DESY FH Seminar

Searching for new scalars, pseudoscalars and $t\bar{t}$ bound states at CMS

Afiq Anuar[1], Jörn Bach[1], Samuel Baxter[1], Alexander Grohsjean[2], **Laurids Jeppe**[1], Jonas Rübenach[1] & Christian Schwanenberger[1,2]

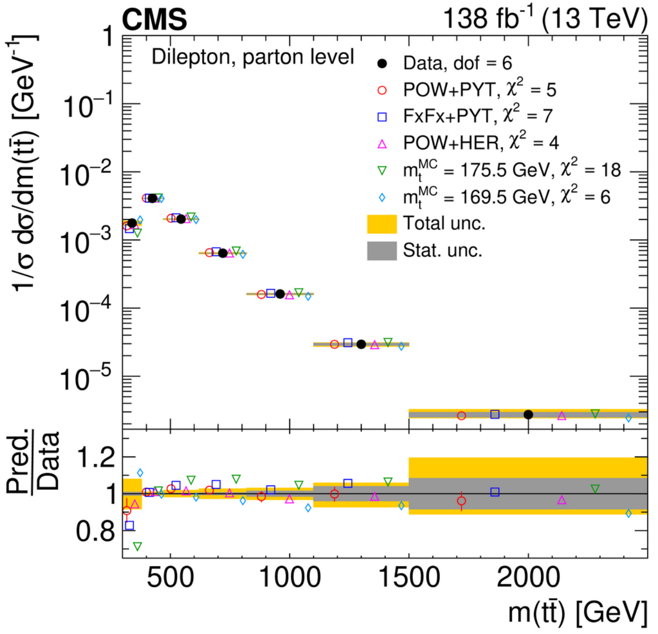
[1]DESY [2]University of Hamburg

17.01.2025 | CMS-PAS-HIG-22-013

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

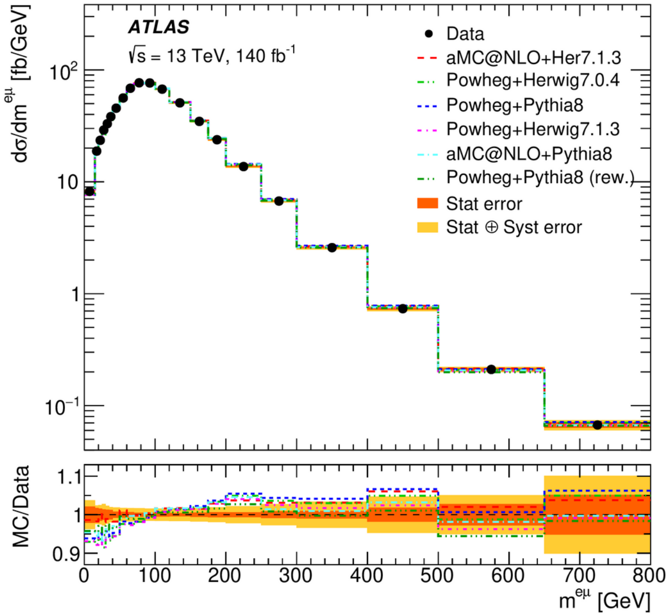
CMS ℓℓ - m_{tt}

CMS-PAS-TOP-20-006



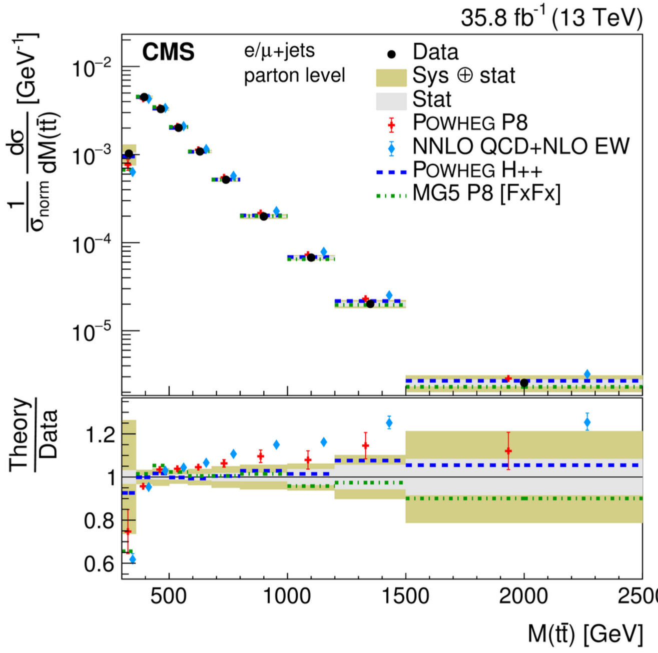
ATLAS eμ - $m_{e\mu}$

JHEP 07 (2023) 141



CMS ℓ+jets - m_{tt}

PRD 97 (2018) 112003



→ good description by theory

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

CMS ℓℓ - m_{tt}
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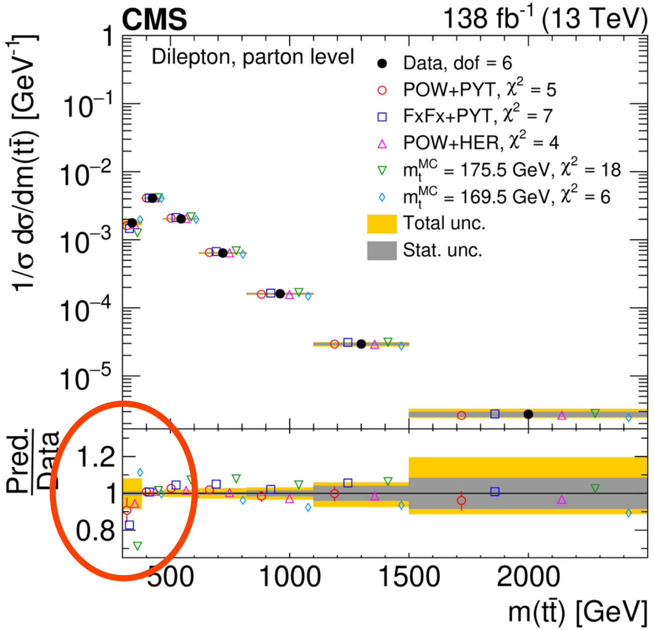

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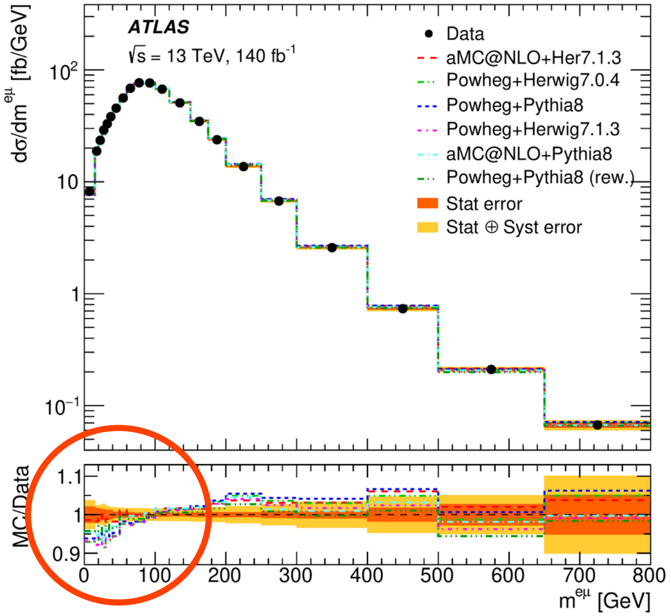
JHEP 07 (2023) 141



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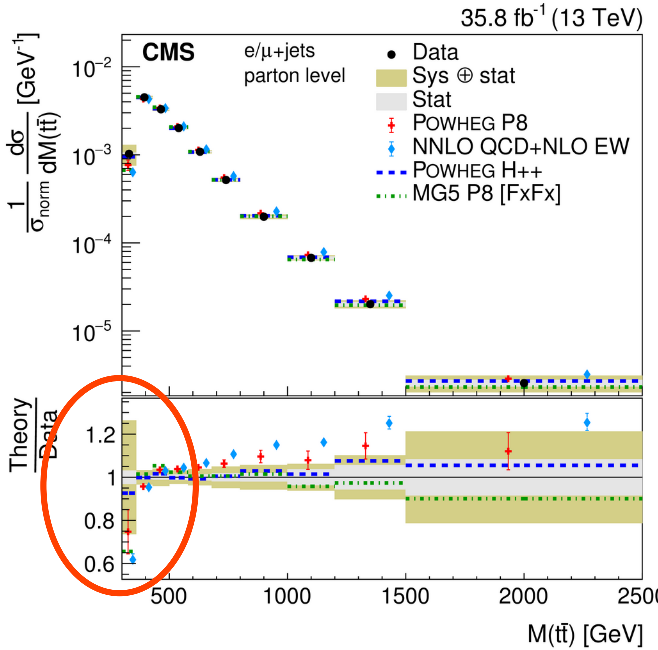
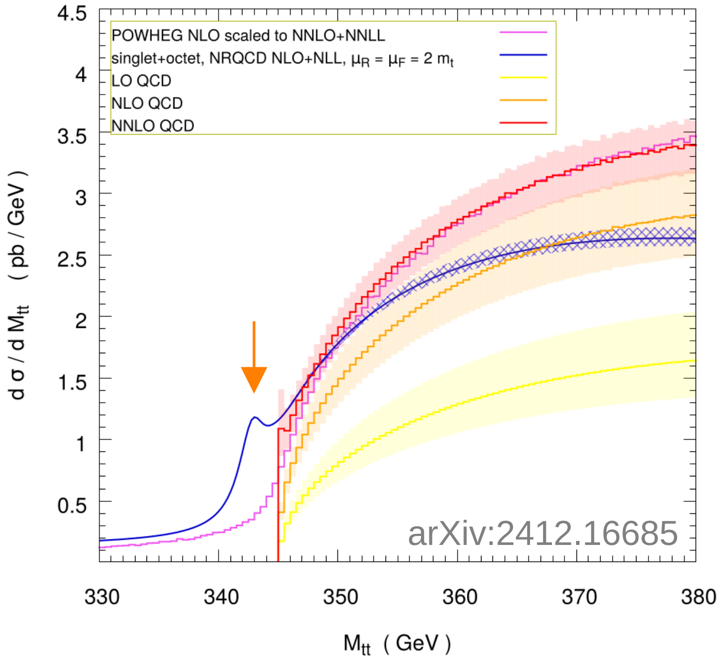
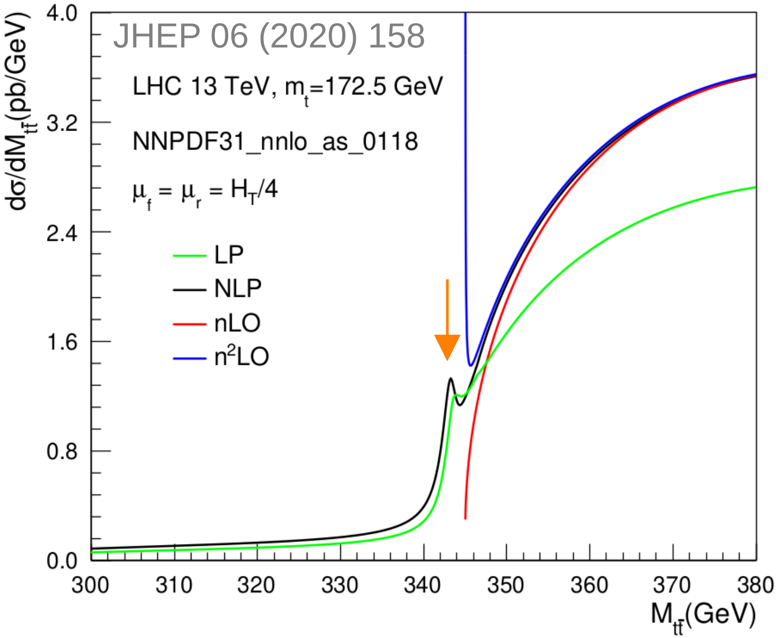


→ good description by theory except for excess in data in threshold region

$t\bar{t}$ bound states

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



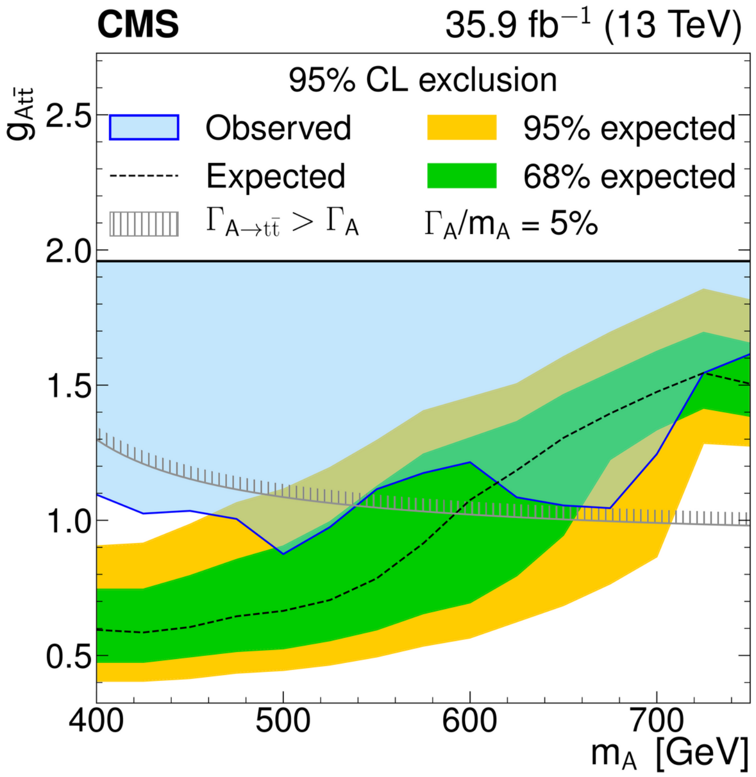


- So far not observed!
- Dominant component: pseudoscalar – can we search for it?

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 ($\ell\ell$) and lepton+jets (ℓj)
- Builds upon previous work by CMS:
  JHEP 04 (2020) 171 (2016 data, 35.9 fb^{-1})
  - ~3σ local excess at low masses!
- Also recent full Run 2 result by ATLAS (JHEP08 (2024) 013) - no excess
  - see Eleanor's talk next!

JHEP 04 (2020) 171

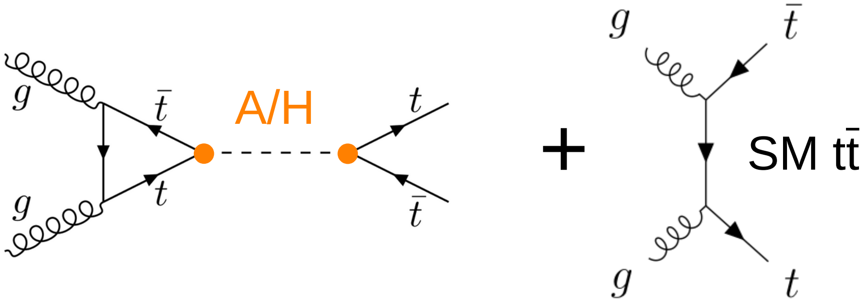


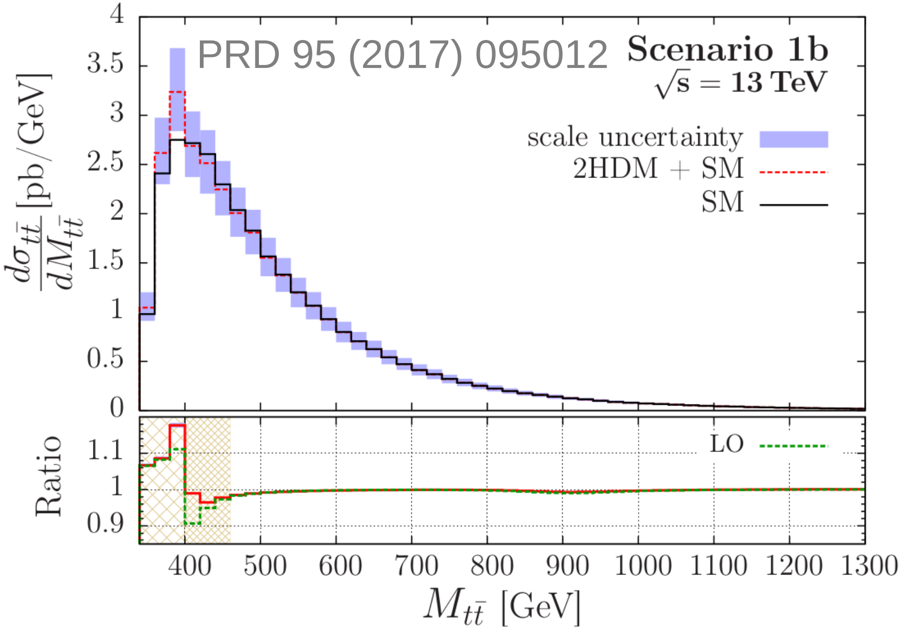
Signal modeling: A/H

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

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

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



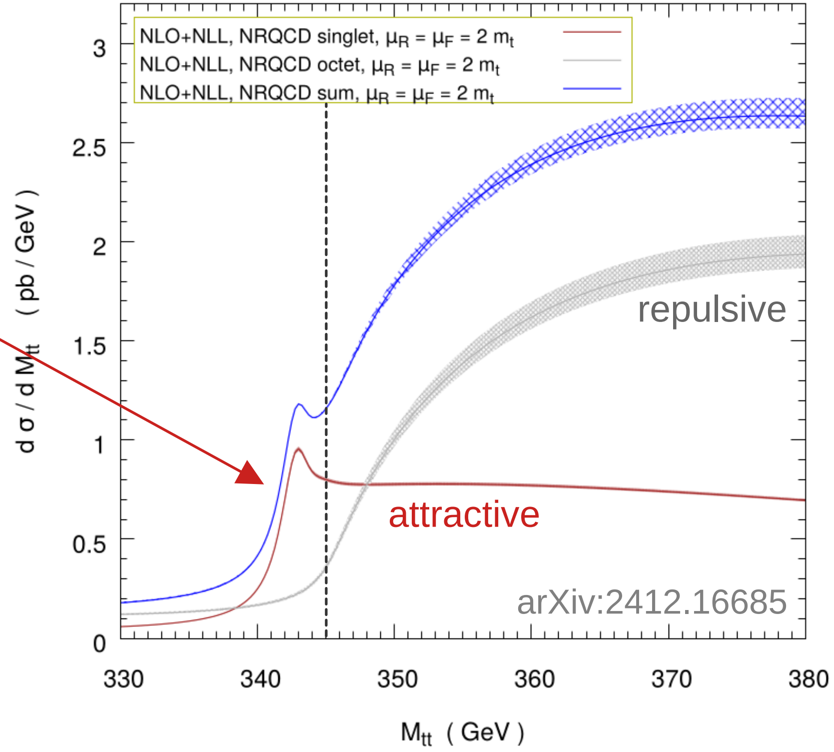


- Same final state as SM $t\bar{t}$ $\rightarrow$ interference $\rightarrow$ peak-dip structure in m_{tt}

Modeling: $t\bar{t}$ bound states

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

- State of the art: non-relativistic QCD (NRQCD)
  - Color-singlet ($^1S_0^{[1]}$) - attractive
    $\rightarrow$ Peak below the $t\bar{t}$ threshold



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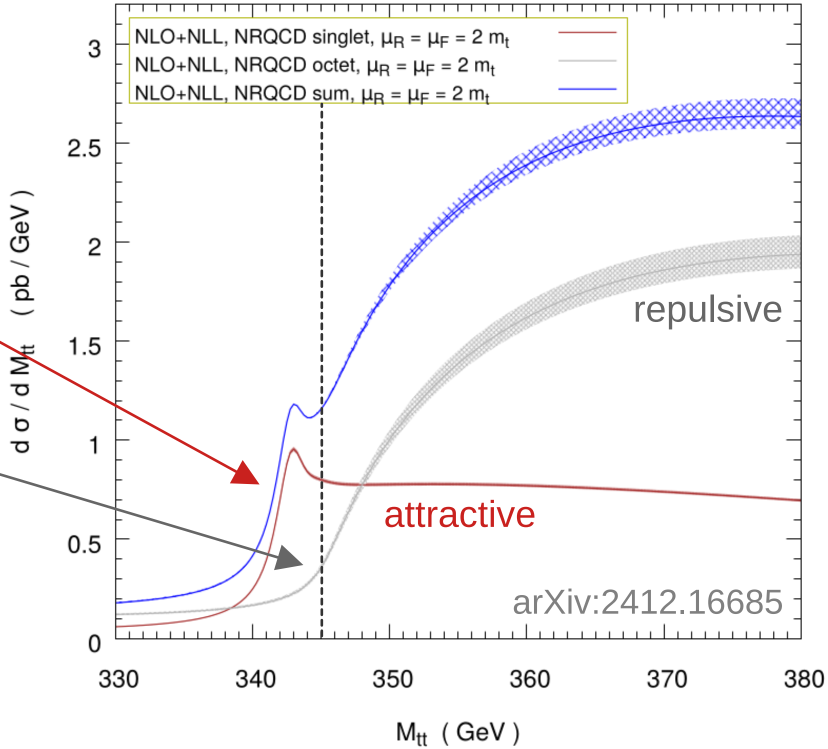
- State of the art: non-relativistic QCD (NRQCD)
  - Color-singlet (${}^1S_0^{[1]}$) - attractive
    $\rightarrow$ Peak below the $t\bar{t}$ threshold
  - Color-octet (${}^1S_0^{[8]}$ or ${}^3S_1^{[8]}$) - repulsive
    $\rightarrow$ Suppressed below the $t\bar{t}$ threshold

See Maria's talk later today!

- Exact lineshape and width below experimental resolution

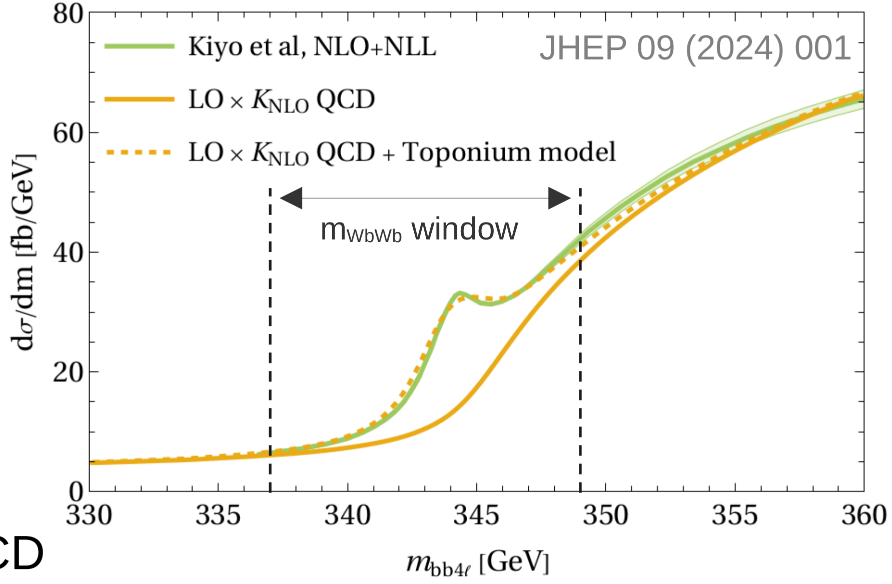


Modeling: $t\bar{t}$ bound states

- Use simplified model for MC simulation: η_t (PRD 104 (2021) 034023, JHEP 03 (2024) 099)
  - 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 - but expected to have small effects [arXiv:2411.18962]



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

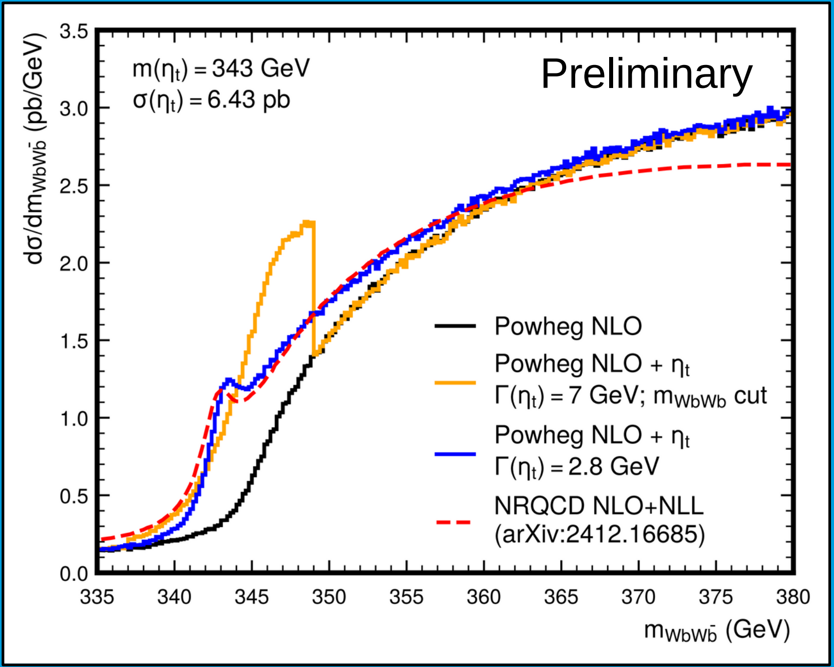
Modeling: $t\bar{t}$ bound states

- Open item: η_t width
- Currently: $\Gamma(\eta_t)$ = 7 GeV
  (PRD 104 (2021) 034023, B. Fuks et al)

  does not match well to NRQCD…

- For publication: investigate moving to $\Gamma(\eta_t) = 2\,\Gamma_t$ = 2.8 GeV
  (JHEP 03 (2024) 099, F. Maltoni et al)

  matches new NRQCD calculation very well!

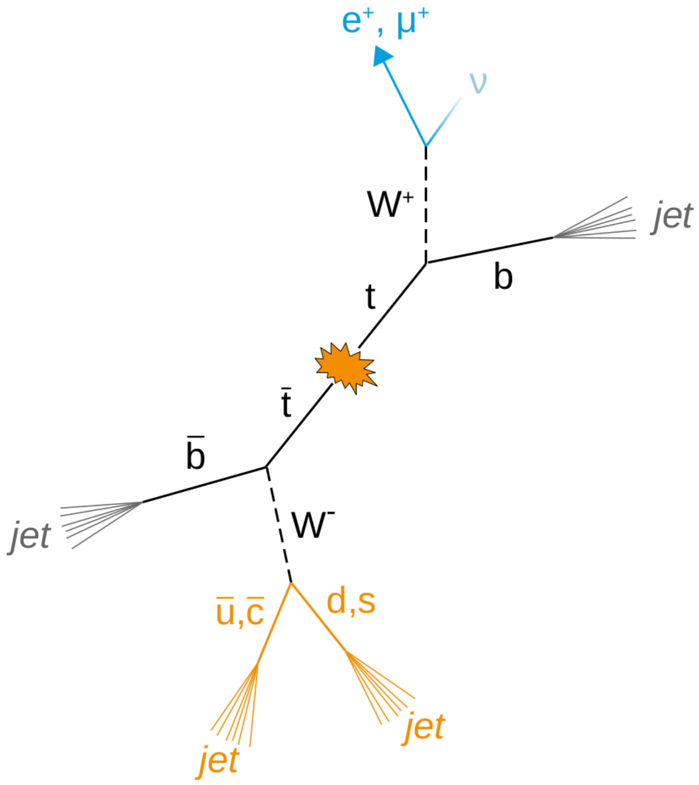


Lepton+jets channel

- 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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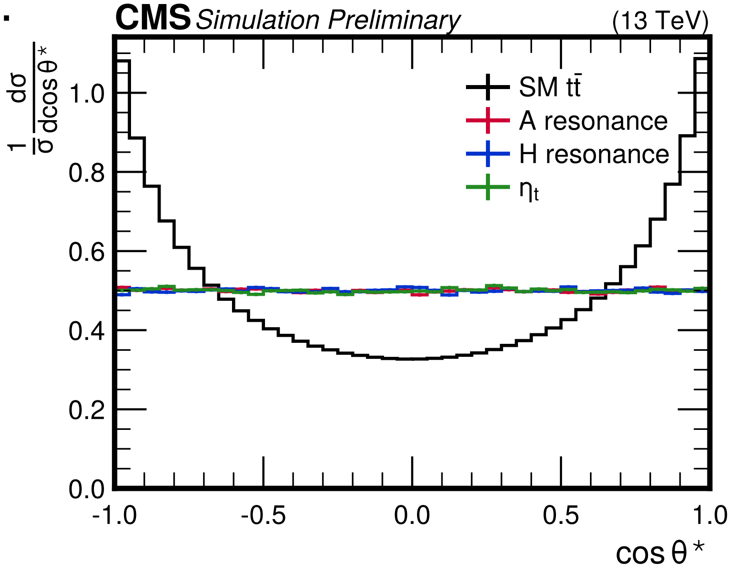
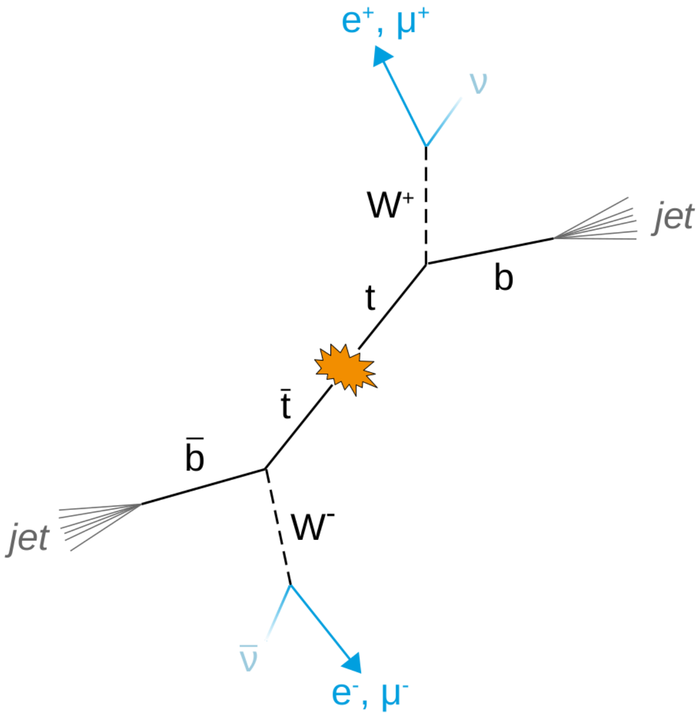
- 2D binning in m_{tt} x $|\cos\theta^*|$
- θ*: scattering angle of leptonic top quark
  - SM $t\bar{t}$: peaks at large cosθ*
  - Signal: isotropic → flat distribution
  - ➔ Sensitive to spin of mediator (but not parity)



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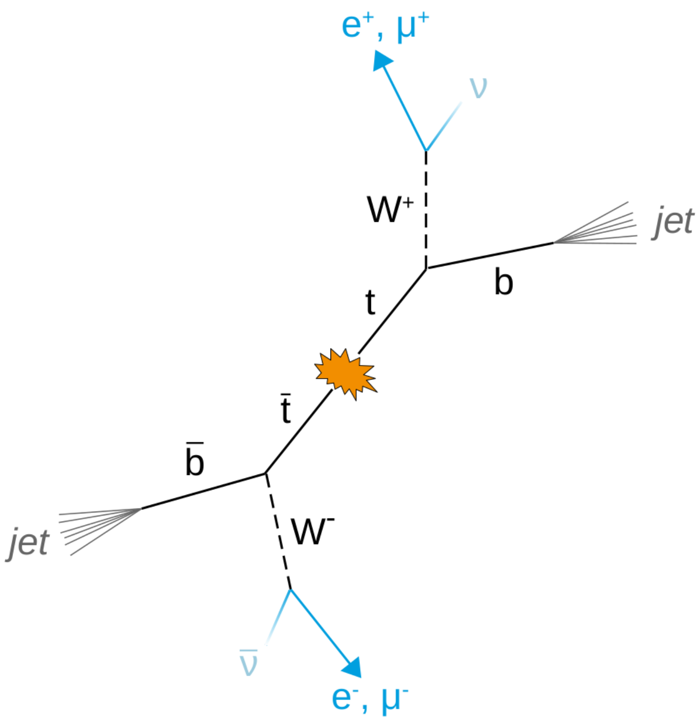
- Analytic reconstruction of $t\bar{t}$ system:
  - Assumptions: all p_T^{miss} from νν, tops and Ws on-shell
  - Assign b jets using likelihood based on $m_{\ell b}$
  - Finite detector resolution: repeat reconstruction 100 times with randomly smeared inputs, take weighted average

  (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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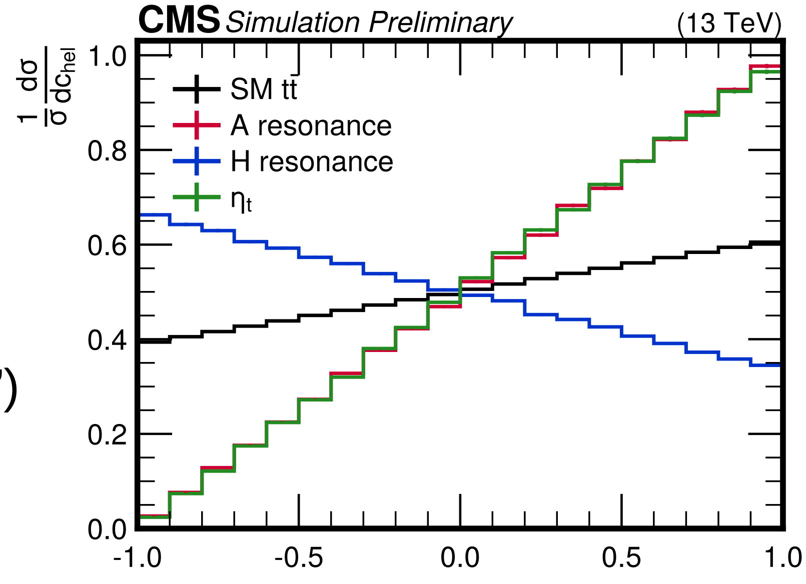

- Variable #1: c_{hel}
  - Boost leptons into rest frames of their parent tops $\rightarrow$ Scalar product between directions of flight
  - Straight line with slope sensitive to $t\bar{t}$ spin state ("D")
  - Maximal for $^1S_0$ (from A / η_t) – separates from SM

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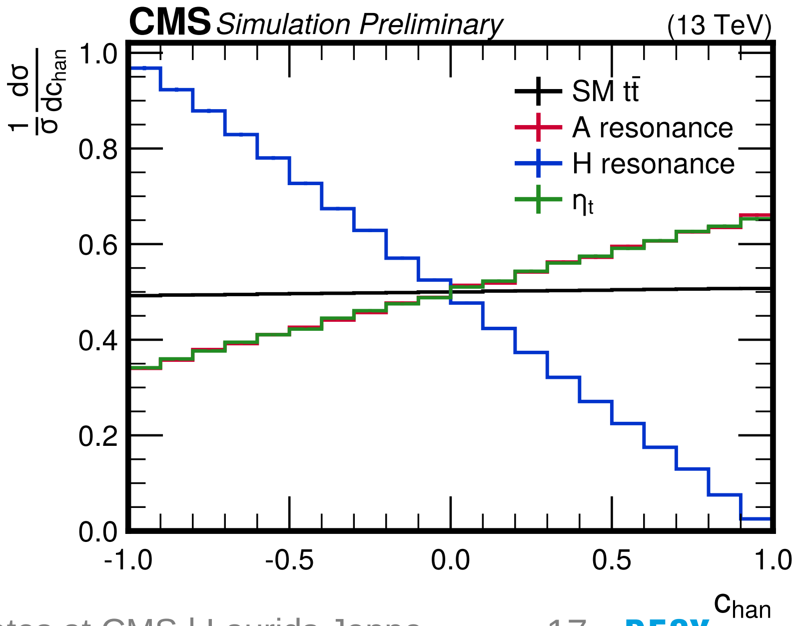


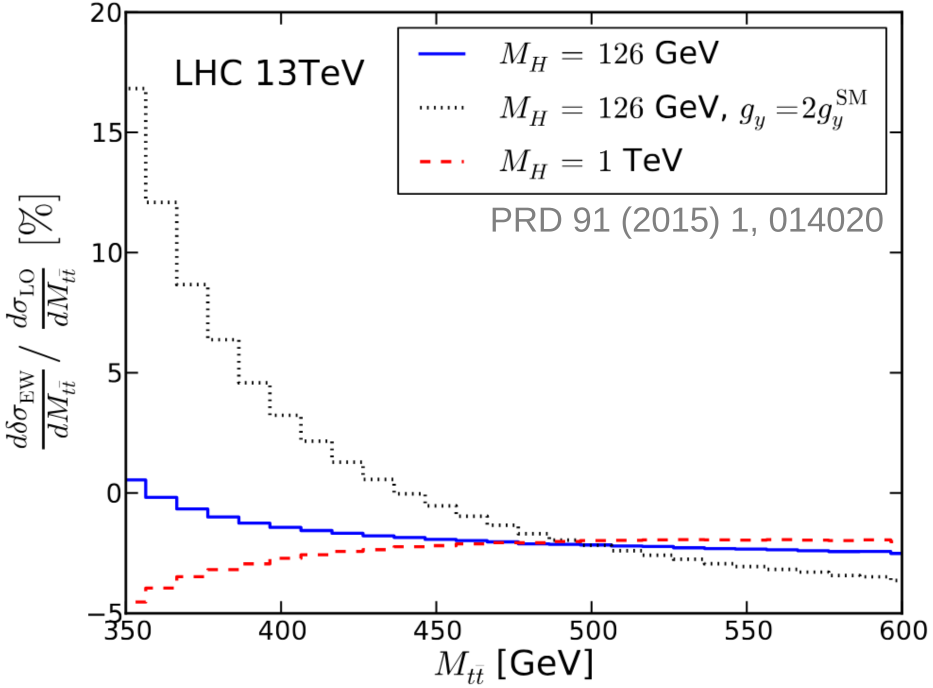
- Variable #2: c_{han}
  - Similar as c_{hel}, separating scalars from SM
  - Maximally negative slope for $^3P_0$ state (from H)
  - Construct similarly from lepton momenta, with sign flip for component parallel to top momentum

➔ 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*
    (EPJC 78 (2018) 537, EPJC 51 (2007) 37)
  - Normalize to NNLO+NNLL cross section
    (CPC 185 (2014) 2930)

NLO EW / LO (%)



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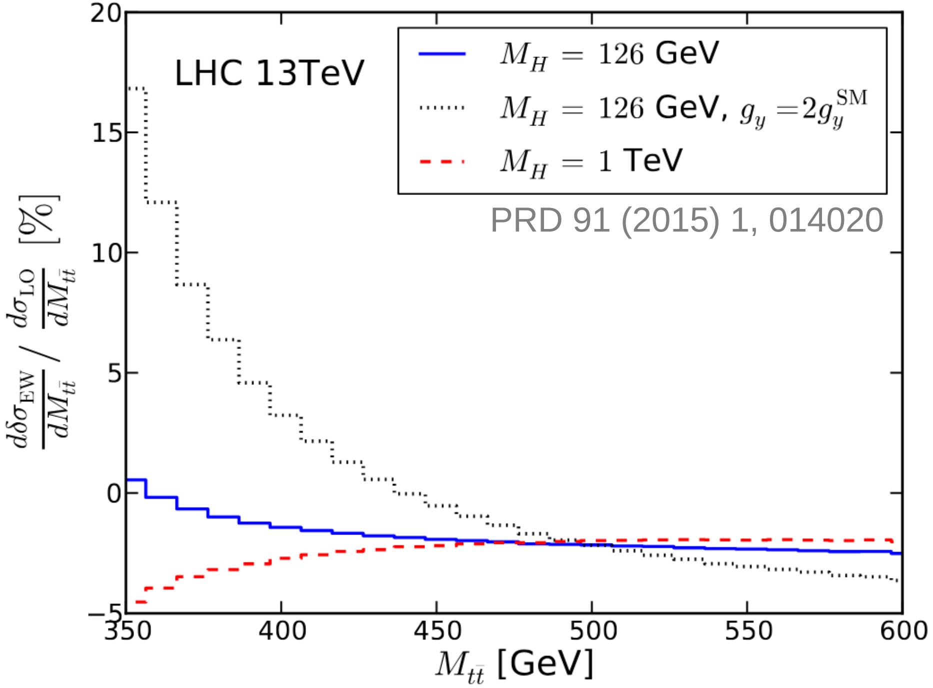
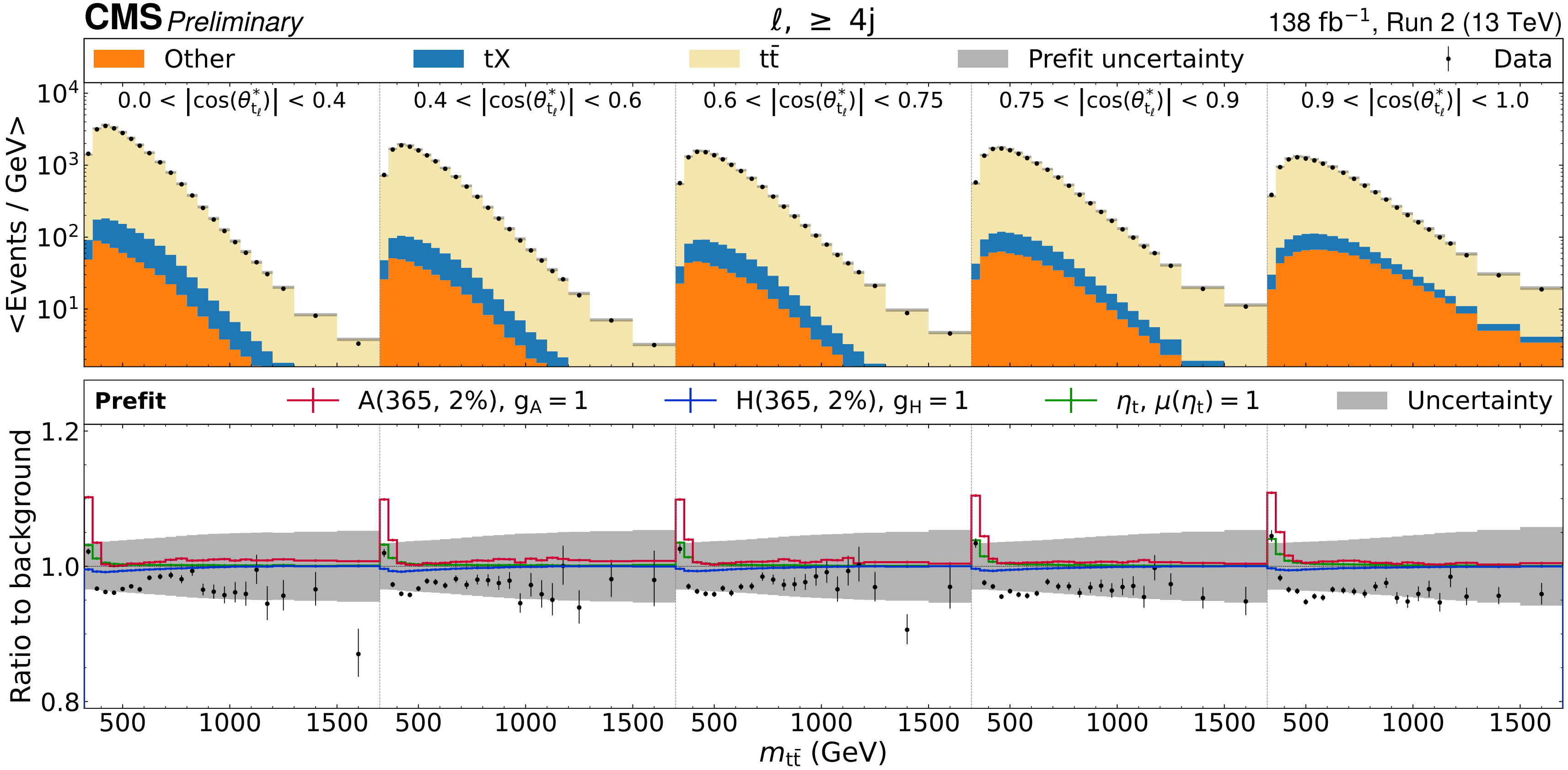


- Other backgrounds: tW, t channel single-top, rare processes (from MC)
- Z+jets in ℓℓ: from MC with data-driven normalization from Z peak sideband
- QCD+EW processes in ℓ+jets: data-driven shape from sideband with no b tags

Prefit distributions: ℓ + ≥4 jets

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



Prefit distributions: $\ell\ell$

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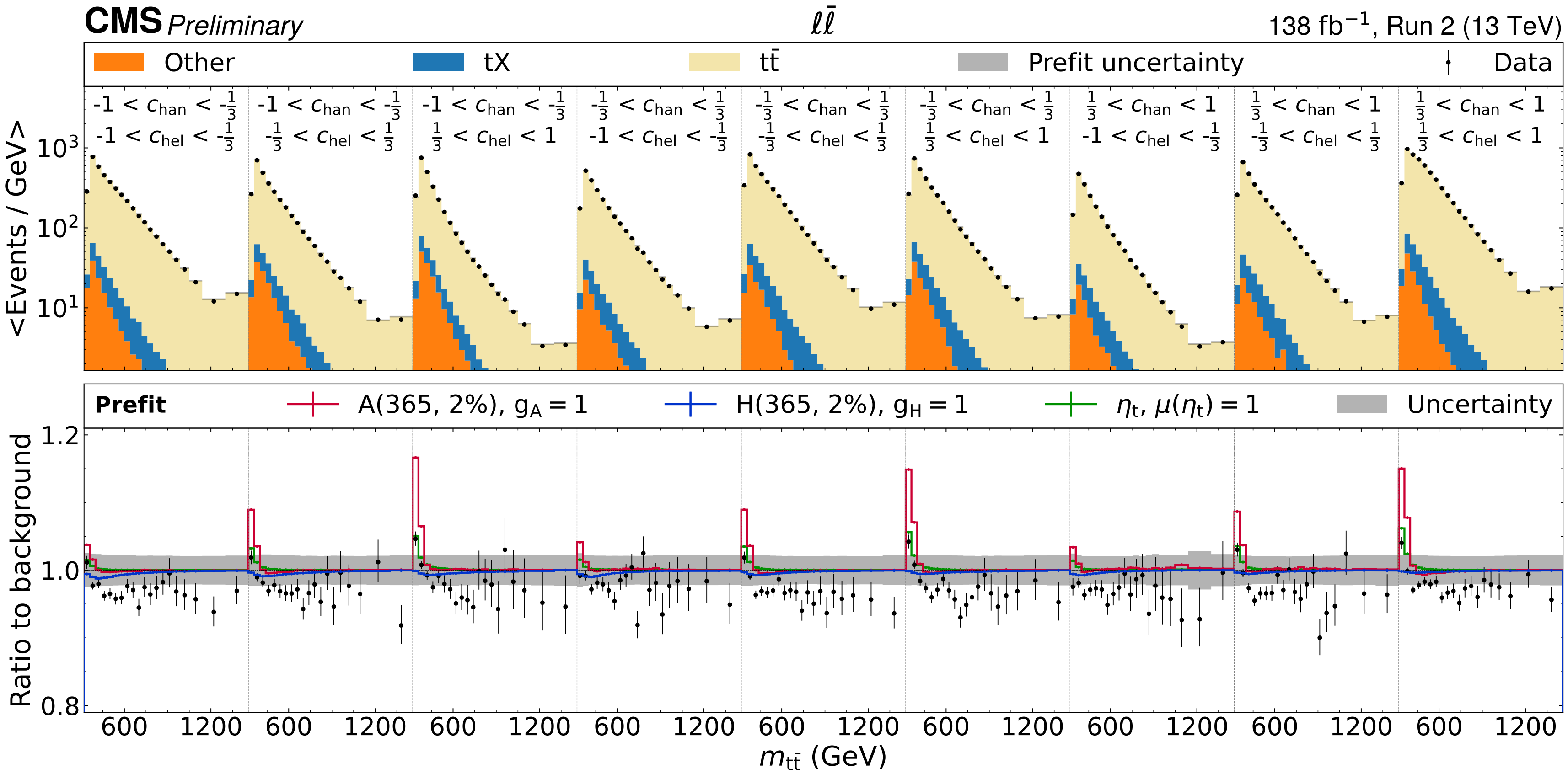
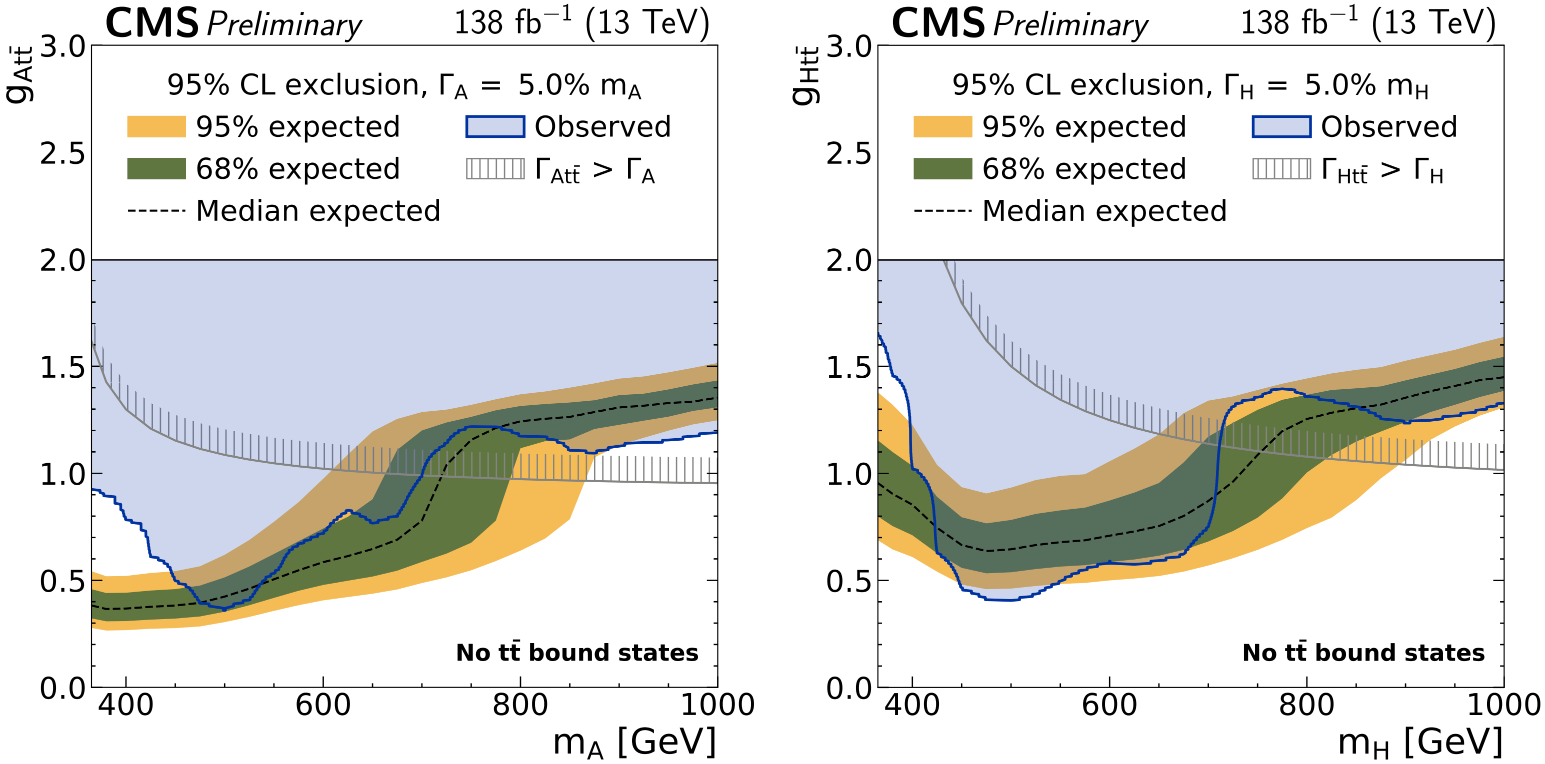


A/H interpretation

- 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_{tt}, stronger for pseudoscalar
  $\rightarrow$ could this be interpreted as a $t\bar{t}$ bound state?
- Extract cross section using the η_t color-singlet (toy) model
  - "cross section" = difference to perturbative prediction

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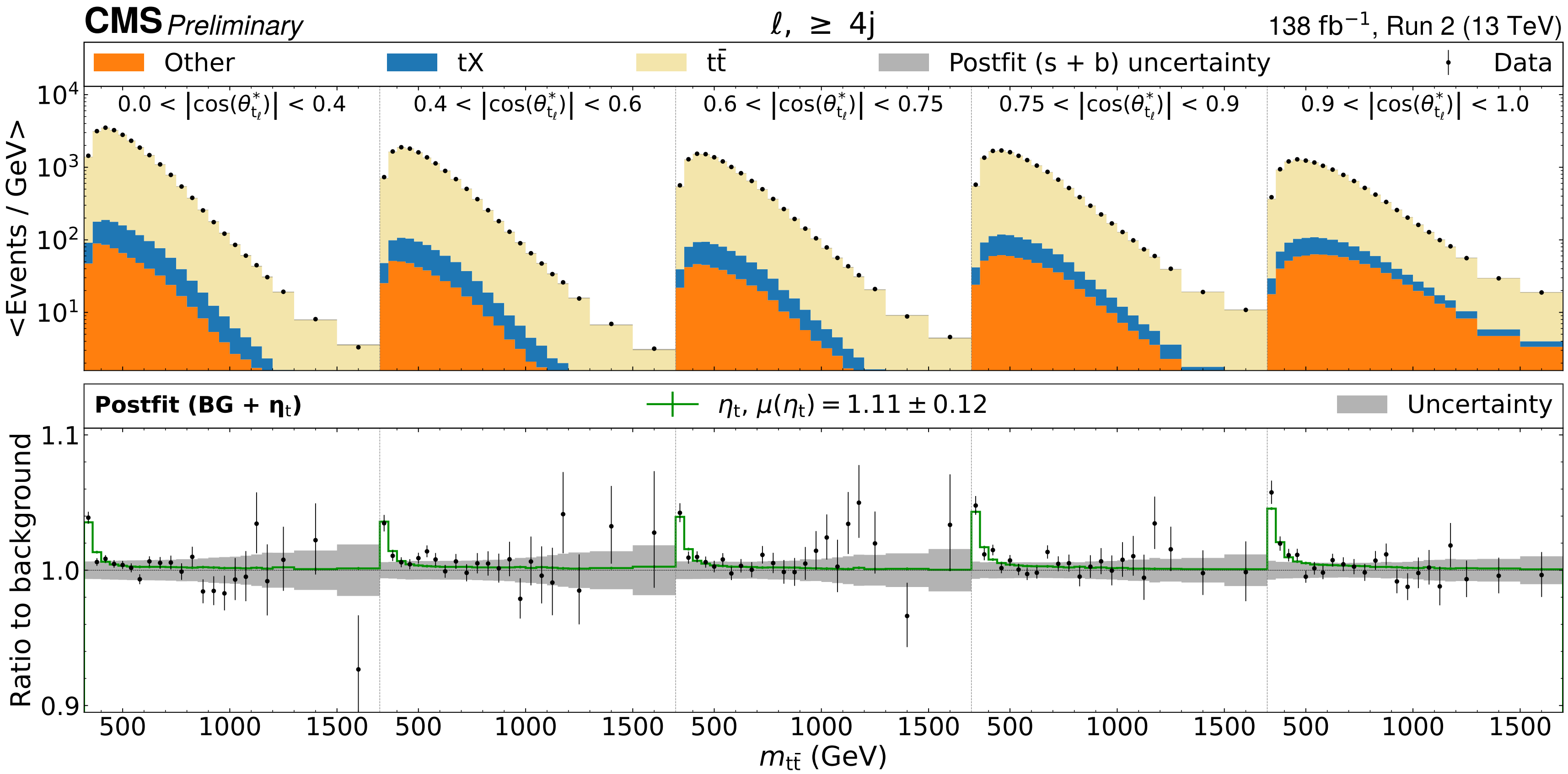
$$\boxed{\sigma(\eta_t) = 7.1 \pm 0.8\,\mathrm{pb}}$$

> 5σ significance!

- Main uncertainties: $t\bar{t}$ background modeling
- Agrees with rough estimate from NRQCD: $\sigma(\eta_t)^{\mathrm{pred}} = 6.43\,\mathrm{pb}$ (PRD 104 (2021) 034023)
- Word of caution: this model is not a complete description of a $t\bar{t}$ bound state!
  - missing e.g. 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 ($\ell\ell$)

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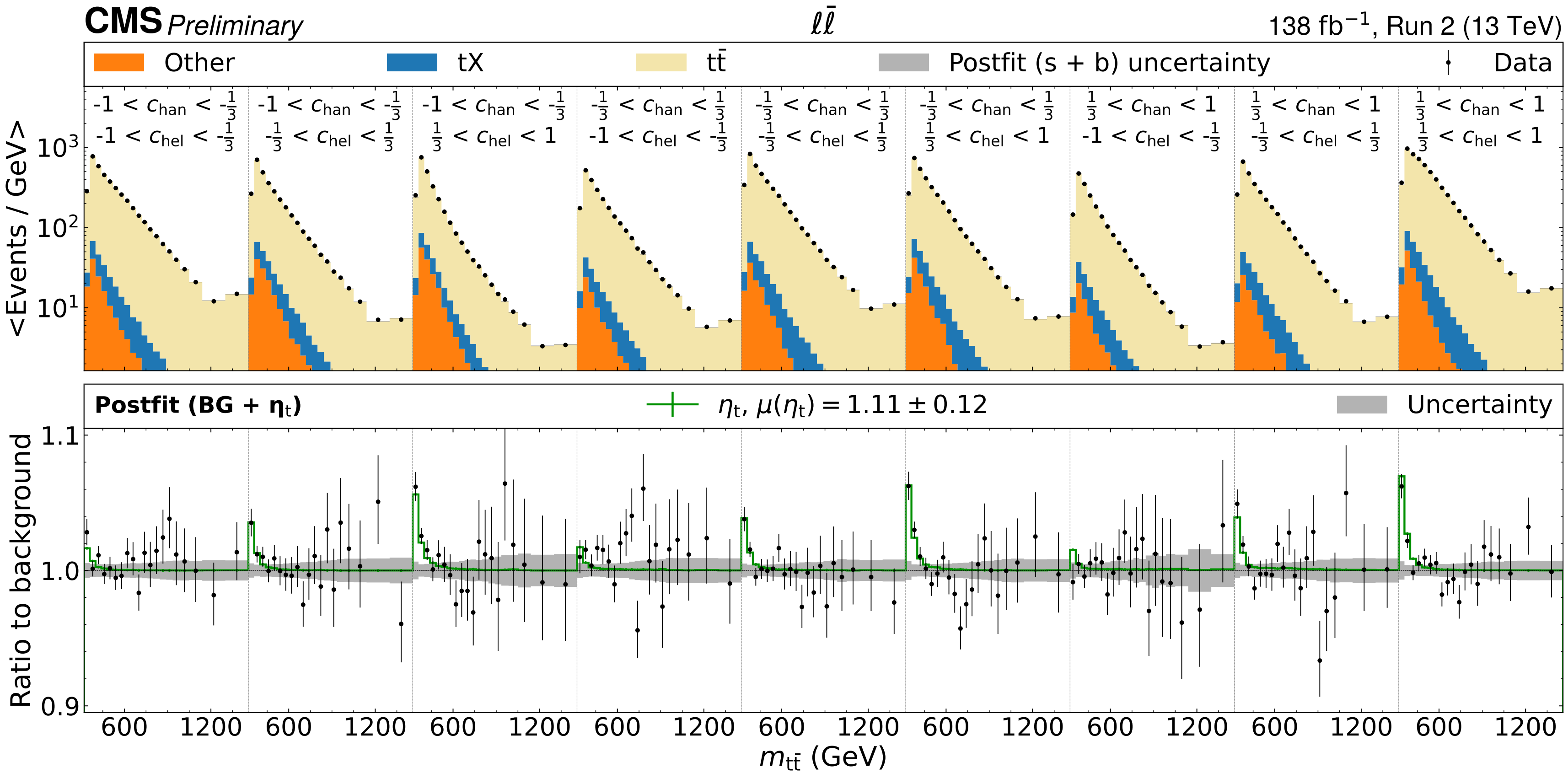

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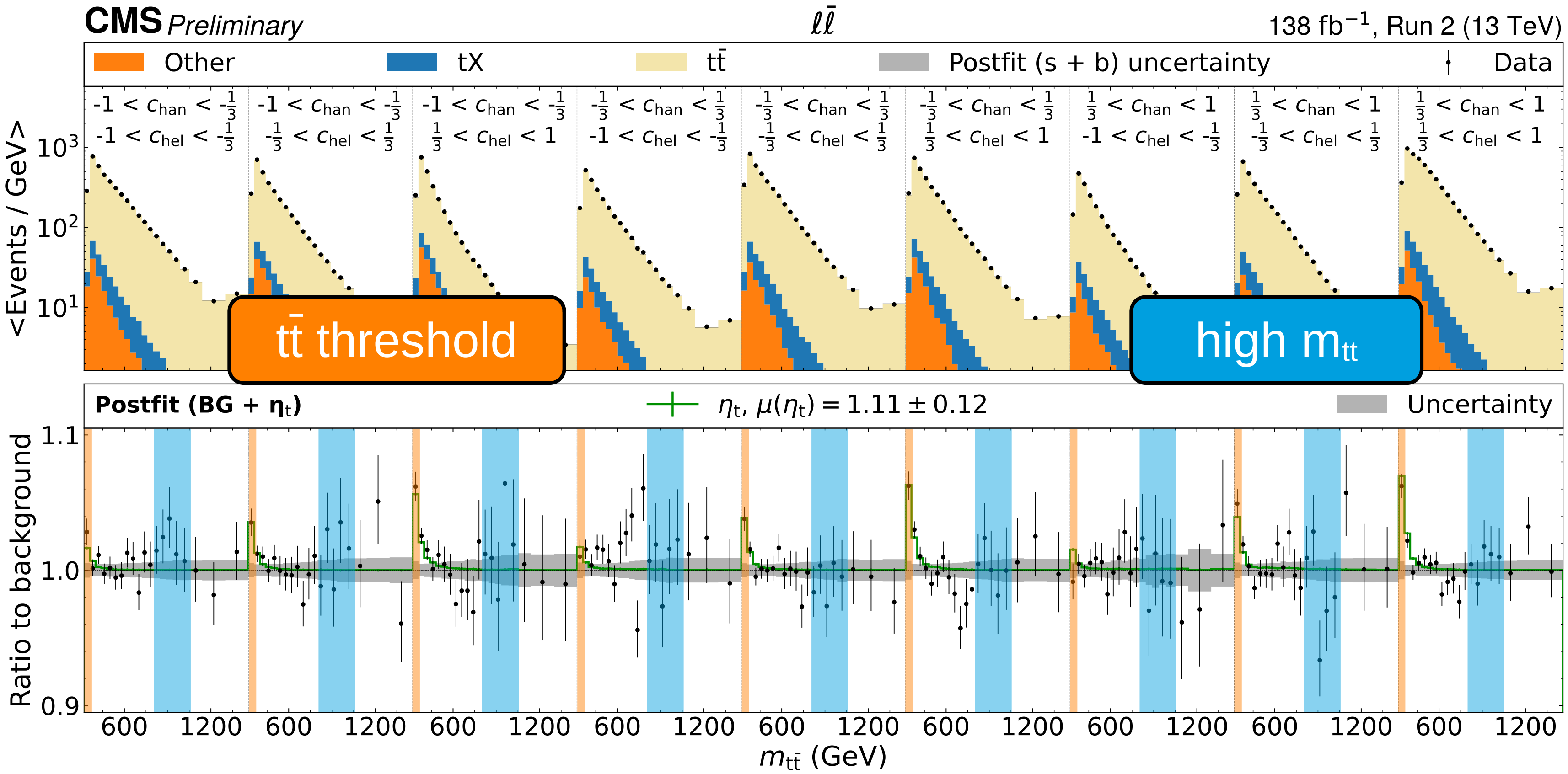
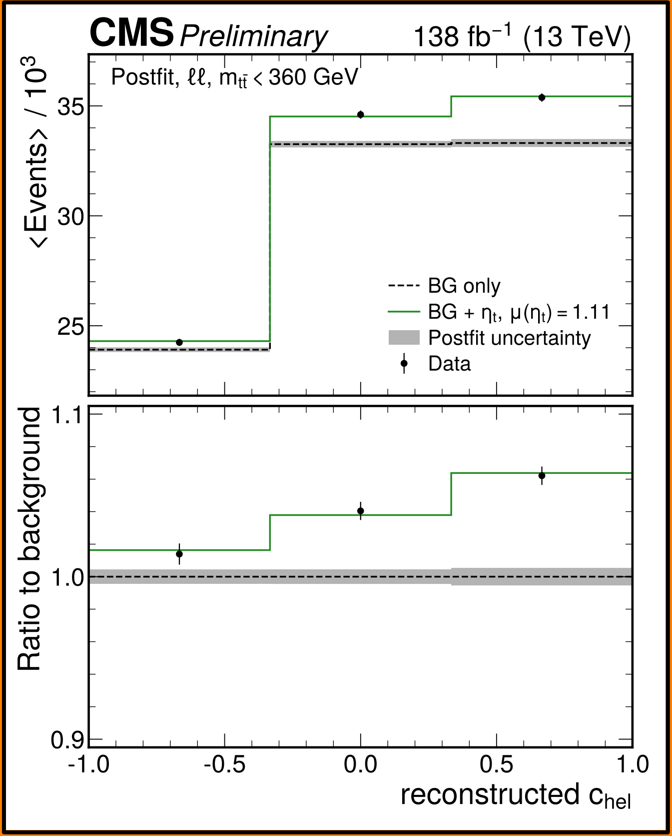
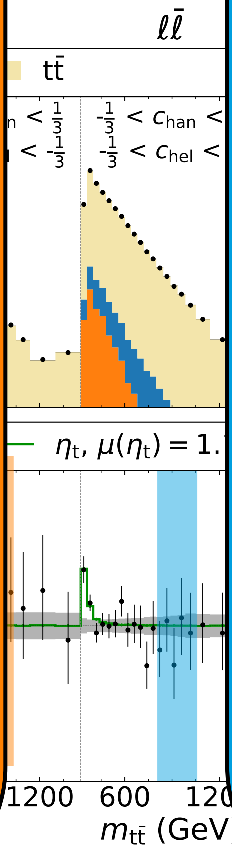


P ... ns: m

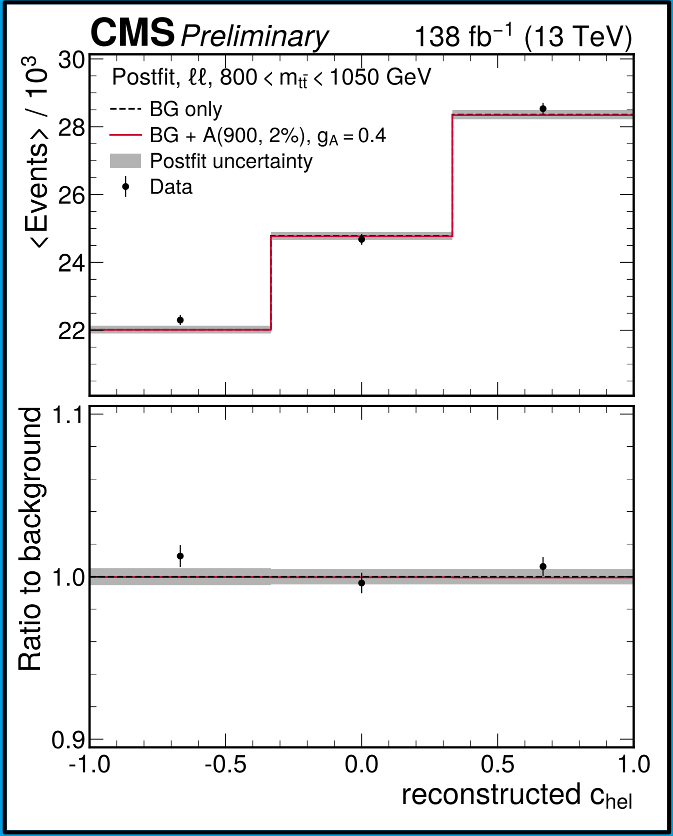
$t\bar{t}$ threshold:
Data shows slope in c_{hel}



el describ



high m_{tt}:
No slope in data

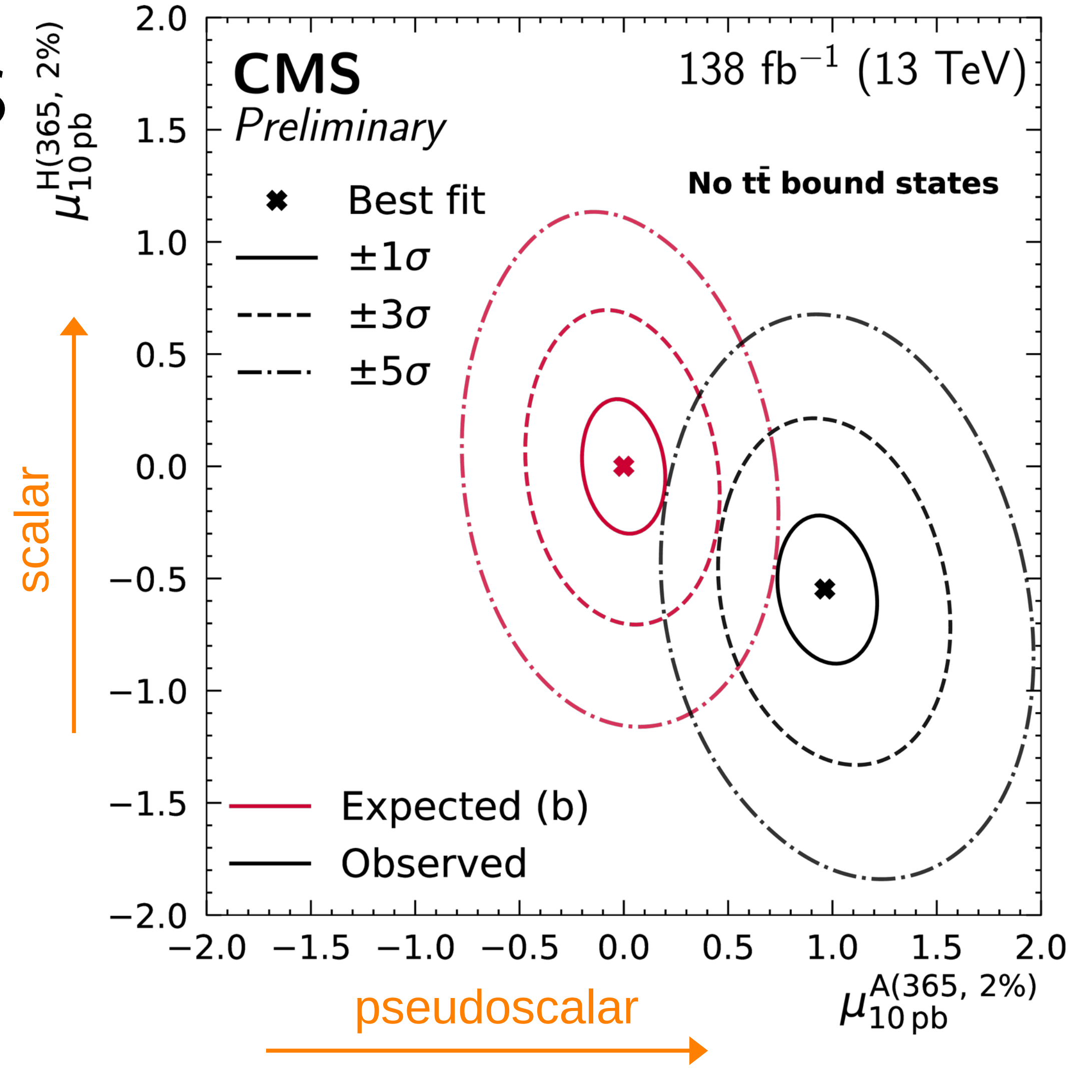


Parity of the excess

- 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

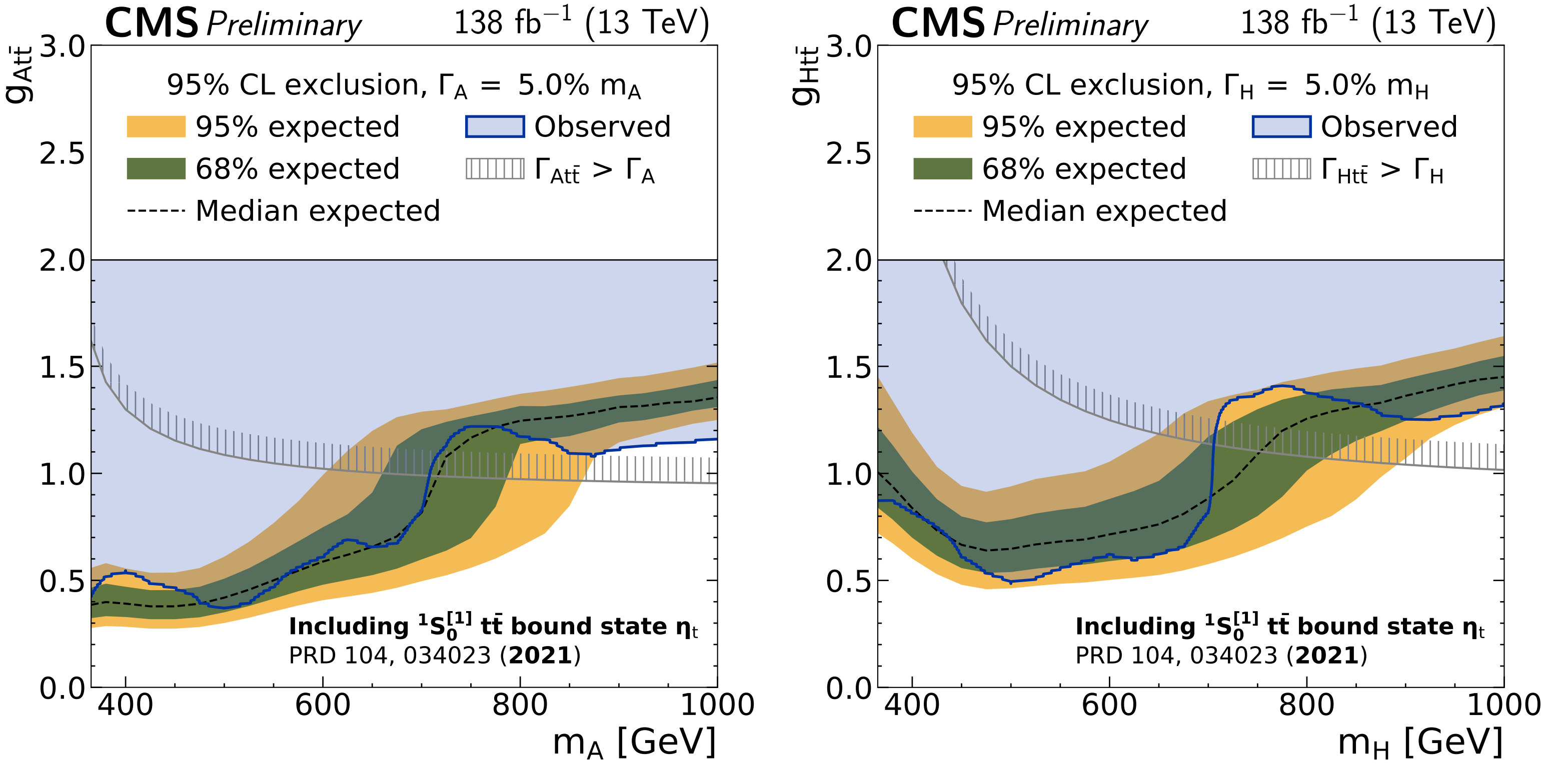


A/H limits including η_t

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

Cannot distinguish η_t and low-mass A

→ Excess no longer present



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 and H with η_t included in the background
- Modeling $t\bar{t}$ bound state effects is still a challenge – any further input from theory welcome
- Whatever the excess is – it is exciting!

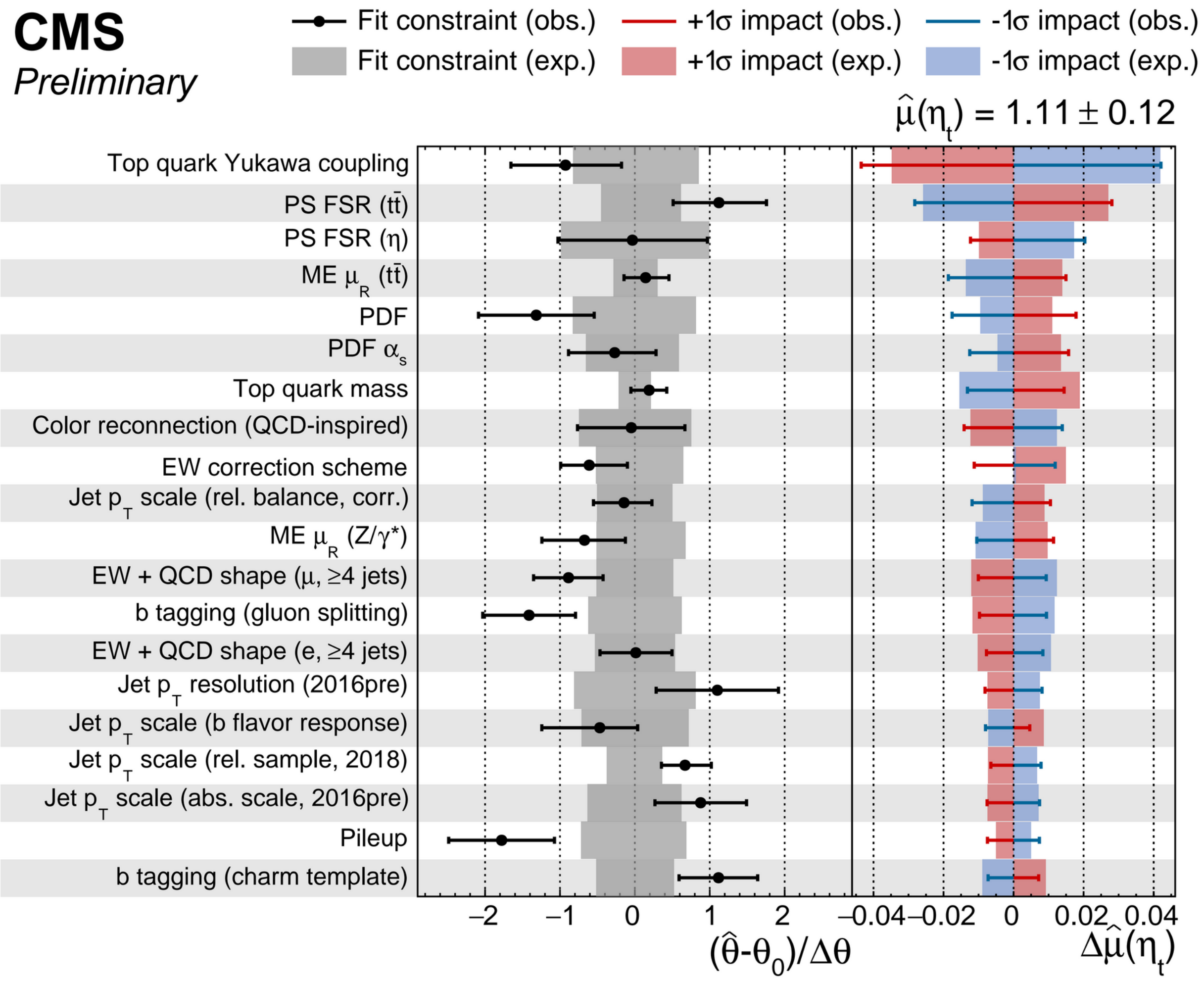
Reference: **CMS-PAS-HIG-22-013**

Backup

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

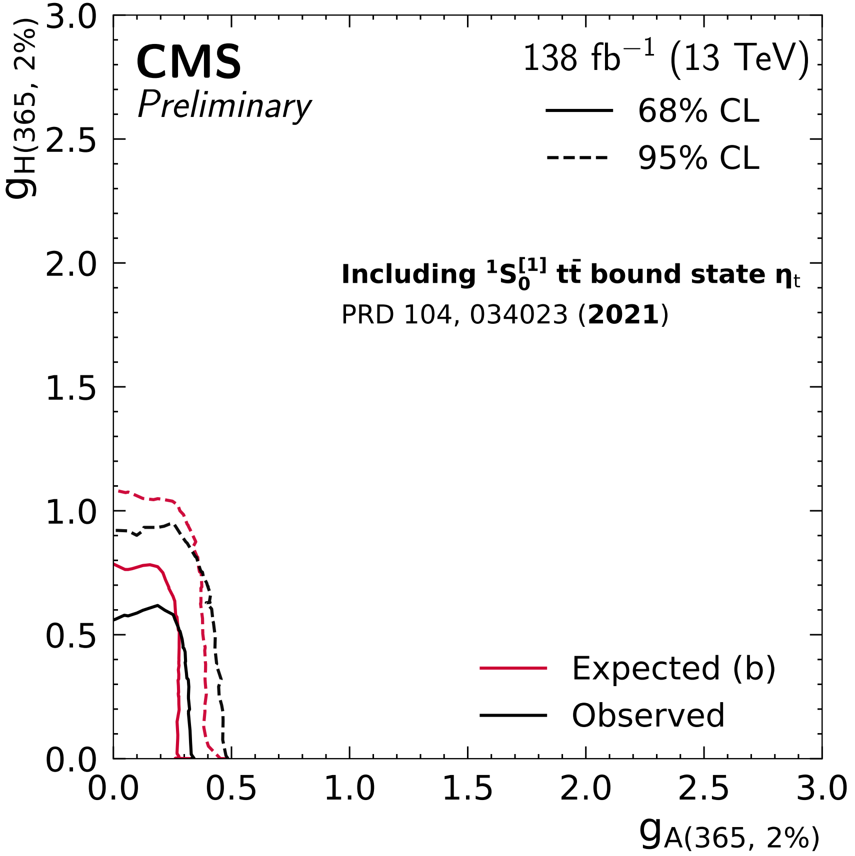
A+H interpretation

- 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

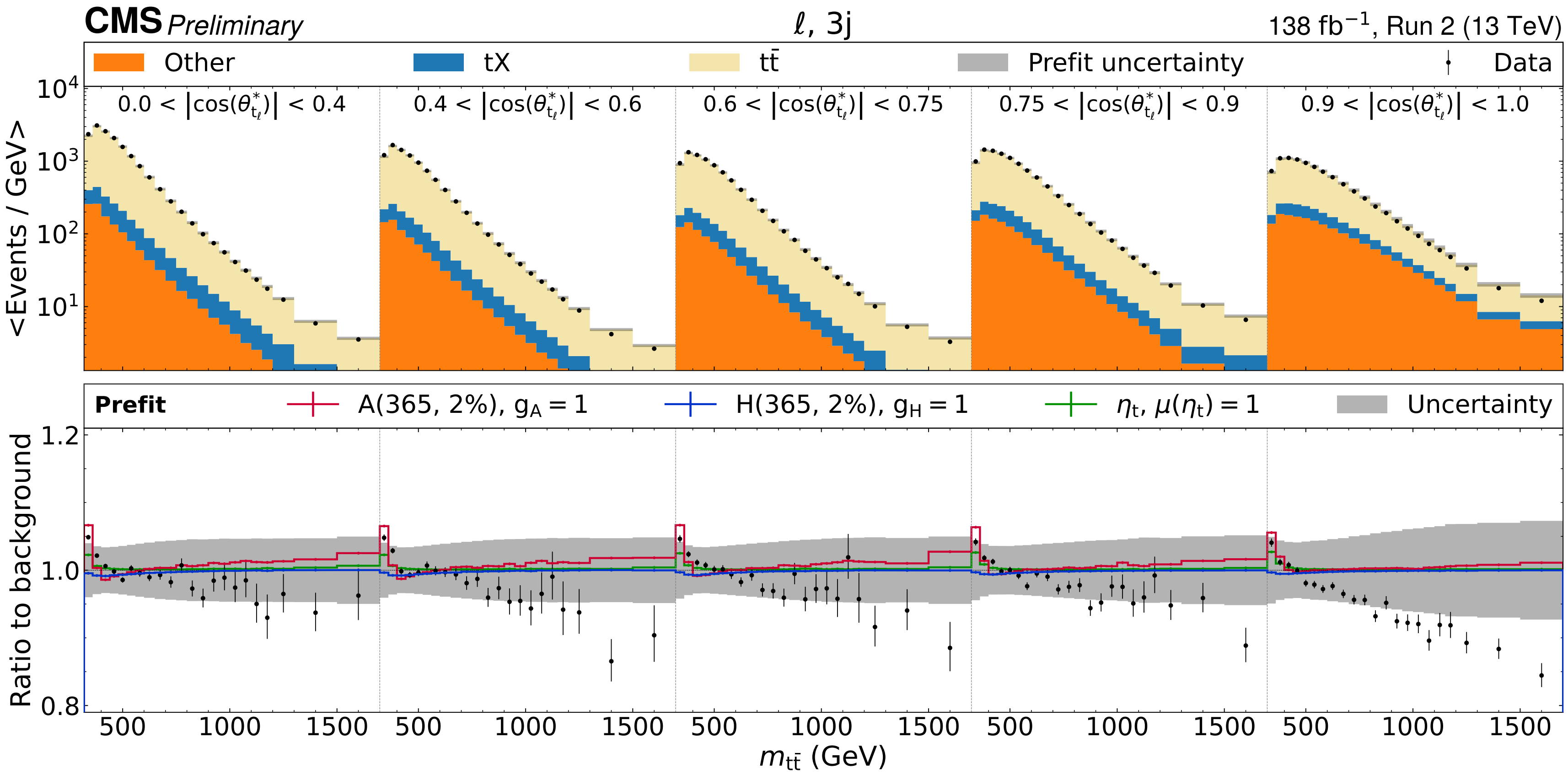
- Input for bounds on concrete BSM models

$m_A = m_H = 365$ GeV, 2% width



Prefit distributions: ℓ + 3 jets

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

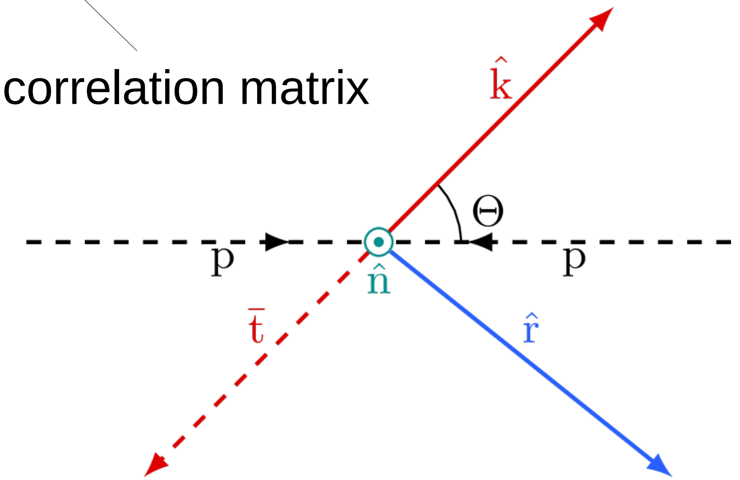


Spin density matrix

- 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:

$$\underbrace{\mathbf{R} = A}_{\text{cross section}} + \underbrace{B_i\sigma_i + \overline{B}_i\overline{\sigma}_i}_{\text{polarization vectors}} + \underbrace{\sigma_i C_{ij}\overline{\sigma}_j}_{\text{correlation matrix}}$$

- 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 $\hat{k}$



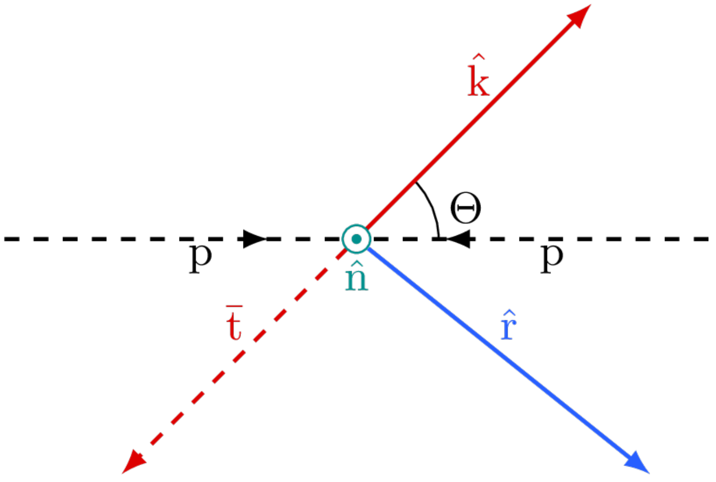
(PRD 100 (2019) 072002)

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 $\hat{r}$

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

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



(PRD 100 (2019) 072002)

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

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

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

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

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

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

$$\sigma^{\text{rew.}} = \underbrace{\sigma^{\text{LO EW}}_{\text{NLO QCD}}}_{\text{Powheg}} \times \frac{\overbrace{\sigma^{\text{NLO EW}}_{\text{LO QCD}}}^{\text{Hathor}}}{\underbrace{\sigma^{\text{LO EW}}_{\text{LO QCD}}}_{\text{MadGraph}}}$$

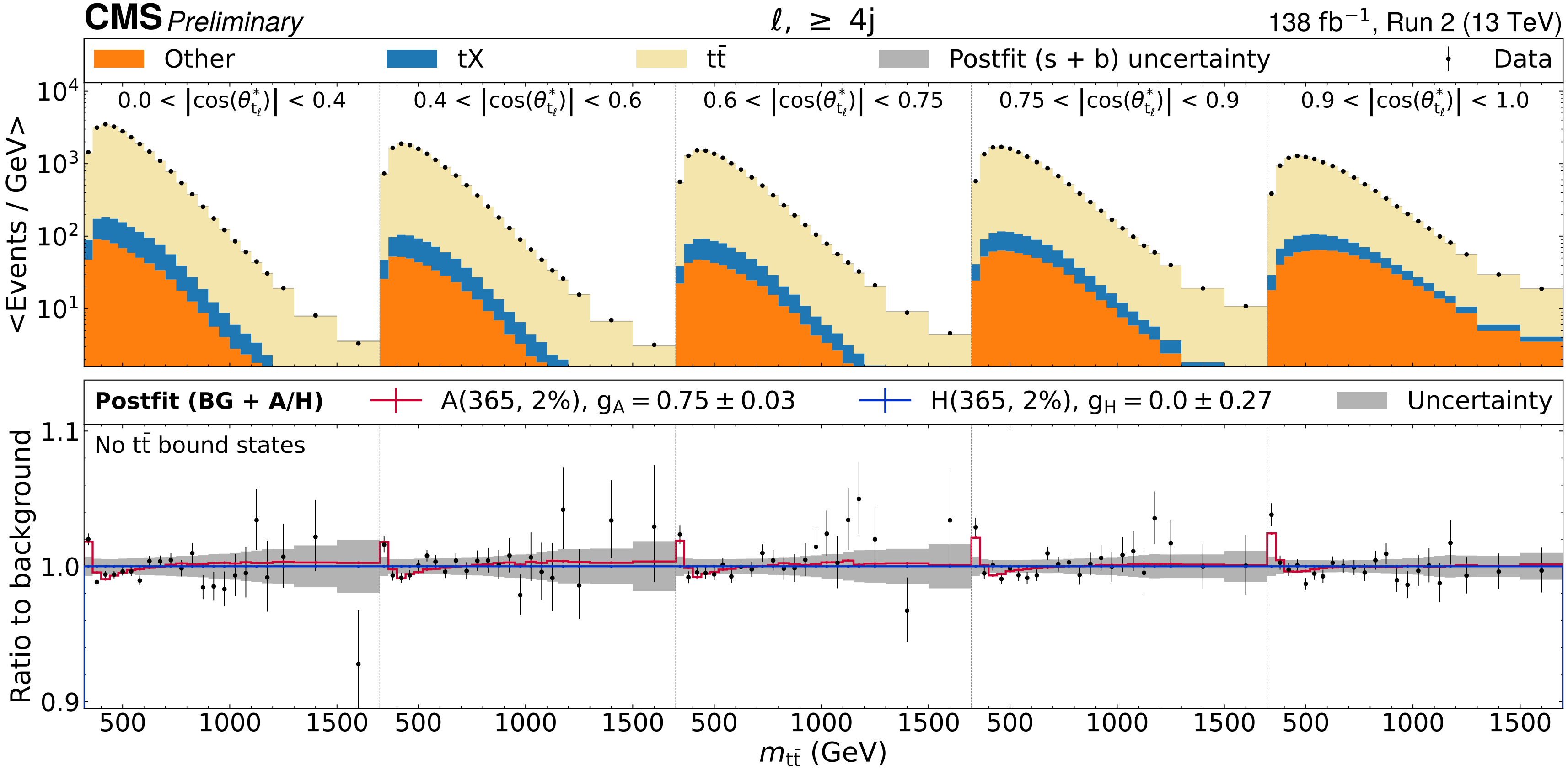
- Alternate choice: additive

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

- Difference treated as systematic uncertainty

Postfit distributions: A/H

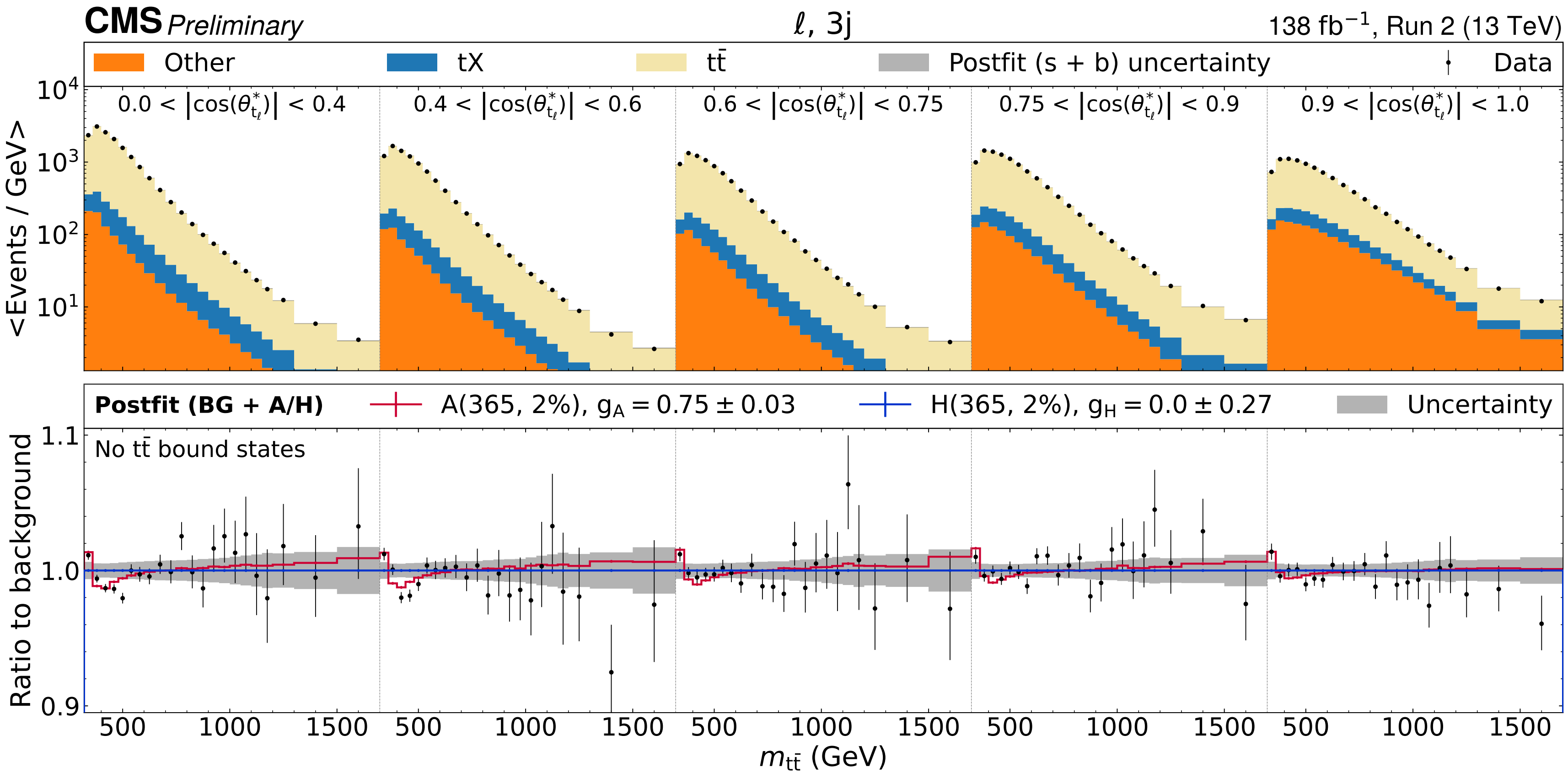
Postfit for A, 365 GeV, 2% width (best fit point)



DESY.

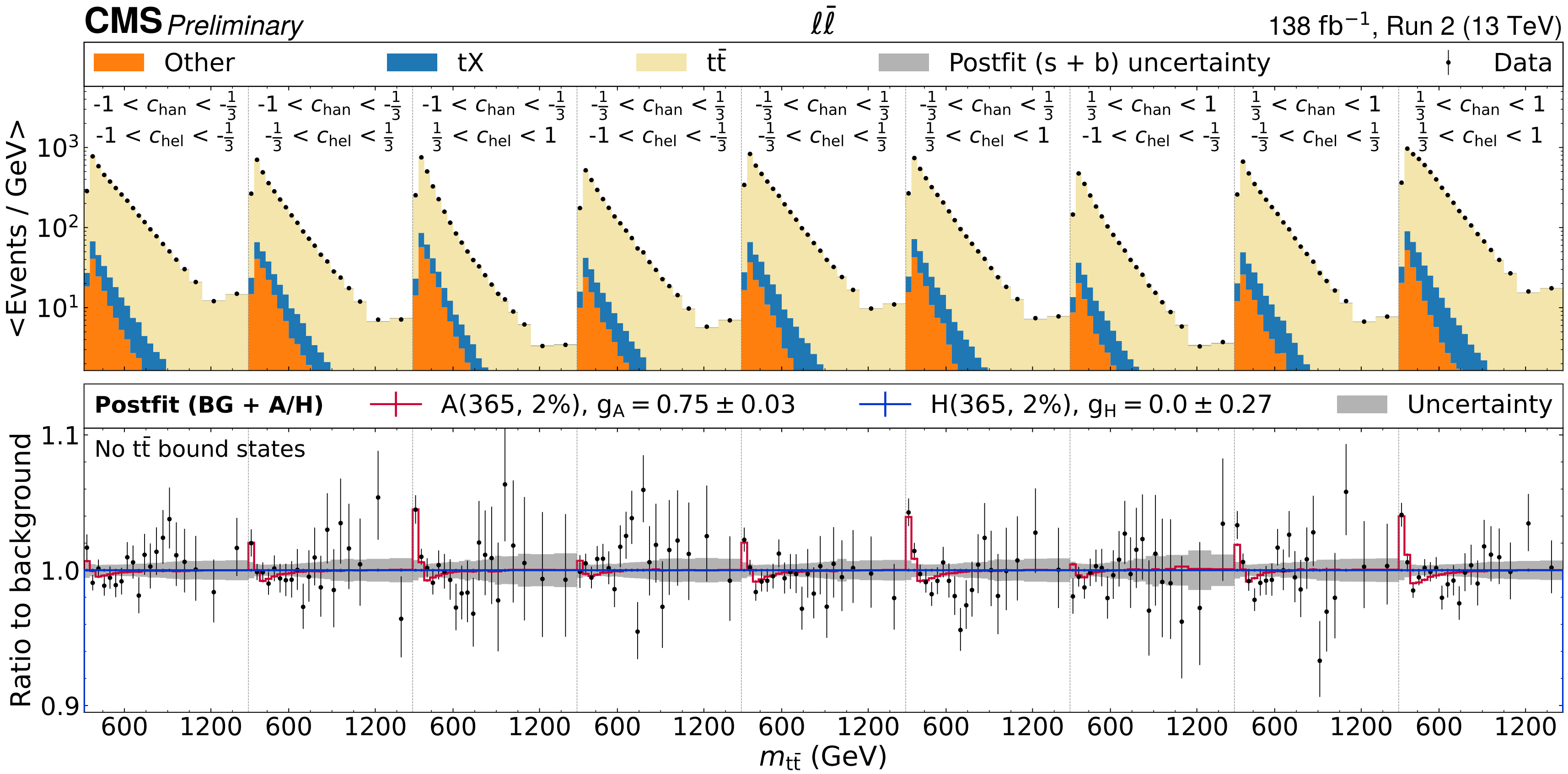
Postfit distributions: A/H

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



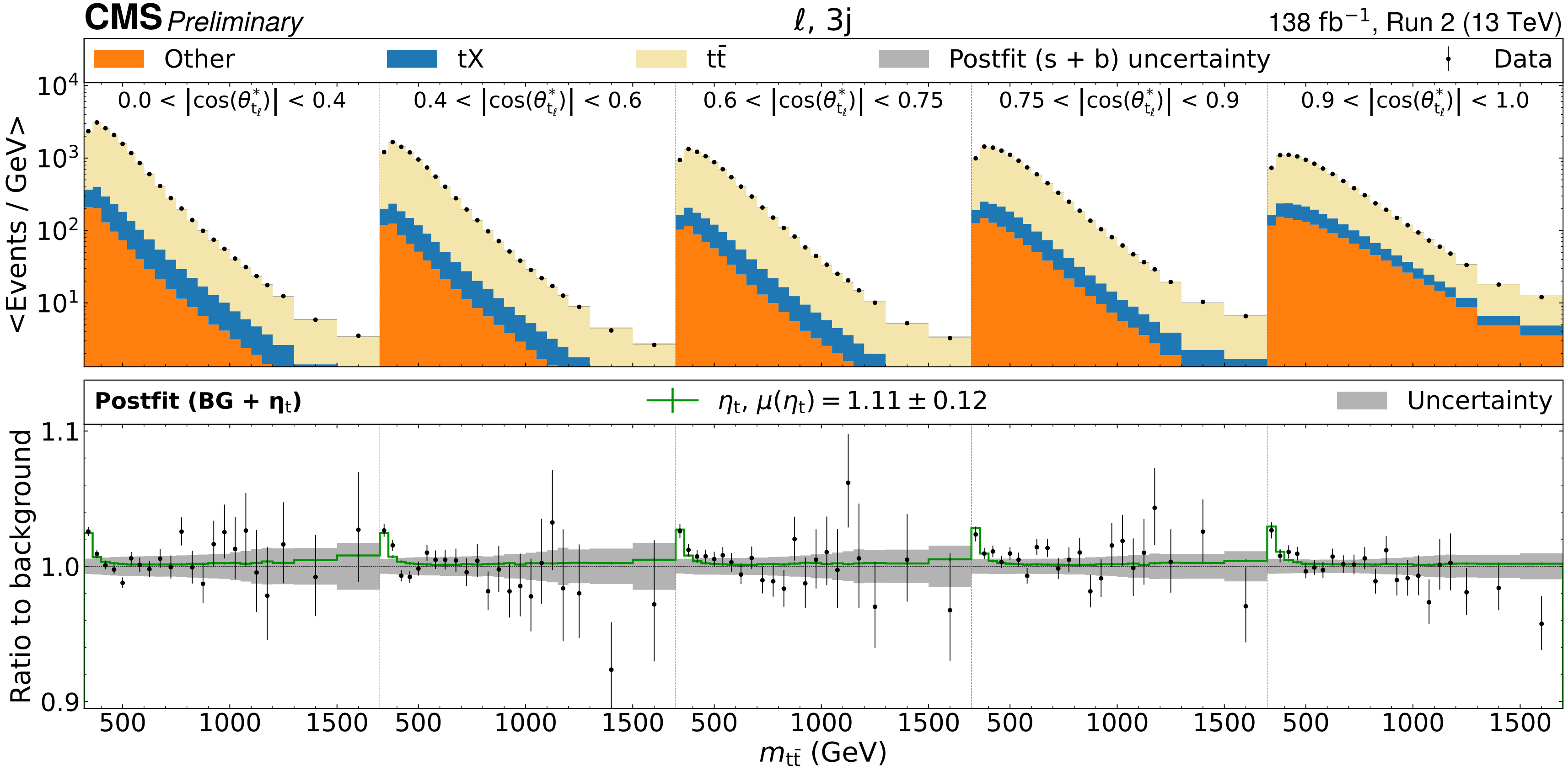
Postfit distributions: A/H

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



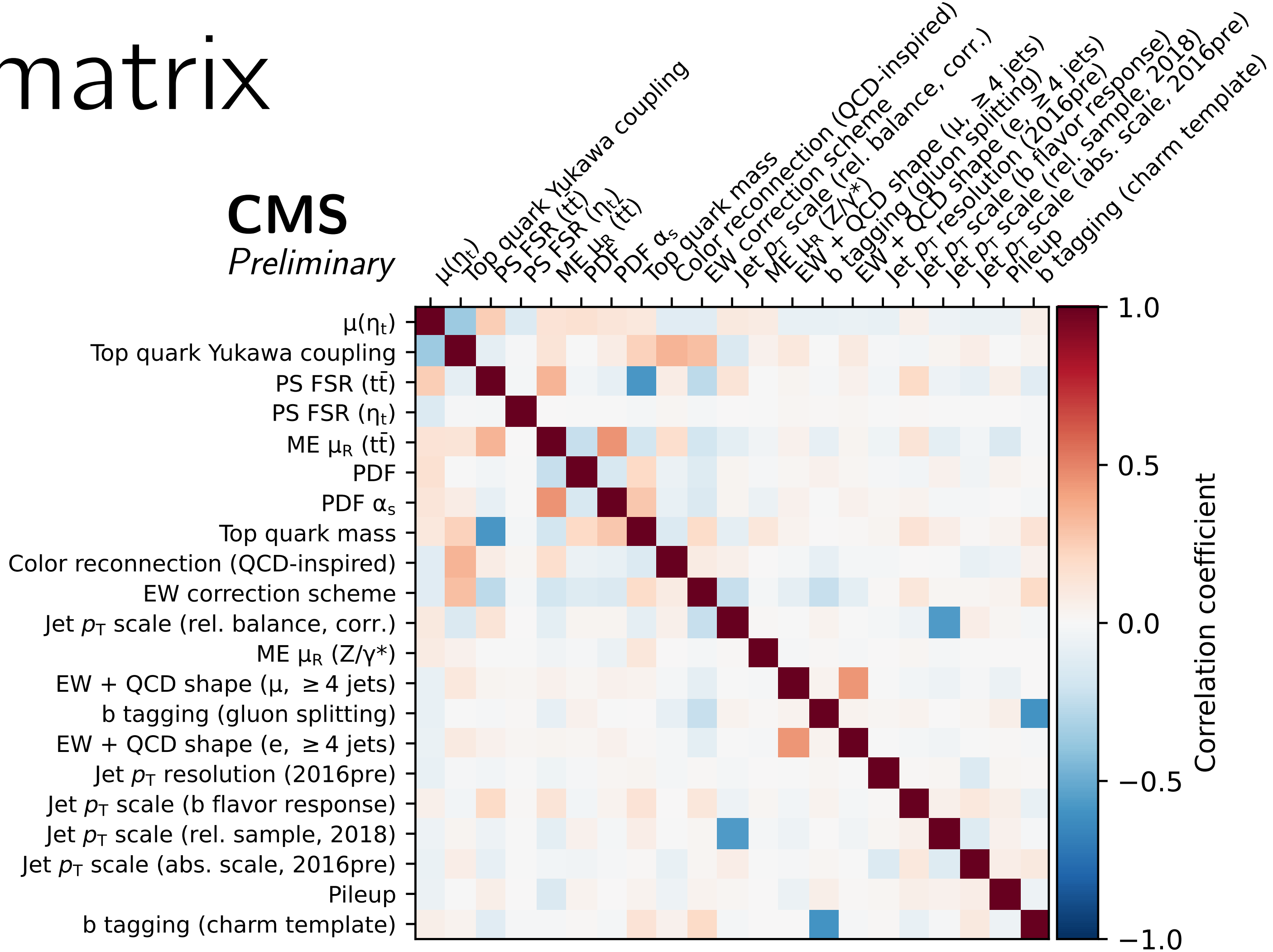
Postfit distributions: η_t

Postfit for η_t



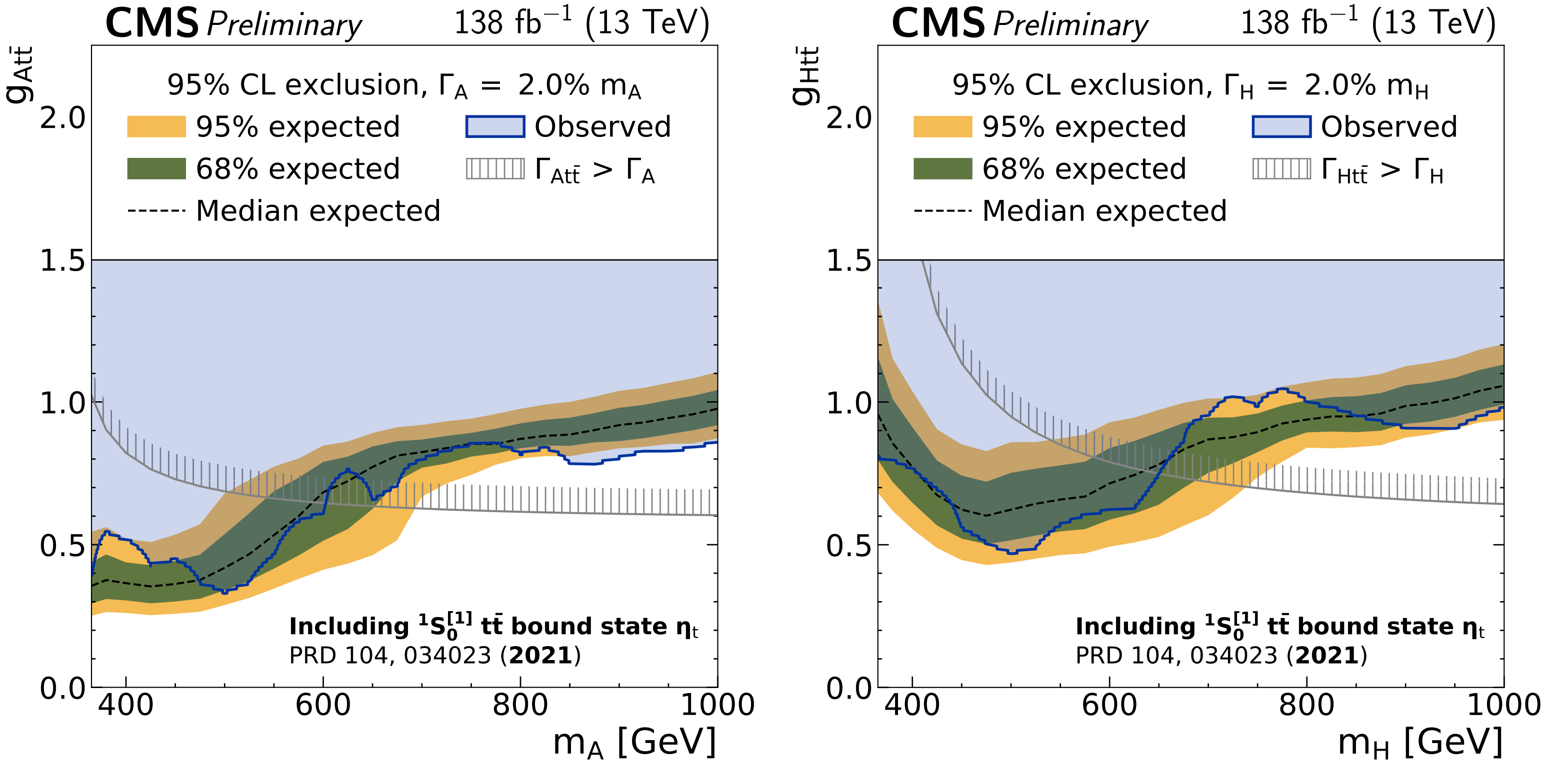
Correlation matrix

- Further assess uncertainty modeling through correlations of nuisance parameters



A/H limits including η_t

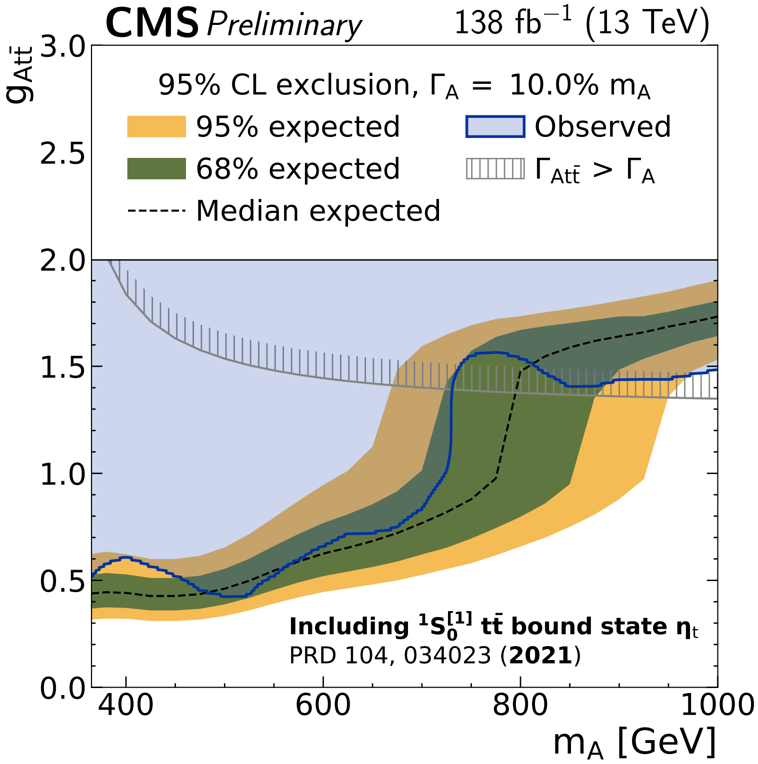
- Limits at different A/H widths

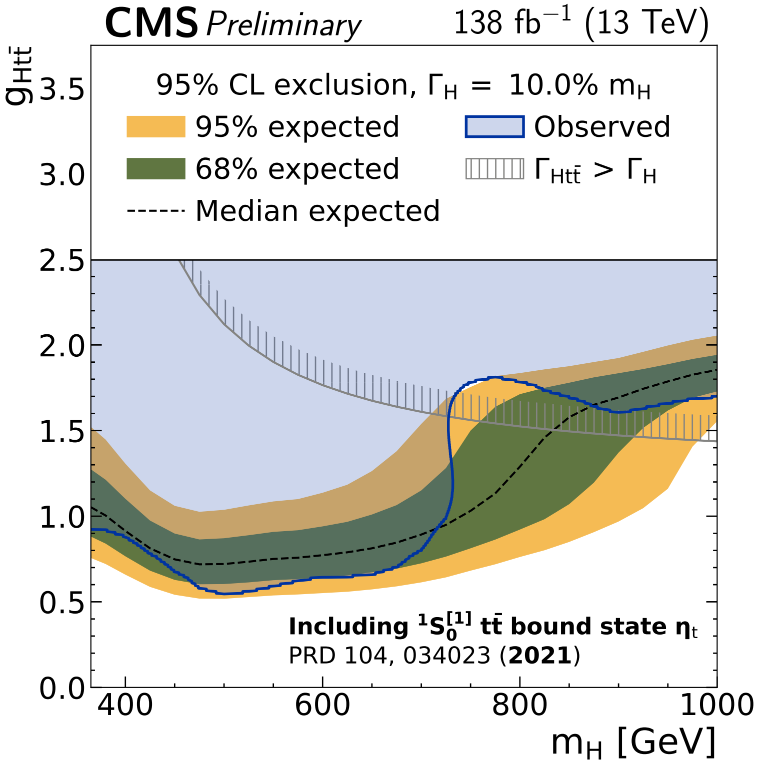


2% width

A/H limits including η_t

- Limits at different A/H widths

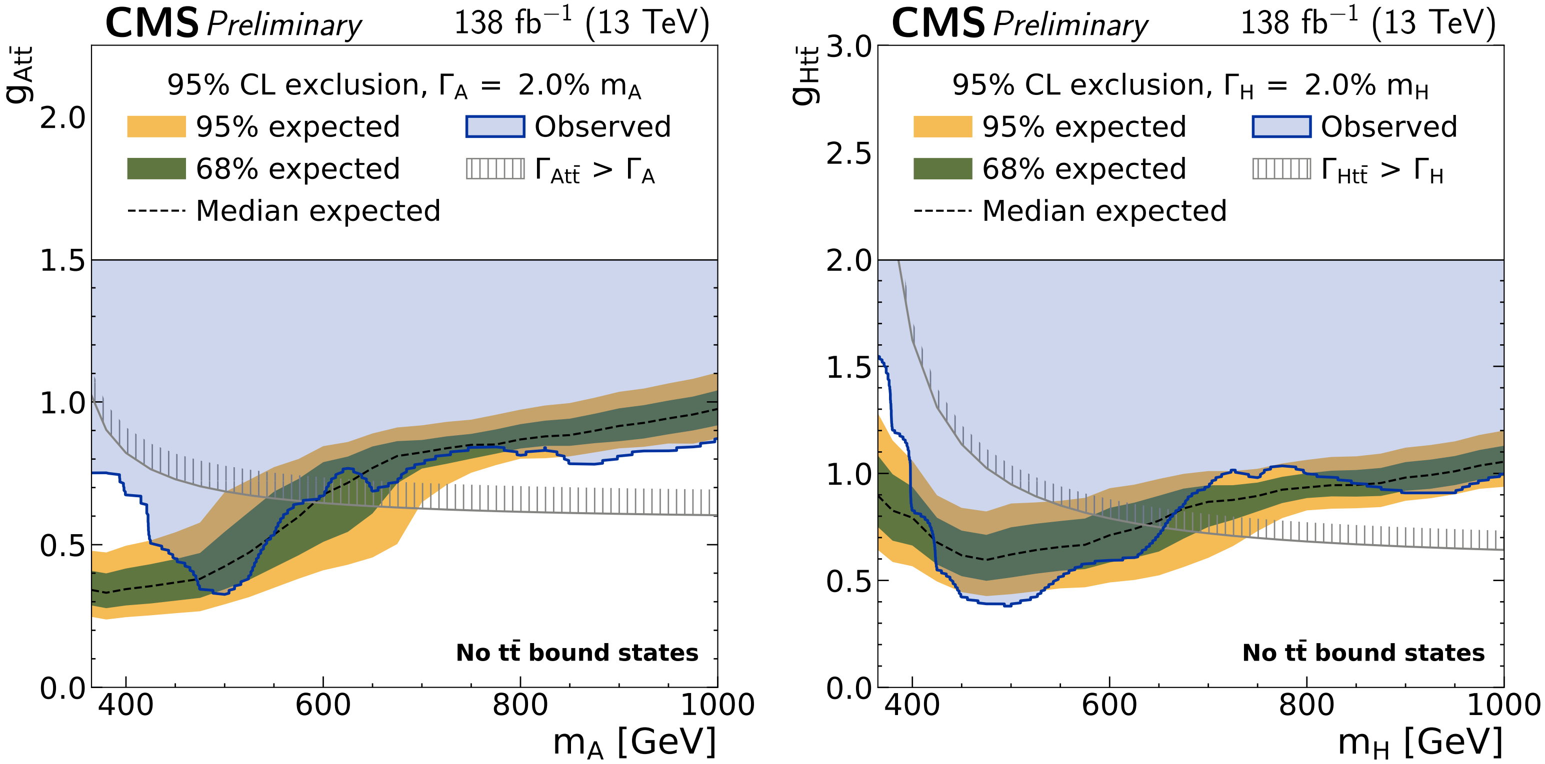




10% width

A/H limits without η_t

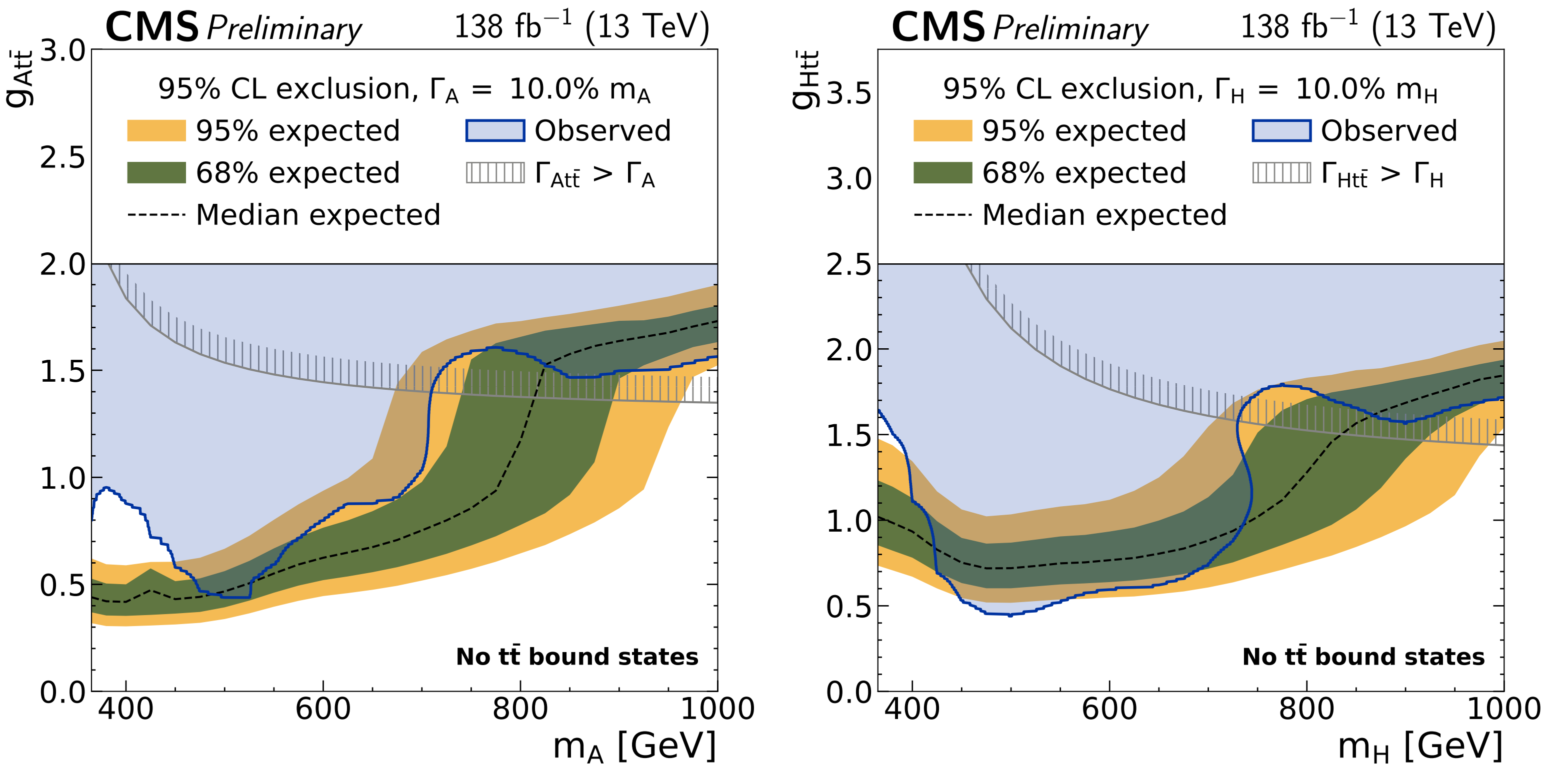
- Limits at different A/H widths for perturbative QCD background only



2% width

A/H limits without η_t

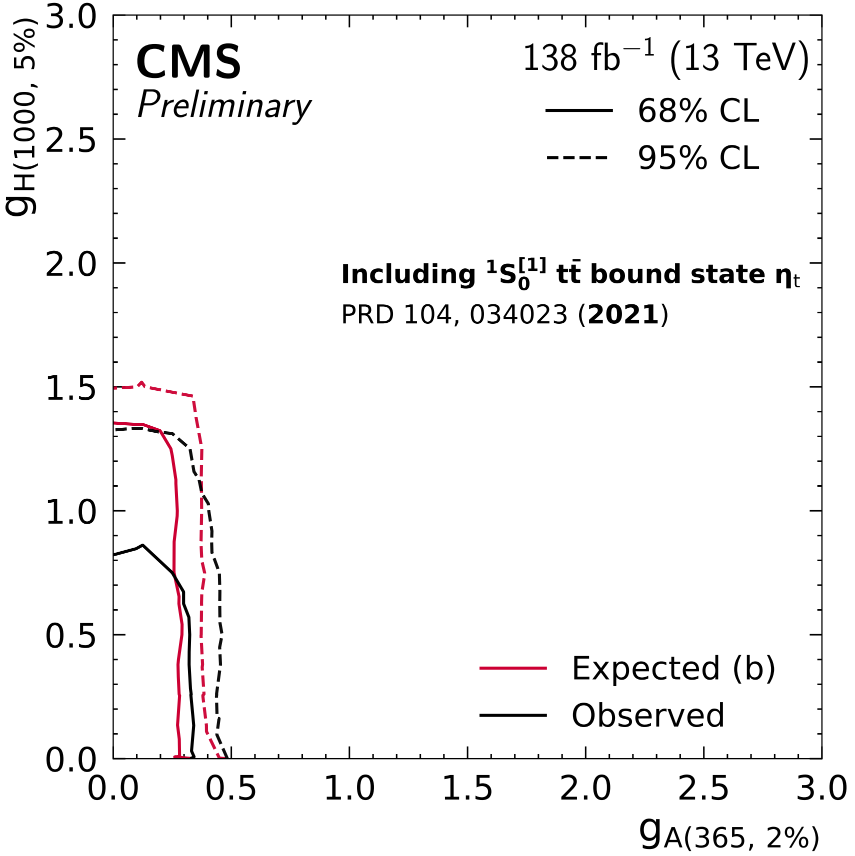
- Limits at different A/H widths for perturbative QCD background only



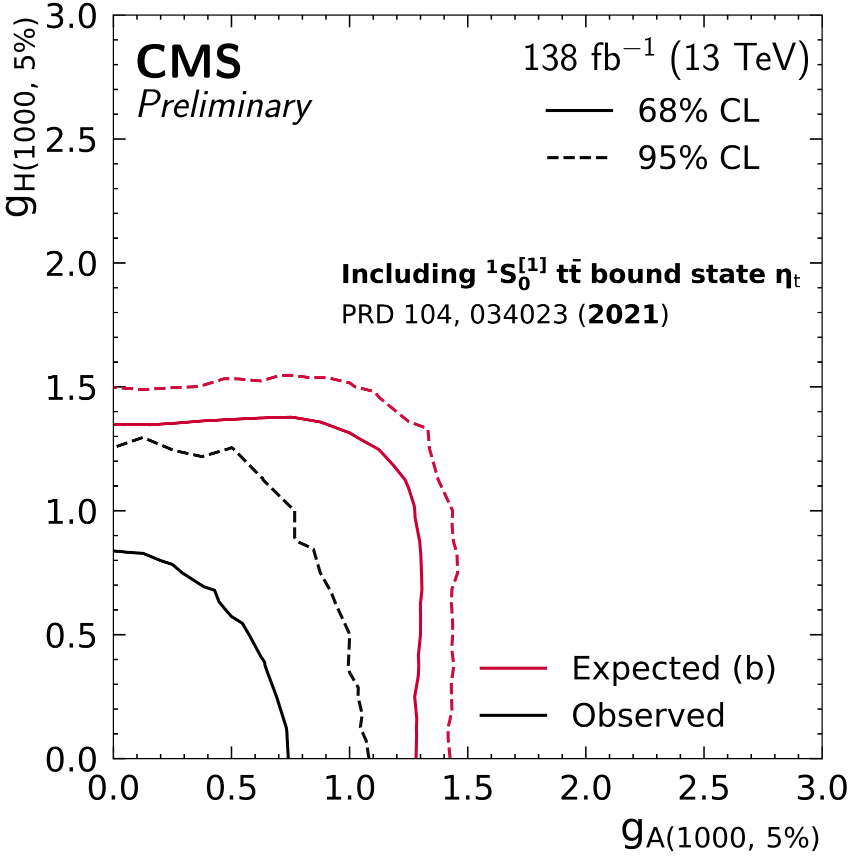
10% width

A+H interpretation

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



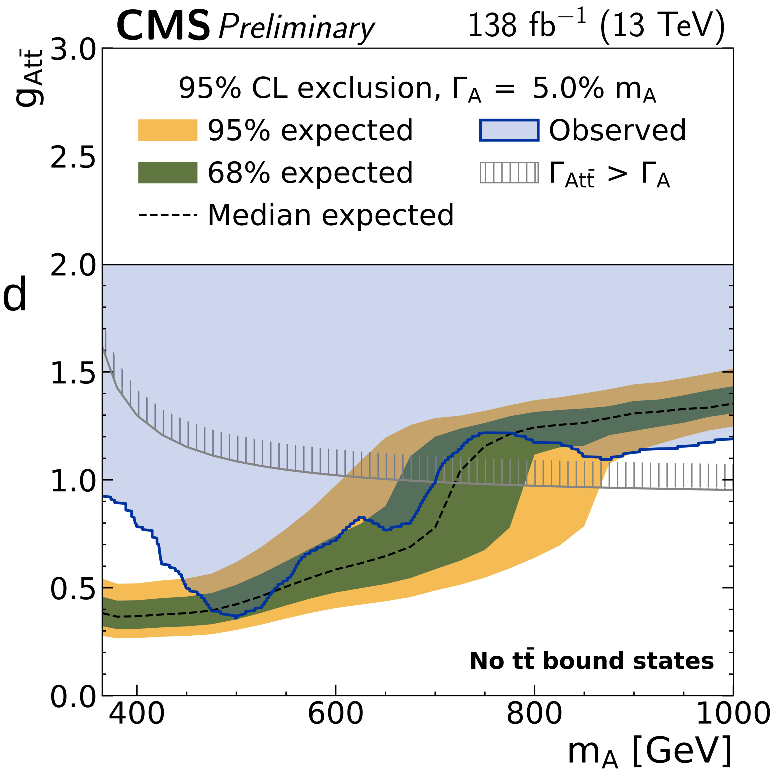
m_A = m_H = 1000 GeV, 5% width



Comparison with ATLAS

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

No η_t included



Pseudoscalar
5% width

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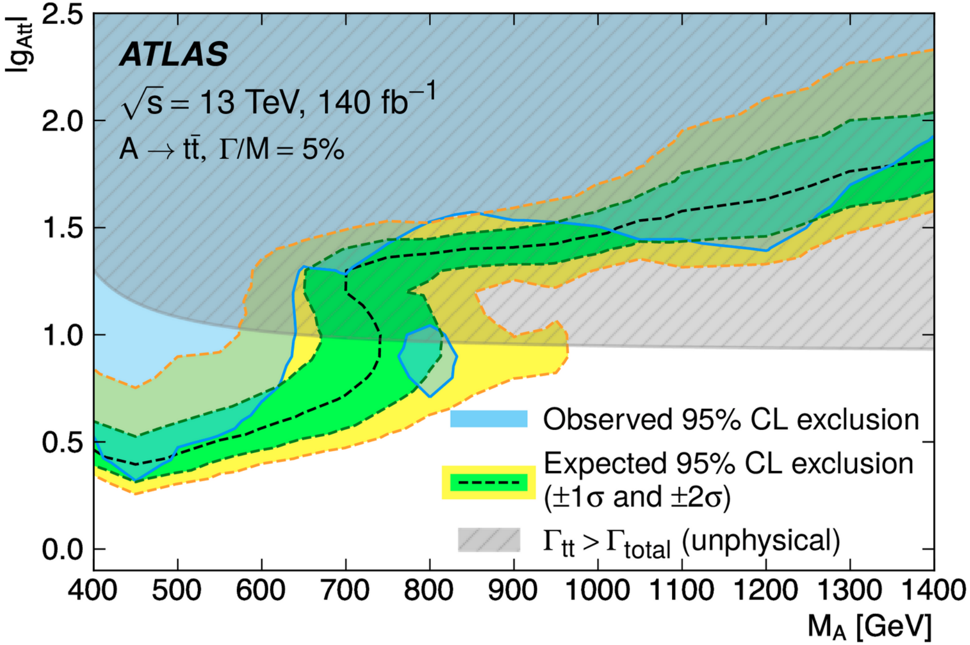

Comparison with ATLAS

- 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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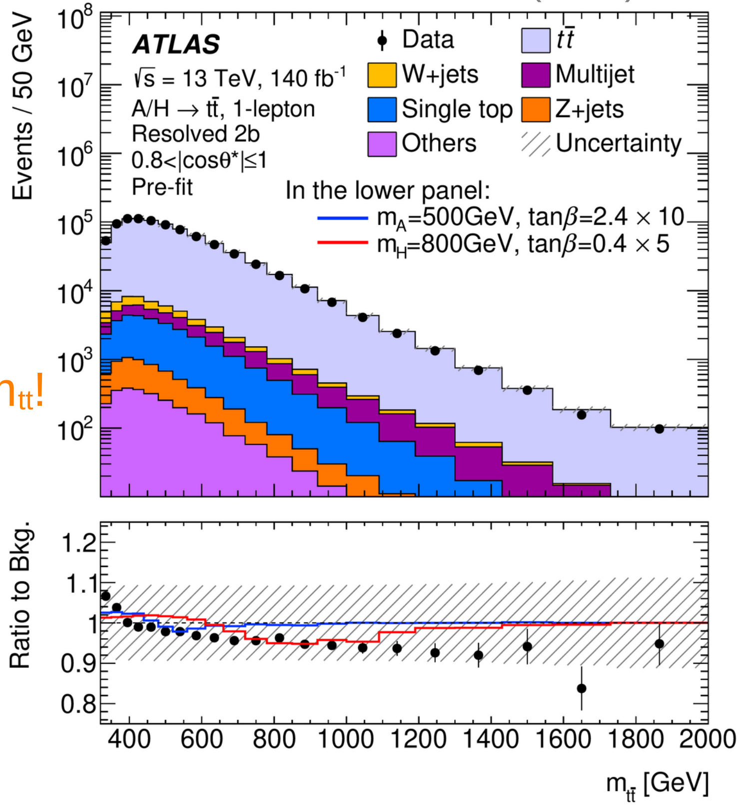

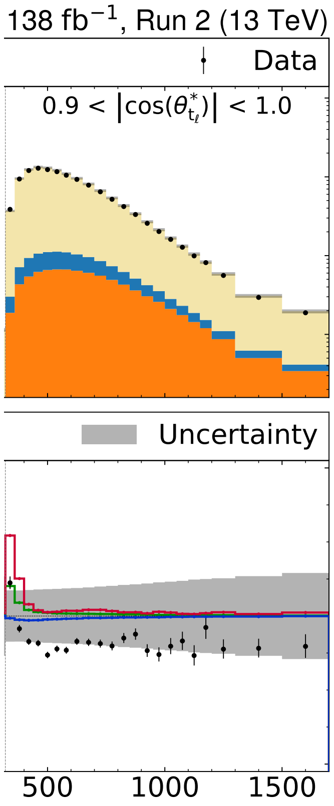

Comparison with ATLAS

- Different channel definitions in ATLAS and CMS
- dilepton: very different strategy
  - CMS: reconstruct $m_{t\bar{t}}$ x c_{hel} x c_{han}
    dominant at the $t\bar{t}$ threshold, i.e. for toponium
  - ATLAS: no top quark reconstruction
    instead: $m_{\ell\ell bb}$ x $\Delta\phi_{\ell\ell}$
    subleading compared to ℓ+jets

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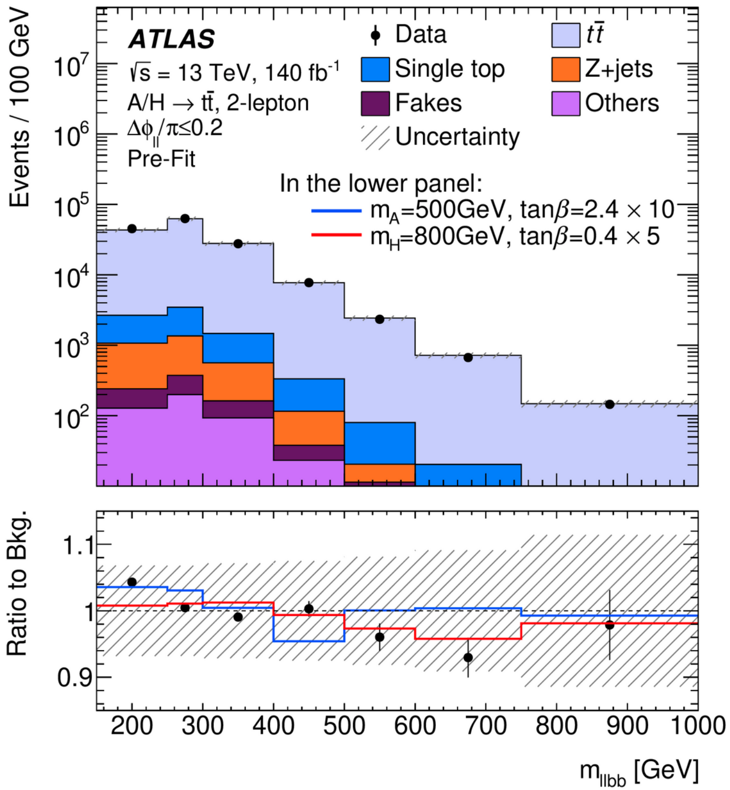
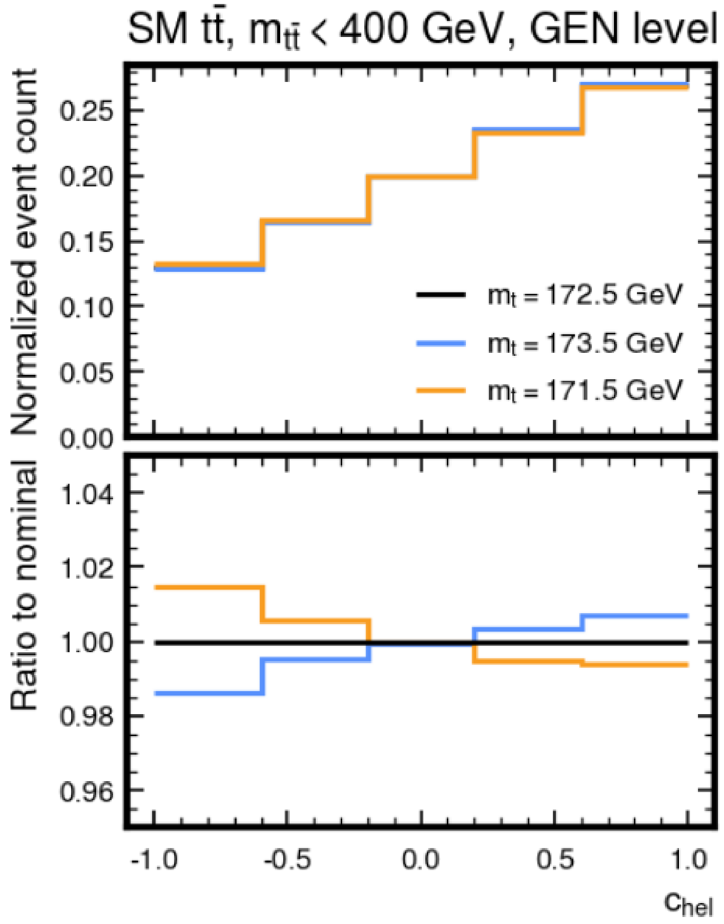


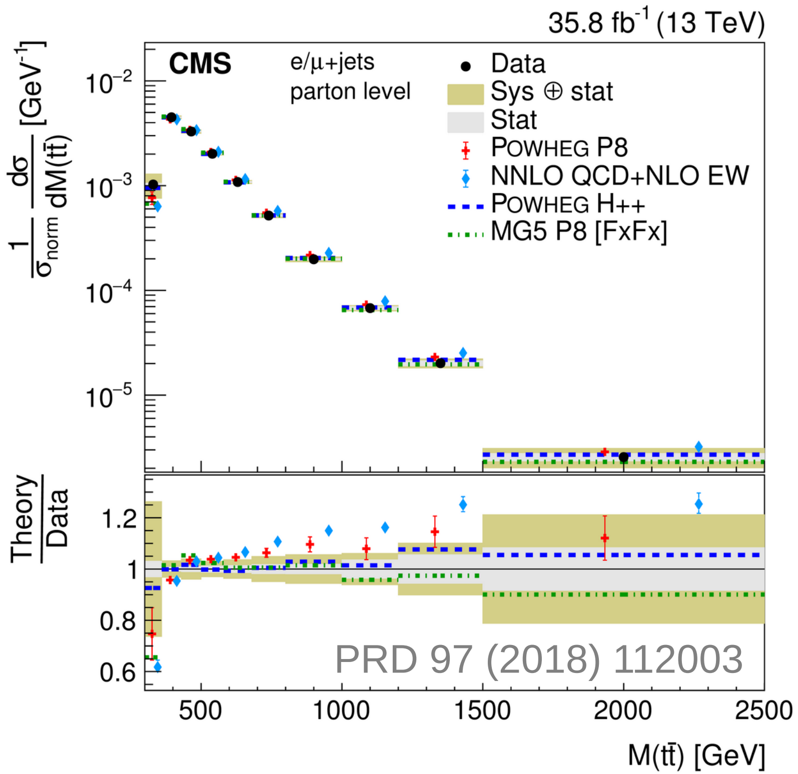
Comparison with ATLAS

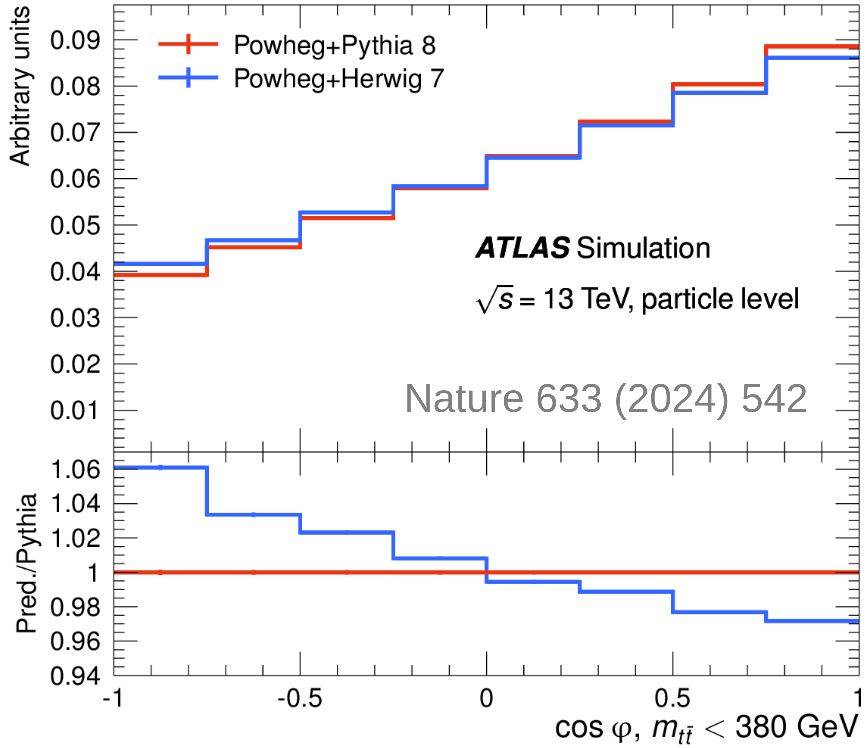
- Different channel definitions in ATLAS and CMS
- dilepton: very different strategy
- From internal studies: inclusion of spin correlations in CMS helps to disentangle signal and systematic uncertainties
- e.g. for downwards shift of top mass:
  - More events at threshold → like signal :(
  - BUT less spin correlation → unlike signal :)
- Similar for many other uncertainties, e.g. for Pythia vs. Herwig in the $t\bar{t}$ BG (next slide)



Pythia vs. Herwig

Herwig vs Pythia: more events at threshold, but less spin correlation
- not easily confused with signal when spin correlations are measured



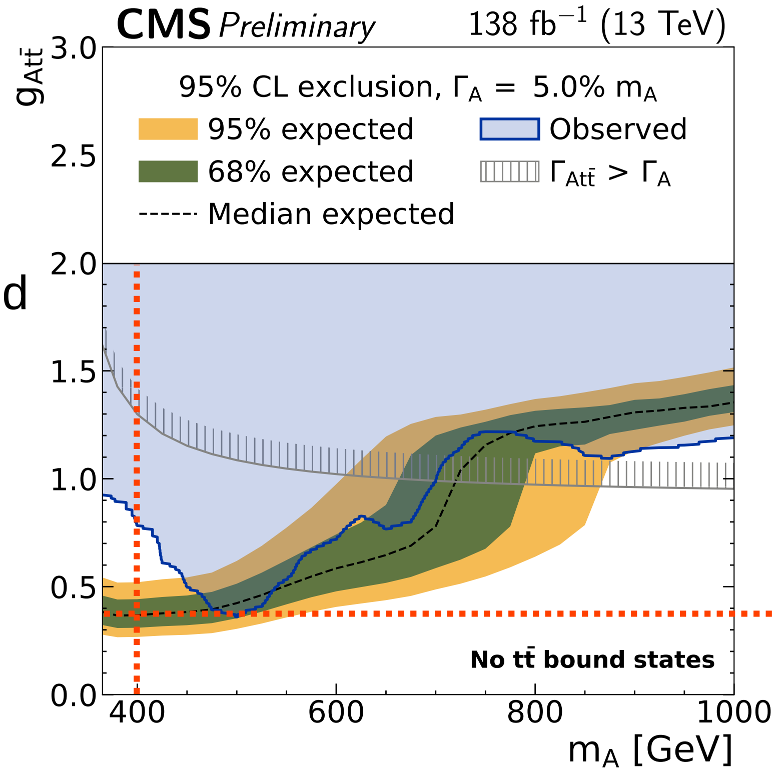


Comparison with ATLAS

- Similar prefit excess & expected limits – but no postfit excess for ATLAS!
- We are comparing as part of the LHC Top Working Group

Pseudoscalar
5% width

No η_t included



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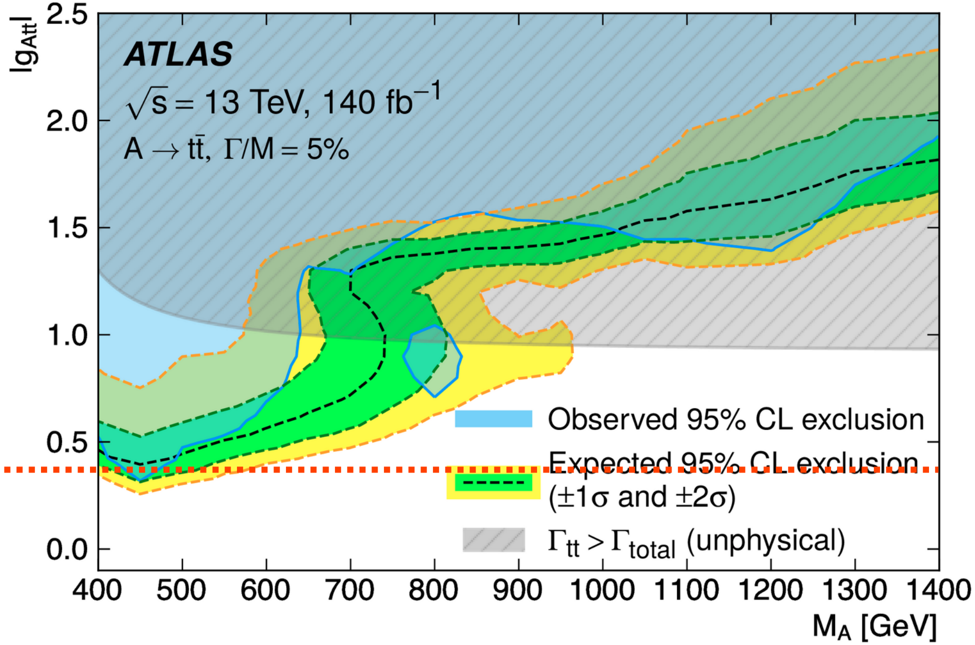
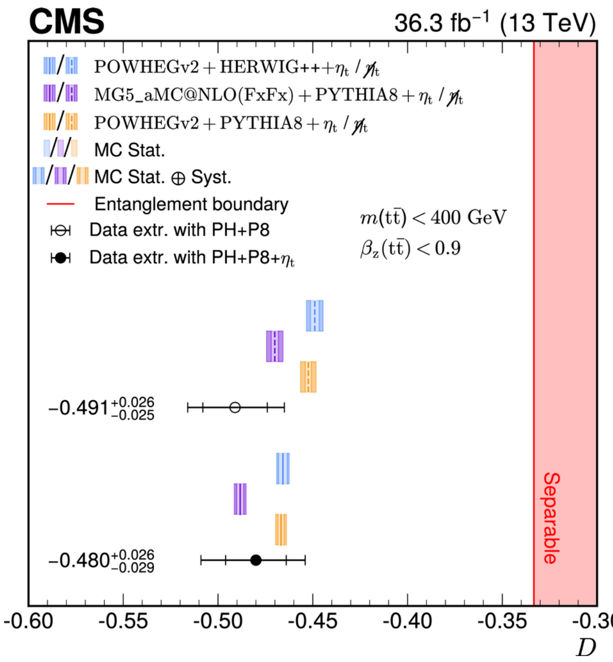


SM: $t\bar{t}$ spin entanglement

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

ROPP 87 117801 (2024)

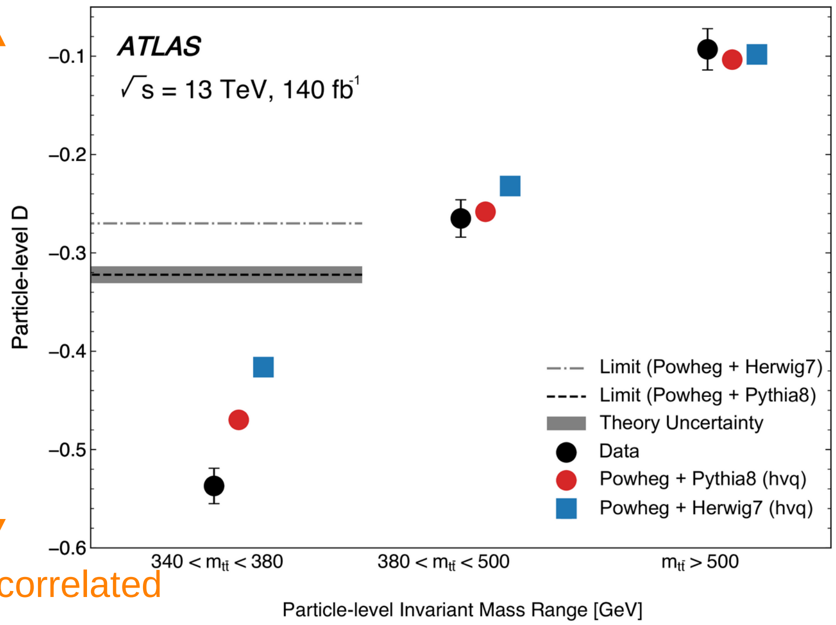


more anticorrelated

less correlated

less correlated

Nature 633 (2024) 542



more anticorrelated

η_t modeling: NLO vs NNLO

- All available NRQCD predictions are done with NLO(+NLL) hard scattering
  - should be compared to NLO fixed order or NLO+PS (e.g. Powheg)
  - The η_t model matches NRQCD well when added on top of NLO Powheg resulting cross section: ~ 6.43 pb
- However: our $t\bar{t}$ predictions are reweighted & rescaled to NNLO+NNLL
  - Necessary to compare with data
  - We choose to add η_t to the NNLO+NNLL-rescaled prediction
  - This amounts to applying a NNLO+NNLL K-factor to the NRQCD prediction