Standard Model (Including Top) Measurements at the LHC

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On behalf of the ATLAS and CMS Collaborations

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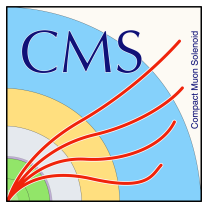


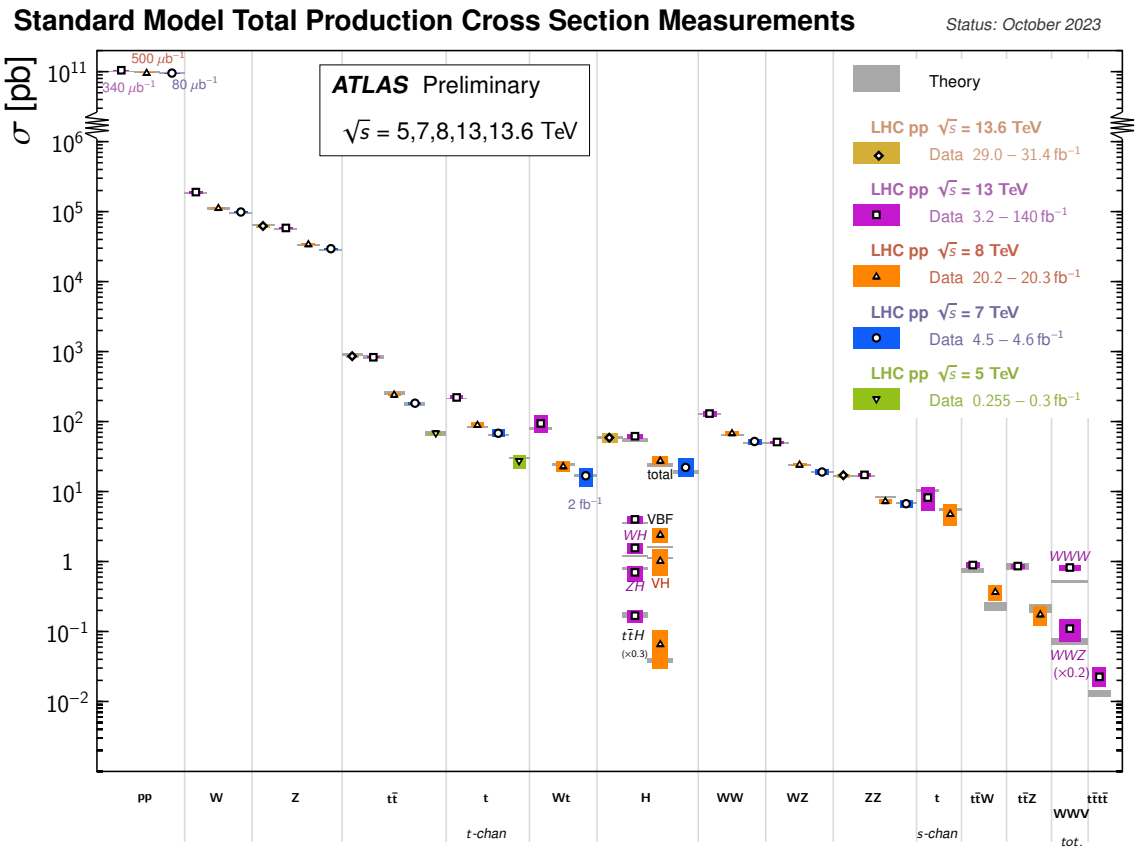
Introduction

O(70) papers and preliminary results on SM and top for ATLAS and CMS since SUSY 2023 - too many to cover in detail today. I will focus on results I think will be of most interest here:

- Measurements of fundamental SM parameters
- Entanglement
- Searches for anomalous couplings and conservation law-violating phenomena
- Measurements including EFT interpretation
- SUSY-search adjacent measurements
- Measurements with Run 3 data

An exhaustive list of all results is in the backup slides

The SM at LHC Runs 1-3



CMS equivalent available here

- Remarkable SM agreement for σ across many orders of magnitude
- Horribly good performance of the SM continues
- But we can test it with unprecedented precision and see if it breaks

Measurements of Fundamental SM Parameters

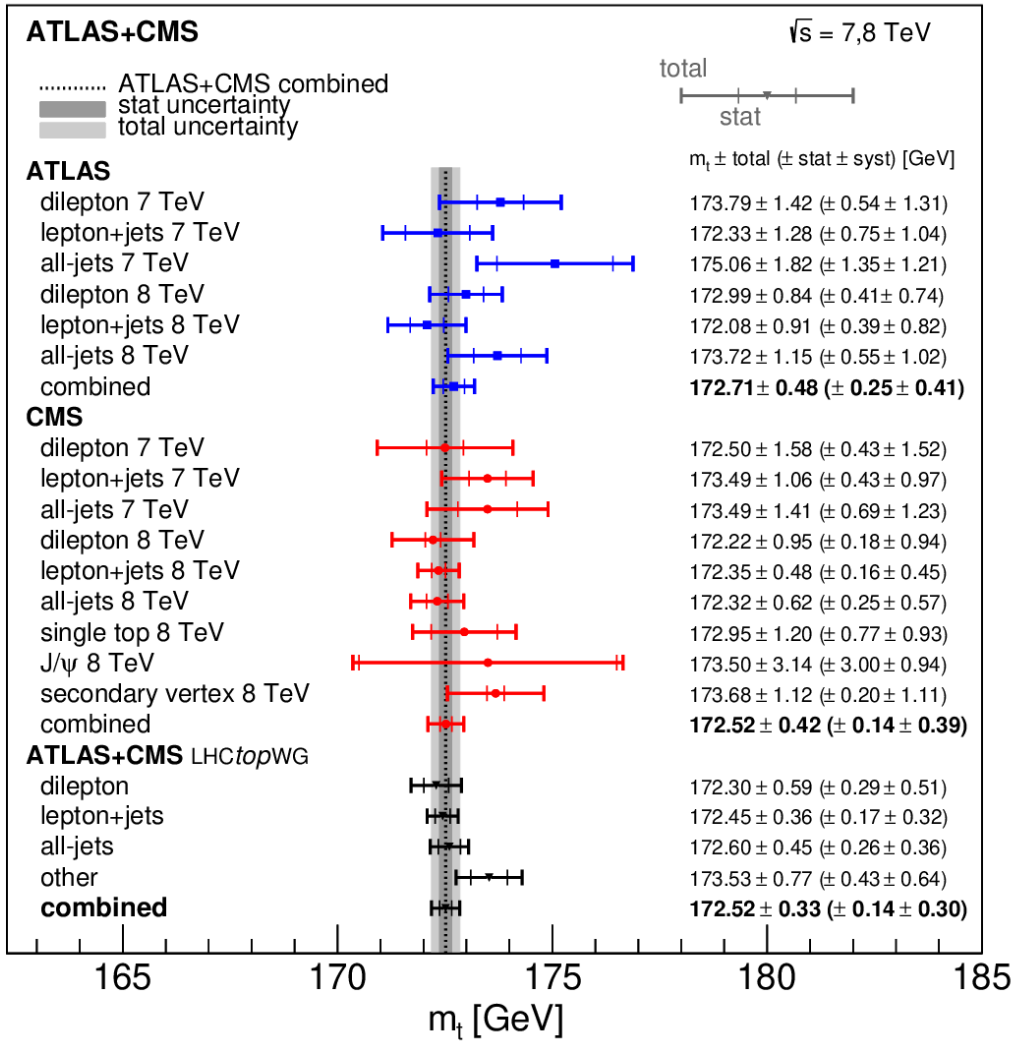
Featuring:

- ATLAS
  - arXiv:2403.15085 Measurement of the W-boson mass and width
  - arXiv:2309.12986 Precise determination of the strong-coupling constant from the recoil of Z bosons
  - Eur. Phys. J. C 84 (2024) 315 Double-diff. Z-boson p_{T} and y distributions in the full phase space
- CMS
  - CMS-PAS-SMP-22-010 Measurement of Drell-Yan forward-backward asymmetry and effective leptonic weak mixing angle
- ATLAS+CMS
  - arXiv:2402.08713 Combination of measurements of the top quark mass from the ATLAS and CMS experiments at $\sqrt{s} = 7$ and 8 TeV

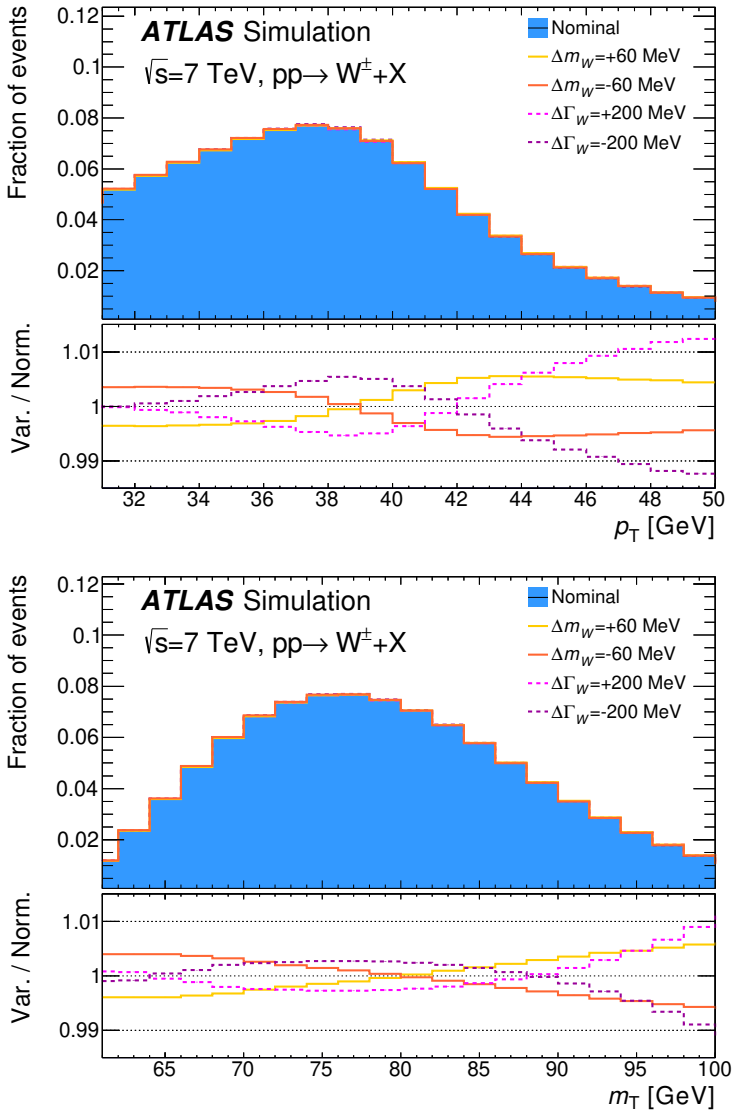
ATLAS+CMS: m_t combination

New combined LHC Run 1 top-mass measurement

- Central value: 172.52 ± 0.33 GeV
- Combined measurements of individual experiments consistent with each other
- Leading systematics:
  - Jet energy scale (especially for *b*-jets)
  - *b*-tagging
  - MC modelling (ME generator, QCD radiation)



ATLAS: m_W and Γ_W

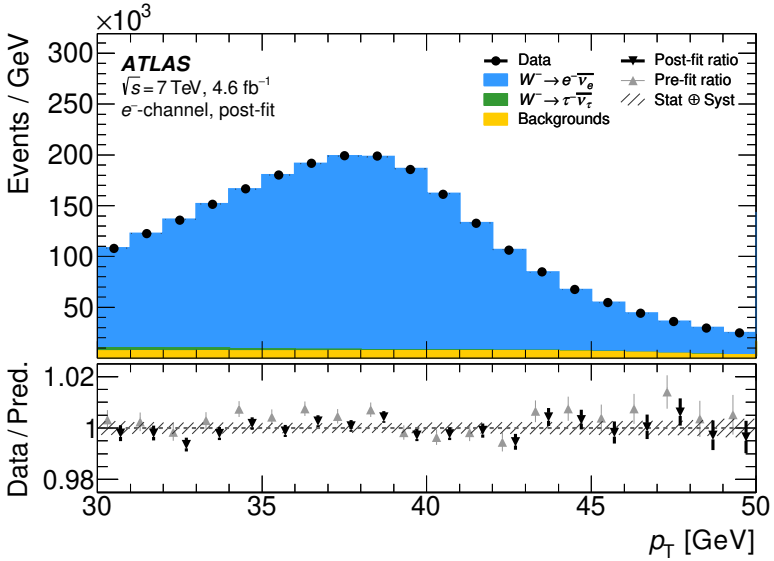


New ATLAS measurement of mass and width of W boson:

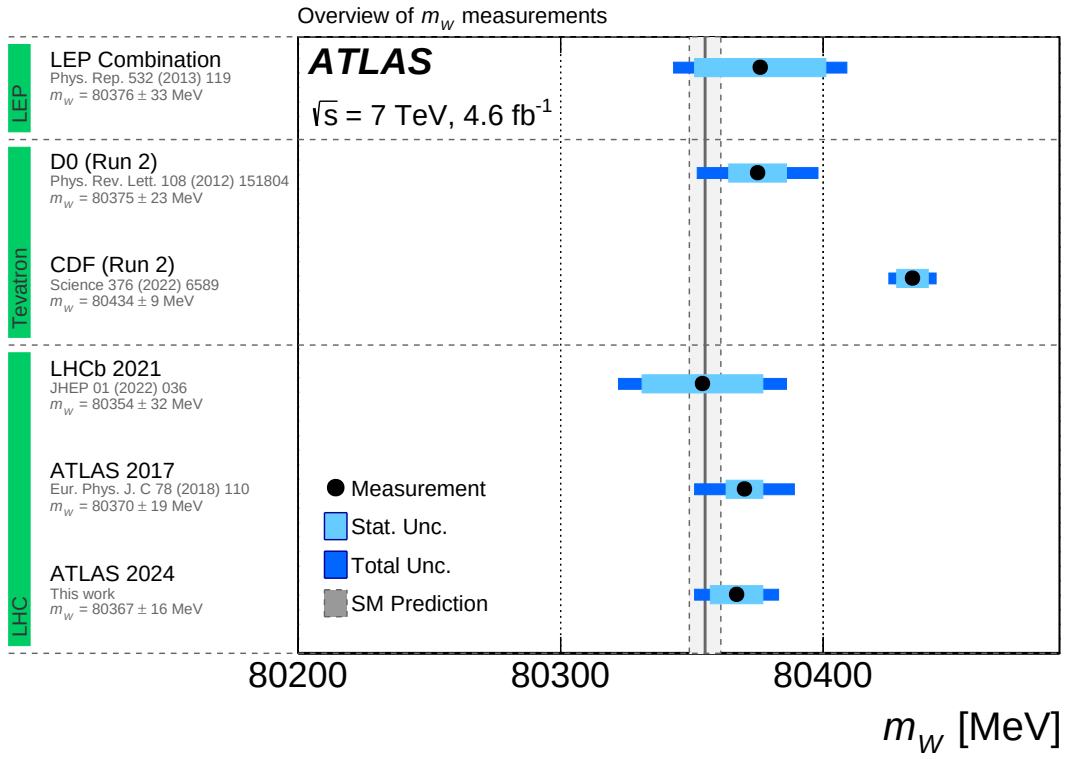
- Uses combined fit of p_T^ℓ and m_T distributions
- Categorise by W charge, decay channel, and $|\eta_\ell|$
- Updates compared to previous m_W:
  - PLH fit instead of separate template fits
  - New Lumi $\rightarrow$ new MJ background
  - Updated Proton PDFs
  - Treat Γ_W as a systematic

Decay channel	$W \rightarrow e\nu$	$W \rightarrow \mu\nu$
Kinematic distributions	p_T^ℓ, m_T	p_T^ℓ, m_T
Charge categories	W^+, W^-	W^+, W^-
$\|\eta_\ell\|$ categories	$[0, 0.6]$, $[0.6, 1.2]$, $[1.8, 2.4]$	$[0, 0.8]$, $[0.8, 1.4]$, $[1.4, 2.0]$, $[2.0, 2.4]$

ATLAS: m_W - I

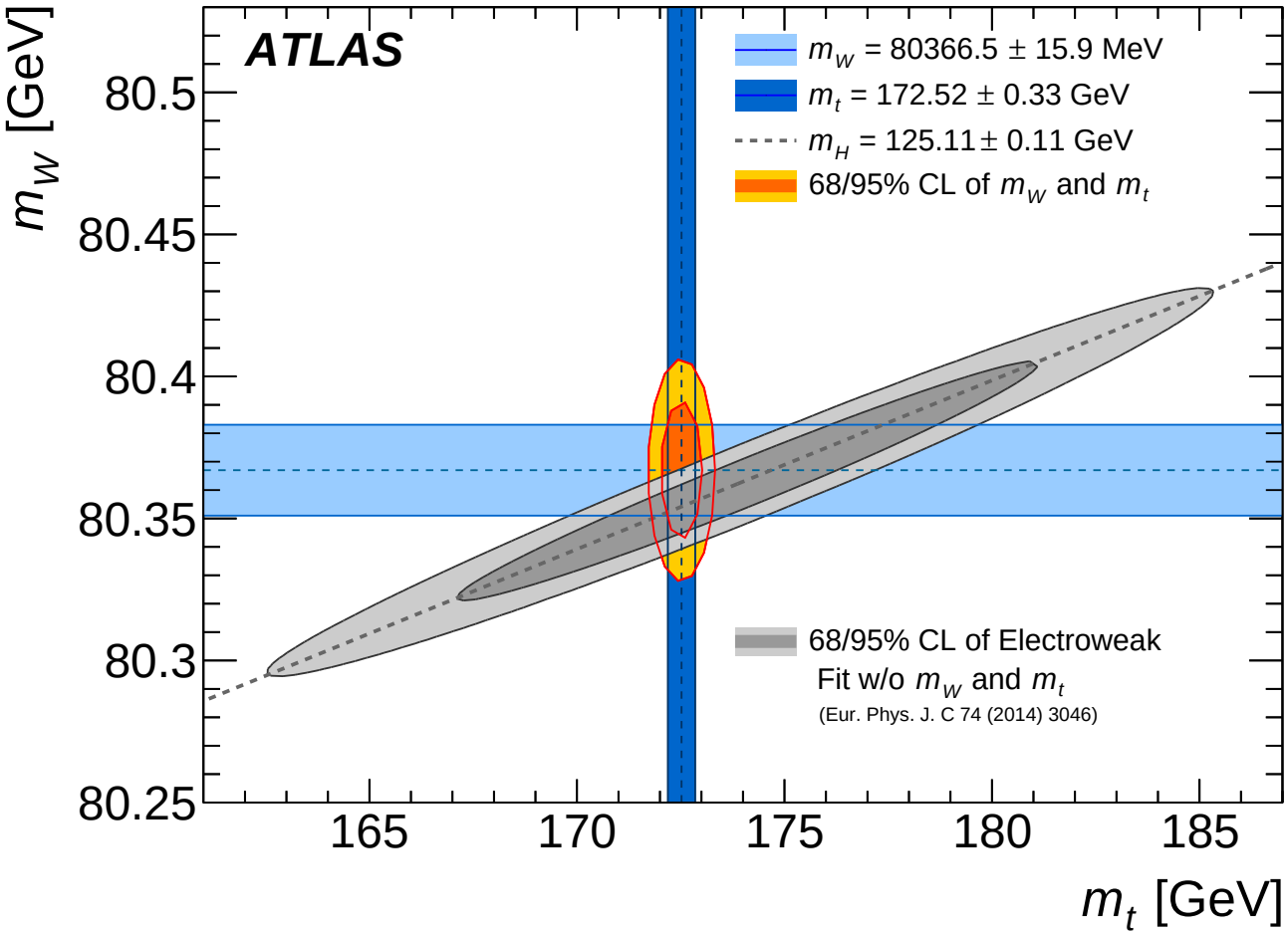


- p_T^ℓ dominates combination for m_W
- ±16 MeV precision
- Compatible with previous measurements (except latest CDF)



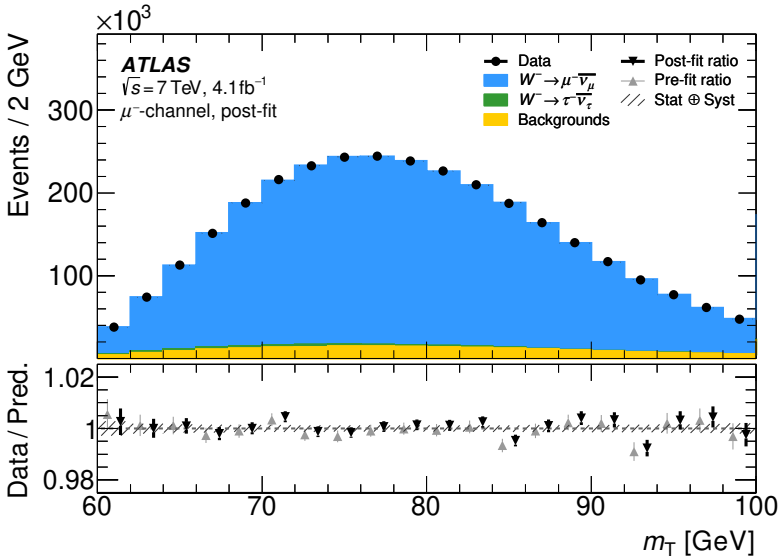
Unc. [MeV]	Total	Stat.	Syst.	PDF	A_i	Backg.	EW	e	μ	u_T	Lumi	Γ_W	PS
p_T^ℓ	16.2	11.1	11.8	4.9	3.5	1.7	5.6	5.9	5.4	0.9	1.1	0.1	1.5
m_T	24.4	11.4	21.6	11.7	4.7	4.1	4.9	6.7	6.0	11.4	2.5	0.2	7.0
Combined	15.9	9.8	12.5	5.7	3.7	2.0	5.4	6.0	5.4	2.3	1.3	0.1	2.3

ATLAS: m_W - II



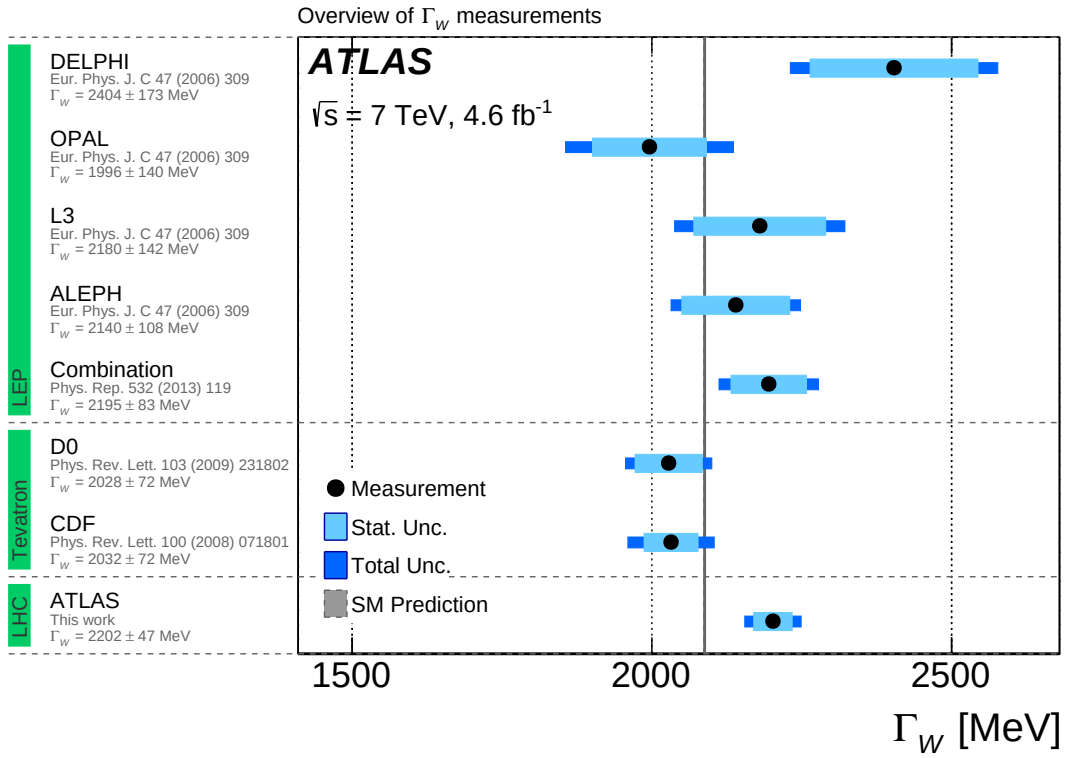
ATLAS m_W, and ATLAS+CMS m_T values consistent with electroweak fit

ATLAS: Γ_W - I



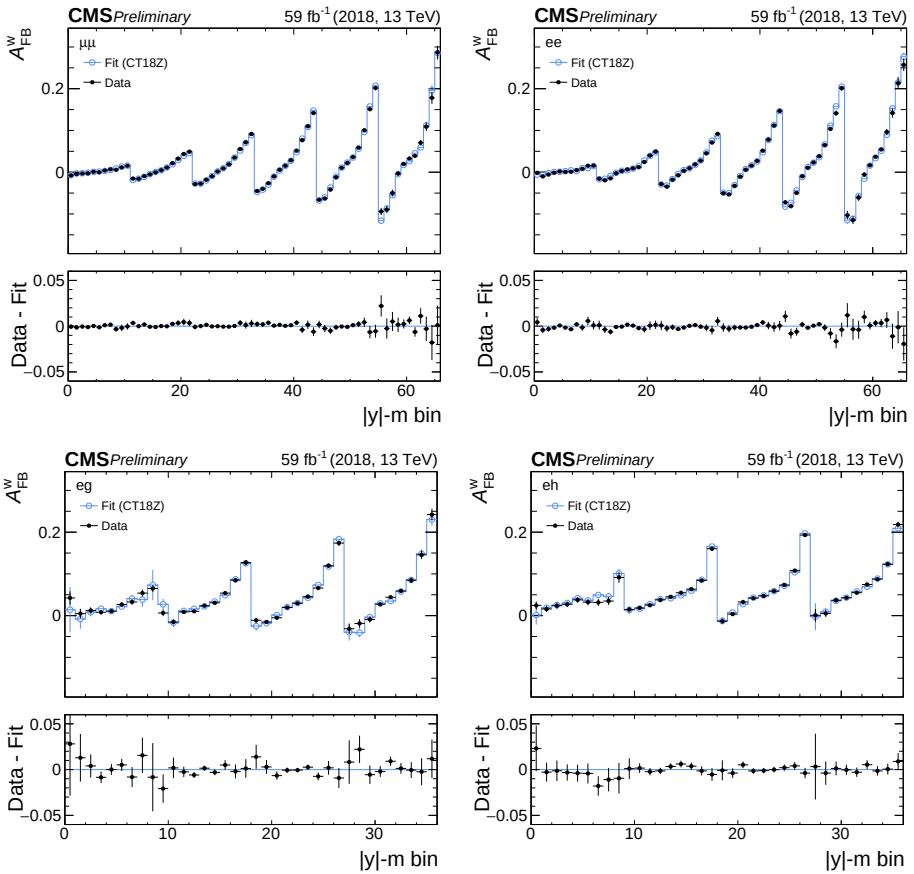
First LHC Γ_W measurement:

- Combination dominated by m_T distribution
- ± 47 MeV Uncertainty
- Within 2-3 standard deviations of SM prediction for Γ_W



Unc. [MeV]	Total	Stat.	Syst.	PDF	A_i	Backg.	EW	e	μ	u_T	Lumi	m_W	PS
p_T^ℓ	72	27	66	21	14	10	5	13	12	12	10	6	55
m_T	48	36	32	5	7	10	3	13	9	18	9	6	12
Combined	47	32	34	7	8	9	3	13	9	17	9	6	18

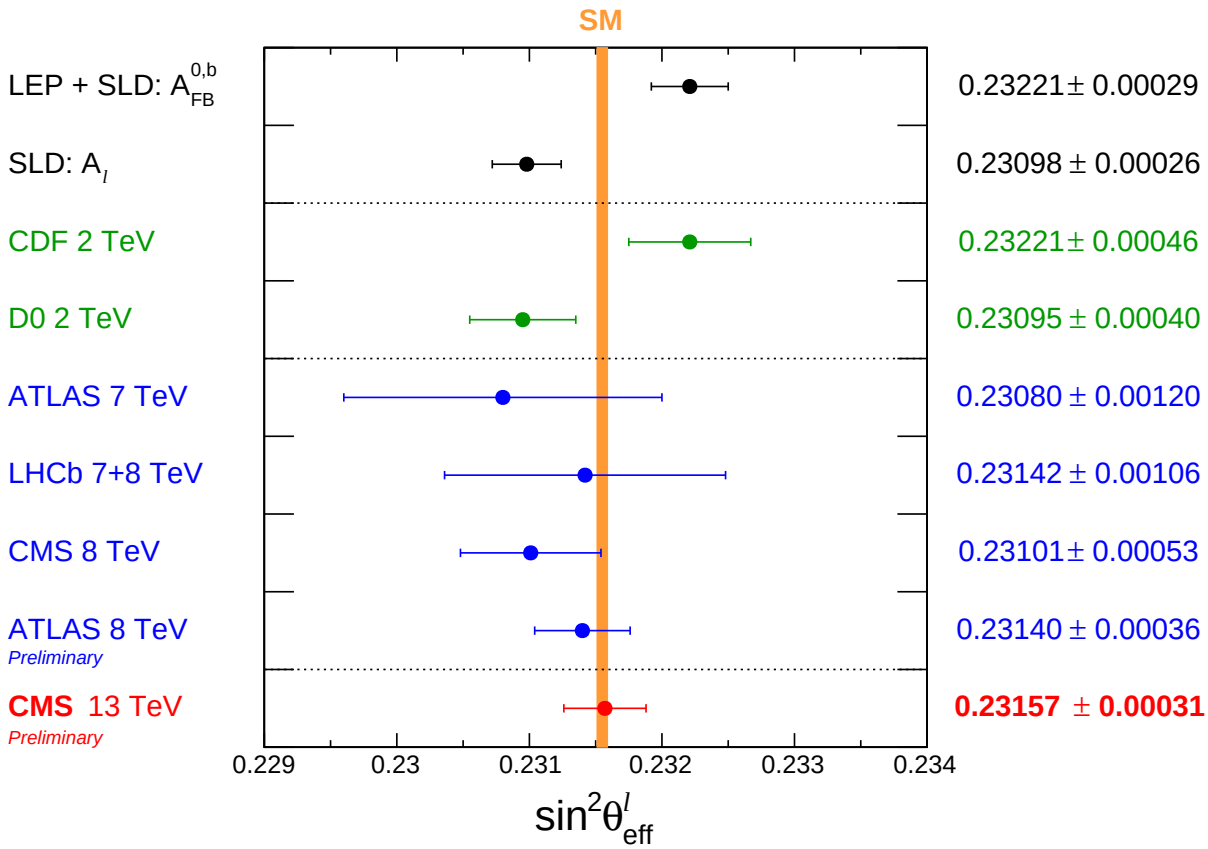
CMS: $\sin\theta_\ell^{\text{eff}}$ - I



- In the SM, $\sin\theta_\ell^{\text{eff}} \approx 1.037 \sin\theta_W$
- It drives the Forward-backwards asymmetry (A_{FB}) in Drell-Yan $\ell^+\ell^-$ production.
- CMS have measured A_{FB} in bins of $m_{\ell\ell}, |y_{\ell\ell}|$
- $54 < m_{\ell\ell}(\text{GeV})) < 150$, $0 < |y_{\ell\ell}| < 3.4$
- From this they are able to extract $\sin\theta_\ell^{\text{eff}}$

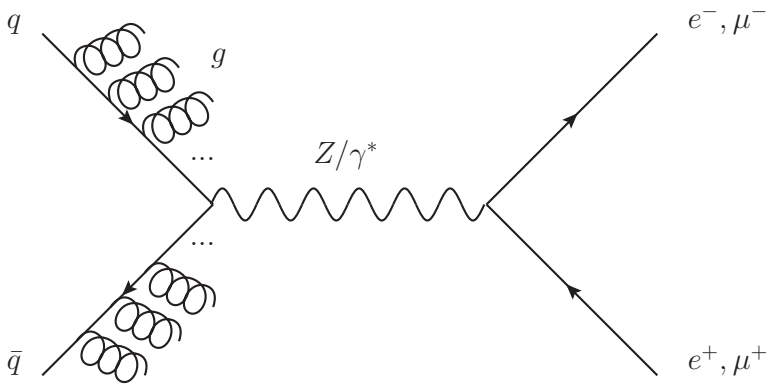
CMS: $\sin\theta^{\text{eff}}_{\ell}$ - II

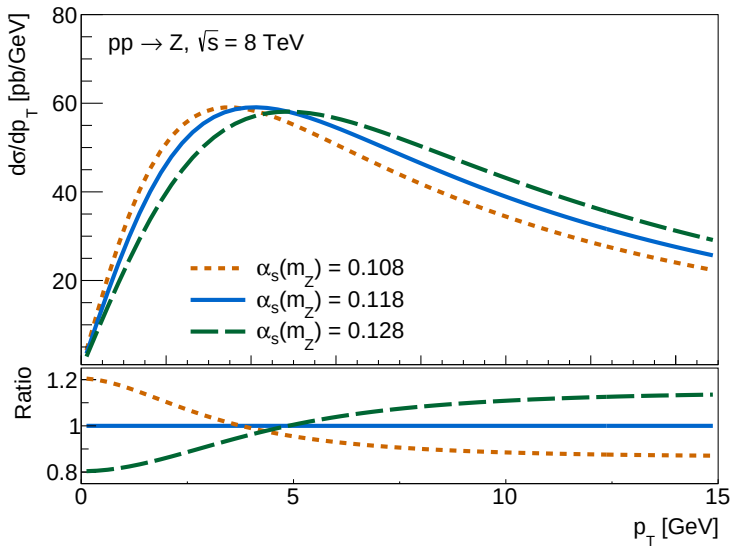
- The most precise hadron-collider measurement
- Compatible with the SM prediction
- Dominated by the PDF uncertainty (A_{FB} is also PDF dependent)



	χ^2	bins	p(%)	$\sin^2\theta^{\ell}_{\text{eff}}$	stat	exp	theo	PDF	MC	bkg	eff	calib	other
$\mu\mu$	241.3	264	82.7	23146 ± 38	17	17	7	30	13	3	2	5	4
ee	256.7	264	59.8	23176 ± 41	22	18	7	30	14	4	5	3	7
eg	119.1	144	92.8	23257 ± 61	30	40	5	44	23	11	12	19	9
eh	104.6	144	99.3	23119 ± 48	18	33	9	37	14	10	16	18	6
$\ell\ell$	730.7	816	98.4	23157 ± 31	10	15	9	27	8	4	6	6	3

ATLAS - α_S from Z-recoil I

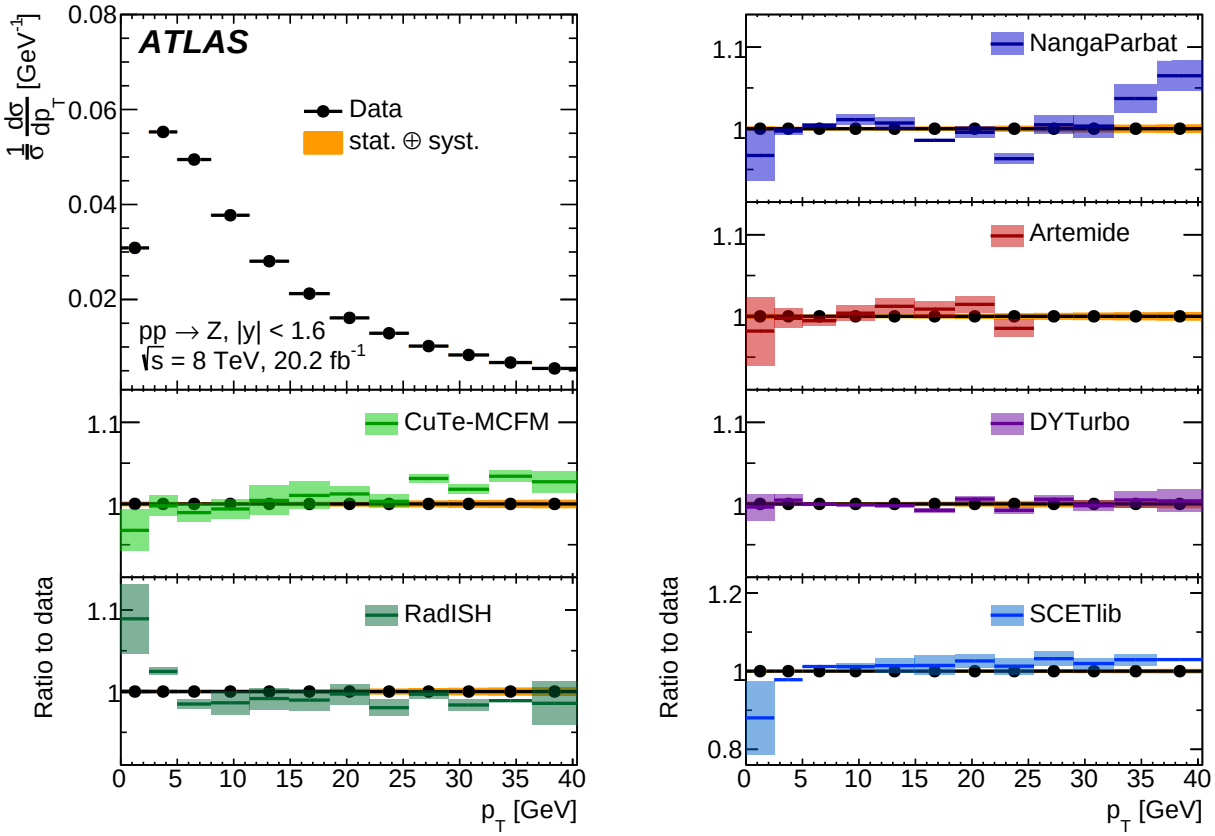




ATLAS published a new double-differential measurement of Z p_T and rapidity in full lepton phase space using 8 TeV data

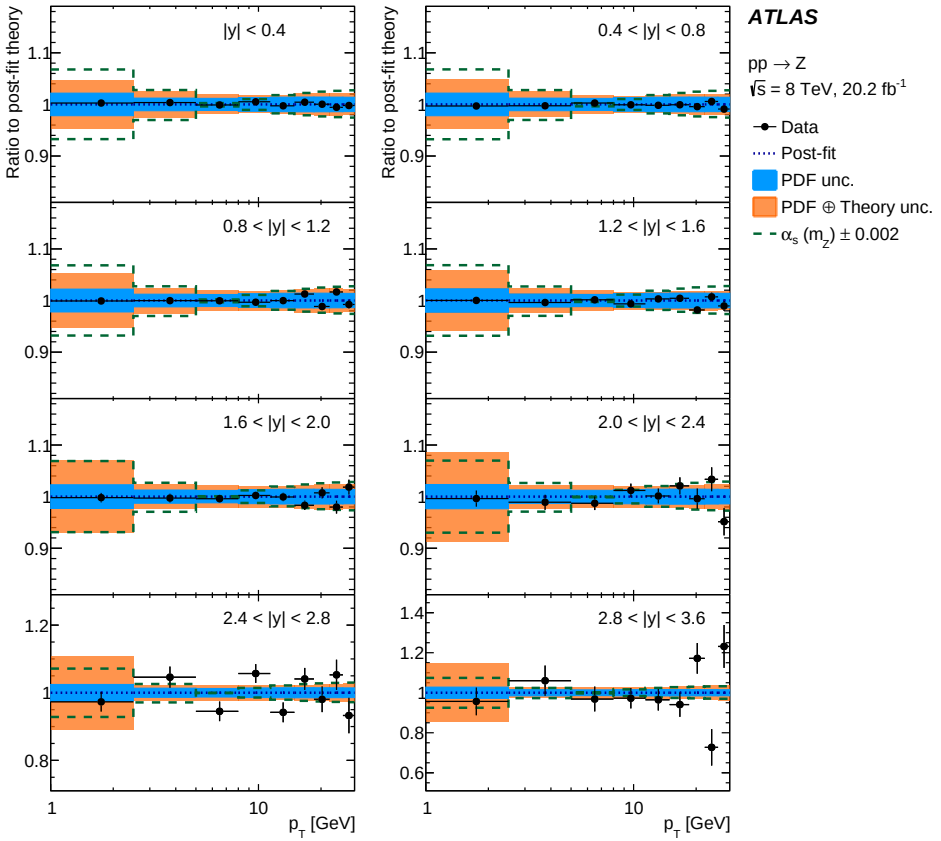
- The p_T distribution is highly sensitive to α_S
- Theory predictions available at N^{3}LO with N^{4}LL low-p_T resummation
- Allows a very high precision extraction of α_S
- Methodology was demonstrated using TeVatron data in S. Camarda et al. Eur. Phys. J.C 84 (2024) 1, 39

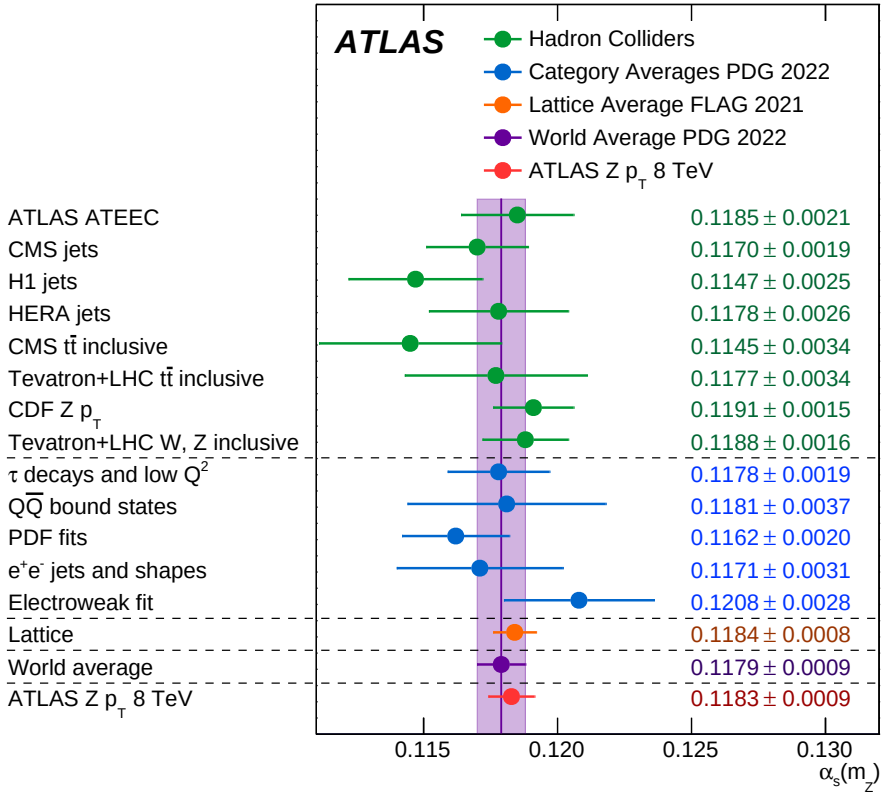
ATLAS - α_S from Z-recoil II



DYTurbo (used for α_S extraction) describes the p_T spectrum well

ATLAS - α_S from Z-recoil III





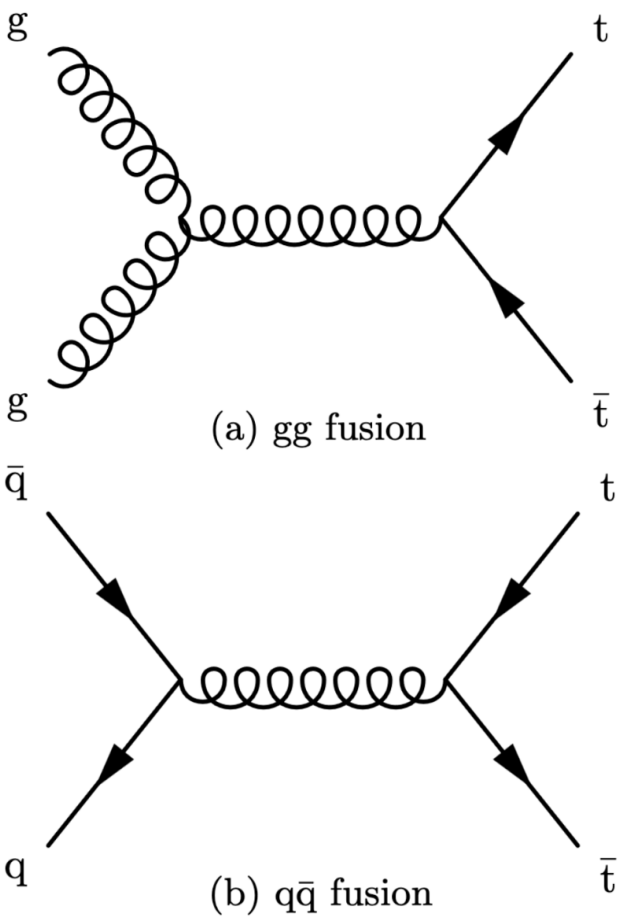
The most precise single experimental determination of α_S

Entanglement Measurements

Featuring:

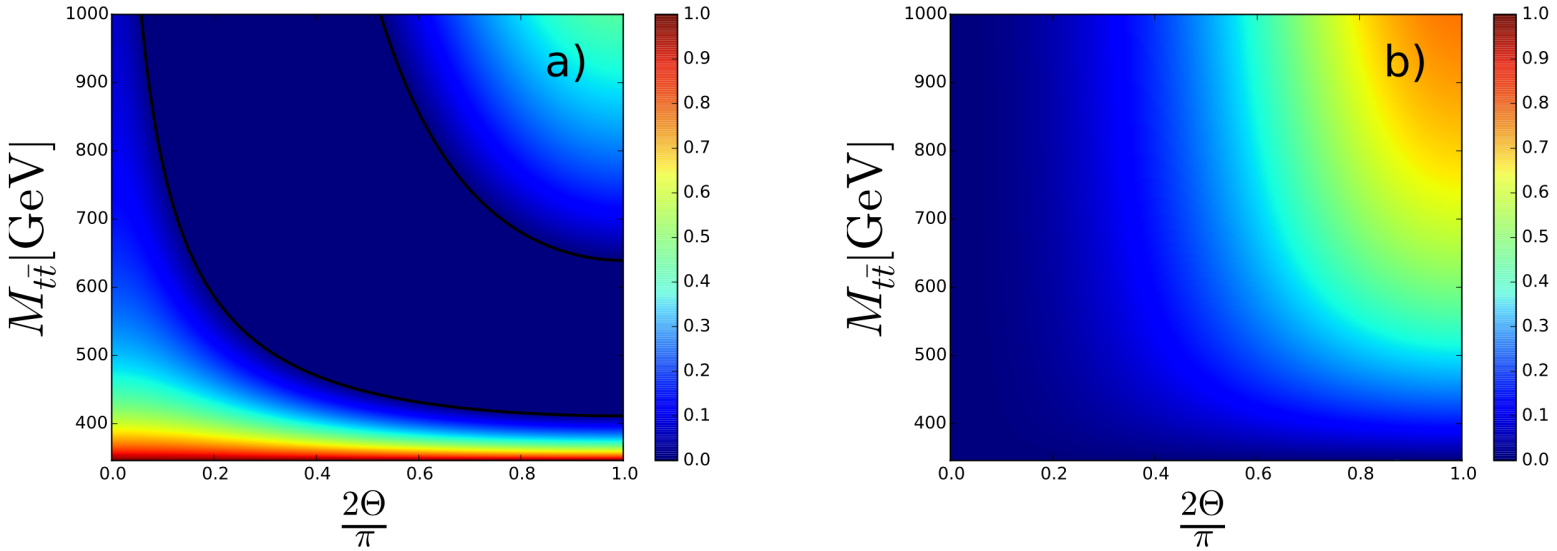
- ATLAS - arXiv:2311.07288 Observation of quantum entanglement in top-quark pairs
- CMS - arXiv:2406.03976 Observation of quantum entanglement in top quark pair production in proton-proton collisions at $\sqrt{s} = 13$ TeV

Quantum Entanglement in Top Quark pairs



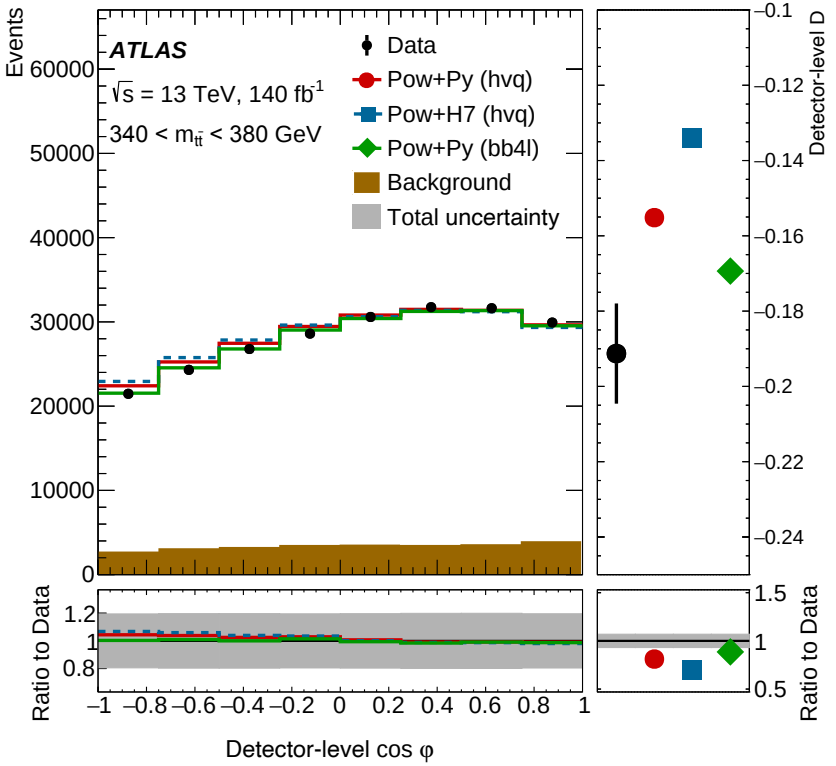
- The heavy mass of the top quark means that it decays before hadronisation
- Properties at decay are a close match to the bare quarks produced in the hard scattering
- By measuring decay angles of decay products, can determine top polarisation and spin-correlation between tops
- Measuring $D = -3.\langle cos\phi \rangle$ (ϕ angle between spin analysers in their parent top rest frames) can test level of entanglement
- in these analyses dileptonic top channel is used, charged leptons are the spin analysers
- $D < -\frac{1}{3}$ is sufficient to claim entanglement

ATLAS Entanglement in Top Quark pairs I



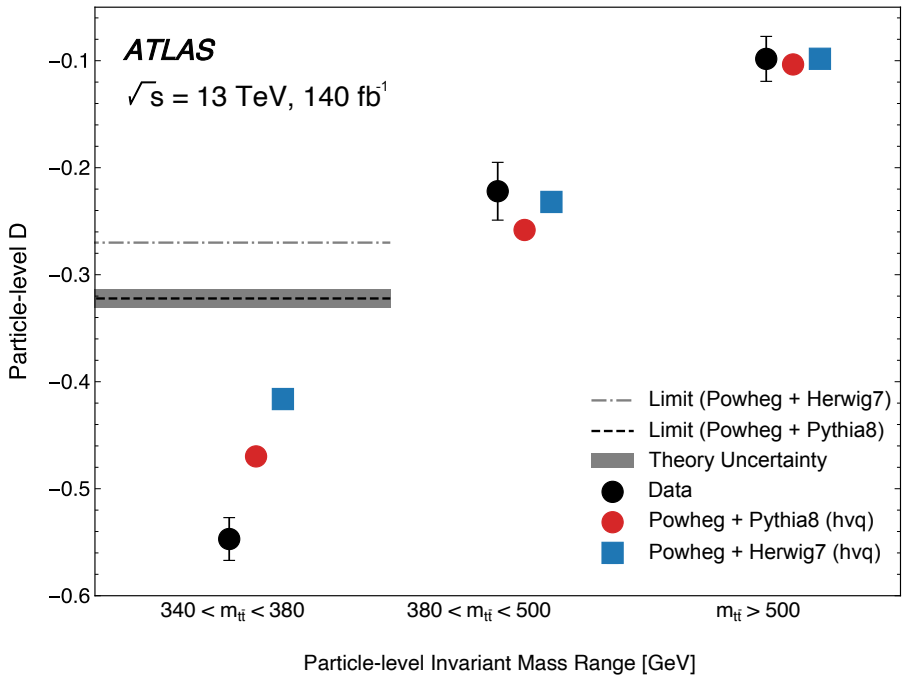
- Figure above (from Afik and Muñoz de Nova, Eur.Phys.J.Plus 136 (2021) 9, 907) shows relative level of entanglement expected for (a) gg- and (b) $q\bar{q}$-initiated processes
- In the LHC environment (90% gg initiated $t\bar{t}$ production), best places to probe would be close to the $t\bar{t}$ threshold or high $m_{t\bar{t}}$, low angle (high θ) scattering events

ATLAS Entanglement in Top Quark pairs II



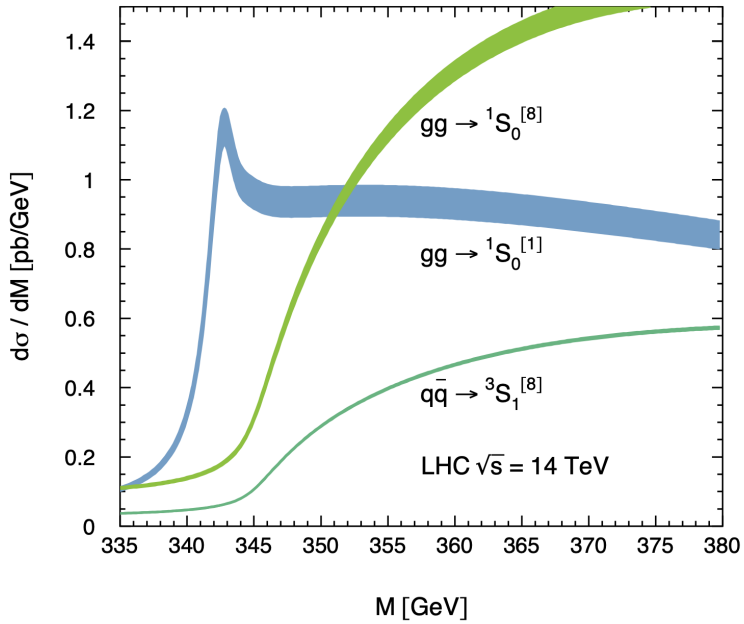
Source of uncertainty	$\Delta D_{\text{observed}}(D=-0.547)$	ΔD [%]	$\Delta D_{\text{expected}}(D=-0.470)$	ΔD [%]
Signal modeling	0.017	3.2	0.015	3.2
Electrons	0.002	0.4	0.002	0.4
Muons	0.001	0.1	0.001	0.1
Jets	0.004	0.7	0.004	0.8
b-tagging	0.002	0.4	0.002	0.4
Pile-up	< 0.001	< 0.1	< 0.001	< 0.1
$E_{\text{T}}^{\text{miss}}$	0.002	0.3	0.002	0.4
Backgrounds	0.010	1.8	0.009	1.8
Total statistical uncertainty	0.002	0.3	0.002	0.4
Total systematic uncertainty	0.021	3.8	0.018	3.9
Total uncertainty	0.021	3.8	0.018	3.9

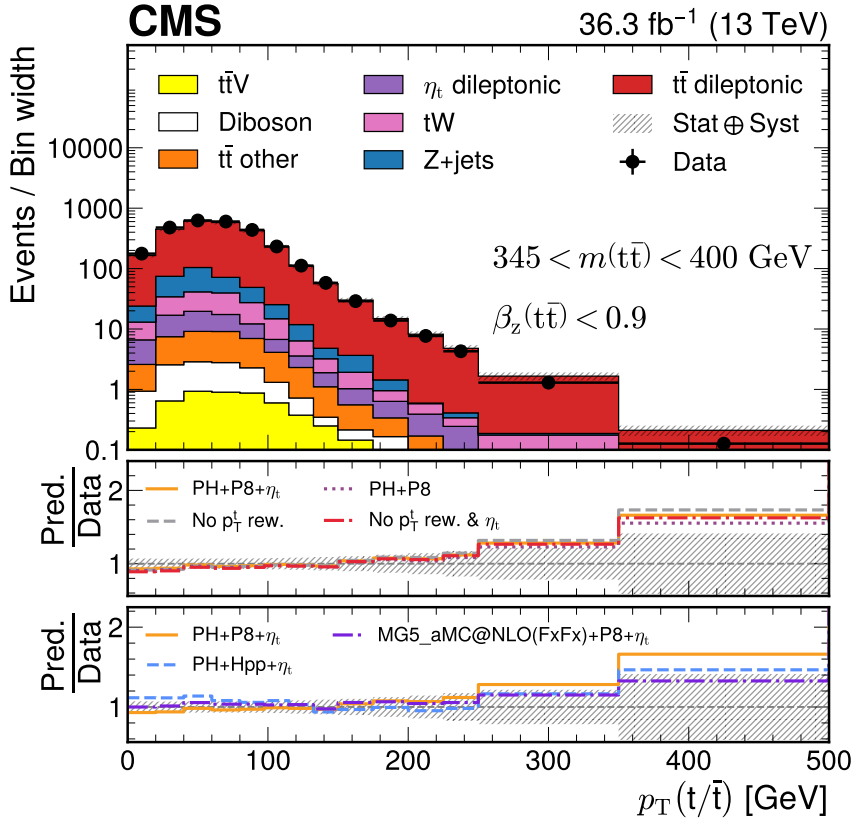
- Measured D greater than 5σ away from scenario with no entanglement
- First observation of entanglement in a pair of quarks



CMS Entanglement in Top Quark pairs I

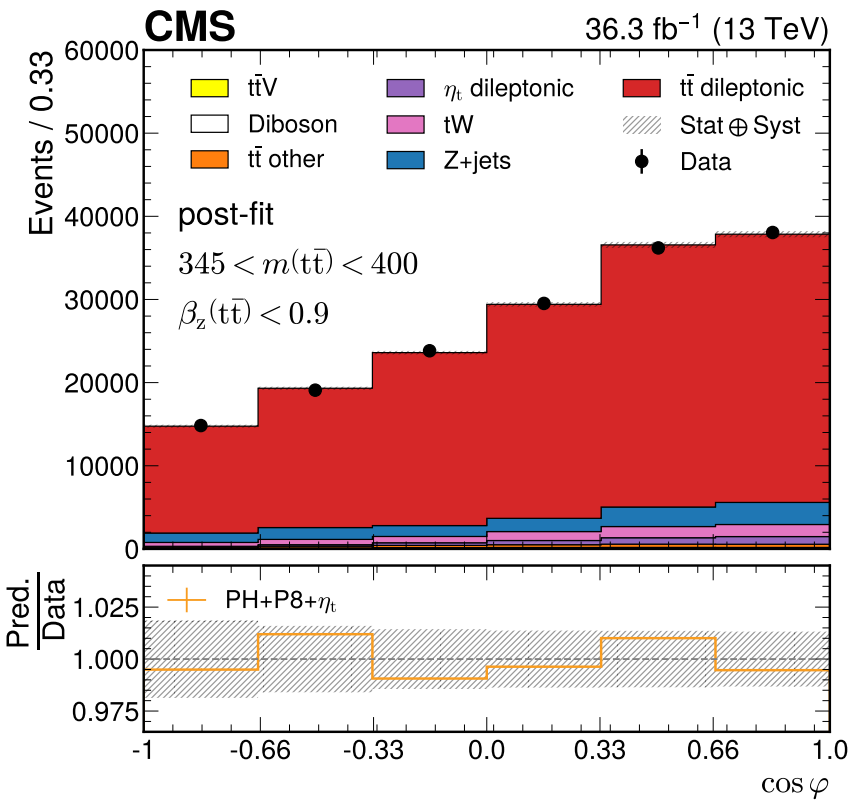
- 'Toponium' ($gg \rightarrow {}^1S_0$) may be a source of extra entanglement: not in ATLAS MC
- CMS took care to try to include it

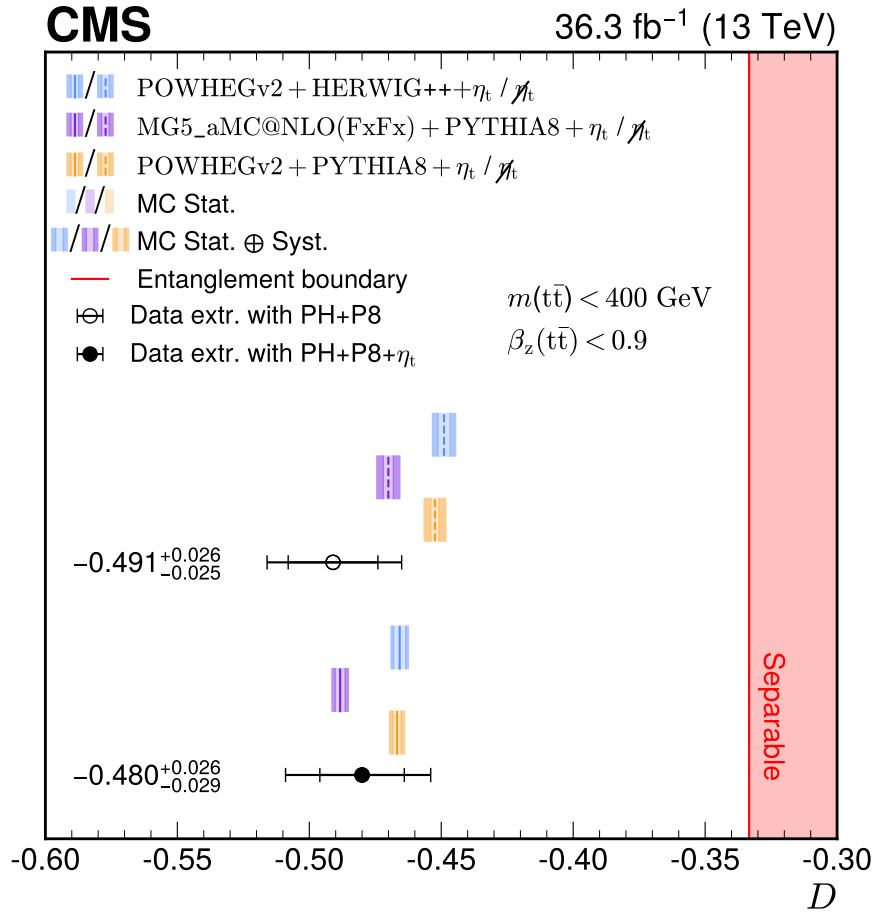




Eur.Phys.J.C 60 (2009) 375-386

CMS Entanglement in Top Quark pairs II



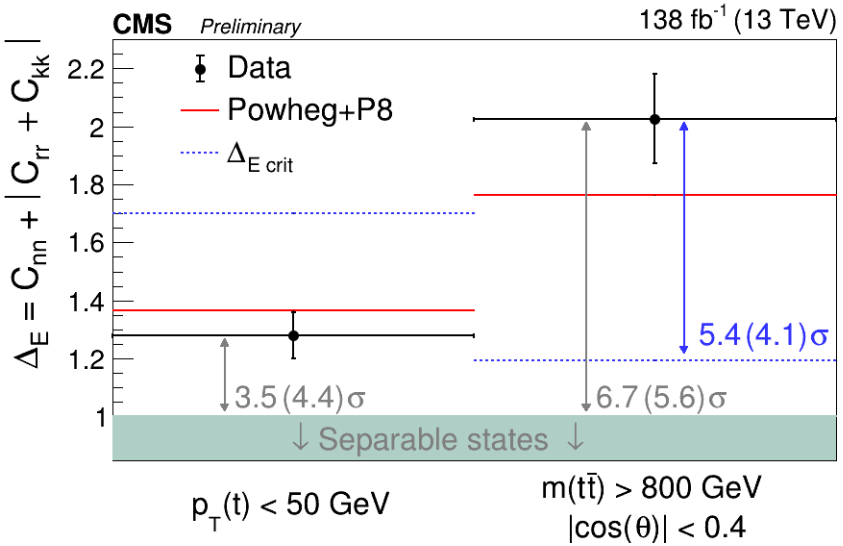


Results confirm observation of entanglement, whether or not toponium contribution is included

CMS Entanglement in Top Quark pairs III

CMS also looked in the l+jets channel at the higher mass region:

- Extracted full top spin correlation and polarisation coefficients in the helicity basis
- From this can extract: $\Delta E = C_{nn} + |C_{kk} + C_{rr}|$
- $\Delta E > 0$ is a necessary and sufficient condition for entanglement
- With this high-mass sample tops are further apart from decays
- Beyond values of $\Delta_{E_{\text{critical}}}$ results cannot be explained by non-quantum communication

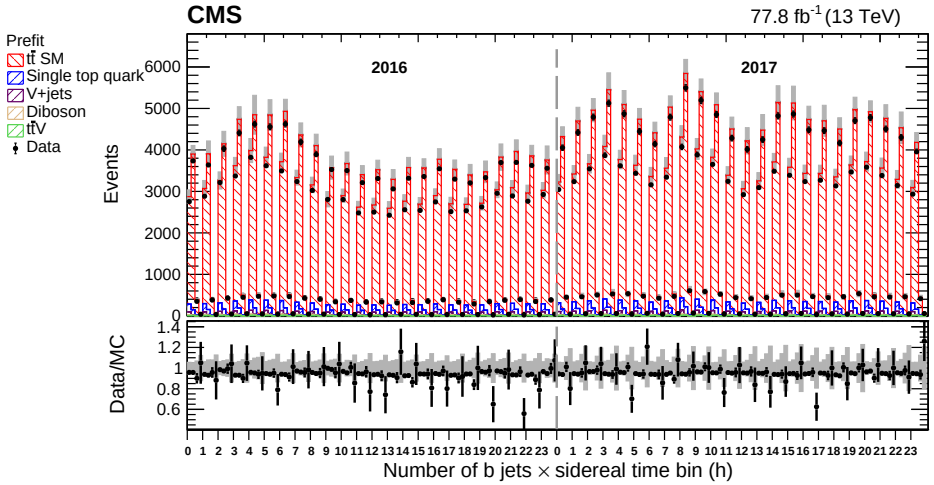


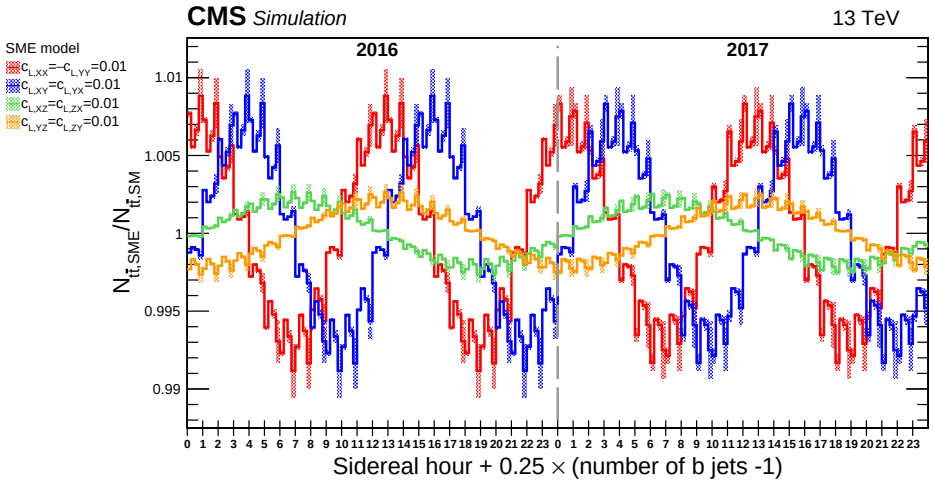
Anomalous Couplings + Conservation Law Tests

Featuring:

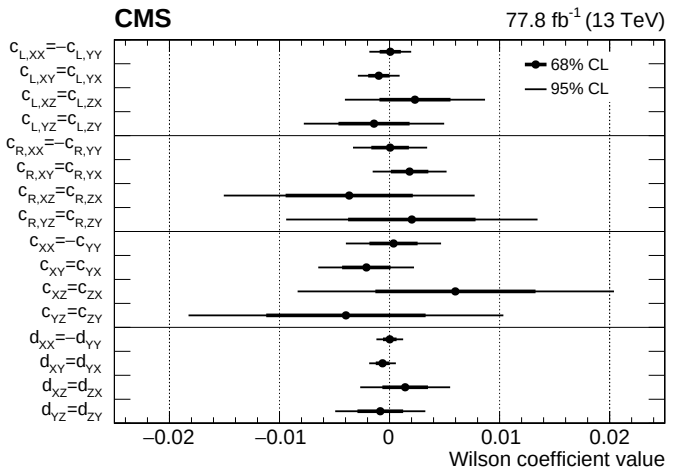
- ATLAS
  - arXiv:2404.02123 FCNC with tHq coupling in the multi lepton channel
  - arXiv:2403.06742 Charged LFV in t quark production and decay
  - arXiv:2403.02133 Test of e-μ universality in W decays from $t\bar{t}$
  - JHEP 12 (2023) 195 Search for tHu and tHc FCNC in with $H \to \gamma\gamma$
- CMS
  - arXiv:2405.14757 Search for Lorentz invariance in $t\bar{t}$
  - arXiv:2402.18461 Search for BNV in t quark prod. and decay
  - arXiv:2312.03199 Search for charged-lepton flavor violation in the production and decay of top quarks using trilepton final states
  - Phys. Rev. D 109 (2024) 072004 Search for FCNC interactions of the top quark in final states with a photon and additional jets
  - CMS-PAS-SMP-22-009 Measurement of the $Z(\nu\bar{\nu}) + \gamma$ production cross section and search for anomalous neutral triple gauge couplings
  - CMS-PAS-SMP-23-005 Observation of $\gamma\gamma \to \tau\tau$ in pp collisions and limits on the anomalous electromagnetic moments of the τ lepton
  - CMS-PAS-TOP-22-002 Search for FCNC tqH interactions

CMS - Lorentz Invariance in $t\bar{t}$



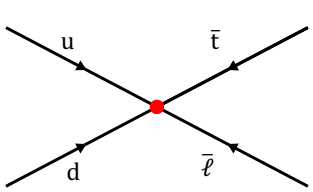


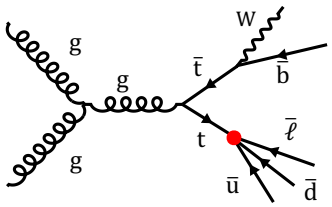
- Quantum gravity theories can break Lorentz Invariance
- CMS investigated this by measuring the $t\bar{t}$ cross section in bins of sidereal time
- Measured Lorentz-violating couplings in SME framework with 1-8 $\times 10^{-3}$ precision

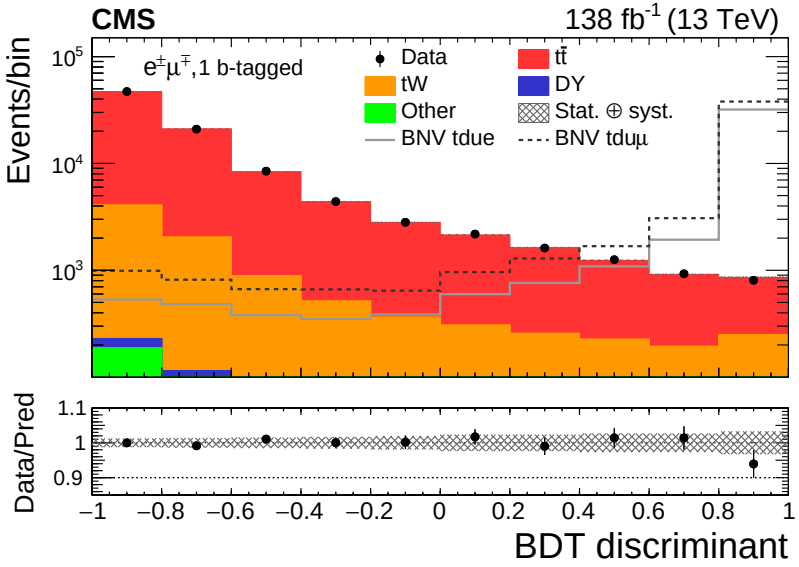


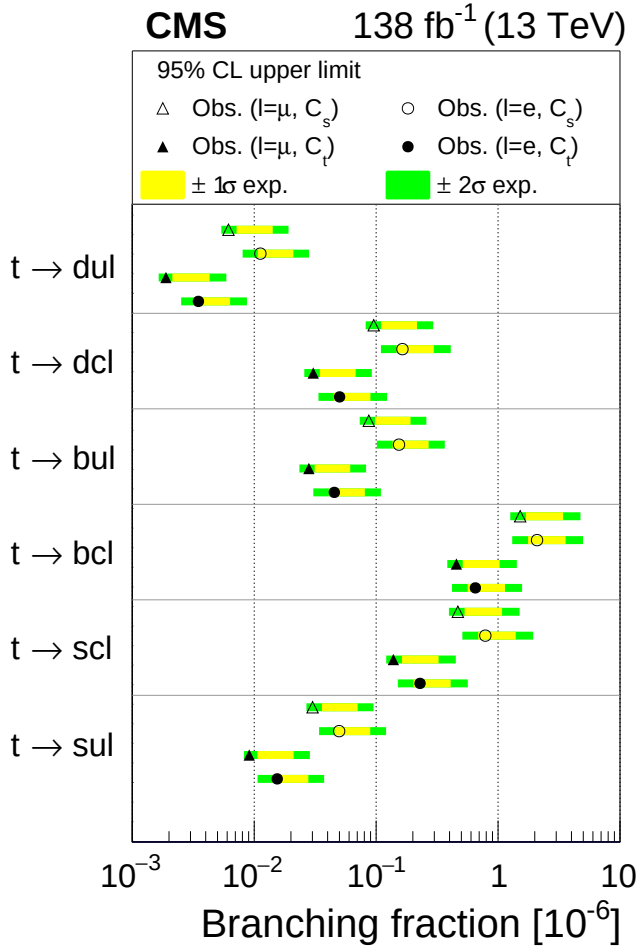
CMS - Baryon Number Violation in $t\bar{t}$

- BNV has been searched for in top decays before
- New CMS search the first to use the single-top production mode
- Coupling limits multiple orders of magnitude better than previous

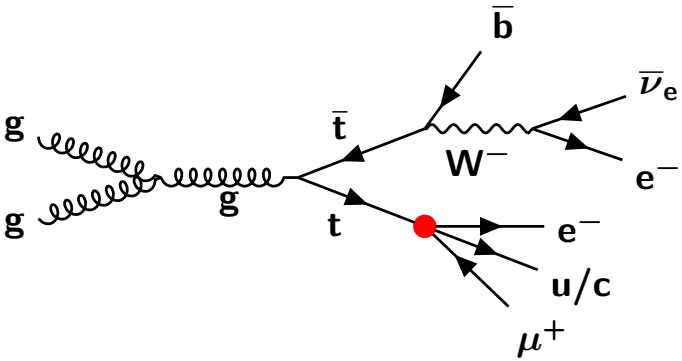


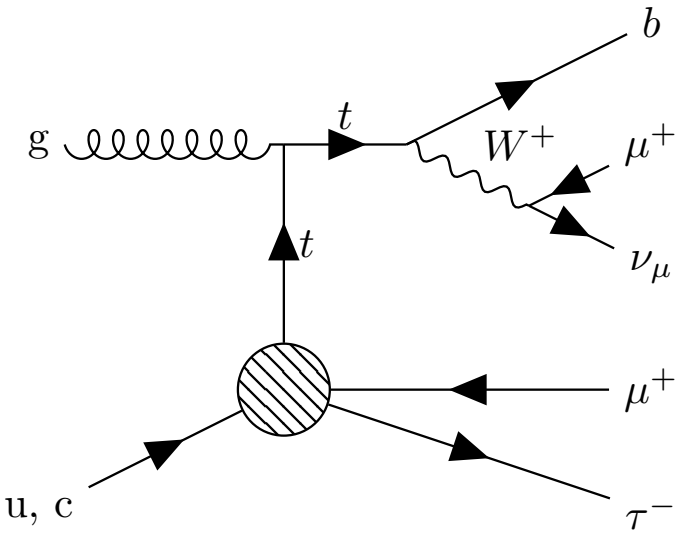




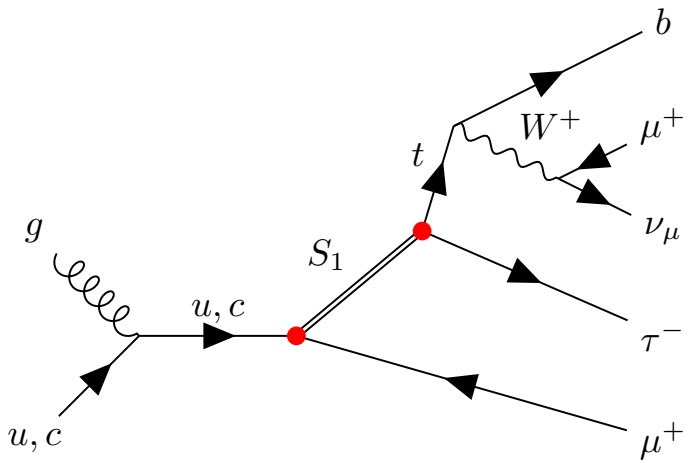


Charged Lepton Flavour Violation I

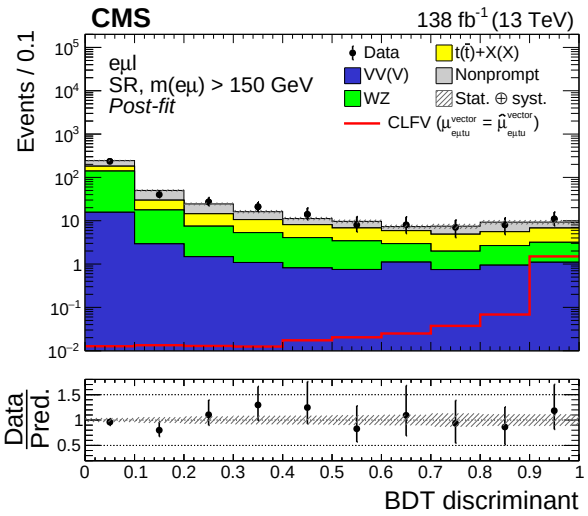


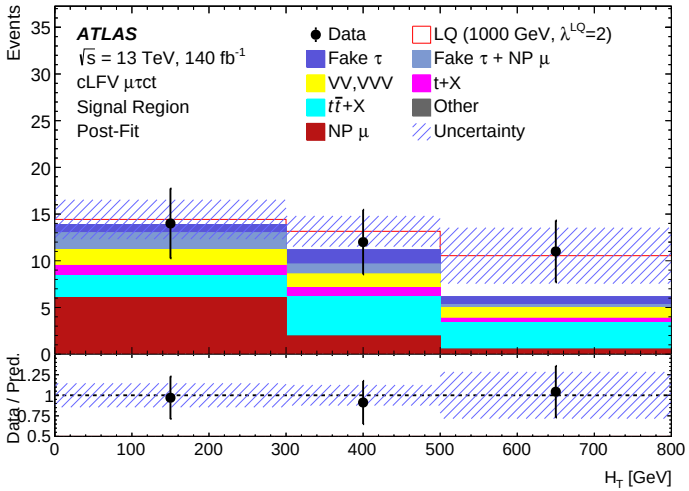


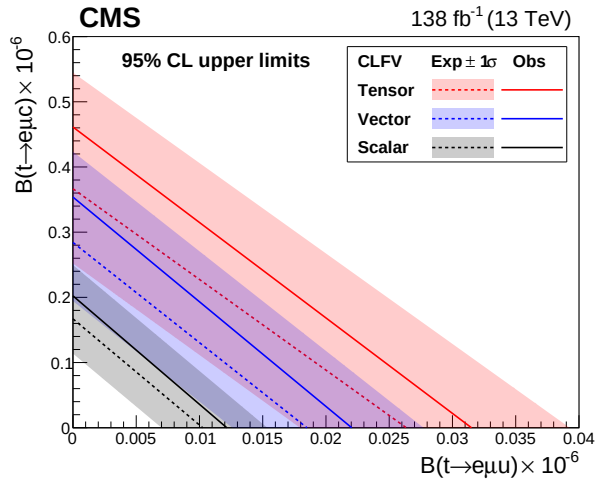
- LFV can also be studied in $t\bar{t}$ decays or t production
- New Searches exploit this in different final states:
  - CMS use $e^{\pm}\mu^{\mp}\ell^{\pm}+\geq 1$ jet
  - ATLAS use $\mu^{\pm}\mu^{\pm}+\tau_{\text{had}}+\geq 1$ jet
- ATLAS also interpret in terms of Scalar LFV leptoquarks

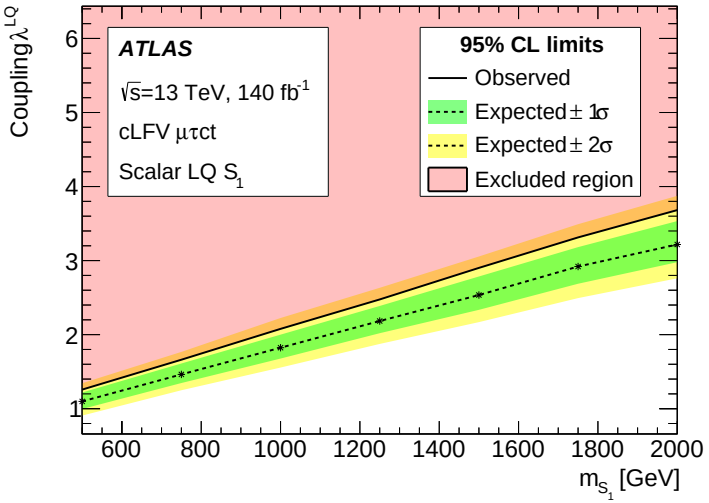


Charged Lepton Flavour Violation II



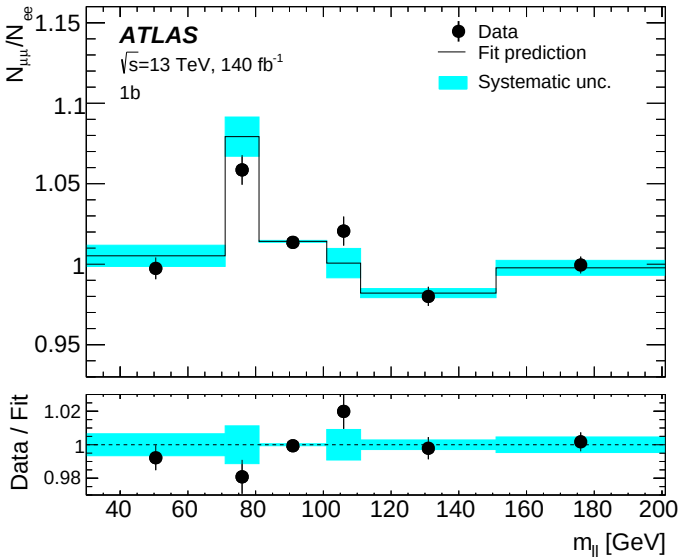


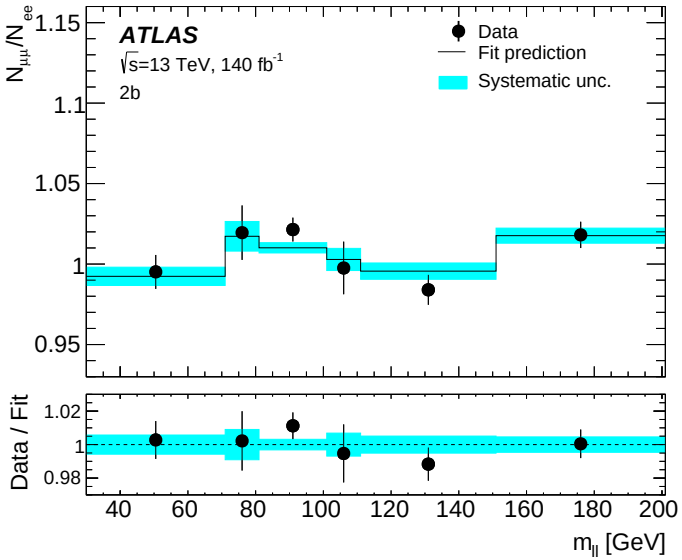




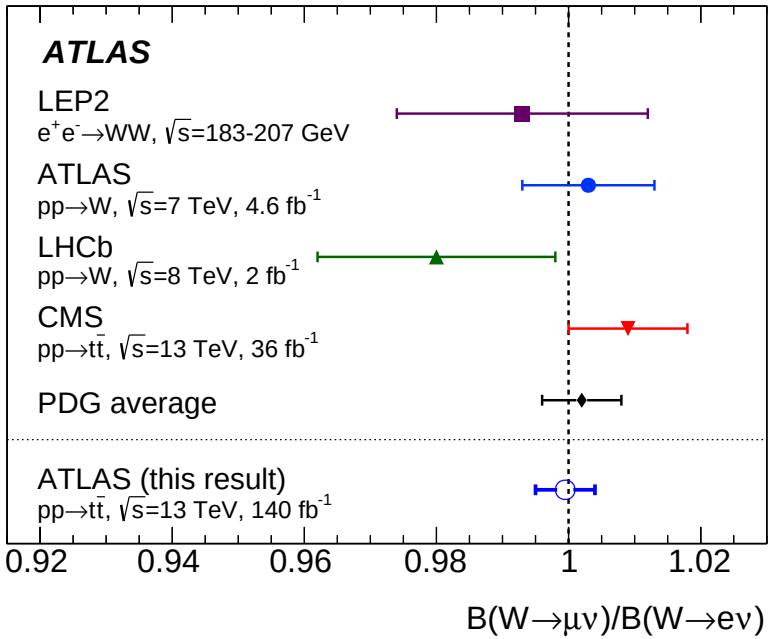
- CMS train BDTs for $t\bar{t}$ and single-t (shown) modes
- ATLAS use the H_T distribution

ATLAS - Charged Lepton Universality Test

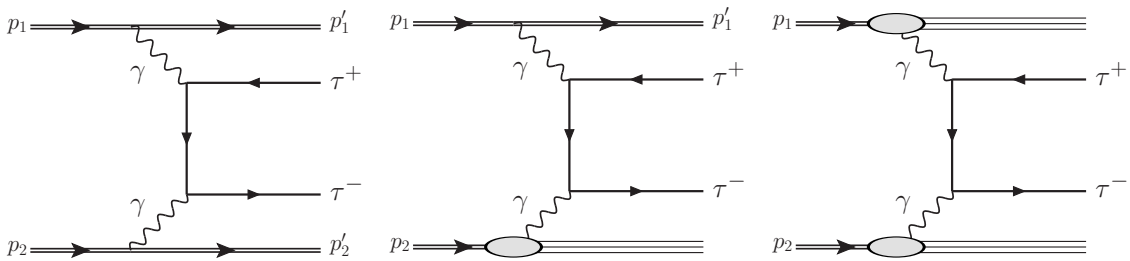


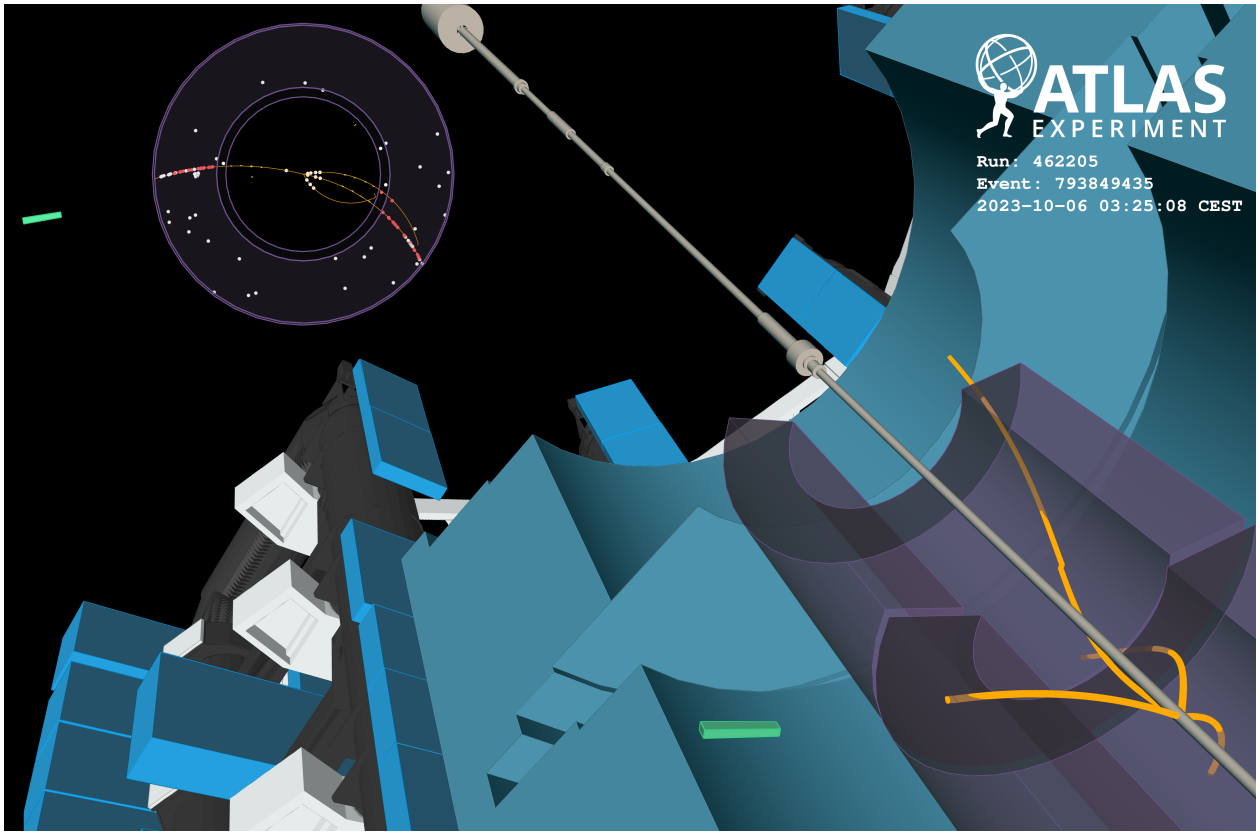


- Can also test lepton universality in W-decays using huge $t\bar{t}$ samples
- Normalise to precise LEP $R_Z^{ee/\mu\mu}$ measurement via a $Z \to \ell\ell$ selection
- Achieves 0.5% precision, better than the previous world average



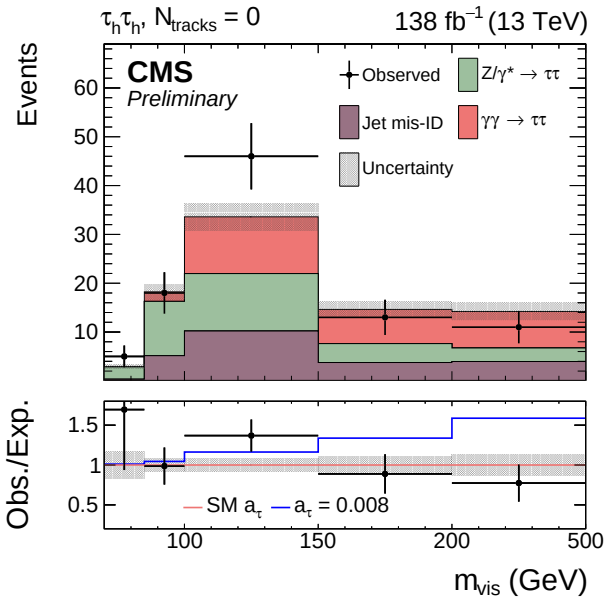
CMS: τ electromagnetic moments - I

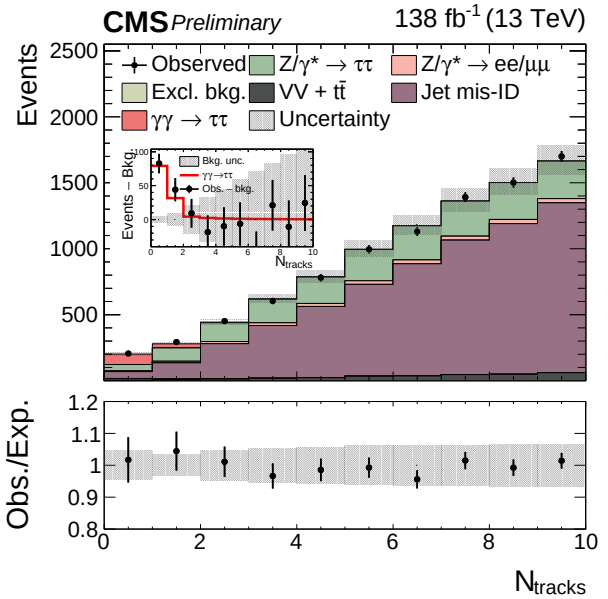




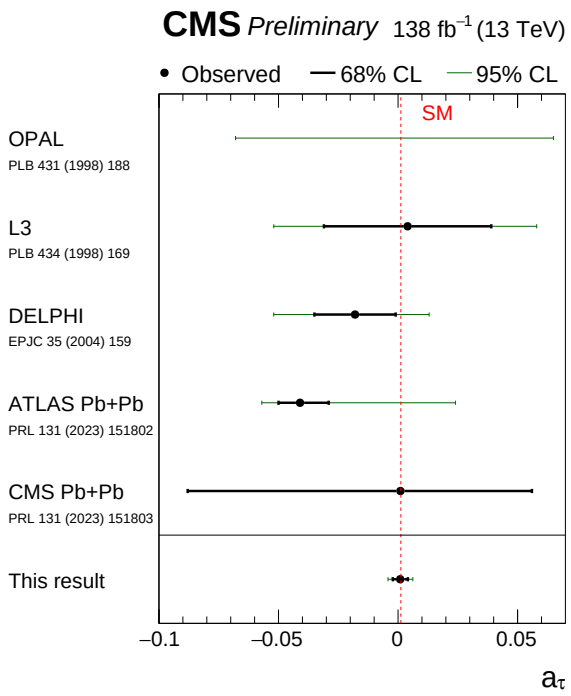
- $\gamma\gamma \to \tau^+\tau^-$ has been observed previously in Ultraperipheral collisions of nuclei at the LHC
- Produces spectacular events
- Can be used to probe tau anomalous magnetic moment a_τ and EDM d_τ

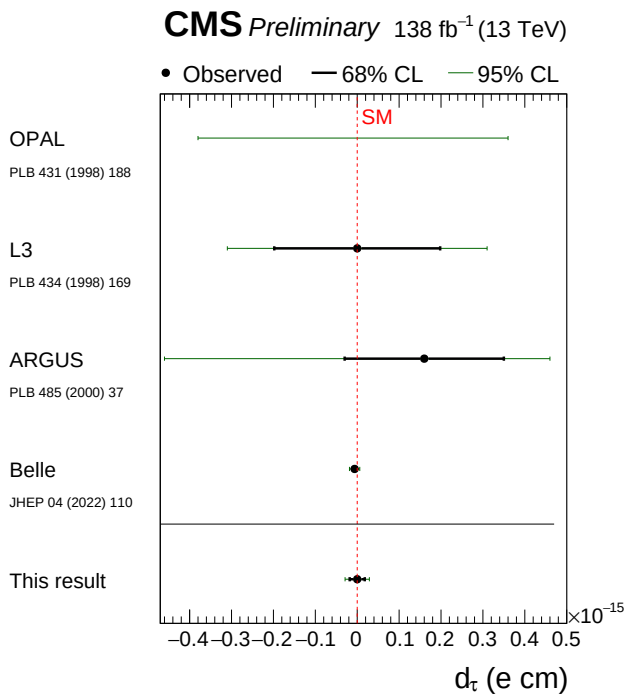
CMS: τ electromagnetic moments - II



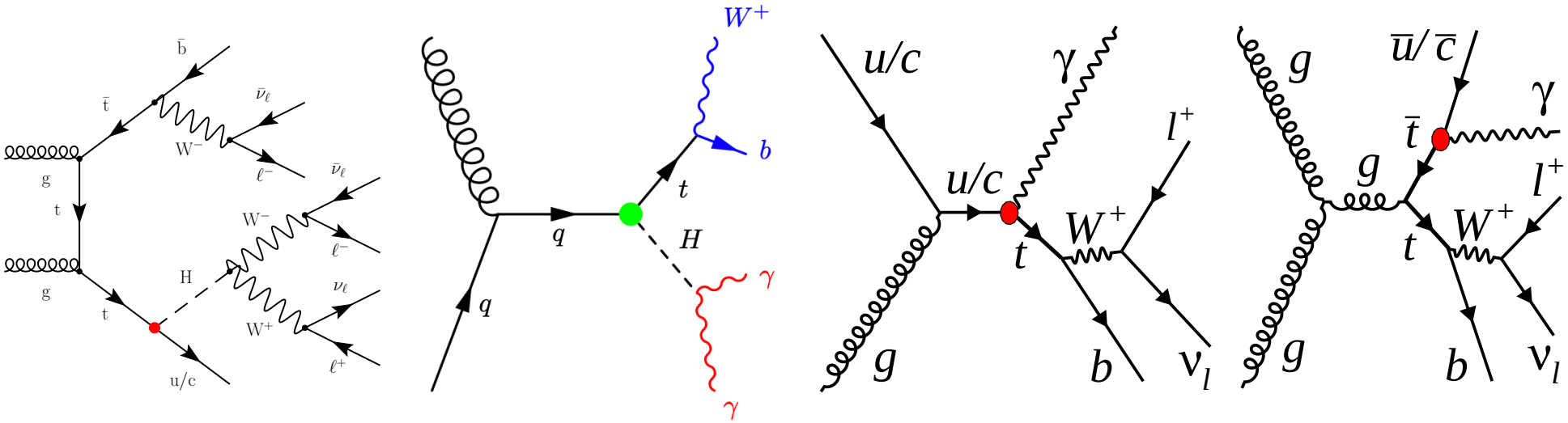


- CMS have now made the first observation of this process in pp collisions
- Sensitivity to a_τ and d_τ via high m_{vis} region
- Most precise determination of a_τ at a collider



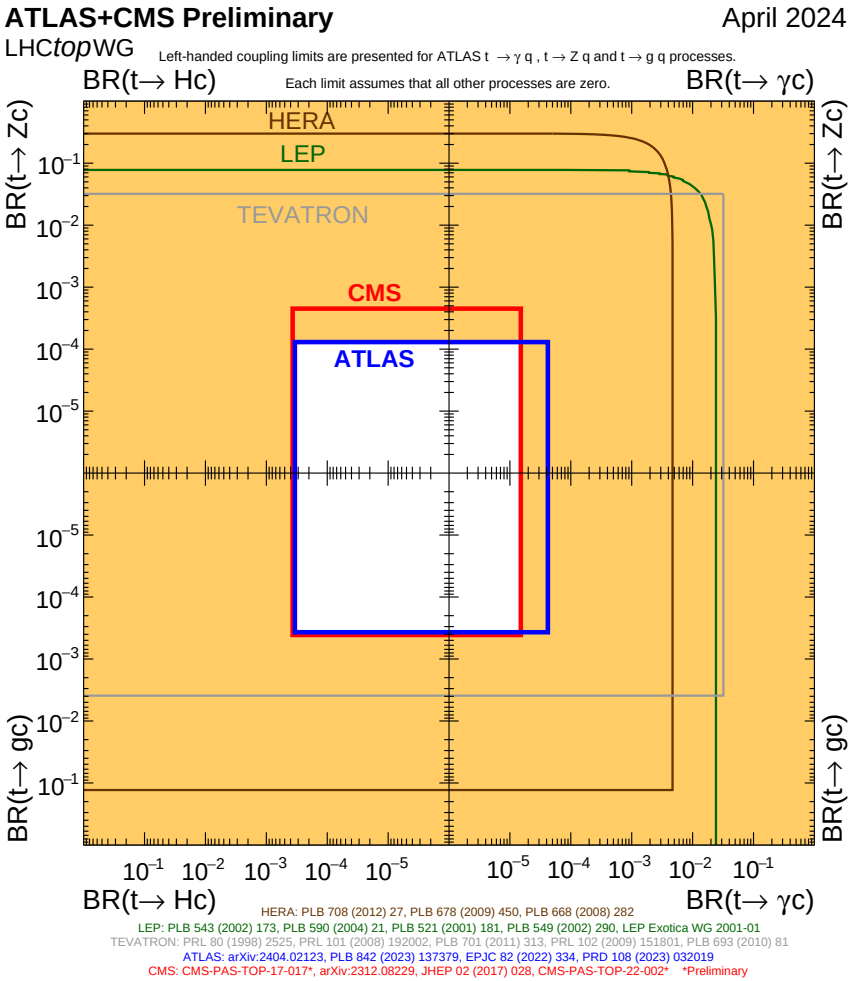


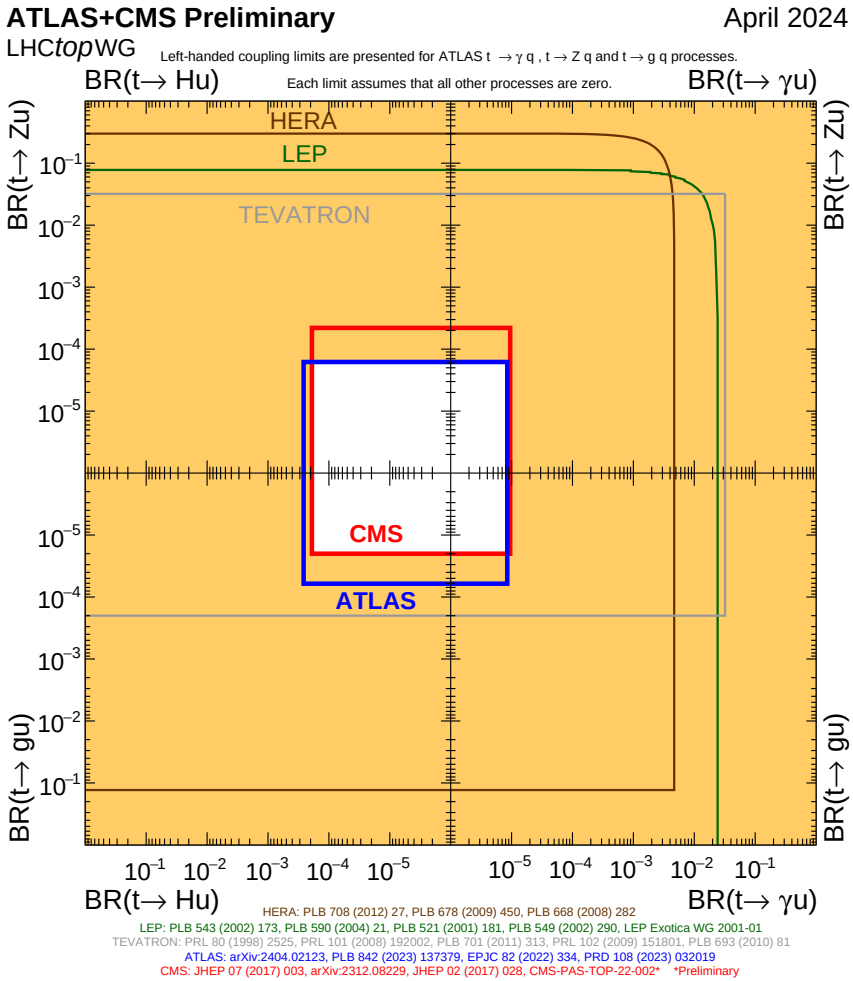
FCNC interactions with the top quark-I



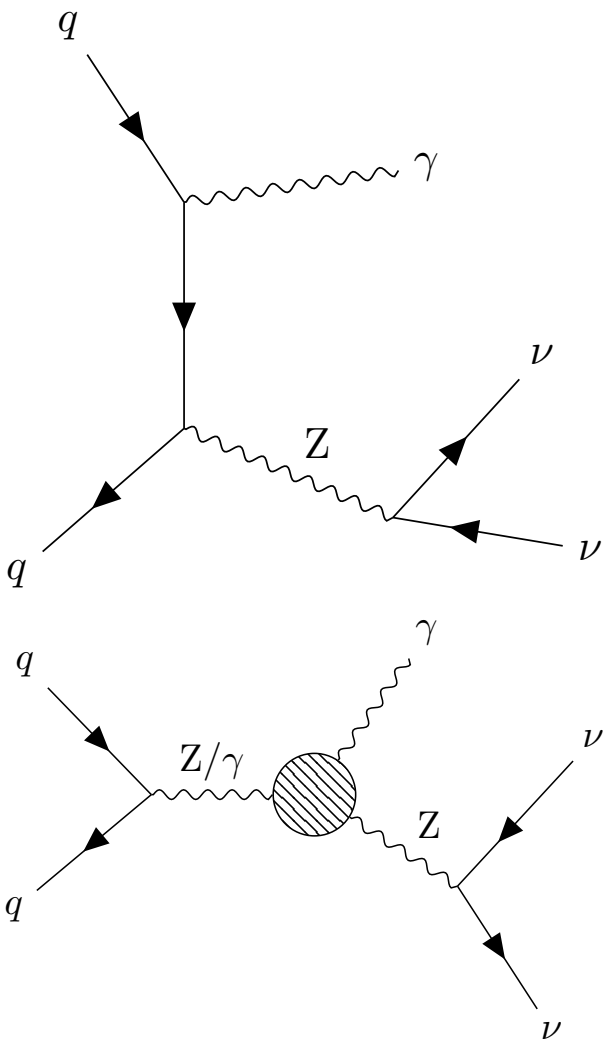
- Our rich top-quark dataset is also a great environment to study Flavour-changing Neutral Currents (FCNC)
- CMS have made new searches for tqH (same-sign lepton final states) and $tq\gamma$ couplings
- ATLAS have made searches for tqH in $\gamma\gamma$ and W^+W^- modes

FCNC interactions with the top quark-II

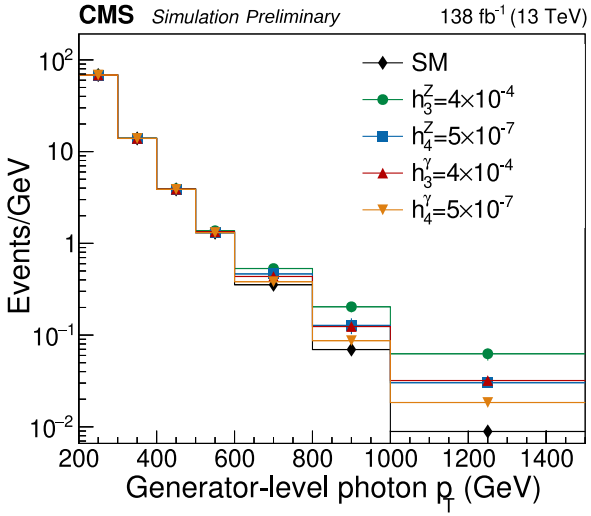


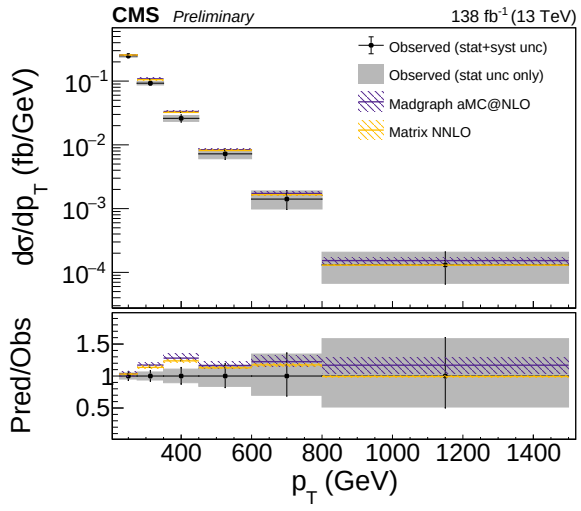


Anomalous TGCs



- CMS Searched for Anomalous $ZZ\gamma$ couplings





- Sensitivity to anomalous couplings via photon p_T

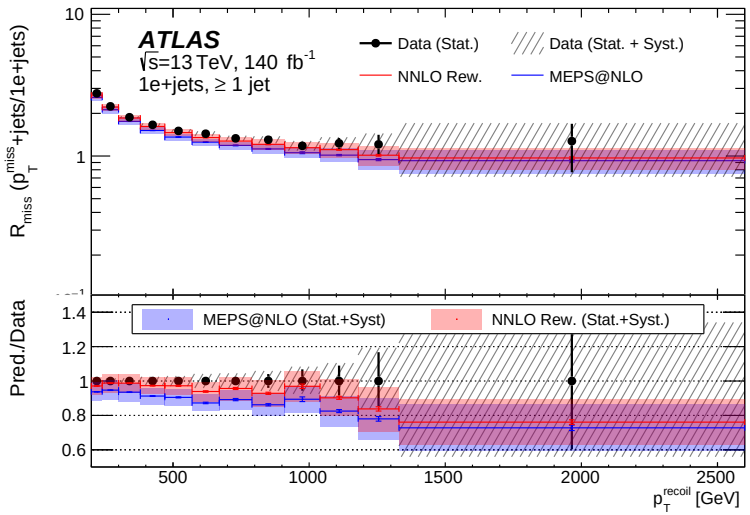
Parameter	Expected	Observed
$h_3^\gamma \times 10^4$	(-2.8, 2.9)	(-3.4, 3.5)
$h_4^\gamma \times 10^7$	(-5.9, 6.0)	(-6.8, 6.8)
$h_3^Z \times 10^4$	(-1.8,1.9)	(-2.2, 2.2)
$h_4^Z \times 10^7$	(-3.7, 3.7)	(-4.1, 4.2)

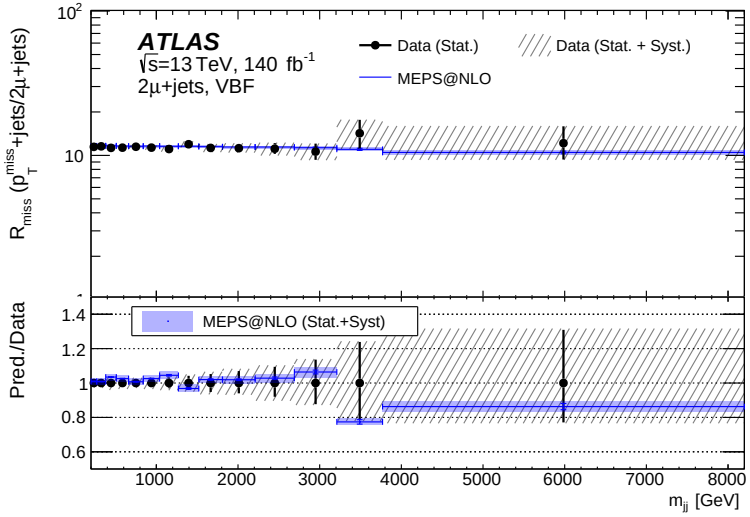
SUSY-adjacent Measurements

Featuring:

- ATLAS
  - arXiv:2403.02793 Differential cross sections for the production of missing transverse momentum and jets
  - JHEP 05 (2024) 131 $t\bar{t}W$ total and differential cross sections
  - 2312.04450 Measurement of $t\bar{t}Z$ total and differential cross sections
  - arXiv:2403.09452 $t\bar{t} + \gamma$ inclusive and differential cross-section measurements
- CMS
  - CMS-PAS-TOP-23-004 Inclusive and differential measurement of top quark cross sections in association with a Z boson
  - arXiv:2312.1166 Evidence for tWZ production in proton-proton collisions at $\sqrt{s} = 13$ TeV in multilepton final states

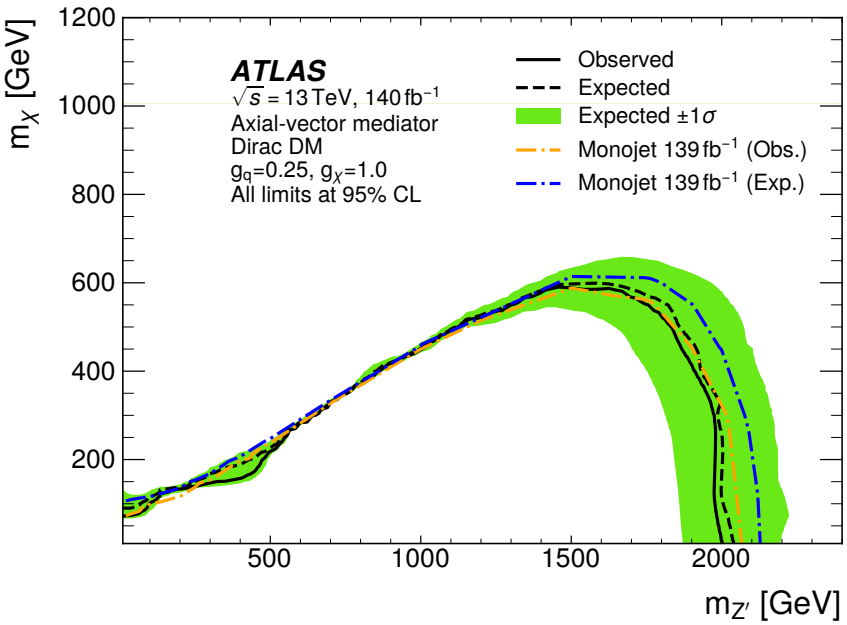
ATLAS: $E_{\mathrm{T}}^{\mathrm{miss}}$ + jets cross-sections - I

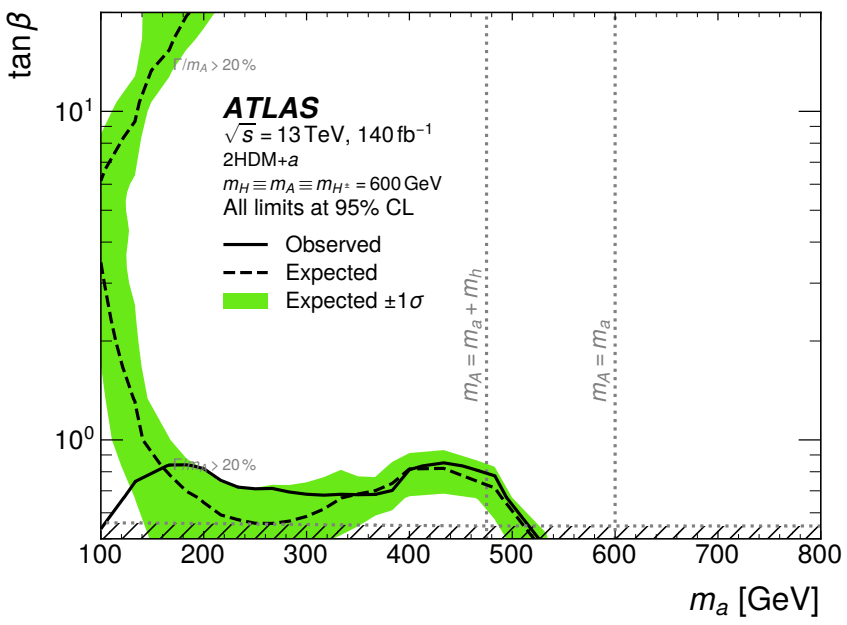




- ATLAS measured missing transverse momentum + jets cross section in inclusive jets and VBF regions
- Built ratios R_{miss} versus cross-sections for other topologies:
  - e or $2e$+jets
  - μ or 2μ+jets
  - γ +jets
- These ratios can be used to set constraints on new physics

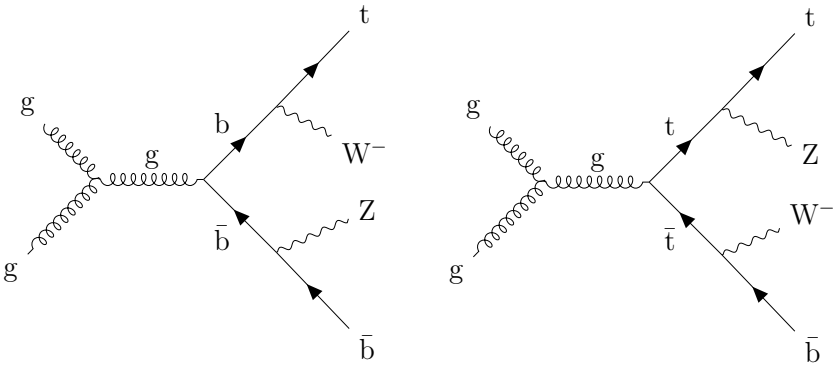
ATLAS: $E_{\mathrm{T}}^{\mathrm{miss}}$+ jets cross-sections - II



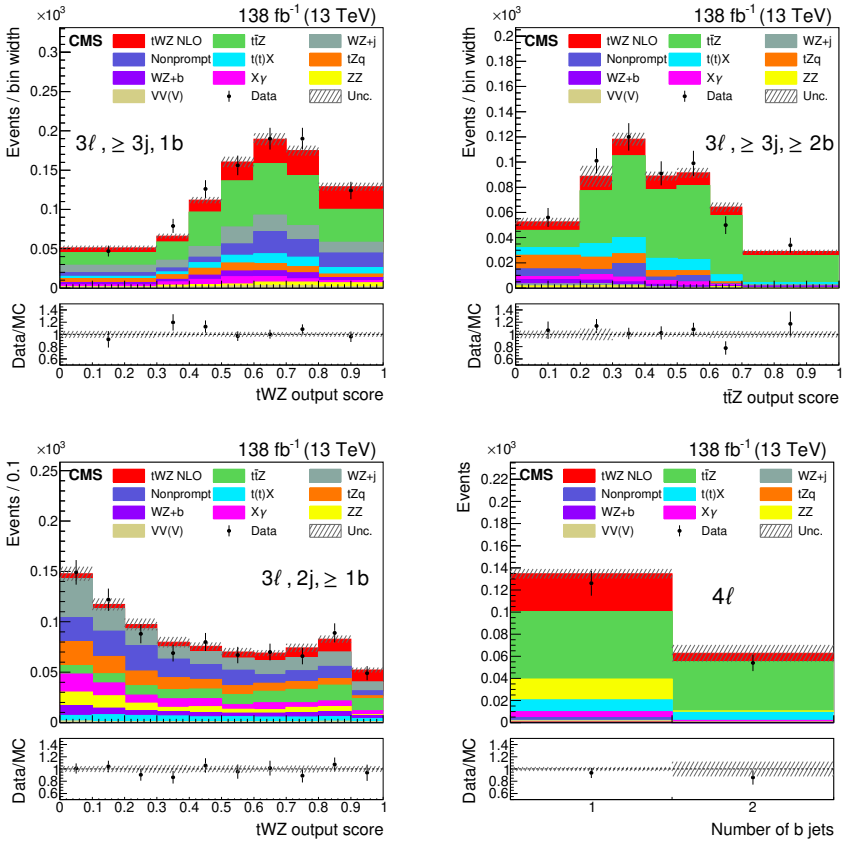


- Examples in the paper of application to
  - Simplified model of a DM candidate
  - 2HDM+a scenario
- In these cases sensitivity broadly similar to dedicated searches for these models
- Unfolded results available: easily reinterpretable

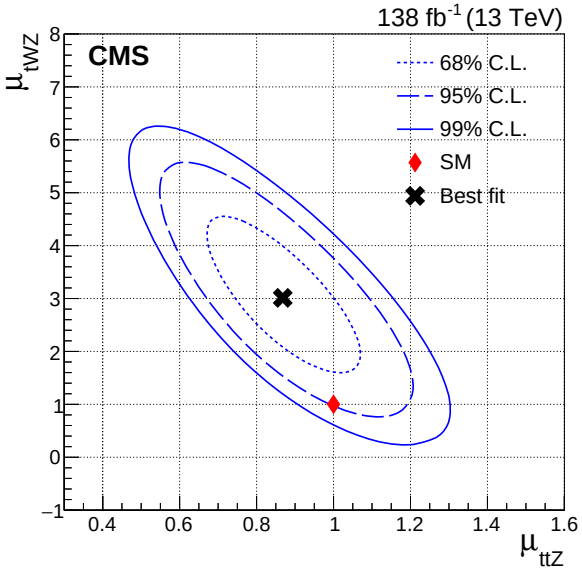
CMS: *tWZ* cross section -I

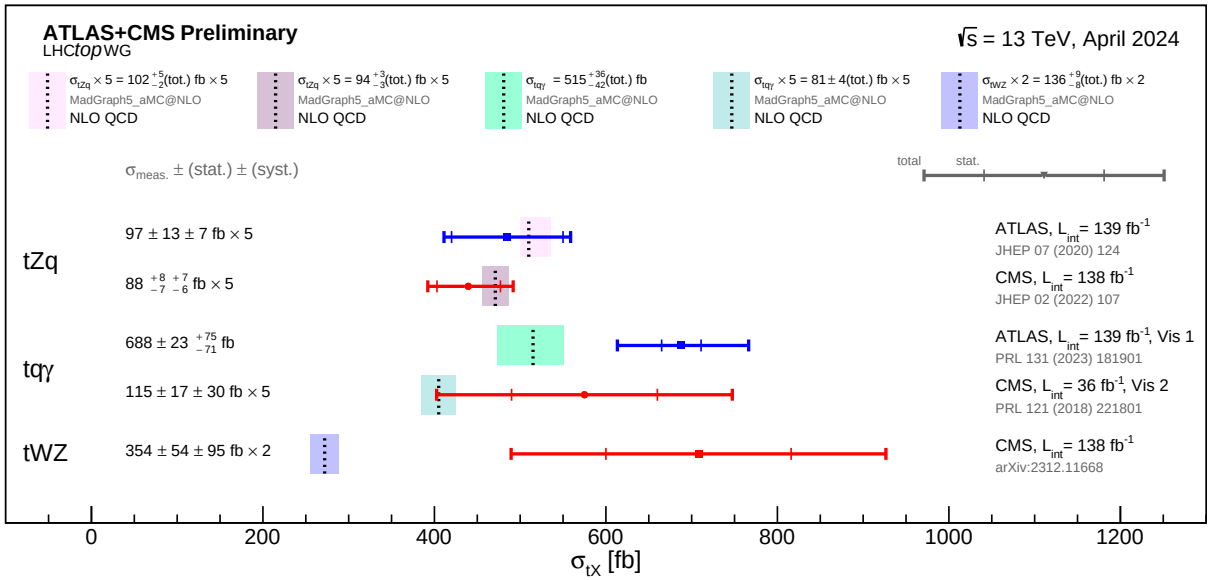


- *tWZ* production is rare in the SM ($\sigma \approx 140$ fb^{-1})
- Challenging to separate from $tt\bar{Z}$ - interferes at NLO
- DNN classifies events as *tWZ*, $t\bar{t}Z$ and 'other background' in 3 jet SRs
- Separate DNN classifies events as *tWZ*, and 'other background' in the 2 jet SRS



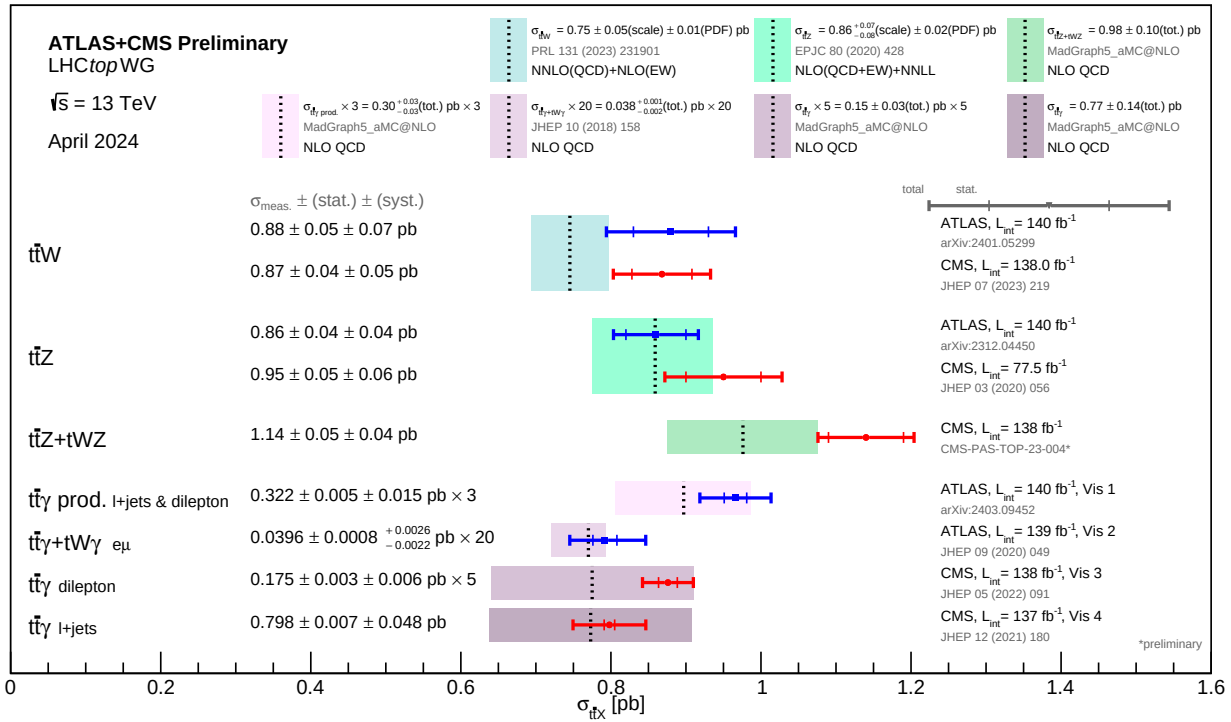
CMS: tWZ cross section -II





- Evidence at 3.4σ for tWZ obtained
- Large dependence on $t\bar{t}Z$ normalisation
- Check with a simultaneous fit to $t\bar{t}Z$ and tWZ shows they are anti-correlated

$t\bar{t} + V$ and $t\bar{t} + \gamma$ cross sections



- Inclusive σ for $t\bar{t}$+vector boson probed with increasing precision
- Now possible to measure these processes differentially
- ATLAS and CMS producing results suitable for interpretation in Top-quark Effective Theory

Measurements with EFT Interpretation

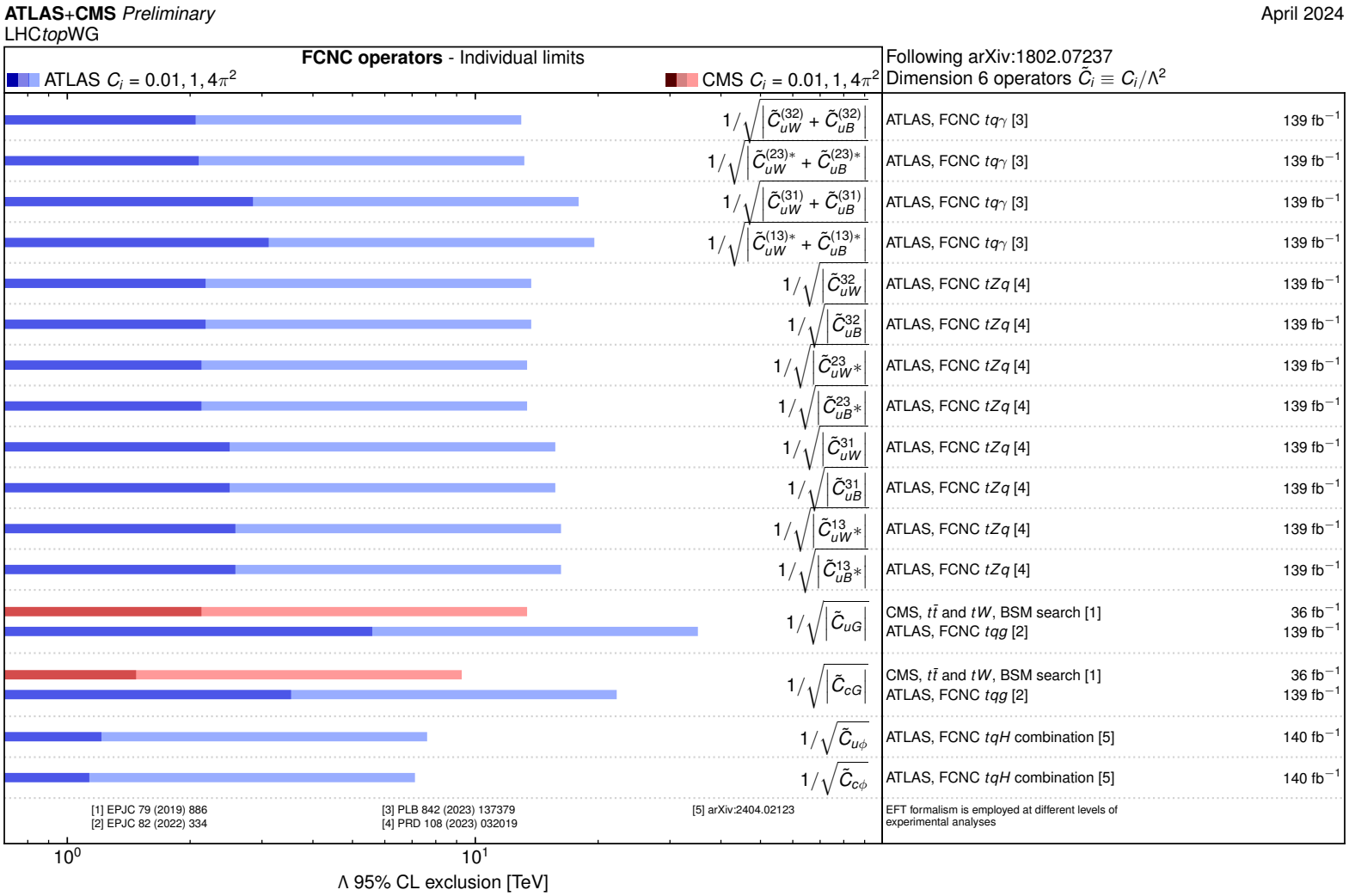
Featuring:

- CMS - JHEP 12 (2023) 068 Search for physics beyond the standard model in top quark production with additional leptons in the context of effective field theory
- Previously mentioned ATLAS+CMS $t\bar{t}V$ and FCNC analyses.

Here I focus on the Top EFT constraints but there are also nice results on operators in diboson production

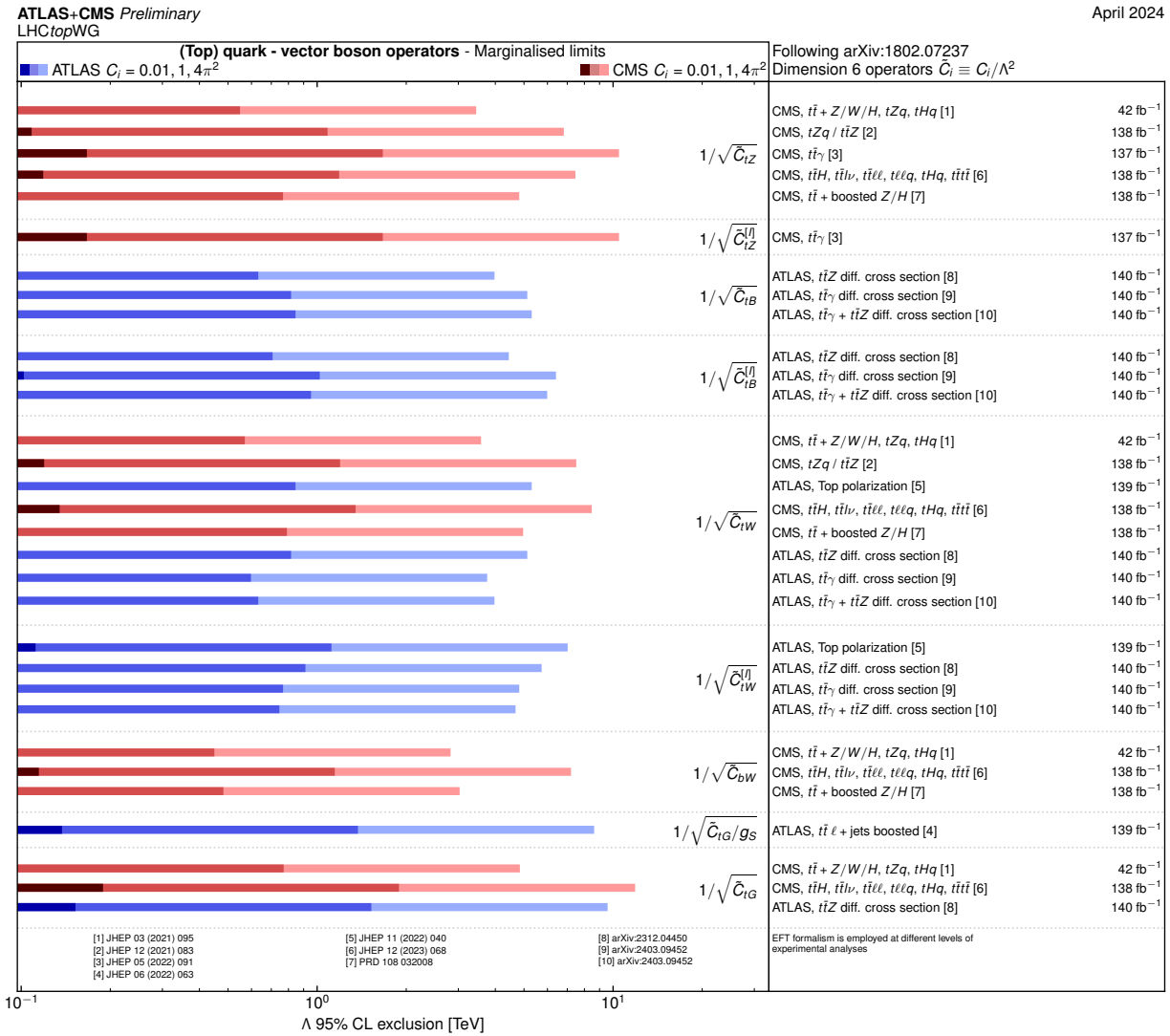
- Results shown here are for dimension 6 operators, generally expressed as bounds on $\frac{c_i}{\Lambda^2}$, where Λ is the energy scale.
- Limits can be re-expressed as bounds on the energy scale, typically assuming a natural value of c_i
- Implicitly assumes $\Lambda \gg$ the energy scale at which the analysis is performed

EFT Constraints - Top FCNC



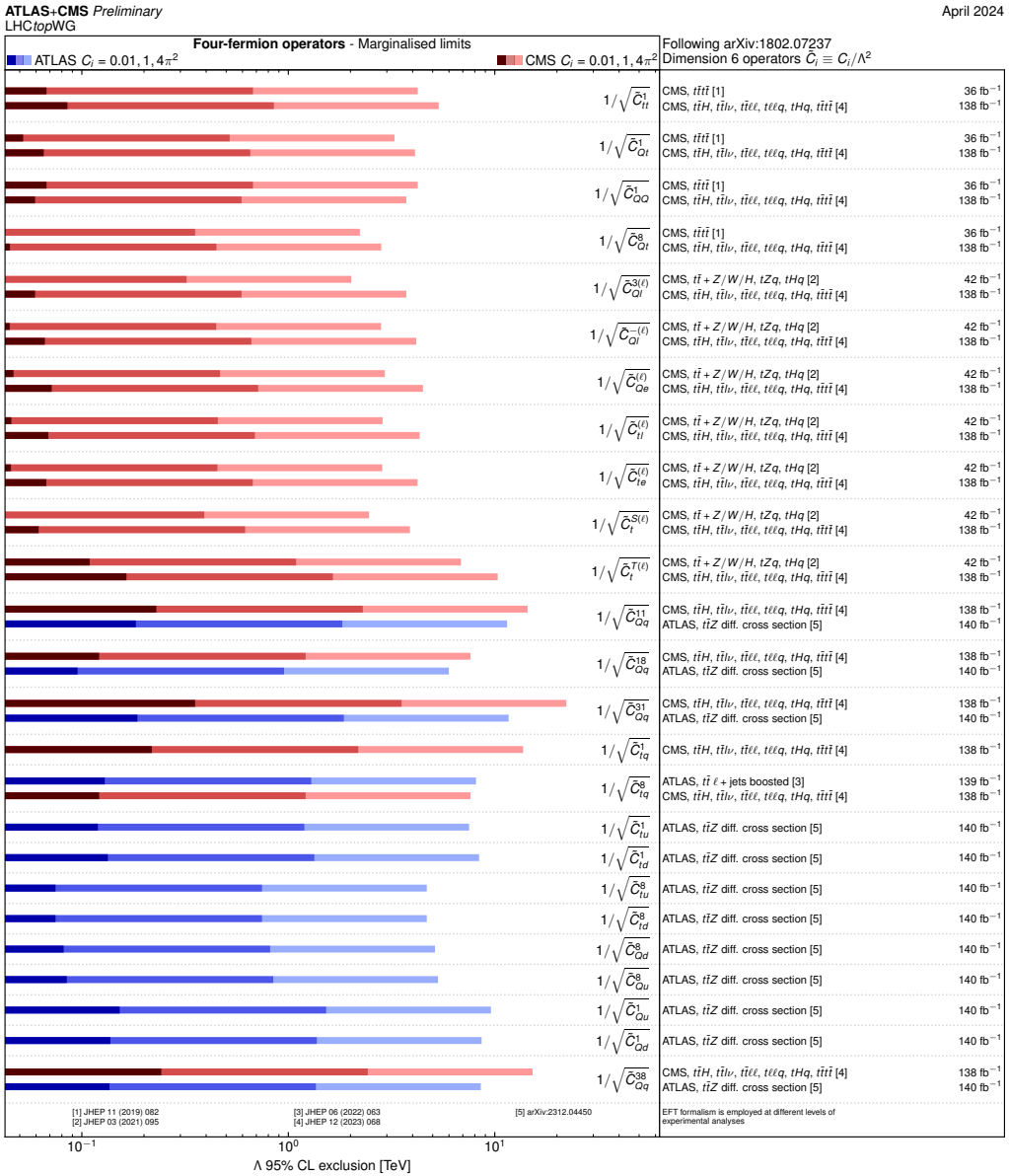
FCNC analyses are probing new energy scales in the 7-20 TeV range

EFT Constraints - Top+Vector Boson



$t\bar{t}V$ analyses are probing new energy scales in the 2-10 TeV range

EFT Constraints - Four-Fermion Operators



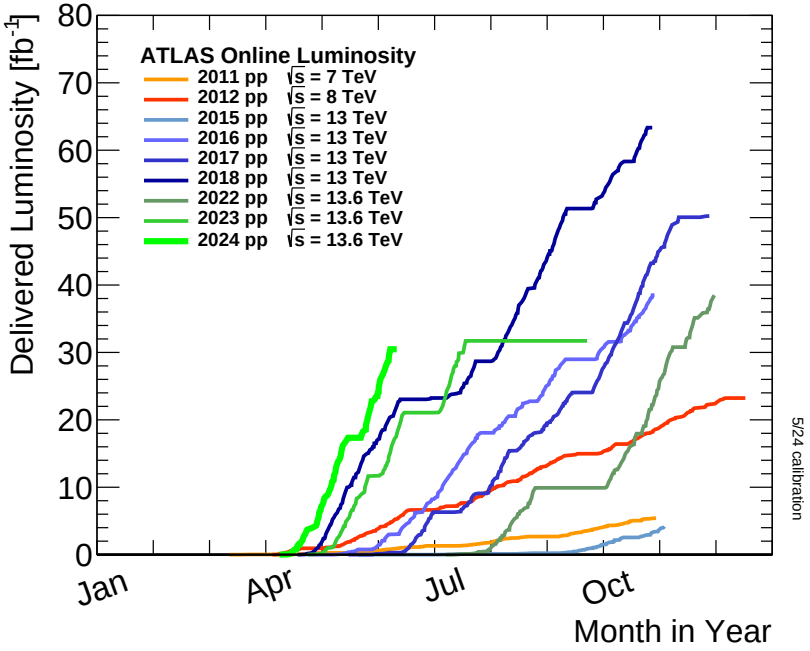
- four-fermion operator constraints probe energy scales in the 2-20 TeV range
- Between them CMS $t\bar{t}$+extra leptons and ATLAS $t\bar{t}Z$ results cover all operators shown in this figure

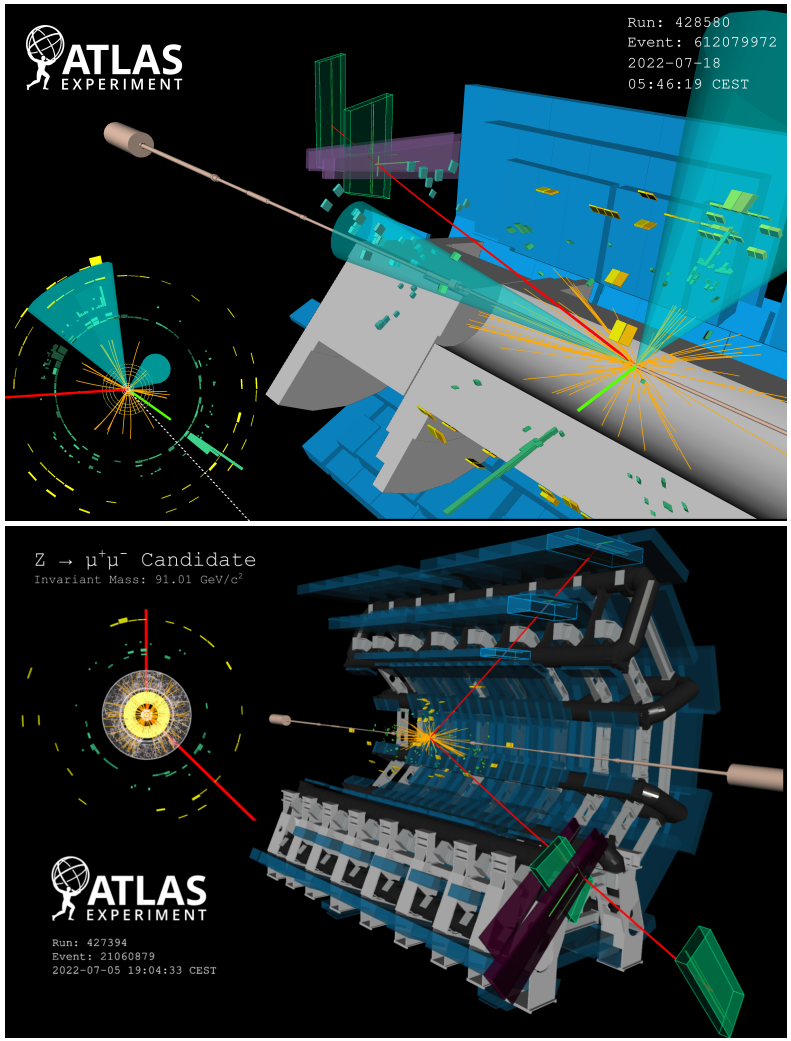
Run 3 Measurements

Featuring:

- ATLAS - Phys. Let. B 854 (2024) 138725 Measurement of vector boson production cross sections and their ratios
- ATLAS - Phys. Let. B 848 (2024) 138376 Measurement of $t\bar{t}$ cross-section and $t\bar{t}/Z$ cross-section ratio at $\sqrt{s} = 13.6$ TeV
- ATLAS - Top Cross section summary plots (includes ATLAS+CMS summaries) ATL-PHYS-PUB-2024-006
- CMS - CMS-PAS-SMP-22-017 Measurement of the inclusive cross section of Z boson production in pp collisions at $\sqrt{s} = 13.6$ TeV
- CMS - JHEP 08 (2023) 204 First measurement of the top quark pair production cross section in proton-proton collisions at $\sqrt{s} = 13.6$ TeV

LHC Run 3 the story so far

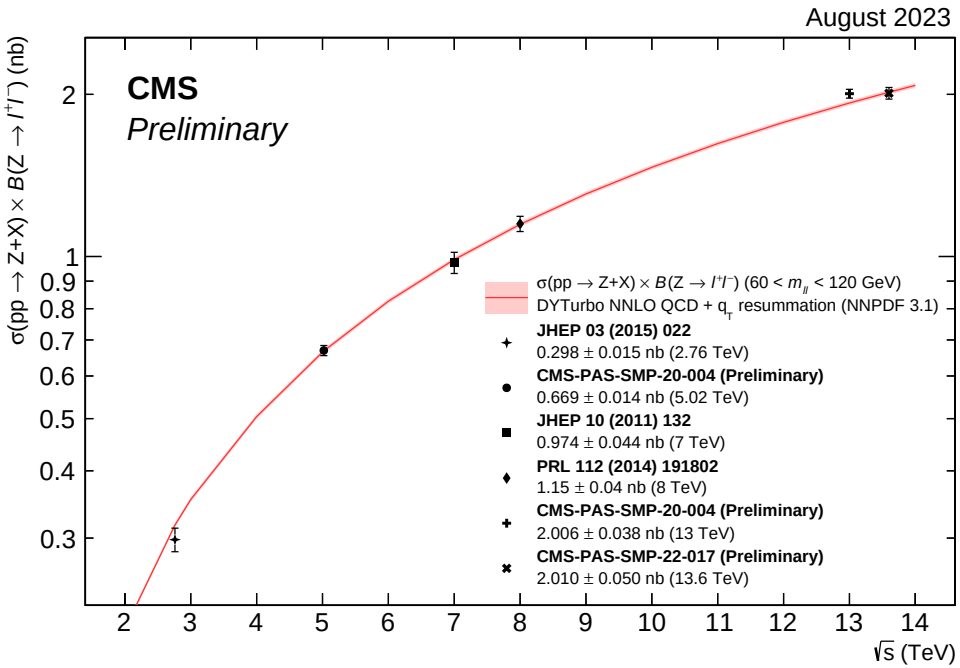


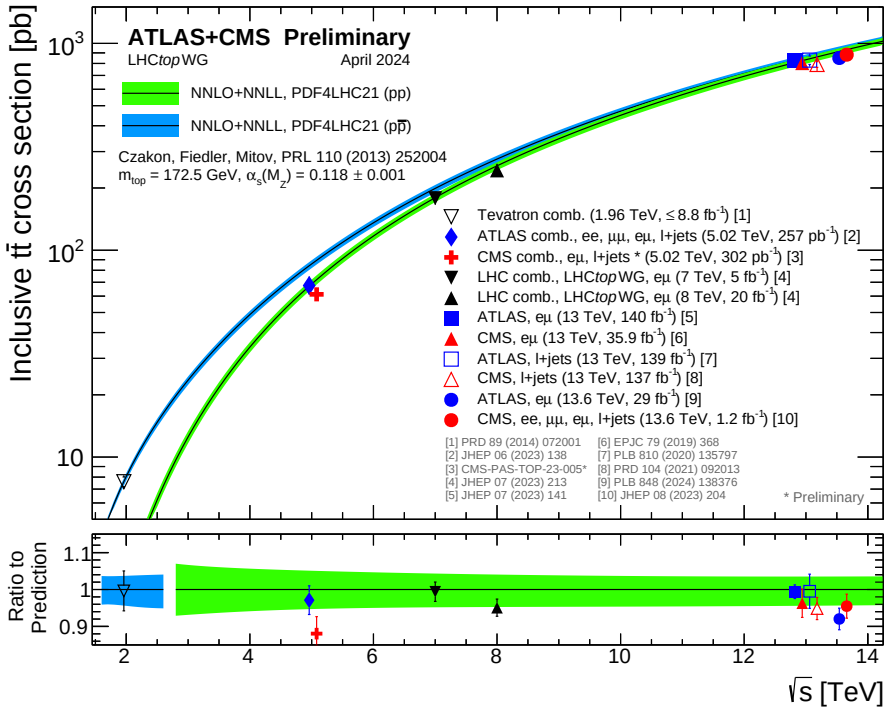


- LHC delivered around 70 fb^{-1} per experiment in 2022-2023
- Experiments are already starting to publish results with this data

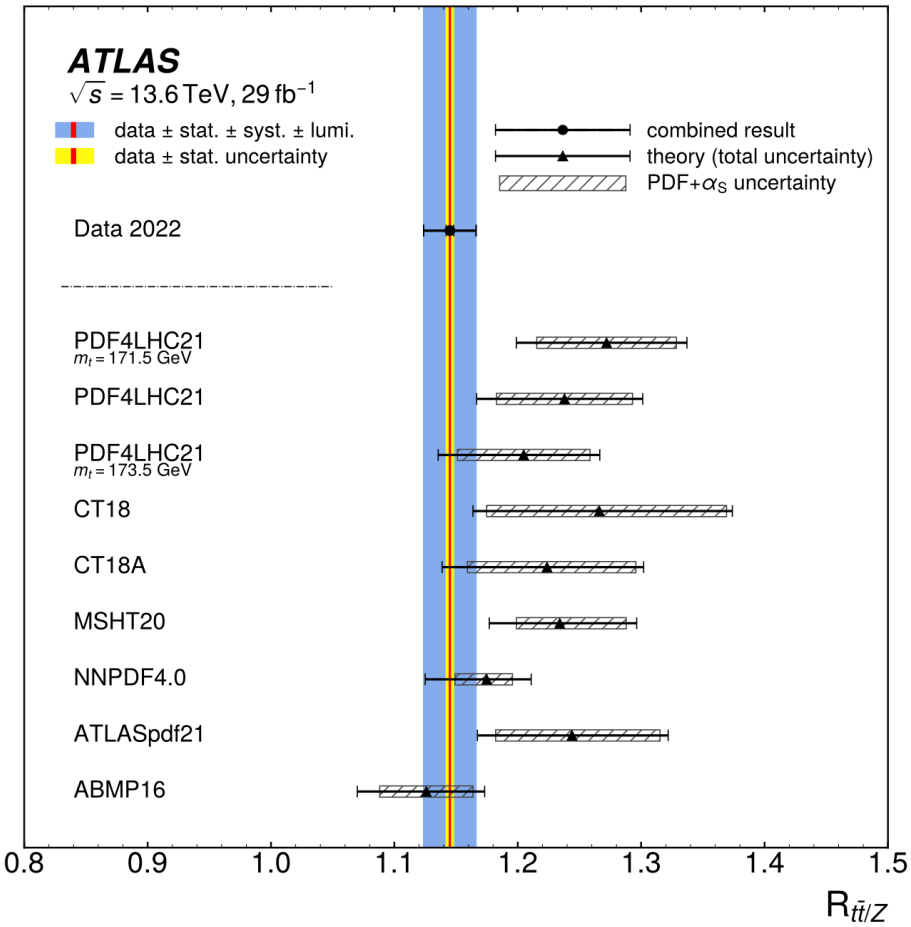
First Run 3 Measurements I

ATLAS + CMS have already made first Run 3 measurements of Z and $t\bar{t}$



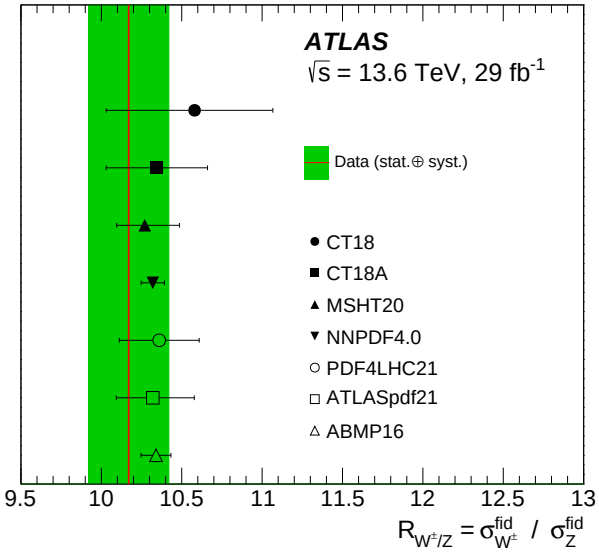


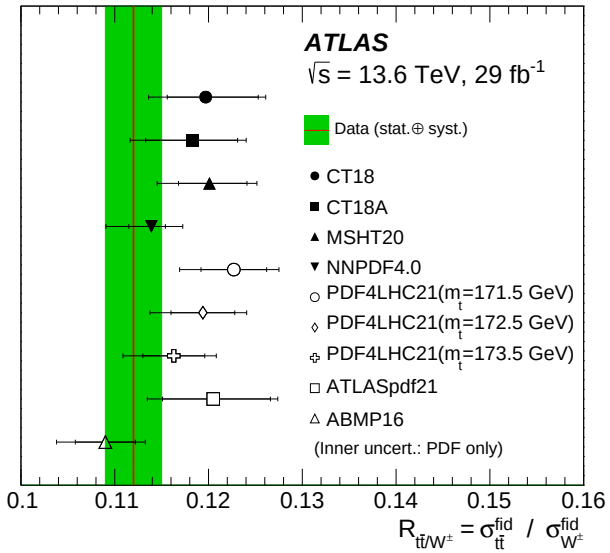
First Run 3 Measurements II



- ATLAS also measured the $t\bar{t}/Z$ ratio (generally sensitive to PDFs)
- Value of the ratio is on the low side but still consistent with expectations from most PDFs

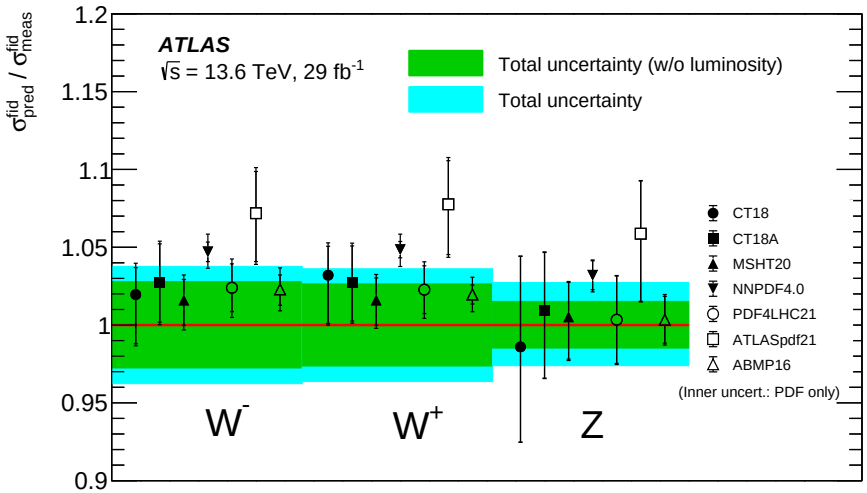
First Run 3 Measurements III





Most recent Run 3 result

- ATLAS measured the W^-, W^+, and Z production cross-sections and their ratios PDFs)
- as with $t\bar{t}$, $W^{\pm}$ cross sections a little lower than expected but not at a significant level



Summary

Summary

- A rich and varied ongoing program of SM (including top) measurements at ATLAS and CMS
- Measurement of cross-sections across 12 orders of magnitude
- Precision measurements of SM observables such as m_W and m_t comfortably surpass the expectations we had before the LHC began
- Large datasets, ever increasing understanding of our detector performance, and advanced ML/statistical techniques allow us to carefully probe for new physics effects such BNV, LFC, LUV, as well as test behaviour like top-quark entanglement
- Well designed measurements are suitable for re-interpretation in new physics models
- Via EFT analysis, new physics at energy scales beyond 10 TeV is now being probed
- I didn't have time to cover other SM work relevant to SUSY analyses such as nice results on jet substructure that is relevant for $W/Z/t$-jet tagging and to test parton shower performance

Back-up

ATLAS SM (inc Top) - I

- [ATLAS-1] arXiv:2405.20206 Measurements of jet cross-section ratios in 13 TeV proton–proton collisions with ATLAS
- [ATLAS-2] arXiv:2405.20041 A simultaneous unbinned differential cross section measurement of twenty-four Z+jets kinematic observables
- [ATLAS-3] arXiv:2405.05048 Underlying-event studies with strange hadrons
- [ATLAS-4] arXiv:2404.06204 Precise measurements of W and Z transverse momentum spectra
- **[ATLAS-5]** arXiv:2403.15085 Measurement of the W-boson mass and width
- [ATLAS-6] arXiv:2403.15296 Electroweak WZ boson pair production in association with two jets
- [ATLAS-7] arXiv:2403.15093 Production cross-section for a Z boson in association with b- or c-jets
- **[ATLAS-8]** Phys. Let. B 854 (2024) 138725 Measurement of vector boson production cross sections and their ratios
- [ATLAS-9] arXiv:2403.04869 Observation of electroweak production of W^+W^- in association with jets
- **[ATLAS-10]** arXiv:2403.02793 Differential cross sections for the production of missing transverse momentum and jets

ATLAS SM (inc Top) - II

- [ATLAS-11] arXiv:2403.02809 Observation and differential cross-section measurements of electroweak $W\gamma jj$ production
- [ATLAS-12] arXiv:2402.16365 Diboson polarization fractions and Radiation Amplitude Zero effect in WZ production
- [ATLAS-13] arXiv:2402.13052 Measurements of Lund subjet multiplicities
- [ATLAS-14] arXiv:2312.03797 Jet substructure in boosted tt events
- [ATLAS-15] Phys. Lett. B 854 (2024) 138705 Measurement of the Z boson invisible width
- [ATLAS-16] JHEP 04 (2024) 026 Measurement of same-sign W boson pair production in association with two jets
- [ATLAS-17] arXiv:2311.09715 Measurement of ZZ production cross-sections in the four-lepton final state
- [ATLAS-18] arXiv:2311.09715 Study of $Z(\rightarrow \ell\ell\gamma)$ decays
- [ATLAS-19] Eur. Phys. J. C 84 (2024) 195 Evidence of pair-production of longitudinally polarised vector bosons and study of CP properties in $ZZ \rightarrow 4\ell$ events
- [ATLAS-20] arXiv:2309.15887 Search for exclusive W boson hadronic decays

ATLAS SM (inc Top) - III

- **[ATLAS-21]** arXiv:2309.12986 Precise determination of the strong-coupling constant from the recoil of Z bosons
- **[ATLAS-22]** Eur. Phys. J. C 84 (2024) 315 Double-differential Z-boson transverse momentum and rapidity distributions in the full phase space
- [ATLAS-23] JHEP 01 (2024) 004 Cross-section measurements of four charged leptons produced in association with two jets
- **[ATLAS-24]** Phys. Let. B 848 (2024) 138376 Measurement of $t\bar{t}$ cross-section and $t\bar{t}/Z$ cross-section ratio at $\sqrt{s} = 13.6$ TeV
- [ATLAS-25] Phys. Lett. B 848 (2024) 138400 Observation of $W\gamma\gamma$ production
- [ATLAS-26] arXiv:2405.05078 Observation of top pair production in proton-lead collisions
- **[ATLAS-27]** arXiv:2404.02123 Search for FCNC with tHq coupling in the multi lepton channel
- [ATLAS-28] arXiv:2403.09452 $t\bar{t} + \gamma$ inclusive and differential cross-section measurements
- **[ATLAS-29]** arXiv:2403.06742 Search for charged lepton flavour violation in top quark production and decay
- [ATLAS-30] arXiv:2403.02126 Single top t-channel total cross-section

ATLAS SM (inc Top) - IV

- **[ATLAS-31]** arXiv:2403.02133 Test of electron-muon lepton universality in W decays from ttbar events
- **[ATLAS-32]** arXiv:2402.08713 ATLAS/CMS Run 1 top mass combination
- **[ATLAS-33]** JHEP 05 (2024) 131 Measurement of $t\bar{t}W$ total and differential cross sections
- **[ATLAS-34]** 2312.04450 Measurement of $tt\bar{Z}$ total and differential cross sections
- **[ATLAS-35]** arXiv:2311.07288 Observation of quantum entanglement in top-quark pairs
- [ATLAS-36] arXiv:2310.01518 Single-top t-channel production cross-section at sqrt(s) = 5.02 TeV
- **[ATLAS-37]** JHEP 12 (2023) 195 Search for tHu and tHc flavor-changing neutral current interactions in top-quark production and decay with $H \to \gamma\gamma$
- [ATLAS-38] ATLAS-CONF-2023-068/ Measurement of differential cross sections in ttbar and ttbar+jets production in the lepton+jets decay mode in pp collisions at $\sqrt{s} = 13$ TeV using 140 fb^{-1} of ATLAS data

CMS SM (inc Top) - I

- [CMS-1] arXiv:2404.18298 Search for the Z boson decay to $\tau\tau\mu\mu$ in proton-proton collisions at $\sqrt{s} = 13$ TeV
- **[CMS-2]** arXiv:2404.16082 Measurement of multijet azimuthal correlations and determination of the strong coupling in proton-proton collisions at $\sqrt{s} = 13$ TeV
- [CMS-3] arXiv:2404.02711 Measurement of differential ZZ+jets production cross sections in pp collisions at $\sqrt{s} = 13$ TeV
- **[CMS-4]** arXiv2402.13864 Measurement of energy correlators inside jets and determination of the strong coupling $\alpha_S(m_Z)$
- [CMS-5] arXiv:2401.14494 Nonresonant central exclusive production of charged-hadron pairs in proton-proton collisions at $\sqrt{s} = 13$ TeV
- [CMS-6] arXiv:2401.11355 Measurement of the double-differential inclusive jet cross section in proton-proton collisions at $\sqrt{s} = 5.02$ TeV
- [CMS-7] arXiv:2312.16669 Measurement of multidifferential cross sections for dijet production in proton-proton collisions at $\sqrt{s} = 13$ TeV
- [CMS-8] JHEP 05 (2024) 116 Measurement of the primary Lund jet plane density in proton-proton collisions at $\sqrt{s} = 13$ TeV
- [CMS-9] Phys. Rev. Lett. 132 (2024) 121901 Observation of $WW\gamma$ production and search for $H\gamma$ production in proton-proton collisions at $\sqrt{s} = 13$ TeV

CMS SM (inc Top) - II

- **[CMS-10]** JHEP 01 (2024) 101 Measurement of the τ lepton polarization in Z boson decays in proton-proton collisions at $\sqrt{s} = 13$ TeV
- [CMS-11] EPJC 84 (2024) 27 Measurement of the production cross section for a W boson in association with a charm quark in proton-proton collisions at $\sqrt{s} = 13$ TeV
- **[CMS-12]** arXiv:2405.14757 Searches for violation of Lorentz invariance in $t\bar{t}$ production using dilepton events in proton-proton collisions at $\sqrt{s} = 13$ TeV
- **[CMS-13]** arXiv:2402.18461 Search for baryon number violation in top quark production and decay using proton-proton collisions at $\sqrt{s} = 13$ TeV
- [CMS-14] arXiv:2402.08486 Differential cross section measurements for the production of top quark pairs and of additional jets using dilepton events from pp collisions at $\sqrt{s} = 13$ TeV
- [CMS-15] arXiv:2312.1166 Evidence for tWZ production in proton-proton collisions at $\sqrt{s} = 13$ TeV in multilepton final states
- **[CMS-16]** Phys. Rev. D 109 (2024) 072004 Search for flavor changing neutral current interactions of the top quark in final states with a photon and additional jets in proton-proton collisions at $\sqrt{s} = 13$ TeV

CMS SM (inc Top) - III

- **[CMS-17]** arXiv:2312.03199 Search for charged-lepton flavor violation in the production and decay of top quarks using trilepton final states in proton-proton collisions at $\sqrt{s} = 13$ TeV
- [CMS-18] PLB 850 (2024) 138478 Search for new Higgs bosons via same-sign top quark pair production in association with a jet in proton-proton collisions at $\sqrt{s} = 13$ TeV
- [CMS-19] arXiv:2310.11231 Search for central exclusive production of top quark pairs in proton-proton collisions at $\sqrt{s} = 13$ TeV with tagged protons
- **[CMS-20]** arXiv:2402.08713 Combination of measurements of the top quark mass from data collected by the ATLAS and CMS experiments at $\sqrt{s} = 7$ and 8 TeV
- [CMS-21] arXiv:2402.08713 Inclusive and differential cross section measurements of $t\bar{t}b\bar{b}$ production in the lepton+jets channel at $\sqrt{s} = 13$ TeV
- **[CMS-22]** JHEP 12 (2023) 068 Search for physics beyond the standard model in top quark production with additional leptons in the context of effective field theory
- **[CMS-23]** CMS-PAS-SMP-22-009 Measurement of the $Z(\nu\bar{\nu}) + \gamma$ production cross section and search for anomalous neutral triple gauge couplings in pp collisions at 13 TeV

CMS SM (inc Top) - IV

- **[CMS-24]** CMS-PAS-TOP-23-005 Measurement of the inclusive $t\bar{t}$ cross section in final states with one lepton and additional jets at 5.02 TeV with 2017 data
- **[CMS-25]** CMS-PAS-TOP-23-004 Inclusive and differential measurement of top quark cross sections in association with a Z boson
- **[CMS-26]** CMS-PAS-TOP-23-001 Probing entanglement in top quark production with the CMS detector
- **[CMS-27]** CMS-PAS-SMP-22-010 Measurement of the Drell-Yan forward-backward asymmetry and of the effective leptonic weak mixing angle using proton-proton collisions at $\sqrt{s} = 13$ TeV
- **[CMS-28]** CMS-PAS-TOP-23-008 Measurement of inclusive and differential cross sections for single top quark production in association with a W boson in proton-proton collisions at $\sqrt{s} = 13.6$ TeV

CMS-29 CMS-PAS-SMP-24-001 Measurement of W^+W^- inclusive and differential cross sections in pp collisions at $\sqrt{s} = 13.6$ TeV with the CMS detector

- **[CMS-30]** CMS-PAS-SMP-23-005 Observation of $\gamma\gamma \to \tau\tau$ in proton-proton collisions and limits on the anomalous electromagnetic moments of the τ lepton

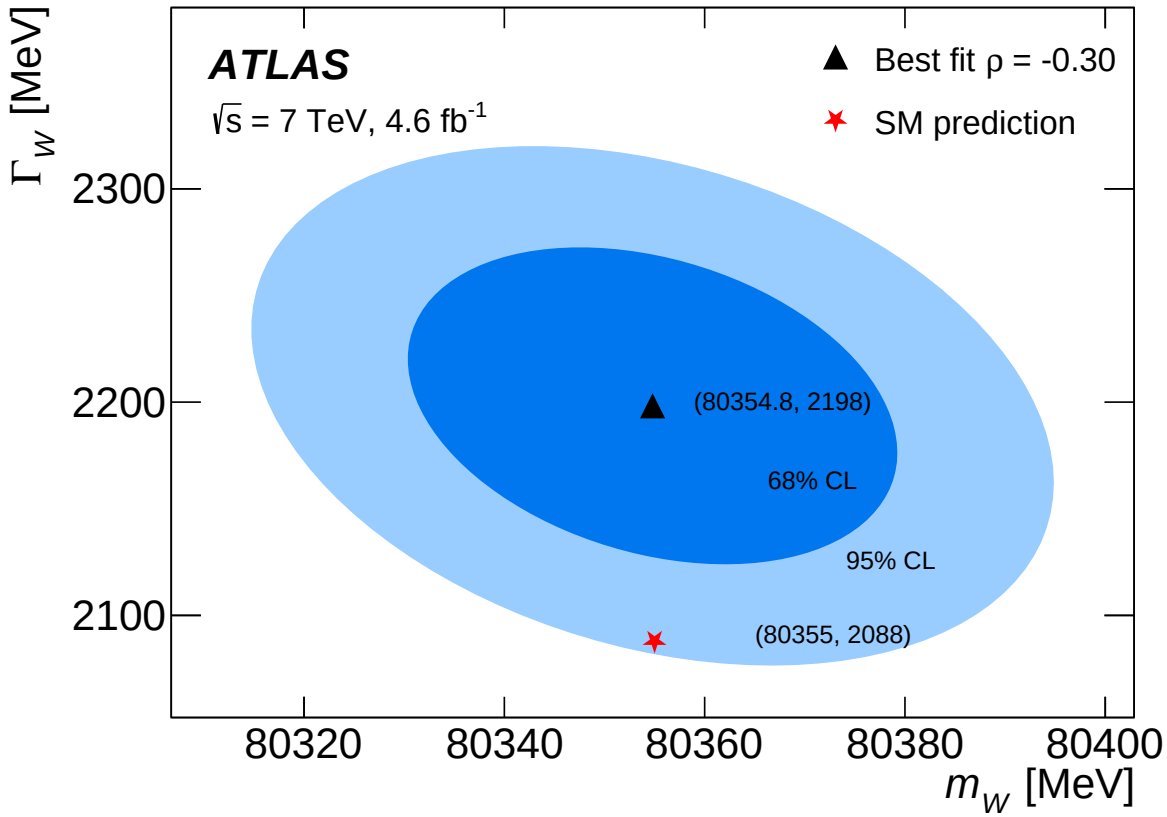
CMS SM (inc Top) - V

- [CMS-31] CMS-PAS-SMP-22-012 Search for the rare decays of the Z and Higgs bosons to a J/Ψ orΨ' meson and a photon in proton-proton collisions at $\sqrt{s} = 13$ TeV
- **[CMS-32]** CMS-PAS-TOP-22-002 Search for flavor-changing neutral current interactions of the top quark and Higgs boson in proton-proton collisions at $\sqrt{s} = 13$ TeV
- **[CMS-33]** CMS-PAS-SMP-22-005 Measurement of azimuthal correlations among jets and determination of the strong coupling in pp collisions at $\sqrt{s} = 13$ TeV
- [CMS-34] CMS-PAS-SMP-19-007 Studies of $Z \to 4\ell$ decays in proton-proton collisions at $\sqrt{s} = 8$ and 13 TeV
- [CMS-35] CMS-PAS-SMP-20-004 Measurement of W and Z boson inclusive cross sections in proton-proton collisions at $\sqrt{s} = 5.02$ and 13 TeV
- [CMS-36] CMS-PAS-SMP-22-017 Measurement of the inclusive cross section of Z boson production in pp collisions at $\sqrt{s} = 13.6$ TeV
- [CMS-37] CMS-PAS-SMP-22-008 Measurement of $W \pm W\pm$ scattering in proton-proton collisions at $\sqrt{s} = 13$ TeV in final states with one tau lepton

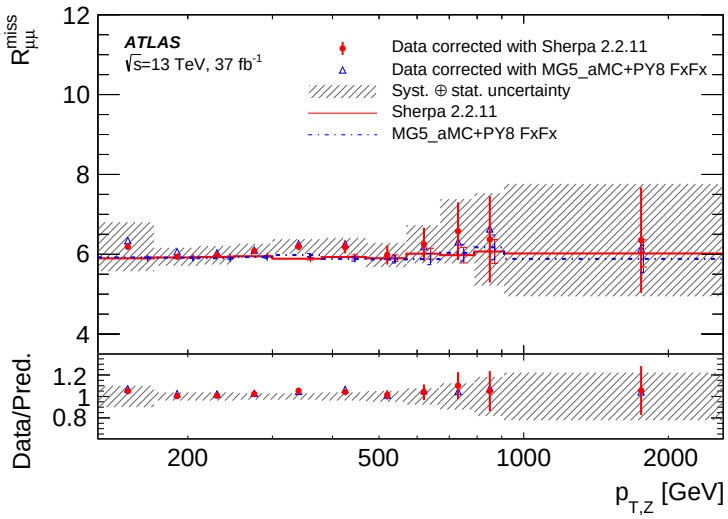
LHCb SM (inc Top) Papers

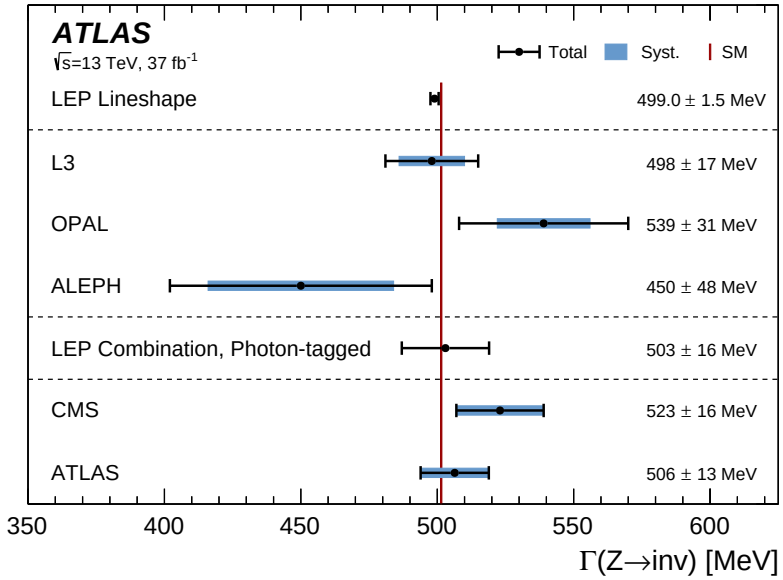
- [LHCb-1] JHEP 02 (2024) 070 - Measurement of the Z boson production cross-section in pp collisions at $\sqrt{s} = 5.02$ TeV

ATLAS: Simultaneous m_W and Γ_W



ATLAS: Z invisible width



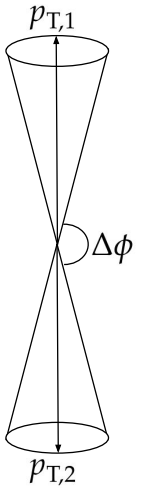


CMS: $\sin\theta_\ell^{\text{eff}}$

PDF	A_{FB} (816 bins)		A_4 (63 bins)	
	χ^2_{min}	$\sin^2\theta^\ell_{\text{eff}}$	χ^2_{min}	$\sin^2\theta^\ell_{\text{eff}}$
NNPDF31	724.7	23121 ± 29	58.5	23120 ± 30
NNPDF40	730.5	23133 ± 24	62.6	23133 ± 25
MSHT20	735.8	23123 ± 30	71.0	23120 ± 32
CT18	728.4	23170 ± 35	62.2	23170 ± 36
CT18Z	730.7	23157 ± 31	61.3	23155 ± 32
CT18A	730.3	23167 ± 28	63.6	23167 ± 28
CT18X	728.5	23173 ± 30	61.8	23177 ± 30

CMS - α_S from Multijet azimuthal correlations I

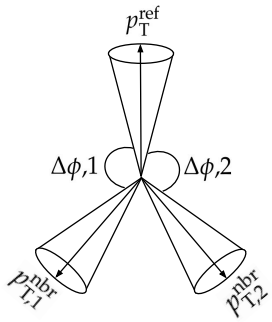
2-jet topology

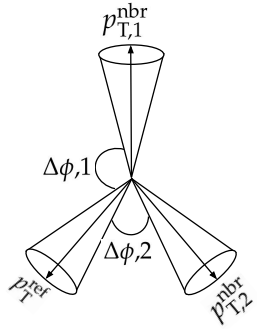


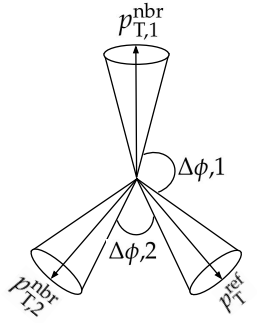
$R_{\Delta\phi}(p_T)$ entries

$\Delta\phi \approx \pi$
Numerator: 0
Denominator: 2

3-jet topology (all jets with $p_T > 100\,\text{GeV}$)







$R_{\Delta\phi}(p_T)$ entries

Numerator: 2
$2\pi/3 < \Delta\phi,1 < 7\pi/8$
$2\pi/3 < \Delta\phi,2 < 7\pi/8$

+

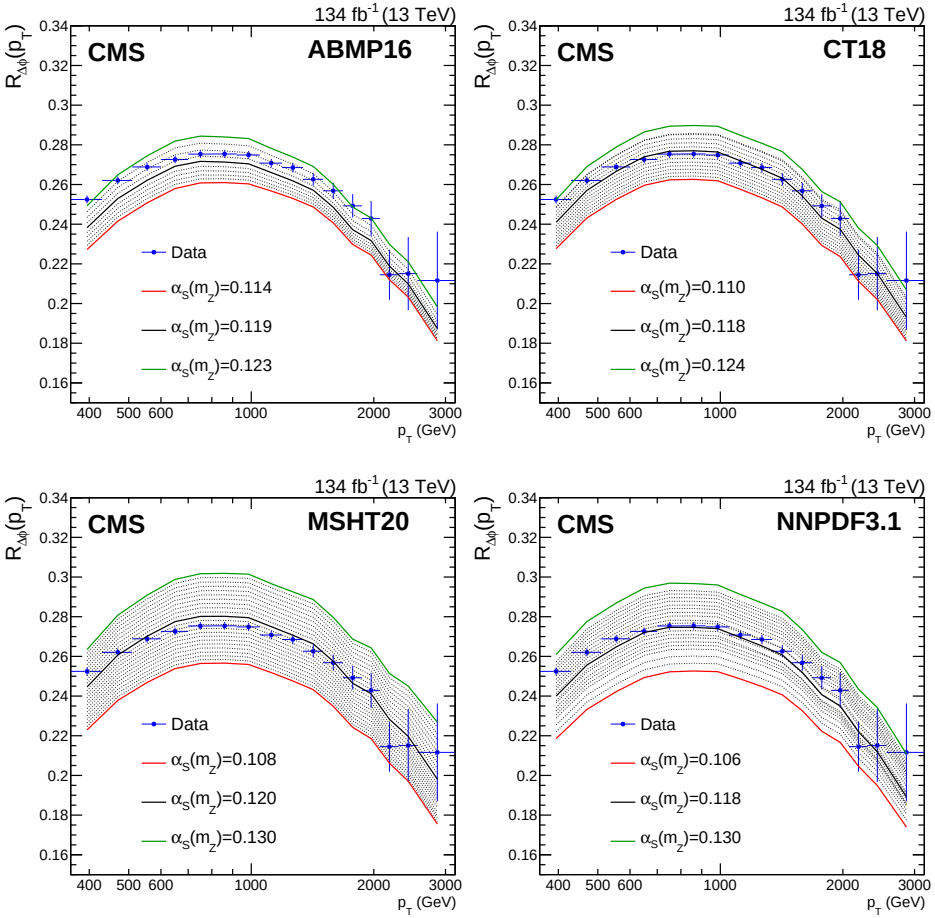
Numerator: 1
$2\pi/3 < \Delta\phi,1 < 7\pi/8$
$\Delta\phi,2 < 2\pi/3$

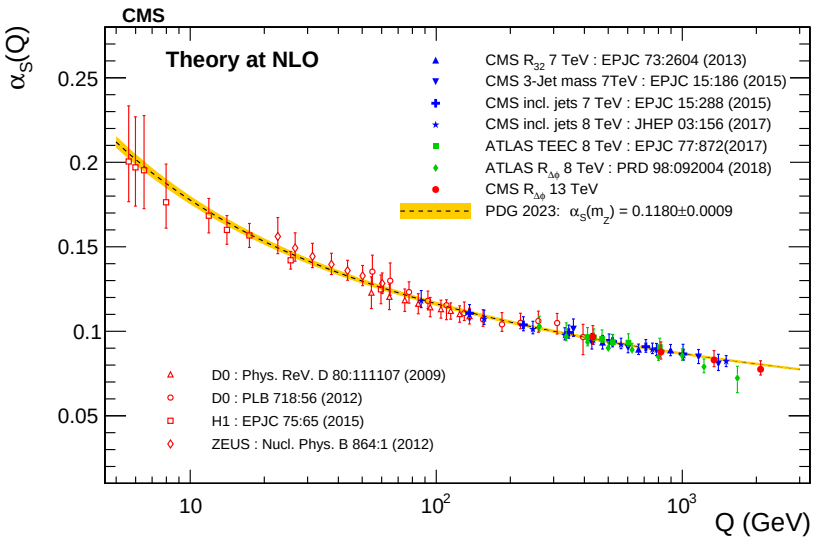
Denominator: 3

+

Numerator: 1
$2\pi/3 < \Delta\phi,1 < 7\pi/8$
$\Delta\phi,2 < 2\pi/3$

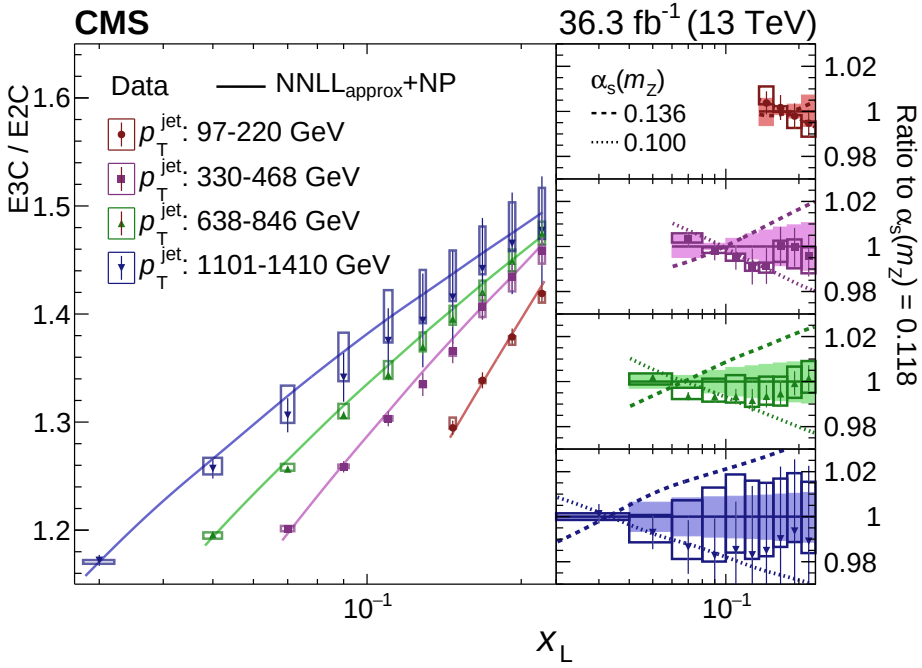
CMS - α_S from Multijet azimuthal correlations II

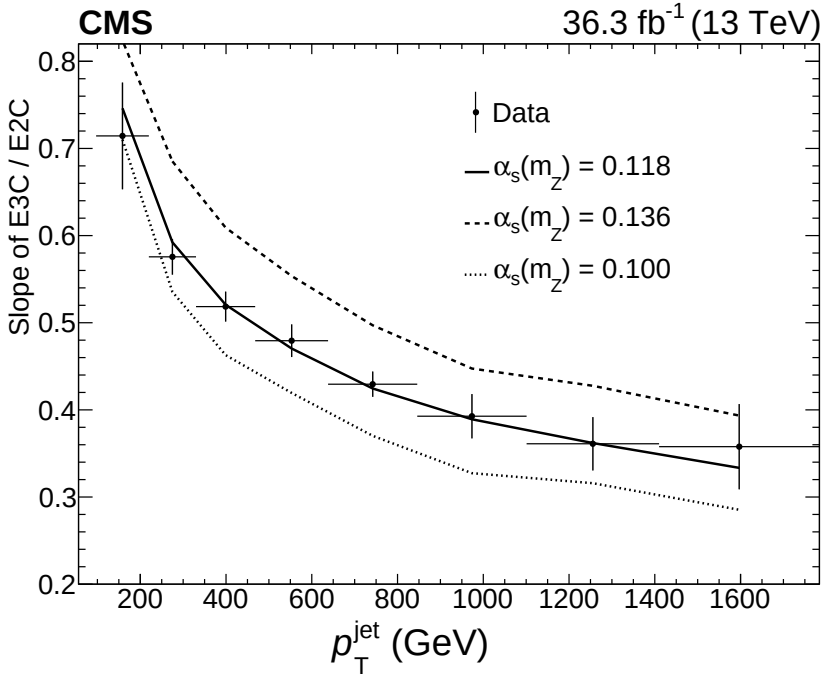




CMS - α_S from jet substructure

Ratio of 2-particle to 3-particle Energy correlators inside jets is sensitive to α_S:





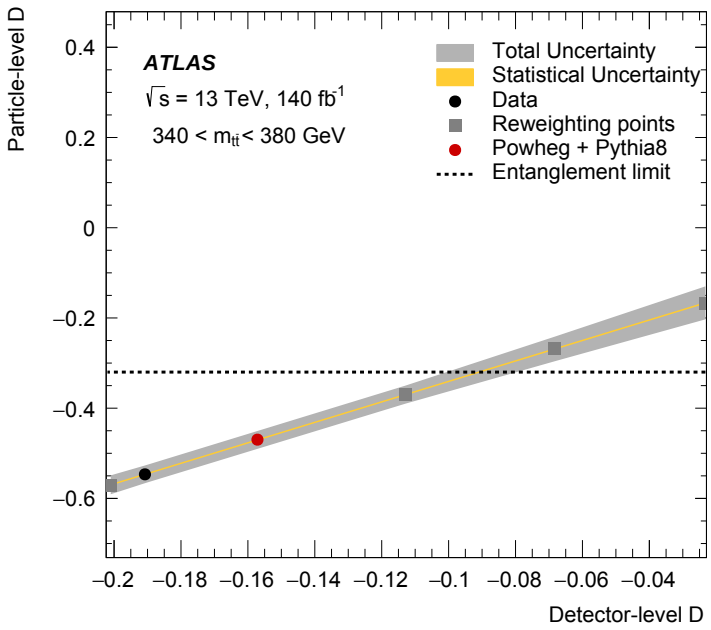
CMS have exploited this to extract :

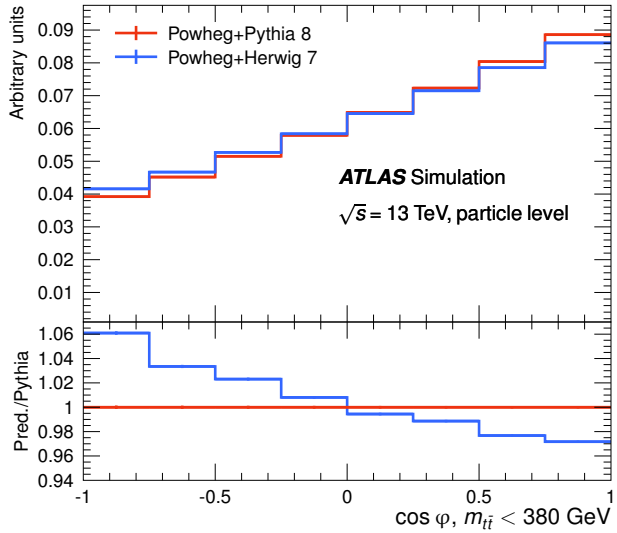
$\alpha_S(m_Z) = 0.1229^{+0.0014}_{-0.0012}\ (\text{stat})\ ^{+0.0030}_{-0.0033}\ (\text{theo})\ ^{+0.0023}_{-0.0036}\ (\text{exp})$

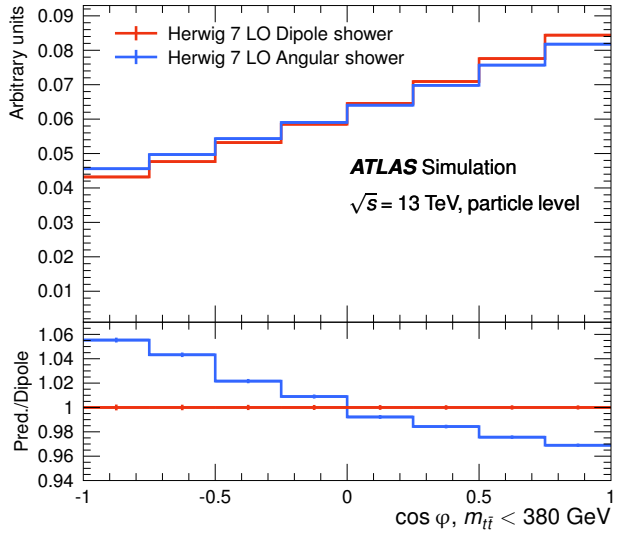
using the slope in the ratio as a function of the η, ϕ distance (x_L) between the pairs being considered.

ATLAS Entanglement

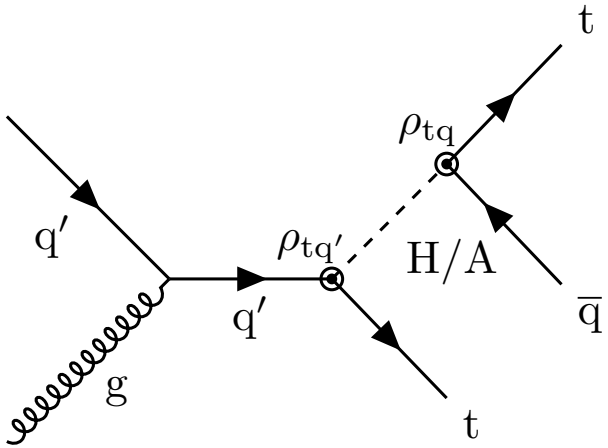
Systematic uncertainty source	Relative size (for SM D value)
Top-quark decay	1.6%
Parton distribution function	1.2%
Recoil scheme	1.1%
Final-state radiation	1.1%
Scale uncertainties	1.1%
NNLO reweighting	1.1%
pThard setting	0.8%
Top-quark mass	0.7%
Initial-state radiation	0.2%
Parton shower and hadronization	0.2%
h_{damp} setting	0.1%

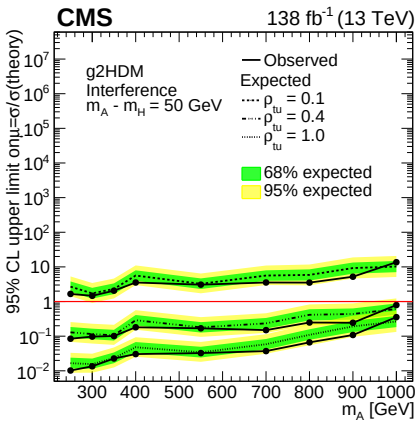


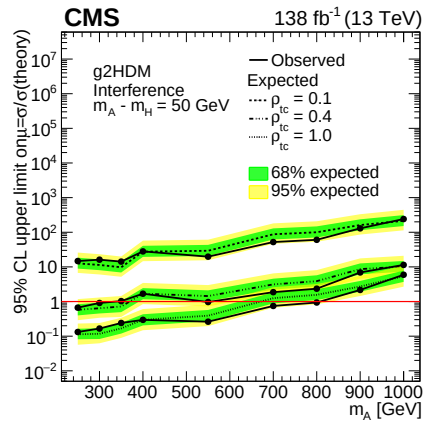


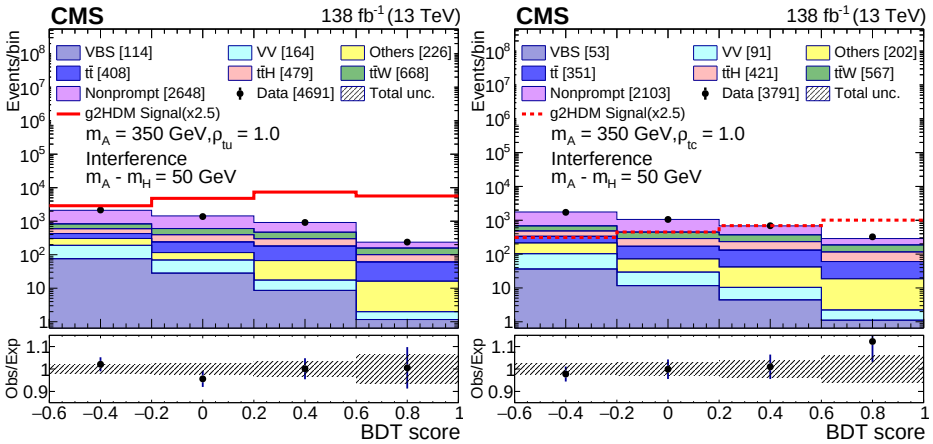


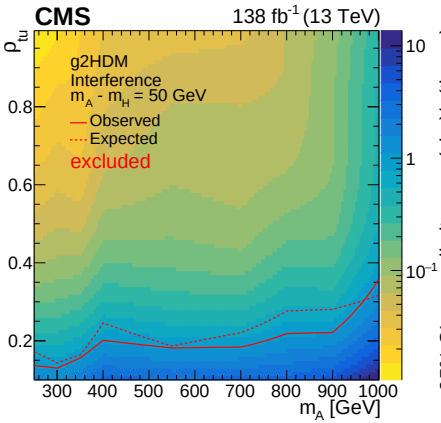
CMS: Same-sign tops+jets - new Higgs-boson contraints

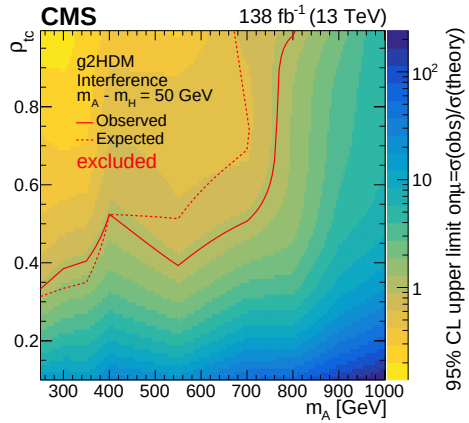




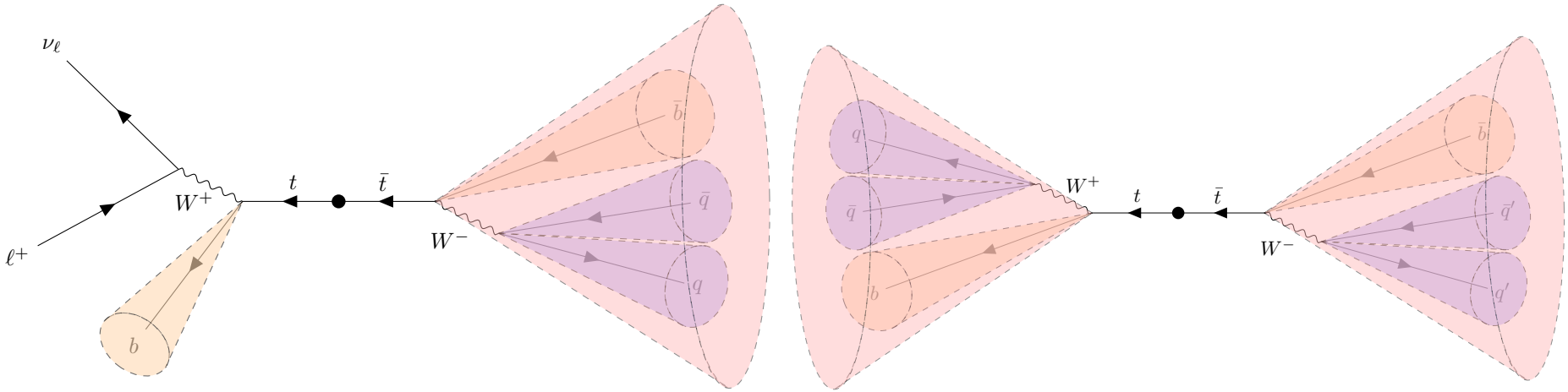




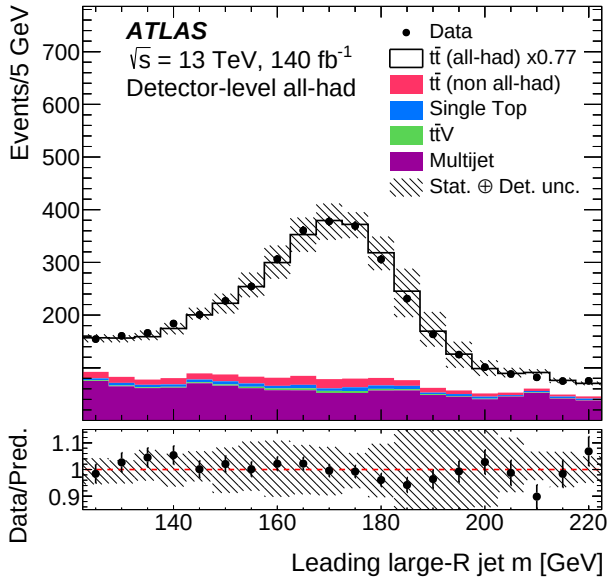




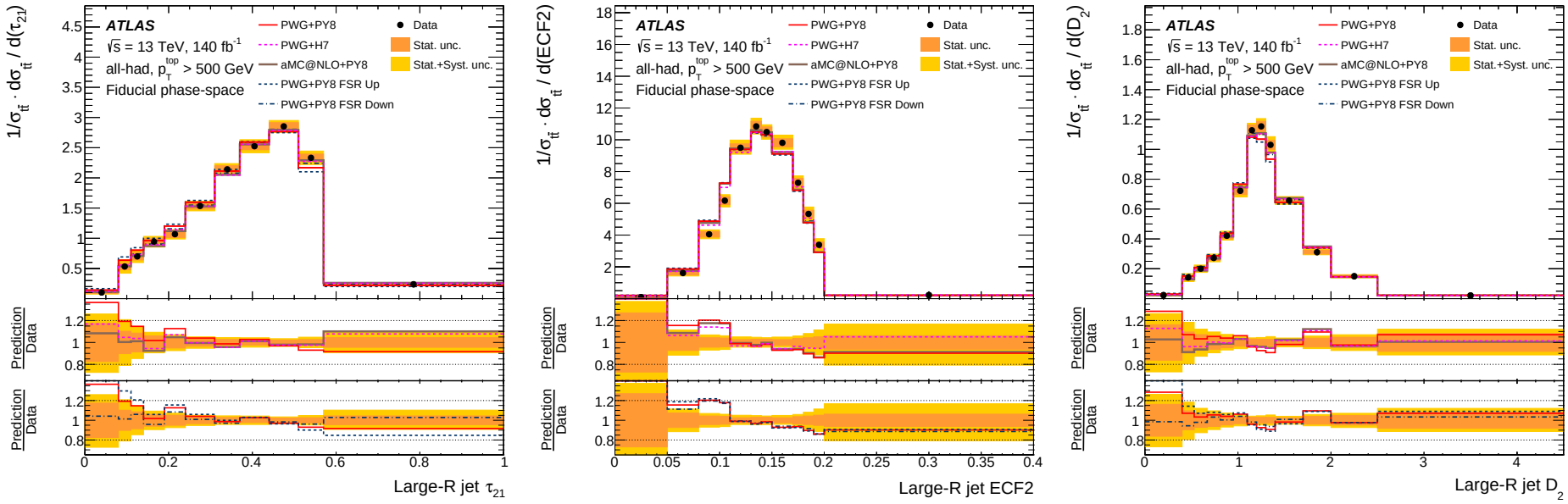
Boosted Top-quark Jets I



- high-p_{T} top-quarks can produce jets containing all the decay produces of the top
- such top jets are an interesting testing ground to study variables designed to distinguish jets with hard substructure from others
- ATLAS have studied this in $t\bar{t}$ events

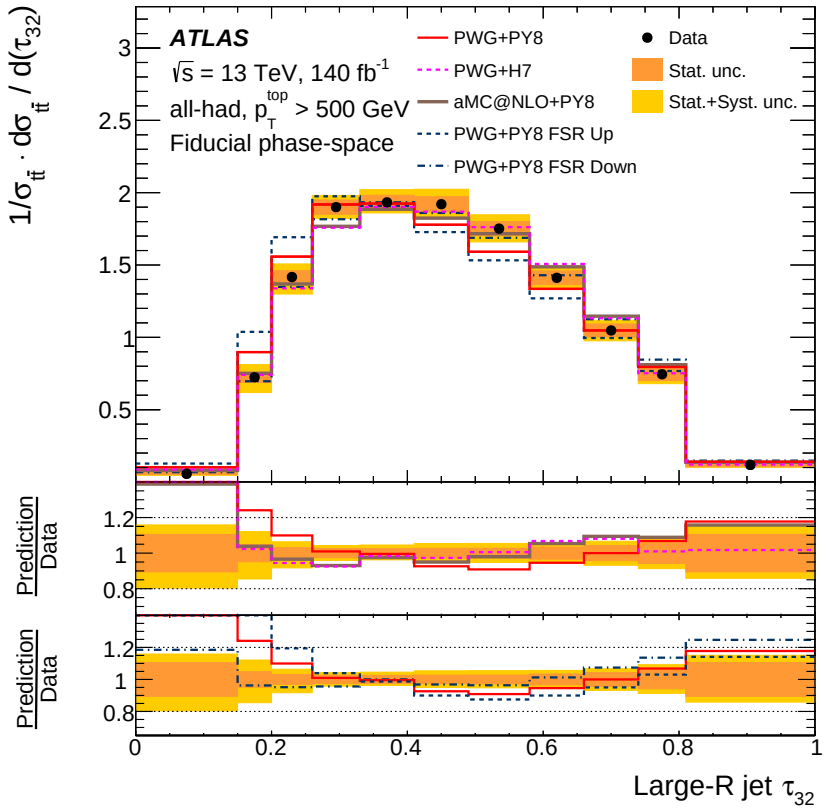


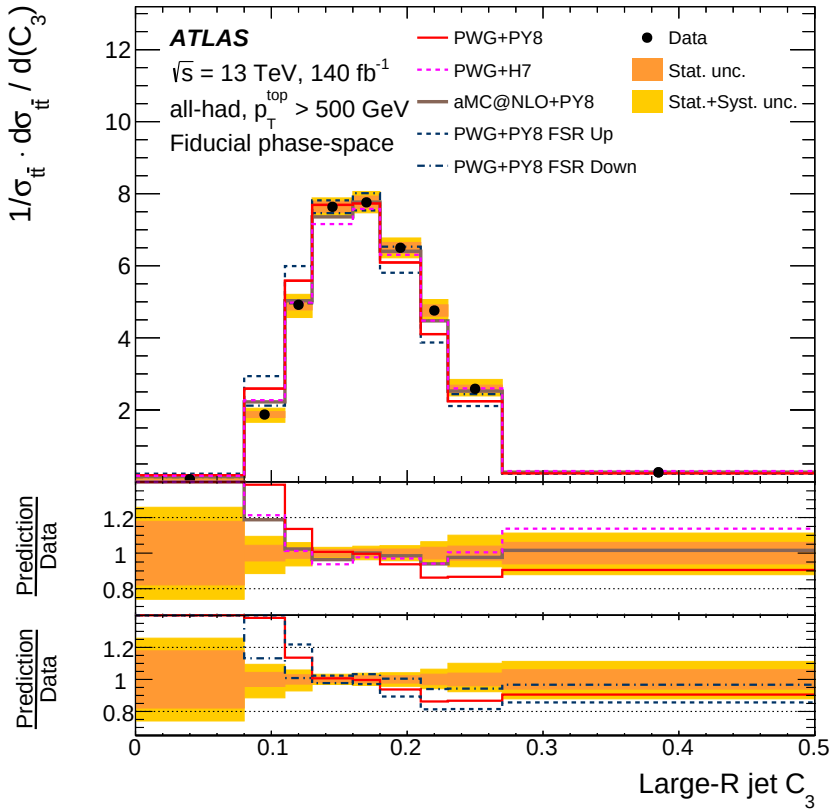
Boosted Top-quark Jets II



Variables designed to distinguish 2-prong like jets from 1 prong are generally well described

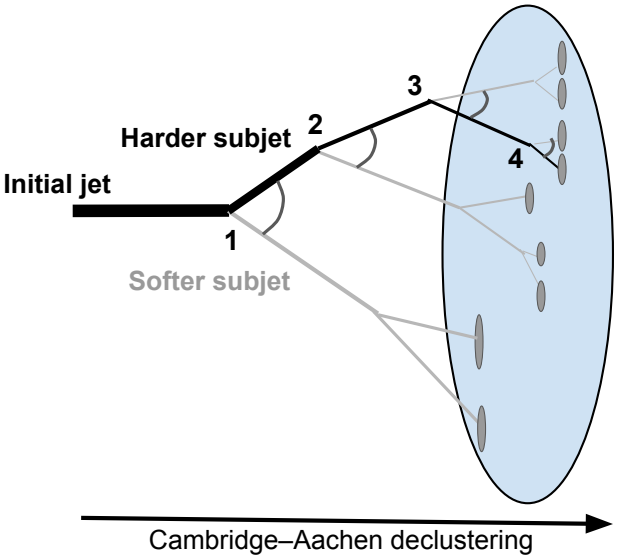
Boosted Top-quark Jets II

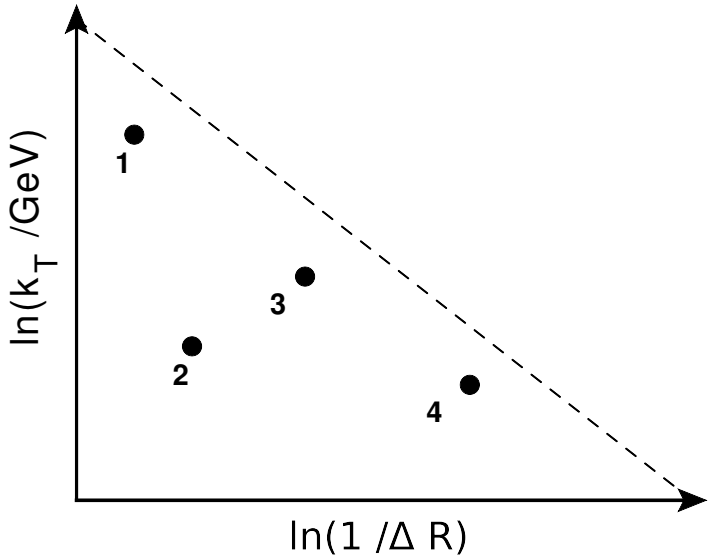


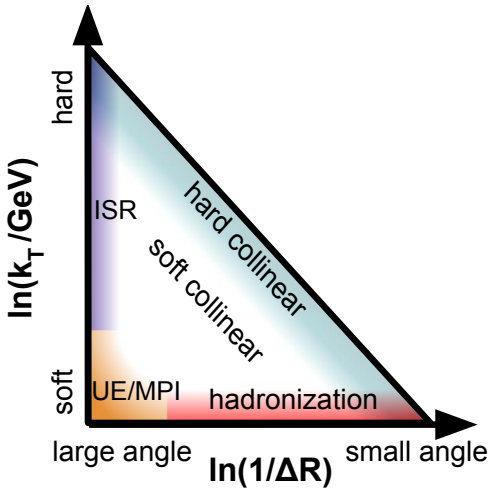


Variables designed to distinguish 3-prong like jets from 2 prong fare worse

The Lund Jet Plane

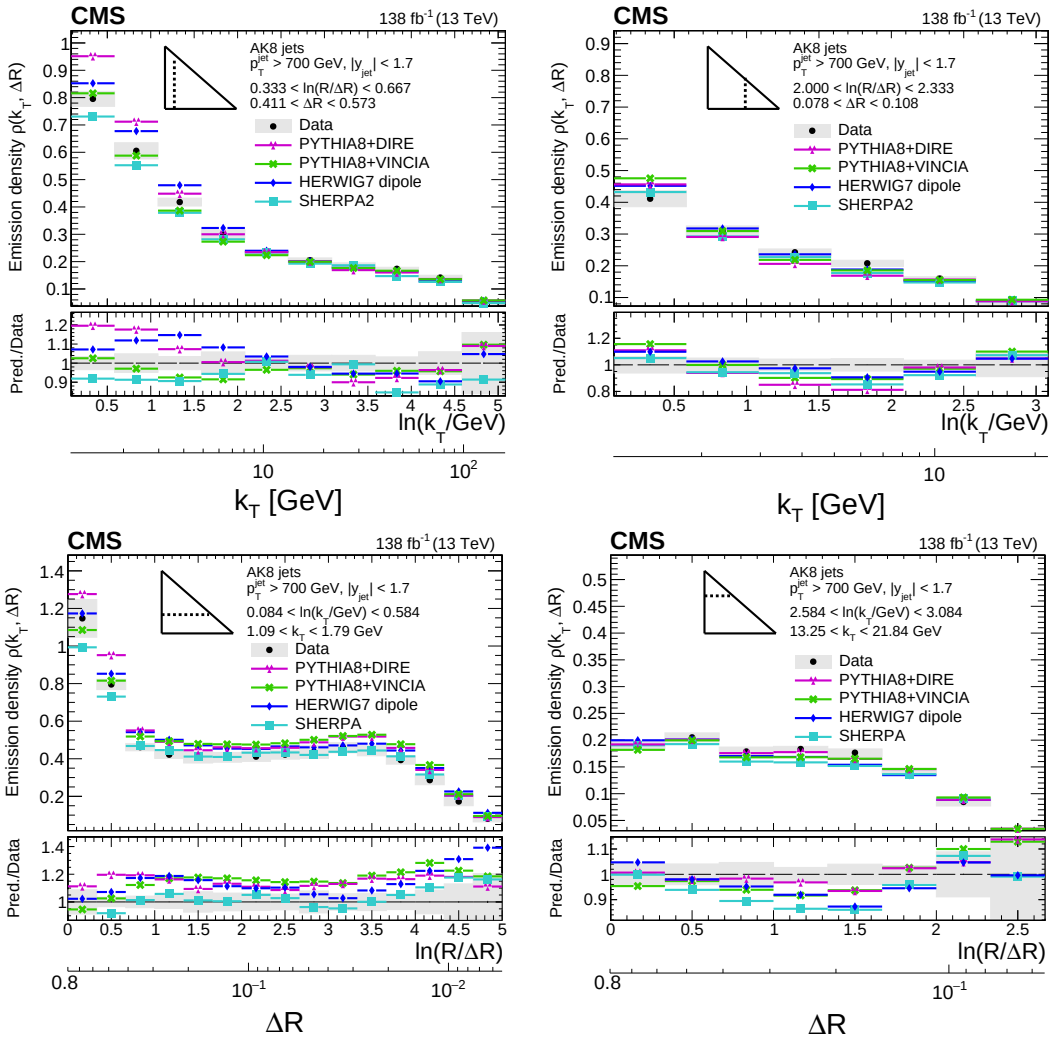






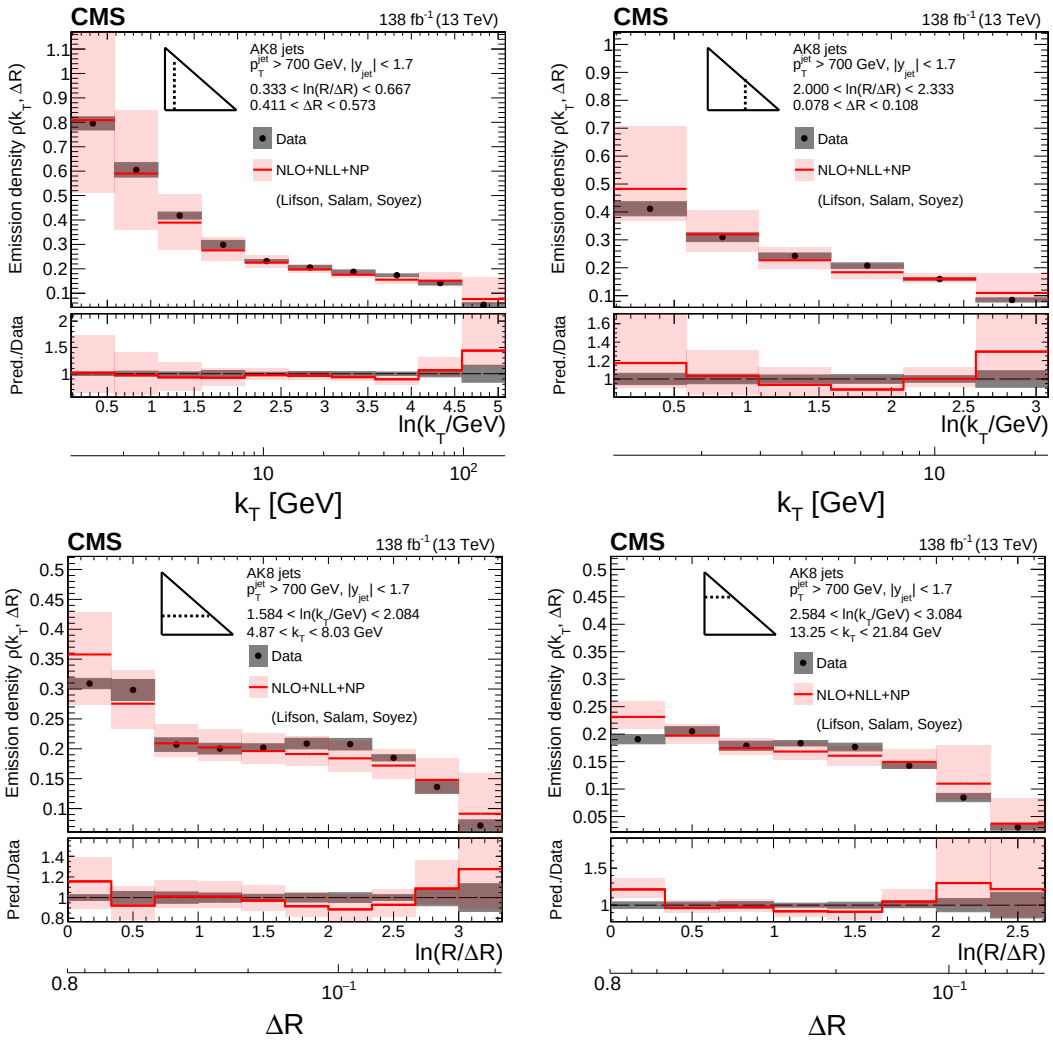
- recluster a jet
- follow splitting history
- identify jet 'core' and emissions
- assign emissions to the 2D plane
- different regions of the plane → different QCD physics

The Lund Jet Plane II



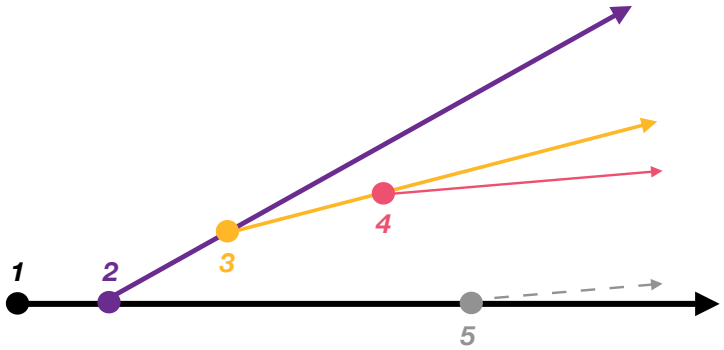
- Monte Carlo can do a reasonable job of describing the plane (Sherpa seems best)
- Analytical calculations also doing a good job

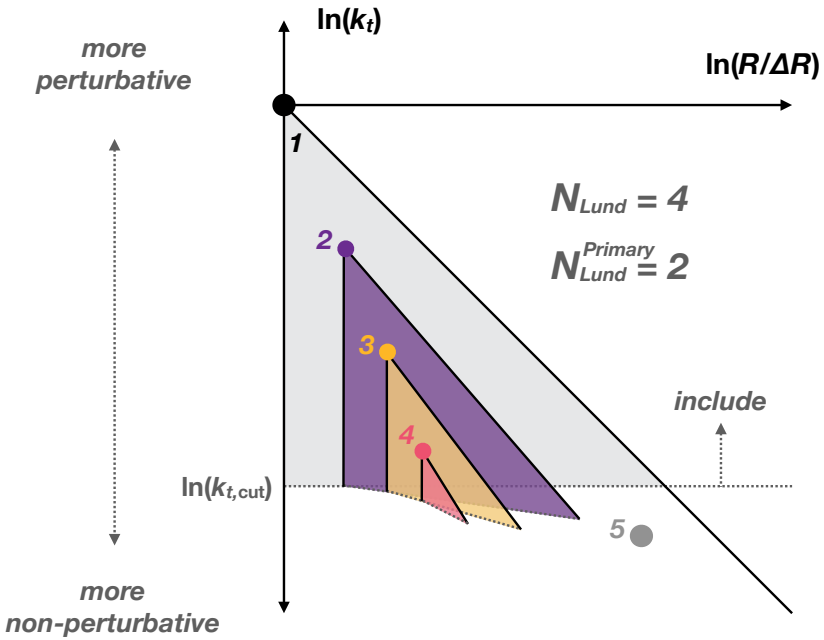
The Lund Jet Plane II



- Monte Carlo can do a reasonable job of describing the plane (Sherpa seems best)
- Analytical calculations also doing a good job

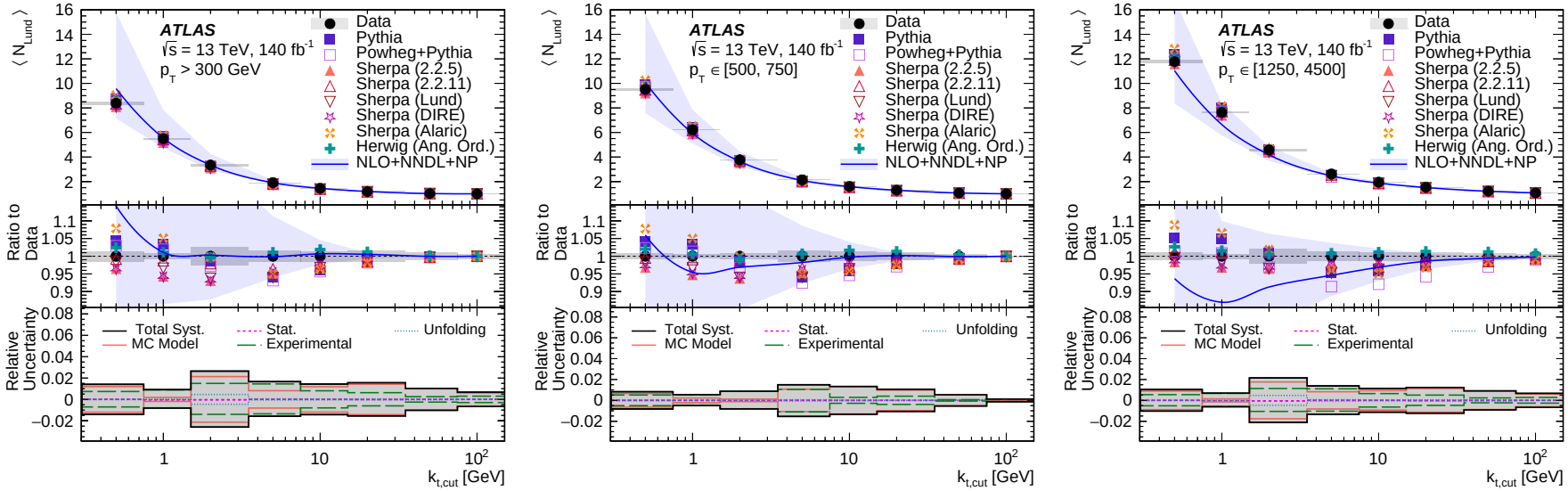
Lund Subjet multiplicities





- Lund Subjet multipicities offer even more information about
- Here each emission is followed further, so long as it is above a certain p_T threshold
- total multiplicity above a given scale gives us more information about the shower (also sensitive to α_S)

Lund Subjet multiplicities



Again MCs and analytical calculations doing well (though analytical calculation undershoots at higher p_T)