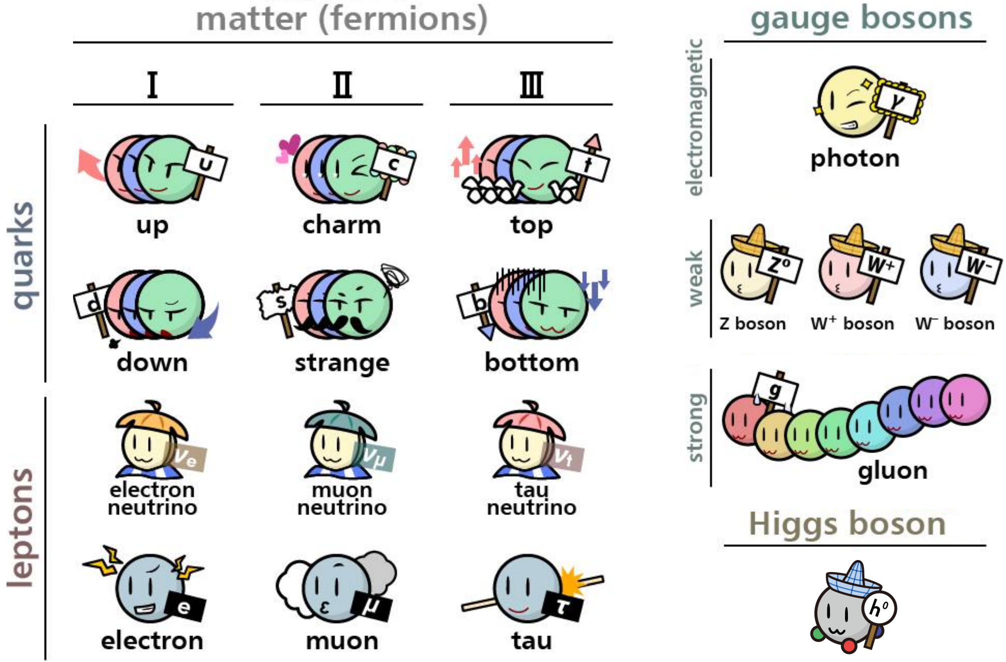
In Search of Top Quark Pairs With Zero Total Angular Momentum

CMS-PAS-HIG-22-013

Afiq Anuar (DESY)

LPHE seminar – 2024/10/28

The standard model of particle physics



cartoons: HiggsTan

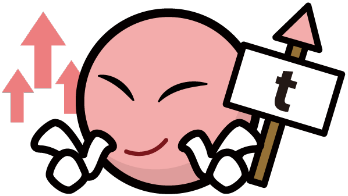
The top quark

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?

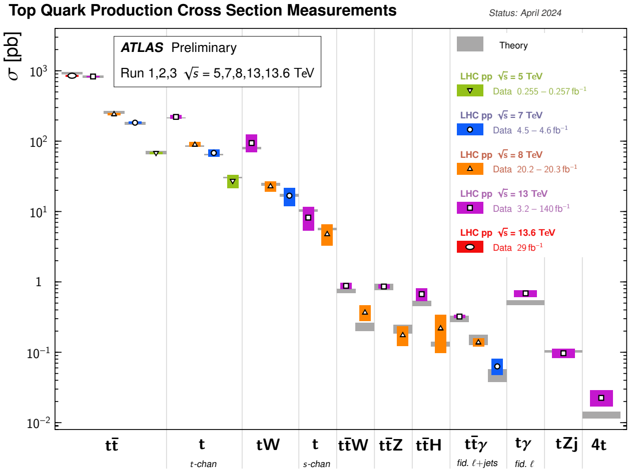
The top quark

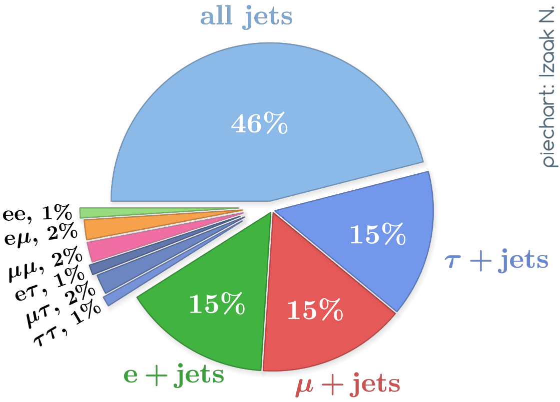
QCD $t\bar{t}$, EWK t + X

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

$t \to Wb$ (BR $\sim$ 1)

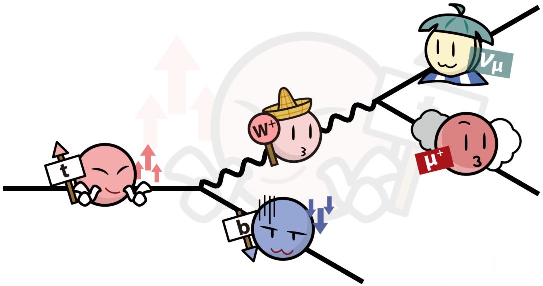
$\Rightarrow$ $t\bar{t}$ classification by W decay modes

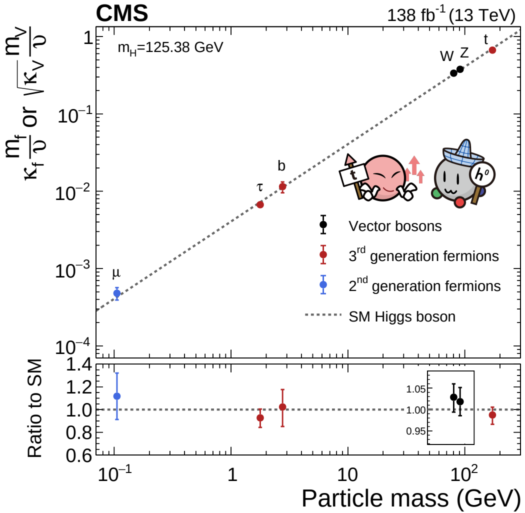




piechart: Izaak N.

The top quark





Nature 607 (2022) 60, LHCtopWG

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

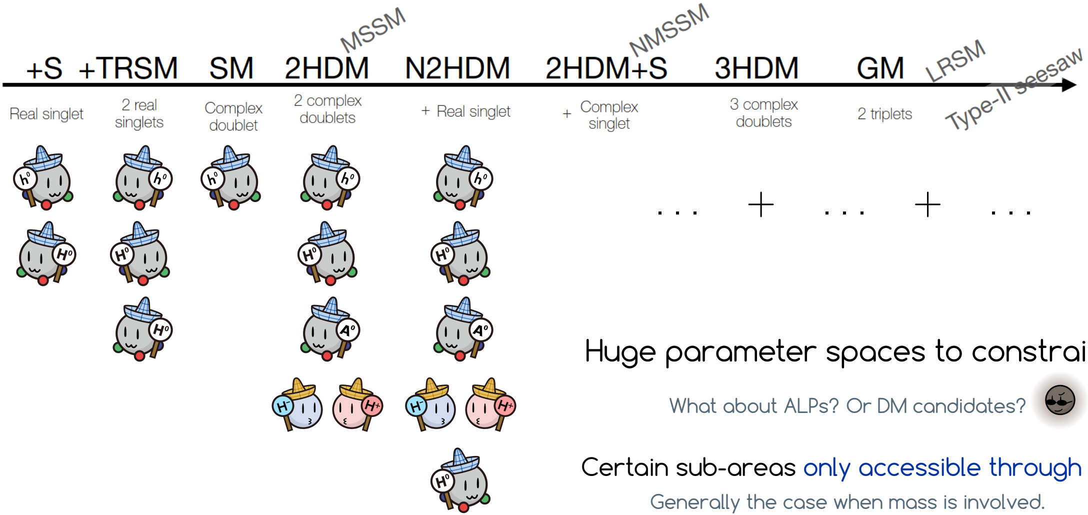
$\ll \Lambda_{QCD}^{-1}$ → observe "bare" quark

172.52 ± 0.33 GeV

→ heaviest in SM. A portal to BSM?

Extending the SM scalar sector

figure: H. Saka



Huge parameter spaces to constrain!

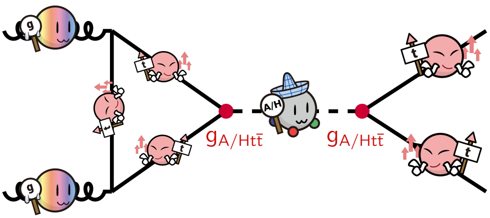
What about ALPs? Or DM candidates?

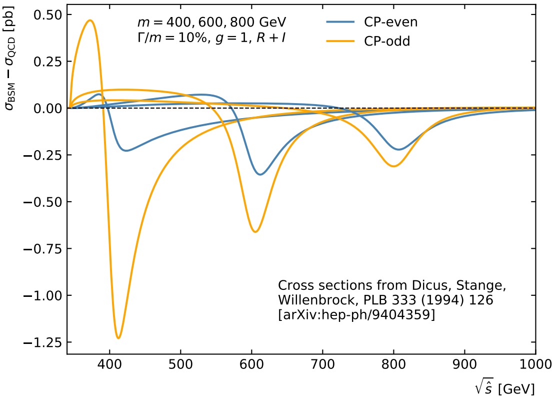
Certain sub-areas **only accessible through $t\bar{t}$!**

Generally the case when mass is involved.

Enter CMS-PAS-HIG-22-013

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



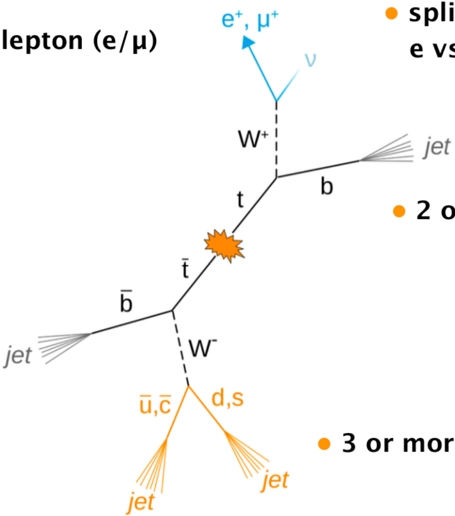


- A is a CP-odd scalar, and H is CP-even
- Yukawa-like coupling with modifiers $g_{A/Ht\bar{t}}$
  - If $m_{A/H} > 2m_t$, direct decays are possible
  - Also dominant, if $g_{A/Ht\bar{t}}$ is $\mathcal{O}(1)$
- Simplifying assumptions:
  - A/H couple only to top quarks
  - CP conserving → A/H don't mix

- Strong interference with QCD $t\bar{t}$ production
- Leads to a peak-dip structure in $m_{t\bar{t}}$
  - Resonant $\propto g^4_{A/Ht\bar{t}}$ and interference $\propto g^2_{A/Ht\bar{t}}$
- Set up as a generic and model-agnostic analysis
  - Free parameters: $m_{A/H}$, $\Gamma_{A/H}$, $g_{A/Ht\bar{t}}$
  - 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

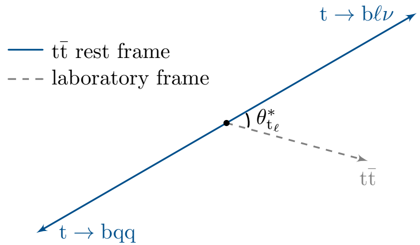


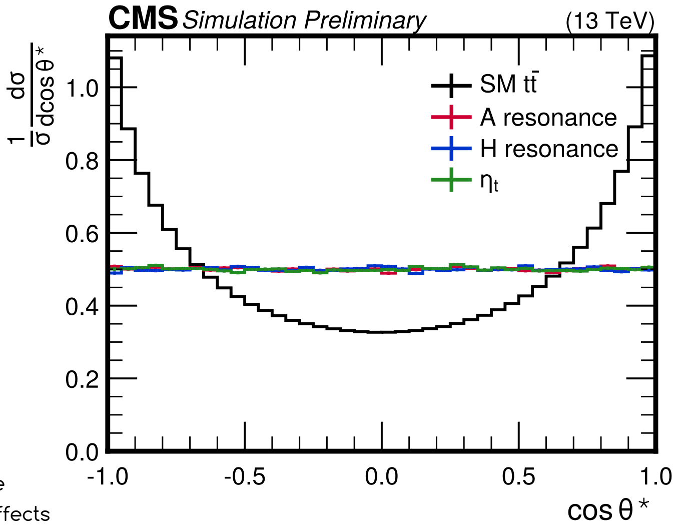
- Reconstruct $t\bar{t}$ system with `NeutrinoSolver` algorithm
  NIM A 736 (2014) 169
  - assign b-jets by maximum likelihood
  - energy correction factor applied for 3 jet events (lost or merged jets)

NIM A 788 (2015) 128

slide: C. Schwanenberger

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



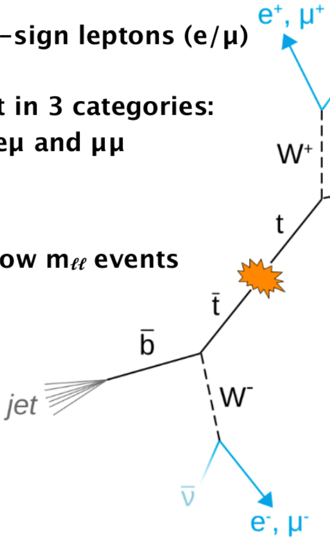


- Flat distribution for resonant A/H
- SM shape from the mixture of helicities
  - Becomes peakier at increasing $m_{t\bar{t}}$
- Use the absolute value in the analysis
  - 5 non-uniform bins based on the SM shape
  - Sign dependence only from CP-violating effects

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**

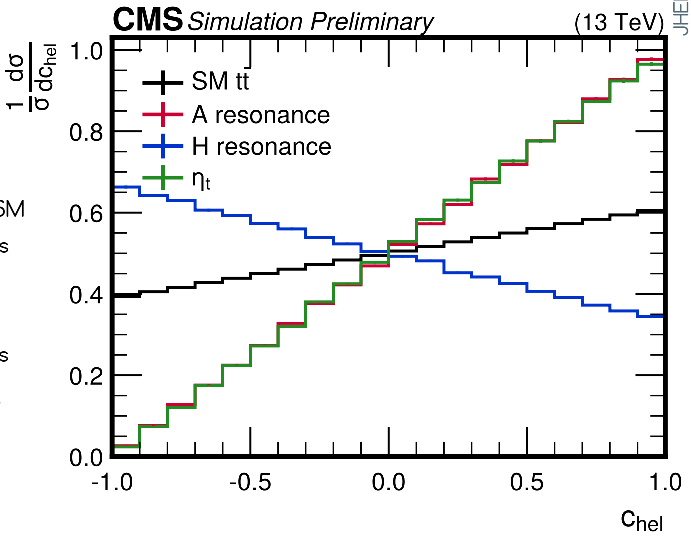


- **cut away Z peak & require p_T^{miss} > 40 GeV in ee/μμ**
- **1 or more b-jets**
- **analytic reconstruction of $t\bar{t}$ system**
  - assumptions: all p_T^{miss} from νν, tops on-shell, Ws on-shell
  - assign b-jets using likelihood, based on $m_{\ell b}$
  - finite detector resolution: repeat reconstruction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

slide: C. Schwanenberger

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

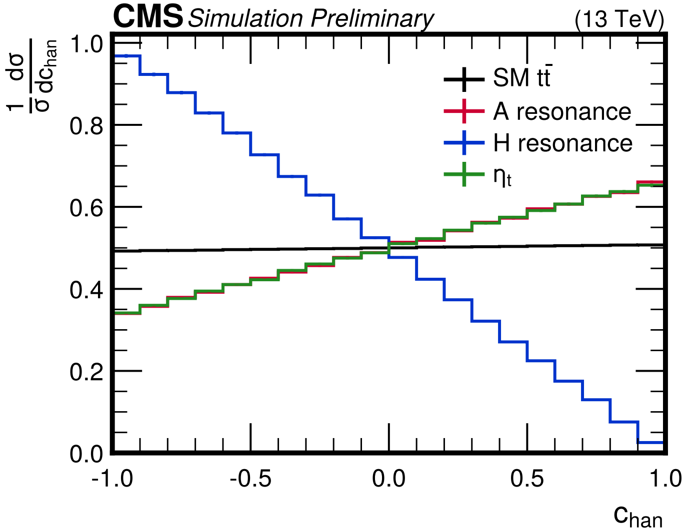
- $c_{hel} = \hat{\ell}^{t} \cdot \hat{\ell}^{\bar{t}}$, with $\hat{\ell}^{t}$ the top spin vectors
  - Also the leptons' direction (in top ZMF)
- Slope $\propto$ trace of the $t\bar{t}$ spin density matrix
- Extremely useful – discriminates A vs H vs SM
  - More precisely, separates the $t\bar{t}$ spin states
  - Resonant A/H $\rightarrow$ pure ${}^{1}S_{0}^{[1]}$ / ${}^{3}P_{0}^{[1]}$ $t\bar{t}$ pairs
- Even more so – $t\bar{t}$ spin state is all c_{hel} sees
  - Generally robust against systematic effects
- Also one of the probes for $t\bar{t}$ entanglement



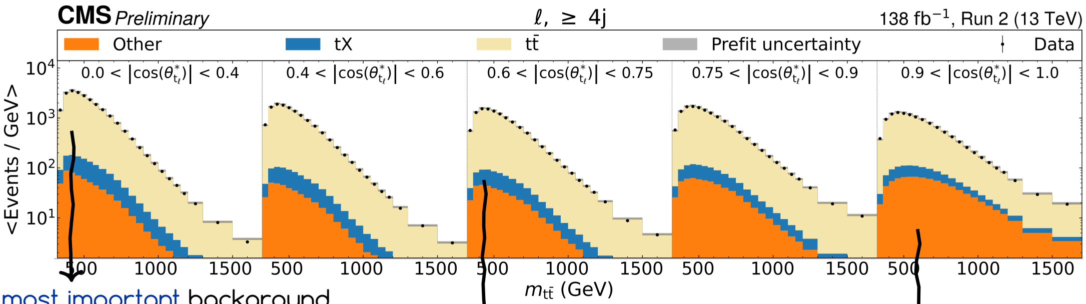
JHEP 12 (2015) 026

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

- 'Like c_{hel}, but for H'
  - One linear combination of the diagonal entries of the spin density matrix in the $\{k, r, n\}$ basis
  - Independent from, and as robust as c_{hel}
- Also a probe for $t\bar{t}$ entanglement
- Use a 3×3 uniform binning for the two

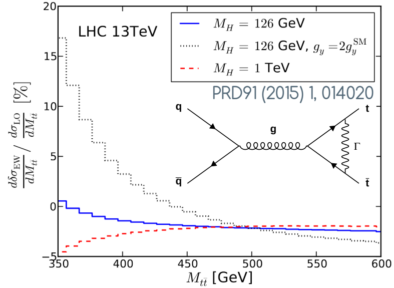


Background modelling



$t\bar{t}$: most important background

- NLO QCD reweighted to NNLO QCD + NLO EW
- Full quadratic y_t dependence on EW correction



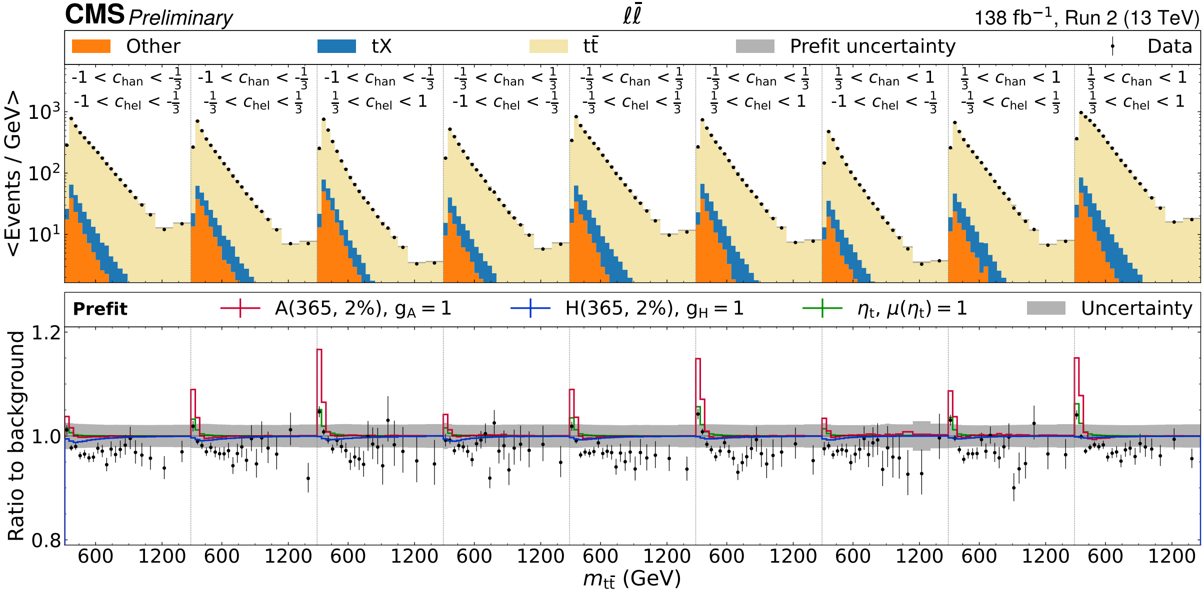
Single top production tX

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

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

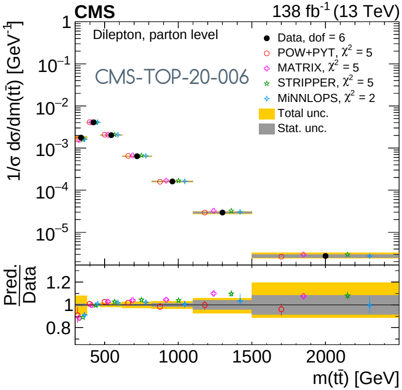
Prefit distribution

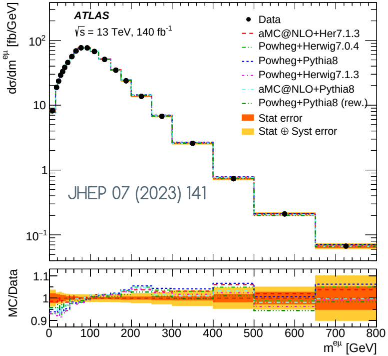


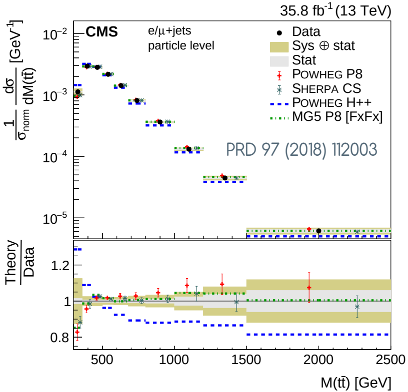
Similar prefit ratios in ℓj– see backup

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

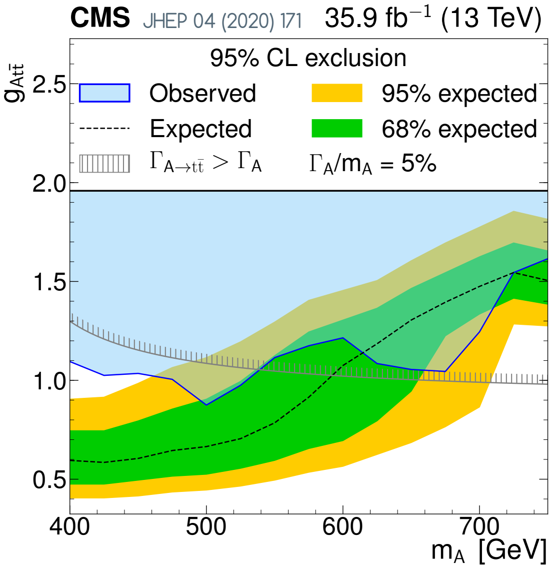
Data – pQCD tension observed at the threshold region in multiple measurements

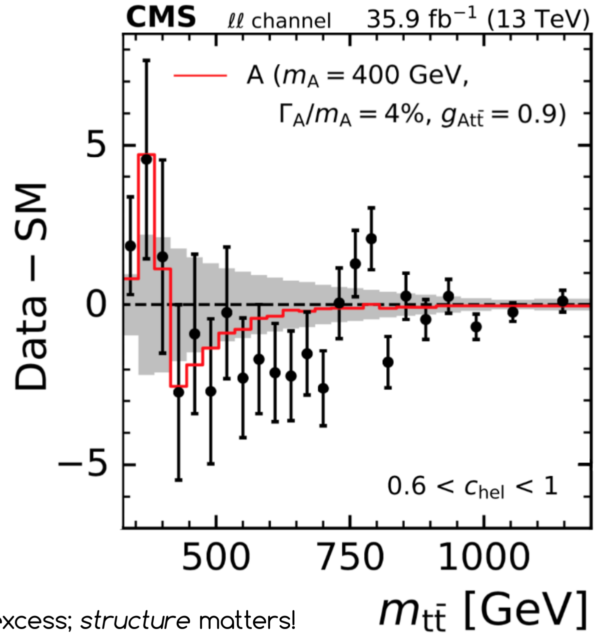






The effect is spin-dependent

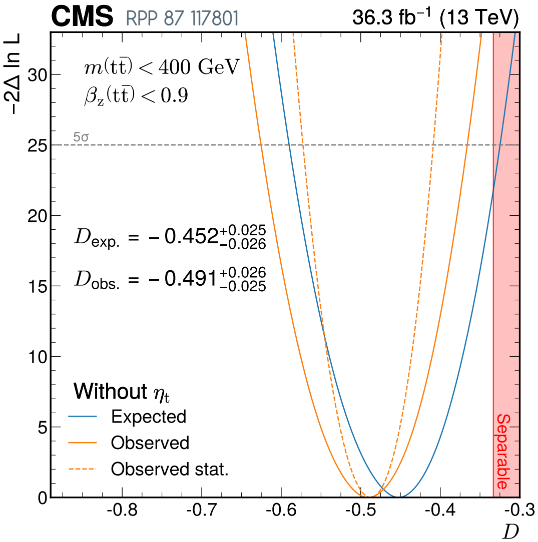


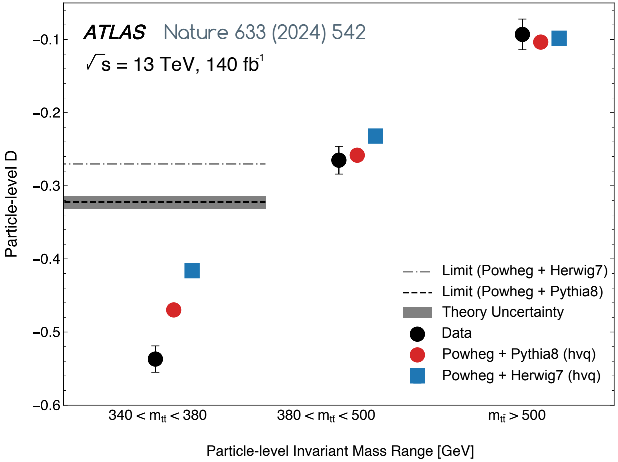


cropping: G. Weiglein

No corresponding H excess; *structure* matters!

. . . and it is reproducible!

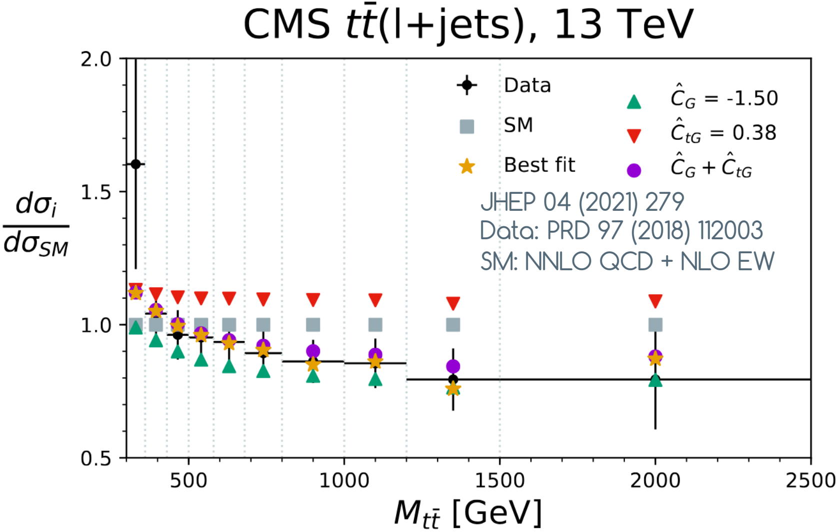




NB: D corresponds to the slope of c_{hel} distribution. $|D| \neq 0 \to$ spin correlation

$D < -1/3$ satisfies the Peres-Horodecki criterion for non-separable states

Would SMEFT operators help? . . . no.



Only the linear terms included. Quadratic c_G is strongly constrained.

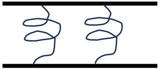
Not much hint from other analyses. Check out J. Ellis' lecture for more info.

Let's talk η_t

The top is... a quark

So it probably does quarky things, like...

Coulombic gluon exchanges:

 +  ...

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

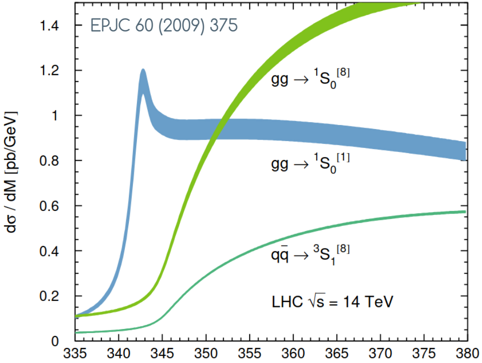
Inducing the Sommerfeld correction:

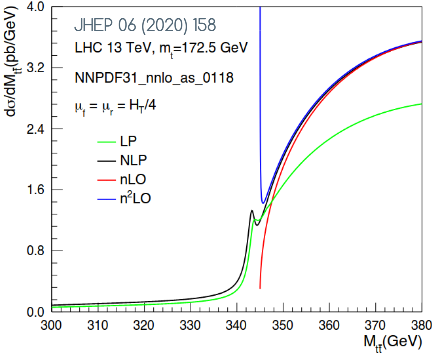
$$J \sim \frac{\alpha_s/\beta}{e^{\pi\frac{\alpha_s}{\beta}} - 1} = 1 + \frac{\alpha_s}{\beta} + \dots$$

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

Essential at the threshold region

left side figures: A. Mitov's TOP2023 slides





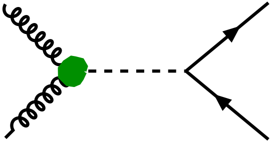
Simplified η_t model

No full MC generator yet, but...

effective descriptions exist: PRD 104, 034023 (2021)

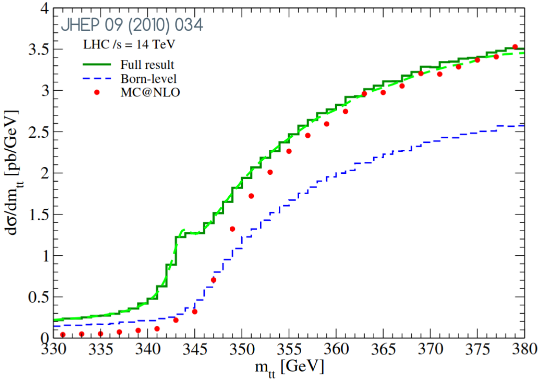
see also: JHEP 03 (2024) 099 and PRD 110 (2024) 5, 054032

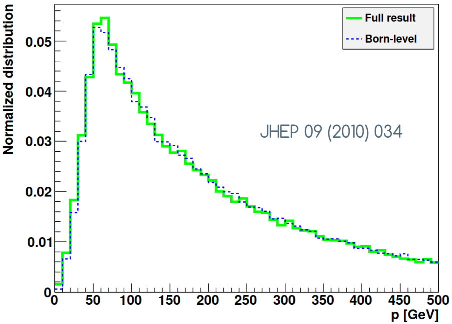
Simplifying, it's implemented as:



- 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

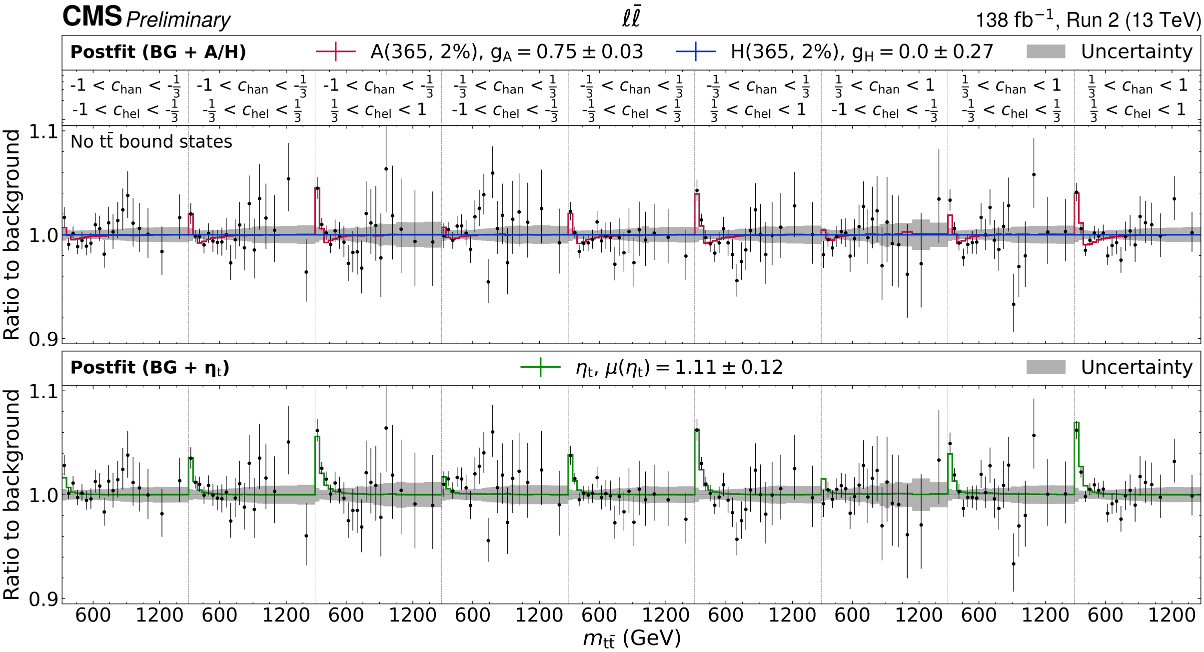
Interpret with caution



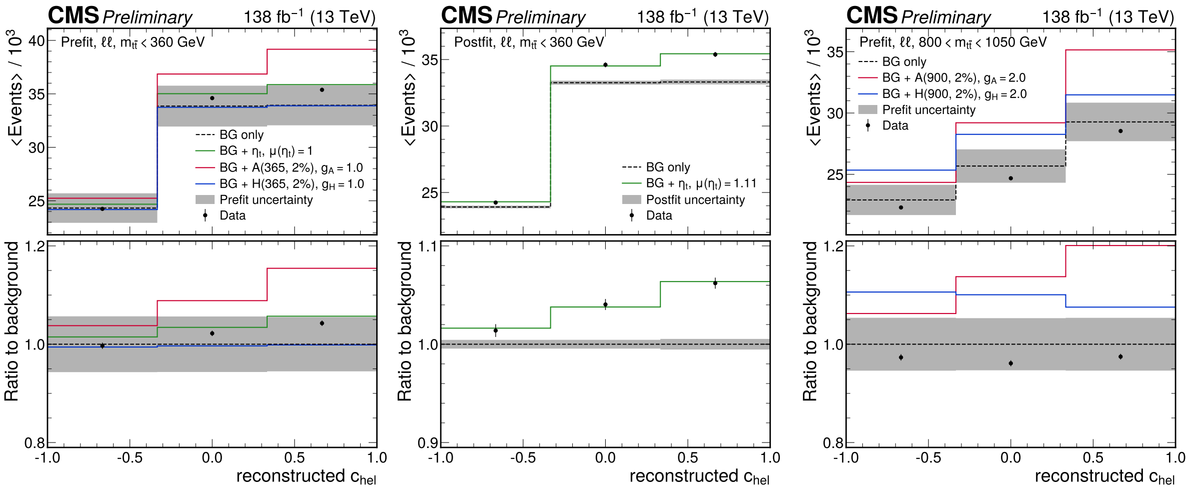


Results

What HIG-22-013 sees

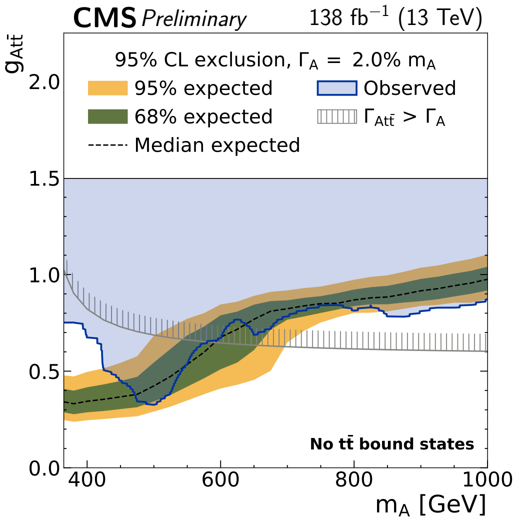


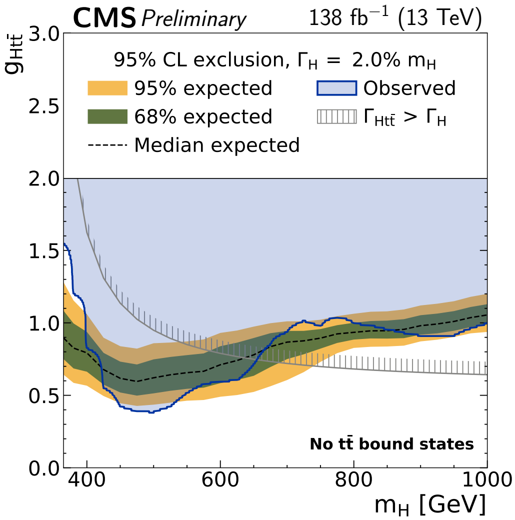
c_{hel} at low and high $m_{t\bar{t}}$



Clear slope at threshold, which is not present at high $m_{t\bar{t}}$

Comparing one signal interpretations

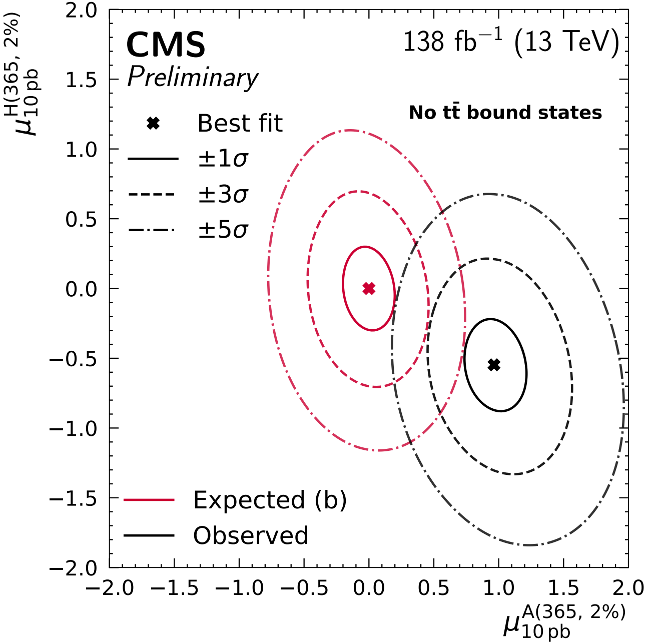




Interpretation	Best-fit point	Difference in $-2\ln L$
η_t	$\mu(\eta_t) = 1.11$	-86.2
Single A boson	$m_A = 365\,\text{GeV}, \Gamma_A/m_A = 2\%, g_{At\bar{t}} = 0.78$	-72.6
Single H boson	$m_H = 365\,\text{GeV}, \Gamma_H/m_H = 2\%, g_{Ht\bar{t}} = 1.45$	-10.4

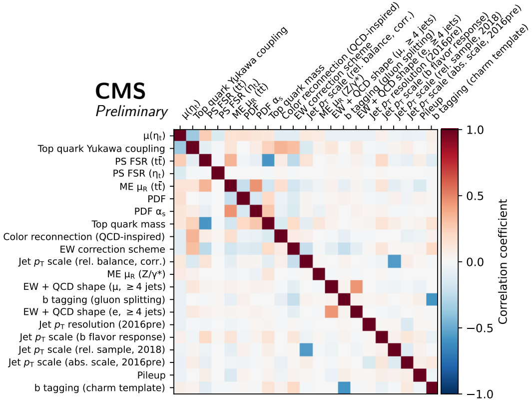
The structure of the excess

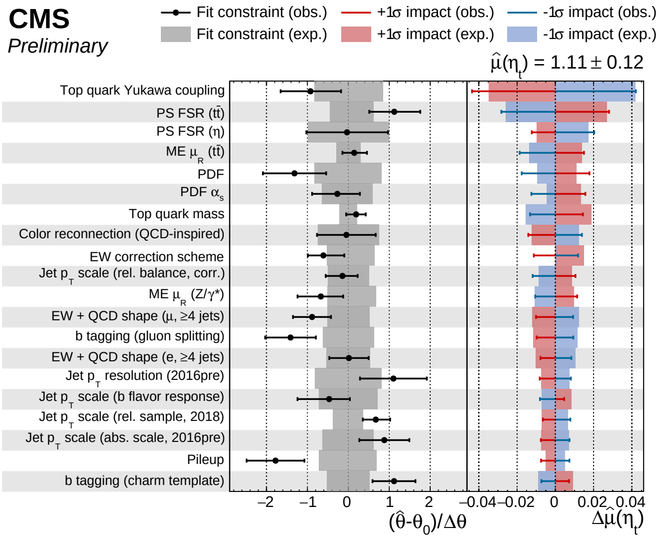
- Quantify the preference of the data in a simultaneous A/H fit
- Only resonance components, with an equal and arbitrary rate
- In other words, use A/H as $^1S_0^{[1]}$ and $^3P_0^{[1]}$ structural proxies
- Clearly, the excess is much more compatible with a $^1S_0^{[1]}$ state



Uncertainties

- Dominant uncertainties: modelling
- Leading: $y_t = 1^{+0.11}_{-0.12}$ [EPJC 79 (2019) 5, 421]
  - Almost 2x the impact of 2nd rank
  - Correlation matrix to reveal degeneracies





The size of the excess

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

$\rightarrow$ the most compatible one signal interpretation of the data, among the ones considered

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

$$\sigma(\eta_t) = 7.14\,\text{pb} \pm 11\%$$

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

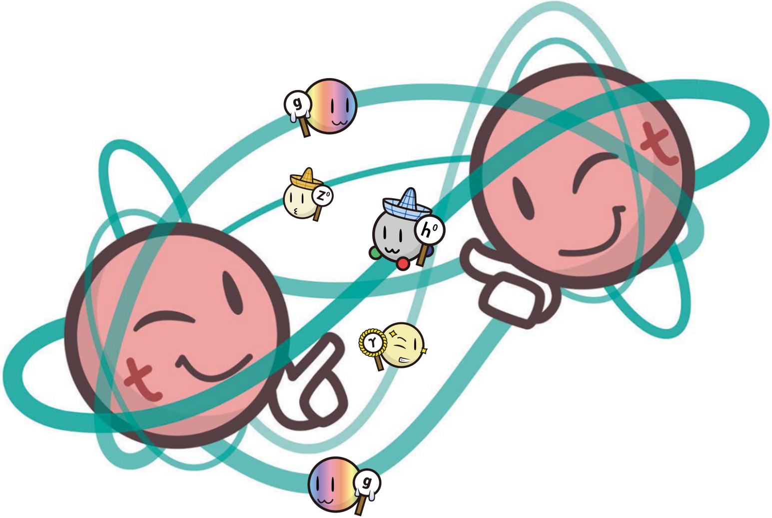
- CMS-PAS-HIG-22-013: search for pseudoscalars and scalars decaying to $t\bar{t}$ (138 /fb)
- $m_{t\bar{t}}$ and spin correlation information is utilized
- $> 5\sigma$ excess is observed at the $t\bar{t}$ threshold, which is compatible with a pseudoscalar
- The size of the excess is quantified in terms of an effective $t\bar{t}$ bound state model
- Work on experimental and theory sides are needed to explain the observation

Exciting times are ahead of us, as we explore the origin of the excess.
For the moment, let's celebrate what we've learned:

- At the threshold, the top spins are not only correlated, but they are also connected

Or, to put it simply...

Top pairs don't only dance together, they also cuddle.



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 → 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

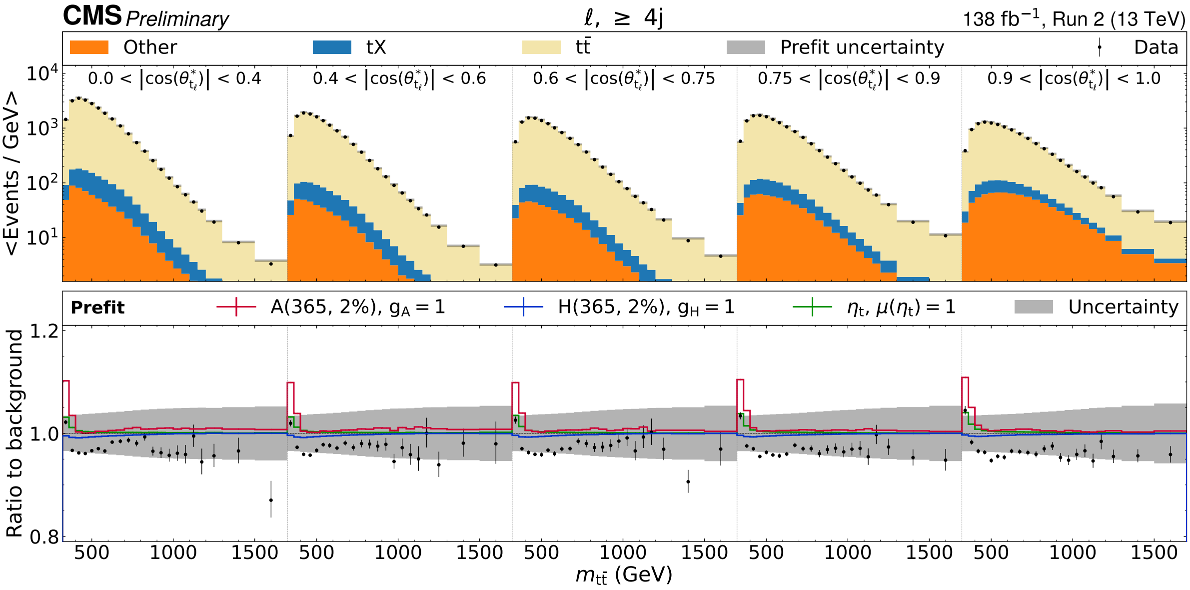
η_t signal modelling:

- 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)

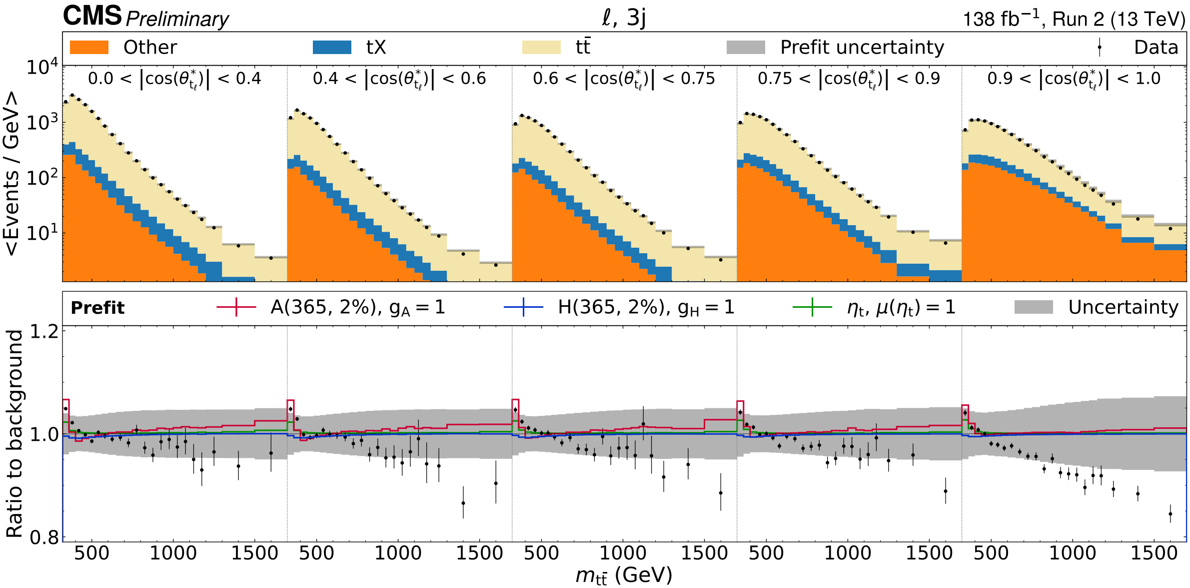
On the experimental side:

- 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

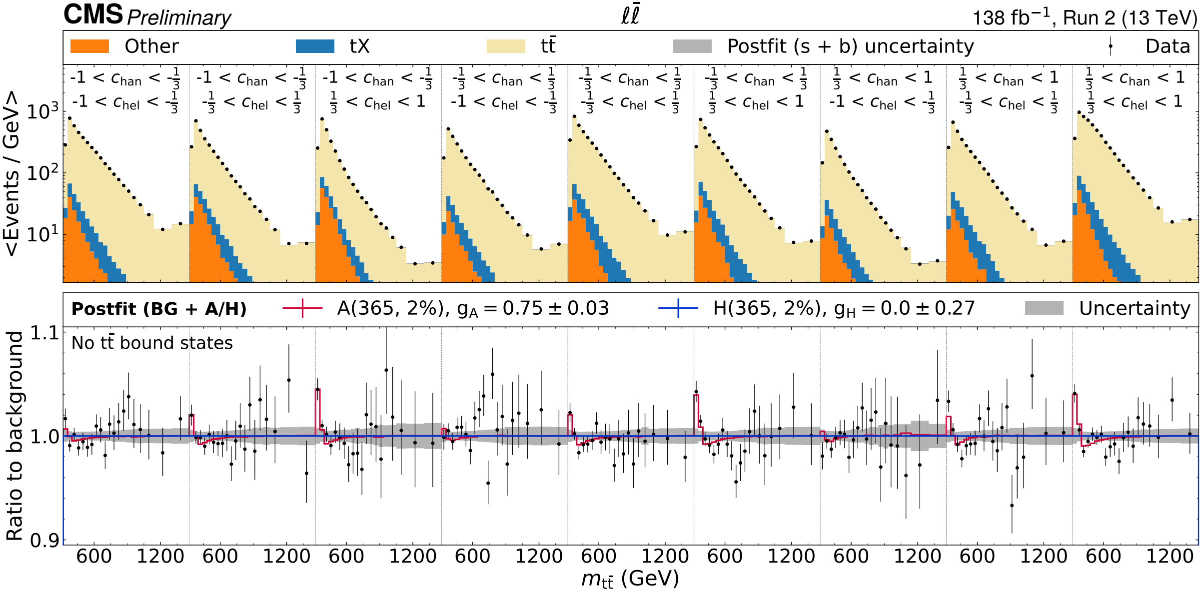
Prefit distribution: ℓ, $\geq$ 4j



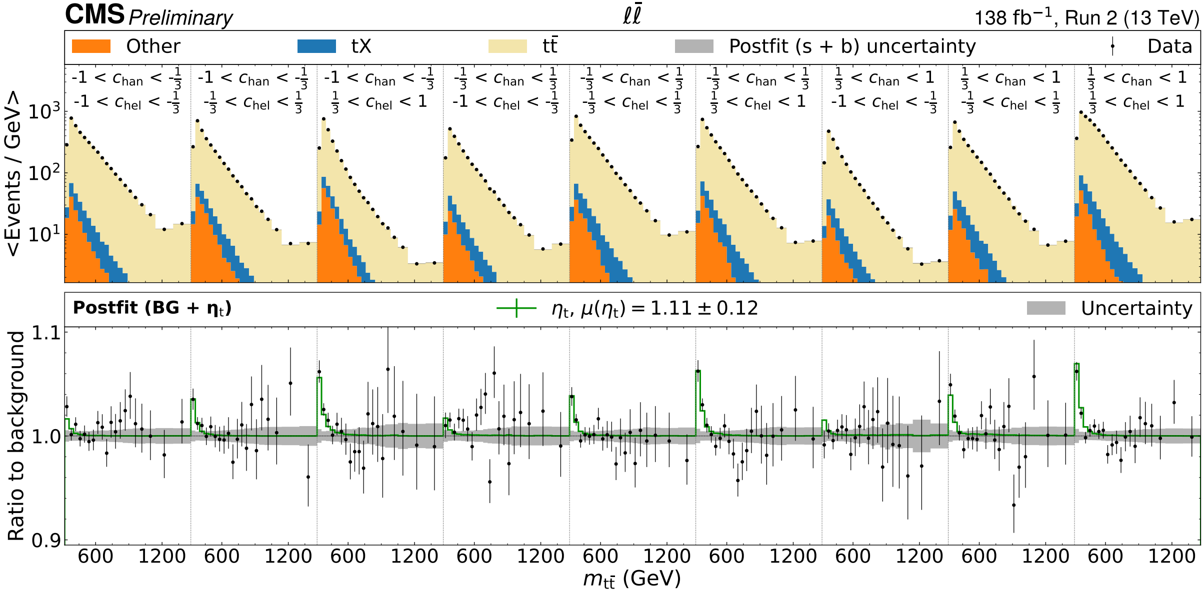
Prefit distribution: ℓ, 3j



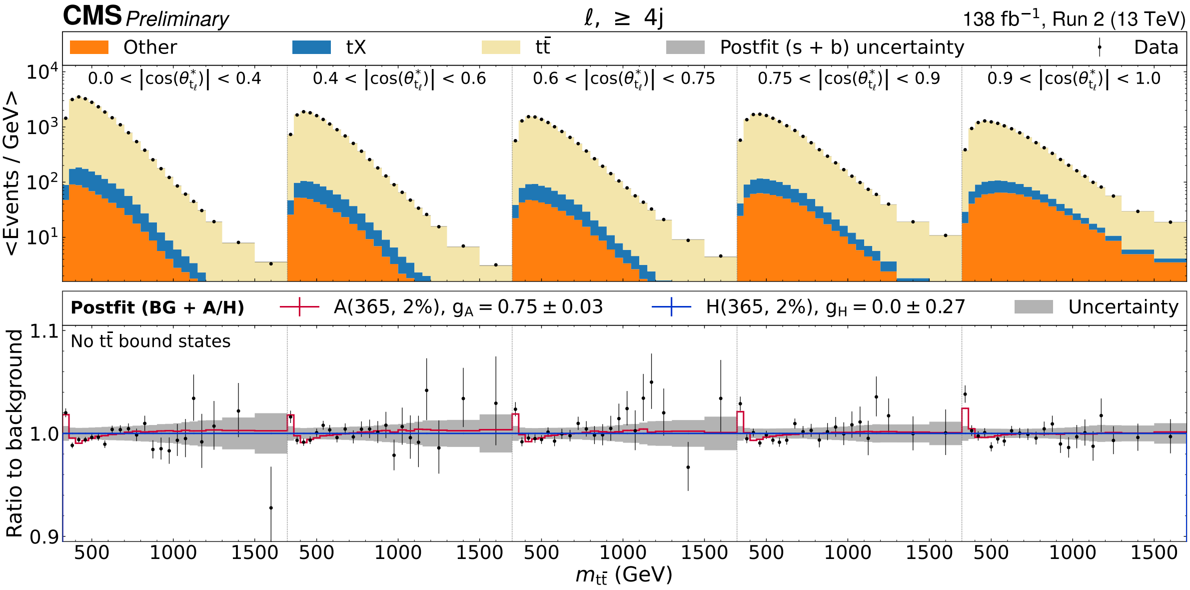
Postfit A/H(365, 2%): $\ell\bar{\ell}$



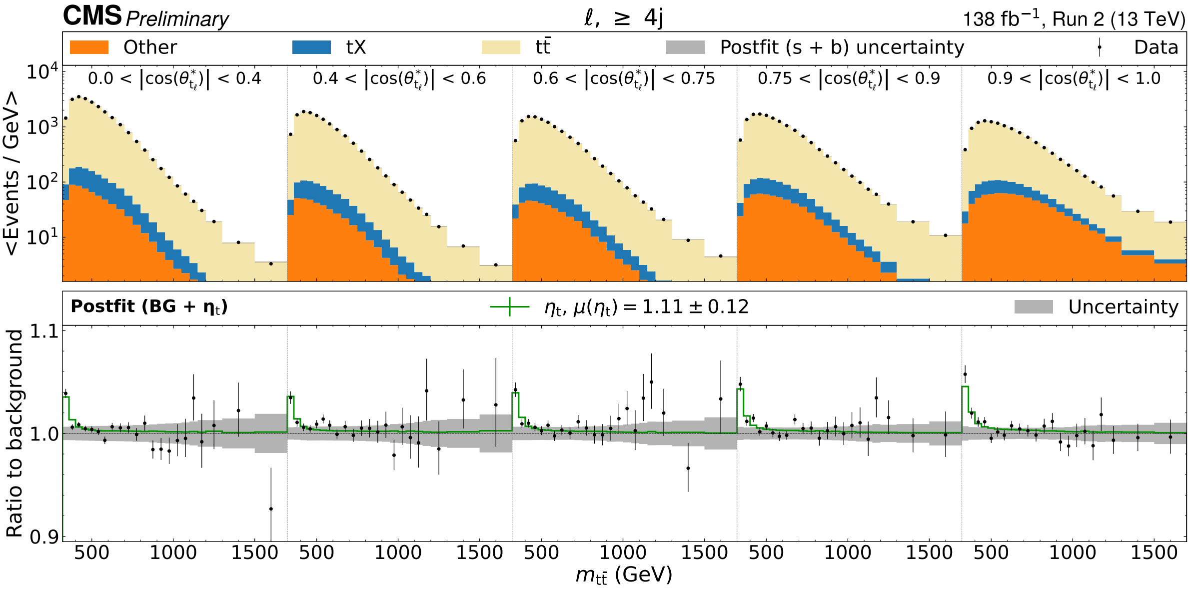
Postfit η_t: $\ell\bar{\ell}$



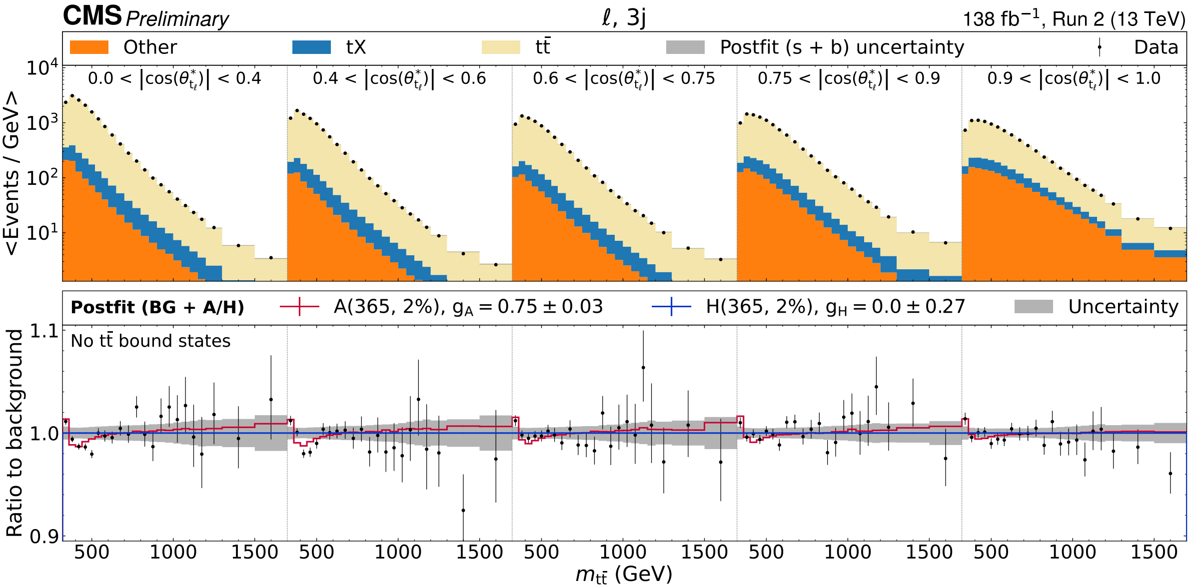
Postfit A/H(365, 2%): ℓ, $\geq$ 4j



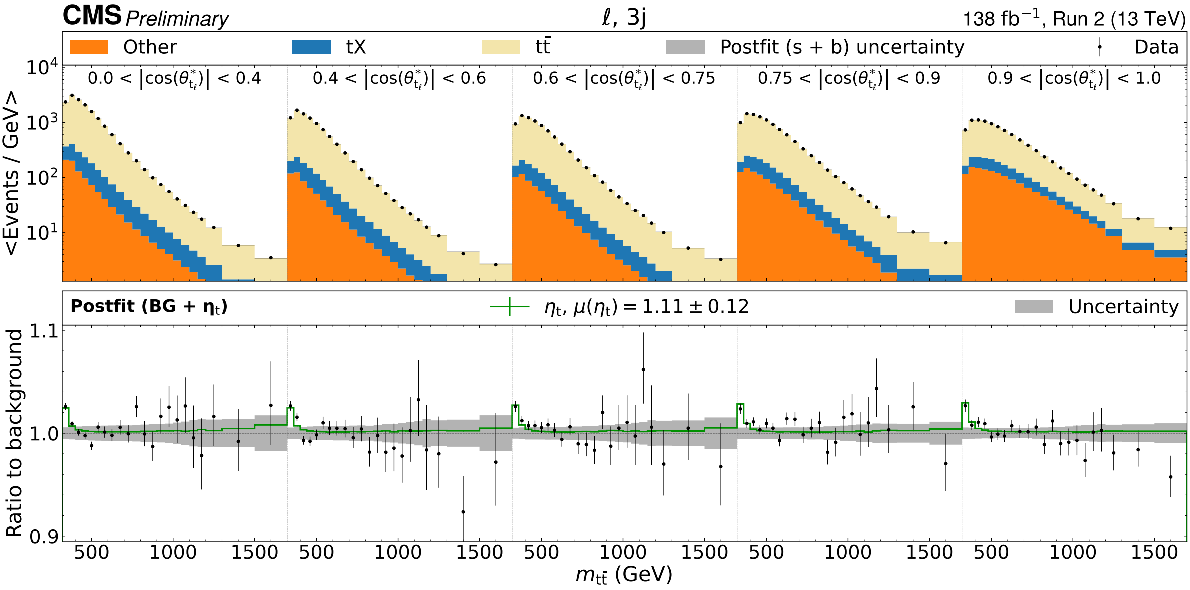
Postfit η_t: ℓ, $\geq$ 4j



Postfit A/H(365, 2%): ℓ, 3j



Postfit η_t: ℓ, 3j



Offshell effects

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

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

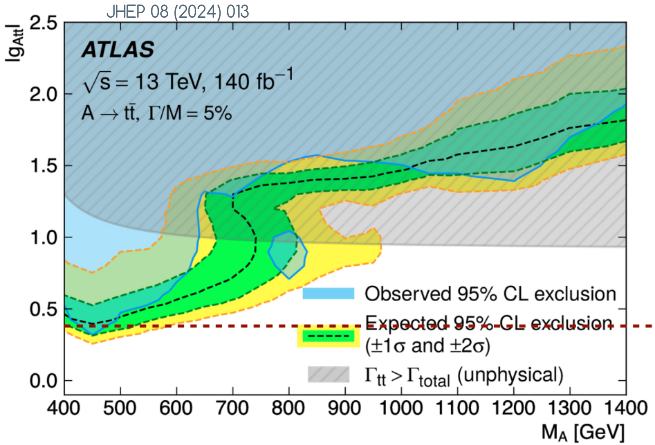
$\rightarrow$ extracted $\sigma(\eta_t)$ is robust against inclusion of offshell effects in background

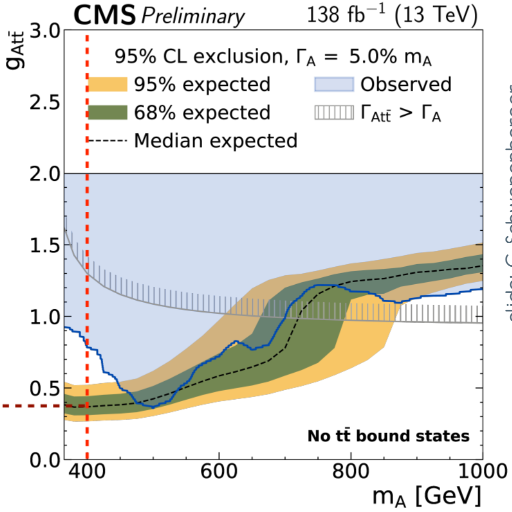
Other generators have also been checked, results are compatible

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.

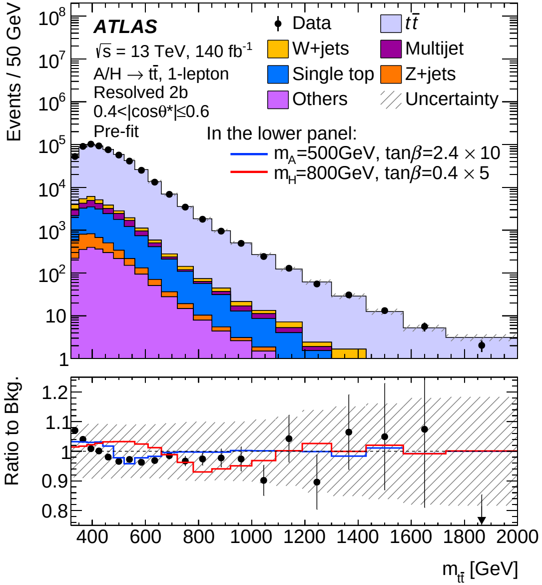


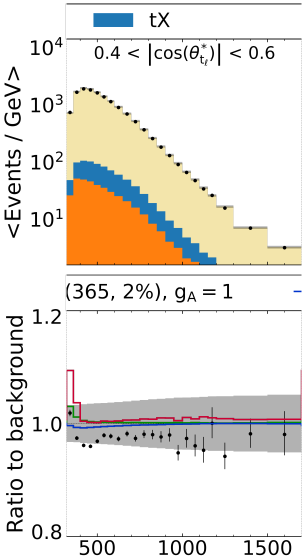


slide: C. Schwanenberger

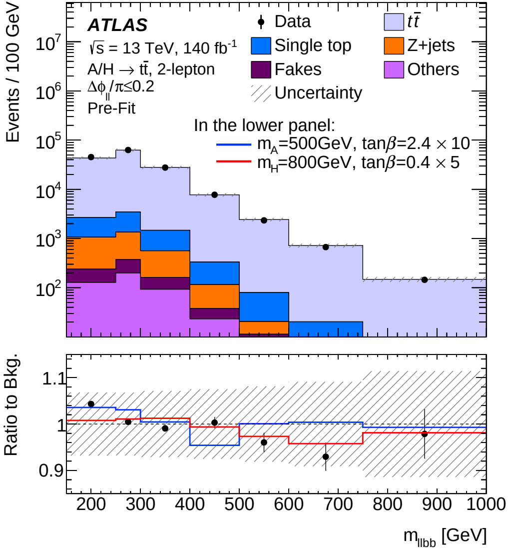
ATLAS – CMS prefit data comparison

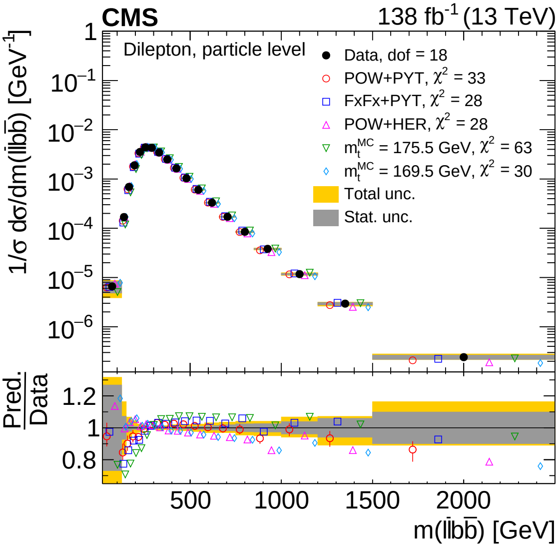
Prefit data vs MC in CMS ℓ, $\geq 4j$ channel's and ATLAS resolved 2b category are similar





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

$t\bar{t}$ matrix element decomposition

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

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

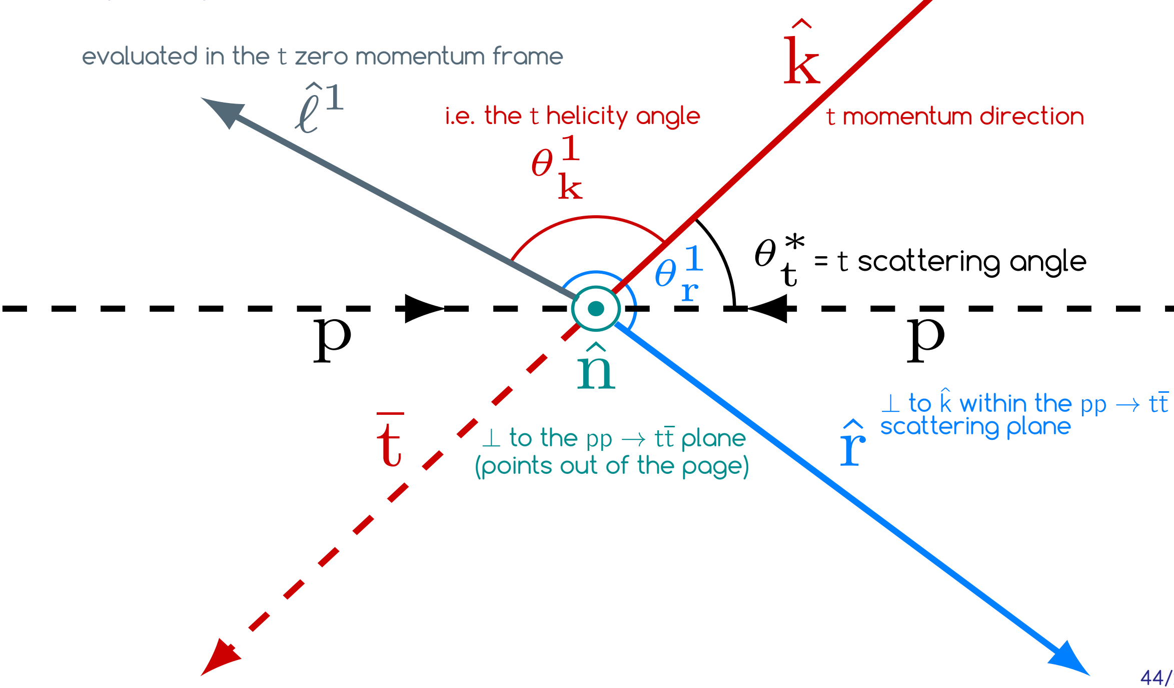
$$A \qquad \vec{B}_a = \begin{pmatrix} x \\ x \\ x \end{pmatrix} \qquad C = \begin{pmatrix} x & x & x \\ x & x & x \\ x & x & x \end{pmatrix}$$

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

$\rightarrow$ top polarization vectors

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

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



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