Experimental studies of the top quark pair production threshold

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DER FORSCHUNG | DER LEHRE | DER BILDUNG

On behalf of the CMS Collaboration

Standard Model at the LHC

10 April, 2025, Durham, UK

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

HELMHOLTZ
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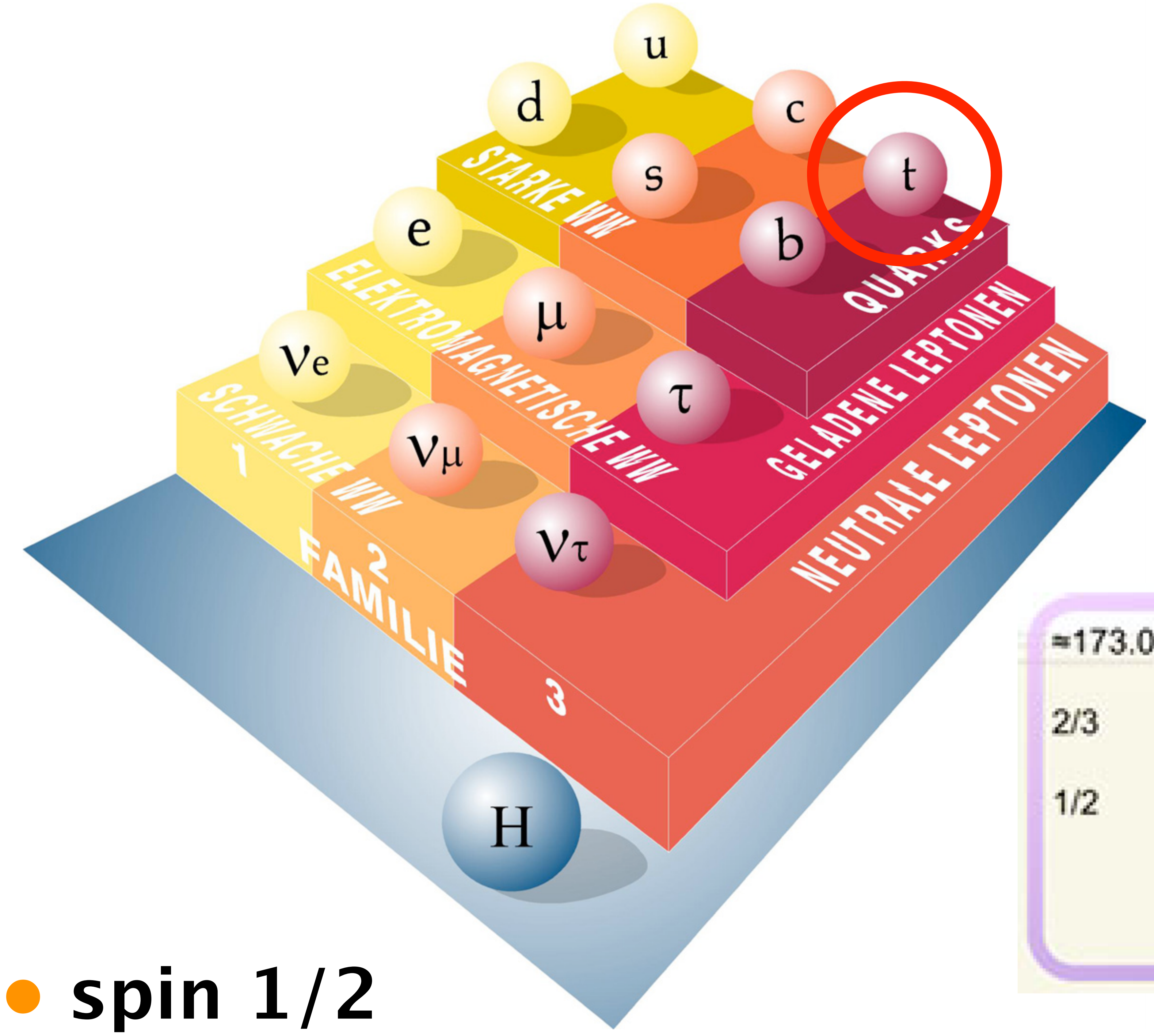
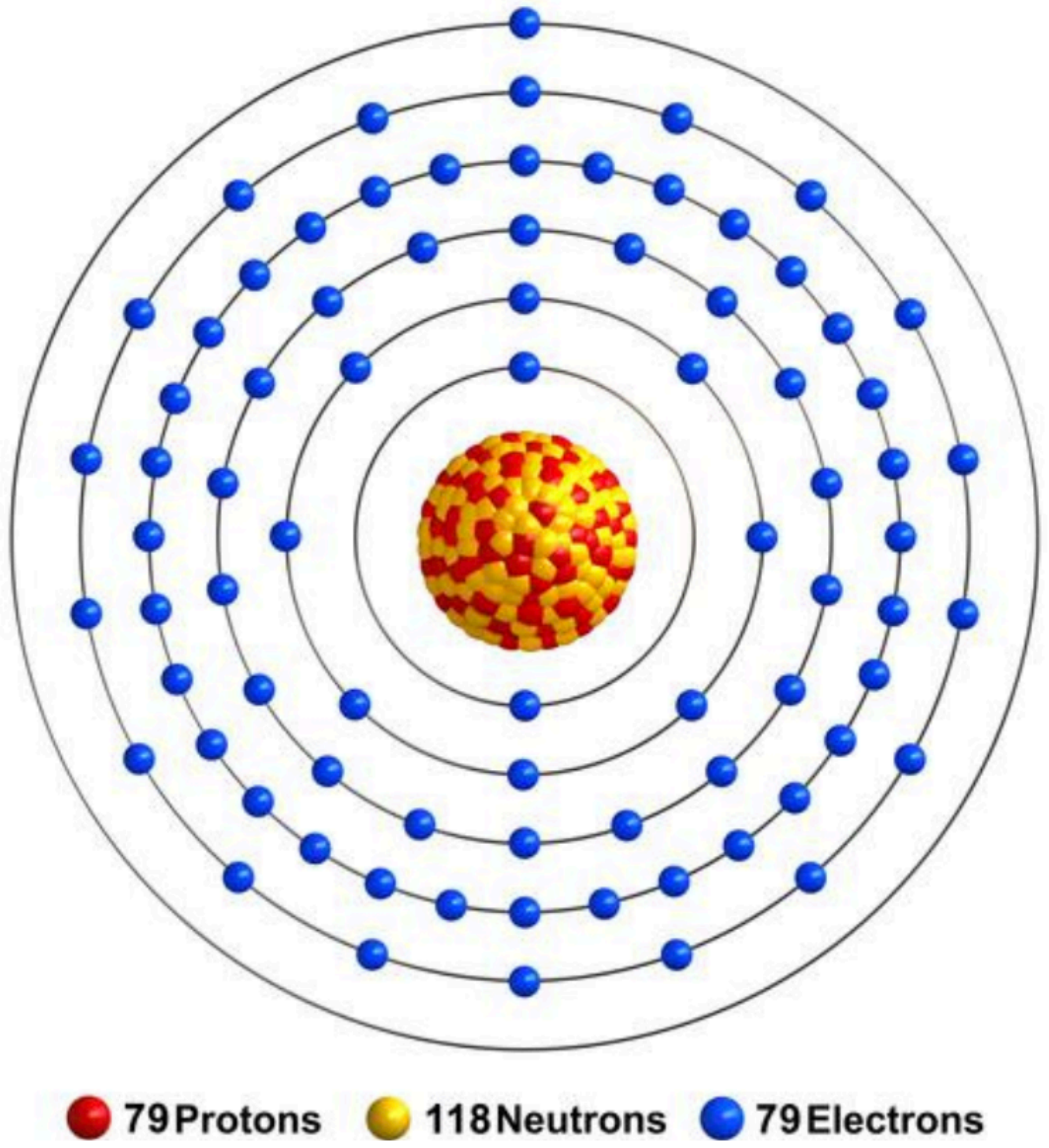
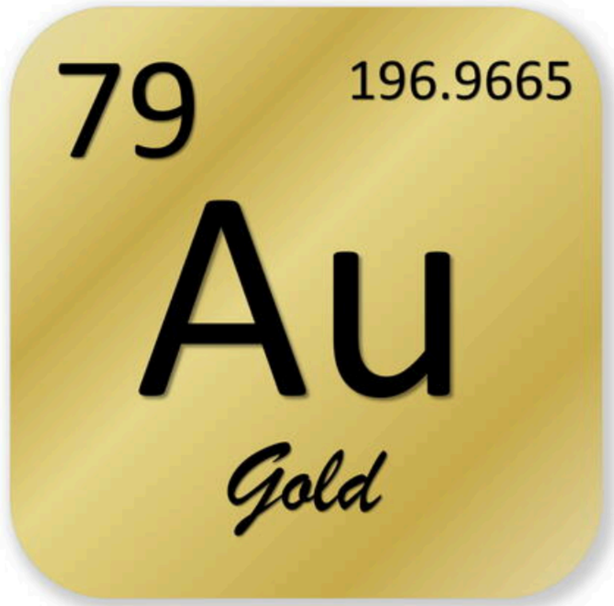
The top quark: Heaviest Elementary Particle



- m_{top}=172.52±0.33 GeV ~weight of gold nucleus





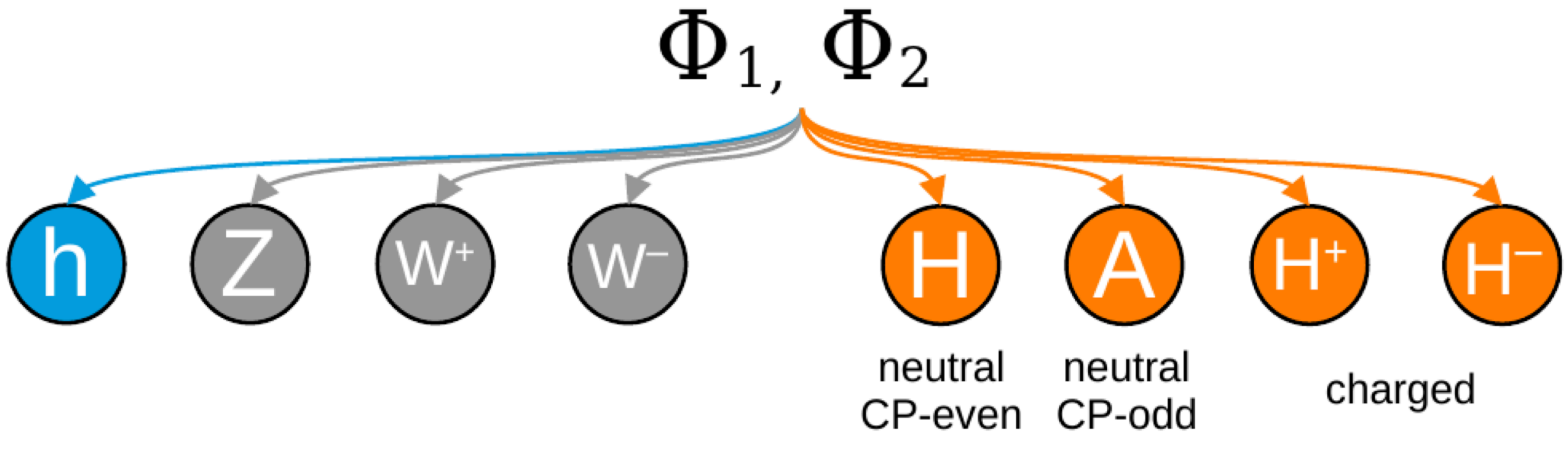
- spin 1/2
- short lifetime: $\tau \sim 5 \cdot 10^{-25}$ s ≪ Λ^{-1}_{QCD}: decays before it fragments
  → observe "naked" quark
- large coupling to Higgs boson ~1
  important role in EWK symmetry breaking?
- do they connect to new (pseudo-)scalars?

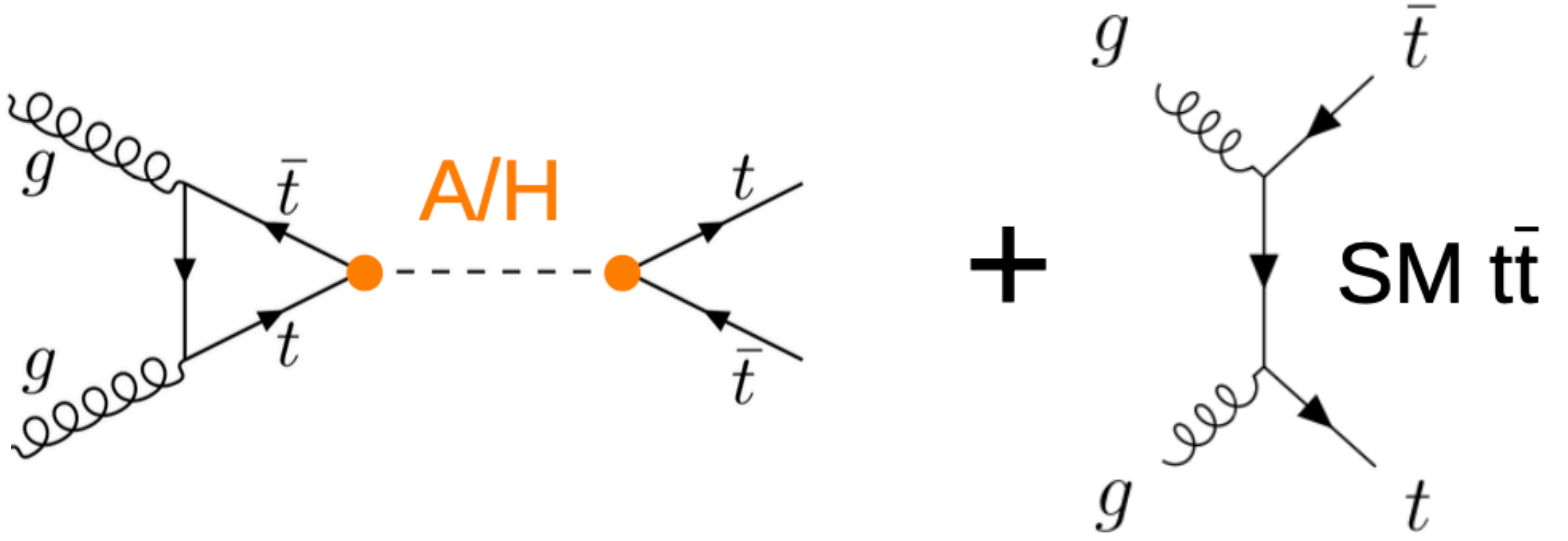
Is the top quark connected to new physics?

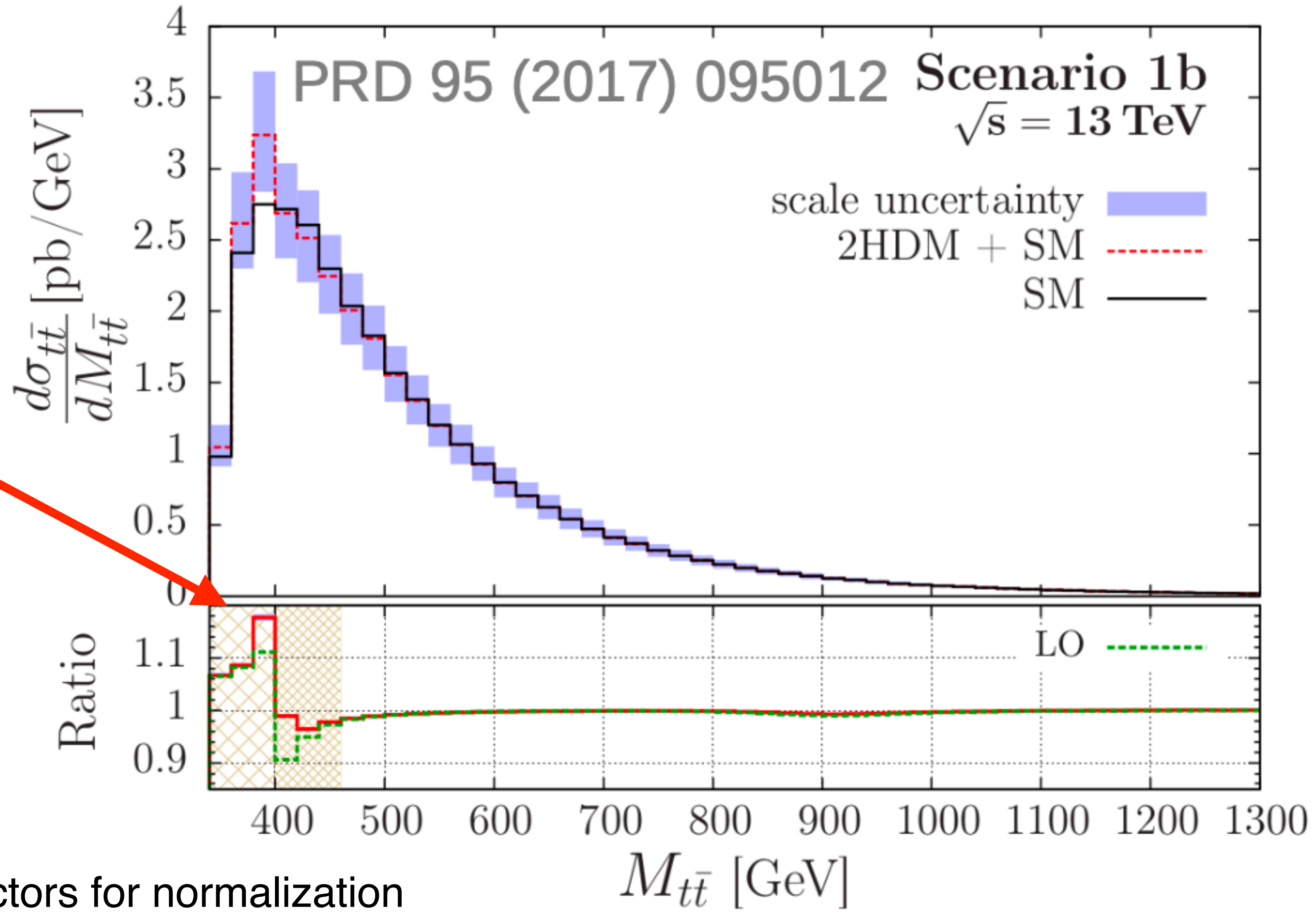
Search for Extensions of the Higgs Sector

2 Higgs Doublet Model (2HDM)

- simplest extended Higgs model







peak-dip structure

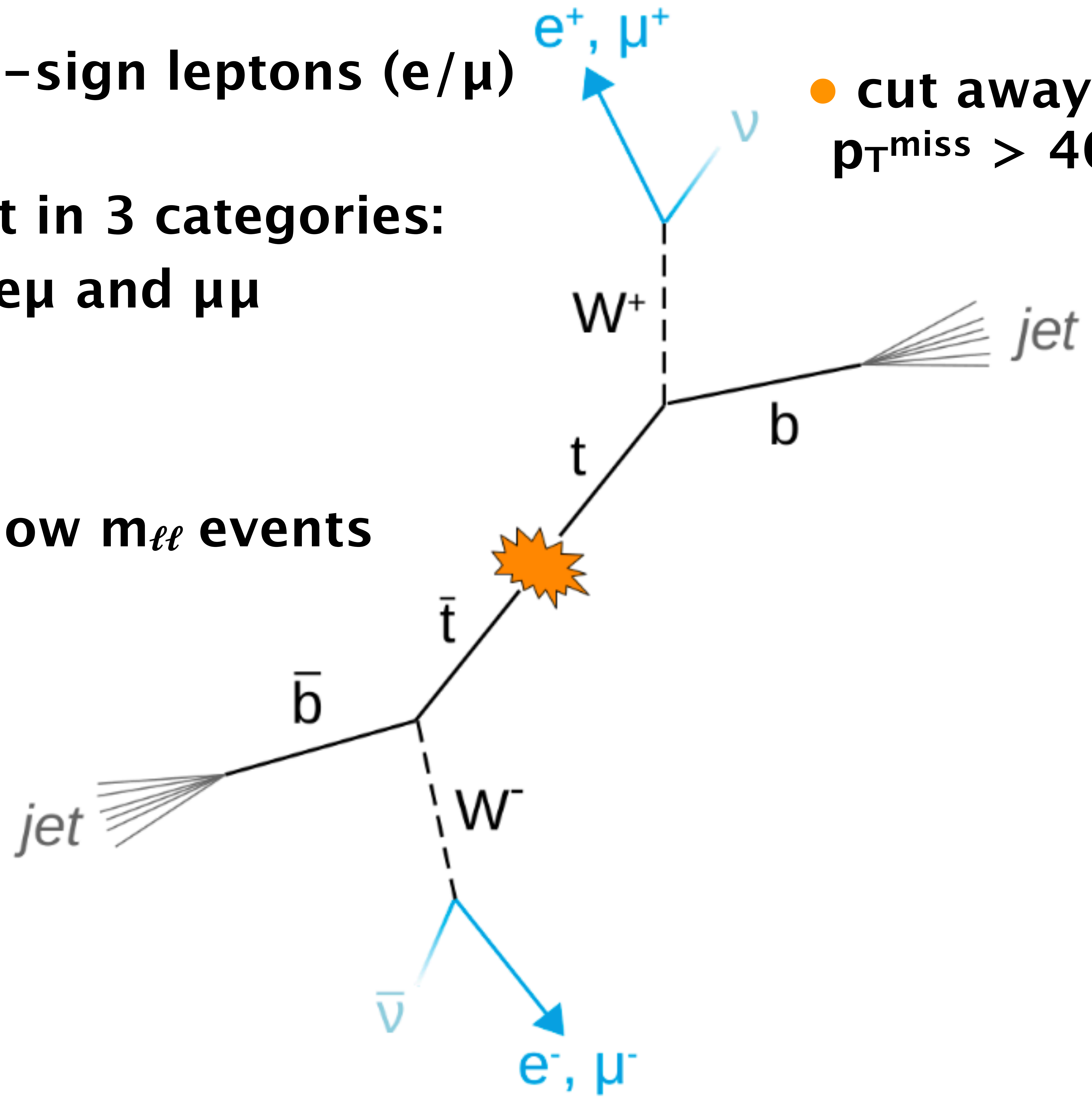
- if couplings are Yukawa-like: strongest couplings to top quarks
- m_A, m_H > $2m_t$: decay to top quark pairs

→ search for resonances in $t\bar{t}$ production

NNLO QCD K-factors for normalization

Event Selection

- exactly two opposite-sign leptons (e/μ)
- split in 3 categories: ee, eμ and μμ
- reject low $m_{\ell\ell}$ events
- 2 or more jets
- cut away Z peak & require p_T^{miss} > 40 GeV in ee/μμ
- 1 or more b-jets



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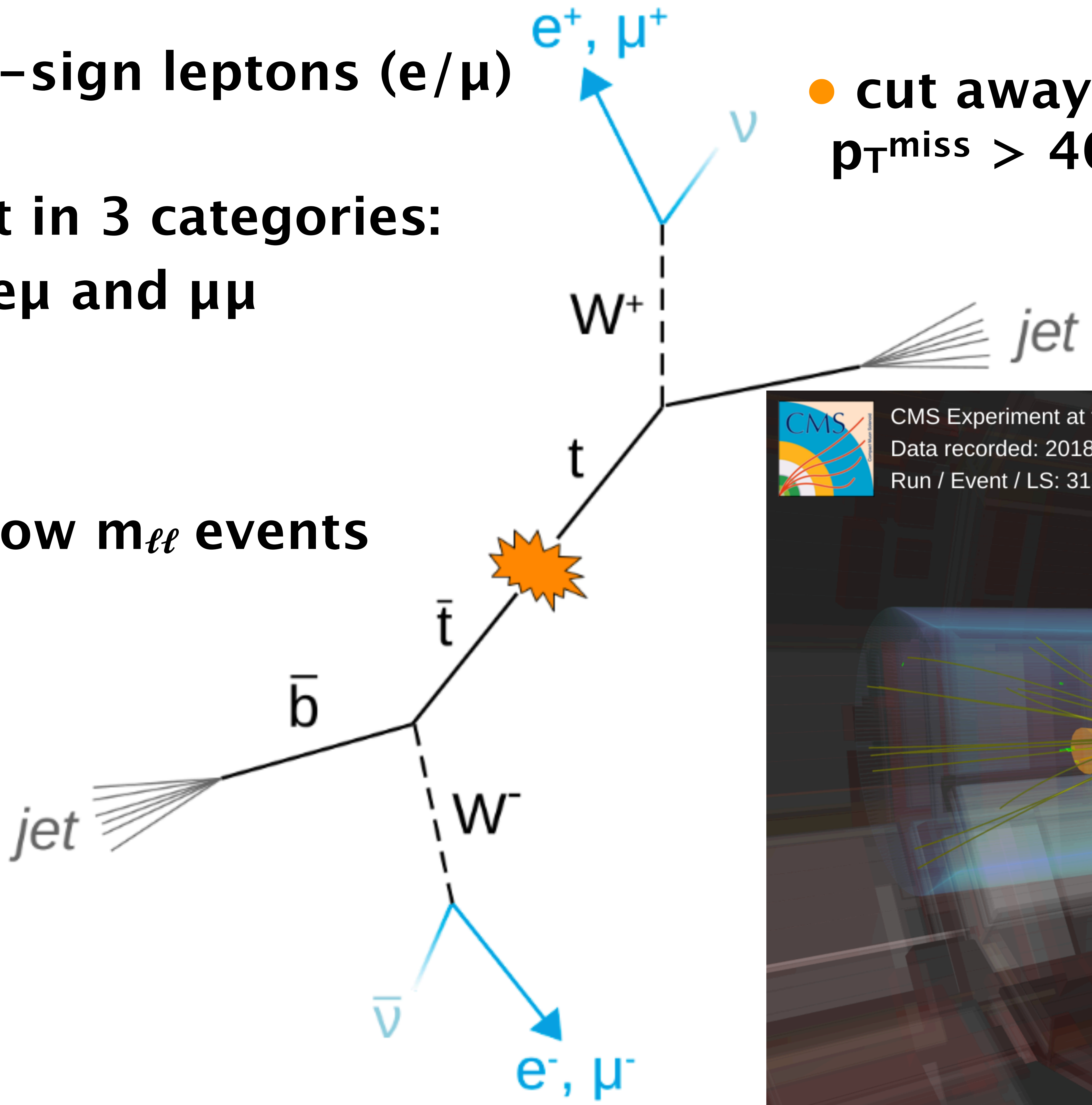

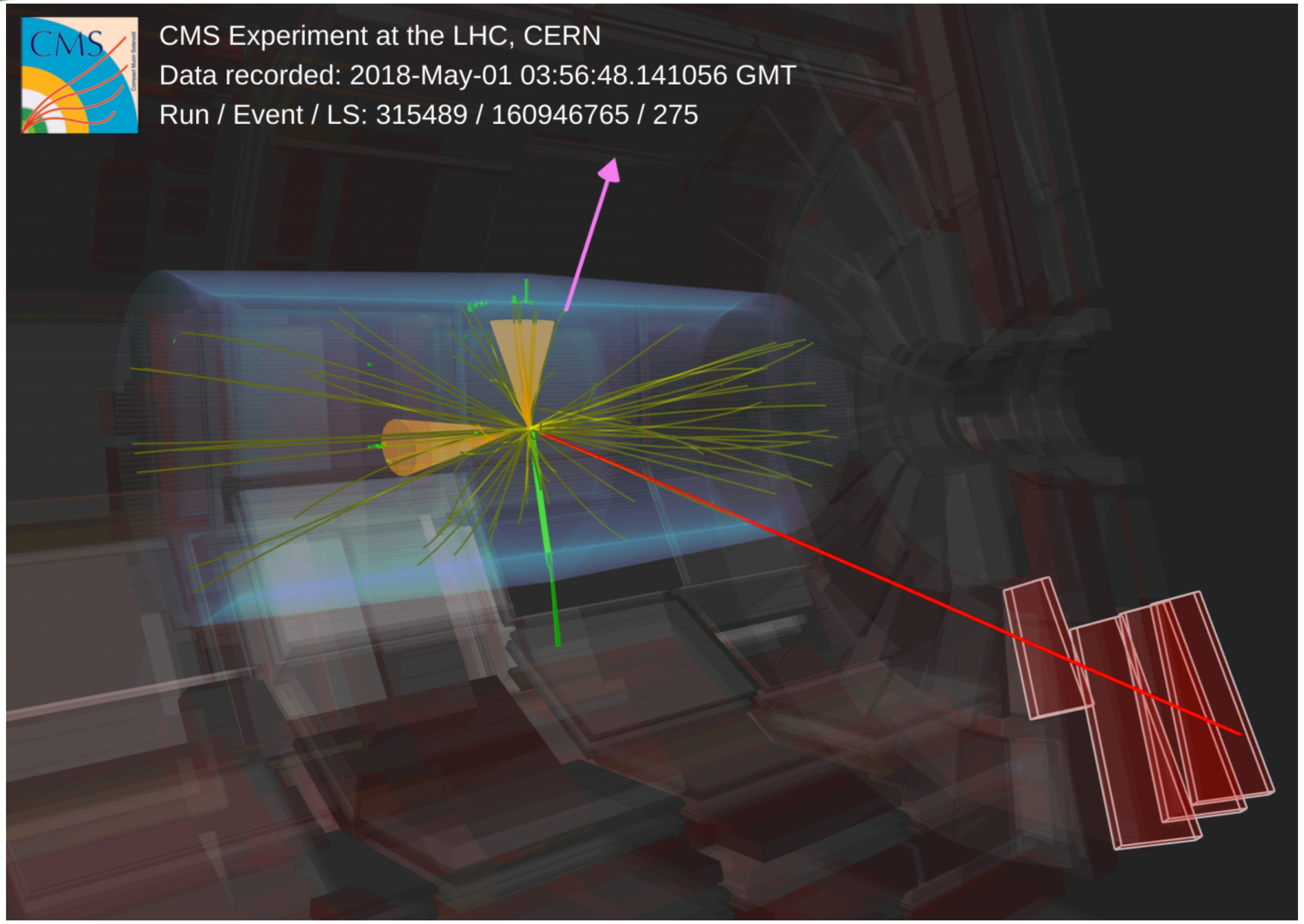

Event Selection and Top Reconstruction

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- split in 3 categories: ee, eμ and μμ
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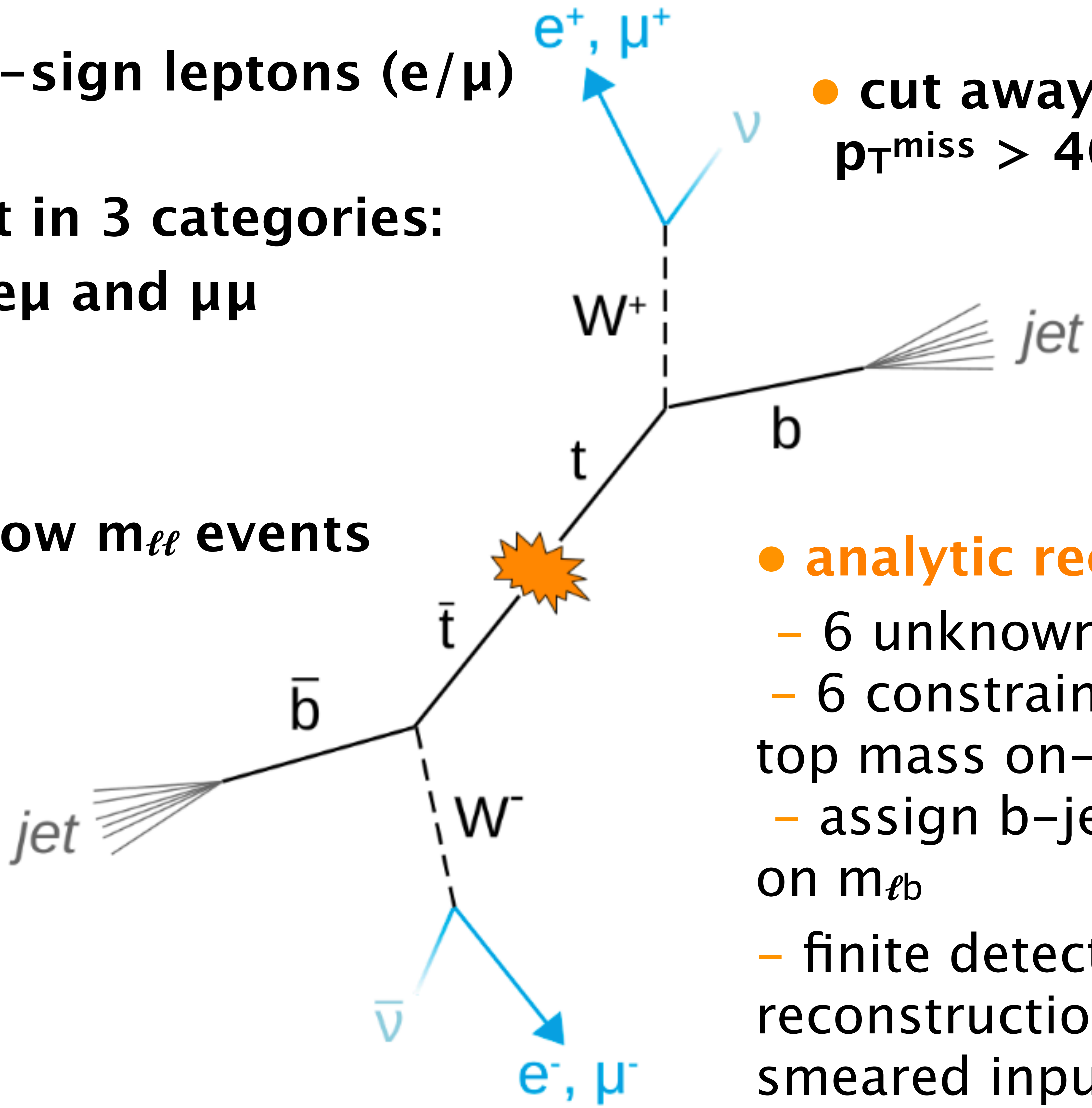
- 2 or more jets



- cut away Z peak & require p_T^{miss} > 40 GeV in ee/μμ
- 1 or more b-jets
- **analytic reconstruction of $t\bar{t}$ system**
  - 6 unknowns (2 massless neutrinos)
  - 6 constraints: all p_T^{miss} from νν, 2x top mass on-shell, 2xW mass on-shell
  - assign b-jets using likelihood, based on $m_{\ell b}$
  - finite detector resolution: repeat reconstruction 100 times with randomly smeared inputs, take weighted average

Event Selection and Spin Correlation

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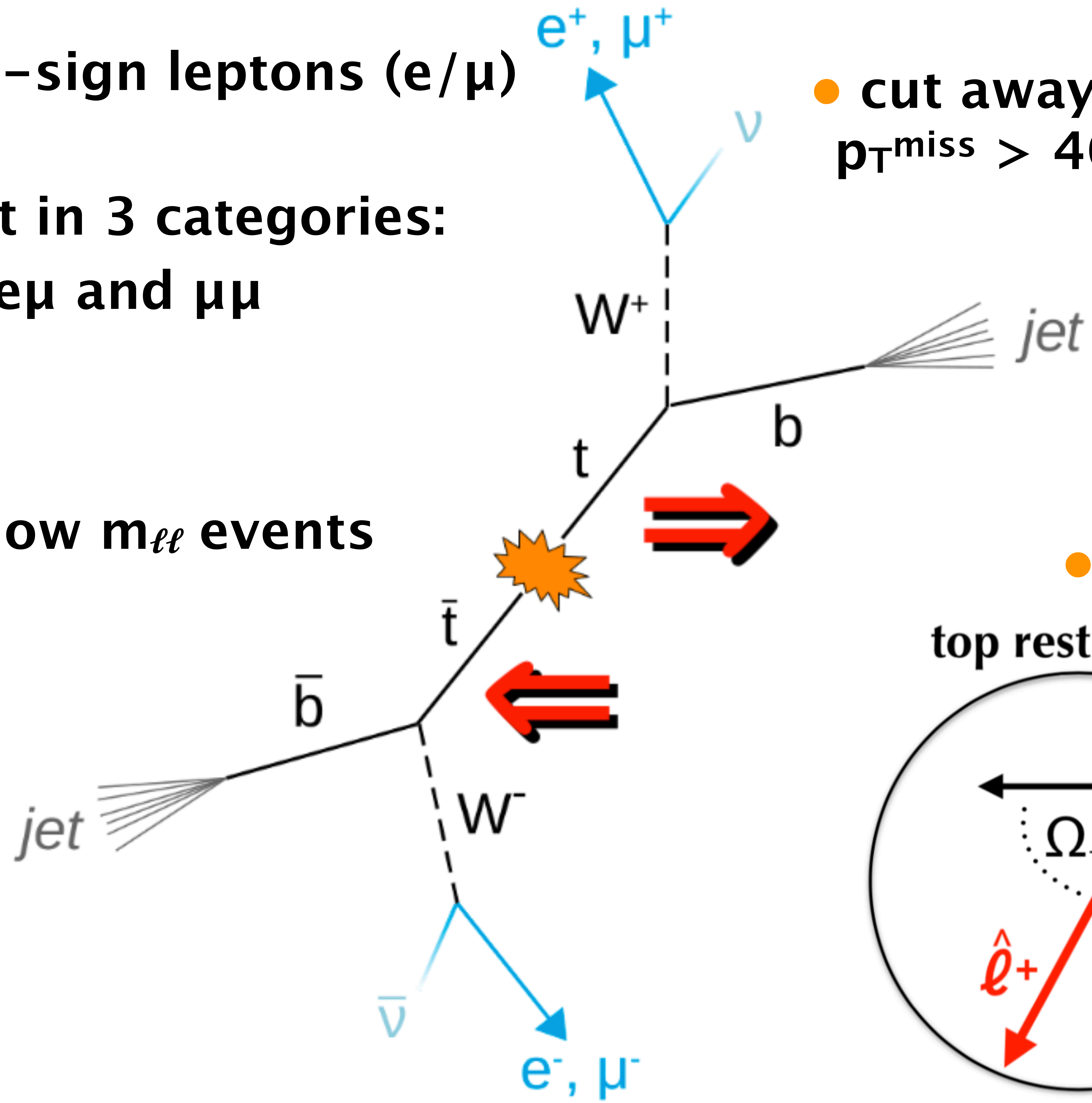
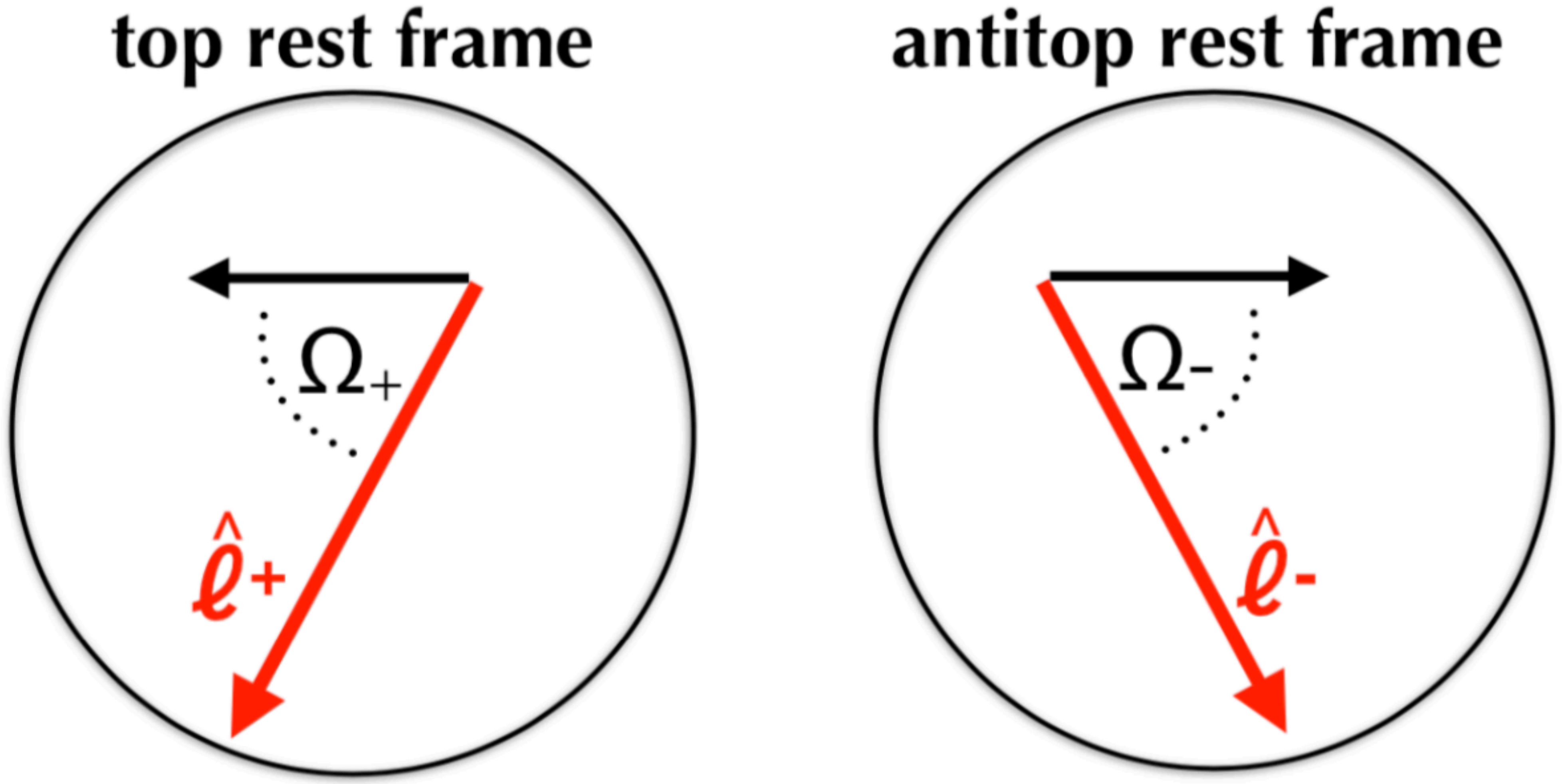
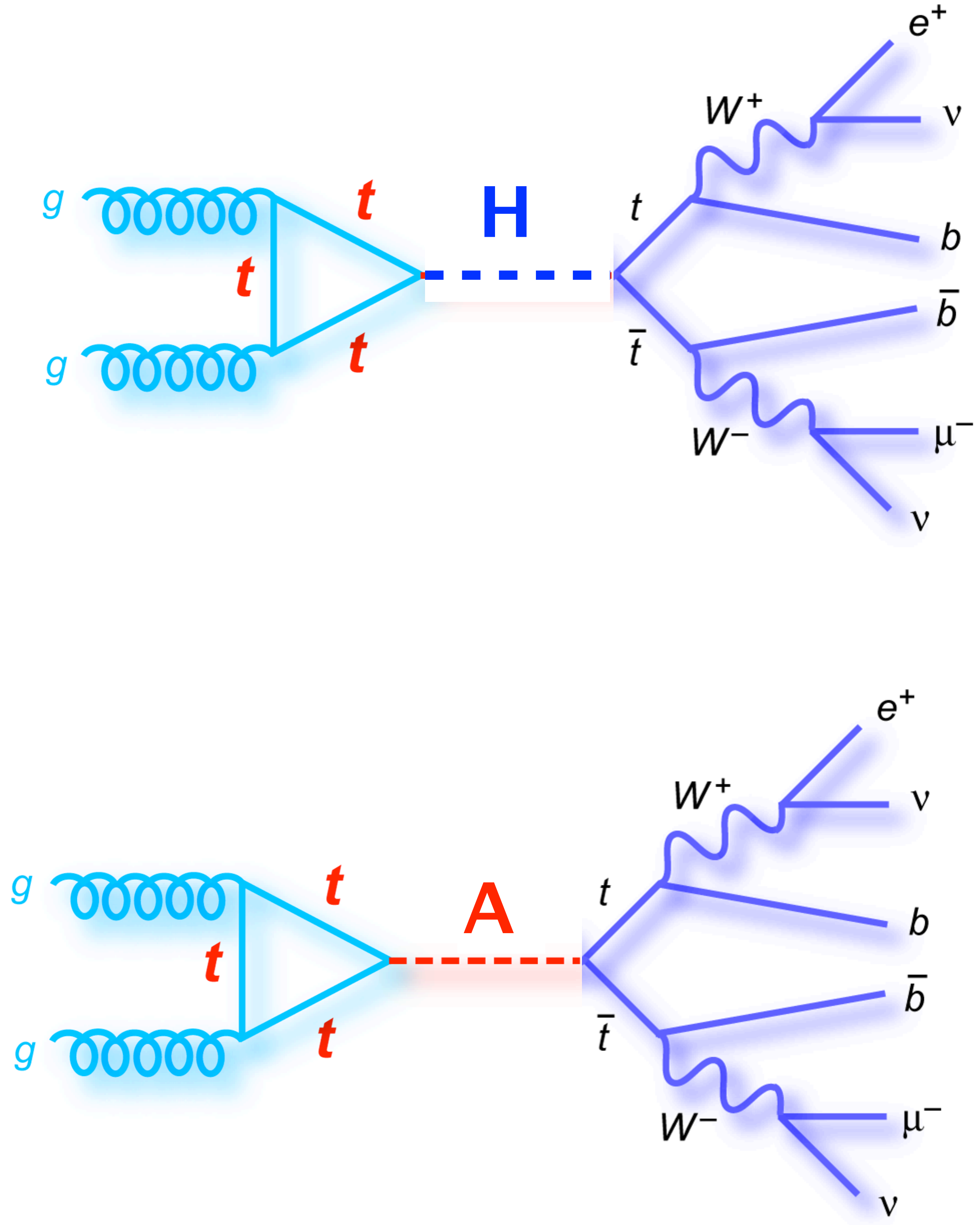


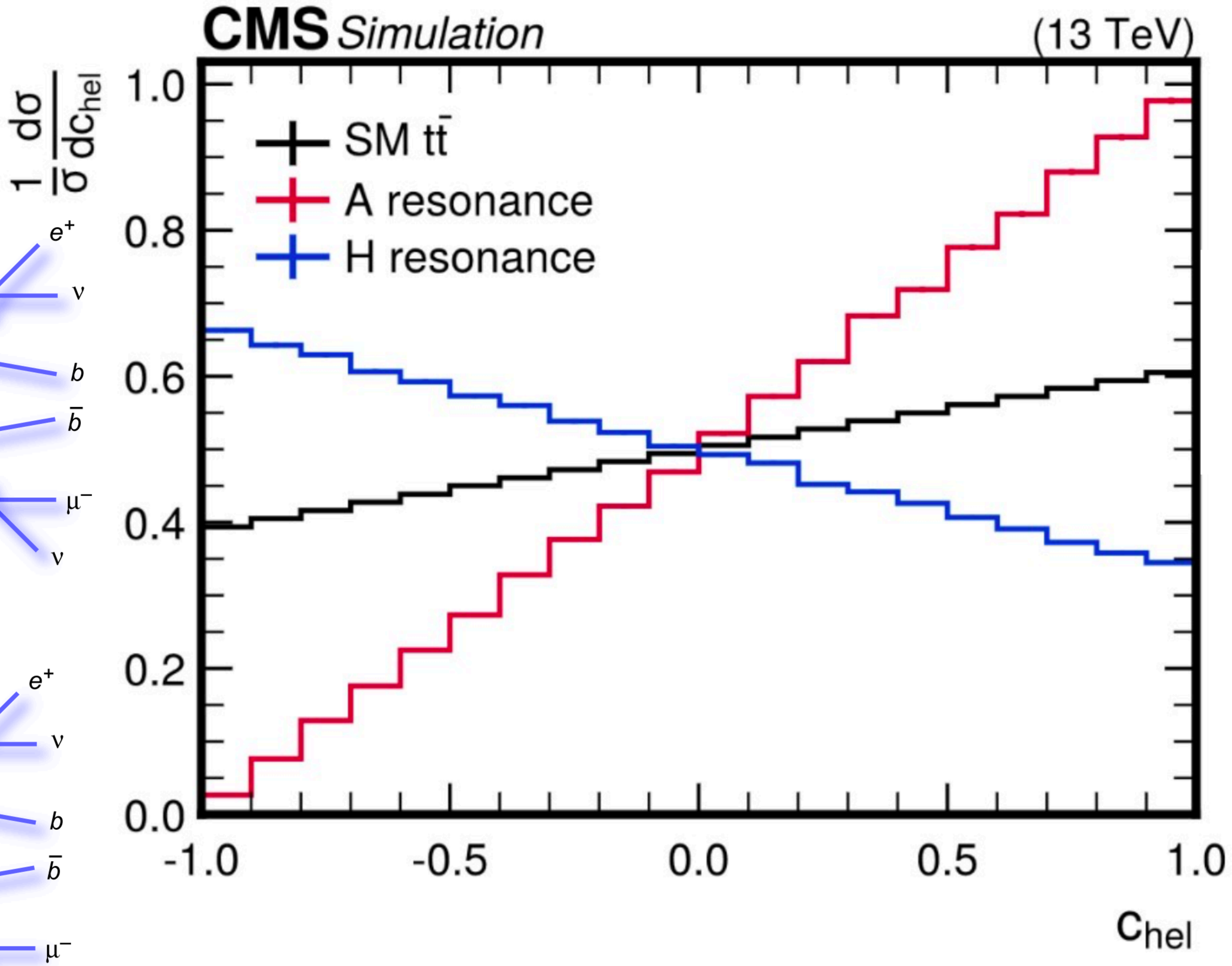
- cut away Z peak & require $p_T^{miss} > 40$ GeV in ee/μμ
- 1 or more b-jets
- $t\bar{t}$ spin correlation

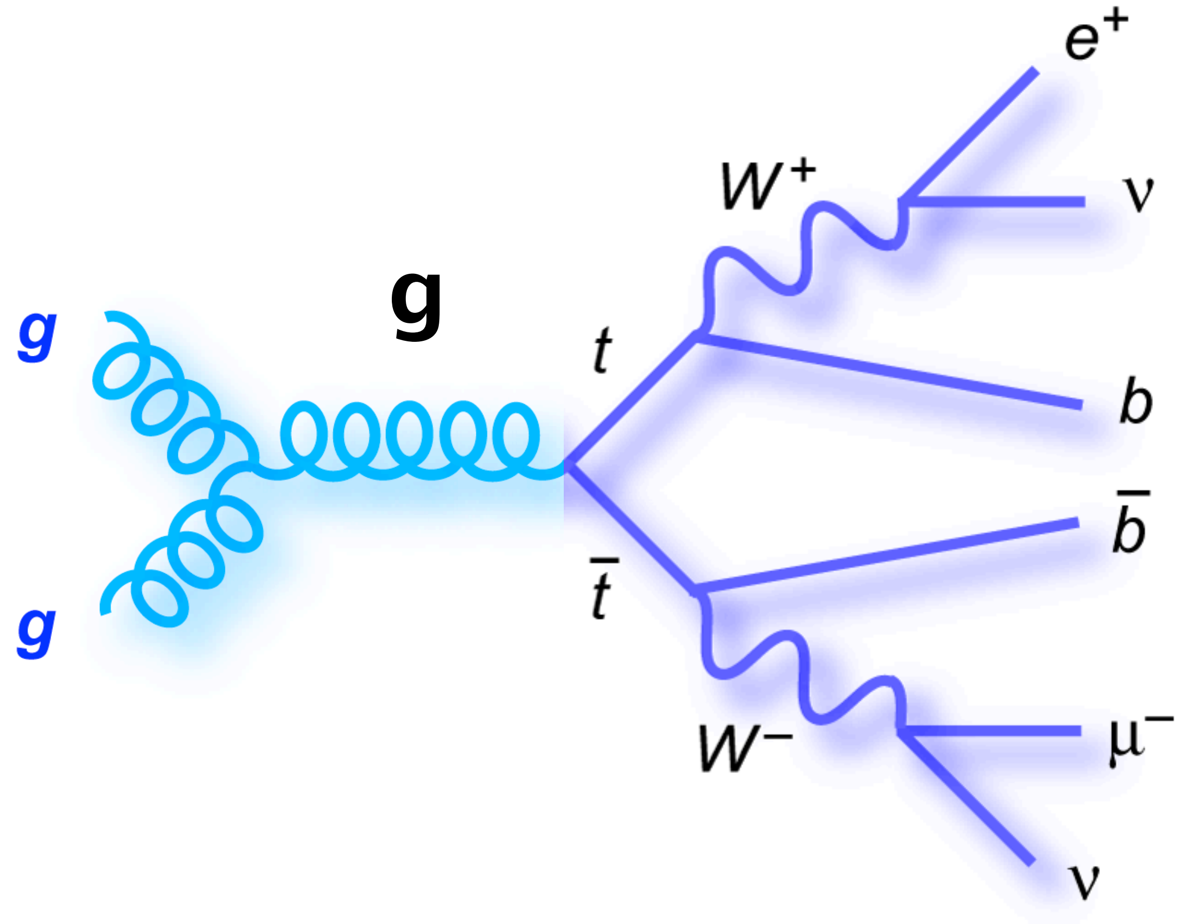


Top-Antitop Quark Spin Correlation

JHEP **12** (2015) 026



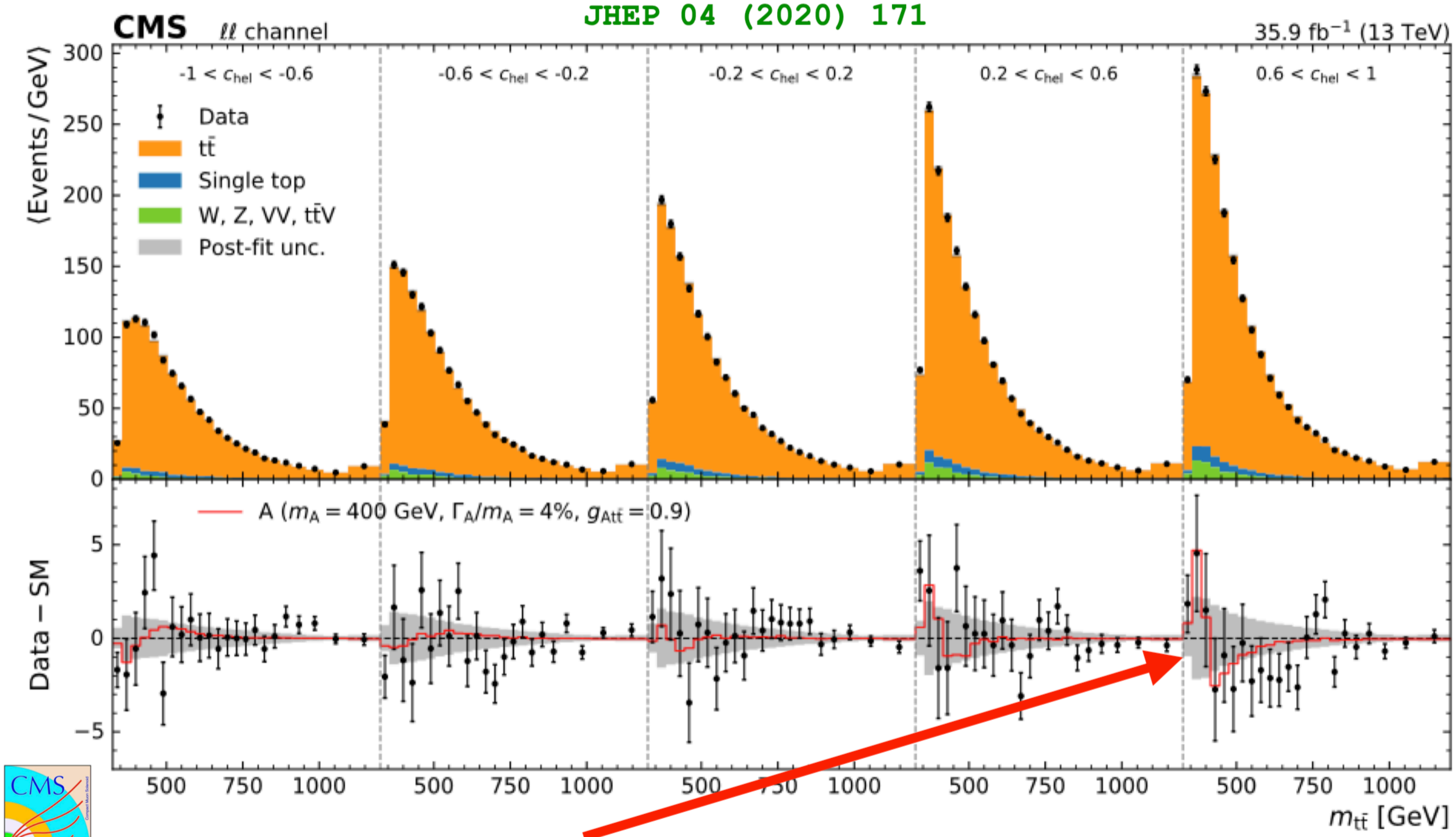




scalar product of charged lepton directions in parent top quark rest frames

→ **separates between pseudoscalar and SM**

Results of the 2016 Data



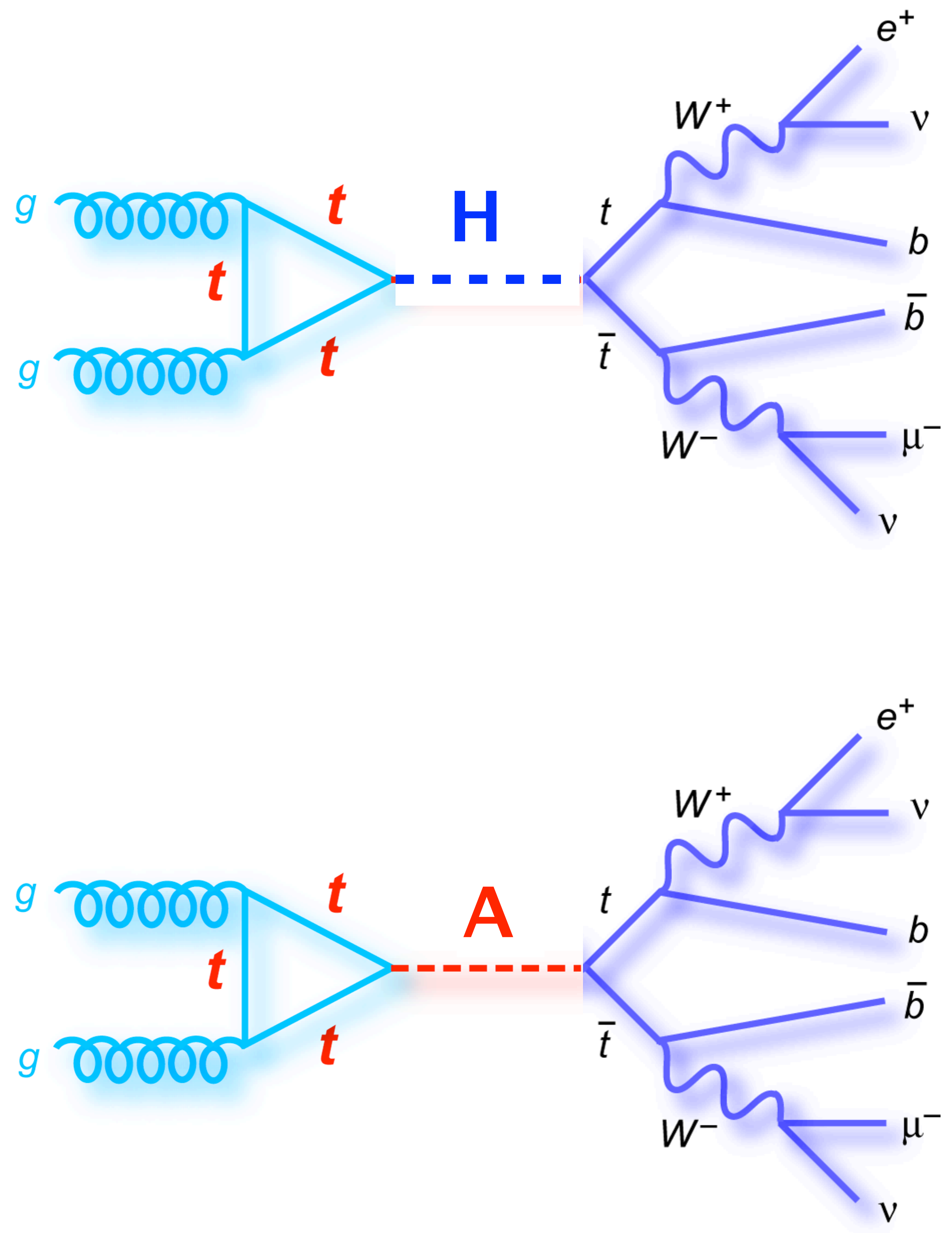
3.5σ local

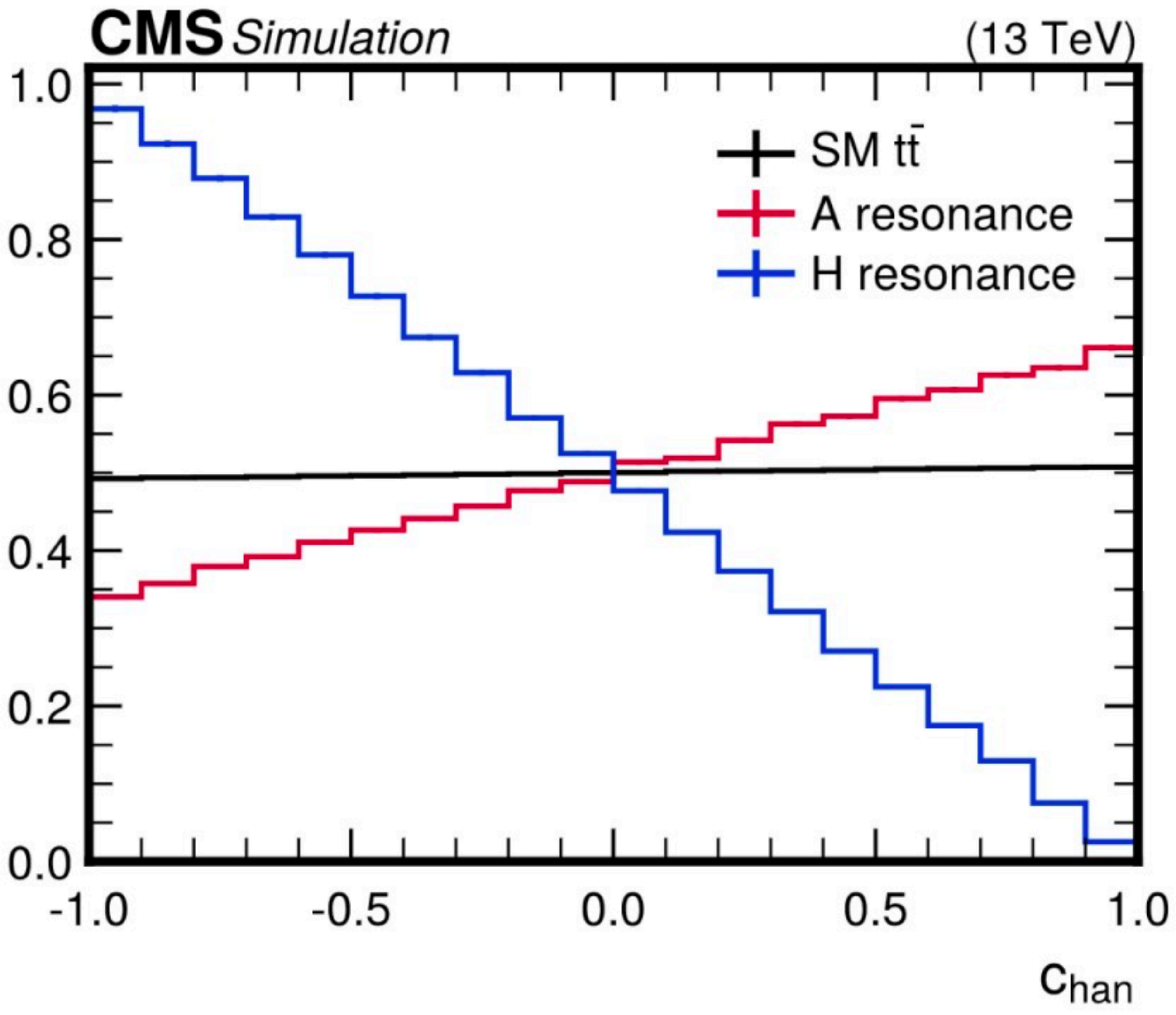
1.9σ global

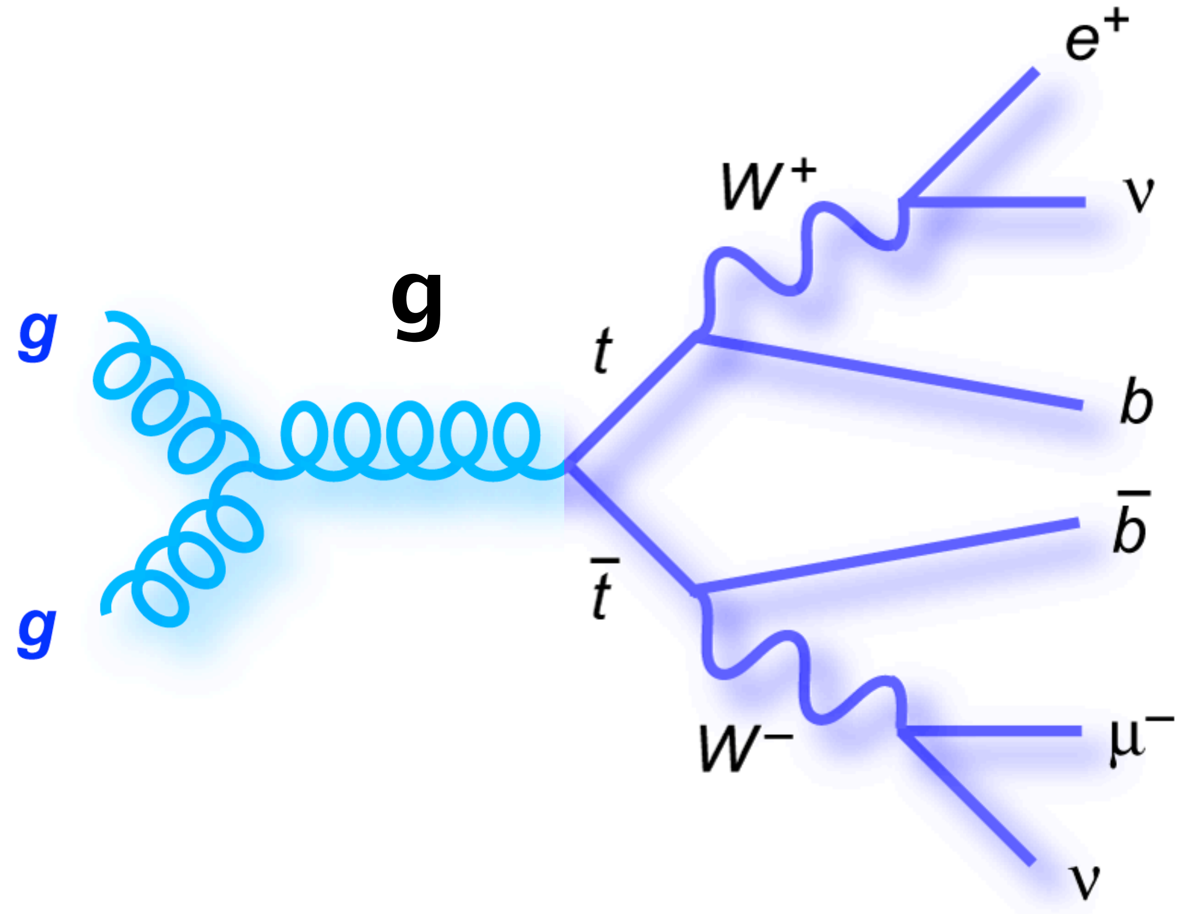
pseudoscalar, m_A=400 GeV

→ pseudoscalar excess at low $m_{t\bar{t}}$

Top-Antitop Quark Spin Correlation: Dilepton



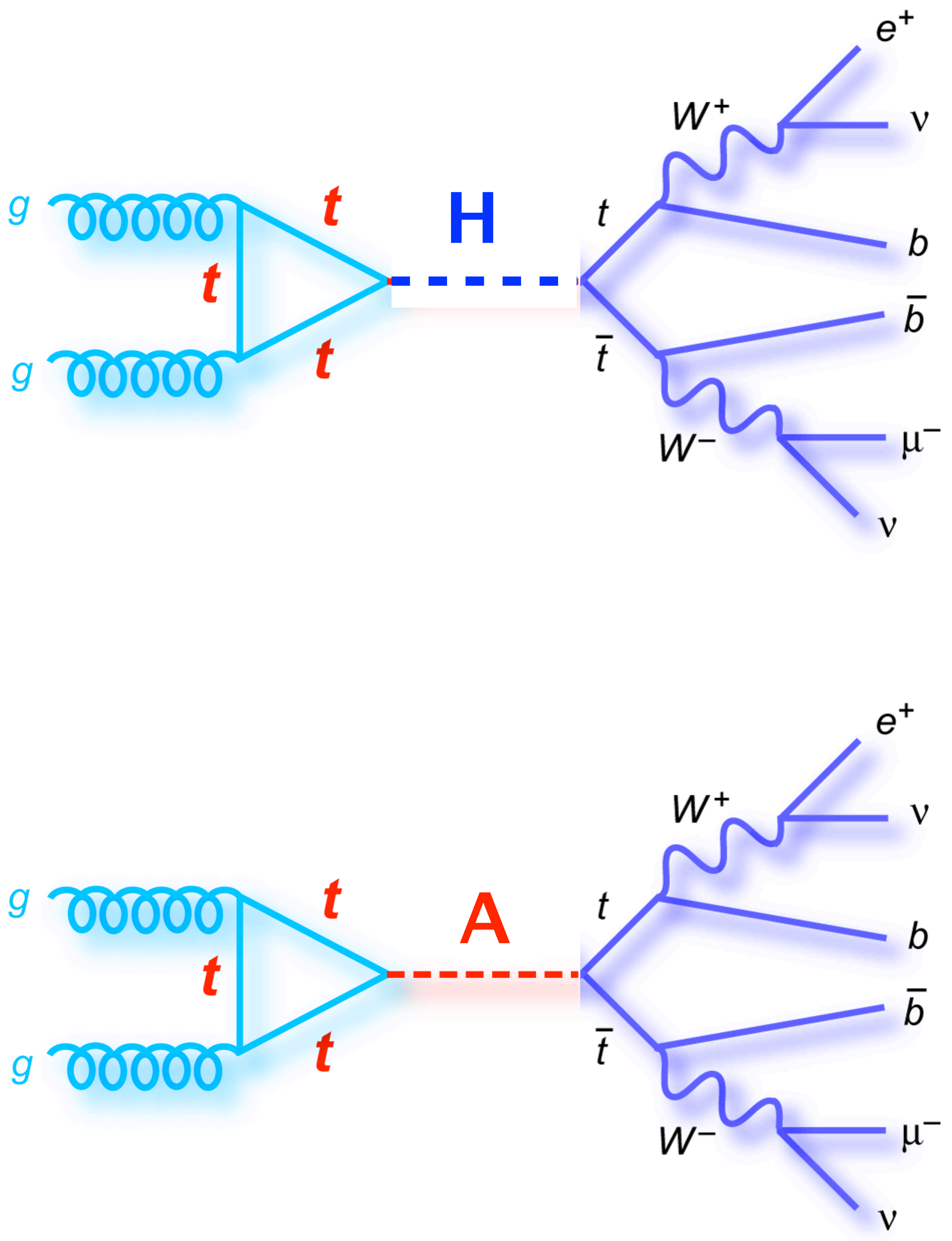


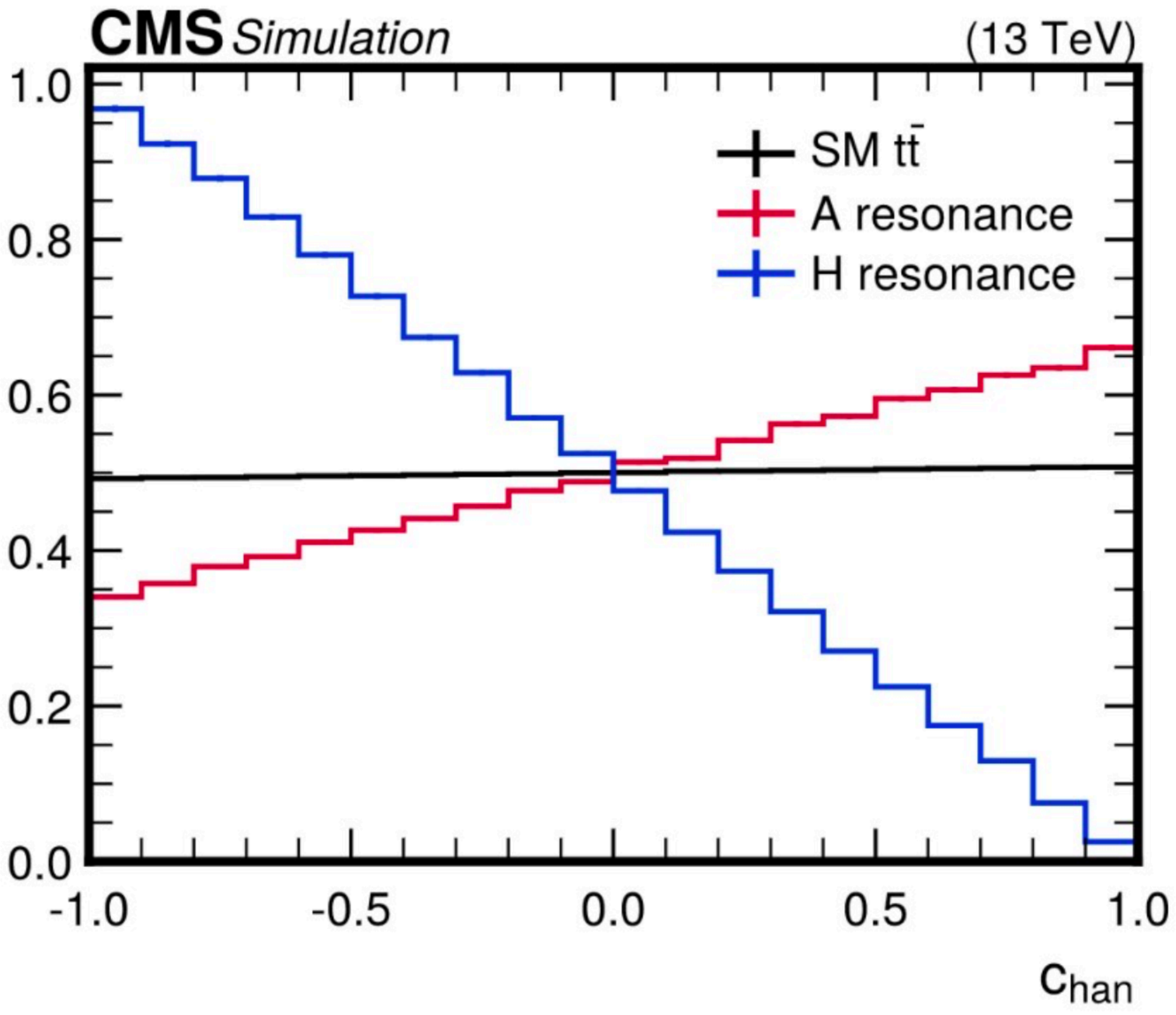


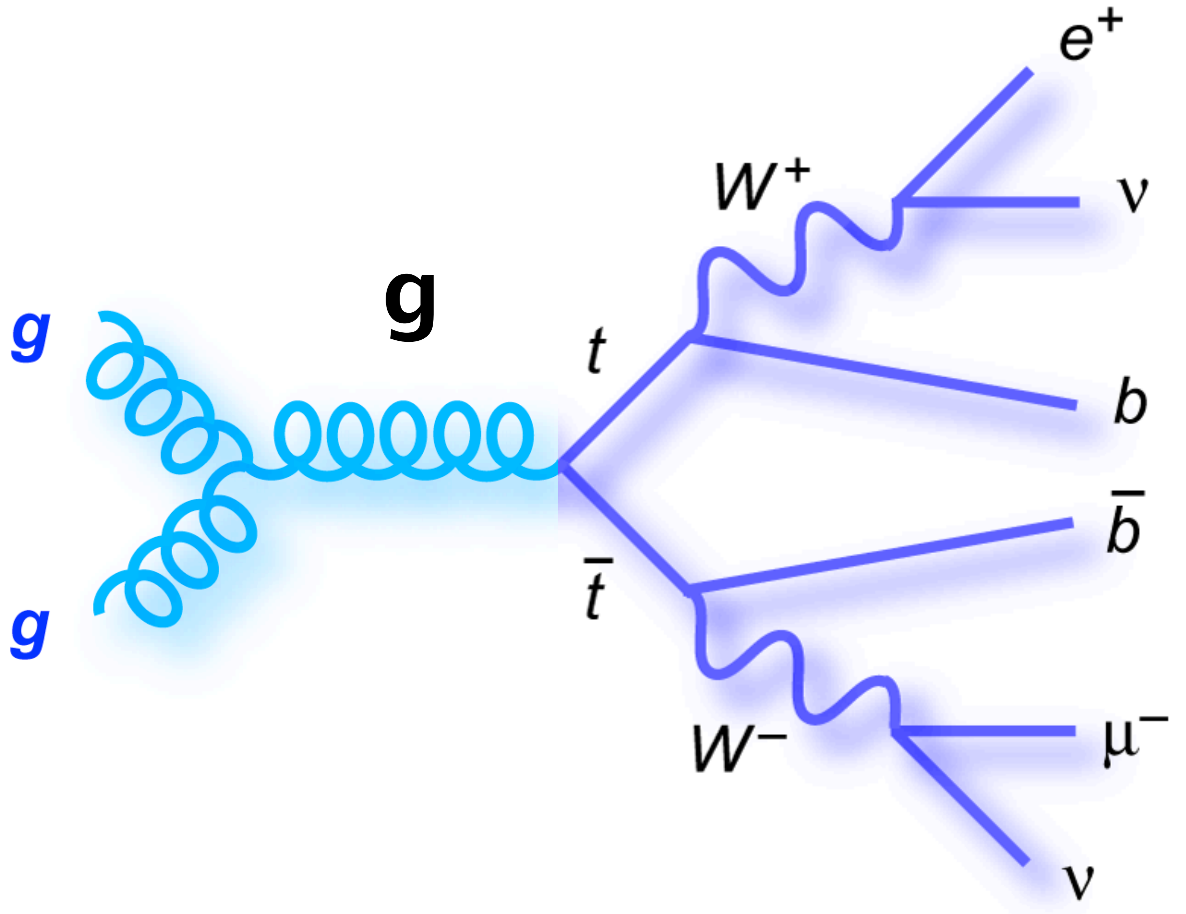
scalar product of charged lepton directions in parent top quark rest frames with a sign flip in top direction

→ **separates between pseudoscalar and scalar**

Top-Antitop Quark Spin Correlation: Dilepton







scalar product of charged lepton directions in parent top quark rest frames with a sign flip in top direction

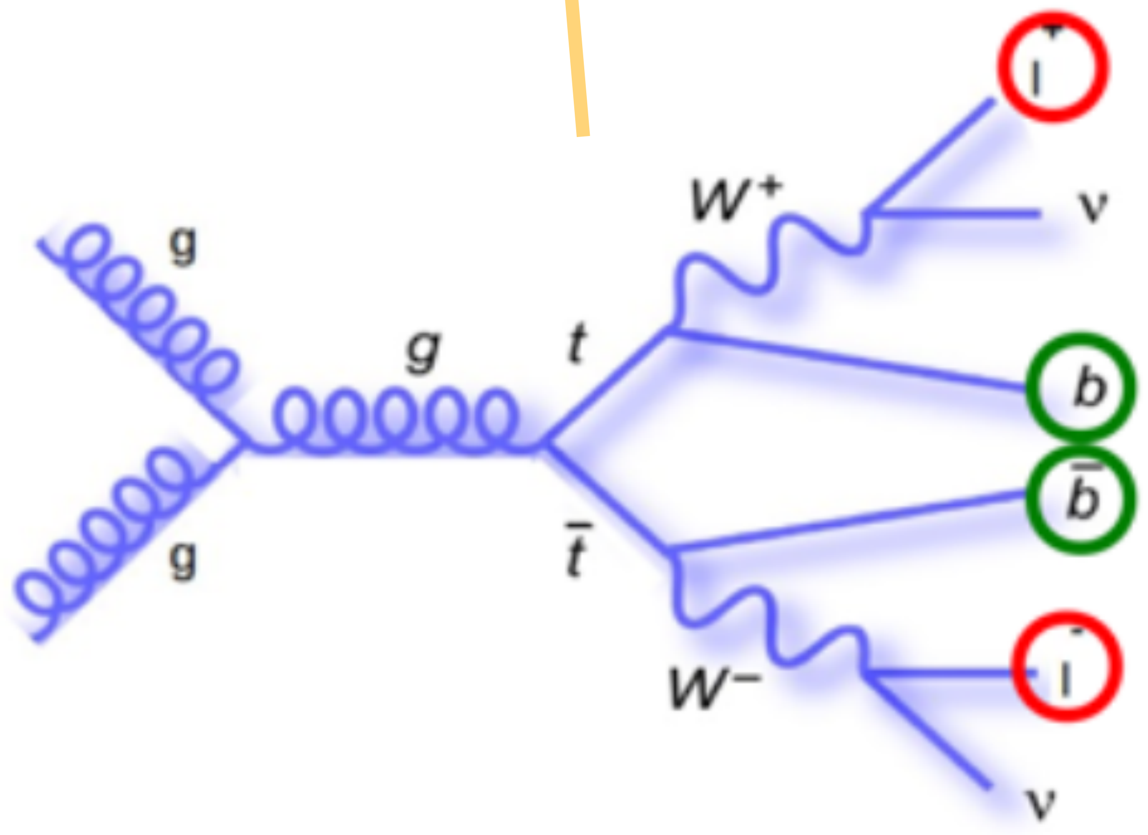
explore 3 variables simultaneously:
$m_{t\bar{t}}$, c_{hel}, c_{han}

→ separates between pseudoscalar and scalar

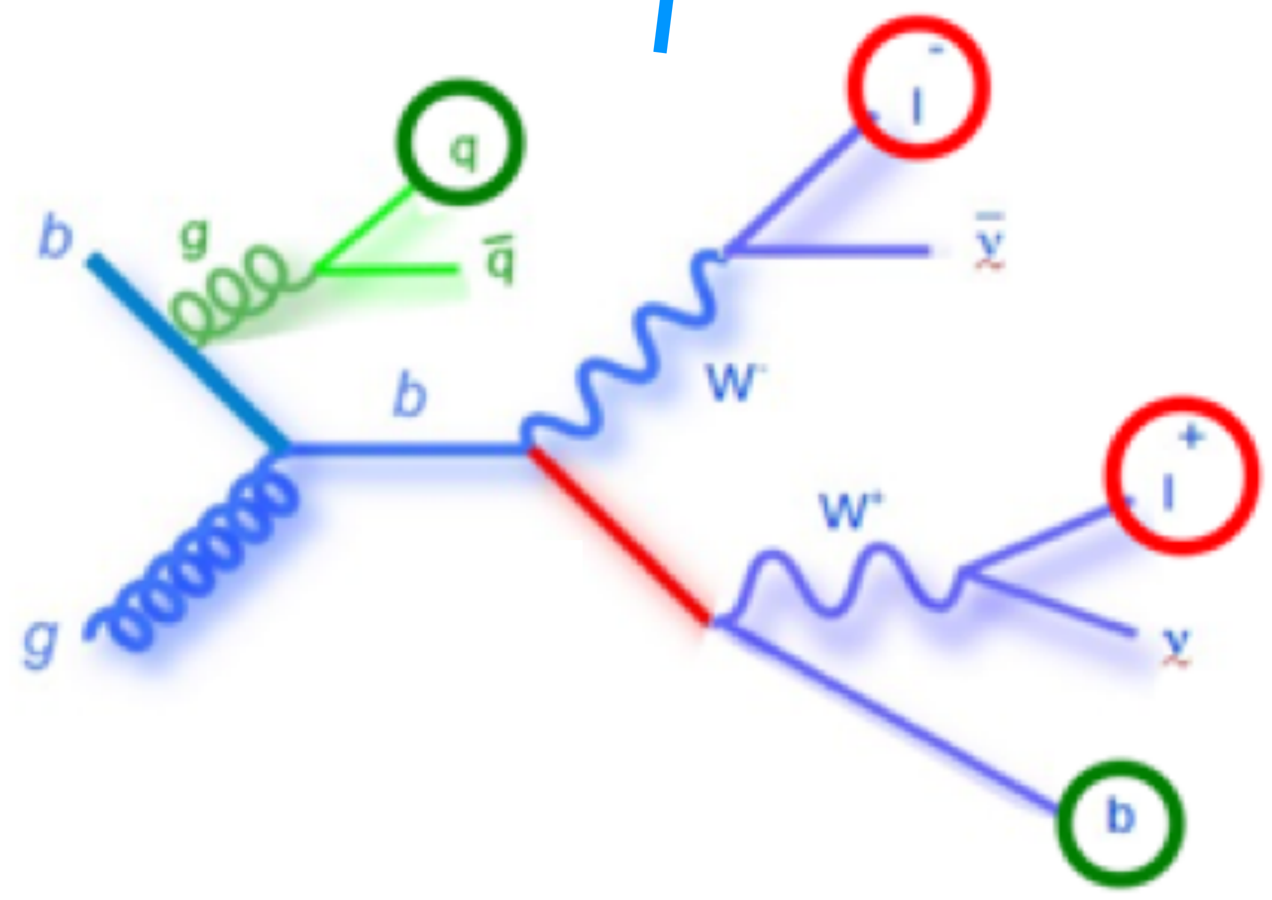
Results and Background Modeling

Top pair production

- Fixed-Order perturbative QCD 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



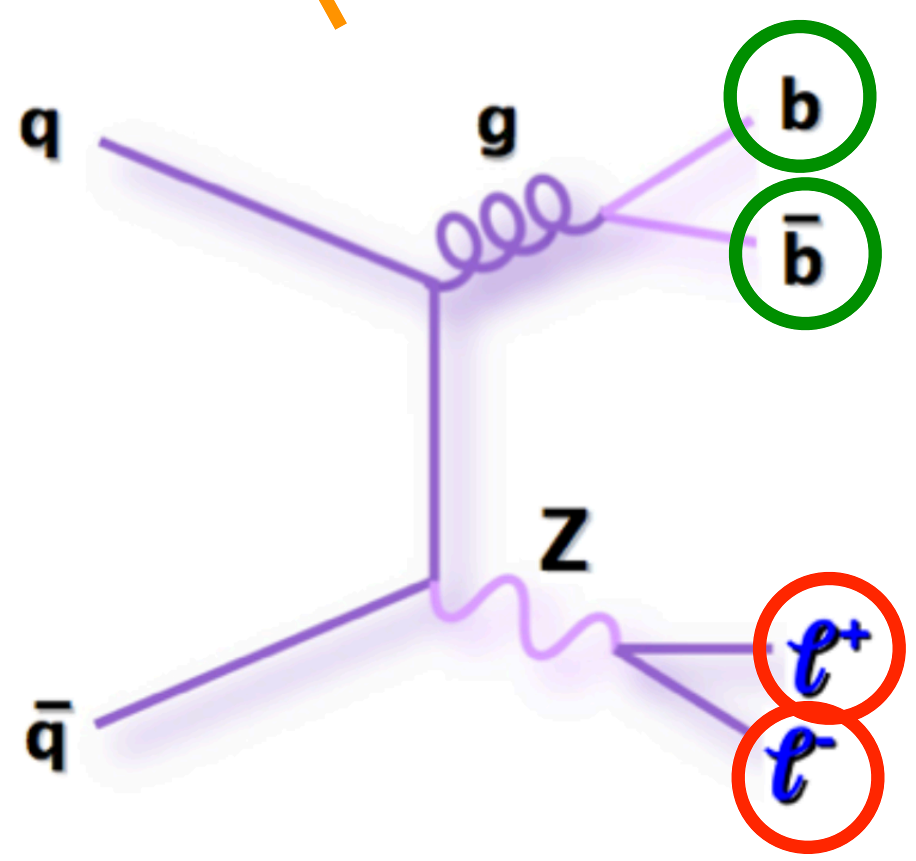
Results and Background Modeling



Single top production

- Wt, t-channel, s-channel
- from MC
- normalised to (N)NLO

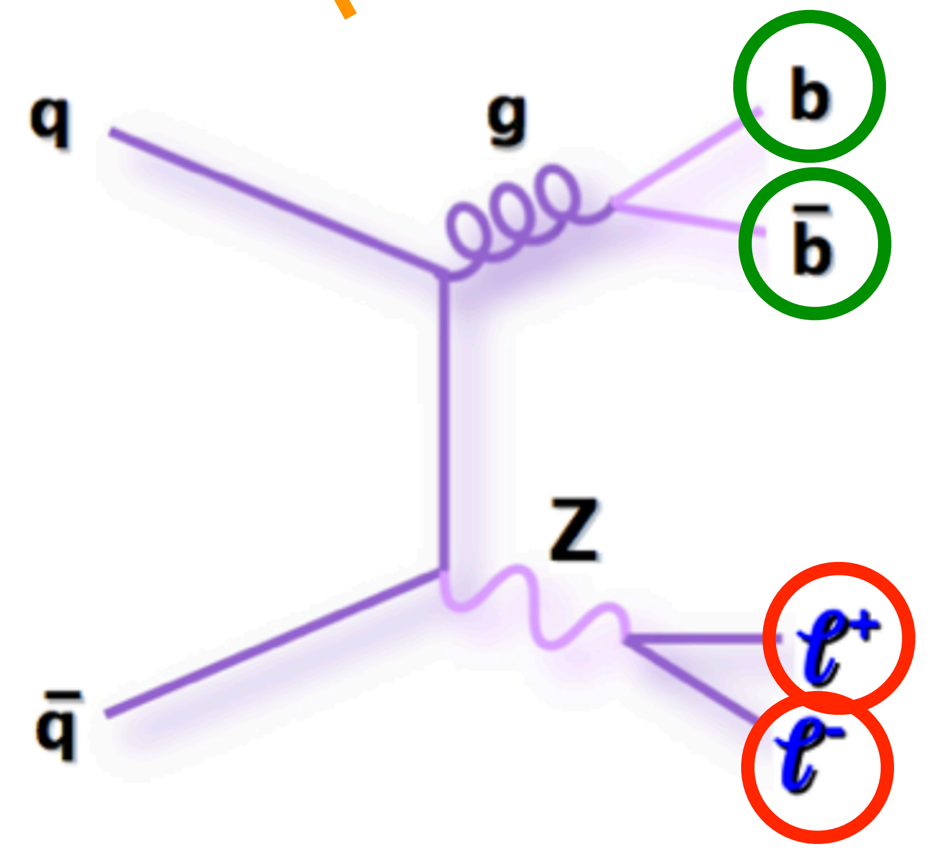
Results and Background Modeling

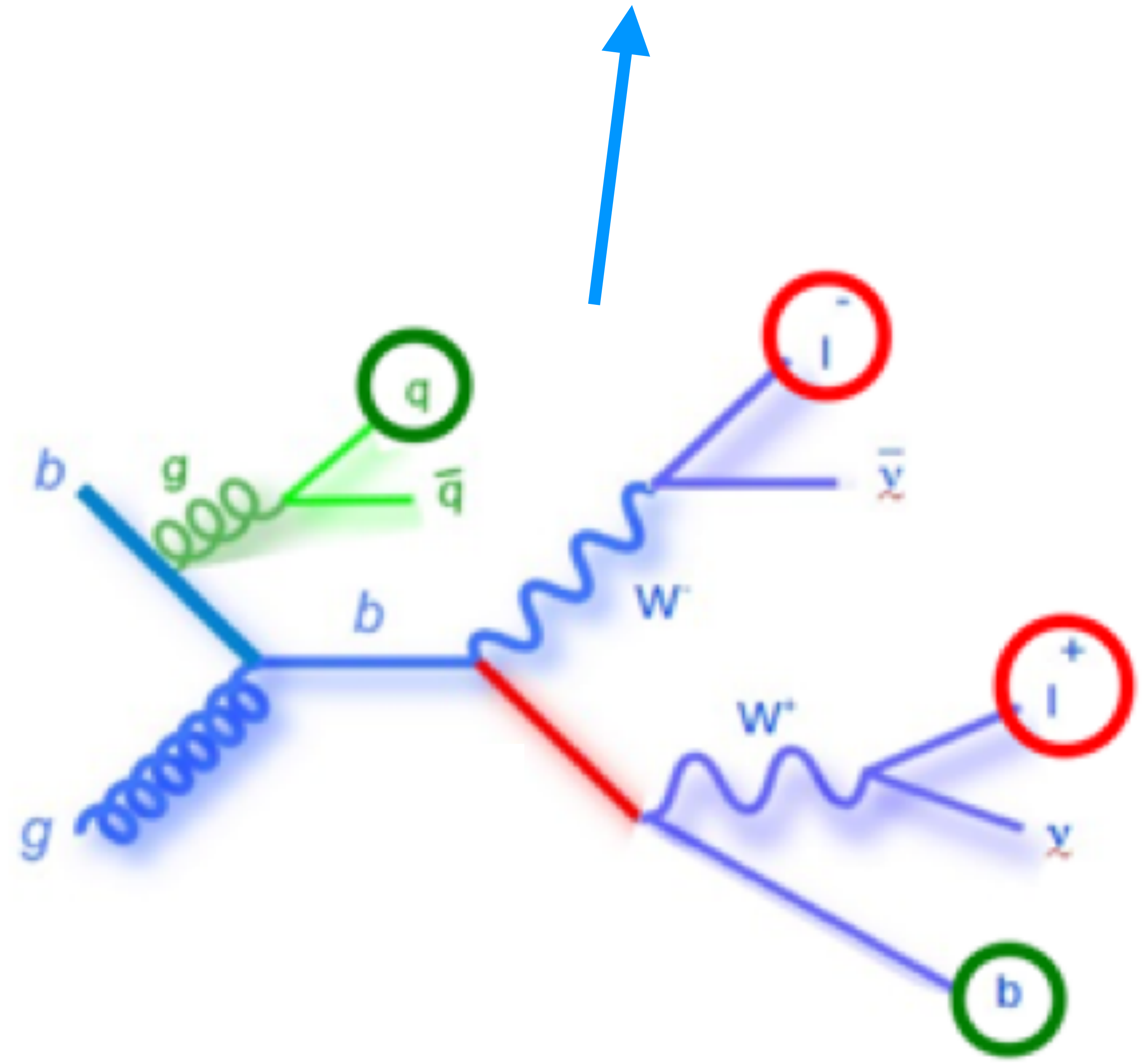


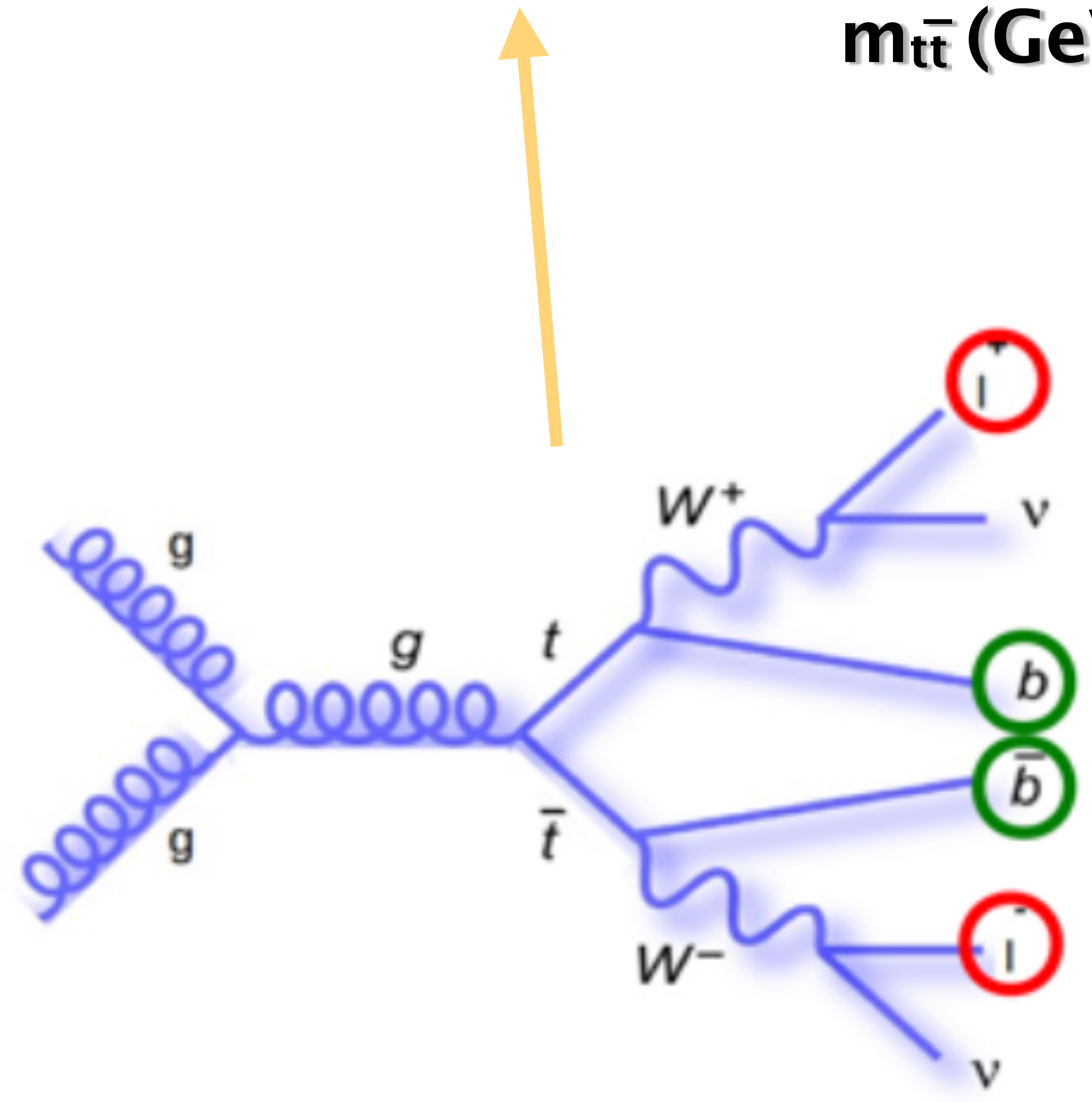
Drell-Yan+jets production

- MiNNLO simulations
- Data-driven normalisation from Z peak

Results and Background Modeling

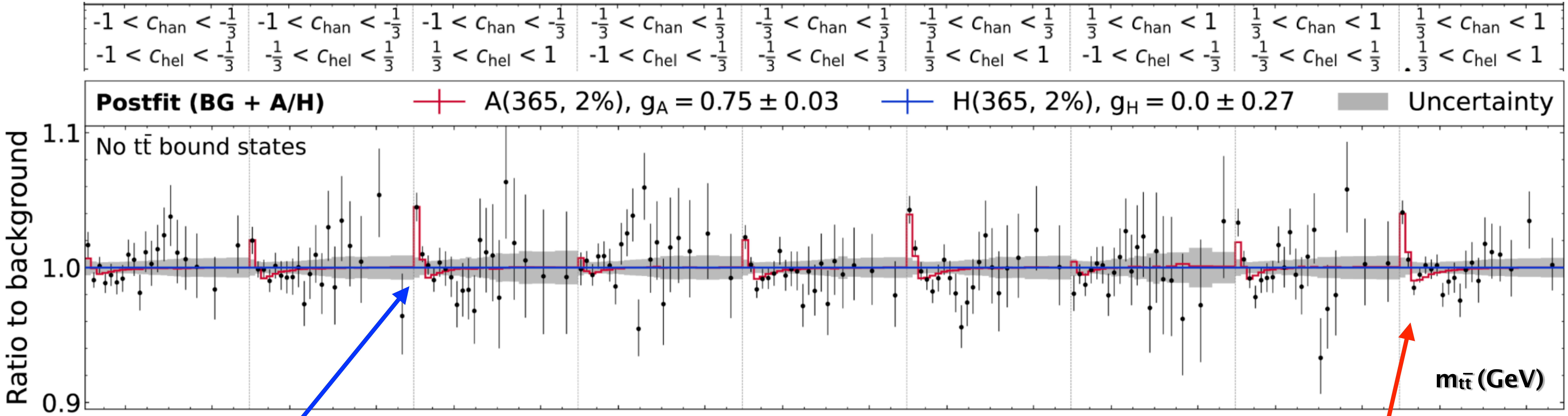


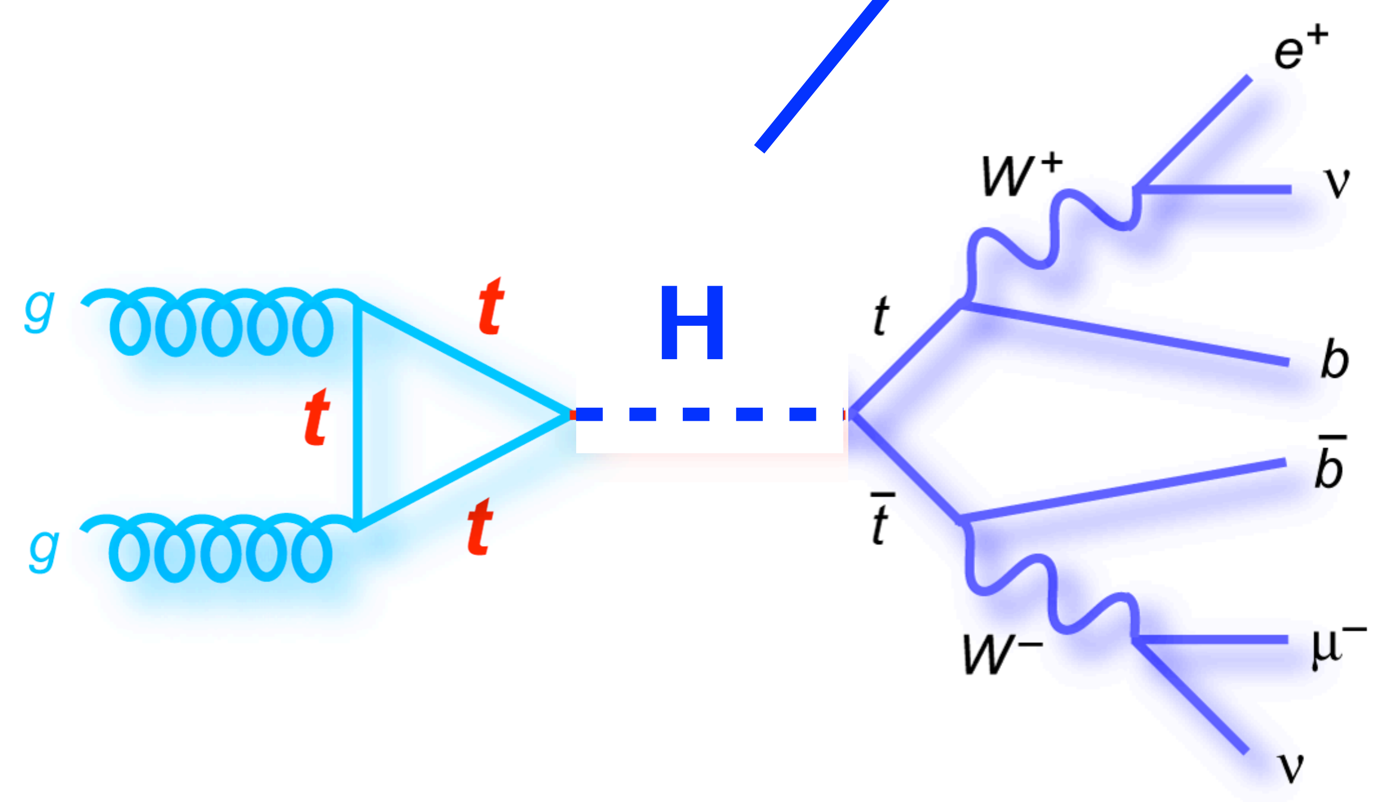




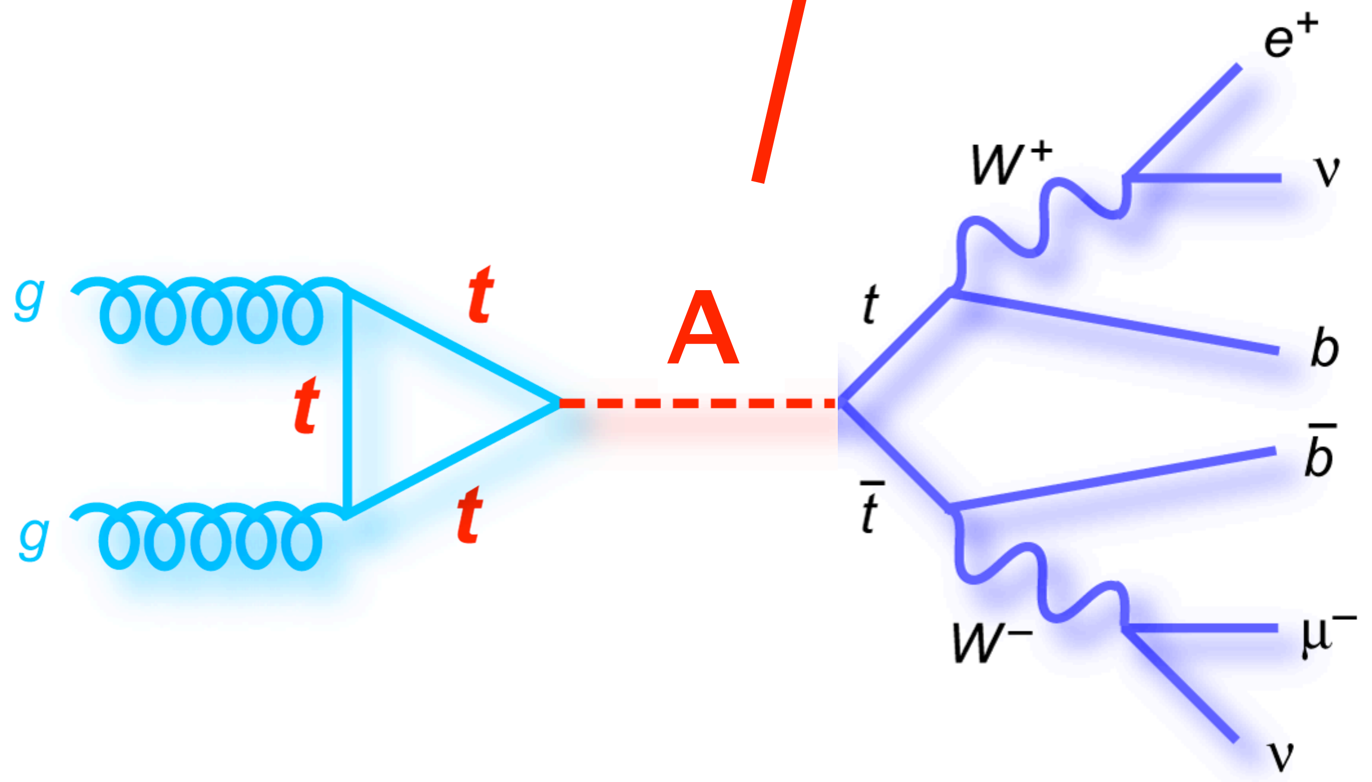
Results of the 2016–2018 Data

138 fb^{-1} of pp collisions at 13 TeV





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



→ pseudoscalar excess at low $m_{t\bar{t}}$

Another Interpretation: $t\bar{t}$ Bound States

Julia Münstermann, Toponium, 2025, cyanotype, 21 x 29.7 cm

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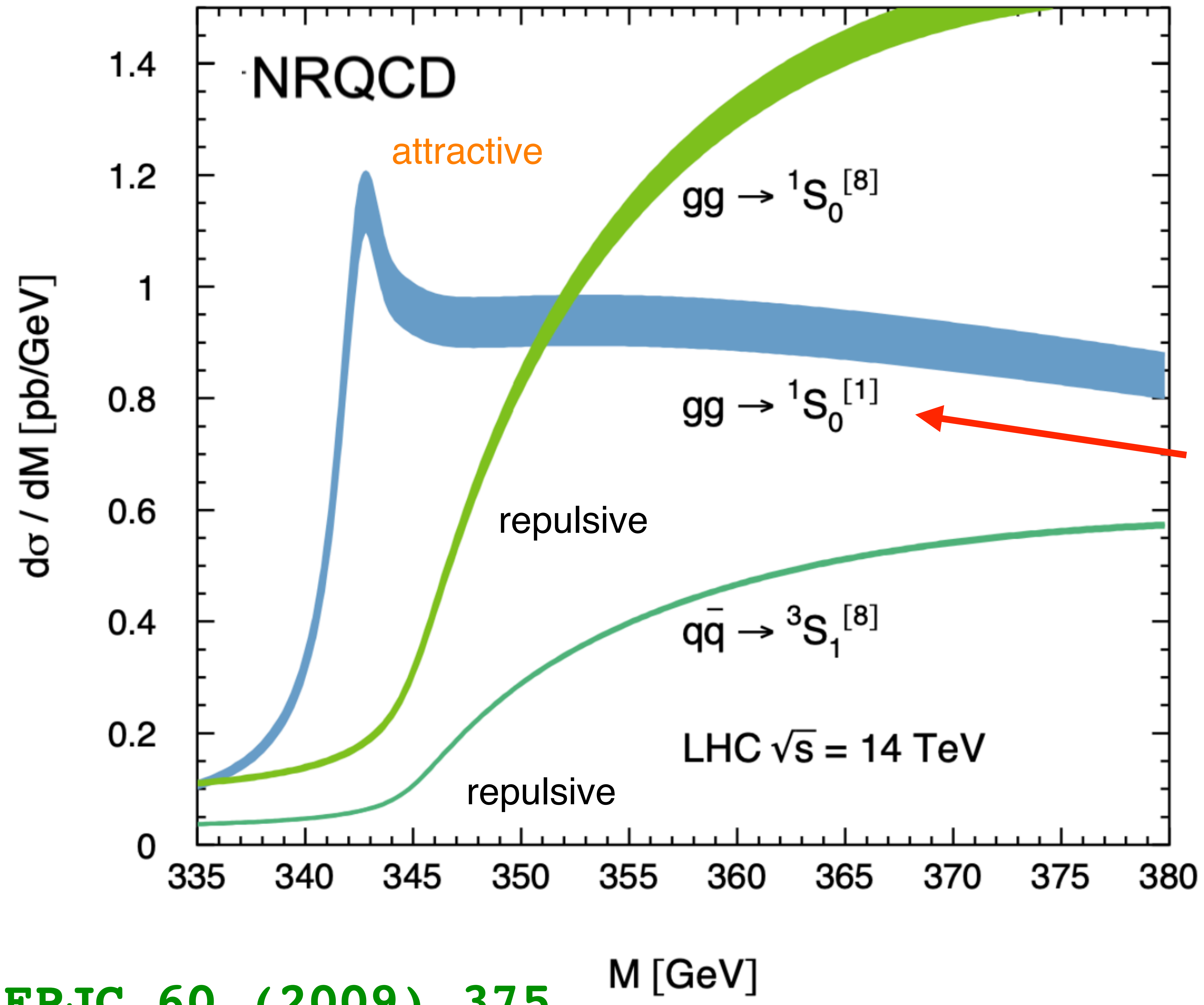
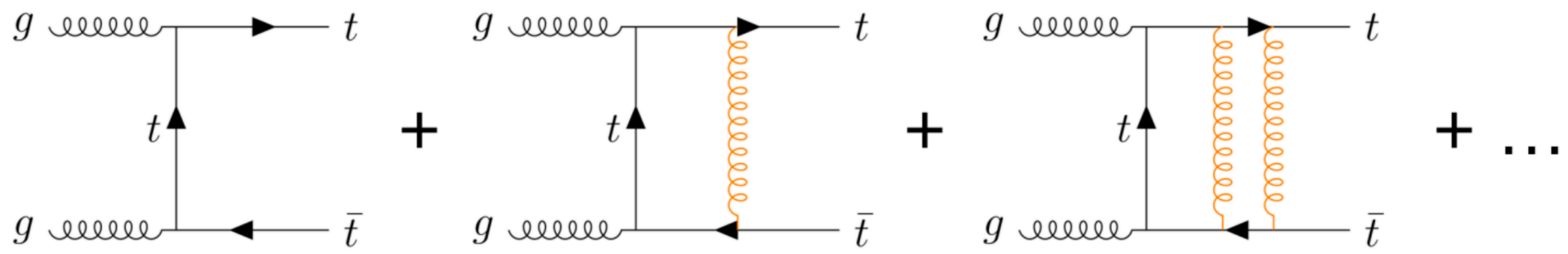


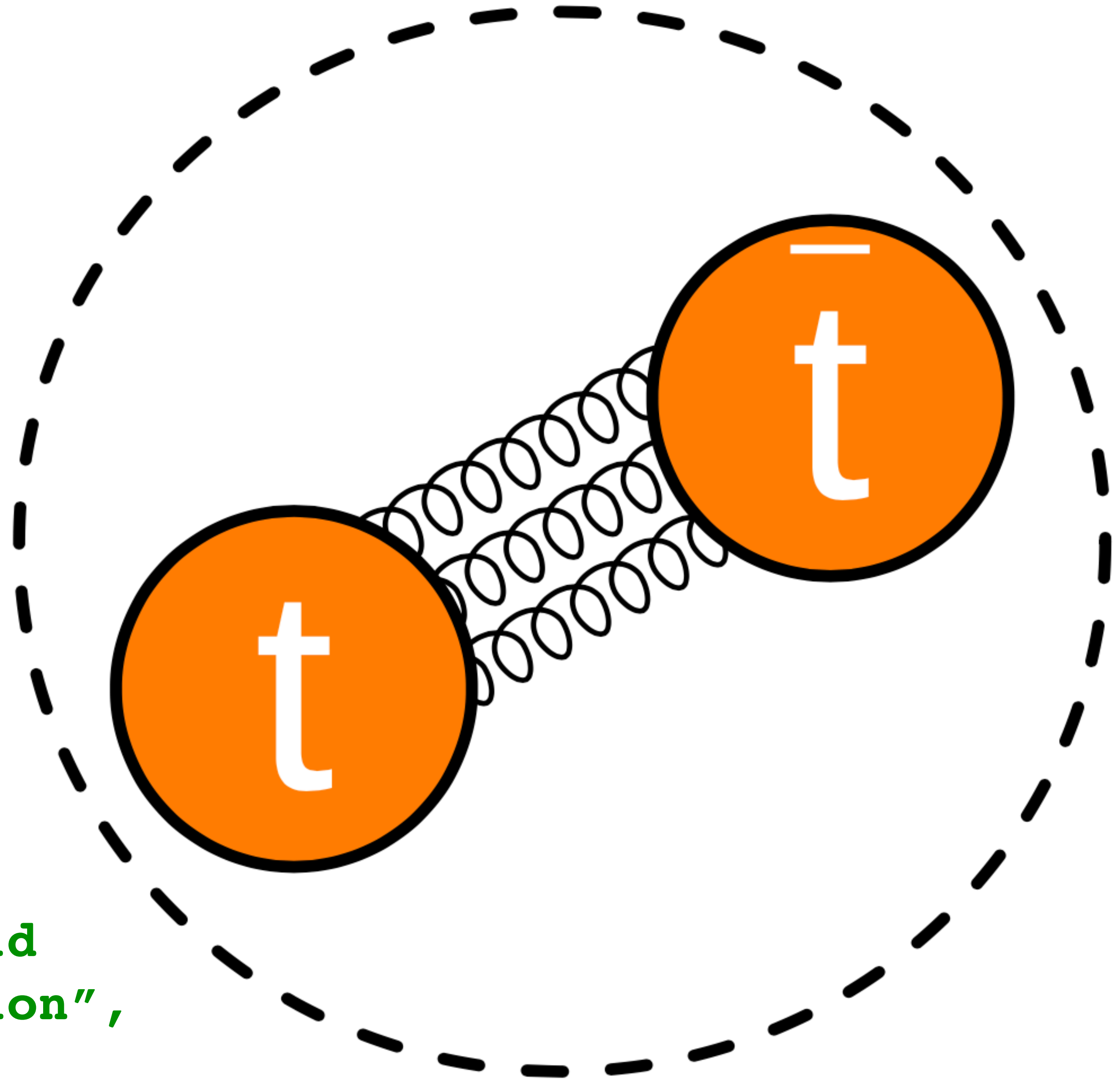
EPJC 60 (2009) 375



See talk by Maria Vittoria Garzelli

pseudoscalar toponium η_t:

$^1S_0^{[1]}$ spin-0, CP-odd, color-singlet



V.S.Fadin, V.A.Khoze, and T.Sjøstrand,“On the threshold behaviour of heavy top production”, Z. Phys. C 48 (1990) 613

→ threshold region is dominated by color-singlet pseudocalar toponium

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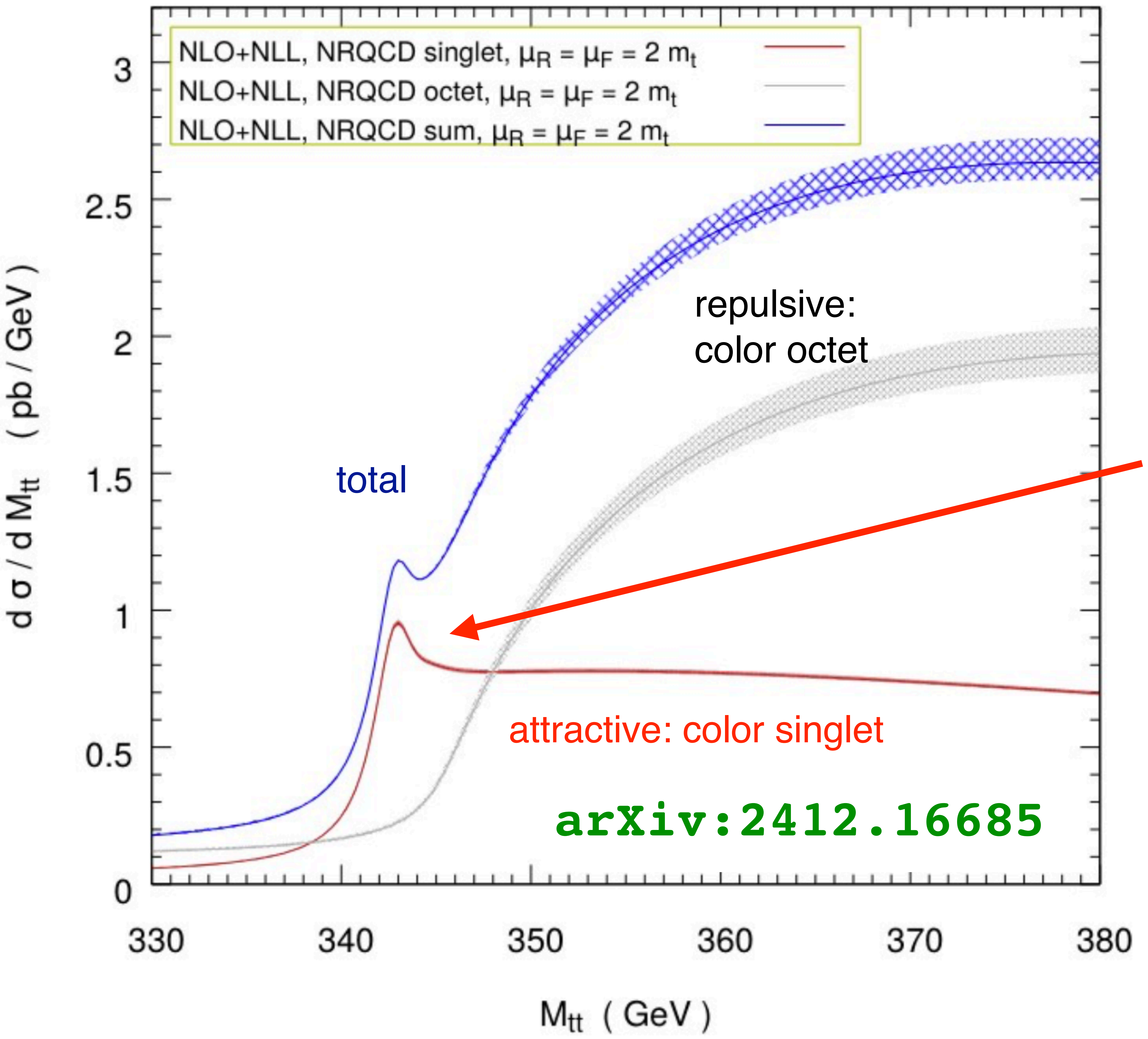

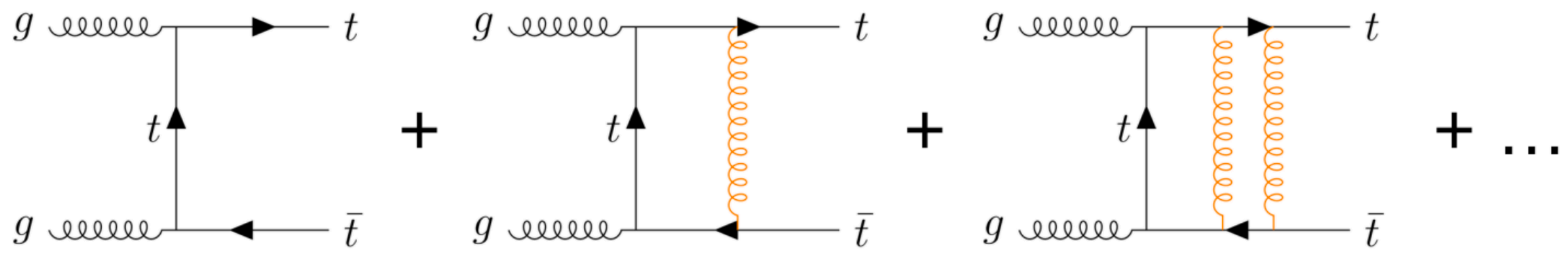

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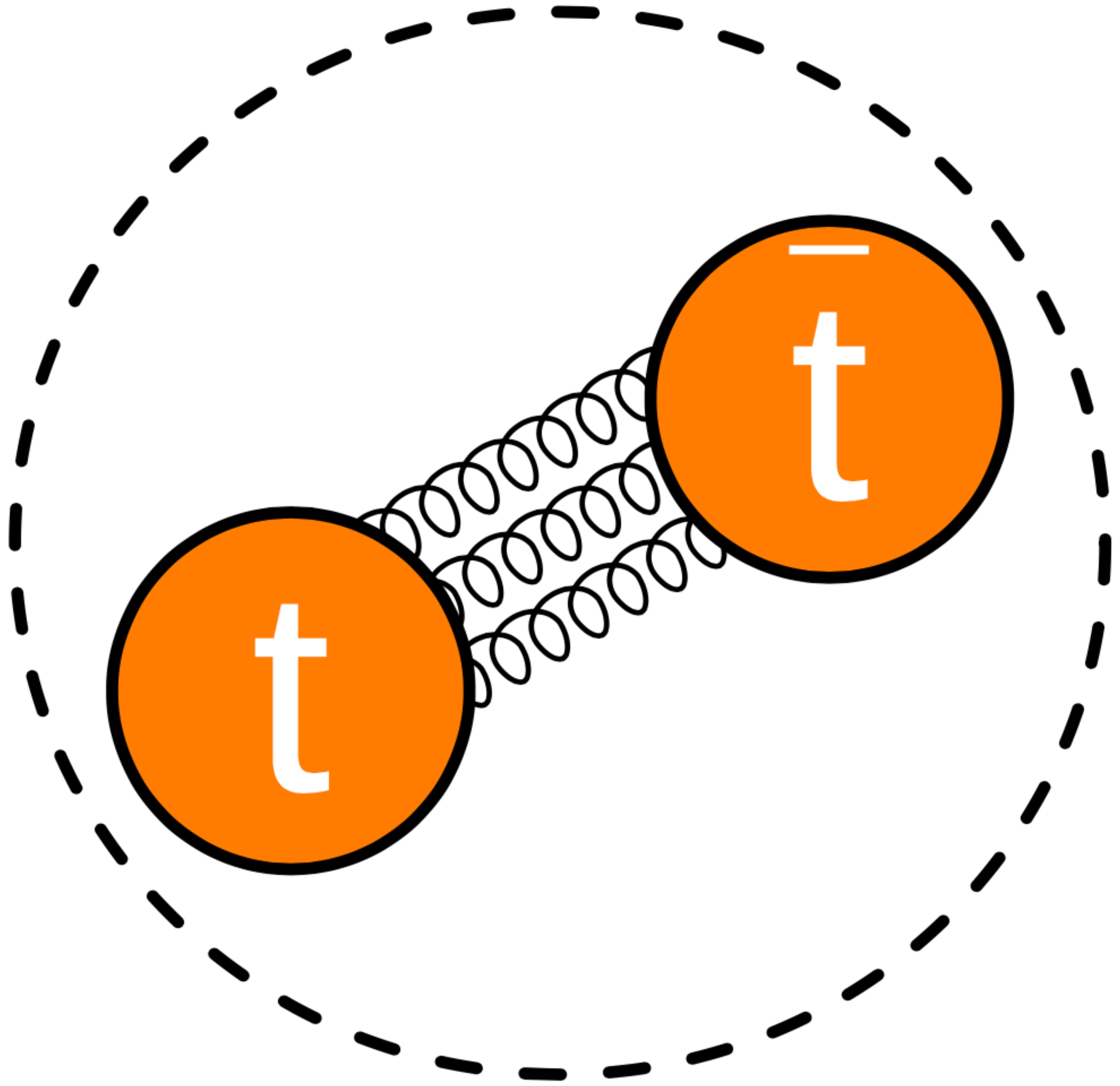

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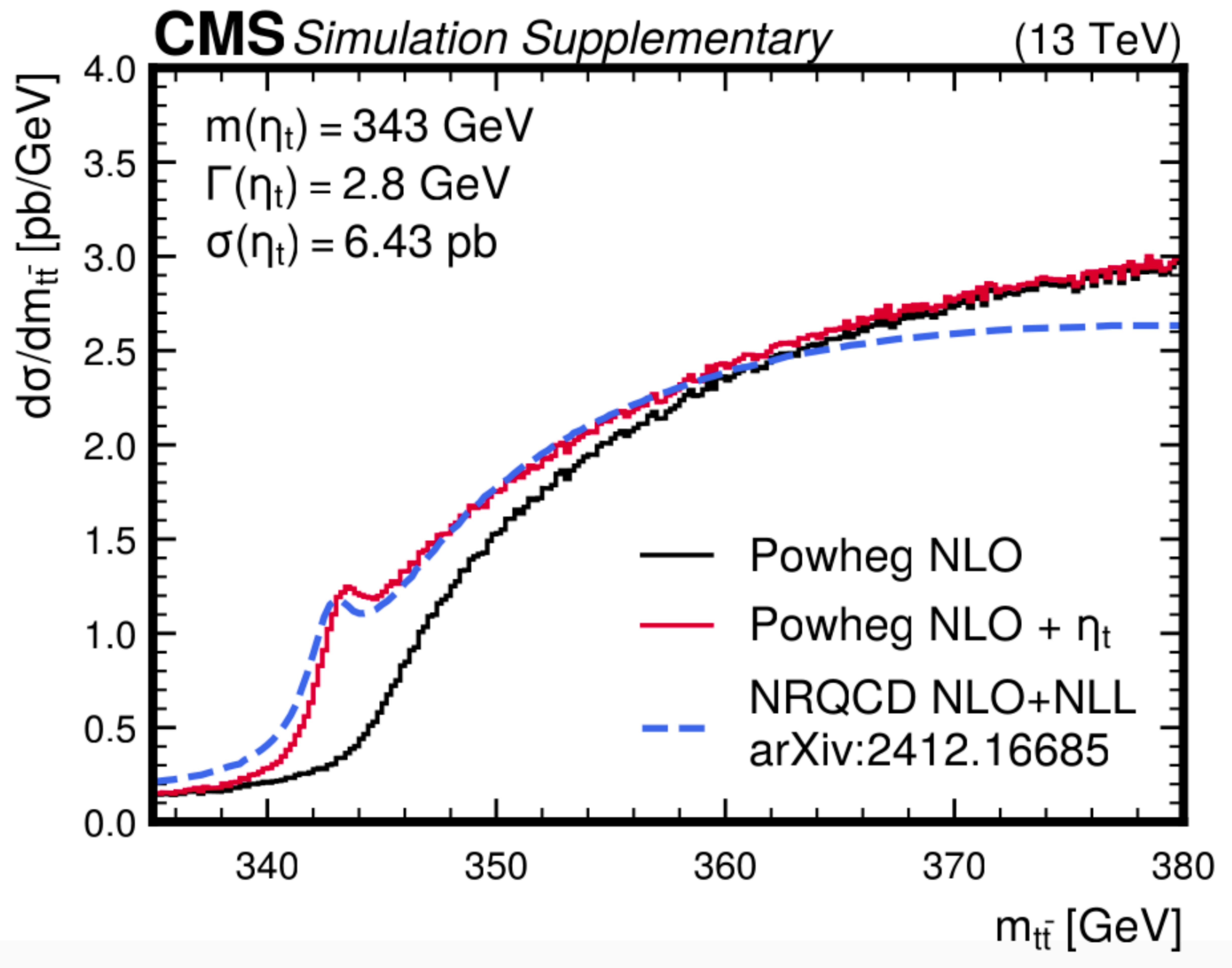

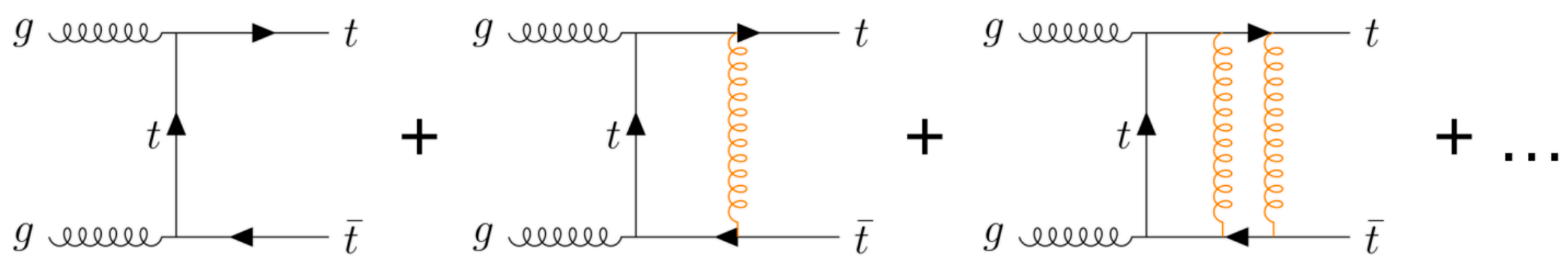

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pseudoscalar toponium η_t:

$^1S_0^{[1]}$ spin-0, CP-odd, color-singlet

scalar toponium χ_t:

$^3P_0^{[1]}$ spin-0, CP-even, color-singlet

(*not shown*)

Approximating $t\bar{t}$ bound states

- simplified model
  JHEP 03 (2024) 099
- generic particle with direct couplings to gluons and tops, mass and width from fit to NRQCD

$m(\eta_t, \chi_t) = 2m_t - 2\text{ GeV} = 343\text{ GeV}$

$\Gamma(\eta_t, \chi_t) = 2\Gamma_t = 2.8\text{ GeV}$

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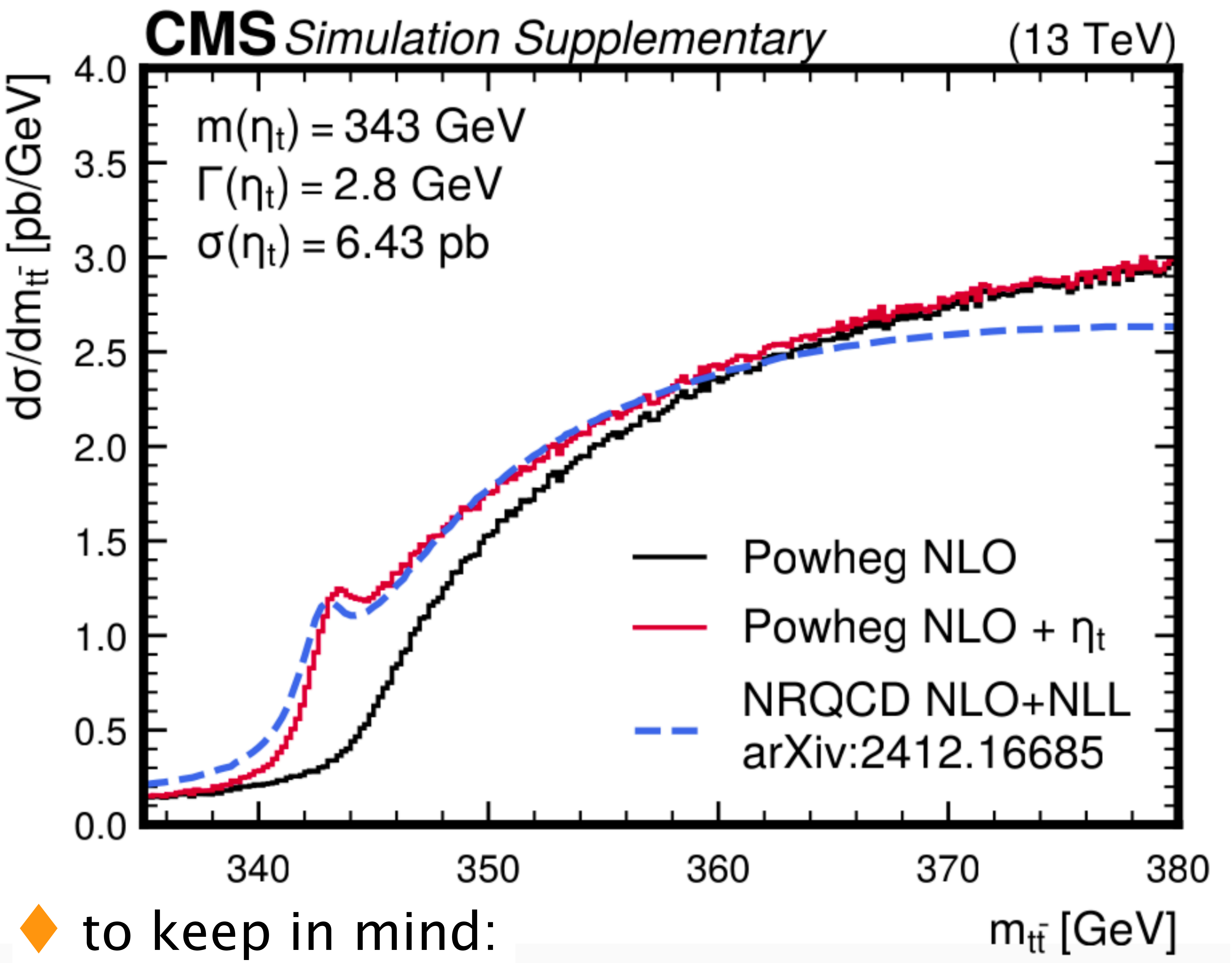

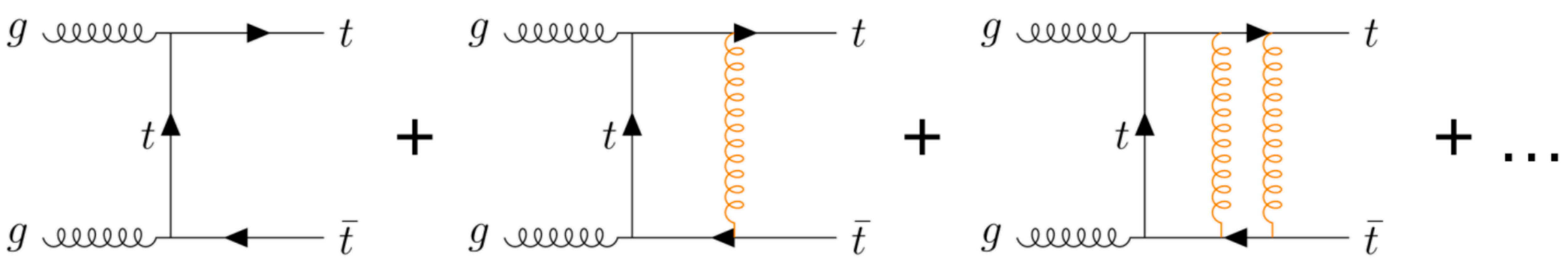

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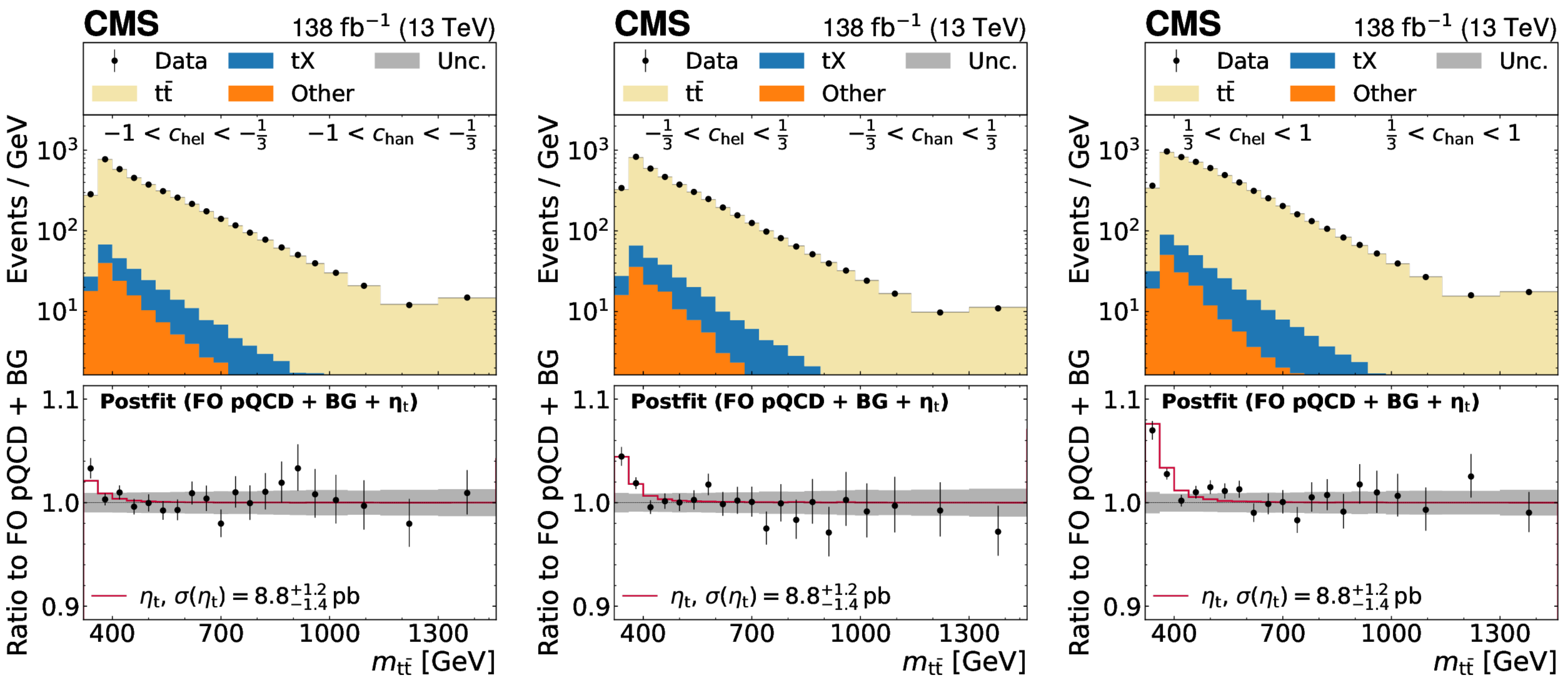
arXiv:2412.15138

♦ to keep in mind:

details of lineshape well below experimental resolution (15% – 25%)

→ looks similar to elementary A resonance, but without interference → minimal separation

Results and Pseudoscalar Toponium Interpretation



arXiv:2503.22382

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

- to keep in mind:

modeling of the $t\bar{t}$ threshold region is challenging and requires further theoretical investigation!

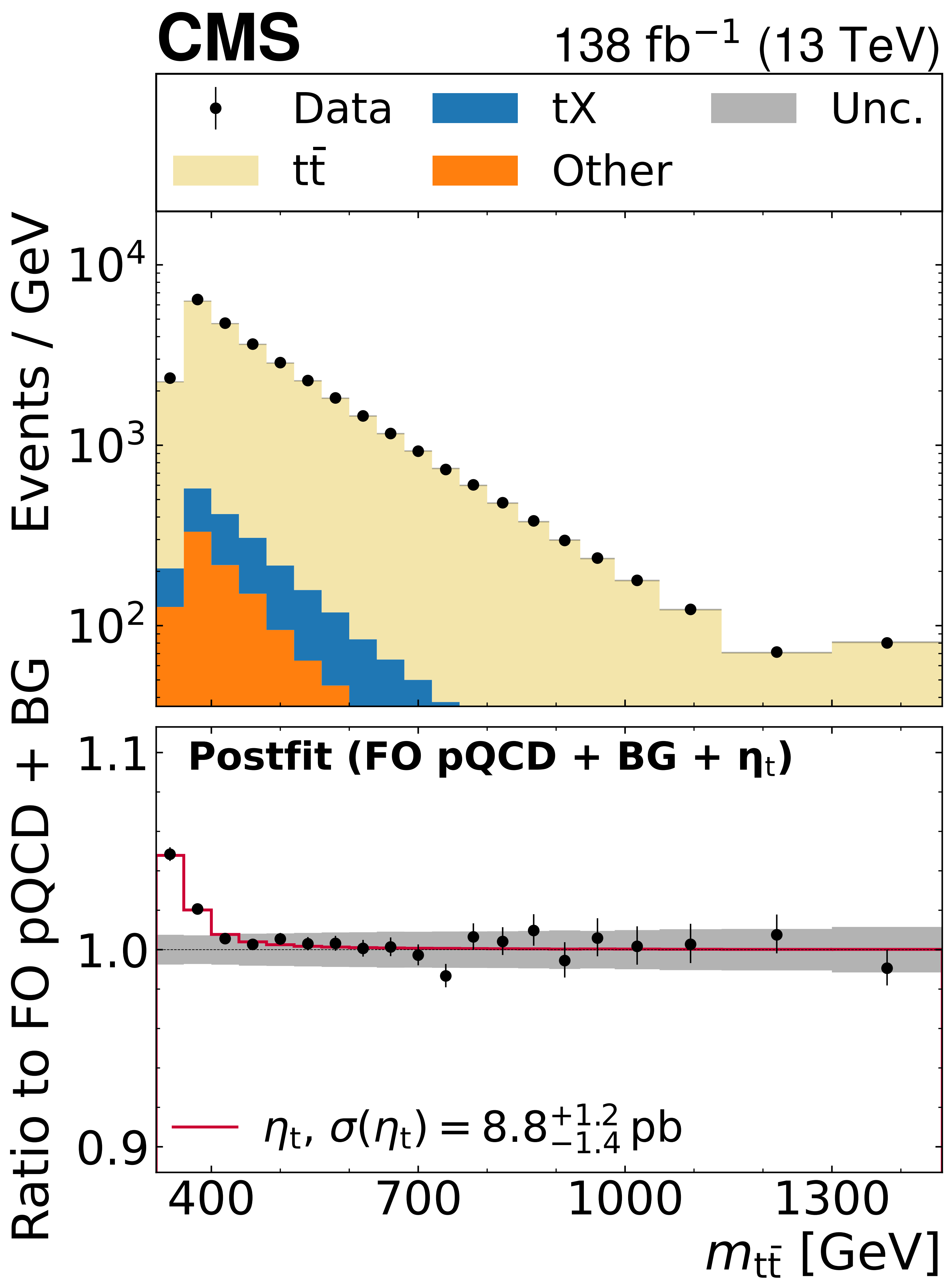
JHEP 09 (2010) 034
PRD 104 (2021) 034023
arXiv:2412.16685

→ exciting excess: >5 standard deviations

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

NRQCD: $\sigma(\eta_t)$ = 6.43 pb

Spin Correlation



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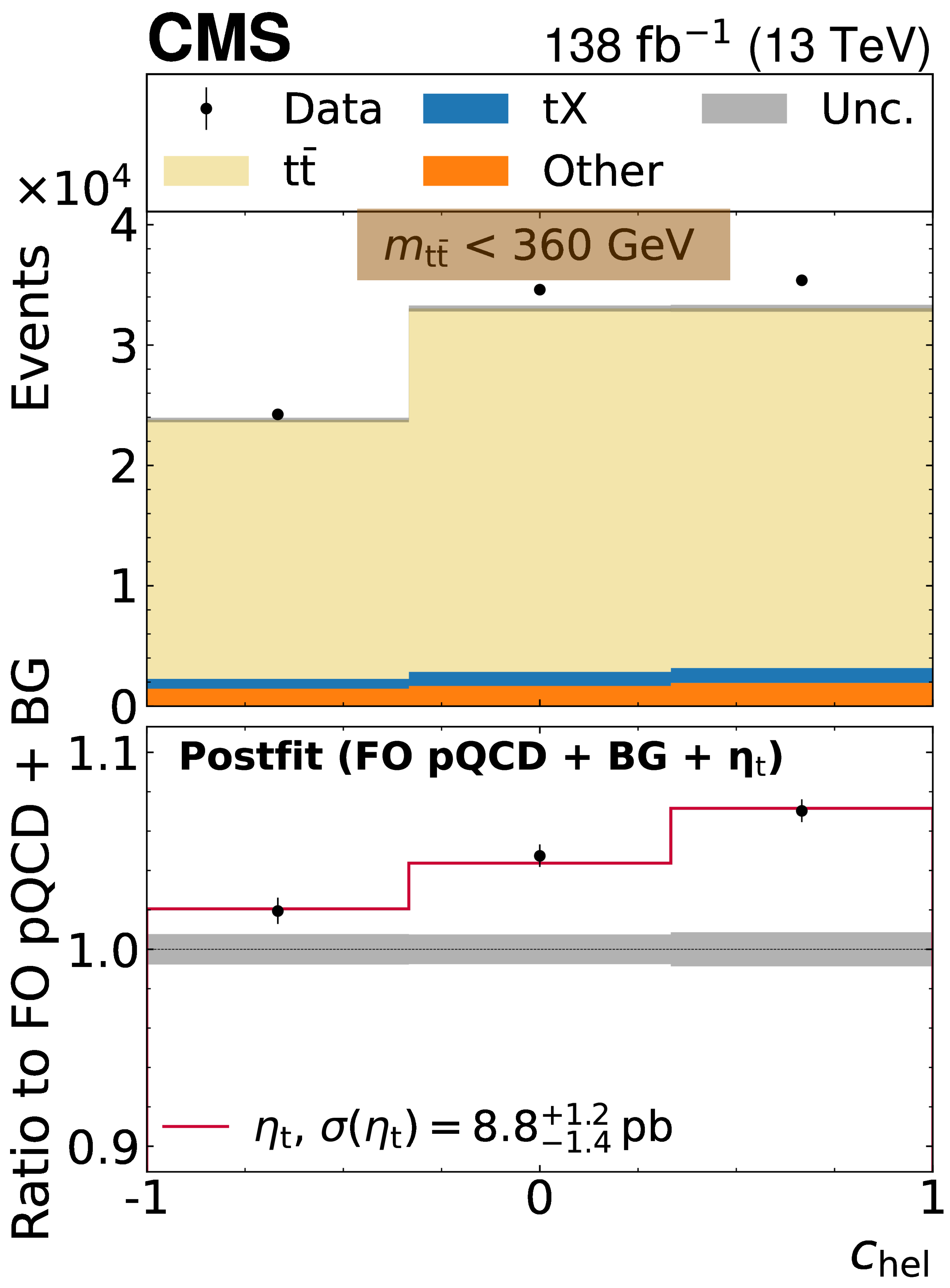

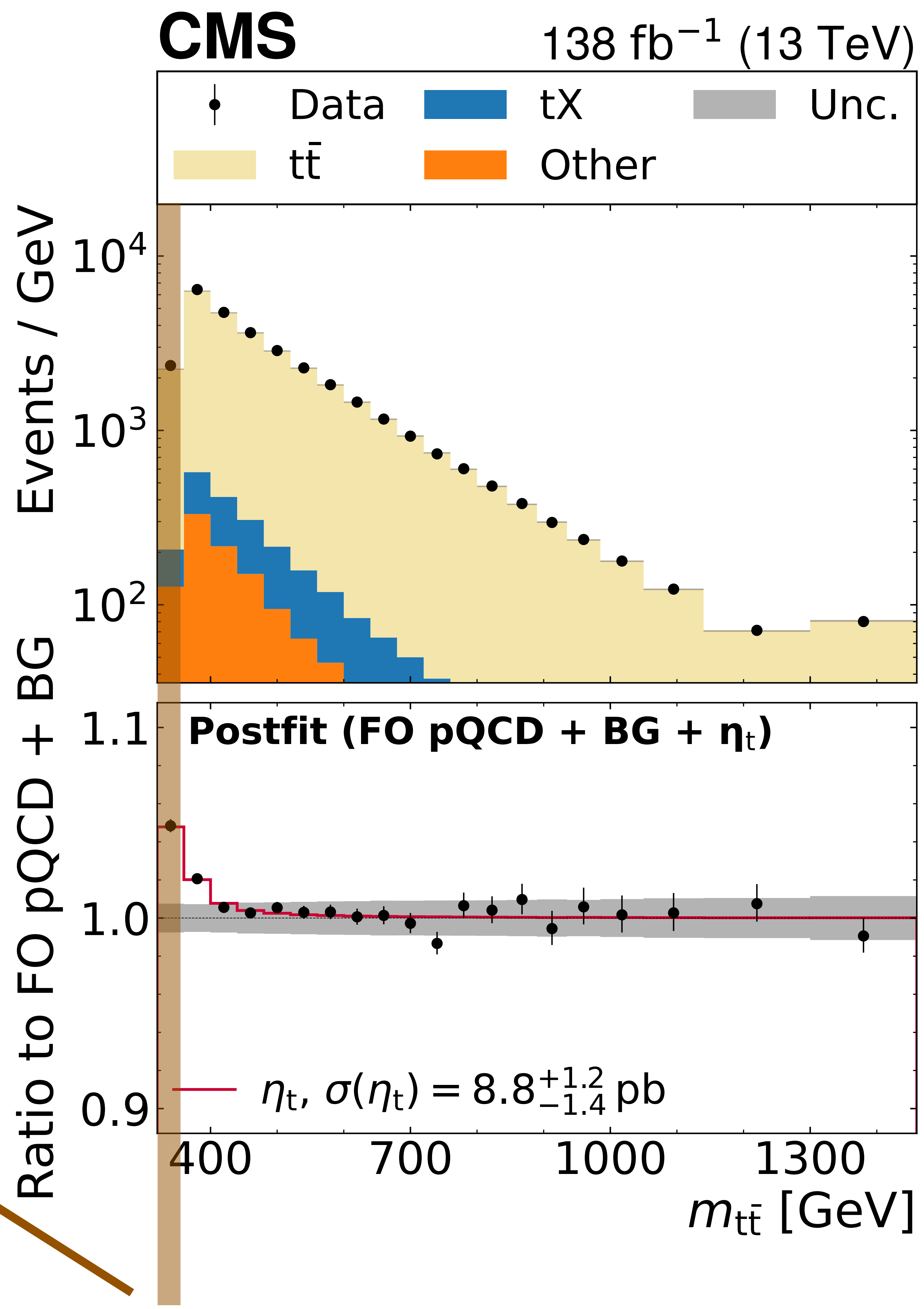

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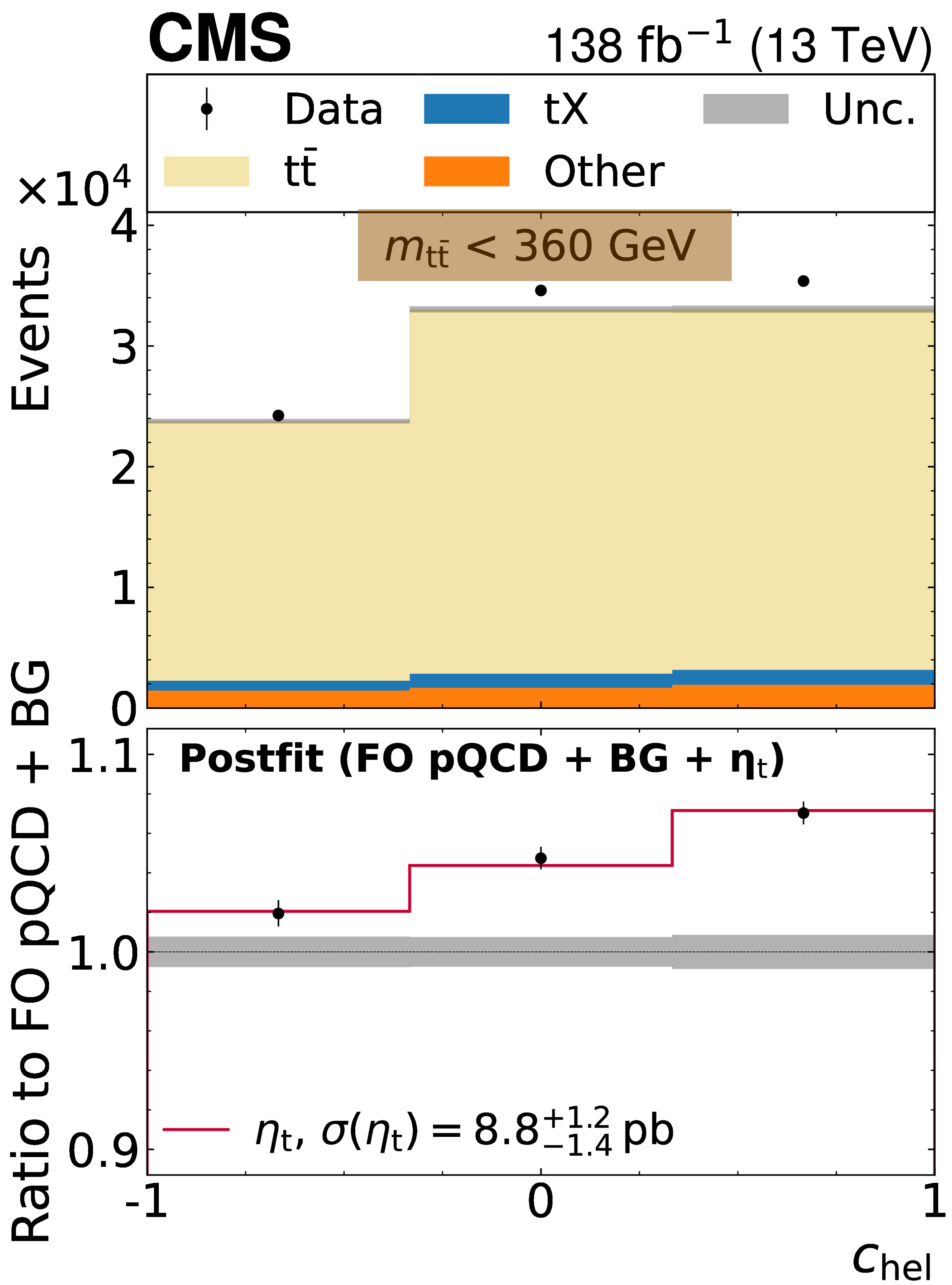
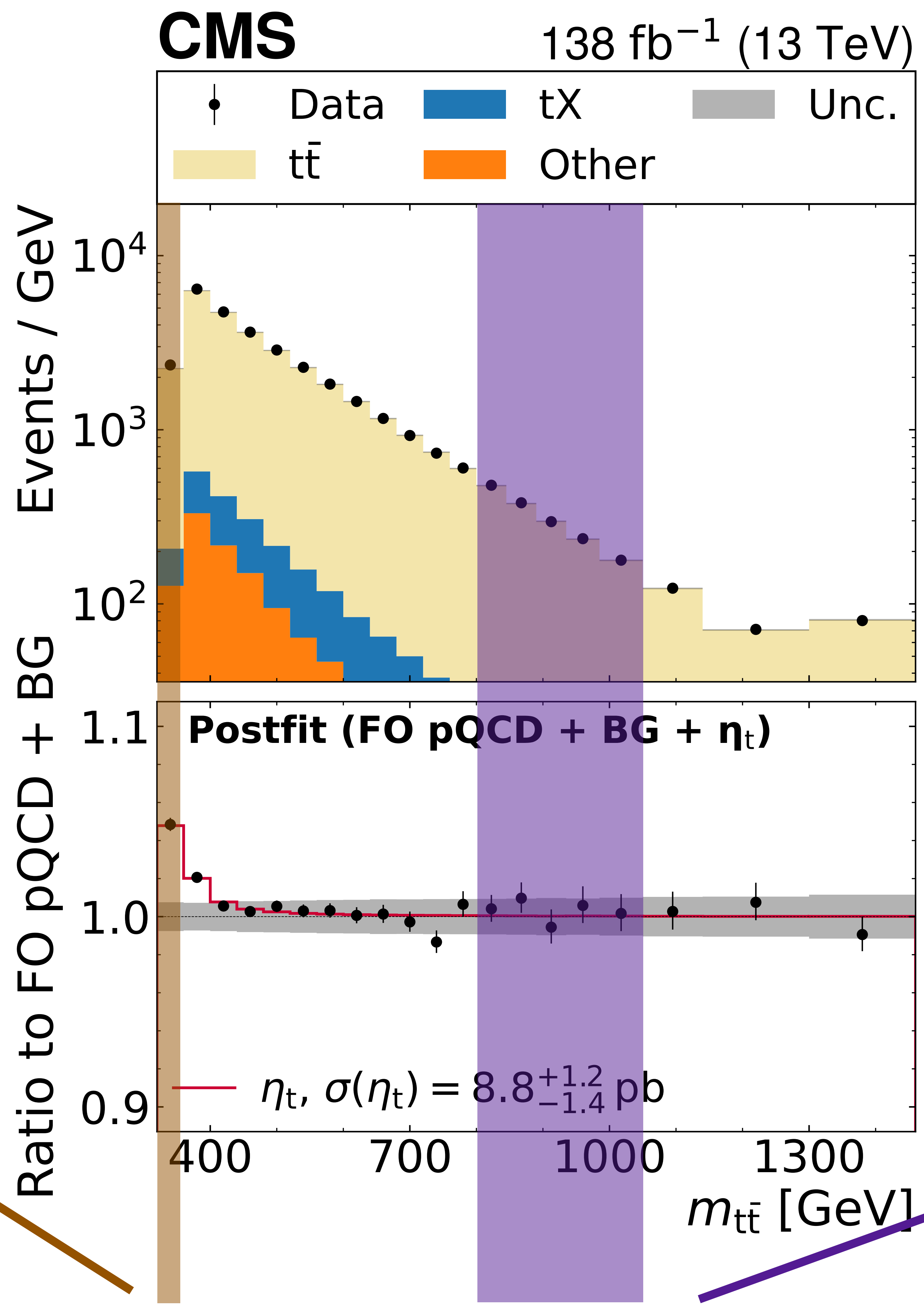
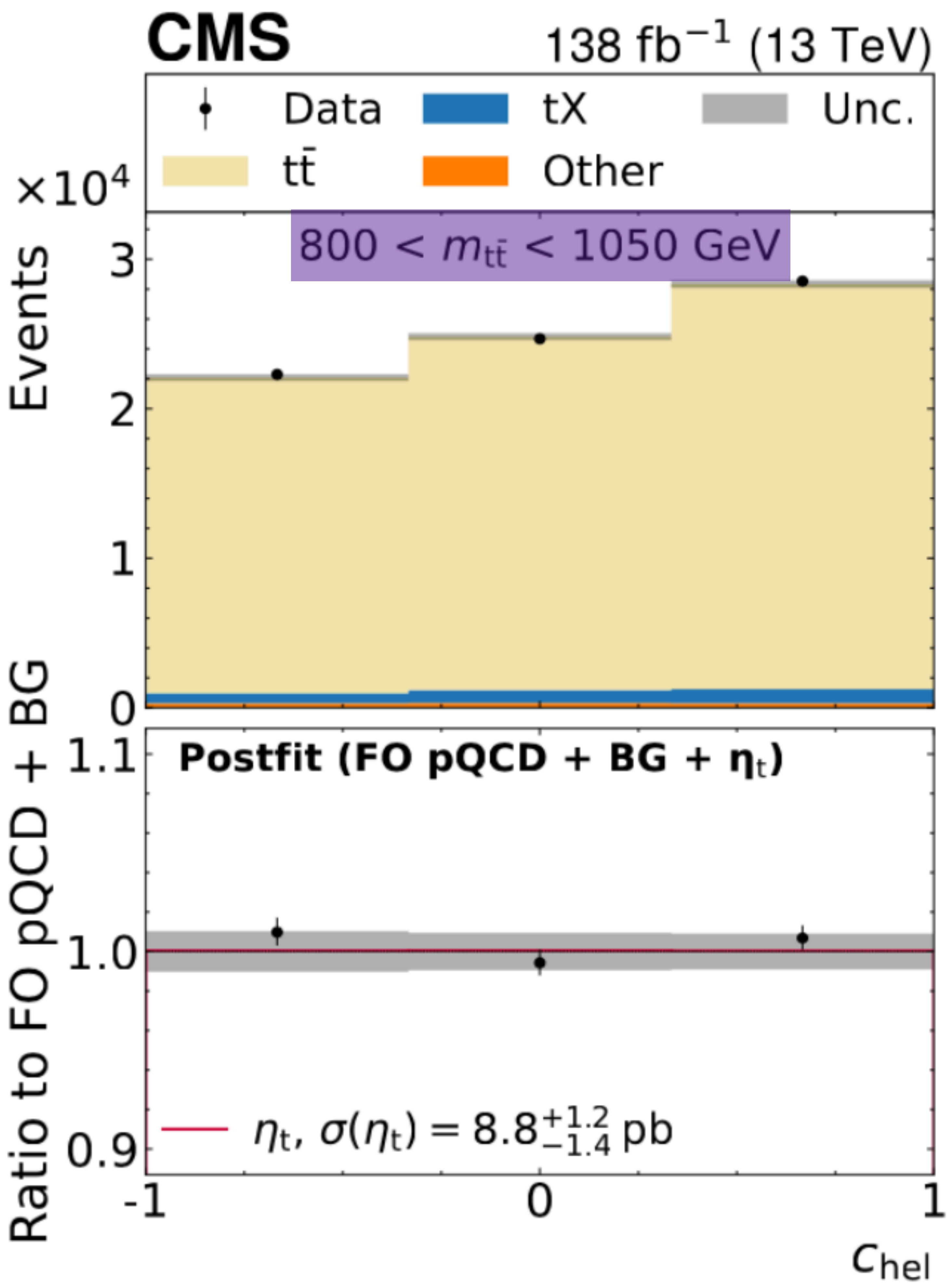
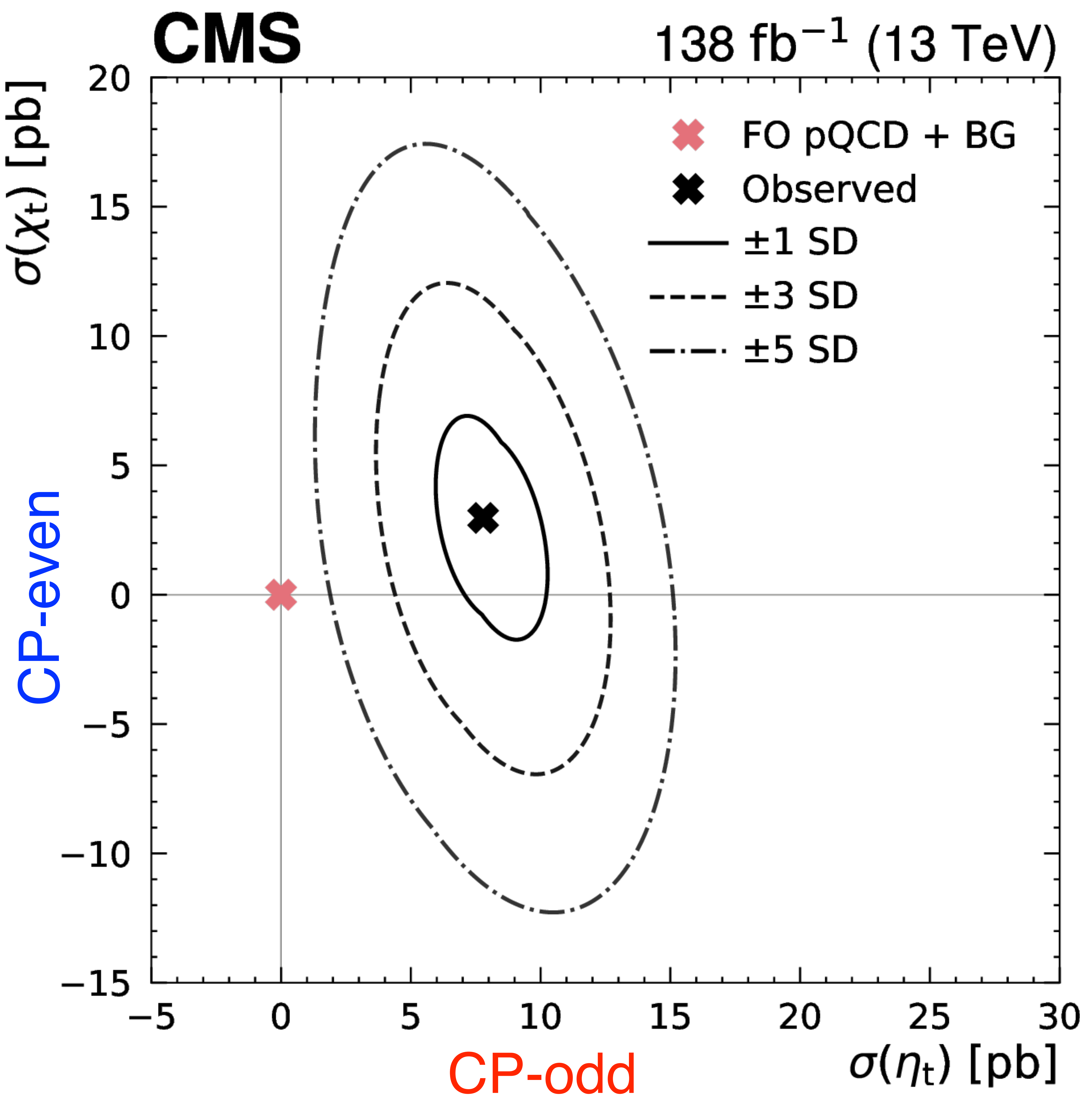






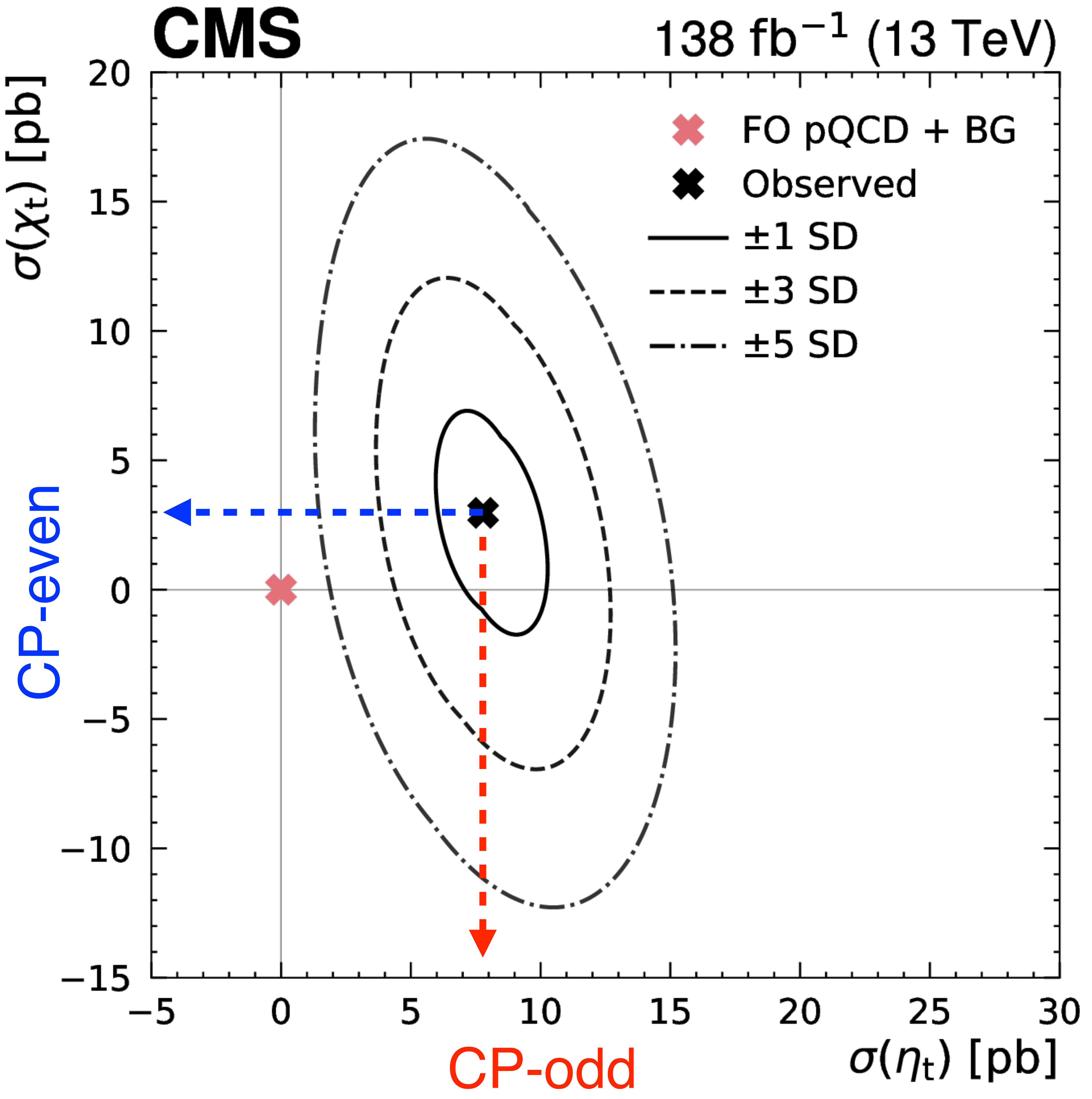
→ pseudoscalar bahaviour

Scalar or Pseudoscalar?



→ **data prefers pseudoscalar over scalar**

Scalar or Pseudoscalar?



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

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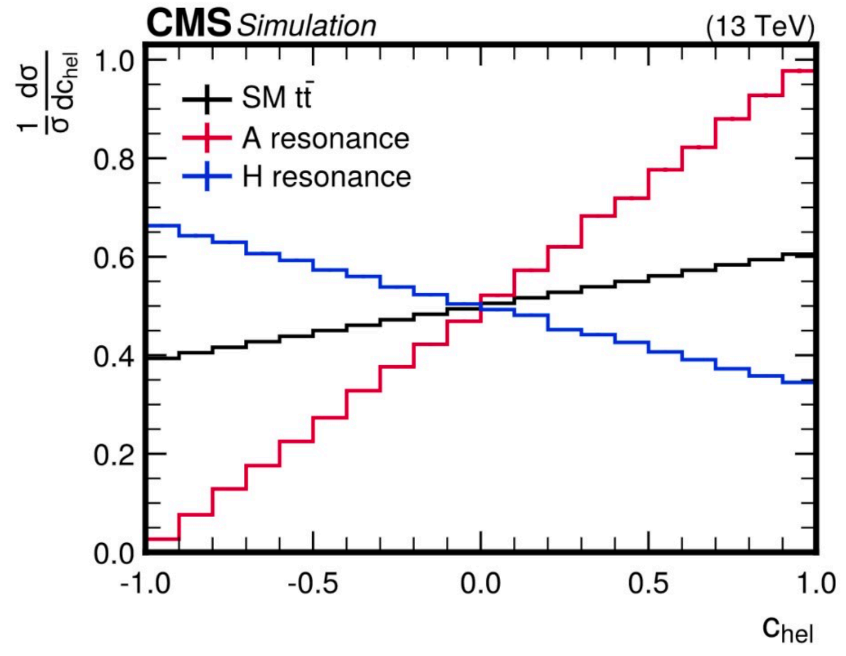

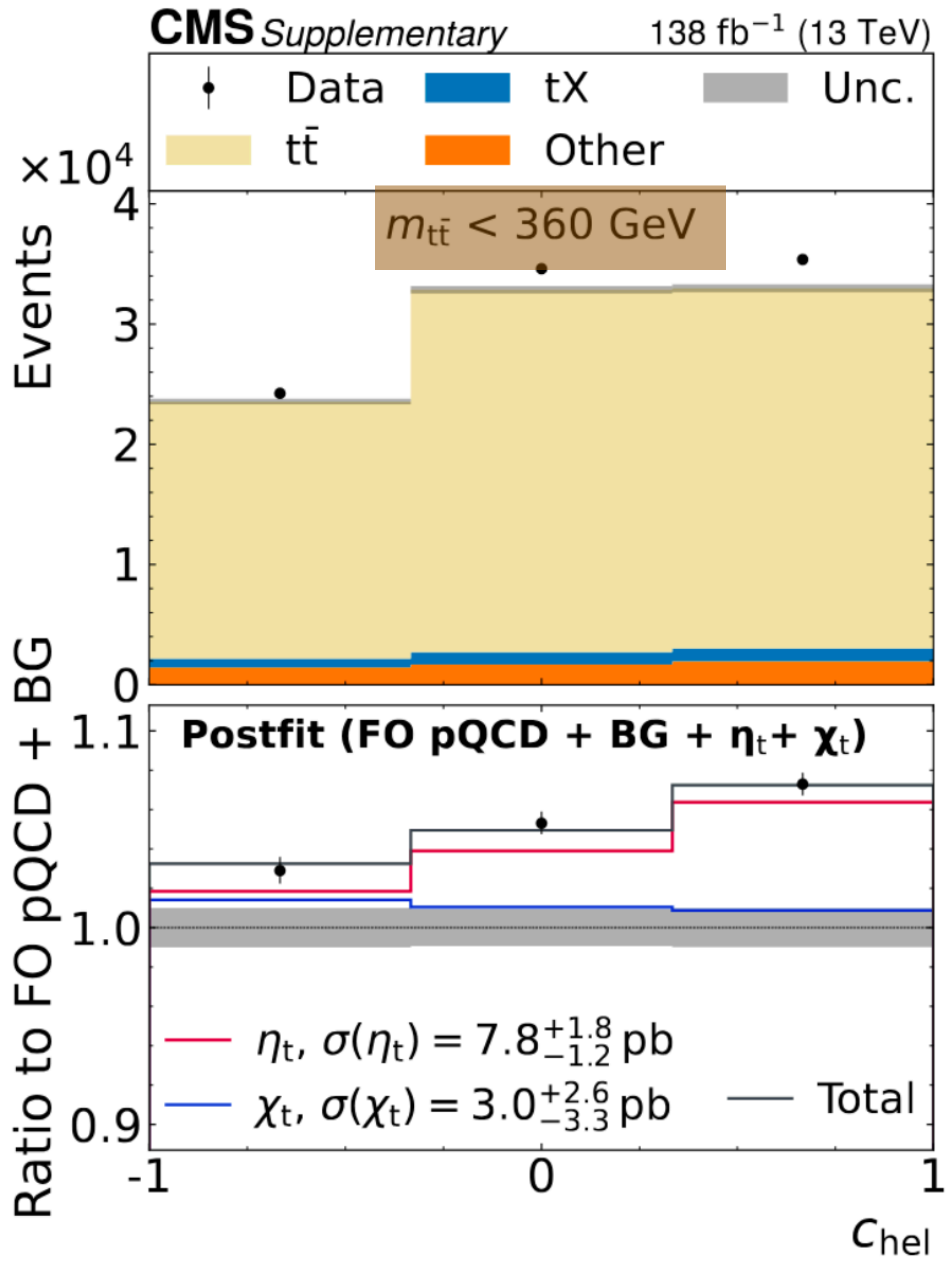

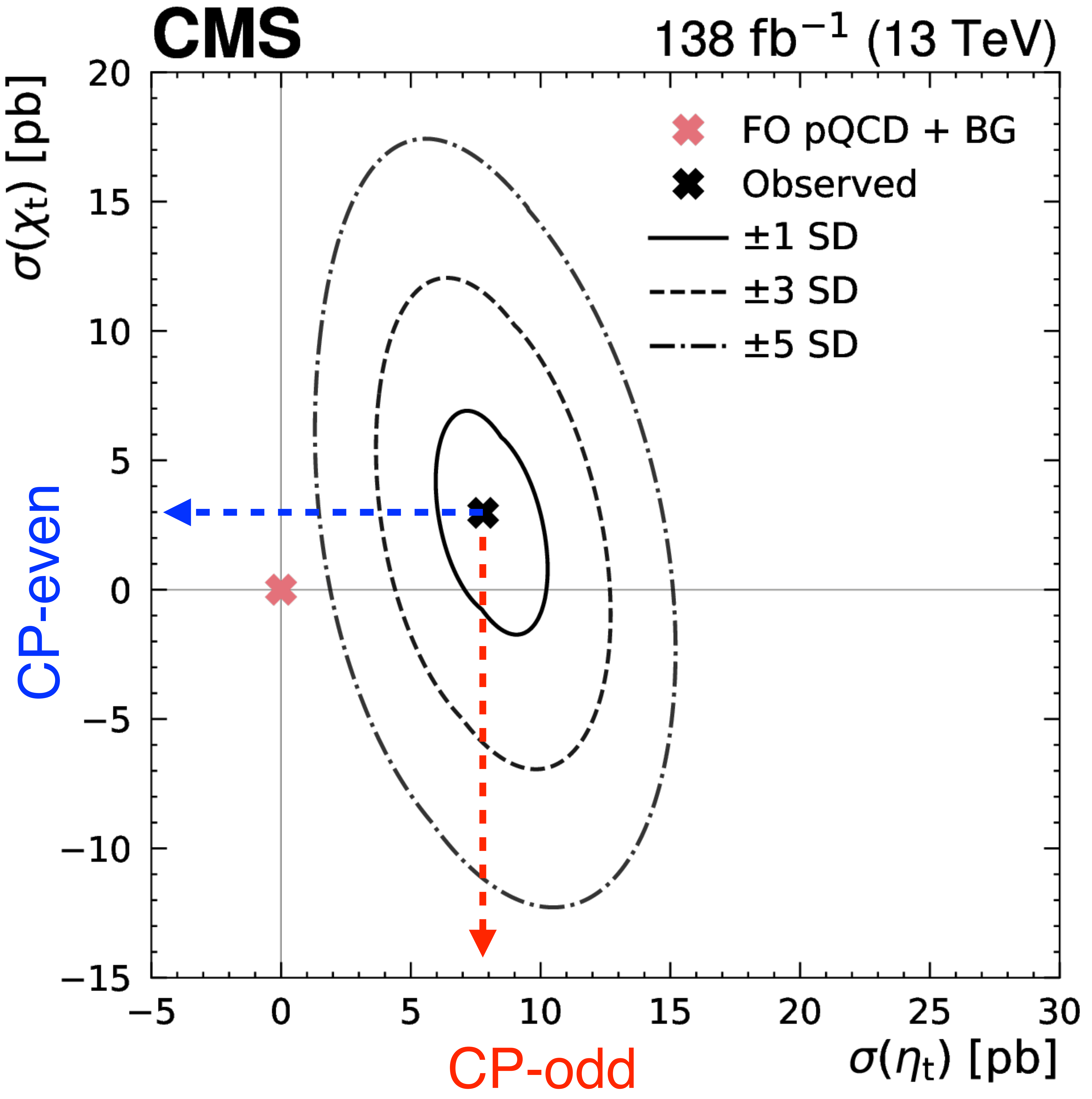

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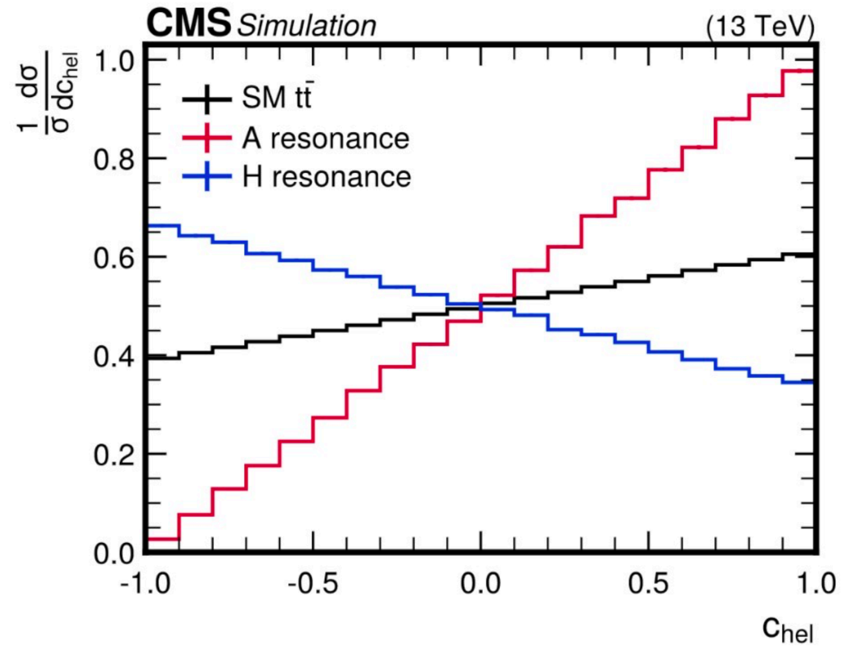
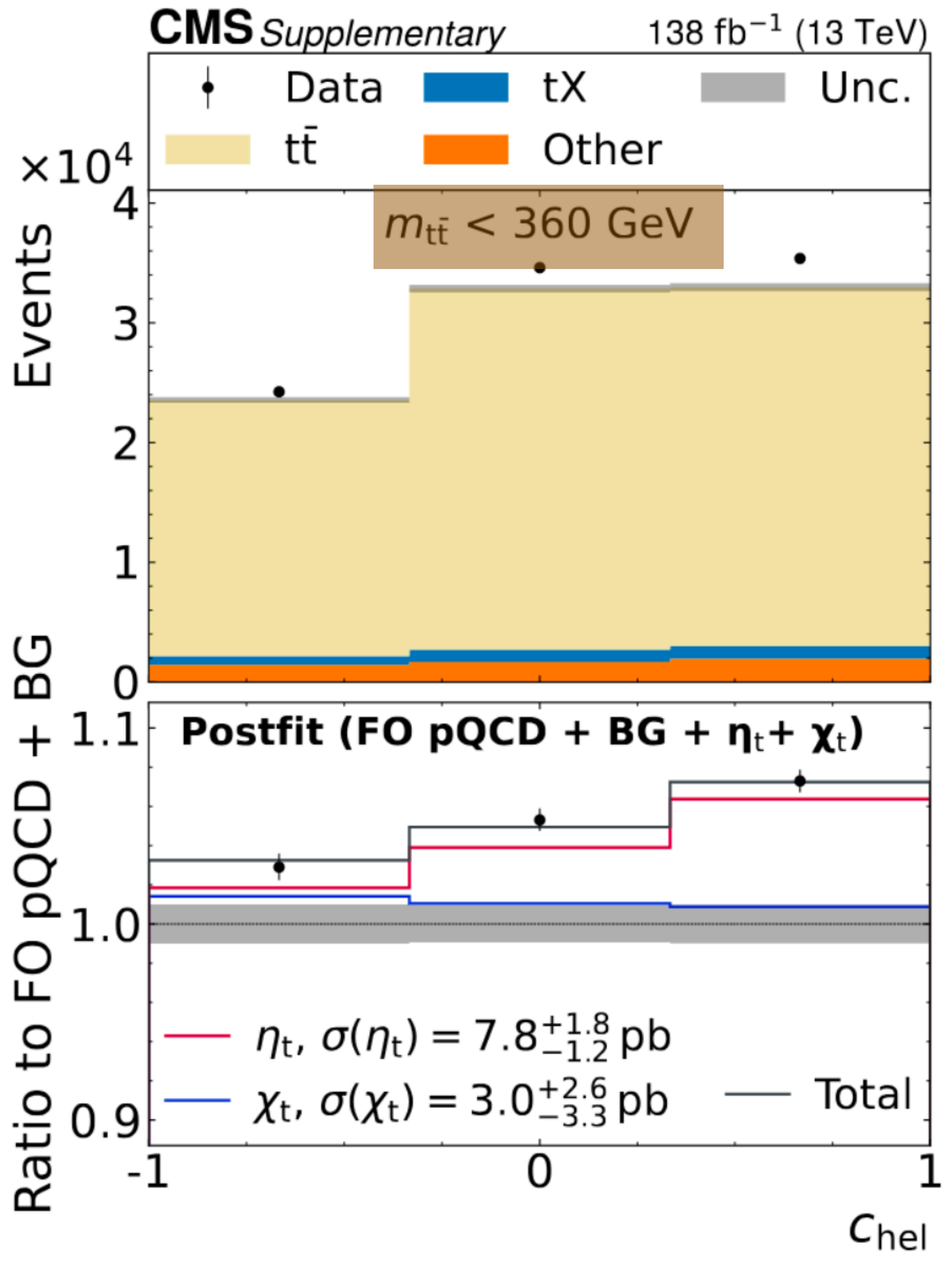
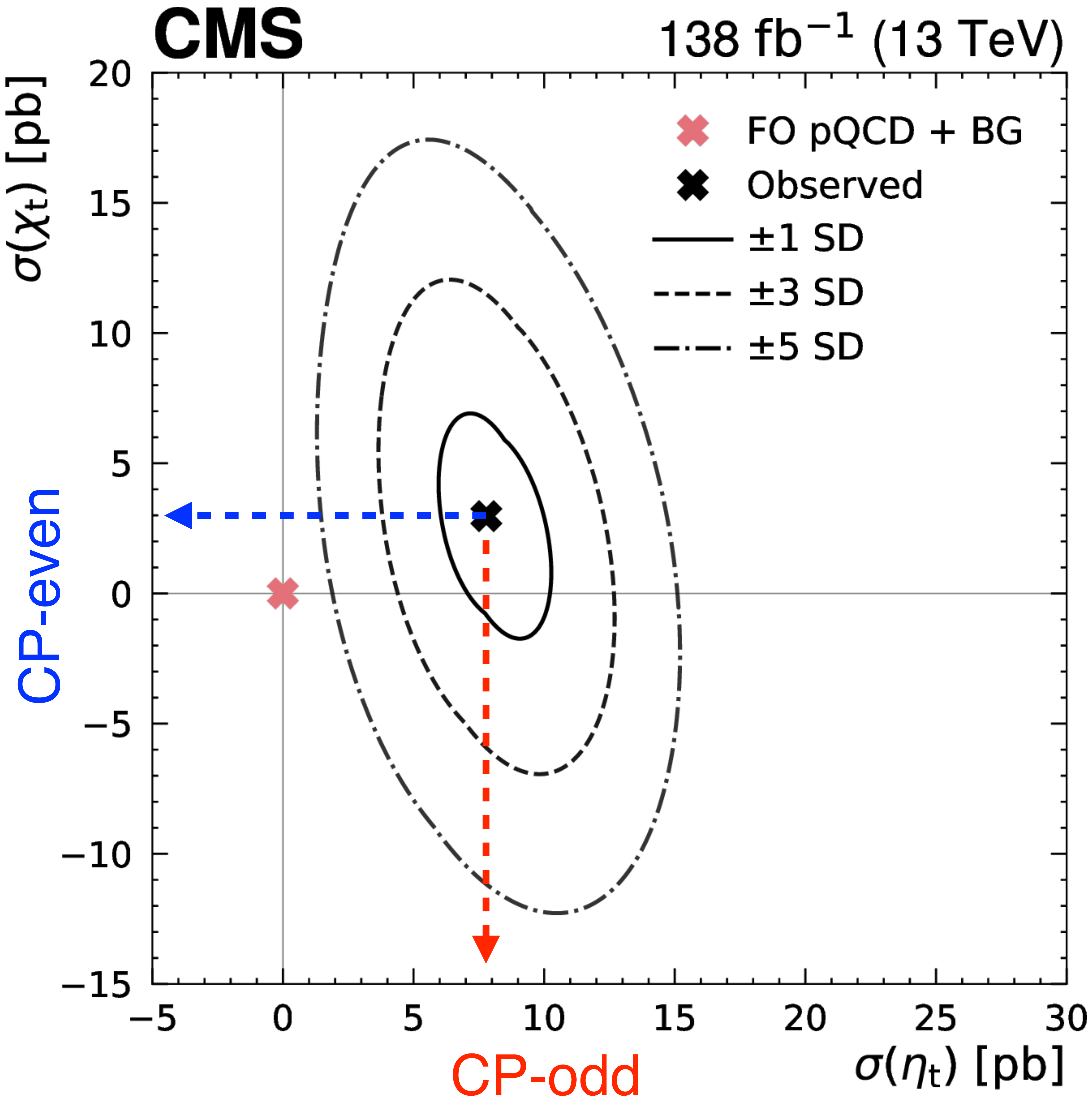
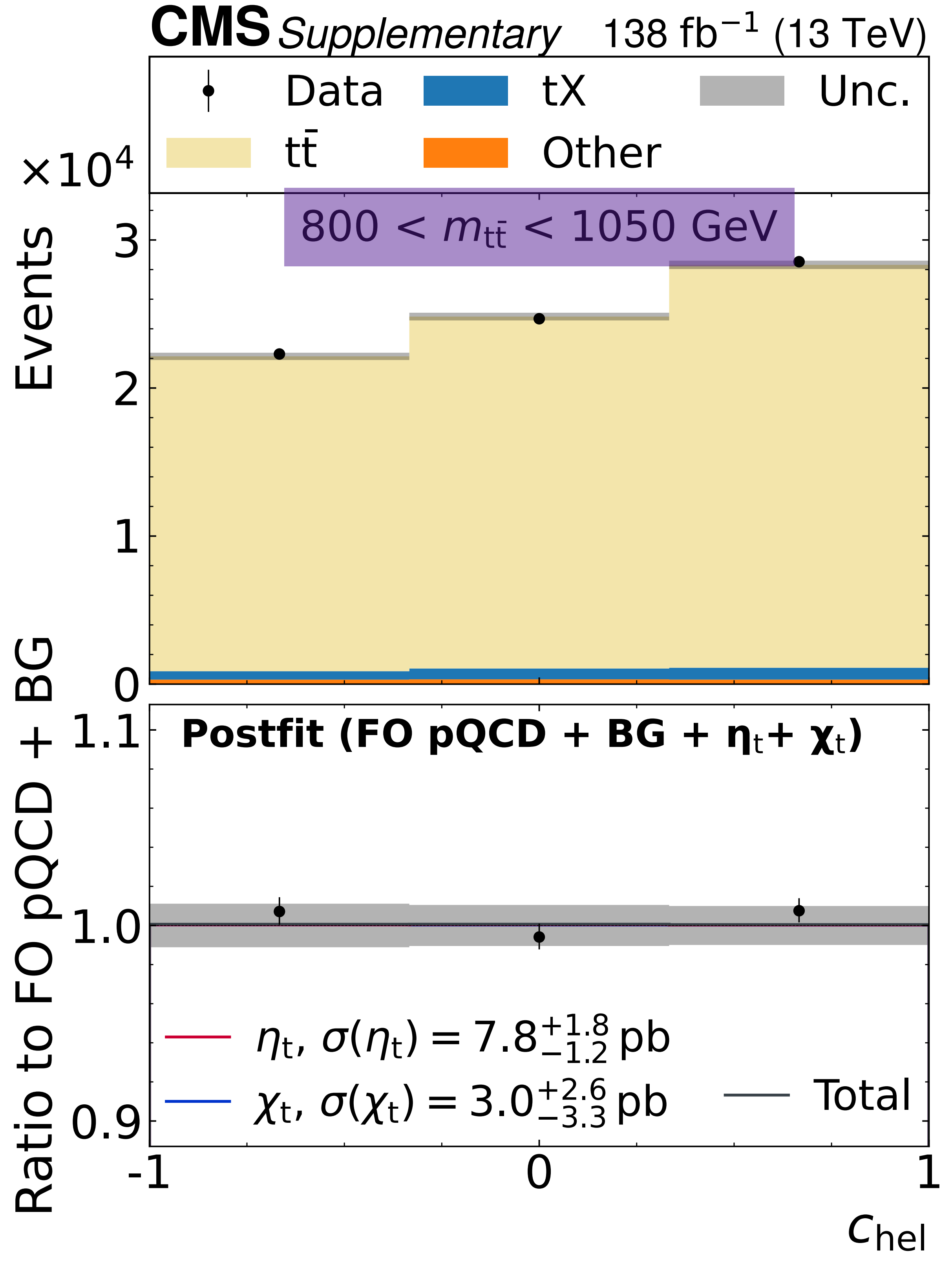




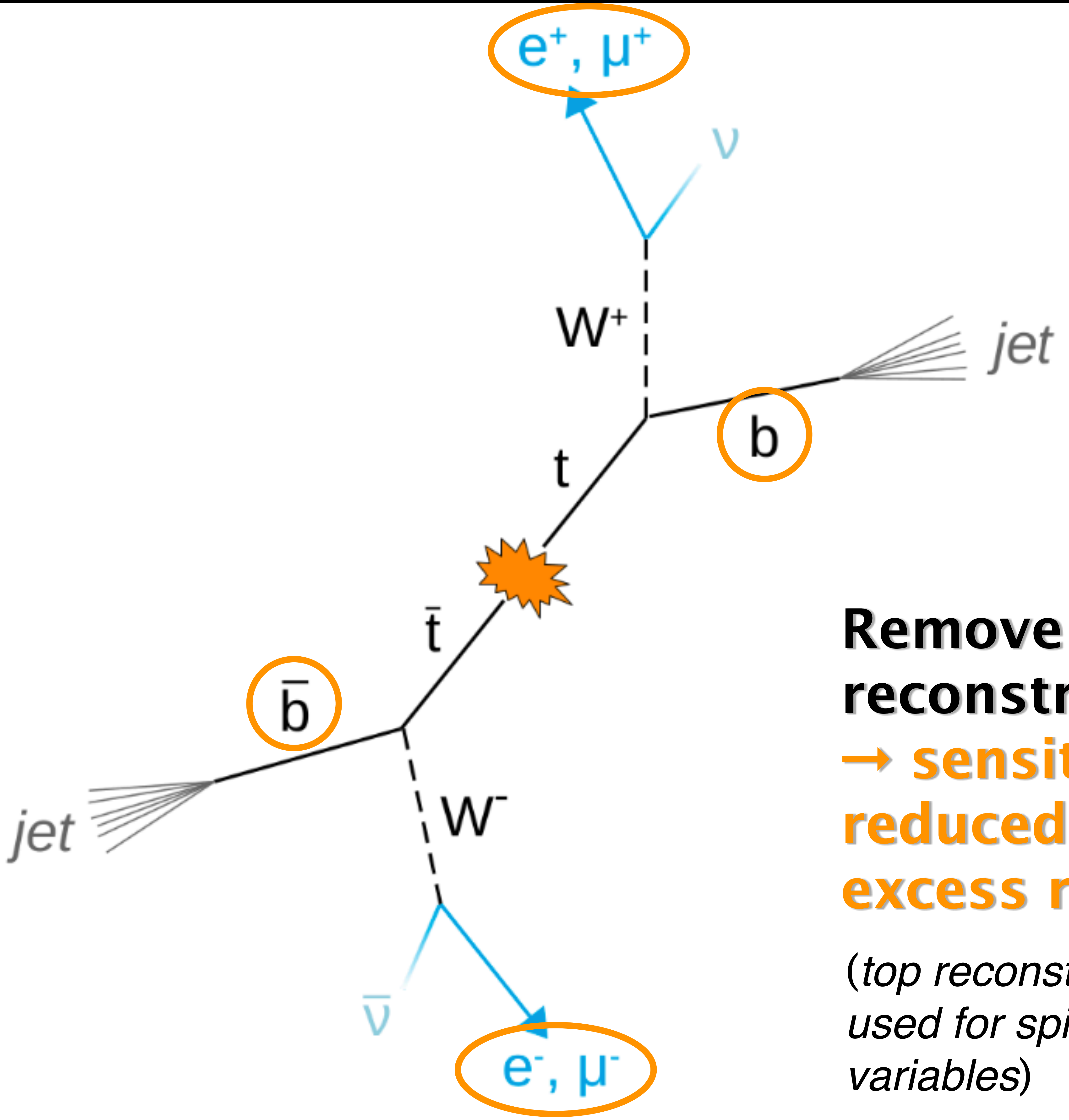


$\sigma(\eta_t) = 7.8^{+1.8}_{-1.2}$ pb
$\sigma(\chi_t) = 3.0^{+2.6}_{-3.3}$ pb



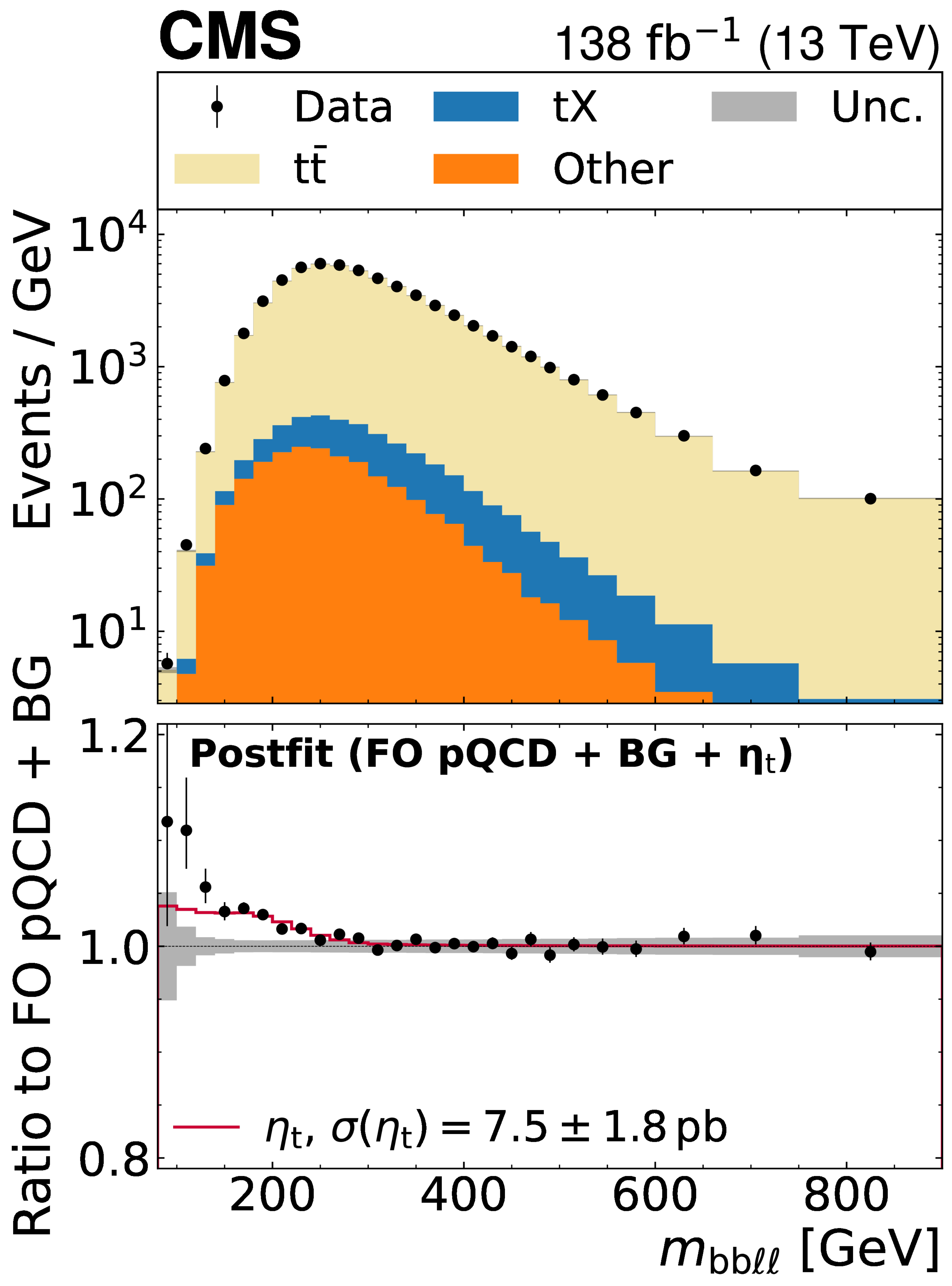
→ **data prefers pseudoscalar over scalar**

Systematics Check: Top Reconstruction

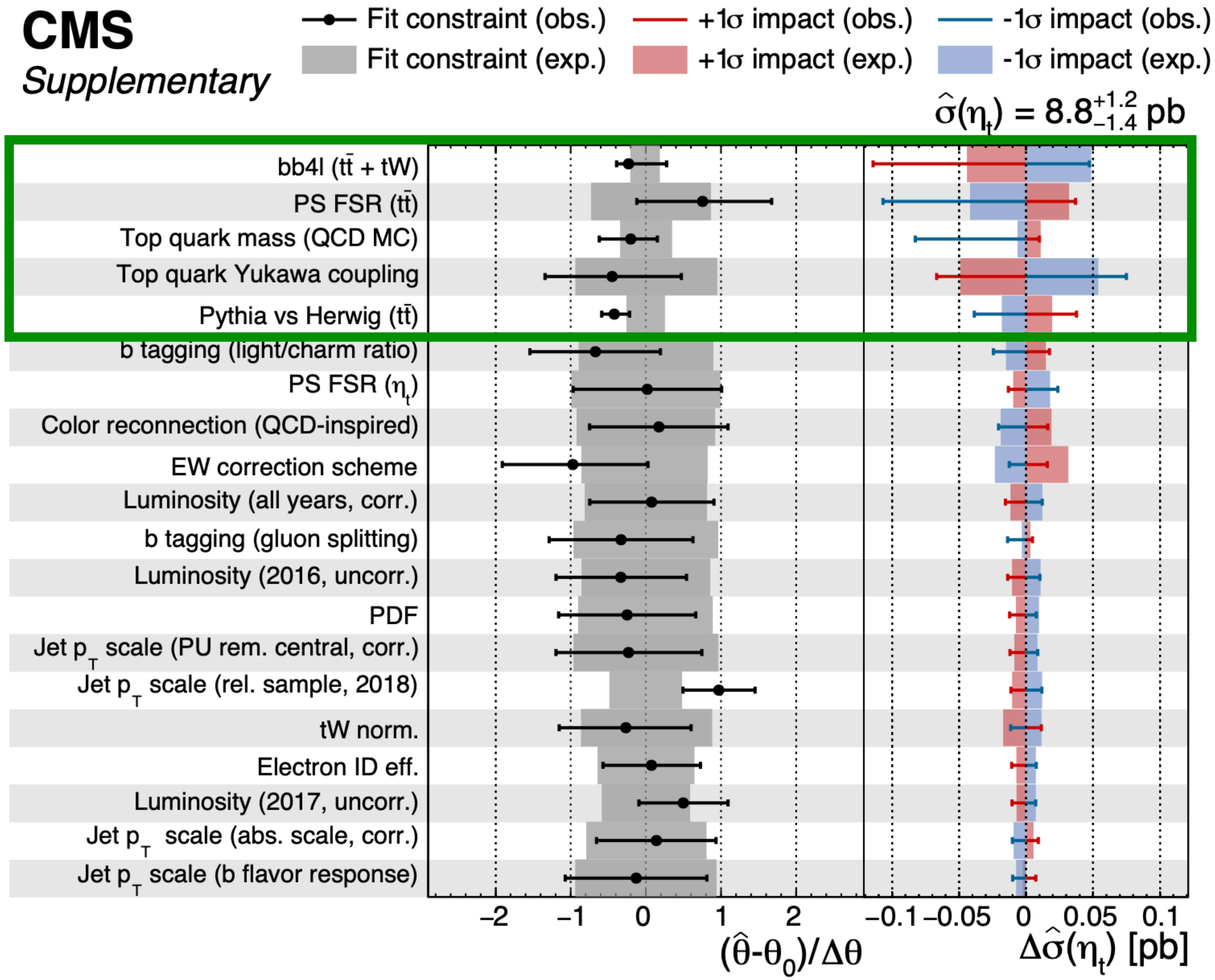


Remove top reconstruction
→ sensitivity reduced, but excess remains

(*top reconstruction still used for spin correlation variables*)



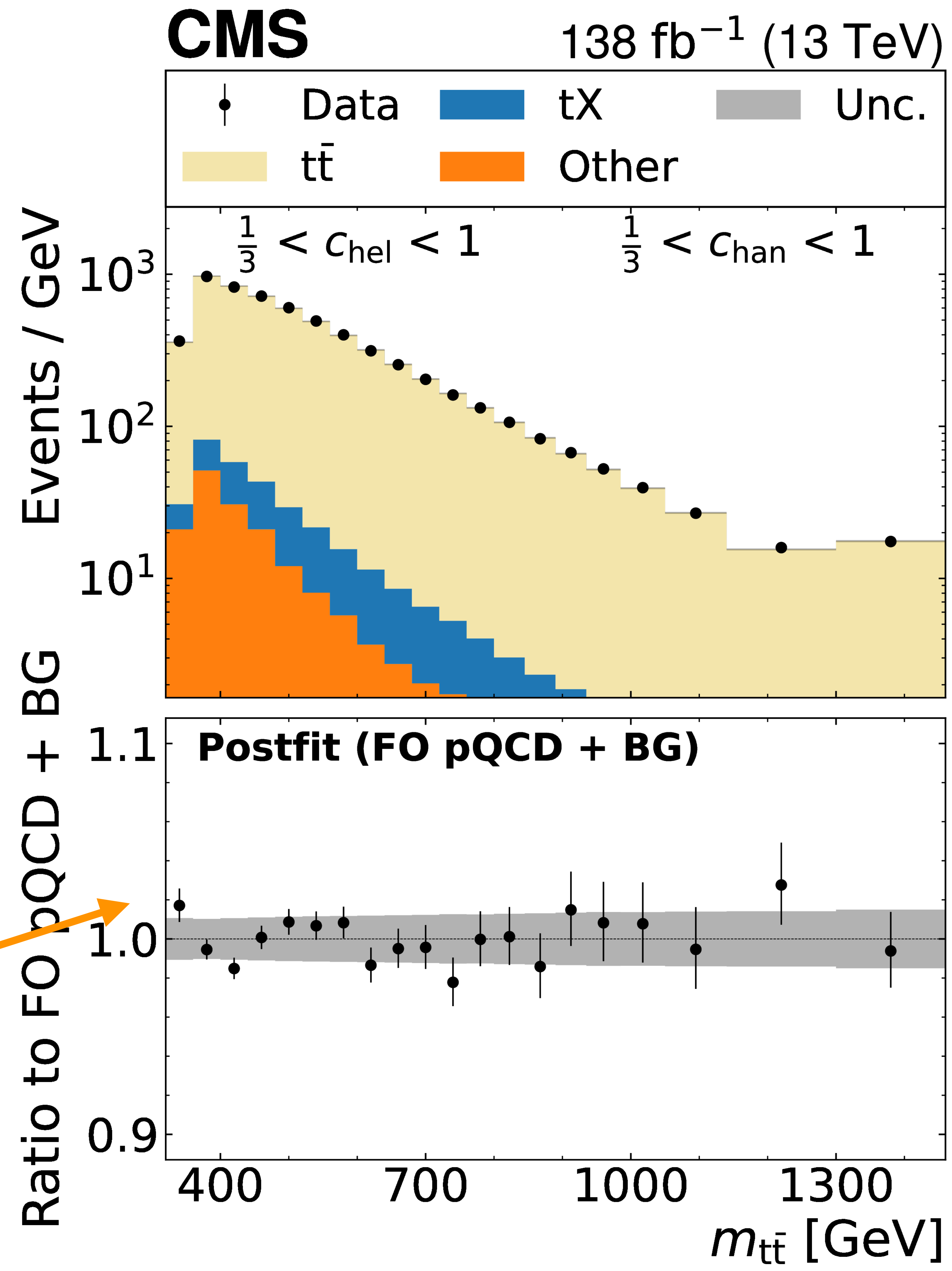
Systematic Uncertainties

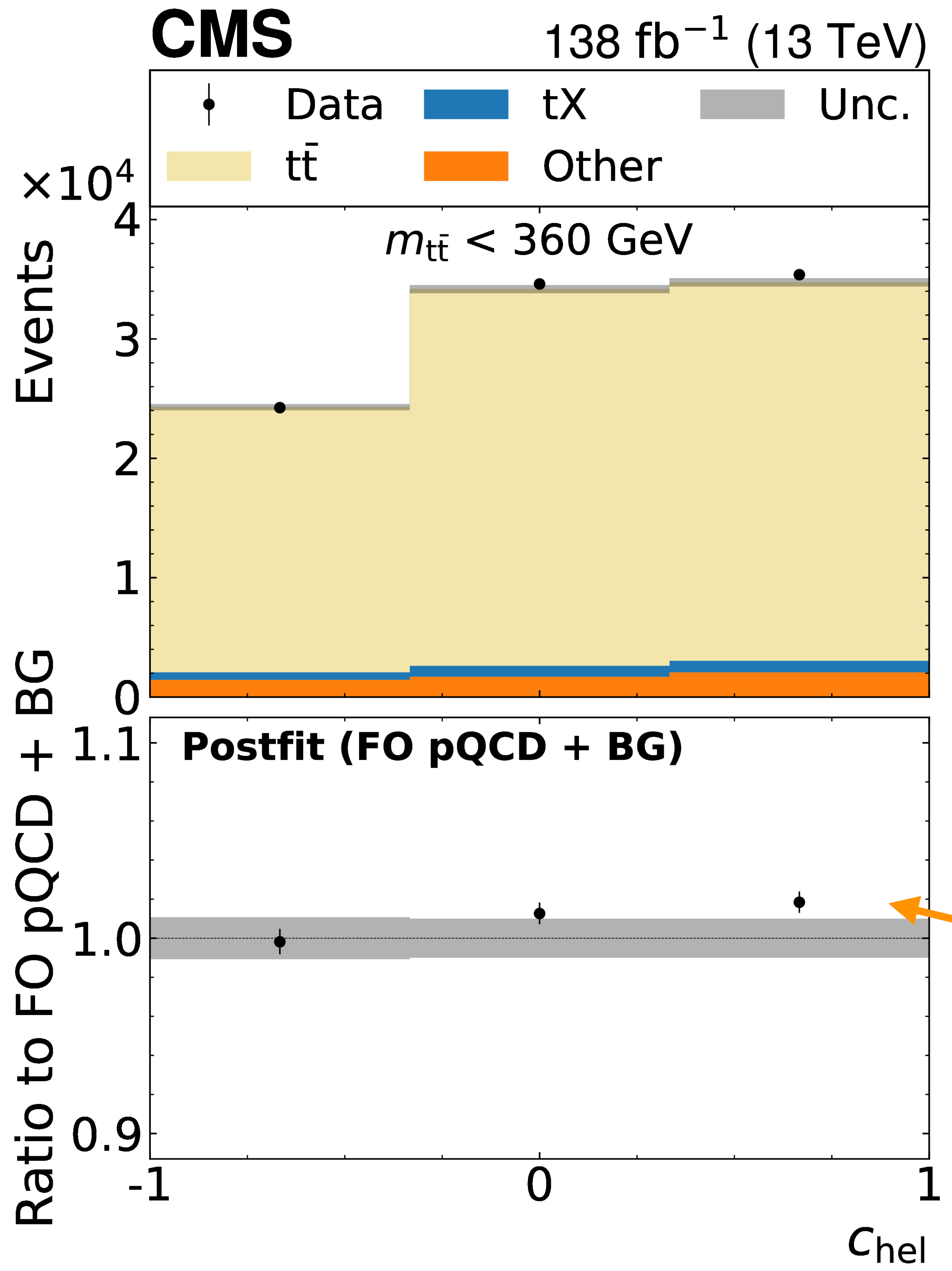


- bb4l generator instead of Powheg:
  - pp → b$\bar{b}$ l+l- ν$\bar{\nu}$
  - off-shell effects included
  - interference between t$\bar{t}$ and tW
- PS FSR:
  - α_s variation in final state radiation
- top quark mass
- top quark Yukawa coupling
- Herwig7 parton shower simulation instead of Pythia8

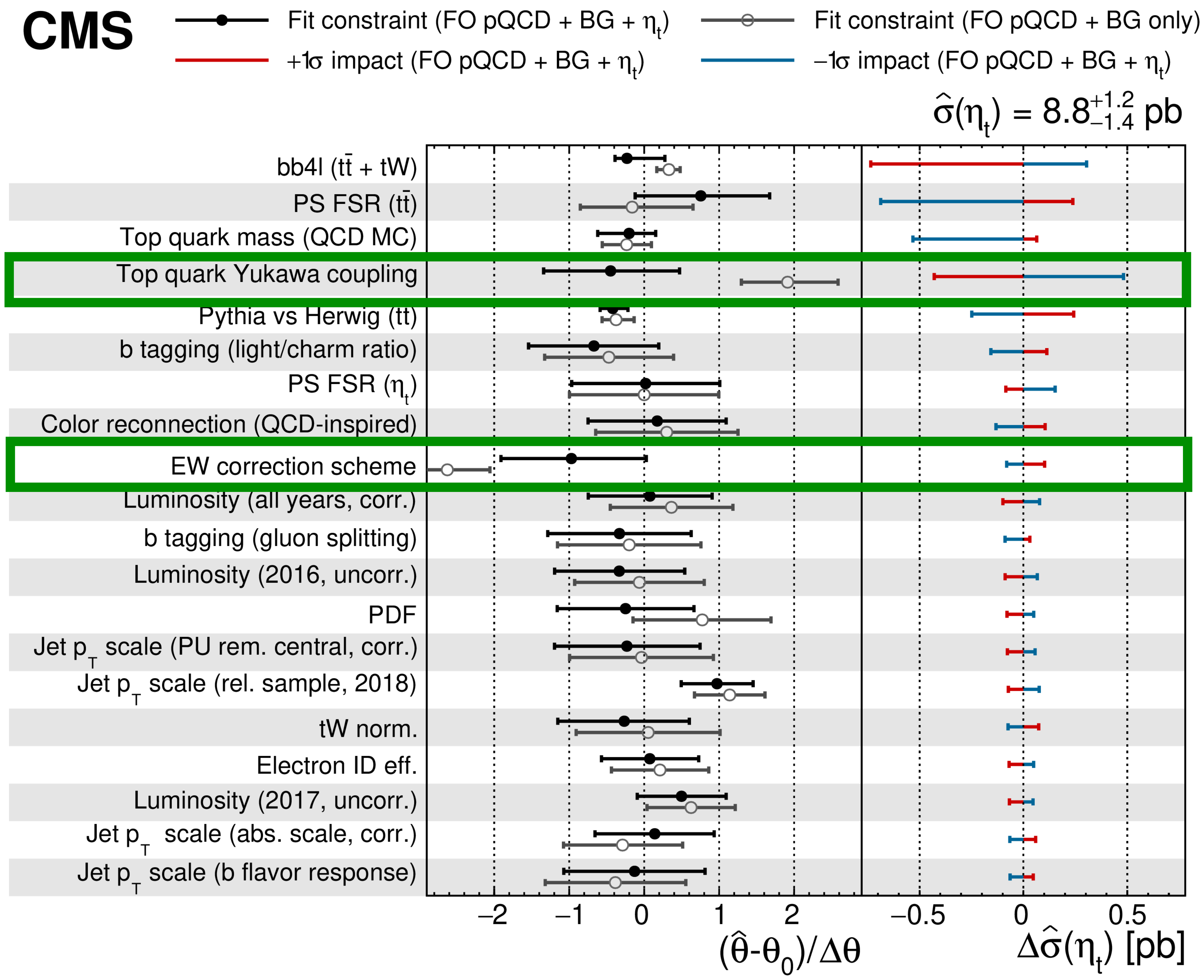
→ uncertainty dominated by t$\bar{t}$ modeling

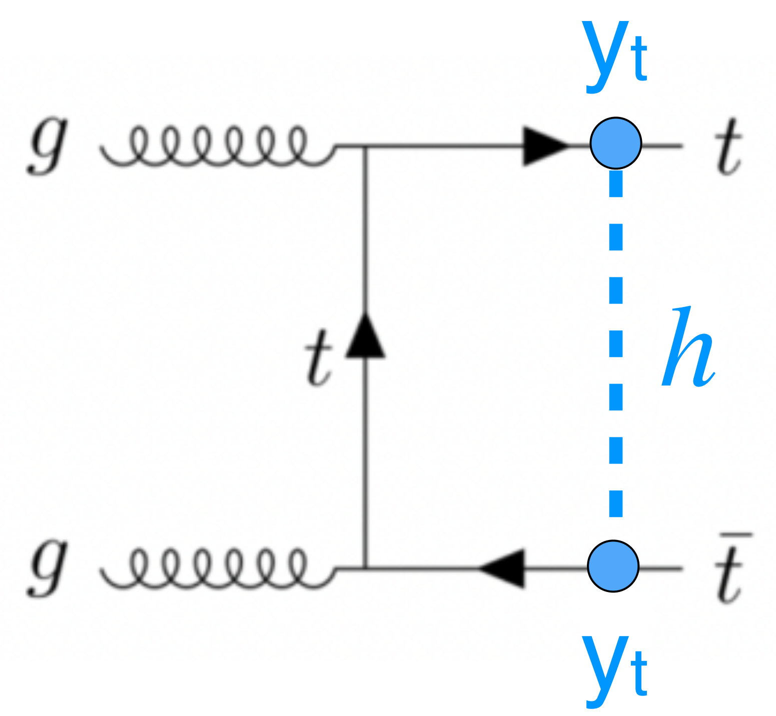
Fit without $t\bar{t}$ Bound State





Fit without $t\bar{t}$ Bound State

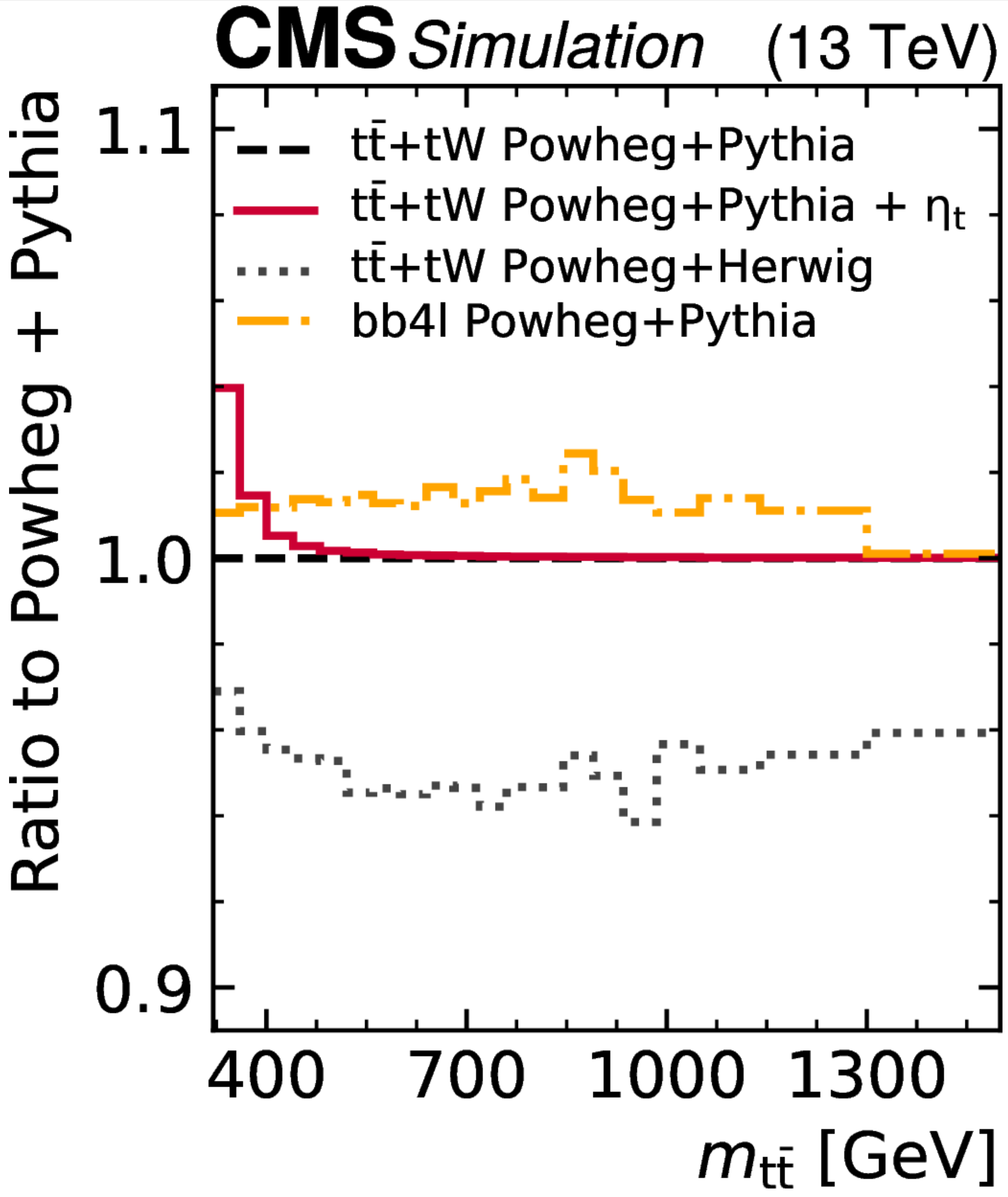




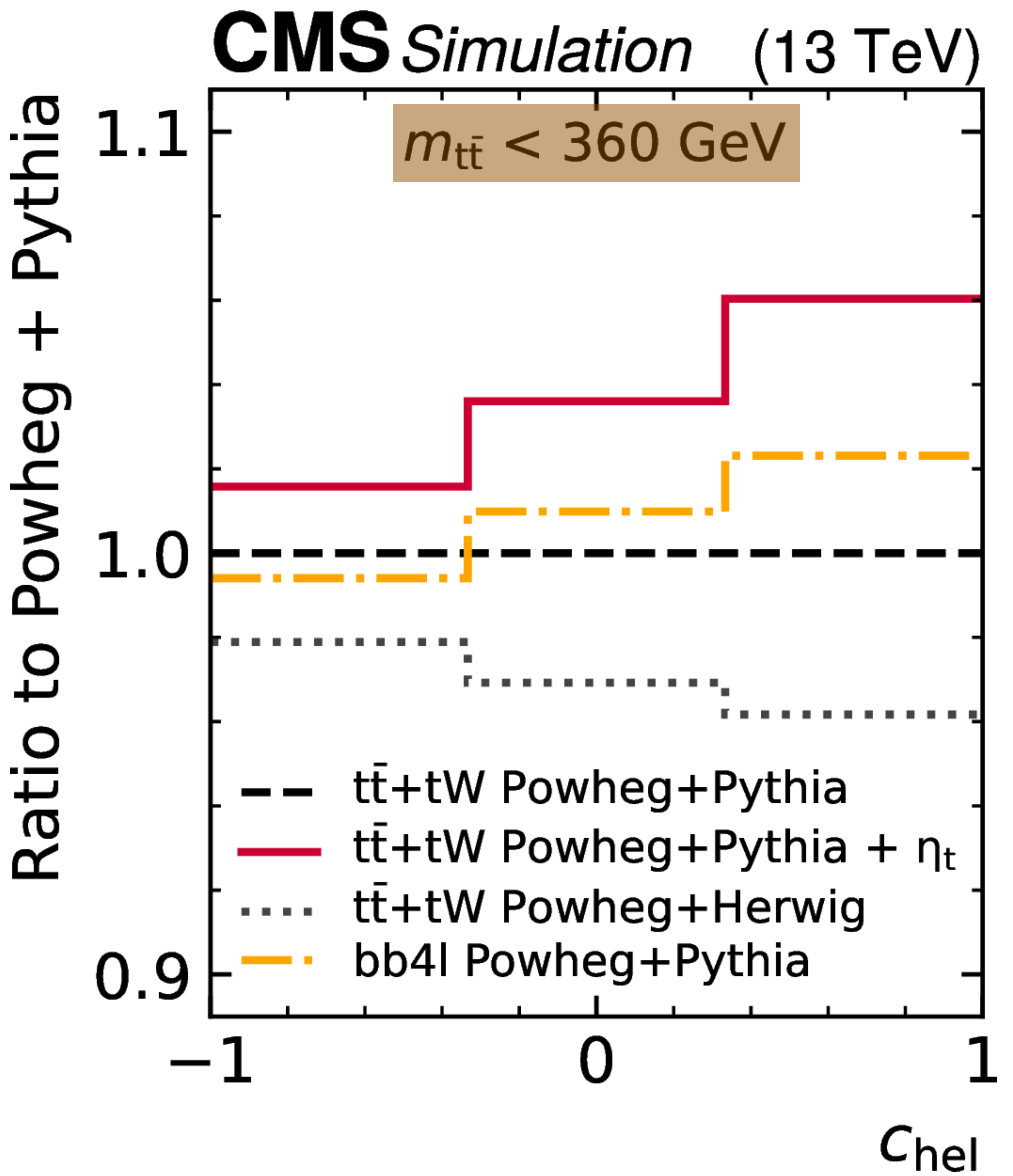
strong pulls to values beyond the SM prediction

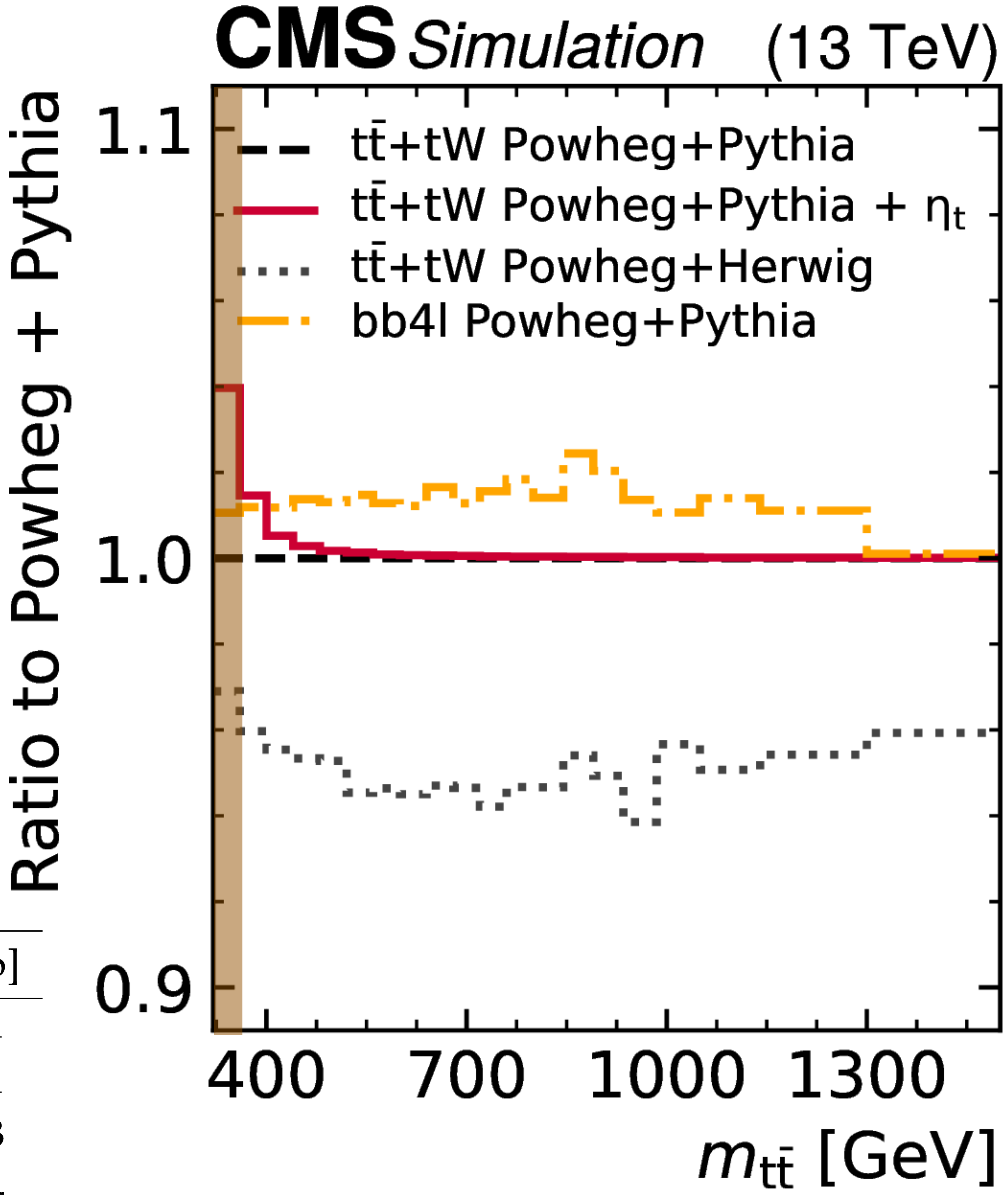
→ observed excess can only be explained by additional contributions to FO pQCD

Alternative fixed order pQCD predictions



Alternative fixed order pQCD predictions

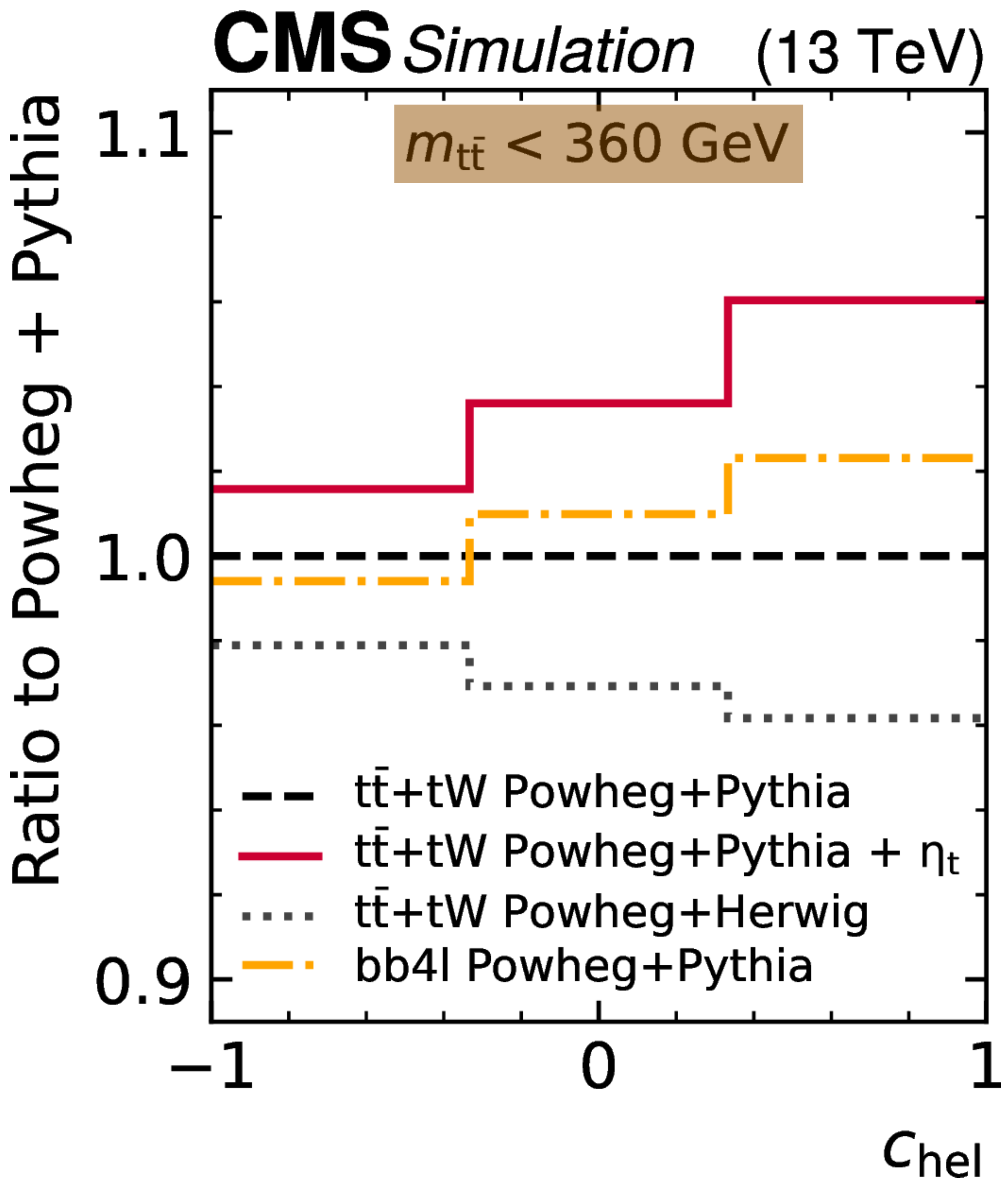


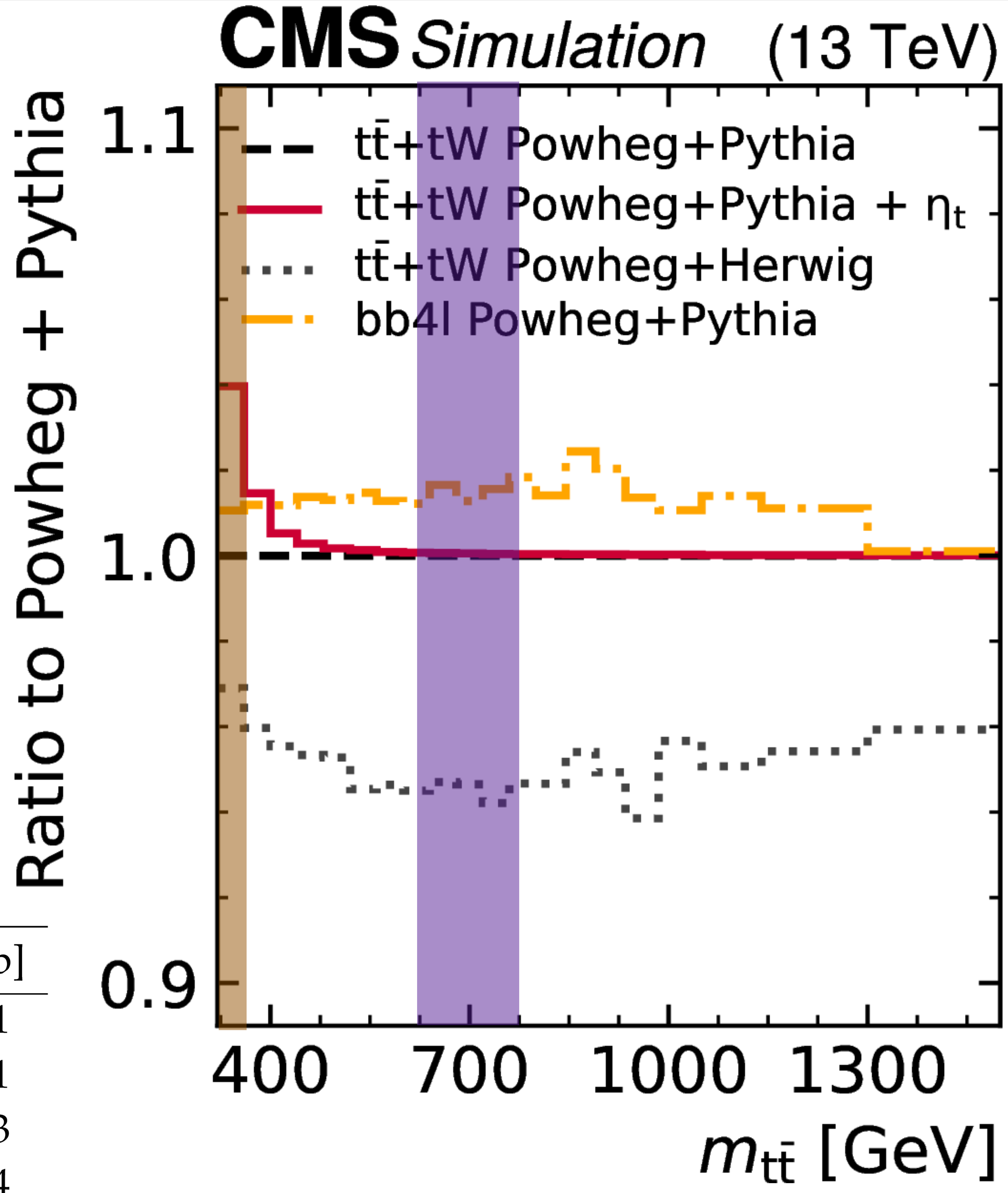


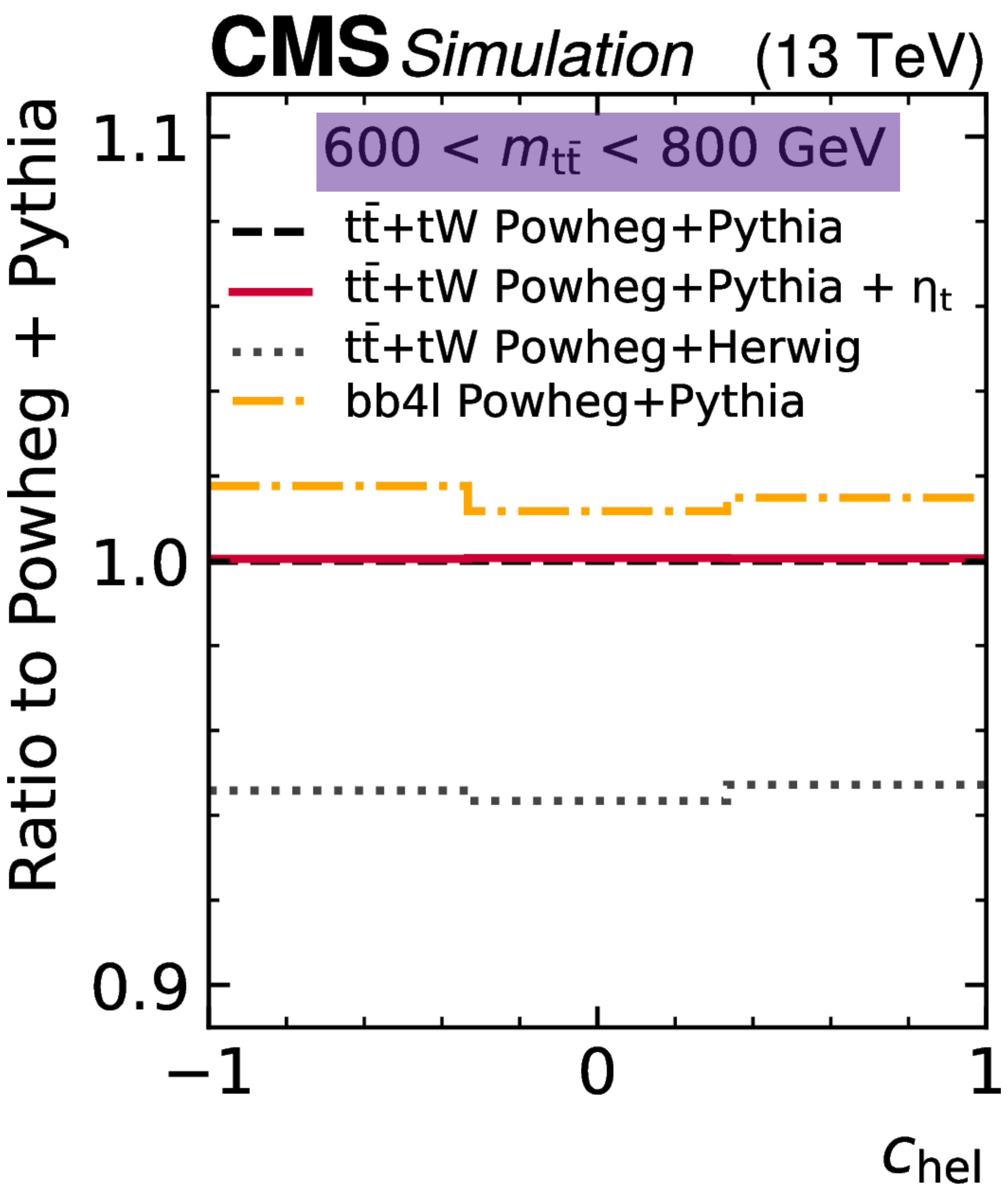
FO pQCD generator setup	$\sigma(\eta_t)$ [pb]
POWHEG v2 hvq + PYTHIA	8.7 ± 1.1
POWHEG v2 hvq + HERWIG	8.6 ± 1.1
MADGRAPH5_aMC@NLO FxFx + PYTHIA	9.8 ± 1.3
POWHEG vRES bb4l + PYTHIA	6.6 ± 1.4
Nominal result	$8.8^{+1.2}_{-1.4}$

→ **excess remains**

Alternative Fixed Order pQCD Predictions







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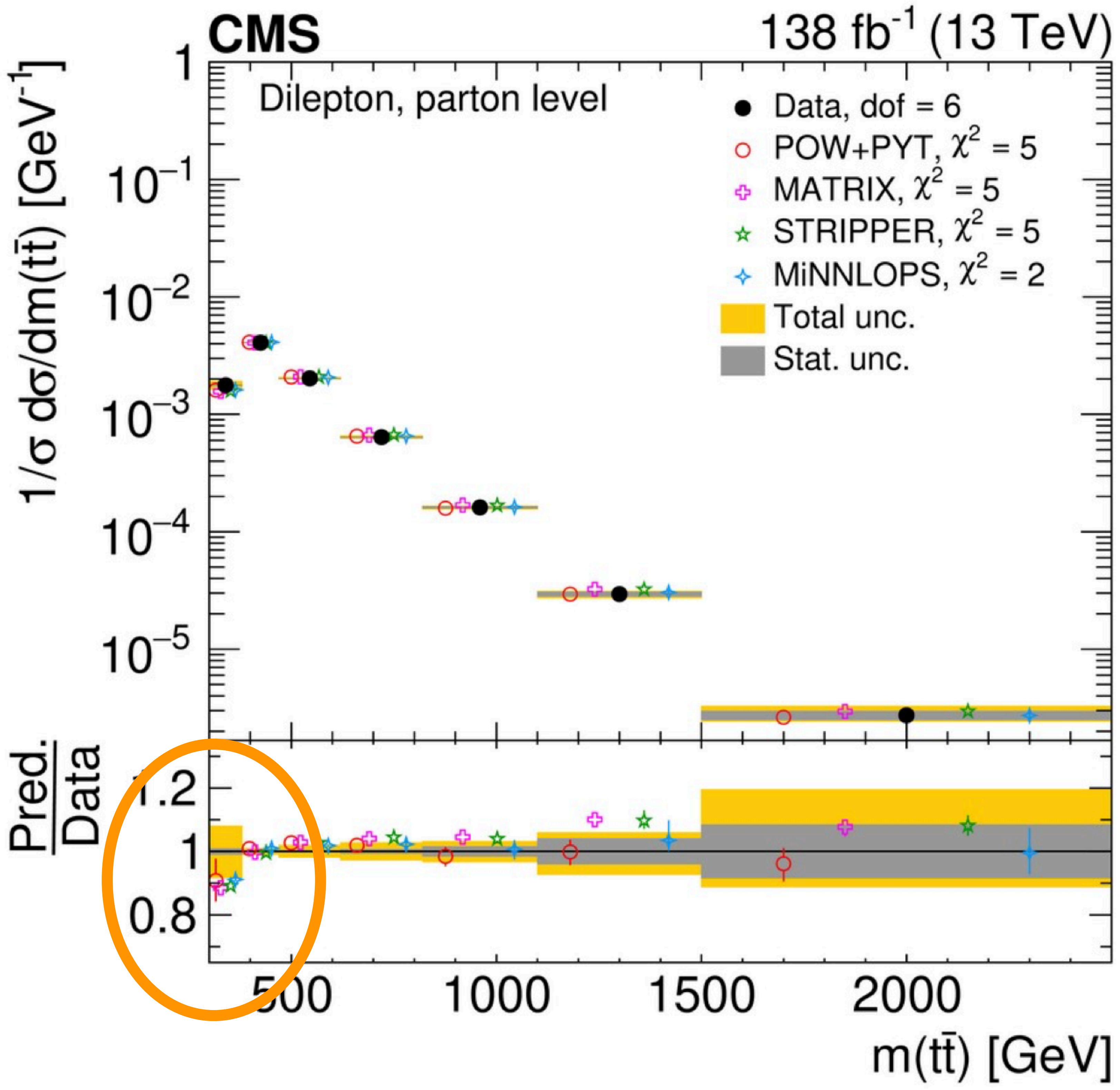
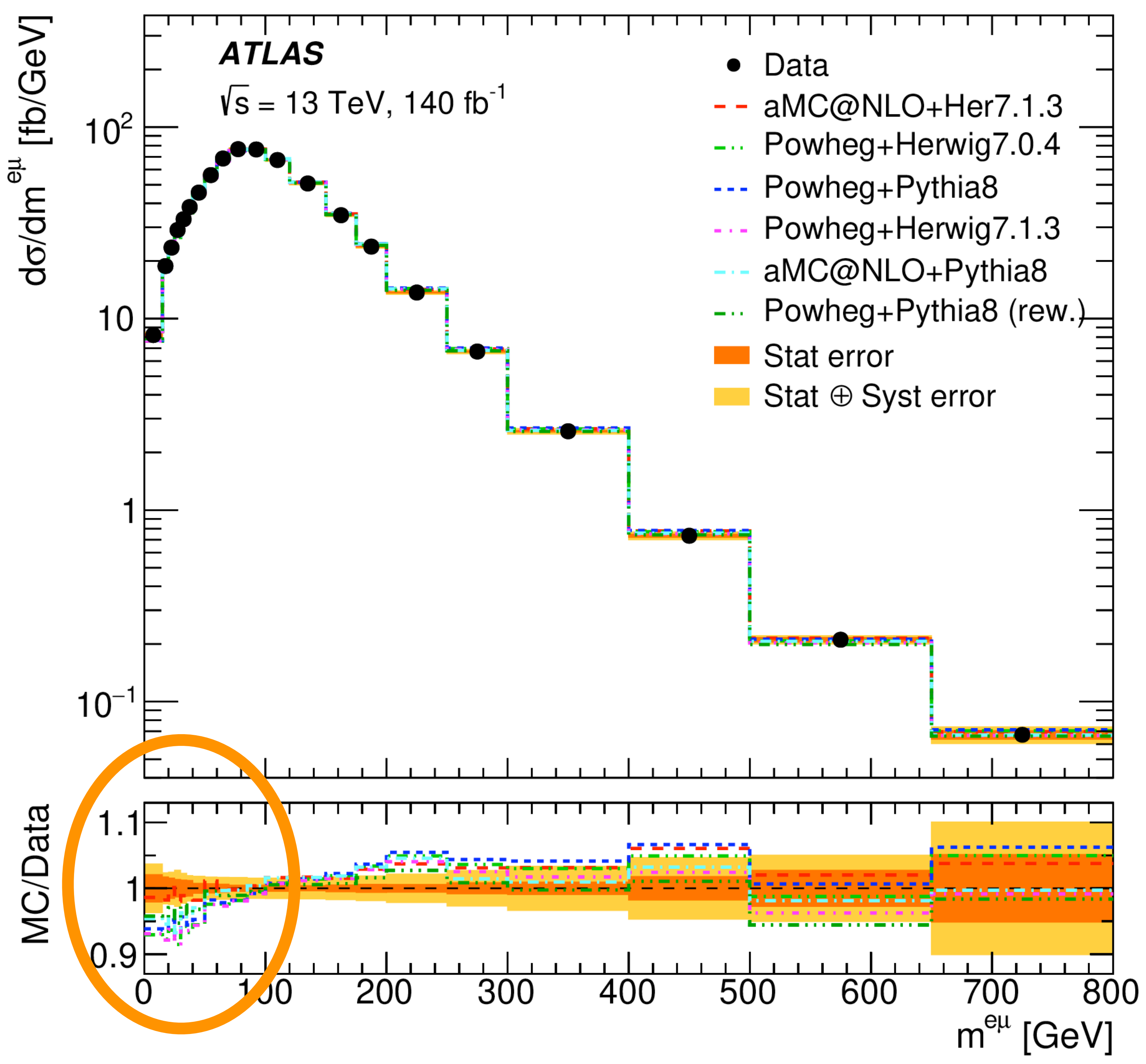
→ **excess remains**

Consistency with other Results: Invariant Mass

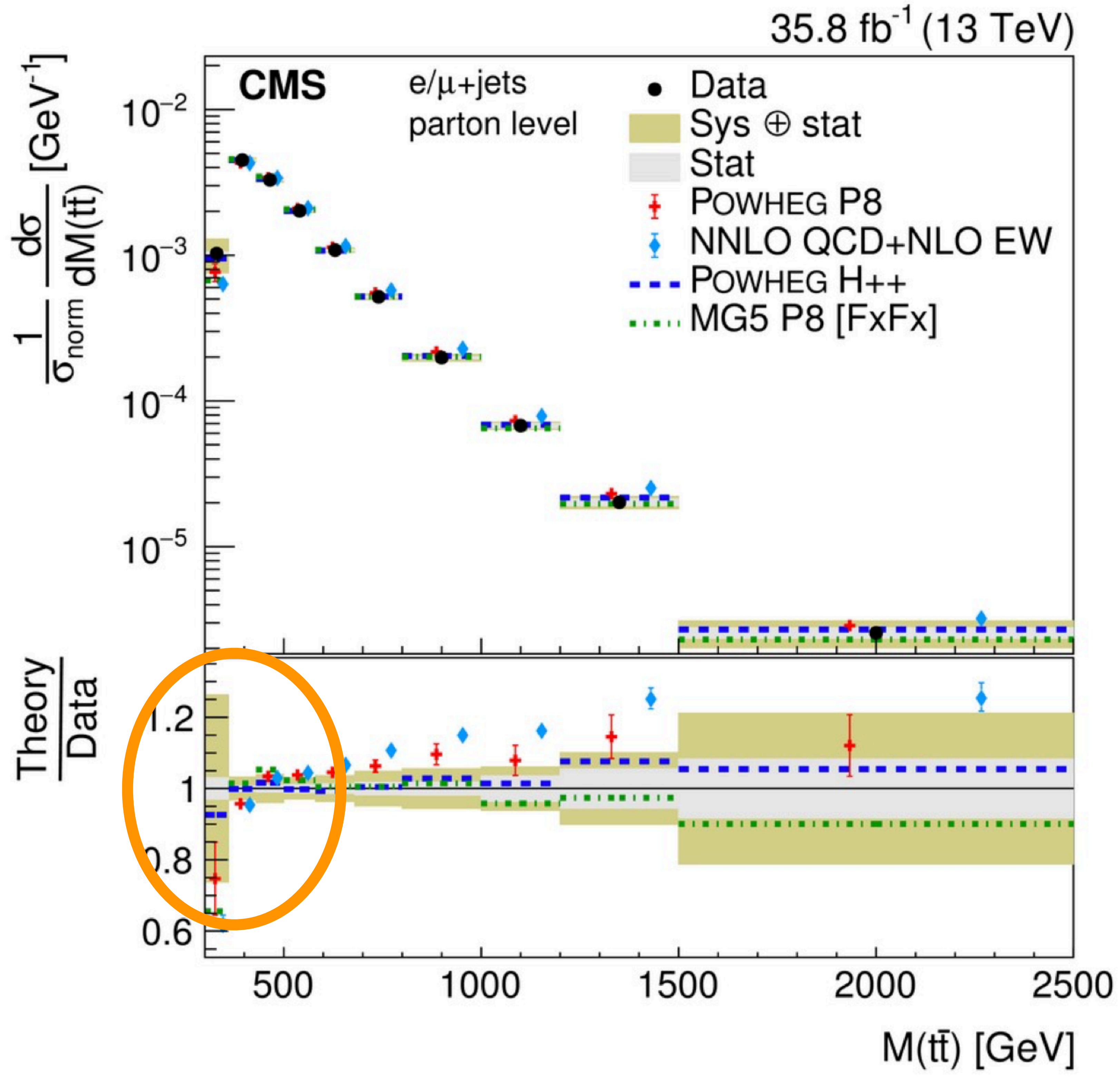
arXiv:2402.08486



JHEP 07 (2023) 141



PRD 97 (2018) 11200



→ **good description by theory except for enhancement in data in threshold region**

Consistency with Other Results: Spin Correlation

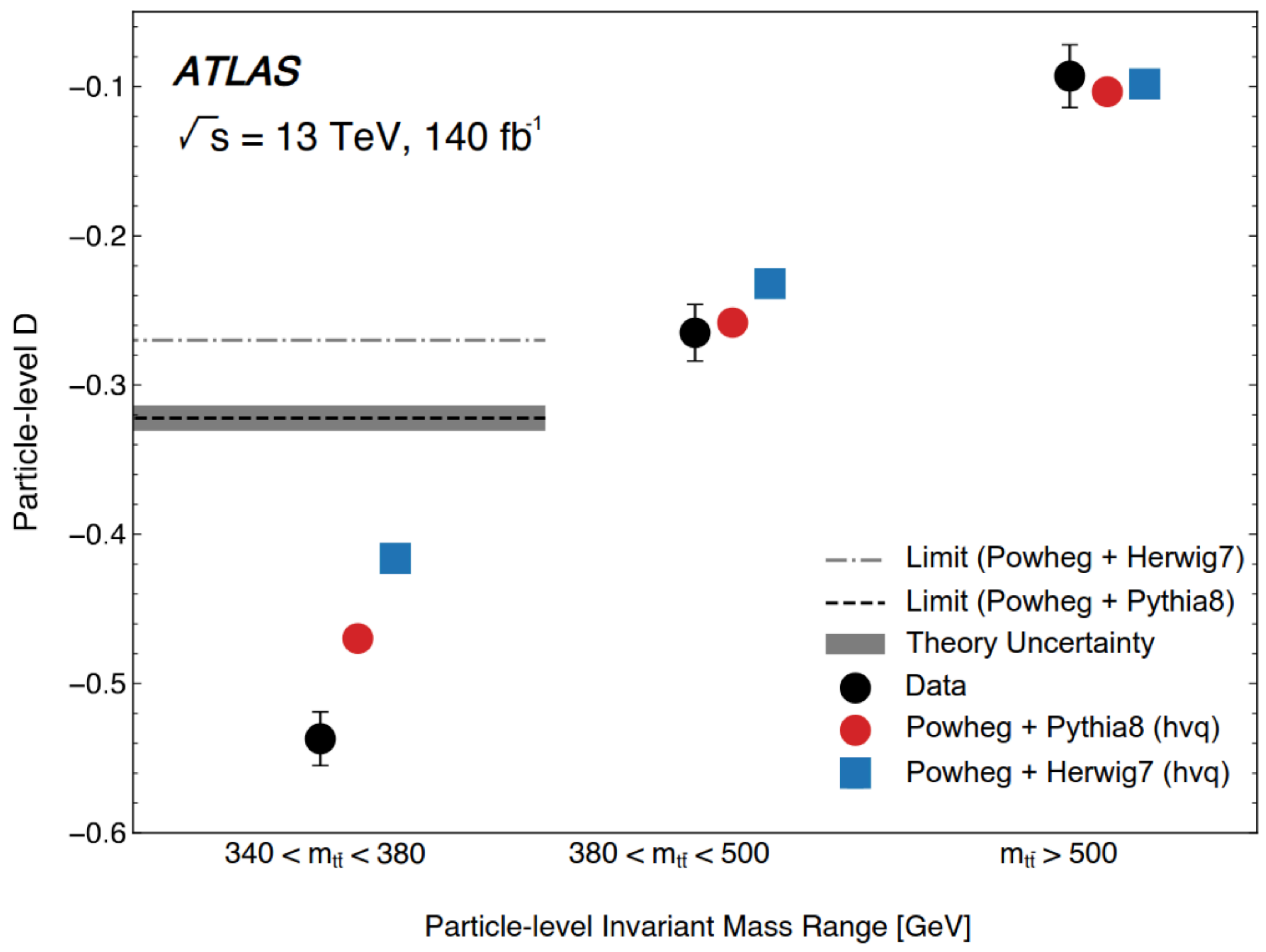
- quantum entanglement analysis

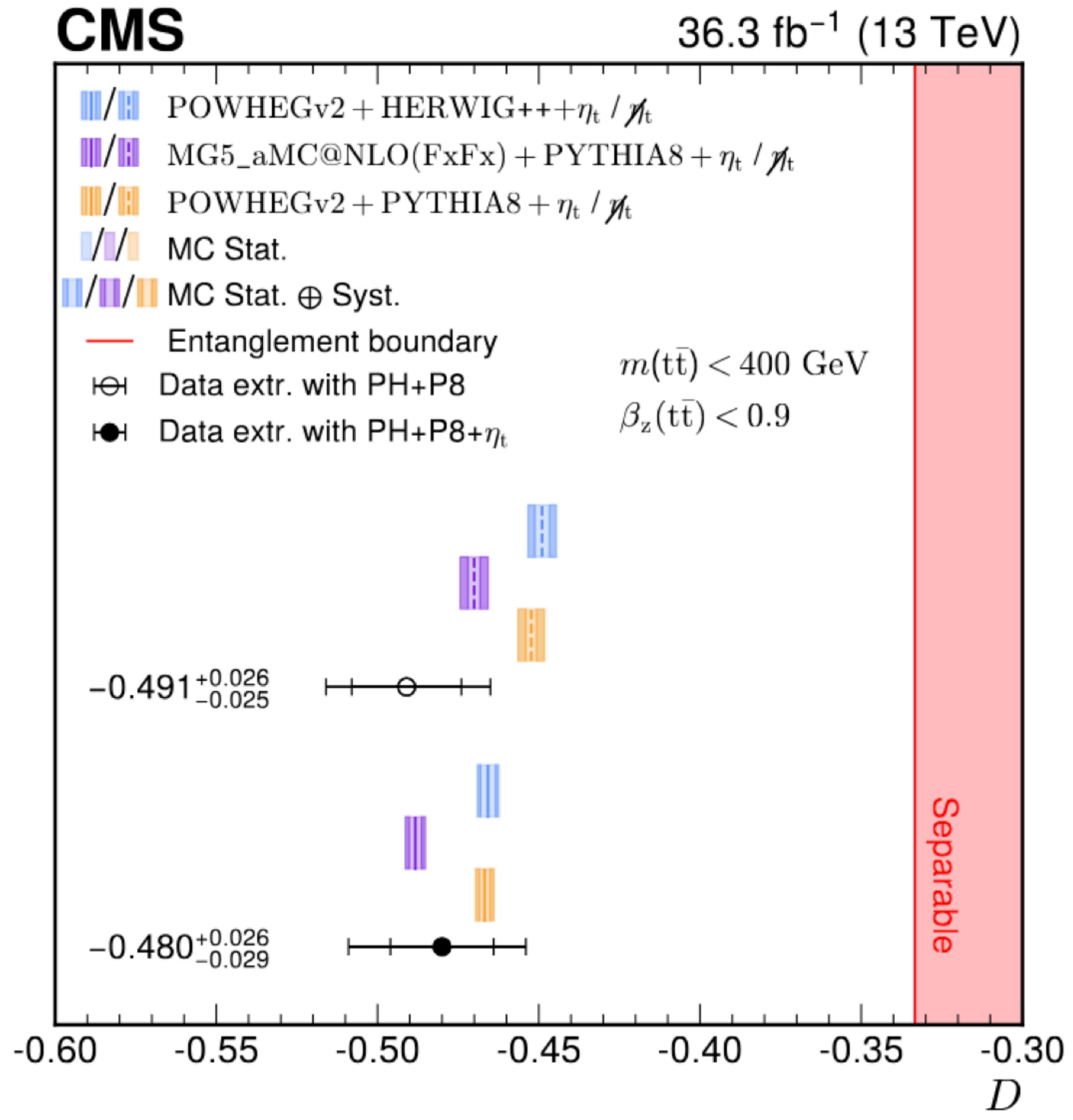
$D = -3\langle C_{hel}\rangle$

Phys. Lett. B 725 (2013) 115
[Corr. ibid. 744 (2015) 413]

RPP 87 (2024) 117801

Nature 633 (2024) 542





→ **data requests stronger slope in C_{hel} at threshold: „our" pseudoscalar excess would fit**

Summary

- search for spin-0 scalars and pseudoscalars in top quark pair events with full CMS Run-2 dataset at $\sqrt{s}$ = 13 TeV using 138 fb^{-1} of CMS data
- observed excess in data at threshold of >5σ significance which remains despite extensive studies of systematics using all our current theoretical knowledge
- excess is consistent with a CP-odd color-singlet $t\bar{t}$ (quasi-)bound state: pseudoscalar toponium η_t
- extracted cross section is in agreement with NRQCD prediction of 6.43 pb for pseudoscalar toponium - but no uncertainties on theory value are given yet…

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

→ caution 1: $t\bar{t}$ threshold region is difficult to model! We rely on current knowledge!

→ caution 2: the other hand we also cannot exclude BSM contributions, e.g. by a new elementary pseudoscalar particle

→ caution 3: ATLAS needs to confirm…

→ pseudoscalar toponium seems to be a valid explanation within the SM

It's exciting…

symmetry
follow
topics

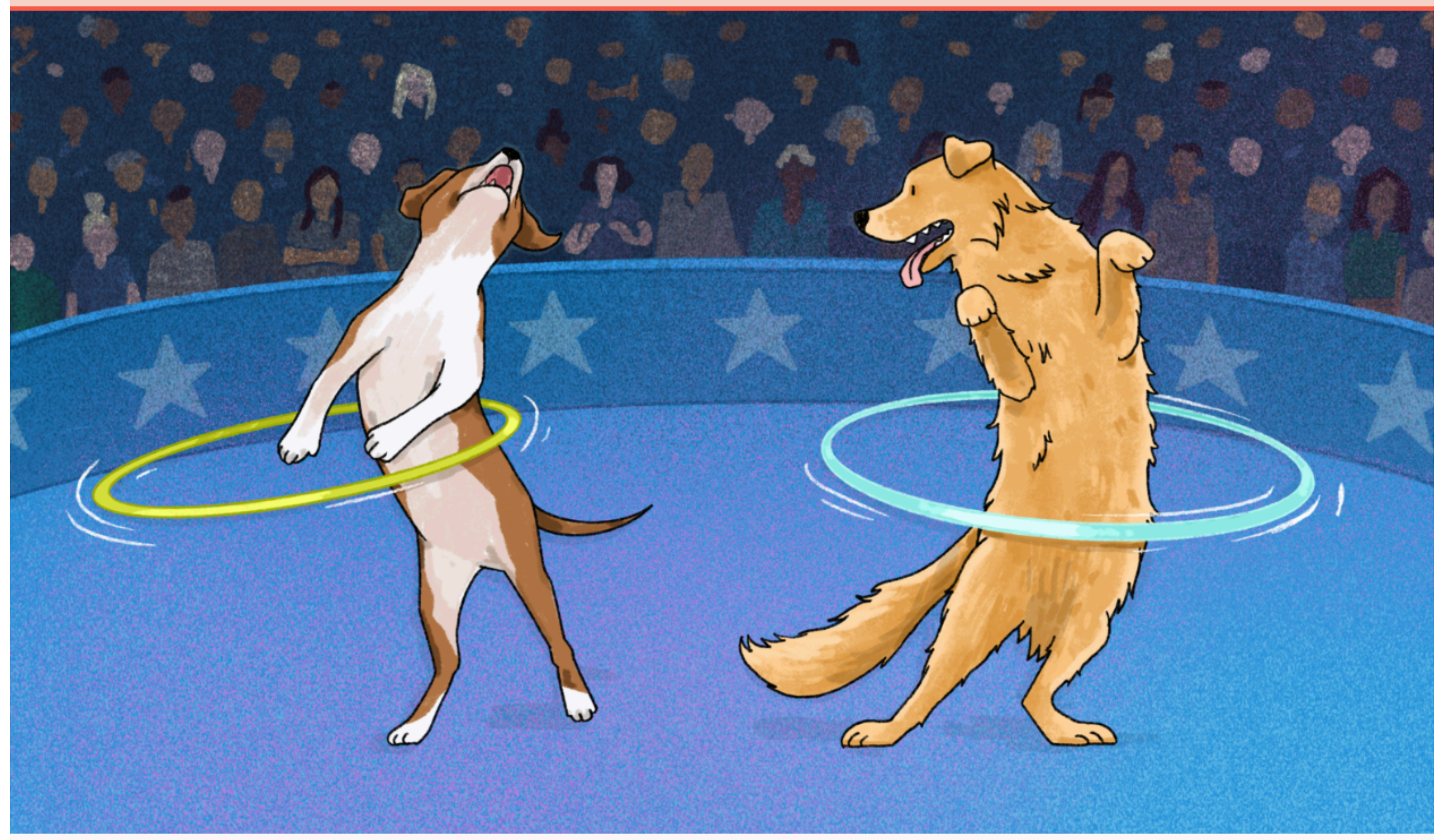


Illustration by Sandbox Studio, Chicago with Corinne Mucha

Don't call it toponium

04/01/25 | By Sarah Charley

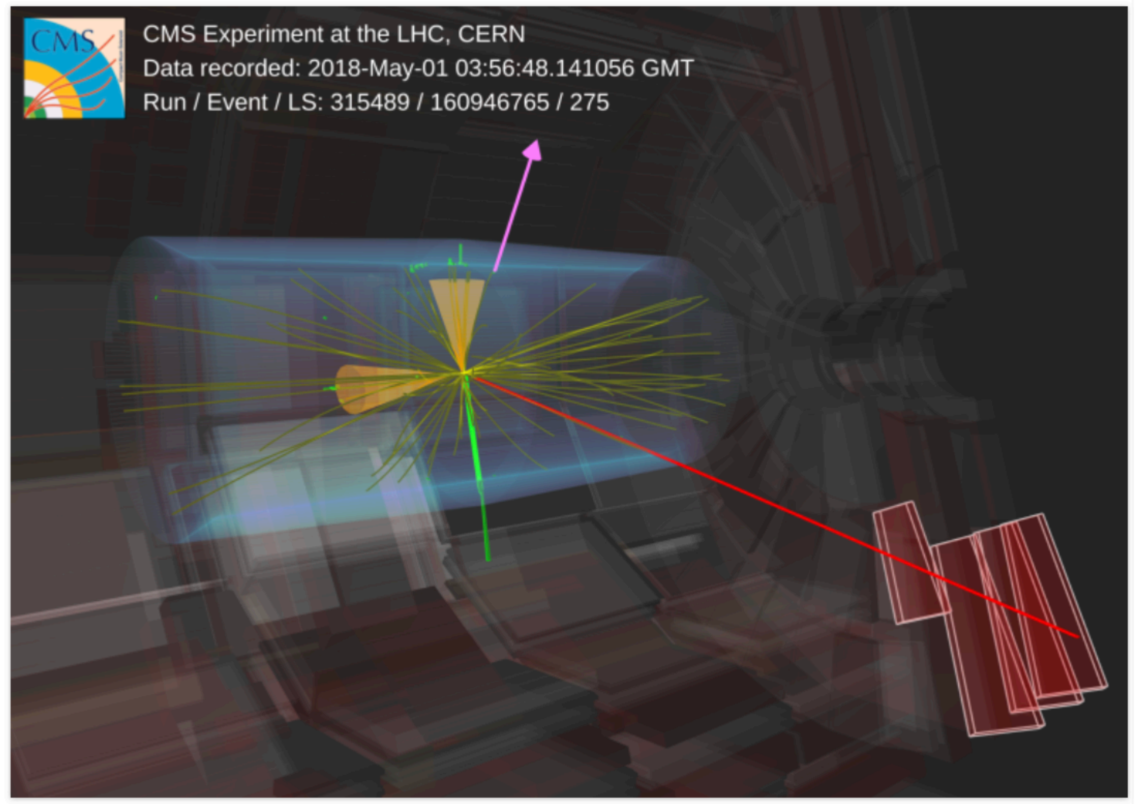
A large and unexpected excess of top quark pairs has the physics community excited, but the interpretation is still up for debate.

By CMS Collaboration

CMS finds unexpected excess of top quarks

Data from the CMS experiment at CERN's Large Hadron Collider reveals an intriguing excess of top-quark pairs, hinting at the first observation of a composite particle with unique properties

3 APRIL, 2025



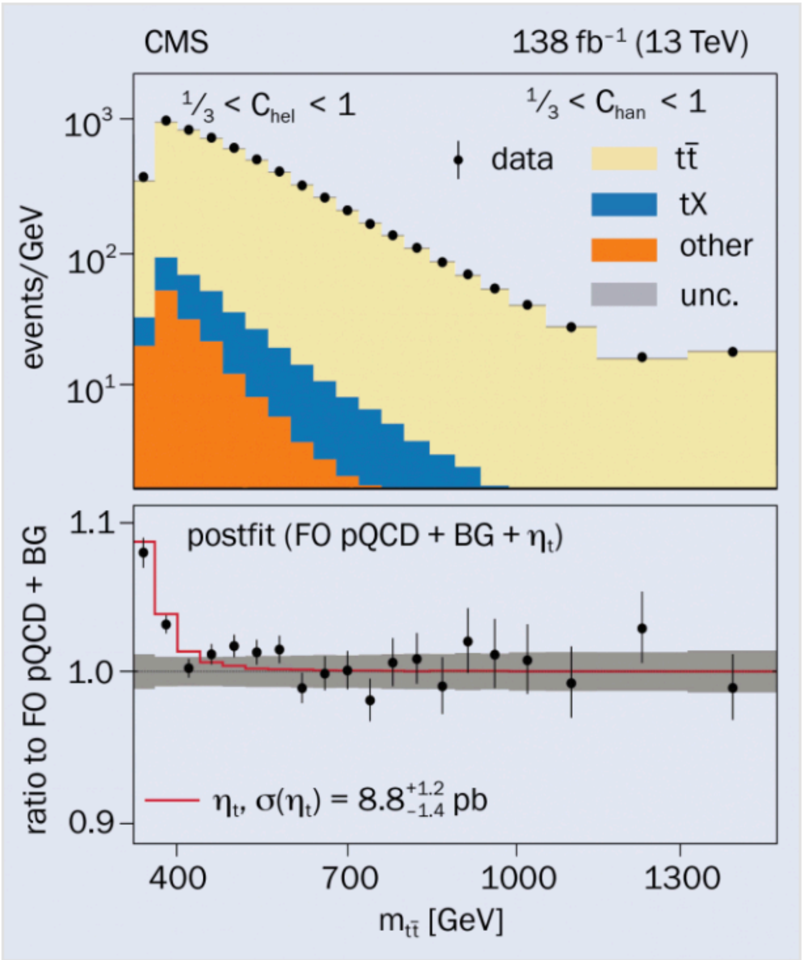
Event display of the excess of top-quark pairs. (Image: CMS collaboration/CERN)

CERNCOURIER Reporting on international high-energy physics

STRONG INTERACTIONS | NEWS

CMS observes top–antitop excess

2 April 2025



CERN's Large Hadron Collider continues to deliver surprises. While searching for additional Higgs bosons, the CMS collaboration may have instead uncovered evidence for the smallest composite particle yet observed in nature – a "quasi-bound" hadron made up of the most massive and shortest-lived fundamental particle known to science and its antimatter counterpart. The findings, which do not yet constitute a discovery claim and could also be susceptible to other explanations, were reported this week at the Rencontres de Moriond conference in the Italian Alps.

TEST BEAM

Deutsches Elektronen-Synchrotron DESY
Ein Forschungszentrum der Helmholtz-Gemeinschaft

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Scientists from the CMS collaboration observe a new effect

DESY/UHH-led detailed study of collisions with top quarks point to unknown structure

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

QUANTUM UNIVERSE

Photo: UHH/Denstorf

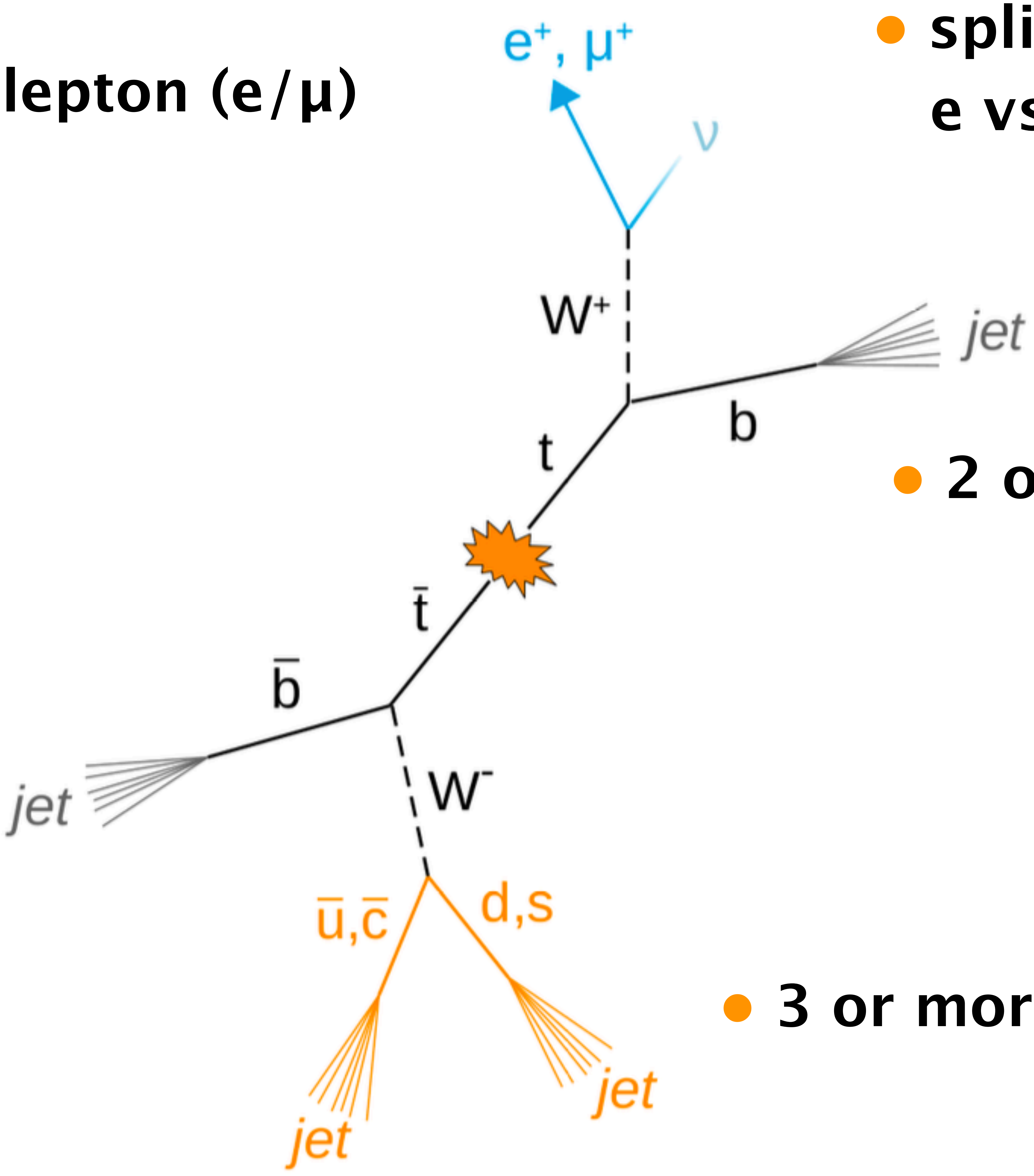
CMS collaboration observes a new effect

Detailed study of collisions with top quarks points to unknown structure

Backup

Selection and Reconstruction: Lepton+Jets Channel

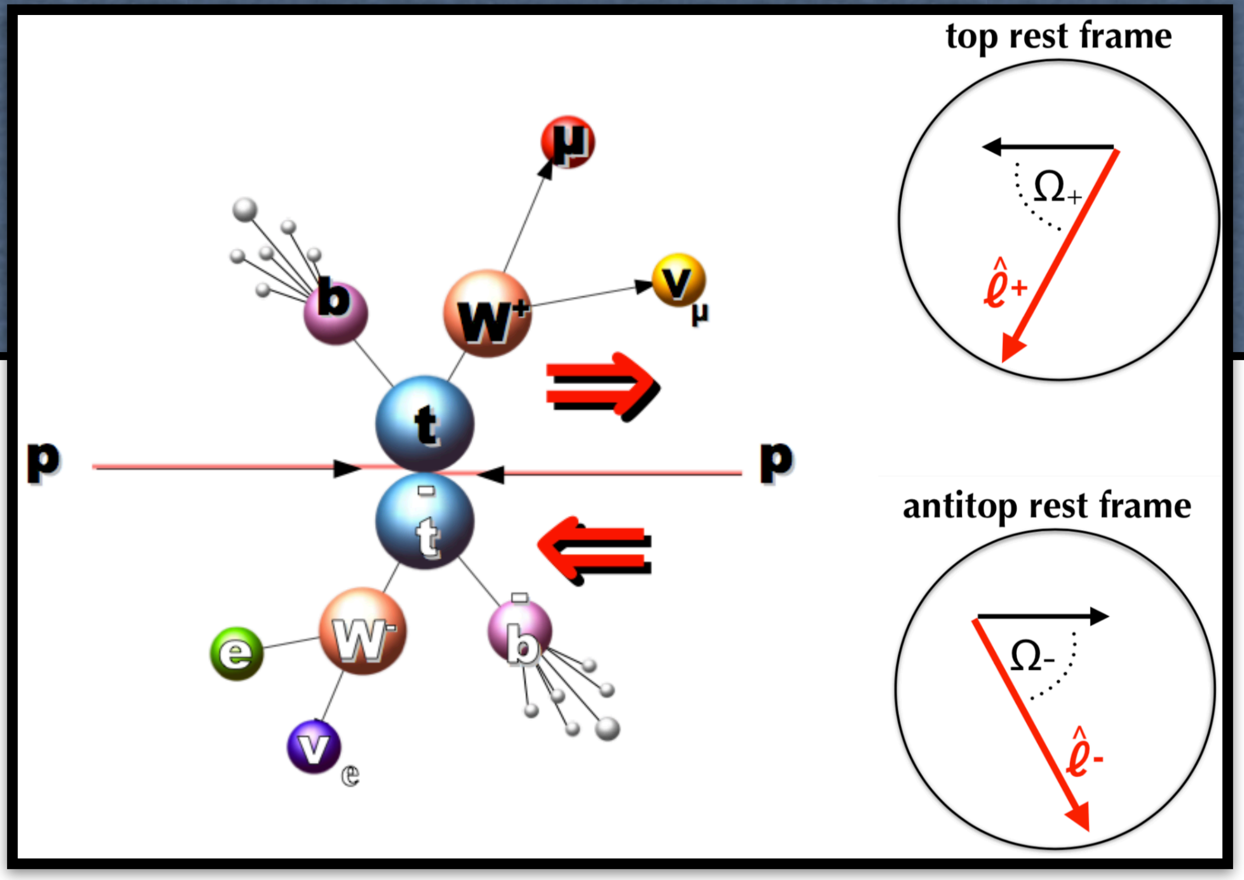
- exactly one lepton (e/μ)
- split in 4 categories: e vs μ and 3 jets vs ≥4 jets
- 2 or more b-jets
- 3 or more jets



- **Reconstruct $t\bar{t}$ system with `NeutrinoSolver` algorithm**
  NIM A 736 (2014) 169
  - assign b-jets by maximum likelihood
  - energy correction factor applied for 3 jet events (lost or merged jets)
  NIM A 788 (2015) 128

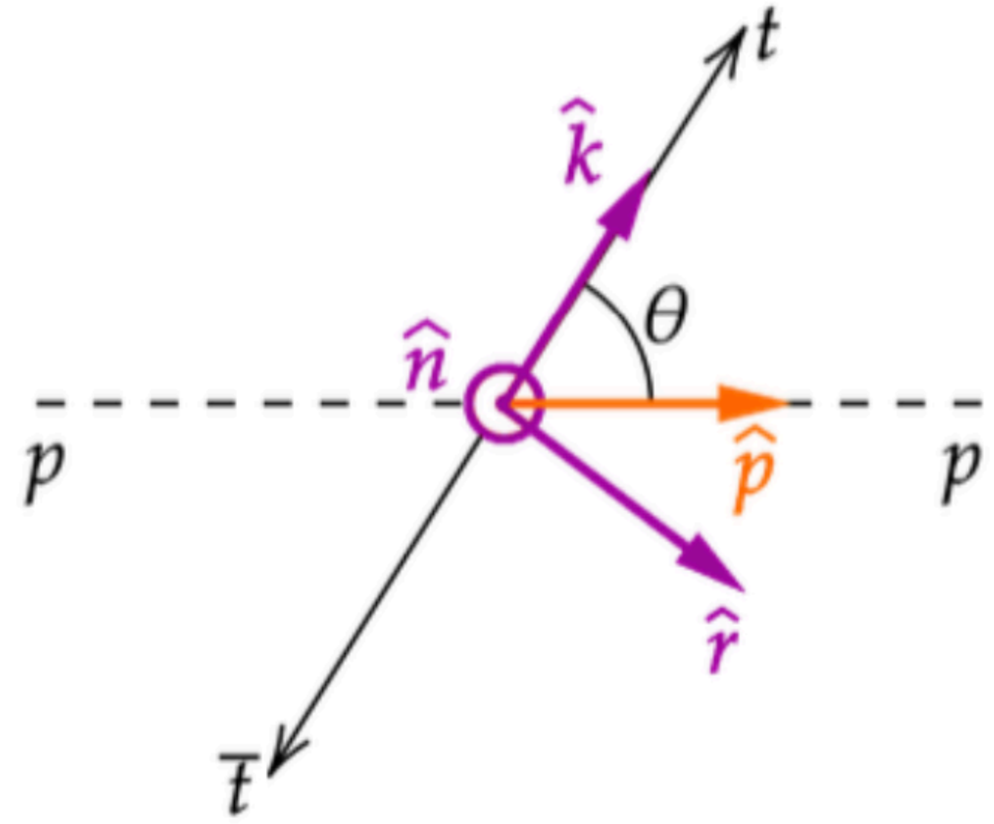
$t\bar{t}$ Spin Density Matrix

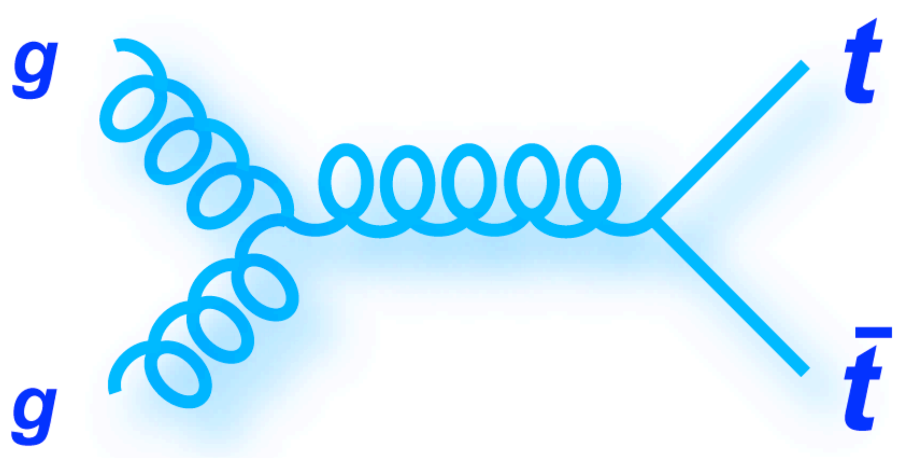
JHEP 12 (2015) 026
Nucl. Phys. B 690 (2004) 81
Phys. Rev. D 58 (1998) 114031



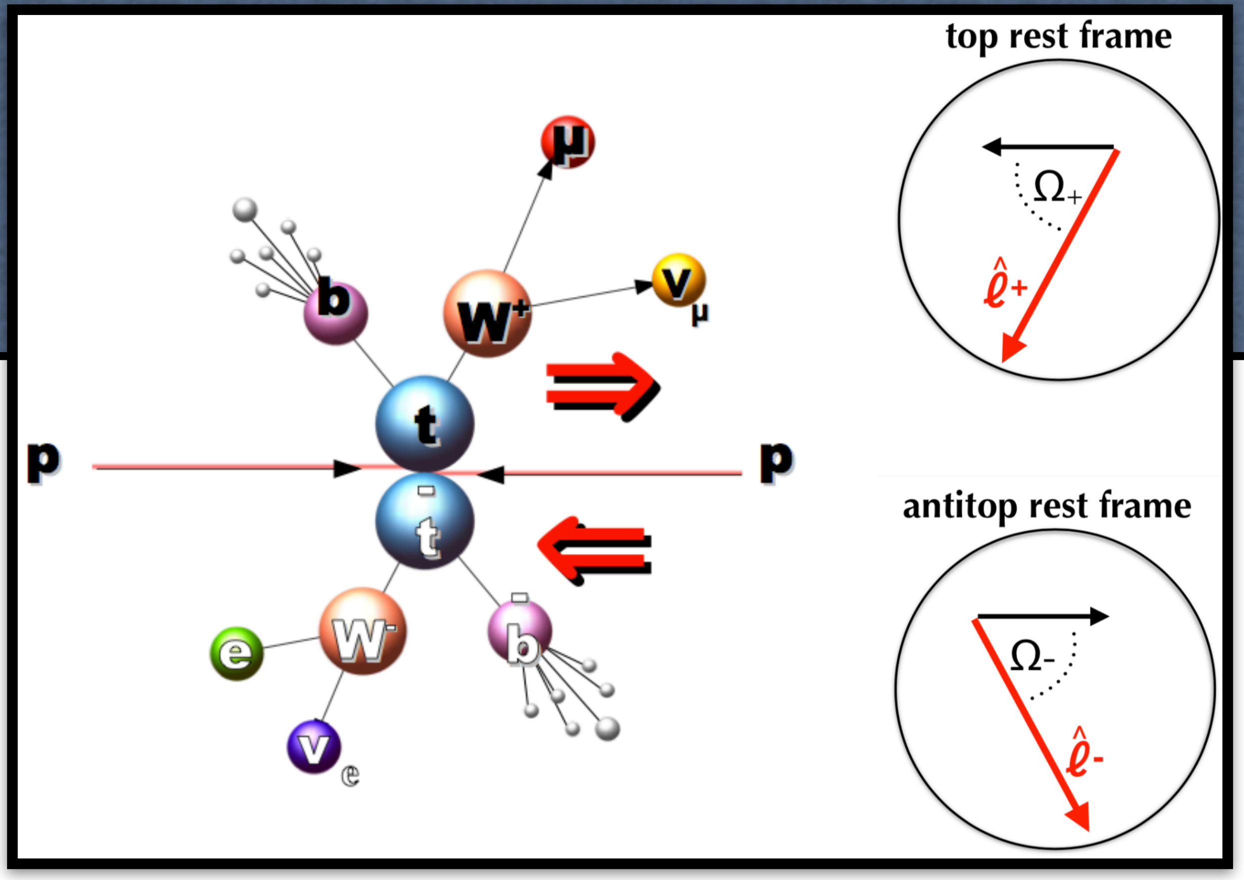
$$|M|^2 \propto A + \vec{B}_1 \cdot \hat{\ell}^1 + \vec{B}_2 \cdot \hat{\ell}^2 - \hat{\ell}^1 \cdot C \cdot \hat{\ell}^2$$

$\hat{\ell}^a$ = top spin vectors





$t\bar{t}$ Spin Density Matrix



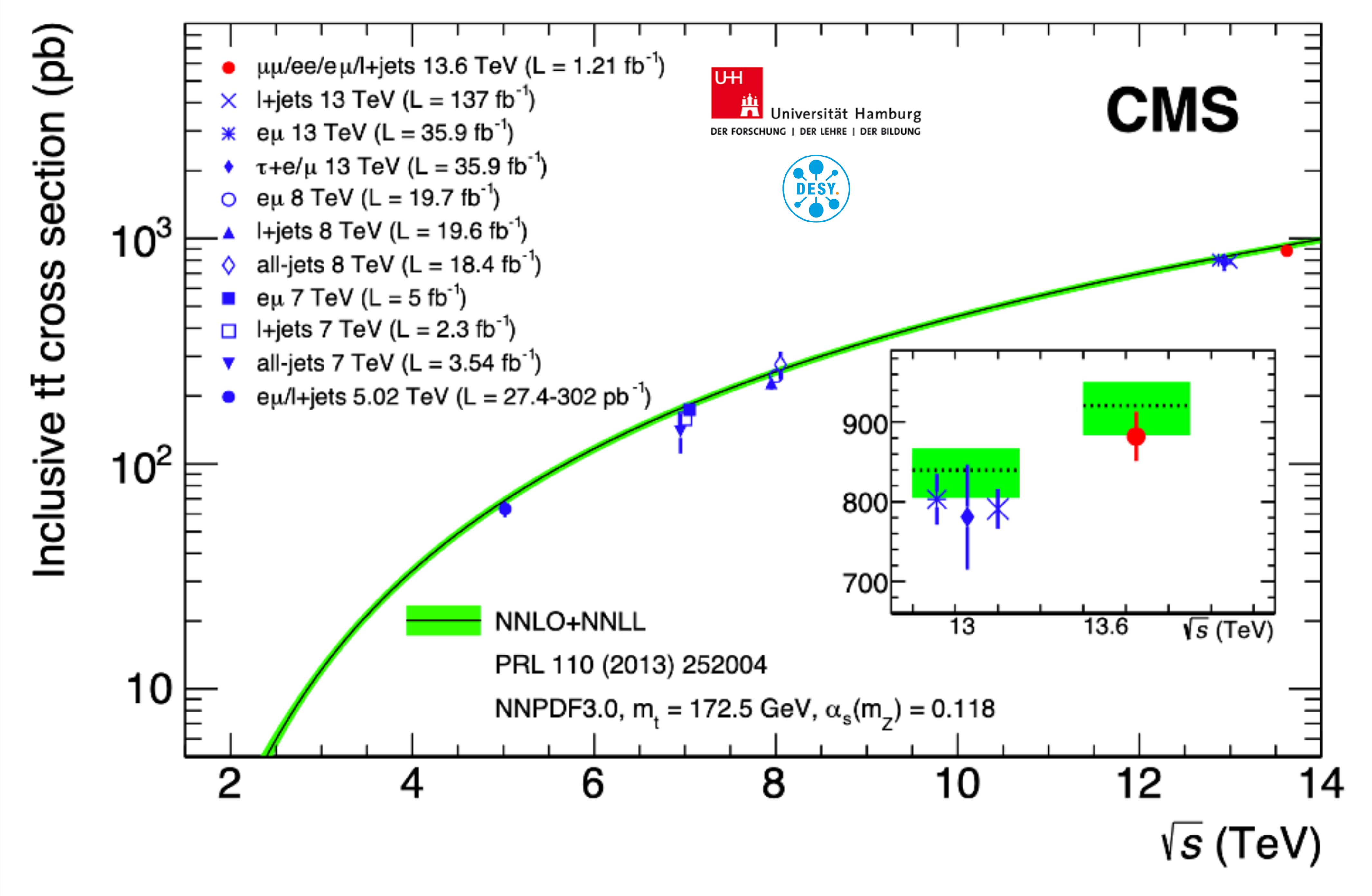
spin-independent:

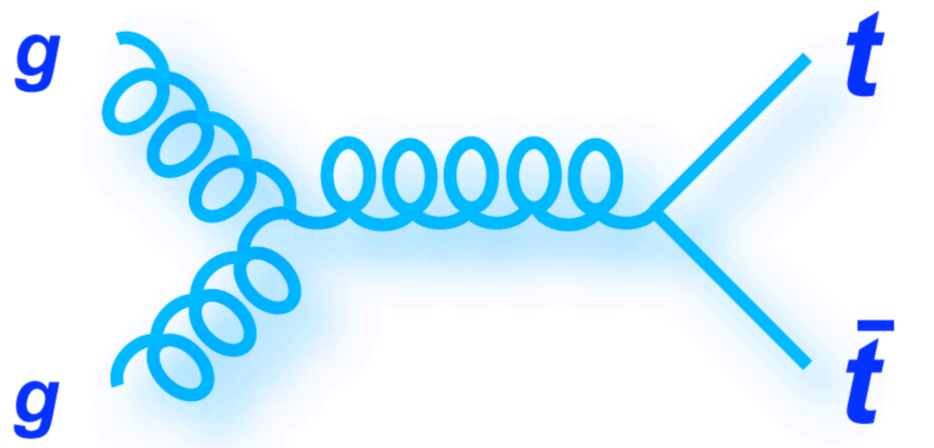
cross section, $m_{t\bar{t}}$, p_T^t, …

$$|M|^2 \propto A + \vec{B}_1 \cdot \hat{\ell}^1 + \vec{B}_2 \cdot \hat{\ell}^2 - \hat{\ell}^1 \cdot C \cdot \hat{\ell}^2$$

$\hat{\ell}^a$ = top spin vectors

JHEP 08, 204 (2023)





$t\bar{t}$ Spin Density Matrix

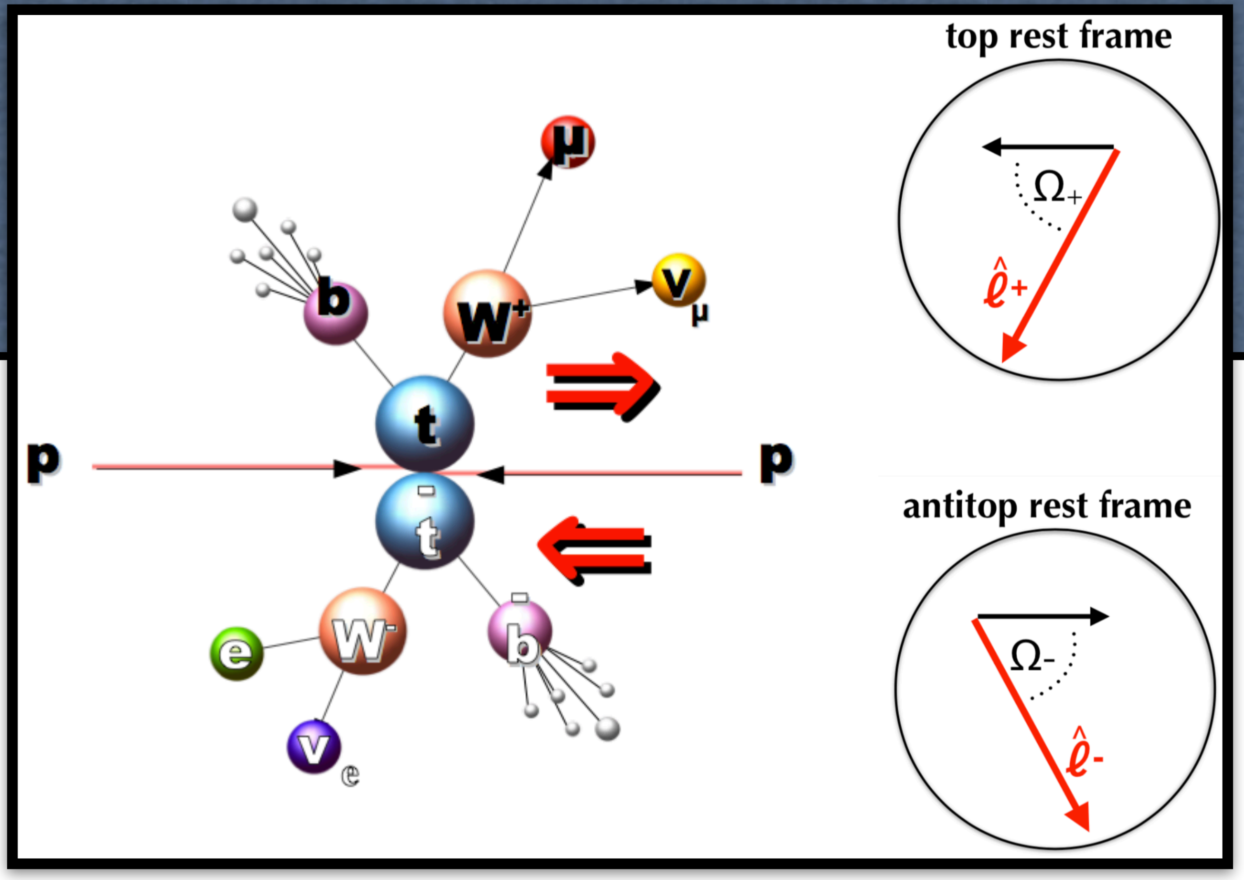
JHEP 12 (2015) 026
Nucl. Phys. B 690 (2004) 81
Phys. Rev. D 58 (1998) 114031

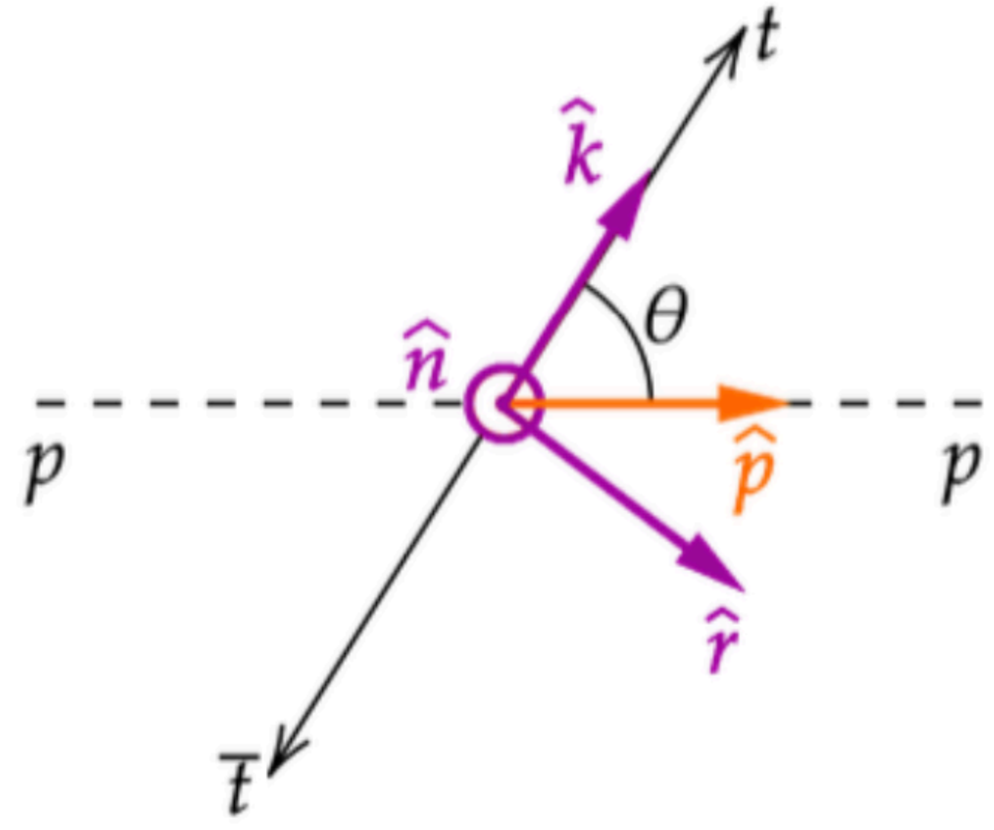
$$\vec{B}_a = \begin{pmatrix} x \\ x \\ x \end{pmatrix}$$

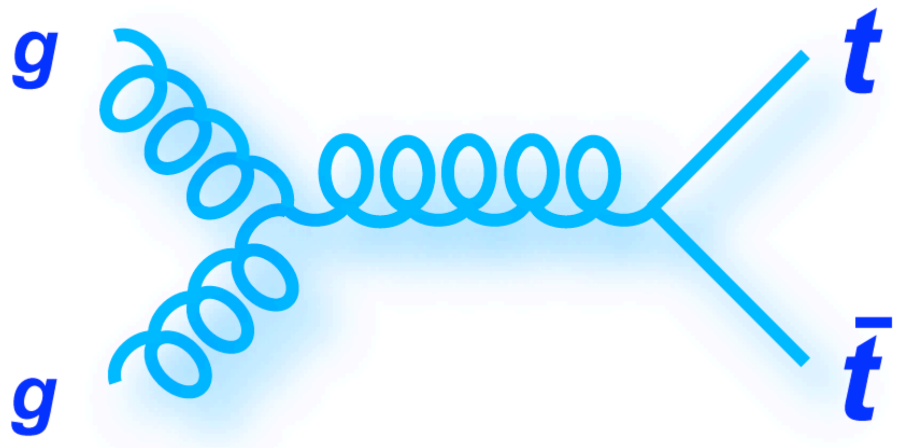
polarization

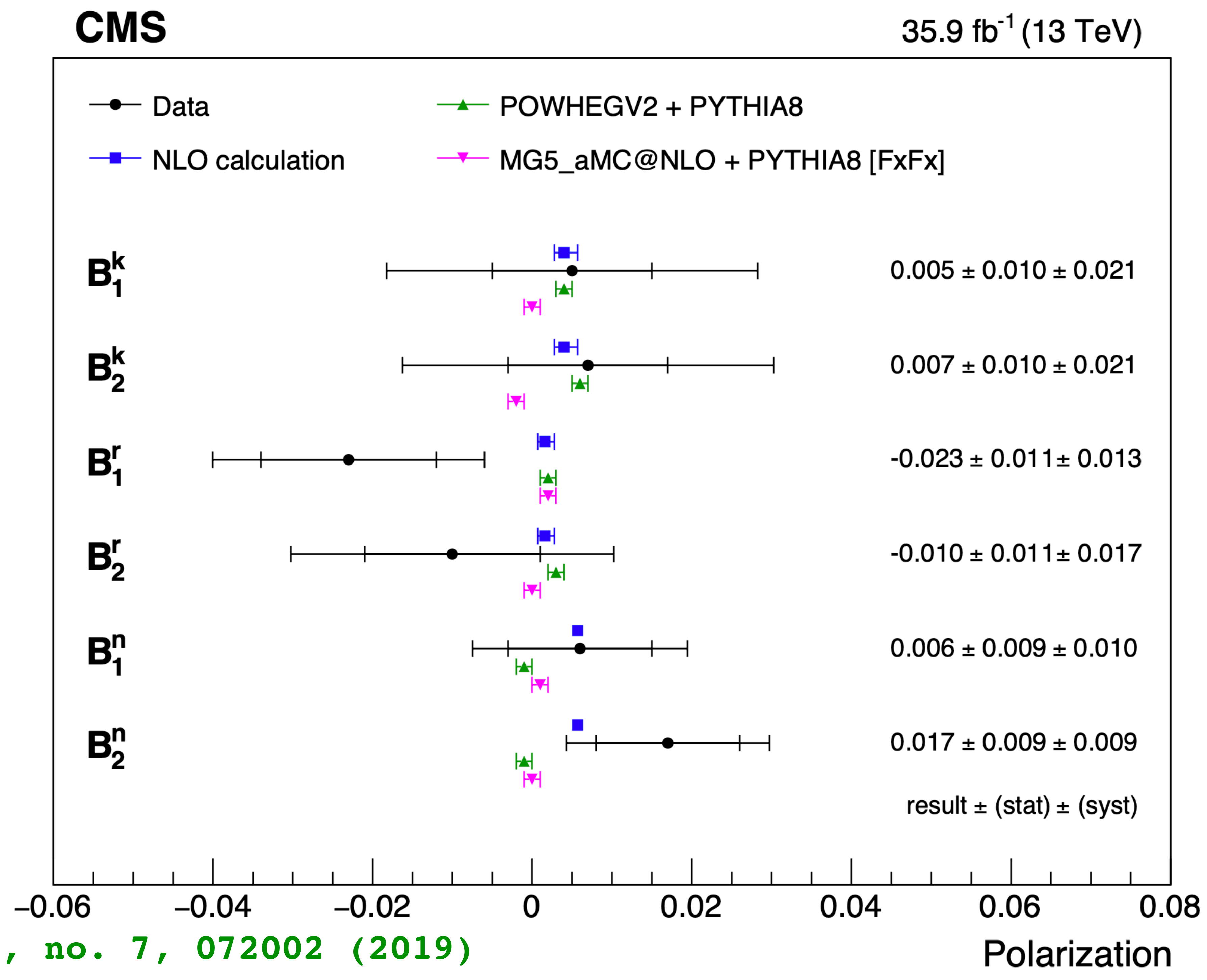
$$|M|^2 \propto A + \vec{B}_1 \cdot \hat{\ell}^1 + \vec{B}_2 \cdot \hat{\ell}^2 - \hat{\ell}^1 \cdot C \cdot \hat{\ell}^2$$

$\hat{\ell}^a$ = top spin vectors



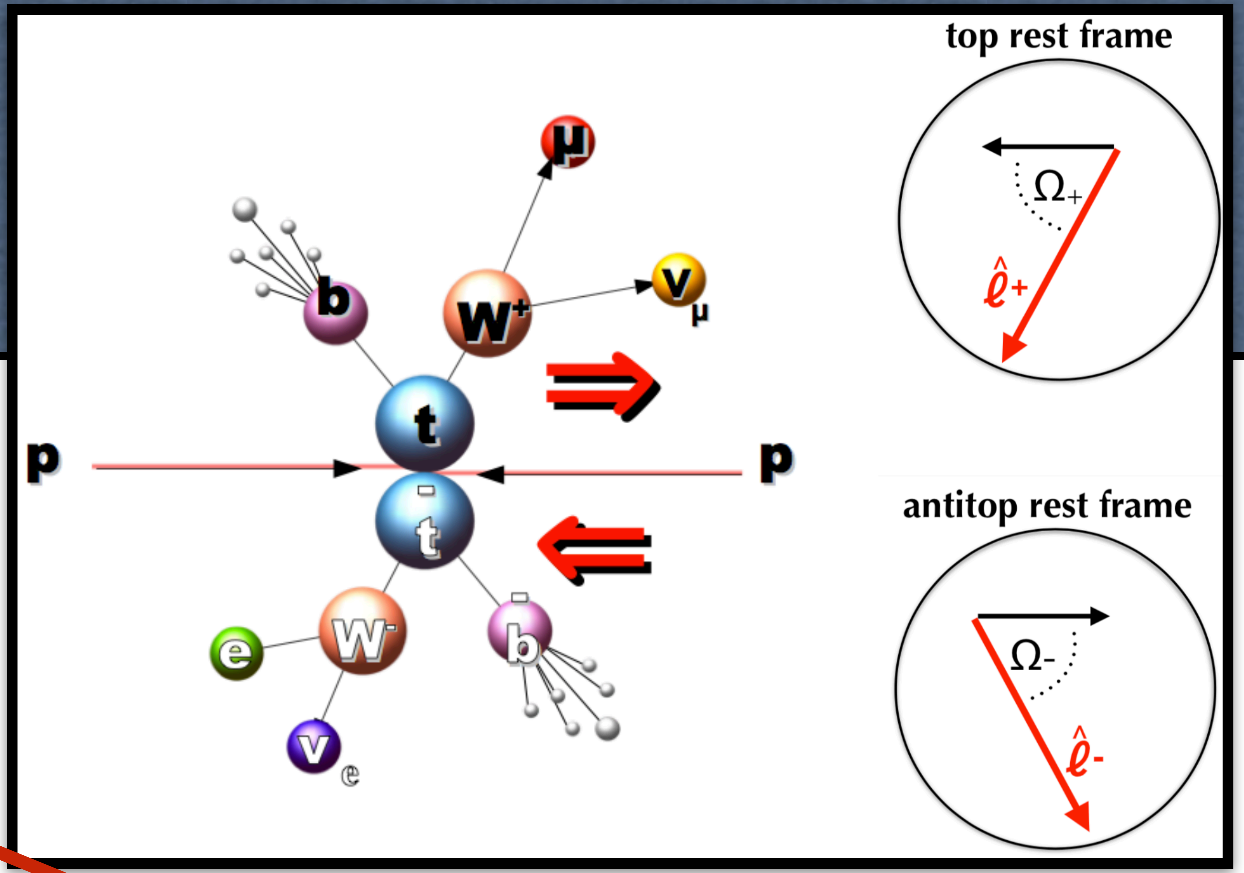






Phys. Rev. D 100, no. 7, 072002 (2019)

$t\bar{t}$ Spin Density Matrix



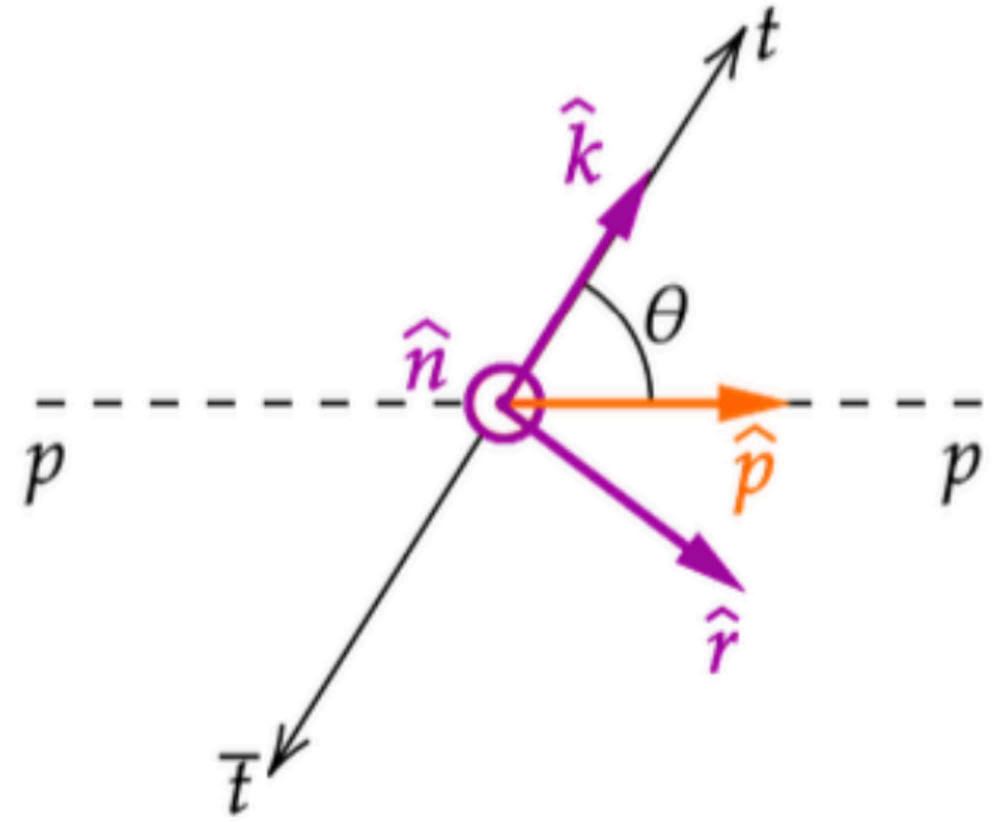
JHEP 12 (2015) 026
Nucl. Phys. B 690 (2004) 81
Phys. Rev. D 58 (1998) 114031

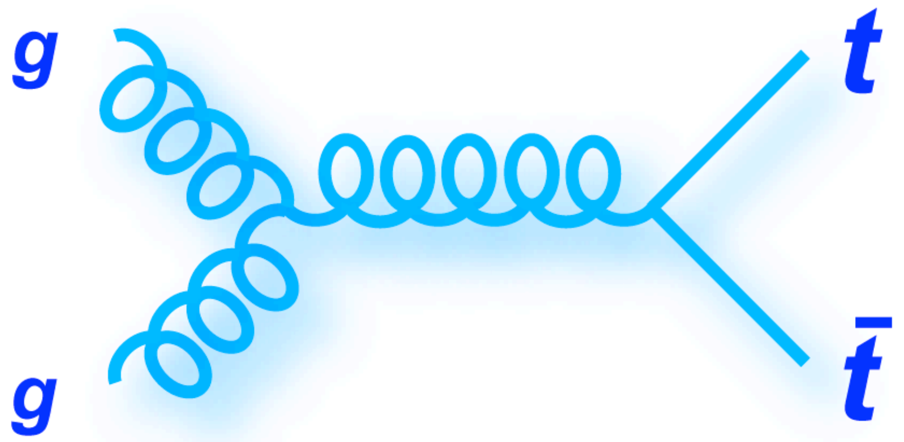
$t\bar{t}$ spin correlation

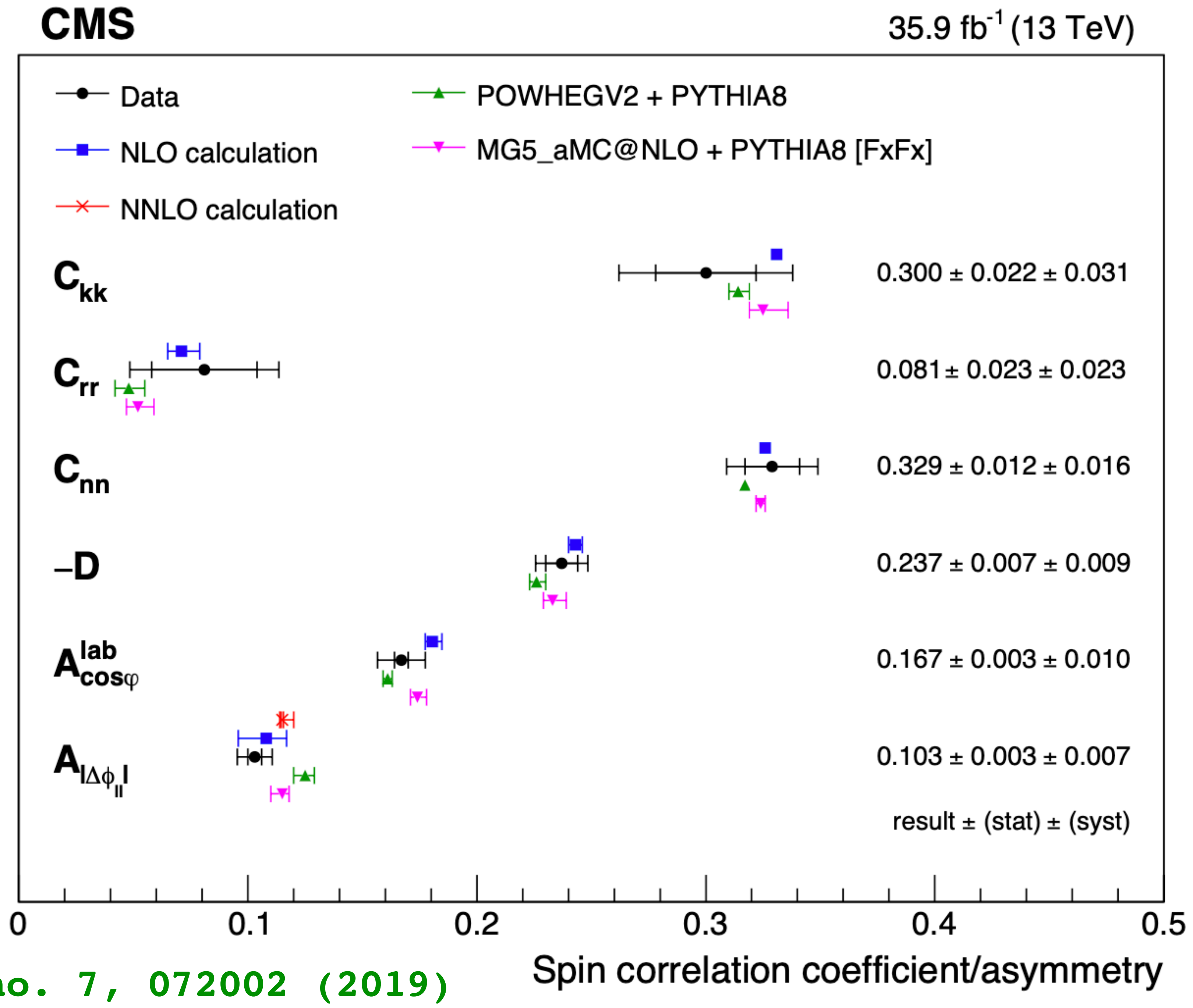
$$C = \begin{pmatrix} x & x & x \\ x & x & x \\ x & x & x \end{pmatrix}$$

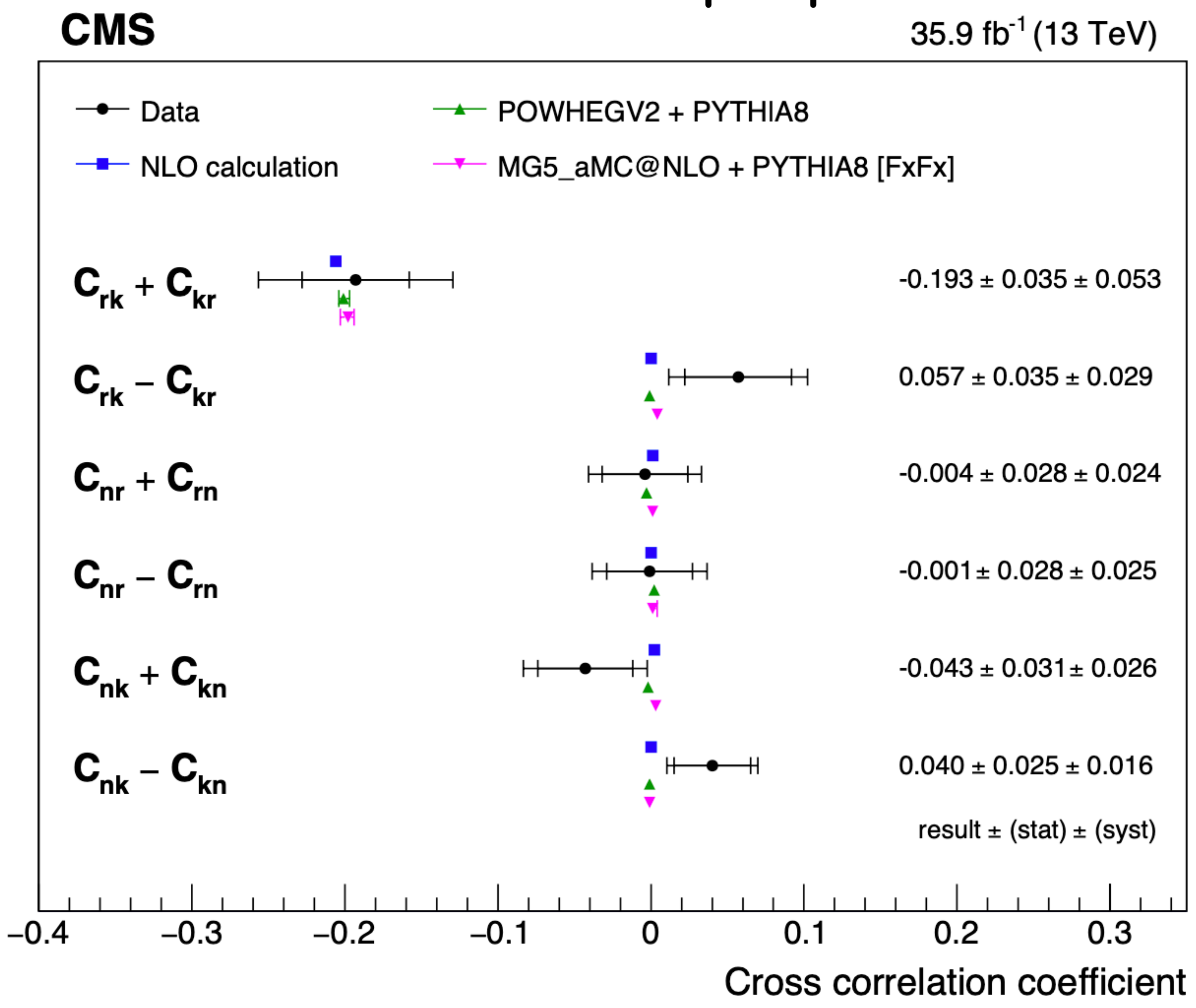
$$|M|^2 \propto A + \vec{B}_1 \cdot \hat{\ell}^1 + \vec{B}_2 \cdot \hat{\ell}^2 - \hat{\ell}^1 \cdot C \cdot \hat{\ell}^2$$

$\hat{\ell}^a$ = top spin vectors









Phys. Rev. D 100, no. 7, 072002 (2019)

$t\bar{t}$ Spin Density Matrix

JHEP 12 (2015) 026
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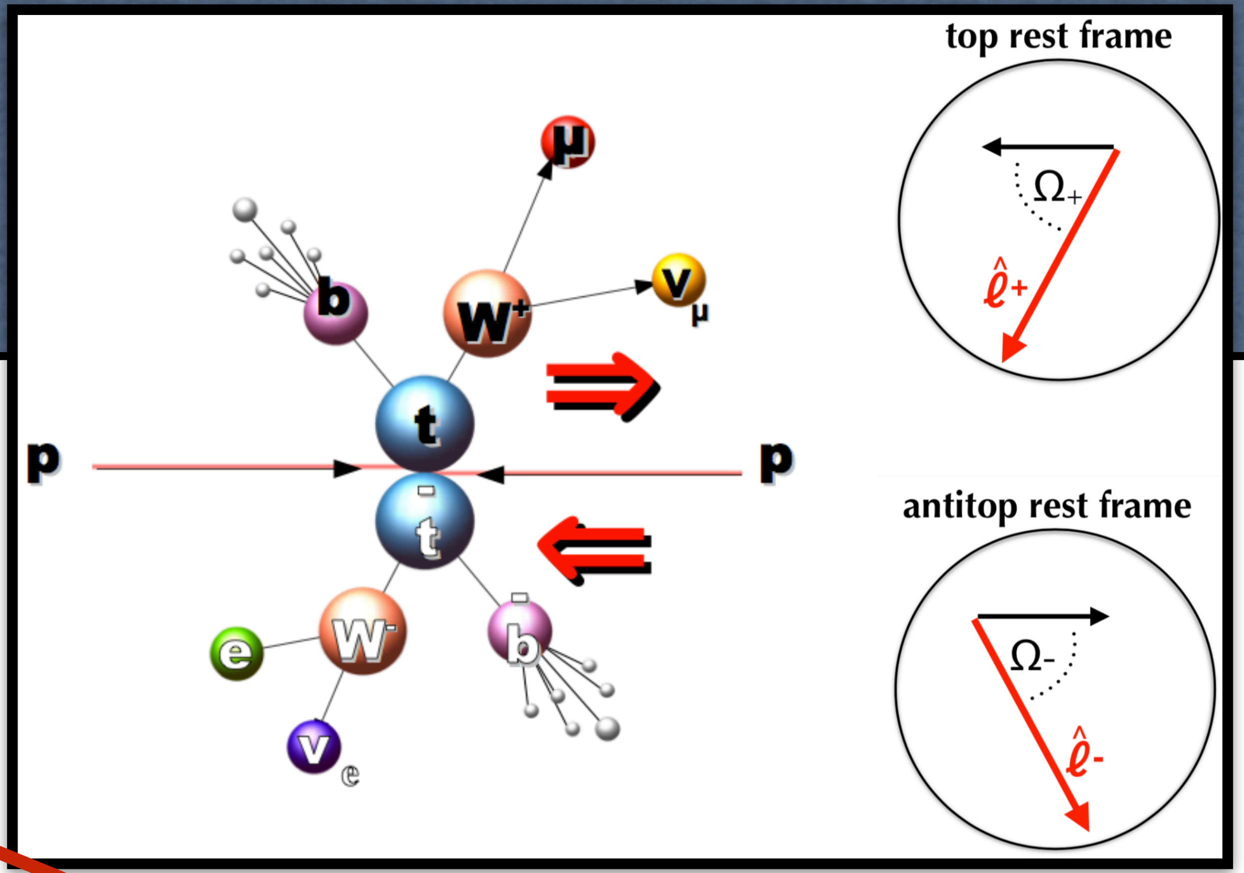
Phys. Rev. D 58 (1998) 114031



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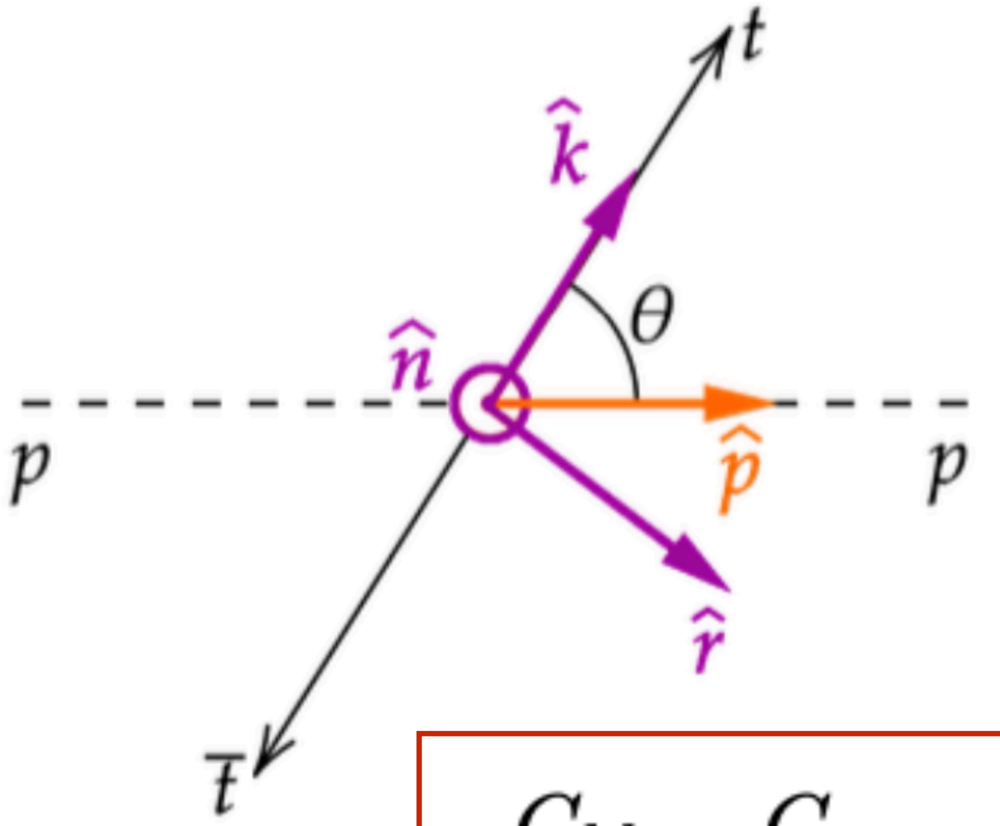
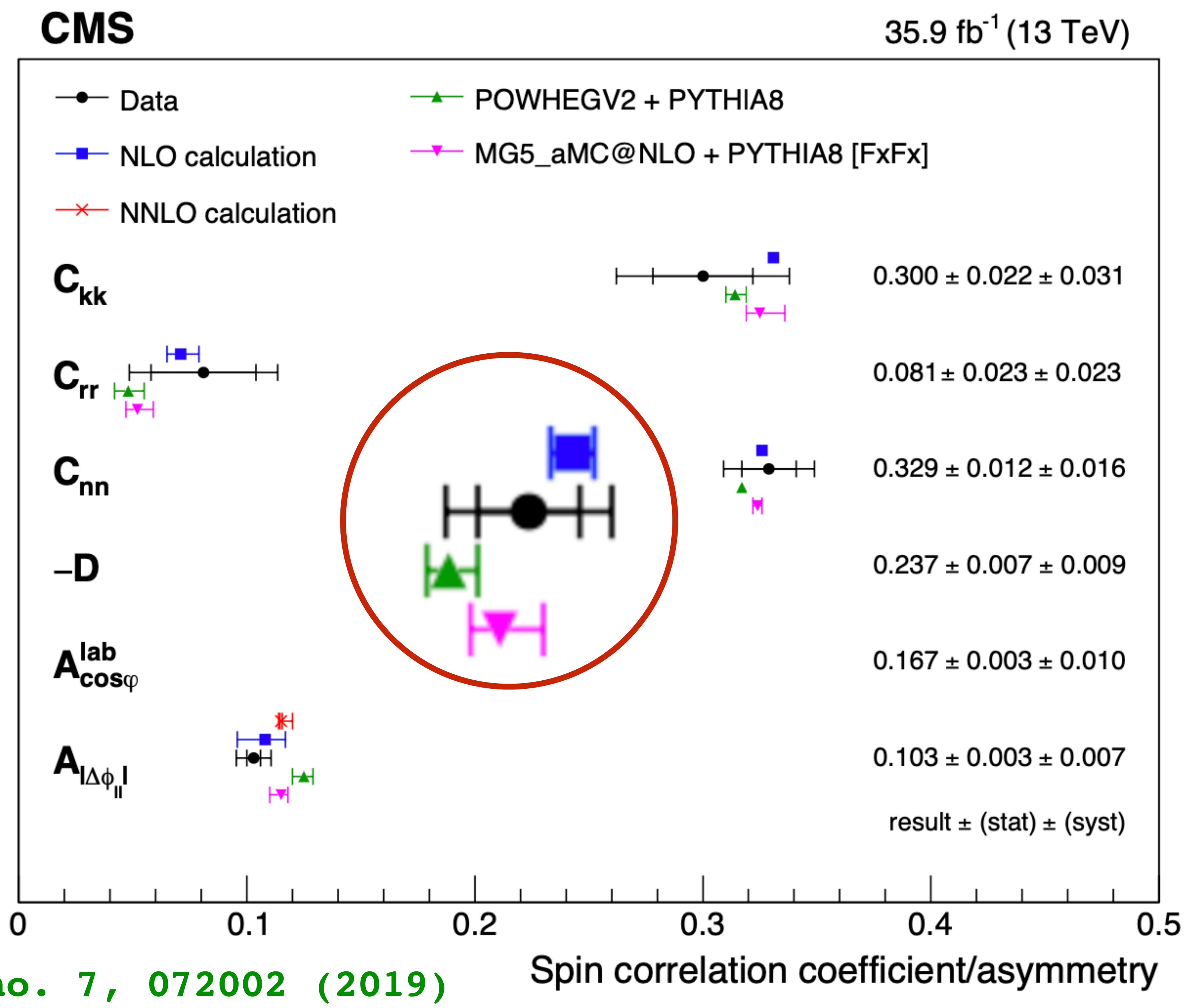
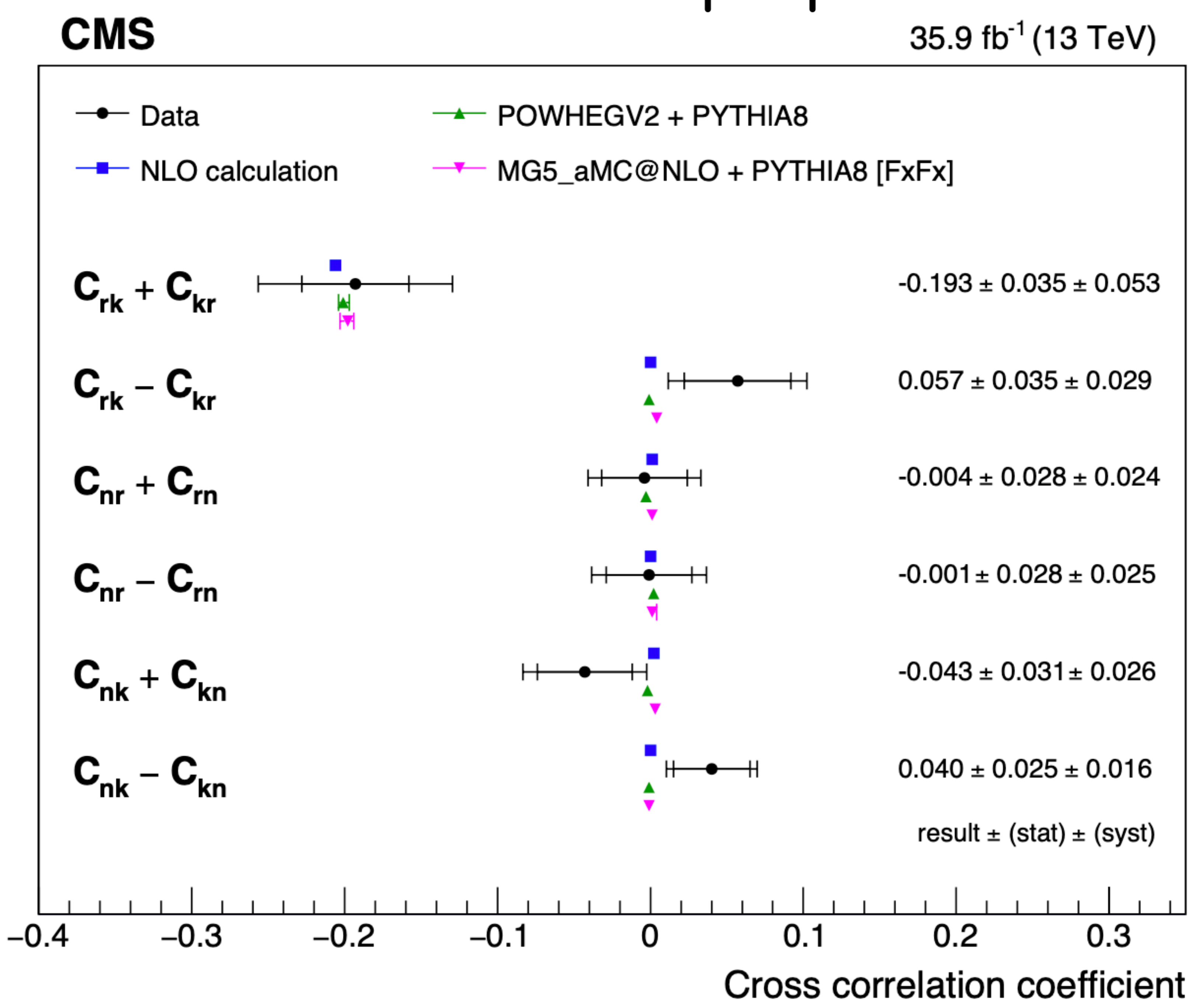


$$-C_{kk} - C_{rr} - C_{nn} \equiv -3\,D$$





Phys. Rev. D 100, no. 7, 072002 (2019)

$t\bar{t}$ Spin Density Matrix

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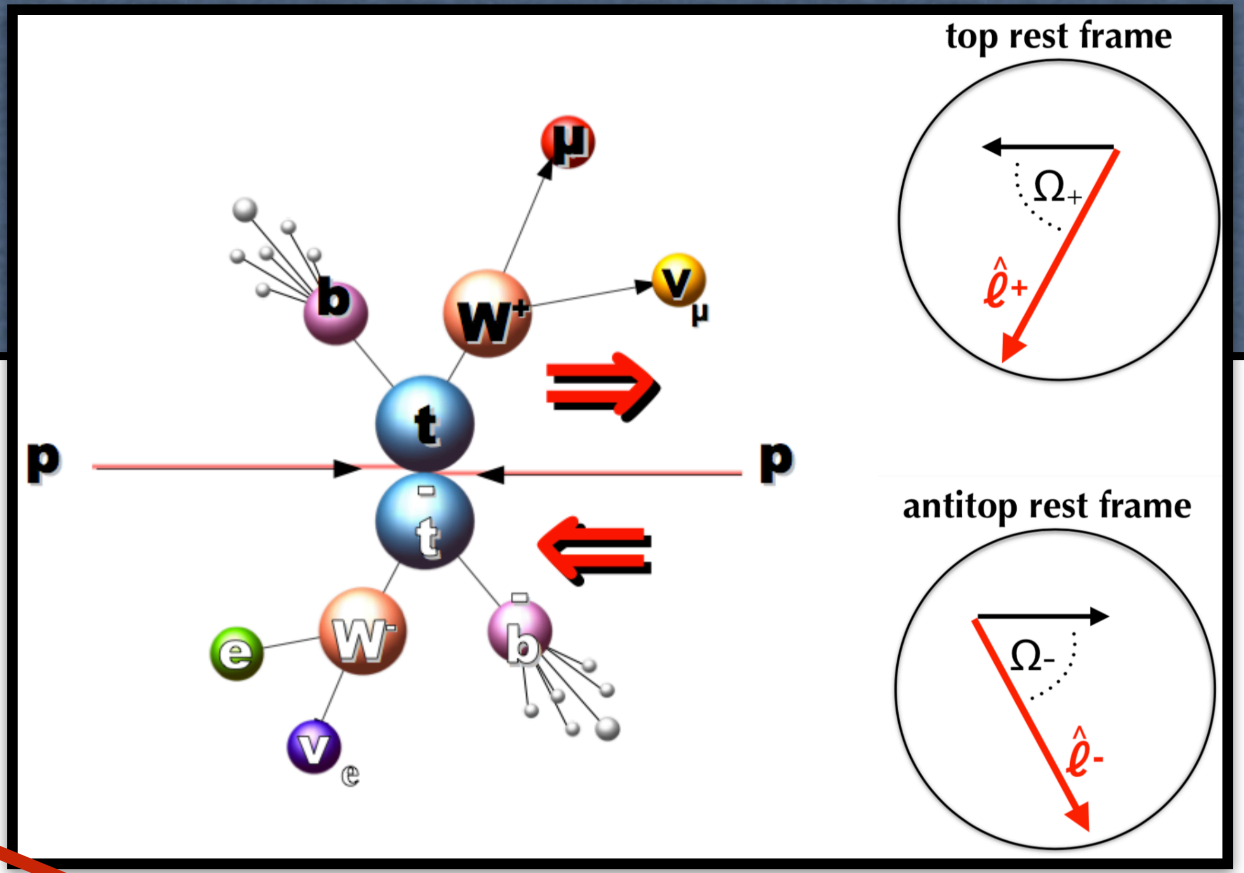

$t\bar{t}$ spin correlation

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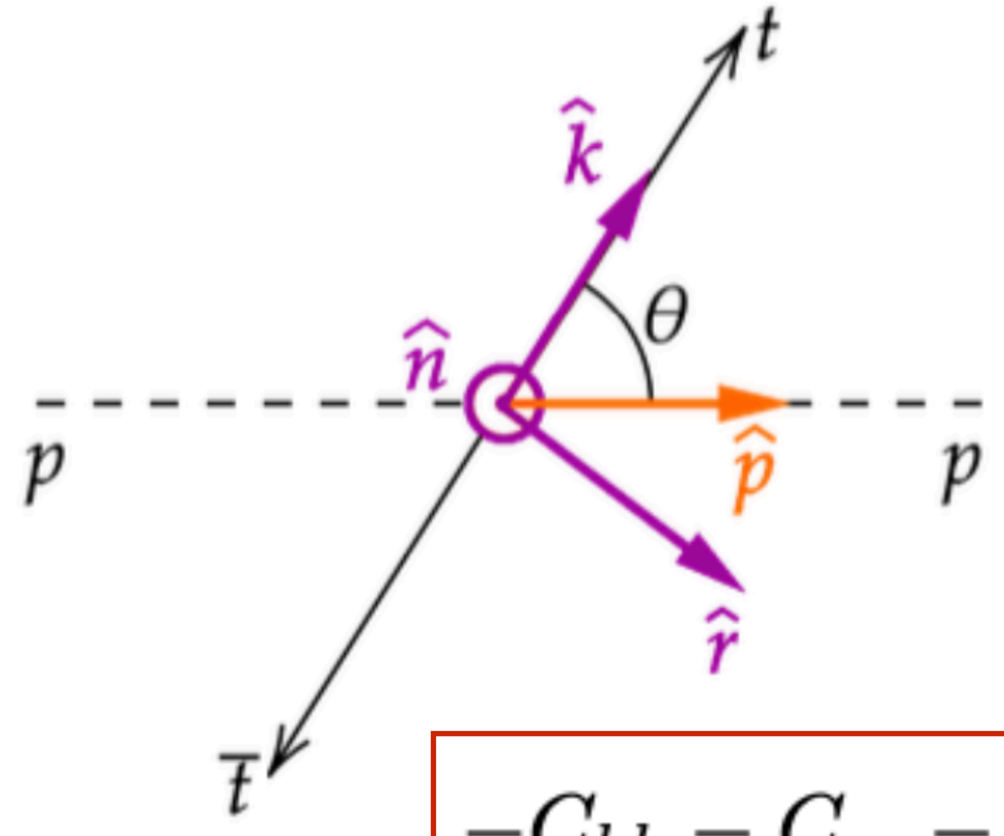
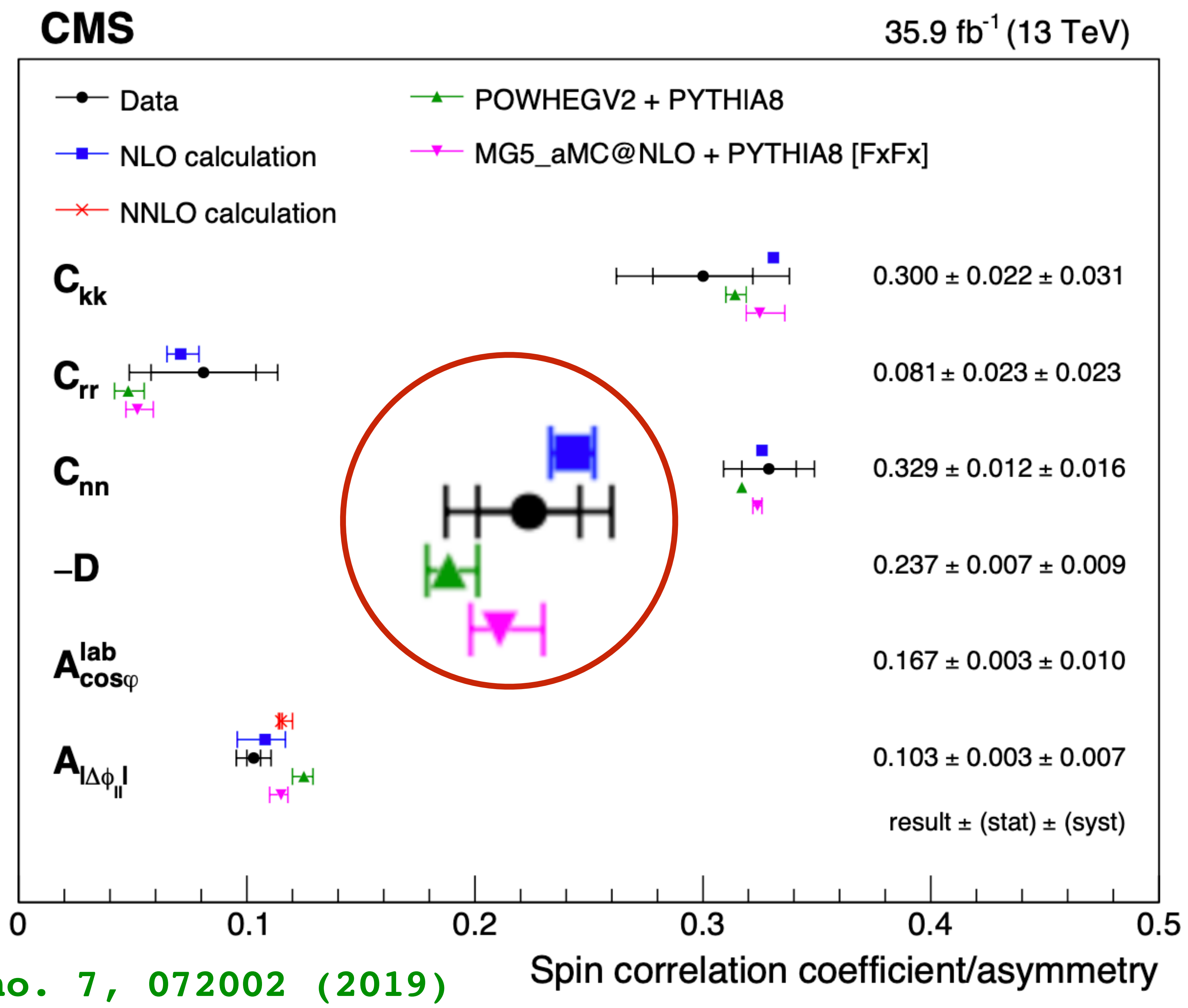
$\hat{\ell}^a =$ top spin vectors

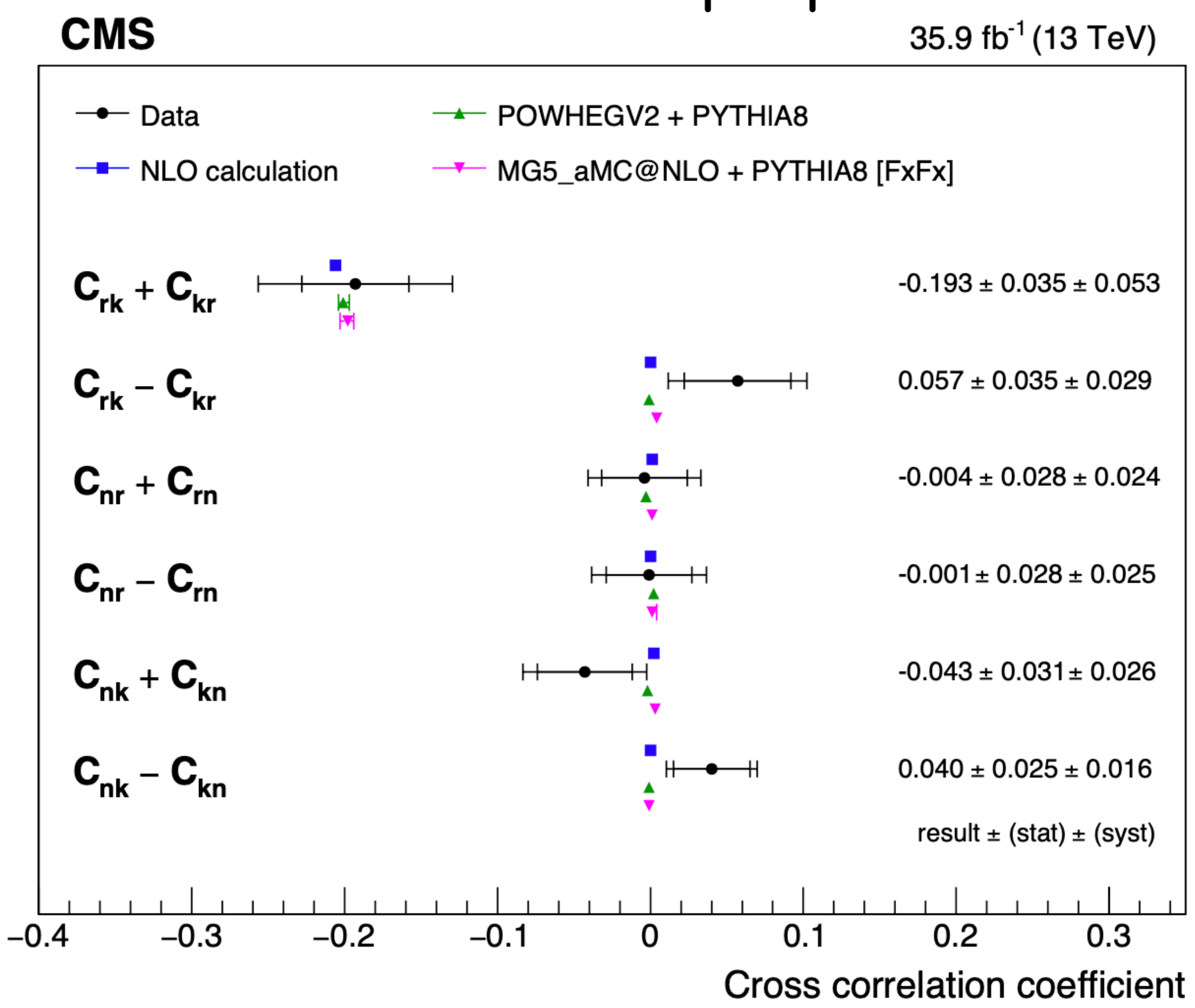


$$-C_{kk} - C_{rr} - C_{nn} \equiv -3\,D$$

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

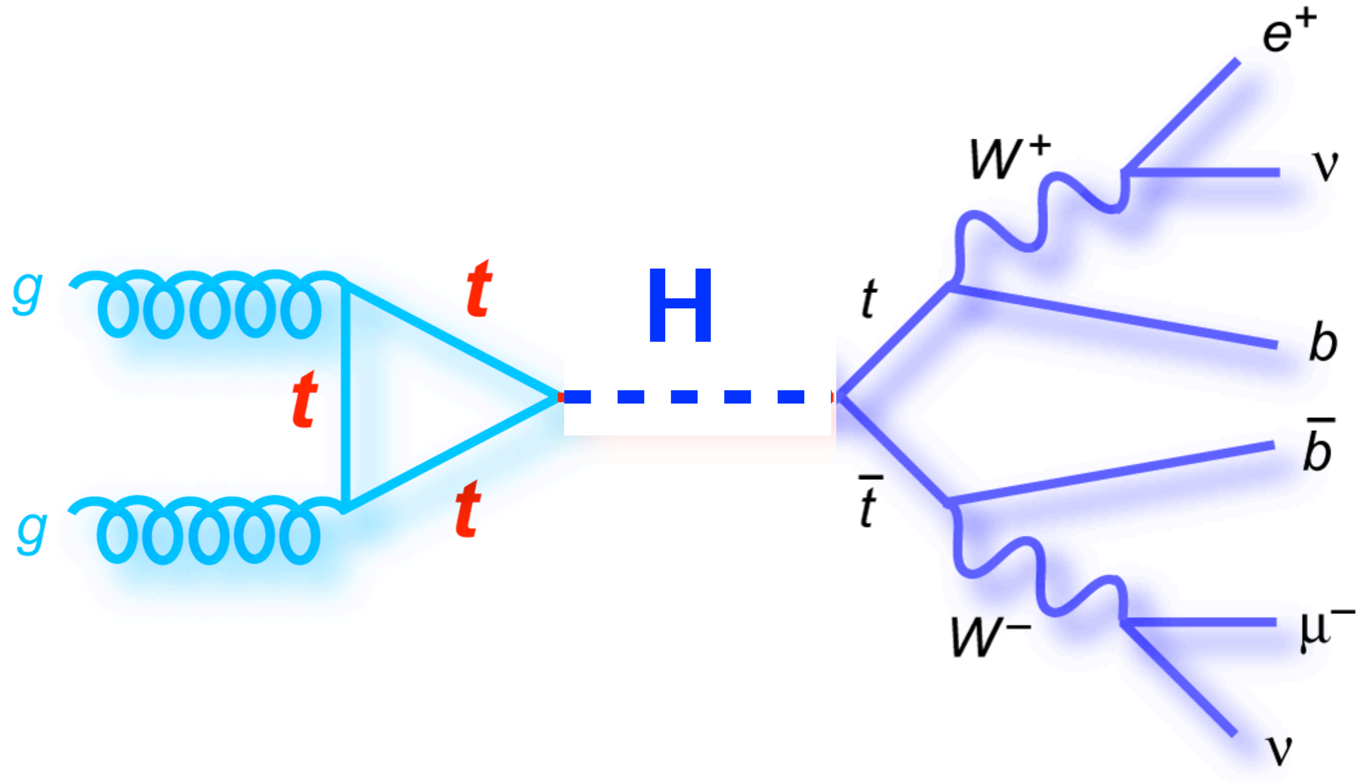
$$c_{han} = +(\hat{\ell}^+)_k(\hat{\ell}^-)_k - (\hat{\ell}^+)_r(\hat{\ell}^-)_r - (\hat{\ell}^+)_n(\hat{\ell}^-)_n$$

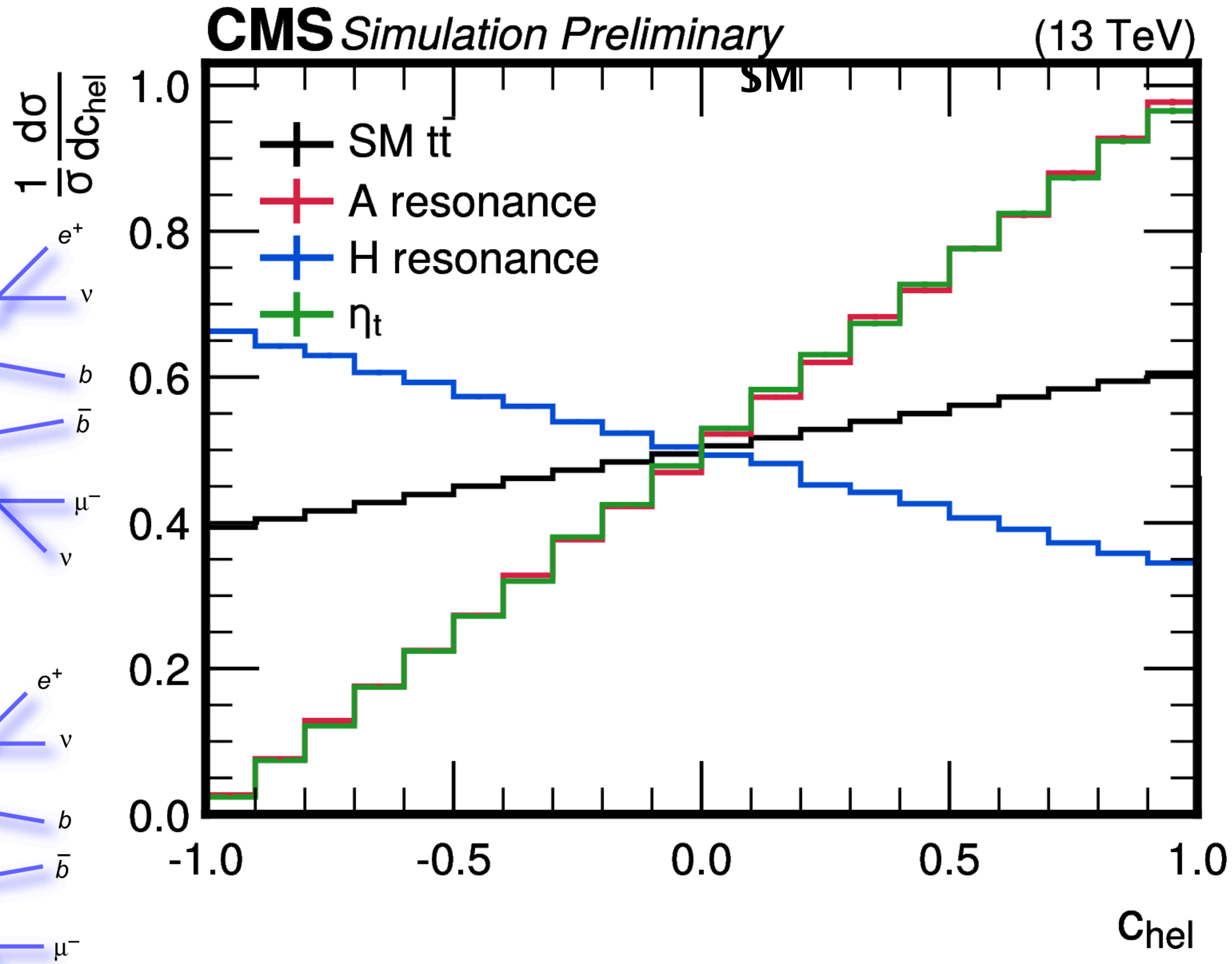


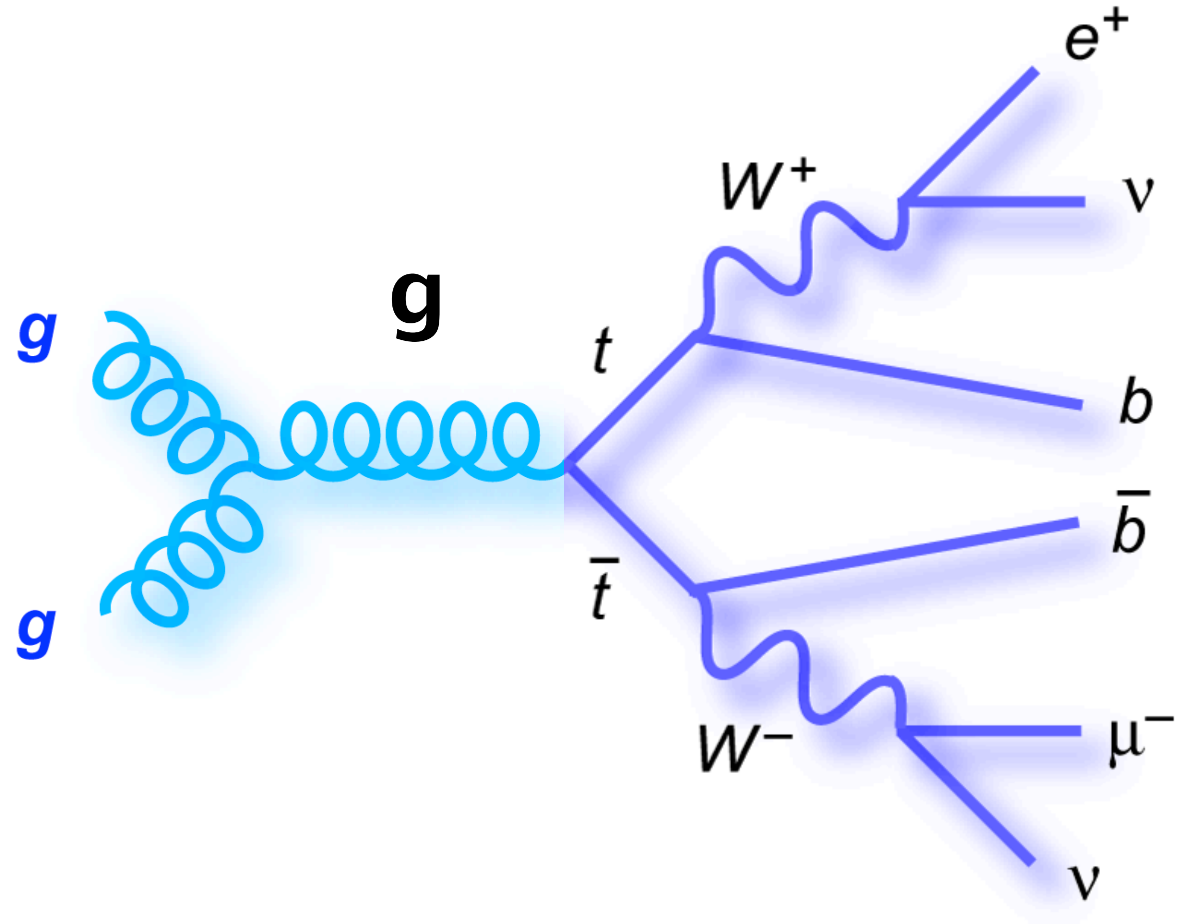


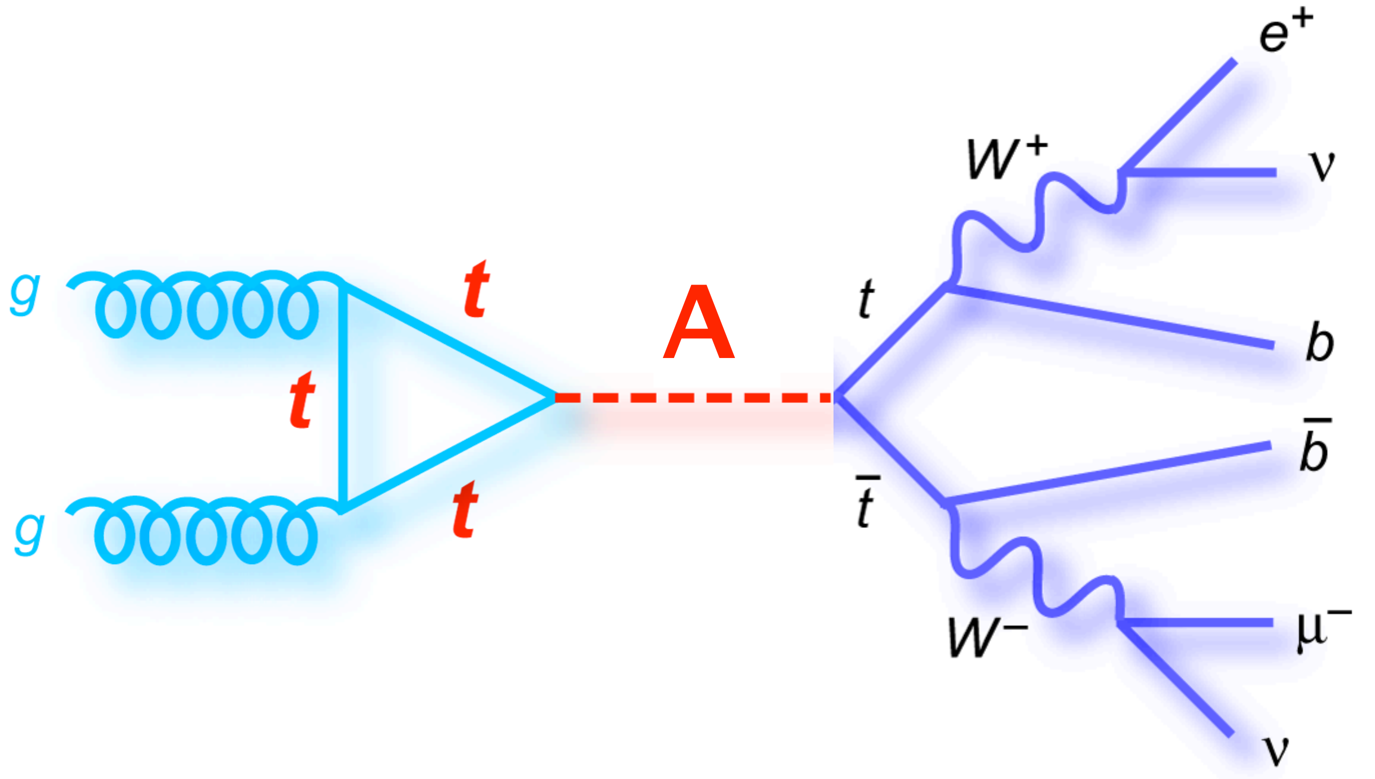
Phys. Rev. D 100, no. 7, 072002 (2019)

Top-Antitop Quark Spin Correlation: Dilepton



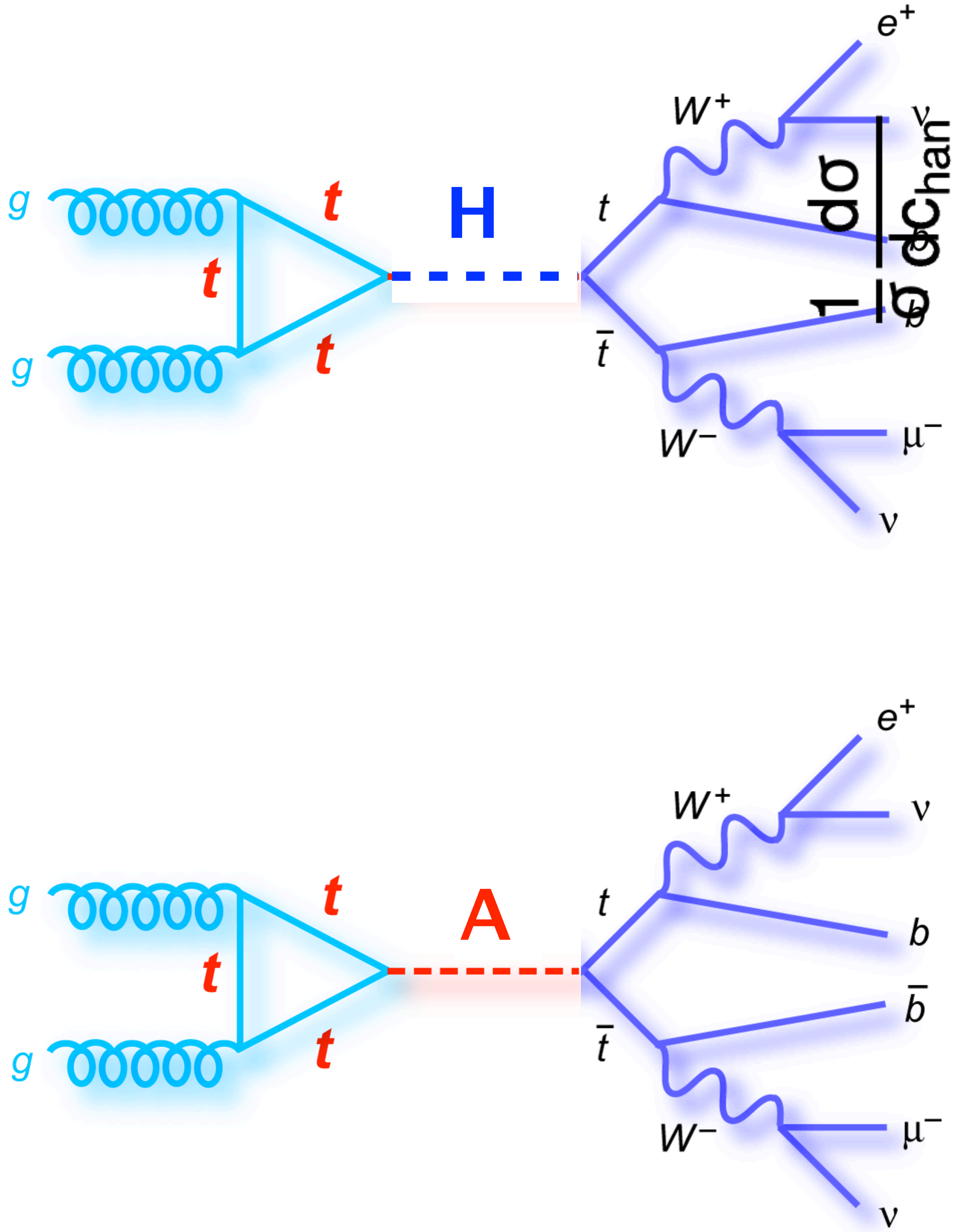


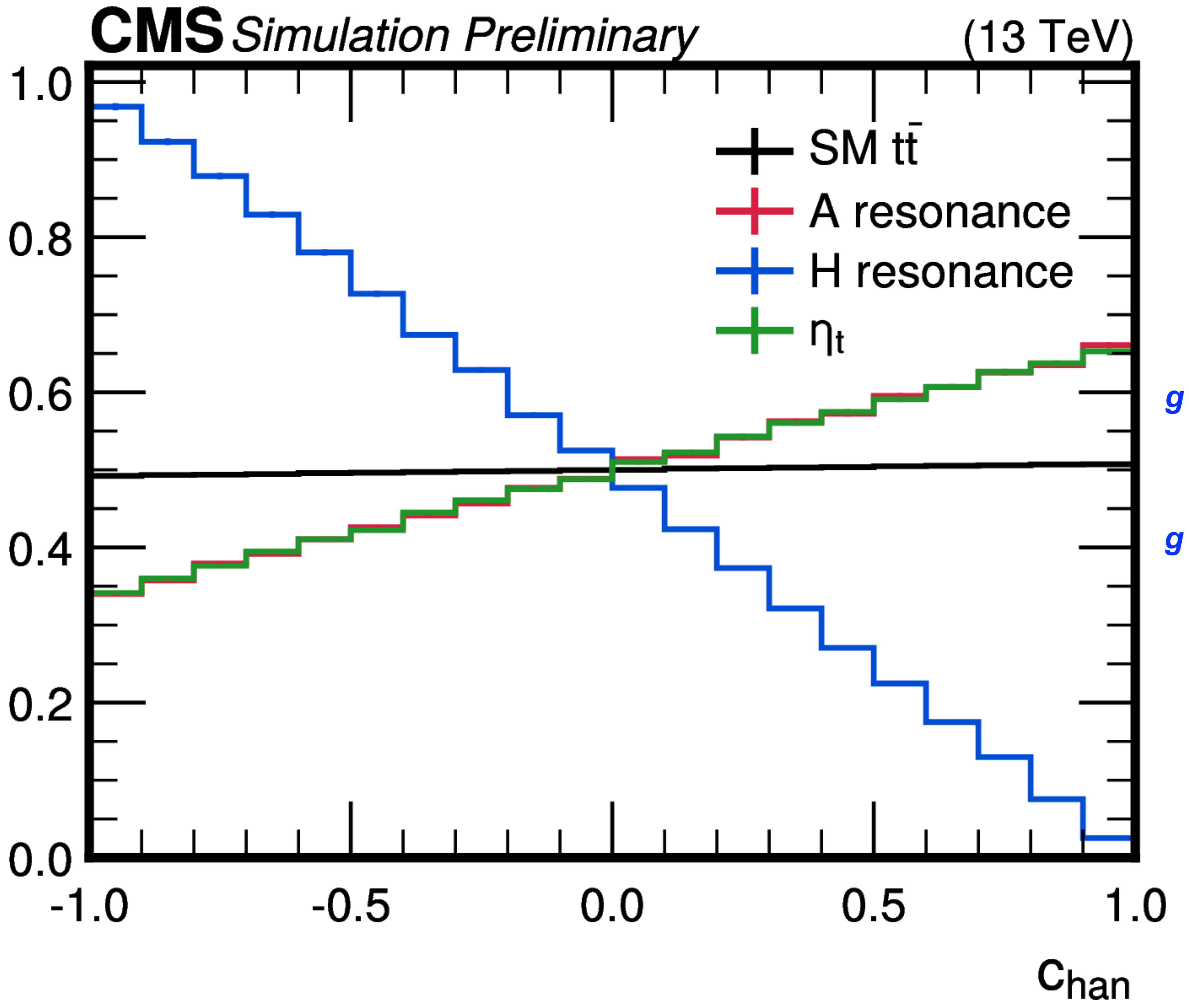


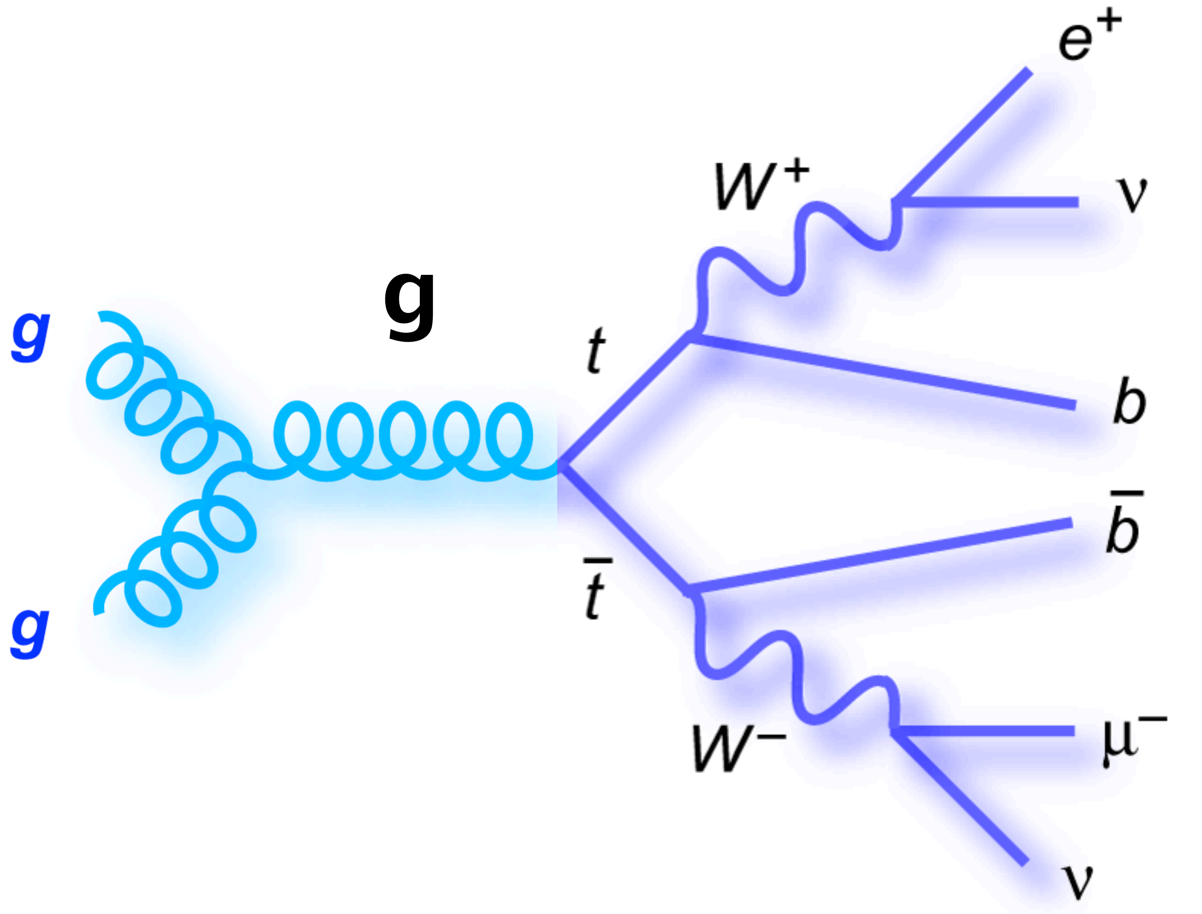


→ **separates between pseudoscalar and SM**

Top-Antitop Quark Spin Correlation: Dilepton



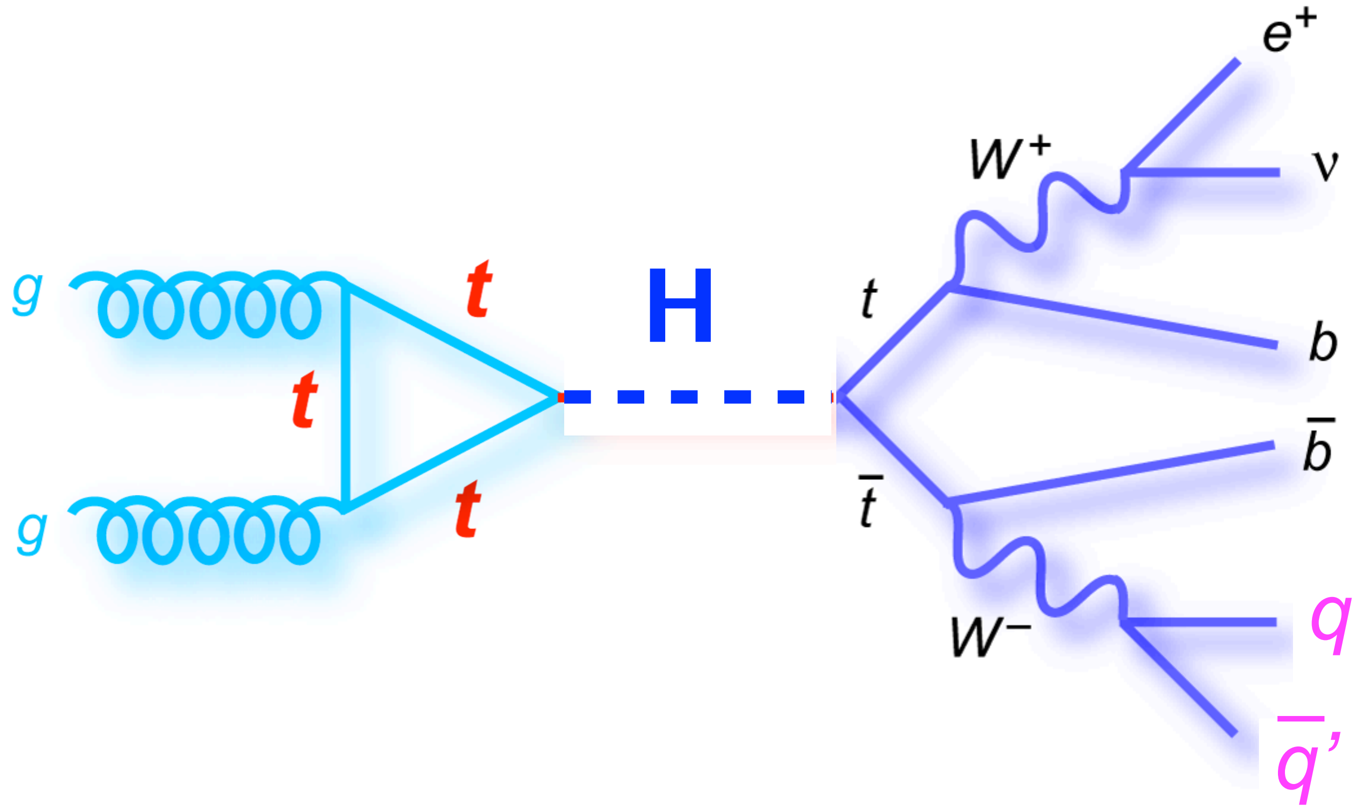


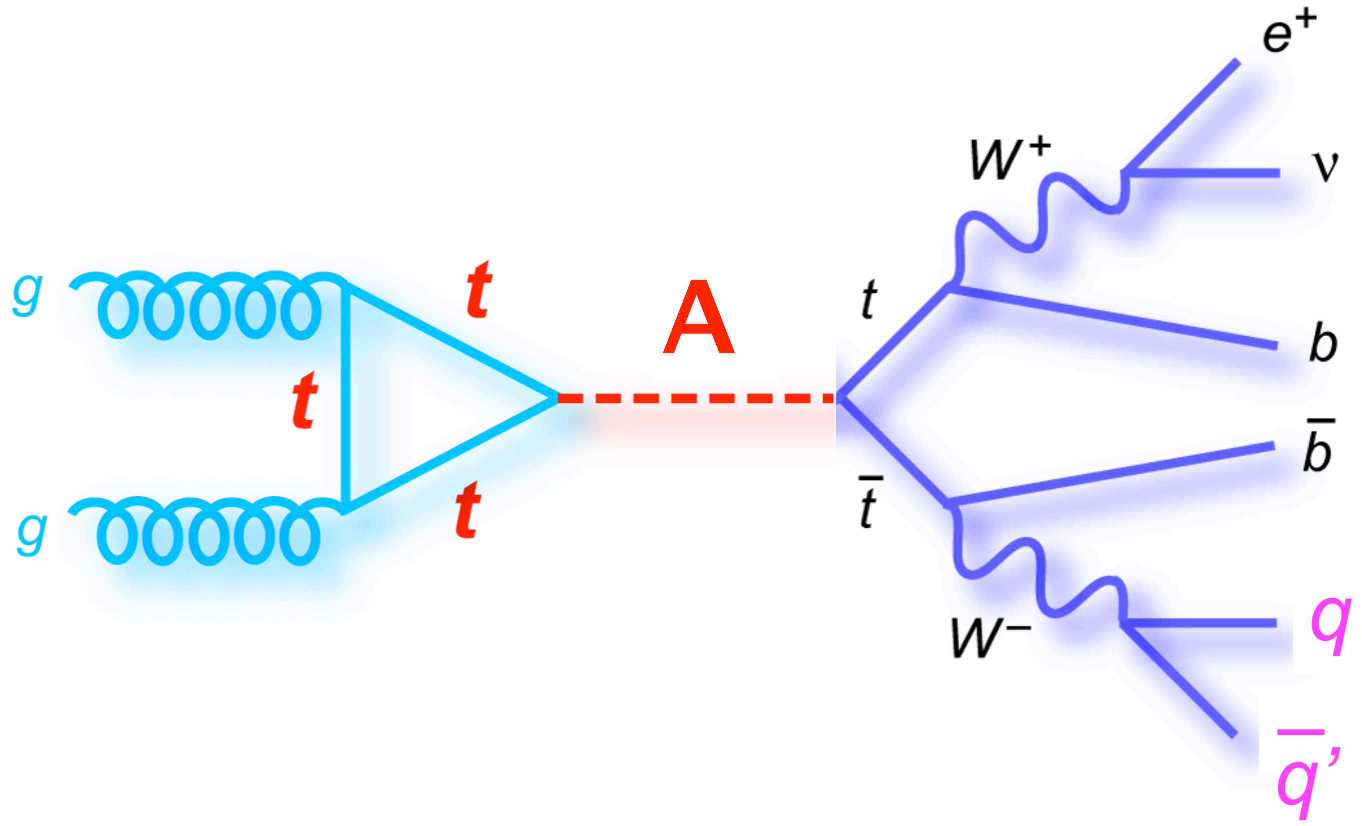


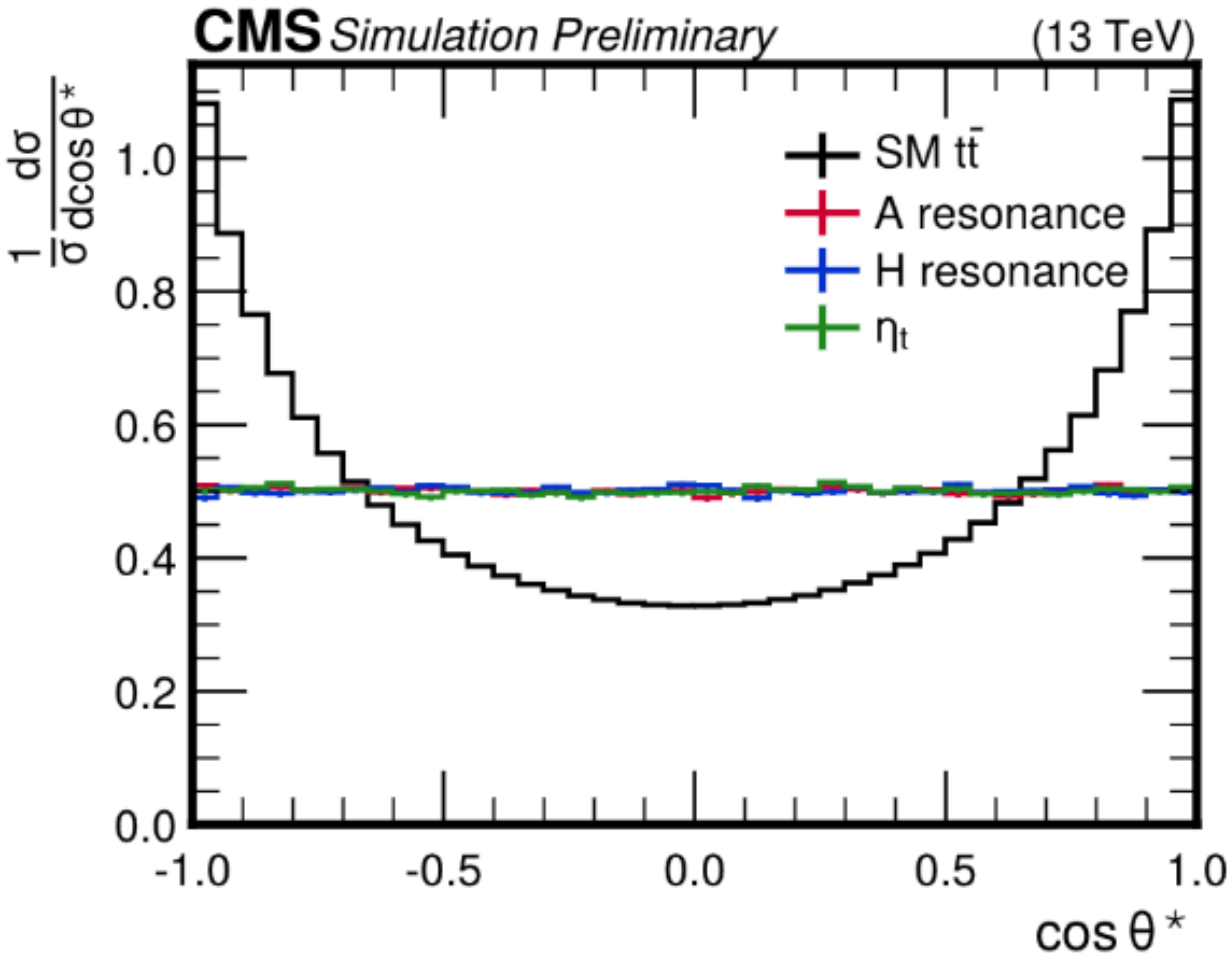
→ separates between pseudoscalar and scalar

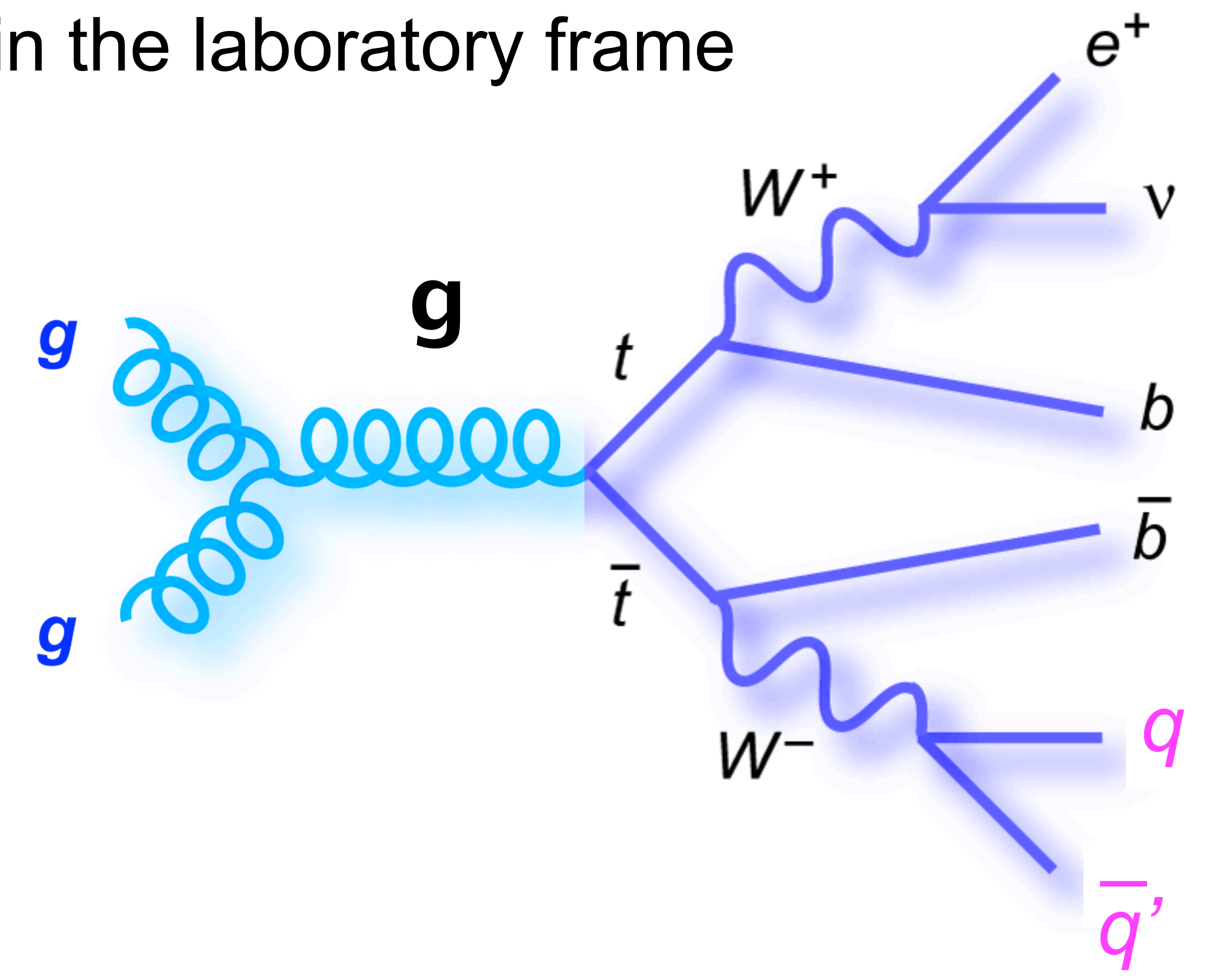
Top Quark Scattering Angle: Lepton+Jets

$\theta*$: angle between the reconstructed leptonically decaying top quark in the $t\bar{t}$ ZMF and the direction of the $t\bar{t}$ system in the laboratory frame







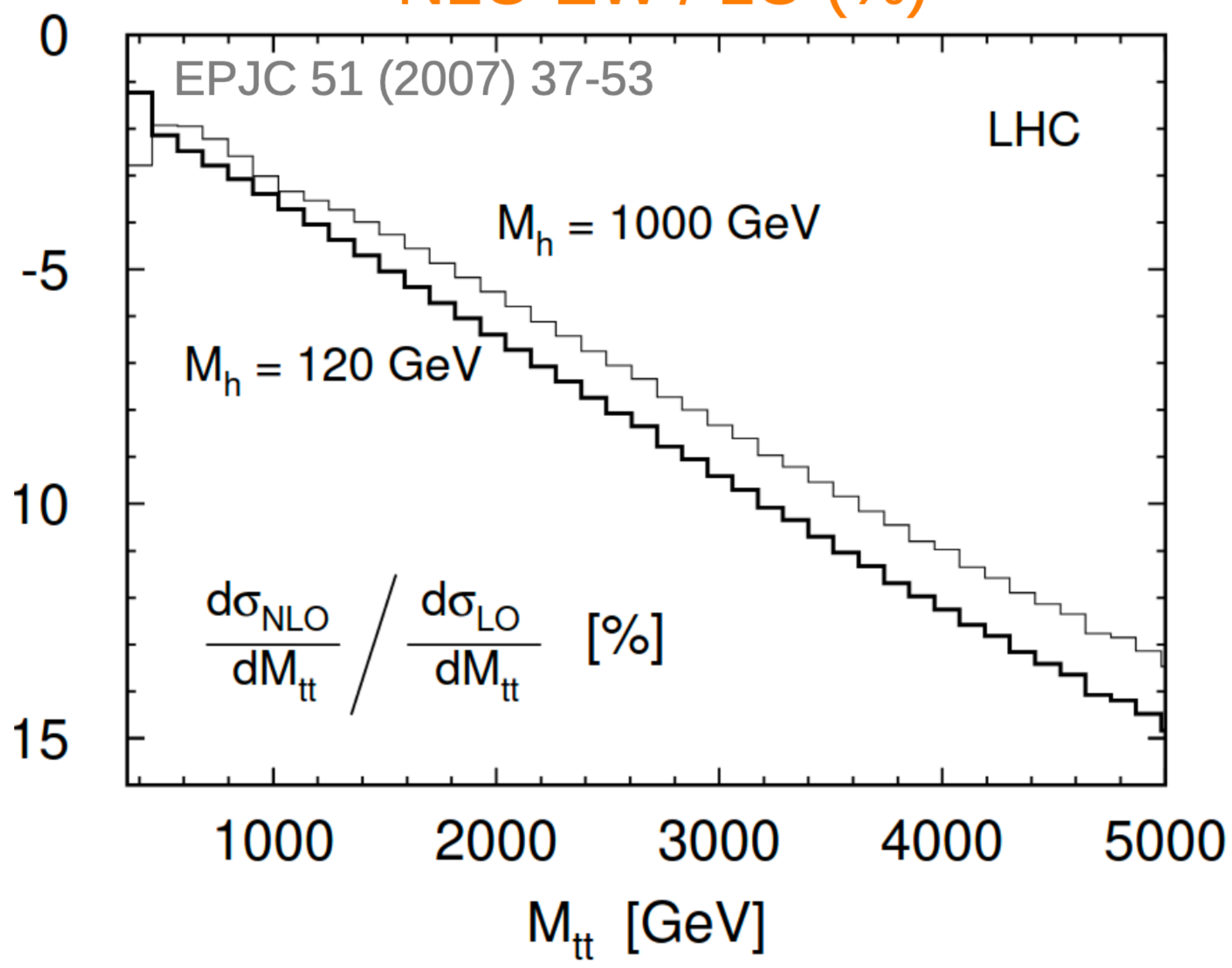


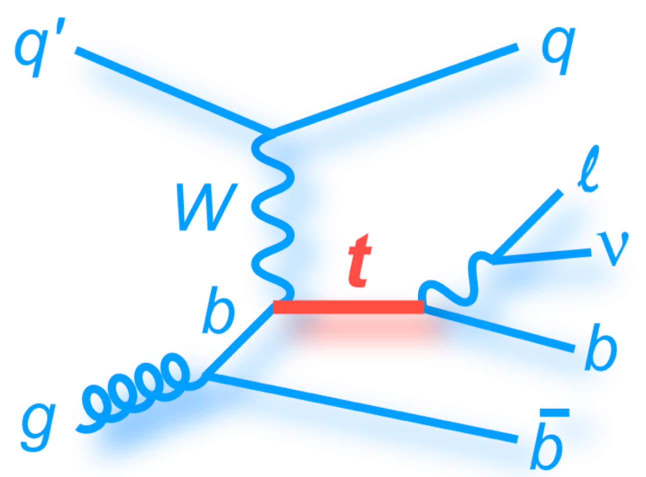
→ **separates between scalar/pseudoscalar and SM**

Background modeling

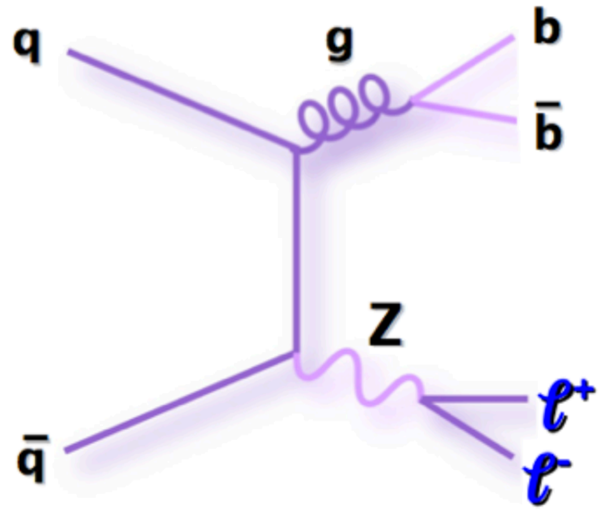
- Major irreducible background: SM top pair production
  - Model from NLO MC (Powheg+Pythia)
  - Correct to NNLO QCD and NLO EW from fixed-order predictions by reweighting in 2D bins of $m_{t\bar{t}}$ and $\cos\theta^*$
  - Normalize to NNLO+NNLL cross section

NLO EW / LO (%)

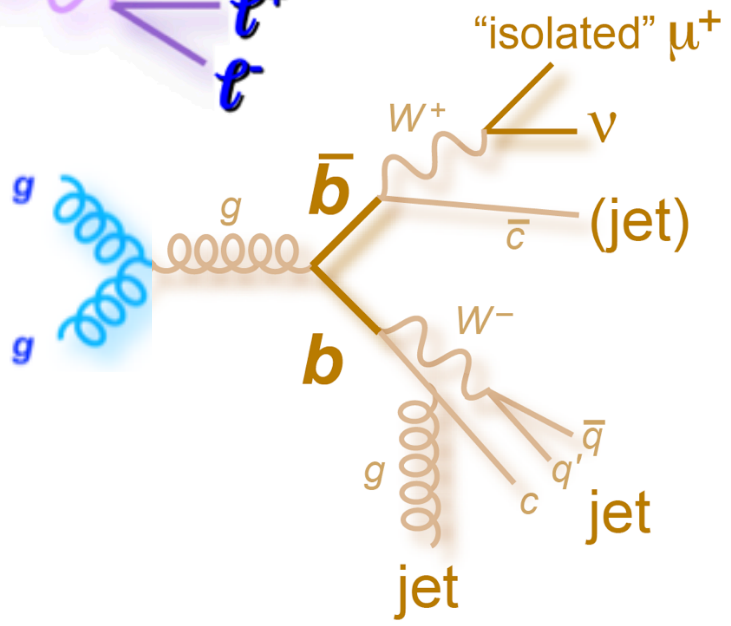


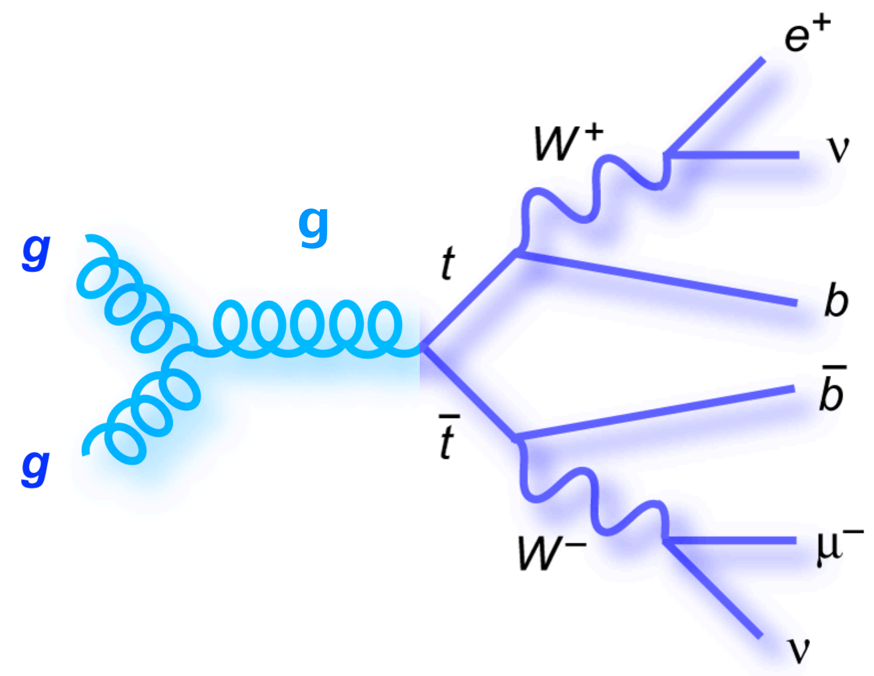


- Other backgrounds: tW, t channel single-top, rare processes (from MC)



- Z+jets in $\ell\ell$: from MC with data-driver normalization from Z peak sideband





- QCD+EW processes in ℓ+jets: data-driven shape from sideband with no b-tags

Results of the 2016 Data

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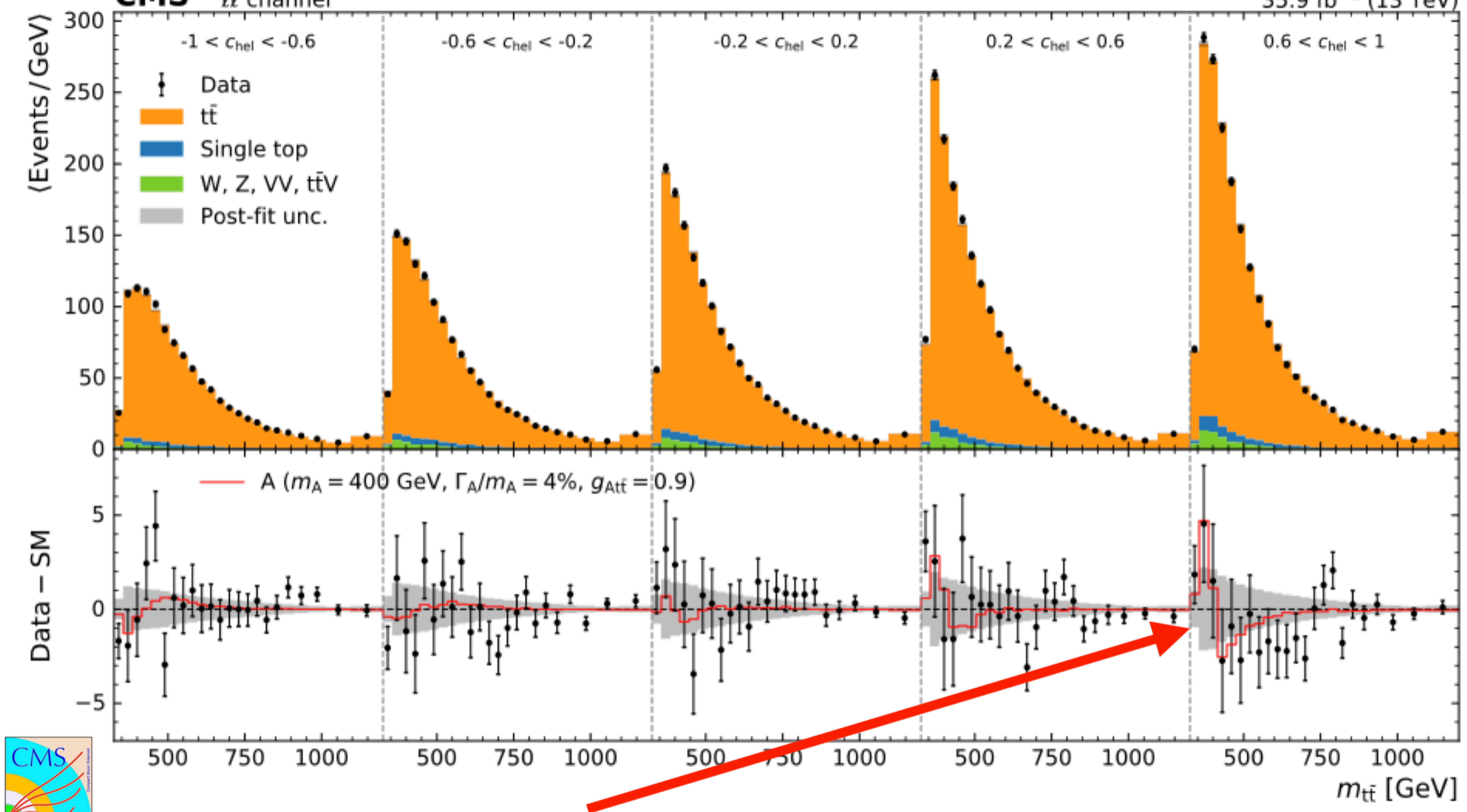
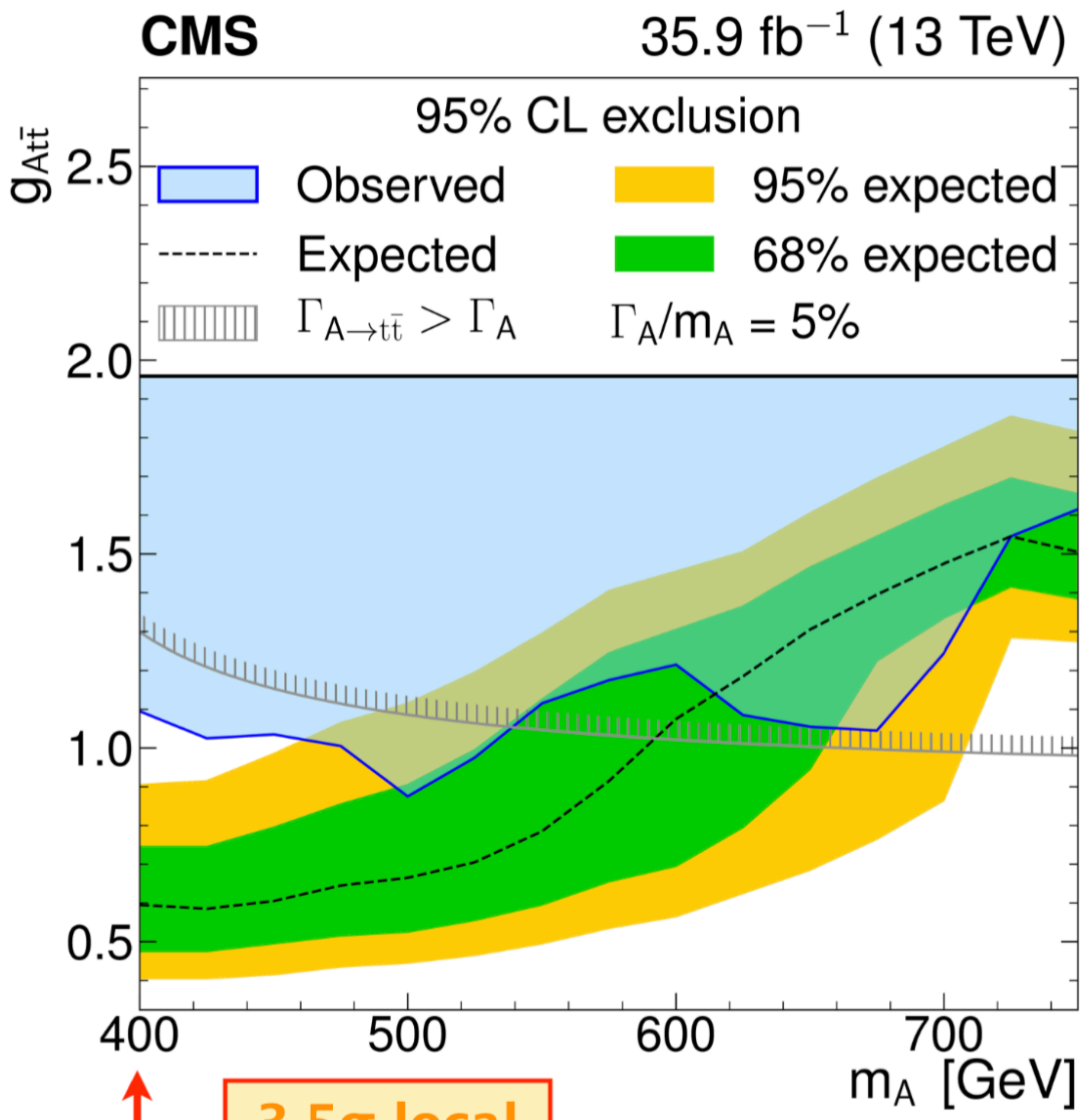


pseudoscalar, m_A=400 GeV



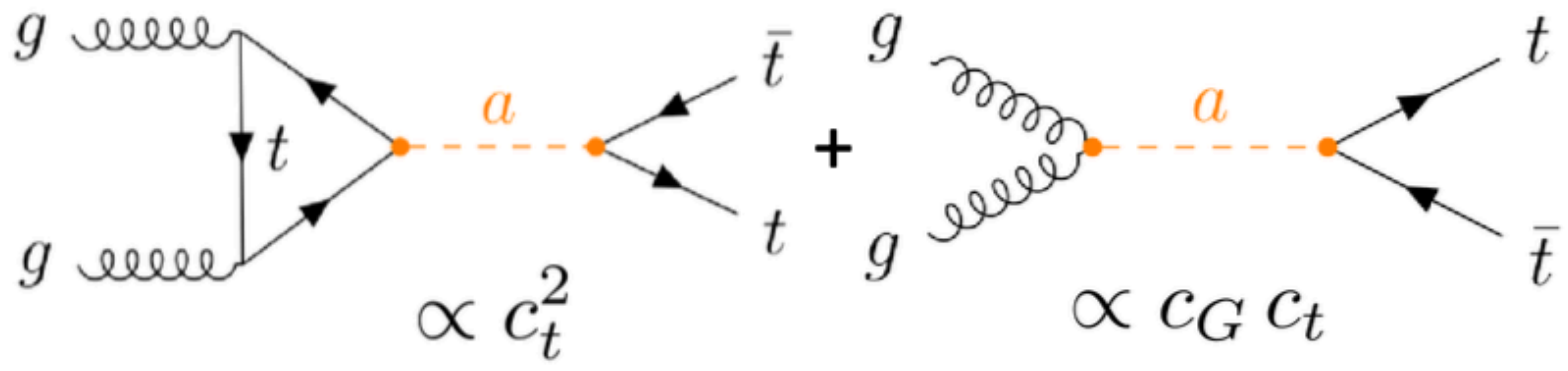
3.5σ local

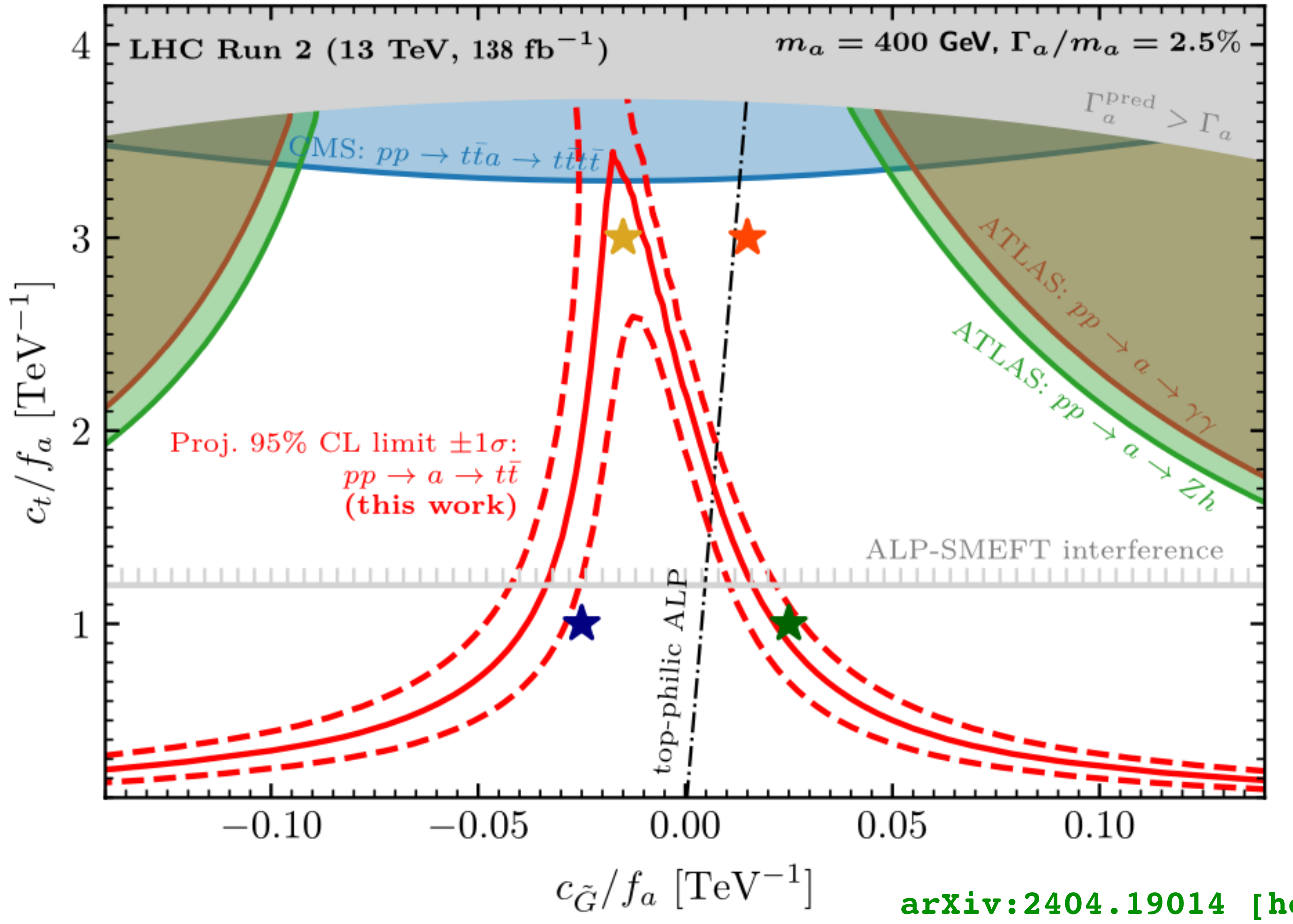
1.9σ global

pseudoscalar

Examples for Interpretations of the Excess

Axion-like particle (ALP)



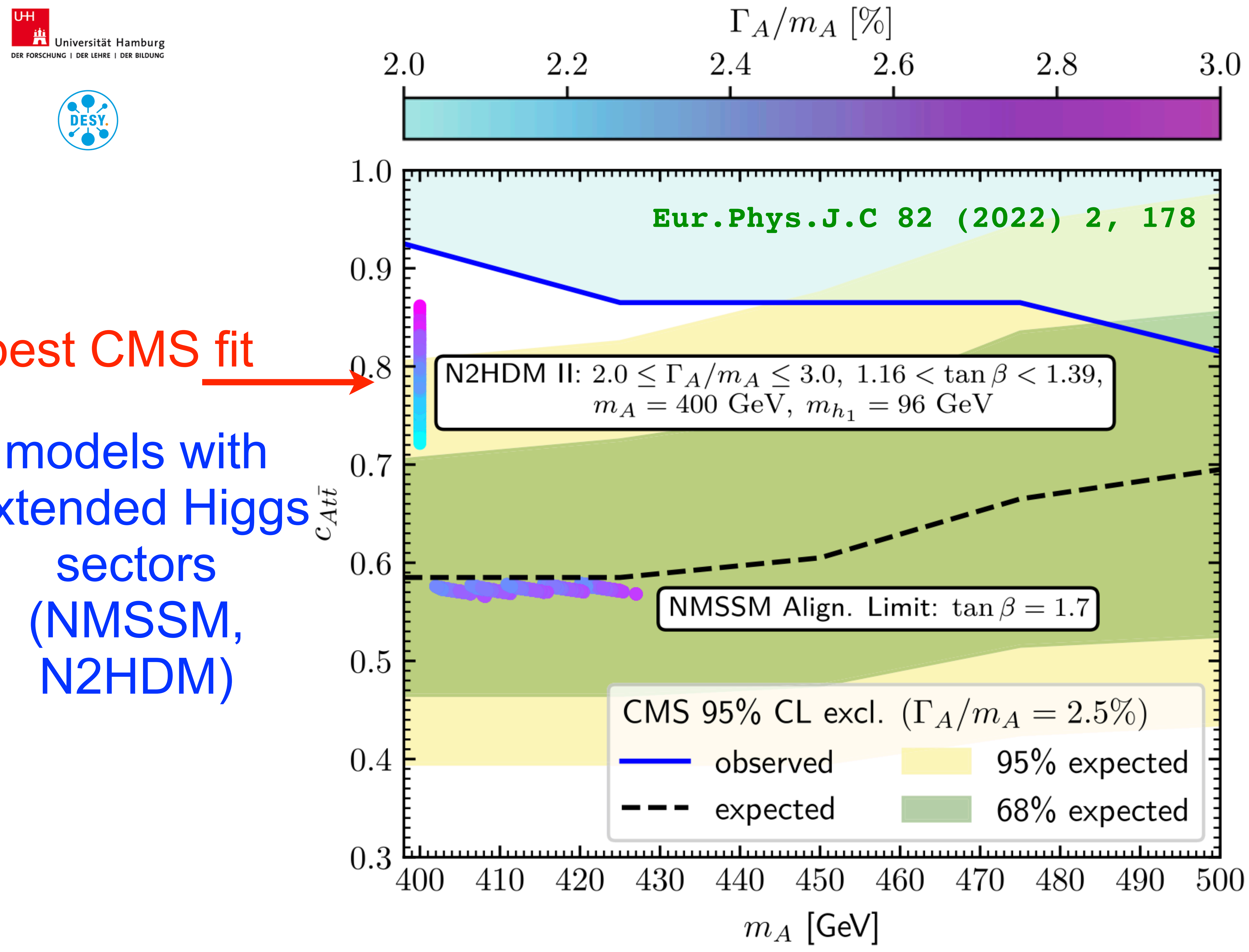


arXiv:2404.19014 [hep-ph]

→ stronger limits for $a \to t\bar{t}$ than other searches

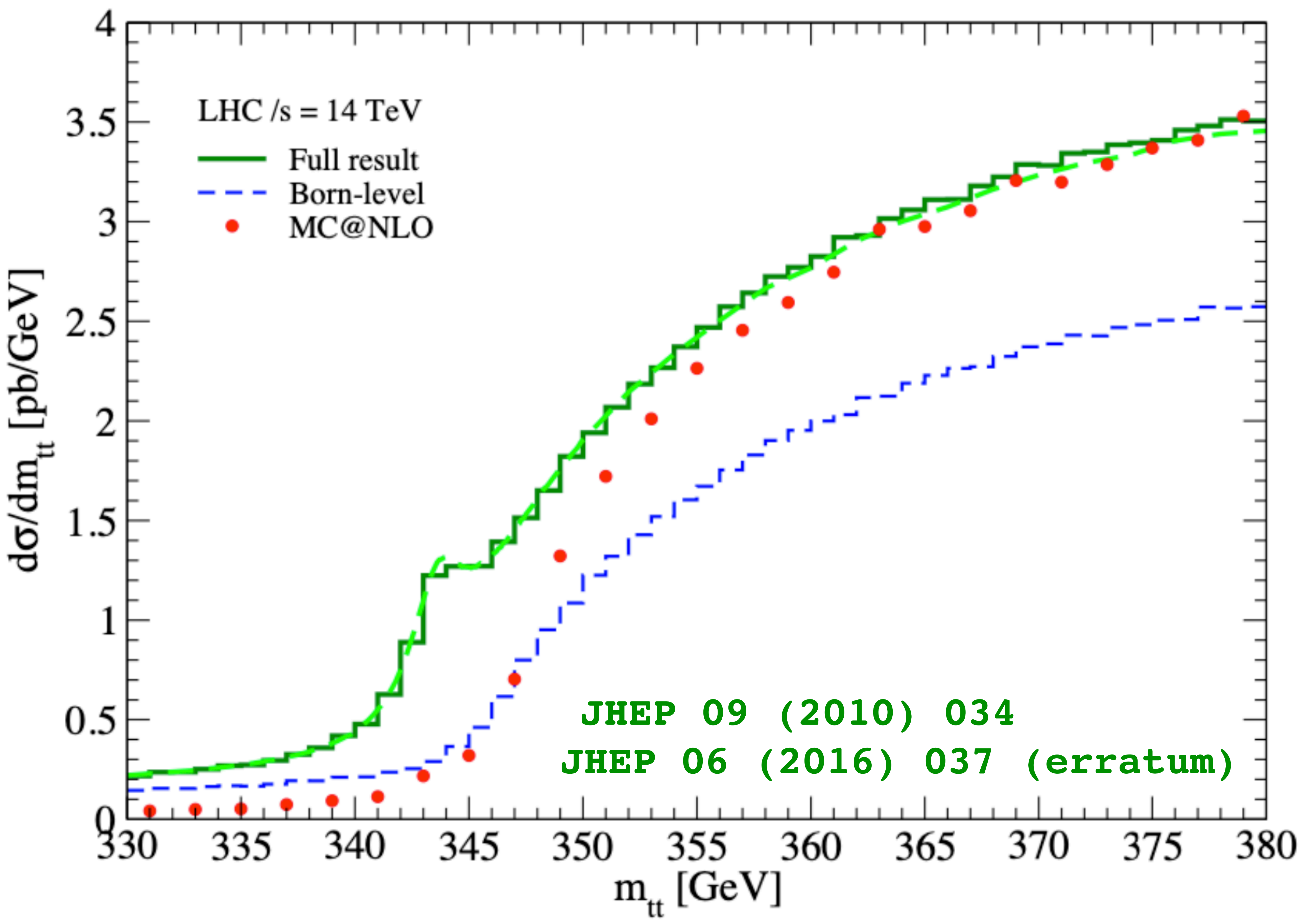
best CMS fit

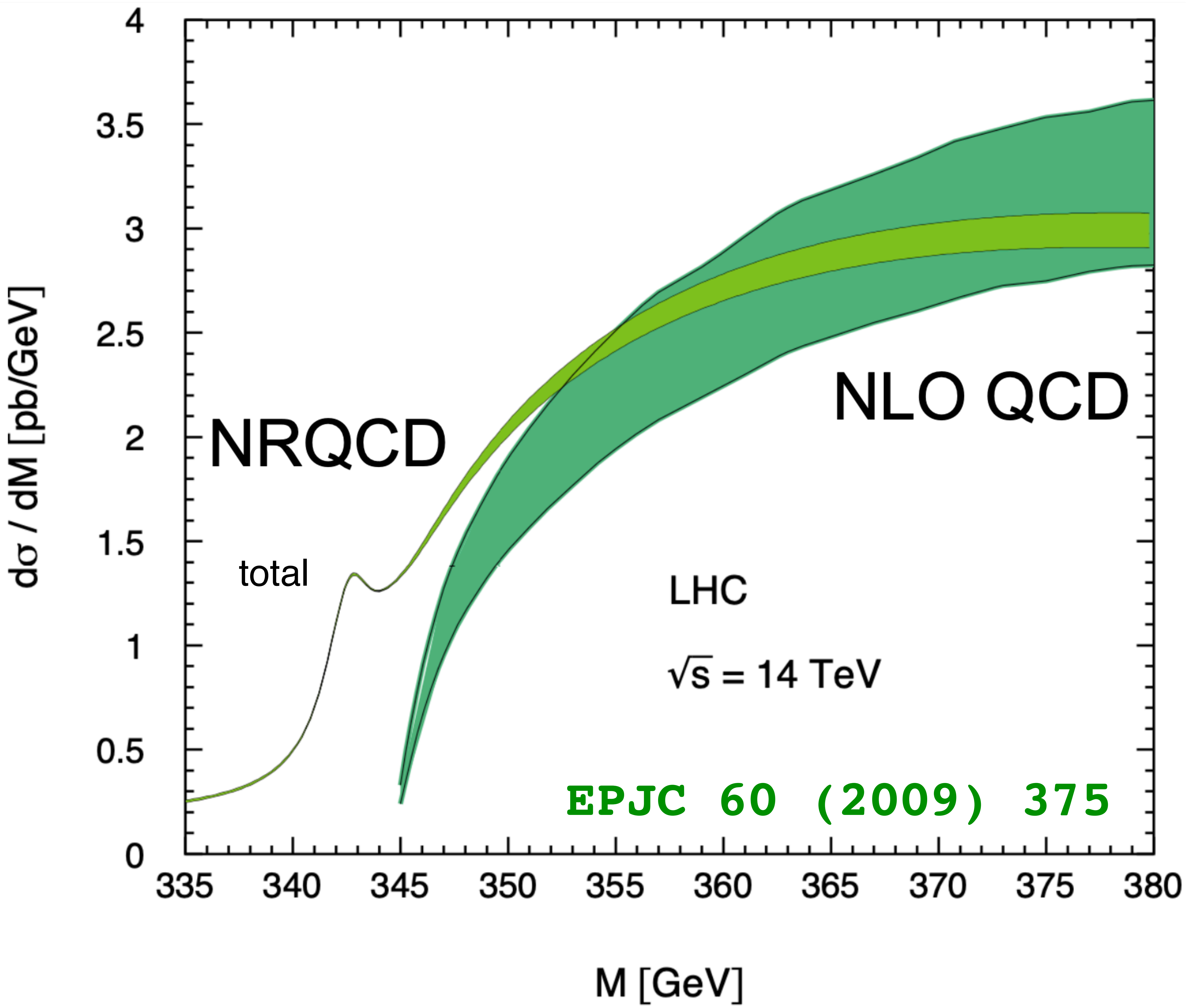
models with extended Higgs sectors (NMSSM, N2HDM)



→ agreement with the $A \to t\bar{t}$ excess at 400 GeV

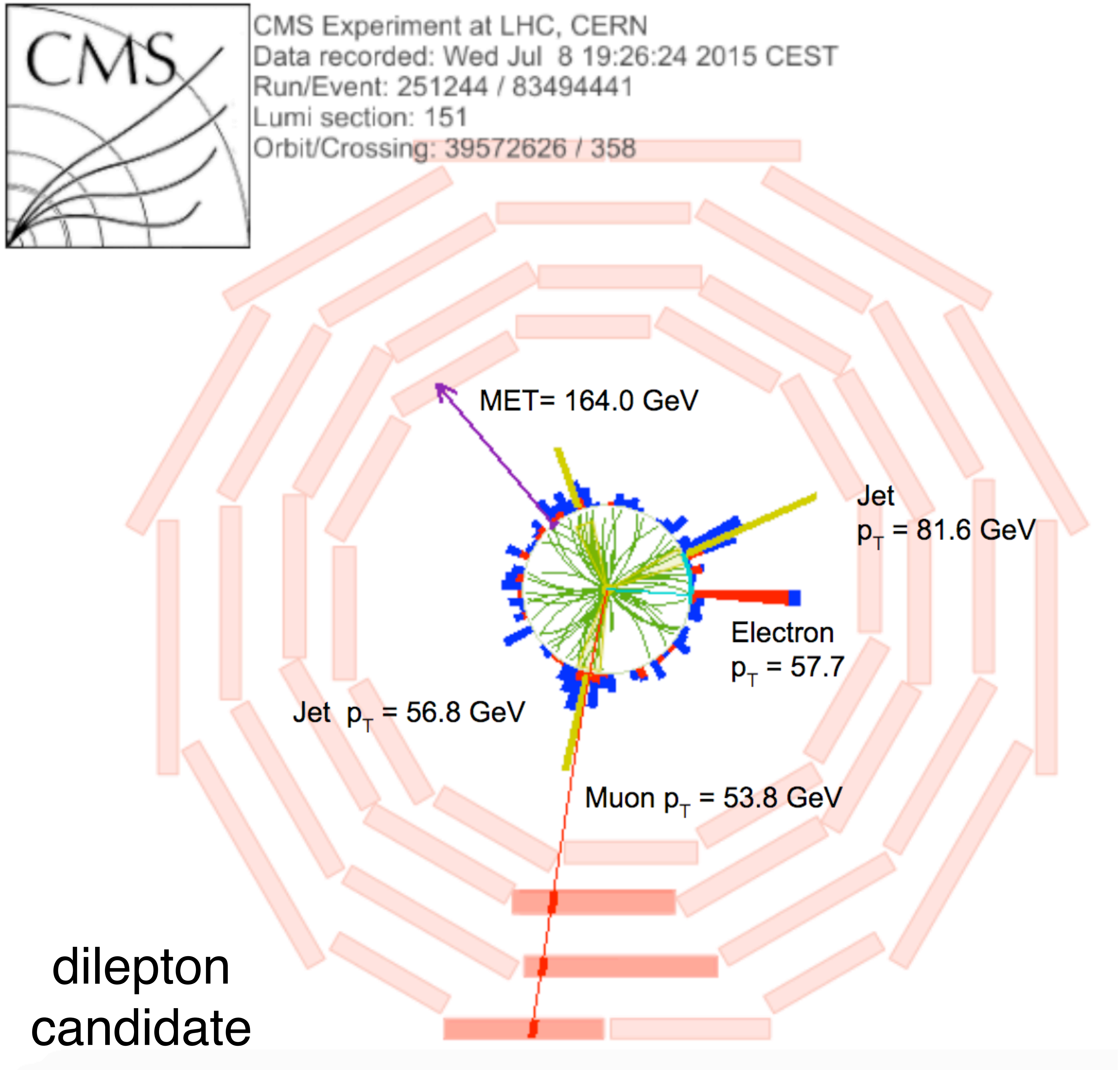
Another Interpretation: $t\bar{t}$ Bound States



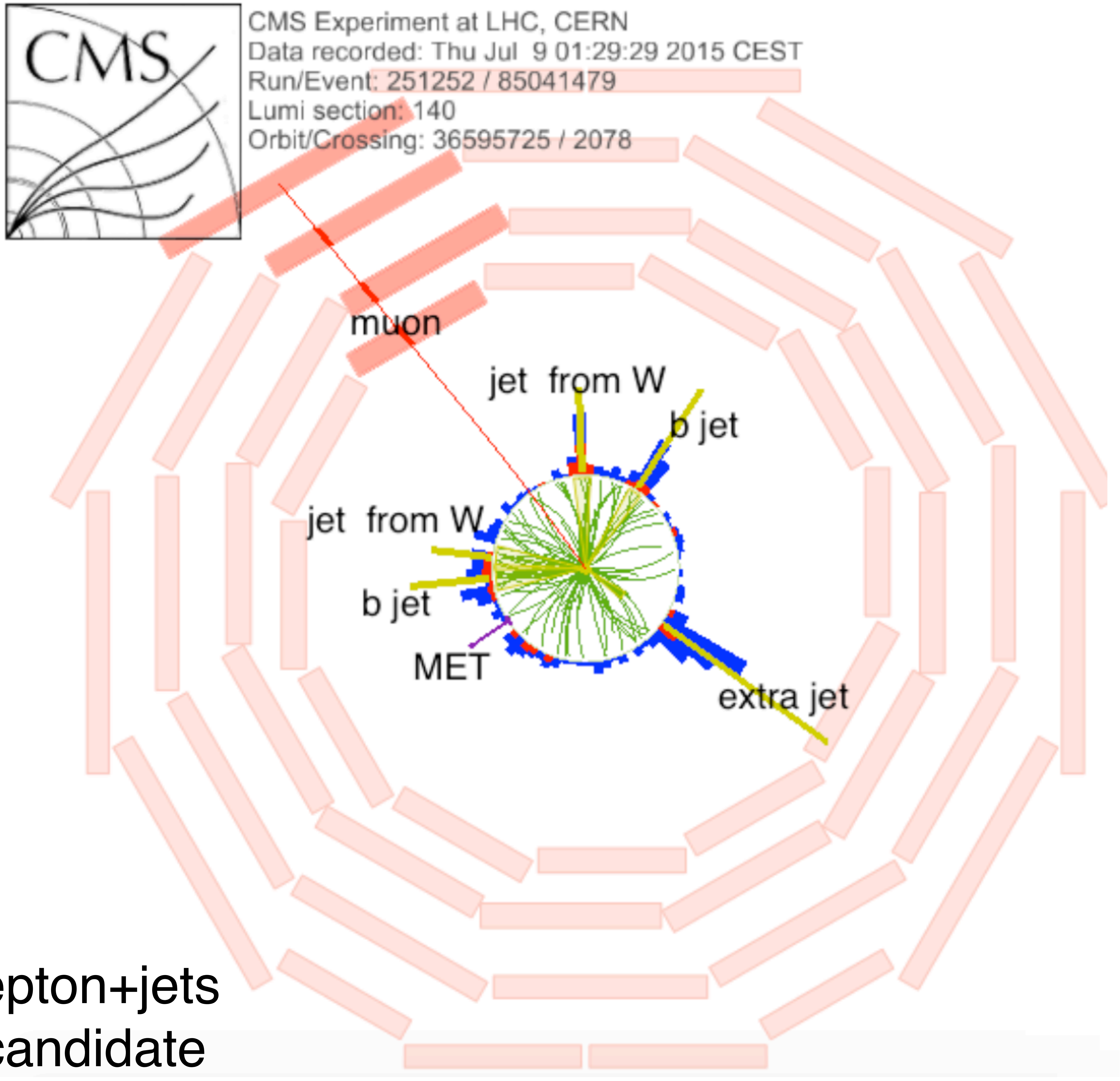


→ **threshold region is dominated by color-singlet pseudocalar toponium**

Results – full Run-2 dataset, 138 pb^{-1}

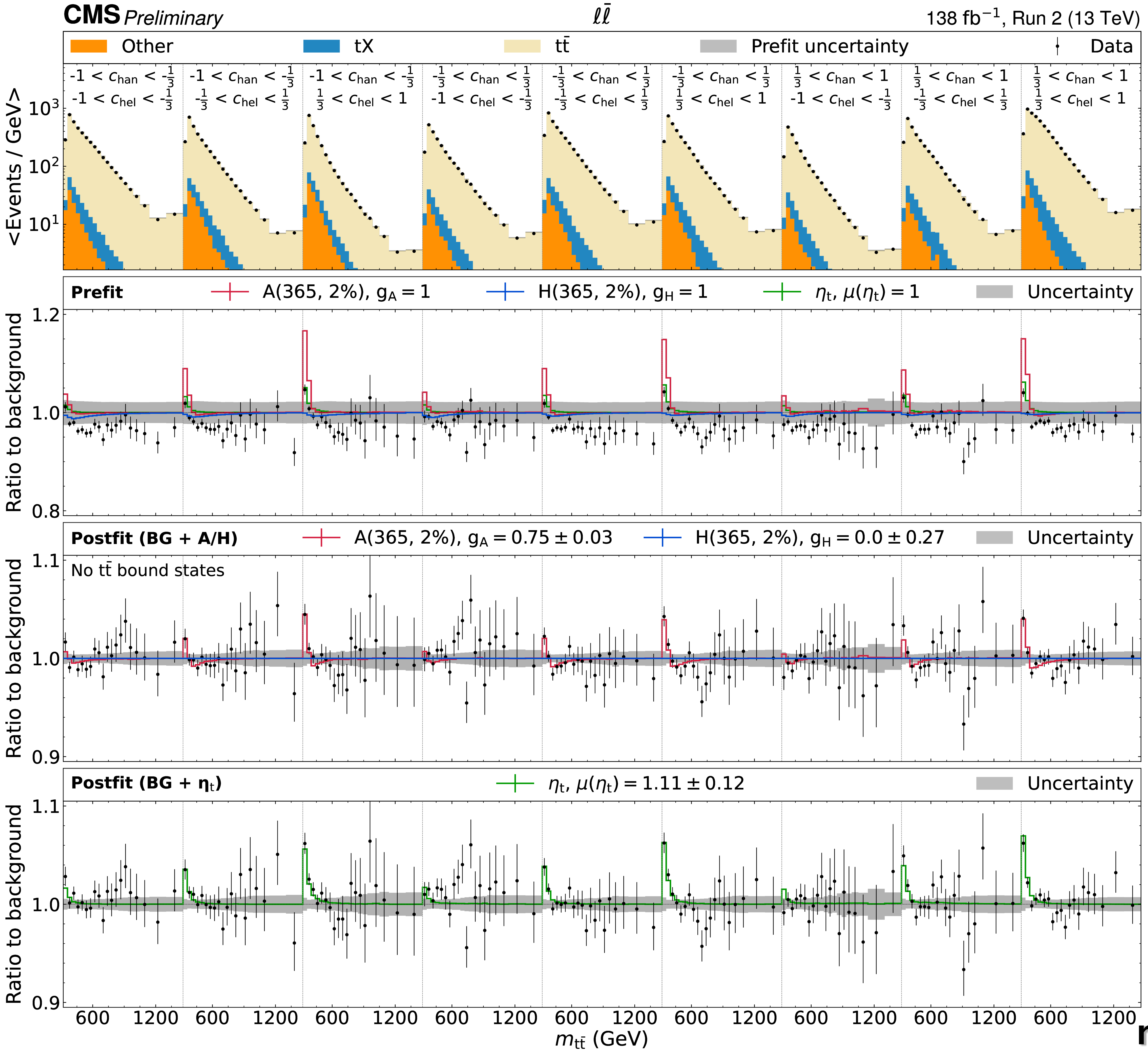


dilepton candidate



lepton+jets candidate

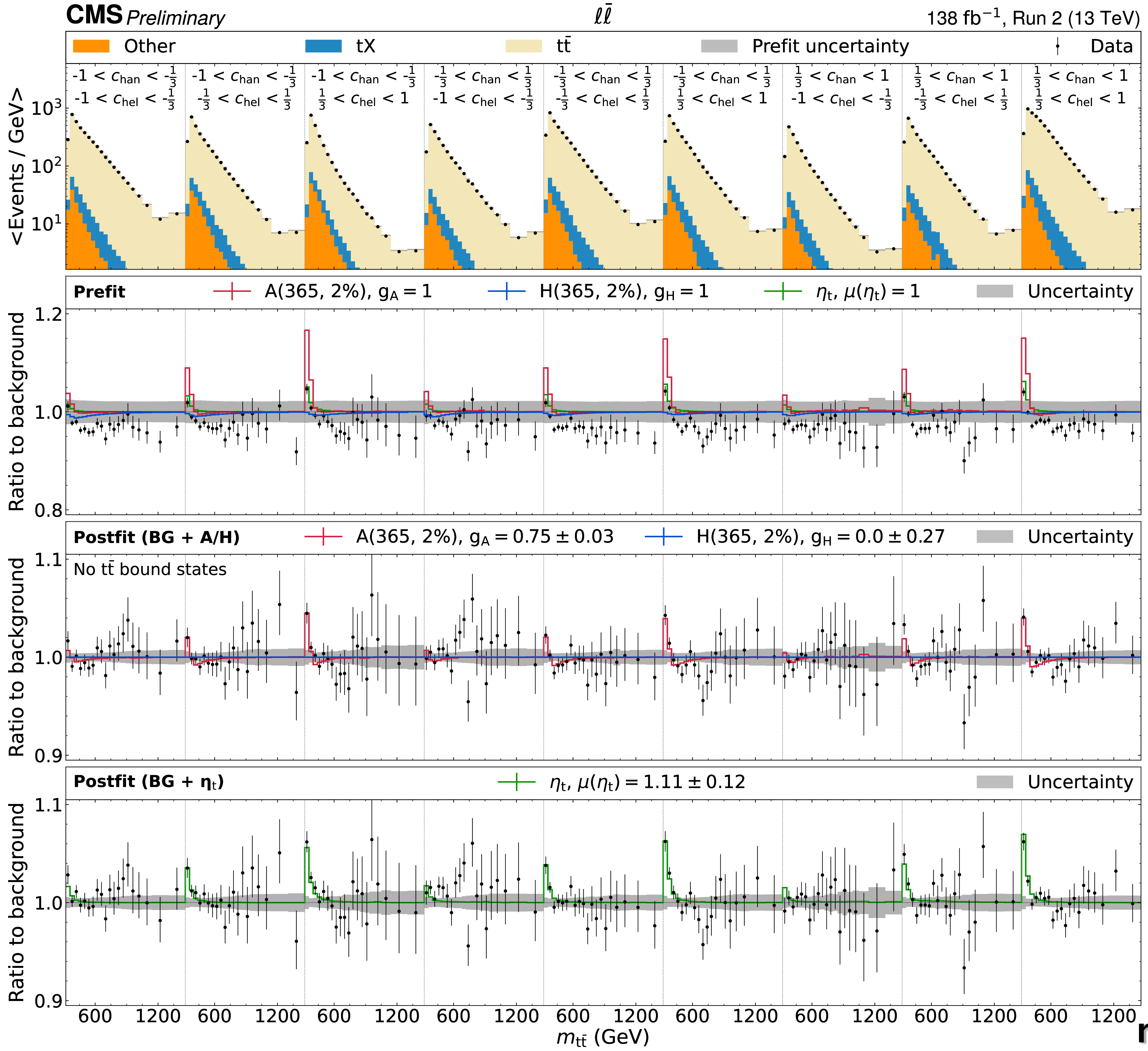
Results – Dilepton



$m_{t\bar{t}}$ (GeV)

Results – Dilepton

Results – Dilepton



$m_{t\bar{t}}$ (GeV)

Results – Dilepton

Results – Dilepton

threshold

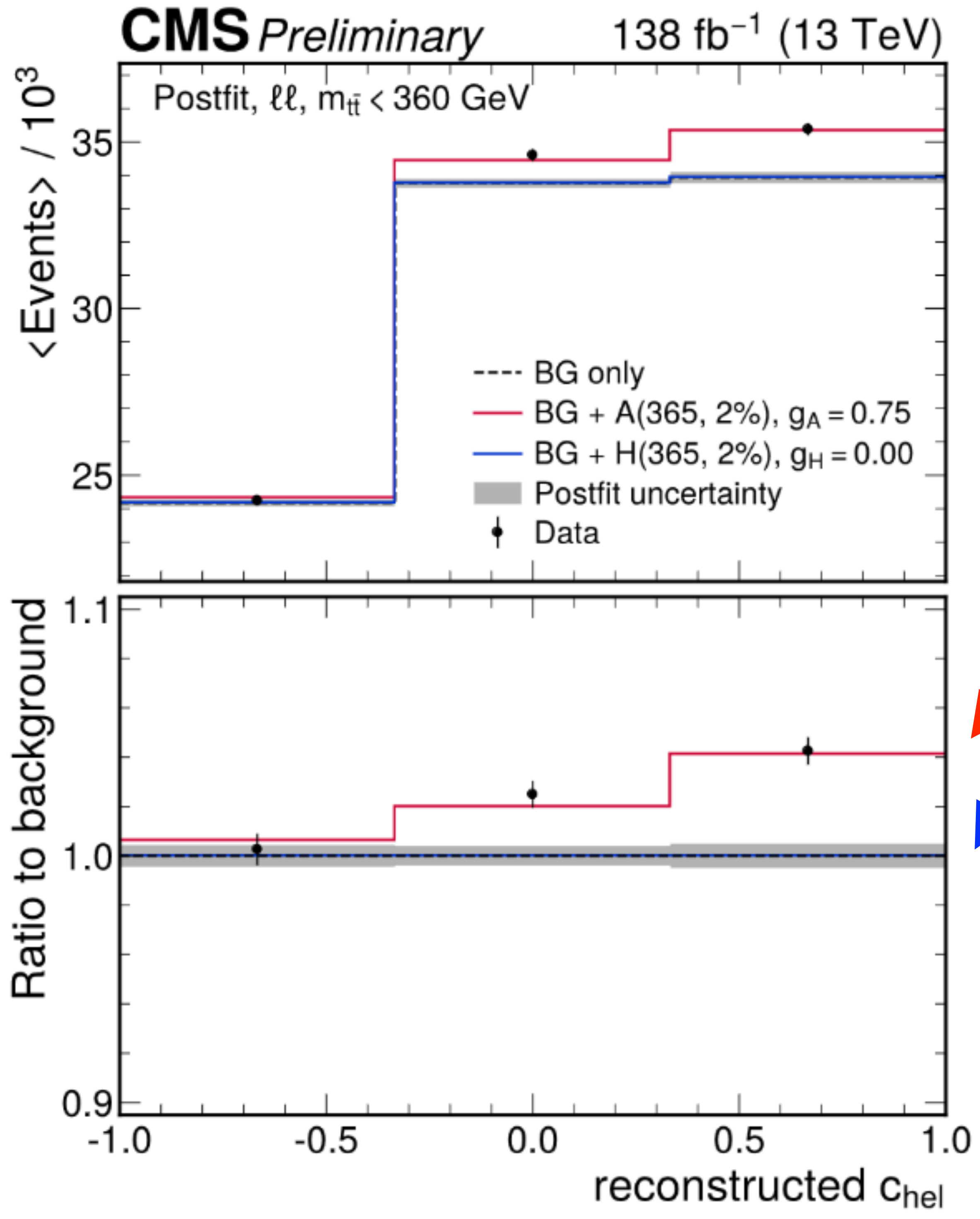
high $m_{t\bar{t}}$

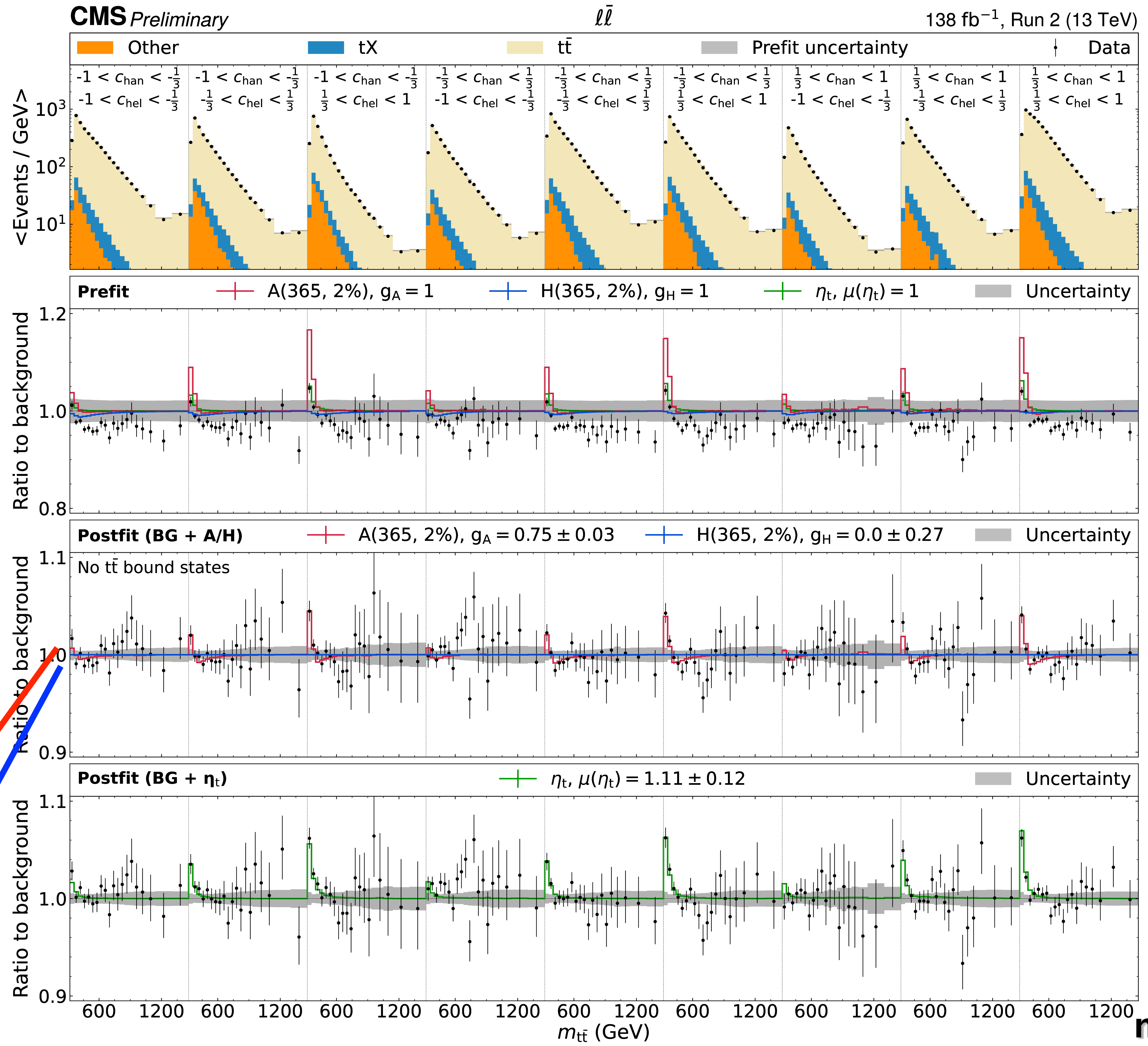
$m_{t\bar{t}}$ (GeV)

Results – Dilepton

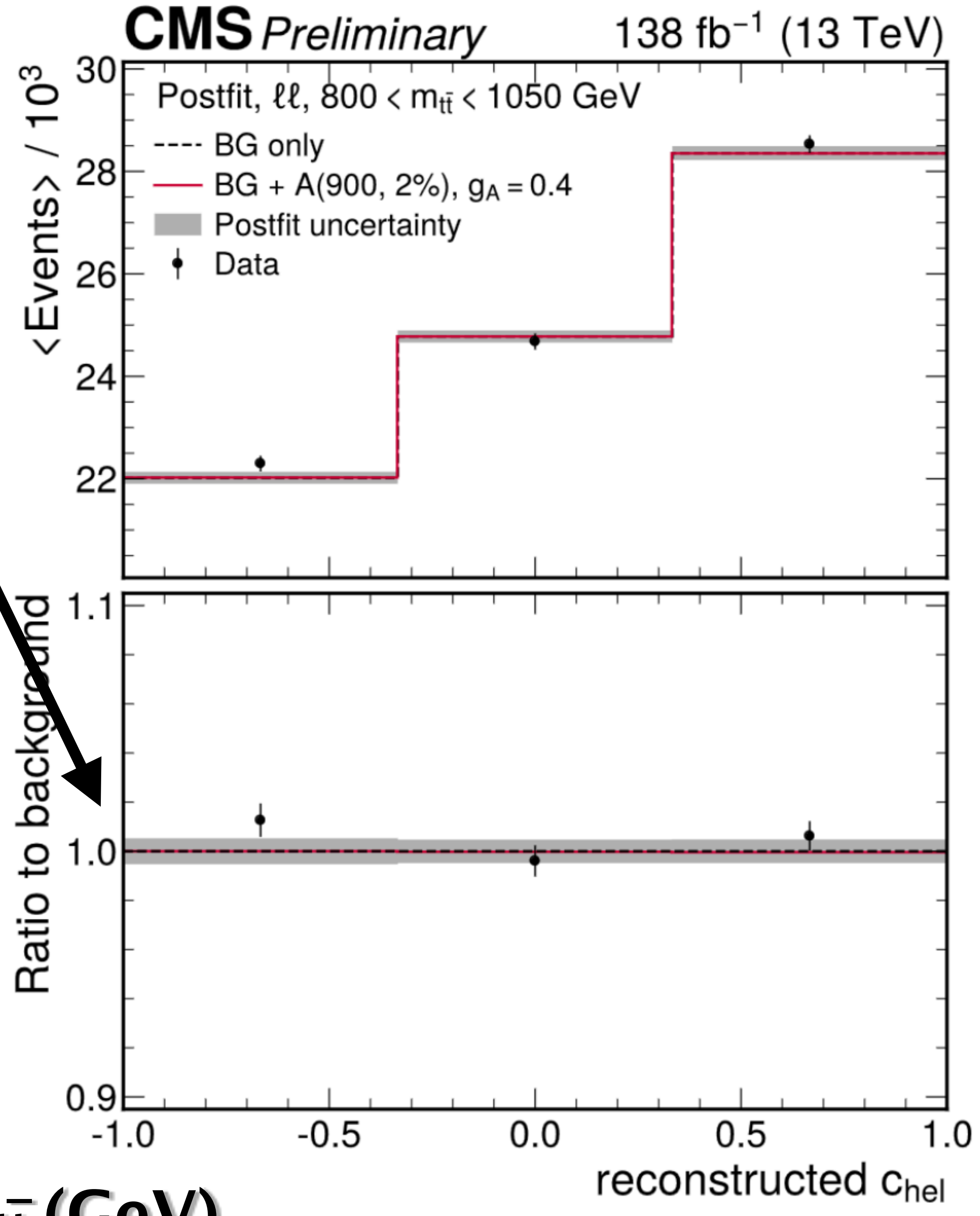
Results – Dilepton

threshold



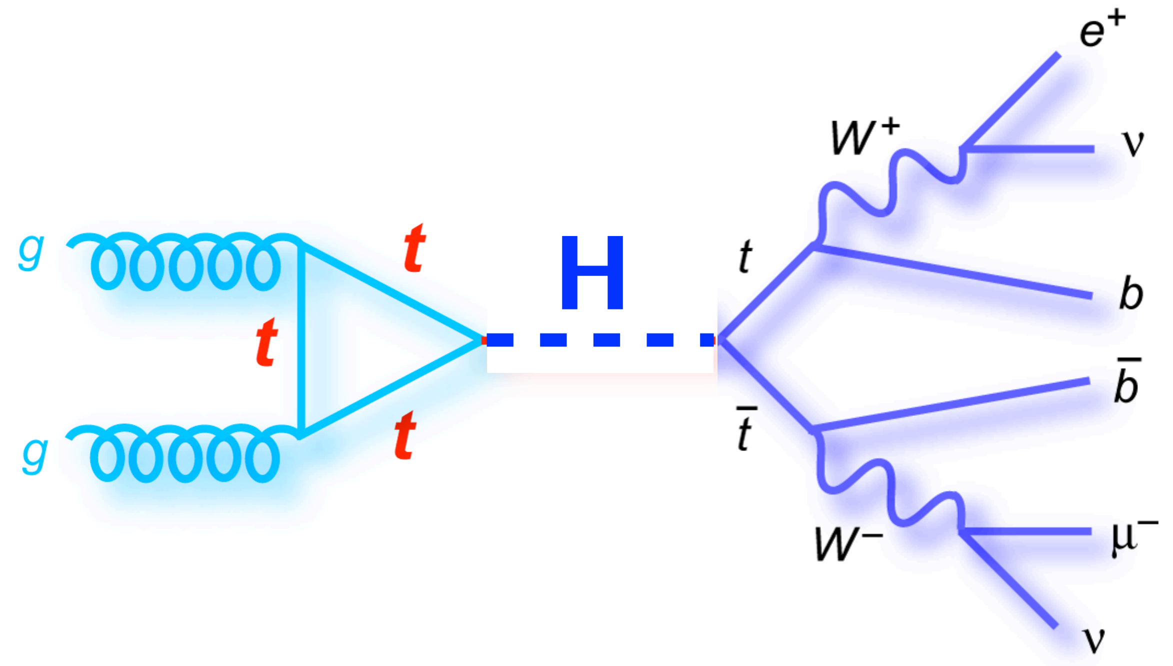


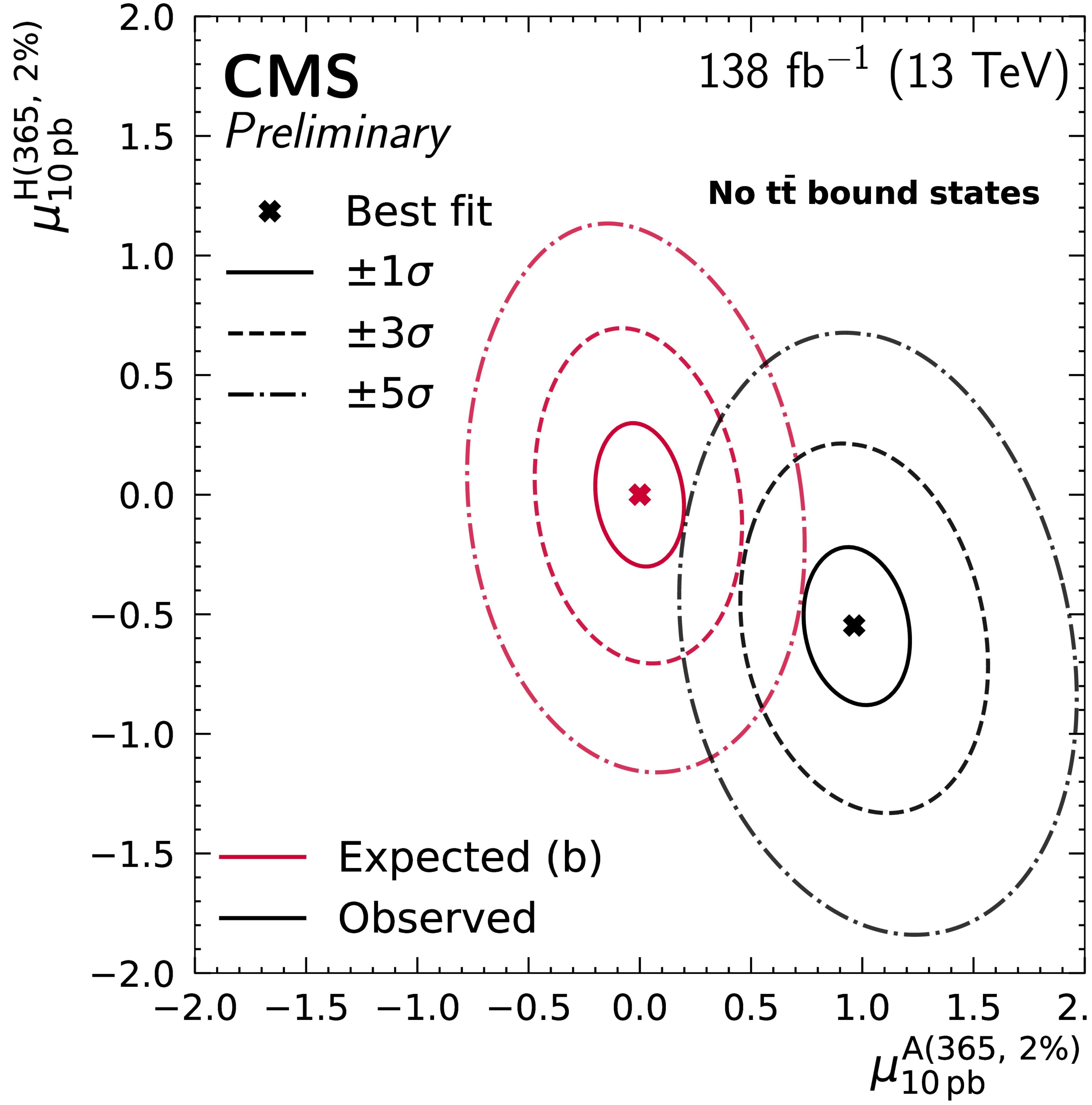
high $m_{t\bar{t}}$



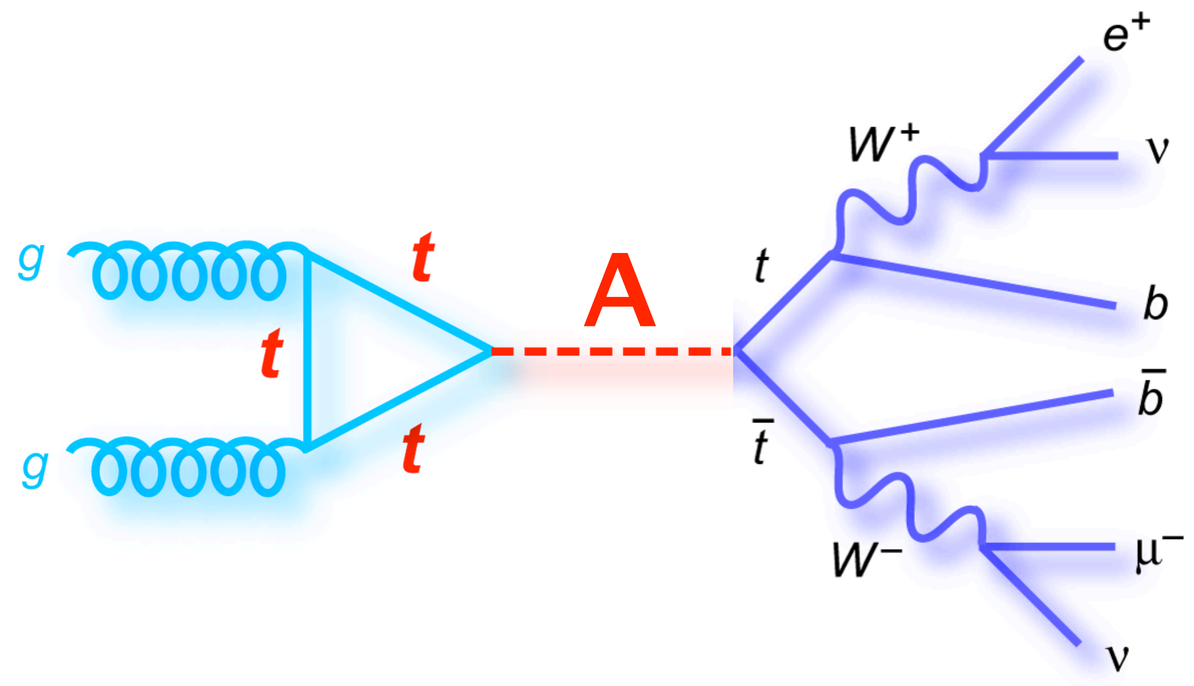
$m_{t\bar{t}}$ (GeV)

Results of A/H interpretation – Combination



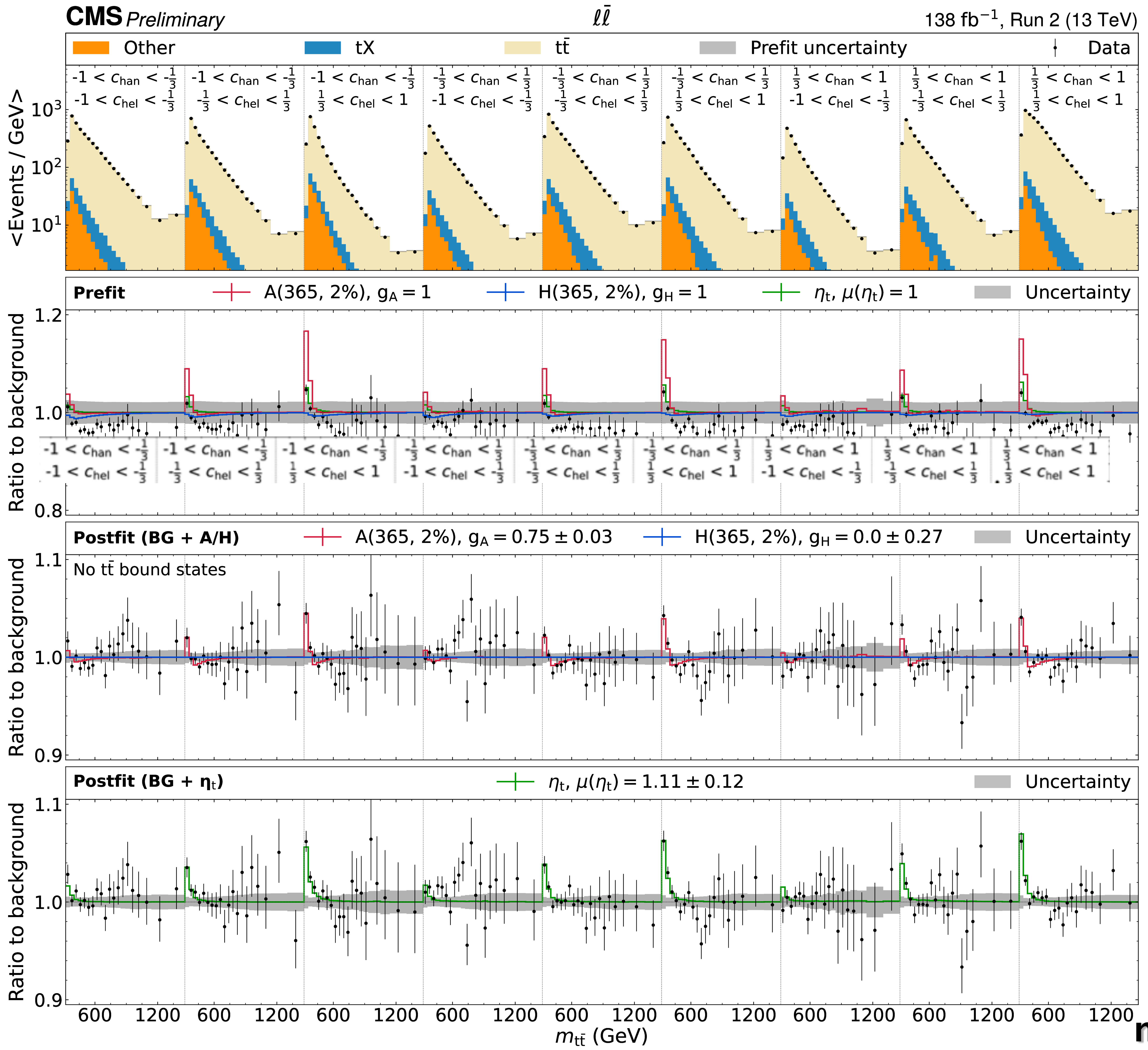


only resonant signal components included



→ data prefers pseudoscalar over scalar

Results – Dilepton

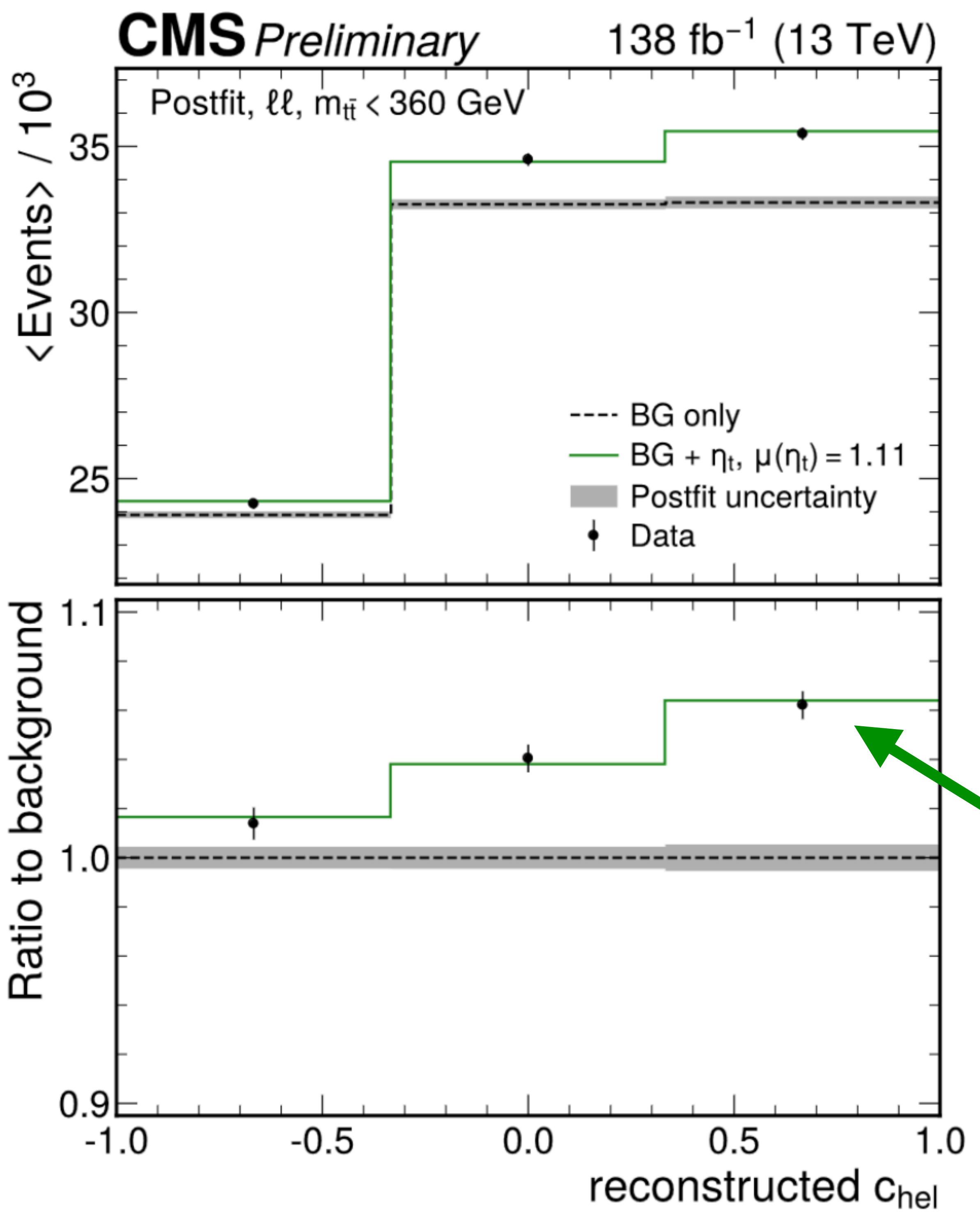


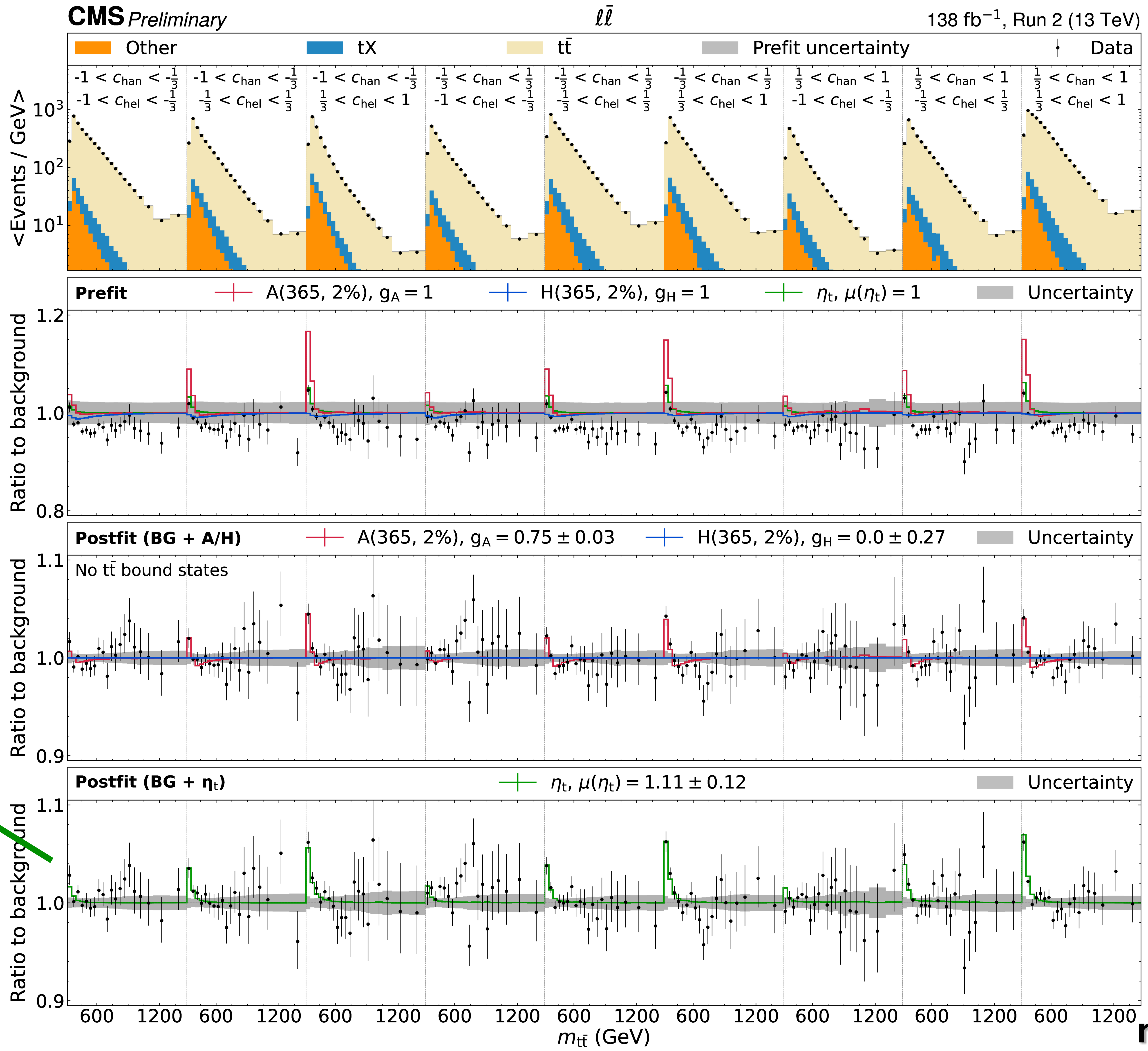
$m_{t\bar{t}}$ (GeV)

Results – Dilepton

Results – Dilepton

threshold

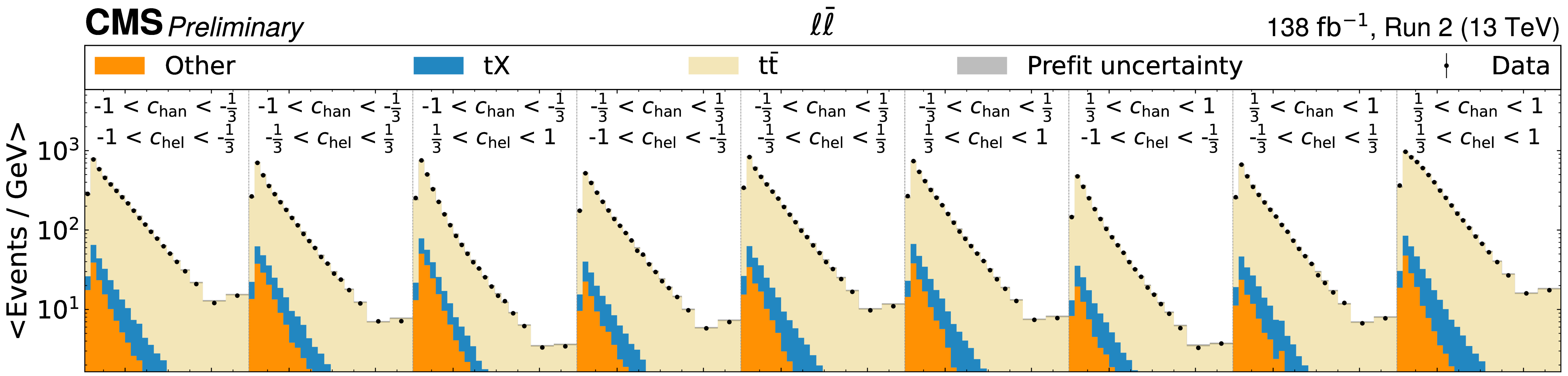




$m_{t\bar{t}}$ (GeV)

→ pseudoscalar bound state model fits to data as well

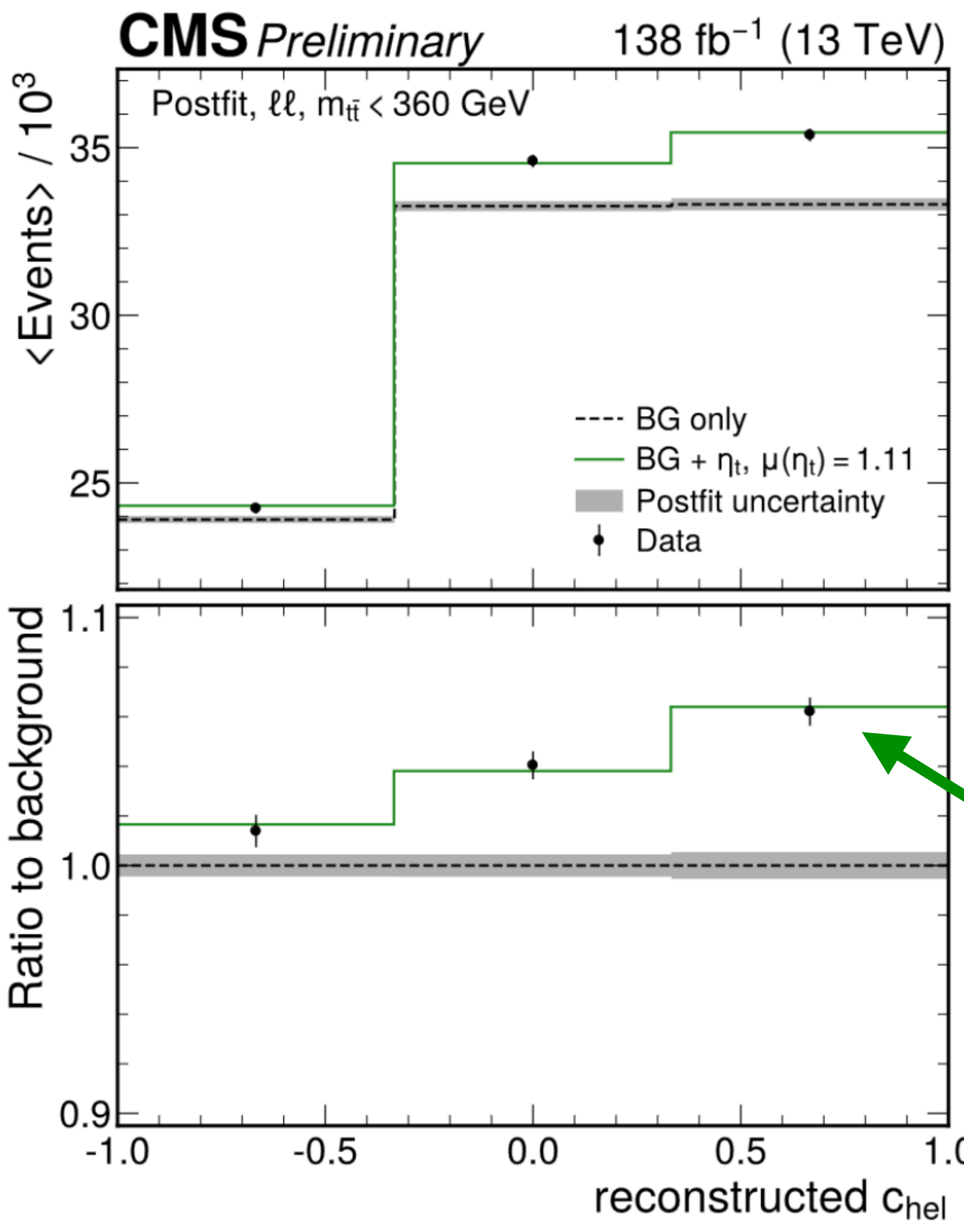
Results – Dilepton

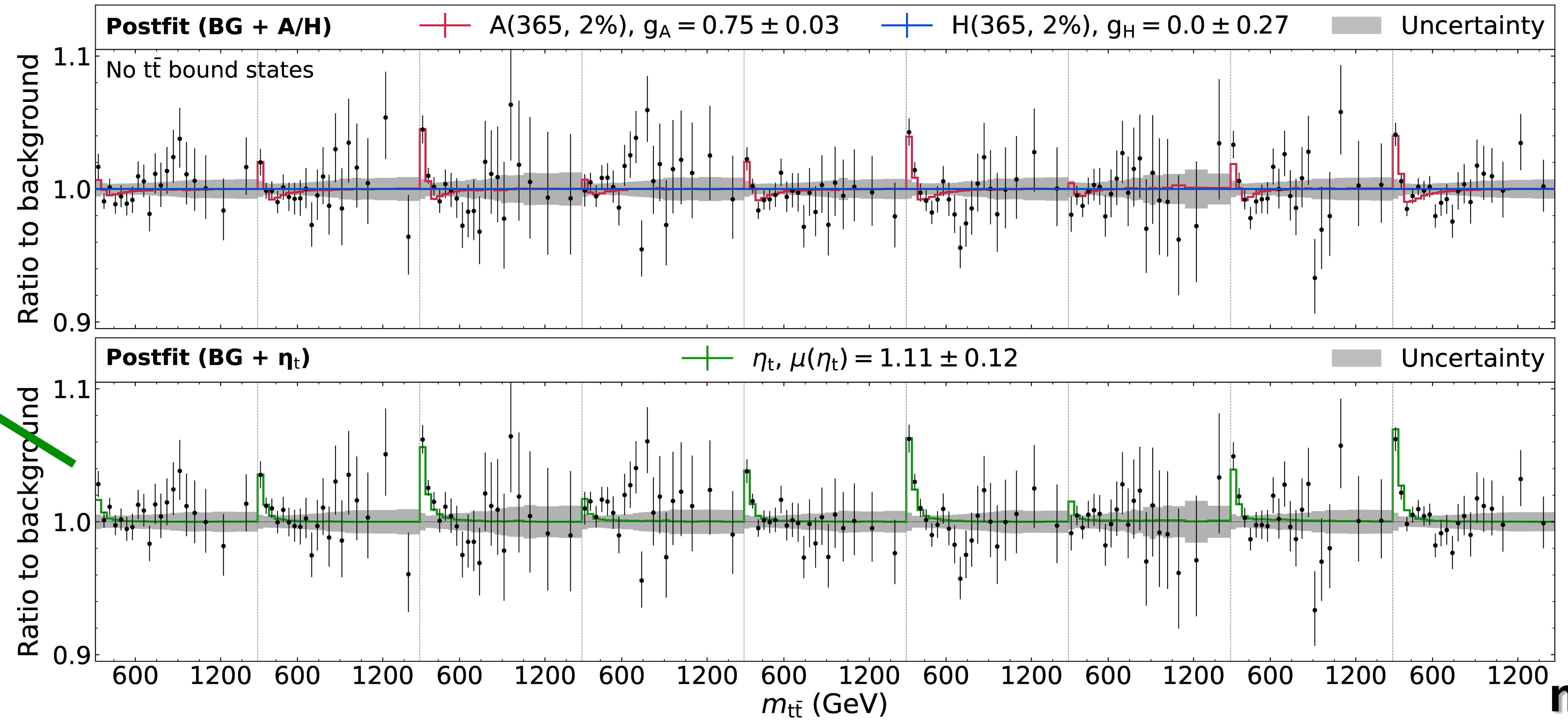


→ pseudoscalar bound state model fits to data as well as pseudoscalar A, but not scalar H

threshold combination

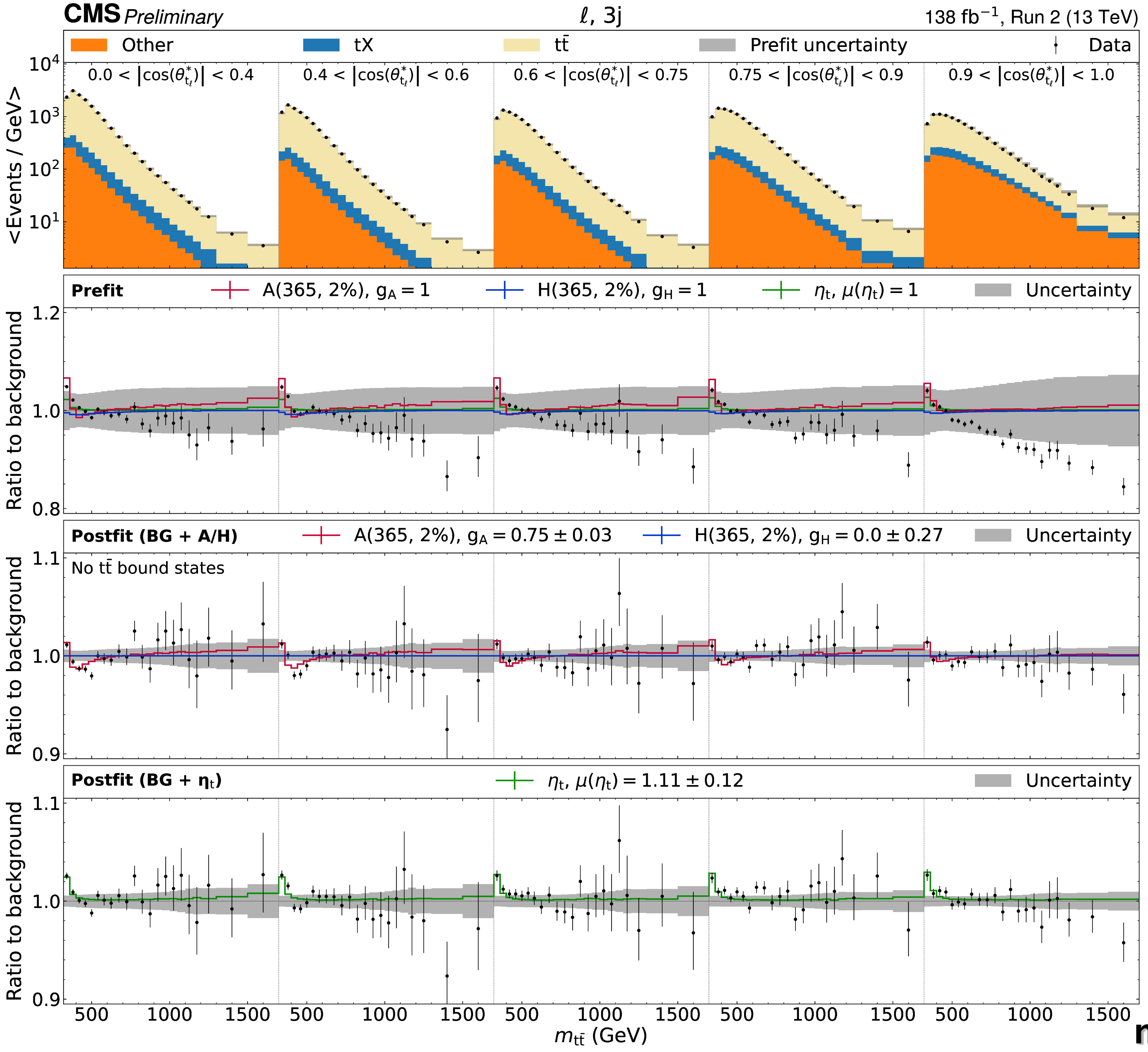
Interpretation	Best-fit point	Difference in $-2\ln L$
η_t	$m_{\eta t}$ = 343 GeV $\mu(\eta_t) = 1.11$	-86.2
Single A boson	$m_A = 365\,\text{GeV}, \Gamma_A/m_A = 2\%, g_{At\bar{t}} = 0.78$	-72.6
Single H boson	$m_H = 365\,\text{GeV}, \Gamma_H/m_H = 2\%, g_{Ht\bar{t}} = 1.45$	-10.4





$m_{t\bar{t}}$ (GeV)

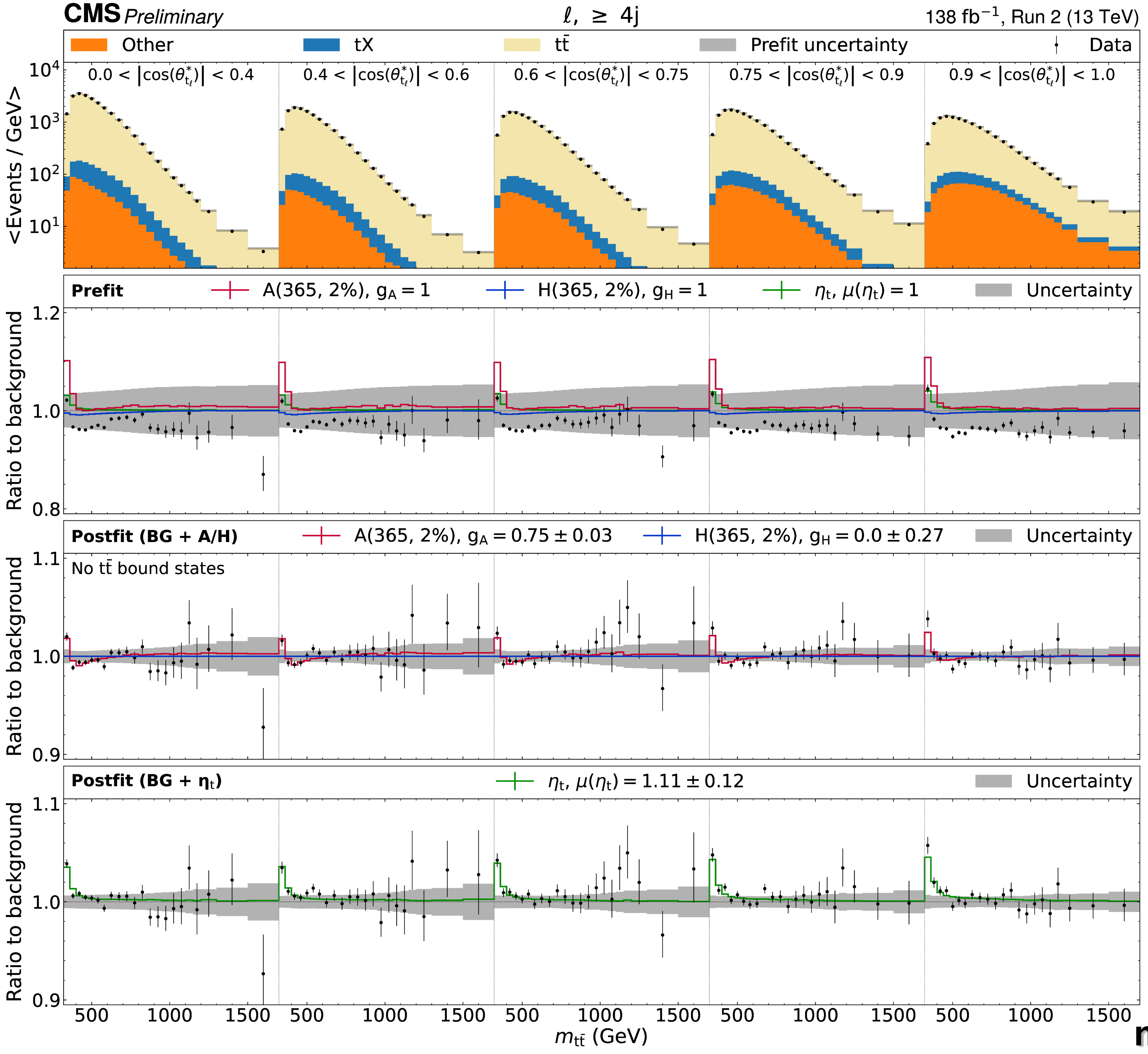
Results – Lepton+3jets



$m_{t\bar{t}}$ (GeV)

→ similar features, but less pronounced

Results – Lepton+≥4jets



m$_{t\bar{t}}$ (GeV)

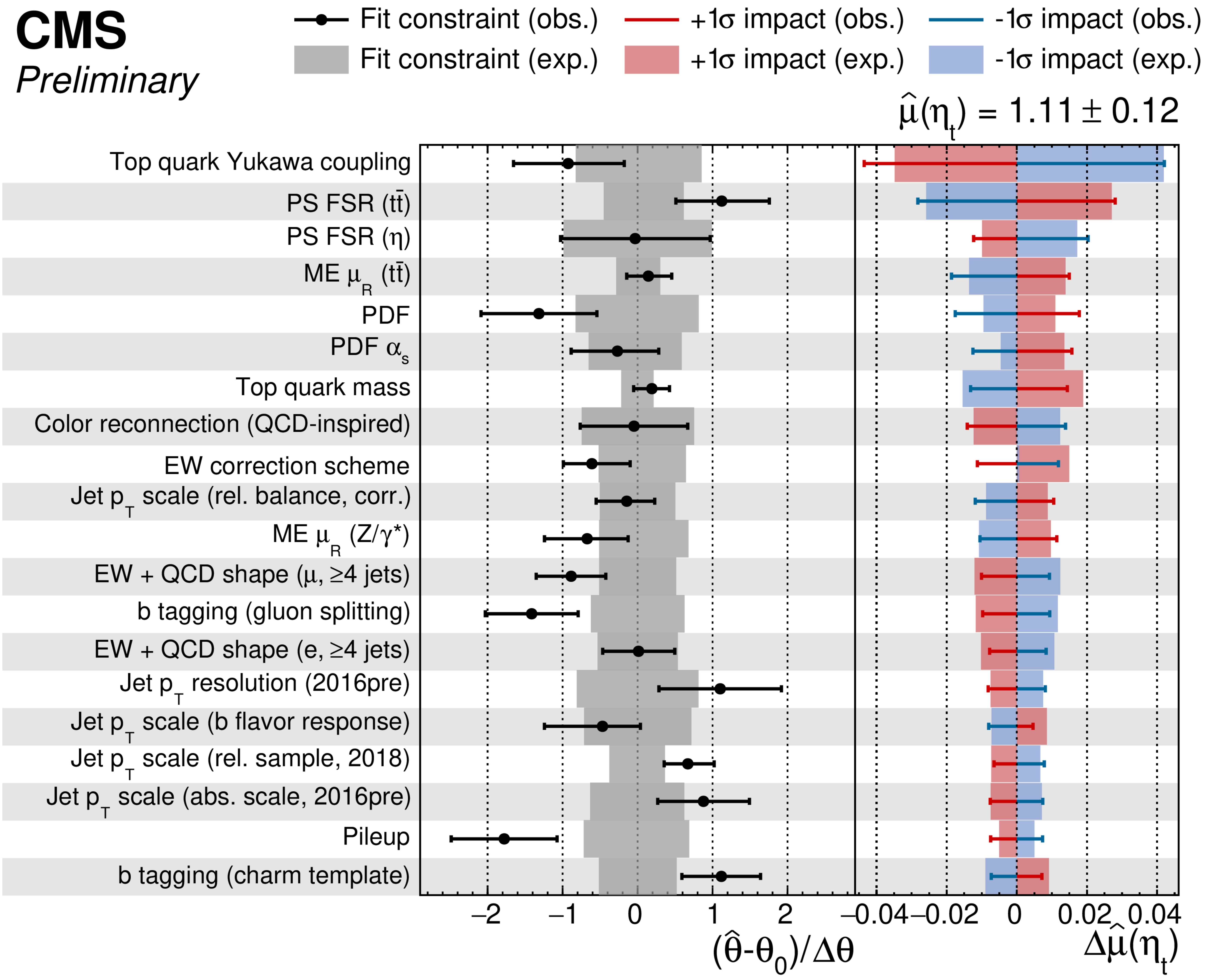
→ **similar features**

Uncertainties

- **Uncertainty on η_t cross section dominated by background modeling**
- **the leading uncertainties are:**
  - Electroweak corrections, including SM Top-Higgs Yukawa:

$$y_t = 1.00^{+0.11}_{-0.12}$$ EPJC 79 (2019) 421

  - parton shower scales
  - missing higher orders
  - PDF and α_s
  - top mass

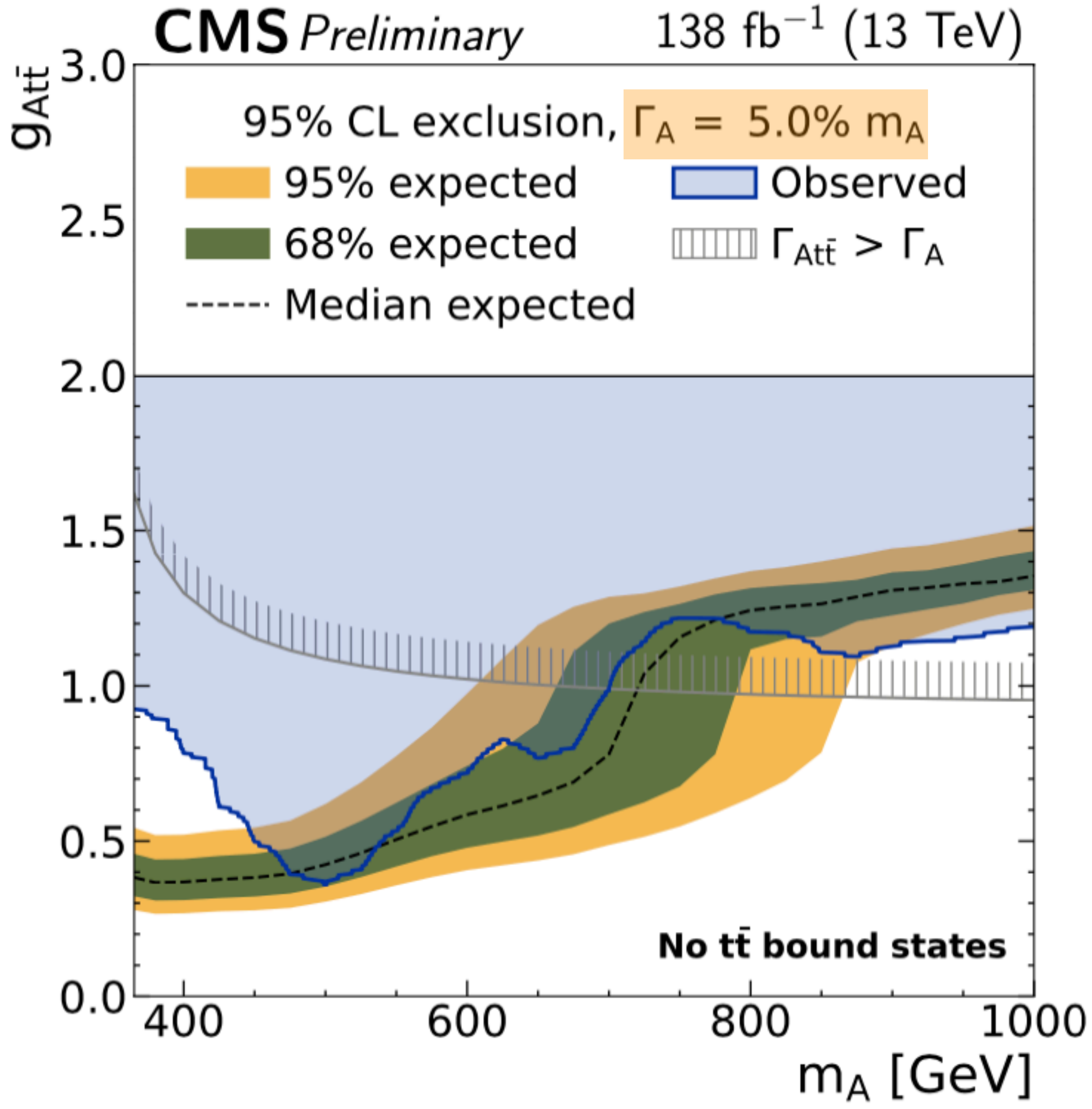


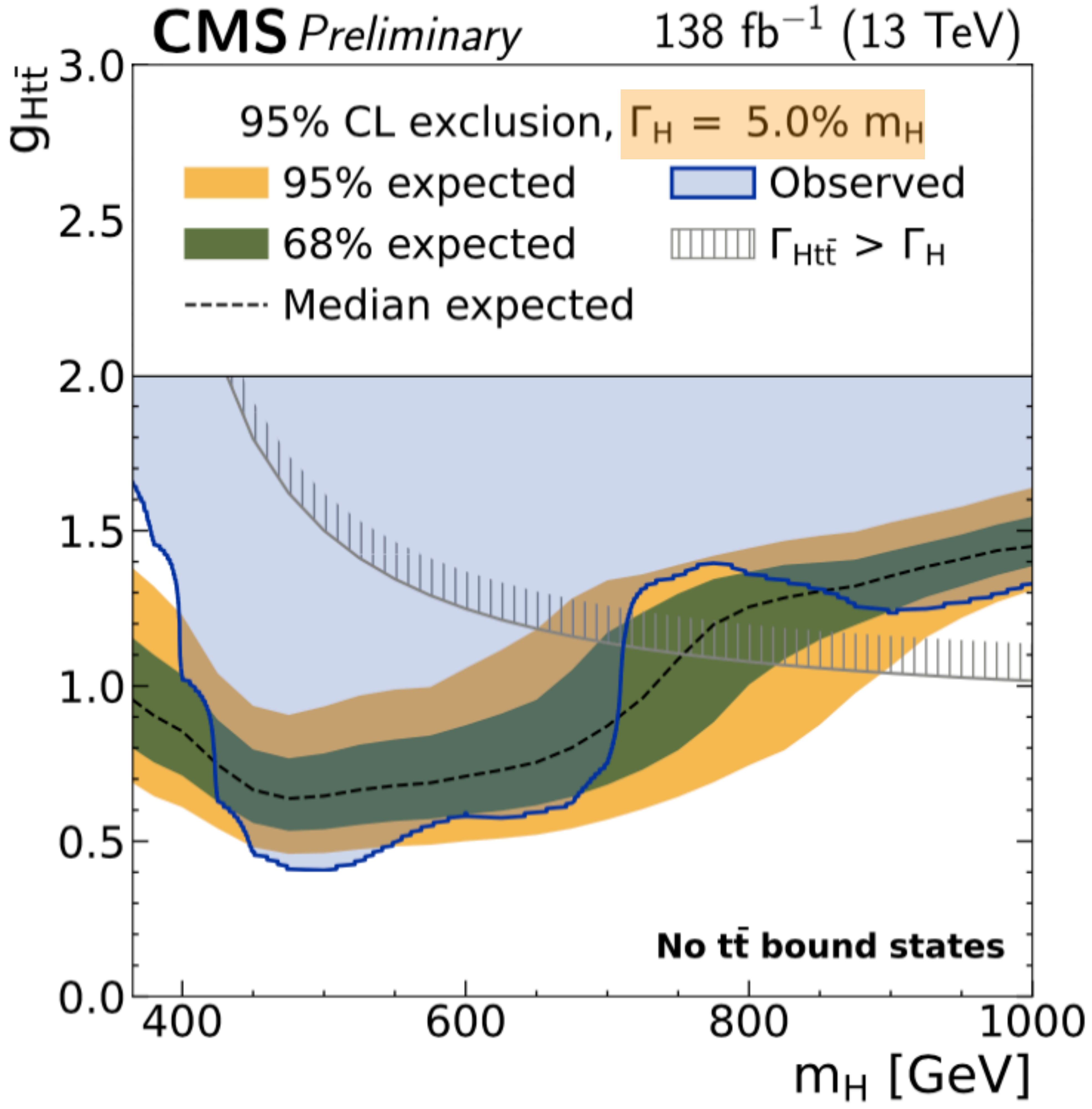
List of systematic uncertainties

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

A/H interpretation: Combination





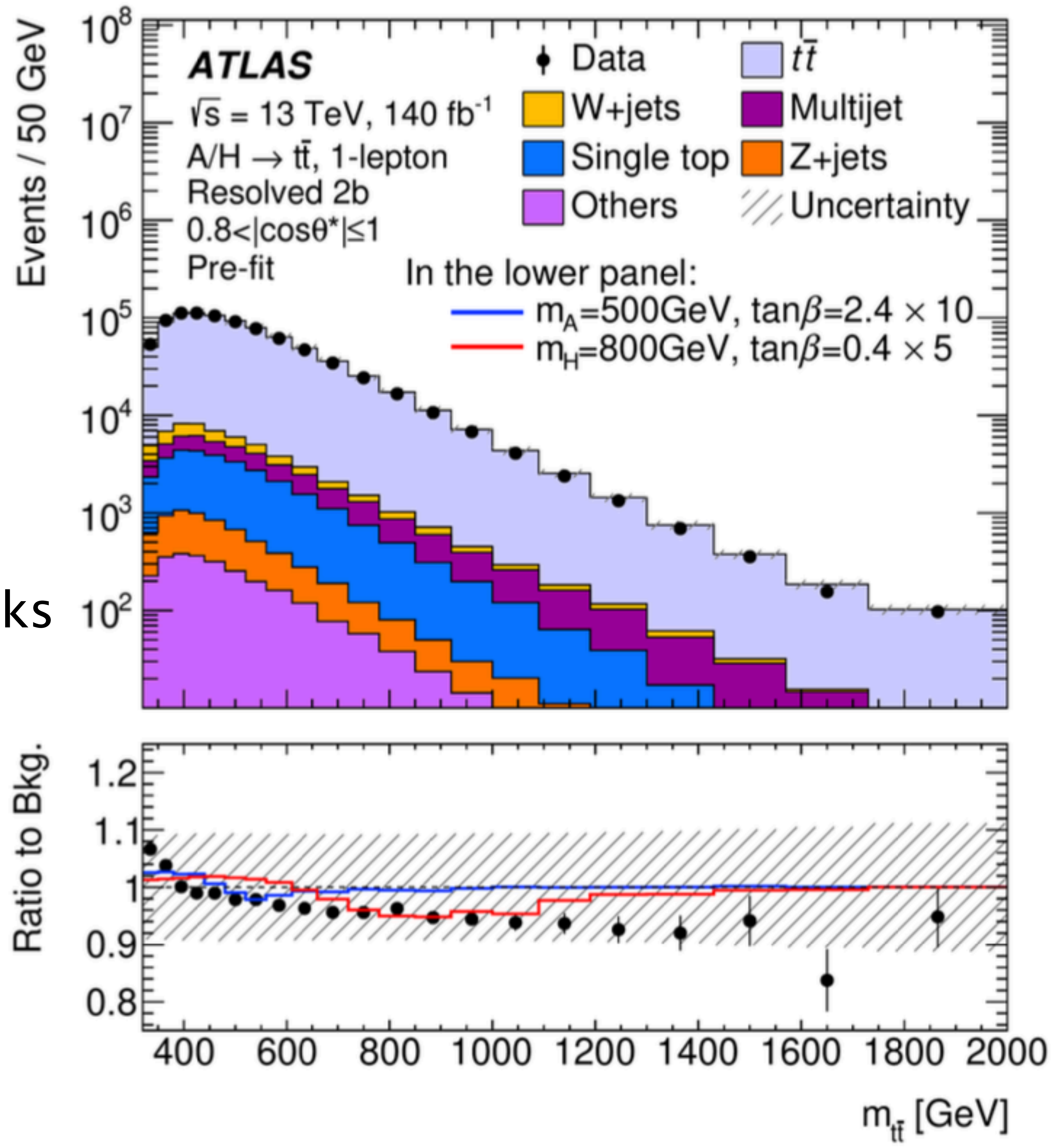
→ excess at low $m_{t\bar{t}}$ is reflected at low A/H masses, but stronger for pseudoscalar A

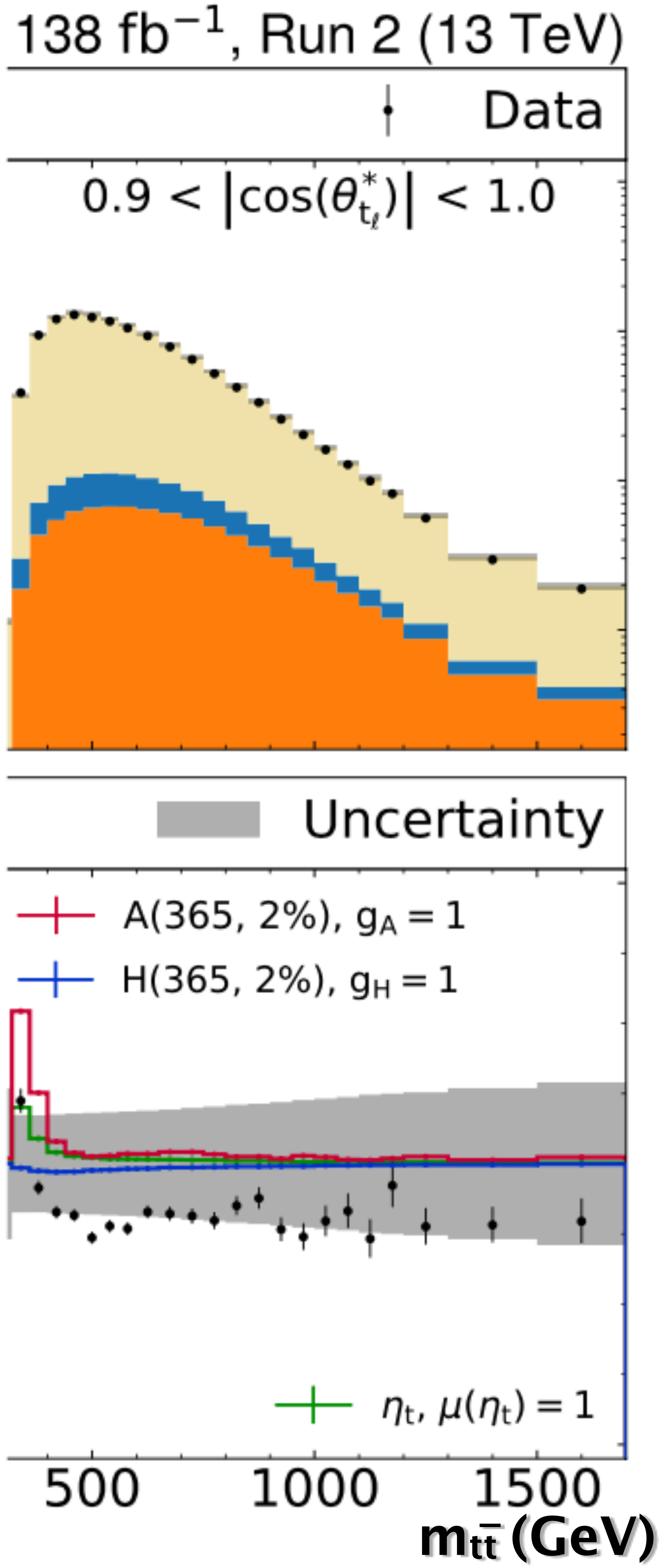
Comparison with ATLAS – prefit

- 1ℓ, 2b, ≥4 jets category for both ATLAS and CMS
  → compare pre-fit distributions
- e.g. look at high |cosθ*|:

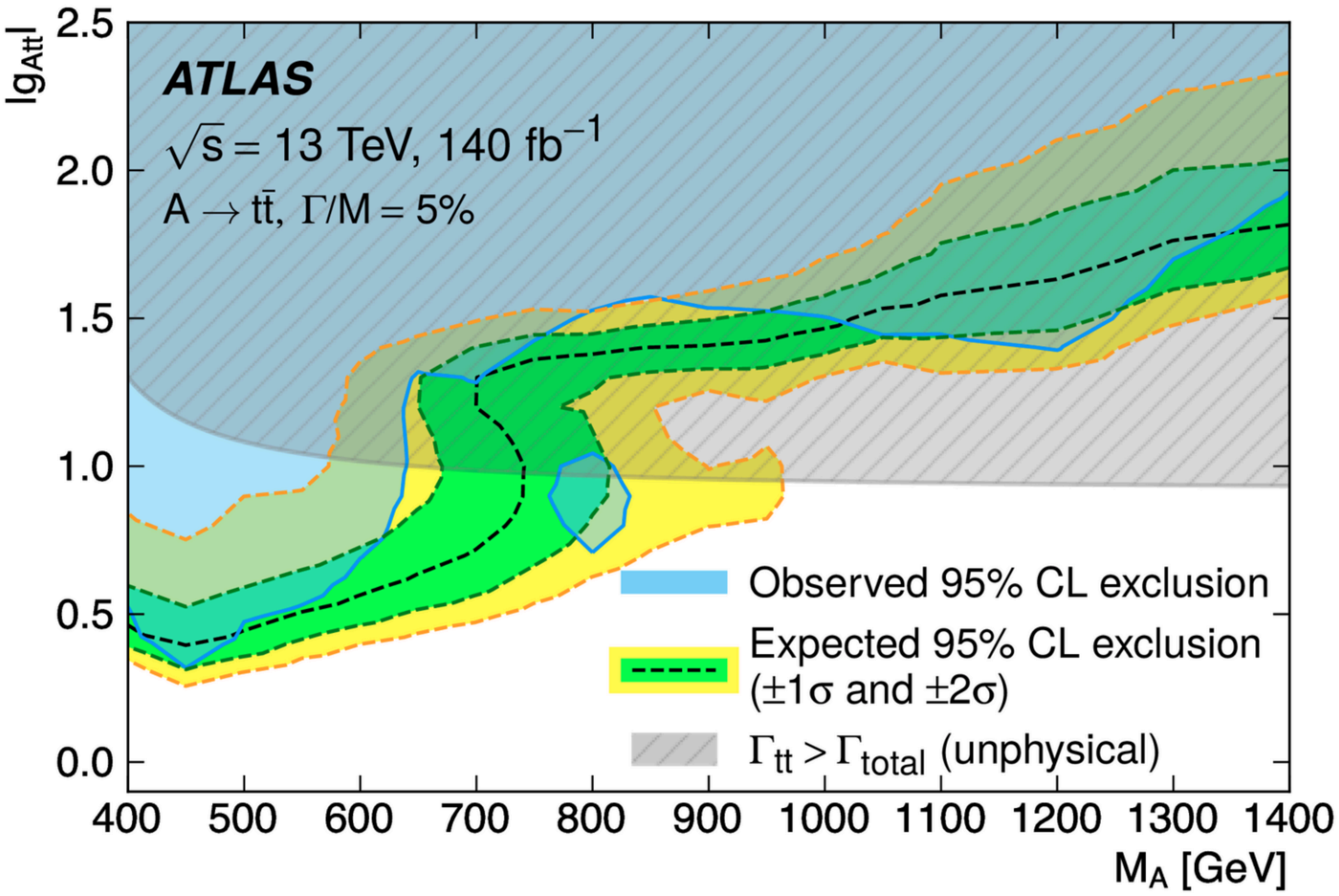
→ **similar excess in data at low $m_{t\bar{t}}$**

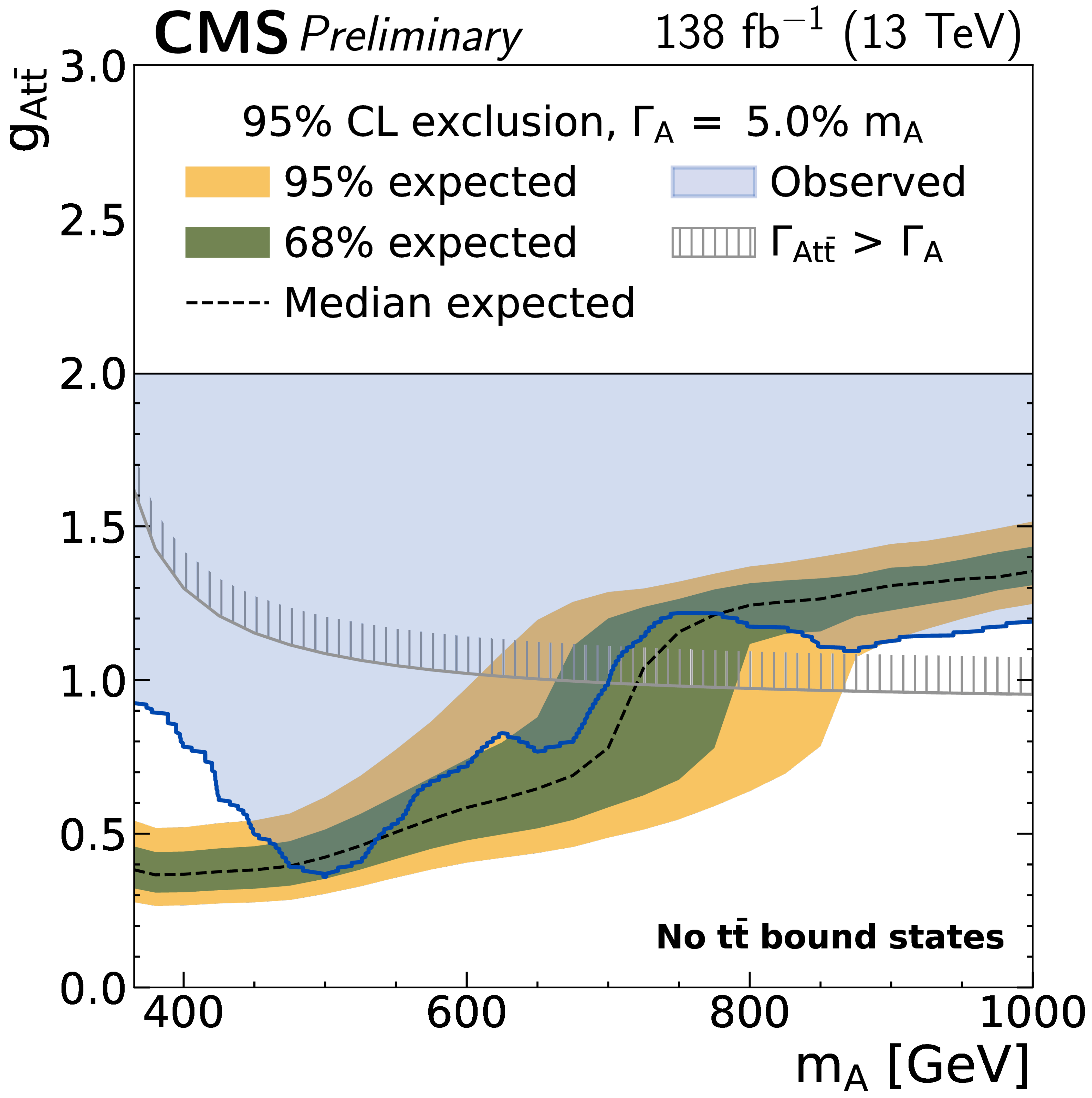
- for dilepton difficult to compare
  - ATLAS does not reconstruct top quarks
  - different variables: $m_{\ell\ell bb}$ vs. $\Delta\varphi_{\ell\ell}$



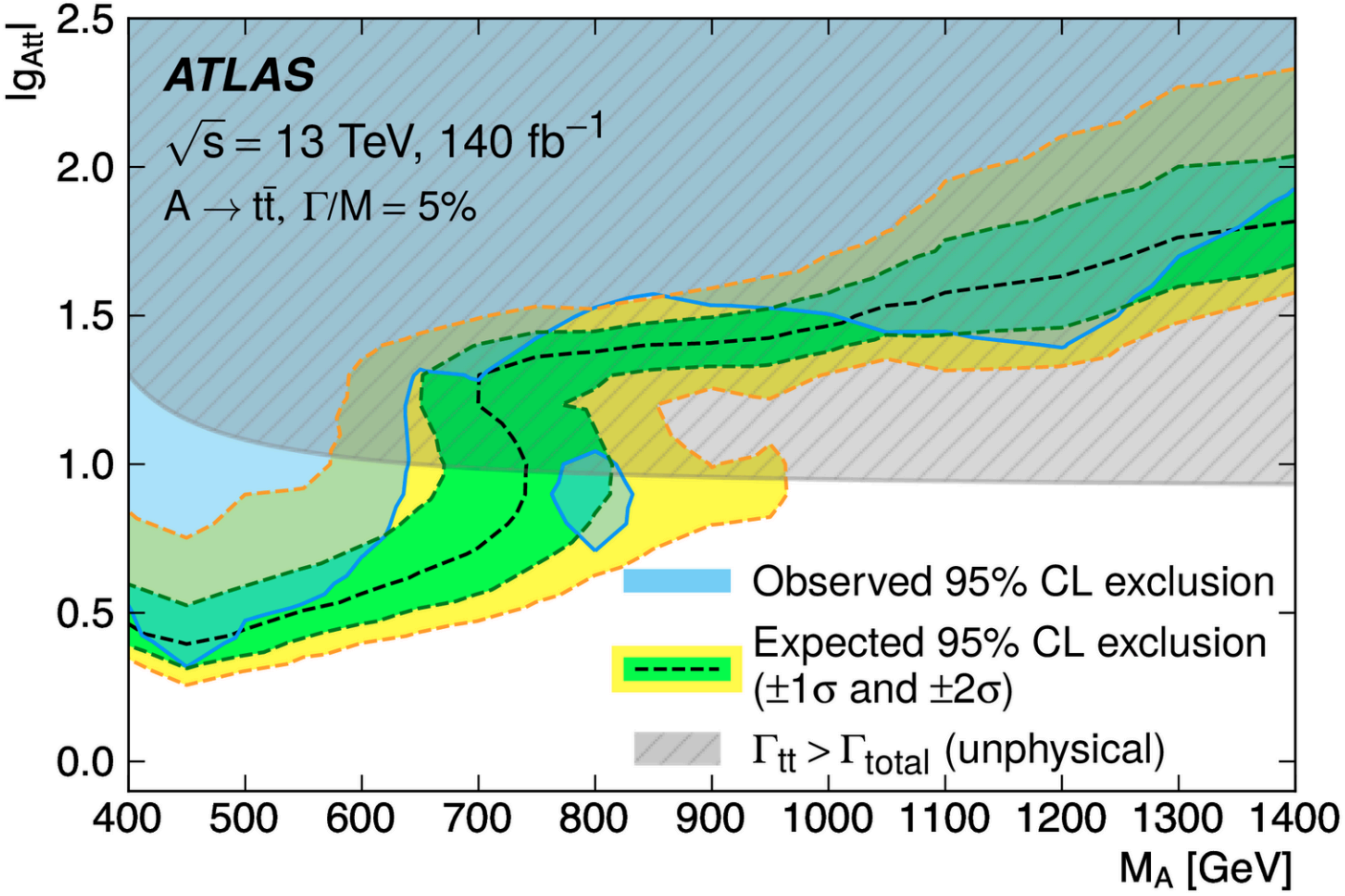


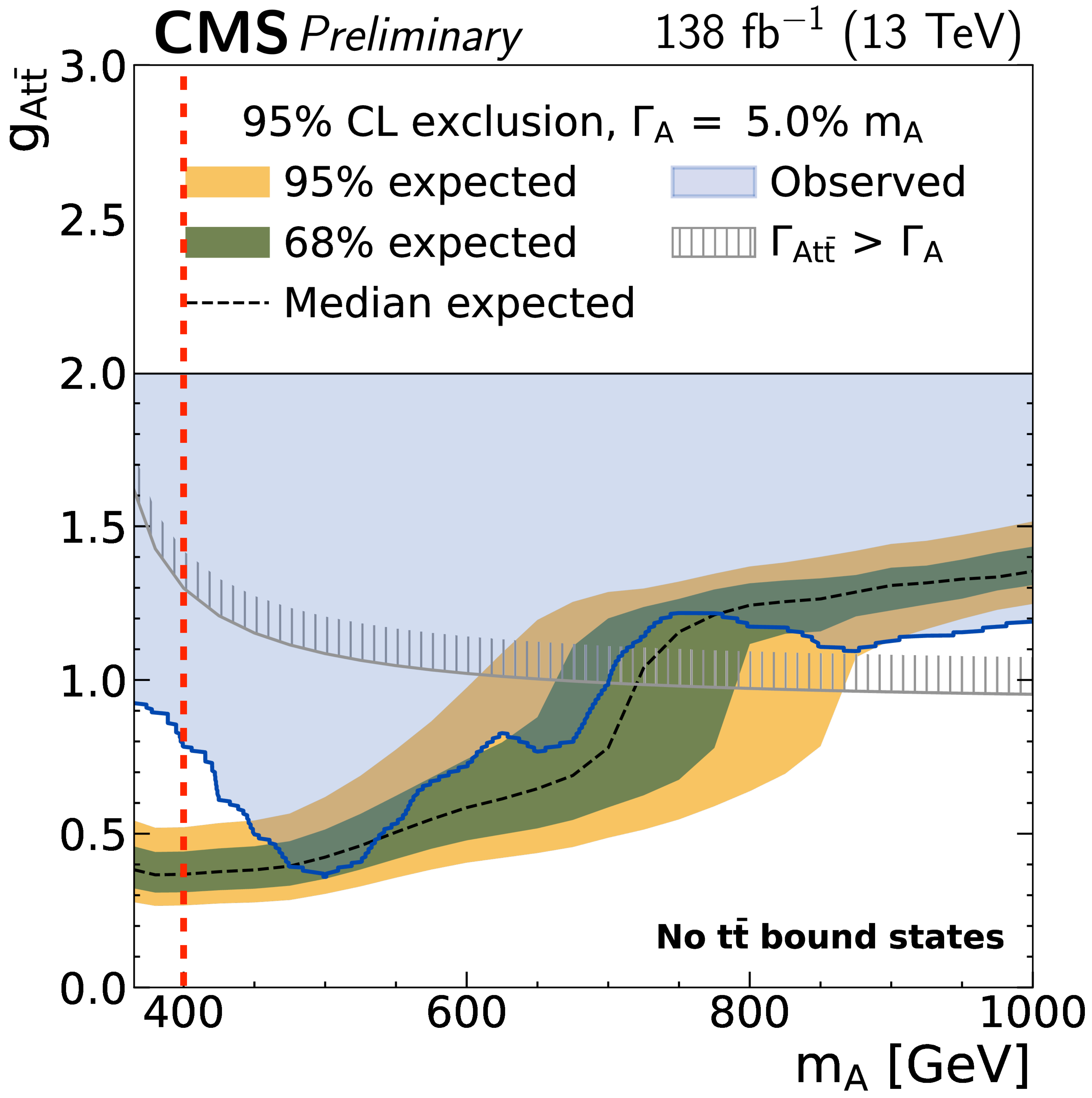
Comparison with ATLAS – limits, combined





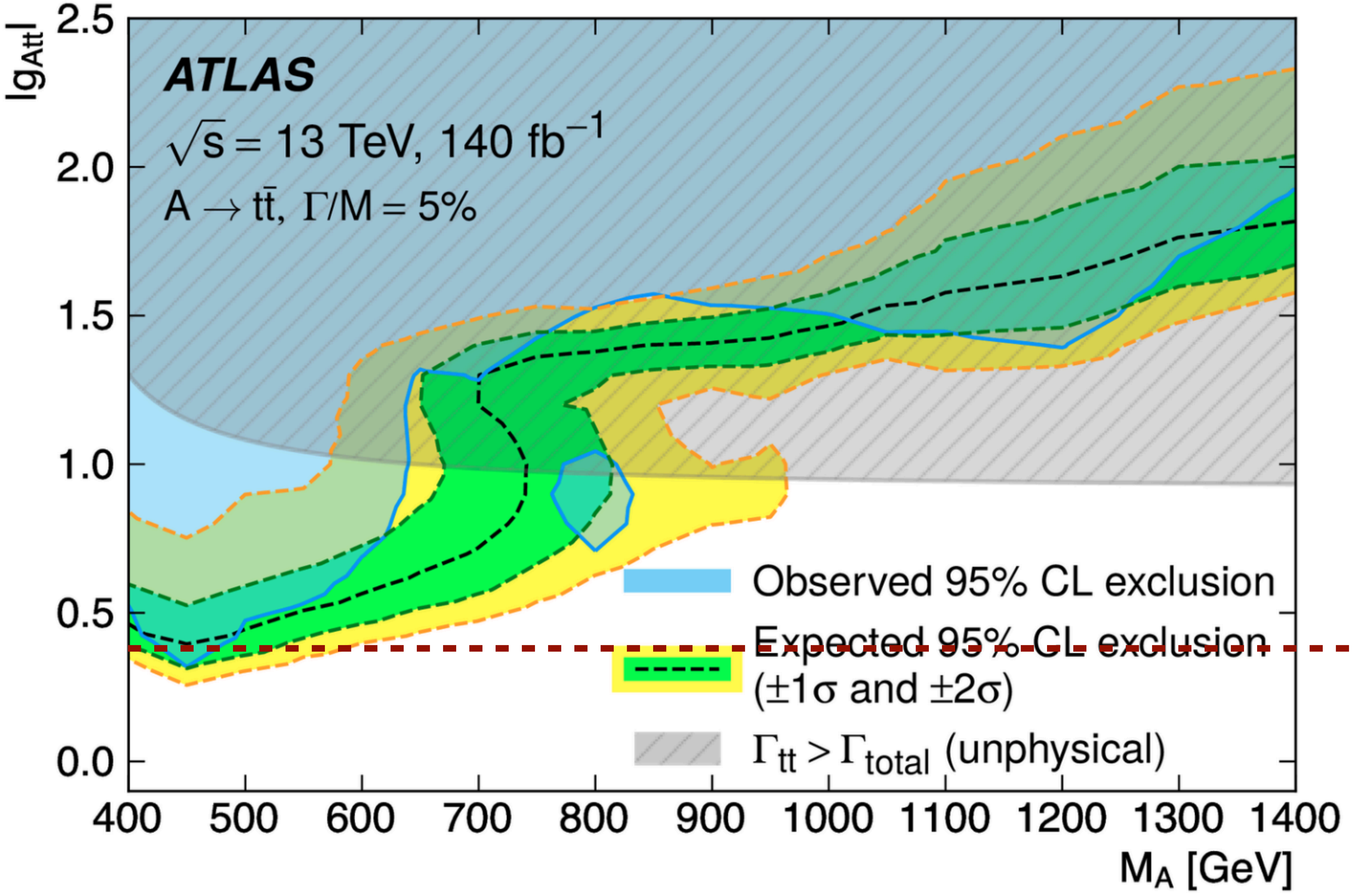
Comparison with ATLAS – limits, combined

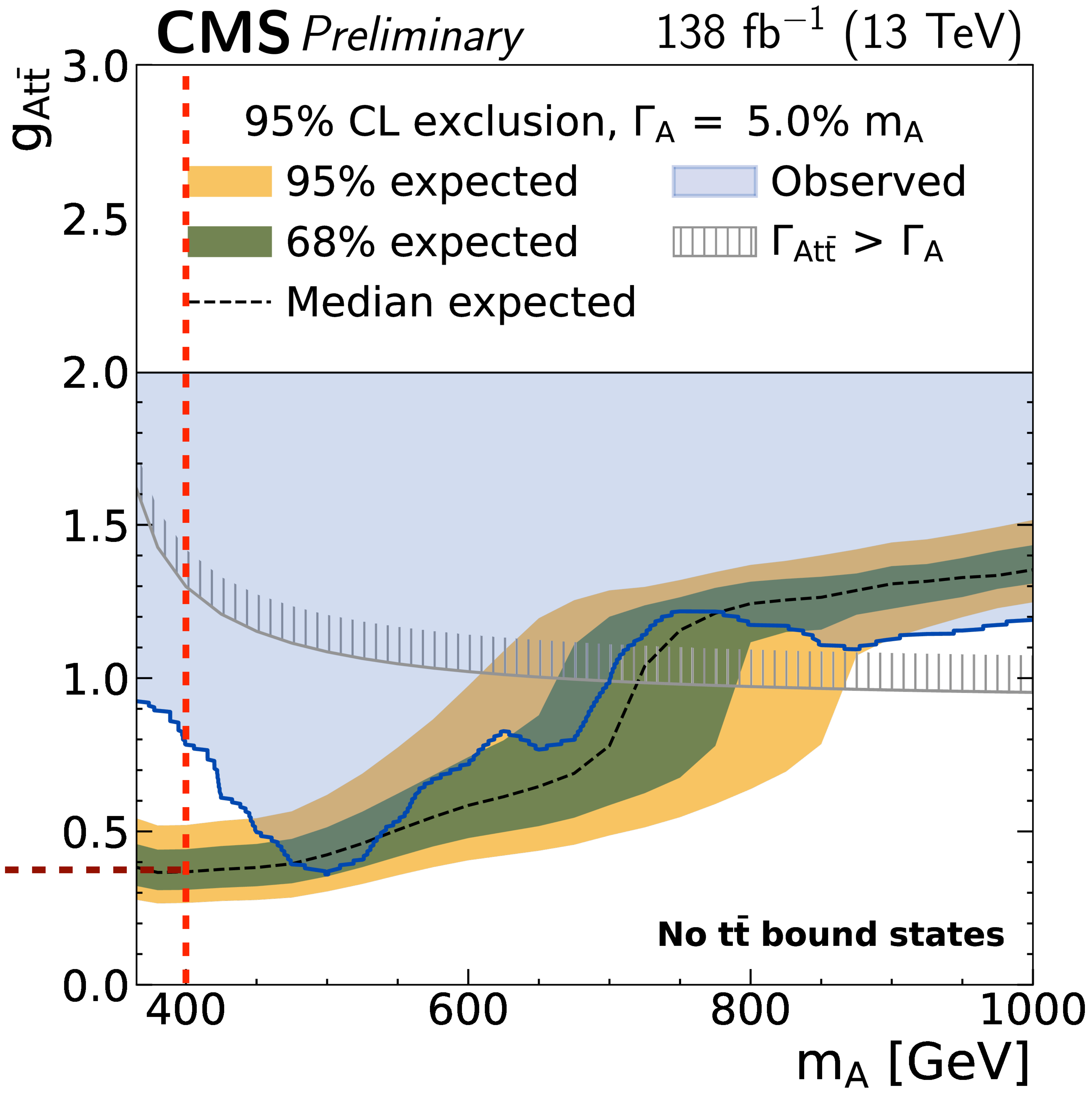




Comparison with ATLAS – limits, combined

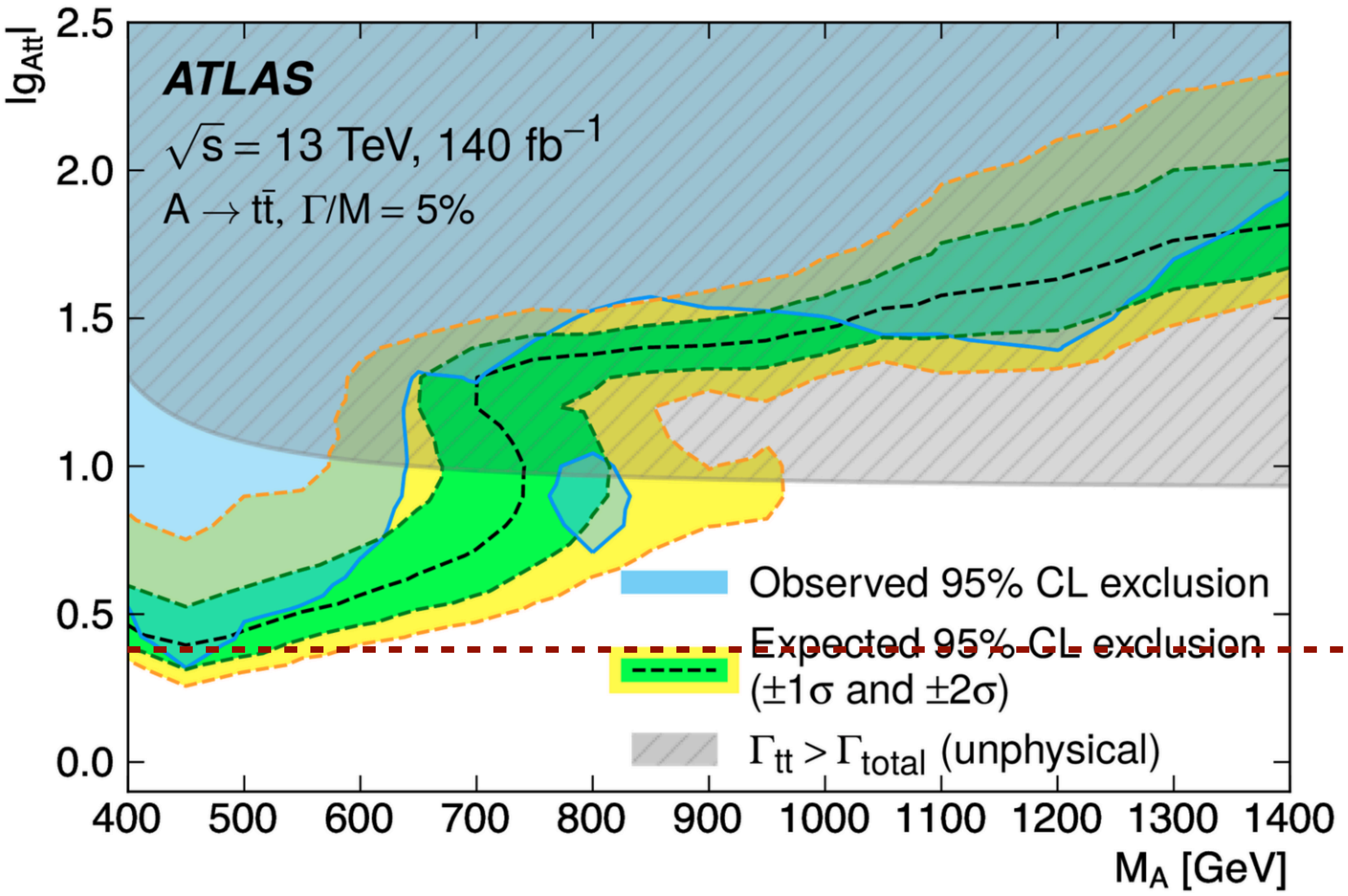
→ **similar expected limits**

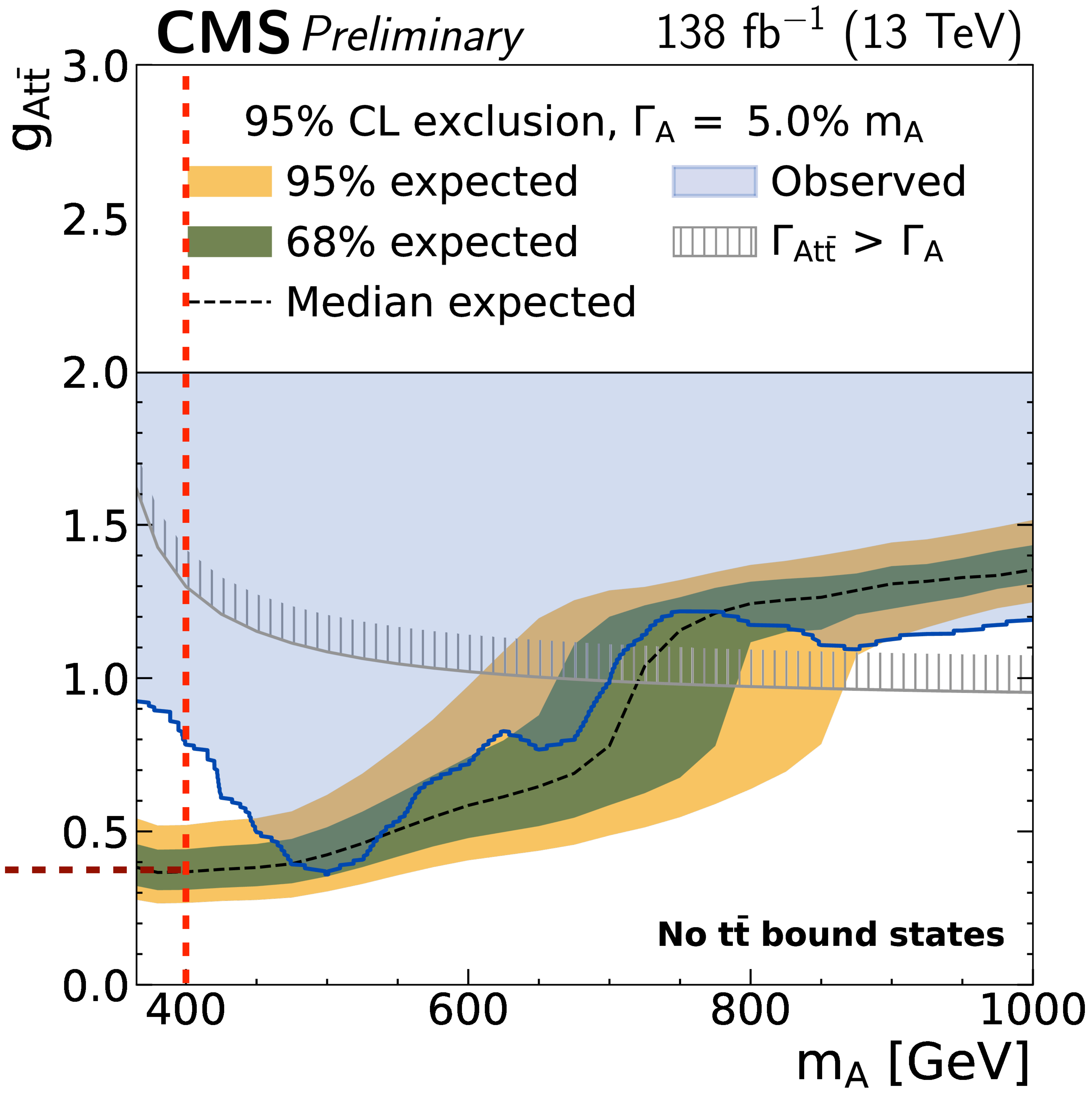




Comparison with ATLAS – limits, combined

- → similar expected limits
- → but no excess in ATLAS postfit
- → **we are comparing…**





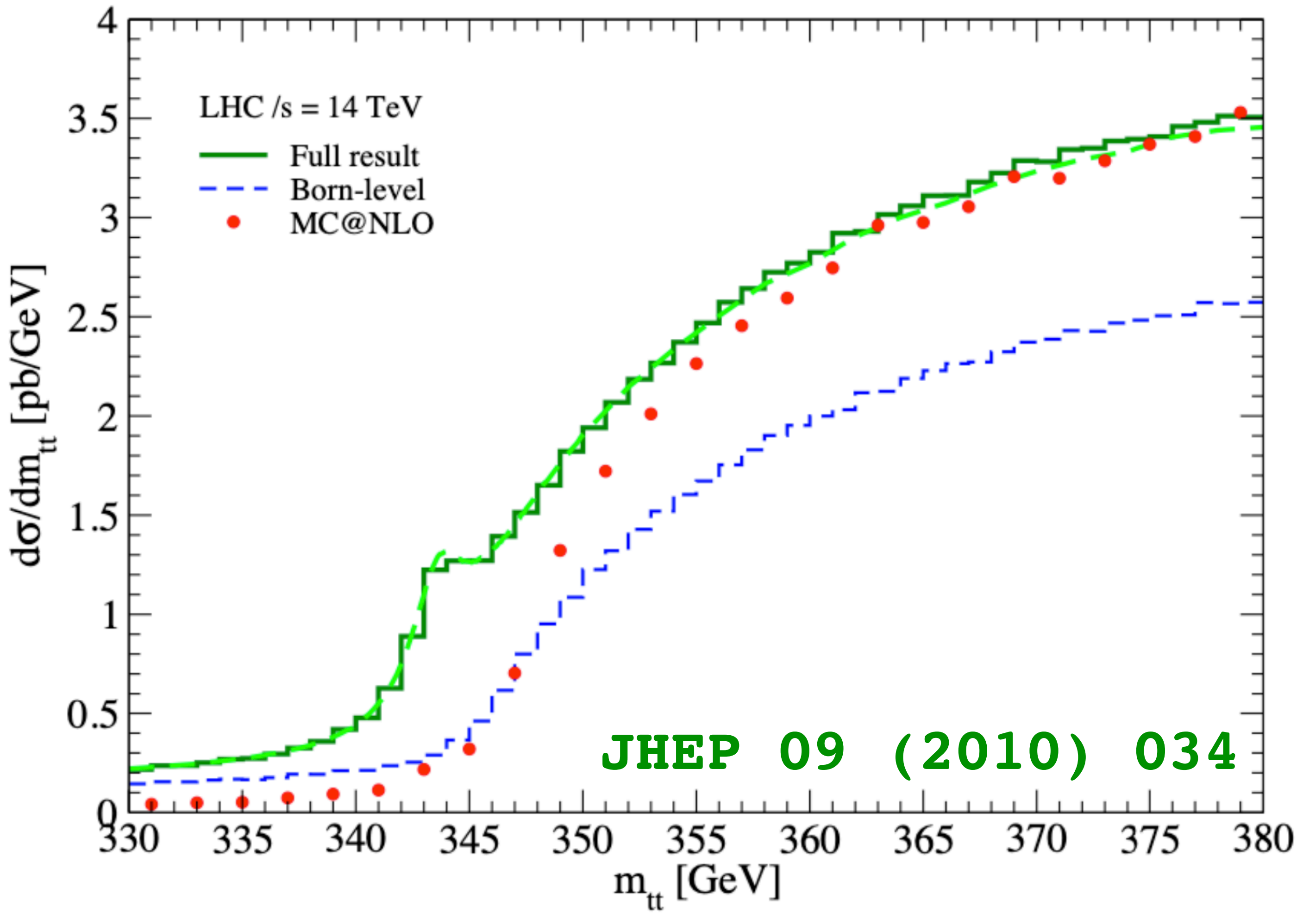
Could it be a pseudoscalar $t\bar{t}$ bound state?

- excess is located in threshold region at low m_{tt} and fits better to pseudoscalar hypothesis

→ could this be interpreted as tt bound state effect (pseudoscalar toponium)?

- extract cross section using the η_t color-singlet model
  - "cross section" = difference to perturbative prediction

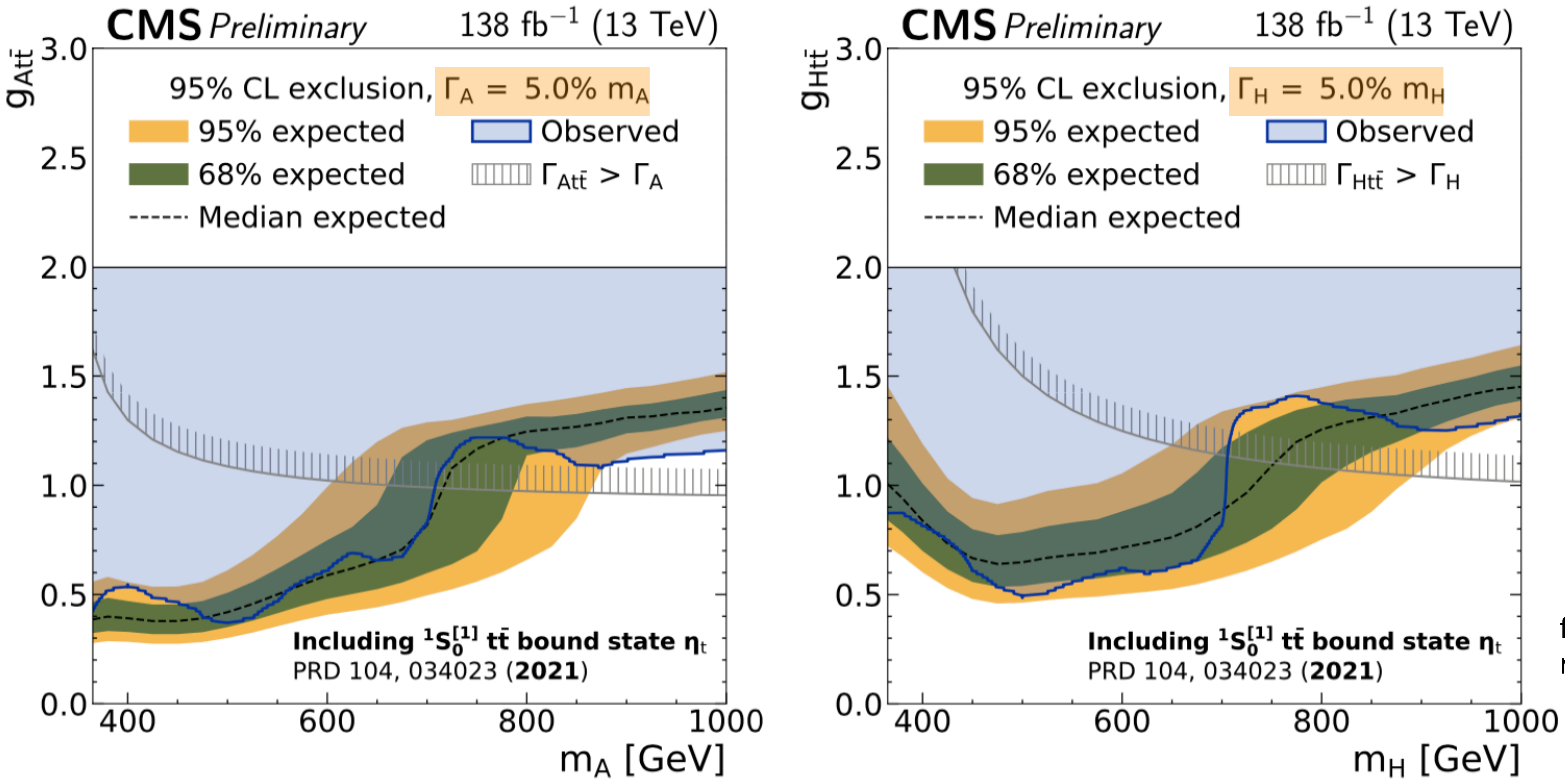
$$\sigma(\eta_t) = 7.1 \pm 0.8\,\mathrm{pb}$$



- agrees with NRQCD prediction: $\sigma(\eta_t)^{\mathrm{pred}} = 6.43\,\mathrm{pb}$ PRD 104 (2021) 034023

- CAUTION: this model is by far not a complete description of a $t\bar{t}$ bound state!
  - missing e.g. color-octet states, these are expected to be small, but e.g. very soft inital state gluons can change a color-octet state into a color-singlet one…
  - difficult to make quantitative statements
  - missing uncertainties

A/H limits including $t\bar{t}$ bound state in background



free-floating normalization

→ **since η_T looks similar as pseudoscalar A, no surprise that excess is no longer present**

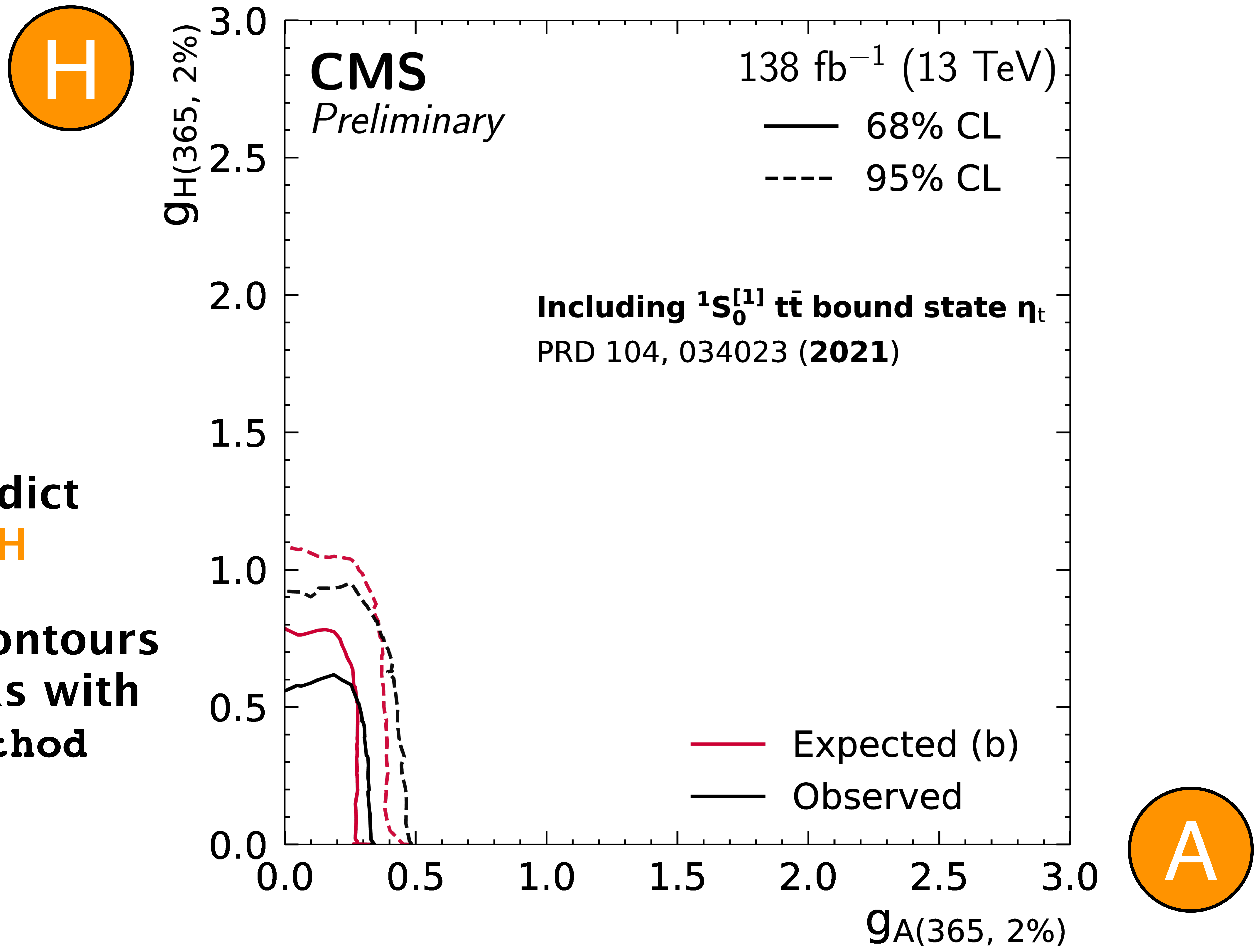
→ **most stringent limits to date!**

Search for A and H simultaneously

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

- model-independent exclusion contours for A vs H couplings to top quarks with `numerical Feldman-Cousins method`

→ stringent limits



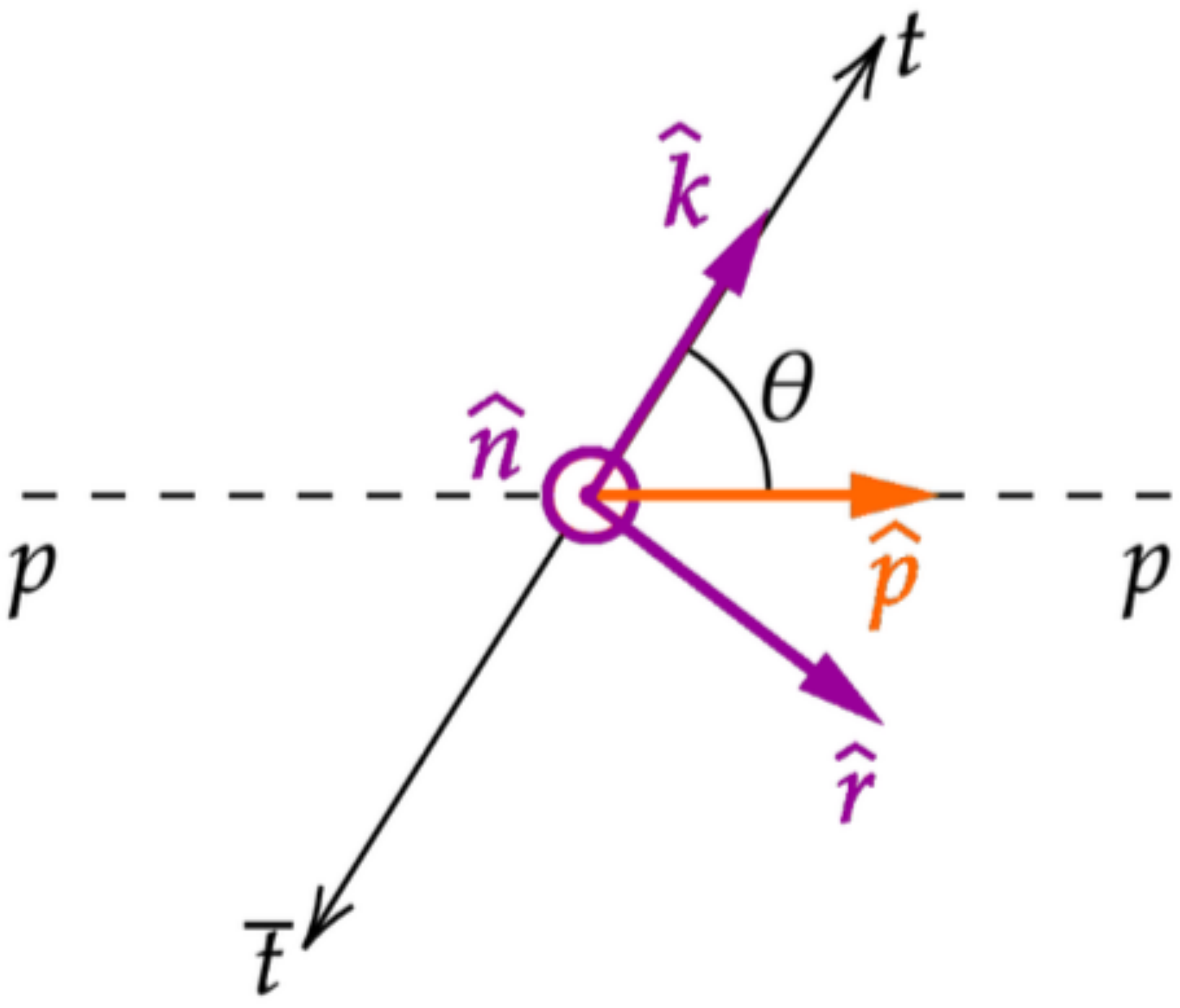
Backup

Definition of $c_{\rm hel}$ and $c_{\rm han}$

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

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

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



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

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

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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 normalisation

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

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

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

Electroweak corrections to top pair production

- 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

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

MadGraph

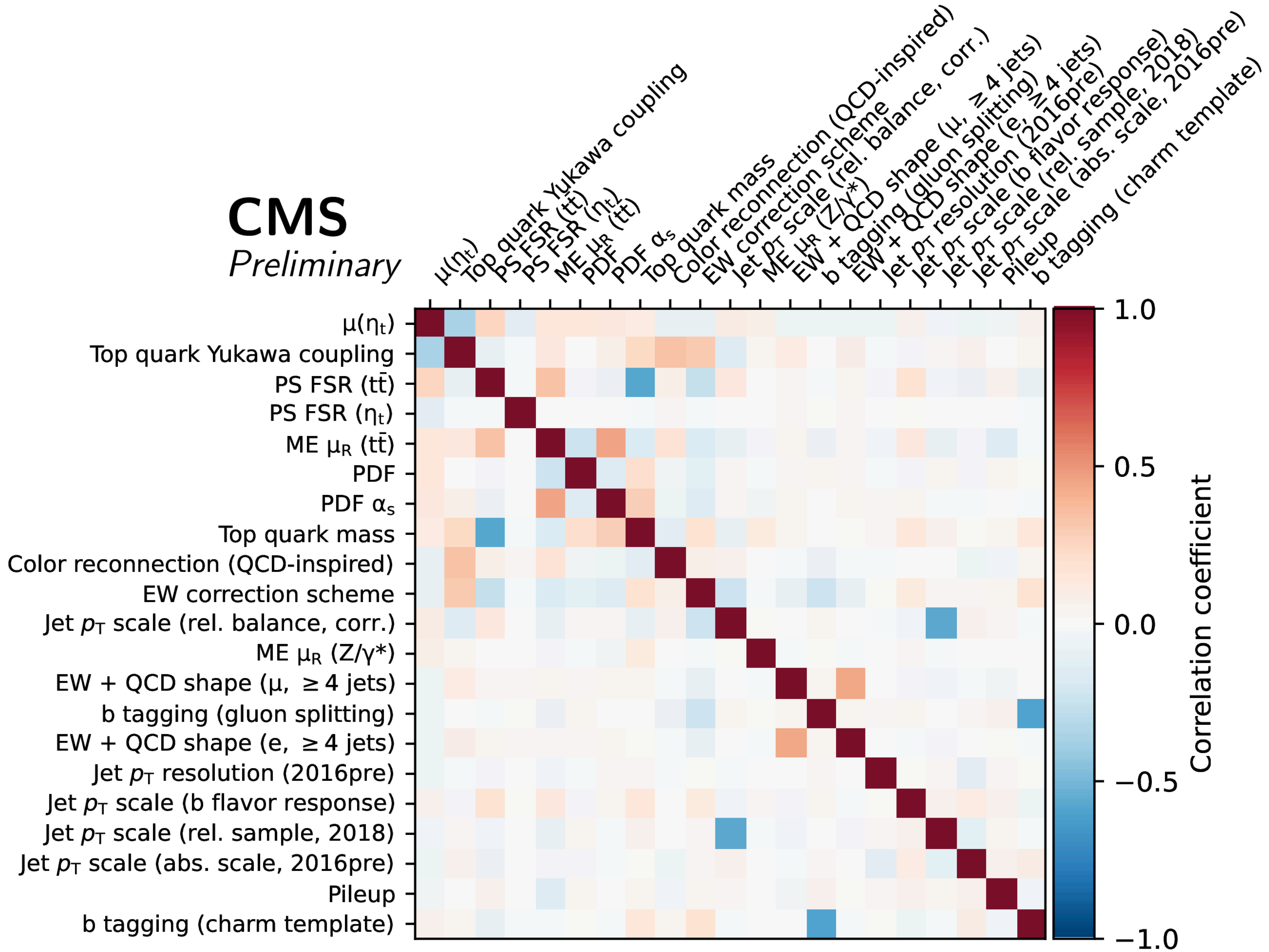
- Alternate choice: additive

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

- Difference treated as systematic uncertainty

Correlation matrix

- assess uncertainty modeling further through correlations of nuisance parameters η_t cross section dominated by background modeling



Systematic uncertainties – shape vs normalisation

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

Table 2: The systematic uncertainties considered in the analysis, indicating the number of corresponding nuisance parameters (if not one) in the statistical model, the type (affecting only normalization or also the shape of the search templates), and the affected processes and analysis channels they are applicable to.

Various sources of uncertainty affect the distributions of the observables used in this analysis, and are implemented as nuisance parameters in the binned maximum-likelihood fit described in Section 7. For each considered experimental and theoretical systematic effect, variations of the predicted signal and background distributions are evaluated. Uncertainties that affect only the normalization of a process are modeled using log-normal constraints as described in Section 4.2 of Ref. [90]. Gaussian constraints are imposed for all other uncertainties, which are referred to as shape uncertainties and can include a log-normal constrained variation of the overall normalization, by modifying the product of the event acceptance and the cross sections of the relevant processes. Unless stated otherwise, all uncertainties are evaluated on signal as well as background processes and treated as fully correlated among the processes, lepton channels, and analysis eras. The uncertainties are summarized in Table 2, and described in detail in the following.

Among the experimental uncertainty sources, those due to jet p_T scale and heavy-flavor jet tagging are important. In addition, MC statistical uncertainties, when grouped together, often outweigh every other individual uncertainty.

Systematic uncertainties – shape vs normalisation

The uncertainty in the jet p_T scale [35] is evaluated by varying the corresponding corrections within their uncertainties, resulting in a total of 17 nuisance parameters that correspond to the absolute and relative jet energy scales, calibration uncertainties in specific detector regions, p_T balance in dijet or Z/γ^* events used in the jet energy calibration, and flavor-dependent jet response split into one source for b quark jets and another for all other. Of these, 12 nuisance parameters affect individual analysis eras. The uncertainty in the jet p_T resolution measured in calibration data is propagated to the scale correction and smearing of the jet p_T resolution in simulation. An uncertainty in the unclustered component of p_T^{miss} is computed by shifting the energies of PF candidates not clustered into jets with $p_T > 15$ GeV according to the energy resolution for each type of PF candidate [42].

Uncertainties in the b tagging efficiency scale factors applied to simulated events are evaluated by varying them within their respective uncertainties [36], independently for heavy-flavor (b and c quarks) and other (light quarks and gluon) jets. We assign 20 nuisance parameters for the heavy-flavor jet scale factors that correspond to the parton shower (PS) modeling, the presence of leptons within the jet, the jet p_T scale, the number of pileup interactions, and differences between different scale factor estimation methods. Of these, 4 nuisance parameters affect individual analysis eras. For the light-flavor jet scale factors, 5 nuisance parameters are assigned, of which 4 affect individual analysis eras.

Uncertainties in the trigger, electron identification, and muon identification scale factors are considered [39, 41], including also effects from the isolation requirement and the track reconstruction at the trigger level. For the single-muon trigger and muon identification scale factors, each uncertainty component is further split into statistical components that are uncorrelated across analysis eras and a correlated systematic component. The effects of the inefficiency caused by the gradual shift in the timing of the inputs of the ECAL L1 trigger [29] are considered by assigning one nuisance parameter each to the 2016pre, 2016post, and 2017 analysis eras.

The effective inelastic proton-proton cross section used for pileup reweighting in the simulation is varied by 4.6% from its nominal value. Additionally, the uncertainty in the integrated luminosity amounts to 1.6% [21–23] and affects the normalization of all simulated processes, and is split into 7 nuisance parameters with different correlation assumptions between the analysis eras.

The prediction of the SM $t\bar{t}$ production is affected by various sources of theoretical uncertainty. The computation of the NLO EW correction, discussed in Section 3, depends on the value of the SM top quark Yukawa coupling through interference with diagrams containing virtual SM Higgs bosons. An uncertainty in the coupling is considered by varying its value by $1.00^{+0.11}_{-0.12}$, where the range is given by the experimental measurement reported in Ref. [91]. Furthermore, the uncertainty in the application scheme of the NLO EW corrections when combined with NNLO QCD corrections is considered by taking the difference between the multiplicative and additive approaches, as recommended in Ref. [67]. The uncertainty in m_t is considered by shifting its value in simulation by ± 3 GeV, and the induced variations are then rescaled by a factor of 1/3 to emulate a more realistic top quark mass uncertainty of 1 GeV [92]. The effect of the choice of μ_R and μ_F in the ME calculation is evaluated by varying these scales independently by a factor of 2 and 1/2. The effects of the m_t, μ_R, and μ_F variations on the acceptance and shape of the search templates are considered at NLO accuracy, while the effects on the overall SM $t\bar{t}$ normalization is considered at NNLO+NNLL accuracy [62, 93]. Decoupling the theoretical nuisance parameters based on their effects—one each for the acceptance and shape, and one additional parameter for the overall SM $t\bar{t}$ normalization—does not alter the conclusions of this analysis.

The scales used to evaluate α_S in the PS simulation of initial- and final-state radiation (ISR and FSR) are also varied independently by a factor of 2 in each direction. The effect of the uncertainties in the underlying event tune is estimated by varying the parameters of the CP5 underlying event tune [47]. Two uncertainties are assigned for the color reconnection model, with one based on the "QCD-inspired" model [94], and the other by switching on the early resonance decay option in PYTHIA 8.240 [95].

Systematic uncertainties – shape vs normalisation

The uncertainty in the matching scale between the ME and the PS is evaluated by varying the POWHEG parameter h_{damp}, which controls the suppression of radiation of additional high-p_{T} jets. The nominal value of h_{damp} in the simulation and its variations are $1.58^{+0.66}_{-0.59}\, m_{\mathrm{t}}$ [96]. The uncertainty arising from the choice of the PDF set is evaluated by reweighting the simulated $\mathrm{t\bar{t}}$ events using 100 replicas of the NNPDF3.1 set. A principal component analysis is performed on the variations from the PDF replicas to construct base variations in the space of the predicted event yields in each bin of the search templates, from which the one with the largest eigenvalue is used as the PDF uncertainty. The second largest eigenvalue is found to be almost two orders of magnitude smaller than the largest one, thus the base variations corresponding to it and smaller eigenvalues are not considered. The uncertainty in the α_{S} parameter used in the PDF set forms a second independent PDF variation uncertainty.

The μ_{R} and μ_{F} scale uncertainties in the Φ signal simulation are treated independently for the resonance and interference components. Compared to the alternative of varying the scales for the two components simultaneously, we found this to be the more conservative option. The effect on the acceptance and shapes of the search templates is considered at LO accuracy, while the effect on signal cross section is considered at NNLO accuracy. The scales used in the PS simulation of ISR and FSR are also varied independently by a factor of 2 in each direction and are treated independently for the resonant and interference components.

The uncertainty in m_{t} for the signal is considered by varying its value in simulation by ± 1 GeV. Its effect on acceptance, shape, and cross section is considered in the same way as μ_{R} and μ_{F} variations. Given that this is a variation on the same physical parameter, it is treated as fully correlated across all signal and background processes. Other theoretical uncertainties in the signal, such as the PDF, are neglected as they are small compared to those already considered.

The η_{t} signal simulation considers μ_{F}, ISR, FSR, and m_{t} uncertainties, affecting only acceptance and shape. They are handled identically to the corresponding variations in the Φ signal simulation, except for the absence of variations on the overall normalization, which is always taken to be freely floating in this analysis. Since the used model describes effective η_{t} production via a contact interaction, without the emission of extra partons at the LO ME level, the model encodes no dependence on α_{S}. Therefore, μ_{R} variations have no effect on the η_{t} prediction.

The μ_{R}, μ_{F}, ISR, and FSR scale uncertainties are also independently considered for the Z/γ^* and single top quark production processes. For these processes, the μ_{R} and μ_{F} uncertainties affect only acceptance and shape, not normalization.

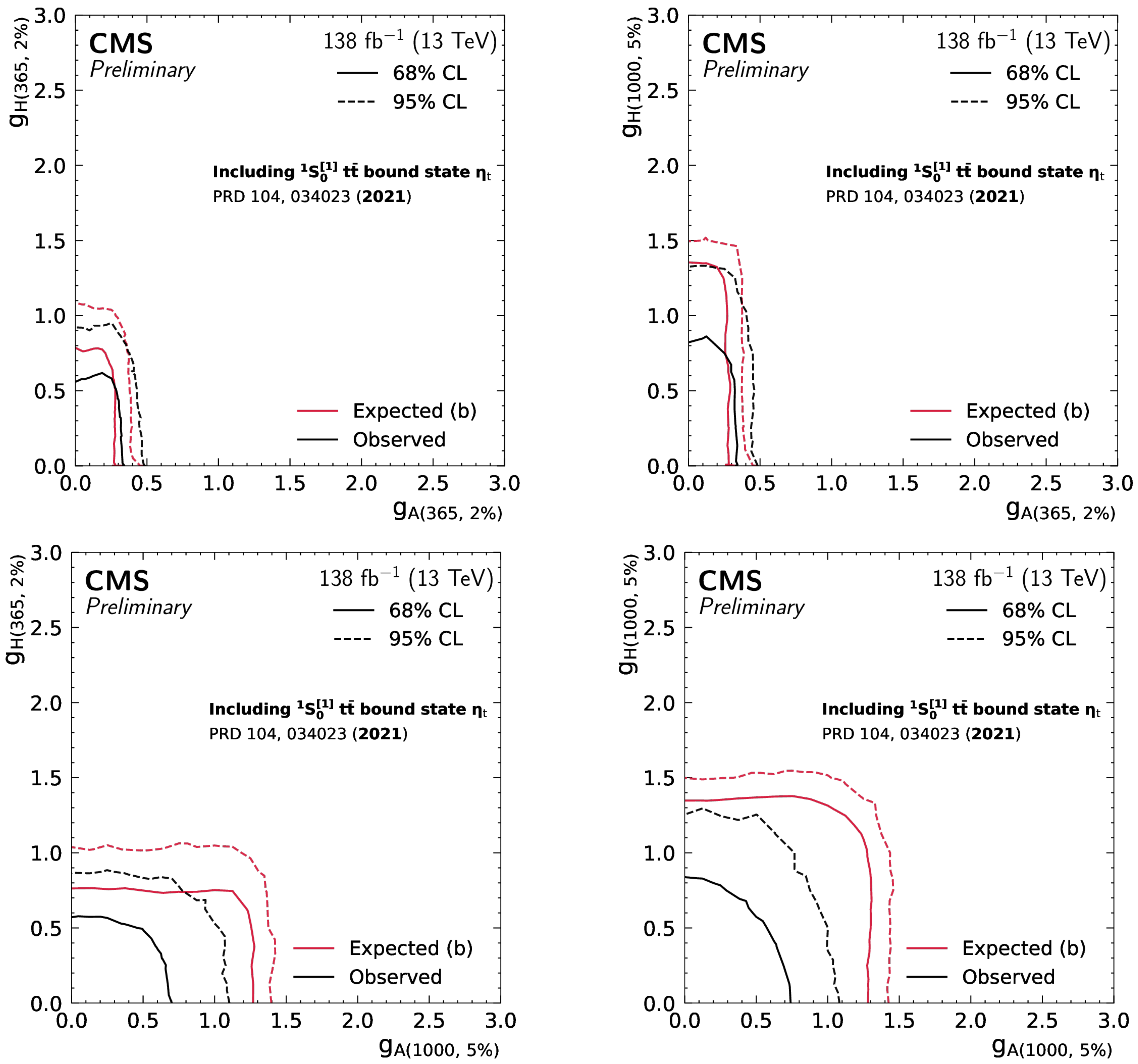
The expected yields for most of the non-$\mathrm{t\bar{t}}$ background processes are derived using theoretical predictions for the cross sections at NLO or higher accuracy. The uncertainties assumed in the normalization of these processes are conservative and always exceed those of the corresponding theoretical computations. For single top quark production, we assign an uncertainty of 15%, based on relevant cross section measurements [97–99]. In the single-lepton channels, the normalization uncertainty of the EW+QCD background estimate evaluated from control samples in data is taken to be 50%, and shape uncertainties as described in Section 4 are considered as well. The uncertainties corresponding to the change in shape induced by varying the b tagging requirements are considered separately for the single-lepton channels, but correlated across analysis eras. Statistical uncertainties in the $\mathrm{t\bar{t}}$ and single top quark subtraction are considered separately for each channel and era. In the $\ell\bar{\ell}$ channels, the uncertainty in the $\mathrm{t\bar{t}V}$ production is taken to be 30% [100, 101]. The uncertainty of the Z/γ^* production is taken to be 5% [102]. To account for the fact that this search probes a restricted region of the phase space of the corresponding processes, we assign a normalization uncertainty of 30% for diboson production, which has little impact on the overall sensitivity due to the small contribution of these processes.

The nominal background prediction is affected by the limited size of the simulated MC event samples. This statistical uncertainty is evaluated using the "light" Barlow–Beeston method [103], by introducing one additional nuisance parameter for every bin of the search distributions. These parameters are uncorrelated across all channels and analysis eras.
Several systematic variations, most notably those constructed from dedicated MC samples, are affected by statistical fluctuations. We suppress these fluctuations with the smoothing procedure described in Ref. [24].

In general, the relative importance of different systematic uncertainties depends greatly on the signal hypothesis, especially the mass of the scalar bosons. Close to the $\mathrm{t\bar{t}}$ production threshold, the variations in the value of the top quark Yukawa coupling and m_{t} become important, while for larger m_{Φ} the PDF, μ_{R}, and μ_{F} variations in the SM $\mathrm{t\bar{t}}$ background become dominant.

Search for A and H simultaneously: more scenarios

H



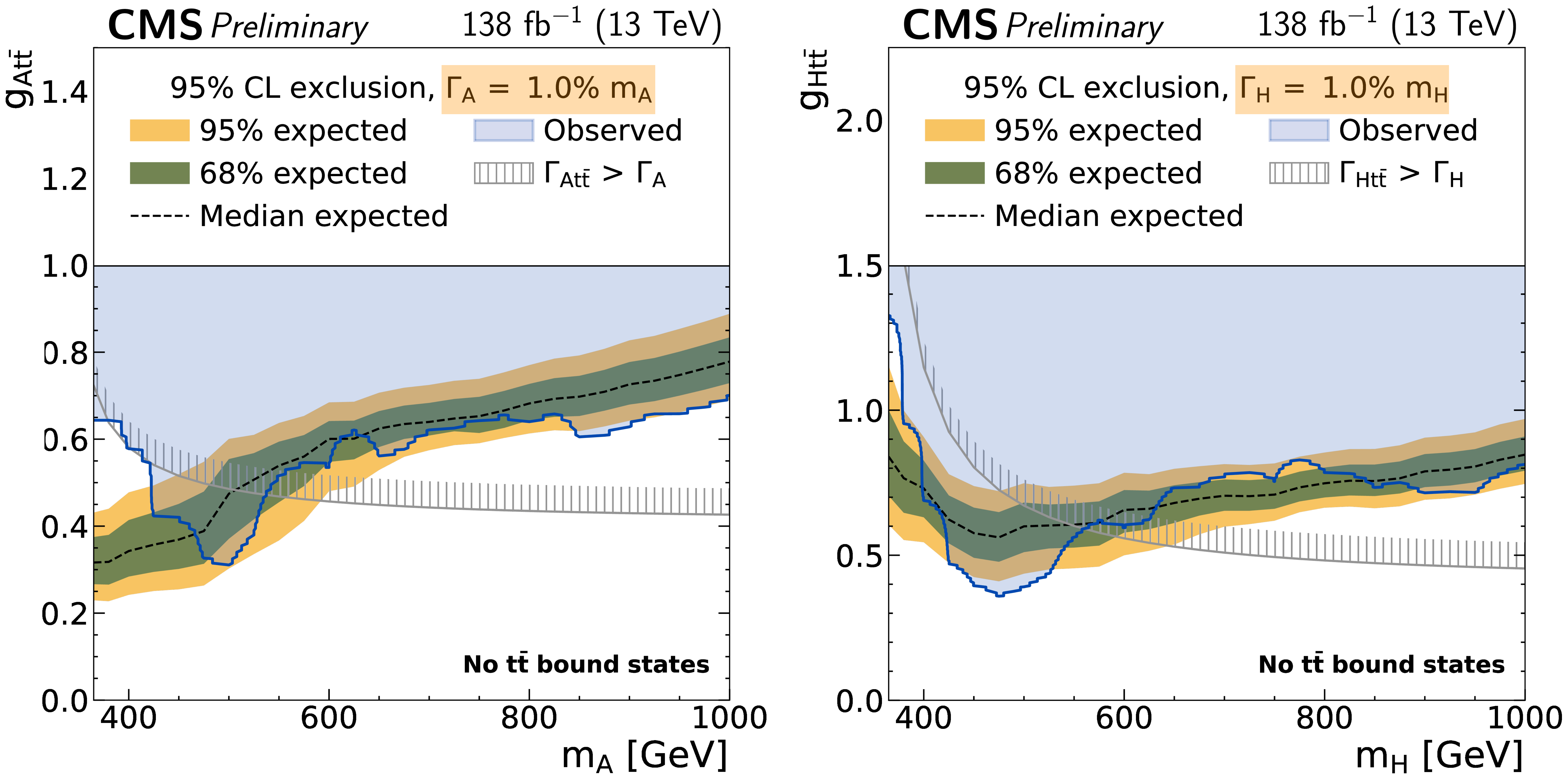
A

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

- **model-independent exclusion contours for A vs H couplings to top quarks with `numerical Feldman-Cousings method`**

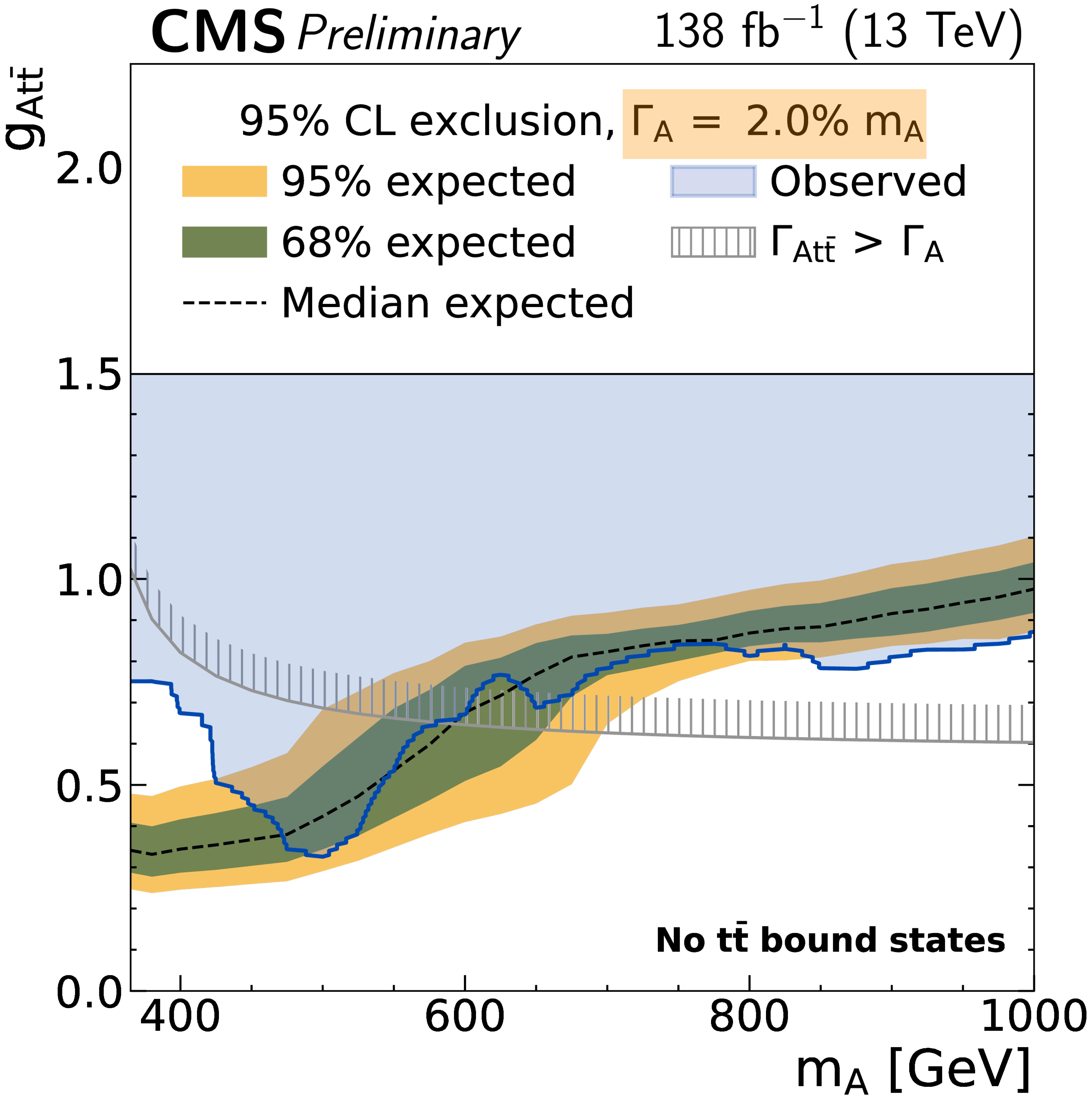
→ **stringent limits**

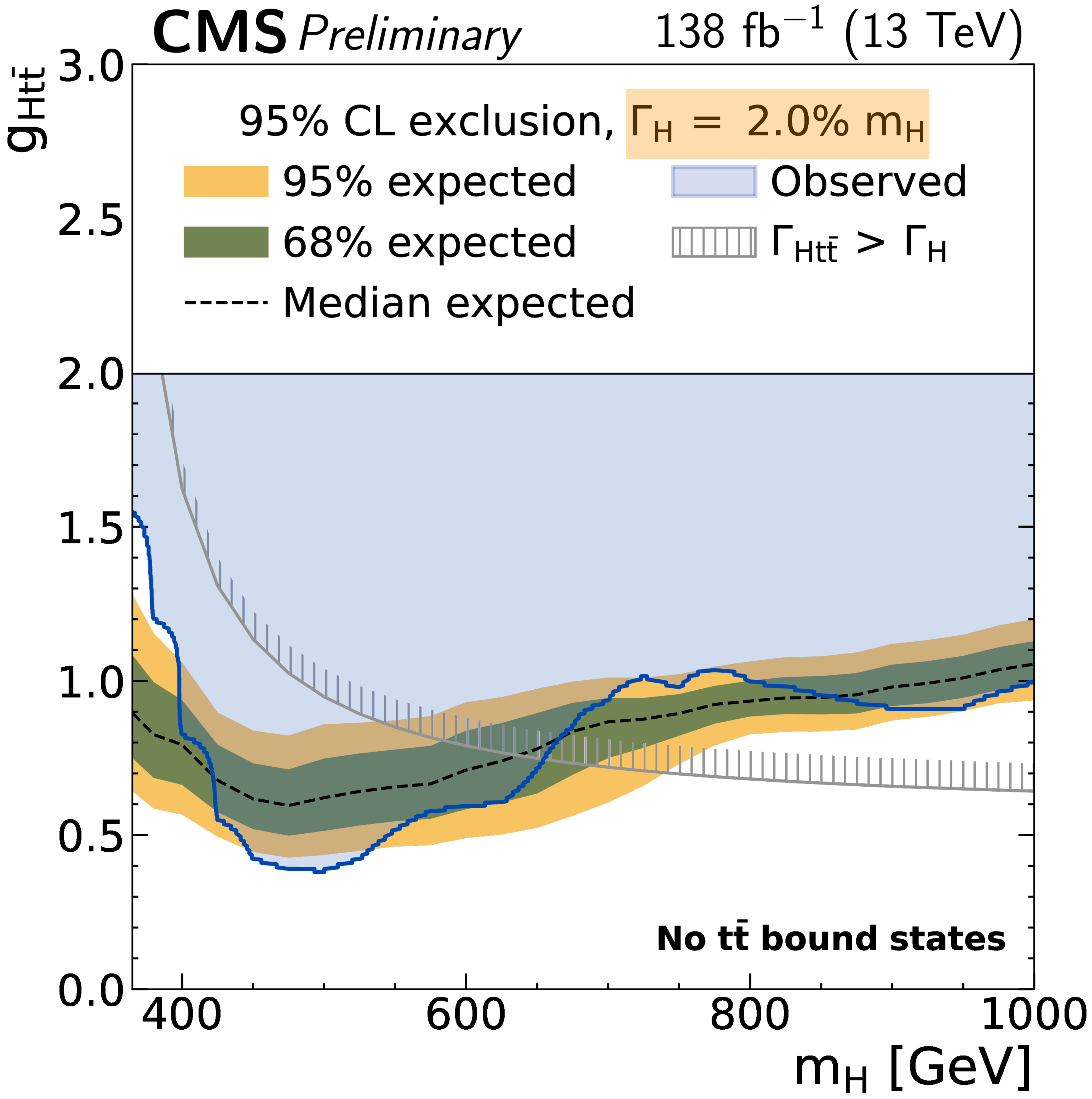
Limits for 1% width: A/H interpretation



→ **excess at low $m_{t\bar{t}}$ is reflected at low A/H masses, but stronger for pseudoscalar A**

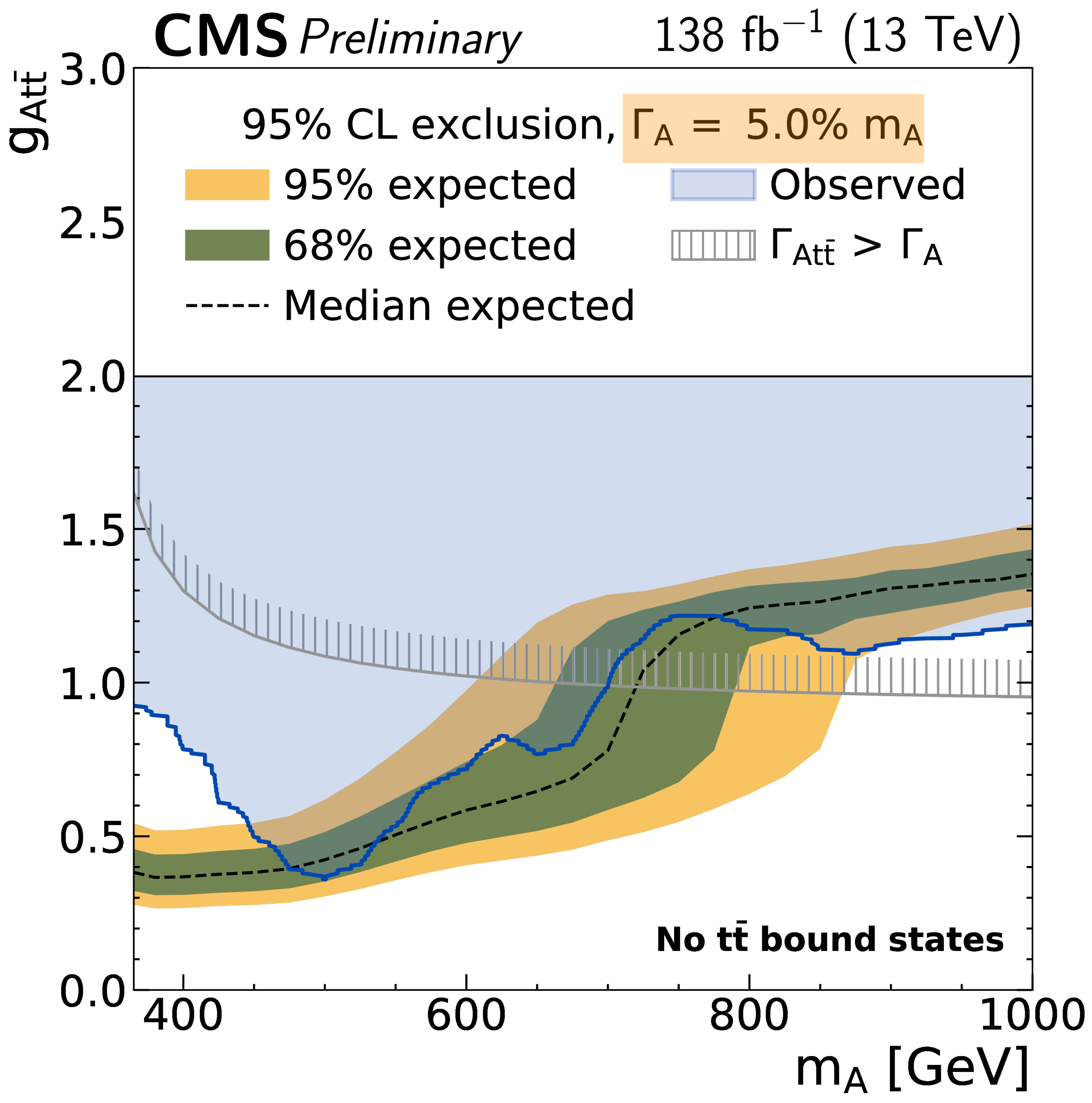
Limits for 2% width: A/H interpretation

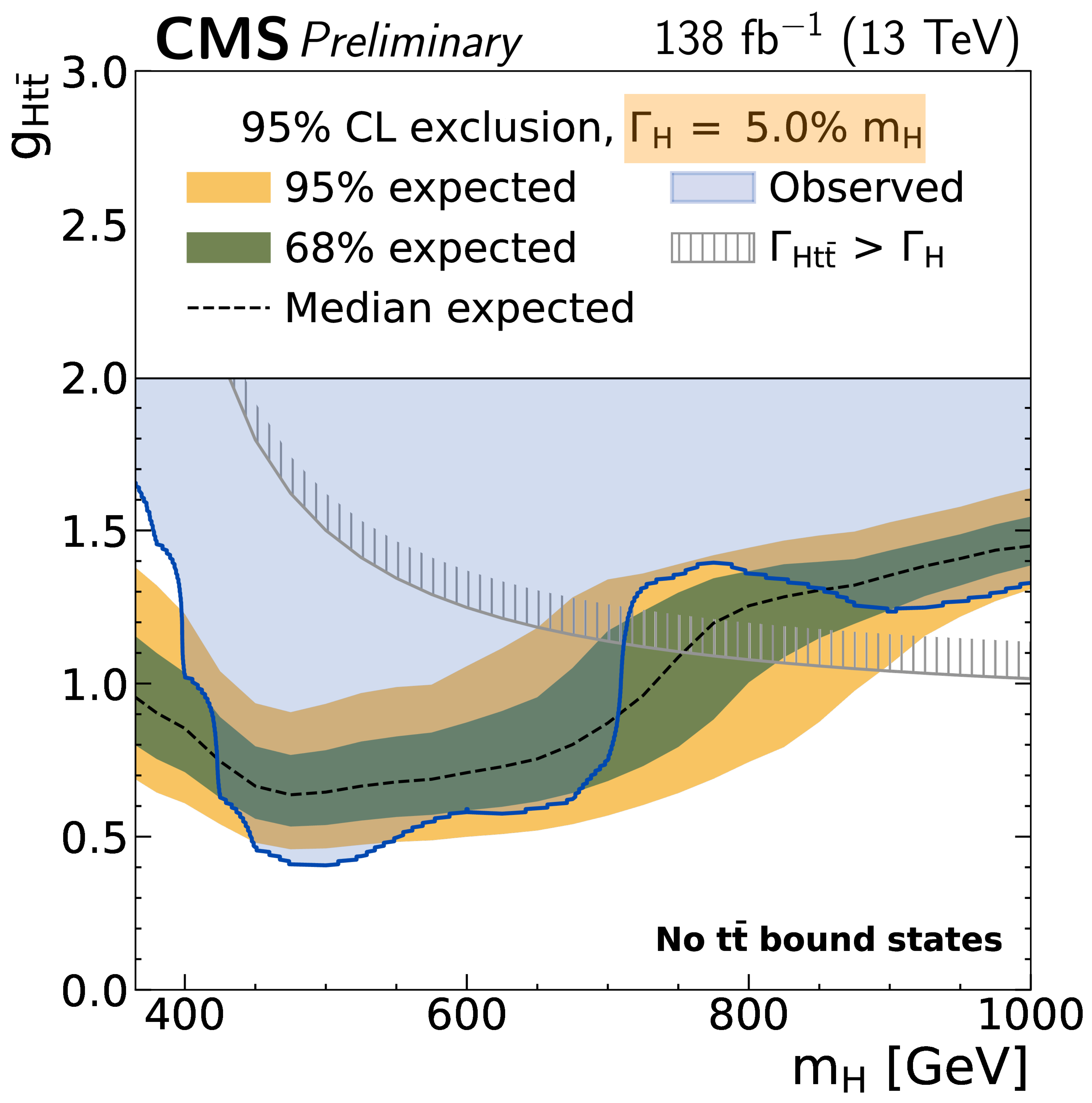




→ excess at low $m_{t\bar{t}}$ is reflected at low A/H masses, but stronger for pseudoscalar A

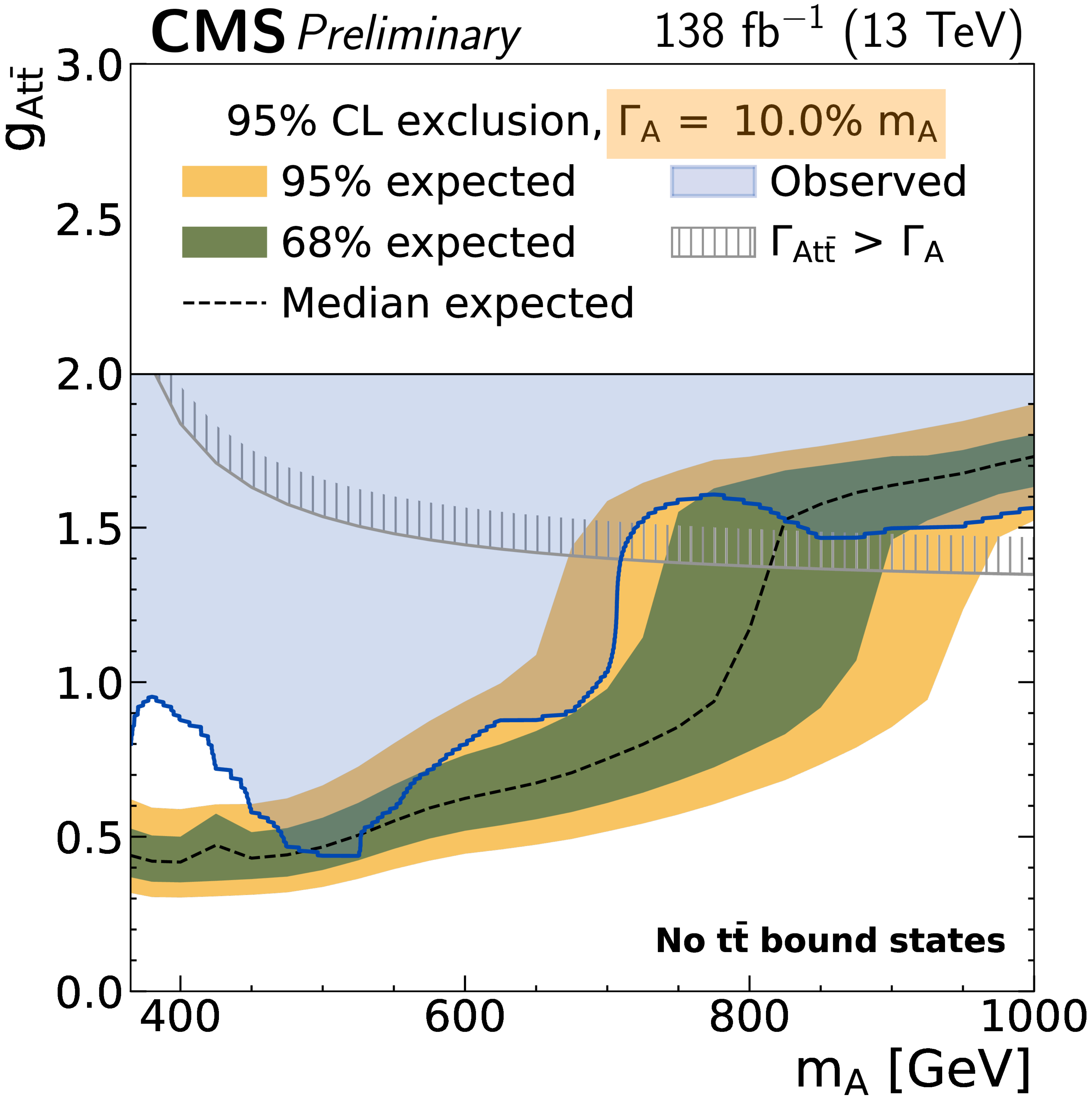
Limits for 5% width: A/H interpretation

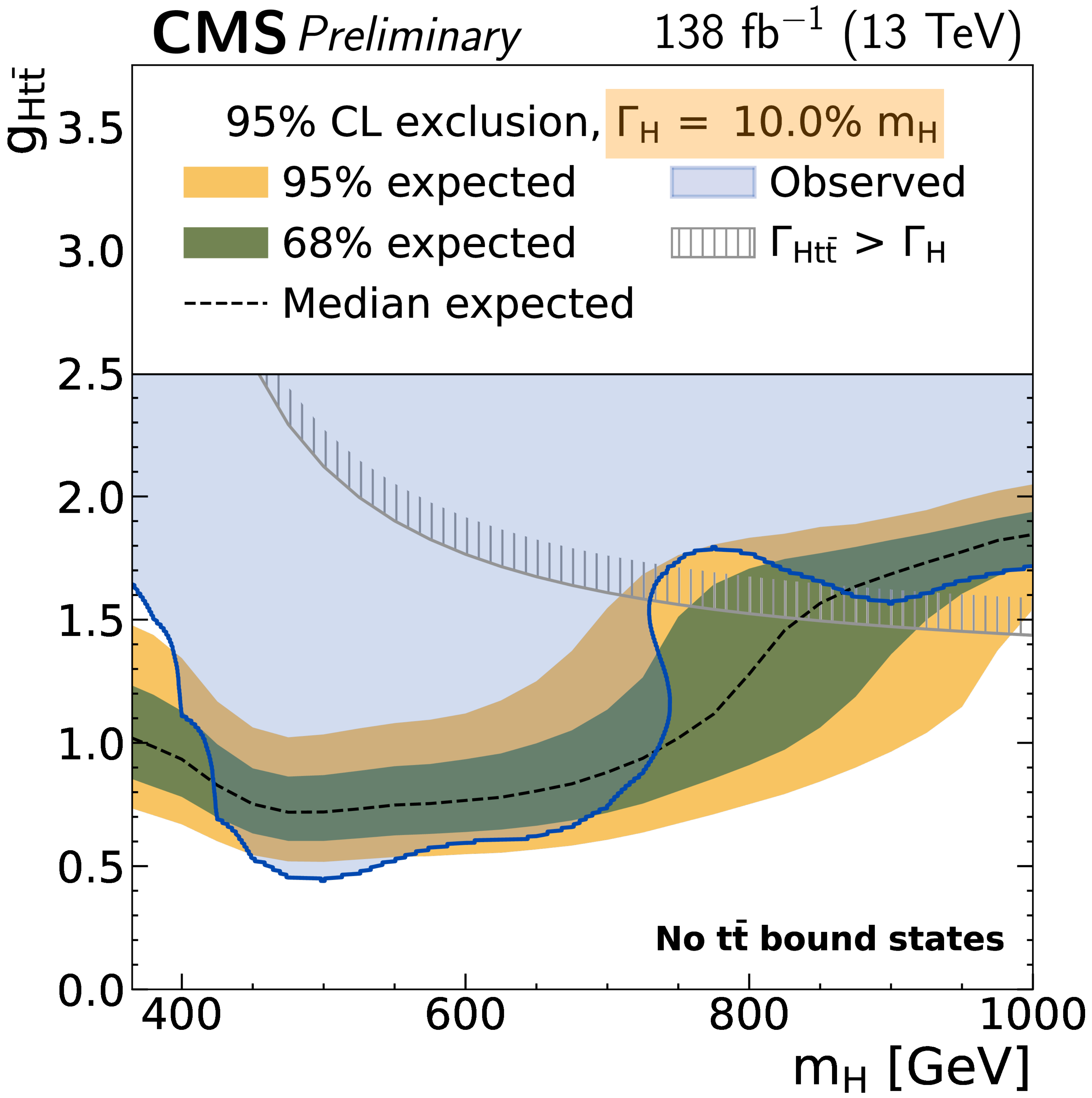




→ excess at low $m_{t\bar{t}}$ is reflected at low A/H masses, but stronger for pseudoscalar A

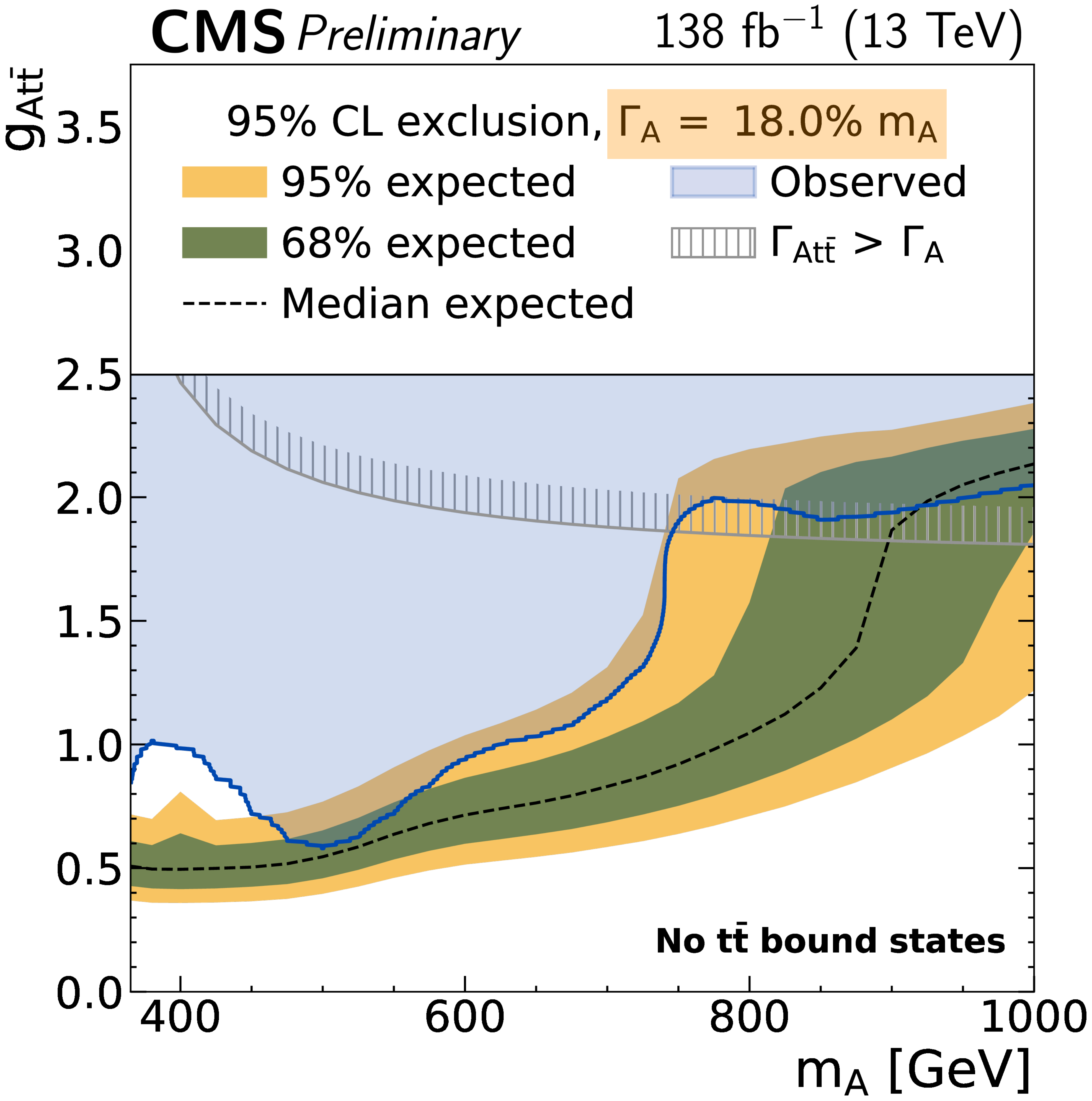
Limits for 10% width: A/H interpretation

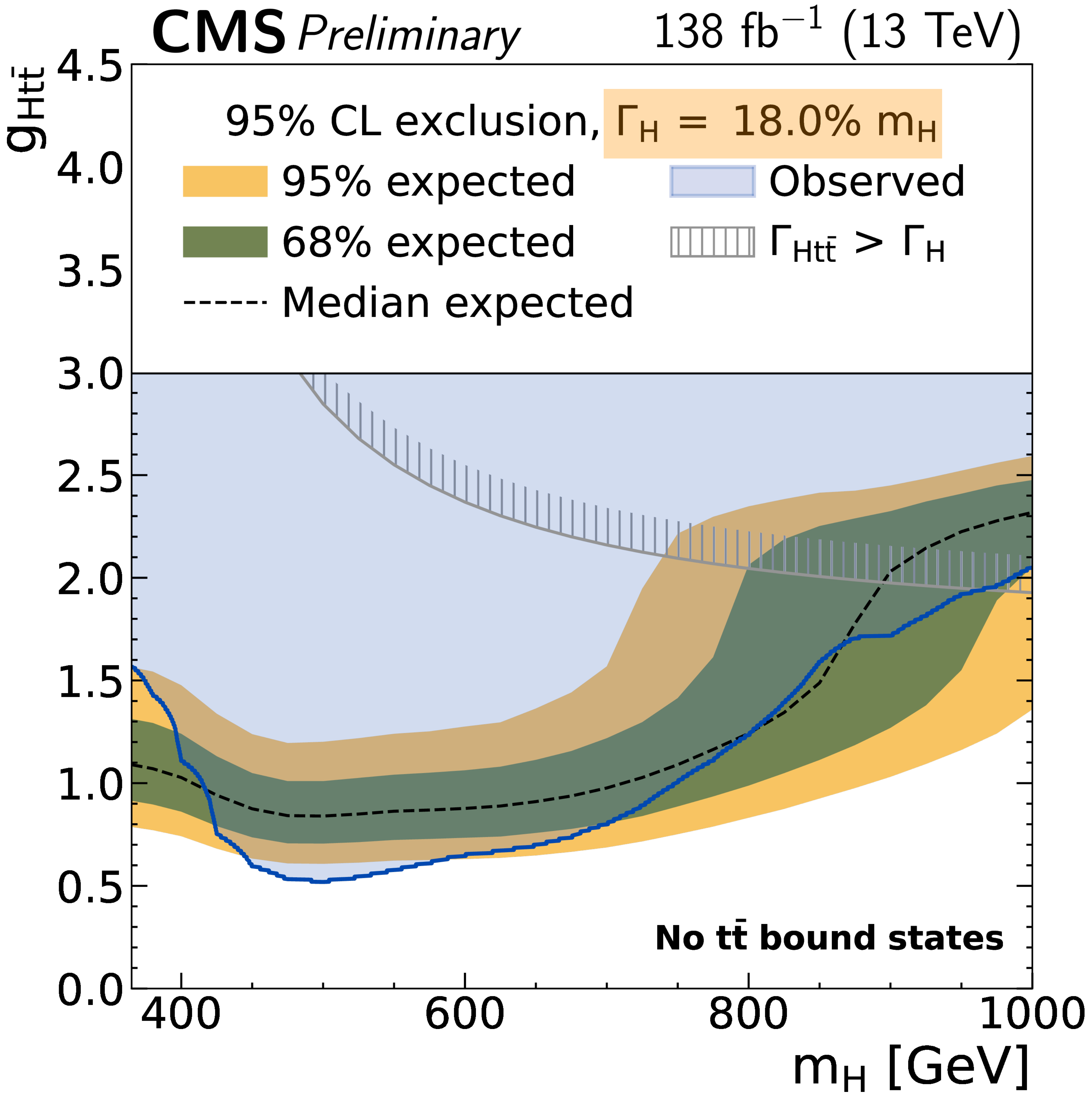




→ excess at low $m_{t\bar{t}}$ is reflected at low A/H masses, but stronger for pseudoscalar A

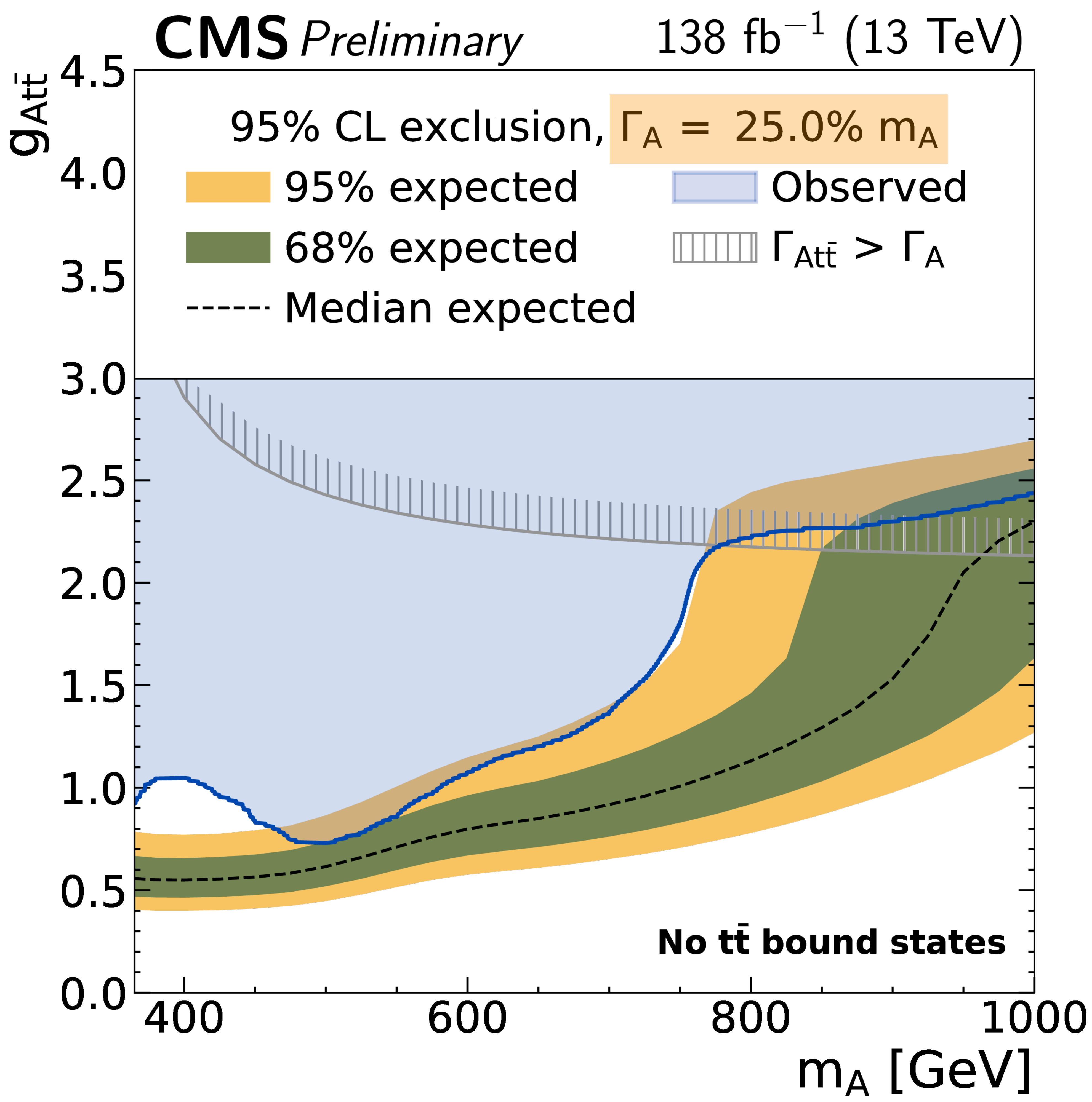
Limits for 18% width: A/H interpretation

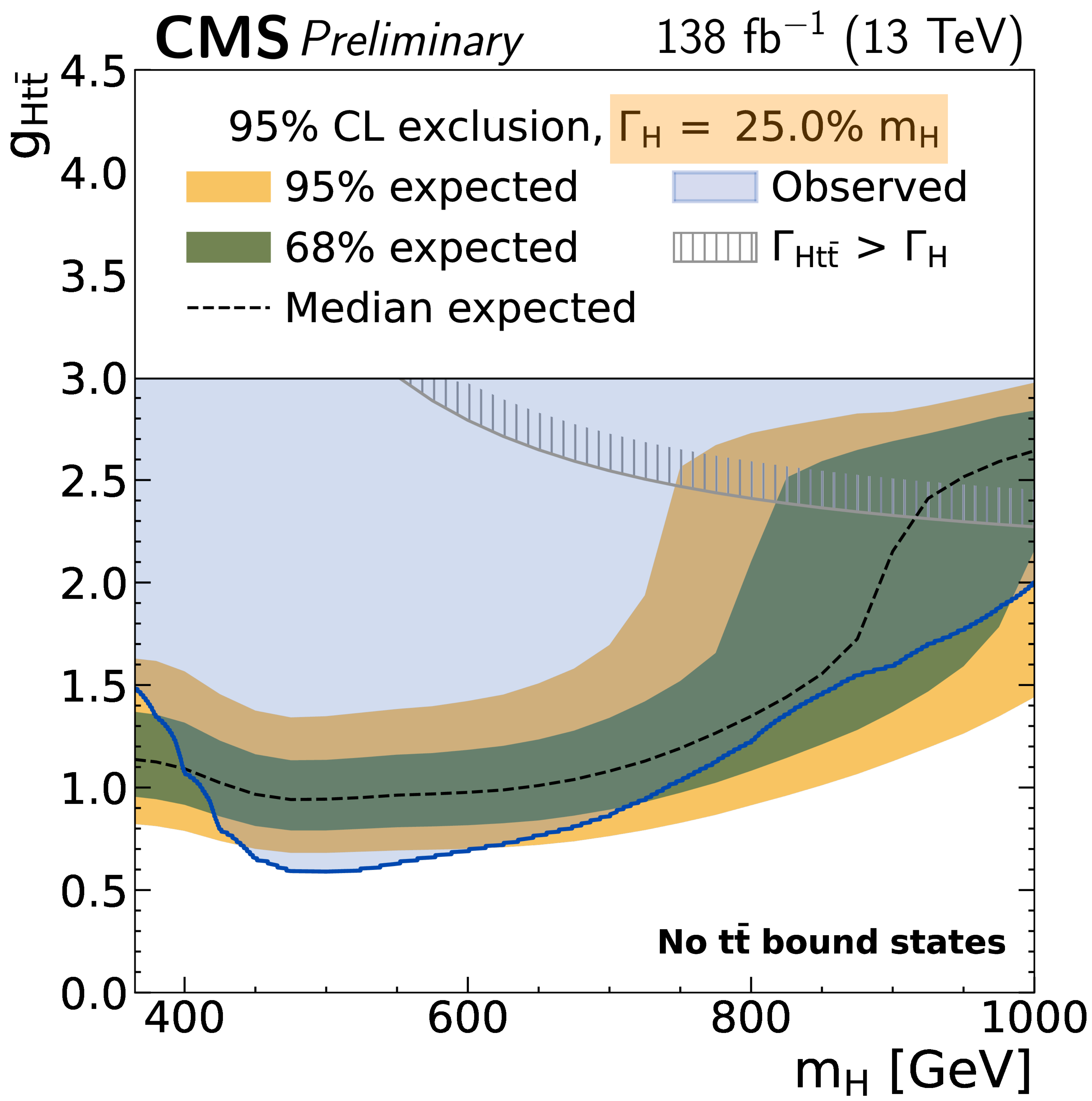




→ excess at low $m_{t\bar{t}}$ is reflected at low A/H masses, but stronger for pseudoscalar A

Limits for 25% width: A/H interpretation

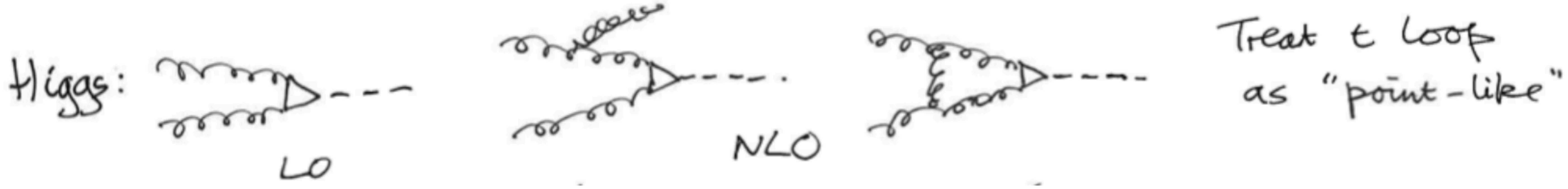




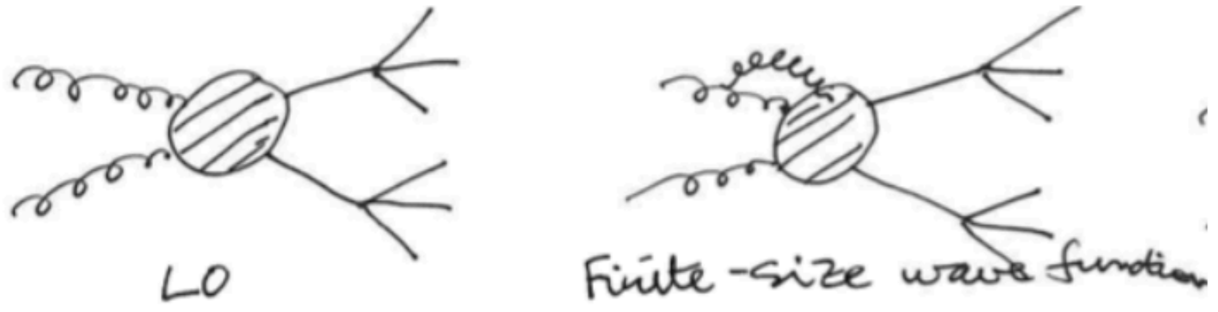
→ excess at low $m_{t\bar{t}}$ is reflected at low A/H masses, but stronger for pseudoscalar A

Toponium production at the LHC

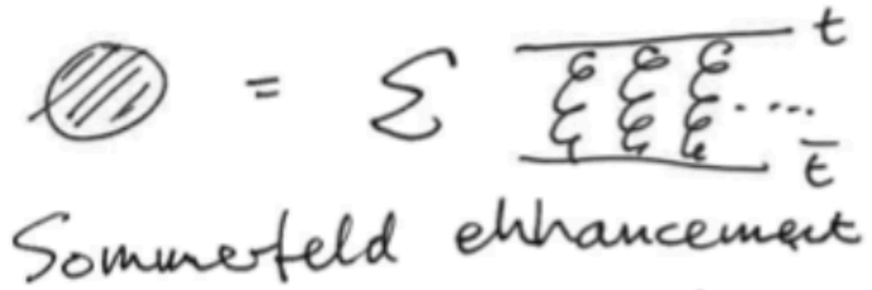
More complicated than Higgs production:



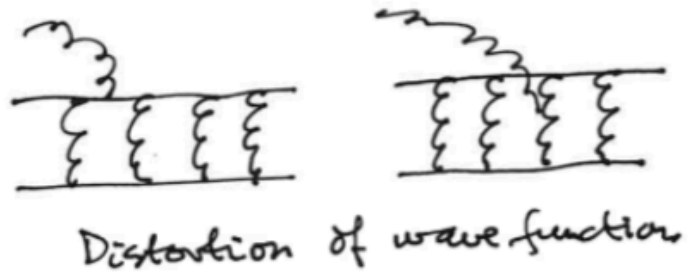
"Small" top loop replaced by "blob" of size $\sim 1/(M_t \alpha_s)$



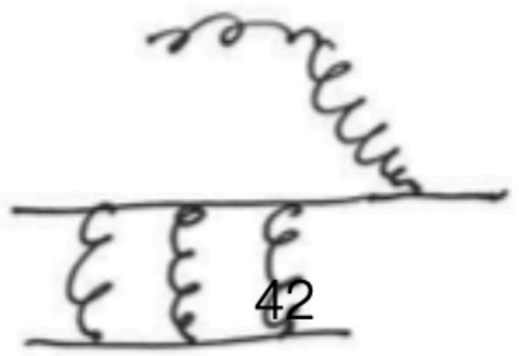
Sommerfeld enhancement of cross section close to $t\bar{t}$ threshold



Distorted by gluon interactions

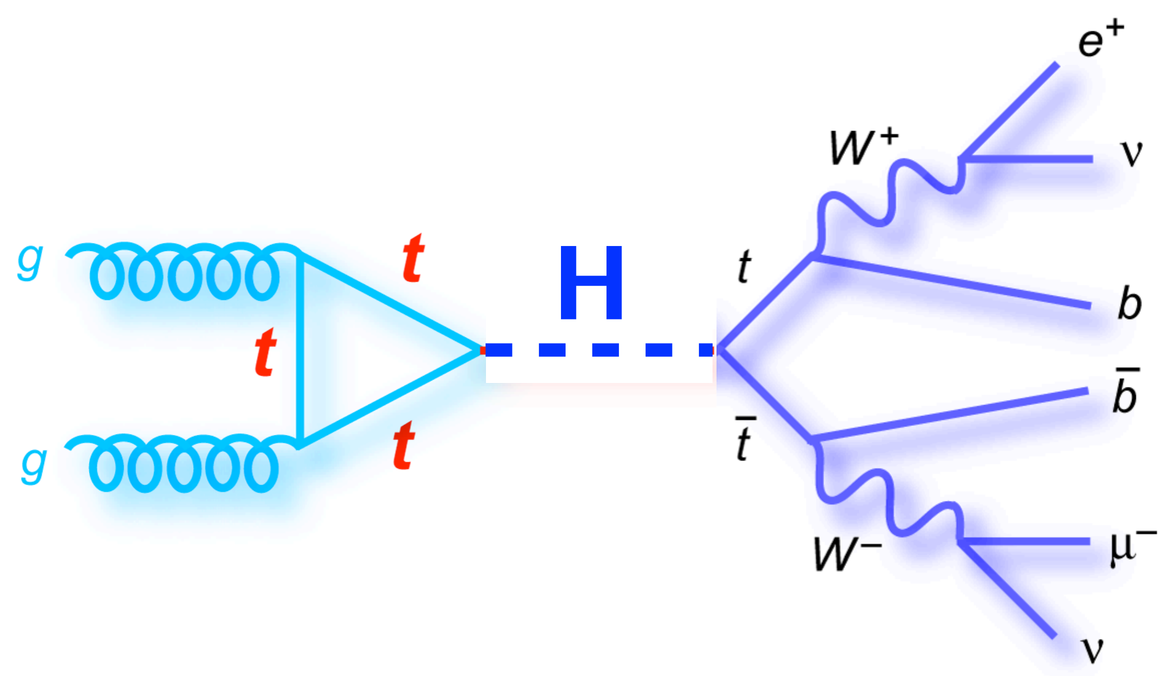


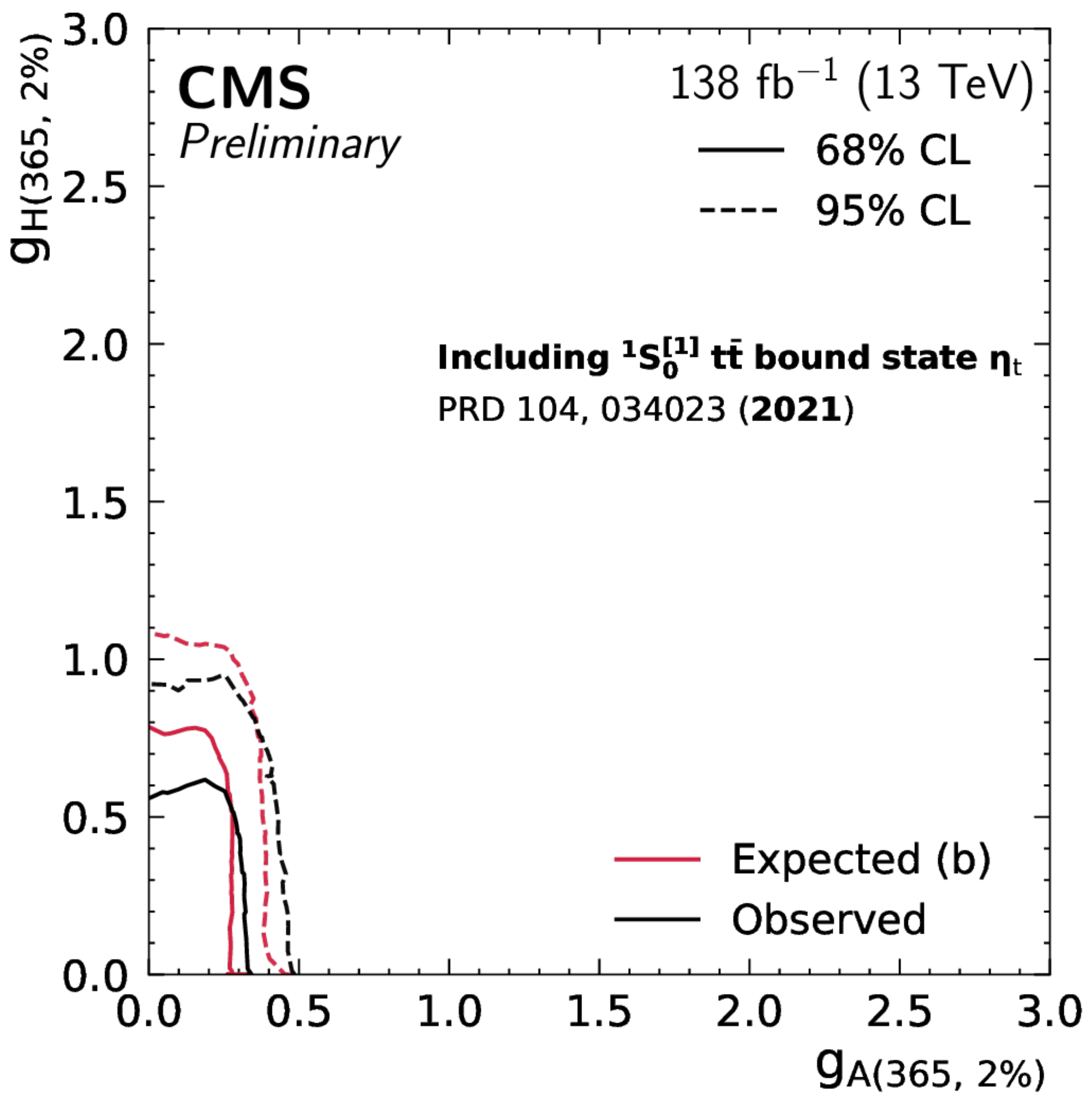
$t\bar{t}$ off-shell, unstable, gluon interactions

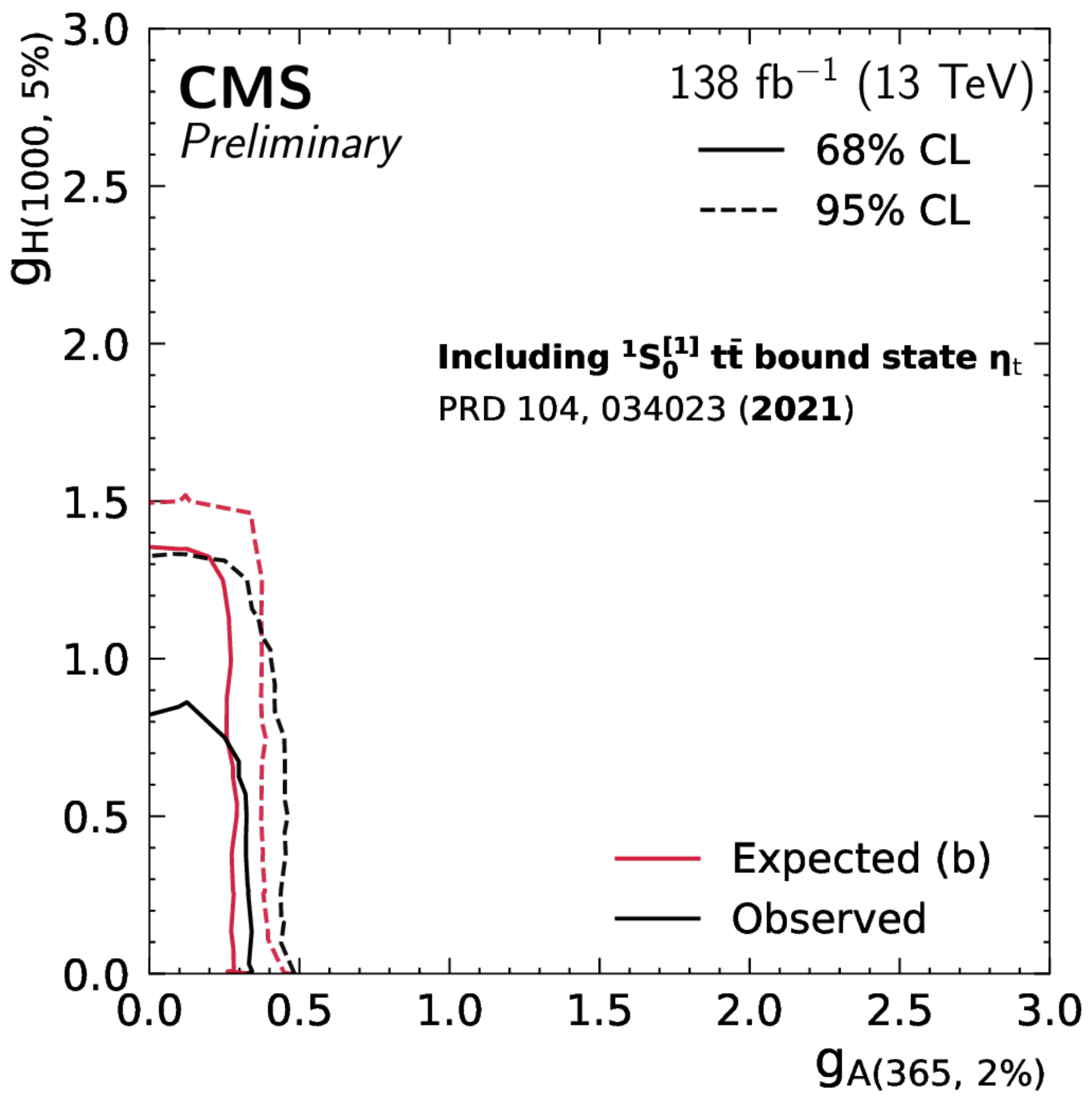


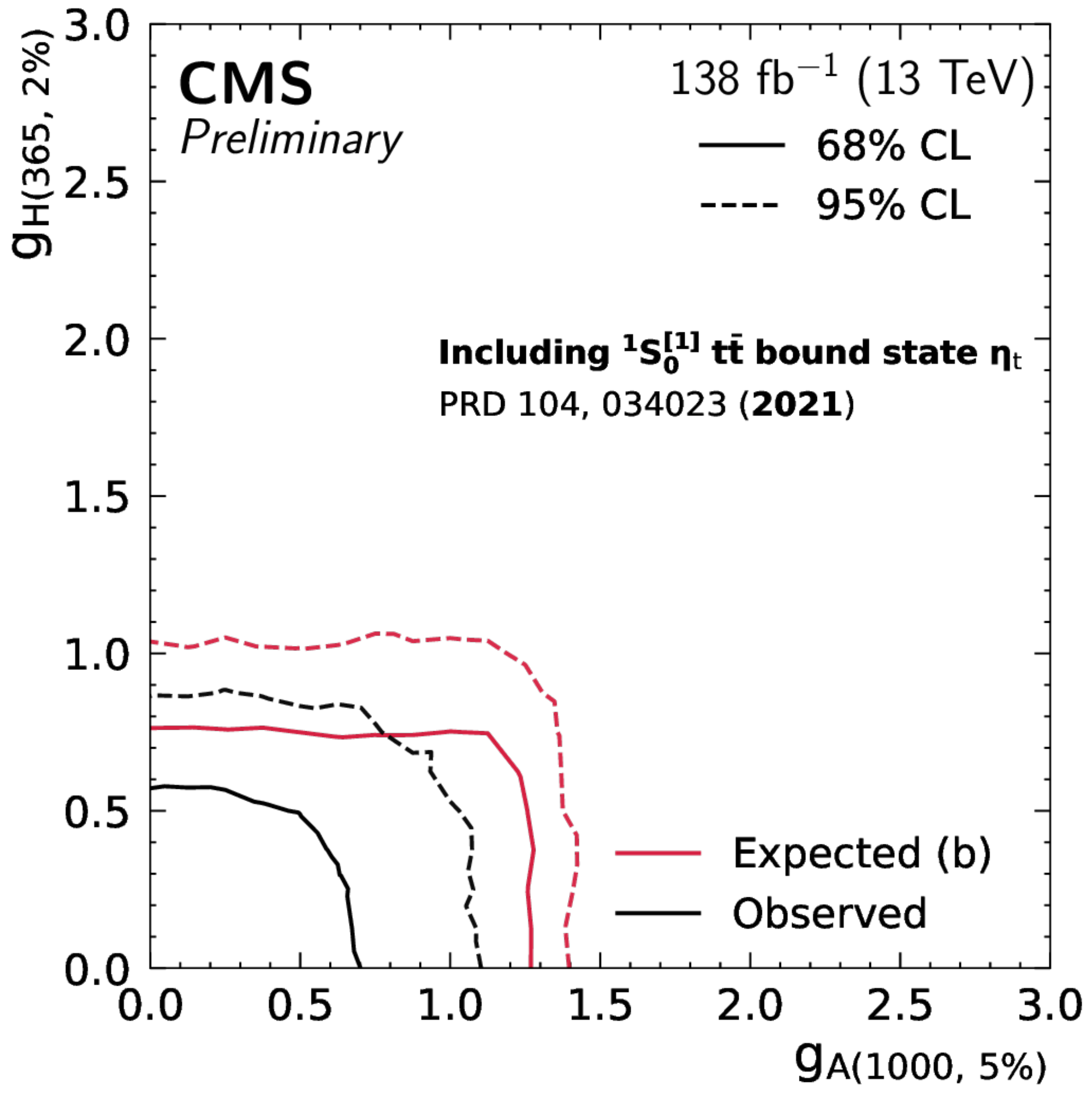
John Ellis

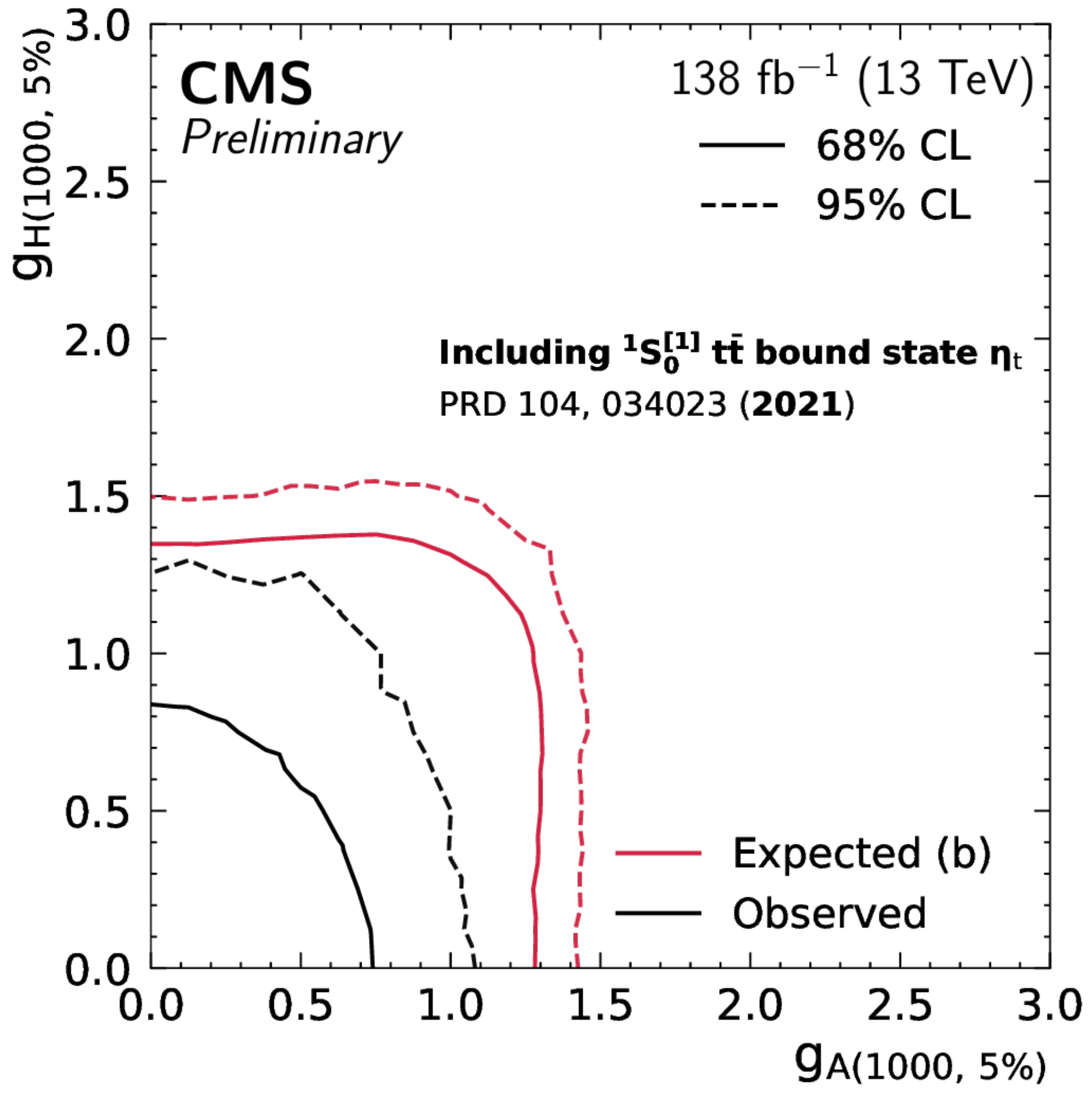
Results of A+H interpretation – Combination

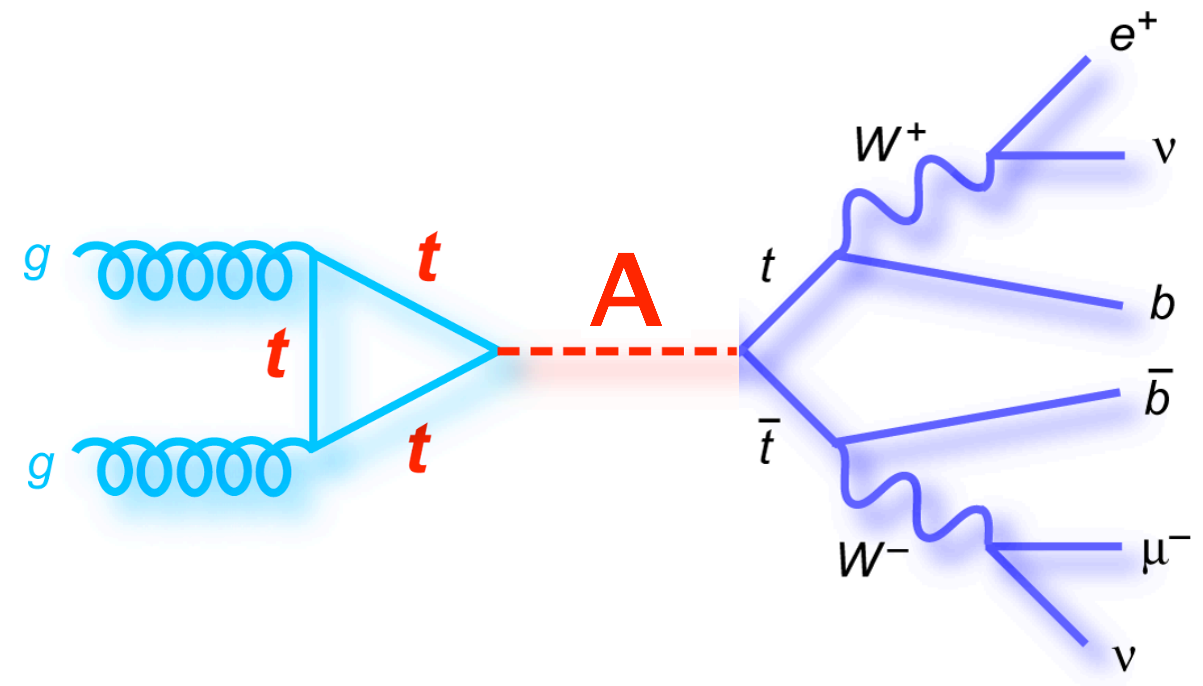






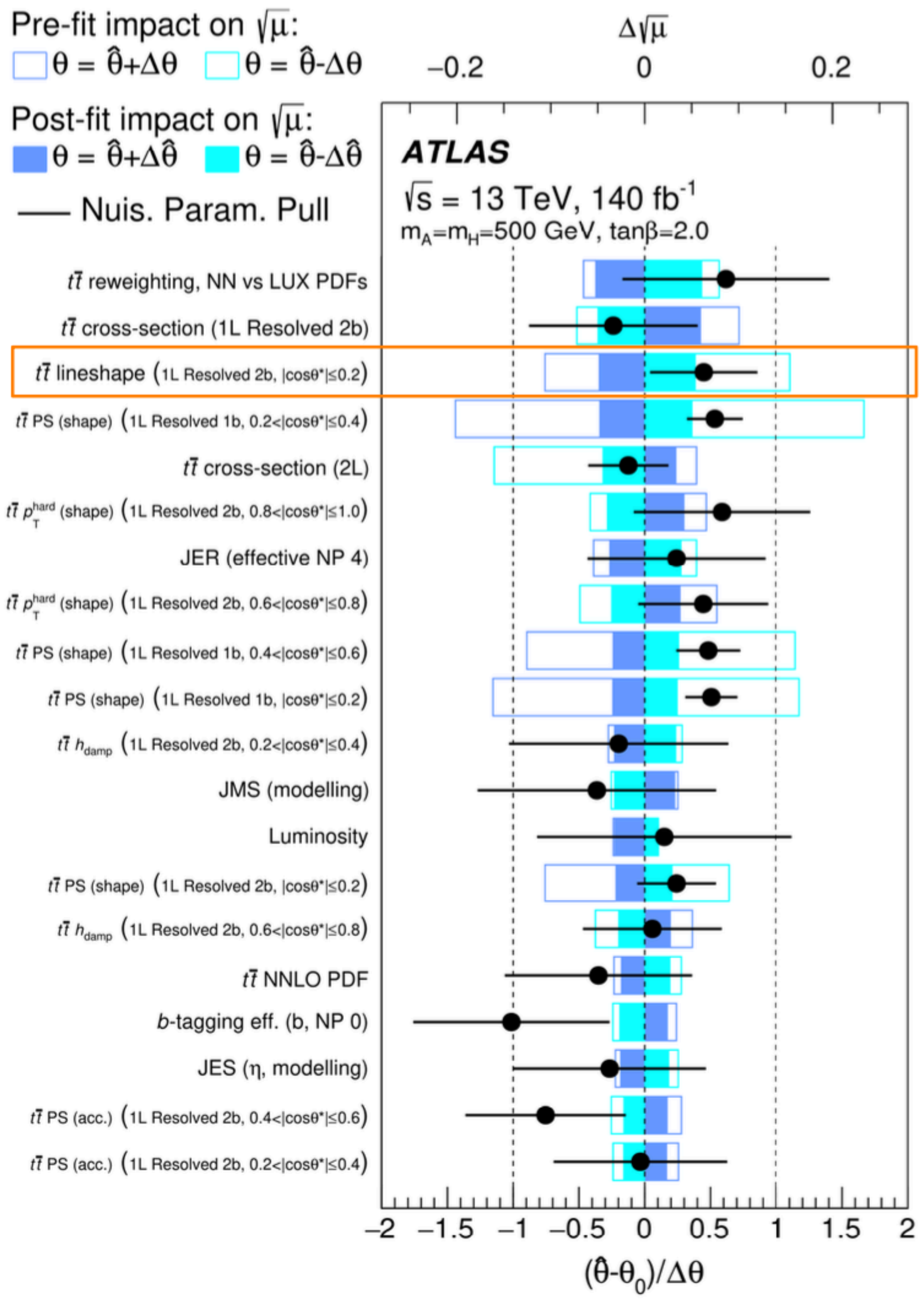




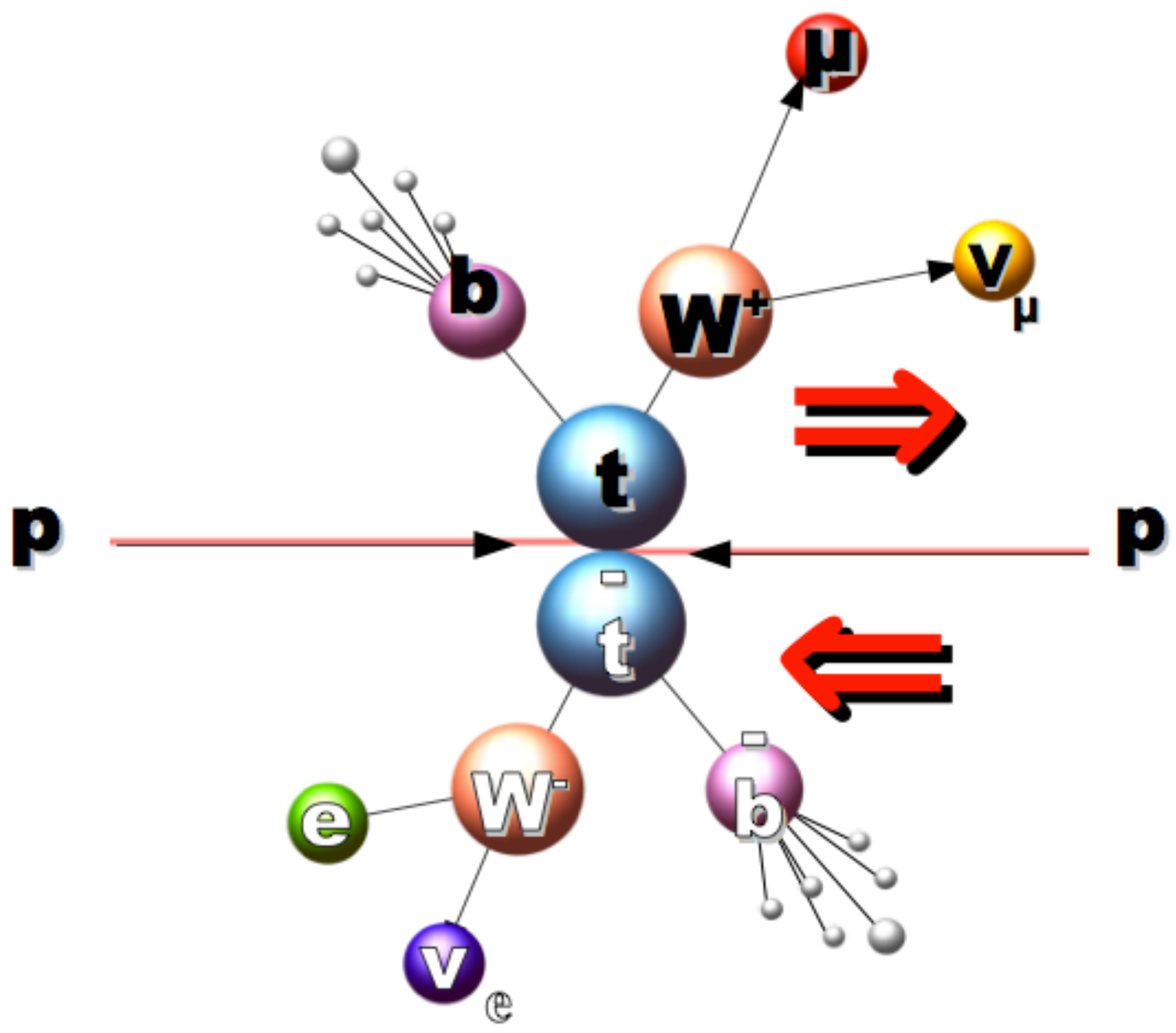


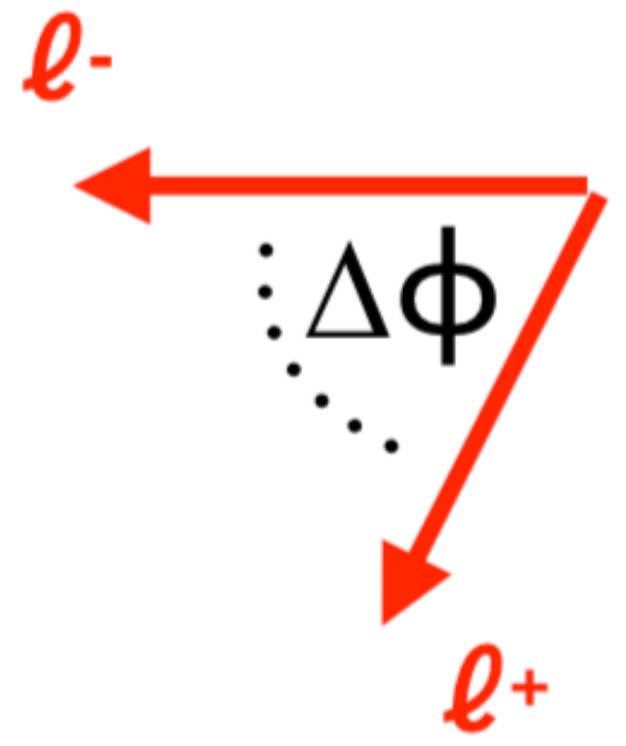
ATLAS uncertainties

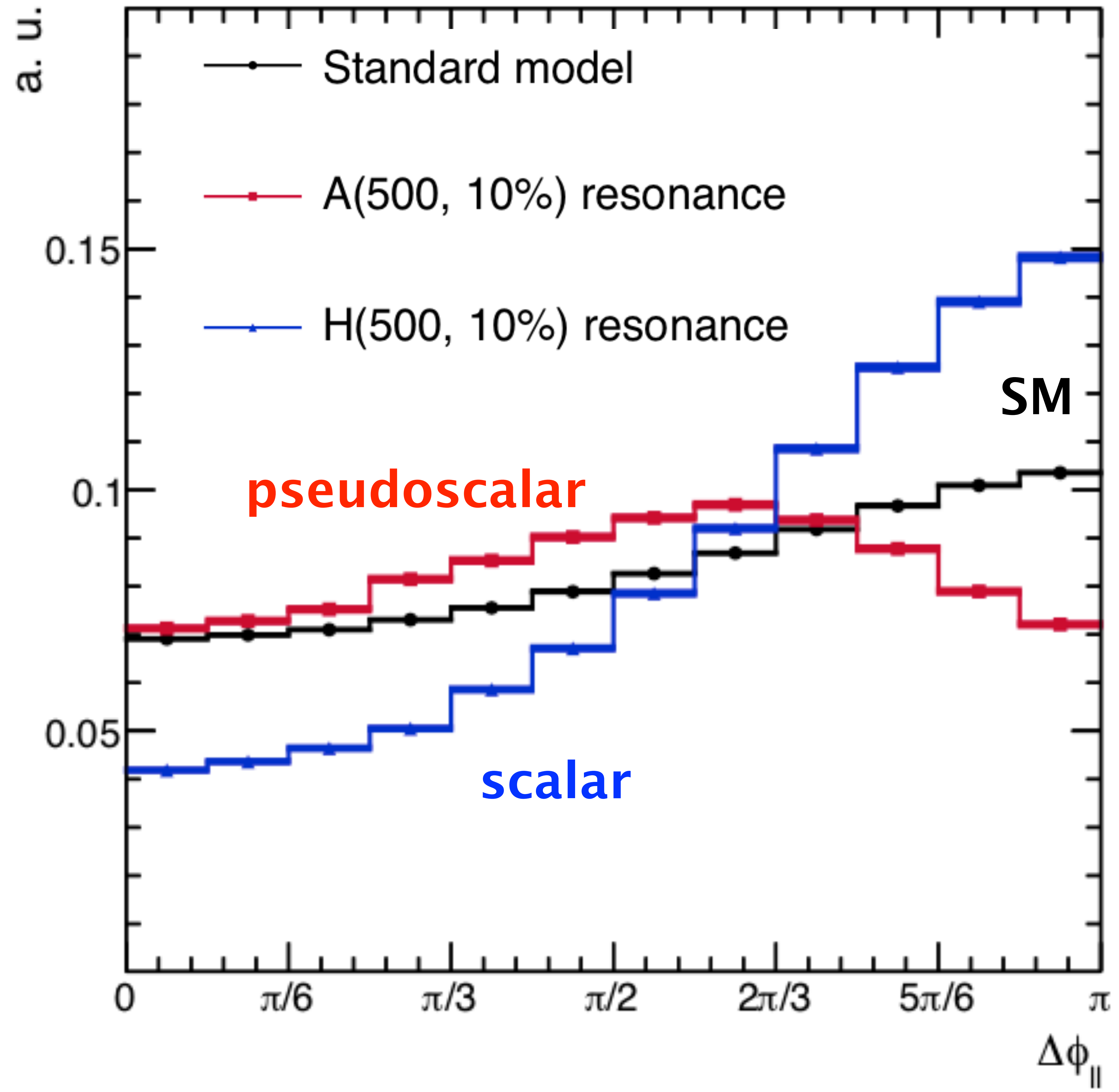
- ATLAS considers different modeling uncertainties, e.g:
  - “$t\bar{t}$ lineshape”: Powheg vs. Powheg+MadSpin
  - Parton shower: Pythia vs. Herwig
  - PDFs in EW corr.: NNPDF vs. LUXQED
- Some of these are uncorrelated between channels and/or between categories in cosθ* / $\Delta\phi_{\ell\ell}$
  - CMS: modeling uncertainties fully correlated
- Impact plot: e.g. lineshape has high impact and is pulled

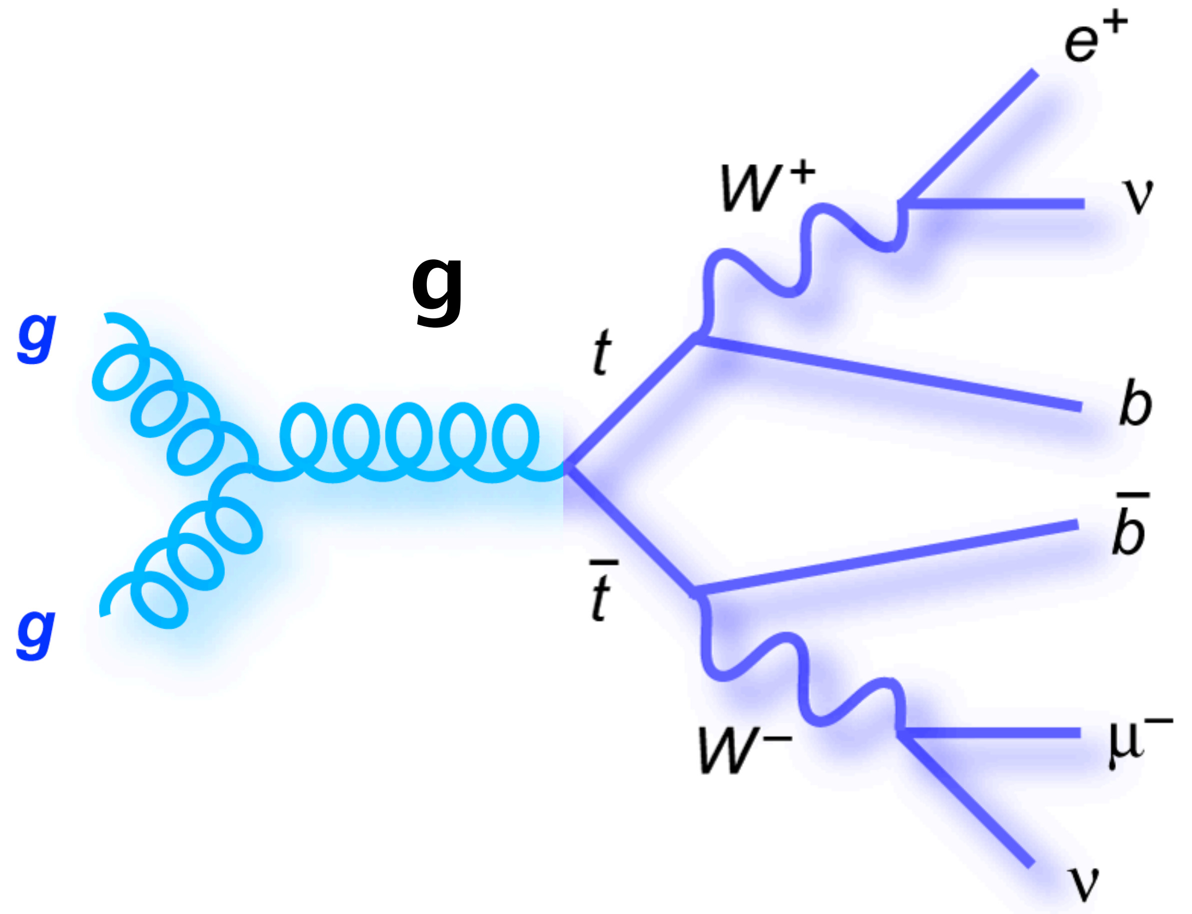


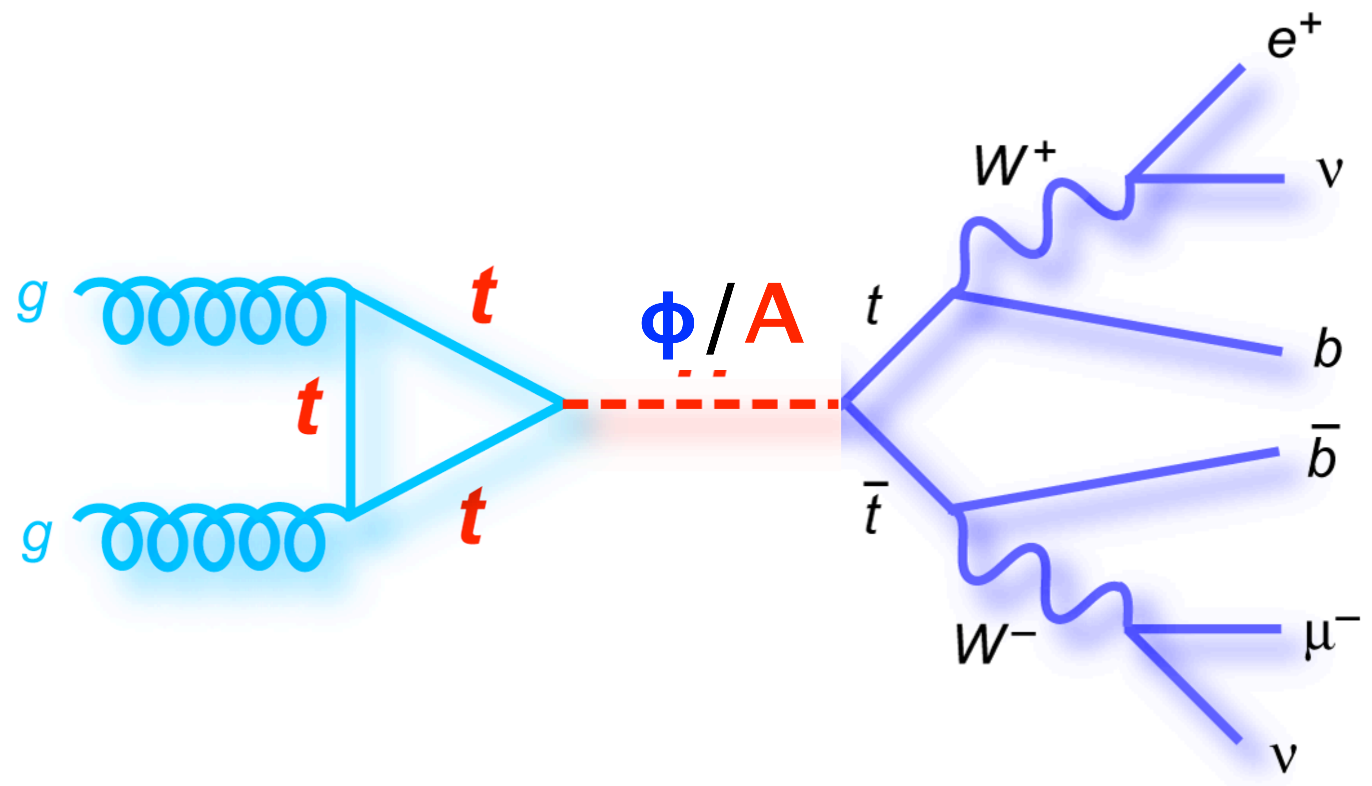
Top-Antitop Quark Spin Correlation





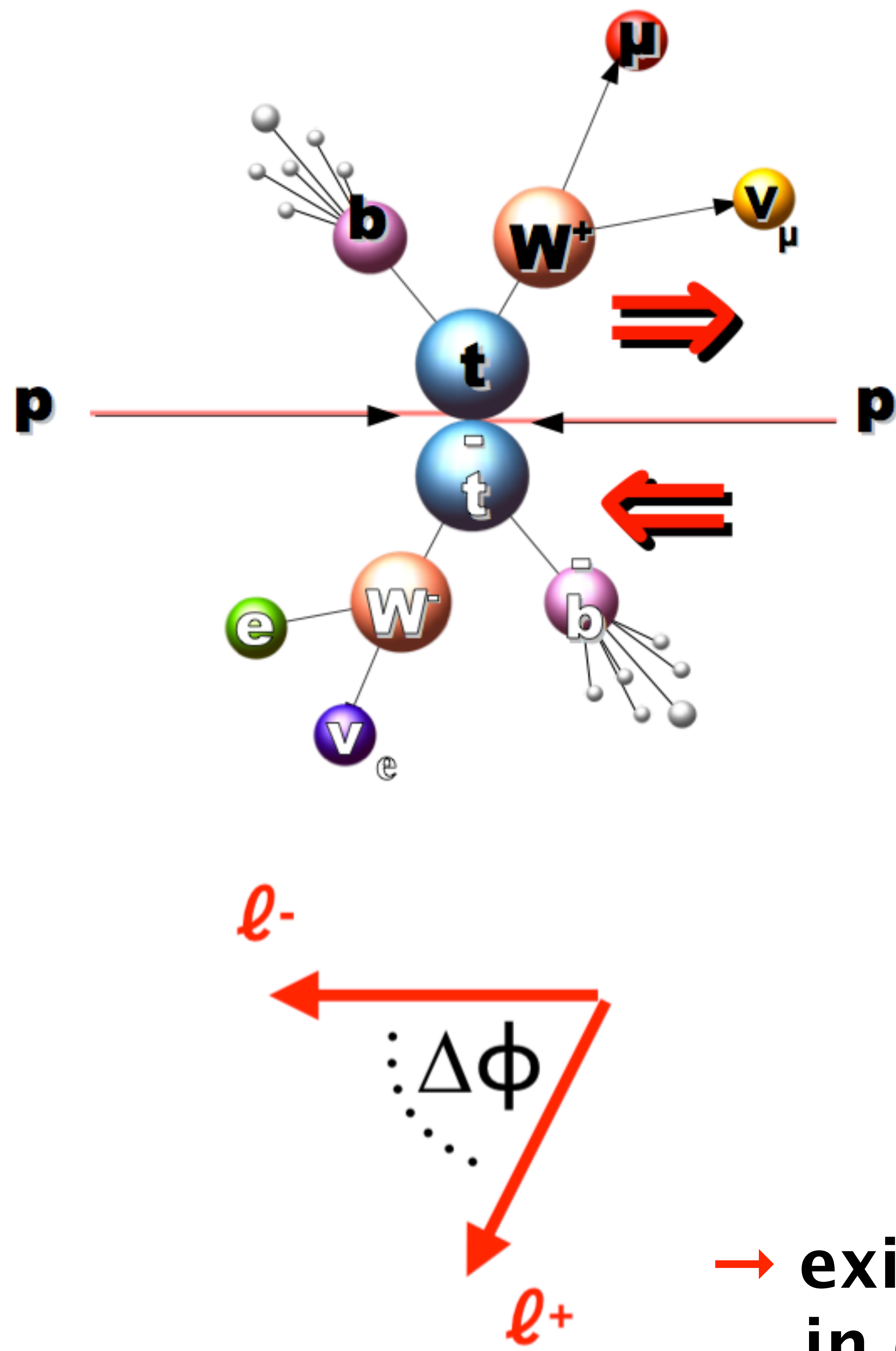


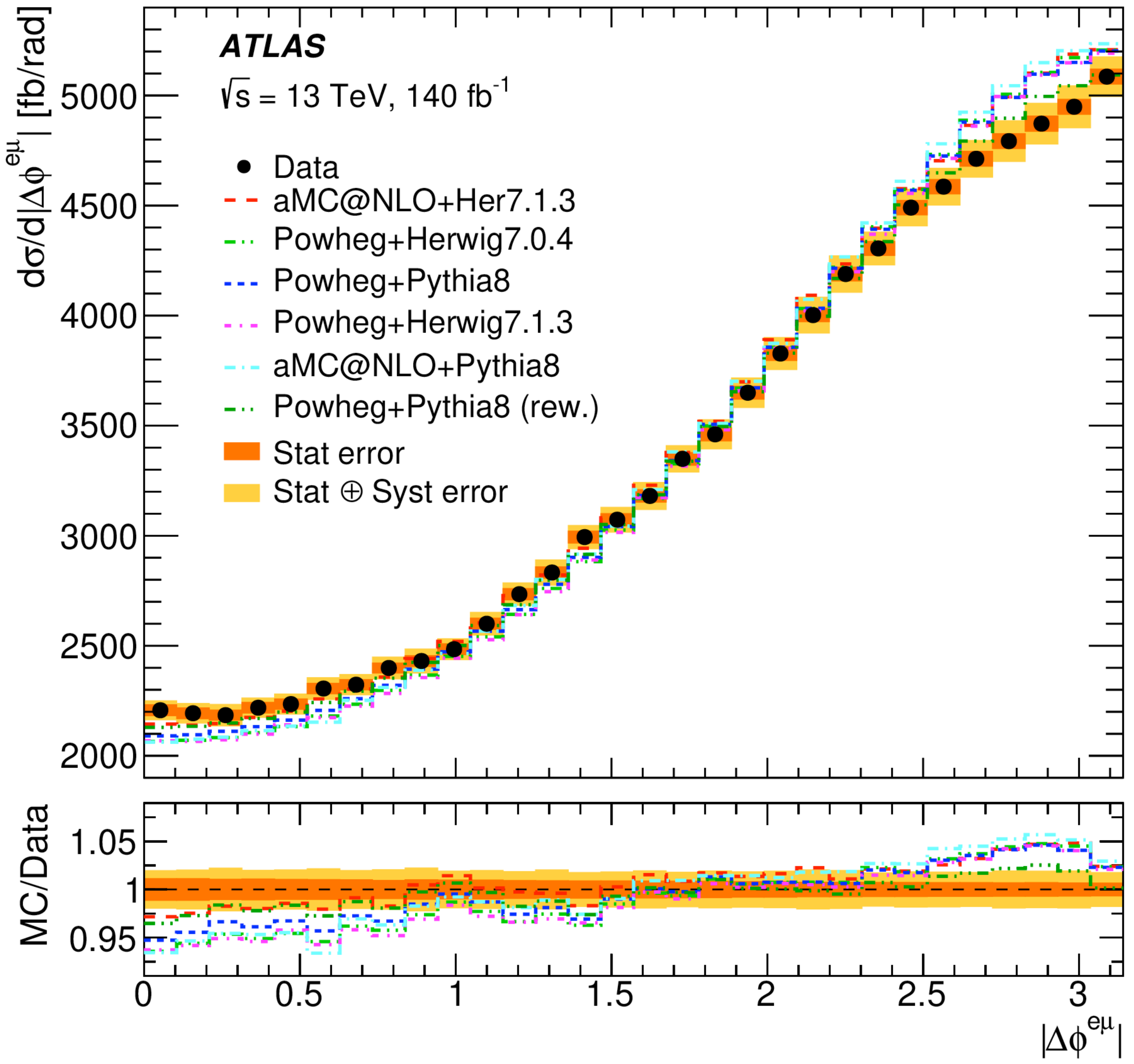


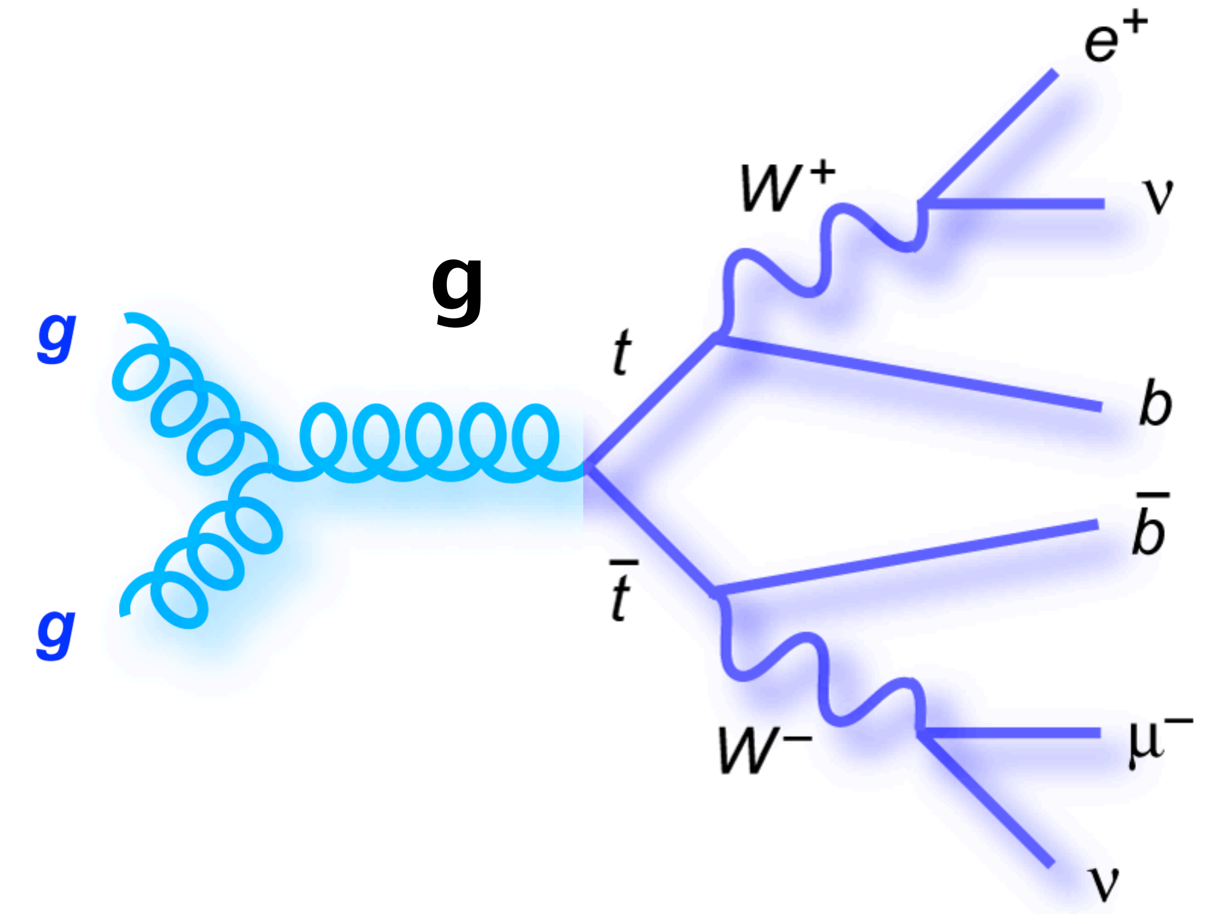


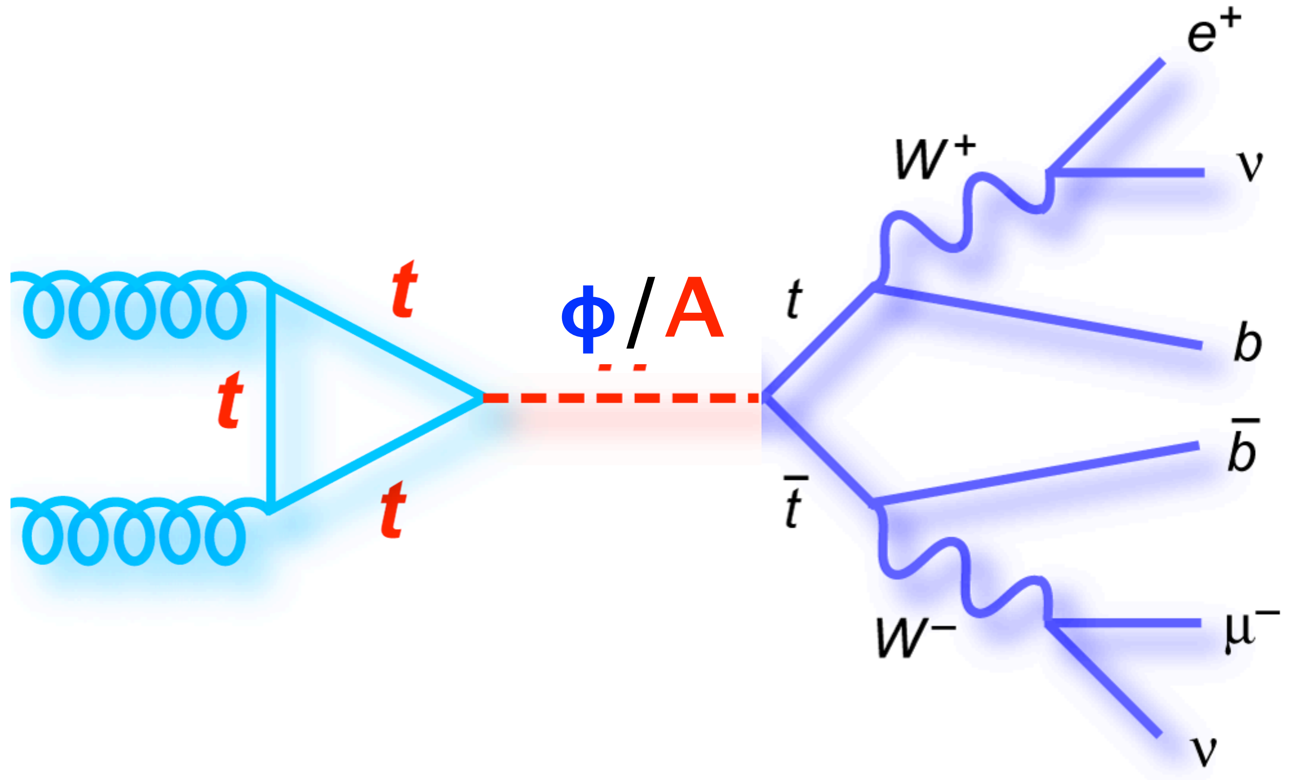
→ **existence of a pseudoscalar would lead to flatter distribution in data corresponding to stronger spin correlation**

Top-Antitop Quark Spin Correlation



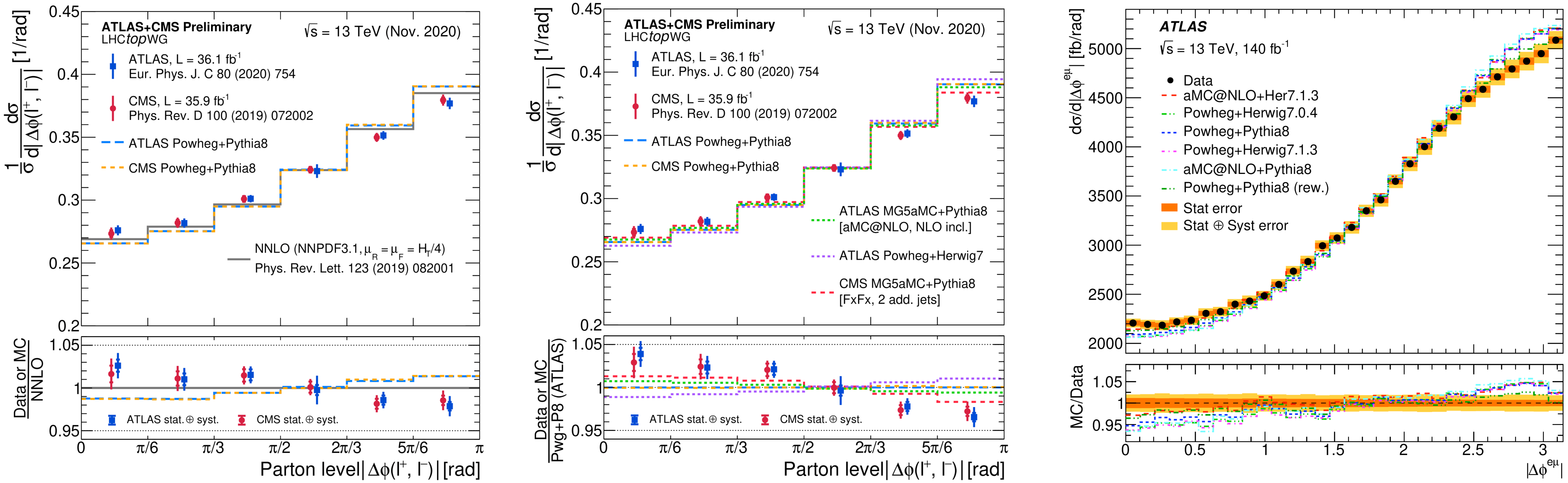






→ **existence of a pseudoscalar would lead to flatter distribution in data corresponding to stronger spin correlation**

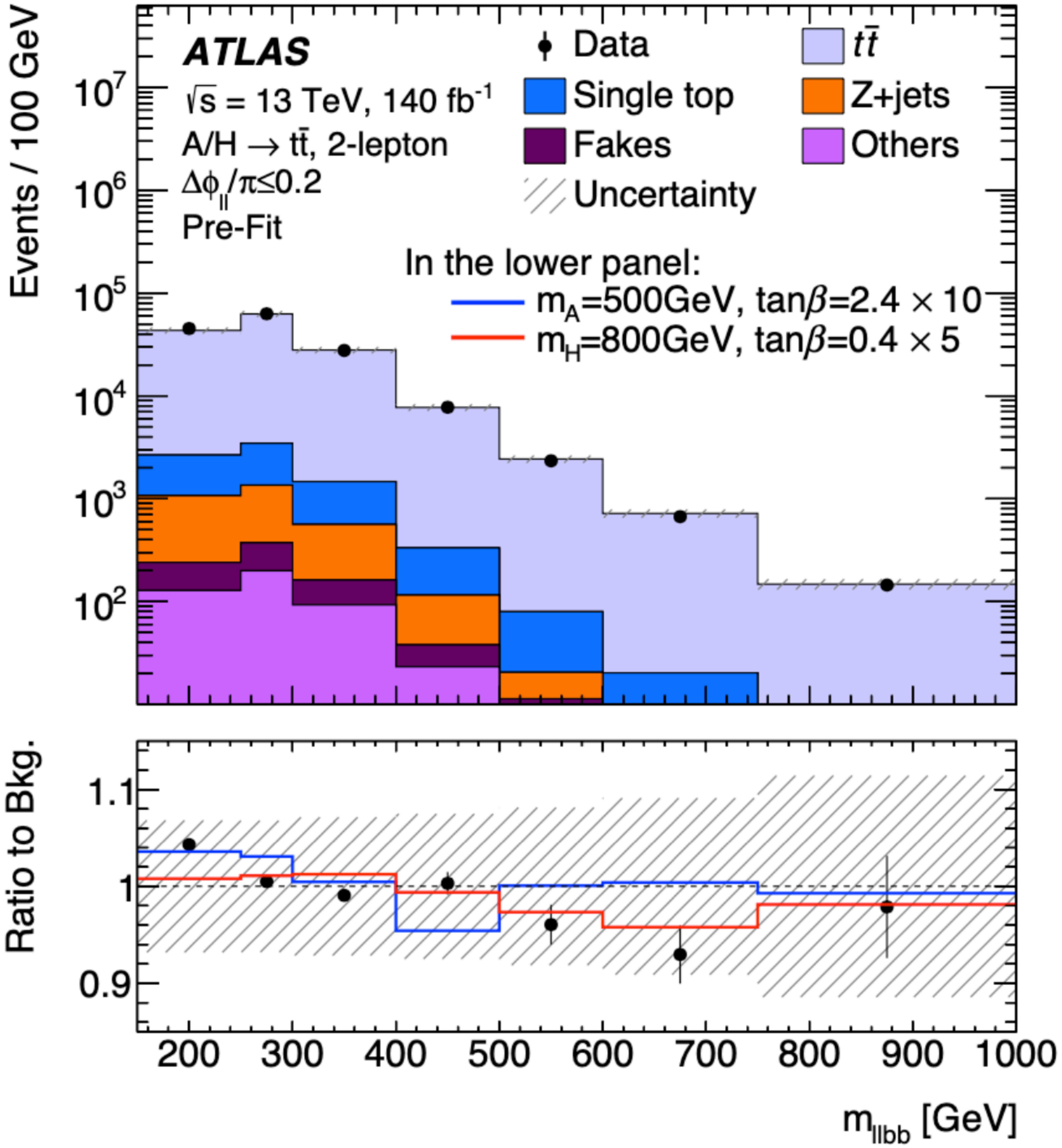
Azimuthal Angle between Leptons in Lab System



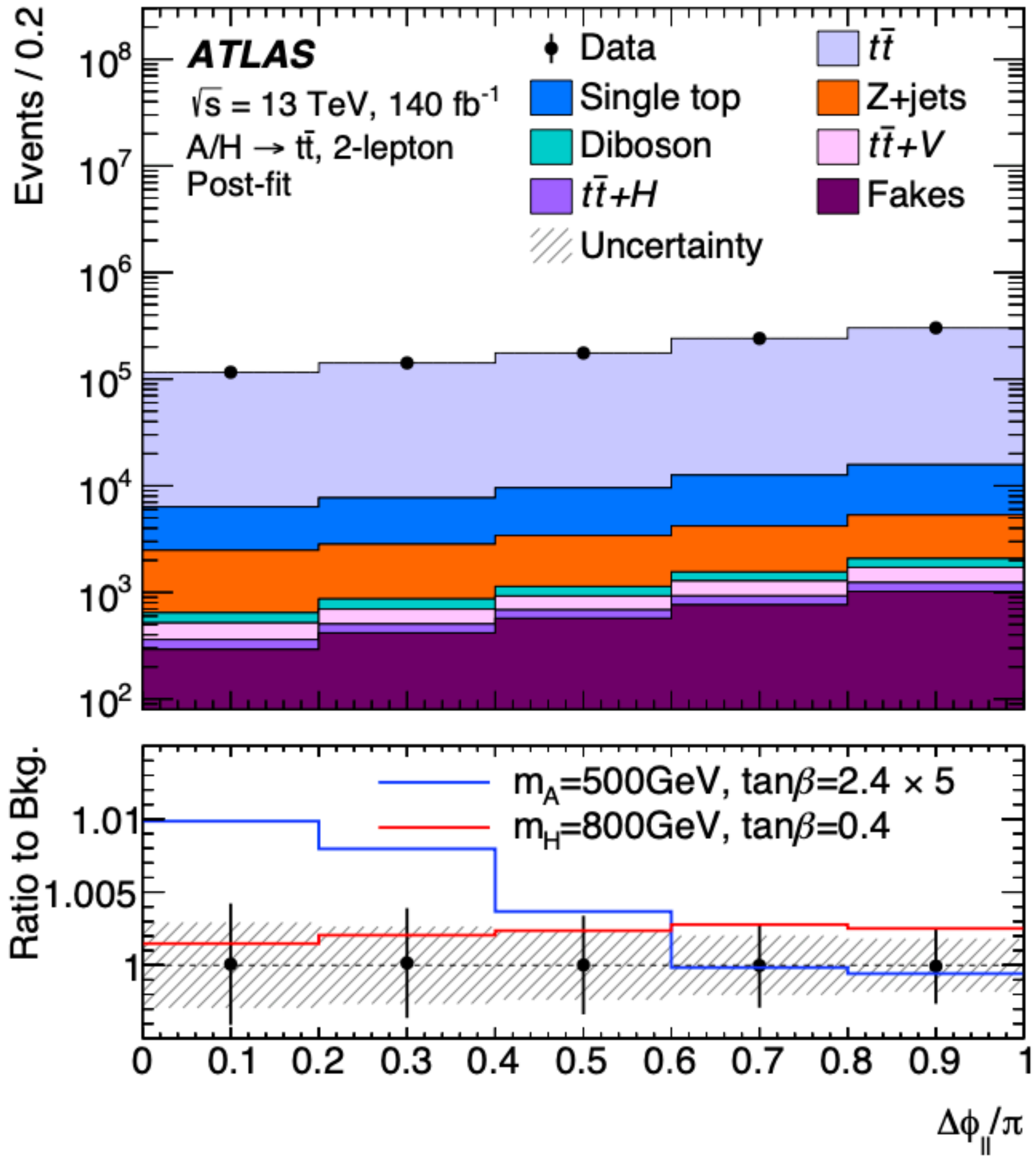
→ **difficult to model**

→ **is a mixture between spin correlation information and kinematics (lab system)**

ATLAS Dilepton prefit



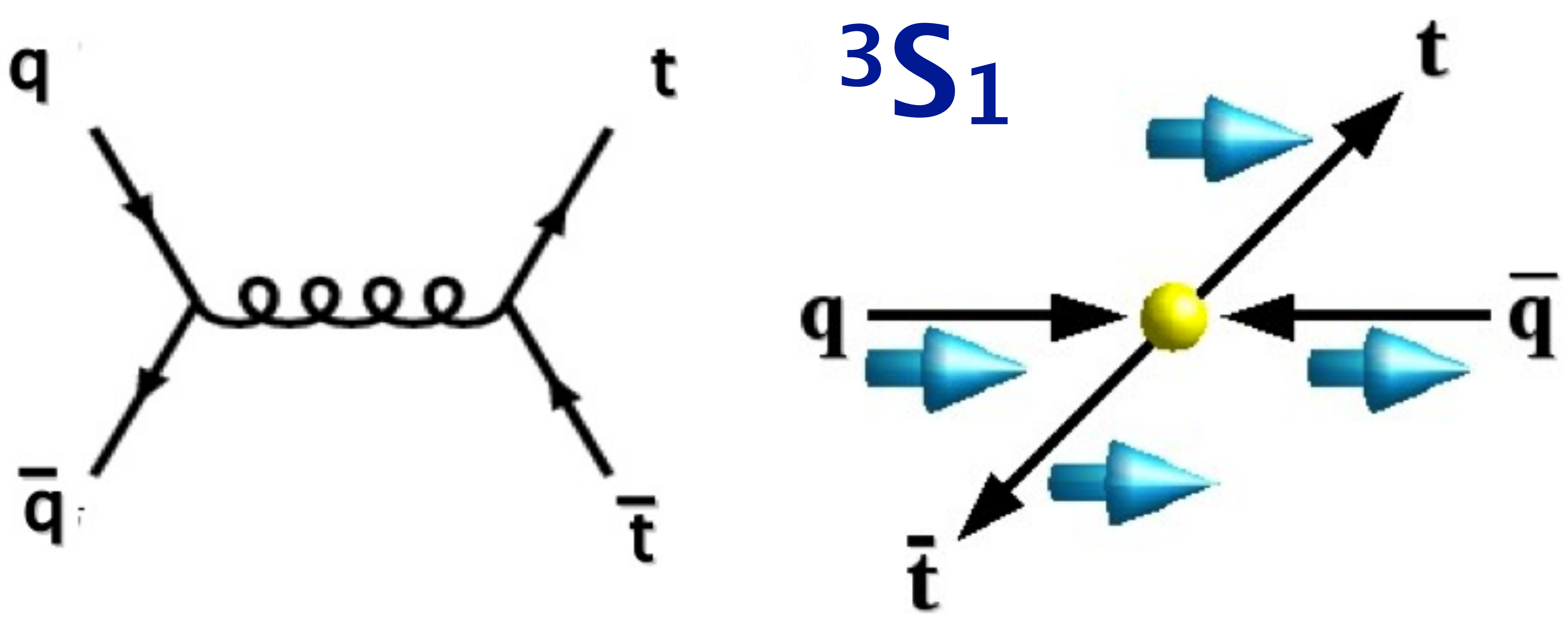
ATLAS Dilepton postfit



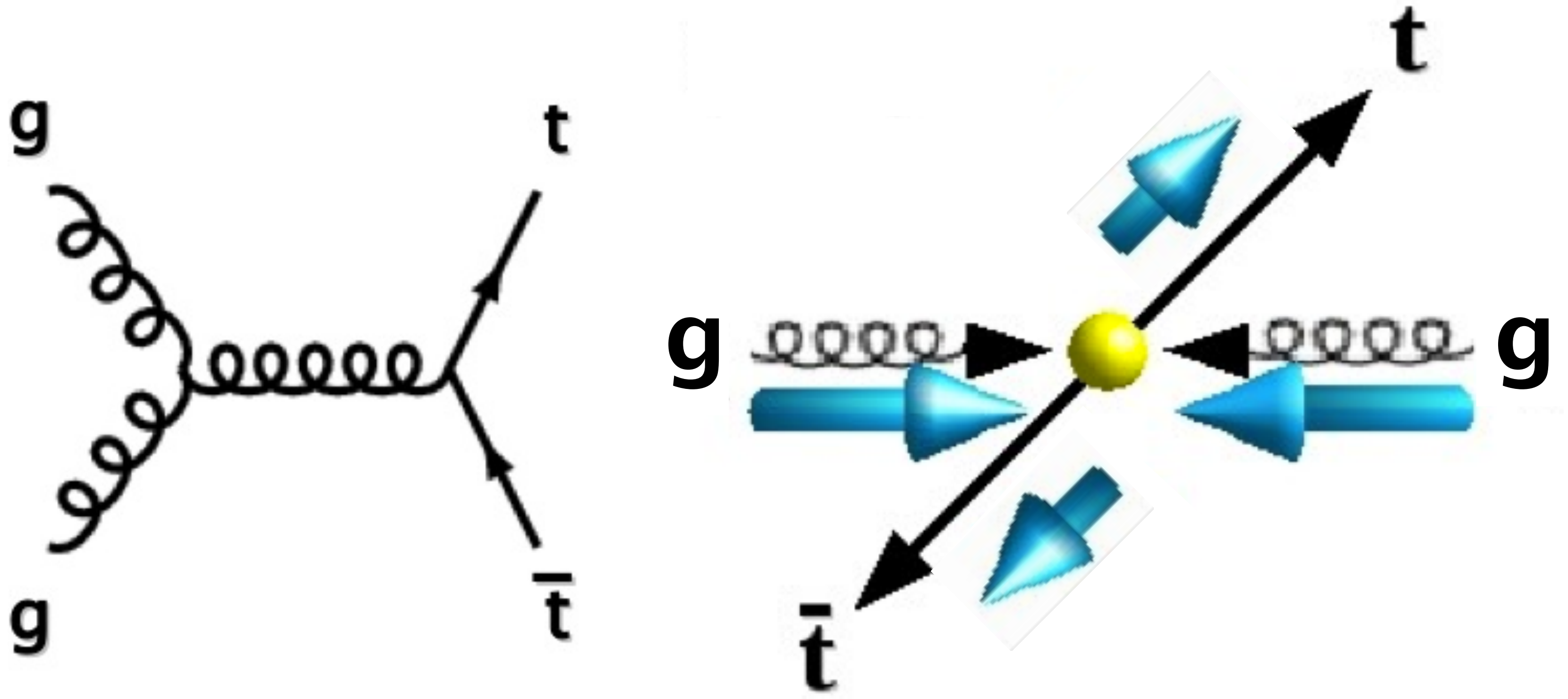
General Backup

Spin correlation strength

$$C = \frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\uparrow\downarrow} - N_{\downarrow\uparrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} + N_{\uparrow\downarrow} + N_{\downarrow\uparrow}}$$



Tevatron



LHC

Tevatron:

- dominated by $q\bar{q}$ annihilation
- $t\bar{t}$ pairs close to the threshold
- beam axis as spin quantisation axis
  NLO QCD: C = 0.78
- optimised "off-diagonal" basis

LHC:

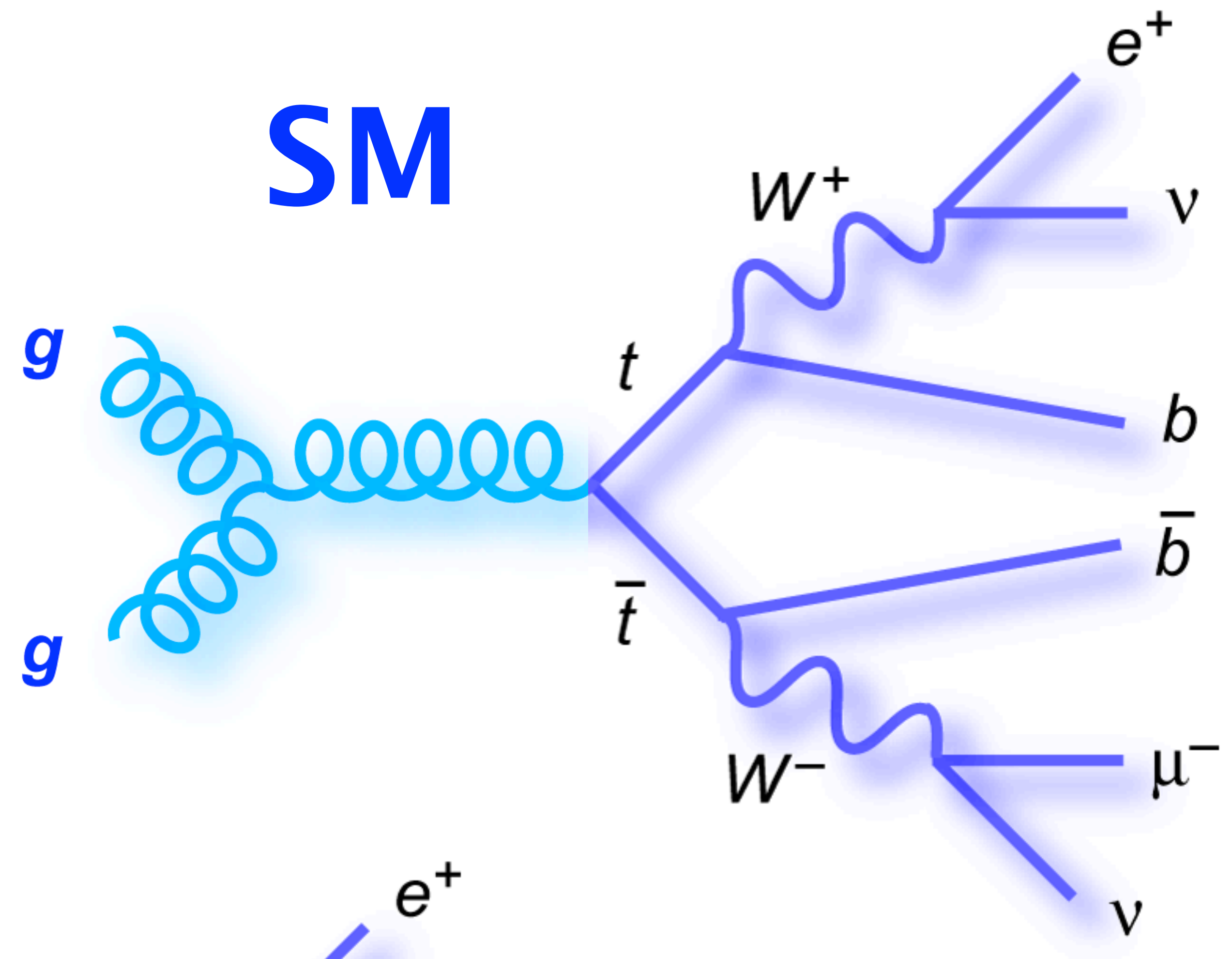
- dominated by gg fusion
- $t\bar{t}$ pairs far off the threshold
- helicity basis as spin quantisation axis
  NLO QCD: C = 0.32
- maximal basis

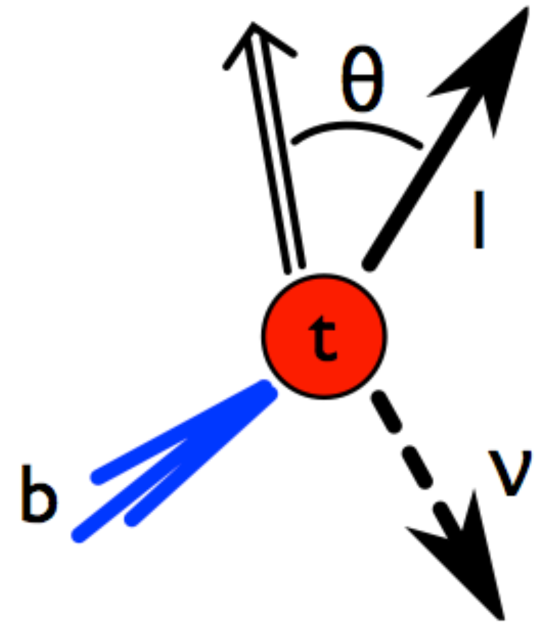
Bernreuther, Brandenburg, Si, Uwer, Nucl. Phys. B690, 81 (2004)

complementary between Tevatron and LHC

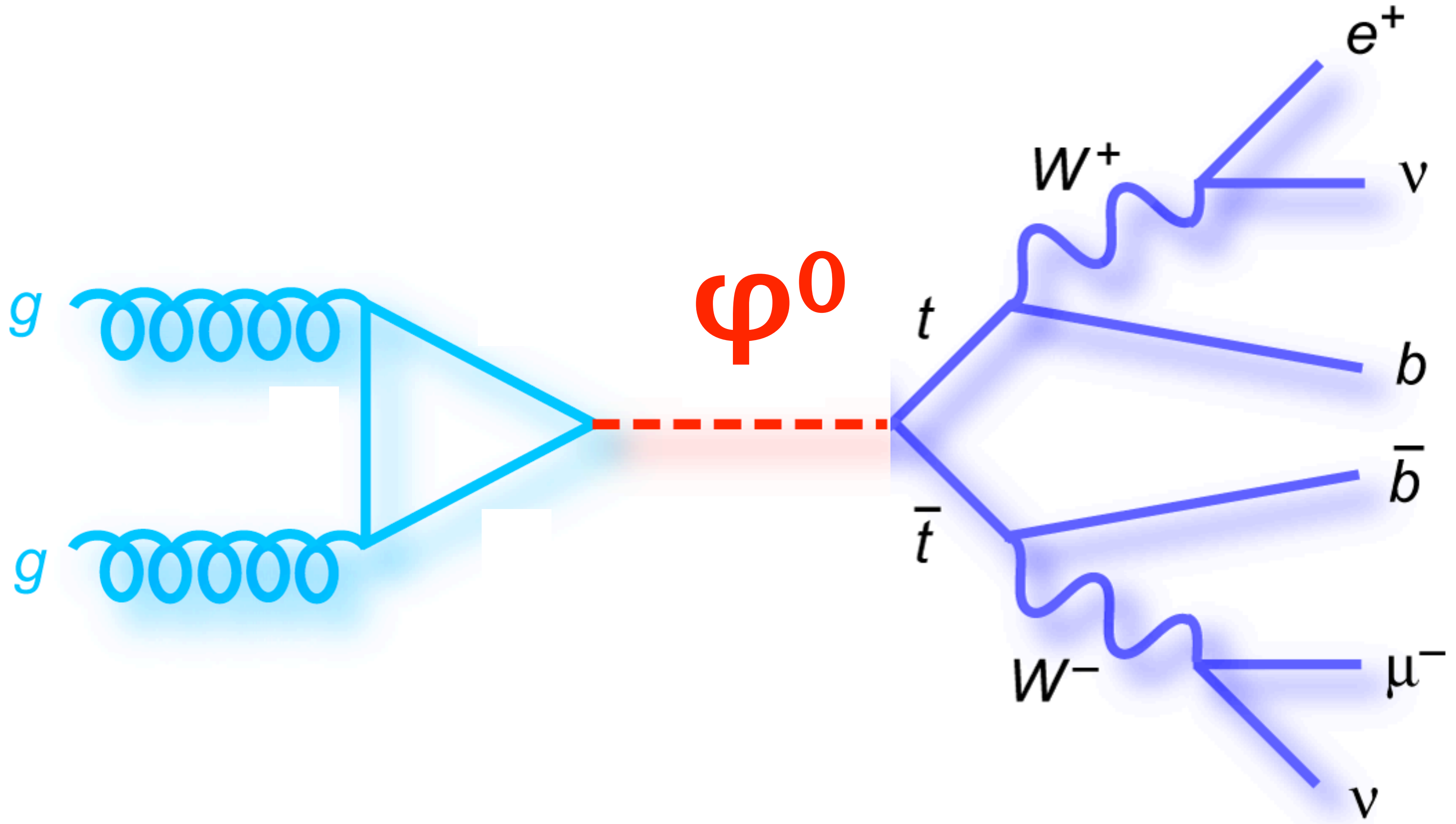
New physics impact on spin correlations

- important test of SM and sensitive search for physics beyond
- analyse the whole chain of top pair production and top decay

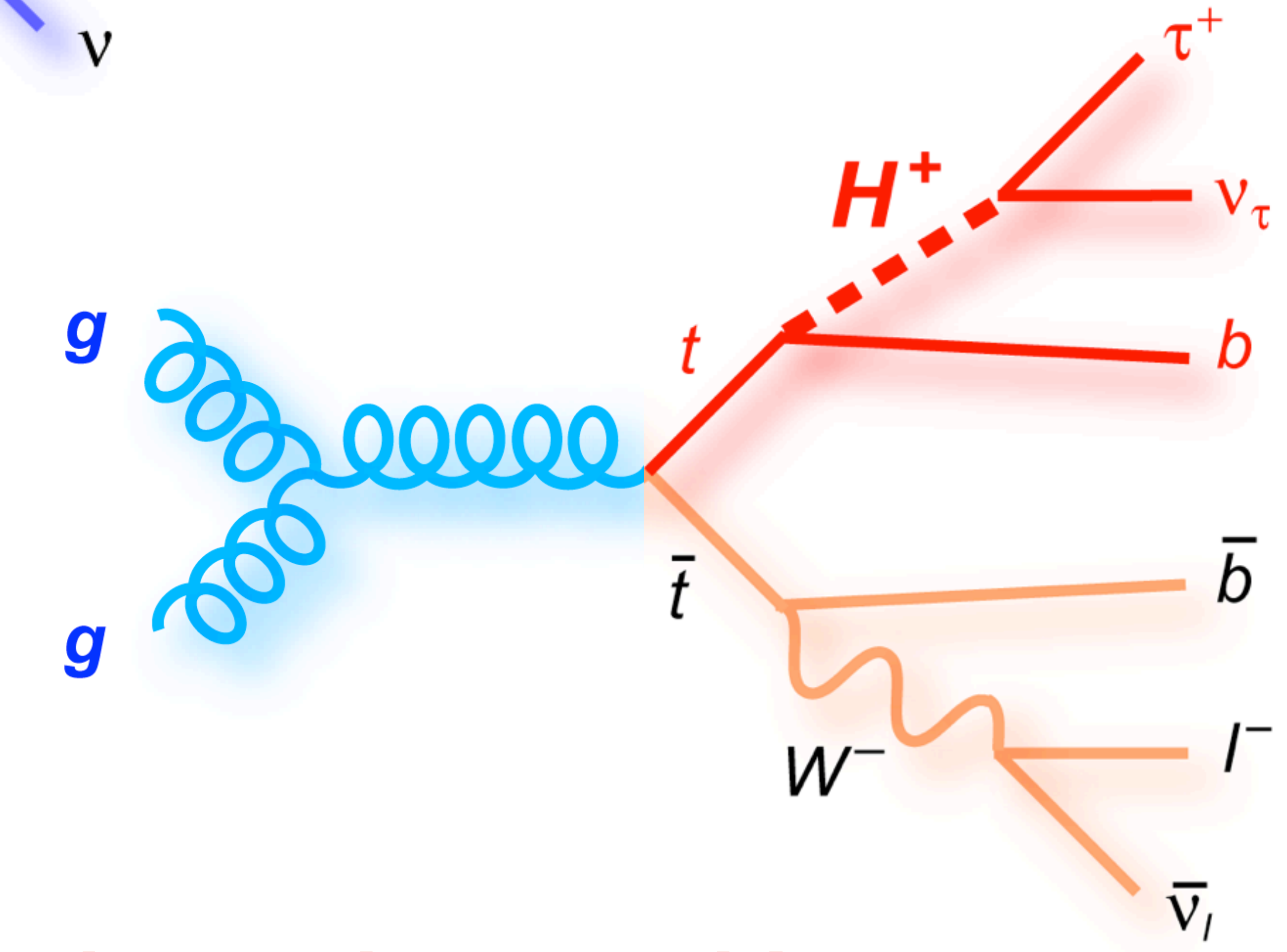




Phys. Lett. B 702, 16 (2011)

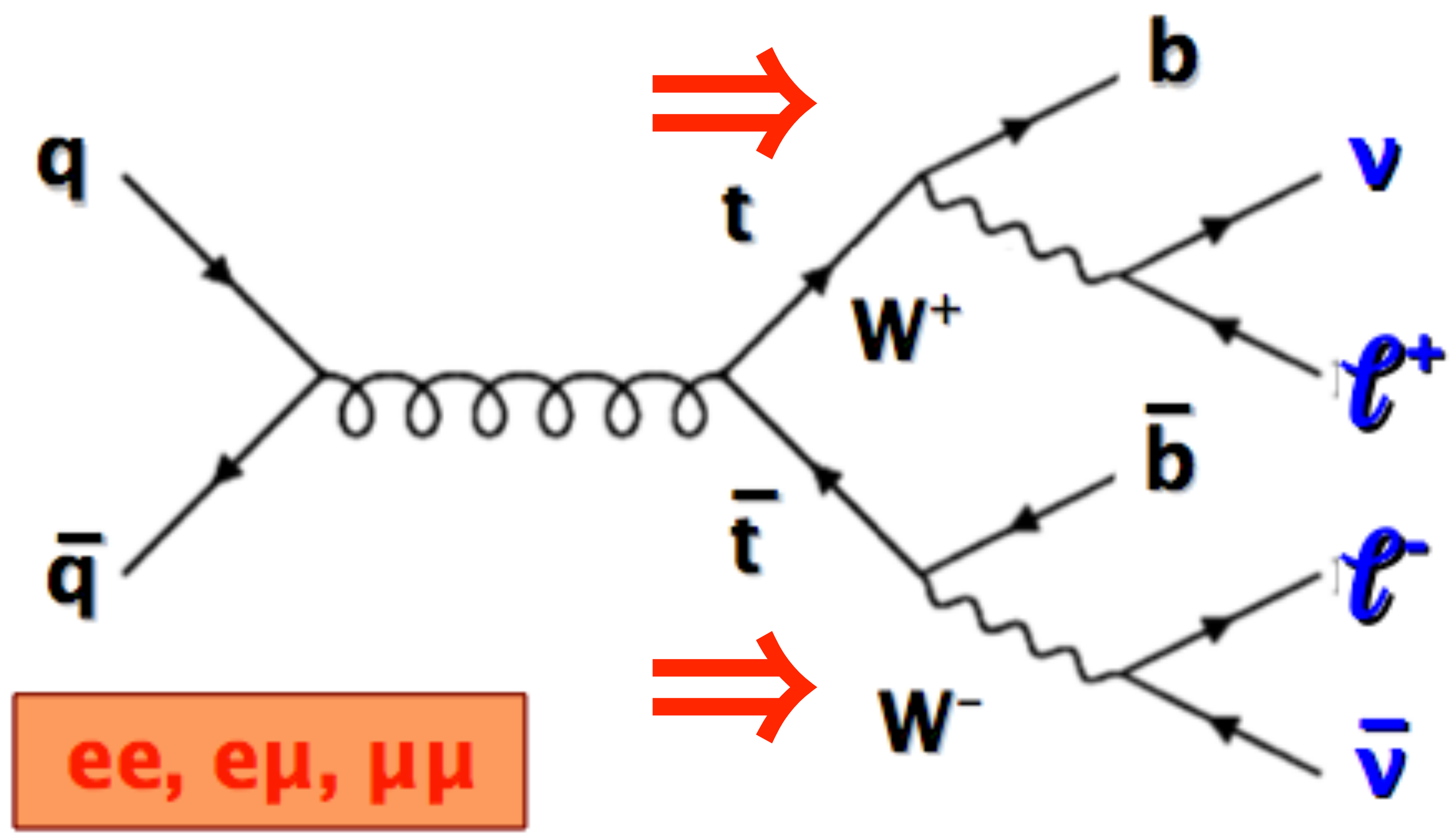


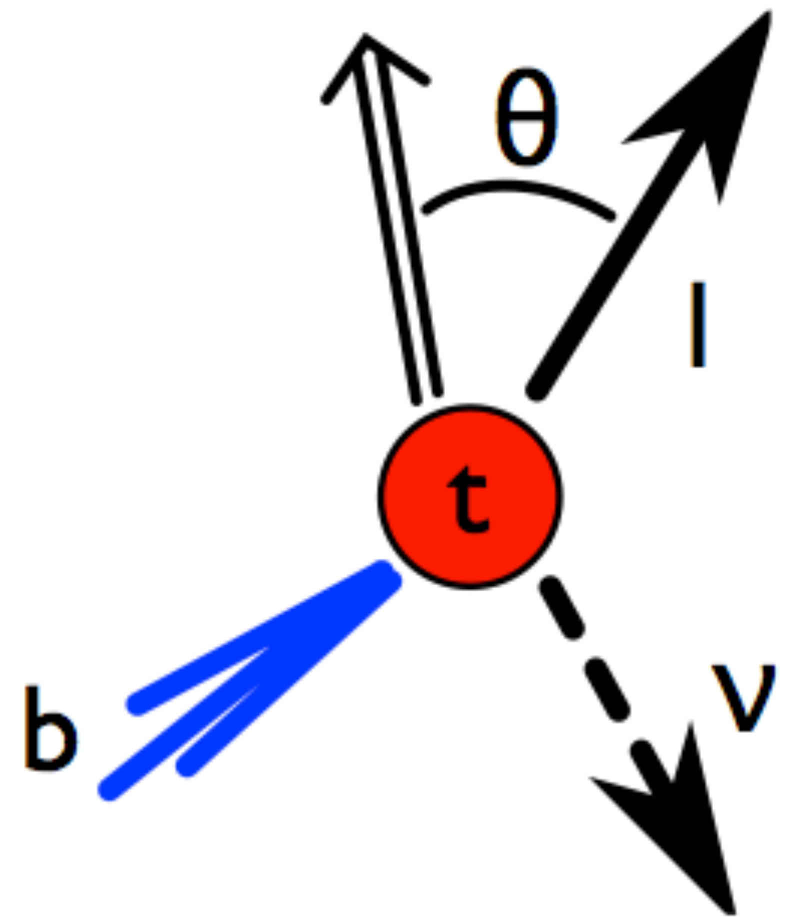
Higgs, KK gravitons, Z’, stop pairs, …



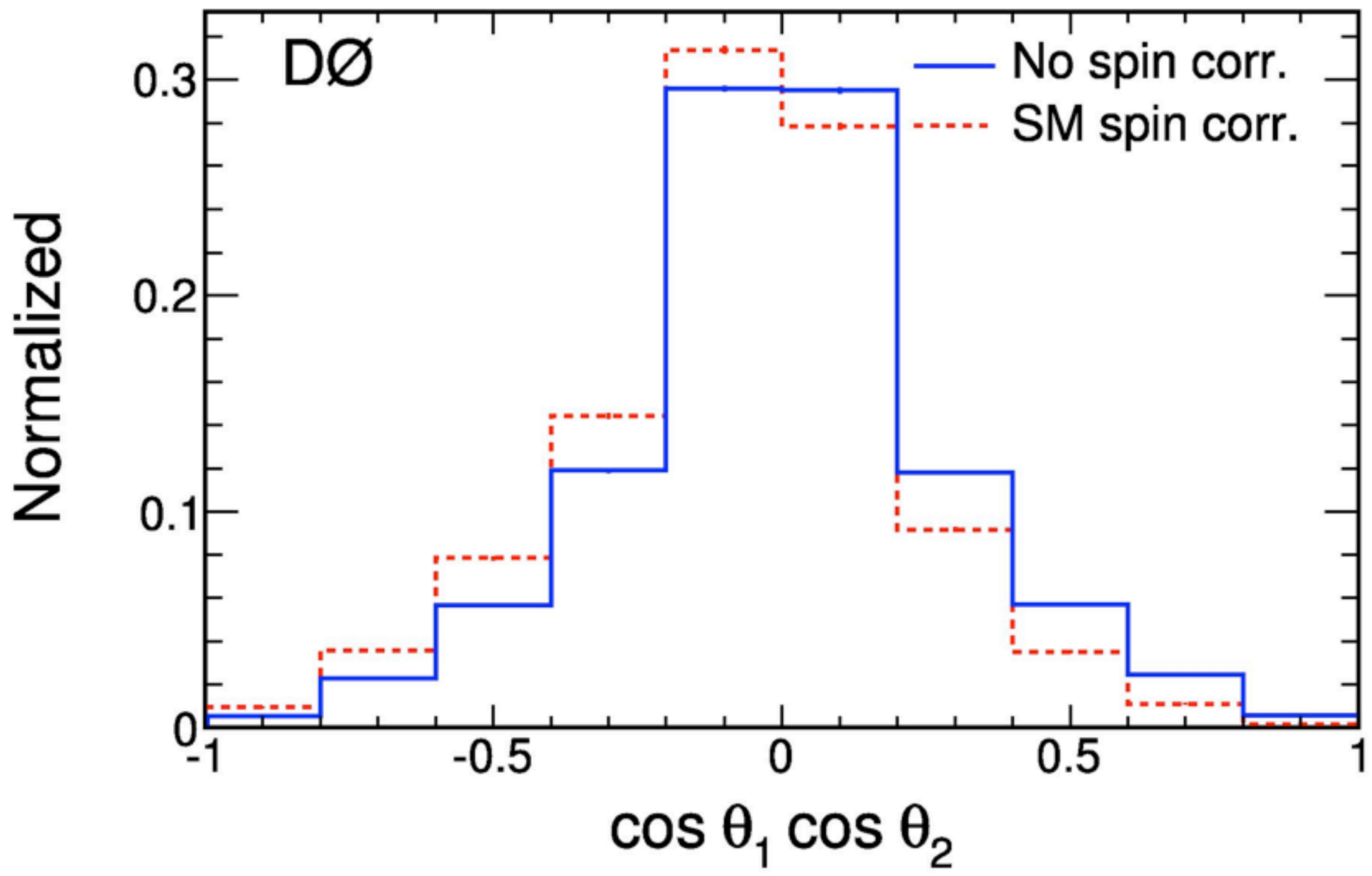
charged Higgs, b’, …

Template Method





with
T. Head
Y. Peters



correlation strength:

$$C = \frac{N(\uparrow\uparrow)+N(\downarrow\downarrow)-N(\uparrow\downarrow)-N(\downarrow\uparrow)}{N(\uparrow\uparrow)+N(\downarrow\downarrow)+N(\uparrow\downarrow)+N(\downarrow\uparrow)}$$

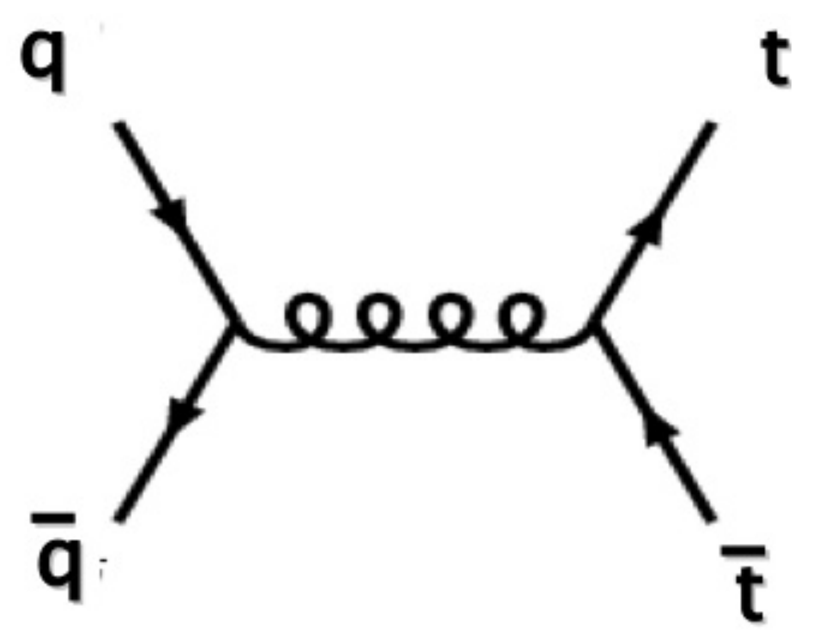
using beam direction as quantization axis

(assuming 100% polarization power for charged leptons)

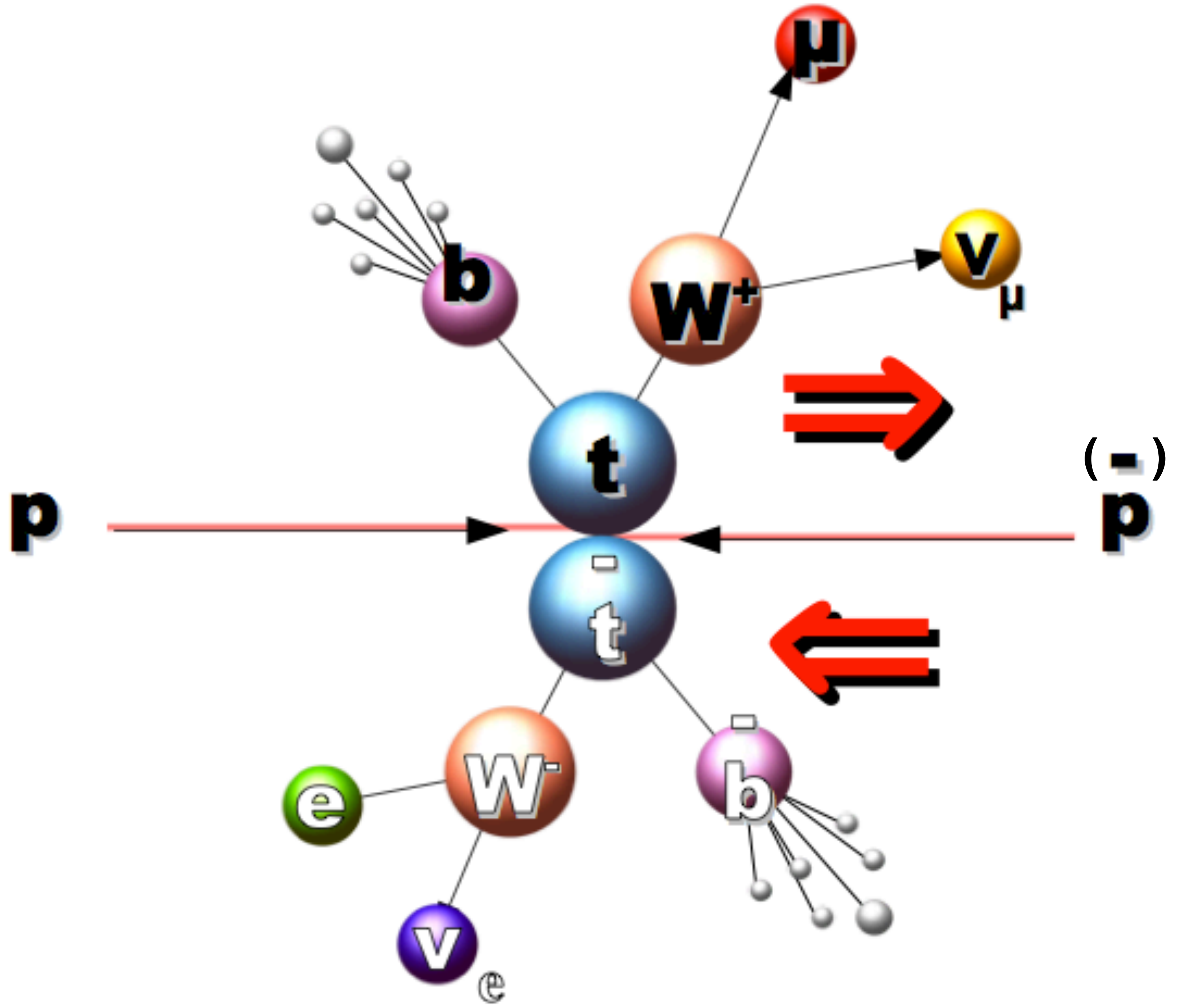
Top Pair Spin Correlation

Top Spin is basically unexplored (2010)

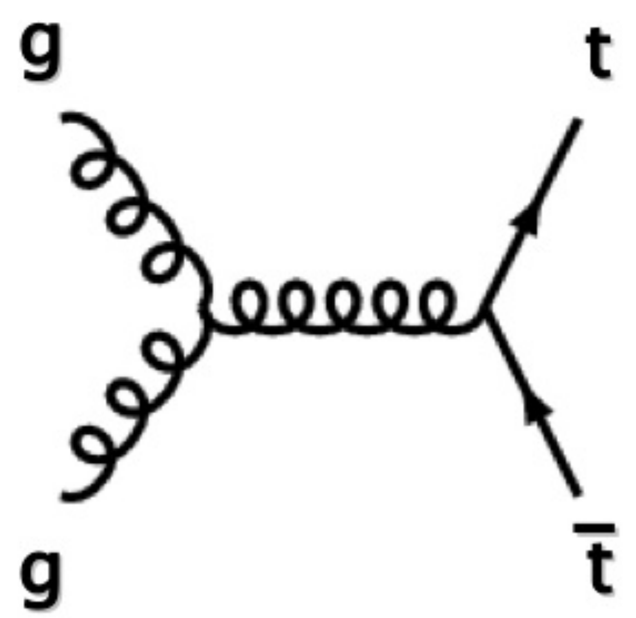
Tevatron



top pair is produced close to kinematical threshold (~in rest)



LHC

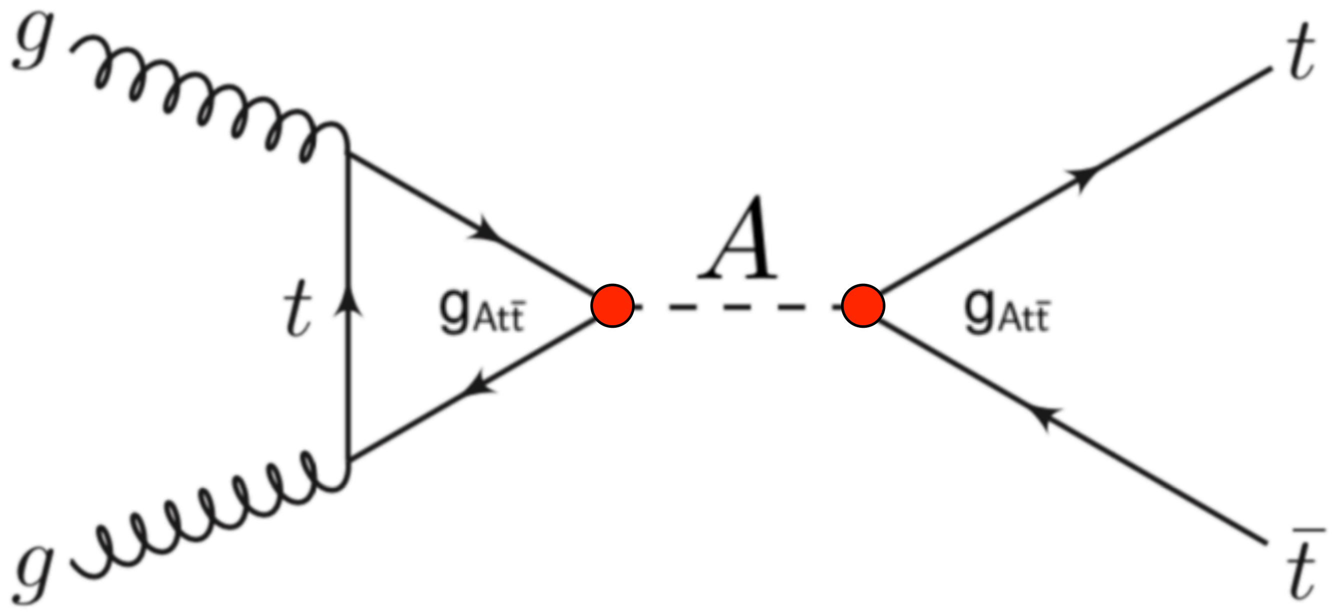


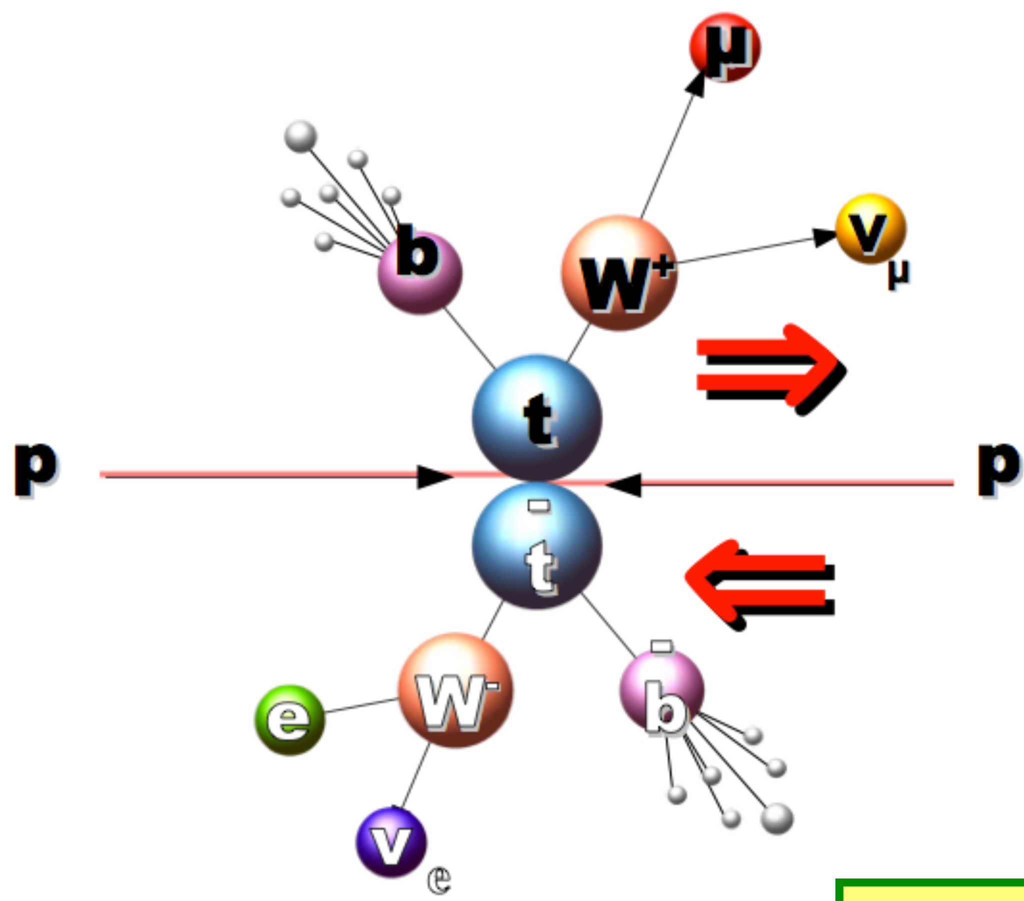
top pair is produced far from kinematical threshold (boosted), too

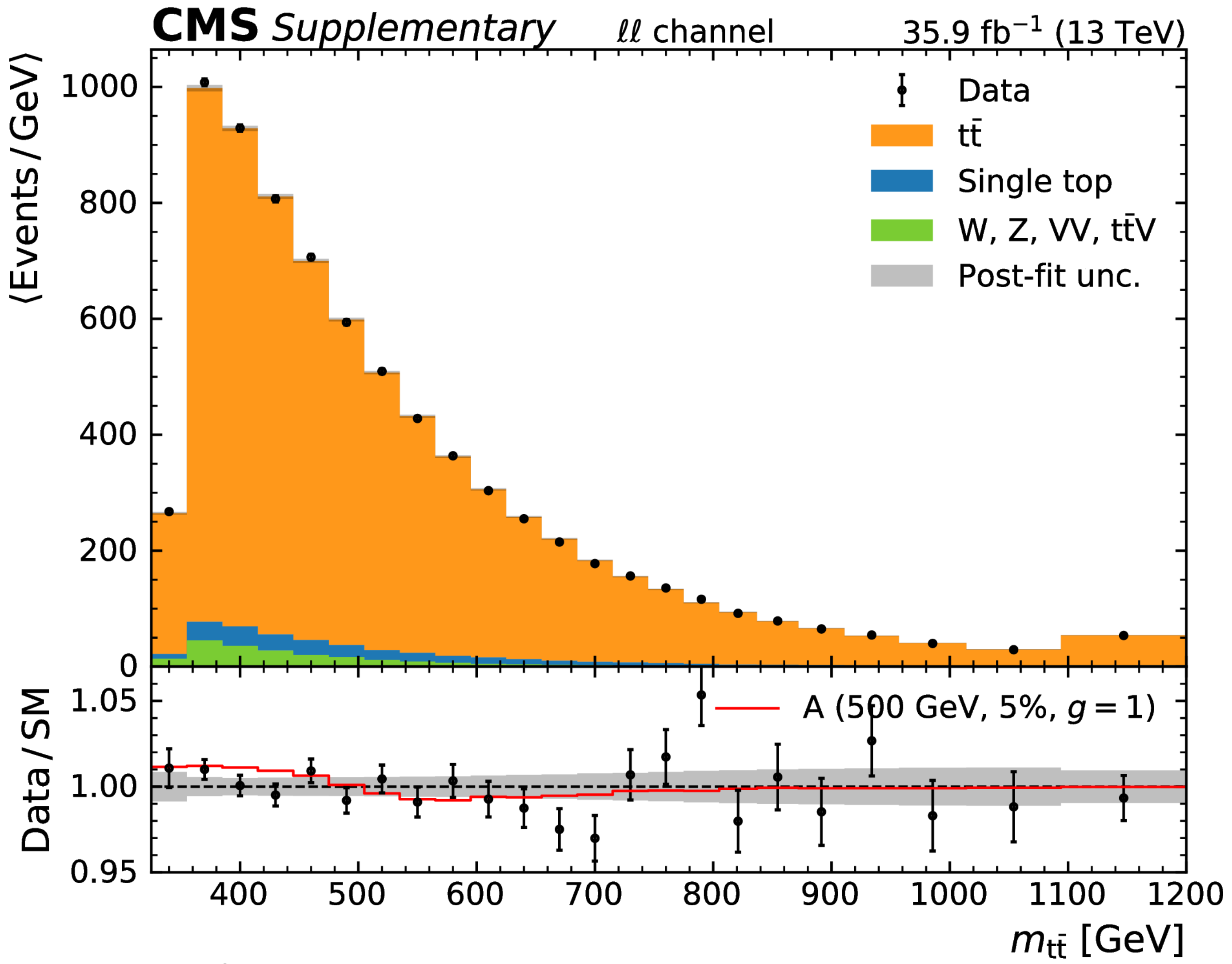
Spin quantization axis

- beam axis
- helicity basis: $h = \vec{S} \cdot \hat{p}, \qquad \hat{p} = \vec{p}/|\vec{p}|$
- optimized bases

Search for a Heavy Pseudoscalar



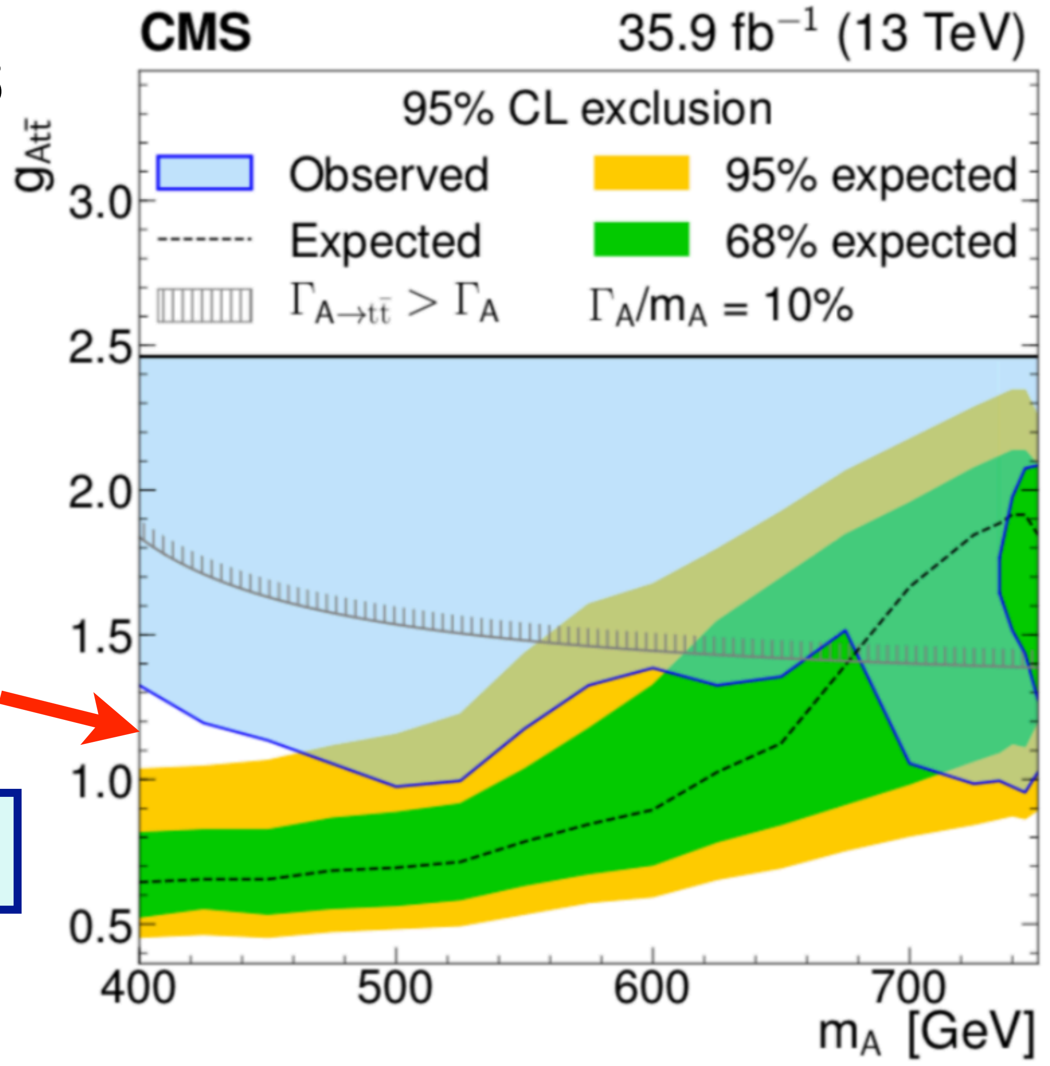




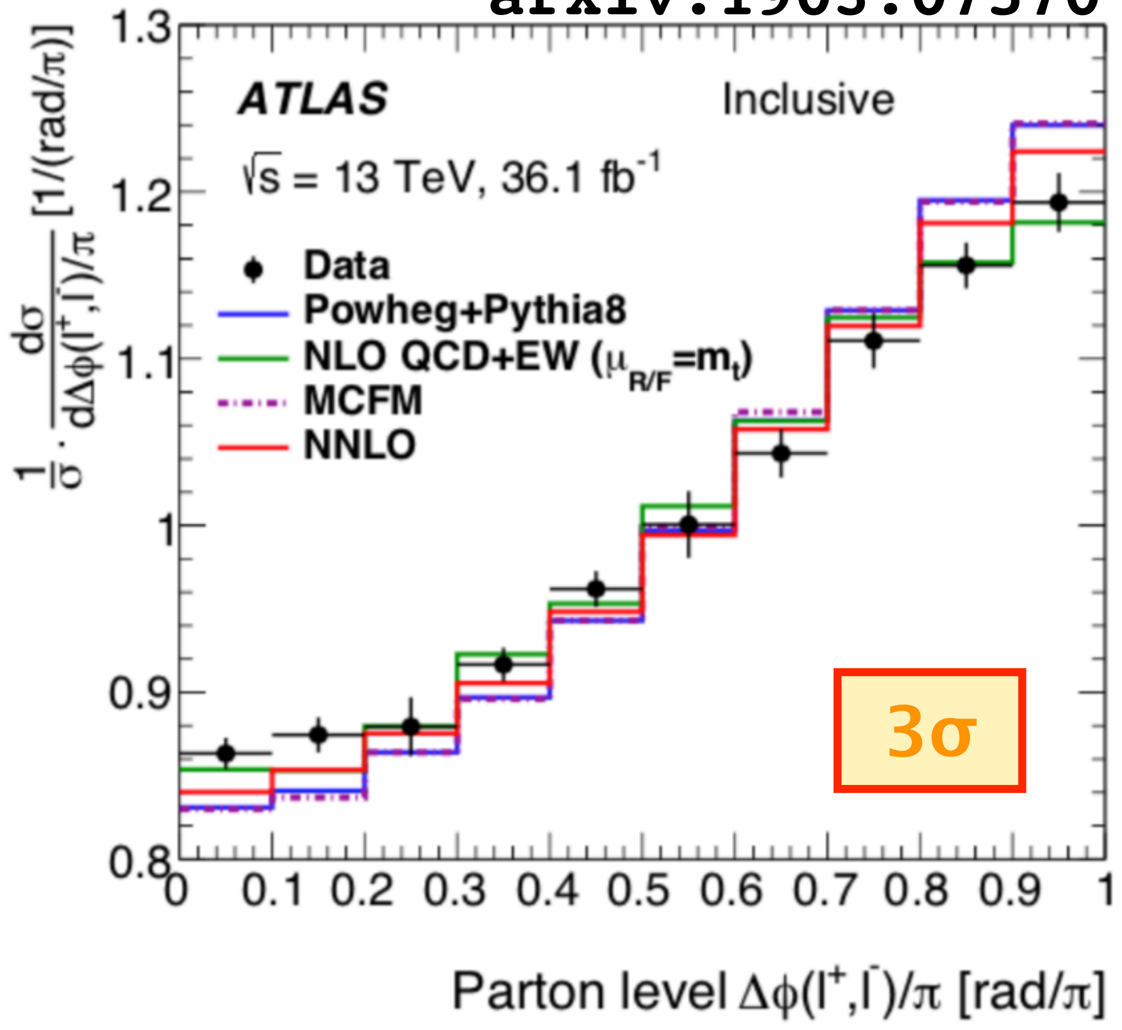
arXiv:1908.01115

3.5σ local

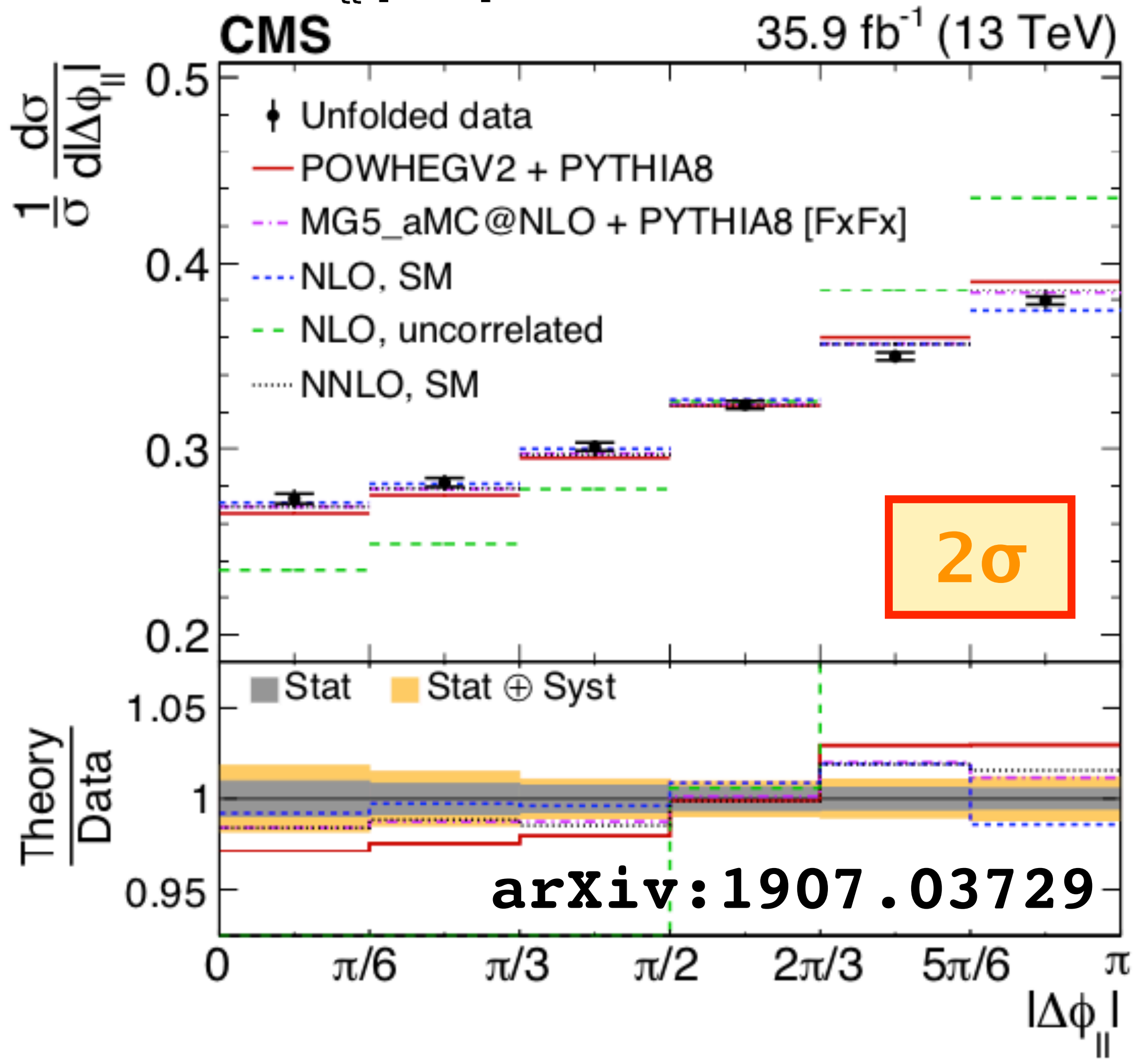
1.9σ global



arXiv:1903.07570

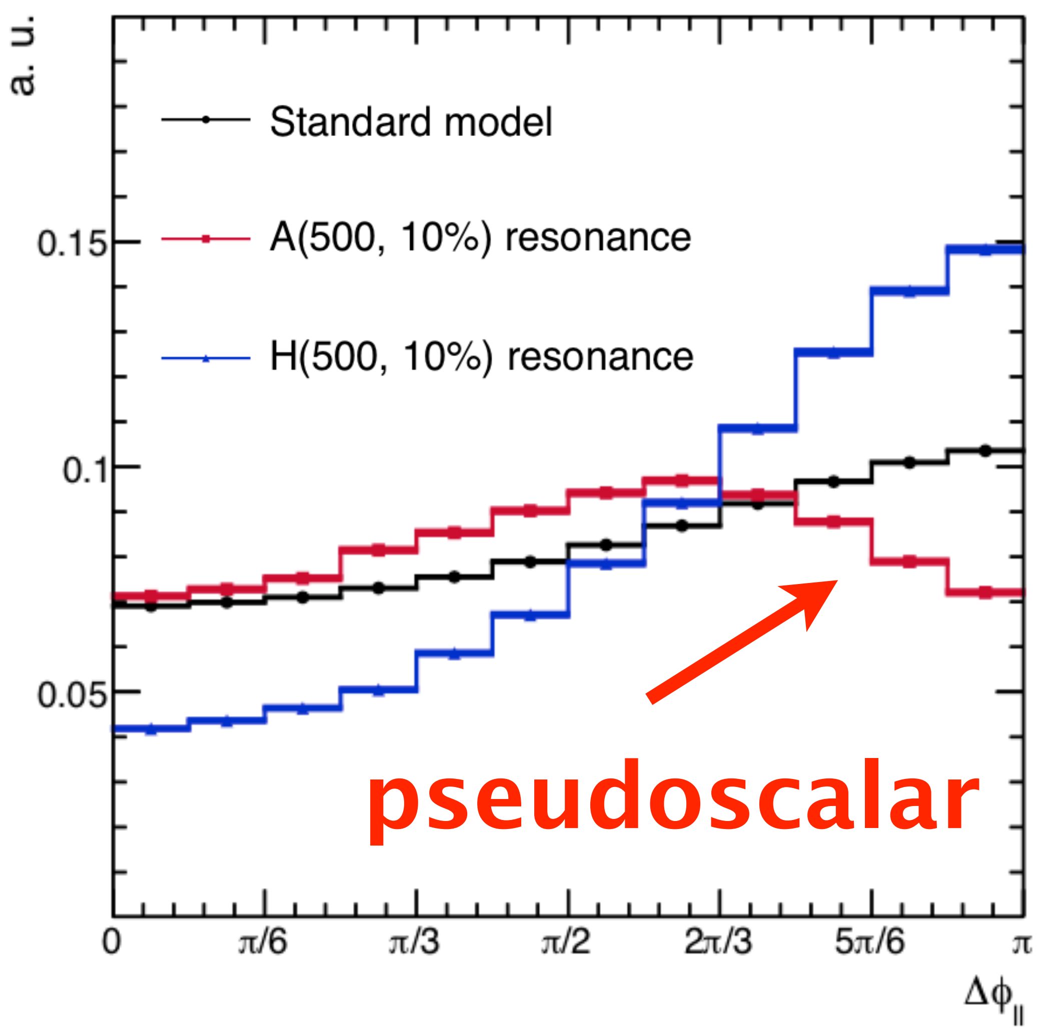


3σ



2σ

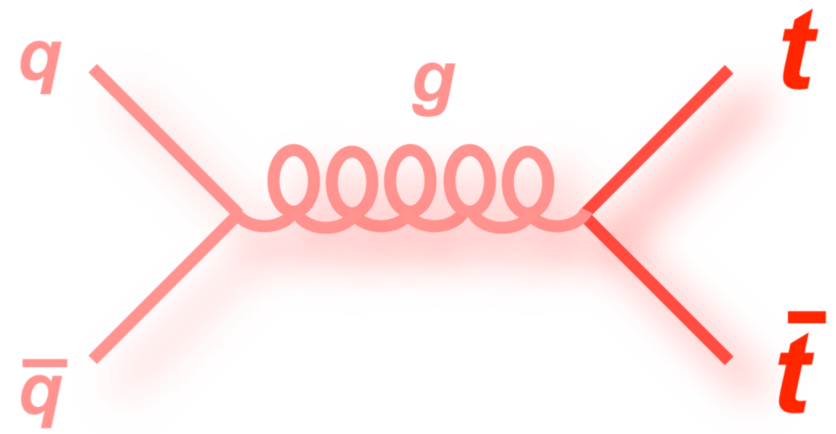
arXiv:1907.03729



pseudoscalar

1/3 Run-2 data → **sensitivity to new physics such as pseudoscalars!**

$t\bar{t}$ production density matrix



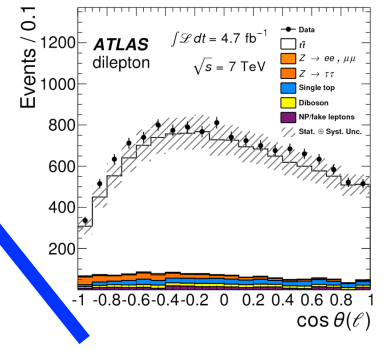
$$q(p_1) + \bar{q}(p_2) \to t(k_1, s_1) + \bar{t}(k_2, s_2)$$

determines cross section and distributions independent of top spin (e.g. p^t_T distribution etc.)

$$|M|^2 \propto A + \mathbf{B}^+ \cdot \mathbf{s}_1 + \mathbf{B}^- \cdot \mathbf{s}_2 + C_{ij} s_{1i} s_{2j} \quad \textbf{(LO)}$$

$b_1^\pm$, $b_2^\pm$ ≠ 0: P-violation (=0 in LO QCD)

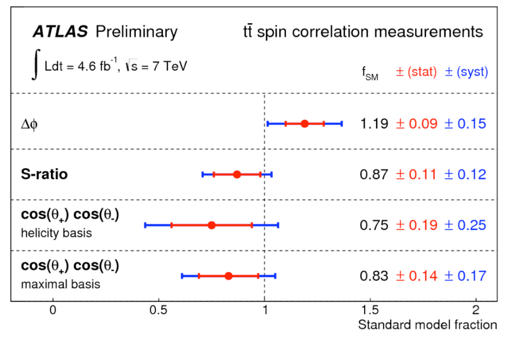
arXiv:1307.6511 [hep-ex]



$b_3^\pm$ ≠ 0: only in NLO QCD, "T"-odd (absorptive parts)

ATLAS-CONF-2013-101

c_1, c_2, c_3, c_4: C-even, P-even ≠0 in LO QCD



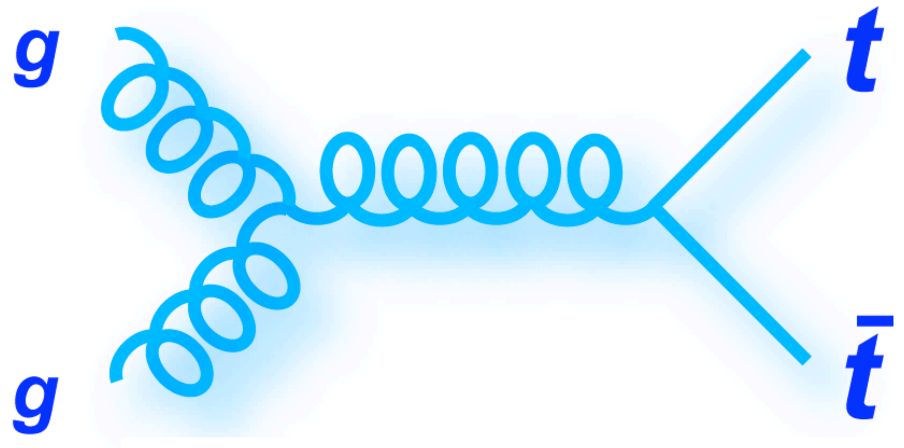
c_5, c_6: P-odd, CP-odd ≠0 only in BSM

$$\tilde{B}_i^\pm = b_1^\pm \hat{p}_i + b_2^\pm \hat{k}_i + b_3^\pm n_i ,$$

$$\tilde{C}_{ij} = c_1 \delta_{ij} + c_2 \hat{p}_i \hat{p}_j + c_3 \hat{k}_i \hat{k}_j + c_4 (\hat{p}_i \hat{k}_j + \hat{k}_i \hat{p}_j) + c_5 \epsilon^{ijl} \hat{p}_l + c_6 \epsilon^{ijl} \hat{k}_l$$

→ **systematic analysis of top quark properties**

Production Density Matrix



determines cross section and distributions independent of top spin (e.g. p^t_T distribution etc.)

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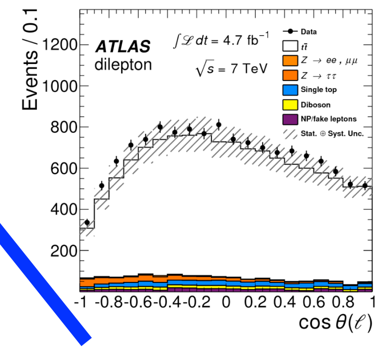

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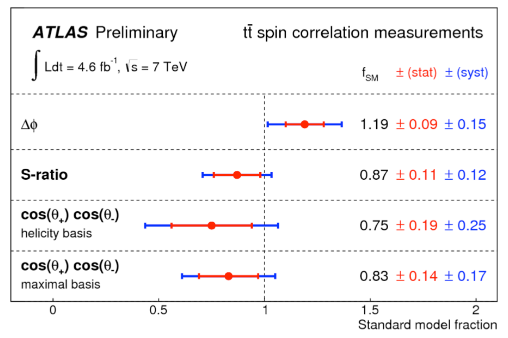
ATLAS-CONF-2013-101

c_1, c_2, c_3, c_4: C-even, P-even ≠0 in LO QCD



$$\tilde{B}_i^\pm = b_1^\pm \hat{p}_i + b_2^\pm \hat{k}_i + b_3^\pm n_i \,,$$

$$\tilde{C}_{ij} = c_1 \delta_{ij} + c_2 \hat{p}_i \hat{p}_j + c_3 \hat{k}_i \hat{k}_j$$

$$+ c_4 (\hat{p}_i \hat{k}_j + \hat{k}_i \hat{p}_j) + c_5 \epsilon^{ijl} \hat{p}_l + c_6 \epsilon^{ijl} \hat{k}_l$$

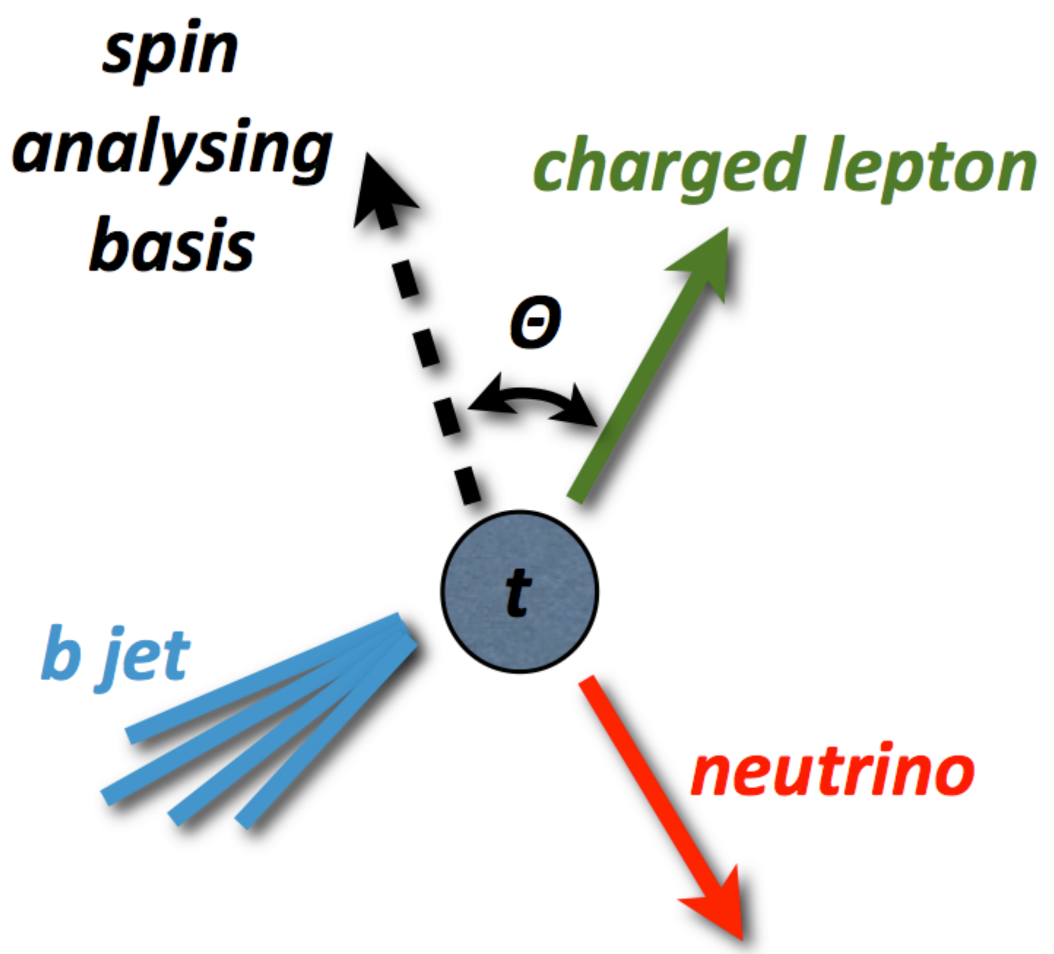
c_5, c_6: P-odd, CP-odd ≠0 only in BSM

→ close collaboration with Bernreuther et al. needed

Polarisation power

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_i}=\frac{1}{2}(1+\alpha_i\cos\theta_i)$$

in $t\bar{t}$ ZMF frame



in top quark rest frame

dilepton channel promises largest sensitivity

Brandenburg, Si, Uwer,
Phys. Lett. B539, 235 (2002)

	b-quark	W^+	l^+	$\bar{d}$-quark or $\bar{s}$-quark	u-quark or c-quark
α_i (LO)	-0.41	0.41	1	1	-0.31
α_i (NLO)	-0.39	0.39	0.998	0.93	-0.31

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1\, d\cos\theta_2}=\frac{1}{4}(1-C\cos\theta_1\cos\theta_2)$$

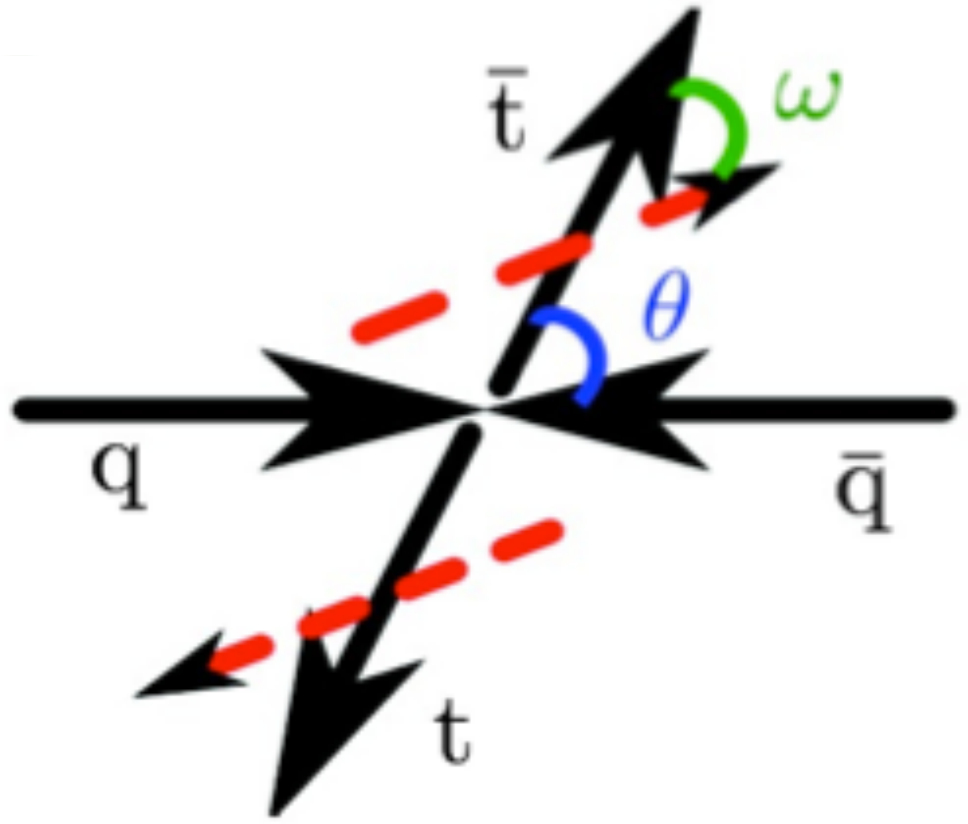
$$\text{where } C=A\alpha_1\alpha_2$$

linear extraction:

A=C

Spin correlation strength

Tevatron



- interpolate between beam and helicity basis
- optimised "off-diagonal" basis

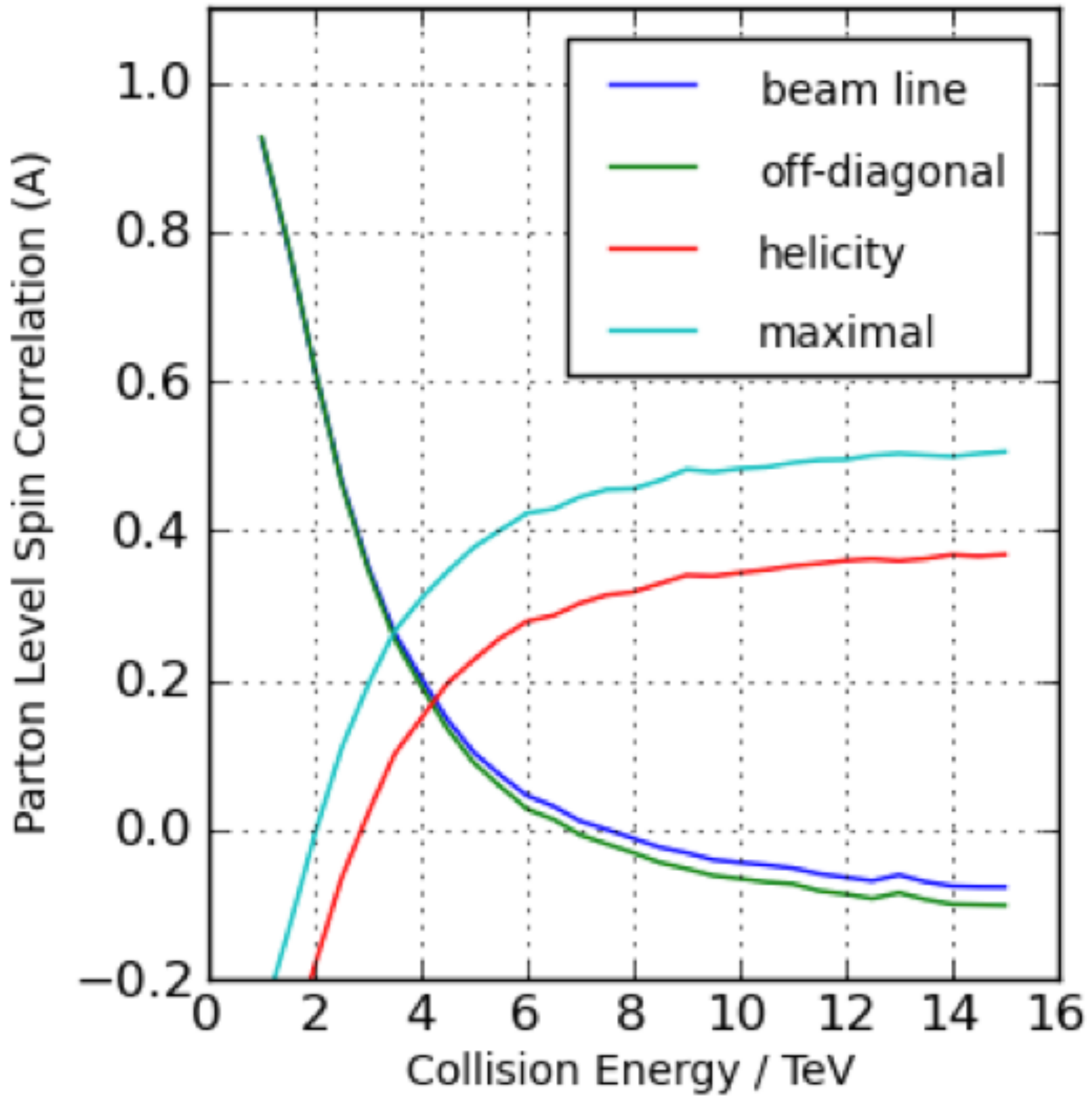
$$\tan\omega = \sqrt{(1-\beta^2)}\tan\theta$$

NLO QCD: A= 0.78

Bernreuther, Brandenburg, Si, Uwer, Nucl. Phys. B690, 81 (2004)

LHC

HERWIG++



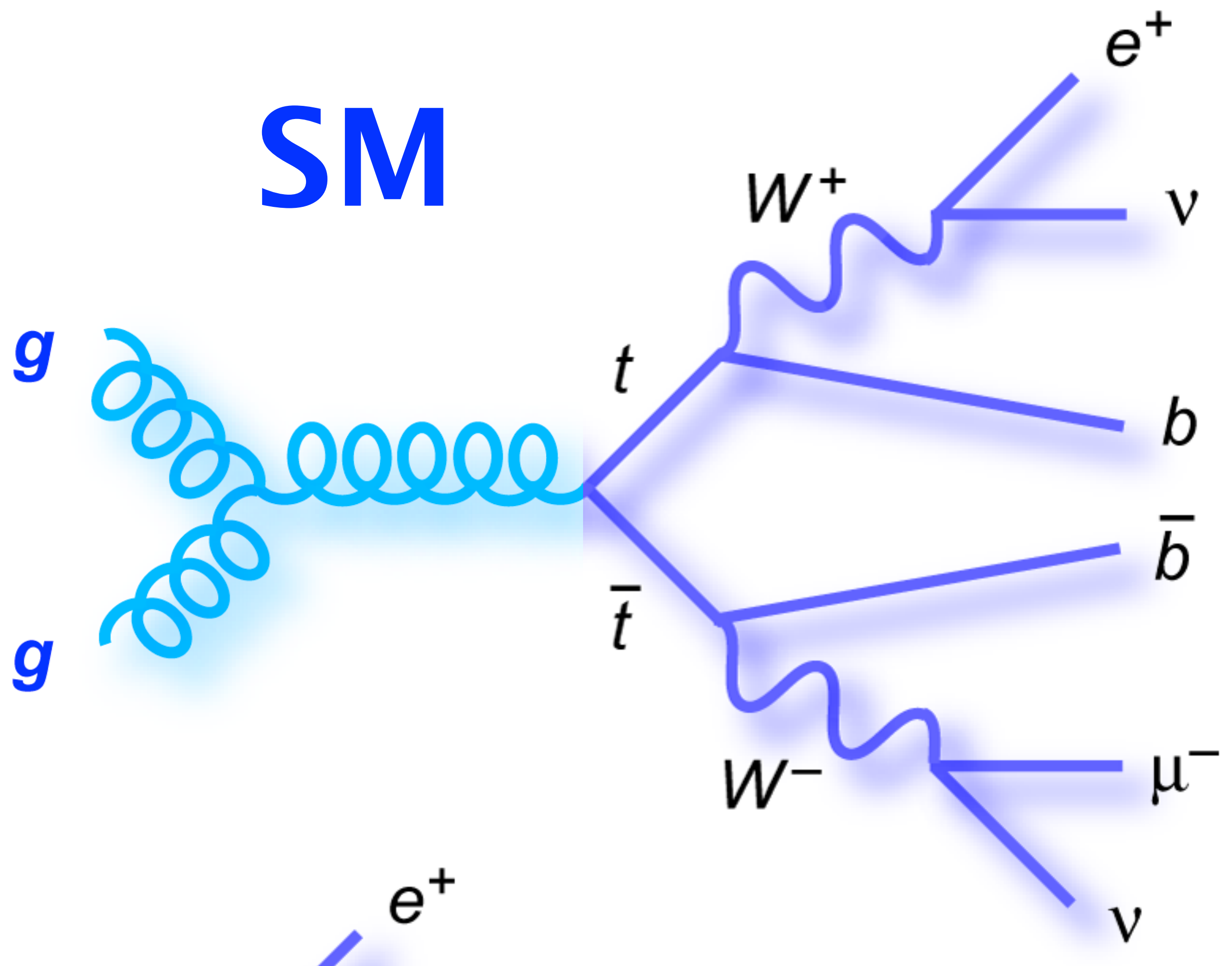
- there is no "optimal" basis for gg fusion on an event-by-event basis
- maximal basis

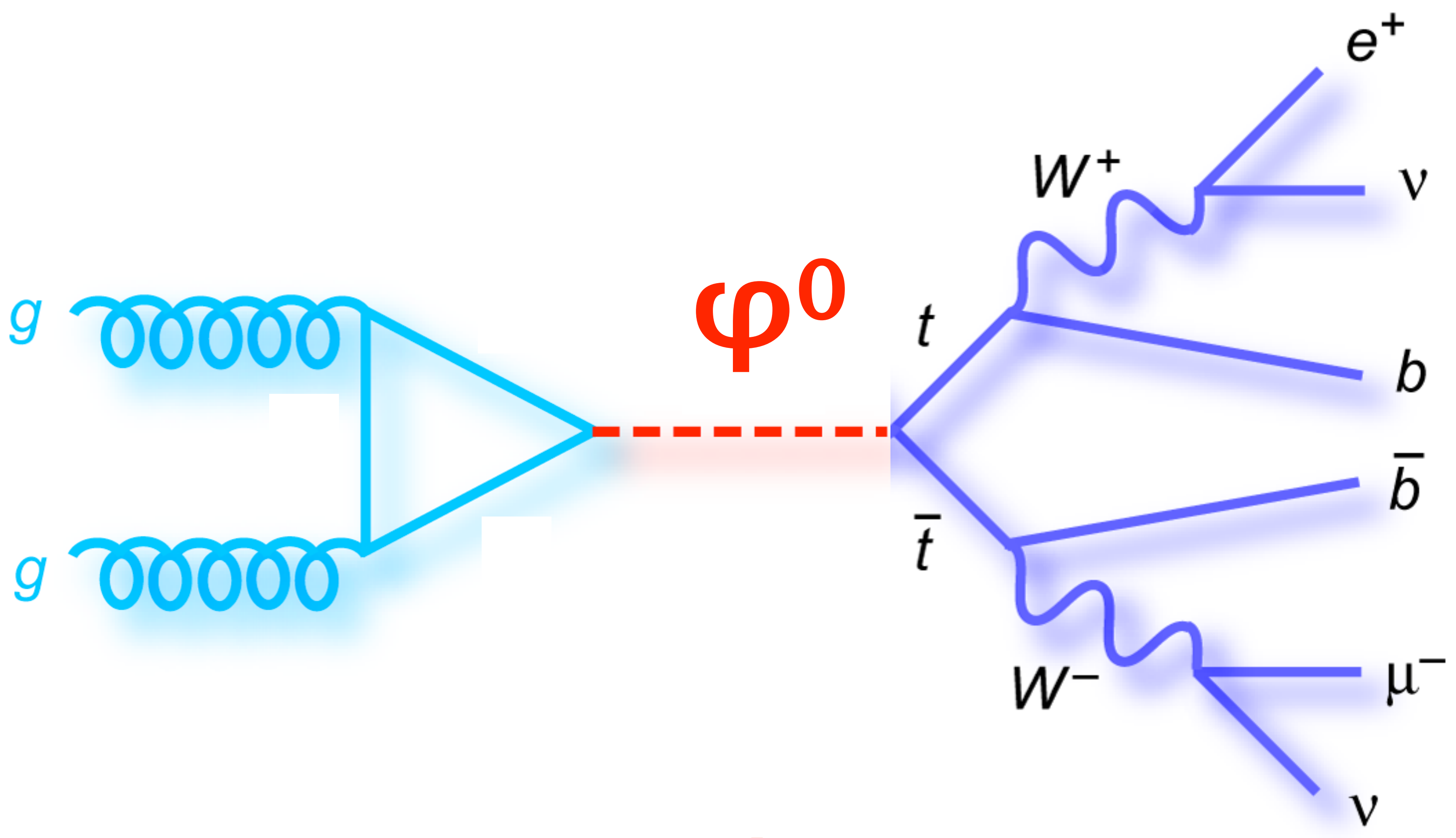
NLO QCD: A = 0.44

Uwer, Phys. Lett., B609:271–276, 2005

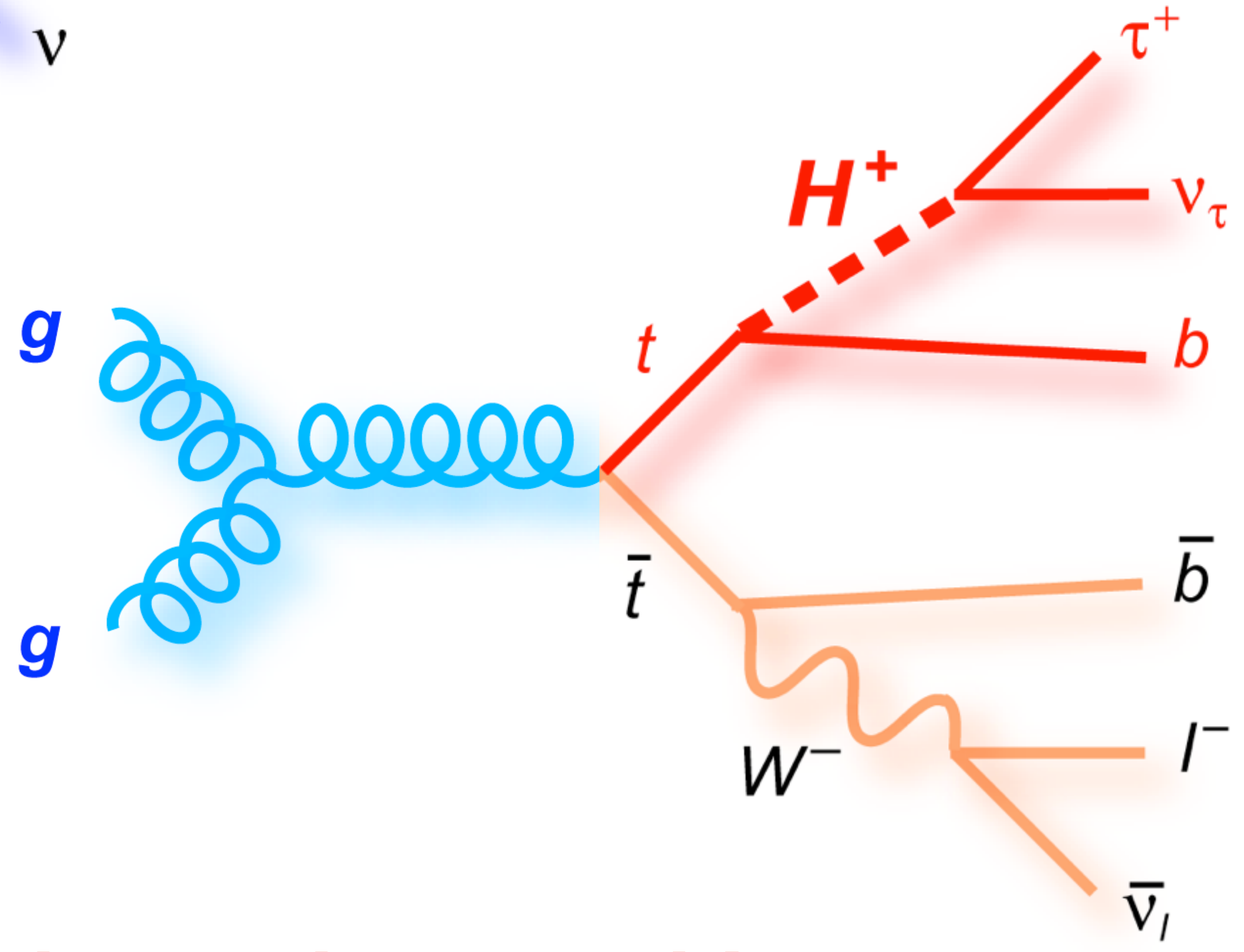
New physics impact on spin correlations

- important test of SM and sensitive search for physics beyond
- analyse the whole chain of top pair production and top decay





Higgs, KK gravitons, Z’, stop pairs, …



charged Higgs, b’, …