Previous, ongoing and future measurements in Dortmund

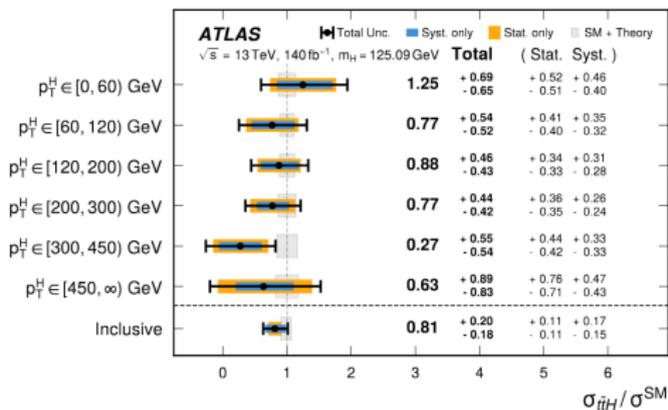**Andrea Knue, Kevin Kröninger**

October 7, 2025

technische universität
dortmund

Top-Higgs coupling and top-quark mass

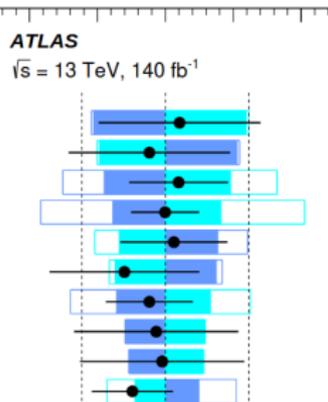# Top-Higgs coupling using $H \to b\bar{b}$ events ► Link latest measurement

- very complex analysis due to irreducible tt background, measured signal strength as function of Higgs p_T
- uncertainty dominated by modelling uncertainties
  - ↪ new diff. $t\bar{t} + b\bar{b}$ measurements allow for better understanding
- measurement published in 2024
- working on this topic since 2013, currently not participating in Run 3 plans

Over the years we managed to measure m_{top} more and more precisely
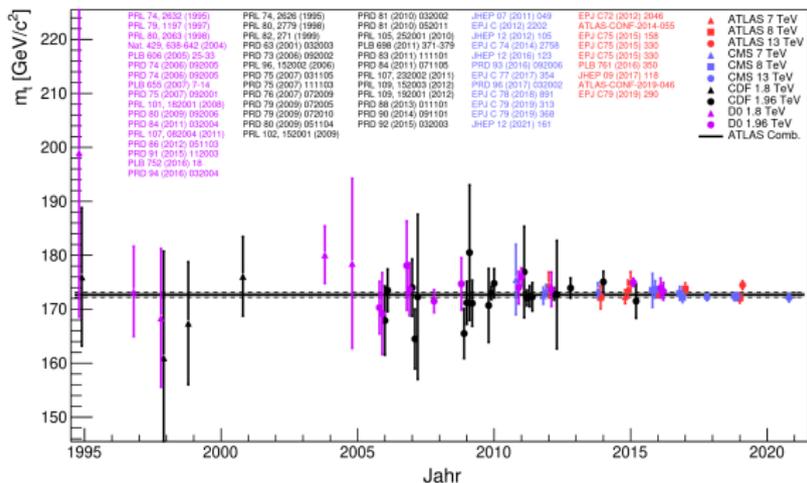
Today: the most precise property of the top quark: $\frac{\sigma_{m_{\text{top}}}}{m_{\text{top}}} < 0.2$ % ▸ LHC combination

Limiting factor of individual measurements: signal modelling
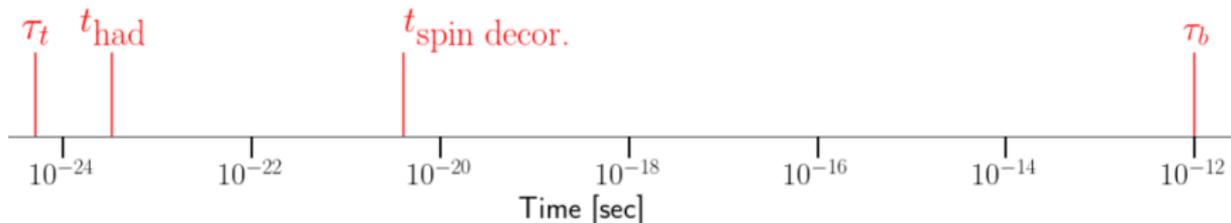
↪ recoil uncertainty (reduced when going from Pythia to Vincia), lineshape uncertainty, etc.

↪ work with the Siegen group on $bb4\ell$ will help with future measurements

↪ currently ongoing measurement should be public early next year, but improvements mentioned only available for next round

Spin properties and threshold effects

Top spin properties:

Top lifetime shorter than hadronisation and spin-decorrelation time!

What are the consequences?

- the top quarks decay before they can form stable hadrons

- the spins of the top and anti-top quark are correlated

- this spin information is passed to the top decay products
  ↪ information is not lost

- sensitive variables for spin information: angular distributions using top decay products

$^3S_1$

q → ← $\bar{q}$

t

$\bar{t}$

$^1S_0$

g → ← g

t

$\bar{t}$
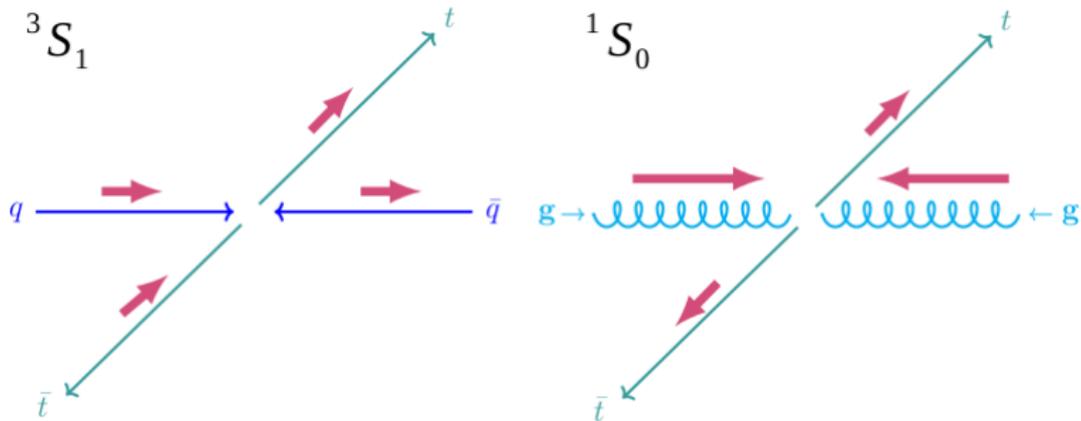
Reminder: State $^{2s+1}L_J$

- $s \mathrel{\hat{=}}$ spin
- $L \mathrel{\hat{=}}$ orbital angular momentum
- $J \mathrel{\hat{=}}$ total angular momentum

Correlation C:

$$C = \frac{N_{\text{parallel}} - N_{anti-parallel}}{N_{\text{parallel}} + N_{anti-parallel}}$$

Want to measure the full density matrix

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_1 d\Omega_2} = \frac{1}{(4\pi)^2}(1 + \vec{B}_1 \cdot \hat{\ell}_1 + \vec{B}_2 \cdot \hat{\ell}_2 - \hat{\ell}_1 \cdot \mathcal{C} \cdot \hat{\ell}_2)$$

- $\hat{\ell}_{1,2}$ describes the charged leptons
- $\vec{B}$ describes the polarisation of the top quarks: $\vec{B} = \begin{pmatrix} B_{x,1} \\ B_{y,1} \\ B_{z,1} \end{pmatrix}$, $\vec{B} = \begin{pmatrix} B_{x,2} \\ B_{y,2} \\ B_{z,2} \end{pmatrix}$
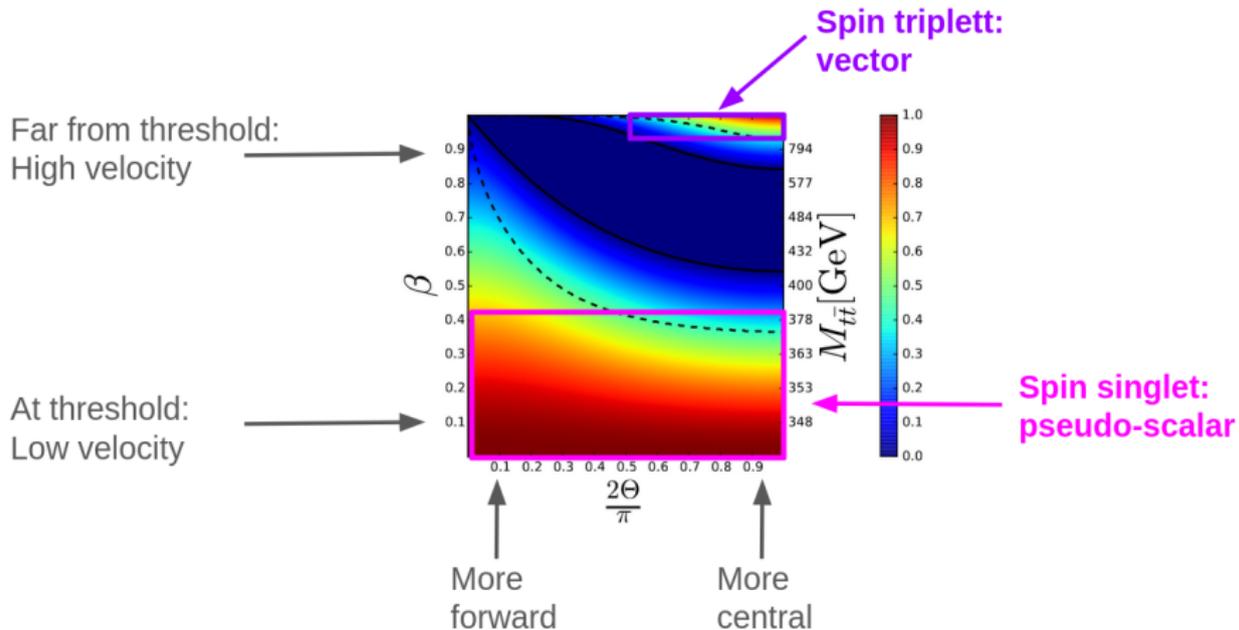- $\mathcal{C}$ is a 3x3 matrix containing the spin correlations

Spin state described by 15 different coefficients:

- polarisations $\vec{B}$ almost zero
- C_{ij} measured from angular distributions of charged leptons

| Expectation values	NLO predictions	Observables
B_+^k	0.0030 ± 0.0010	$\cos\theta_+^k$
B_-^k	0.0034 ± 0.0010	$\cos\theta_-^k$
B_+^n	0.0035 ± 0.0004	$\cos\theta_+^n$
B_-^n	0.0035 ± 0.0004	$\cos\theta_-^n$
B_+^r	0.0013 ± 0.0010	$\cos\theta_+^r$
B_-^r	0.0015 ± 0.0010	$\cos\theta_-^r$
$C(k,k)$	0.318 ± 0.003	$\cos\theta_+^k \cos\theta_-^k$
$C(n,n)$	0.332 ± 0.002	$\cos\theta_+^n \cos\theta_-^n$
$C(r,r)$	0.055 ± 0.009	$\cos\theta_+^r \cos\theta_-^r$
$C(n,k) + C(k,n)$	0.0023	$\cos\theta_+^n \cos\theta_-^k + \cos\theta_+^k \cos\theta_-^n$
$C(n,k) - C(k,n)$	0	$\cos\theta_+^n \cos\theta_-^k - \cos\theta_+^k \cos\theta_-^n$
$C(n,r) + C(r,n)$	0.0010	$\cos\theta_+^n \cos\theta_-^r + \cos\theta_+^r \cos\theta_-^n$
$C(n,r) - C(r,n)$	0	$\cos\theta_+^n \cos\theta_-^r - \cos\theta_+^r \cos\theta_-^n$
$C(r,k) + C(k,r)$	-0.226 ± 0.004	$\cos\theta_+^r \cos\theta_-^k + \cos\theta_+^k \cos\theta_-^r$
$C(r,k) - C(k,r)$	0	$\cos\theta_+^r \cos\theta_-^k - \cos\theta_+^k \cos\theta_-^r$

Far from threshold: High velocity

Spin triplett: vector

At threshold: Low velocity

**Spin singlet: pseudo-scalar**

More forward

More central

➢ at threshold: $C_{rr} > 0$, $C_{kk} > 0$, therefore $\Delta_E = tr\,[\boldsymbol{C}] = -3D > 0$

➢ working currently on two ongoing measurements, one at the threshold, one at large top p_T

EPJC 60 (2009) 375-386

total

color-octet

color-singlet

LHC $\sqrt{s}$ = 14 TeV
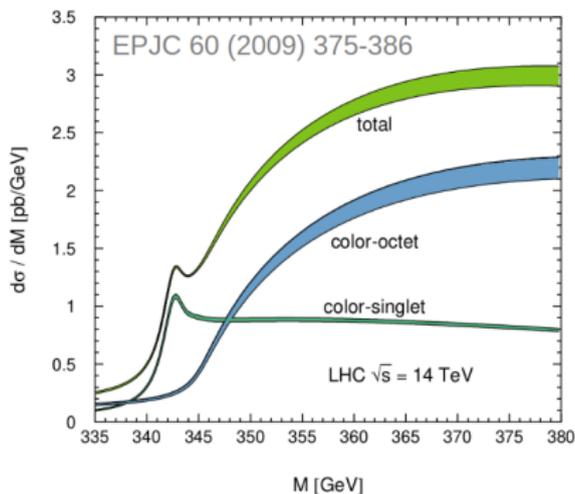
- at threshold: non-perturbative regime, Coulomb-like interaction
  ↪ quark velocities low, described by non-relativistic QCD (NRQCD)

- colour singlet: $^1S_0^{[0]}$: attractive potential: $\quad V(r) = -\frac{4}{3}\frac{\alpha_S}{r}$
  ↪ peak below production threshold

- colour octet: $\quad ^1S_0^{[8]}$: repulsive potential: $\quad V(r) = \frac{1}{6}\frac{\alpha_S}{r}$
  ↪ little contribution below threshold

So what actually happens at the production threshold?
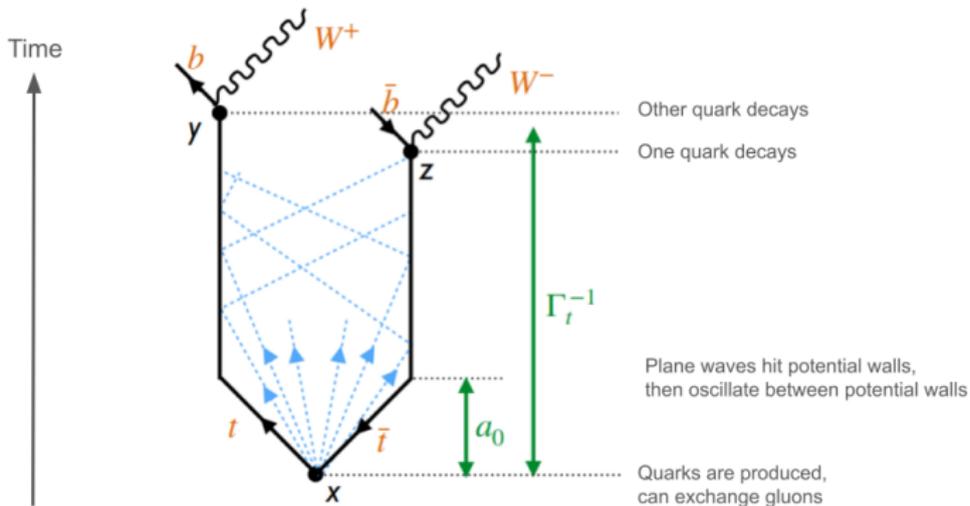
- here: top and anti-top do **not** annihilate each other
- "toponium" decays because one of the tops decays
- do not see resonance, would be visible as cross-section enhancement near threshold
- this effect is currently not included in our standard MC
- basic strategy: look at low $m_{t\bar{t}}$ values to check if something is missing!

- recent CMS search: fitted cross-section of bound pseudo-scalar $t\bar{t}$ state `▸ Link`
  - $\hookrightarrow \sigma(\eta_t) = 7.1 \pm 0.8$ pb, in agreement with NRQCD prediction
  - $\hookrightarrow$ have taken dilepton and lepton+jets channel into account
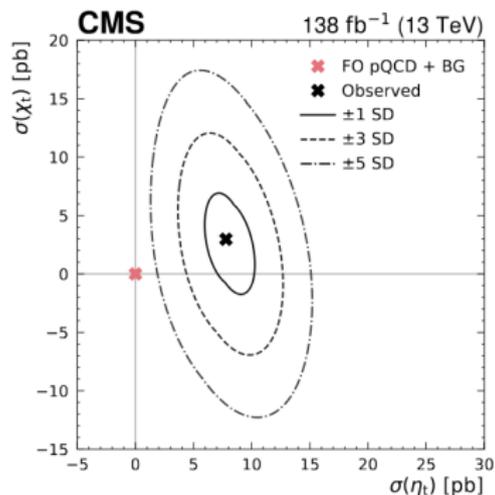
- followed up by a paper recently: `▸ arXiv:2503.22382`
  - $\hookrightarrow$ only dilepton channel, $\sigma(\eta_t) = 8.8\pm^{+1.2}_{-1.4}$ pb
  - $\hookrightarrow$ adding uncertainties (Pythia vs Herwig, standard $t\bar{t}$ vs. $bb4\ell$)
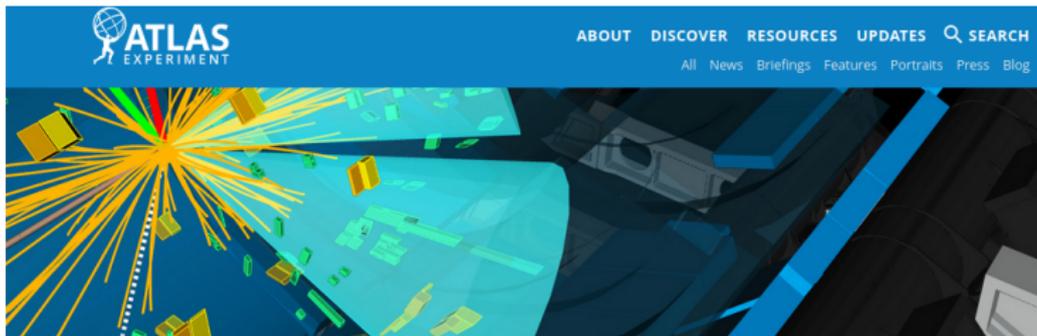 - $\hookrightarrow$ pseudo-scalar simulated with $m = 343$ GeV and $\Gamma = 2.8$ GeV

Abstract:

"The observed enhancement is consistent with the production of a color-singlet pseudoscalar quasi-bound toponium state, as predicted by nonrelativistic quantum chromodynamics."

Significance $> 5\sigma$

New preliminary ATLAS result in the dilepton channel `▶ ATLAS-CONF-2025-008`

ATLAS EXPERIMENT

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Physics Briefing

Tags:
top quark
physics results
EPS 2025

Bound to be discovered? ATLAS explores top-quark interactions near threshold

7 July 2025 | By ATLAS Collaboration

The top quark is a bit of a loner. While other quarks can join together to form bound states called hadrons, the top quark's extremely short lifetime means it decays almost instantly – disappearing before it can form a long-lasting bond.

- similar strategy as CMS, but improved modelling of pseudo-bound state by B. Fuks
- observed significance of 7.7σ, cross-section 9.0 ± 1.3 pb
- paper about to be published in dilepton channel
- currently working on lepton+jets channel (will be combined with dilepton in 2nd paper)

Top physics, B physics and EFT interpretation

Connection between top physics and B-physics: Compare processes:
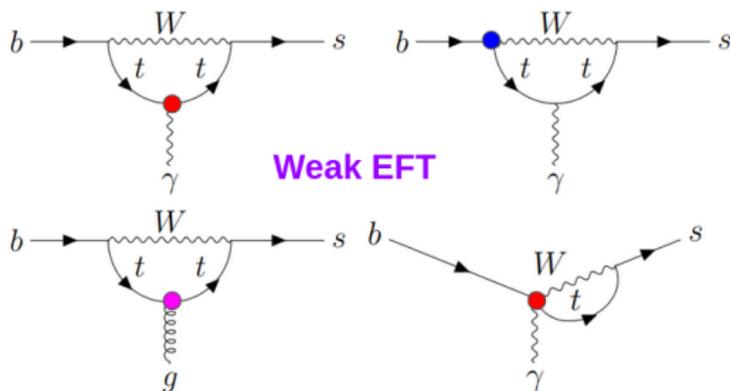
Top SM

Top EFT
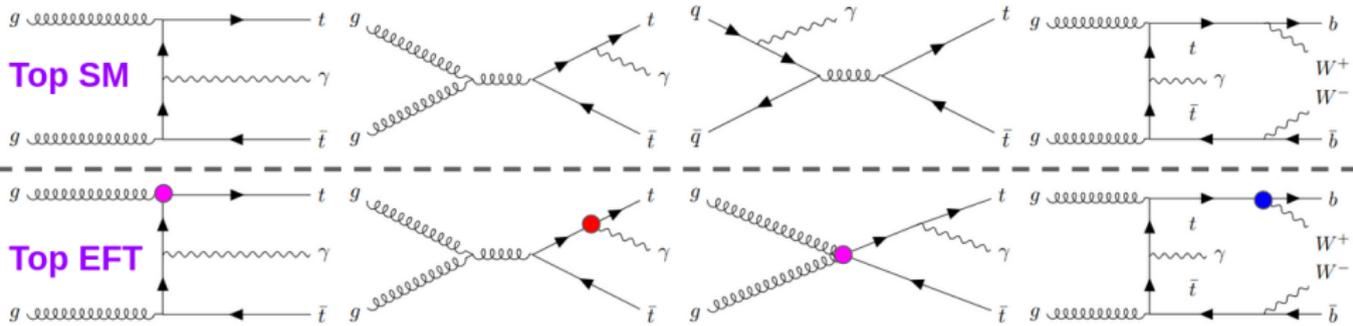
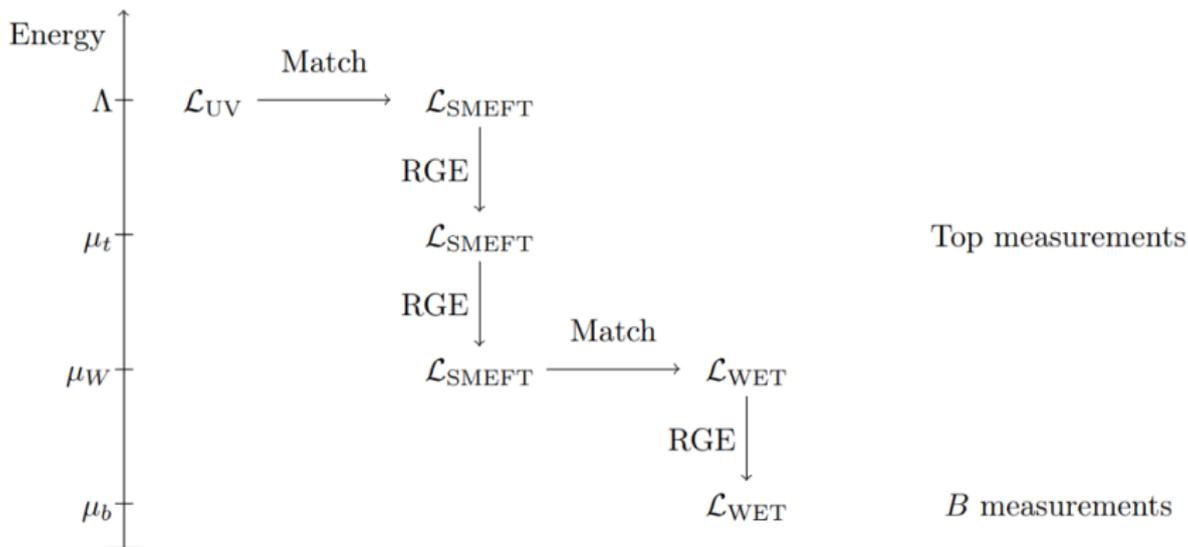Look here at operators for third-generation quarks and bosons:

$$O_{uB} = (\bar{q}_L \sigma^{\mu\nu} u_R)\, \tilde{\varphi} B_{\mu\nu},$$

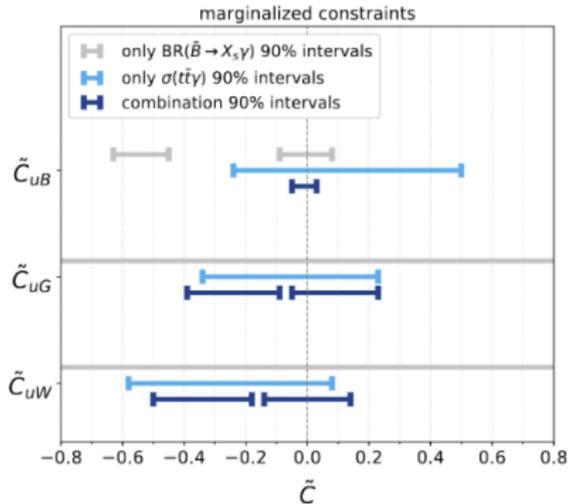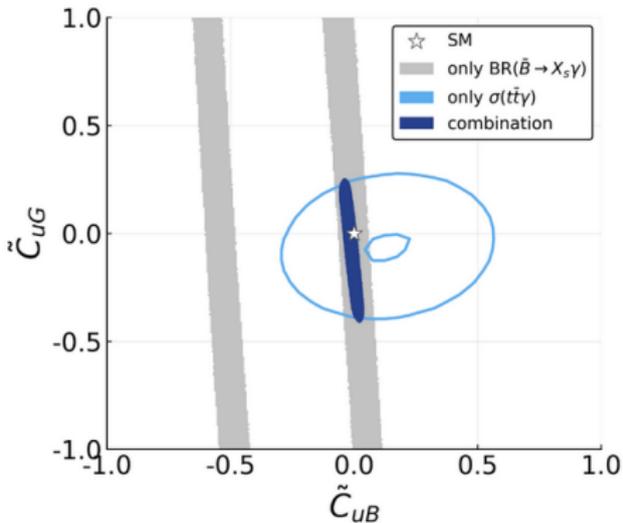$$O_{uG} = (\bar{q}_L \sigma^{\mu\nu} T^A u_R)\, \tilde{\varphi} G^A_{\mu\nu},$$

$$O_{uW} = (\bar{q}_L \sigma^{\mu\nu} \tau^I u_R)\, \tilde{\varphi} W^I_{\mu\nu},$$

Weak EFT

- Different processes can be sensitive to the same operators
- Note: energy scales very different here (top mass much higher than b mass), need to match the operators between SMEFT and WET (weak EFT)

Energy

Λ $\mathcal{L}_{\mathrm{UV}}$ $\xrightarrow{\text{Match}}$ $\mathcal{L}_{\mathrm{SMEFT}}$

           RGE $\downarrow$

μ_t $\mathcal{L}_{\mathrm{SMEFT}}$ Top measurements

           RGE $\downarrow$

μ_W $\mathcal{L}_{\mathrm{SMEFT}}$ $\xrightarrow{\text{Match}}$ $\mathcal{L}_{\mathrm{WET}}$

                     RGE $\downarrow$

μ_b $\mathcal{L}_{\mathrm{WET}}$ B measurements

Now combine the information:

- Gray line/bands: 90% confidence intervals from BR measurement only
- Light blue: 90% confidence intervals from tt+photon measurement only
- Dark blue: combination of the two: improved posterior regions for marginalized parameters (right)

Many more papers on this topic:

- increasing number of measurements also means increasing complexity:
- check for statistical overlap between measurements
- take into account correlation between uncertainties ▸ Phys.Rev.D 102 (2020) 115019
- need to consider EFT operators also for background processes
- References: ▸ EPJC Vol 80, 136 (2020)
  - ▸ JHEP Vol 2021, 10, (2021) $\rightarrow$ more operators, processes, future experiments
  - ▸ JHEP 11(2023) 110 $\rightarrow$ global fit with b, top, Z, Drell-Yan processes
  - ▸ arXiv:2307.06150

Top and Beauty synergies in SMEFT-fits at present and future colliders

Stefan Bißmann, Cornelius Grunwald, Gudrun Hiller, and Kevin Kröninger

Fakultät Physik, TU Dortmund, Otto-Hahn-Str.4, D-44221 Dortmund, Germany

We perform global fits within Standard Model Effe   More Synergies from Beauty, Top, Z and Drell-Yan Measurements in SMEFT
top-quark pair production processes and decay with
transitions and $Z \to b\bar{b}$ with a   Cornelius Grunwald,[1,*] Gudrun Hiller,[1,2,†] Kevin Kröninger,[1,‡] and Lara Nollen[1,§]
using projections for the HL-LHC and Belle II, an

Synergies of Drell-Yan, top and beauty in global SMEFT fits   *hn-Str.4, D-44221 Dortmund, Germany*
                                                               f Physics and Astronomy, University of Sussex,
                                                               Brighton, BN1 9QH, United Kingdom

CORNELIUS GRUNWALD, GUDRUN HILLER, KEVIN KRÖNING   **Constraining top-quark couplings combining top-quark and B decay observables**

TU Dortmund University, Department of Physics, Otto-Hal   DO-TH 19/17
Dortmund, Germany

Stefan Bißmann [a,1], Johannes Erdmann [b,1], Cornelius Grunwald [c,1], Gudrun Hiller [d,1], Kevin Kröninger [e,1]

[1] Fakult Physik, TU Dortmund, 44221 Dortmund, Germany

What are the open points for all these measurements?

Common theme: $t\bar{t}$ modelling

- modelling of $t\bar{t}$+heavy flavour in $ttH(bb)$
- top mass uncertainty: need $bb4\ell$, Vincia
- need to replace Pythia vs. Herwig uncertainty with more modular uncertainty
- need NLO decays and propagation of spin correlation to the parton shower

Threshold modelling

- NR QCD modelling, <u>opportunity for collaboration with research area 1 group</u>

EFT interpretation

- a lot of room to find or set limits on new physics on different energy and mass scales, many of the CmF measurements are providing inputs!
- flavour assumptions have large influence on interpretation
- ↪ suggestion: <u>build sustainable platform for global fits with long-term effort</u>

Other measurements/expertise in Dortmund

- other properties measurements (W helicity)

- differential cross-section measurements (boosted/resolved) in $t\bar{t}$, b-fragmentation, colour reconnection

- MC tuning/modelling studies

- flavour tagging

- top-related searches for exotic particles in boosted final states

- search for same-sign tops (EFT)

- CKM measurements (t-channel)

- rare top processes, e.g. $tq\gamma$ observation

- development of statistical tools

Backup

- here: top and anti-top do <u>not</u> annihilate each other
- "toponium" decays because one of the tops decays
- do not see resonance, would be visible as cross-section enhancement near threshold
- this effect is currently not included in our standard MC
- basic strategy: look at low $m_{t\bar{t}}$ values to check if something is missing!
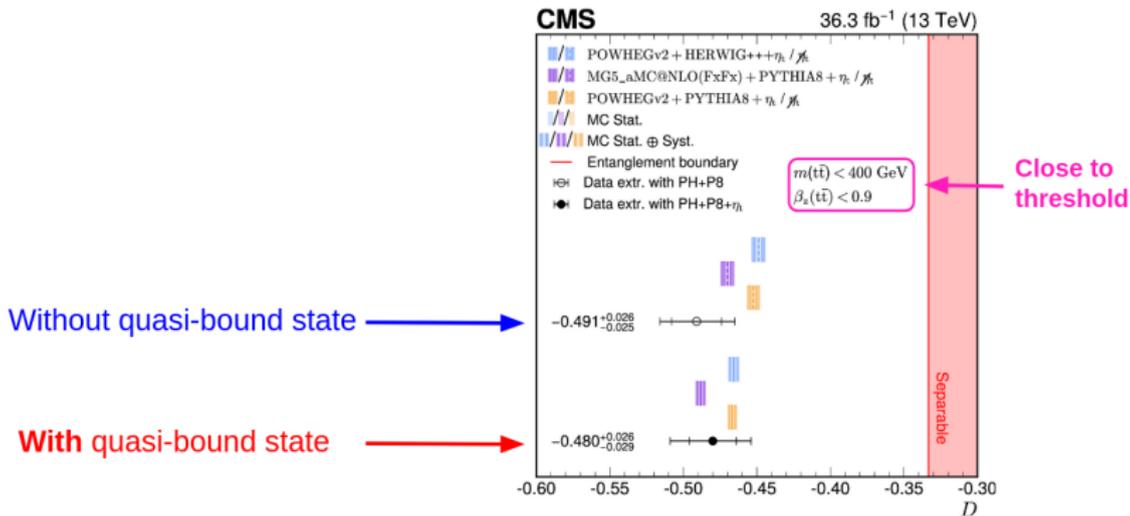

TOPQ-2018-15
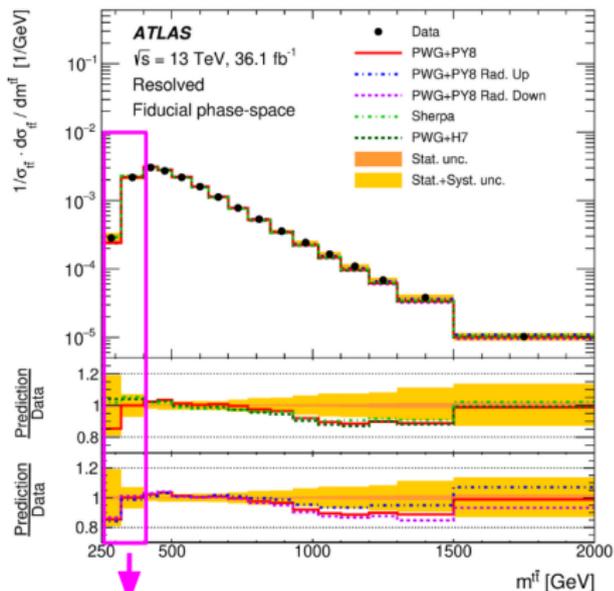
Several MC generators show deviations: also large uncertainties from tt modelling

- have also seen in entanglement measurements that toponium modelling can play a role
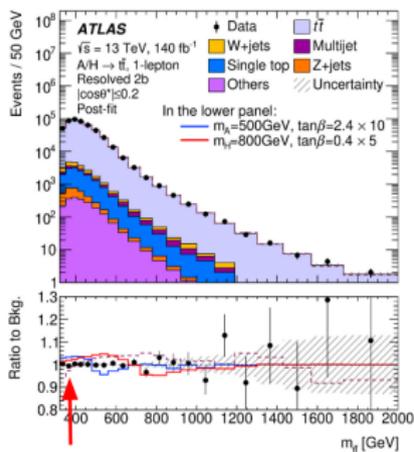
  ▶ Rep. Prog. Phys. 87 (2024) 117801

Without quasi-bound state →

With quasi-bound state →

Close to threshold

- "toponium" sample here: modelled as pseudo-scalar resonance

- mass: $2 \cdot m_{\text{top}} -$ Binding energy = 343 GeV, $\Gamma = 7$ GeV

- sample only includes resonant color-singlet contribution

Major points to be addressed for such an analysis in ATLAS:

1. Simulation of "toponium" process

2. NNLO reweighting to be applied

   ↪ data has softer p_T and $m_{t\bar{t}}$ spectra than simulation

   ↪ standard NNLO reweighting in ATLAS has too coarse binning in $m_{t\bar{t}}$ and a different m_{top} value than our nominal MC

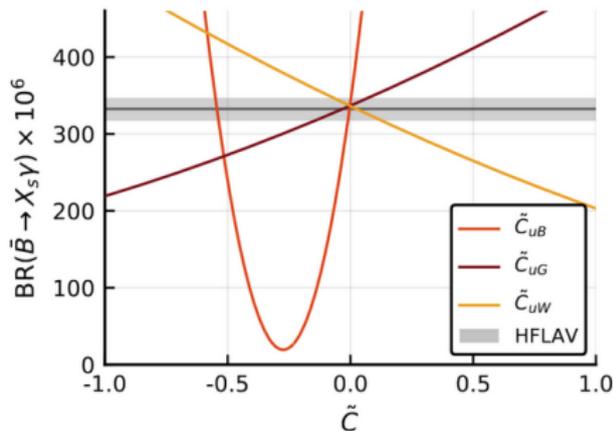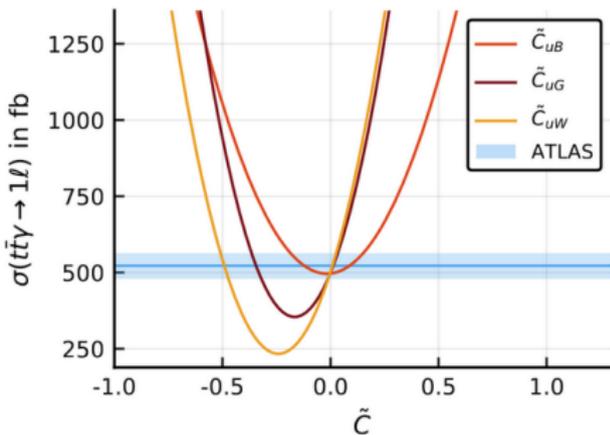3. $t\bar{t}$ background model: adequate to use in profile LH fit?
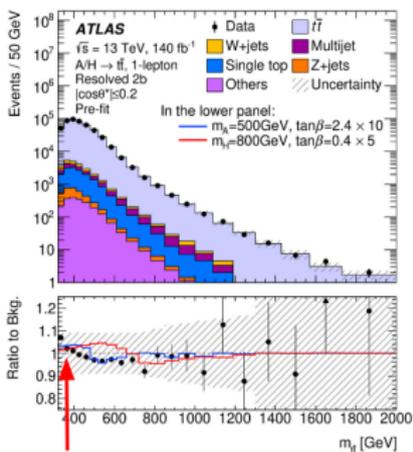
Slope visible pre-fit   **Gone post-fit**

Sensitivity of the measurements to the Wilson coefficients

- Here: vary one coefficient at a time and set others to zero
- See dependence of tt+photon cross-section on Wilson coefficients
- Blue/gray horizontal lines: measurement of cross-section/branching ratio
- What happens if we combine this information? Use EFTFitter tool.