QCD and top-quark physics
Current status from the experiment

CORFU 2023
Workshop on Future Accelerators

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Javier Jiménez Peña

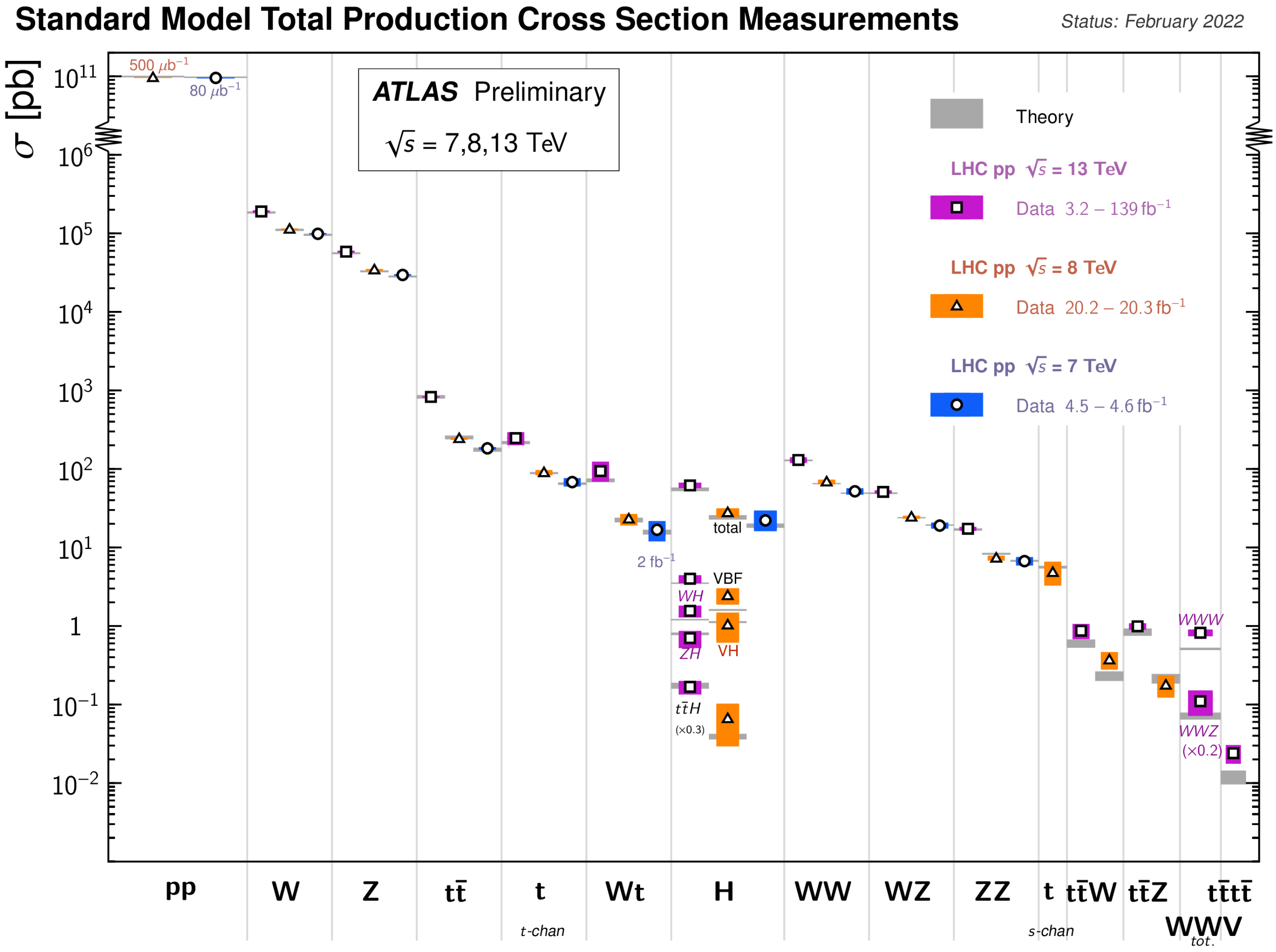
IFAE Barcelona

On behalf of ATLAS and CMS Collaborations

Introduction

Introduction

- ATLAS and CMS are testing EW and QCD predictions in a wide range of processes.
- Exploring process rates over 9 orders of magnitude, from Z, W and top pair to rare processes as multiboson or four tops.
- Precise experimental results allow to test higher order calculations in QCD.



Further information

- Many results by **ATLAS and CMS** in the topic to cover them all.
- What follows is a selection of recent results focused in **QCD** or involving **top quarks**.
- Apologies for not covering other LHC experiments as ALICE

ATLAS and CMS are further testing the validity of the Standard Model through:

Differential cross-sections

Rare processes

Properties measurements

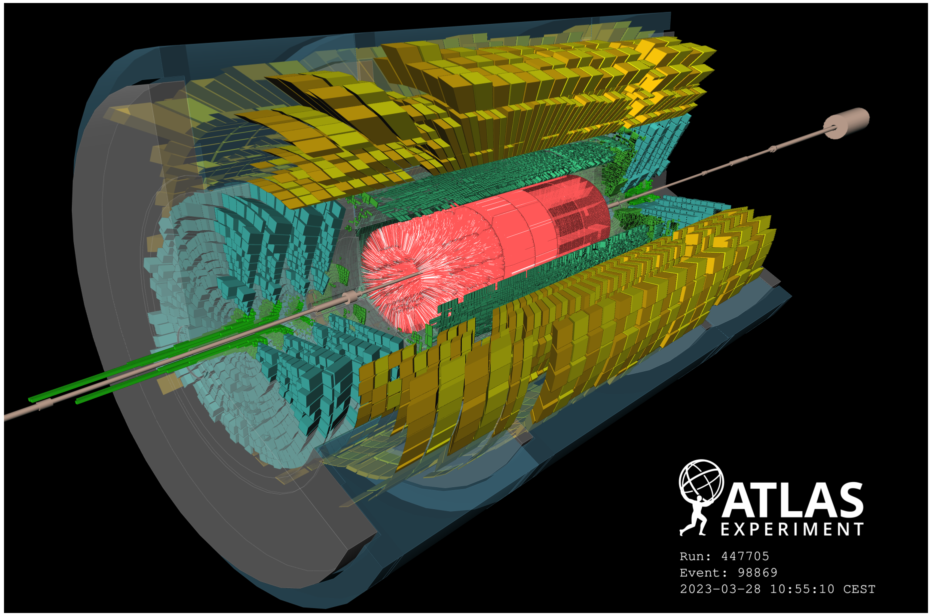
Tests of new physics with SM EFT

Searches

For further results, visit:

ATLAS Public page (Physics briefings)

CMS Public page (Physics briefings)



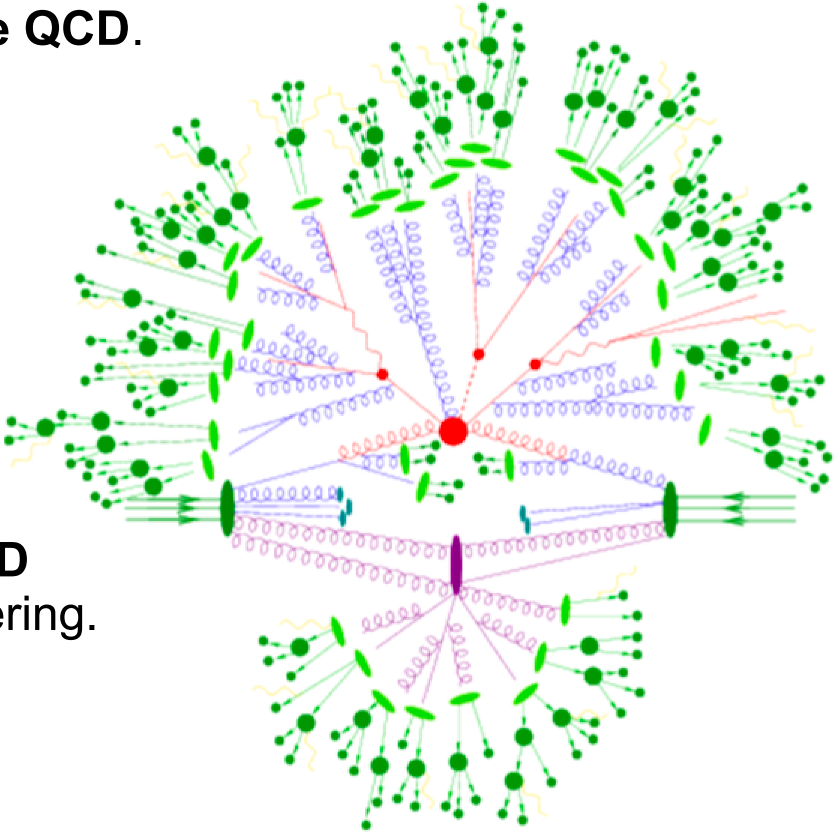
Splash event from March 23

QCD

QCD production at the LHC

Hard and **Soft** **QCD** are the dominant production methods at the LHC.

All LHC observations depend on the **modeling of the QCD**.



Large momentum QCD measurements are versatile and can tackle many fundamental aspects:

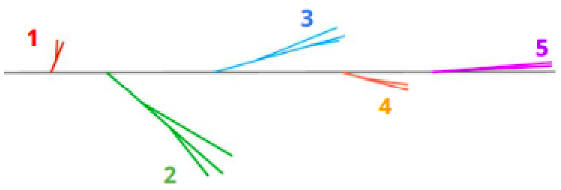
- Strong coupling (α_S), PDFs, test Resummation/PS, background for BSM physics

However, is also fundamental to understand **soft QCD** phenomena: Diffraction, low mu events, parton scattering.

Dedicated measurements with ALPHA and TOTEM.

Both **ATLAS** and **CMS** have a deep program for both hard and soft **QCD**

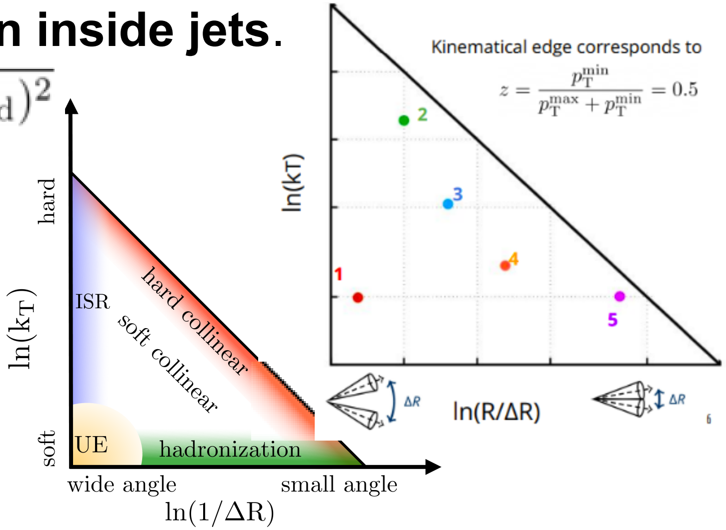
Lund jet plane density



Full Run-2 measurement of **Lund jet plane density** in dijet events:

LJP = **2D representation** of phase space of **emission inside jets**.

- Splitting angle: $\Delta R = \sqrt{(y_{\mathrm{soft}} - y_{\mathrm{hard}})^2 + (\phi_{\mathrm{soft}} - \phi_{\mathrm{hard}})^2}$
- Relative transverse momentum: $k_{\mathrm{T}} = p_{\mathrm{T}} \Delta R$

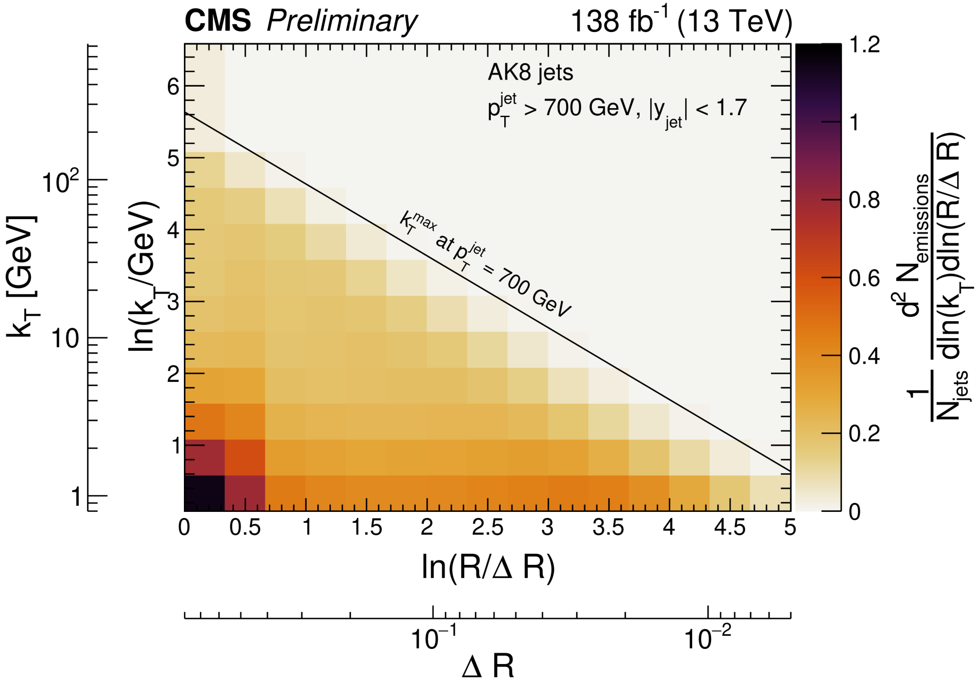


Measurement of jet-averaged density of emissions

$$\frac{1}{N_{\mathrm{jets}}} \frac{d^2 N_{\mathrm{emissions}}}{d\ln(k_{\mathrm{T}})\, d\ln(R/\Delta R)} \approx \frac{2}{\pi} C_{\mathrm{R}} \alpha_{\mathrm{S}}(k_{\mathrm{T}})$$

- Done for **anti-kT jets with R = 0.4 and 0.8**
- Reclustered with Cambridge/Aachen
- Includes charged constituents with p_T > 1 GeV
  - better angular and momentum resolution
  - better PU control

Inclusive dijet selection: p_T > 700 GeV, |y| < 1.7

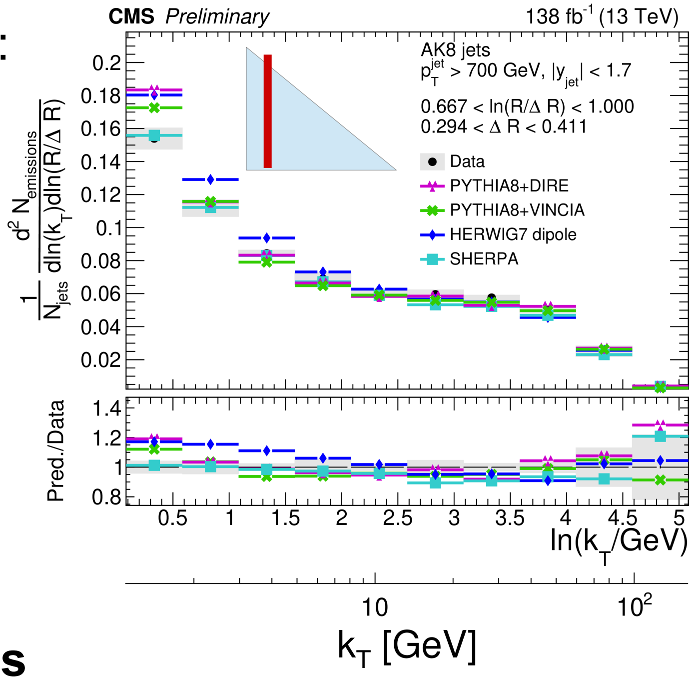


Lund jet plane density

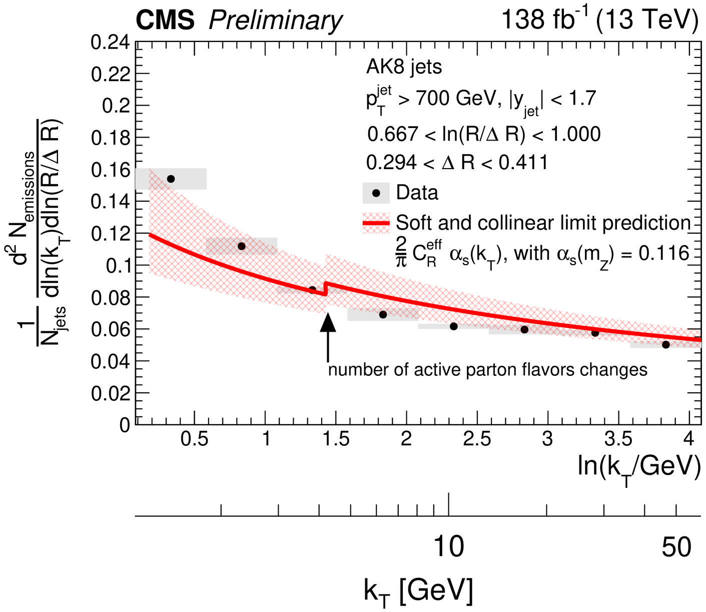
Measurement **compared with** different **theory** predictions:

- Project Lund jet plane in **slices of ΔR and k_T** to test:
  - Parton shower calculations
  - Jet substructure technique developments.
  - PDFs and running of strong coupling constant.

Tested various showers models in Pythia8, Sherpa, and various recoil schemes in Herwig.



In the soft and collinear limit, **the running of $\alpha_s(Q^2)$ sculpts the Lund jet plane density**:

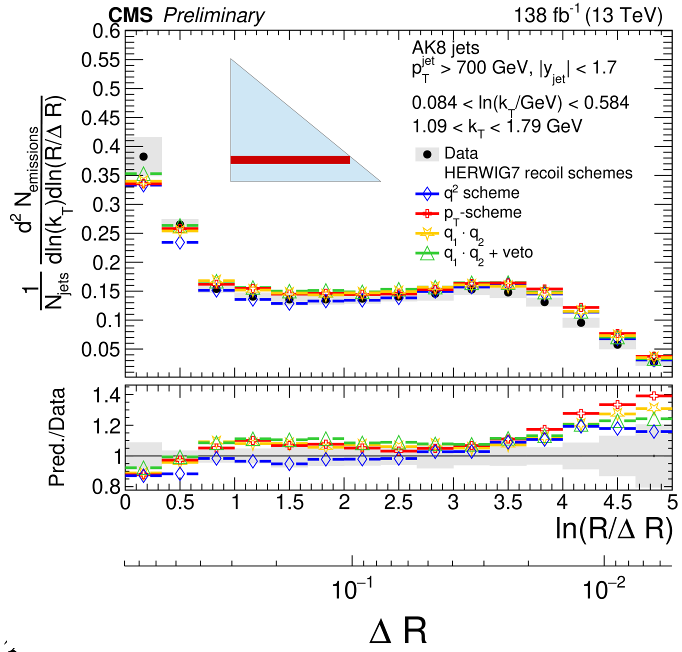


Achieved precision:

~2-7% (20% at edge)

Major uncertainties:

- Modeling of parton shower, hadronization.
- Track resolution.



arXiv:2301.09351

Strong coupling estimation in multijet events

Full Run-2 estimation of the **running of the strong coupling (α_s)** in multijet events.

Event shape observables are used:

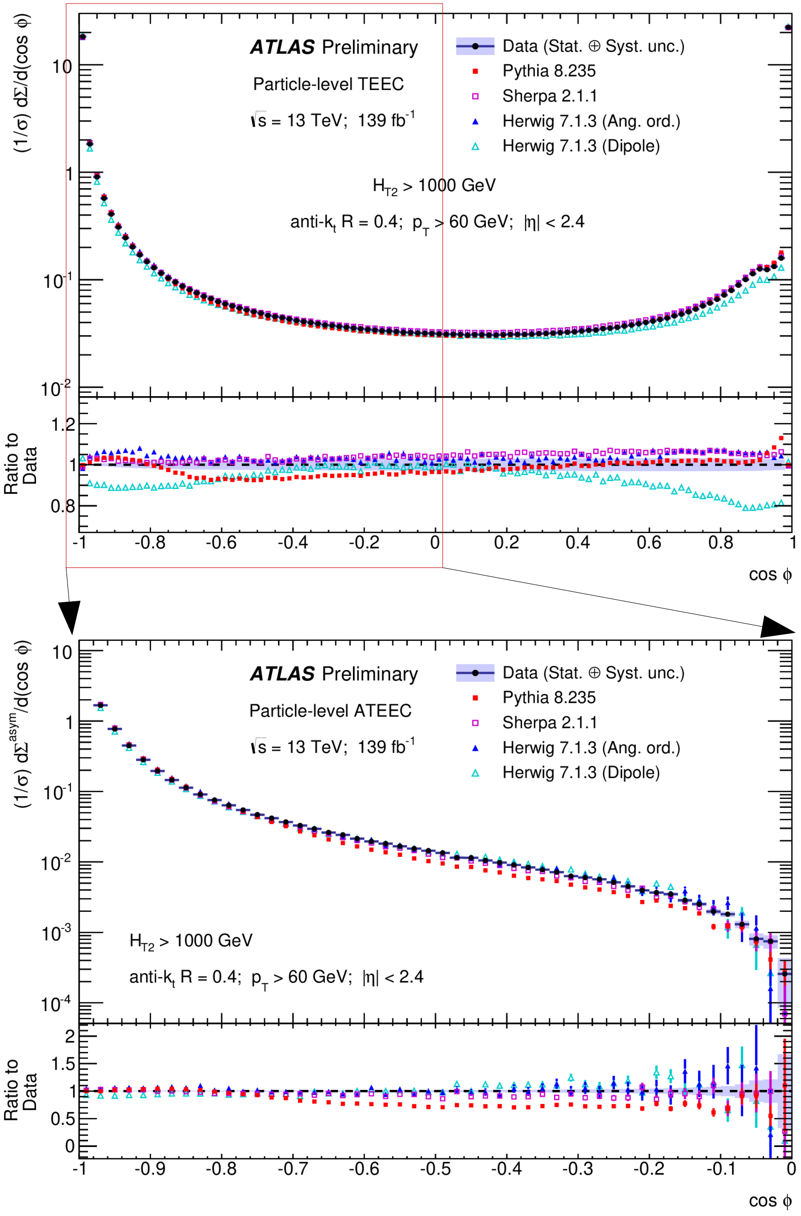
- **Transverse Energy-Energy Correlation** (TEEC): transverse-energy-weighted azimuthal angular distribution of produced jet pairs in the final state.

$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} = -\frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E_{Ti}^{A}E_{Tj}^{A}}{(\sum_k E_{Tk}^{A})^2}\delta(\cos\phi - \cos\phi_{ij})$$

- **Associated Azimutal asymmetries** (ATEEC): TEEC forward-backward asymmetry in Φ

$$\frac{1}{\sigma}\frac{d\Sigma^{asym}}{d\cos\phi} = \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\phi} - \frac{1}{\sigma}\frac{d\Sigma^{asym}}{d\cos\phi}\bigg|_{\pi-\phi}$$

- **Large sensitivity** to QCD radiation and $\boldsymbol{\alpha_s(Q^2)}$.
- **Reduced sensitivity to Infra Red** divergences compared to alternative observables.

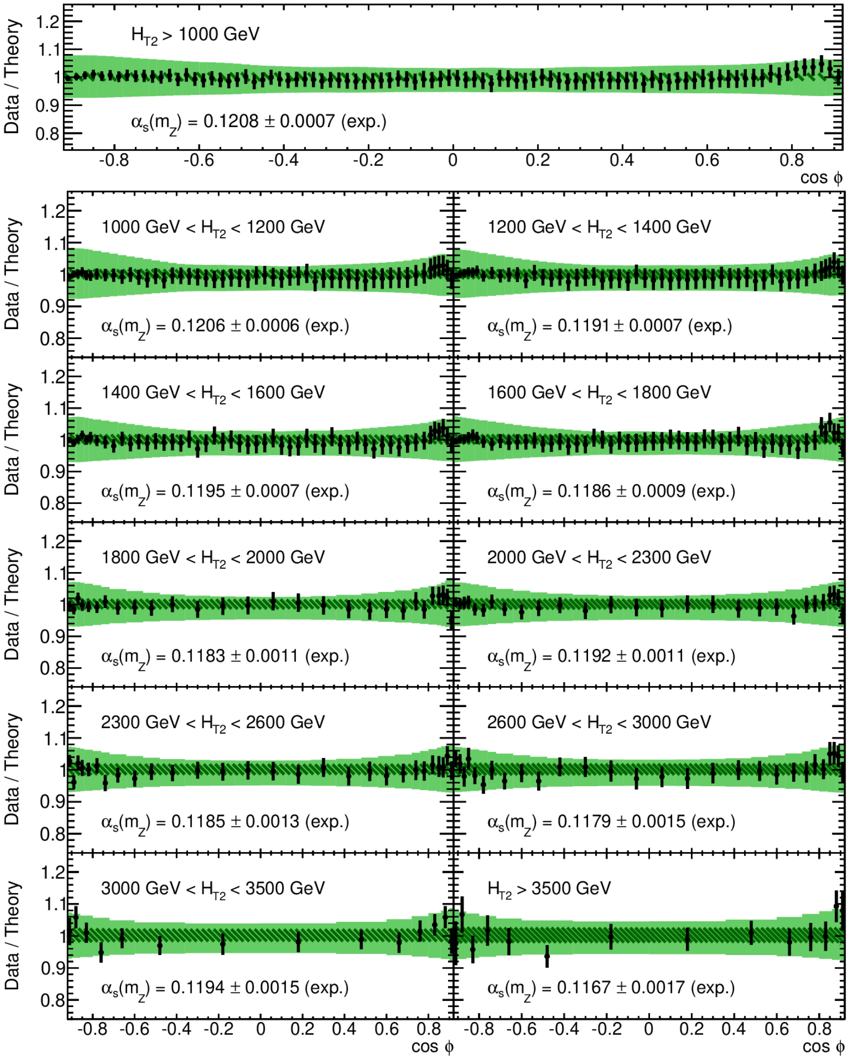


arXiv:2301.09351

Strong coupling estimation in multijet events

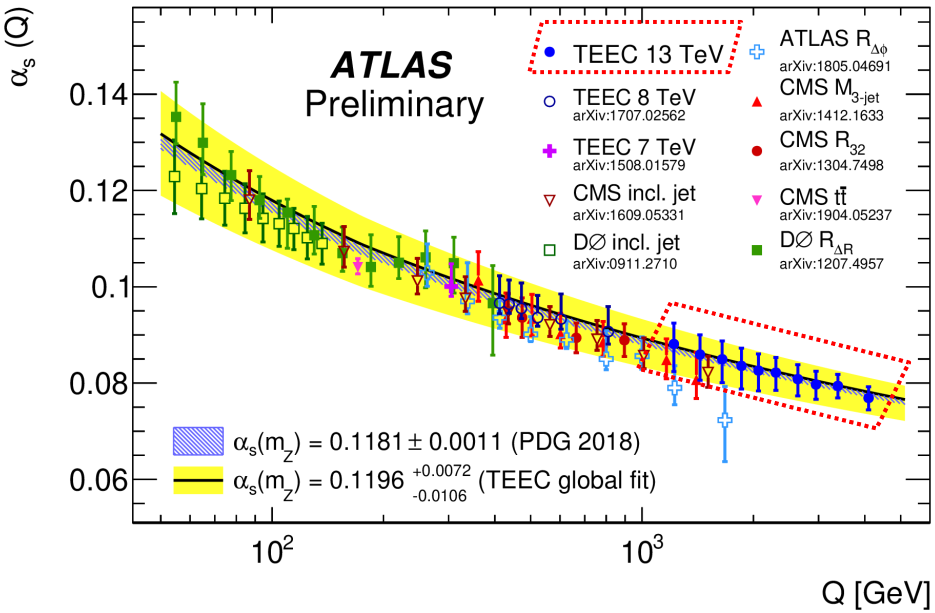
Extract α_s from **fit of theoretical predictions** of TEEC and ATEEC:

- Fit in bins of $H_{T}^{2} = p_{T}^{1} + p_{T}^{2}$ and extract α_s in each bin.



- H_T^2> 1 TeV: trigger efficiency ≈ 100%
- Excellent agreement between data and theory.
- Theoretical predictions obtained with NNLO calculations (3-jets XS)

$$\alpha_s(m_Z) = 0.1196 \pm 0.0004\ (\text{exp.})\ ^{+0.0072}_{-0.0105}\ (\text{theo.})$$



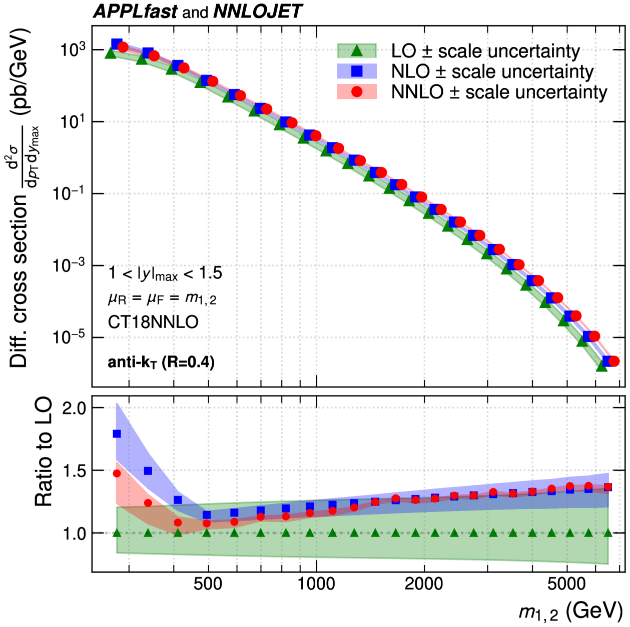
Multidifferential dijet cross-section

CMS-PAS-SMP-21-008

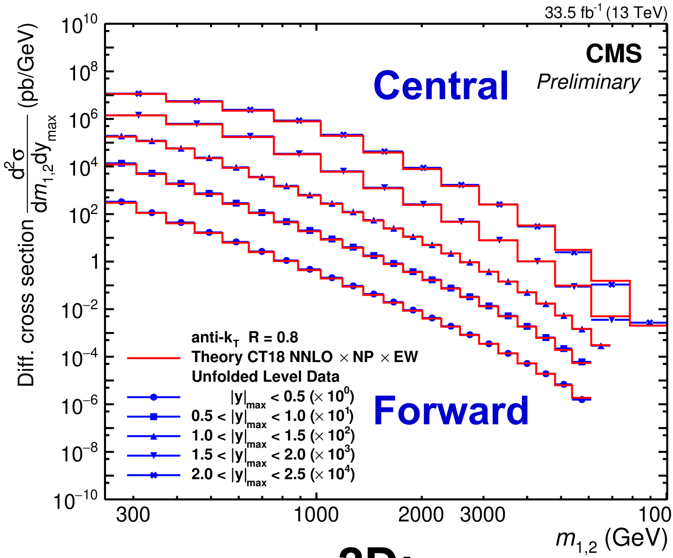
2D and 3D dijet production measured in 2016 data.

- **2D:** in rapidity y_{max} and invariant mass $m_{1,2}$.
- **3D:** rapidity separation y*, total boost y_b and $m_{1,2}$ or the average dijet $<p_T>$.
- Done both for R=0.4 and R=0.8 anti-kT jets.

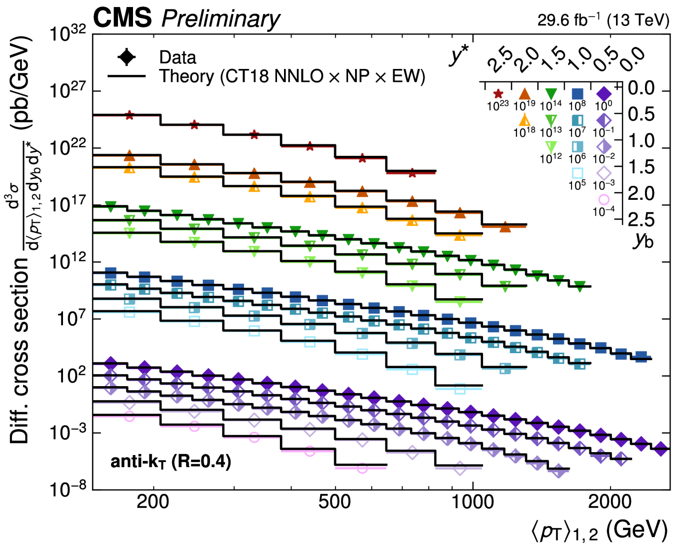
Unfolded to particle level & compared to fixed order NNLO calculations of pQCD from NNLOJET:



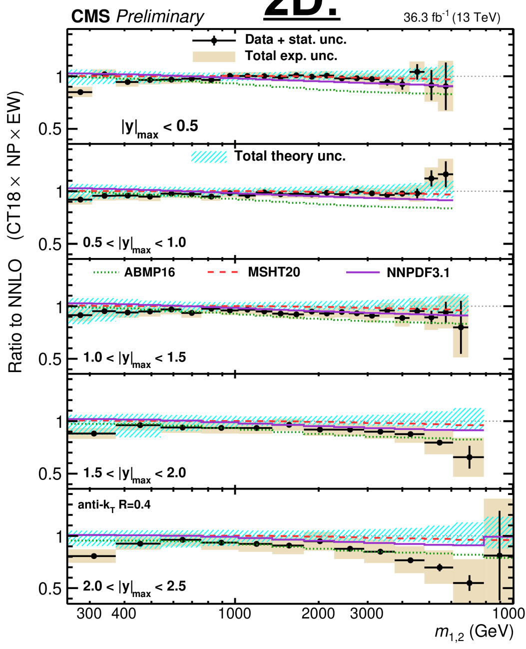
2D:



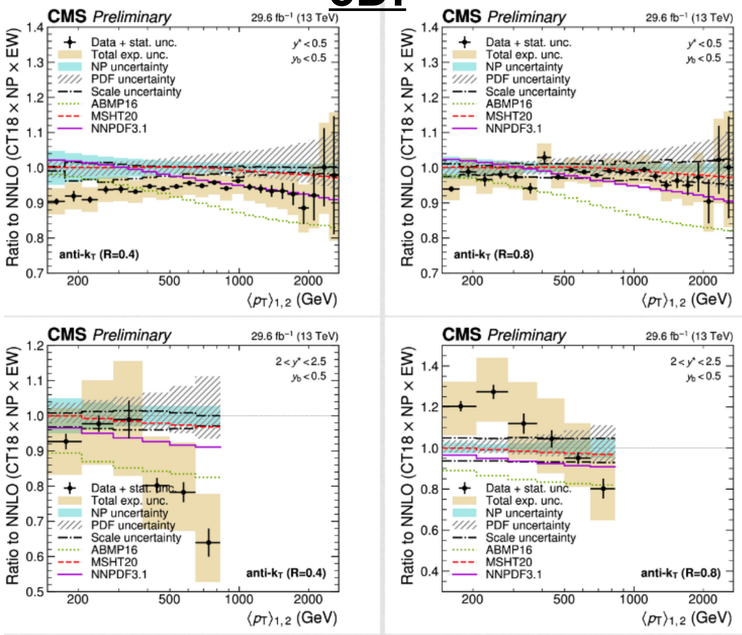
3D:



2D:



3D:



Multidifferential dijet cross-section

CMS-PAS-SMP-21-008

Extract PDFs and α_s from measurement.

HERA DIS data used in combination with this measurement for PDF extraction:

- Use only R=0.8 data, more reliable predictions.
- α_S fixed to $\alpha_S(m_Z) = 0.118$
- Hera data restricted to Q^2_{min} of 10 GeV.

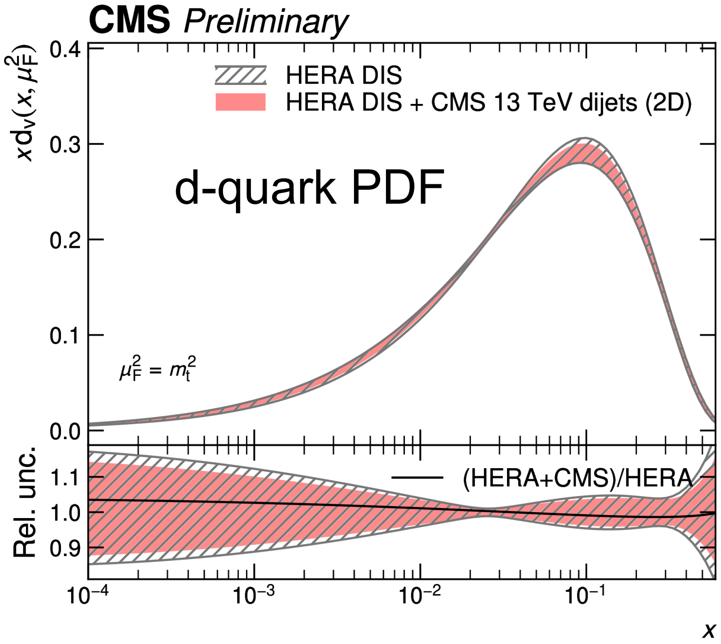
- **General reduction of systematic** uncertainties **with** the **use of CMS data**.
- Good agreement between predictions with and without CMS data.

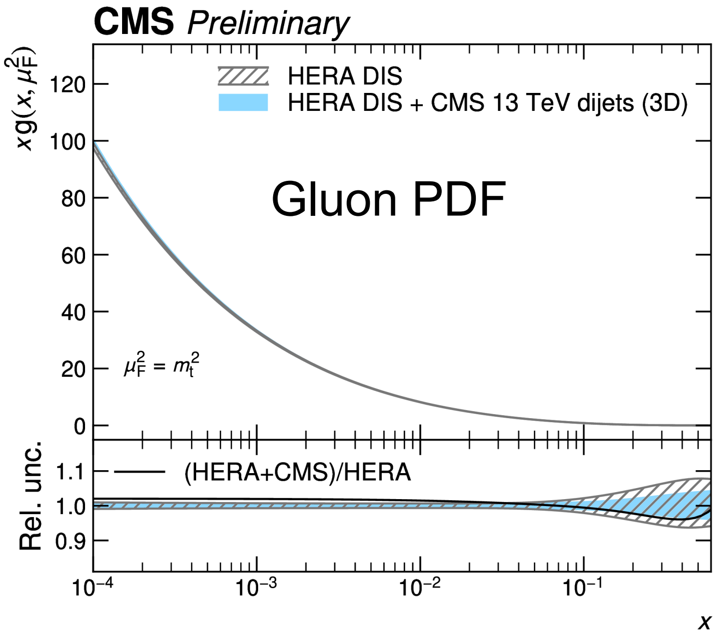
Both 2D and 3D results are used to measure $\alpha_S(m_Z)$:

2D: $\alpha_S(m_Z) = 0.1201 \pm 0.0012$ (fit) ± 0.0008 (scale) ± ± 0.0008 (model) ± 0.0005 (param.)

3D: $\alpha_S(m_Z) = 0.1201 \pm 0.0010$ (fit) ± 0.0005 (scale) ± ± 0.0008 (model) ± 0.0006 (param.)

Within 1 sigma of global average





Inclusive photon production at 13 TeV

arXiv:2302.00510

Full Run-2 measurement of the **inclusive isolated photon production**.

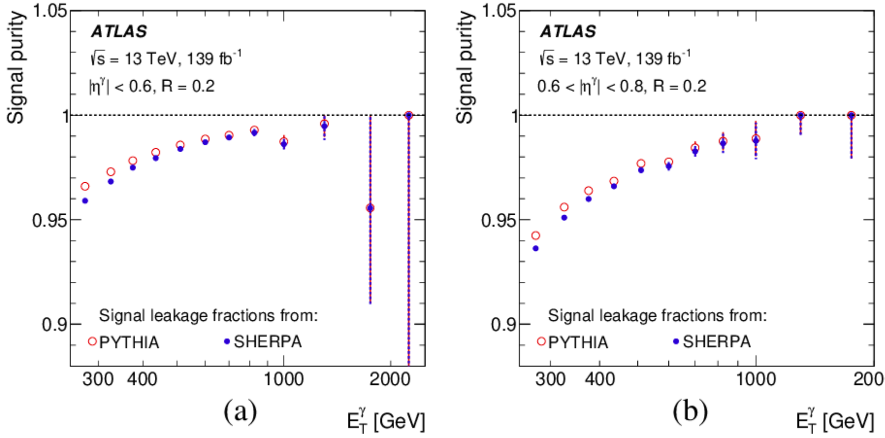
Important test of perturbative QCD:

- Constraints on the PDF (especially for gluon-PDF, thanks to qg → qγ)

Select isolated photons to **remove photons inside jets**:

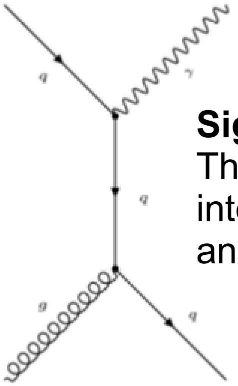
- Cone-based isolation: R = 0.2 and 0.4

Dependence of XS on photon isolation studied as function of R, η^{γ} and E_T^{γ}:



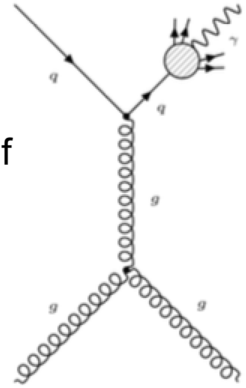
Photon produced through two main processes

Direct process

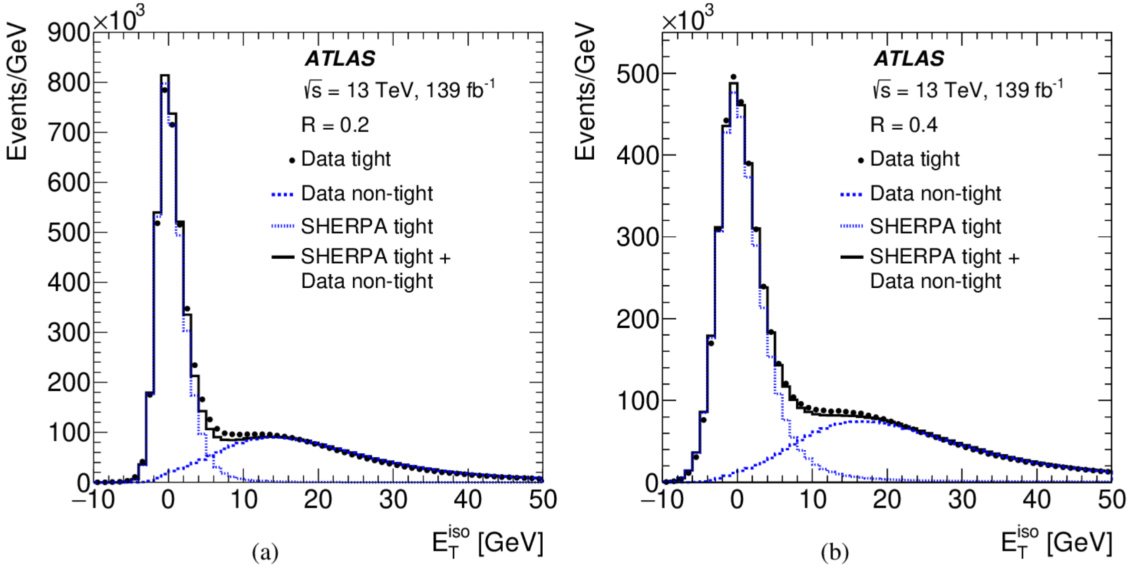


Signal:
The process of interest of the analysis.

Fragmentation process



Background:
Photons produced inside jets due to neutral mesons decays.



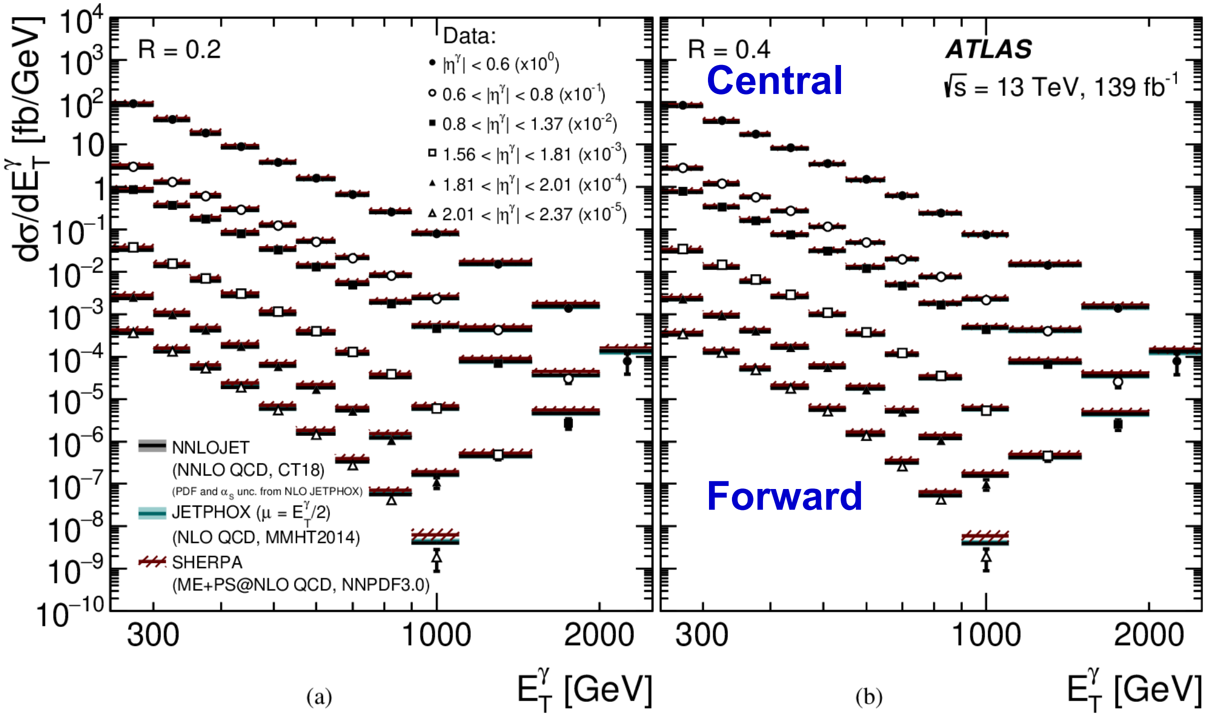
Inclusive photon production at 13 TeV

Unfold results in **bins of $|\eta^{\gamma}|$** and **compare** results with different pQCD predictions:

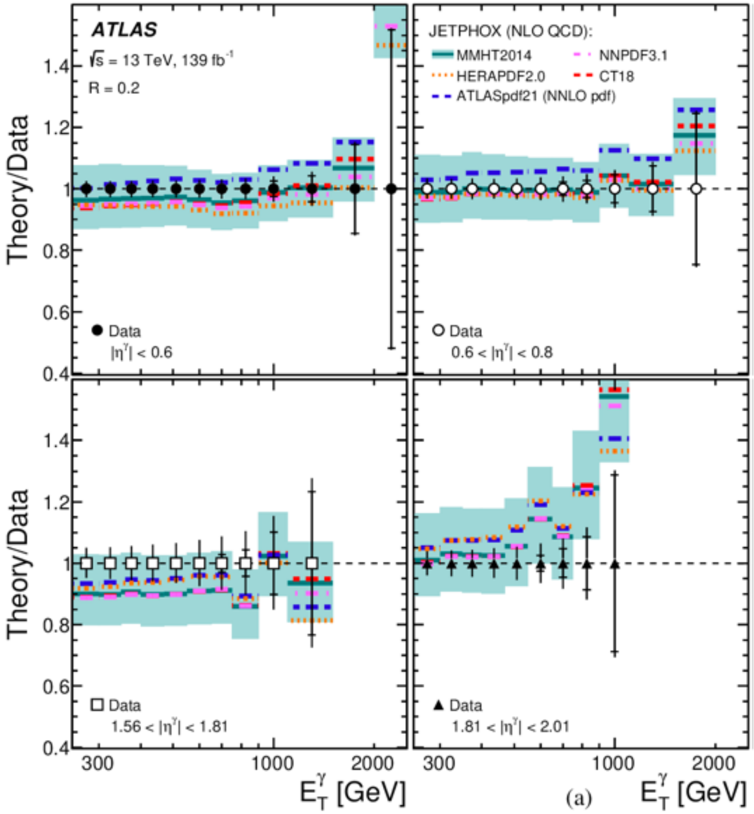
- SHERPA 2.2.2: γ + 0,1,2j @NLO + 3,4j@LO
- JETPHOX (NLO) and NNLOJET (NNLO)
- Predictions using different PDF sets.

Results given in two isolation cone-radii and with a finer η^{γ} binning.:

Well described by the fixed-order QCD predictions in most of the investigated phase-space region.



(a) (b)

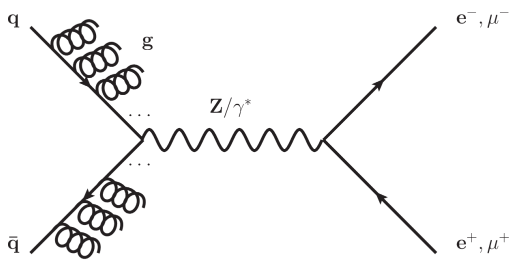


(a)

Strong coupling constant with Z boson

ATLAS-CONF-2023-015
Briefing

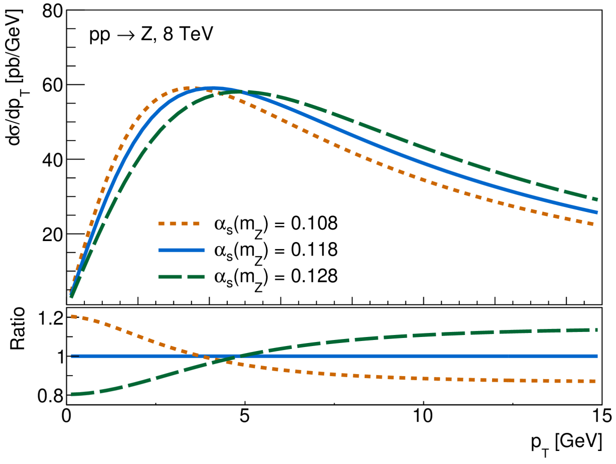
- Full **Run-1** dataset (20.2 ifb) at 8 TeV used for **precise determination of $\alpha_s(m_Z)$.**
- Extracted from **transverse-momentum** distribution of Z bosons: ATLAS-CONF-2023-013.
- Observable: low-momentum Sudakov region $p_T(Z)$ by DY.
- **Not included in PDF fits**: No problem with correlations.
- Non-zero $p_T(Z)$ caused by ISR of partons (strong force).

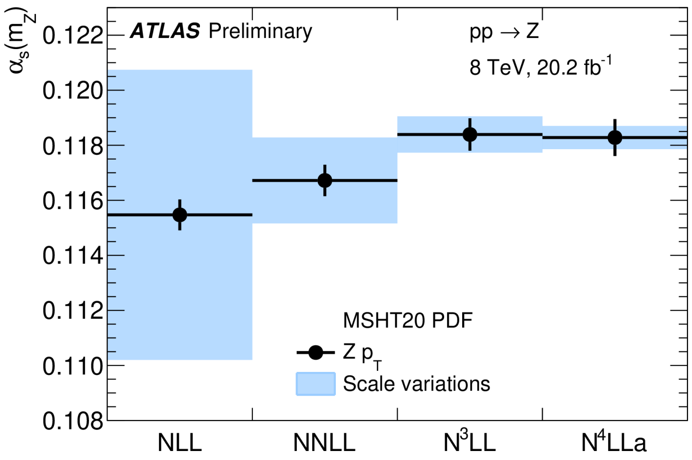


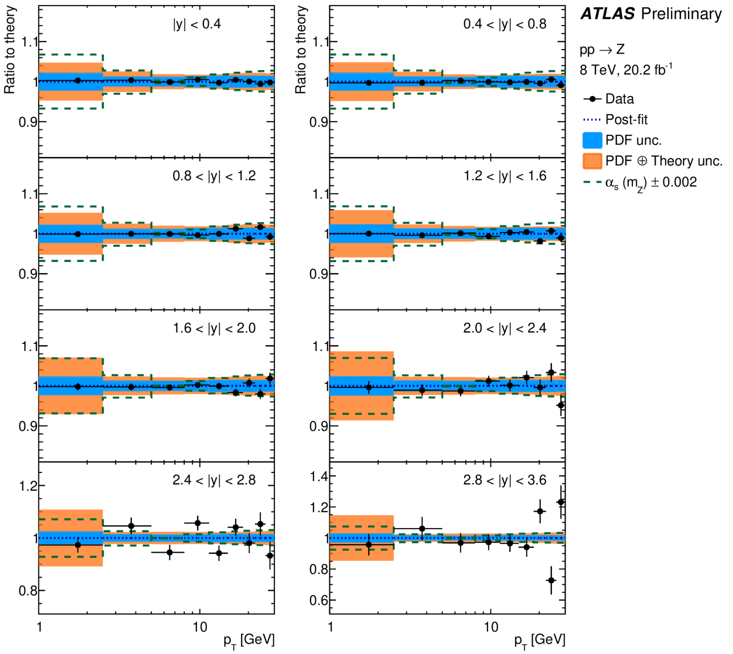
Most precise experimental measurement of the strong coupling.

$$\alpha_s(m_Z) = 0.11828 +0.00084 -0.00088\ (0.74\%)$$

First based on N4LLa+N3LO pred. in perturbative QCD.







Postfit 2D Z XS
vs $p_T(Z)$ and $y(Z)$

Strong coupling constant with Z boson

ATLAS-CONF-2023-015
Briefing

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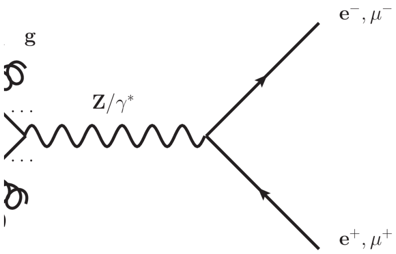
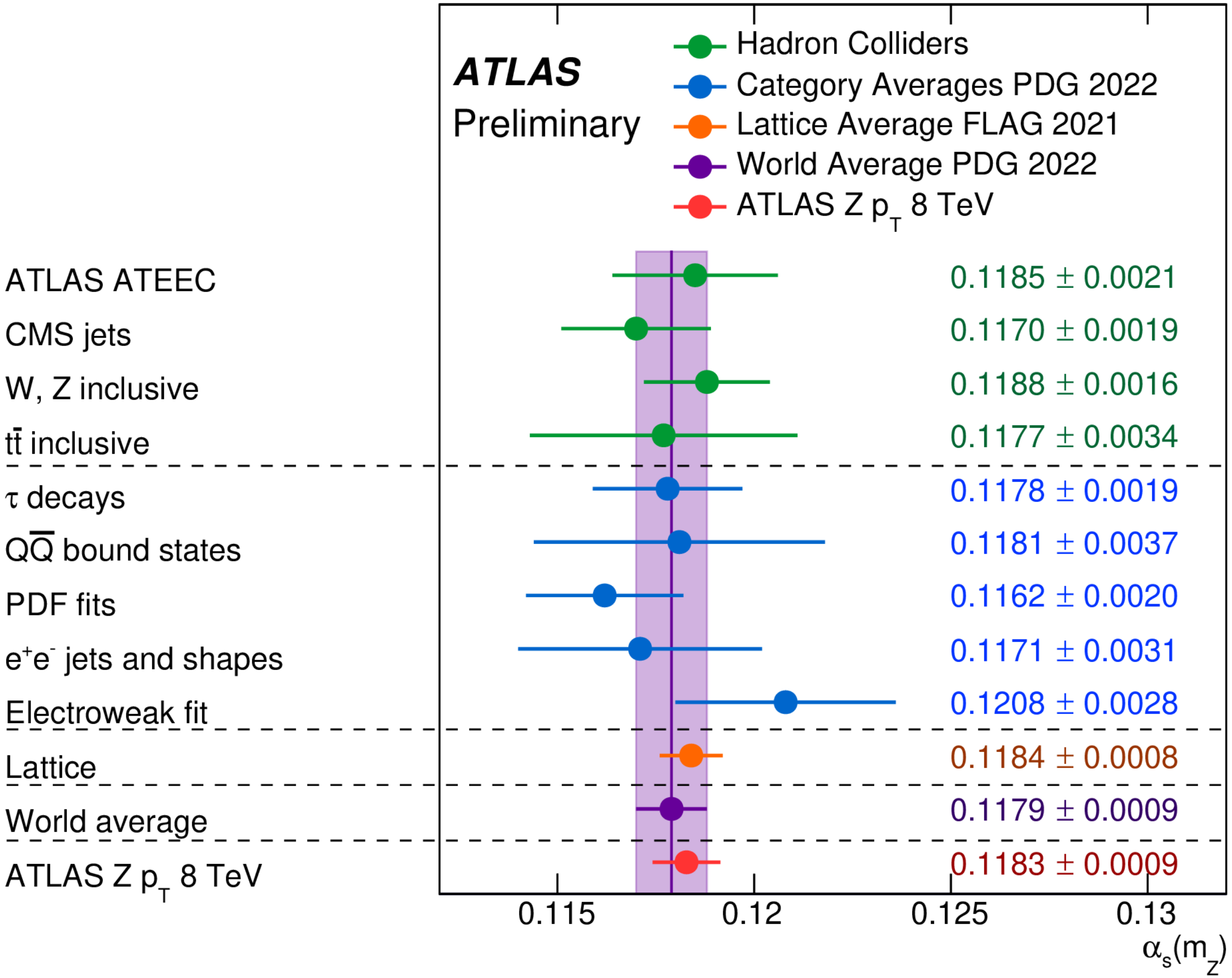
- Extracted from **transverse-momentum** distribution of Z bosons: ATLAS-CONF-2023-013.

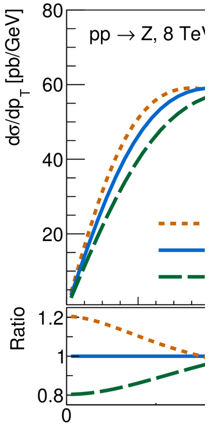
Most

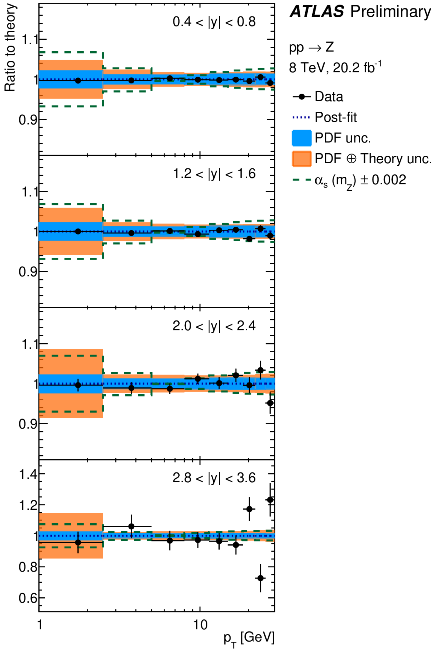
αS(m

First







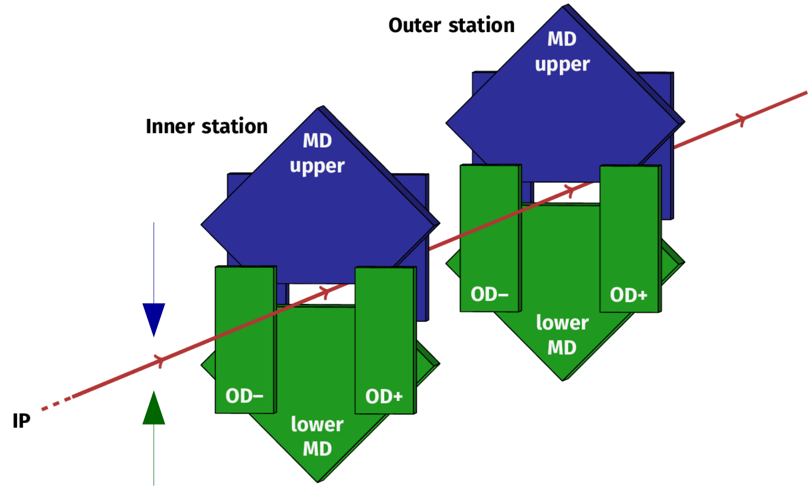


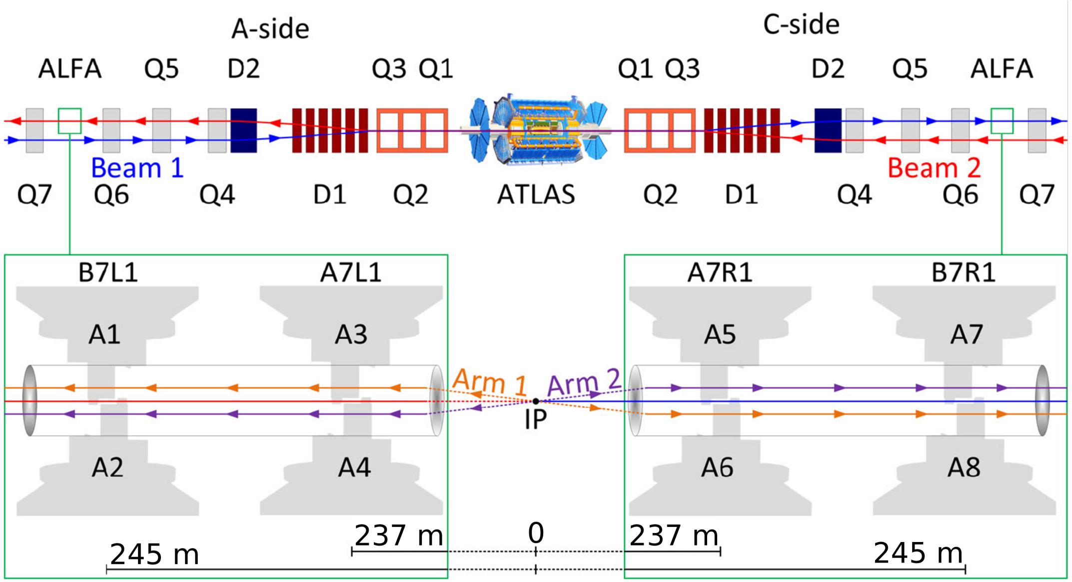
2D Z XS
vs p_T(Z) and y(Z)

Elastic Scattering β* = 2.5km with ATLAS

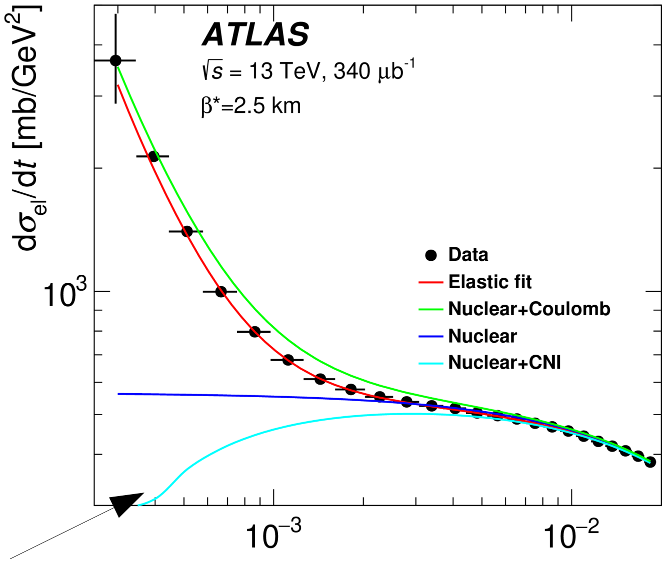
Arxiv:2207.12246
Physics briefing

- ATLAS is also testing **low energy QCD** predictions with the **use of ALFA**.
- ALFA subdetector is a pair of tracking detectors **situated at 240 m from the IP**.
- Each set is housed in a movable Roman Pot that can approach beam up to 1 mm.





- **ALFA: Designed to measure proton-proton elastic scattering**.
- Done with a LHC special run of high β* : gives the proton beams a very small angular spread.
- Measured differentially in the Mandelstam t variable



*CNI = Coulomb-nuclear interference

Elastic Scattering β* = 2.5km with ATLAS

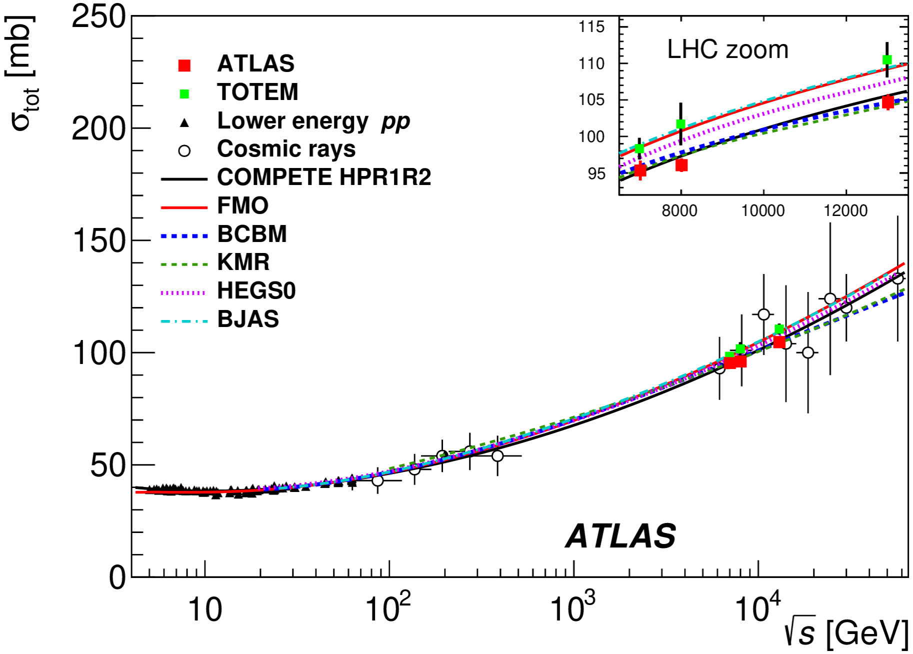
Arxiv:2207.12246
Physics briefing

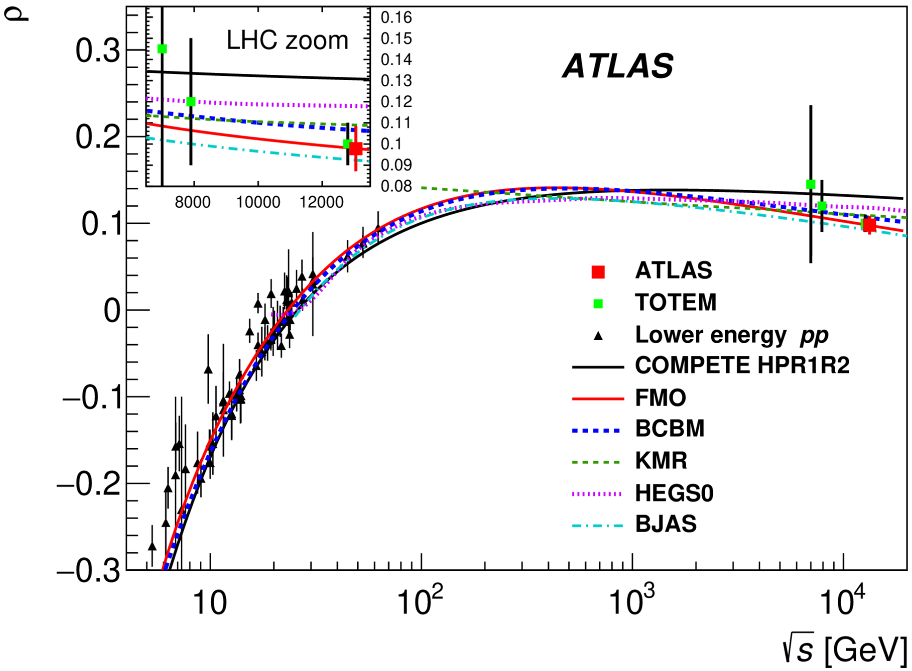
- Elastic scattering linked to other processes occurring on proton-proton interactions.
- **Total proton-proton cross section** (σ_{tot}) measured through **optical theorem**:

$$\sigma_{tot}^2 = \frac{16\pi}{1+\rho^2} \frac{d\sigma_{el}}{dt}\Bigg|_{t\to 0}$$

t = Mandelstam Variable

- **Ratio of the real vs imaginary parts** of the elastic-scattering amplitude (ρ).
- Complex phase between the Coulomb and the nuclear amplitudes, **directly affecting the interference contribution**. **(CNI)**
- Needs the high β* configuration for sensitivity.

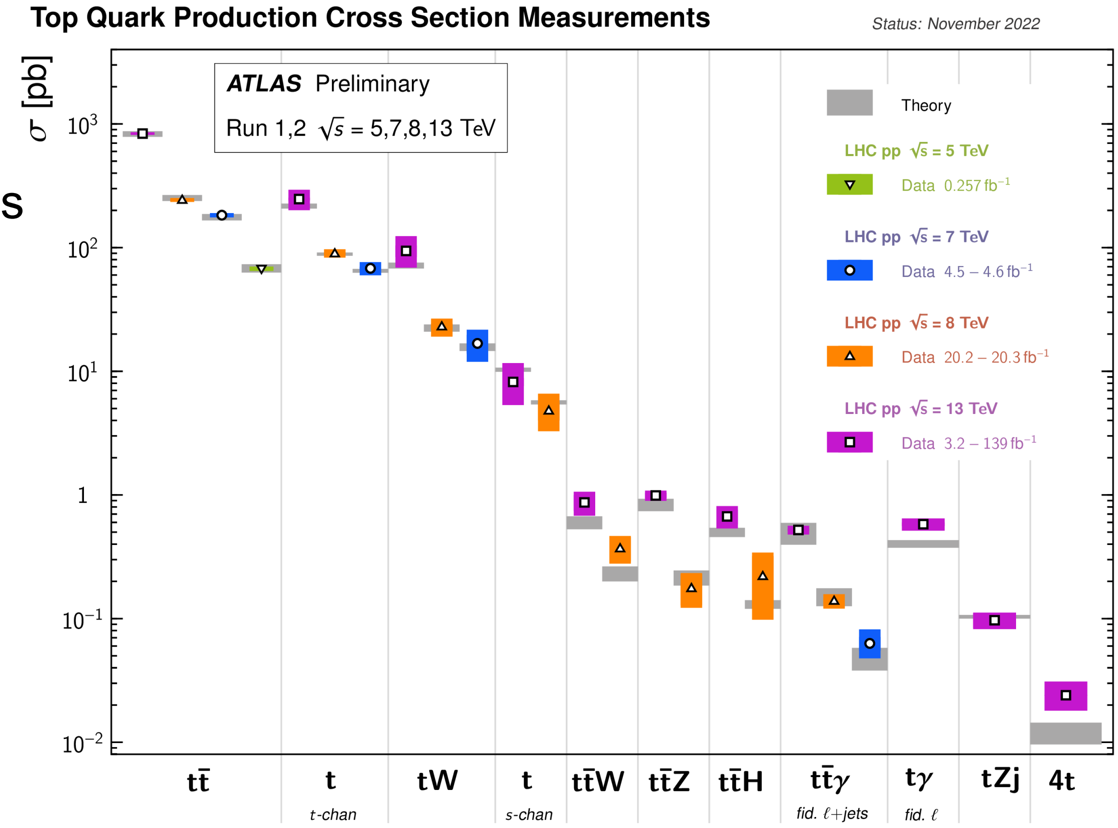




Top quark physics

Top quark intro

- The top quark is the heaviest elementary particle known.
- The only quark that largely affects the stability of the Higgs mass.
- The only particle with $y_t \sim 1$: strongly coupled to Higgs sector.
- The only quark that decays before hadronizing: ~free quark
- It does it ~100% through Wtb vertex: allows accessing top quark polarization.
- Large number of production mechanisms: pair production (QCD), single top (EW) and many associated production mechanism.
- Cross-section ranges several order of magnitudes.



LHC is a top quark factory

Extensively studied by

ATLAS and **CMS**

New Run-3 data!

LHC Run 3: σ($t\bar{t}$) at 13.6 TeV

CMS: $t\bar{t}$ XS at 13.6 TeV

arXiv.2303.10680
Briefing

- Combined analysis: **dilepton and lep+jets**
- **Split** by lepton flavour & jet/b-jet multiplicity.
- Data from 27 Jul to 03 Aug 2022: 1.21 fb

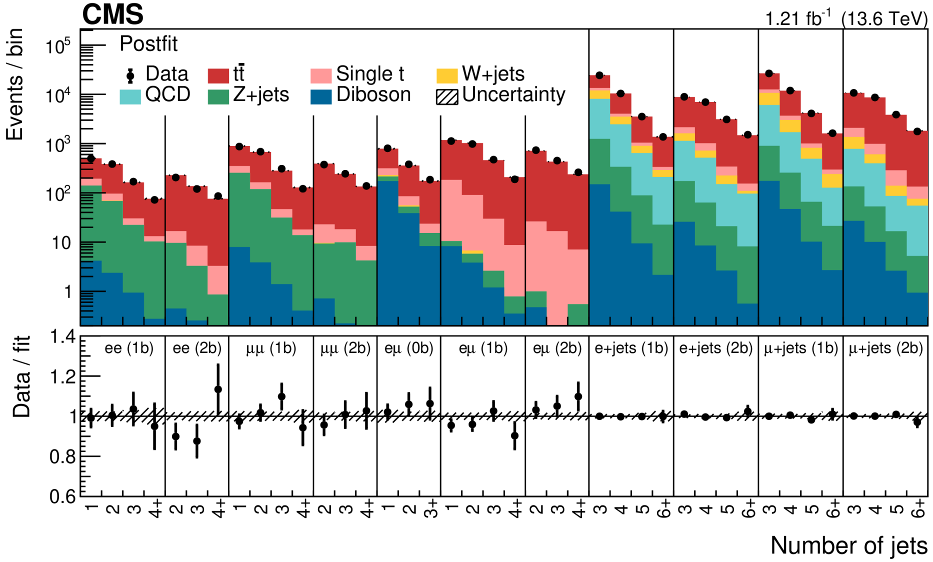
- Normalization of **Z-jets** obtained in **sideband CR** with $|m_{ll} - m_Z| < 15$ GeV.
- **Two CR for QCD** multijet in lep+jets: non-isolated leptons to derive template, region with only 1 b-jet to extract normalization.

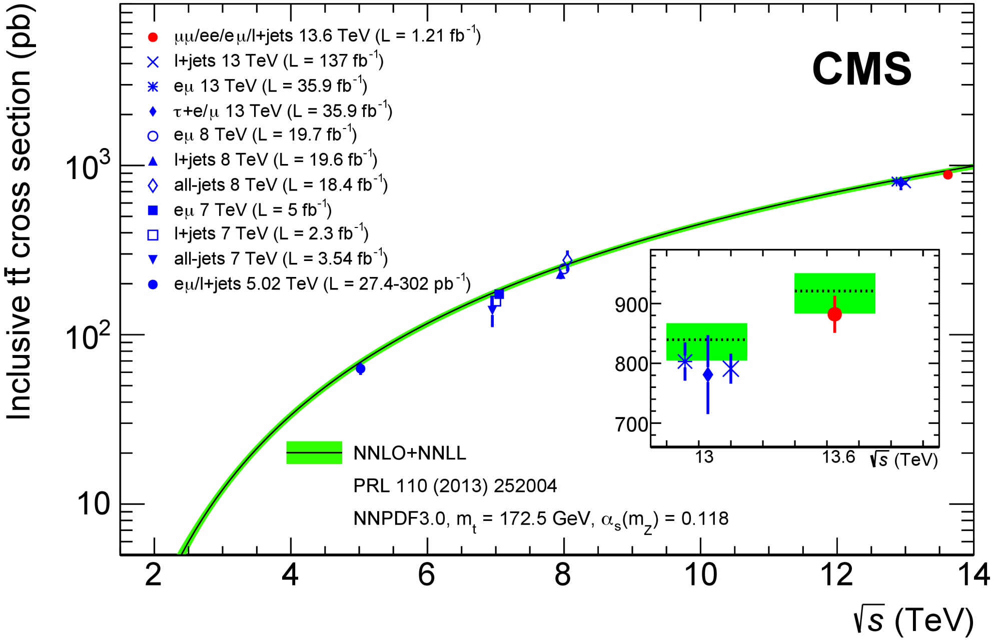
- Simultaneous extraction of **b-tag efficiency**.
- Shift in W mass in l+jets to crosscheck JES.
- **Lepton ID efficiencies**: **T&P** from Z+jets events as function of **p_T and $|\eta|$**

- **Luminosity uncertainty is the dominant** uncertainty, followed by lepton identification and b-tagging efficiency

$\sigma(t\bar{t})$ = 882 ± 23 (stat+syst) ± 20 (lumi) pb

Precision = **3.5%**





ATLAS: Z, $t\bar{t}$ XS and $t\bar{t}$/Z at 13.6 TeV

ATLAS-CONF-2023-006
Briefing

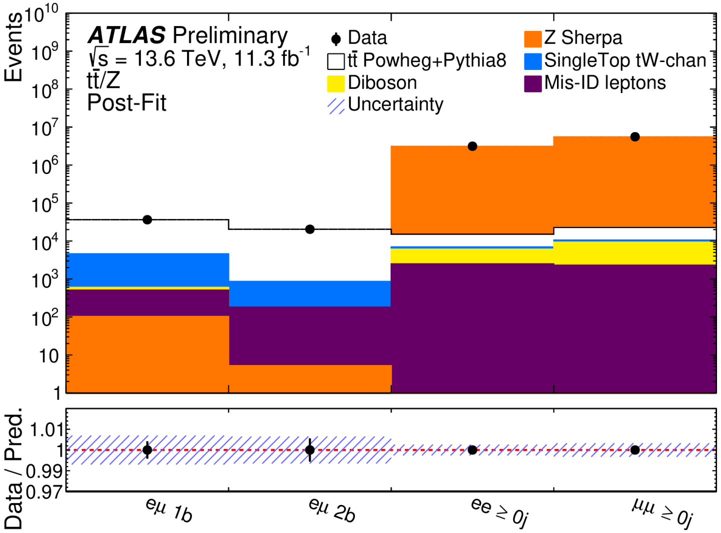
- Combined extraction of **σ(Z→ll) and σ($\bar{t}$t)**: **ee and μμ channels for Z, emu for $\bar{t}$t** (1b,2b).
- Also **$t\bar{t}$/Z XS ratio**: reduction of uncertainties and sensitivity to gluon/quark PDFs.
- **In situ measurement of ε_b**: efficiency to reconstruct +tag exactly 1 b-jet.
- Two profile likelihood fits: either σ($t\bar{t}$) or R(tt/Z).

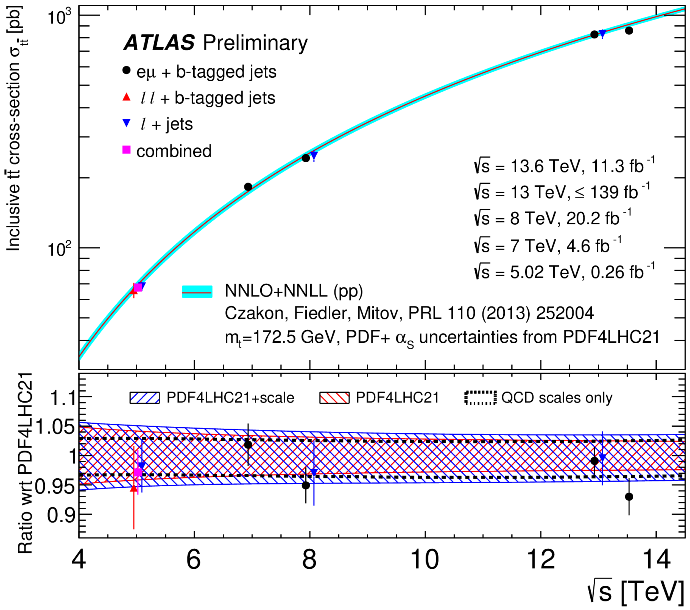
σ($t\bar{t}$) = 859 ± 4 (stat.) ± 22 (syst.) ± 19 (lumi.) pb. **(3.4%)**

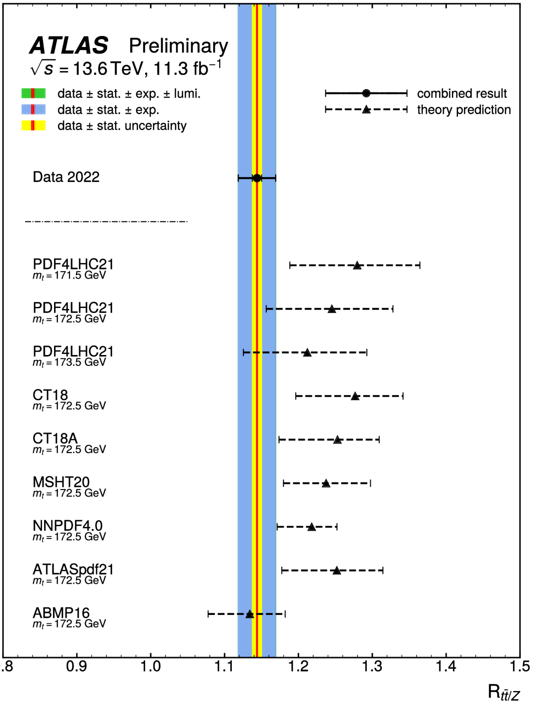
σ(Z→ll) = 751 ± 0.3 (stat.) ± 15 (syst.) ± 17 (lumi.) pb.

R($t\bar{t}$/Z) = 1.144 ± 0.006 (stat.) ± 0.022 (syst.) ± 0.003 (lumi.)

Category		**Uncert.** [%]		
		$\sigma_{t\bar{t}}$	$\sigma^{\text{fid.}}_{Z\to\ell\ell}$	$R_{t\bar{t}/Z}$
$t\bar{t}$	$t\bar{t}$ parton shower/hadronisation	1.1	0.01	1.0
	$t\bar{t}$ scale variations	0.2	< 0.01	0.2
	Top quark p_T reweighting	0.6	0.02	0.5
Z	Z scale variations	0.2	0.5	0.3
Bkg.	Single top modelling	0.4	0.01	0.4
	Diboson modelling	0.1	0.06	< 0.01
	Mis-Id leptons	0.5	0.1	0.5
Lept.	Electron reconstruction	1.0	1.1	0.5
	Muon reconstruction	1.5	1.2	0.8
	Lepton trigger	0.4	0.7	0.8
Jets/tagging	Jet reconstruction	0.4	0.1	0.3
	Flavour tagging	0.2	0.01	0.2
	PDFs	0.4	0.2	0.4
	Pileup	1.1	1.1	< 0.01
	Luminosity	2.3	2.2	0.3
	Systematic Uncertainty	3.5	3.0	2.0
	Statistical Uncertainty	0.5	0.03	0.5
	Total Uncertainty	3.5	3.0	2.0





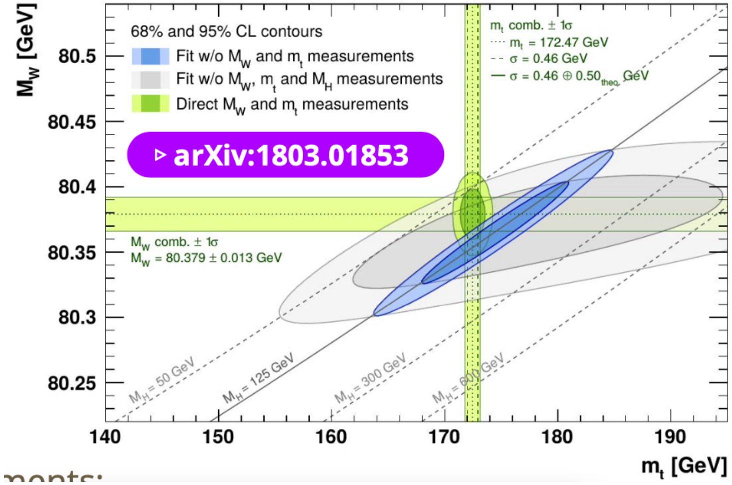


Top quark mass

Top quark mass intro

- m_{top} + m_W + m_H measurements: probe the validity of the SM
- Important to determine SM vacuum stability

(not yet including latest W mass measurements)



▹ arXiv:1803.01853

Direct measurements:

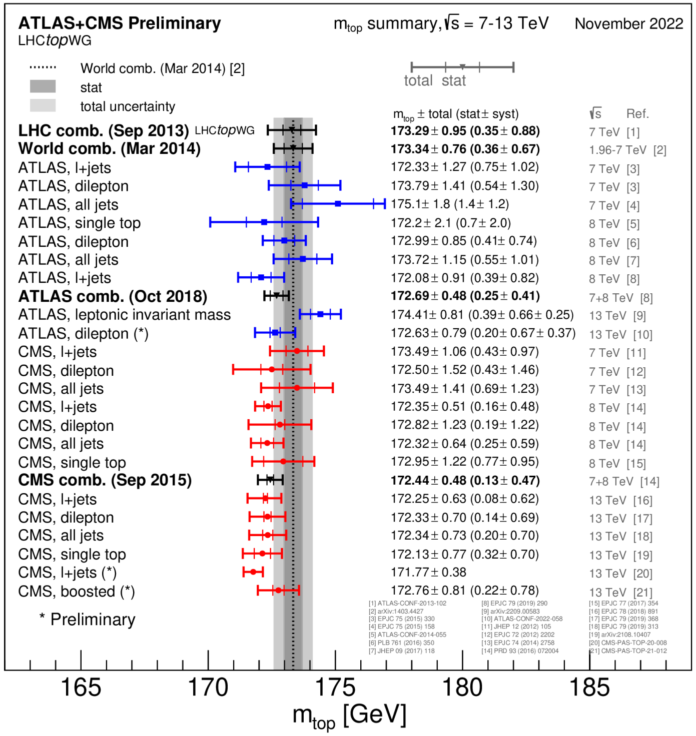
Fixed parameter in the generator: **MC mass**.

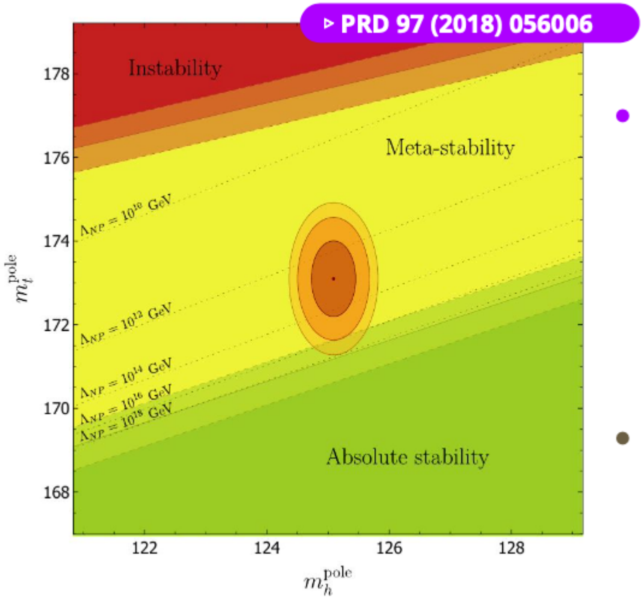
Relies on jet, parton shower, non-perturbative effects.

Total or partial invariant mass of top decay products.

Latest summary plots:

ATL-PHYS-PUB-2022-050



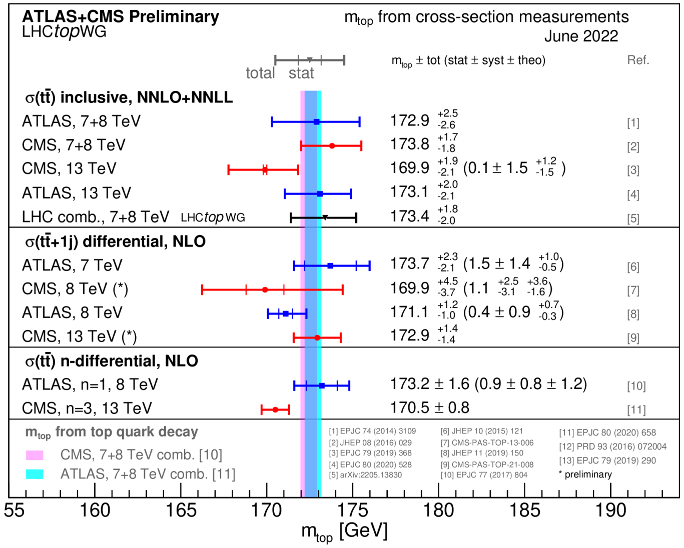


▹ PRD 97 (2018) 056006

Indirect measurements:

Well defined renormalization scheme: e.g. **pole mass**

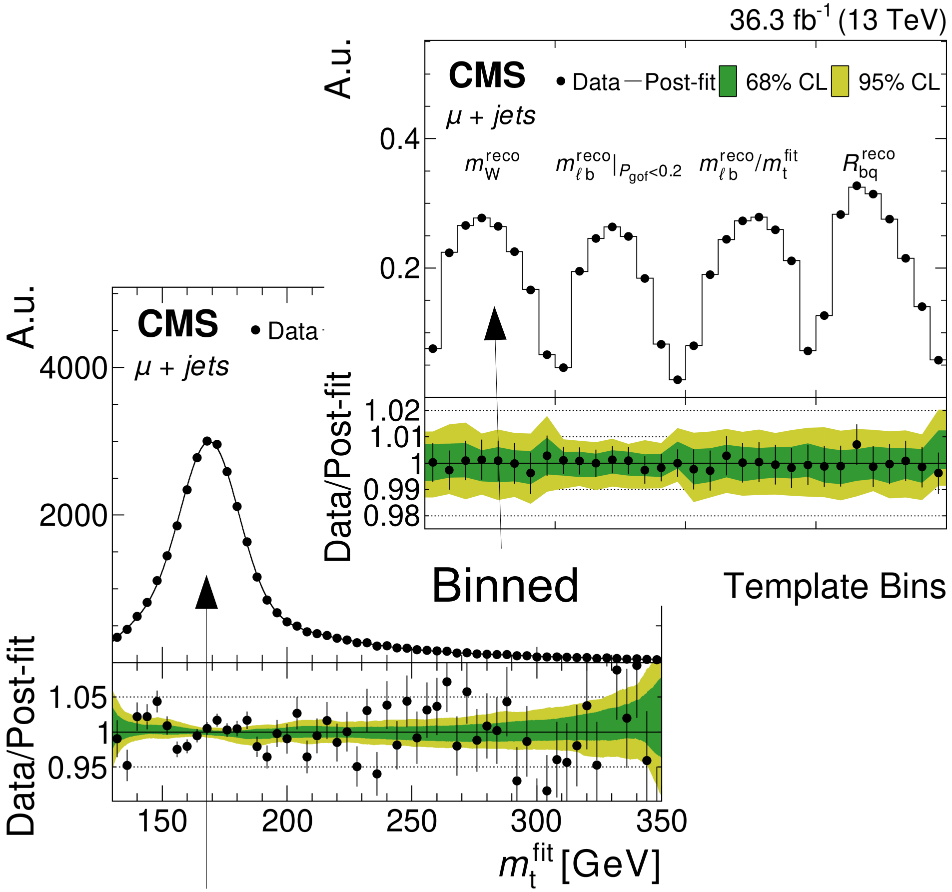
From cross sections (inclusive or differential)



Profile likelihood fit of m(top) in l+jets

arXiv:2302.01967
Briefing

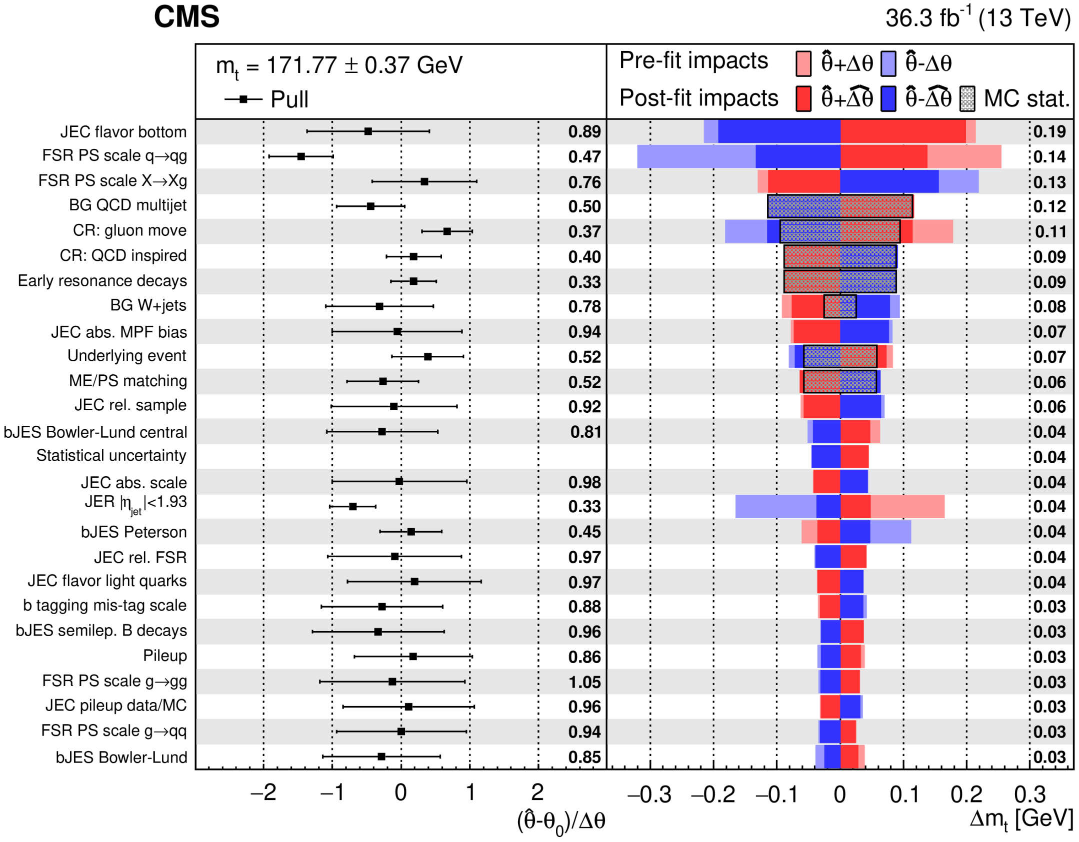
- For each event, **m_t^{fit} is extracted from a kinematic fit.**
- m(top) extracted from simultaneous fit to **5 observables** with a profile likelihood: In situ constraints of systematic uncertainties: m_t^{fit}, m_W, m_{lb}, m_{lb}/m_t^{fit}, R_{bq}.
- Most precise measurement of the top quark mass to date:
- **m(top) = 171.77 +- 0.37 GeV**



Binned

Template Bins

Unbinned

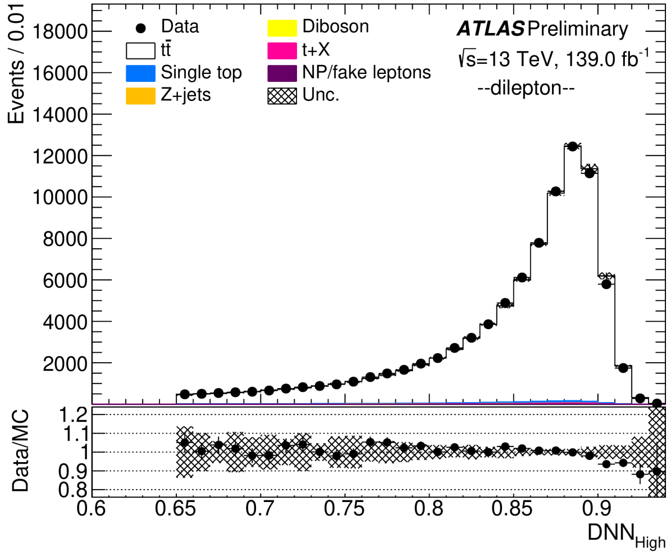


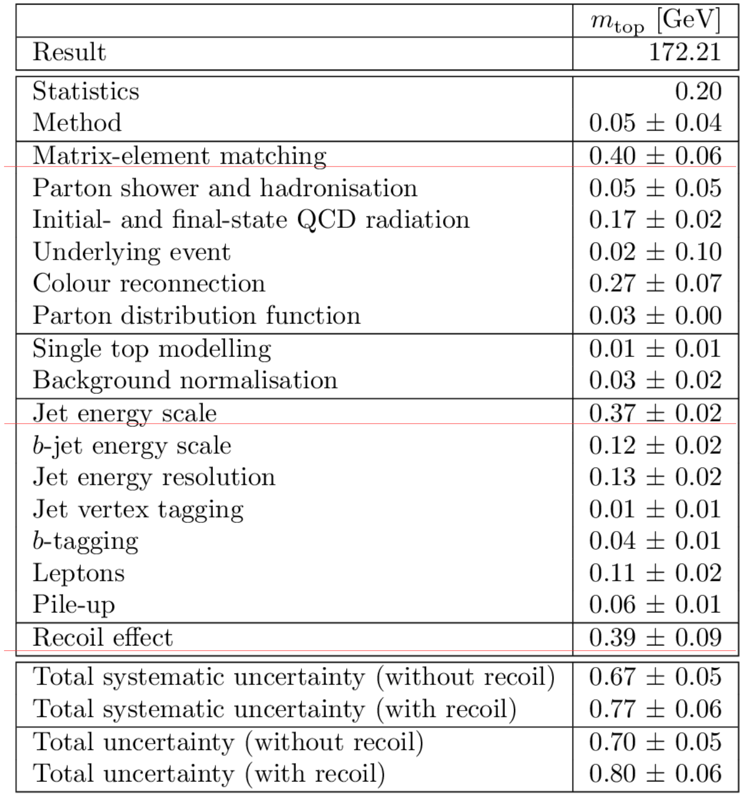
Template fit of m(top) in dilepton

- **DNN for event reconstruction**: selects right pairing of leptons and b-jets.
- From each event, **use only lb pair with largest p_T^{lb}**.
- Further selection: DNN_{High} > 0.65, p_T^{lb} > 160 GeV and selected lb pair contains b-jet with largest p_T.

- Unbinned likelihood fit calibrated with MC (Powheg+Pythia)

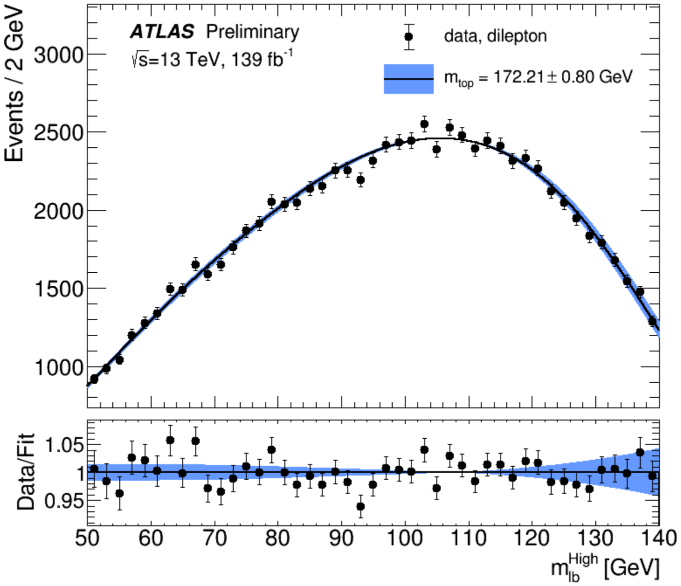
m_{top} = 172.21 +- 0.20 (stat) +- 0.67 (syst) +- 0.39 (recoil)





	m_{top} [GeV]
Result	172.21
Statistics	0.20
Method	0.05 ± 0.04
Matrix-element matching	0.40 ± 0.06
Parton shower and hadronisation	0.05 ± 0.05
Initial- and final-state QCD radiation	0.17 ± 0.02
Underlying event	0.02 ± 0.10
Colour reconnection	0.27 ± 0.07
Parton distribution function	0.03 ± 0.00
Single top modelling	0.01 ± 0.01
Background normalisation	0.03 ± 0.02
Jet energy scale	0.37 ± 0.02
b-jet energy scale	0.12 ± 0.02
Jet energy resolution	0.13 ± 0.02
Jet vertex tagging	0.01 ± 0.01
b-tagging	0.04 ± 0.01
Leptons	0.11 ± 0.02
Pile-up	0.06 ± 0.01
Recoil effect	0.39 ± 0.09
Total systematic uncertainty (without recoil)	0.67 ± 0.05
Total systematic uncertainty (with recoil)	0.77 ± 0.06
Total uncertainty (without recoil)	0.70 ± 0.05
Total uncertainty (with recoil)	0.80 ± 0.06

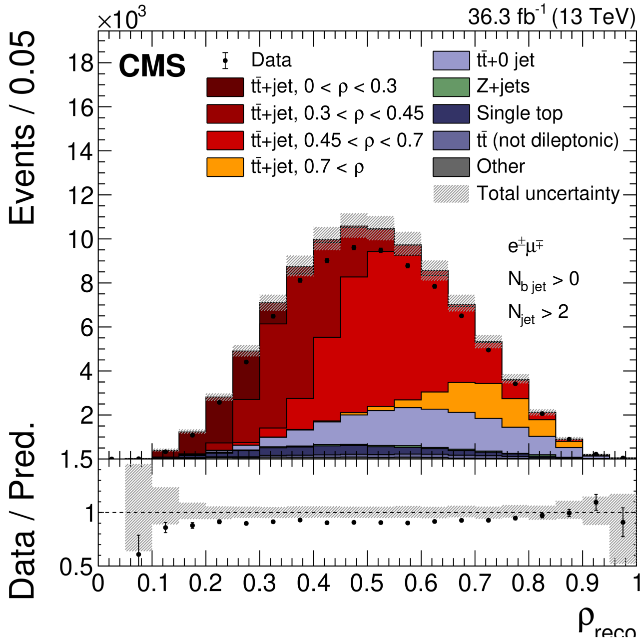
- New measurement improves Run-1 result.
- Precision limited by modelling and Jet Energy Scale unc.
- New significant unc: radiation recoil scheme

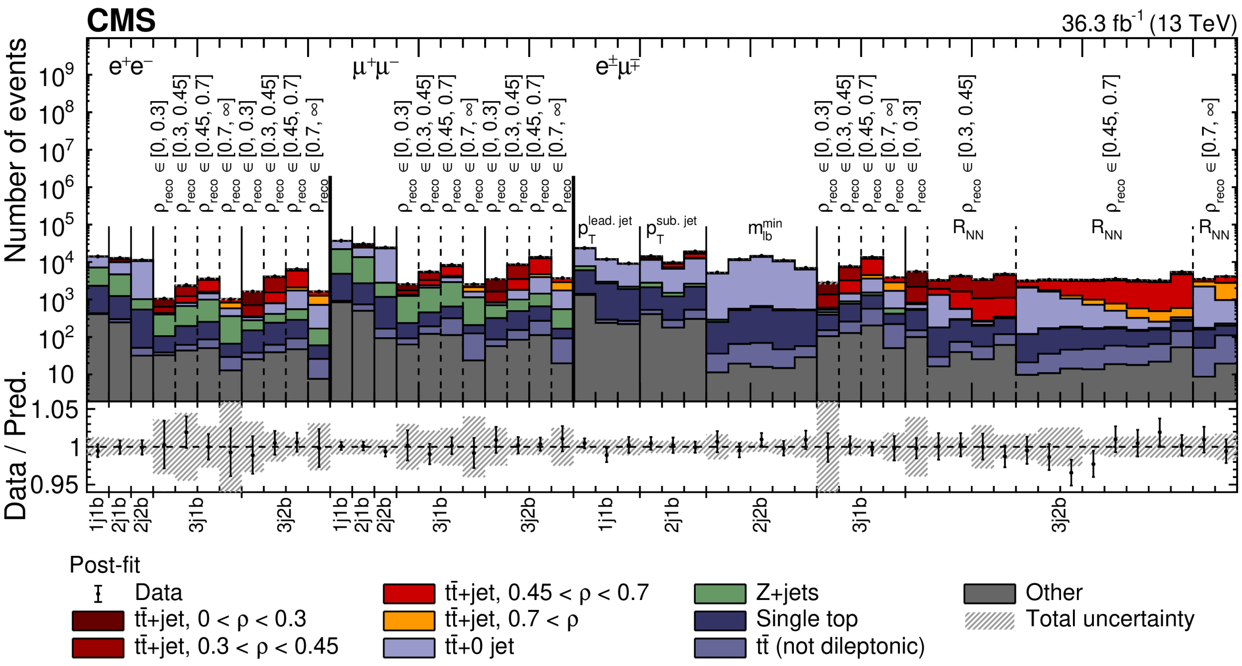


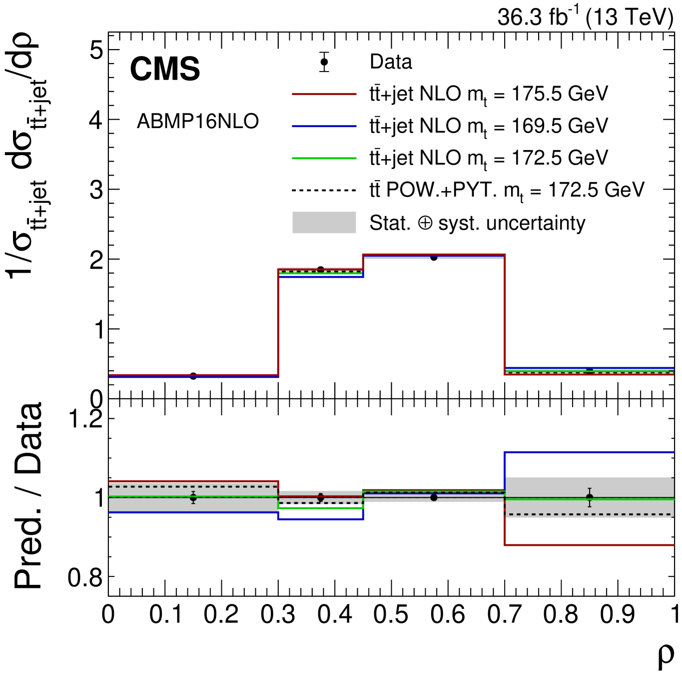
Top quark pole mass in tt+jet dilepton events

arXiv:2207.02270

- **Jet emission in ttbar is sensitive to m_t^{pole}.**
- Using **$\rho \sim 1/M(tt+j)$** to extract the pole mass.
- **MVA** to calculate ρ_{reco} and for S/B discrimination with two hypotheses: tt+j and tt. RNN = s(tt+j)/[s(tt+j)+s(tt)]
- **Profile likelihood** unfolding, combining several regions.
- **Split** by lepton flavour, jet/b-jet multiplicity, ρ_{reco} and RNN.
- **m_t^{pole} = 172.94 +- 1.37 GeV**
- Compared to NLO predictions





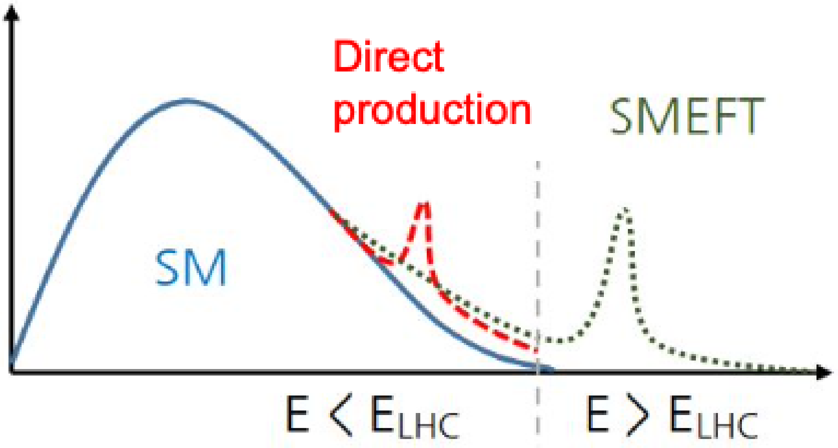


SM Effective Field Theory

Effective Field Theory extension of SM

Lack of clear evidence of new physics at the LHC:

- New physics may lie above the experimental energy scale



Indirect searches may provide hints!

SMEFT extends the SM Lagrangian

$$\mathcal{L}_{SM}(\varphi) + \mathcal{L}_{Dim6}(\varphi) + \cdots$$

Wilson coefficients

EFT operator

$$\mathcal{L}_{\mathrm{Eff}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$

UV scale

Interesting to study EFT with top quarks:

Large mass and Yukawa coupling O(~1).

Rich environment of production modes.

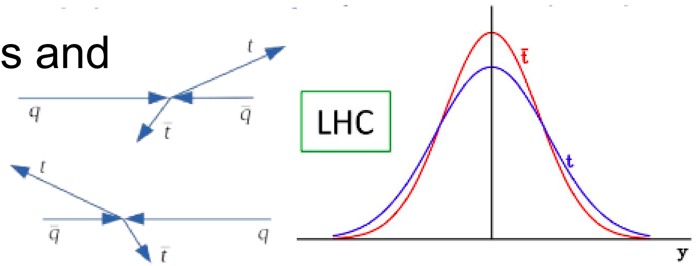
Access to top quark polarization.

Charge asymmetry in top production

arXiv:2208.12095

- **Slight central-forward difference** in rapidity between top quarks and antiquarks in top pair production **at the LHC**, quantified as:

$$A_C = \frac{N(|y_t|>|y_{\bar{t}}|)-N(|y_t|<|y_{\bar{t}}|)}{N(|y_t|>|y_{\bar{t}}|)+N(|y_t|<|y_{\bar{t}}|)}$$



Arising from interference effects among **QCD diagrams at NLO**:

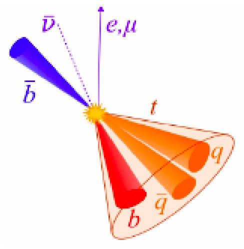
- Introduced by quark-antiquark initiated production, but **diluted by gluon-gluon** production.

Asymmetries exhibit kinematic dependence, **enhanced in BSM**:

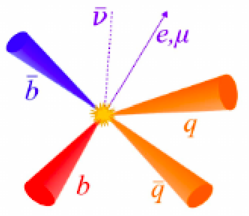
- Sensitivity of AC to EFT coefficients **complementary** to cross section measurements

ATLAS measurement with Full Run 2 data: Single and dilepton.

- **Single lepton:** split by b-jet multiplicity and boosted/resolved jet topologies. Use of a BDT for top reconstruction.



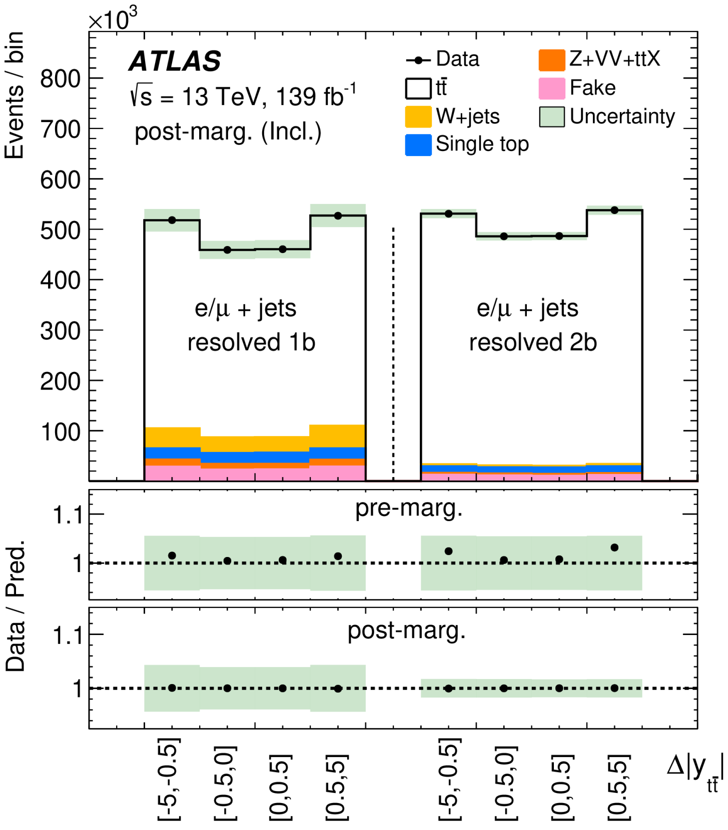
boosted



resolved

- **Dilepton:** split by lepton flavour and b-jet multiplicity. Also measure lepton charge asymmetry.

$$A_C^{\ell\bar{\ell}} = \frac{N(\Delta|\eta_{\ell\bar{\ell}}| > 0) - N(\Delta|\eta_{\ell\bar{\ell}}| < 0)}{N(\Delta|\eta_{\ell\bar{\ell}}| > 0) + N(\Delta|\eta_{\ell\bar{\ell}}| < 0)} \qquad \Delta|\eta_{\ell\bar{\ell}}| = |\eta_{\bar{\ell}}| - |\eta_{\ell}|$$



Charge asymmetry in top production

arXiv:2208.12095

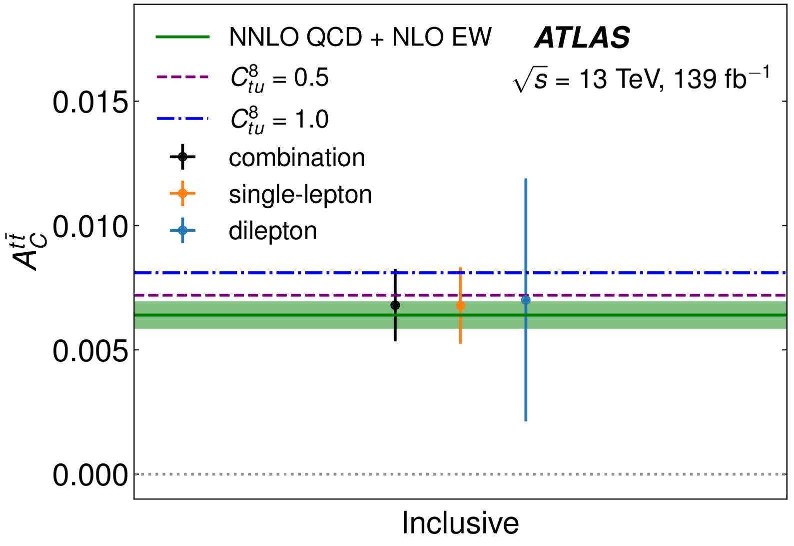
Δ|y| (Δ|η|) distributions corrected to parton level
using Fully Bayesian Unfolding approach

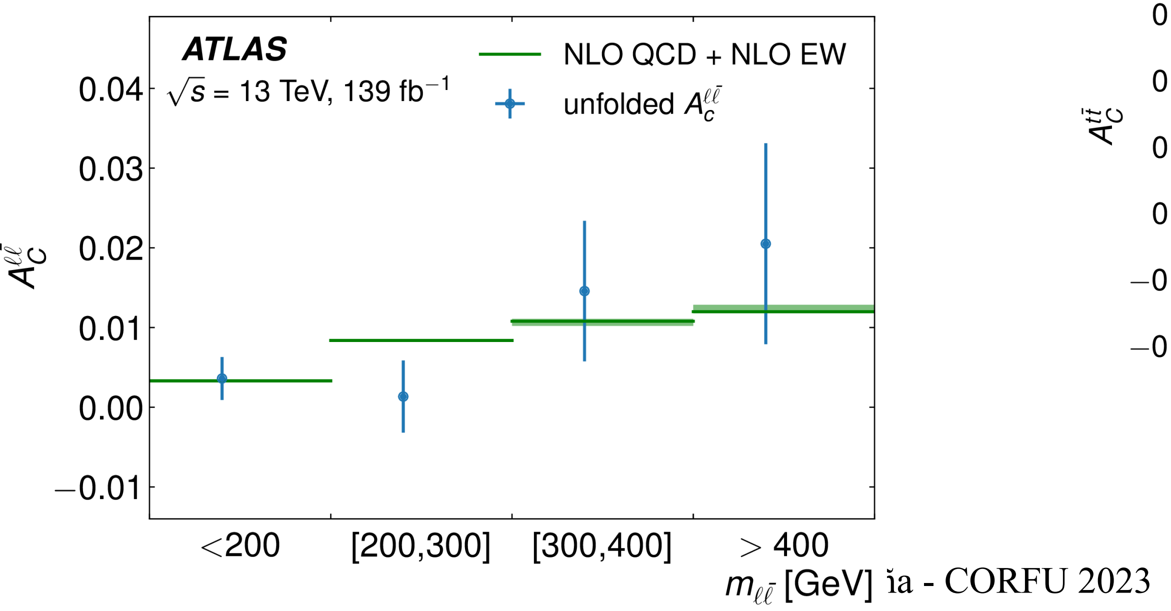
A_C measured inclusively and **differentially** as a function of m_{tt}, $p_{T,tt}$, $\beta_{z,tt}$ in the dilepton, lepton+jets channel and simultaneously.

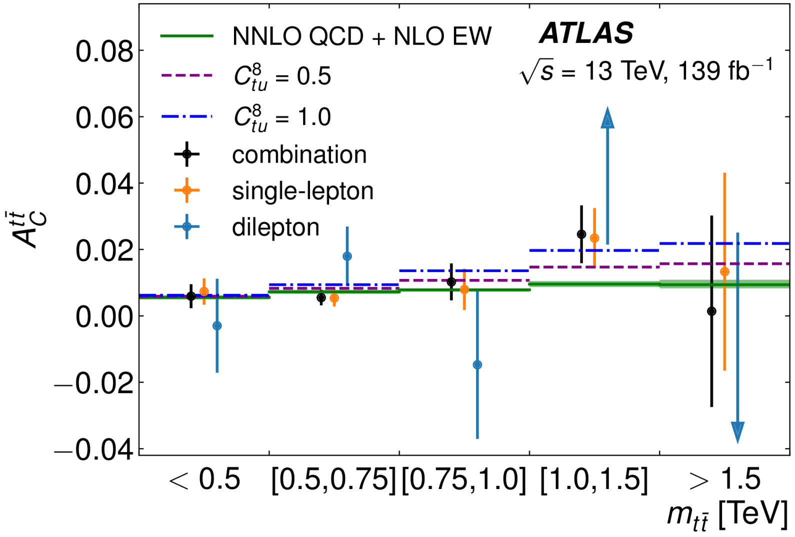
$$A_C = 0.0068 \pm 0.0015 \text{ (4.7 } \sigma \text{ from } A_C = 0)$$

$A^{\ell\ell}_C$ measured inclusively and differentially as a function of $m_{\ell\ell}$, $p_{T,\ell\ell}$, $\beta_{z,\ell\ell}$.

All results are compatible with SM predictions.







Charge asymmetry also in:

tt+gamma: arXiv:2212.10552

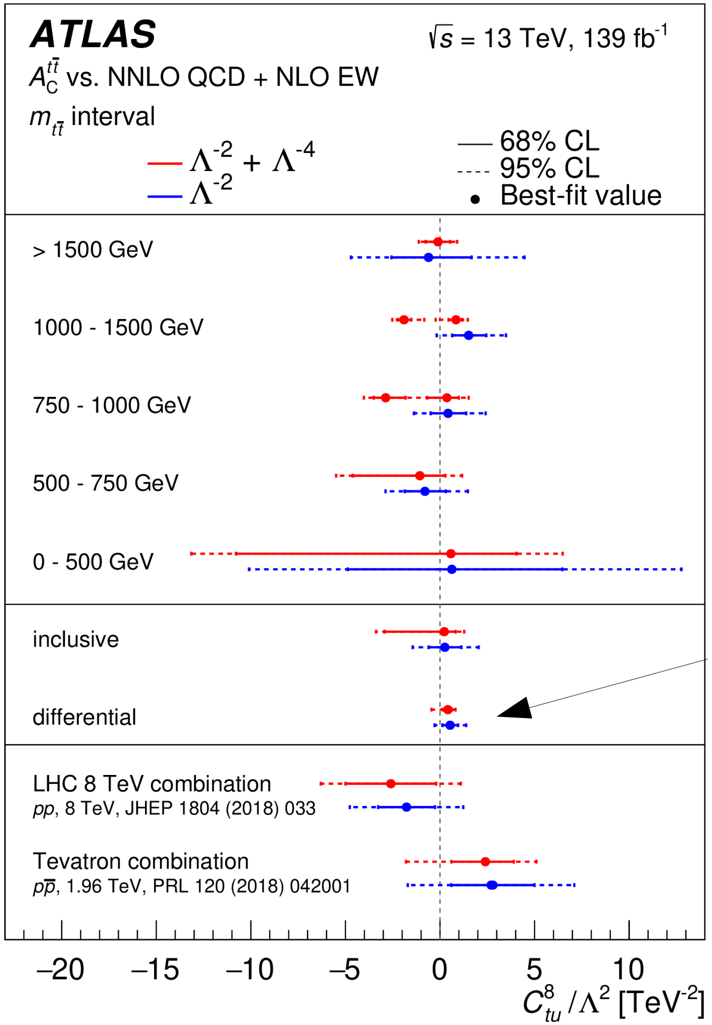
ttW: ATLAS-CONF-2023-019

Charge asymmetry in top production

arXiv:2208.12095

Combined results interpreted in the SMEFT framework:

- Constraint from the **differential measurement: factor >2 stronger** than the one from inclusive measurement (sensitivity increases with m_{tt})

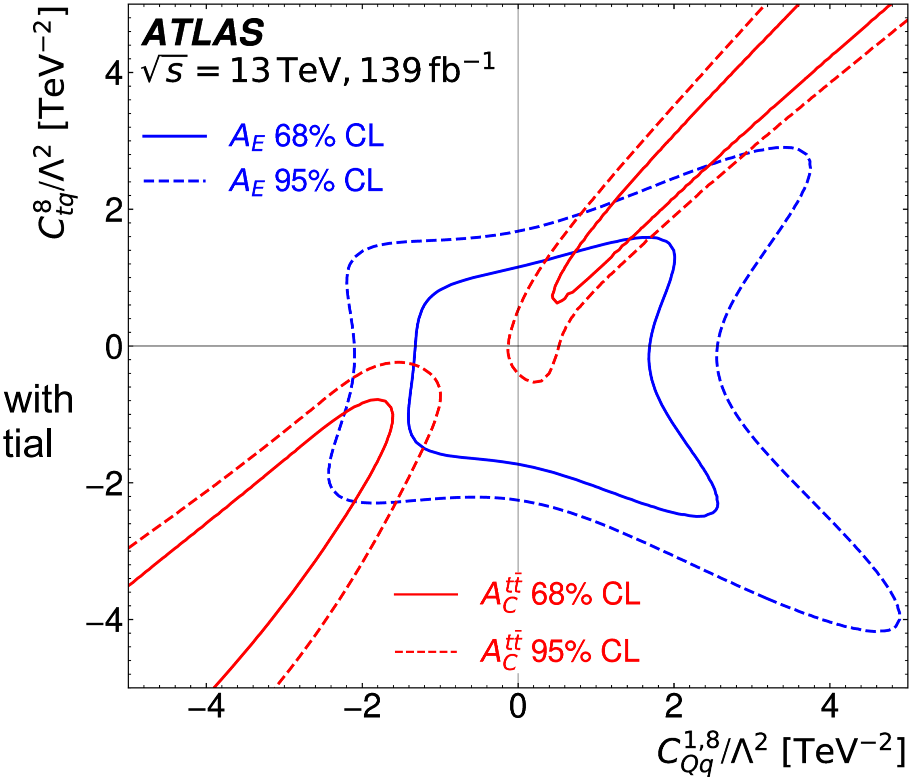


Big gain with differential

Energy asymmetry, A_E

Eur. Phys. J. C 82 (2022) 374

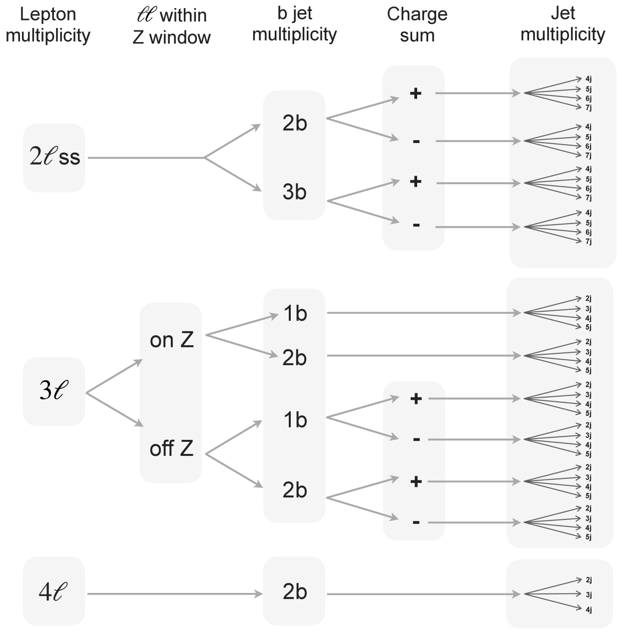
- Complementary measurement.
- Probe blind directions of A_C .



EFT search in top with additional leptons

- A search of new physics effects using the EFT framework.
- Targets top quark production **with additional final-state leptons.**
- EFT effects incorporated into event weights of MC samples:
  - **Provides detector level predictions with correlations** and interference between EFT operators and SM.
- **A total of 26 WCs:** 4 heavy quarks and 2 heavy quarks with 2 light quarks, 2 leptons or bosons.
- **Included processes: ttH, tHq, tttt, ttll, ttlv** & **tllq** (ttZ, ttW & tZq)
- Data is divided into **several categories** based on lepton, jet and b-jet multiplicities, total lepton charge
- 3-lepton category further divided into On-/Off-shell Z boson.
- A total of **43 event categories**: increases statistical power given the different mixtures of physic processes.

Event categorization

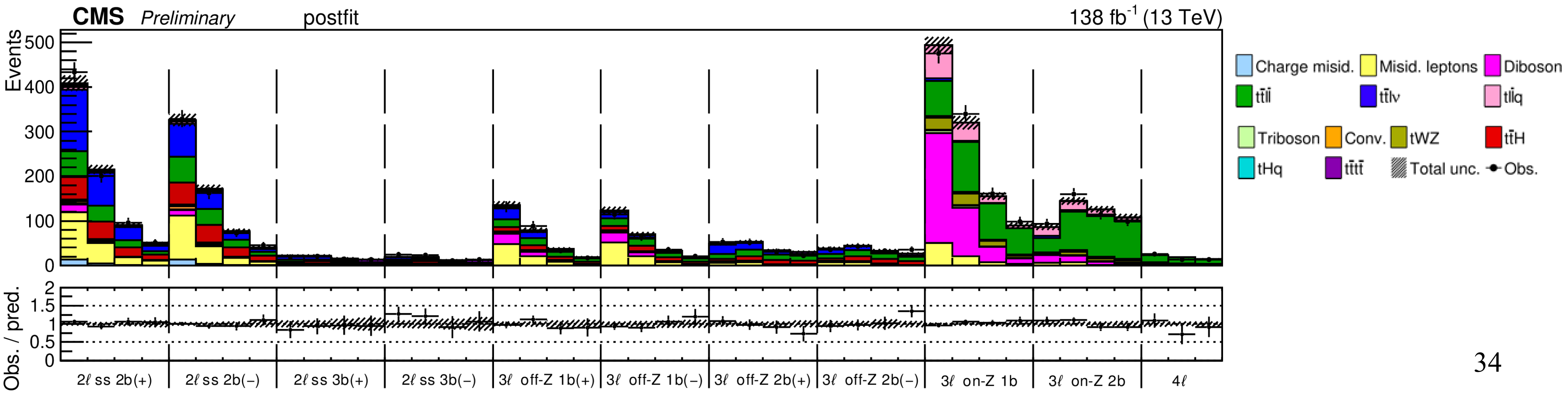


Lepton multiplicity | $\ell\ell$ within Z window | b jet multiplicity | Charge sum | Jet multiplicity

2ℓss
2b
\+ 4j 5j 6j 7j
\- 4j 5j 6j 7j
3b
\+ 4j 5j 6j 7j
\- 4j 5j 6j 7j

3ℓ
on Z
1b 2j 3j 4j 5j
2b 2j 3j 4j 5j
off Z
1b
\+ 2j 3j 4j 5j
\- 2j 3j 4j 5j
2b
\+ 2j 3j 4j 5j
\- 2j 3j 4j 5j

4ℓ
2b 2j 3j 4j



EFT search in top with additional leptons

Sensitivity to EFT is given through the **event yields** of each category: **Quadratic with WCs.**

To increase sensitivity to EFT, each of the 43 event categories is **binned into a differential distribution.** About a **factor two improvement in sensitivity.**

Two kinematical variables:

1) The **maximum transverse momenta** among all possible pairs of leptons and/or jets: $p_T(lj0)$

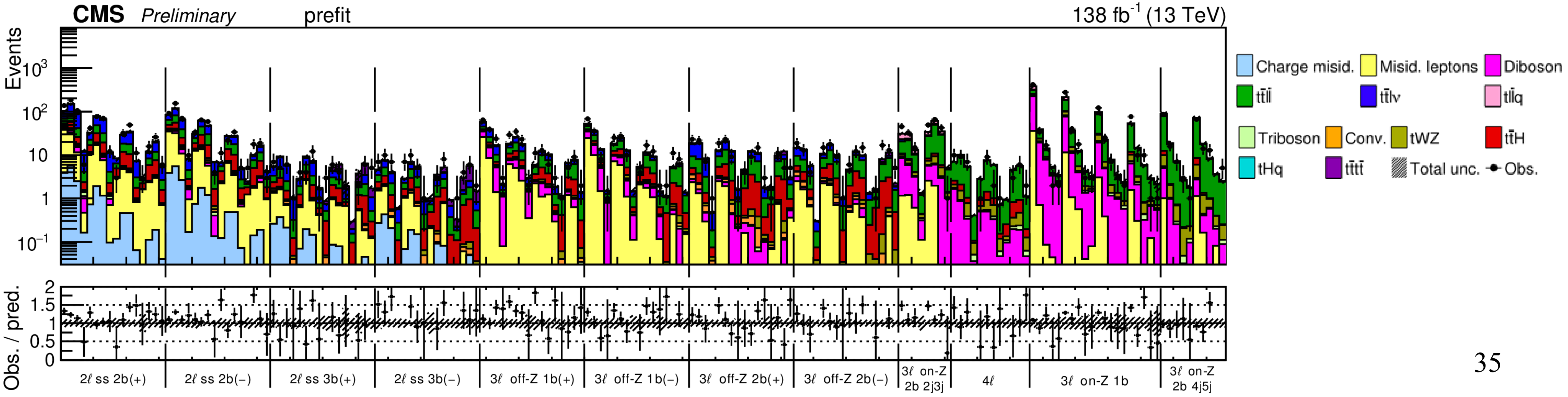
- Sensitivity to a broad range of EFT effect that grow with energy. Used in most categories.

2) **Transverse momenta of the on-shell Z boson**: $p_T(Z)$

- Sensitivity to EFT operators involving Z boson: modify Z kinematics. Used in 3l on-shell.

Background dominated by **WZ production:** estimated simulations and validated in **CRs.**

Non-prompt leptons contribution estimated using data driven techniques.

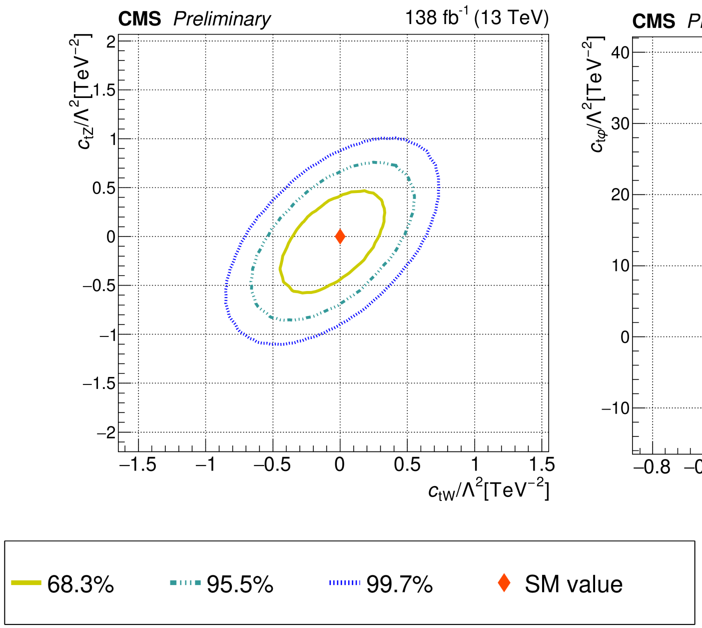


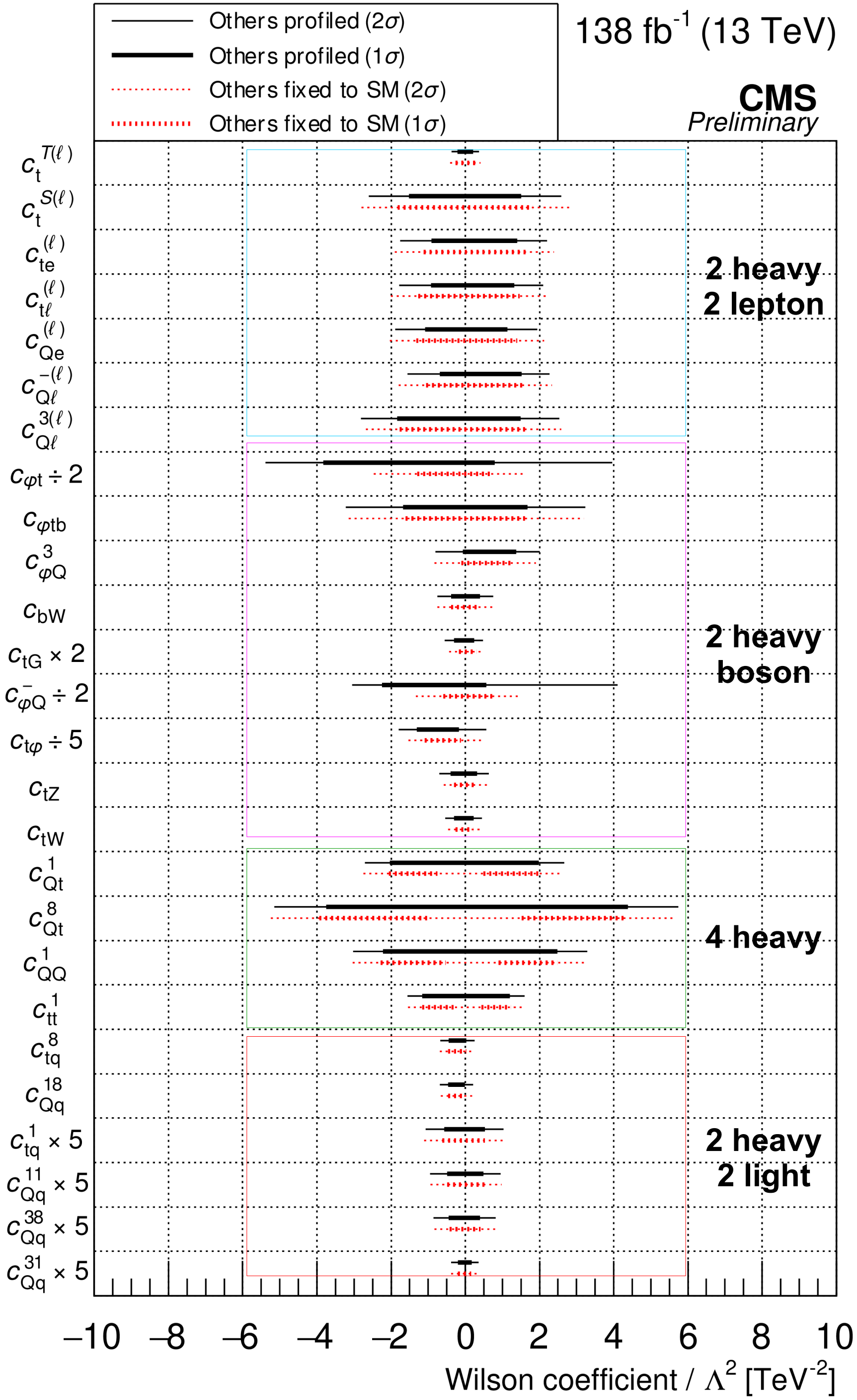
EFT search in top with additional leptons

- **Profile Likelihood fit** across **all bins**, each treated as an independent Poisson measurement.
- Each bin total **yield parametrized quadratically by the 26 WCs.**
- Systematic uncertainties treated as NPs.

- Two approaches for 1σ and 2σ confidence levels:
  - Rest of the WCs profiled.
  - Rest of the WCs fixed to SM value (=0)
- 2D scans for a subset of WCs.

All measured values are in agreement with SM.

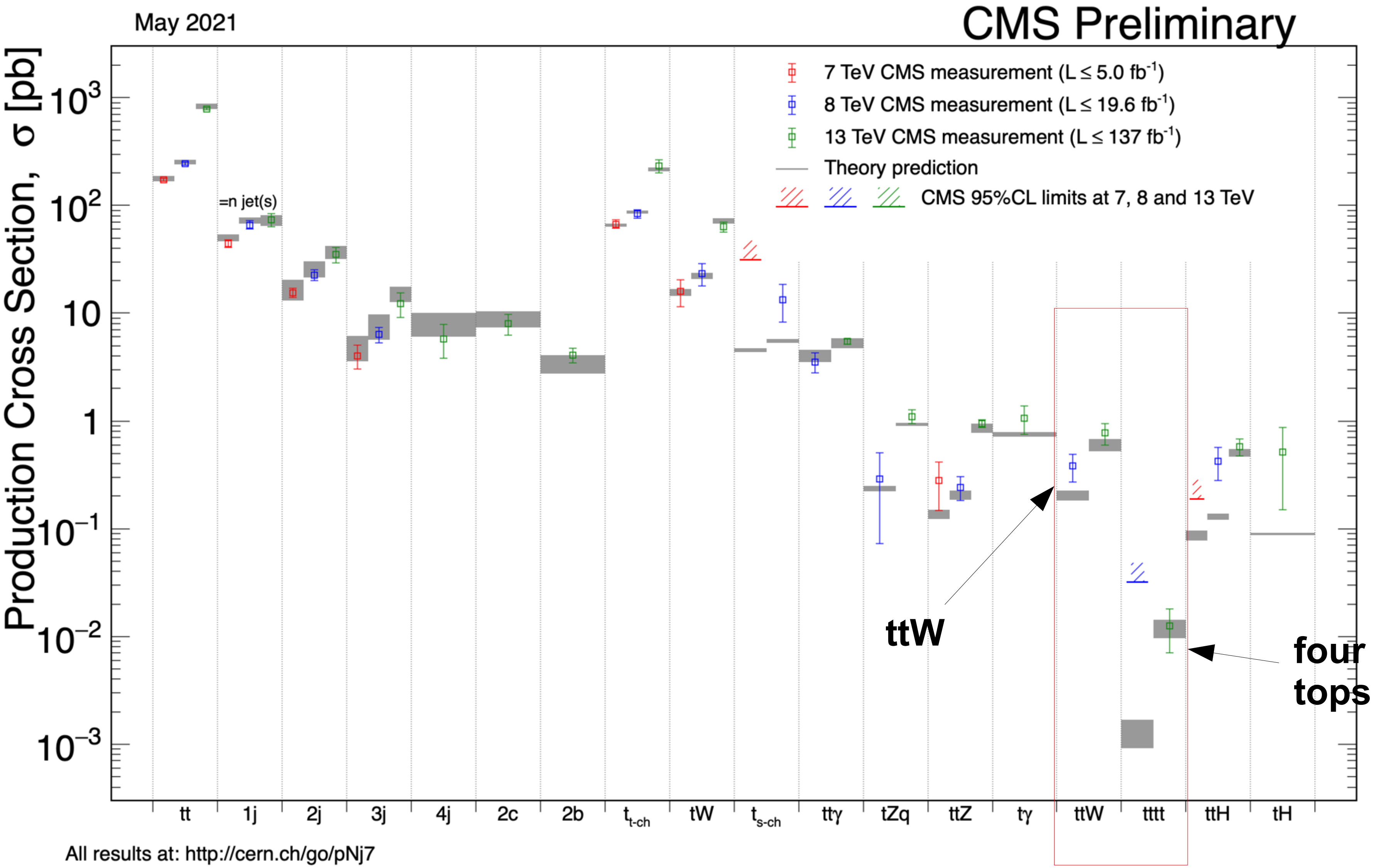




Rare processes

Rare process intro

The study of **rare processes allow to test SM predictions in high energy regimes** where deviations from the SM could be favored.



arXiv:2208.06485

Inclusive σ(ttW) at 13 TeV

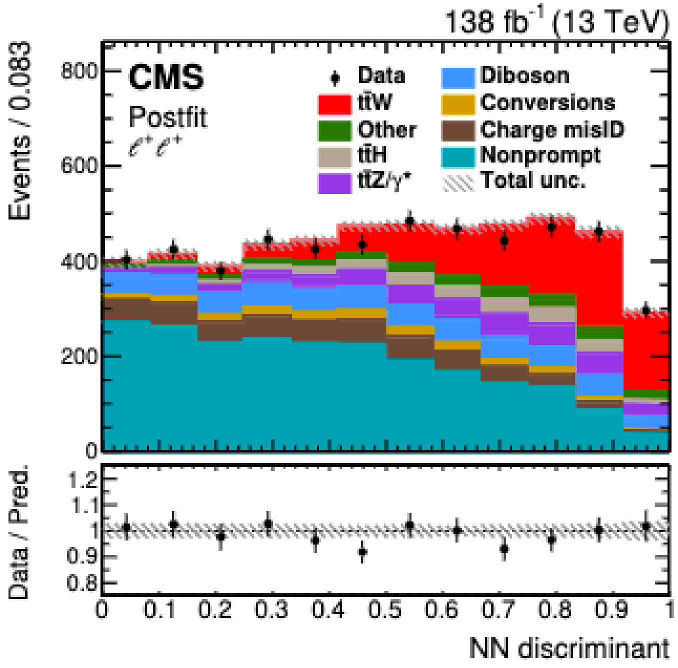
Events selected in **two main regions**:

2 SS leptons (semi-leptonic ttbar decay) :

- Dominant bkg from: ttH & ttZ, charge mis-ID, non-prompt lepton.
- Dedicated multiclass NN to separate signal and bkgs.

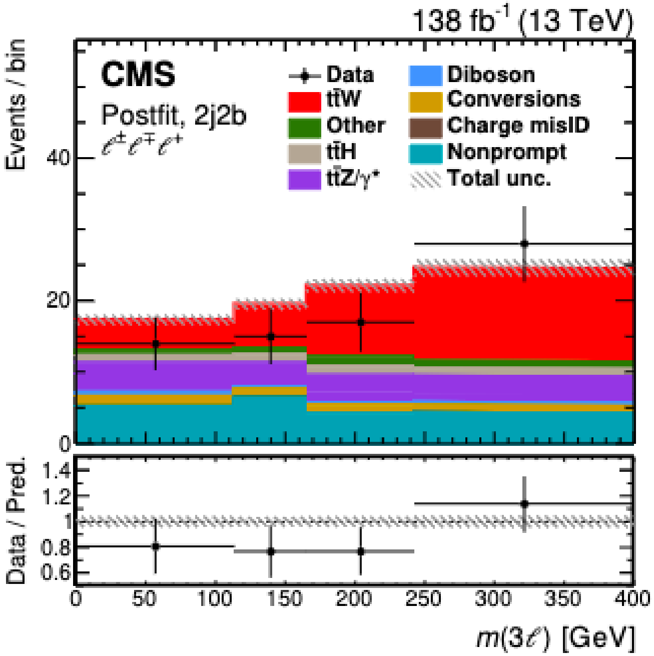
3 leptons (dileptonic ttbar decay) :

- Events categorized based on the number of b jets and lepton charge.



ttW extracted doing a fit to all SRs and CR.

- NN score used in 2l, and m(3l) in 3l.
- Dominant uncertainty from e charge mis-ID, lumi, b-tagging and normalization of ttH, VVV and ttVV.
- The large number of regions employed in the fit allows to constrain the uncertainty.



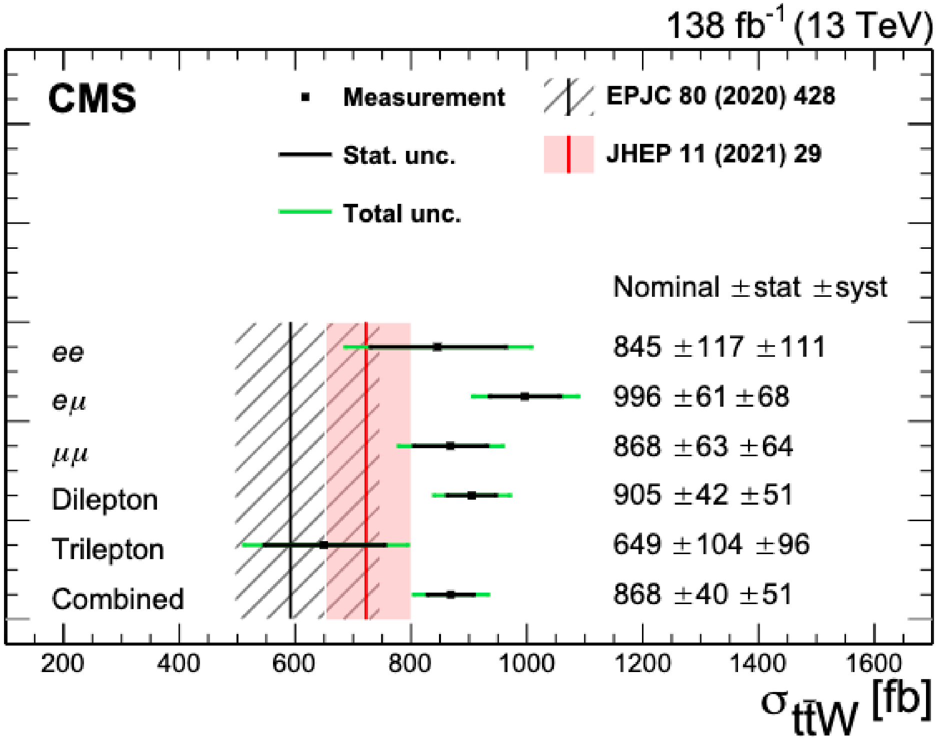
arXiv:2208.06485

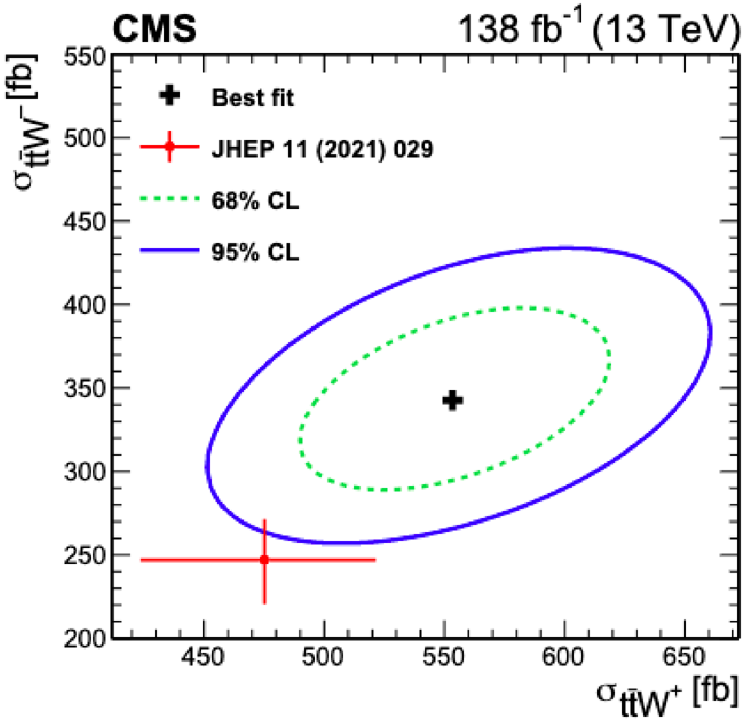
Inclusive σ(ttW) at 13 TeV

- **σ measured for ttW** and also for **ttW$^+$ and ttW$^-$** together with the ttW$^+$ /ttW$^-$ **ratio**.
- Obtained value of **σ(ttW)** is **slightly higher than the SM expectations**.
- Better compatibility with the NLO (EW&QCD) prediction obtained with an improved NLO FxFx-merging scheme.

σ(ttW) = 868 +- 40 (stat) +- 51 (syst) fb. Compatible at 2σ with SM.

- Main uncertainties: Statistical, ttH norm, luminosity, b-tagging and charge mis-ID.

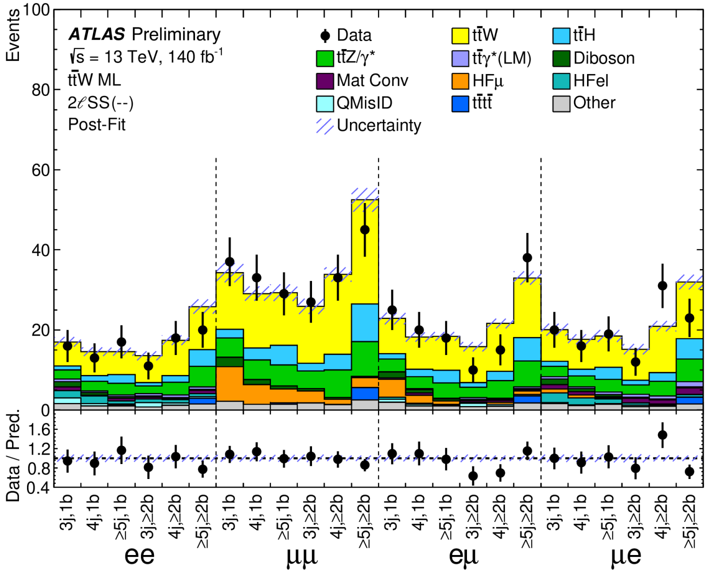


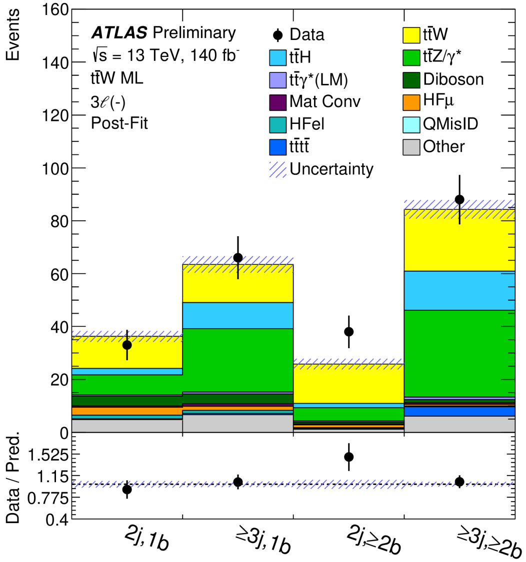


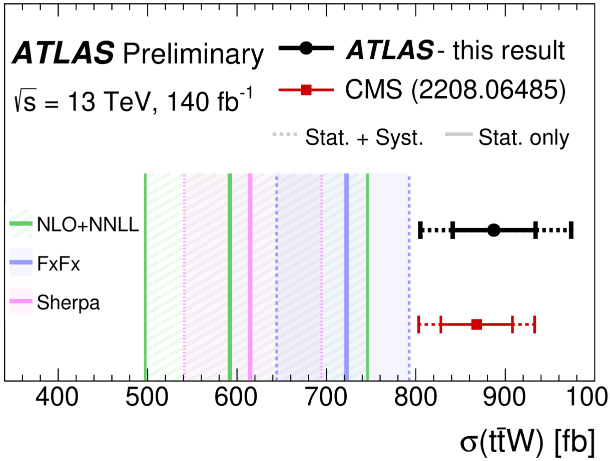
Inclusive σ(ttW) at 13 TeV

ATLAS-CONF-2023-019
Briefing

- **Similar measurement from ATLAS: 2LSS or 3L**
- **Split** by lepton charges-flavors, and jet and b-jet multiplicities:
- Simultaneous **profile likelihood fit** to data in 56 Signal and 10 Control Regions.





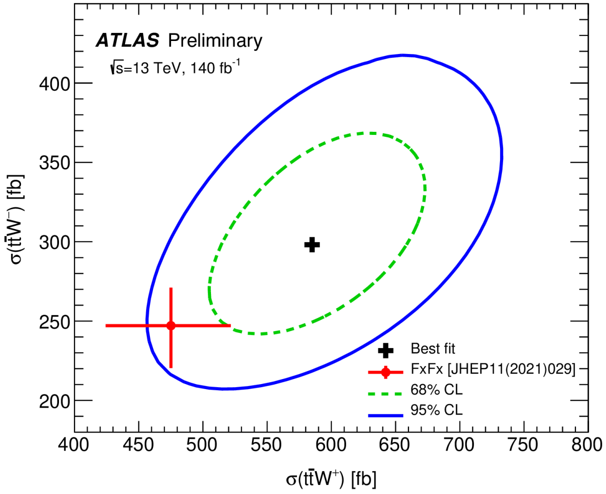


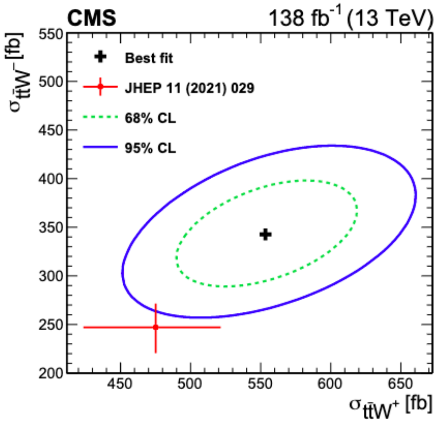
σ(ttW) = 890 +- 50 (stat) +- 70 (syst) fb.

Compatible at **1.5σ with SM.**

Main uncertainties:

Statistical, ttW ME and PS modeling, prompt-lepton norm and lepton isolation

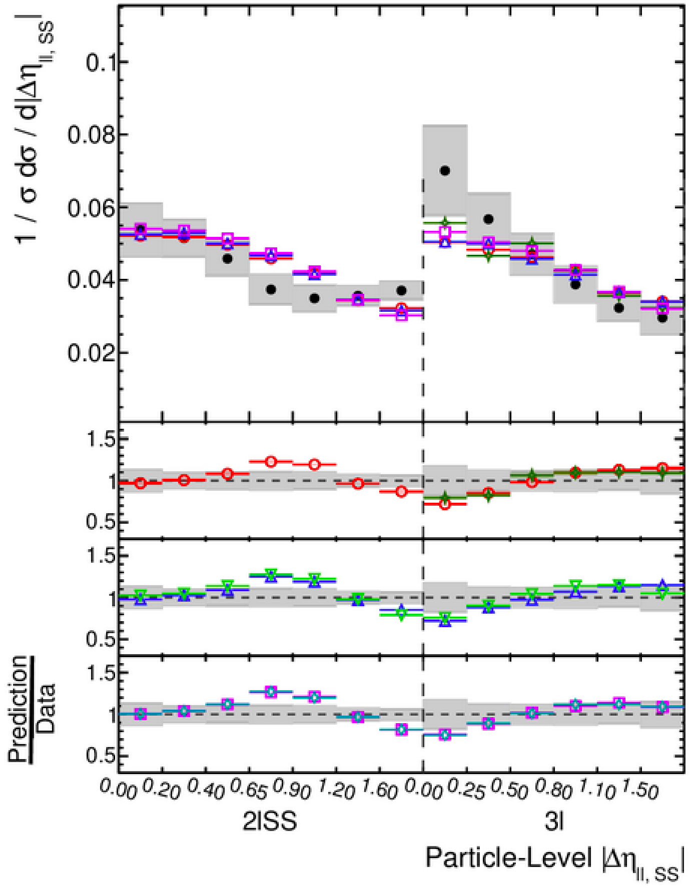




ATLAS-CONF-2023-019
Briefing

Differential σ(ttW) at 13 TeV

- **Differential XS extracted:** Unfolded to particle-level with a profile likelihood method.
- **Several observables** are compared to theoretical predictions: e.g. $|\Delta\eta_{ll,\ SS}|$
- Generally in **good agreement** with the normalised differential cross-section results.
- Some tensions observed in normalised XS, but overall agreement is good when considering statistical and systematic correlation: **p-value > 0.5**



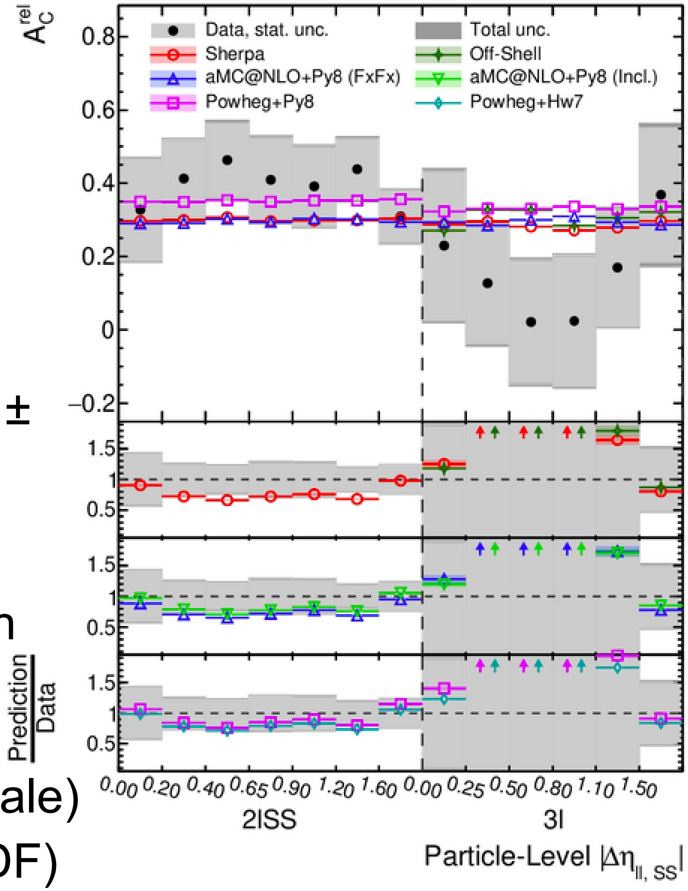
- The **relative charge asymmetry** has been measured:

$$A_C^{\mathrm{rel}} = \frac{\sigma(t\bar{t}W^+) - \sigma(t\bar{t}W^-)}{\sigma(t\bar{t}W^+) + \sigma(t\bar{t}W^-)}$$

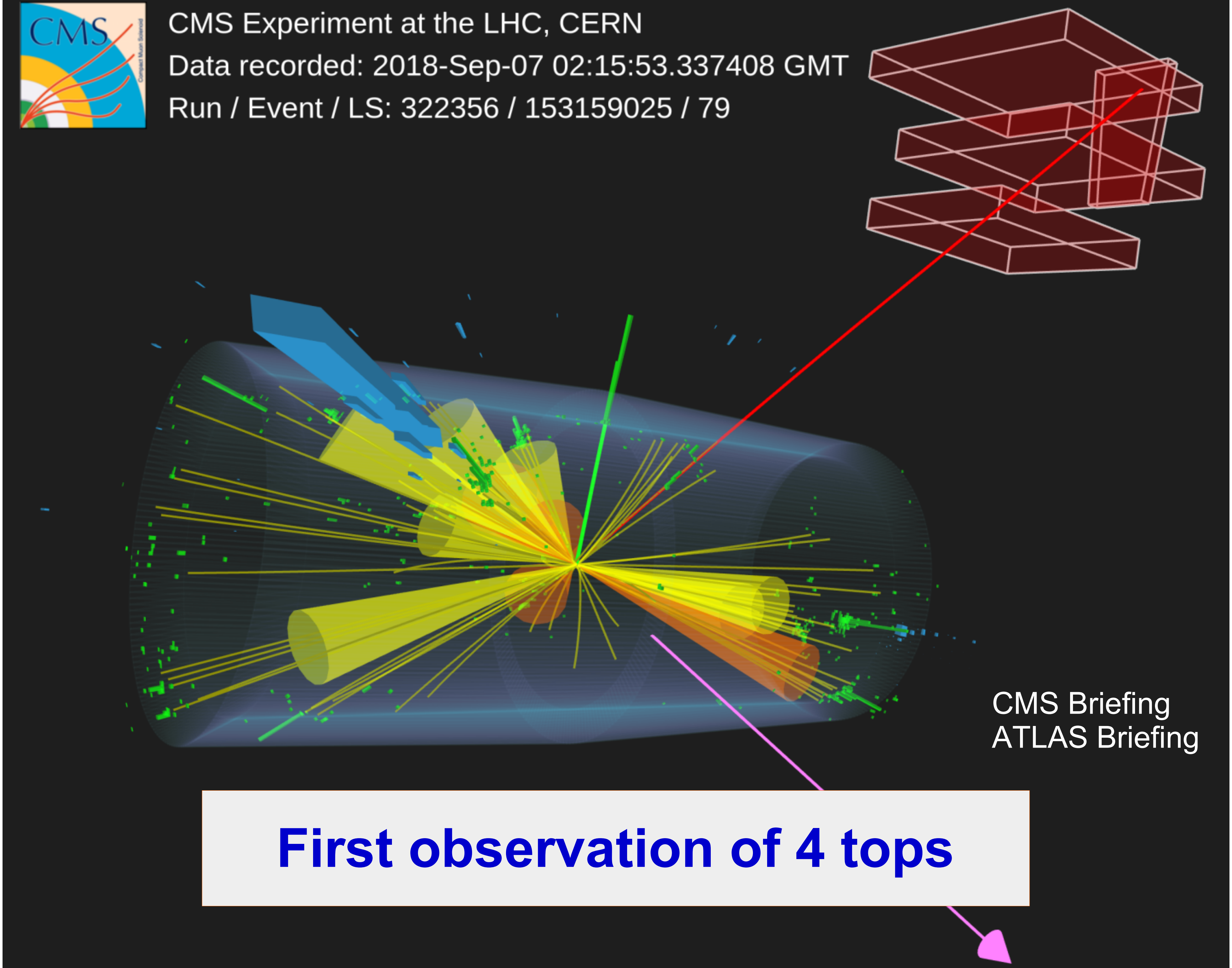
A_C^{rel} = 0.32 ± 0.05 (stat) ± ± 0.03 (syst)

- In **good agreement** with Sherpa prediction:

A_C^{rel} = 0.322 ± 0.003 (scale) ± 0.007 (PDF)

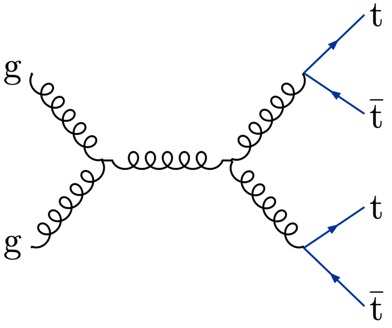


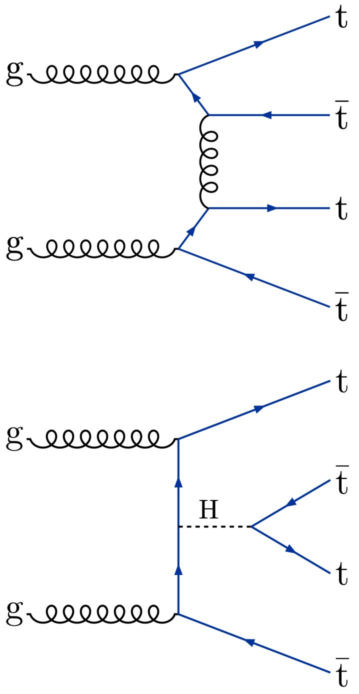
First observation of 4 tops



CMS Briefing
ATLAS Briefing

Four top production at the LHC





One of the heaviest final states accessible at the **LHC**:

- NLO QCD: $\sigma(t\bar{t}t\bar{t})$ = 12 fb ±20% [JHEP 02 (2018) 031]
- NLO+NLL: $\sigma(t\bar{t}t\bar{t})$ = 13.4 fb ±11% [arXiv:2212.03259]

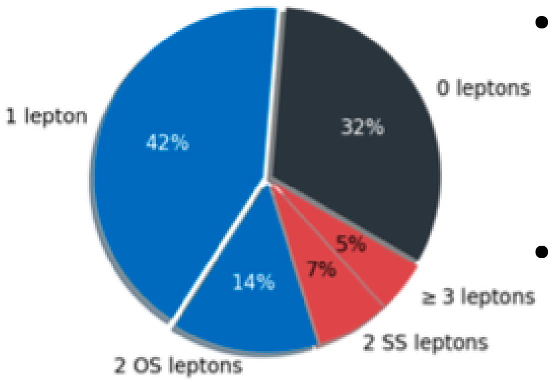
$\sigma(tttt)/\sigma(tt) \approx 10^{-5}$

Natural sensitivity to many BSM models

- Top quark-higgs Yukawa coupling and its CP properties.
- EFT four heavy fermion operators.

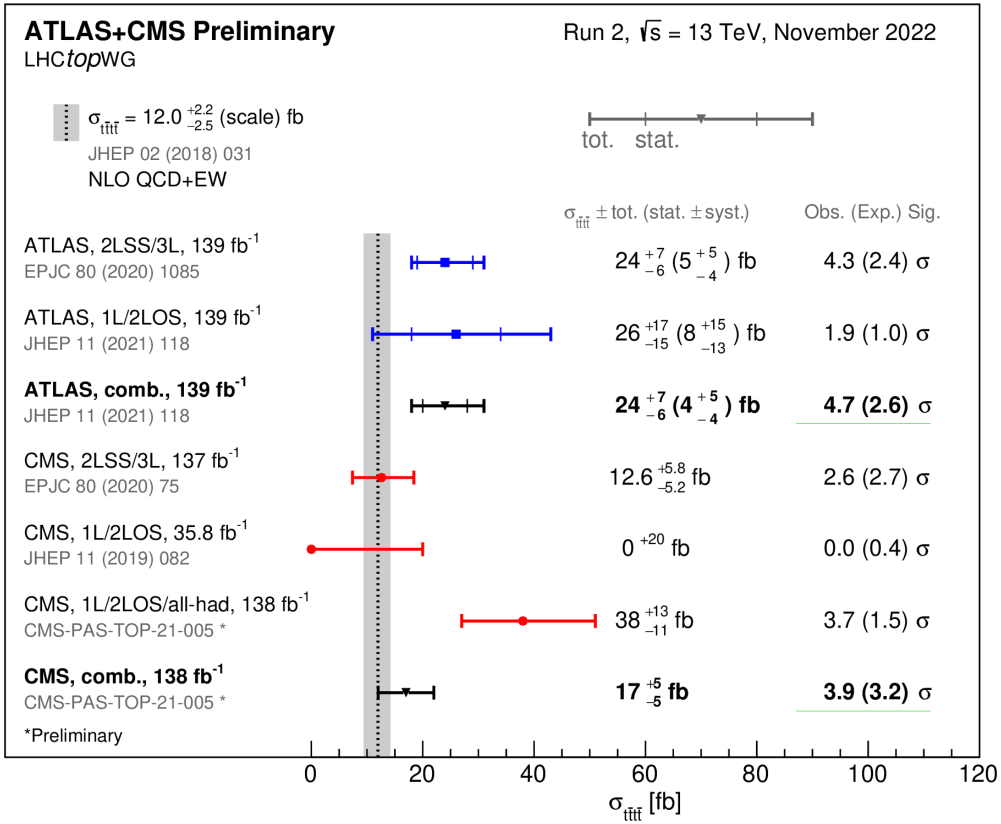
Final state: **high multiplicity** of jets and b-jets

- Analysis strategy varies with the number of leptons from top quark decays



Golden channel

- Evidence observed both by ATLAS and CMS in preliminary analyses
- Motivated a re-analysis of Run 2 dataset



CMS-PAS-TOP-22-013
arXiv:2303.15061

Multilepton: the golden channel

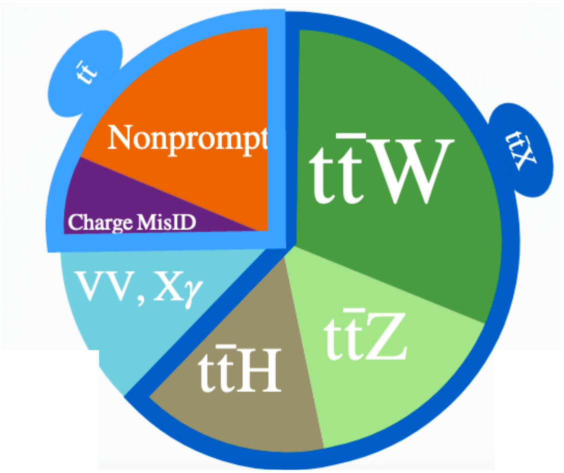
Multilepton final state is the most sensitive channel:

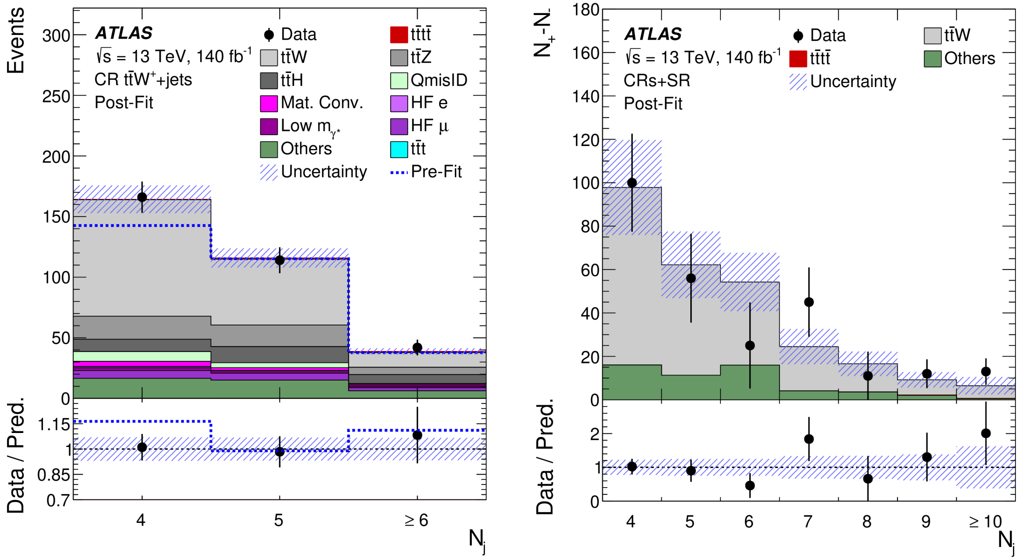
- Re-analyze various channels in ATLAS and CMS: **2LSS, 3L and 4L.**

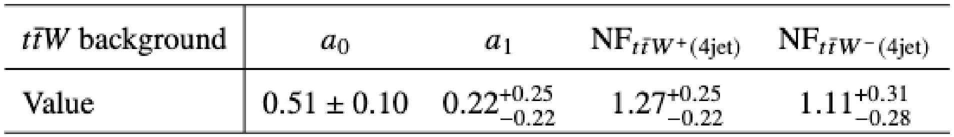
Physical backgrounds: mainly ttX: ttW, ttH and ttZ + jets.

- CMS: Simultaneous fit of σ(tttt), σ(ttZ) and σ(ttW). MC for ttH.
- ATLAS: MC for ttZ and ttH. A combination of simulation and **data driven approach for ttW+jets** (hard to model)

Backgrounds







$t\bar{t}W$ background	a_0	a_1	$\mathrm{NF}_{t\bar{t}W^+(4\mathrm{jet})}$	$\mathrm{NF}_{t\bar{t}W^-(4\mathrm{jet})}$
Value	0.51 ± 0.10	$0.22^{+0.25}_{-0.22}$	$1.27^{+0.25}_{-0.22}$	$1.11^{+0.31}_{-0.28}$

Instrumental backgrounds:

Non prompt / fake leptons:

- CMS: e/μ p_T and |η| parametrization.
- ATLAS: Templates from MC to extract normalization.

Charge Mis-Identification:

- Using same sign Z→ll sideband.

CMS-PAS-TOP-22-013
arXiv:2303.15061

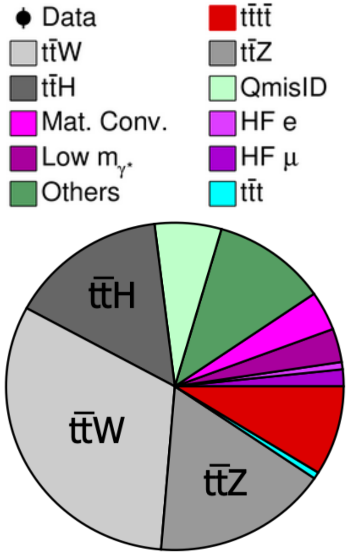
Event selection and strategy

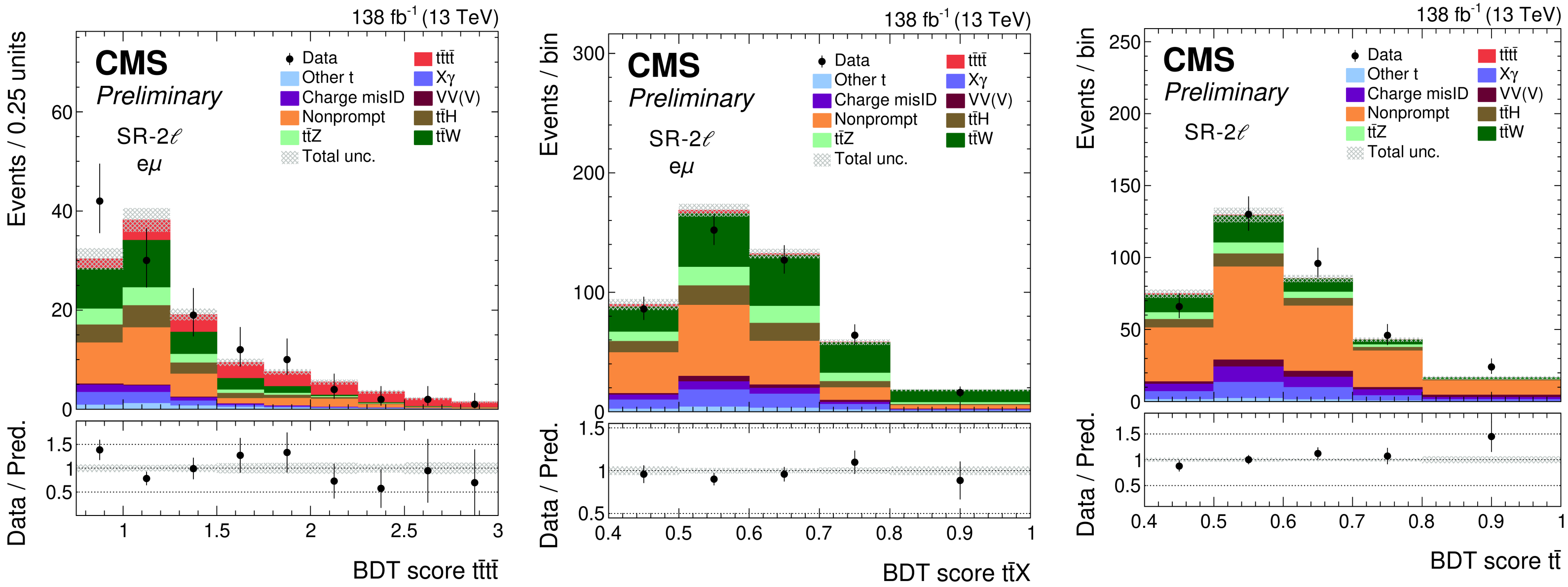
CMS: Event categorization depending of jet and b-jet multiplicities and $H_T = \Sigma_{\mathrm{lep,jet}}\ p_T$

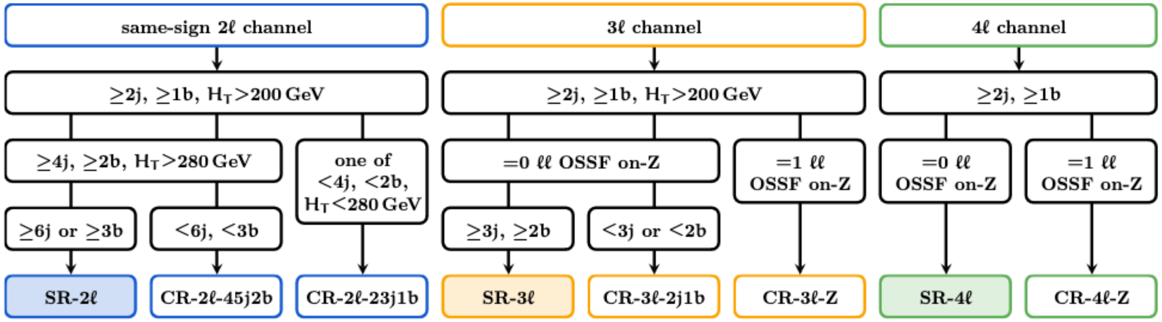
Use of a **multiclass BDT** to split events in tttt, ttX and tt

ATLAS signal region:

>= 6 jets, >= 2 b-jets, and H_T >= 500 GeV







ATLAS uses **Graph Neural Network**:

- Nodes: jets, e, μ and MET 4 momenta, flavour, charge, type...
- Edges: nodes angular separation.
- Global: jet multiplicity.

Better sensitivity than BDT (12%)

CMS-PAS-TOP-22-013
arXiv:2303.15061

Signal extraction

ATLAS and CMS have observed (individually) the production of **four top quarks for the first time**!

ATLAS: simultaneous profile likelihood fit to data to GNN score and 8 CR.

$$\sigma_{t\bar{t}t\bar{t}} = 22.5^{+4.7}_{-4.3}(\text{stat})\,^{+4.6}_{-3.4}(\text{syst})\text{ fb} = 22.5\,^{+6.6}_{-5.5}\text{ fb}.$$

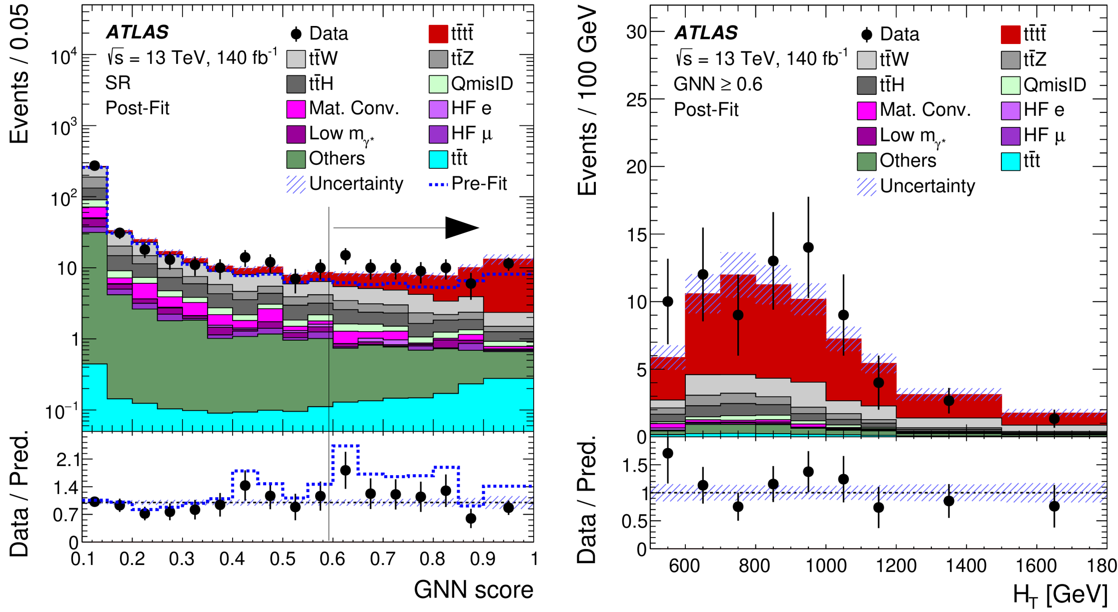
$$\mu = 1.9 \pm 0.4(\text{stat})\,^{+0.7}_{-0.4}(\text{syst}) = 1.9\,^{+0.8}_{-0.5}.$$

CMS: simultaneous profile likelihood fit to data in SR and CR. Fitted distributions include:

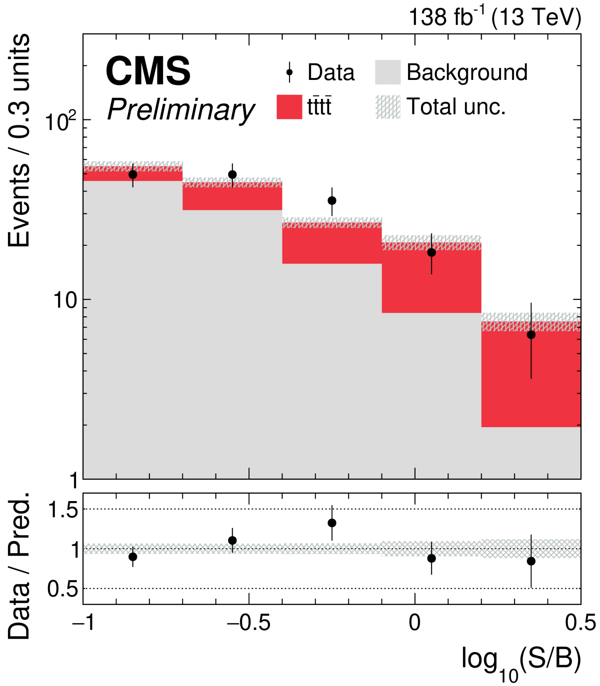
- BDT scores in the SR.
- BDT output score of ttbar in CR
- Jet multiplicity in Z CR (3l and 4l)

SM agreement

$\sigma(\mathrm{pp} \rightarrow \mathrm{t\bar{t}t\bar{t}}) = 17.9\,^{+3.7}_{-3.5}\,(\text{stat})\,^{+2.4}_{-2.1}\,(\text{syst})\,\text{fb},$	1.1 σ
$\sigma(\mathrm{pp} \rightarrow \mathrm{t\bar{t}W}) = 997 \pm 58\,(\text{stat})\,^{+79}_{-72}\,(\text{syst})\,\text{fb},$	2.3 σ
$\sigma(\mathrm{pp} \rightarrow \mathrm{t\bar{t}Z}) = 1134\,^{+52}_{-43}\,(\text{stat}) \pm 86\,(\text{syst})\,\text{fb}.$	2.2 σ



Significance: 6.1 σ (4.3 σ).



Significance: 5.5 σ (4.9 σ).

CMS-PAS-TOP-22-013
arXiv:2303.15061

Uncertainties and interpretation

Statistical and signal modeling are the largest uncertainties in both measurements.

From the experimental side, b-jet tagging and the jet energy scale.

Additional important uncertainties are:

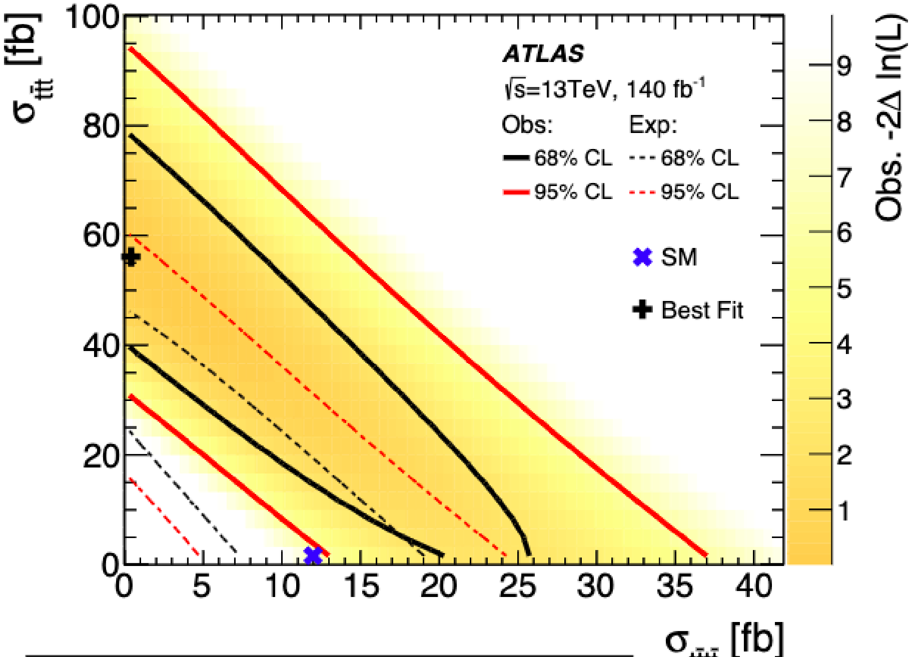
ATLAS: Parton Shower and Hadronization, ttW modeling.

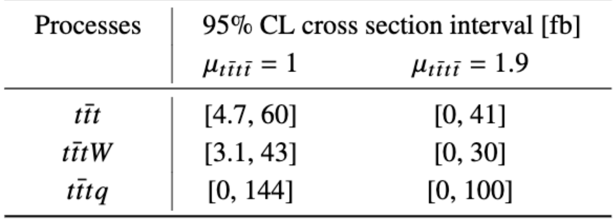
CMS: Modeling of ttX+jets and ttX+b-jets.

CMS: small 2σ excess for **ttZ** and **ttW** as in dedicated measurements.

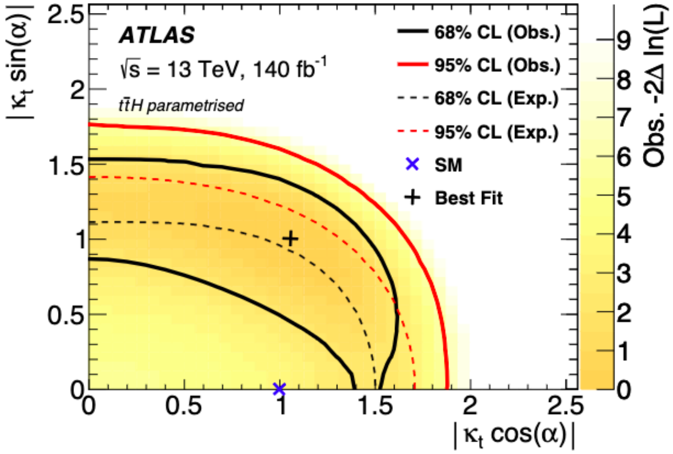
ATLAS: derives 95% CL for **ttt** production assuming the SM and measured σ(tttt).

Results also used to set BSM limits: **Top Yukawa** for example:





Processes	95% CL cross section interval [fb]	
	$\mu_{t\bar{t}t\bar{t}} = 1$	$\mu_{t\bar{t}t\bar{t}} = 1.9$
$t\bar{t}t$	[4.7, 60]	[0, 41]
$t\bar{t}tW$	[3.1, 43]	[0, 30]
$t\bar{t}tq$	[0, 144]	[0, 100]



Conclusions

ATLAS and CMS are extensively testing the SM with a wide program of measurements.

A selection of results of QCD and top physics have been presented.

No BSM signs unfortunately.

Larger datasets allow to go differentially (2D and 3D): allow to further test theory predictions and get a better understanding of fundamental QCD.

The properties of the top quark are studied in detail: Mass, XS, Asymmetries, polarization...

EFT SM as tool to find sign BSM signs: more global approaches are been pursued.

Rare events are started to be studied in detail. Some observed for the first time: Four tops.

Machine learning techniques are increasingly important.

And Run-3 is ongoing with plenty of new data to come.

Many thanks for your attention!

Conclusions

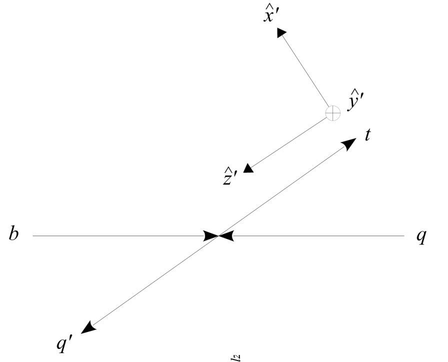
- To be written

Many thanks for your attention!

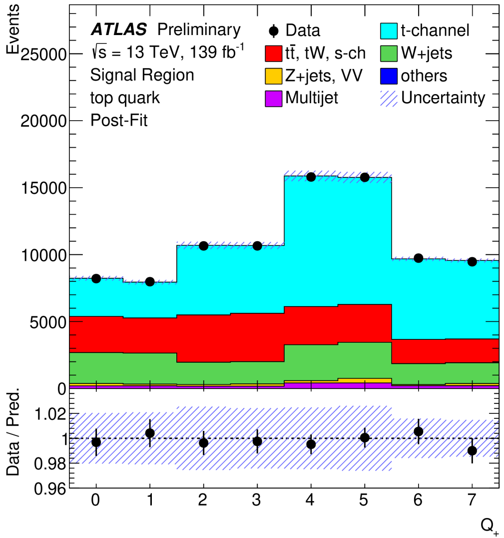
BACK UP SLIDES

Single top quark polarization

- Full 13 TeV data (139 fb^{-1}) used to measure single top quark polarization.
- In the t-channel at LO, top (antitop) quarks are produced with their spin aligned along the direction of the spectator (incoming) quark.
- The spin information is transferred to the top quark decays.

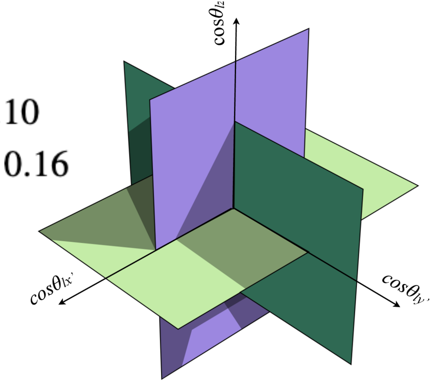


- 3D space divided into 8 Octants. Polarization vector extracted from ML fit.



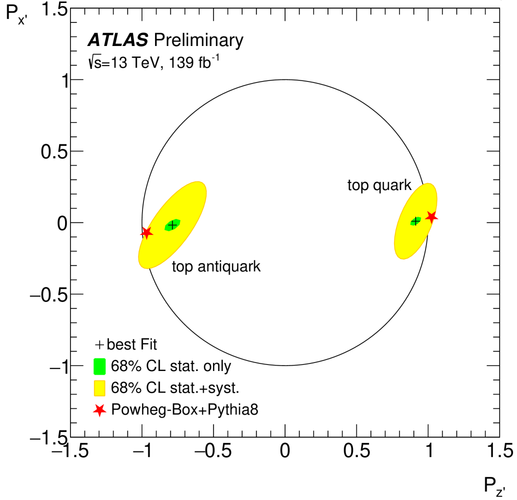
top $$P_{x'} = 0.01 \pm 0.18,\ P_{y'} = -0.029 \pm 0.027,\ P_{z'} = 0.91 \pm 0.10$$

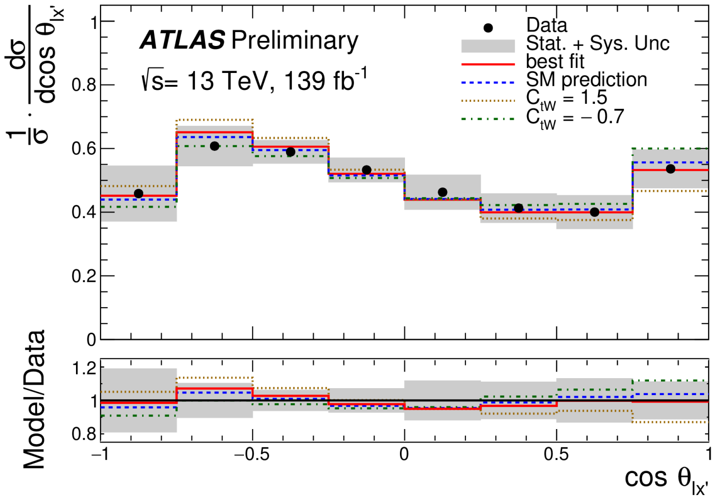
antitop $$P_{x'} = -0.02 \pm 0.200,\ P_{y'} = -0.007 \pm 0.051,\ P_{z'} = -0.79 \pm 0.16$$

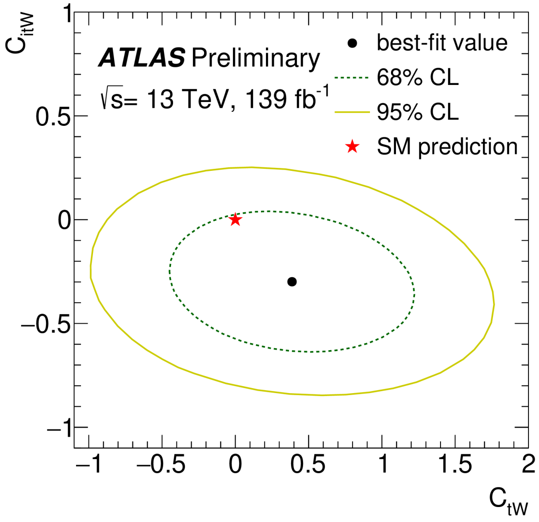


- Unfolded angular distributions at particle level used to test SM EFT extension of Wtb vertex.

$$C_{tW} \in [-0.7, 1.5] \text{ and } C_{itW} \in [-0.7, 0.2]$$







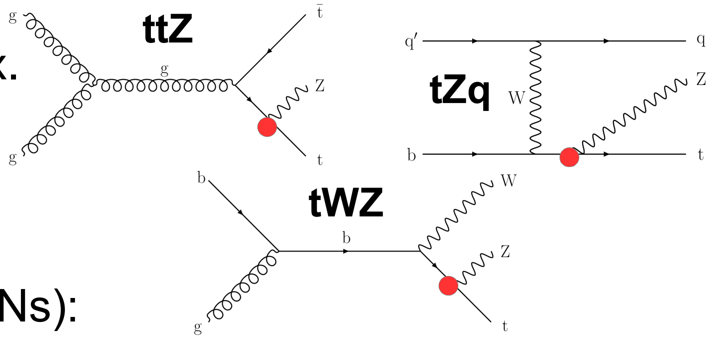
In agreement with SM.

Major syst: JER, JES & signal and background modeling.

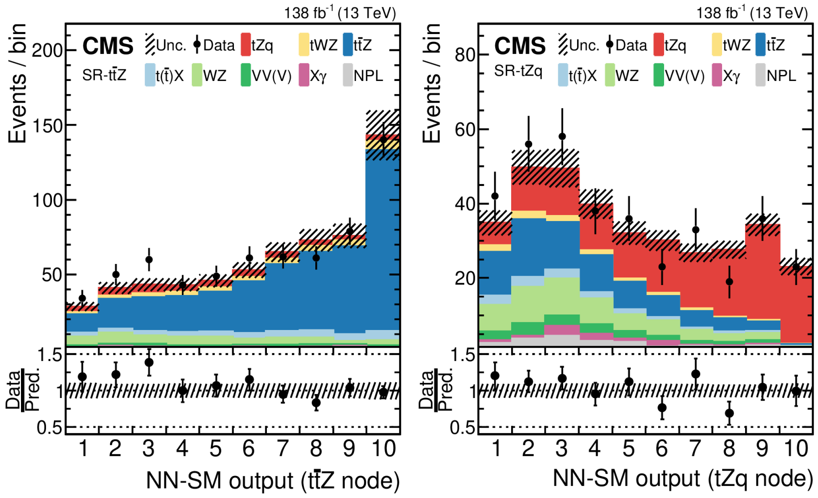
Proving EFT with ttZ vertex in multi lepton

CMS-TOP-21-001
Briefing

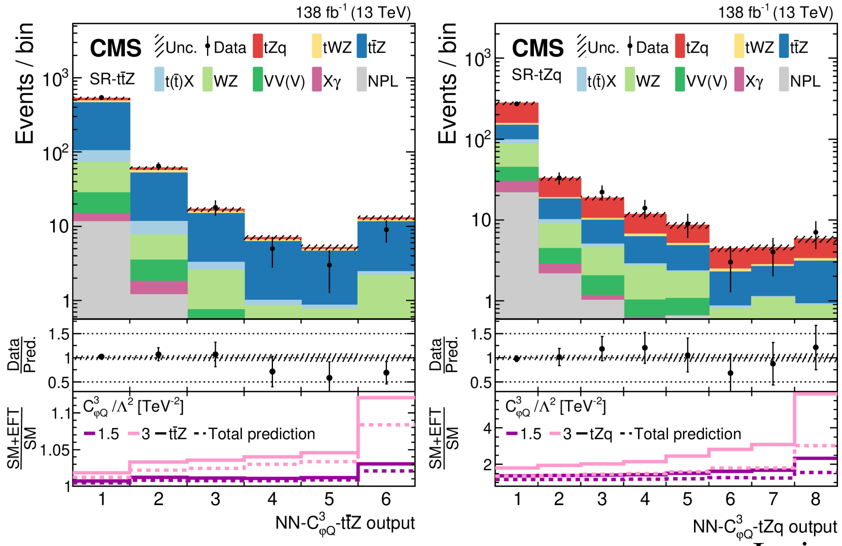
- Full 13 TeV data (138 fb^{-1}) to test SM EFT extension of ttZ vertex.
- Five Dim-6 operators considered: O_{tZ}, O_{tW}, $O^{3}_{\varphi Q}$, $O^{-}_{\varphi Q}$, $O_{\varphi t}$



Multiclass



Binary classifiers

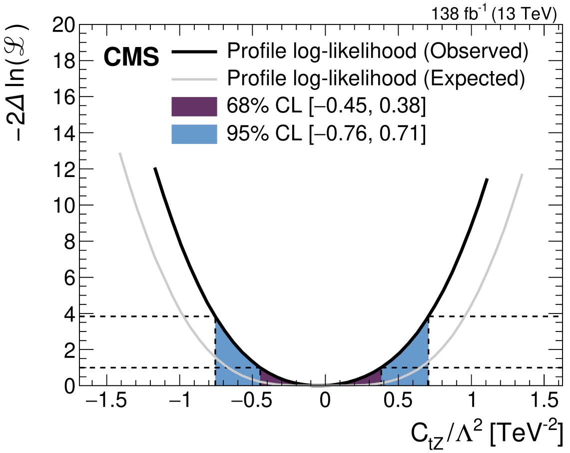


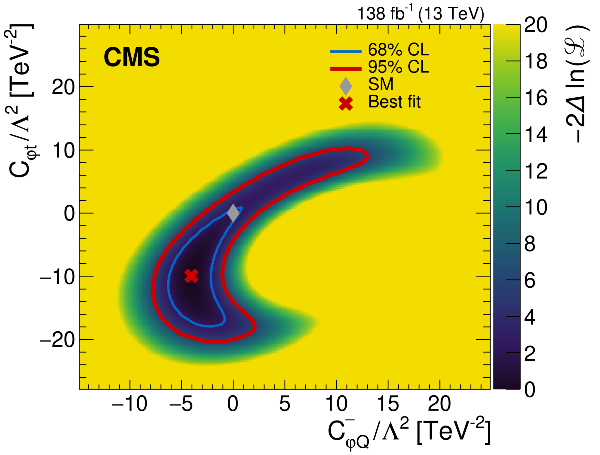
Extensive use of MVA (NNs):

- **Multiclass** classifier divides SR in tZq, ttZ and bckgd SRs.
- **Binary classifiers** separate SM events from WCs ≠ 0.
- Used to design observables with optimal sensitivity.

- Compatibility of WCs with data from a simultaneous ML fit to data in six categories (4 SR, 2 CR)
- Done for each WC, fixing the rest or for all 5 WCs free.

In agreement with SM.

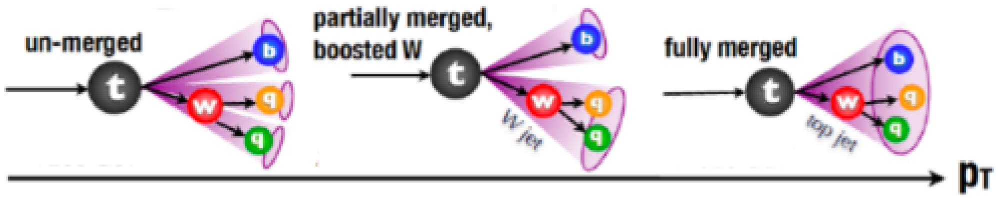


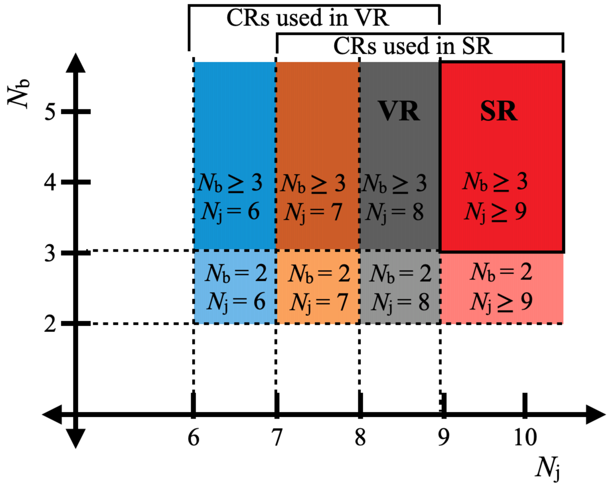


arXiv:2303.03864

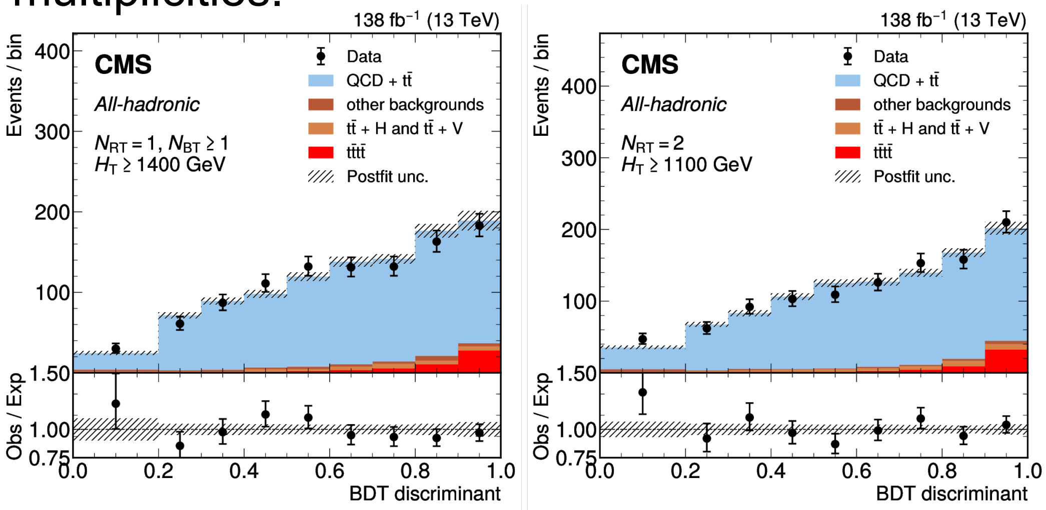
Four top production at CMS: All Hadronic

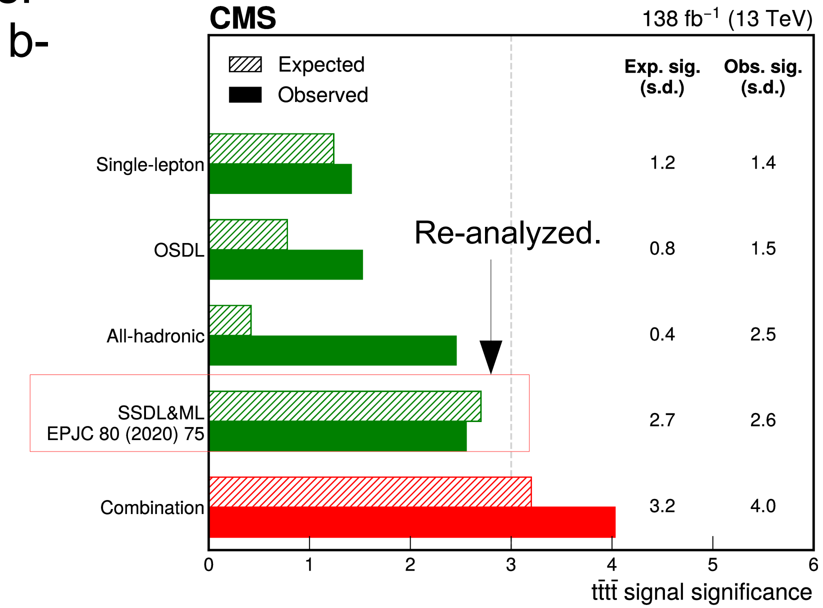
- First time all hadronic channel used in 4-top searches
- SR divided depending on top topology (boosted and resolved) and in H_T .





- Main backgrounds from QCD multijet and ttbar+jets: Data driven estimated in CRs with different jet and b-multiplicities.





Combination with results from other final states: **σ = 17 ± 4 (stat) ± 3 (syst) fb**