Measurements of top quark production cross-sections with the ATLAS detector

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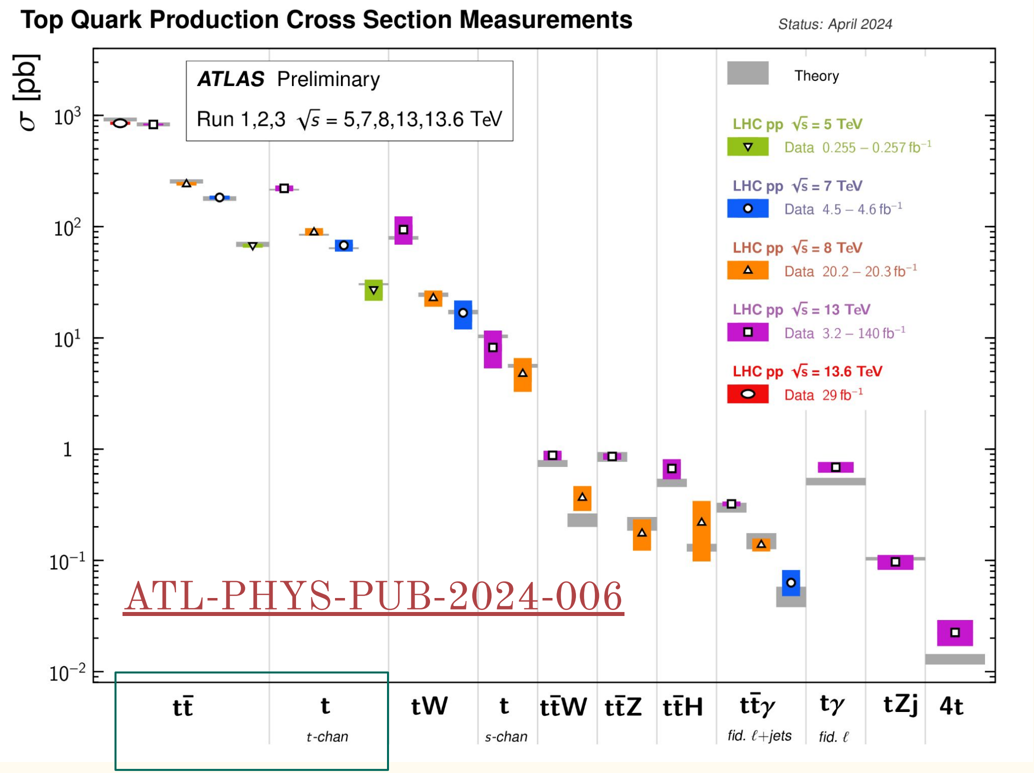
ICHEP 2024 July 18th 2024, Praga (Czech Republic)

Top quark:

- **Heaviest** elementary particle: special connection with Higgs Boson
- $\boldsymbol{\tau_{top} \ll 1/\Lambda_{QCD}}$ → quasi-free particle
- Enters in fundamental **SM** mechanisms
- Portal for **new physics**? **(BSM)**

Measuring top cross section (σ):

- Many processes, several orders of magnitude
- Test for precision QCD/EW **predictions**, for MC **simulations**
- Study **fragmentation**, jet **substructure**, …
- Provide inputs for **fundamental SM parameters** (e.g. m_{top}, α_s, V_{tb})
- Inputs for **PDFs**
- **Background** description for BSM



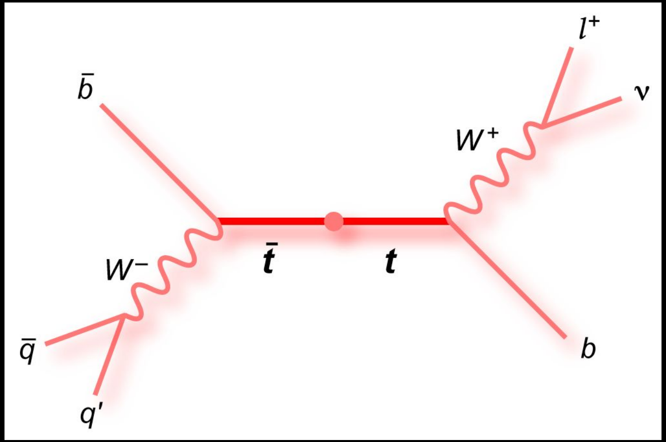
This talk: recent tt̄ and single top σ results

tt̄ + *γ/V* @ ATLAS: Jan Hahn's talk

tt̄ + *HF* @ ATLAS: Ricardo Goncalo's talk

Top properties & mass @ ATLAS: Pavol Strizenec's talk

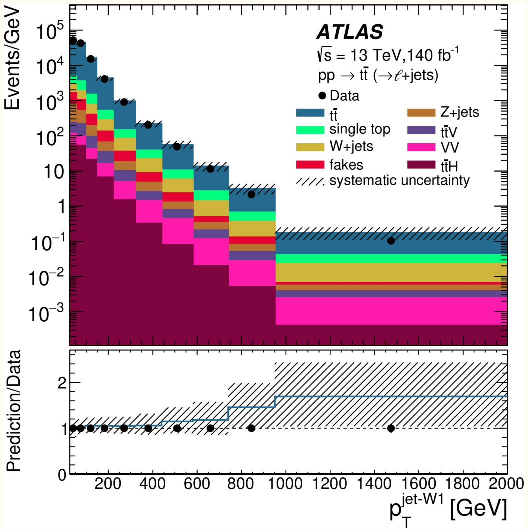
Top pairs σ measurements



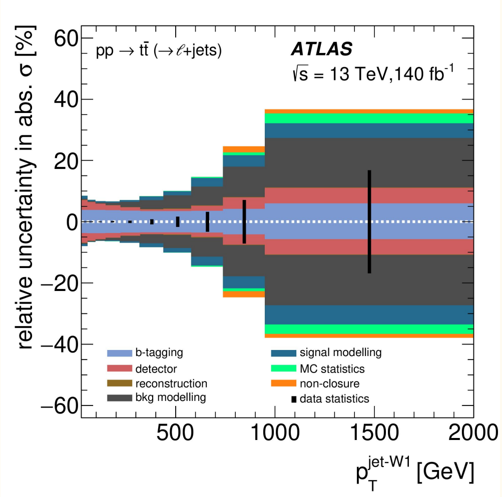
Jet observables in $t\bar{t}$ @ 13 TeV, full run-2

NEW

arXiv:2406.19701 *submitted to JHEP*



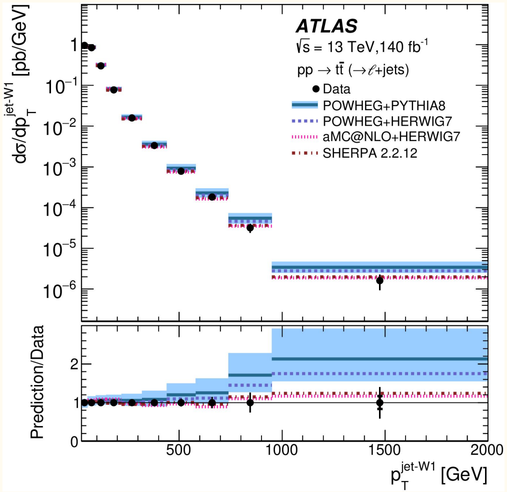
- *ℓ+jets* selection; $t\bar{t}$, $t\bar{t}$+1 jet, $t\bar{t}$+2 jets
- Focus on **jets observables**, sensitive to ISR/FSR
- Pseudo-top reconstruction algorithm:
  - 2 highest p_T *b*-tagged jets: ***b*-jets**
  - 2 non-tagged jets with m_{jj} closest to m_W: ***W*-jets**
  - Neutrino from E_T^{miss} + m_W constraint
  - $\mathbf{W_{lep}}$ and $\mathbf{W_{had}}$ can be thus reconstructed
  - Highest p_T jets not used in algorithm identified as **ISR jets** in $t\bar{t}$+1 jet, $t\bar{t}$+2 jets regions
- **Particle-level (Iterative Bayesian Unfolding, IBU)** differential cross sections
- Dominant uncertainties: *b*-tagging, jet energy scale/reso, modelling, background (depending on bin)

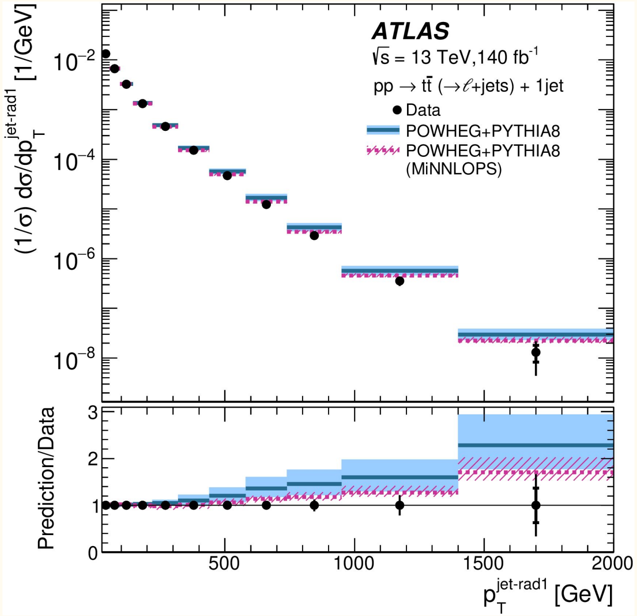


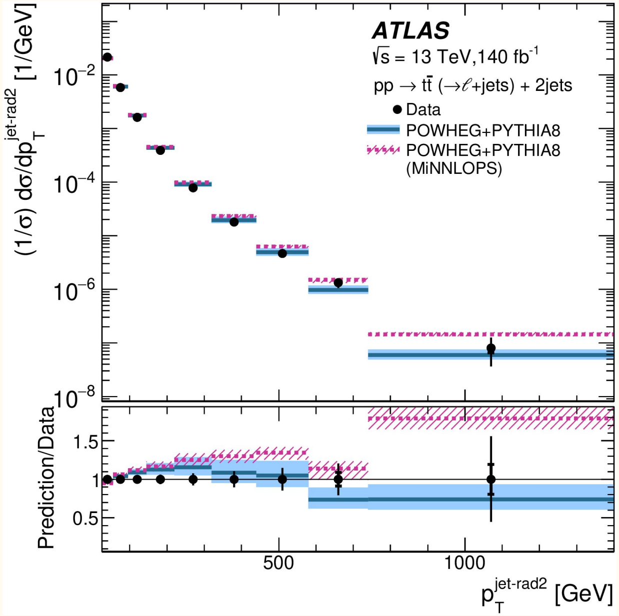
Jet observables in $t\bar{t}$ @ 13 TeV, full run-2

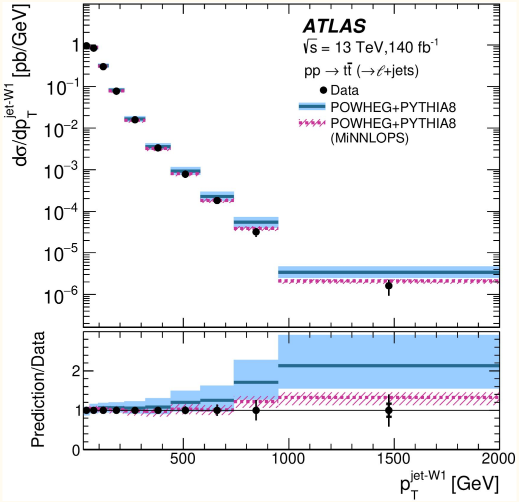
arXiv:2406.19701 *submitted to JHEP*

- Results compared with **NLO+PS MC** predictions
- Comparison also with **NNLO+PS setup** (MINNLOPS)
  - data/prediction improvement in several observables
  - slightly worse description of $p_T^{\text{jet-rad2}}$









Jet observables in $t\bar{t}$ @ 13 TeV, full run-2

arXiv:2406.19701 *submitted to JHEP*

Data-MC agreement for normalised σ

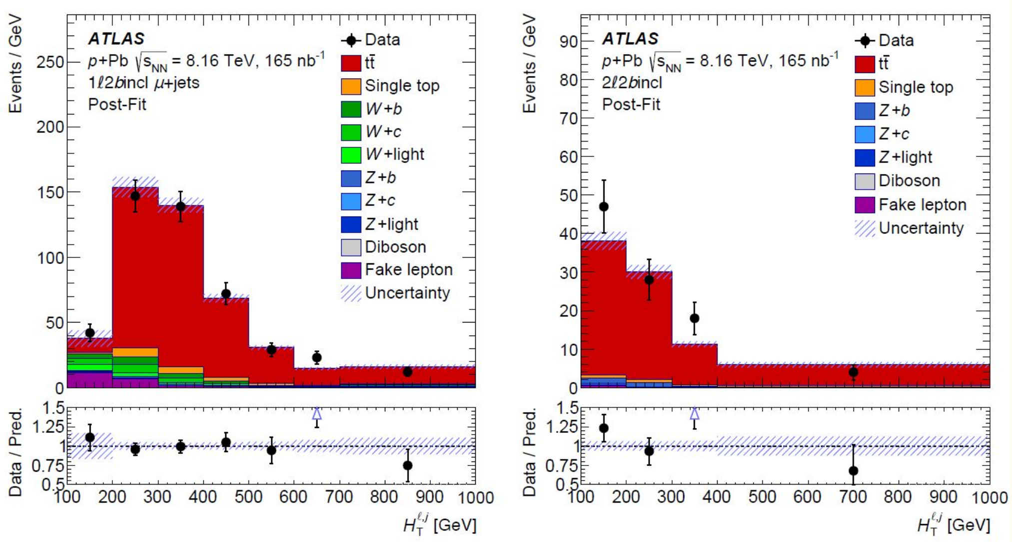
Data-MC agreement is quantified with a χ^2 calculated both for absolute and normalised cross sections for all observables

Prediction		Pwg+Py8		Pwg+Hw7		aMC@NLO+Hw7		Sherpa 2.2.12		Pwg+Py8 MiNNLOPS	
Observable	NDF	χ^2	p-value	χ^2	p-value	χ^2	p-value	χ^2	p-value	χ^2	p-value
$p_T^{\text{jet-W1}}$	9	12.0	0.21	16.0	0.074	13.0	0.19	19.0	0.024	14.0	0.13
$\lvert y^{\text{jet-W1}}\rvert$	9	63.0	< 0.01	76.0	< 0.01	65.0	< 0.01	56.0	< 0.01	13.0	0.17
$p_T^{\text{jet-W2}}$	7	7.9	0.34	9.8	0.20	8.0	0.33	13.0	0.064	8.2	0.31
$\lvert y^{\text{jet-W2}}\rvert$	9	134.0	< 0.01	220.0	< 0.01	219.0	< 0.01	103.0	< 0.01	25.0	< 0.01
$\lvert\Delta y^{\text{jet-W1 - jet-W2}}\rvert$	9	7.0	0.63	8.2	0.52	7.9	0.54	6.1	0.73	5.2	0.81
$\lvert\Delta\phi^{\text{jet-W1 - jet-W2}}\rvert$	9	9.5	0.39	12.0	0.21	13.0	0.17	11.0	0.25	8.7	0.47
$p_T^{\text{jet-rad1}}$	10	9.4	0.50	9.5	0.48	8.5	0.58	10.3	0.42	12.0	0.29
$\lvert y^{\text{jet-rad1}}\rvert$	9	49.0	< 0.01	80.0	< 0.01	68.0	< 0.01	42.0	< 0.01	21.0	0.011
$\lvert\Delta\phi^{\text{toplep - jet-rad1}}\rvert$	6	2.8	0.83	3.0	0.80	2.7	0.85	2.9	0.82	2.5	0.87
$\lvert\Delta\phi^{\text{tophad - jet-rad1}}\rvert$	6	2.6	0.86	2.9	0.82	2.2	0.90	2.6	0.85	2.1	0.91
$\lvert\Delta\phi^{\text{jet-W1 - jet-rad1}}\rvert$	9	7.7	0.56	11.0	0.27	6.3	0.71	8.6	0.47	5.6	0.78
$m^{t\bar{t}\text{ - jet-rad1}}$	7	9.1	0.24	9.8	0.20	7.9	0.35	7.8	0.35	8.2	0.31
$p_T^{\text{jet-rad2}}$	8	12.0	0.13	13.0	0.11	11.0	0.22	10.5	0.23	14.0	0.072
$\lvert y^{\text{jet-rad2}}\rvert$	9	24.0	< 0.01	45.0	< 0.01	38.0	< 0.01	30.0	< 0.01	16.0	0.069
$\lvert\Delta y^{\text{jet-rad1 - jet-rad2}}\rvert$	9	5.6	0.78	15.0	0.090	7.7	0.57	5.9	0.75	6.4	0.70
$\lvert\Delta\phi^{\text{jet-rad1 - jet-rad2}}\rvert$	9	25.0	< 0.01	69.0	< 0.01	33.0	< 0.01	15.0	0.084	26.0	< 0.01
$\lvert\Delta\phi^{\text{toplep - jet-rad2}}\rvert$	6	12.0	0.072	15.0	0.018	12.0	0.062	13.0	0.036	8.5	0.21
$\lvert\Delta\phi^{\text{tophad - jet-rad2}}\rvert$	6	4.7	0.59	5.5	0.49	4.8	0.57	4.6	0.59	2.6	0.86
$\lvert\Delta\phi^{\text{jet-W1 - jet-rad2}}\rvert$	9	12.0	0.23	22.0	< 0.01	18.0	0.040	14.0	0.13	11.0	0.26
$m^{\text{jet-rad1 - jet-rad2}}$	8	14.0	0.094	16.0	0.042	12.0	0.15	10.0	0.26	14.0	0.085

Observation of $t\bar{t}$ in p+Pb @ 8.16 TeV

arXiv:2405.05078
Submitted to JHEP

- $t\bar{t}$ in *HI* **different** wrt *pp* due to:
  - **initial** state (nPDFs vs PDFs)
  - **final** state (QGP properties)
- *p+Pb* provides nPDF data in poorly constrained **high x** region
- MC/data overlay for better underlying event description



Source	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ unc. up [%]	unc. down [%]
Jet energy scale	+4.6	-4.1
$t\bar{t}$ generator	+4.5	-4.0
Fake-lepton background	+3.1	-2.8
Background	+3.1	-2.6
Luminosity	+2.8	-2.5
Muon uncertainties	+2.3	-2.0
W+jets	+2.2	-2.0
b-tagging	+2.1	-1.9
Electron uncertainties	+1.8	-1.5
MC statistical uncertainties	+1.1	-1.0
Jet energy resolution	+0.4	-0.4
$t\bar{t}$ PDF	+0.1	-0.1
Systematic uncertainty	+8.3	-7.6

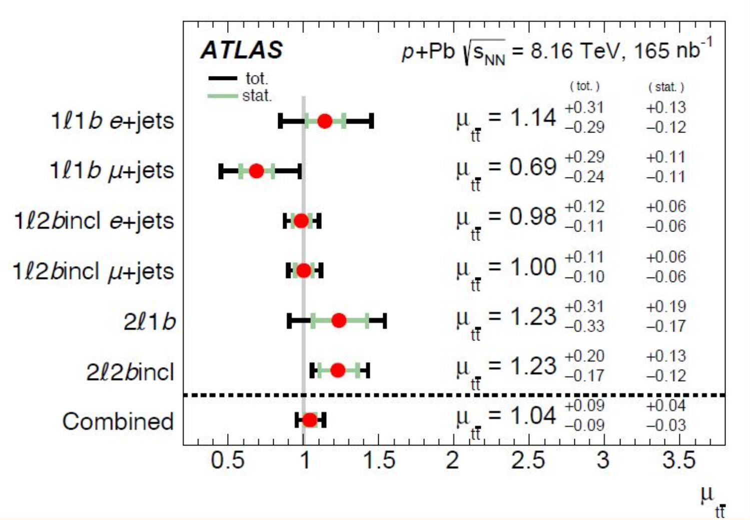
- *ℓ+jets* and *ℓℓ* channels
- **6 regions** depending on ℓ and b-jet multiplicity
- μ_{tt} from **binned likelihood fit** to $H_T^{\ell,j}$, i.e. scalar sum of lepton and jets p_T

Poster by Santu Mondal

Observation of $t\bar{t}$ in p+Pb @ 8.16 TeV

arXiv:2405.05078
Submitted to JHEP

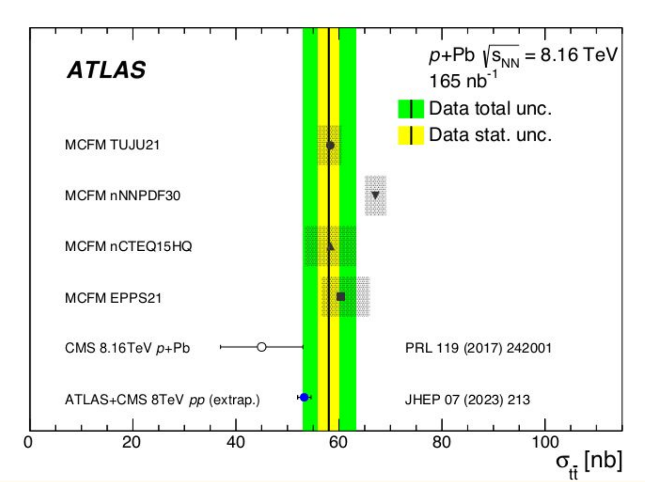
$$\sigma_{t\bar{t}} = \mu_{t\bar{t}} \cdot A_{\text{Pb}} \cdot \sigma^{\text{th}}_{t\bar{t}}$$

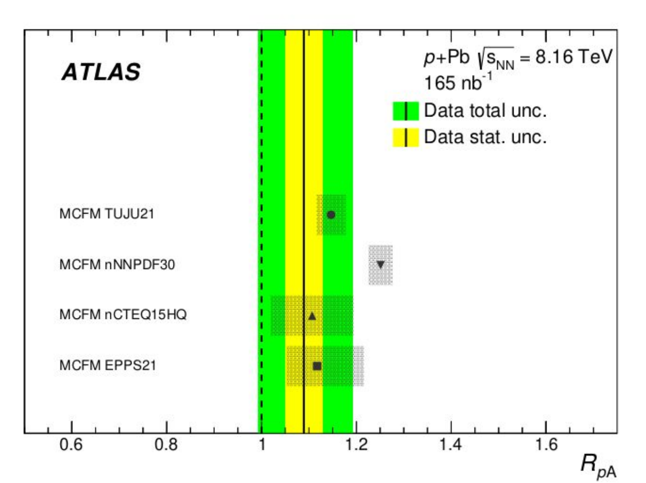


- Results in 6 regions and combined
- **>5σ significance**
- first observation in $\ell\ell$ channel

$$R_{pA} = \frac{\sigma^{p+\text{Pb}}_{t\bar{t}}}{A_{\text{Pb}} \cdot \sigma^{pp}_{t\bar{t}}}$$

- comparisons with *NLO MCFM* scaled to NNLO QCD σ for different **nPDF sets**
- σ measured with 9% uncertainty
- Compatible with CMS and with extrapolated *pp* σ

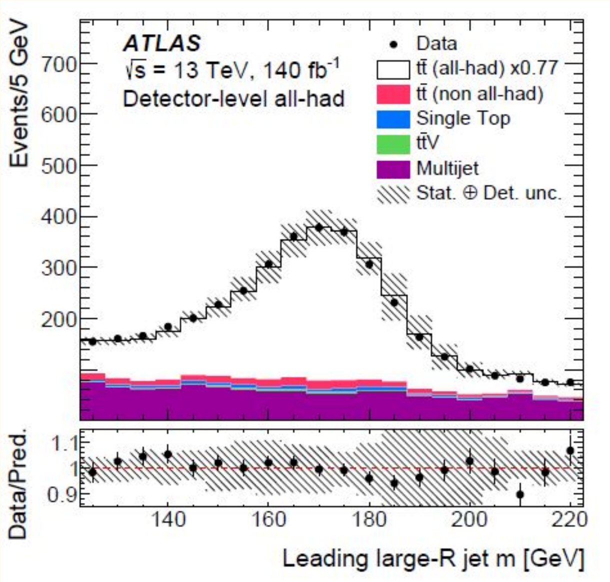


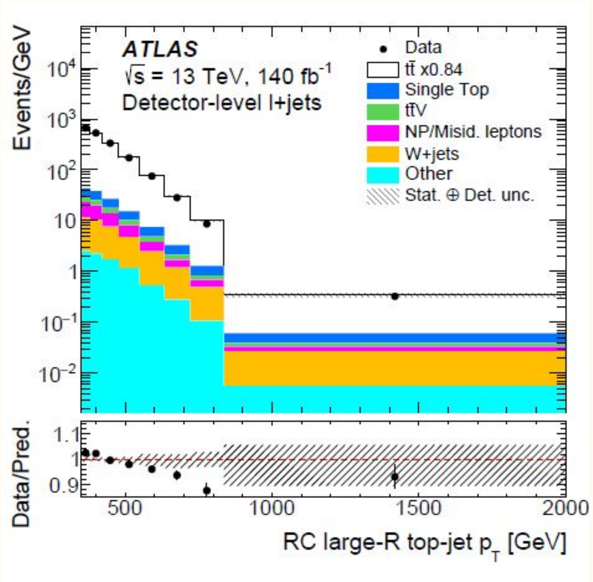


Jet substructure in $t\bar{t}$ @ 13 TeV, full run-2

PRD 109 (2024) 112016

- **Boosted** hadronic decays of tops → **large jets**
- **Substructure** of jets: sensitive to precision modelling of QCD effects, important for taggers
- Measurement performed in *ℓ+jets* and *all-had*





ℓ+jets:

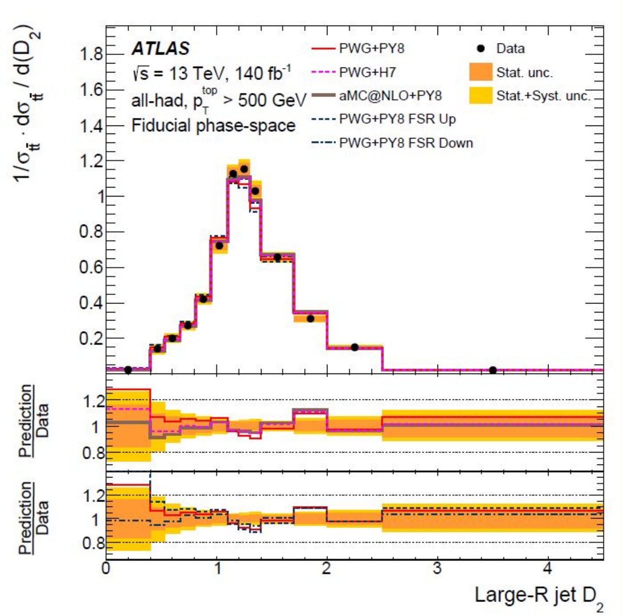
- use small-R jets + large **reclustered** (RC) jets
- top-jet p_T>350 GeV
- Bkg from MC (except fake leptons)

all-had:

- large-R **trimmed** jets + variable-R track jets for b-tagging
- top jets p_T>500, 350 GeV
- **top tagging applied**: tag& probe approach to avoid bias
- 16 regions depending on *b*- and top-tagging multipl.

Jet substructure in $t\bar{t}$ @ 13 TeV, full run-2

PRD 109 (2024) 112016

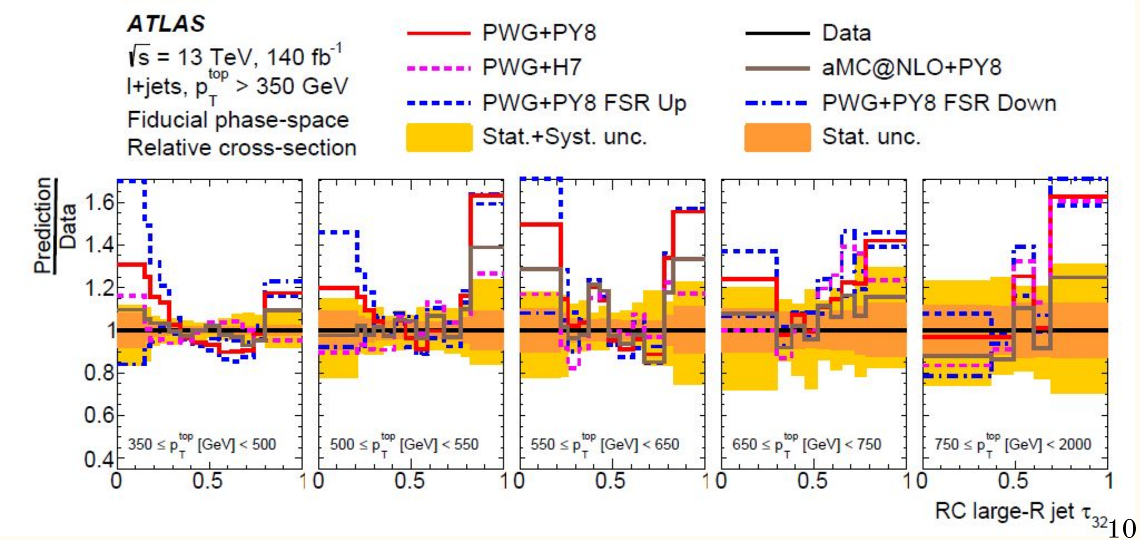


Measurements **unfolded** (IBU) to **particle level** for:

- N-subjettines variables τ_3, τ_{32}, τ_{21}
- Energy-correlation variables ECF, D_2 and C_3
- Generalised angularities LHA and $p_T^{d,*}$

Dominant uncertainties: FSR, parton sh., jet energy meas.

Sets of *1D* and *2D* **differential** measurements compared with NLO ME+PS simulations



Jet substructure in $t\bar{t}$ @ 13 TeV, full run-2

PRD 109 (2024) 112016

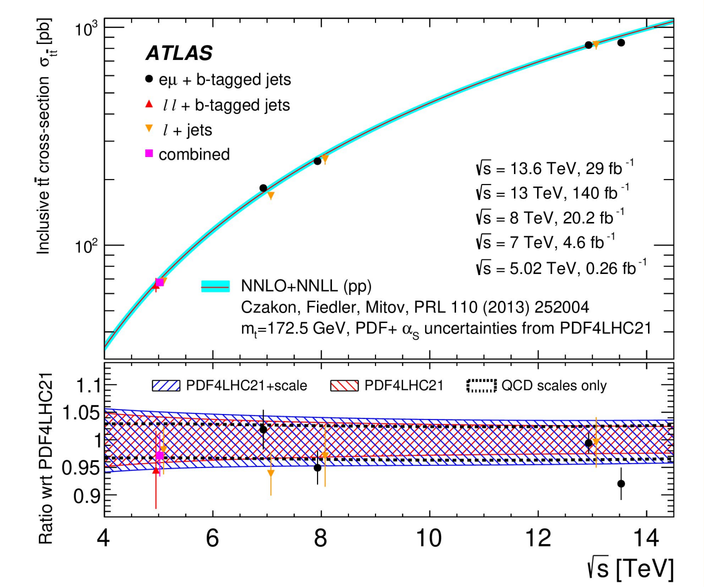
Observable	PWG+PY8		PWG+H7		aMC@NLO+PY8		PWG+PY8(FSR Up)		PWG+PY8(FSR Down)	
	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value
τ_{32}	54/12	<0.01	19/12	0.09	15/12	0.24	165/12	<0.01	40/12	<0.01
τ_{21}	14/14	0.41	7/14	0.92	16/14	0.32	42/14	<0.01	8/14	0.91
τ_3	36/11	<0.01	42/11	<0.01	14/11	0.23	130/11	<0.01	23/11	0.02
$ECF2$	25/18	0.13	13/18	0.78	15/18	0.69	31/18	0.03	24/18	0.14
D_2	20/16	0.20	17/16	0.39	20/16	0.20	37/16	<0.01	15/16	0.49
C_3	11/14	0.65	6/14	0.97	3/14	1.00	35/14	<0.01	3/14	1.00
$p_{\mathrm{T}}^{\mathrm{d},*}$	27/12	<0.01	10/12	0.58	11/12	0.53	56/12	<0.01	24/12	0.02
LHA	14/17	0.65	9/17	0.92	20/17	0.29	14/17	0.69	19/17	0.32
D_2 vs. m^{top}	61/42	0.03	62/42	0.02	59/42	0.05	118/42	<0.01	44/42	0.37
D_2 vs. $p_{\mathrm{T}}^{\mathrm{top}}$	71/56	0.08	68/56	0.13	70/56	0.11	107/56	<0.01	93/56	<0.01
τ_{32} vs. m^{top}	153/42	<0.01	72/42	<0.01	56/42	0.07	413/42	<0.01	77/42	<0.01
τ_{32} vs. $p_{\mathrm{T}}^{\mathrm{top}}$	153/50	<0.01	103/50	<0.01	57/50	0.23	360/50	<0.01	114/50	<0.01

ℓ+jets channel
(*all-had* in backup)

- *ℓ+jets* and *all-had* use different jets but results >90% correlated
- FSR Up PWG+Py8 in poor agreement with data, data favors lower FSR scale (higher $\boldsymbol{\alpha}_s^{\mathrm{FSR}}$)
- τ_{32} often poorly modelled by NLOME+PS
- aMC@NLO+Py8 compatible with data for all variables
- Results complement previous studies:
  - Focus on **boosted top**, with all-had channels giving access to **very high $\mathbf{p_T}$**
  - **Track-based substructure** improves resolution and reduces uncertainties

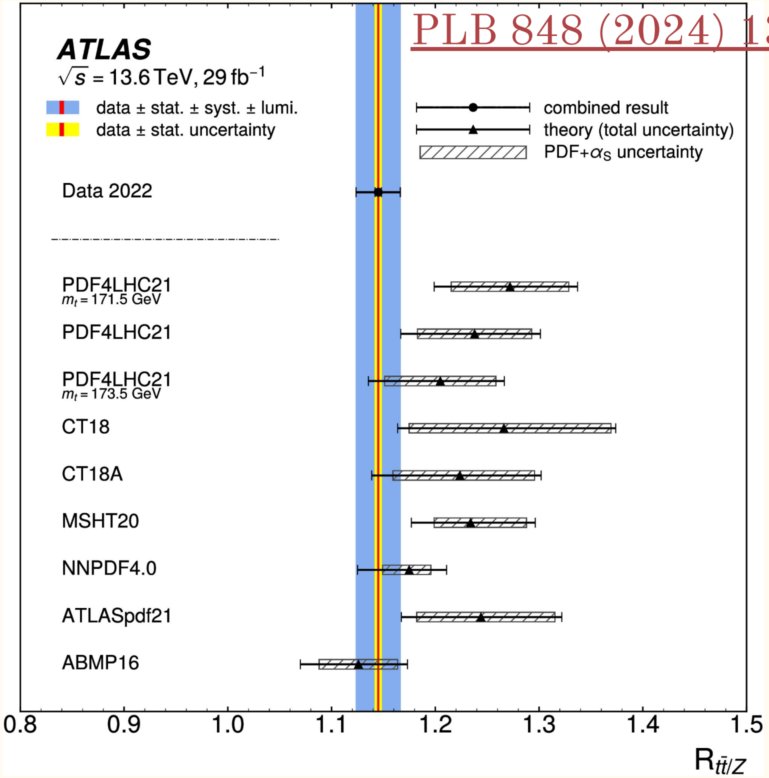
$t\bar{t}$ /Z @ 13.6 TeV, run-3

- **First measurement @ 13.6 TeV**
- Sensitive to PDFs, test of pQCD
- $ee/\mu\mu$ for Z; $e\mu$ with 1 and 2 b-jets for $t\bar{t}$
  - In-situ b-tagging calibration
- Profiled likelihood fit in the 4 SRs



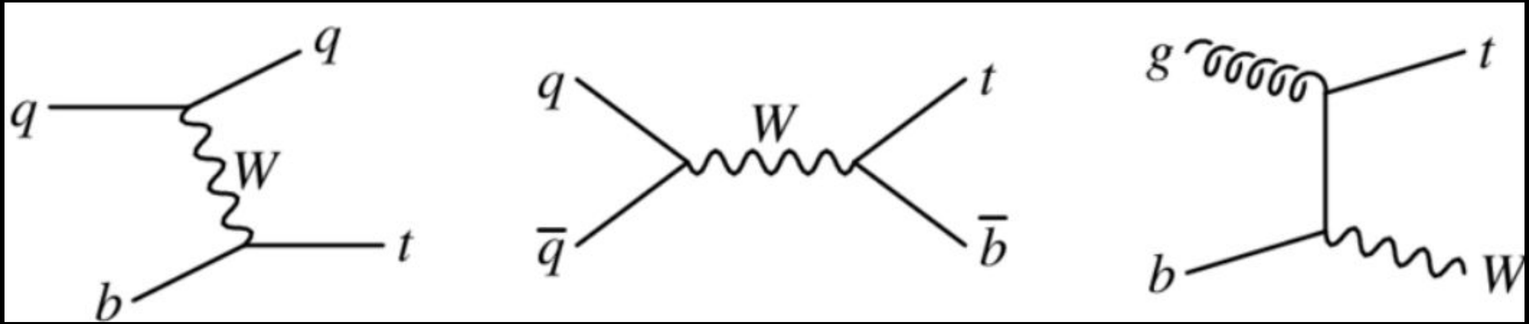
$$R_{t\bar{t}/Z} = 1.145 \pm 0.003(\text{stat.}) \pm 0.021(\text{syst.}) \pm 0.002(\text{lumi.})$$

PLB 848 (2024) 138376



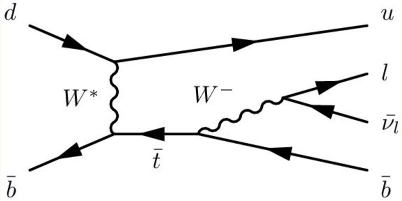
- 3% precision on $t\bar{t}$ and (fiducial) Z σ
  - dominated by **lumi uncertainty**
- 2% precision on ratio
  - Uncertainties cancel out, **modelling** and **bkg** dominant uncertainties

Single top σ measurements

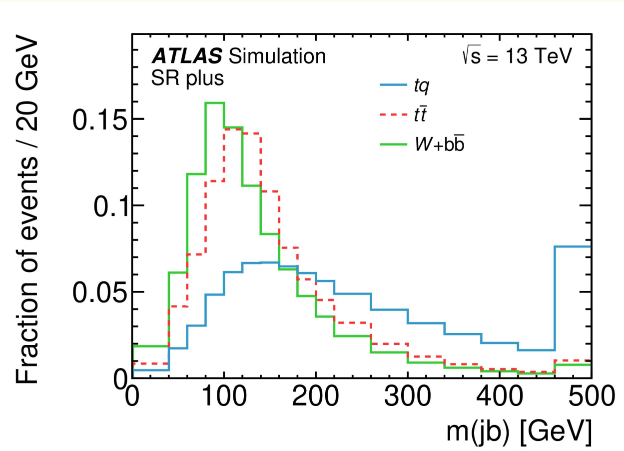


t-channel @ 13 TeV, full run-2

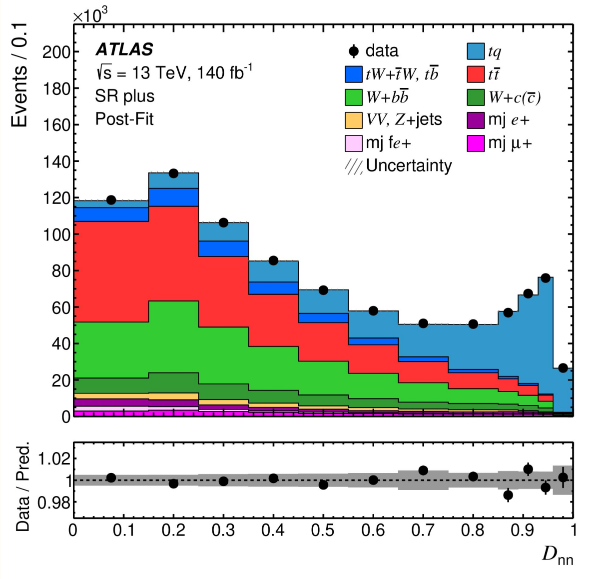
JHEP 05 (2024) 305



- PDF(u)≠PDF(d) → σ(tq)≠σ($\bar{\text{t}}q$)
- Measurement of the two **σ**, **sum** and **ratio**
- Events with exactly 1 e/μ, 1 ***b*-jet** with |η|<2.5, 1 **non-*b*-jet** |η|<4.5 +other kinematic cuts



$$p_T(\ell) > 40\,\text{GeV} \cdot \frac{|\Delta\phi(j_1, \ell)|}{\pi}$$



- **Neural Network (NN)** to select signal
  - Uses also a top reconstruction algorithm output
  - 17 variables (see backup)
  - most powerful: m_{jb}
- σ measured with **binned likelihood fit** to:
  - D_{NN} in SR (i.e. NN score)
  - $\Delta\varphi(E_T^{miss},\ell)$ in low p_T muon CRs
  - *Yields* in low E_T^{miss} electron CRs

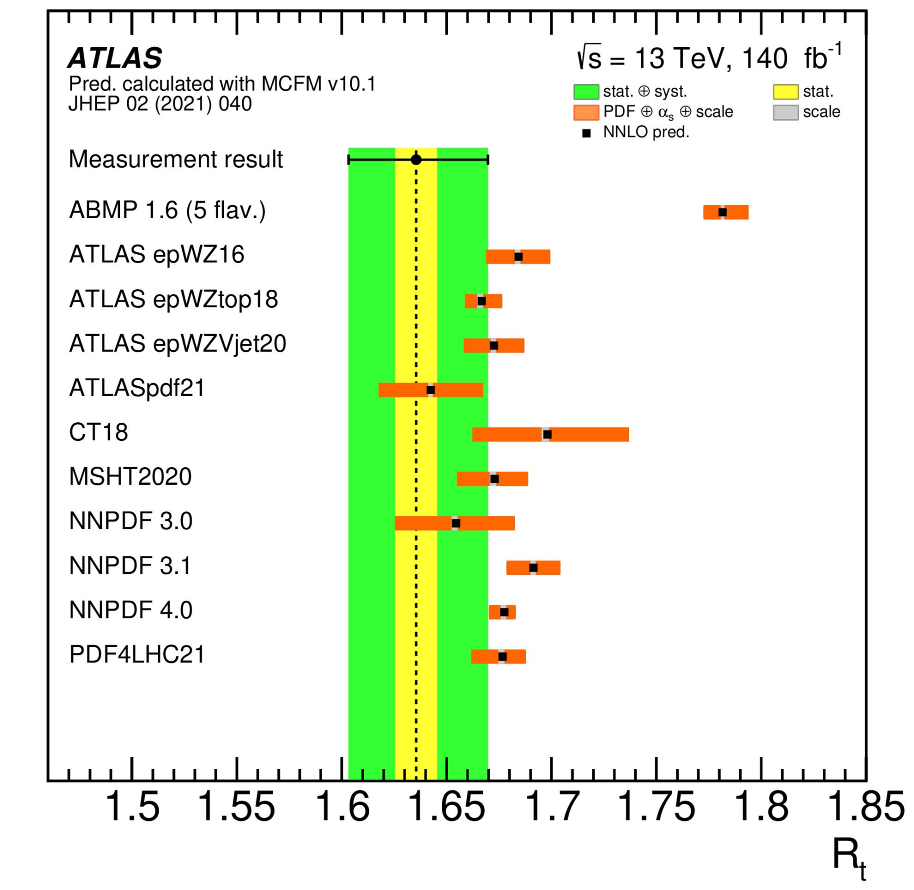
t-channel @ 13 TeV, full run-2

JHEP 05 (2024) 305

- Uncertainties for absolute σ dominated by **modelling uncertainties**: matching scale, parton shower, FSR
- Ratio dominated by uncertainties on ***W+c* modelling** and **parton shower**

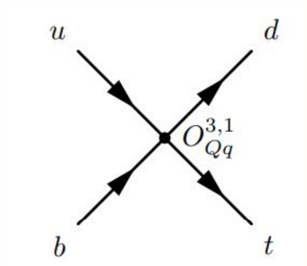
$$\sigma(tq) = 137^{+8}_{-8}\,\text{pb} \quad \text{and} \quad \sigma(\bar{t}q) = 84^{+6}_{-5}\,\text{pb}$$

$$\sigma(tq+\bar{t}q) = 221^{+13}_{-13}\,\text{pb} \quad \text{and} \quad R_t = 1.636^{+0.036}_{-0.034}$$



t-channel @ 13 TeV, full run-2: interpretations

[JHEP 05 (2024) 305](#)



EFT interpretation:

- **4-quark operator** changes kinematics of events
- Operator coupling with **Higgs** changes yields

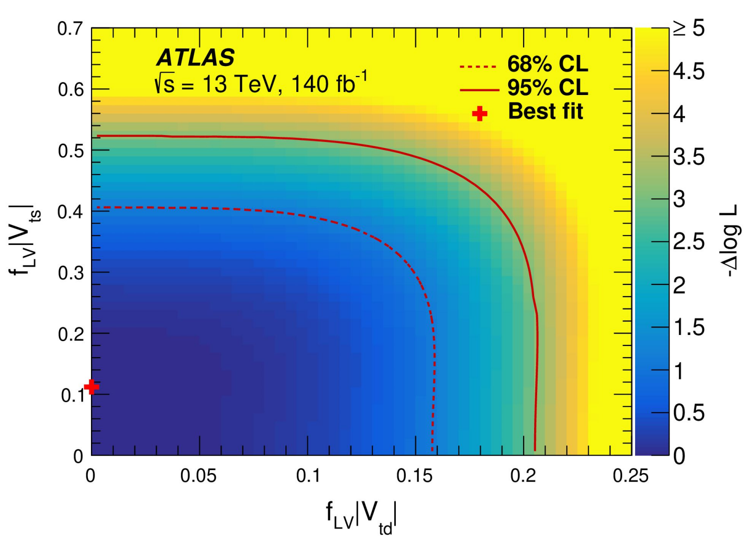
$$-0.37 < C_{Qq}^{3,1}/\Lambda^2 < 0.06$$

$$-0.87 < C_{\phi Q}^{3}/\Lambda^2 < 1.42$$

Assuming CKM unitarity, from total σ measurements it is found:

$$f_{\mathrm{LV}} \cdot |V_{tb}| = 1.015 \pm 0.031$$

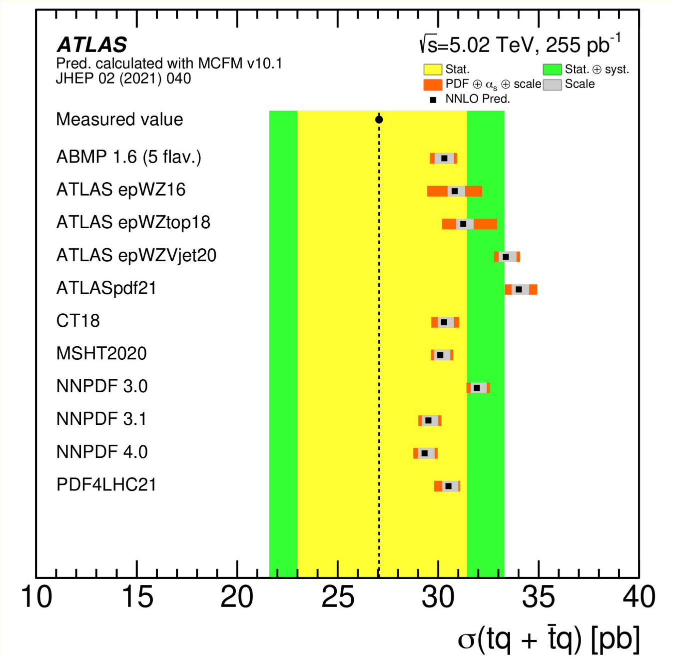
Limits are presented also for scenarios where $|V_{ts}|$ and/or $|V_{td}|$ are not neglected

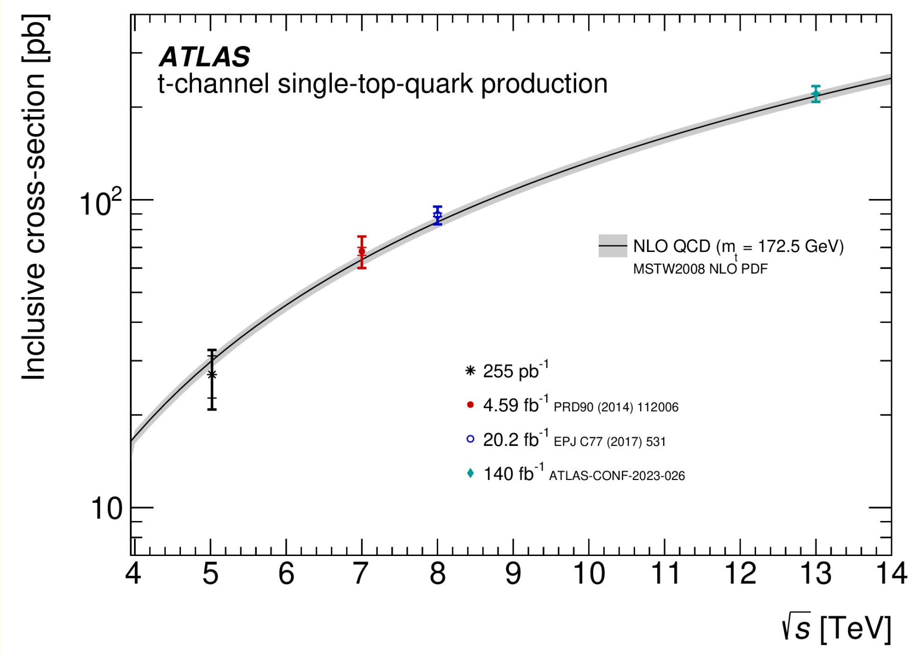


t-channel observation @ 5.02 TeV

PLB 854 (2024) 138726

- Independent measurement at **different energy**
- Analysis similar to previous slides, with BDT with 9 variables

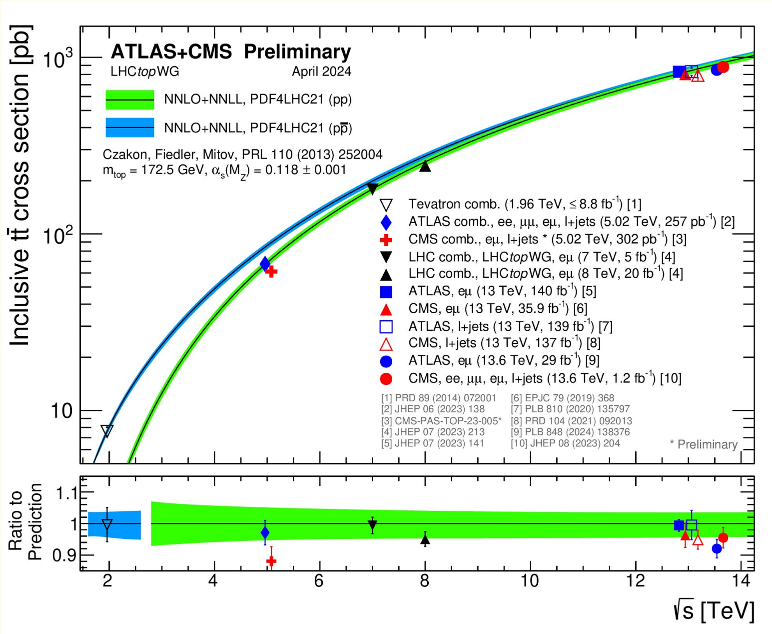




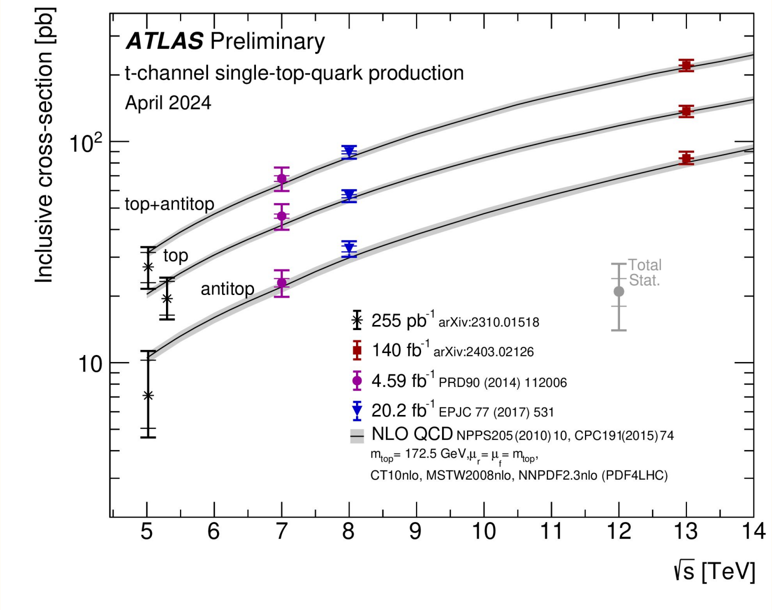
- σ have stat~syst unc.
- Ratio is stat limited
- Comparison with different PDFs
- $f_{\mathrm{LV}} \cdot |V_{tb}| = 0.94^{+0.11}_{-0.10}$

Conclusion

ATL-PHYS-PUB-2024-006



- Presented recent $\mathbf{t\bar{t}}$ and **single-top** cross section measurement from ATLAS
- Results in *p+Pb* or 5/13.6 TeV *pp* provide info in **different regimes**



- **High precision** and thorough **differential studies** show strengths and limitations of current predictions
- **BSM interpretations** e.g. with EFT operators
- **Run-3** in progress, more stat being collected
  - Most measurements syst-limited, must use data to improve syst