In Search of Top Quark Pairs With Zero Total Angular Momentum

CMS-PAS-HIG-22-013

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LPNHE seminar – 2024/11/04

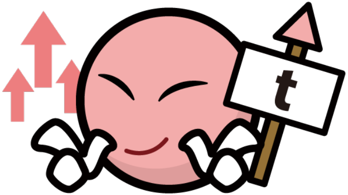
The top quark

QCD $t\bar{t}$, EWK $t + X$

Other modes e.g. $t\bar{t}t\bar{t}$ are much rarer

$t \to Wb$ (BR ~ 1)

$\Rightarrow$ $t\bar{t}$ classification by W decay modes



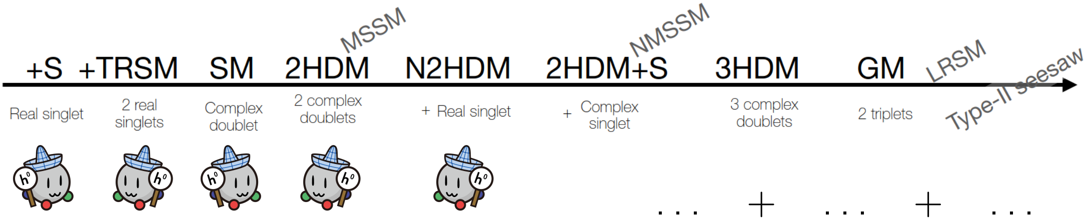
$\mathcal{O}\left(10^{-25}\right)$ s

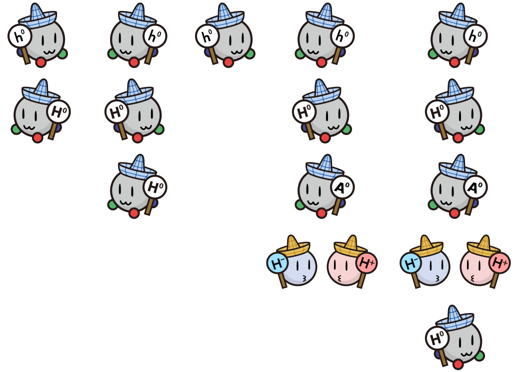
$\ll \Lambda_{QCD}^{-1} \to$ observe "bare" quark

172.52 ± 0.33 GeV

$\to$ heaviest in SM. A portal to BSM?

Extending the SM scalar sector

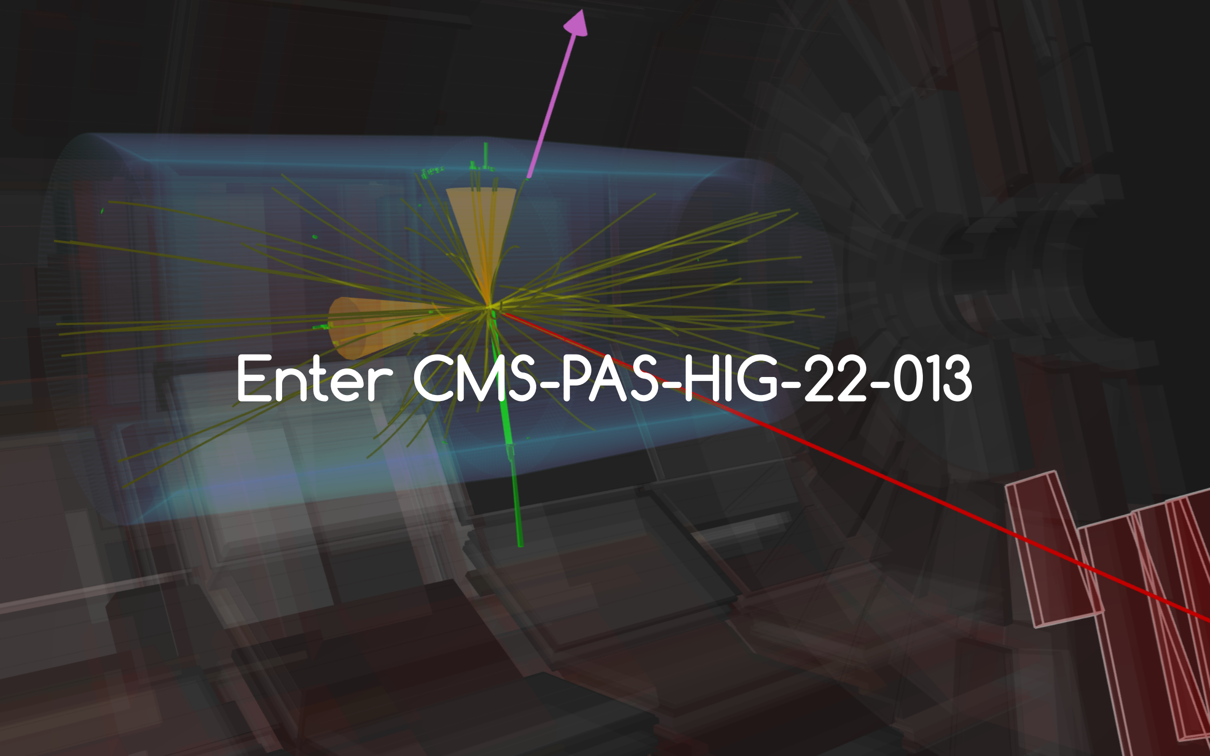




Huge parameter spaces to constrain!

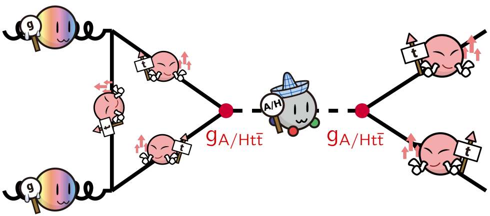
What about ALPs? Or DM candidates?

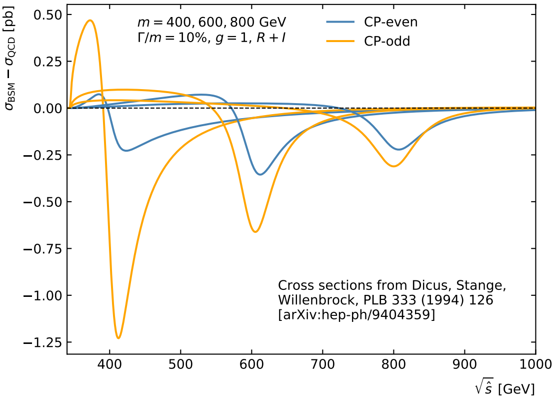
Certain areas only accessible through $t\bar{t}$!


Enter CMS-PAS-HIG-22-013

Theoretical set-up

Signal: gluon fusion $A/H \to t\bar{t}$



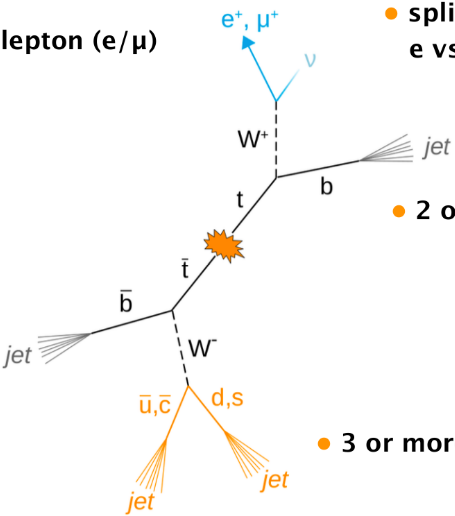


- A is a CP-odd scalar, and H is CP-even
- Yukawa-like coupling with modifiers $g_{A/Ht\bar{t}}$
  - If $m_{A/H} > 2m_t$, direct decays are possible
  - Dominant, if $g_{A/Ht\bar{t}}$ is $\mathcal{O}(1)$
- Simplifying assumptions:
  - A/H couple only to top quarks
  - CP conserving → A/H don't mix

- Strong interference with QCD $t\bar{t}$ production
- Leads to a peak-dip structure in $m_{t\bar{t}}$
  - Requires care: signal rate can be 0
- Set up as a generic and model-agnostic analysis
  - Free parameters: $m_{A/H}$, $\Gamma_{A/H}$, $g_{A/Ht\bar{t}}$
  - Matchable e.g. in type-II 2HDM: $g_{At\bar{t}} = \tan^{-1}\beta$
  - Performed in ℓj and $\ell\bar{\ell}$ final states

ℓj analysis selection

- exactly one lepton (e/μ)
- split in 4 categories: e vs μ and 3 jets vs ≥4 jets
- 2 or more b-jets
- 3 or more jets

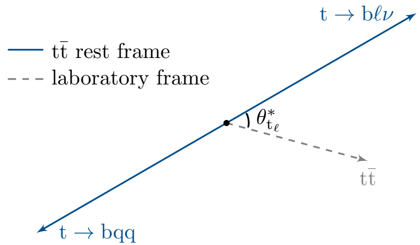


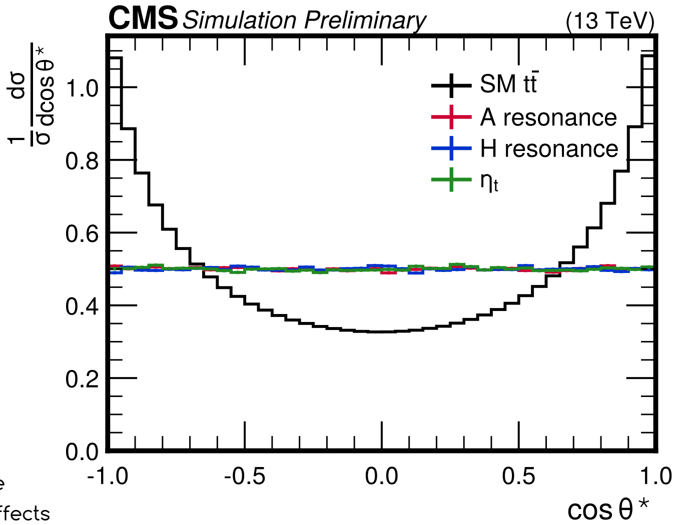
- Reconstruct $t\bar{t}$ system with `NeutrinoSolver` algorithm
  NIM A 736 (2014) 169
  - assign b-jets by maximum likelihood
  - energy correction factor applied for 3 jet events (lost or merged jets)

NIM A 788 (2015) 128

slide: C. Schwanenberger

ℓj angular variable: $|\cos\theta^*_t|$



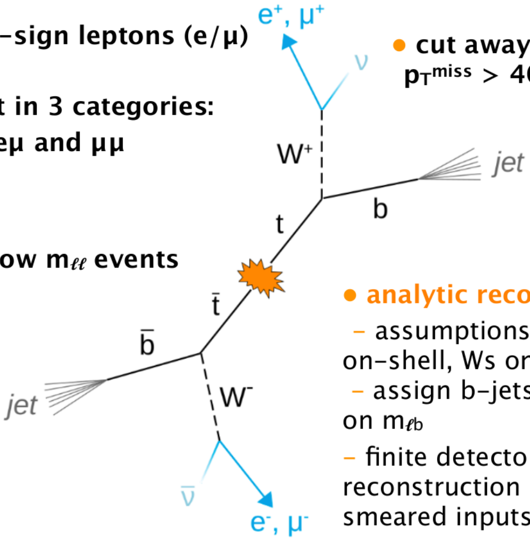


- Flat distribution for resonant A/H
- SM shape from the mixture of helicities
  - Becomes peakier at increasing $m_{t\bar{t}}$
- Use the absolute value in the analysis
  - 5 non-uniform bins based on the SM shape
  - Sign dependence only from CP-violating effects

sketch: JHEP 04 (2020) 171

$\ell\bar{\ell}$ analysis selection

- **exactly two opposite-sign leptons (e/μ)**
- **split in 3 categories: ee, eμ and μμ**
- **reject low $m_{\ell\ell}$ events**
- **2 or more jets**



- **cut away Z peak & require p_T^{miss} > 40 GeV in ee/μμ**
- **1 or more b-jets**
- **analytic reconstruction of $t\bar{t}$ system**
  - assumptions: all p_T^{miss} from νν, tops on-shell, Ws on-shell
  - assign b-jets using likelihood, based on $m_{\ell b}$
  - finite detector resolution: repeat reconstruction 100 times with randomly smeared inputs, take weighted average

slide: C. Schwanenberger

$\ell\bar{\ell}$ analysis strategy: $t\bar{t}$ spin density matrix

$$|\mathcal{M}|^2 \propto A + \vec{B}_1 \cdot \hat{\ell^1} + \vec{B}_2 \cdot \hat{\ell^2} - \hat{\ell^1} \cdot C \cdot \hat{\ell^2}$$

$\Rightarrow [1, 2] \equiv [t, \bar{t}]$ $\Rightarrow \hat{\ell^i} =$ top spin vectors

$$A \qquad \vec{B}_i = \begin{pmatrix} \times \\ \times \\ \times \end{pmatrix} \qquad C = \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ \times & \times & \times \end{pmatrix}$$

$\rightarrow$ spin-independent
σ, $m_{t\bar{t}}$, $p_T^t \ldots$

$\rightarrow$ top polarization vectors

$\rightarrow$ $t\bar{t}$ spin correlation matrix

Each $\times$ is directly related to a distribution of one observable

$\ell\bar{\ell}$ angular variable 1: c_{hel}

- $c_{hel} = \hat{\ell}^1 \cdot \hat{\ell}^2$, whose slope $D = -\mathrm{Tr}[C]/3$
- Discriminates A vs H vs SM
  - Or rather, the $t\bar{t}$ spin states
  - Resonant A/H → pure ${}^1S_0^{[1]}$ / ${}^3P_0^{[1]}$ $t\bar{t}$ pairs

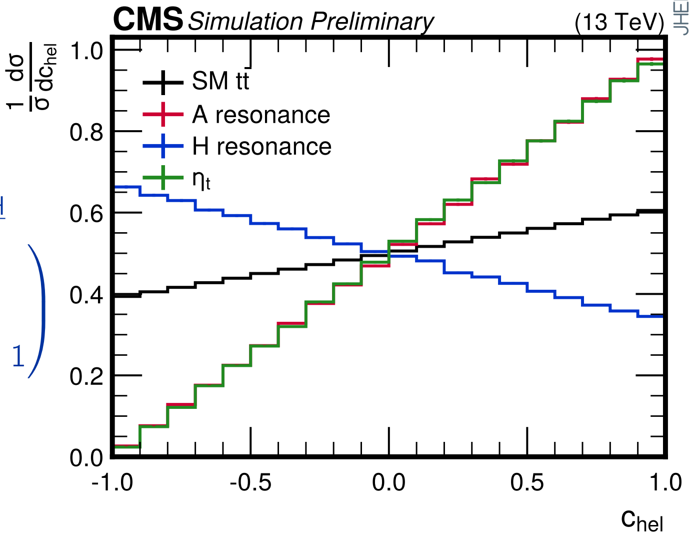
Resonant A

$$\begin{pmatrix} -1 & & \\ & -1 & \\ & & -1 \end{pmatrix}$$

Resonant H

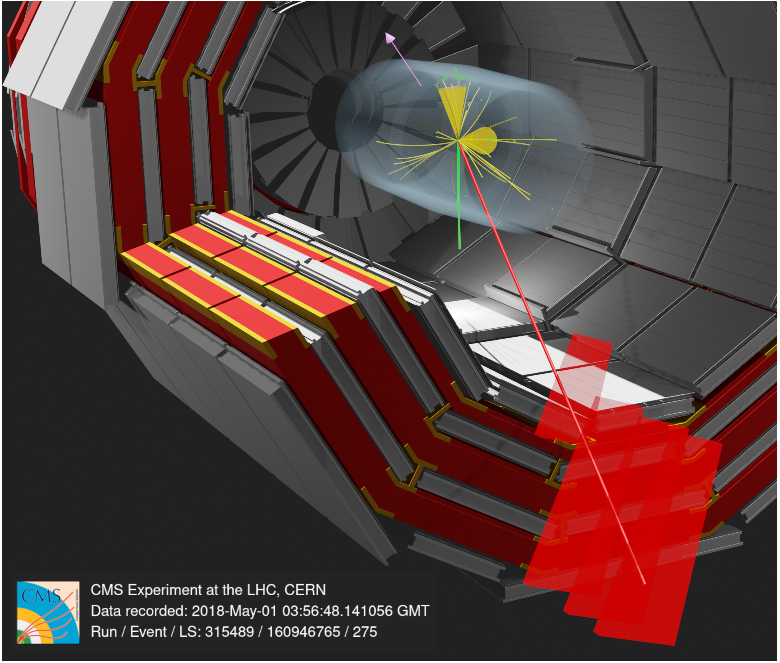
$$\begin{pmatrix} -1 & & \\ & 1 & \\ & & 1 \end{pmatrix}$$

- **Unsung benefit** – $t\bar{t}$ spin state is all c_{hel} sees
  - Robust against systematic effects



JHEP 12 (2015) 026

It's all about alignment



Muon

Electron

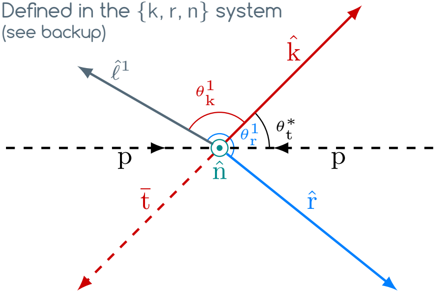
b jets

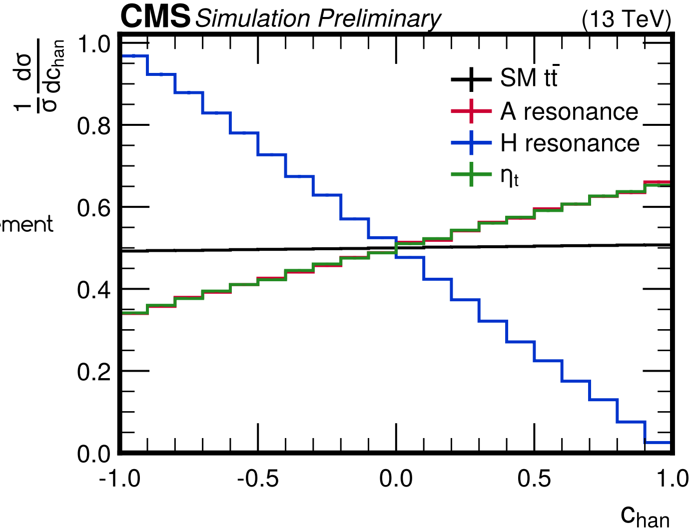
$\not{p}_T$

$\ell\bar{\ell}$ angular variable 2: c_{han}

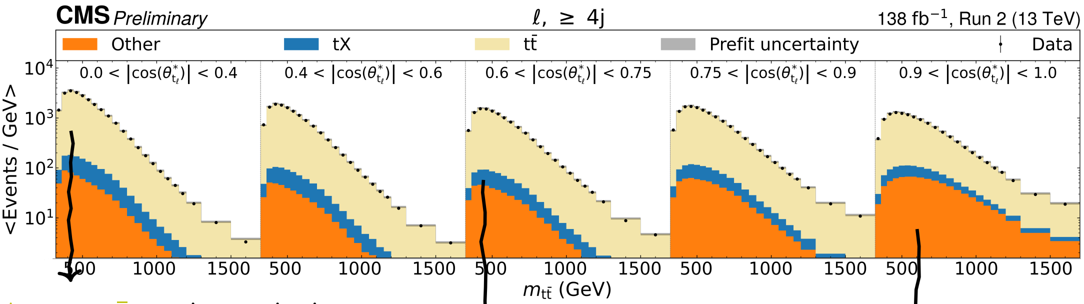
- As cute as c_{hel}, H discrimination done well
  - Linear comb. of C diagonal entries
  - Equally: flip one $\hat{\ell}$ wrt k axis, then take dot product
- Use a 3 × 3 uniform binning for the two
- Bonus: either can probe quantum entanglement

Defined in the $\{k, r, n\}$ system
(see backup)



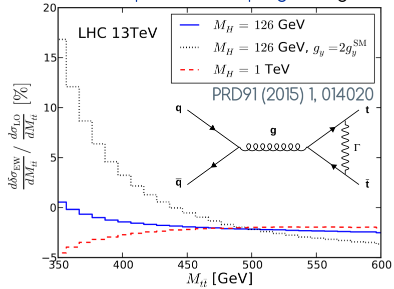


Background modelling



SM top pair $t\bar{t}$: most important

- NLO QCD reweighted to NNLO QCD + NLO EW
- Unc. on top Yukawa coupling through EW correction



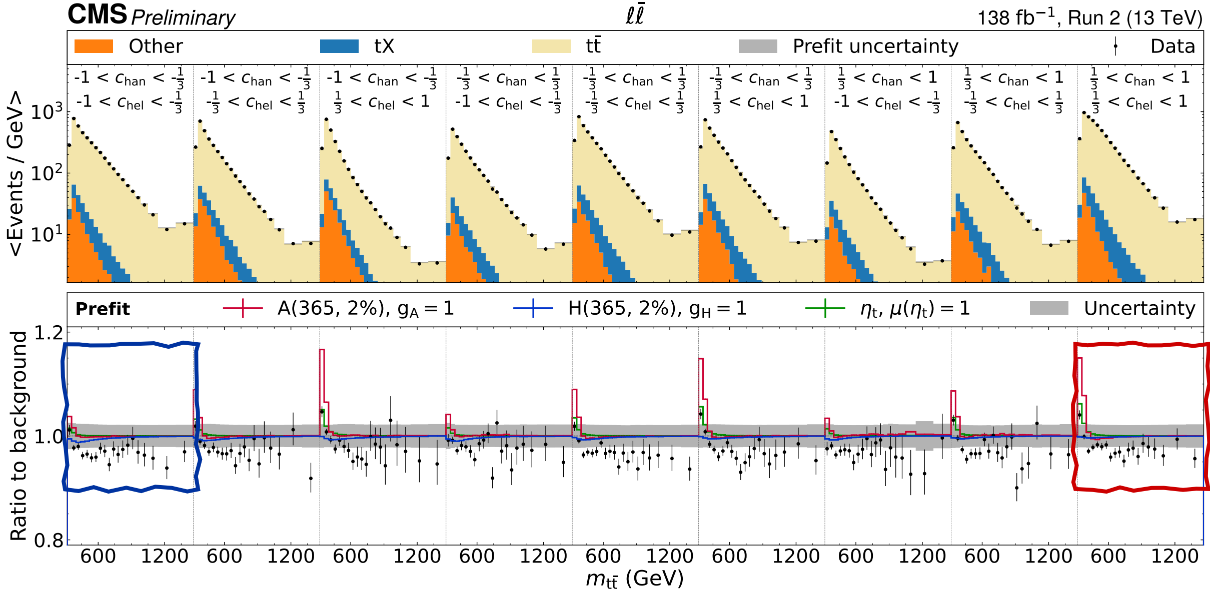
Single top tX

- NLO QCD MC for all three modes
- t-channel important in ℓj, tW in $\ell\bar{\ell}$

Other minor backgrounds

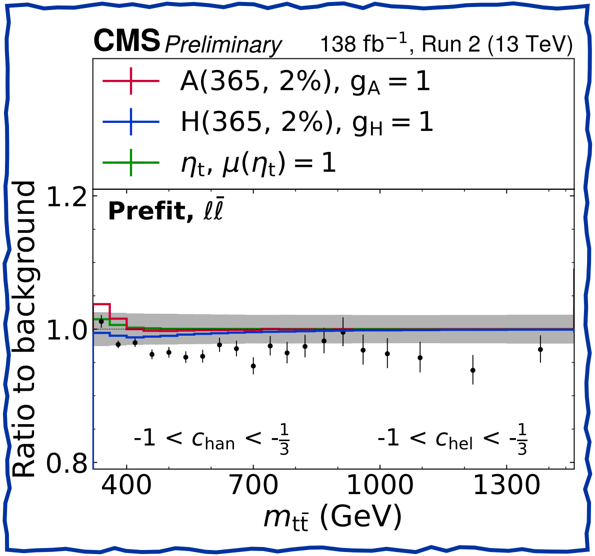
- ℓj: multijet QCD + EW in b-tag sideband CRs
- $\ell\bar{\ell}$: NNLO $Z/\gamma^* \to \ell\bar{\ell}$, NLO $t\bar{t}V$, LO VV MCs

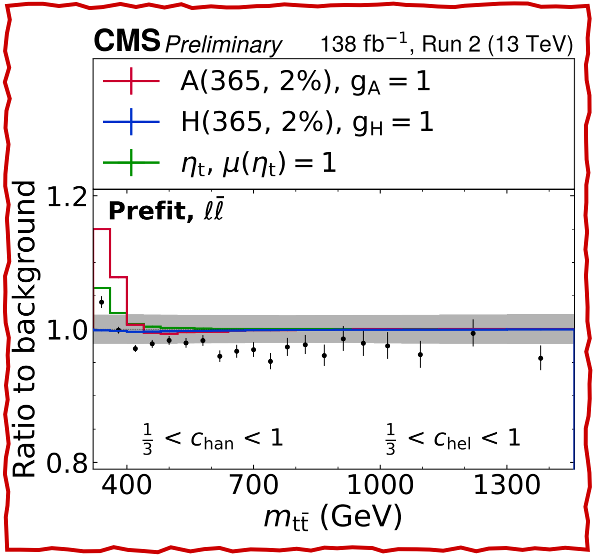
Prefit distribution



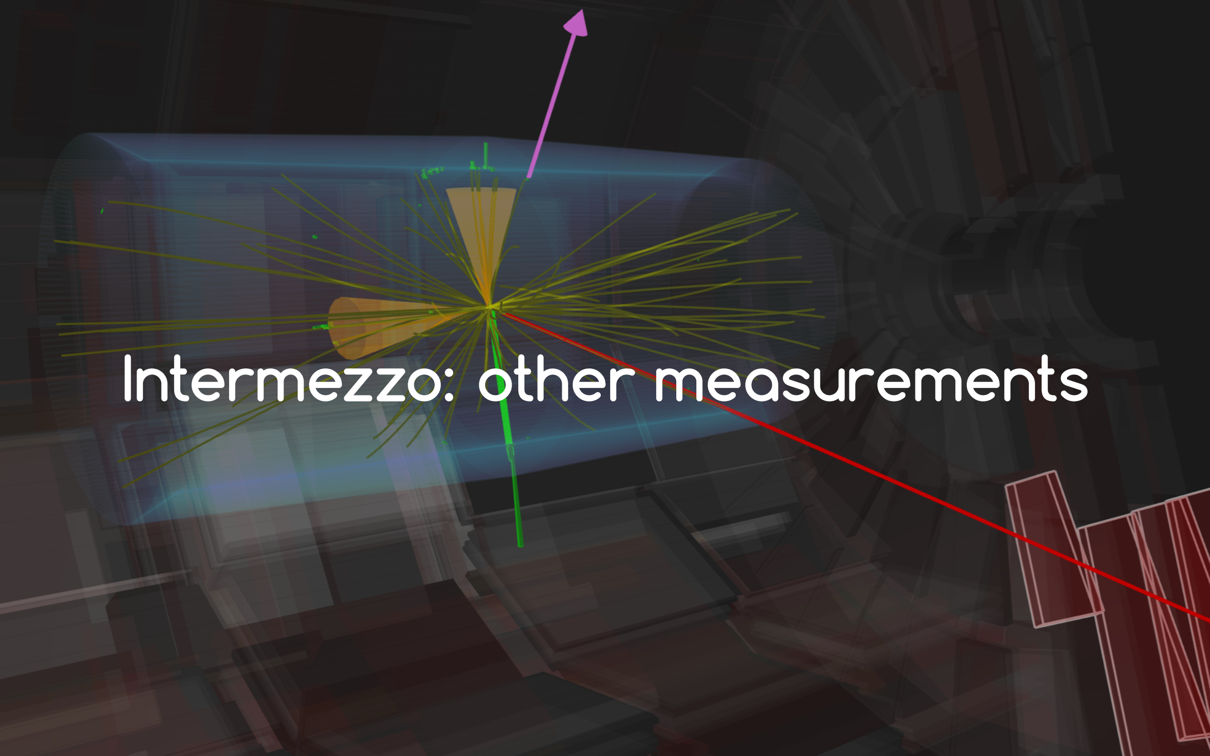
Similar prefit ratios in ℓj – see backup

Prefit background expectation



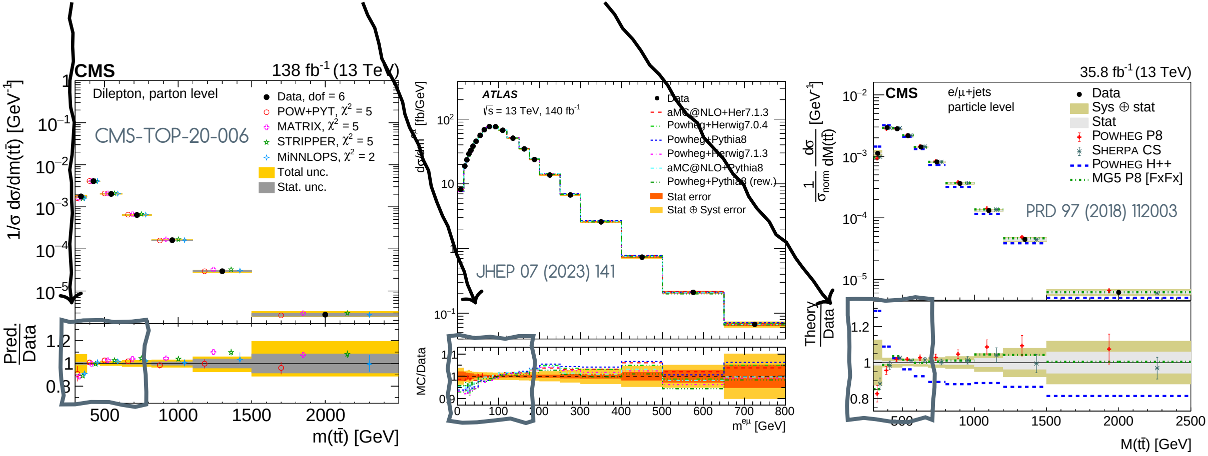


Intermezzo: other measurements

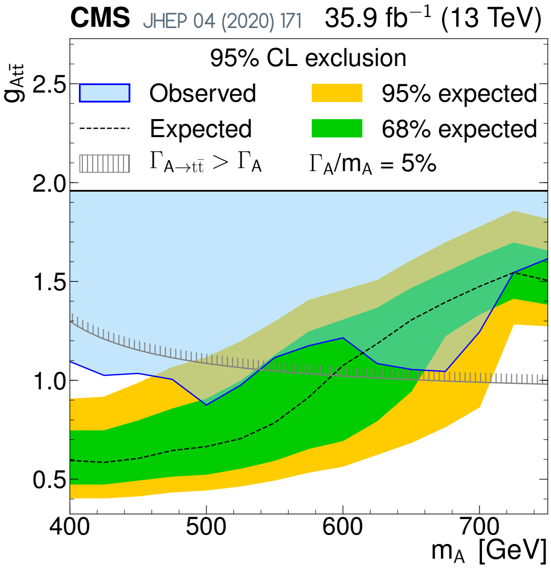


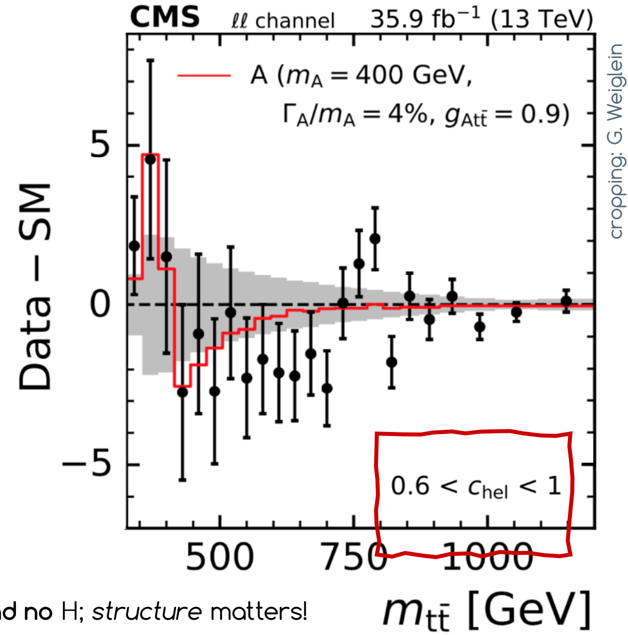
What to expect from $m_{t\bar{t}}$?

Data – pQCD tension observed at the threshold region in multiple measurements



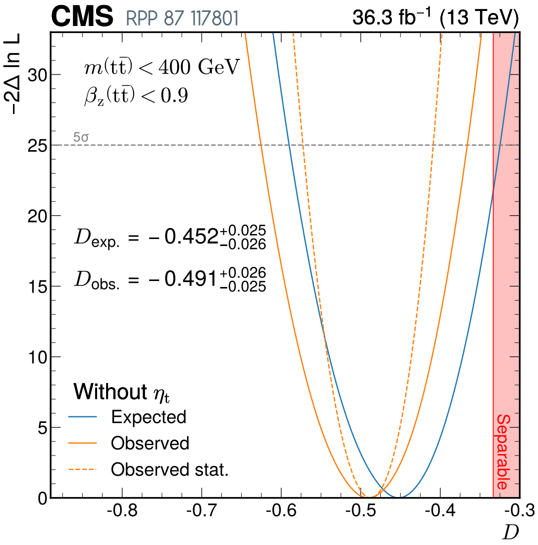
The effect is spin-dependent...

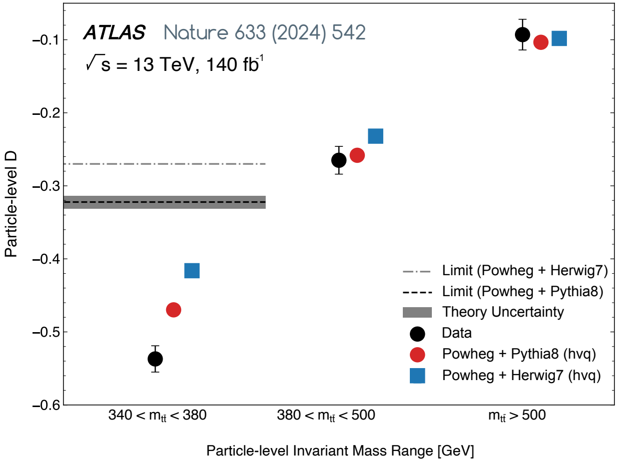




3.5σ local A **excess, and no** H; *structure* matters!

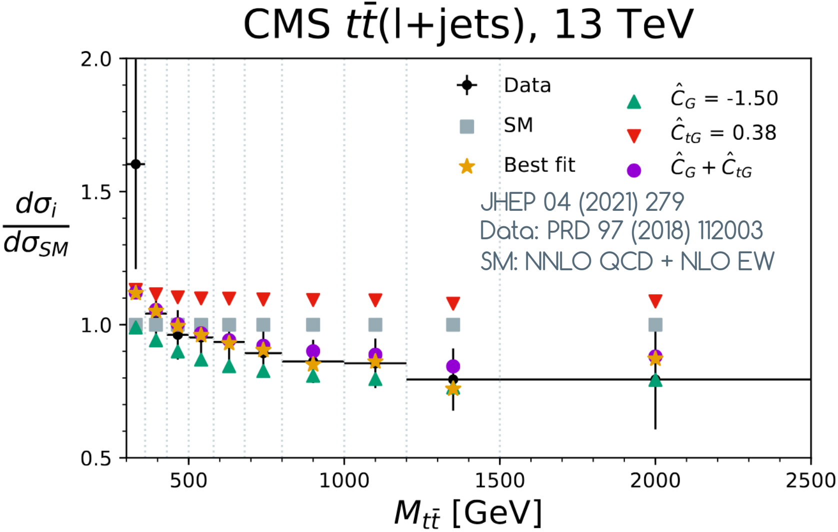
...and it is reproducible!





$D < -1/3 \rightarrow$ the $t\bar{t}$ pair is entangled (Peres-Horodecki criterion)

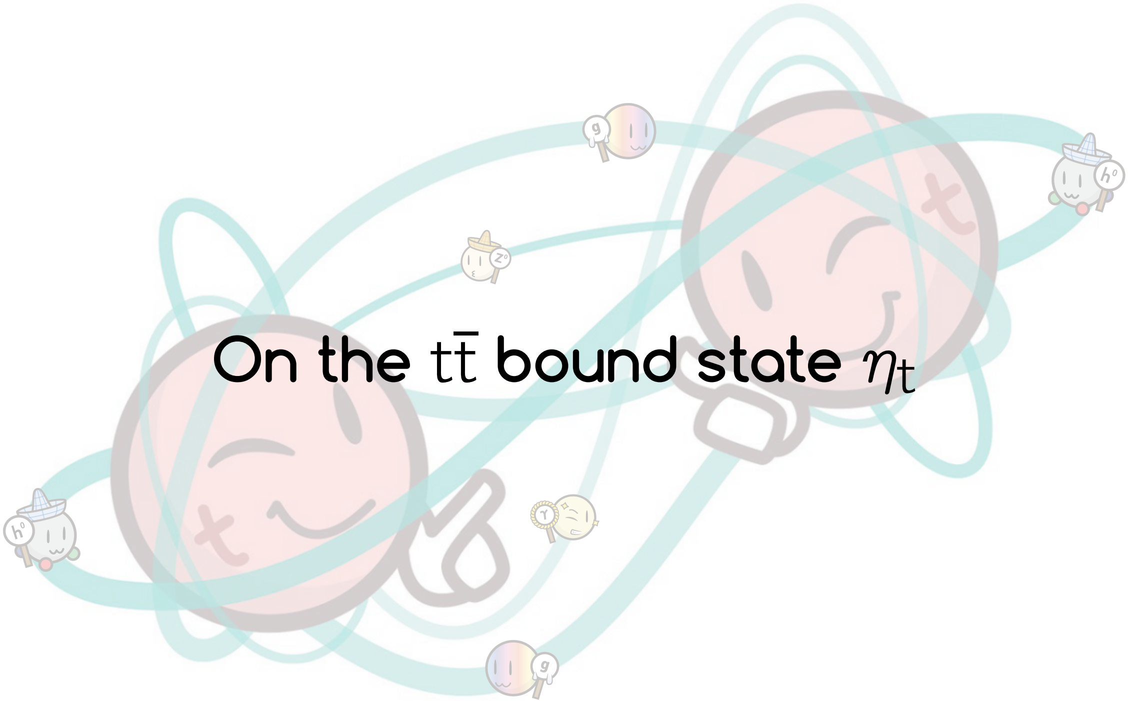
Would SMEFT operators help? ...no.



Both C_G and C_{tG} are more tightly constrained, once other data is considered.

Not much hint from other analyses. Check out J. Ellis' lecture for more info.

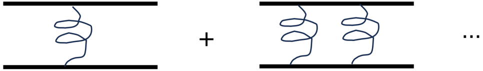
On the $t\bar{t}$ bound state η_t



The top is... a quark

So it probably does quarky things, like...

Coulombic gluon exchanges:



$$\sim \frac{\alpha_s}{\beta} \qquad \sim \left(\frac{\alpha_s}{\beta}\right)^2$$

, β = tops' relative velocity

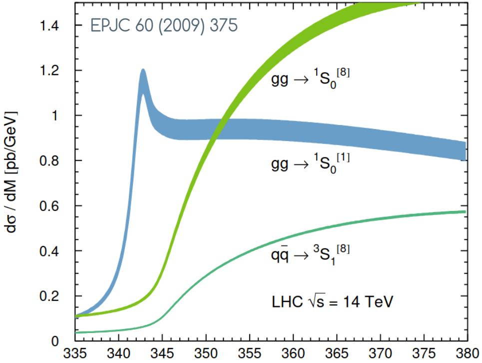
Inducing the Sommerfeld correction:

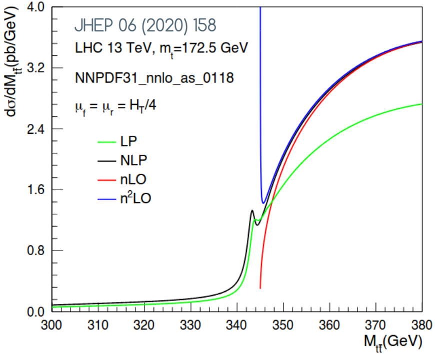
$$J \sim \frac{\alpha_s/\beta}{e^{\pi\frac{\alpha_s}{\beta}} - 1} = 1 + \frac{\alpha_s}{\beta} + \ldots$$

Summed over all singlet and octet hard $t\bar{t}$ states

Essential at the threshold region

Fixed-order pQCD doesn't give this effect. Resummation is needed.





left side figures: A. Mitov's TOP2023 slides

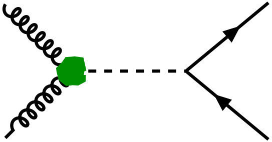
Effective η_t model

No full MC generator yet, but…

effective descriptions exist: PRD 104, 034023 (2021)

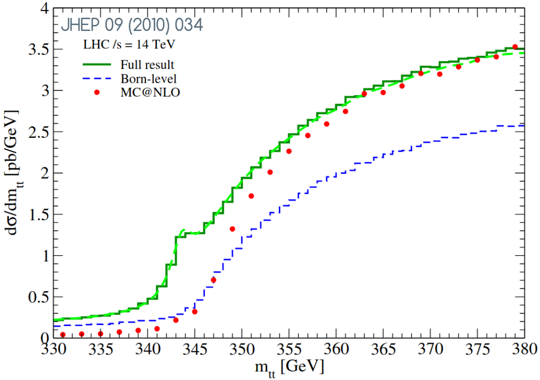
see also: JHEP 03 (2024) 099 and PRD 110 (2024) 5, 054032

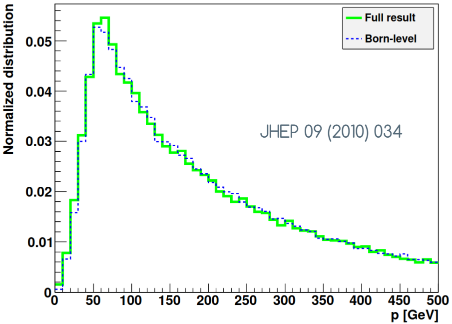
Simplifying, it's implemented as:



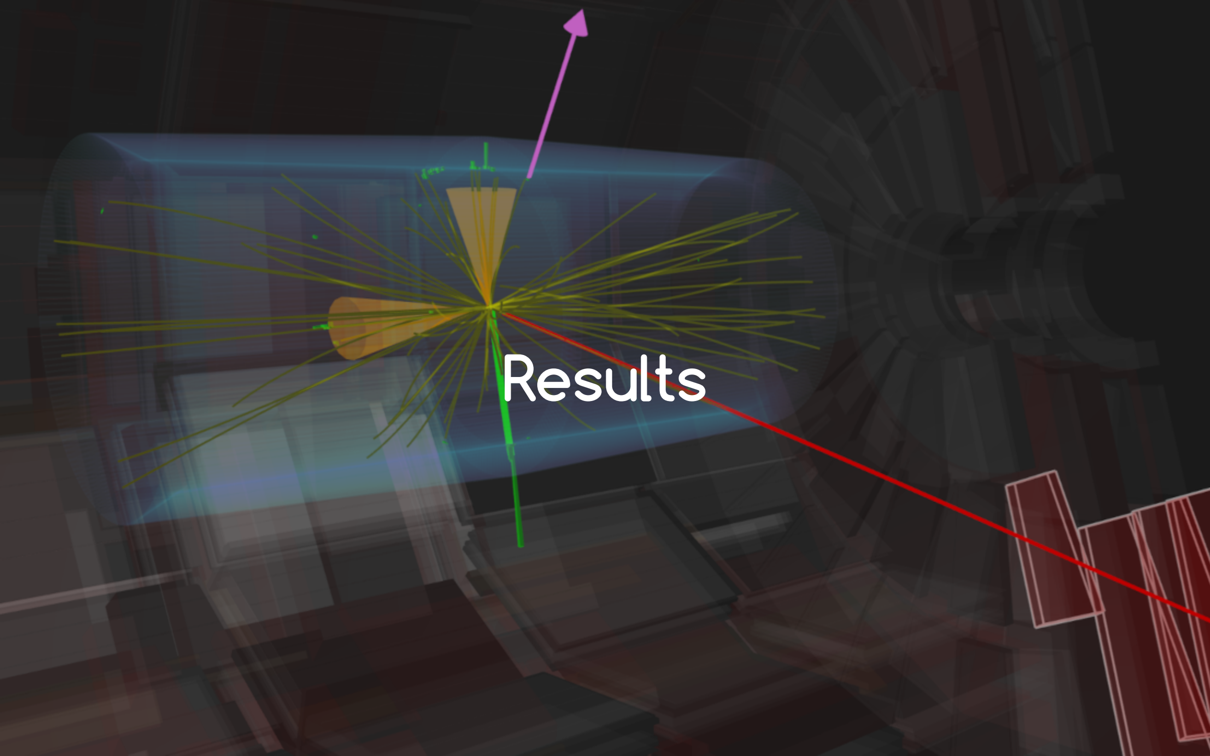
- Generic singlet state coupling to gluons and tops
- A-like resonance: 343 GeV mass, 7 GeV width
- Allow off-shell tops
- 6.43 pb nominal rate [JHEP 09 (2010) 034]
- Exact – effective lineshape differences below experimental resolution (~20%)

Interpret with caution

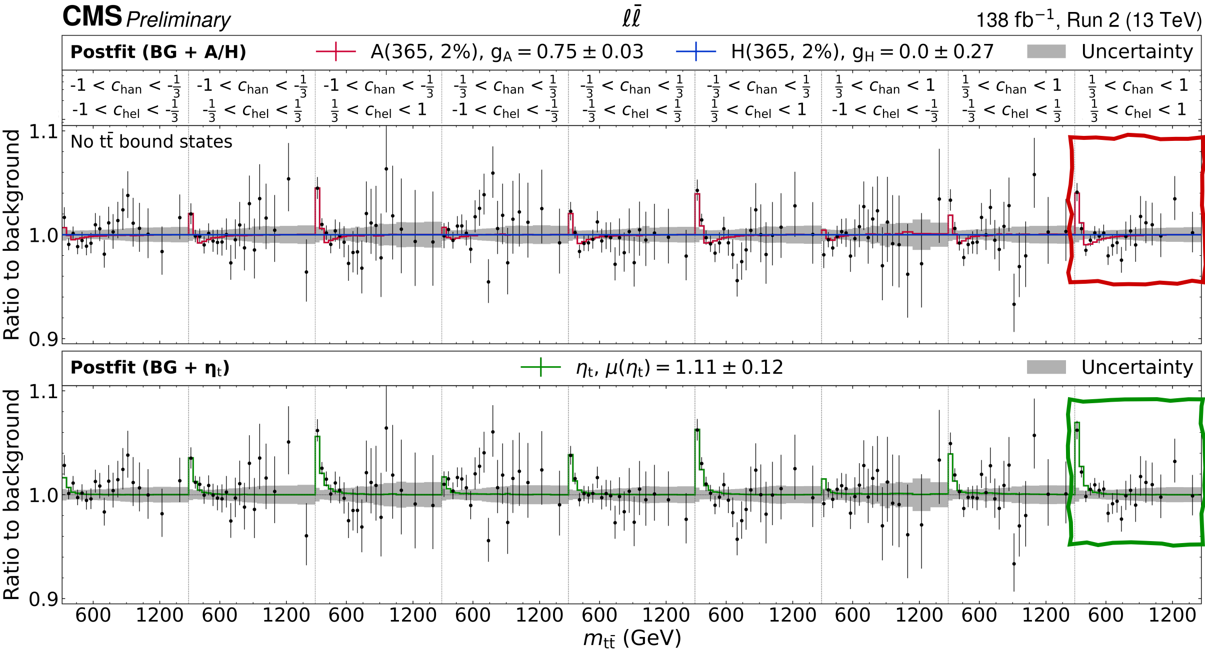




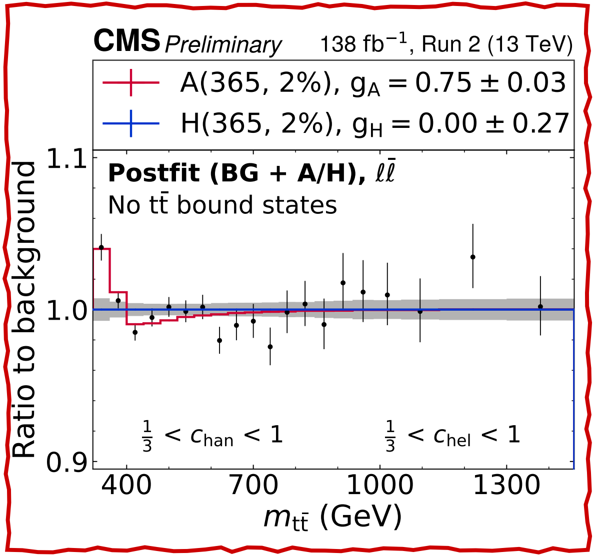
Results

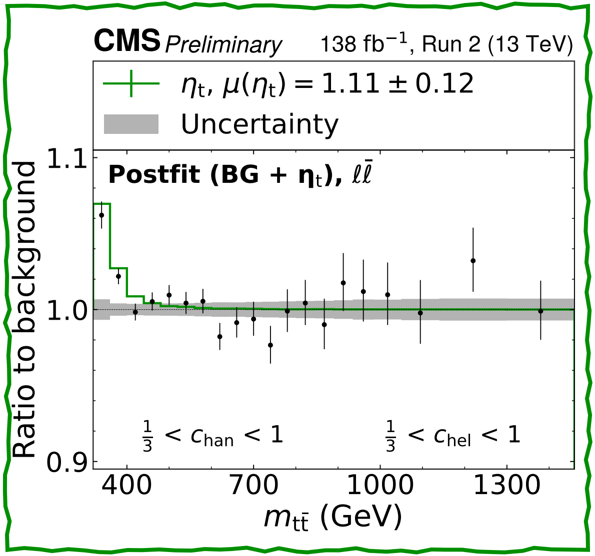


What HIG-22-013 sees



A or effective η_t? Difficult question!





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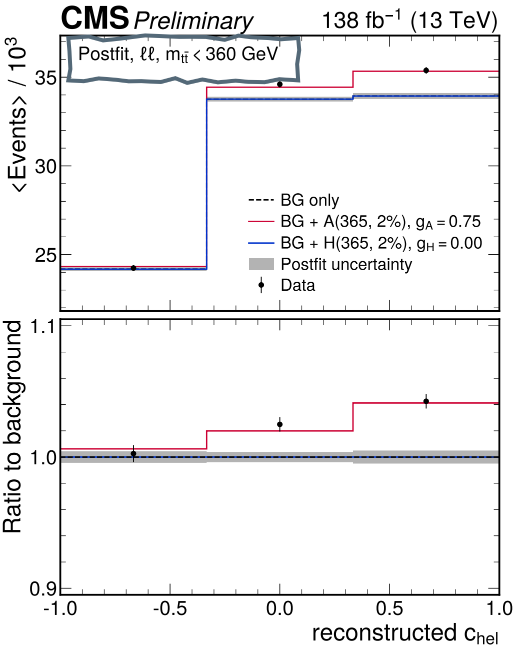
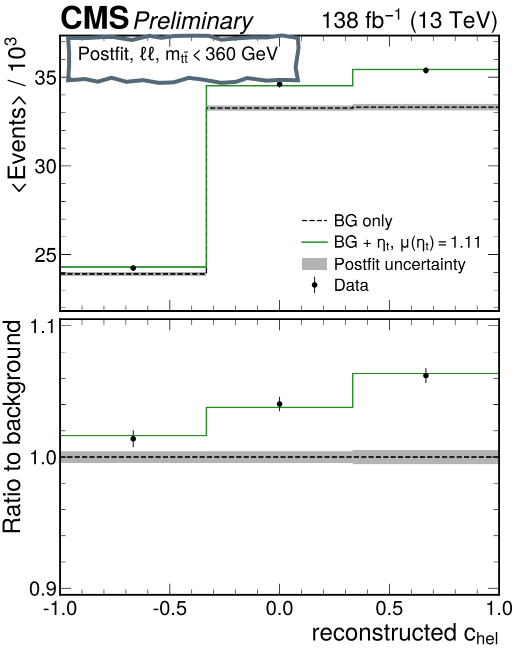
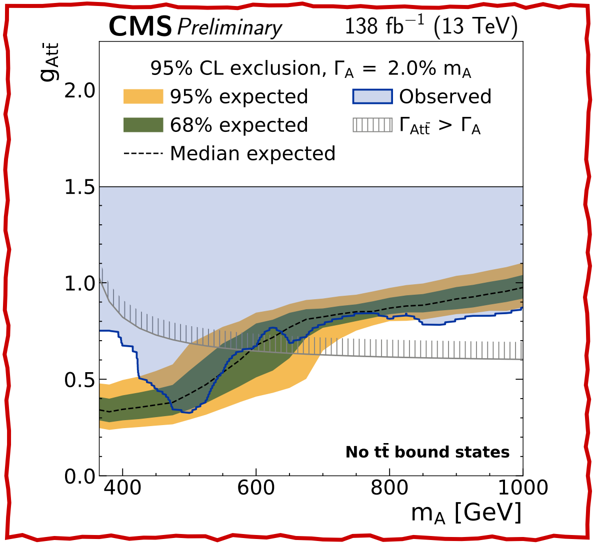
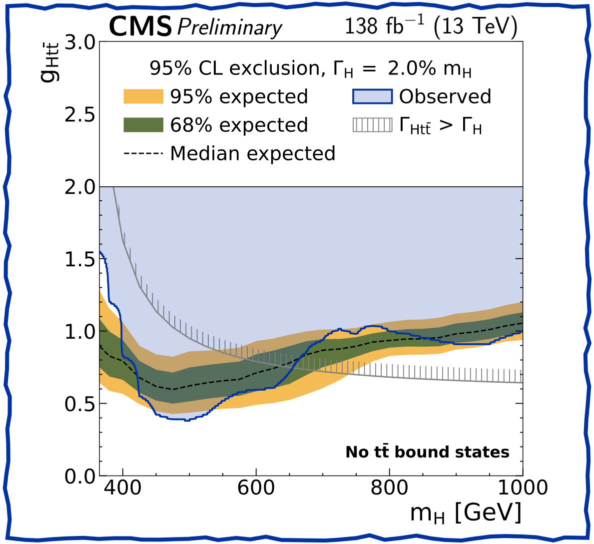




One signal interpretations

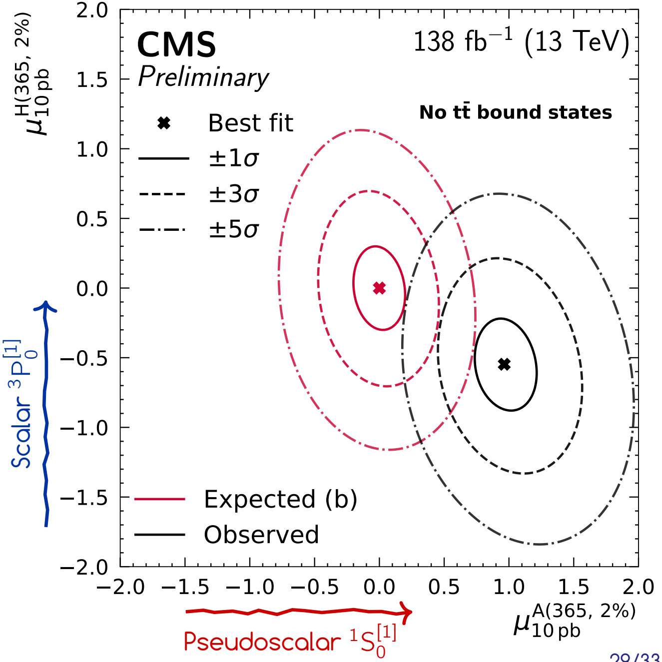




Interpretation	Best-fit point	Difference in $-2\ln L$
η_t	$\mu(\eta_t) = 1.11$	-86.2
Single A boson	$m_A = 365\,\text{GeV}$, $\Gamma_A/m_A = 2\%$, $g_{At\bar{t}} = 0.78$	-72.6
Single H boson	$m_H = 365\,\text{GeV}$, $\Gamma_H/m_H = 2\%$, $g_{Ht\bar{t}} = 1.45$	-10.4

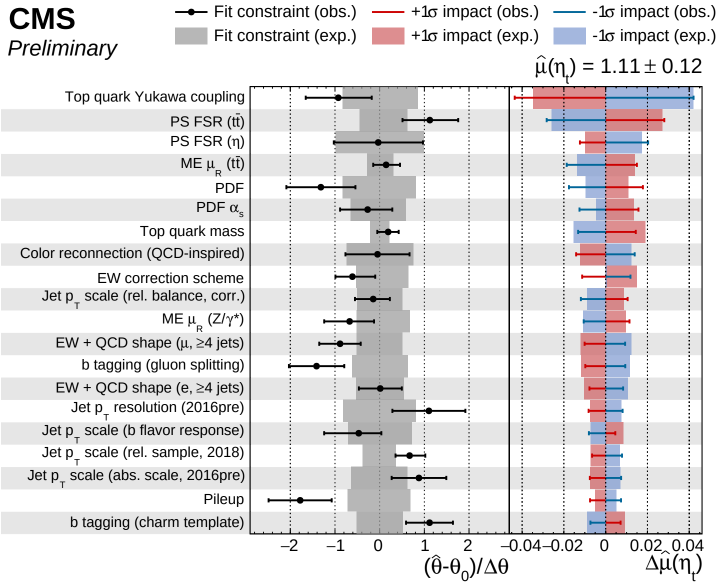
The structure of the excess

- Quantify the preference of the data in a simultaneous A/H fit
- Only resonance components, with an equal and arbitrary rate
- In other words, use A/H as ${}^1S_0^{[1]}$ and ${}^3P_0^{[1]}$ structural proxies
- Clearly, the excess is much more compatible with a ${}^1S_0^{[1]}$ state



Uncertainties

- Dominant uncertainties: modelling
- Leading: $y_t = 1^{+0.11}_{-0.12}$
  - Prior from EPJC 79 (2019) 5, 421
  - Almost 2x the impact of 2nd rank
- PS FSR scales highly relevant
  - Directly affecting $m_{t\bar{t}}$



The size of the excess

We can extract the size of the excess under the effective η_t assumption

→ the most compatible one signal interpretation of the data, among the ones considered

"Cross section" = difference between the data and the pQCD predictions:

$$\sigma(\eta_t) = 7.1 \pm 0.8\,\text{pb}$$

To be compared with the NRQCD prediction [PRD 104, 034023 (2021)]: $\sigma(\eta_t)_{\text{pred}} = 6.43\,\text{pb}$

Interpret with caution: missing uncertainties, color octet initial states, radiation…

Please view the number as an experimental input to guide further theorybuilding

Closing remarks

- CMS-PAS-HIG-22-013: search for pseudoscalars and scalars decaying to $\mathrm{t\bar{t}}$ (138 /fb)
- Invariant mass and spin correlation distributions are utilized
- $> 5\sigma$ excess is observed at the $\mathrm{t\bar{t}}$ threshold: compatible with a pseudoscalar
  - It has persisted through all the stringent checks we've performed so far
- The size of the excess is quantified in terms of an effective $\mathrm{t\bar{t}}$ bound state model
- Work on experimental and theory sides are needed to explain the observation

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The origin of the excess remains to be explored...

Exciting times ahead!

The Exotics – HIG-22-013 $\ell\bar{\ell}$ and combination team

Left to right: Christian Schwanenberger, AA, Laurids Jeppe, Jonas Rübenach, Alexander Grohsjean

Dominic Stafford

Samuel Baxter

Jörn Bach

Backup

HIG-22-013 MC and objects summary

SM background processes:

- $t\bar{t}$: POWHEGV2 + PYTHIA8 rwgt. with Matrix/Hathor
  - NLO QCD $\rightarrow$ NNLO QCD + NLO EW in 2D $m_{t\bar{t}} \times \cos\Theta$
  - Full quadratic y_t dependence (NP: $y_t = 1^{+0.11}_{-0.12}$)
  - NPs: $m_t \pm 1$ GeV, ME & I/FSR scales, h_{damp}, PDFs, EW scheme
- tX: t-, s-, and tW single top
  - NPs: ME & I/FSR scales, 15% rate
- DY: POWHEG MiNNLO + PYTHIA8 + Photos (only $\ell\bar{\ell}$)
  - Rate from data (R_{in}, R_{out} method)
  - NPs: ME & I/FSR scales, rate from $\sigma_{t\bar{t}}/\sigma_{DY}$ ratio [ref]
- Minor:
  - $\ell\bar{\ell}$: $t\bar{t}V$ and VV from MC, with a 30% rate
  - ℓj: QCD + EW from data; NPs: 50% rate and shapes from b-tag scores and top subtraction

A/H signal modelling:

- LO MC with custom model in MG5_aMC@NLO:
  - Gluon-fusion A/H coupling only to tops w/ full loop
  - Separately for resonant and interference signal
  - Post-generation ME reweighting
  - NPs: $m_t \pm 1$ GeV, ME & I/FSR scales (split res. and int.)
- NNLO rate with SusHi:
  - Gluon fusion k-factors within a type-2 2HDM context
  - Evaluated at $g_{A/Ht\bar{t}} = 1$
  - Disallow non-top loops
  - Interference k-factors following JHEP 10 (2016) ansatz

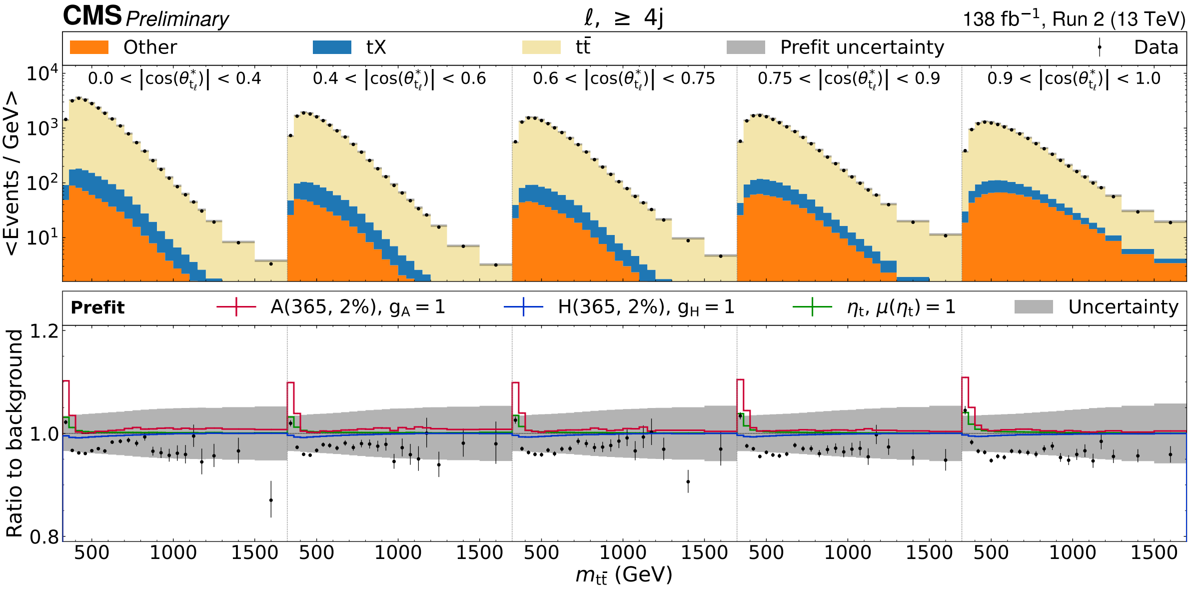
Effective η_t signal modelling:

- LO MC with model by B. Fuks et al, 2021:
  - A-like resonance: 343 GeV mass, 7 GeV width
  - Allow off-shell tops, cut within $m_{WbWb} = 343 \pm 6$ GeV
  - No NR Hamiltonian reweighting (negligible)
  - 6.43 pb nominal rate
  - NPs: same as A/H (no μ_R)

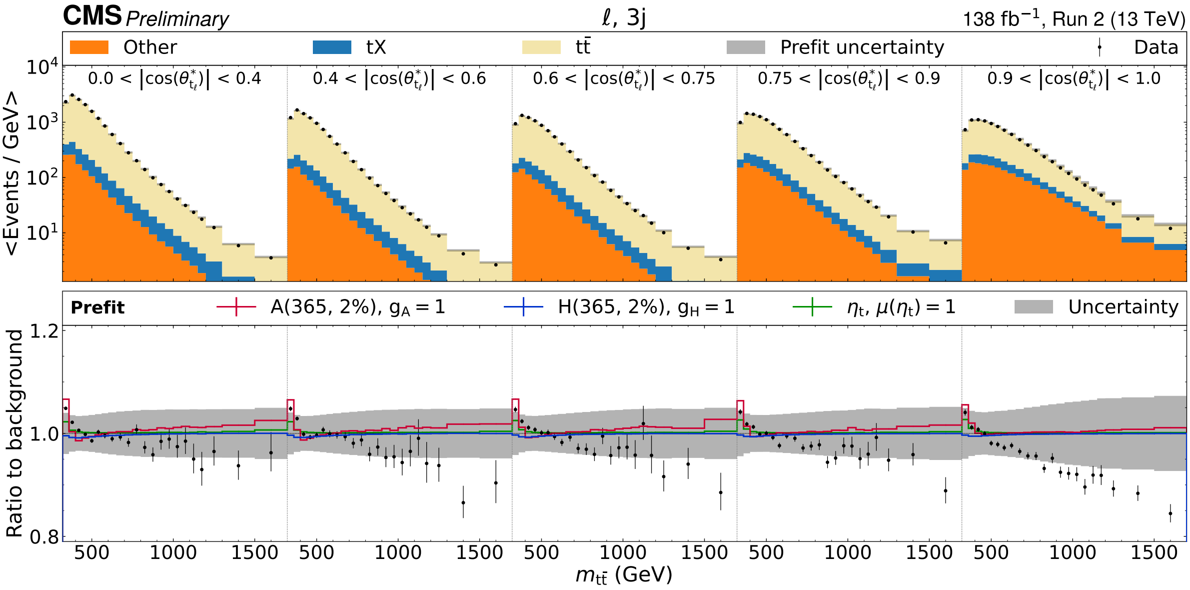
On the experimental side:

- Standard CMS UL Run 2 recipes:
  - Leptons: efficiency SFs for reco., ID, iso. and trigger
  - Jets: JER and reduced JEC sources
  - b-tag: HF jets with subsource breakdown, and LF jets
  - Type-1 corr. PF MET (unclustered contrib. as NP)
  - Luminosity, PU reweighting, L1 prefiring

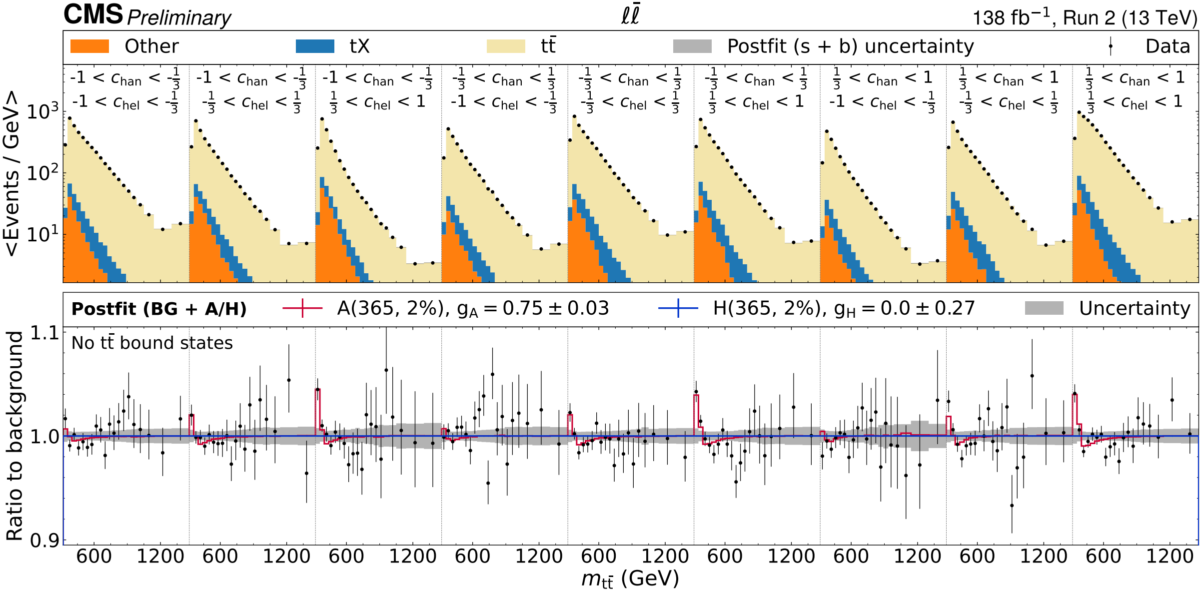
Prefit distribution: ℓ, $\geq 4j$



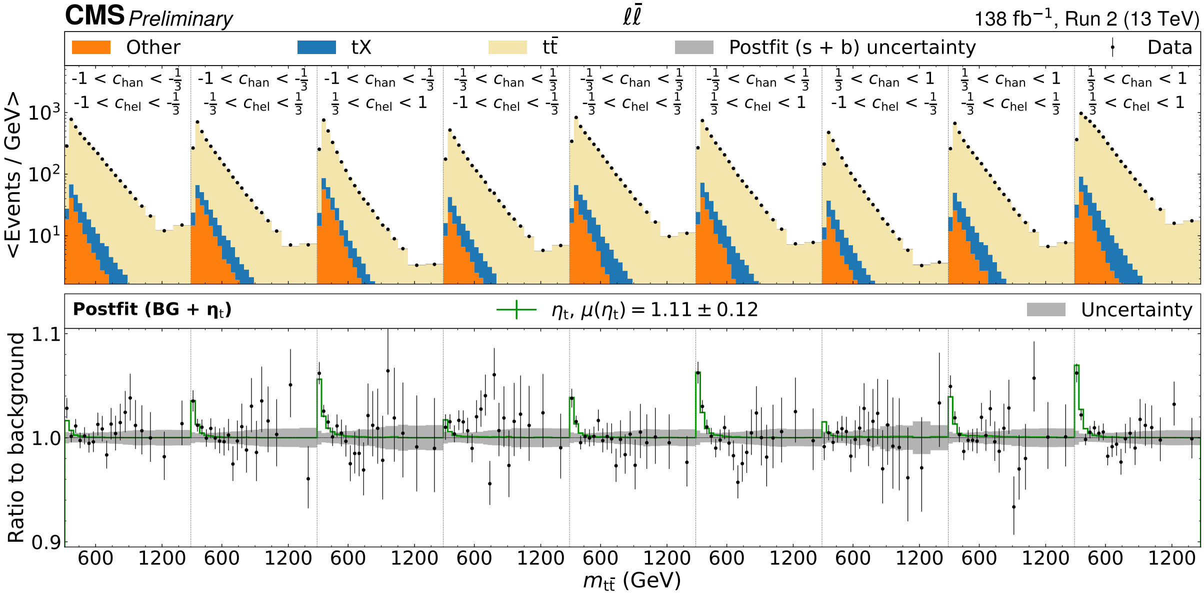
Prefit distribution: ℓ, 3j



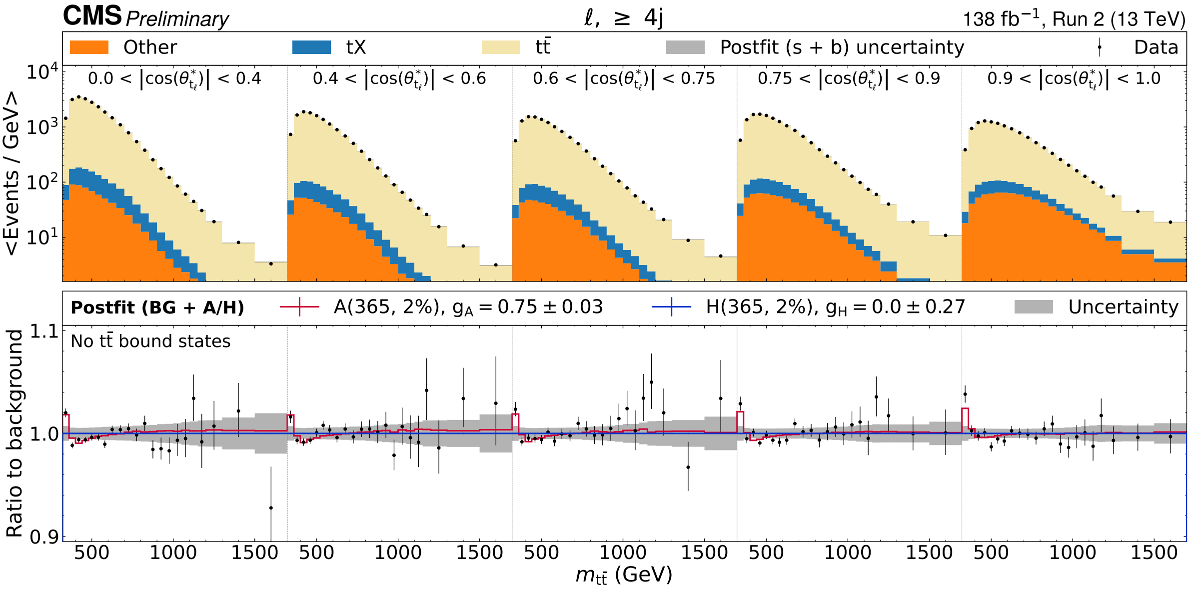
Postfit A/H(365, 2%): $\ell\bar{\ell}$



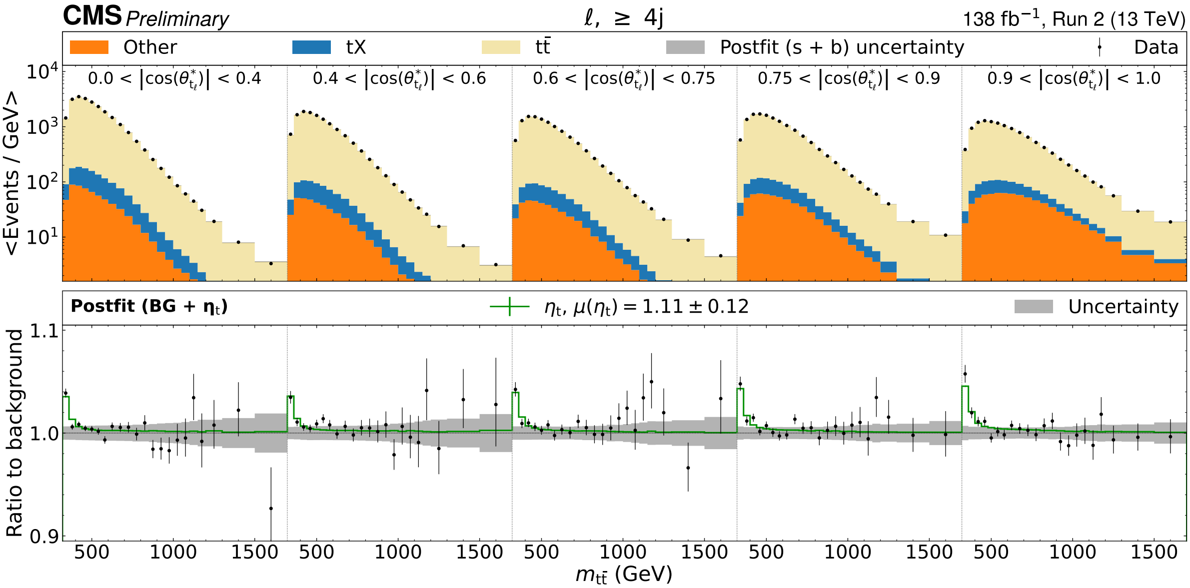
Postfit effective η_t: $\ell\bar{\ell}$



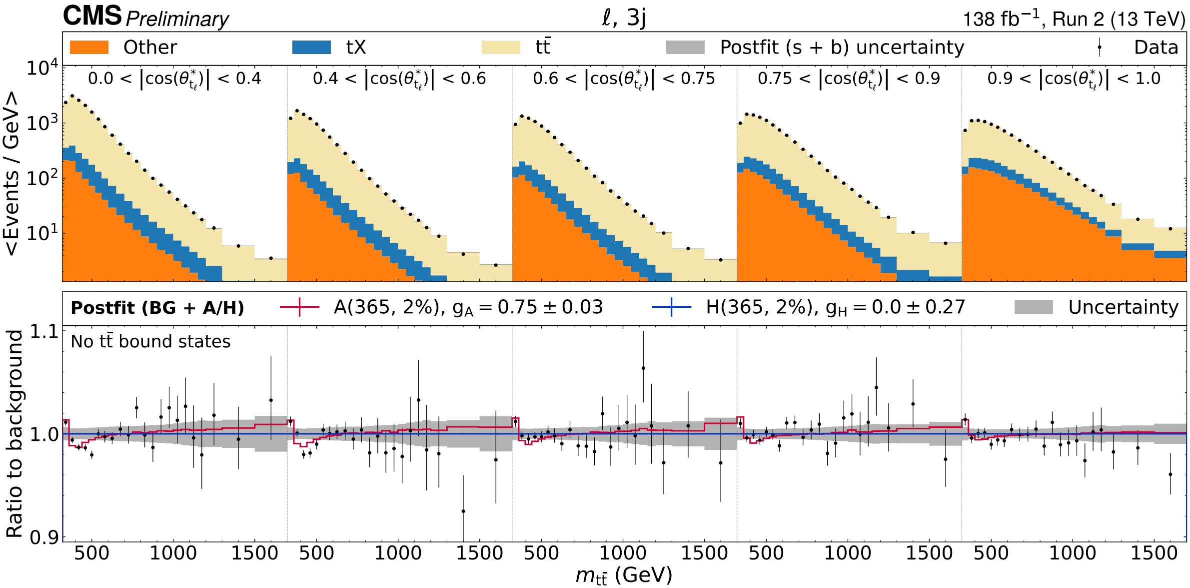
Postfit A/H(365, 2%): ℓ, $\geq$ 4j



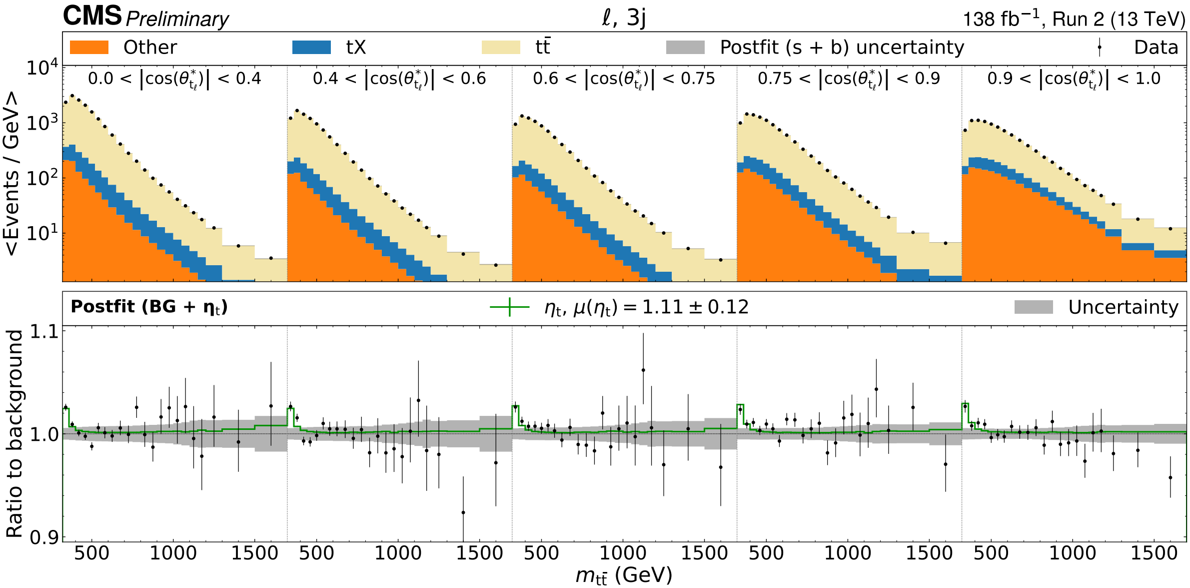
Postfit effective η_t: ℓ, $\geq$ 4j



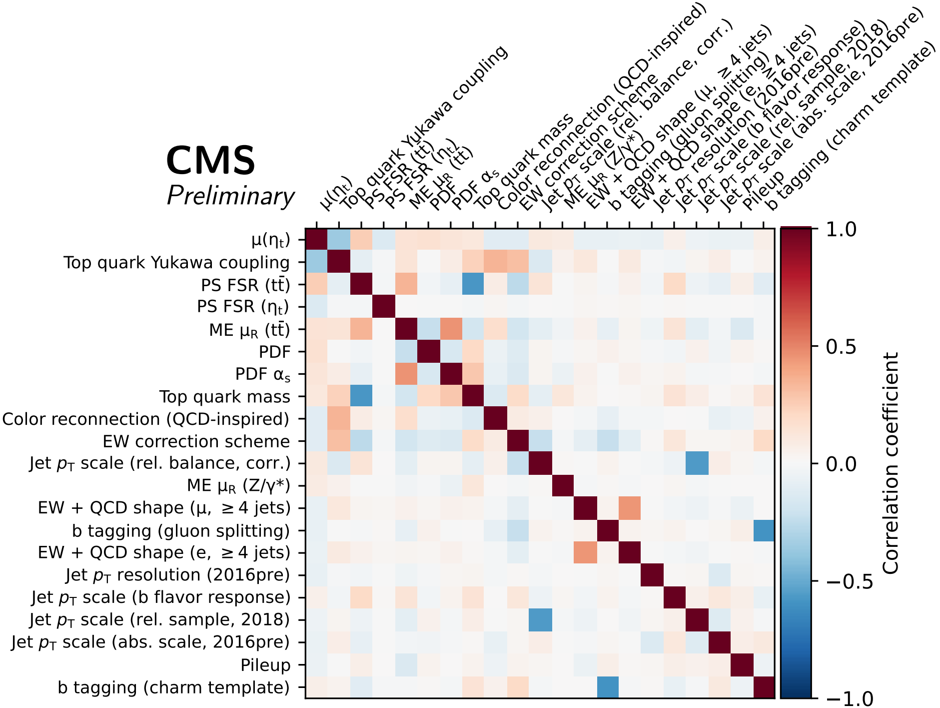
Postfit A/H(365, 2%): ℓ, 3j



Postfit effective η_t: ℓ, 3j



Correlations



Offshell effects

Check performed only in $\ell\bar{\ell}$ channel

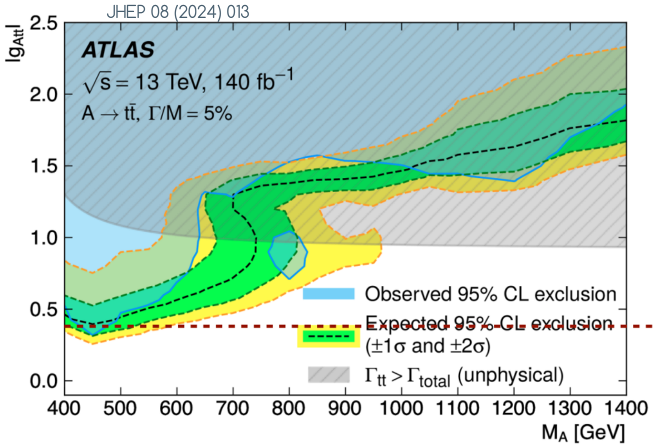
No change in absolute uncertainty, and significance remains $> 5\sigma$

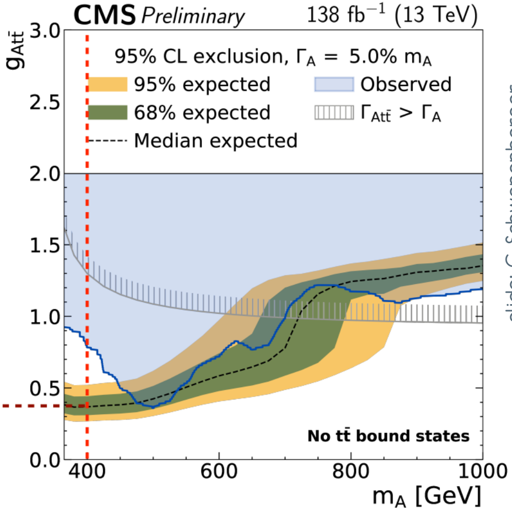
$\rightarrow$ extracted $\sigma(\eta_t)$ is robust against inclusion of offshell effects in background
Other generators have also been checked, results are compatible

Prediction for SM $t\bar{t}$ and tW	Extracted η_t cross section	Uncertainty
`b_bbar_4l` (POWHEG vRES)	5.9 pb	18%
Default (POWHEG v2)	7.5 pb	13%

ATLAS – CMS $g_{At\bar{t}}$ limit comparison

Similar expected sensitivity.

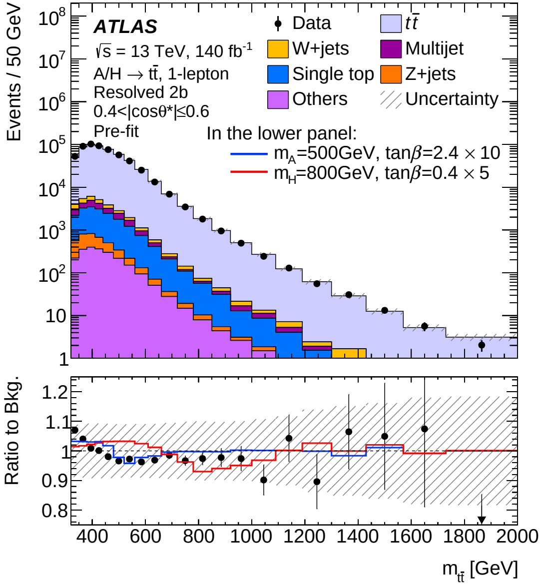


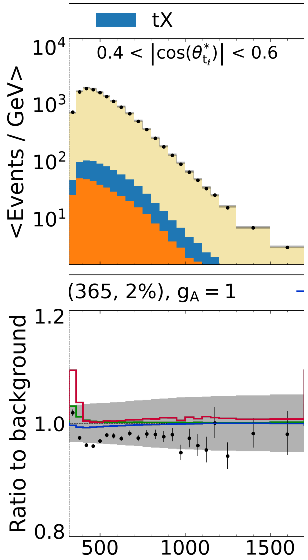


slide: C. Schwanenberger

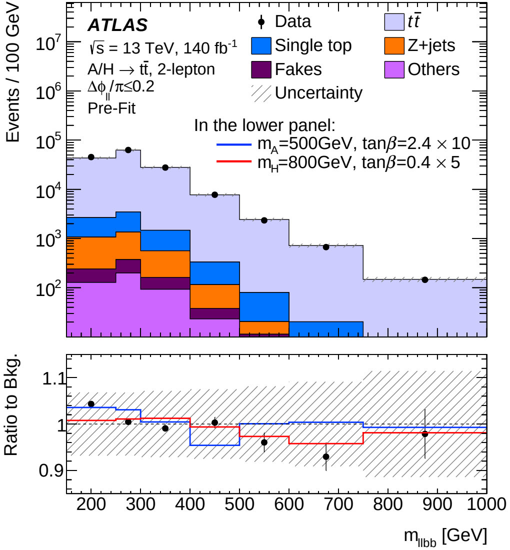
ATLAS – CMS prefit data comparison

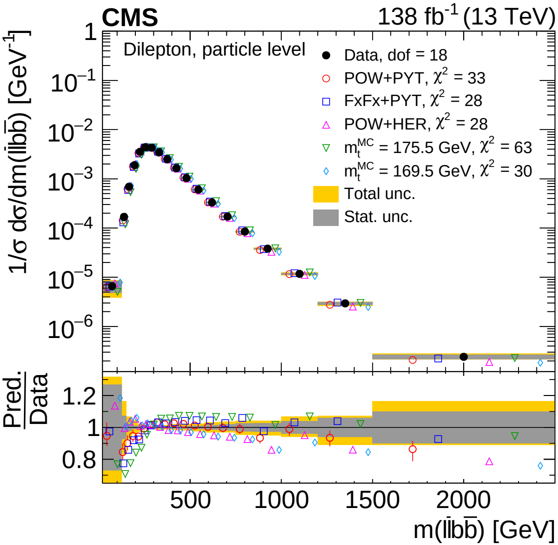
Prefit data vs MC in CMS $\ell, \geq 4j$ channel's and ATLAS resolved 2b category are similar





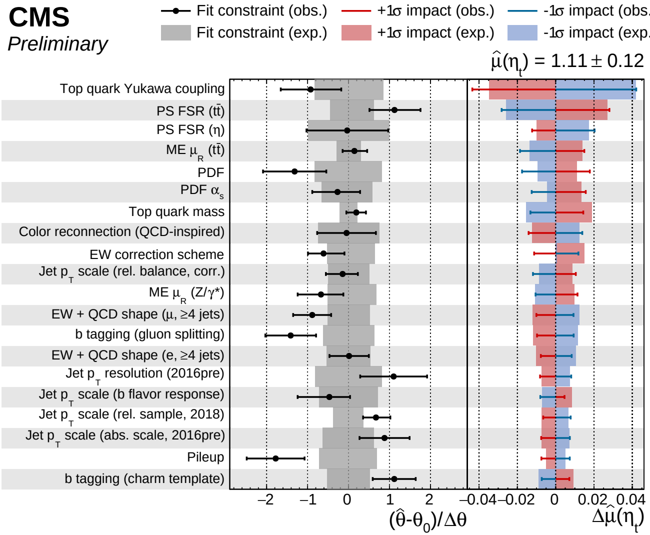
ATLAS – CMS $m_{b\bar{b}\ell\bar{\ell}}$

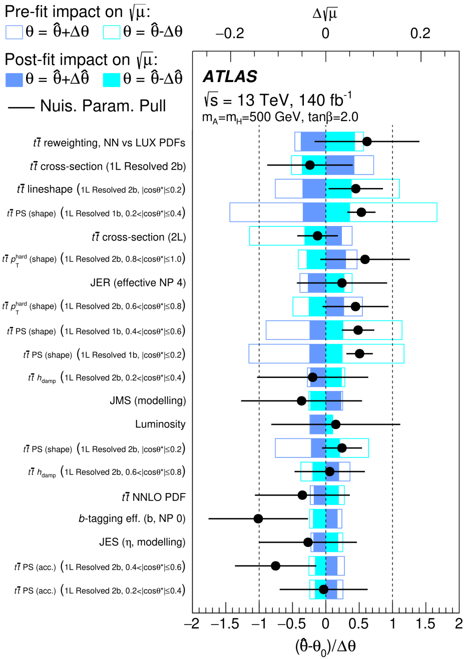




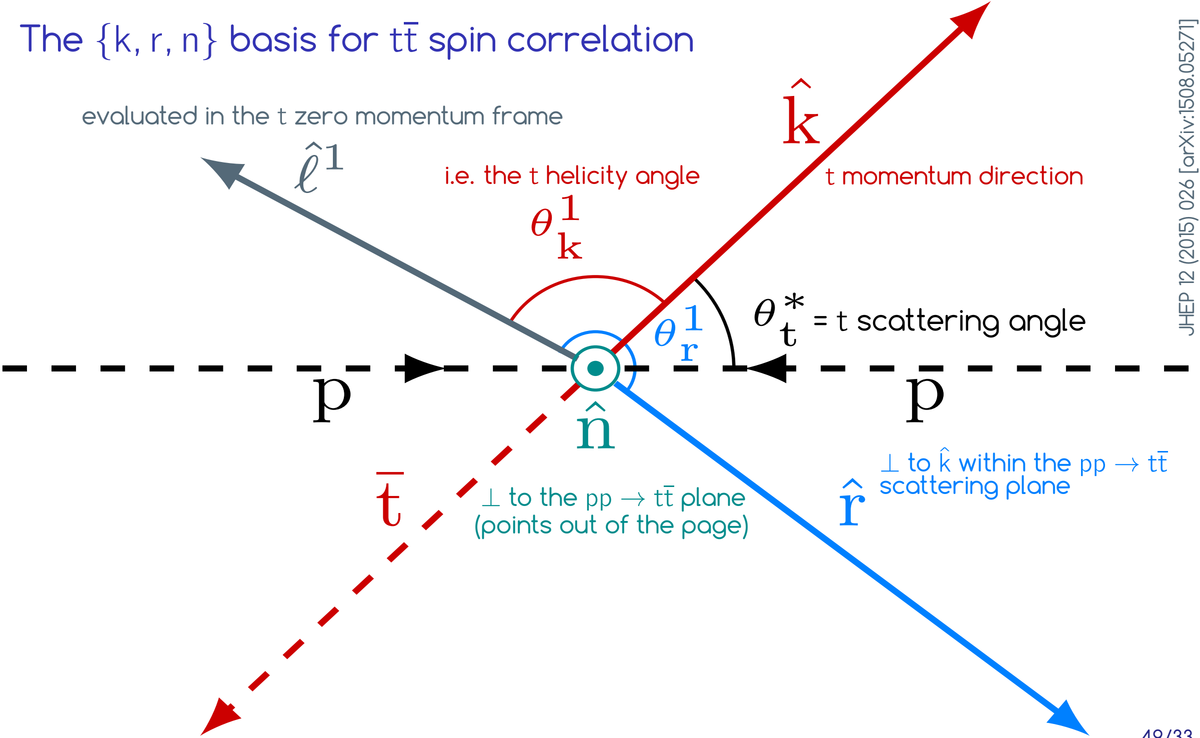
CAUTION: not one to one. CMS result is inclusive in $\Delta\phi_{\ell\ell}$: CMS-TOP-20-006

ATLAS – CMS uncertainties





The {k, r, n} basis for $t\bar{t}$ spin correlation



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