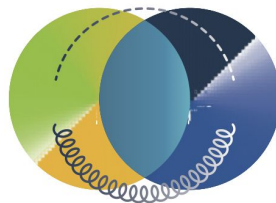


ATLAS results on Top Properties and Threshold Region



Bundesministerium
für Forschung, Technologie
und Raumfahrt



color
meets
flavor



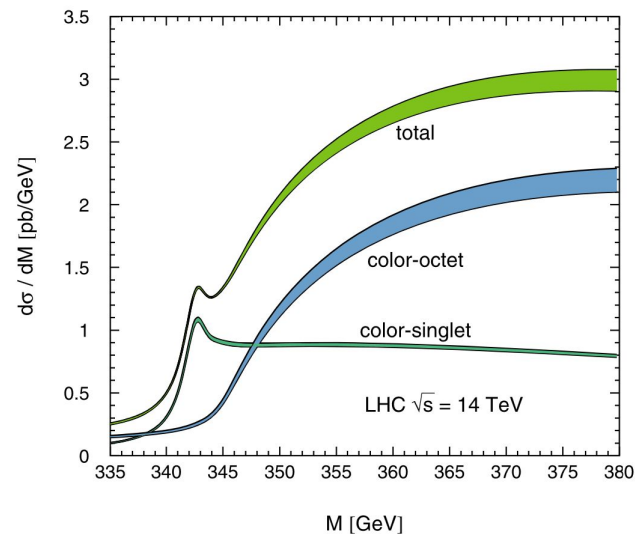
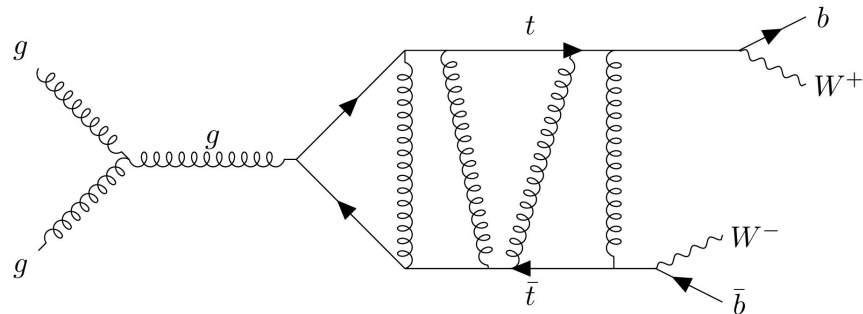
ATLAS
EXPERIMENT

QCD@LHC 2026 - 09/26

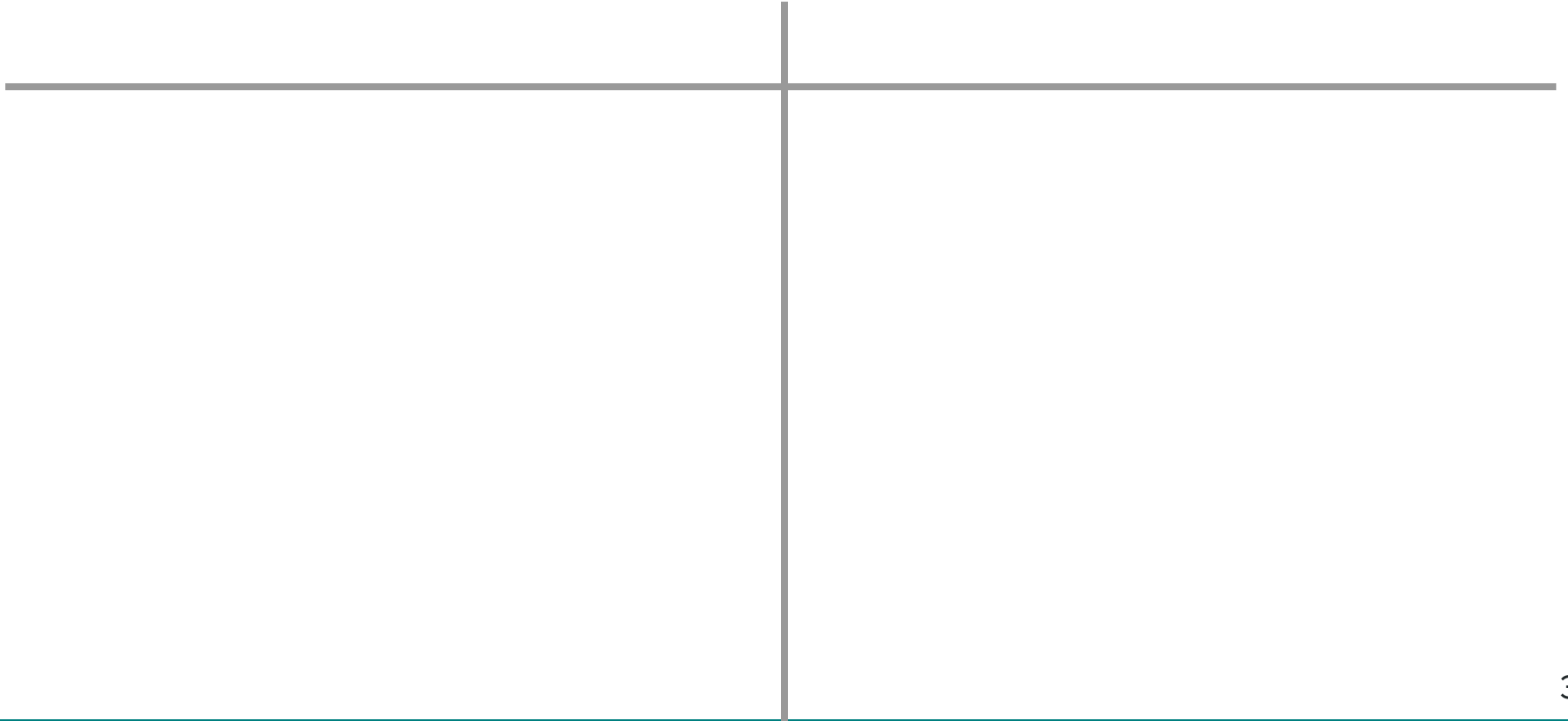
Lucas Cremer on behalf of the ATLAS collaboration - TU Dortmund | ATLAS

Why is the Threshold Region interesting?

- $t\bar{t}$ close to its production threshold, i.e. $m_{t\bar{t}} \approx 2m_t \approx 345 \text{ GeV}$
- $\mathcal{O}(10^8)$ $t\bar{t}$ events (inclusive) produced
- NRQCD including quasi-bound state formation (“toponium”)
 - expected in 1% of $t\bar{t}$ events
 - originally not included in MC simulations
 - measured by CMS [Rep. Prog. Phys. 88 087801](#)
- sensitivity to multiple top properties (Y_t, m_t)



Modelling the “Toponium” effect



Modelling the “Toponium” effect

$1S_0$

- approximate toponium effect with a scalar resonance
- manually set parameters to position resonance at threshold
- pure spin-singlet
(expected for dominant contribution of “toponium”)
- easy to compute

Modelling the “Toponium” effect

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GFRW $t\bar{t}$

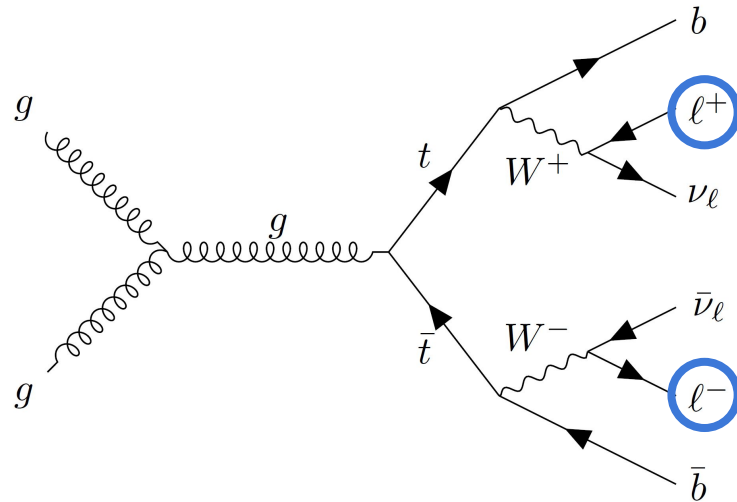
- based on NRQCD Green’s function describing the $t\bar{t}$ system
- use Green’s function (GF) to reweight (RW) $t\bar{t}$ matrix elements
- close to spin-singlet
- harder to compute

Searching for “Toponium”

[ATLAS Rep. Prog. Phys. 89 057801](#)

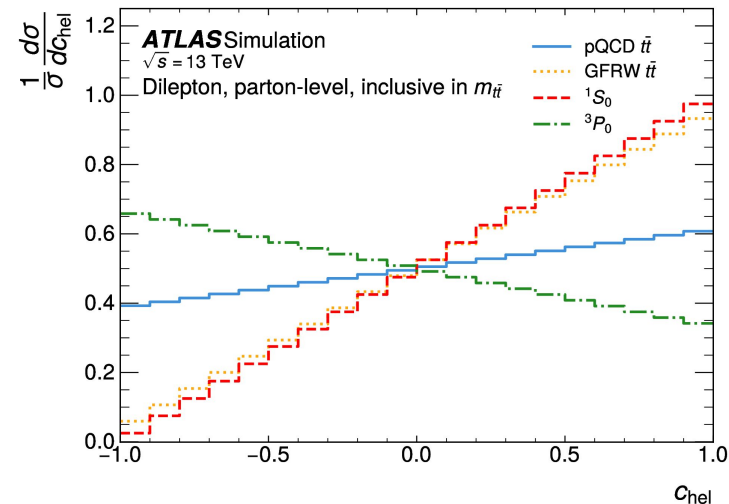
Dedicated Search

- **dedicated analysis in dileptonic $t\bar{t}$ events**
(full event reconstruction)



Dedicated Search

- dedicated analysis in dileptonic $t\bar{t}$ events (full event reconstruction)
- angular variables provide separation power as “toponium” close to a spin singlet



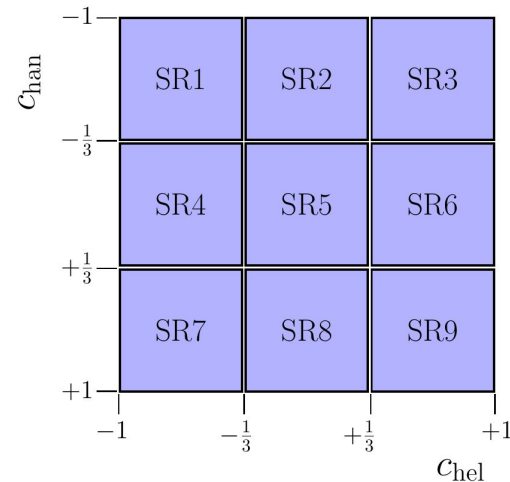
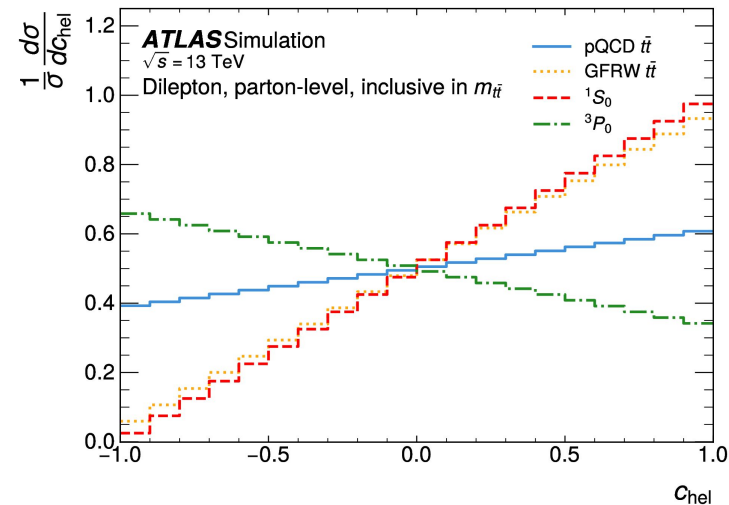
$$c_{\text{hel}} = \cos(\theta_{\ell\bar{\ell}})$$

$$c_{\text{han}} = \cos(\theta_{\ell'\ell})$$

(lepton momenta in the top quark rest frames)

Dedicated Search

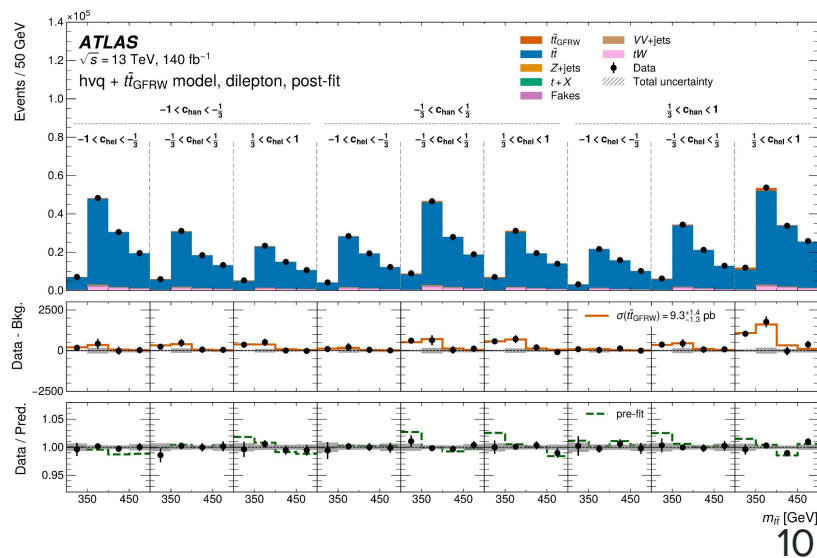
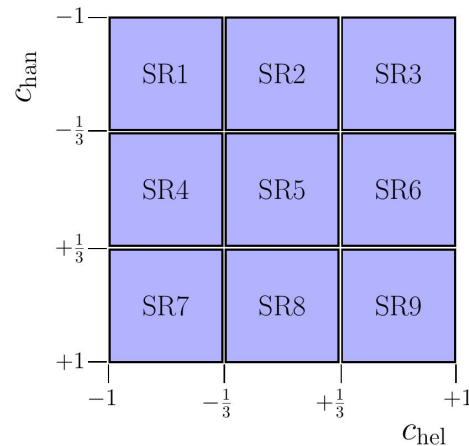
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- 9 Signal Regions (SR) based on angular variables in the $t\bar{t}$ center-of-mass frame



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- observation via fit in $m_{t\bar{t}}$:

$$\sigma = 9.3_{-1.3}^{+1.4} \text{ pb} \quad (8\sigma) \quad \text{🎉}$$

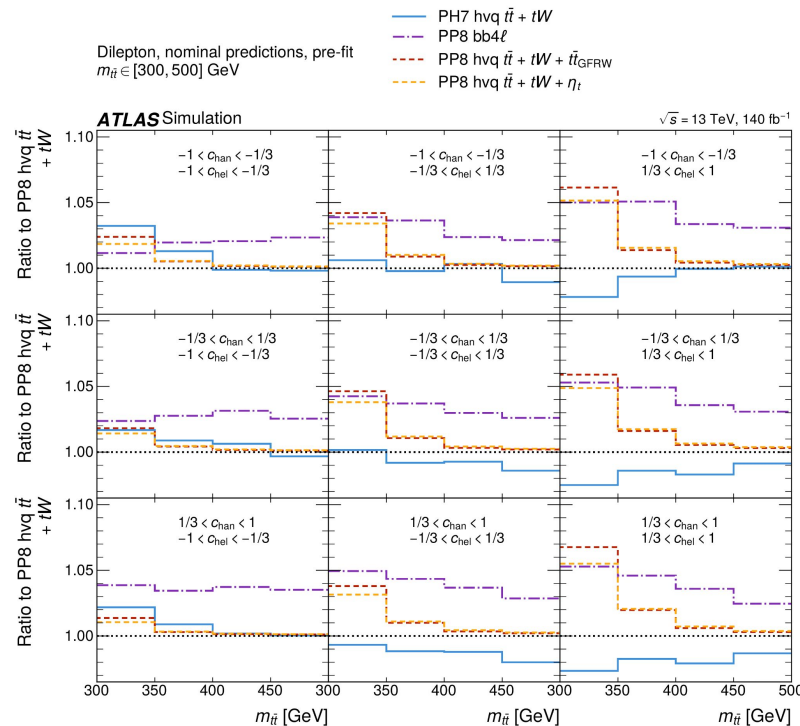


Dedicated Search

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- on-going work in getting a more complete simulation

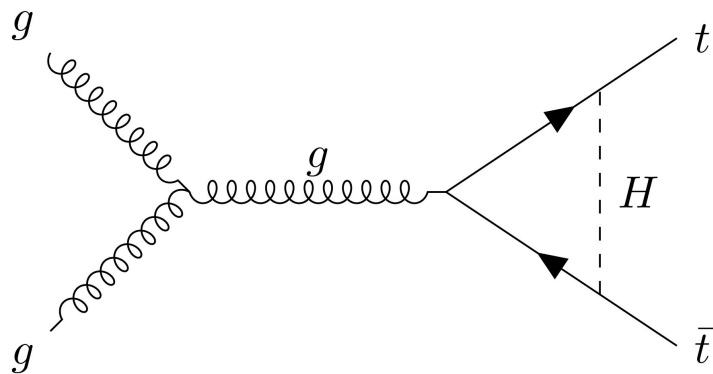


Measuring the Yukawa Coupling

[JHEP 2026, 117 \(2026\)](#)

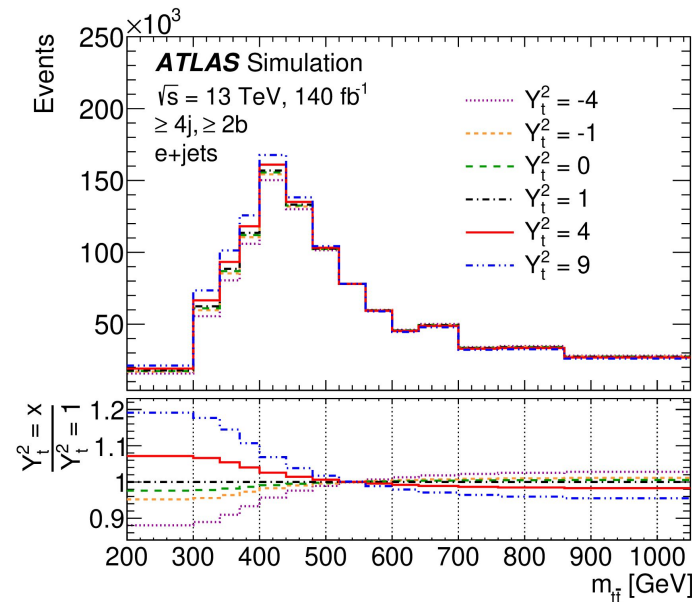
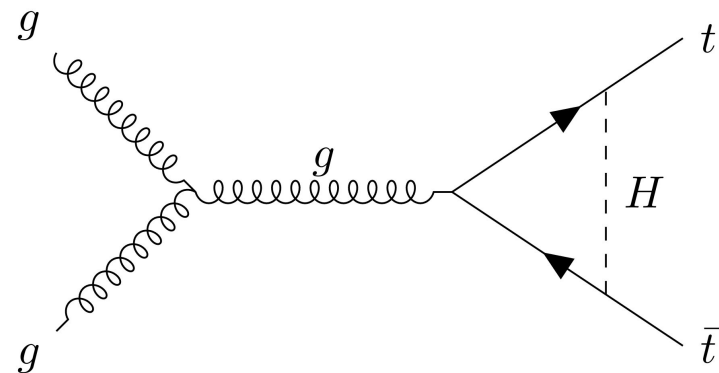
Y_t via $t\bar{t}$

- $\sigma_{t\bar{t}}$ sensitive to top-yukawa coupling (especially in threshold region)
- provides complementary approach to traditional measurements of Y_t



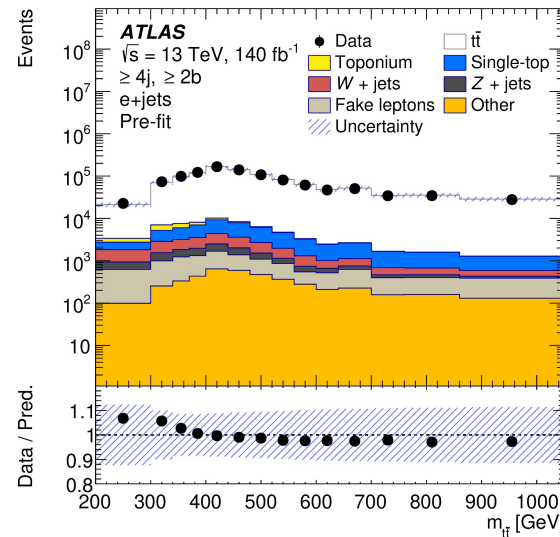
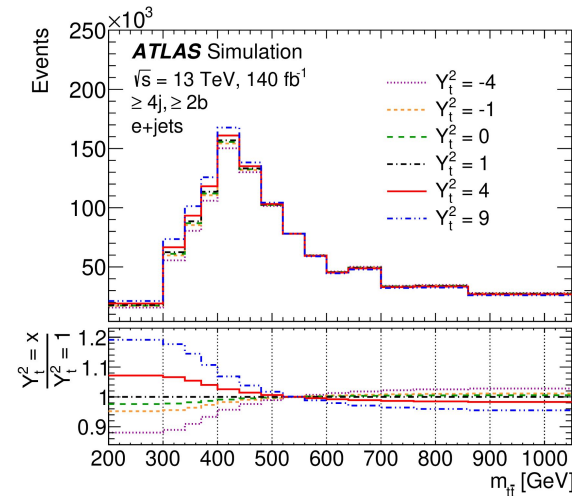
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(Y_t^2 to stabilise fit as dependence is quadratic)



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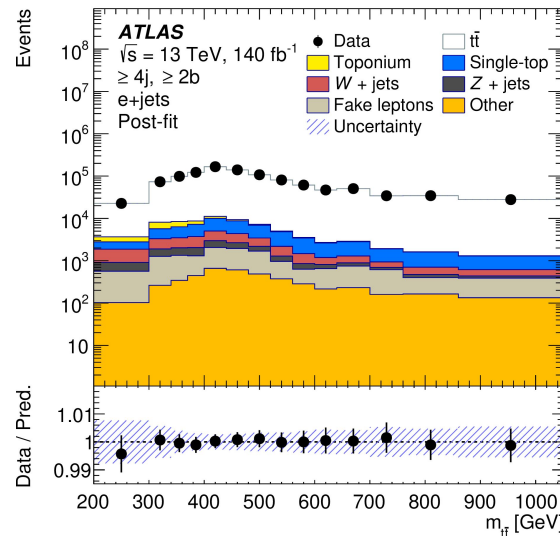
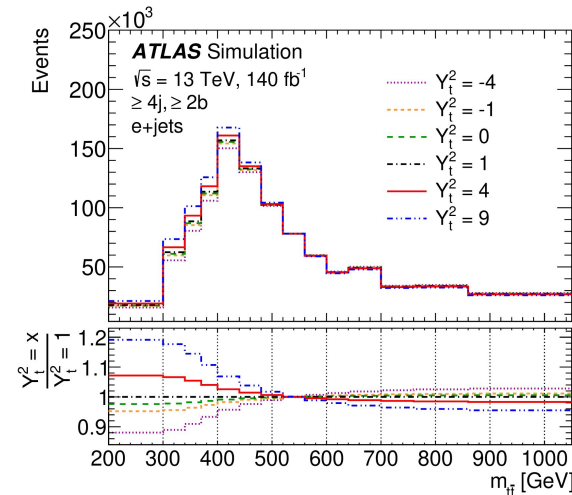
PreFit

Y_t via $t\bar{t}$

- $\sigma_{t\bar{t}}$ sensitive to top-yukawa coupling (especially in threshold region)
- provides complementary approach to traditional measurements of Y_t
- template fit in $m_{t\bar{t}}$ (Y_t^2 to stabilise fit as dependence is quadratic)
- result:

$$Y_t^2 = 1.3 \pm 1.7$$

$$Y_t < 2.1$$



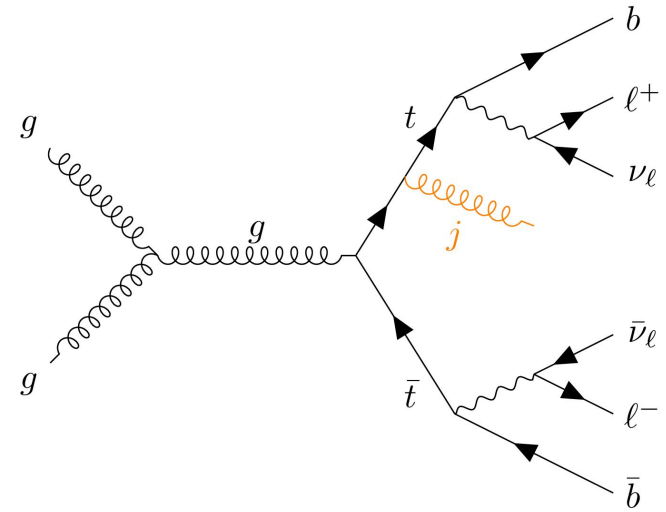
Postfit

Measuring the Top-Quark Mass

[JHEP 2025, 23 \(2025\)](#), [JHEP 2026, 99 \(2026\)](#)

m_t via $t\bar{t} + 1j$

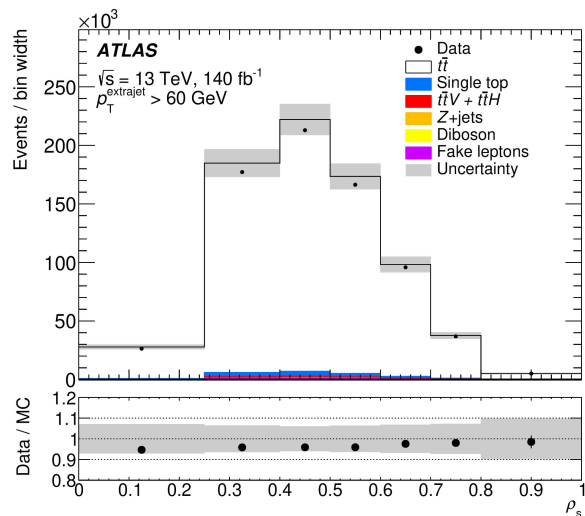
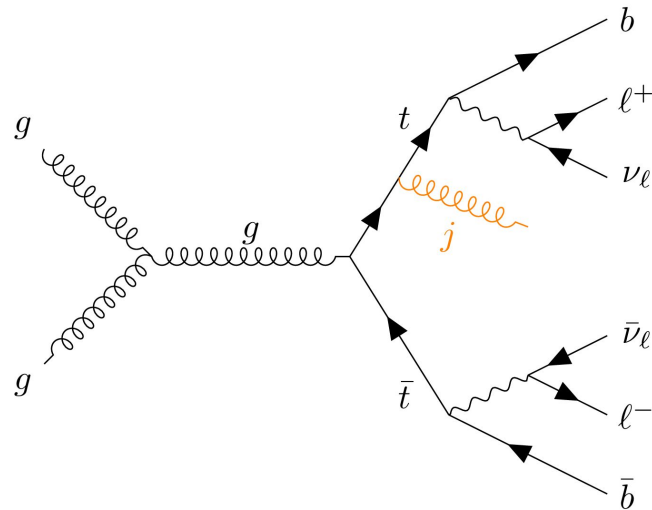
- extract mass from differential cross-section at parton level



m_t via $t\bar{t} + 1j$

- extract mass from differential cross-section at parton level
- unfold ρ_s to parton level

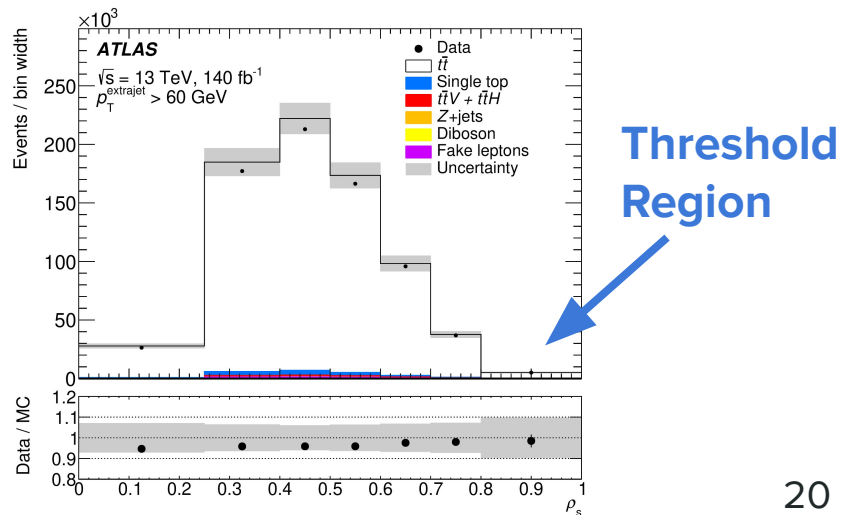
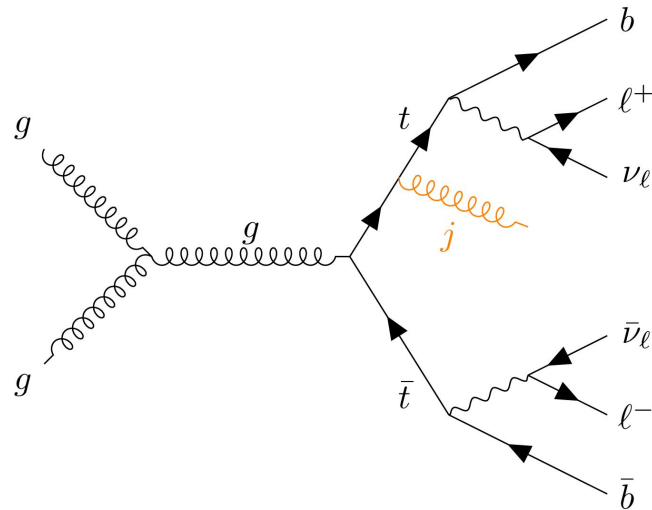
$$\rho_s = \frac{2m_0}{m_{t\bar{t}j}}$$



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- extract mass from differential cross-section at parton level
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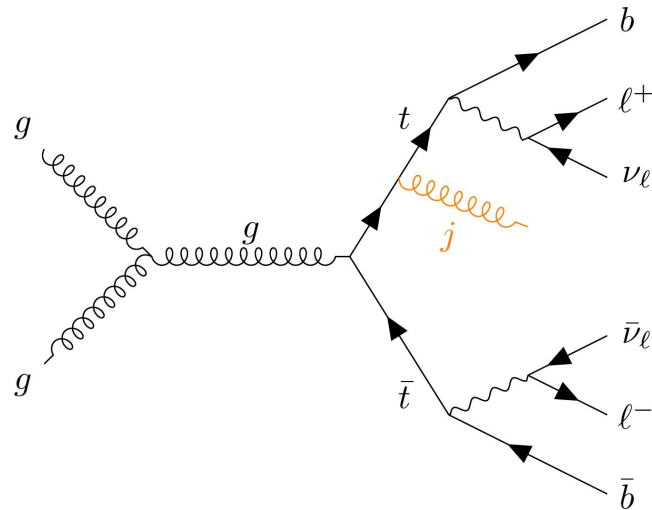
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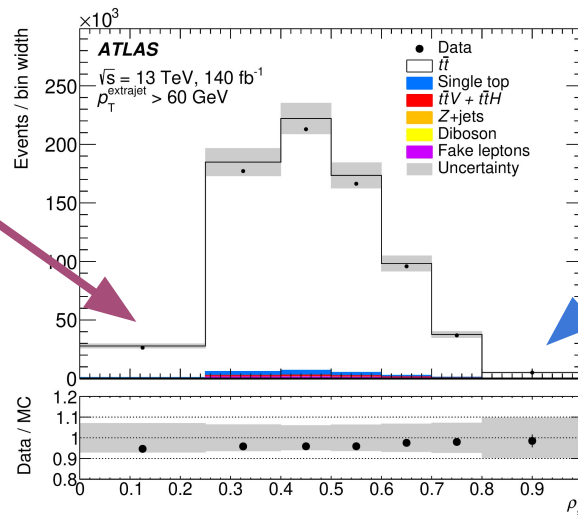
m_t via $t\bar{t} + 1j$

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- unfold ρ_s to parton level

$$\rho_s = \frac{2m_0}{m_{t\bar{t}j}}$$



High
Energies



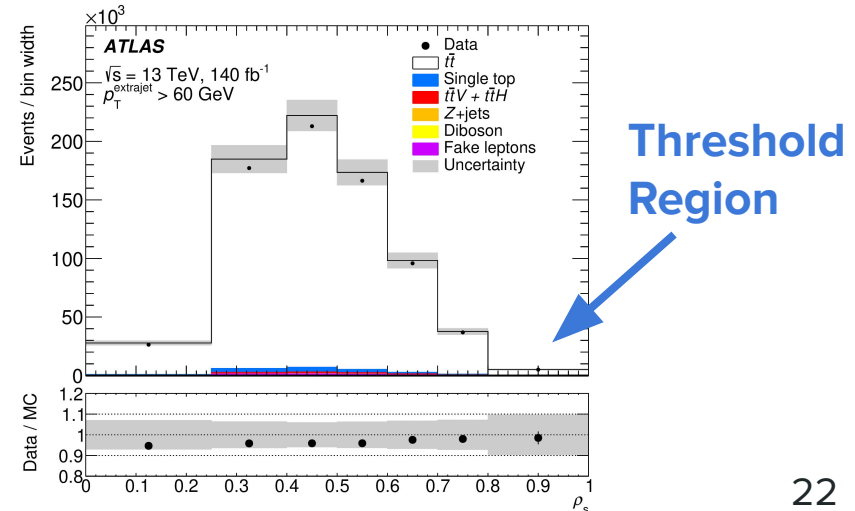
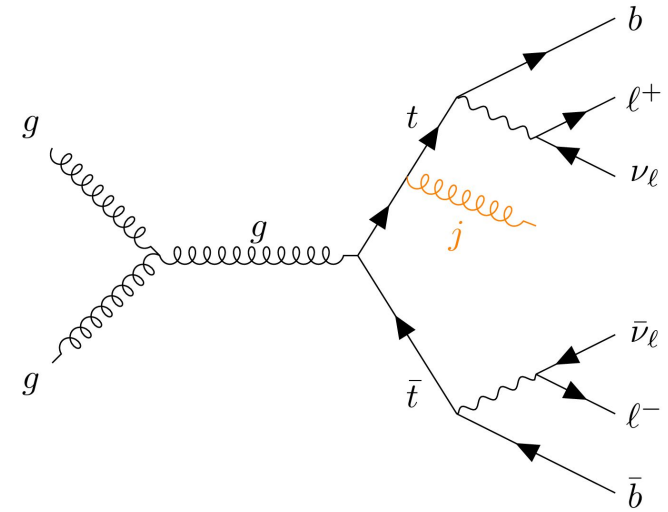
Threshold
Region

m_t via $t\bar{t} + 1j$

- extract mass from differential cross-section at parton level
- unfold ρ_s to parton level

$$\rho_s = \frac{2m_0}{m_{t\bar{t}j}}$$

- highest sensitivity to m_t in threshold region



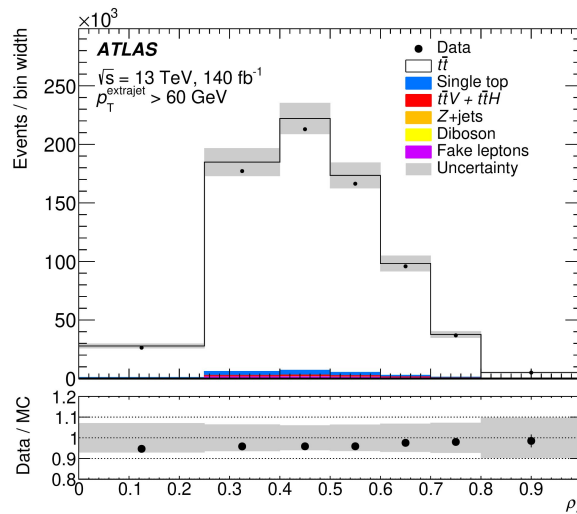
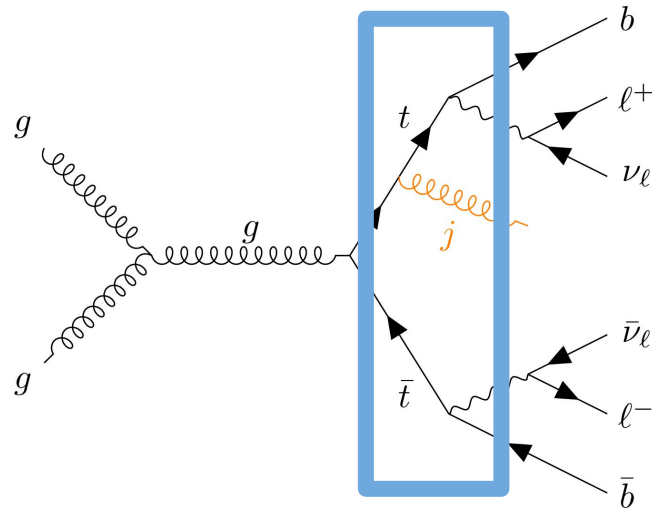
m_t via $t\bar{t} + 1j$

- extract mass from differential cross-section at parton level
- unfold ρ_s to parton level

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- highest sensitivity to m_t in threshold region
- unfold to parton level

2 $\rightarrow$ 3



m_t via $t\bar{t} + 1j$

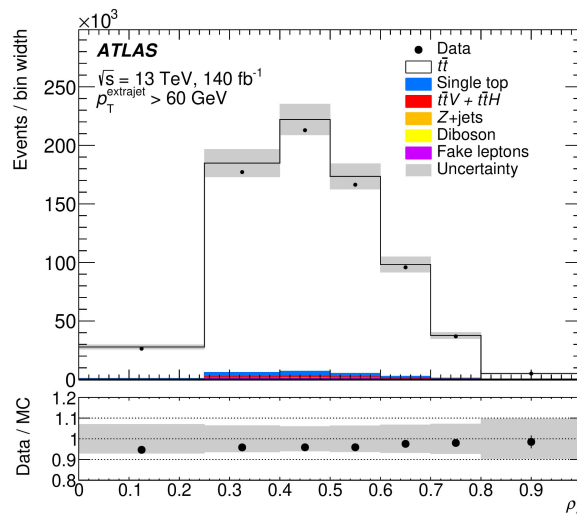
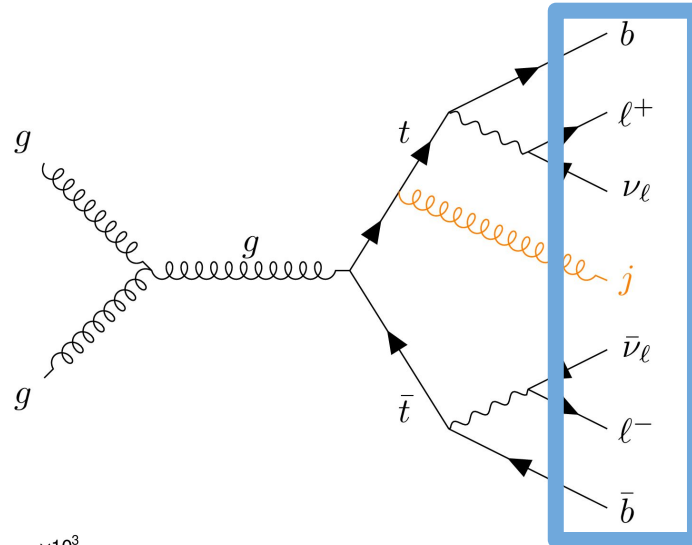
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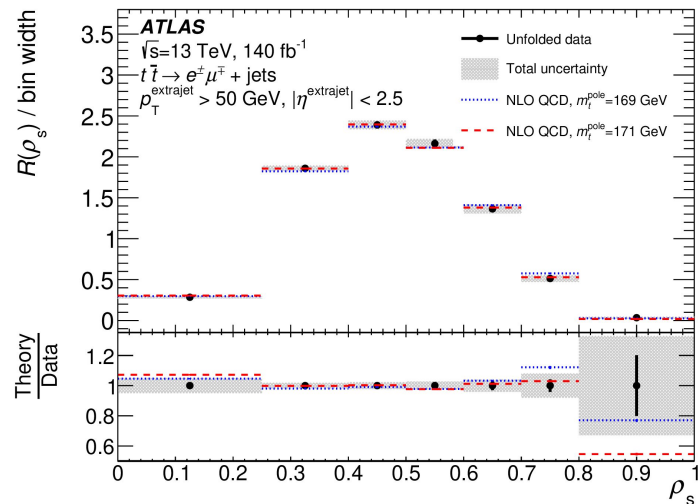
$$2 \rightarrow 3$$

$$2 \rightarrow 7$$

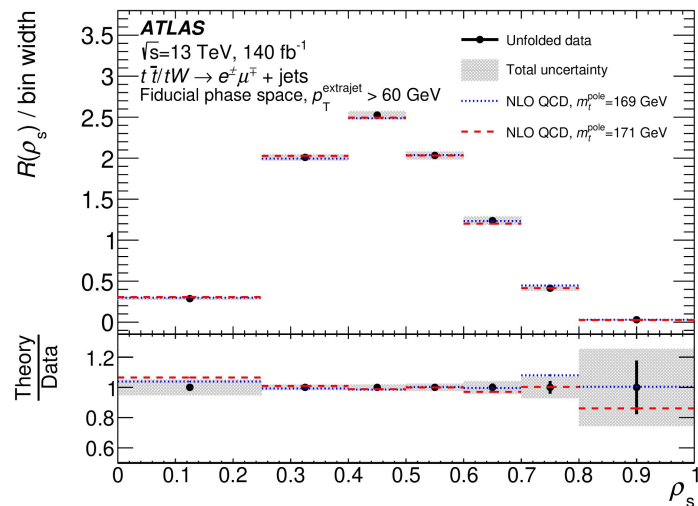


m_t via $t\bar{t} + 1j$

Unfolded Distributions:



2 → 3



2 → 7

m_t via $t\bar{t} + 1j$

- mass values obtained via χ^2 fit

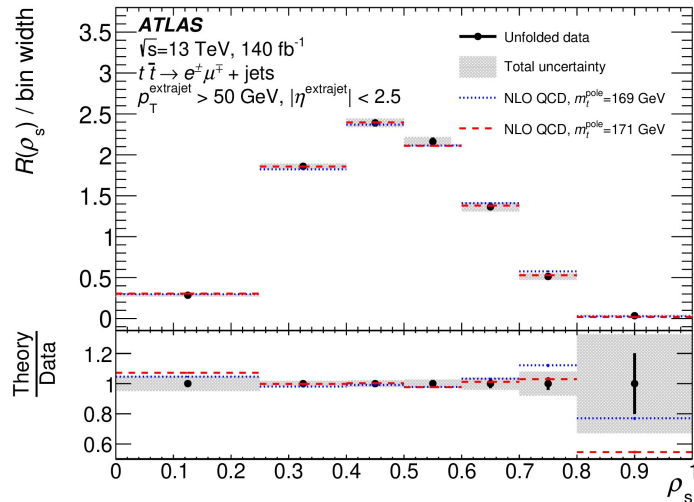
$2 \rightarrow 3$

$$m_t = 170.73^{+1.47}_{-1.44} \text{ GeV}$$

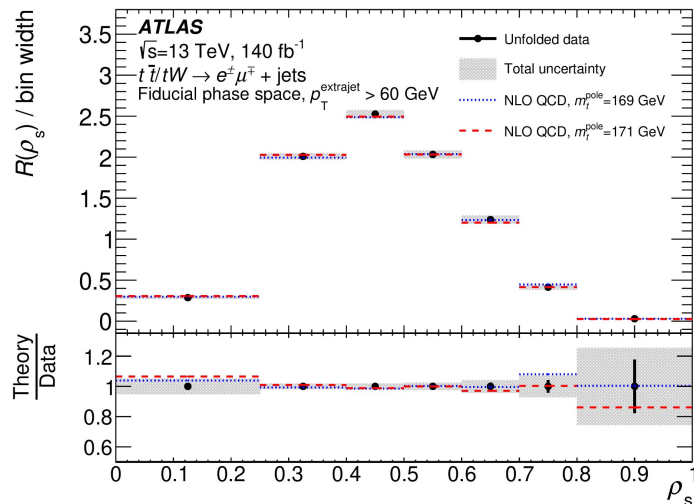
$2 \rightarrow 7$

$$m_t = 171.69^{+1.91}_{-2.24} \text{ GeV}$$

- $2 \rightarrow 7$ less sensitivity to m_t in threshold region



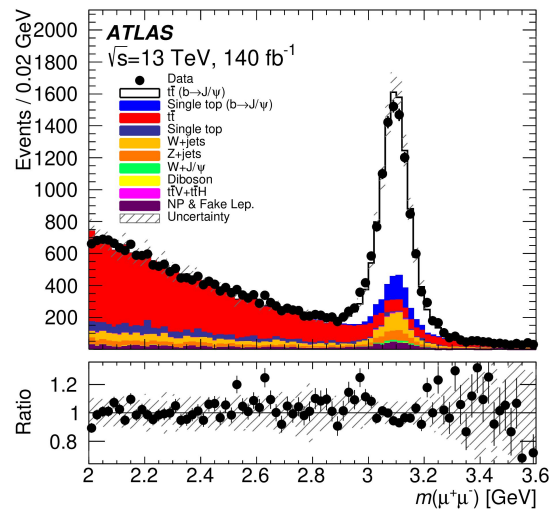
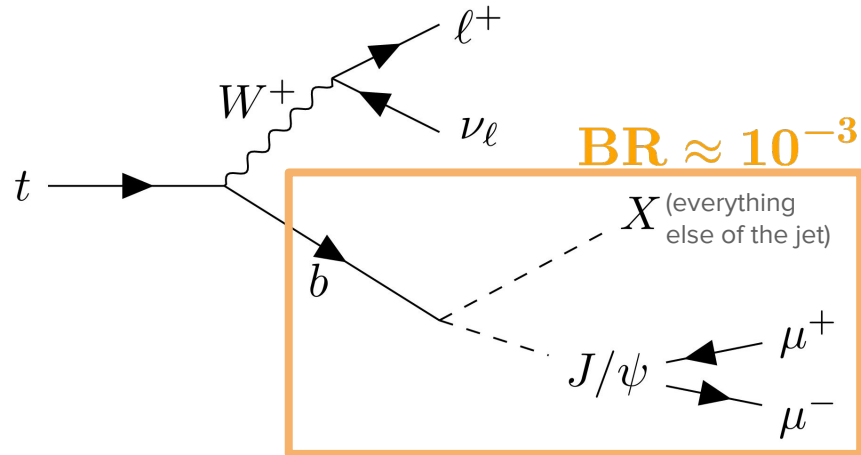
$2 \rightarrow 3$



$2 \rightarrow 7$

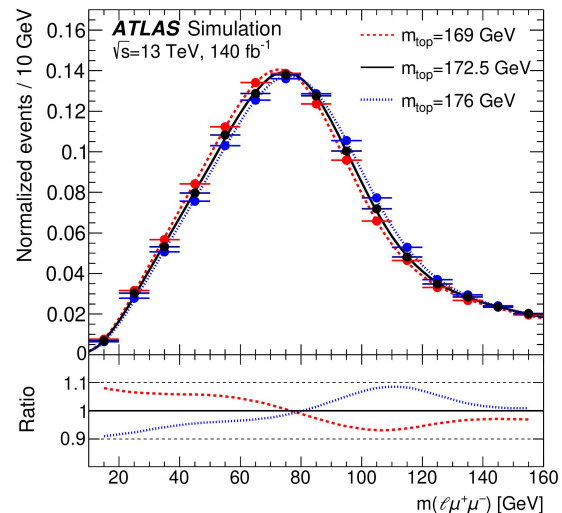
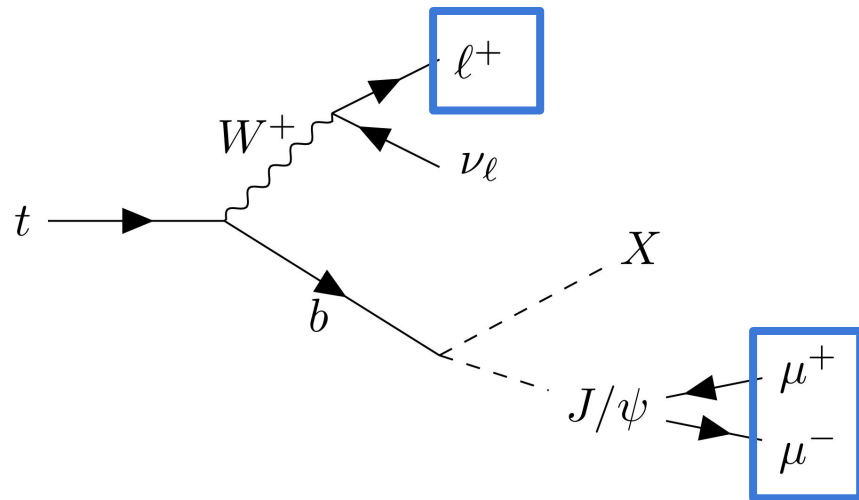
m_t via J/ψ

- **motivation:** less sensitive to jet reconstruction



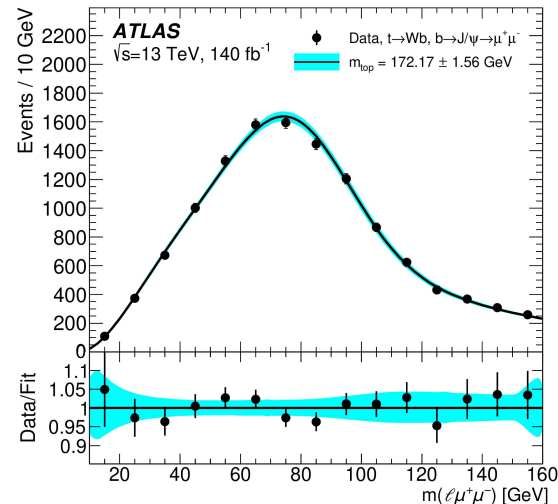
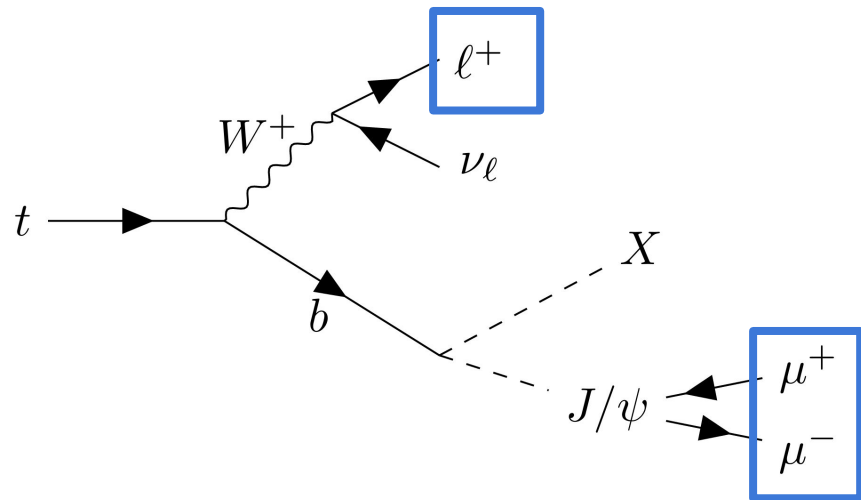
m_t via J/ψ

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- use $t\bar{t}$ and single top-quark events
- **template fit** in $m(\ell\mu^+\mu^-)$



m_t via J/ψ

- **motivation:** less sensitive to jet reconstruction
- use $t\bar{t}$ and single top-quark events
- **template fit** in $m(\ell\mu^+\mu^-)$
- $m_t = 172.17 \pm 0.80(\text{stat})\text{GeV}$
 $\pm 0.81(\text{syst})$
 $\pm 1.07(\text{recoil})$
- **recoil:** which particle is assigned the recoil of secondary gluon emission in parton shower (*recoil-to-top* vs. *recoil-to-b*)

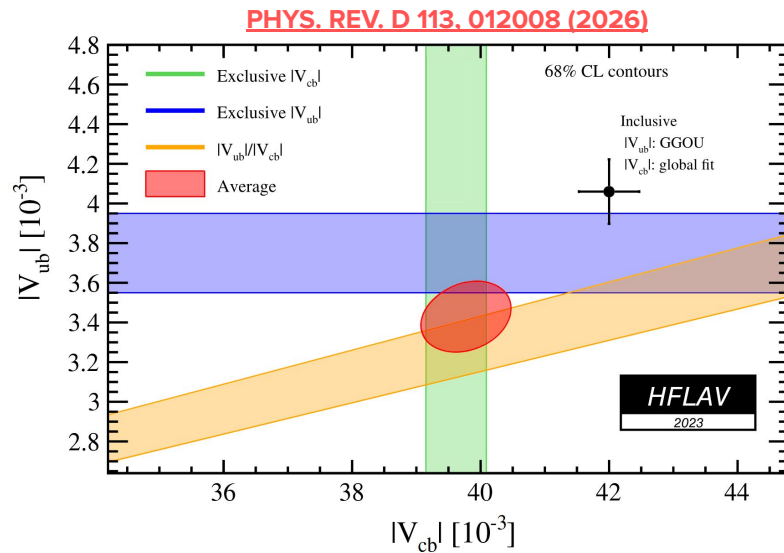


Measuring CKM Matrix Element V_{cb}

[JHEP 2026, 78 \(2026\)](#)

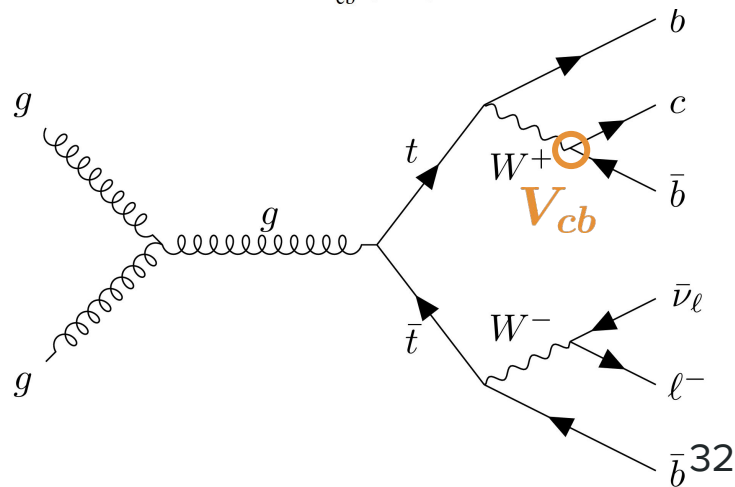
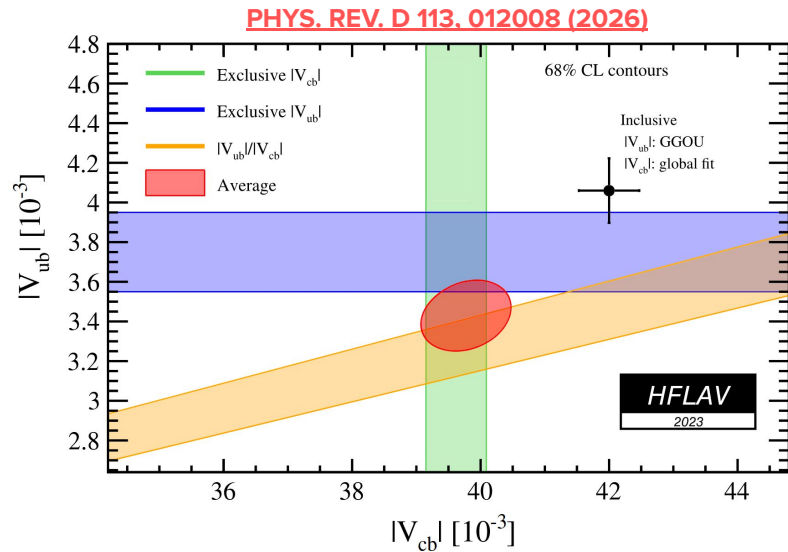
V_{cb} via $t\bar{t}$

- 3σ tension in measurements using B hadron decay



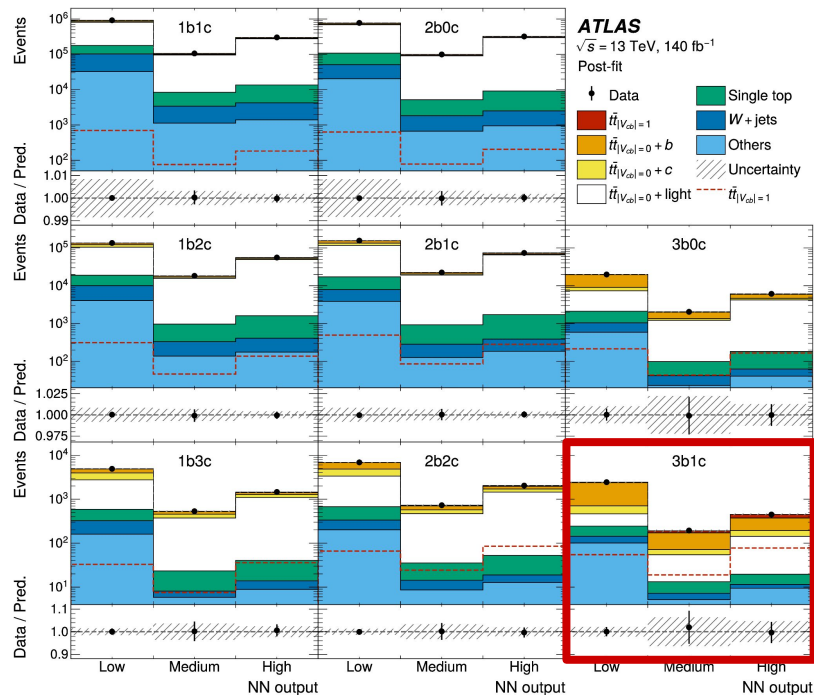
V_{cb} via $t\bar{t}$

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- $t\bar{t}$ provides complementary measurement at perturbative scales



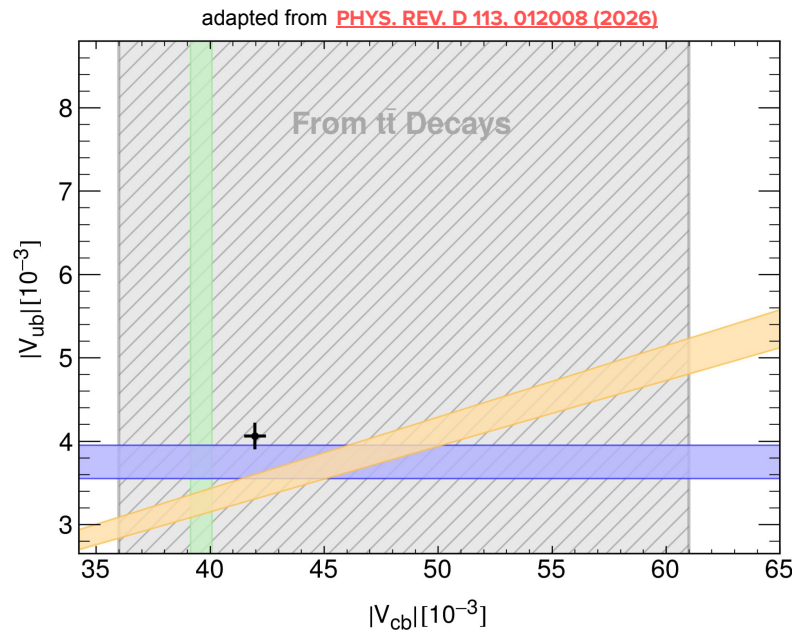
V_{cb} via $t\bar{t}$

- 3σ tension in measurements using B hadron decay
- $t\bar{t}$ provides complementary measurement at perturbative scales
- 8 regions based on heavy-flavour tags
 - μ of $|V_{cb}|$, $t\bar{t}$, $t\bar{t} + c$, $t\bar{t} + b$
 - c-tagging efficiencies and mistag rates
 (same data as default calibration)



V_{cb} via $t\bar{t}$

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- 8 regions based on heavy-flavour tags
 - μ of $|V_{cb}|$, $t\bar{t}$, $t\bar{t} + c$, $t\bar{t} + b$
 - c-tagging efficiencies and mistag rates(same data as default calibration)
- **result:** $|V_{cb}| = (50^{+11}_{-14}) \times 10^{-3}$
(equally limited by modelling & statistical uncertainties)



Conclusion

- observation of excess at threshold, could be explained by NRQCD including quasi-bound state
 - better modelling of NRQCD required
- threshold region sensitive to multiple top-quark properties
- able to complement traditional measurements with $t\bar{t}$ measurements
 - testing fundamental SM parameters

Observation of “Toponium”	$\sigma = 9.3_{-1.3}^{+1.4} \text{ pb}$
m_t via $t\bar{t} + 1j$	$m_t = 170.73_{-1.44}^{+1.47} \text{ GeV}$
m_t via J/ψ	$m_t = 172.17 \pm 1.56 \text{ GeV}$
$ V_{cb} $ via $t\bar{t}$	$ V_{cb} = (50_{-14}^{+11}) \times 10^{-3}$
Y_t via $t\bar{t}$	$Y_t < 2.1$

Backup

Signs in traditional $t\bar{t}$ Measurements

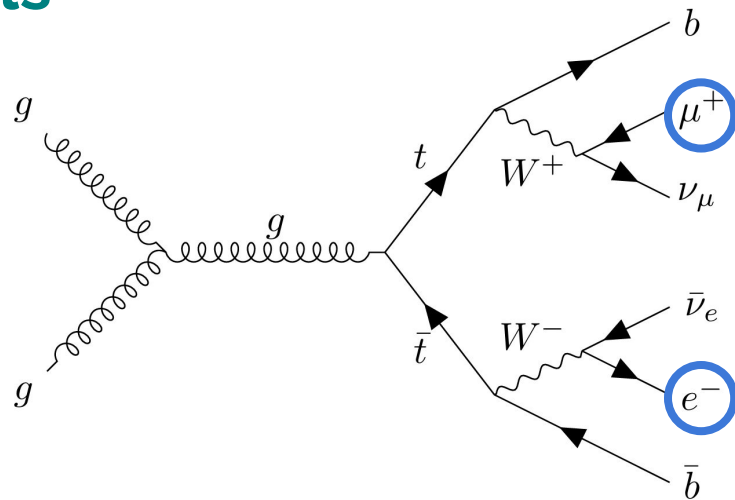
[ATLAS arXiv 2605.02341](#)

- $t\bar{t}$ cross-sections measurements are getting very precise $\rightarrow$ 1.3% uncertainty for inclusive

Signs in traditional $t\bar{t}$ Measurements

[ATLAS arXiv 2605.02341](#)

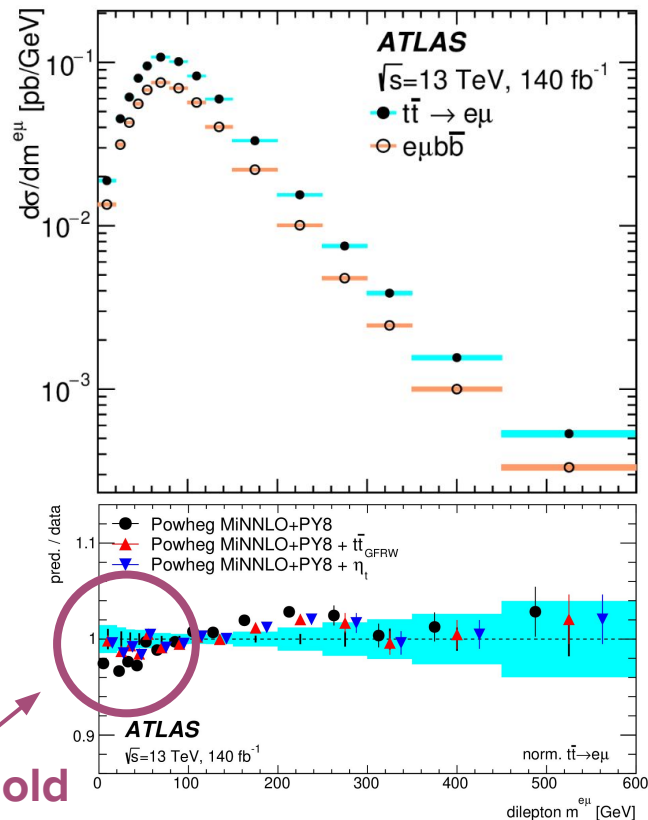
- $t\bar{t}$ cross-sections measurements are getting very precise $\rightarrow$ 1.3% uncertainty for inclusive
- reinterpretation of differential cross-sections in the dileptonic channel of $t\bar{t}$



Signs in traditional $t\bar{t}$ Measurements

ATLAS arXiv 2605.02341

- $t\bar{t}$ cross-sections measurements are getting very precise $\rightarrow$ 1.3% uncertainty for inclusive
- reinterpretation of differential cross-sections in the dileptonic channel of $t\bar{t}$
- cross-section as function of $m^{e\mu}$ (+ various more)
- agreement improved by adding “toponium” simulation

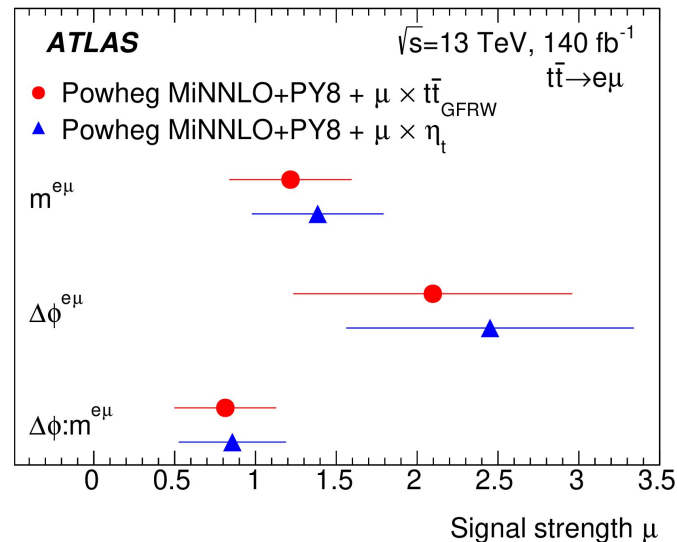


Threshold
Region

Signs in traditional $t\bar{t}$ Measurements

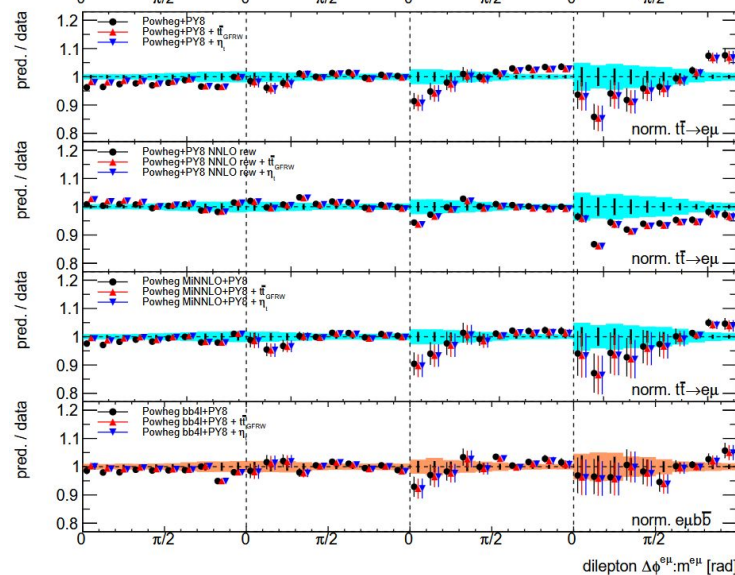
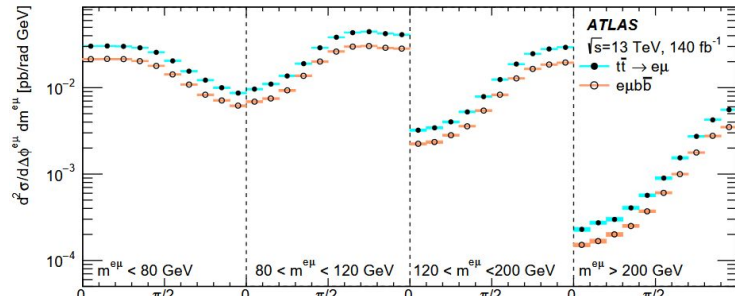
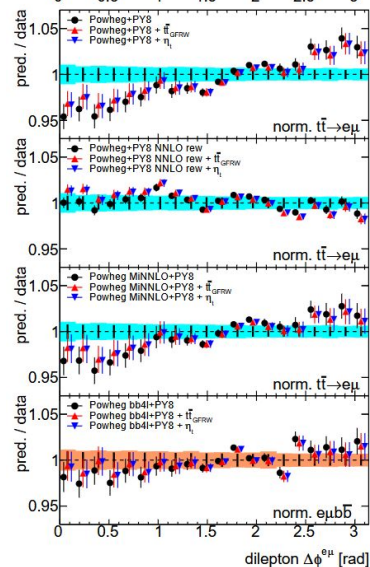
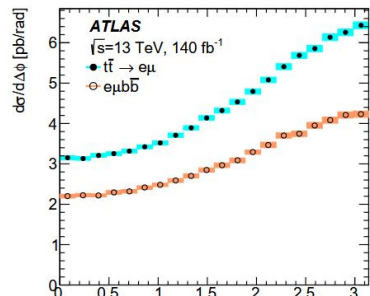
ATLAS arXiv 2605.02341

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- reinterpretation of differential cross-sections in the dileptonic channel of $t\bar{t}$
- cross-section as function of $m^{e\mu}$ (+ various more)
- agreement improved by adding “toponium” simulation
- measured signal over prediction $\mu = 1.22 \pm 0.38$ ($> 3\sigma$)
(strongly depended on model and measured distribution) $\rightarrow$ Daniel’s talk



Azimuthal Angle & 2D Distributions for Reinterpretation of differential $t\bar{t}b\bar{b}$ measurement

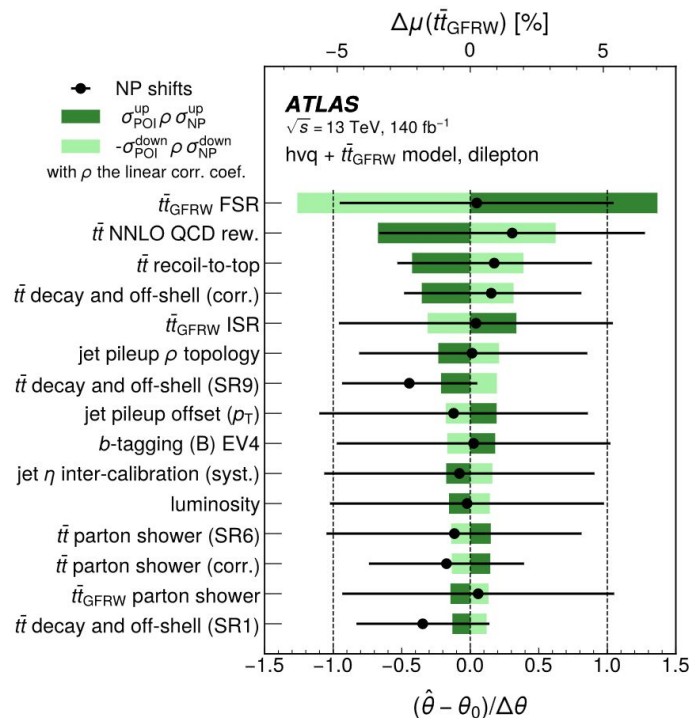
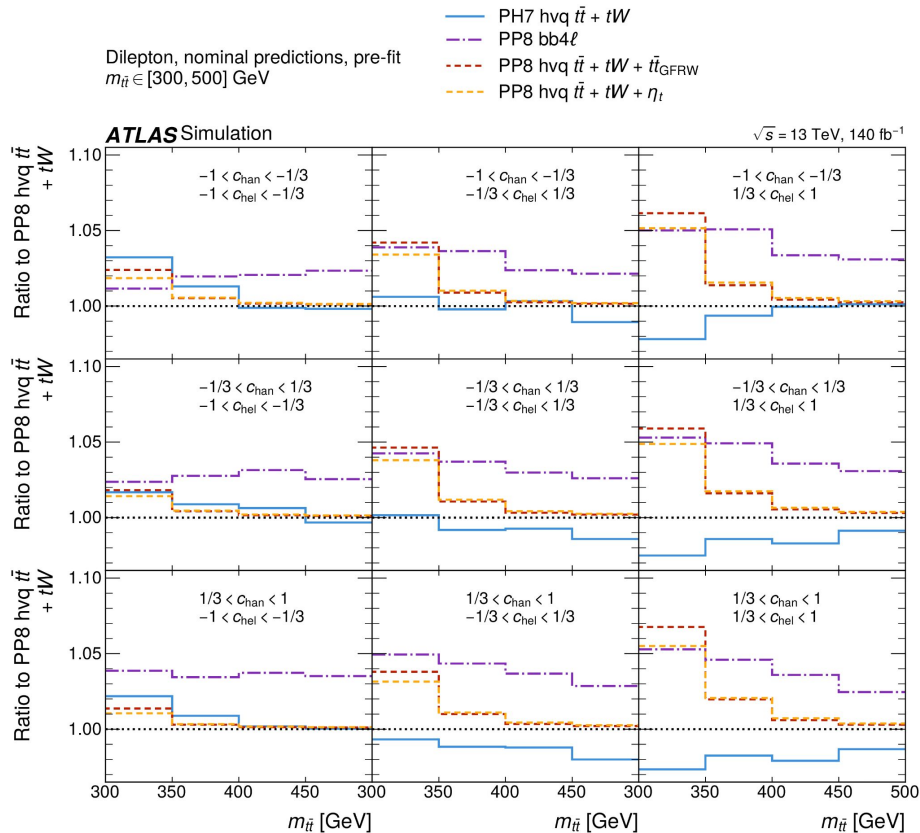
ATLAS arXiv 2605.02341



Event Selection for Observation of “Toponium”

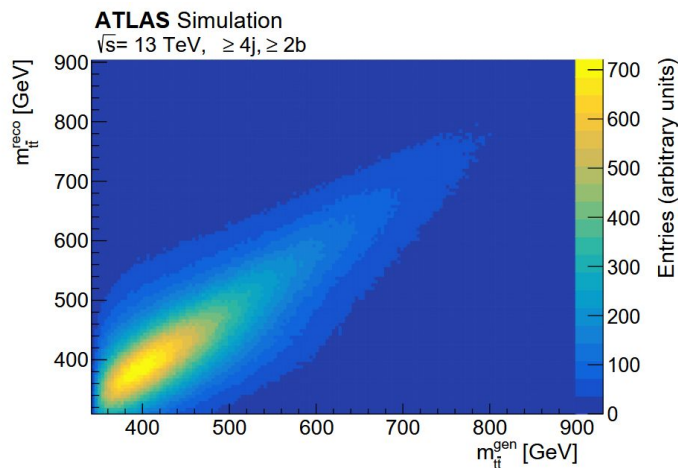
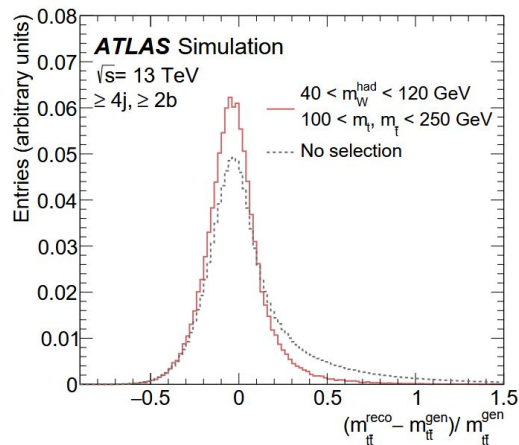
SRs	CR-Z	CR-Fakes
$= 2\ell$ with $p_T(\ell) \geq 10$ GeV ≥ 1 trigger-matched lepton with $p_T \geq 25/27/28$ GeV ≥ 2 jets with $p_T \geq 25$ GeV ≥ 1 b -tagged jet (70% efficiency WP) $m_{\ell\ell} \geq 15$ GeV for ee and $\mu\mu$ events $m_{t\bar{t}} \leq 500$ GeV		
$E_T^{\text{miss}} \geq 60$ GeV for OSSF events		—
$\ell^\pm \ell'^\mp$	$e^\pm e^\mp / \mu^\pm \mu^\mp$	$\ell^\pm \ell'^\pm$
$ m_{\ell\ell} - m_Z \geq 10$ GeV	$ m_{\ell\ell} - m_Z \leq 10$ GeV	$ m_{\ell\ell} - m_Z \geq 10$ GeV

Model Comparison & Systematics for Obs. of “Toponium”



Top Yukawa

- semileptonic final state
- 1 lepton, ≥ 4 jets, ≥ 2 btags
 - $ET_{\text{miss}} > 30$ GeV, $m_{\text{TW}} > 30$ GeV (e+jets)
 - $ET_{\text{miss}} + m_{\text{TW}} > 60$ GeV (mu+jets)
- dedicated algorithm for $t\bar{t}$ reconstruction



Event Selection & Systematics for m_t in $tt + 1j$

- 1 electron & 1 muon (opposite charge)
- $ET_{\text{miss}} > 30$ GeV
- $\Rightarrow 2$ btagged jets
- leading non-btagged jet has $p_T > 50$ GeV (is considered the extra jet)

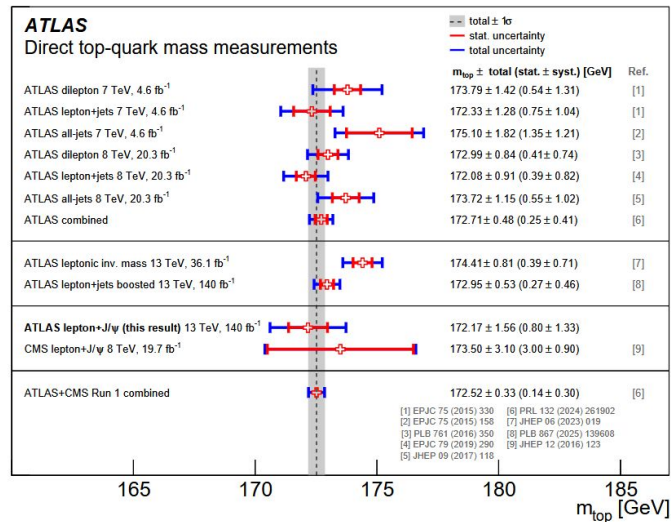
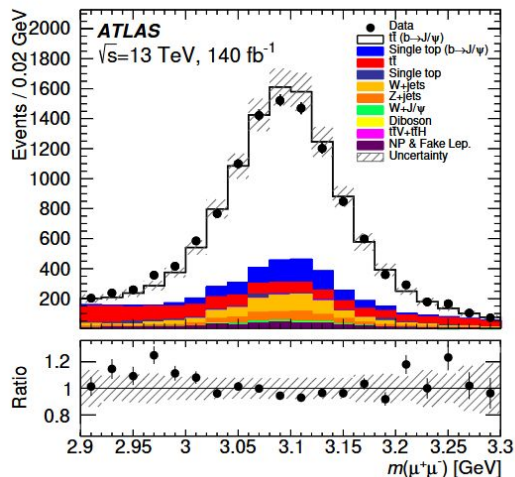
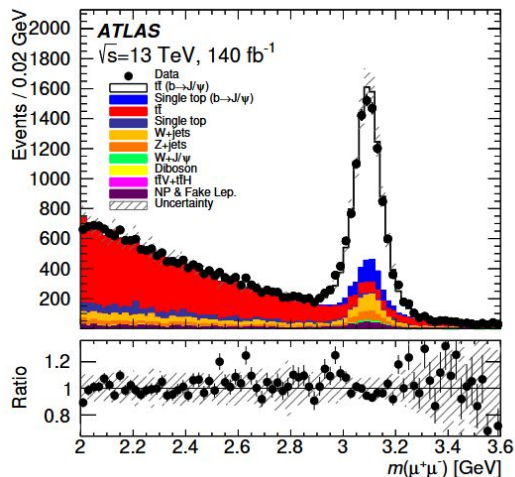
Uncertainty source	Δm_t^{pole} [GeV]	MC stat. unc. [GeV]
Data statistics	0.33	-
Detector unc.		
b -tagging and mistag	0.44	0.06
Jets	0.65	0.06
Leptons	0.25	0.06
Others	0.18	0.06
Modeling unc.		
MC statistical uncertainty	0.08	-
Backgrounds normalization	0.02	-
Single-top modeling	0.03	0.06
m_t^{MC} dependence	0.10	0.09
PS Recoil model	0.68	0.06
Parton shower	0.43	0.14
Underlying event	0.39	0.12
Color reconnection	0.13	0.08
ME+PS matching: p_T^{hard}	0.09	0.06
ME+PS matching: h_{damp}	0.26	0.06
ME+PS matching: line shape	0.38	0.12
3D NNLO reweight	0.21	0.06
PDF	0.26	0.06
Initial-state radiation	0.24	0.06
Final-state radiation	0.04	0.16
Factorization scales	0.09	0.06
Renormalization scales	0.03	0.06
Theory unc.		
Scale variations	+0.34 -0.28	+0.05 -0.06
PDF $\oplus \alpha_S$	0.24	+0.06 -0.06
Total	+1.47 -1.44	-

Event Selection J/Psi

- $=1$ isolated lepton
- ≥ 2 jets with ≥ 1 btag
- 2 soft muons originating from 1 vertex
- consistent with Jpsi mass
- $p_T(l \text{ mumu}) > 25 \text{ GeV}$
- $10 \text{ GeV} < m(l \text{ mumu}) < 160 \text{ GeV}$

Parameterisation, $m_{l\mu\mu}$ distribution and comparison with old values for m_t via Jpsi

$$f(x|m_0, k) = \frac{1}{\sqrt{2\pi \cdot \ln(k) \cdot x}} \exp\left(\frac{-\ln^2(x/m_0)}{2\ln^2(k)}\right)$$



Event Selection & NN distribution for V_{cb} measurement

- ==1 lepton
- ==4 jets
- ≥ 2 b or c tags, ≥ 1 btag

