Observation of a pseudoscalar excess

at the top quark pair production threshold

Alexander Grohsjean

on behalf of the

CMS Collaboration

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

EXZELLENZCLUSTER
QUANTUM UNIVERSE

TOP LHC France 2025

29th of April 2025

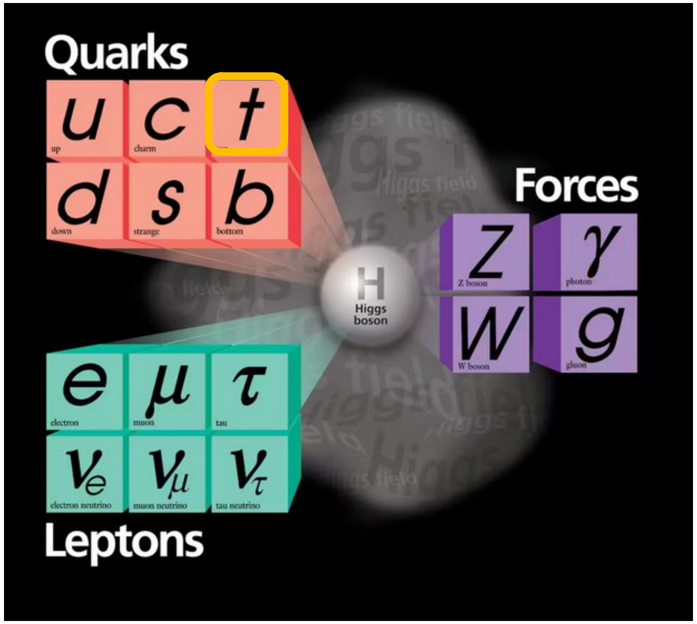
based on
arXiv:2503.22382
HIG-22-013

Needless to say: Tops are special

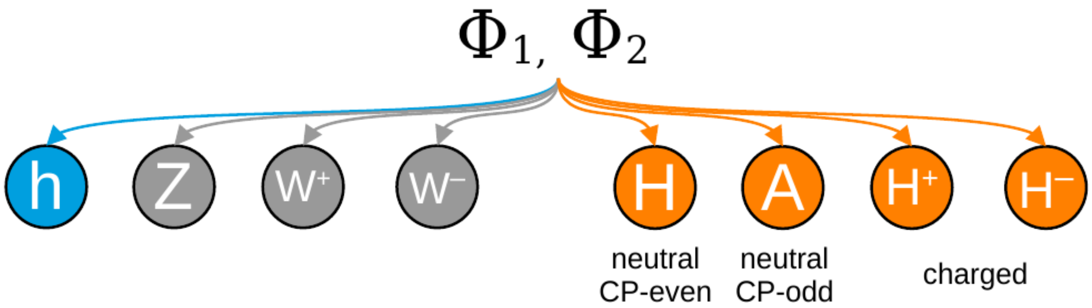
- short lifetime of $O(10^{-25})$ s
  → top spin propagated to decay products
  → fingerprint of $t\bar{t}$ production mode

- heaviest elementary particle:
  172.52 ± 0.33 GeV (PRL 132 (2024) 261902)

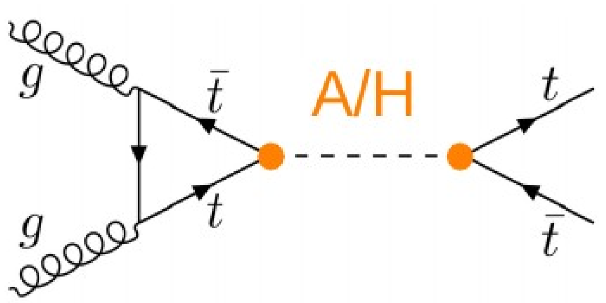
- Yukawa-like top couplings close to 1
  → potential key to finding new (pseudo)-scalars



Two Higgs Doublet Model – Type II



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



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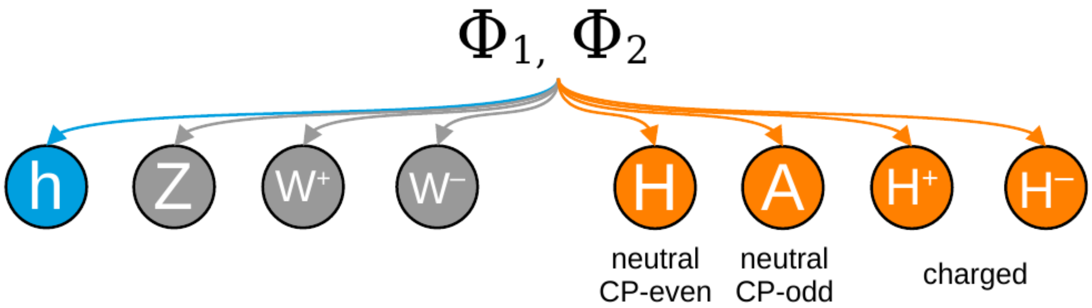

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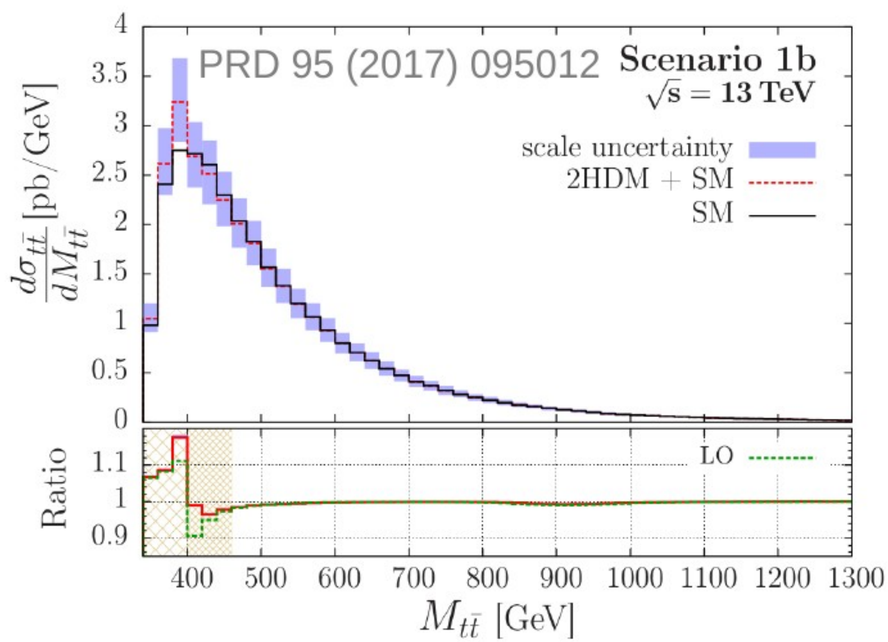
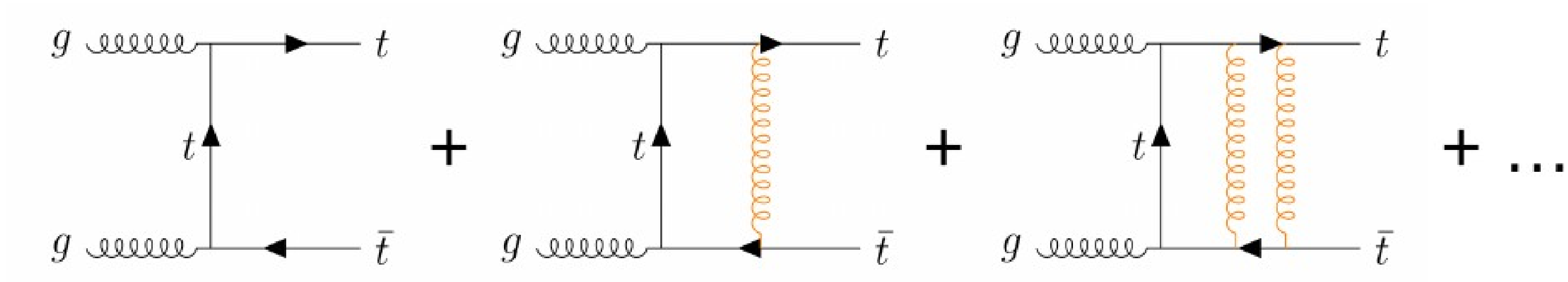
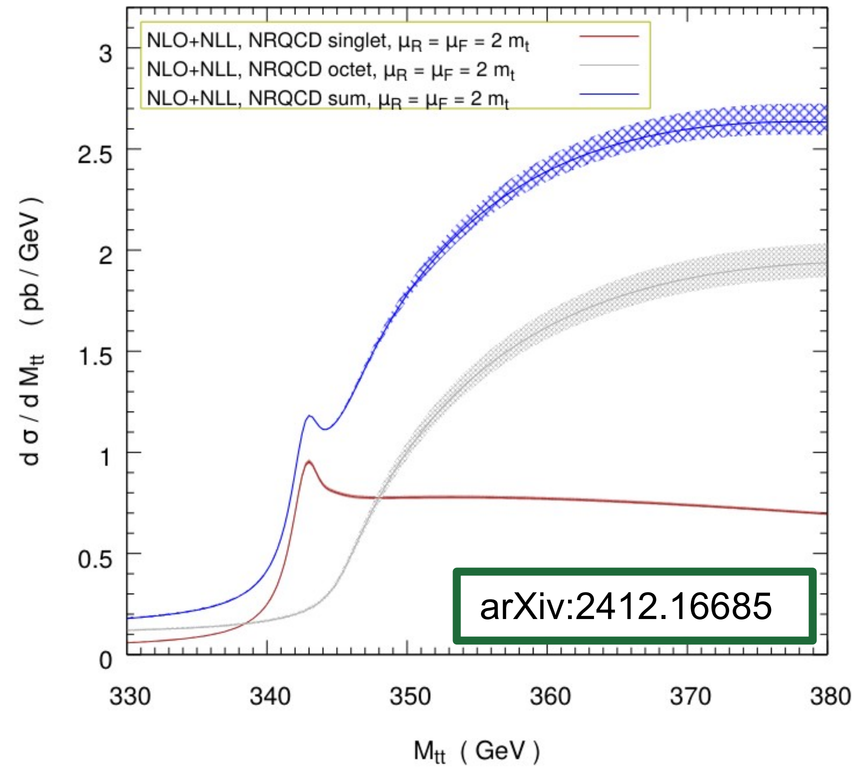
- strong couplings of A/H to top quarks
  - $m_{A/H} > 2m_t$:
    $t\bar{t}$ final states promising for a discovery
  - interference with SM:
    dip-peak in invariant $t\bar{t}$ mass spectrum

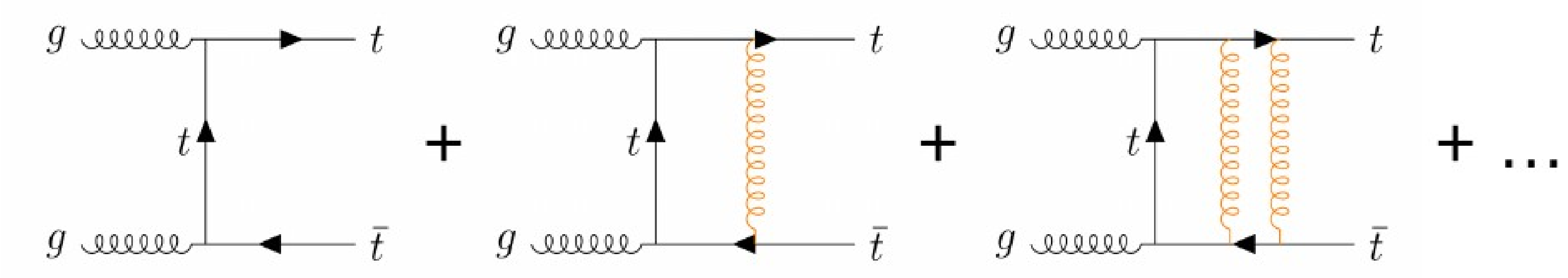


SM Pseudoscalars: $t\bar{t}$ Quasi-Bound States



- color singlet ($^1S_0[1]$) - attractive
  → peak below the $t\bar{t}$ threshold
- color octet ($^1S_0[8]$ or $^3S_1[8]$) - repulsive
  → contributions small below threshold





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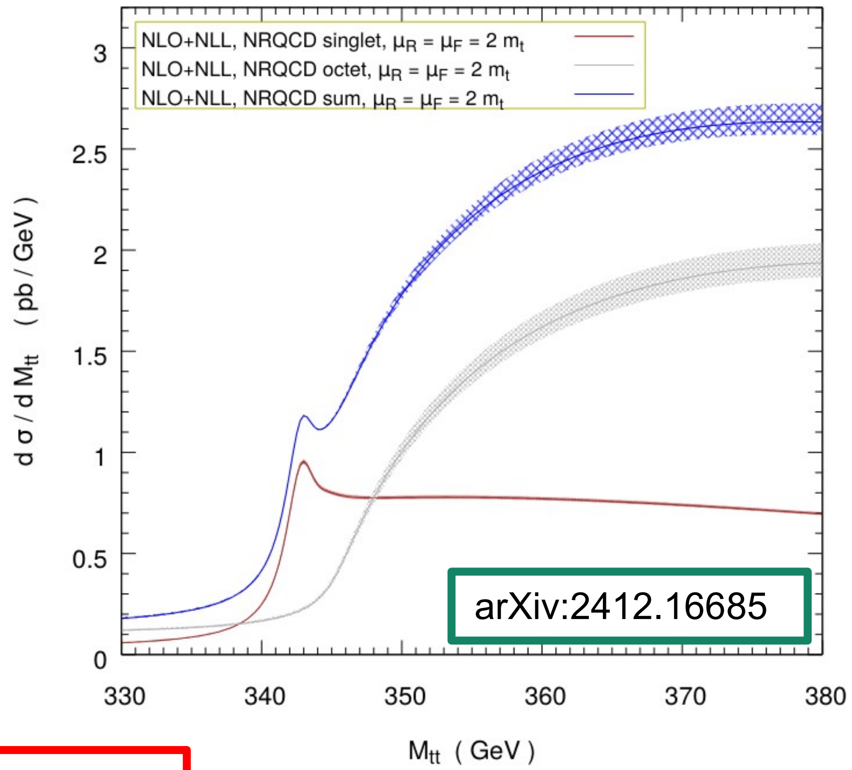


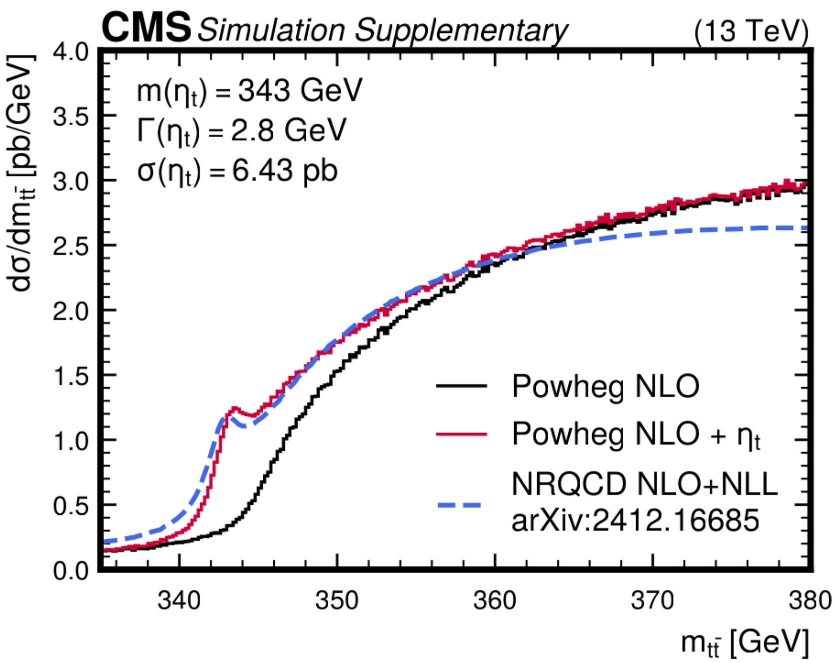
How to get non-relativistic contributions from Monte Carlo ?

Approximating $t\bar{t}$ Quasi-Bound States

- simplified η_t model inspired by JHEP 03 (2024) 099
  - generic color-singlet, CP-odd, spin-0 particle
  - direct couplings to gluons and tops
  - mass/width from fit to NRQCD:

$$\boxed{\begin{array}{c} m_{\eta t} = 343 \text{ GeV} \\ \Gamma_{\eta t} = 2\,\Gamma_t = 2.8 \text{ GeV} \end{array}}$$

- to keep in mind:
  - details of lineshape well below experimental resolution (15% - 25%)
  - very similar signature as low-mass A resonance without interference

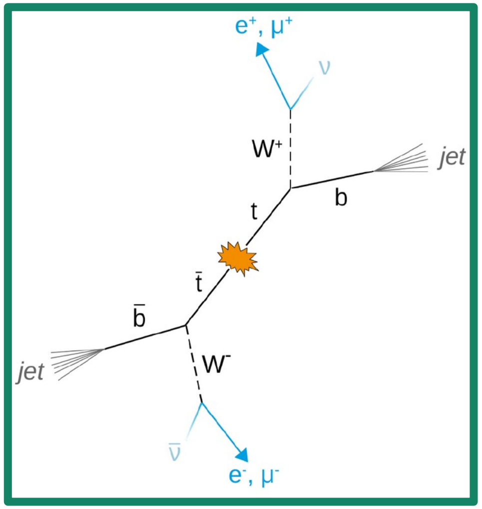


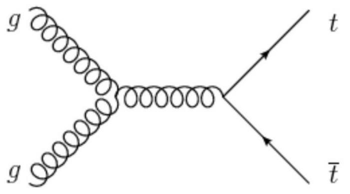
Experimental Setup

- 138 fb^{-1} of pp collisions at 13 TeV (2016 - 2018)

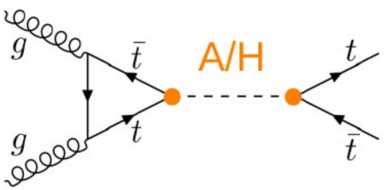
- dilepton final state

- explore invariant $t\bar{t}$ mass and differences in production
  - distinguish mixture of states from pure scalar





vs.



  - distinguish $^1S_0$ (A/η_t) from $^3P_0$ (H) $t\bar{t}$ spin states

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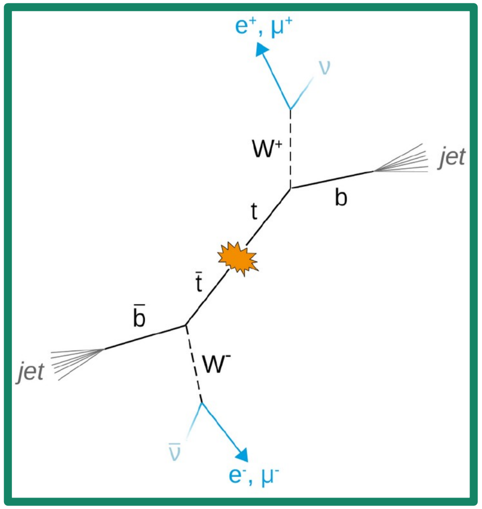

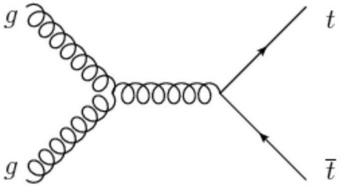

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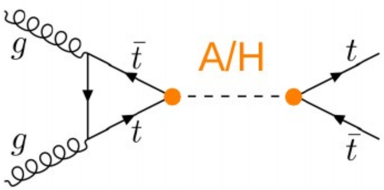

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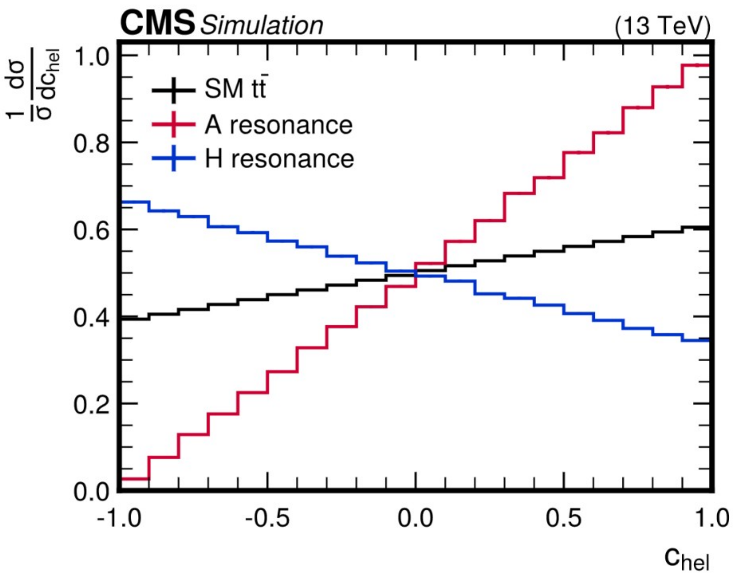
    - c_{hel}: scalar product of leptons in parent top rest frame



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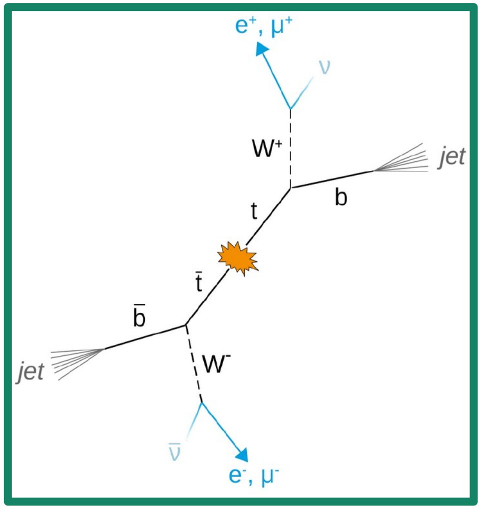

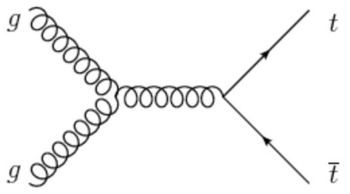

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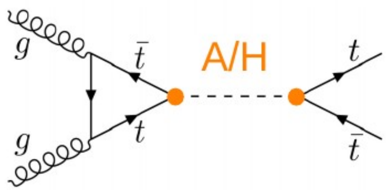

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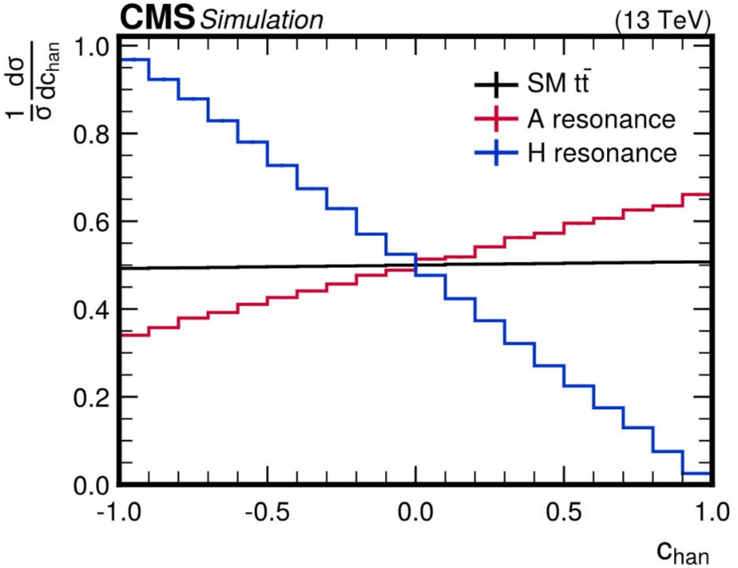

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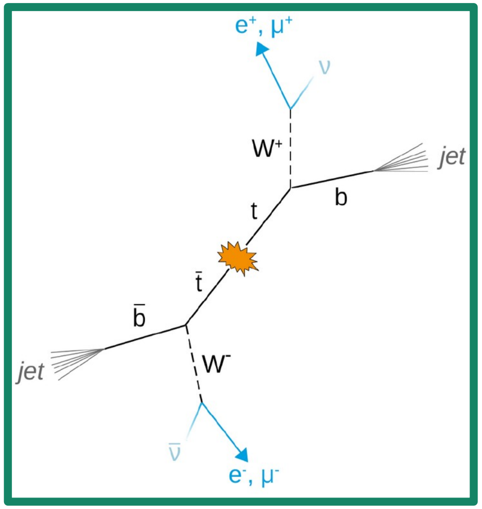

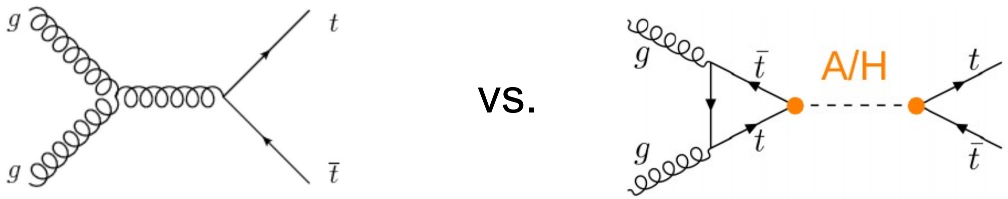

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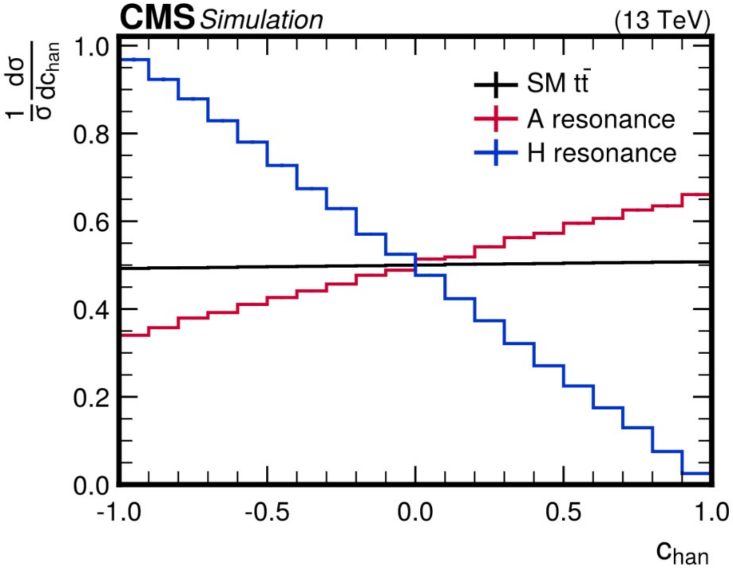
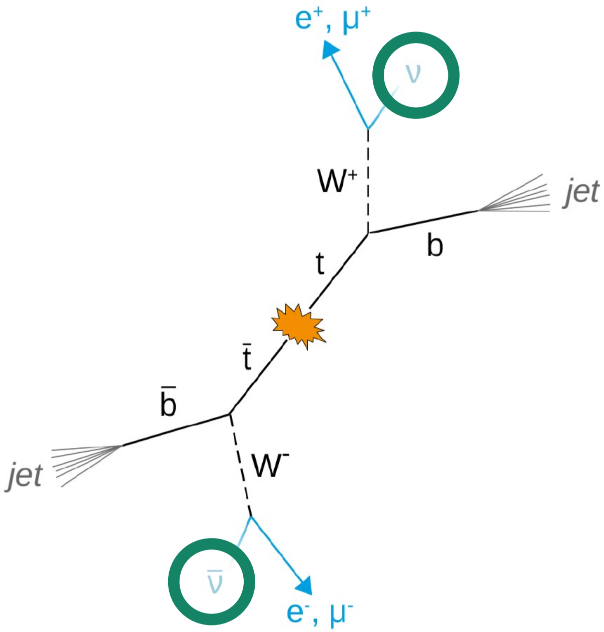


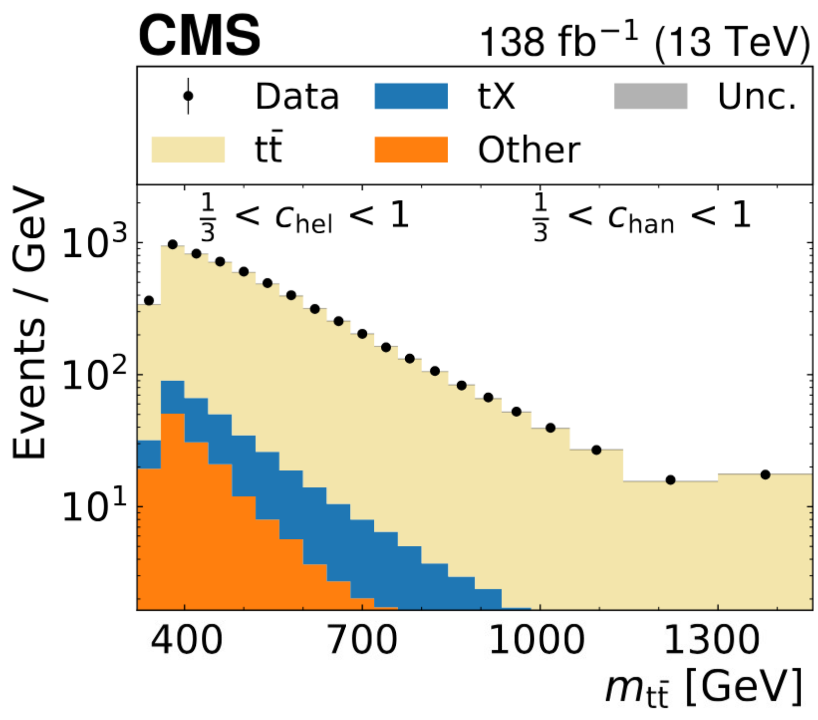
3 search variables: $m_{t\bar{t}}$ x c_{hel} x c_{han}

Analytic Event Reconstruction

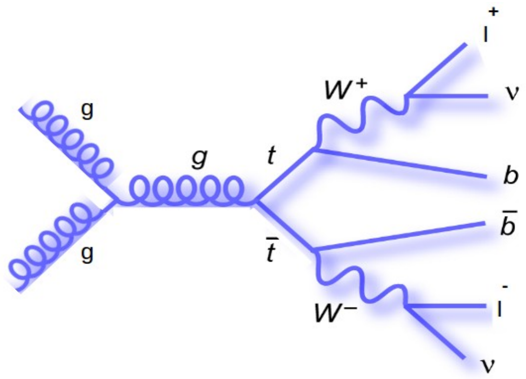


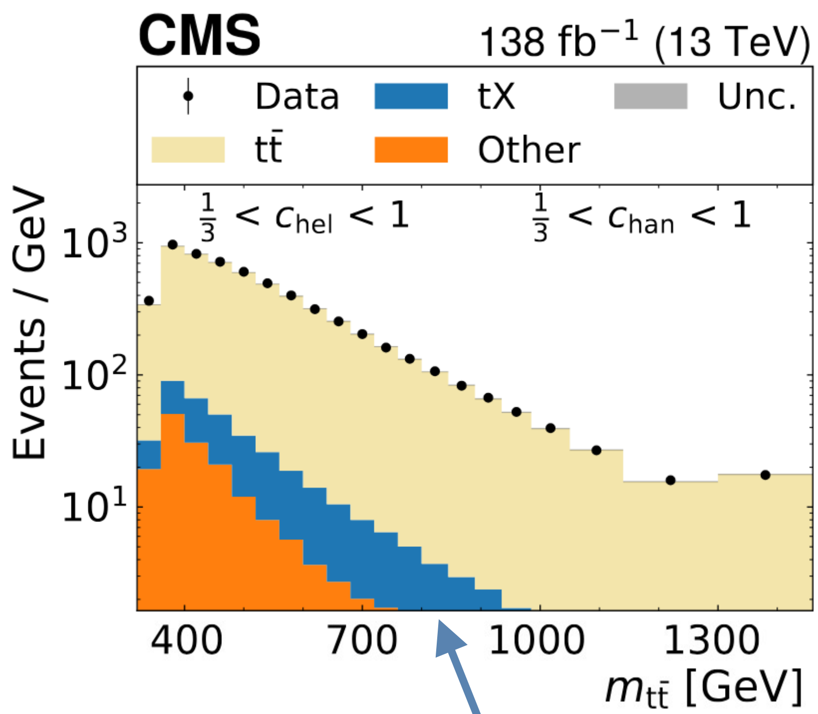
- key to all observables: reconstruction of $t\bar{t}$ event
- 6 unknowns (2 massless ν's)
- 6 constraints:
  - p_T^{miss} from ν's
  - 2 x top and 2 x W masses
- assign b-jets using m_{lb}-based likelihood
- finite detector resolution:
  - repeat 100 times with smeared inputs

Background Modeling

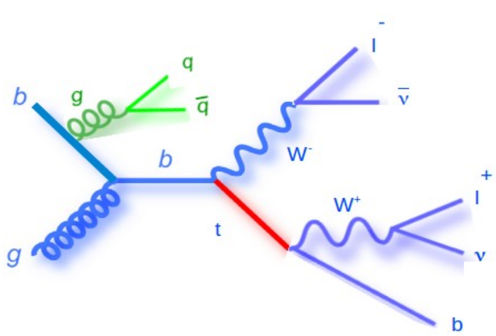


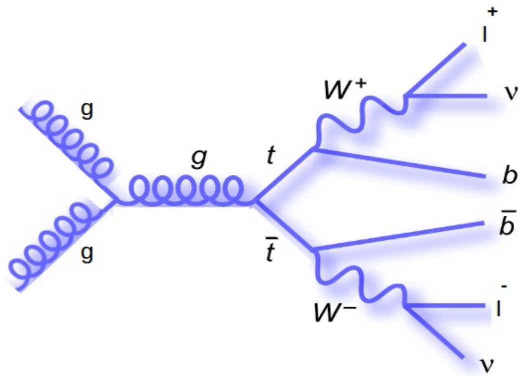
- major background: SM $t\bar{t}$
  - NLO MC (Powheg+Pythia 8)
  - reweighting to NNLO QCD and NLO EW in bins of $m_{t\bar{t}}$ vs. cosθ* (EPJC 78 (2018) 537, EPJC 51 (2007) 37)
  - normalize to NNLO+NNLL cross section (CPC 185 (2014) 2930)

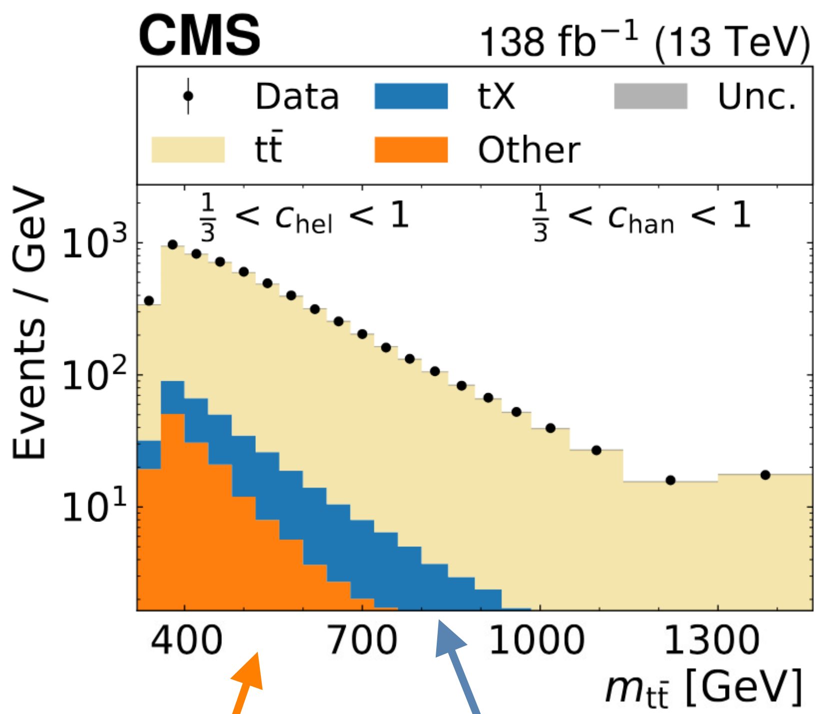




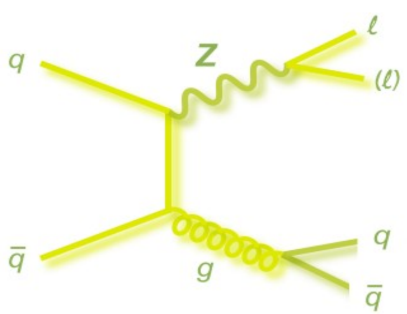
- major background: SM $t\bar{t}$
- tW, t-channel, s-channel single-top
  - from MC
  - scaled to (N)NLO

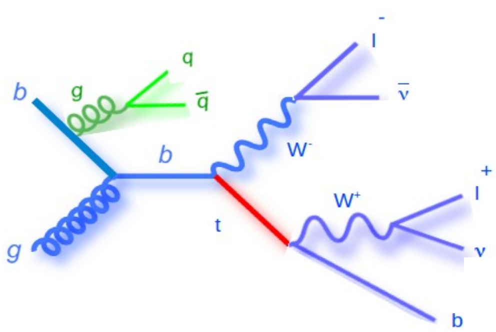


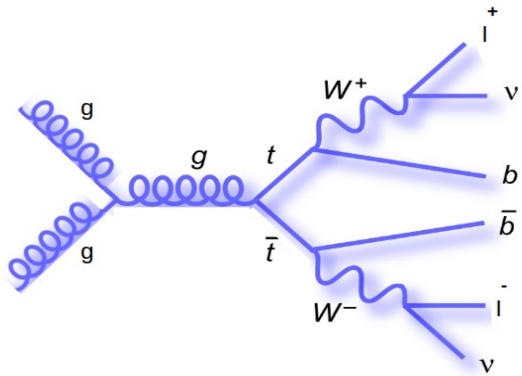




- major background: SM $t\bar{t}$
- tW, t-channel, s-channel single-top
- DY+jets
  - MiNNLO simulations
  - data-driven normalization from Z peak

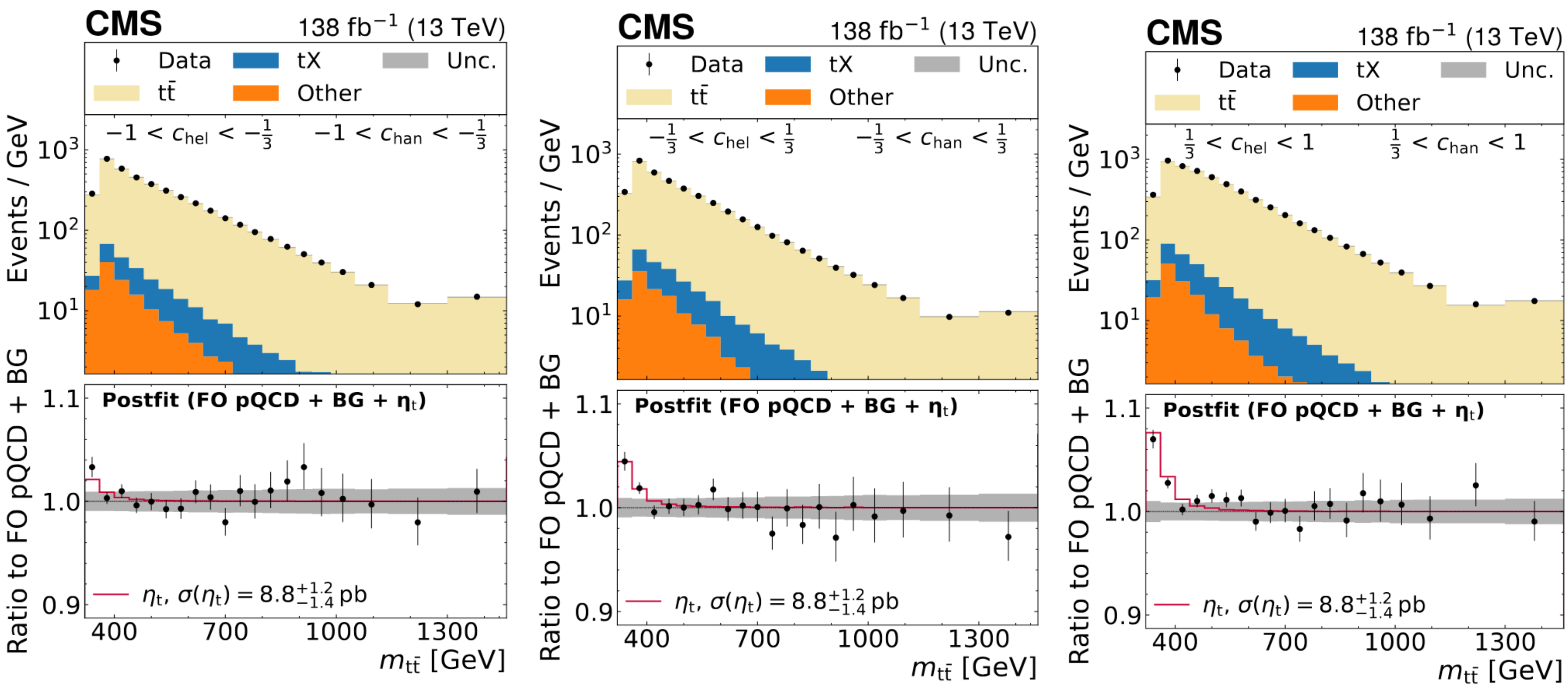






- profile-likelihood fit to 20 bins of $m_{t\bar{t}}$ x 3 bins of c_{hel} x 3 bins of c_{han}
- interpretation in terms of η_t

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



Result well compatible with NRQCD prediction of $\sigma_{\eta t}$ = 6.43 pb

PRD 104 (2021) 034023

Putting all together

- profile-likelihood fit to 20 bins of $m_{t\bar{t}}$ x 3 bins of c_{hel} x 3 bins of c_{han}
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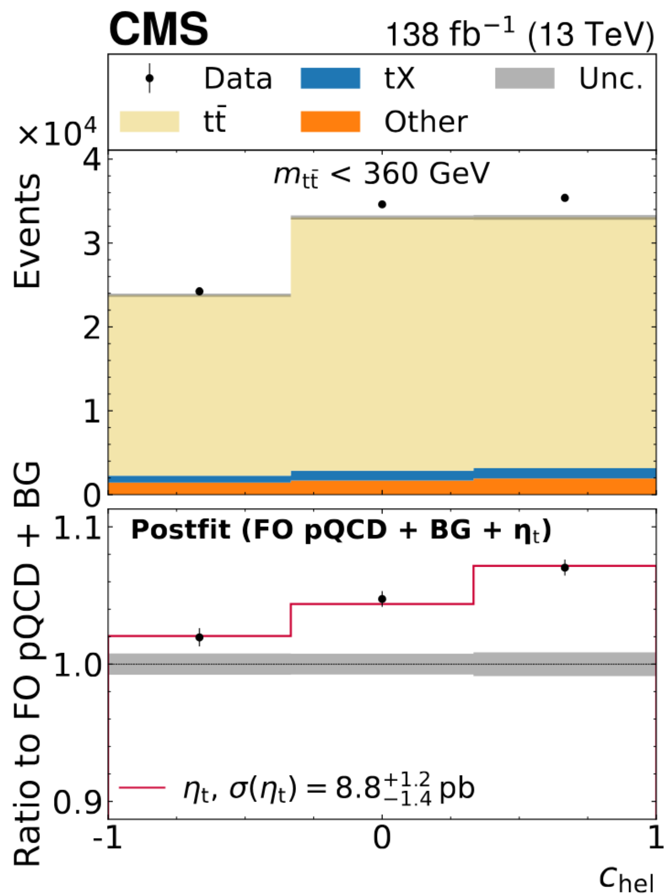

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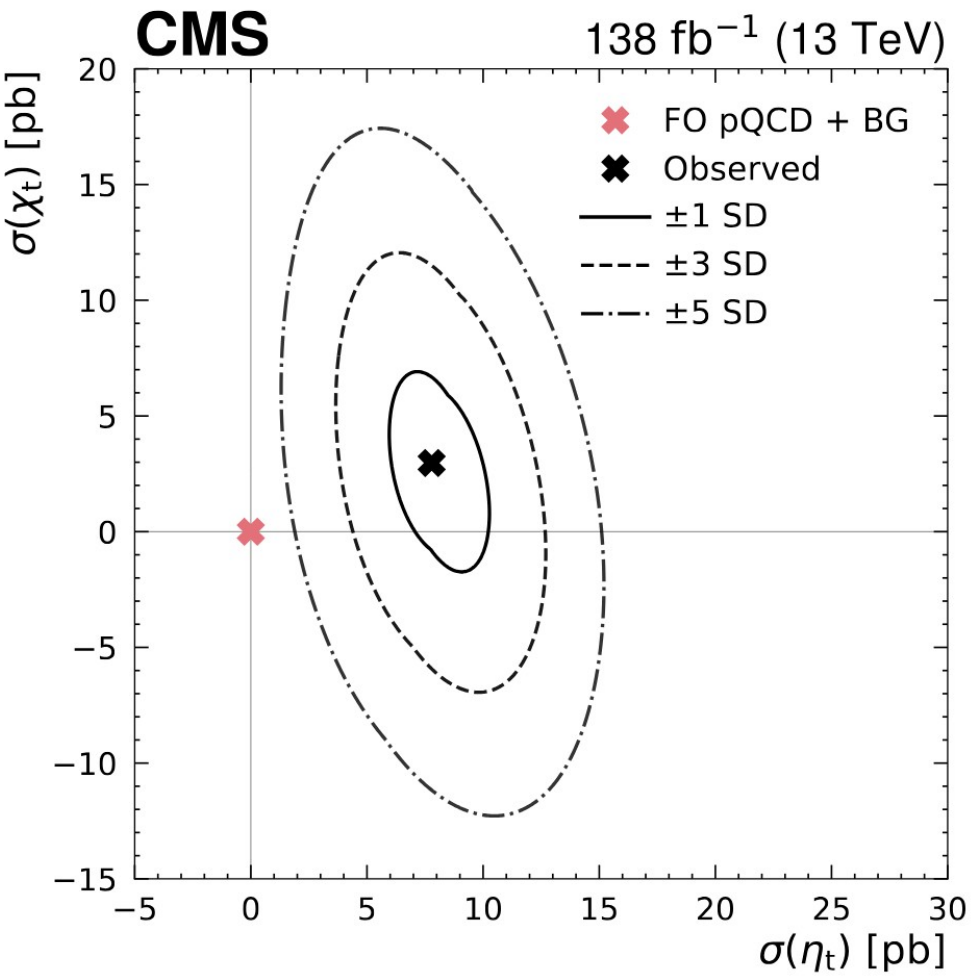
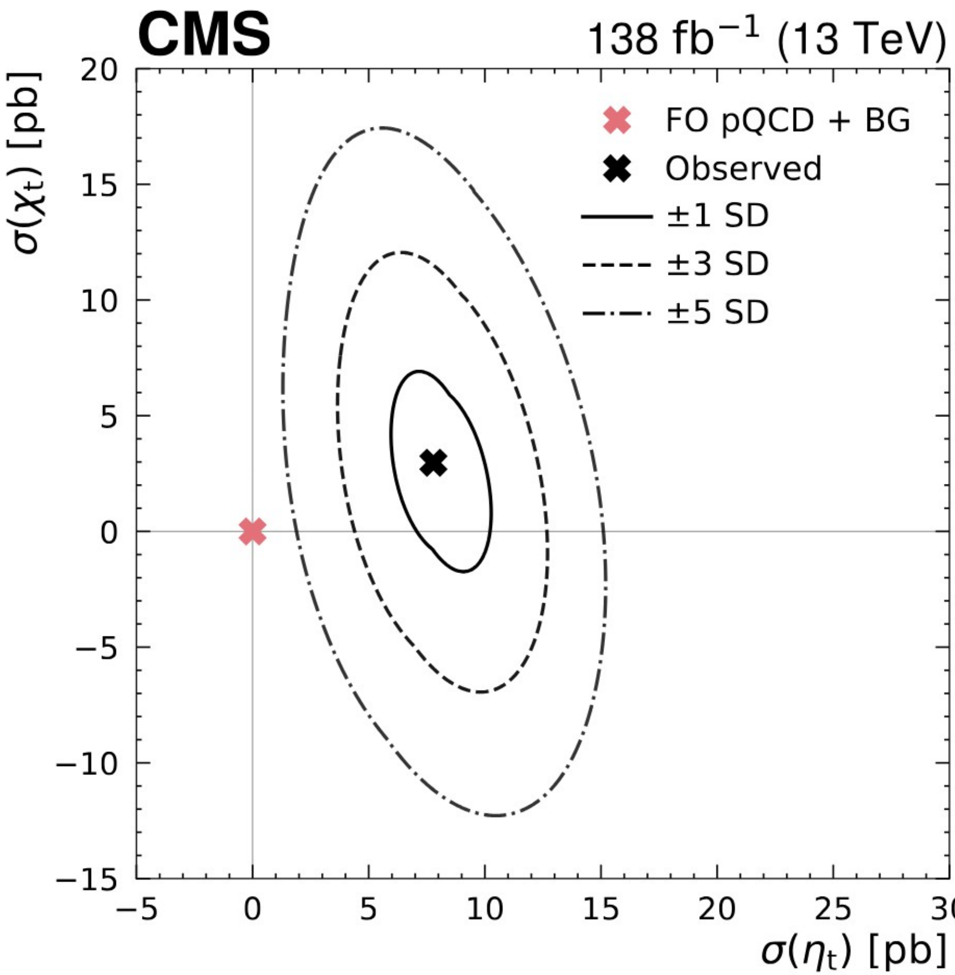
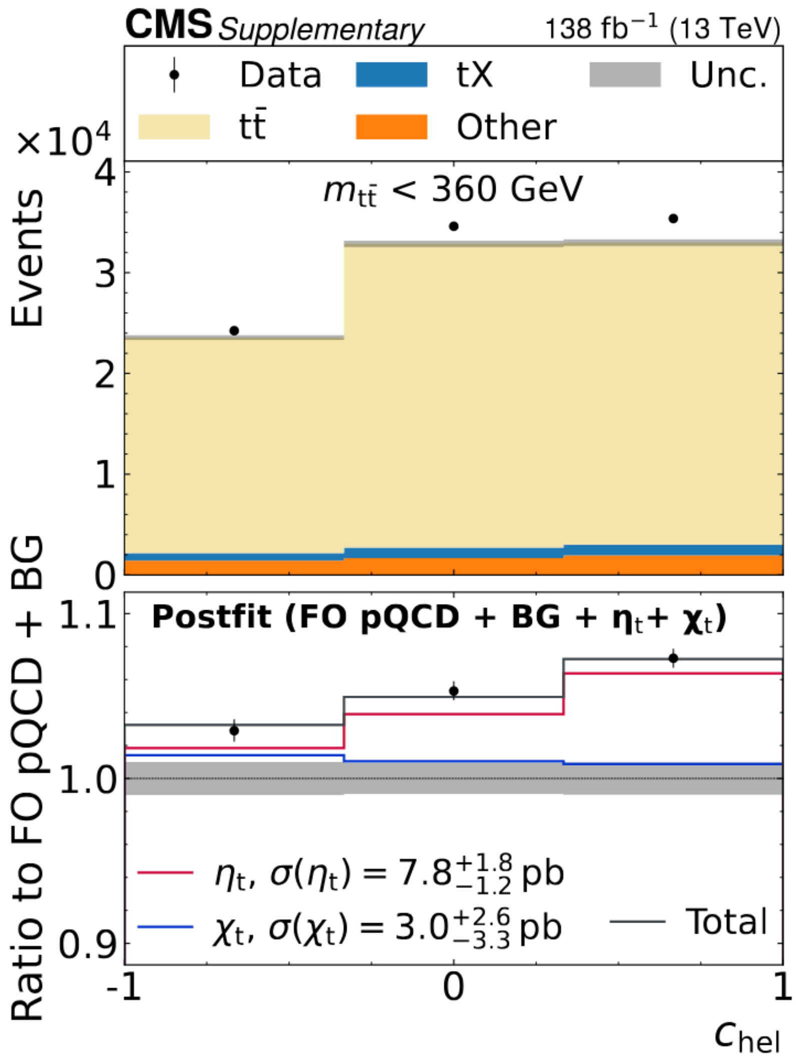
Scalar or Pseudoscalar?



η_t, $\sigma(\eta_t) = 7.8^{+1.8}_{-1.2}$ pb
χ_t, $\sigma(\chi_t) = 3.0^{+2.6}_{-3.3}$ pb

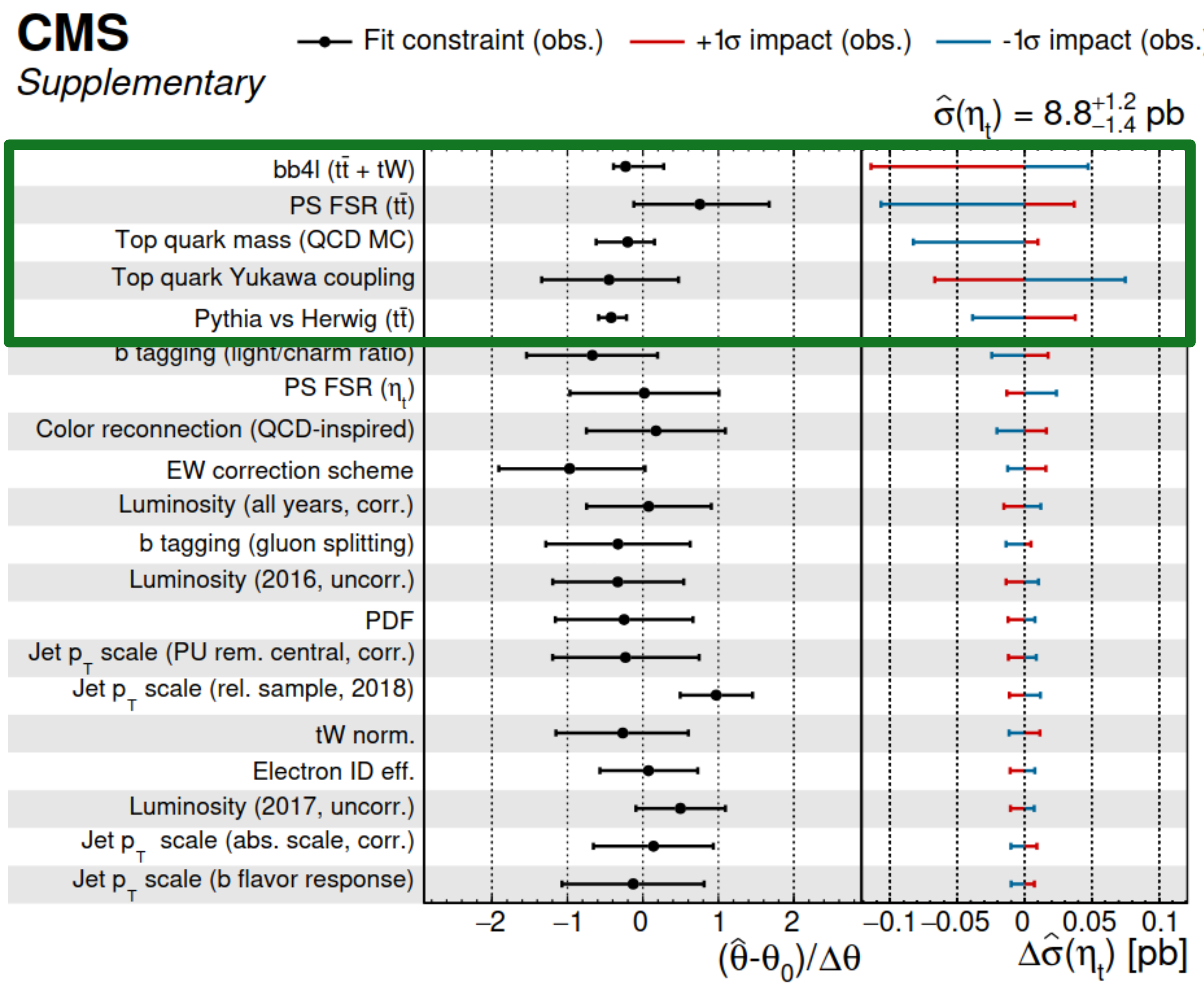
Scalar or Pseudoscalar?





Excess best compatible with pseudoscalar hypothesis !

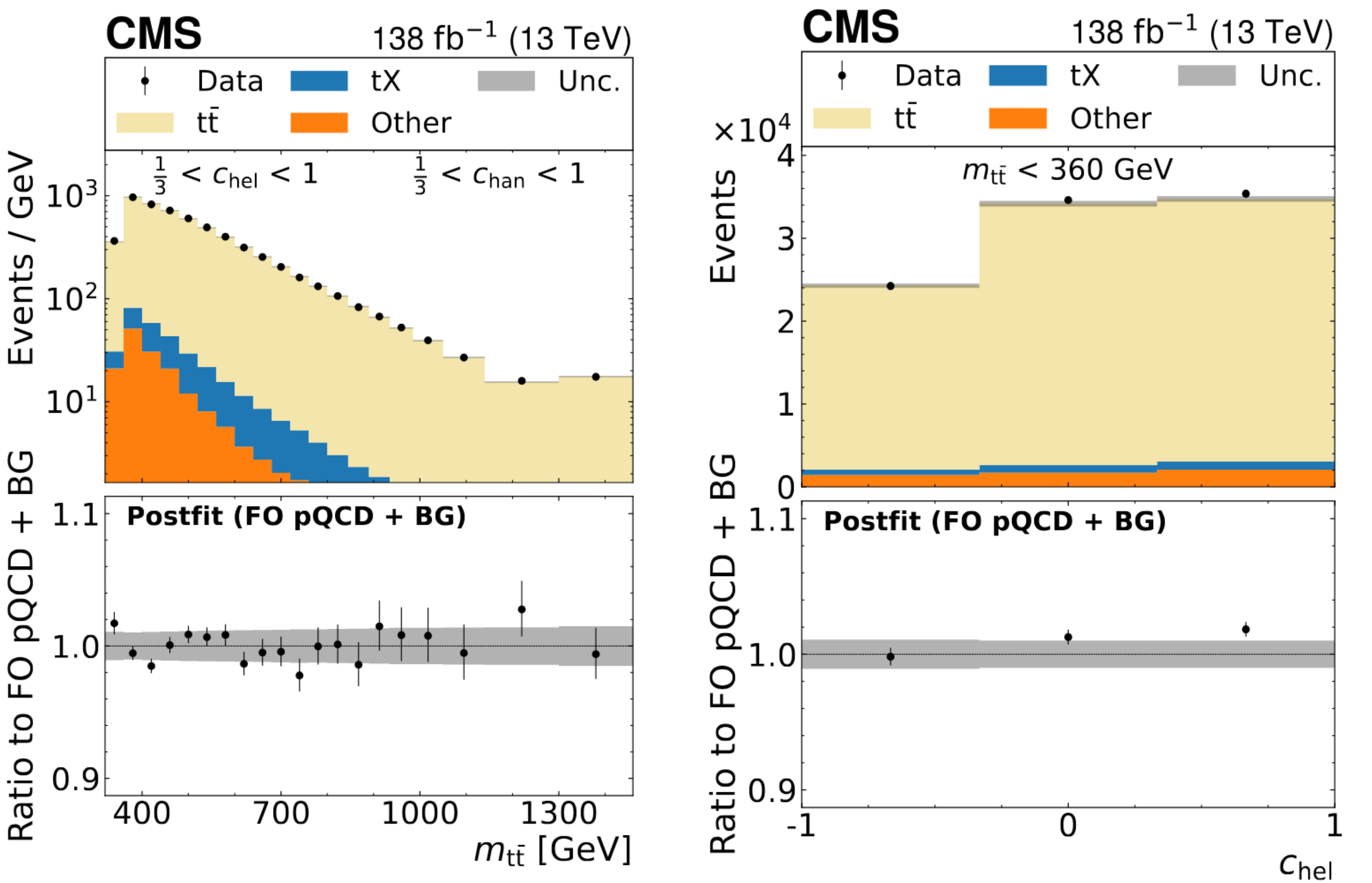
Systematics Uncertainties



- bb4l:
  - $pp \to b\bar{b}l^+l^-\nu\bar{\nu}$ @ NLO
  - off-shell effects
  - interference $t\bar{t}$ and tW
- PS FSR:
  - α_S in final state radiation
- top quark mass and Yukawa coupling
- Herwig7 as alternative parton shower model

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

Background-Only Fits



- residual discrepancies in $m_{t\bar{t}}$ and c_{hel}

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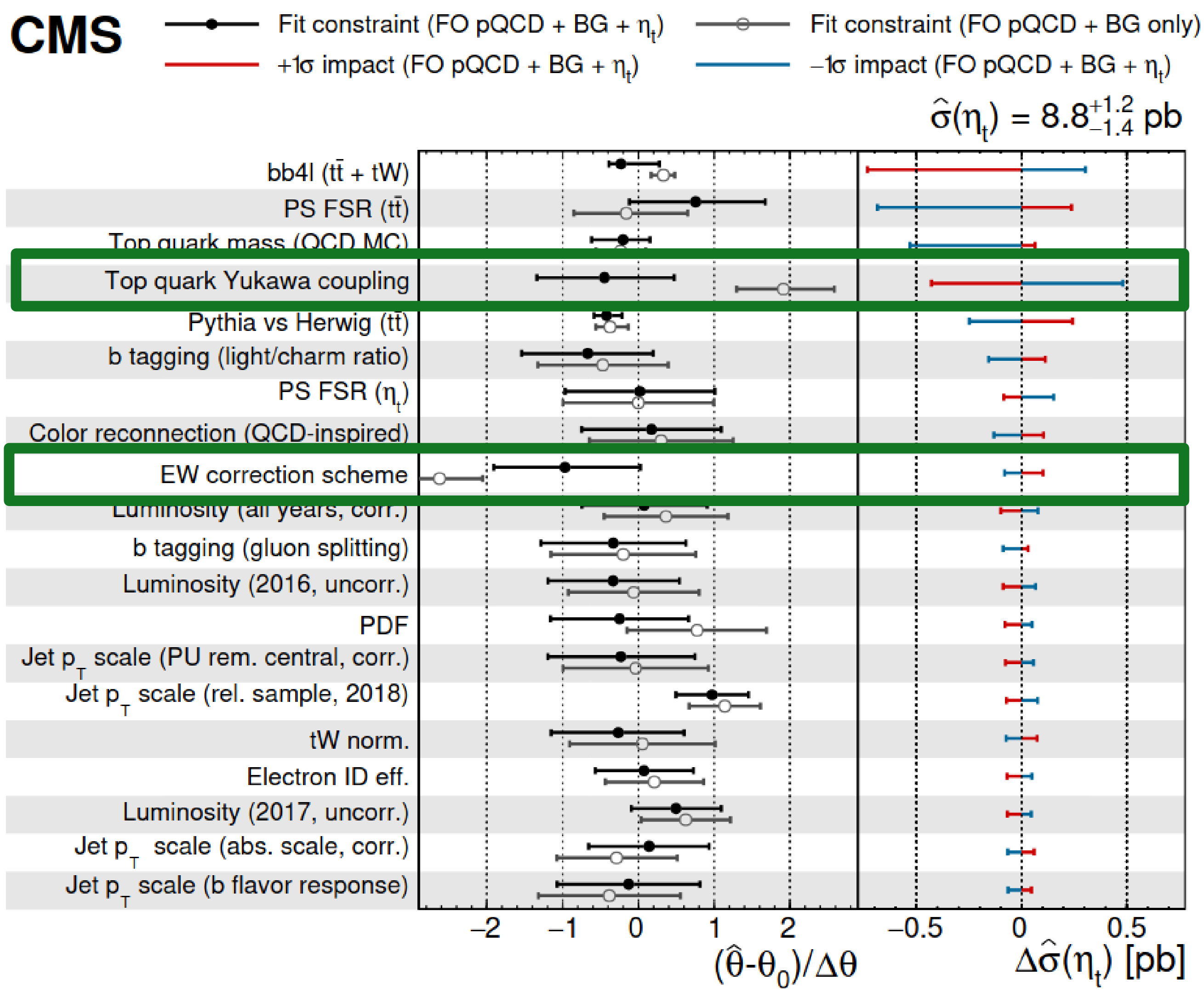
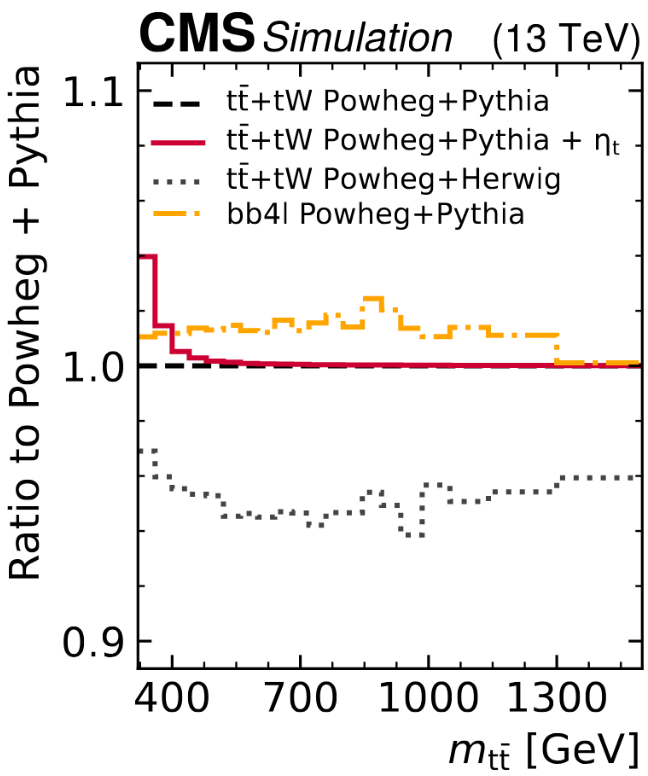


- residual discrepancies in $m_{t\bar{t}}$ and c_{hel}
- strong pull in top Yukawa coupling and electroweak correction scheme

Observed excess can only reasonably be explained with additional contributions !

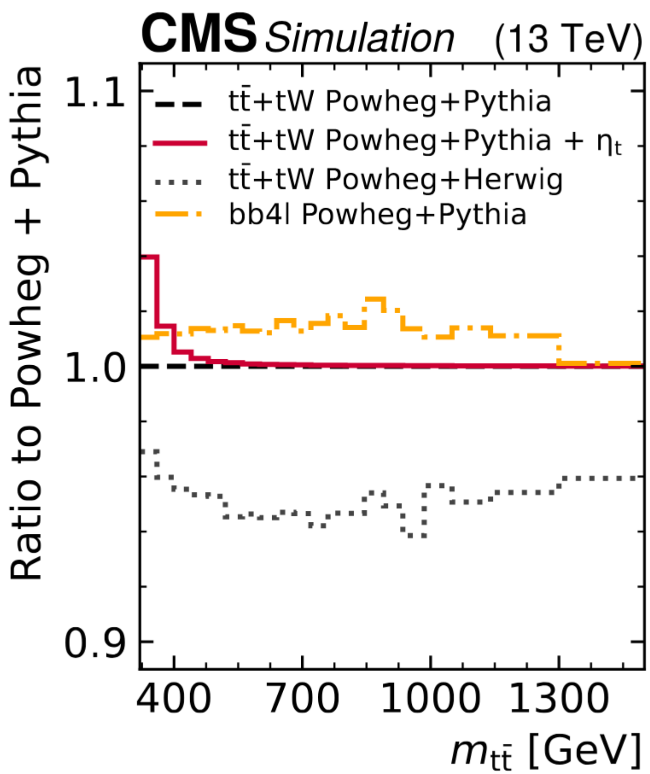
Alternative Monte Carlo Predictions

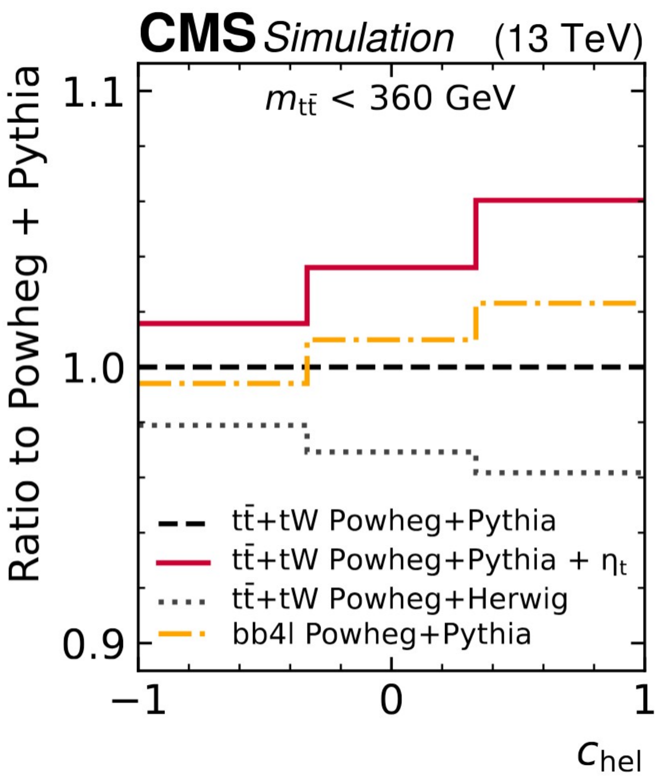
- increased nr. of events at low $m_{t\bar{t}}$ in Herwig7
- similar shapes in bb4l vs nominal Powheg



Alternative Monte Carlo Predictions

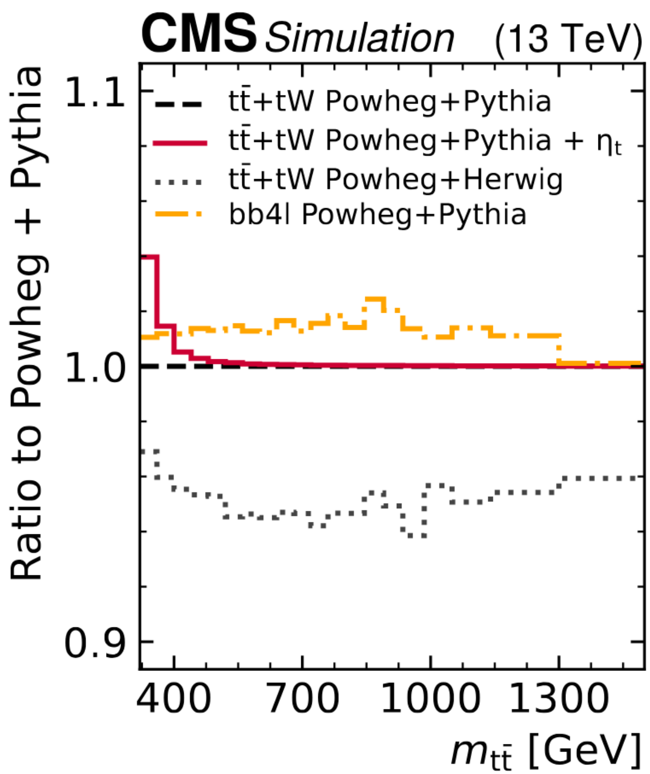
- less slope in c_{hel} for Herwig7
- increased slope for bb4l

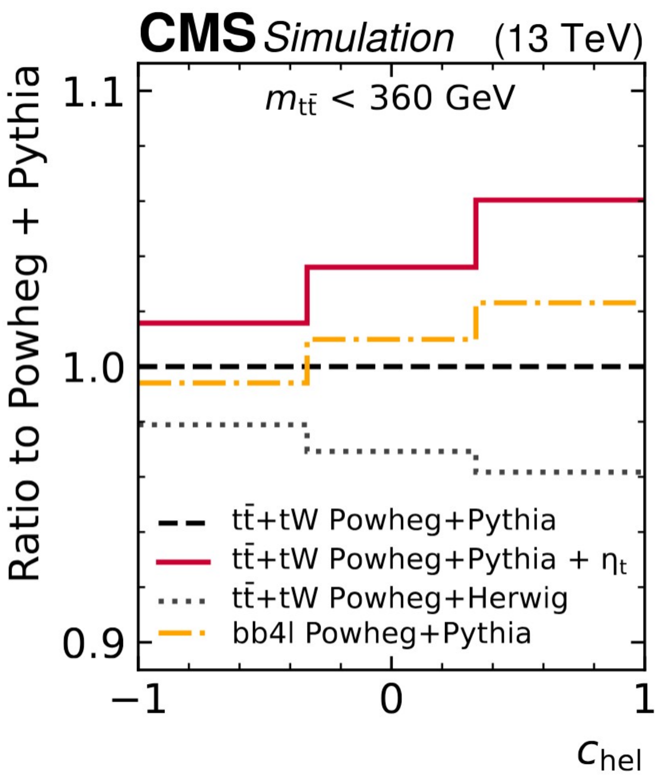




Alternative Monte Carlo Predictions

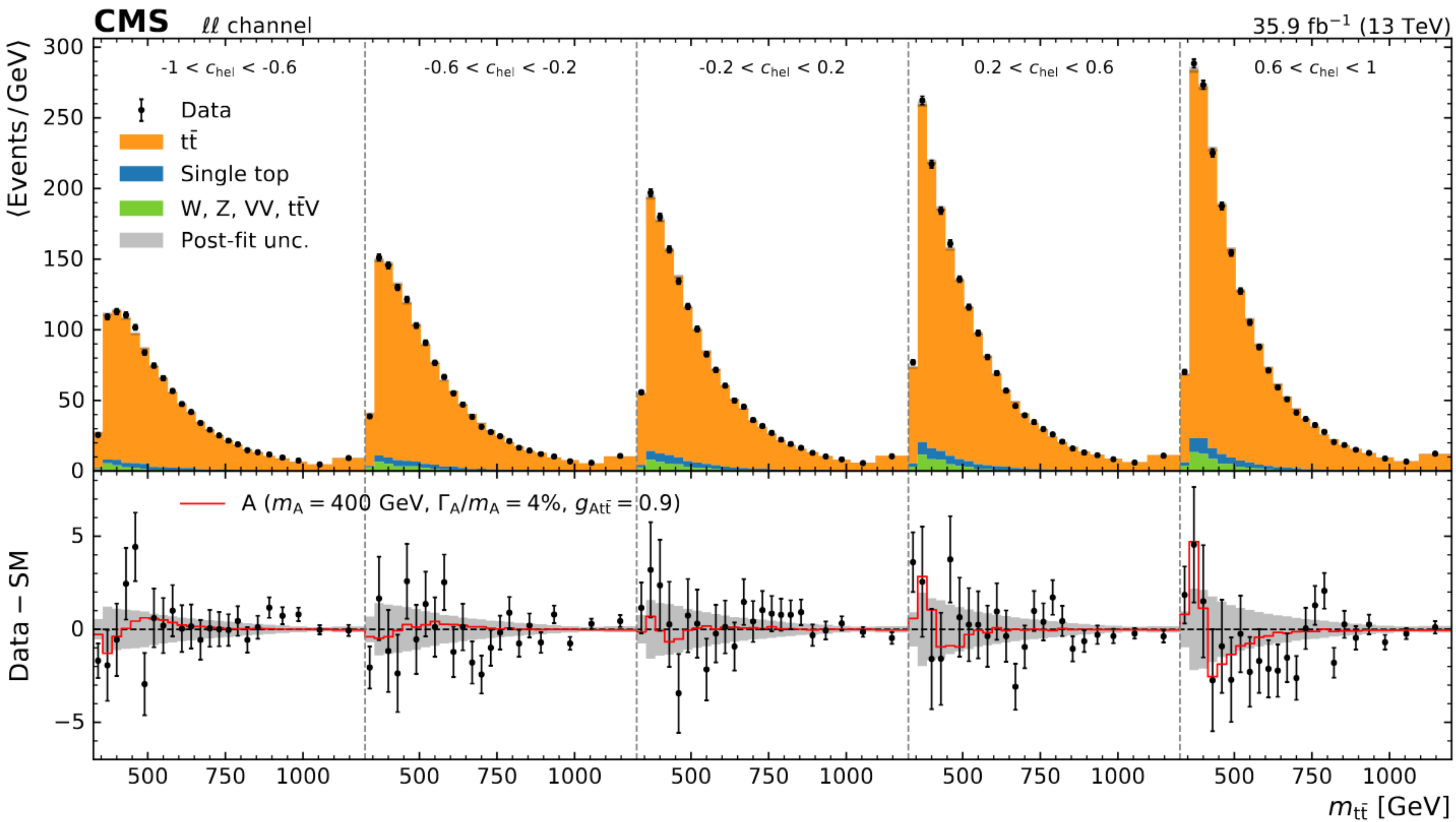
FO pQCD generator setup	$\sigma(\eta_t)$ [pb]
POWHEG v2 hvq + PYTHIA	8.7 ± 1.1
POWHEG v2 hvq + HERWIG	8.6 ± 1.1
POWHEG vRES bb4l + PYTHIA	6.6 ± 1.4
Nominal result	$8.8^{+1.2}_{-1.4}$





Excess confirmed for alternative background models !

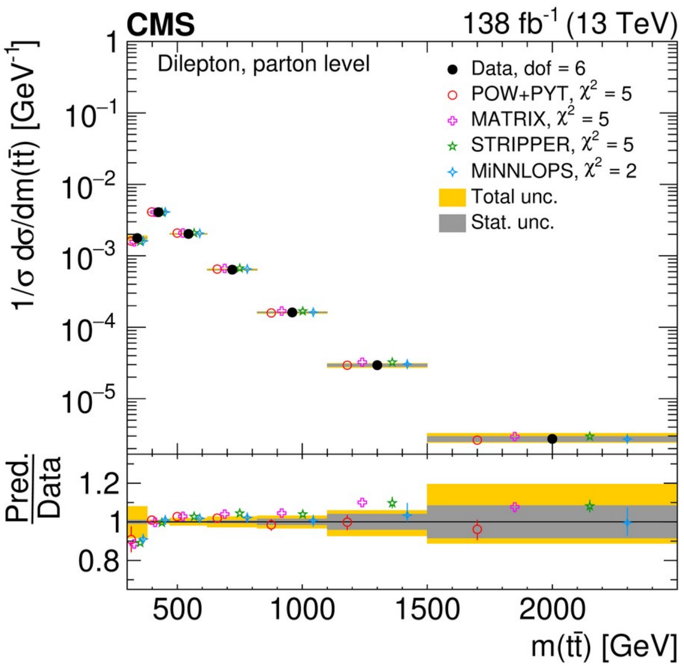
First Hints – JHEP 04 (2020) 171



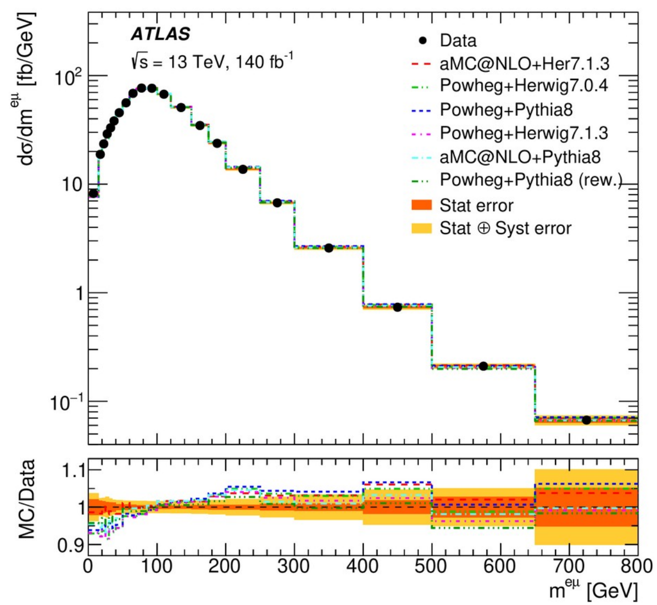
3.5 σ local excess – best match for a pseudoscalar of 400 GeV (lowest mass point tested)

Consistency with Other Results: Invariant $t\bar{t}$ Mass

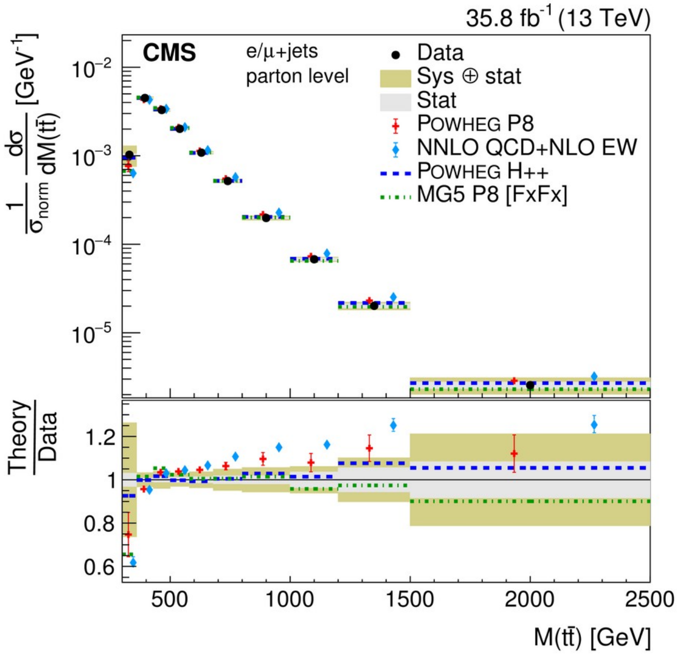
- tension in $m_{t\bar{t}}$ between data and pQCD at the threshold region in multiple measurements



CMS, arXiv:2402.08486



ATLAS, JHEP 07 (2023) 141

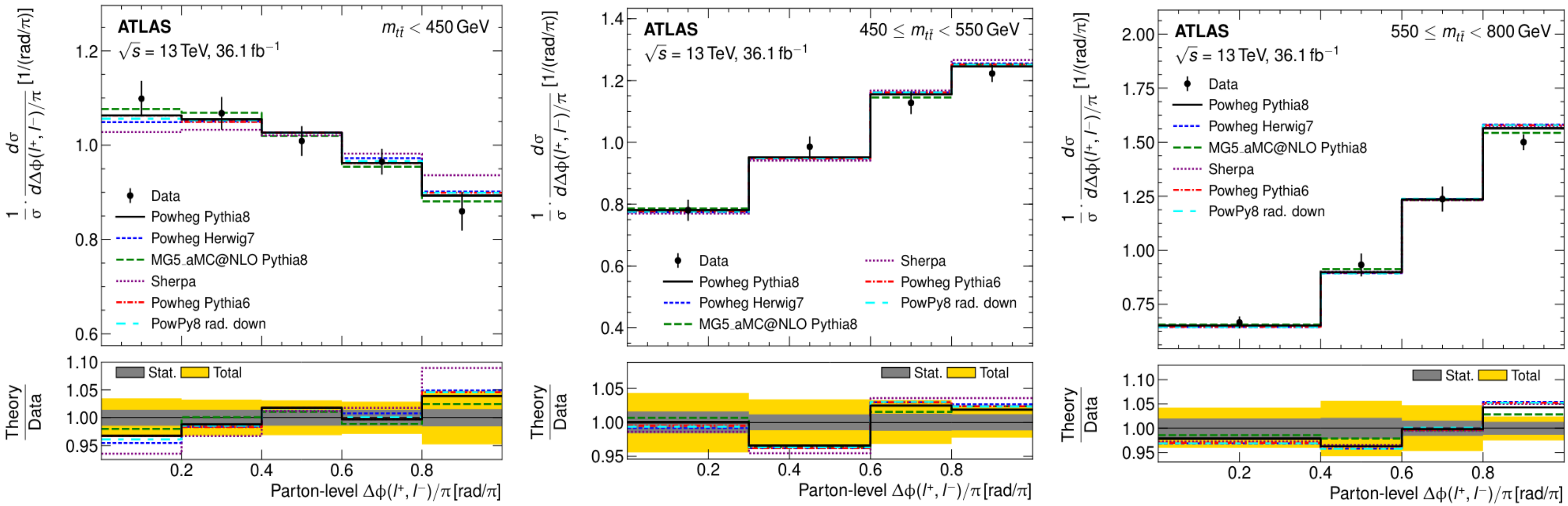


CMS, PRD 97 (2018) 112003

Consistency with Other Results: Azimuthal lepton angle

- largest deviation at threshold
  - significant differences between generators
  - slopes in higher $m_{t\bar{t}}$ bins

ATLAS, EPJC 80 (2020) 754



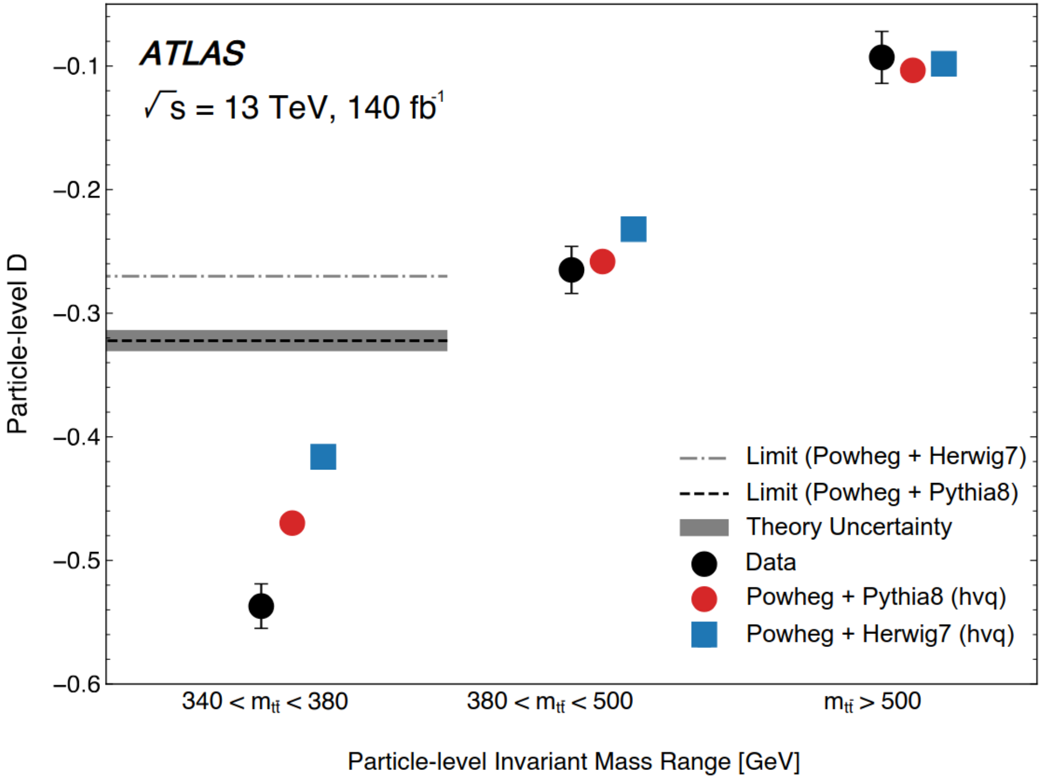
$m_{t\bar{t}}$ < 450 GeV

450 < $m_{t\bar{t}}$ < 550 GeV

550 < $m_{t\bar{t}}$ < 800 GeV

Difference between azimuthal lepton angles highly affected by modelling – Reduced sensitivity

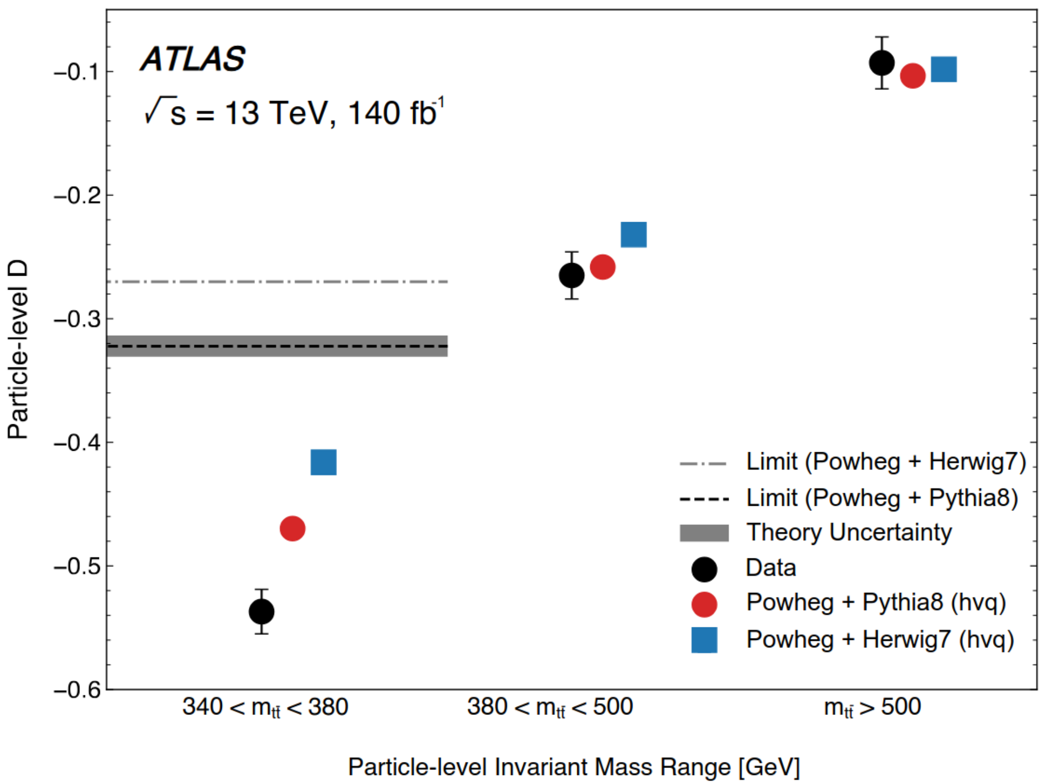
- recent entanglement measurements at threshold point to stronger slopes D
  → missing pseudoscalar contributions

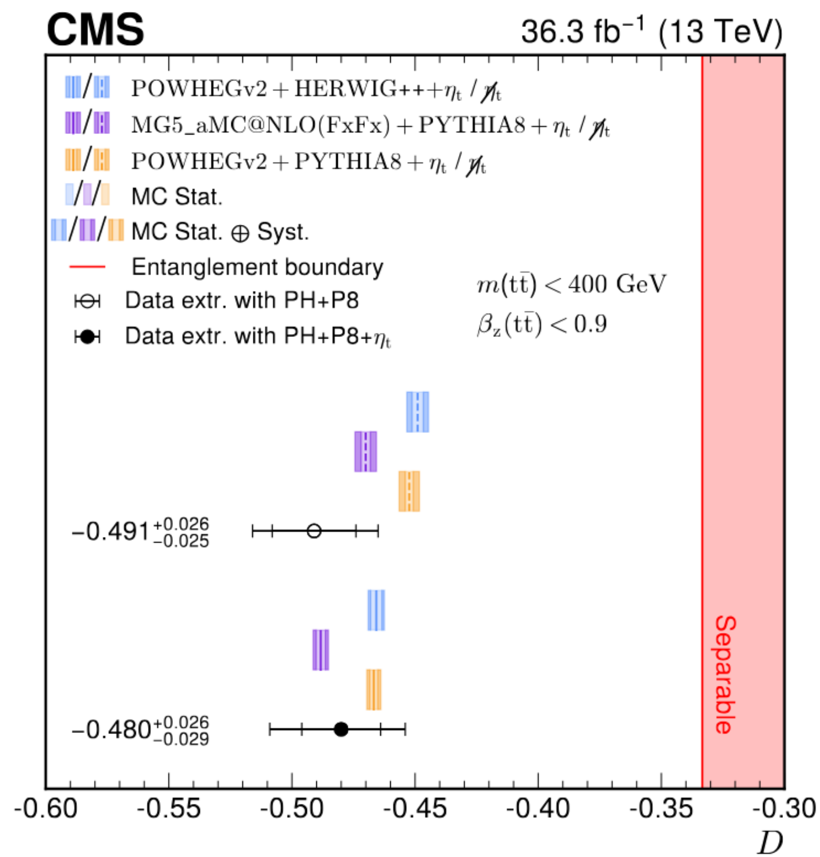


ATLAS, Nature 633 (2024) 542

Consistency with Other Results: Spin Correlation

- recent entanglement measurements at threshold point to stronger slopes D
  → missing pseudoscalar contributions





ATLAS, Nature 633 (2024) 542

CMS, RPP 87 (2024) 117801

Closing Remarks

Symmetry Magazine
CMS Briefing
CERN News

- significant excess in data at low $m_{t\bar{t}}$
  - fits well simplified model of $t\bar{t}$ bound state η_t

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

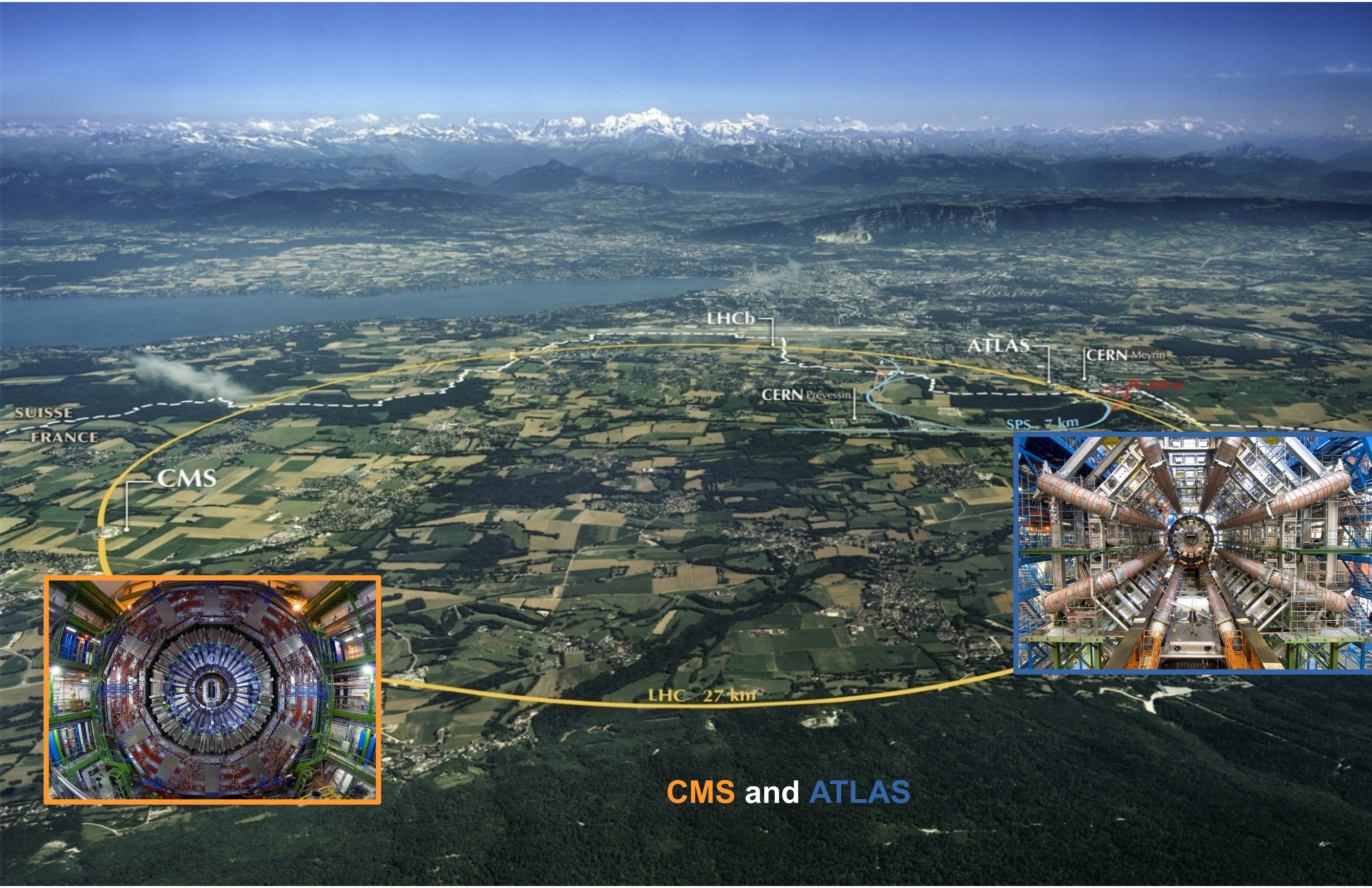
  - observed significance well above 5 standard deviations
  - excess cannot be explained by systematic uncertainties or alternative background models

- looking forward to
  - further improved background modeling crucial to increase knowledge on η_t
  - better theory input needed on the MC modeling of η_t

- next experimental steps
  - measurement in semileptonic channel
  - confirmation from ATLAS

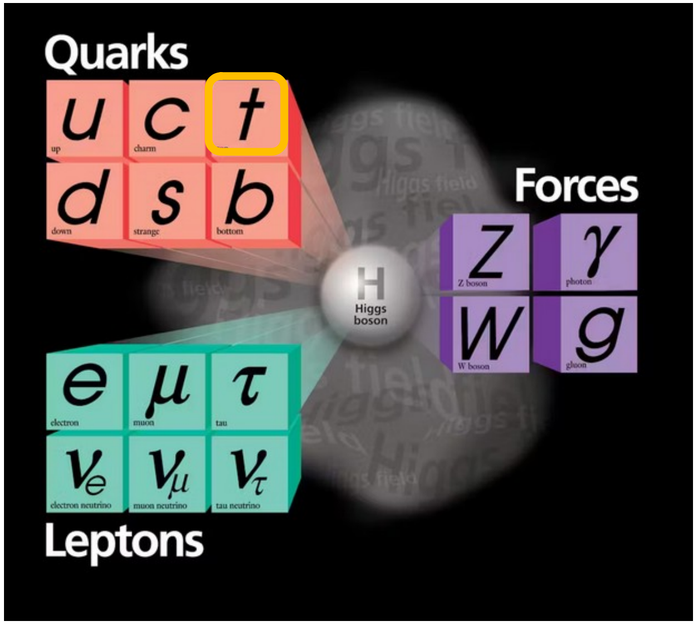
Exciting excess at $t\bar{t}$ threshold – Opening up a new chapter 30 years after the top discovery !

BACK-UP


LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
LHC 27 km
CMS and ATLAS

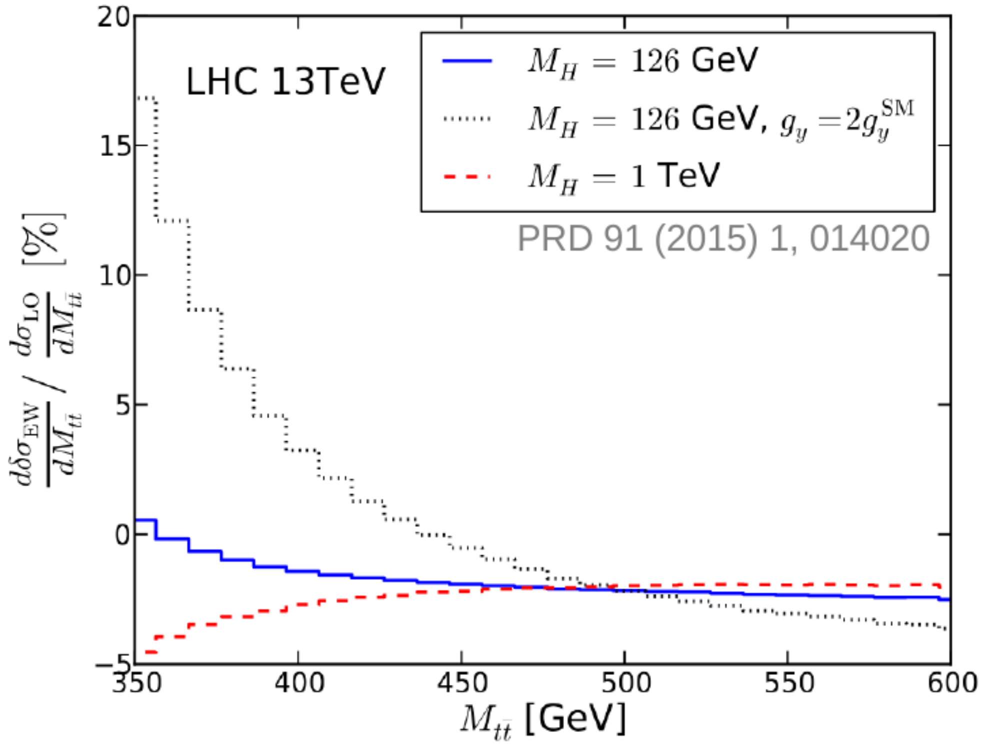
Top Quarks

- top quarks are special
- short lifetime of O(10^{-25}) s
  → top spin propagated to decay products
  → fingerprint of $t\bar{t}$ production mode
- heaviest elementary particle:
  172.52 ± 0.33 GeV (PRL 132 (2024) 261902)
- Yukawa-like top couplings close to 1
  → potential key to finding new (pseudo)-scalars



Background Modeling

NLO EW / LO (%)



Mllbb Result