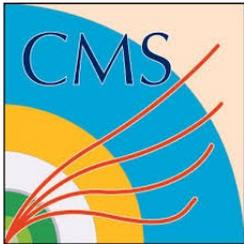


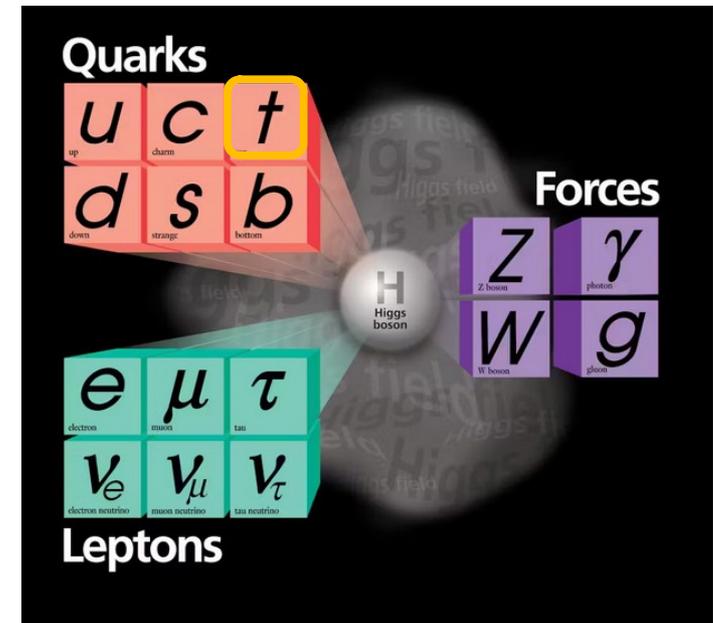
Twists in Top: Searching for (pseudo)scalar $t\bar{t}$ production

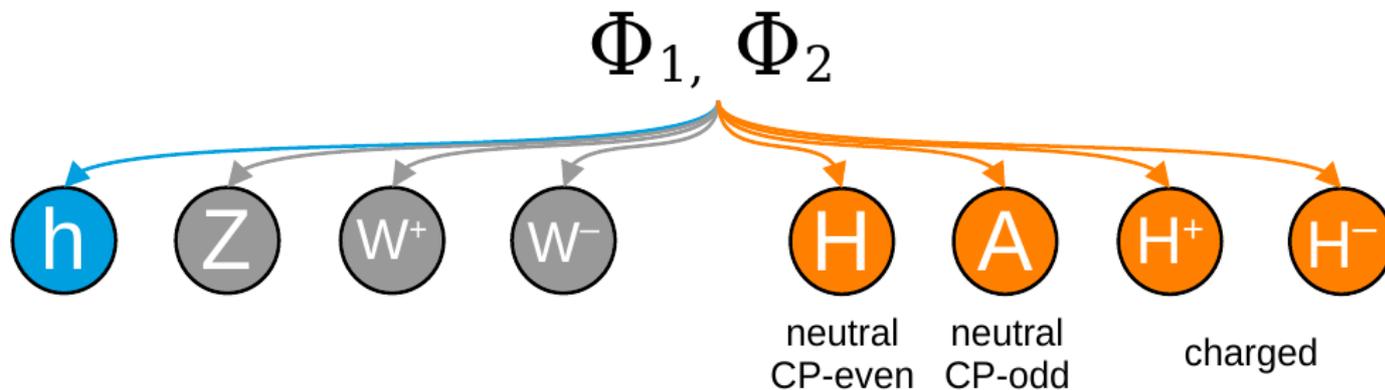
Alexander Grohsjean



28th of February 2025

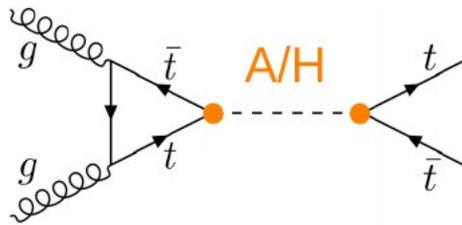
- ◆ top quarks are special
- ◆ short lifetime of $O(10^{-25})$ s
→ top spin propagated to decay products
- ◆ heaviest elementary particle:
 172.52 ± 0.33 GeV (PRL 132 (2024) 261902)
- ◆ top-Higgs coupling close to 1
→ top might be a key in finding (pseudo)-scalars beyond the SM



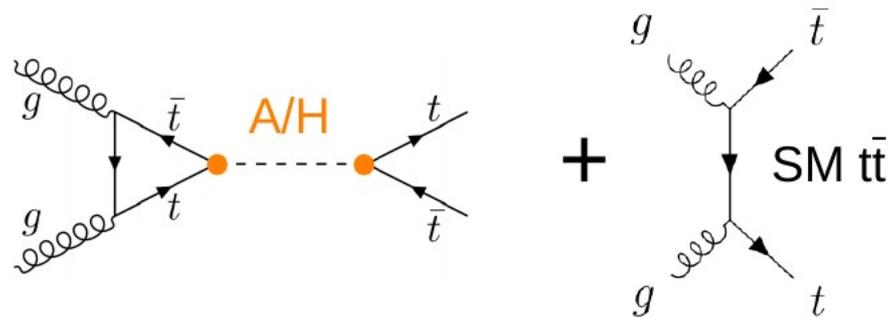


- ◆ extend SM by one complex SU(2) doublet
- ◆ four additional degrees of freedom: $H/A/H^+/H^-$
- ◆ up-type quarks couple to ϕ_1 , down-type quarks and charged fermions to ϕ_2
- ◆ strong couplings to top quarks:
if $m_{A/H} > 2m_t \rightarrow t\bar{t}$ final states promising for a discovery

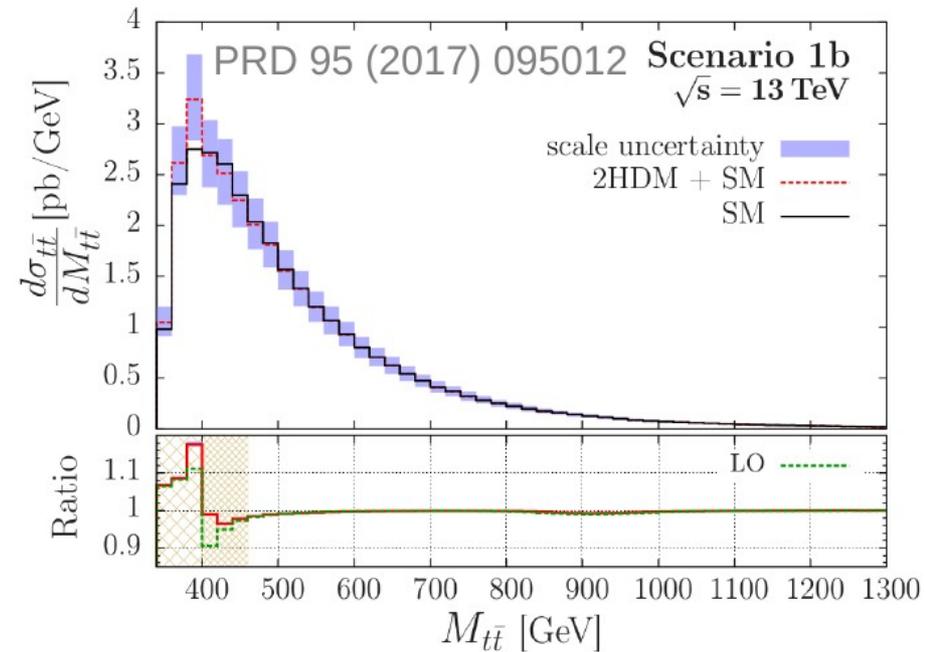
- ◆ A/H production in gluon fusion via top quark loop



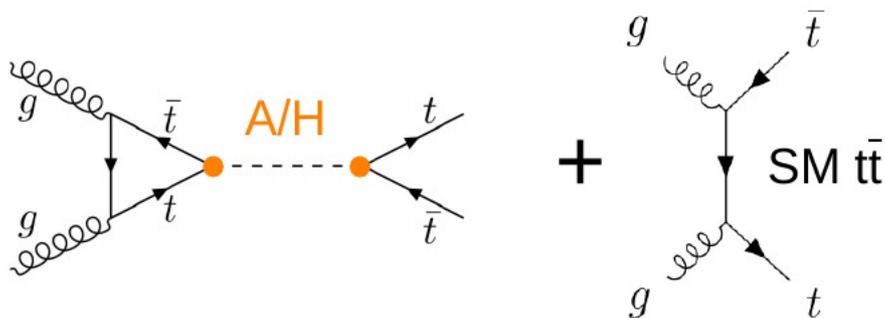
- ◆ A/H production in gluon fusion via top quark loop



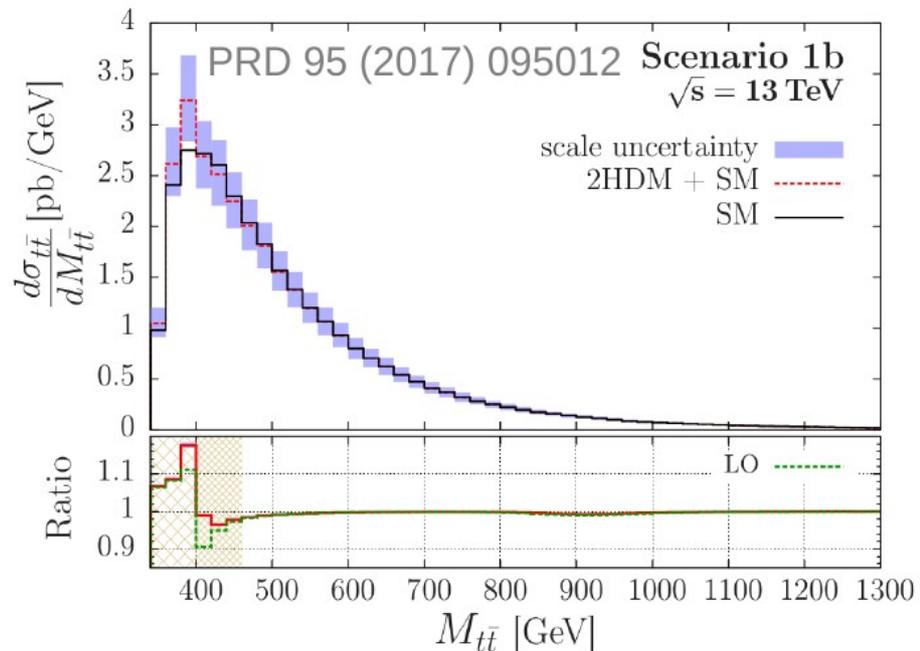
- ◆ same final state as SM $t\bar{t}$ \rightarrow interference
 \rightarrow peak-dip structure in $m_{t\bar{t}}$



- ◆ A/H production in gluon fusion via top quark loop



- ◆ same final state as SM $t\bar{t}$ \rightarrow interference
 \rightarrow peak-dip structure in $m_{t\bar{t}}$



- ◆ MC realization:

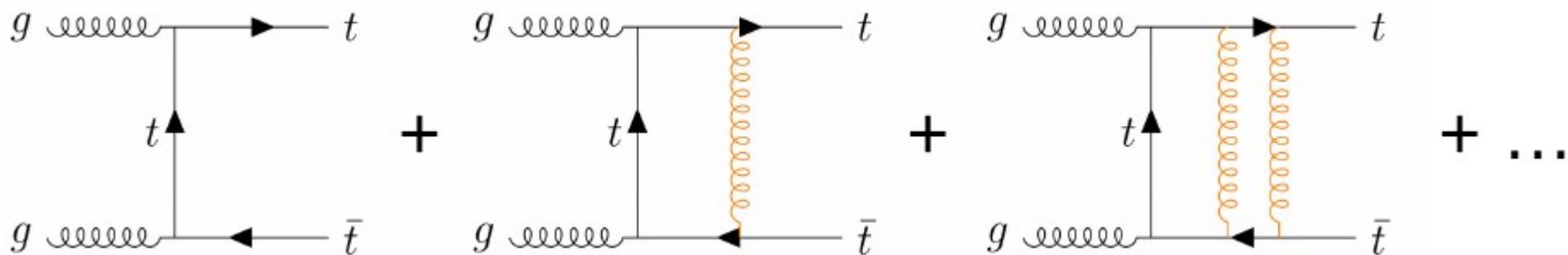
- generic A/H UFO at LO in QCD
- free parameters: masses, widths, coupling modifiers g_A/g_H

$$\mathcal{L}_A^{\text{int}} = ig_{A t\bar{t}} \frac{m_t}{v} \bar{t} \gamma_5 t A$$

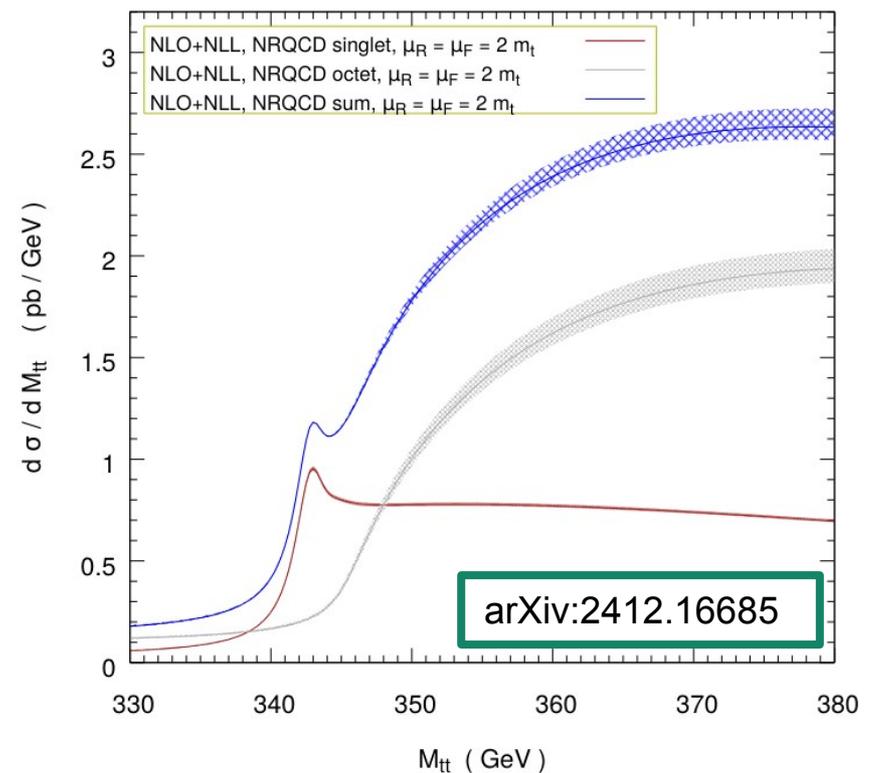
$$\mathcal{L}_H^{\text{int}} = -g_{H t\bar{t}} \frac{m_t}{v} \bar{t} t H$$

- ◆ NNLO QCD K-factors for normalization (SusHi, CPC 184 (2013) 1605)

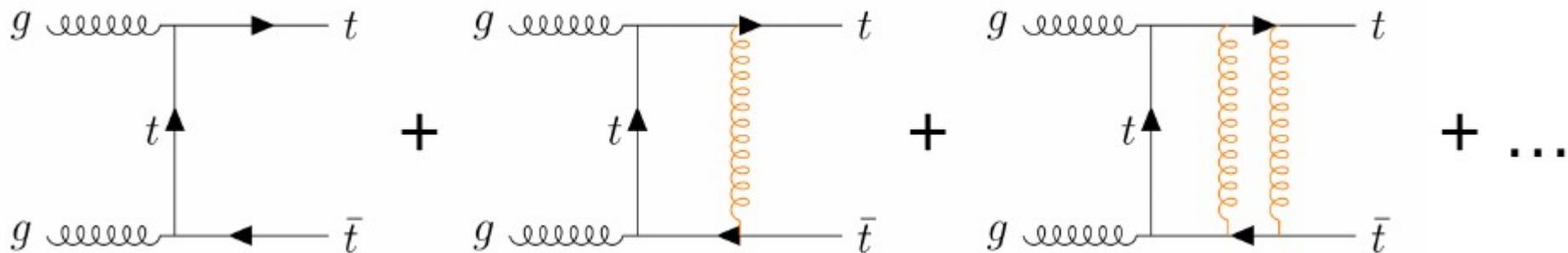
SM Pseudoscalars: $t\bar{t}$ Quasi-Bound States



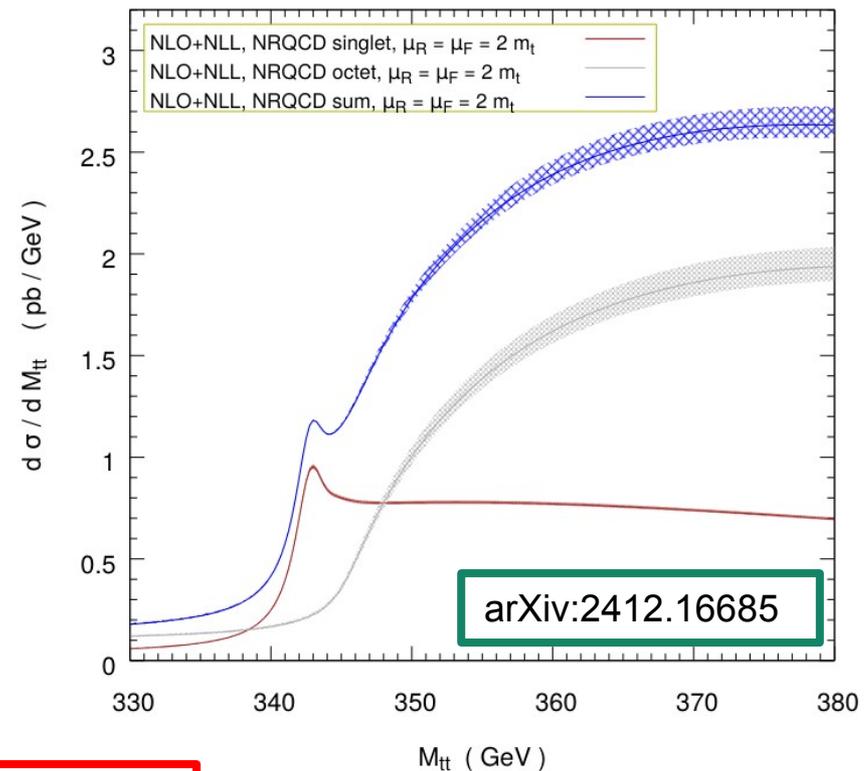
- ◆ use non-relativistic QCD
- ◆ **color singlet** ($^1S_0[0]$) - attractive
→ peak below the $t\bar{t}$ threshold
- ◆ **color octet** ($^1S_0[8]$ or $^3S_1[8]$) - repulsive
→ expected to be small below threshold



SM Pseudoscalars: $t\bar{t}$ Quasi-Bound States



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→ expected to be small below threshold



How to get non-relativistic contributions from Monte Carlo ?

- ◆ simplified η_t model for MC simulation (Fuks et al., PRD 104 (2021) 034023)
 - generic spin-0, color-singlet state η_t
 - couplings to gluons and tops (pseudoscalar)
 - mass from fit to NRQCD: $m_{\eta_t} = 343$ GeV

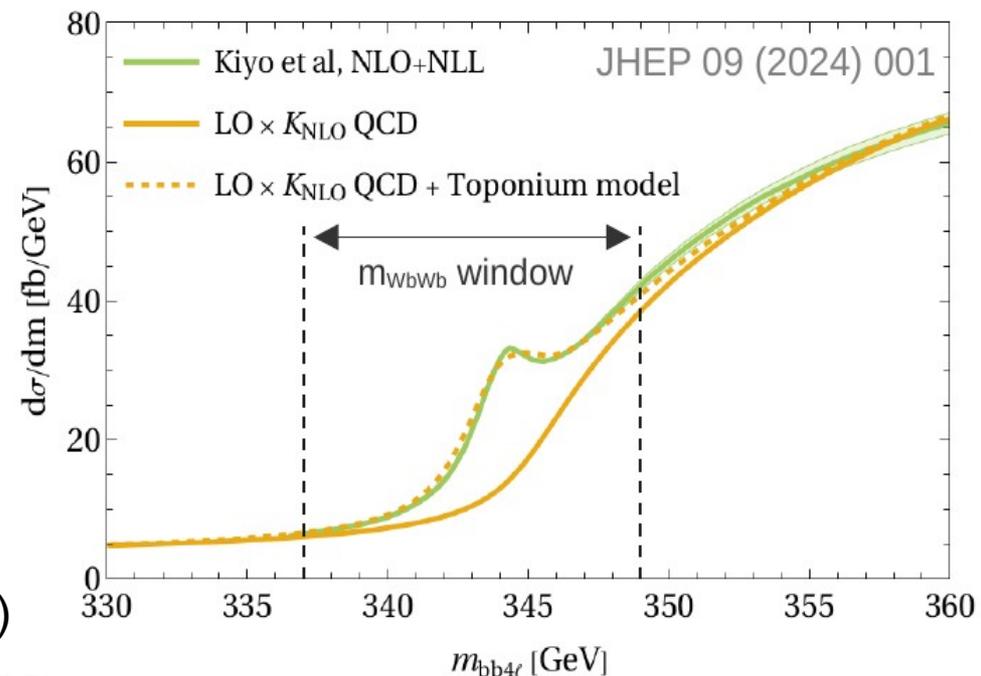
- ◆ pick large η_t width but restrict mass

window to 337 – 349 GeV for

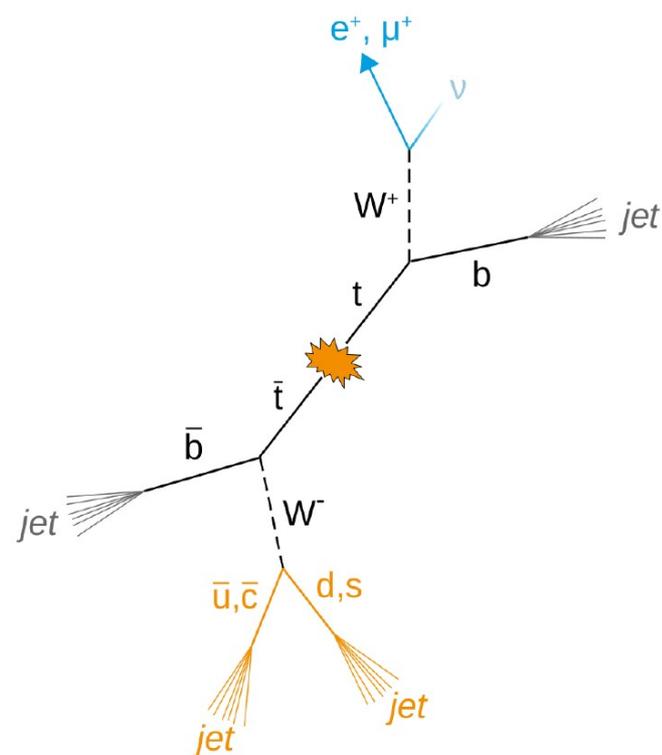
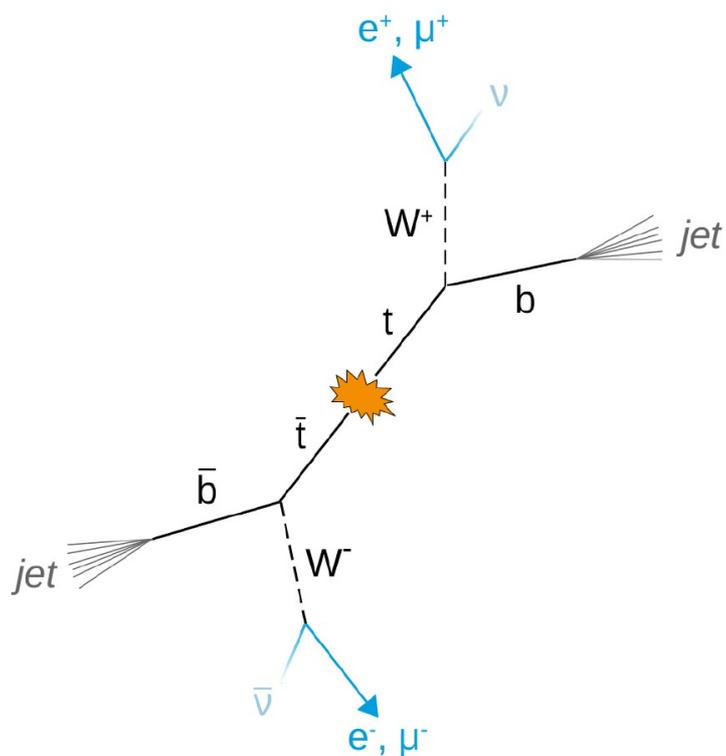
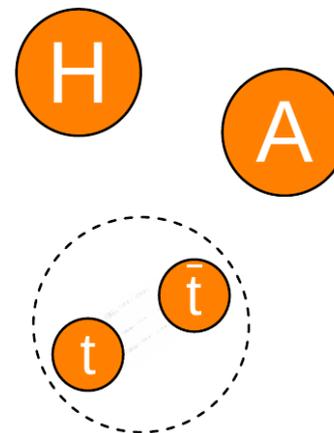
$p p > \eta_t > W b W b$

- ◆ to remember:

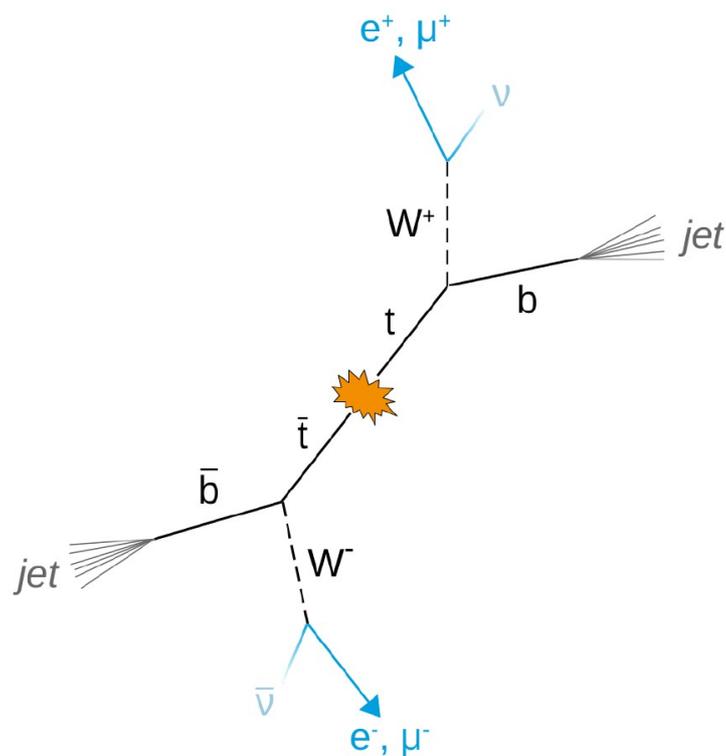
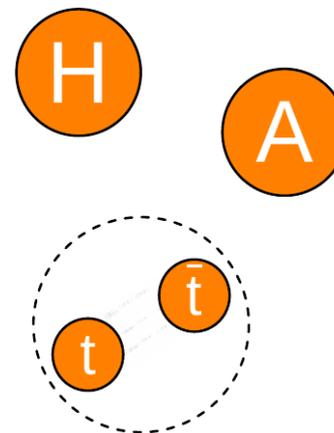
- details of lineshape well below experimental resolution (15% - 25%)
- very similar signature as low-mass A resonance but no interference



- ◆ explore full Run II data set at 13 TeV with 138 fb^{-1} recorded between 2016 and 2018
- ◆ two analysis channels: dilepton (ll) and lepton+jets (ljets)

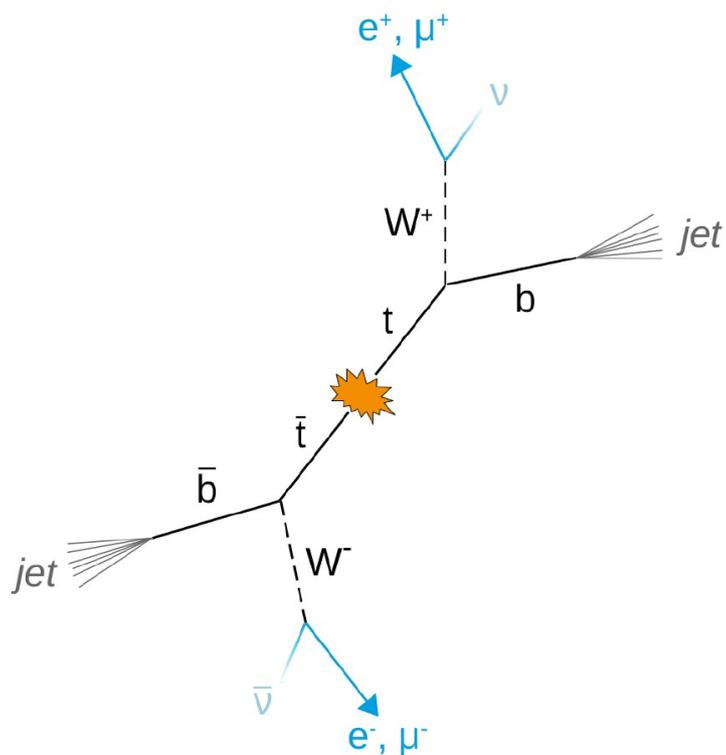
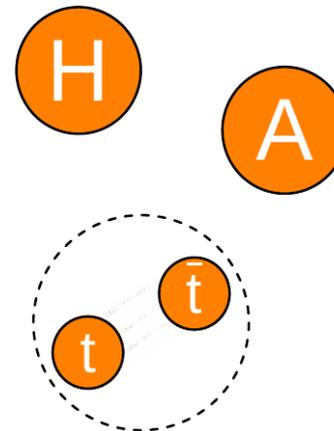


- ◆ explore full Run II data set at 13 TeV with 138 fb^{-1} recorded between 2016 and 2018
- ◆ two analysis channels: dilepton (ll) and lepton+jets ($ljets$)



- ◆ key to $t\bar{t}$ mass analytic reconstruction of $t\bar{t}$ system
 - 6 unknowns (2 ν 's)
 - 6 constraints:
 - ◆ p_T^{miss} from ν 's
 - ◆ top and W masses
 - assign b-jets using m_{lb} -based likelihood
 - finite detector resolution:
 - ◆ repeat 100 times with smeared inputs

- ◆ explore full Run II data set at 13 TeV with 138 fb^{-1} recorded between 2016 and 2018
- ◆ two analysis channels: dilepton ($\ell\ell$) and lepton+jets (ℓjets)



- ◆ key to $t\bar{t}$ mass and spin correlation

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

1

spin-independent

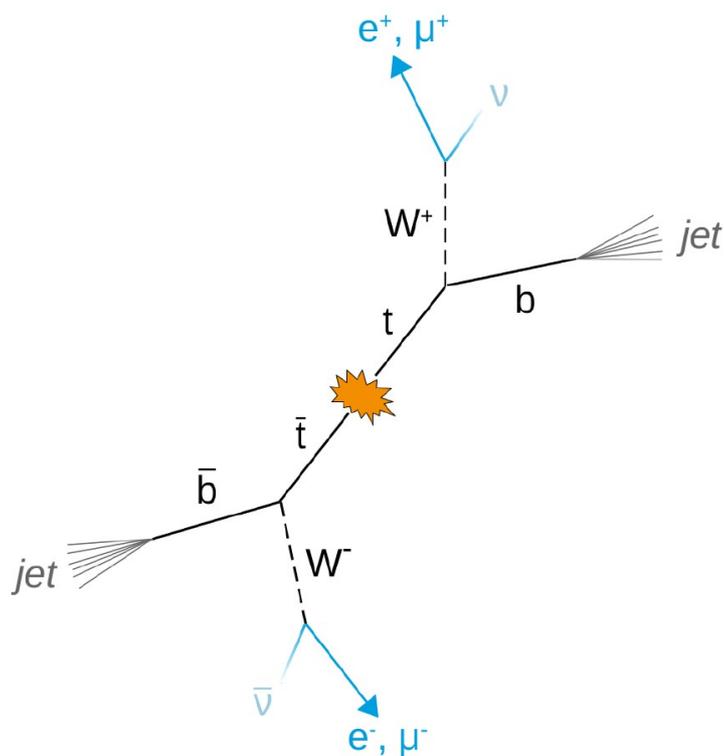
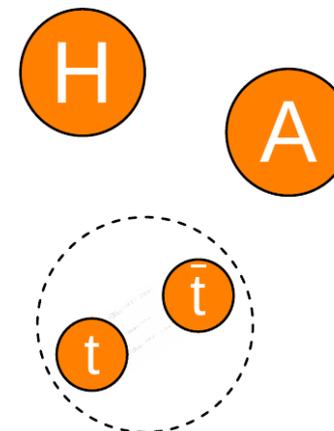
$$\vec{B}_{1/2} = \begin{pmatrix} x \\ x \\ x \end{pmatrix}$$

top polarization

$$C = \begin{pmatrix} x & x & x \\ x & x & x \\ x & x & x \end{pmatrix}$$

spin correlation

- ◆ explore full Run II data set at 13 TeV with 138 fb⁻¹ recorded between 2016 and 2018
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1

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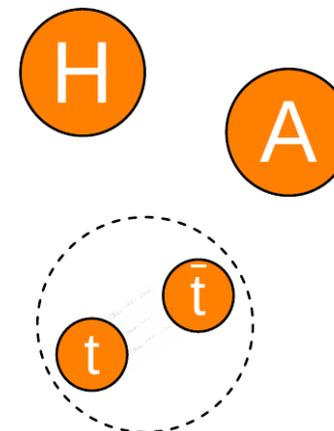
top polarization

$$C = \begin{pmatrix} x & x & x \\ x & x & x \\ x & x & x \end{pmatrix}$$

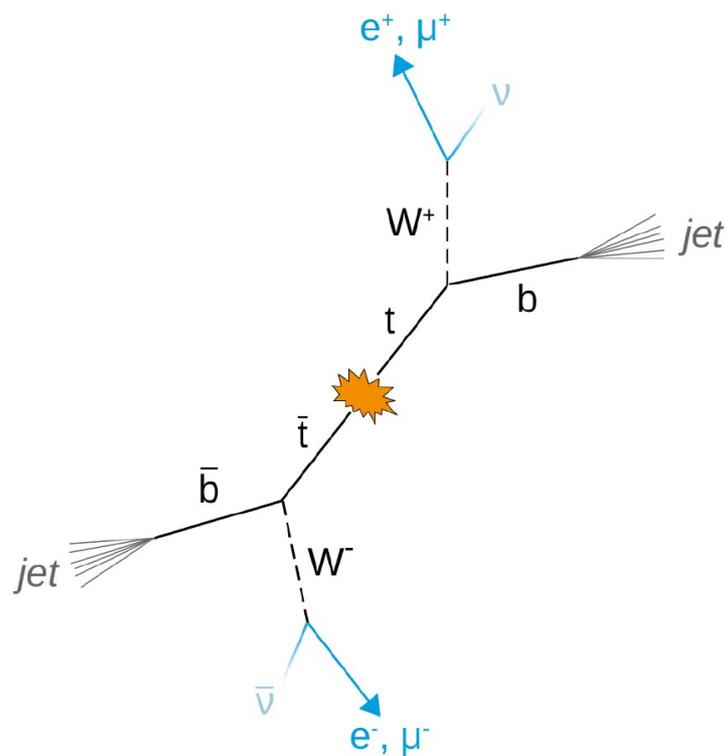
spin correlation

- ◆ A/H and $\eta_t \rightarrow t\bar{t}$ in a pure 1S_0 or 3P_0 spin state

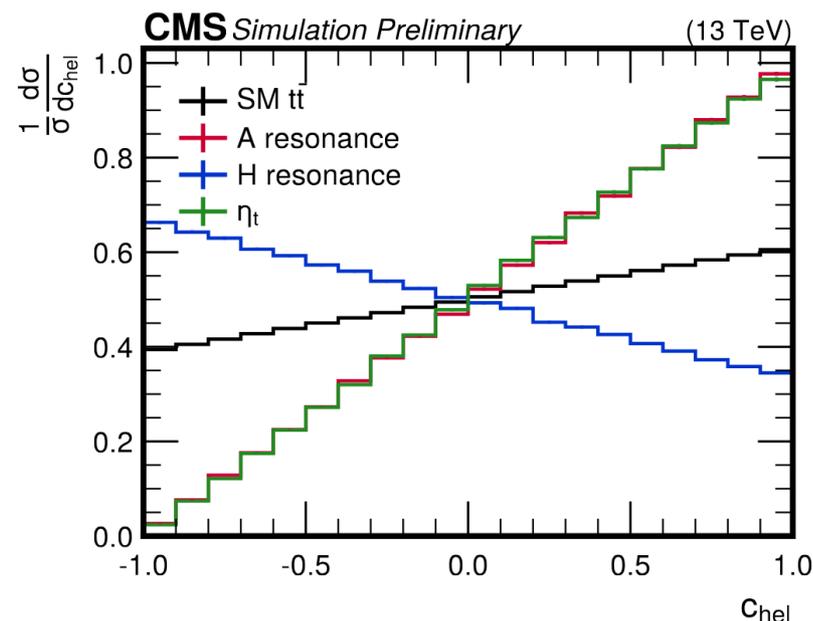
$$\begin{pmatrix} -1 & & \\ & -1 & \\ & & -1 \end{pmatrix} \quad \begin{pmatrix} -1 & & \\ & 1 & \\ & & 1 \end{pmatrix}$$



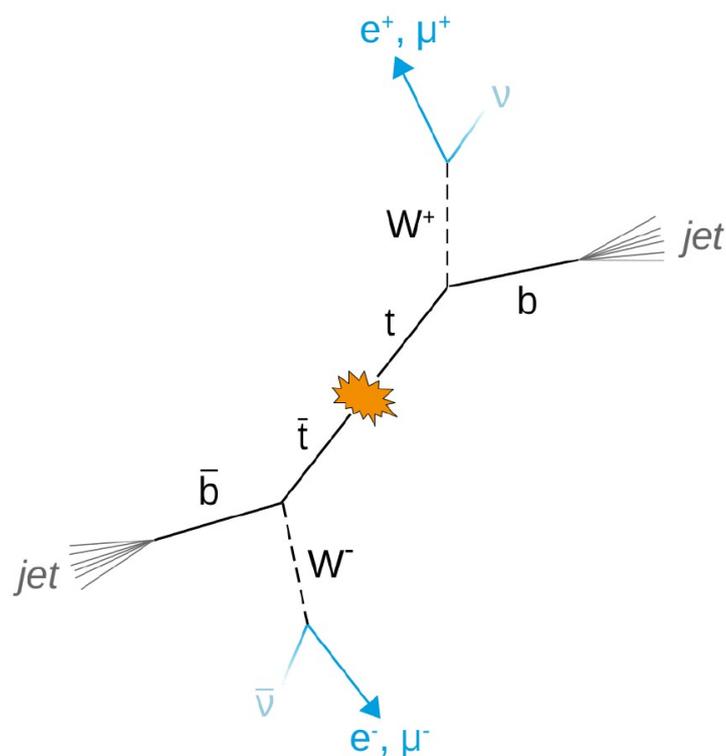
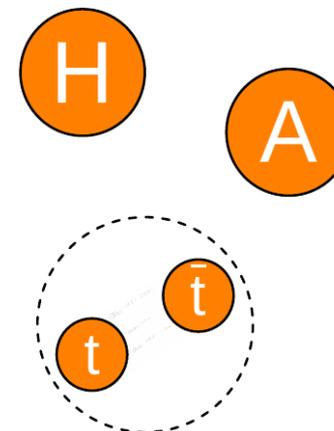
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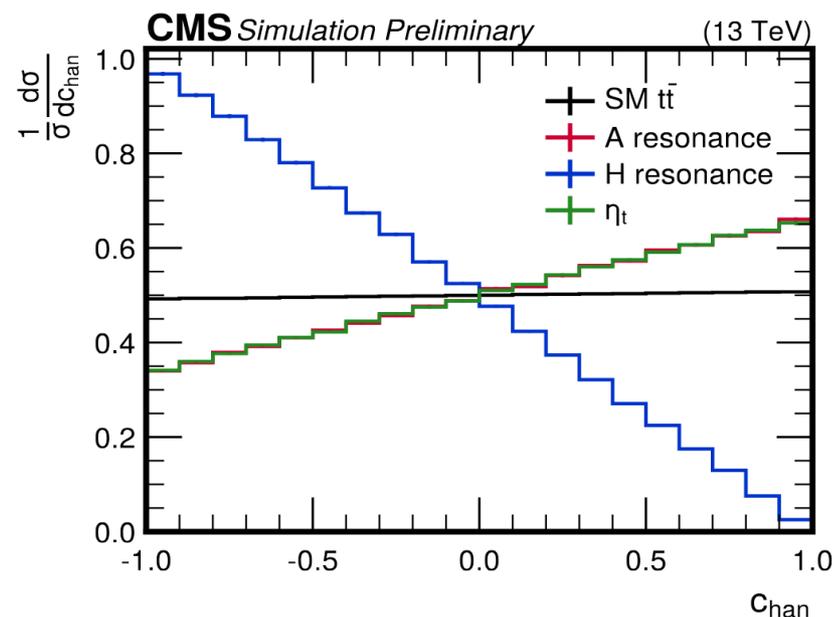
- ◆ key to $t\bar{t}$ mass and spin correlation
- ◆ C_{hel} : scalar product of leptons in parent top rest frame



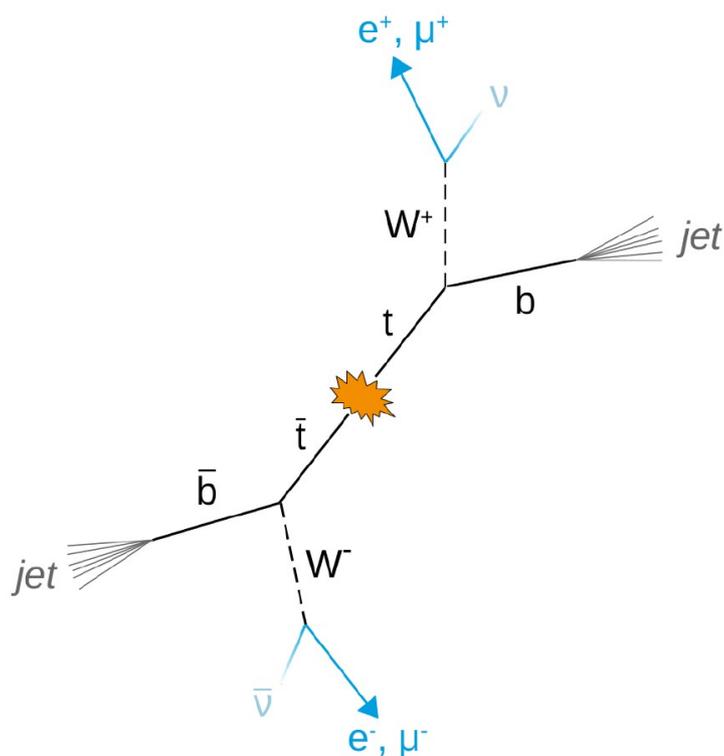
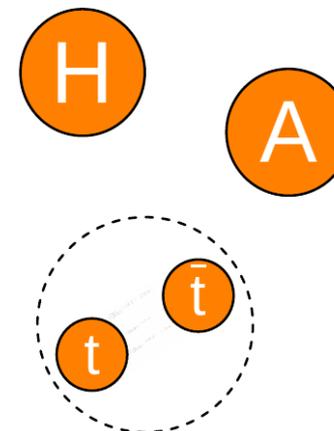
- ◆ explore full Run II data set at 13 TeV with 138 fb^{-1} recorded between 2016 and 2018
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- ◆ key to $t\bar{t}$ mass and spin correlation
- ◆ C_{hel} : scalar product of leptons in parent top rest frame
- ◆ C_{chan} : scalar product of leptons with sign flip in top direction

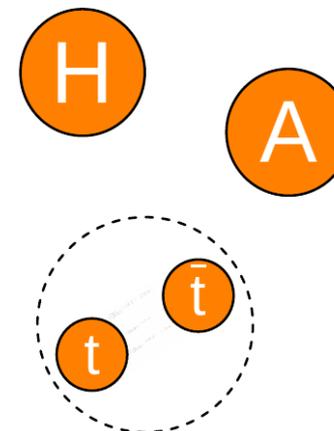


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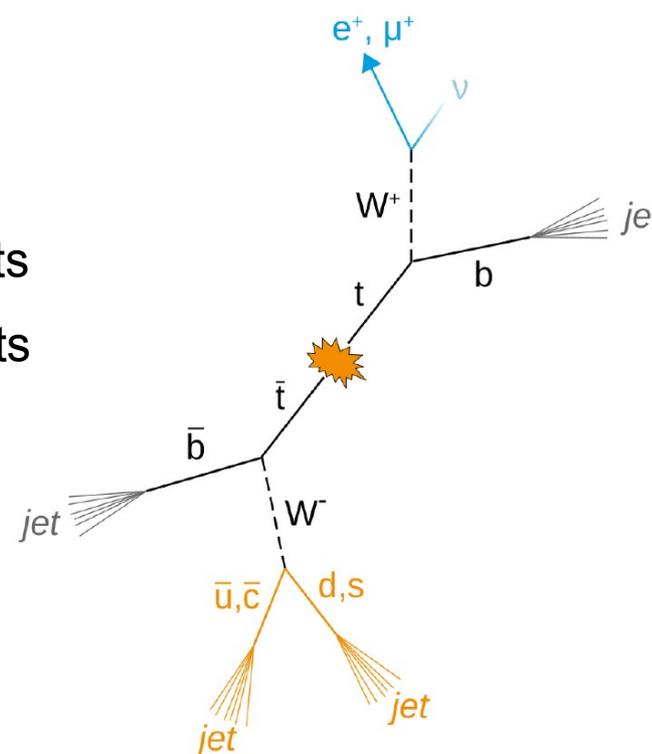


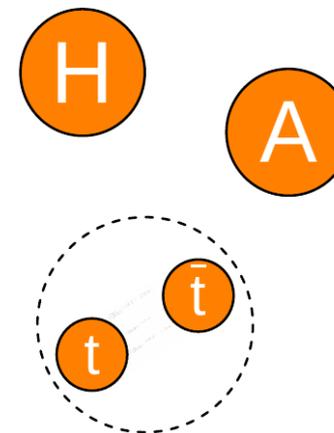
- ◆ key to $t\bar{t}$ mass and spin correlation
- ◆ C_{hel} : scalar product of leptons in parent top rest frame
- ◆ C_{han} : scalar product of leptons with sign flip in top direction

3 search variables in ll: $m_{t\bar{t}} \times C_{\text{hel}} \times C_{\text{han}}$



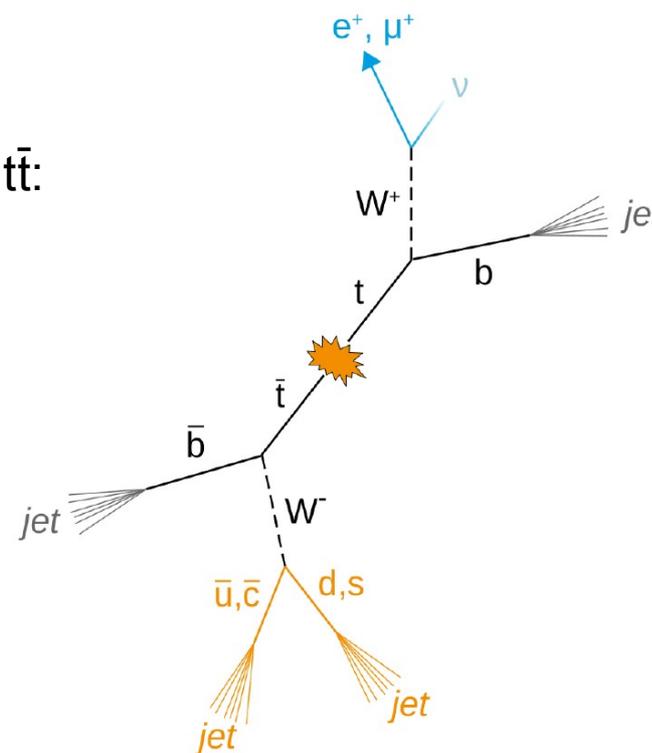
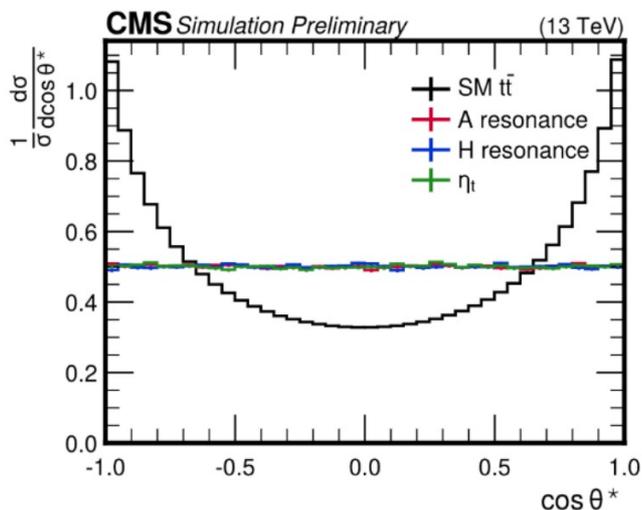
- ◆ explore full Run II data set at 13 TeV with 138 fb^{-1} recorded between 2016 and 2018
- ◆ two analysis channels: dilepton (ll) and lepton+jets (ljets)
- ◆ reconstruct $t\bar{t}$ system with geometric approach (NIM A 736 (2014) 169)
- ◆ maximize sensitivity by using events with just 3 jets
 - energy correction factor for lost or merged jets (NIM A 788 (2015) 128)





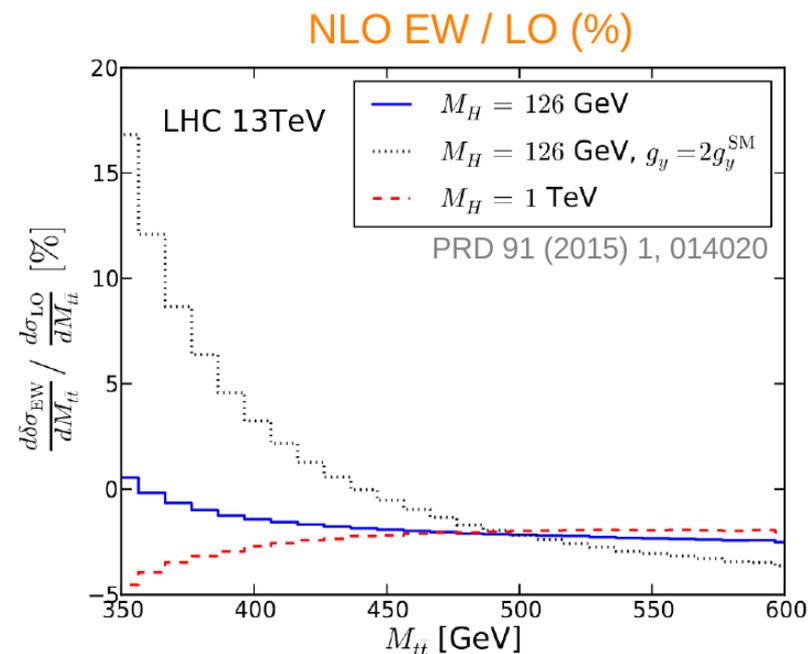
- ◆ explore full Run II data set at 13 TeV with 138 fb⁻¹ recorded between 2016 and 2018
- ◆ two analysis channels: dilepton (ll) and lepton+jets (ljets)

- ◆ reconstruct $t\bar{t}$ system with geometric approach
- ◆ use emission angle of leptonic top with respect to $t\bar{t}$:
 - flat for A/H/ η_t

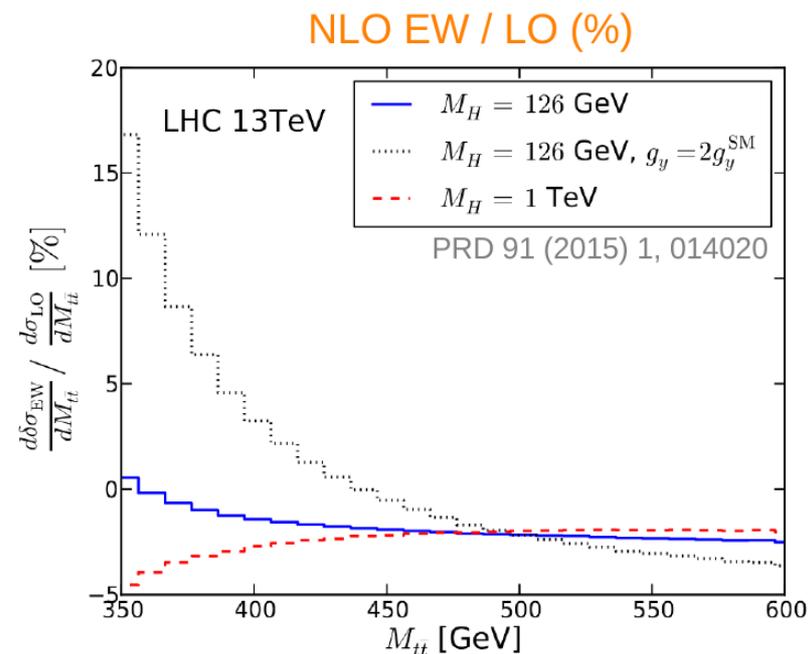


2 search variables in ljets: $m_{t\bar{t}} \times \cos \theta^*$

- ◆ major irreducible background: SM $t\bar{t}$
 - NLO MC (Powheg+Pythia 8)
 - correct to NNLO QCD and NLO EW fixed-order predictions
 - ◆ reweighting in bins of $m_{t\bar{t}}$ vs. $\cos\theta^*$
 - ◆ EPJC 78 (2018) 537, EPJC 51 (2007) 37
 - normalize to NNLO+NNLL cross section
 - ◆ CPC 185 (2014) 2930



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 - normalize to NNLO+NNLL cross section
 - ◆ CPC 185 (2014) 2930



- ◆ other backgrounds: tW , t-channel single-top, rare processes (from MC)
- ◆ Z+jets in ll : MiNNLO predictions with data-driven normalization around Z peak
- ◆ QCD processes in l jets: data-driven shape from sideband with no b-tags

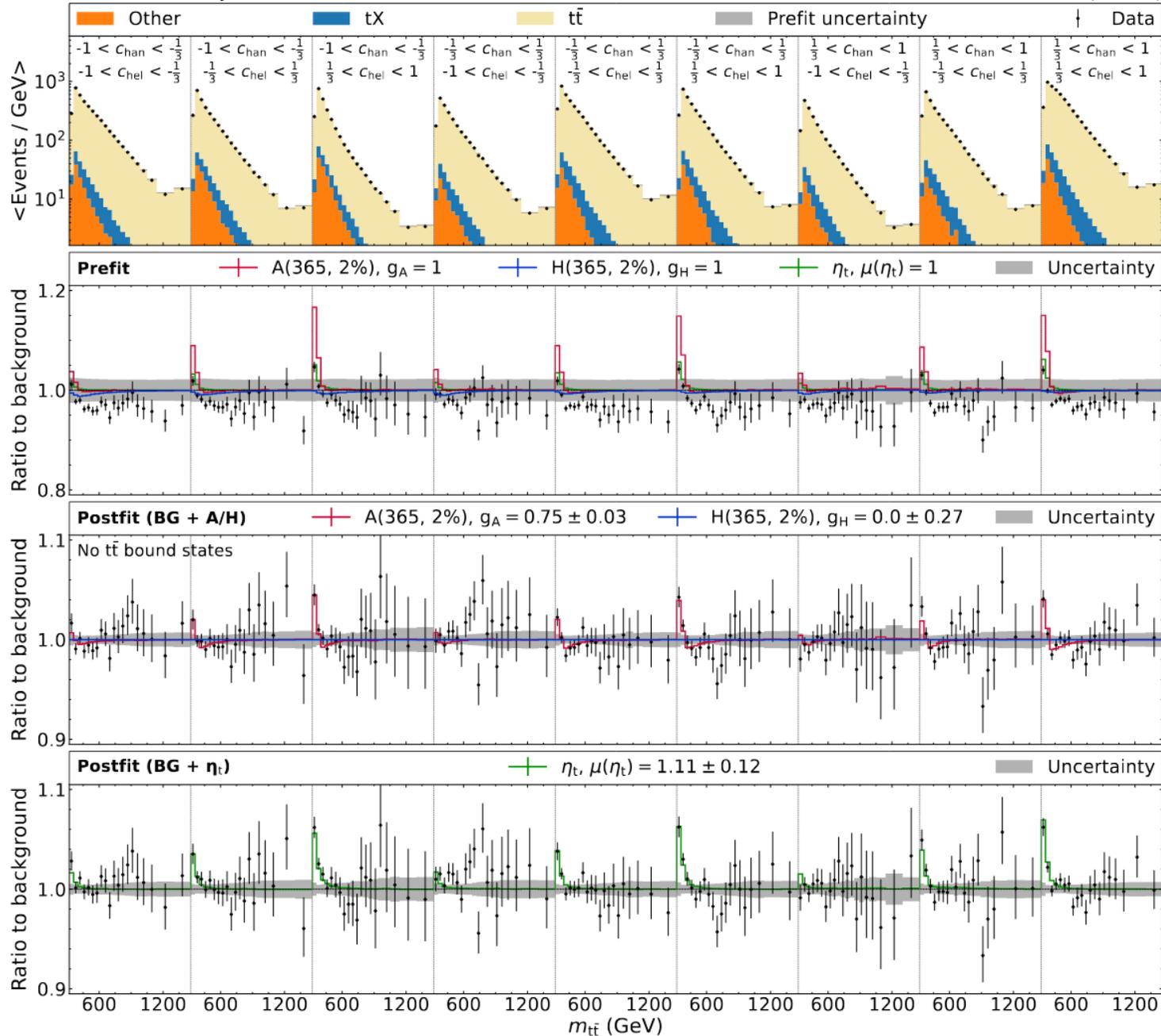
Results II Channel



CMS Preliminary

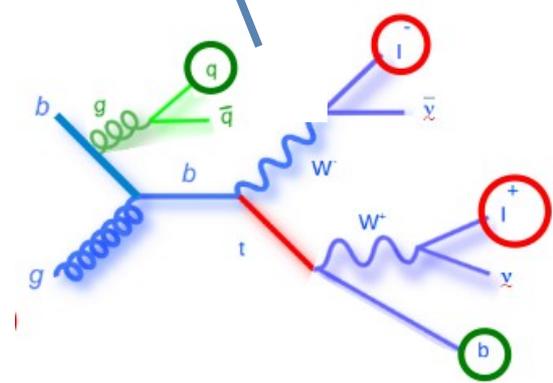
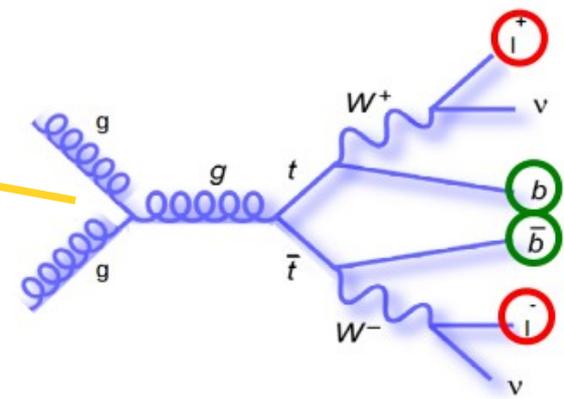
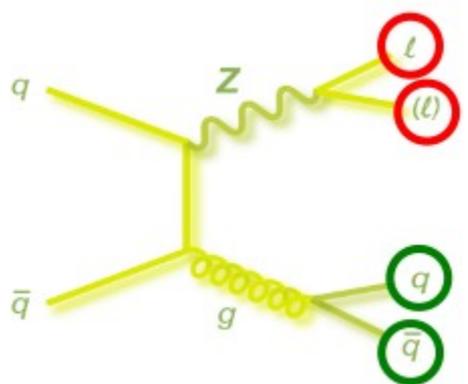
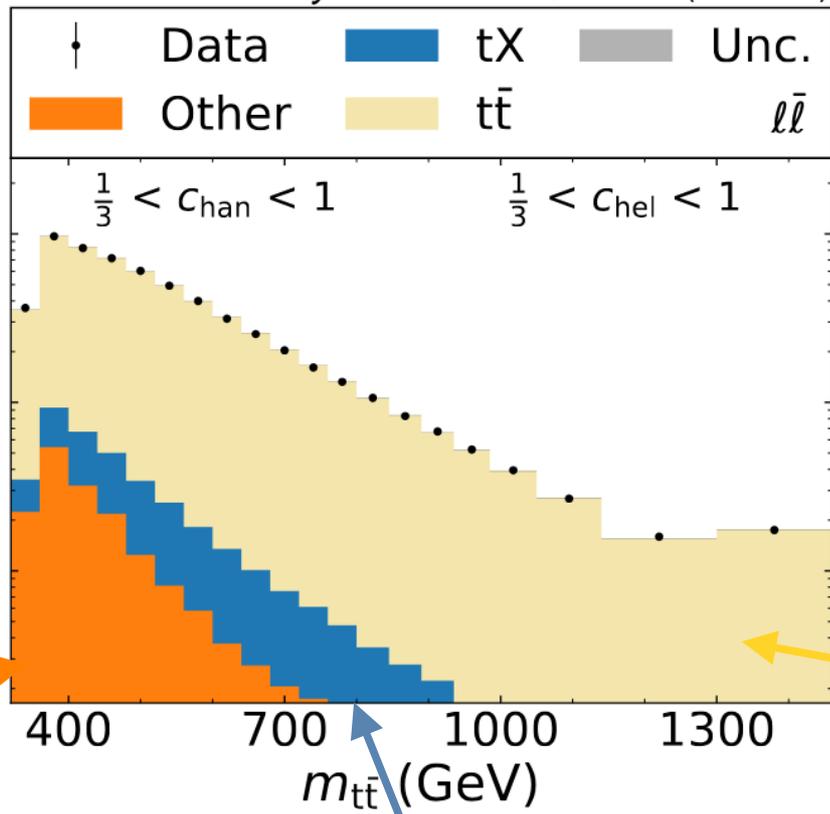
$\ell\bar{\ell}$

138 fb⁻¹, Run 2 (13 TeV)

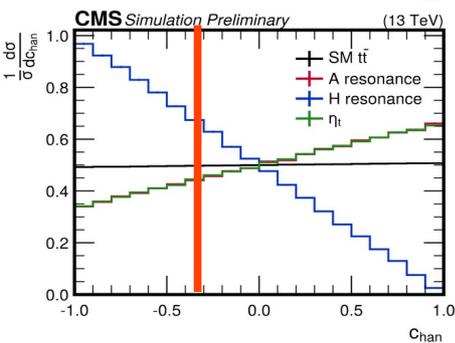
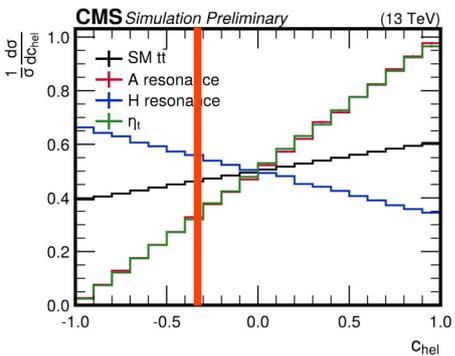
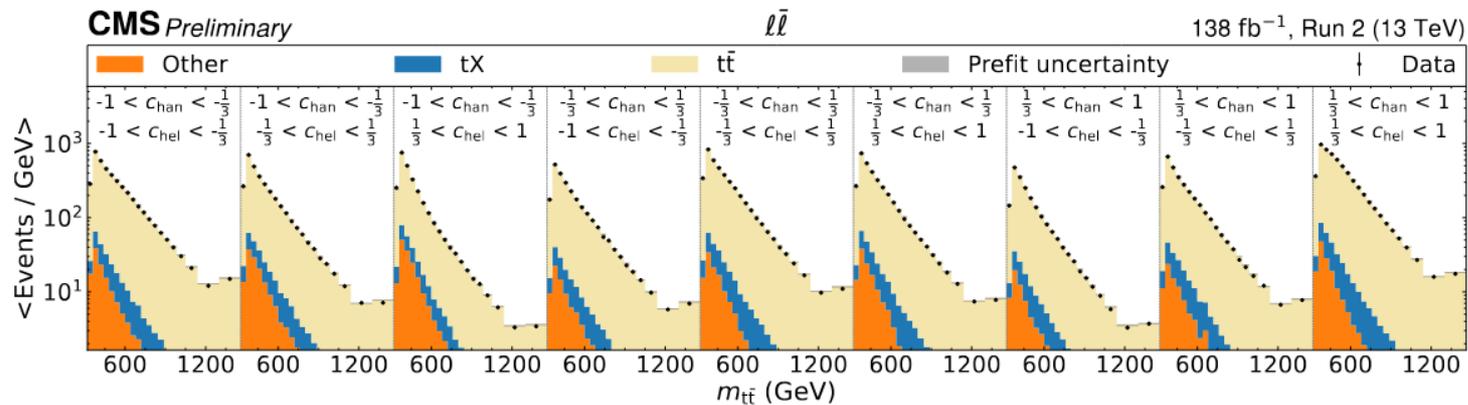


Results II Channel

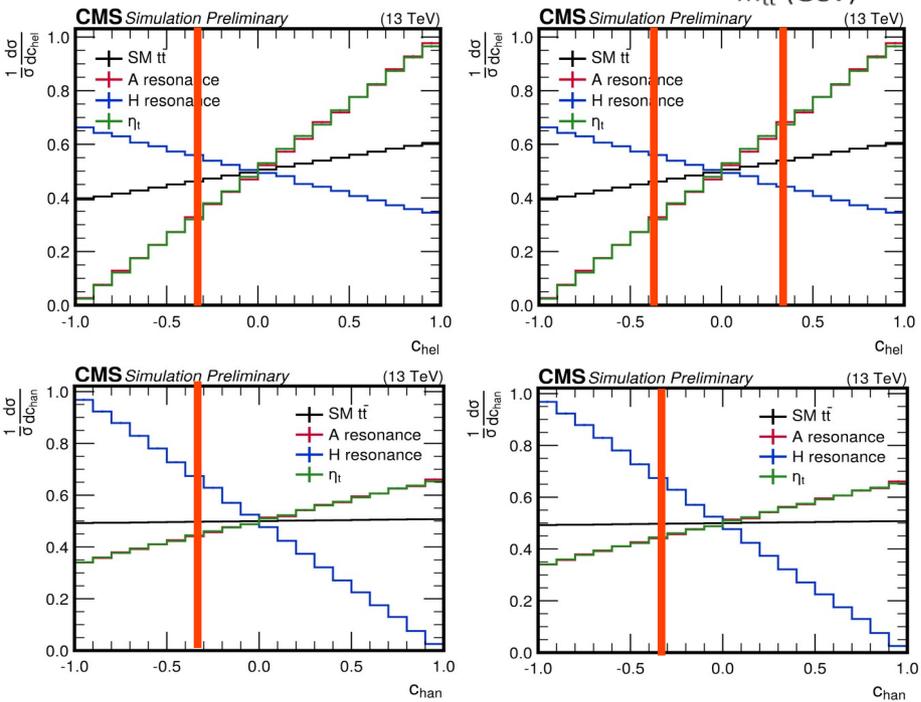
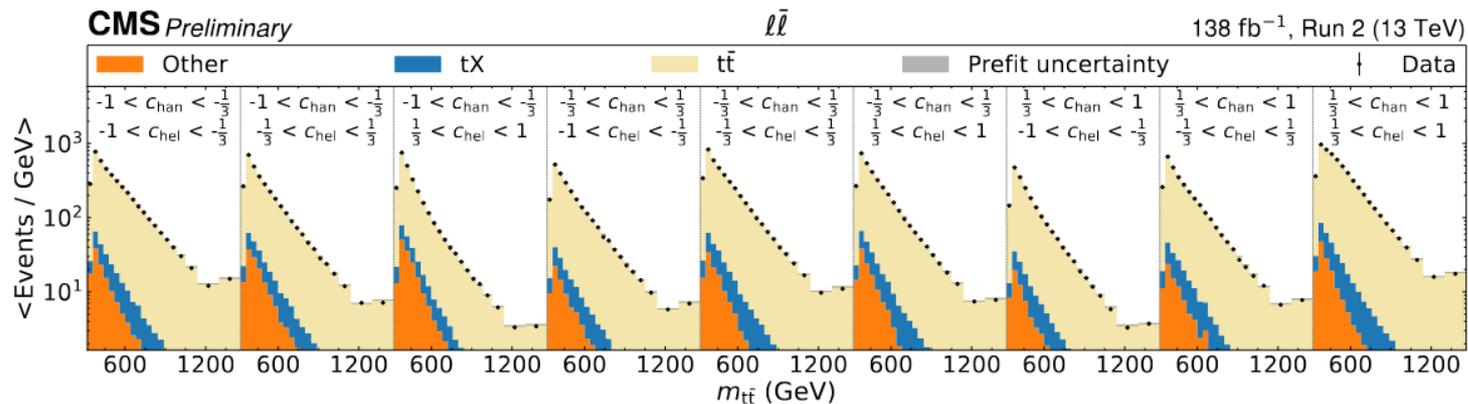
CMS Preliminary 138 fb⁻¹, Run 2 (13 TeV)



Results II Channel

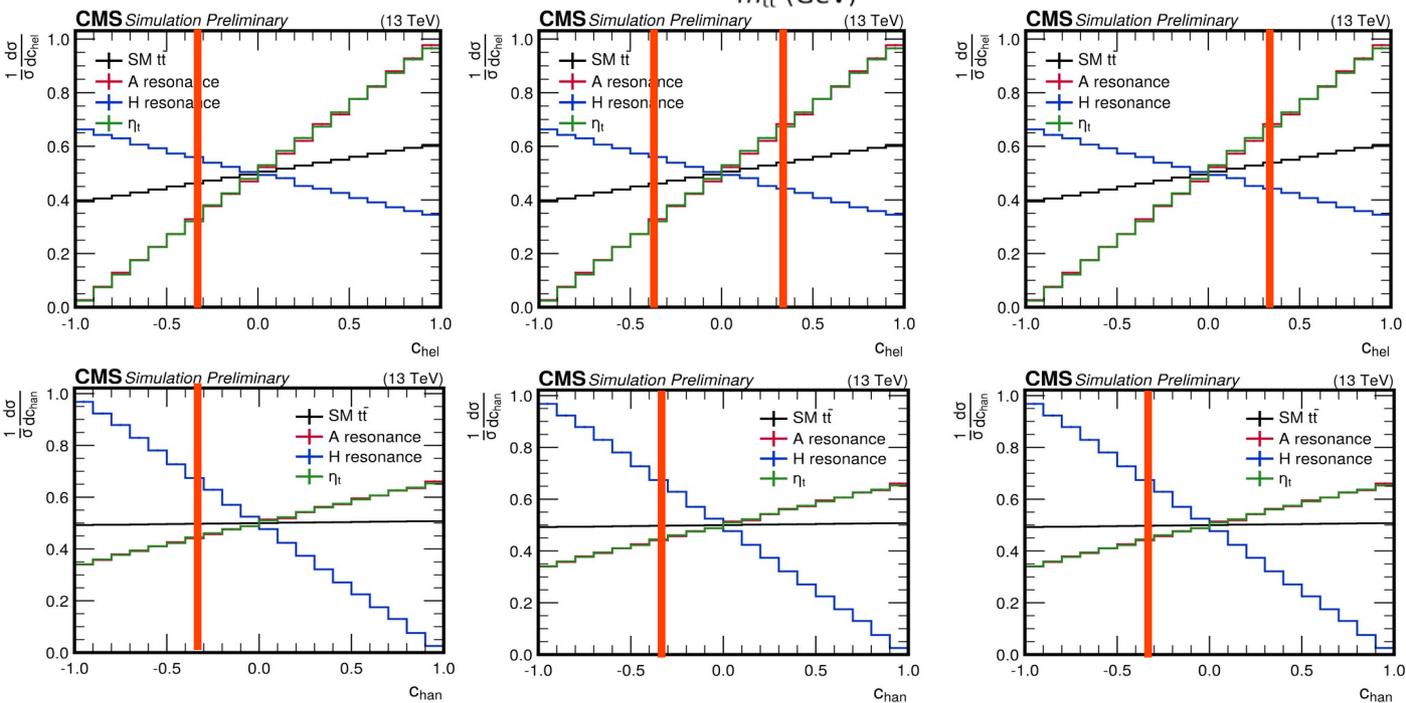
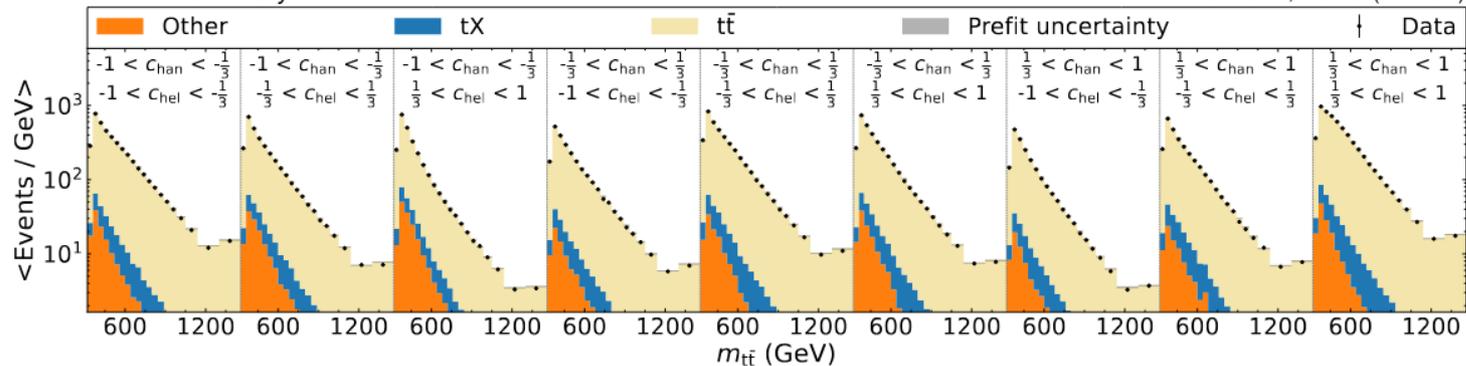


Results II Channel



Results II Channel

CMS Preliminary $\ell\bar{\ell}$ 138 fb⁻¹, Run 2 (13 TeV)

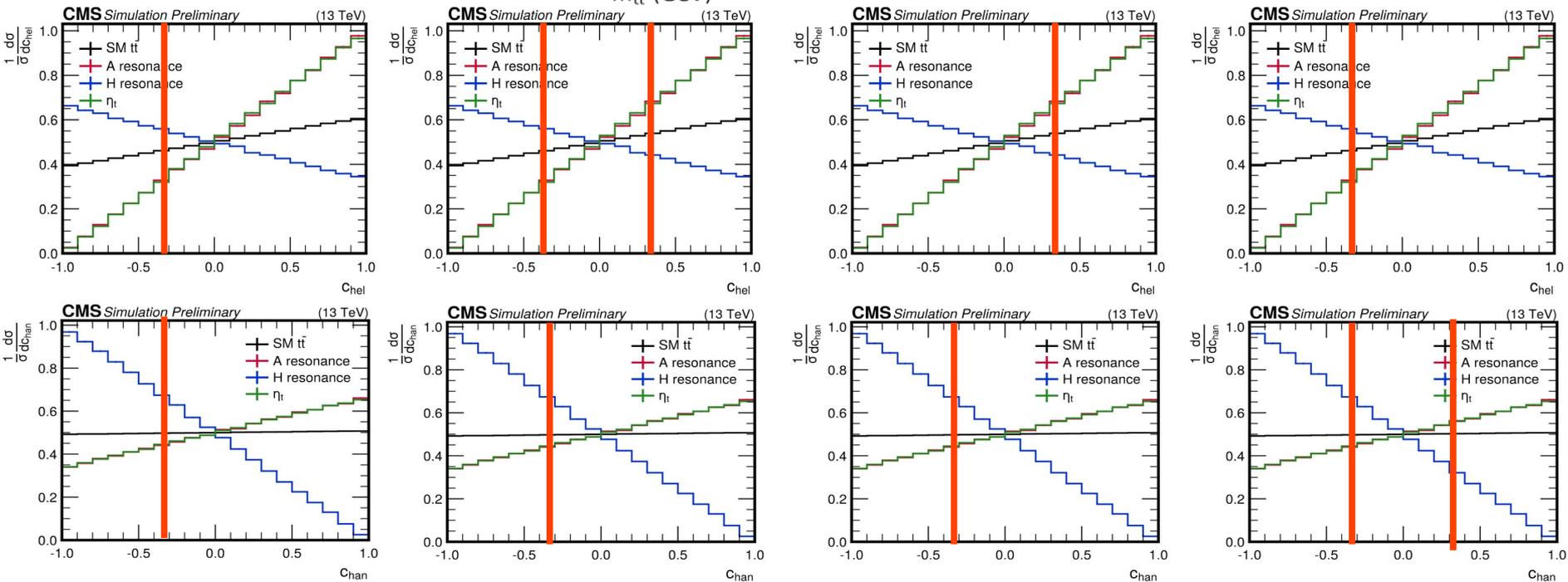
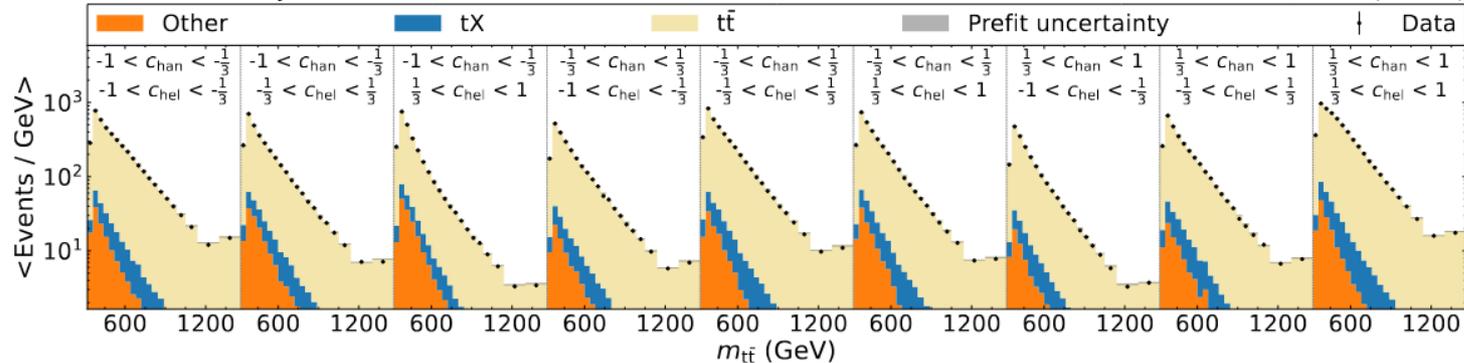


Results II Channel

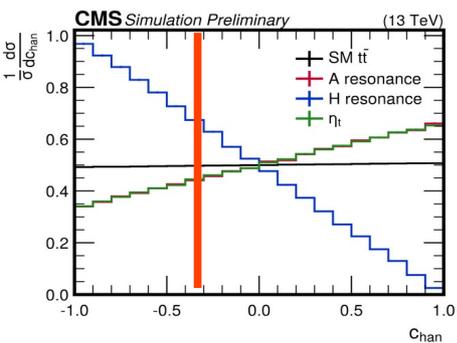
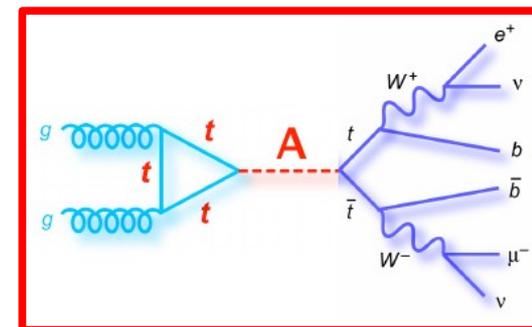
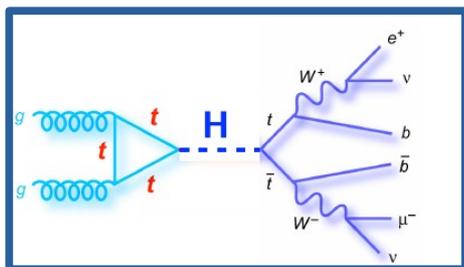
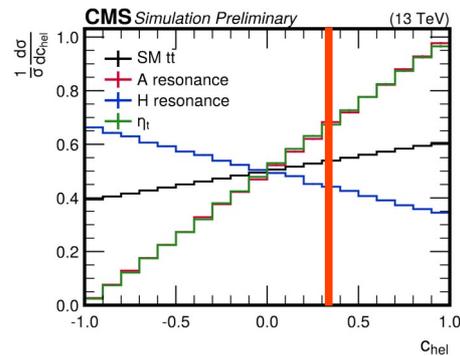
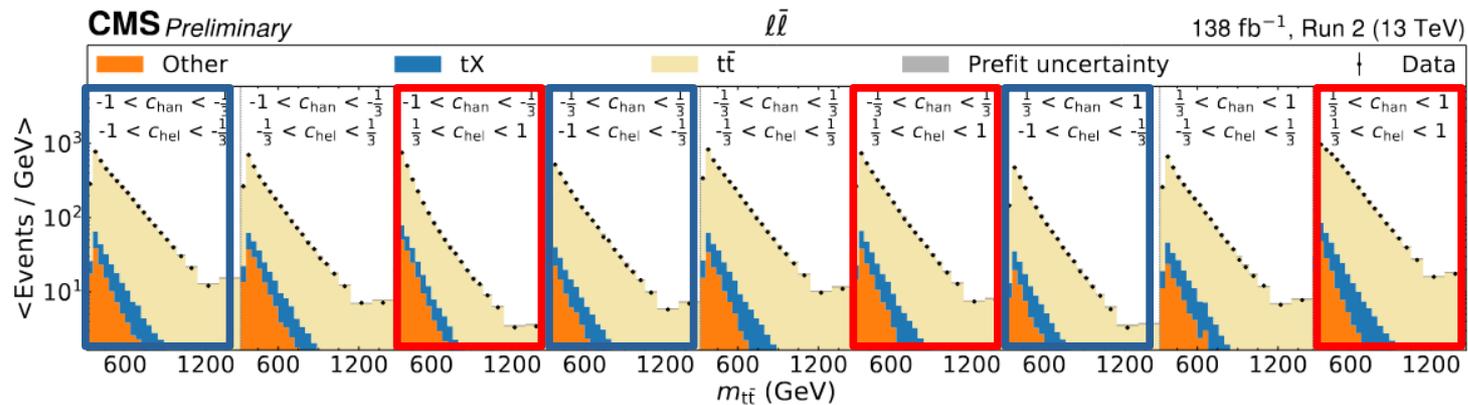
CMS Preliminary

$\ell\bar{\ell}$

138 fb⁻¹, Run 2 (13 TeV)



Results II Channel

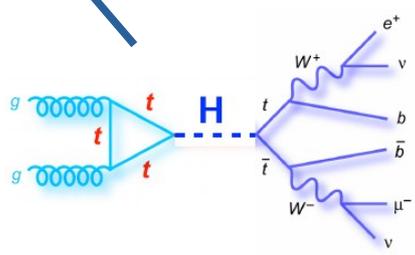
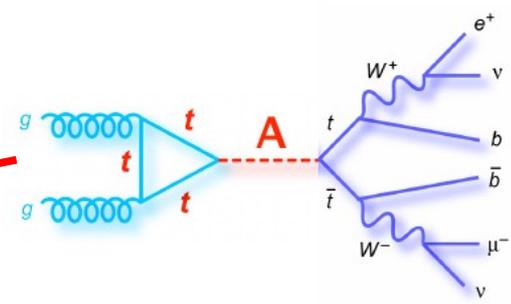
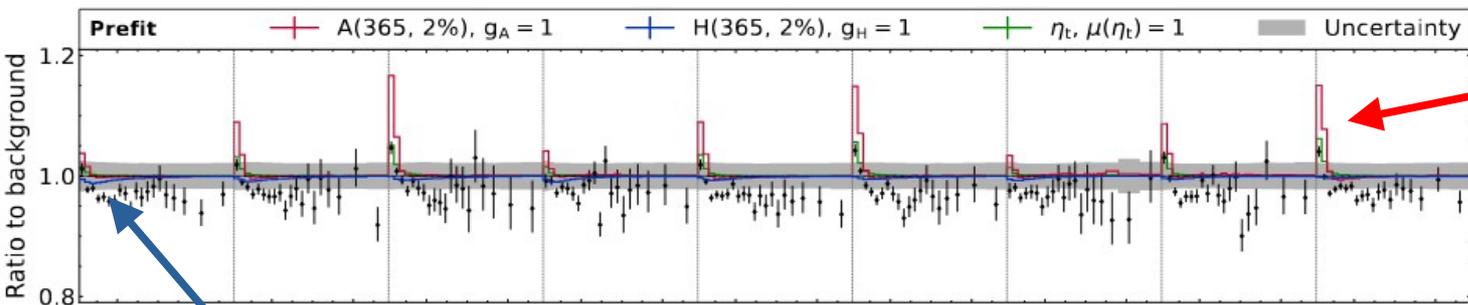
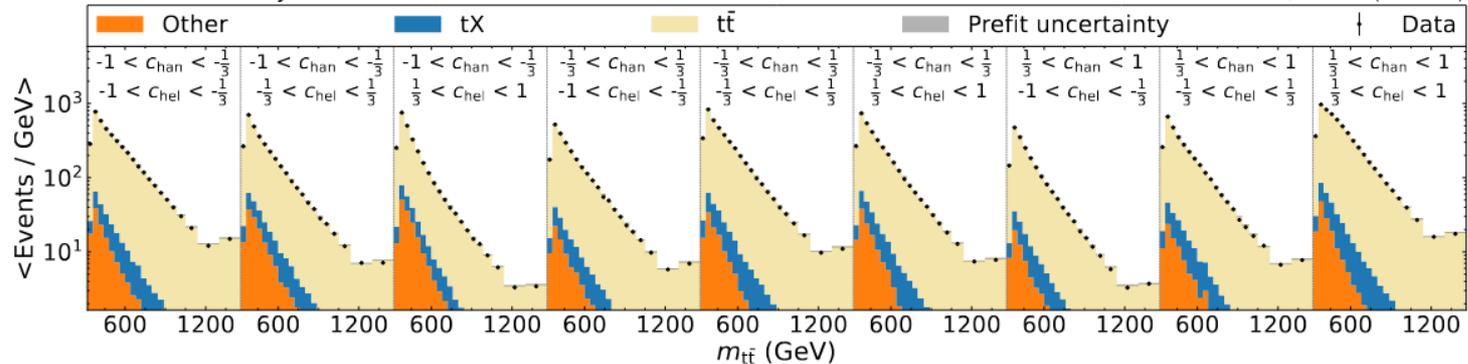


Results II Channel

CMS Preliminary

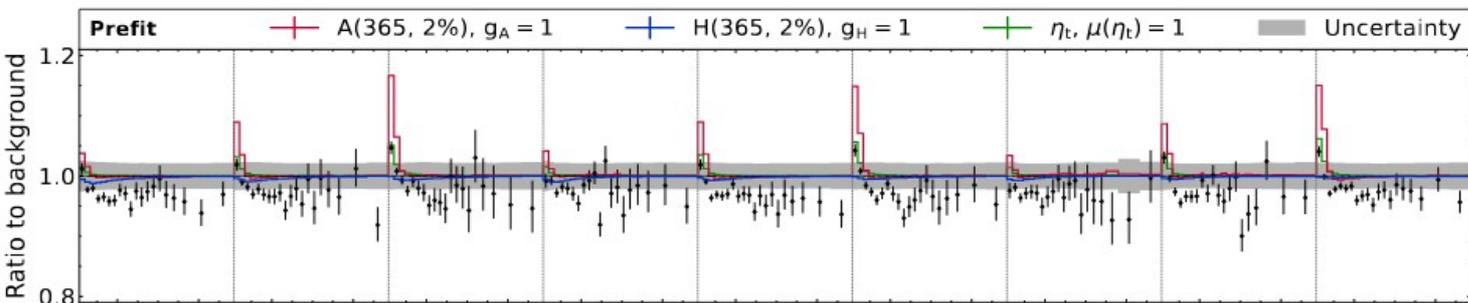
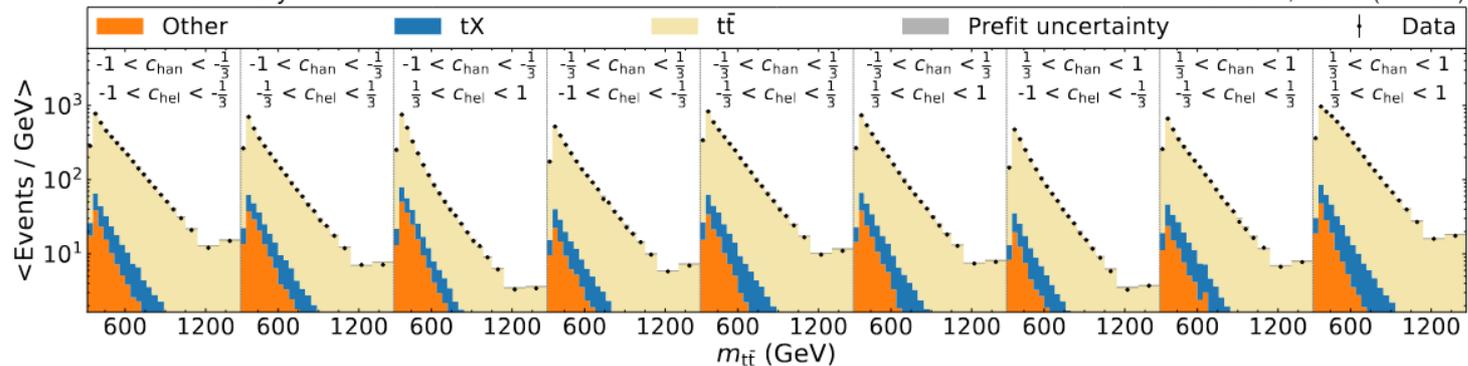
$\ell\bar{\ell}$

138 fb⁻¹, Run 2 (13 TeV)

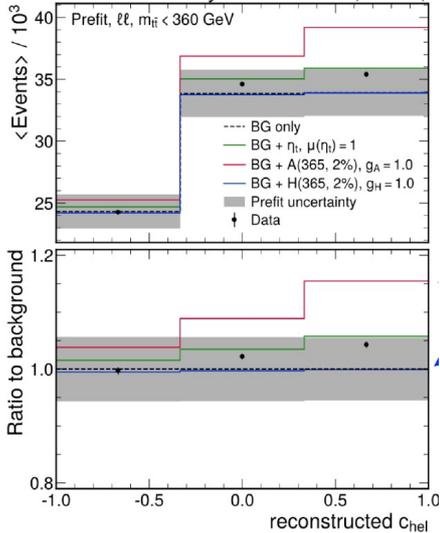


Results II Channel

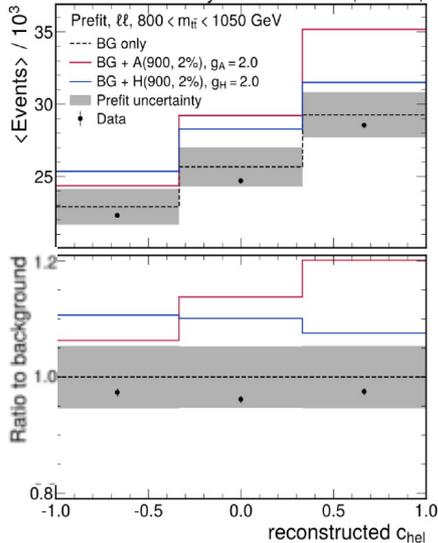
CMS Preliminary $\ell\bar{\ell}$ 138 fb⁻¹, Run 2 (13 TeV)



CMS Preliminary 138 fb⁻¹ (13 TeV)

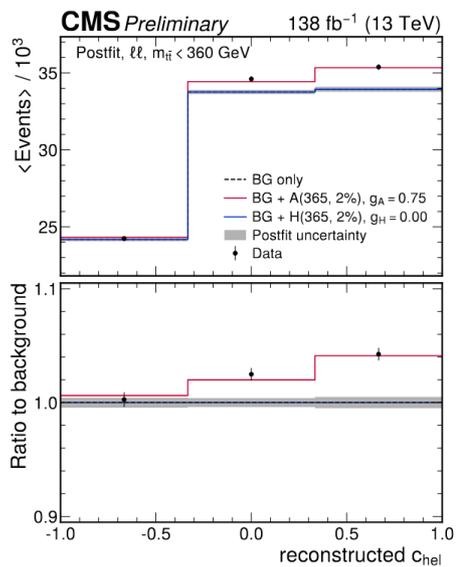
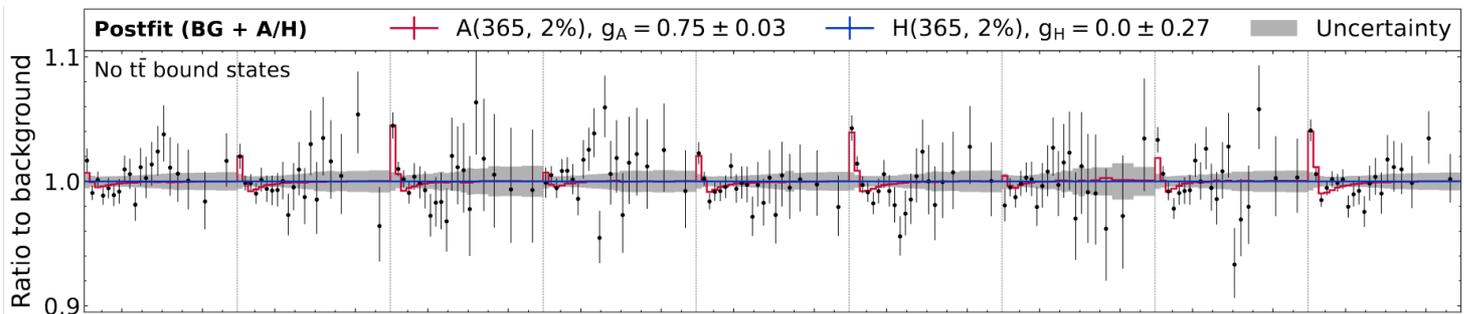
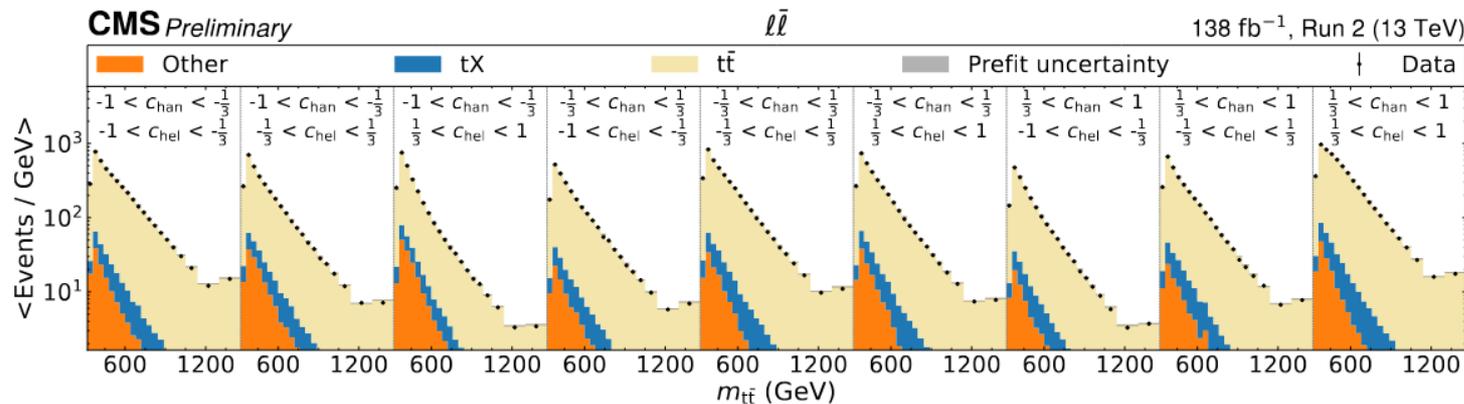


CMS Preliminary 138 fb⁻¹ (13 TeV)



- ◆ C_{hel} slope at threshold prefit
- ◆ flat for high $m_{t\bar{t}}$

Results II Channel



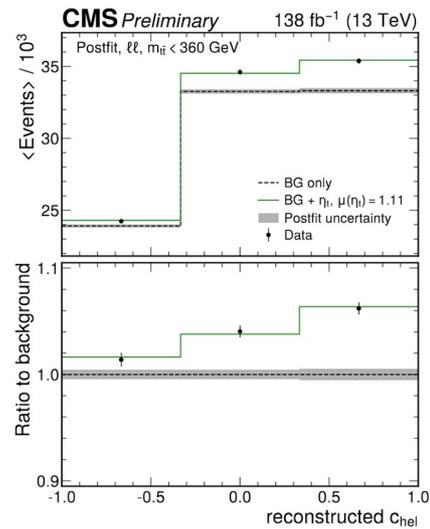
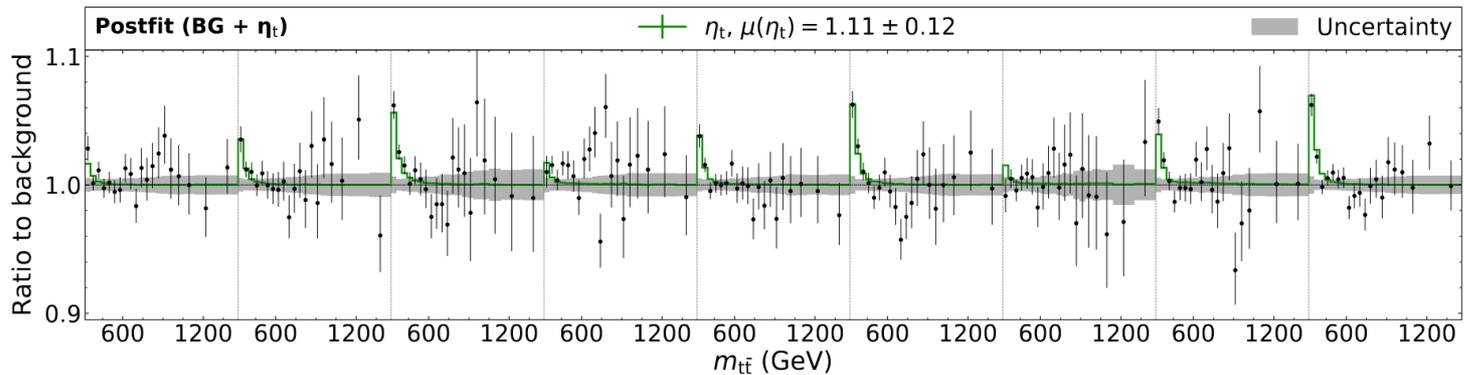
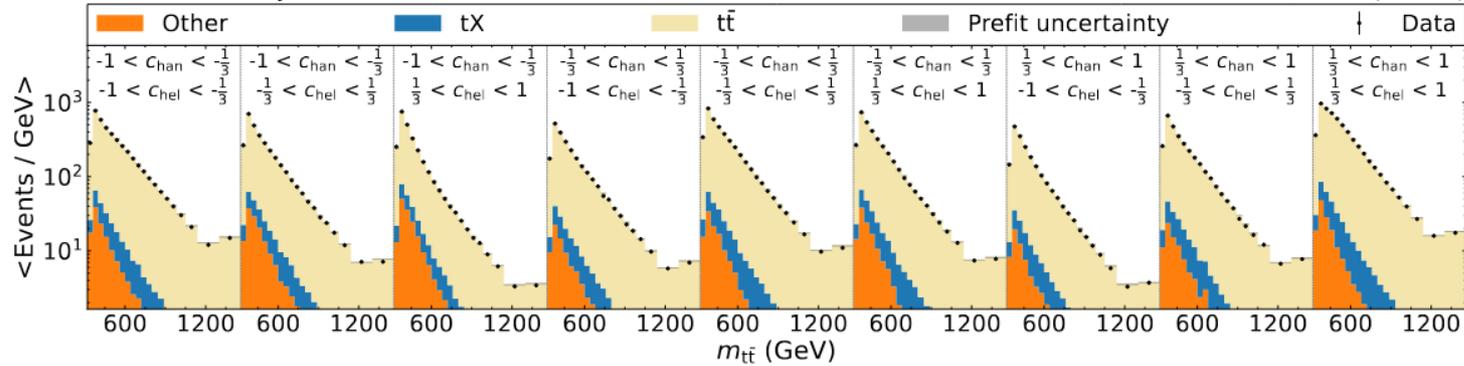
- ◆ c_{hel} discrepancy fits
- A very well at threshold

Results II Channel

CMS Preliminary

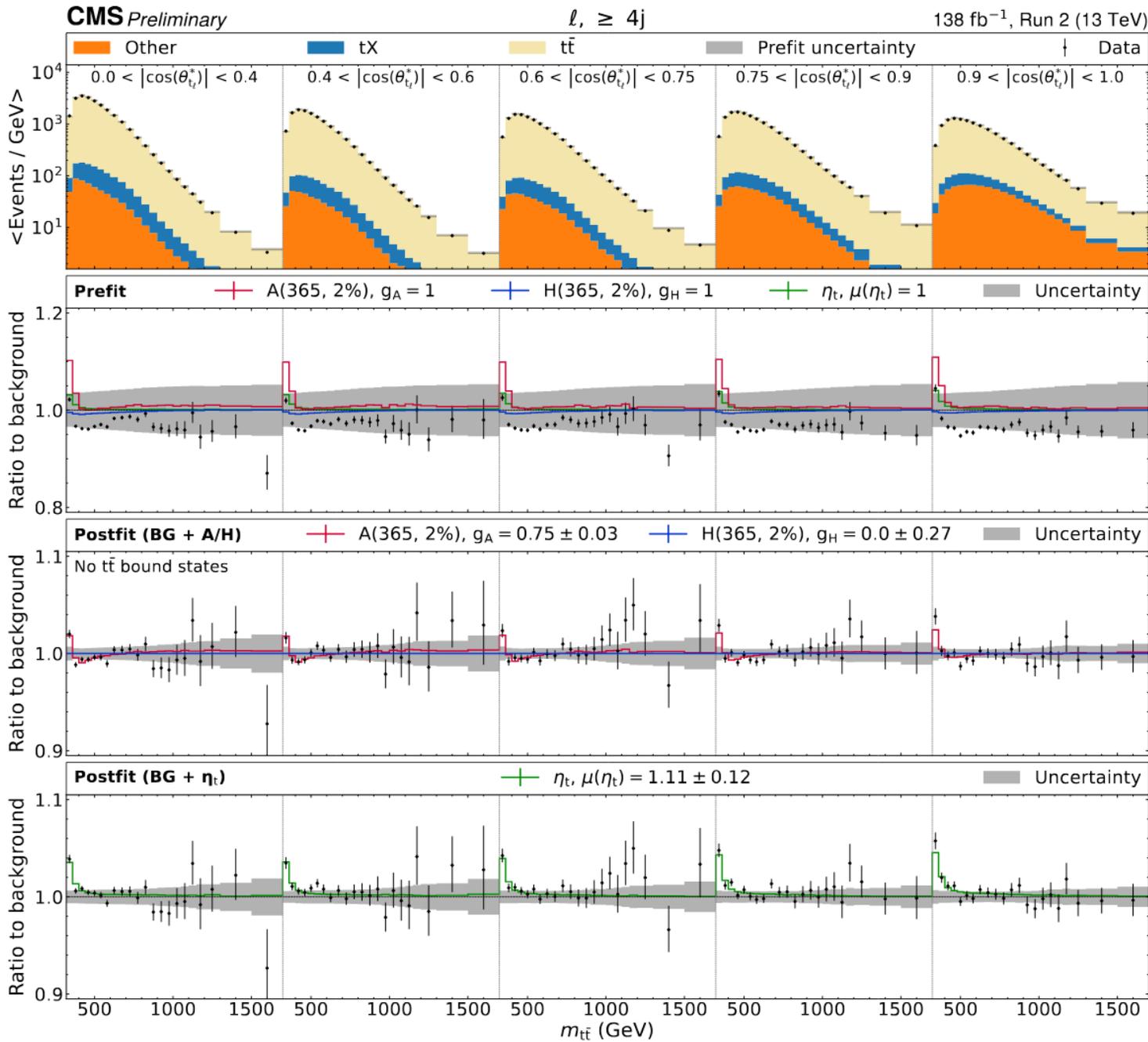
$\ell\bar{\ell}$

138 fb⁻¹, Run 2 (13 TeV)



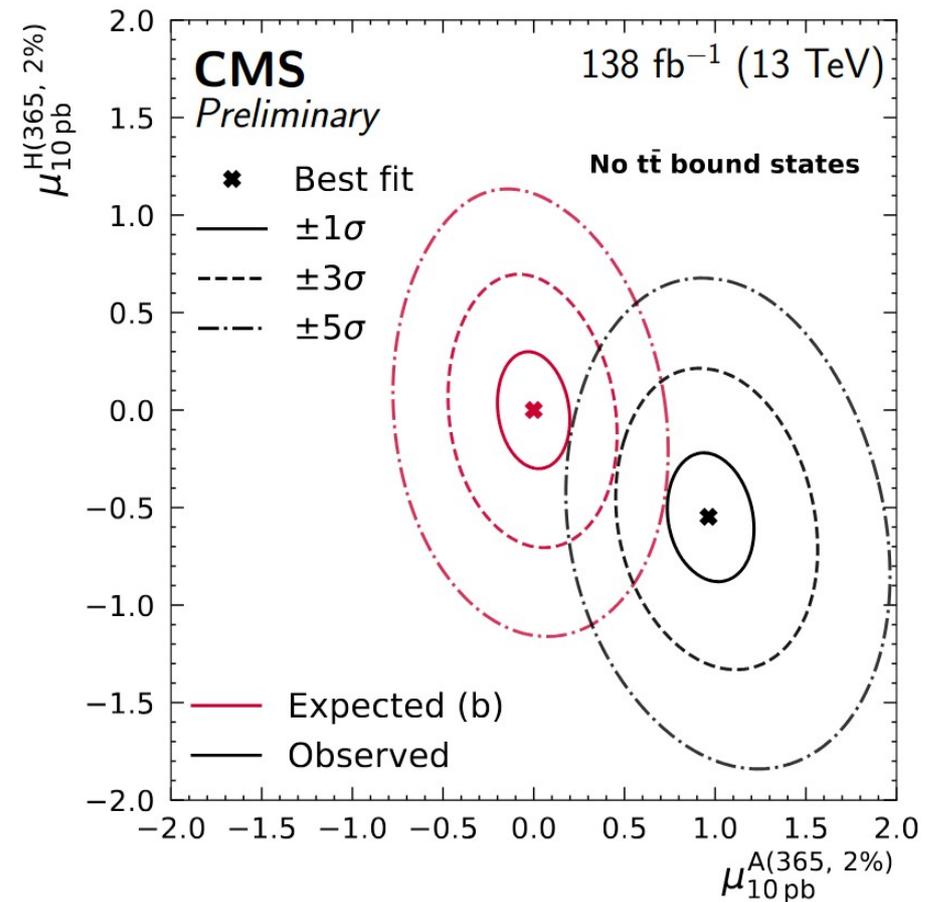
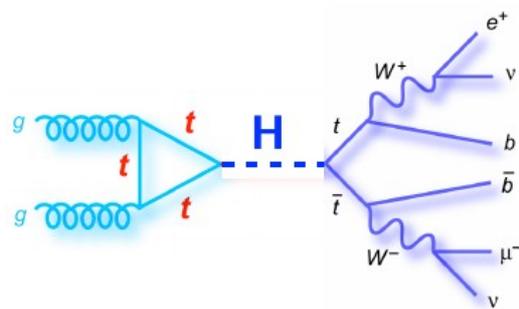
- ◆ C_{hel} discrepancy fits
- η_t very well at threshold

L4Jets Result

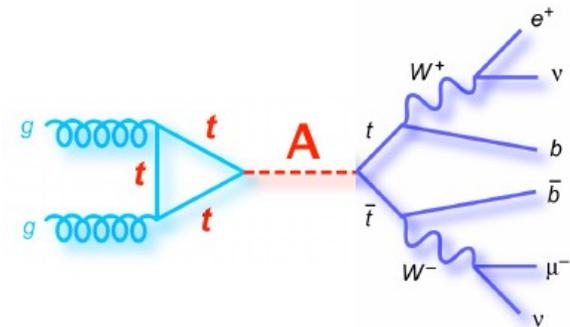


consistent picture in
ll and ljets channels

Scalar or Pseudoscalar?

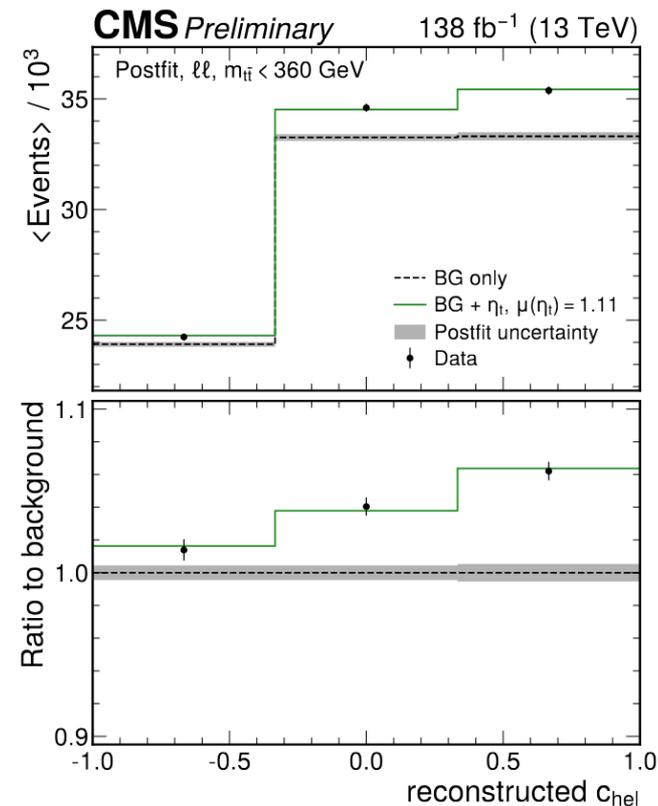


- ◆ simultaneous fit of A/H to data
- ◆ use closest (available) mass to threshold: 365 GeV
- ◆ consider only resonant component with equal and arbitrary rate



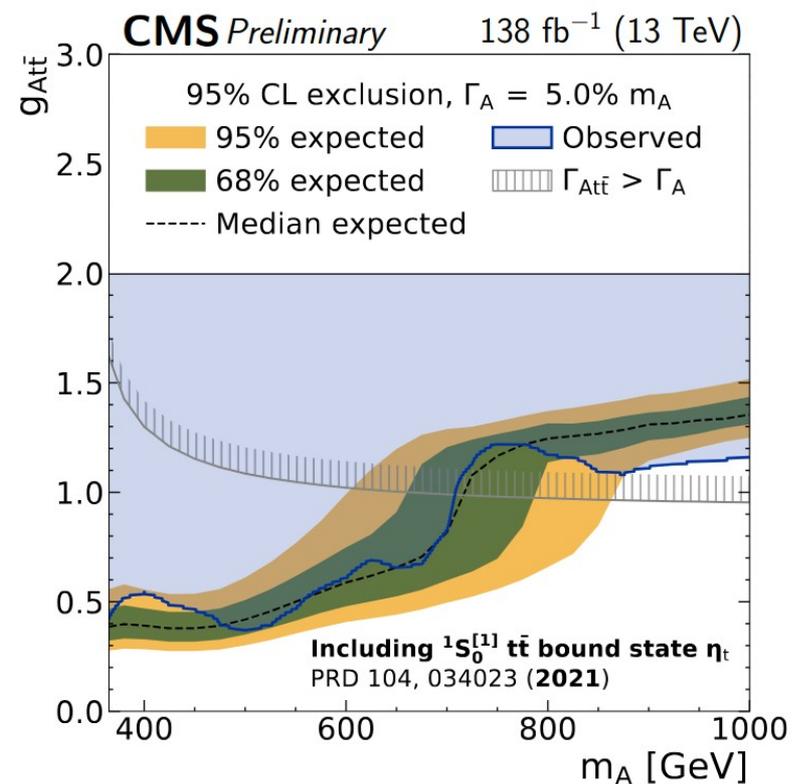
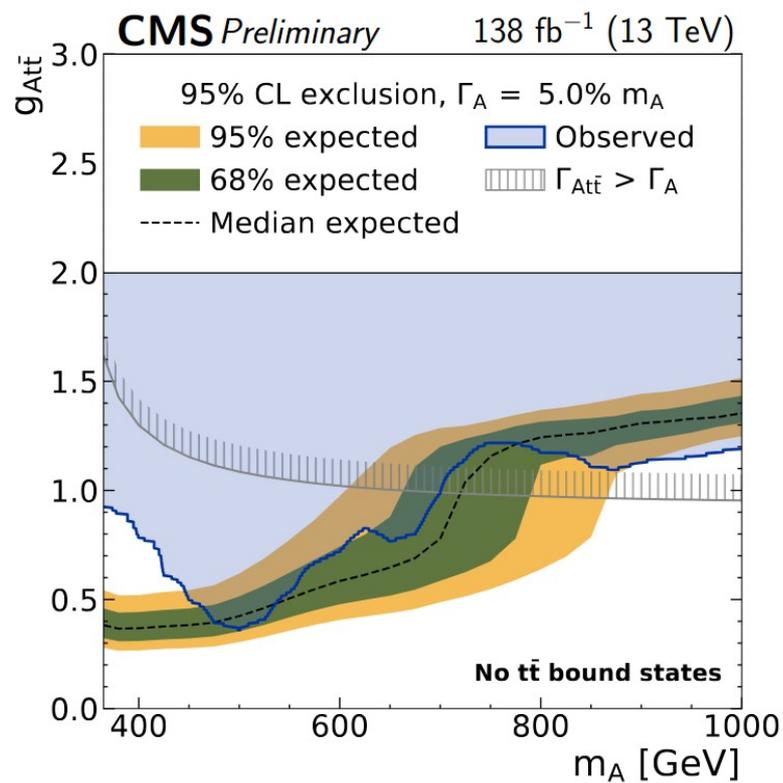
excess best compatible with pseudoscalar hypothesis

- ◆ “Cross section” = difference between the data and the pQCD predictions:
 - $\sigma(\eta_t) = 7.1 \pm 0.8$ pb
- ◆ comparing to NRQCD prediction:
 - $\sigma(\eta_t)^{\text{pred}} = 6.43$ pb (PRD 104 (2021) 034023)
- ◆ interpret with caution: missing uncertainties on model, kinematic effects on efficiencies, soft gluon radiation, . . .
- ◆ number should be considered as an experimental input for further theory building



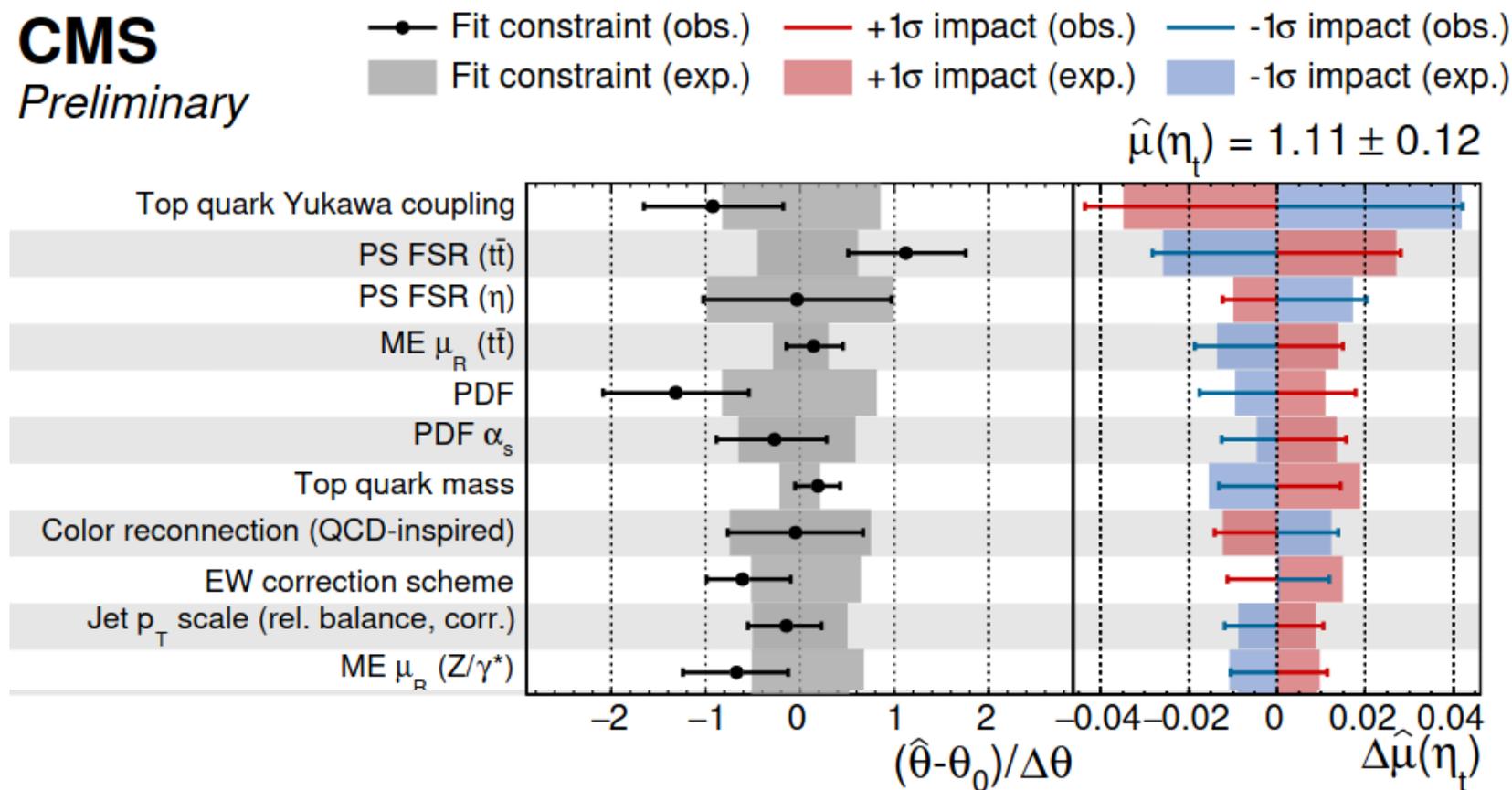
good agreement with available predictions

- ◆ impact on BSM limits, e.g. A



- ◆ uncertainties dominated by background modeling

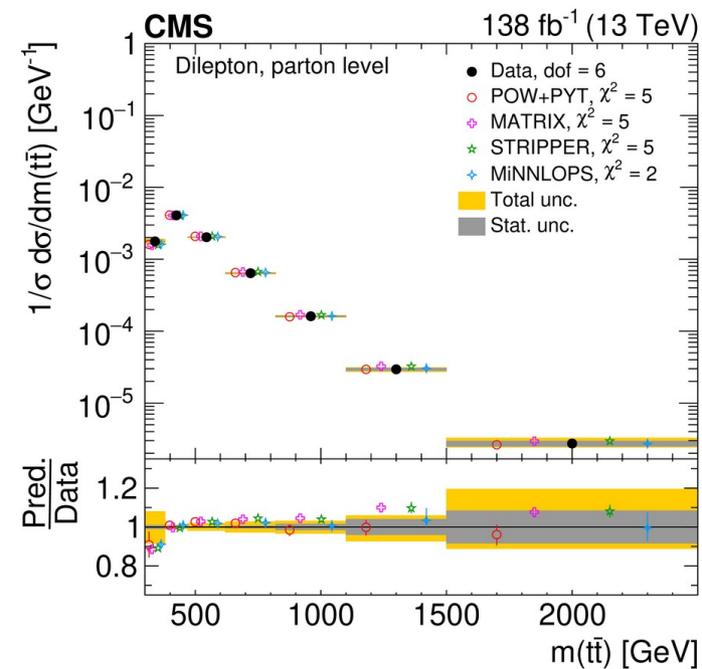
CMS
Preliminary



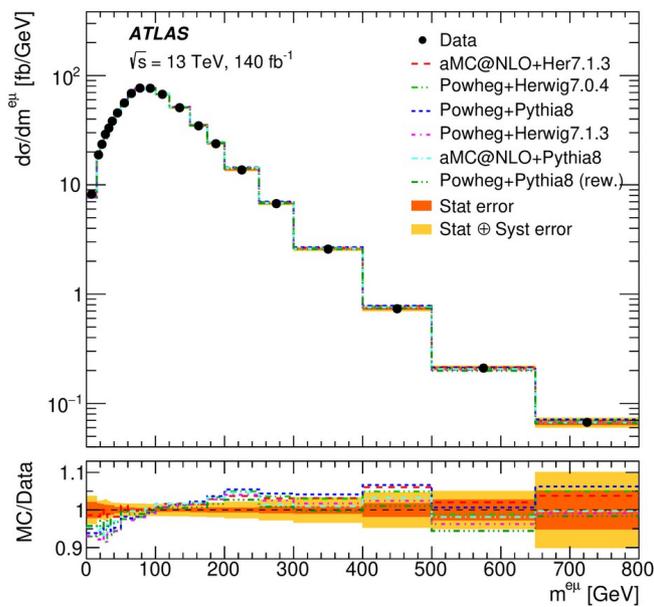
Consistency with Other Results: Invariant Masses



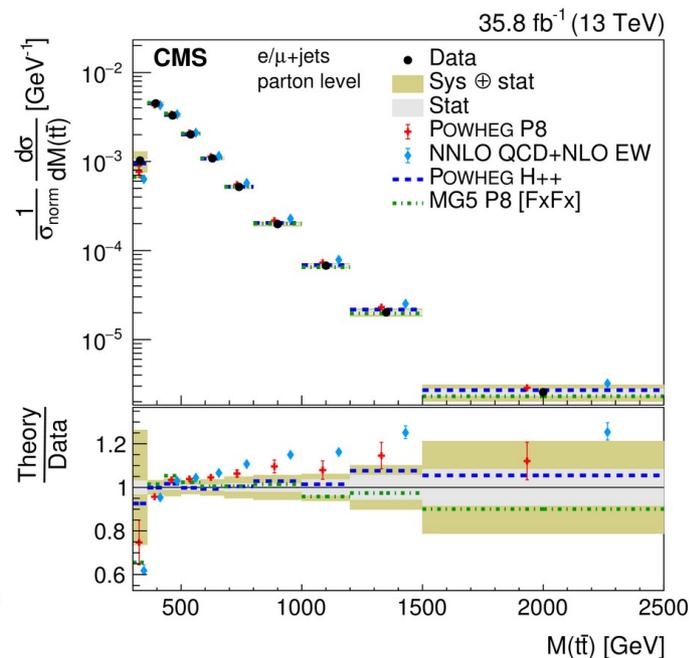
- ◆ tension in $m_{\bar{t}t}$ between data and pQCD at the threshold region in multiple measurements



CMS, arXiv:2402.08486



ATLAS, JHEP 07 (2023) 141

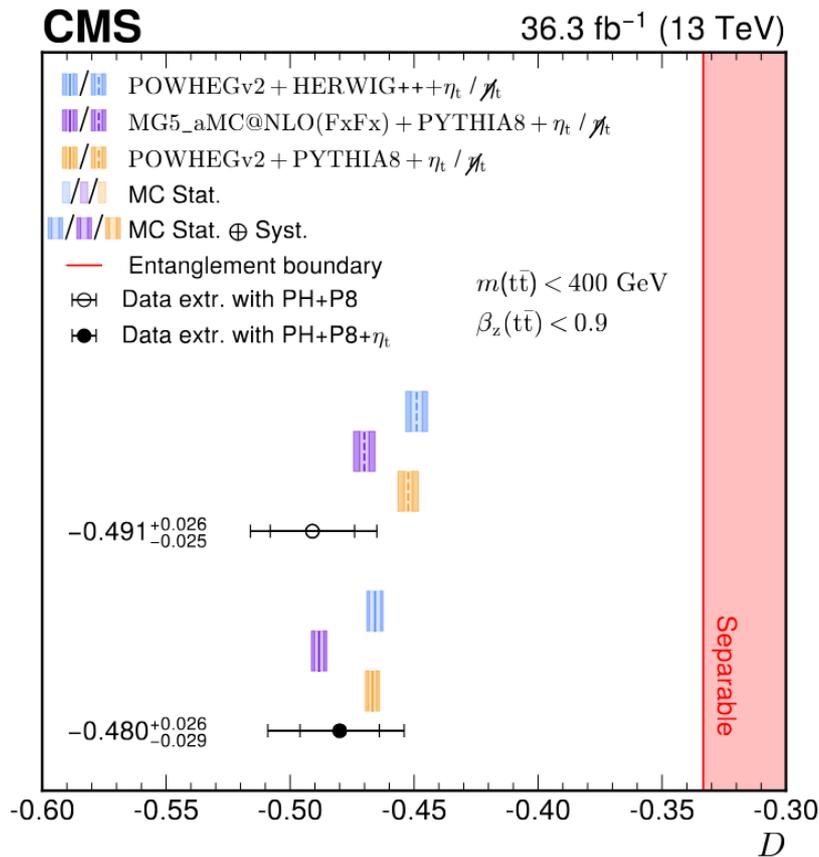


CMS, PRD 97 (2018) 112003

Consistency with Other Results: Spin Correlation



- ◆ tension in $m_{t\bar{t}}$ between data and pQCD at the threshold region in multiple measurements
- ◆ recent entanglement measurements at threshold point to stronger slopes D
 - pseudoscalar contributions

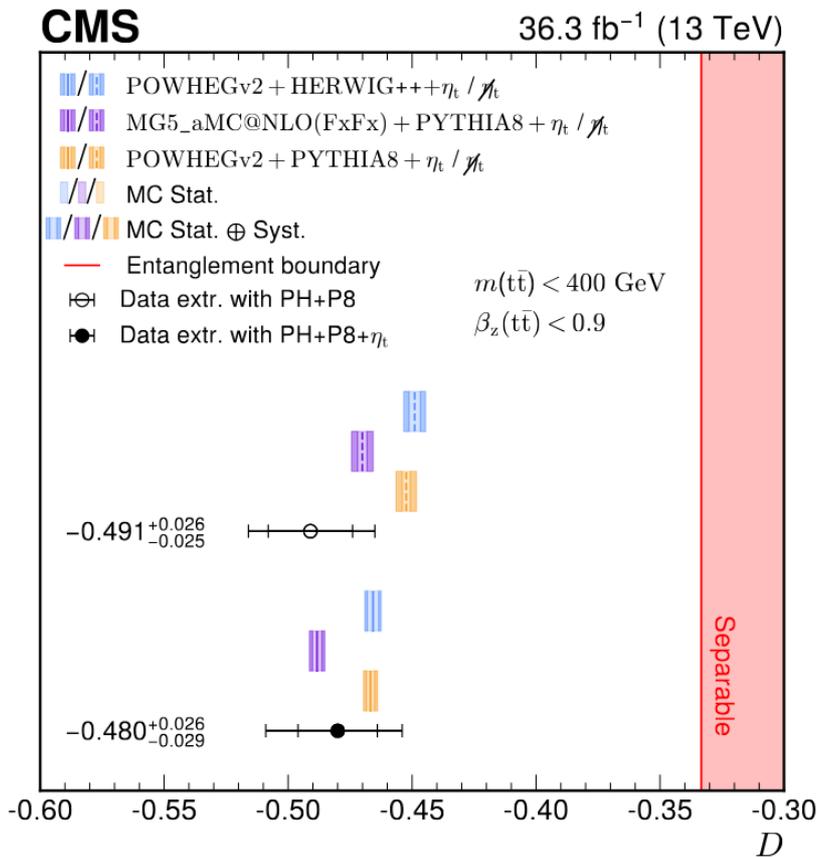


CMS, RPP 87 (2024) 117801

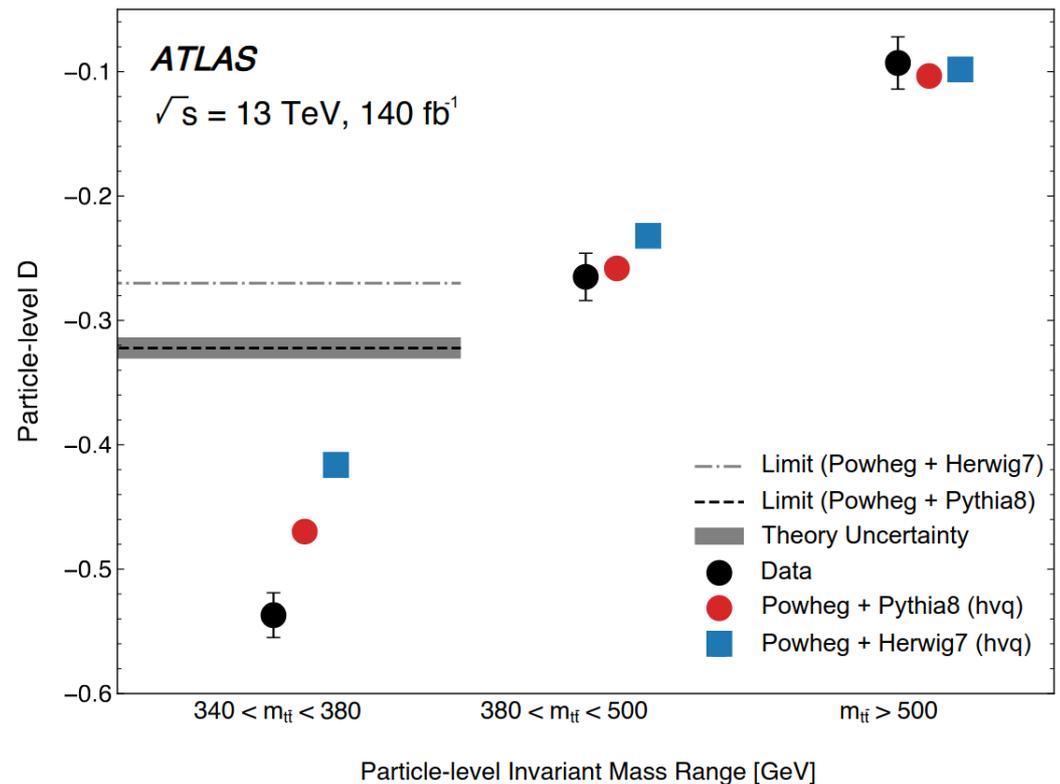
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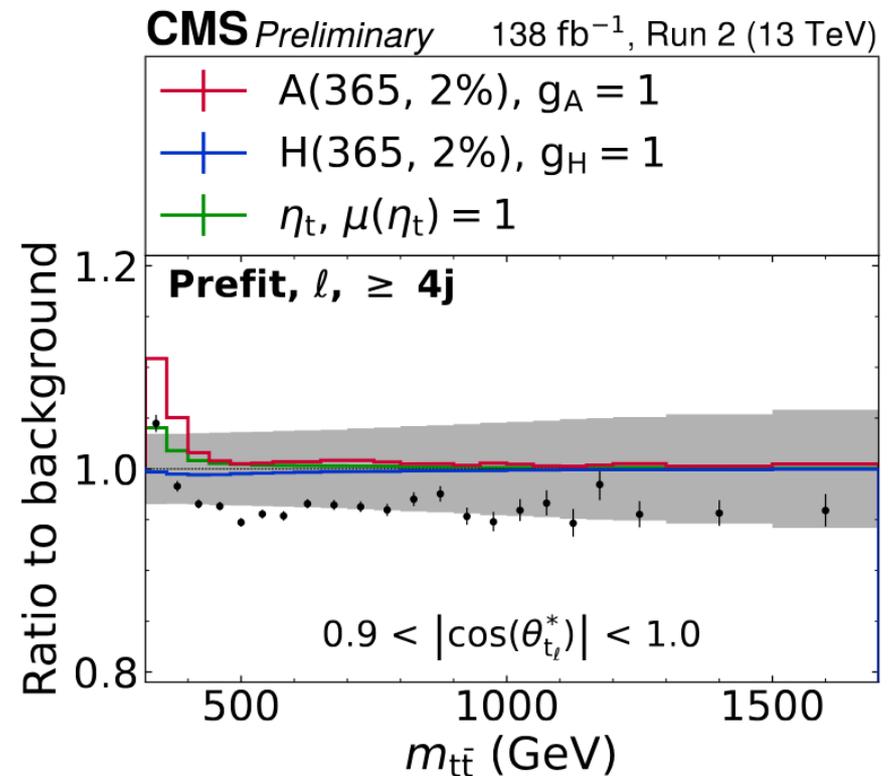
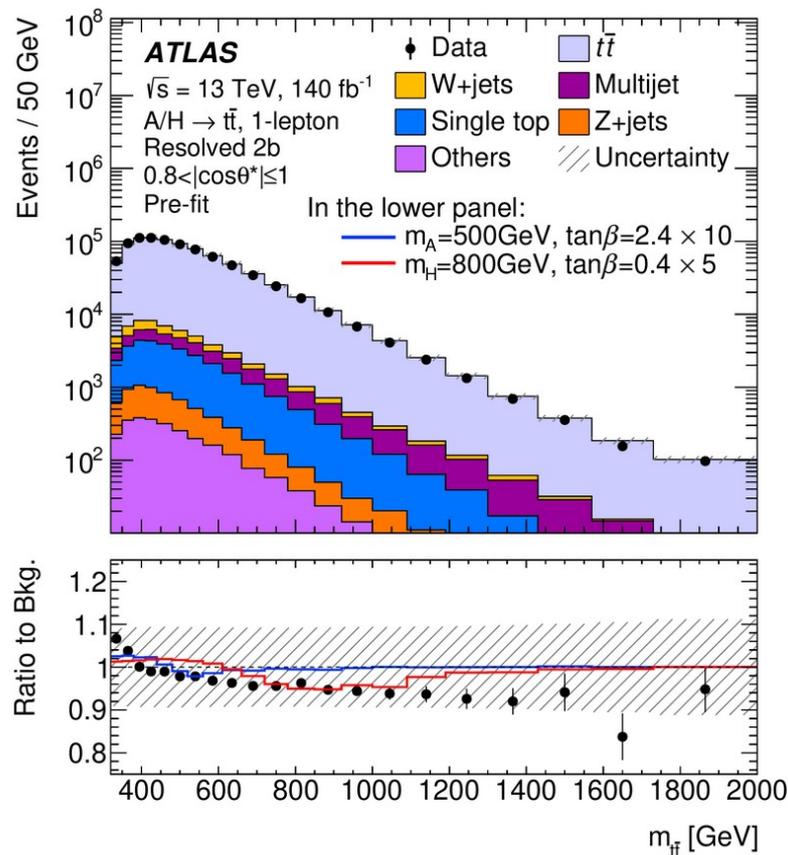


CMS, RPP 87 (2024) 117801



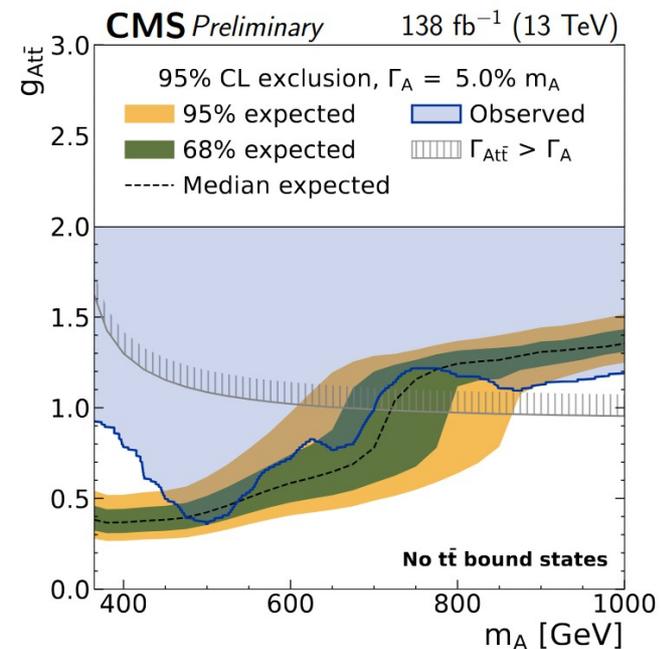
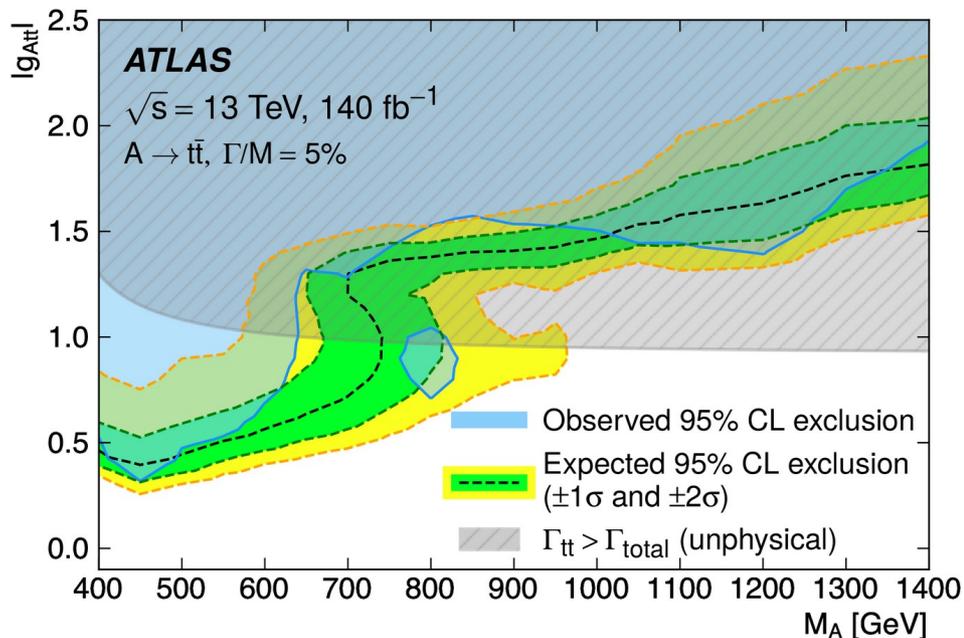
ATLAS, Nature 633 (2024) 542

- ◆ 1l, 2b, ≥ 4 jets category for both ATLAS and CMS
 - compare pre-fit distributions
 - e.g. at high $|\cos\theta^*|$: similar excess in data at low $m_{t\bar{t}}$



- ◆ 1l, 2b, ≥ 4 jets category for both ATLAS and CMS
 - compare pre-fit distributions
 - e.g. at high $|\cos\theta^*|$: similar excess in data at low $m_{\tilde{t}\tilde{t}}$

- ◆ for dilepton difficult to compare
 - no reconstruction of top quarks/spin in the ATLAS result
 - different variables: m_{llbb} vs. $\Delta\phi_{ll}$



dedicated spin observables robust against systematics – key difference?

- ◆ search for new spin-0 (pseudo)scalars in $t\bar{t}$ final states with full Run 2 dataset
 - dilepton and lepton+jets channels, using $m_{t\bar{t}}$, angular and spin observables

- ◆ observed excess in data at low $m_{t\bar{t}}$
 - fits well simplified model of a $t\bar{t}$ bound state η_t or a generic pseudoscalar A
 - stringent limits on A/H with η_t included in the background

- ◆ for the future:
 - confirmation from ATLAS !
 - probe of other channels
 - further improved background modeling crucial to increase knowledge on η_t
 - better theory input needed on the MC modeling of η_t

Whatever the excess is – It is exciting !

