LHCTopWG Open Meeting

Search for heavy scalar or pseudoscalar states in $t\bar{t}$ events at CMS

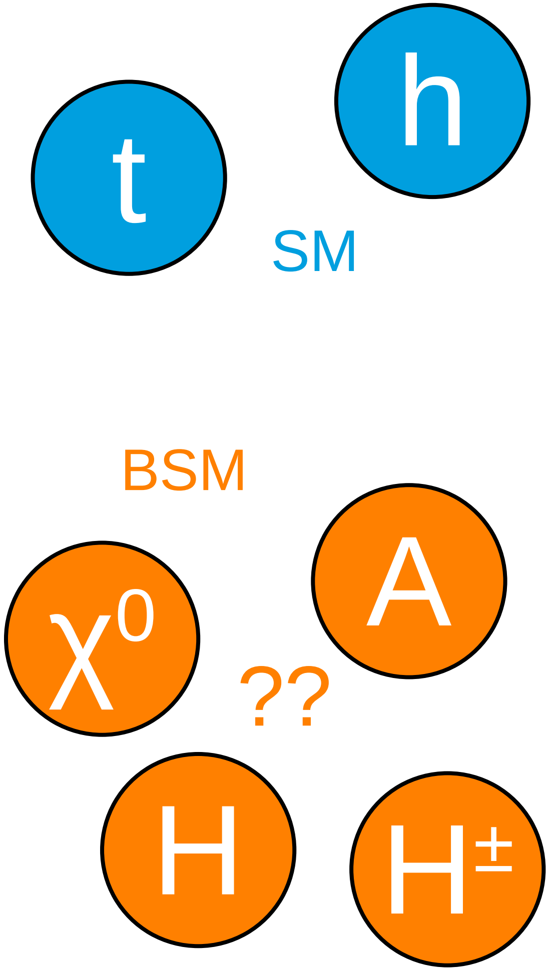
Laurids Jeppe for the CMS collaboration

13.11.2024 | CMS-PAS-HIG-22-013

Motivation: BSM!

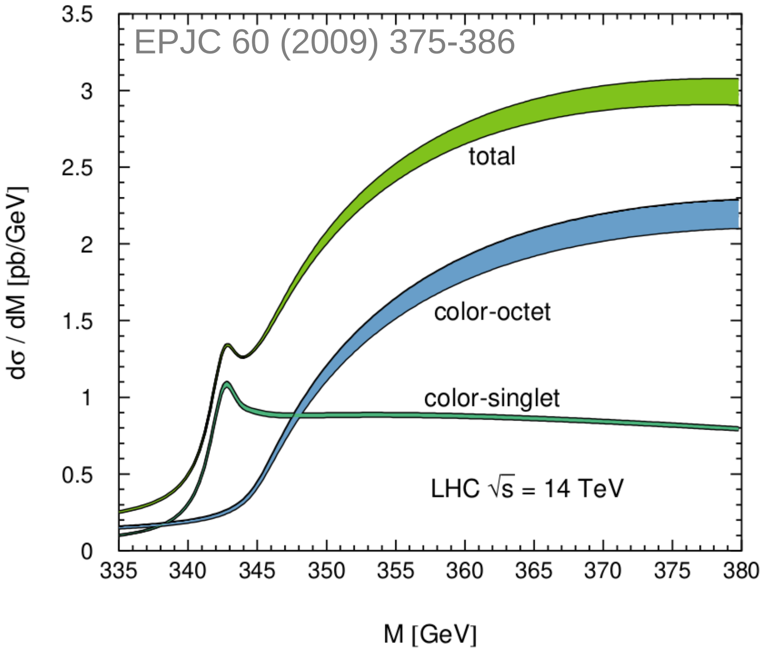
- We know there is BSM – but where is it?
- Many models predict extended Higgs sectors e.g. 2HDM, MSSM…
  $\rightarrow$ new scalar or pseudoscalar states
- If couplings are Yukawa-like: strongest coupling to top quark
- If mass > $2m_t$: decay to $t\bar{t}$ is dominant in large areas of parameter space

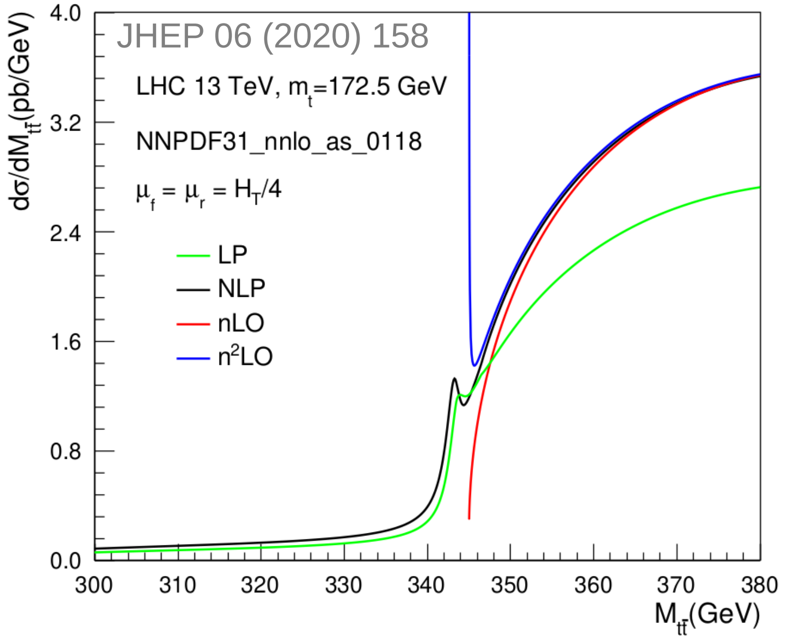
$\rightarrow$ search for heavy (pseudo)scalars in $t\bar{t}$ final states



Motivation: $t\bar{t}$ bound states?

- SM predicts $t\bar{t}$ (quasi-)bound states below the $t\bar{t}$ threshold



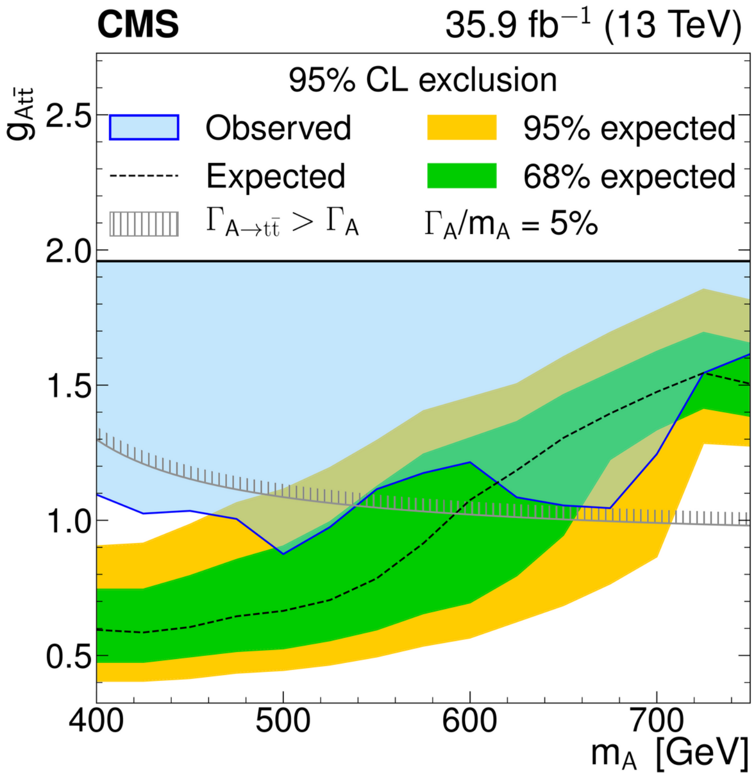


- Not observed yet (but there are hints: differential $t\bar{t}$, entanglement...)
- Dominant component: pseudoscalar – can we search for it?

Overview of the search

- Search for new spin-0 (pseudo)scalars in $t\bar{t}$ final states with full Run 2 dataset (138 fb^{-1})
- Make use of invariant $t\bar{t}$ mass, angular and spin correlation observables
- Two analysis channels:
  dilepton (ℓℓ) and lepton+jets (ℓj)
- Builds upon previous work by CMS:
  JHEP 04 (2020) 171 (2016 data, 35.9 fb^{-1})
- Also recent full Run 2 result by ATLAS
  (JHEP08 (2024) 013)

JHEP 04 (2020) 171

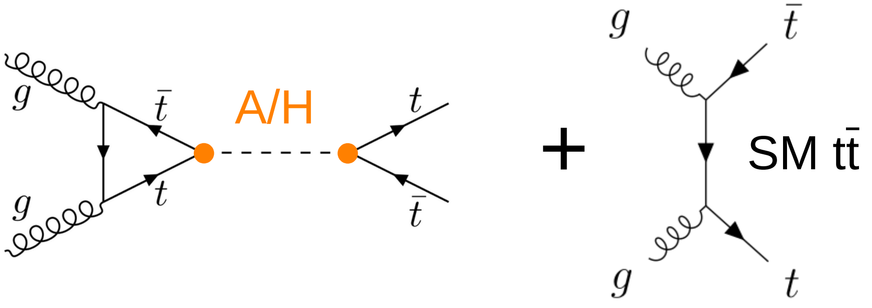


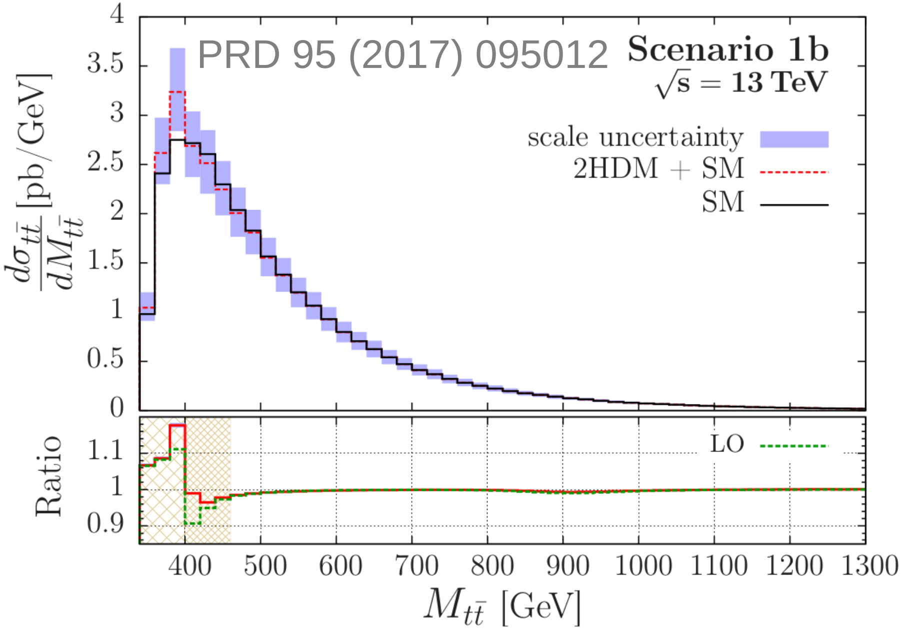
Signal modeling

$$\mathcal{L}_A^{\text{int}} = i g_{\text{A}\text{t}\bar{\text{t}}} \frac{m_\text{t}}{v} \bar{\text{t}} \gamma_5 \text{t} \text{A}$$

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

- Generic heavy pseudoscalar (A) or scalar (H) coupling solely to top quarks
- Production in gluon fusion via top quark loop





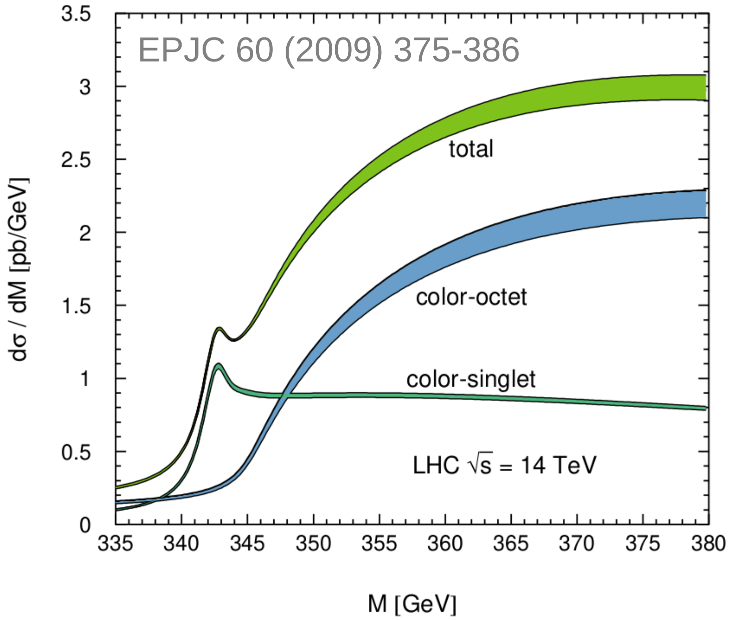
- Same final state as SM $t\bar{t}$ $\rightarrow$ interference $\rightarrow$ peak-dip structure in m_{tt}
- Free parameters: masses, widths, g_A / g_H
- Use NNLO QCD K-factors for normalization

Modeling: $t\bar{t}$ bound state effects

- State of the art: non-relativistic QCD (NRQCD)
  - Color-singlet (${}^1S_0^{[1]}$) - attractive
    $\rightarrow$ Peak below the $t\bar{t}$ threshold
  - Color-octet (${}^1S_0^{[8]}$ or ${}^3S_1^{[8]}$) - repulsive
    $\rightarrow$ Expected to be small below the $t\bar{t}$ threshold

- Lineshape and width not exactly known
  - but below experimental resolution

See e.g.
PRD 110 (2024) 5, 054032
JHEP 03 (2024) 099
PRD 104 (2021) 3, 034023
etc.

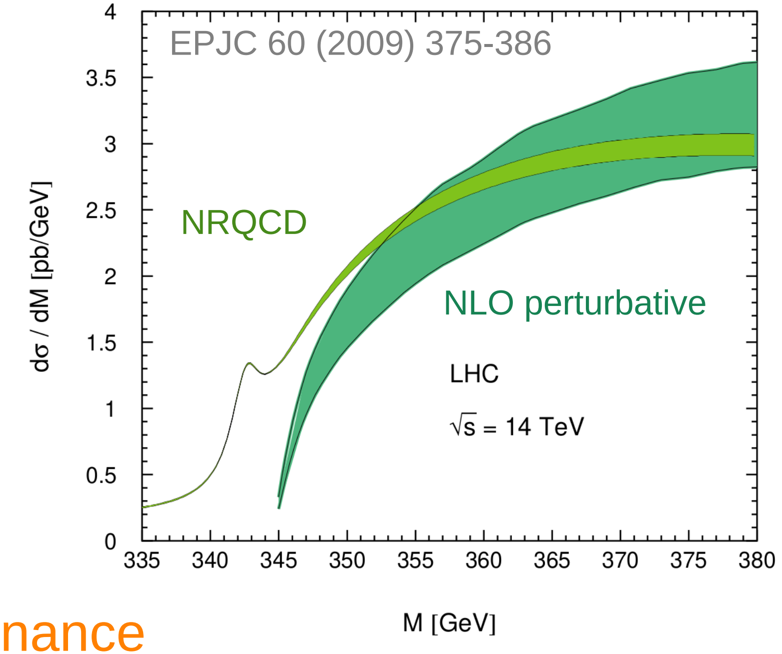


Modeling: $t\bar{t}$ bound state effects

- Use simplified model for MC simulation: η_t (PRD 104 (2021) 034023)
  - Generic spin-0, color-singlet state η_t
  - Couplings to gluons and tops (pseudoscalar)
  - Fit mass from NRQCD:

$$m_{\eta_t} - 2m_t = -2\,\mathrm{GeV} \quad \Rightarrow \quad m_{\eta_t} = 343\,\mathrm{GeV}$$

  - Restrict to $m_{\mathrm{WbWb}} \in [337, 349]\,\mathrm{GeV}$ to not influence $t\bar{t}$ continuum as predicted by perturbative QCD
  - Not available yet: by-event reweighting to NRQCD



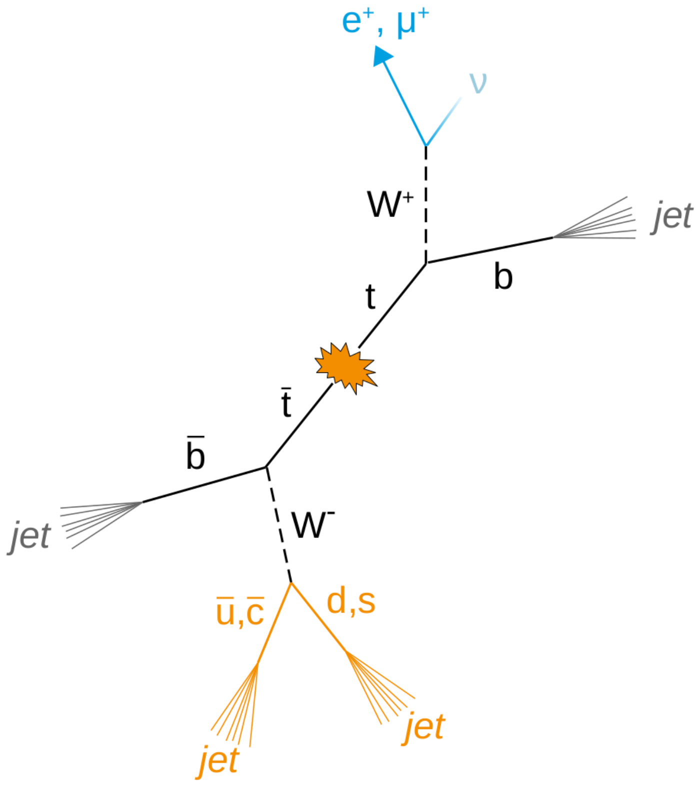
- Result: very similar signature as low-mass A resonance

Lepton+jets channel

- Require exactly one lepton (e/μ), 3 or more jets and 2 or more b tags
- Split into 4 categories: e vs μ and 3 jets vs 4+ jets

(NIM A 736 (2014) 169-178)

- Reconstruct $t\bar{t}$ system with NeutrinoSolver algorithm:
  - Assign b jets by maximum likelihood
  - Energy correction factor applied for 3 jet events (lost or merged jets) (NIM A 788 (2015) 128-136)



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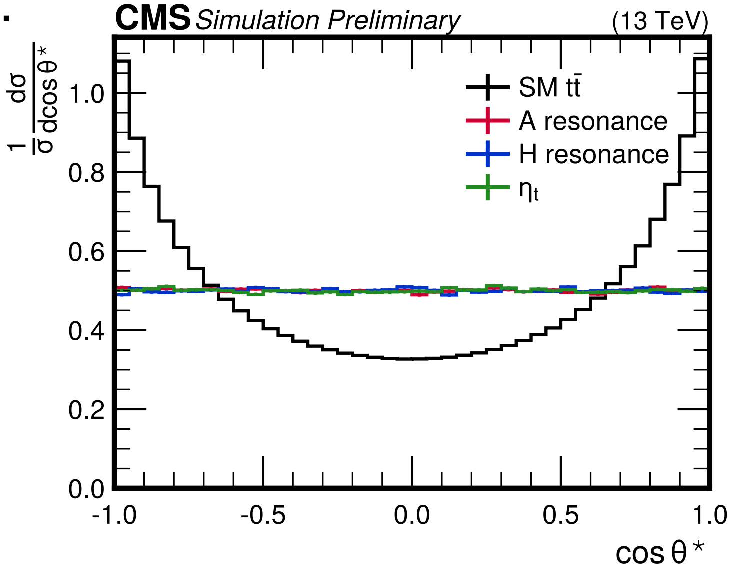
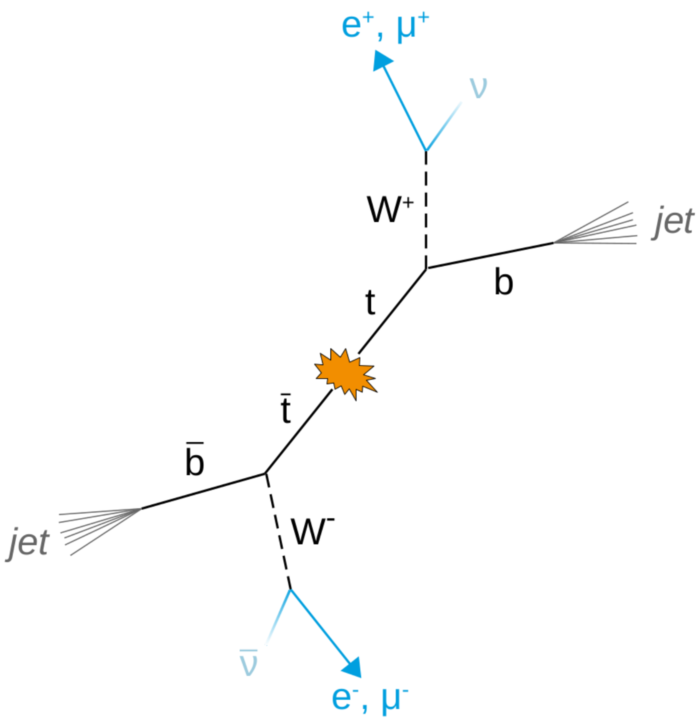
  - Energy correction factor applied for 3 jet events (lost or merged jets) (NIM A 788 (2015) 128-136)
- 2D binning in m_{tt} x $|\cos\theta^*|$
- θ*: scattering angle of leptonic top quark
  - SM $t\bar{t}$: peaks at large cosθ*
  - A/H signal: isotropic → flat distribution
  - ➔ Sensitive to spin of mediator (but not parity)



Dilepton channel

- Exactly two opposite-sign leptons (e/μ), at least 2 jets, and at least 1 b tag
- Split by lepton flavor: ee, eμ and μμ
- Reject low-$m_{\ell\ell}$ events
  Cut away Z peak & require p_T^{miss} > 40 GeV in ee/μμ



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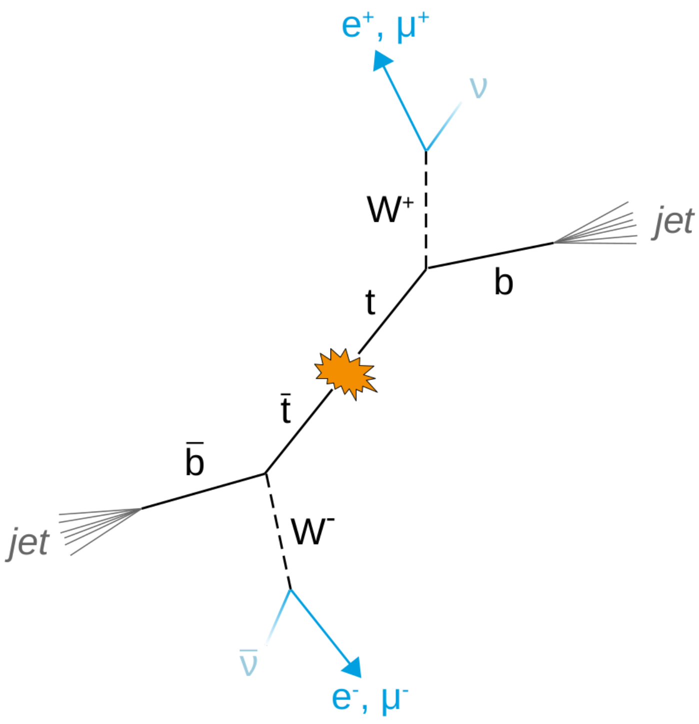
- Analytic reconstruction of $t\bar{t}$ system:
  - Assumptions: all p_T^{miss} from νν, tops and Ws on-shell
  - Assign b jets using likelihood based on $m_{\ell b}$
  - Finite detector resolution: repeat reconstruction 100 times with randomly smeared inputs, take weighted average

  (EPJC 75 (2015) 11, 542; PRD 73 (2006) 054015)



Spin correlation observables

- Both A/H and η_t predict $t\bar{t}$ production in a pure $t\bar{t}$ spin state:
  $^1S_0$ or $^3P_0$ (from A / η_t resp. H)
- Top decays before hadronization $\rightarrow$ transfer spin information to decay products
- Construct spin correlation observables from tops & leptons

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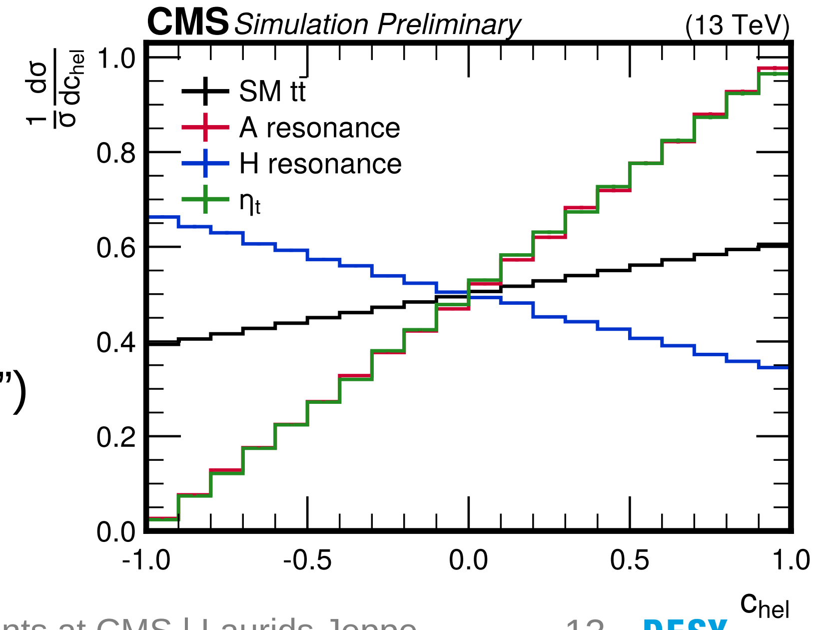

- Variable #1: c_{hel}
  - Boost leptons into rest frames of their parent tops $\rightarrow$ Scalar product between directions of flight
  - Straight line with slope sensitive to $t\bar{t}$ spin state ("D")
  - Maximal for $^1S_0$ (from A / η_t) – separates from SM

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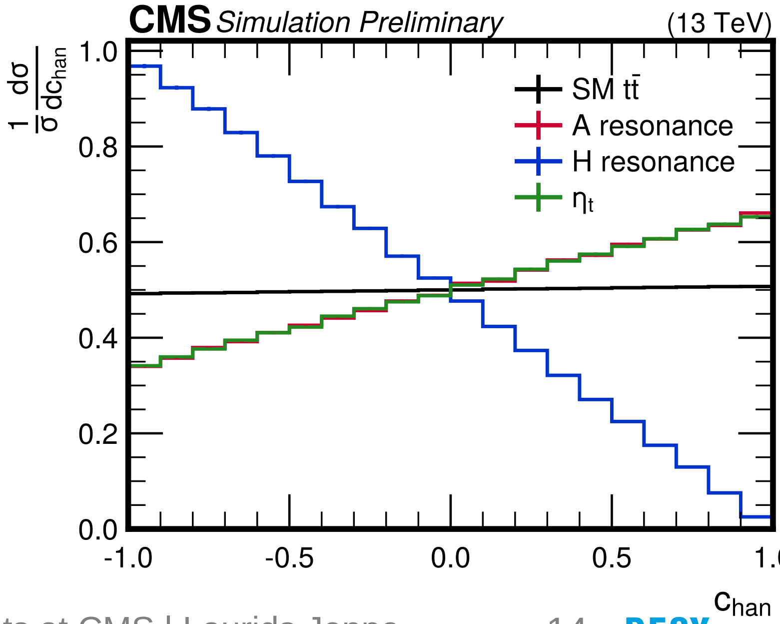


- Variable #2: c_{han}
  - Similar as c_{hel}, separating scalars from SM
  - Maximally negative slope for $^3P_0$ state (from H)
  - Construct similarly from lepton momenta, with sign flip for component parallel to top momentum

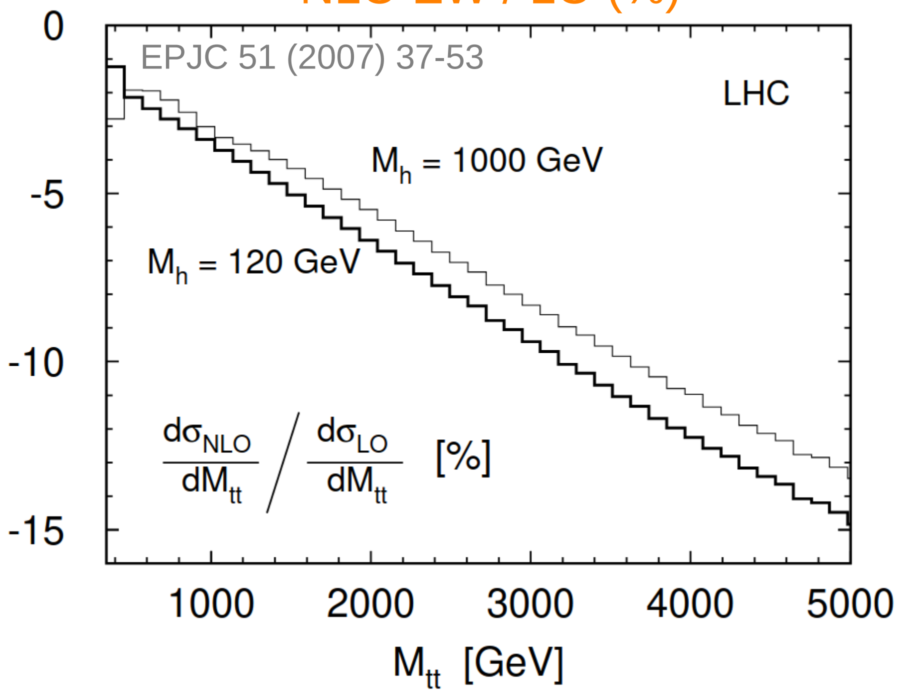
➔ 3 search variables in dilepton: m_{tt} x c_{hel} x c_{han}

Background modeling

- Major irreducible background: SM $t\bar{t}$
  - Model from NLO MC (Powheg+Pythia)
  - Correct to NNLO QCD and NLO EW from fixed-order predictions by reweighting in 2D bins of m_{tt} and cosθ*

    NNLO QCD: Matrix (EPJC 78 (2018) 537)
    NLO EW: Hathor (EPJC 51 (2007) 37)
  - Normalize to NNLO+NNLL cross section (CPC 185 (2014) 2930)

NLO EW / LO (%)



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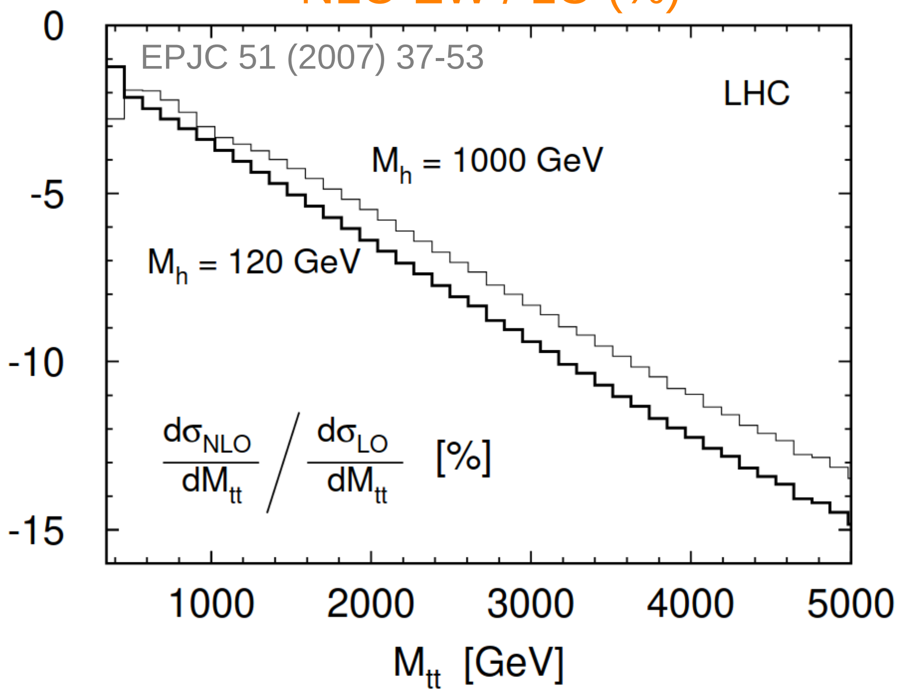
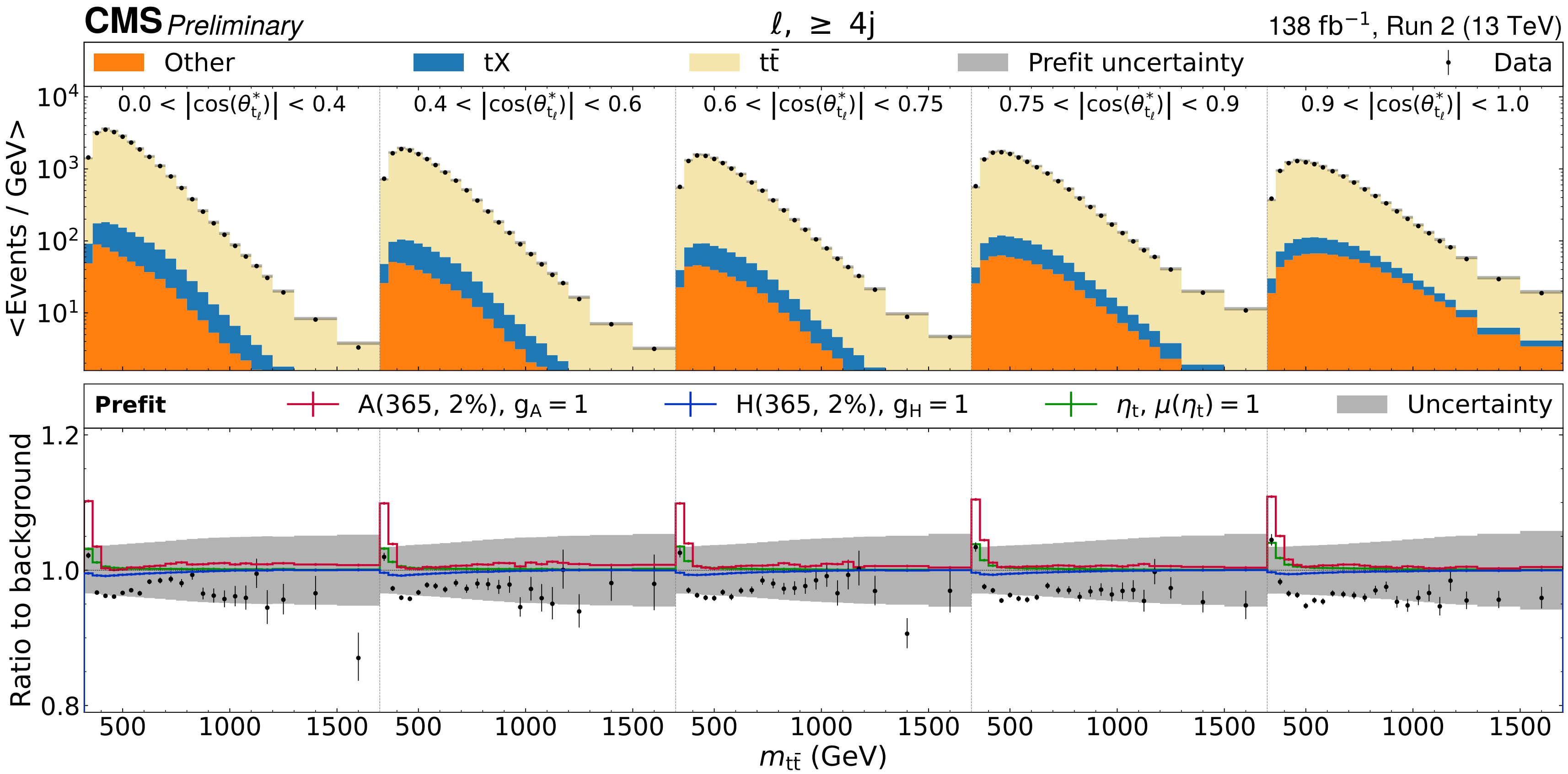


- Other backgrounds: tW, t channel single-top, rare processes (from MC)
- Z+jets in ℓℓ: from MC with data-driven normalization from Z peak sideband
- QCD+EW processes in ℓ+jets: data-driven shape from sideband with no b tags

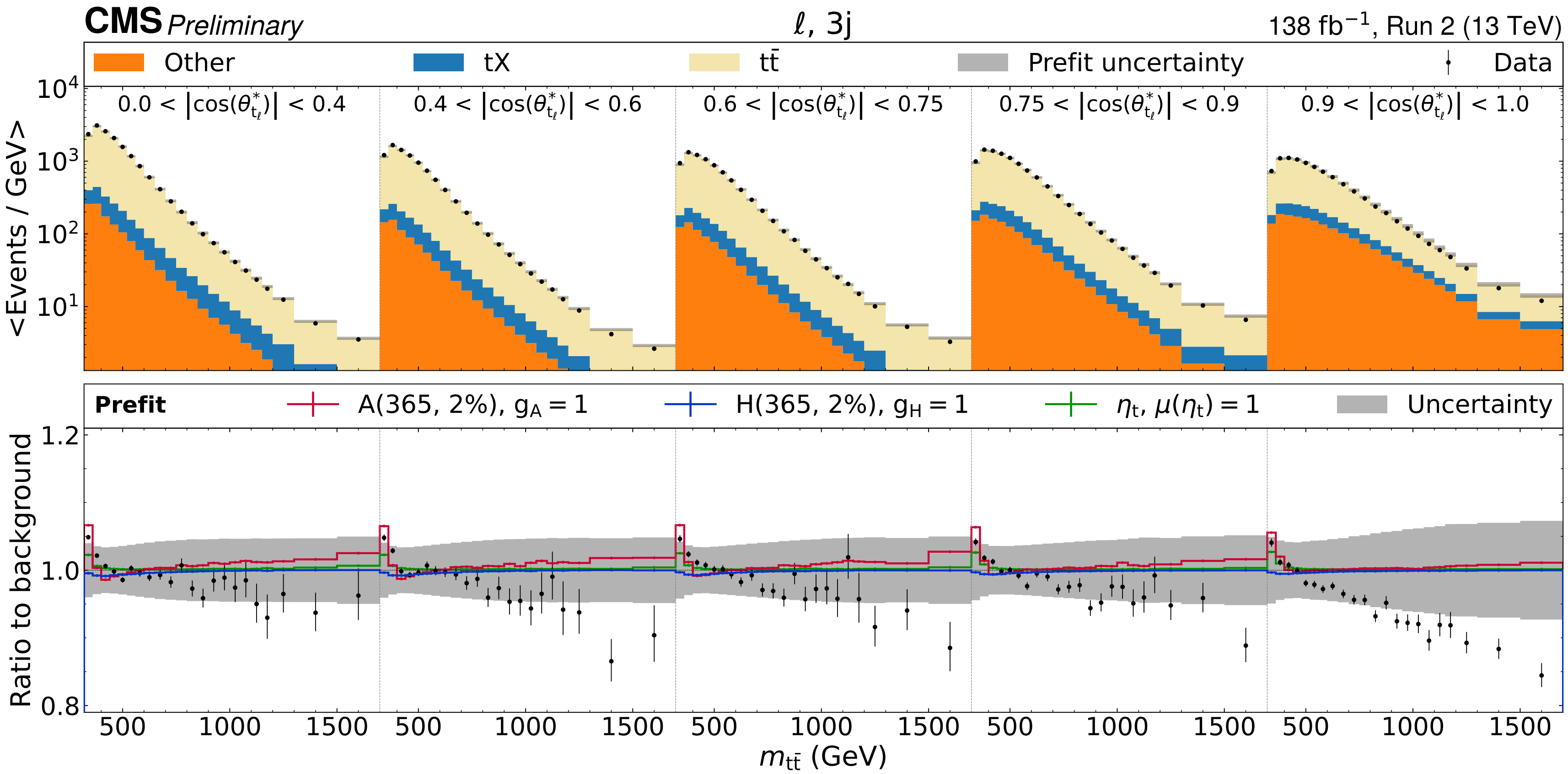
Prefit distributions: ℓ + ≥4 jets

Differences between data and prediction observed in low m_{tt} bins!



Prefit distributions: ℓ + 3 jets

Differences between data and prediction observed in low m_{tt} bins!



Prefit distributions: ℓℓ

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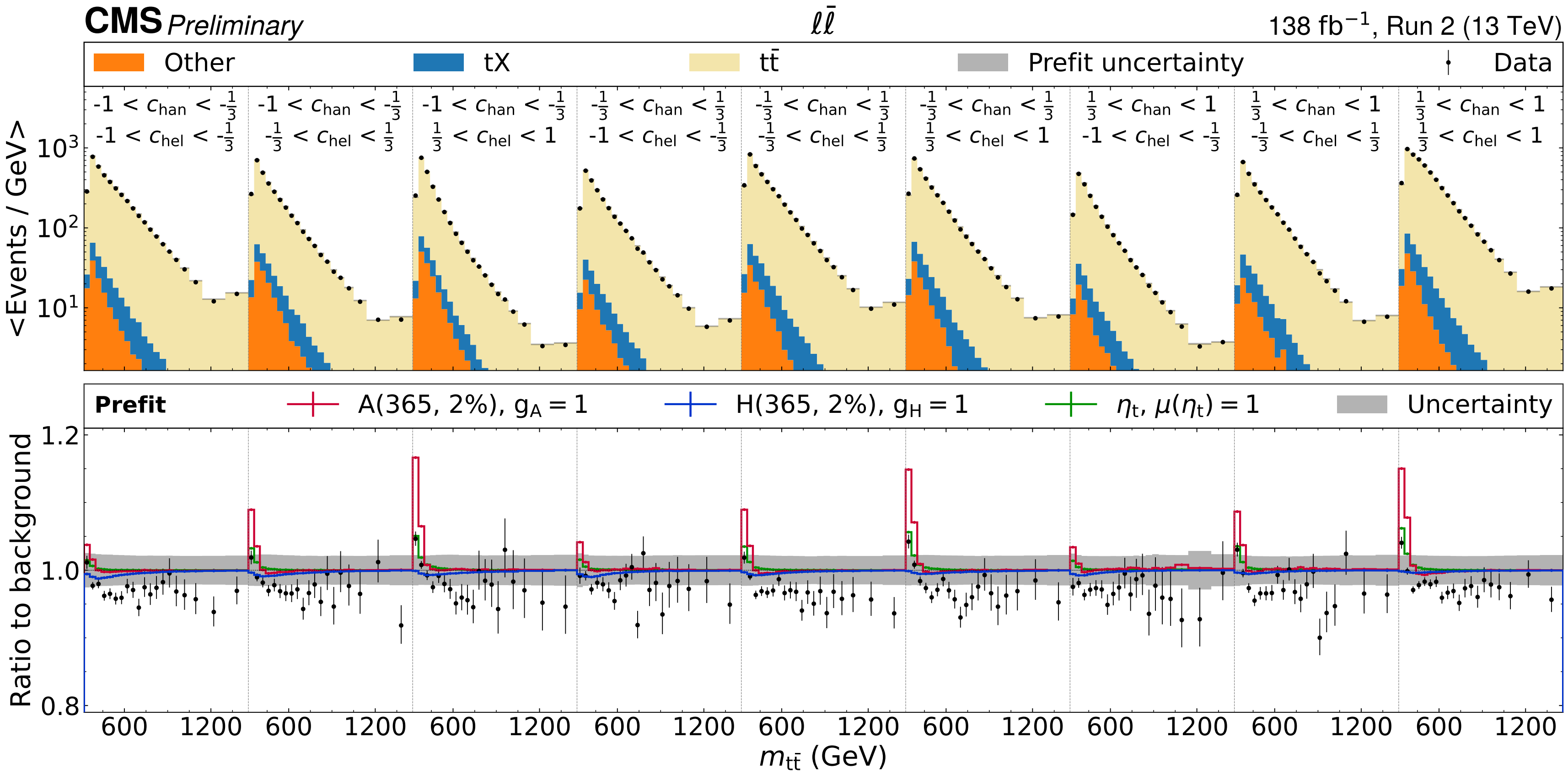
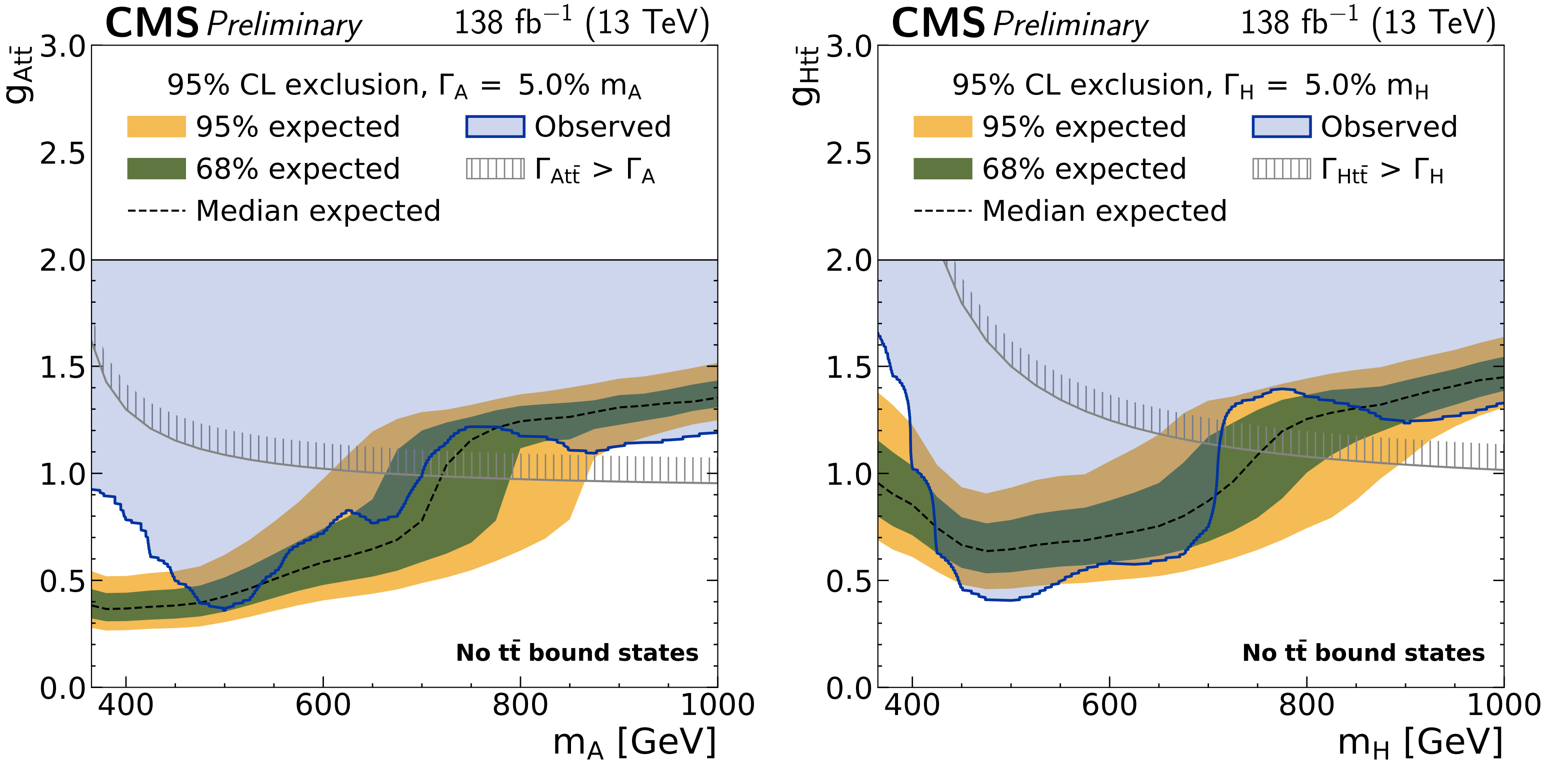


A/H interpretation

- Limits on A or H using only the perturbative QCD+EW background model
- Excess at low m_{tt} visible at low A/H masses – stronger for A



A/H width:
5%

$t\bar{t}$ bound state?

- Excess is located at low $m_{t\bar{t}}$, stronger for pseudoscalar
  $\rightarrow$ could this be interpreted as $t\bar{t}$ bound state effects?
- Extract cross section using the η_t color-singlet model
  - “cross section” = difference to perturbative prediction

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

- Agrees with NRQCD prediction: $\sigma(\eta_t)^{\mathrm{pred}} = 6.43\,\mathrm{pb}$

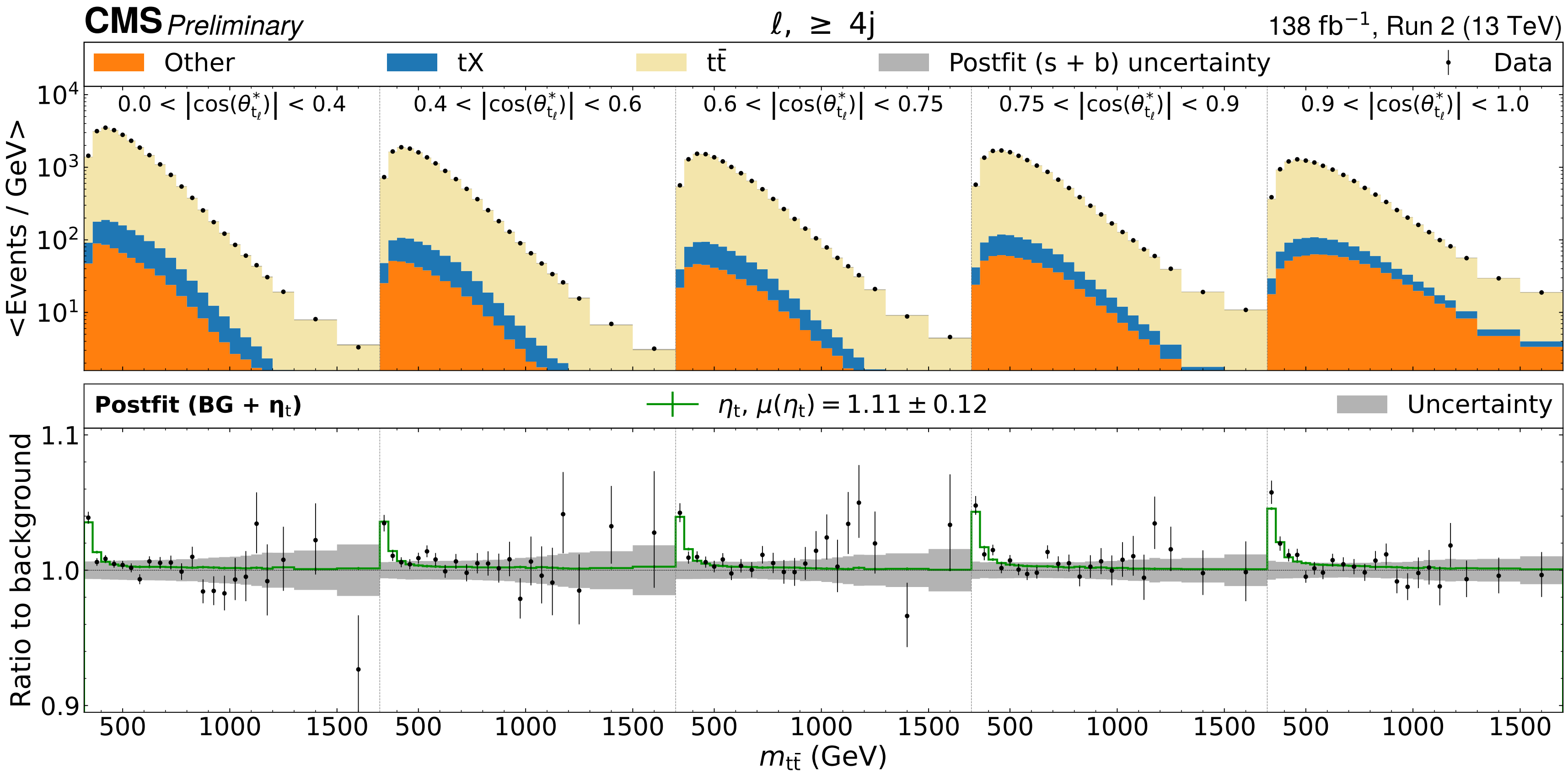
(PRD 104 (2021) 034023)

(JHEP 09 (2010) 034)

- Word of caution: this model is not a complete description of a $t\bar{t}$ bound state!
  - missing e.g. color-octet states - expected to be small
    soft initial state gluons – could change color-octet into singlet states
    etc...

Postfit distributions: η_t (ℓ + ≥4 jets)

Postfit for η_t model describing the data well



Postfit distributions: η_t (ℓℓ)

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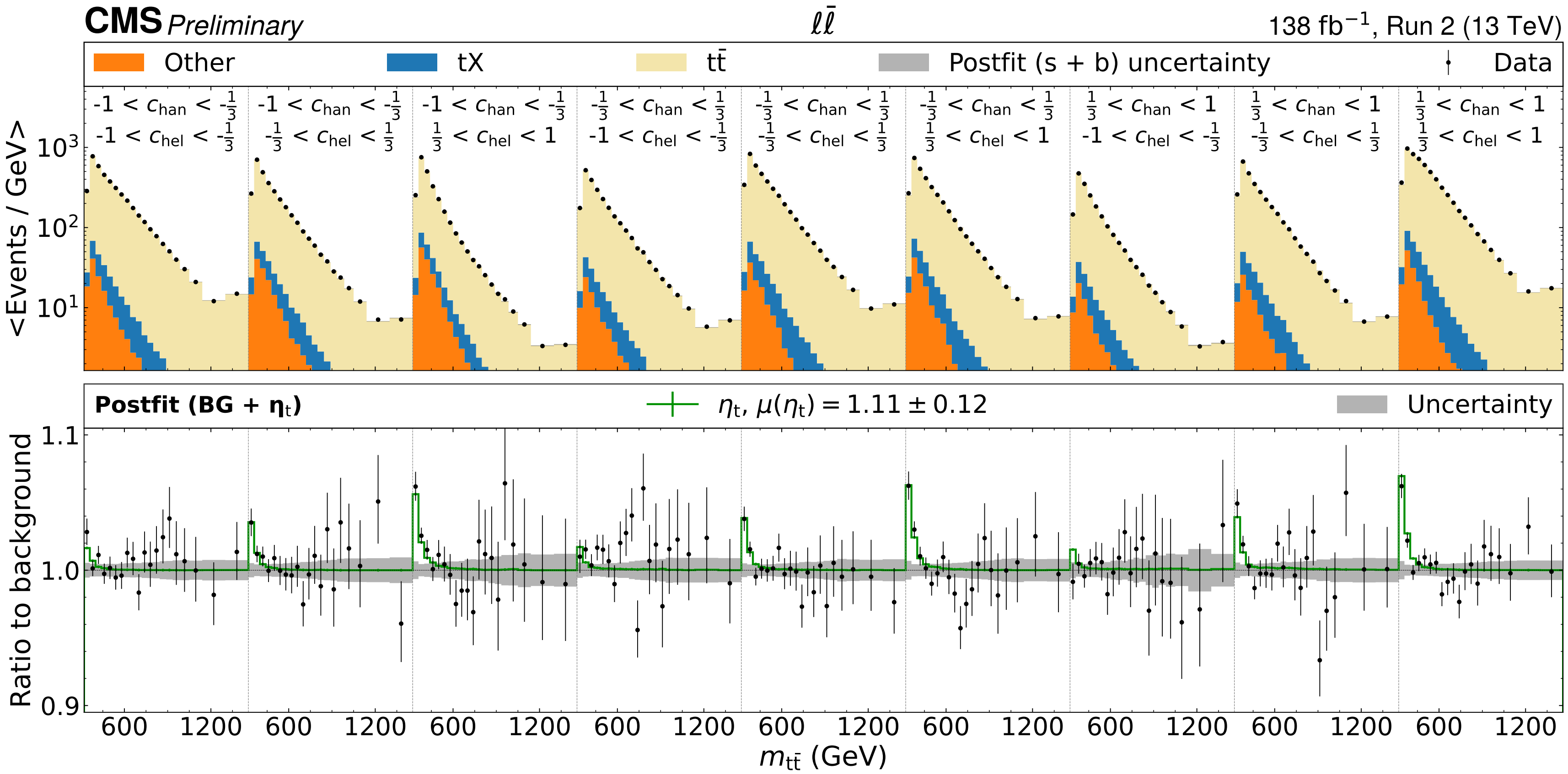

Postfit distributions: η_t ($\ell\ell$)

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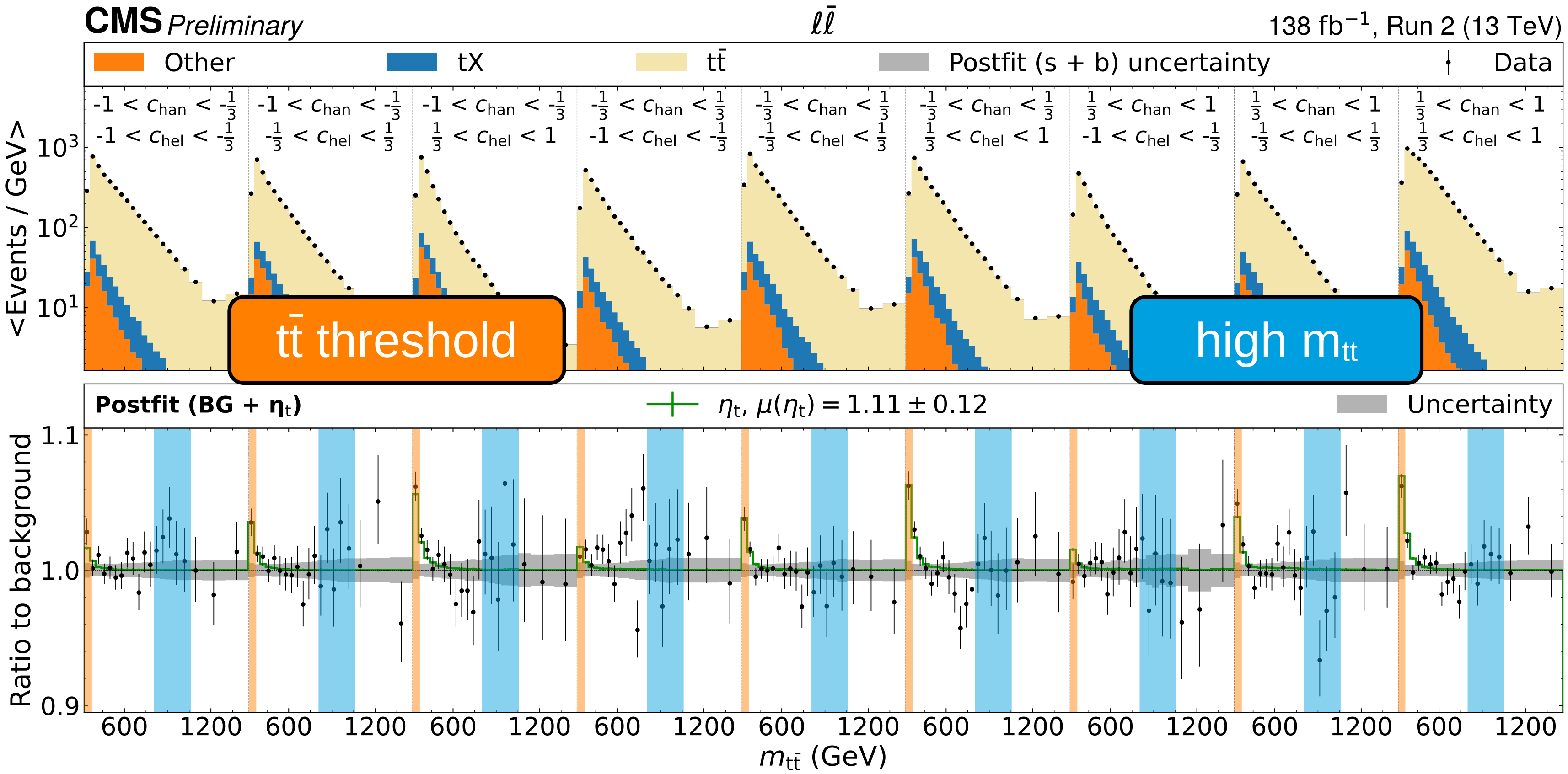
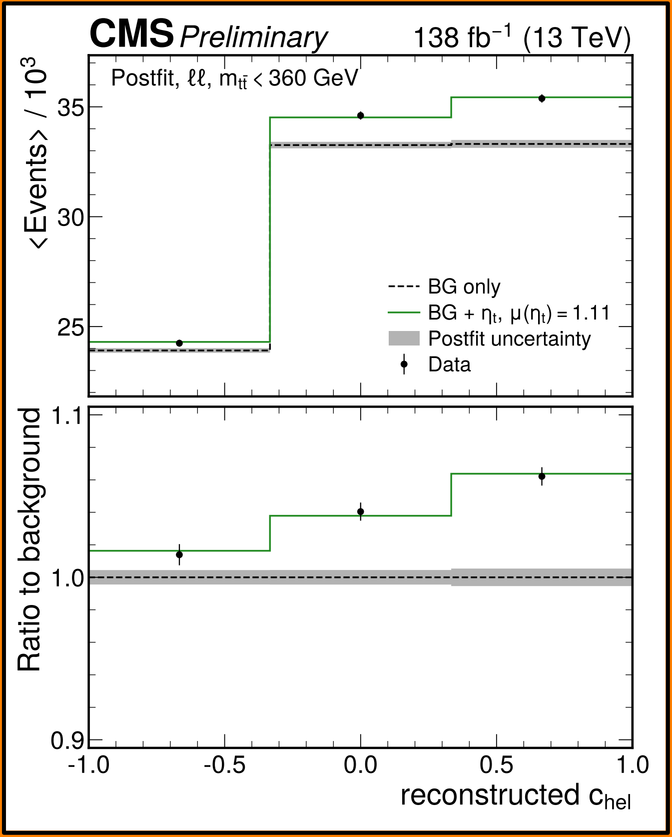
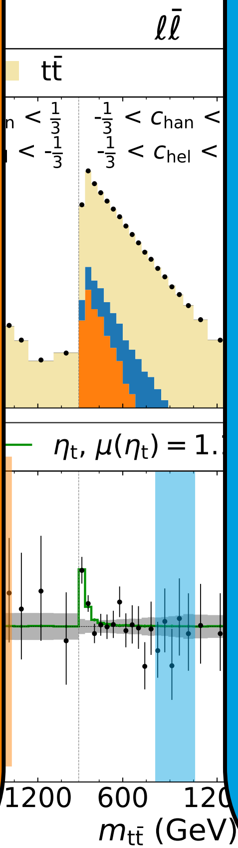


Po… ns: m…

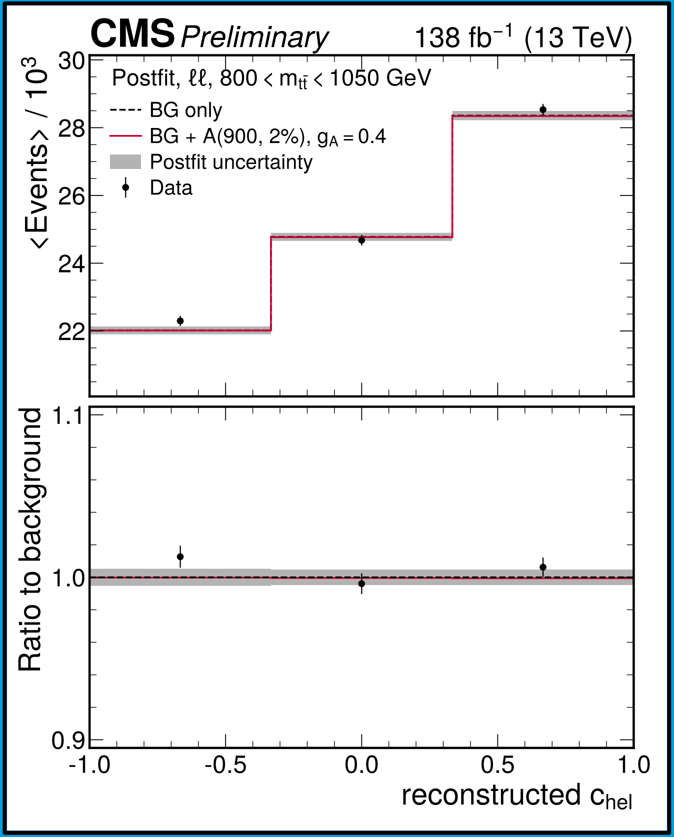
…el describ…

$t\bar{t}$ threshold:
Data shows slope in c_{hel}





high m_{tt}:
No slope in data

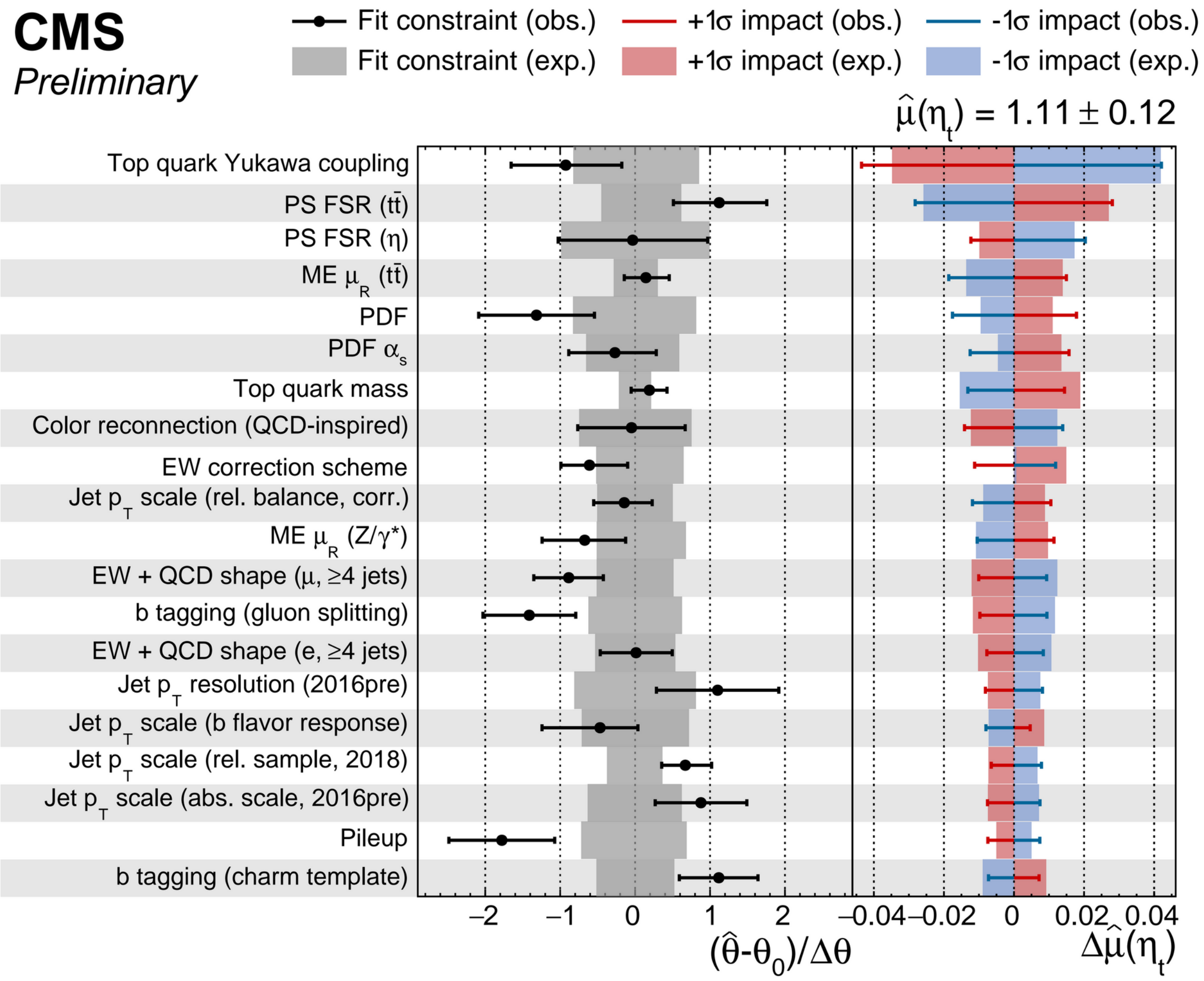


Uncertainties

- Uncertainty on η_t cross section dominated by background modeling

- Leading systematic sources:
  - EW corrections, including SM Top-Higgs Yukawa:

    $y_t = 1.00^{+0.11}_{-0.12}$ (EPJC 79 (2019) 421)
  - Parton shower scales
  - Missing higher orders
  - PDF
  - Top mass



Checks of the result

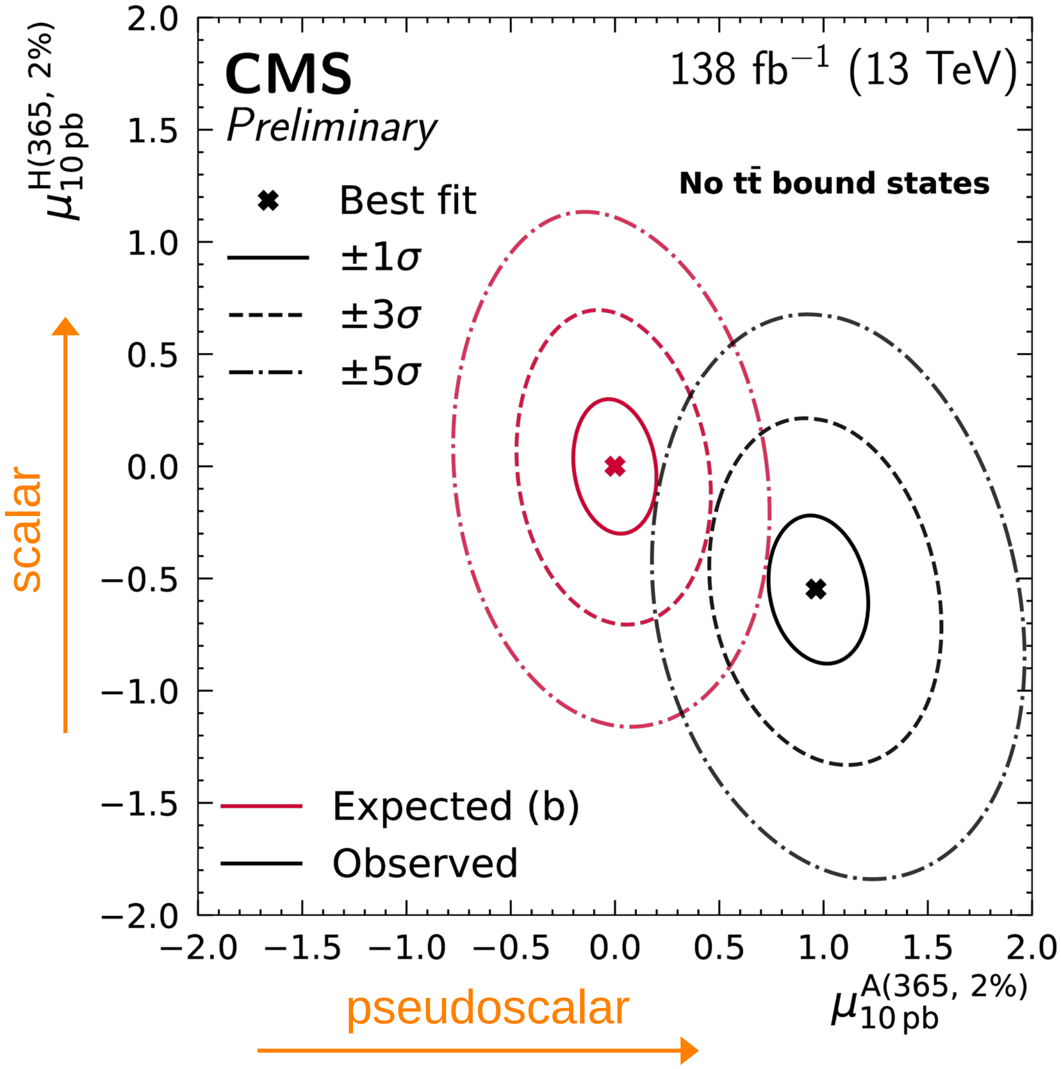
- Off-shell effects in $t\bar{t}$ MC – only approximate in Powheg+Pythia (NWA)
  - Check with Powheg `bb4l` (complete off-shell NLO calculation of pp → $b\bar{b}\ell\bar{\ell}\nu\bar{\nu}$)
  - Only available in dilepton for now
  - Redo our extraction with `bb4l` for the $t\bar{t}$+tW prediction in $\ell\ell$ only

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%

  - Results compatible at ~ 2 SD – excess clearly present also with `bb4l`
- Further checks:
  - different generators for SM $t\bar{t}$ (aMC@NLO+Pythia, Powheg+Herwig)
  - different treatment of NNLO QCD/NLO EW corrections
  - decorrelation of several syst. uncs (e.g. top mass)
- All checks compatible with nominal within uncertainty of result

Parity of the excess

- Can we quantify whether the excess is scalar or pseudoscalar?
- Take low-mass A/H resonances as proxies for pure $^1S_0$ and $^3P_0$ $t\bar{t}$ states
- ➔ 2D fit with arbitrary signal strengths

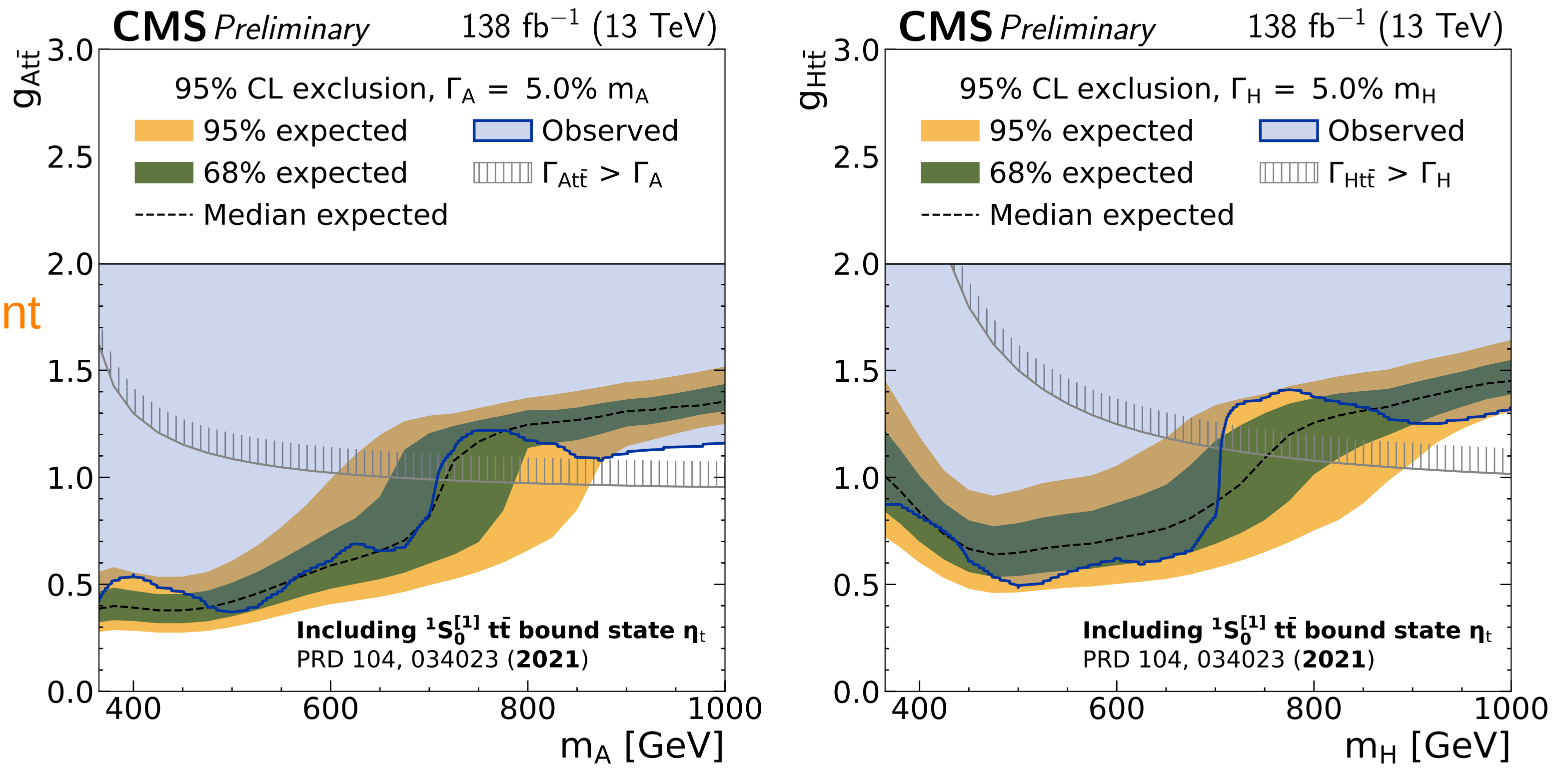


- Data prefers pure $^1S_0$ / pseudoscalar
- scalar component compatible with 0 at the level of ~ 2 SD

A/H limits including η_t

- QCD + η_t describes data well → set (BSM) A/H limits
  → η_t added as an additional BG process with free-floating normalization

Excess no longer present



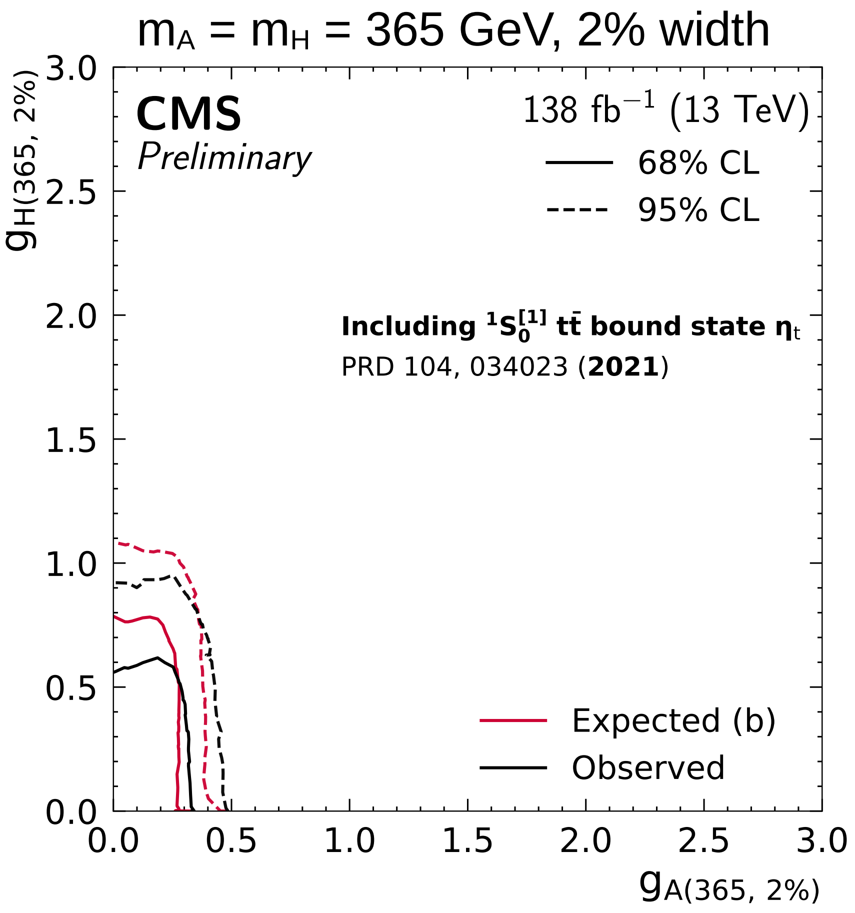
A/H width: 5%

A+H interpretation

- BSM models (e.g. 2HDM) often predict the simultaneous presence of A and H

➔ Model-independent exclusion contours for both A and H couplings
  - numerical Feldman-Cousins method

- Input for bounds on concrete BSM models



Summary

- 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_{tt}, angular and spin observables
- Observed excess in data at low m_{tt} – consistent with pseudoscalar
  - Interpretations in terms of a simplified model of a $t\bar{t}$ bound state η_t or a generic pseudoscalar A and scalar H
  - Extracted cross section for a parametrized η_t (toy) model (PRD 104 (2021) 034023)
- Set stringent limits on A, H, and A+H with η_t included in the background
- For the future:
  An improved non-relativistic QCD calculation of $t\bar{t}$ bound state effects is crucial!
  Input from theory welcome
- Whatever the excess is – it is exciting!

Reference: **CMS-PAS-HIG-22-013**

Backup

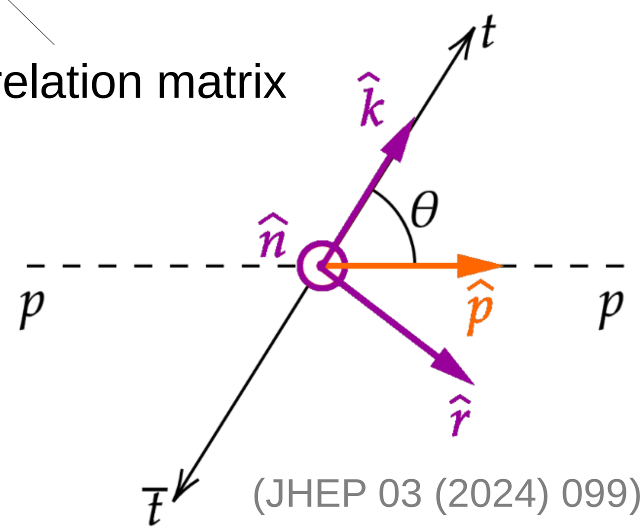
Spin density matrix

- Both A/H and η_t predict $t\bar{t}$ production in a pure $t\bar{t}$ spin state: $^1S_0$ or $^3P_0$ (from A / η_t resp. H)
- Encoded in spin density matrix:

$$\mathbf{R} = A + B_i\sigma_i + \overline{B}_i\overline{\sigma}_i + \sigma_i C_{ij}\overline{\sigma}_j$$

cross section — polarization vectors — correlation matrix

- Choose helicity basis $\{\hat{k}, \hat{r}, \hat{n}\}$:
  - $\hat{k}$: direction of flight of the top quark
  - $\hat{r}$ and $\hat{n}$: orthogonal to $\hat{k}$

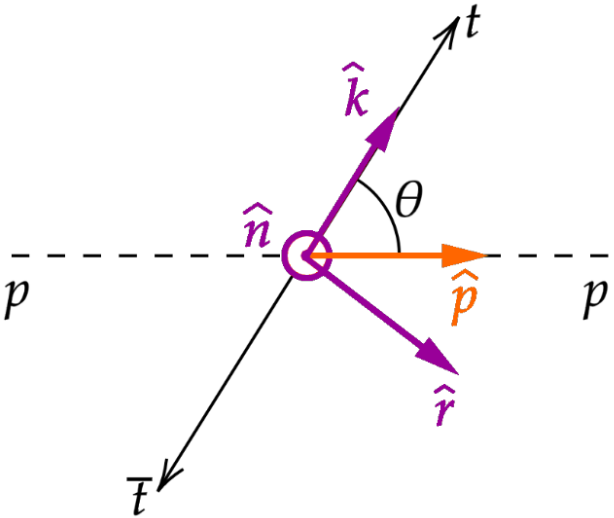


(JHEP 03 (2024) 099)

Definition of c_{hel} and c_{han}

- Start in $t\bar{t}$ rest frame, boost leptons into rest frames of their parent tops
- Define lepton three-momenta $\hat{\ell}^+$ and $\hat{\ell}^-$ w.r.t $\{\hat{k}, \hat{r}, \hat{n}\}$ basis:
  - $\hat{k}$: direction of flight of the top quark
  - $\hat{r}$: orthogonal to $\hat{k}$ in the scattering plane
  - $\hat{n}$: orthogonal to $\hat{k}$ and $\hat{r}$

$$c_{\mathrm{hel}} = -(\hat{\ell}^+)_k(\hat{\ell}^-)_k - (\hat{\ell}^+)_r(\hat{\ell}^-)_r - (\hat{\ell}^+)_n(\hat{\ell}^-)_n$$
$$c_{\mathrm{han}} = +(\hat{\ell}^+)_k(\hat{\ell}^-)_k - (\hat{\ell}^+)_r(\hat{\ell}^-)_r - (\hat{\ell}^+)_n(\hat{\ell}^-)_n$$



- It can be shown that they follow a straight line with

$$\frac{1}{\sigma}\frac{d\sigma}{dc_{\mathrm{hel}}} = \frac{1}{2}\left(1 - D\, c_{\mathrm{hel}}\right) \qquad \frac{1}{\sigma}\frac{d\sigma}{dc_{\mathrm{han}}} = \frac{1}{2}\left(1 + D^{(k)}\, c_{\mathrm{han}}\right)$$

(JHEP 03 (2024) 099)

List of systematic uncertainties

Experimental

- Jet energy corrections - split into 11 subsources
- Jet energy resolution
- Unclustered p^{T}_{miss} (uncorrelated between years)
- Luminosity – correlated and decorrelated parts between years
- Pileup
- Trigger efficiencies (separate for ℓℓ / ℓj)
- Electron efficiencies (reco. & ID)
- Muon efficiencies – split into syst. and stat.
- B tagging and mistagging efficiencies
  - B tagging split into subsources
- L1 ECAL prefiring (where applicable)
- Data-driven EW+QCD BG (ℓ+jets) : shape & rate (50%) uncorrelated between channels
- Data-driven Z+jets normalization (ℓℓ)

Theory

- Factorization & renormalization scales:
  - $t\bar{t}$, tW, tq, Z+jets; η_t (BG or signal), A/H signal
  - Uncorrelated between processes
  - $t\bar{t}$: including cross section variation
- Same for initial & final state radiation PS scales
- MC top mass: ±1GeV (interpolated from ±3GeV)
  - Also including cross section variations
- ME-PS matching (h_{damp})
- Underlying event tune
- Color reconnection: 3 different samples
- PDF: PCA performed on final templates from 100 replicas → only leading component considered
- PDF α_s
- Electroweak corrections:
  - SM Higgs-Top Yukawa coupling (1 +0.11 -0.12)
  - EW correction scheme (additive v. multiplicative)
- Minor BG cross sections: 15% for tW and tq; 30% for Diboson and $t\bar{t}$+X

List of MC generators

Process	QCD order	ME Generator
$t\bar{t}$	NLO	POWHEG v2 (hvq)
tW	NLO	POWHEG v2 (ST_wtch)
Z+jets	NNLO	POWHEG v2 (Zj MiNNLO)
t-channel single top	NLO	POWHEG v2 (ST_tch) + MADSPIN
s-channel single top	NLO	MG5_aMC@NLO
$t\bar{t}W$	NLO	MG5_aMC@NLO
$t\bar{t}Z$	NLO	MG5_aMC@NLO
WW, WZ & ZZ	LO	PYTHIA 8.2
A/H signal	LO	MG5_aMC@NLO
η_t signal	LO	MG5_aMC@NLO

Data-driven Z+jets normalization

- b jets in Z+jets are known to be badly modeled in MC – might lead to wrong normalization after requiring >= 1 btag
- Take normalization from Z peak sideband ($R_{in/out}$ method)
- Use weaker assumption than standard $R_{in/out}$ ("ratio of ratios"):
  Get $R_{in/out}$ in 0 b tag sideband; take "ratio of ratios" for ≥ 1 and 0 btags from MC

$$\frac{(R^{\geq 1b}_{in/out})_{data}}{(R^{\geq 1b}_{in/out})_{MC}} = \frac{(R^{0b}_{in/out})_{data}}{(R^{0b}_{in/out})_{MC}} \rightarrow \mathrm{SF} = \frac{(N^{\geq 1b}_{out})_{data}}{(N^{\geq 1b}_{out})_{MC}} = \frac{(N^{\geq 1b}_{in})_{data}}{(N^{\geq 1b}_{in})_{MC}} \frac{(R^{0b}_{in/out})_{MC}}{(R^{0b}_{in/out})_{data}}.$$

with $N_{data} = N^{\ell\ell}_{data} - 0.5 N^{e\mu}_{data} k_{\ell\ell}, \quad \text{where } k_{ee} = \frac{1}{k_{\mu\mu}} = \sqrt{\frac{N^{ee}_{data}}{N^{\mu\mu}_{data}}}$

EW corrections to $t\bar{t}$

- Our EW correction (Hathor) is NLO in EW but LO in QCD
- Ambiguity on how to apply EW corrections to (N)NLO simulation
- Nominal choice: multiplicative

Hathor

Powheg

$$\sigma^{\text{rew.}} = \sigma^{\text{LO EW}}_{\text{NLO QCD}} \times \frac{\sigma^{\text{NLO EW}}_{\text{LO QCD}}}{\sigma^{\text{LO EW}}_{\text{LO QCD}}}$$

MadGraph

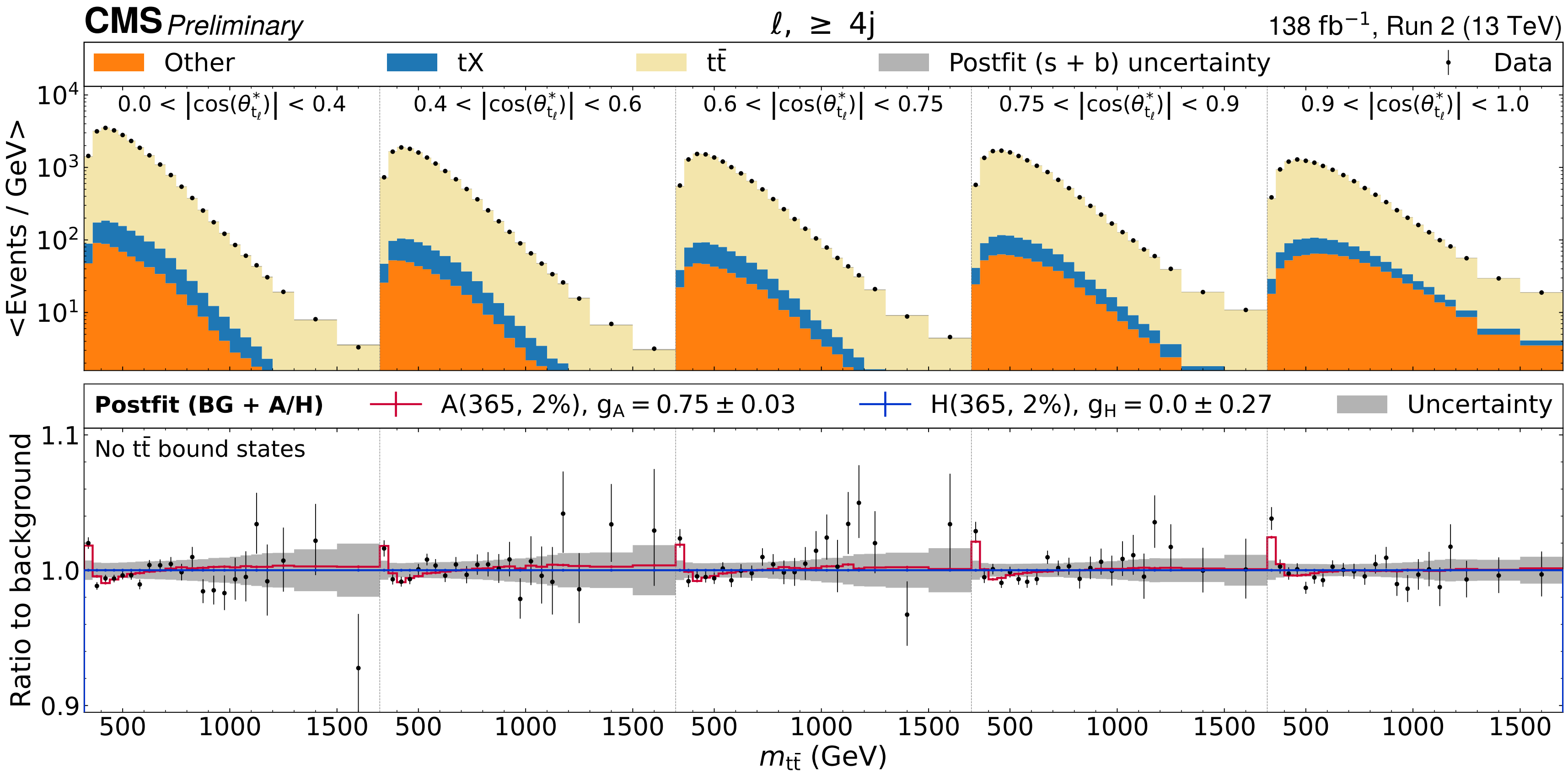
- Alternate choice: additive

$$\sigma^{\text{rew.}} = \sigma^{\text{LO EW}}_{\text{NLO QCD}} + \sigma^{\text{NLO EW}}_{\text{LO QCD}} - \sigma^{\text{LO EW}}_{\text{LO QCD}}$$

- Difference treated as systematic uncertainty

Postfit distributions: A/H

Postfit for A, 365 GeV, 2% width (best fit point)



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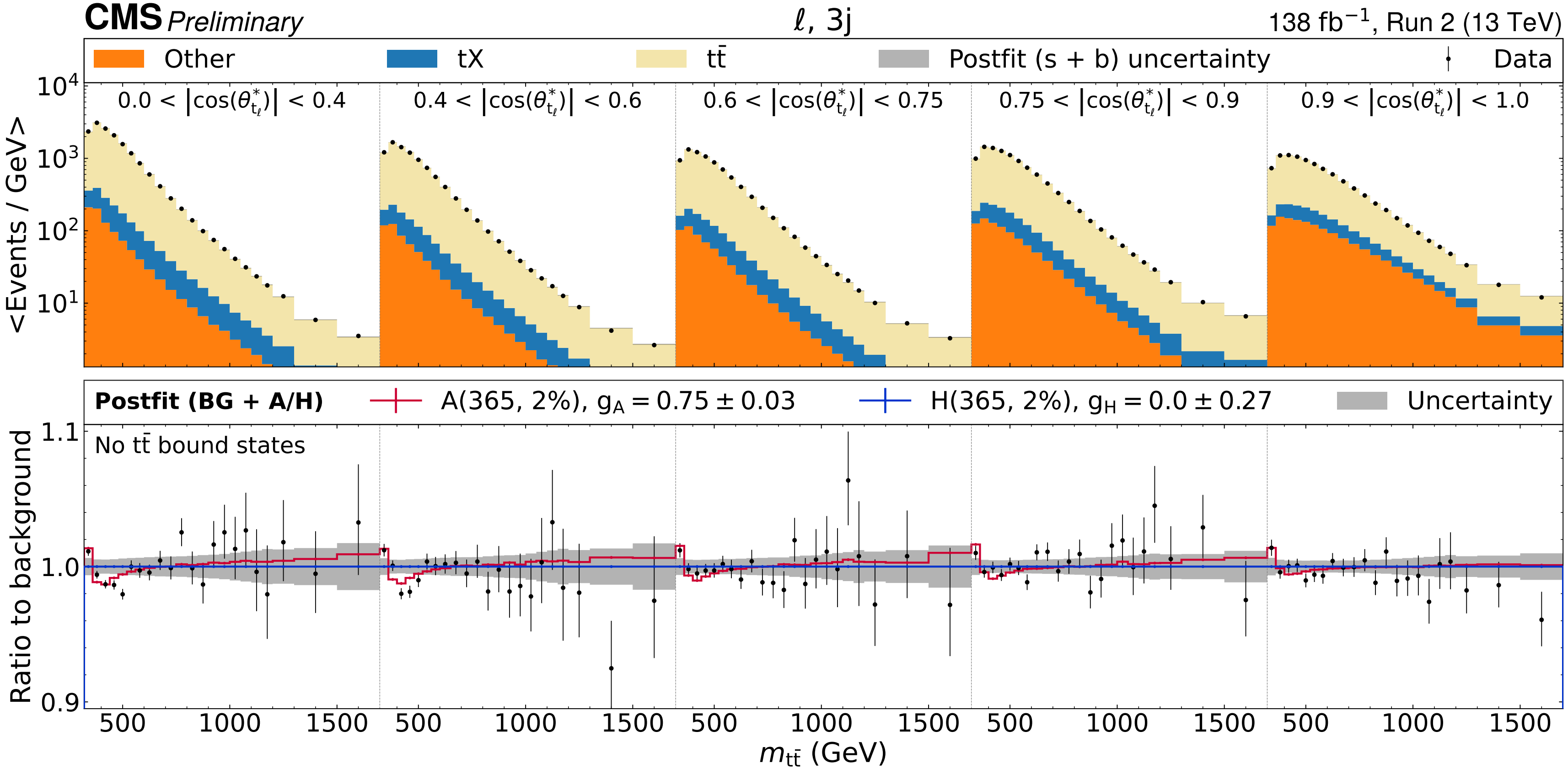
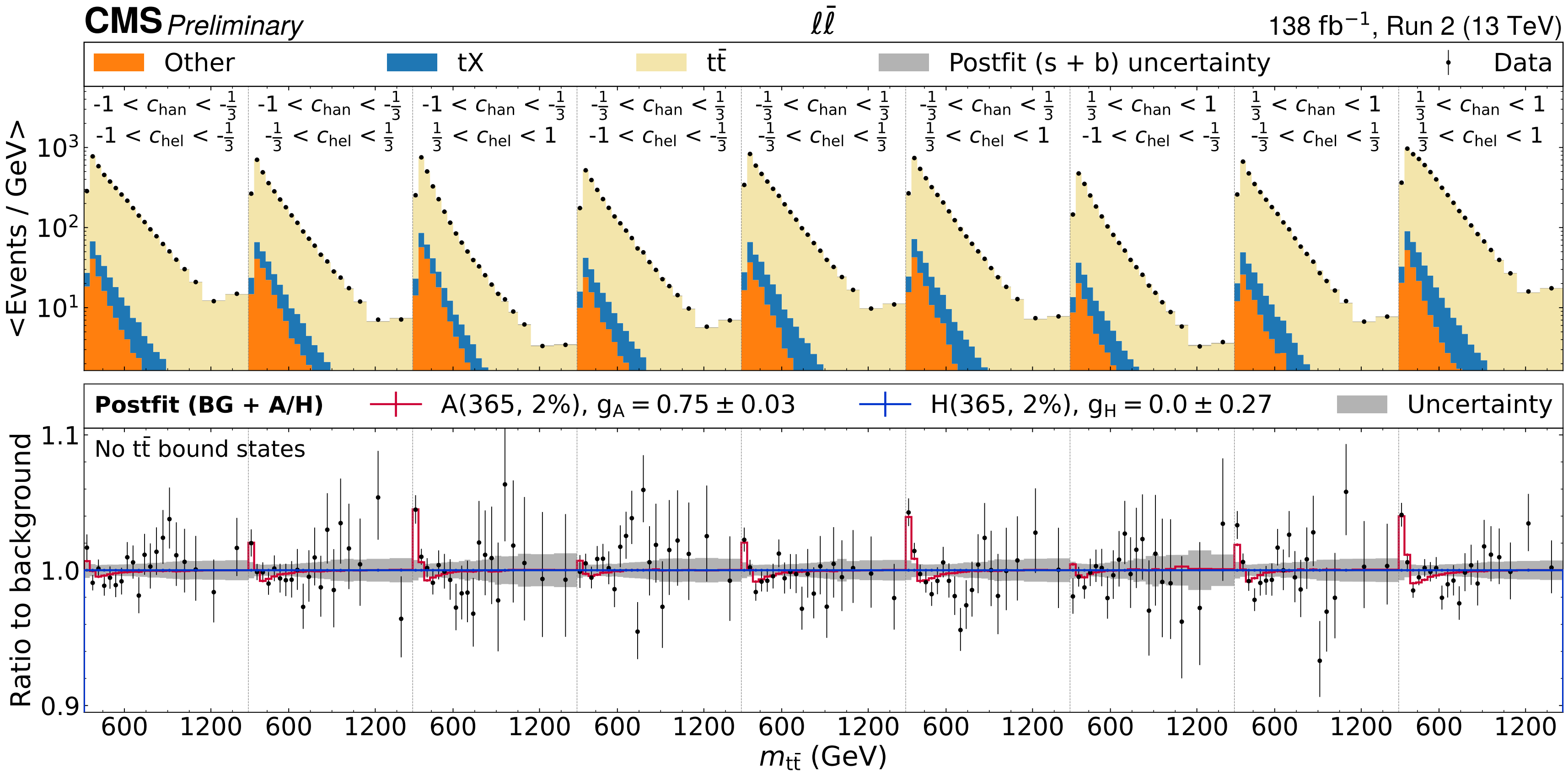


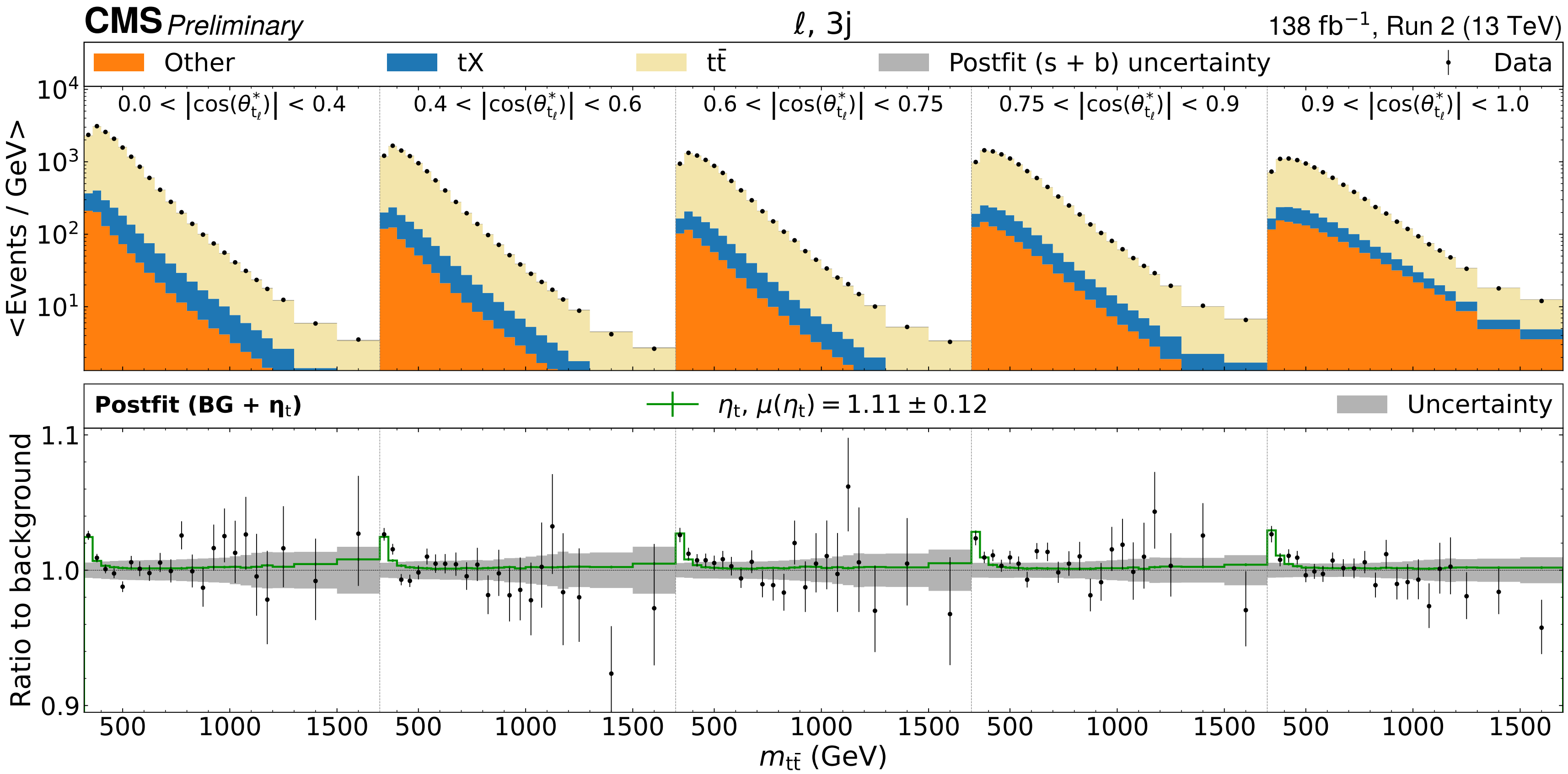
Postfit distributions: A/H

Postfit for A, 365 GeV, 2% width (best fit point)



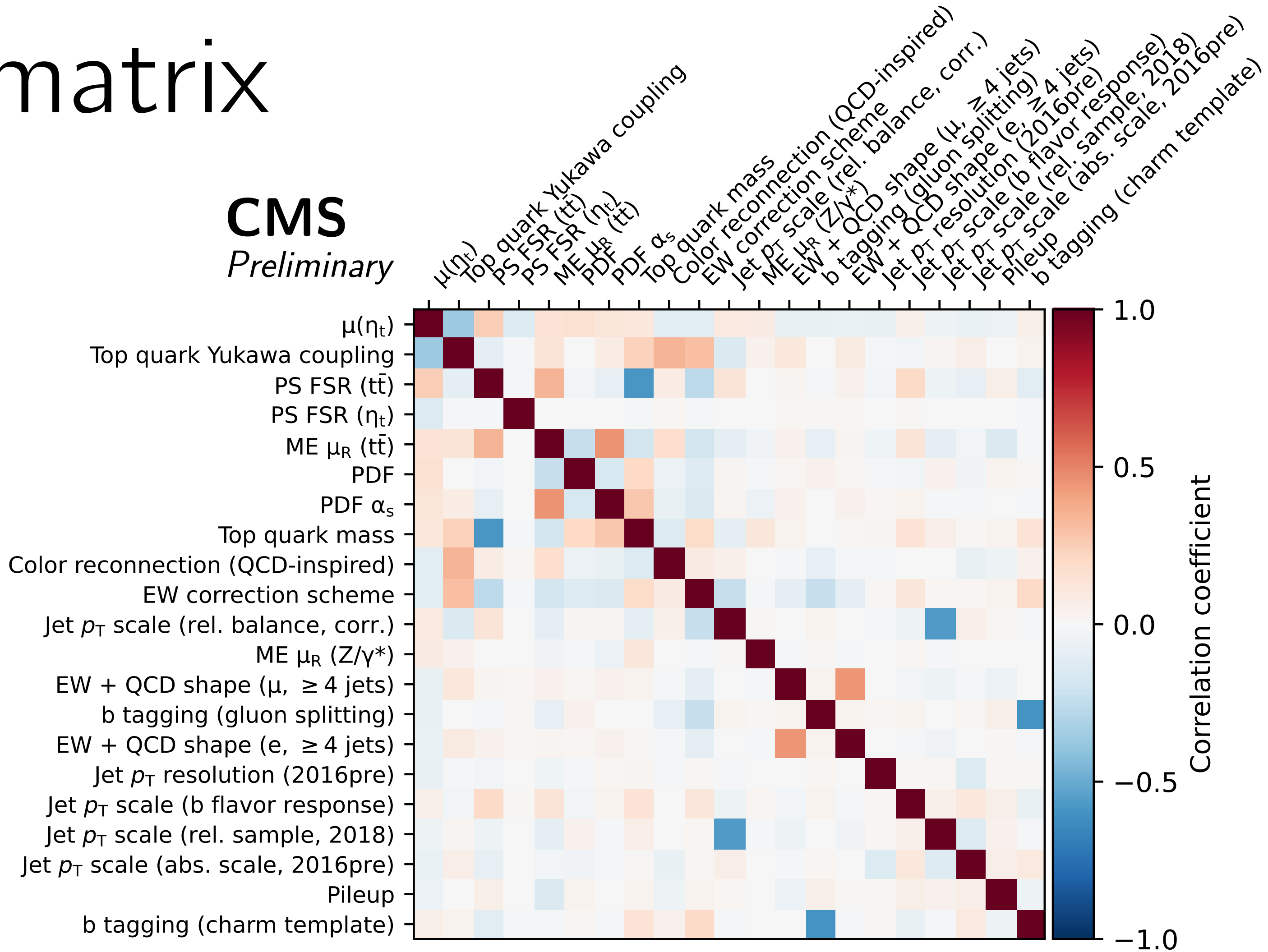
Postfit distributions: η_t

Postfit for η_t



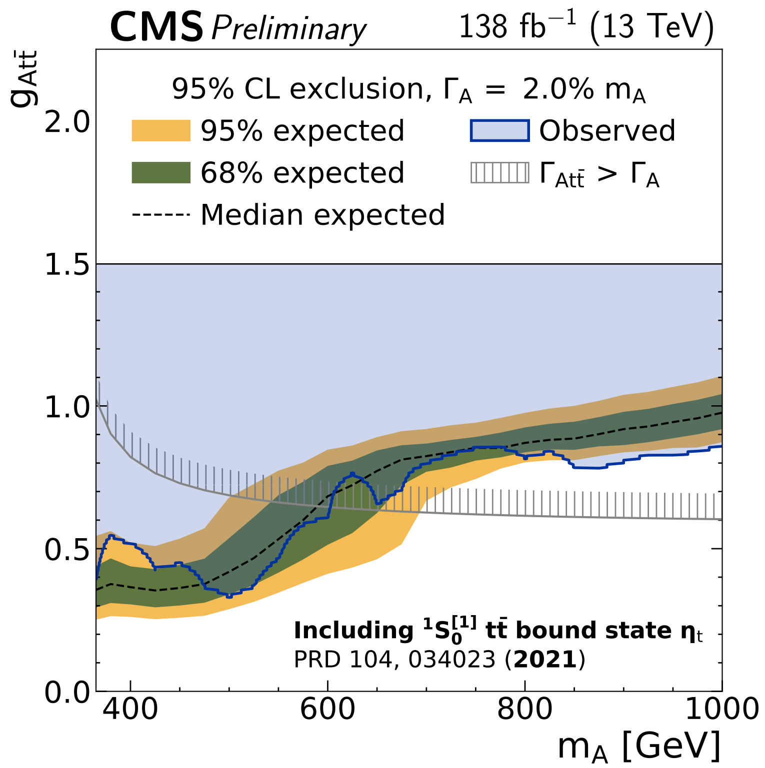
Correlation matrix

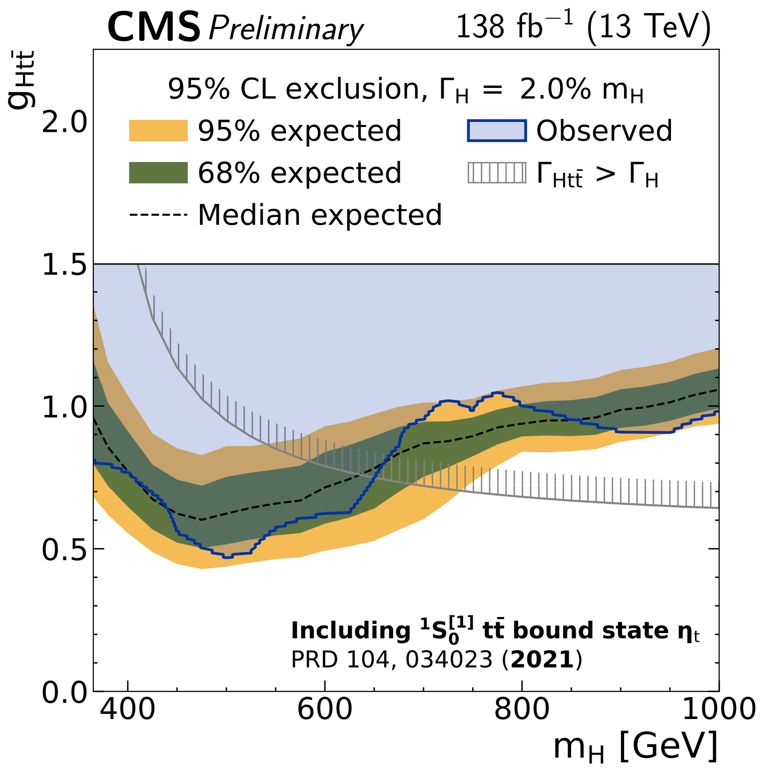
- Further assess uncertainty modeling through correlations of nuisance parameters



A/H limits including η_t

- Limits at different A/H widths

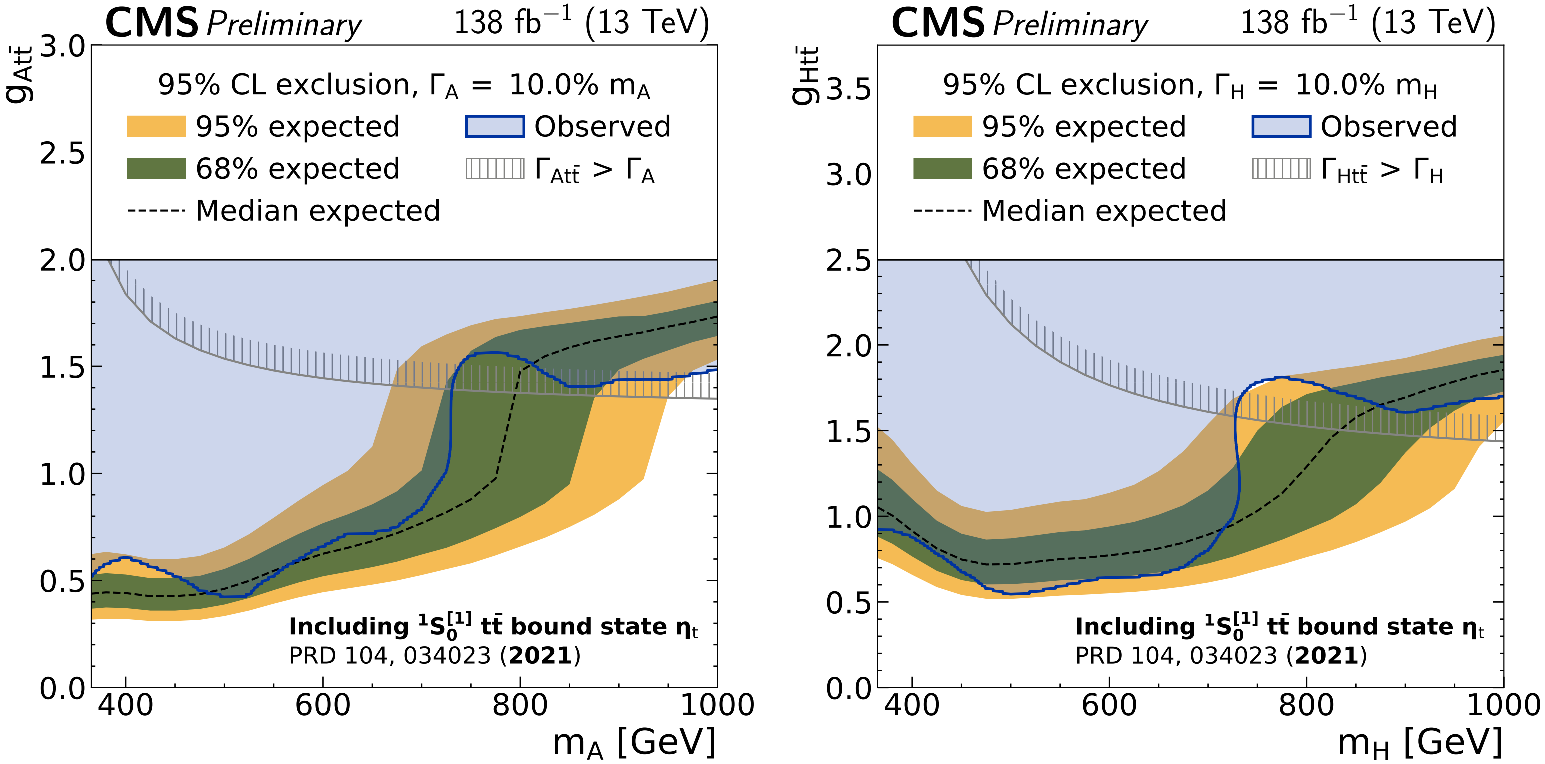




2% width

A/H limits including η_t

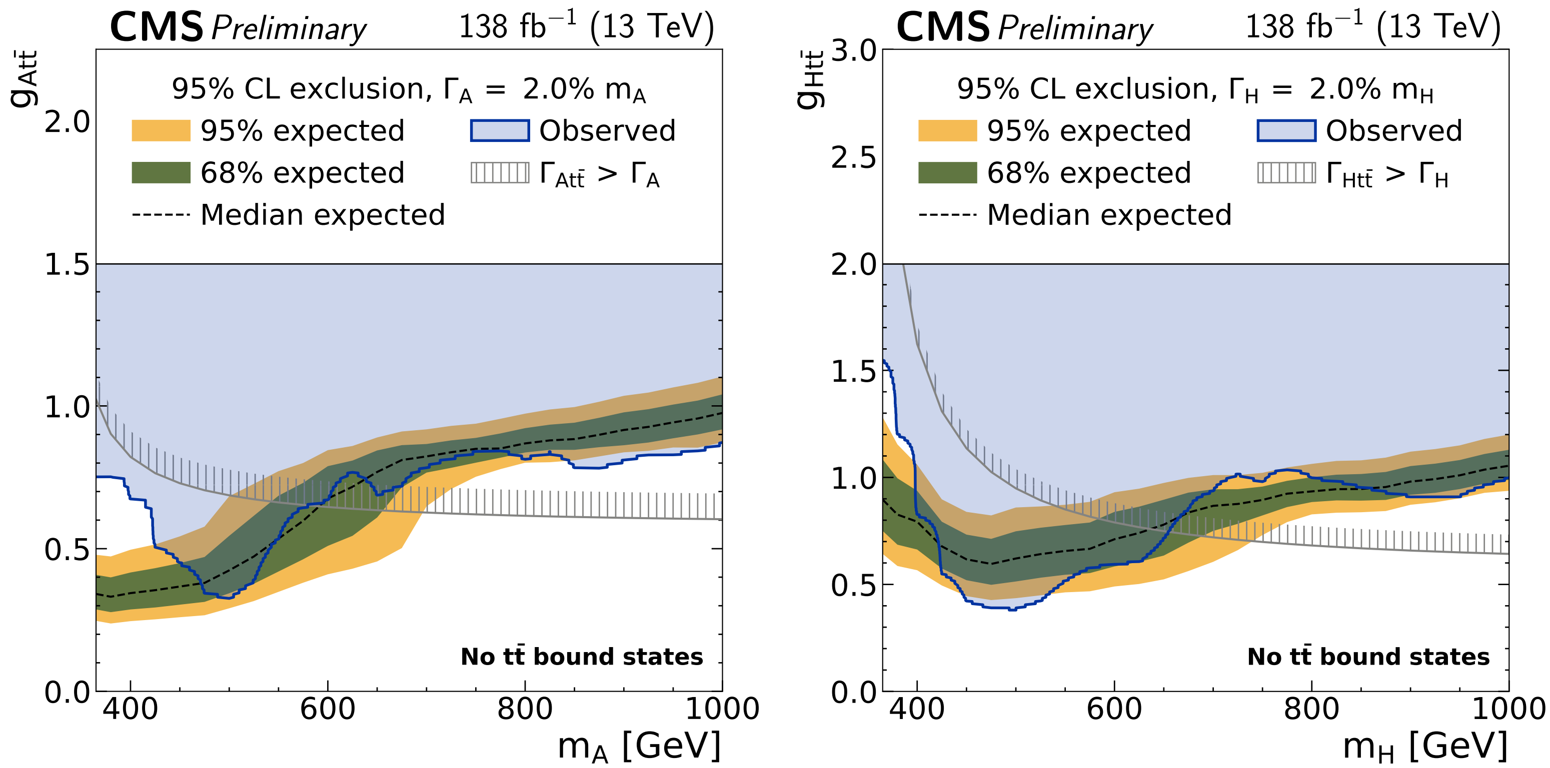
- Limits at different A/H widths



10% width

A/H limits without η_t

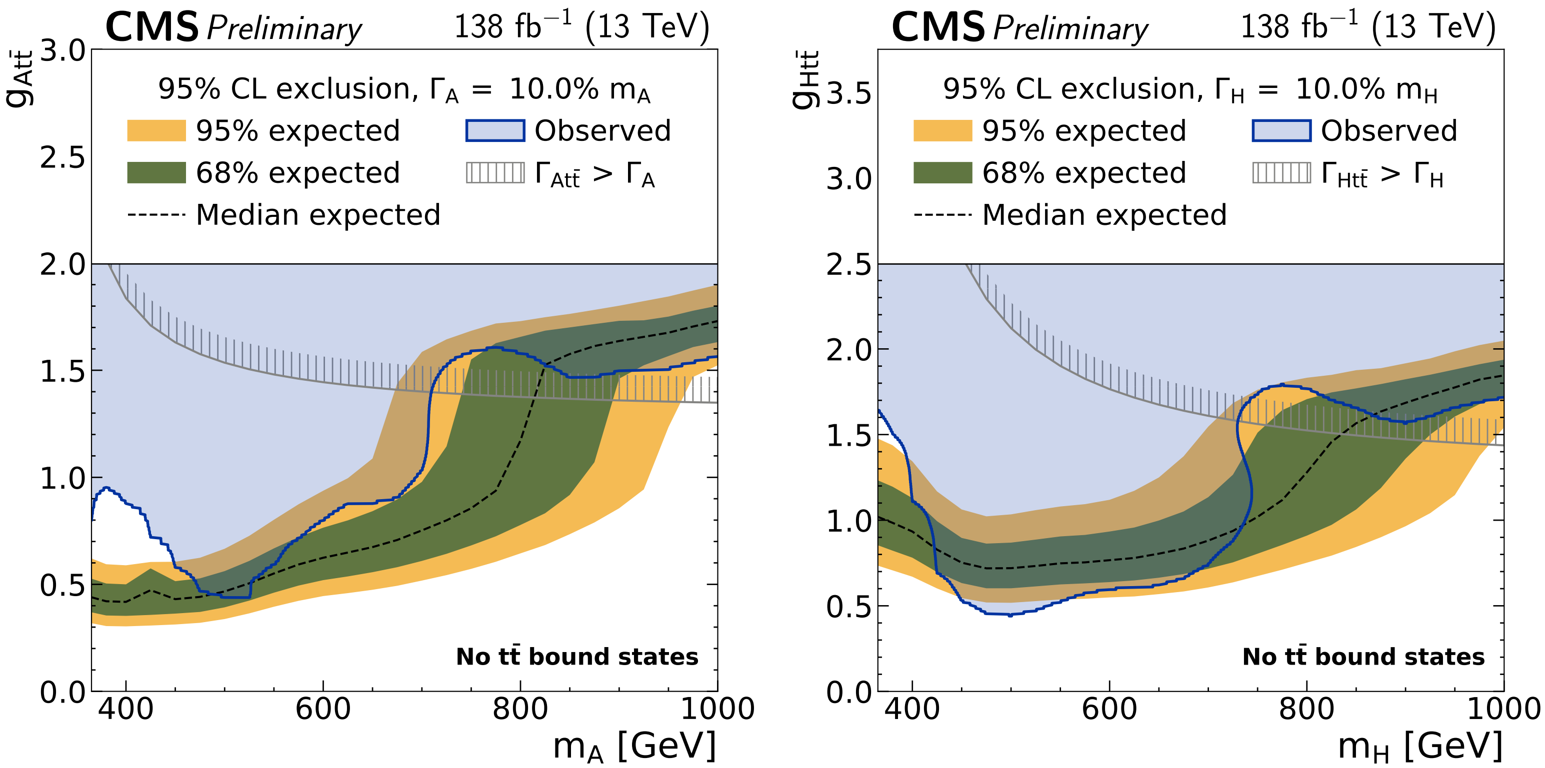
- Limits at different A/H widths for perturbative QCD background only



2% width

A/H limits without η_t

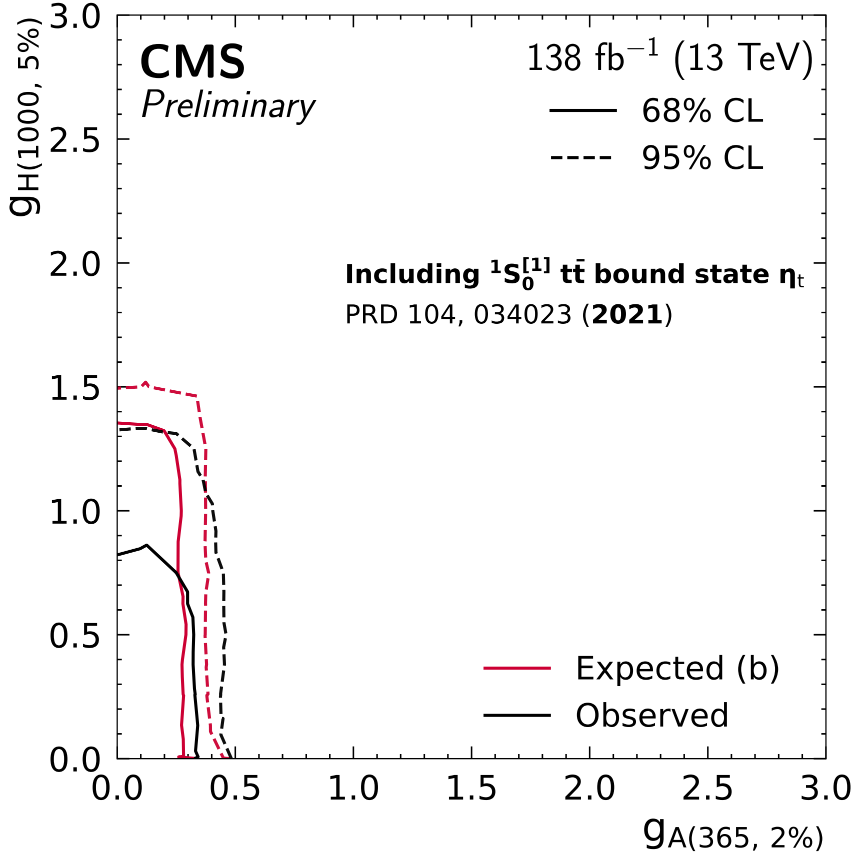
- Limits at different A/H widths for perturbative QCD background only



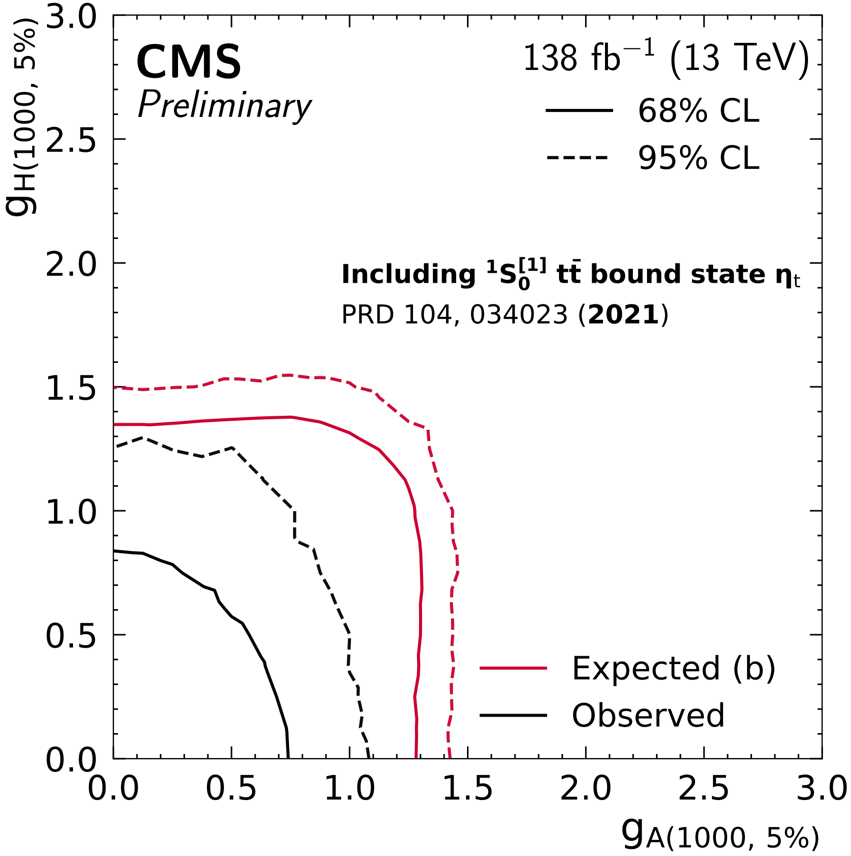
10% width

A+H interpretation

m_A = 365 GeV, 2% width; m_H = 1000 GeV, 5% width



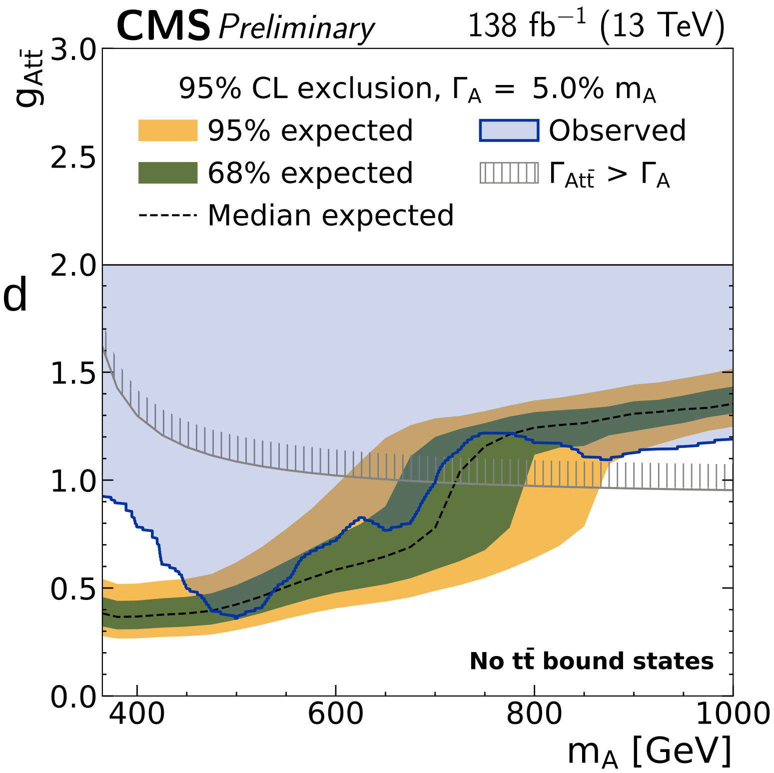
m_A = m_H = 1000 GeV, 5% width



Comparison with ATLAS

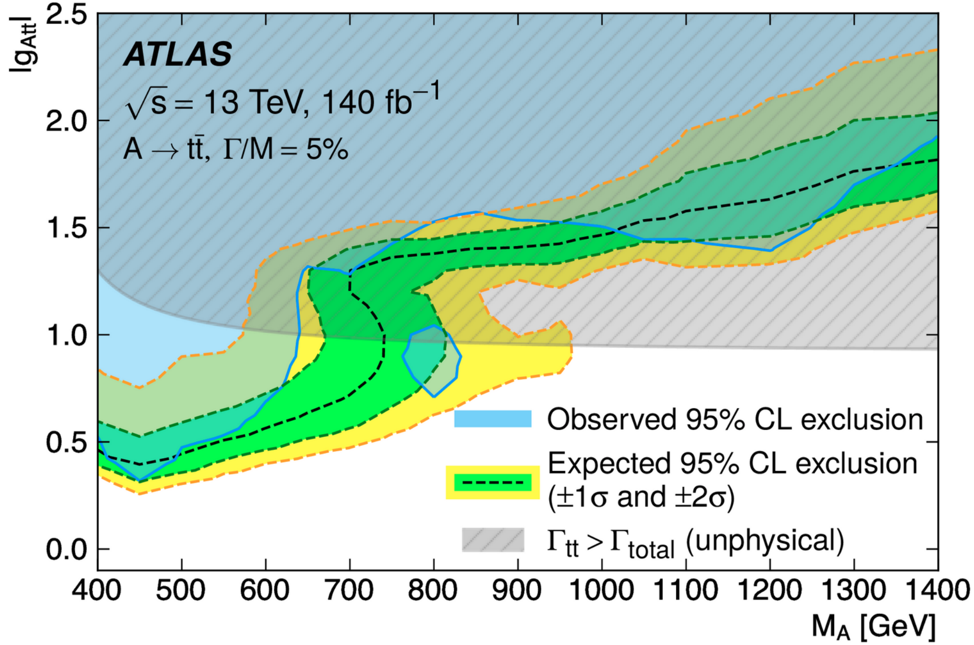
- Similar full Run 2 ATLAS result: does not see any postfit excess! why?

No η_t included



Pseudoscalar
5% width

JHEP08 (2024) 013



Comparison with ATLAS

- Different channel definitions in ATLAS and CMS
- ℓ+jets resolved:
  - ATLAS: 1ℓ, 1b, ≥4 jets
  - CMS: 1ℓ, 2b, 3 jets
  - both: 1ℓ, 2b, ≥4 jets
    → compare pre-fit distributions!
  - Similar prefit excess in data at low m_{tt}!

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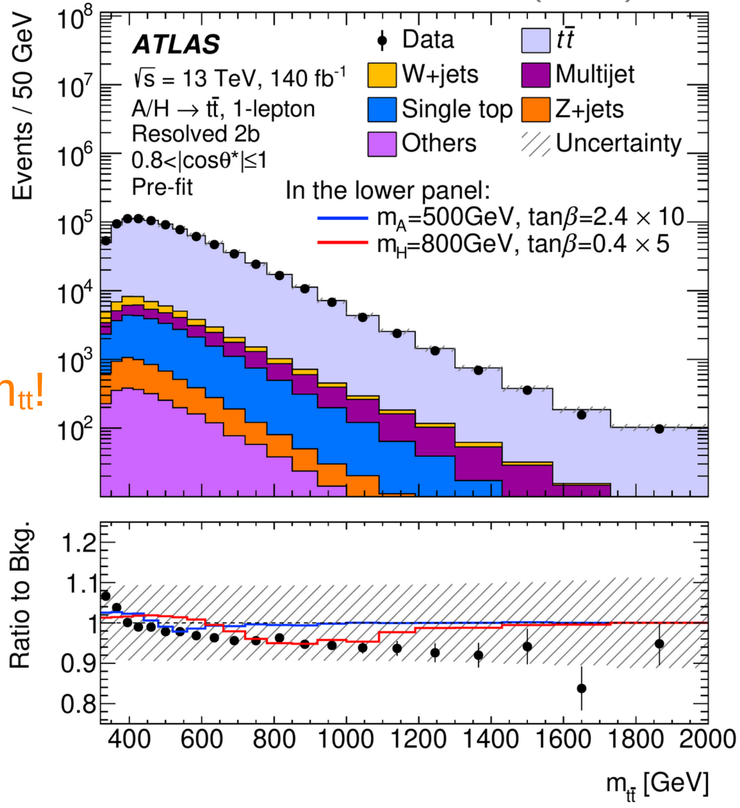

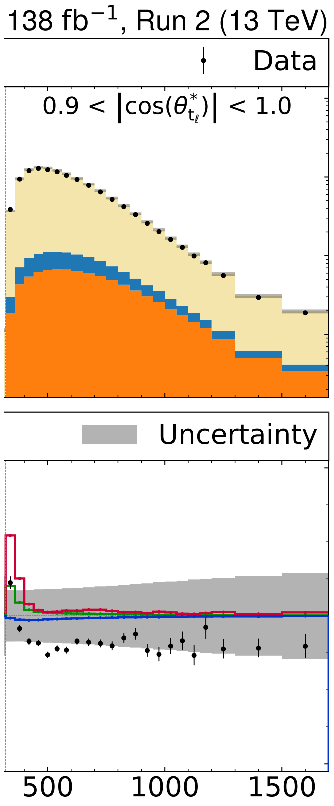

Comparison with ATLAS

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- ℓ+jets resolved:
  - ATLAS: 1ℓ, 1b, ≥4 jets
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  - both: 1ℓ, 2b, ≥4 jets
    → compare pre-fit distributions!
  - Similar prefit excess in data at low m_{tt}!

- dilepton: difficult to compare
  - CMS: reconstruct m_{tt} x c_{hel} x c_{han}
  - ATLAS: no top quark reconstruction instead: $m_{\ell\ell bb}$ x $\Delta\phi_{\ell\ell}$

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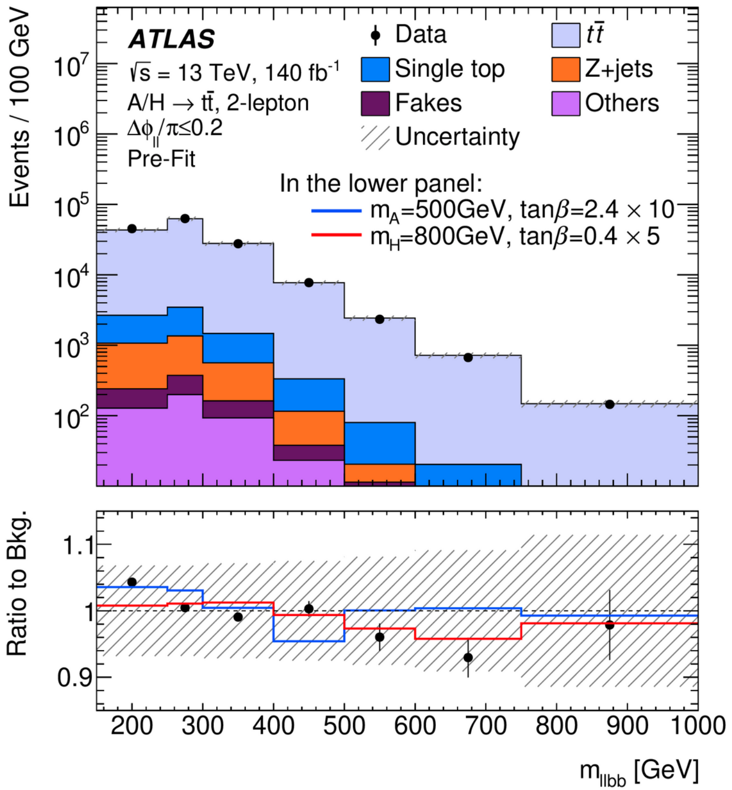
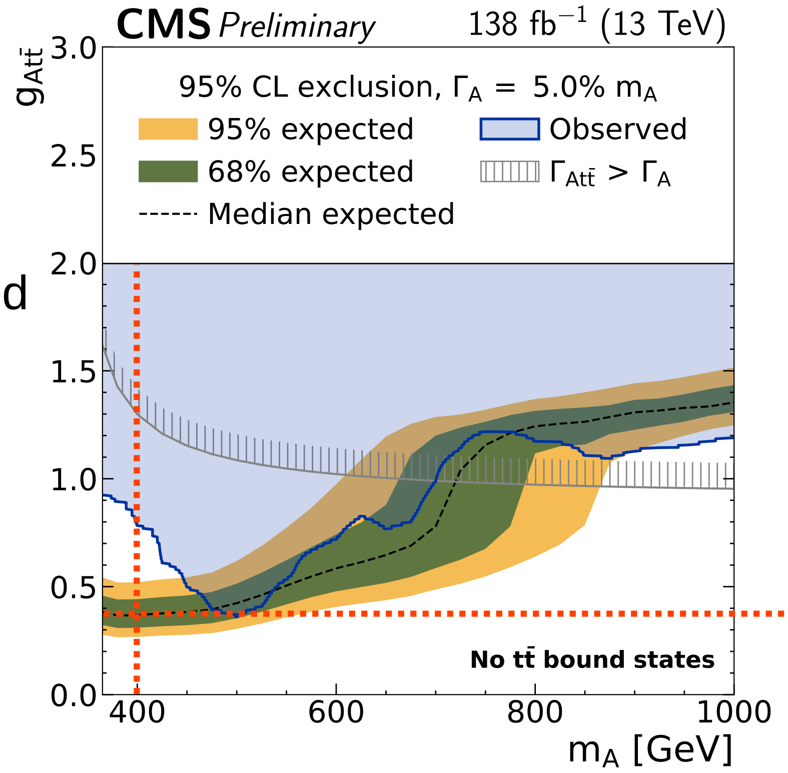


Comparison with ATLAS

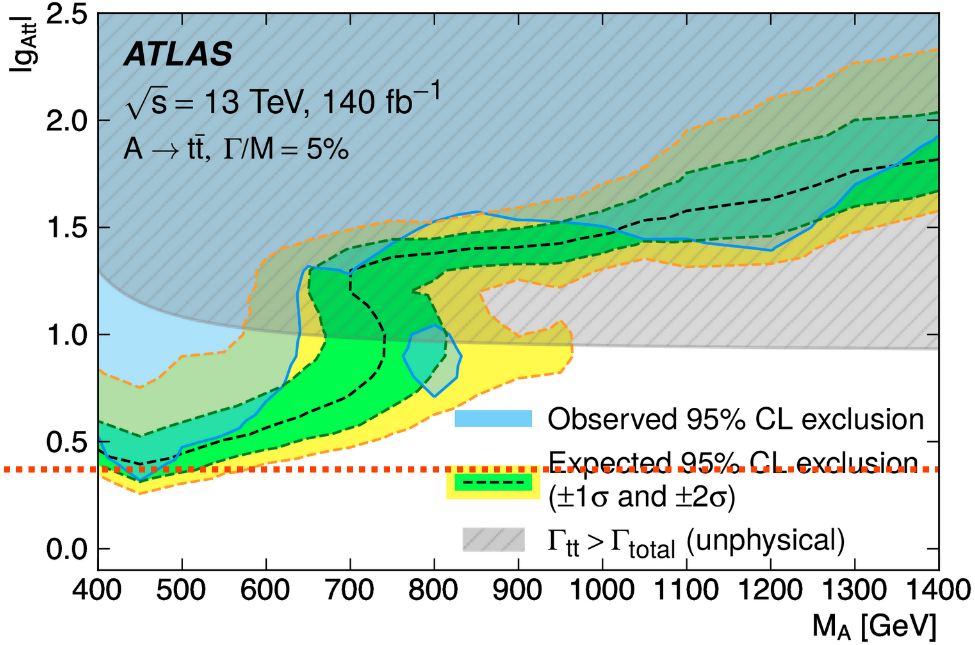
- Similar prefit excess & expected limits – but no postfit excess for ATLAS!
- We are comparing in detail...

Pseudoscalar
5% width

No η_t included



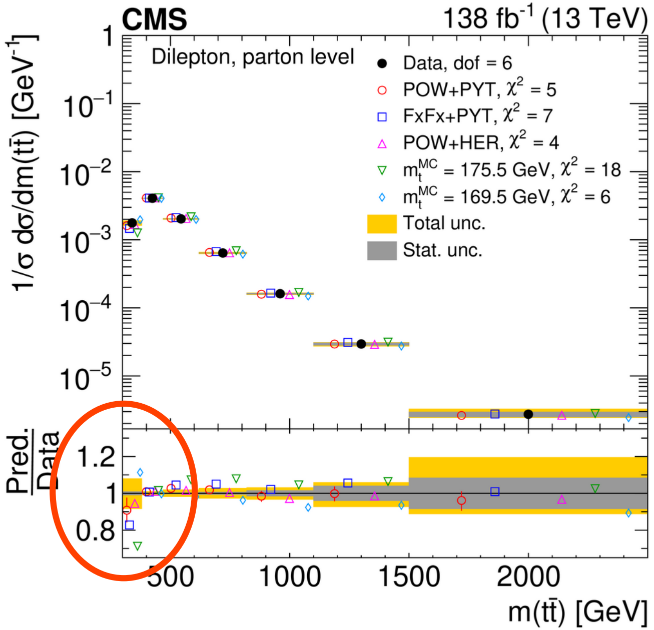
JHEP08 (2024) 013



SM: $t\bar{t}$ differential measurements

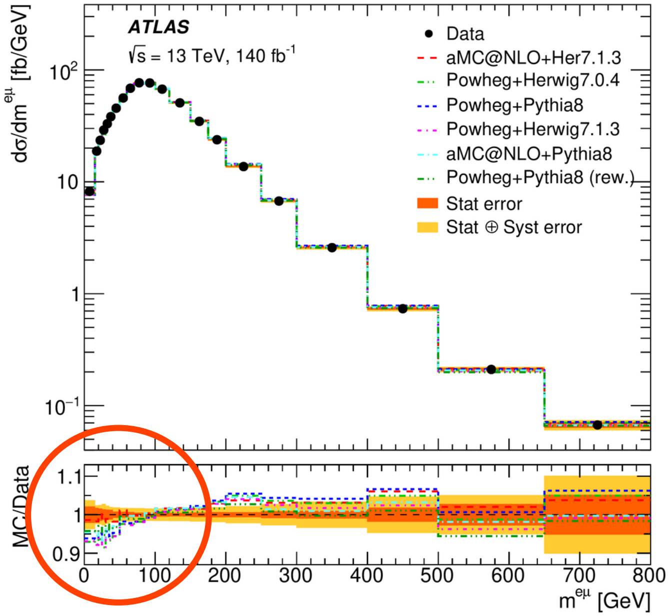
CMS ℓℓ - m_{tt}

CMS-PAS-TOP-20-006



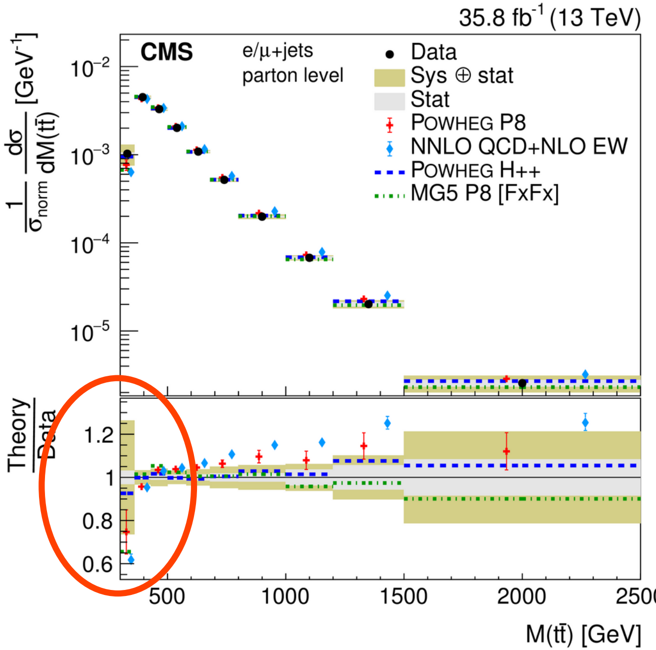
ATLAS eμ - $m_{e\mu}$

JHEP 07 (2023) 141



CMS ℓ+jets - m_{tt}

PRD 97 (2018) 112003

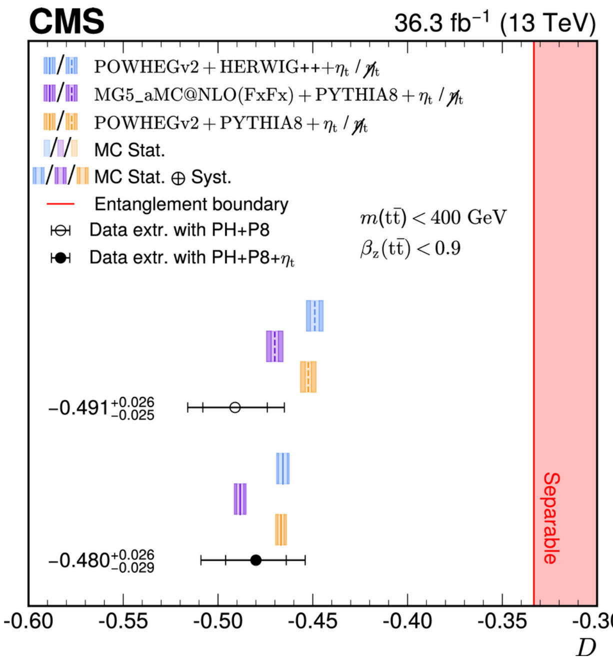


→ good description by theory except for excess in data in threshold region

SM: $t\bar{t}$ spin entanglement

- Measured quantity: D "≈ strength of $t\bar{t}$ spin correlation" (oversimplified)

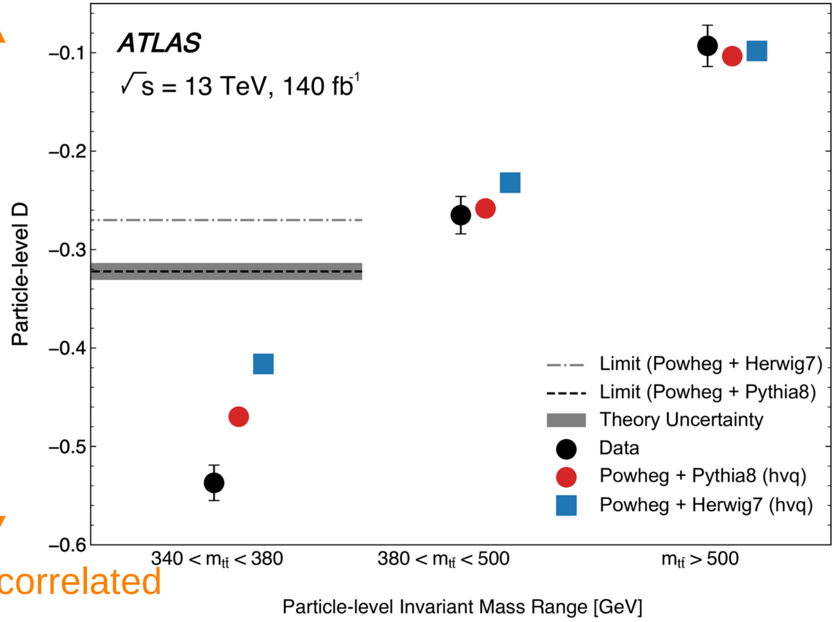
ROPP 87 117801 (2024)



more anticorrelated less correlated

less correlated

Nature 633 (2024) 542



more anticorrelated