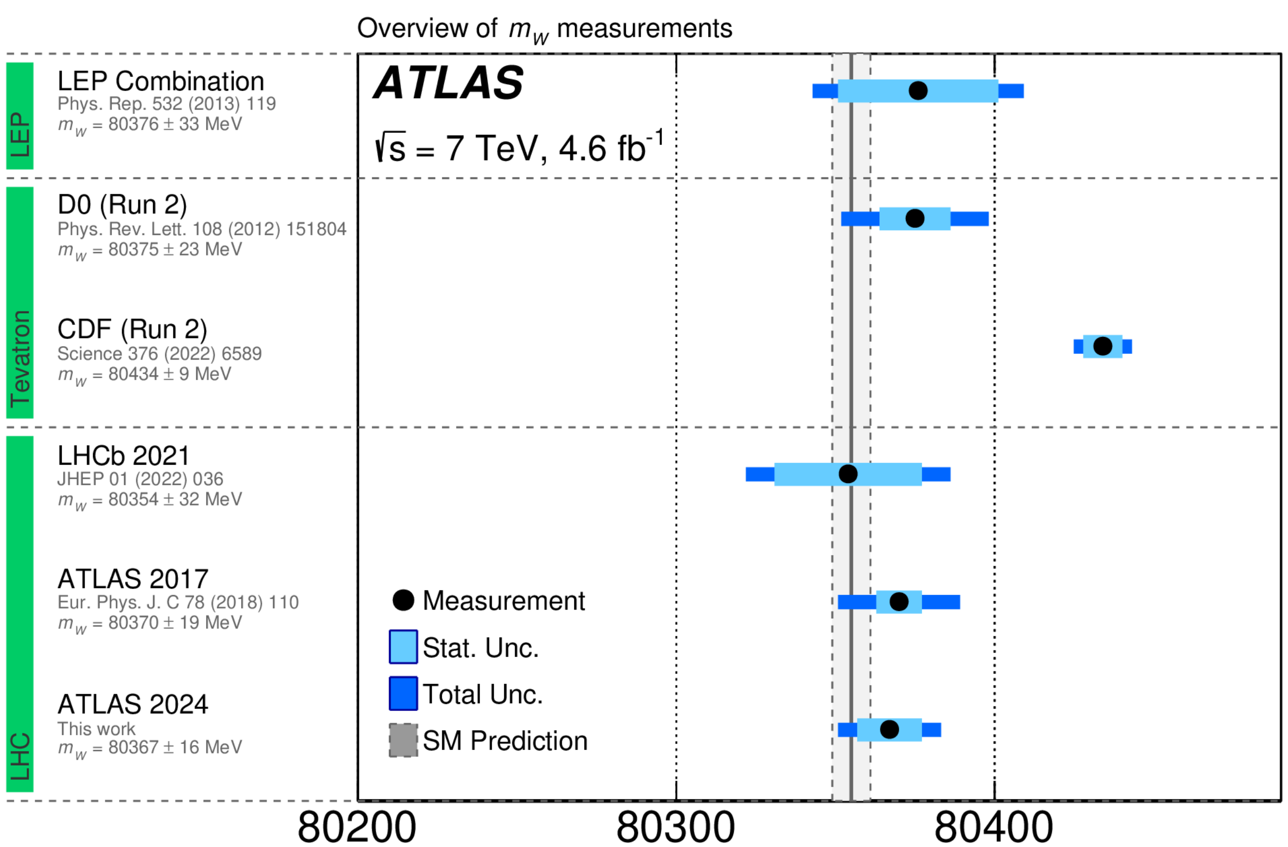
- Improved measurement of **m_W** and first measurement of **Γ_W** at LHC
  - Using Run1 pp data at 7 TeV
  - From $p_T(l)$ and $m_T(W)$ distributions in $W \rightarrow l\nu$

arxiv:2403.15085

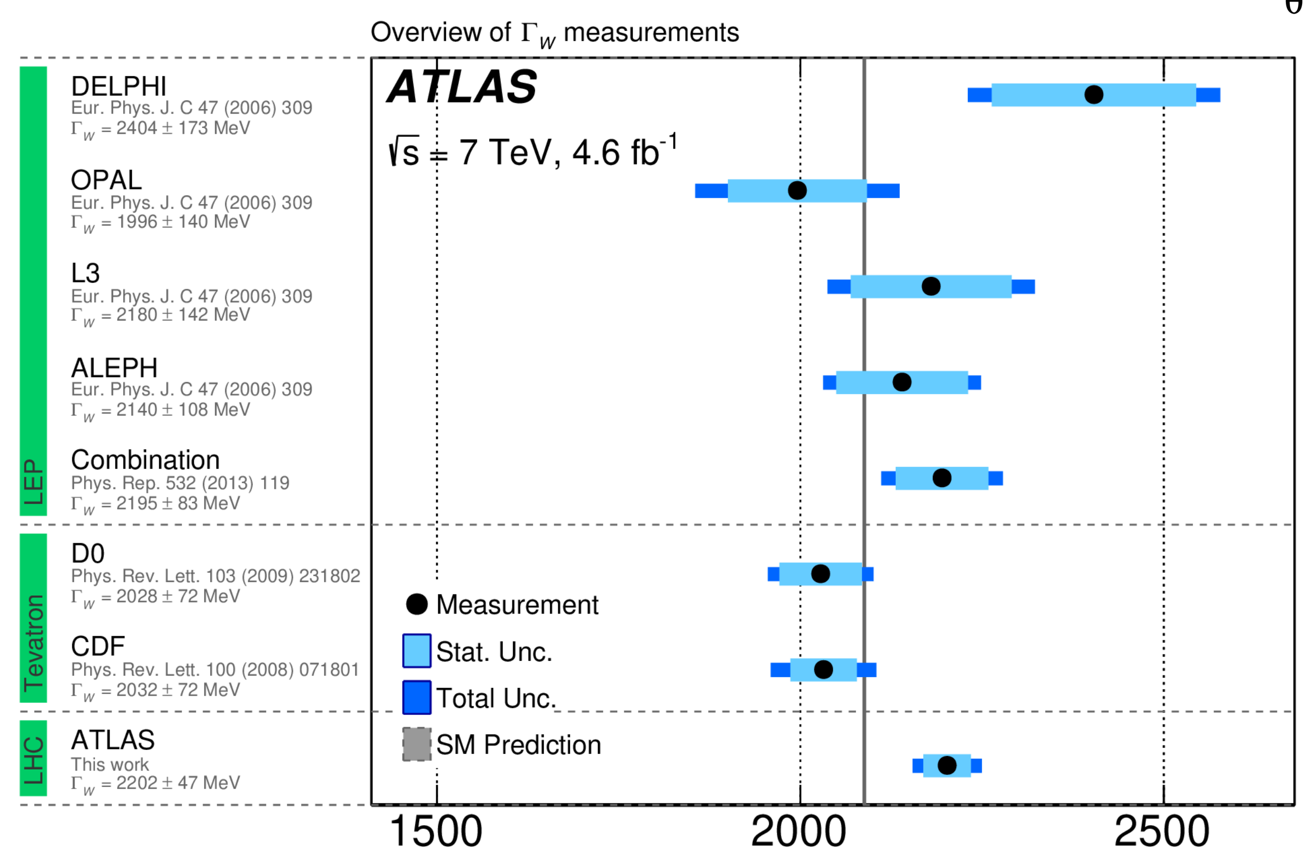
New m_W measurement by CMS
LHC Seminar **tomorrow**







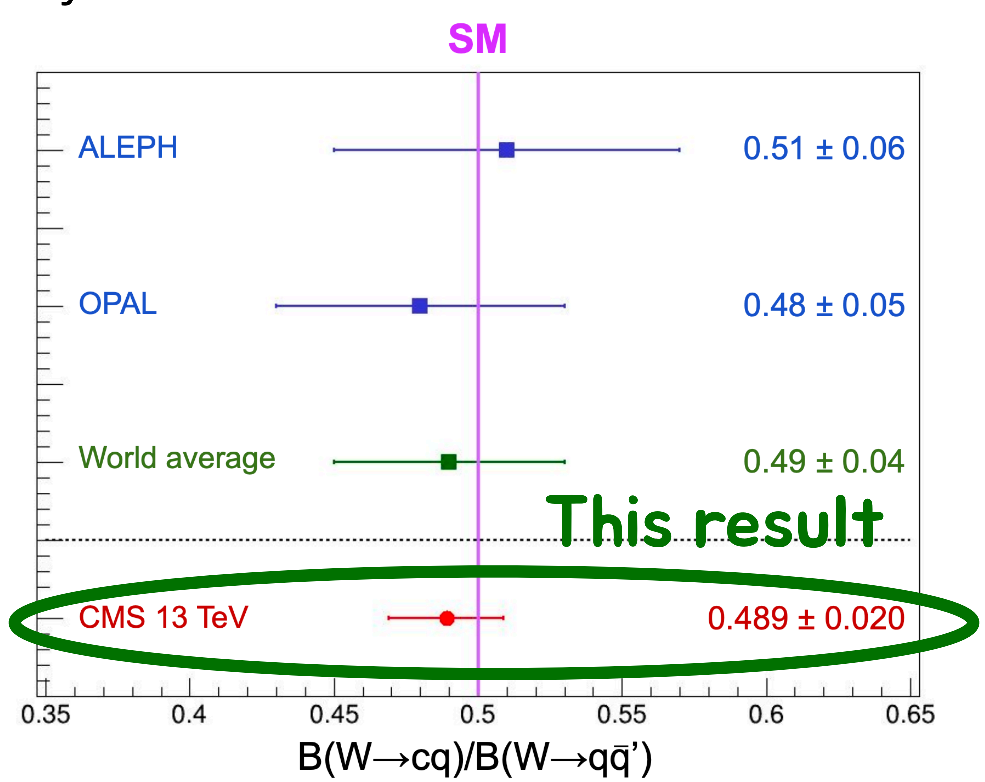
$$m_W = 80367 \pm 16 \text{ MeV}$$



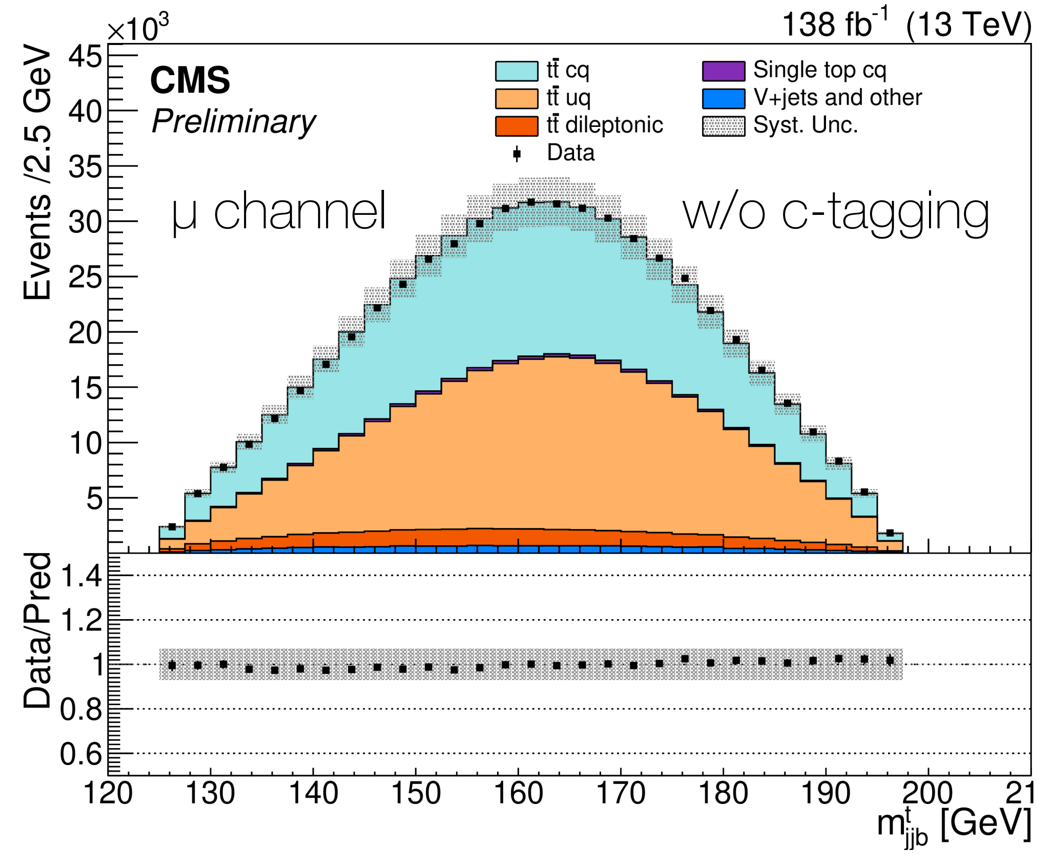
$$\Gamma_W = 2202 \pm 47 \text{ MeV}$$

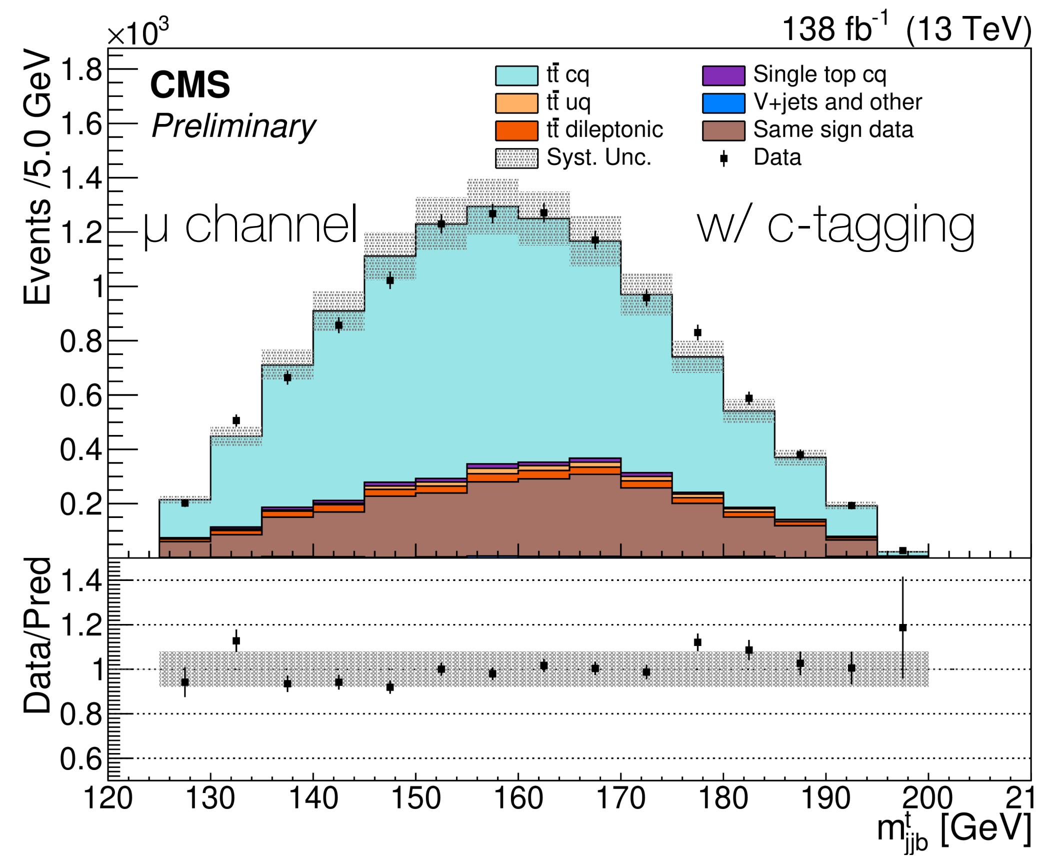
W boson hadronic decay branching fractions

- Measurement of $R_c^W = \mathscr{B}(W \to cq)/\mathscr{B}(W \to q\bar{q}')$ from $t\bar{t}$ events in semi-leptonic final state
  - Exploiting dedicated $c \to X\mu\nu$ **tagger**
  - Most precise measurement of R_c (4%)
  - Factor of 2 improvement w.r.t. world average
  - Dominant systematic uncertainty: charm tagging efficiency



$$R_c^W = 0.498 \pm 0.005 \text{ (stat.)} \pm 0.019 \text{ (sys.)}$$

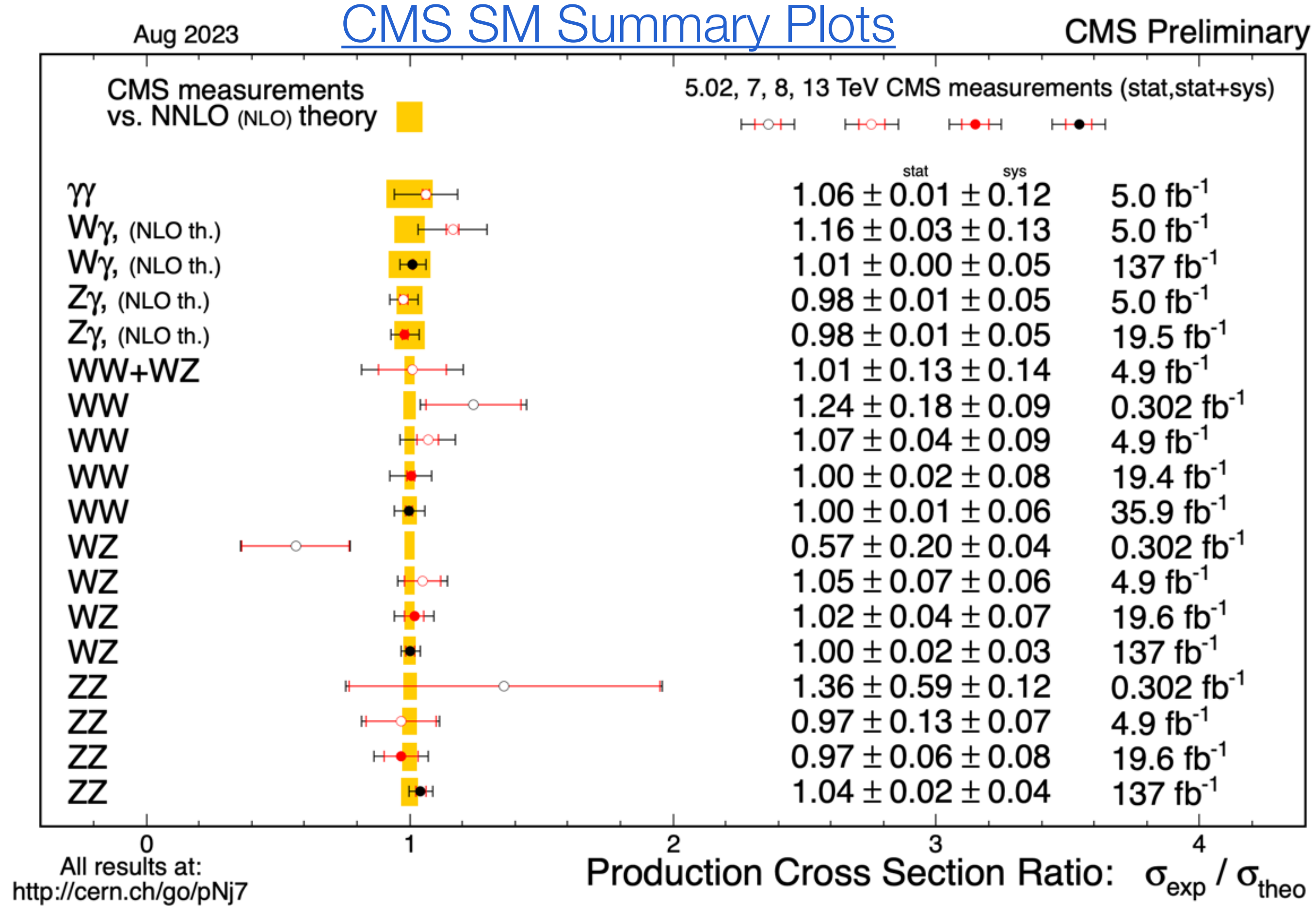


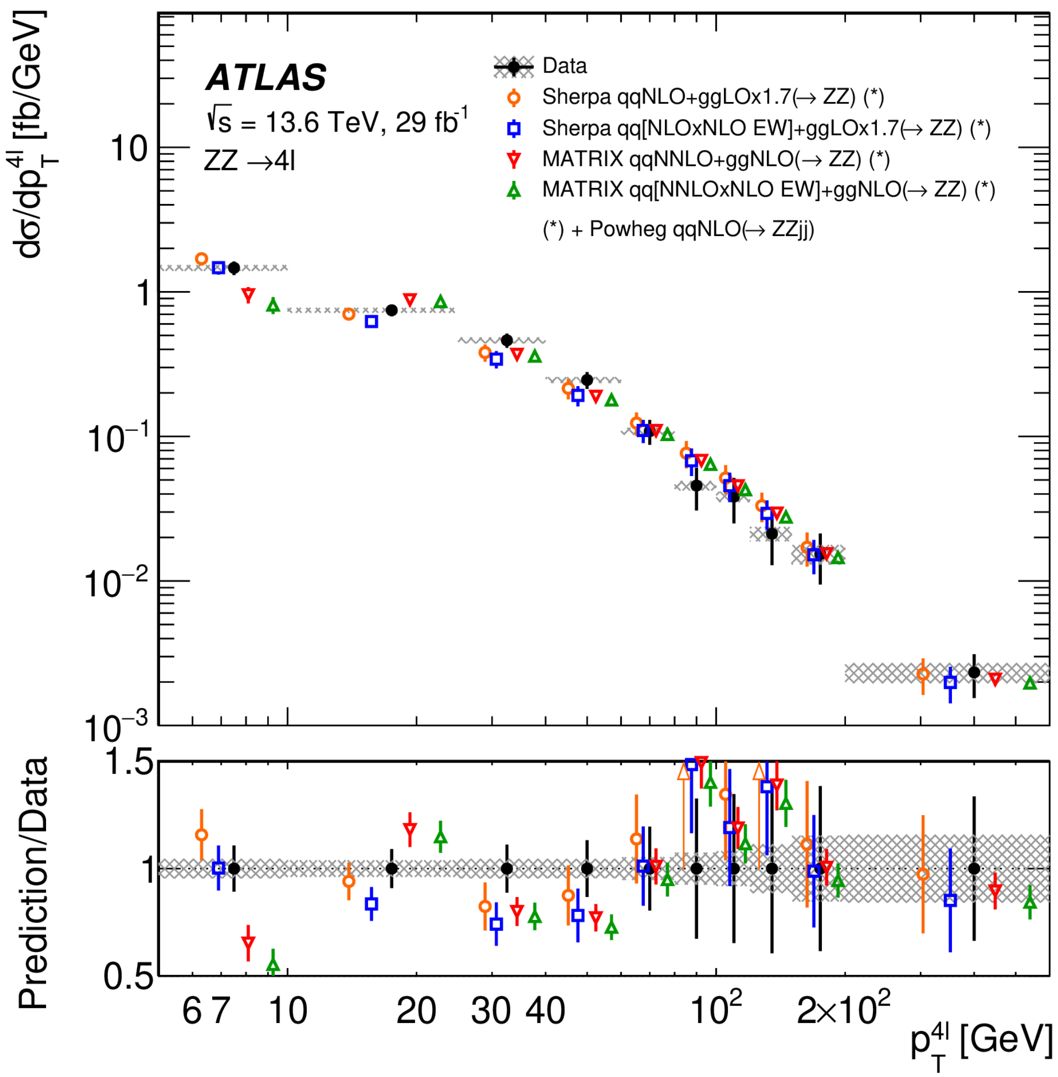


Di-boson production

- Extensive measurements of **di-boson** production
  - New inclusive and differential measurements on Run3 data

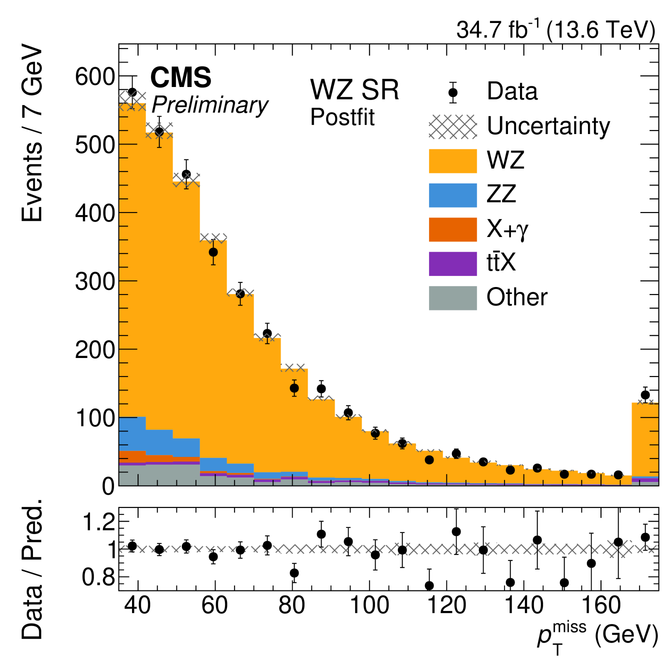
CMS SM Summary Plots

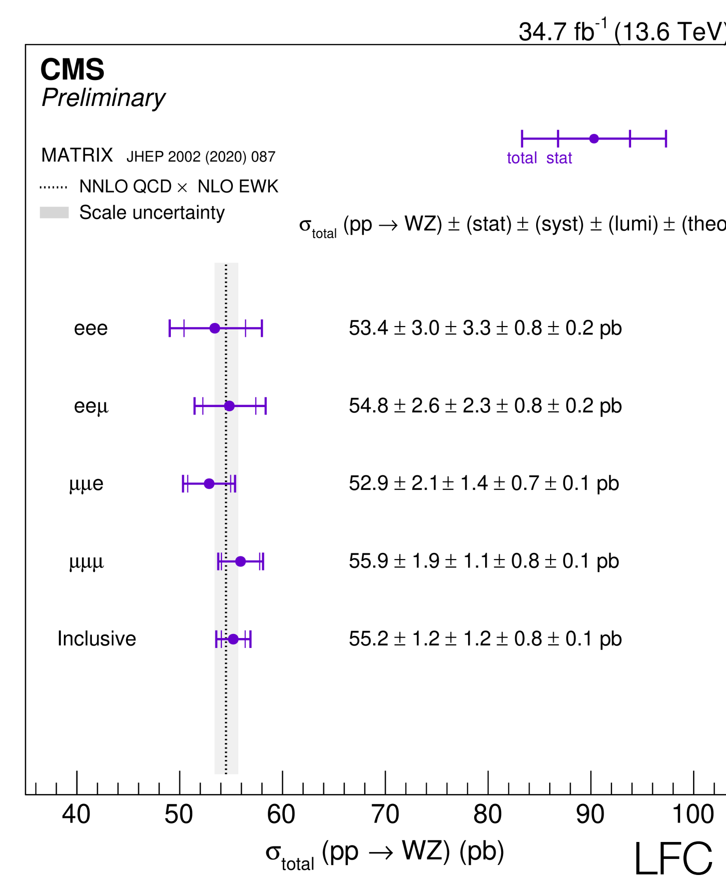




Differential ZZ at 13.6 TeV

PLB 855 (2024) 138764





Inclusive WZ at 13.6 TeV

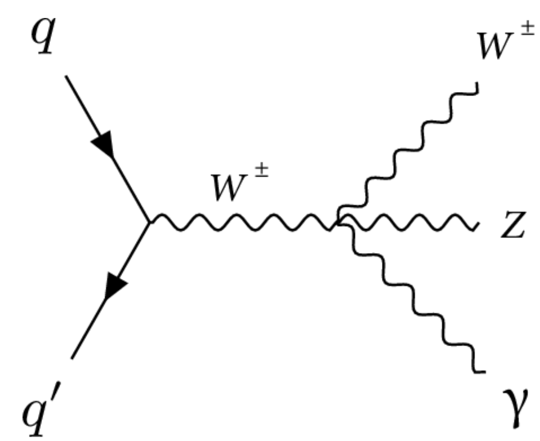
CMS-PAS-SMP-24-005

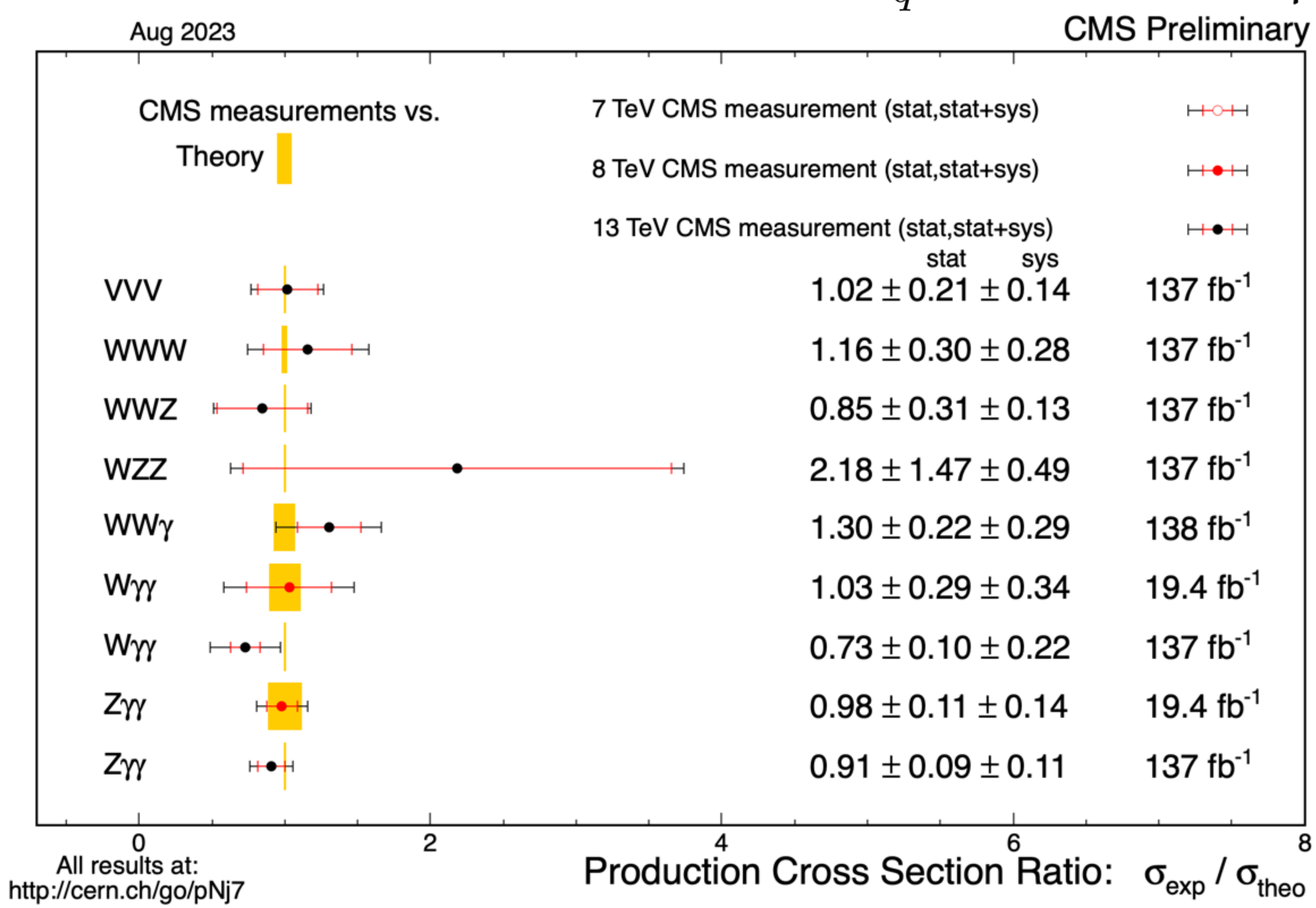
Tri-boson production

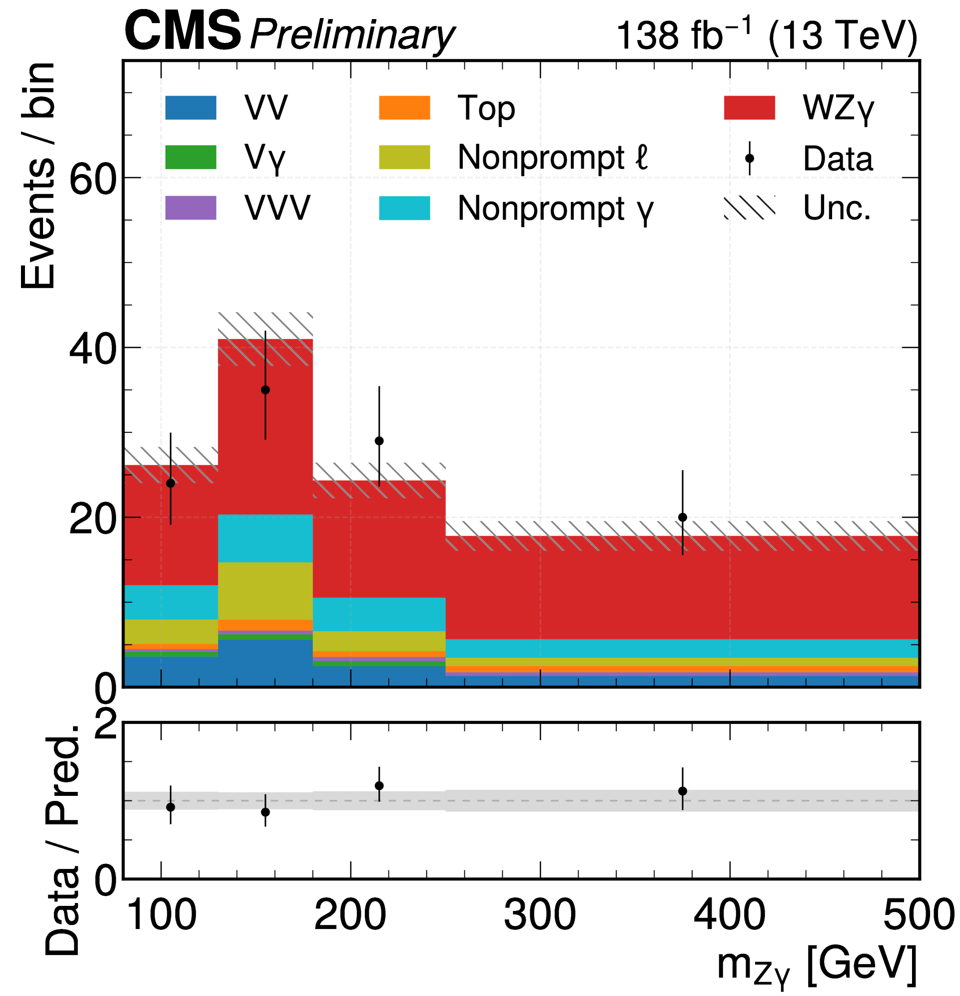
- **Tri-boson** productions very rare processes, some of them only now accessible at the LHC
- Give access to triple gauge couplings (TGCs) and quartic gauge couplings (**QGCs**)

WZγ observation

CMS-PAS-SMP-22-018







Process	SR
VV	13.0 ± 0.3
VVV	0.69 ± 0.05
Vγ	1.38 ± 0.76
Top	3.34 ± 0.55
Nonprompt ℓ	12.9 ± 2.8
Nonprompt γ	15.8 ± 2.2
WZG signal	60.8 ± 3.5
Total background	48.5 ± 3.7
Total prediction	109 ± 5
Observed	108

[ATLAS's WZγ PRL 132 (2024) 021802]

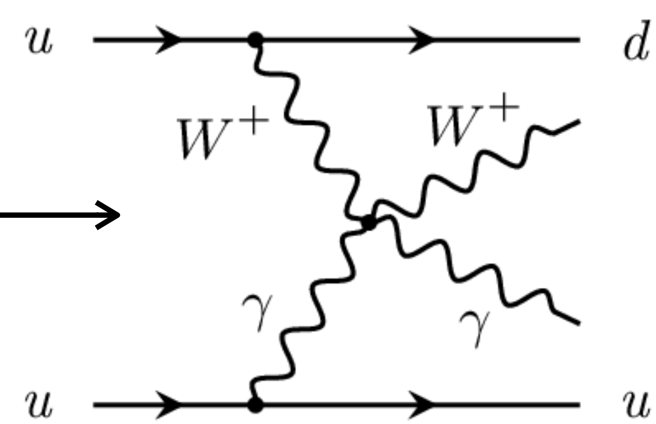
CMS SM Summary Plots

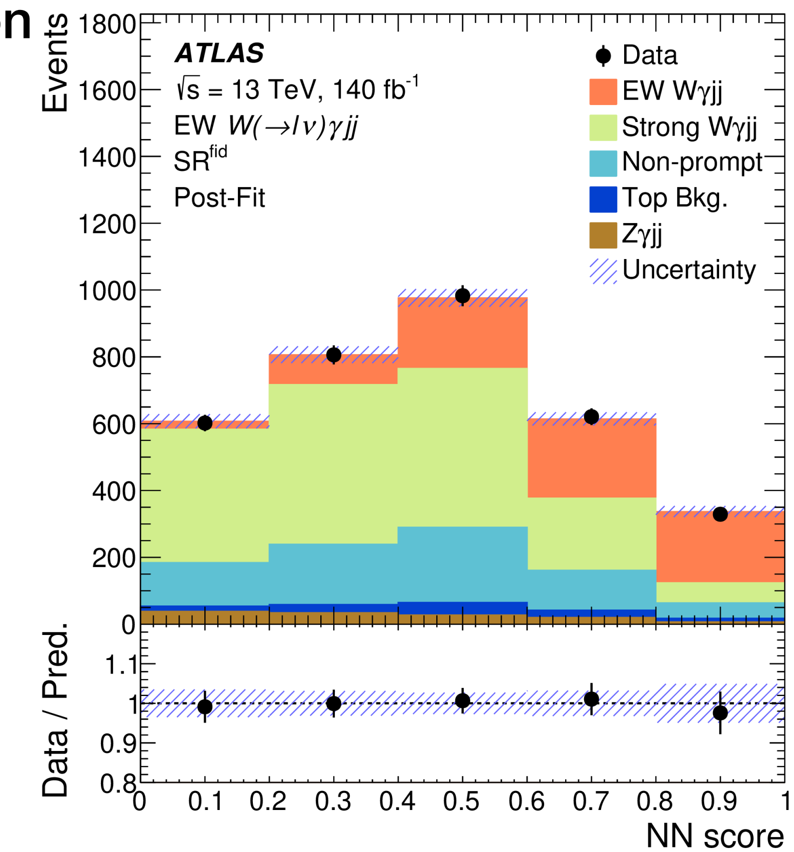
Vector Boson Scattering

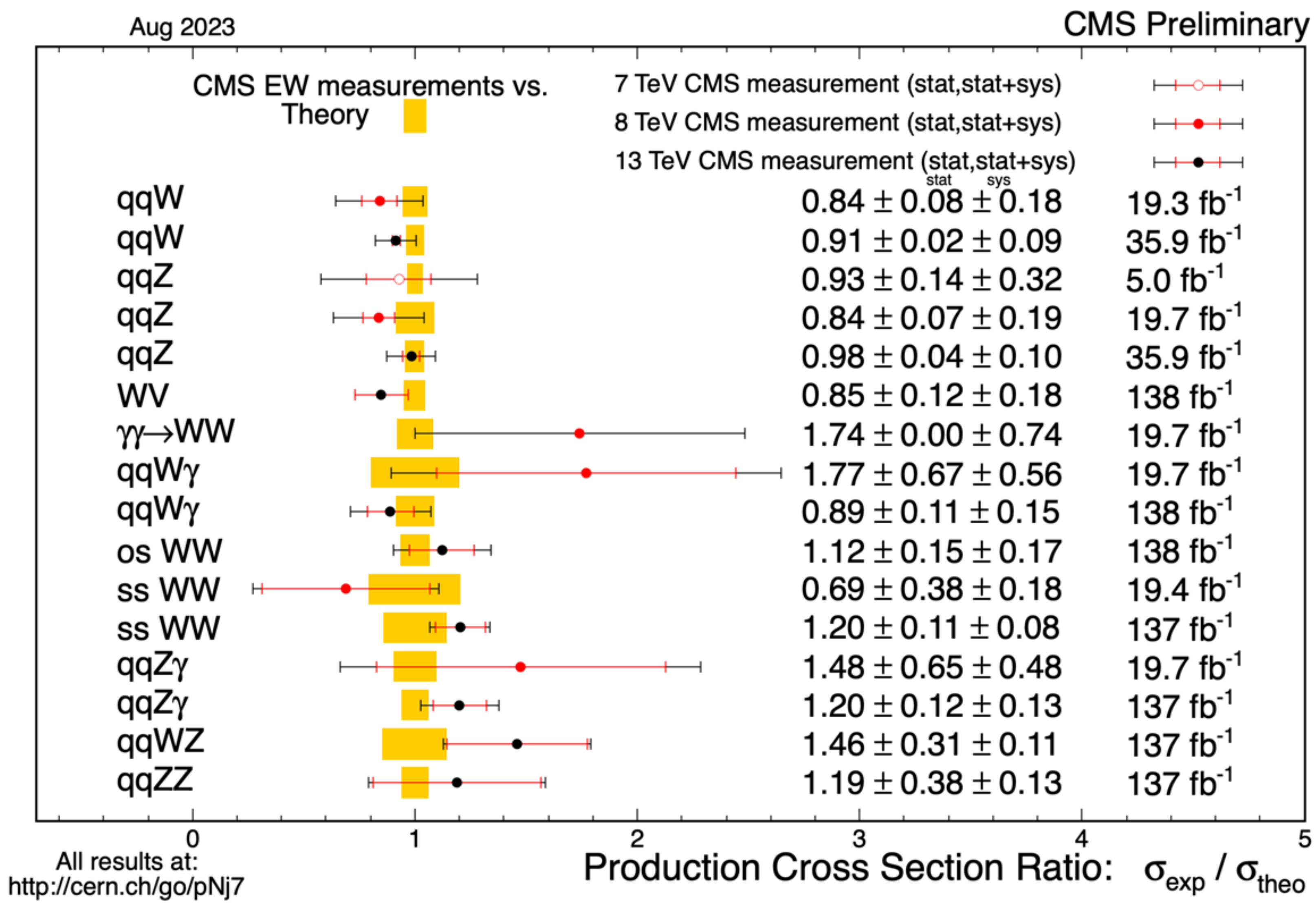
Wγjj observation and differential cross-section

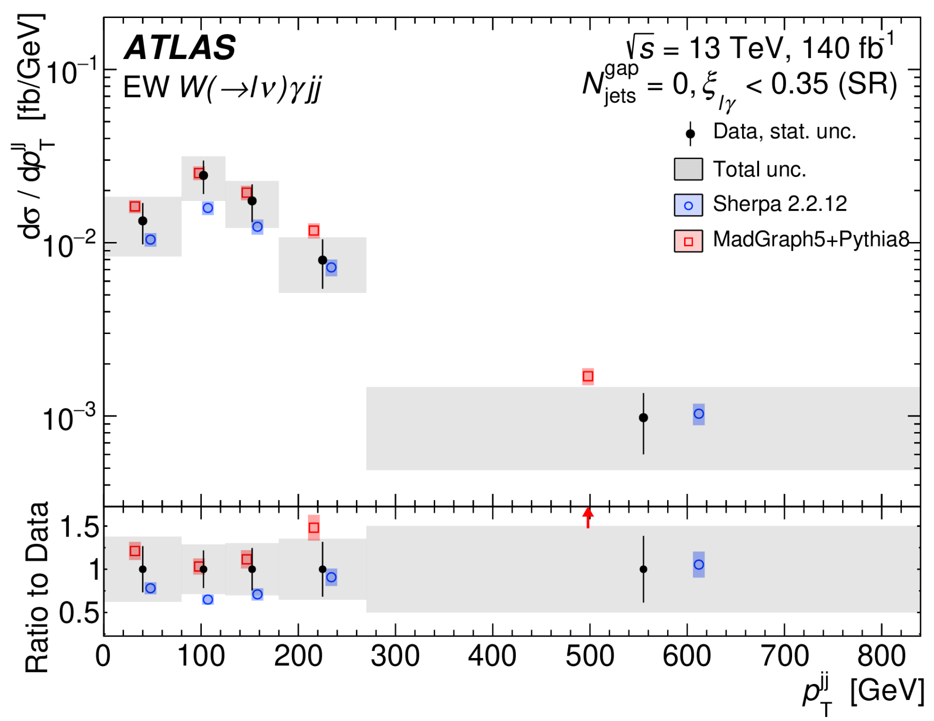
arxiv:2403.02809

- QGCs experimentally accessible also in **Vector Boson Scattering** ⟶









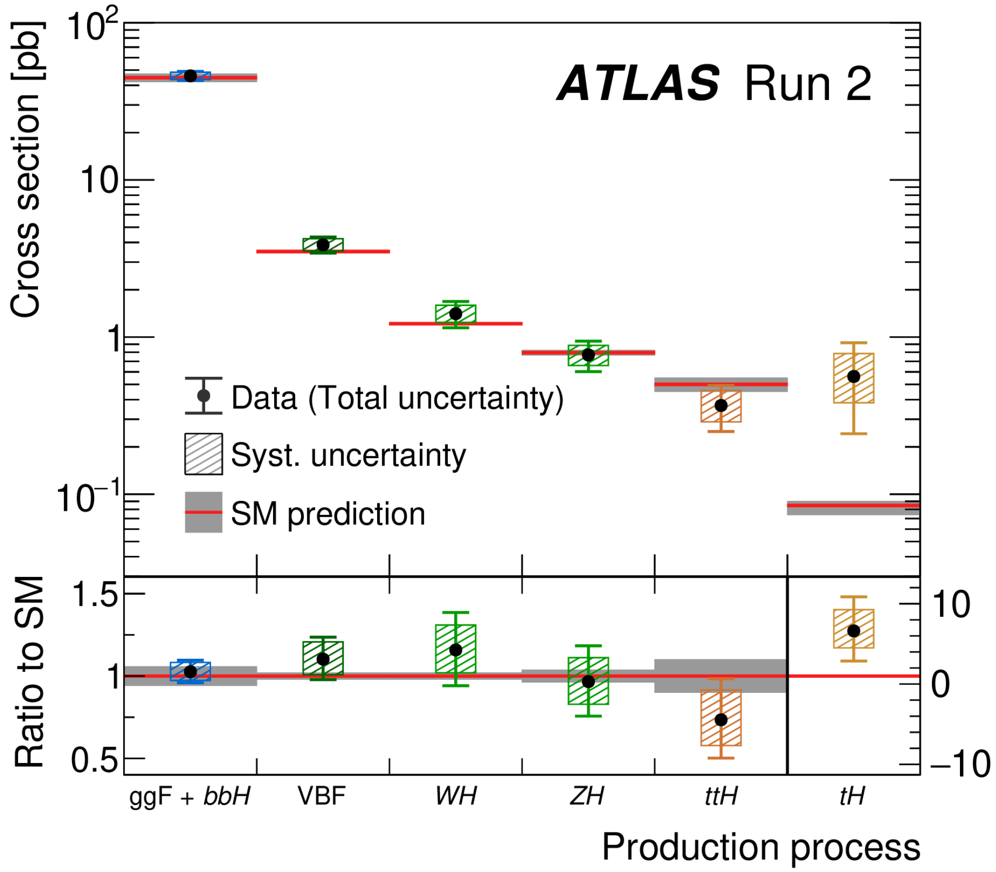
CMS SM Summary Plots

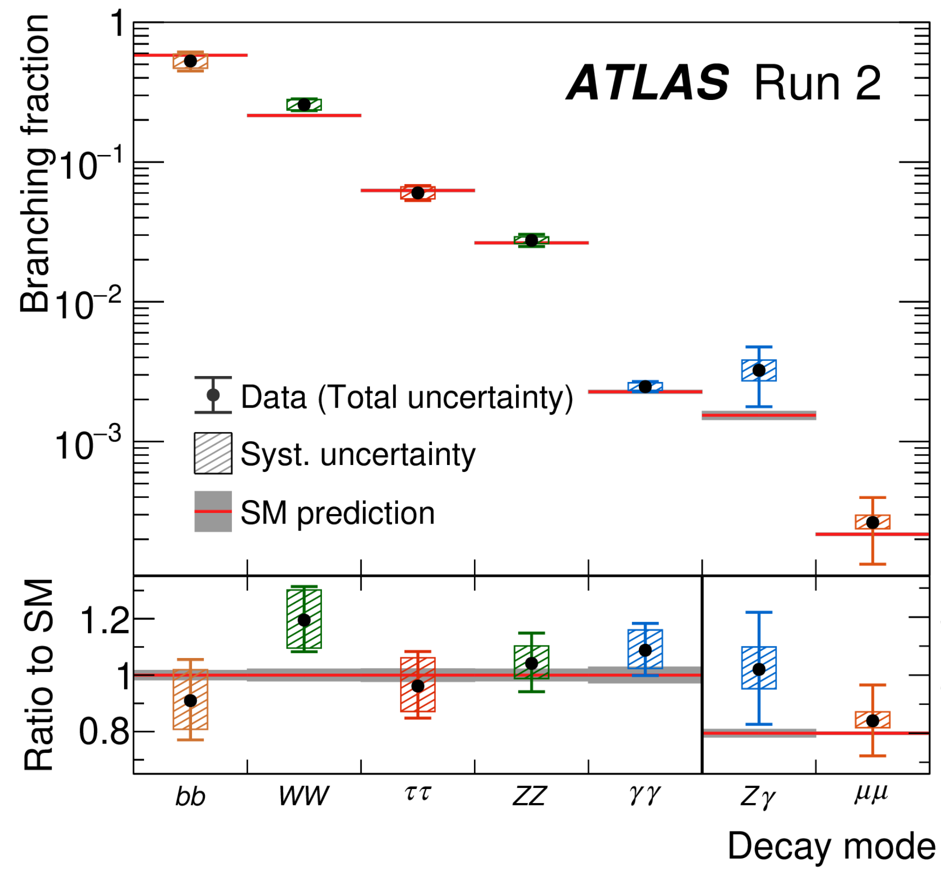
[CMS's Wγjj PRD 108 (2023) 032017]

Higgs boson physics

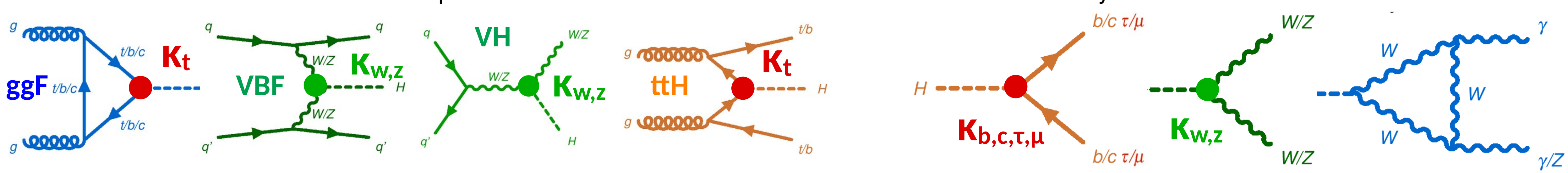
[More in P. Francavilla's talk tomorrow]

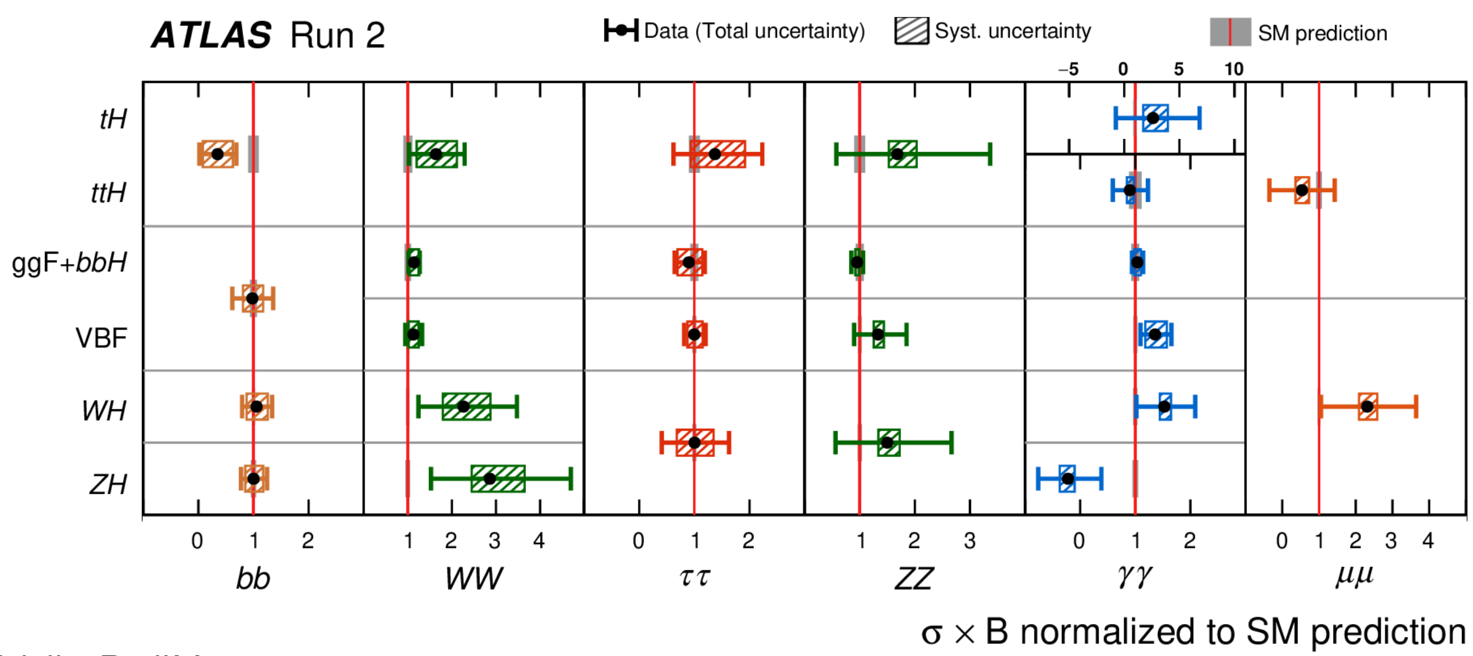
Higgs boson production and decay





[Nature 607 (2022) 52](#)
[Nature 607 (2022) 60](#)

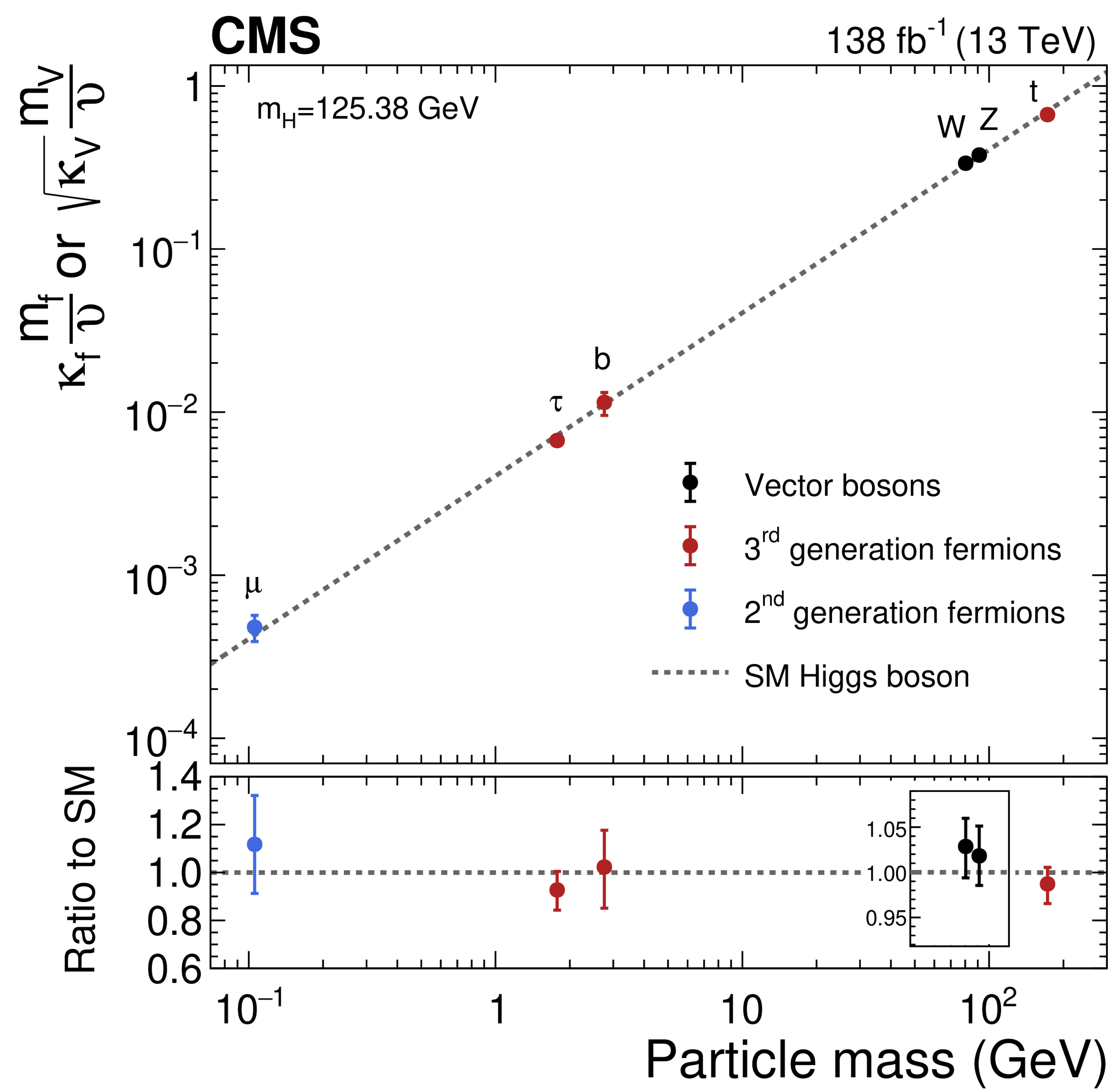


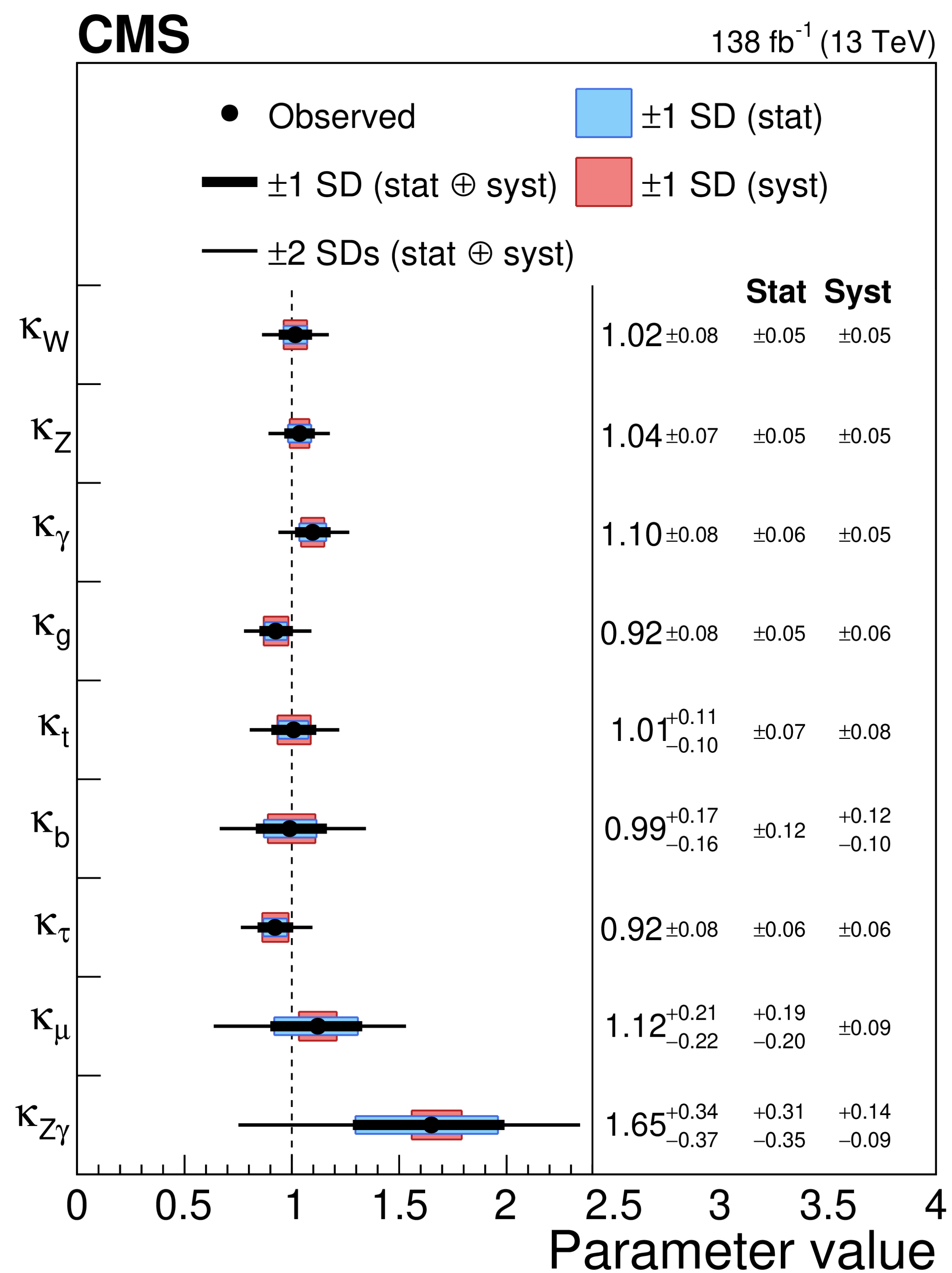


- Main production modes and decay modes assessed with Run2 data
  - Next in line: tH and H→cc
- Re-discovery with Run3 data

Higgs boson couplings

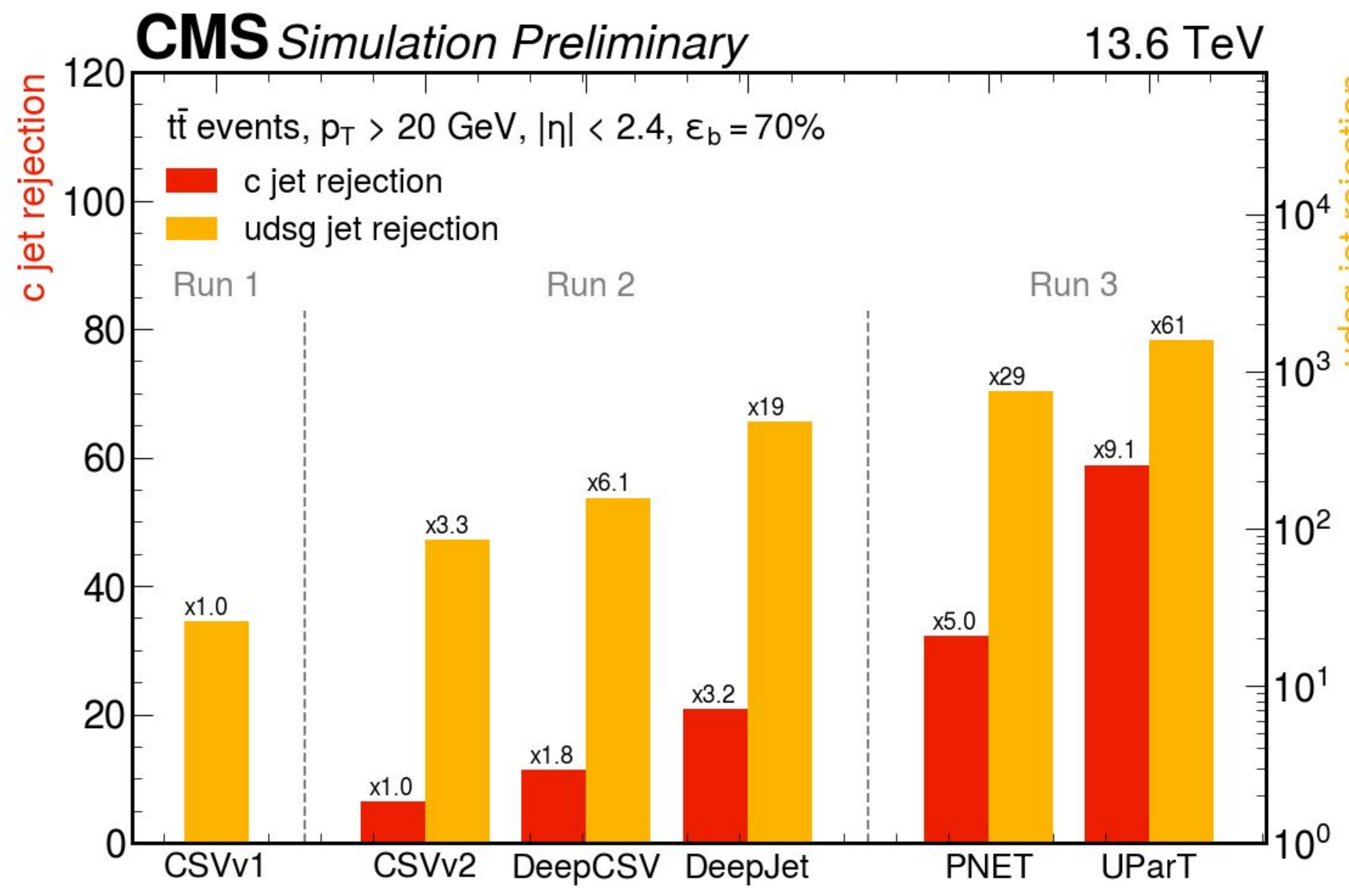
Nature 607 (2022) 52
Nature 607 (2022) 60



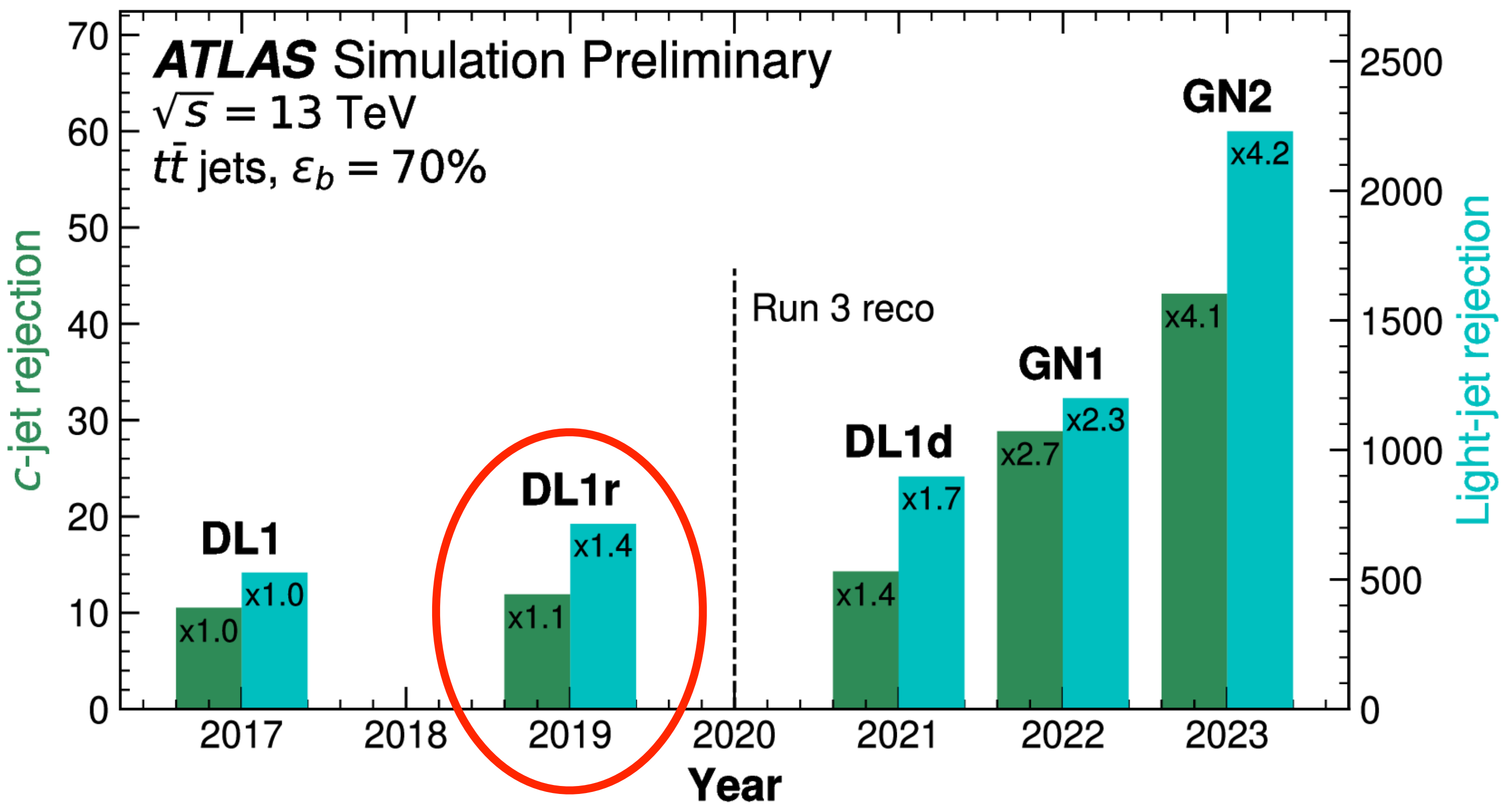


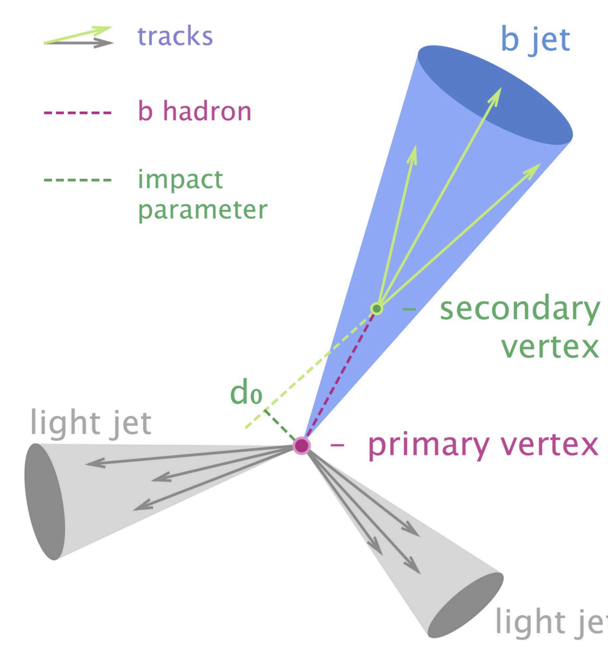
Using Machine Learning - Flavour tagging

- Machine learning techniques heavily used for flavour tagging
- Impressive development over the years, using more sophisticated architectures
- Latest developments not yet used in the analyses



[CMS-DP-2024-066](CMS-DP-2024-066)

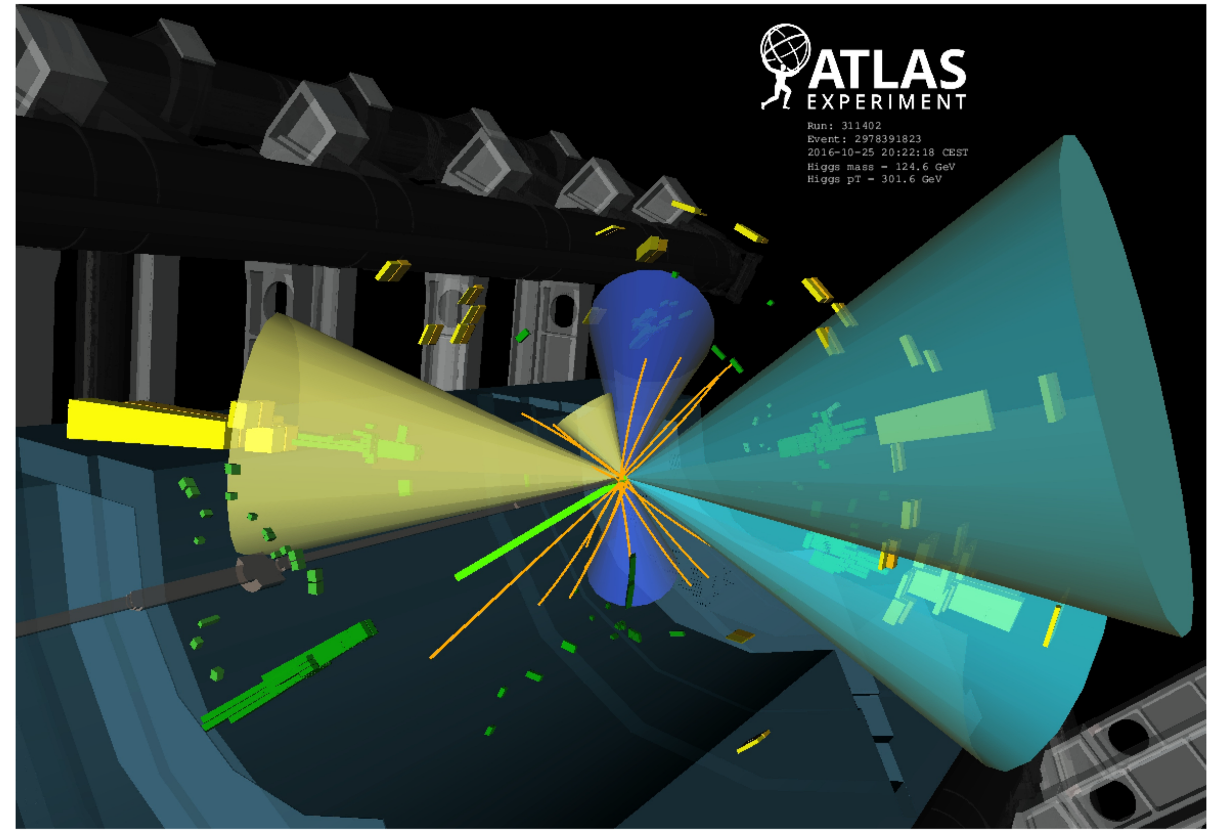


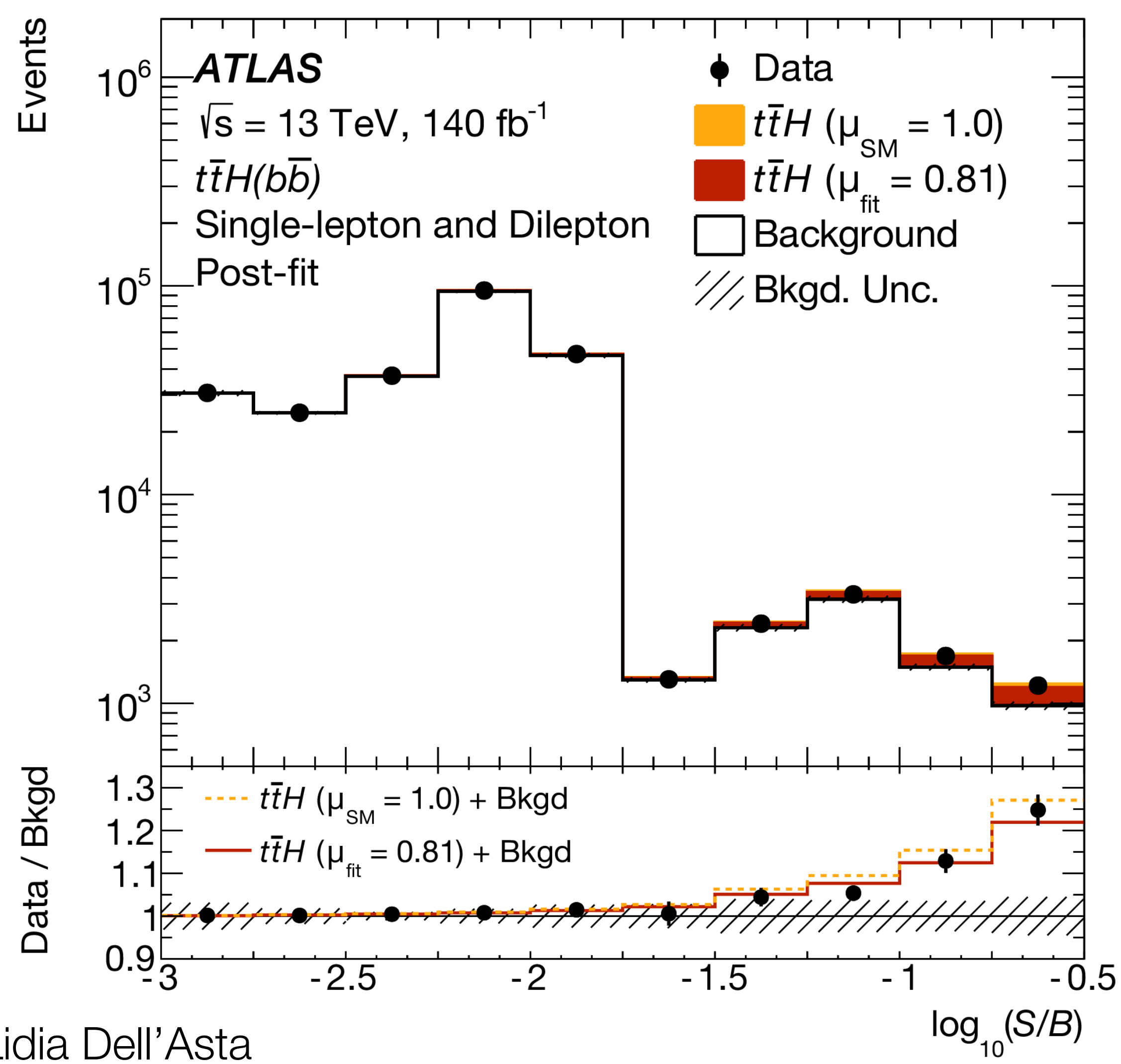


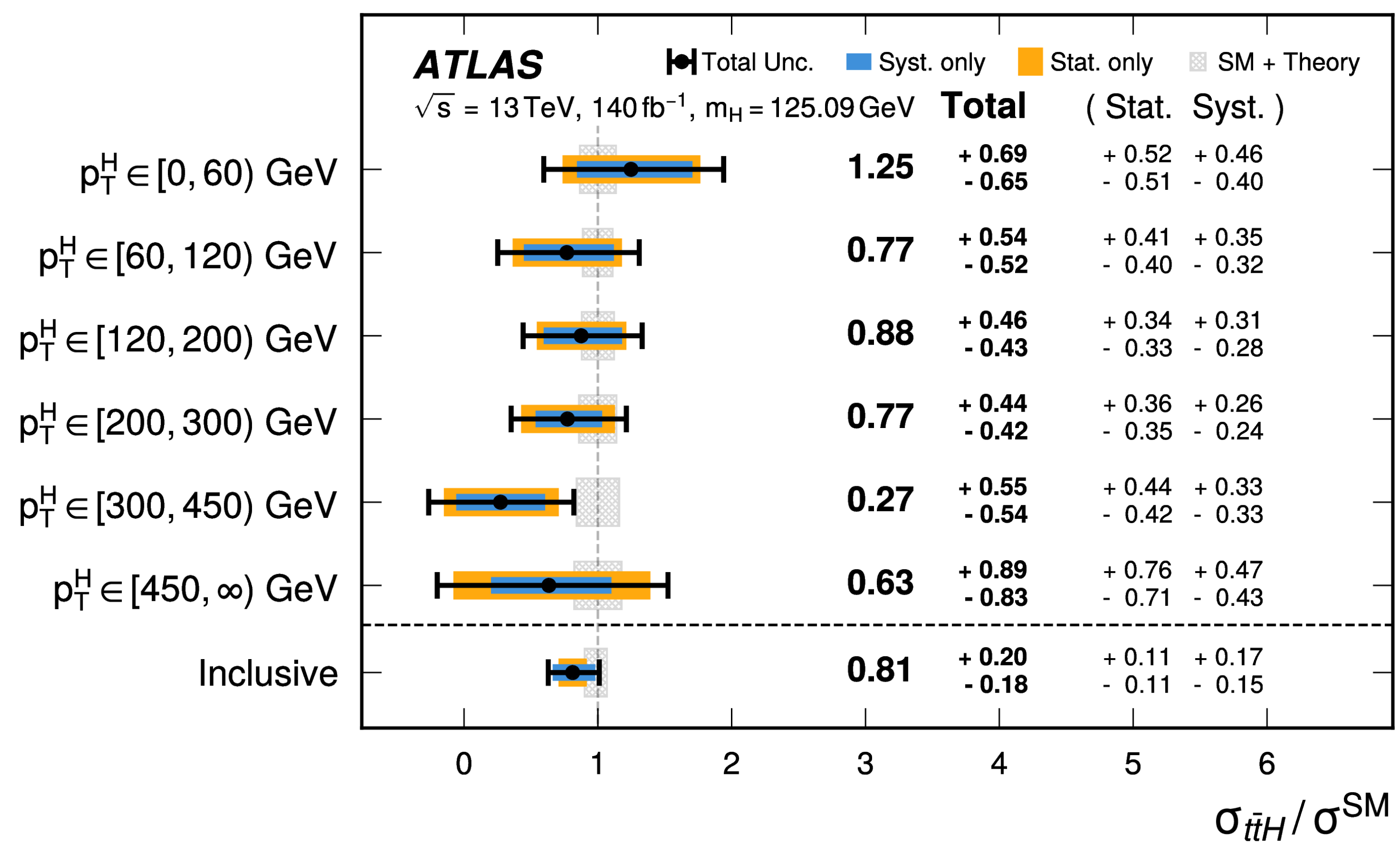
FTAG-2023-01

ttH(→bb)

- Re-analysis of ttH(→bb) analysis at 13 TeV [JHEP 06 (2022) 97] with
  - improved b-tagging (DL1r, see before)
  - state-of-the-art machine learning
  - improved modeling of backgrounds ($t\bar{t}$ + heavy flavour, see later)
- Overall uncertainty improved by factor of 1.8, 4.6σ observed significance (5.4σ expected)



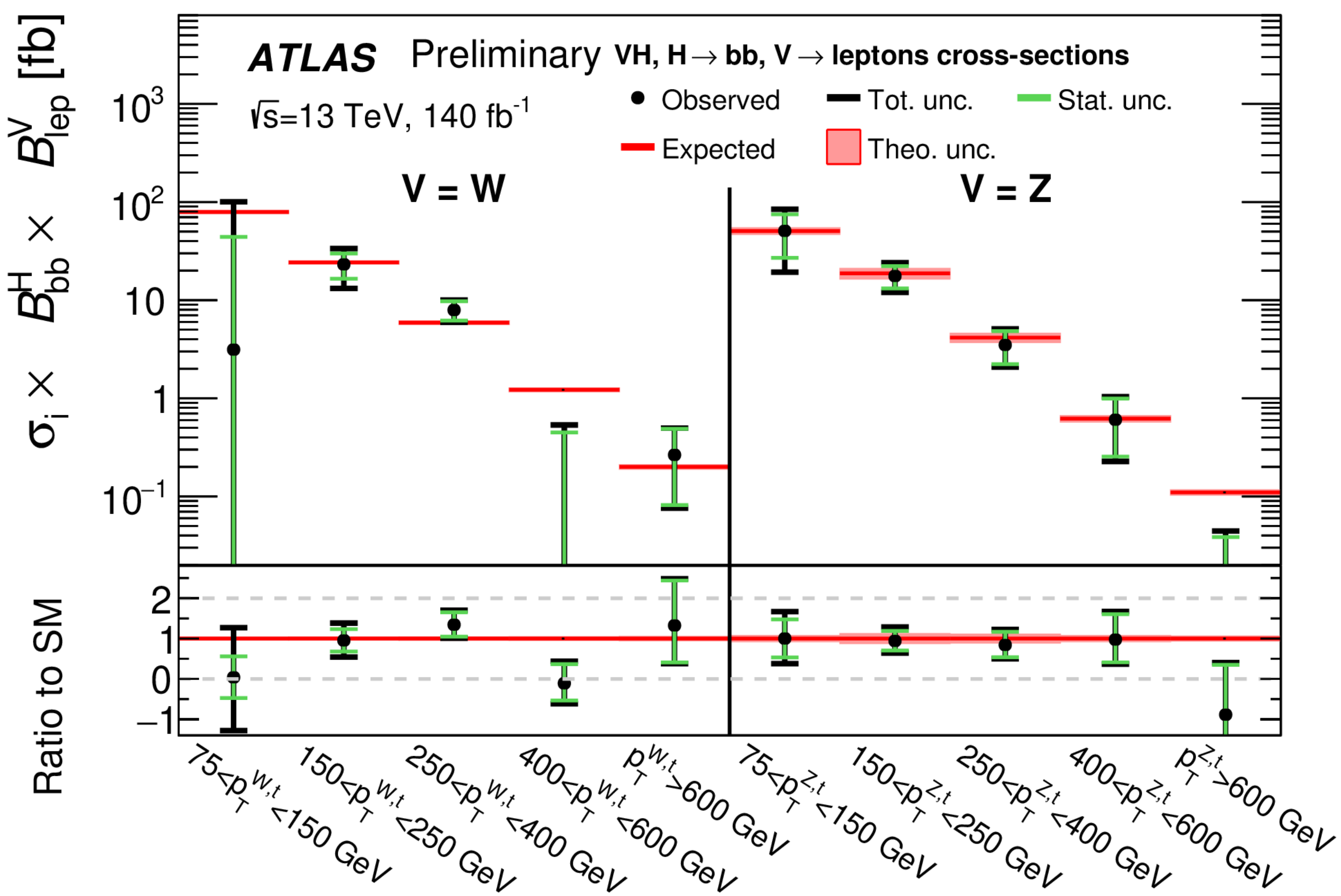


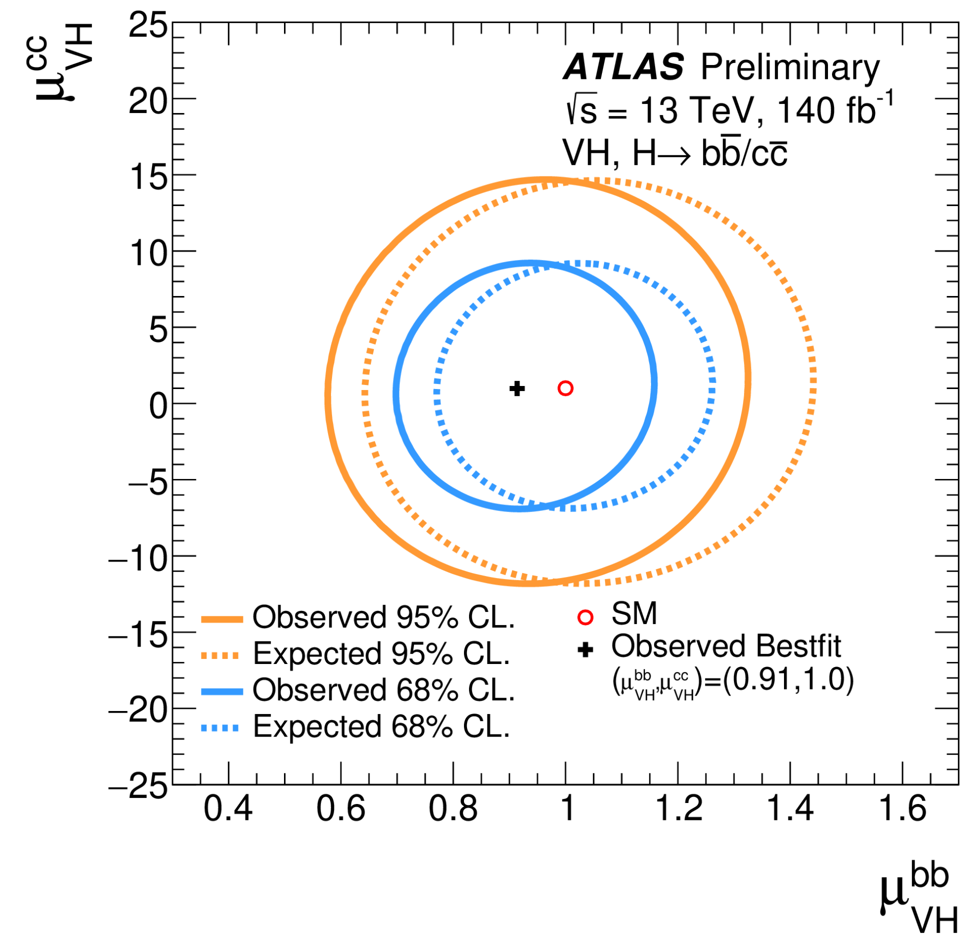


VH(→bb/cc)

- Re-analysis of previous VH(→bb/cc) analyses at 13 TeV
  - improved b-tagging (DL1r, see before)
  - introduced BDT discriminant for boosted events
- Observation of WH(→bb) with 5.3σ significance
  - Uncertainty on VH(→bb) improved by ~20%
- Best observed limit (11 x SM) on VH(→cc)

ATLAS-CONF-2024-010

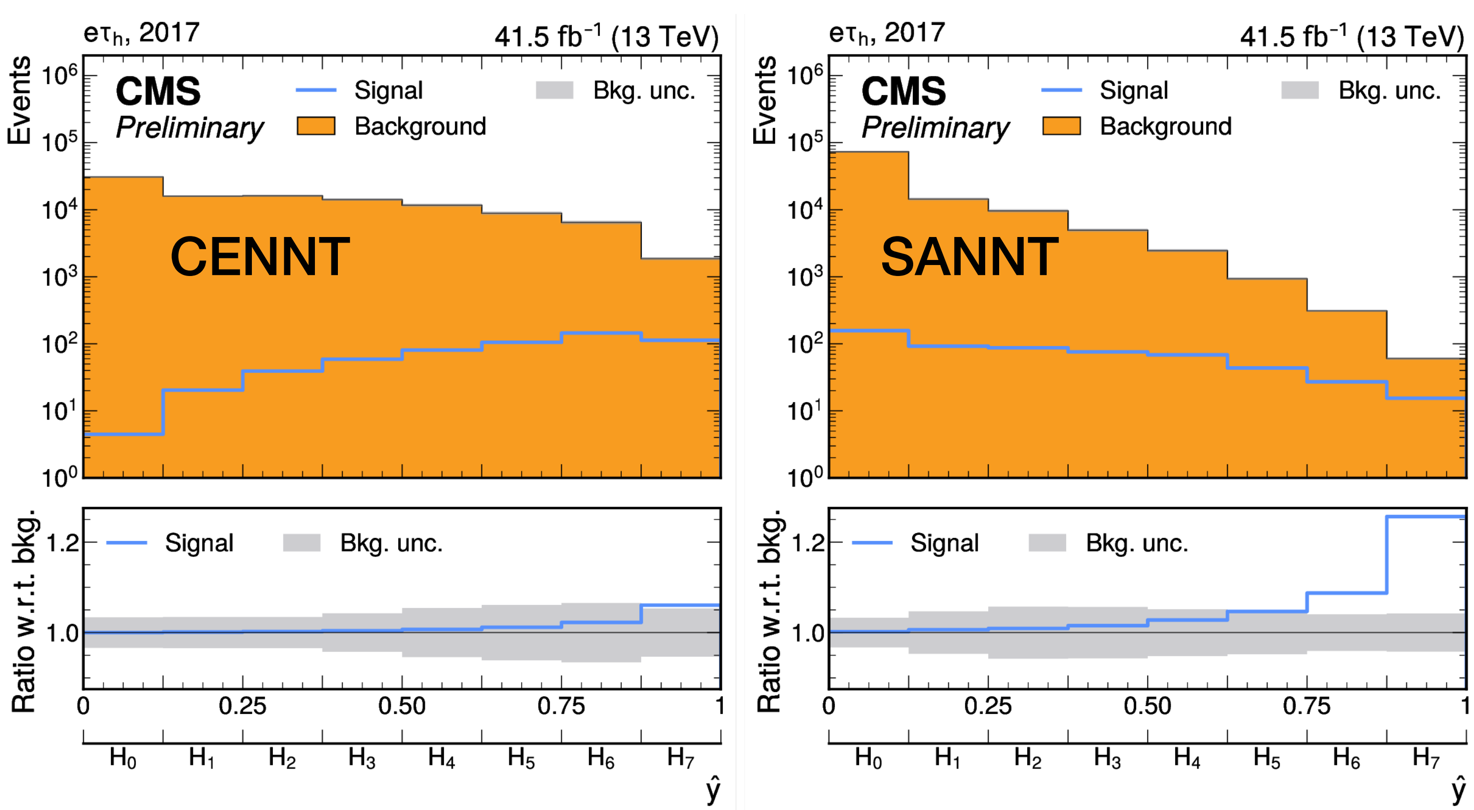


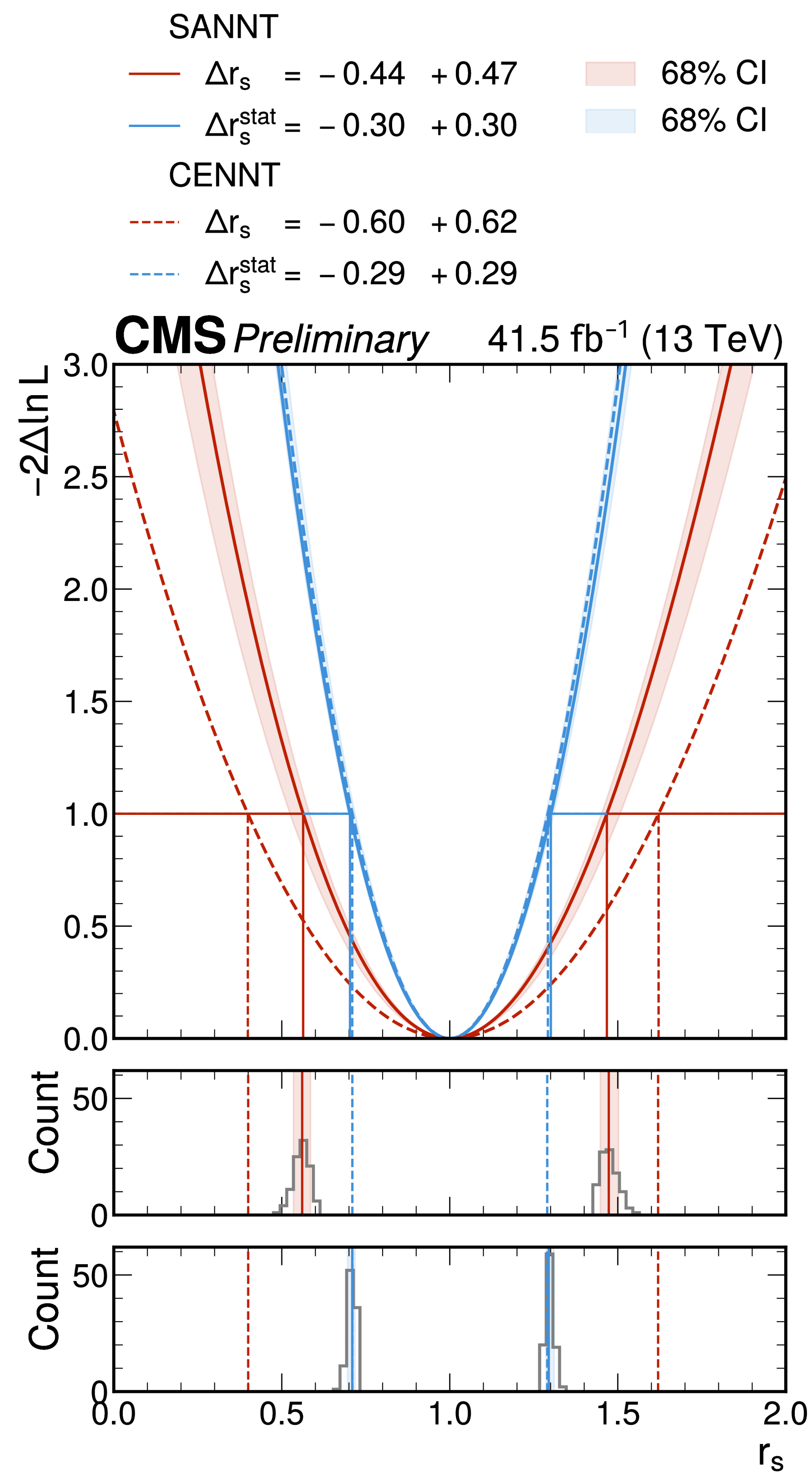


[CMS's VH(→cc) PRL 131 (2023) 061801]

Using ML - Dealing with systematics

- Standard classifier training (cross-entropy-based NN training, CENNT) optimizes for signal vs. background discrimination without considering systematics and other effects that affect the ultimate figure: uncertainty $\Delta(r_s)$ on a physics parameter
- New systematics aware NN training (SANNT) proof of principle (applied to $H \rightarrow \tau\tau$ in 2017), to directly optimize for min. $\Delta(r_s)$ in the neural network training
- CENNT optimizes for separation, while SANNT concentrates signal in bins with smaller background uncertainty
- Total systematic uncertainty improved by 25%

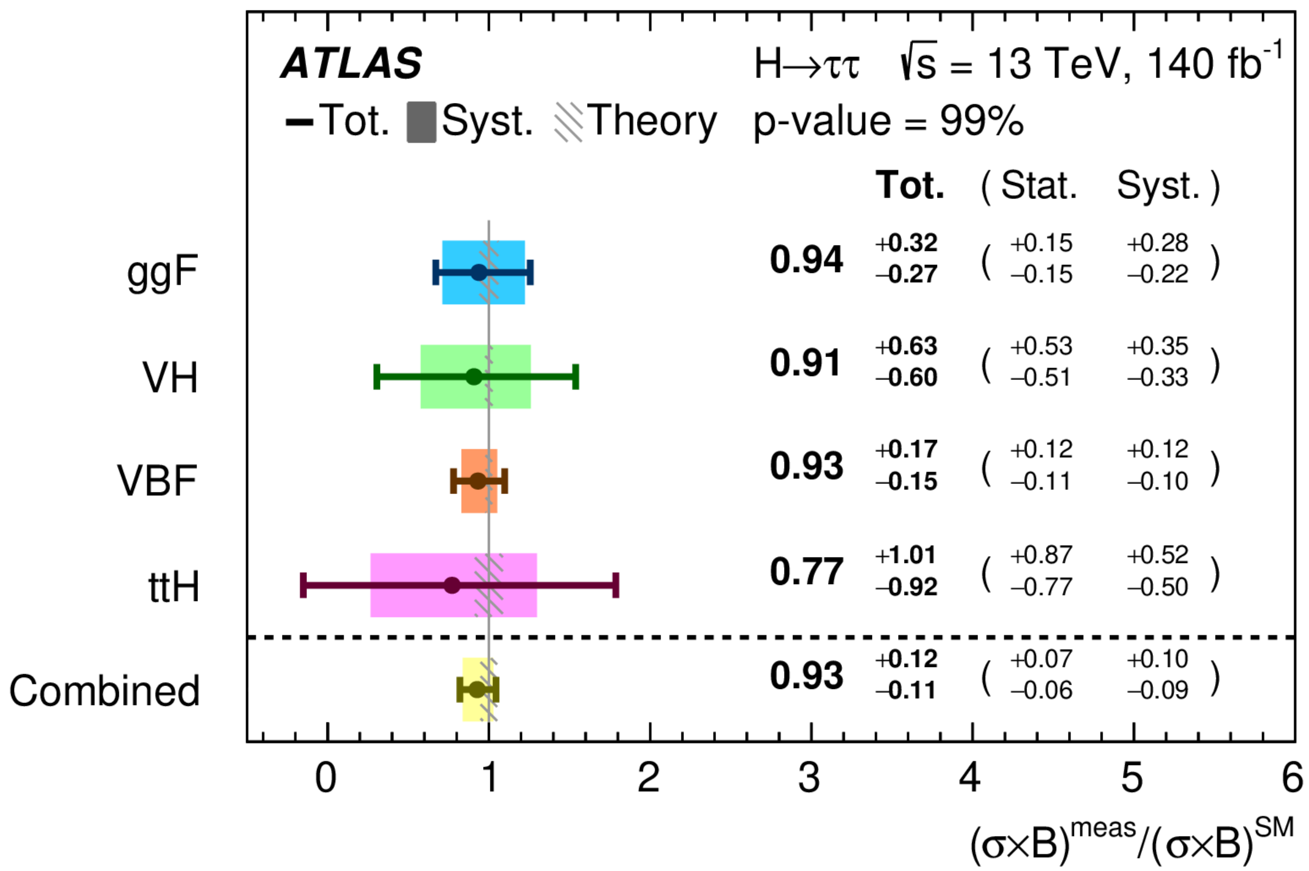




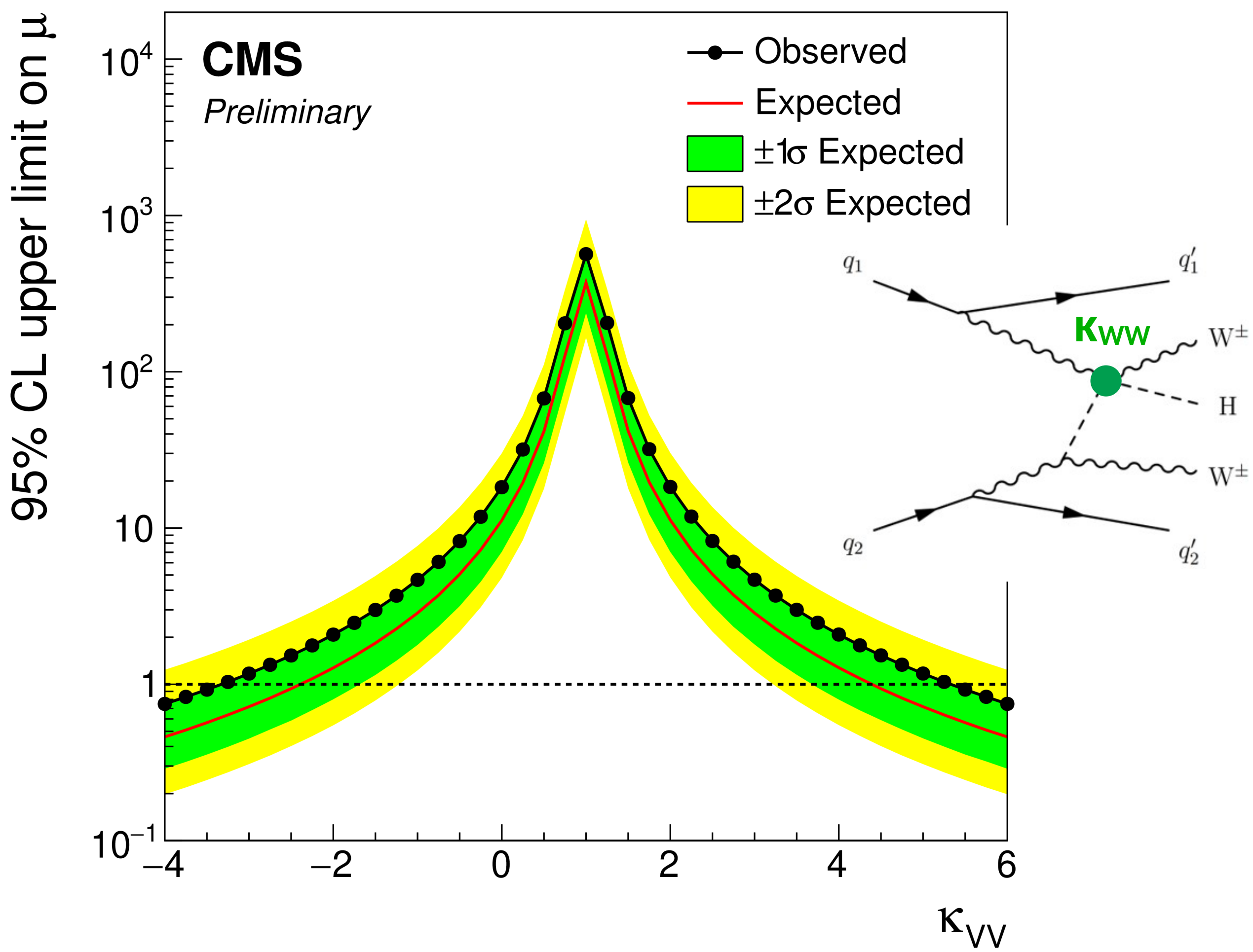
CMS-PAS-MLG-23-005

VBF H(→ττ) and VBS WWH(→bb)

- Re-analysis of H(→ττ) analysis at 13 TeV [JHEP 08 (2022) 175], improving VBF and ttH
  - Most precise single measurement of VBF

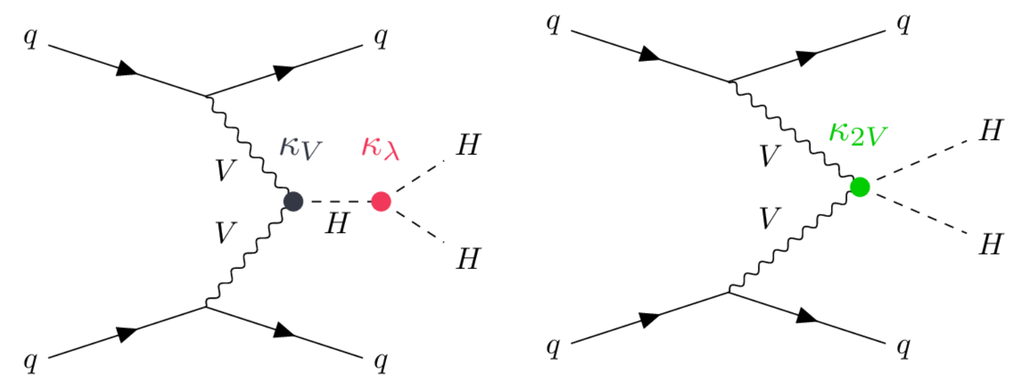


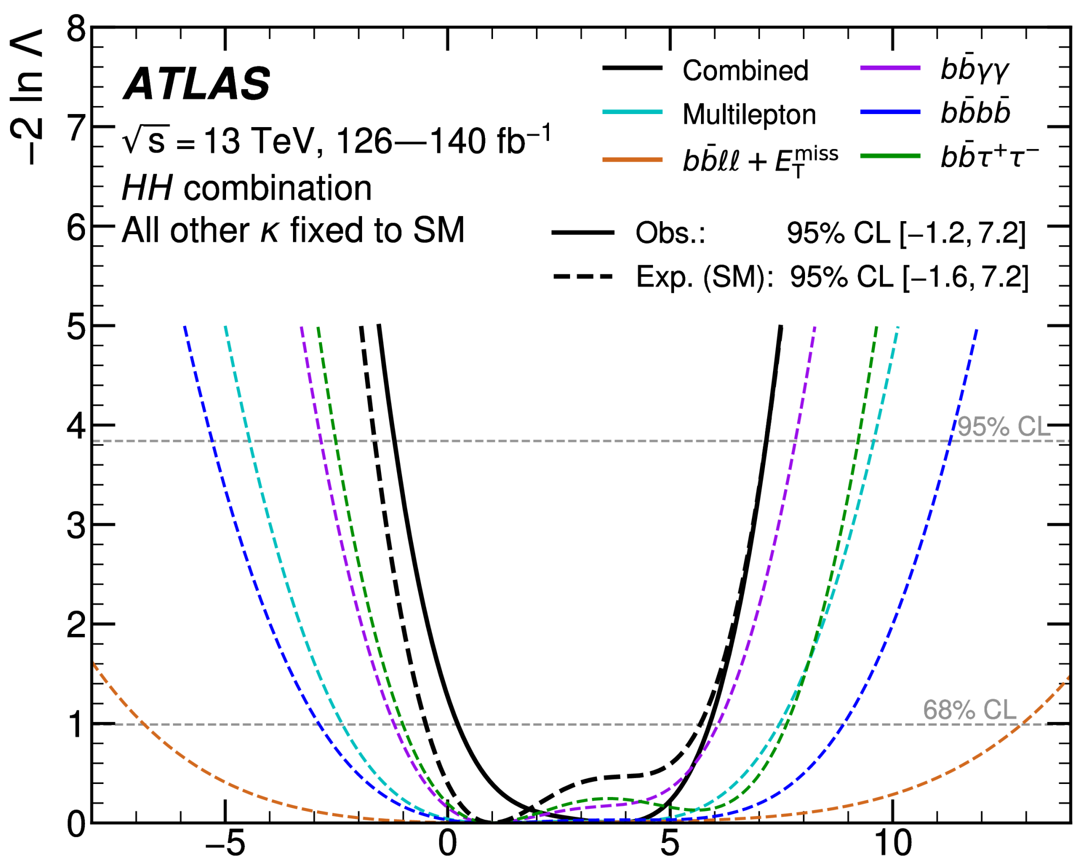
- Search for H(→bb) + WW(→lvlv) in Vector Boson Scattering
  - First analysis targeting κ_{VV} using single Higgs boson VBS production

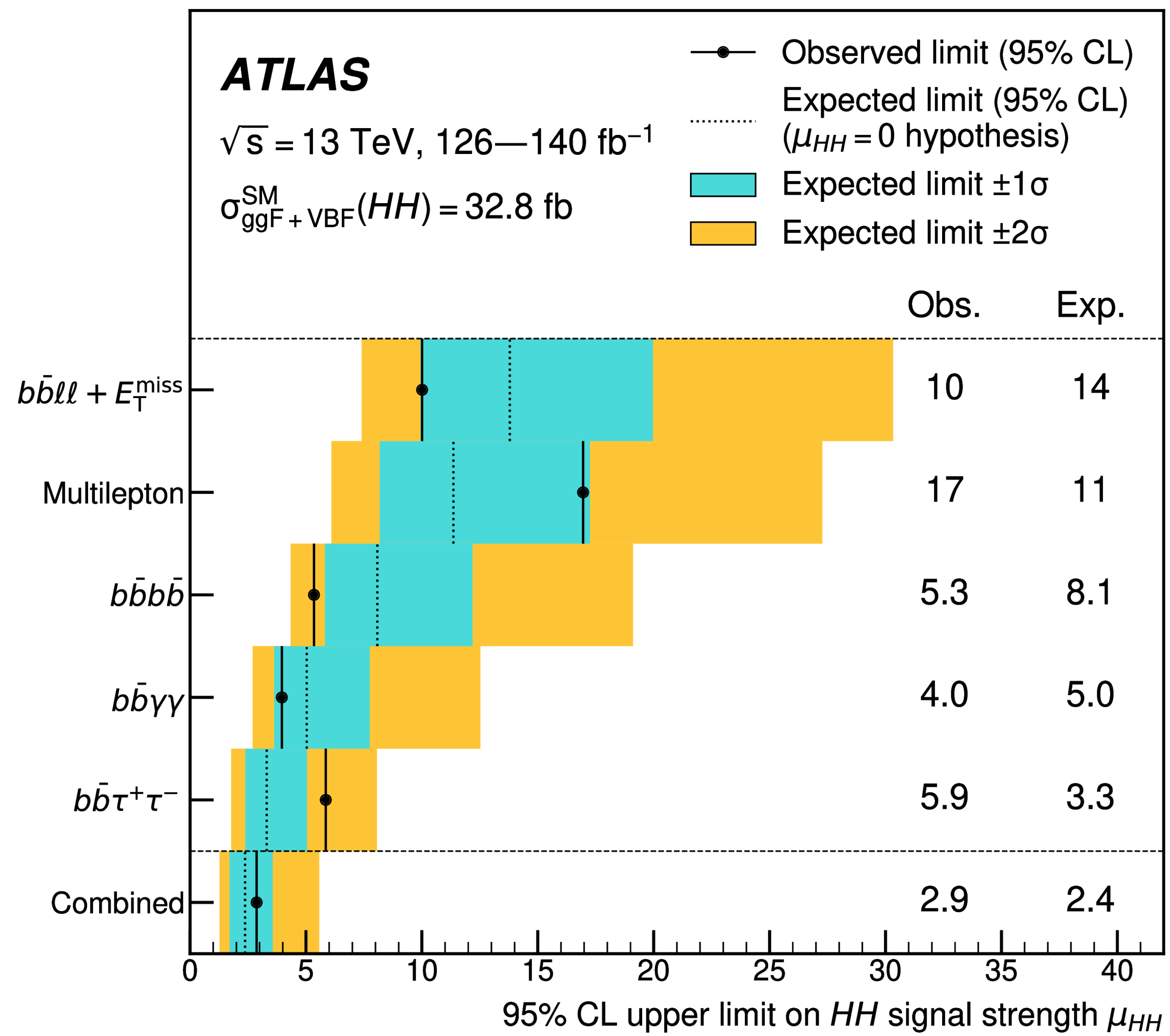


DiHiggs production

- Actively searching for diHiggs production
  - Access triple Higgs boson coupling, κ_λ
  - Also accesses other interactions, e.g. VVHH (κ_{VV})
- Exploring all possible final states
- New ATLAS combination of all searches
  - HH → bbττ + bbγγ + bbbb + multi-leptons + bbll+E_T^{miss}
- Uncertainty on μ_{HH} now ~1





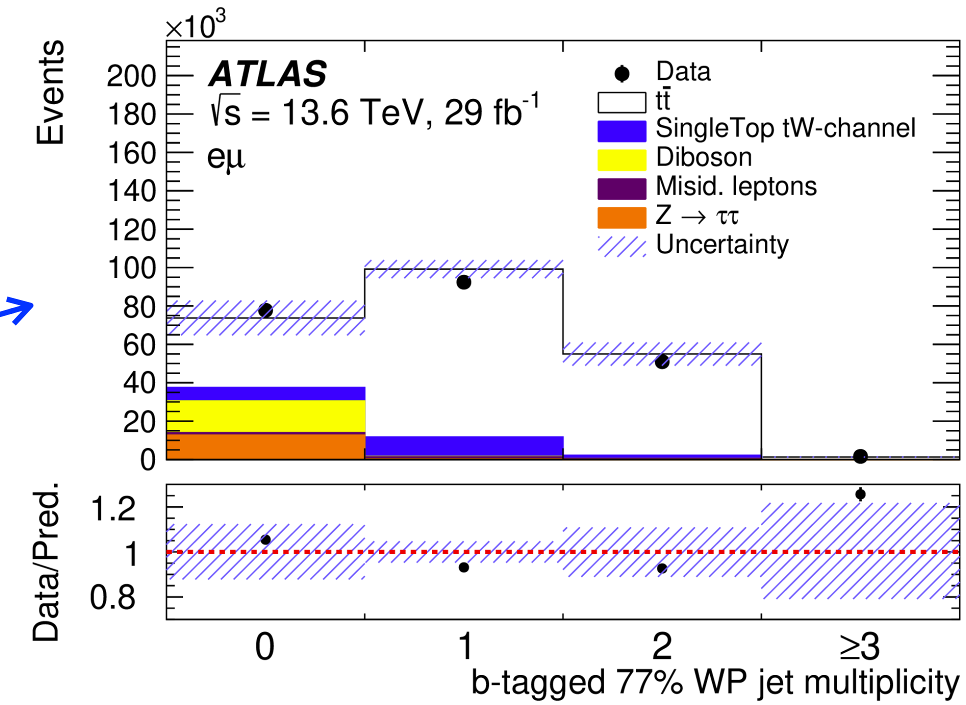


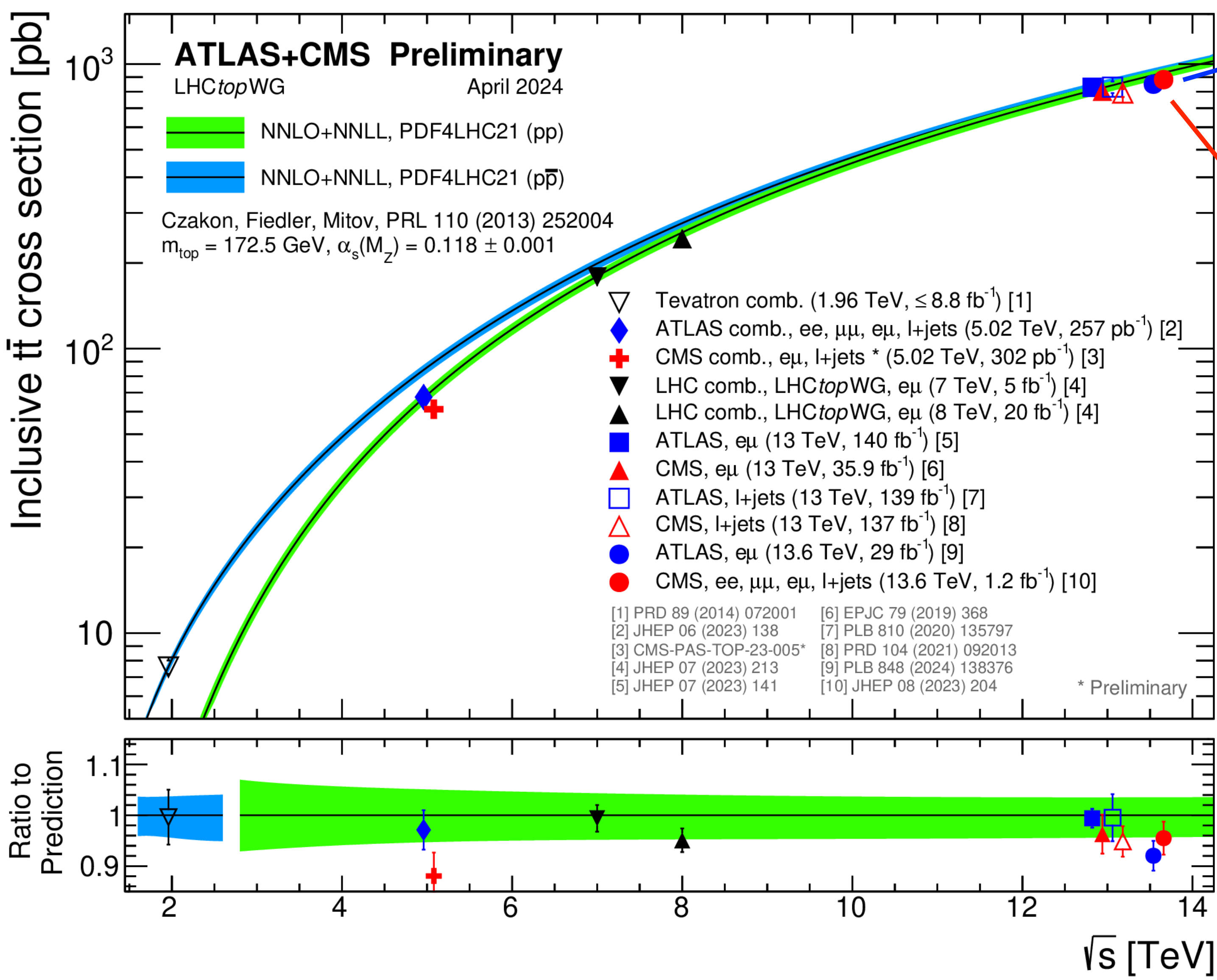
Top quark physics

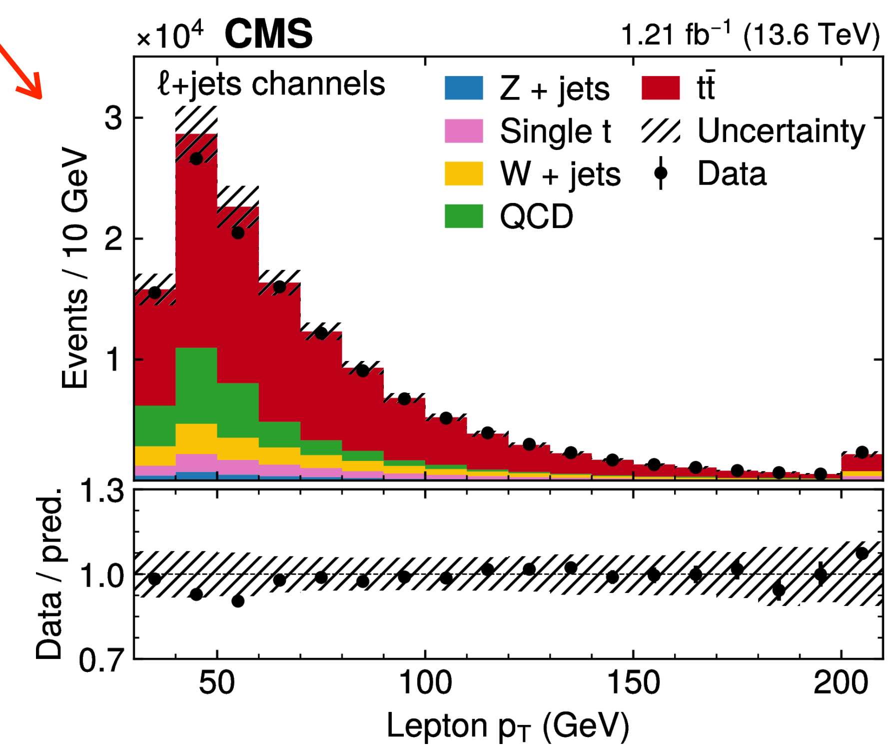
Top quark pair production

- **$t\bar{t}$ production** measured at all $\sqrt{s}$ in various final states, including fully hadronic
  - Run1 ATLAS and CMS measurements combined
  - New measurements on Run3 data, reaching ~3% uncertainty on inclusive cross-section

PLB 848 (2024) 138376





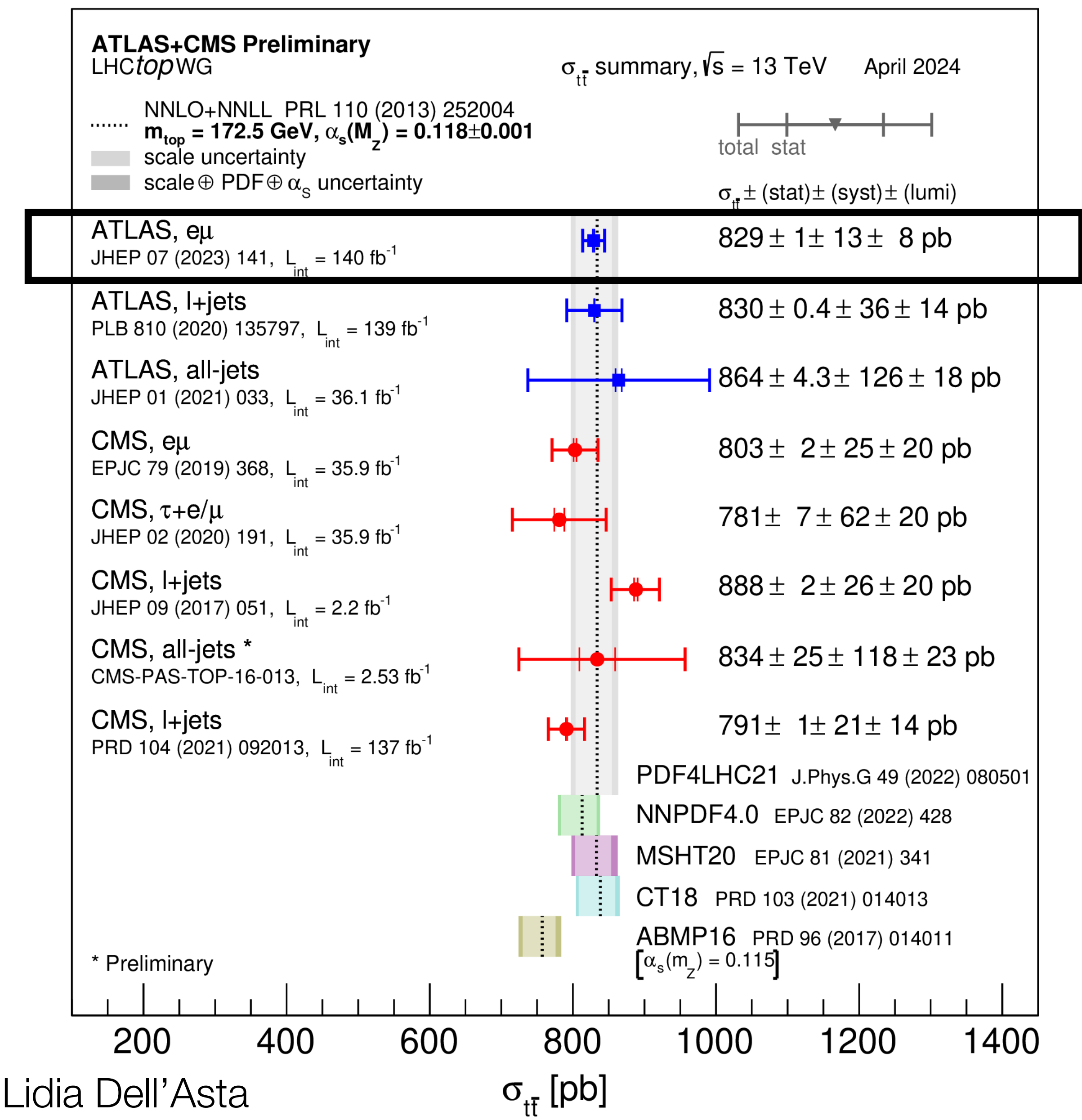


LHC Top WG Summary Plots

JHEP 08 (2023) 204

Top quark pair production

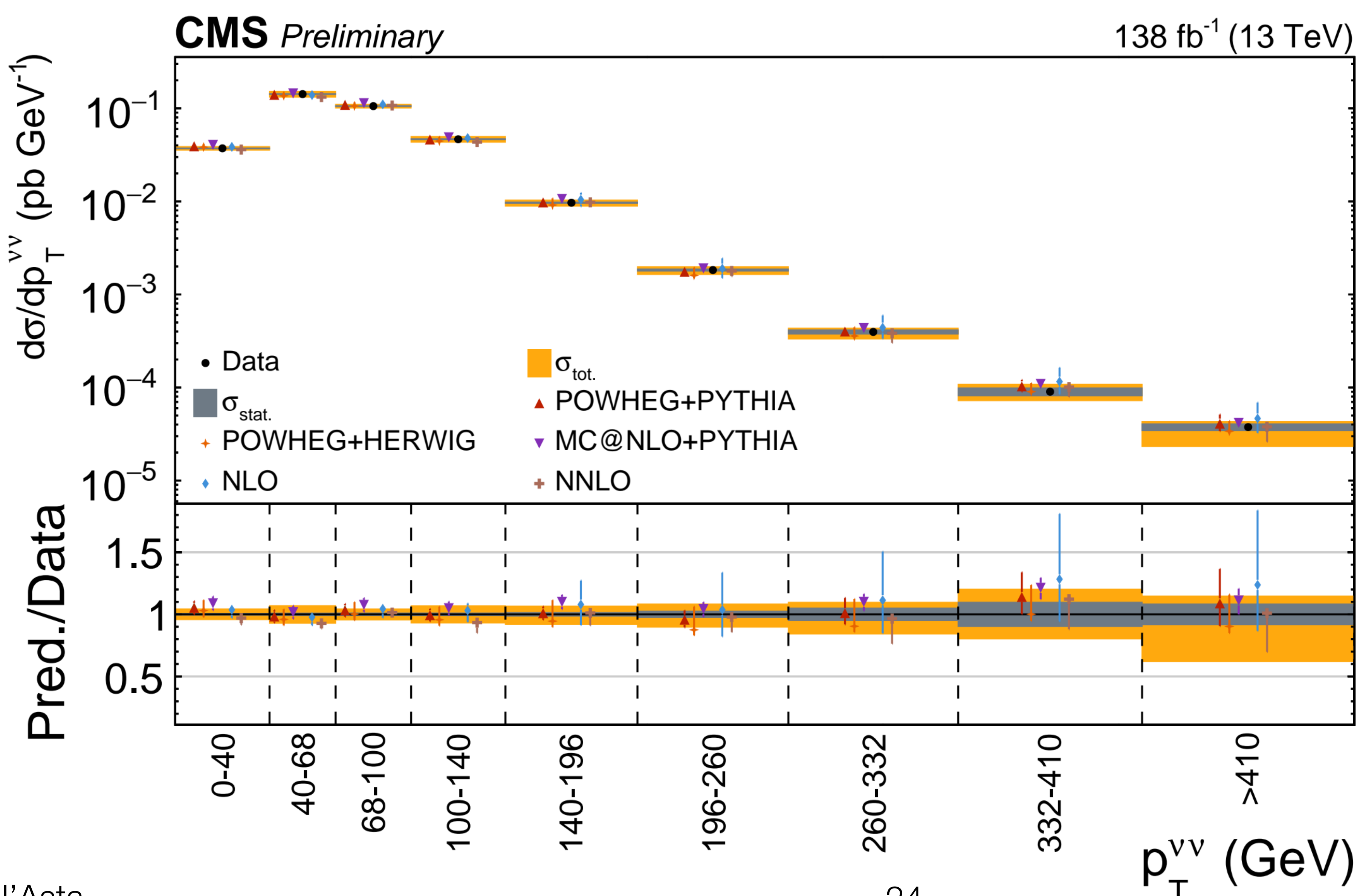
- **Inclusive** $t\bar{t}$ cross-section measurements with experimental uncertainties comparable to theoretical ones
  - ATLAS, Run2, in the eμ channel reaching 1.8% uncertainty: luminosity is the main single source of uncertainty

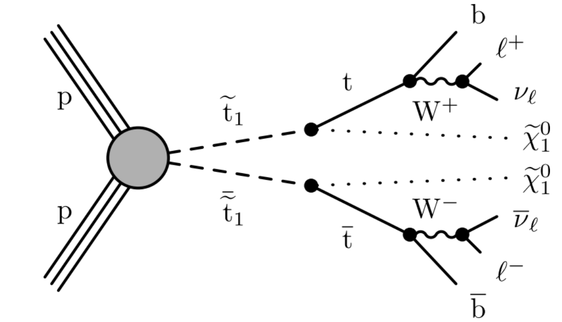


Source of uncertainty	$\Delta\sigma^{\text{fid}}_{t\bar{t}}/\sigma^{\text{fid}}_{t\bar{t}}$ [%]	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ [%]
Data statistics	0.15	0.15
MC statistics	0.04	0.04
Matrix element	0.12	0.16
h_{damp} variation	0.01	0.01
Parton shower	0.08	0.22
$t\bar{t}$ + heavy flavour	0.34	0.34
Top p_{T} reweighting	0.19	0.58
Parton distribution functions	0.04	0.43
Initial-state radiation	0.11	0.37
Final-state radiation	0.29	0.35
Electron energy scale	0.10	0.10
Electron efficiency	0.37	0.37
Electron isolation (in situ)	0.51	0.51
Muon momentum scale	0.13	0.13
Muon reconstruction efficiency	0.35	0.35
Muon isolation (in situ)	0.33	0.33
Lepton trigger efficiency	0.05	0.05
Vertex association efficiency	0.03	0.03
Jet energy scale & resolution	0.10	0.10
b-tagging efficiency	0.07	0.07
$t\bar{t}/Wt$ interference	0.37	0.37
Wt cross-section	0.52	0.52
Diboson background	0.34	0.34
$t\bar{t}V$ and $t\bar{t}H$	0.03	0.03
Z+jets background	0.05	0.05
Misidentified leptons	0.32	0.32
Beam energy	0.23	0.23
Luminosity	0.93	0.93
Total uncertainty	1.6	1.8

Top quark pair production

- **Differential** and double-differential $t\bar{t}$ cross-section measurements as a function of several lepton kinematic variables
  - CMS, Run2, now looking also at the invisible part of the event: differential measurement w.r.t. νν system kinematics in eμ final state
    - DNN to improve E_T^{miss} measurement
    - New mean of distinguishing SM vs BSM scenarios





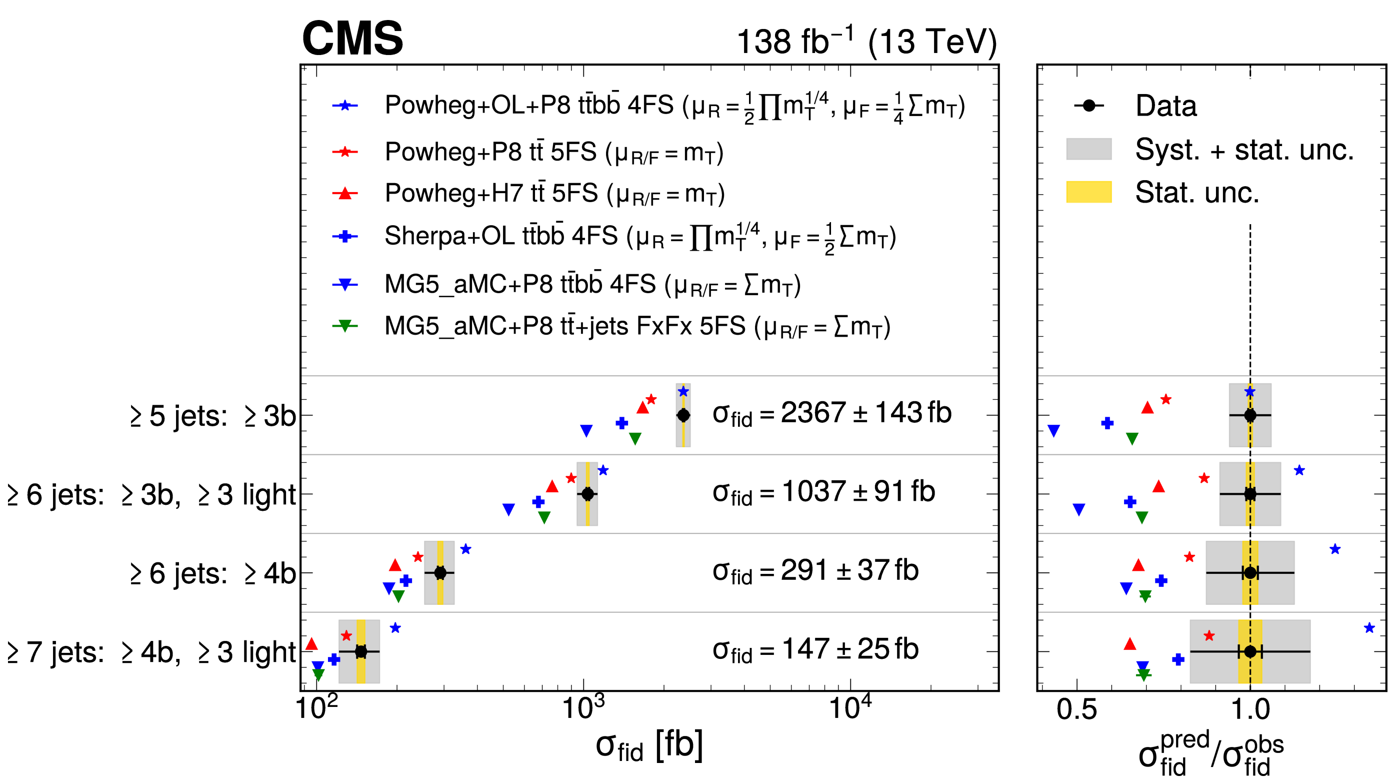
Example: stop pair production with two neutrinos and two neutralinos

CMS-PAS-TOP-24-001

Top quark pair + heavy flavour jets

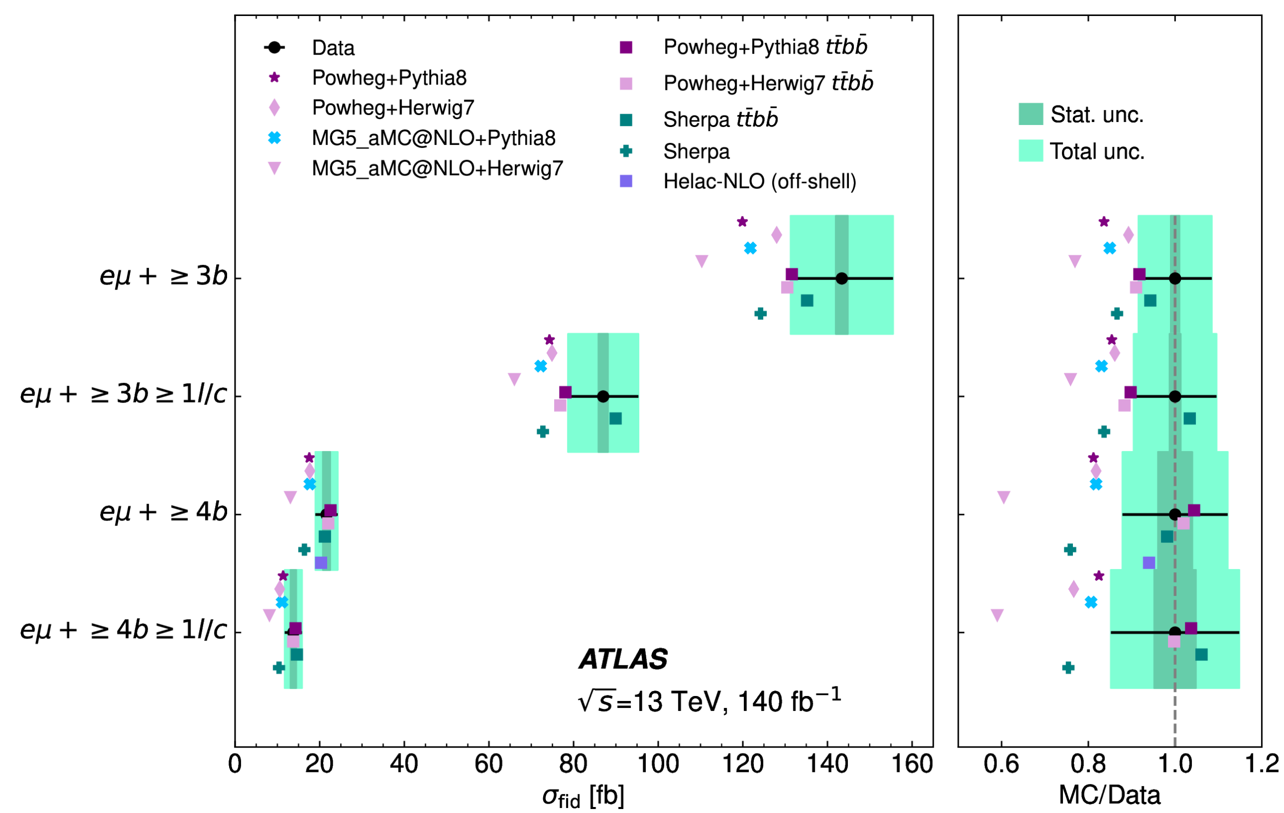
- **$t\bar{t}$ + heavy flavour jets** important irreducible background to $t\bar{t}H(bb)$ and difficult to simulate
- Extensive differential cross-section measurements, both in eμ (ATLAS) and l+jets (CMS) channels

CMS - l+jets



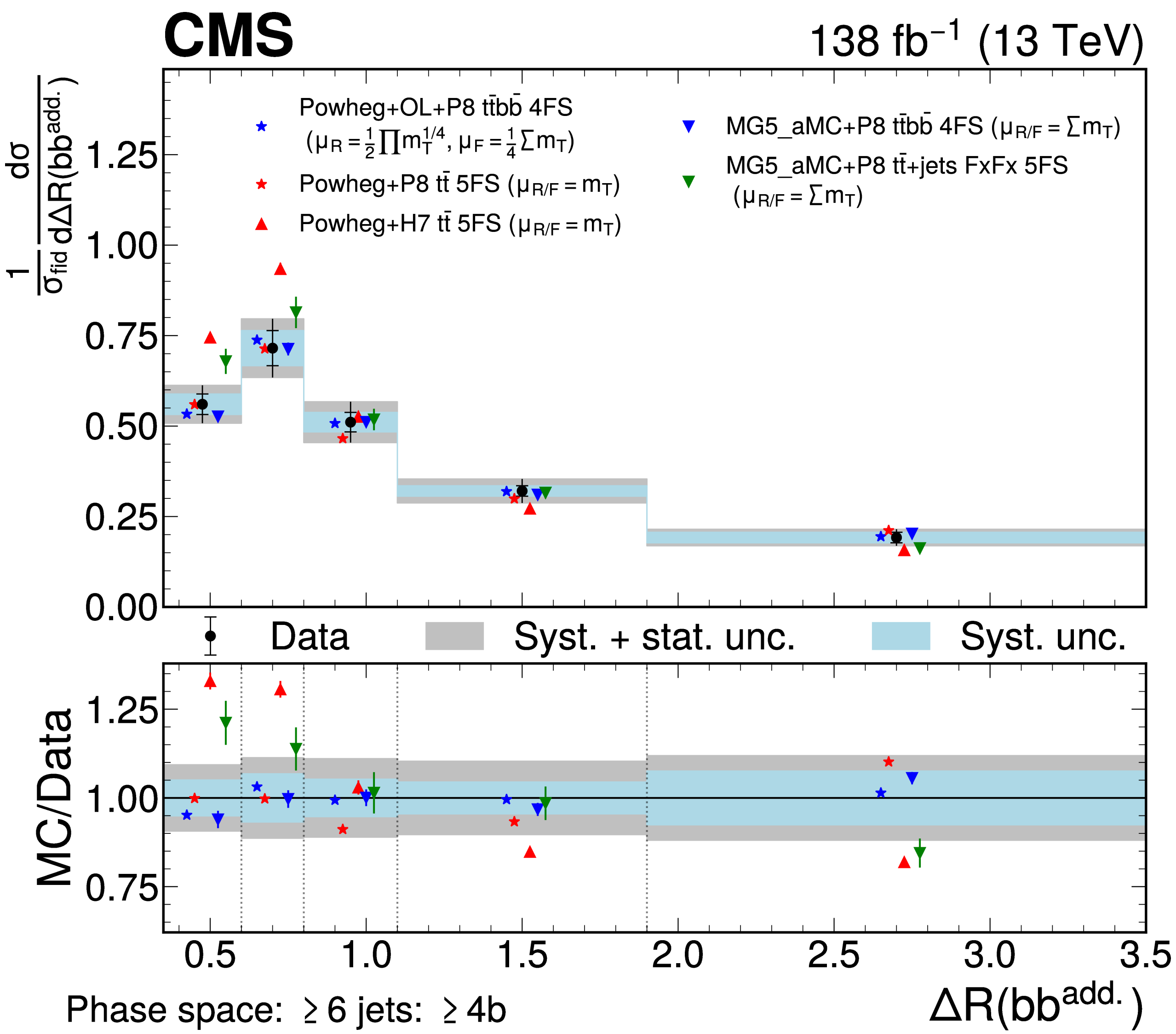
[JHEP 05 (2024) 042](https://doi.org/10.1007/JHEP05(2024)042)

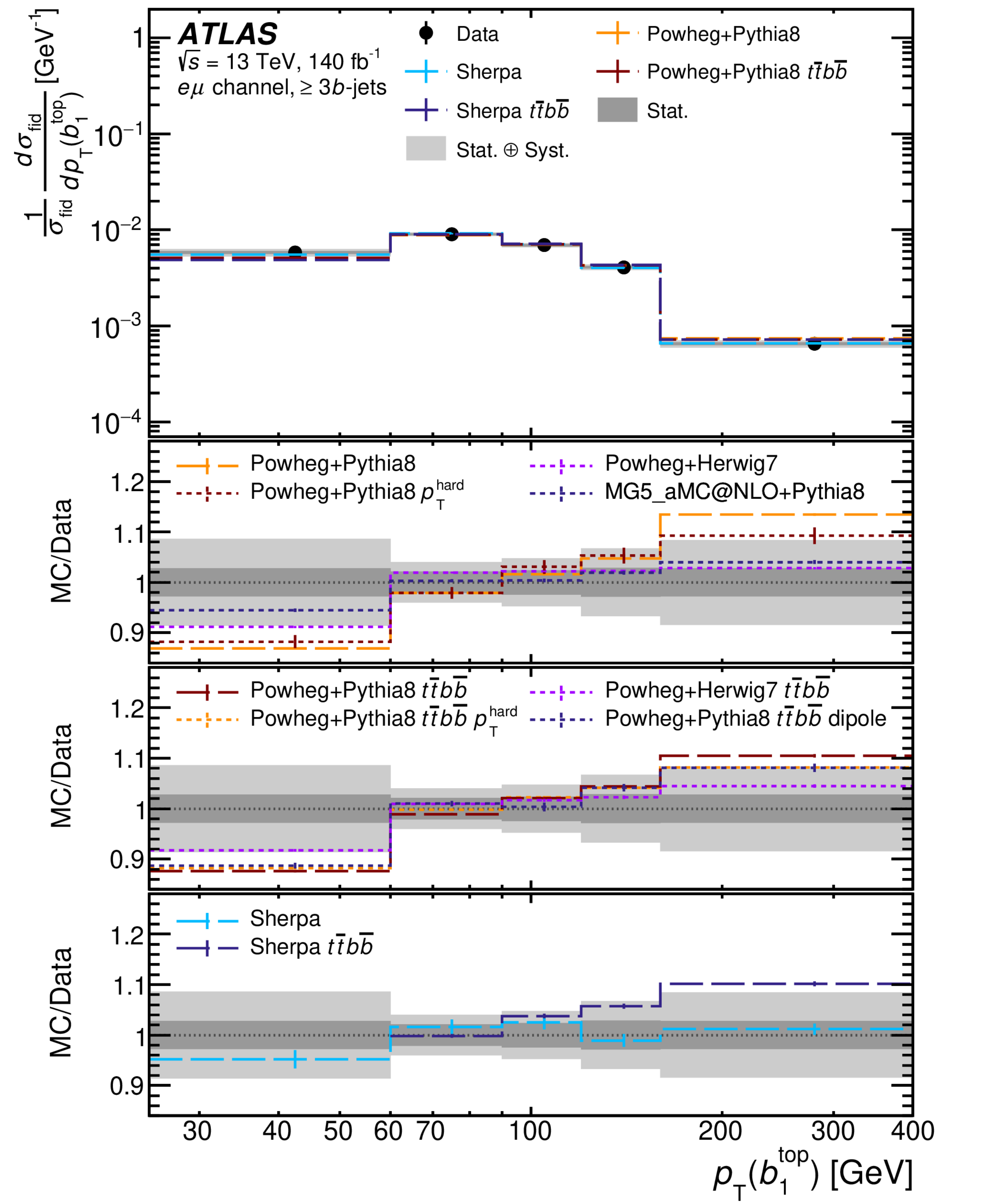
ATLAS - eμ



arXiv:2407.13473

Top quark pair + heavy flavour jets

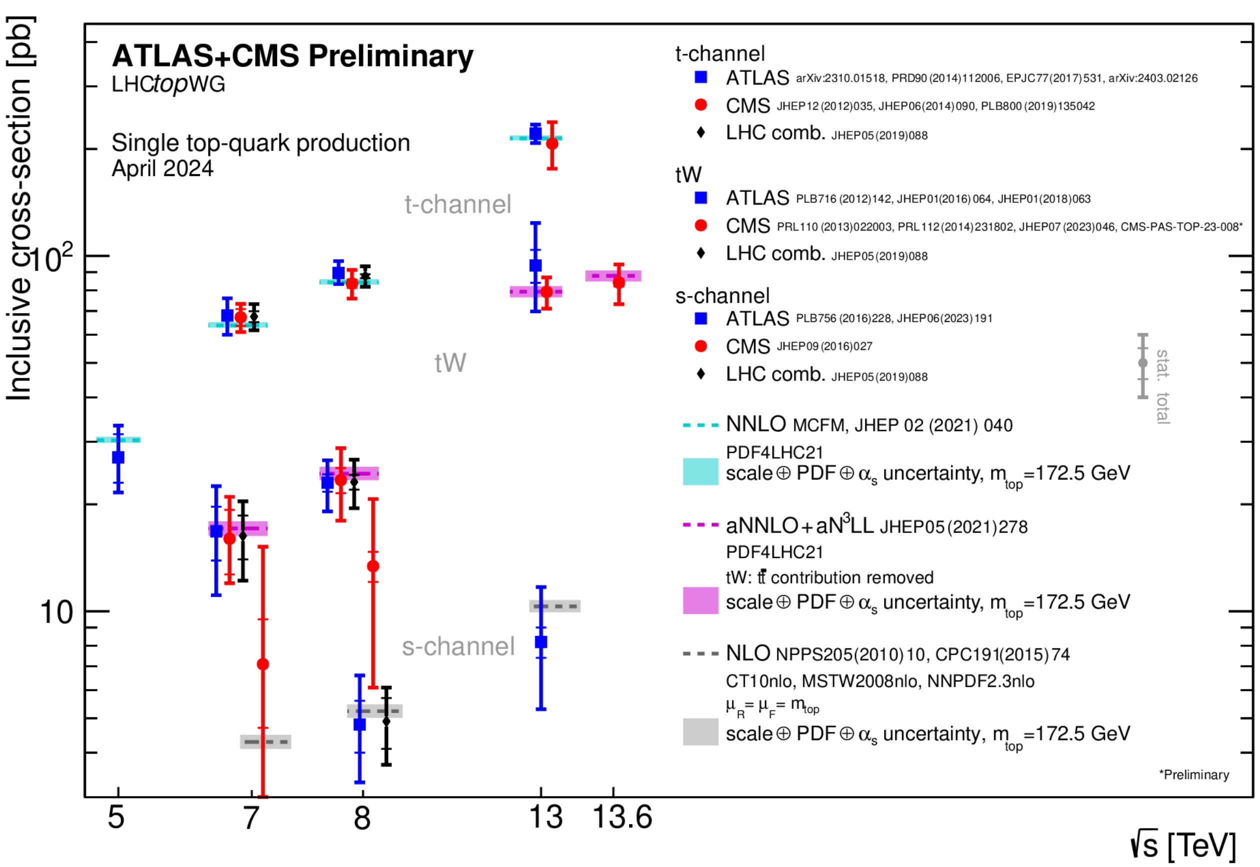


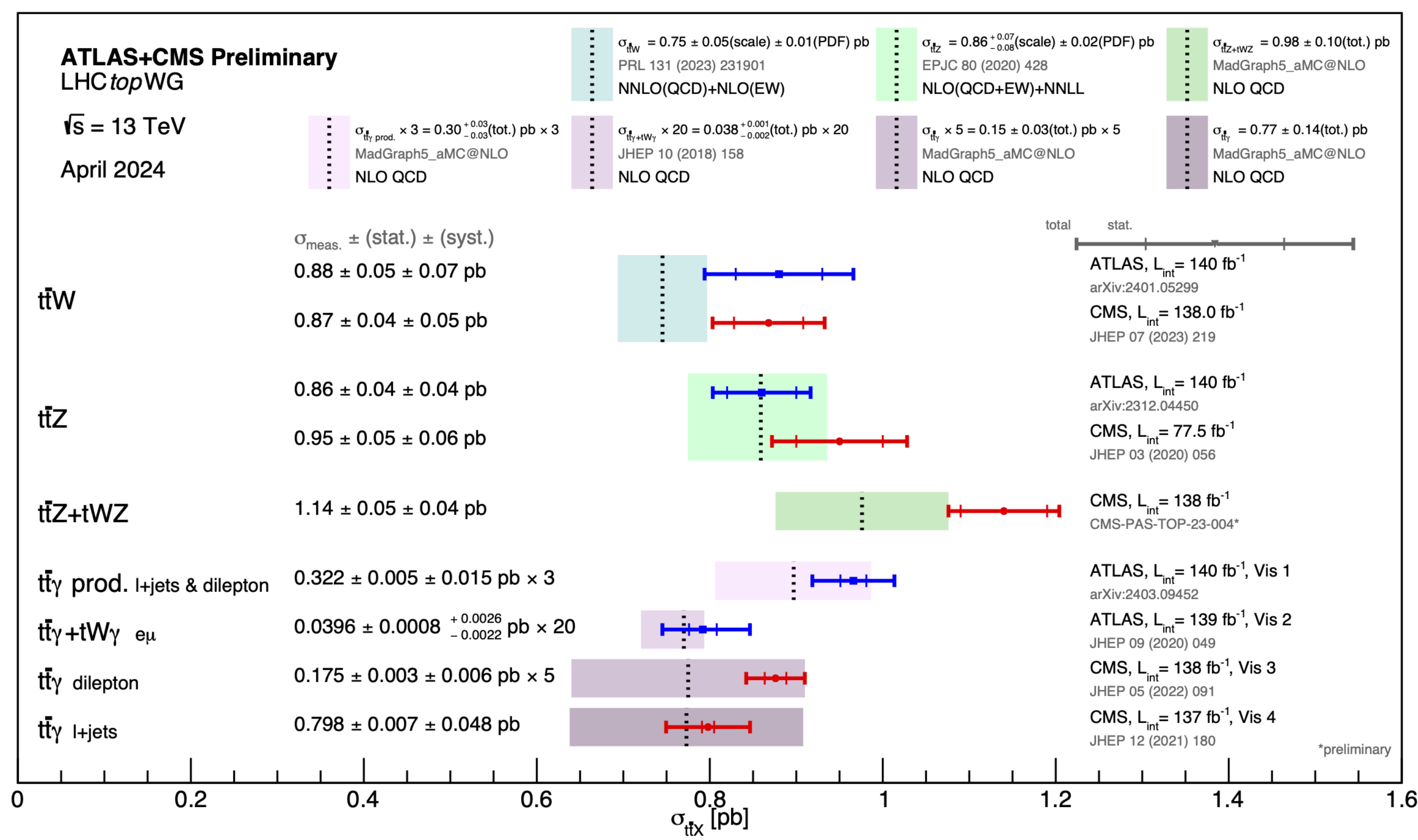


[JHEP 05 (2024) 042](#) [arXiv:2407.13473](#)

Single top quark and associated productions

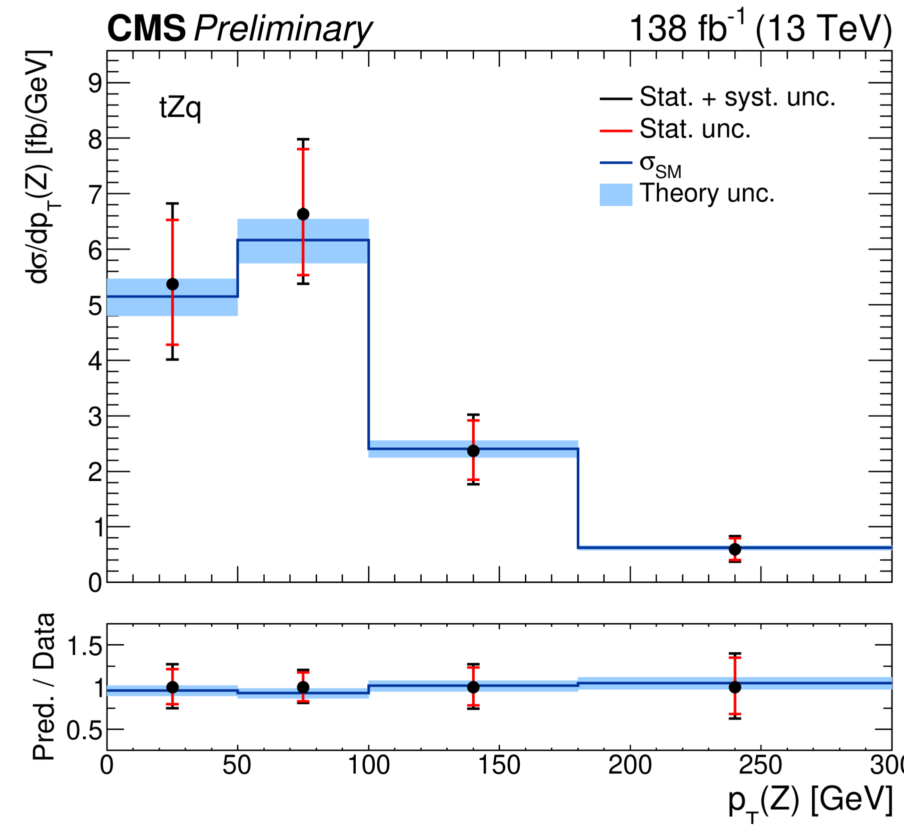
- All three main **single top quark** production channels measured at all √s
  - Both inclusive and differential cross-section measurements
  - Some recent results:
    - measurement of tW at 13 TeV [ATLAS, arxiv:2407.15594]
    - measurement of tW at 13.6 TeV [CMS, CMS-PAS-TOP-23-008]
- **Rare** associated productions, **$t\bar{t}$+X** and t+X (X = W, Z, γ) measured as well
  - recent $t\bar{t}\gamma$ inclusive and differential measurement [ATLAS, arxiv:2403.09452]
  - 5 to 10% precision on $t\bar{t}\gamma$, $t\bar{t}Z$ and $t\bar{t}W$ inclusive cross-sections

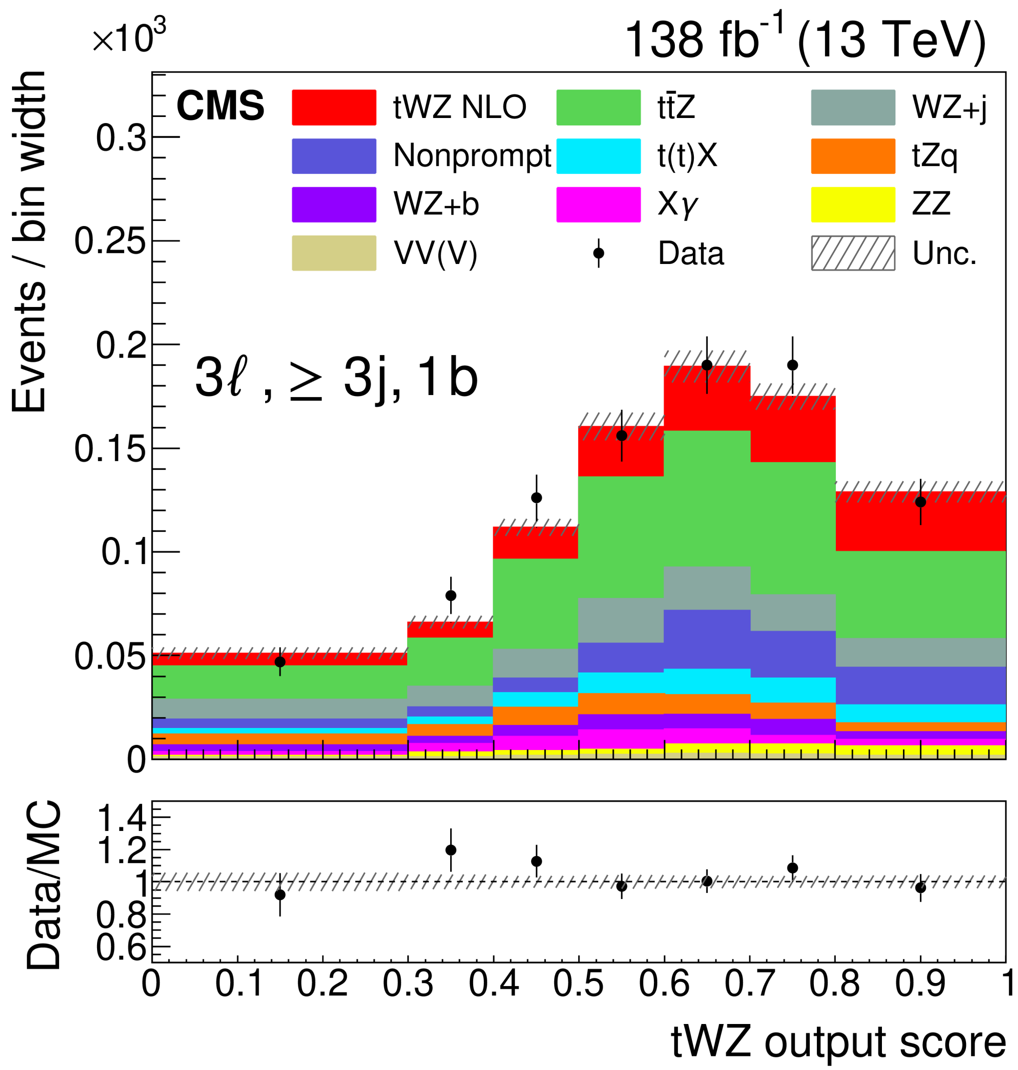


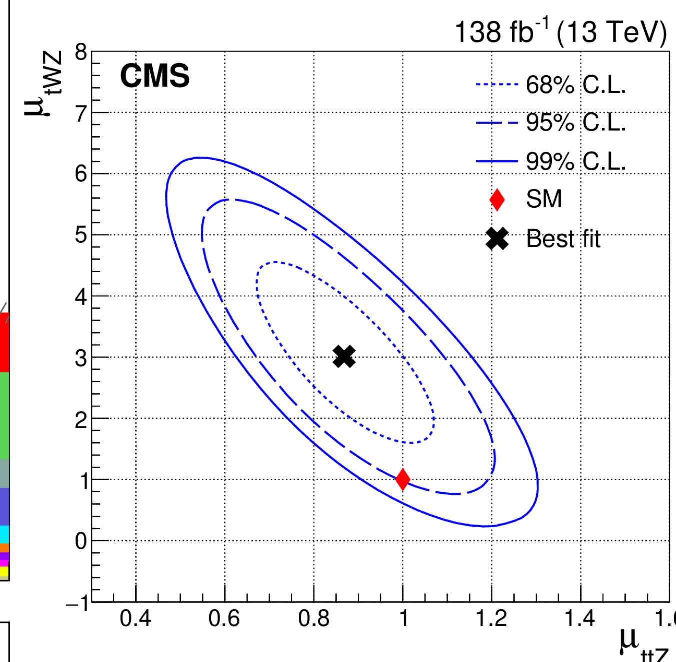


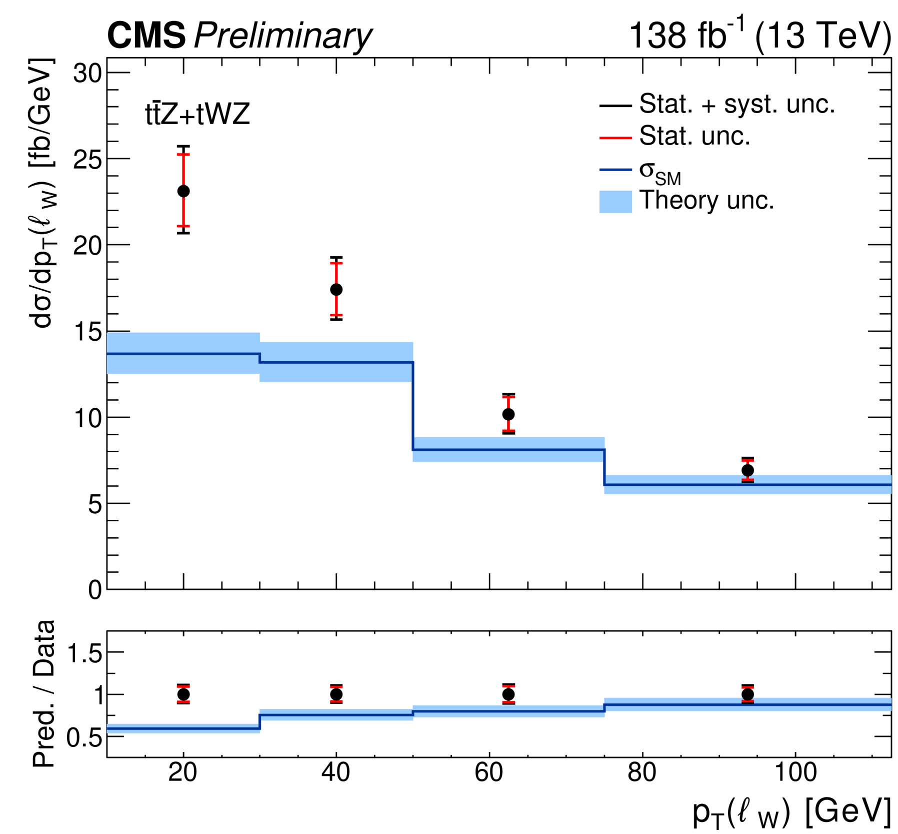
Rare processes - $t\bar{t}Z$, tZq and tWZ

- $t\bar{t}Z$, tZq and tWZ: all the ways to study t-Z coupling
    - tWZ interferes with $t\bar{t}Z$ at NLO (like $t\bar{t}$ and tW)
- Evidence for **tWZ** production, with 3.4σ observed significance
    - Cross-section 2σ from SM prediction (136 fb @13TeV)
- Differential measurements of all three processes







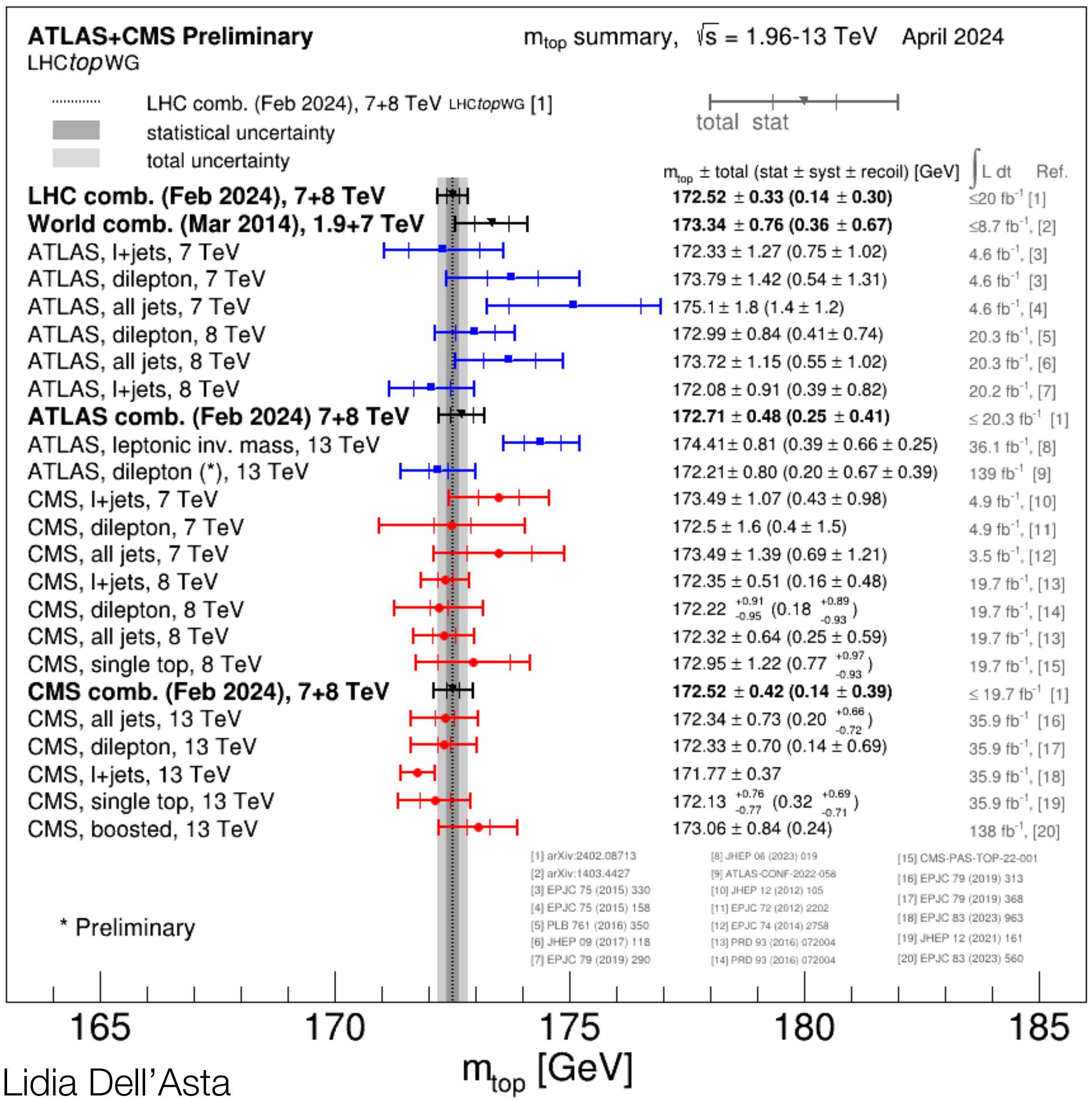


PLB 855 (2024) 138815

CMS-PAS-TOP-23-004

Top quark mass

- Indirect measurements from cross section measurements (~1% precision)
- Direct measurements from top quark decay products
  - Boosted topologies and alternative methods (soft muon in jet) also explored
- New ATLAS + CMS combination
  - 15 measurements from Run1 both at 7 and 8 TeV



Uncertainty category	Uncertainty impact [GeV]		
	LHC	ATLAS	CMS
b-JES	0.18	0.17	0.25
b tagging	0.09	0.16	0.03
ME generator	0.08	0.13	0.14
JES 1	0.08	0.18	0.06
JES 2	0.08	0.11	0.10
Method	0.07	0.06	0.09
CMS b hadron $\mathcal{B}$	0.07	—	0.12
QCD radiation	0.06	0.07	0.10
Leptons	0.05	0.08	0.07
JER	0.05	0.09	0.02
CMS top quark p_T	0.05	—	0.07
Background (data)	0.05	0.04	0.06
Color reconnection	0.04	0.08	0.03
Underlying event	0.04	0.03	0.05
g-JES	0.03	0.02	0.04
Background (MC)	0.03	0.07	0.01
Other	0.03	0.06	0.01
l-JES	0.03	0.01	0.05
CMS JES 1	0.03	—	0.04
Pileup	0.03	0.07	0.03
JES 3	0.02	0.07	0.01
Hadronization	0.02	0.01	0.01
p_T^{miss}	0.02	0.04	0.01
PDF	0.02	0.06	<0.01
Trigger	0.01	0.01	0.01
Total systematic	0.30	0.41	0.39
Statistical	0.14	0.25	0.14
Total	0.33	0.48	0.42

$$m_t = 172.52 \pm 0.14\ (stat.) \pm 0.30\ (syst.)\ \text{GeV}$$

PRL 132 (2024) 261902

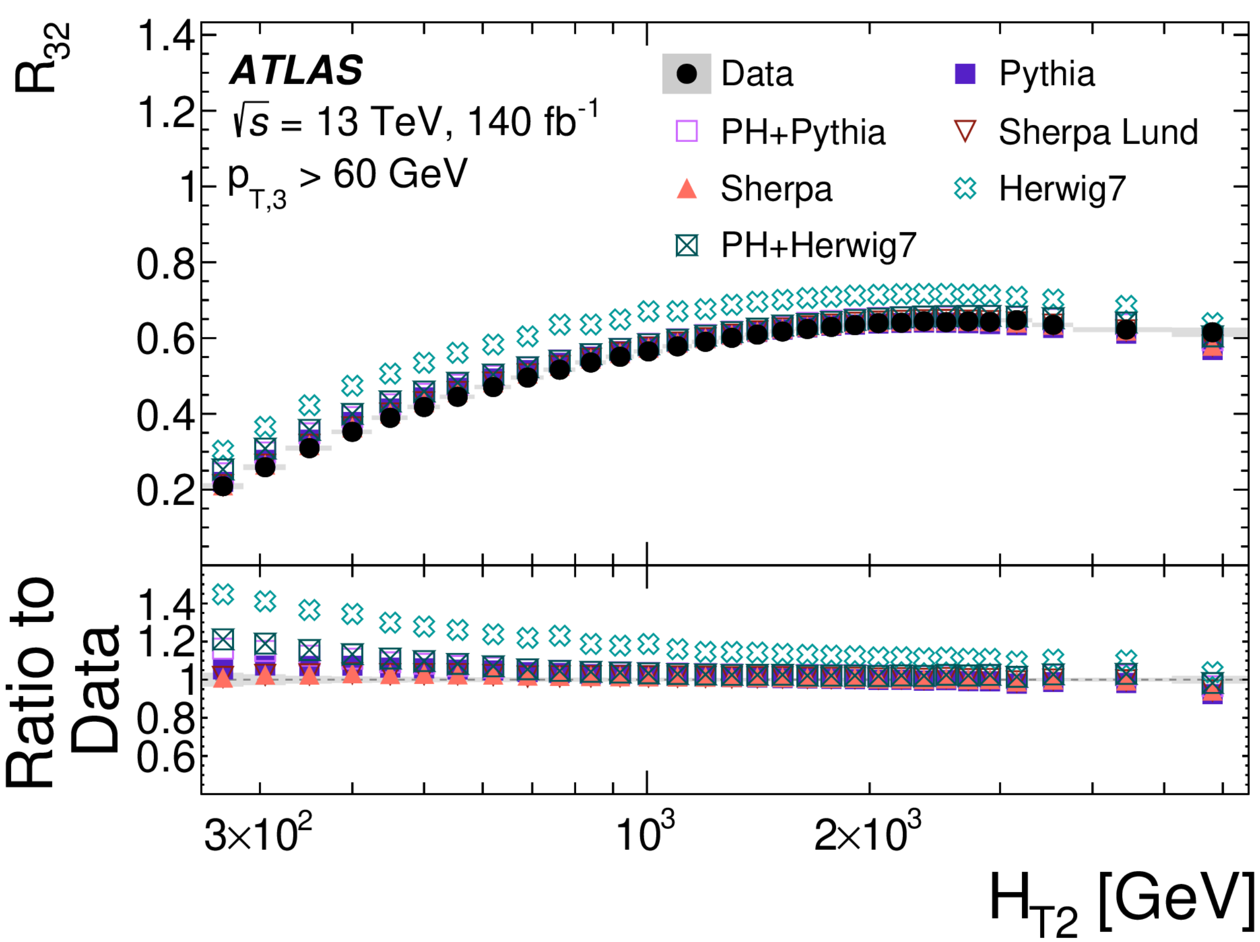
Conclusions

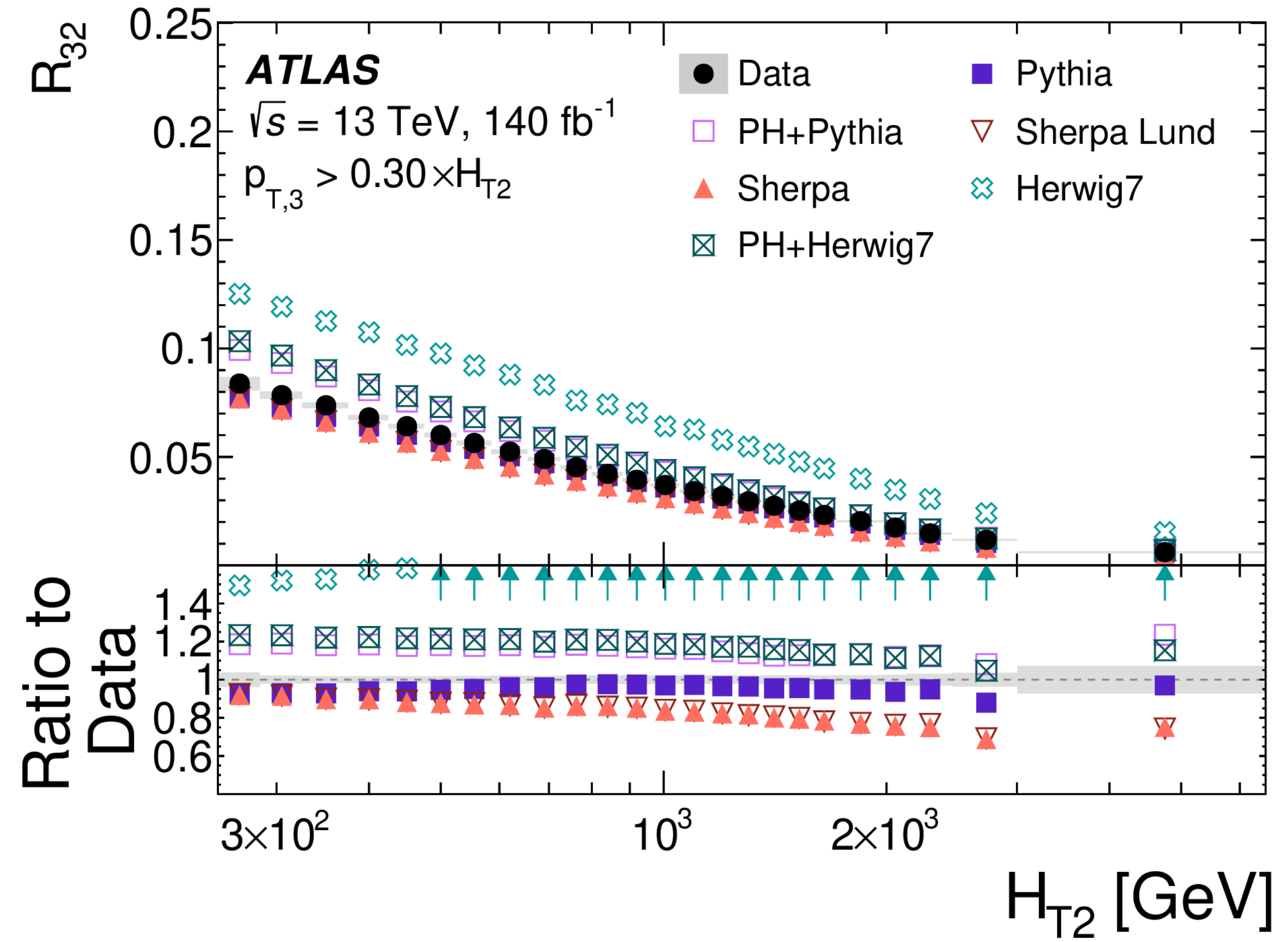
- Presented status of electroweak, Higgs boson and top quark physics at the LHC
- Huge amount of data collected allows to:
  - make precise measurements, e.g. W boson mass…
  - look for very rare processes, e.g. diHiggs, tWZ…
- Usage of machine learning is boosting:
  - object identification, e.g. b-tagging
  - analysis strategies, e.g. systematics aware NN training
- Many other very interesting measurements (no time to show everything today), e.g.:
  - Lepton Flavour Universality tests [arxiv:2403.02133, PRD 105 (2022) 072008]
  - 4tops observation [EPJ C 83 (2023) 496, PLB 847 (2023) 138290]
- Run3 is ongoing
  - More data than Run2 already collected
  - Expect 300 fb^{-1} before next long shutdown before HL-LHC
- Stay tuned!

BackUp

Jet cross-section ratios

- Measurement of cross-sections and ratios of inclusive jet multiplicity bins, as a function of various observables
  - Then construct ratios of the inclusive jet-multiplicity bins, sensitive to α_s
- Good description by Pythia of $R_{3/2}$ vs H_{T2} at low and high scales.





arxiv:2405.20206