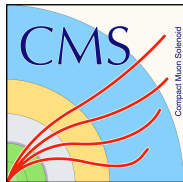


In Search of Spin-0 Resonances Decaying to Top Quark-Antiquark Pairs

CMS-PAS-HIG-22-013

Afiq Anuar (DESY)

Imperial College London – HEP seminar
2025/01/29



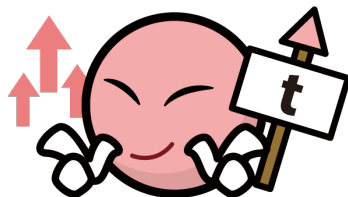
The top quark



QCD $t\bar{t}$, EWK $t + X$
Other modes e.g. $t\bar{t}t\bar{t}$ are much rarer



$t \rightarrow Wb$ (BR ~ 1)
 $\Rightarrow t\bar{t}$ classification by W decay modes



$\mathcal{O}(10^{-25})$ s
 $\ll \Lambda_{\text{QCD}}^{-1} \rightarrow$ observe “bare” quark



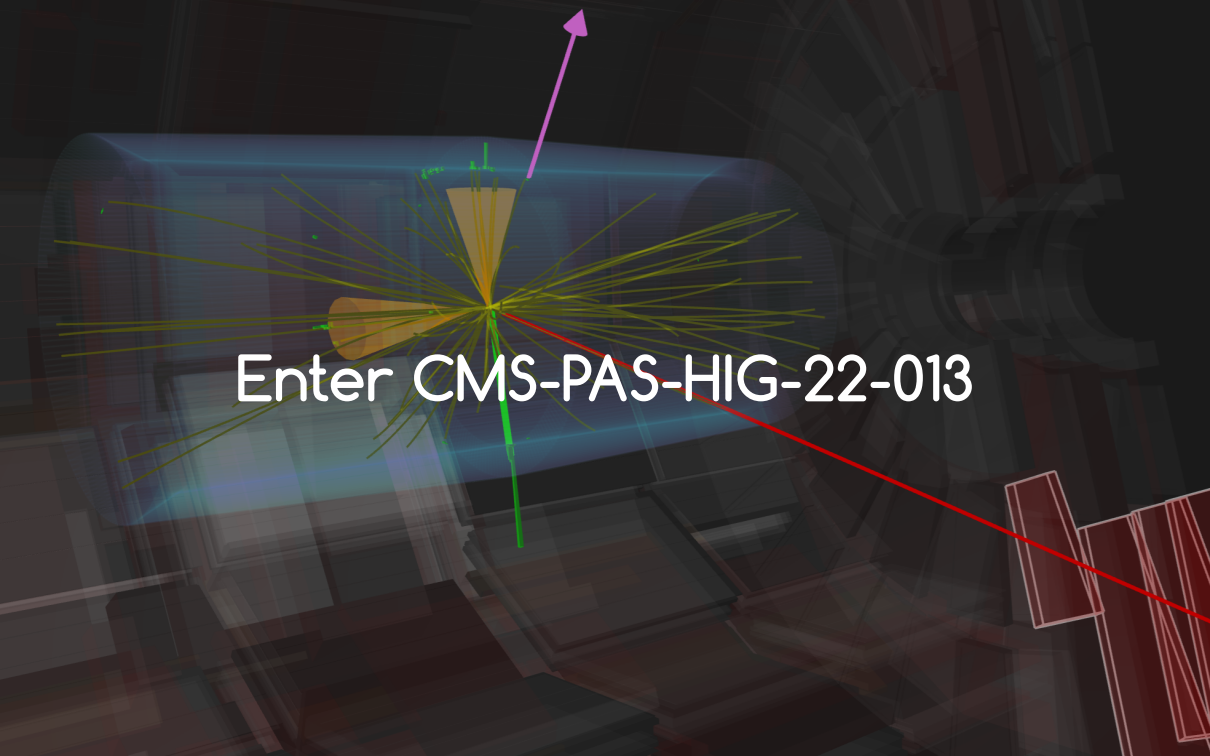
172.52 ± 0.33 GeV
 $\rightarrow$ heaviest in SM. A portal to BSM?

figure: H. Saka



What about ALPs? Or DM candidates? 🤖

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

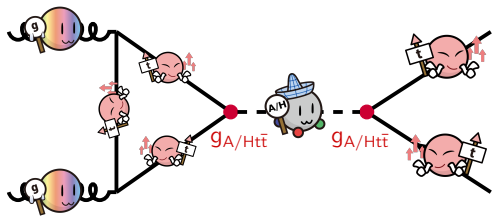


A 3D visualization of particle tracks within a detector, likely the CMS experiment. The background shows a complex, dark, and metallic structure representing the detector's internal components. A central point of interaction is shown with numerous yellow lines radiating outwards, representing particle tracks. Two orange cones are visible, one pointing upwards and one pointing downwards from the interaction point. A pink arrow points upwards from the interaction point, and a red line extends from the interaction point towards the bottom right corner. The text "Enter CMS-PAS-HIG-22-013" is overlaid in the center.

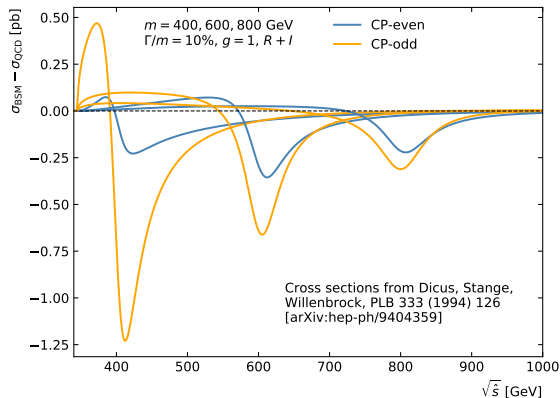
Enter CMS-PAS-HIG-22-013

Theoretical set-up

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



- 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 $\rightarrow A/H$ 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 $l\bar{l}$ and $l\bar{l}$ final states

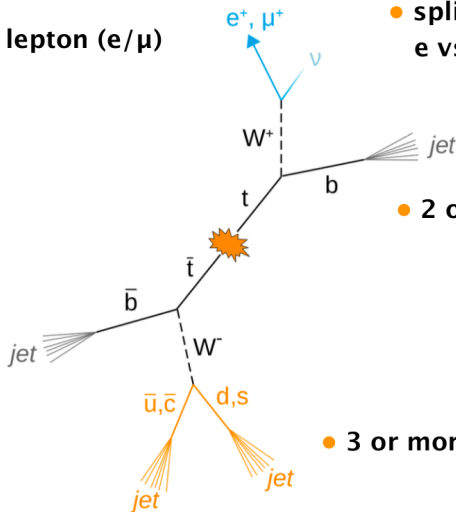
ℓj analysis selection

- 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**

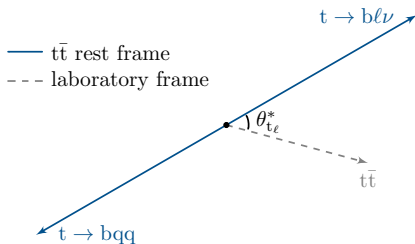
NIM A 736 (2014) 169

- assign b-jets by maximum likelihood

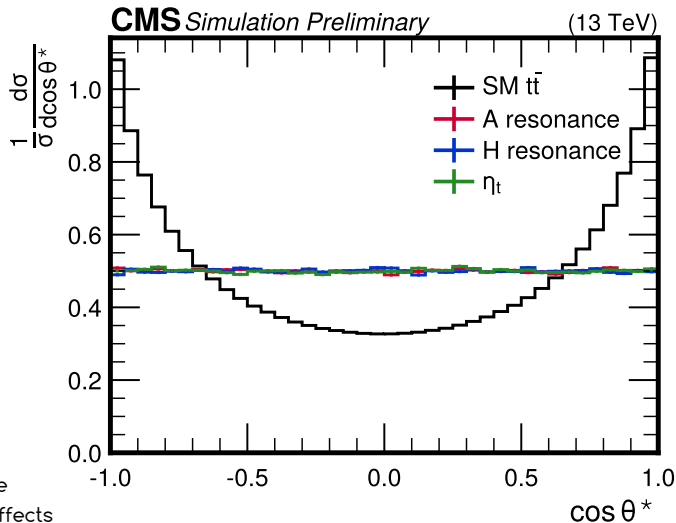
- energy correction factor applied for 3 jet events (lost or merged jets)

NIM A 788 (2015) 128

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



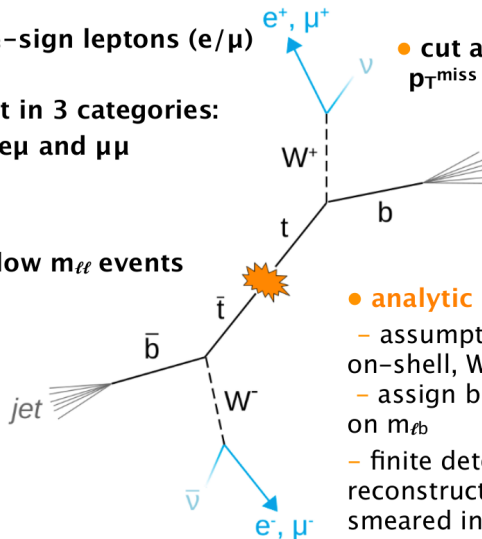
$\ell\ell$ analysis selection

- exactly two opposite-sign leptons (e/μ)

- split in 3 categories:
 ee , $e\mu$ and $\mu\mu$

- reject low $m_{\ell\ell}$ events

- 2 or more jets



- cut away Z peak & require
 $p_{T}^{\text{miss}} > 40 \text{ GeV}$ in $ee/\mu\mu$

- 1 or more b-jets

- **analytic reconstruction of $t\bar{t}$ system**

- assumptions: all p_{T}^{miss} from $\nu\bar{\nu}$, tops on-shell, W s 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

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

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

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

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

→ spin-independent
 $\sigma, m_{t\bar{t}}, p_T^t \dots$

→ top polarization vectors

→ $t\bar{t}$ spin correlation matrix

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

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

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

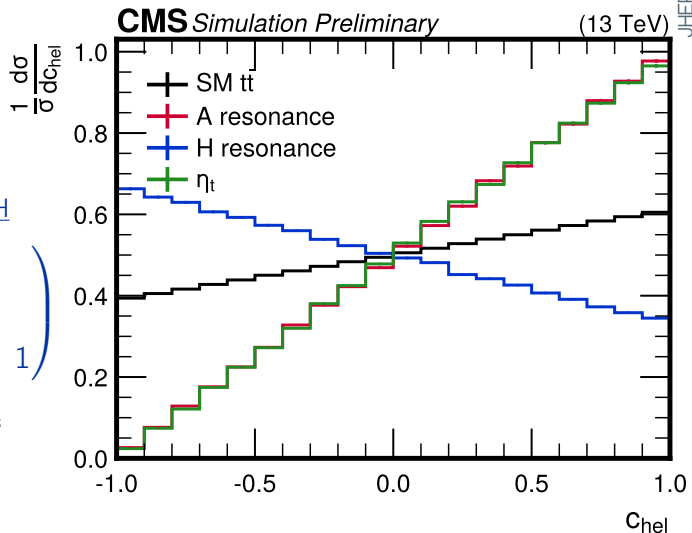
Resonant A

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

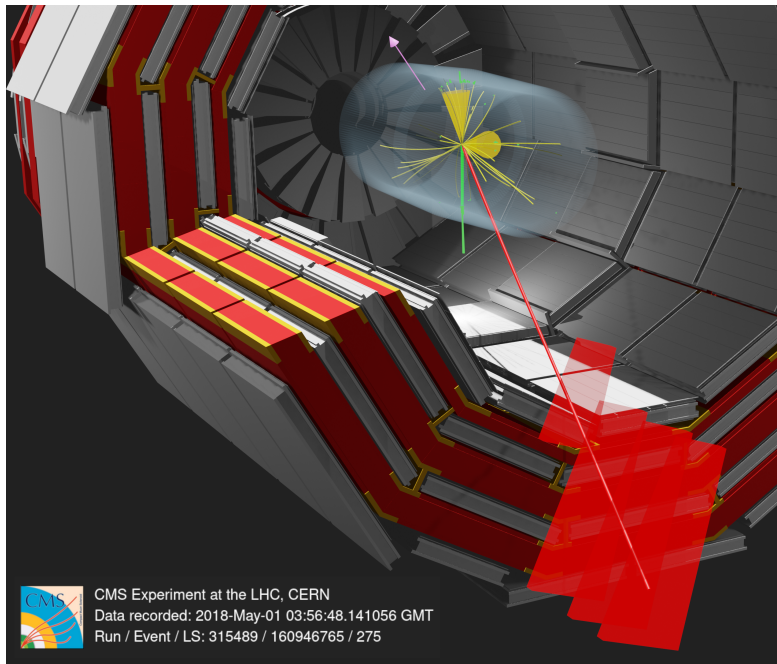
Resonant H

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

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



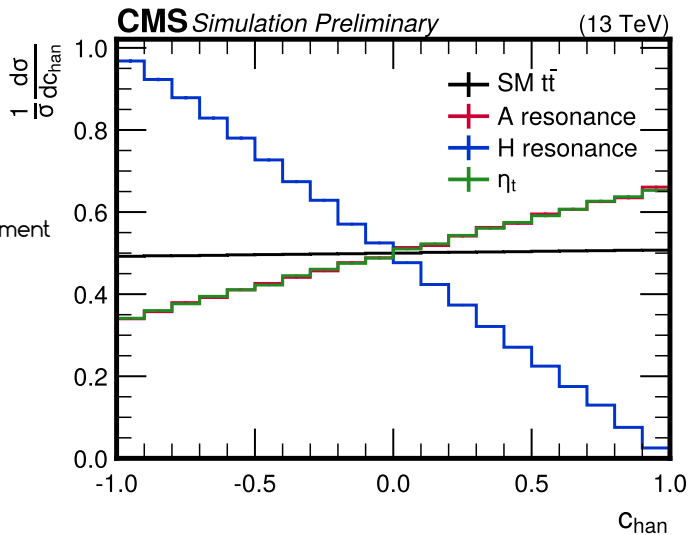
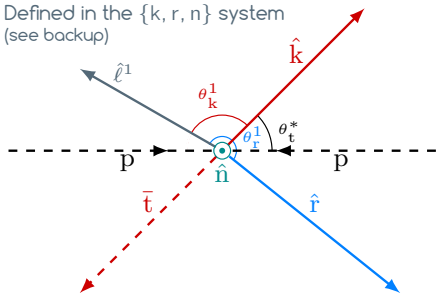
It's all about alignment



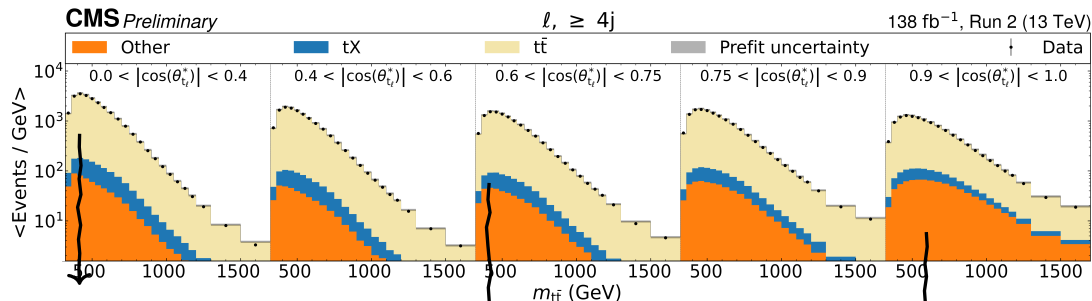
$\ell\ell$ angular variable 2: c_{chan}

- 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)

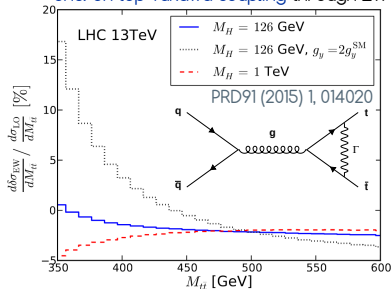


Background modelling



FO pQCD top pair t $\bar{t}$: most important

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



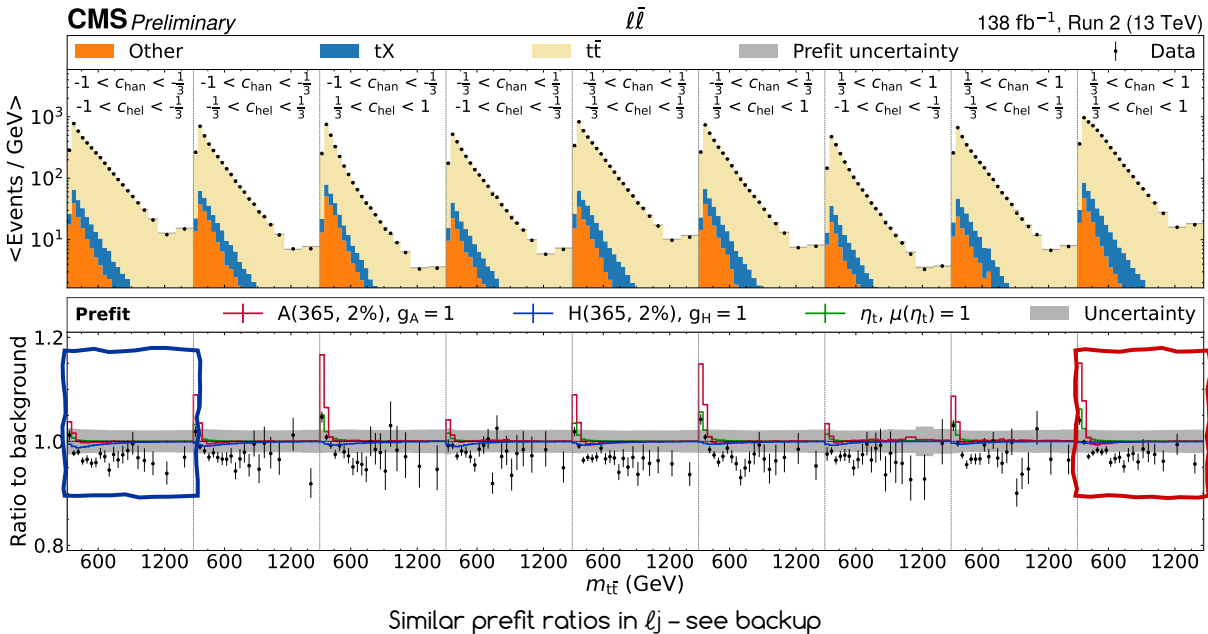
Other minor backgrounds

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

Single top tX

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

Prefit distribution

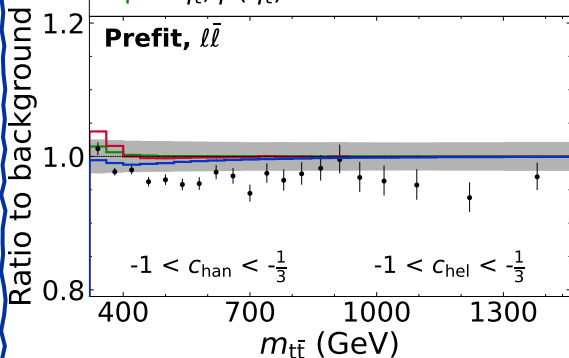


Prefit background expectation

CMS Preliminary 138 fb⁻¹, Run 2 (13 TeV)

- A(365, 2%), $g_A = 1$
- H(365, 2%), $g_H = 1$
- η_t , $\mu(\eta_t) = 1$

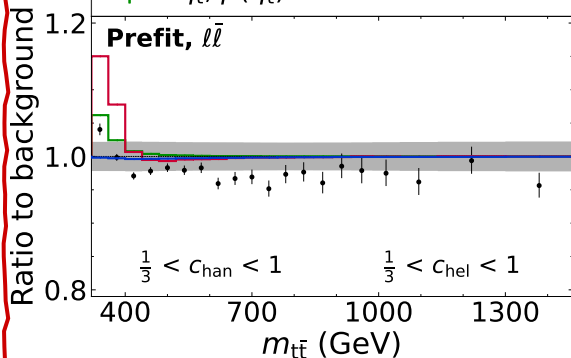
Prefit, $\ell\bar{\ell}$

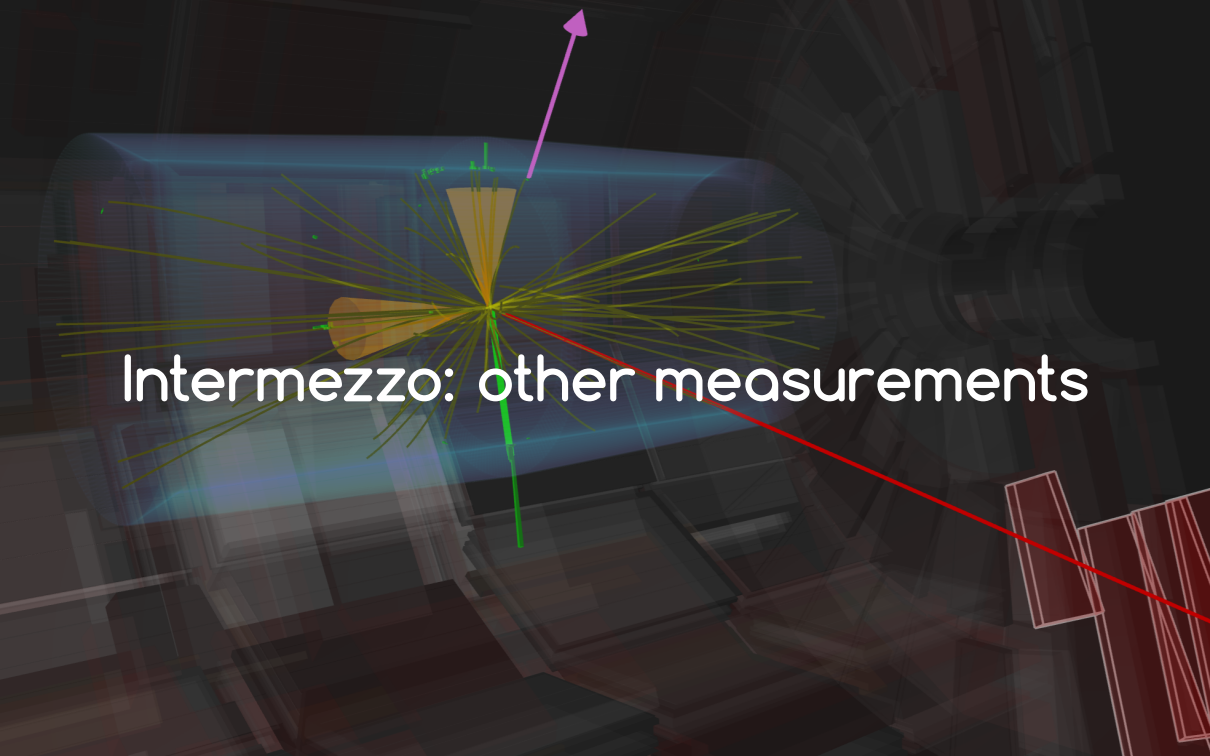


CMS Preliminary 138 fb⁻¹, Run 2 (13 TeV)

- A(365, 2%), $g_A = 1$
- H(365, 2%), $g_H = 1$
- η_t , $\mu(\eta_t) = 1$

Prefit, $\ell\bar{\ell}$

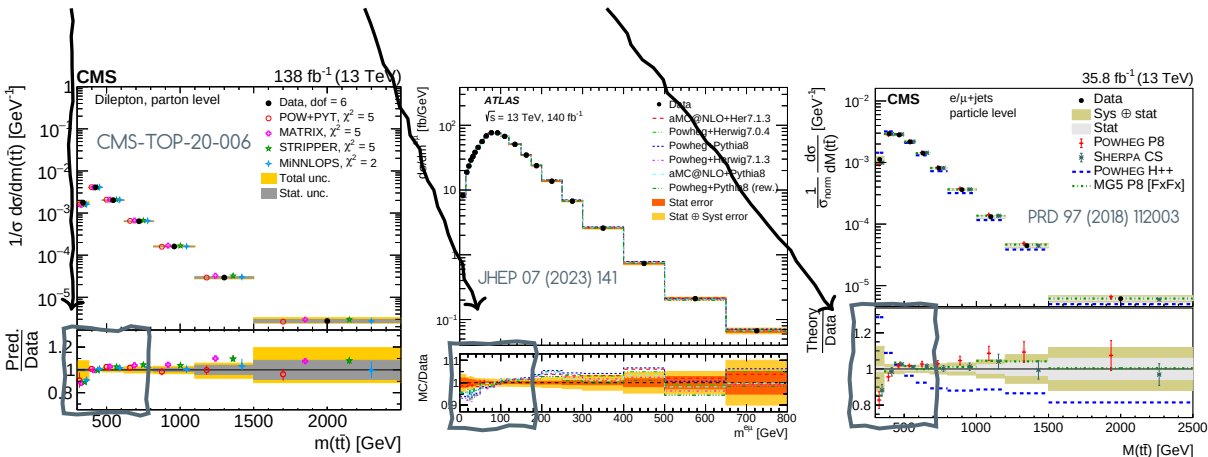




Intermezzo: other measurements

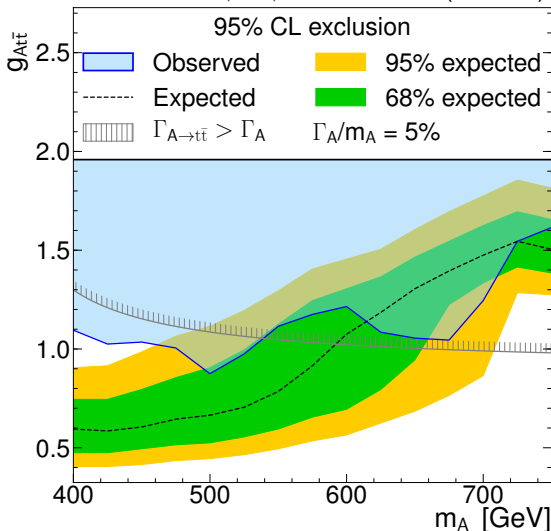
What to expect from $m_{t\bar{t}}$?

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



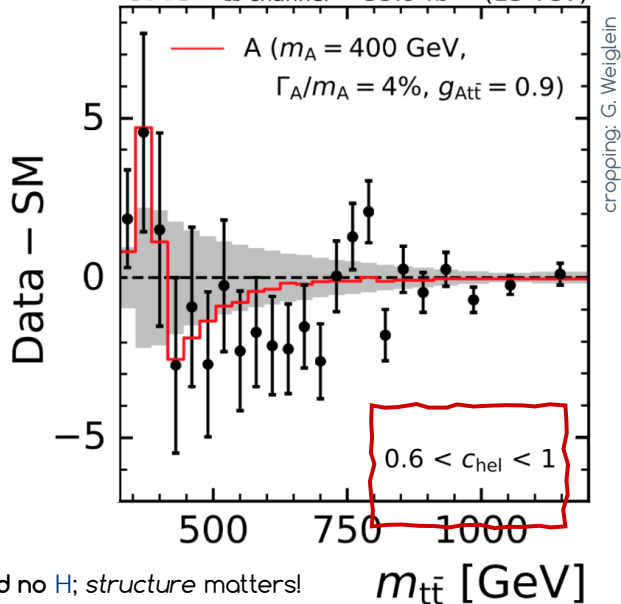
The effect is spin-dependent...

CMS JHEP 04 (2020) 171 35.9 fb⁻¹ (13 TeV)

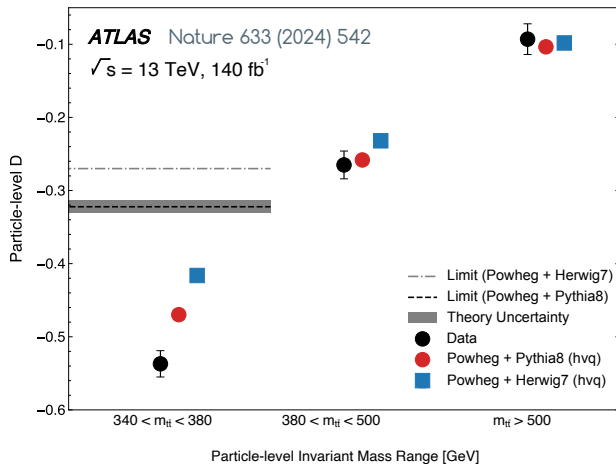
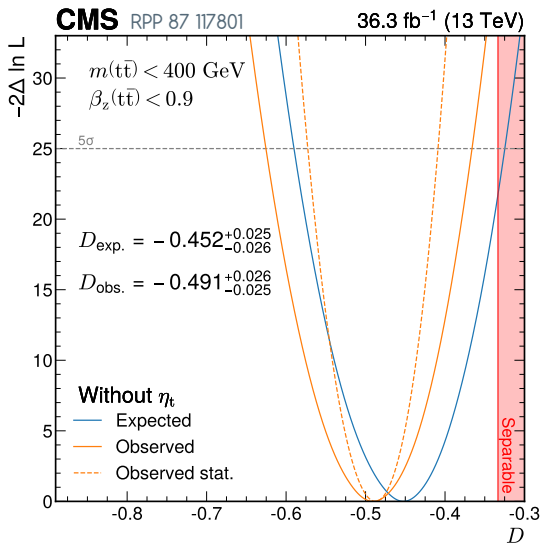


3.5 σ local A excess, and no H ; structure matters!

CMS $\ell\ell$ channel 35.9 fb⁻¹ (13 TeV)

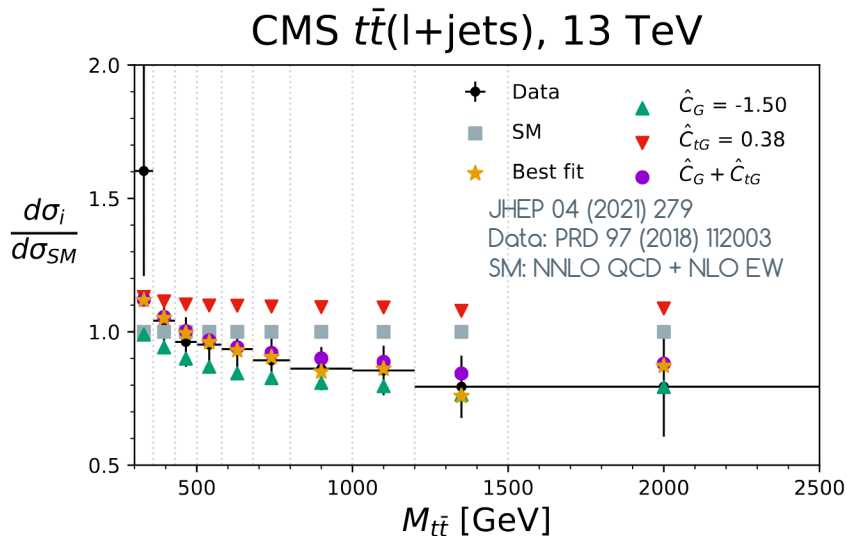


...and it's been reproduced!



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

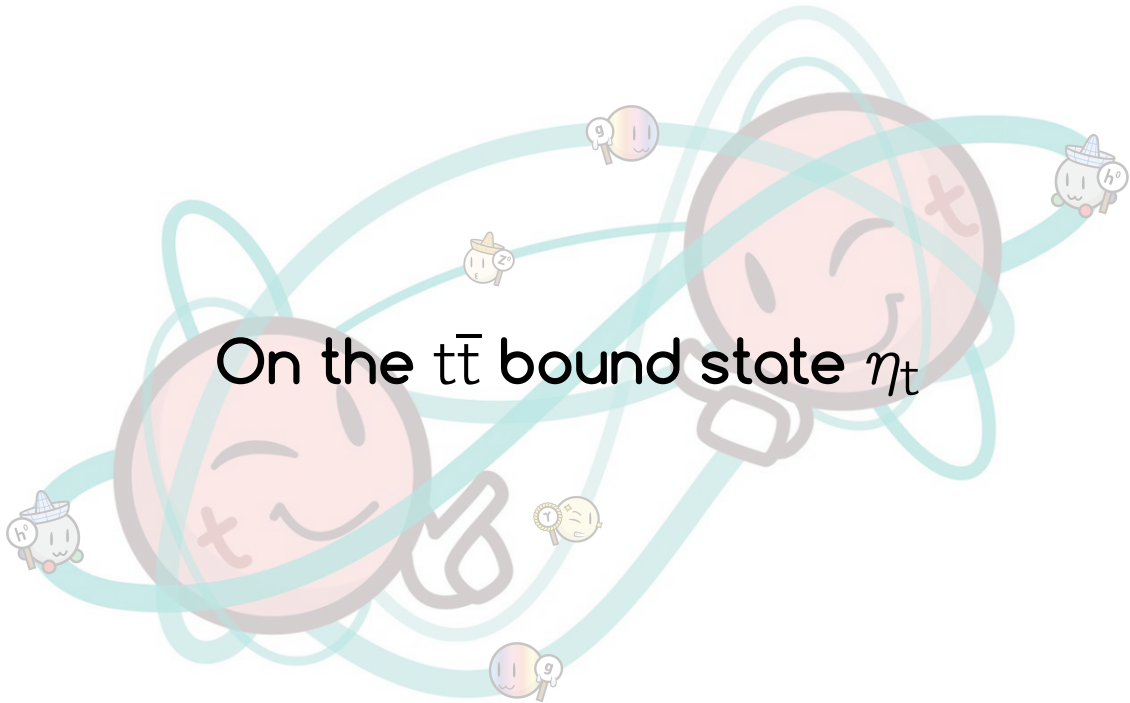
Would SMEFT operators help? ...no.



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.

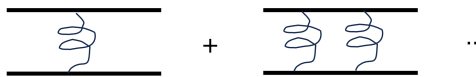
On the $t\bar{t}$ bound state η_t



The top is...a quark

So it probably does quarky things, like...

Coulombic gluon exchanges:



$$\sim \frac{\alpha_s}{\beta} \quad + \quad \sim \left(\frac{\alpha_s}{\beta} \right)^2, \quad \beta = \text{tops' relative velocity}$$

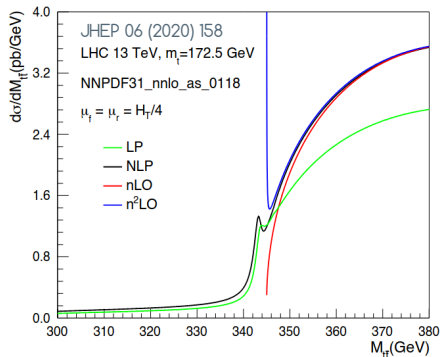
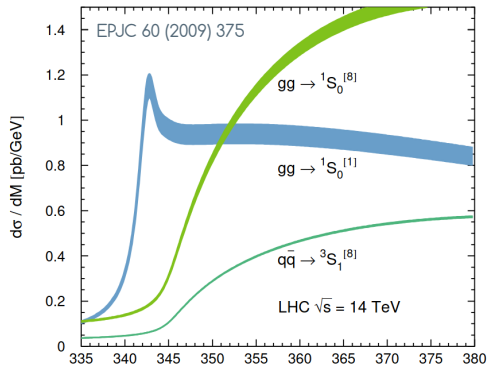
Inducing the Sommerfeld correction:

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

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.



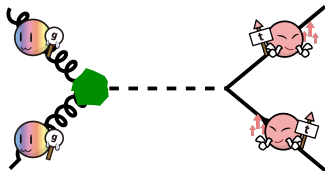
Effective η_t model

No full MC generator yet, but...

effective descriptions exist: PRD 104, 034023 (2021)

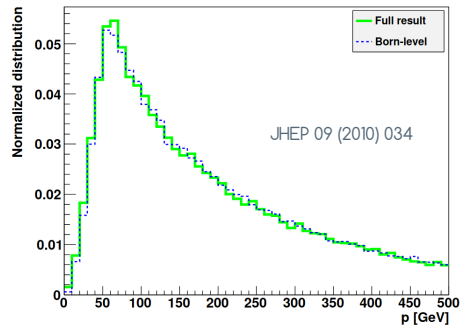
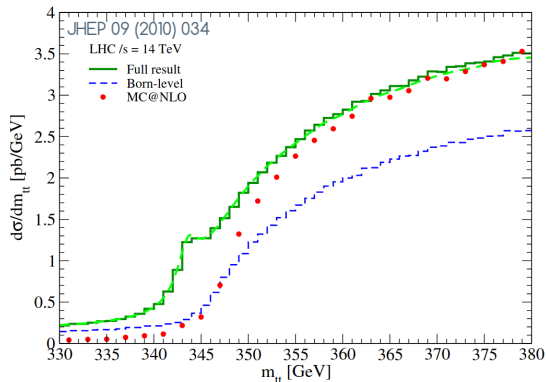
see also: JHEP 03 (2024) 099 and PRD 110 (2024) 5, 054032

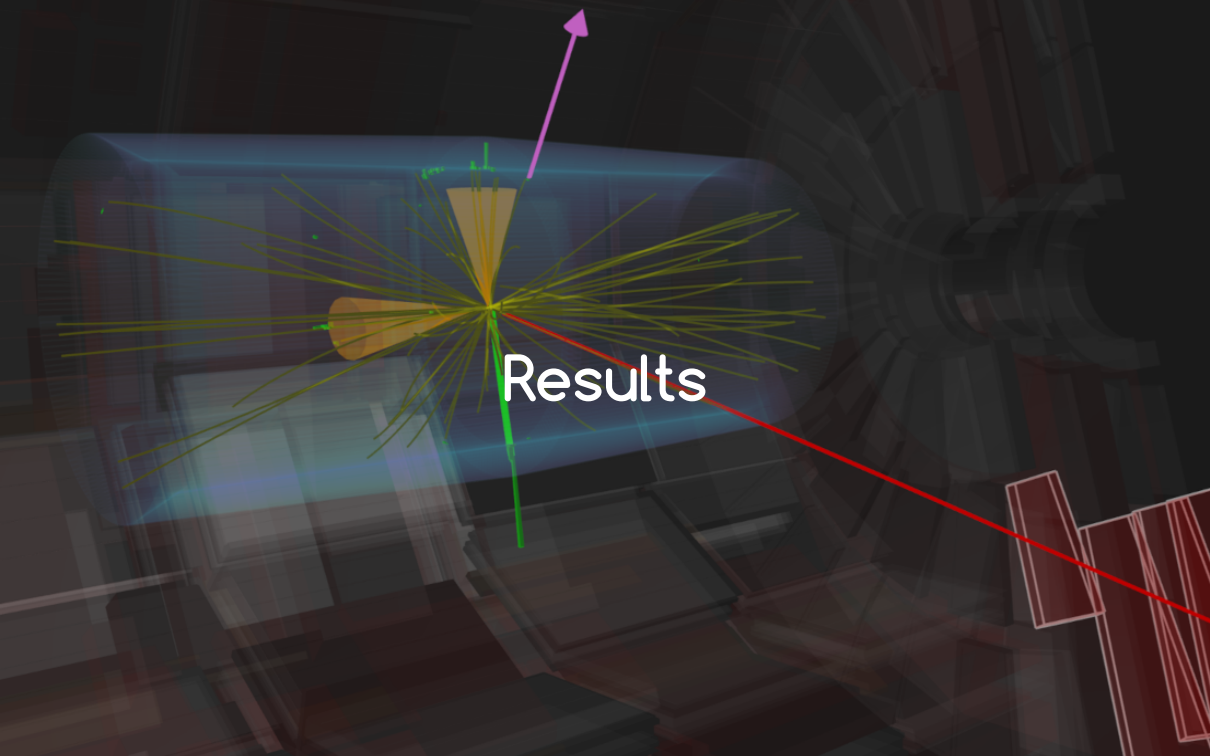
Simplifying, it's implemented as:



- A-like singlet state: 343 GeV mass, 7 GeV width
- Allow off-shell tops
- 6.43 pb nominal rate [JHEP 09 (2010) 034]
- Exact lineshape below exp. resolution ($\sim 20\%$)

Interpret with caution





Results

What HIG-22-013 sees

CMS Preliminary

$\ell\bar{\ell}$

138 fb⁻¹, Run 2 (13 TeV)

Postfit (BG + A/H)

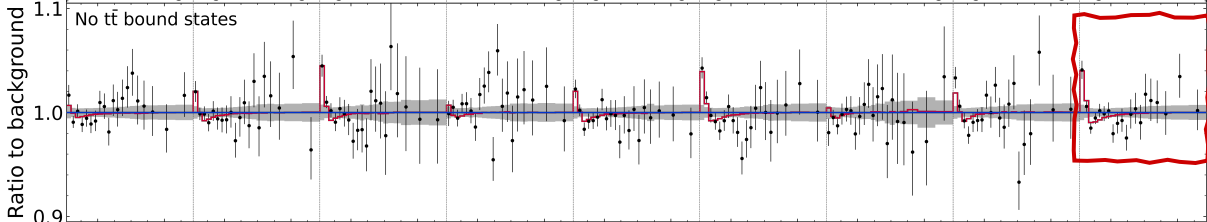
+ A(365, 2%), $g_A = 0.75 \pm 0.03$

+ H(365, 2%), $g_H = 0.0 \pm 0.27$

 Uncertainty

$-1 < C_{\text{chan}} < -\frac{1}{3}$ $-1 < C_{\text{hel}} < -\frac{1}{3}$	$-1 < C_{\text{chan}} < -\frac{1}{3}$ $-\frac{1}{3} < C_{\text{hel}} < \frac{1}{3}$	$-1 < C_{\text{chan}} < -\frac{1}{3}$ $\frac{1}{3} < C_{\text{hel}} < 1$	$-\frac{1}{3} < C_{\text{chan}} < \frac{1}{3}$ $-1 < C_{\text{hel}} < -\frac{1}{3}$	$-\frac{1}{3} < C_{\text{chan}} < \frac{1}{3}$ $-\frac{1}{3} < C_{\text{hel}} < \frac{1}{3}$	$-\frac{1}{3} < C_{\text{chan}} < \frac{1}{3}$ $\frac{1}{3} < C_{\text{hel}} < 1$	$\frac{1}{3} < C_{\text{chan}} < 1$ $-1 < C_{\text{hel}} < -\frac{1}{3}$	$\frac{1}{3} < C_{\text{chan}} < 1$ $-\frac{1}{3} < C_{\text{hel}} < \frac{1}{3}$	$\frac{1}{3} < C_{\text{chan}} < 1$ $\frac{1}{3} < C_{\text{hel}} < 1$
---	--	---	--	---	--	---	--	---

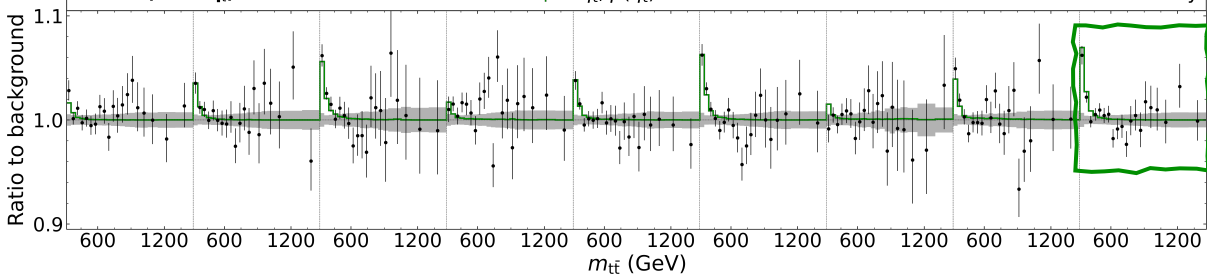
No $t\bar{t}$ bound states



Postfit (BG + η_t)

+ η_t , $\mu(\eta_t) = 1.11 \pm 0.12$

 Uncertainty

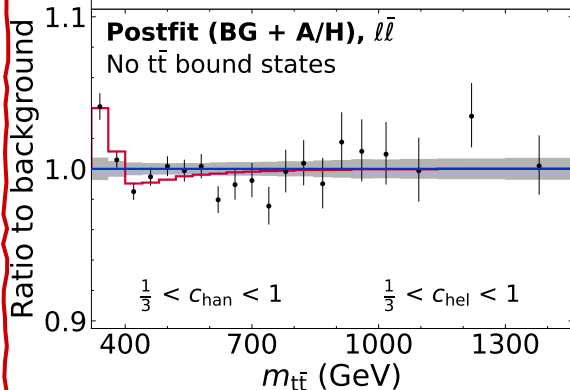


A or effective η_t ? Difficult question!

CMS Preliminary 138 fb⁻¹, Run 2 (13 TeV)

- + A(365, 2%), $g_A = 0.75 \pm 0.03$
- + H(365, 2%), $g_H = 0.00 \pm 0.27$

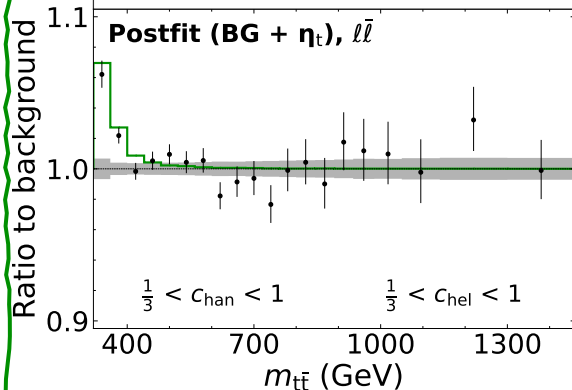
Postfit (BG + A/H), $\ell\bar{\ell}$
No $t\bar{t}$ bound states



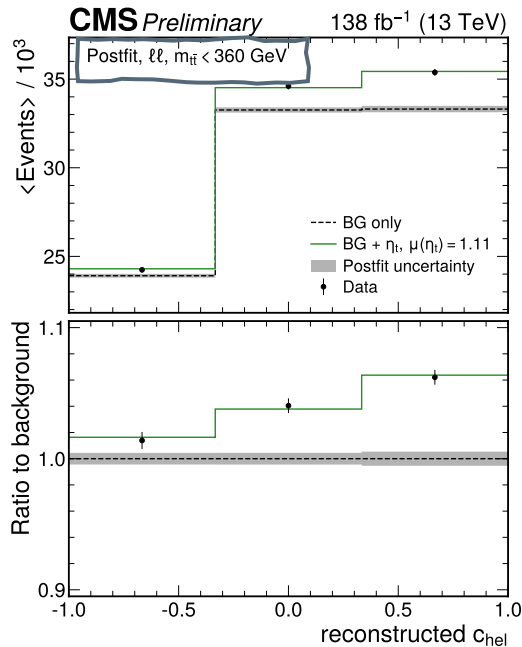
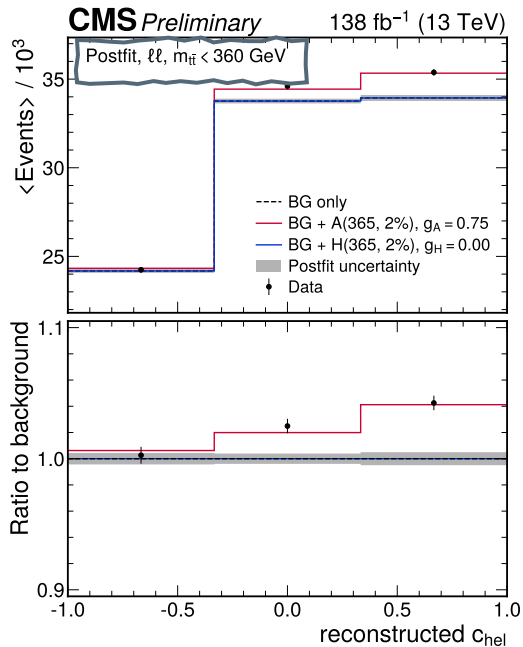
CMS Preliminary 138 fb⁻¹, Run 2 (13 TeV)

- + η_t , $\mu(\eta_t) = 1.11 \pm 0.12$
- Uncertainty

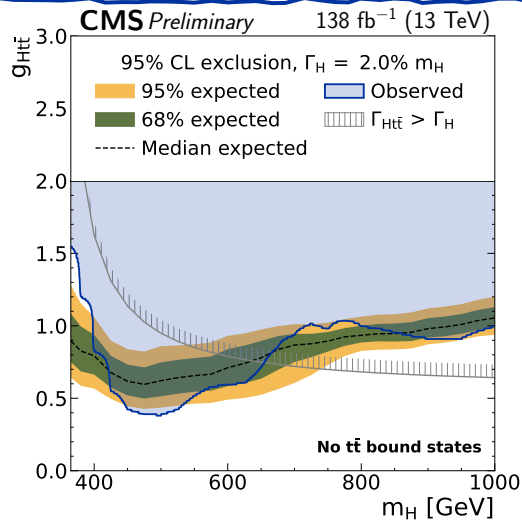
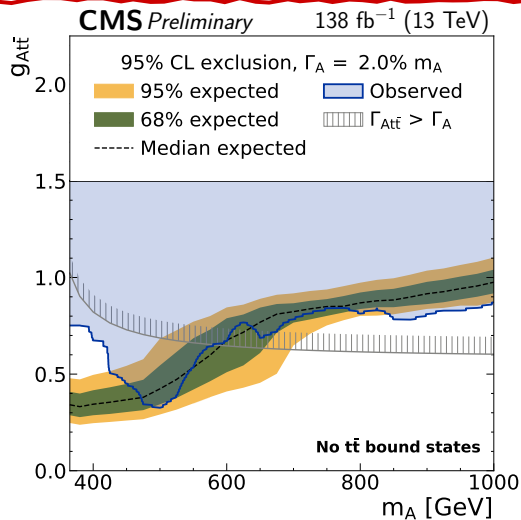
Postfit (BG + η_t), $\ell\bar{\ell}$



A or effective η_t ? Difficult question!



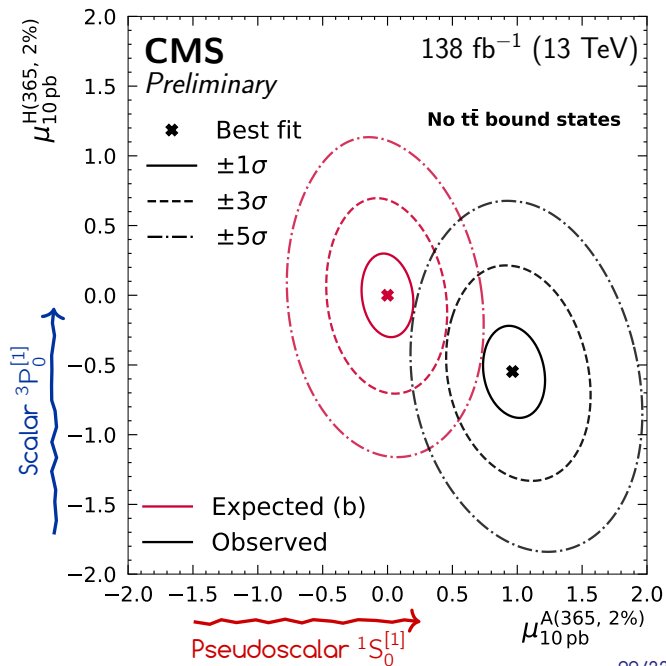
One signal interpretations



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

The structure of the excess

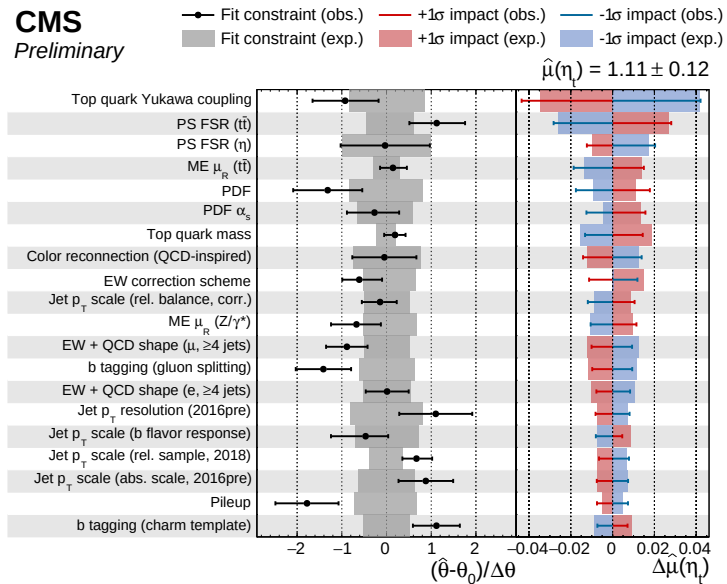
- Use resonant A/H as $^1S_0^{[1]}$ and $^3P_0^{[1]}$ structural proxies



Uncertainties

- Dominant uncertainties: **modelling**
- **Leading:** $y_t = 1^{+0.11}_{-0.12}$
 - Prior from [EPJC 79 \(2019\) 5, 421](#)
- PS FSR scales highly relevant
 - Directly affecting $m_{t\bar{t}}$

CMS
Preliminary



Putting it together

Extract the size of the excess **under the effective η_t assumption**

→ **the most compatible one signal interpretation** of the data

“Cross section” = difference between the data and the pQCD predictions:

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

Cf. 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 $t\bar{t}$ (138 /fb)
- Invariant mass and spin correlation distributions are utilized
- $> 5\sigma$ excess is observed at the $t\bar{t}$ threshold: compatible with a pseudoscalar
 - It has persisted through all the stringent checks so far
- The size of the excess is quantified in terms of an effective $t\bar{t}$ bound state model
- Work on experimental and theory sides are needed to explain the observation

Closing remarks

- CMS-PAS-HIG-22-013: search for pseudoscalars and scalars decaying to $t\bar{t}$ (138 /fb)
- Invariant mass and spin correlation distributions are utilized
- $> 5\sigma$ excess is observed at the $t\bar{t}$ threshold: compatible with a pseudoscalar
 - It has persisted through all the stringent checks so far
- The size of the excess is quantified in terms of an effective $t\bar{t}$ bound state model
- Work on experimental and theory sides are needed to explain the observation

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

Exciting times ahead!

The Exotics – HIG-22-013 *ll* and combination team

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

Dominic Stafford

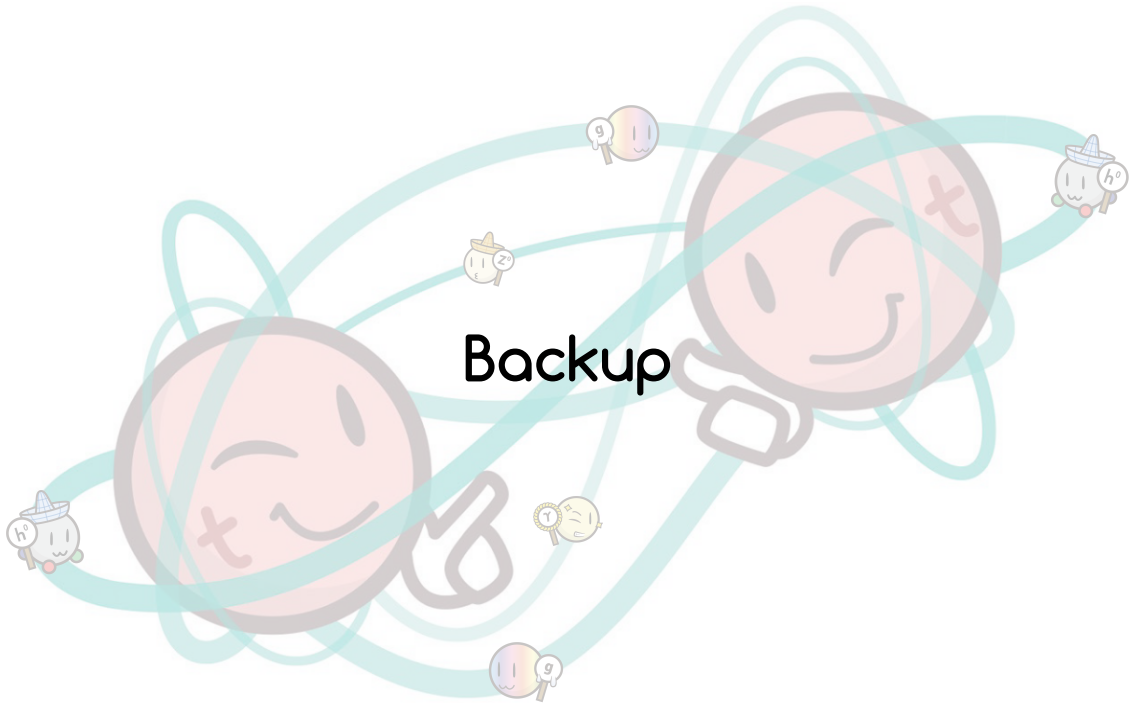


Samuel Baxter



Jörn Bach





HIG-22-013 MC and objects summary

SM background processes:

- $t\bar{t}$: POWHEG2 + 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

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.)

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)

- DY: POWHEG MiNNLO + PYTHIA8 + Photos (only $\ell\ell$)
 - Rate from data ($R_{\text{in}}, R_{\text{out}}$ method)
 - NPs: ME & I/FSR scales, rate from $\sigma_{t\bar{t}}/\sigma_{\text{DY}}$ ratio [ref]

- Minor:
 - $\ell\ell$: $t\bar{t}V$ 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

- 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

On the experimental side:

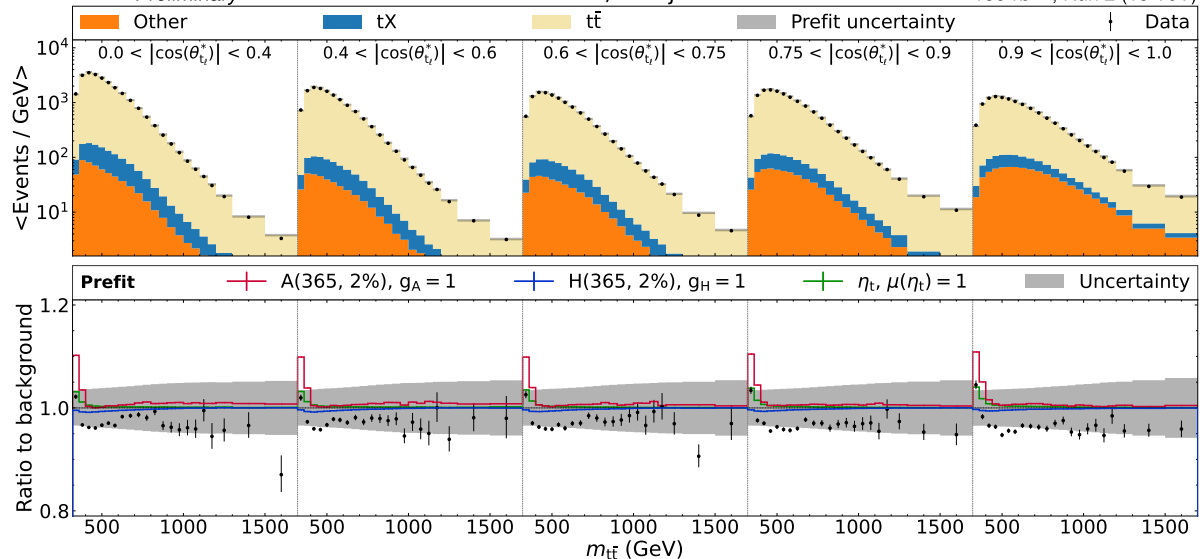
- Standard CMS UL Run 2 recipes:
 - Leptons: efficiency SFs for reco., ID, iso. and trigger
 - Jets: JER and reduced JEC sources
 - b-tag: HF jets with subsource breakdown, and LF jets
 - Type-1 corr. PF MET (unclustered contrib. as NP)
 - Luminosity, PU reweighting, L1 prefire

Prefit distribution: $\ell, \geq 4j$

CMS Preliminary

$\ell, \geq 4j$

138 fb⁻¹, Run 2 (13 TeV)

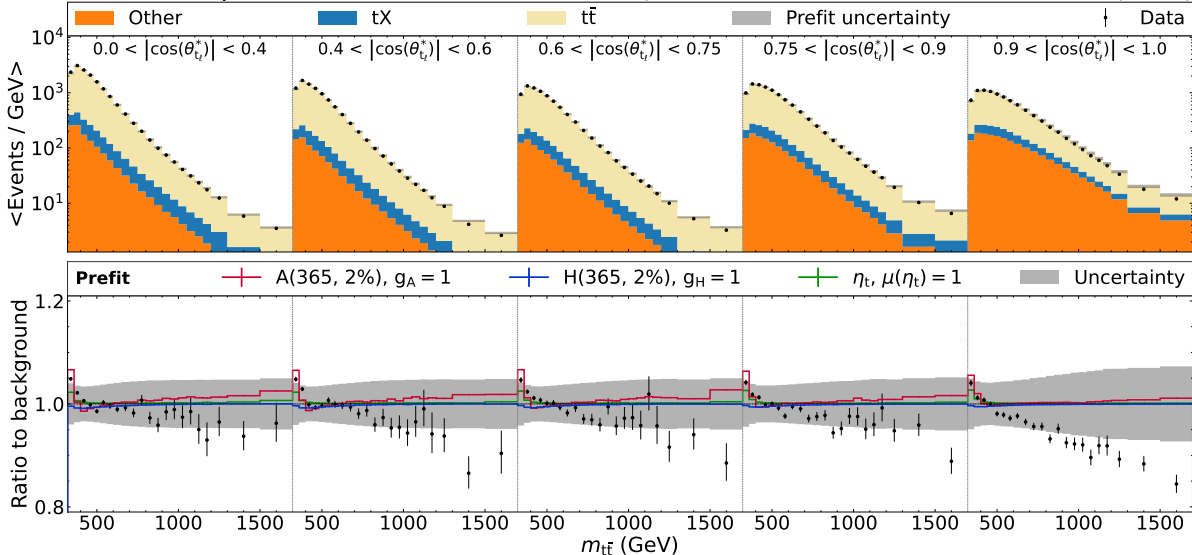


Prefit distribution: $\ell, 3j$

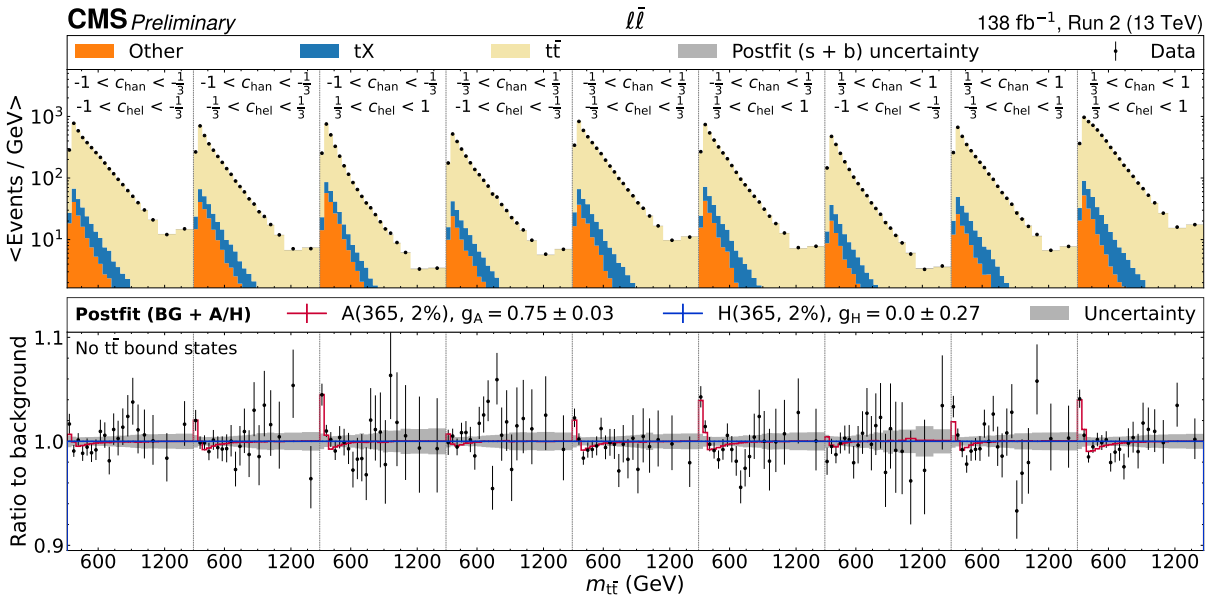
CMS Preliminary

$\ell, 3j$

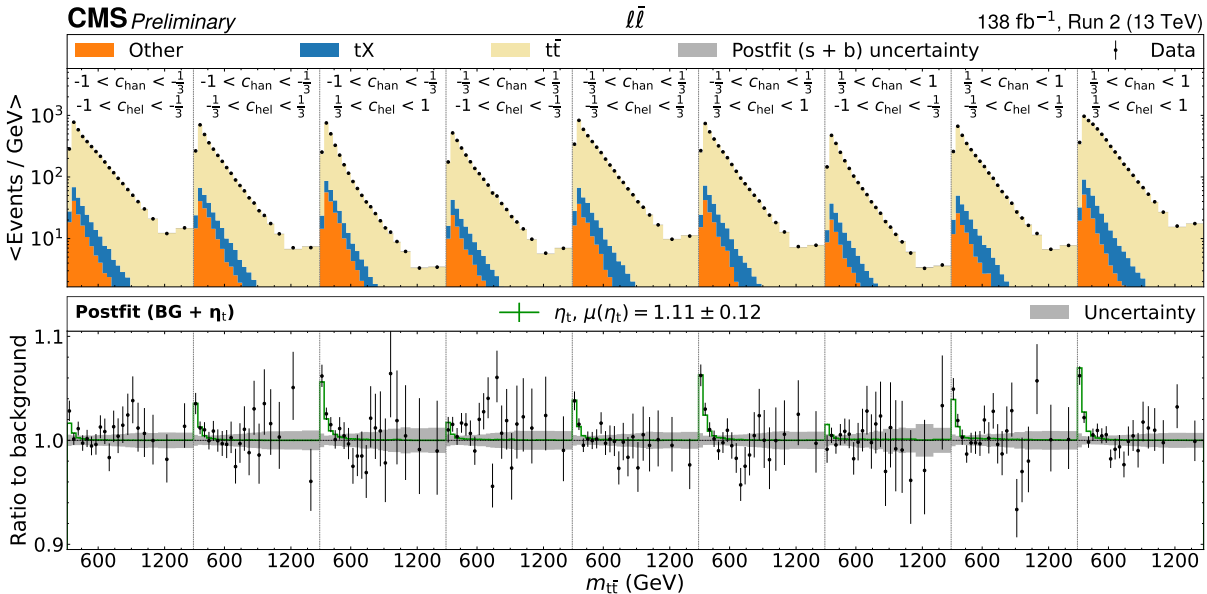
138 fb⁻¹, Run 2 (13 TeV)



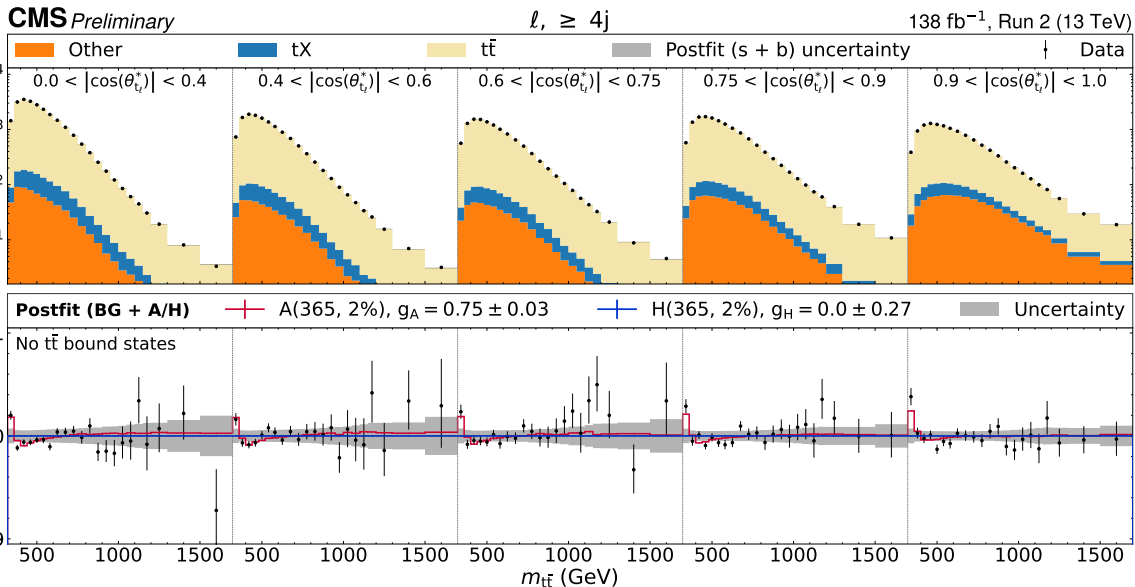
Postfit A/H(365, 2%): $\ell\bar{\ell}$



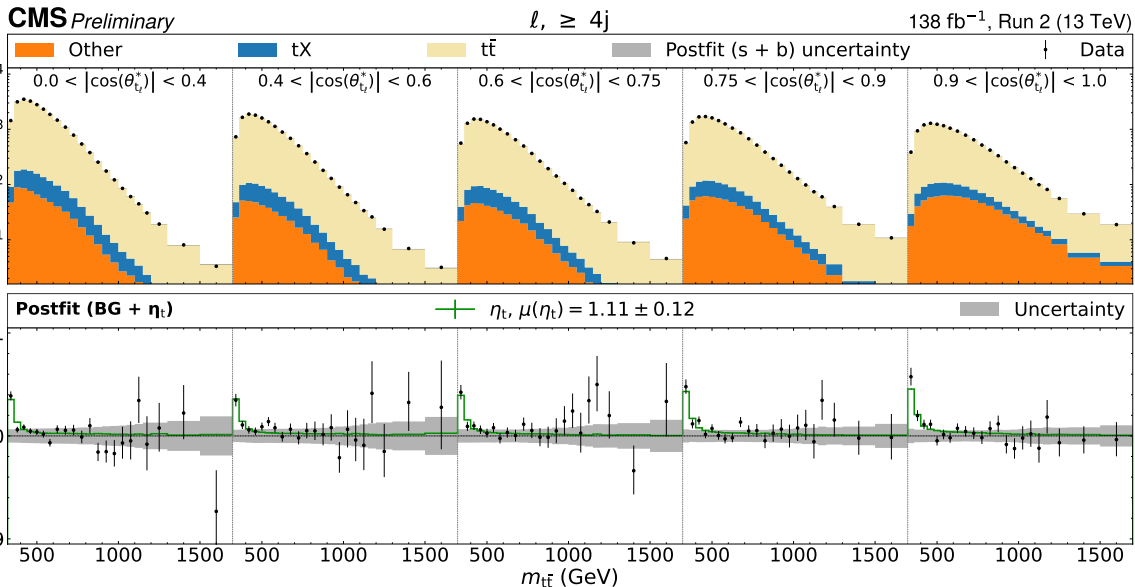
Postfit effective η_t : $\ell\bar{\ell}$



Postfit A/H(365, 2%): $\ell, \geq 4j$



Postfit effective η_t : $\ell, \geq 4j$

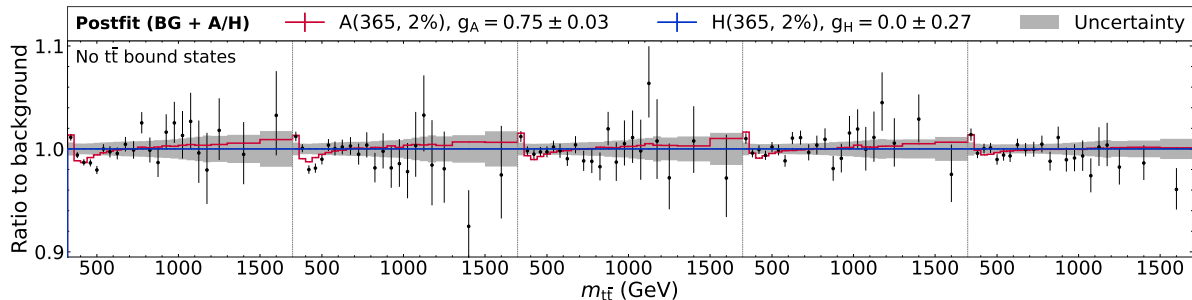
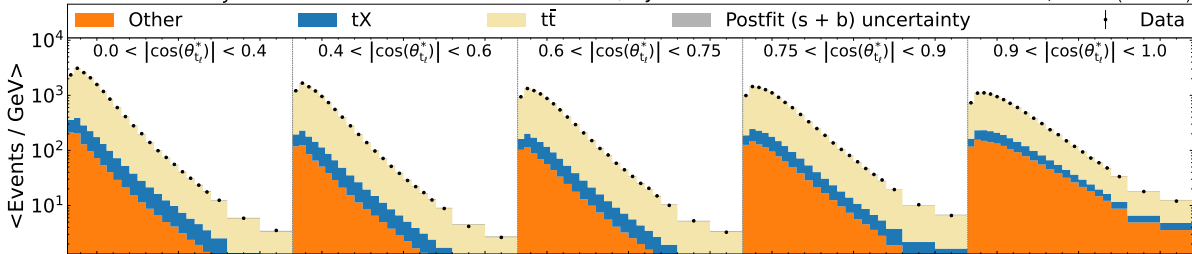


Postfit A/H(365, 2%): $\ell, 3j$

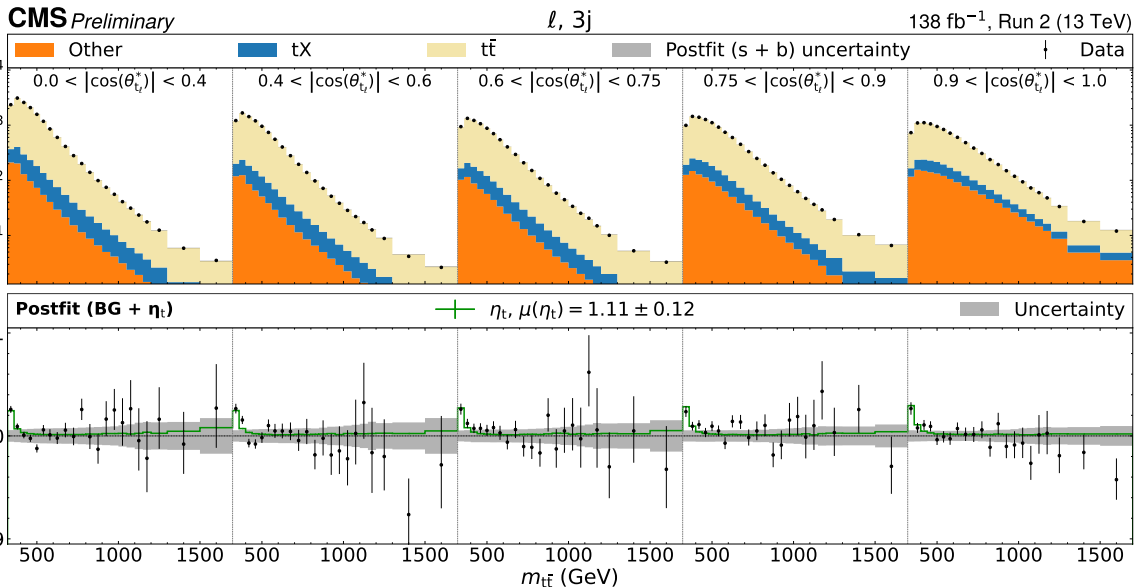
CMS Preliminary

$\ell, 3j$

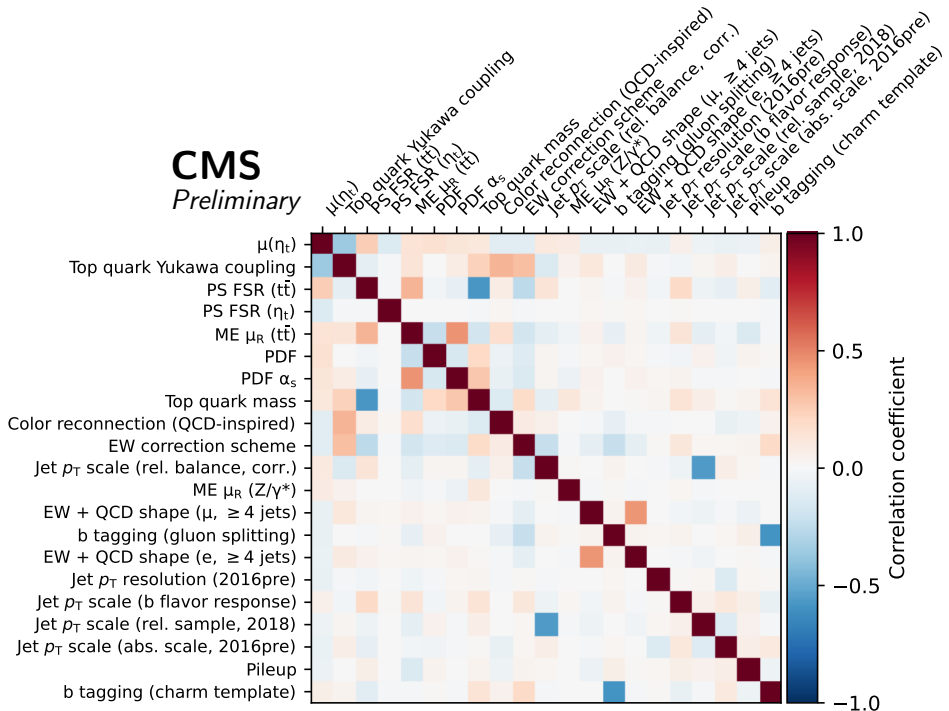
138 fb⁻¹, Run 2 (13 TeV)



Postfit effective η_t : $\ell, 3j$



Correlations



Offshell effects

Check performed **only in $\ell\ell$** channel

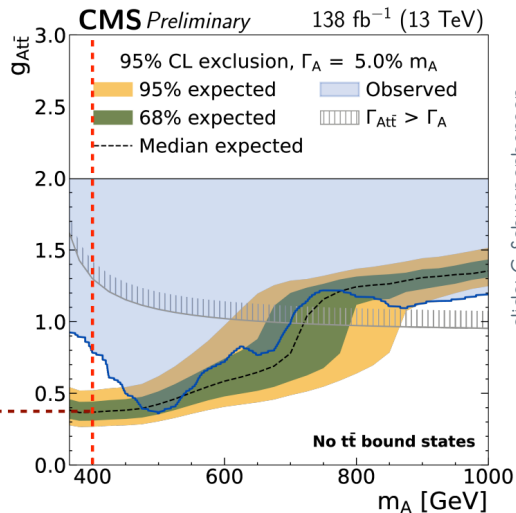
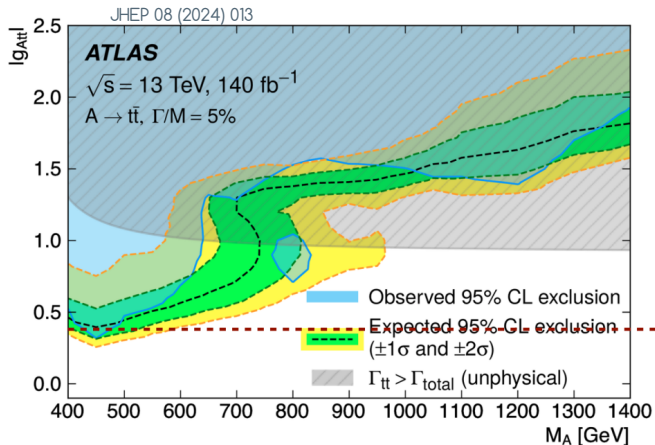
No change in absolute uncertainty, and significance remains $> 5\sigma$

→ 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 $g_{A\bar{t}\bar{t}}$ limit comparison

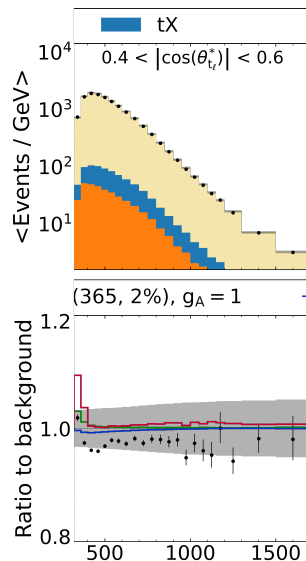
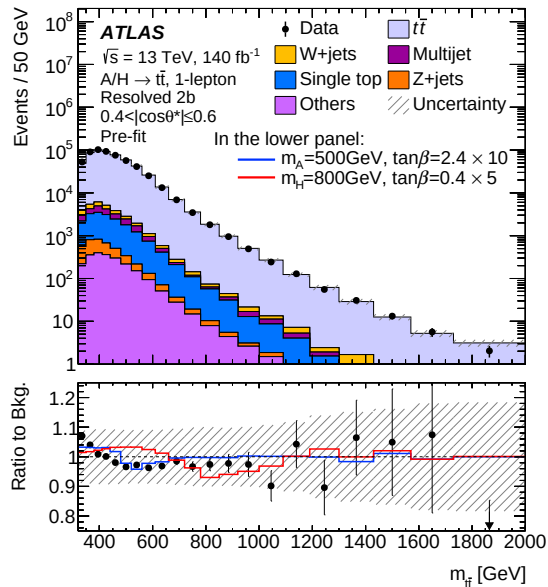
Similar expected sensitivity.

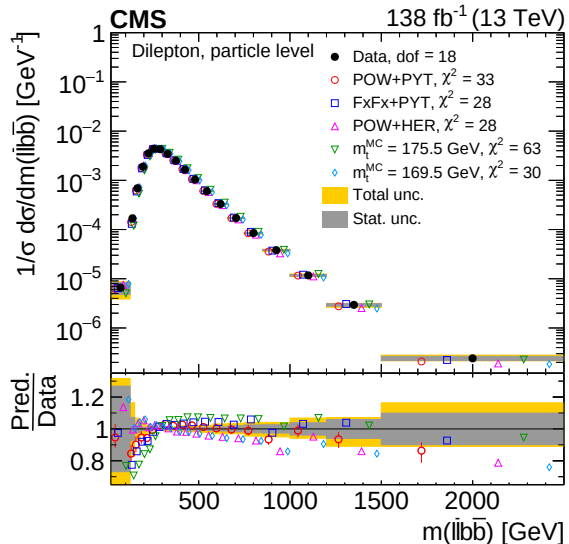
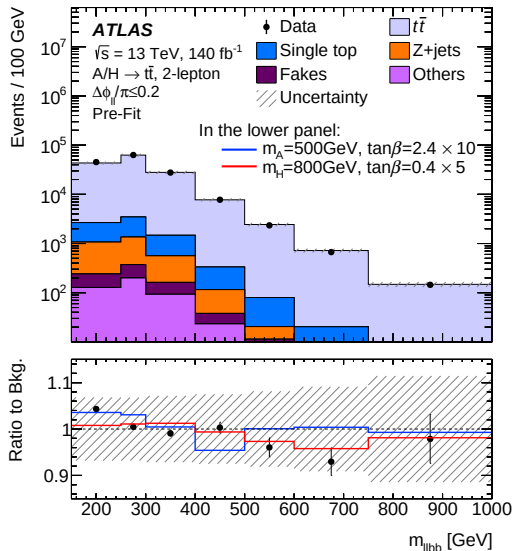


slide: C. Schwanenberger

ATLAS – CMS prefit data comparison

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





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

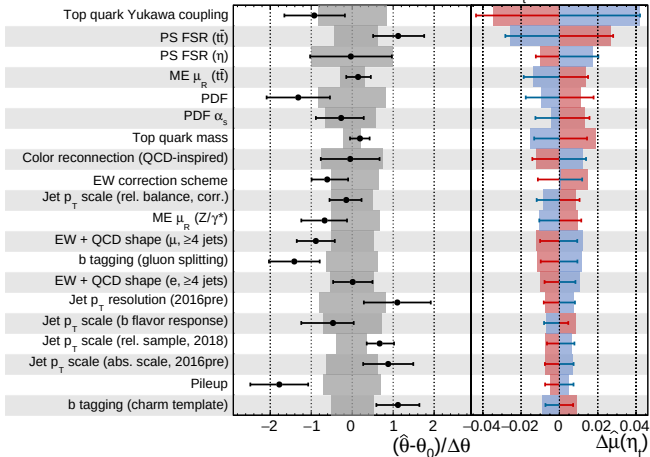
ATLAS – CMS uncertainties

CMS

Preliminary

—●— Fit constraint (obs.) —●— +1 σ impact (obs.) —●— -1 σ impact (obs.)
 —■— Fit constraint (exp.) —■— +1 σ impact (exp.) —■— -1 σ impact (exp.)

$$\hat{\mu}(\eta) = 1.11 \pm 0.12$$



Pre-fit impact on $\sqrt{\mu}$:

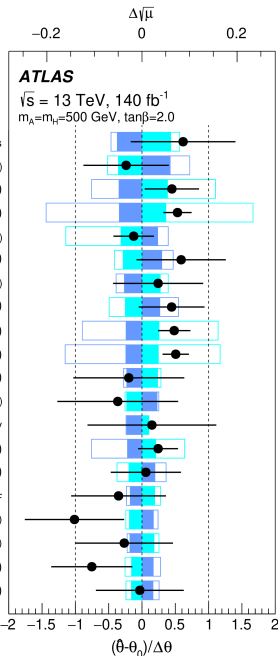
□ $\theta = \hat{\theta} + \Delta\theta$ □ $\theta = \hat{\theta} - \Delta\theta$

Post-fit impact on $\sqrt{\mu}$:

■ $\theta = \hat{\theta} + \Delta\hat{\theta}$ ■ $\theta = \hat{\theta} - \Delta\hat{\theta}$

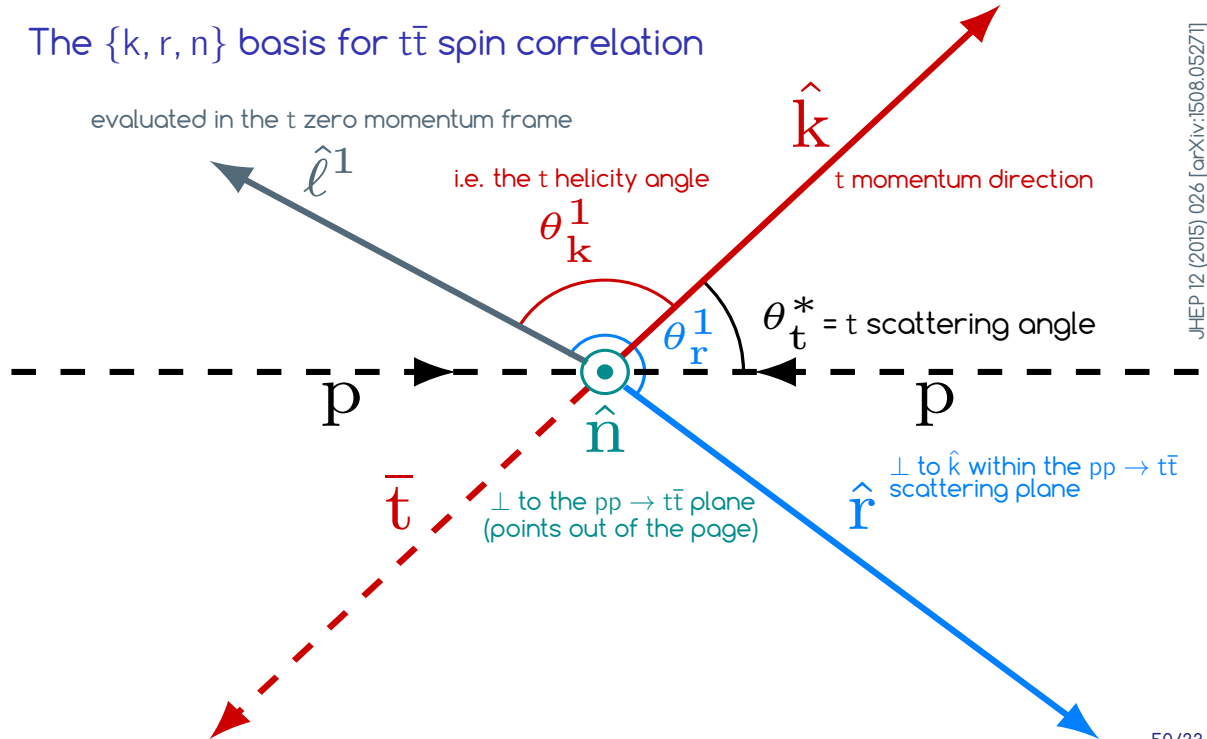
— Nuis. Param. Pull

$t\bar{t}$ reweighting, NN vs LUX PDFs
 $t\bar{t}$ cross-section (1L Resolved 2b)
 $t\bar{t}$ lineshape (1L Resolved 2b, $|\cos\theta^*| \leq 0.2$)
 $t\bar{t}$ PS (shape) (1L Resolved 1b, $0.2 < |\cos\theta^*| \leq 0.4$)
 $t\bar{t}$ cross-section (2L)
 $t\bar{t}$ p_T^{had} (shape) (1L Resolved 2b, $0.8 < |\cos\theta^*| \leq 1.0$)
 JER (effective NP 4)
 $t\bar{t}$ p_T^{had} (shape) (1L Resolved 2b, $0.6 < |\cos\theta^*| \leq 0.8$)
 $t\bar{t}$ PS (shape) (1L Resolved 1b, $0.4 < |\cos\theta^*| \leq 0.6$)
 $t\bar{t}$ PS (shape) (1L Resolved 1b, $|\cos\theta^*| \leq 0.2$)
 $t\bar{t}$ η_{damp} (1L Resolved 2b, $0.2 < |\cos\theta^*| \leq 0.4$)
 JMS (modelling)
 Luminosity
 $t\bar{t}$ PS (shape) (1L Resolved 2b, $|\cos\theta^*| \leq 0.2$)
 $t\bar{t}$ η_{damp} (1L Resolved 2b, $0.6 < |\cos\theta^*| \leq 0.8$)
 $t\bar{t}$ NNLO PDF
 b -tagging eff. (b, NP 0)
 JES (η , modelling)
 $t\bar{t}$ PS (acc.) (1L Resolved 2b, $0.4 < |\cos\theta^*| \leq 0.6$)
 $t\bar{t}$ PS (acc.) (1L Resolved 2b, $0.2 < |\cos\theta^*| \leq 0.4$)



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

evaluated in the t zero momentum frame



Spin density matrix at LO QCD

arXiv:2407.01672

QCD production	$\overline{\sum} \mathcal{M} ^2$	spin correlation matrix C_{ij}
$q\bar{q} \rightarrow t\bar{t}$	$\kappa_q (2 - \beta^2 s_\theta^2)$	$\begin{pmatrix} \frac{(2-\beta^2)s_\theta^2}{2-\beta^2 s_\theta^2} & 0 & -\frac{2c_\theta s_\theta \sqrt{1-\beta^2}}{2-\beta^2 s_\theta^2} \\ 0 & \frac{-\beta^2 s_\theta^2}{2-\beta^2 s_\theta^2} & 0 \\ -\frac{2c_\theta s_\theta \sqrt{1-\beta^2}}{2-\beta^2 s_\theta^2} & 0 & \frac{2c_\theta^2 + \beta^2 s_\theta^2}{2-\beta^2 s_\theta^2} \end{pmatrix}$
$gLgR \rightarrow t\bar{t}$	$\kappa_g \beta^2 s_\theta^2 (2 - \beta^2 s_\theta^2)$	
$gLgL/gRgR \rightarrow t\bar{t}$	$\kappa_g (1 - \beta^4)$	$\begin{pmatrix} \frac{\beta^2-1}{\beta^2+1} & 0 & 0 \\ 0 & \frac{\beta^2-1}{\beta^2+1} & 0 \\ 0 & 0 & -1 \end{pmatrix}$