

ATLAS & CMS measurements
of the $t\bar{t}$ cross section,
including off-shell and near threshold

60th Rencontres de Moriond EW, 21/03/2026
Baptiste Ravina (CERN)



LHC is a top quark factory → Run 2 gives us access to O(100M) $t\bar{t}$ events

Precision measurements of the $t\bar{t}$ cross section...

- using a low-pileup environment [JHEP 04 \(2025\) 099](#) 
- or a very clean dilepton channel, with in-situ lepton and b-jet efficiencies [TOPQ-2024-12](#) 

... allow us to test off-shell effects...

- targeting single/double resonant interference [TOPQ-2023-31](#) 
- and focusing on the visible final state [TOPQ-2024-12](#) 

... for which we need dedicated modelling...

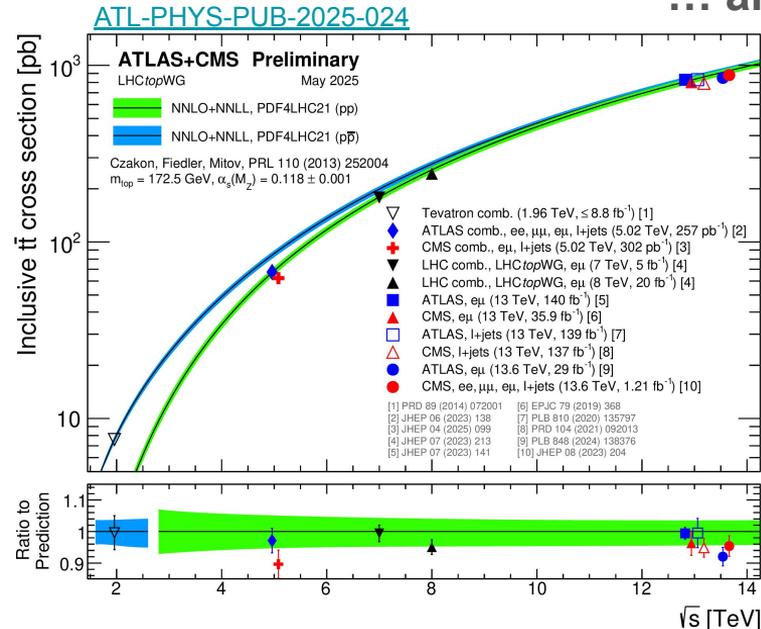
- with coherent uncertainties [ATL-PHYS-PUB-2025-036](#) 

... and which come with reconstruction challenges...

- how to deal with neutrinos? [see backup] [TOP-24-001](#) 

... but enable fundamental physics at the threshold!

- “toponium” [Rep. Prog. Phys. 88 \(2025\) 087801](#) & [TOPQ-2025-11](#) 
- top Yukawa [JHEP 01 \(2026\) 117](#) 

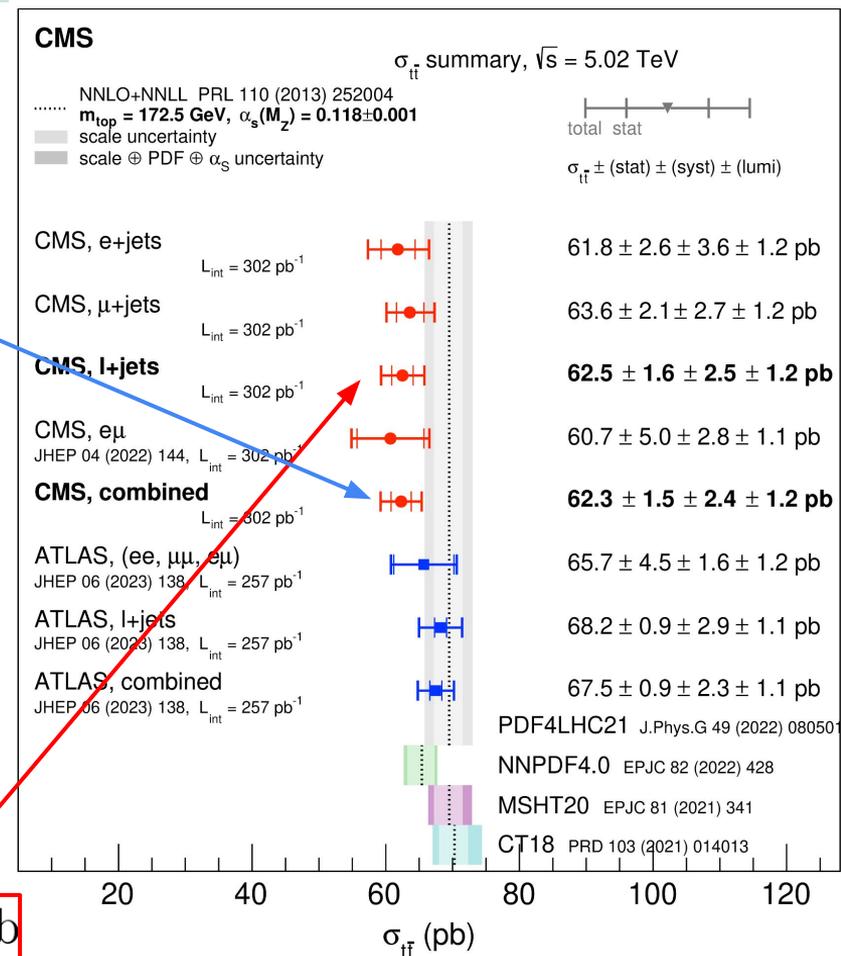


Measuring the $t\bar{t}$ cross section precisely



Using a **small**, but **low-pileup dataset** of $t\bar{t}$ events

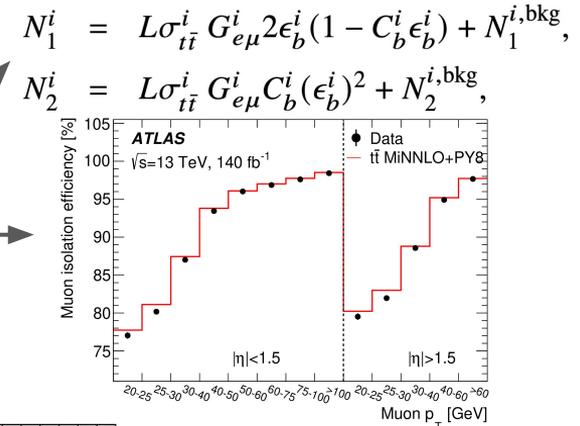
- pp collisions at $\sqrt{s}=5.02$ TeV, $L=302\text{pb}^{-1}$ in 2017, $\langle\mu\rangle=2$ [$\langle\mu\rangle=33$ in standard conditions!]
 \rightarrow **very clean!**
- Lepton+jets final state, and **combination** with previous result in dilepton $e\mu$
- MVA to separate $t\bar{t}$ from W +jets [other backgrounds: tW from simulation, minor QCD multijets data-driven]
- Maximum Likelihood fit in bins of b /jet multiplicities
- Main uncertainties** from **ME/PS matching**, **b -tagging** and **trigger efficiencies**
- NNLO+NNLL: $\sigma(t\bar{t}) = 69.5^{+3.5}_{-3.7}$ pb
- Leptons+jets result:



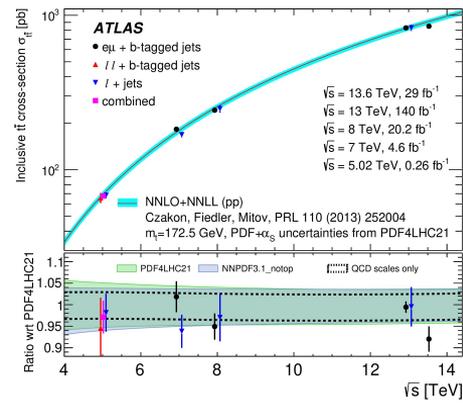
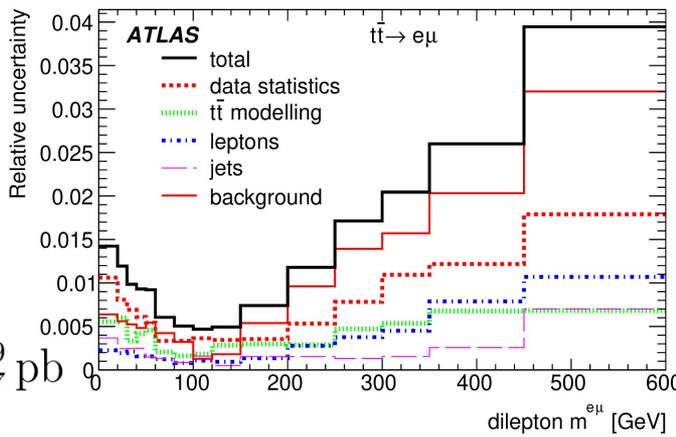
$$\sigma(t\bar{t}) = 62.5 \pm 1.6 (\text{stat.})^{+2.6}_{-2.5} (\text{syst.}) \pm 1.2 (\text{lumi.}) \text{ pb}$$

Using the cleanest channel (full Run 2)

- Final state with $e\mu+b$ -jets is **extremely clean**, low BR but still **$\sim 1\text{M}$ events**
- Build on previous measurements: **b-jet counting** and **in-situ lepton isolation efficiencies** + **new MiNNLOps** \rightarrow extract $t\bar{t}$ cross section **inclusively** [1.3% unc.], **fiducially**, and **differentially** in leptonic observables



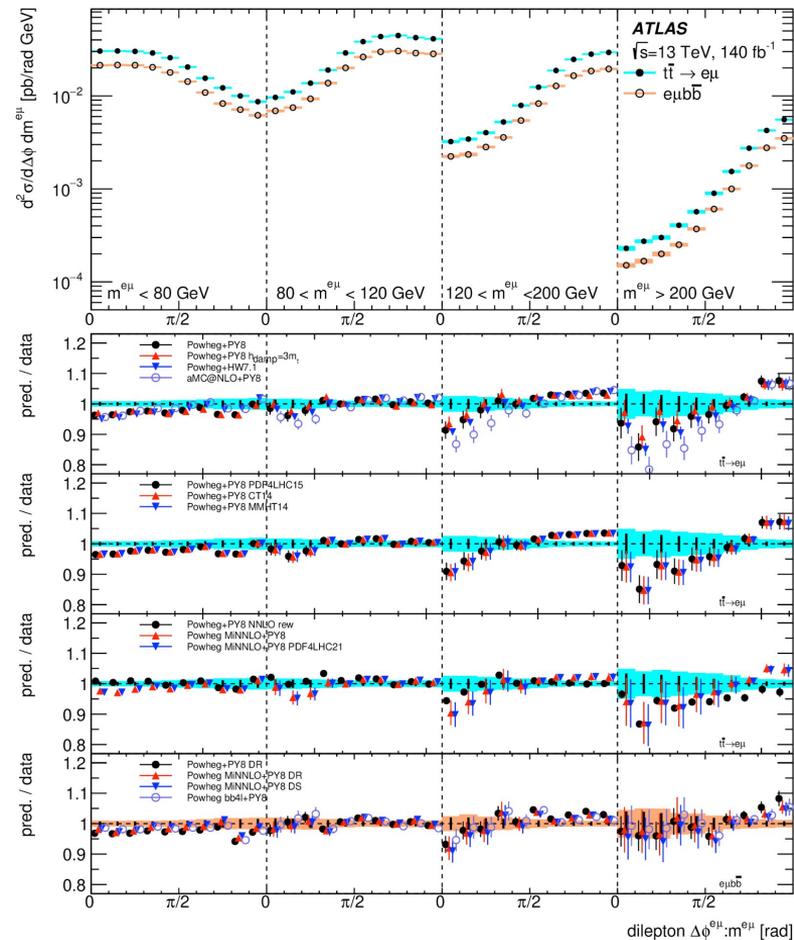
- Differential measurements limited by stat uncertainty, also **$tW/t\bar{t}$ interference** at high- p_T and **$t\bar{t}$ modelling** at low- p_T



• NNLO+NNLL: $\sigma(tt) = 834_{-37}^{+29}$ pb

$\sigma(tt) = 829.3 \pm 1.3$ (stat.) ± 8.0 (syst.) ± 7.3 (lumi.) ± 1.9 (beam) pb

Using the cleanest channel (full Run 2)



Generator	p_T^{ℓ}	$ \eta^{\ell} $	$p_T^{e\mu}$	$m^{e\mu}$	$ y^{e\mu} $	$\Delta\phi^{e\mu}$	$p_T^e + p_T^\mu$	$E^e + E^\mu$	$p_T^{\ell,max}$	$p_T^{\ell,min}$
N_{dof}	12	8	10	14	8	19	9	11	11	10
χ^2 values										
POWHEG + PY8	35.2	19.7	12.5	49.8	11.6	22.7	34.9	14.7	32.0	27.4
POWHEG + PY8 $h_{damp} = 3m_t$	38.9	20.1	20.2	50.1	11.0	24.0	41.0	15.3	36.3	30.6
POWHEG + HW7.1	32.5	15.9	20.4	92.9	10.2	71.3	27.6	12.2	26.6	20.9
aMC@NLO + PY8	16.2	16.7	15.4	35.2	12.0	30.5	27.5	13.5	12.5	17.4
POWHEG + PY8 PDF4LHC15	33.7	15.2	12.0	47.3	8.7	22.3	33.8	13.3	30.3	26.0
POWHEG + PY8 CT14	32.8	12.6	11.8	44.6	8.0	22.4	33.0	12.7	29.4	25.3
POWHEG + PY8 MMHT14	33.0	19.0	11.5	48.2	9.5	22.0	33.1	13.5	29.6	25.5
POWHEG + PY8 NNLO rew	16.4	14.9	11.7	33.6	12.8	16.5	24.6	11.3	14.3	14.6
POWHEG MiNNLO + PY8	15.4	12.3	7.2	25.9	11.7	23.6	20.9	7.5	12.1	12.5
POWHEG MiNNLO + PY8 PDF4LHC21	15.6	12.8	7.5	25.6	12.6	25.2	21.3	10.2	11.8	13.1

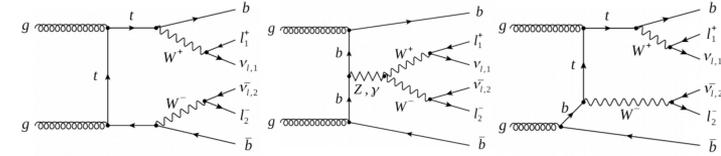
Generator	$ \eta^{\ell} \times m^{e\mu}$	$ y^{e\mu} \times m^{e\mu}$	$ \Delta\phi^{\ell} \times m^{e\mu}$
N_{dof}	35	19	39
χ^2 values			
POWHEG + PY8	72.7	46.0	79.9
POWHEG + PY8 $h_{damp} = 3m_t$	74.2	44.9	78.3
POWHEG + HW7.1	122.2	67.4	150.8
aMC@NLO + PY8	63.0	34.2	63.2
POWHEG + PY8 PDF4LHC15	69.9	43.7	77.2
POWHEG + PY8 CT14	68.8	42.2	74.9
POWHEG + PY8 MMHT14	71.6	47.3	78.5
POWHEG + PY8 NNLO rew	71.0	33.8	71.0
POWHEG MiNNLO + PY8	44.8	26.7	50.2
POWHEG MiNNLO + PY8 PDF4LHC21	44.3	27.0	49.7

- **Powheg hvq +PY8/HW7:** poor modelling when sensitive to top p_T .
- **Rewighting to NNLO helps.**
- **aMC@NLO+P8 is better out of the box.**
- **MiNNLO+P8 is best**, but $p_T(l)$ still slightly harder than data, and trouble modelling $\Delta\phi^{e\mu}:m^{e\mu}$.
- **Clear excess at low $m^{e\mu}$** [which is the threshold region...]

Challenges in off-shell modelling

Echoes from the top: non/resonant production

- **Previously:** interference of $t\bar{t}$ and tW at NLO QCD
 → model using separate MCs + DR/DS schemes
 → **not gauge-invariant, leads to large uncertainties.**

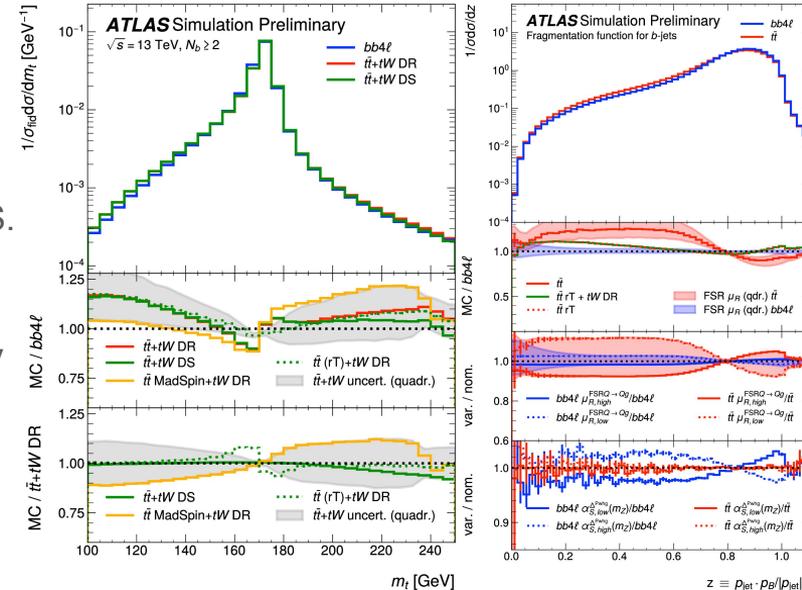


Doubly-, singly-, and non-resonant $bbl\nu$ final states

- Also assume **NWA** in the decays, with **“lineshape” uncertainty** comparing **Powheg vs MadSpin**.
- **With $bb4l$:** $2 \rightarrow 6$ process at NLO QCD.
 - No more **NWA**, **full interference** of $t\bar{t}/tW$ and **off-shell effects**, NLO-accurate **spin correlations**.
 - Drop the MadSpin “lineshape” uncertainty, drop DR/DS.

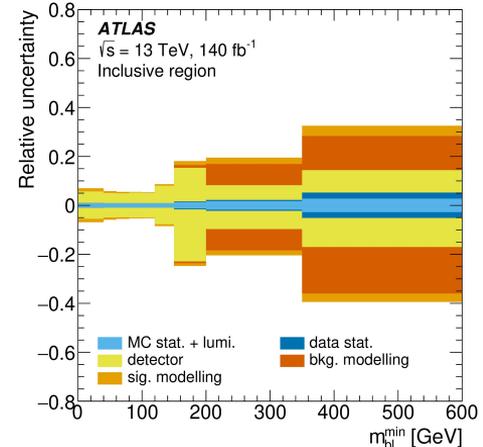
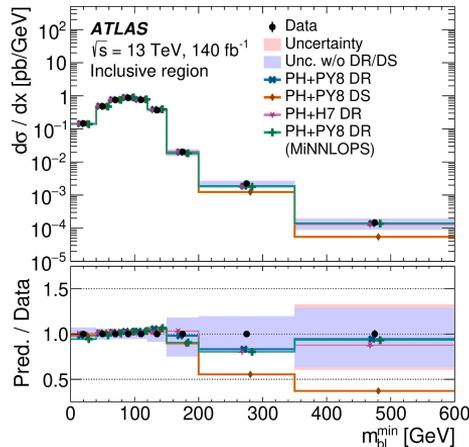
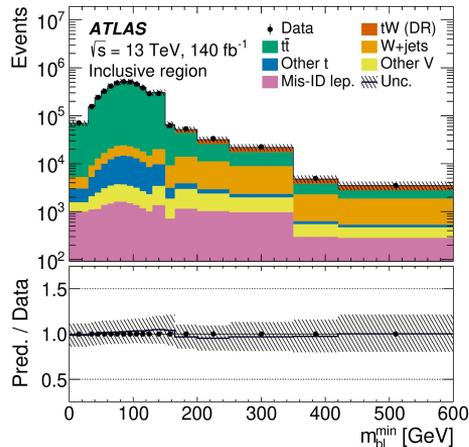
- First gluon emission from the top quark decay can already appear in Powheg $bb4l$ → less affected by Pythia splitting kernel variations, but gains sensitivity to $\alpha_s(m_Z)$ in the Powheg Sudakov

- Currently **lacking NNLO prediction for $bb4l$** , but progress being made [\[JHEP 10 \(2025\) 195\]](#)



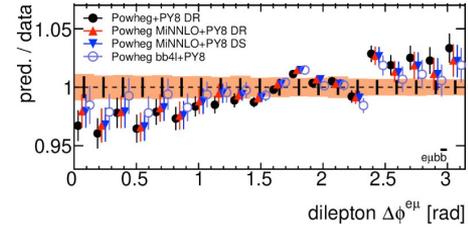
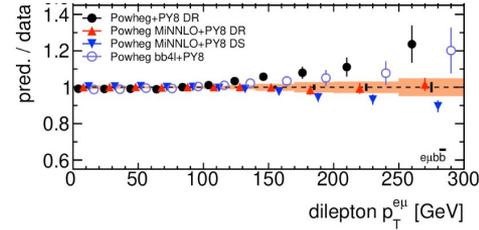
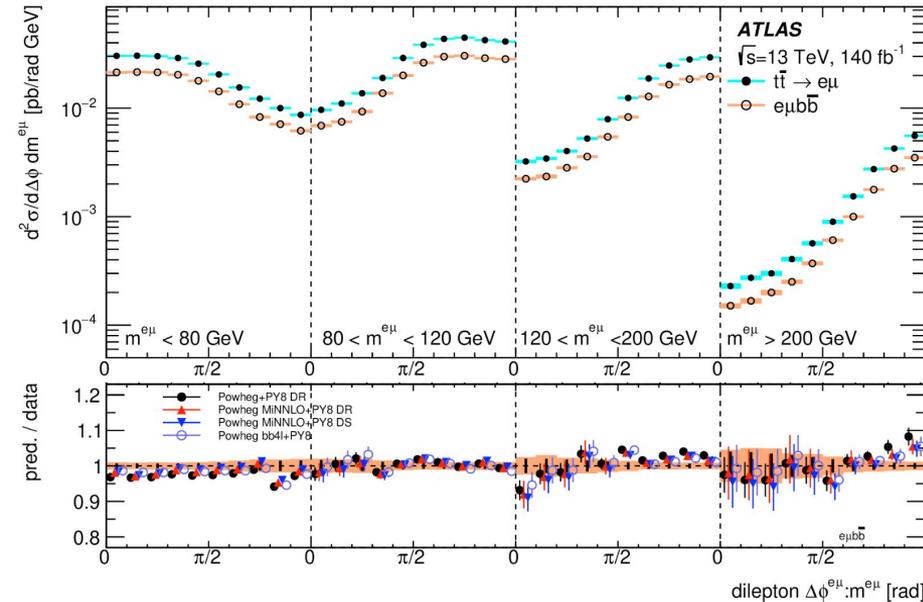
See also [ATL-PHYS-PUB-2021-042](#)

- Measured in the dileptonic [JHEP 02 (2026) 153] and semi-leptonic final states [this talk]
- **3 measurements in one**, all unfolded to particle-level [with TUnfold]:
 - “**inclusive**”: largest cross section, use m_{bl}^{\min} as proxy to the interference effects
 - “**search-like**”: high- p_T , high-MET, high- m_{bl}
 - “**hadronic W**”: tighten the W selection to remove backgrounds
- **Inclusive region: discrepancies** between predictions in **tails of m_{bl}^{\min}** , with large modelling uncertainties (DR/DS, W+jets)



Fully off-shell: $e\mu+bb$ cross section

- Avoid the complexities of modelling $t\bar{t}$ vs tW and their interference, and instead look at $e\mu+bb \rightarrow$ **direct test of the Powheg bb4l generator:** performs very well, so does **MINNLO $t\bar{t}+tW$ DS**

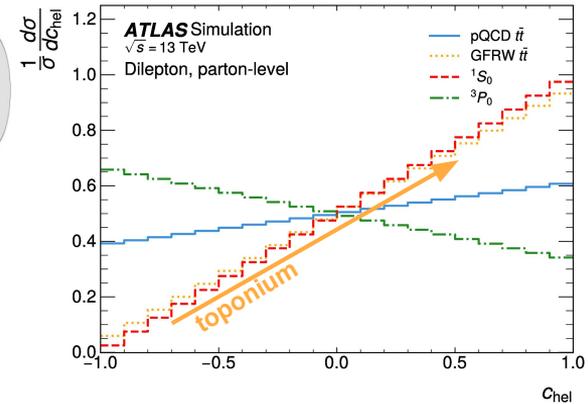
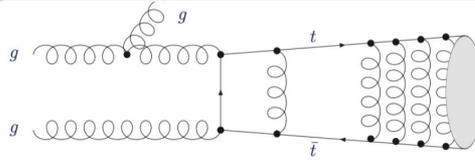


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N_{dof}	12	8	10	14	8	19	9	11	11	10
χ^2 values										
PowHEG + PY8 DR	26.9	12.0	10.1	48.6	14.7	23.8	34.5	28.0	32.5	35.3
PowHEG MINNLO + PY8 DR	12.4	6.4	1.4	31.4	14.4	26.7	15.3	17.9	16.4	14.9
PowHEG MINNLO + PY8 DS	10.8	6.6	6.0	25.8	14.4	26.1	14.0	17.1	14.3	13.1
PowHEG bb4l + PY8	15.5	11.2	3.1	20.5	14.7	21.4	20.5	18.6	19.2	21.8
χ^2 values										
Generator	$ \eta^\ell \times m^{e\mu}$	$ y^{e\mu} \times m^{e\mu}$	$ \Delta\phi^\ell \times m^{e\mu}$							
N_{dof}	35	19	39							
PowHEG + PY8 DR	63.7	37.0	75.3							
PowHEG MINNLO + PY8 DR	49.1	29.3	60.9							
PowHEG MINNLO + PY8 DS	41.9	24.5	54.5							
PowHEG bb4l + PY8	47.8	23.7	66.0							

Focusing on the threshold

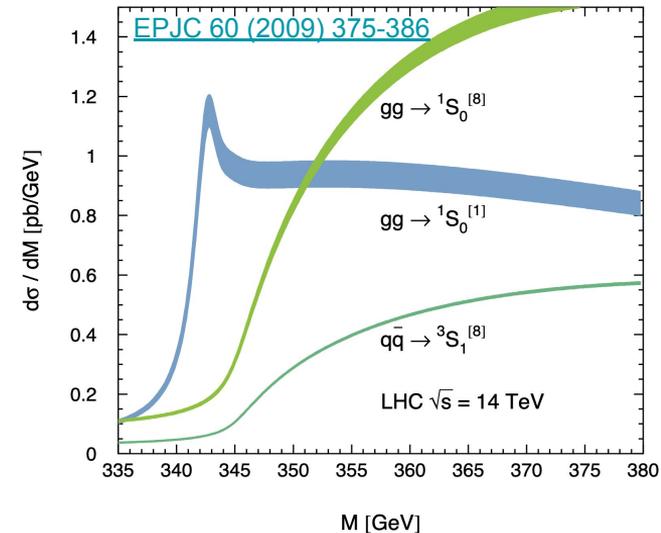
Excess at the threshold: quasi-bound state ?

- **Quasi-bound states** [“toponium”] expected to manifest near the top pair production threshold as a spin-singlet → use spin-sensitive observables + $m_{t\bar{t}}$

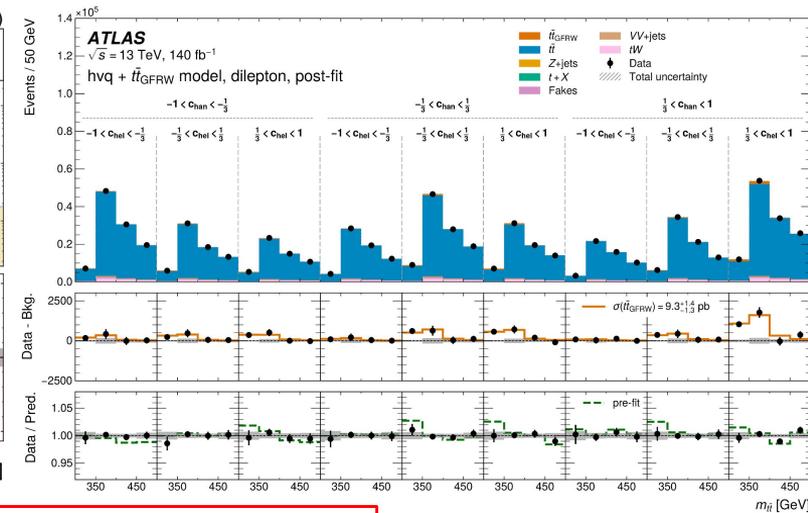
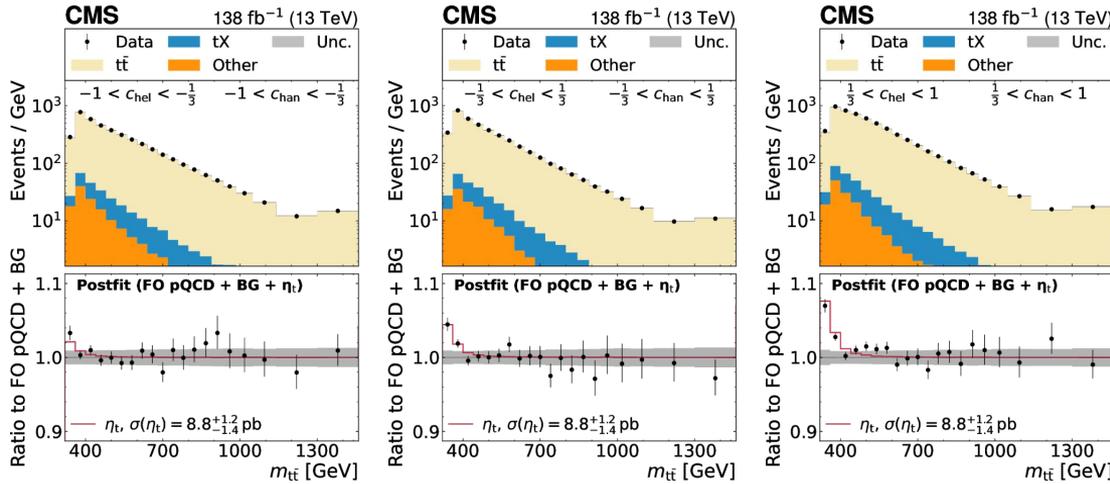


- **Model the signal** [not present in pQCD MC!] either
 - as a **pseudo-scalar resonance** with couplings tuned to reproduce NRQCD predictions (**CMS**),
 - or project $t\bar{t}$ LO QCD ME onto a spin-singlet and reweight using **NRQCD Green's functions (ATLAS)**;➤ add on top of Powheg+Pythia 8 hvq or bb4l.
- Perform a detector-level fit in the dilepton channel [leptons as top quark spin analysers].

- ATLAS: specifically focus on the threshold, $m_{t\bar{t}} < 500$ GeV



Excess at the threshold: quasi-bound state !



$$\sigma(t\bar{t}_{GFRW}) = 9.3^{+1.1}_{-1.0} \text{ (stat.)} \pm 0.8 \text{ (syst.) pb}$$

$$\sigma(\eta_t) = 8.8 \pm 0.5 \text{ (stat.)}^{+1.1}_{-1.3} \text{ (syst.) pb}$$

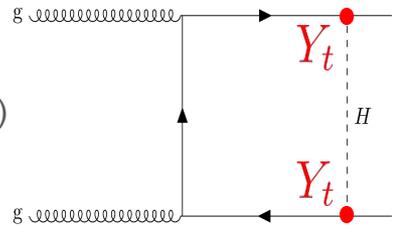
- Both ATLAS & CMS report a **>5 σ excess**, near threshold and behaving like spin-singlet toponium
- Measured cross sections are **compatible with each other** but **~(40 \pm 20)% higher** than a NRQCD-inspired prediction of 6.43pb. [PRD 104, 034023 (2021)] [Fit with bb4l baseline yield slightly lower cross section.]
- Large impact of $t\bar{t}$ modelling systematics on both results!**

Check the backup for further evidence of the signal in $t\bar{t} \rightarrow e\mu + b\bar{b}$!

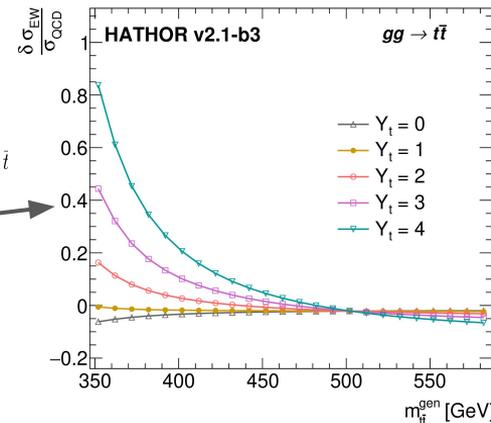
- Large top quark mass $\Leftrightarrow g_t \sim 1$
 - can be measured directly in $t\bar{t}H/tH$, from top loops in ggF and $H\gamma\gamma$, or from off-shell Higgs in $4t$ ops ($t\bar{t}H \rightarrow t\bar{t}H$)
 - here, use **semi-leptonic $t\bar{t}$ events near threshold**, allowing the **exchange of virtual Higgs** \rightarrow **sensitivity to Y_t^2** , but also to **BSM in the loop**

- Parameterisation of **EW loop effects** in $(m_{t\bar{t}}, \cos\theta^*, Y_t^2)$ obtained from HATHOR

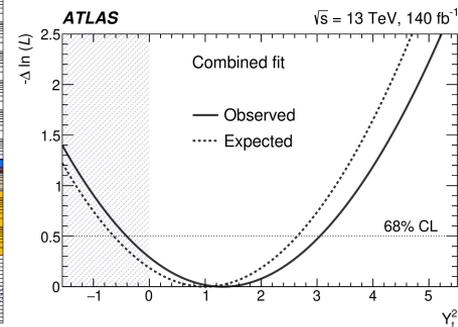
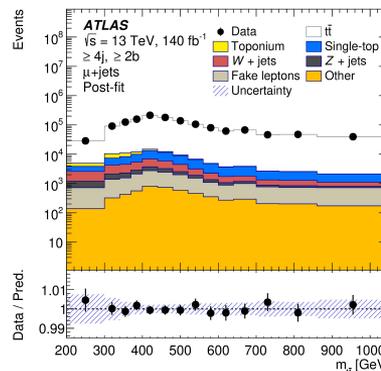
- fit $m_{t\bar{t}}$ at detector-level \rightarrow linear in Y_t^2
- include negative Y_t^2 samples to stabilise the fit
- toponium included according to prediction [+uncertainties]
- results dominated by **$t\bar{t}$ modelling** and **JES unc.**
- comparable upper limit as from indirect 4t**ops



$$Y_t = \frac{g_t}{g_t^{\text{SM}}}$$



Region	Expected Y_t^2	Observed Y_t^2	95% CL _s upper limit on Y_t	
			Expected	Observed
e +jets	$1.0_{-2.0}^{+2.1}$	$1.3_{-2.1}^{+2.2}$	< 2.3	< 2.4
μ +jets	$1.0_{-1.8}^{+1.8}$	$1.1_{-1.9}^{+1.9}$	< 2.1	< 2.2
Combined	$1.0_{-1.6}^{+1.6}$	$1.3_{-1.7}^{+1.7}$	< 2.1	< 2.1



- **Very precise measurements** of the $t\bar{t}$ cross sections obtained in Run 2
 - using dedicated low- μ runs, and at high- μ with pure and well understood dileptonic events
 - starting to look at off-shell topologies too: $t\bar{t} \rightarrow WbWb \rightarrow e\mu+bb$
- **Technical challenges** are being addressed
 - better understanding of the E_T^{miss} spectrum in dileptonic $t\bar{t}$ [see Backup]
 - state-of-the-art **bb4l** MC being deployed [NNLO corrections next?]
- Enabling **fundamental physics at the top threshold**
 - indirect measurement of the Top Yukawa
 - first observation of quasi-bound state (“toponium”) formation

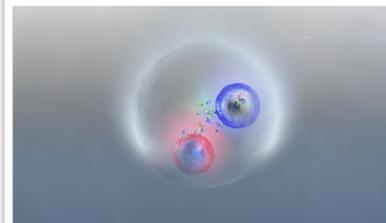
More top results from
ATLAS

More top results from
CMS

Elusive romance of top-quark pairs observed at the LHC

The CMS and ATLAS experiments at CERN's Large Hadron Collider have observed an unforeseen feature in the behaviour of top quarks that suggests that these heaviest of all elementary particles form a fleeting union

8 JULY 2025



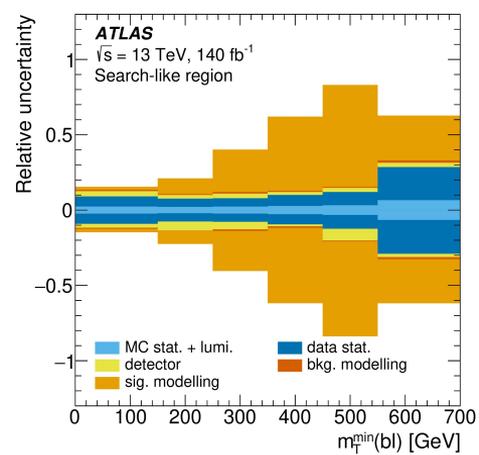
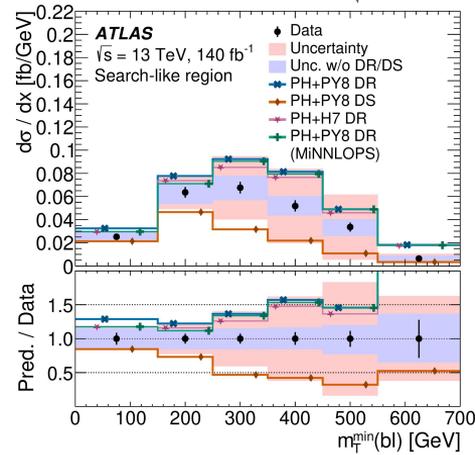
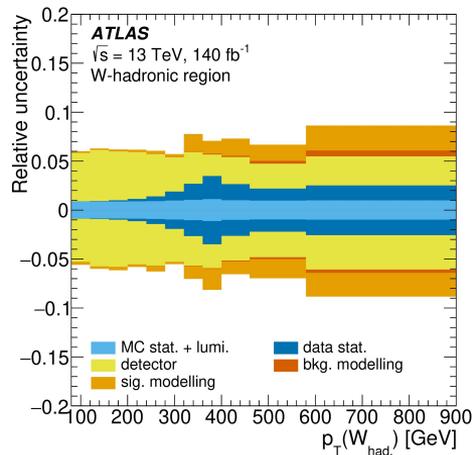
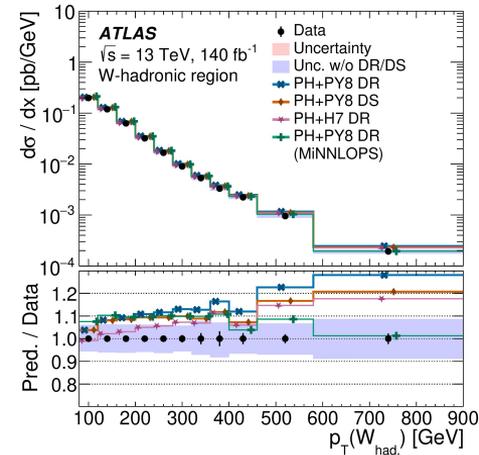
Artist's impression of the short-lived union of a top quark and a top antiquark formed by the exchange of gluons. (Image: G. Dominguez/CERN)

LHC as a *precision machine* → much more to be done with **Run 3!**

Backup

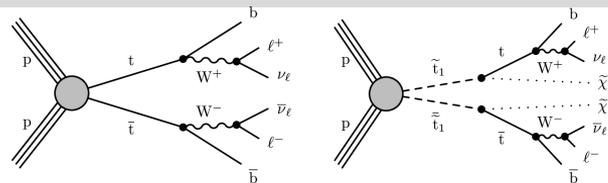
Measurement of the WbWb process

- **W-hadronic region:** similar to inclusive region, but **reduced background uncertainties**. **MINNLOps+P8 provides best description at high- $p_T(W_{had})$** , but still imperfect. Powheg hvq+H7 better at low- $p_T(W_{had})$.
- **Search-like region:** **very sensitive to DR/DS uncertainties**, other uncertainties much lower. **None of the models describe the data well**, but data enveloped by DR and DS predictions.



Missing energy spectrum \sim di-neutrino \pm corrections

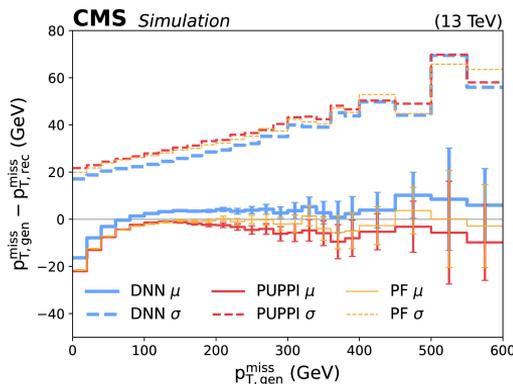
- **2 neutrinos** in dileptonic final state \rightarrow **major challenge** for top reconstruction, but could also be used to **uncover BSM!**



- $p_T^{\text{miss}} \sim p_T^{\nu\nu}$?

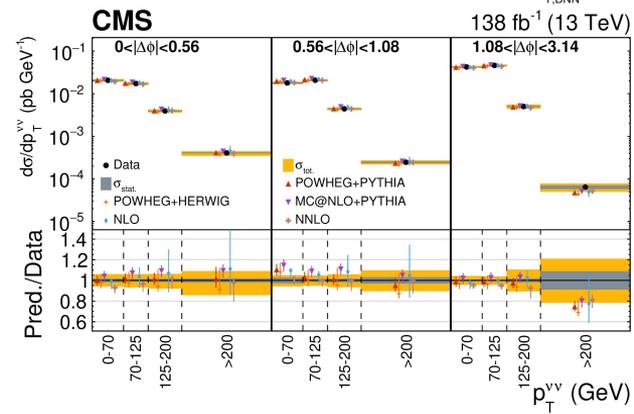
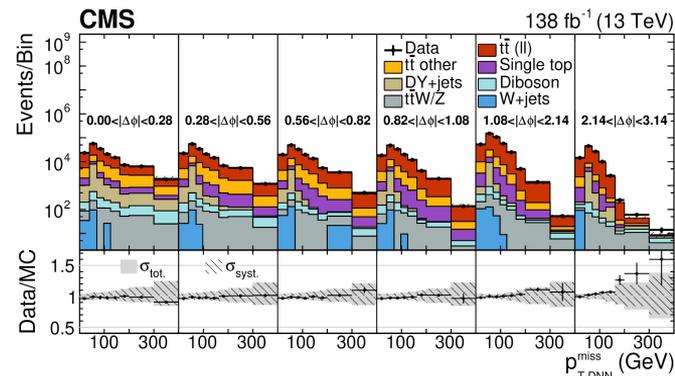
- additional ν 's from HF decay
- mis-measured jets & leptons
- train a DNN to correct p_T^{miss} !

- Consider $\min[\Delta\phi(p_T^{\text{miss}}, l)] \rightarrow$ *larger values for BSM*

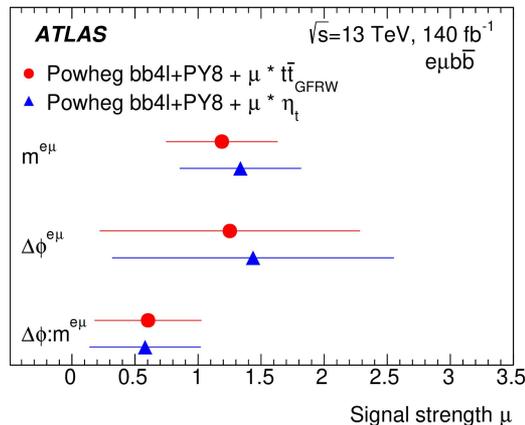
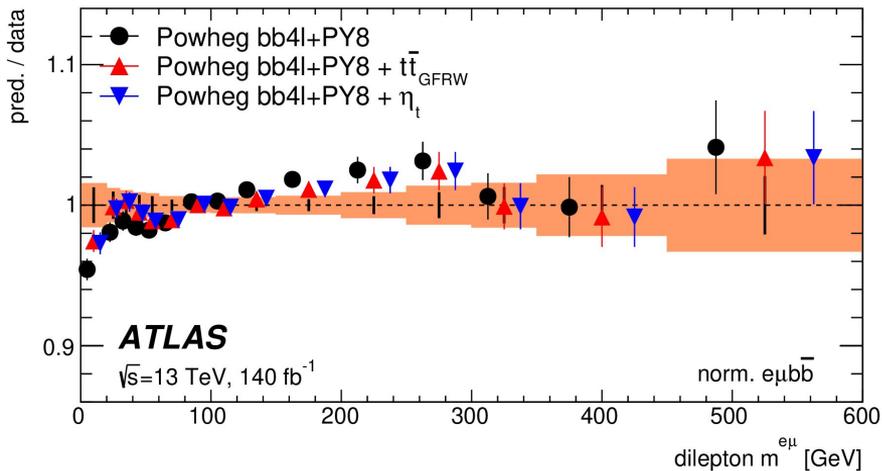


- **Good agreement with most MCs and with NNLO FO.**

- Leading uncertainties: **JES** and **tW/tt overlap** for p_T , **lepton reconstruction** at large $\Delta\phi$.



Evidence of toponium formation from $t\bar{t} \rightarrow e\mu + b\bar{b}$



- Adding either model of the toponium signal **improves the description of the data at threshold**

- Fitting **MiNNLOps + GFRW- $t\bar{t}$** yields **evidence for toponium formation:**

$$\mu = 1.22 \pm 0.38$$

$$\sigma(tt_{\text{GFRW}}) = 7.8 \pm 2.4 \text{ pb}$$

