



Results on Top Quark Cross Section Measurements and Recent Progress on Modelling

QCD@LHC 2026 - Oxford (28/09 - 02/10)

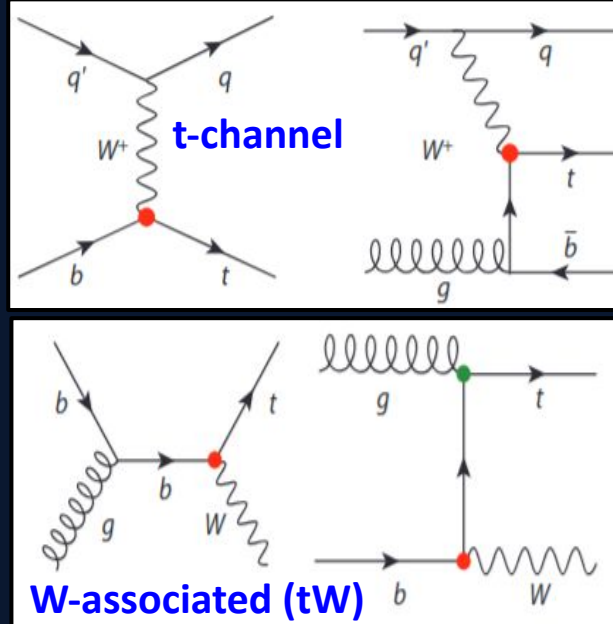
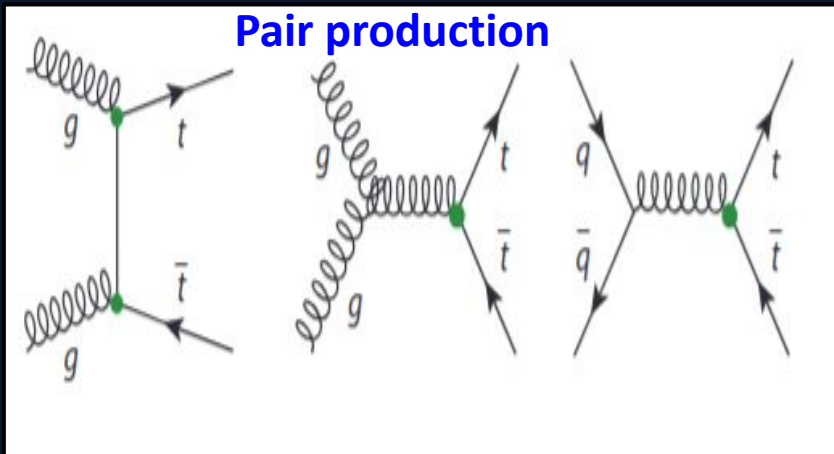
Daniel Ernani Martins Neto
For the ATLAS Collaboration



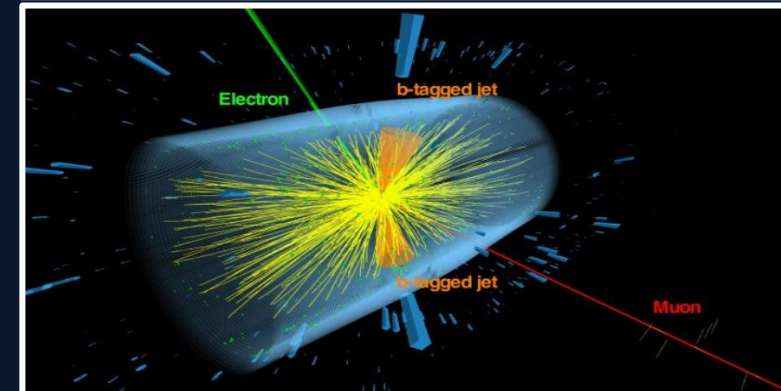
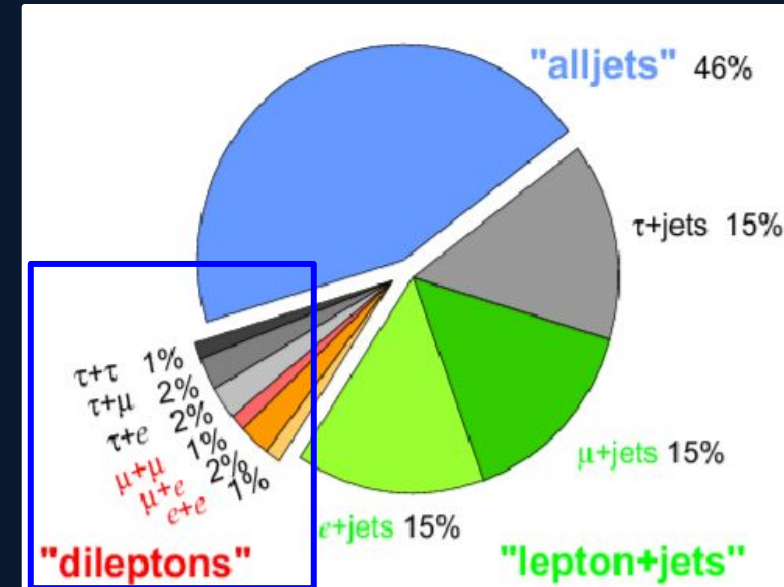
Top Quark Physics: The Essentials

- Mass $\approx 172.5 \text{ GeV}/c^2$, electric charge $+\frac{2}{3}e$. Discovered in 1995 by CDF and DØ at Fermilab
- Decays almost exclusively via $t \rightarrow Wb$ (mean lifetime of $\approx 5 \times 10^{-25} \text{ s}$) — the top quark decays before it can hadronize
- At $\sqrt{s} = 13 \text{ TeV}$, gluon-gluon fusion dominates - $t\bar{t}$ pair production is the leading top-quark process

Production mechanisms

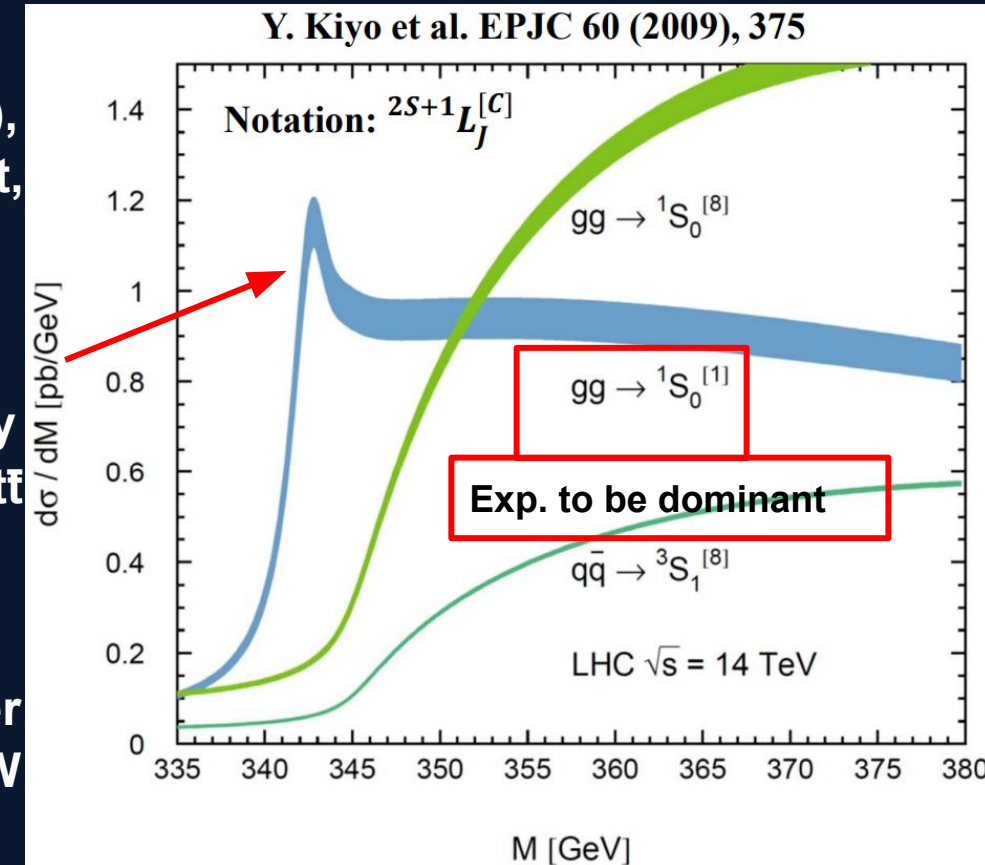


$$W \rightarrow l\nu (\sim 30\%) / qq' (\sim 70\%)$$



Why the $t\bar{t}$ Threshold Matters?

- **Quasi-bound states (“toponium”)**: Near $m(t\bar{t}) \approx 345$ GeV ($\approx 2 \times m_t$), non-relativistic QCD (NRQCD) predicts a colour-singlet, spin-singlet enhancement
- **Not similar to the charmonium and bottomonium**: tops decay before hadronize - Quasi-bound state is an effect of the Xs in $t\bar{t}$ threshold (not like J/ψ or Y)
- **A “hard” modelling problem**: NRQCD effects, missing higher-order pQCD terms (resummation of α_s/v), off-shell top decays and $t\bar{t}/tW$
Giovanni's talk: [Uncertainties of \$t\bar{t}\$ at threshold](#)
- For a detailed analysis of $t\bar{t}$ Xs at threshold: [Lucas's talk](#)



- Broader than the resonances formed by the lighter quarks, but narrower than the current experimental resolution

Three Complementary Probes of the $t\bar{t}$ Threshold

All the analyses exploit the same ATLAS Run 2 dataset (140 fb^{-1} , $\sqrt{s} = 13 \text{ TeV}$)

Analysis

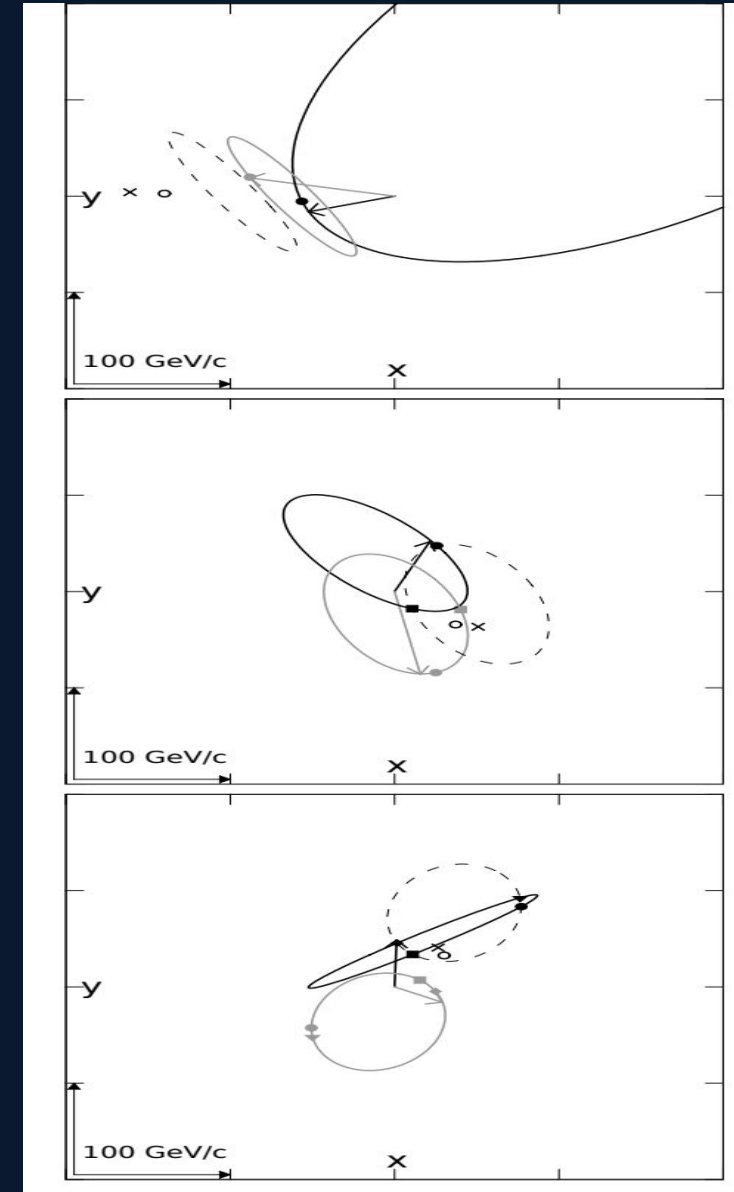
Approach

- 1 Precision $e\mu$
[Eur. Phys. J. C 86 \(2026\) no.5, 470](#) → Baseline inclusive + differential $e\mu$ cross-section (double b-tagging): provides the dataset, and the first hint of an excess
- 2 Diff. $WWb\bar{b}$ measurement
[JHEP 07 \(2026\) 028](#)
[JHEP 02 \(2026\) 153](#) → Direct test of $t\bar{t}/tW$ modelling - Single and dilepton channels
- 3 $e\mu$ threshold study
[CERN-EP-2026-107](#) → Reinterprets analysis 1's published $e\mu$ distributions with a dedicated correlation fit

One consistent picture: pQCD alone does not describe the data near threshold

$t\bar{t}$ reconstruction - ellipse method

- Full reconstruction of the $t\bar{t}$ system ([See: Nucl. Instrum. Meth. A 736 \(2014\), 169-178](#)). Main challenge: the treatment of two undetected neutrinos
- For each $t \rightarrow b\ell\nu$ decay, we require $m(\ell\nu b) = m_{\text{top}} = 172.5 \text{ GeV}$ and $m(\ell\nu) = m_W = 80.4 \text{ GeV}$ restricts the $p_T(\nu)$ solution to an ellipse in the transverse plane
- **MET links the two ellipses**: the sum $p_T(\nu) + p_T(\bar{\nu})$ must equal the measured MET — this shifts the $\bar{\nu}$ ellipse and turns it into a second (dashed) constraint on ν itself
- **Solutions: intersections with 0, 2, or 4 crossings**; if multiple, smallest $m(t\bar{t})$ wins. If there is no intersection: m_{top} , m_W resampled (Gaussian, $\times 100$) until a solution is found
- **Efficiency**: a solution is found for **$\sim 95\%$ of $t\bar{t}$ dilepton events (h ν q and $t\bar{t}_{\text{GFRW}}$ alike)** - $m(t\bar{t})$ resolution: **$\sim 22\%$ at threshold, improving to $\sim 18\%$ at $m(t\bar{t}) \approx 500 \text{ GeV}$**



Precise measurement of the $t\bar{t}$ production XS in $e\mu$ events

- Event selection

- Exactly $1e + 1\mu$, opposite charge
- $e\mu$ angular overlap veto: rejects $|\Delta\theta|, |\Delta\phi| < 0.15$
- Samples with exactly: **1 or 2 b-tagged jets** (70% WP for the inc./diff. and 77% WP for $e\mu b\bar{b}$)

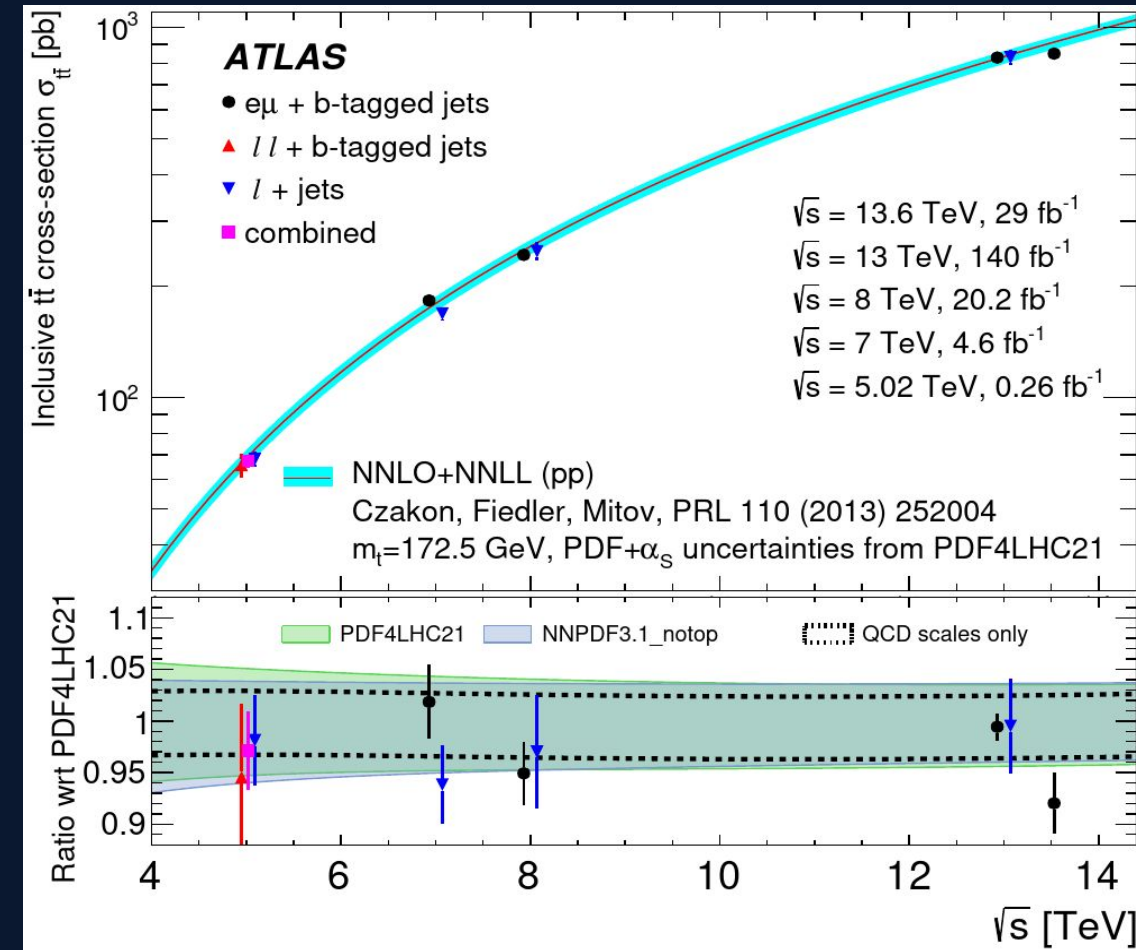
- Selected Events

- **576.725** evt. with **1 b-tag** (**~88% $t\bar{t}$ purity**)
- **314.961** with **2 b-tags** (**~96% $t\bar{t}$ purity**)
- **378.266** $e\mu$ evt. with **2 b-tags** (77% WP) for the $e\mu b\bar{b}$ diff. measurement

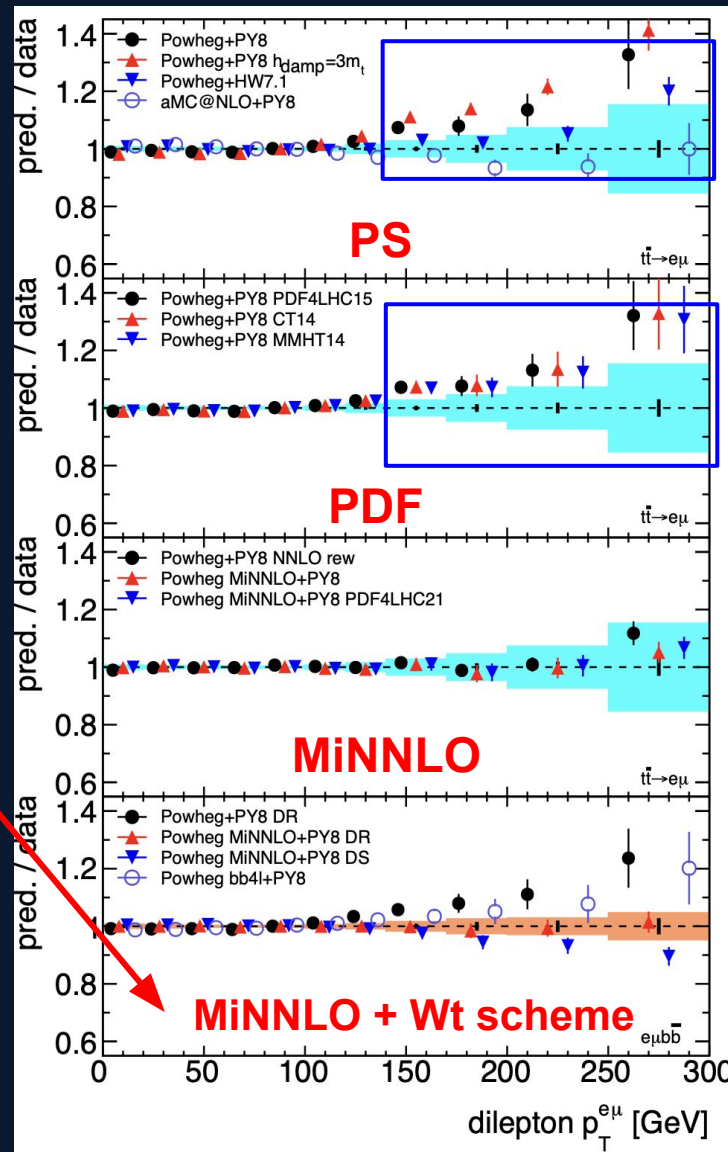
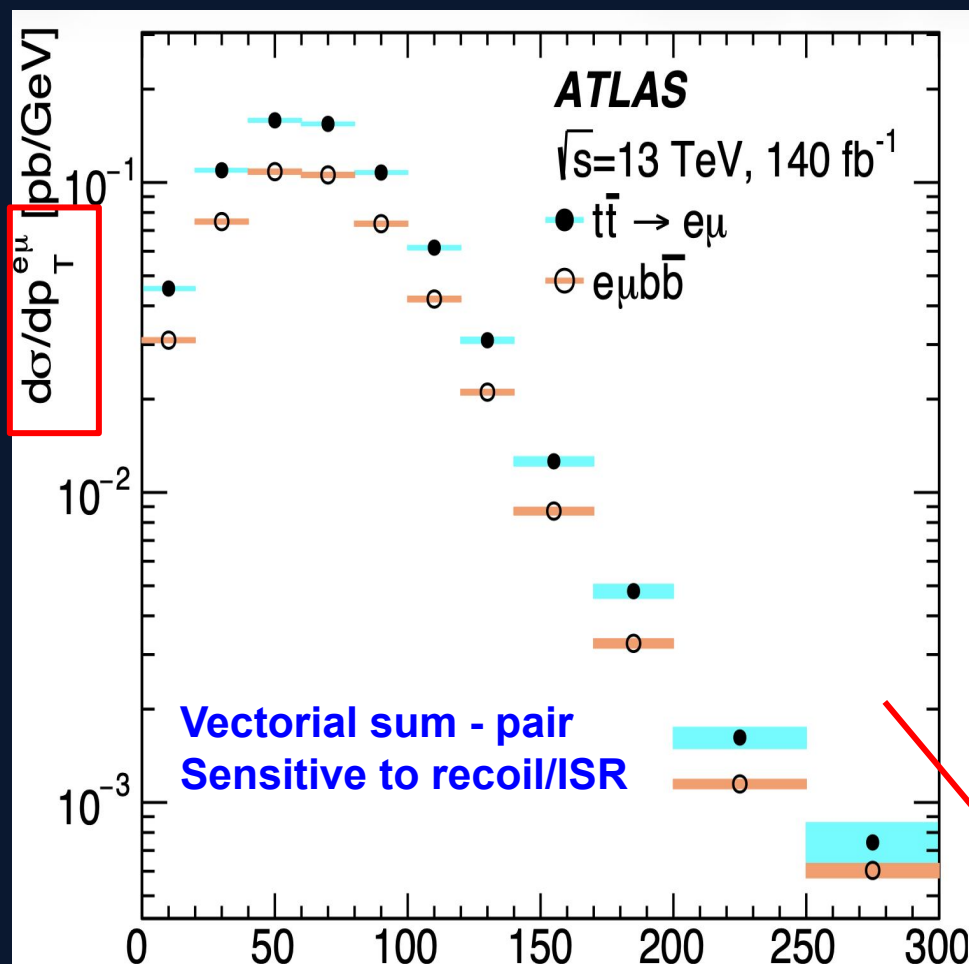
- Systematics

- Calibration via LUCID2 + inner det./cal. $\sim 0.89\%$
- PDF (0.47%) > QCD scale (0.31%) > hadronisation (0.29%), dominated by the PDF uncertainty

- Visually this result has $\sim 1/3$ of the uncertainty of the theoretical prediction
- **It is the most precise ever made**



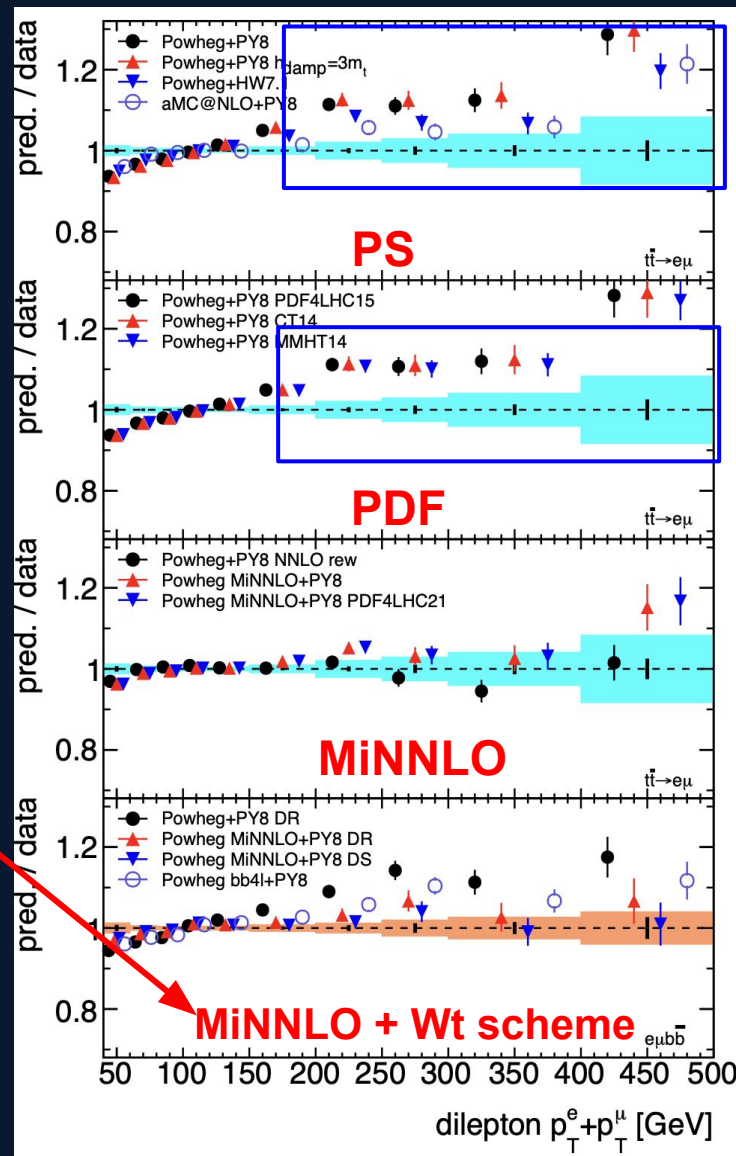
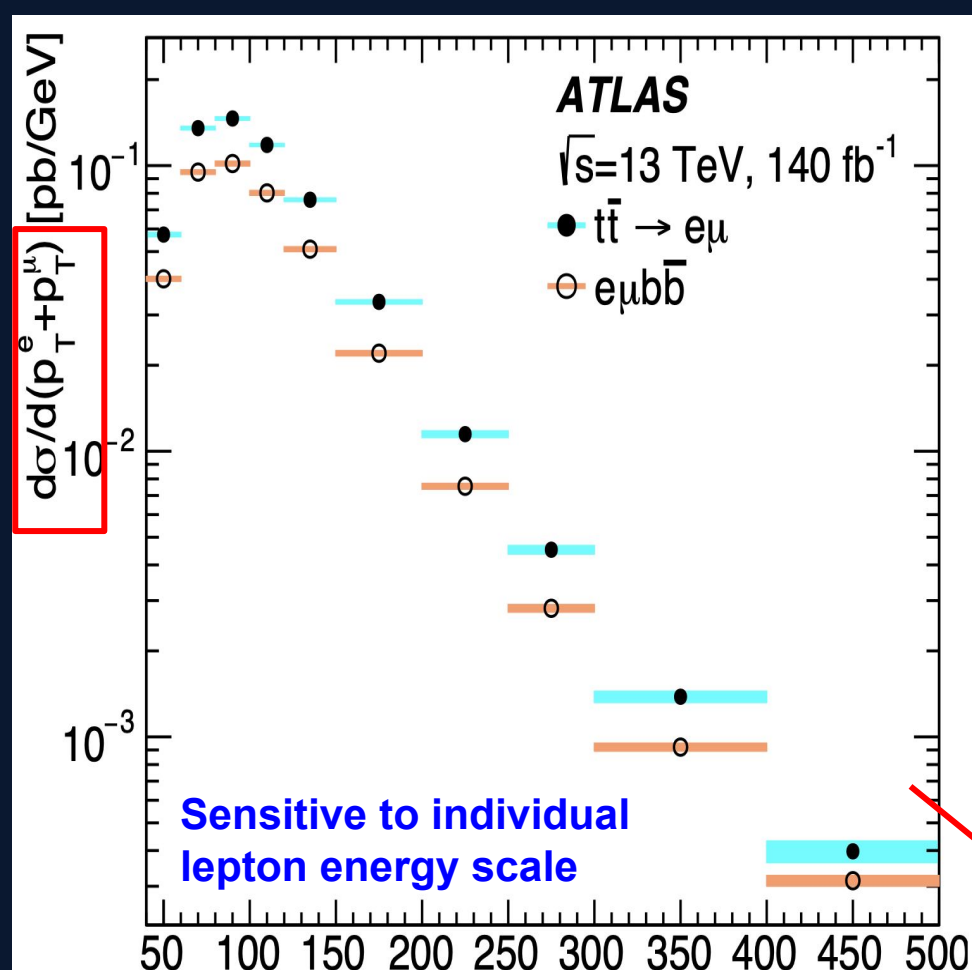
Precise measurement of the $t\bar{t}$ production XS in $e\mu$ events



- **hvq+Pythia** with h_{damp} diverging at high p_T
- **Strong** divergence observed also when considering different PDF "flavours"
- The winner takes all - **MiNNLO** is the one that best describes data and is promoted to the baseline model in both channels: $e\mu$ and $e\mu b\bar{b}$

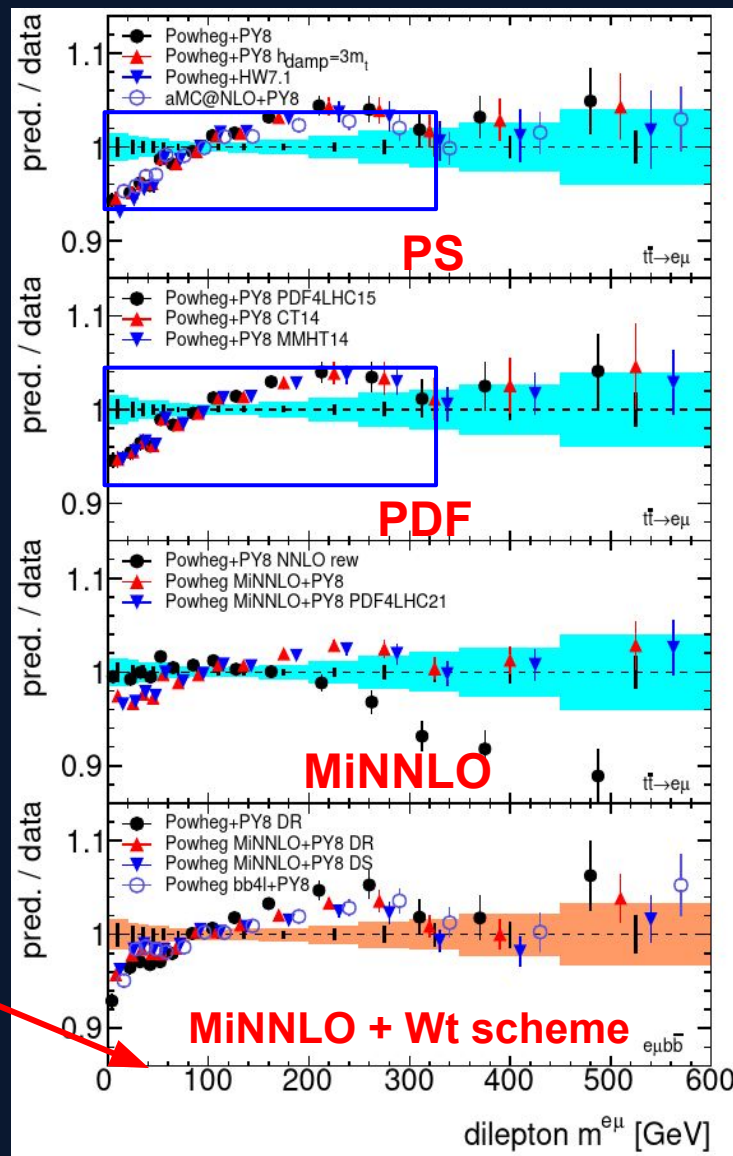
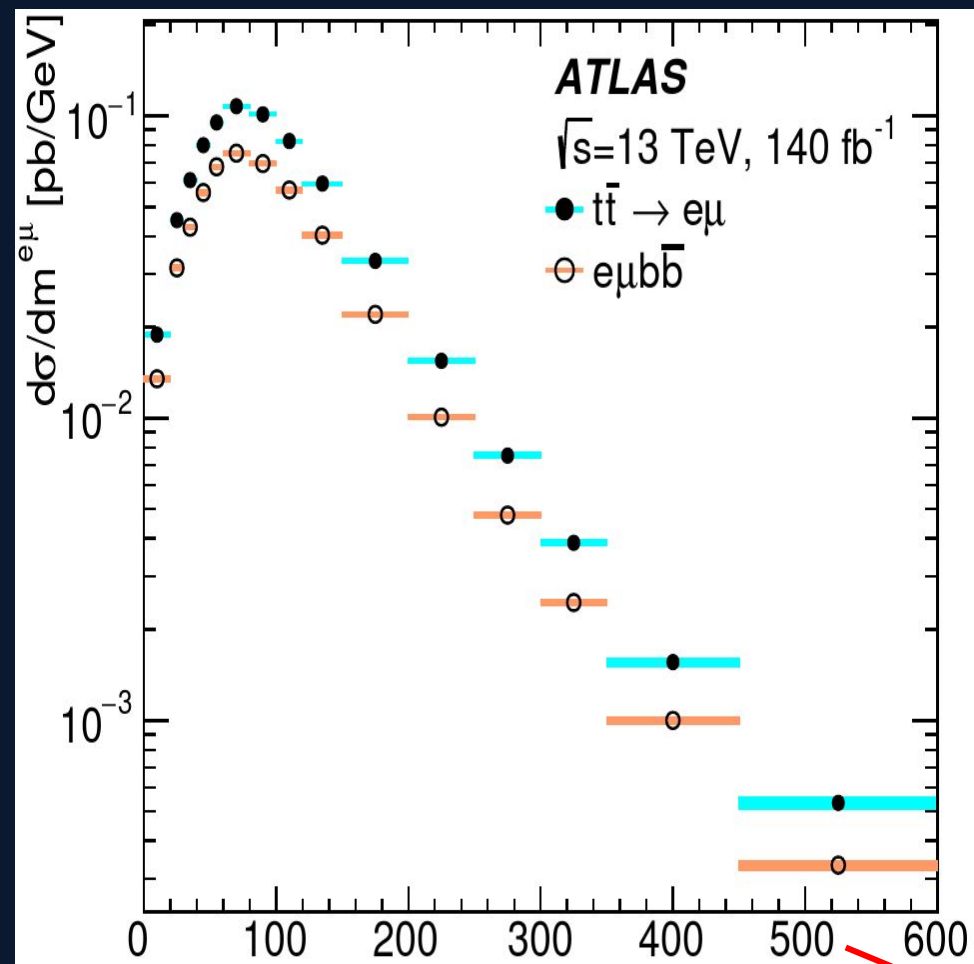
PS = parton shower (Pythia/Herwig/hdamp)
 PDF = PDF set
 MiNNLO = NNLO reweighting/MiNNLO variants
 Full model information in backup

Precise measurement of the $t\bar{t}$ production XS in $e\mu$ events



- **h_{vq}+Pythia** with h_{damp} still diverges at high p_T
- Here even the **best model (MiNNLO)** struggle to describe data at high p_T - has a χ^2 probability of only $\sim 1\%$ here
- Quest for the "holy grail" model continues ...

Precise measurement of the $t\bar{t}$ production XS in $e\mu$ events



- **MiNNLO** describes data better than **h_vq** at higher values of $m(e\mu)$
- Also the simple change of PDFs is not capable to describe data reasonably
- No prediction describes well the $m(e\mu)$ distribution at low values, where clearly there is an excess of data
- **Maybe a reinterpretation with other contributions?**

Precise measurement of the $t\bar{t}$ production XS in $e\mu$ events

Results

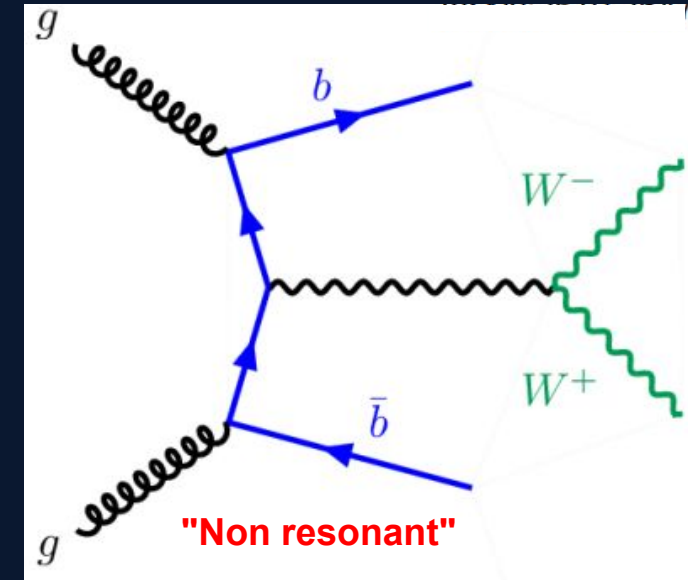
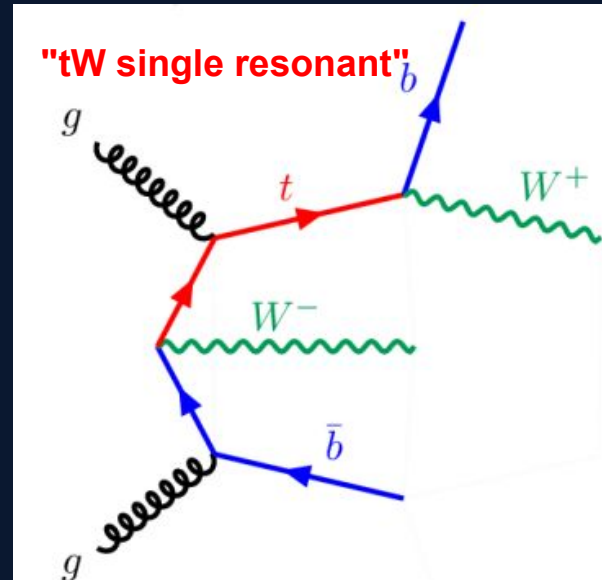
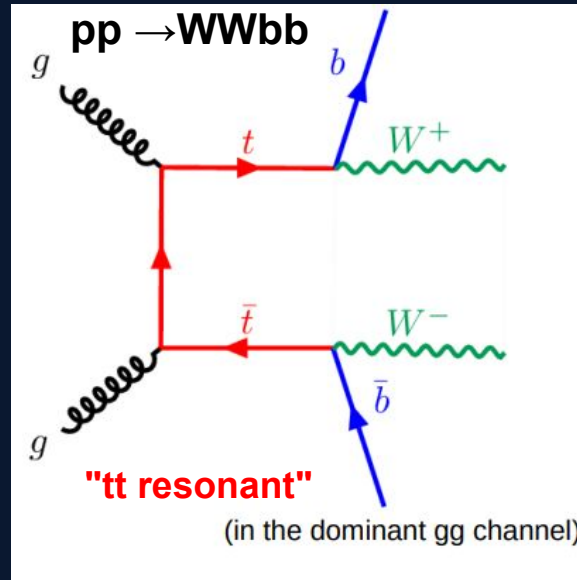
- $\sigma(t\bar{t}) = 829.3 \pm 1.3$ (stat) ± 8.0 (syst) ± 7.3 (lumi) ± 1.9 (beam) pb with total uncertainty of 1.3%, this is the most precise measurement to date (down from 1.8%)
- 10 single-diff. + 3 double-diff. XS measured; best described by Powheg MiNNLO and bb4l, less well by Powheg hvq
- Still the low- $m(e\mu)$ excess remains unexplained — a residual, not resolved by generator or PDF choice...

Generator N_{dof}	p_T^ℓ 12	$ \eta^\ell $ 8	$p_T^{e\mu}$ 10	$m^{e\mu}$ 14	$ y^{e\mu} $ 8	$\Delta\phi^{e\mu}$ 19	$p_T^e + p_T^\mu$ 9	$E^e + E^\mu$ 11	$p_T^{\ell,\text{max}}$ 11	$p_T^{\ell,\text{min}}$ 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 $h_{\text{damp}} = 3m_t$	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
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

"What if we extend these $e\mu$ distributions to test sensitivity to quasi-bound states?"

Differential WWb $\bar{b}$ measurement

W $^+$ W $^-$ b $\bar{b}$ final states: fundamental process to study tt threshold production or m $_b$ distributions



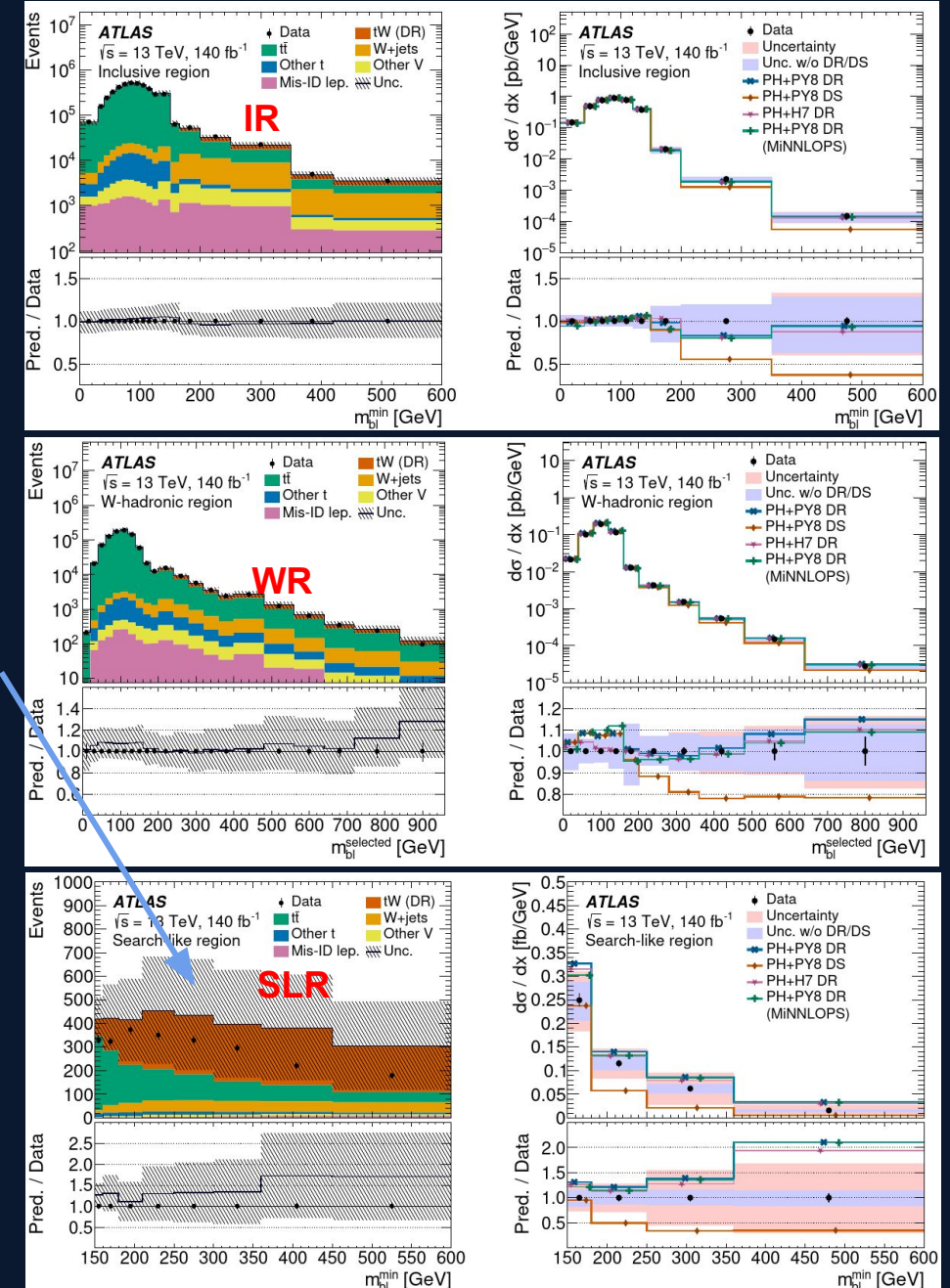
- **DR vs DS:** DR removes "double-resonant" NLO amplitudes from tW production; DS is a subtraction term in the NLO tW cross-section that locally cancels $t\bar{t}$ contributions $\Rightarrow$ WWb $\bar{b}$ DR/DS modelling uncertainty
- **bb4l:** full NLO $pp \rightarrow WWb\bar{b} \rightarrow \ell\nu\ell'\nu'b\bar{b}$ in a single calculation, with resonance-aware PS matching — avoids the DR/DS split, and the lineshape (top-decay) treatment, entirely ([ATL-PHYS-PUB-2025-036](#))
- **Two dedicated ATLAS differential measurements now test this directly:** single-lepton ([JHEP 07 \(2026\) 028](#)) and dilepton ([JHEP 02 \(2026\) 153](#))

Differential WWb $\bar{b}$ measurement - single lepton channel

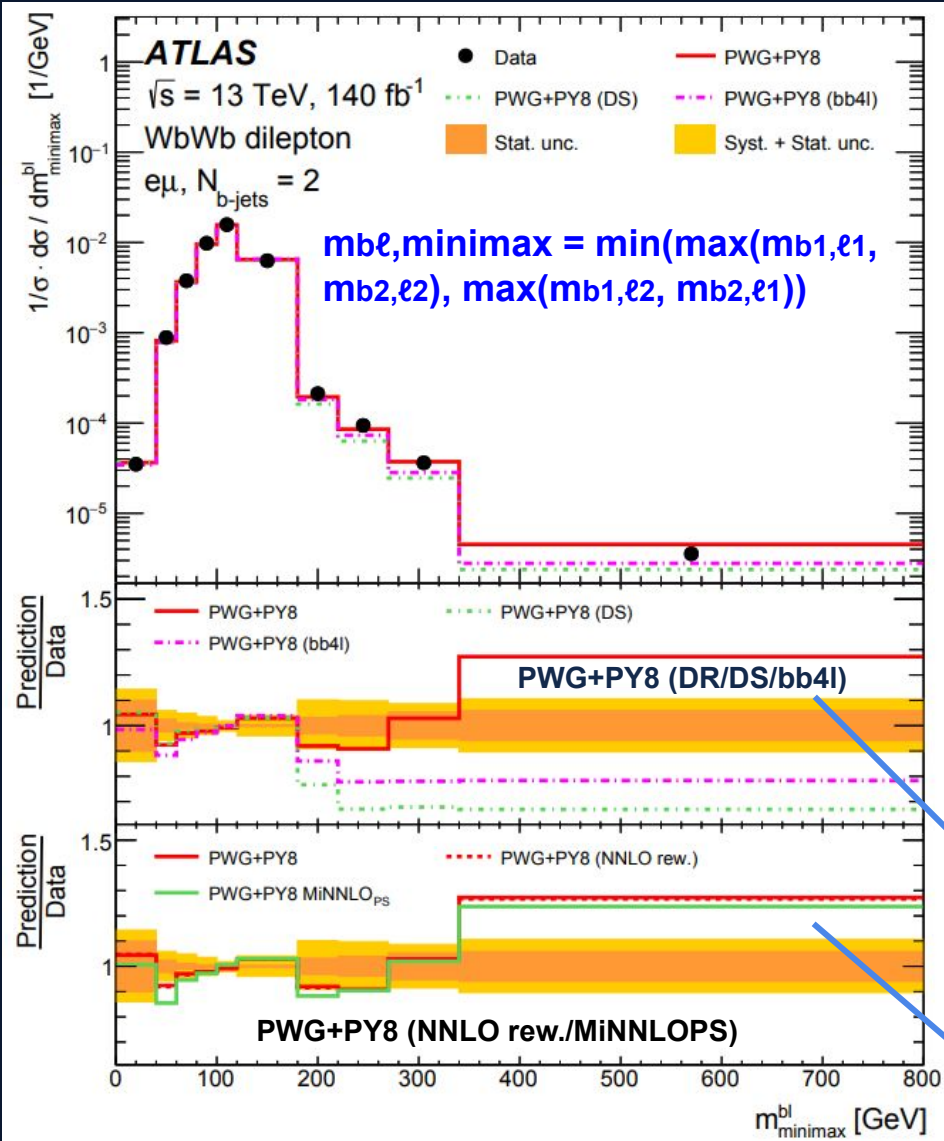
- Direct test of $t\bar{t}/tW$ modelling - [JHEP 07 \(2026\) 028](#)
- Dedicated differential measurement of the $1\ell + \geq 4$ jets (≥ 2 b-tag) WWb $\bar{b}$ final state, in three regions of increasing sensitivity to $t\bar{t}/tW$ interference:

IR $\rightarrow$ WR $\rightarrow$ SLR

- SLR isolates the off-shell/interference-dominated tail via **$m_{b\bar{b}}(\text{min}) \geq 150$ GeV**. Where the highest discrepancy is observed
- No single prediction: **DR, DS, Herwig(DR), MiNNLOPS**, describes all regions simultaneously; Disagreement grows toward the SLR, the phase space most sensitive to interference
- This is the dedicated study behind the **DR/DS interference systematic already carried in the threshold analyses** — not just a generator comparison



Differential WWb5 measurement - Dilepton channel



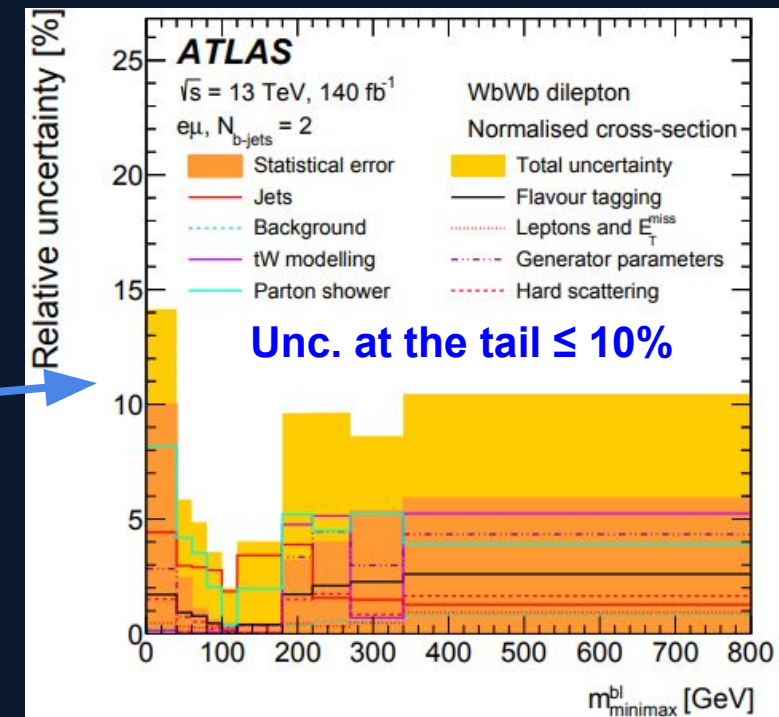
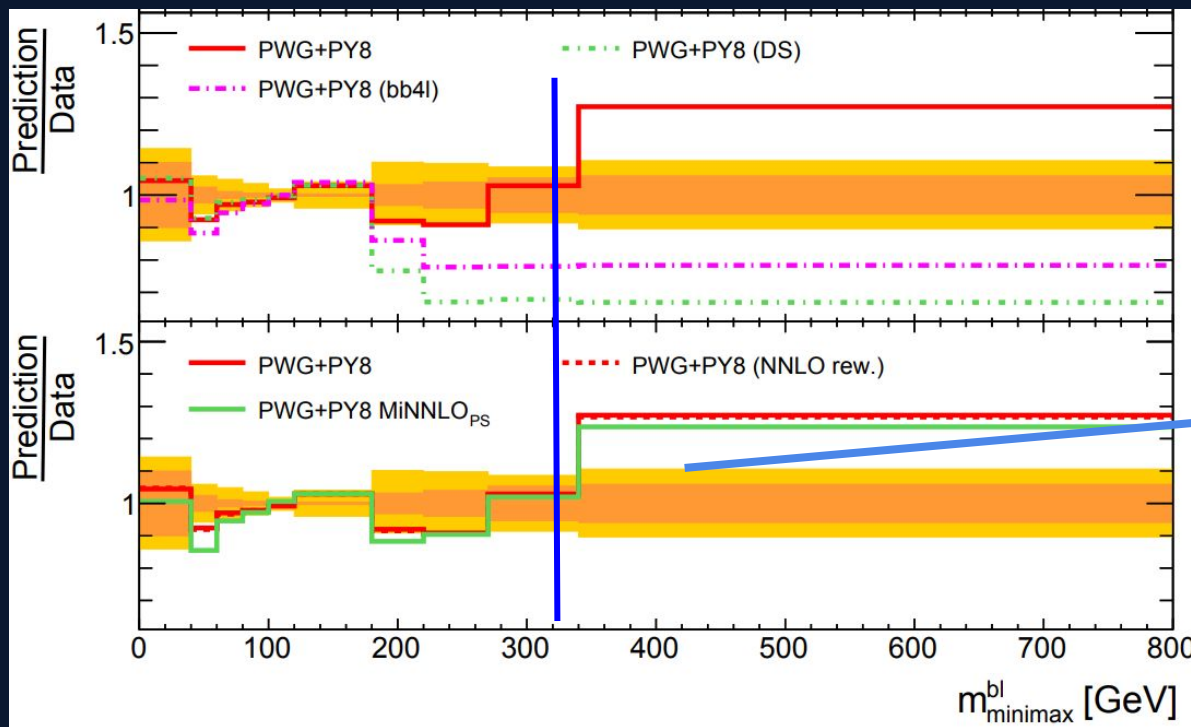
- **Companion measurement:** same $e\mu$ final state- [JHEP 02 \(2026\) 153](#)
- **Selection:**
 - opposite-charge $e\mu$ pair, $N_{b\text{-tags}} \geq 2$ (70% WP)
- **$mb_{\ell, \text{minimax}}$:** observable most sensitive to $t\bar{t}/tW$ interference in this channel

Models

PWG + PY8 (**DR**) → Standard
 PWG + PY8 (**DS**) → Alternative
 PWG + PY8 (**bb4l**) → Full NLO

PWG + PY8 → (**NNLO reweighted**) [$t\bar{t}$ + NLO tW]
 PWG + PY8 → (**MiNNLO_{ps}**) [$t\bar{t}$ + NLO tW]

Differential WWb5 measurement - Dilepton channel



- **bb4l describes the tail best:** Data/MC gap reaches 30–40% for DR/DS, ~20–30% for the NNLO-reweighted prediction, smallest for bb4l
- **Full NLO treatment of interference and lineshape simultaneously:** removes the need for separate DR/DS and lineshape systematics in this channel
- This is the direct evidence behind the **DR/DS interference systematic already carried in the threshold analyses** — not just a generator comparison, a measurement that resolves which choice the data "prefers"

$t\bar{t}$ threshold effects in $e\mu$ diff. distributions

- **Data Sample**

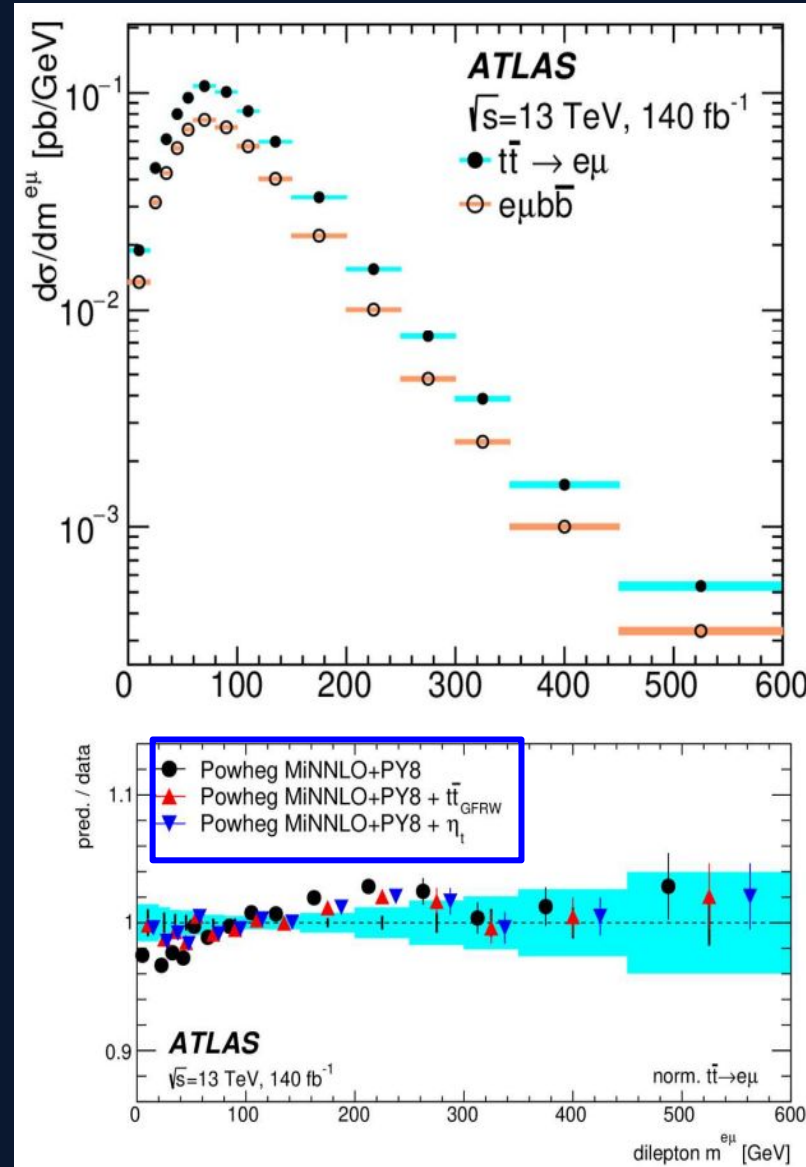
- fully reuses the selection and published distributions from [Eur. Phys. J. C 86 \(2026\) no.5, 470](#)

- **Event selection**

- 2D $\Delta\phi(e\mu) \times m(e\mu)$ distribution
- It uses the full bin-to-bin correlations of the data/predictions

- **Distributions**

- $m_{e\mu}$, $\Delta\phi_{e\mu}$ and $\Delta\phi_{e\mu}$ in coarse bins of $m_{e\mu}$
- Variables are sensitive to the production of the quasi-bound $t\bar{t}$ state are analysed using the $t\bar{t} \rightarrow e\mu b\bar{b}\nu\bar{\nu}$ and $t\bar{t} \rightarrow e\mu + X$ events



$$\chi^2/\text{NDF} = 25.9/14$$

MiNNLO+PY8

Adding $t\bar{t}_{\text{GFRW}}$ or η_t
improves the agreement

$$\chi^2/\text{NDF} = 16.5/14$$

MiNNLO+PY8+ $t\bar{t}_{\text{GFRW}}$

$t\bar{t}$ threshold effects in $e\mu$ diff. distributions

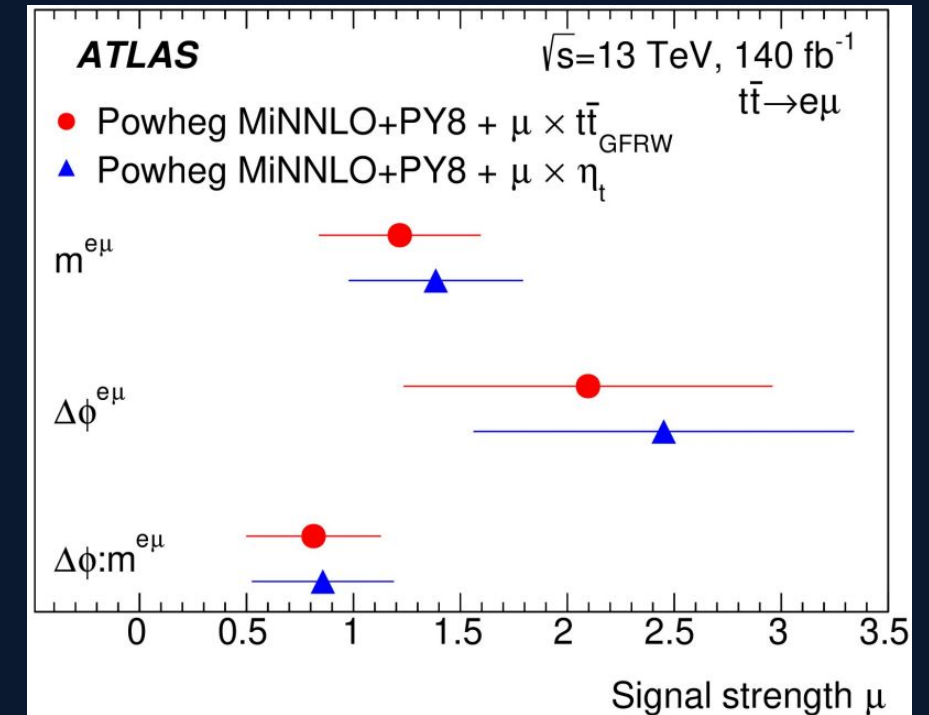
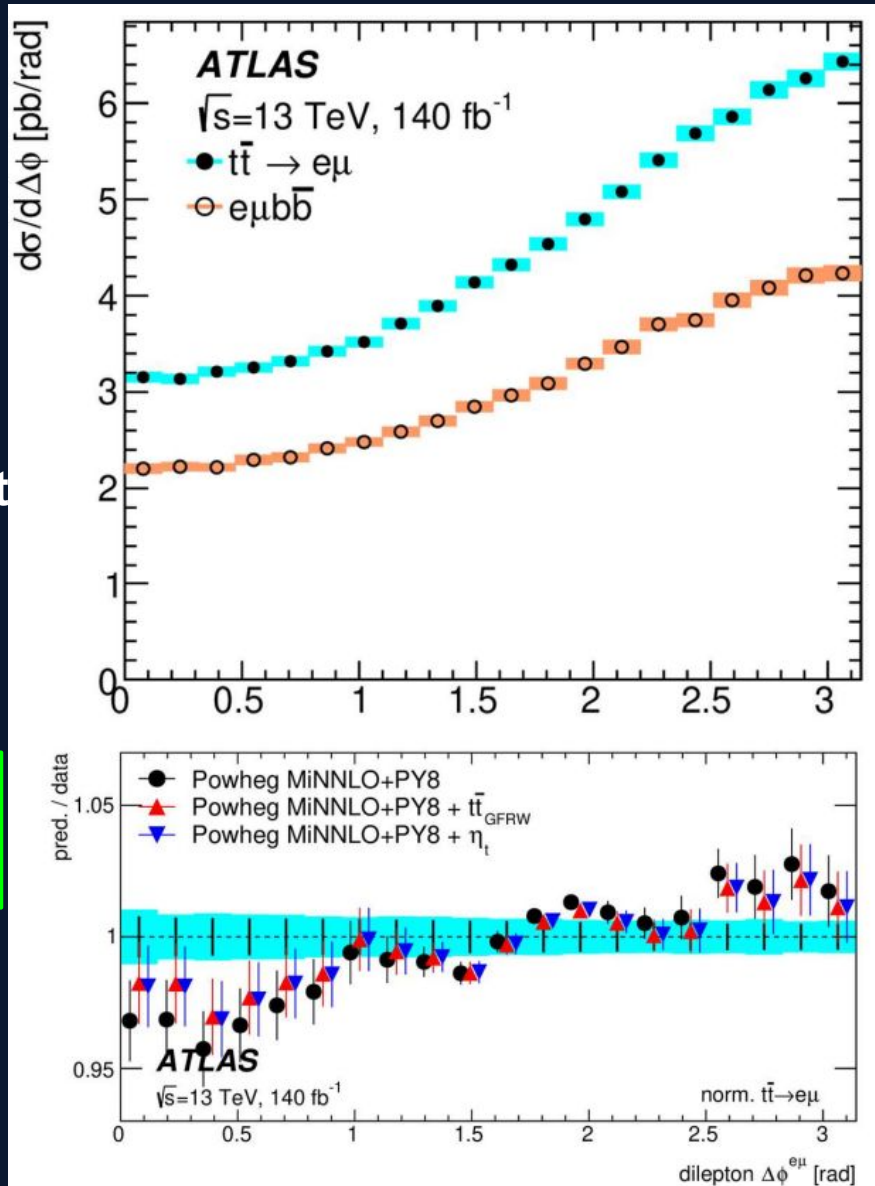
$\chi^2/\text{NDF} = 23.6/19$
MiNNLO+PY8



Adding $t\bar{t}_{\text{GFRW}}$ or η_t
improves the agreement



$\chi^2/\text{NDF} = 16.7/19$
MiNNLO+PY8+ $t\bar{t}_{\text{GFRW}}$



- Fit to $m(e\mu)$ with floating signal strength
 $\mu(t\bar{t}_{\text{GFRW}}) = 1.22 \pm 0.38$

Differ from 0 by more than 3σ :

- $\sigma(t\bar{t}_{\text{GFRW}}) = 7.8 \pm 2.4$ pb (Observed)
- $\sigma(t\bar{t}_{\text{GFRW}}) = 6.43$ pb (Predicted)

Conclusions

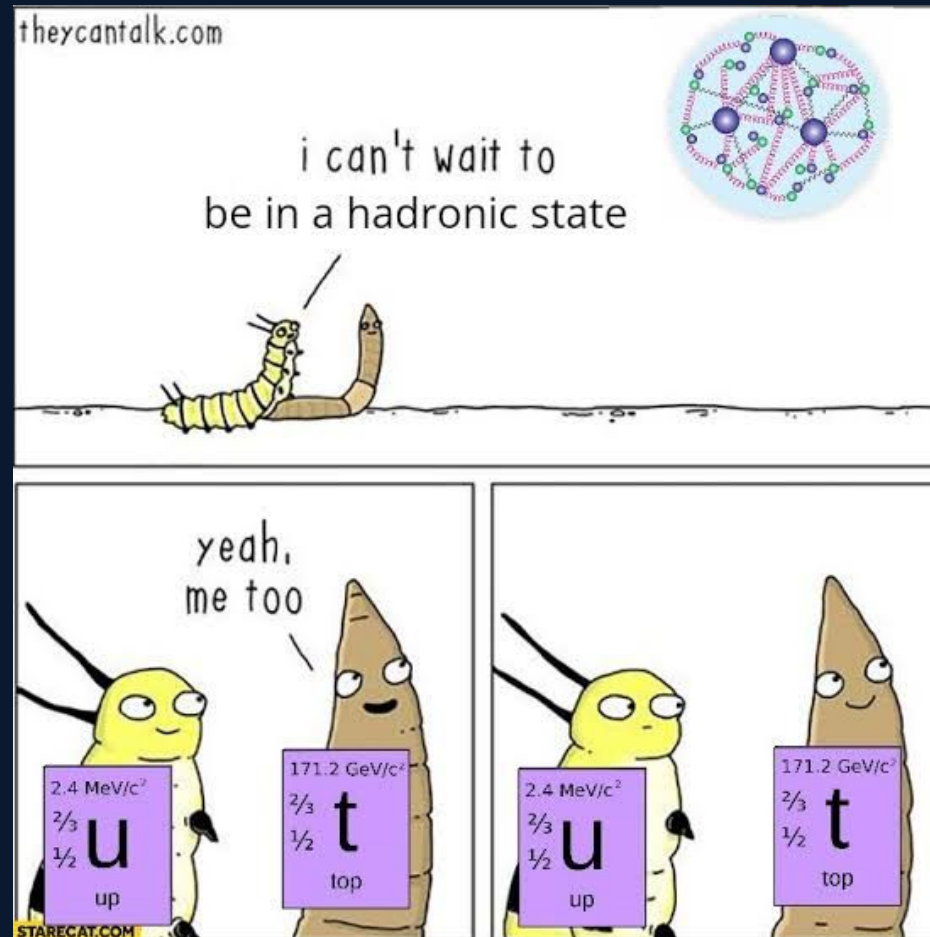
- **Analysis 1 (Precision $e\mu$):** the low- $m(e\mu)$ excess survives every standard modelling correction — PS, PDF, even the best baseline (MiNNLO) only fixes p_T , not the mass tail
- **Analysis 2 (Diff. $WWb\bar{b}$):** not generic mismodelling — a dedicated interference study shows $bb4l$, which treats $t\bar{t}/tW$ interference and lineshape correctly at NLO, describes the data best in the tail, in both channels — direct evidence the residual has a physical origin, not a generator artifact
- **Analysis 3 ($e\mu$ threshold study):** reinterpreting the same $e\mu$ distributions with full bin-to-bin correlations gives a **$>3\sigma$ excess***, compatible with a colour-singlet, spin-singlet S-wave quasi-bound $t\bar{t}$ state

	Cross section (pb)	Method
Analysis 3	7.8 ± 2.4	fit in $m(e\mu)$
Predicted (NRQCD)	6.43 (reference)	-

* *Consistent with the independent angular-fit result presented in Lucas's talk (9.3 pb, $>8\sigma$)*

- Run 3 data, improved generator-level NRQCD models, and ongoing $bb4l$ validation (dilepton complete, single-lepton in progress) should sharpen this picture, with implications for BSM searches

Thank you!



Back up slides

Systematics breakdown

Precise measurement of the $t\bar{t}$ production XS in $e\mu$ events

Group	Uncertainty source	$\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	$\Delta G_{e\mu}/G_{e\mu}$ (%)	$\Delta C_b/C_b$ (%)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)	$\Delta\sigma_{t\bar{t}}^{\text{fid}}/\sigma_{t\bar{t}}^{\text{fid}}$ (%)
$t\bar{t}$ mod.	Data statistics				0.16	0.16
	$t\bar{t}$ matrix element matching	0.01	0.02	0.02	0.01	0.00
	QCD scale variation	0.29	0.07	0.02	0.31	0.09
	$t\bar{t}$ hadronisation	0.23	0.06	0.06	0.29	0.00
	Initial/final state radiation	0.04	0.03	0.09	0.16	0.17
	$t\bar{t}$ heavy-flavour production	0.00	0.00	0.17	0.17	0.17
	Parton distribution functions	0.47	0.05	-	0.47	0.08
Lept.	Simulation statistics	0.07	0.04	0.05	0.05	0.04
	Electron identification	0.12	0.12	-	0.14	0.14
	Muon identification	0.13	0.13	-	0.14	0.14
	Electron charge mis-id	0.05	0.05	-	0.06	0.06
	Lepton trigger	0.10	0.10	0.00	0.11	0.11
	Electron energy scale	0.04	0.04	0.00	0.05	0.05
	Electron energy resolution	0.01	0.01	0.00	0.01	0.01
	Muon momentum scale	0.01	0.01	0.00	0.02	0.02
	Muon momentum resolution	0.00	0.00	0.00	0.00	0.00
	Electron isolation	0.10	0.10	-	0.11	0.11
	Muon isolation	0.12	0.12	-	0.13	0.13
Jet/ b	Jet energy scale	-	-	0.05	0.02	0.02
	Jet energy resolution	-	-	0.03	0.06	0.06
	Pileup jet veto	-	-	0.00	0.02	0.02
	b -tagging efficiency	-	-	0.01	0.13	0.13
	b -tag mistagging	-	-	0.02	0.02	0.02
Bkg.	Single-top cross-section	-	-	-	0.40	0.40
	Single-top/ $t\bar{t}$ interference	-	-	-	0.28	0.28
	Single-top modelling	-	-	-	0.30	0.30
	Z+jets extrapolation	-	-	-	0.02	0.02
	Diboson cross-sections	-	-	-	0.01	0.01
	Diboson modelling	-	-	-	0.05	0.05
	Misidentified leptons	-	-	-	0.18	0.18
	Analysis systematics	0.66	0.29	0.22	0.97	0.74
L/E_b	Integrated luminosity	-	-	-	0.89	0.89
	Beam energy	-	-	-	0.23	0.23
	Total uncertainty	0.66	0.29	0.22	1.34	1.19

Models

hvq, MiNNLO and bb4 ℓ are different ways to compute pure pQCD
tt_{GFRW} and η_t add the quasi-bound-state effect on top of one of them.

Model	Description
<i>pQCD baselines (production, before adding quasi-bound-state effects)</i>	
hvq (Powheg v2 hvq)	NLO matrix element for ttbar production (stable, on-shell tops); decay added afterwards by the parton shower at LO accuracy. The oldest / simplest baseline of the three.
Powheg MiNNLO + PY8	Production computed at NNLO (MiNNLO_PS method) + parton shower — describes top and lepton pT better than hvq. Preferred baseline in papers 1 and 3.
Powheg bb4 ℓ	Computes the full $\ell\ell'vv + bb$ final state at NLO in one go — includes ttbar/Wt interference and off-shell effects directly. Used for the e μ bb measurement. Still to be tuned for best settings
<i>Quasi-bound-state add-ons (added on top of a pQCD baseline above)</i>	
tt _{GFRW} (Green's Function ReWeighting)	Reweights a MadGraph LO sample using the NRQCD Green's function (Coulomb gauge) to model the quasi-bound-state; normalised to 6.43 pb (analytic calculation).
η_t (simplified pseudoscalar model)	Simpler alternative: a narrow pseudoscalar resonance. Same approach originally used in the CMS observation paper.

Models

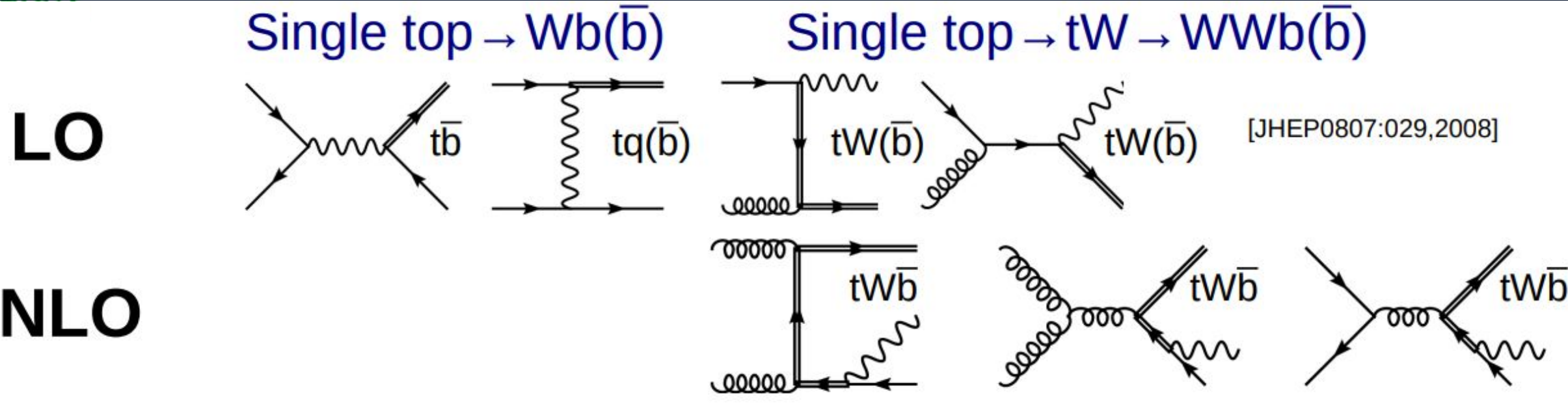
Precise measurement of the $t\bar{t}$ production XS in $e\mu$ events

Group	Matrix element	PDF set	Parton shower	Comments
$t\bar{t}$ -1	POWHEG	NNPDF3.0	PYTHIA8	$h_{\text{damp}} = 3m_t$
	POWHEG	NNPDF3.0	PYTHIA8	
	POWHEG	NNPDF3.0	HERWIG7.1.3	
	AMC@NLO	NNPDF3.0	PYTHIA8	
$t\bar{t}$ -2	POWHEG	PDF4LHC15	PYTHIA8	
	POWHEG	CT14	PYTHIA8	
	POWHEG	MMHT14	PYTHIA8	
$t\bar{t}$ -3	POWHEG	NNPDF3.0	PYTHIA8	NNLO reweighting ($p_T(t)$, $p_T(t\bar{t})$, $m(t\bar{t})$) Baseline
	POWHEG MiNNLO	NNPDF3.0	PYTHIA8	
	POWHEG MiNNLO	PDF4LHC21	PYTHIA8	
$e\mu b\bar{b}$	POWHEG	NNPDF3.0	PYTHIA8	Wt diagram removal
	POWHEG MiNNLO	NNPDF3.0	PYTHIA8	Wt diagram removal, baseline
	POWHEG MiNNLO	NNPDF3.0	PYTHIA8	Wt diagram subtraction
	POWHEG $bb4l$	NNPDF3.0	PYTHIA8	Complete $e\mu\nu\bar{\nu}b\bar{b}$

Differential $WWb\bar{b}$ measurement - single lepton channel

DR: remove “double resonant” NLO amplitudes from tW production

DS: subtraction term in NLO tW X-sec to locally cancel tt contributions



Differential WWb $\bar{b}$ measurement - single lepton channel

Requirements		
preselection	$N_{b\text{-jets}}$	≥ 2
	$N_\ell(p_T > 10 \text{ GeV})$	$= 1$
	$E_T^{\text{miss}} + m_T^\ell$	$\geq 60 \text{ GeV}$
	$p_T(\ell)$	$\geq 30 \text{ GeV}$
IR	N_{jets}	≥ 4
WR	N_{jets}	≥ 3
	$p_T(W_{\text{had.}})$	$\geq 80 \text{ GeV}$
	$60 < m(W_{\text{had.}}) < 100 \text{ GeV}$	
SLR	N_{jets}	≥ 4
	$m_{b\ell}^{\text{min}}$	$\geq 150 \text{ GeV}$
	$p_T(j_1), p_T(j_2)$	$\geq 50 \text{ GeV}$
	$p_T(b_1), p_T(b_2)$	$\geq 160, 50 \text{ GeV}$
	$1.4 < \Delta R(b_1, b_2)$	
	$E_T^{\text{miss}} \geq -0.625 p_T(\ell) + 270 \text{ GeV}$	

Table 4: χ^2 and p -values for each variable (rows) for each prediction (columns) for the absolute differential cross-section in the IR. All systematic uncertainties described in Section 5 are included, with no additional uncertainties included on the predictions under test.

Inclusive region	PH+PY8 DR		PH+PY8 DS		PH+H7 DR		PH+PY8 DR (MiNNLOPS)	
Observable	χ^2 / NDF	p -value	χ^2 / NDF	p -value	χ^2 / NDF	p -value	χ^2 / NDF	p -value
$m_{b\ell}^{\text{min}}$	7.27 / 9	0.61	10.15 / 9	0.34	6.00 / 9	0.74	23.72 / 9	<0.01
$p_T(\ell)$	31.67 / 11	<0.01	19.70 / 11	0.05	13.11 / 11	0.29	7.54 / 11	0.75
m_T^ℓ	11.20 / 8	0.19	7.91 / 8	0.44	12.13 / 8	0.15	3.68 / 8	0.88
$m_T^{\text{min}}(b\ell)$	21.17 / 8	0.01	7.49 / 8	0.48	16.54 / 8	0.04	17.34 / 8	0.03

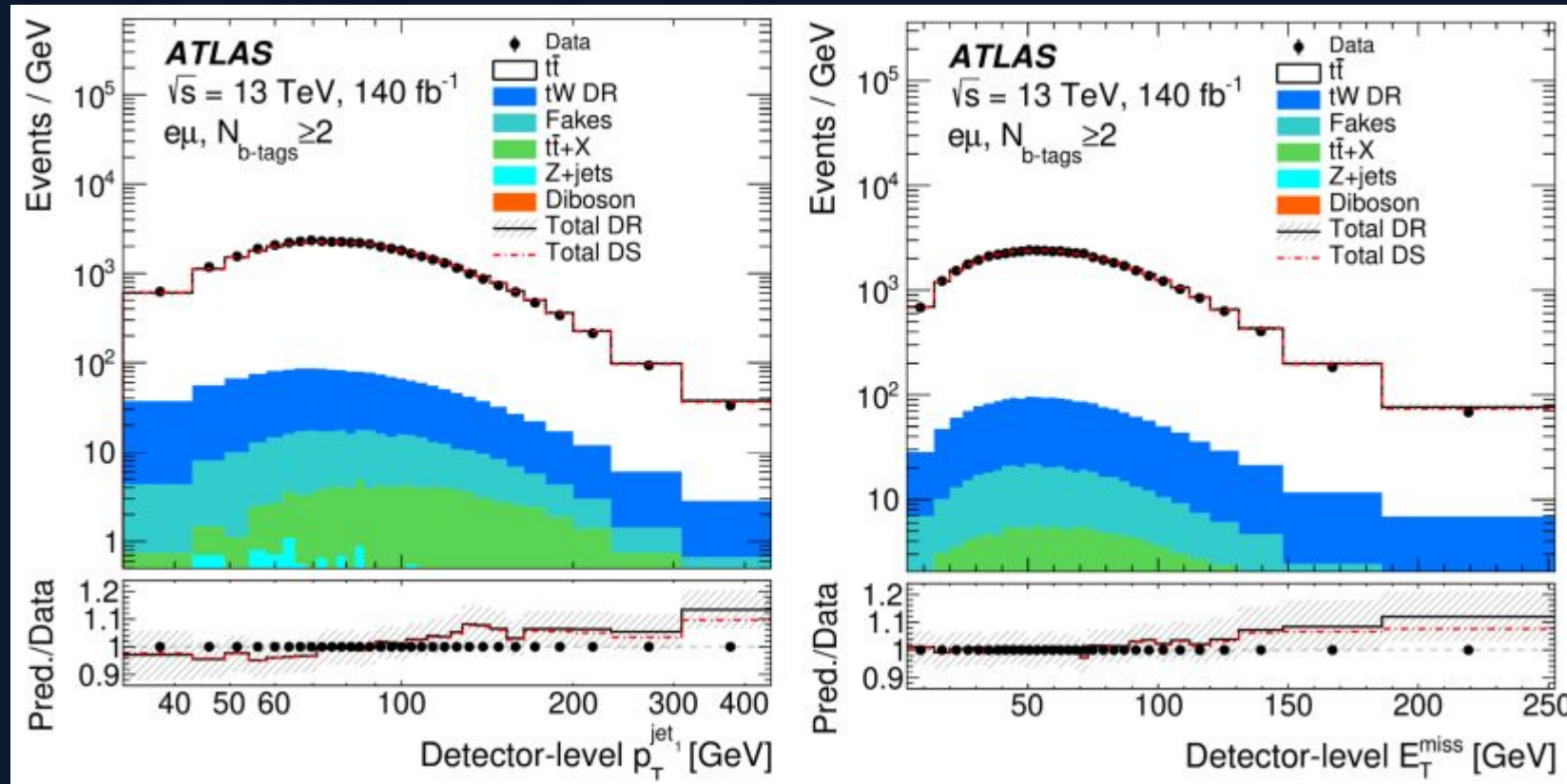
Table 5: χ^2 and p -values for each variable (rows) for each prediction (columns) for the absolute differential cross-section in the WR. All systematic uncertainties described in Section 5 are included, with no additional uncertainties included on the predictions under test.

W-hadronic region	PH+PY8 DR		PH+PY8 DS		PH+H7 DR		PH+PY8 DR (MiNNLOPS)	
Observable	χ^2 / NDF	p -value	χ^2 / NDF	p -value	χ^2 / NDF	p -value	χ^2 / NDF	p -value
$m_{b\ell}^{\text{selected}}$	15.65 / 10	0.11	26.84 / 10	<0.01	6.95 / 10	0.73	30.53 / 10	<0.01
$p_T(b_1)$	25.50 / 9	<0.01	20.56 / 9	0.01	10.19 / 9	0.34	13.62 / 9	0.14
$p_T(W_{\text{had.}})$	20.79 / 11	0.04	14.32 / 11	0.22	10.99 / 11	0.44	7.28 / 11	0.78
$y(W_{\text{had.}})$	14.81 / 12	0.25	14.13 / 12	0.29	7.96 / 12	0.79	11.99 / 12	0.45
m_{bW}^{minimax}	22.37 / 11	0.02	44.24 / 11	<0.01	12.72 / 11	0.31	34.33 / 11	<0.01
$m(W_{\text{had.}}, b\bar{b}\ell)$	5.37 / 10	0.87	7.83 / 10	0.65	2.08 / 10	1.00	4.54 / 10	0.92

Table 6: χ^2 and p -values for each variable (rows) for each prediction (columns) for the absolute differential cross-section in the SLR. All systematic uncertainties described in Section 5 are included, with no additional uncertainties included on the predictions under test.

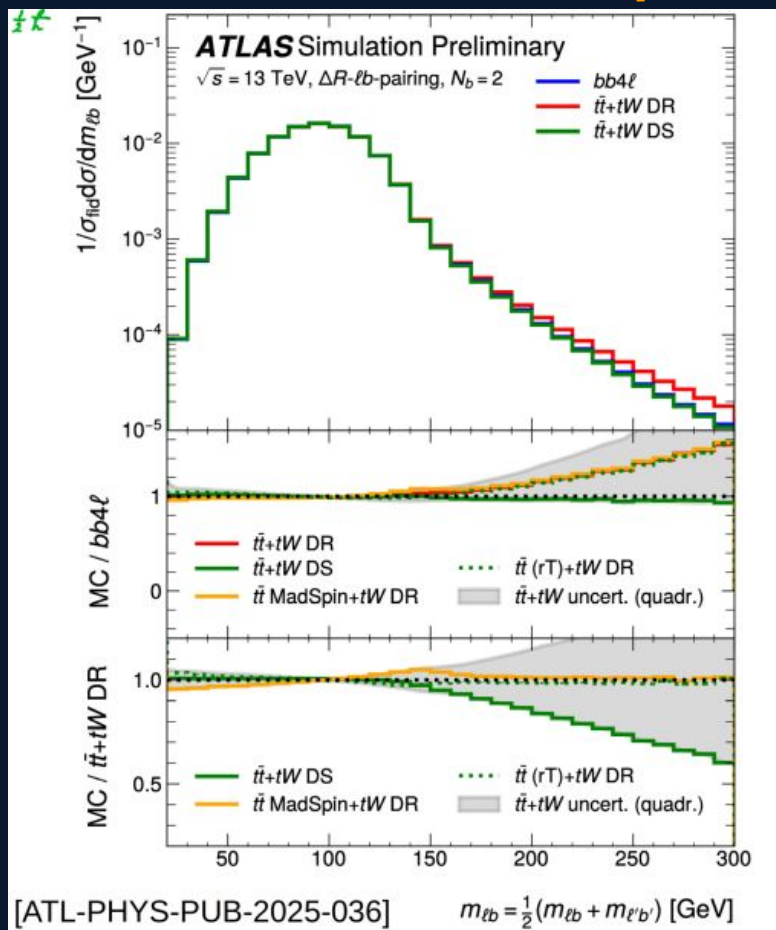
Search-like region	PH+PY8 DR		PH+PY8 DS		PH+H7 DR		PH+PY8 DR (MiNNLOPS)	
Observable	χ^2 / NDF	p -value	χ^2 / NDF	p -value	χ^2 / NDF	p -value	χ^2 / NDF	p -value
$m_{b\ell}^{\text{min}}$	9.57 / 4	0.05	7.57 / 4	0.11	9.21 / 4	0.06	10.73 / 4	0.03
$p_T(b_2)$	17.11 / 5	<0.01	4.12 / 5	0.53	14.72 / 5	0.01	13.00 / 5	0.02
m_T^ℓ	0.41 / 4	0.98	4.24 / 4	0.38	0.30 / 4	0.99	0.58 / 4	0.96
$m_T^{\text{min}}(b\ell)$	11.54 / 6	0.07	2.76 / 6	0.84	10.01 / 6	0.12	10.45 / 6	0.11

Differential WWb5 measurement - Dilepton channel



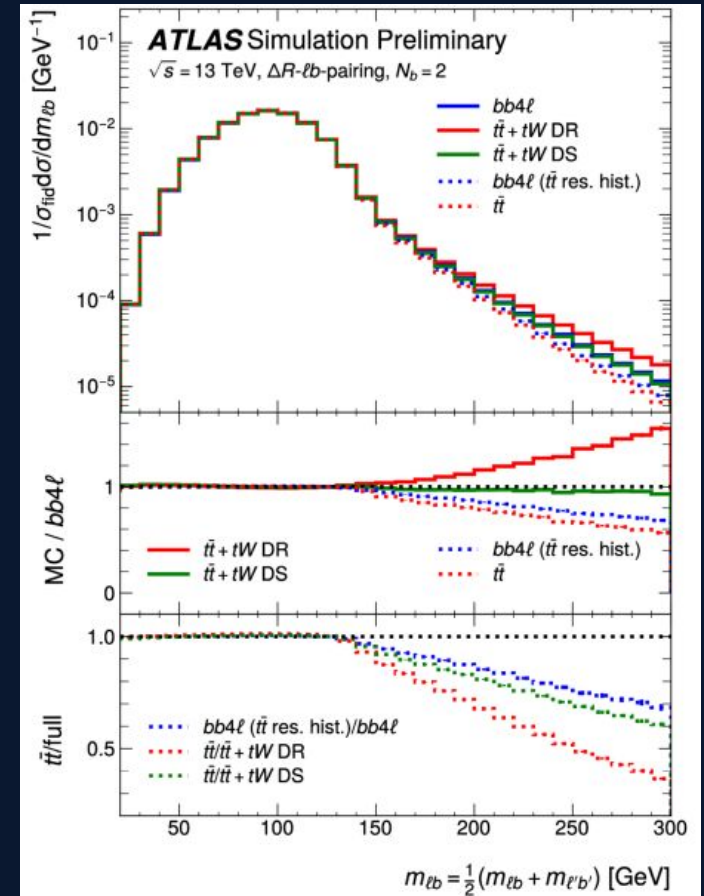
- Good description of $p_T(\text{jets})$ and MET
- The "problem" is more localized specifically in variables sensitive to interference

bb4l vs DR/DS/lineshape



- **bb4l vs $t\bar{t}+tW$ (DR) vs $t\bar{t}+tW$ (DS)** in terms of $m_{\ell b}$
- bb4l correct at NLO for these issues $\Rightarrow$ DR/DS and lineshape uncertainties not needed

$m_{\ell b}$ tail differences



- **Resonance-history decomposition**: within bb4l, events are projected onto their $t\bar{t}$ or tW resonance history, isolating each contribution shape in $m_{\ell b}$
- tW fraction reaches $\sim 30\%$ in the $m_{\ell b}$ tail — $t\bar{t}+tW$ MCs (DR/DS) predict even larger fractions there
- Quantifies how much interference is actually present in the tail

XS close to the $t\bar{t}$ threshold

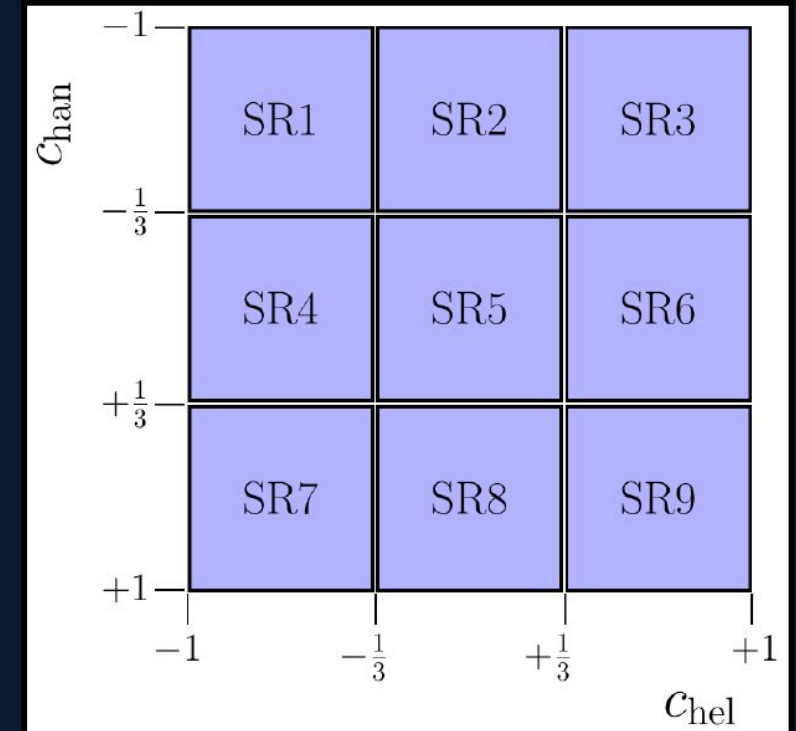
- Final state selection

- $\text{MET} > 60 \text{ GeV}$ for $(ee/\mu\mu)$
- ≥ 2 jets, ≥ 1 is b -tagged with 70% WP
- $m_{\ell\ell} \geq 15 \text{ GeV}$ and rejected if close to Z^0 mass
- $m(t\bar{t}) \leq 500 \text{ GeV}$
- $t\bar{t}$ system reconstruction: ellipse method

- Distributions

- C_{hel} — cosine of the lepton helicity angle in the $t\bar{t}$ rest frame (max. slope for spin-singlet states)
- C_{han} — same angle with the sign flipped along the top-quark direction (max. slope for spin-triplet states)

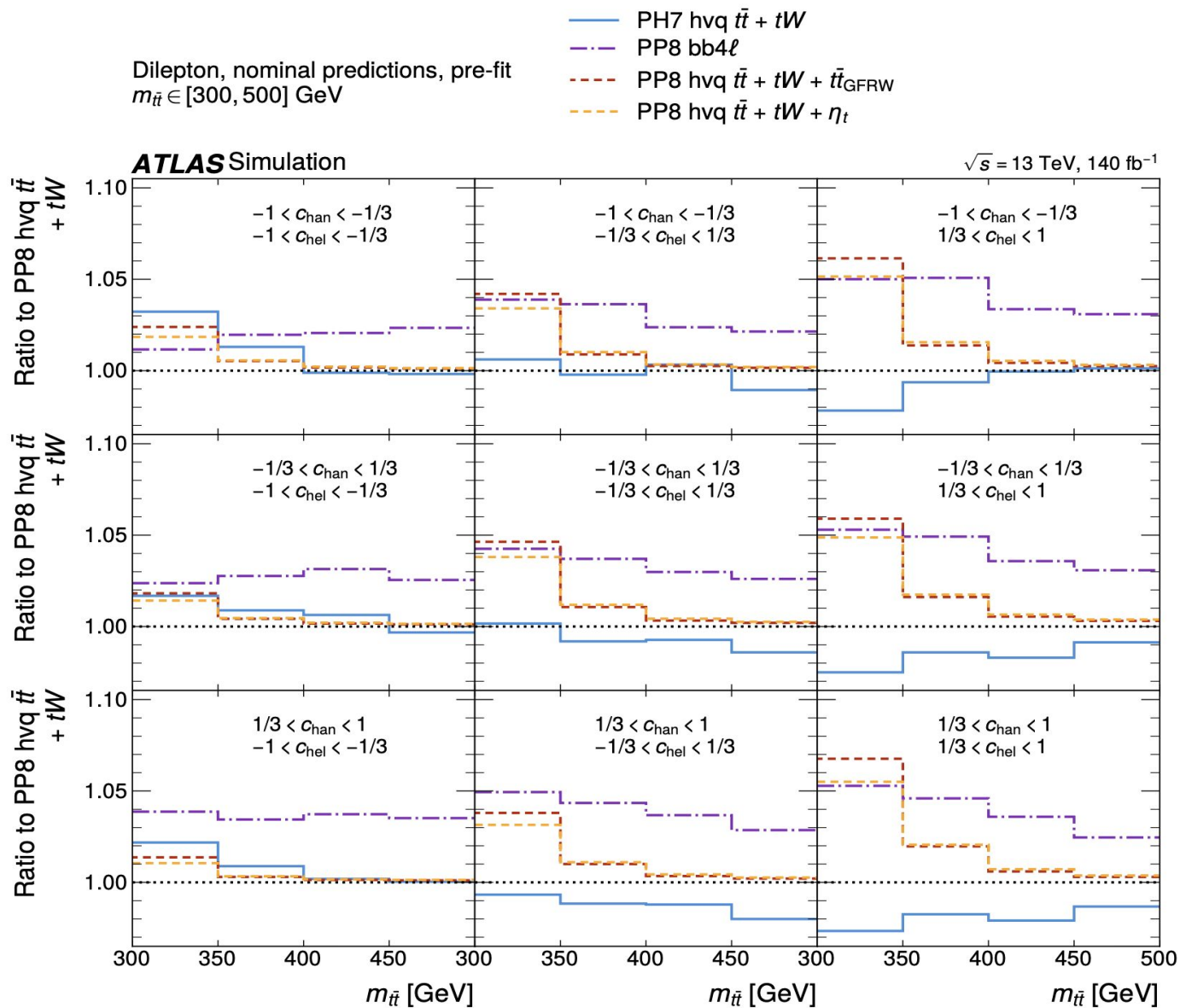
SRs are defined depending on the values of C_{hel} and C_{han}



Contribution: quasi-bound states to the data

- Binned profile-likelihood fit to 9 signal regions (SRs) and 4 control regions (CRs) for background evaluation

XS close to the $t\bar{t}$ threshold - Modelling

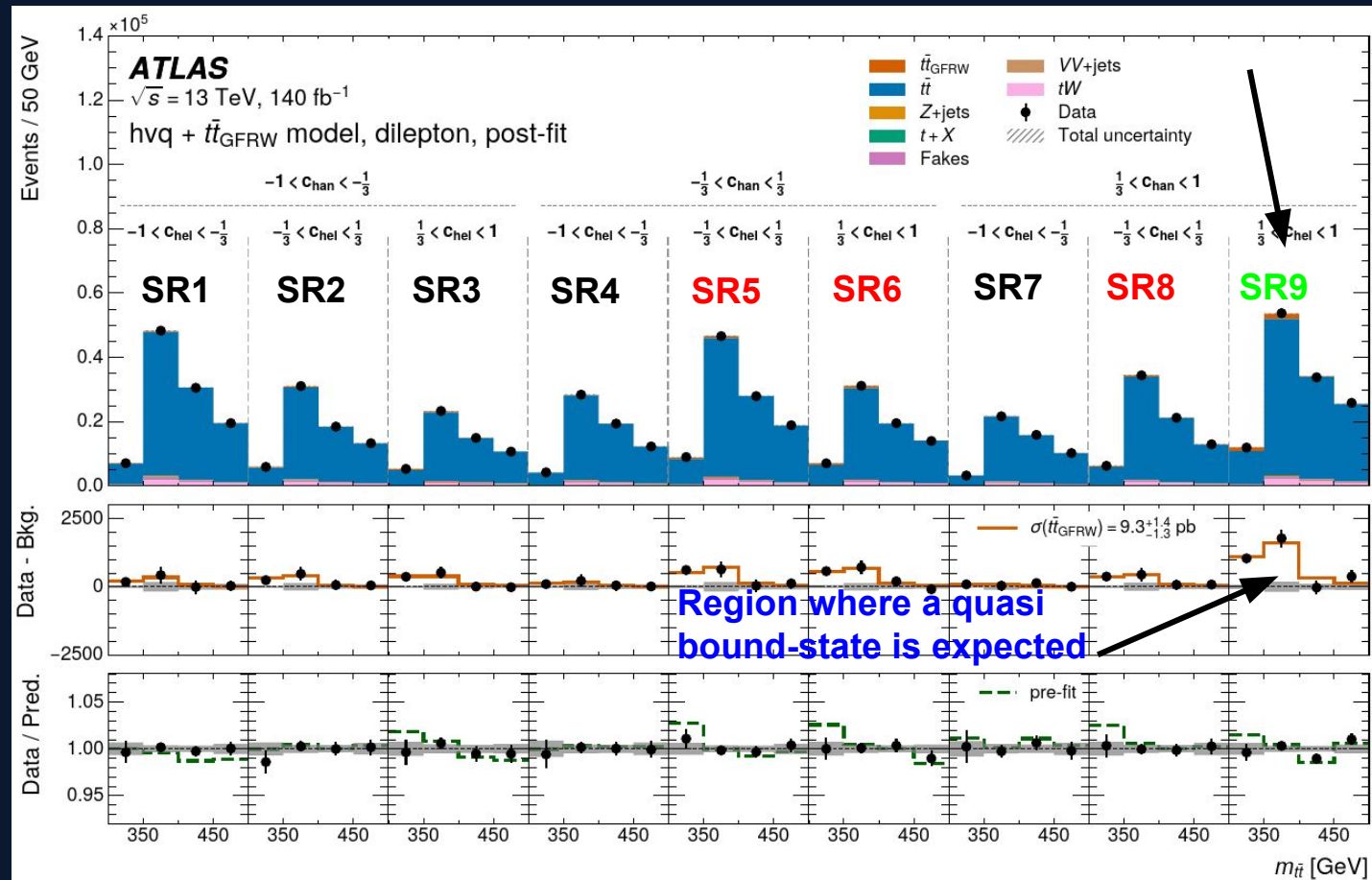


Different models, what to expect ?

- **bb4 ℓ / (hvq+tW)** → How the off-shell effect changes the shape of $m(t\bar{t})$
- **(hvq+tW+t $\bar{t}$ GFRW) / (hvq+tW)** → how the signal (quasi-bound state) change the shape of $m(t\bar{t})$
- The **off-shell effect in bb4 ℓ** modelling is more or less spread equally by the four $m(t\bar{t})$ bins
- However, **the t $\bar{t}$ GFRW concentrates in the lowest $m(t\bar{t})$ bins**
- What is more striking is that the excess concentrates where the $t\bar{t}$ quasi-bound state signal is expected

XS close to the $t\bar{t}$ threshold - Results

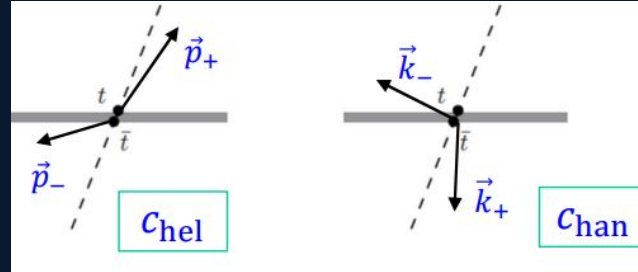
- $\mu = \sigma_{meas}/\sigma_{theory}$: Six normalisation factors with several sources of systematics included as NPs
- $\sigma_{t\bar{t}GFRW} = 9.3(+1.4/-1.3)\text{pb}$ against the analytic prediction (6.43 pb). The baseline hvq model (pure pQCD) is rejected with observed significance higher than 8σ (6σ expected)
- Excess concentrated in the lowest $m(t\bar{t})$ bins, at SR5, SR6, SR8, SR9, at high C_{hel}
- The alternative simplified η_t model gives $\sigma = 13.1\text{ pb}$, also excluded at $> 8\sigma$ (4σ expected)
- Lucas's talk: [Top properties at threshold](#)



Systematics

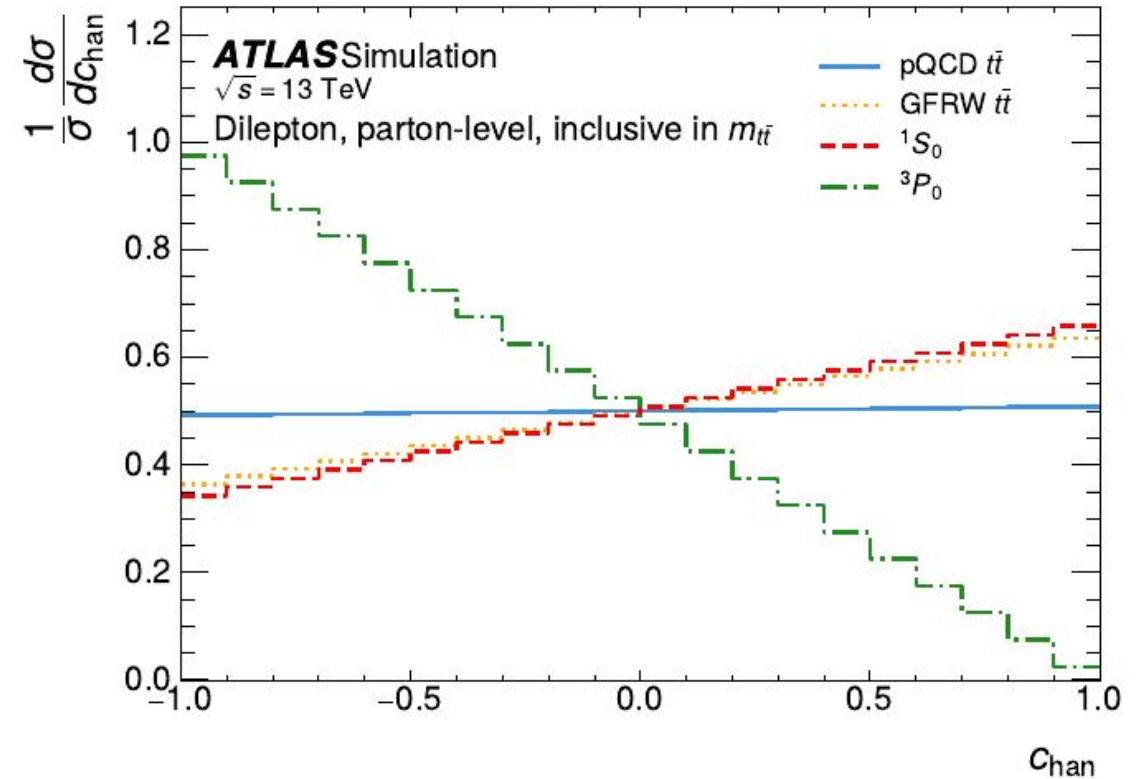
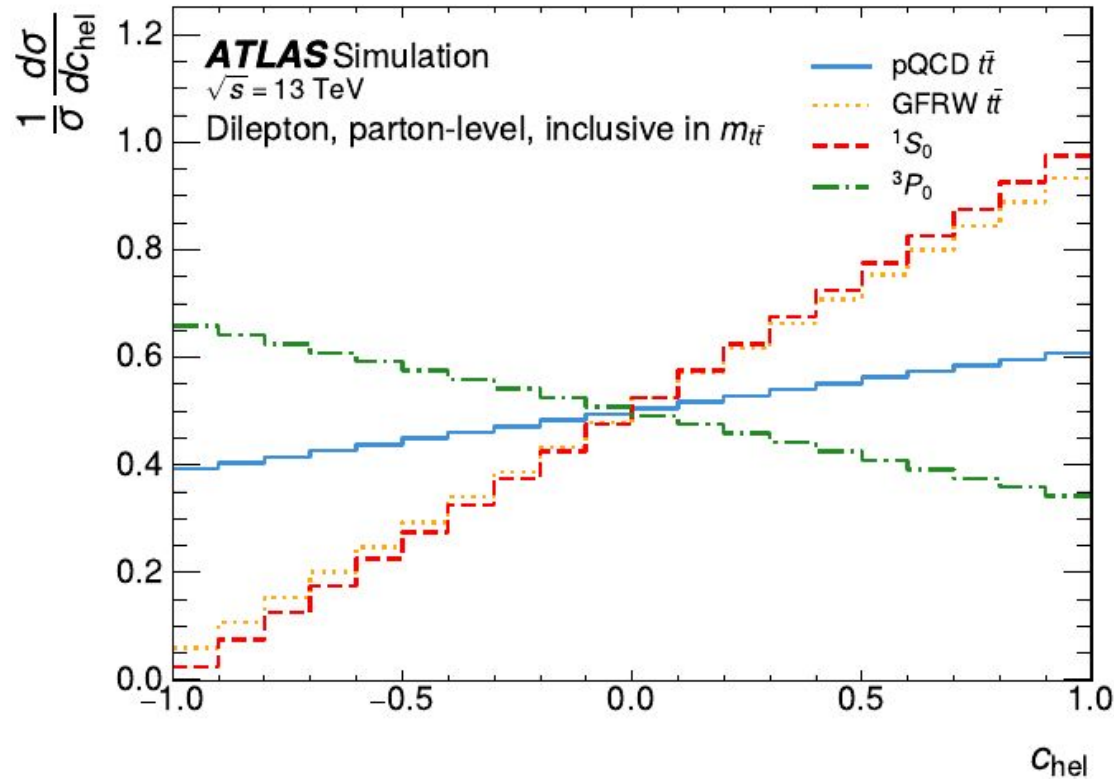
- $t\bar{t}_{GFRW} \sim 6.9\%$ FSR (largest individual effect) and ISR
- pQCD $t\bar{t}$ modelling $\sim 4.7\%$ - scale choice in the NNLO QCD
- Decays/off-shell effect, recoil-to-top and JES pile-up $\sim 1.5\%$

XS close to the threshold - Rep. Prog. Phys. 89 (2026) 057801



- C_{hel} is sensitive to 1S_0

- C_{chan} is sensitive to 3P_0



Observation of a pseudoscalar excess at the tt production threshold

[Rept. Prog. Phys. 88 \(2025\) no.8, 087801](#)

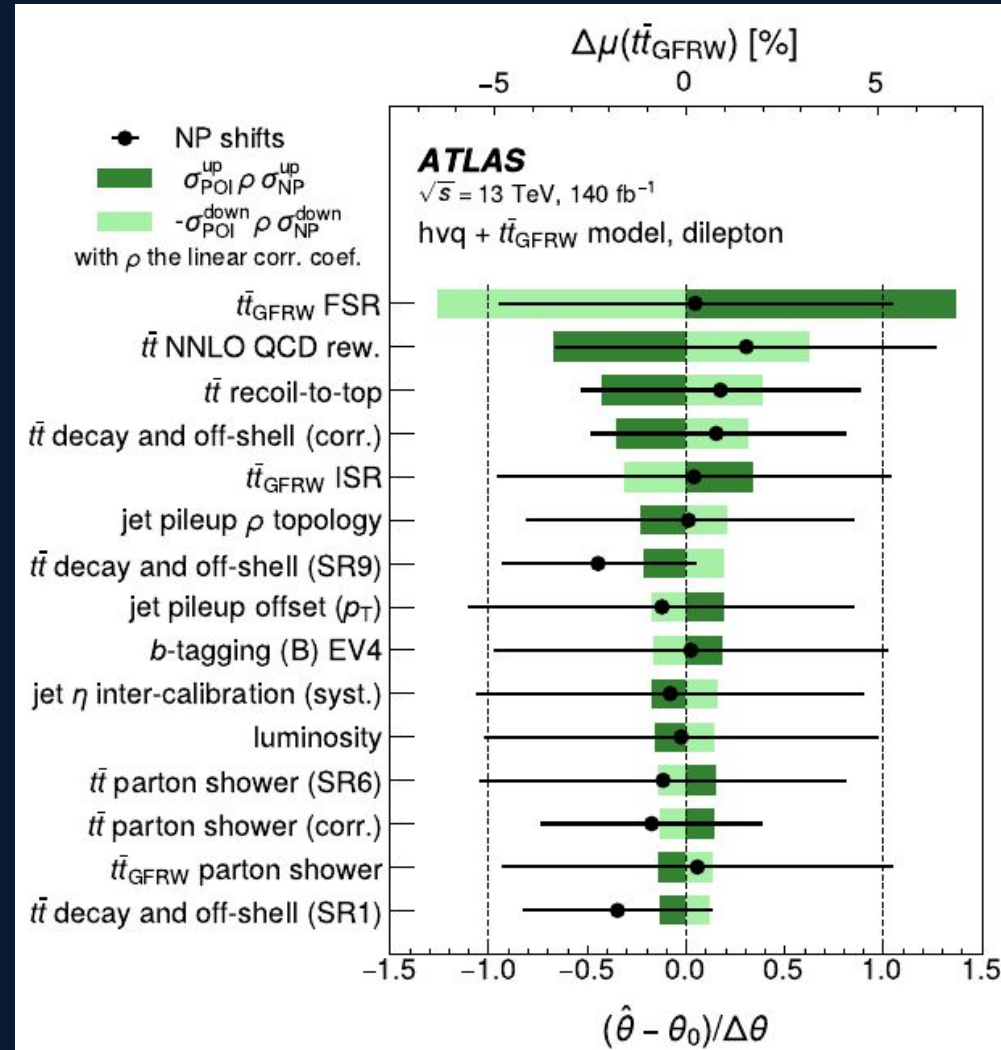
FO pQCD generator setup	$\sigma(\eta_t)$ [pb]
POWHEG v2 hvq + PYTHIA	8.7 ± 1.1
POWHEG v2 hvq + HERWIG	8.6 ± 1.1
MADGRAPH5_aMC@NLO FxFx + PYTHIA	9.8 ± 1.3
POWHEG vRES bb4l + PYTHIA	6.6 ± 1.4
Nominal result	$8.8^{+1.2}_{-1.4}$

CMS Collaboration

CMS and ATLAS converges to values of the same order of magnitude

Systematics breakdown

tt XS close to the threshold
Rep. Prog. Phys. 89 (2026) 057801



tt threshold effects in eμ diff. distributions

CERN-EP-2026-107

