Top-quark physics highlights from ATLAS and CMS

Michele Pinamonti

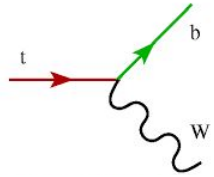
(INFN Sezione Trieste, Gruppo Collegato di Udine)

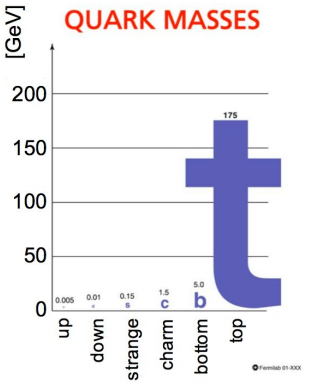
on behalf of the ATLAS and CMS Collaborations

XV Latin American Symposium on High Energy Physics

Cinvestav - Mexico City
4–8 November 2024

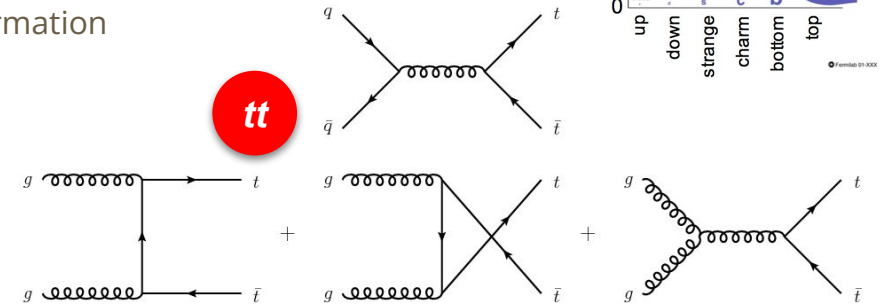
The top quark



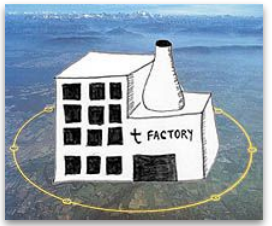


- **Heaviest** elementary particle:
  - strongest coupling with Higgs - Yukawa coupling $y_t = 1$
    - connection to **EW Symmetry Breaking** ?
  - decays before hadronising & preserving spin information

- **Copious production** at the LHC:
  - **strong** pair production: *tt*
  - EW **single production**: single-top
  - **associated** production:
    tt+γ/W/Z/H, tt+bb, tt+tt...



- **Why studying *tt̄* production**?
  - *tt̄* final states involving most parts of detectors → **test process**
  - precision determination of top-quark properties: m_t...
  - to **search** for **BSM** physics
  - **background** to many rare SM and BSM processes
  - opportunity to test **quantum information** at colliders

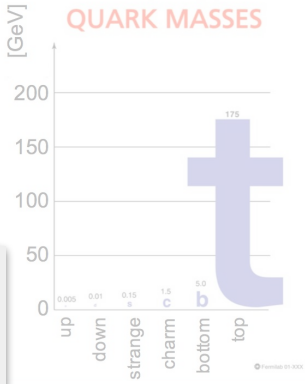


The top quark - II

- **Heaviest** elementary particle:
  - strongest coupling with Higgs - Yukawa coupling $y_t \approx 1$
    - connec
  - decays befor
- **Copious produc**
  - **strong** pair p
  - EW **single production**: single-top
  - **associated** production:
    tt+γ/W/Z/H, tt+bb, tt+tt…

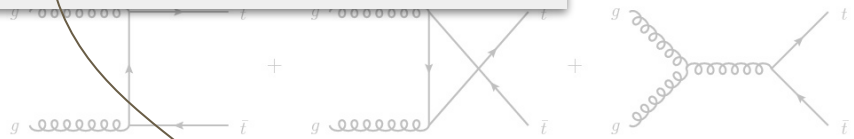
▹ CMS result

▹ ATLAS result



In this presentation:
- a **selection*** of recent **LHC** results of particular interest
- addressing these three **points**

**: personal and potentially biased*



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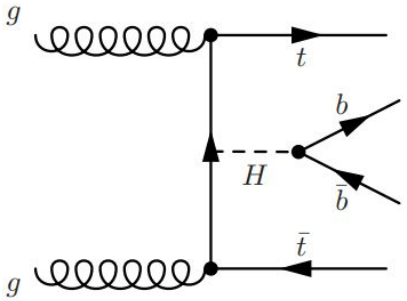
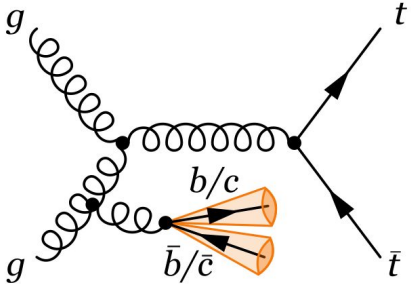
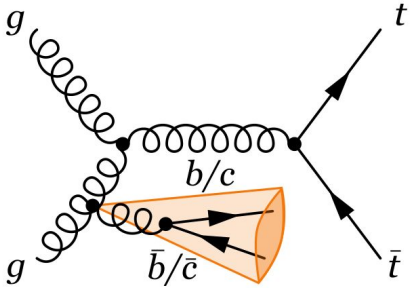
$t\bar{t}$ + heavy-flavour jets

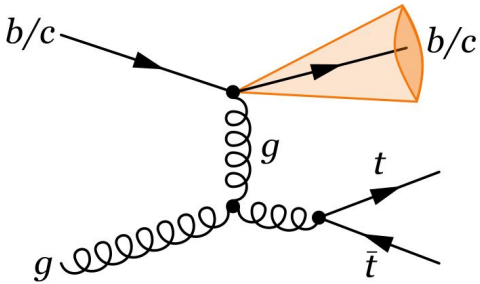


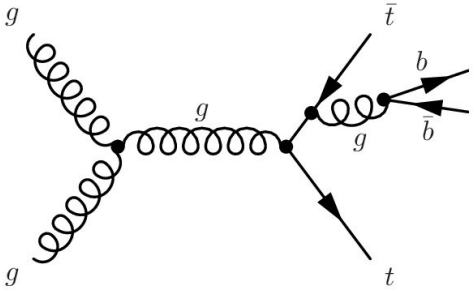
- $t\bar{t}$ production in association with *b*- or *c*-jets dominant **background** for:
  - important SM process measurements (**$t\bar{t}H$ and four-tops**)
  - BSM searches (**vector-like quarks, SUSY…**)

- **Modelling** of these processes challenging:
  - **multi-scale** processes
  - finite *b*- and *c*-quark **mass** inclusion
  - large uncertainties from perturbative and non-perturbative QCD
  - from different measurements and searches,
    data preferring **higher cross sections** than predictions





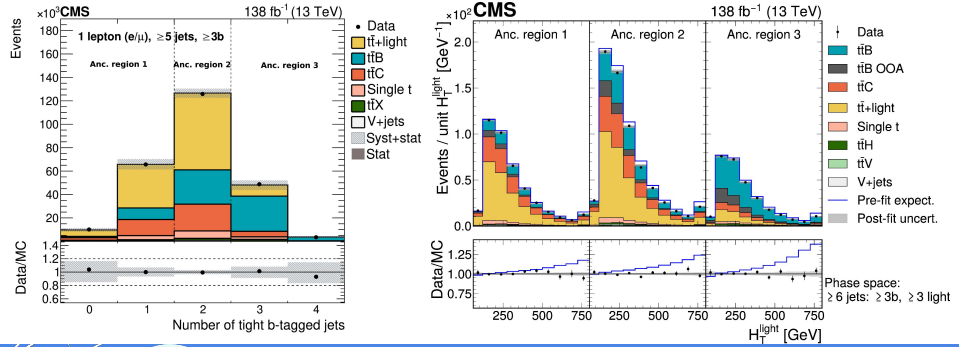




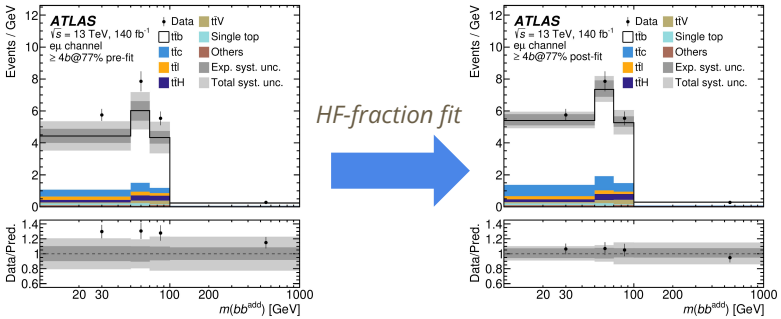
$t\bar{t}$ + b-jets measurement - ATLAS & CMS

- Measuring $t\bar{t}$ + additional *b*-jets → inclusive and normalized differential cross sections **@particle-level**
  - in different **fiducial regions**, targeting $t\bar{t}$+2*b*, $t\bar{t}$+1*b*, $t\bar{t}$+*1/2b+additional jets*
  - differential distributions measured both for **all *b*-jets** and for **additional *b*-jets** (i.e. *not coming from tops)*

- **CMS** - **ℓ+jets** channel: ▹ **JHEP 05 (2024) 042**
  - *b*-jet – top assignment:
    - with MC record history @particle-level
    - **via DNN reconstruction** @detector-level
  - **Profile likelihood unfolding**:
    - using finer **binning** @detector-level
    - **ancillary variables** to define S- and B-enriched categories, fitted together



- **ATLAS** - dilepton ***eμ***: ▹ **arXiv:2407.13473 [hep-ex]**
  - *b*-jet – top assignment:
    - **same reconstruction algorithm** both @particle- and detector-level
    - based on combination of various ΔR
  - **Data-driven rescaling** of **light/*c*/b fractions** in $t\bar{t}$+jets before Iterative Bayesian Unfolding
    - based on 3rd highest *b*-tagging score



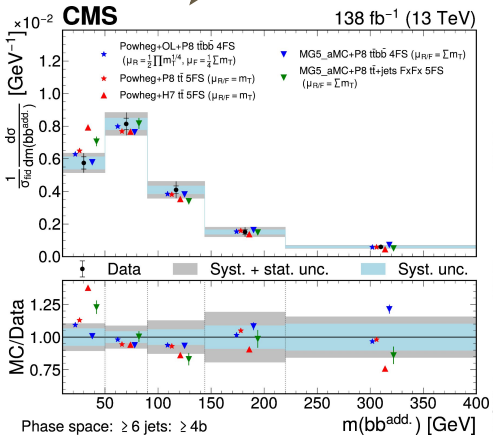
tt̄ + b-jets measurement - ATLAS & CMS - II

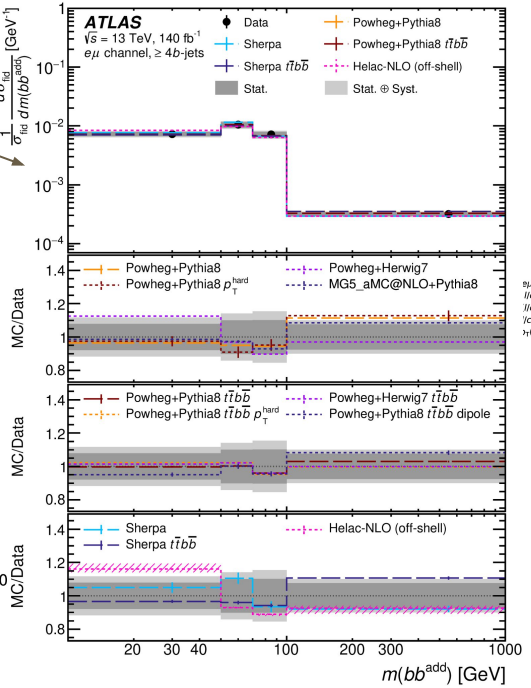
- **Results** on **differential distributions**:
  - no single generator setup able to describe all distributions...

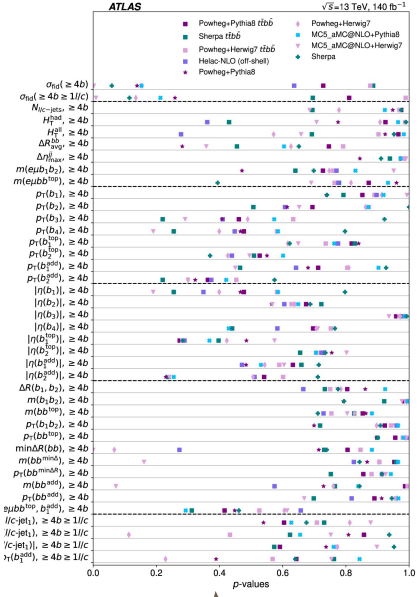
Observable		5j3b	6j4b	6j3b3l	7j4b3l
σ_{fid}	Inclusive cross section	✓	✓	✓	✓
Global observables					
N_{jets}	Jet multiplicity	✓	✓		
N_{b}	b jet multiplicity	✓			
H_{T}'	Scalar p_{T} sum of all jets	✓	✓		
H_{T}^{b}	Scalar p_{T} sum of all b jets	✓	✓		
$H_{\text{T}}^{\text{light}}$	Scalar p_{T} sum of all light jets			✓	✓
Observables related to b jets					
$p_{\text{T}}(\text{b}_3)$	p_{T} of third hardest b jet	✓	✓		
$\lvert\eta(\text{b}_3)\rvert$	$\lvert\eta\rvert$ of third hardest b jet	✓	✓		
$p_{\text{T}}(\text{b}_4)$	p_{T} of fourth hardest b jet		✓		
$\lvert\eta(\text{b}_4)\rvert$	$\lvert\eta\rvert$ of fourth hardest b jet		✓		
Observables considering all pairs of b jets (bb)					
$\Delta R_{\text{bb}}^{\text{avg}}$	Average ΔR of all bb pairs		✓		
$m_{\text{bb}}^{\text{max}}$	Highest invariant mass among all bb pairs		✓		
Observables related to the pair of b jets closest in ΔR (bb^{extra})					
$p_{\text{T}}(\text{b}^{\text{extra}})$	p_{T} of leading extra b jet		✓		
$\lvert\eta(\text{b}_1^{\text{extra}})\rvert$	$\lvert\eta\rvert$ of leading extra b jet		✓		
$p_{\text{T}}(\text{b}_2^{\text{extra}})$	p_{T} of subleading extra b jet		✓		
$\lvert\eta(\text{b}_2^{\text{extra}})\rvert$	$\lvert\eta\rvert$ of subleading extra b jet		✓		
$\Delta R(\text{bb}^{\text{extra}})$	ΔR of bb^{extra} pair		✓		
$\lvert\eta(\text{bb}^{\text{extra}})\rvert$	$\lvert\eta\rvert$ of bb^{extra} pair		✓		
$m(\text{bb}^{\text{extra}})$	invariant mass of bb^{extra} pair		✓		
$p_{\text{T}}(\text{bb}^{\text{extra}})$	p_{T} of bb^{extra} pair		✓		
Observables related to the pair of b jets not from $\text{t}\bar{\text{t}}$ decay ($\text{bb}^{\text{add.}}$)					
$p_{\text{T}}(\text{b}_1^{\text{add.}})$	p_{T} of leading additional b jet		✓*		
$\lvert\eta(\text{b}_1^{\text{add.}})\rvert$	$\lvert\eta\rvert$ of leading additional b jet		✓*		
$p_{\text{T}}(\text{b}_2^{\text{add.}})$	p_{T} of subleading additional b jet		✓*		
$\lvert\eta(\text{b}_2^{\text{add.}})\rvert$	$\lvert\eta\rvert$ of subleading additional b jet		✓*		
$\Delta R(\text{bb}^{\text{add.}})$	ΔR of $\text{bb}^{\text{add.}}$ pair		✓*		
$\lvert\eta(\text{bb}^{\text{add.}})\rvert$	$\lvert\eta\rvert$ of $\text{bb}^{\text{add.}}$ pair		✓*		
$m(\text{bb}^{\text{add.}})$	invariant mass of $\text{bb}^{\text{add.}}$ pair		✓*		
$p_{\text{T}}(\text{bb}^{\text{add.}})$	p_{T} of $\text{bb}^{\text{add.}}$ pair		✓*		
Observables related to extra light jets					
$p_{\text{T}}(\text{l}_1^{\text{extra}})$	p_{T} of leading extra light jet			✓	✓
$\lvert\Delta\phi(\text{l}_1^{\text{extra}}, \text{b}_{\text{soft}})\rvert$	$\Delta\phi$ of leading extra light jet and softest b jet			✓	✓

list of variables unfolded (CMS)

example of unfolded distributions



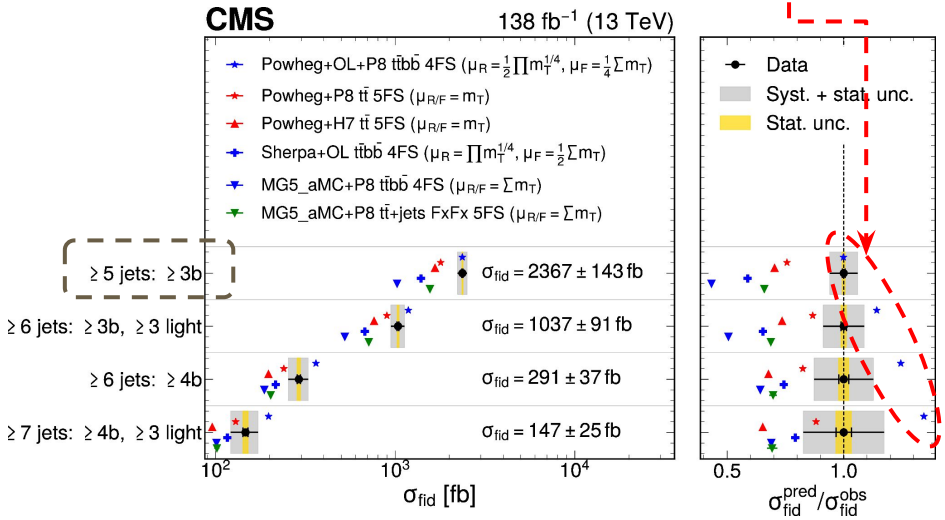


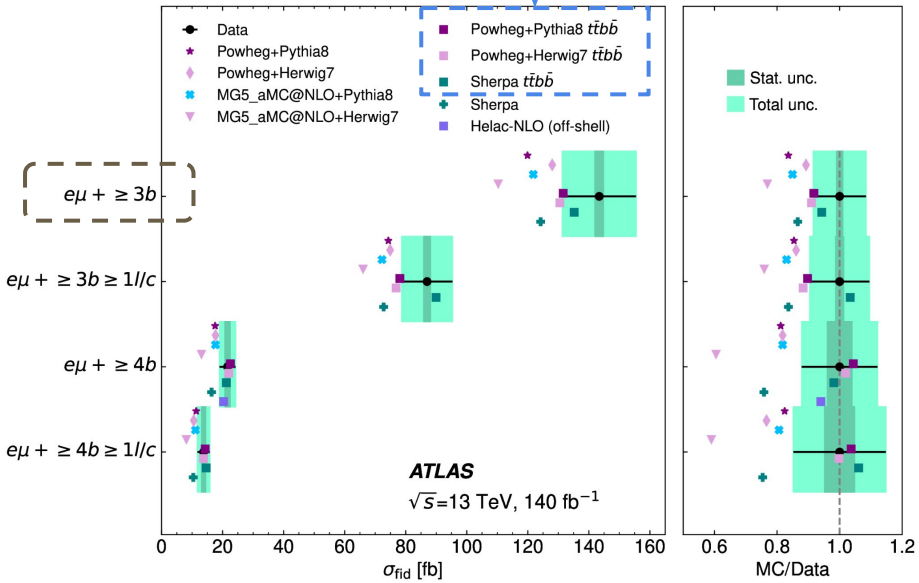


distribution of p-values quantifying goodness of description by all testes predictions (ATLAS)

$t\bar{t}$ + b-jets measurement - ATLAS & CMS - III

- Inclusive cross-section **results**:
  - **measurements** generally **above predictions** - especially for ***$t\bar{t}$+1b***
    - but for **particular choice of scales** (CMS)
    - **dedicated *$t\bar{t}+b\bar{b}$*** MC samples in better in agreement (ATLAS)

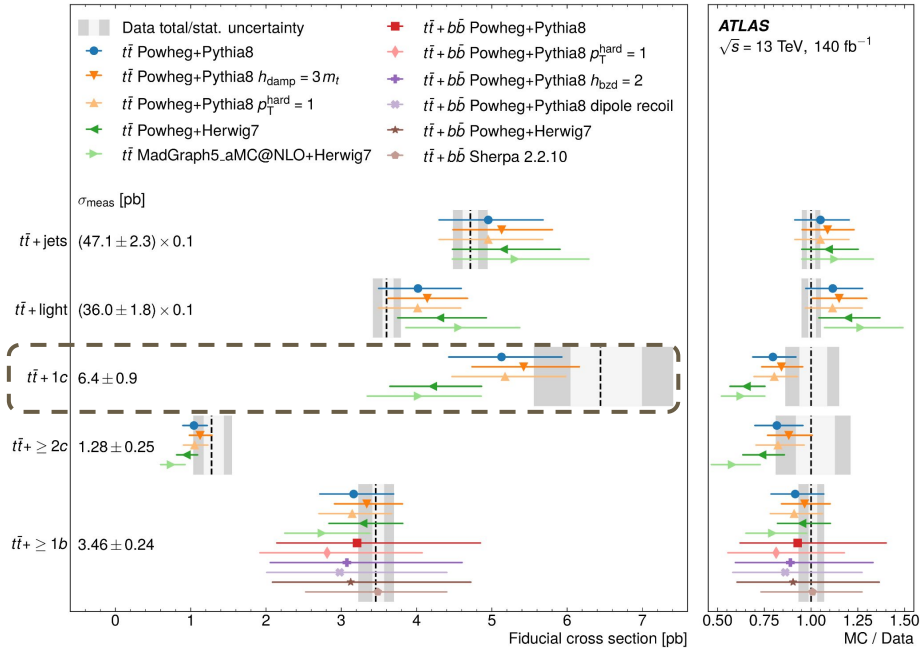


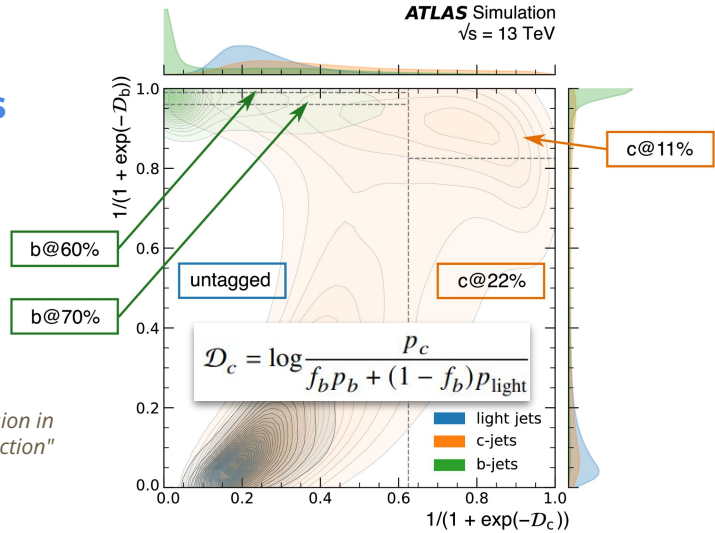


$t\bar{t}$ + c-jets measurement - ATLAS

▹ arXiv:2409.11305 [hep-ex]

- Measuring *$t\bar{t}$+2c-* and *$t\bar{t}$+1c-jets* **incl. fiducial cross-sections**
  - combining 1ℓ and 2ℓ channels
- **Custom** flavor tagging algorithm **"*b*/*c*-tagger"**:
  - SRs + CRs defined vs. number of *b*- and *c*-tagged jets

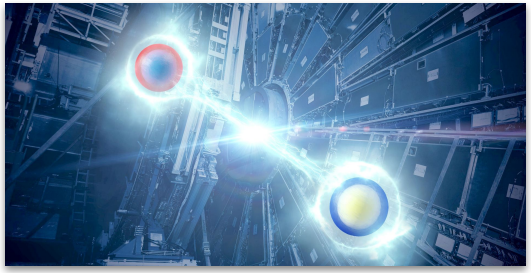




Physics briefings
"Decoding top quarks: Precision in heavy-flavour partner production"

- **Profile-likelihood fits**
  using ***$m_{c\bar{c}}$*-distribution** in SRs + single bin in CRs:
  - free-floating normalisations for *$t\bar{t}$+b-* and *$t\bar{t}$*+light-jets
- **Results:**
  - all tested MC setups underpredict *$t\bar{t}$+c-*jets, in particular ***$t\bar{t}$+1c***

$t\bar{t}$ spin correlation and entanglement



- $t\bar{t}$ pairs predicted (*and verified*) to have **correlated spins**:
  - t and $\bar{t}$ spins accessed via decay-product angular *distributions*
  - allow to study **quantum mechanics effects**:
    - quantum **entanglement**: "*spin correlations beyond classical*"
    - **Bell's inequality** violation: "*exclusion of hidden-variable effects*"

Spin correlations ⊆ Entanglement ⊆ Bell's inequality violation

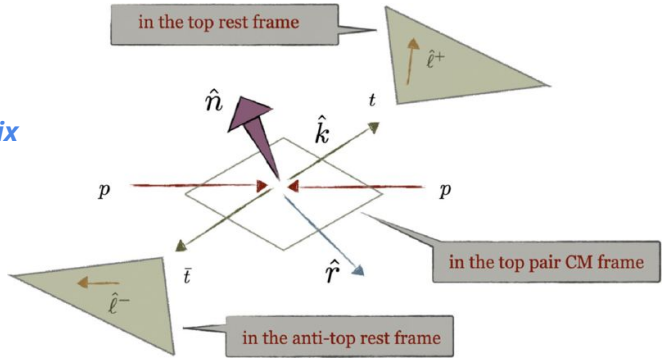
- All $t\bar{t}$ spin information encoded in "**spin density matrix**":
  - for dilepton $t\bar{t}$ (ℓ *spin-analysing power = 1*):

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_+ d\Omega_-} = \frac{1}{(4\pi)^2}\left(1 + \mathbf{B}^+ \cdot \hat{\ell}^+ + \mathbf{B}^- \cdot \hat{\ell}^- - \hat{\ell}^+ \cdot \mathbb{C} \cdot \hat{\ell}^-\right)$$

polarization vectors

spin-correlation matrix

$$\begin{bmatrix} C_{nn} & C_{nr} & C_{nk} \\ C_{rn} & C_{rr} & C_{rk} \\ C_{kn} & C_{kr} & C_{kk} \end{bmatrix}$$



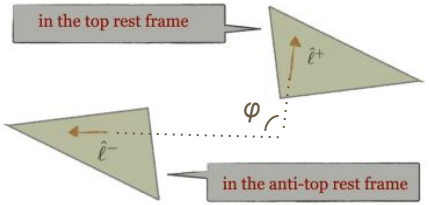
- **Entanglement markers** defined as combinations of *C* matrix elements

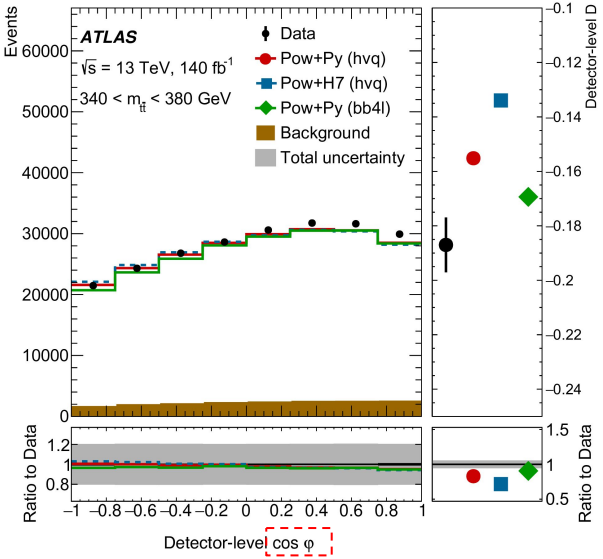
(e.g. see EPJP(2021)136:907 *(Afik et al.)*, PRL127(2021)16,161801 *(Fabbrichesi et al.)*)

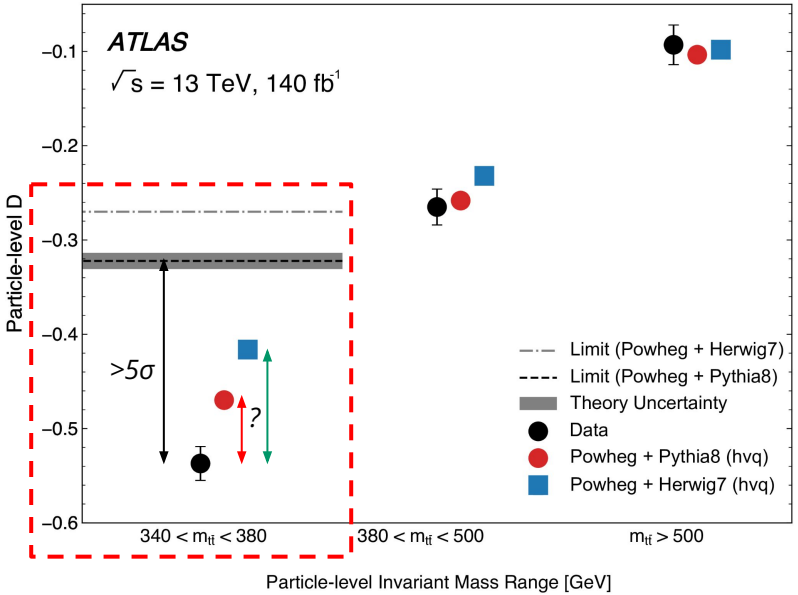
Observation of Entanglement - ATLAS

▹ Nature 633 (2024) 542

- ***eμ*** channel, ***tt̄* system reconstructed** with *Ellipse* method
- Entanglement marker ***D*** defined as $-\frac{1}{3}(C_{nn}+C_{rr}+C_{kk})$
  - @parton-level: $D < -\frac{1}{3} \Rightarrow$ entangled system
  - *D* obtained **from angle btw. leptons** in top rest frames φ: $D = -3\langle\cos\varphi\rangle$





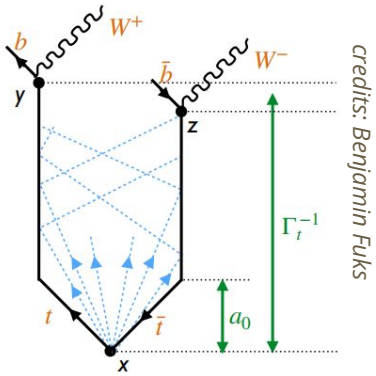


- Measurement @**particle-level**, in narrow **low-$m_{tt̄}$ region**:
  - *tt̄* ~ entirely in spin-singlet state → maximally entangled

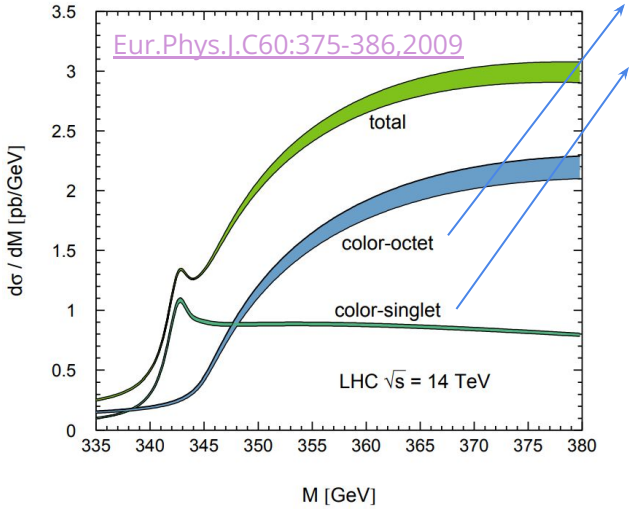
- **> 5σ** over no-entanglement hypothesis
- **Discrepancy** observed btw. data and predictions from NLO+PS simulation:
  - data "*more entangled*" than MC (!!)

$t\bar{t}$ threshold / "toponium" effects

- Non-relativistic QCD (**NRQCD**) predicts "**quasi-bound-state**" effects at $t\bar{t}$ production threshold:
  - gluon exchanges before the top decay
  - still before actual hadronisation time (*not an actual hadron*)



credits: Benjamin Fuks



colour-octet Θ → *repulsive* (but small at threshold)
colour-singlet η_t → *attractive* → **peak** below threshold

} ***"toponium" states***

- **Toy model** (B. Fuks et al. Phys. Rev. D 104, 034023 (2021)):
  - generic colourless (colour-singlet) pseudo-scalar state η_t

$$\mathcal{L}_{\eta_t} = \frac{1}{2}\partial_\mu \eta_t \partial^\mu \eta_t - \frac{1}{2} m_{\eta_t} \eta_t^2 - \frac{1}{4} g_{gg} \eta_t G^a_{\mu\nu} \tilde{G}^{a\mu\nu} - i g_{tt} \eta_t \bar{t} \gamma_5 t$$

$$m_{\eta_t} = 344 \text{ GeV} \qquad \Gamma_{\eta_t} \approx 7 \text{ GeV} \qquad \sigma(13 \text{ TeV}) \sim 6.5 \text{ pb}$$

  - coupling to tops and gluons, parameters from fits to NRQCD
  - MC simulation:

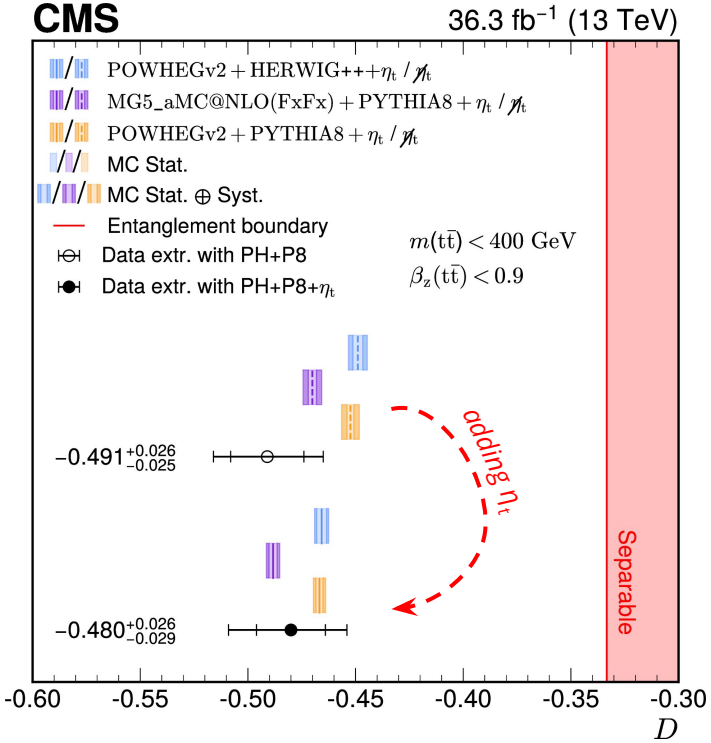
Lagrangian → FeynRules / UFO → MG5aMC Pythia 8

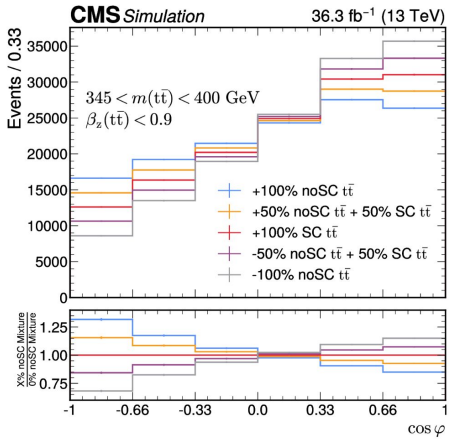
- ***Complete model*** expected soon!

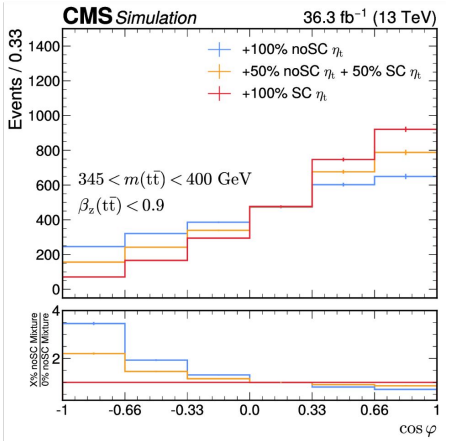
Observation of Entanglement - CMS

▹ arXiv:2406.03976 [hep-ex]

- ***eμ/ee/μμ*** channels, **kinematic reconstruction** of *tt̄* system with smearing and weighting
- Same observable ***D*** extracted from *cosφ*:
  - **low-$m_{t\bar{t}}$** selection + cut on ***tt̄* system velocity**
  - *D* measured @ **parton-level** with **binned likelihood fit**
    (templates obtained mixing with "no-SC" MC sample)







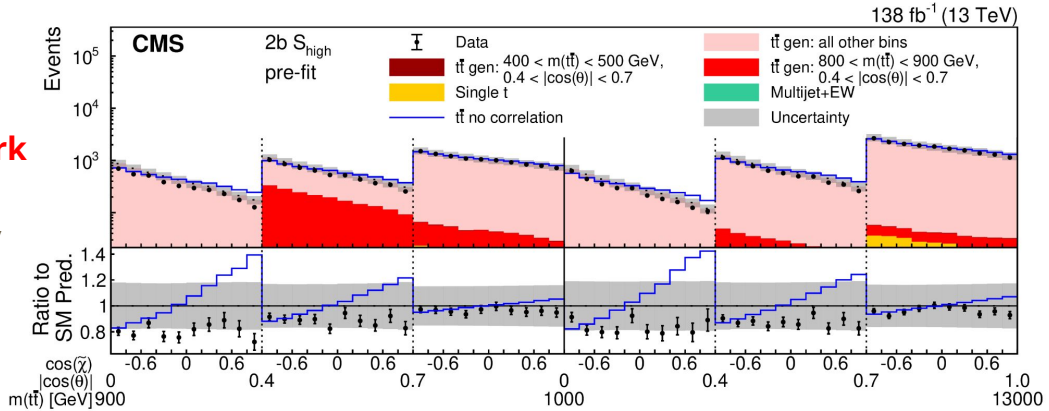
- Inclusion of toy-model ***η_t*** ($\sigma(\eta_t)$ = 6.43 ± 0.90 pb)
  - restoring agreement btw. measurement and MC predictions
- **Entanglement observed** with > 5σ significance
  - **both** with and without η_t inclusion in the model

Spin Density & Entanglement - CMS

▹ arXiv:2409.11067 [hep-ex]

- **ℓ+jets $t\bar{t}$ selection** → allow to access spin correlation and entanglement at **higher $m_{t\bar{t}}$**
- **Binned likelihood fit** to extract:
  - full **spin-density matrix** (polarization & spin correlation)
  - **entanglement** markers D and $\tilde{D}$ (modified version for high-mass region)
    - extracted both from C_{ij} and directly from dedicated angles χ and $\tilde{\chi}$

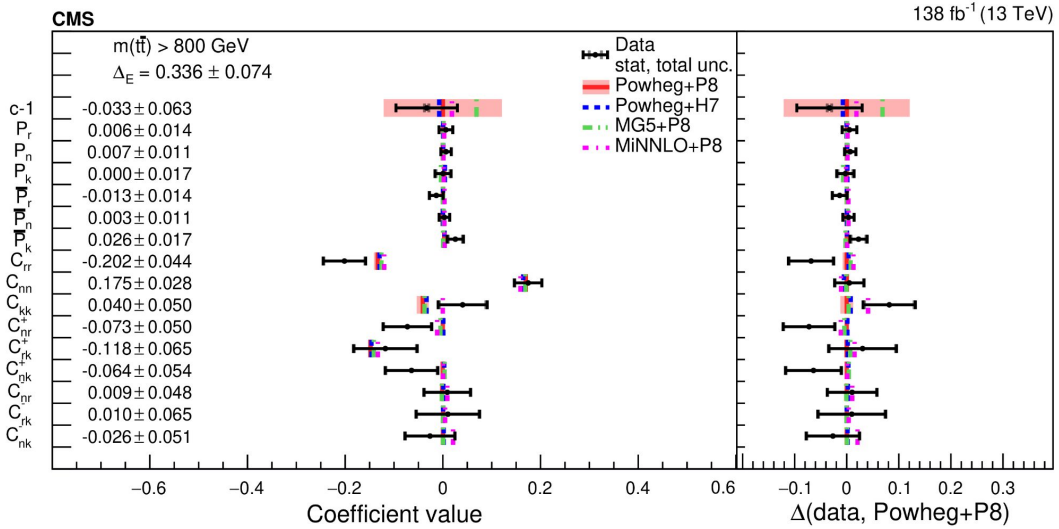
- $t\bar{t}$ system reconstruction with **DNN**:
  - also **assigning jet to down-type quark** from W *(needed to assess spin correlations)*
    - b-tagging information internally used to tag c-jets
  - cuts on reconstructed masses and DNN output to enhance fraction of well-reconstructed events

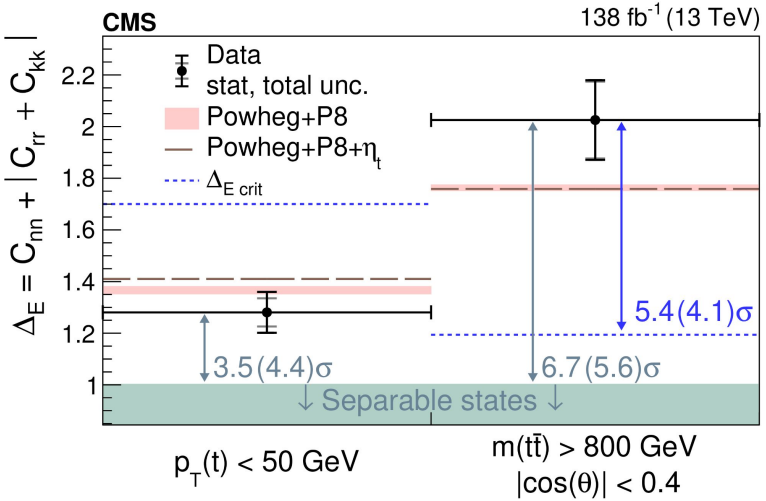


- Events **categorized** vs. number of b-tagged jets and vs. DNN output
- Measurements **in bins** of **$m_{t\bar{t}}$ vs. $|cos(\theta)|$** and **p_T^t vs. $|cos(\theta)|$**

Spin Density & Entanglement - CMS - II

- All **results** mostly in agreement with SM predictions
  - *inclusion of η_t needed at low $m_{t\bar{t}}$*





- **High-$m_{t\bar{t}}$ entanglement** observation important to ensure its **QM-nature**:
  - $m_{t\bar{t}}$ > 800 GeV → 80% $t\bar{t}$ ***space-like separated*** ⇒ effect not explainable by classical information exchange
  - ΔE_{crit} defined for this purpose

⇒ Step toward ***Bell's Inequalities Viol. test*** *(possible only at large $m_{t\bar{t}}$ and small $|\cos\theta|$)*

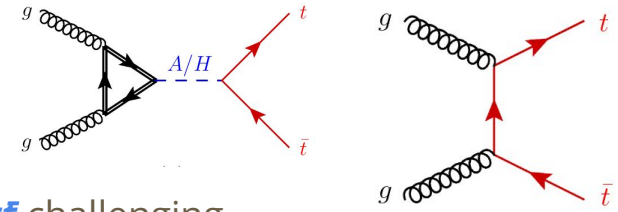
Search for Heavy Higgs to $t\bar{t}$

- Many BSM rely on an extended Higgs sector
- Two-Higgs-Doublet-Models (**2HDM**) represent almost-minimal, natural and general extension:
  - predict 5 states: *h, H, A, H^+, H^-*
  - if *h* identified with SM Higgs, with identical couplings → "**alignment limit**":
    - *A/H* couplings with *W* and *Z* → 0
    - couplings with ℓ, *u* and *d* depend on tan*β* *(with Yukawa hierarchy of couplings holding)*
    - depending on tan*β*, *A/H* coupling with $t\bar{t}$ could be the only relevant one!

2HDM

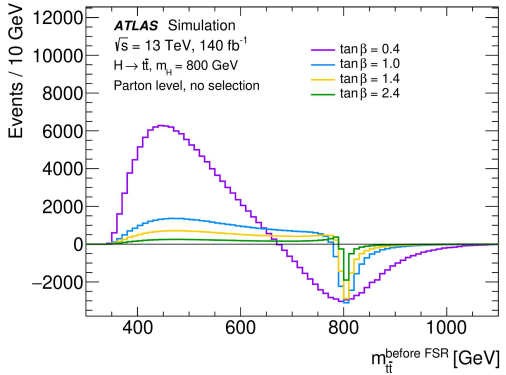
	Type I	Type II
ξ_h^u	$\sin(\beta-\alpha)+\cos(\beta-\alpha)/\tan\beta$	$\sin(\beta-\alpha)+\cos(\beta-\alpha)/\tan\beta$
ξ_h^d	$\sin(\beta-\alpha)+\cos(\beta-\alpha)/\tan\beta$	$\sin(\beta-\alpha)-\cos(\beta-\alpha)*\tan\beta$
ξ_h^l	$\sin(\beta-\alpha)+\cos(\beta-\alpha)/\tan\beta$	$\sin(\beta-\alpha)-\cos(\beta-\alpha)*\tan\beta$
ξ_H^u	$\cos(\beta-\alpha)-\sin(\beta-\alpha)/\tan\beta$	$\cos(\beta-\alpha)-\sin(\beta-\alpha)/\tan\beta$
ξ_H^d	$\cos(\beta-\alpha)-\sin(\beta-\alpha)/\tan\beta$	$\cos(\beta-\alpha)+\sin(\beta-\alpha)*\tan\beta \to 0$
ξ_H^l	$\cos(\beta-\alpha)-\sin(\beta-\alpha)/\tan\beta$	$\cos(\beta-\alpha)+\sin(\beta-\alpha)*\tan\beta \to 0$
ξ_A^u	$1/\tan\beta$	$1/\tan\beta$
ξ_A^d	$-1/\tan\beta$	$\tan\beta \to 0$
ξ_A^l	$-1/\tan\beta$	$\tan\beta \to 0$

alignment limit: cos(β-α) = 0
τ coupling → 0 (in Type-II)



- **Search for A/H → *tt̄*** challenging, due to huge **SM *tt̄* background**:
  - large systematic uncertainties *(both from perturbative and non-perturbative QCD)*
  - interference effects *("peak-deep" structure)*

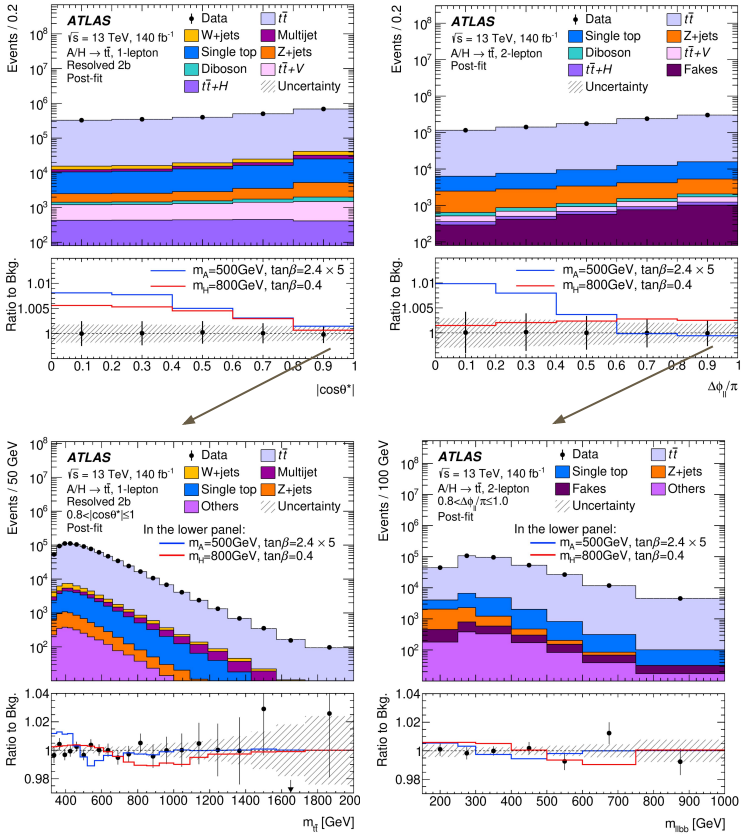
(plot from IHEP 08 (2024) 013)



Search for Heavy Higgs to tt̄ - ATLAS

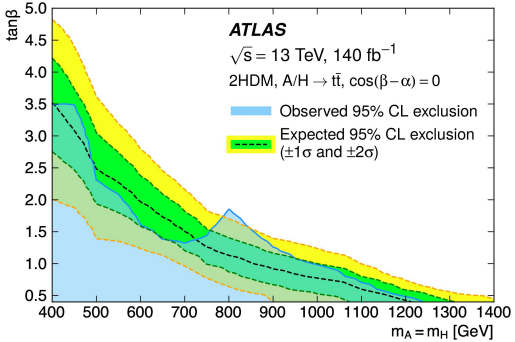
▹ JHEP 08 (2024) 013

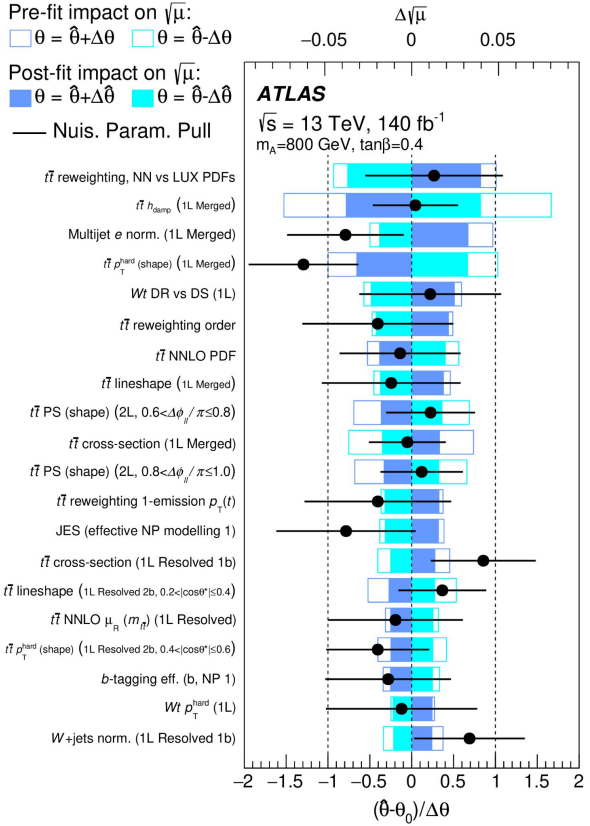
- **1ℓ channel**:
  - semi-boosted event category targeting mass ~ 1 TeV
  - $t\bar{t}$ system reconstructed with χ^2 method
  - events split bins of **top scattering angle, cosθ***
  - $m_{t\bar{t}}$ reco fit in each cosθ* bin
- **2ℓ channel**:
  - "visible invariant mass" $m_{\ell\ell bb}$ fitted
  - splitting in $\mathbf{\Delta\phi_{\ell\ell}}$ to get sensitivity from **spin correlations**
- $t\bar{t}$ kinematics **reweighted** to **NNLO-QCD+NLO-EW** predictions from Czakon et al. (JHEP 10 (2017) 186)
  - iterative-recursive reweighting to correct $m_{t\bar{t}}$ and top p_T at the same time using published distributions
  - complete set of **systematic variations** derived from theory predictions, replacing and reducing uncertainties on NLO+PS predictions



Search for Heavy Higgs to tt̄ - ATLAS - II

- Results extracted for a **fine grid of signal benchmarks** for *A* and *H* with mass 400 GeV – 1.4 TeV
  - **interference** with SM *tt̄* fully taken into account, with **interference term scaled by √μ** in profile likelihood fit
- ***tt̄* modelling** systematic uncertainties still largest source of uncertainty



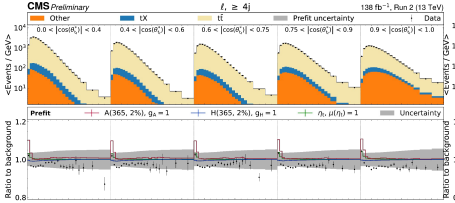


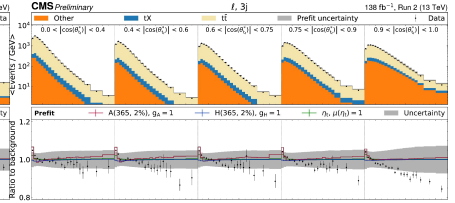
- Results interpreted in 2HDM Type-II with m_H=m_A and hMSSM
  - in addition, generic exclusion limits are derived separately for single different choices of their mass and total width
- **Good agreement with B-only hypothesis**:
  - in the whole tested mass range
  - extending **exclusion limits to > 1 TeV** for low tan*β*

Search for Heavy Higgs to tt̄ - CMS

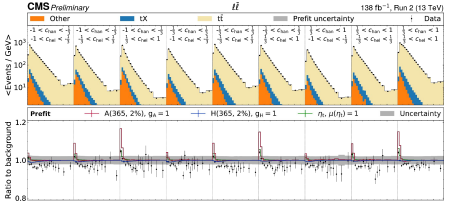
CMS-PAS-HIG-22-013

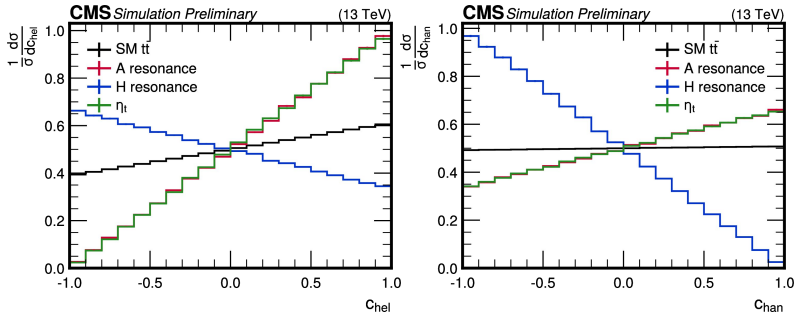
- **1ℓ channel**:
  - system reconstruction with likelihood method
  - 3-jets events included *(with dedicated reconstruction)*
  - 2D fit: $m_{t\bar{t}}$ vs. cosθ*





- **2ℓ channel**:
  - system reconstruction with *Sonnenschein* method *(analytic reconstruction)*, with random smearing replicas
  - 3D fit: $m_{t\bar{t}}$ vs. C_{hel} *(scalar product of ℓ directions in helicity frame)* vs. C_{han} *(same but flipping one sign)*



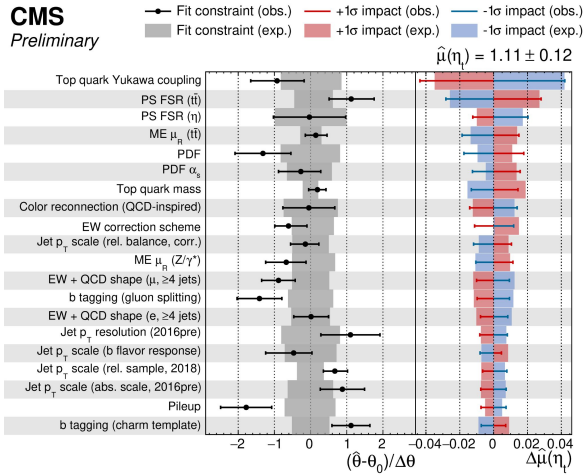


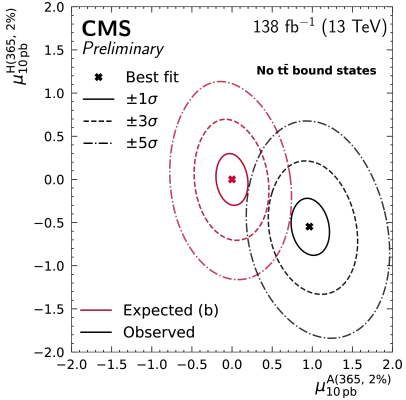
(probing spin correlations + A vs. H separation)

- *tt̄* **reweighted** to **NNLO-QCD** (MATRIX) + **EW corrections** (HATHOR)
  - 2D $m_{t\bar{t}}$ vs. cosθ*
- **"toponium" effect (η_t)** added to background model

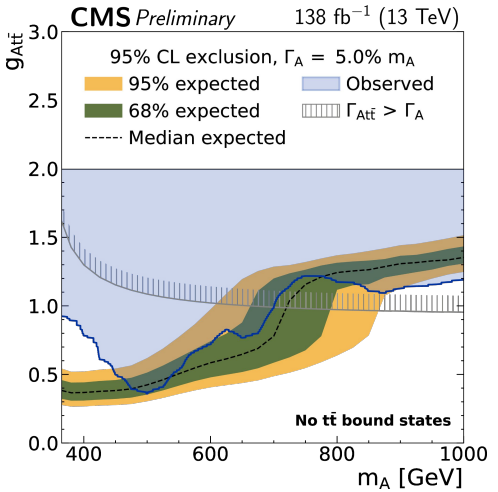
Search for Heavy Higgs to tt̄ - CMS - II

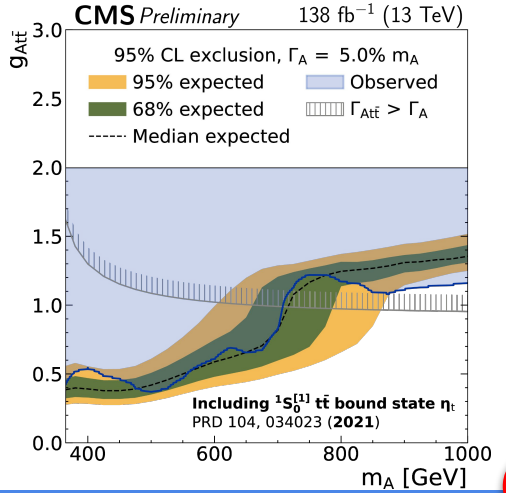
- **Results**:
  - testing single *H/A* scanning model parameters *(mass, coupling and width)*
  - testing simultaneous presence of *A* and *H*
  - **without including toponium** in background
    → **excess** compatible with *A* at *tt̄* threshold
  - **including** η_t in background model
    → **no excess**





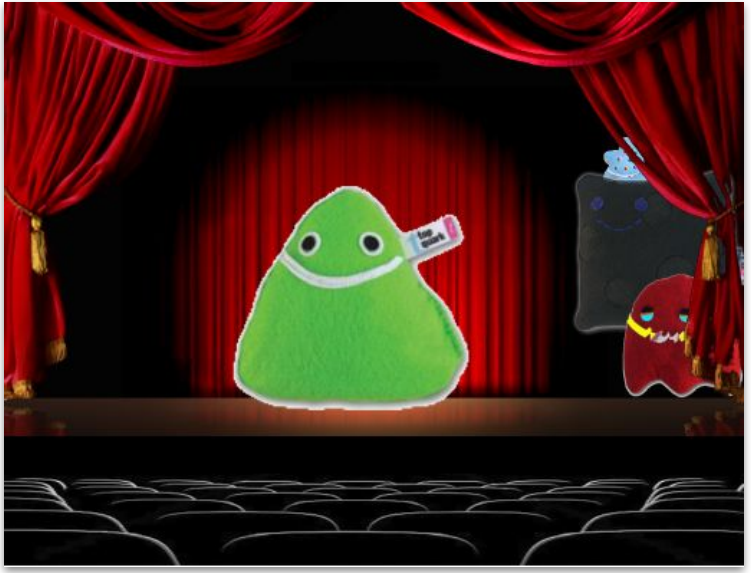
- **fitting toponium cross section**:
  $\sigma(\eta_t)$ = 7.1 pb ± 11%
  (non-rel.-QCD prediction ~6.4 pb)
- toponium state **observed** (with >5σ) and its **pseudo-scalar nature** tested





Conclusions

- **Selected highlights** in top -quark physics presented:
  - all based on **Run 2 data**
  - many new results from ATLAS and CMS recently released
  - … and many will come in the near future!



- Hoping to have shown that the top quark is still a **fresh** and **exciting** research field:
  - we are still learning from the top!

- **Bonus** - comprehensive reviews of ATLAS and CMS results also recently released:
  - ATLAS Run-2 Top Physics Review: ▹ arXiv:2404.10674 [hep-ex]
  - CMS Top Mass Measurements Review: ▹ arXiv:2403.01313 [hep-ex]

Backup

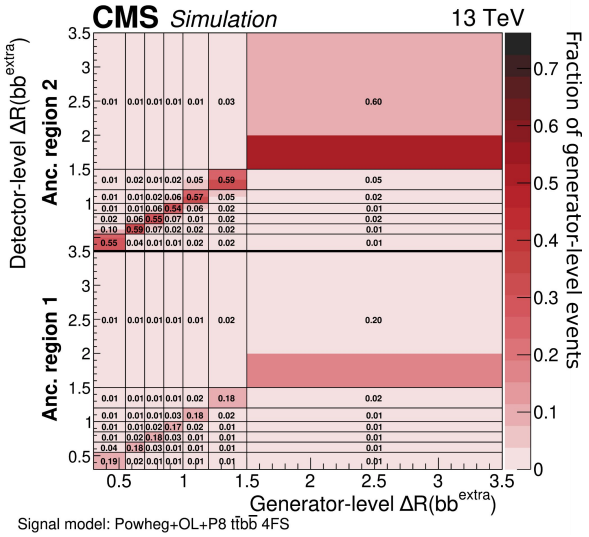
More on CMS excess

- Recent paper: https://arxiv.org/pdf/2410.08609
  - concludes that excess not compatible with 2HDM in reasonable scenarios

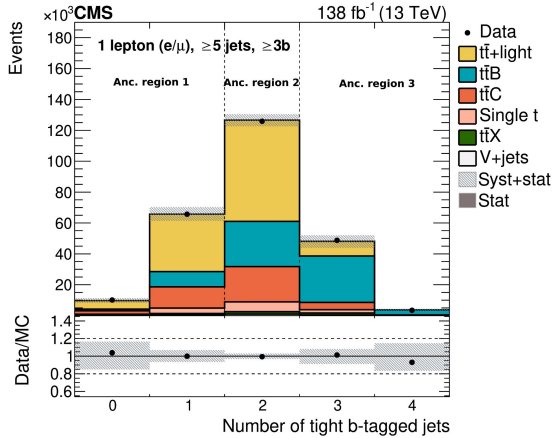
tt̄ + b-jets measurement - CMS

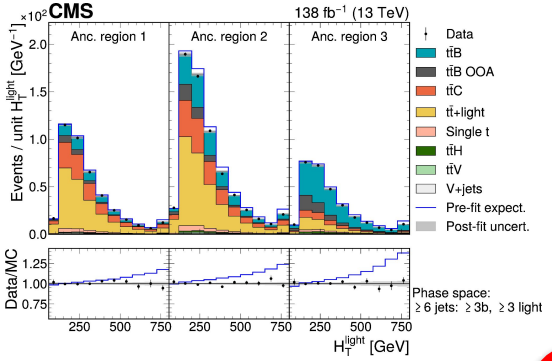
- **ℓ+jets** channel *tt̄* selection with **additional *b*-tagged jets**
  - 3 fiducial regions: tt̄+bb̄, tt̄+b and tt̄bb̄/tt̄b+j
- Measuring inclusive and normalized differential cross sections **@particle-level**
- 2 approaches for observable definition:
  - no matching to tops
  - **matching** between b-jets and tops *(with MC record history @particle-level and via **DNN** @detector-level)*
- **Profile likelihood unfolding**:
  - using finer **binning** @detector-level
  - **ancillary variables** used to define S- and B-enriched categories, fitted together

▹ JHEP 05 (2024) 042



Signal model: Powheg+OL+P8 tt̄bb̄ 4FS

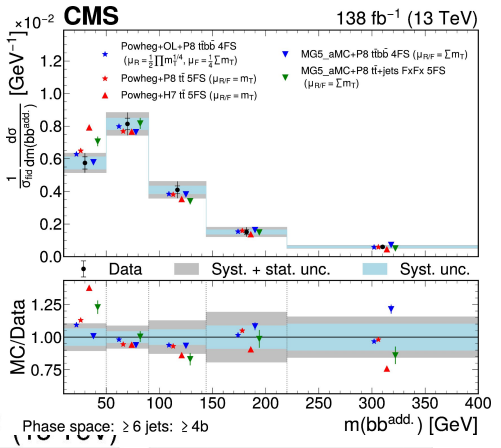


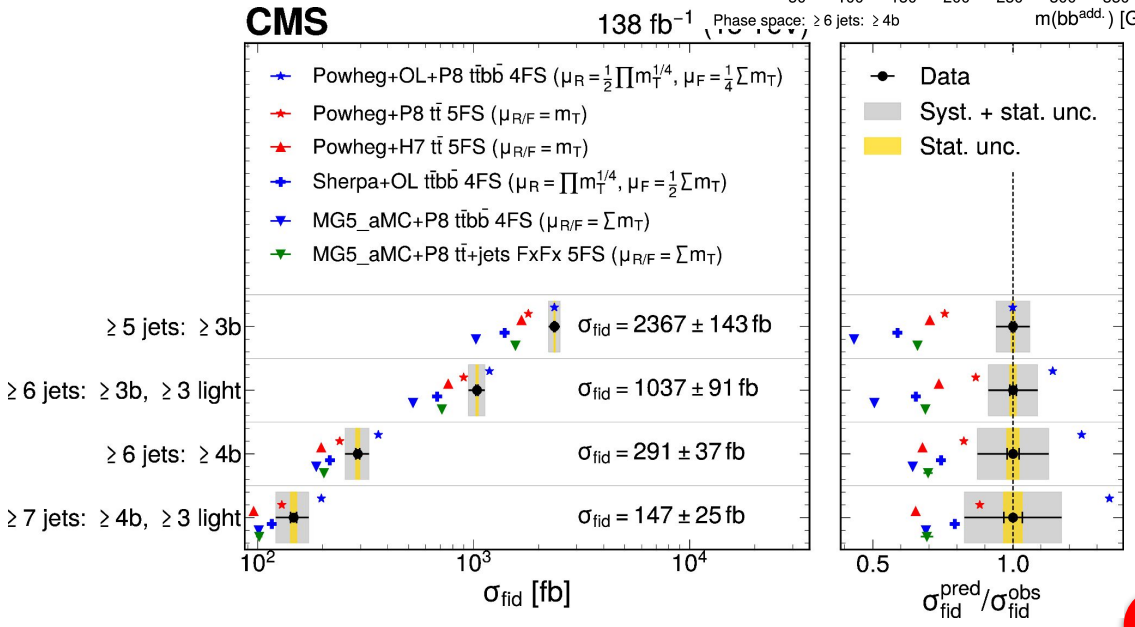


$t\bar{t}$ + b-jets measurement - CMS - II

	Observable	5j3b	6j4b	6j3b3l	7j4b3l
σ_{fid}	Inclusive cross section	✓	✓	✓	✓
Global observables					
N_{jets}	Jet multiplicity	✓	✓		
N_{b}	b jet multiplicity	✓			
H_{T}^{l}	Scalar p_{T} sum of all jets	✓	✓		
H_{T}^{b}	Scalar p_{T} sum of all b jets	✓	✓		
$H_{\text{T}}^{\text{light}}$	Scalar p_{T} sum of all light jets			✓	✓
Observables related to b jets					
$p_{\text{T}}(\text{b}_3)$	p_{T} of third hardest b jet	✓	✓		
$\lvert\eta(\text{b}_3)\rvert$	$\lvert\eta\rvert$ of third hardest b jet	✓	✓		
$p_{\text{T}}(\text{b}_4)$	p_{T} of fourth hardest b jet		✓		
$\lvert\eta(\text{b}_4)\rvert$	$\lvert\eta\rvert$ of fourth hardest b jet		✓		
Observables considering all pairs of b jets (bb)					
$\Delta R_{\text{bb}}^{\text{avg}}$	Average ΔR of all bb pairs		✓		
$m_{\text{bb}}^{\text{max}}$	Highest invariant mass among all bb pairs		✓		
Observables related to the pair of b jets closest in ΔR (bb^{extra})					
$p_{\text{T}}(\text{b}_1^{\text{extra}})$	p_{T} of leading extra b jet		✓		
$\lvert\eta(\text{b}_1^{\text{extra}})\rvert$	$\lvert\eta\rvert$ of leading extra b jet		✓		
$p_{\text{T}}(\text{b}_2^{\text{extra}})$	p_{T} of subleading extra b jet		✓		
$\lvert\eta(\text{b}_2^{\text{extra}})\rvert$	$\lvert\eta\rvert$ of subleading extra b jet		✓		
$\Delta R(\text{bb}^{\text{extra}})$	ΔR of bb^{extra} pair		✓		
$\lvert\eta(\text{bb}^{\text{extra}})\rvert$	$\lvert\eta\rvert$ of bb^{extra} pair		✓		
$m(\text{bb}^{\text{extra}})$	invariant mass of bb^{extra} pair		✓		
$p_{\text{T}}(\text{bb}^{\text{extra}})$	p_{T} of bb^{extra} pair		✓		
Observables related to the pair of b jets not from $t\bar{t}$ decay ($\text{bb}^{\text{add.}}$)					
$p_{\text{T}}(\text{b}_1^{\text{add.}})$	p_{T} of leading additional b jet		✓*		
$\lvert\eta(\text{b}_1^{\text{add.}})\rvert$	$\lvert\eta\rvert$ of leading additional b jet		✓*		
$p_{\text{T}}(\text{b}_2^{\text{add.}})$	p_{T} of subleading additional b jet		✓*		
$\lvert\eta(\text{b}_2^{\text{add.}})\rvert$	$\lvert\eta\rvert$ of subleading additional b jet		✓*		
$\Delta R(\text{bb}^{\text{add.}})$	ΔR of $\text{bb}^{\text{add.}}$ pair		✓*		
$\lvert\eta(\text{bb}^{\text{add.}})\rvert$	$\lvert\eta\rvert$ of $\text{bb}^{\text{add.}}$ pair		✓*		
$m(\text{bb}^{\text{add.}})$	invariant mass of $\text{bb}^{\text{add.}}$ pair		✓*		
$p_{\text{T}}(\text{bb}^{\text{add.}})$	p_{T} of $\text{bb}^{\text{add.}}$ pair		✓*		
Observables related to extra light jets					
$p_{\text{T}}(\text{lj}_1^{\text{extra}})$	p_{T} of leading extra light jet			✓	✓
$\lvert\Delta\phi(\text{lj}_1^{\text{extra}}, \text{b}_{\text{soft}})\rvert$	$\Delta\phi$ of leading extra light jet and softest b jet			✓	✓

- **No single generator** setup able to describe all distributions
- Inclusive measurements **above most predictions** *(but for particular choice of scales)*

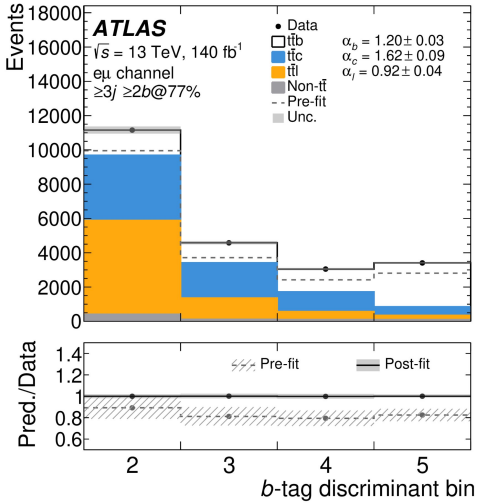


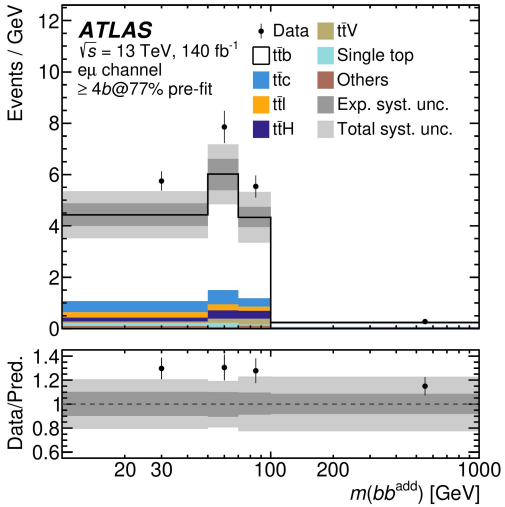


tt̄ + b-jets measurement - ATLAS

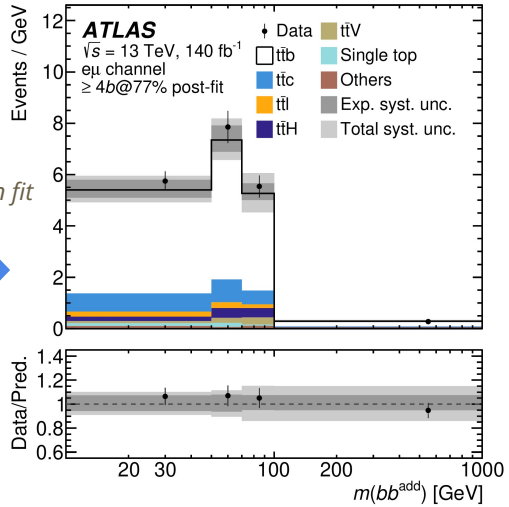
- ***eμ* channel** only considered
- *b*-jet to top assignment via **reconstruction algorithm**
  - both @particle- and detector-level - based on combination of **various ΔR**
- **Data-driven rescaling** of **light/*c*/*b* fractions** in *tt̄*+jets prior to unfolding (Iterative Bayesian Unfolding)
  - based on 3rd highest *b*-tagging score

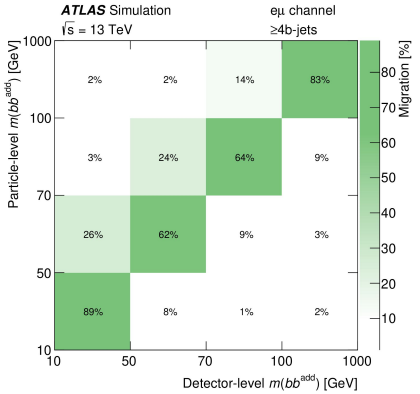
▹ arXiv:2407.13473 [hep-ex]





HF-fraction fit





$t\bar{t}$ + b-jets measurement - ATLAS - II

- **Results**:
  - none of the available predictions describes all observables…
  - **dedicated $t\bar{t}+b\bar{b}$** MC samples better in agreement with inclusive cross sections