Twists in Top:

Searching for (pseudo)scalar $t\bar{t}$ production

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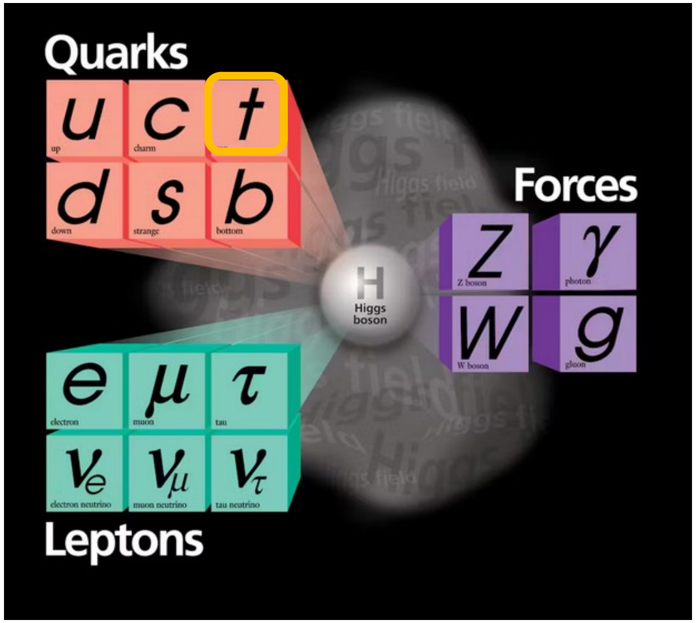
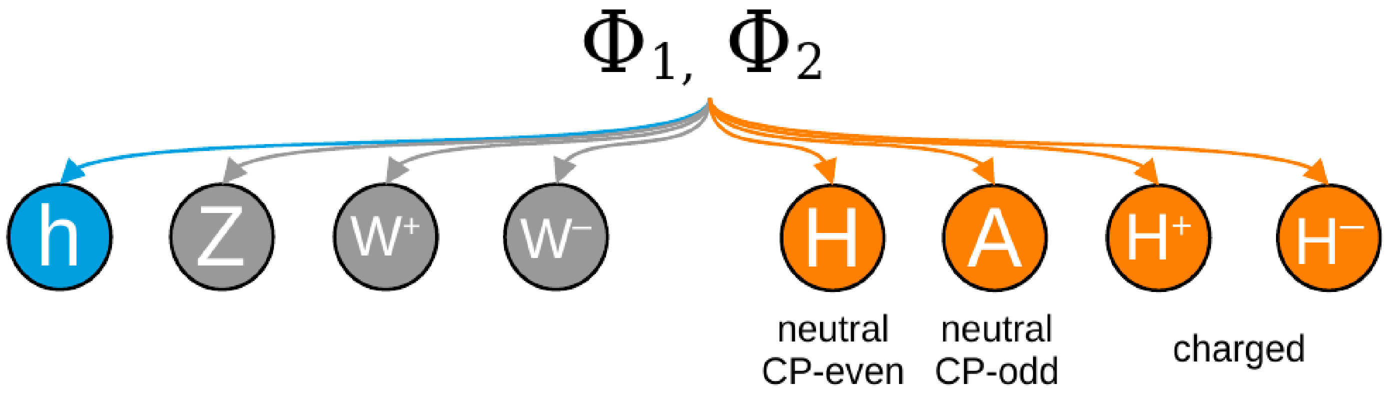
EXZELLENZCLUSTER
QUANTUM UNIVERSE

- top quarks are special
- short lifetime of $O(10^{-25})$ s
  $\rightarrow$ top spin propagated to decay products
- heaviest elementary particle:
  172.52 ± 0.33 GeV (PRL 132 (2024) 261902)



- top-Higgs coupling close to 1
  $\rightarrow$ top might be a key in finding (pseudo)-scalars beyond the SM

Two Higgs Doublet Model – Type II

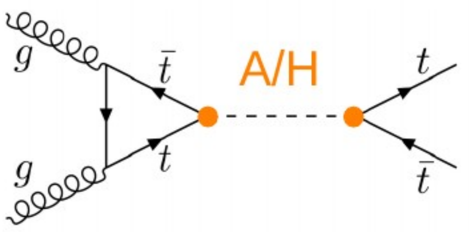


- extend SM by one complex SU(2) doublet
- four additional degrees of freedom: $H/A/H^+/H^-$
- up-type quarks couple to ϕ_1, down-type quarks and charged fermions to ϕ_2
- strong couplings to top quarks:

  if $m_{A/H} > 2m_t \rightarrow t\bar{t}$ final states promising for a discovery

A/H → $t\bar{t}$ Signal at the LHC

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



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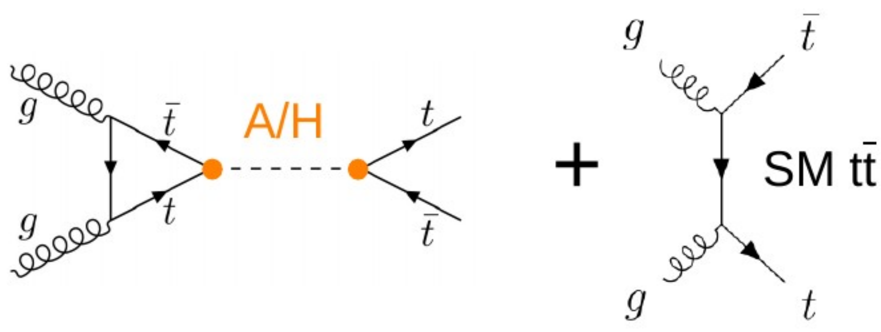

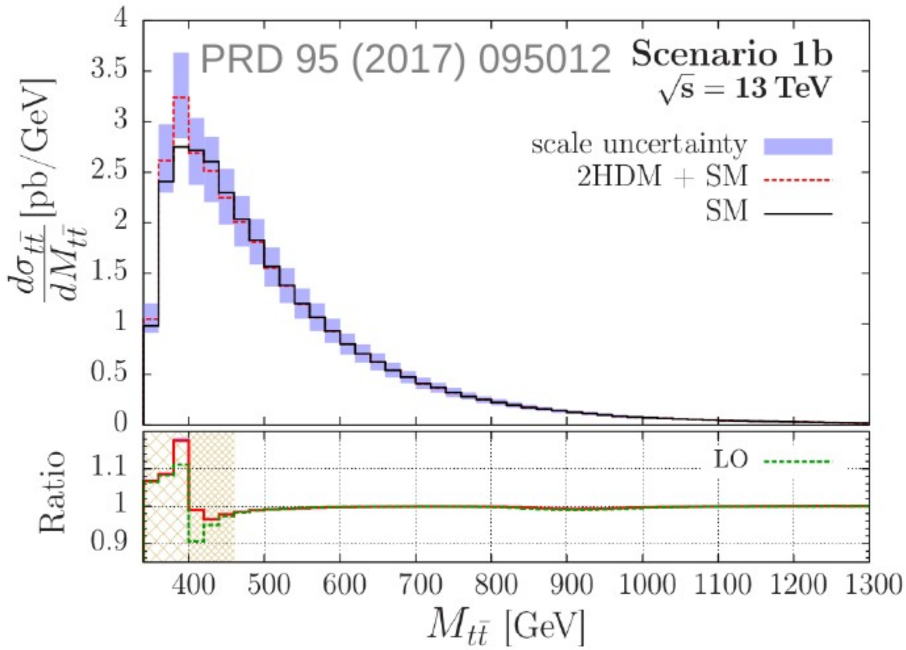

- same final state as SM $t\bar{t}$ → interference
  → peak-dip structure in $m_{t\bar{t}}$

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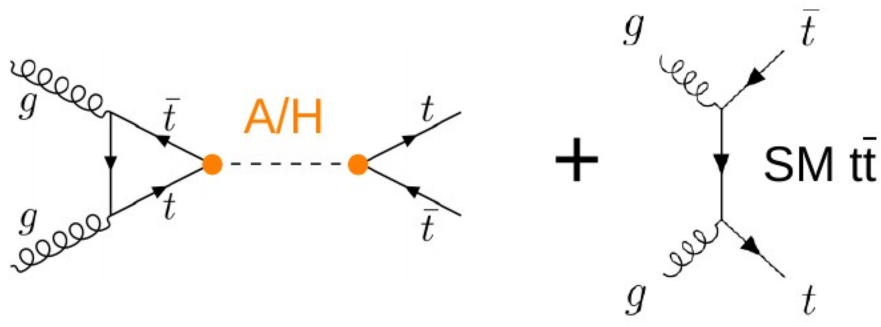
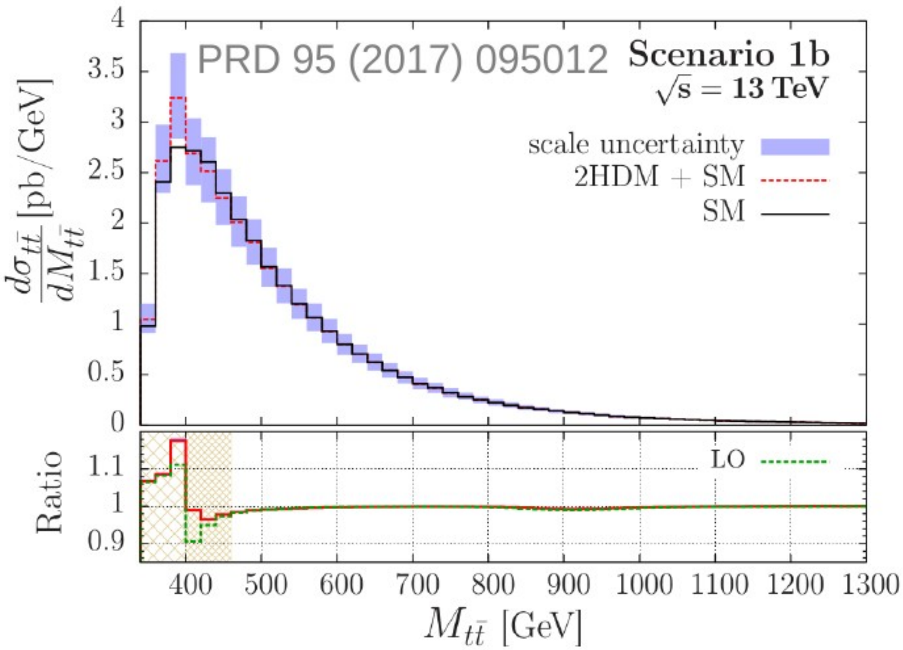




- same final state as SM $t\bar{t}$ → interference
  → peak-dip structure in $m_{t\bar{t}}$

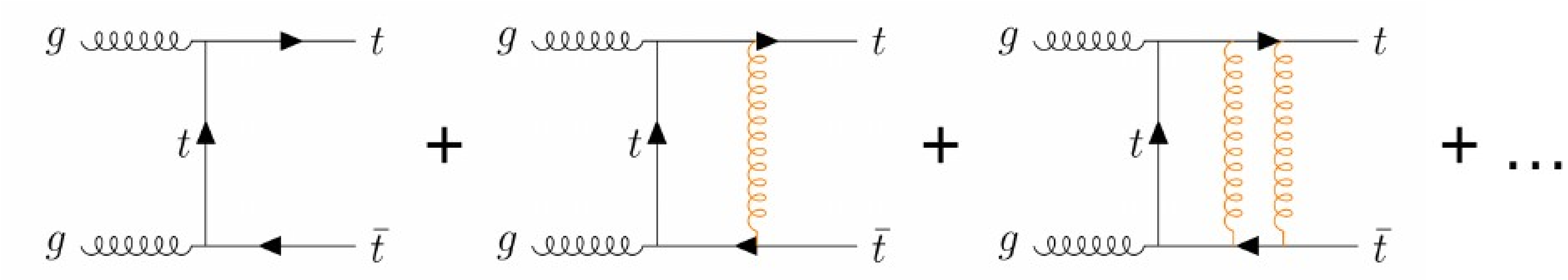
- MC realization:
  - generic A/H UFO at LO in QCD
  - free parameters: masses, widths, coupling modifiers g_A/g_H

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

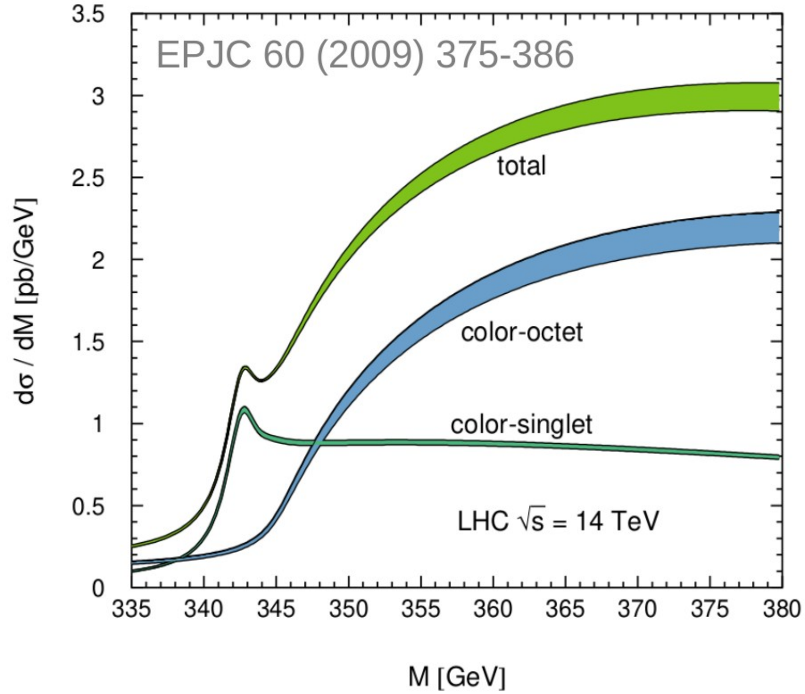
$$\mathcal{L}_H^{\mathrm{int}} = -g_{\mathrm{Ht\bar{t}}} \frac{m_t}{v} \bar{t}tH$$

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

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



- use non-relativitic QCD
- color-singlet (attractive)
  → peak below the $t\bar{t}$ threshold
- color-octet (repulsive)
  → expected to be small below threshold



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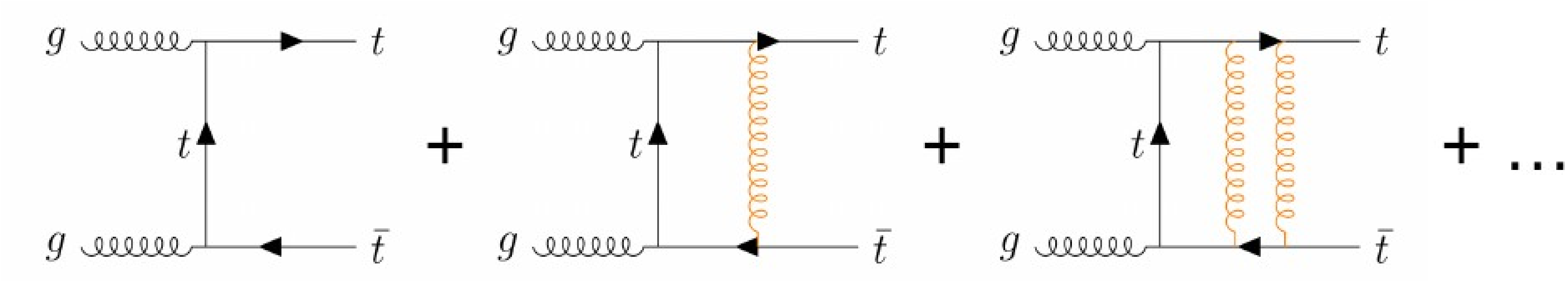

- use non-relativitic QCD
- color-singlet (attractive)
  → peak below the $t\bar{t}$ threshold
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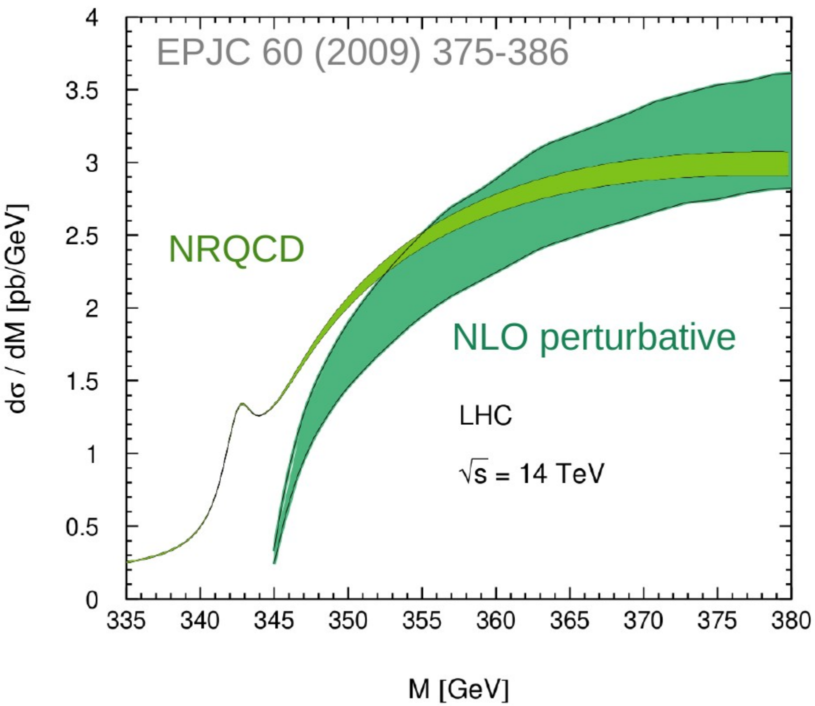
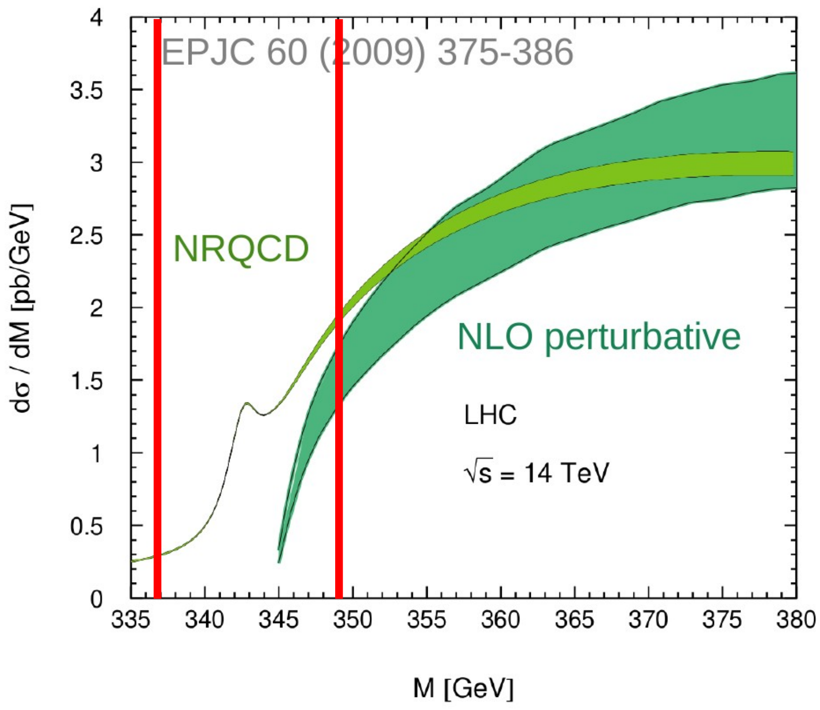
- difficulties: matching to NLO pQCD



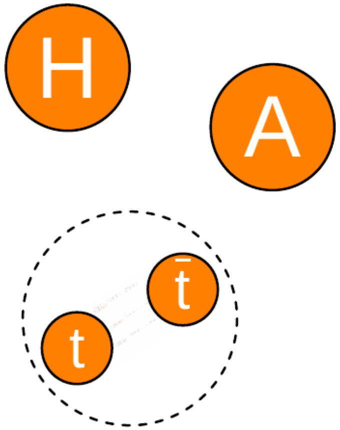
- simplified η_t model for MC simulation (Fuks et al., PRD 104 (2021) 034023)
  - generic spin-0, color-singlet state η_t
  - couplings to gluons and tops (pseudoscalar)
  - mass from fit to NRQCD: $m_{\eta t}$ = 343 GeV

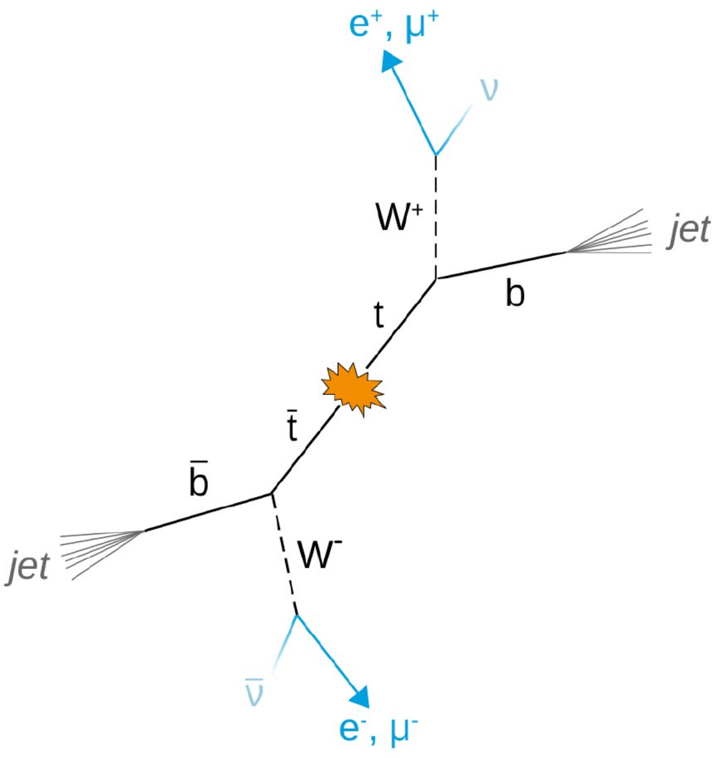
- pick large η_t width but restrict mass window to 337 – 349 GeV for p p > η_t > W b W b

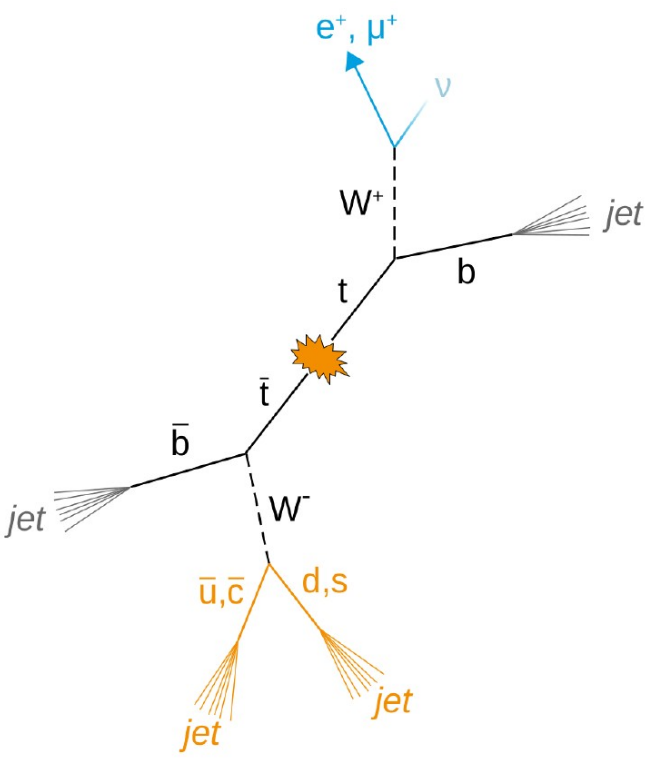


- to remember:
  - details of lineshape well below experimental resolution (15% - 25%)
  - very similar signature as low-mass A resonance

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







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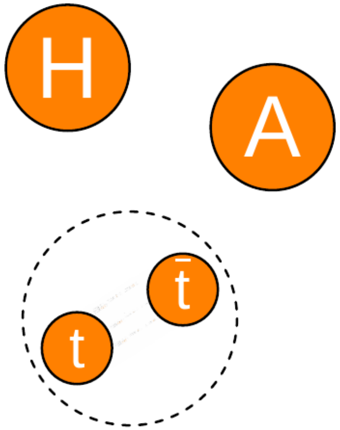

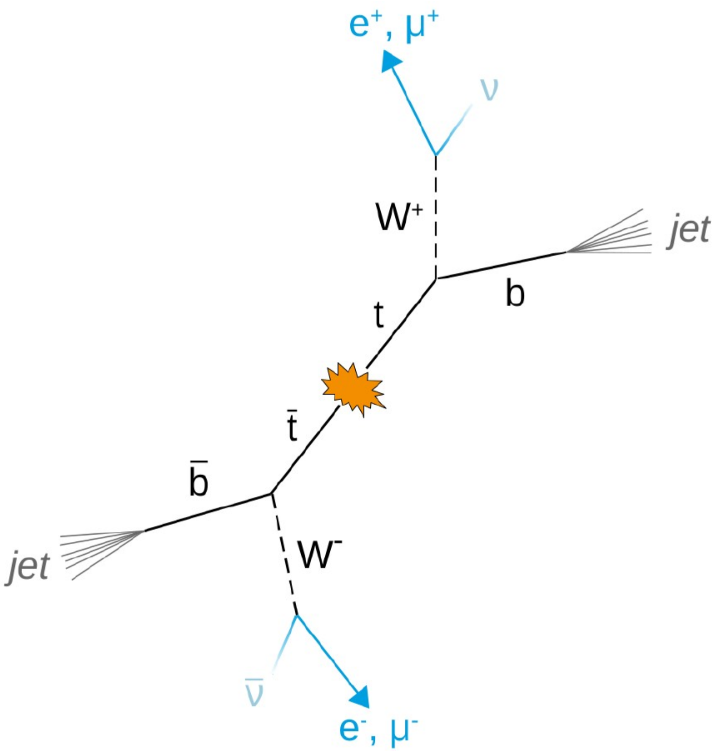

- key to $t\bar{t}$ mass

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

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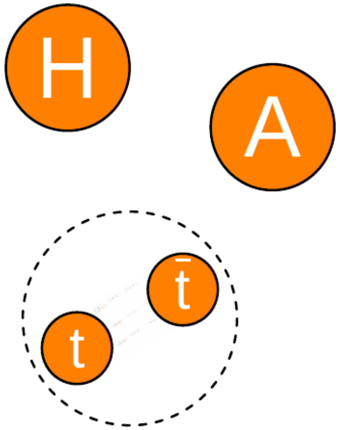

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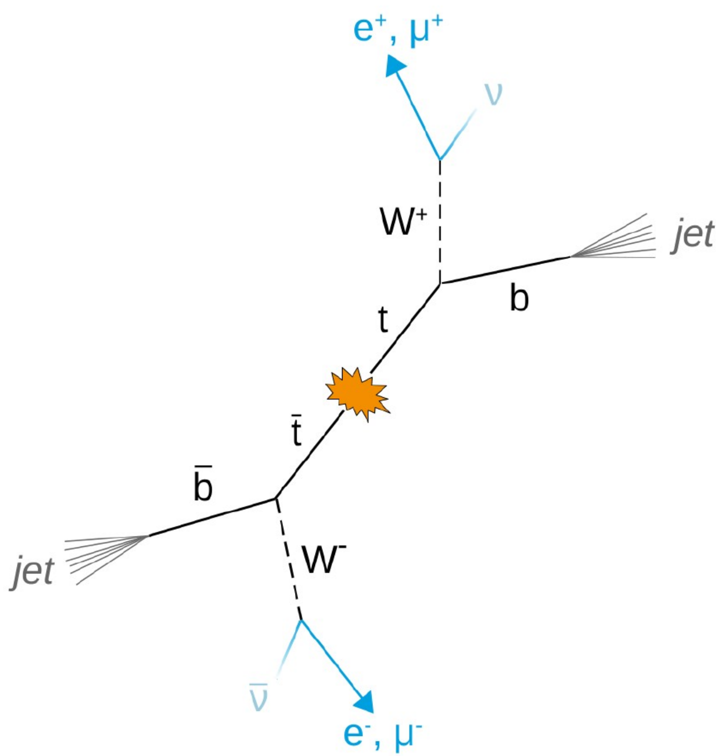

- key to $t\bar{t}$ mass and spin correlation

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

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

spin-independent | **top polarization** | **spin correlation**

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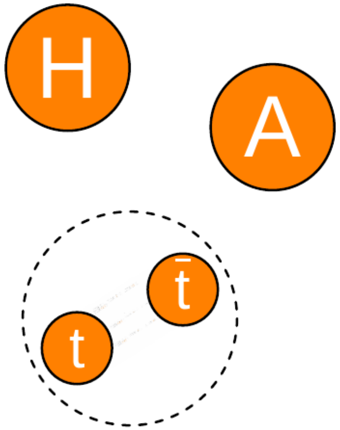

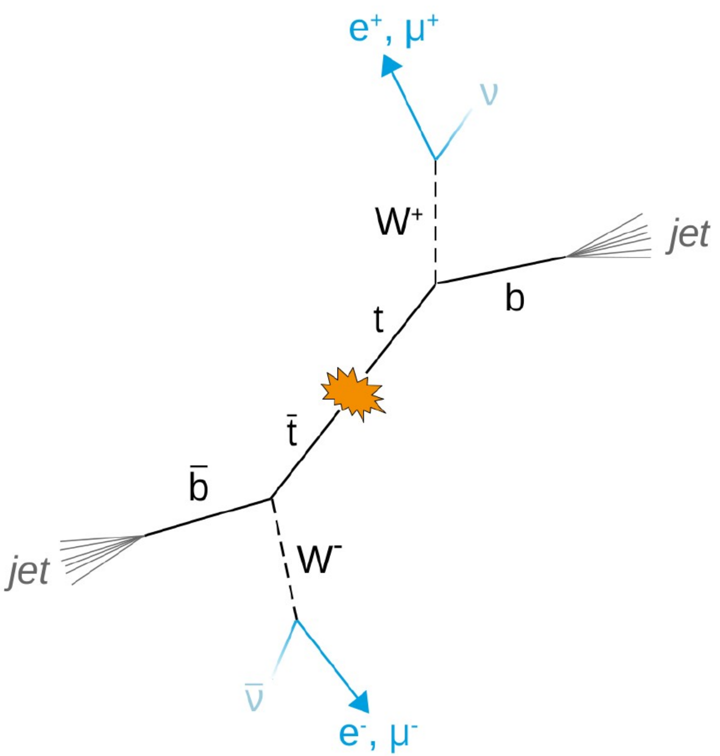

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spin-independent — top polarization — spin correlation

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

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

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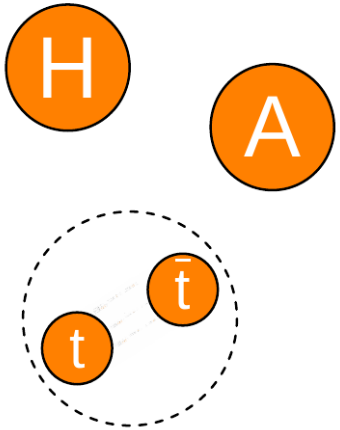

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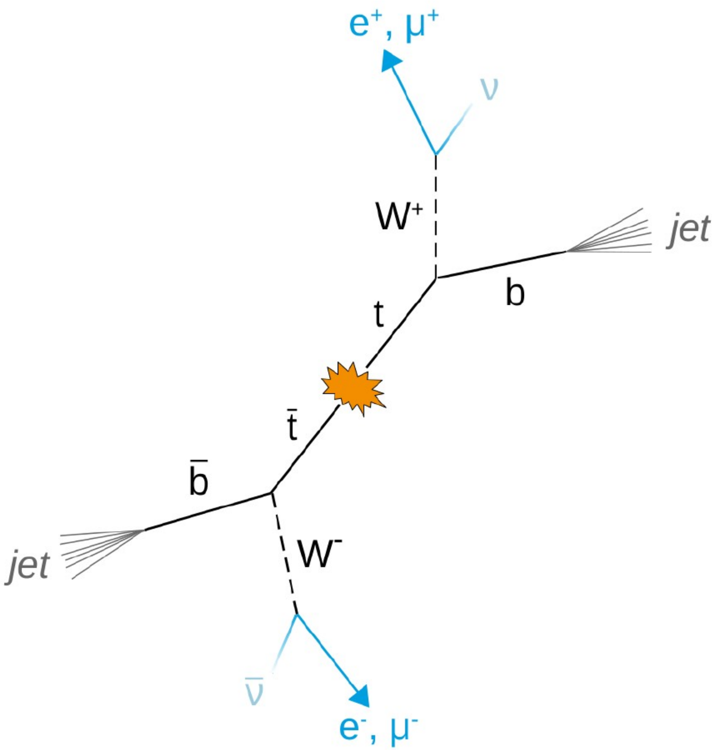
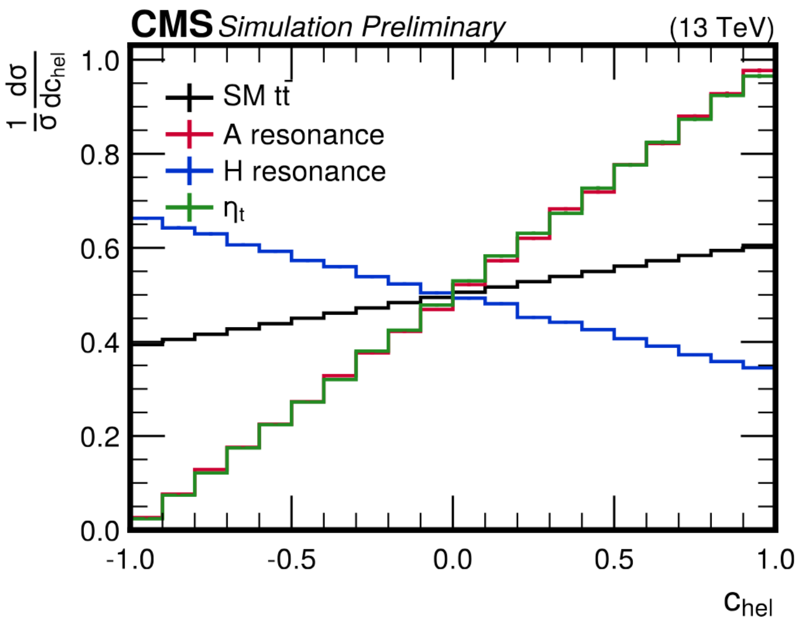


- key to $t\bar{t}$ mass and spin correlation
- c_{hel}: scalar product of leptons in parent top rest frame



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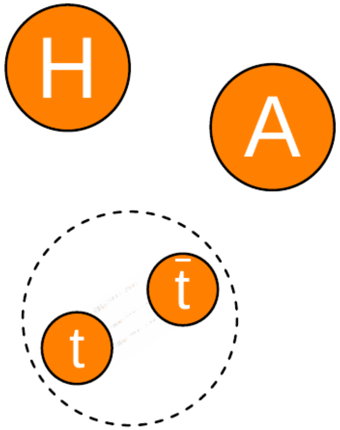

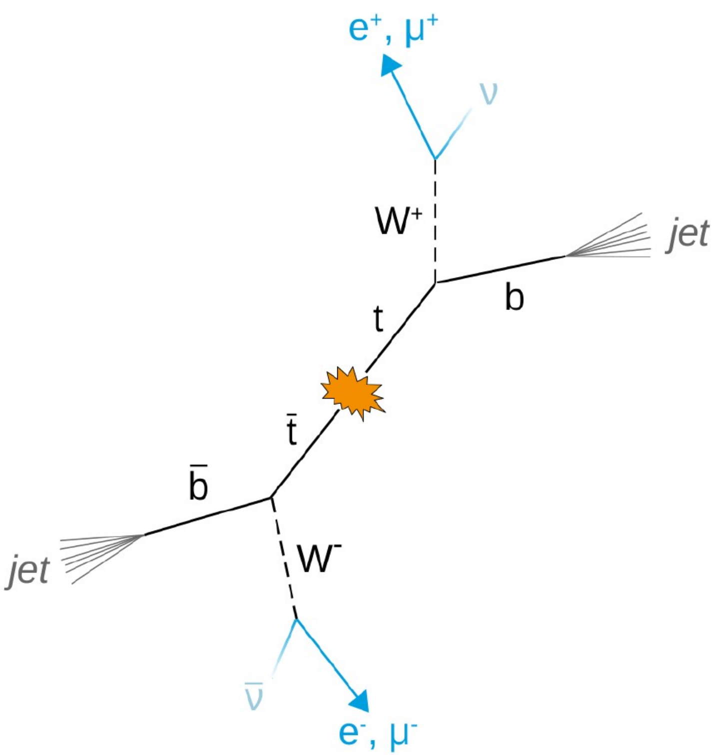

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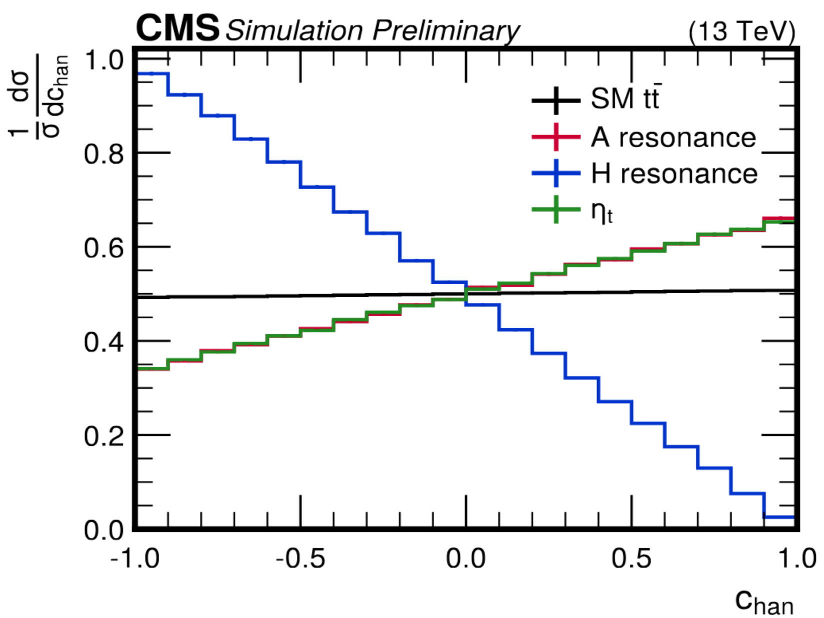
- c_{han}:scalar product of leptons with sign flip in top direction



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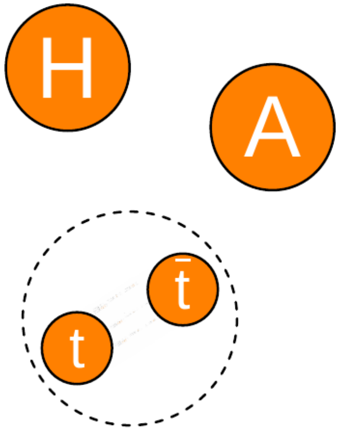

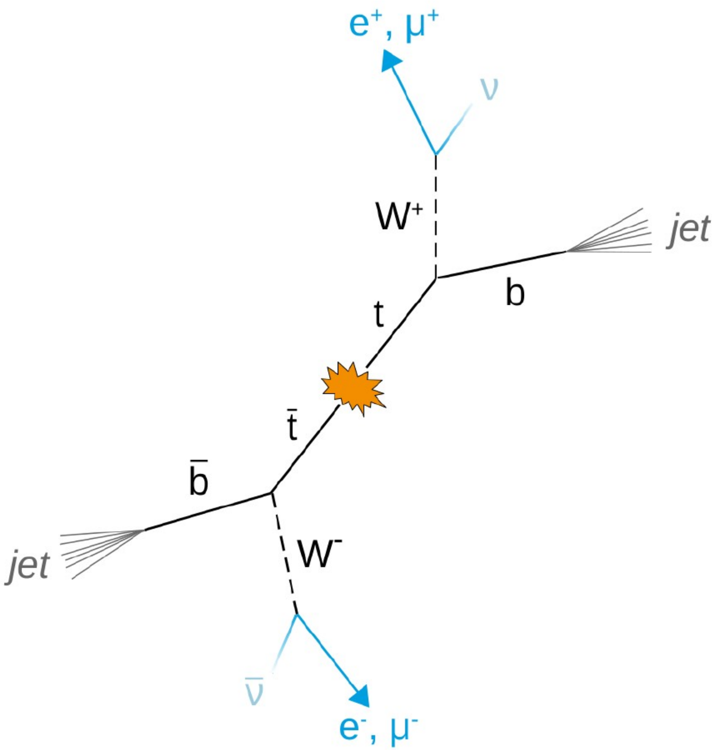

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3 search variables in ll: $m_{t\bar{t}}$ x c_{hel} x c_{han}

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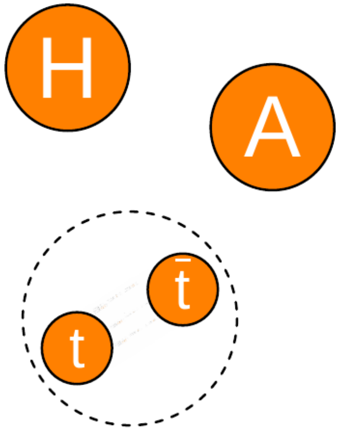
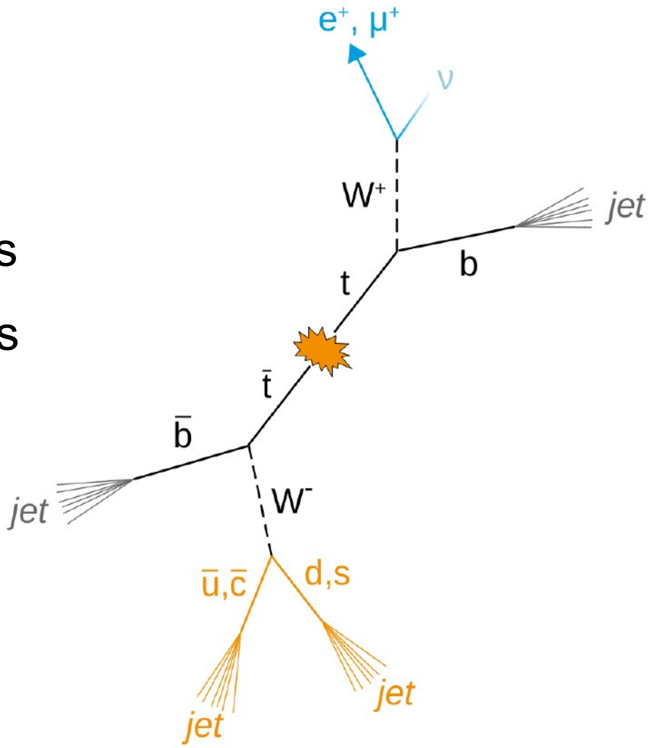


- explore full Run II data set at 13 TeV with 138 fb^{-1} recorded between 2016 and 2018
- two analysis channels: dilepton (ll) and lepton+jets (ljets)

- reconstruct $t\bar{t}$ system with geometric approach (NIM A 736 (2014) 169)
- maximize sensitivity by using events with just 3 jets
  - energy correction factor for lost or merged jets (NIM A 788 (2015) 128)



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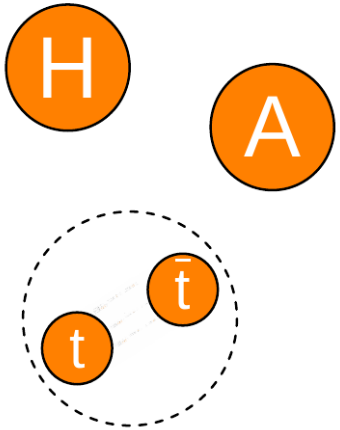
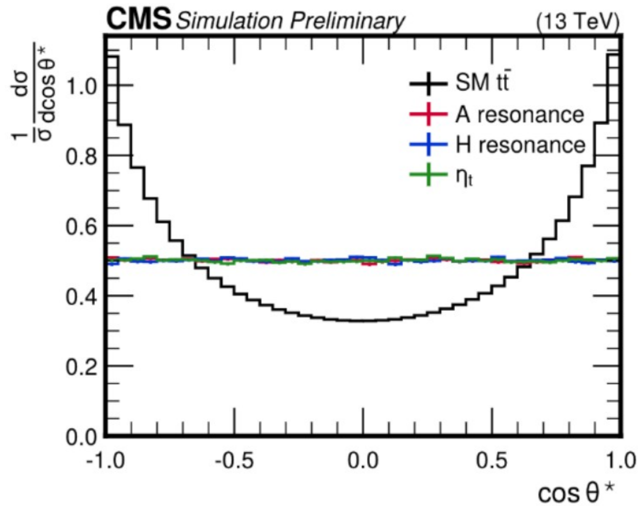
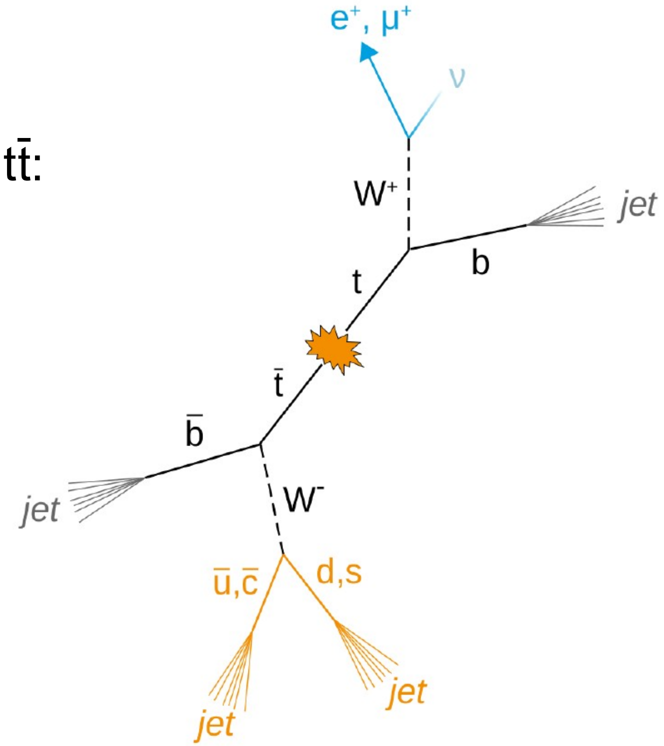


- reconstruct $t\bar{t}$ system with geometric approach
- use emission angle of leptonic top with respect to $t\bar{t}$:
  - flat for A/H/η_t



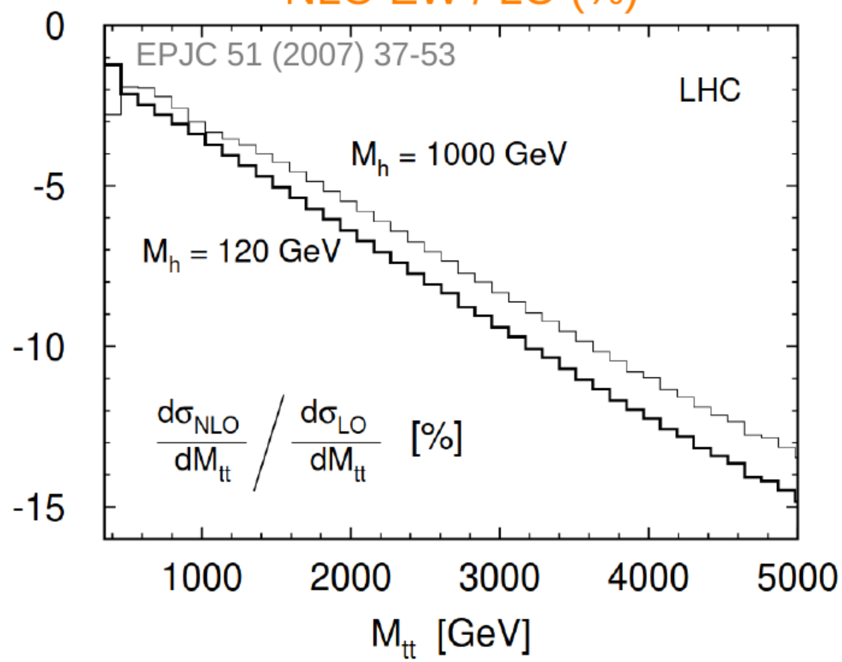


2 search variables in ljets: $m_{t\bar{t}}$ x cos θ*

Background Modeling

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

NLO EW / LO (%)



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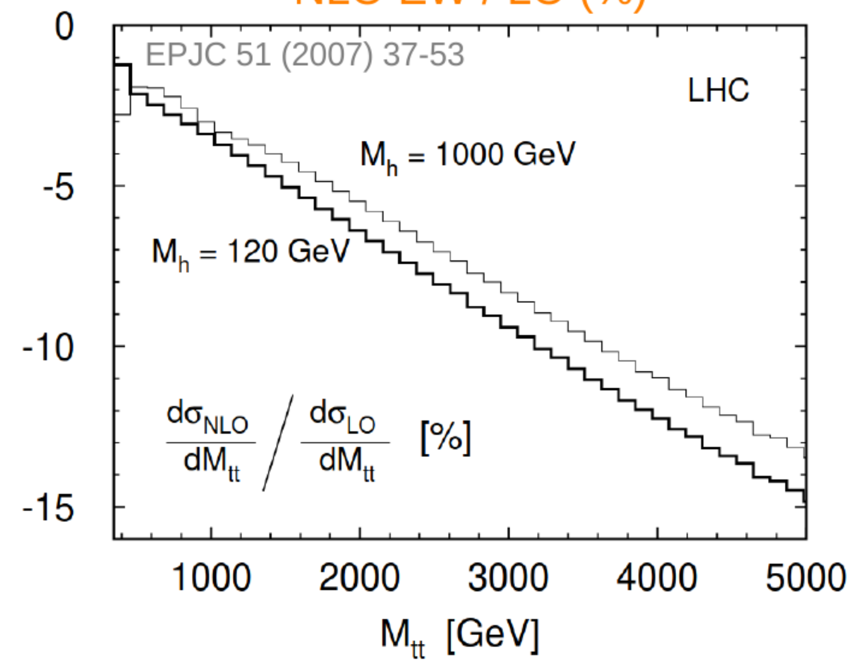
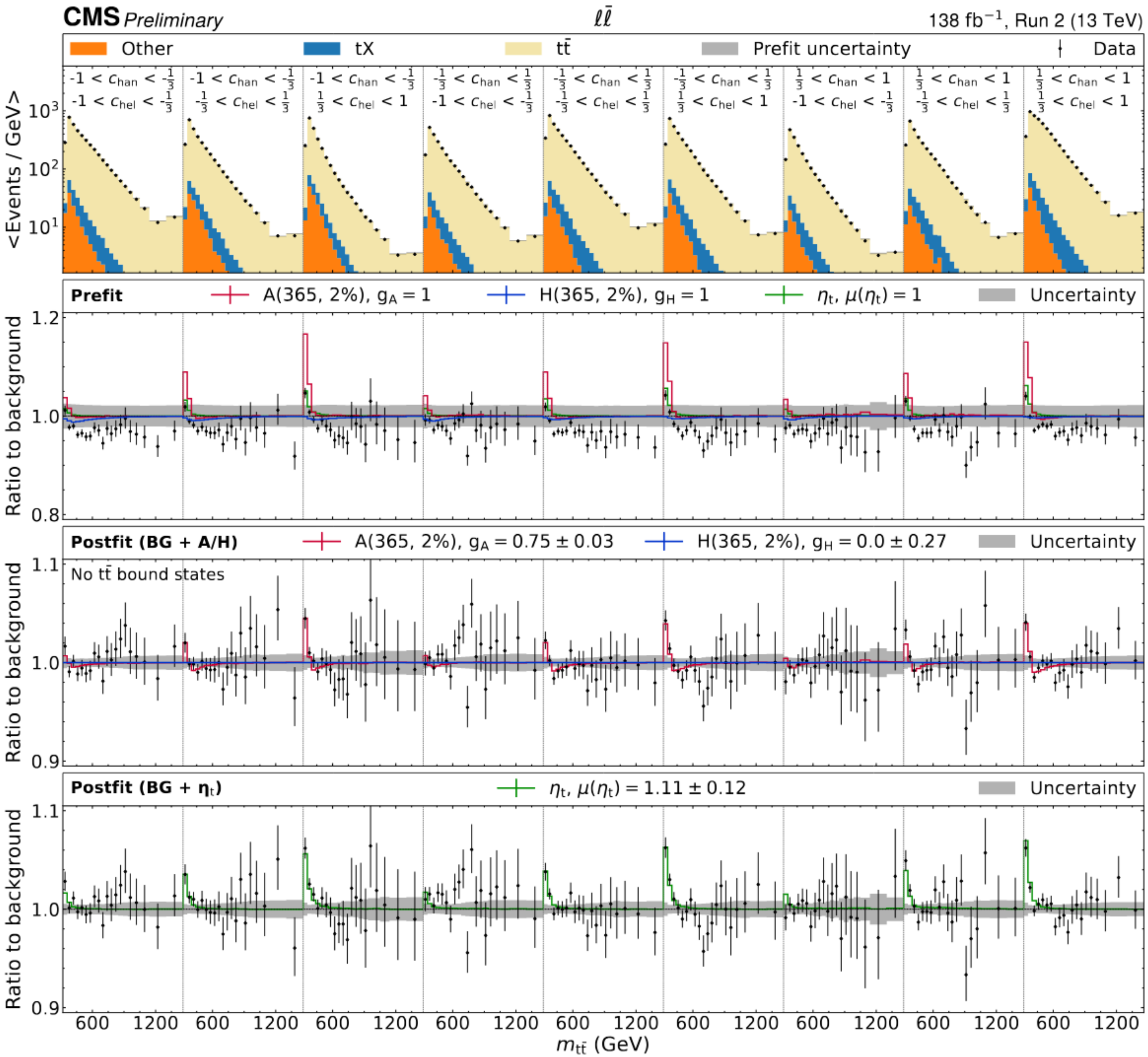


- other backgrounds: tW, t-channel single-top, rare processes (from MC)
- Z+jets in ll: MiNNLO predictions with data-driven normalization around Z peak
- QCD processes in ljets: data-driven shape from sideband with no b-tags

Results ll Channel



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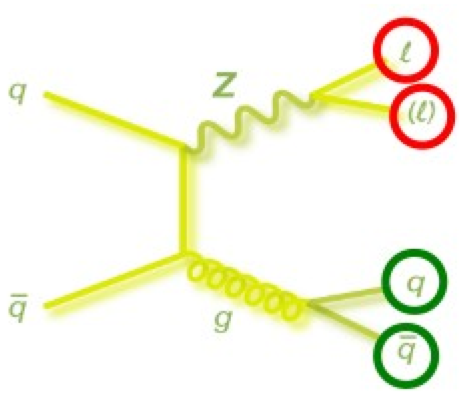

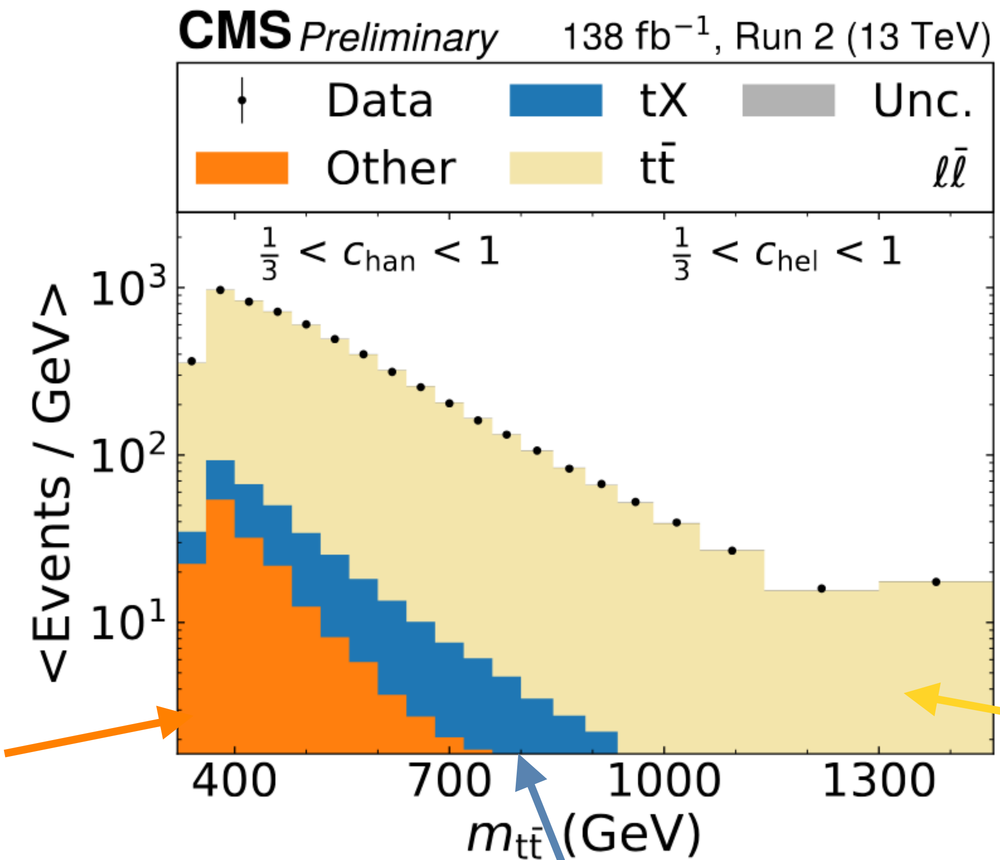

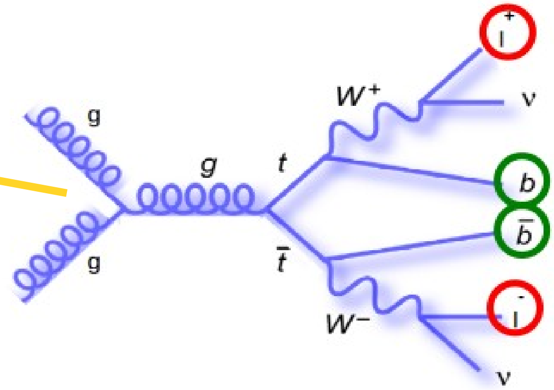

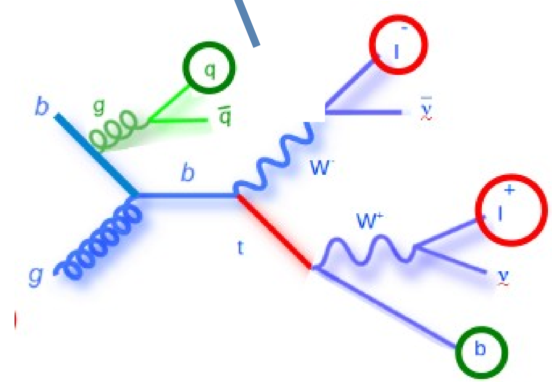

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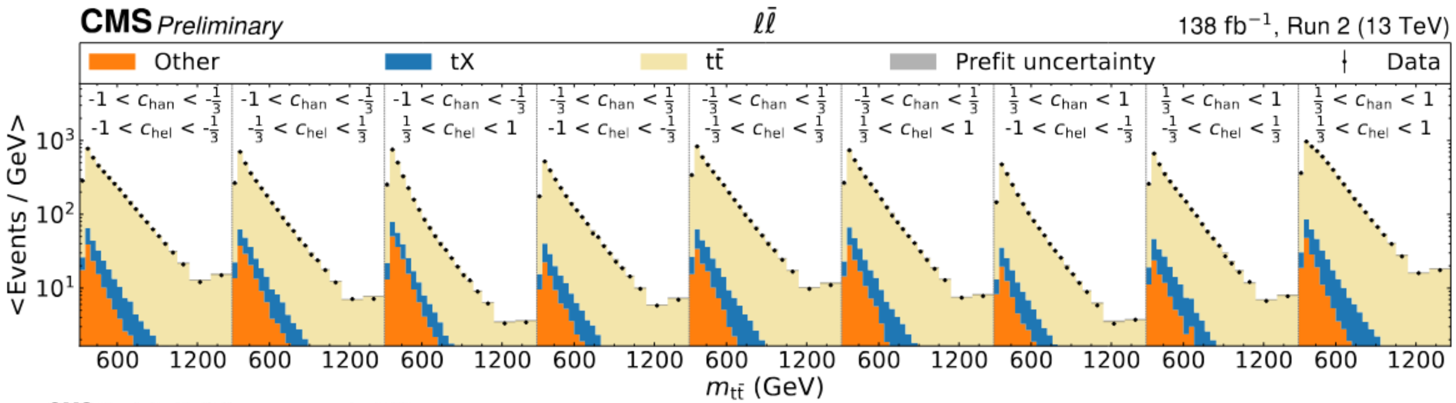

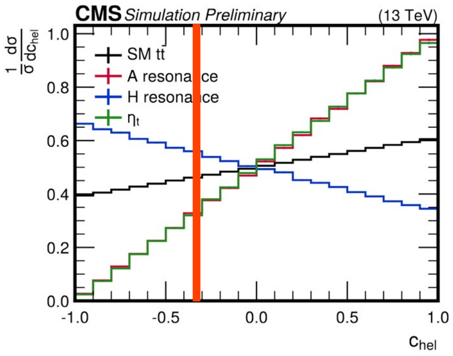

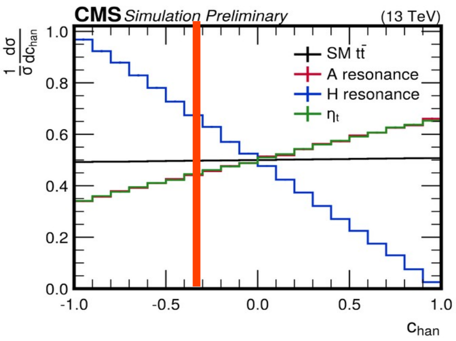

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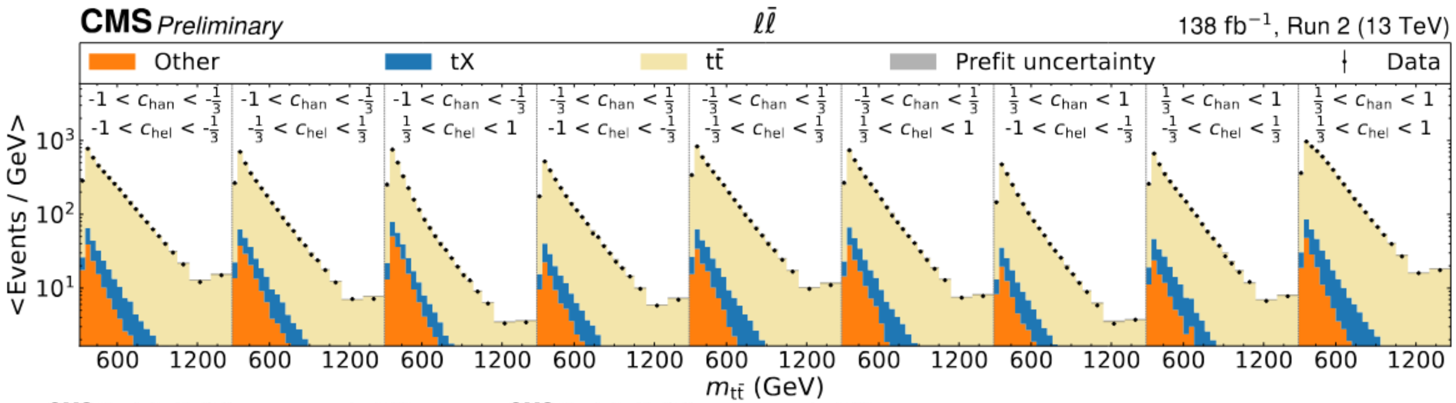

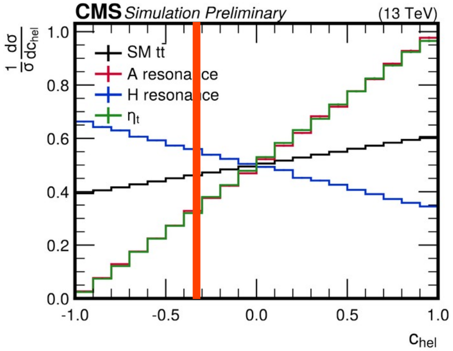

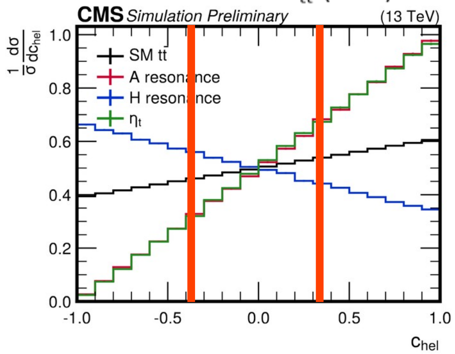

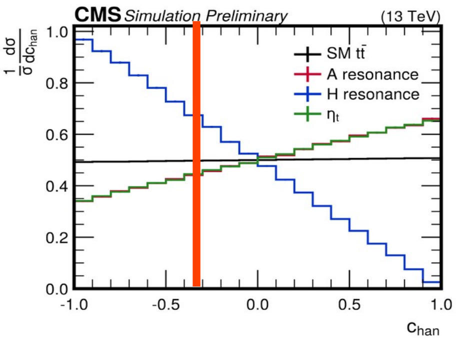

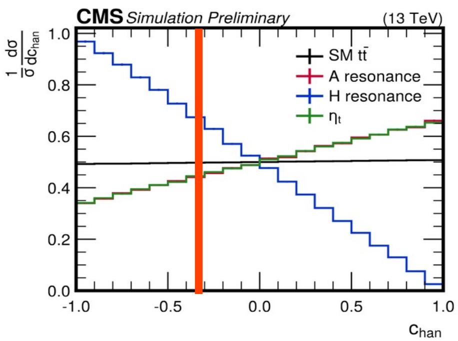

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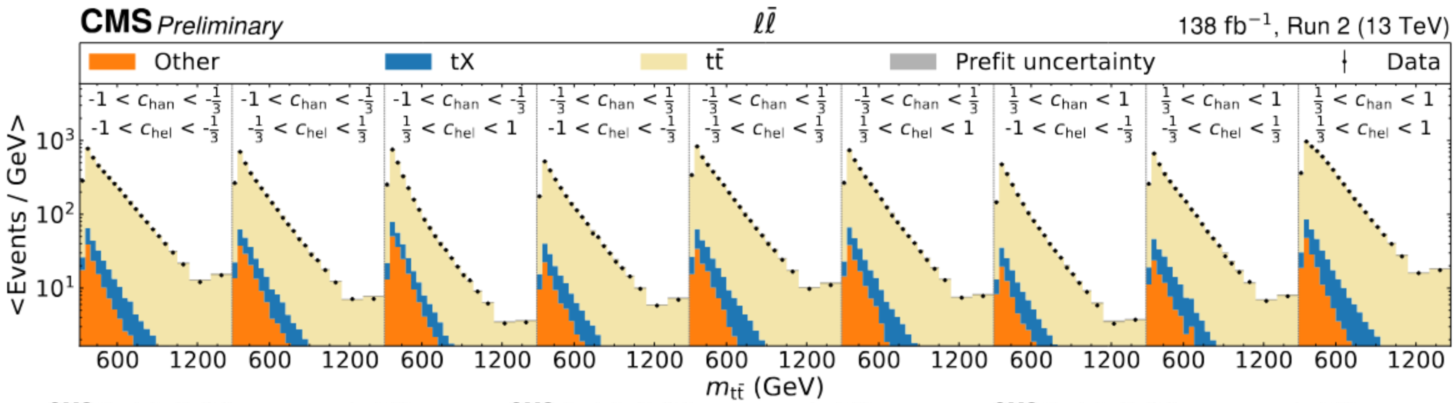

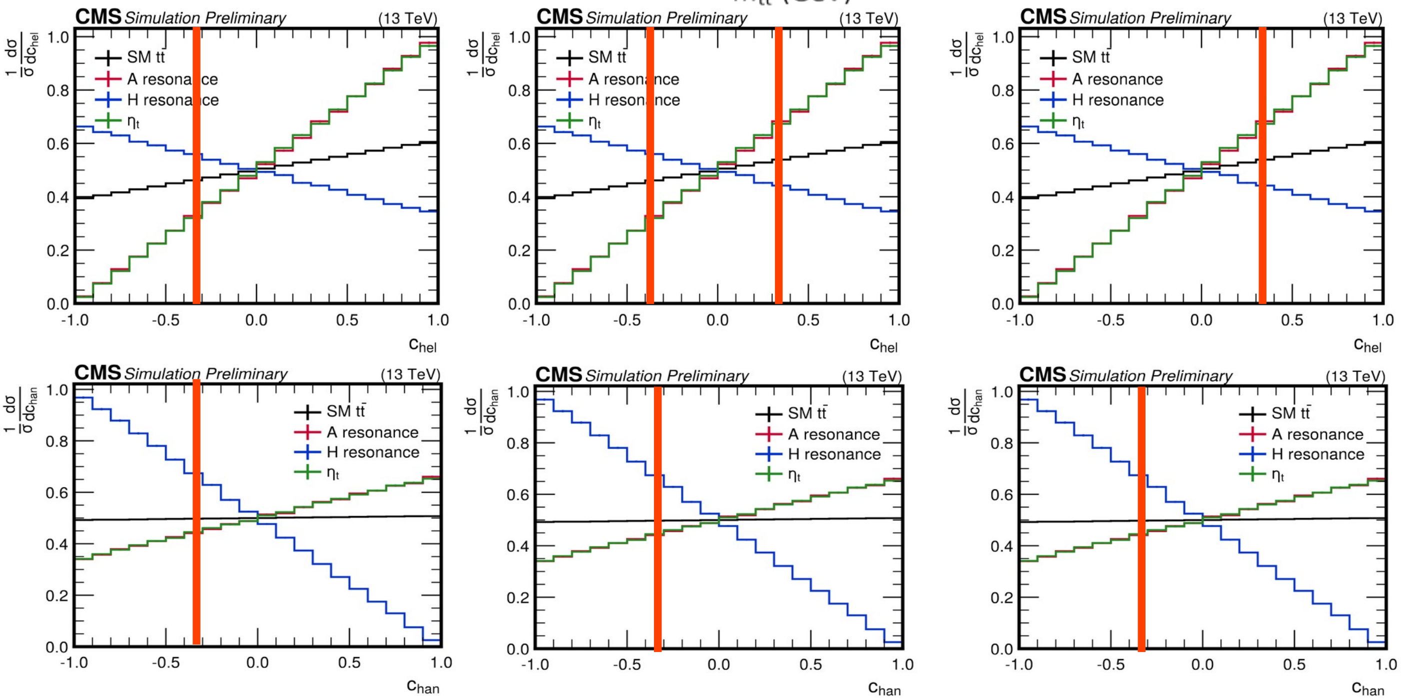

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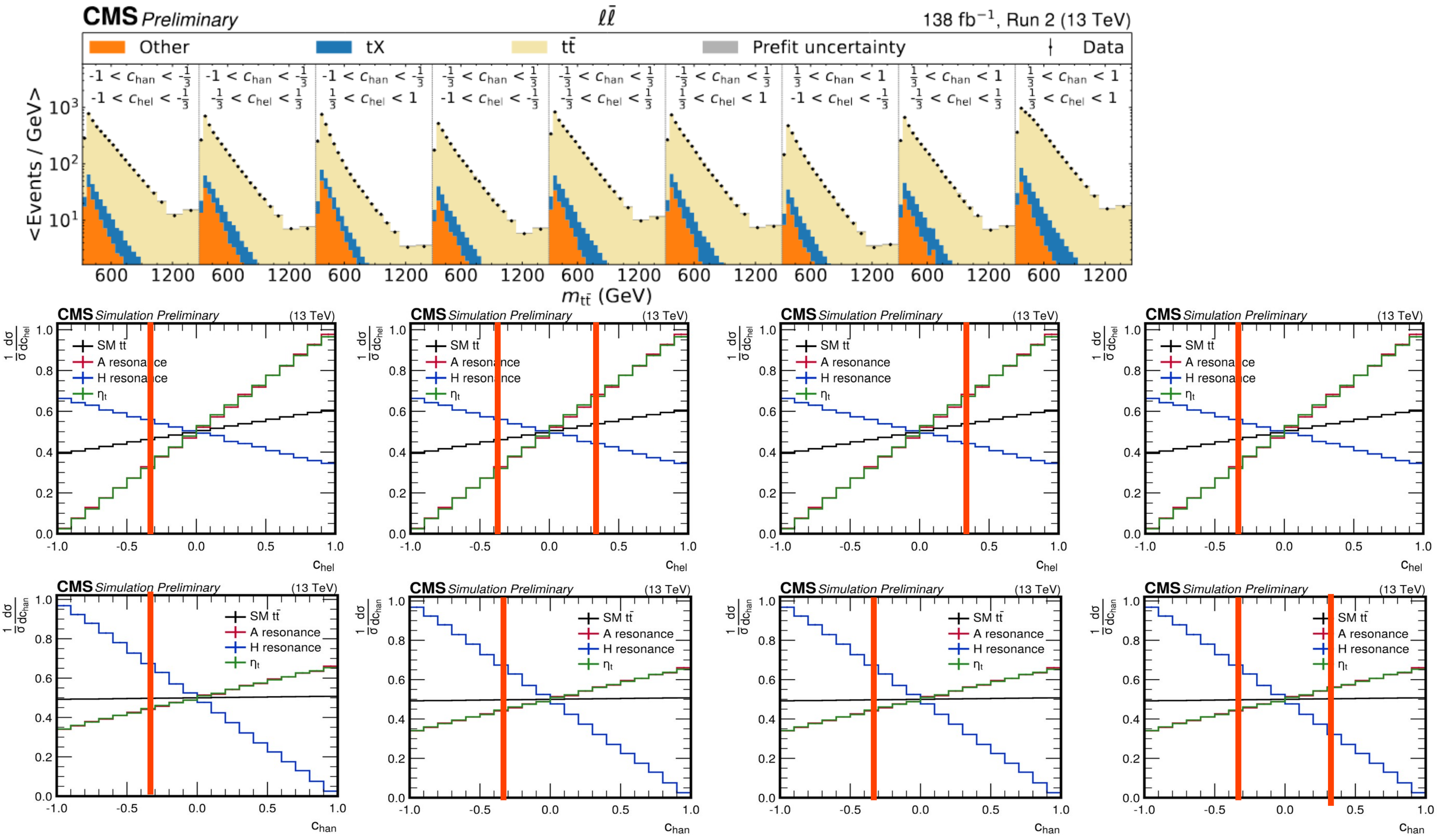

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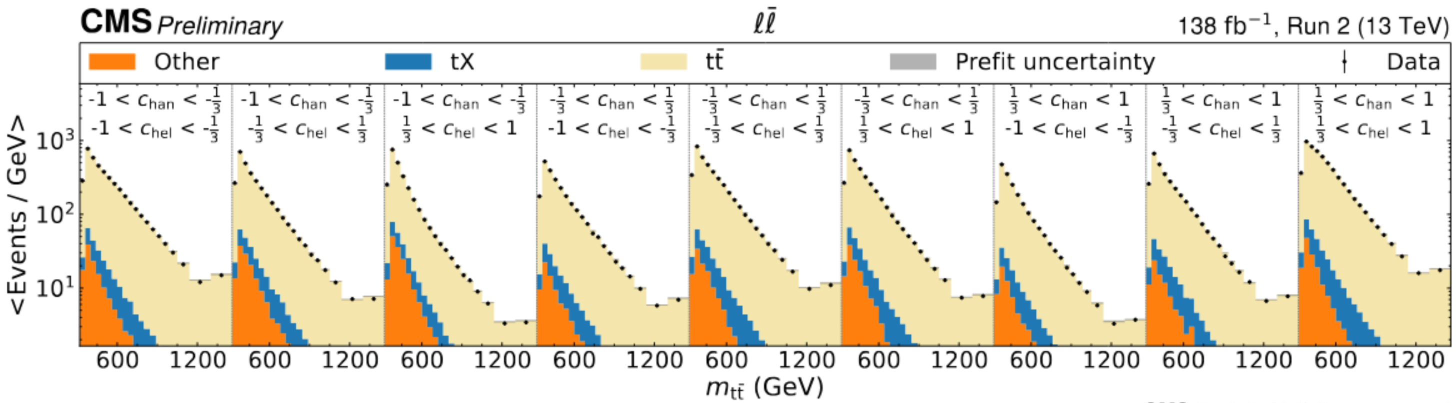
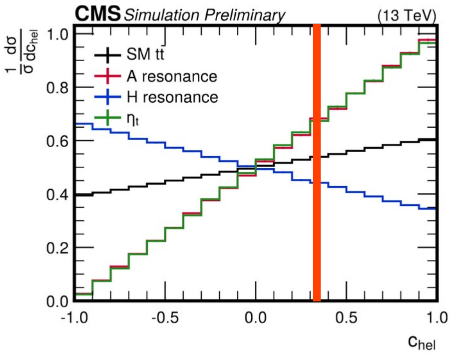
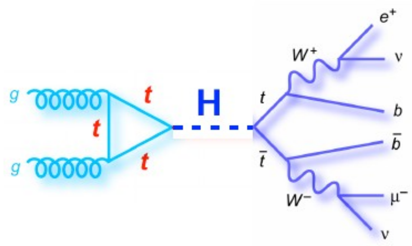
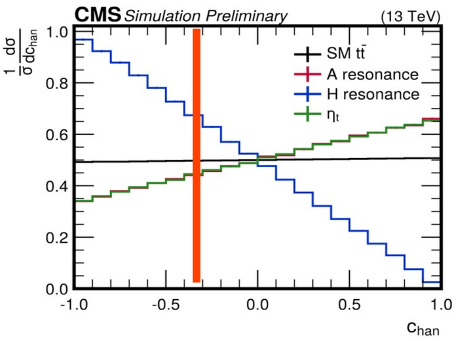
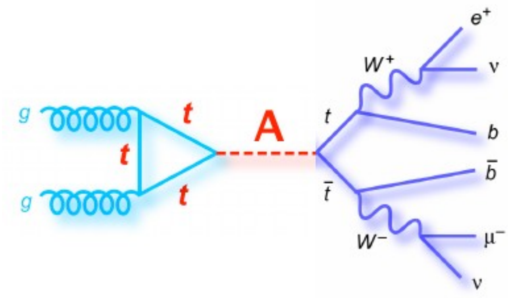


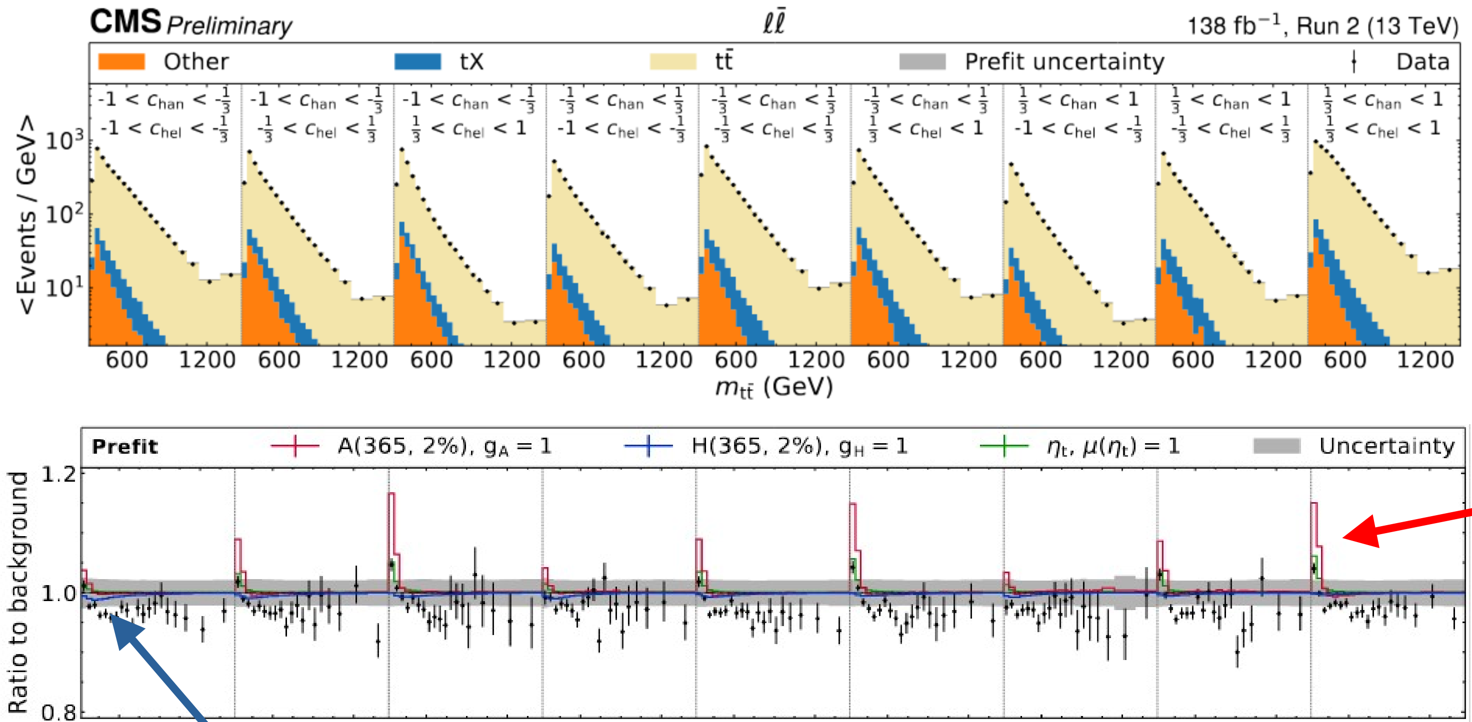


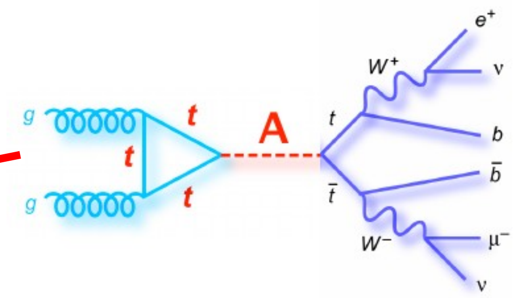


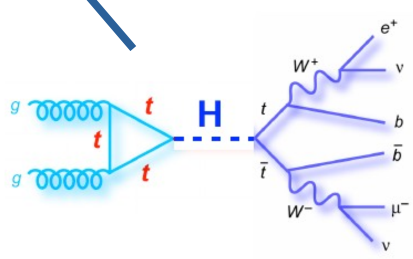




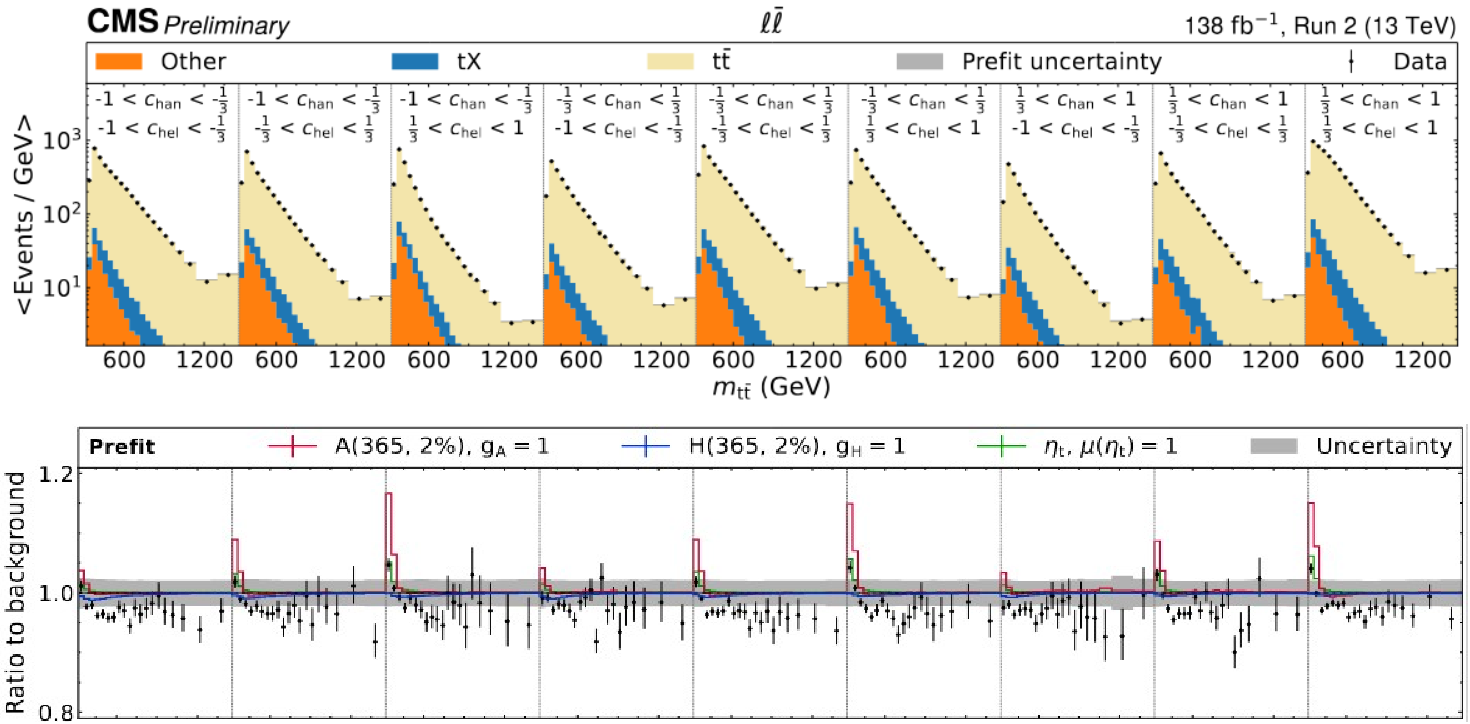
Results ll Channel

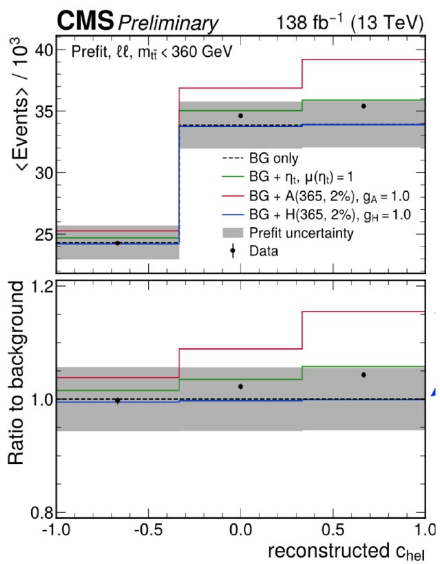


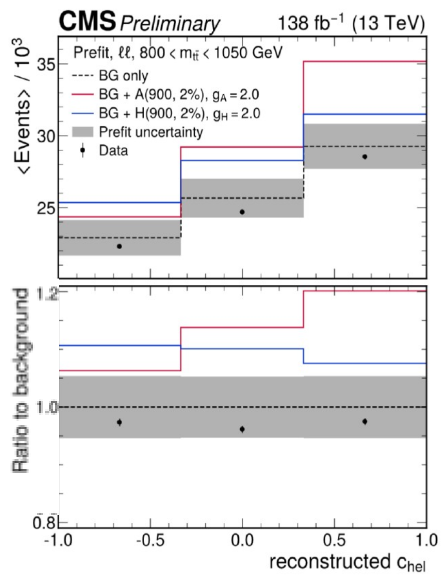




Results ll Channel

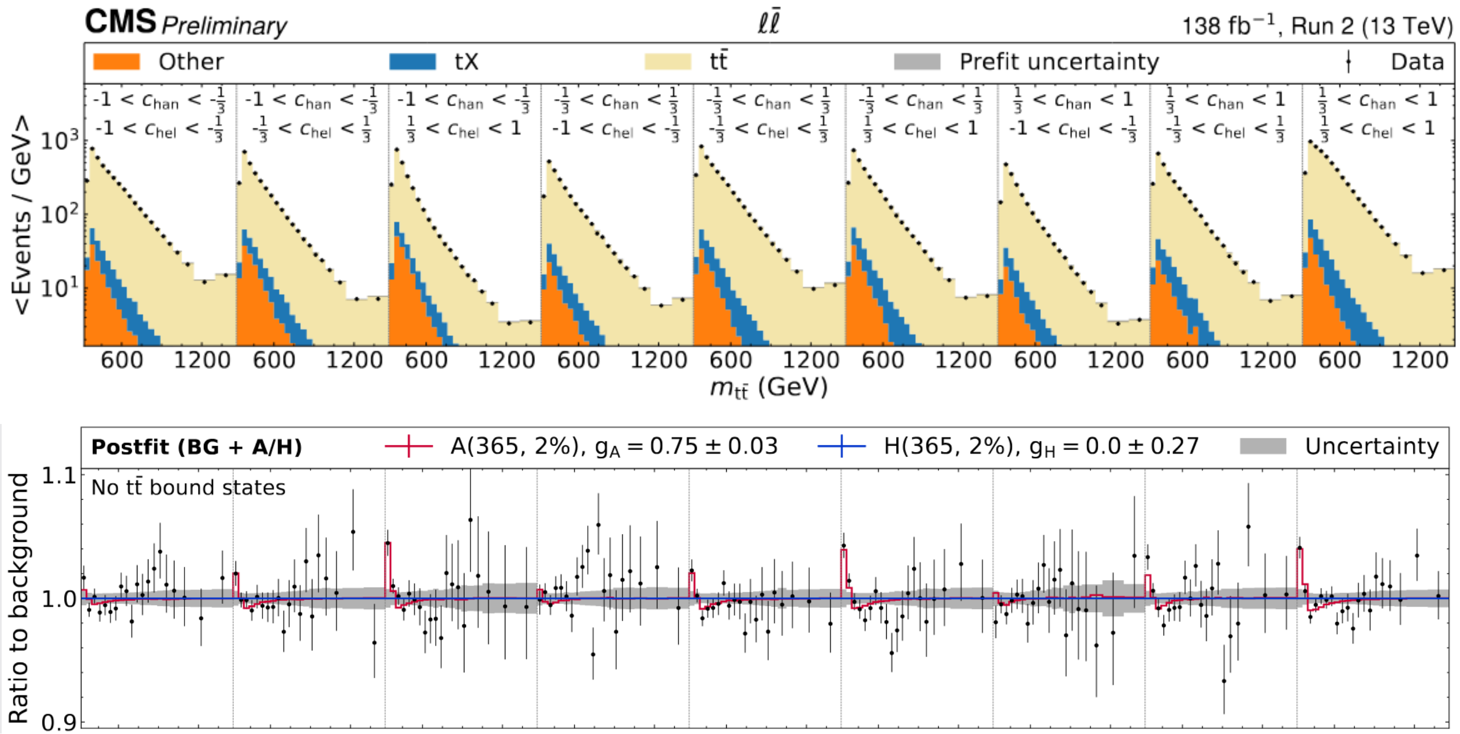


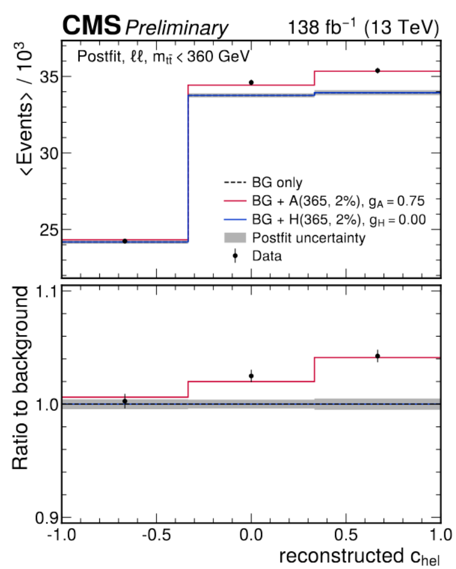




- c_{hel} slope at threshold prefit
- flat for high $m_{t\bar{t}}$

Results ll Channel

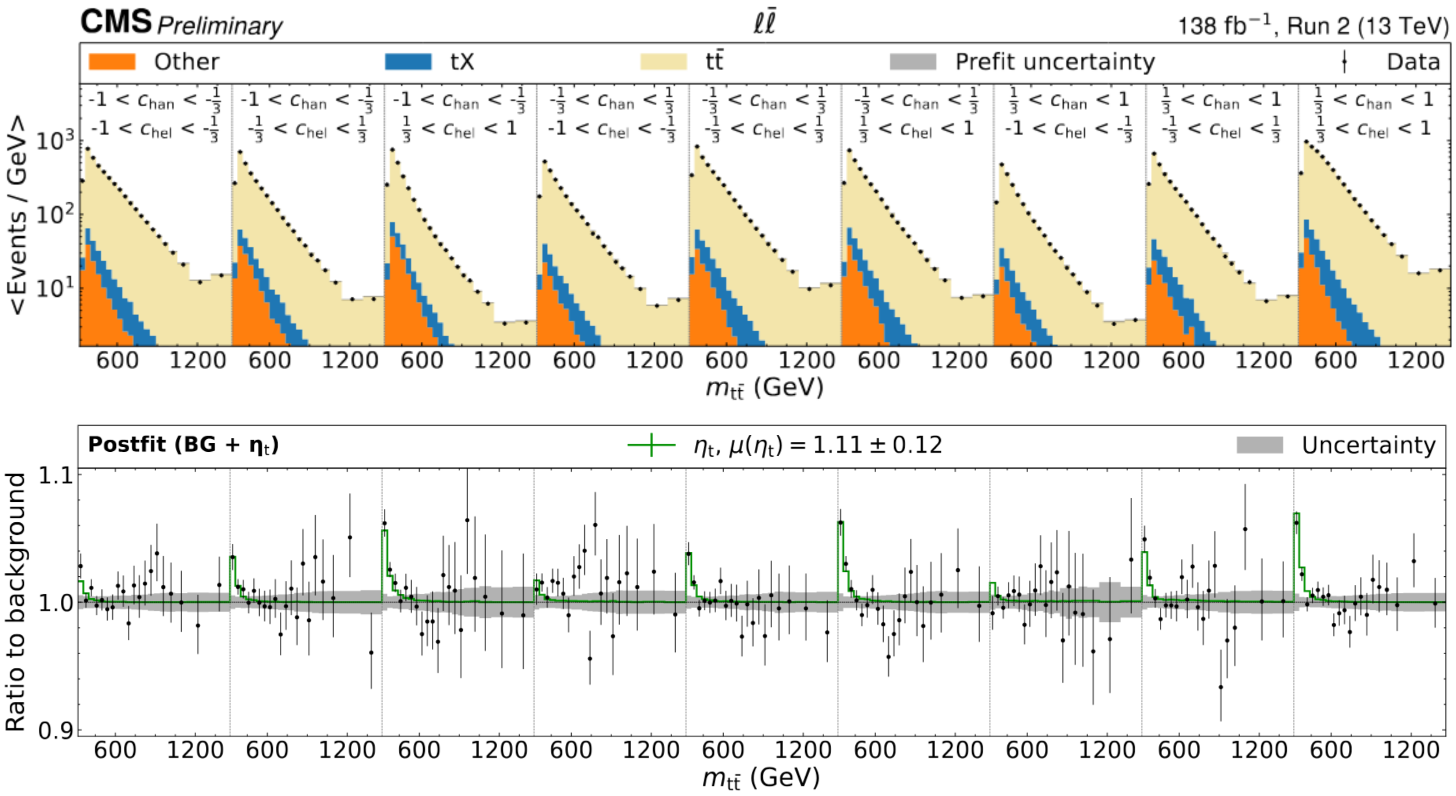


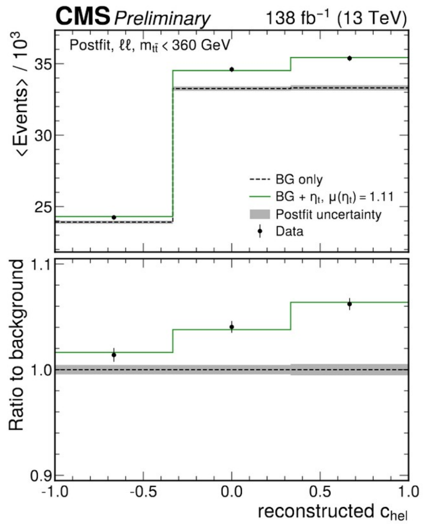


- c_{hel} discrepancy fits

  A very well at threshold

Results ll Channel

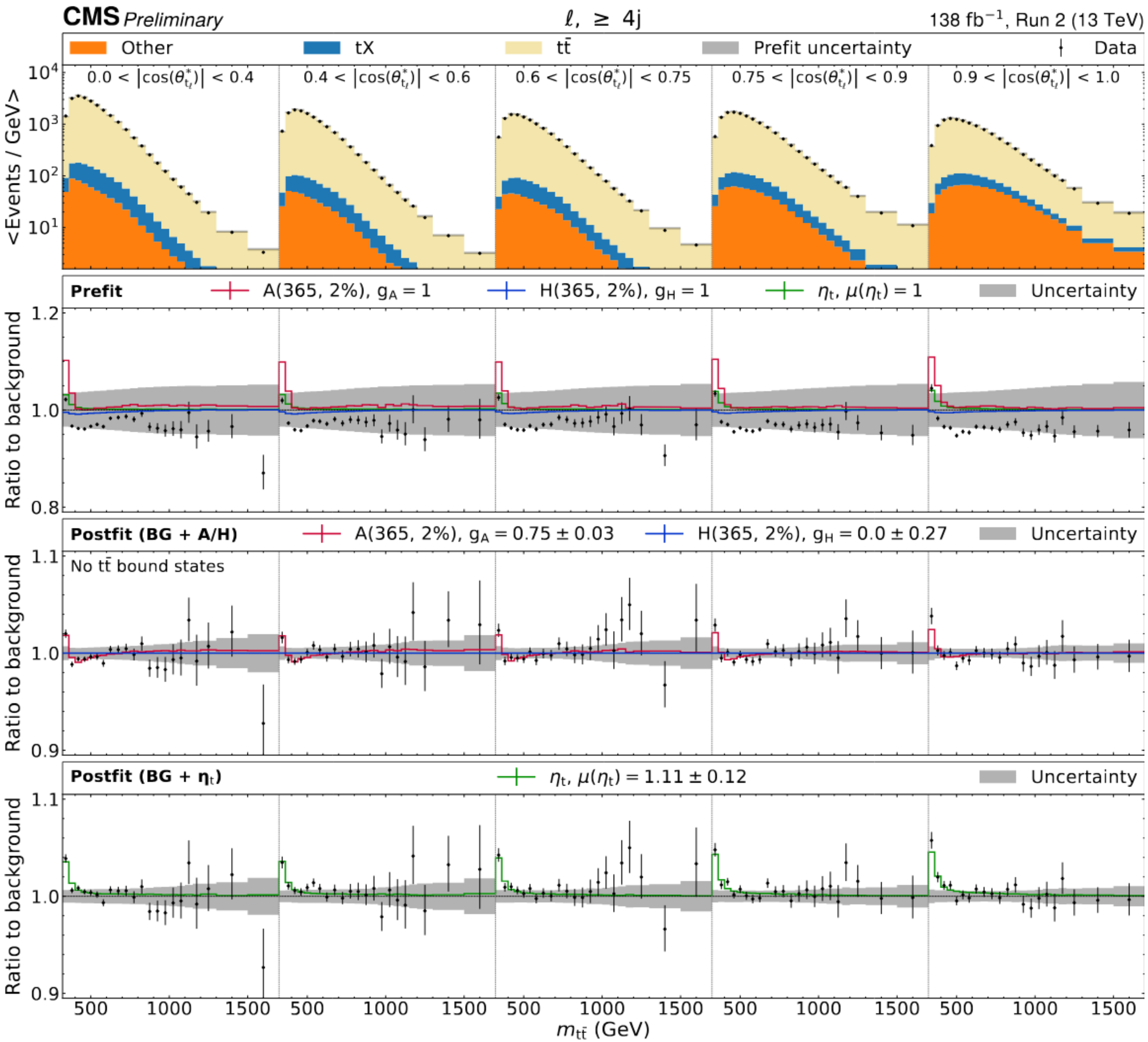




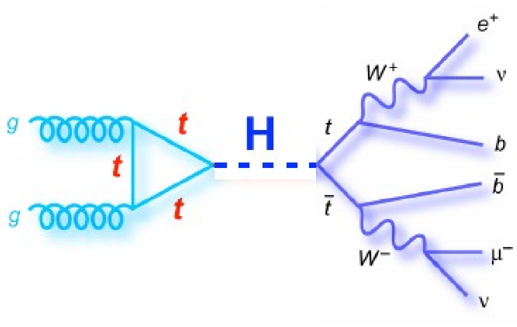
- c_{hel} discrepancy fits

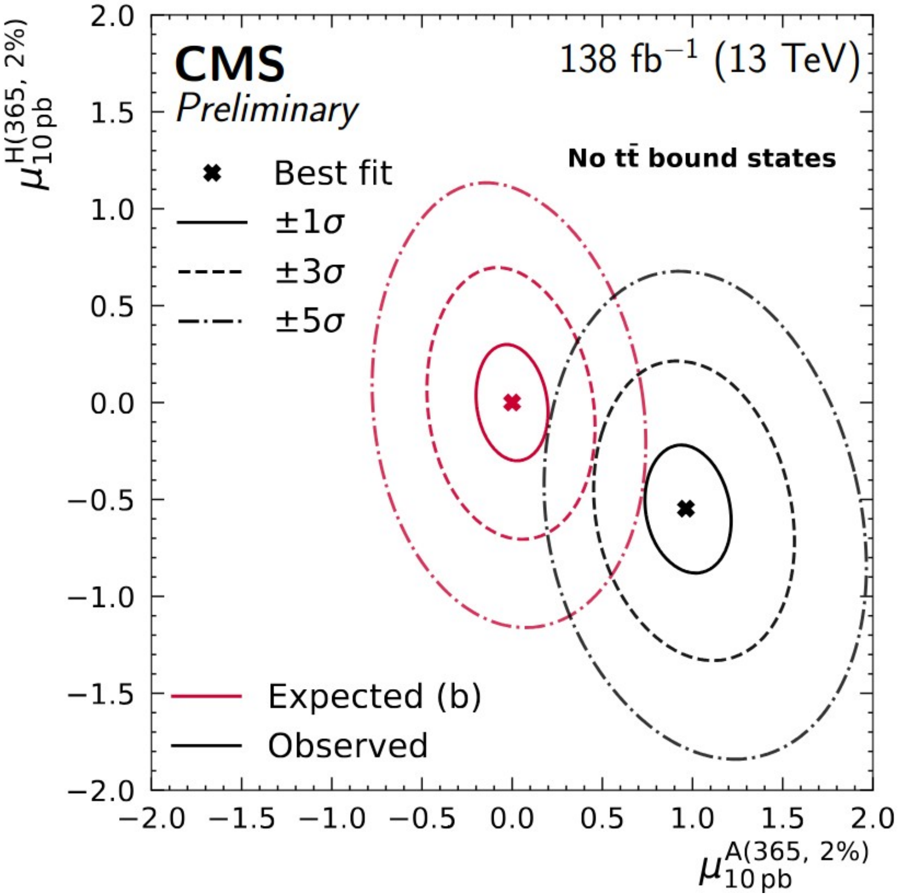
  η_t very well at threshold

L4Jets Result

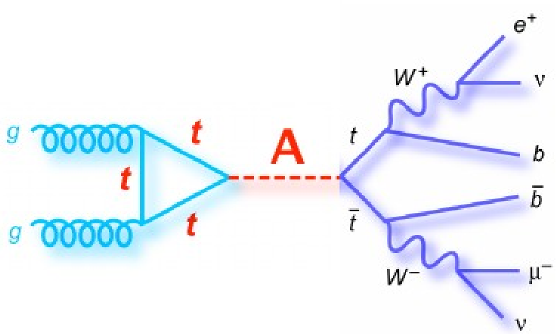


consistent picture in ll and ljets channels





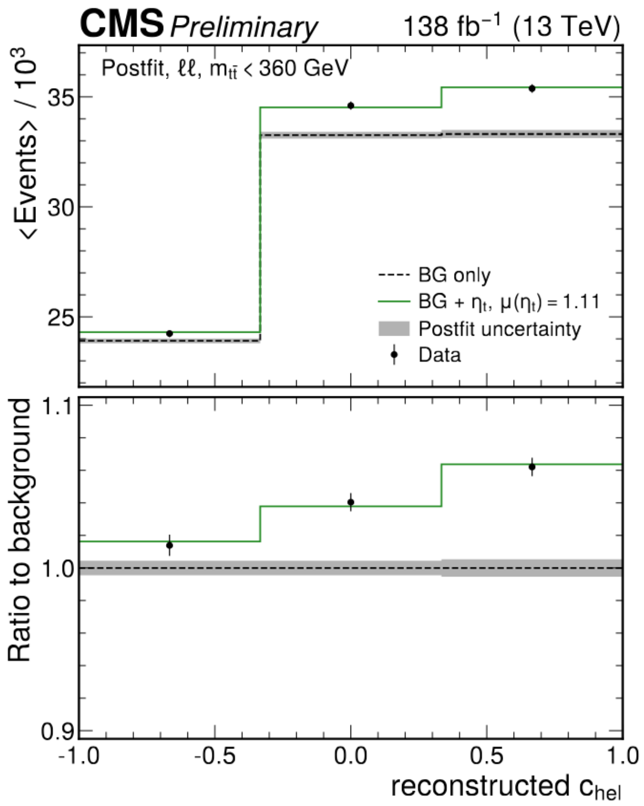
- simultaneous fit of A/H to data
- use closest (available) mass to threshold: 365 GeV
- consider only resonant component with equal and arbitrary rate



excess best compatible with pseudoscalar hypothesis

Quantifying η_t

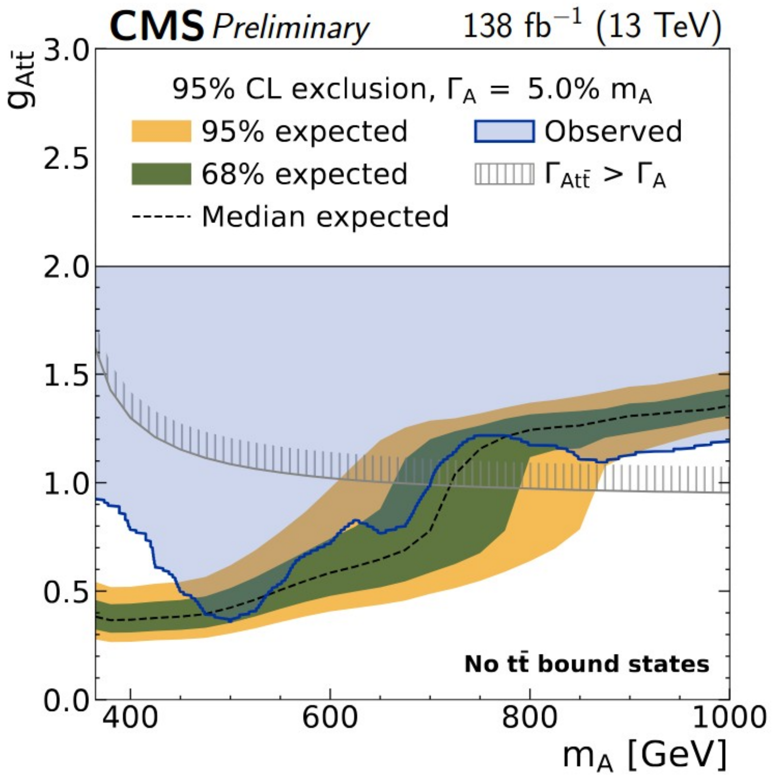
- "Cross section" = difference between the data and the pQCD predictions:
  - $\sigma(\eta_t) = 7.1 \pm 0.8$ pb
- comparing to NRQCD prediction:
  - $\sigma(\eta_t)^{pred} = 6.43$ pb (PRD 104 (2021) 034023)
- interpret with caution: missing uncertainties on model, kinematic effects on efficiencies, soft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

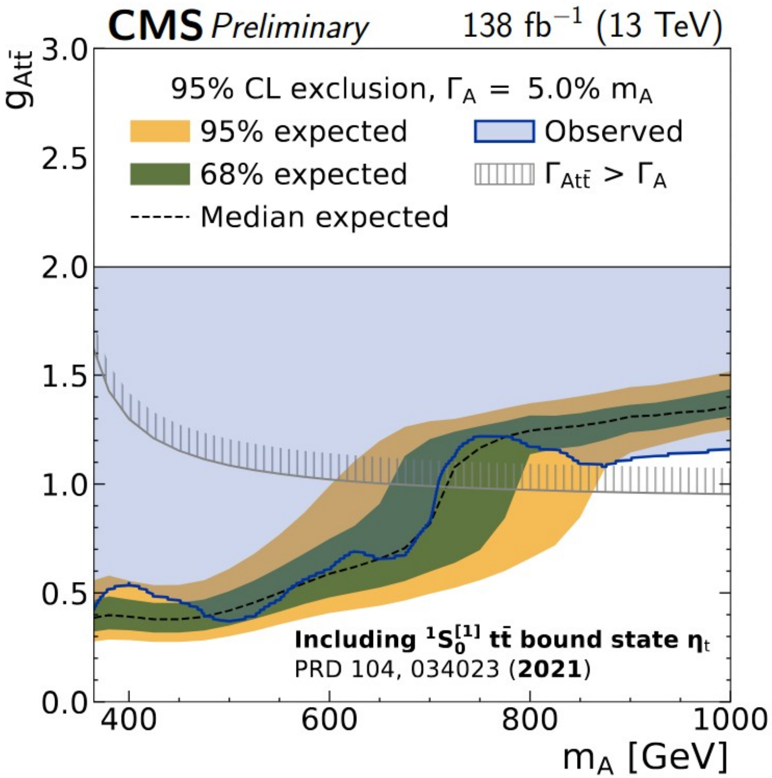


good agreement with available predictions

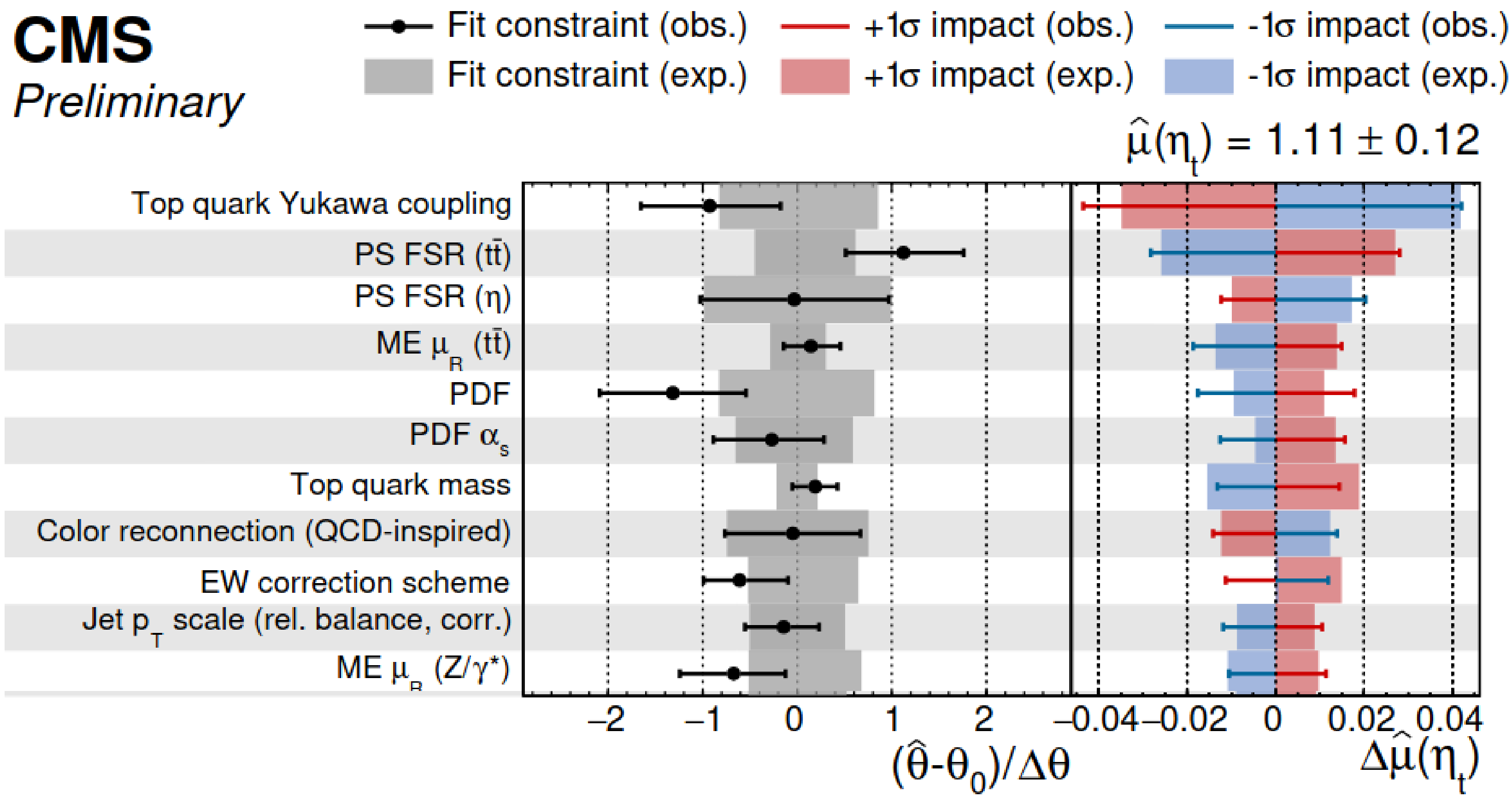
Quantifying η_t

- impact on BSM limits, e.g. A



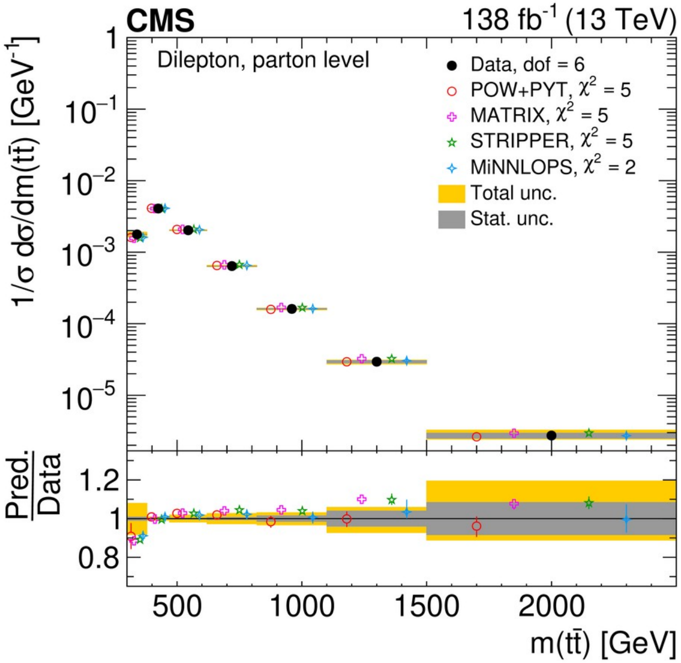


- uncertainties dominated by background modeling

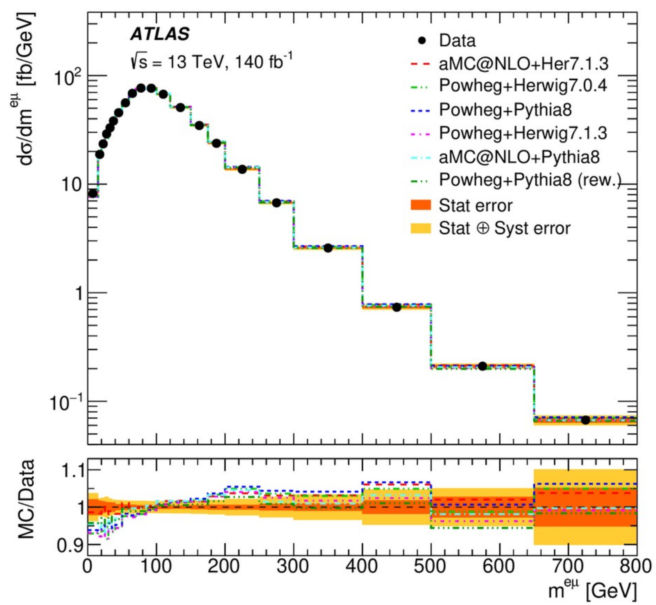


Consistency with Other Results: Invariant Masses

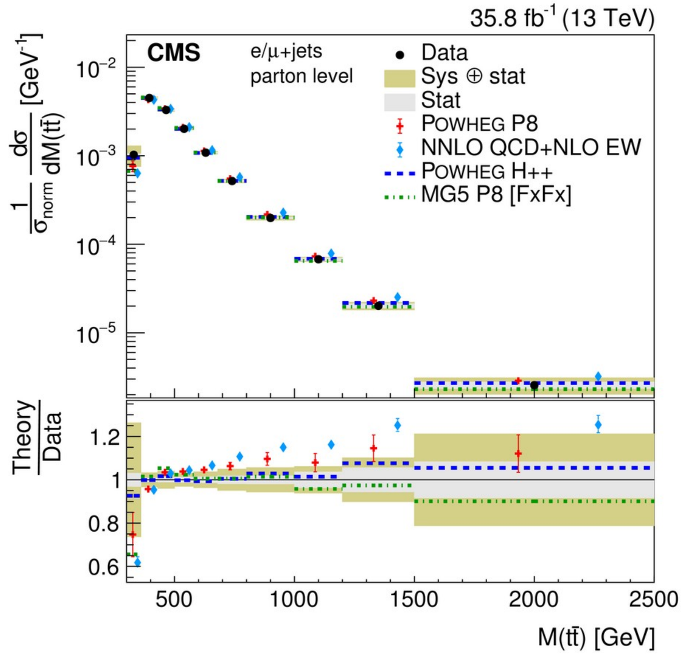
- tension in $m_{t\bar{t}}$ between data and pQCD at the threshold region in multiple measurements



CMS, arXiv:2402.08486



ATLAS, JHEP 07 (2023) 141

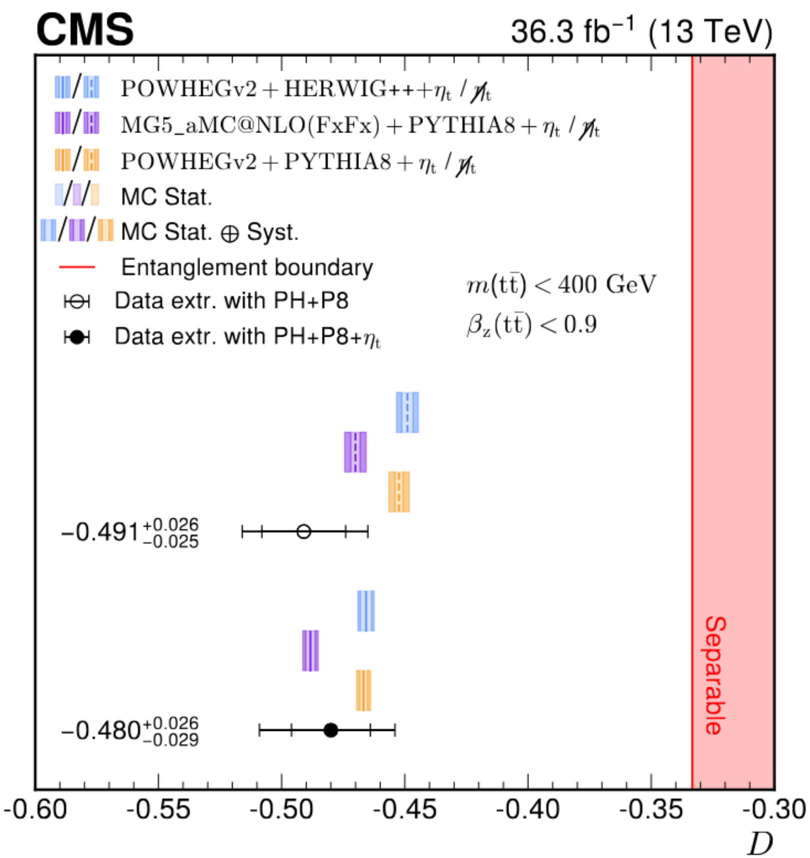


CMS, PRD 97 (2018) 112003

Consistency with Other Results: Spin Correlation

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

  → pseudoscalar contributions



CMS, RPP 87 (2024) 117801

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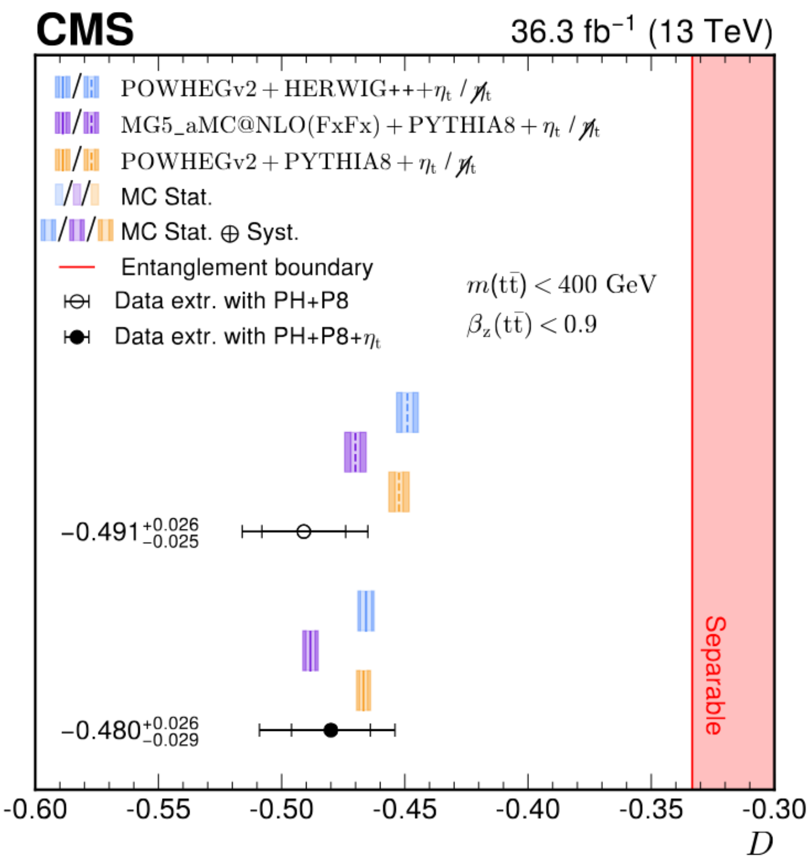
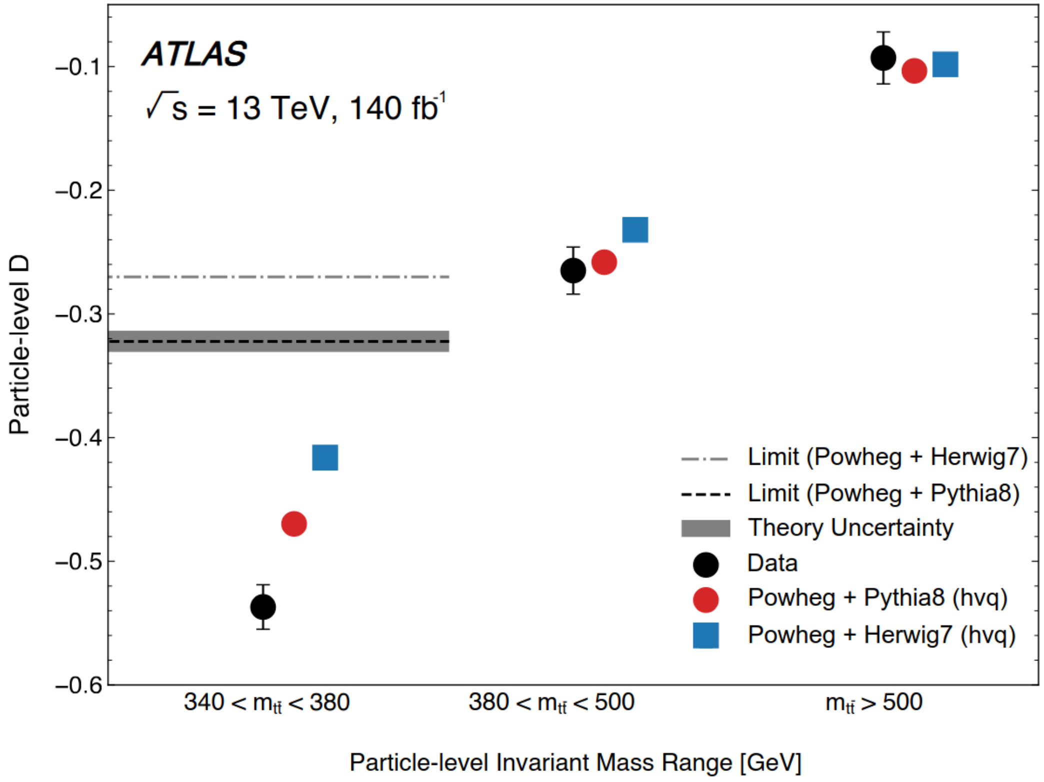
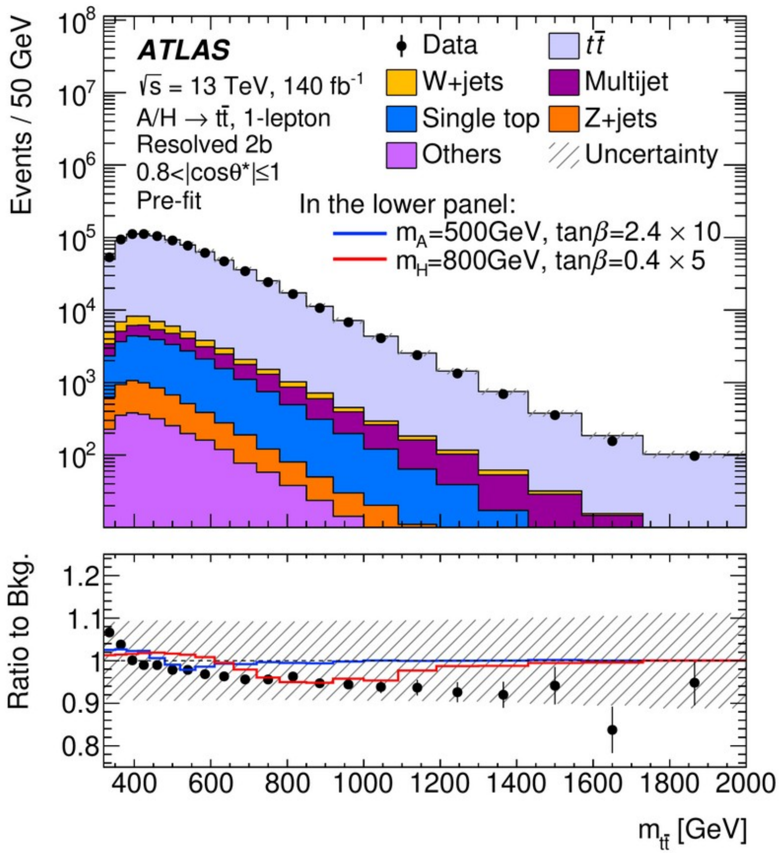


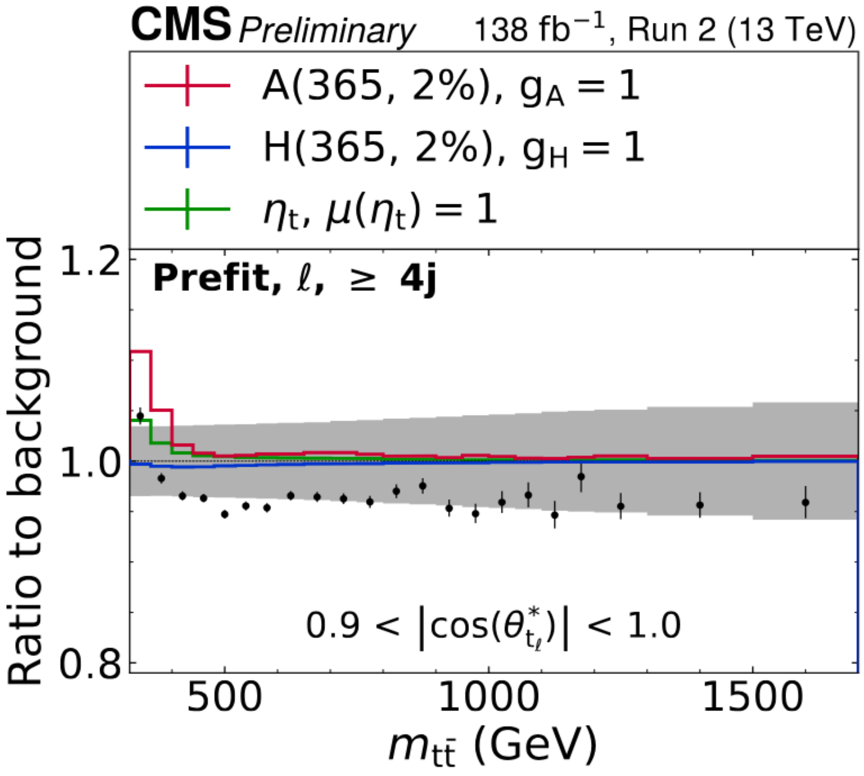


CMS, RPP 87 (2024) 117801

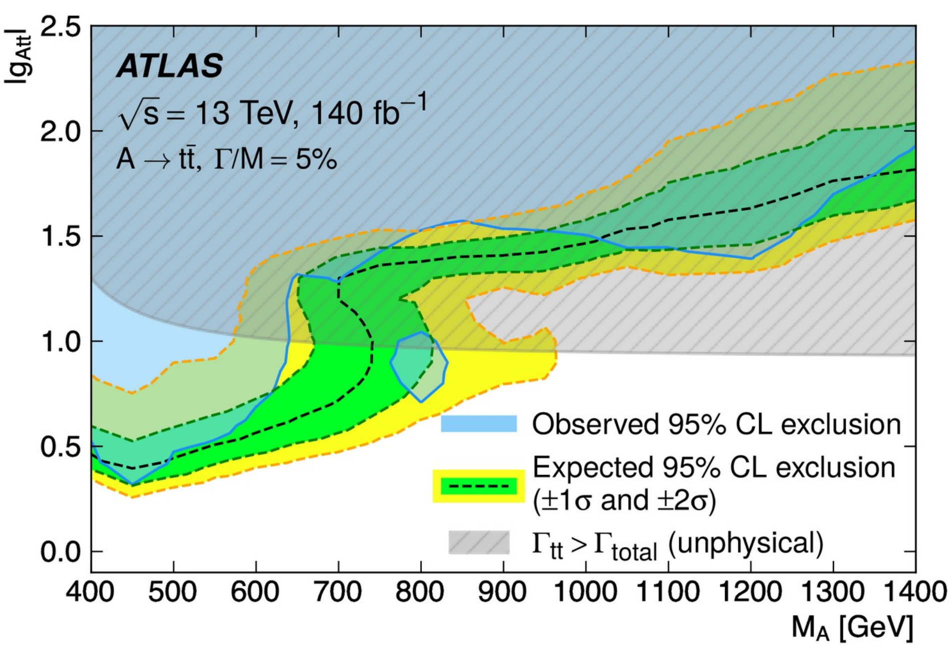
ATLAS, Nature 633 (2024) 542

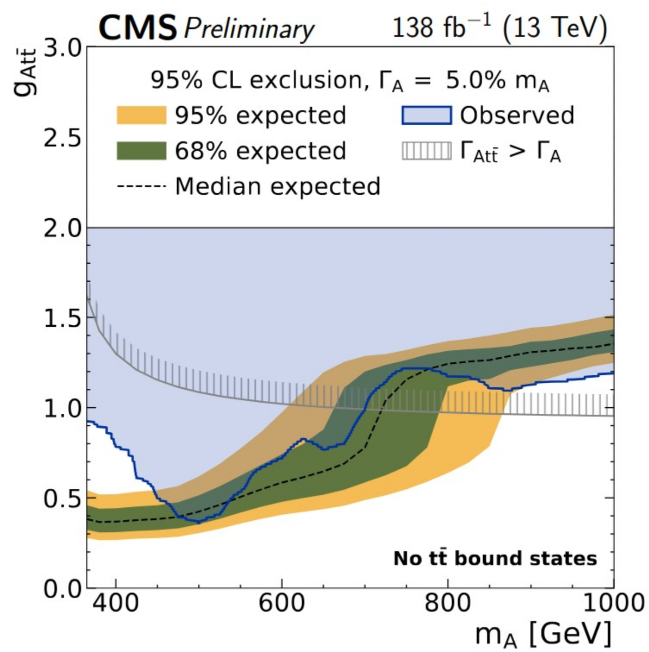
- 1l, 2b, ≥4 jets category for both ATLAS and CMS
  - compare pre-fit distributions
  - e.g. at high |cosθ*|: similar excess in data at low $m_{t\bar{t}}$





- 1l, 2b, ≥4 jets category for both ATLAS and CMS
  - compare pre-fit distributions
  - e.g. at high |cosθ*|: similar excess in data at low $m_{t\bar{t}}$
- for dilepton difficult to compare
  - no reconstruction of top quarks/spin in the ATLAS result
  - different variables: m_{llbb} vs. $\Delta\varphi_{ll}$





dedicated spin observables robust against systematics – key difference?

Closing Remarks

CMS-PAS-HIG-22-013

- search for new spin-0 (pseudo)scalars in $t\bar{t}$ final states with full Run 2 dataset
  - dilepton and lepton+jets channels, using $m_{t\bar{t}}$, angular and spin observables
- observed excess in data at low $m_{t\bar{t}}$ – 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 specific η_t (toy) model (PRD 104 (2021) 034023)
  - stringent limits on A/H with η_t included in the background
- for the future:
  - a complete non-relativistic QCD calculation of $t\bar{t}$ bound state effects is crucial!
  - theory input needed

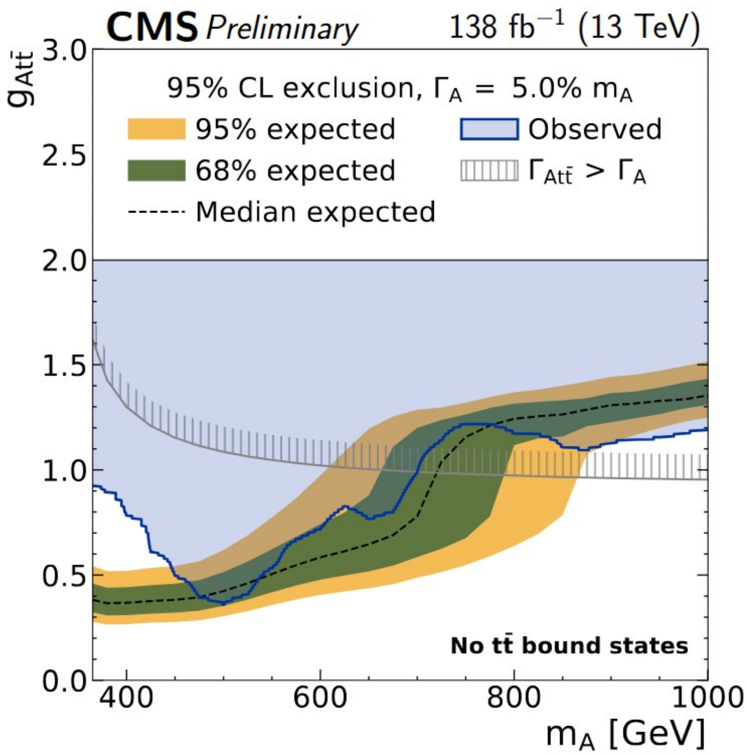
Whatever the excess is – It is exciting !

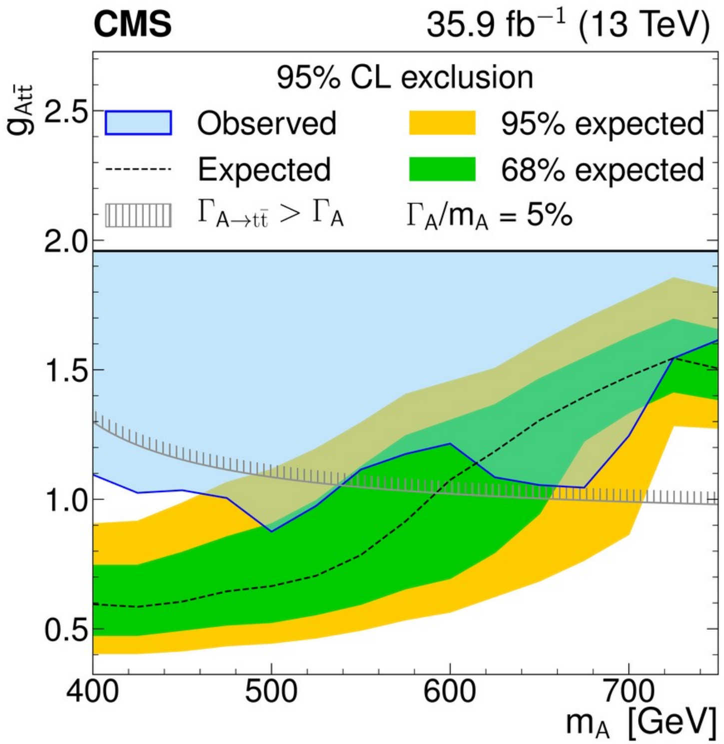
BACK-UP


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

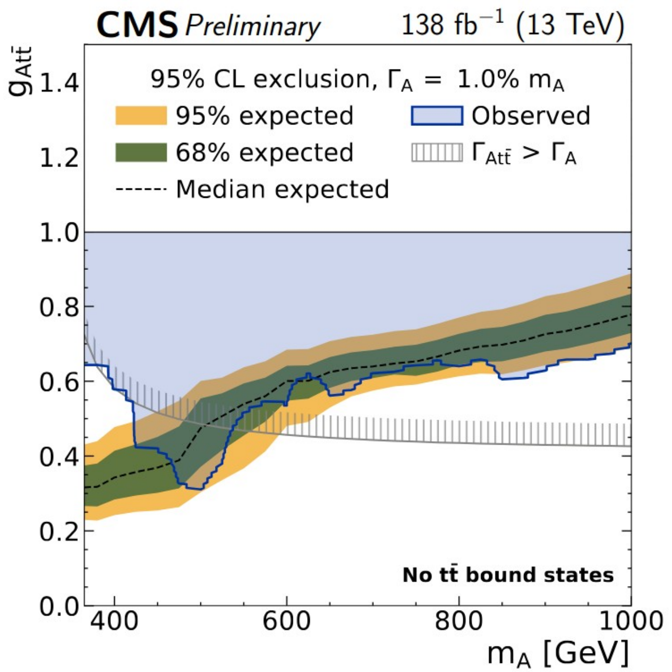
Consistency with Other Results: Previous A/H Search

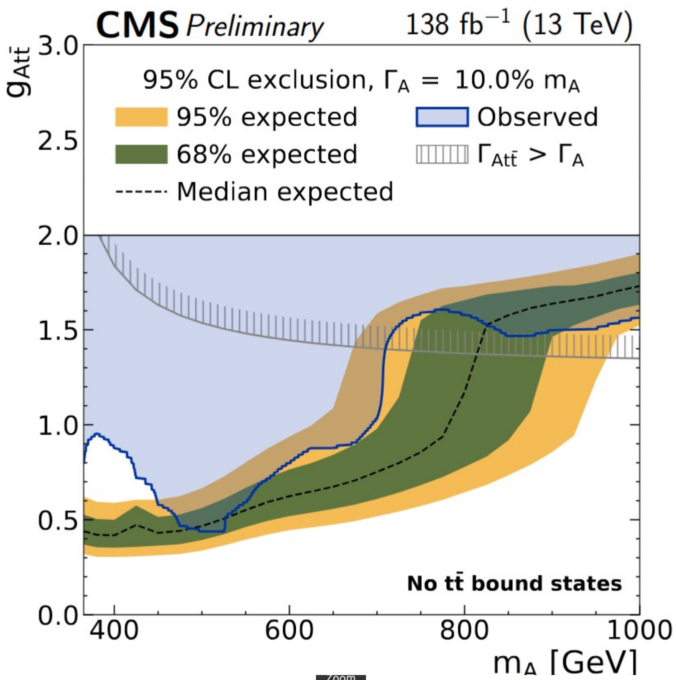
- first A/H search at CMS based on data recorded in 2016 (JHEP 04 (2020) 171)

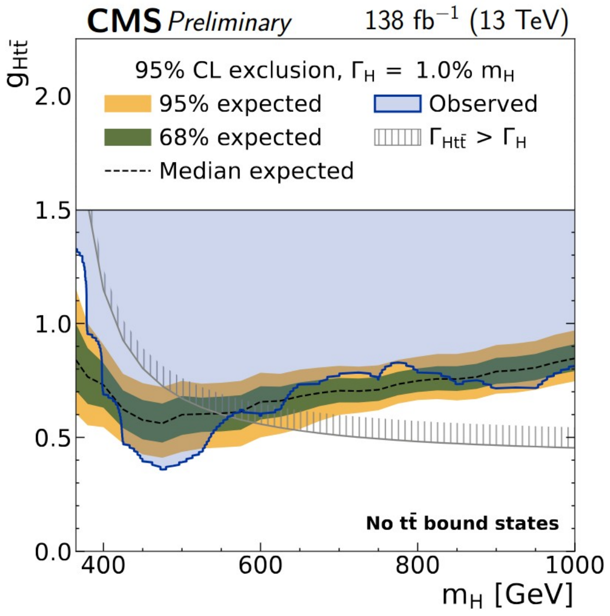


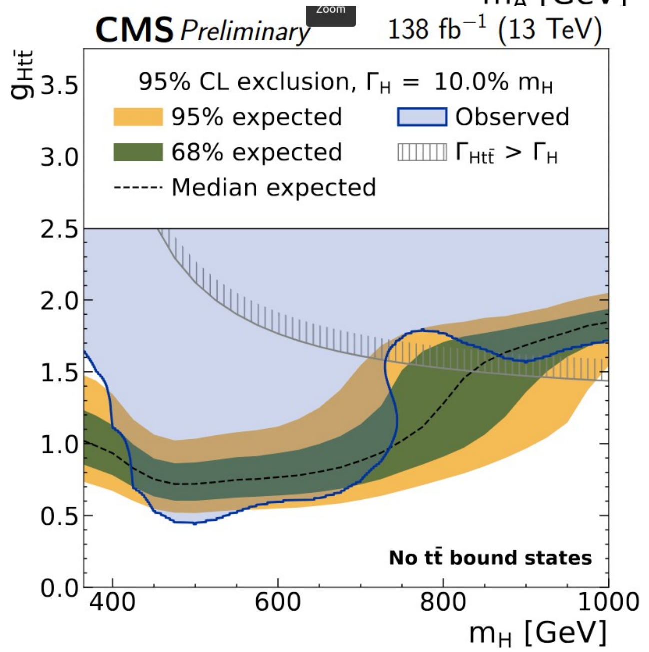


Limits without Toponium

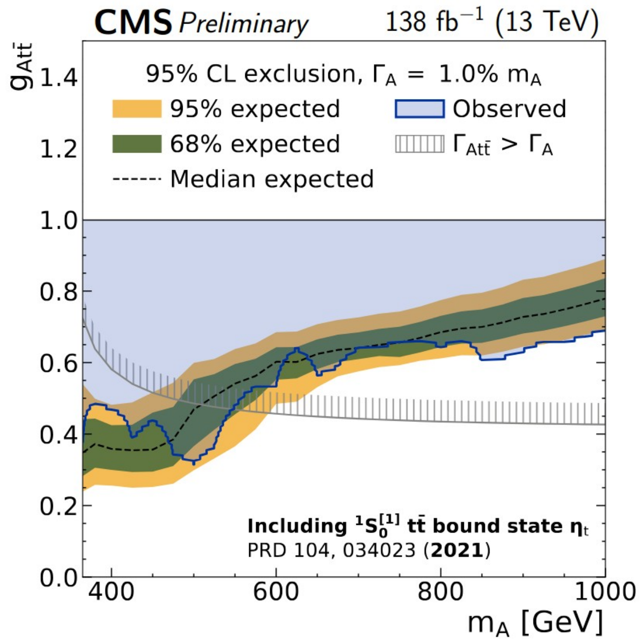


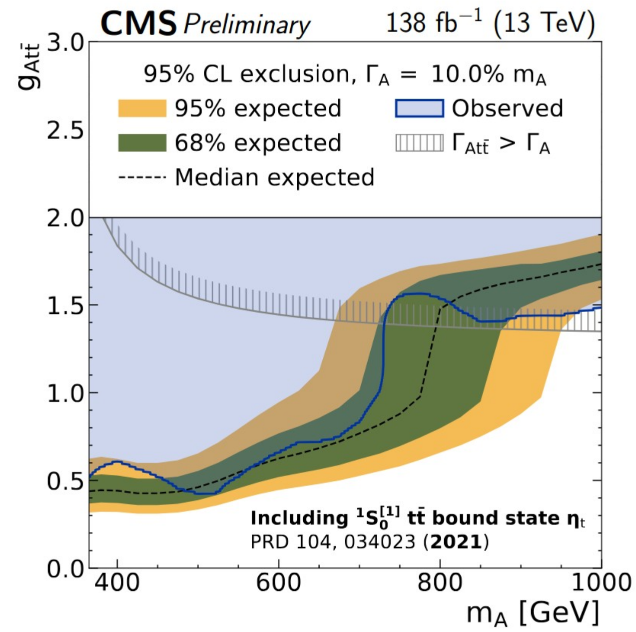


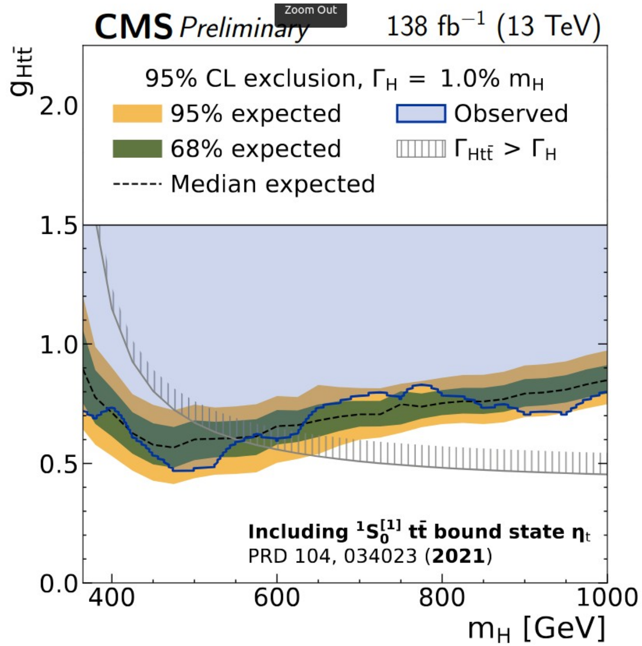


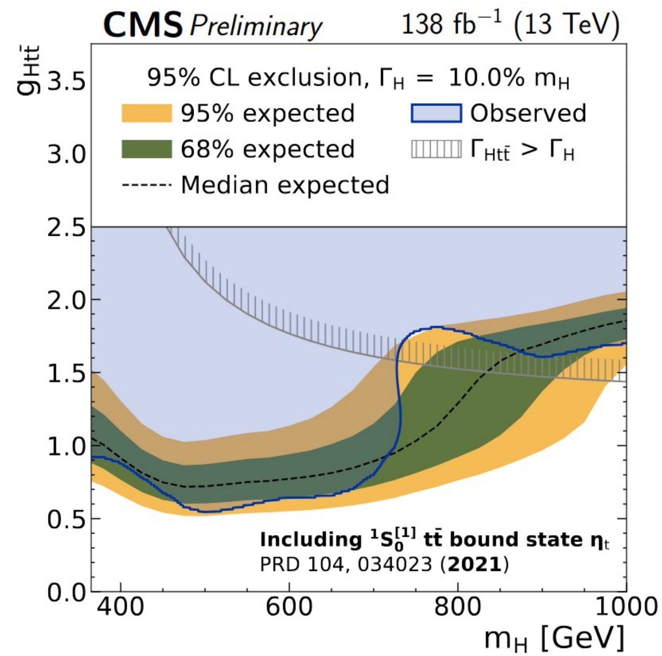


Limits with Toponium

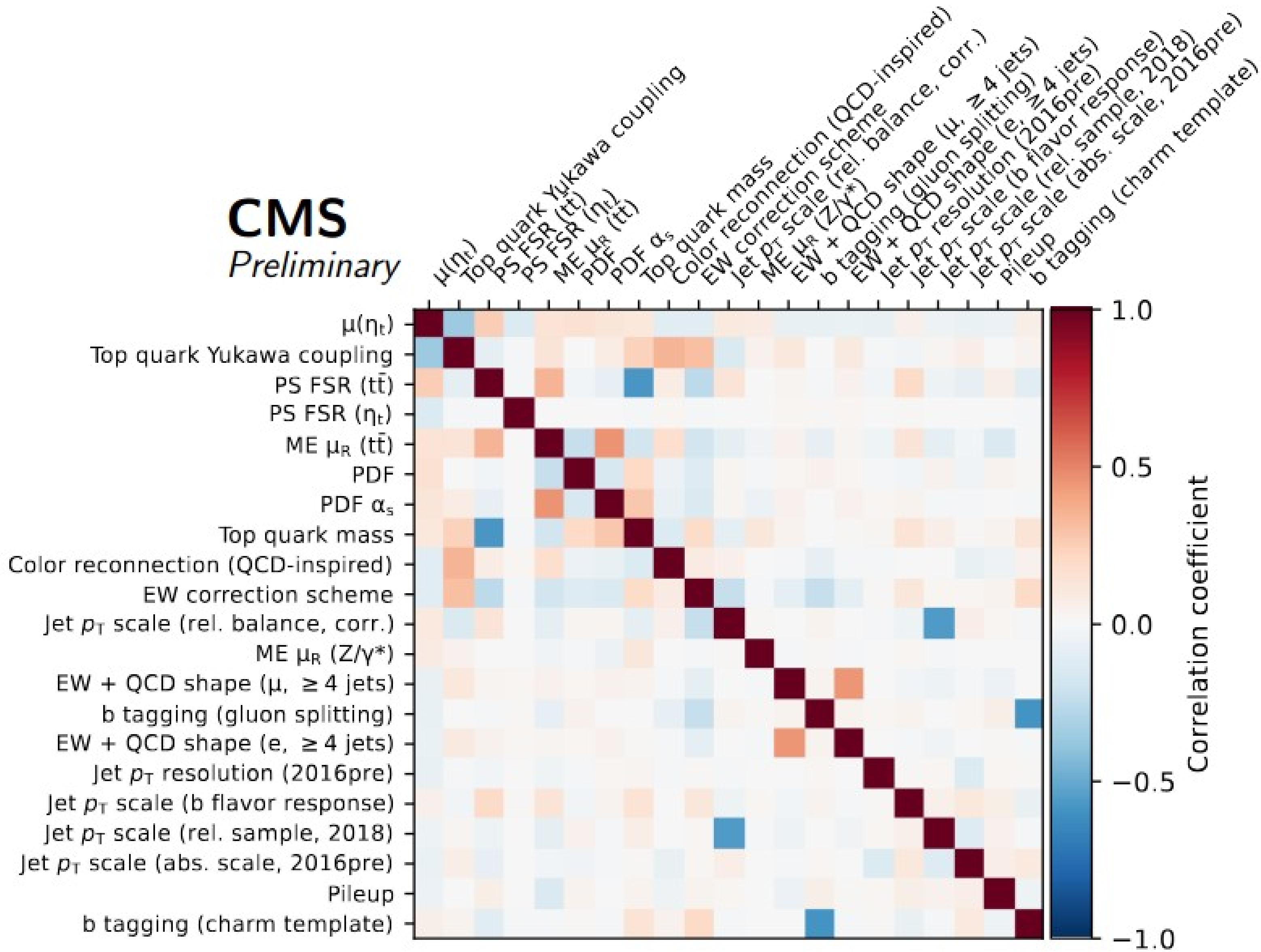






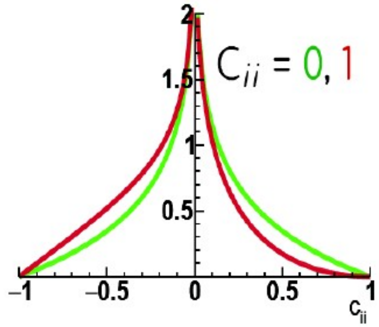


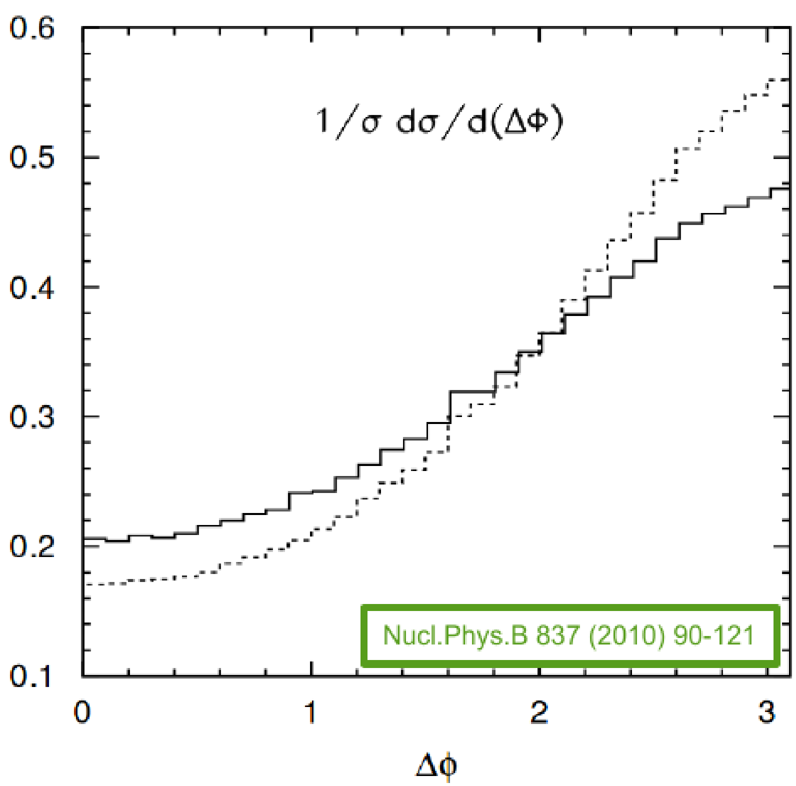
Systemtic Correlations

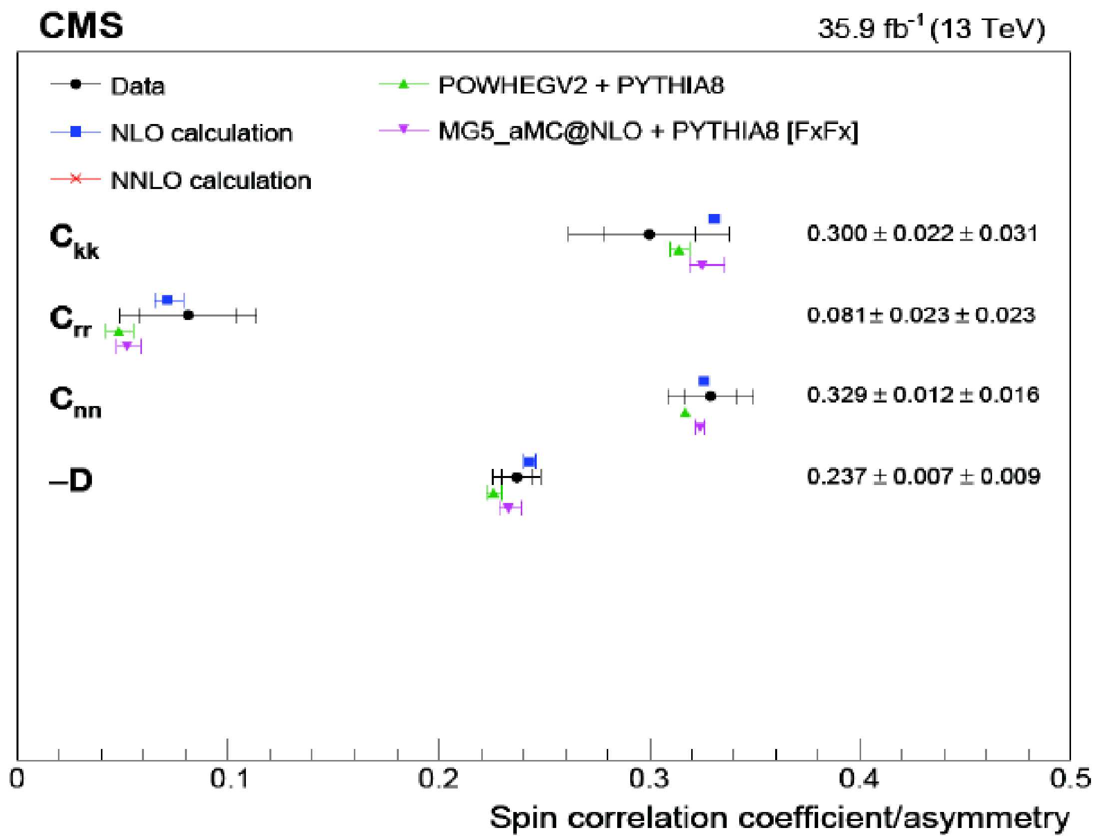


The Problem of delta phi and the Strength of D

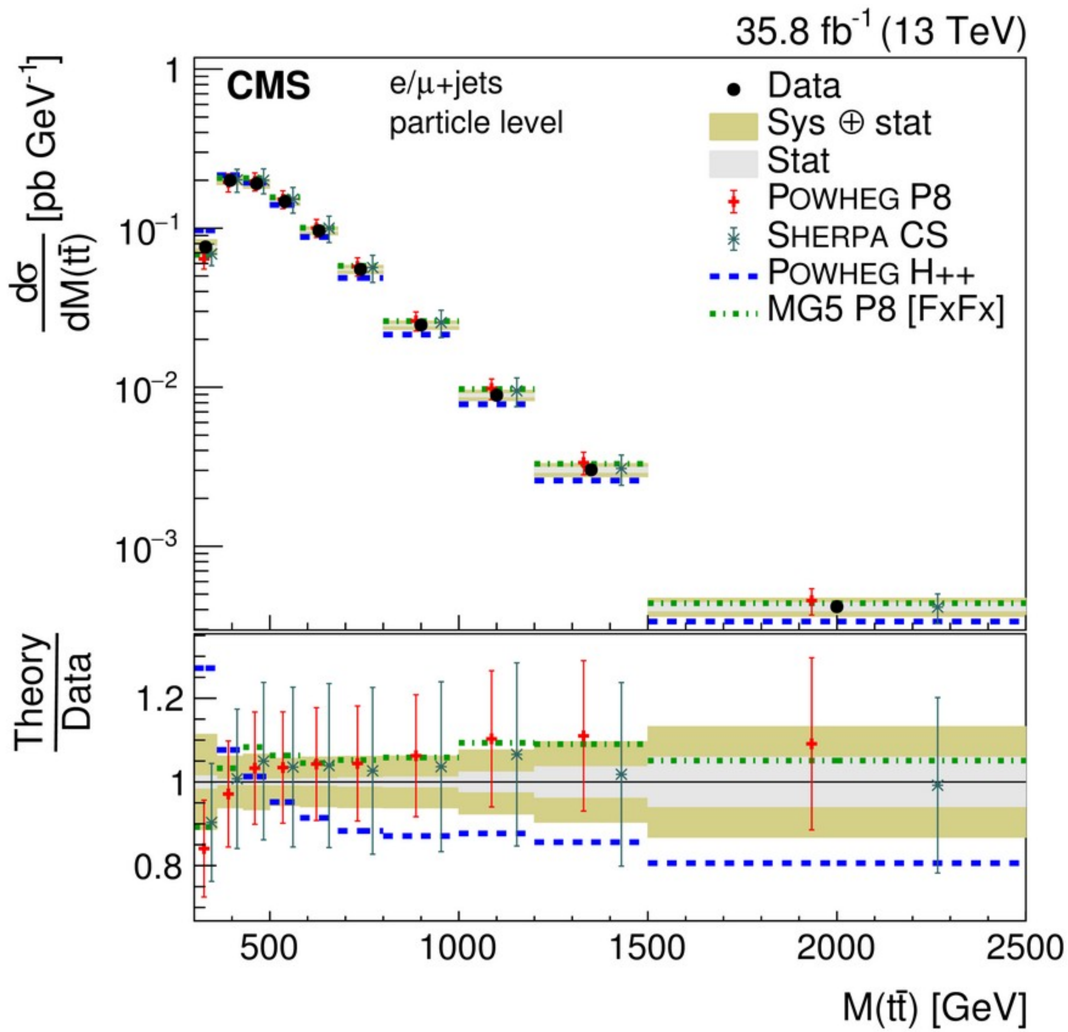
- convolution of boost and spin
- large NNLO correction in extrapolation to full phase space







Unfolding Systematics at Threshold - Modeling



Systematics Details

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

Systematics Details

Uncertainty (# of parameters)	Type	Process	Channel
Jet p_T scale (17)	shape	all	all
Jet p_T resolution (4)	shape	all	all
Unclustered p_T^{miss} (4)	shape	all	all
b tagging heavy-flavor jets (20)	shape	all	all
b tagging light-flavor jets (5)	shape	all	all
Single-electron trigger	shape	all	ej
Single-muon trigger (5)	shape	all	μj
Dilepton triggers (12)	shape	all	ee, eμ, $\mu\mu$
Electron identification (2)	shape	all	ej, ee, eμ
Muon identification (10)	shape	all	μj, eμ, $\mu\mu$
ECAL L1 trigger inefficiency (3)	shape	all	all
Pileup	shape	all	all
Integrated luminosity (7)	norm.	all	all
Top quark Yukawa coupling	shape	SM $t\bar{t}$	all
EW correction scheme	shape	SM $t\bar{t}$	all
m_t	shape	SM $t\bar{t}$, Φ, η_t	all
ME μ_R (5)	shape	SM $t\bar{t}$, Φ, single top, Z/γ^*	all
ME μ_F (6)	shape	SM $t\bar{t}$, Φ, η_t, single top, Z/γ^*	all
PS ISR (6)	shape	SM $t\bar{t}$, Φ, η_t, single top, Z/γ^*	all
PS FSR (6)	shape	SM $t\bar{t}$, Φ, η_t, single top, Z/γ^*	all
Color reconnection (2)	shape	SM $t\bar{t}$	all
h_{damp}	shape	SM $t\bar{t}$	all
PDF (2)	shape	SM $t\bar{t}$	all
Single top quark normalization	norm.	Single top	all
EW+QCD normalization	norm.	Data-driven EW+QCD	ℓj
EW+QCD shape (20)	shape	Data-driven EW+QCD	ℓj
$t\bar{t}V$ normalization	norm.	$t\bar{t}V$	$\ell\ell$
Z/γ^* normalization	norm.	Z/γ^*	$\ell\ell$
Diboson normalization	norm.	Diboson	$\ell\ell$
MC statistical (3920)	shape	all	all

EW Corrections

- 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 — Hathor

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

MadGraph

- Alternate choice: additive

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

- Difference treated as systematic uncertainty