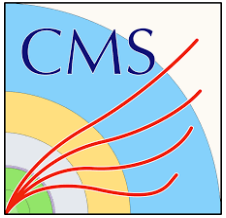
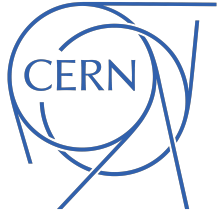
KCETA Colloquium

Probing the top quark pair production threshold at the LHC

Laurids Jeppe (CERN)

Karlsruhe, 28.10.2026 | laurids.jeppe@cern.ch





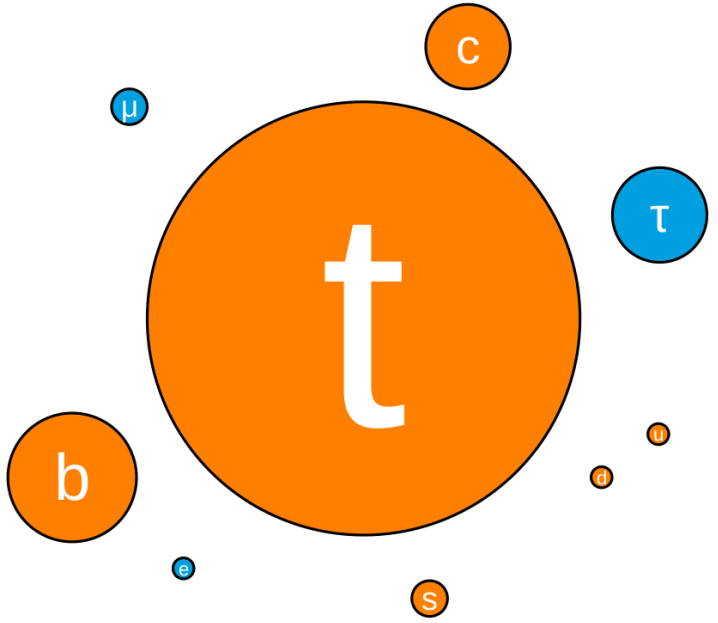
The top quark and us

- The top quark is special:
  - Short lifetime ~ 10^{-25} s
  - Decays before hadronizing - bare quark

  ➔ access to spin properties

  - Heaviest elementary particle
  - Largest coupling to Higgs

  ➔ gateway to new physics:
  e.g. additional Higgs sectors

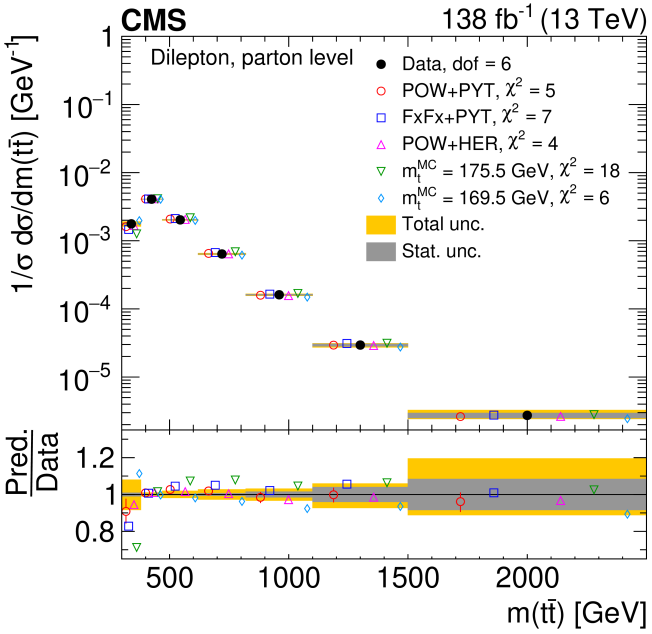


- **Understanding the top is crucial for SM and BSM physics!**

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

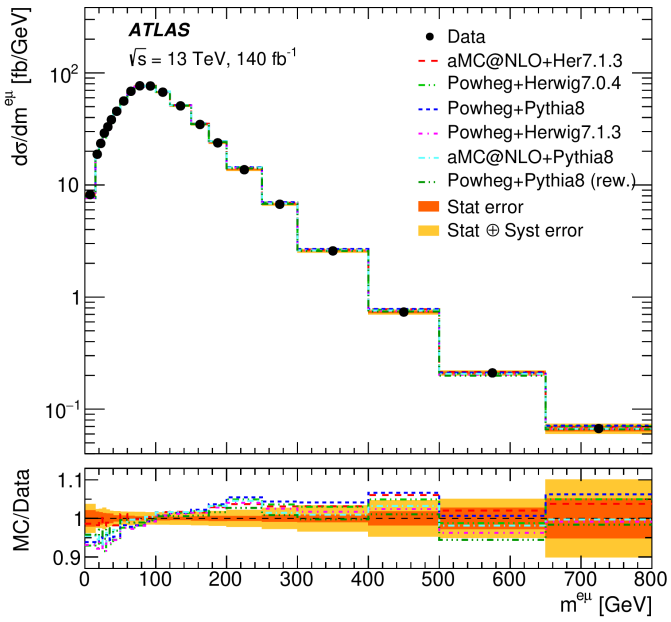
CMS ℓℓ - m_{tt}

CMS-PAS-TOP-20-006



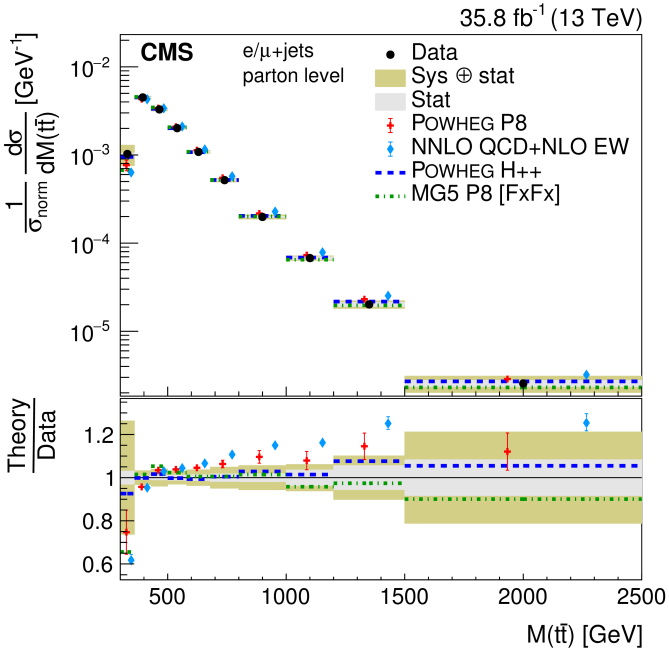
ATLAS eμ - $m_{e\mu}$

JHEP 07 (2023) 141



CMS ℓ+jets - m_{tt}

PRD 97 (2018) 112003

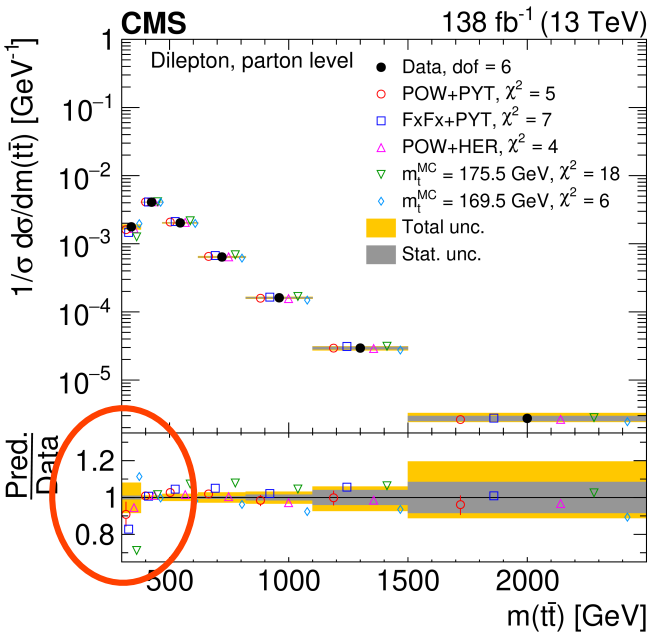


→ good description by MC

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

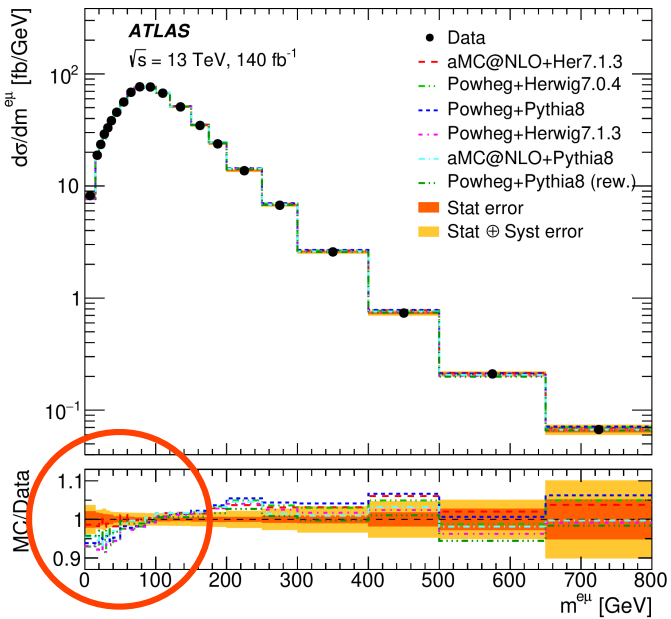
CMS ℓℓ - m_{tt}

CMS-PAS-TOP-20-006



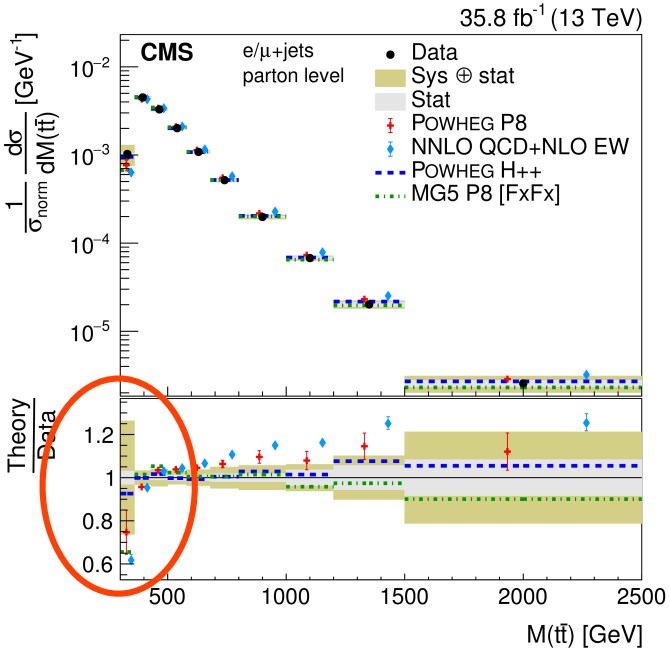
ATLAS eμ - $m_{e\mu}$

JHEP 07 (2023) 141



CMS ℓ+jets - m_{tt}

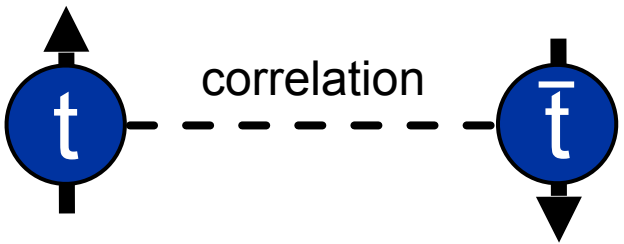
PRD 97 (2018) 112003



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

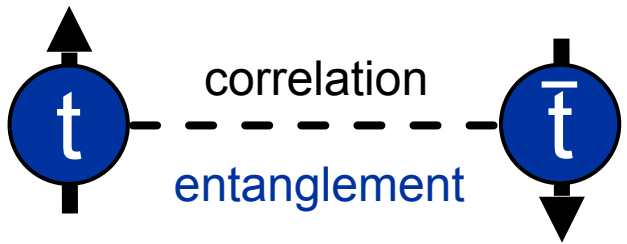
SM: $t\bar{t}$ spin correlation

- Top quarks are spin-½ fermions
- Spins of t and $\bar{t}$ in $t\bar{t}$ are correlated in the SM
- Spin information is transferred to top decay products – measurable at LHC



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

- Top quarks are spin-½ fermions
- Spins of t and $\bar{t}$ in $t\bar{t}$ are correlated in the SM
- Spin information is transferred to top decay products – measurable at LHC



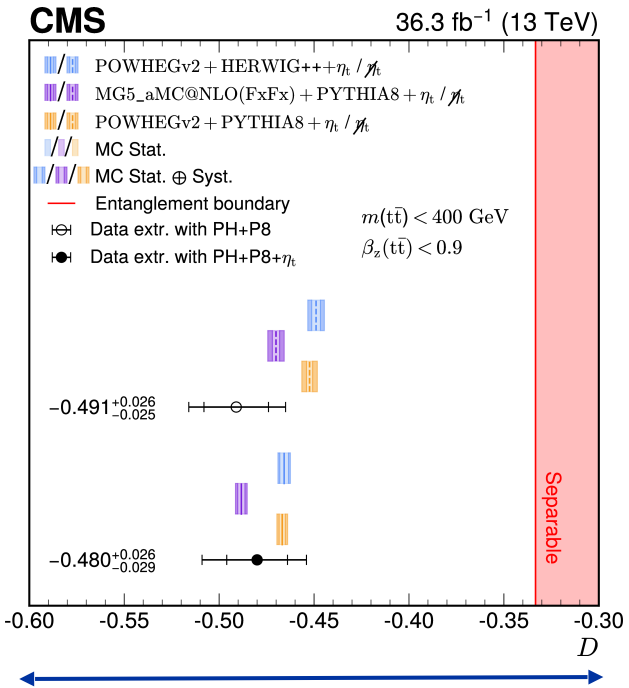
- Aside: Not just correlated, but also entangled!
  Measure $t\bar{t}$ spin entanglement → test of fundamental QM at high energies

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

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

somewhat oversimplified, more later…

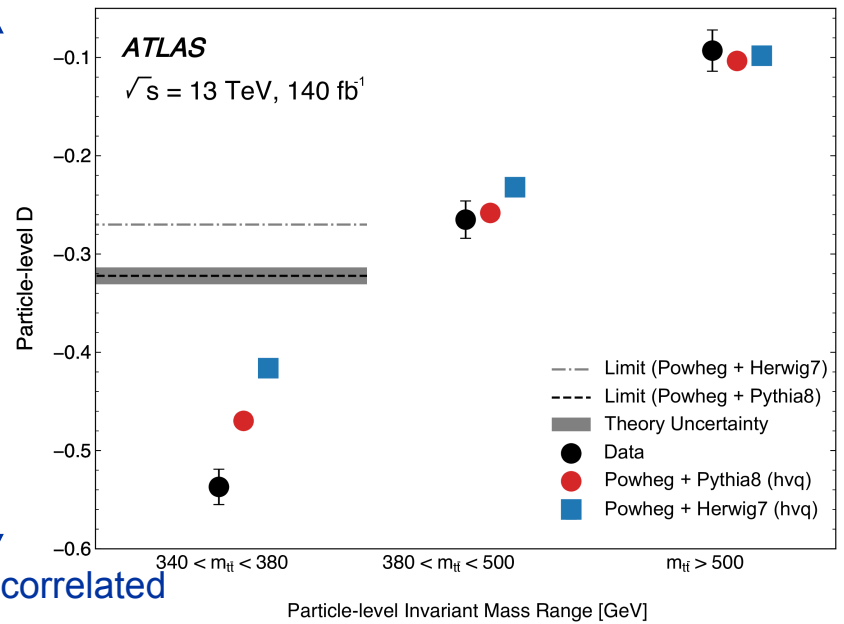
ROPP 87 117801 (2024)



more anticorrelated ⟷ less correlated

less correlated

Nature 633 (2024) 542



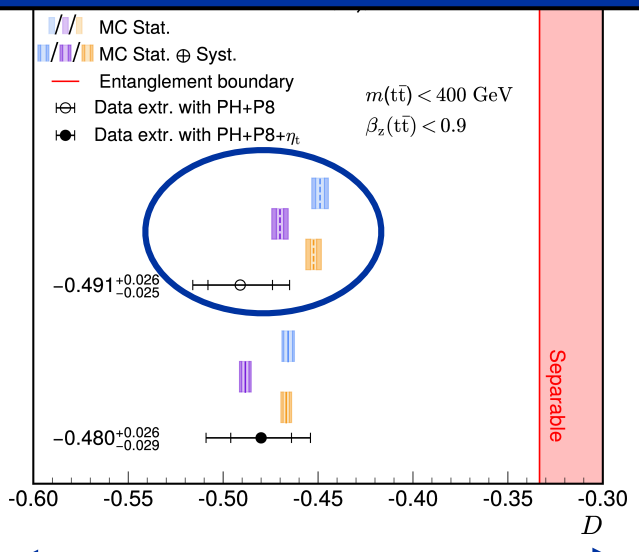
more anticorrelated

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

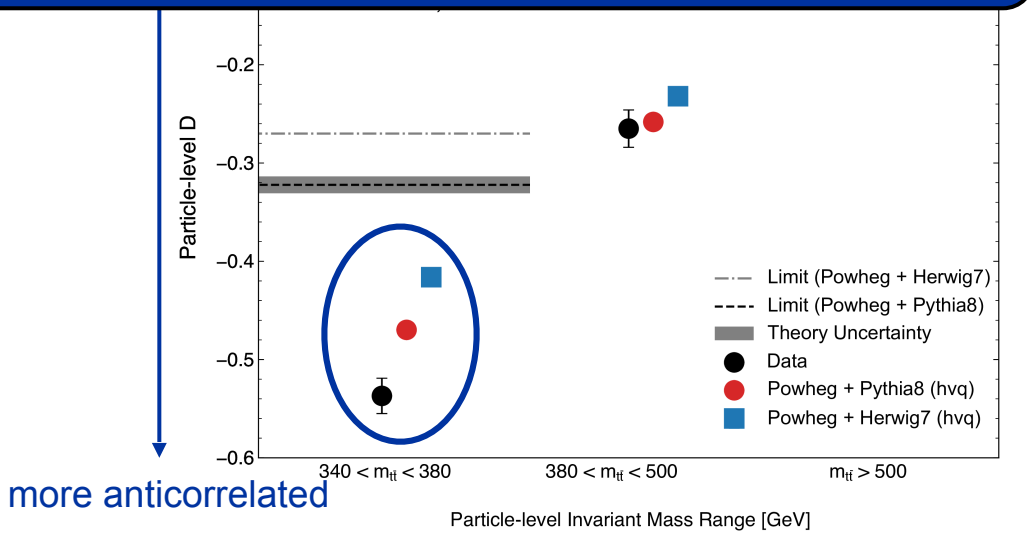
- Measured quantity: D "≈ strength of $t\bar{t}$ spin correlation"

somewhat oversimplified, more later…

Data shows stronger anti-correlation than prediction close to the threshold!
… only by 1σ though



more anticorrelated — less correlated



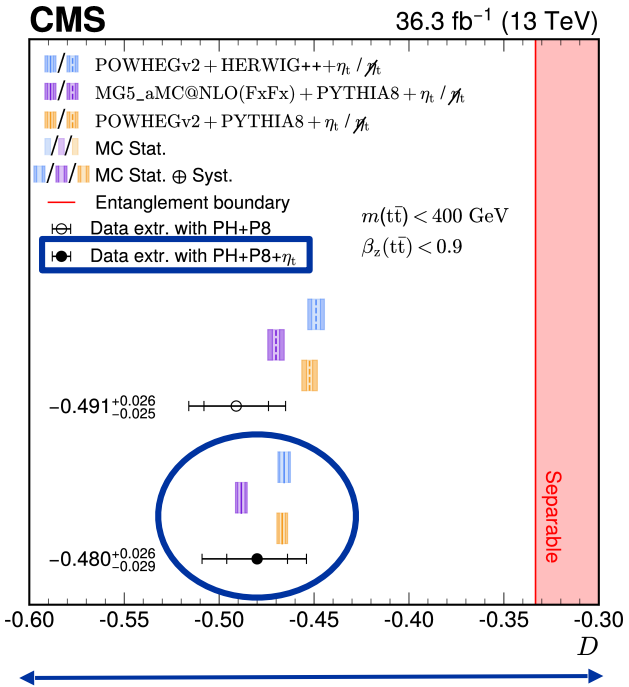
more anticorrelated

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

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

somewhat oversimplified, more later…

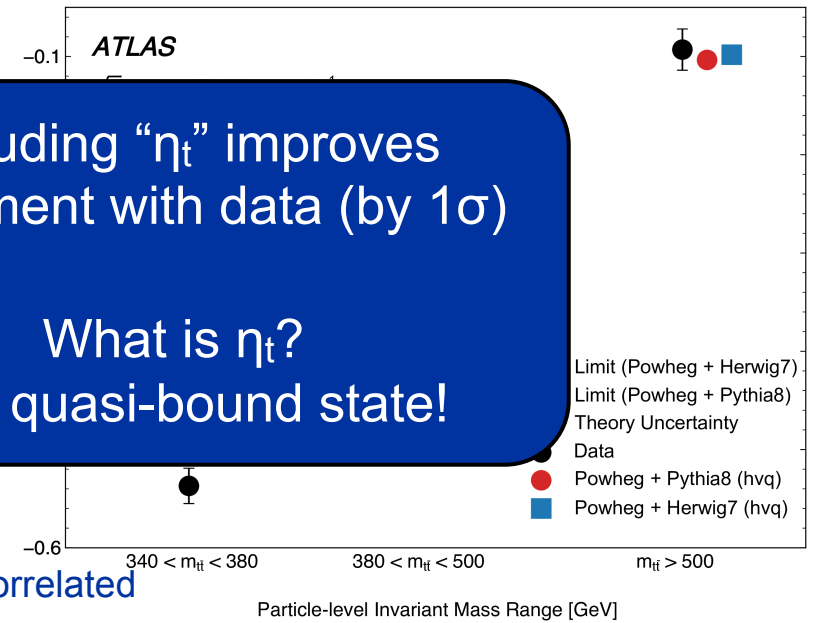
ROPP 87 117801 (2024)



more anticorrelated ⟷ less correlated

uncorrelated

Nature 633 (2024) 542



more anticorrelated

Including "η_t" improves agreement with data (by 1σ)

What is η_t?
→ $t\bar{t}$ quasi-bound state!

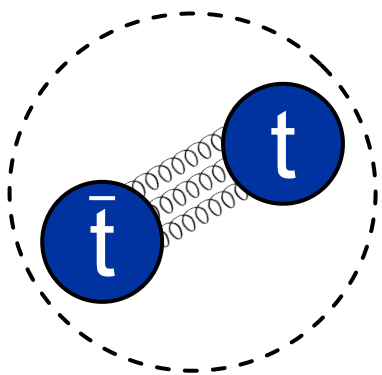
$t\bar{t}$ bound states?

- All quarks other than the top are known to form bound states (quarkonia)
- Simple estimate by analogy to positronium:

binding energy $E_b = -\frac{1}{2}\frac{m_q}{2}\left(C^{[1]}\alpha_S\right)^2$ with $C^{[1]} = \frac{4}{3}$ for color-singlet

for $t\bar{t}$: $E_b \approx -2\,\mathrm{GeV}$ system should be bound!

$r_b \approx 0.01\,\mathrm{fm}$ smallest known composite object



$t\bar{t}$ bound states?

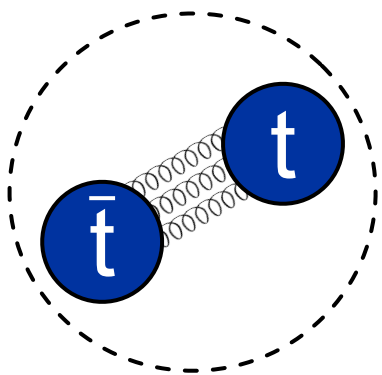
- All quarks other than the top are known to form bound states (quarkonia)
- Simple estimate by analogy to positronium:

binding energy $E_b = -\frac{1}{2}\frac{m_q}{2}\left(C^{[1]}\alpha_S\right)^2$ with $C^{[1]} = \frac{4}{3}$ for color-singlet

for $t\bar{t}$: $E_b \approx -2\,\mathrm{GeV}$ system should be bound!

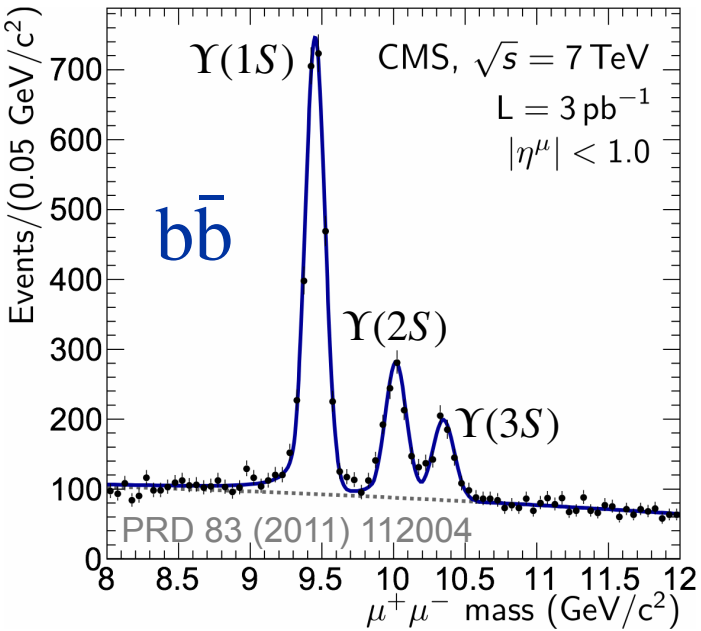
$r_b \approx 0.01\,\mathrm{fm}$ smallest known composite object

- However: short lifetime / large width: $\Gamma \approx 2\Gamma_t = 2.8\,\mathrm{GeV} \sim E_b$
  - Classical argument: top decays before bound state can form
    → no *stable* bound state, but…



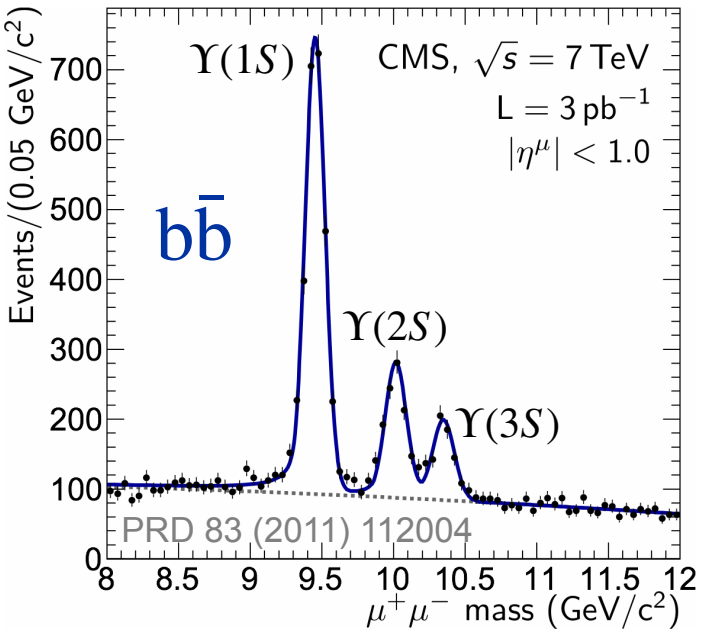
$t\bar{t}$ bound states: NRQCD

- more quantitative: non-relativistic QCD (NRQCD)

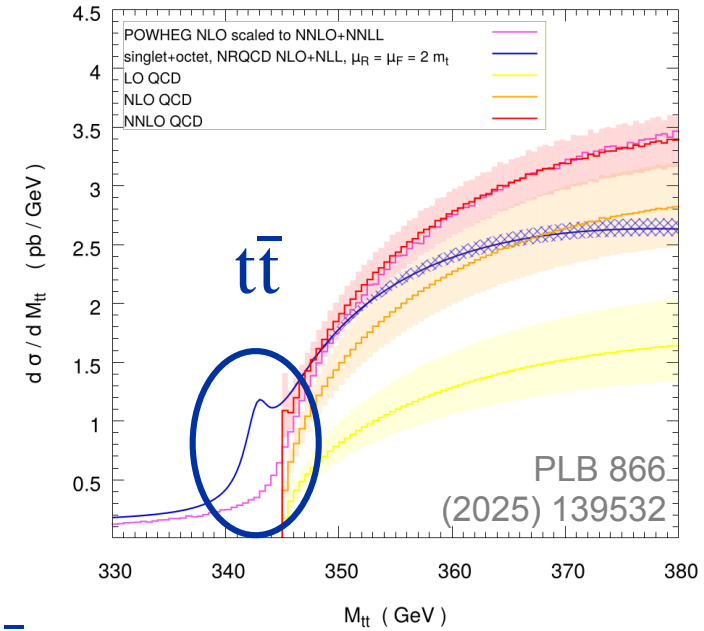


$t\bar{t}$ bound states: NRQCD

- more quantitative: non-relativistic QCD (NRQCD)



finite width



one broad peak around the $t\bar{t}$ threshold!

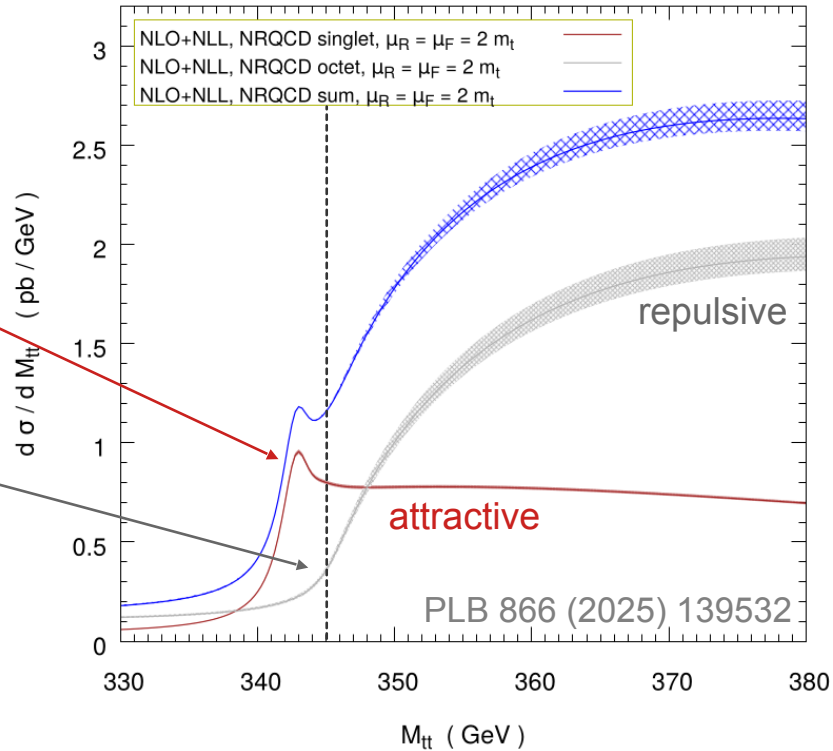
"quasi-bound state"

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

See e.g.
PLB 866 (2025) 139532
PRD 110 (2024) 5, 054032
JHEP 03 (2024) 099
PRD 104 (2021) 3, 034023
etc.

- Results of NRQCD calculations:
  - Color-singlet ($^1S_0^{[1]}$) - attractive
    → Peak below the $t\bar{t}$ threshold
    CP-odd / pseudoscalar spin state!
  - Color-octet ($^1S_0^{[8]}$ or $^3S_1^{[8]}$) - repulsive
    → Suppressed below the $t\bar{t}$ threshold

→ pseudoscalar-like enhancement at low $m_{t\bar{t}}$

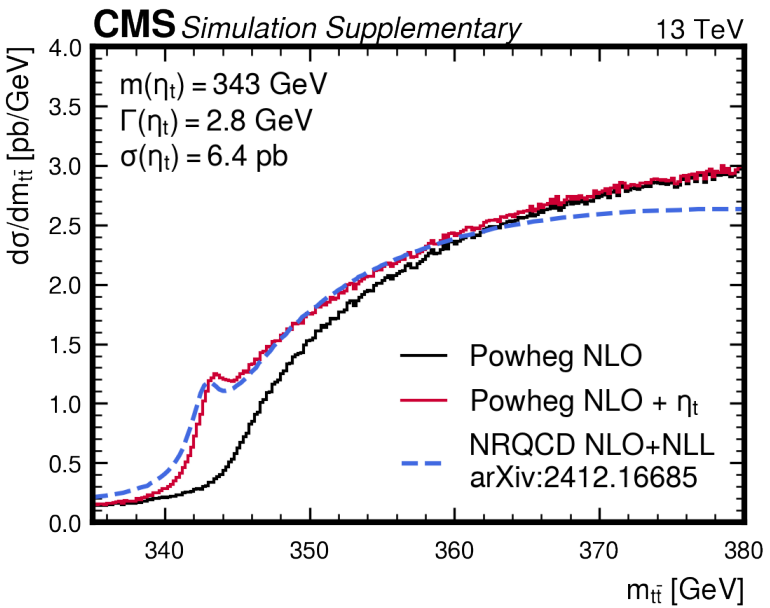


Modeling of the $t\bar{t}$ threshold in MC

- Ideal case: use one MC that describes both threshold and continuum
- However, not available until very recently: [Nason, Pelliccioli, Re, Rottoli, arXiv:2607.09539]

(PRD 104 (2021) 034023, JHEP 03 (2024) 099)

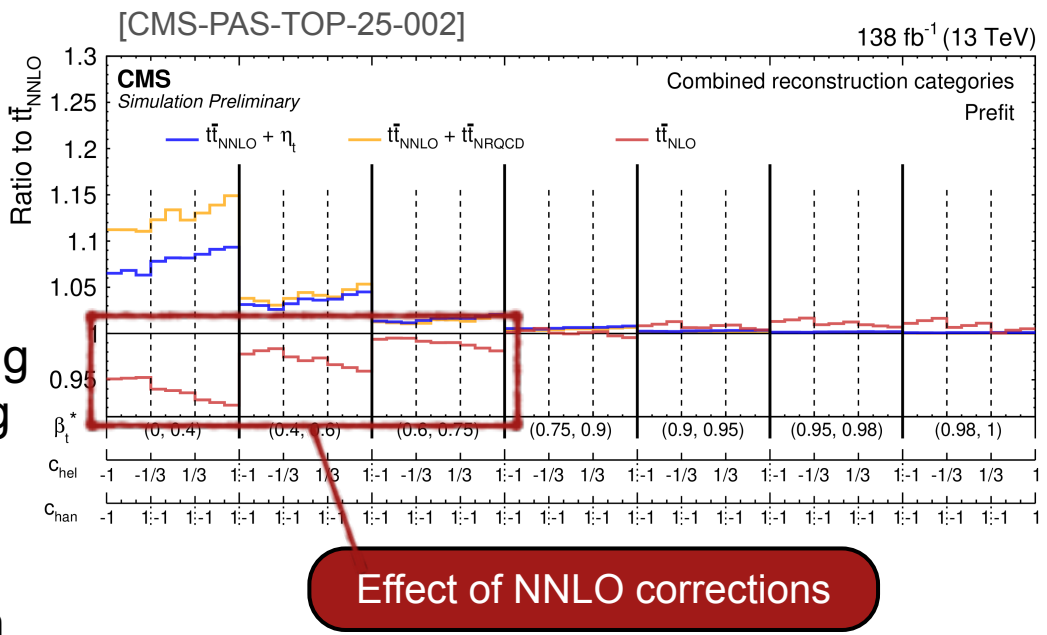
- Instead simplified model for MC simulation: η_t
  - Additional pseudoscalar state with couplings to gluons and tops
  - Fit mass and width from NRQCD



→ Stack on top of ordinary pQCD $t\bar{t}$ simulation!
Fits well to NRQCD prediction for $m_{t\bar{t}}$

Background modeling

- Major irreducible “background”: $t\bar{t}$
  - Model from NLO MC (Powheg+Pythia)
  - Correct to NLO EW from fixed-order predictions by 2D reweighting (EPJC 51 (2007) 37)
    and to NNLO QCD (either 2D reweighting to MATRIX or ML reweighting to Powheg $t\bar{t}$ MiNNLO+PS) (PRL 127 062001)
  - Normalize to NNLO+NNLL cross section (CPC 185 (2014) 2930)



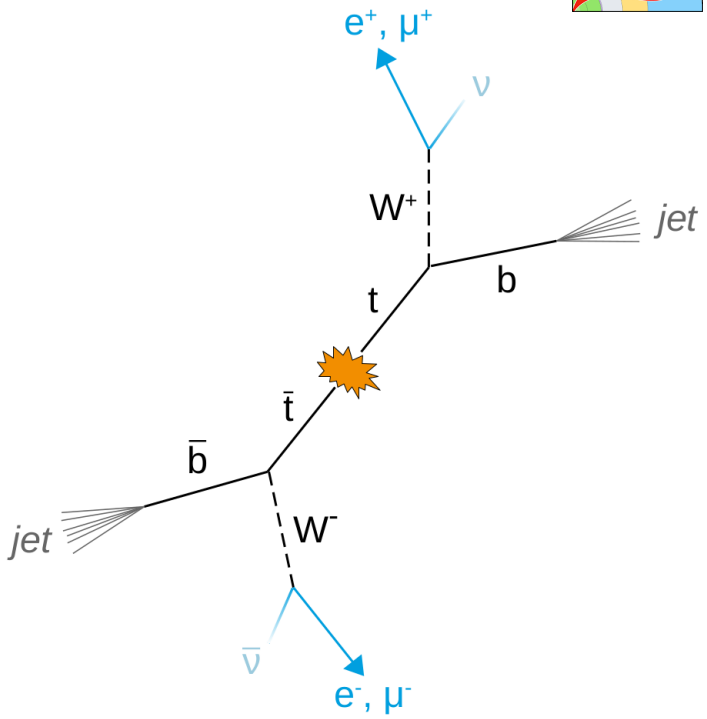
- Other MC-based backgrounds: tW, t-channel single-top

CMS dilepton analysis

RoPP 88 087801 (2025)

Dilepton selection

- 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



- Analytic reconstruction of $t\bar{t}$ system starting from leptons, b jets and MET
  - Conservation of momentum + mass constraints on top and W —> 4th order polynomial equations

- Only non-top BG: Z+jets (MC with data-driven normalization)

Spin density matrix

- At the threshold, $t\bar{t}$ is produced in a pure $^1S_0$ (pseudoscalar) $t\bar{t}$ spin state

- 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

Spin density matrix

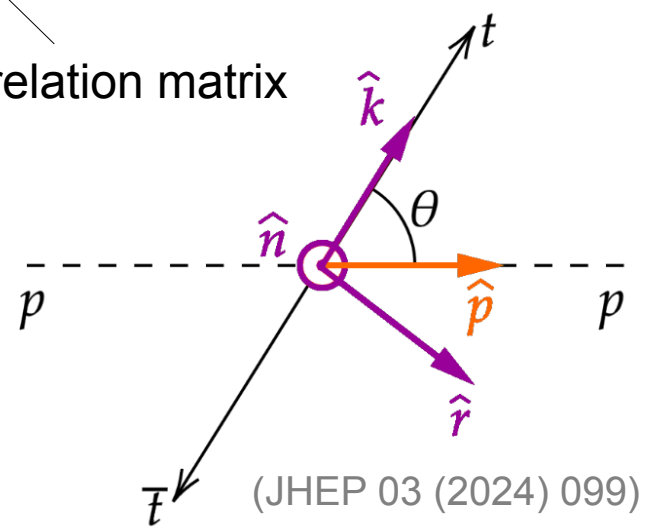
- At the threshold, $t\bar{t}$ is produced in a pure $^1S_0$ (pseudoscalar) $t\bar{t}$ spin state

- 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)

Spin correlation observables

- Top decays before hadronization → transfer spin information to decay products
- Construct spin correlation observables from tops & leptons
  - Leptons boosted into rest frames of their parent tops (“helicity frames”)

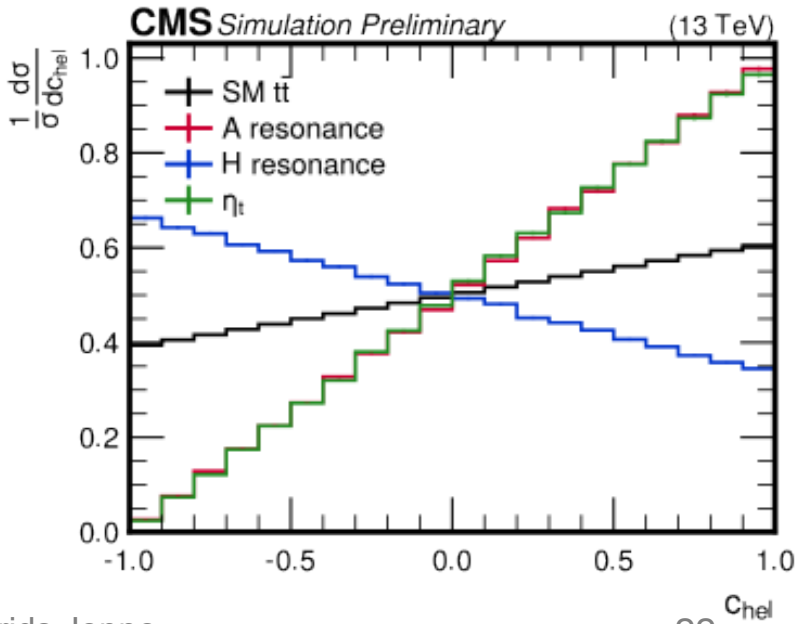
Spin correlation observables

- Top decays before hadronization → transfer spin information to decay products
- Construct spin correlation observables from tops & leptons
  - Leptons boosted into rest frames of their parent tops (“helicity frames”)

- Variable #1: C_{hel}
  - Scalar product between lepton directions of flight
  - Straight line with slope sensitive to $t\bar{t}$ spin state:

$$D = \frac{1}{3}\mathrm{Tr}\left[\mathbf{C}\right]$$ — spin correlation matrix

  - Maximal for $^1S_0$ (from η_t) – separates from SM

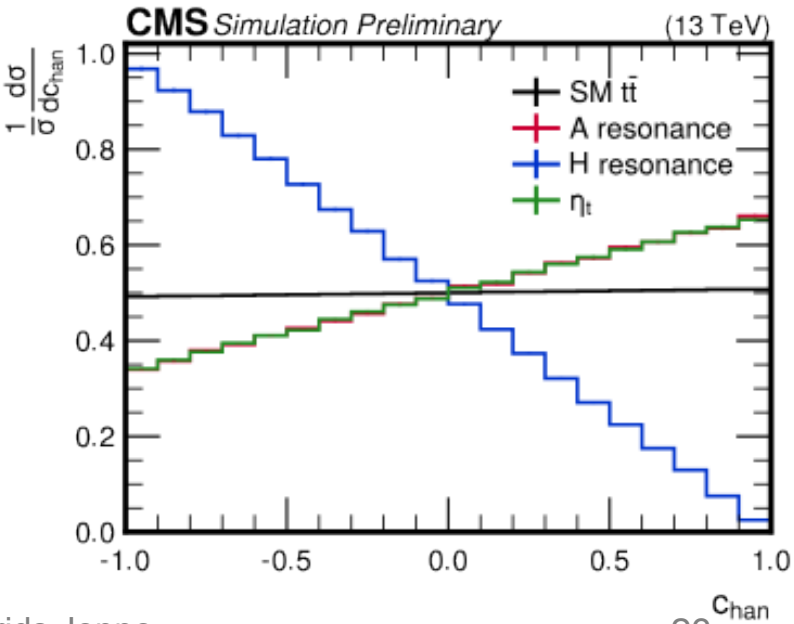


Spin correlation observables

- Top decays before hadronization → transfer spin information to decay products
- Construct spin correlation observables from tops & leptons
  - Leptons boosted into rest frames of their parent tops (“helicity frames”)

- Variable #2: c_{han}
  - Similar as c_{hel}, separating scalars from SM
  - Maximally negative slope for $^3P_0$ state
  - Construct similarly from lepton momenta, with sign flip for *k* component in helicity basis:

$$D^{(k)} = \frac{1}{3}(C_{kk} - C_{rr} - C_{nn})$$



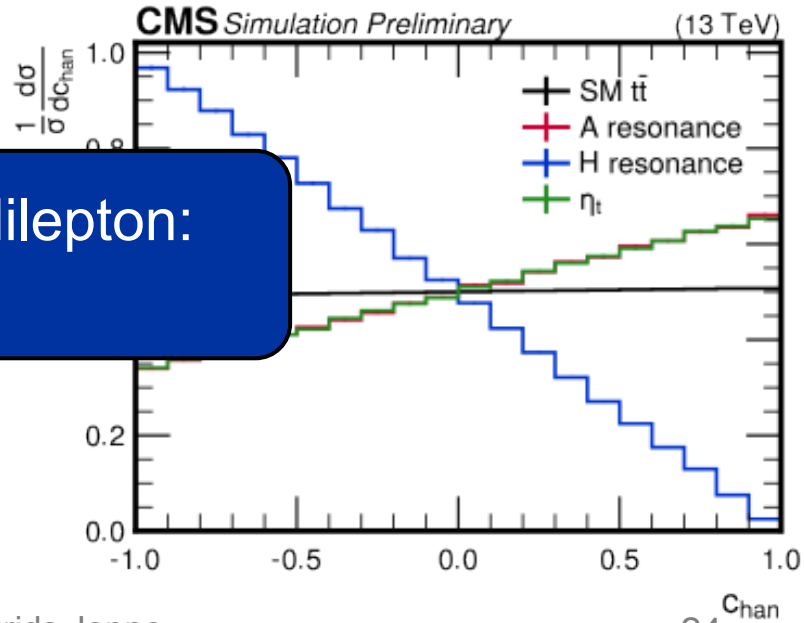
Spin correlation observables

- Top decays before hadronization → transfer spin information to decay products
- Construct spin correlation observables from tops & leptons
  - Leptons boosted into rest frames of their parent tops (“helicity frames”)

- Variable #2: c_{han}
  - Similar as c_{hel}, s
  - Maximally nega
  - Construct simila
    sign flip for *k* component in helicity basis:

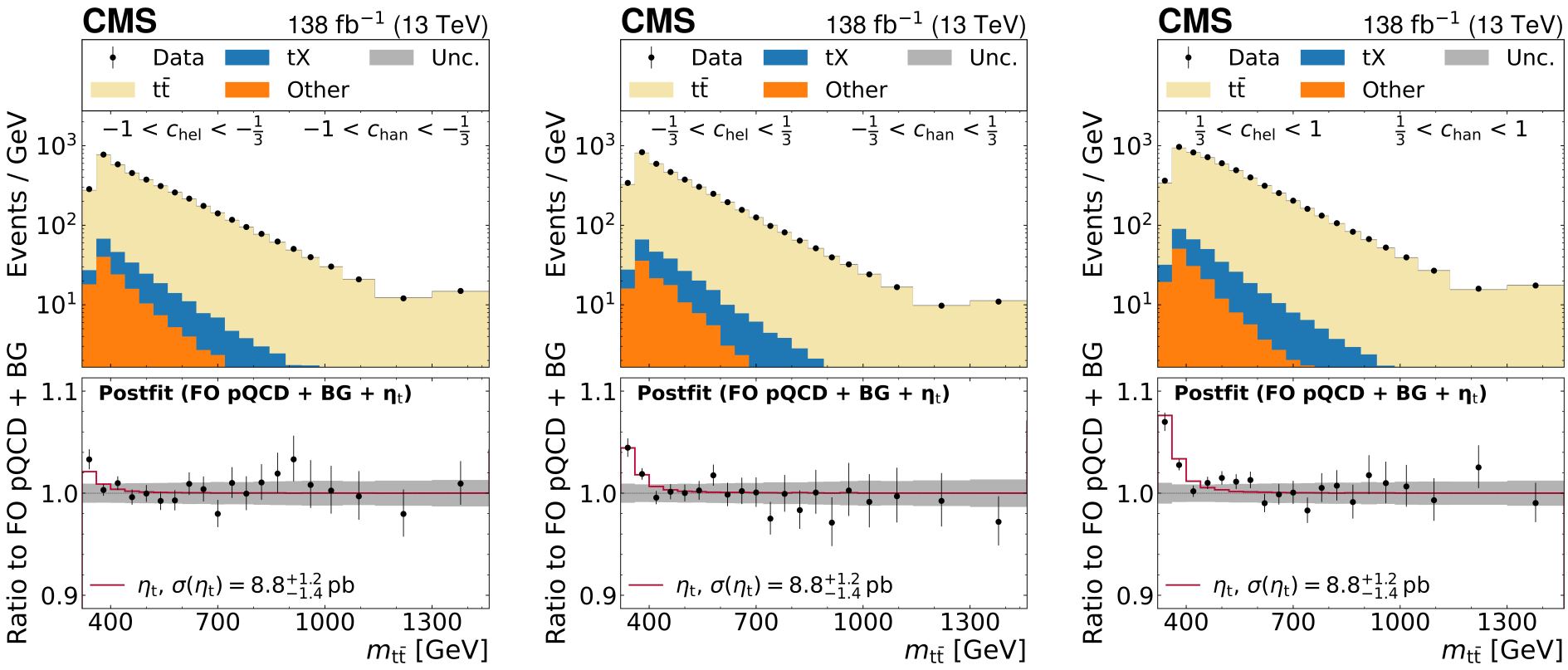
$$D^{(k)} = \frac{1}{3}(C_{kk} - C_{rr} - C_{nn})$$

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



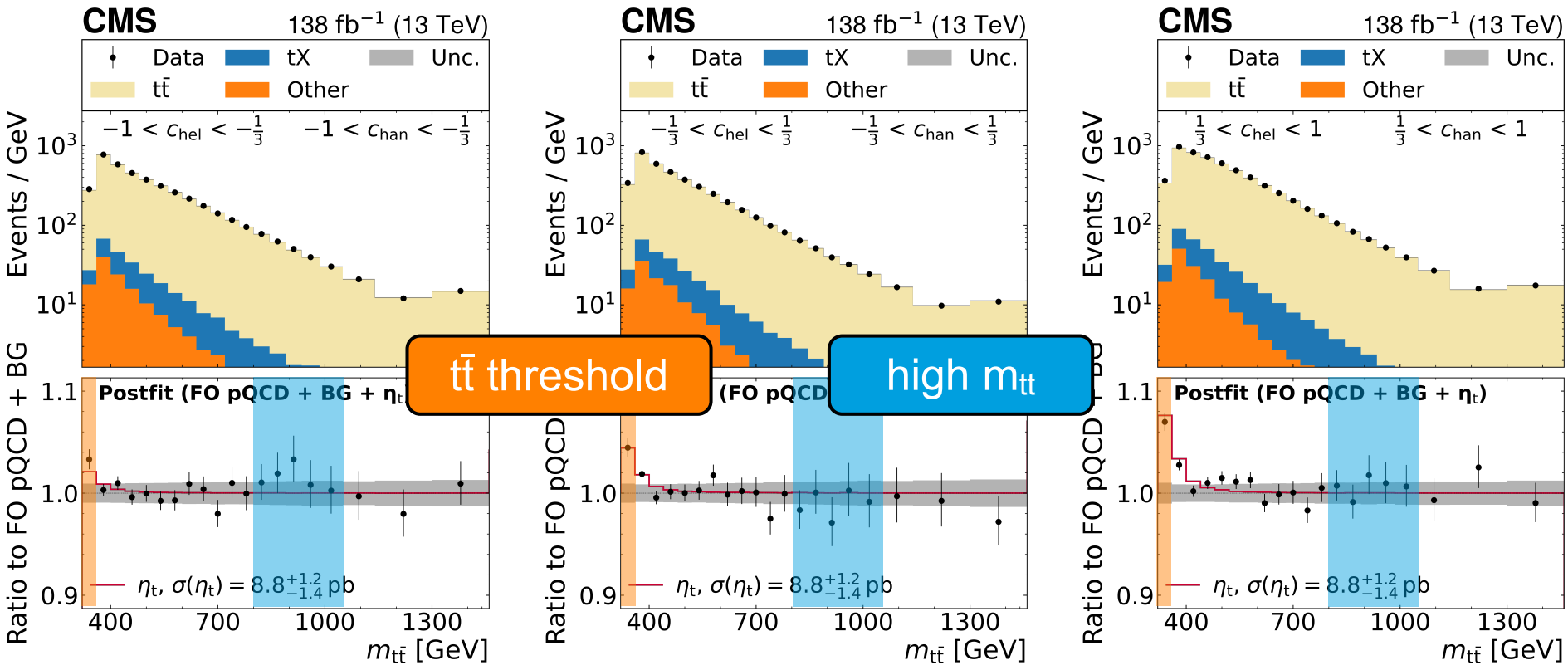
Postfit distributions: η_t

η_t model describes the data well after the fit



Postfit distributions: η_t

η_t model describes the data well after the fit



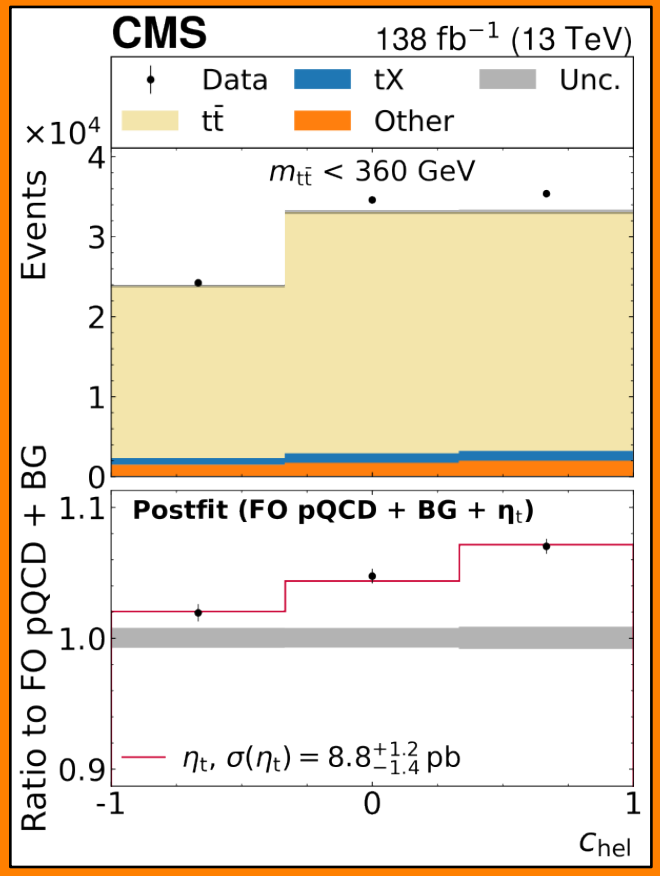
PRD 00 007801 (2025)

P…s: η_t

…s the dat…

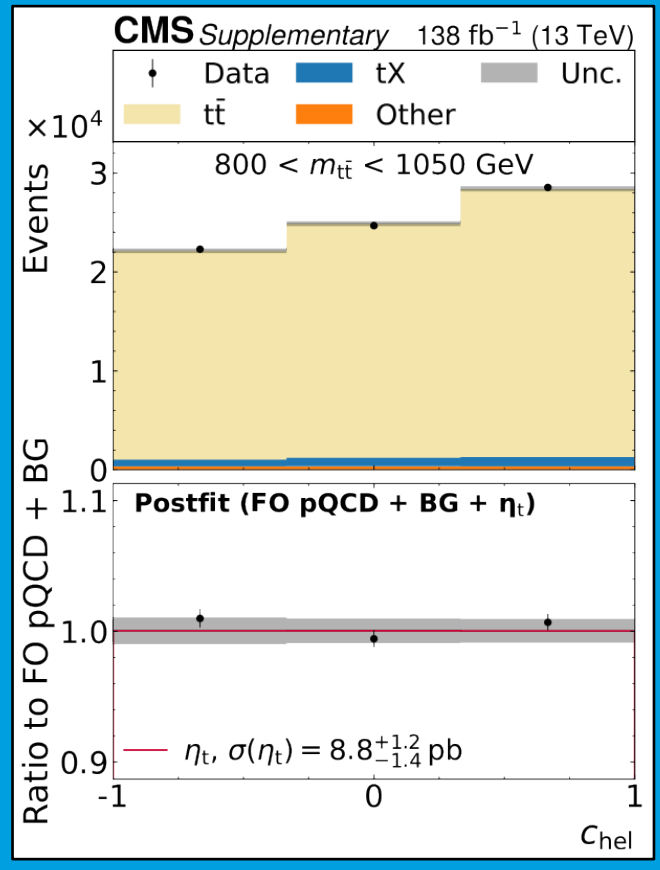
$t\bar{t}$ threshold:

Data shows slope in c_{hel}



high $m_{t\bar{t}}$:

No slope in data



RoPP 88 087801 (2025)

$t\bar{t}$ bound state?

- Excess is located at low m_{tt}, pseudoscalar-like in c_{hel}
  → could this be interpreted as a $t\bar{t}$ quasi-bound state?
- Extract cross section using the simplified η_t model
  - "cross section" = difference to perturbative prediction

RoPP 88 087801 (2025)

$t\bar{t}$ bound state?

- Excess is located at low m_{tt}, pseudoscalar-like in c_{hel}
  → could this be interpreted as a $t\bar{t}$ quasi-bound state?
- Extract cross section using the simplified η_t model
  - "cross section" = difference to perturbative prediction

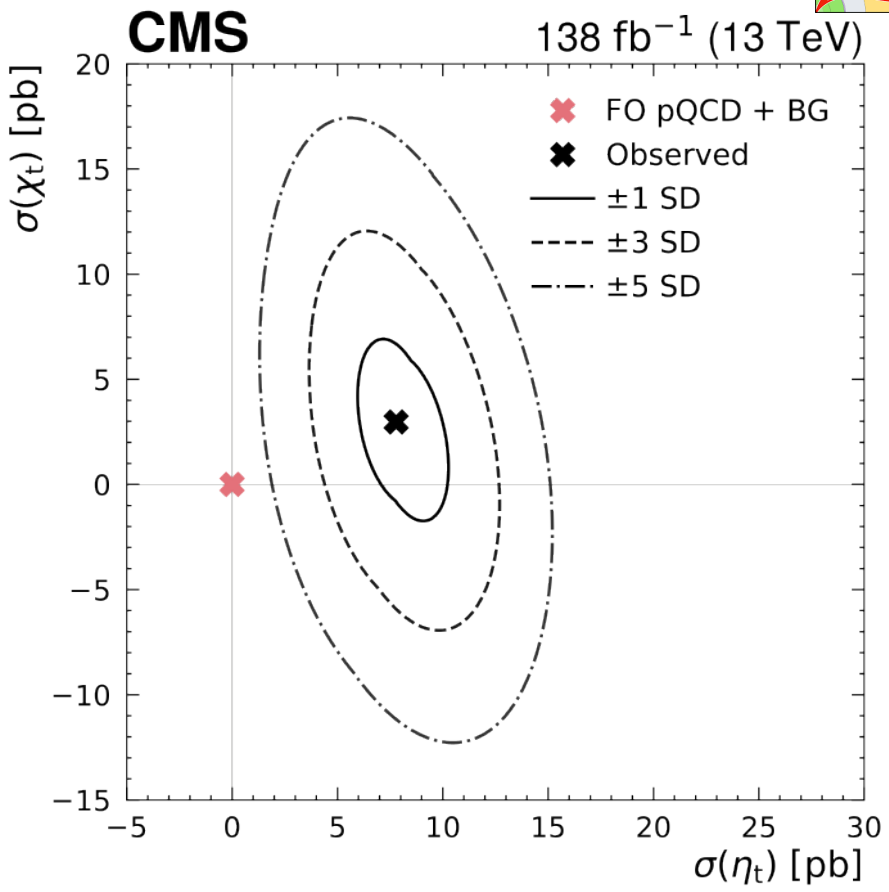
$$\sigma(\eta_t) = 8.8 \pm 0.5\,(\text{stat})\,^{+1.1}_{-1.3}\,(\text{syst})\,\text{pb} = 8.8\,^{+1.2}_{-1.4}\,\text{pb}$$

> 5σ significance!

- Main uncertainties: $t\bar{t}$ background modeling
- Word of caution: this model is not a complete description of a $t\bar{t}$ bound state!

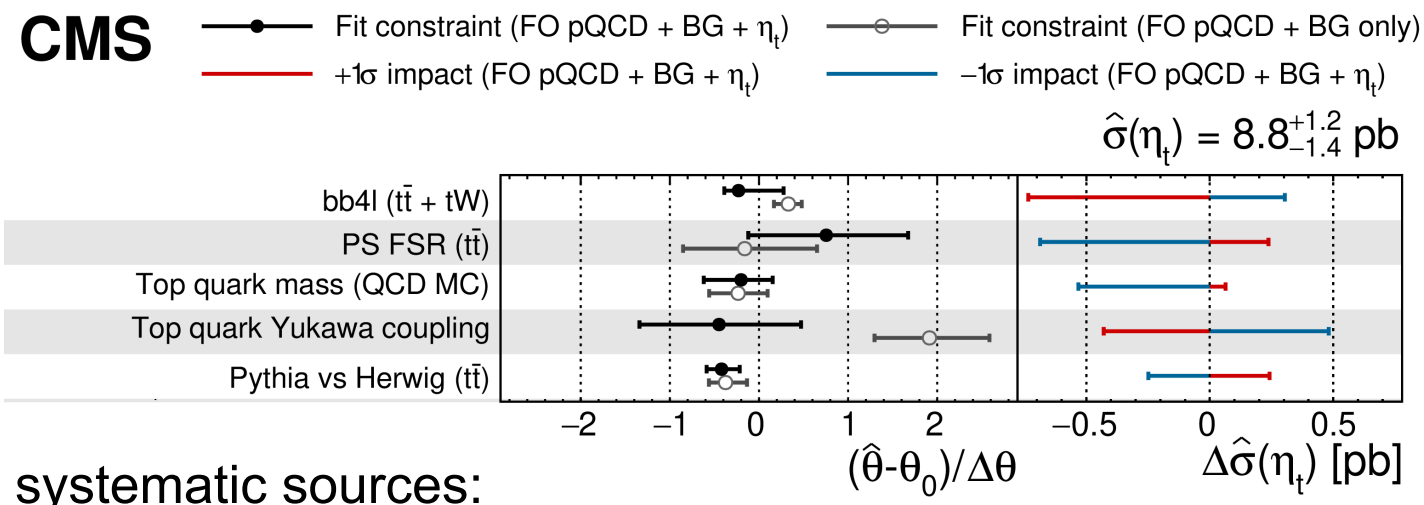
Scalar vs. pseudoscalar

- Can we quantify whether the excess is scalar or pseudoscalar?
- introduce χ_t: scalar $t\bar{t}$ bound state ($^3P_0$ $t\bar{t}$ spin state)
  - similar simplified model as η_t
- Perform 2D fit with η_t and χ_t as signals
- non-zero η_t by > 5 standard deviations
- χ_t compatible with zero by 1 sigma



Uncertainties

- Uncertainty on η_t cross section dominated by background modeling

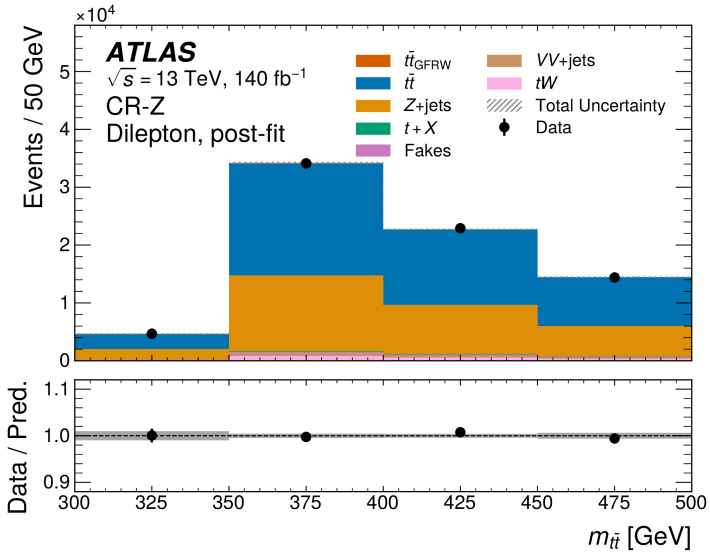


- Leading systematic sources:
  - Comparison to other $t\bar{t}$ MC generators: bb4l, Pythia vs. Herwig
  - EW corrections, including SM Top-Higgs Yukawa: $y_t = 1.00^{+0.11}_{-0.12}$ (EPJC 79 (2019) 421)
  - Parton shower, top mass

ATLAS dilepton analysis

ATLAS dilepton analysis

- Very similar analysis strategy to CMS!
  - Similar event selection, similar reconstruction (“ellipse method”)
  - Control regions to constrain Z+jets and fake lepton backgrounds
  - Same fit variables: m_{tt} x c_{hel} x c_{han}
- Differences:
  - Fit only $m_{t\bar{t}} < 500$ GeV - no constraints from modeling of the bulk
  - Differences in $t\bar{t}$ modeling - details still under investigation



GRFW bound state model

[Fuks, Hagiwara, Ma, Zheng, EPJC 85 (2025) 157]

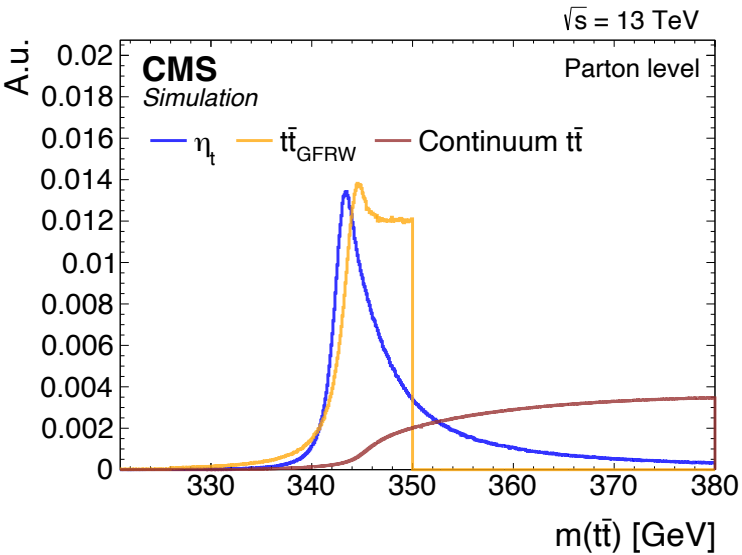
- Signal model for $t\bar{t}$ bound state: Green's function-reweighted $t\bar{t}$ ($t\bar{t}_{GRFW}$)
  - Calculate color-singlet $gg \to t\bar{t}$ in MadGraph at LO
  - Reweight matrix element by ratio of Green's functions:

$$|\mathcal{M}|^2 \quad \to \quad |\mathcal{M}|^2 \left| \frac{\widetilde{G}(E; p^*)}{\widetilde{G}_0(E; p^*)} \right|^2$$

Including Coulomb potential

Free top quarks

  - Restrict to $m_{t\bar{t}} < 350\,\text{GeV}$ and $p^* < 50\,\text{GeV}$ since high $m_{t\bar{t}}$ region will be overestimated otherwise
- CMS η_t model also considered as an alternative



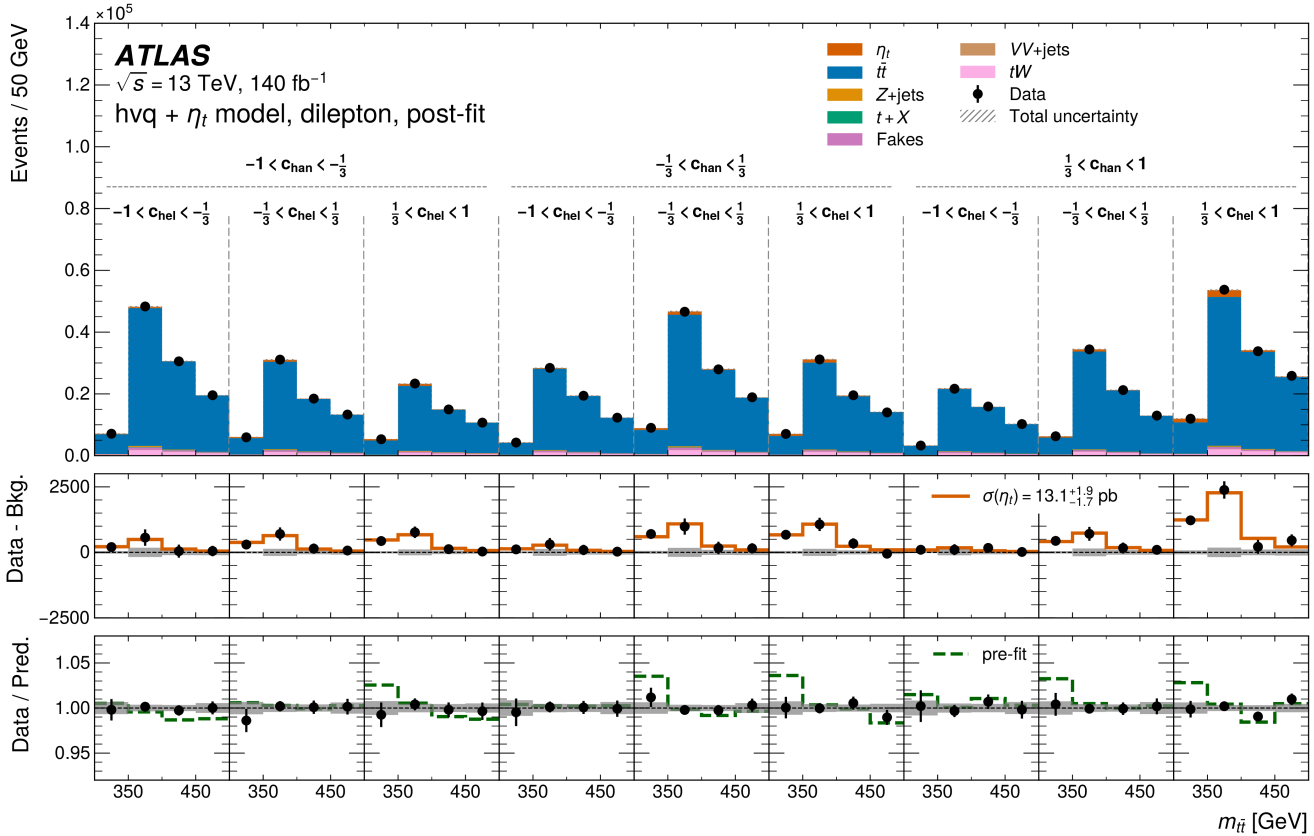
ATLAS dilepton results

$$\sigma(t\bar{t}_{\mathrm{GRFW}}) = 9.3^{+1.4}_{-1.3}\,\mathrm{pb}$$

$$\sigma(\eta_t) = 13.1^{+1.9}_{-1.7}\,\mathrm{pb}$$

Similar excess —> confirmation

η_t result is directly comparable to CMS —> ~2σ tension…



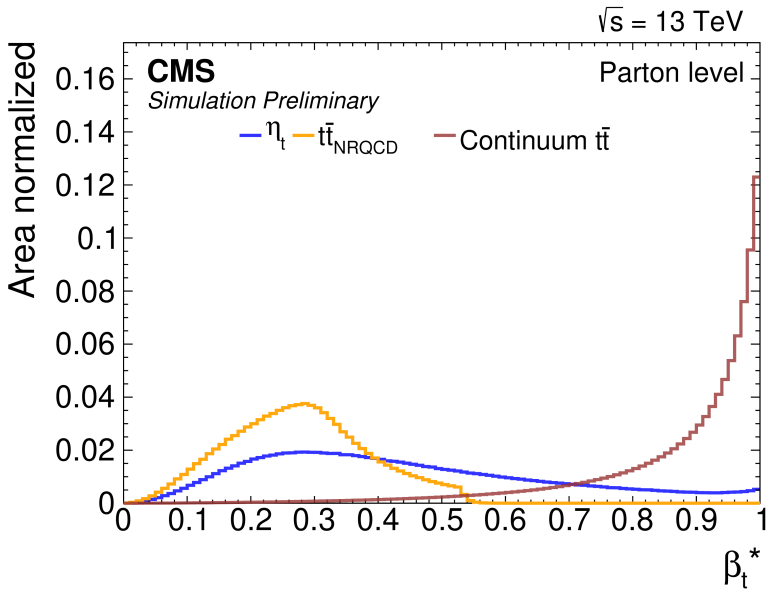
CMS Single-lepton analysis

Single-lepton analysis

arXiv:2608.19546
submitted to *RoPP*

- e/μ + (b) jets, full Run 2, $138\,\mathrm{fb}^{-1}$
- Use relative top quark velocity β_t^* instead of $m_{\mathrm{t\bar{t}}}$
  - Naturally discriminates non-relativistic part of $\mathrm{t\bar{t}}$
  - Ratio observable: partial cancellation of e.g. jet energy uncertainties

$$\sqrt{1-\beta_t^{*2}} = \frac{2m(t_\ell)m(t_h)}{m(t\bar{t})^2 - m(t_\ell)^2 - m(t_h)^2}$$



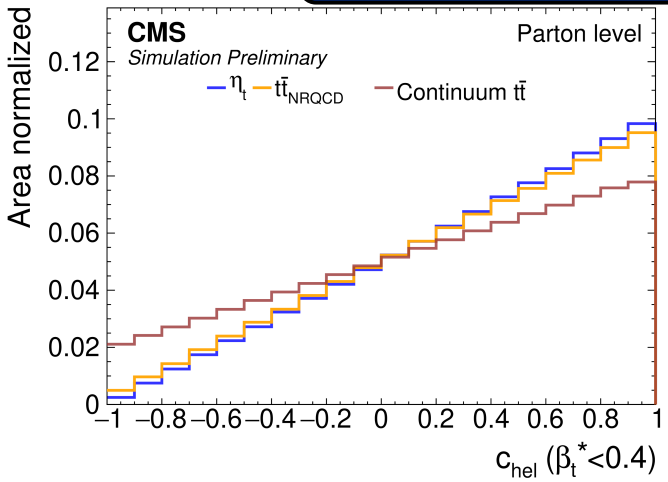
Single-lepton analysis

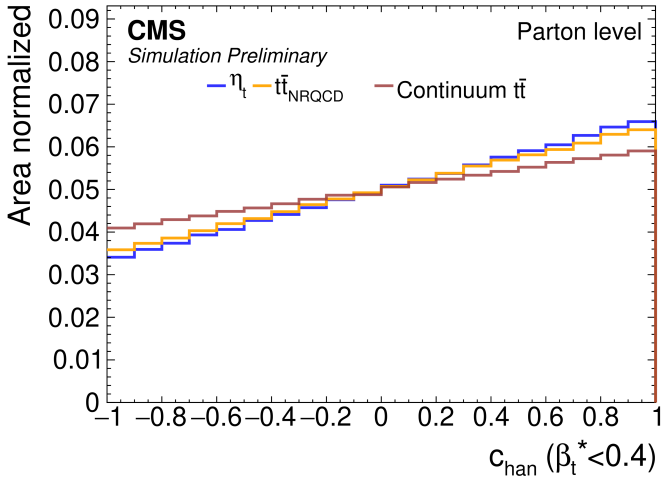
arXiv:2608.19546
submitted to *RoPP*

- e/μ + (b) jets, full Run 2, $138\,\mathrm{fb}^{-1}$
- Use relative top quark velocity β_t^* instead of $m_{\mathrm{t\bar{t}}}$

- Combine with spin correlations c_{hel} and c_{han}
- Problem: in hadronic top decay, the down-type quark carries the spin information!

→ use neural network for correct jet assignment

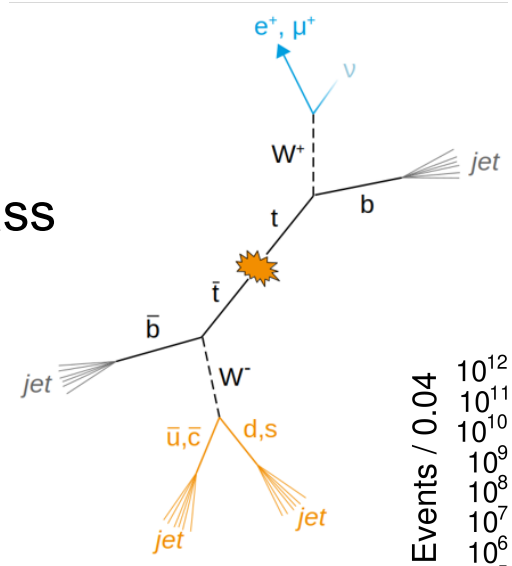


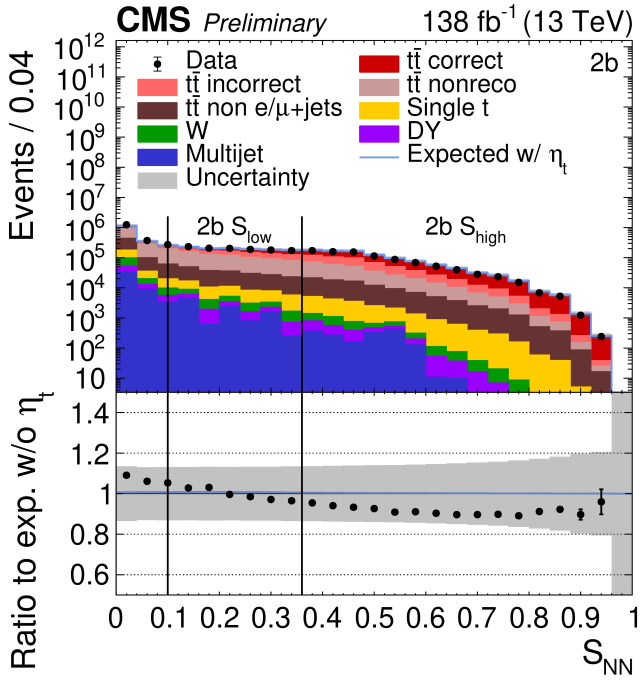


Reconstruction

arXiv:2608.19546
submitted to *RoPP*

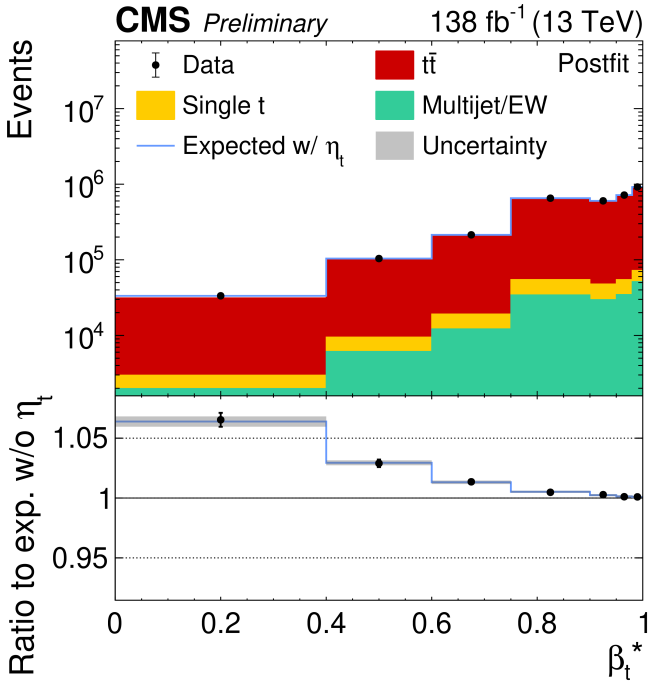
- Neutrino momentum from MET & W mass constraint
- Assign jets to legs based on NN:
  - Inputs: jets & lepton momenta, b-tagging, MET
  - Pick combination with highest score S_{NN}
- Reject $S_{NN} < 0.1$ to suppress backgrounds
- Use score to define low- and high-purity regions
- QCD multijet and W+jets backgrounds: from data in sideband



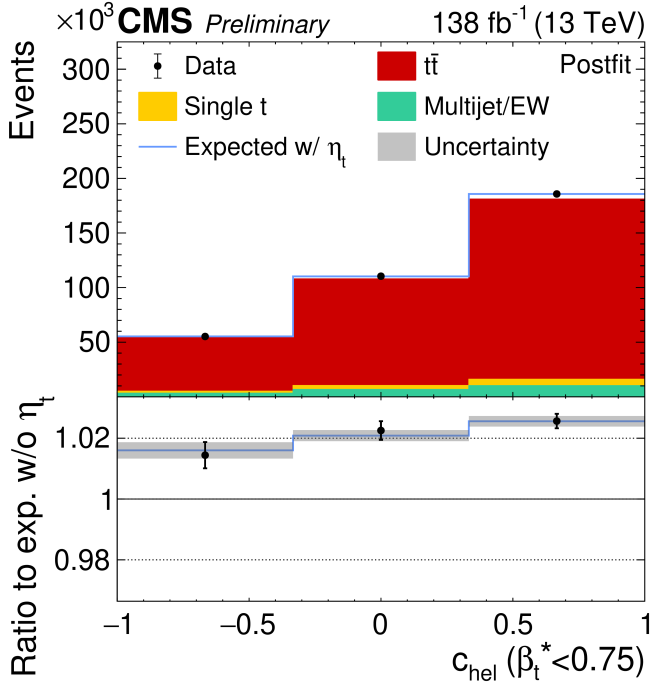


Single lepton results

arXiv:2608.19546
submitted to *RoPP*



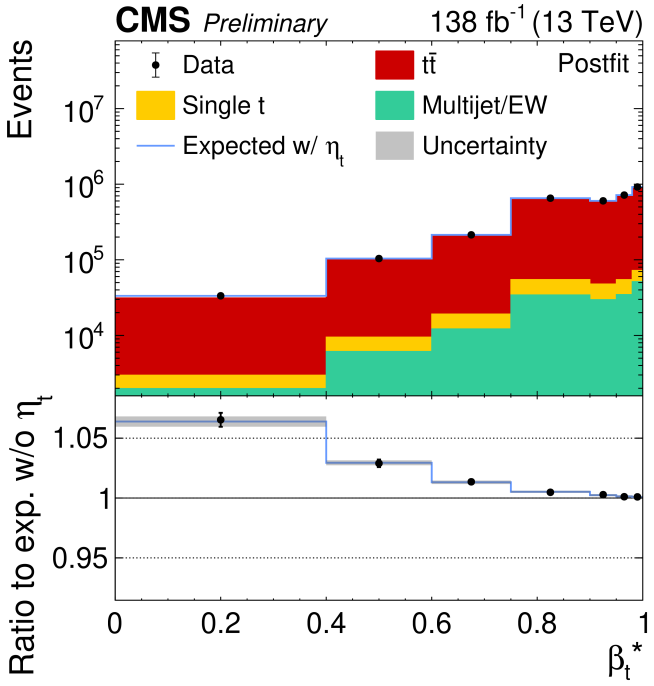
Clear excess at low β_t^*



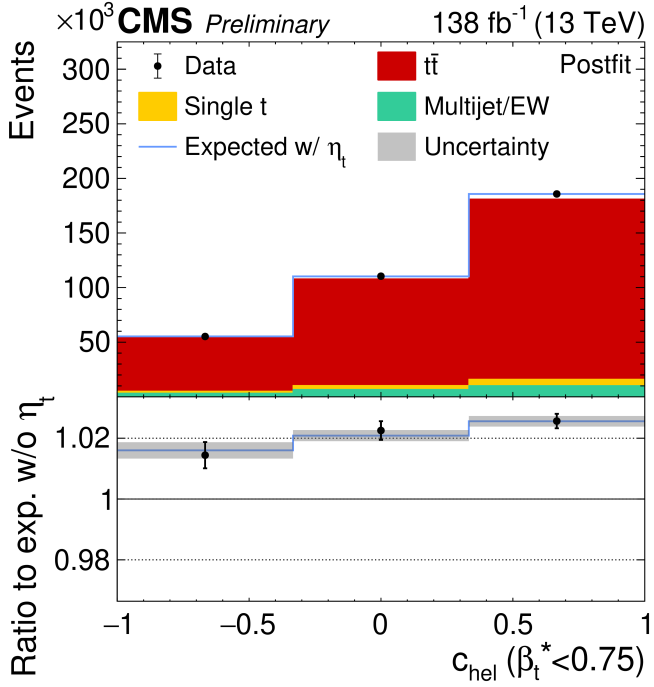
Slight pseudoscalar-like slope in c_{hel}

Single lepton results

arXiv:2608.19546
submitted to *RoPP*



Clear excess at low β_t^*



Slight pseudoscalar-like slope in c_{hel}

$$\sigma(\eta_t) = 5.1 \pm 0.9\mathrm{pb}$$

>5 SD significance

Single lepton results

arXiv:2608.19546
submitted to *RoPP*

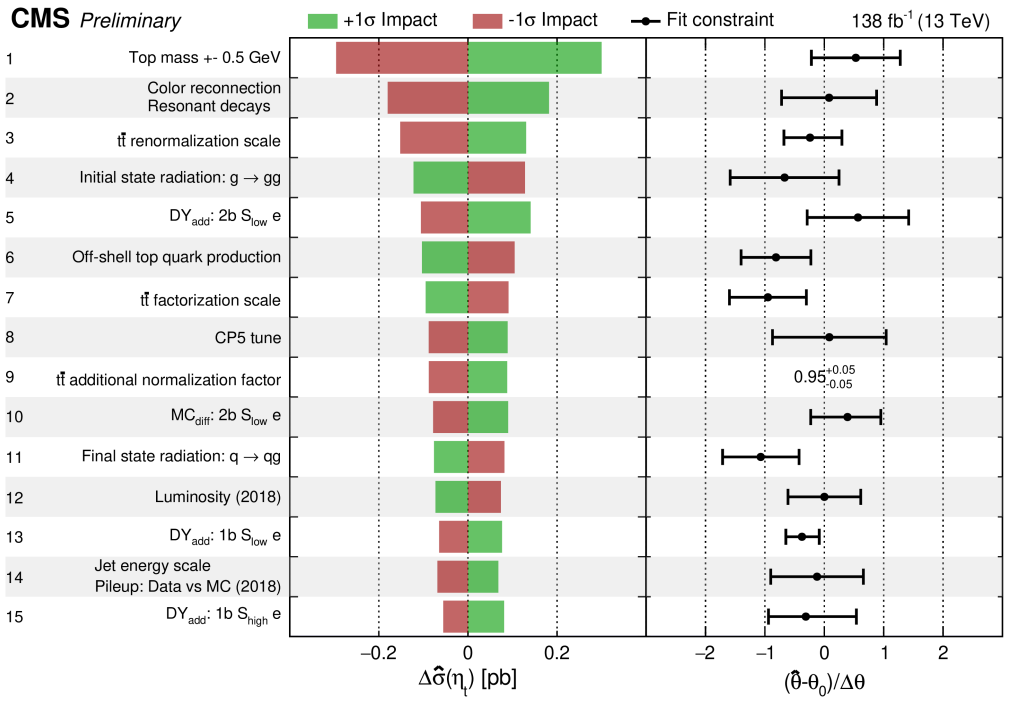
- Uncertainties dominated by $t\bar{t}$ modeling:

  Top mass, color reconnection, matrix element scales, parton shower

- Also check $t\bar{t}_{GRFW}$ (like ATLAS):

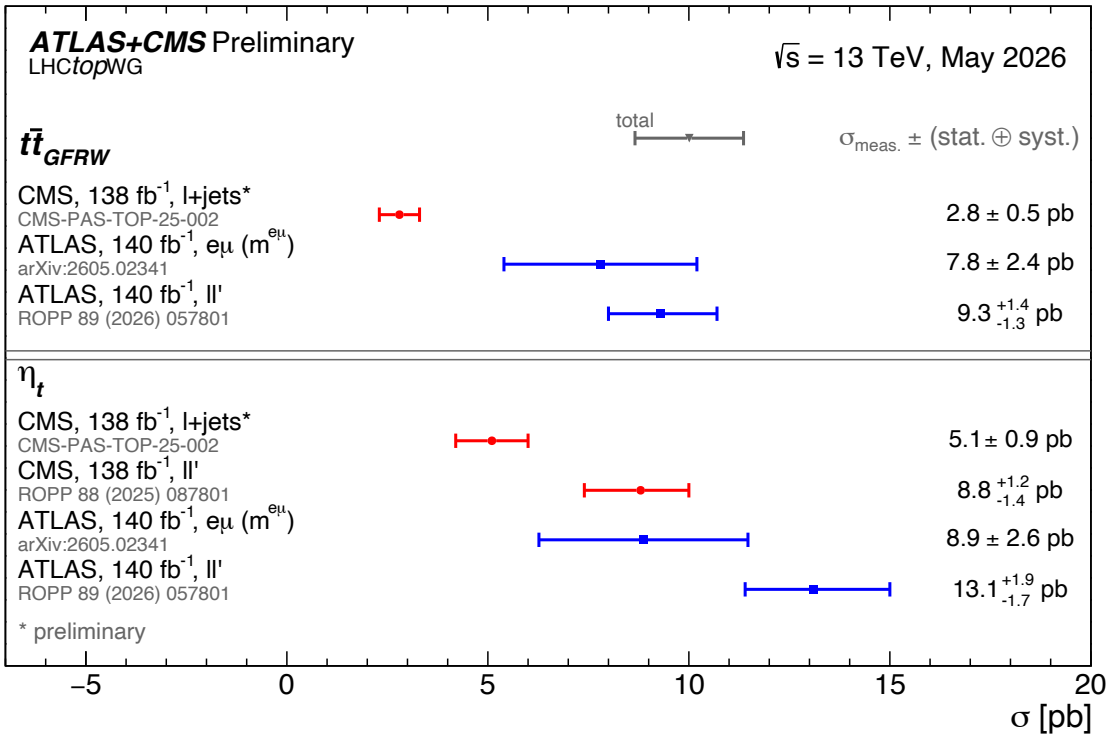
$$\sigma(t\bar{t}_{GRFW}) = 2.8 \pm 0.5 \text{pb}$$

differences between $t\bar{t}_{GRFW}$ and η_t consistent with ATLAS



Result comparison

Experimental



Predictions

$$\sigma \approx 6.43\text{pb}$$

[Sumino & Yokoya 09]
[Fuks, Hagiwara, Ma, Zheng 21]

Original simple estimate from NRQCD

$$\sigma = 4.15^{+1.43}_{-1.47}\text{pb}$$

[Garzelli, Limatola, Moch, Steinhauser, Zenaiev 26]

Obtained from NRQCD, with NLO+PS from Powheg subtracted

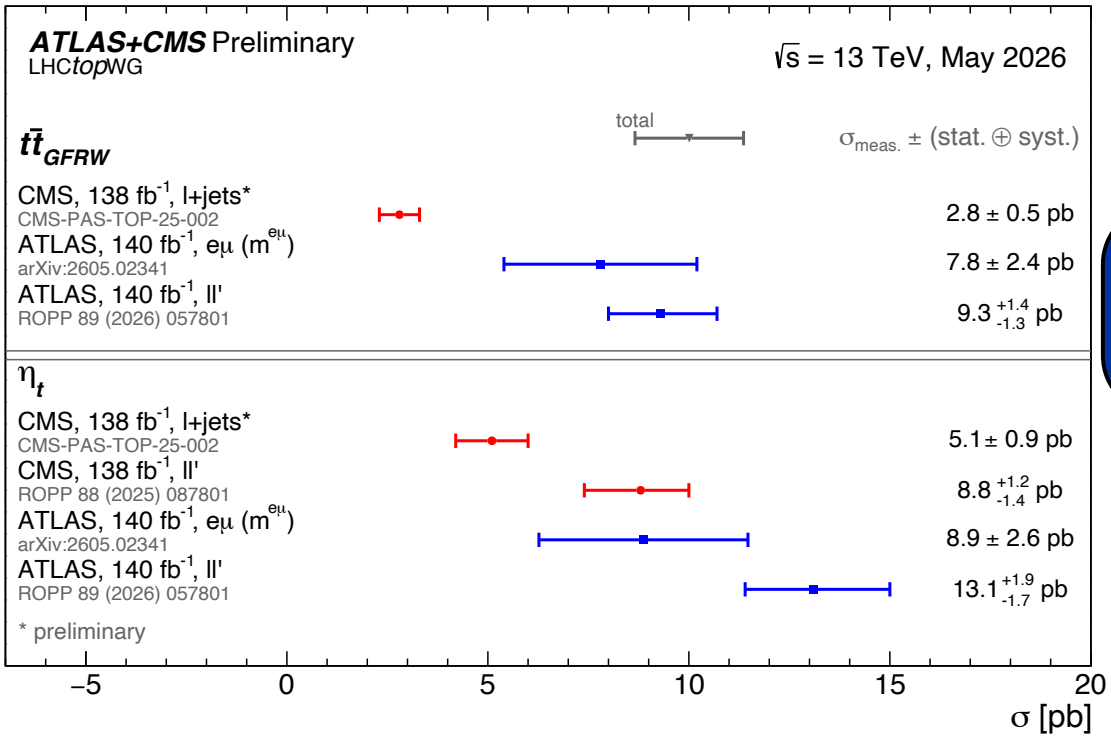
$$\sigma \approx 3.35\text{pb}$$

[Nason, Pelliccioli, Re, Rottoli 26]

Fully perturbative using Powheg (`thr2`);
NLO without threshold corrections subtracted

Result comparison

Experimental



Predictions

$$\sigma \approx 6.43\text{pb}$$

[Sumino & Yokoya 09]
[Fuks, Hagiwara, Ma, Zheng 21]

Original simple estimate from NRQCD

$\sigma = 4.15^{+1.43}$pb

Difference between CMS results under investigation
prime suspect: NNLO corrections

Tension between ATLAS and CMS to be understood

$$\sigma \approx 3.35\text{pb}$$

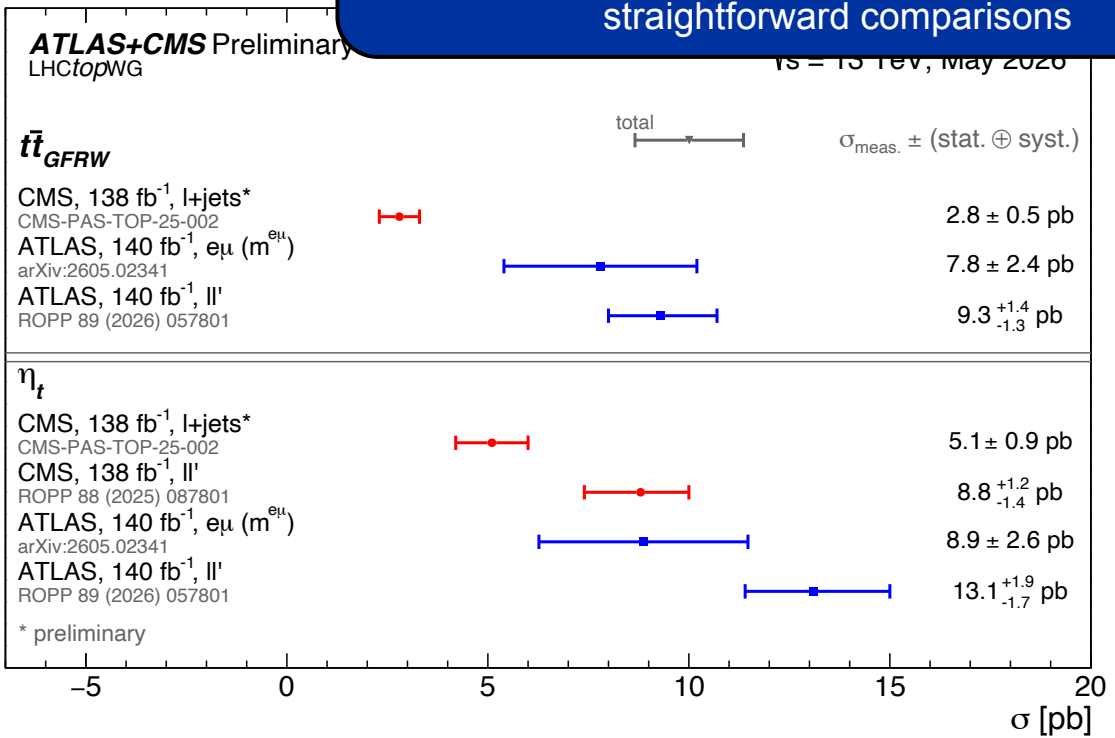
[Nason, Pelliccioli, Re, Rottoli 26]

Fully perturbative using Powheg (`thr2`);
NLO without threshold corrections subtracted

Result comparison

Predictions seem to be below experimental results

> future: use new MC generators in analyses for more straightforward comparisons



Predictions

$$\sigma \approx 6.43\text{pb}$$

[Sumino & Yokoya 09]
[Fuks, Hagiwara, Ma, Zheng 21]

Original simple estimate from NRQCD

$$\sigma = 4.15^{+1.43}_{-1.47}\text{pb}$$

[Garzelli, Limatola, Moch, Steinhauser, Zenaiev 26]

Obtained from NRQCD, with NLO+PS from Powheg subtracted

$$\sigma \approx 3.35\text{pb}$$

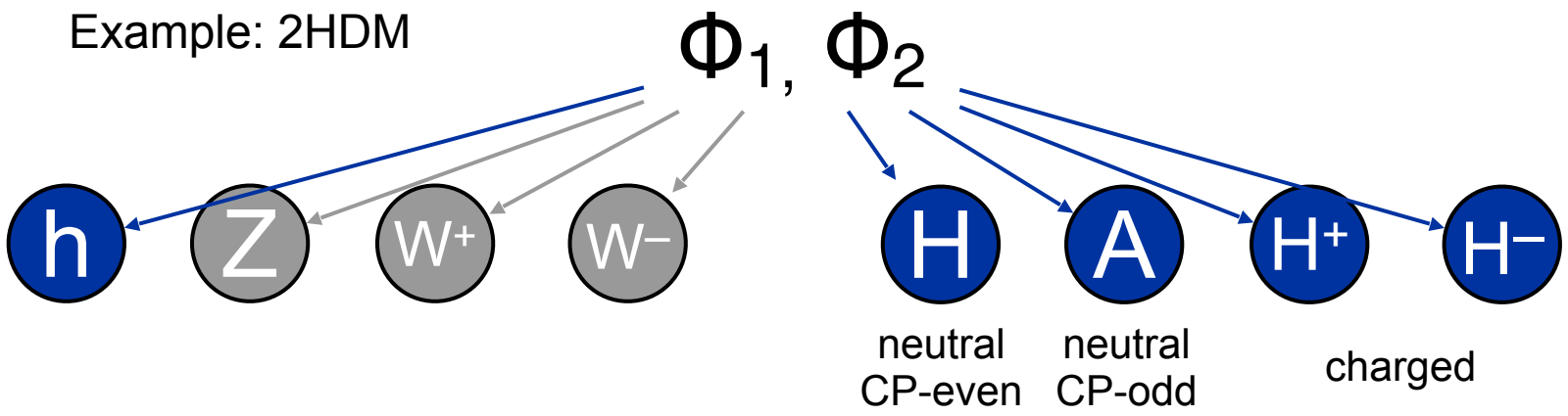
[Nason, Pelliccioli, Re, Rottoli 26]

Fully perturbative using Powheg (`thr2`);
NLO without threshold corrections subtracted

What about BSM?

Additional Higgs bosons

- SM Higgs: complex SU(2) doublet ϕ → one real scalar after symmetry breaking
- Many BSM models predict additional Higgs bosons
  e.g. Two-Higgs Doublet Model (2HDM), Supersymmetry, …



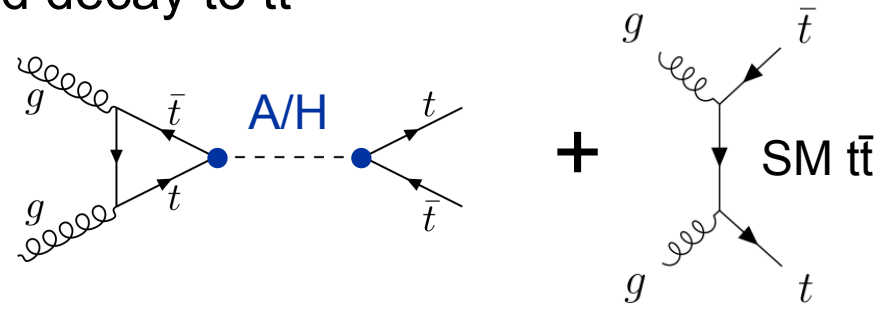
- If $m_{A/H} > 2m_t$: decay to $t\bar{t}$ → search in $t\bar{t}$ final states

Additional bosons in $t\bar{t}$

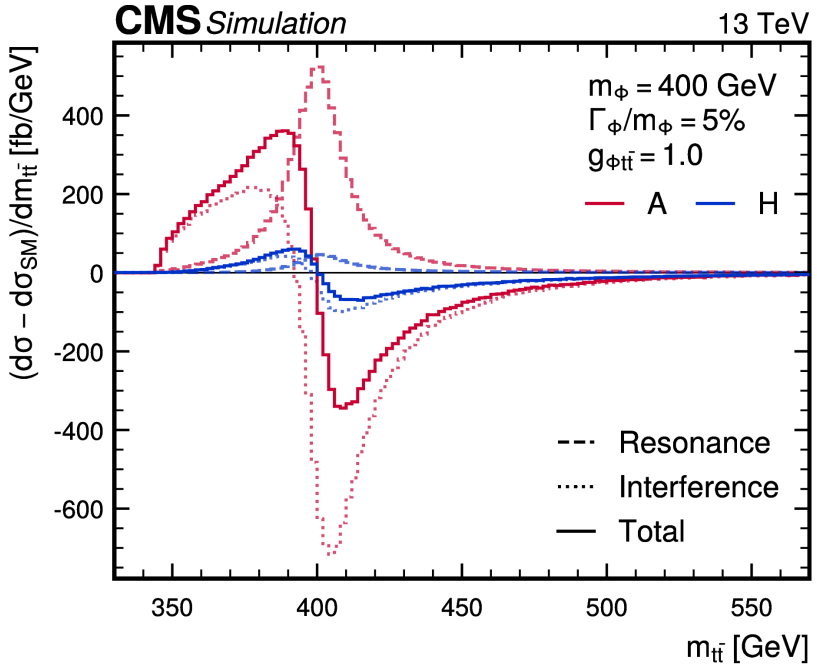
- Additional bosons predicted in many BSM models: e.g. Two-Higgs Doublet Model, SUSY, ...
- Here: generic heavy pseudoscalar (A) or scalar (H) coupling solely to top quarks
- Production in gluon fusion via top quark loop and decay to $t\bar{t}$

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

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



- Same final state as SM $t\bar{t}$ → interference → peak-dip structure in invariant mass $m_{t\bar{t}}$

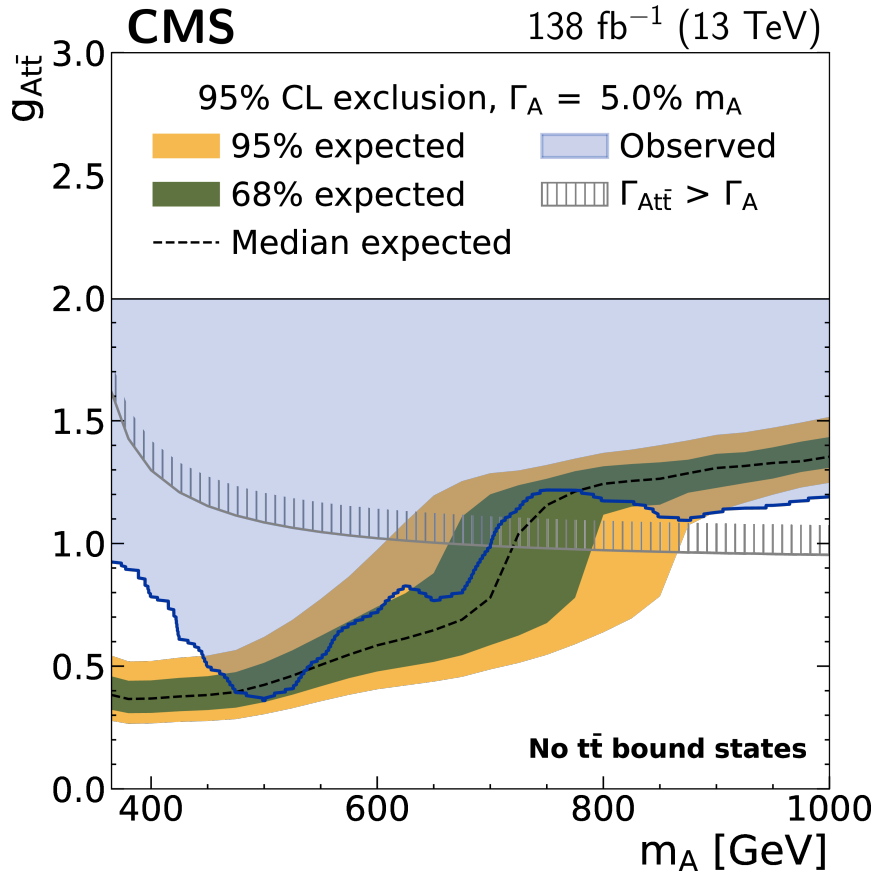


BSM interpretation

- At the current level of precision: cannot distinguish $t\bar{t}$ bound states and BSM pseudoscalars

➔ alternative interpretation as BSM (pseudo)scalars A and H

- Statistical combination with lepton+jets decay channel
- Limits on coupling g_{Att} of new state to top quarks

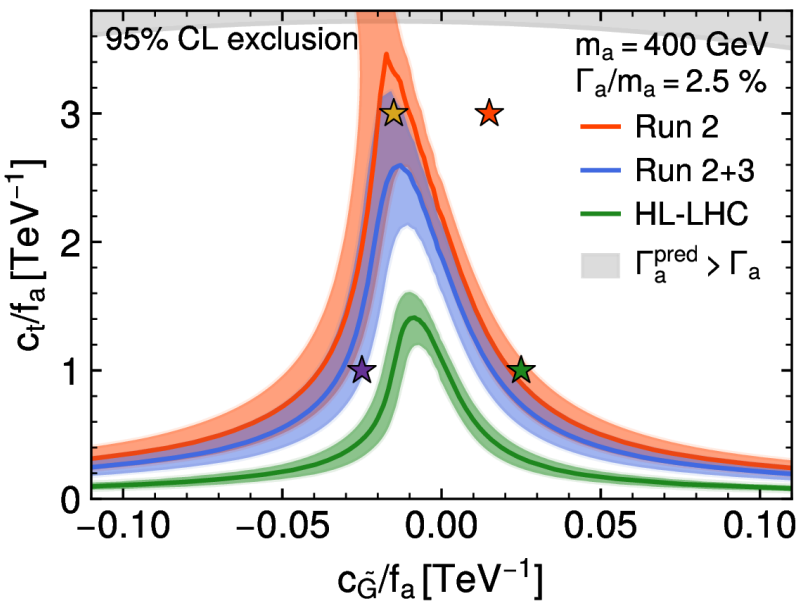


Further BSM ideas

Many more BSM interpretations possible!

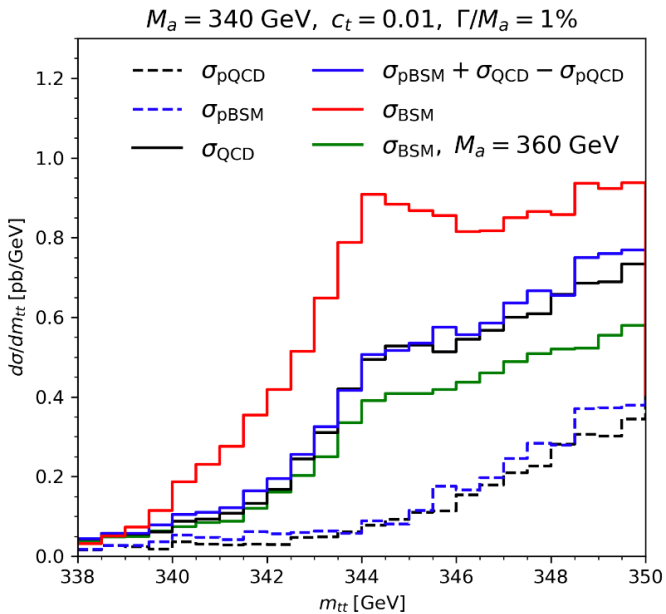
Axion-Like Particles in $t\bar{t}$

[Anuar, Biekötter, Biekötter, Grohsjean, Heinemeyer, LJ, Schwanenberger, Weiglein, JHEP 12 (2024) 197]



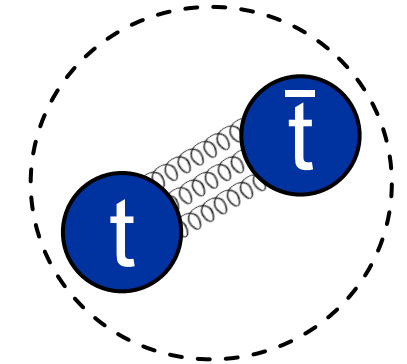
Bound state effects on top of BSM scalars

[Flacke, Fuks, Kim, Kim, Lee, Munoz-Aillaud, PLB 879 (2026) 140613]



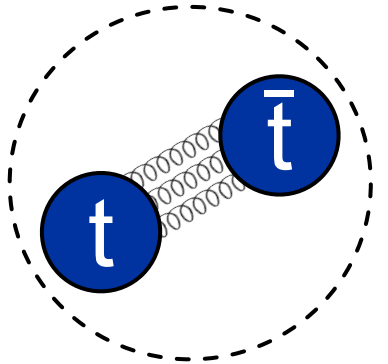
What next?

- Toponium physics is only just starting!
- We need…
  - better understanding of $t\bar{t}$ threshold modeling
    resummation, parton showers, off-shell effects, …
    large synergy with top mass measurements!
    already great progress since publication of first results!



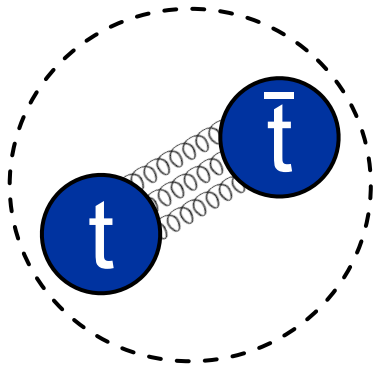
What next?

- Toponium physics is only just starting!
- We need…
  - better understanding of $t\bar{t}$ threshold modeling
    resummation, parton showers, off-shell effects, …
    large synergy with top mass measurements!
    already great progress since publication of first results!
  - better $t\bar{t}$ reconstruction (e.g. with ML)
    improved resolution (both m_{tt} and spin correlations)
    but also: control over systematic uncertainties



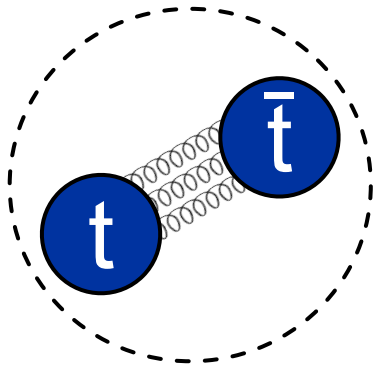
What next?

- Toponium physics is only just starting!
- A few ideas:
  - unfolded differential measurement
    we do not have the resolution to resolve the m_{tt} lineshape,
    but we could measure other distributions at low m_{tt}
    e.g. Δy, $m_{b\ell}$, full spin correlation matrix, …



What next?

- Toponium physics is only just starting!
- A few ideas:
  - unfolded differential measurement
    we do not have the resolution to resolve the m_{tt} lineshape,
    but we could measure other distributions at low m_{tt}
    e.g. Δy, $m_{b\ell}$, full spin correlation matrix, …
  - Other channels: $\eta_t \rightarrow \gamma\gamma$
    could help distinguishing toponium & BSM interpretations!
    but branching ratio extremely small ($\sim 10^{-5}$)…
    different experimental challenges: photon ID & resolution



Summary

- Observation of an excess at the $t\bar{t}$ threshold
  - Dilepton (CMS & ATLAS) and lepton+jets (CMS), full Run 2
  - Interpretation using simplified $t\bar{t}$ bound state model:

dilepton CMS: $\sigma(\eta_t) = 8.8^{+1.2}_{-1.4}\text{pb}$ — *RoPP* 88 087801 (2025)

dilepton ATLAS: $\sigma(\eta_t) = 13.1^{+1.9}_{-1.7}\,\text{pb}$ — *RoPP* 89 057801 (2025)

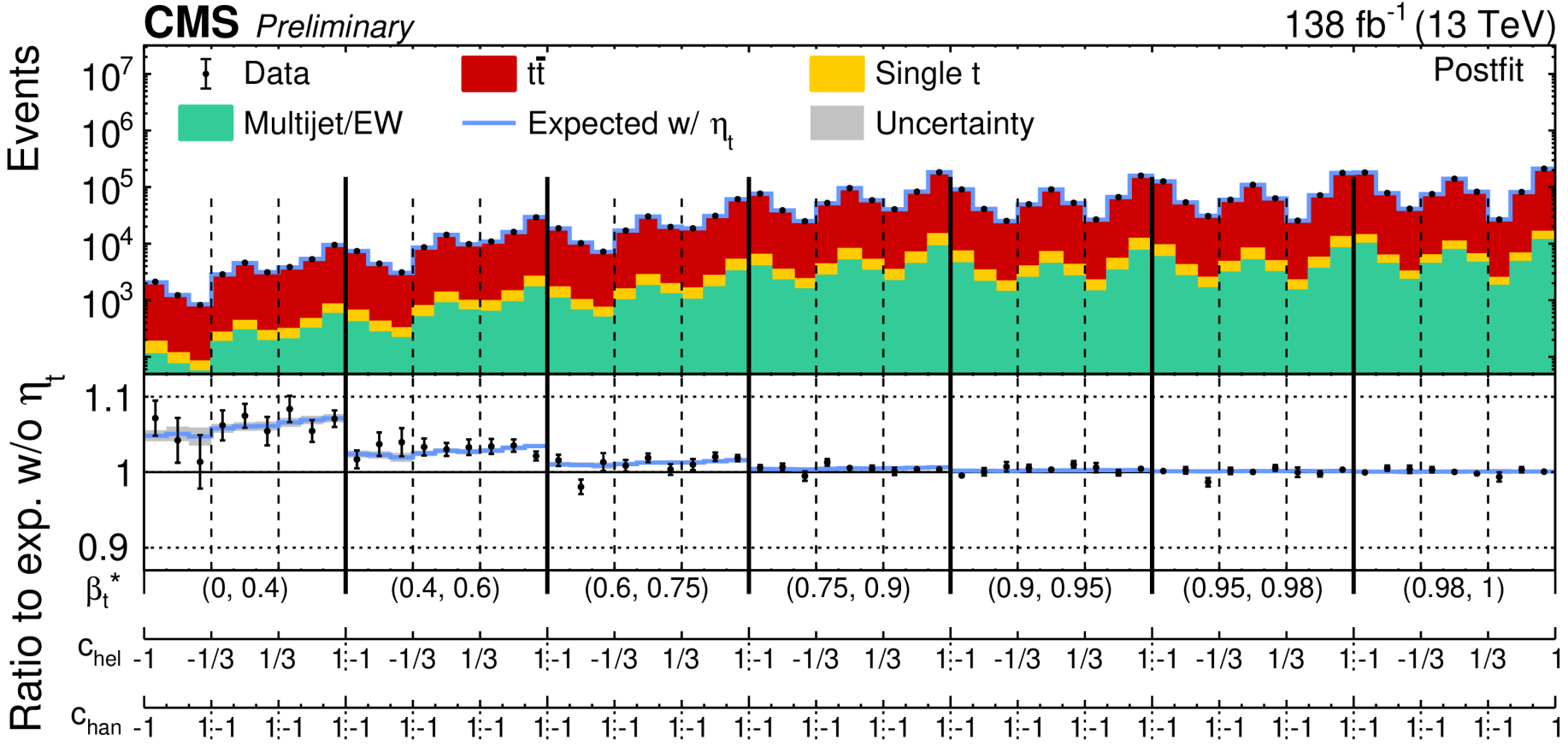
lepton+jets: $\sigma(\eta_t) = 5.1 \pm 0.9\text{pb}$ — arXiv:2608.19546



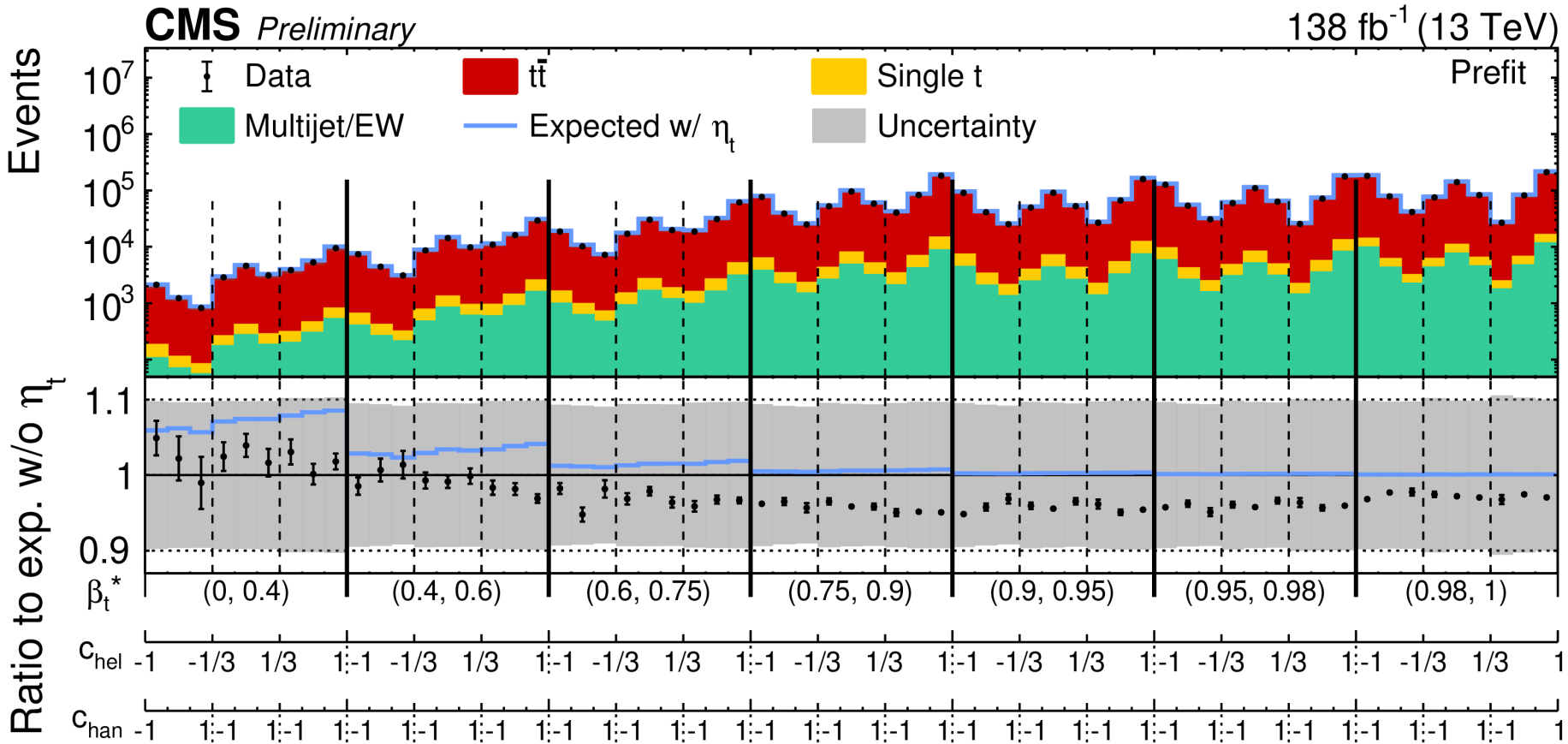
- Differences between the CMS and ATLAS results to be understood
- Main limitation: modeling of both $t\bar{t}$ threshold and continuum
  - Great theory progress already - more advanced MC available

Backup

Single lepton: full postfit



Single lepton: full prefit

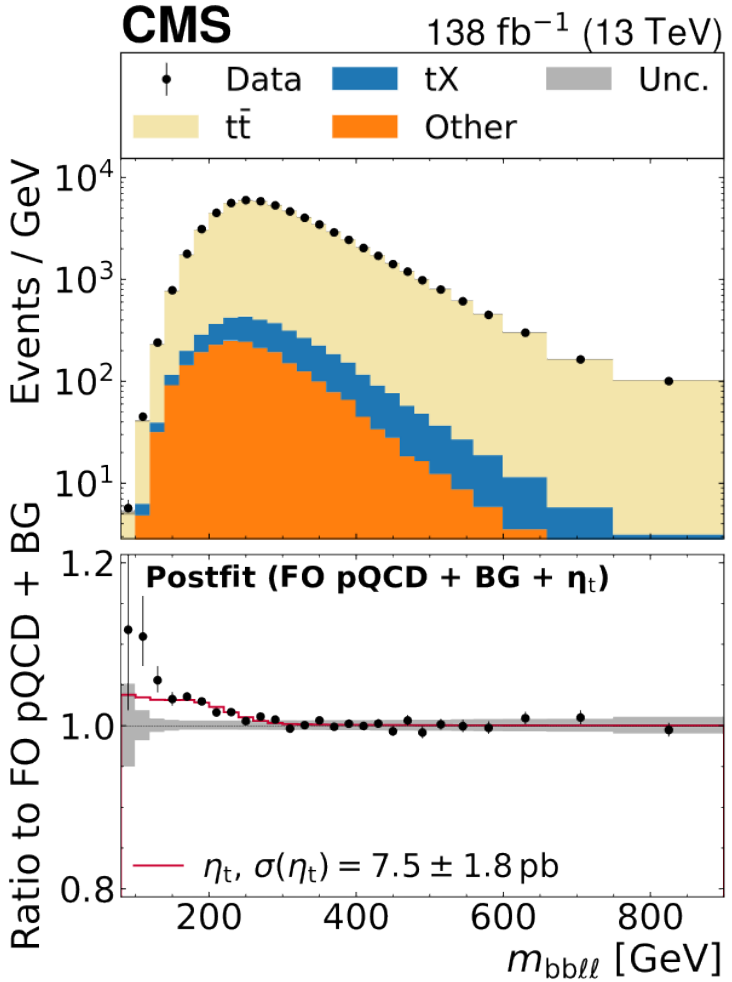


Checks of the result

How do we make sure the excess is real?

→ Check alternative variables: $m_{bb\ell\ell}$ instead of $m_{t\bar{t}}$

- Sidestep possible biases from $t\bar{t}$ reconstruction
- Repeat full fit: consistent with main result

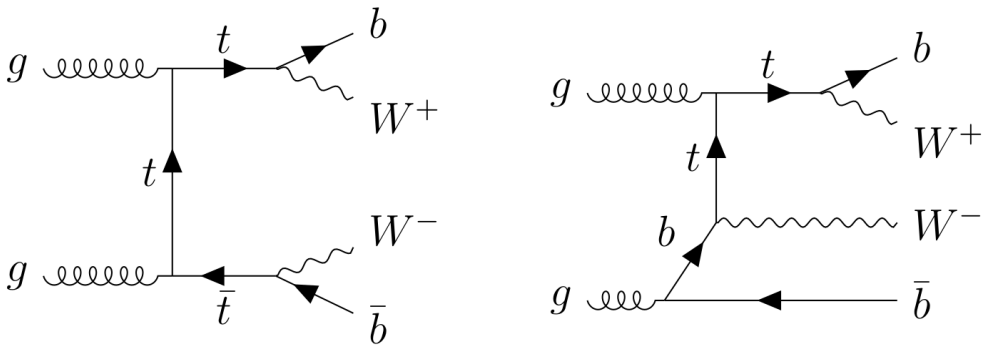


Checks of the result

How do we make sure the excess is real?

→ Check alternative generators for continuum $t\bar{t}$ (+ tW)

Powheg bb4l + Pythia
off-shell $t\bar{t}$ & $t\bar{t}$/tW interference at full NLO



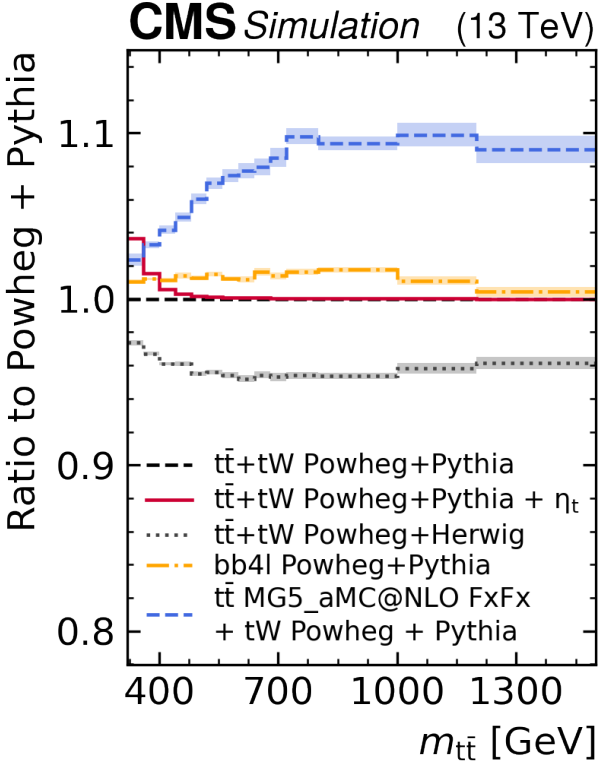
Powheg + Herwig
different parton shower
& hadronization model

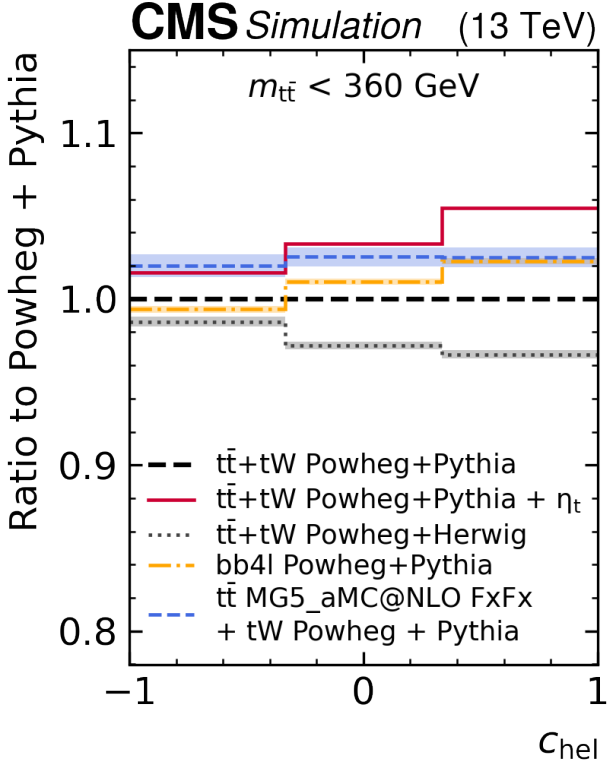
aMC@NLO fXfX + Pythia
different NLO matching
scheme

Checks of the result

How do we make sure the excess is real?

→ Check alternative generators for continuum $t\bar{t}$ (+ tW)





Significant differences in $m_{t\bar{t}}$ and c_{hel}!

bb4l: higher slope in c_{hel}, but no peak in $m_{t\bar{t}}$

Herwig: enhancement in $m_{t\bar{t}}$ at threshold, but reduced slope in c_{hel}

Checks of the result

How do we make sure the excess is real?

→ Check alternative generators for continuum $t\bar{t}$ (+ tW)

$\sigma(\eta_t)$ results for different generators:

FO pQCD generator setup	$\sigma(\eta_t)$ [pb]
POWHEG v2 hvq + PYTHIA	8.7 ± 1.1
POWHEG v2 hvq + HERWIG	8.6 ± 1.1
MADGRAPH5_aMC@NLO FxFx + PYTHIA	9.8 ± 1.3
POWHEG vRES bb4l + PYTHIA	6.6 ± 1.4
Nominal result	$8.8\,^{+1.2}_{-1.4}$

Excess confirmed for all generators!

Largest difference in η_t cross section: bb4l
~ 1.5 SD lower

→ For nominal result:

Add difference between Powheg $t\bar{t}$/bb4l & Pythia/Herwig as nuisances

Spin correlation observables

- Formal definitions of c_{hel} and c_{han}:

$$c_{\mathrm{hel}} = \hat{\ell}_t^+ \cdot \hat{\ell}_{\bar{t}}^- = +(\hat{\ell}_t^+)_k(\hat{\ell}_{\bar{t}}^-)_k + (\hat{\ell}_t^+)_r(\hat{\ell}_{\bar{t}}^-)_r + (\hat{\ell}_t^+)_n(\hat{\ell}_{\bar{t}}^-)_n$$

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

normalized components of (anti)lepton three-momenta in helicity basis

which leads to

$$\frac{1}{\sigma}\frac{d\sigma}{dc_{\mathrm{hel}}} = \frac{1}{2}\left(1 - D\, c_{\mathrm{hel}}\right) \qquad D = \frac{1}{3}\mathrm{Tr}\left[\mathbf{C}\right]$$

spin correlation matrix

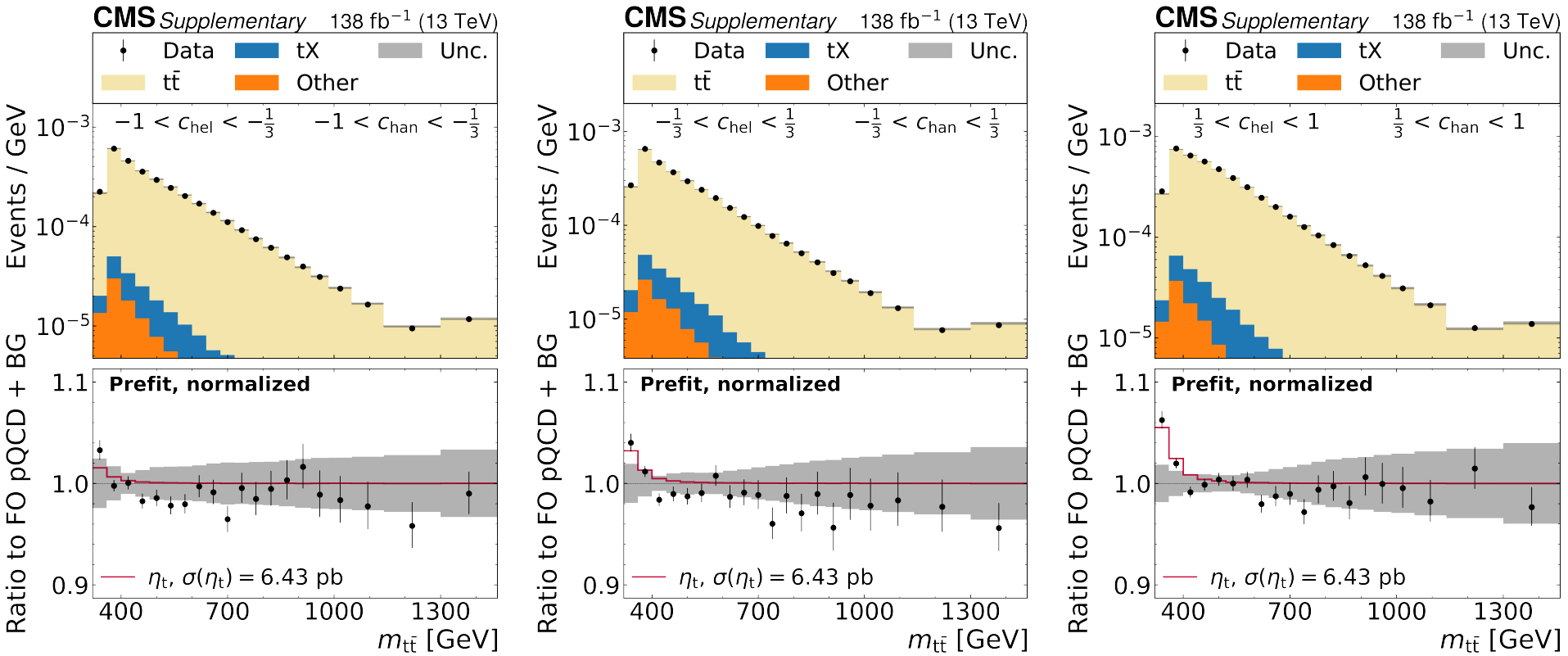
$$\frac{1}{\sigma}\frac{d\sigma}{dc_{\mathrm{han}}} = \frac{1}{2}\left(1 + D^{(k)} c_{\mathrm{han}}\right) \qquad D^{(k)} = \frac{1}{3}\left(C_{kk} - C_{rr} - C_{nn}\right)$$

$t\bar{t}$ reconstruction

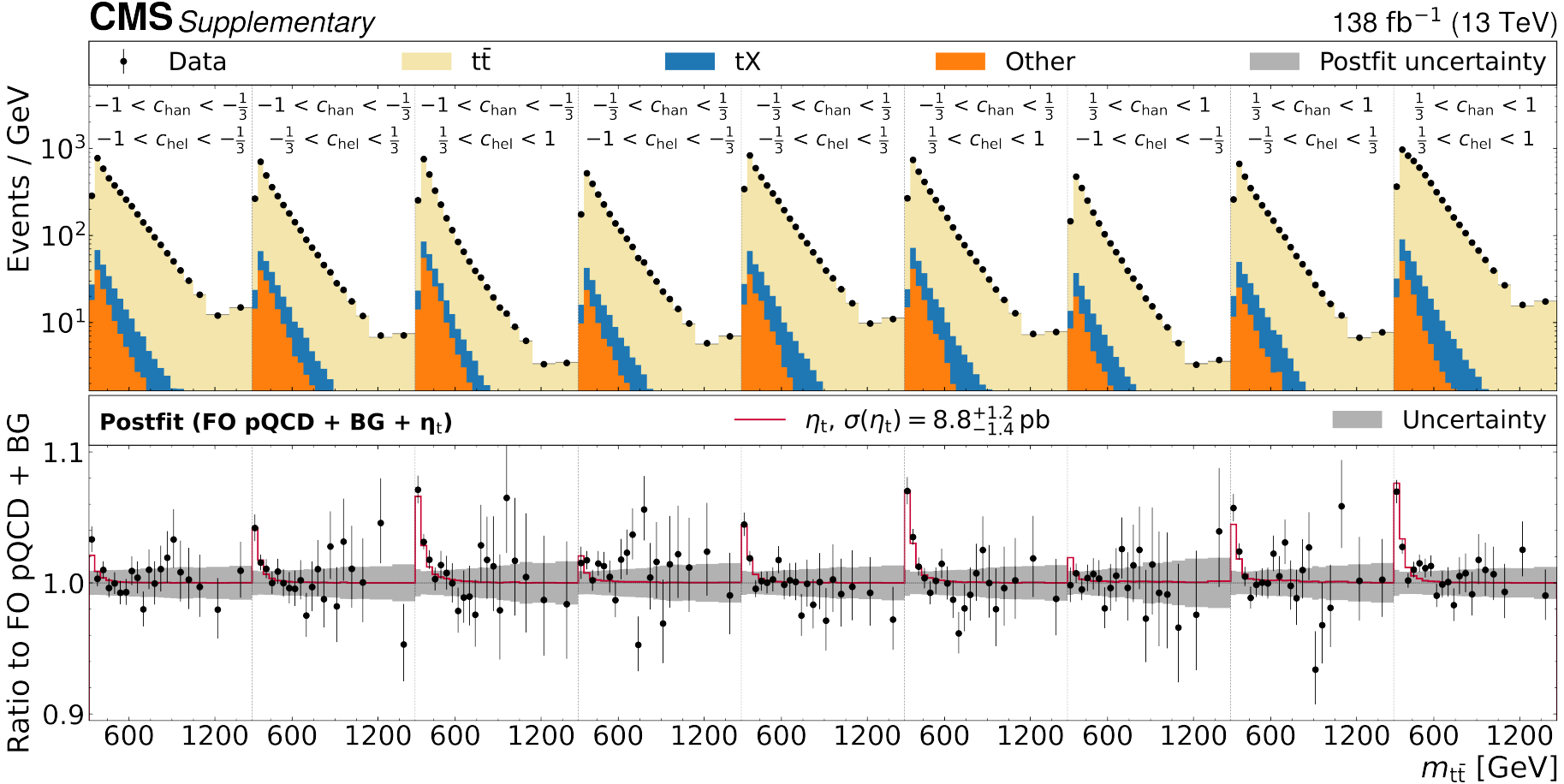
1) assign b jets to leptons based on $m_{\ell b}$
2) Assumptions: all $p_{\mathrm{T}}^{\mathrm{miss}}$ from neutrinos, tops and Ws on-shell
3) conservation of energy & momentum → solve for neutrino momenta (4th order polynominal equations)
4) if multiple solutions: use that with lowest $m_{t\bar{t}}$
5) to account for mismeasurement of b jets & $p_{\mathrm{T}}^{\mathrm{miss}}$: repeat 100 times per event with random smearings
6) use weighted average of those repeats that gave physical solution

Prefit distributions

Differences between data and prediction observed in low $m_{t\bar{t}}$ bins!



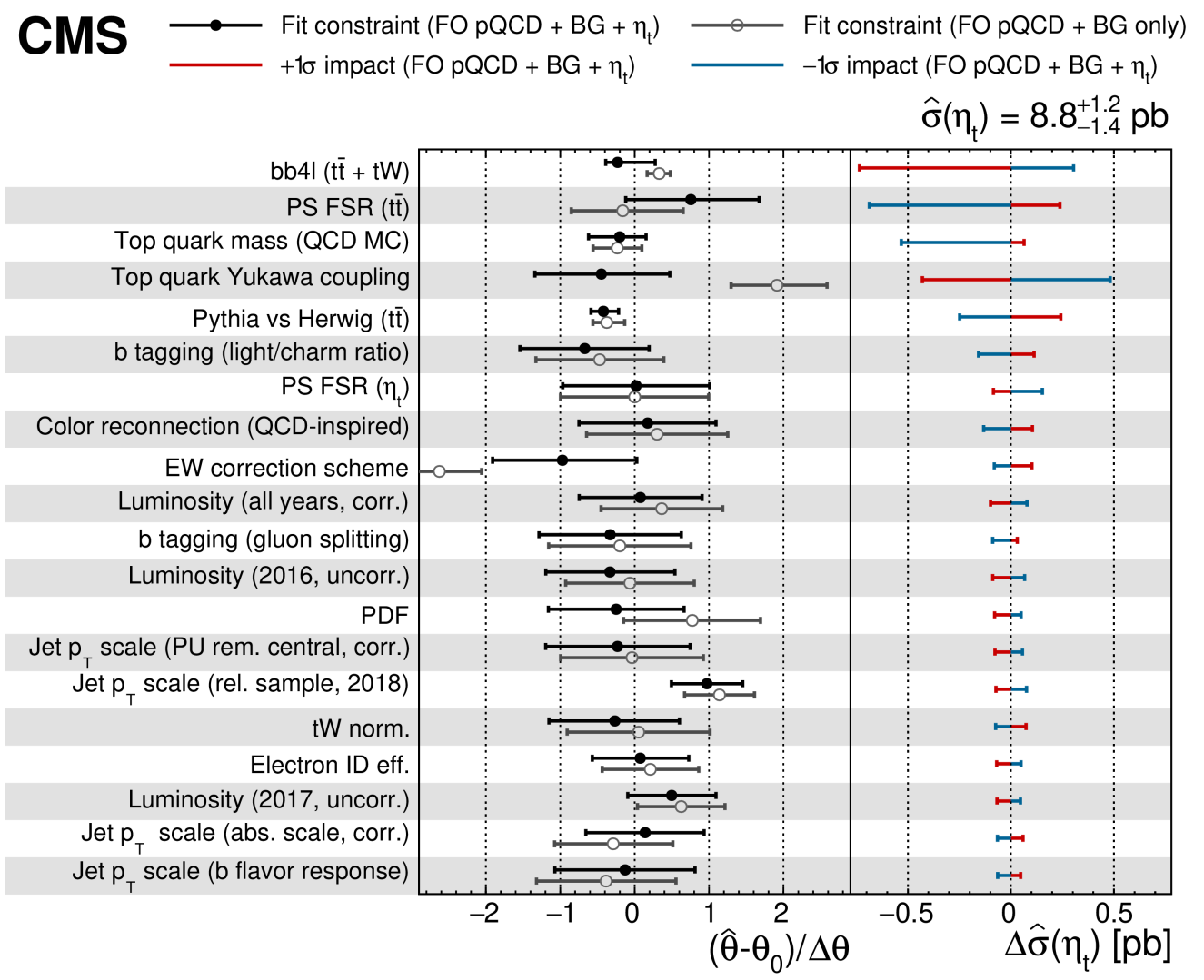
3D postfit distributions: η_t



Impacts

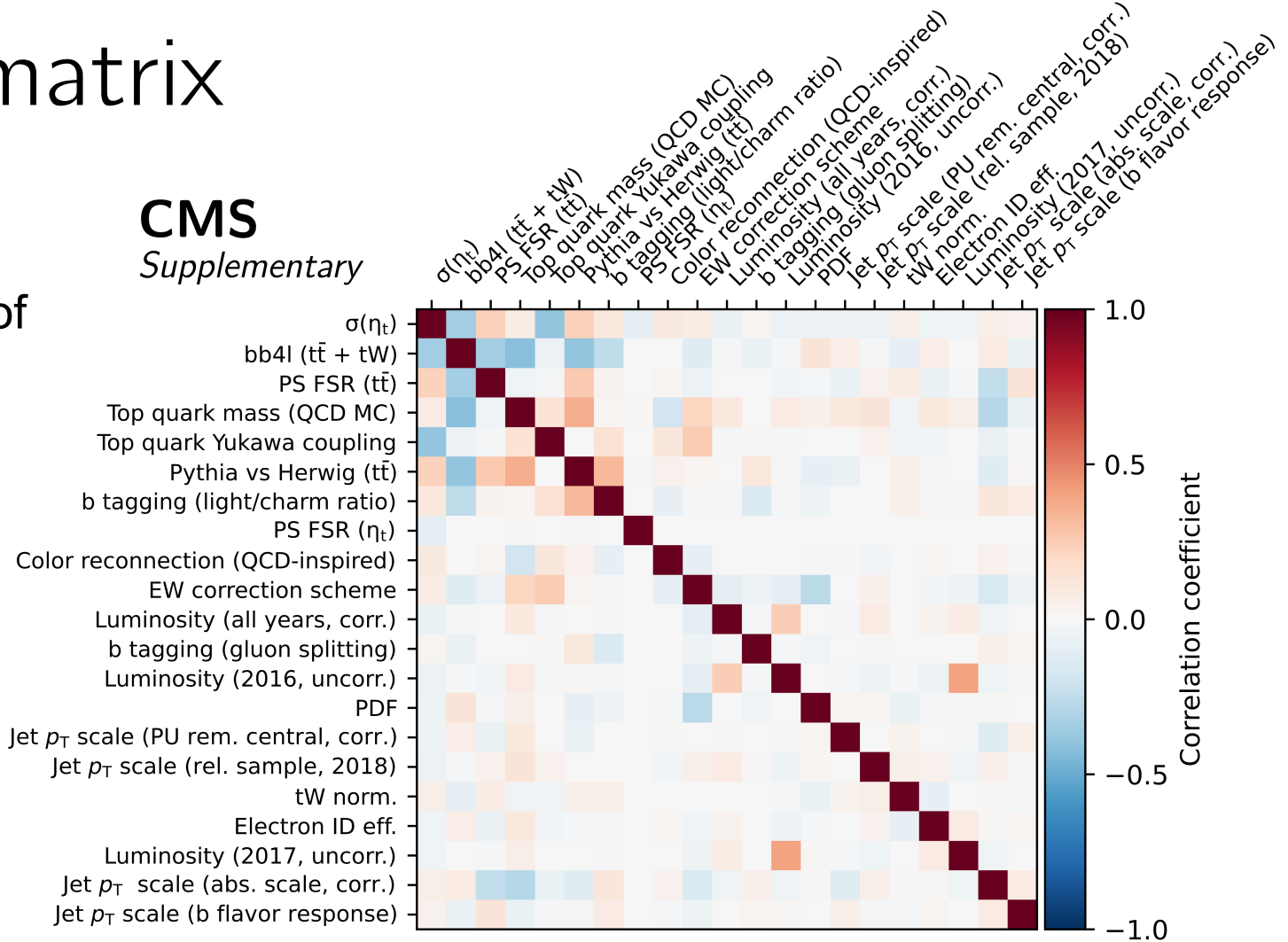
Leading uncertainties:

- Comparisons to bb4l and Herwig
- EW corrections: Yukawa coupling, correction scheme
- $t\bar{t}$ FSR, matching
- top mass
- η_t modeling (FSR)



Correlation matrix

- Further assess uncertainty modeling through correlations of nuisance parameters



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 $N_{data} = N^{\ell\ell}_{data} - 0.5 N^{e\mu}_{data} k_{\ell\ell}$, 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

Powheg: $\sigma^{\text{LO EW}}_{\text{NLO QCD}}$ × Hathor: $\frac{\sigma^{\text{NLO EW}}_{\text{LO QCD}}}{\sigma^{\text{LO EW}}_{\text{LO QCD}}}$ MadGraph

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

- Alternate choice: additive

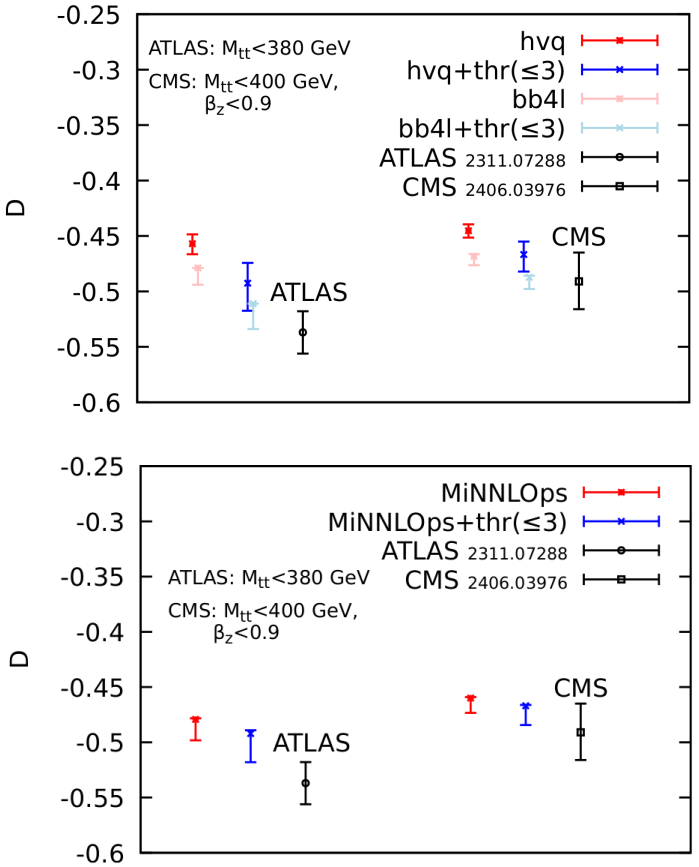
$$\sigma^{\text{rew.}} = \sigma^{\text{LO EW}}_{\text{NLO QCD}} + \sigma^{\text{NLO EW}}_{\text{LO QCD}} - \sigma^{\text{LO EW}}_{\text{LO QCD}}$$

- Difference treated as systematic uncertainty

Fully perturbative predictions?

arXiv:2505.00096 (P. Nason, E. Re, L. Rottoli)

- Try to get predictions for D and m_{tt} close to the threshold using a fully perturbative approach
  - if your cut is sufficiently inclusive (e.g. m_{tt} < 380 GeV): insensitive about details of peak → integrate over it
- Is this a ”bound state” or “threshold corrections” ?
  - Nason et al: “bound states” are only terms $\propto \alpha_S^5$
  - To me this is a semantic difference…
- Are these corrections already (partly) included in “normal” higher-order MCs?
  - Powheg $t\bar{t}$ MiNNLO$_{PS}$ – not yet checked in CMS…
  - MATRIX NNLO doesn’t seem to show it – but that is stable-top level



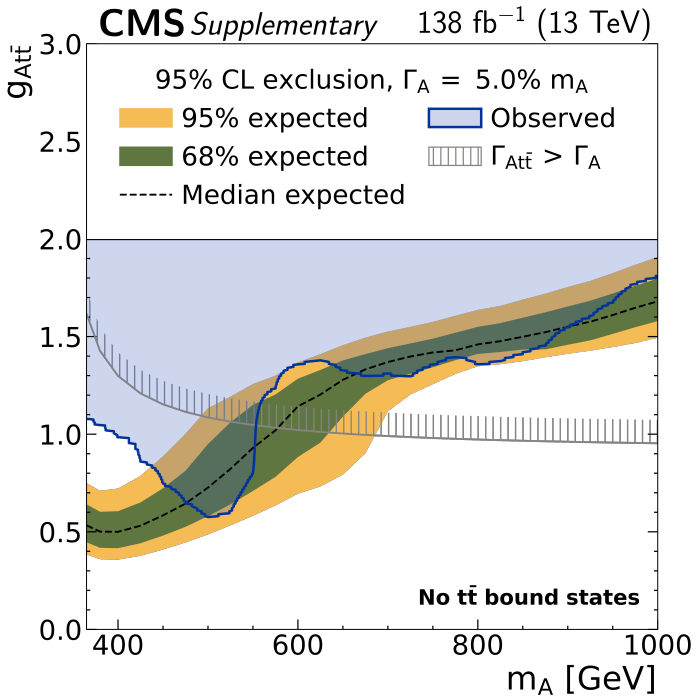
Limits on A/H

- Set limits on couplings of A/H to top over large mass range
- Two scenarios on how to treat η_t:

η_t as additional free-floating BG:

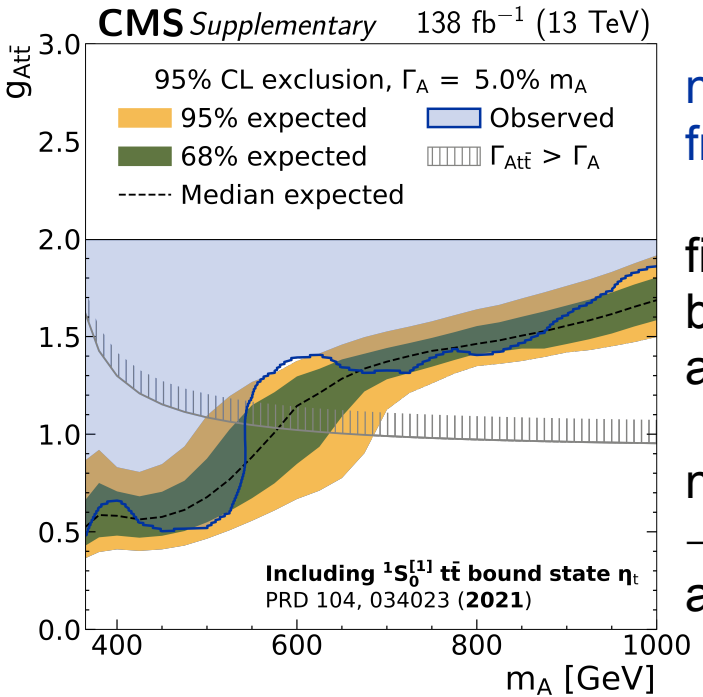
fit can choose between A/H and η_t

η_t is preferred → excess is absorbed



no η_t:

excess visible in limits



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

