Rare (EW) processes at the LHC

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on behalf of the ATLAS and CMS collaborations

Lepton Photon 2023

Melbourne, Australia

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Thanks to the organizers for organizing a wonderful conference in a marvelous city.

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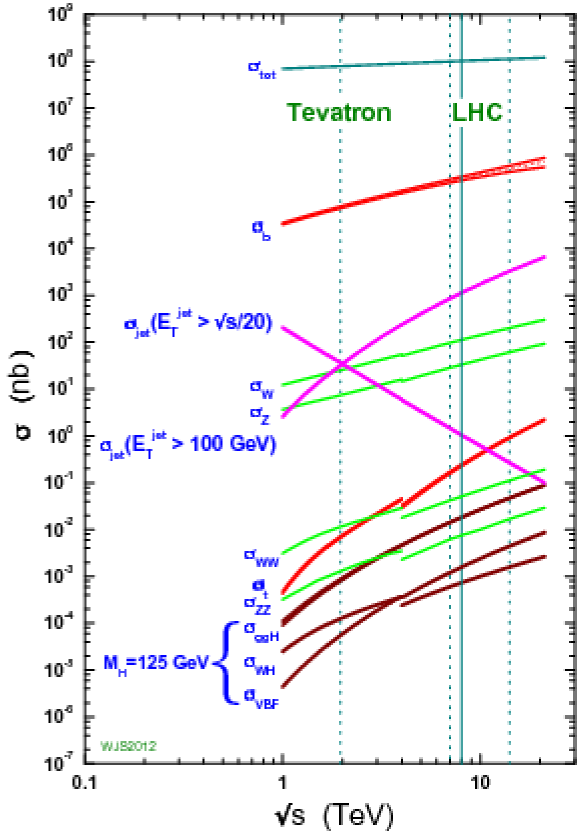
Rare processes: how rare exactly?

At ICHEP2012 in Melbourne, ATLAS+CMS announced observation of a rare process.

Higgs production @ 8 TeV ~ 20 pb << W,Z, top production << inelastic cross section



A needle in a haystack in 2012, precision physics in 2023 [see Linda’s and Joao’s talks]

Rare processes: how rare exactly?

At ICHEP2012 in Melbourne, ATLAS+CMS announced observation of a rare process.

In 2023 we have more a lot more hay + a pile of needles + …?

In this talk, we will use Run 2 data to dig even deeper, exploring fb-level cross sections and looking for **”new Standard Model physics”**

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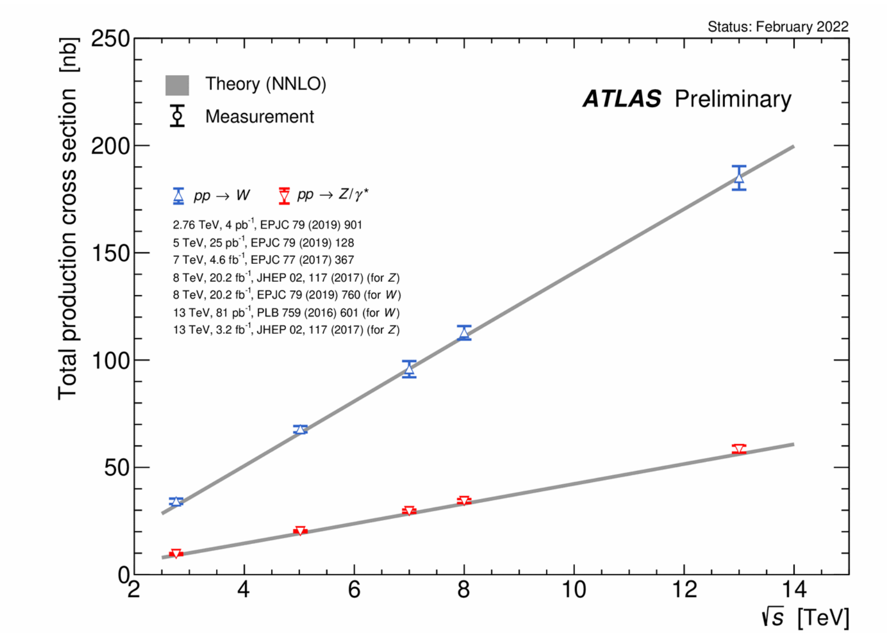
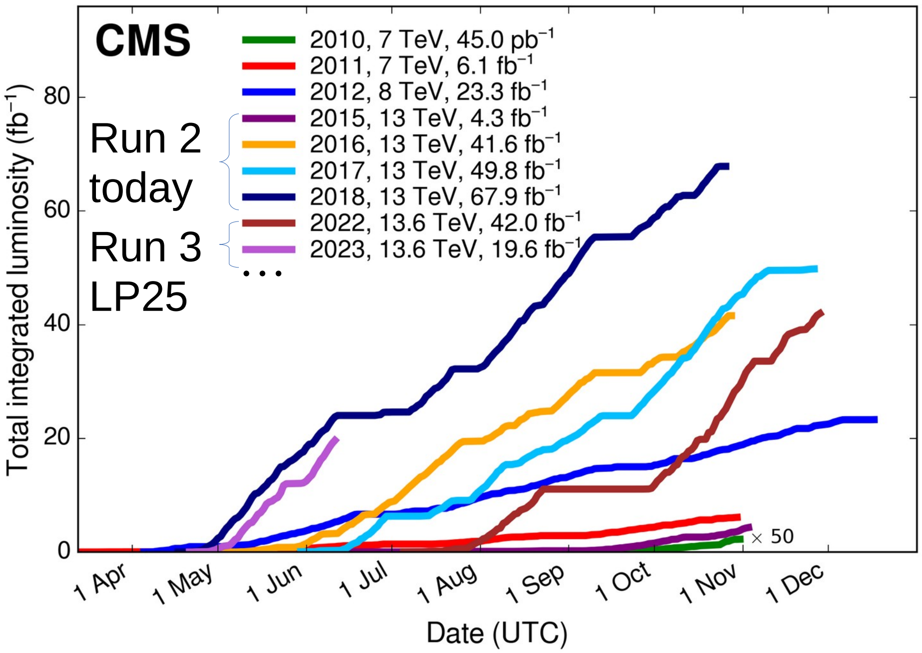
Addressing the challenge of rare processes

First ingredient: the most powerful machine

- processes with multiple massive objects (W, Z, H, t): we need the c.o.m. energy
- cross sections (before applying BR) are down to 10 fb: we need the int. luminosity
- we thank the LHC for excellent performance in run 2 and look forward to run 3 data





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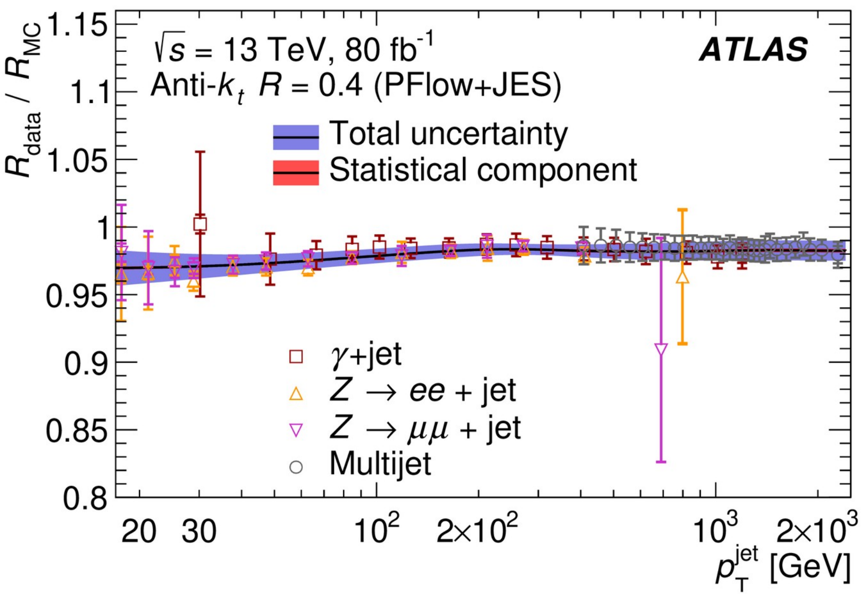
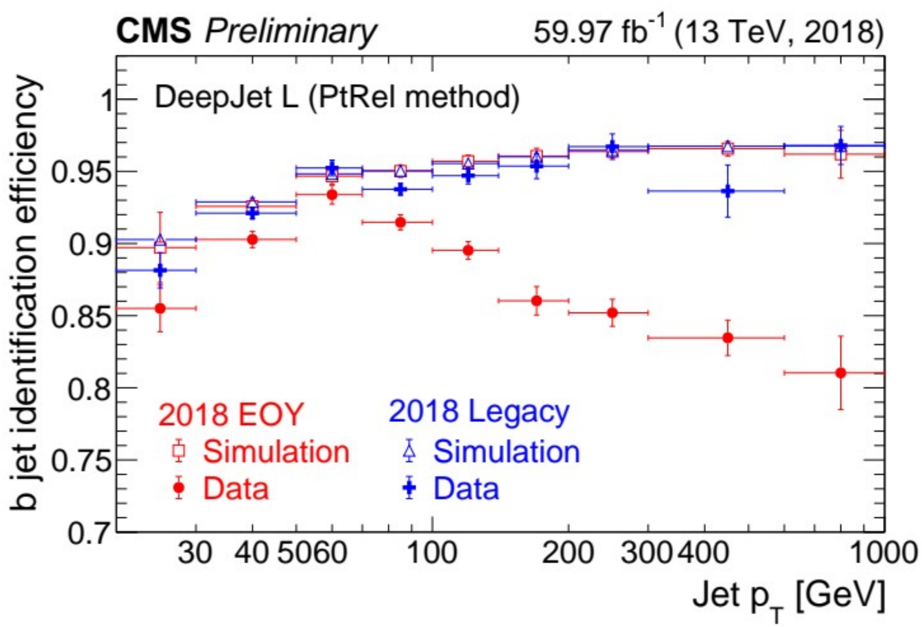
Addressing the challenge of rare processes

Second ingredient: the most powerful detectors & calibrations

- dig out rare processes from under orders of magnitude of “known physics”
- control of fake leptons and jet and b-jet multiplicity are crucial for sensitivity
- calibrations of lepton SF, b-tagging efficiency, jet response are key systematics
- results are made possible by a large effort in detector operation and performance



ATLAS run 2 jet calibration arXiv:2007.02645



CMS DeepJet tagging arXiv:2008.10519

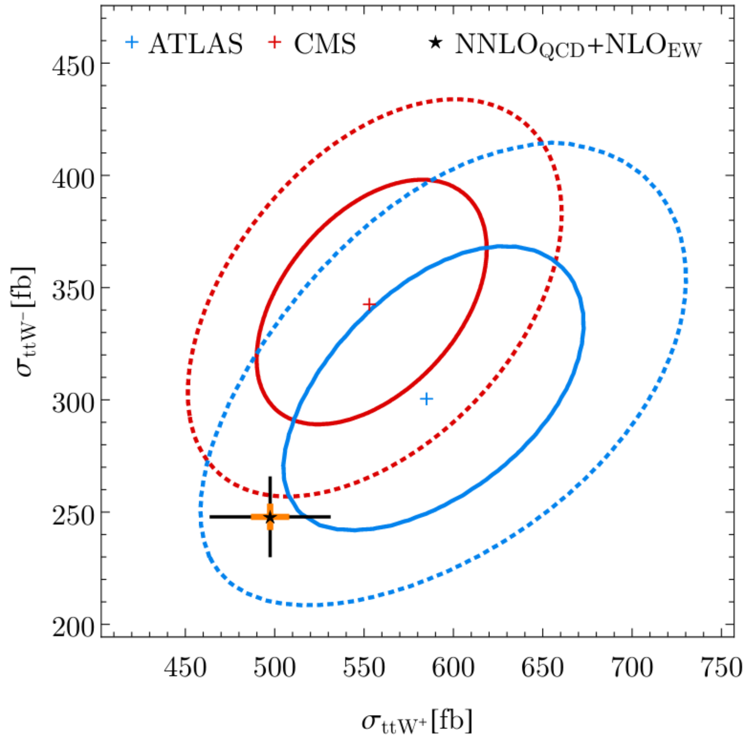
Addressing the challenge of rare processes

Third ingredient: the most powerful predictions

- precise cross section preditions (fixed-order, mixed QCD/EW, with resummation)
- precise event generators for complex multi-scale processes
- we thank the theory community for providing these and look forward to the next “N”

pp → ttH, ttW are available at NNLO

arXiv:2210.07846 (ttH), arXiv:2306.16311 (ttW)



Addressing the challenge of rare processes

Fourth ingredient: the most powerful analysis techniques

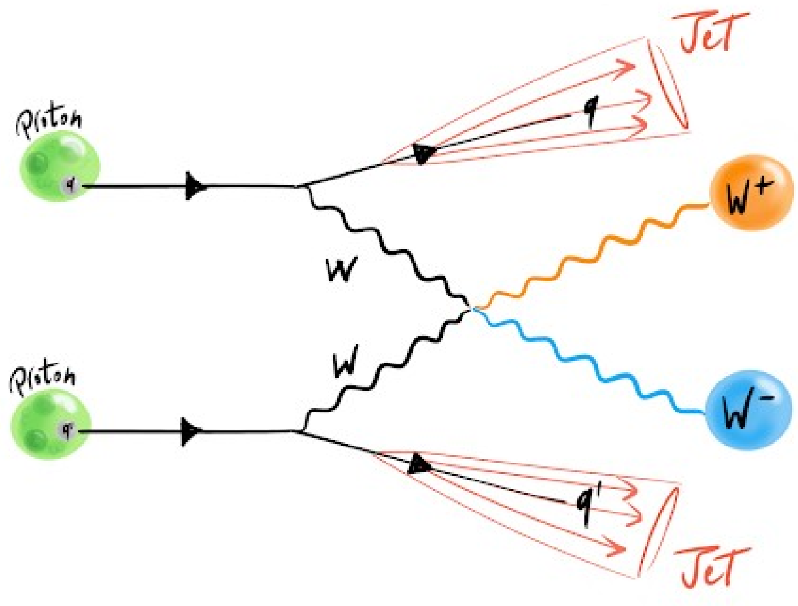
- profile-likelihood fits can deal with multiple floating “signals”
- state of the art machine learning algorithms to maximize separation
- we thank the broader community developing these crucial tools

Your signal is my background!

YOUR background is MY signal!

A real challenge in searches for rare processes is the control of other rare processes

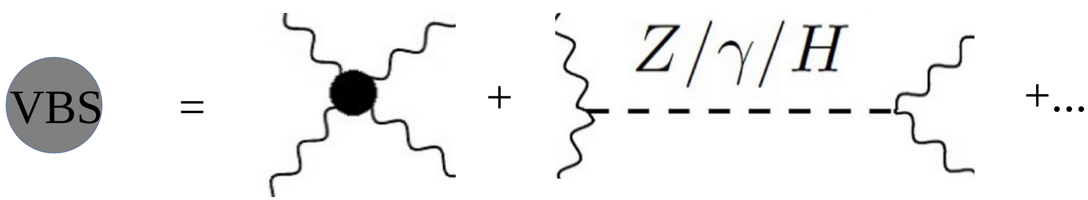
New results in Vector Boson Scattering



Electroweak VV and VV'

Observed first VBS processes early in run 2
PRL120 (2018) 081801
PLB 793 (2019) 469

Many outgoing boson combinations observed since: WW, WZ, ZZ, Zγ, Wγ

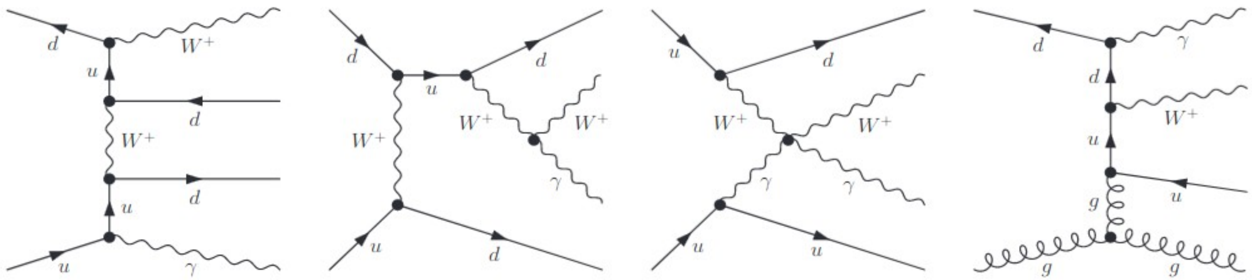


In the SM there are intricate cancellations between Feynman amplitudes involving quartic gauge boson interactions, trilinear gauge boson couplings, and Higgs exchange. Modifications of any of the couplings can lead to sizable cross section increases for longitudinally polarized vector bosons.

Powerful input to SMEFT fits, see e.g. Ethier et al. 2020, Diogo Buarque et al., 2022

New VBS observation: CMS Wγ

arXiv:2212.12592



Clear experimental signature:

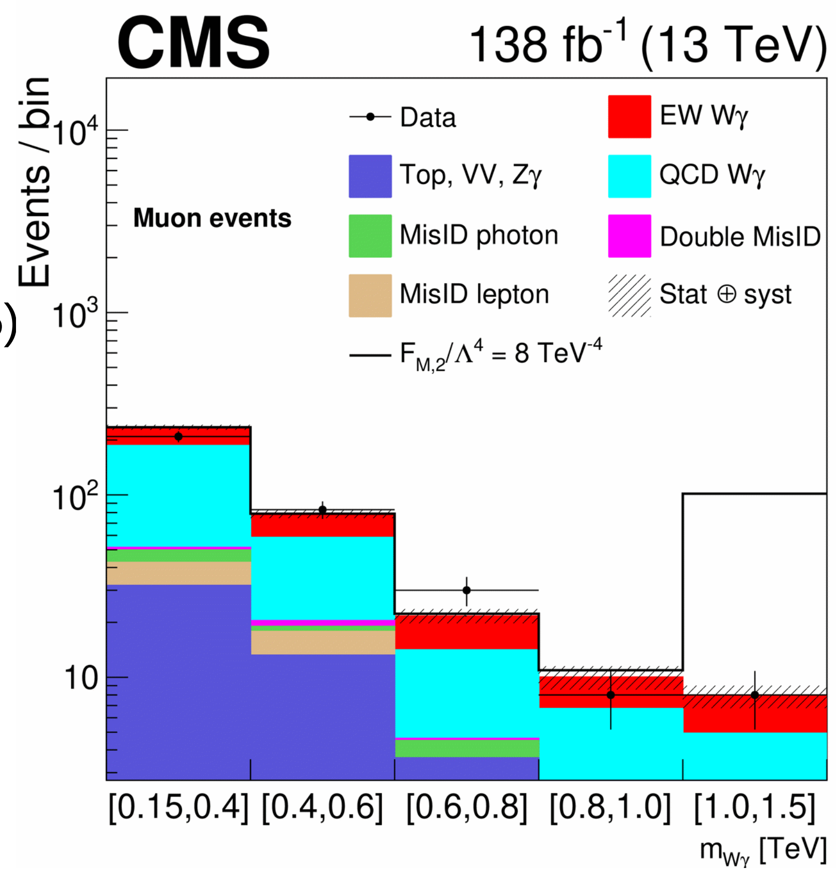
- electron/muon, E_T^{miss} (p_T > 25 GeV)
- isolated photon candidate (p_T > 25 GeV)
- jets (p_T > 50 GeV, m_{jj} > 500 GeV, $\Delta|\eta|$ > 2.5)

EW production: $23.5^{+4.9}_{-4.7}$ fb

Total (QCD+EW&VBS): 113±13 fb

Bounds on 15 D8 parameters for QGCs

See also Li Yuan in BSM track



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New VBS observation: ATLAS Zγ

arXiv:2305.19142

See CMS observation and earlier evidence from ATLAS and CMS

See also Walter Hopkins in BSM track

Clear experimental signature:

- Z candidate (e^+e^- or $\mu^+\mu^-$, $m_{ll}+m_{ll\gamma}$ > 182 GeV)
- isolated photon candidate (p_T > 25 GeV)
- jets (p_T > 50 GeV, m_{jj} > 150/500 GeV, $\Delta|y|$ > 1)

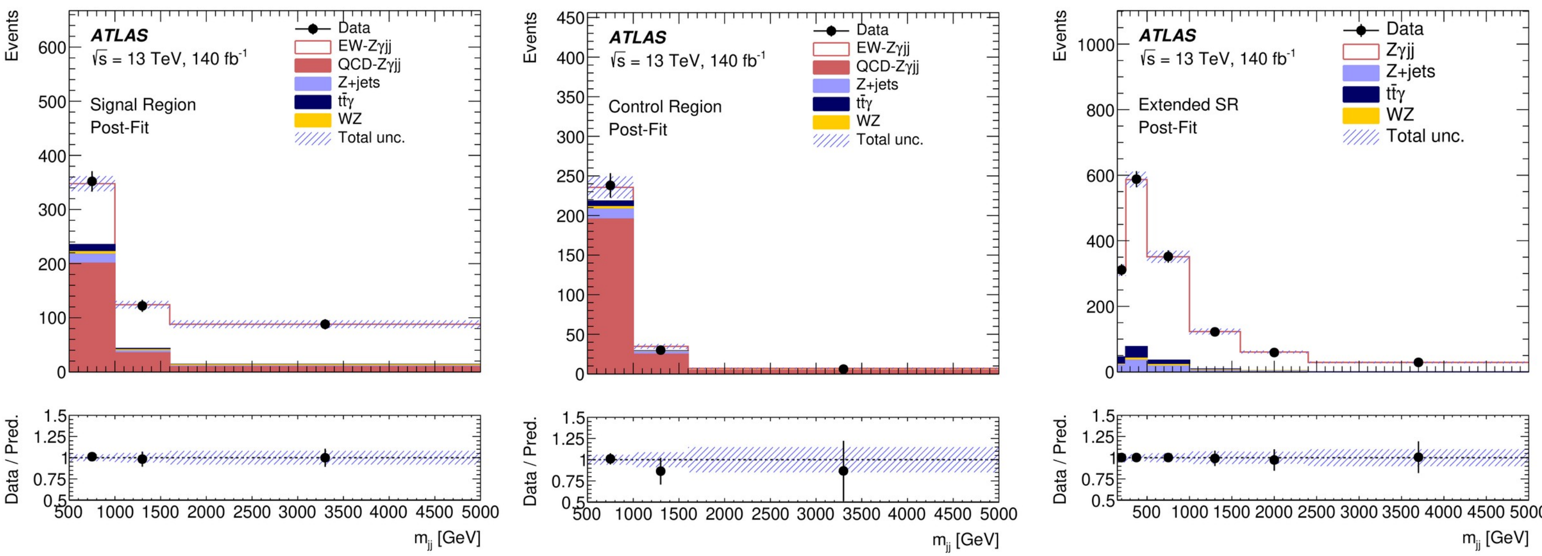
Distinguish EW and QCD production with centrality (EW >0.4, QCD <0.4)

$$\zeta(Z\gamma) = \left|\frac{y_{Z\gamma} - (y_{j_1} + y_{j_2})/2}{y_{j_1} - y_{j_2}}\right|$$

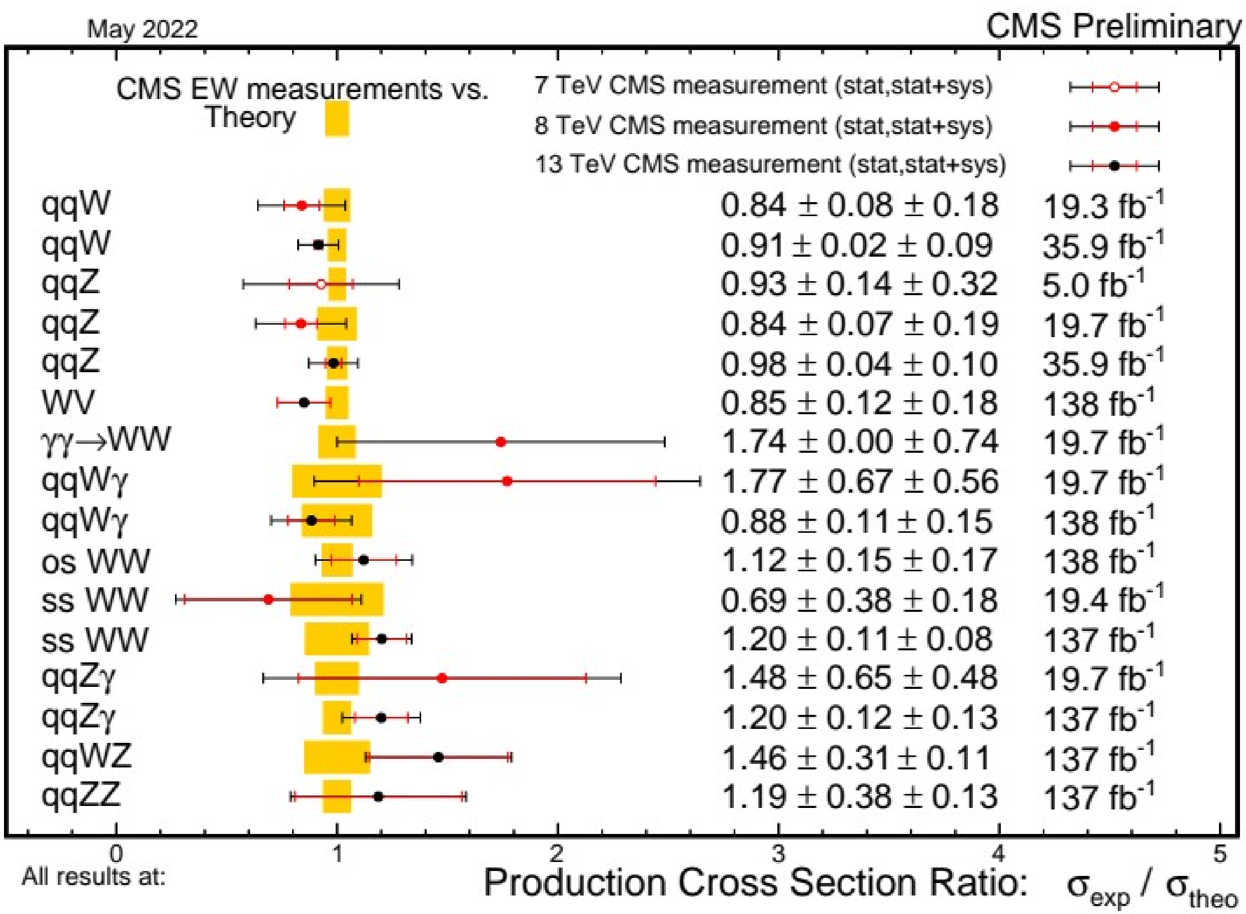
EW production: 3.6 ± 0.5 fb (SM = 3.5 ± 0.2 fb)

QCD production

Total fiducial cross section (QCD+EW): $16.8^{+2}_{-1.8}$ fb



Vector-boson-scattering summary - CMS



Link to this plot

ATLAS version

Fiducial x-sec measurements of VBS production reach O(1 fb)

Inputs for global analyses of TGC, QGC and Higgs couplings

Towards a polarized VBS measurement

CMS PLB812 (2020)
ATLAS PLB843 (2023)

Total VV+jets rate >> EW production >> VBS production >> long. polarized VBS

Can we access the longitudinally polarized production experimentally?

CMS PLB arXiv:2009.09429:

"electroweak production of same-sign $W^{\pm}W^{\pm}$ boson pairs with at least one of the W bosons longitudinally polarized […] with an observed (expected) significance of 2.3 (3.1) standard deviations."

So, not there yet, but we're getting close!!

The pp → WZ test bench:

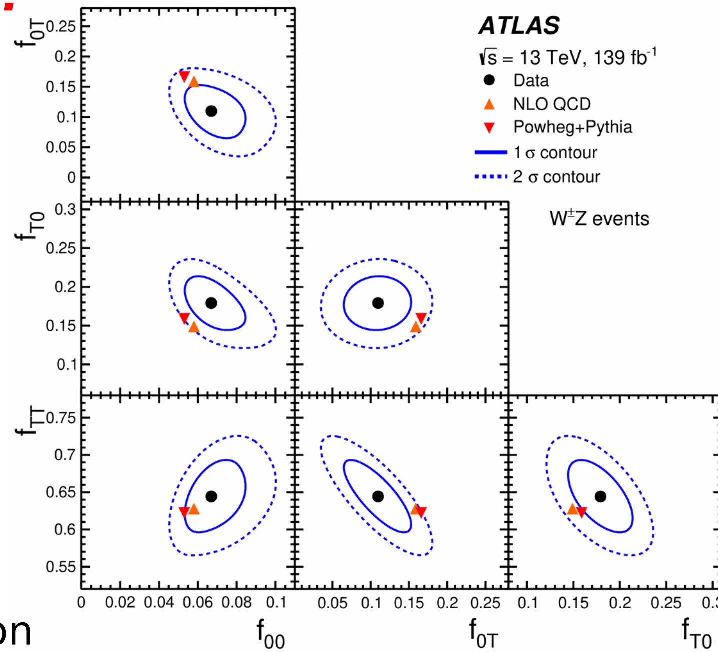
CMS JHEP07 (2021) arXiv:2110.11231

"The first observation of longitudinally polarized W bosons in WZ production is reported"

ATLAS PLB843 (2023), arXiv:2211.09345

"The simultaneous pair-production of longitudinally polarised vector bosons […] with a significance of 7.1 standard deviations."

https://atlas.cern/Updates/Physics-Briefing/WZ-Polarisation



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BRAND NEW: ATLAS pp → ZZ polarization

ATLAS-CONF-2023-038

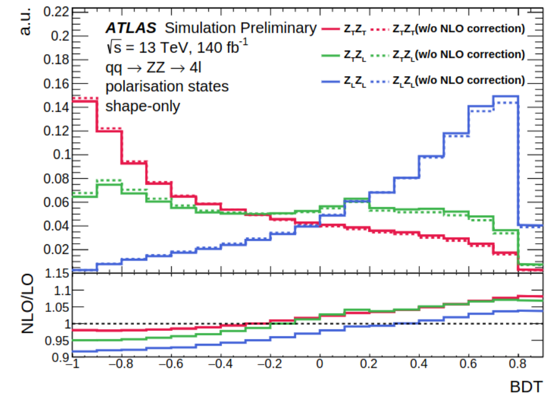
Select pp → ZZ → 4 leptons : ~3000 events

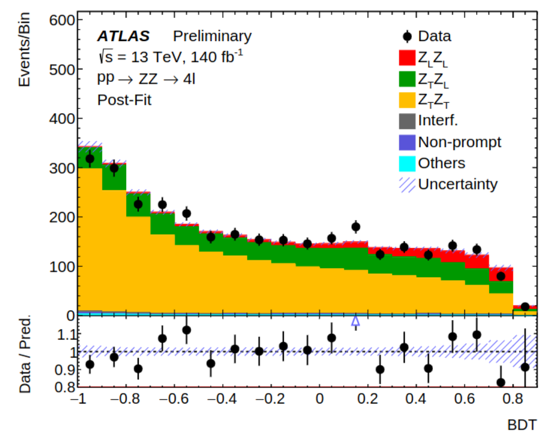
Templates for TT, TL/LT and LL production include NLO corrections from Denner et al.
A. Denner and G. Pelliccioli, JHEP 10 (2021) 097, arXiv: 2107.06579 [hep-ph]

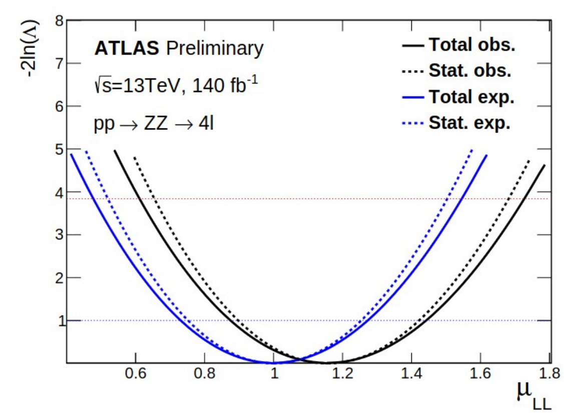
BDT to distinguish TT, TL, LT, LL using only angular observables (kinematics is powerful, but prone to modelling uncertainties)

Fit yields 220 ± 50 $Z_L Z_L$ events: **evidence (4.3 σ)** for pair-production of longitudinally polarised vector bosons

σ_{fid} = 2.4 ± 0.6 fb (SM= 2.1 + 0.1 fb)
23% (stat.) ± 7% (modelling) ± 1% (detector)







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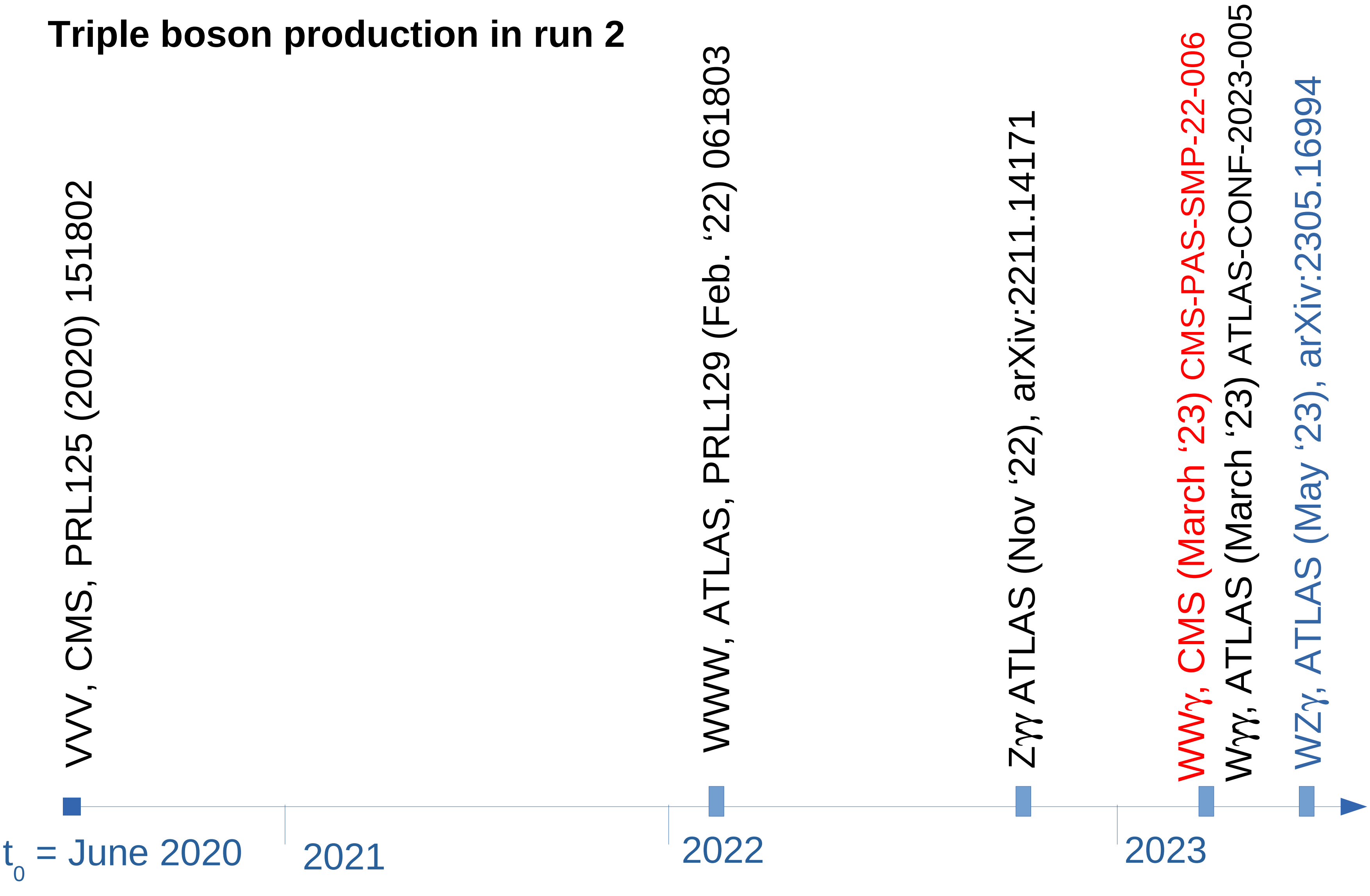
The era of tri-boson production

CMS-PAS-SMP-22-006
ATLAS-CONF-2023-005

Triple boson production in run 2



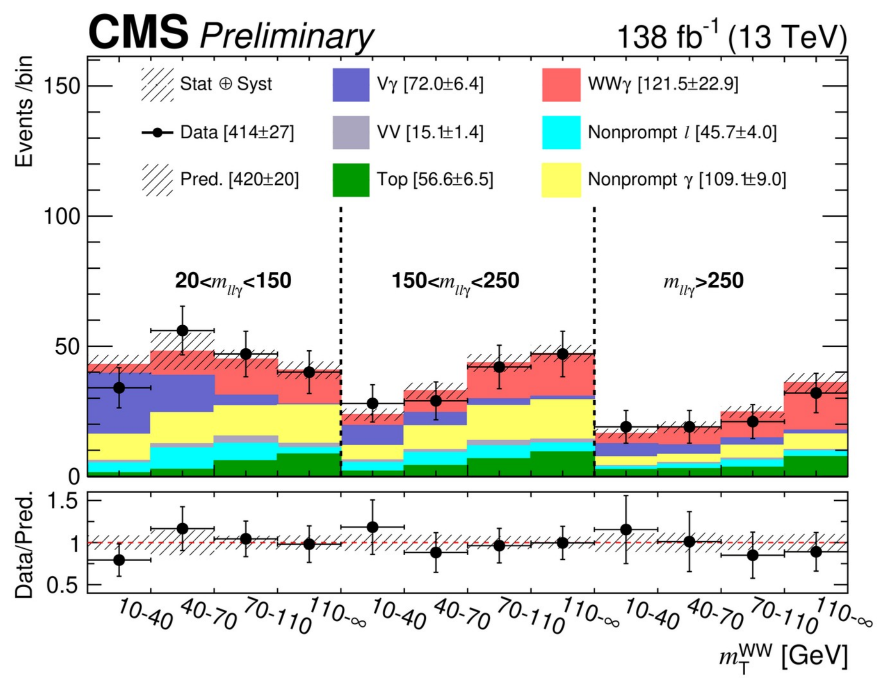
Observation of pp → WWγ

CMS observes WWγ production (5.6σ) !

Fiducial cross section: 6.0 ± 1.7 fb, in good agreement with NLO QCD

Measurement also interpreted as $q\bar{q} \rightarrow H\gamma$, with $H \rightarrow WW$

Bounds on light-quark Yukawa couplings

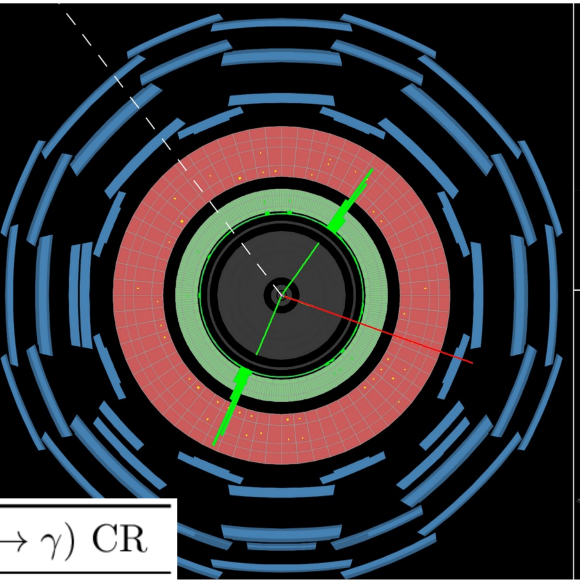


Process	$\sigma_{\rm up}$ pb exp.(obs.)	Yukawa couplings limits exp.(obs.)
$u\bar{u} \rightarrow H + \gamma \rightarrow e\mu\gamma$	0.067 (0.085)	$\lvert\kappa_u\rvert \leq$13000 (16000)
$d\bar{d} \rightarrow H + \gamma \rightarrow e\mu\gamma$	0.058 (0.072)	$\lvert\kappa_d\rvert \leq$14000 (17000)
$s\bar{s} \rightarrow H + \gamma \rightarrow e\mu\gamma$	0.049 (0.068)	$\lvert\kappa_s\rvert \leq$1300 (1700)
$c\bar{c} \rightarrow H + \gamma \rightarrow e\mu\gamma$	0.067 (0.087)	$\lvert\kappa_c\rvert \leq$110(200)

[9] H. Khanpour et al., "Probing Higgs boson couplings in H+γ production at the LHC", PLB773 (2017) 462, arXiv:1702.05753.
[10] J. A. Aguilar et al., "Higgs boson couplings to light quarks through h + γ production", PRD 103 (2021), arXiv:2008.12538.
[11] A. Falkowski et al., "Light quark Yukawas in triboson final states", JHEP 04 (2021) 023, arXiv:2011.09551.

Observation of WZγ production

ATLAS arXiv:2305.16994



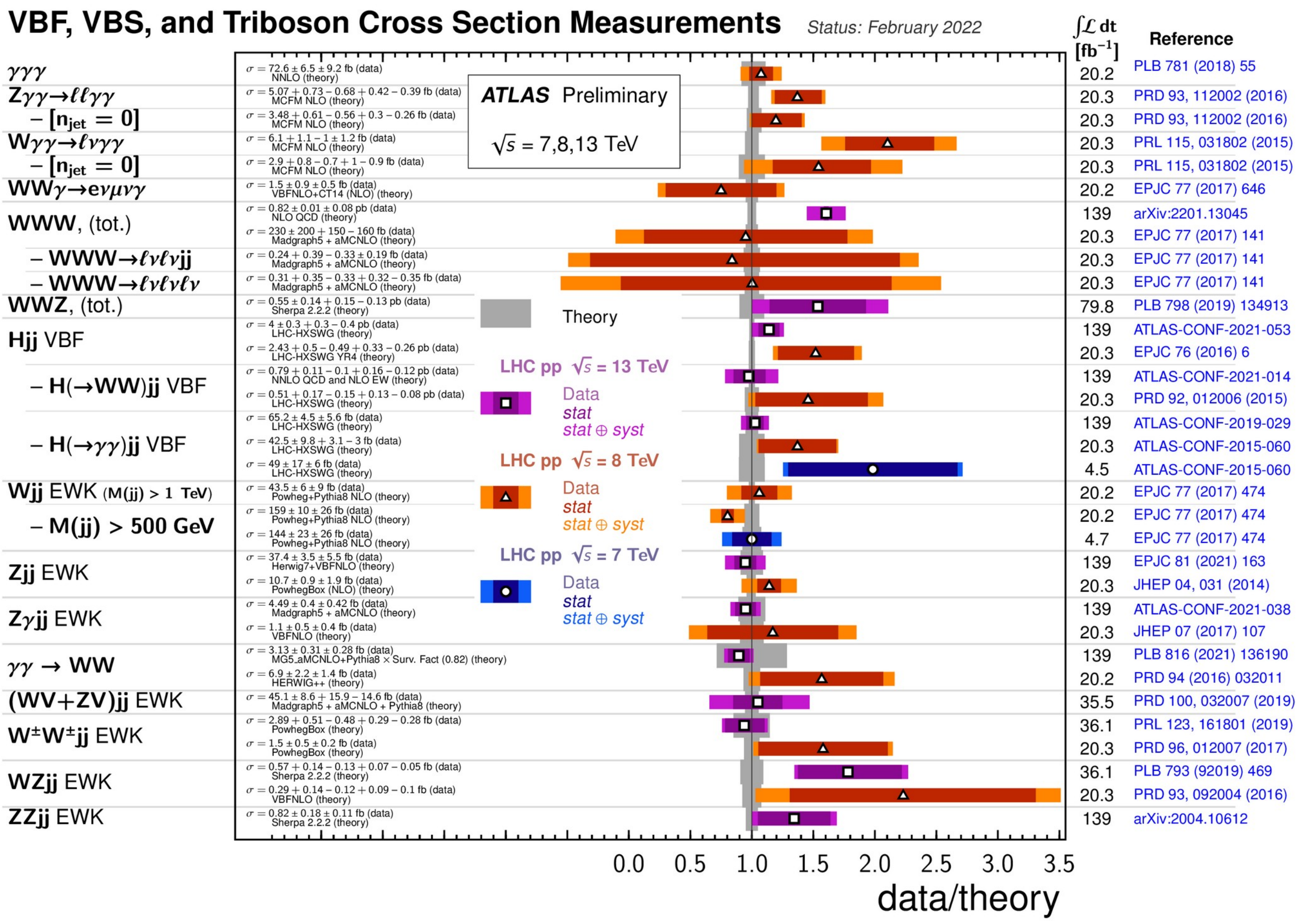
ATLAS observes WZγ production (6.3σ) !
Focus on leptonic W and Z bosons decay
Clear signature → clean selection (S/B~2)
Fiducial cross section: 2.01 ± 0.30(stat.) ± 0.16(syst.)fb.
SM prediction: 1.50 ± 0.06fb

Process	SR	$ZZ\gamma$ CR	$ZZ(e\to\gamma)$ CR
$WZ\gamma$	92 ± 15	0.21 ± 0.07	0.56 ± 0.14
$ZZ\gamma$	10.7 ± 2.3	23 ± 5	1.8 ± 0.4
$ZZ(e\to\gamma)$	3.0 ± 0.6	0.028 ± 0.020	30 ± 6
$Z\gamma\gamma$	1.05 ± 0.32	0.15 ± 0.06	0.29 ± 0.10
Nonprompt background	30 ± 6	-	-
Pileup γ	1.9 ± 0.7	-	-
Total yield	139 ± 12	23 ± 5	33 ± 6
Data	139	23	33

Sources	
Photon ide	
Electron id	
Electron–pl	
Muon ident	
Missing E_T	
Lepton fake	
Photon fak	
Prompt lep	
Prompt pho	
Pile-up γ b	
Signal PDF	
Integrated	
$Z\gamma\gamma$ cross-s	
Signal MC	
Background MC statistics	0.4
Data statistics in loose-lepton and/or loose-photon region	5.4
Total systematic uncertainty	7.7
$ZZ\gamma$ and $ZZ(e\to\gamma)$ normalisation	2.6
Data statistics	14.8
Total statistical uncertainty	15.1

Limited by statistics: 92 signal events
Even dominant systematics are limited by statistics → Improve with more data

Summary of rare SM processes



Link to this plot

CMS version

The era of triple-boson measurements has begun!

The SM provides precise predictions; measurements will get better quickly

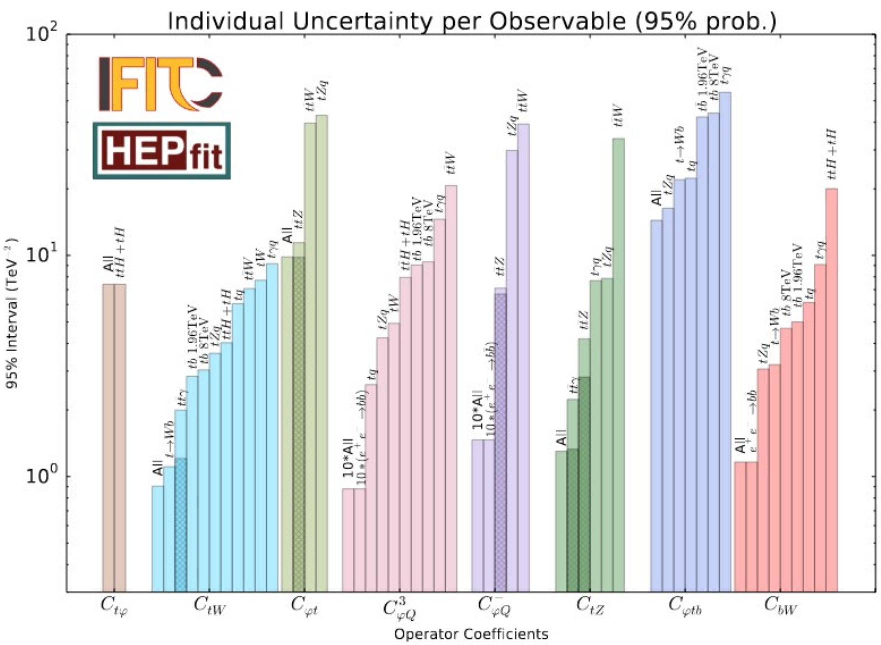
Rare top production processes at the LHC

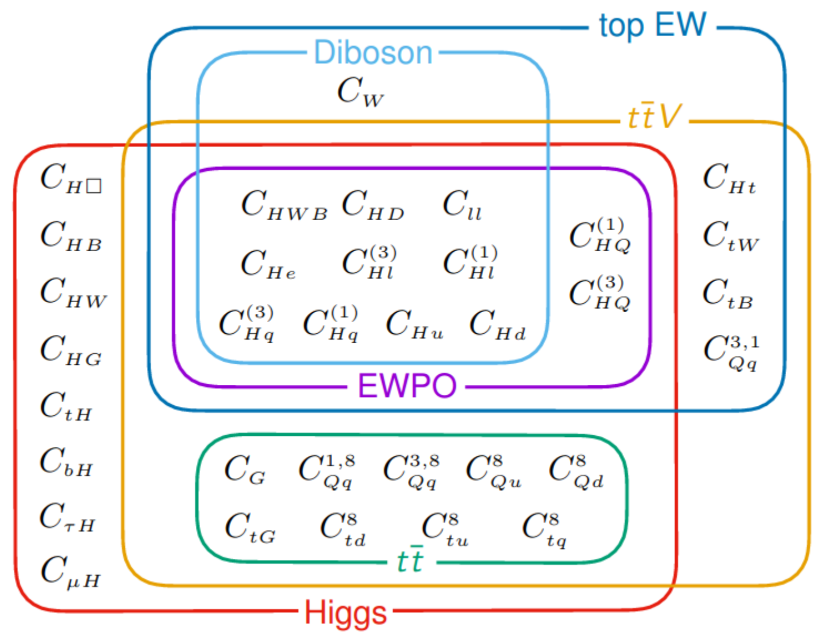
Tevatron and LHC have characterized top quark QCD couplings precisely

Charged-current tWb interaction constrained by single top and W-helicity

Couplings with γ/Z/H probed directly in top+X production for the first time
- ttZ, tZq, ttγ, tγq, ttH, ttW observed in run 2

ArXiv:2107.13917



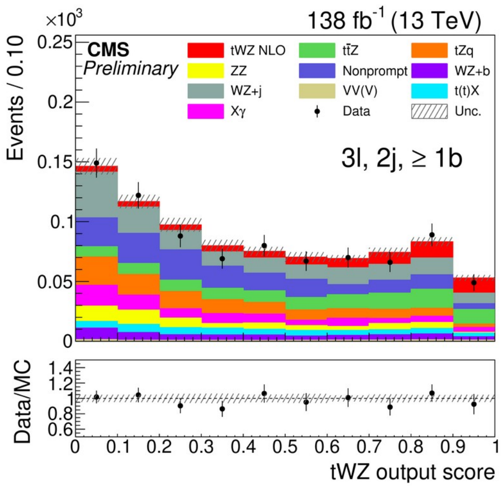


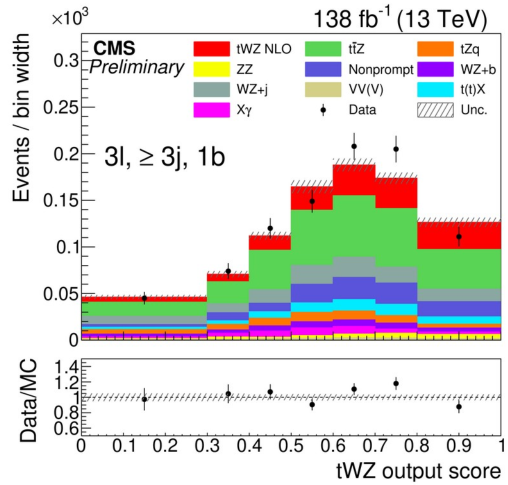
Constraining electro-weak couplings that were not probed directly before (as the top quark escaped scrutiny at LEP) + the top Yukawa coupling

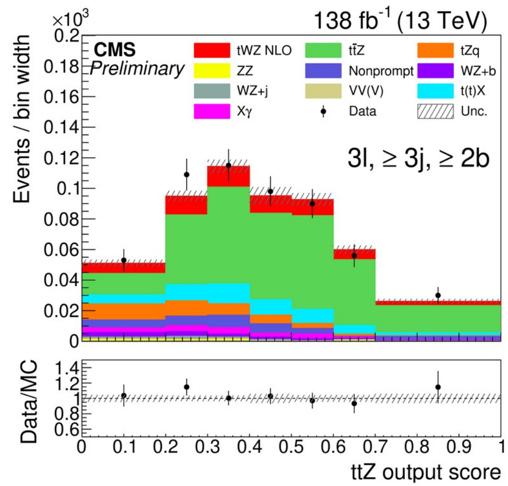
Evidence for tWZ production

CMS-PAS-TOP-22-008

The pp → tWZ process probes bW → tZ scattering; enhances SMEFT sensitivity
El Faham et al., arXiv:2111.03080, Maltoni et al., arXiv:1904.05637







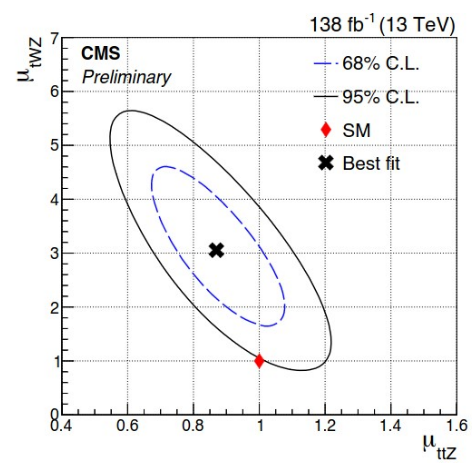
Difficulties: signal (4FS/5FS, DR/DS), and ttZ modelling

Expected : 136 ± fb (1.4 σ)

Measured : 370 ± 50 (stat) ± 10 (syst) fb (3.5 σ) Evidence!

2.1 σ above the SM expectations.

"The uncertainty associated with the ttZ normalization is found to have the dominant contribution to the systematic uncertainties. The reason of this behavior lies in the very similar nature of the tWZ and ttZ processes, observed as an anti-correlation feature in the statistical analysis."



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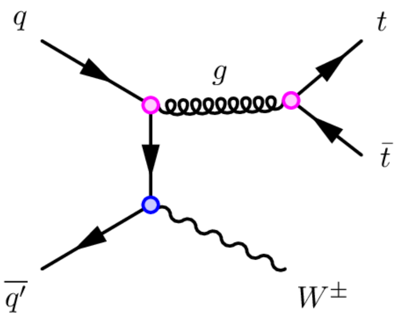
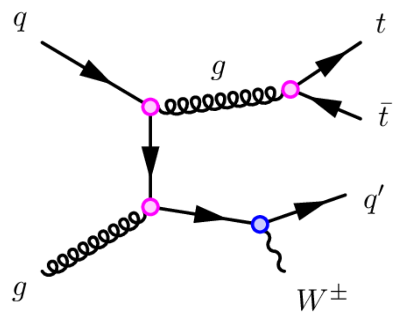
Rare associated top quark production: ttW



LO QCD ($\alpha\alpha_s^2$)

q$\bar{\text{q}}$ initial state

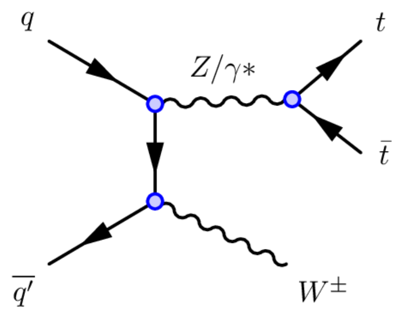
363 fb ± 20%



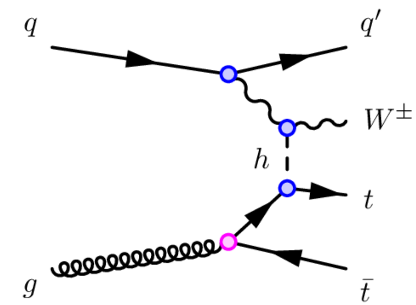
+NLO QCD ($\alpha\alpha_s^3$)

qg production opens up

544 fb ± 11%



+Tree-level EW (α^3)



+Mixed QCD/EW ($\alpha^3\alpha_s$)

t-W scattering

577 fb ± 11%

Numbers from JHEP 02 (2018) 031. See JHEP 08 (2019) 039 for resummation, EPJC 81 (2021) for off-shell contribution and JHEP 11 (2021) 029 LHC LHC top & Higgs WG Sep '22: reference = 720 ± 80 fb (Frederix & Tsinikos) LHC top WG June '23: aNNLO prediction: 745 ± 52 fb (Grazzini et al.)

A complex process made up of well-known g$t\bar{t}$ (o) and tWb (o) couplings

Hard: "Surprisingly" large NLO QCD correction + formally sub-dominant EW corrections

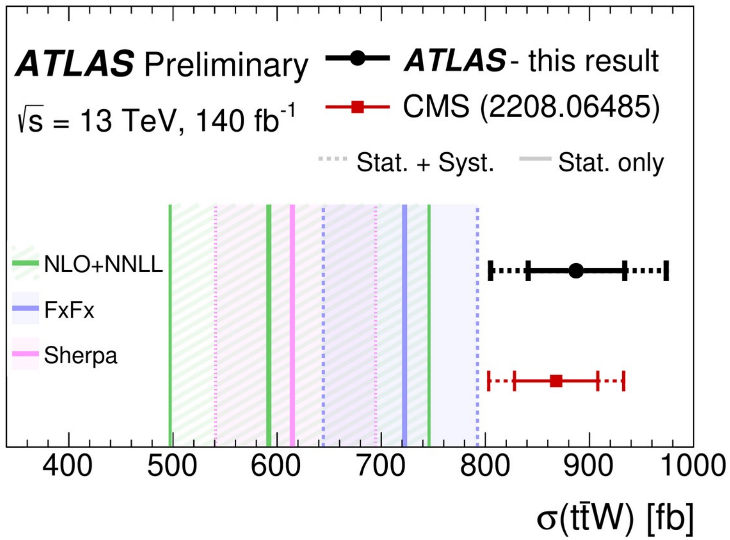
Important: The most important source of same-sign and three-lepton events

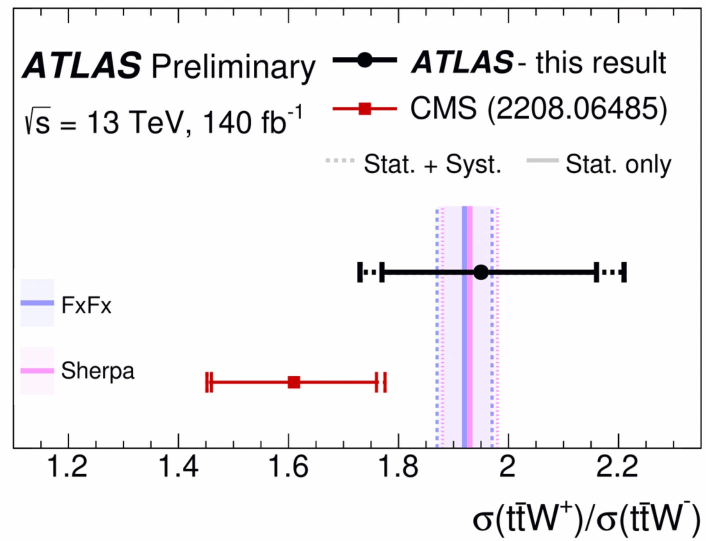
Rare associated top quark production: ttW

ATLAS: 890 ± 50 (stat) ± 70 (syst) ATLAS-CONF-2023-19

CMS: 870 ± 40 (stat) ± 51 (syst) fb arXiv:2208.06485

Both ATLAS and CMS see a slight excess (1.5σ each) wrt NLO





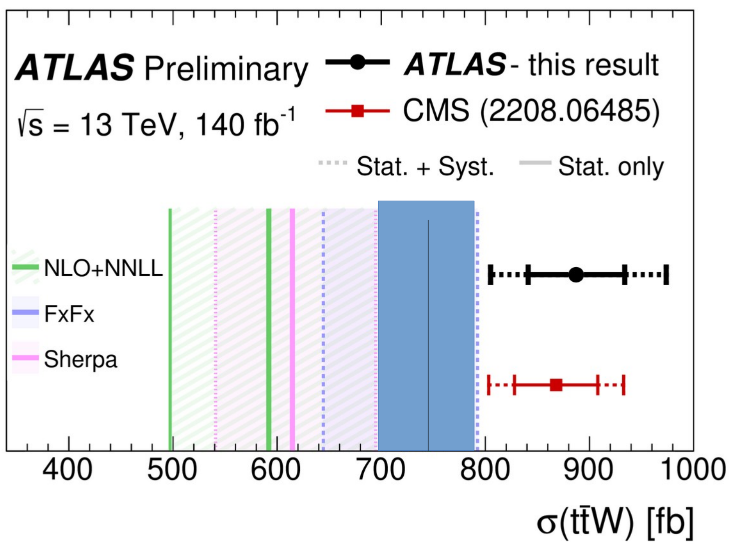
CMS measured a smaller asymmetry; not confirmed by ATLAS

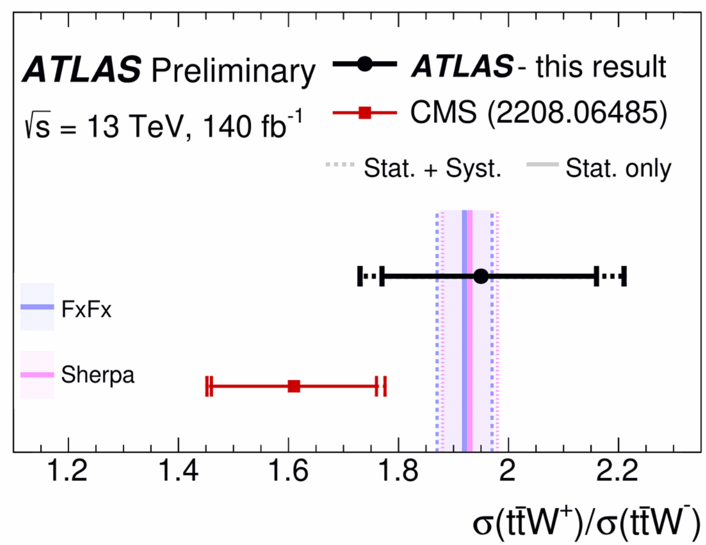
Rare associated top quark production: ttW

ATLAS: 890 ± 50 (stat) ± 70 (syst) ATLAS-CONF-2023-19

CMS: 870 ± 40 (stat) ± 51 (syst) fb arXiv:2208.06485

NNLO SM: 745 ± 50 fb (Buonocuore et al.) arXiv:2306.16311



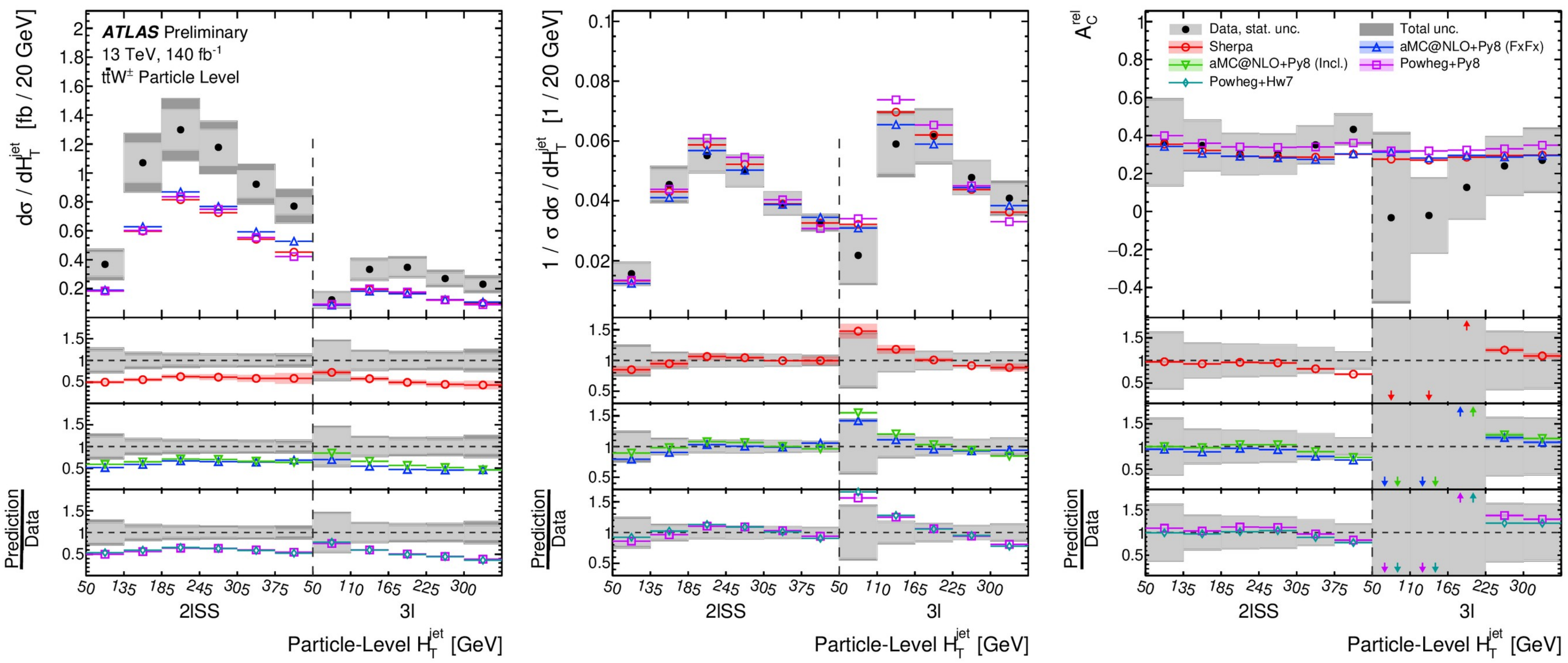


Slight excess is still there wrt NNLO prediction

Rare associated top quark production: ttW

Differential analysis

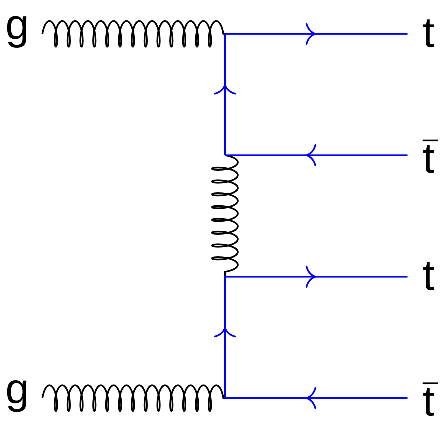
ATLAS-CONF-2023-19



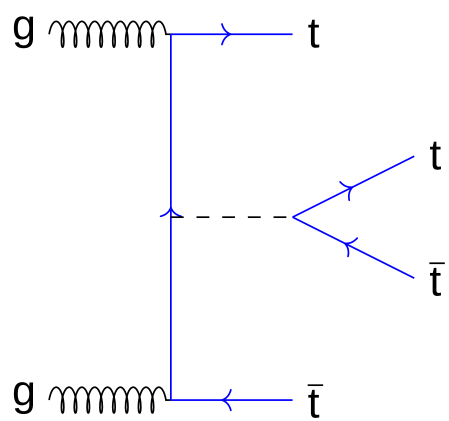
No obvious shape differences between data and SM predictions

New rare processes: tttt

QCD production (α_s^4)



Higgs-mediated production ($\alpha_s^2 y_t^4$)



A simple process that probes uncharted tttt and ttH couplings

Standard Model prediction: extremely rare at O(10 fb)

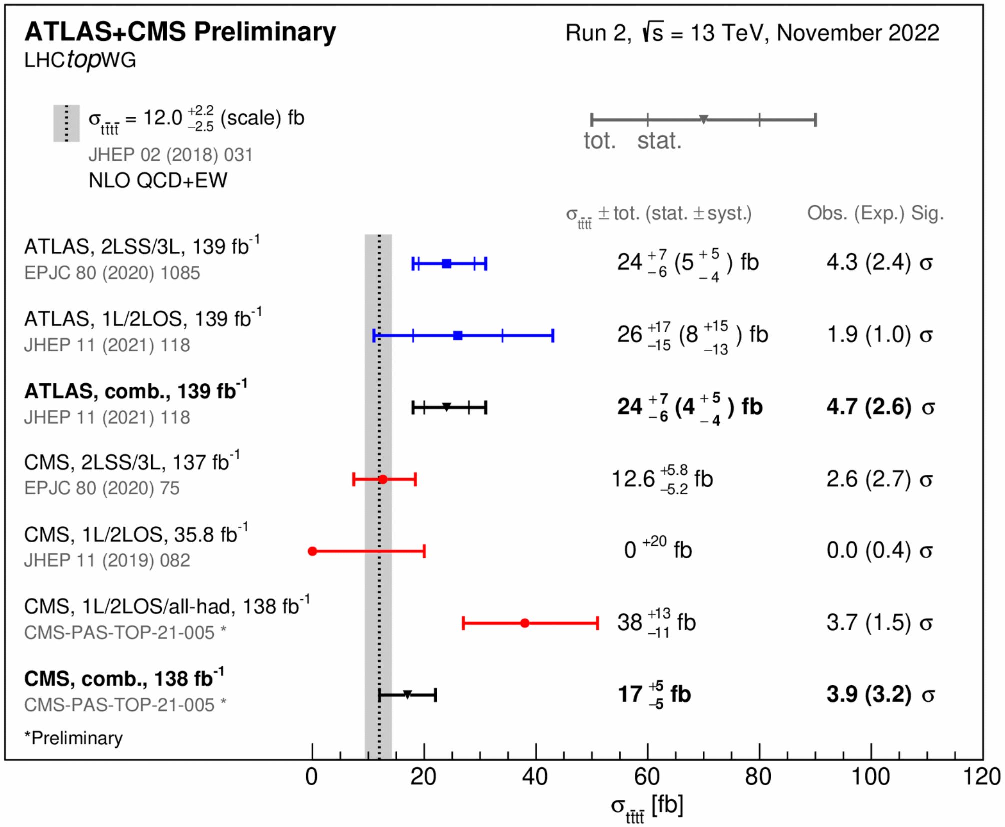
NLO QCD + EW: 12 fb ± 20% (Frederix '17) NLO + NNLL: 13.4 fb+7%-14% (van Beekveld ‘22)

Strong enhancement possible in SUSY, 2HDM, compositeness scenarios

Lillie, Shu, Tait (2008): “We find that a composite top can result in an enhancement of the tttt production rate at the LHC (of as much as 10^3 compared to the Standard Model four top rate)”.

The search for 4top production

After 4 years of data taking + another 4 years analyzing the data



Status at TOP22 in Durham:

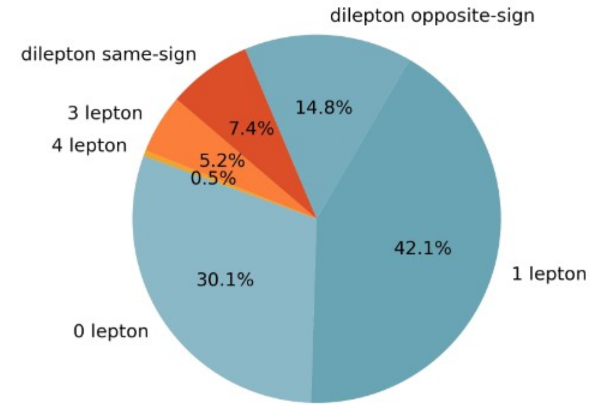
ATLAS had done a same-sign + multi-lepton analysis and a 1-lepton + 2-lepton opposite sign analysis
combined significance: 4.7 sigma

CMS had done all that and even added an all-hadronic analyis
combined significance: 3.9 sigma

Strong evidence in both experiments, but no observation!

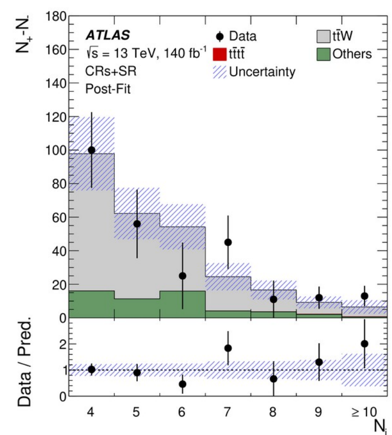
Refined re-analysis of run 2 in same-sign & multi-lepton

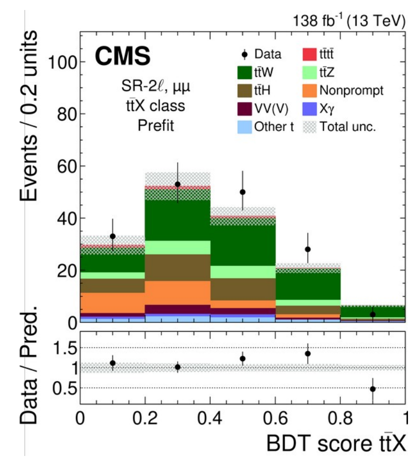
Focus on the most powerful channels: Same-Sign & Multi-Lepton
→ uses fraction of total production: **several 10s of events**
→ requires **control over non-prompt leptons**



Save every signal event: 13.4 fb (~ 2000 evts/exp.)
→ lower cuts on leptons (ATLAS: 15 GeV, CMS: 10 GeV)
→ lower cuts on jets (ATLAS: 20 GeV, CMS: 25 GeV)
→ highest b-tagging efficiency (ATLAS: 77%, CMS: 90%)

Irreducible background from ttW, ttZ, ttH, O(1 pb)
Complex processes; need description of ttX+HF
→ S/B separation with multi-variate analysis
→ data-driven normalization
(ATLAS: ttH, CMS: ttH/ttZ/ttW)
→ data-driven shape (ATLAS: ttW)



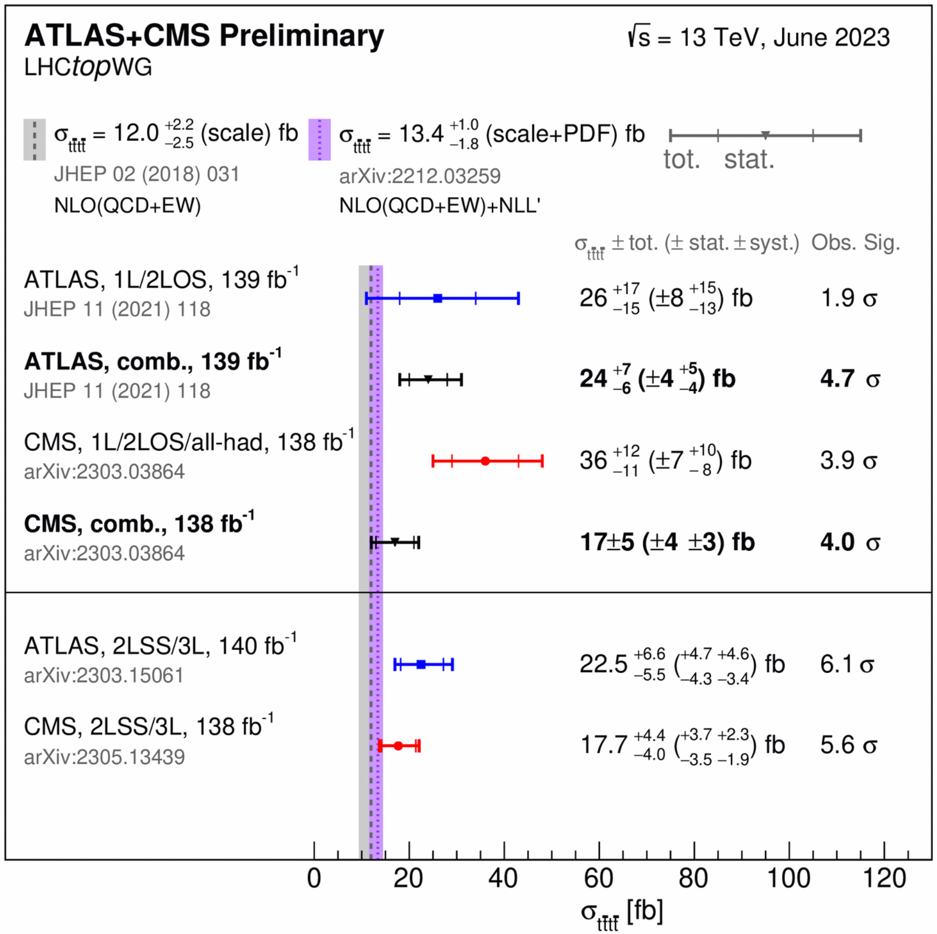


Expected sensitivity increases strongly
→ ATLAS: 2.4σ → 4.3σ (4.7σ with new ref. xsec)
→ CMS: 2.7σ → 4.9σ

Data makes you smarter!!

The search for 4top production

After 4 years of data taking + another 4 years analyzing the data



At Moriond '23:

Both collaborations presented a re-analysis of the most powerful channel: better signal acceptance, better calibrations, better ML discriminant, better background estimates…

Double observation!

ATLAS: **6.1σ** EPJC83 (2023) 496,
https://atlas.cern/Updates/Physics-Briefing/observation-4tops

CMS: **5.6σ** arXiv:2305.13439

Precision for rare processes

SM prediction

$13.4^{+1.0}_{-1.8}$ fb

Tiny Standard Model rate (van Beekveld et al.)

ATLAS

$22.5^{+6.6}_{-5.5}$ fb

ATLAS refined same-sign & multi-lepton analysis

CMS

$17.9^{+4.4}_{-4.1}$ fb

CMS refined same-sign & multi-lepton analysis

Measured cross section compatible with SM (incl. 4-top + 3-top) within 2σ (ATLAS) / 1σ (CMS). Stay tuned!

See: V. Wachirapusitanand, D. Dobur & T. Barillari in Collider Precision track + poster by H. Potti

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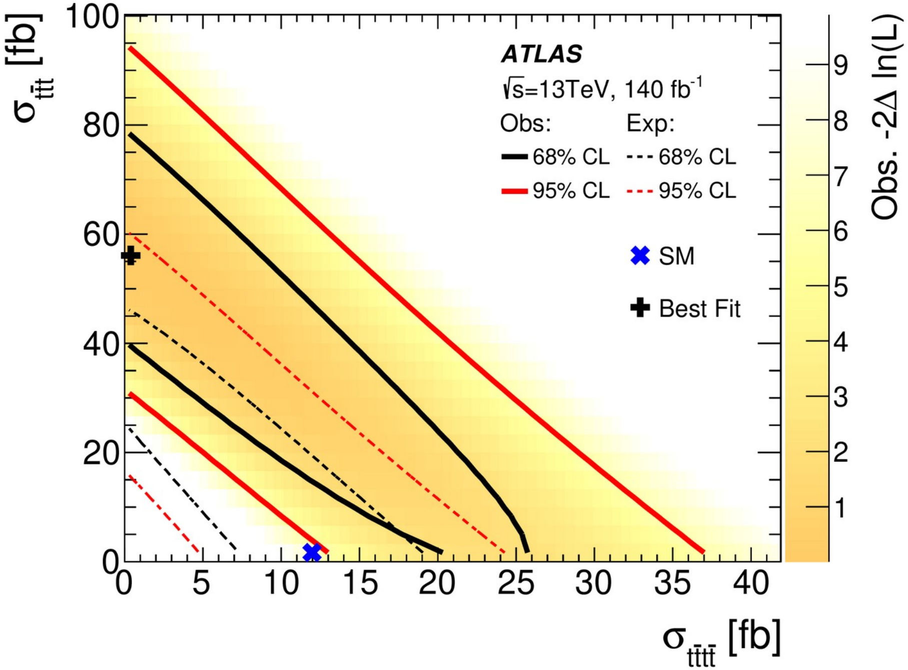
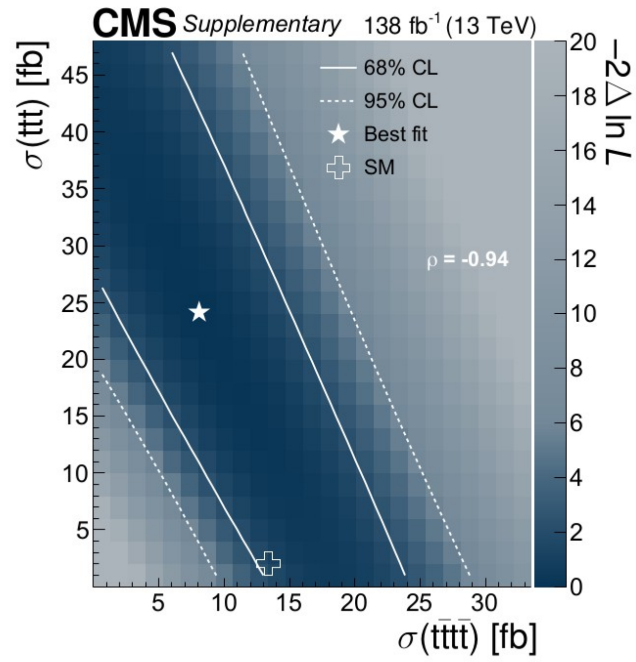
Three-top-quark production

In the SM 3-top-quark (tttq + tttW) is 10 times less abundant than 4-top-production
A background with a surprisingly large impact (and/or a new target for searches)

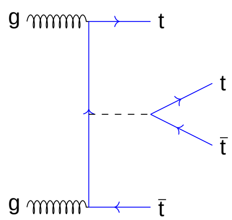




In the 4-top search, 3-top is treated as a background with a 20% (CMS) or 35% (ATLAS) uncertainty (LO/NLO QCD)
If both rates are floated freely, analyses cannot disentangle 4top and 3top effectively; future analyses to clarify signal composition
Modelling must improve for a robust separation and modelling uncertainties must be refined

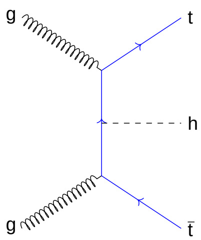
Anonymous CMS member: for now, let's settle on 3½ top

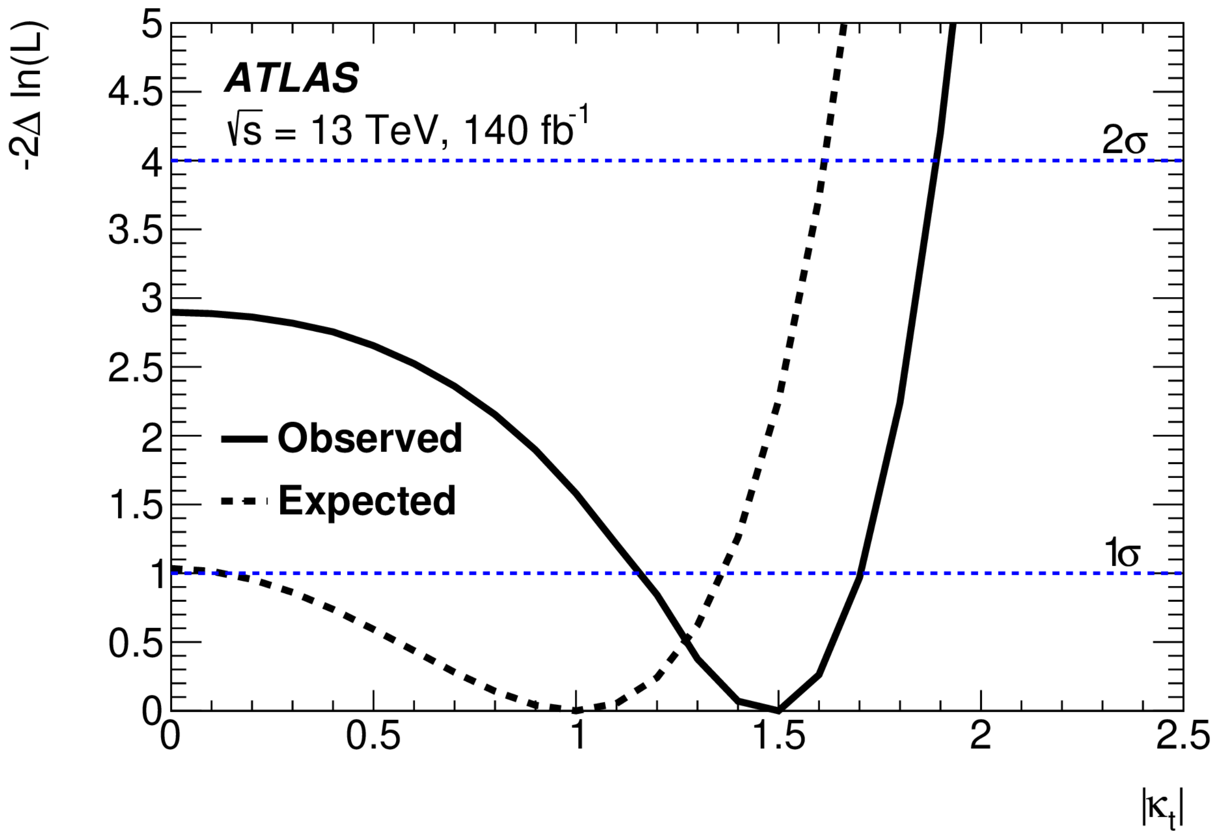
4-top and the Yukawa coupling



4-top production through Higgs depends on top Yukawa

Additional sensitivity through ttH background





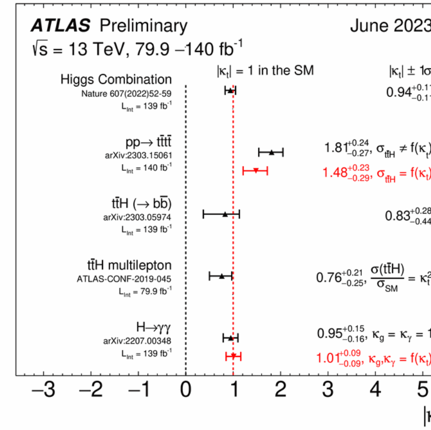
Preferred interval:

$k_t = 1.48^{+0.23}_{-0.29}$

Cornering the top quark Yukawa coupling

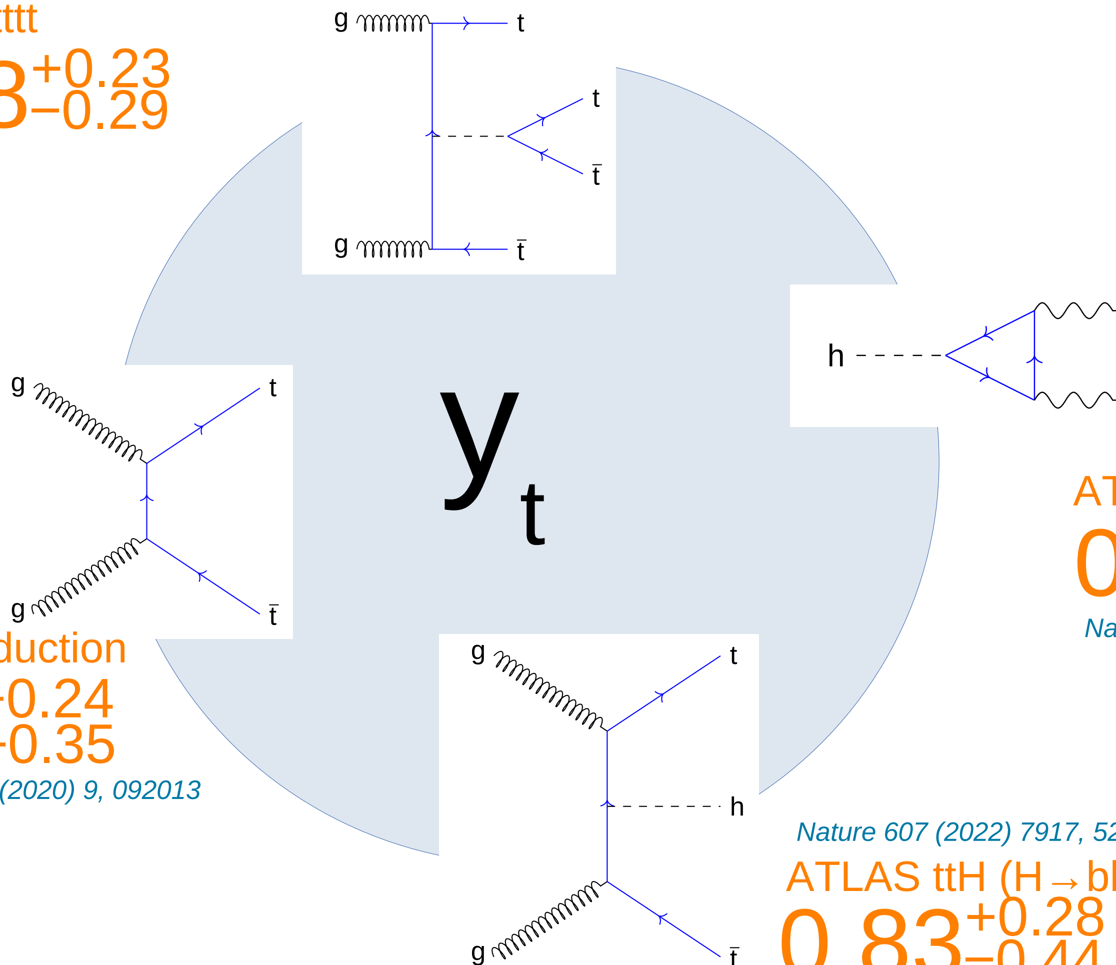
Direct (i.e. tree-level) bounds: ttH and tttt

Loop-induced bounds: $H\rightarrow\gamma\gamma$, $gg\rightarrow H$, $pp\rightarrow t\bar{t}$



ATLAS summary plot

EPJC83 (2023) 496,
ATLAS tttt
$1.48^{+0.23}_{-0.29}$



Nature 607 (2022) 7917, 60-68
CMS Higgs
$1.01^{+0.11}_{-0.10}$

ATLAS Higgs
$0.94^{+0.11}_{-0.11}$
Nature 607 (2022) 7917, 52-59

CMS tt production
$1.16^{+0.24}_{-0.35}$
Phys.Rev.D 102 (2020) 9, 092013

Nature 607 (2022) 7917, 52-59
ATLAS ttH ($H\rightarrow bb$)
$0.83^{+0.28}_{-0.44}$

Summary

LHC run 2 data open up a whole range of "new SM physics", rare SM processes that were previously inaccessible

vector-boson-scattering
tri-boson production
associated top quark production
four-top-quark production

Today's rare processes; tomorrow's precision physics
→ improved and complementary sensitivity to SM and SMEFT parameters
Preparing to dig even deeper in run 3 and HL-LHC
→ longitudinally polarized VBS, tWZ, ttt, tH, di-Higgs production…. BSM physics?

Specific challenges:
- treatment of multiple signals
- modelling of complex processes (handing over to Davide Napoletano)

Check out the "collider precision" and "BSM" parallel tracks for more
Keep an eye on the public results pages of ATLAS and CMS

A challenge: combinable measurements

A wealth of rare processes has been found and there's more to come

→ important handles to overconstrain global fits of SM/EFT parameters

But: many processes yield similar and complex final states

→ hard to isolate processes cleanly

Provide data in flexible and unbiased format

→ complete likelihood with correlations

→ avoid subtracting SM backgrounds

→ fit bkg. to data or fit "multiple signals"

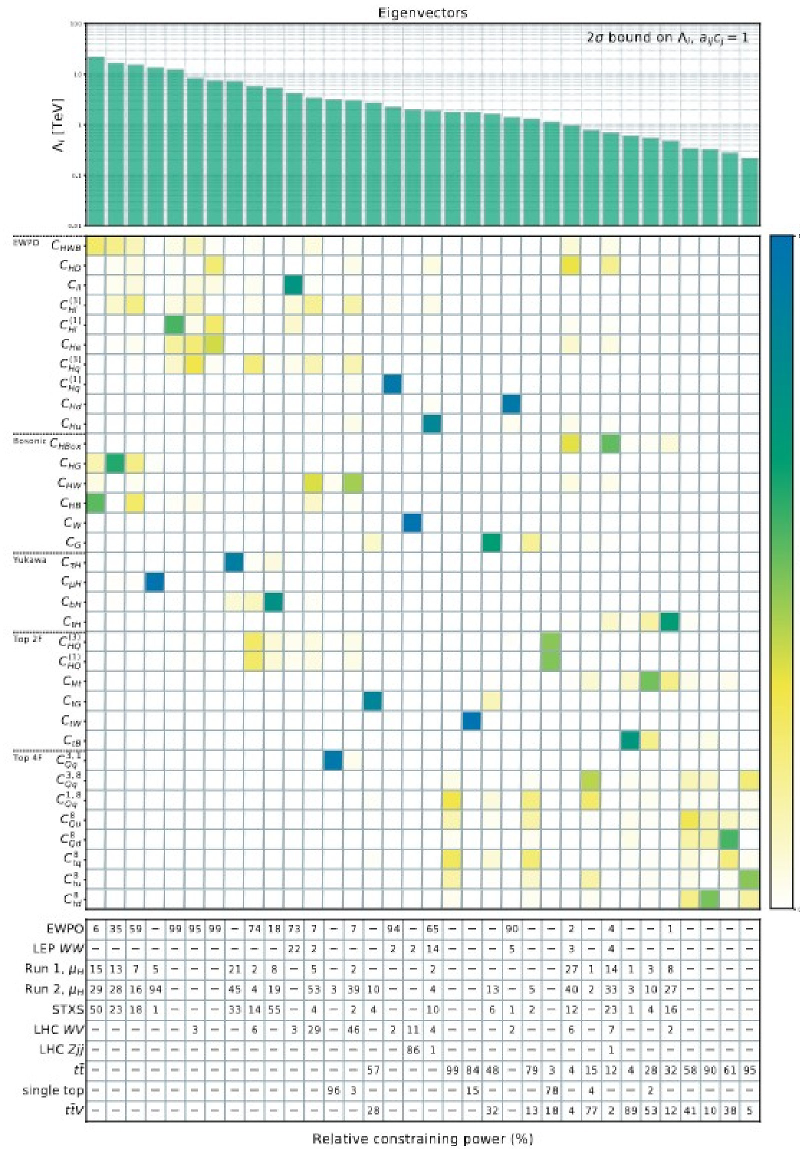


Figure from: Ellis et al., arXiv:2012.02779

A challenge: modelling of rare processes

Our rare processes are no longer statistics-limited

→ go differential, measure asymmetries, find new, still more rare, processes

→ AND (last but not least) work on systematics

Modelling of rare processes (ttZ, ttW, tttt, ttt, tWZ) is challenging

→ multiple scales, large EW corrections, complex and CPU-intensive diagrams, multi-leg

→ several measurements with larger-than-SM cross sections (ttW~1.4, tqγ~1.4, tttt~2)

→ several processes not observed yet (tWZ, ttt, ...)

CMS: scale and PDF variations

ATLAS: scale and PDF variations **+ two-point comparisons**

Neither is very satisfactory; replaced by a more refined estimate

I get to leave this challenge for the Davide Napoletano!

Addressing the challenge of rare processes

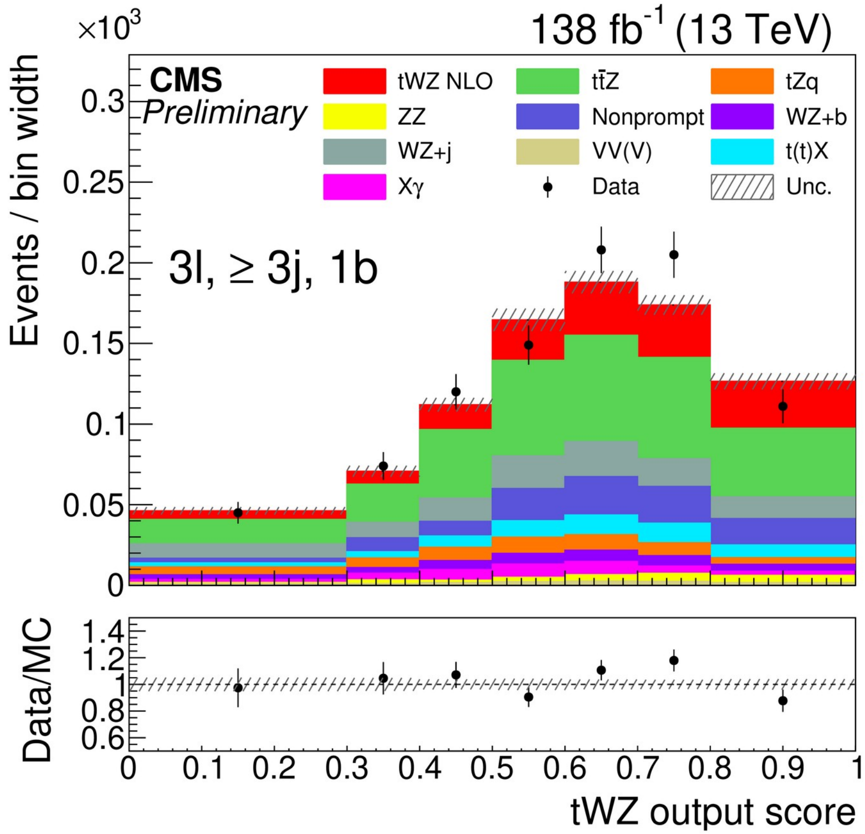
Fourth ingredient: the most powerful analysis techniques

- profile-likelihood fits can deal with multiple floating “signals”
- state of the art machine learning algorithms to maximize separation
- we thank the broader community developing these crucial tools

Deep Neural Network output score for tWZ signal (136 fb in the SM) and ttZ background (863 fb in the SM) (one out of multiple Signal Regions + Control Regions for ZZ and WZ)

From: evidence for tWZ, CMS-PAS-TOP-22-008

Similar issues in separating tttt-ttW-ttt

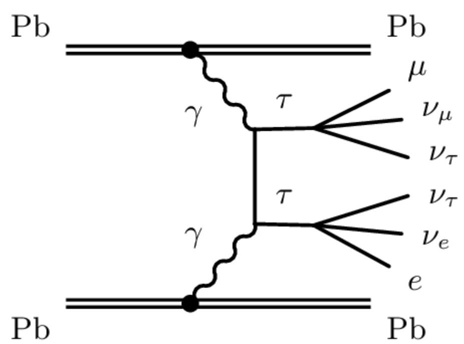


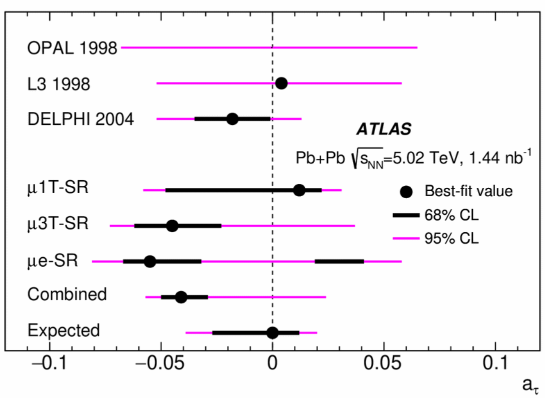
Scope of this talk

Covered: Searches for rare SM processes at the LHC

Related, and only covered superficially in this talk:
Measurements are a test of the SM/EFT → Valentina Cairo & Rick Gupta
SM parameter extractions (m_t, α_s, Higgs couplings) → Linda Finco & Joao Da Costa

Observation of τ-lepton pair production in ultraperipheral lead-lead collisions (γγ→ττ)





ATLAS
arXiv:2204.13478
For more photon-initiated physics, see
CMS/TOTEM:
arXiv:2211.16320

Bounds on g-2 of the tau lepton of similar precision as current best bounds from LEP

Not covered:
Exotica/SUSY (Chen & Liu + BSM track)
Higgs properties (Linda Finco + precision track)
Flavour (Giri & Feuillard + flavour track)

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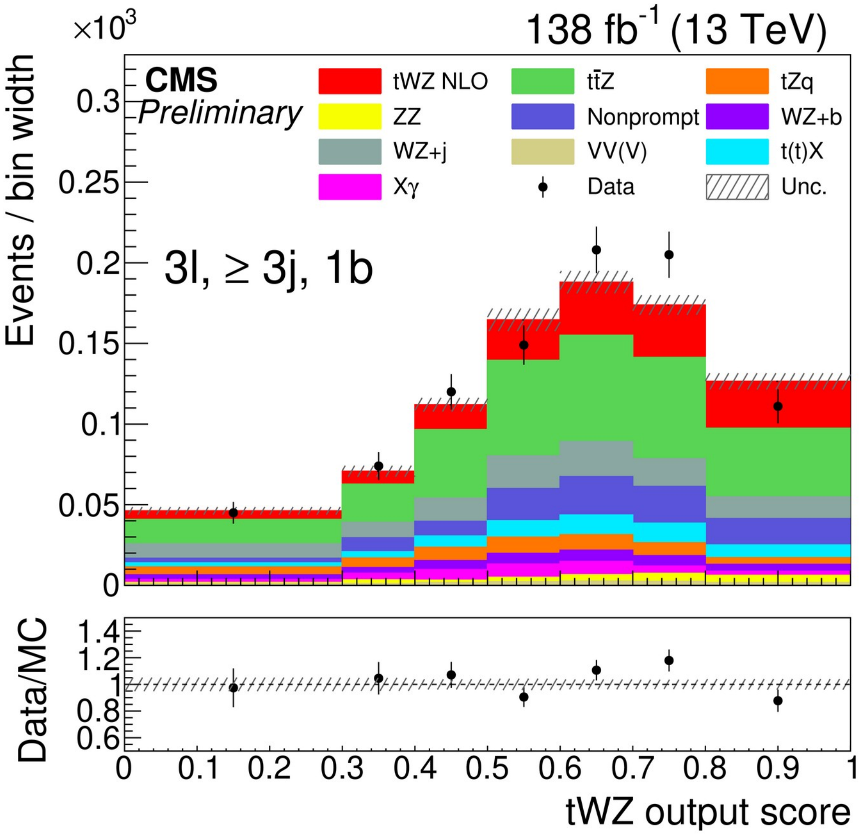

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