

Top quark production at the $t\bar{t}$ threshold at CMS



Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

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DESY, University of Hamburg



On behalf of the CMS Collaboration



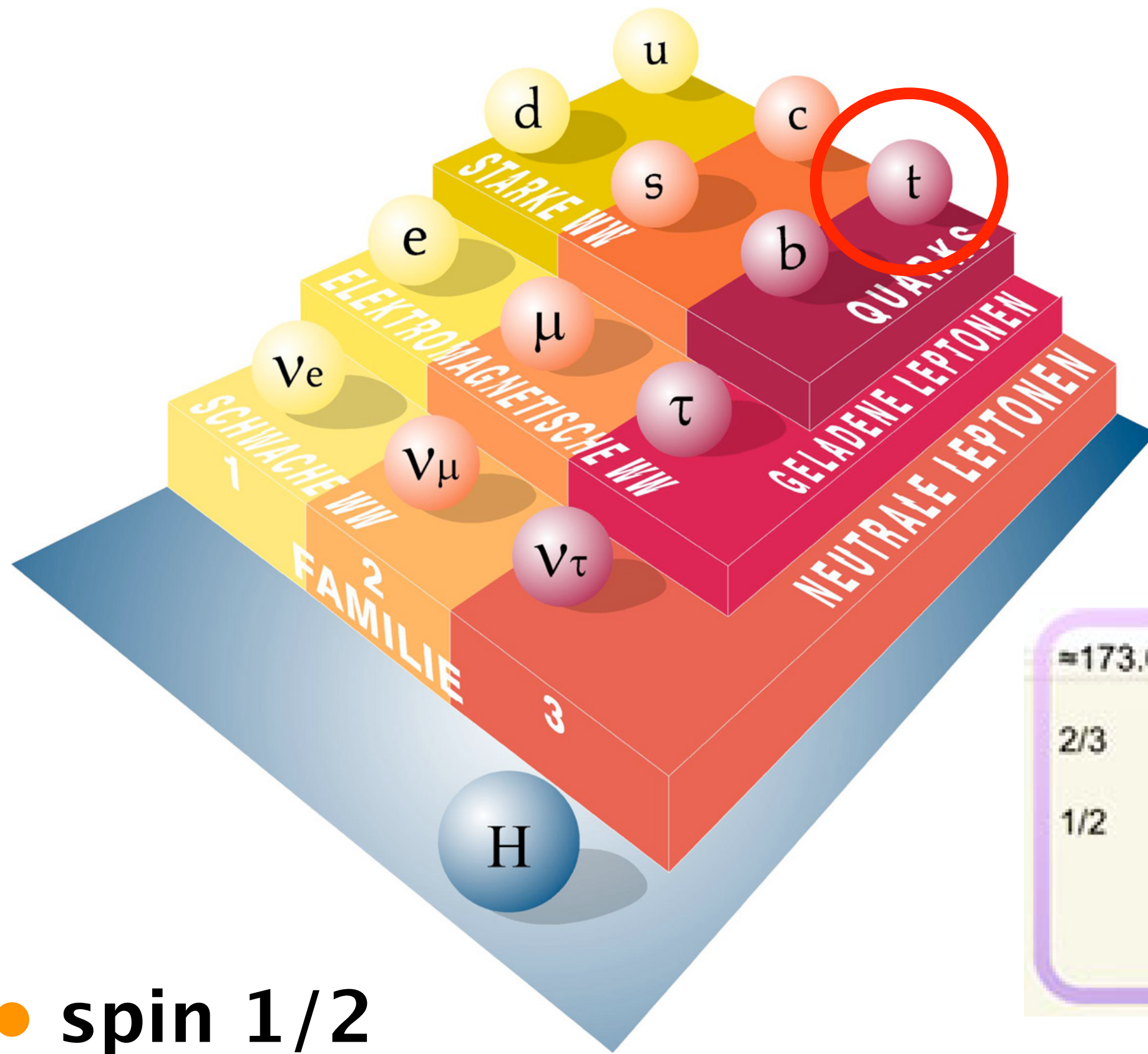
EPS-HEP Conference

7 July, 2025, Marseille, France

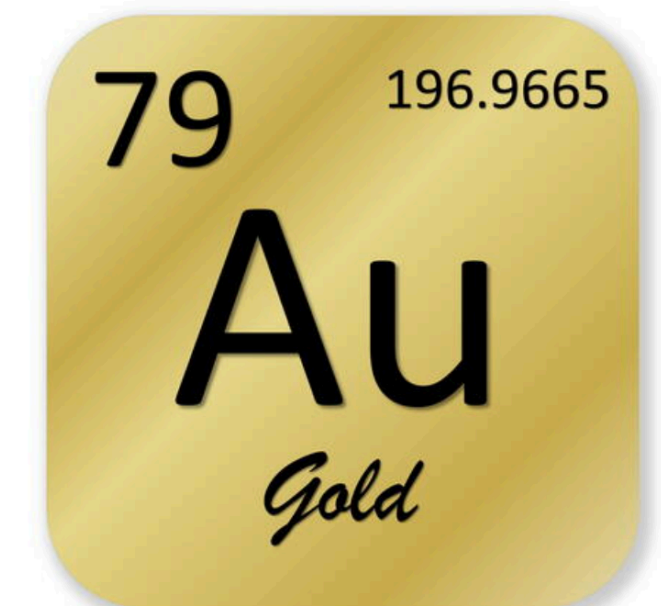
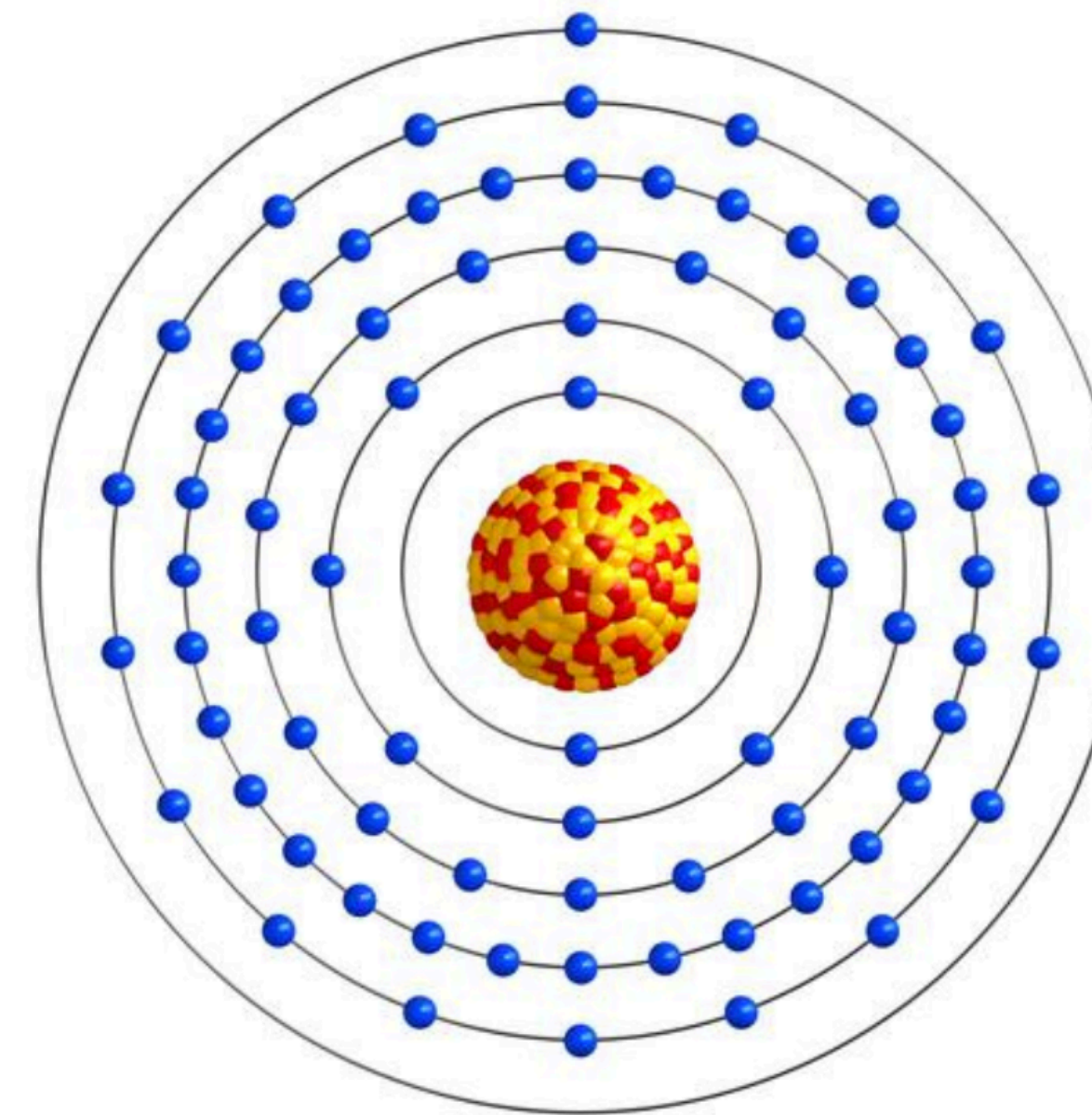
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

HELMHOLTZ
SPITZENFORSCHUNG FÜR
GROSSE HERAUSFORDERUNGEN

The top quark: Heaviest Elementary Particle



- $m_{\text{top}} = 172.52 \pm 0.33 \text{ GeV} \sim \text{weight of gold nucleus}$



● 79Protons ● 118Neutrons ● 79Electrons



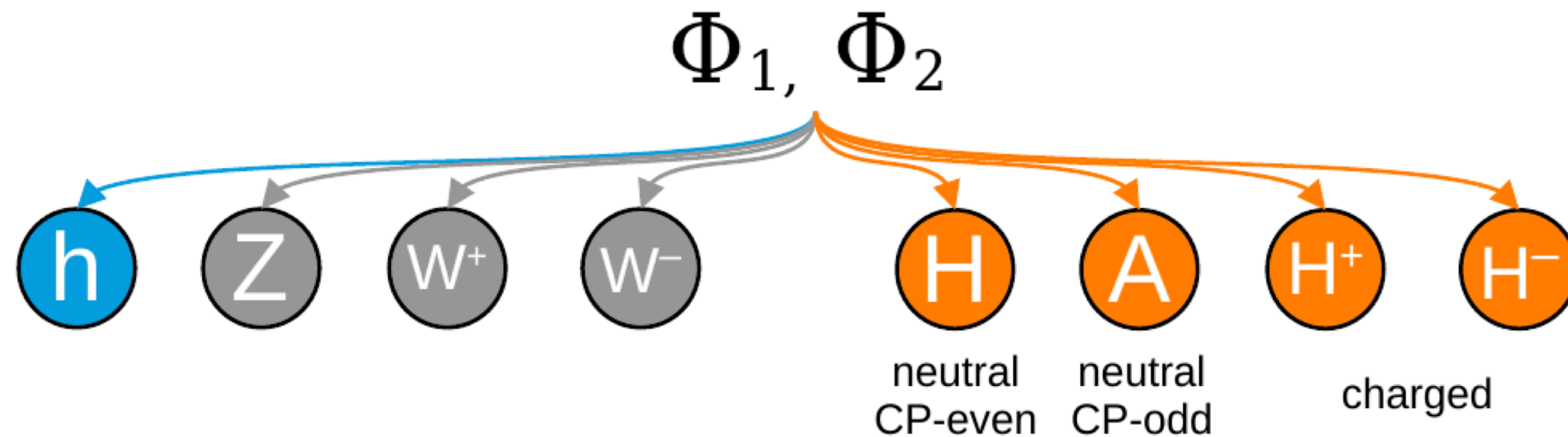
- spin 1/2
- short lifetime: $\tau \sim 5 \cdot 10^{-25} \text{ s} \ll \Lambda^{-1}_{\text{QCD}}$: decays before it fragments
→ observe “naked” quark
- large coupling to Higgs boson ~ 1
important role in EWK symmetry breaking?
- do they connect to new (pseudo-)scalars?

Is the top quark connected to new physics?

Search for Extensions of the Higgs Sector

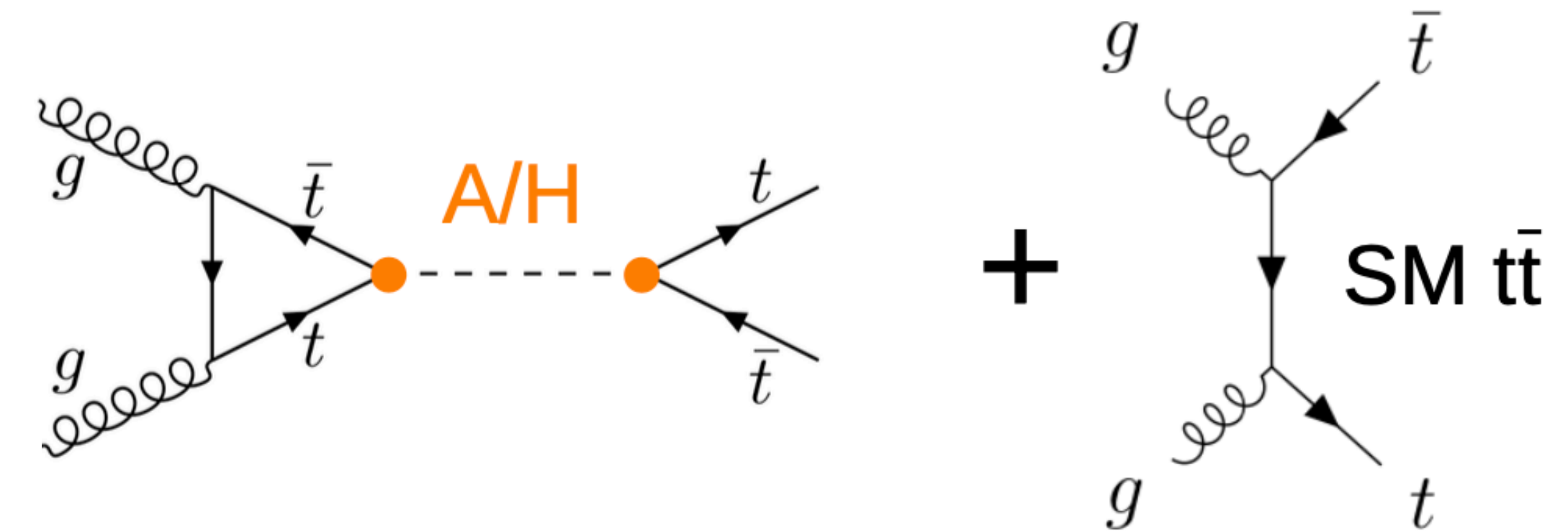
2 Higgs Doublet Model (2HDM)

- simplest extended Higgs model

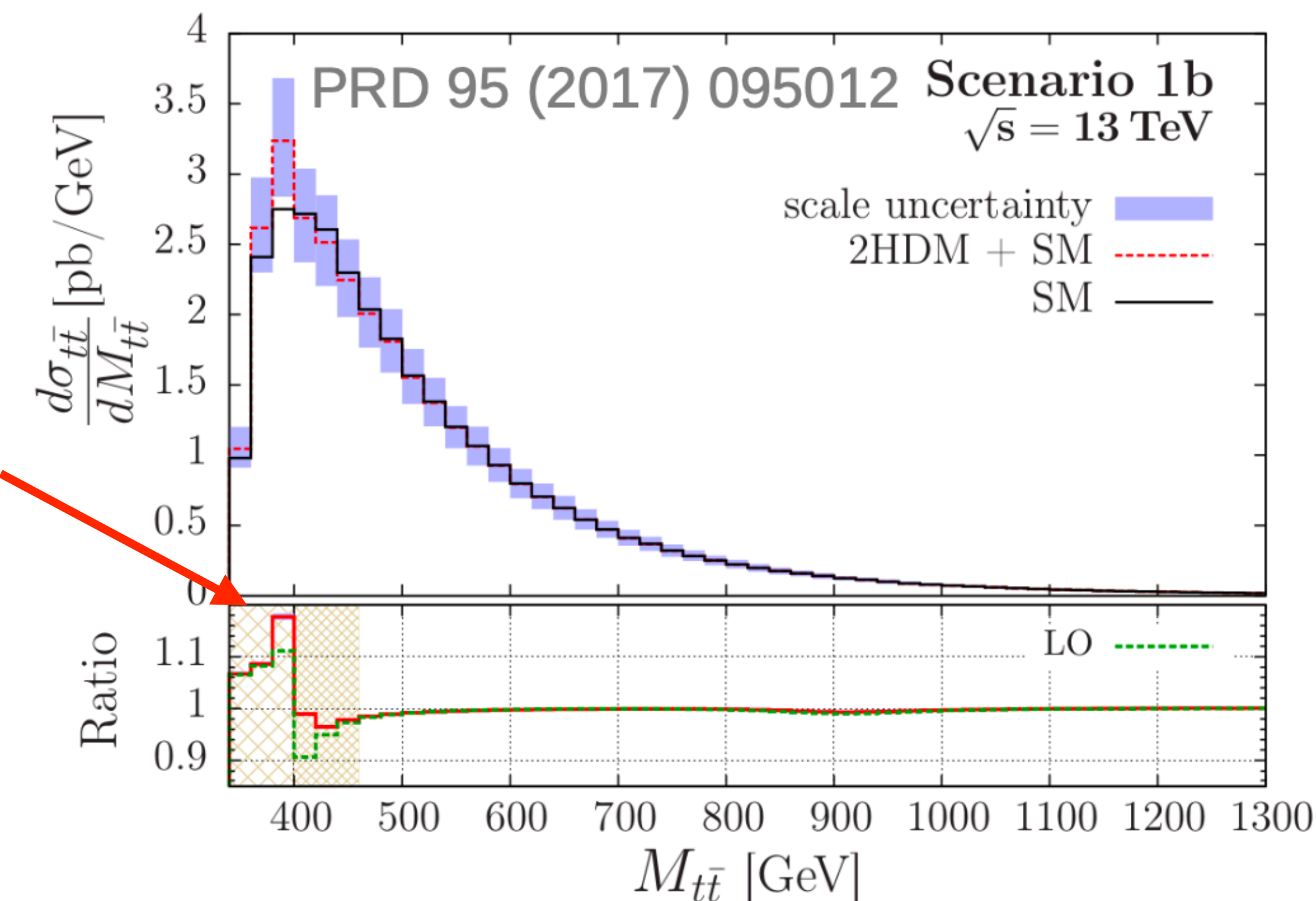


- if couplings are Yukawa-like:
strongest couplings to top quarks
- $m_A, m_H > 2m_t$: decay to top quark pairs

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

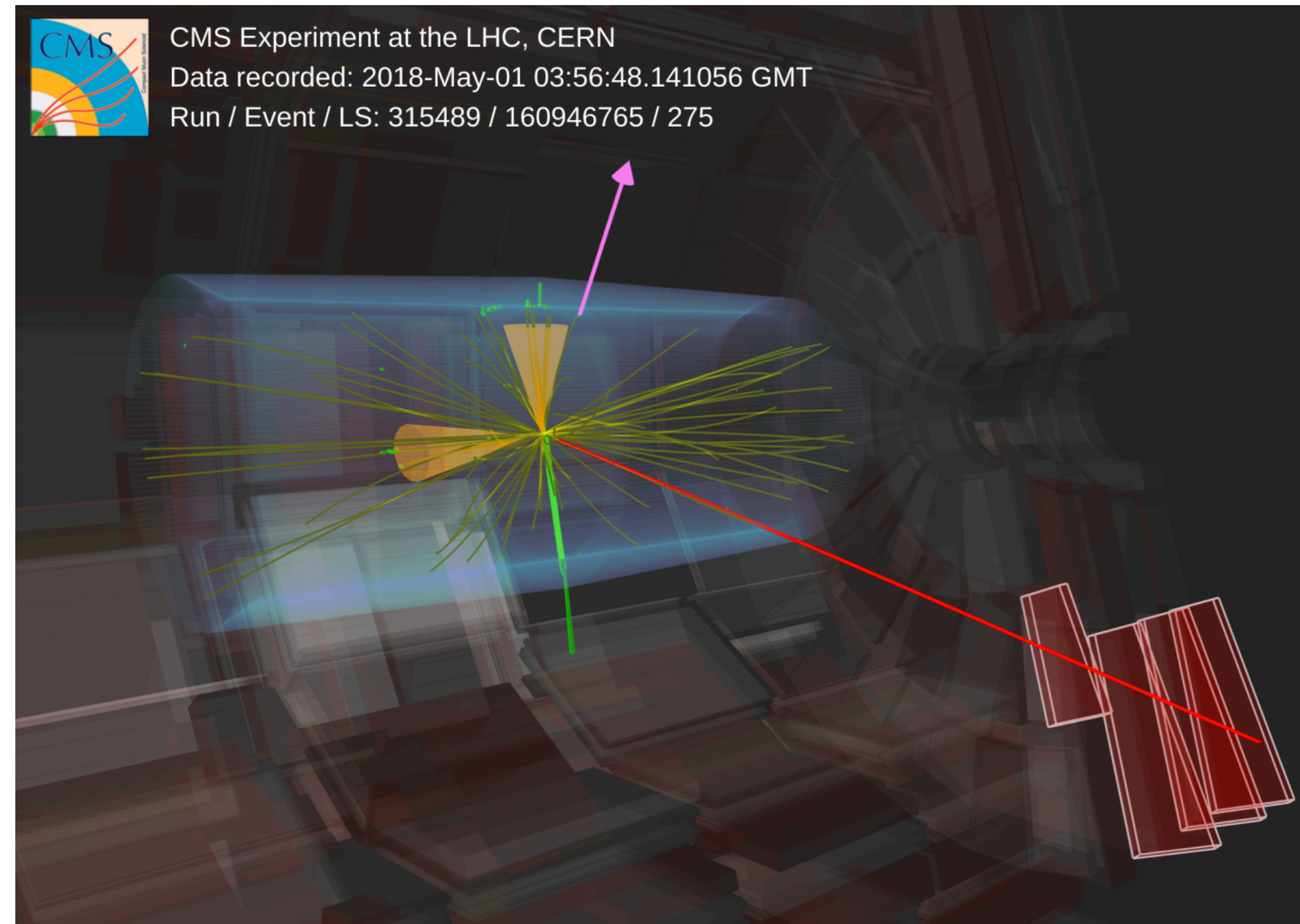
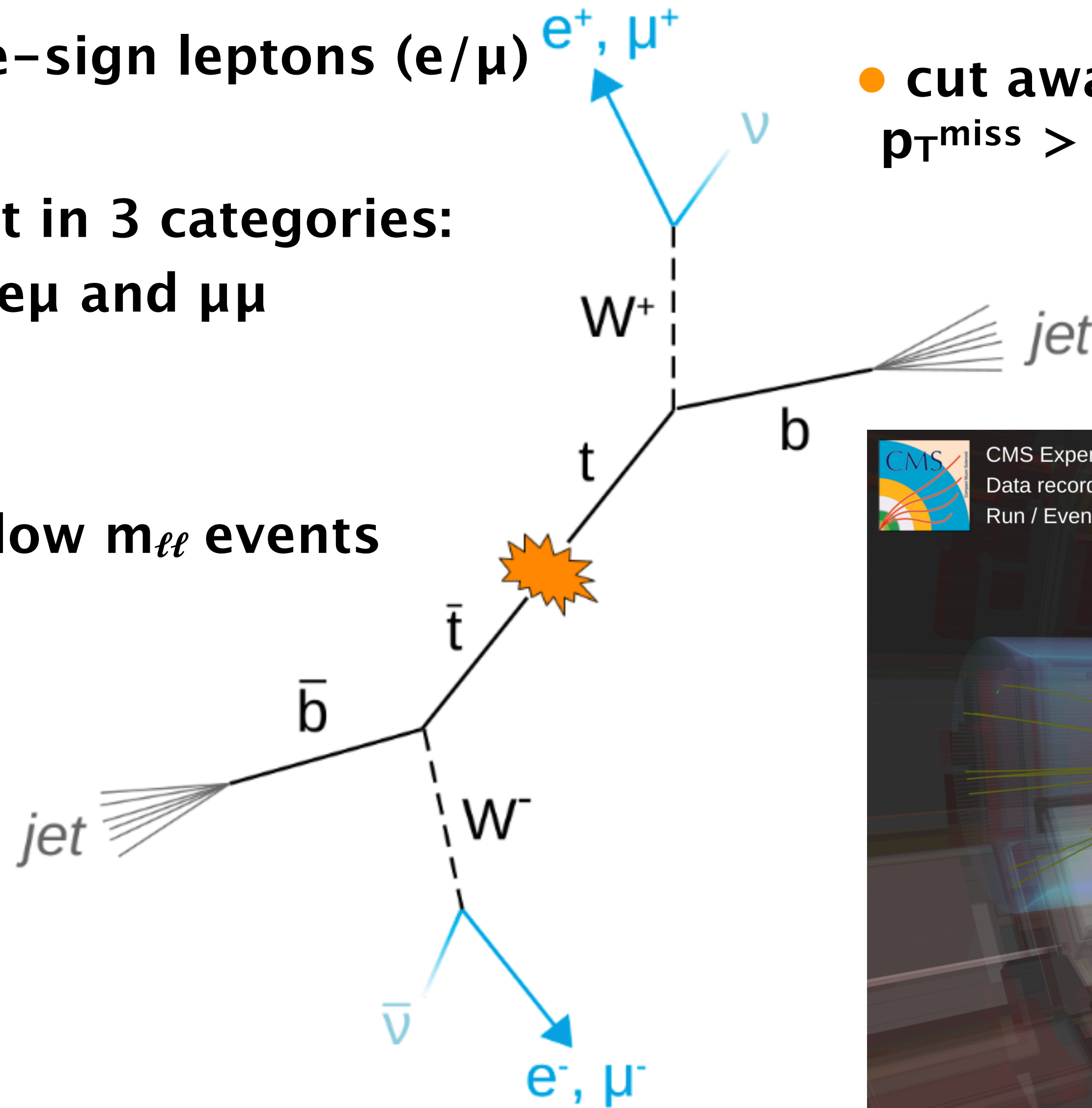


peak-dip structure



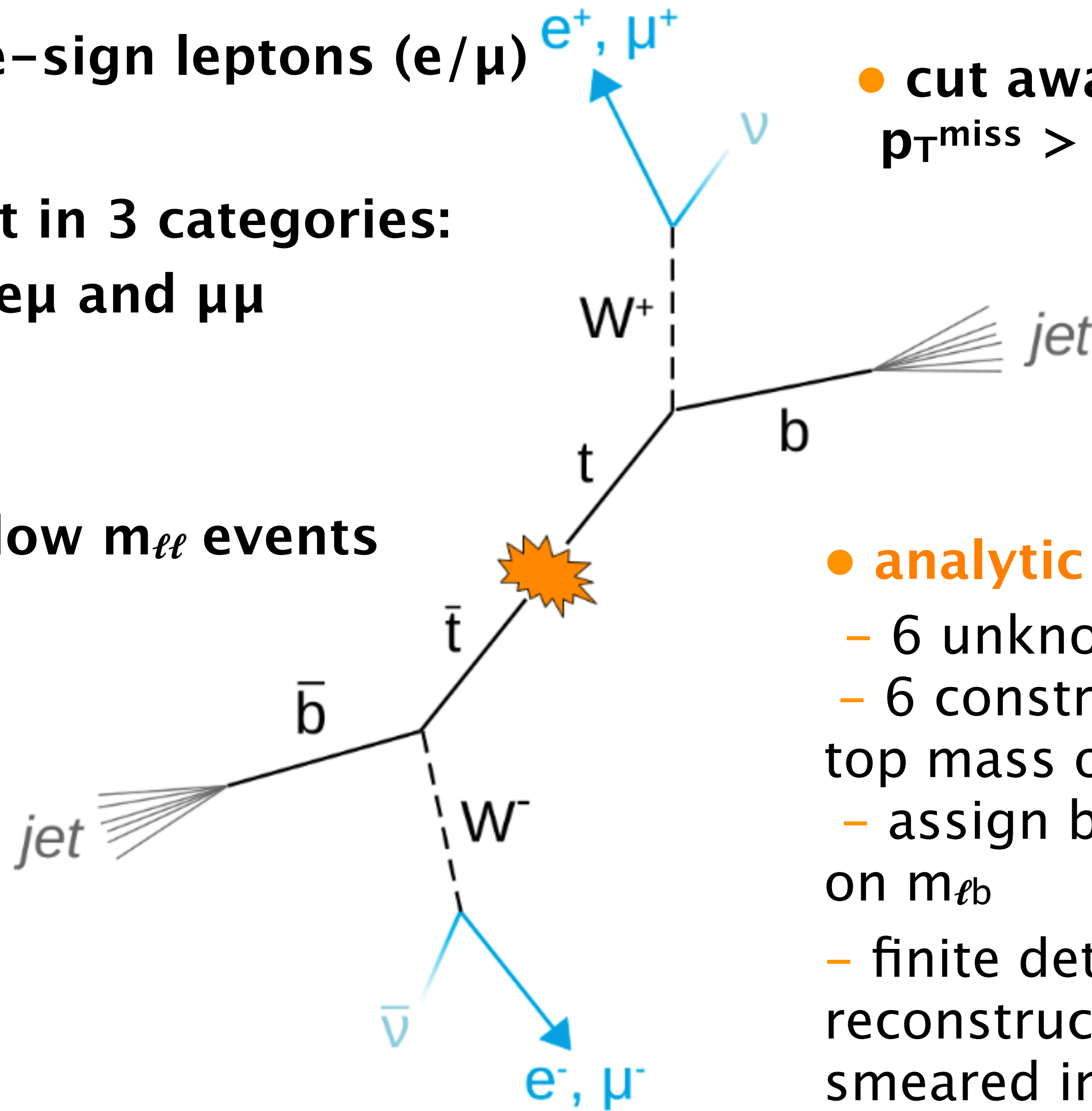
Event Selection: Dilepton Channel

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



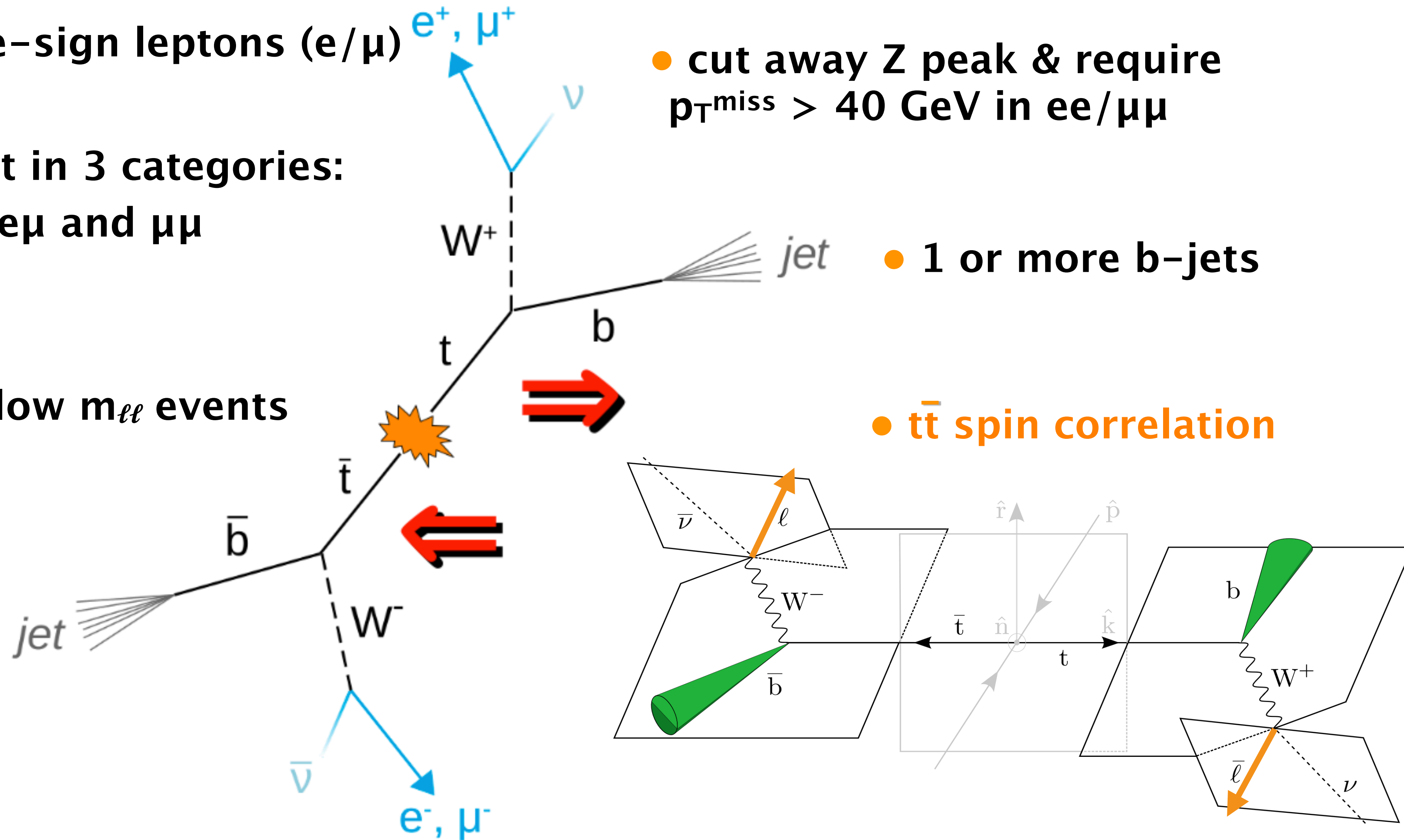
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- 2 or more jets
- cut away Z peak & require $p_T^{\text{miss}} > 40 \text{ GeV}$ in $ee/\mu\mu$
- 1 or more b-jets
- analytic reconstruction of $t\bar{t}$ system
 - 6 unknowns (2 massless neutrinos)
 - 6 constraints: all p_T^{miss} from $\nu\bar{\nu}$, 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



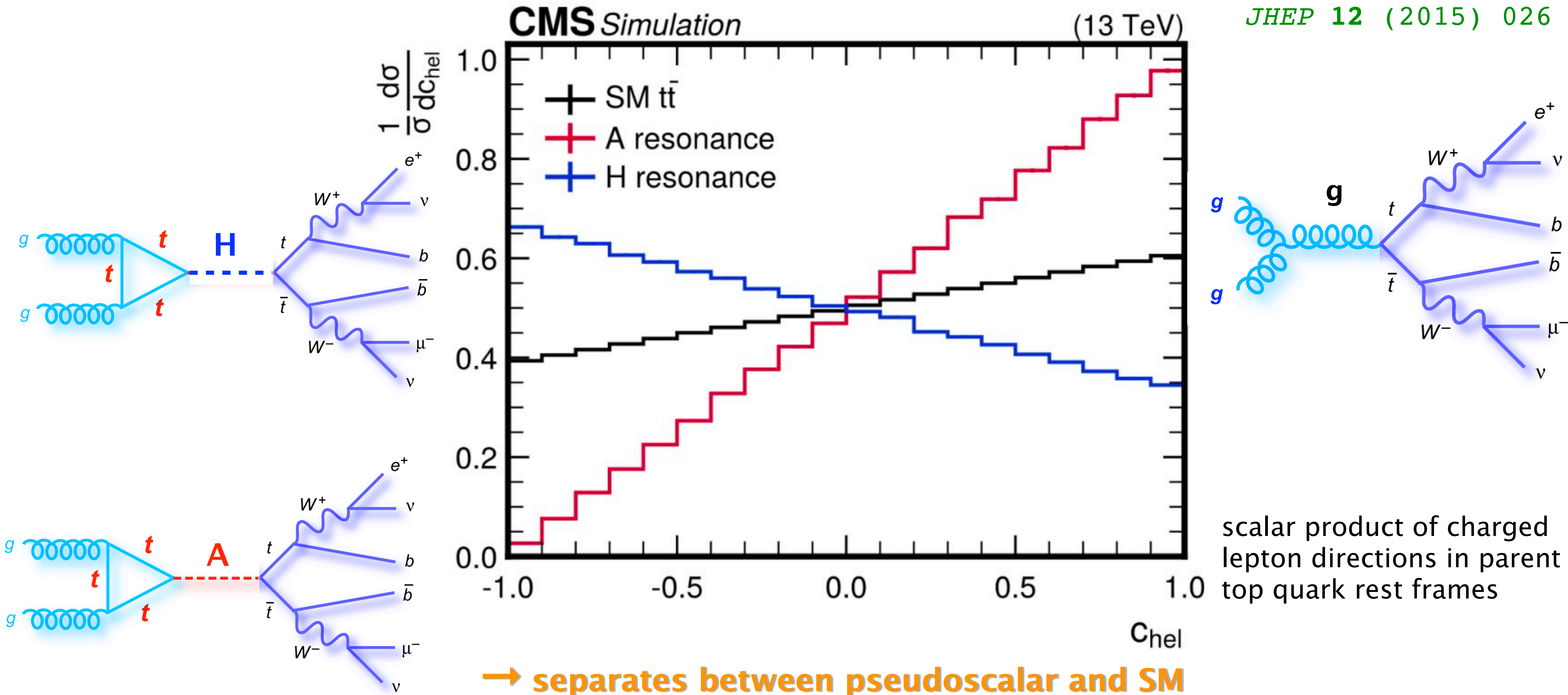
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- 1 or more b-jets
- reject low $m_{\ell\ell}$ events
- $t\bar{t}$ spin correlation
- 2 or more jets

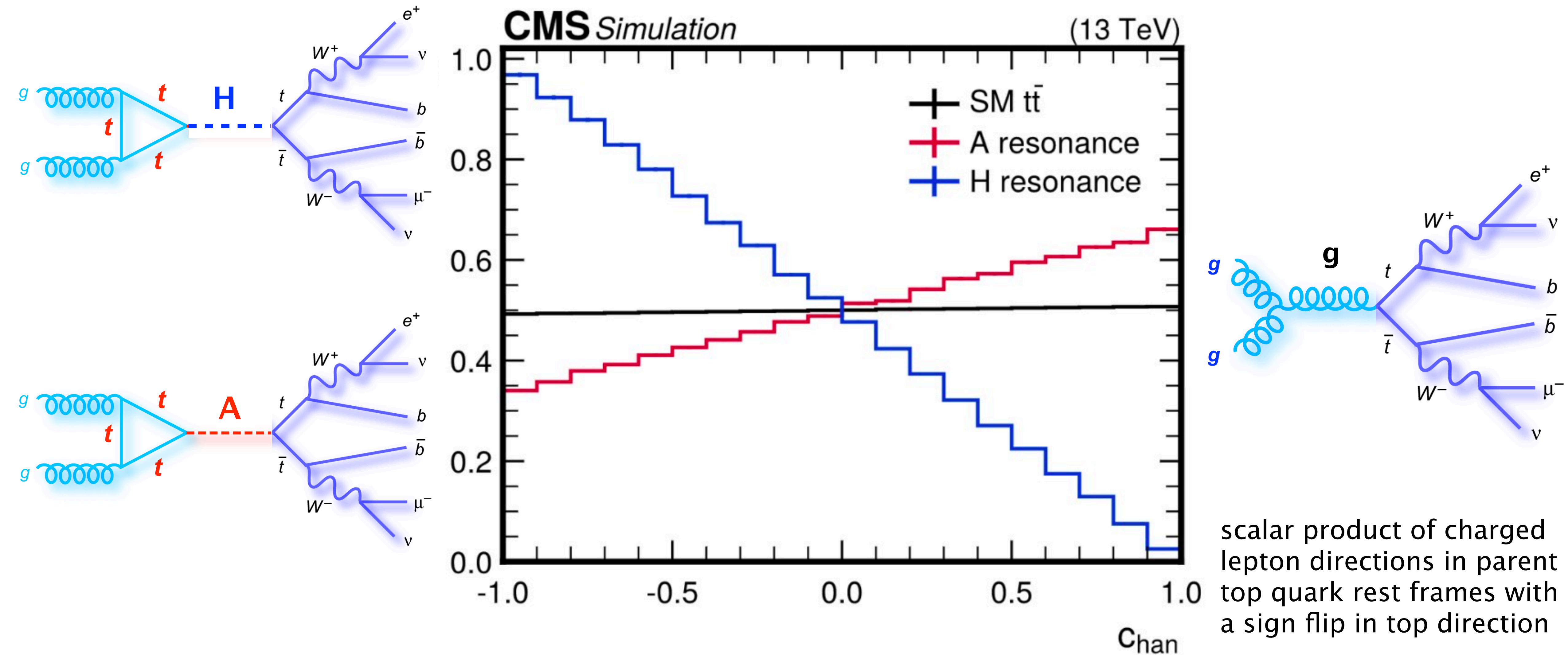


Top-Antitop Quark Spin Correlation

JHEP 12 (2015) 026

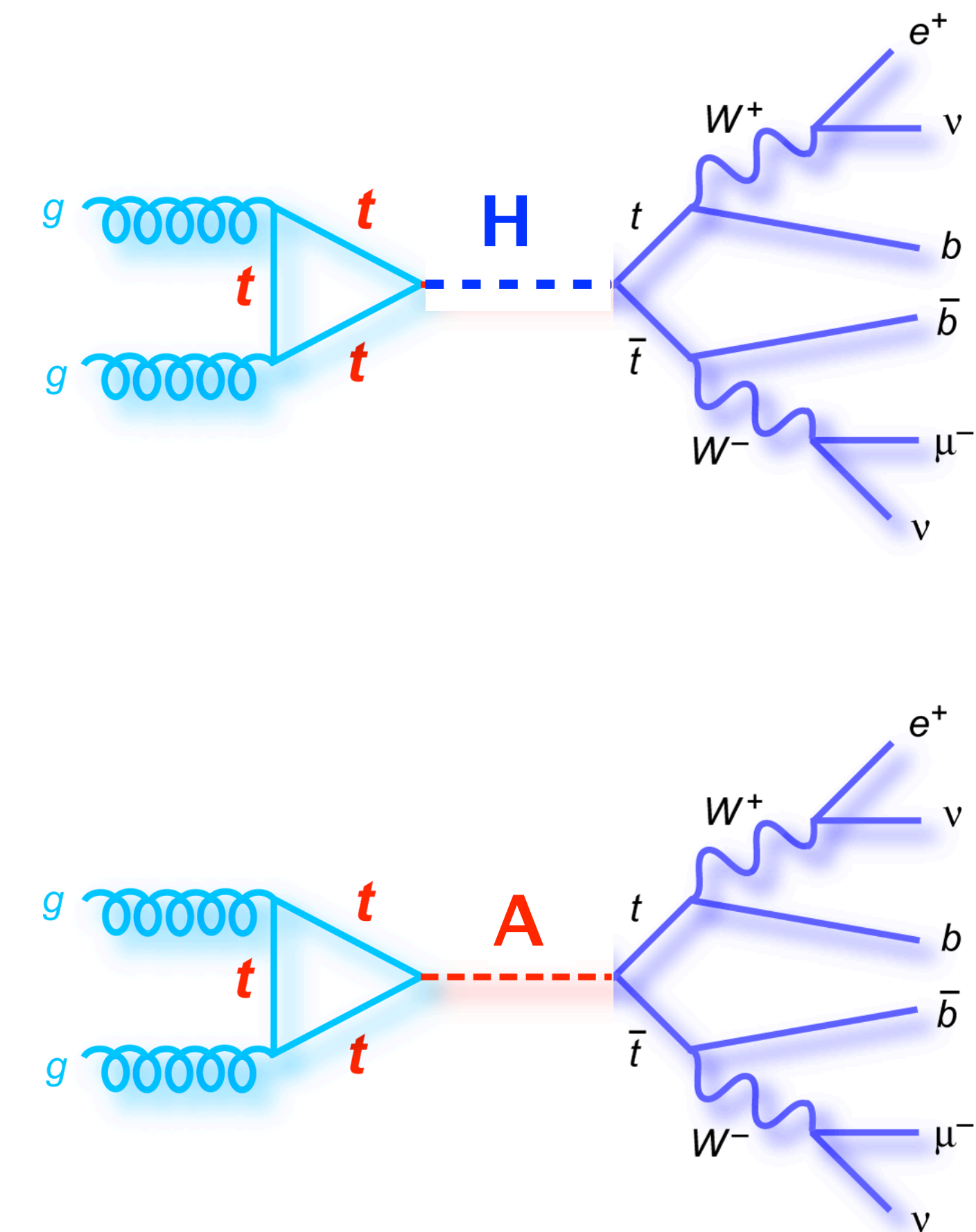


Top-Antitop Quark Spin Correlation: Dilepton

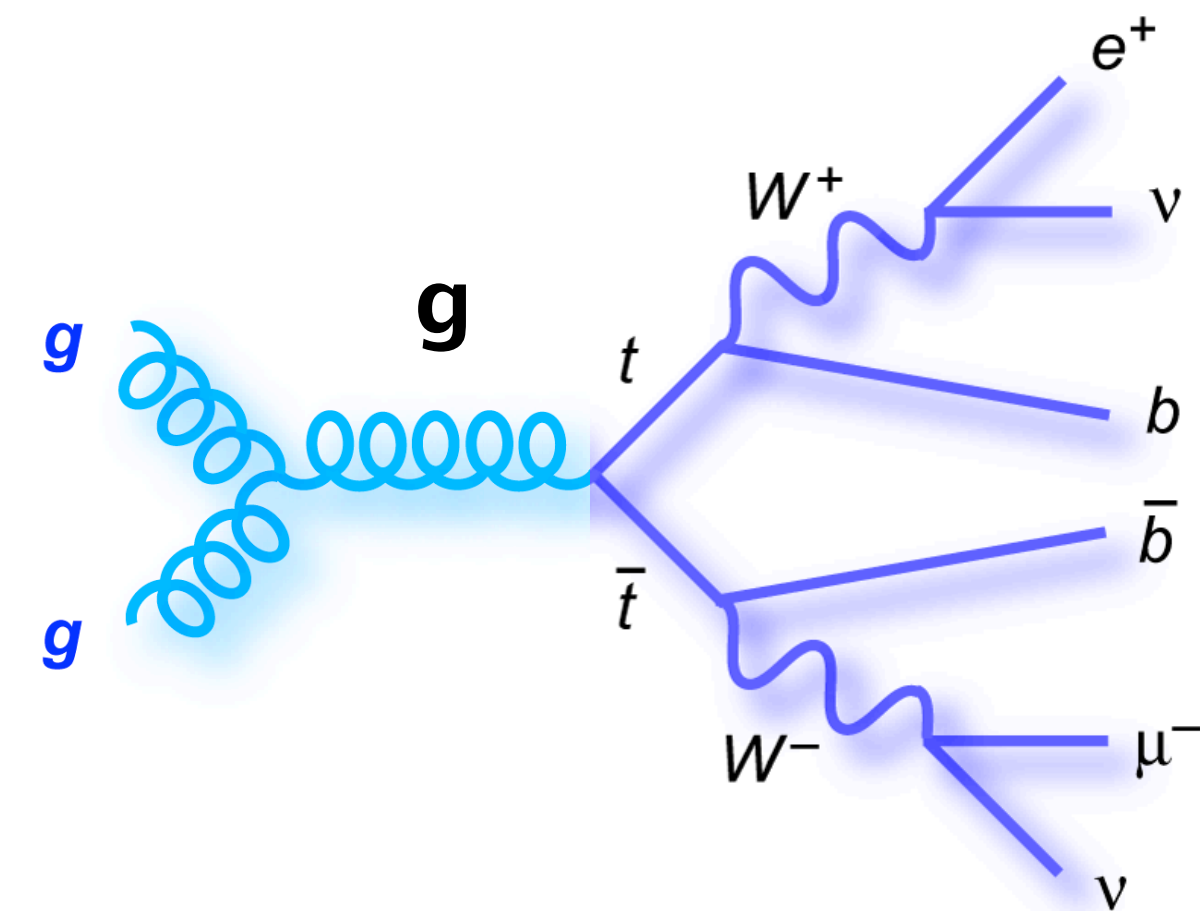
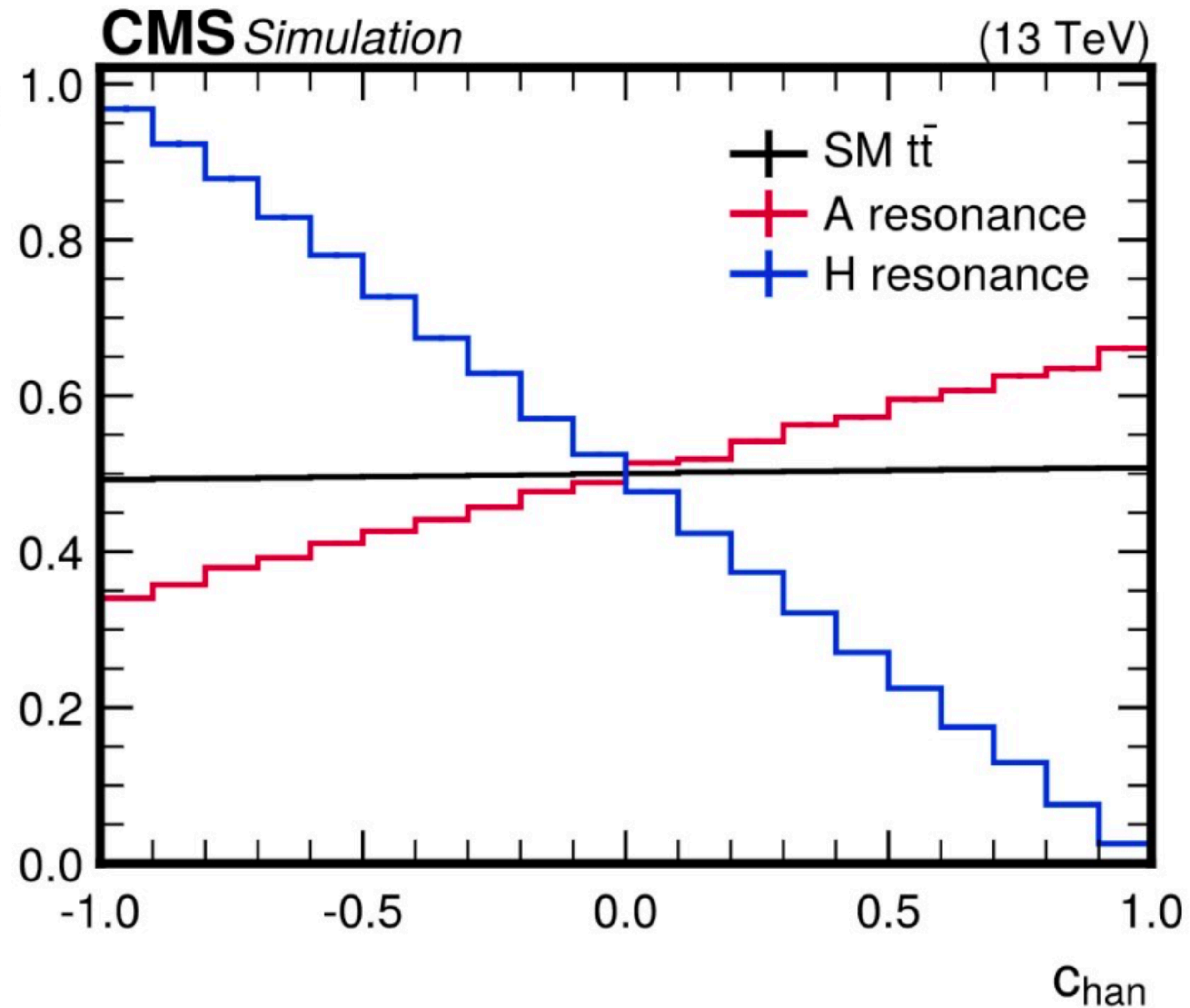


→ separates between pseudoscalar and scalar

Top-Antitop Quark Spin Correlation: Dilepton



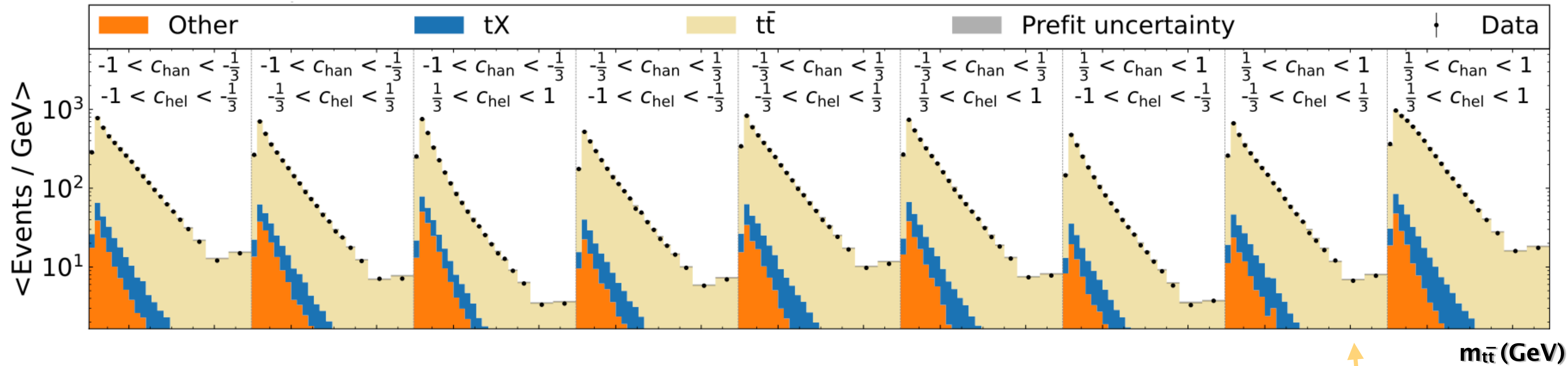
explore 3 variables simultaneously:
 $m_{t\bar{t}}$, C_{hel} , C_{chan}



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

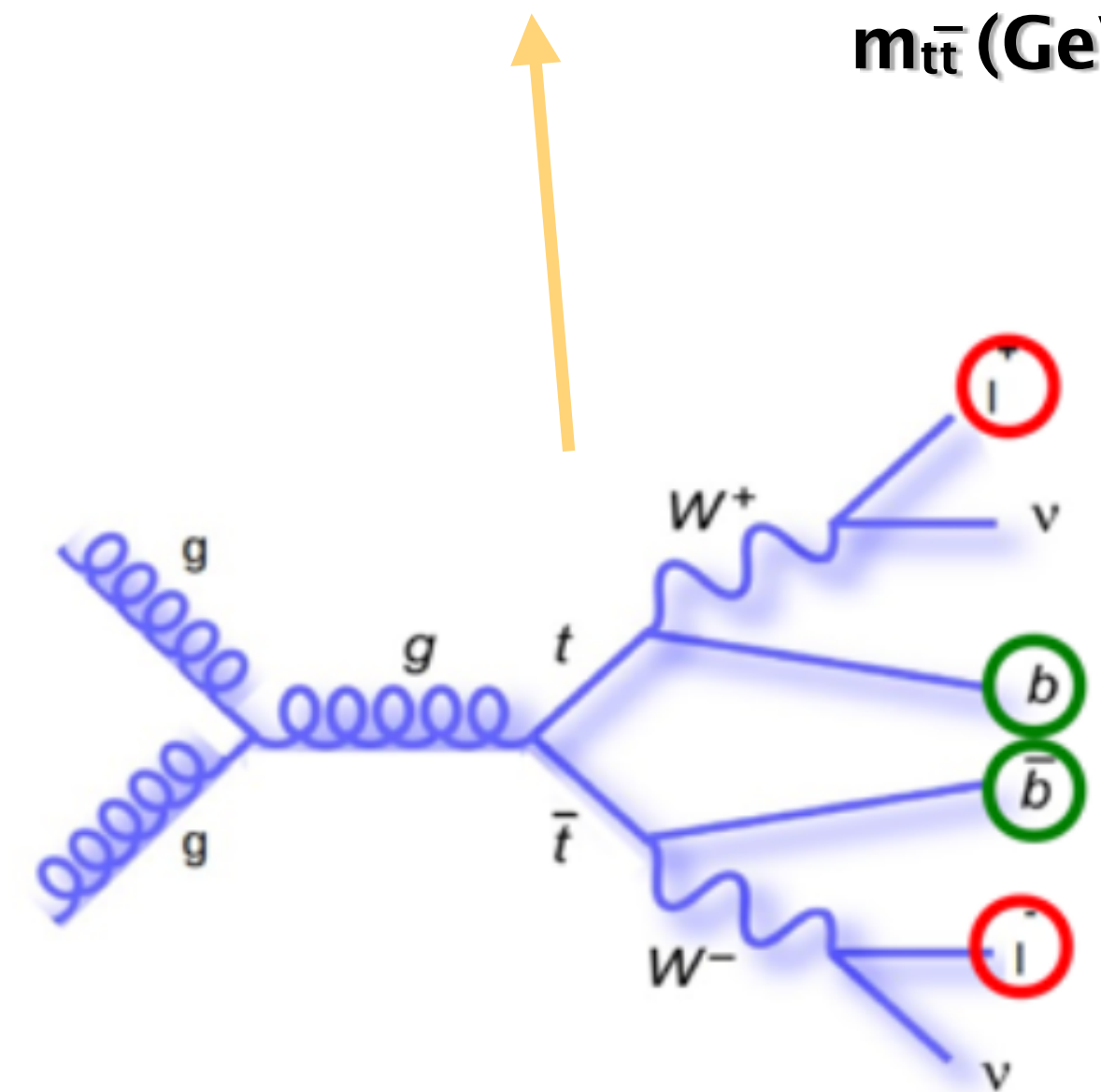
→ separates between pseudoscalar and scalar

Results and Background Modeling

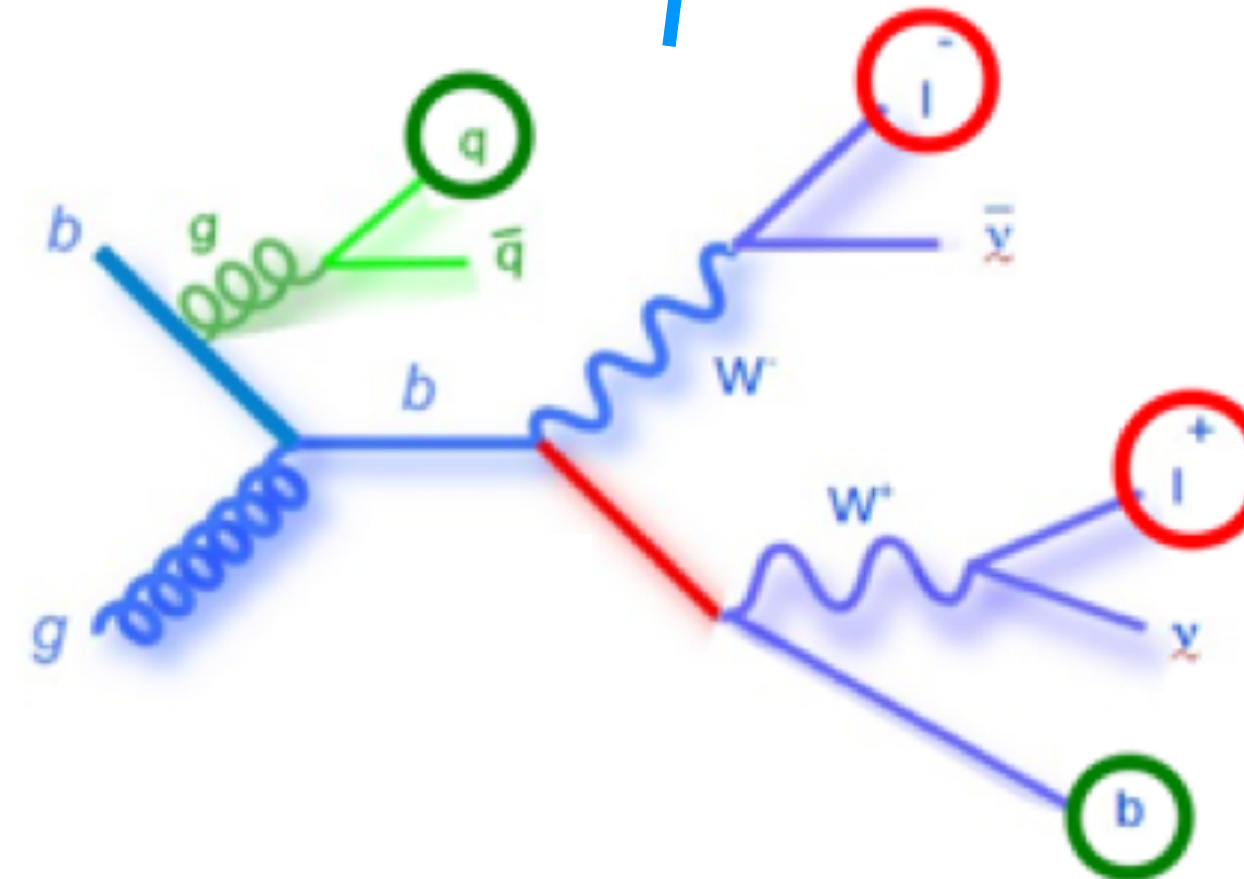
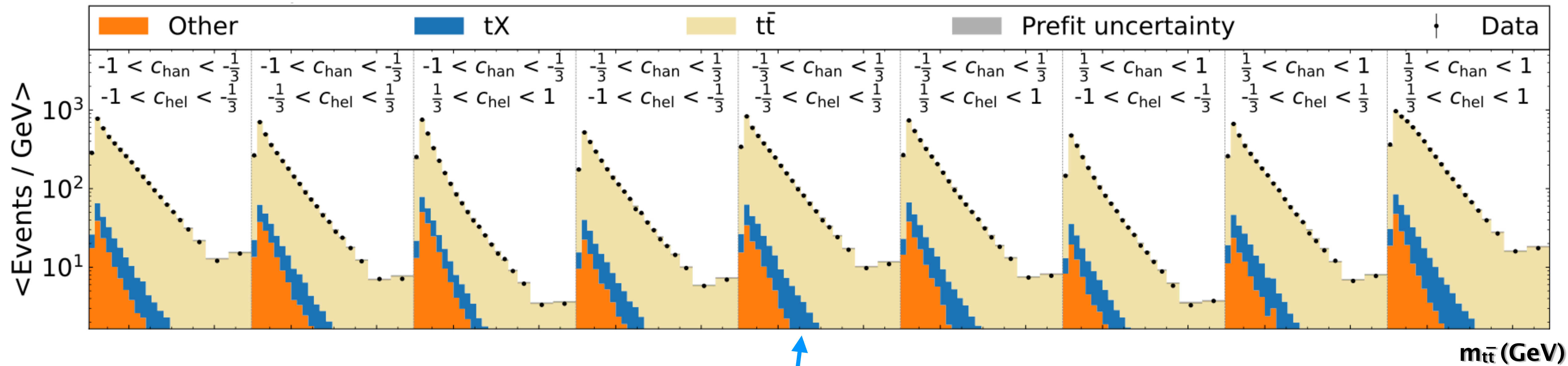


Top pair production

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



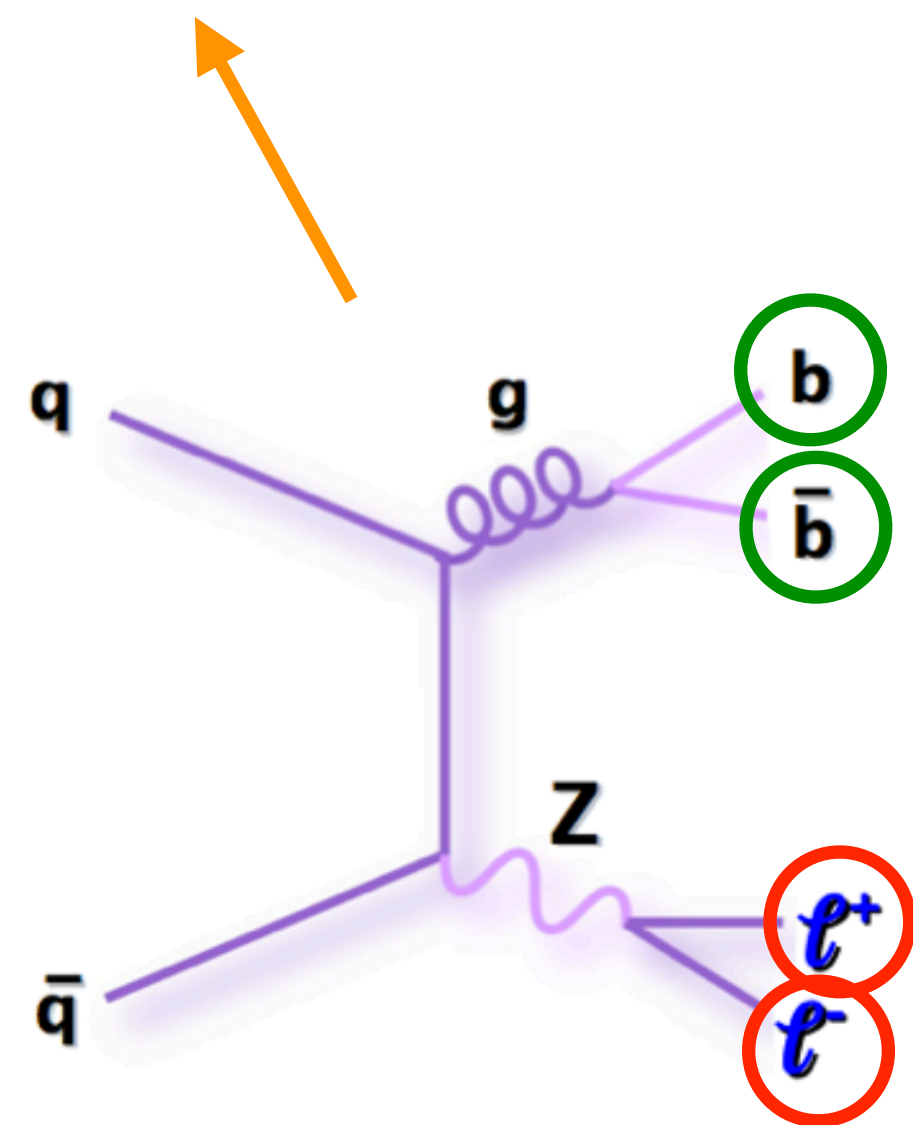
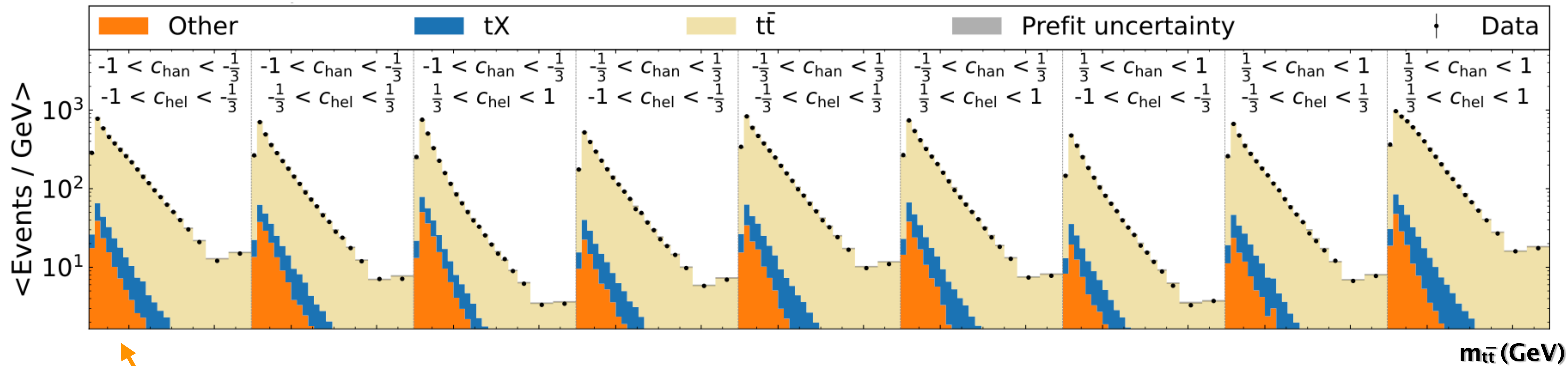
Results and Background Modeling



Single top production

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

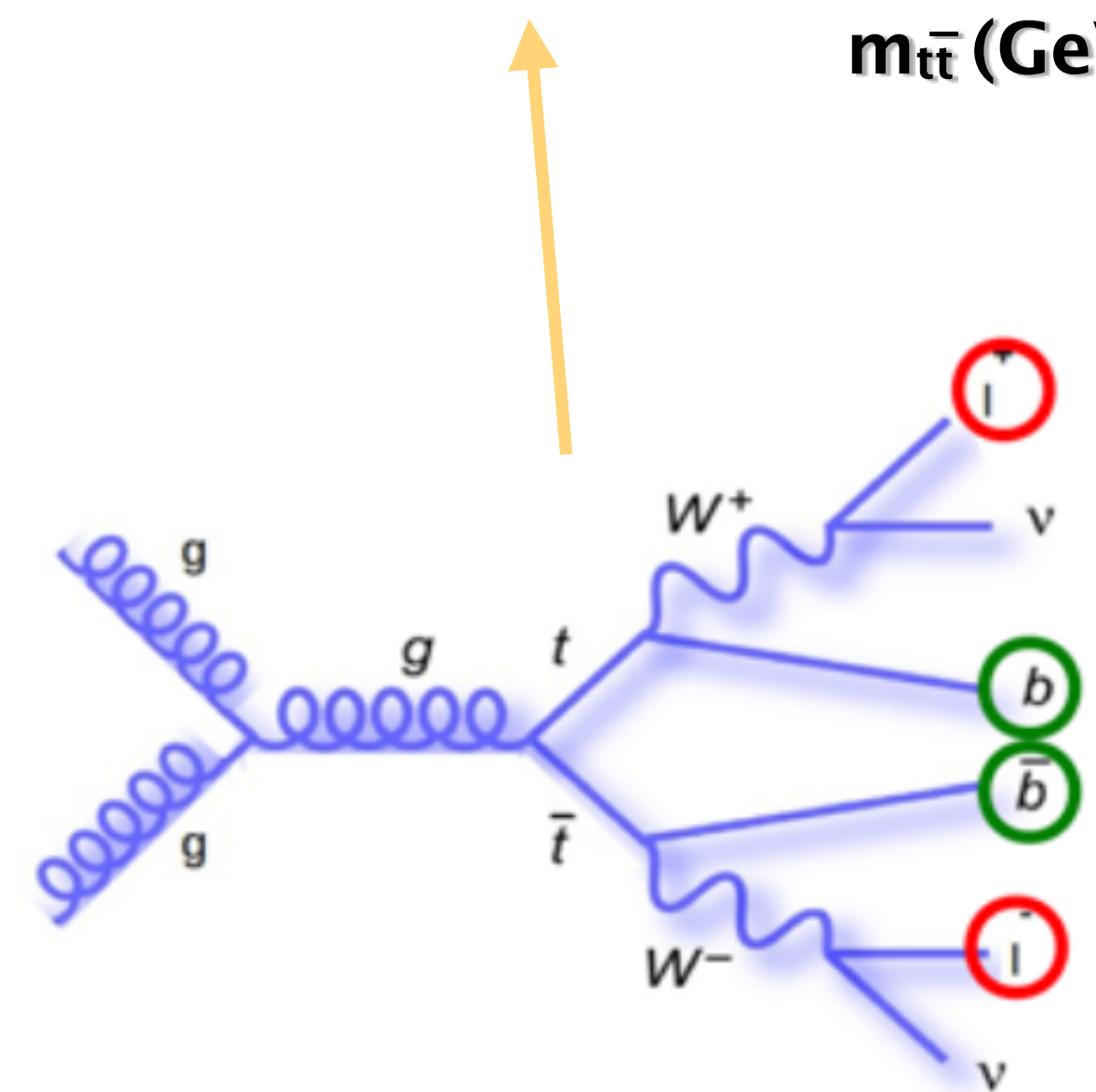
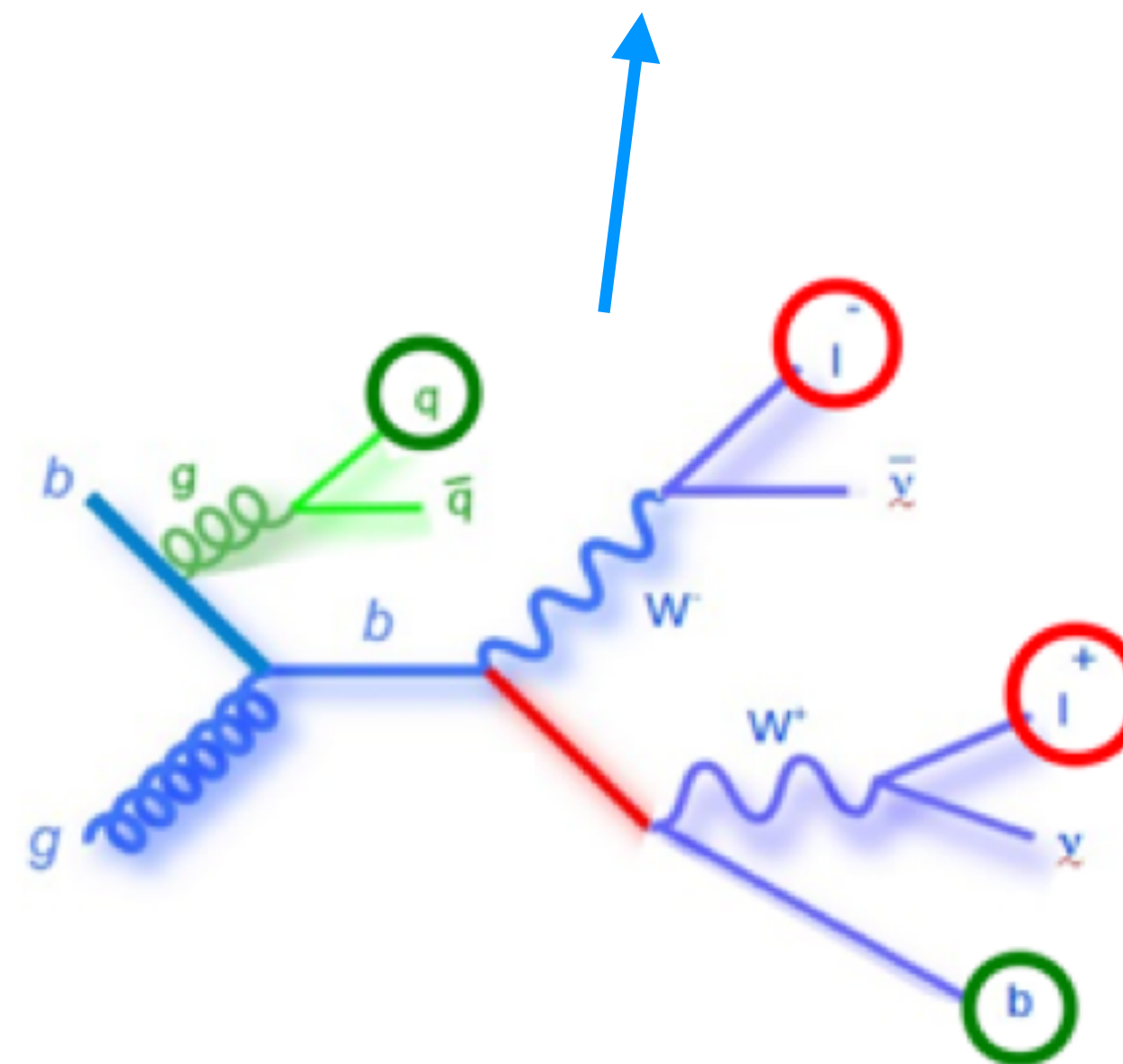
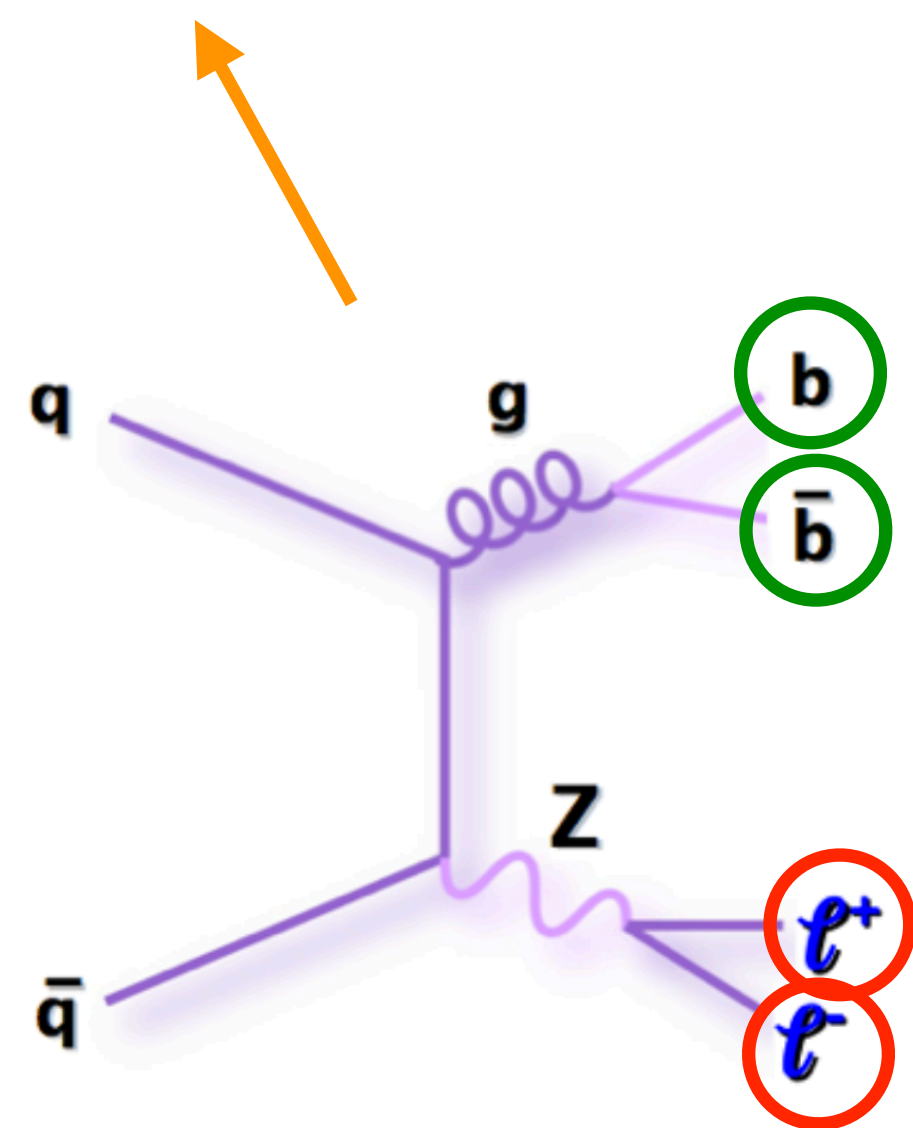
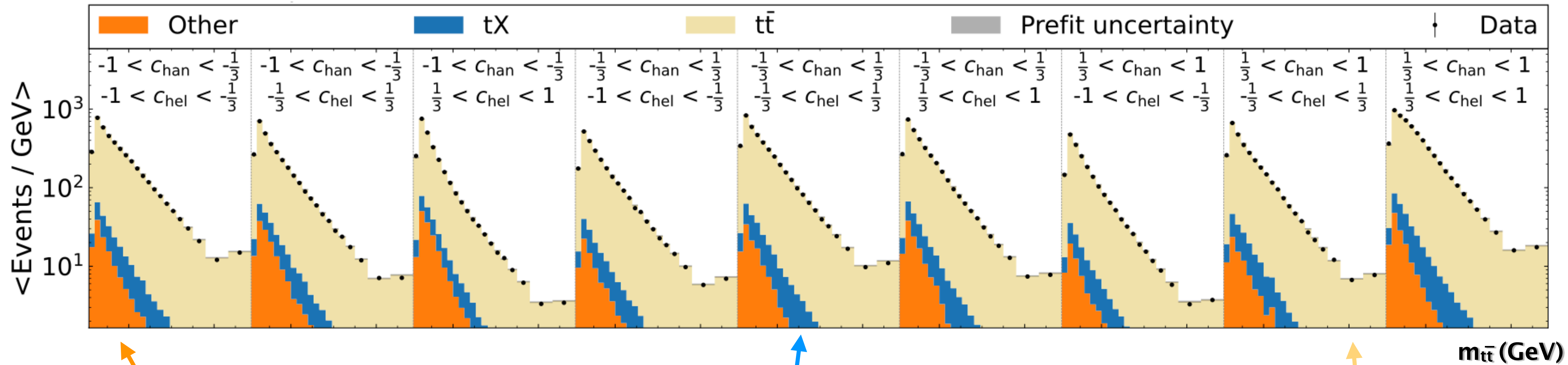
Results and Background Modeling



Drell-Yan+jets production

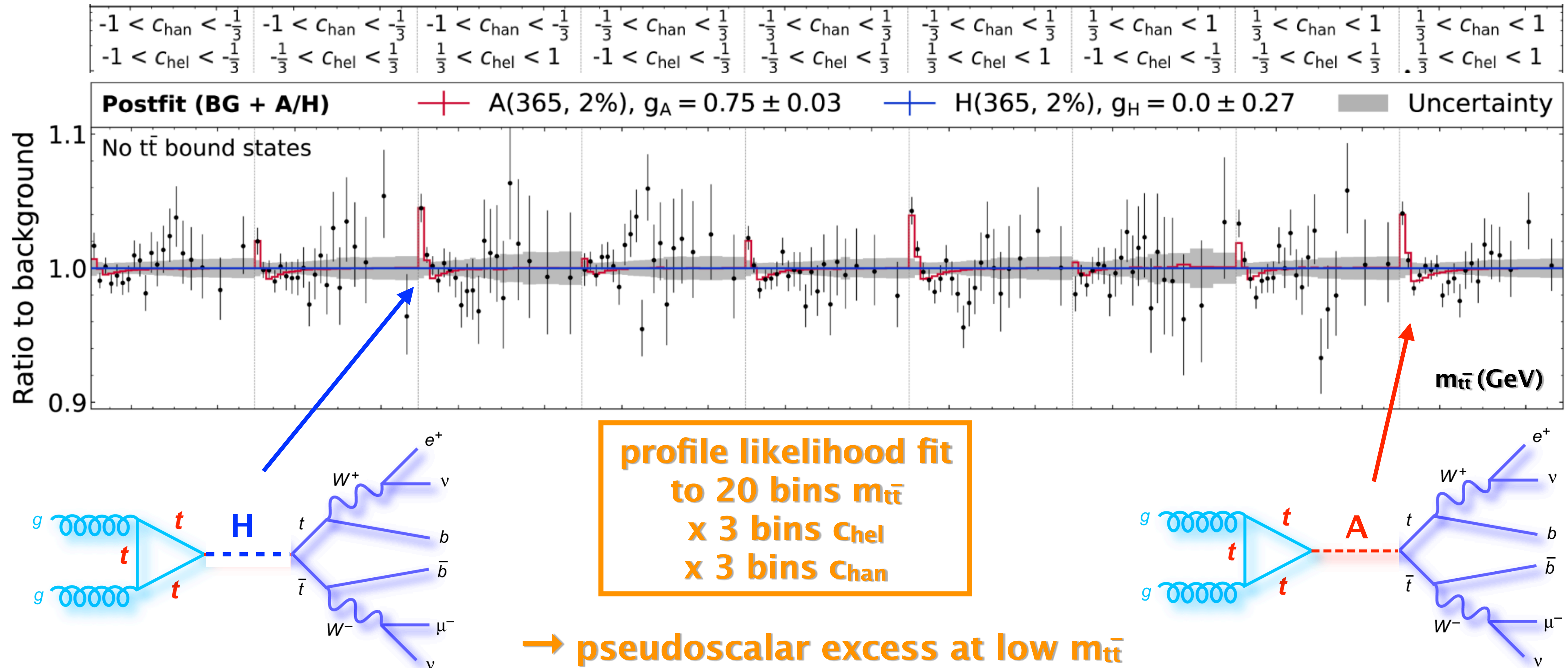
- MiNNLO simulations
- Data-driven normalisation from Z peak

Results and Background Modeling

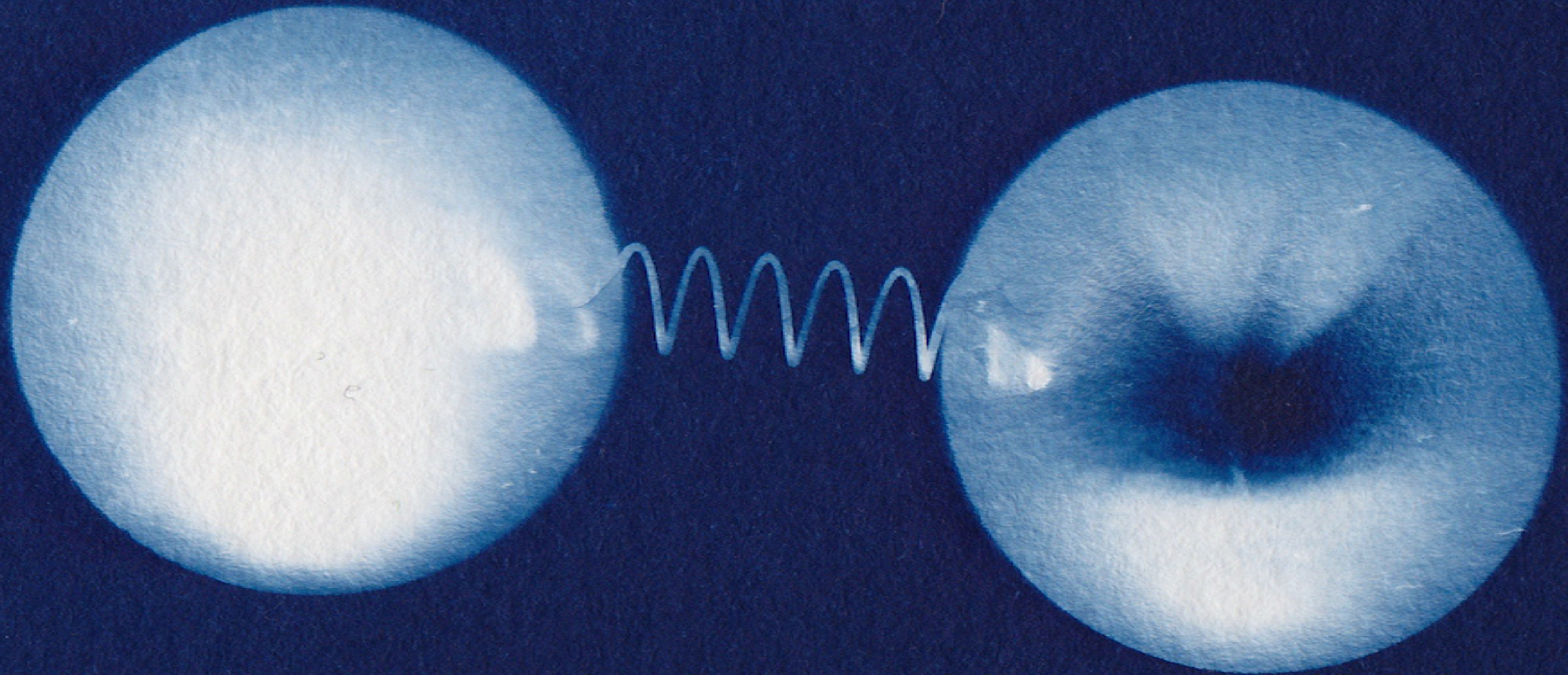


Results of the 2016–2018 Data

138 fb⁻¹ of pp collisions at 13 TeV

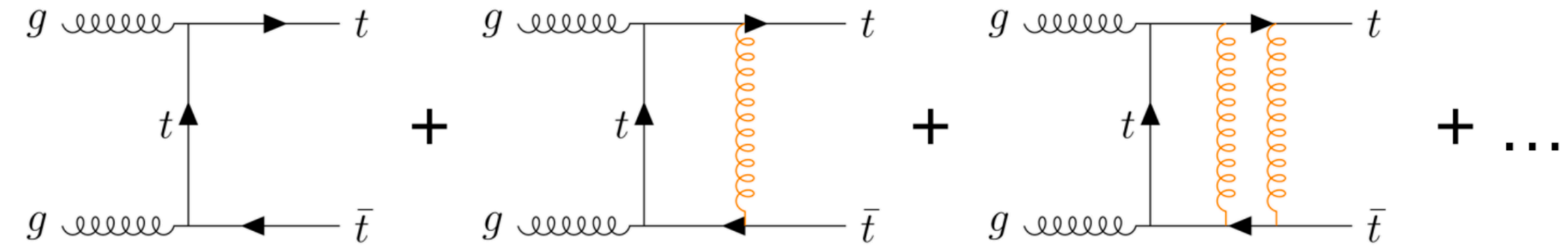
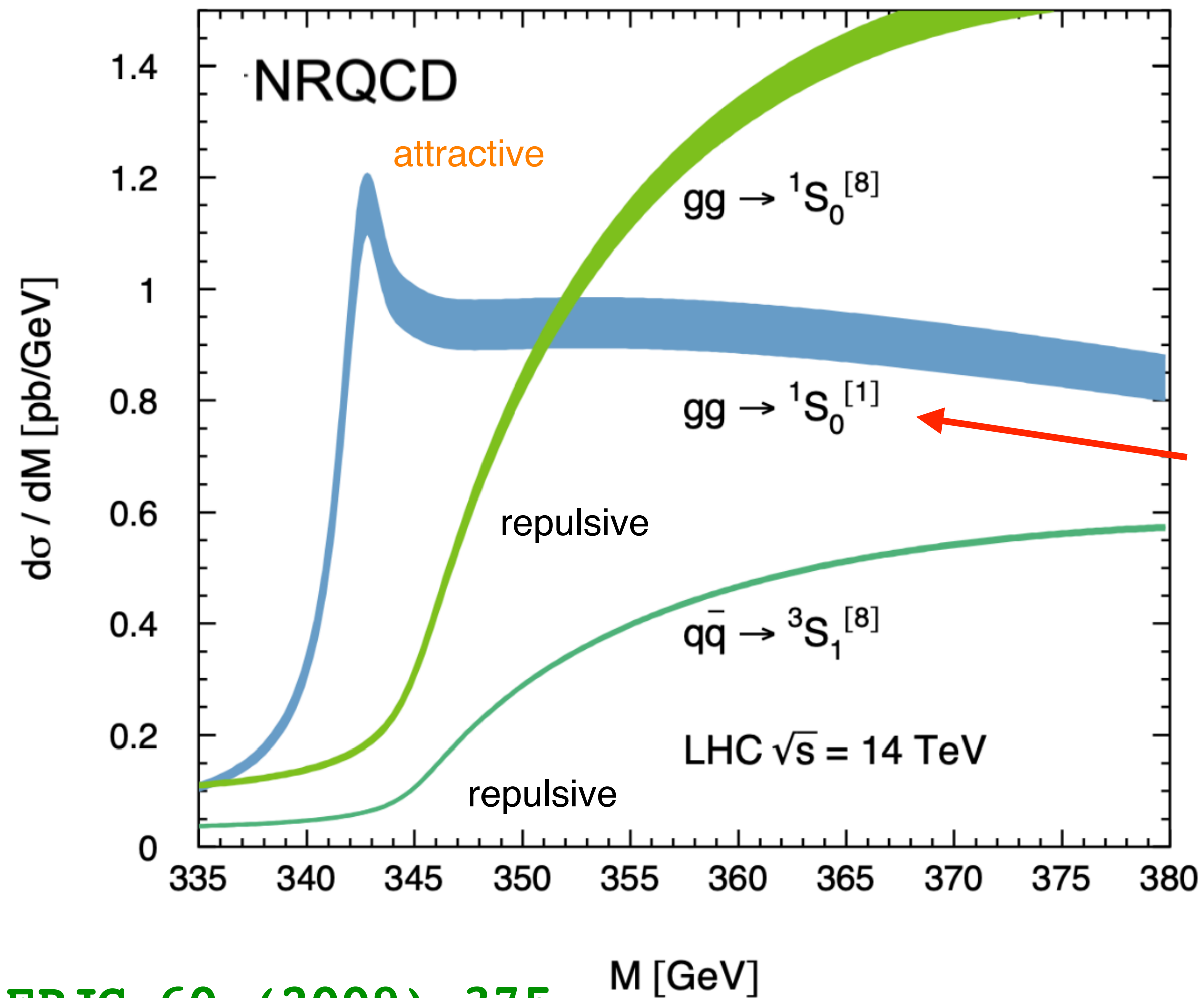


Another Interpretation: $t\bar{t}$ Bound States

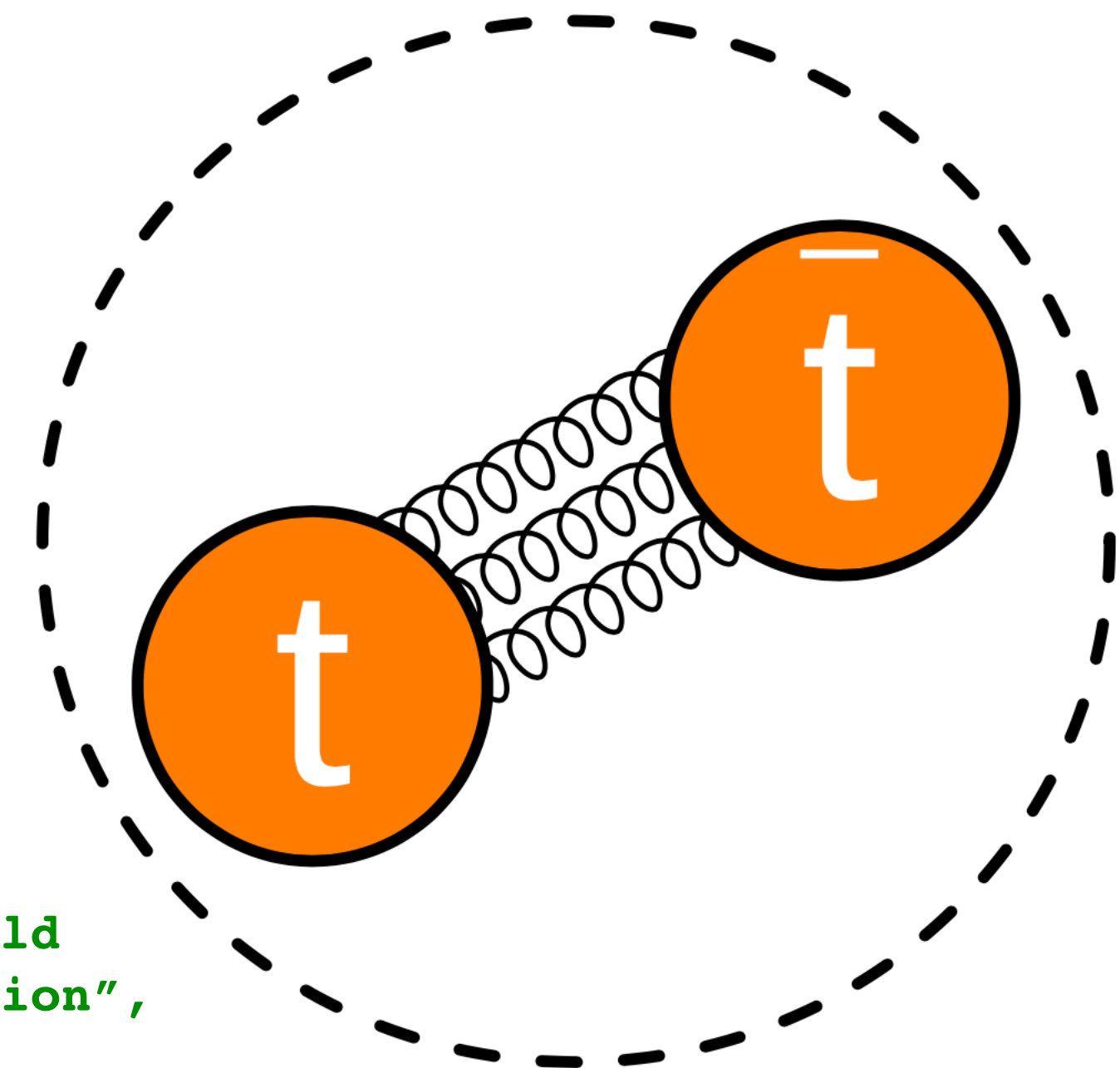


Julia Münstermann, Toponium, 2025, cyanotype, 21 x 29.7 cm

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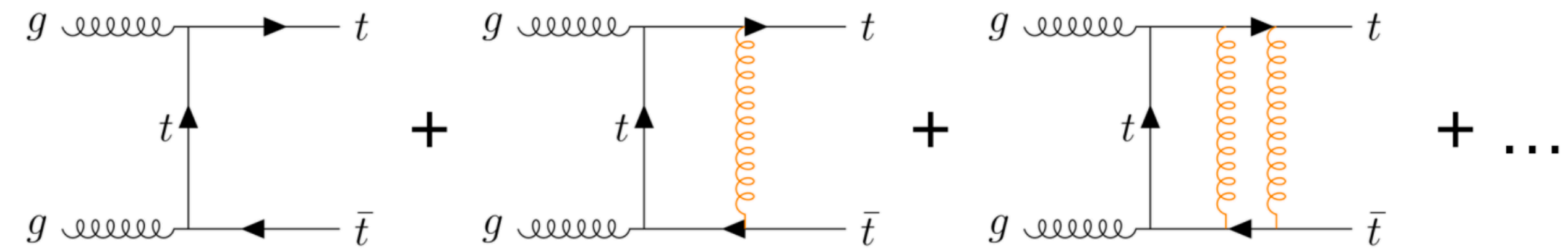
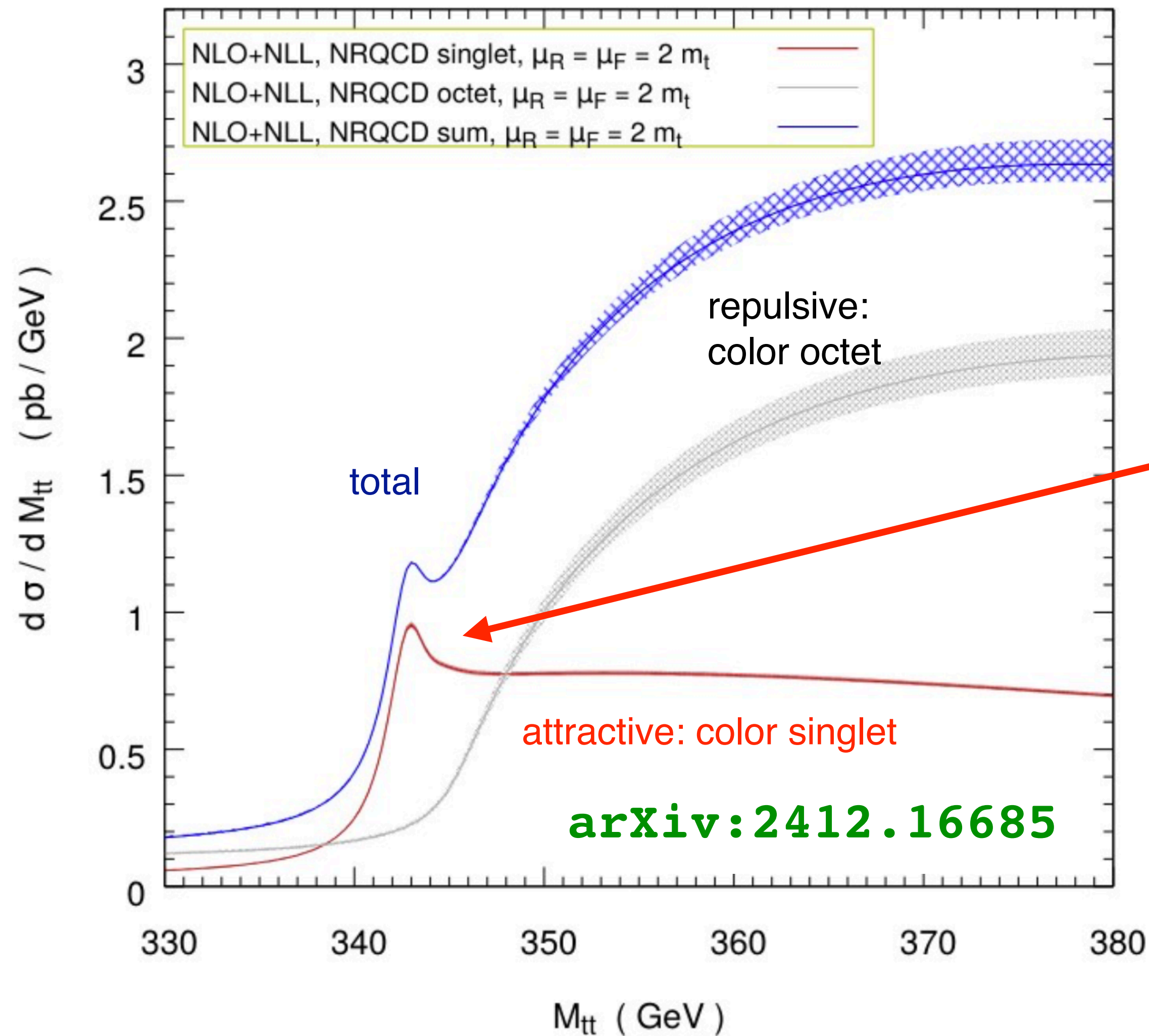
pseudoscalar toponium η_t :
 ${}^1S_0^{[1]}$ spin-0, CP-odd,
 color-singlet



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

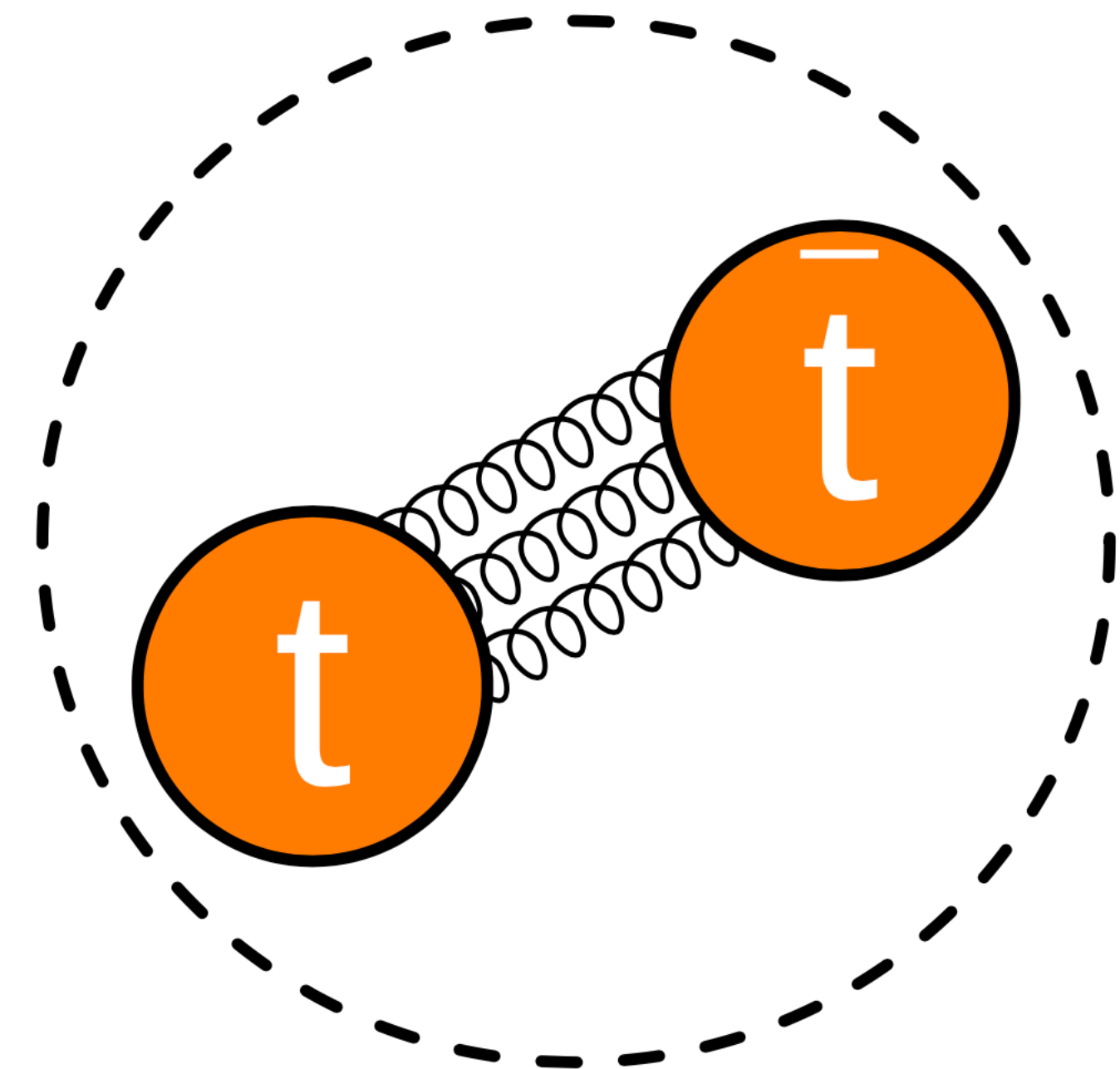
→ threshold region is dominated by color-singlet pseudocalar toponium

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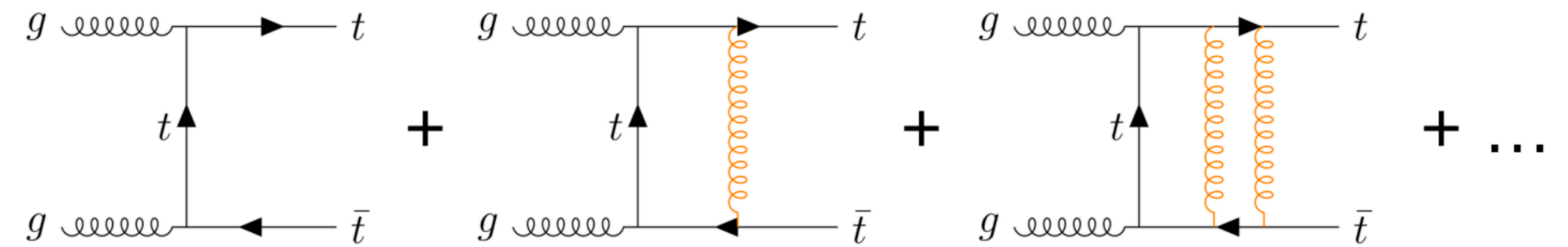
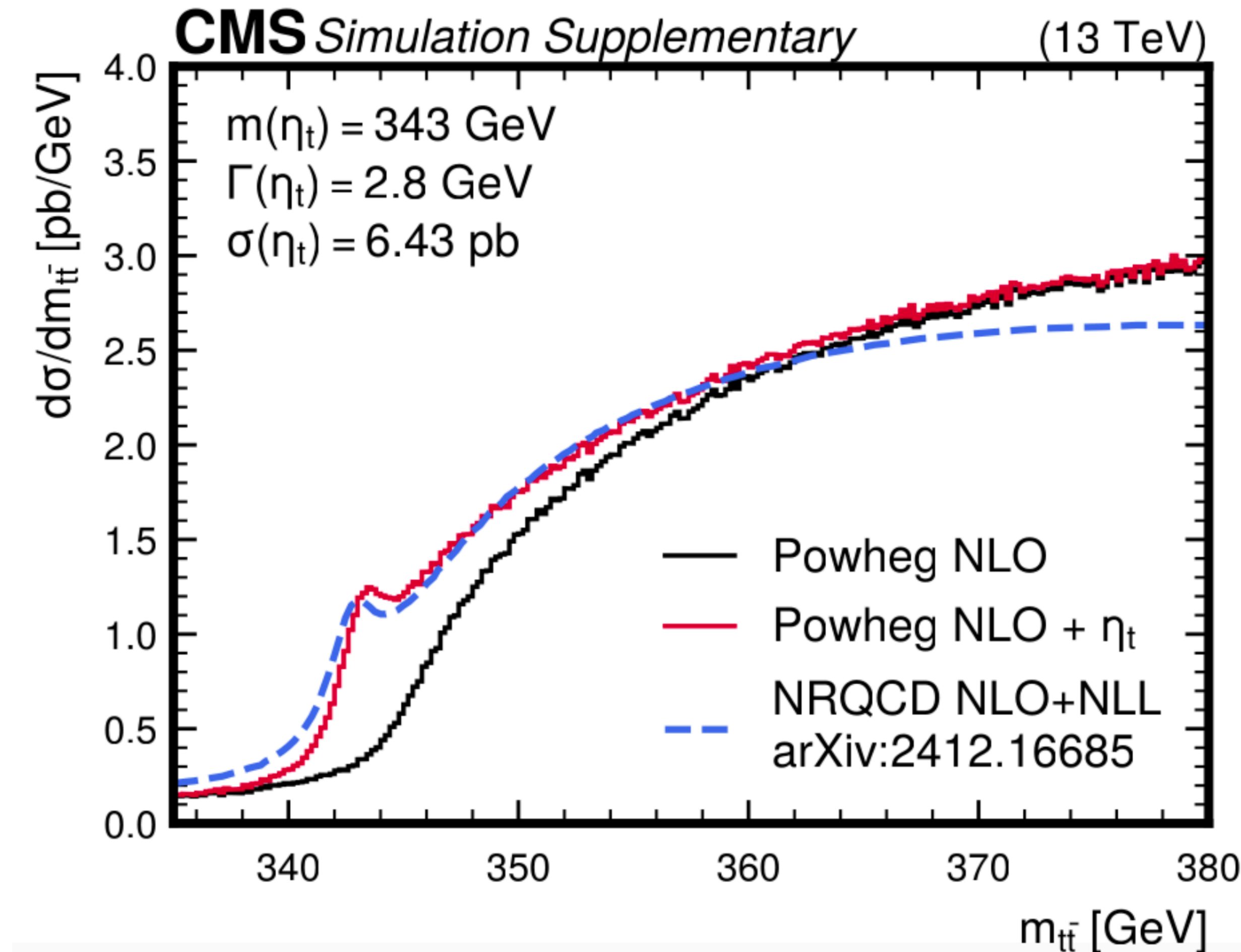
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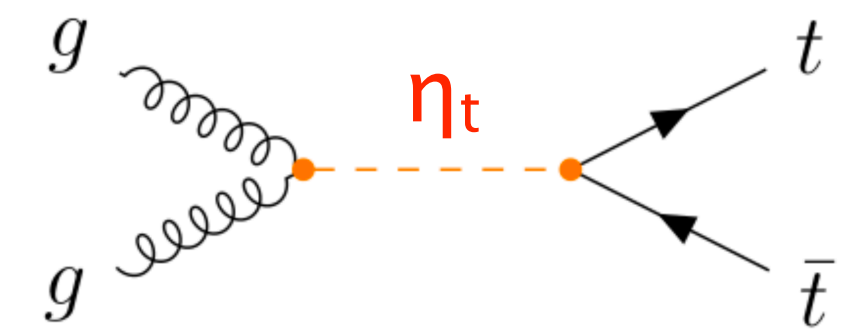
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Approximating $t\bar{t}$ bound states

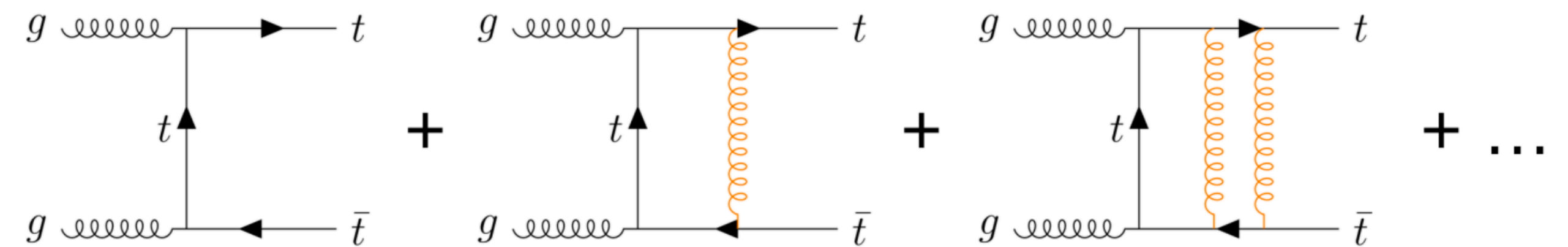
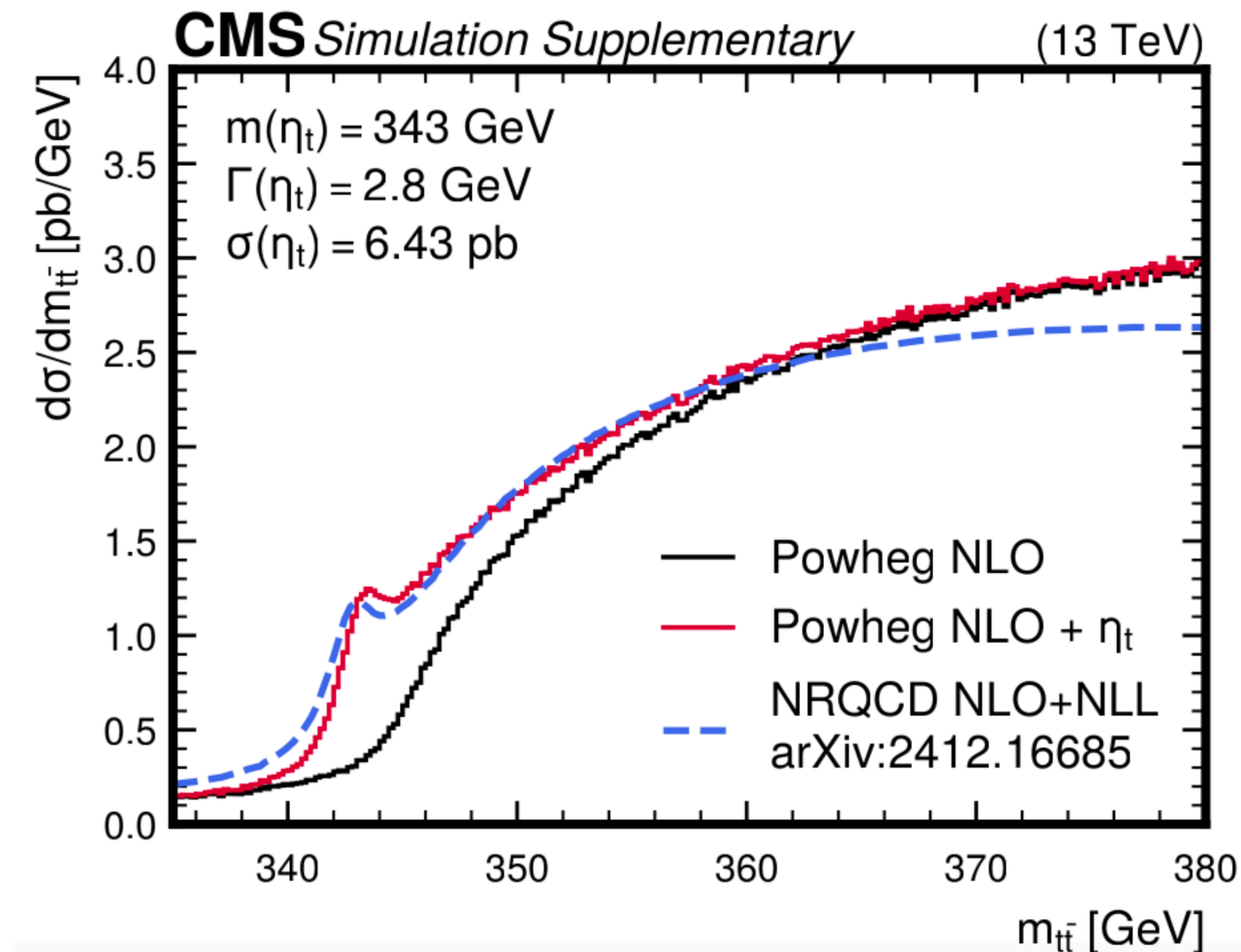
- simplified model
JHEP 03 (2024) 099
- generic particle with direct couplings to gluons and tops, mass and width from fit to NRQCD

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

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

→ threshold region is dominated by color-singlet pseudocalar toponium

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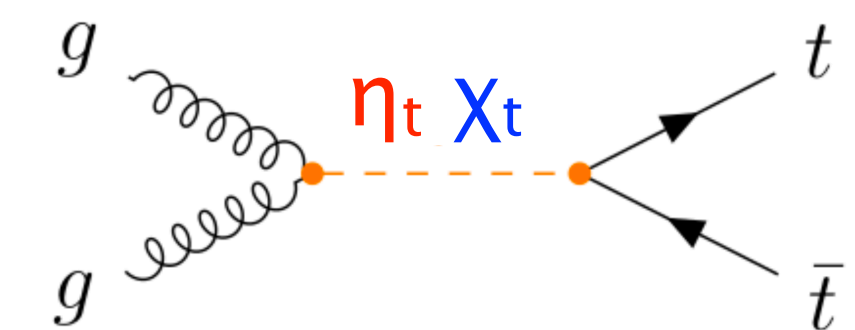


pseudoscalar toponium η_t :

$1S_0^{[1]}$ 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

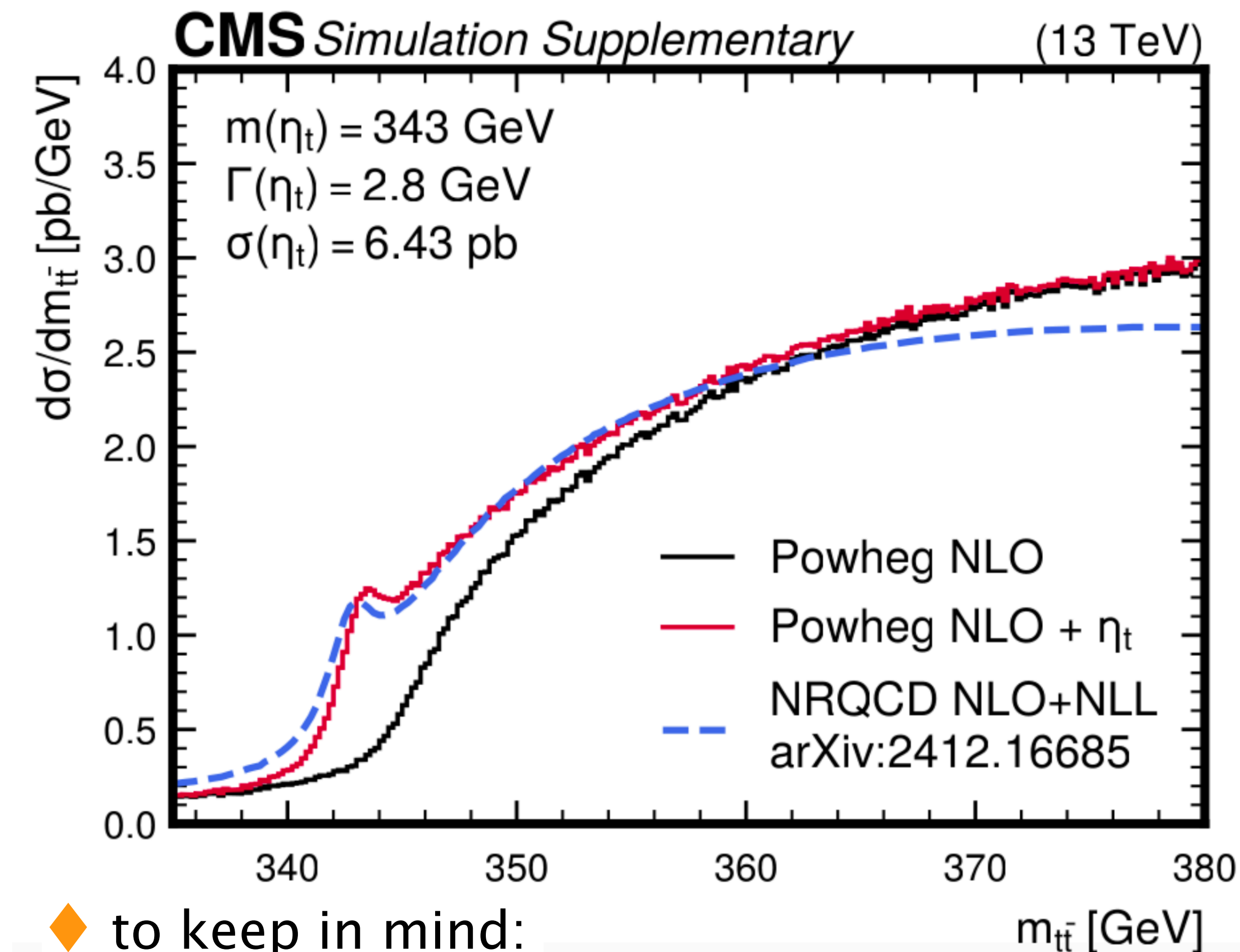
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JHEP 03 (2024) 099
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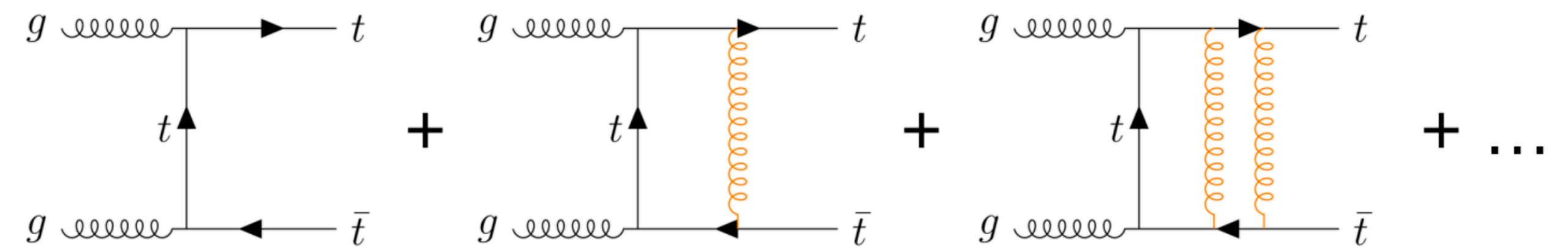
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Another Interpretation: $t\bar{t}$ Bound States



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

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

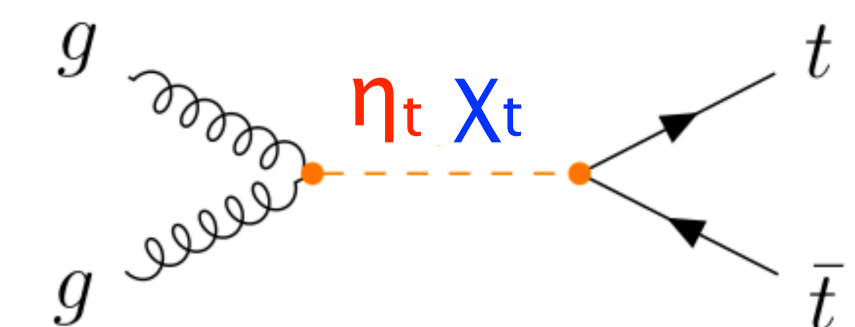


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Approximating $t\bar{t}$ bound states

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JHEP 03 (2024) 099
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arXiv:2412.15138

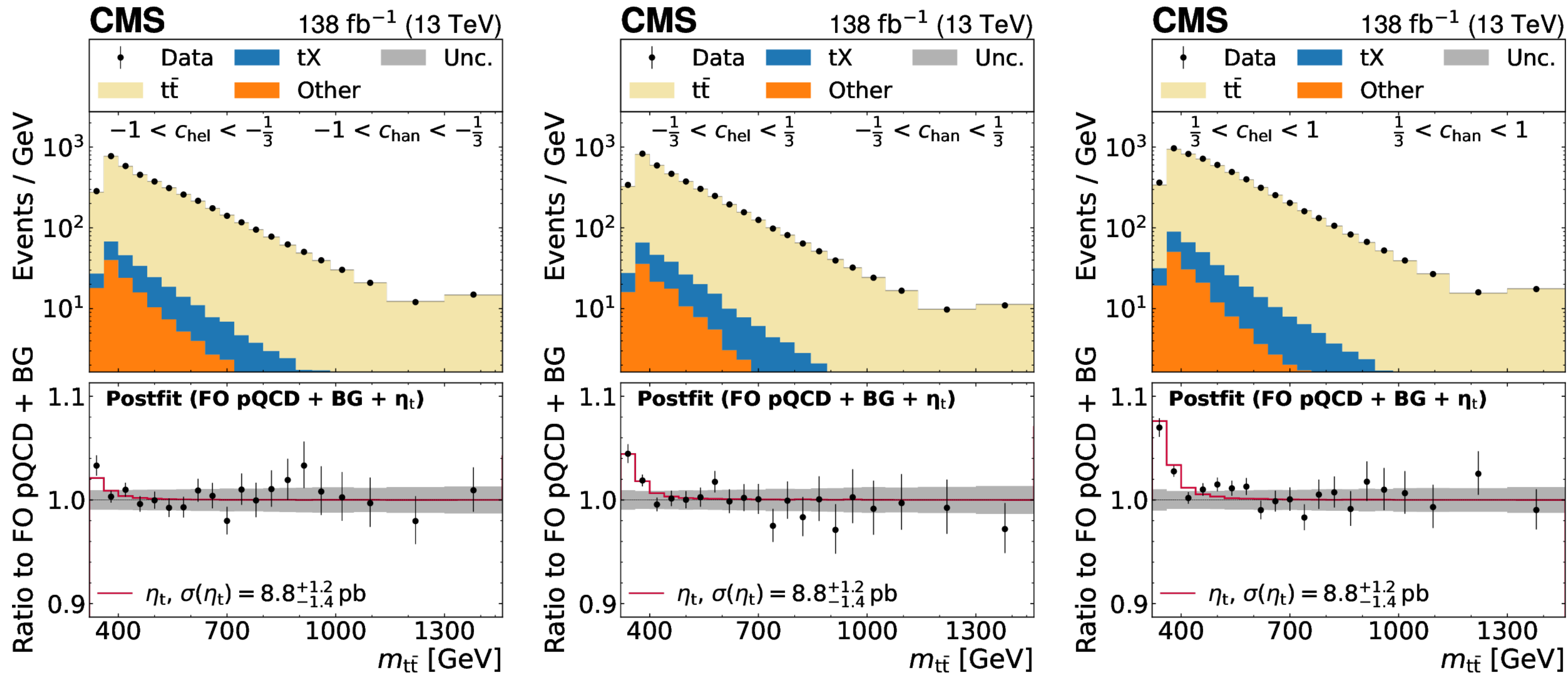
Results and Pseudoscalar Toponium Interpretation

[arXiv:2503.22382](https://arxiv.org/abs/2503.22382)

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

♦ 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](https://arxiv.org/abs/2412.16685)

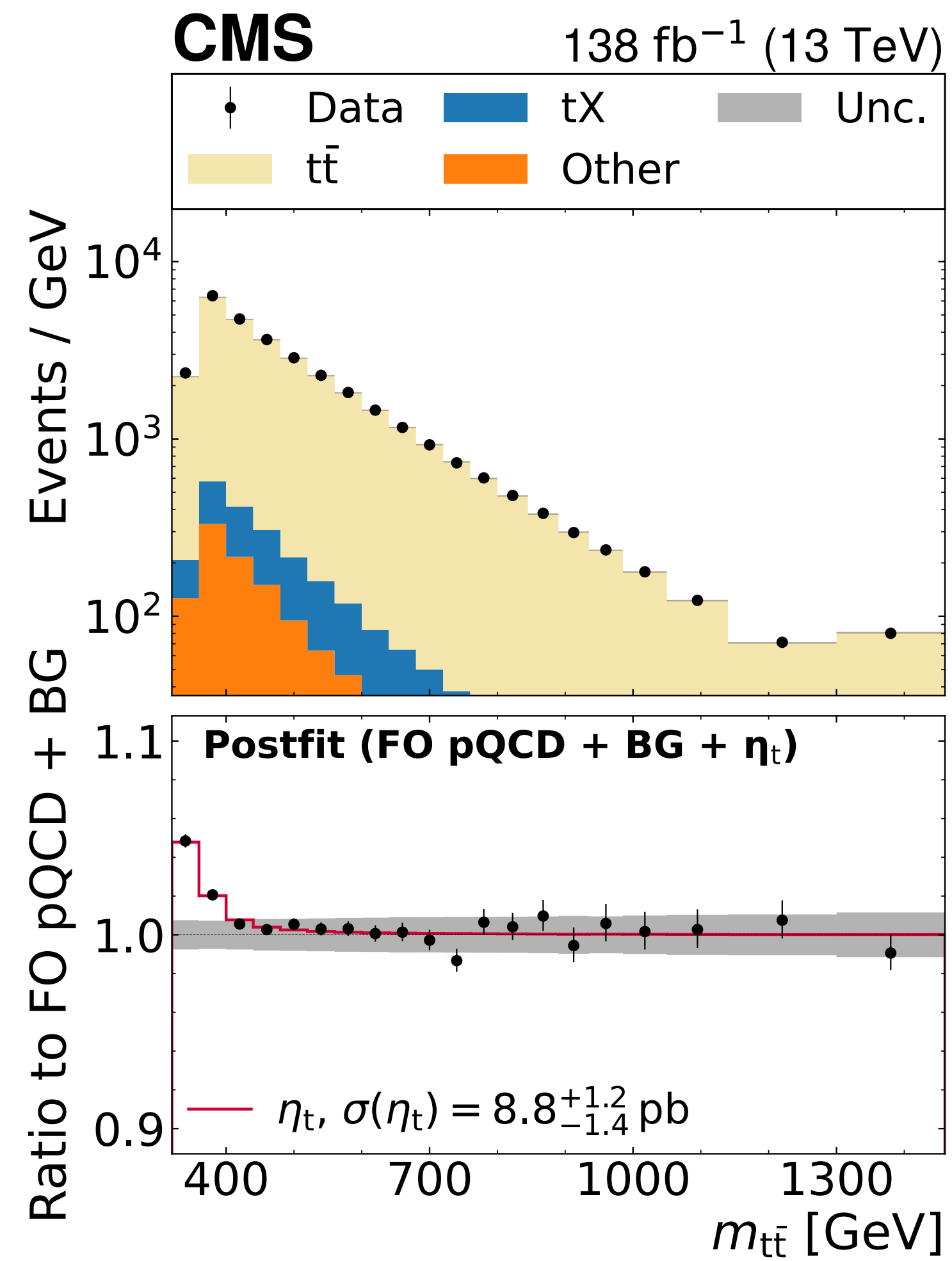


→ exciting excess: > 5 standard deviations

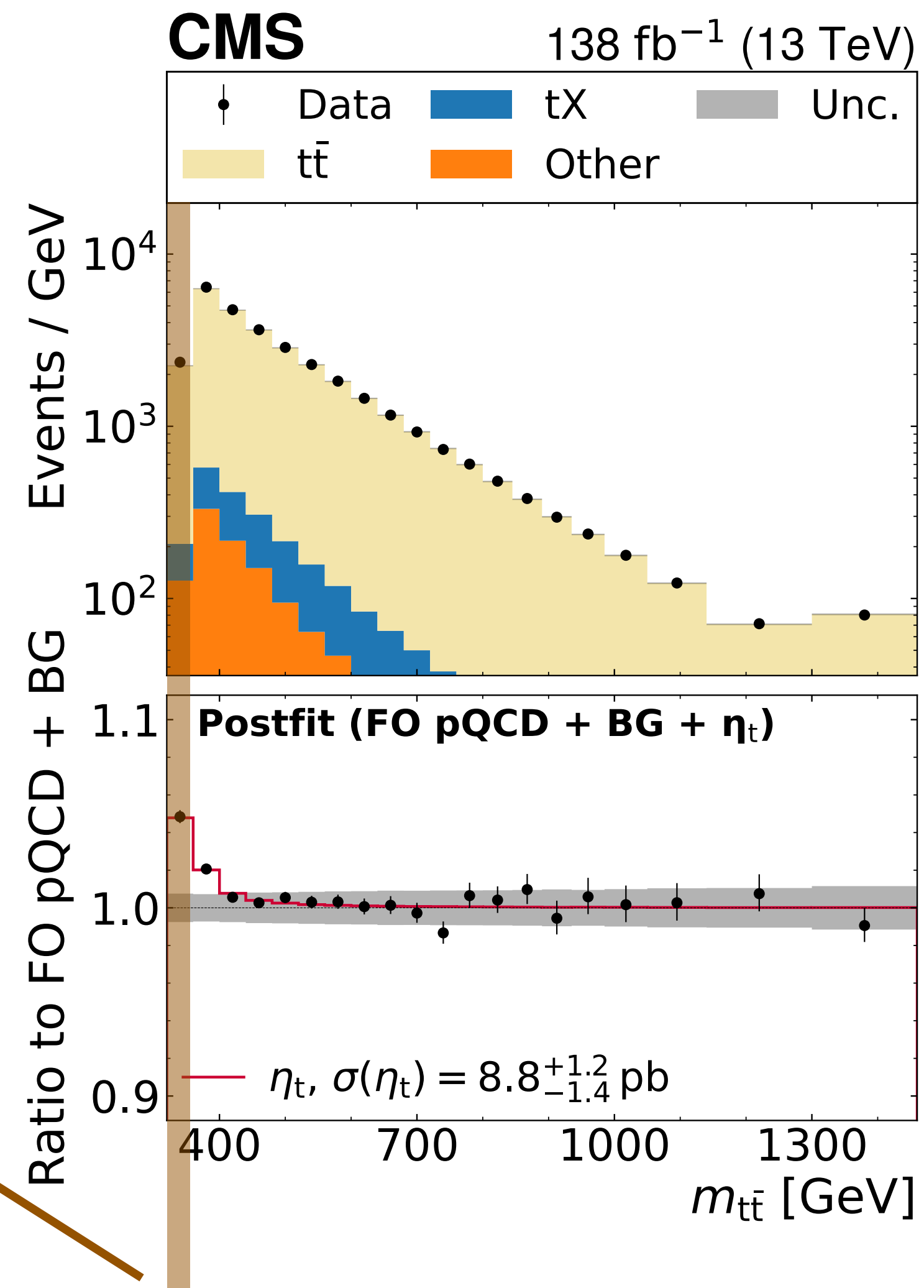
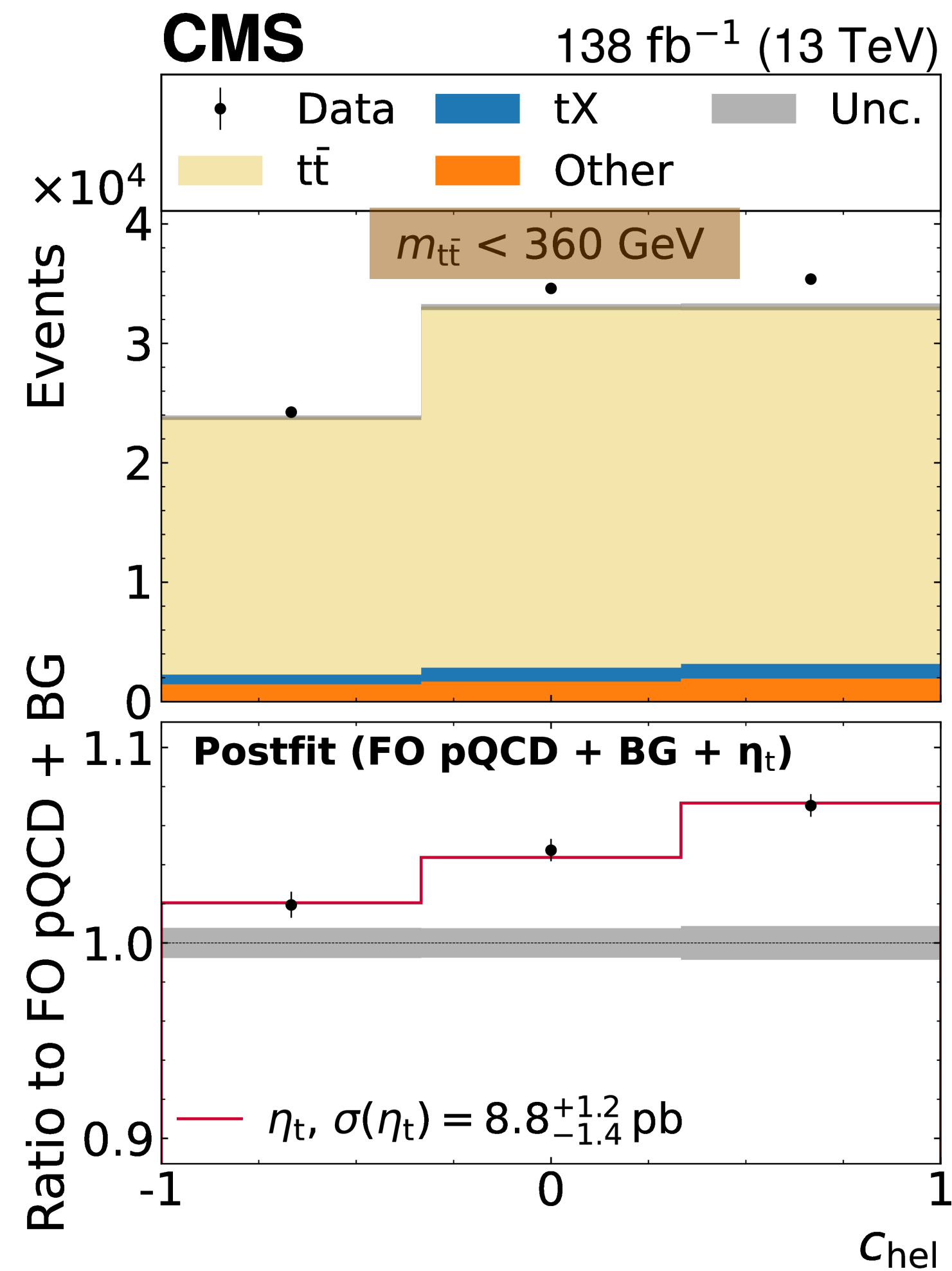
$$\sigma(\eta_t) = 8.8 \pm 0.5 (\text{stat}) {}^{+1.1}_{-1.3} (\text{syst}) \text{ pb} = 8.8 {}^{+1.2}_{-1.4} \text{ pb.}$$

$$\text{NRQCD: } \sigma(\eta_t) = 6.4 \text{ pb}$$

Spin Correlation

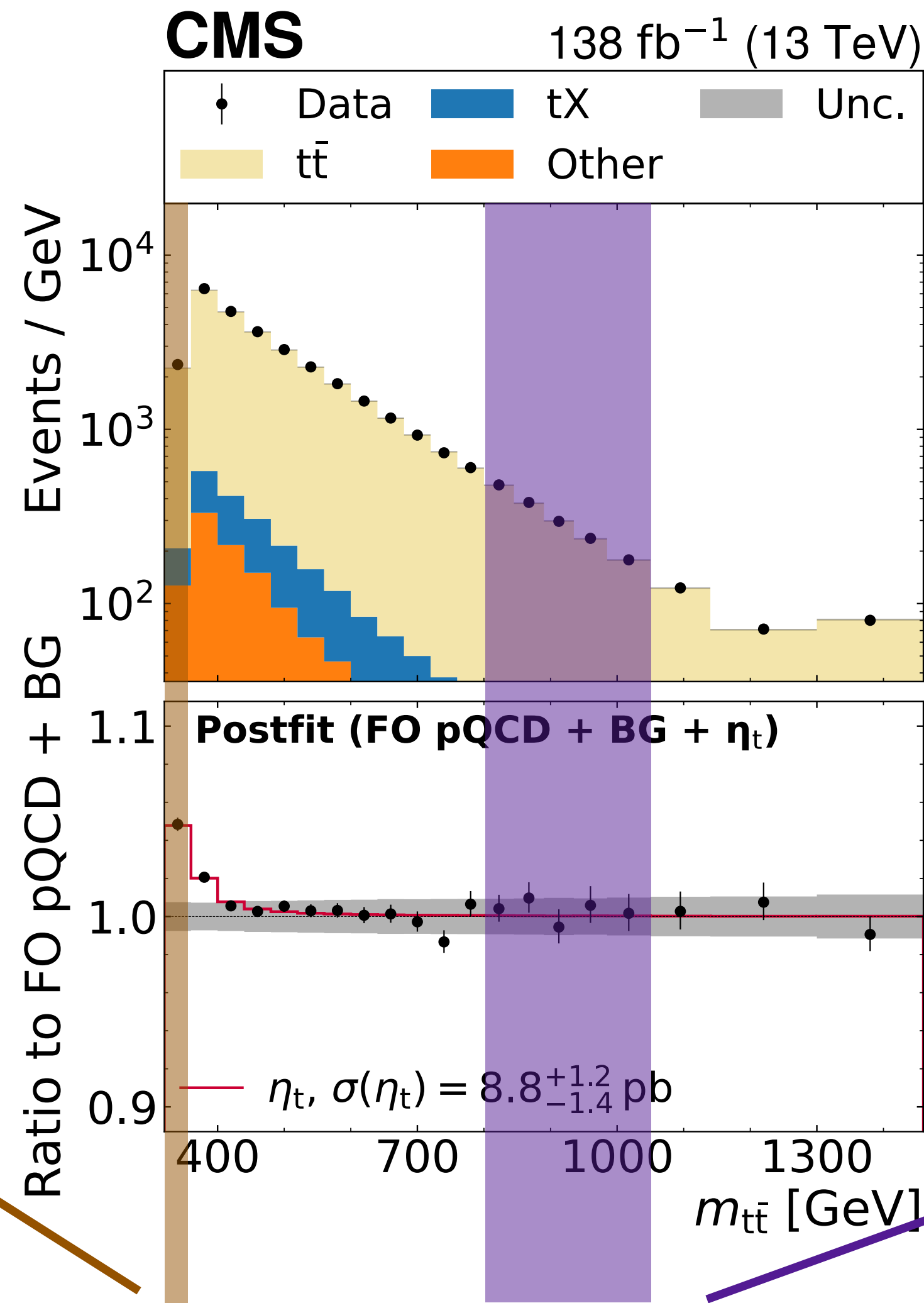
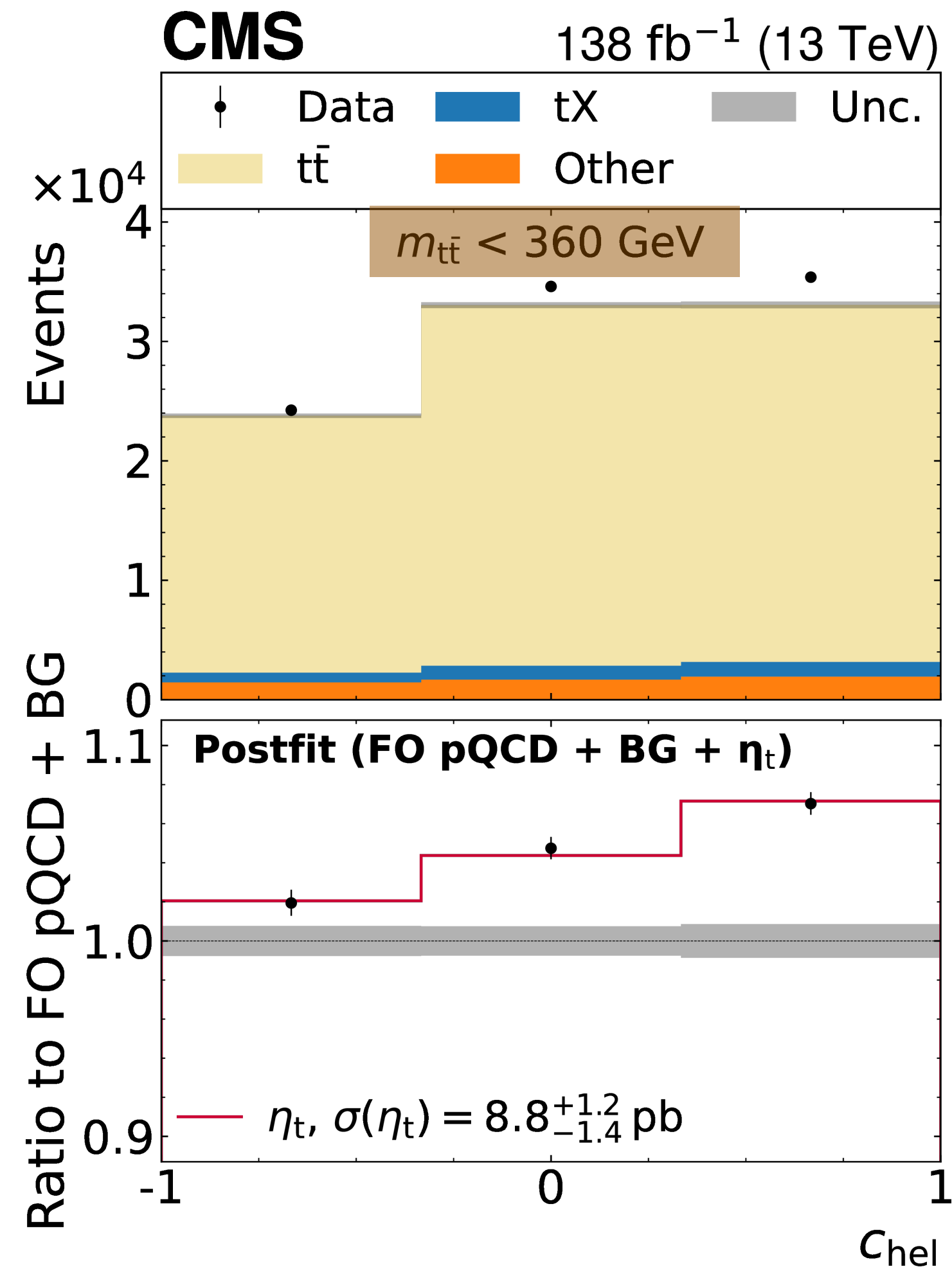


Spin Correlation

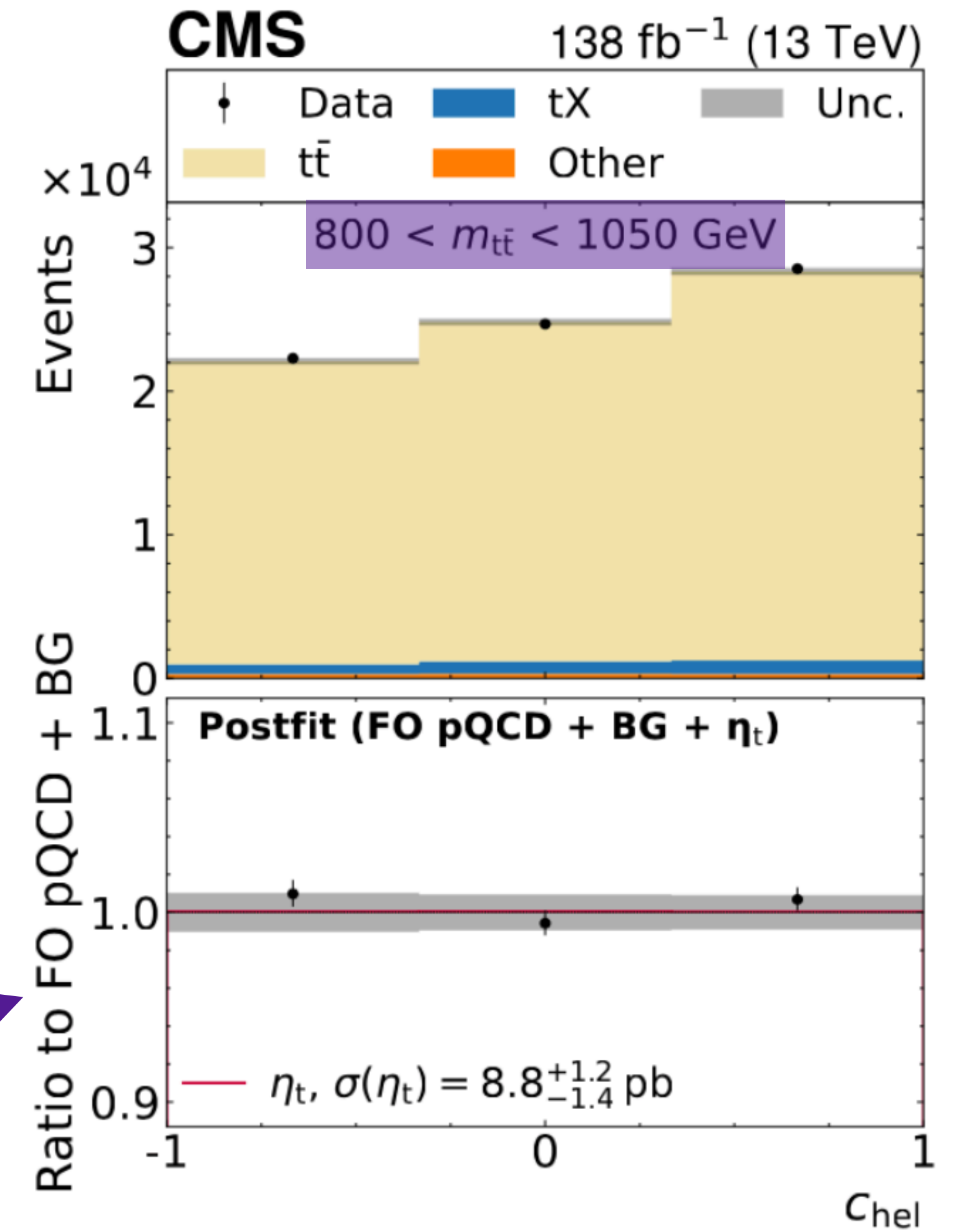


→ pseudoscalar behaviour

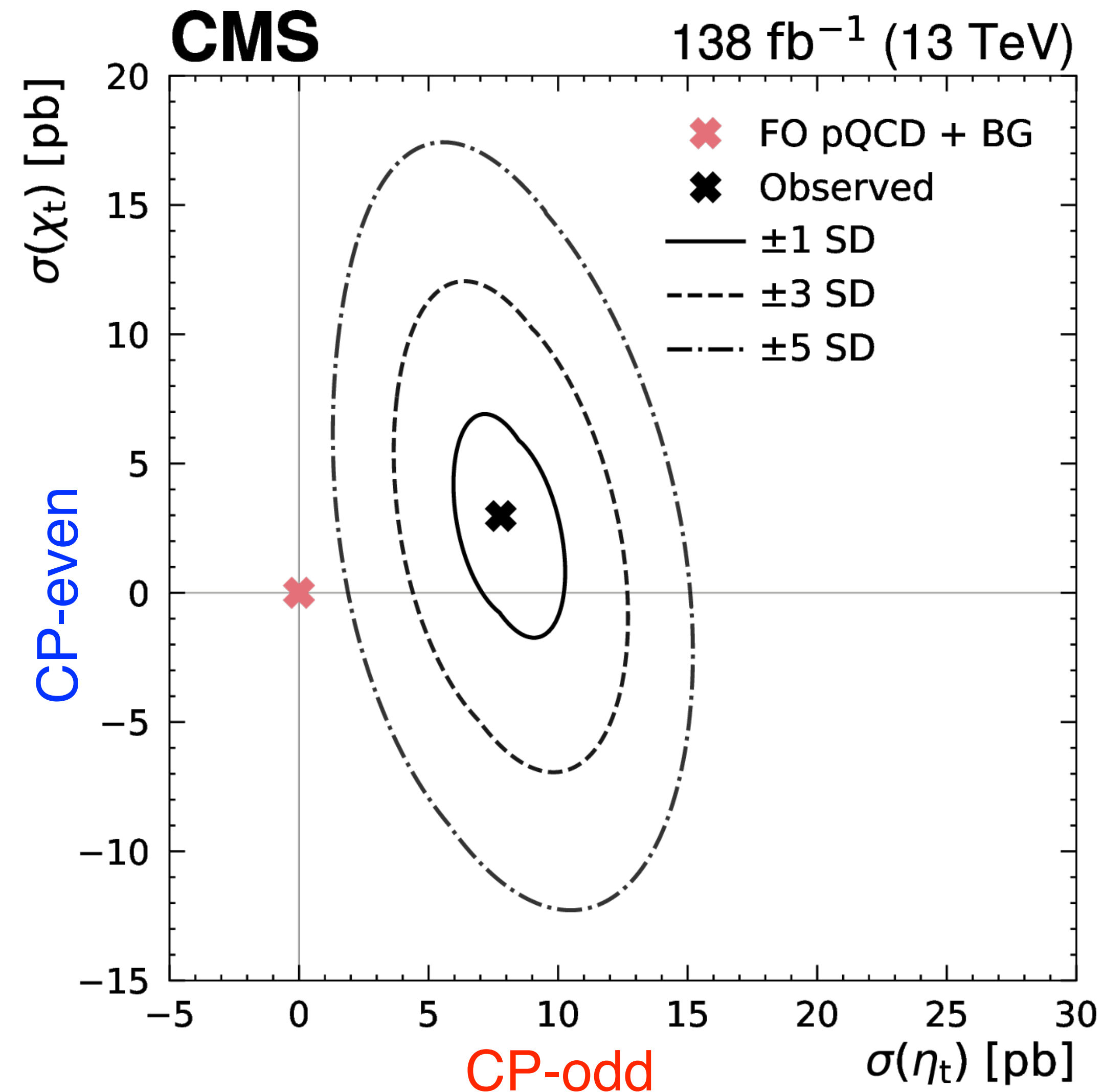
Spin Correlation



→ pseudoscalar bahaviour

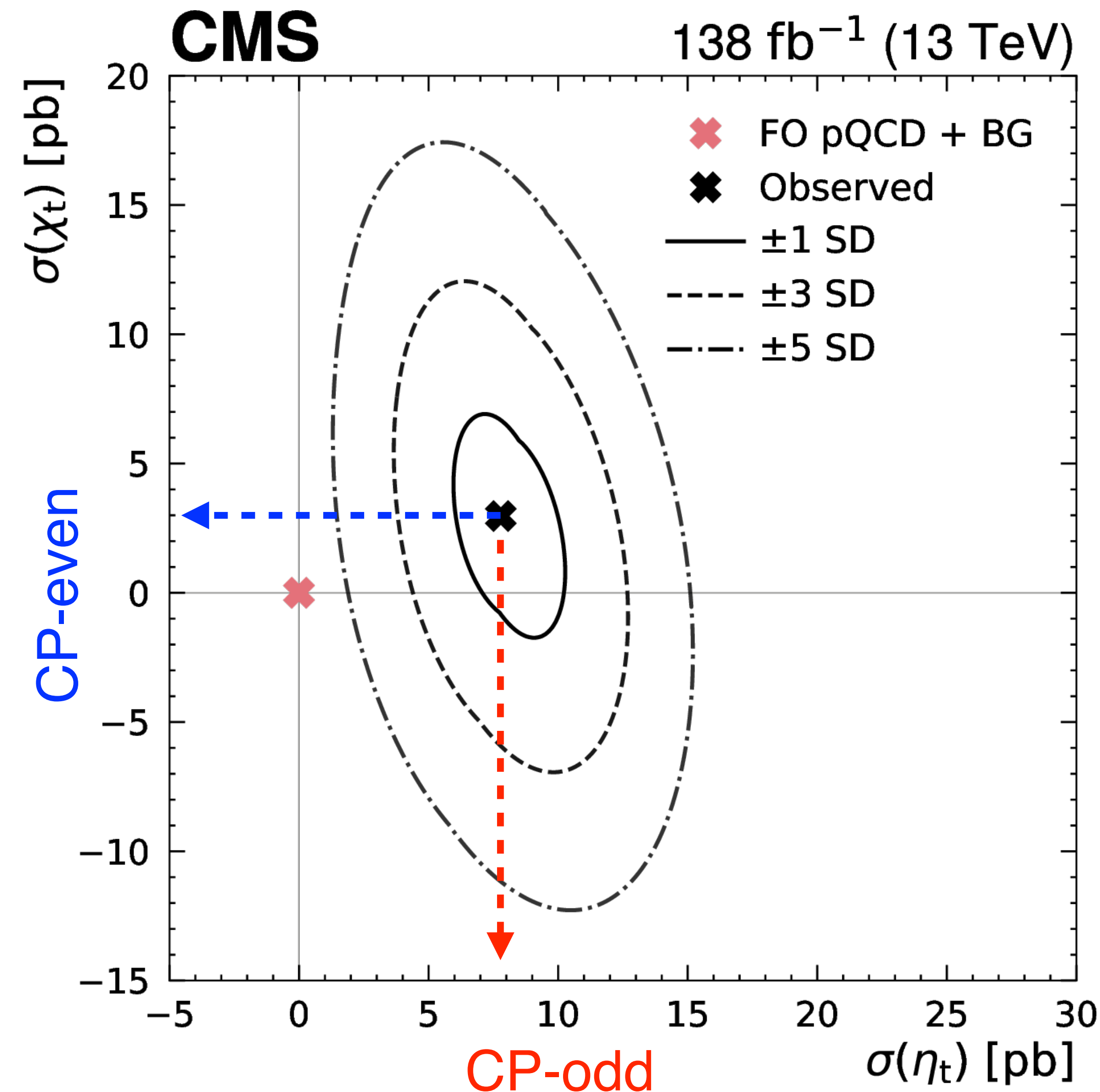


Scalar or Pseudoscalar?



→ data prefers pseudoscalar over scalar

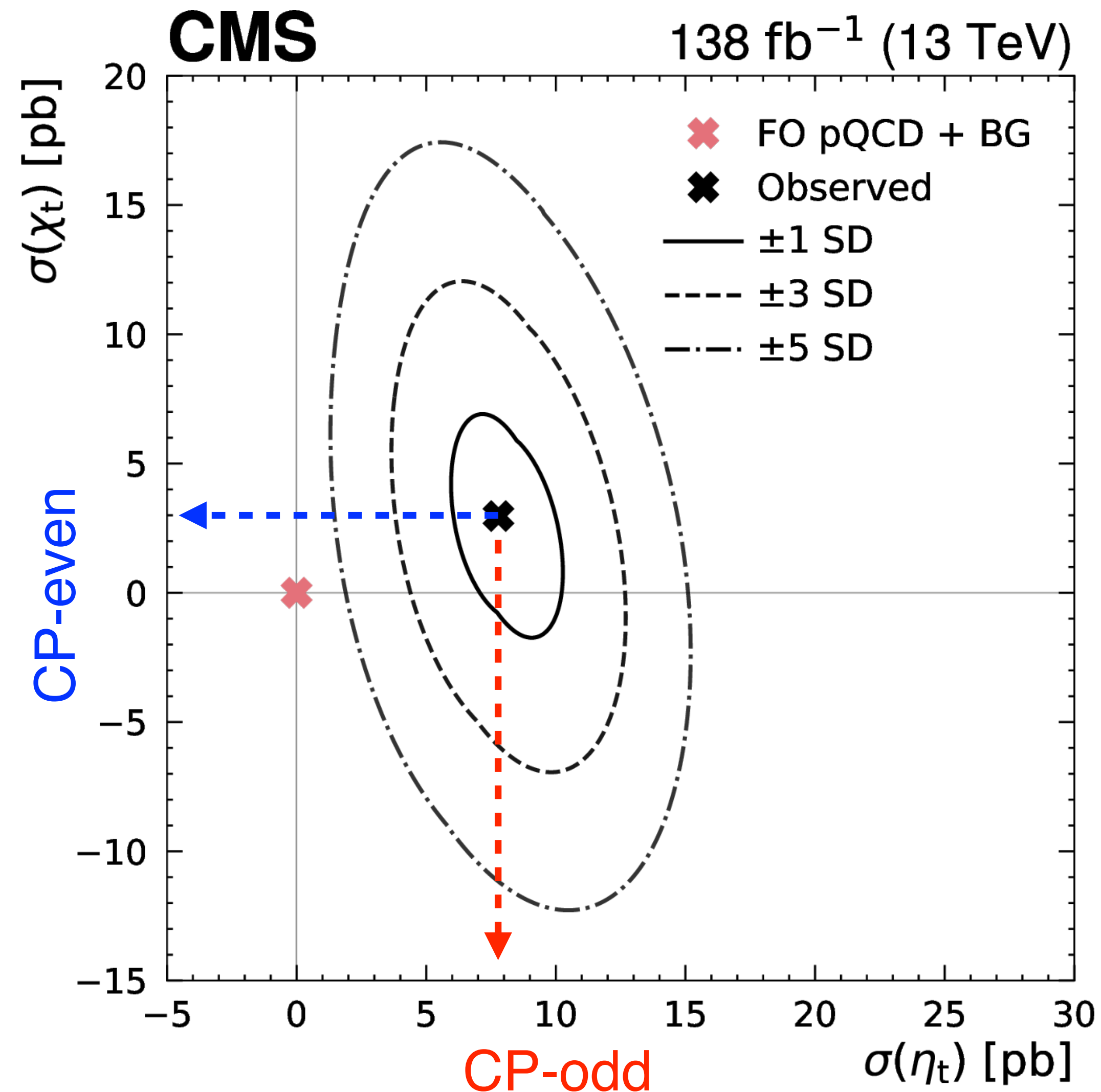
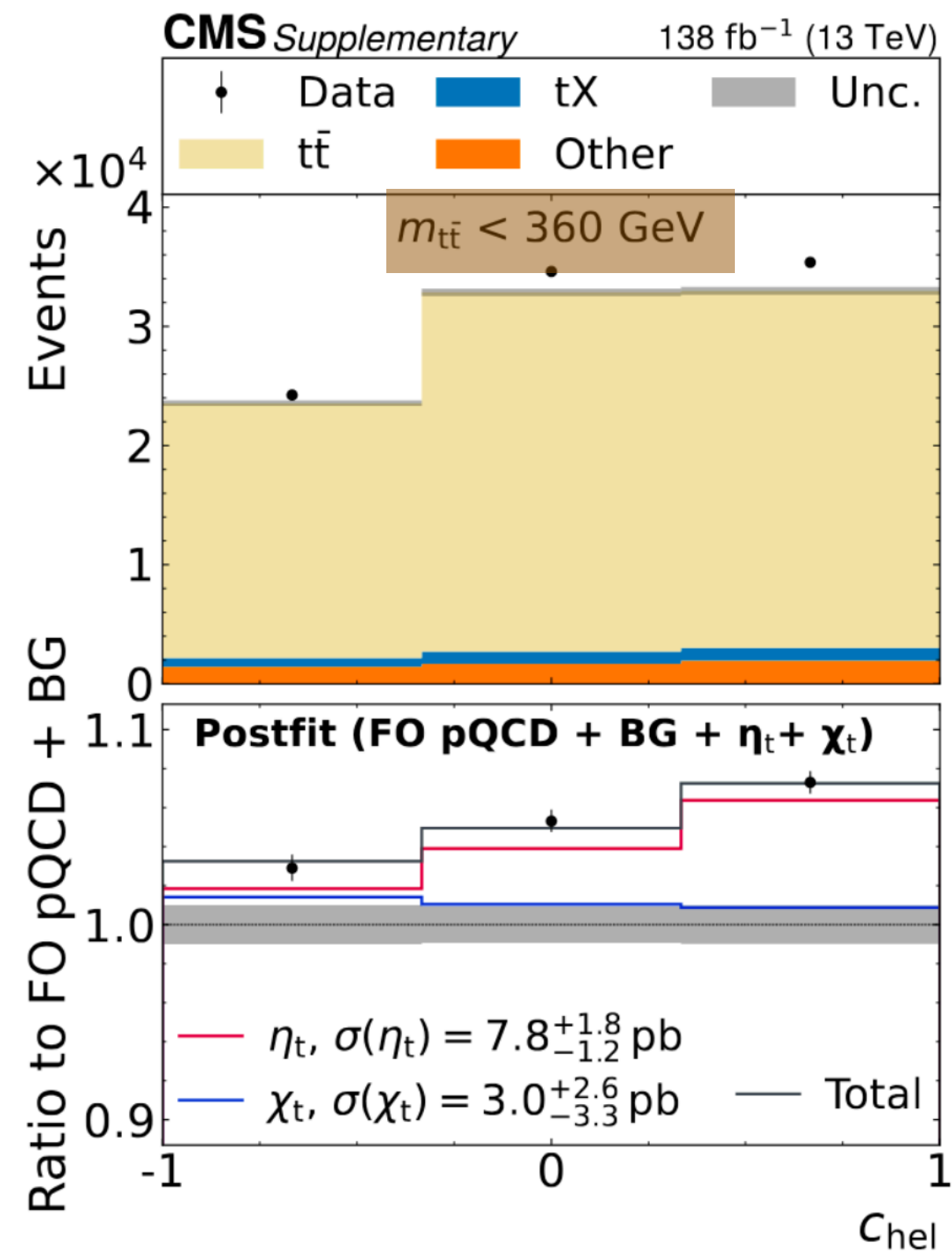
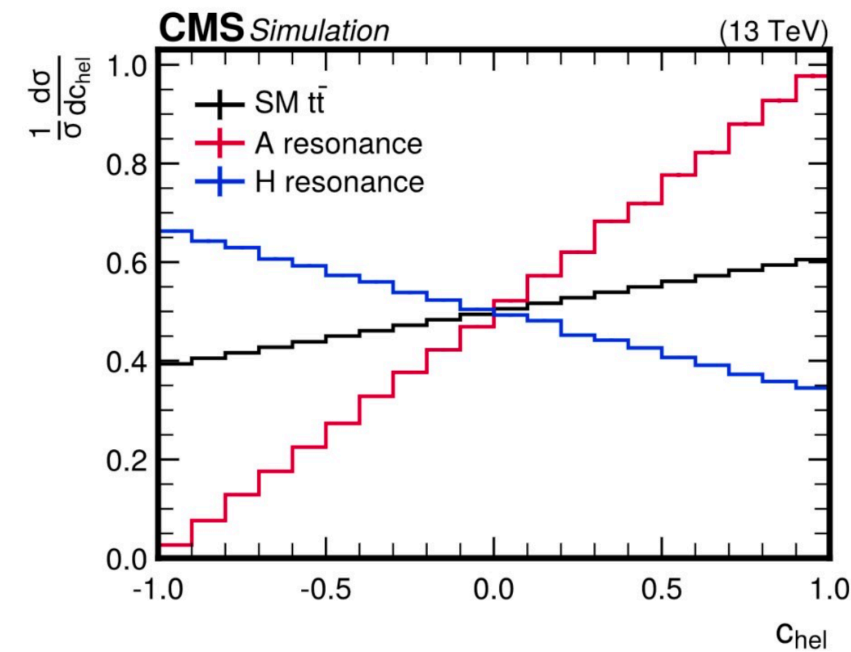
Scalar or Pseudoscalar?



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

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Scalar or Pseudoscalar?



→ data prefers pseudoscalar over scalar

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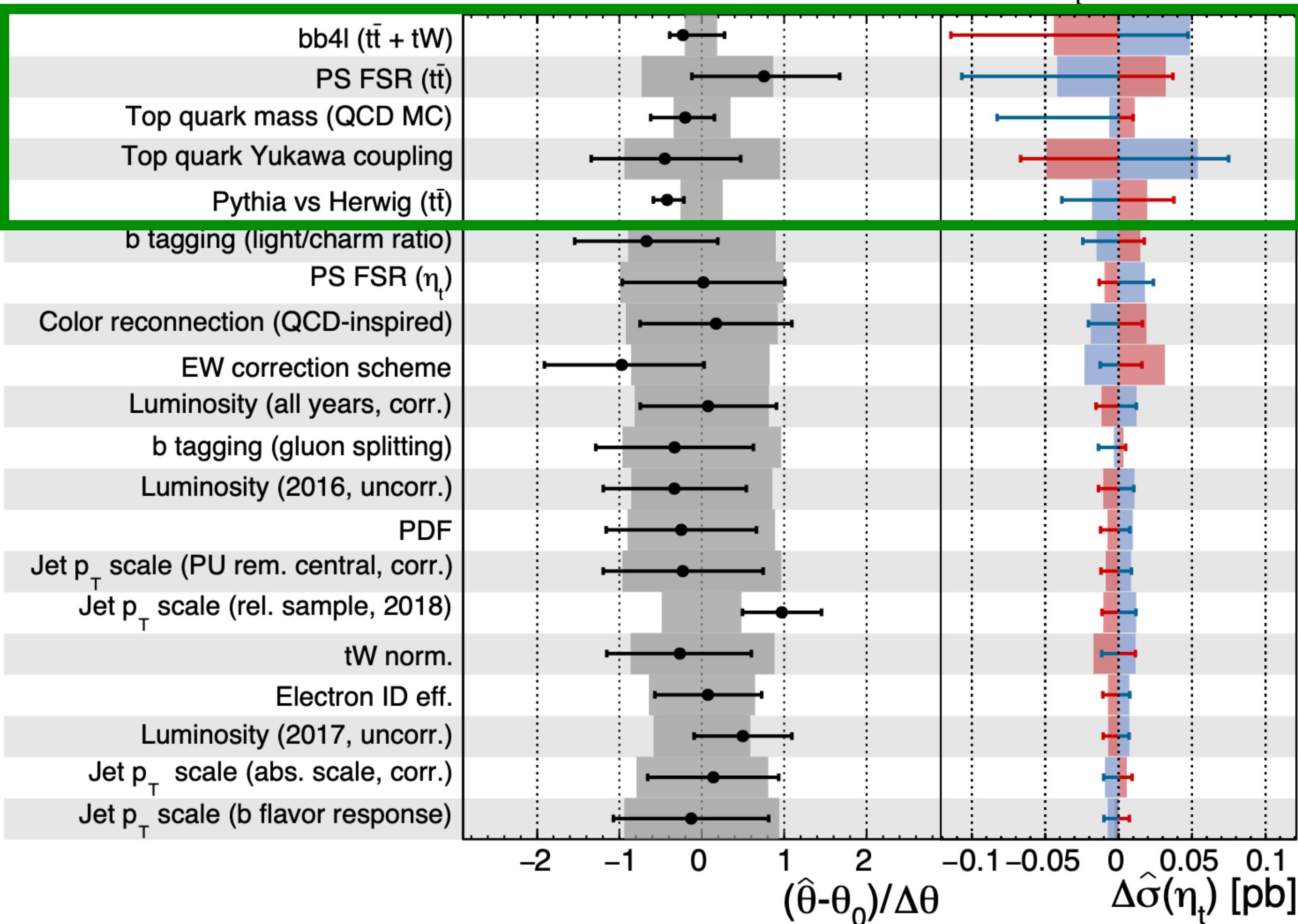
$$\sigma(\chi_t) = 3.0^{+2.6}_{-3.3} \text{ pb}$$

Systematic Uncertainties

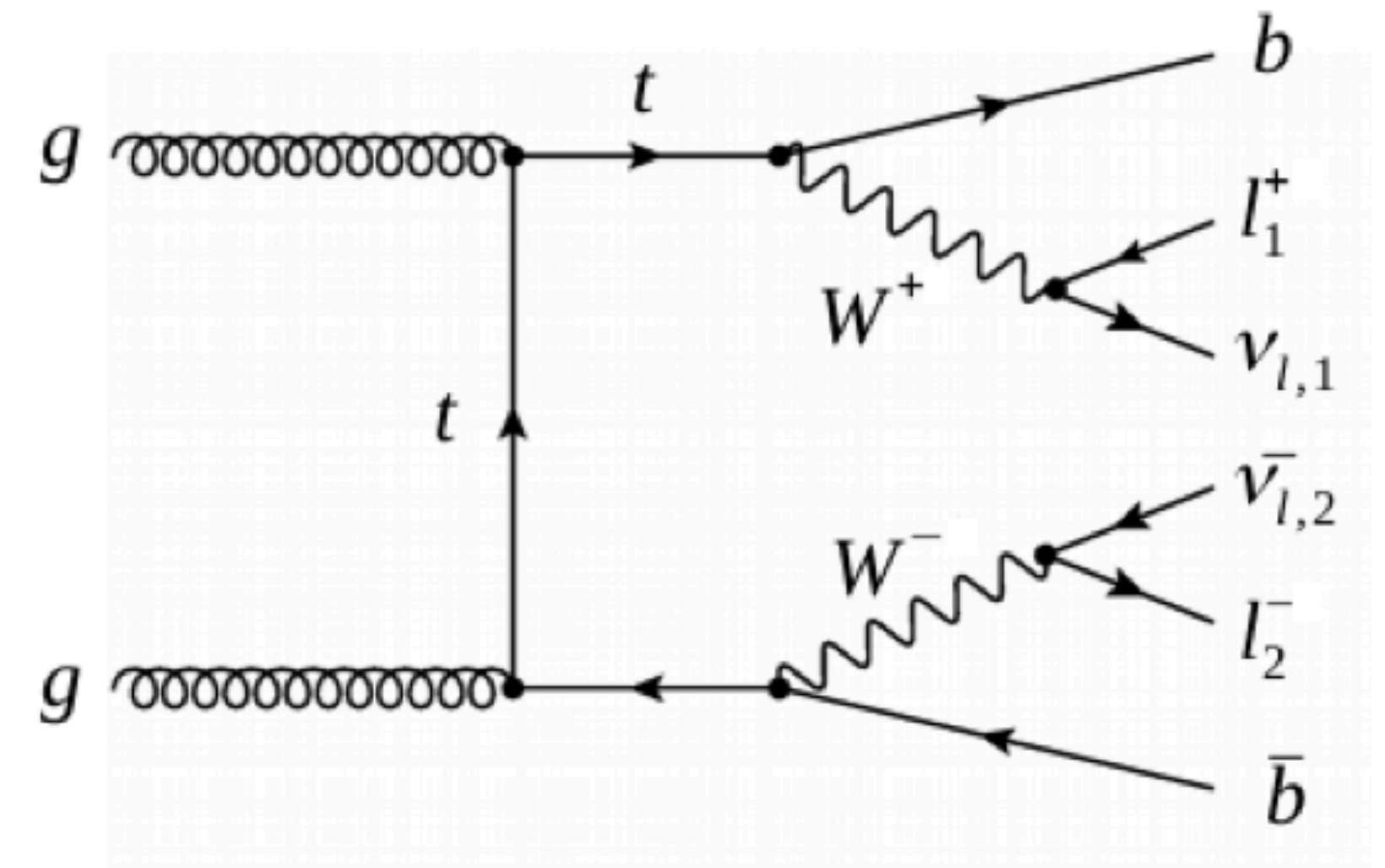
CMS
Supplementary

—●— Fit constraint (obs.) — +1 σ impact (obs.) — -1 σ impact (obs.)
 ■ Fit constraint (exp.) ■ +1 σ impact (exp.) ■ -1 σ impact (exp.)

$$\hat{\sigma}(\eta_t) = 8.8^{+1.2}_{-1.4} \text{ pb}$$



- bb4l generator instead of Powheg:
- $pp \rightarrow b\bar{b} l^+ l^- \nu\bar{\nu}$



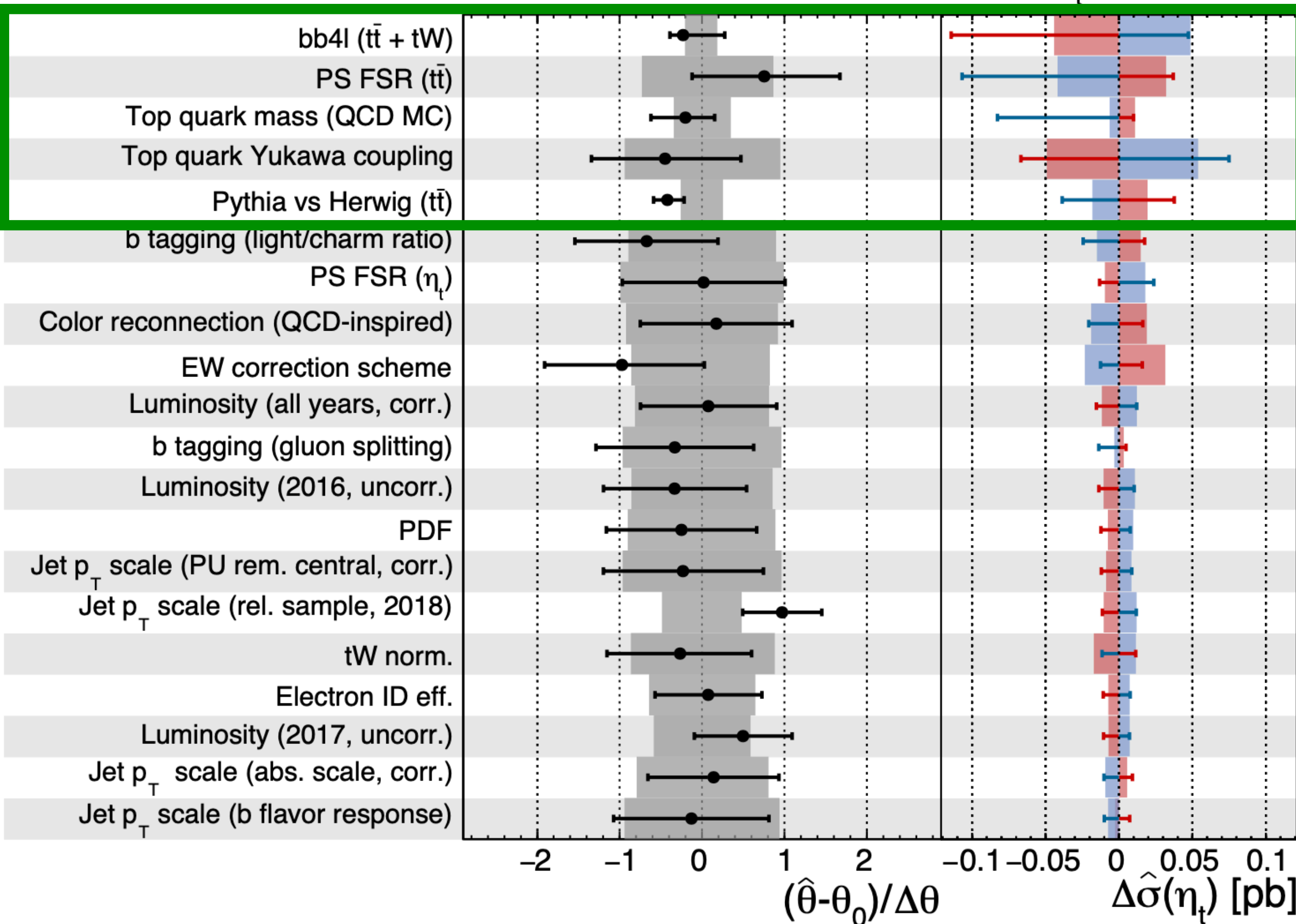
→ uncertainty dominated by $t\bar{t}$ modeling

Systematic Uncertainties

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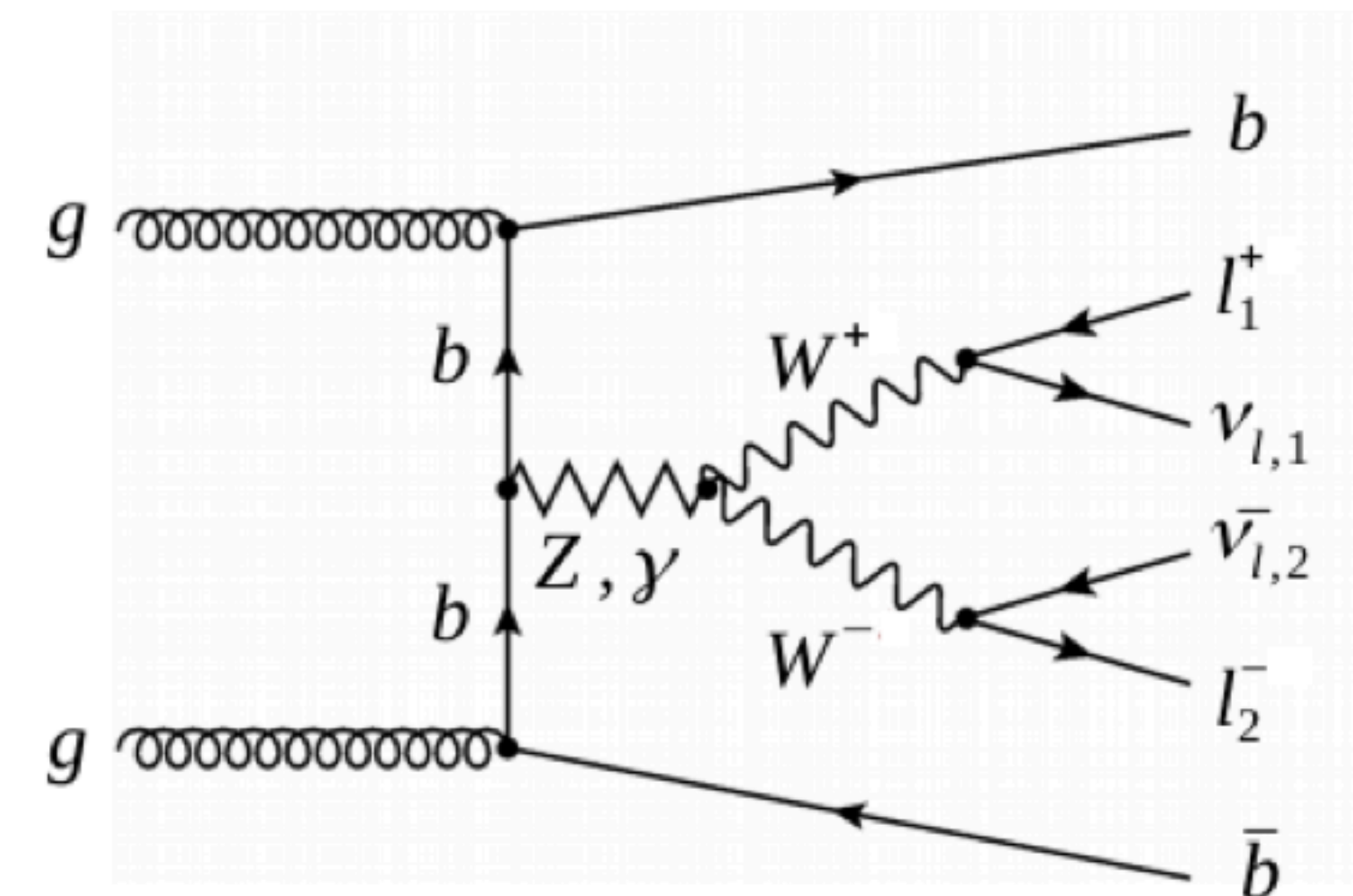
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● bb4l generator instead of Powheg:

— $pp \rightarrow b\bar{b} l^+ l^- \nu\bar{\nu}$

— off-shell effects included



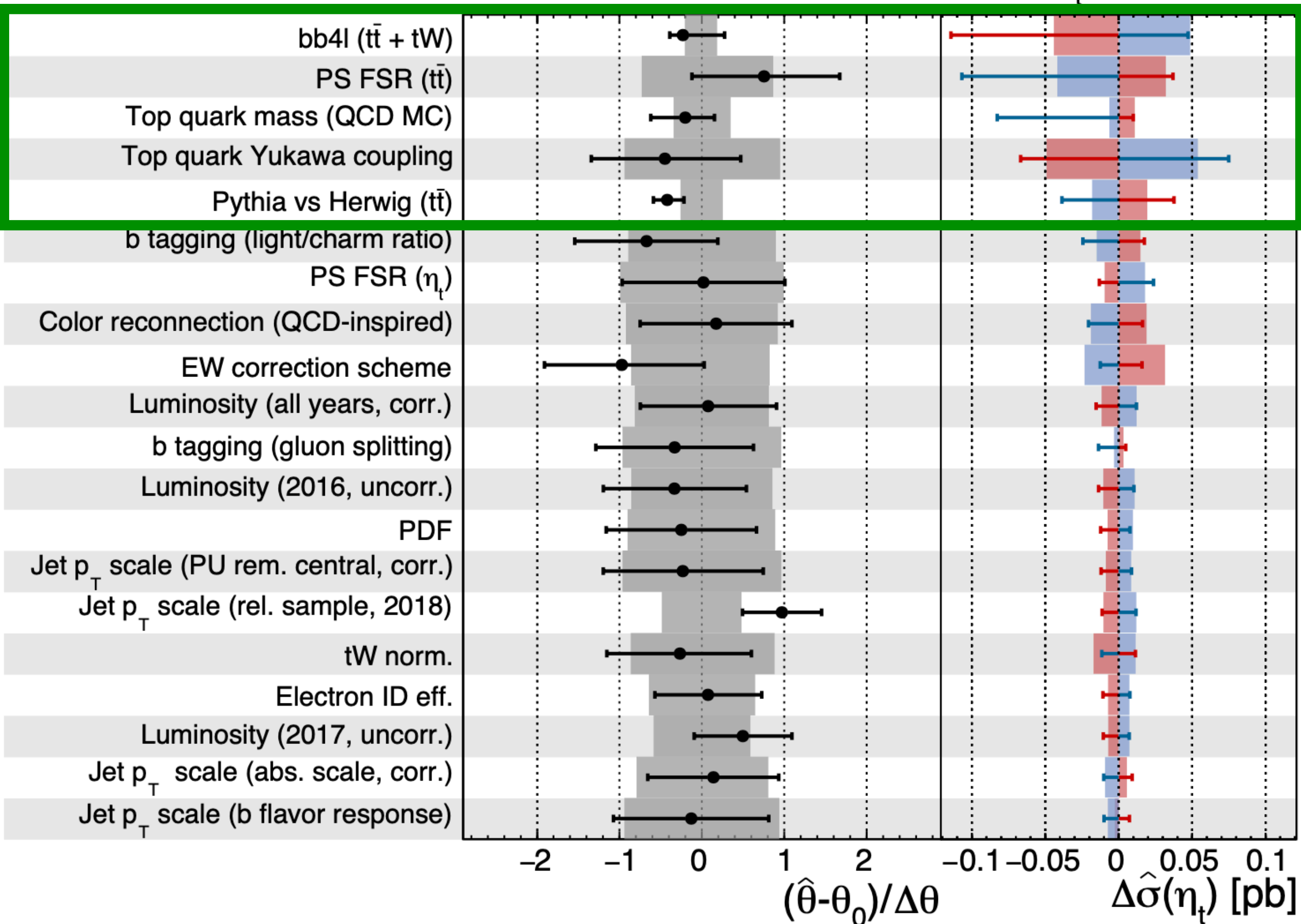
→ **uncertainty dominated by $t\bar{t}$ modeling**

Systematic Uncertainties

CMS
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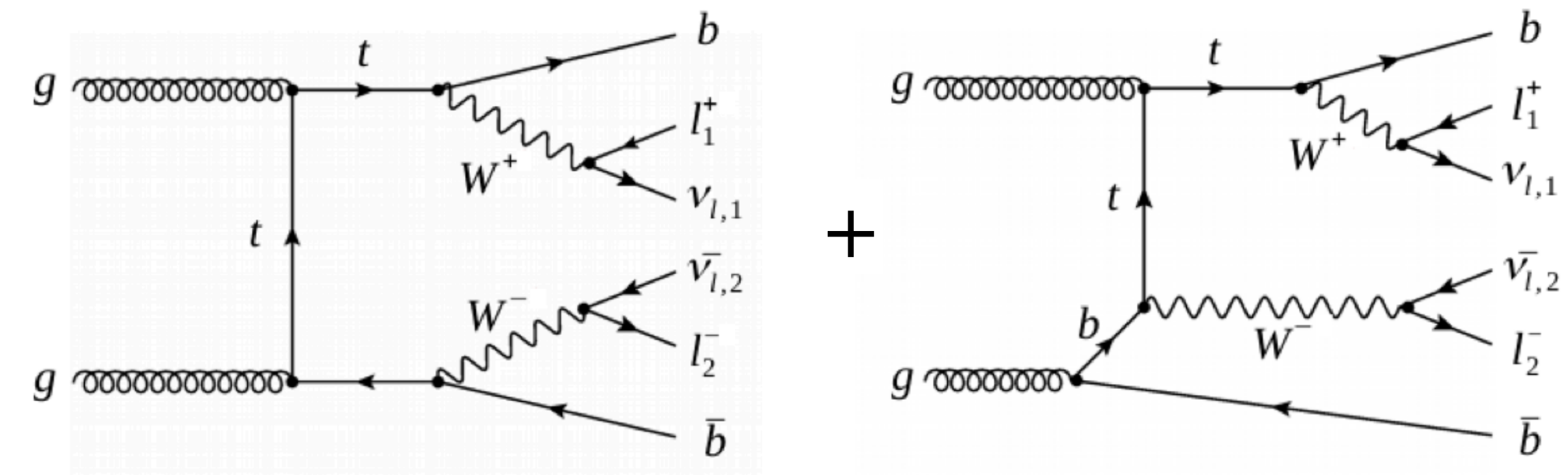
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• bb4l generator instead of Powheg:

- $pp \rightarrow b\bar{b} l^+ l^- \nu\bar{\nu}$
- off-shell effects included
- interference between $t\bar{t}$ and tW



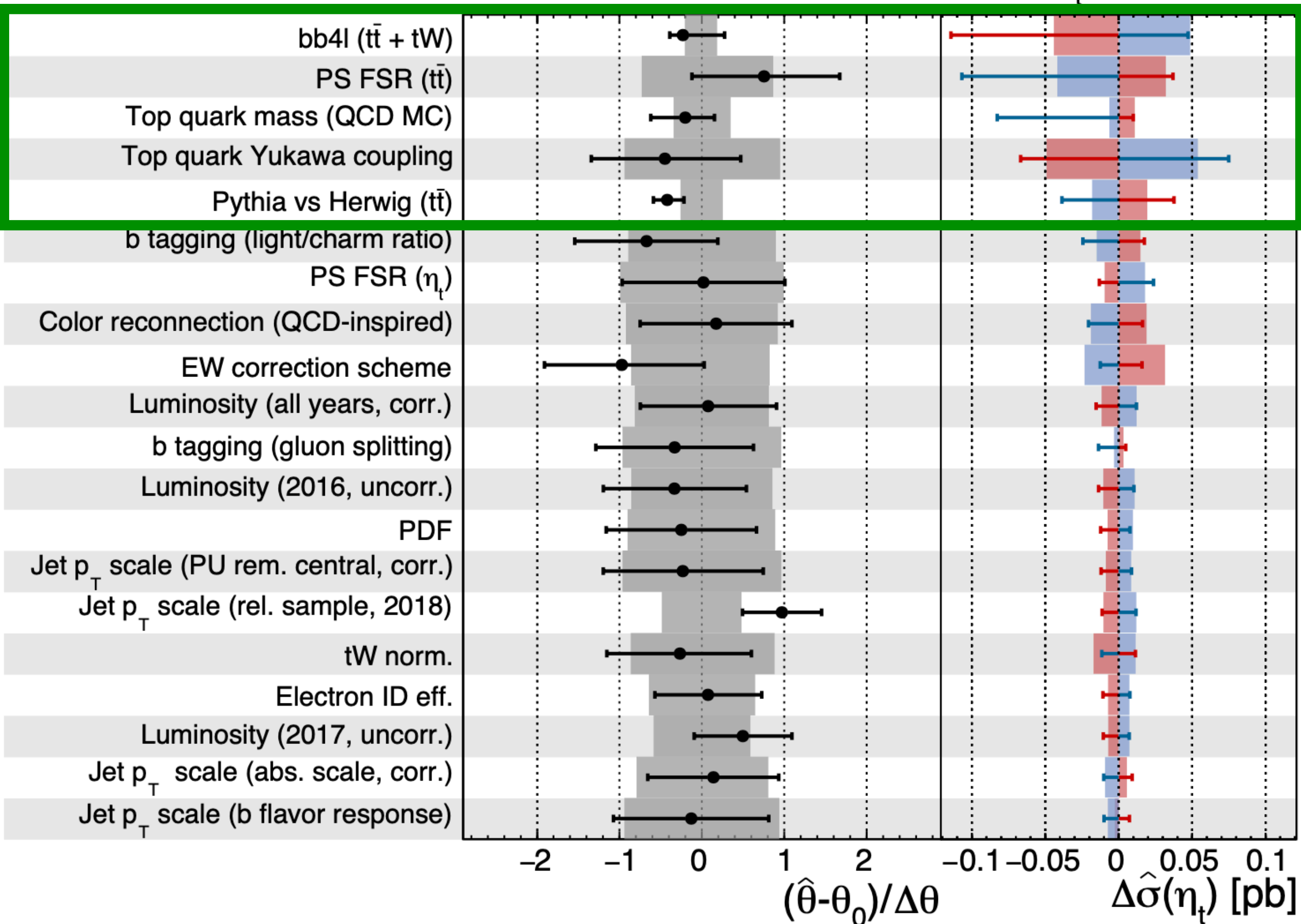
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Systematic Uncertainties

CMS
Supplementary

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$$\hat{\sigma}(\eta_t) = 8.8^{+1.2}_{-1.4} \text{ pb}$$

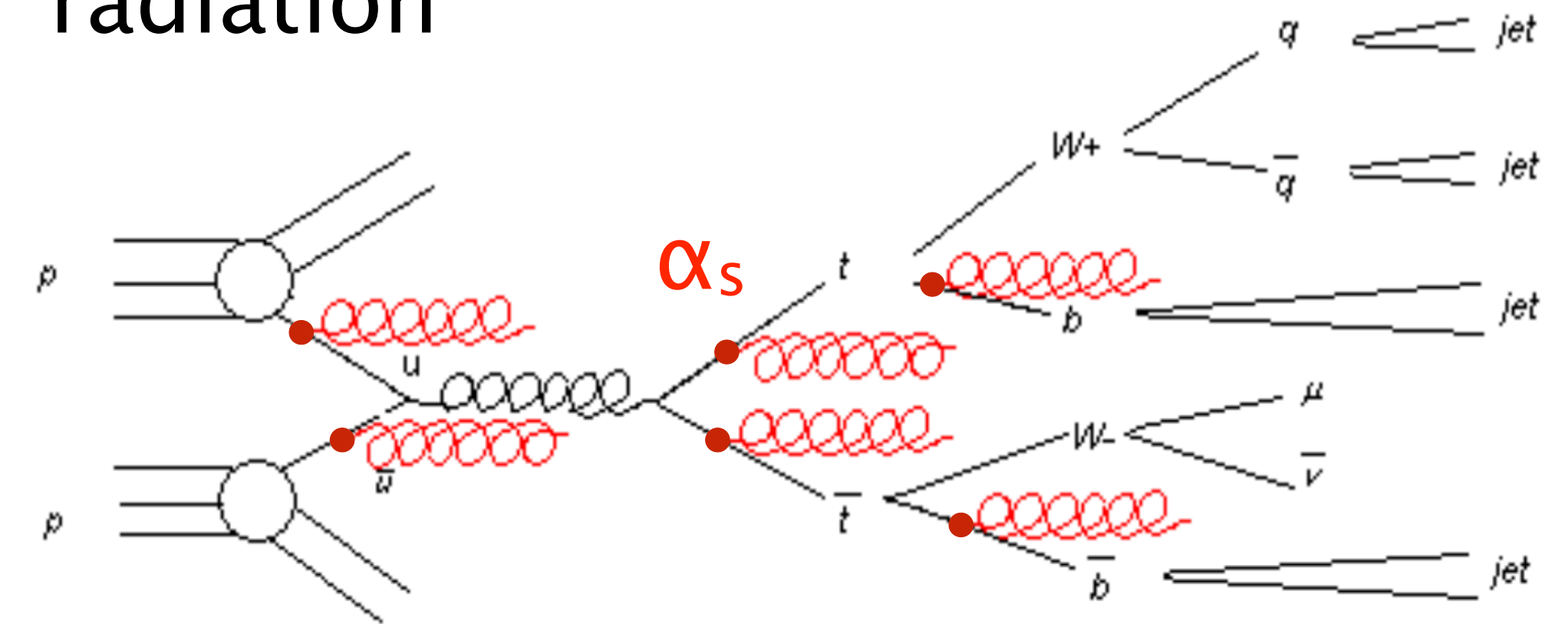


• bb4l generator instead of Powheg:

- $pp \rightarrow b\bar{b} l^+ l^- \nu\bar{\nu}$
- off-shell effects included
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• PS FSR:

- α_s variation in final state radiation



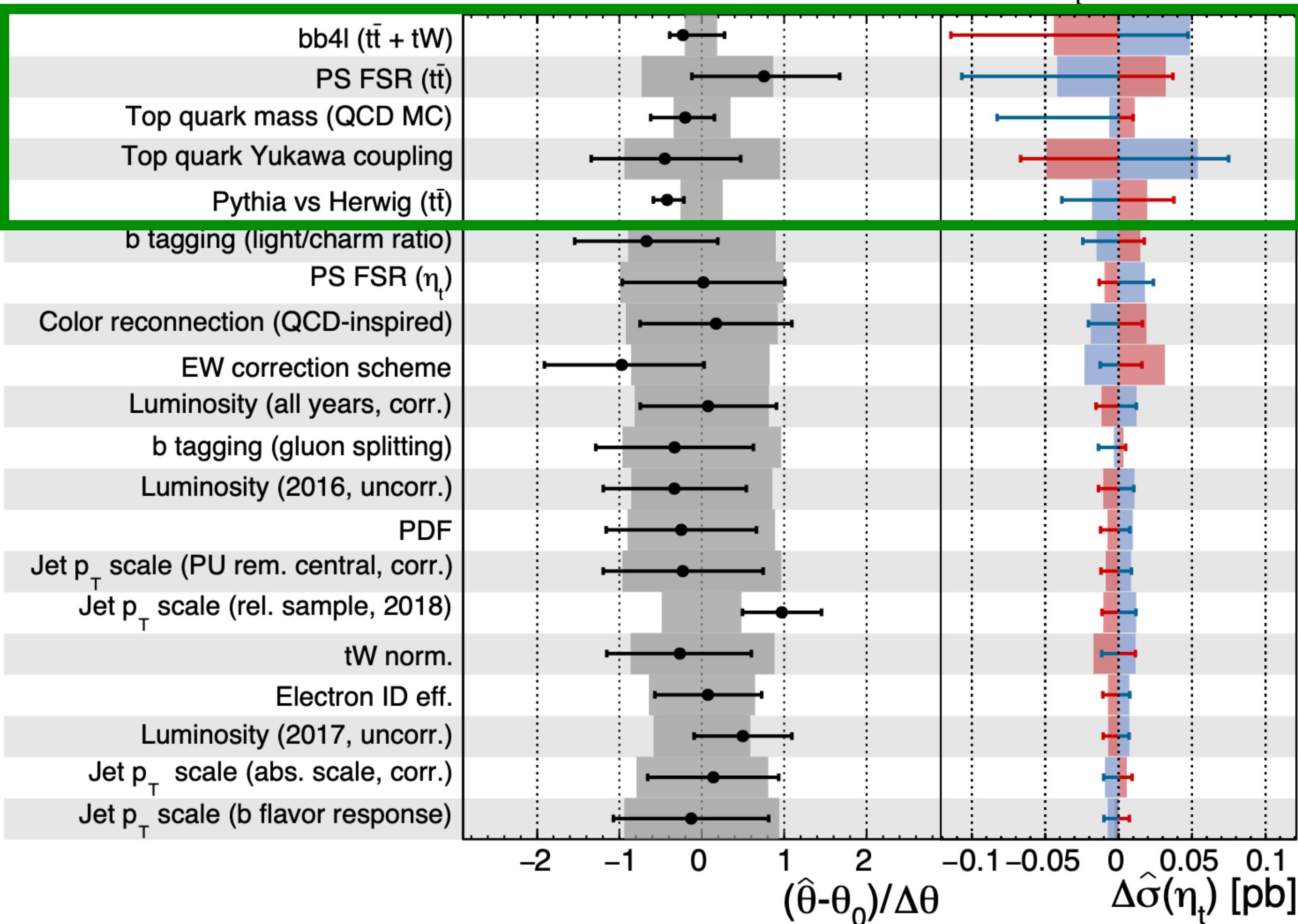
→ uncertainty dominated by $t\bar{t}$ modeling

Systematic Uncertainties

CMS
Supplementary

—●— Fit constraint (obs.) —●— Fit constraint (exp.)
— +1 σ impact (obs.) — +1 σ impact (exp.)
— -1 σ impact (obs.) — -1 σ impact (exp.)

$$\hat{\sigma}(\eta_t) = 8.8^{+1.2}_{-1.4} \text{ pb}$$



- bb4l generator instead of Powheg:
 - $pp \rightarrow b\bar{b} l^+ l^- \nu\bar{\nu}$
 - off-shell effects included
 - interference between $t\bar{t}$ and tW
- PS FSR:
 - α_s variation in final state radiation
- top quark mass

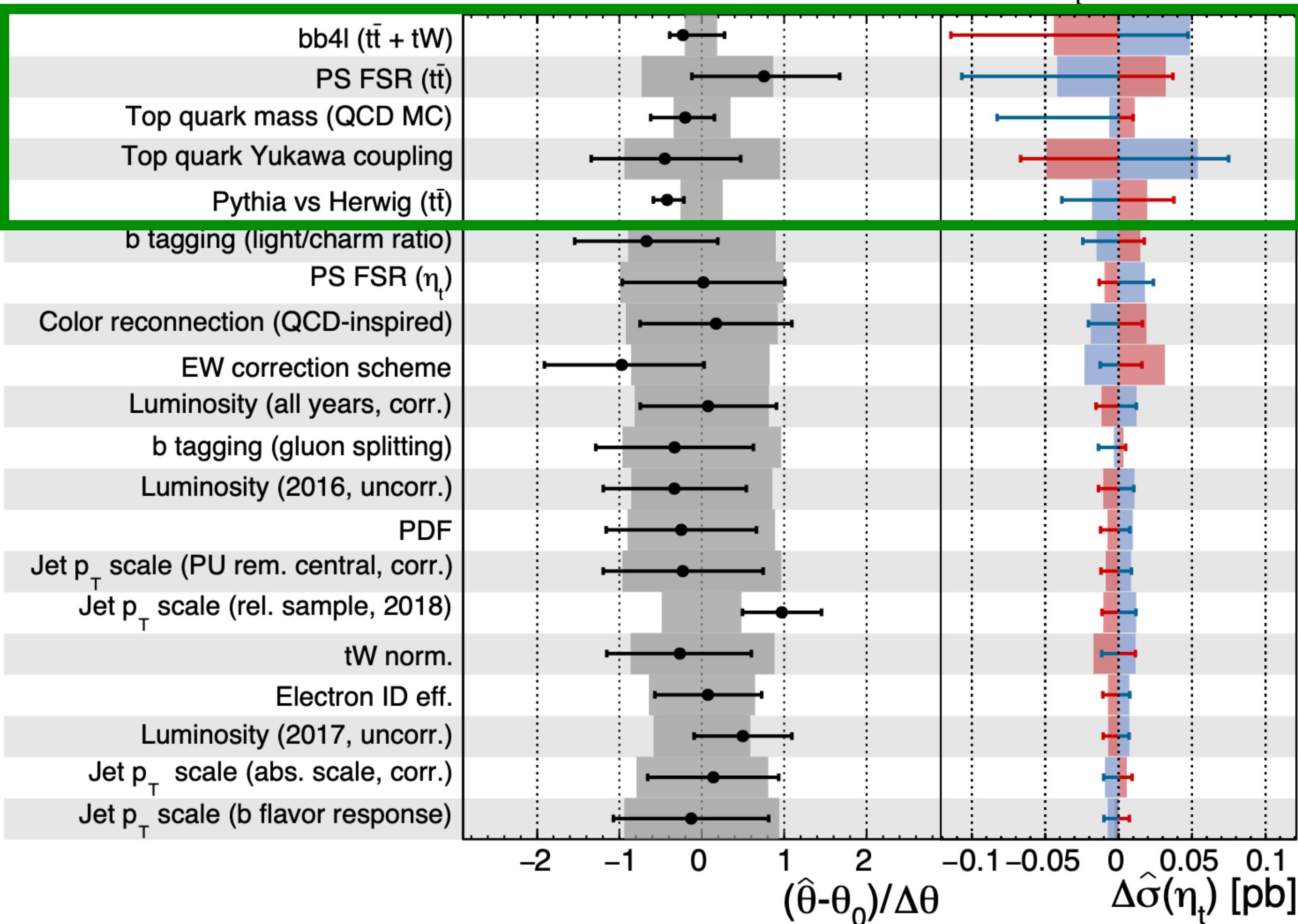
→ **uncertainty dominated by $t\bar{t}$ modeling**

Systematic Uncertainties

CMS
Supplementary

—●— Fit constraint (obs.) — +1 σ impact (obs.) — -1 σ impact (obs.)
 ■ Fit constraint (exp.) ■ +1 σ impact (exp.) ■ -1 σ impact (exp.)

$$\hat{\sigma}(\eta_t) = 8.8^{+1.2}_{-1.4} \text{ pb}$$



- bb4l generator instead of Powheg:
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 - α_s variation in final state radiation
- top quark mass
- top quark Yukawa coupling

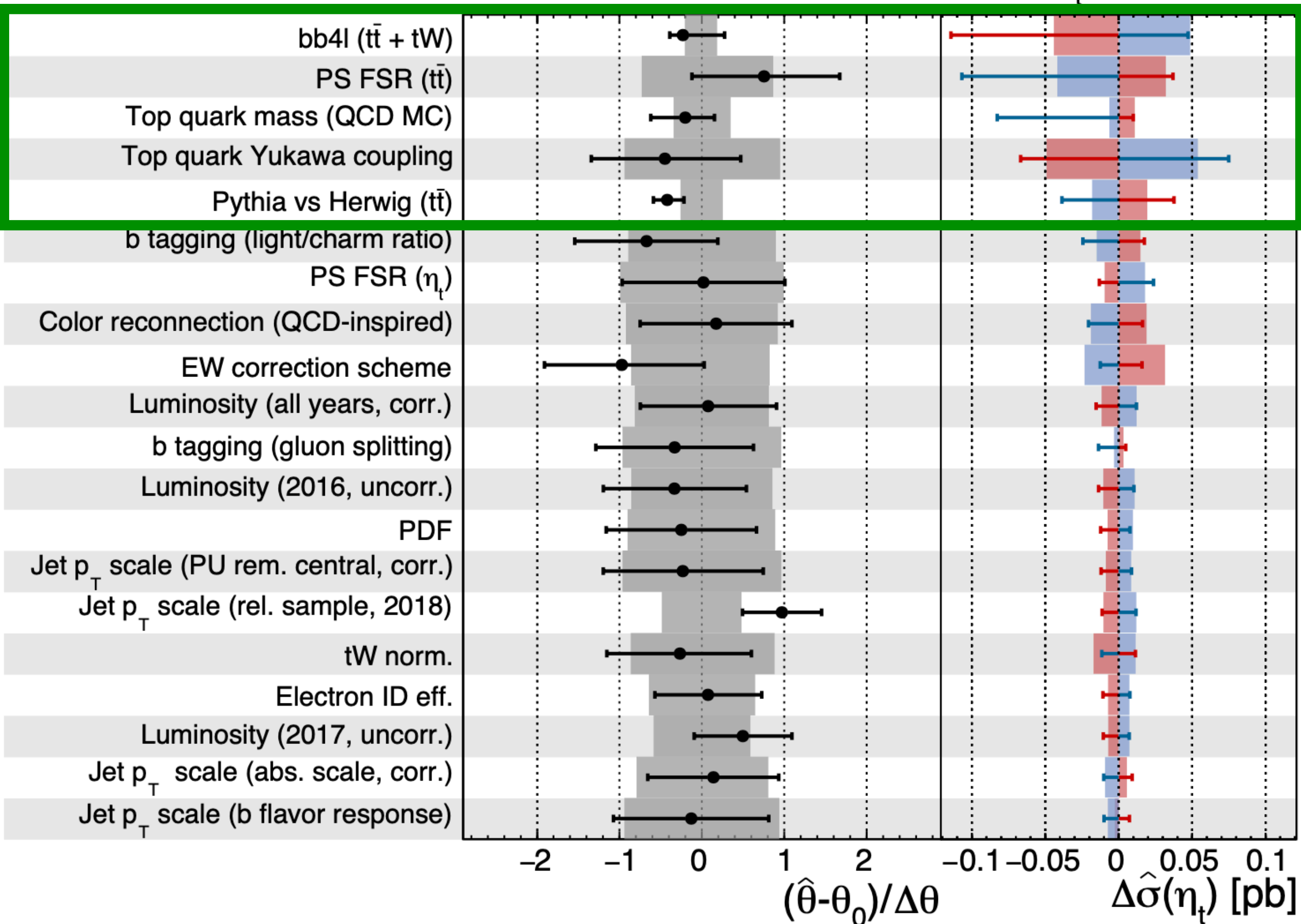
→ **uncertainty dominated by $t\bar{t}$ modeling**

Systematic Uncertainties

CMS
Supplementary

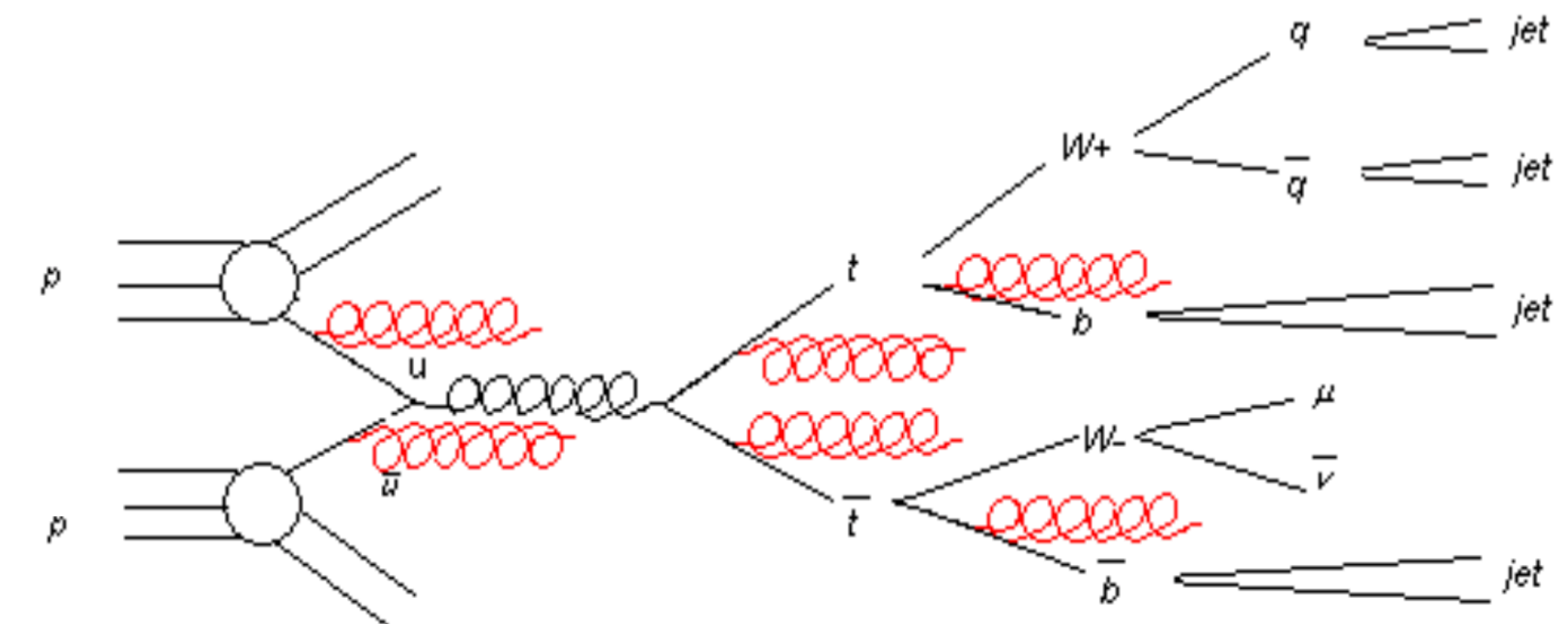
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• bb4l generator instead of Powheg:

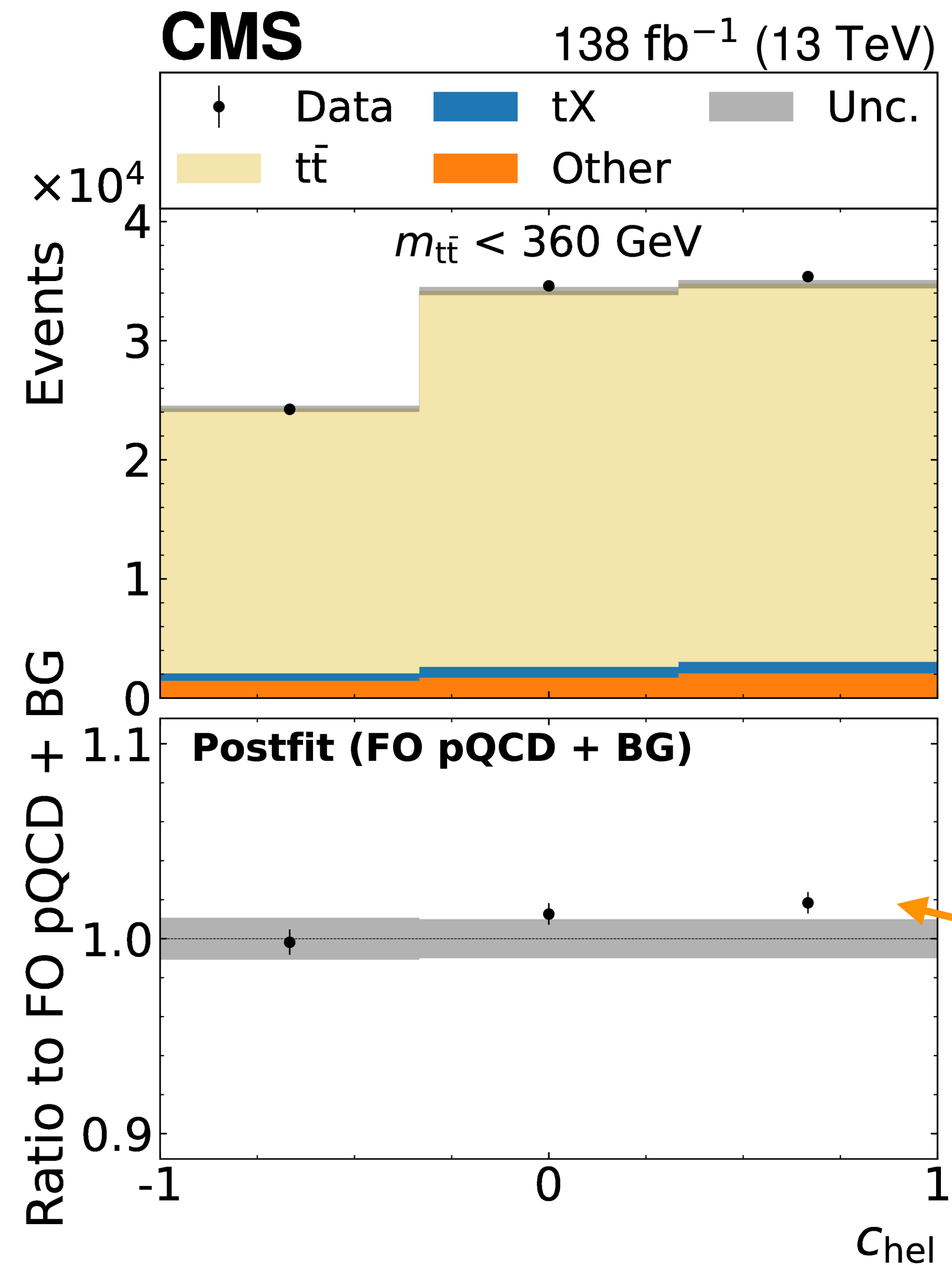
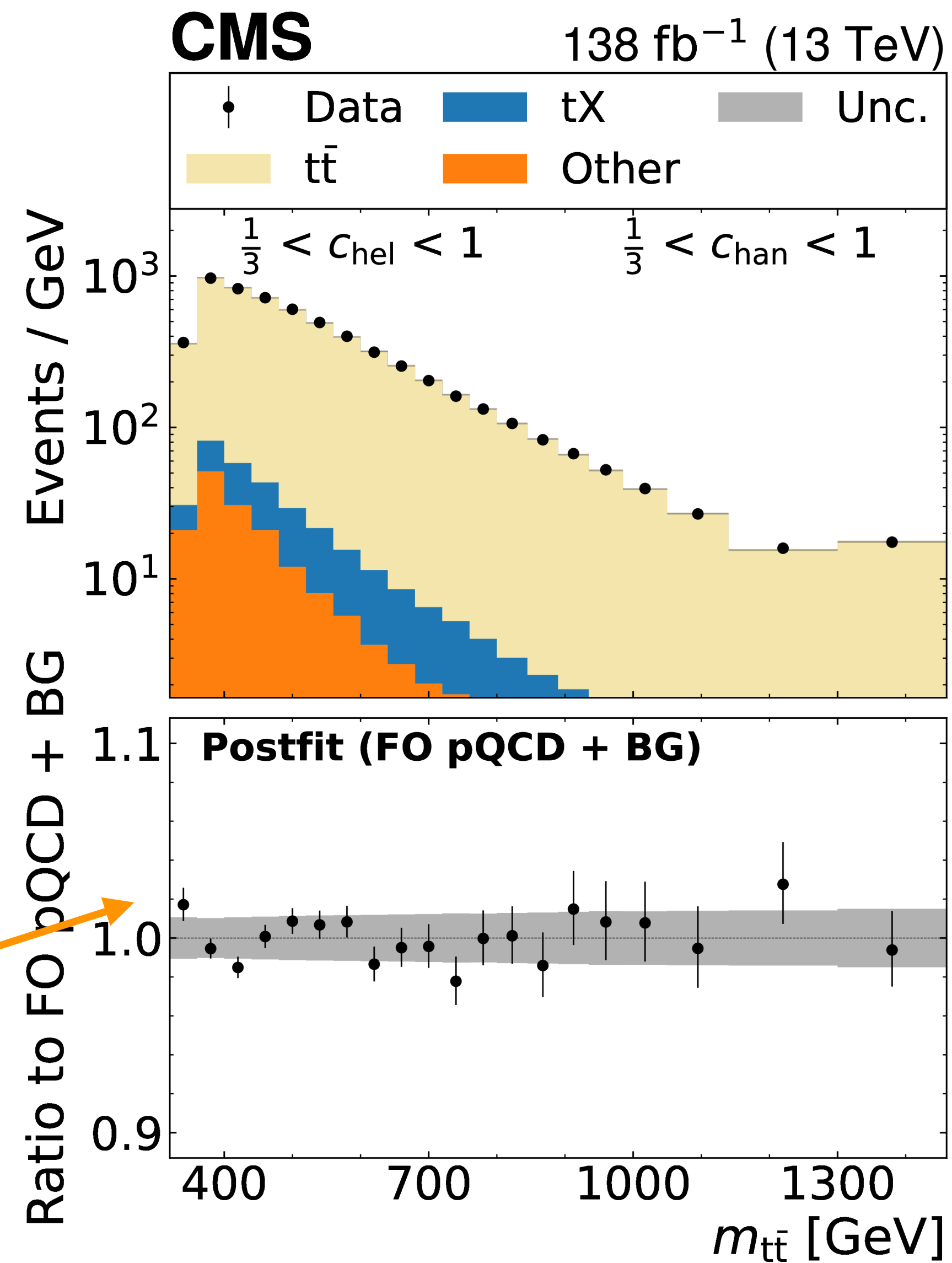
- $pp \rightarrow b\bar{b} l^+ l^- \nu\bar{\nu}$
- off-shell effects included
- interference between $t\bar{t}$ and tW



• Herwig7 parton shower simulation instead of Pythia8

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

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

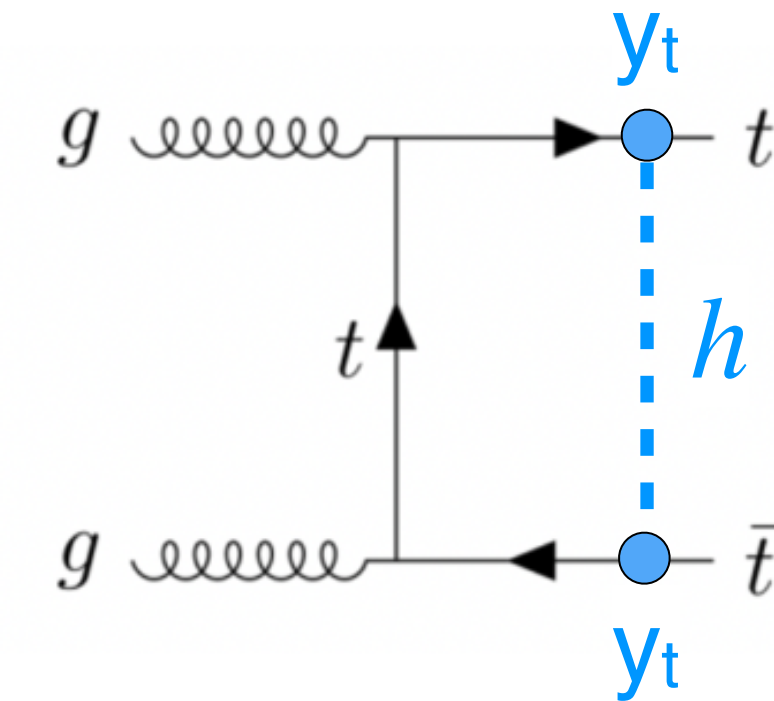


Fit without $t\bar{t}$ Bound State

CMS

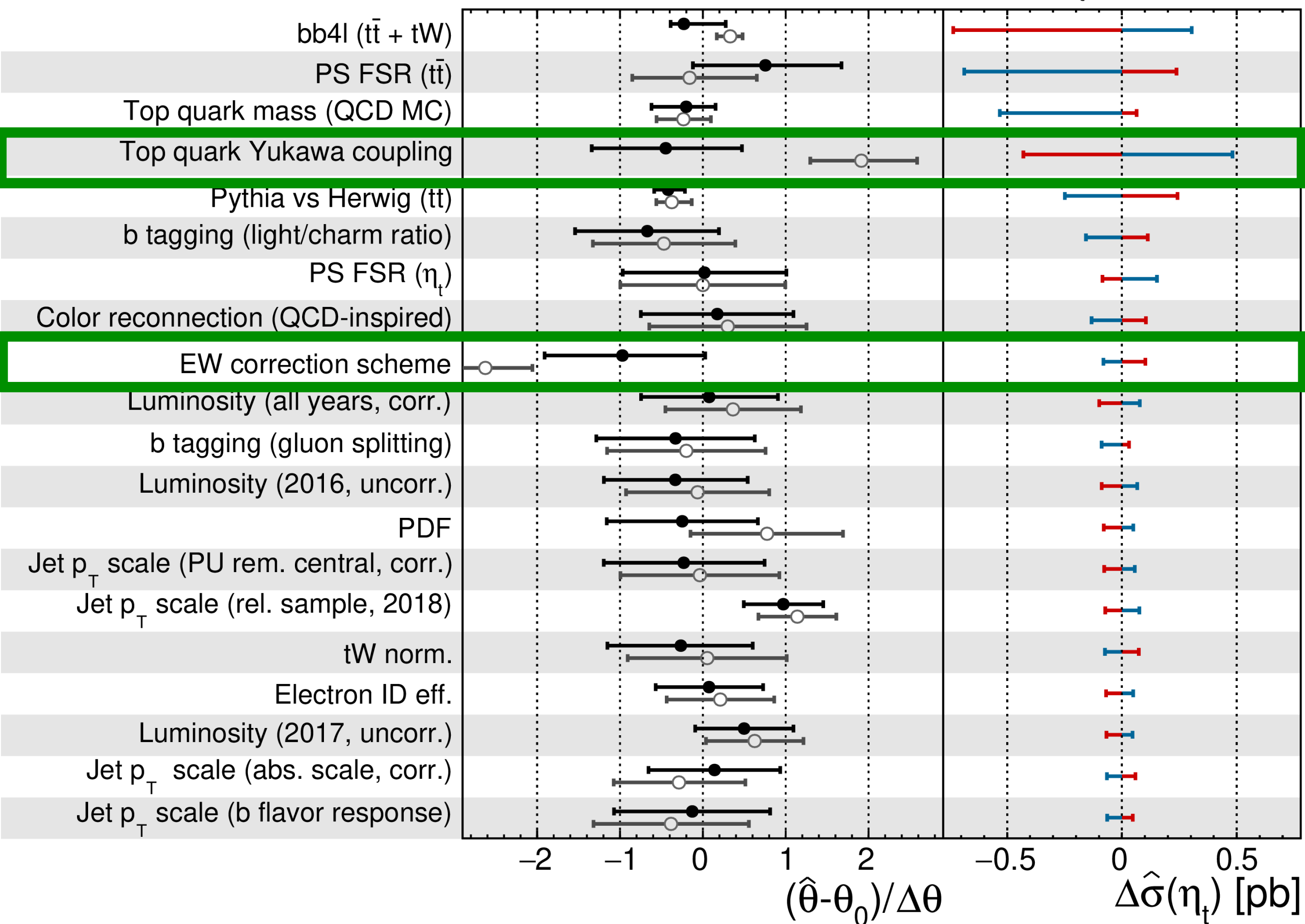
- Fit constraint (FO pQCD + BG + η_t)
- Fit constraint (FO pQCD + BG only)
- +1 σ impact (FO pQCD + BG + η_t)
- -1 σ impact (FO pQCD + BG + η_t)

$$\hat{\sigma}(\eta_t) = 8.8^{+1.2}_{-1.4} \text{ pb}$$

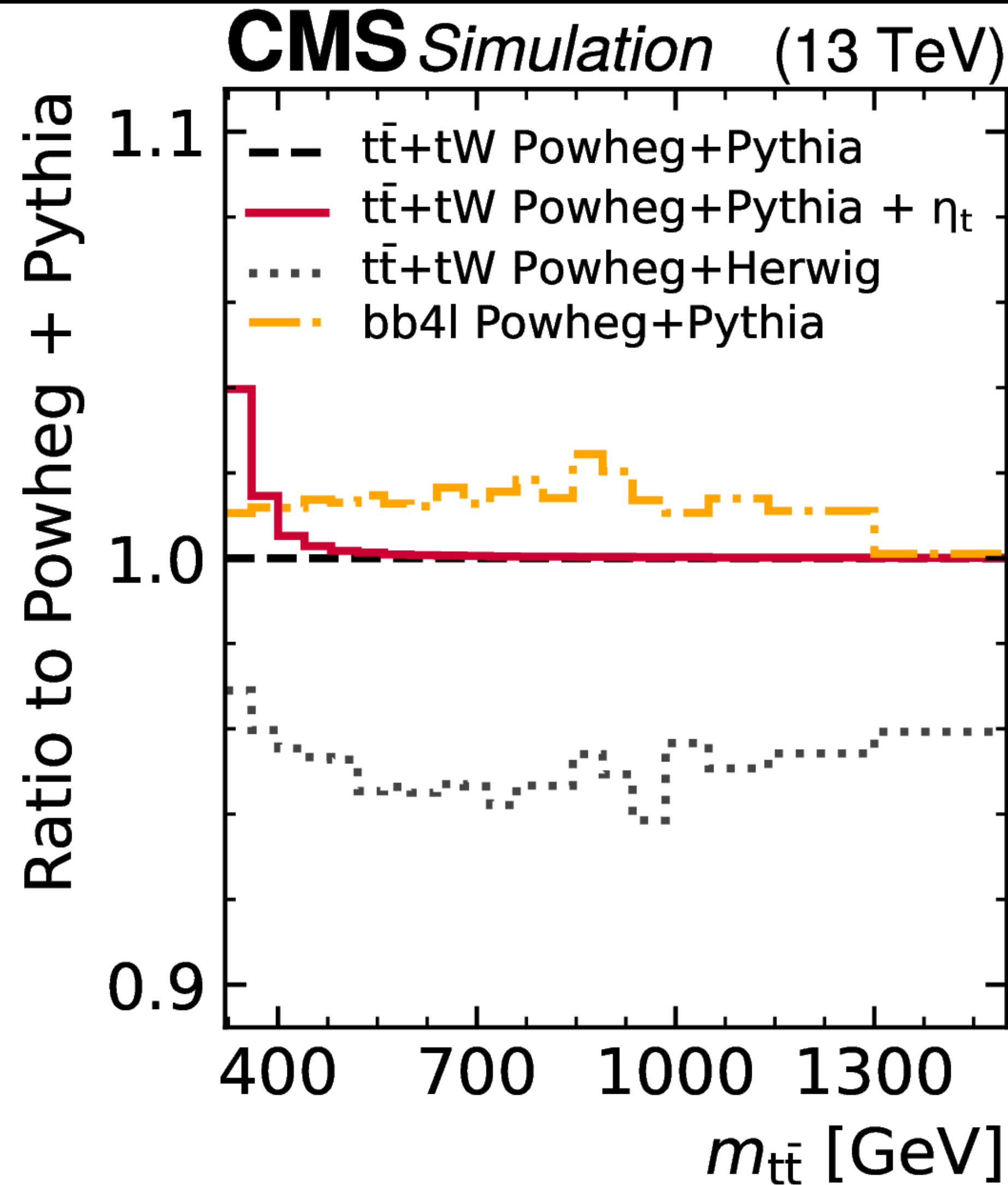


strong pulls to values beyond the SM prediction

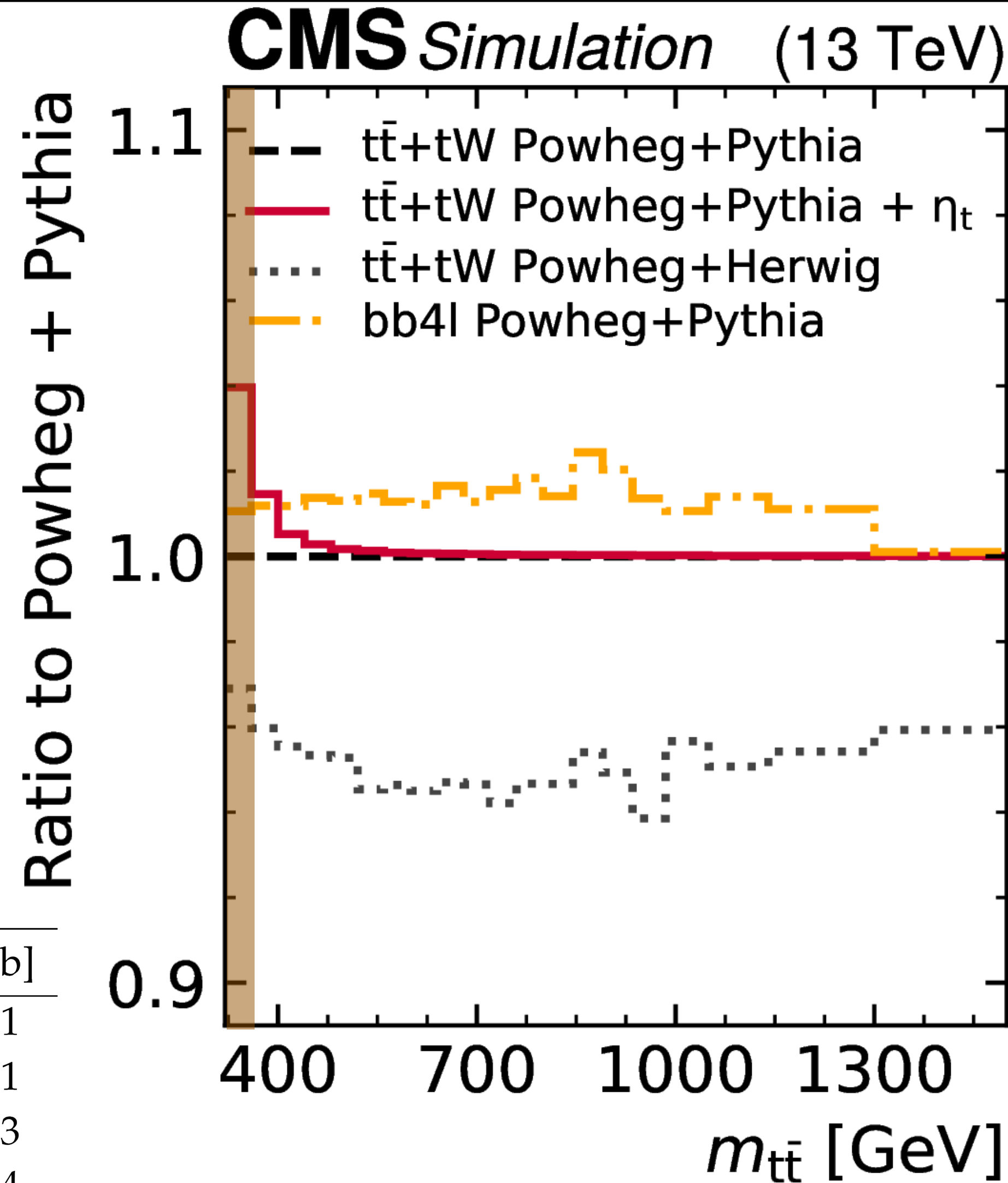
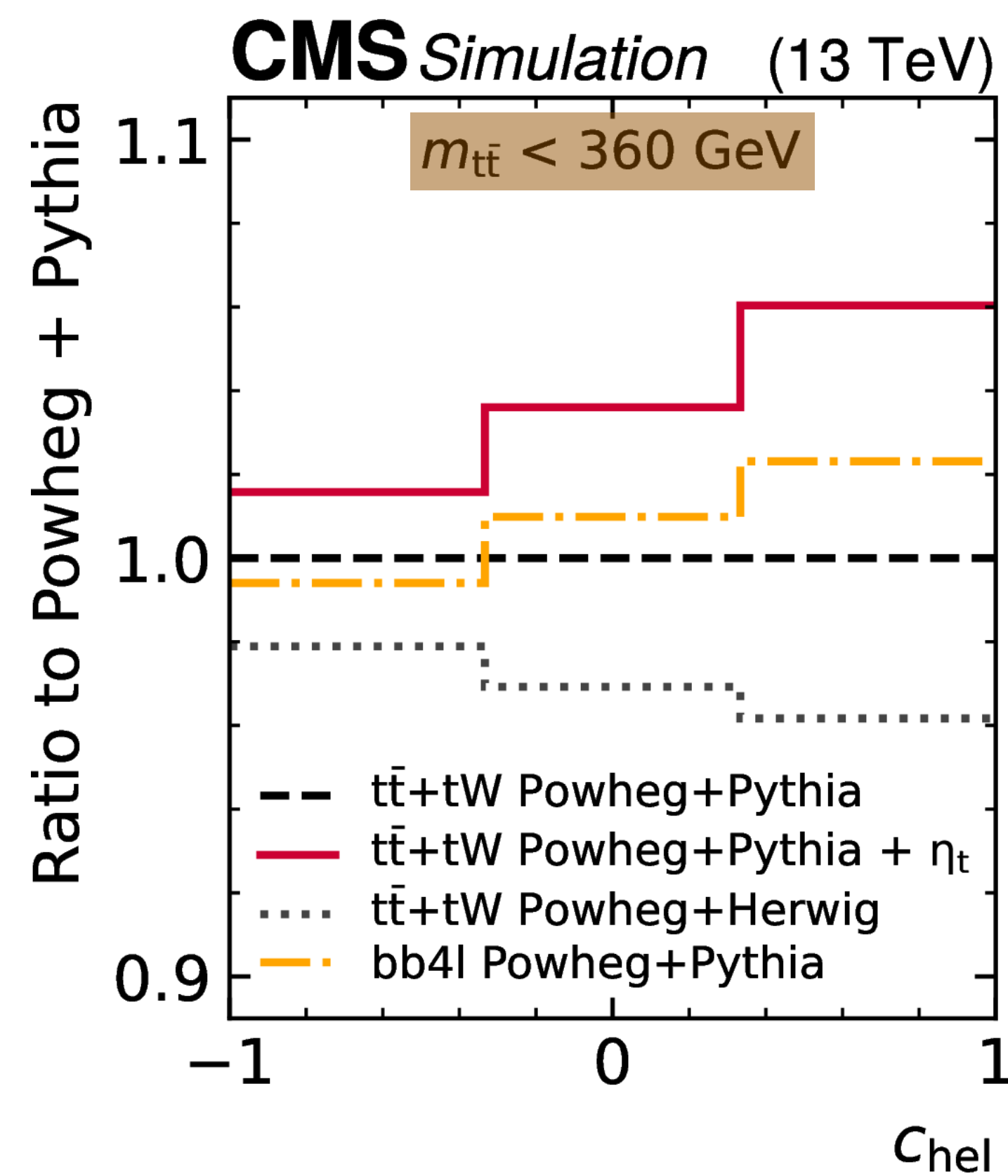
→ observed excess can only be explained by additional contributions to FO pQCD



Alternative fixed order pQCD predictions



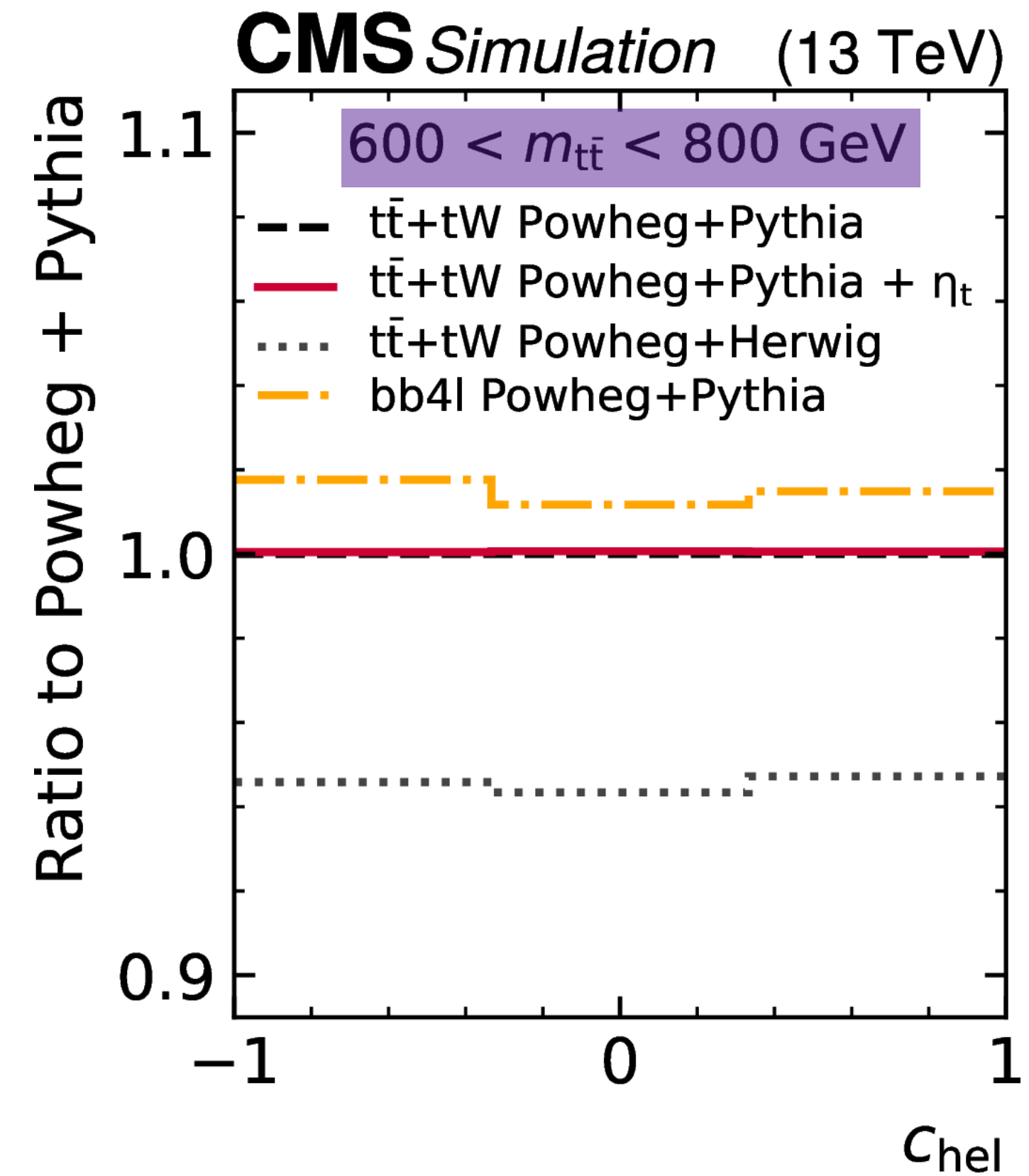
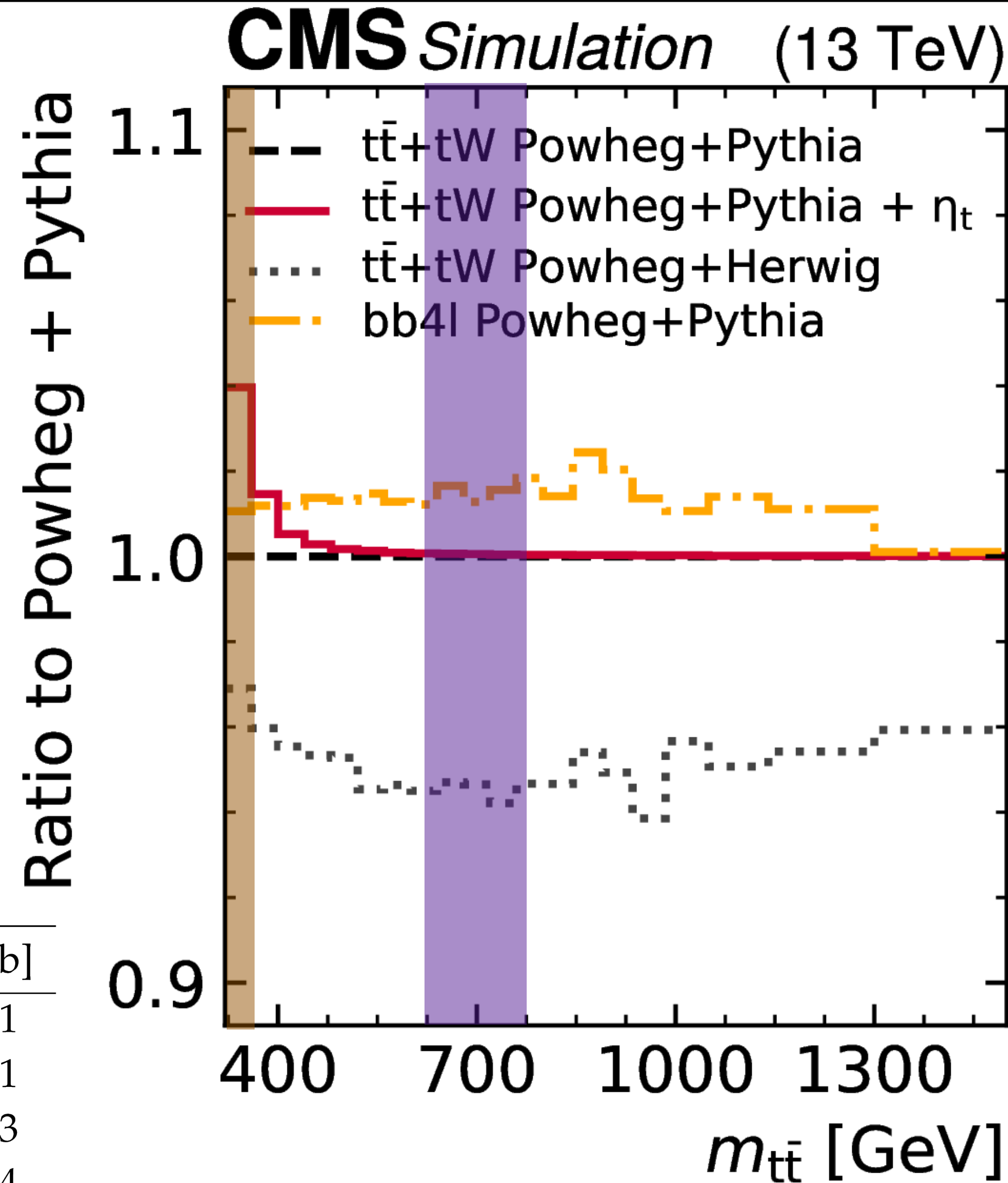
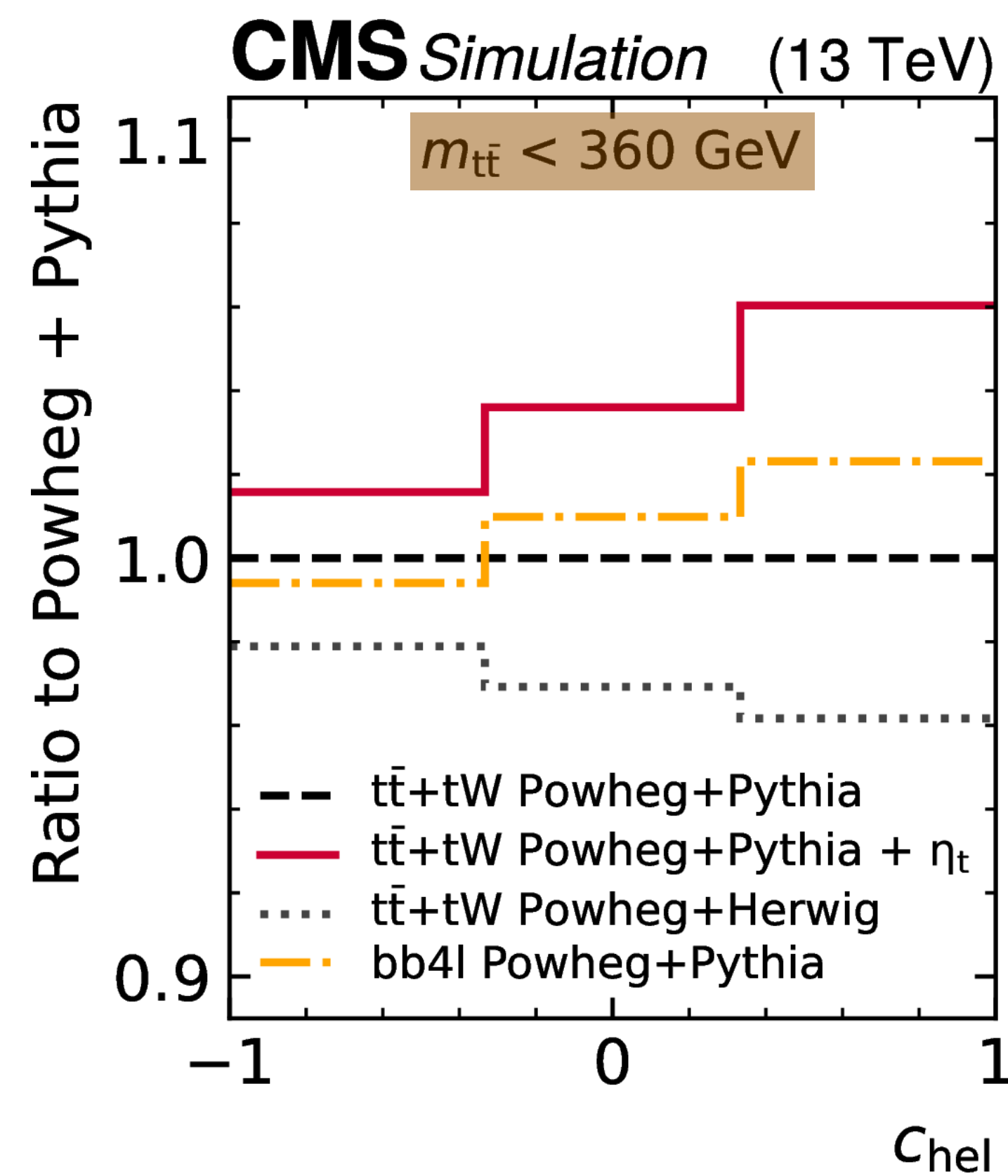
Alternative fixed order pQCD predictions



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

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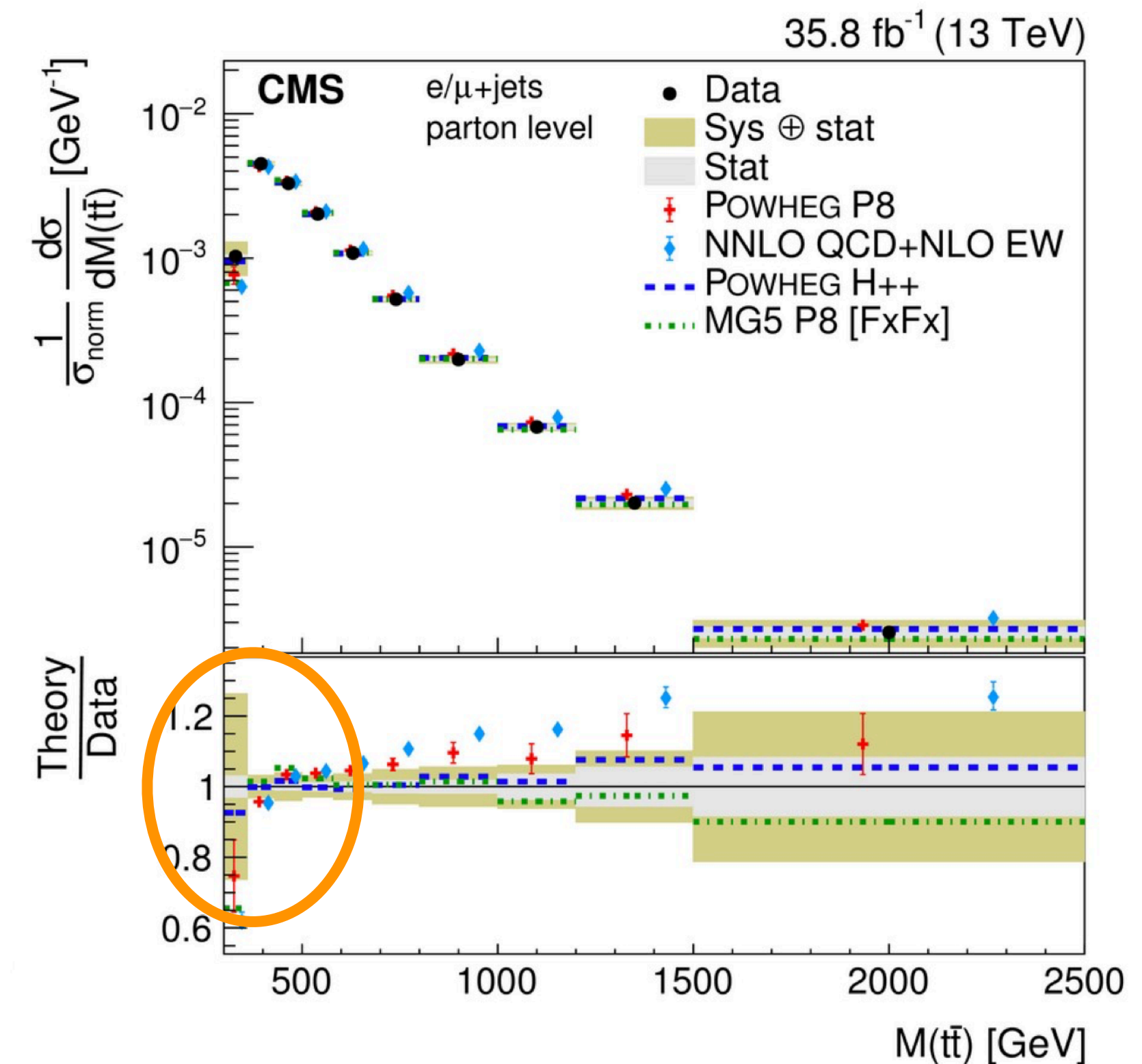
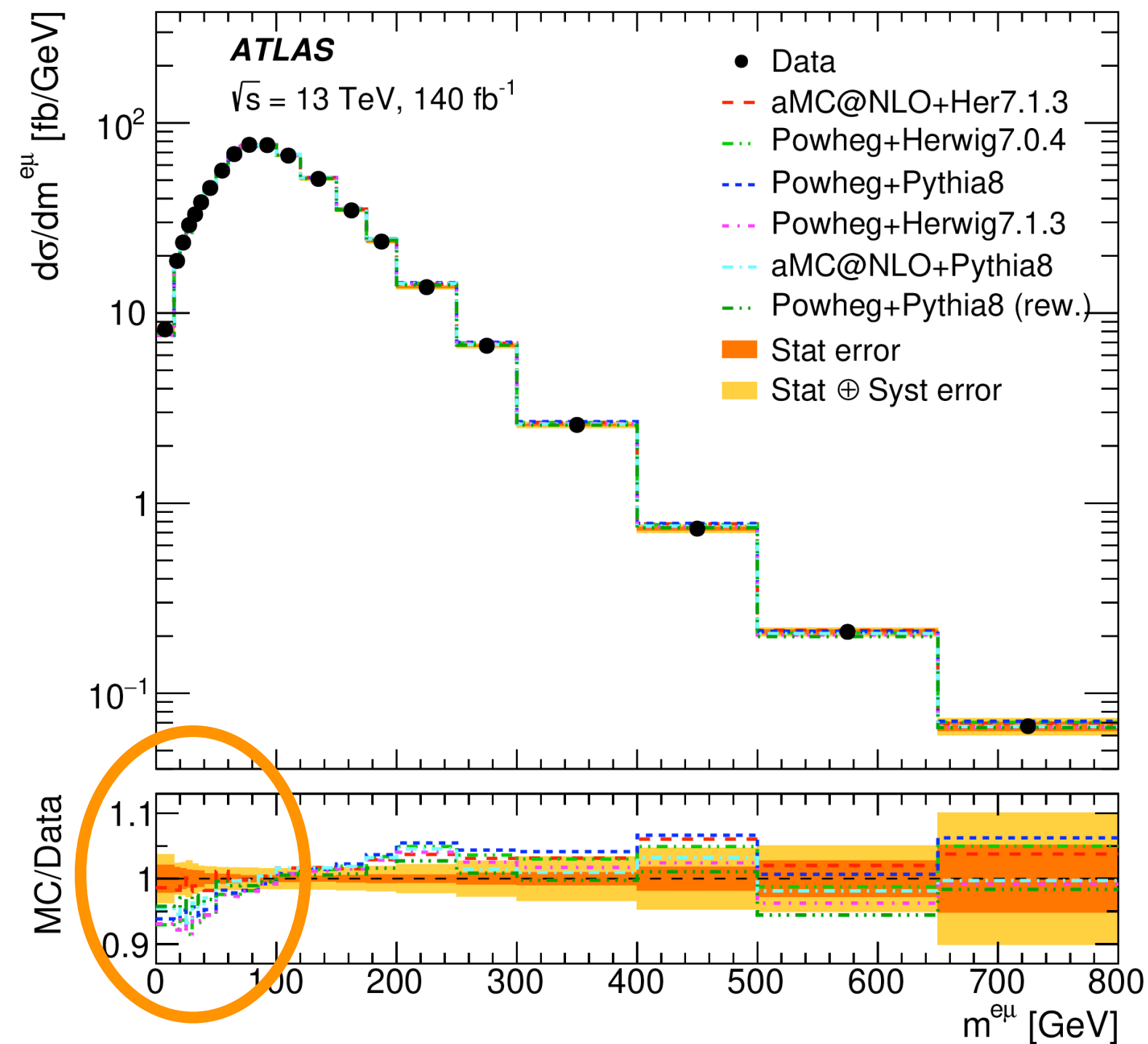
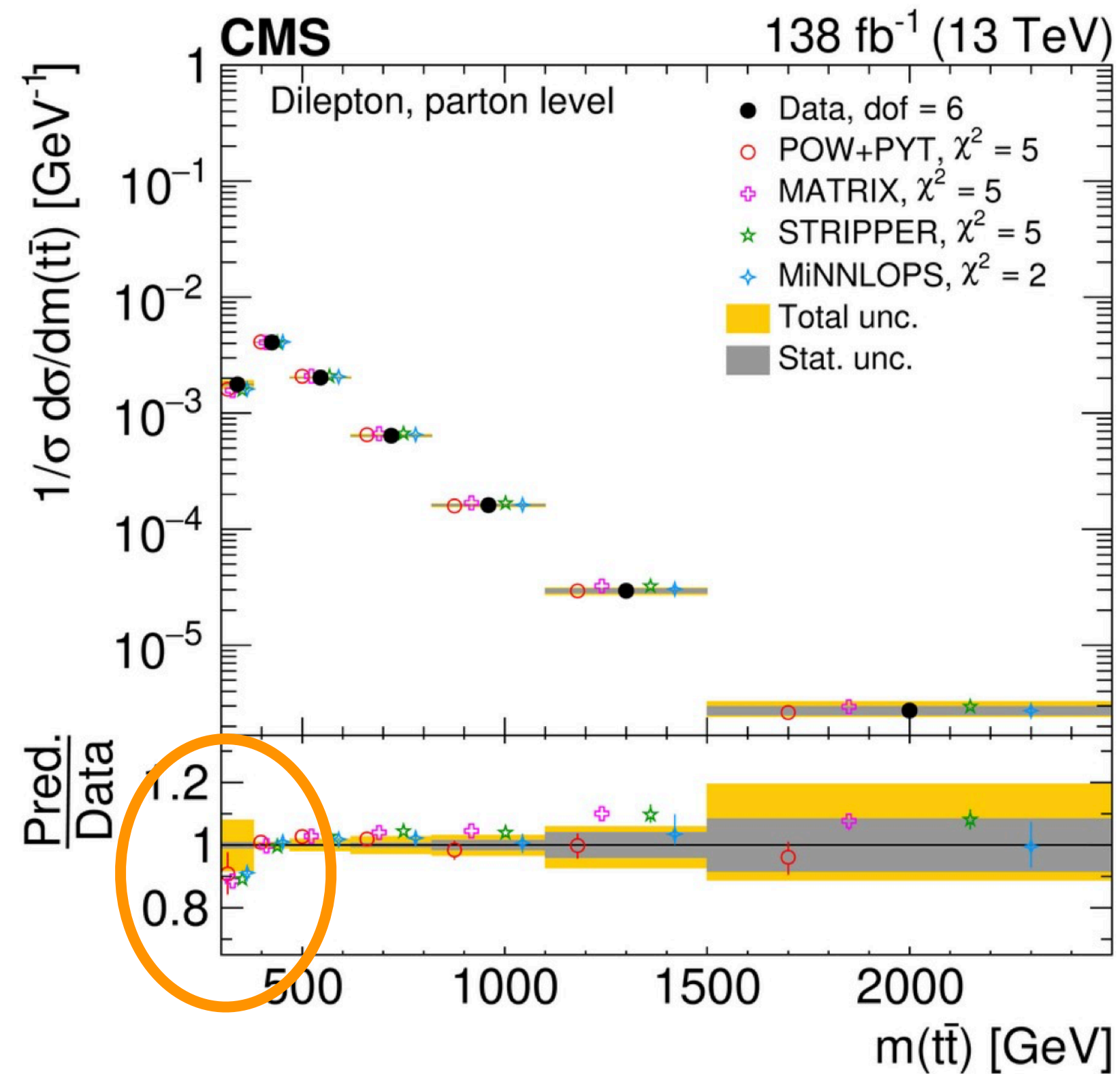
→ excess remains

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

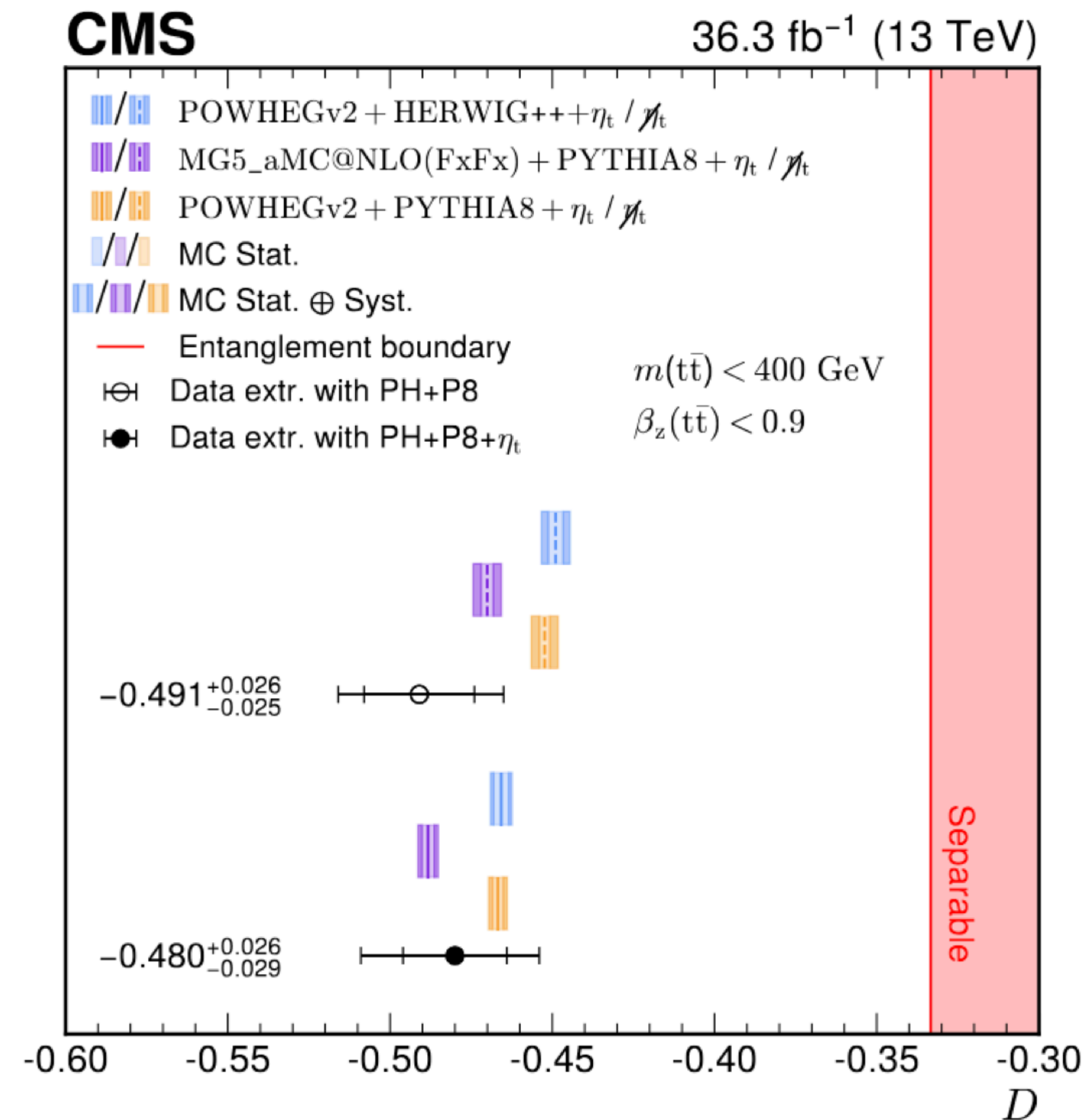
- quantum entanglement analysis

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

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

$$C_{\text{hel}} = \cos \varphi$$

RPP 87 (2024) 117801



See talk by Efe Yazgan

→ data requests stronger slope in c_{hel} at threshold: „our“ pseudoscalar excess would fit

Summary

- **observed excess** of CMS data ($\sqrt{s} = 13 \text{ TeV}$, 138 fb^{-1}) at top pair production threshold with **$>5\sigma$ significance**
- consistent with a **CP-odd color-singlet $t\bar{t}$ (quasi-)bound state: η_t**
- extracted cross section

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

in agreement with NRQCD prediction of 6.4 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... **See next talk!**

Summary

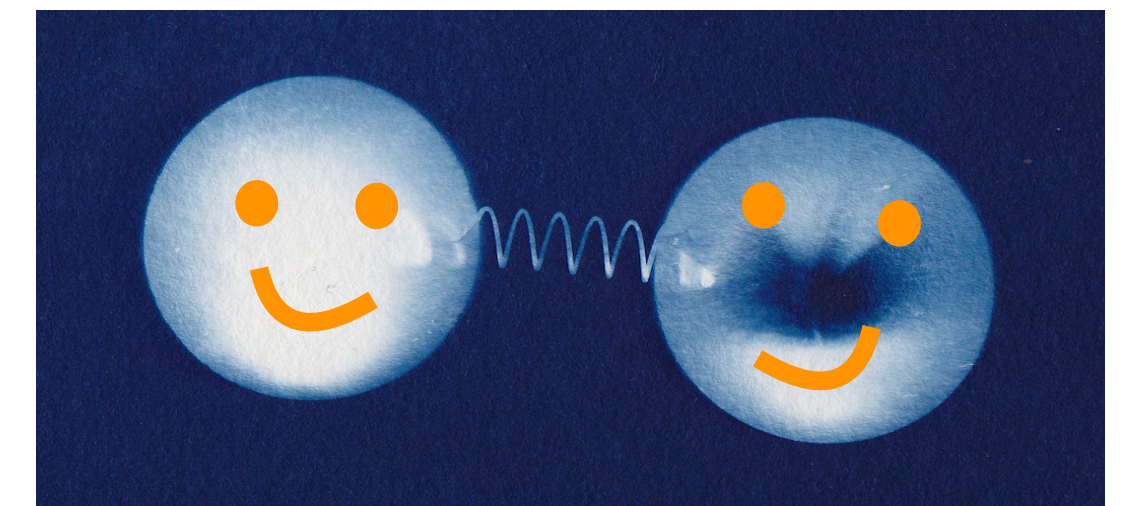
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- **caution 3:** ATLAS needs to confirm... **See next talk!**

by Heifeng Li



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

Backup

It's exciting...

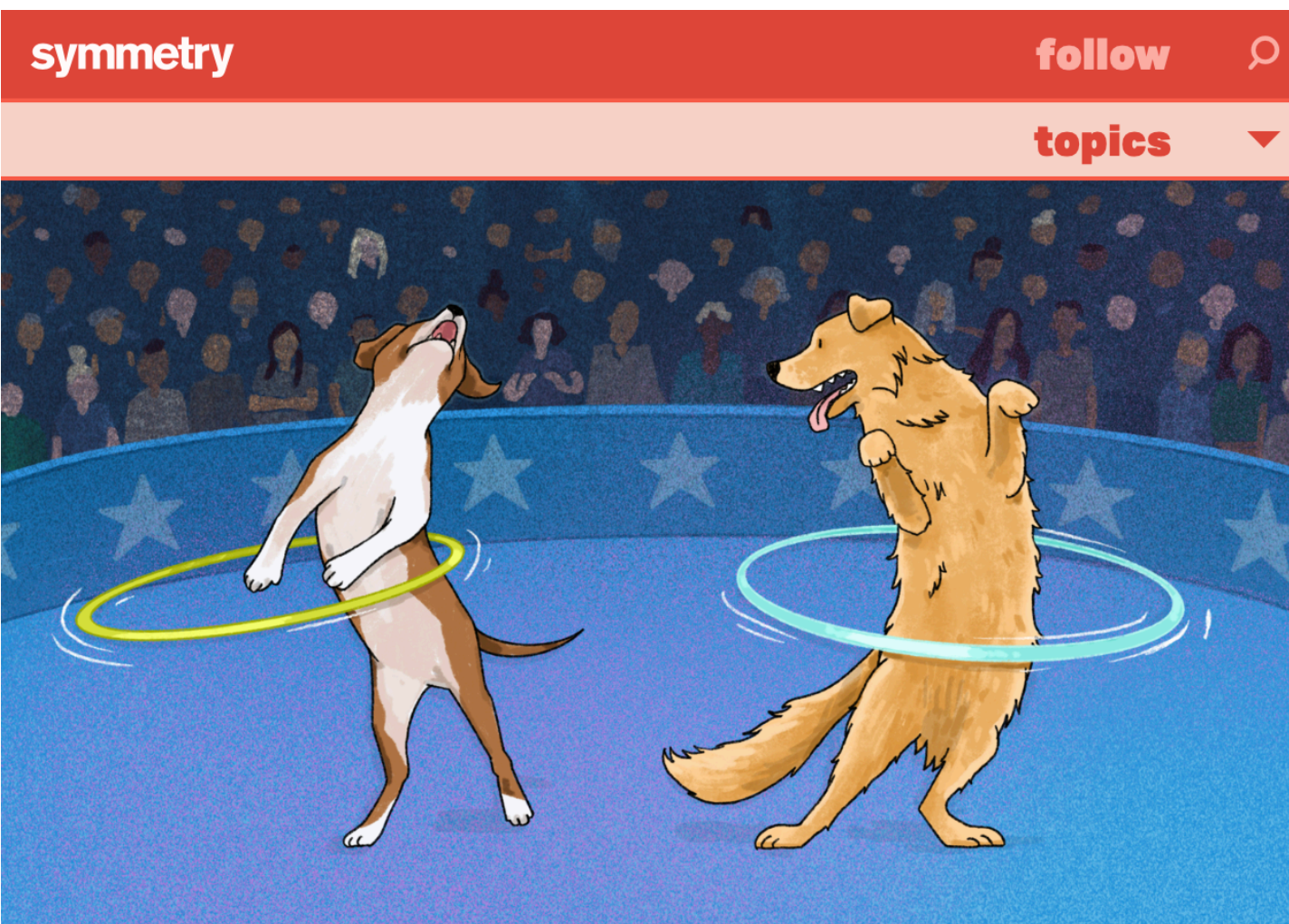


Illustration by Sandbox Studio, Chicago with Corinne Mucha

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.



Deutsches Elektronen-Synchrotron DESY
Ein Forschungszentrum der Helmholtz-Gemeinschaft

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Home / Events & News / News / Scientists from the CMS collaboration observe a new effect

Scientists from the CMS collaboration observe a new effect

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

TEST BEAM



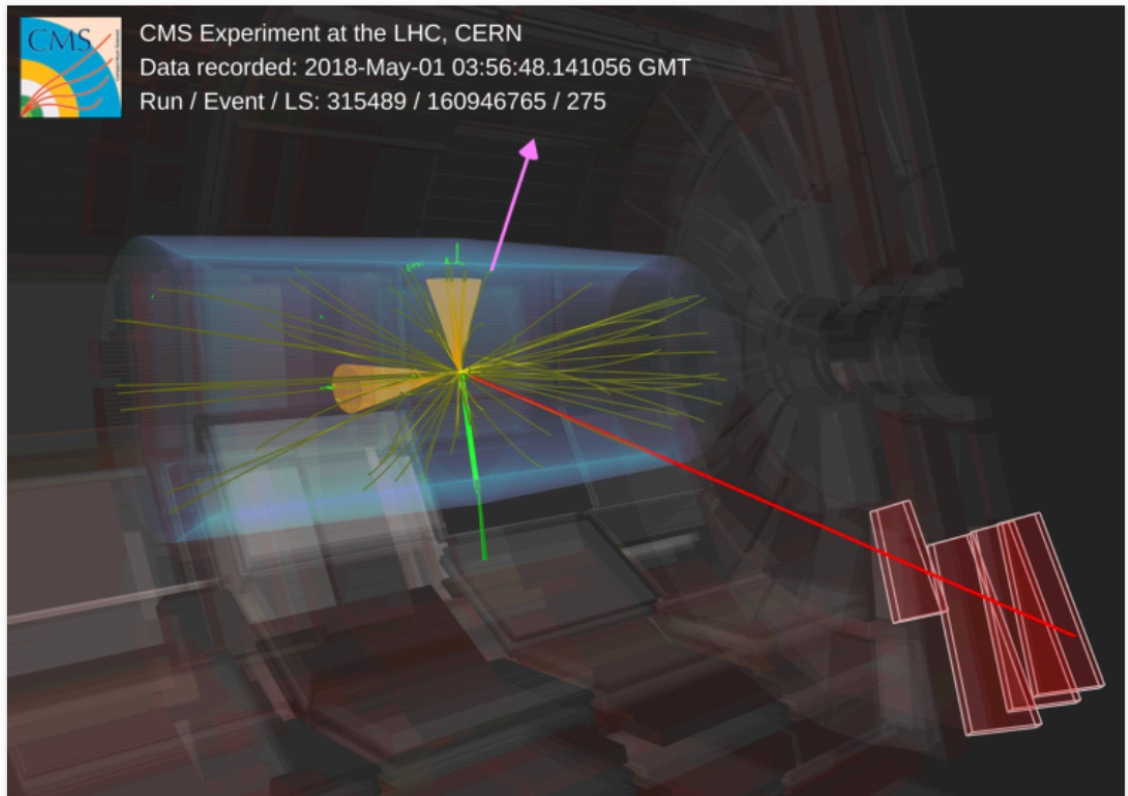
By CMS Collaboration



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

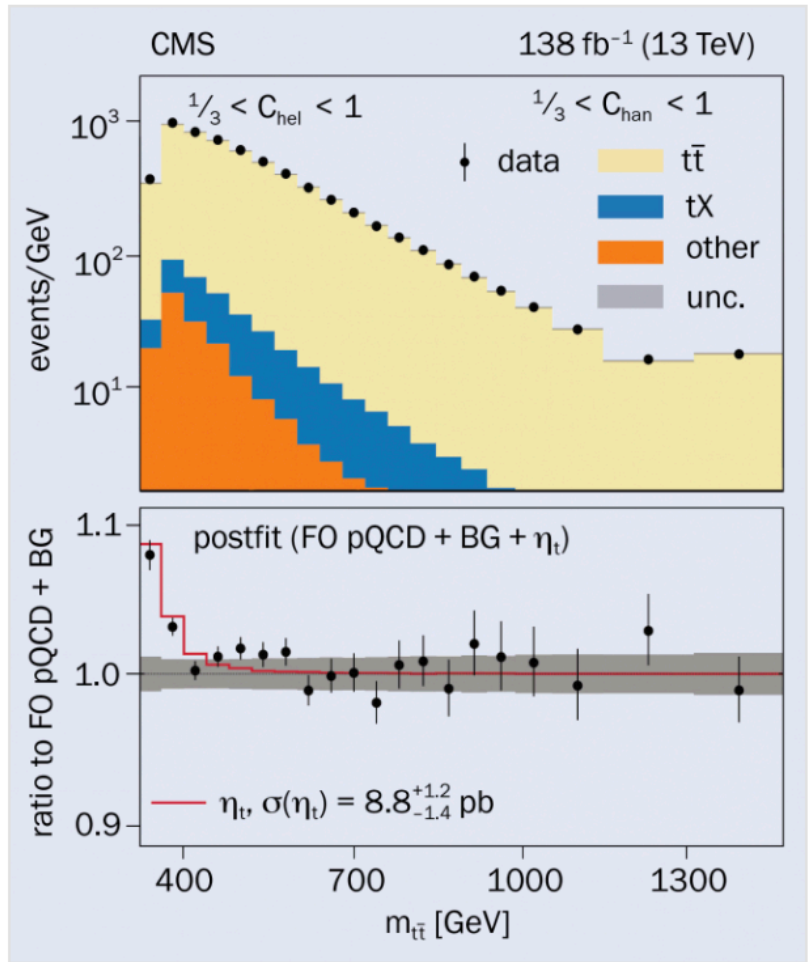


Event display of the excess of top-quark pairs. (Image: CMS collaboration/CERN)

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.



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





Dominic Stafford



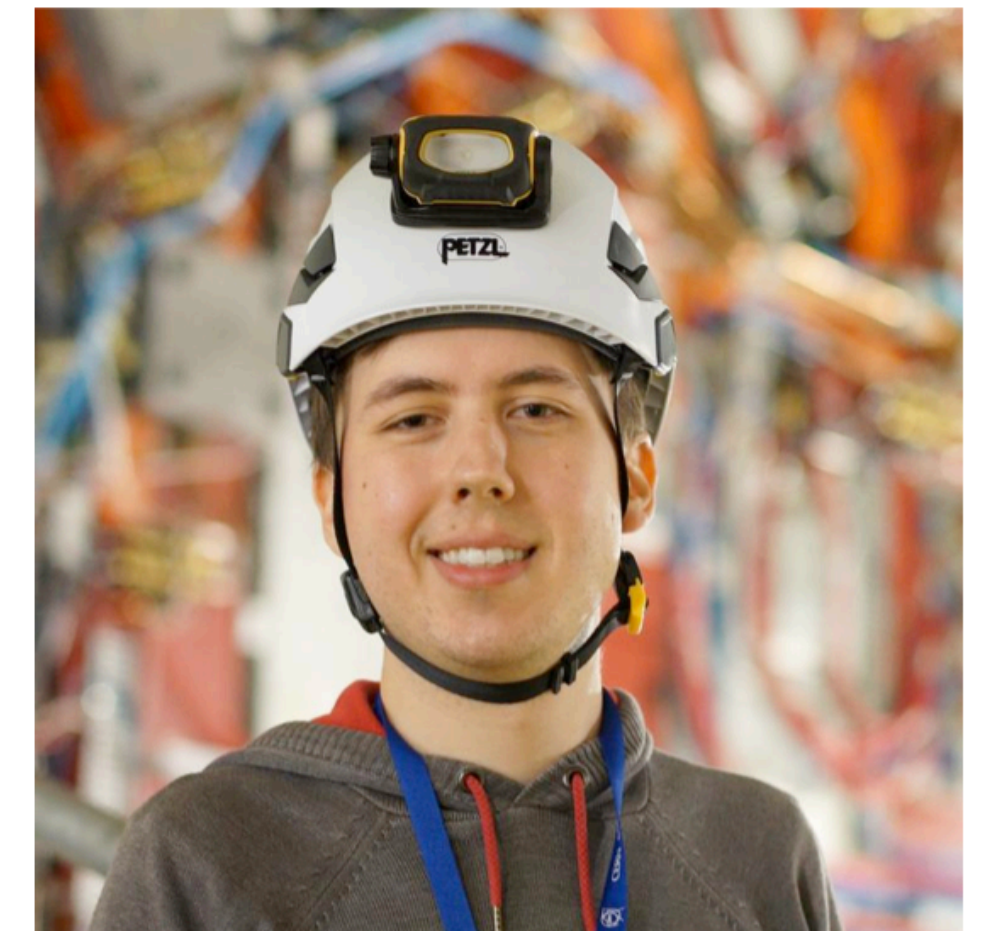
Alexander Grohsjean
team co-leader



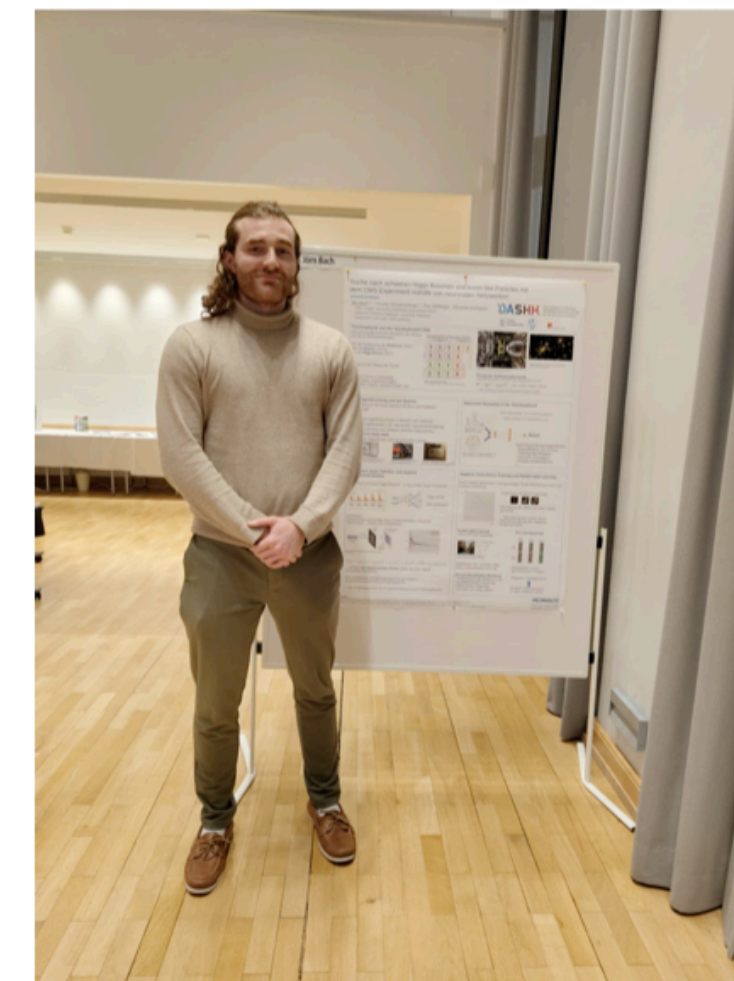
Laurids Jeppe



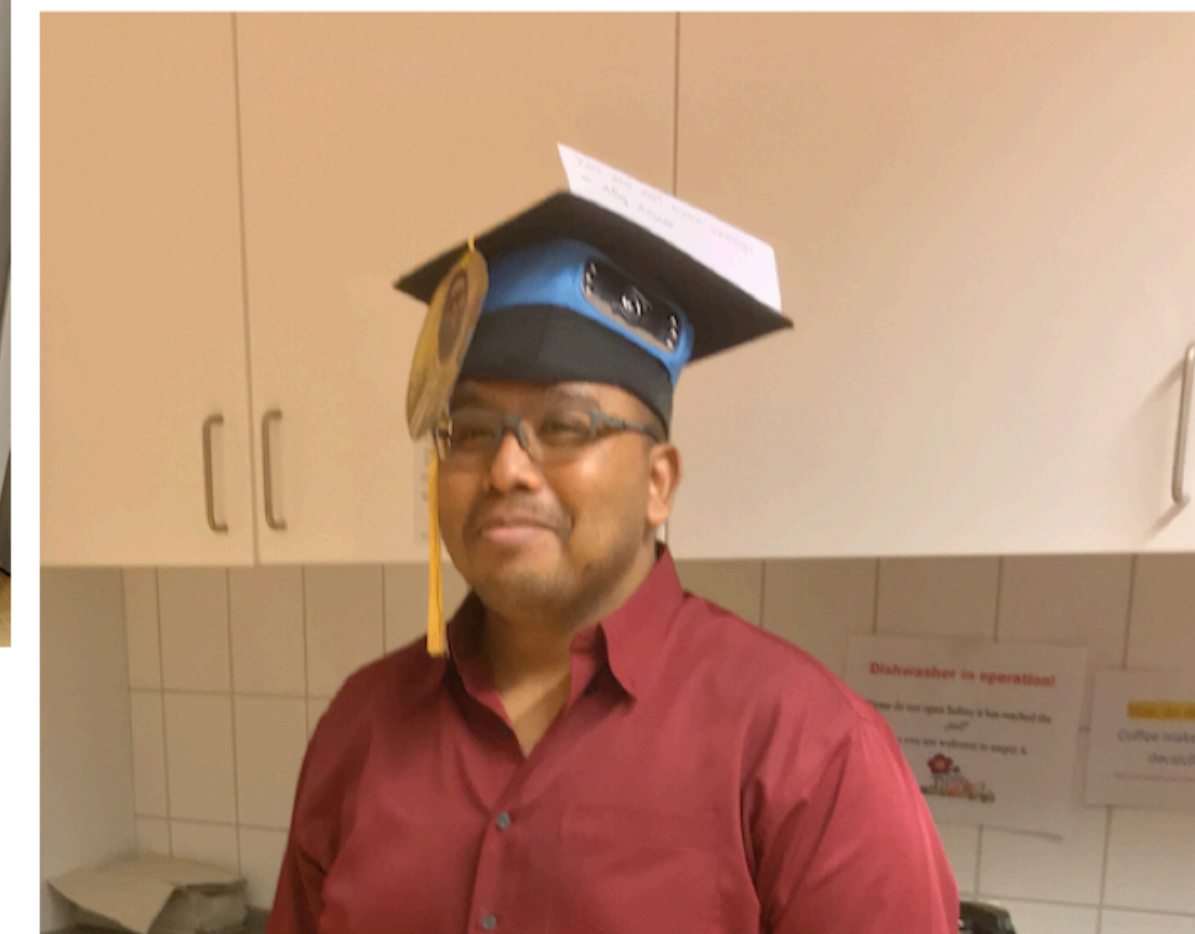
Samuel Baxter



Jonas Rübenach

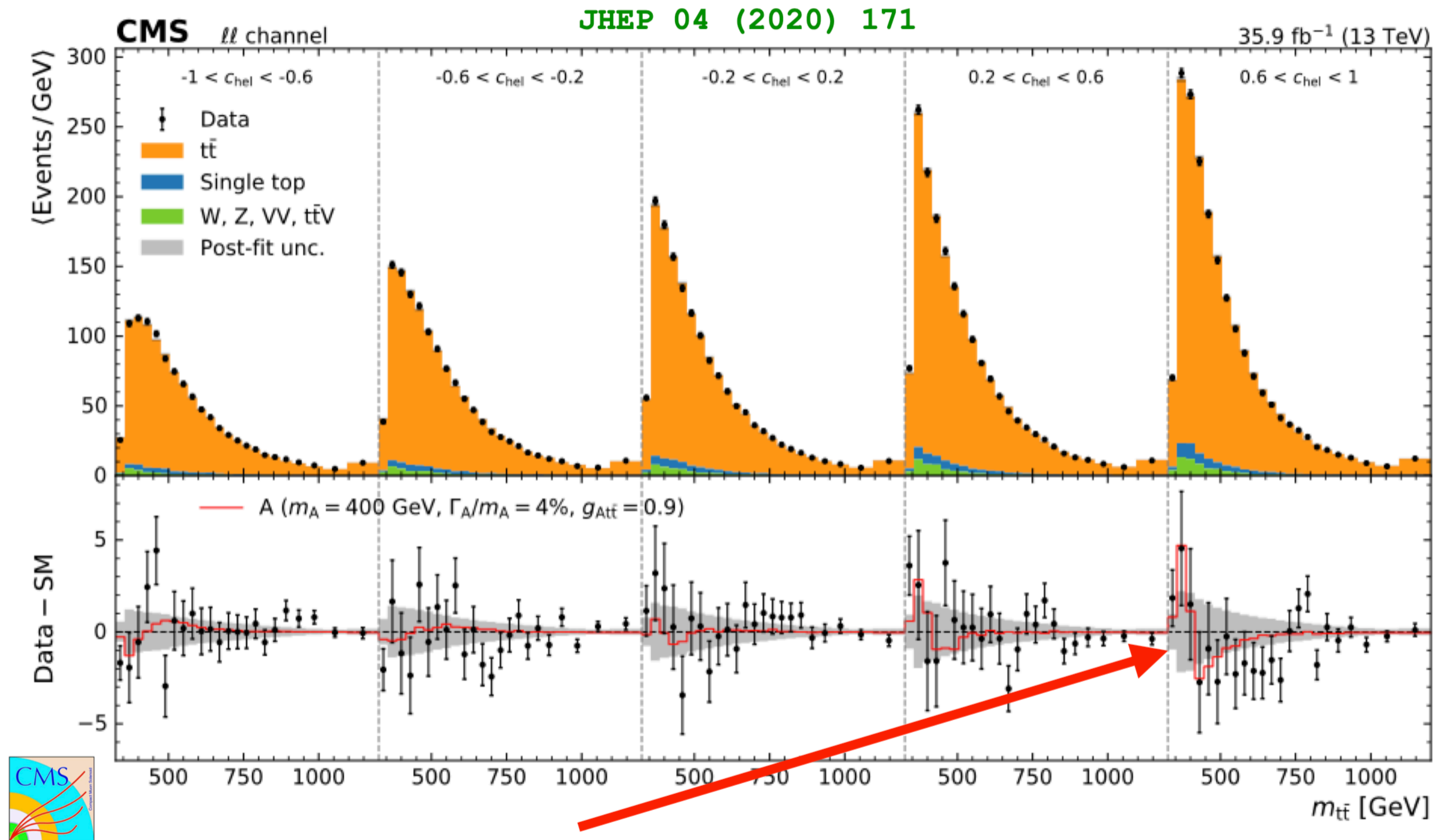


Jörn Bach



Afqi Anuar

Results of the 2016 Data



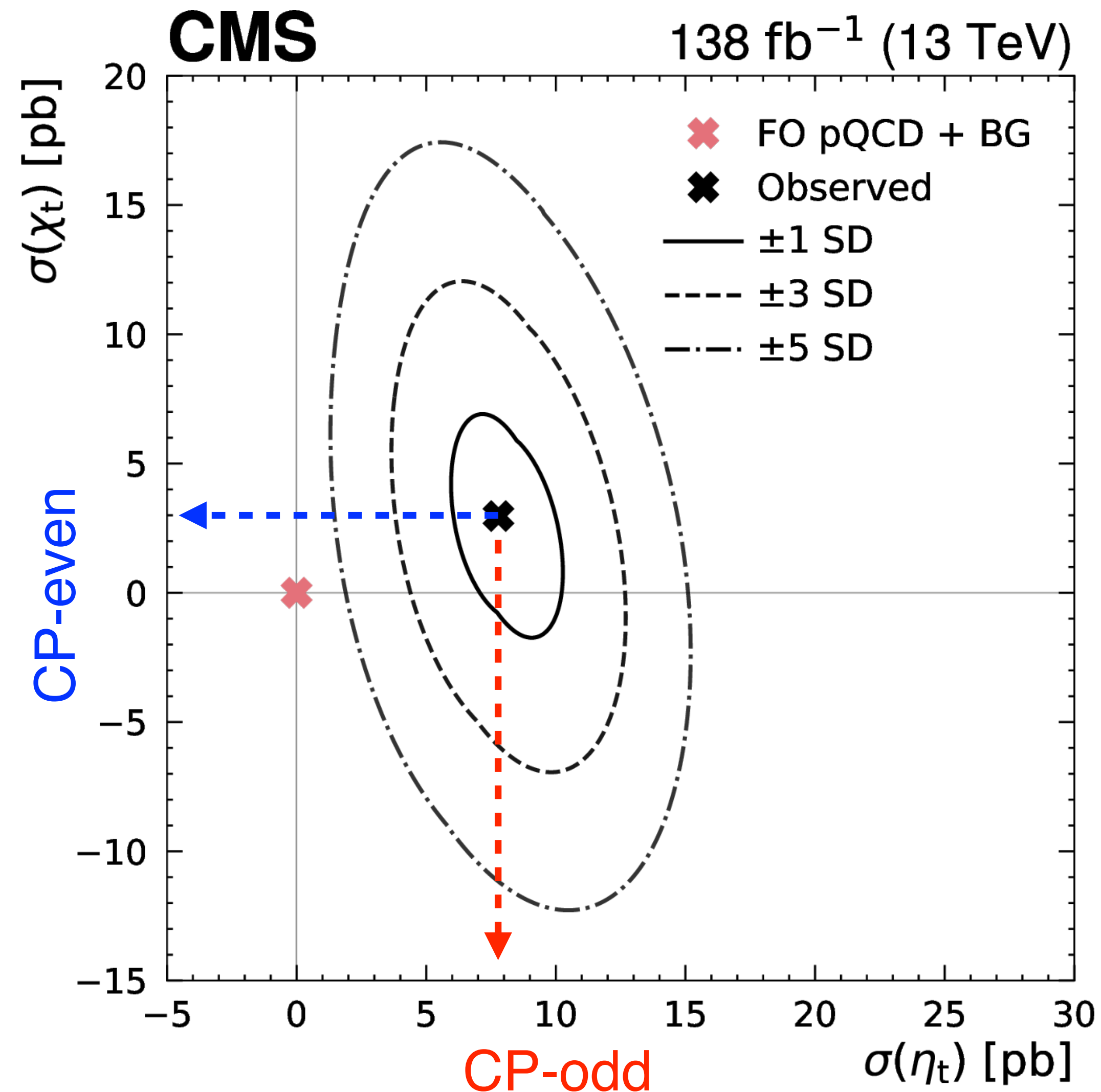
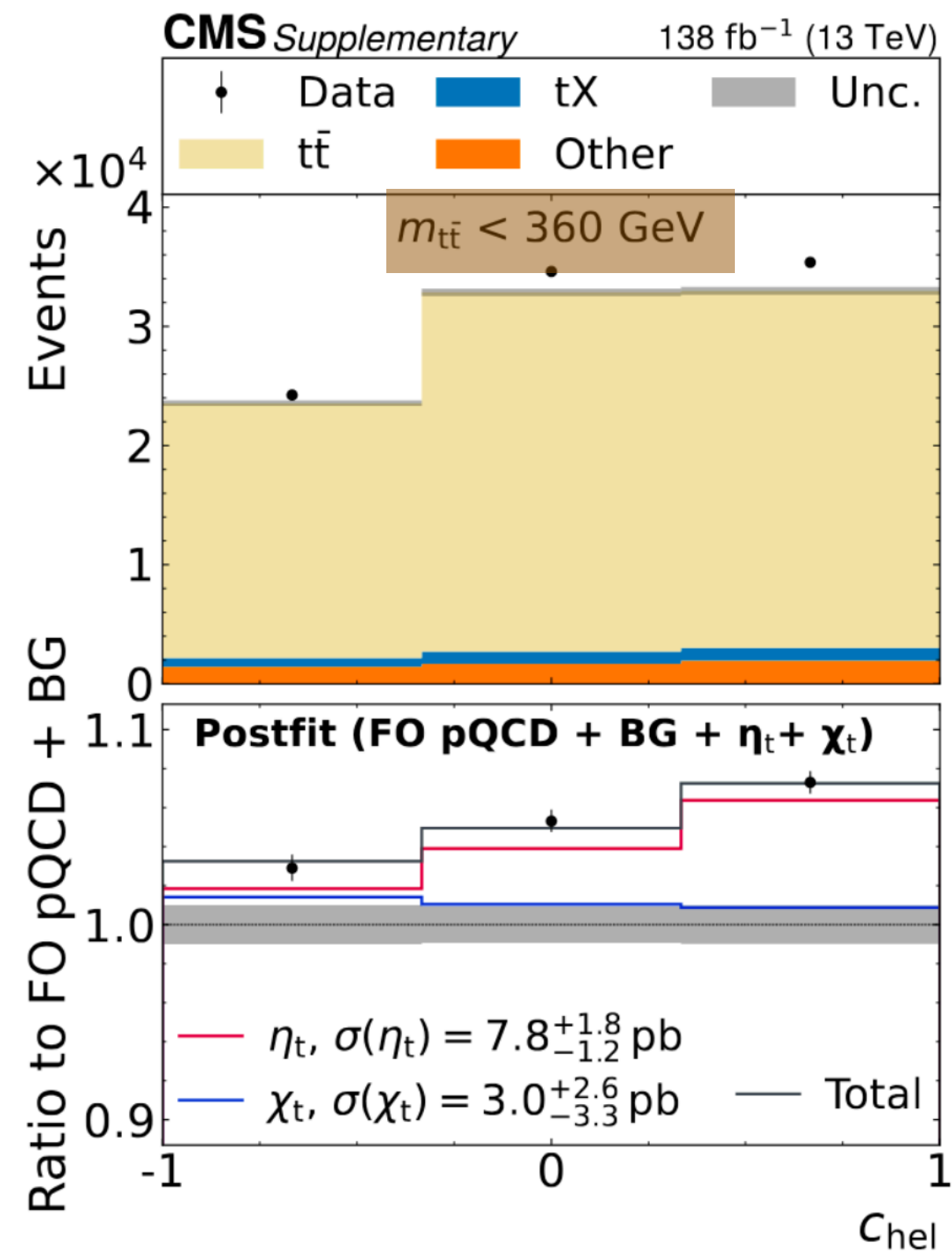
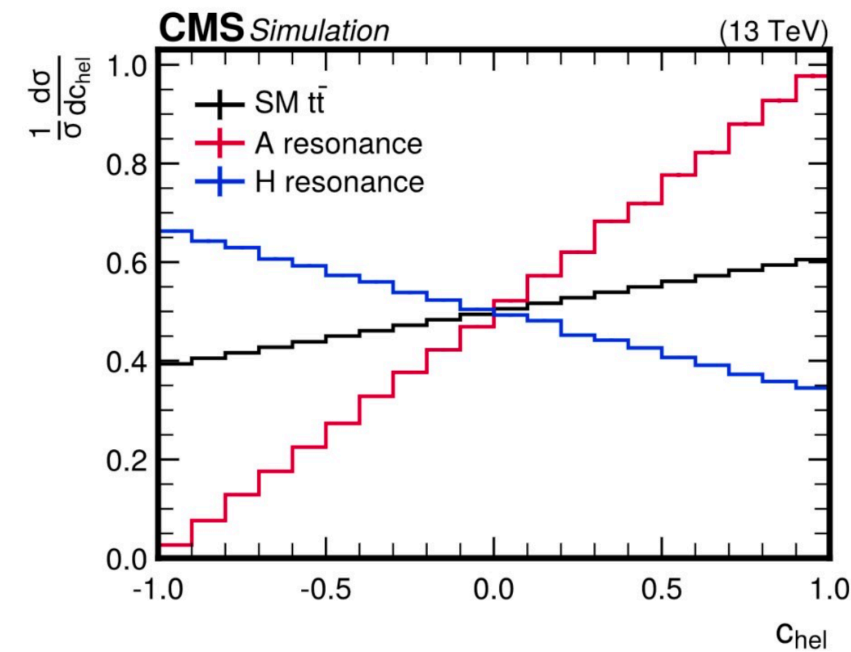
3.5 σ local

1.9 σ global

pseudoscalar, $m_A = 400$ GeV

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

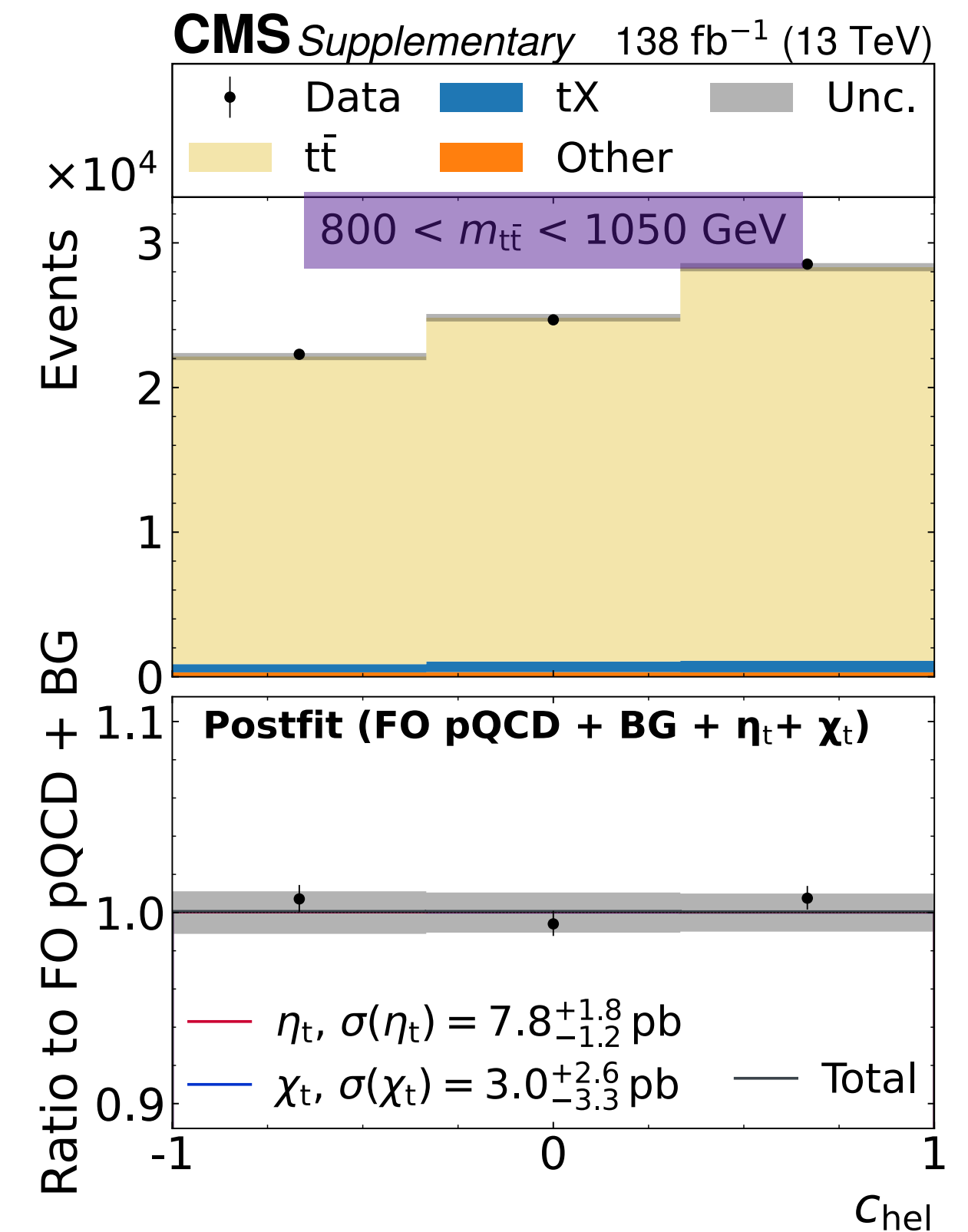
Scalar or Pseudoscalar?



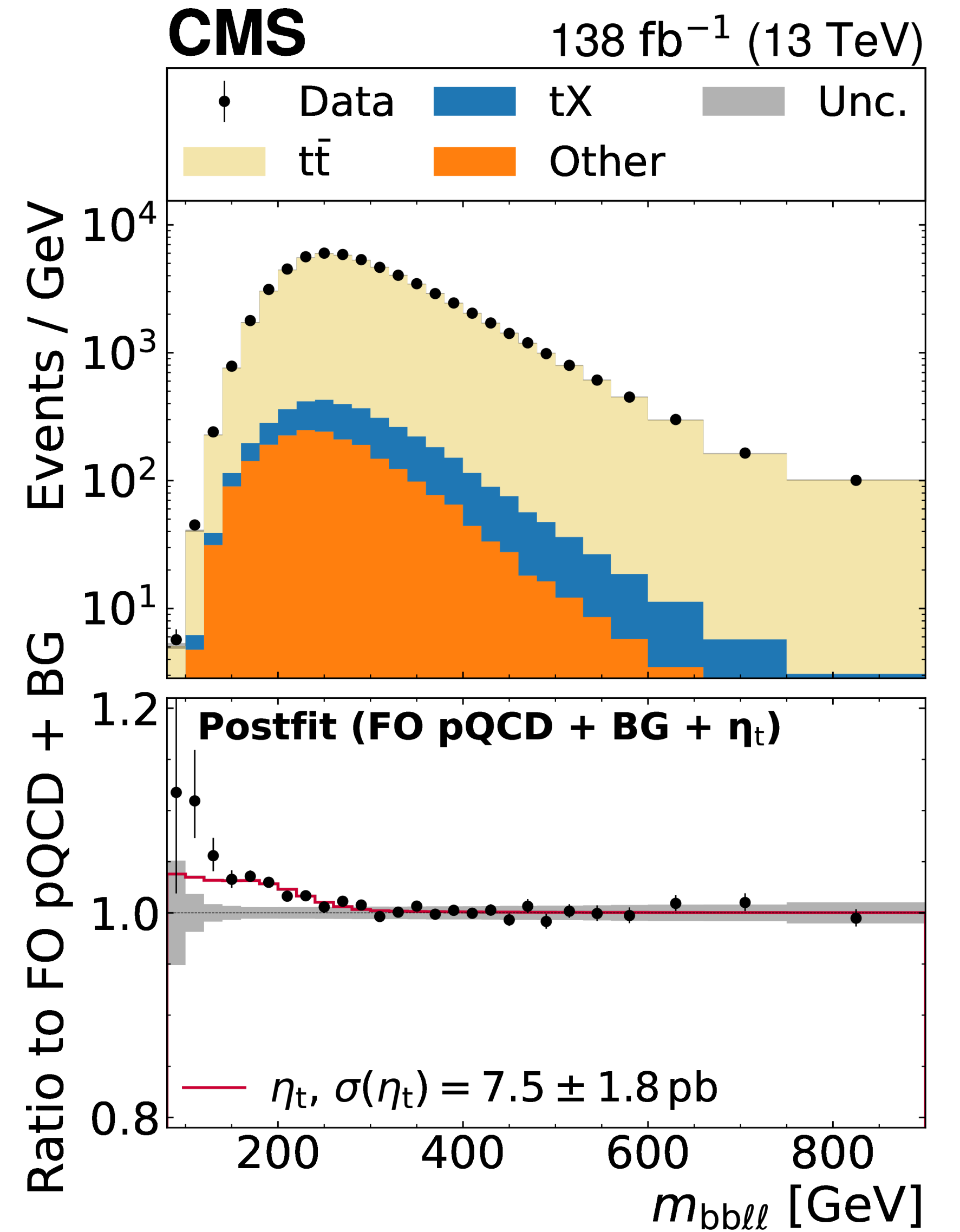
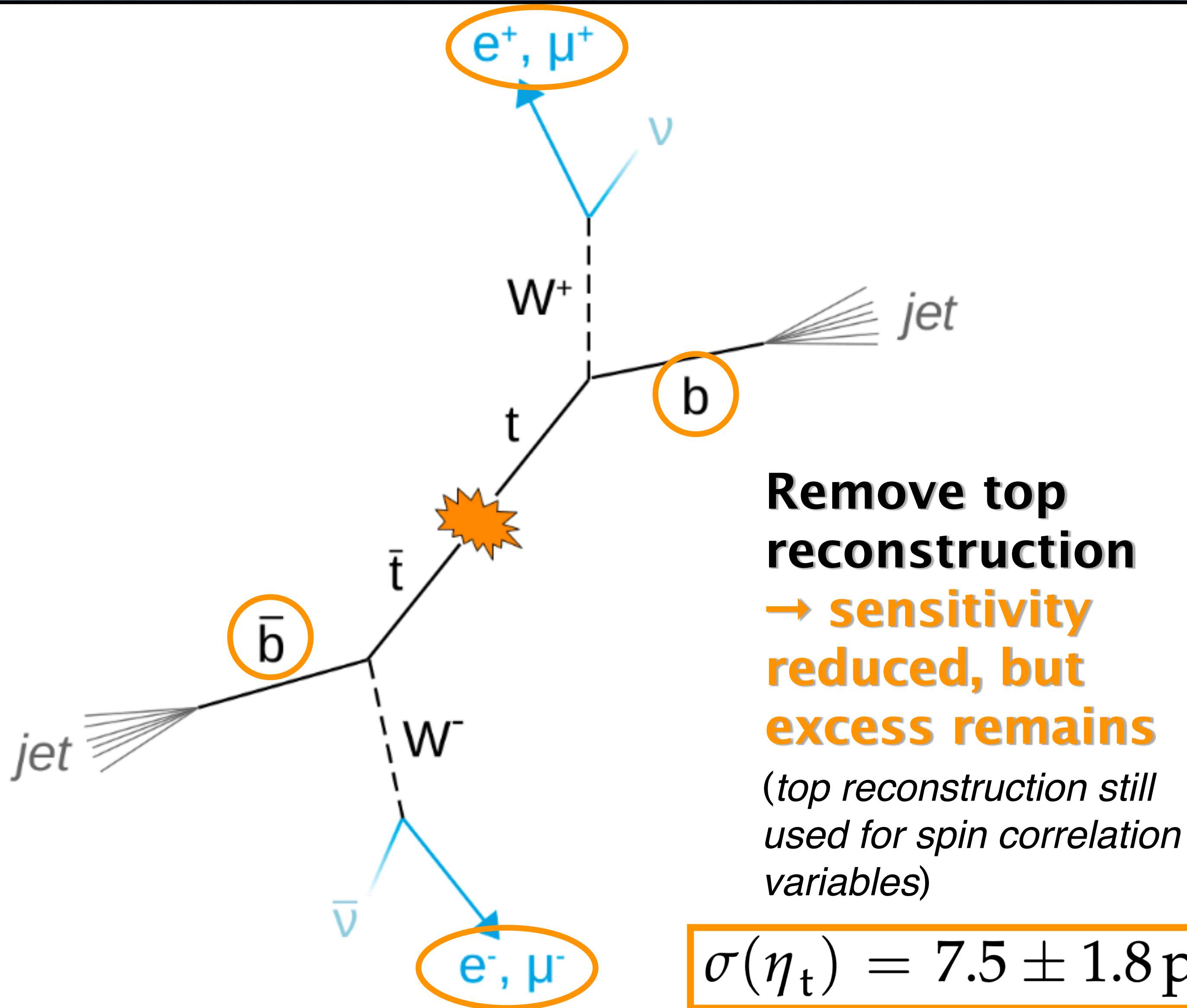
→ data prefers pseudoscalar over scalar

$$\sigma(\eta_t) = 7.8^{+1.8}_{-1.2} \text{ pb}$$

$$\sigma(\chi_t) = 3.0^{+2.6}_{-3.3} \text{ pb}$$



Systematics Check: Top Reconstruction



Definition of c_{hel} and c_{han}

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

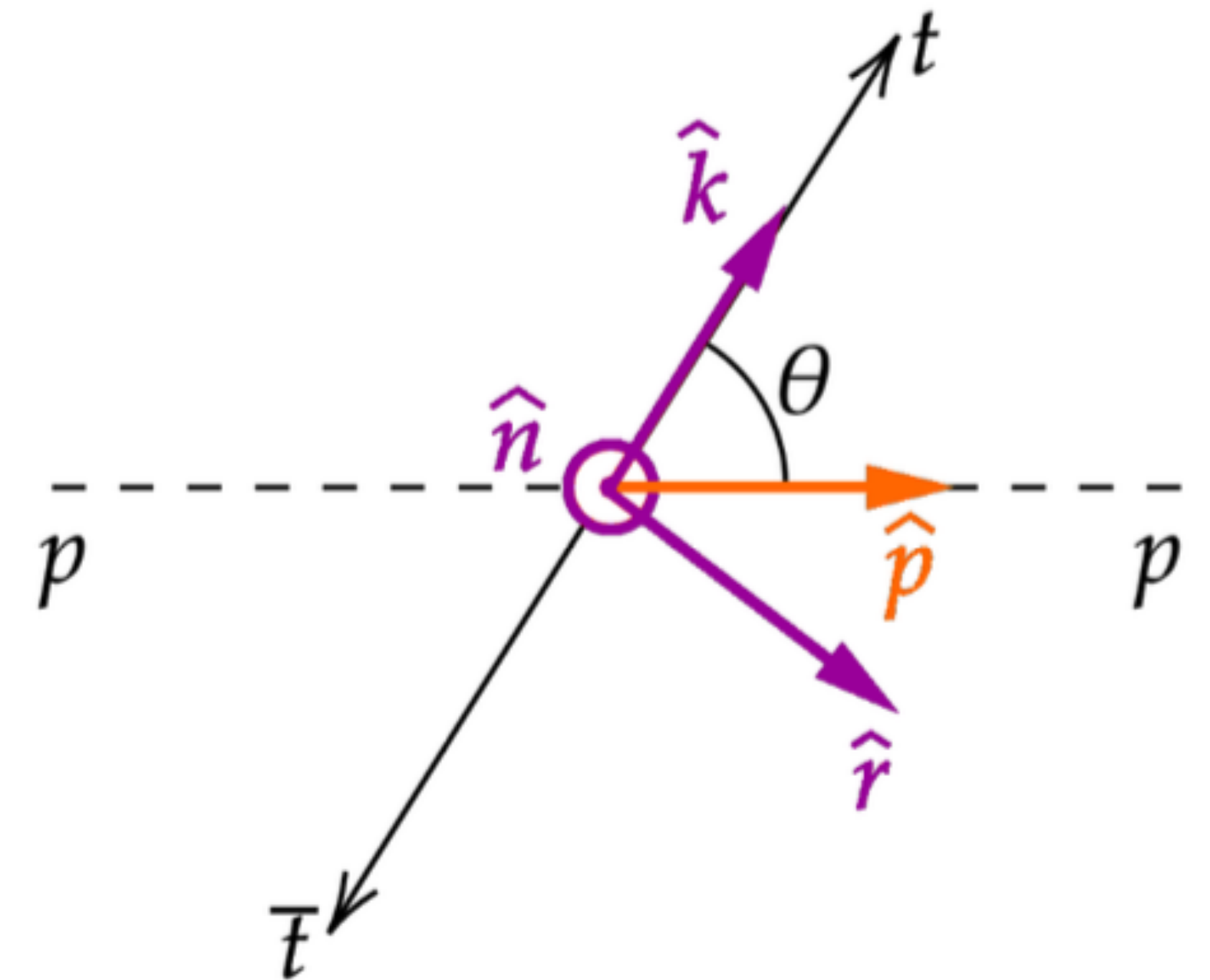
- $\hat{k}$: direction of flight of the top quark
- $\hat{r}$: orthogonal to $\hat{k}$ in the scattering plane
- $\hat{n}$: orthogonal to $\hat{k}$ and $\hat{r}$

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

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

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

$$\frac{1}{\sigma} \frac{d\sigma}{dc_{\text{hel}}} = \frac{1}{2} (1 - D c_{\text{hel}}) \quad \frac{1}{\sigma} \frac{d\sigma}{dc_{\text{han}}} = \frac{1}{2} \left(1 + D^{(k)} c_{\text{han}} \right) \quad (\text{JHEP 03 (2024) 099})$$

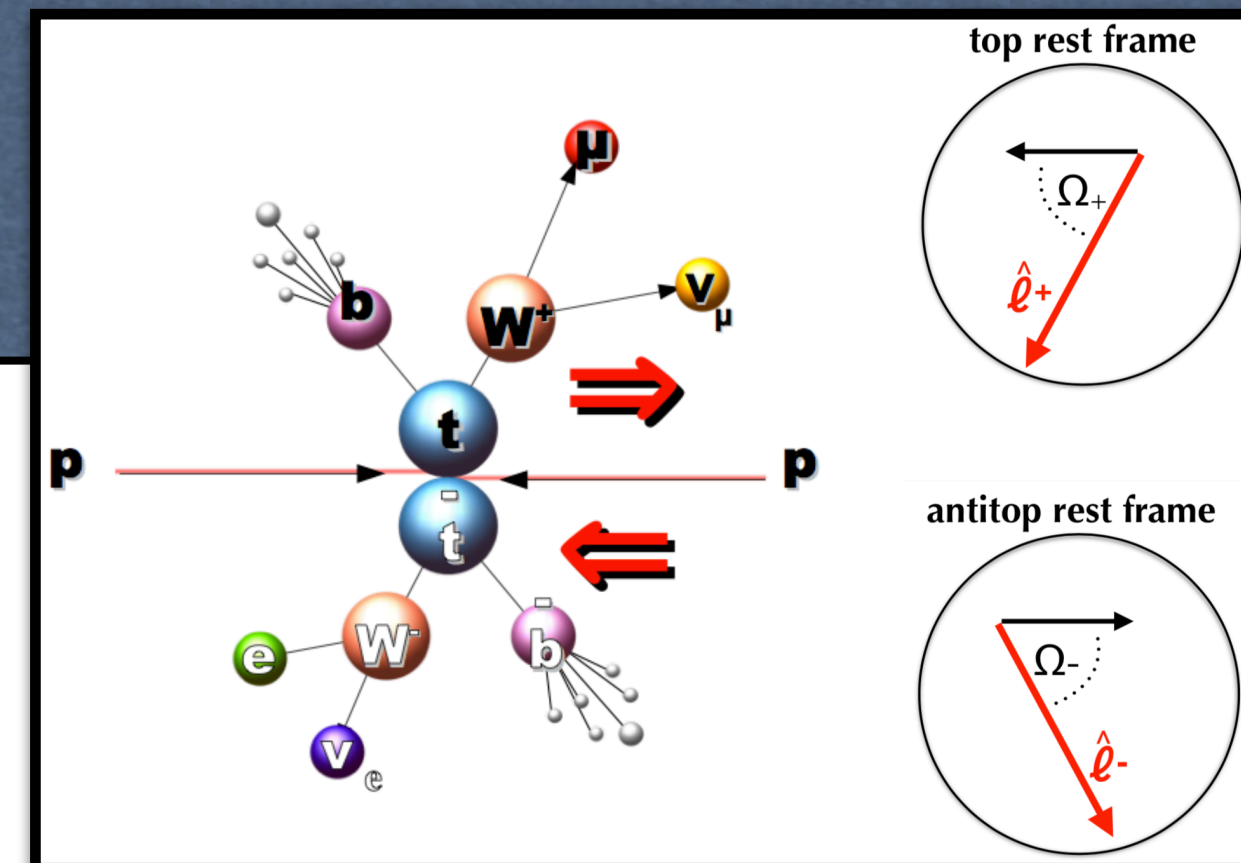


$t\bar{t}$ Spin Density Matrix

JHEP 12 (2015) 026

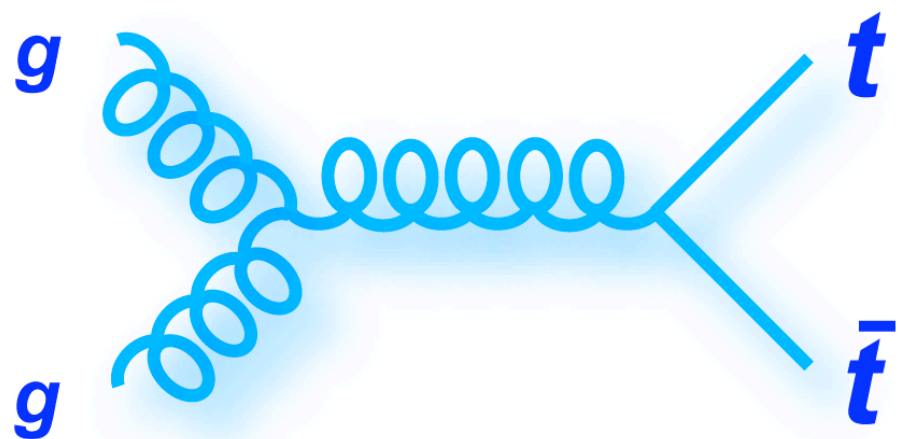
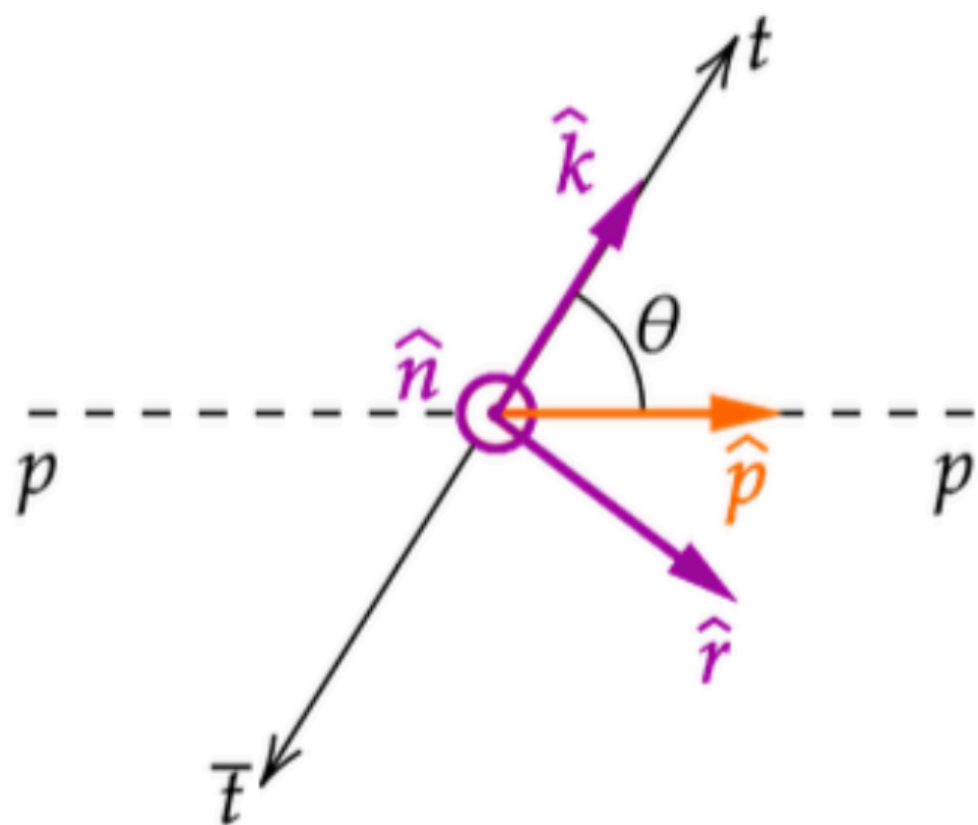
Nucl. Phys. B 690 (2004) 81

Phys. Rev. D 58 (1998) 114031



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

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

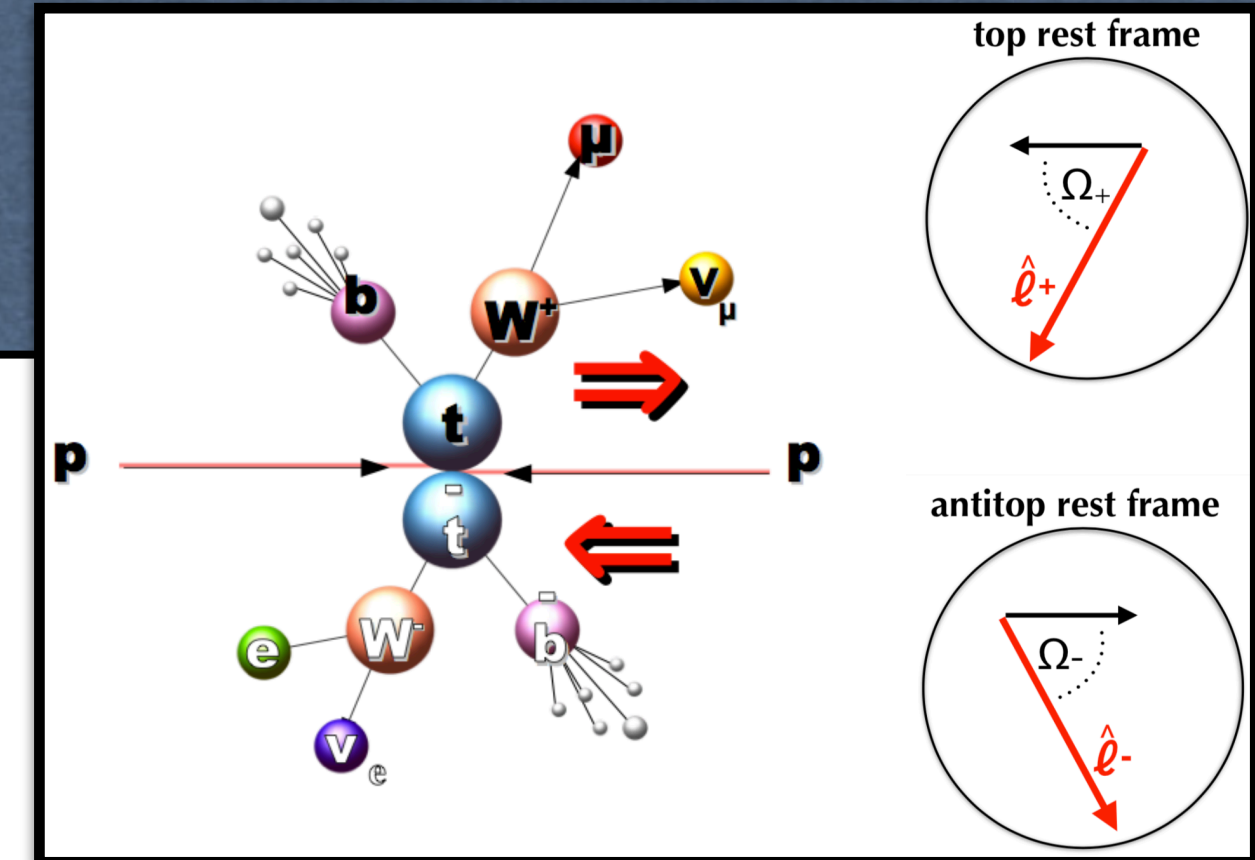


$t\bar{t}$ Spin Density Matrix

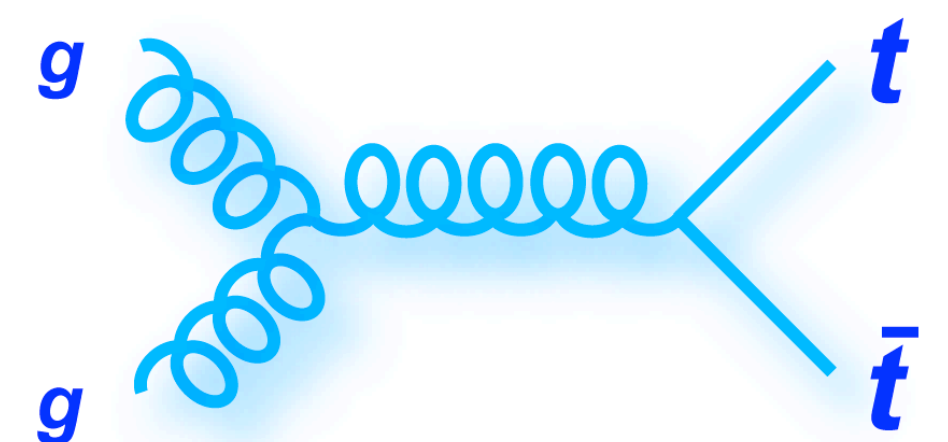
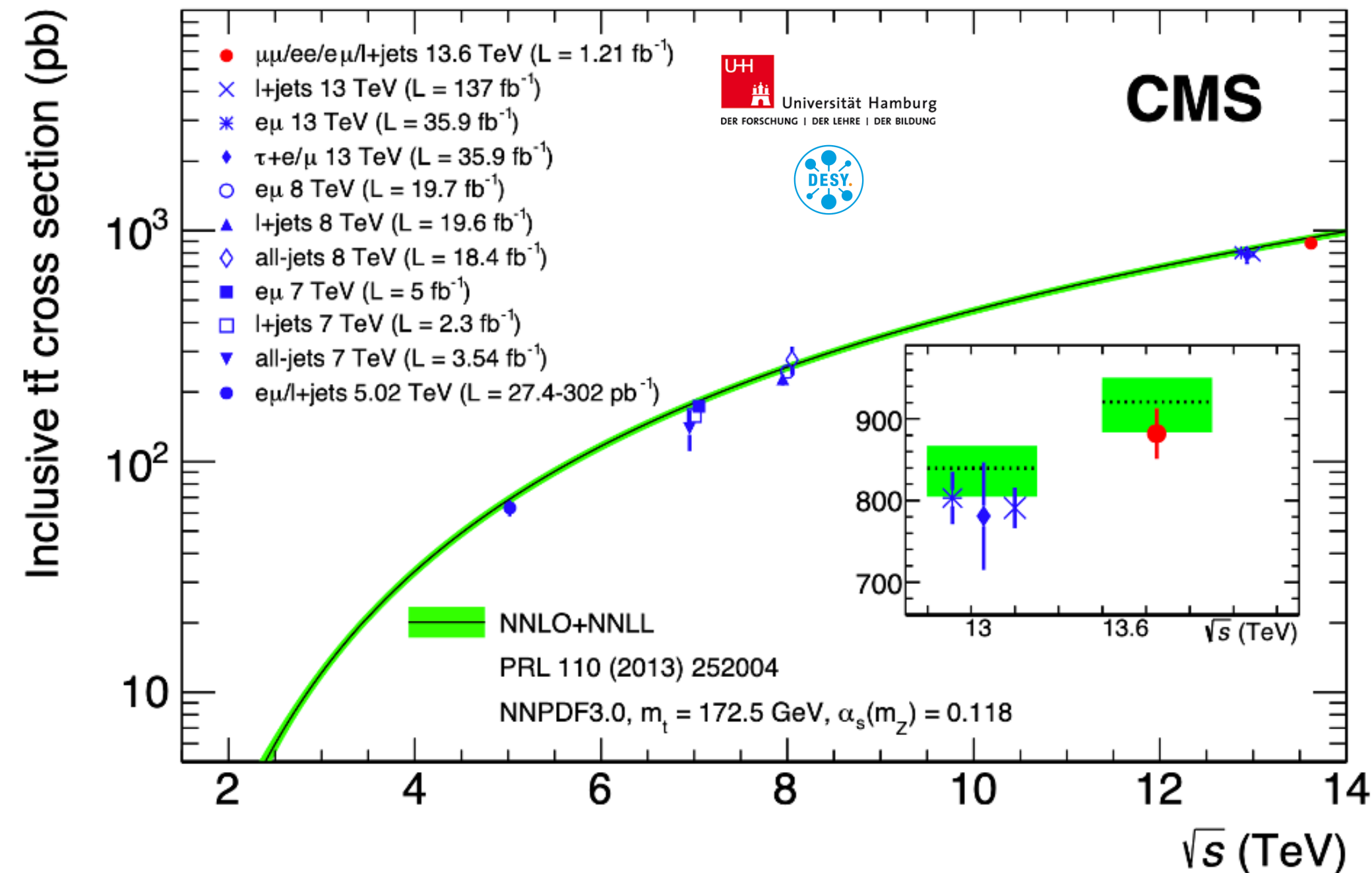
spin-independent:
 cross section, $m_{t\bar{t}}$, p_T^t , ...

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

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JHEP 08, 204 (2023)



$\bar{t}t$ Spin Density Matrix

JHEP 12 (2015) 026

Nucl. Phys. B 690 (2004) 81

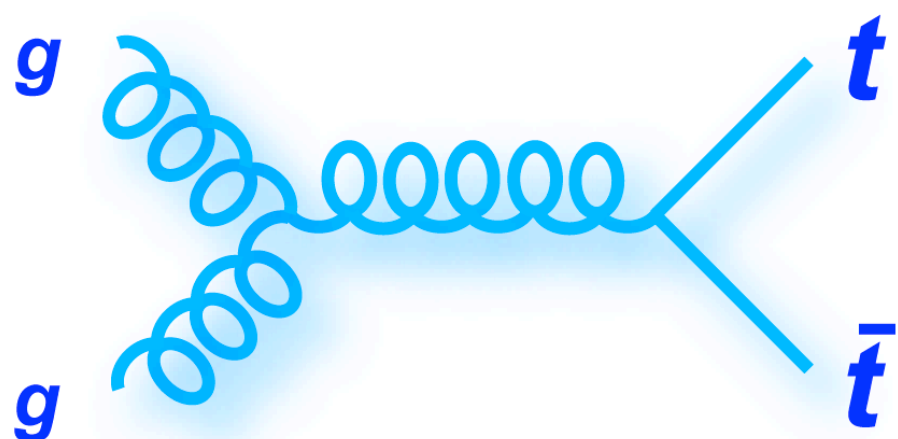
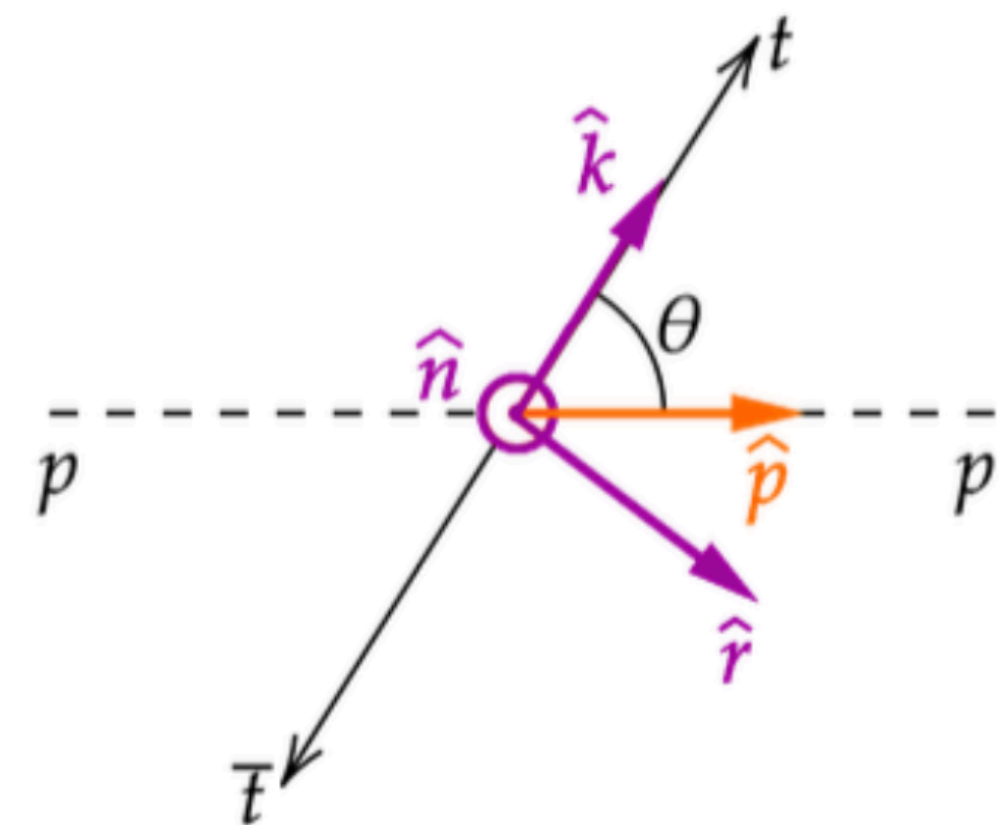
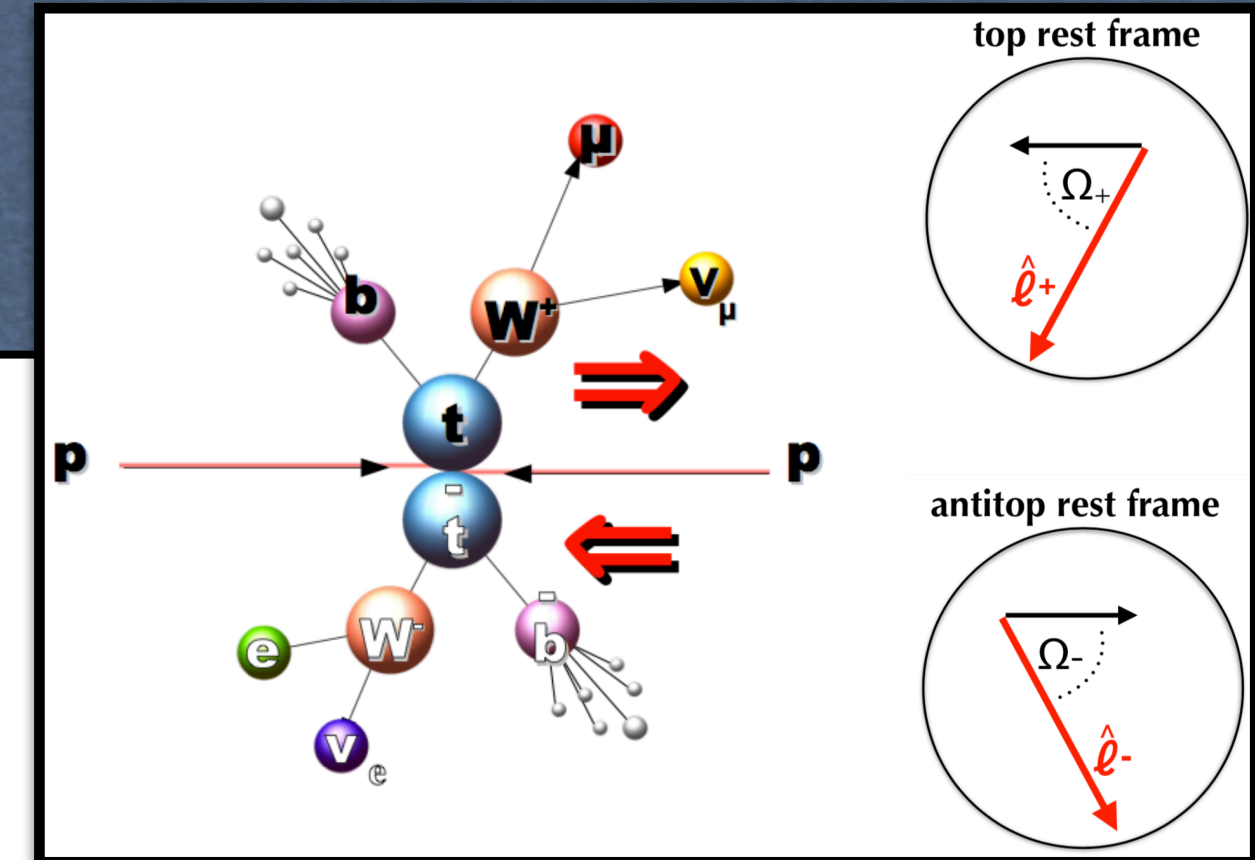
Phys. Rev. D 58 (1998) 114031

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

polarization

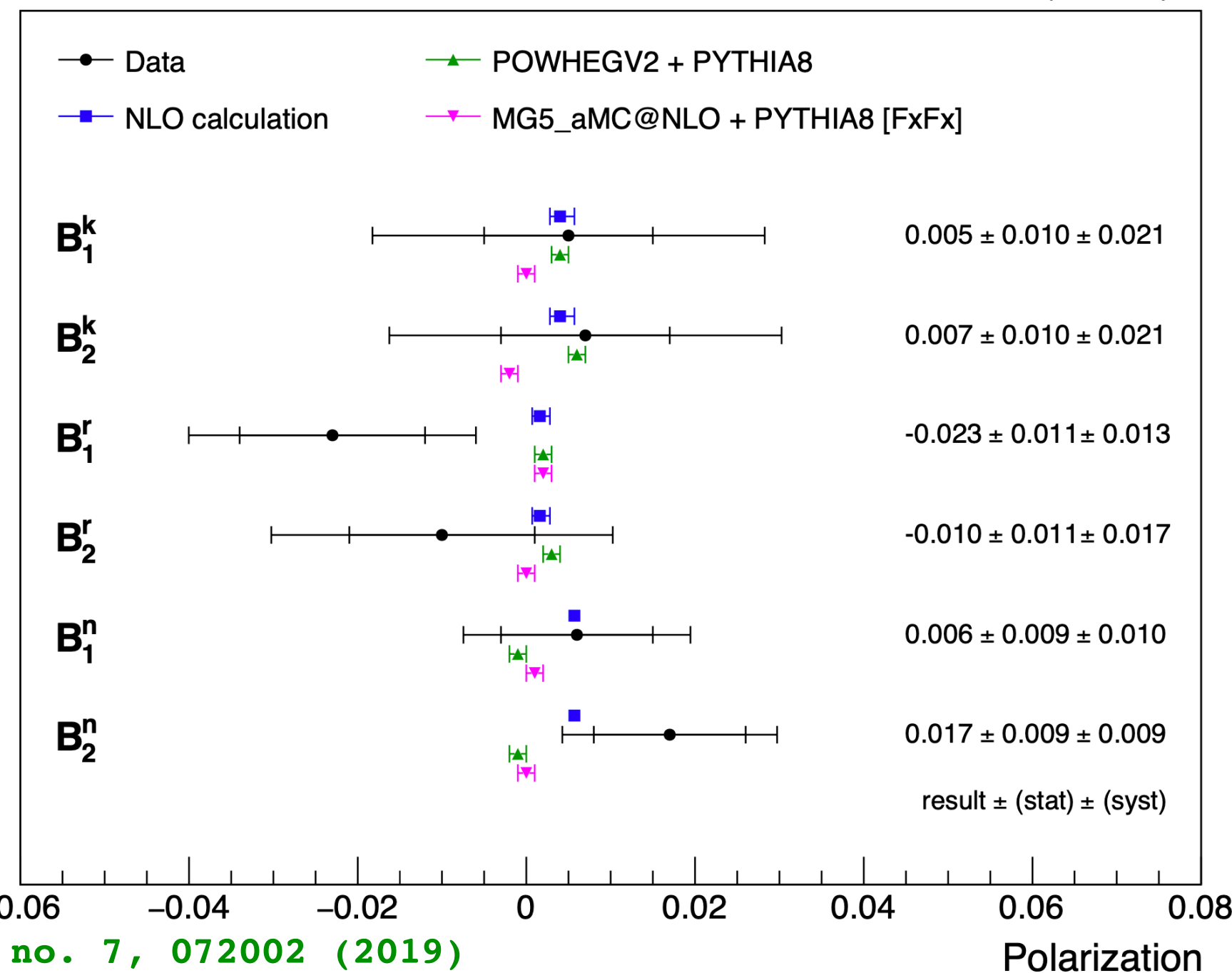
$$|M|^2 \propto A + \vec{B}_1 \cdot \hat{\ell}^1 + \vec{B}_2 \cdot \hat{\ell}^2 - \hat{\ell}^1 \cdot C \cdot \hat{\ell}^2$$

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



CMS

35.9 fb⁻¹ (13 TeV)



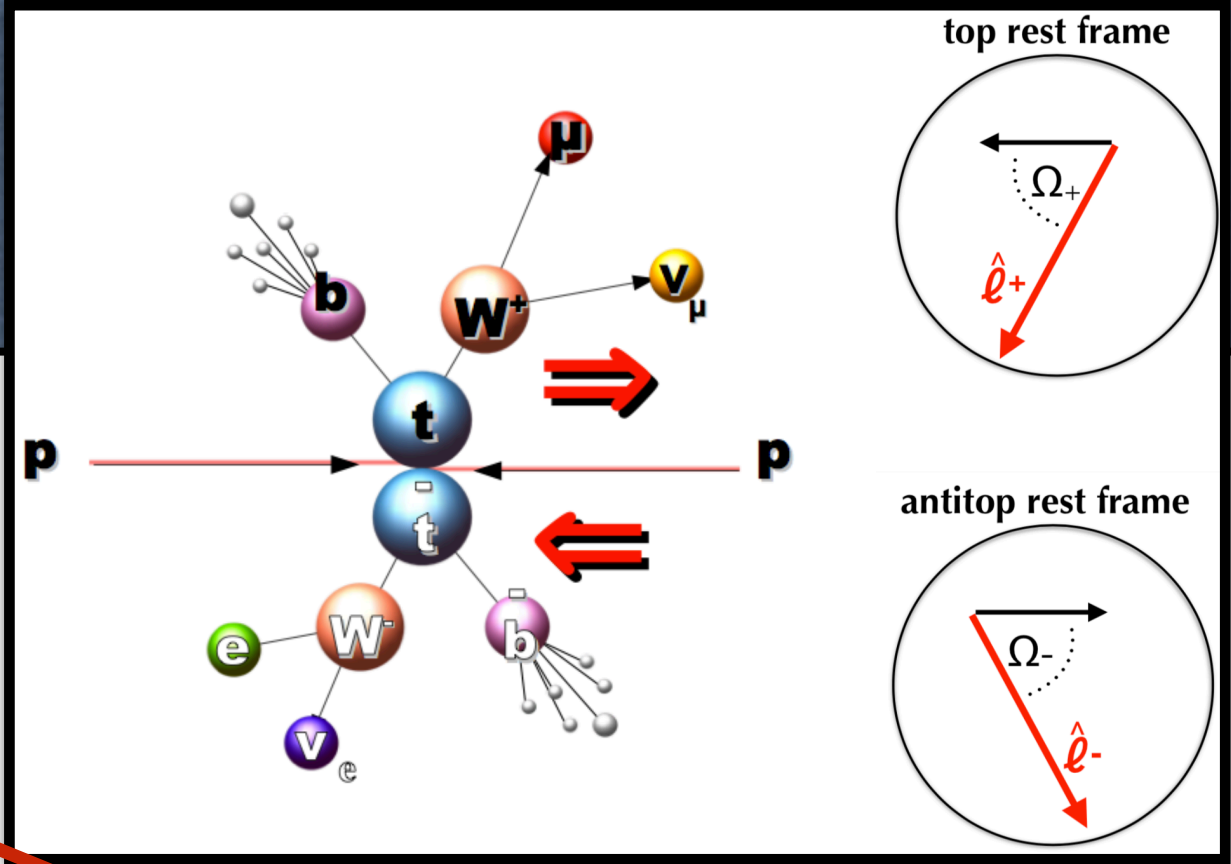
Phys. Rev. D 100, no. 7, 072002 (2019)

t $\bar{t}$ Spin Density Matrix

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

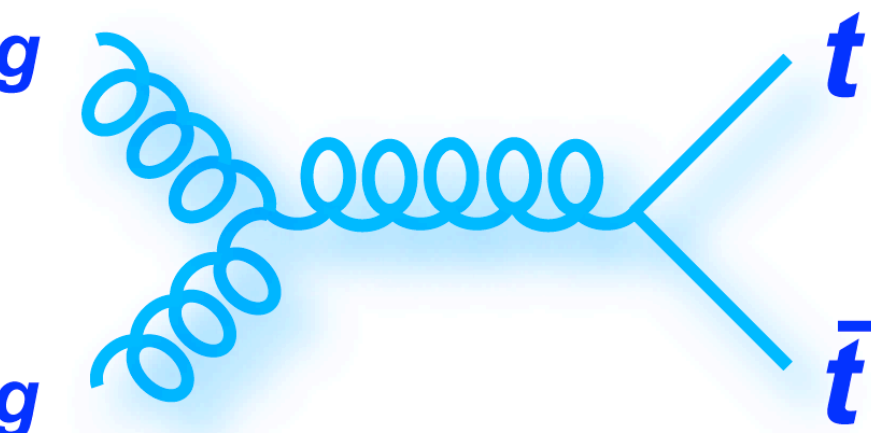
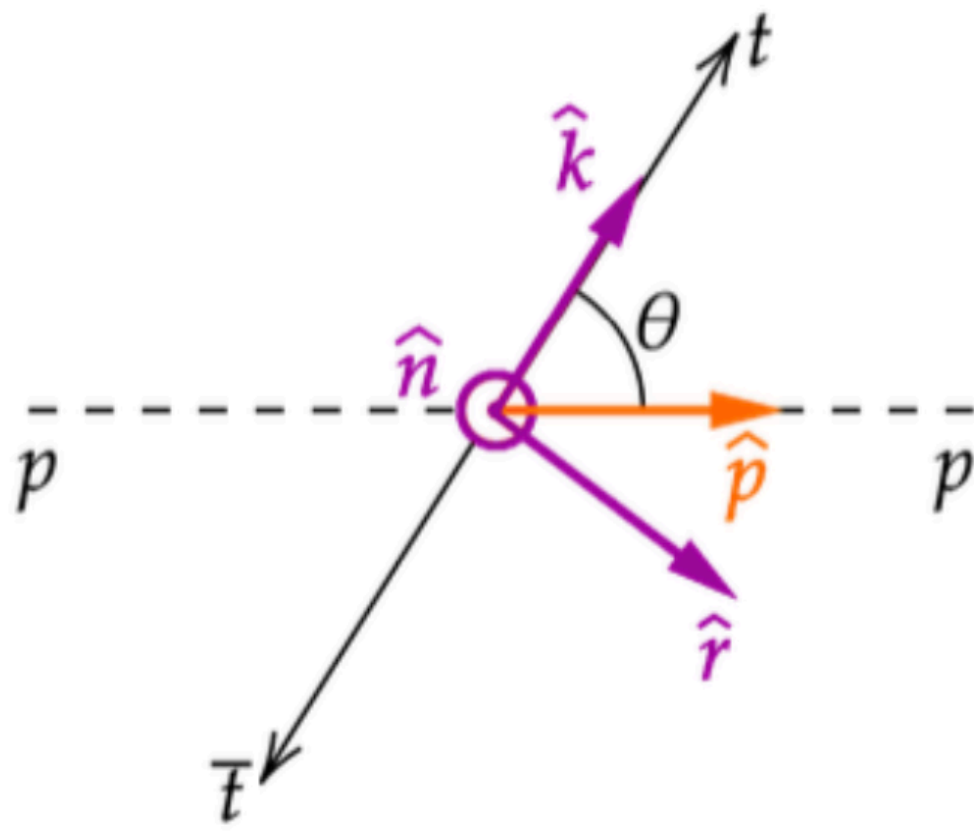
t $\bar{t}$ spin correlation

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

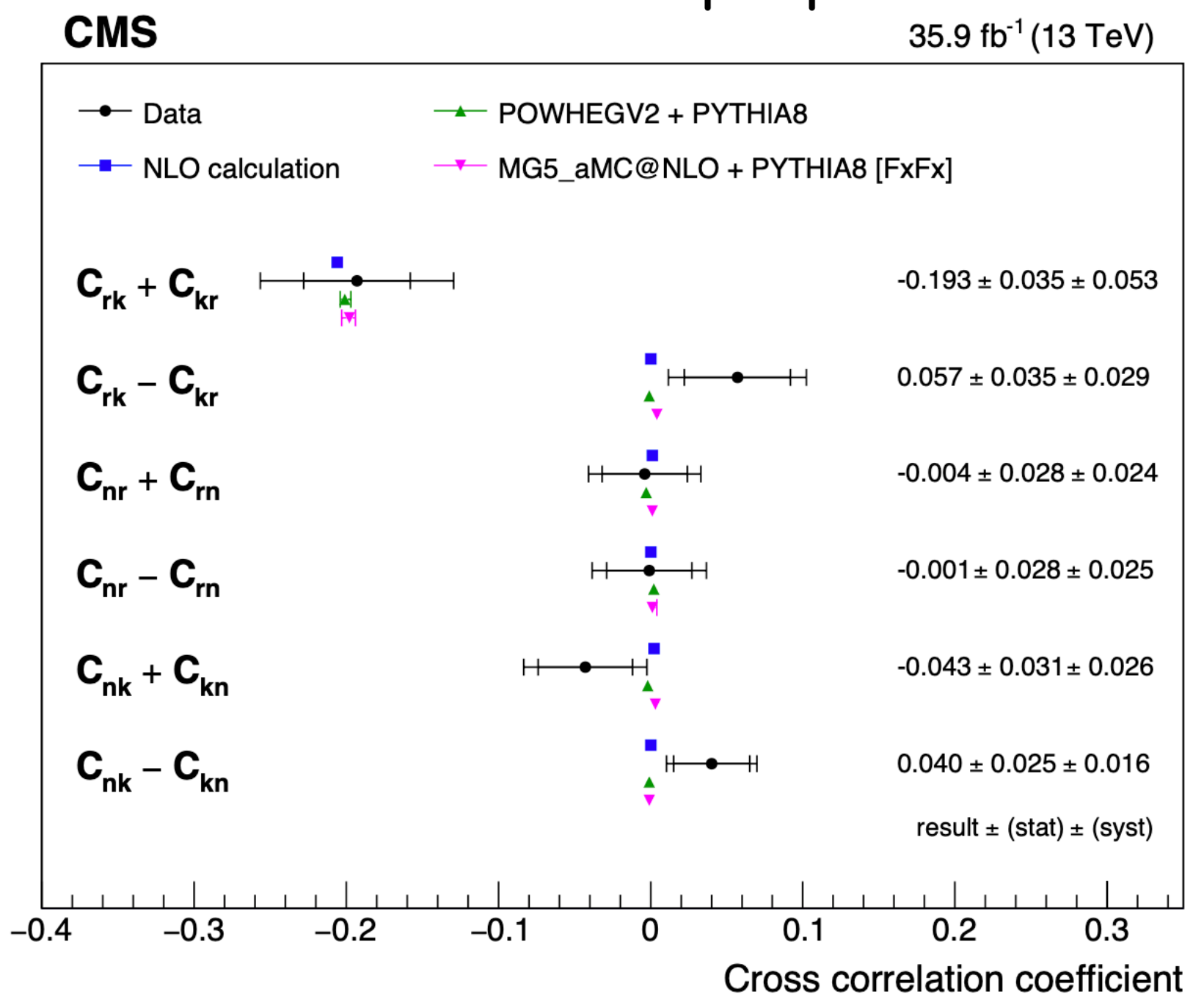
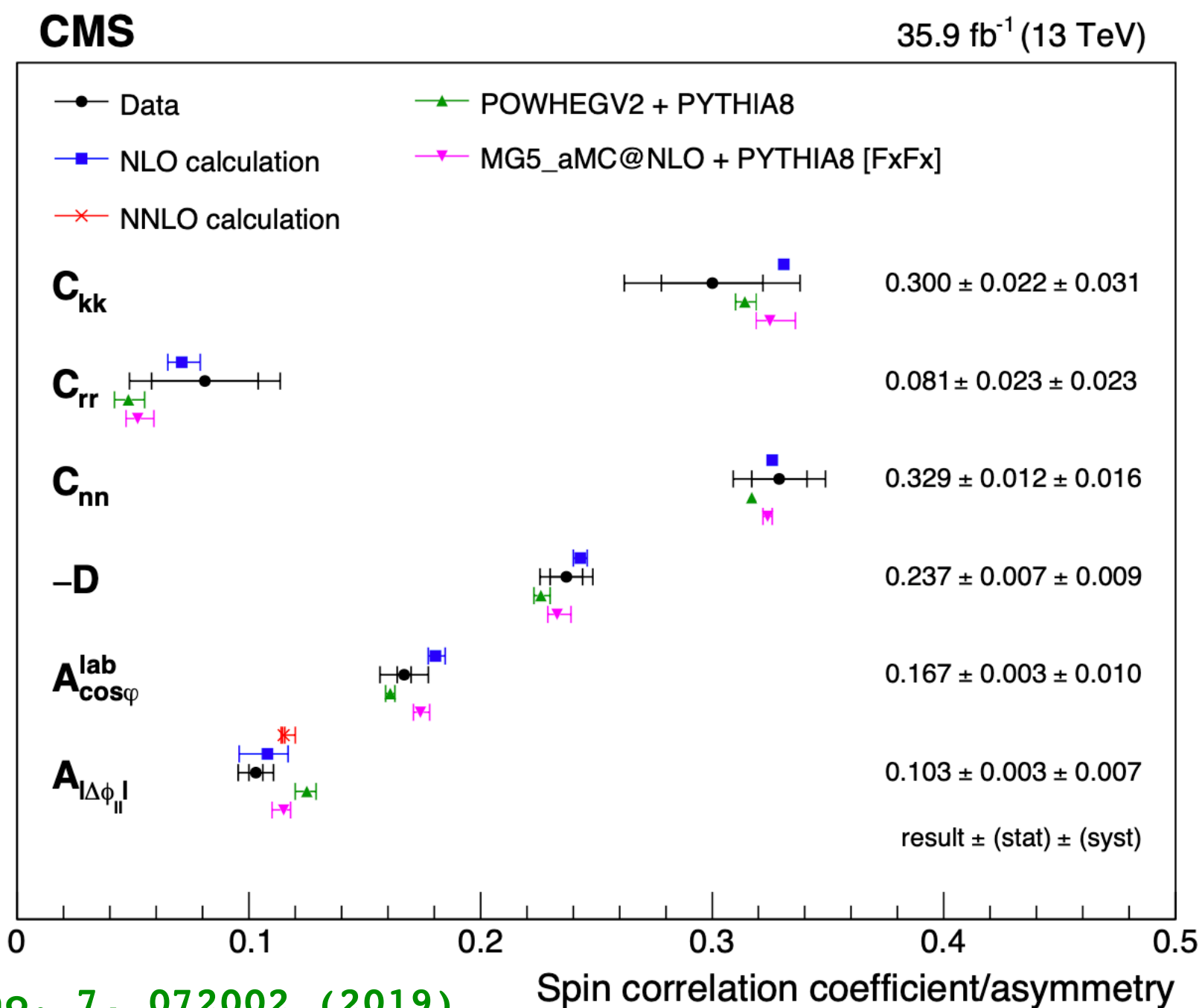


$$|M|^2 \propto A + \vec{B}_1 \cdot \hat{\ell}^1 + \vec{B}_2 \cdot \hat{\ell}^2 - \hat{\ell}^1 \cdot C \cdot \hat{\ell}^2$$

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



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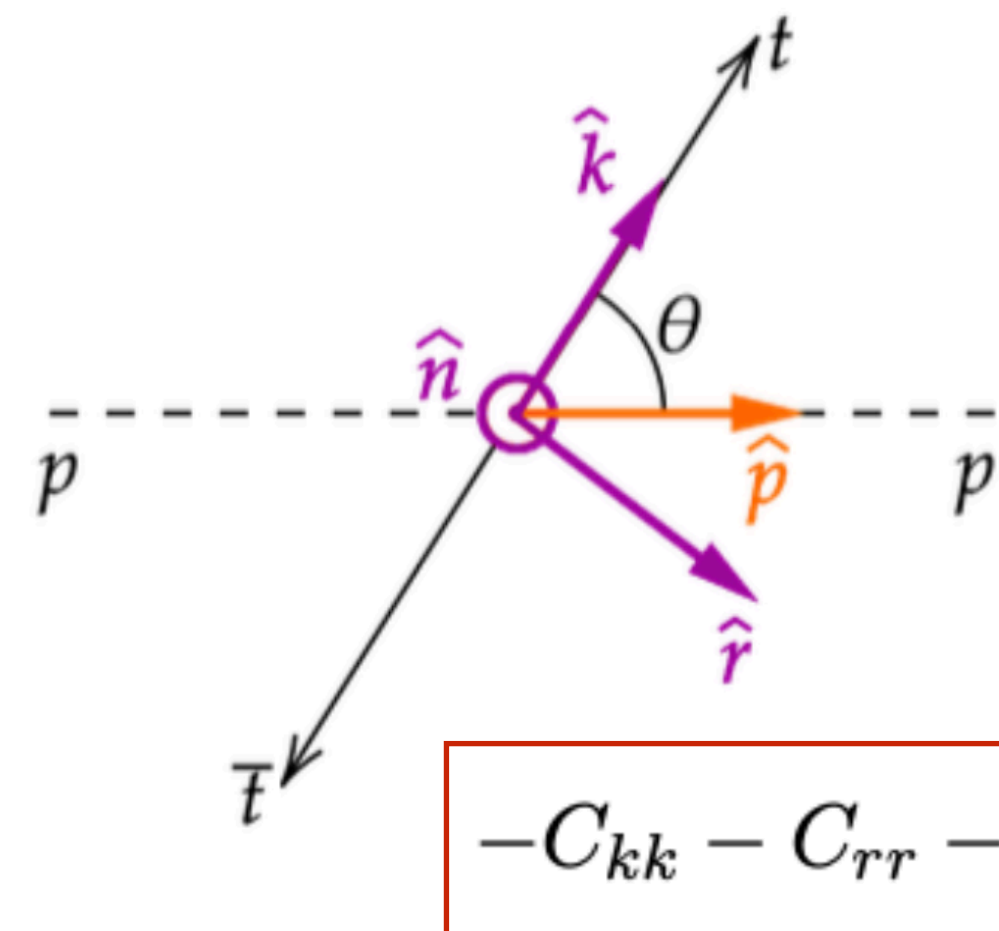
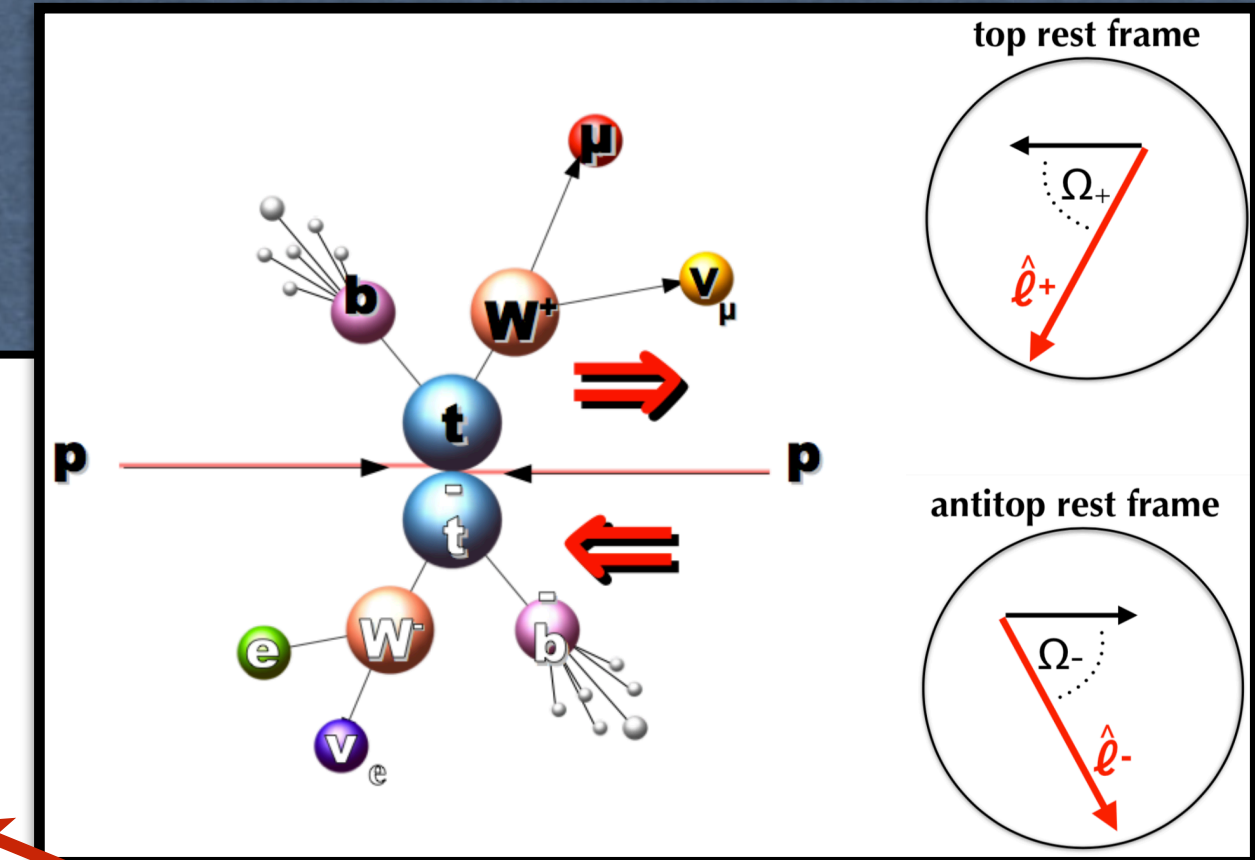
JHEP 12 (2015) 026
Nucl. Phys. B 690 (2004) 81
Phys. Rev. D 58 (1998) 114031

$t\bar{t}$ spin correlation

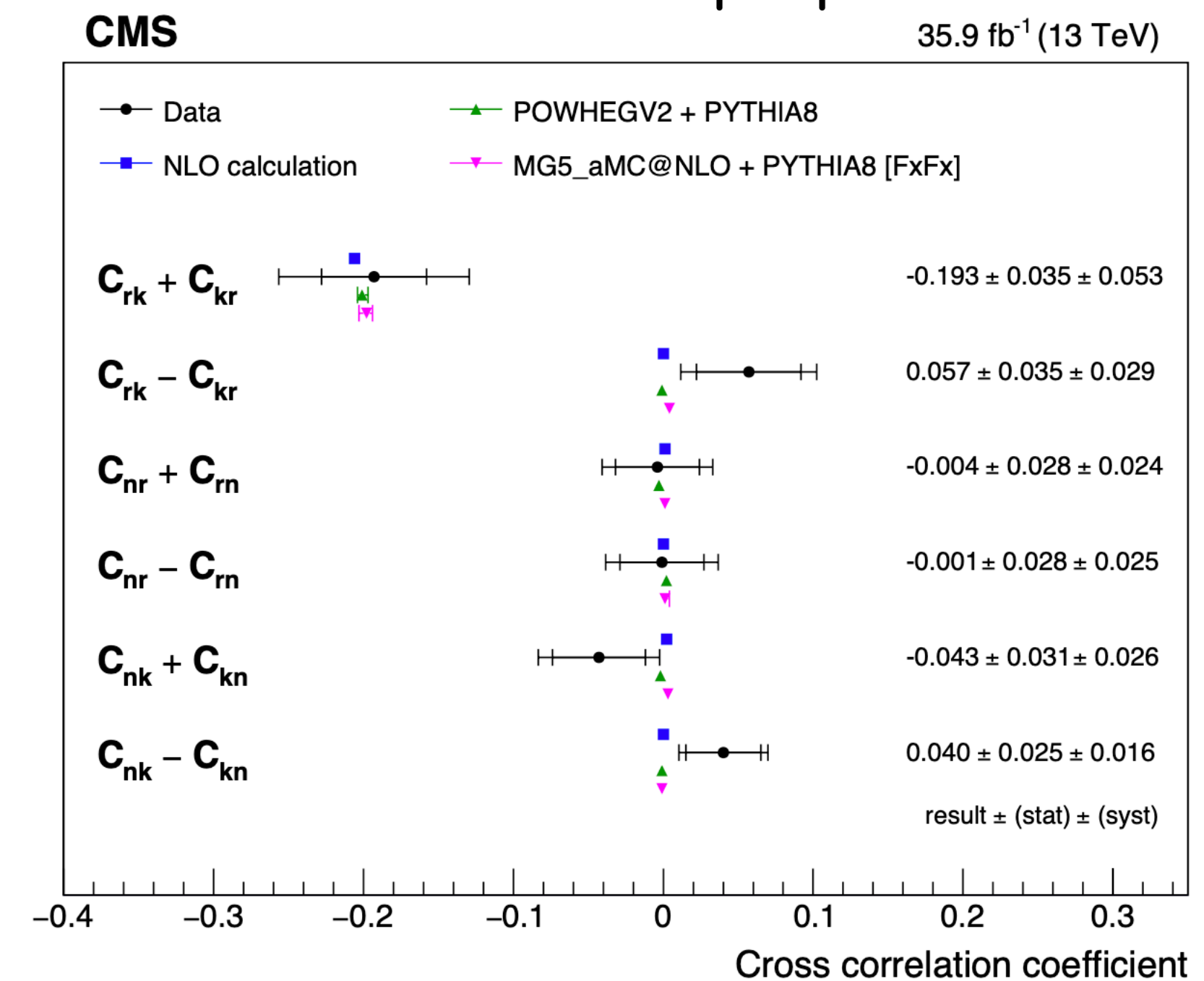
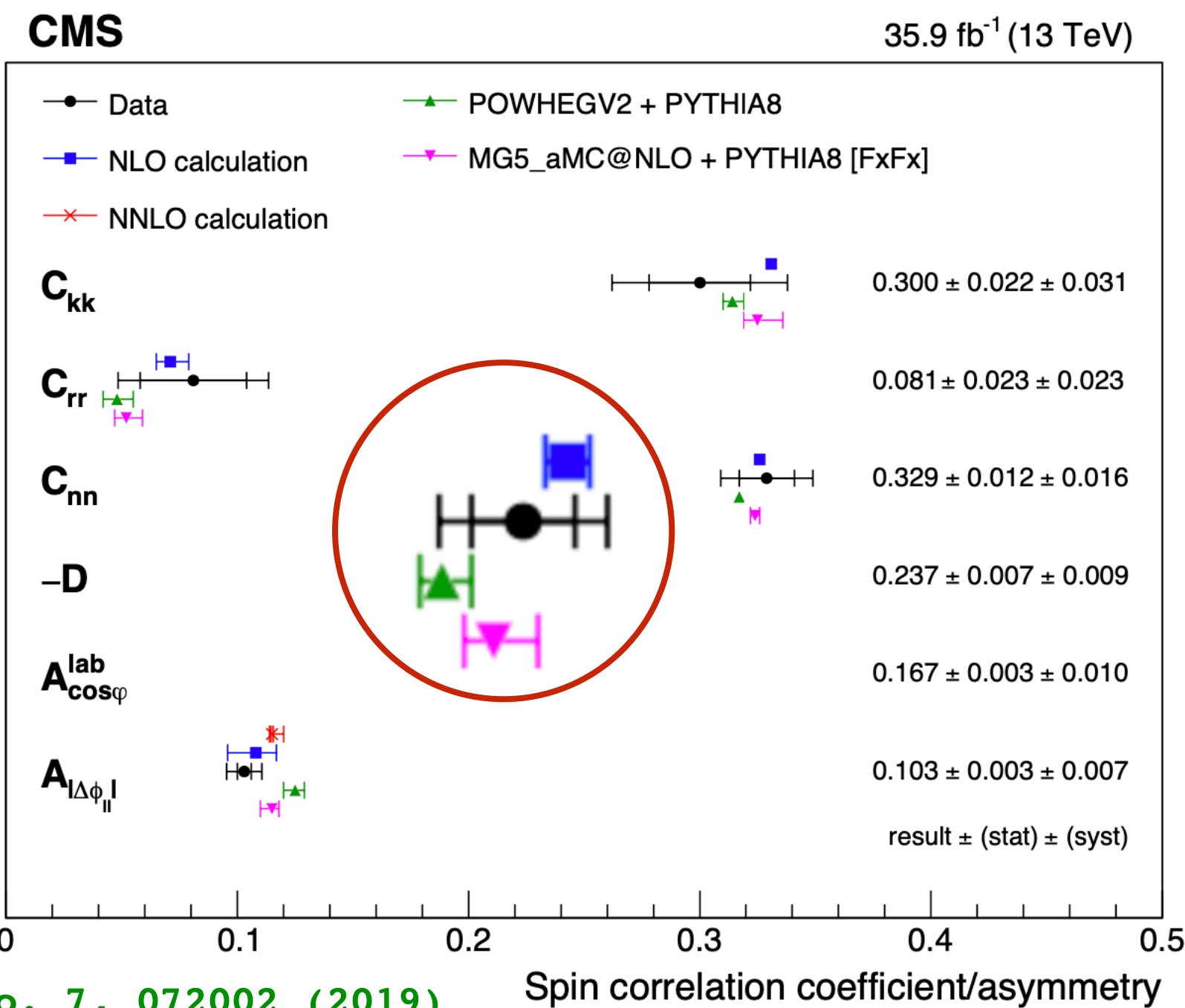
$$C = \begin{pmatrix} x & x & x \\ x & x & x \\ x & x & x \end{pmatrix}$$

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

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



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



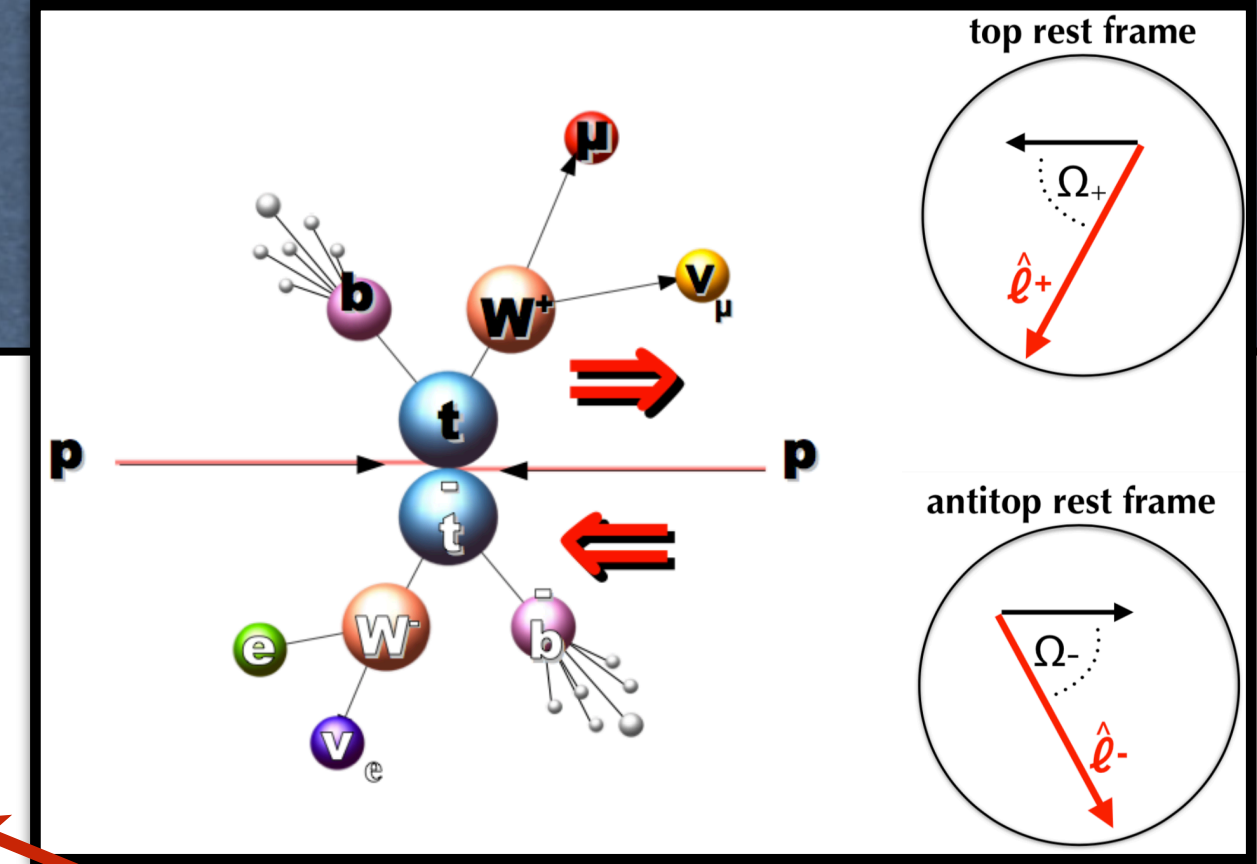
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t $\bar{t}$ Spin Density Matrix

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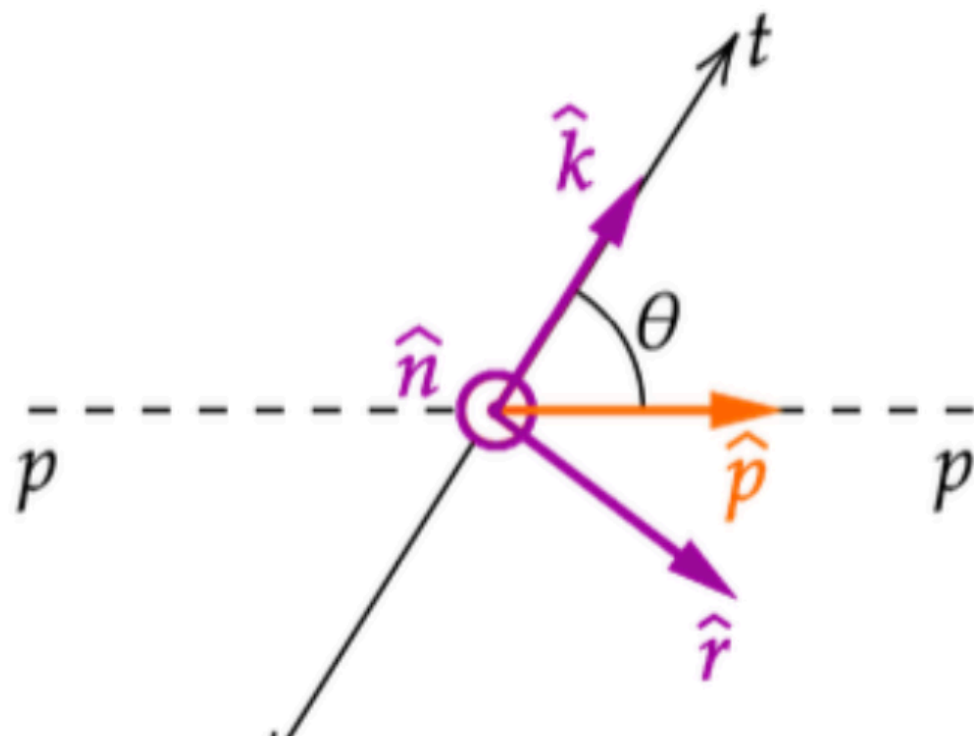
t $\bar{t}$ spin correlation

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



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

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

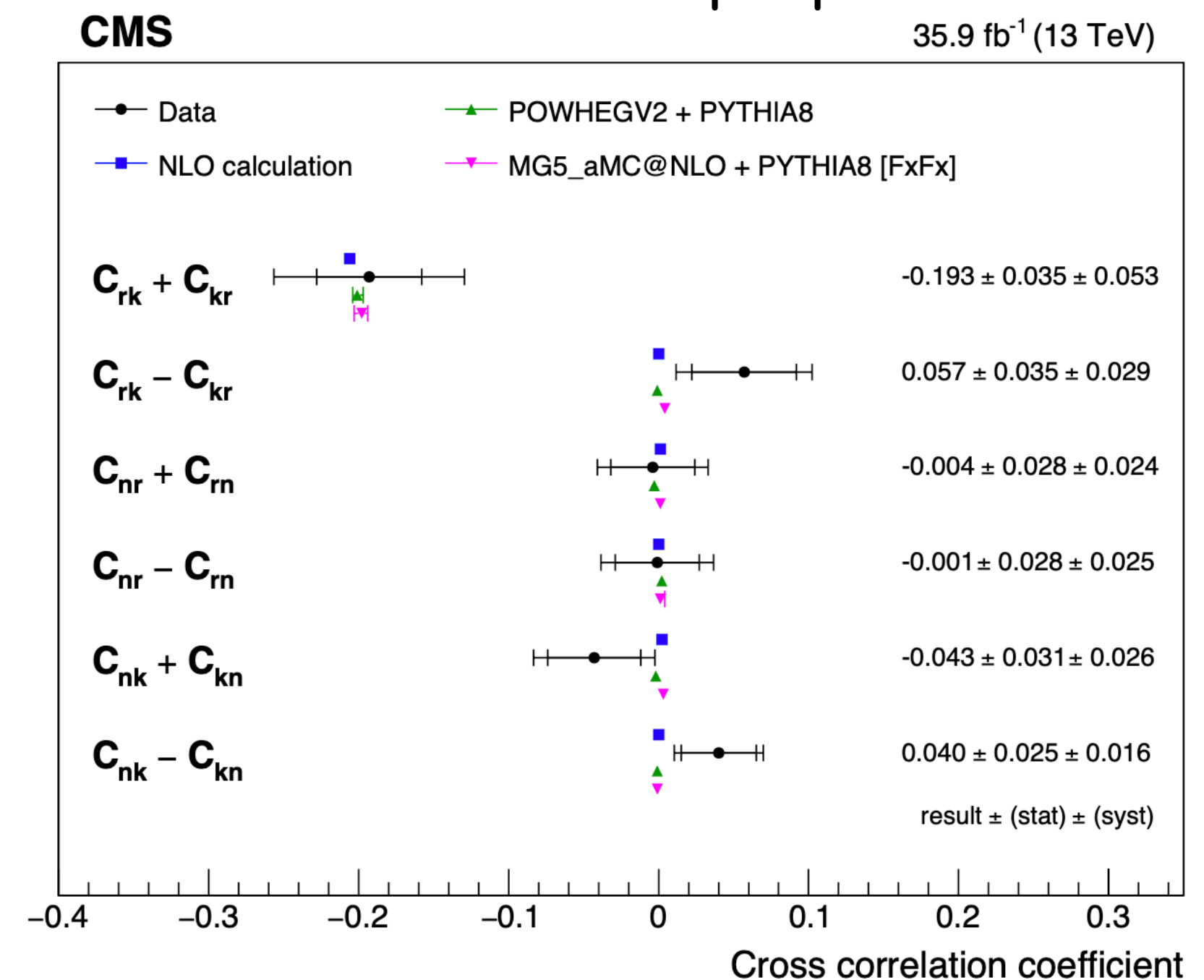
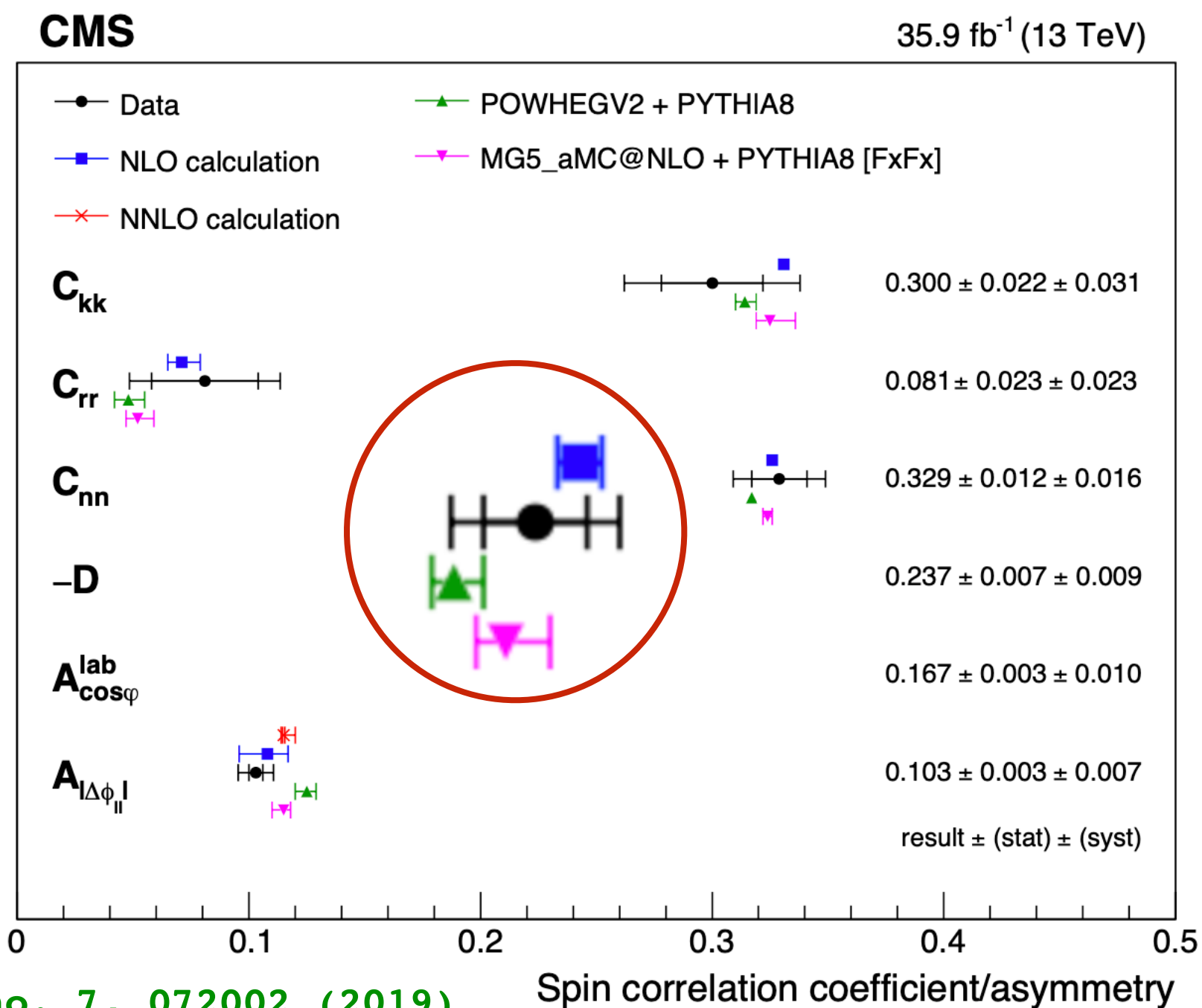


$$-C_{kk} - C_{rr} - C_{nn} \equiv -3D$$

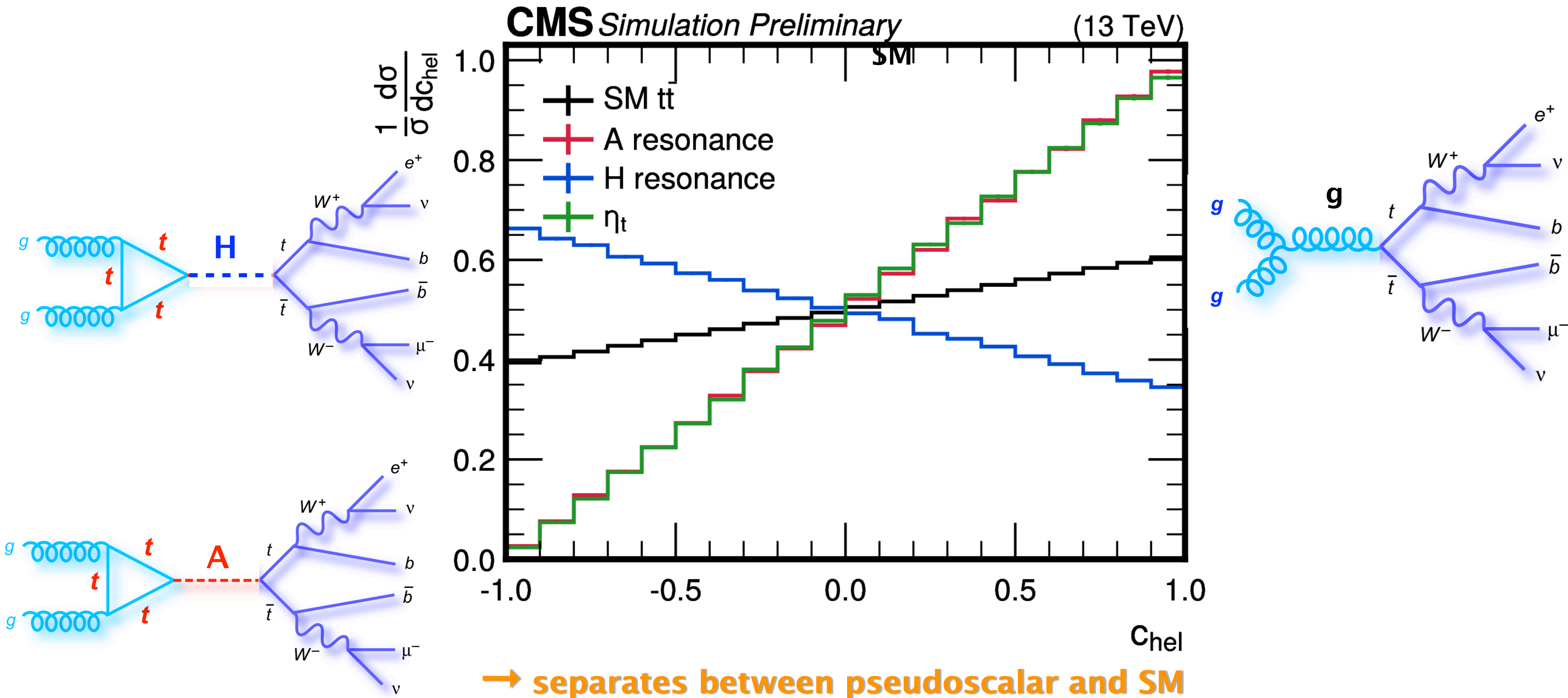
$$c_{\text{hel}} = -(\hat{\ell}^+)_k(\hat{\ell}^-)_k - (\hat{\ell}^+)_r(\hat{\ell}^-)_r - (\hat{\ell}^+)_n(\hat{\ell}^-)_n$$

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

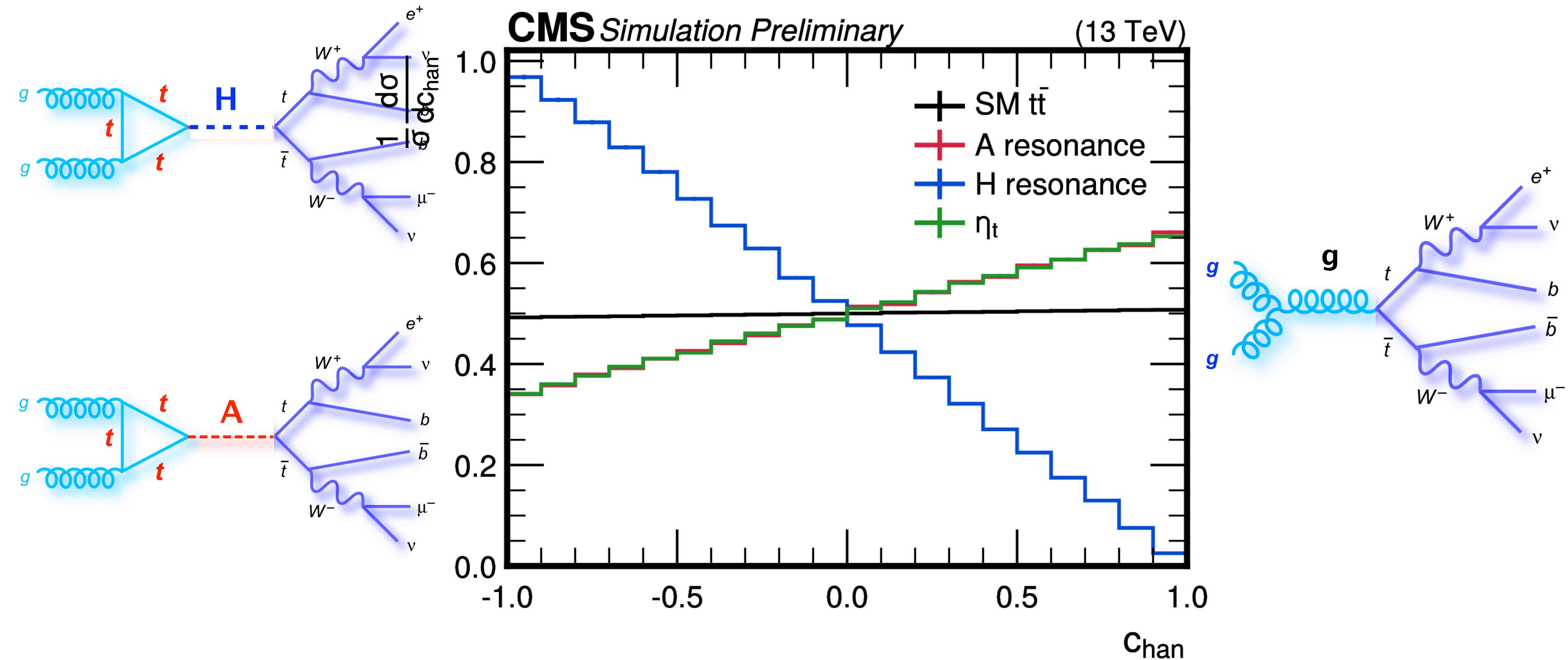
Phys. Rev. D 100, no. 7, 072002 (2019)



Top-Antitop Quark Spin Correlation: Dilepton



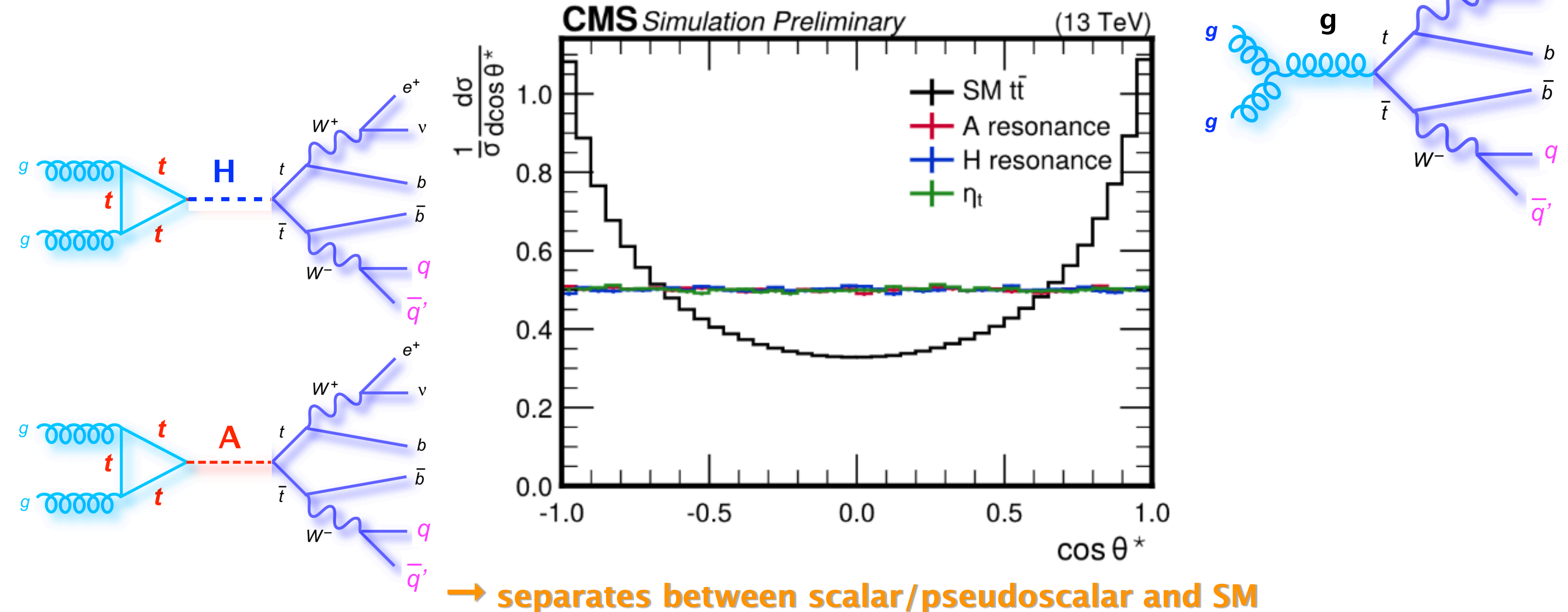
Top-Antitop Quark Spin Correlation: Dilepton



→ separates between pseudoscalar and scalar

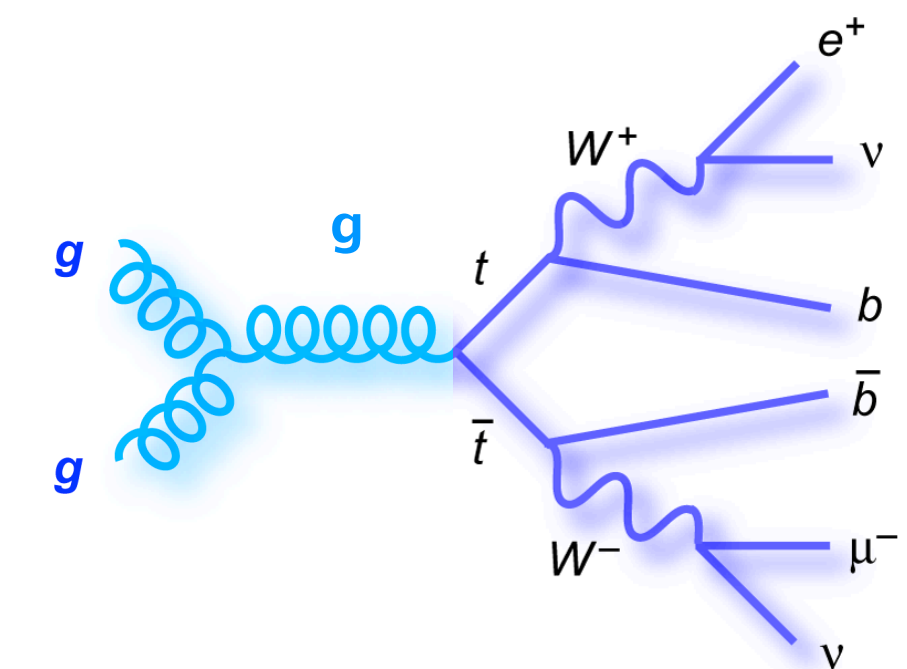
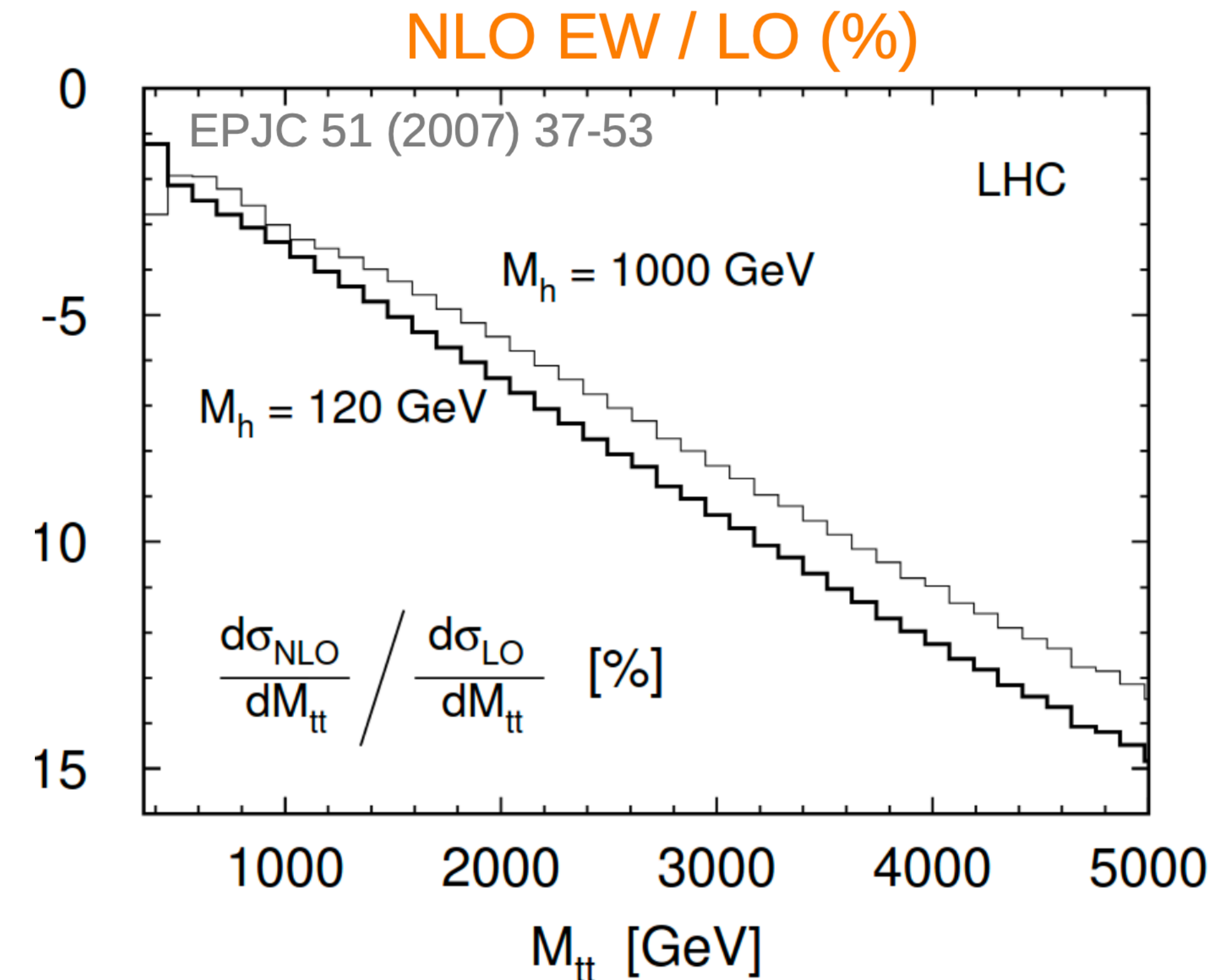
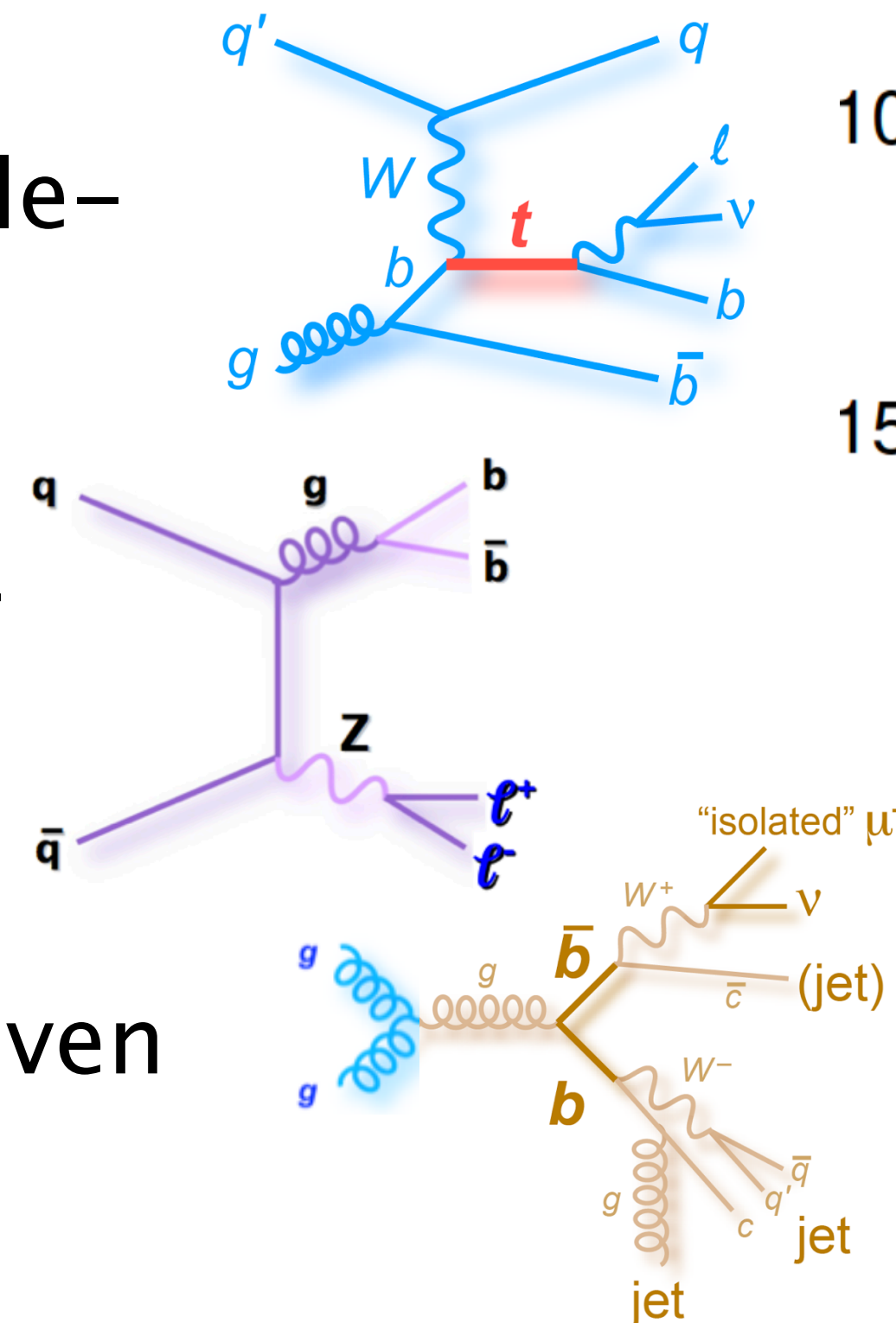
Top Quark Scattering Angle: Lepton+Jets

θ^* : 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



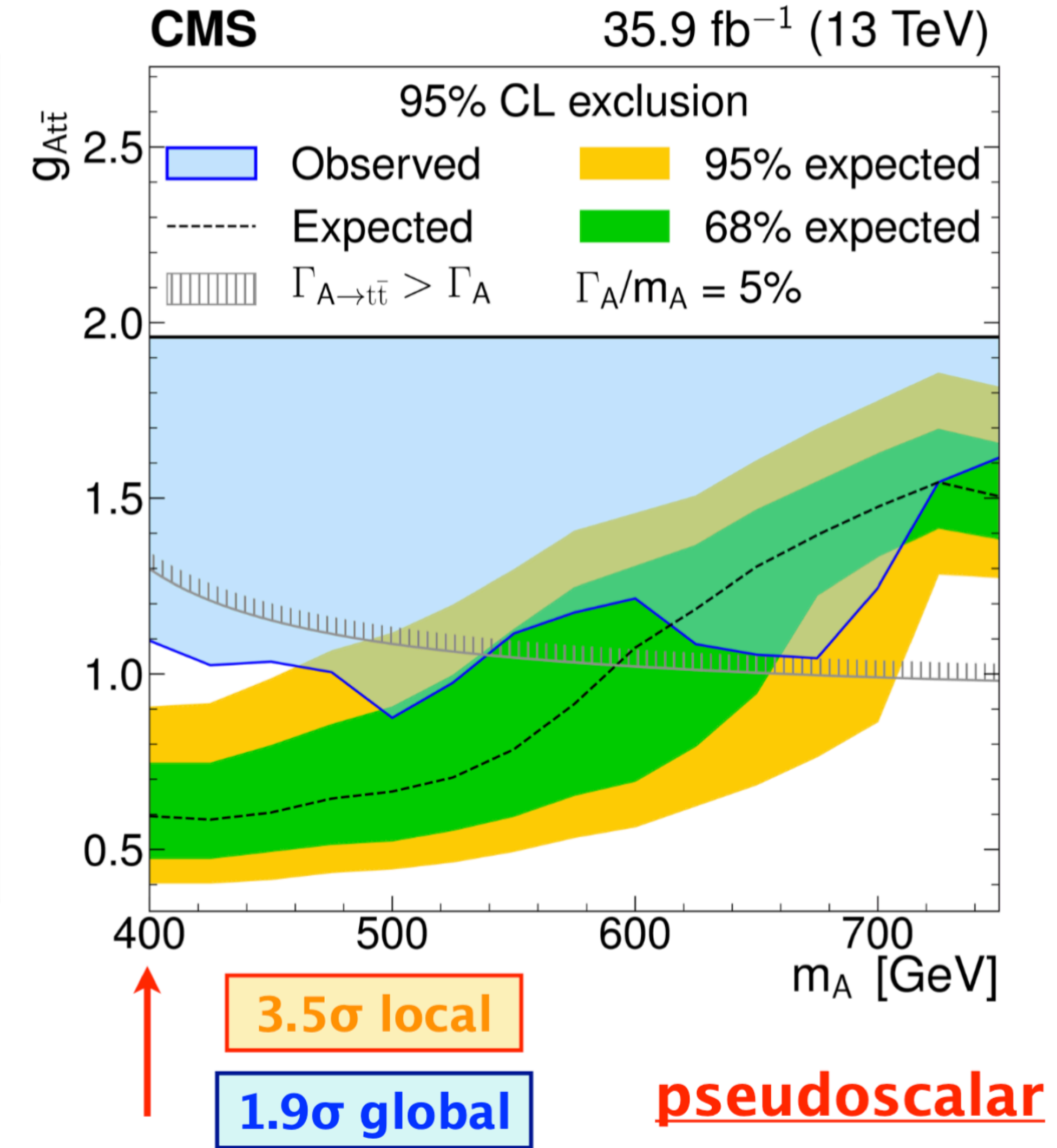
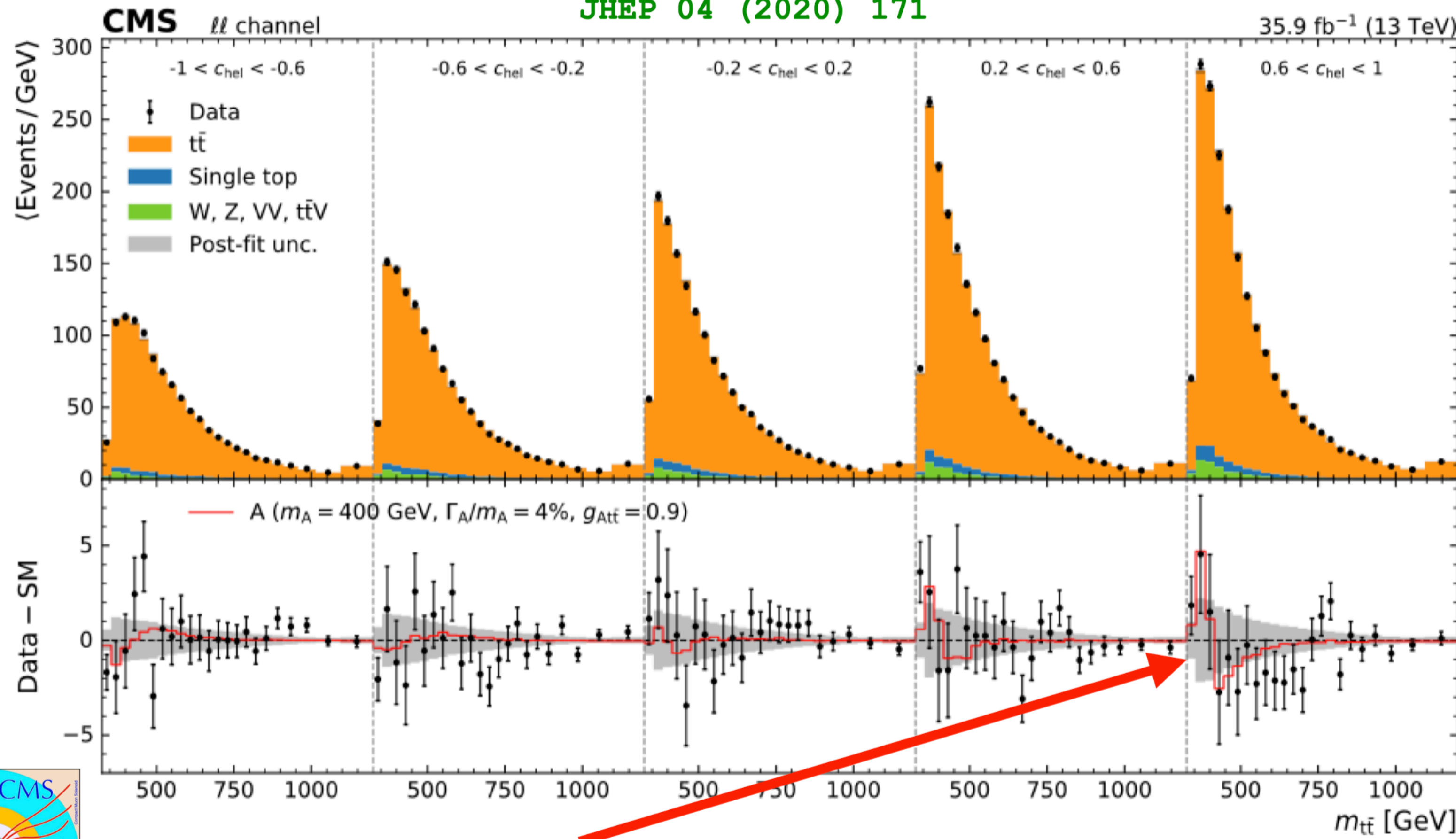
Background modeling

- 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
- 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



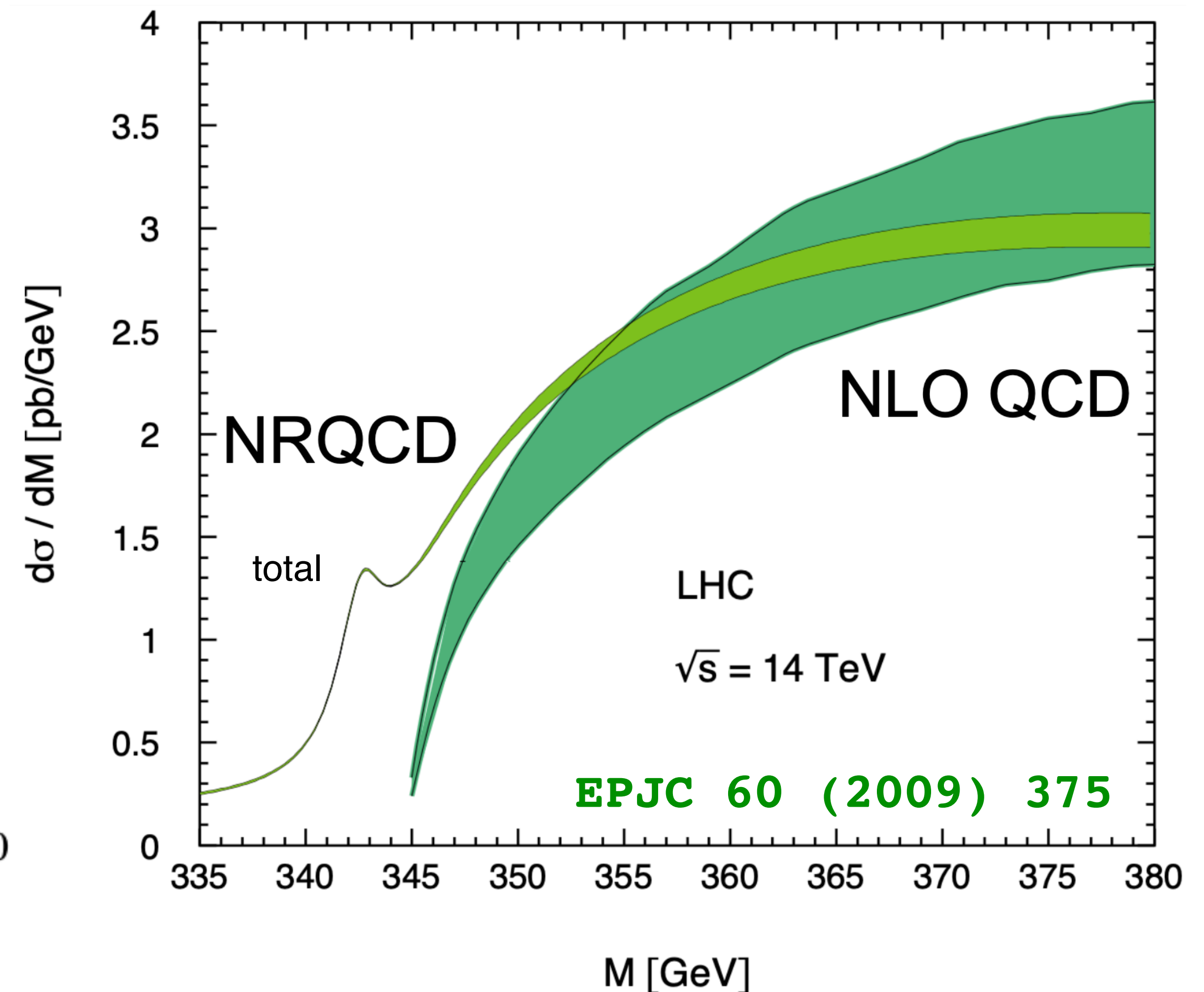
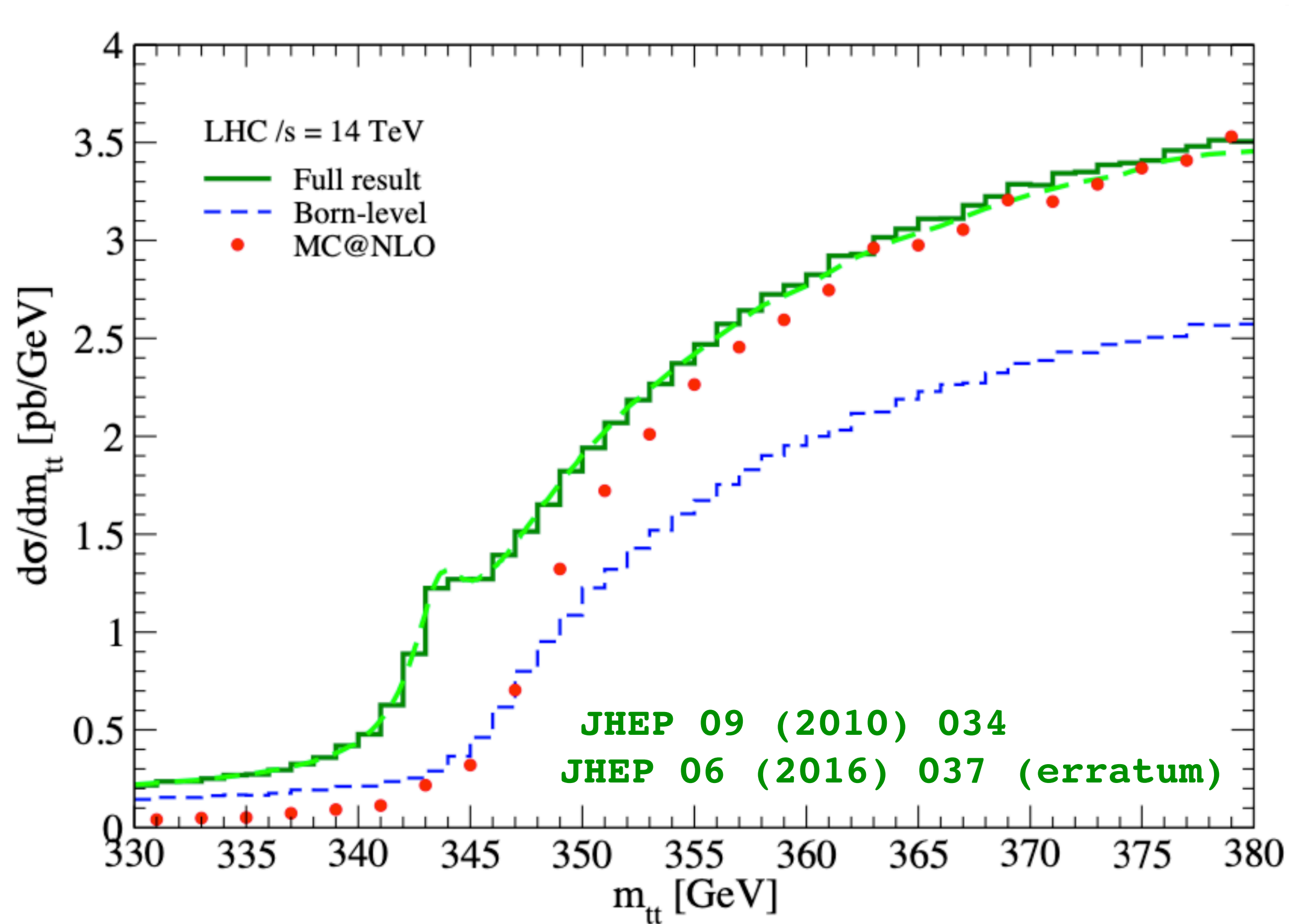
Results of the 2016 Data

JHEP 04 (2020) 171



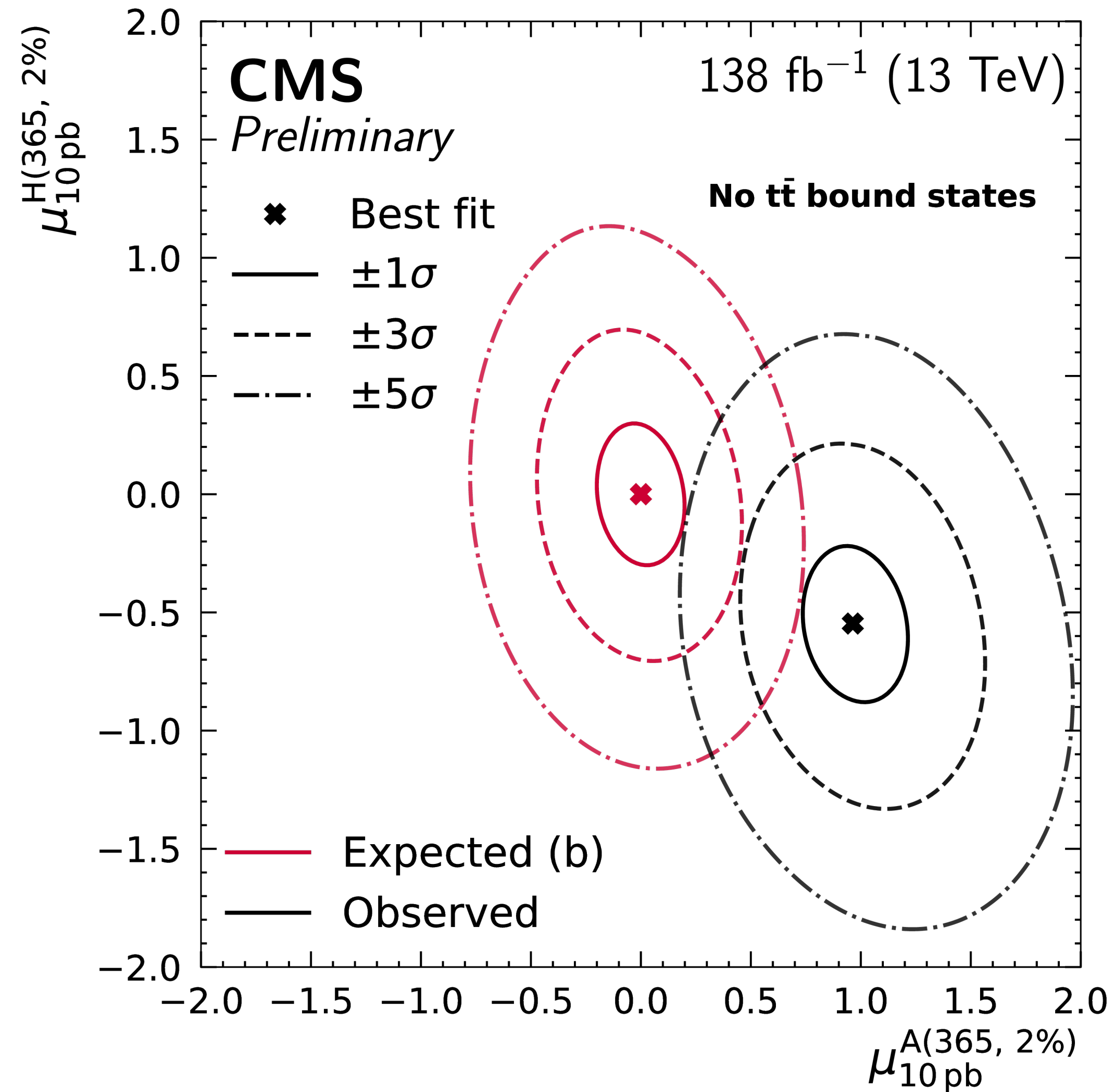
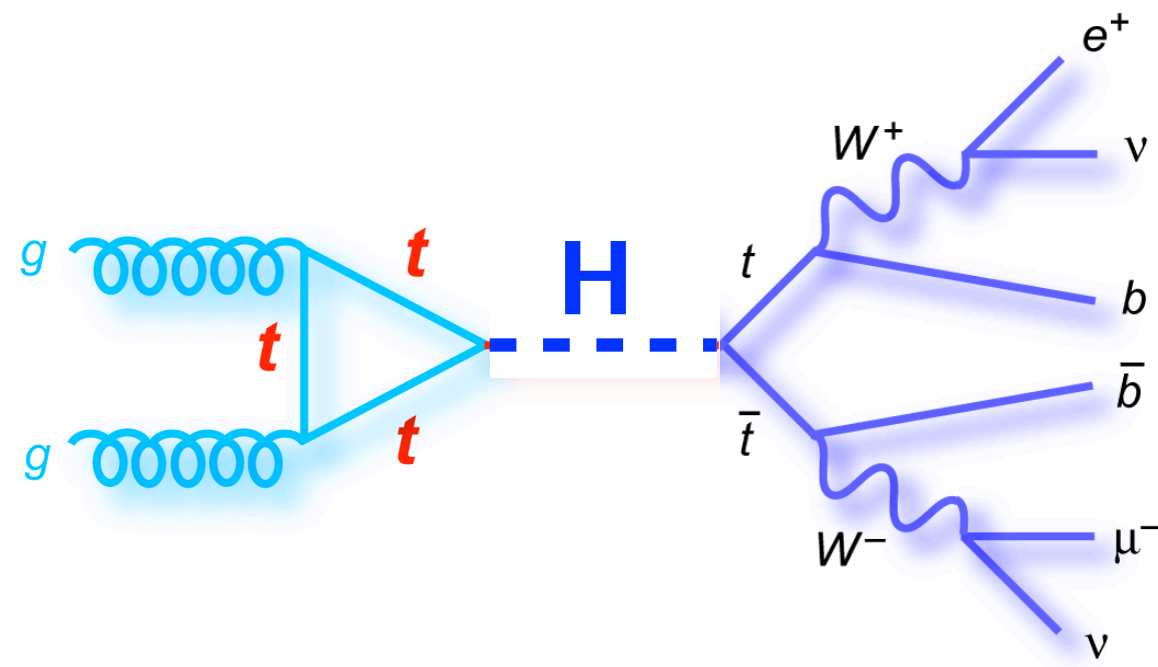
pseudoscalar, $m_A=400$ GeV

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

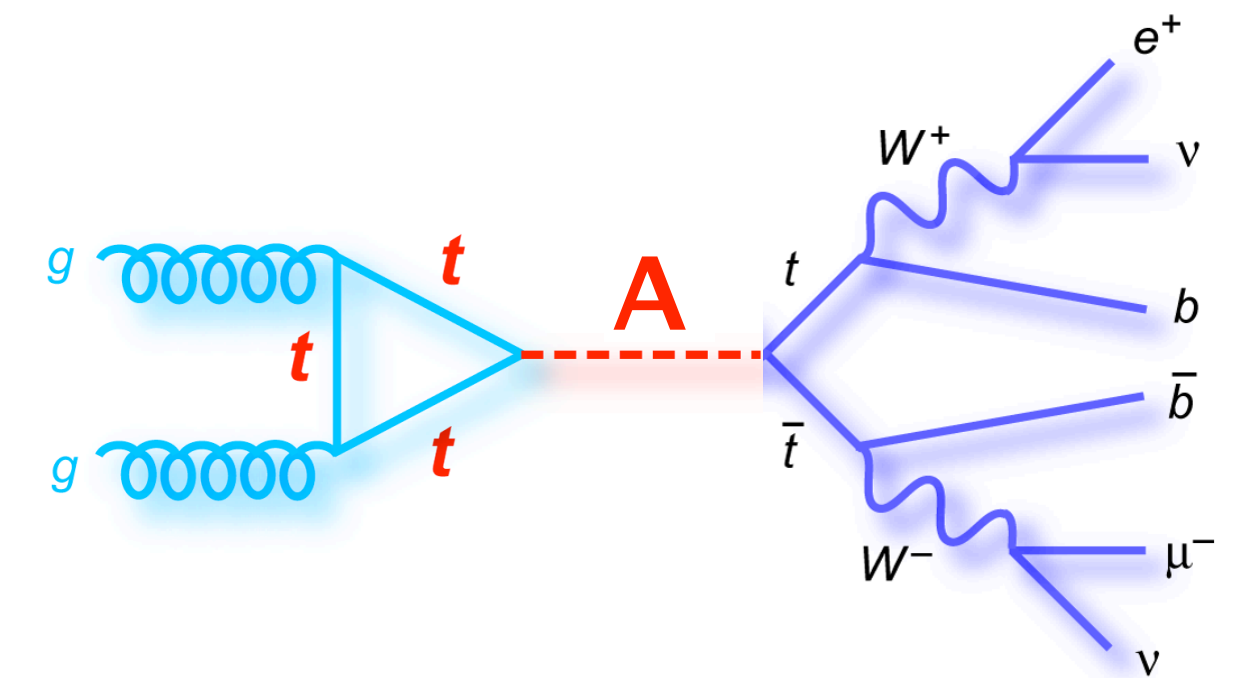


→ threshold region is dominated by color-singlet pseudocalar toponium

Results of A/H interpretation – Combination



only resonant signal components included



→ data prefers pseudoscalar over scalar

Selection and Reconstruction: Lepton+Jets Channel

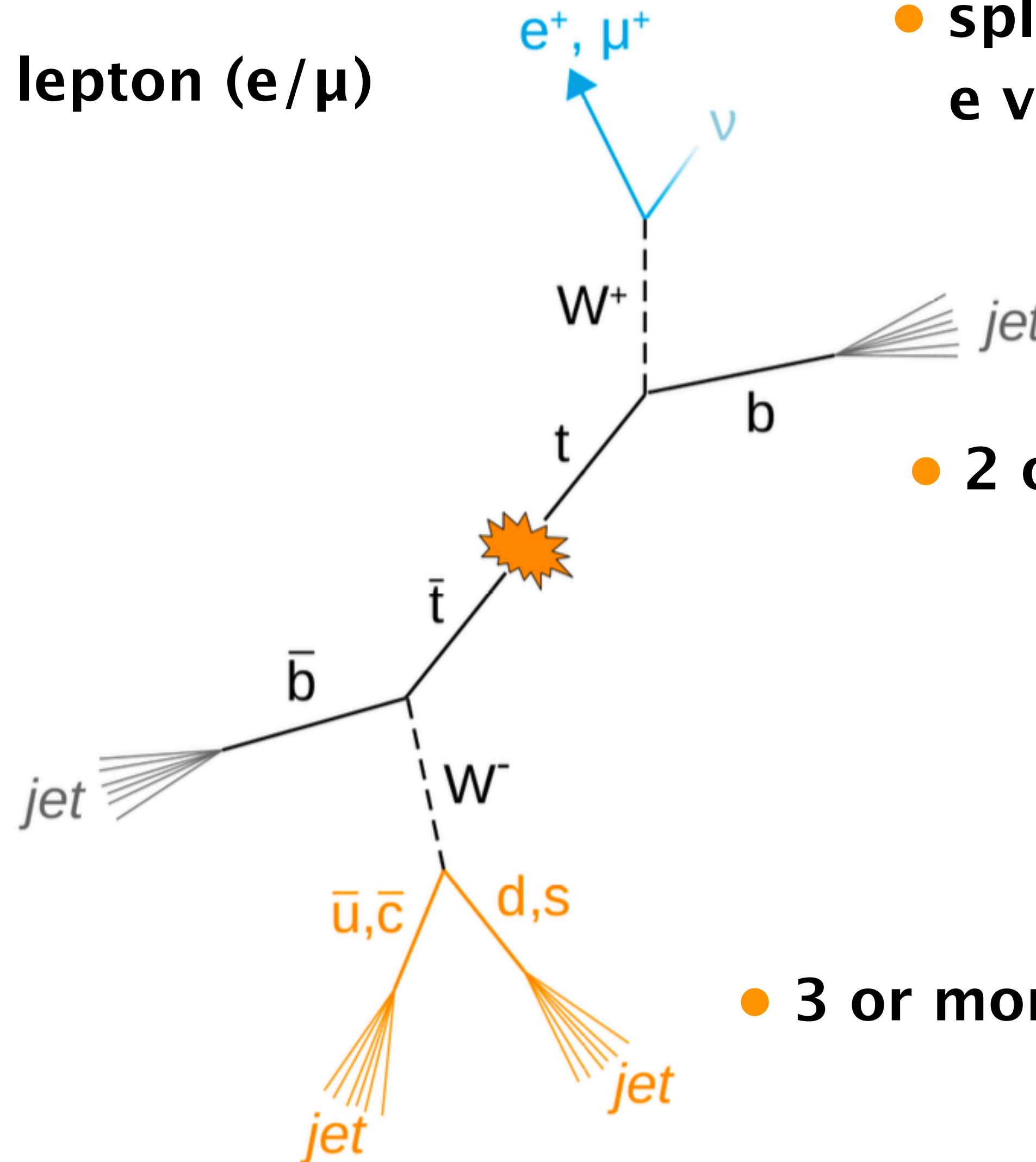
- exactly one lepton (e/μ)

- split in 4 categories:
 e vs μ and 3 jets vs ≥ 4 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)

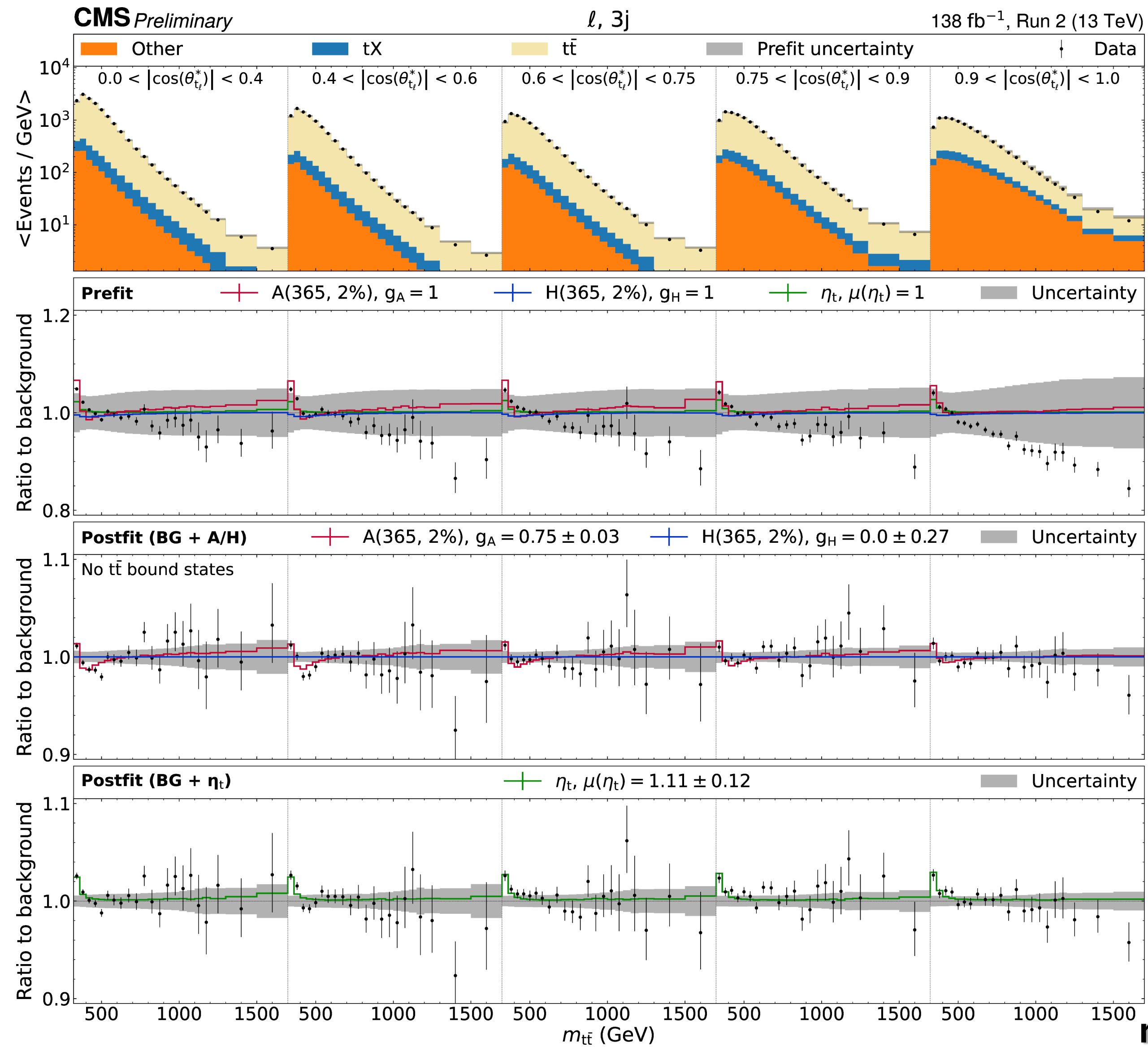
NIM A 788 (2015) 128



- 2 or more b-jets

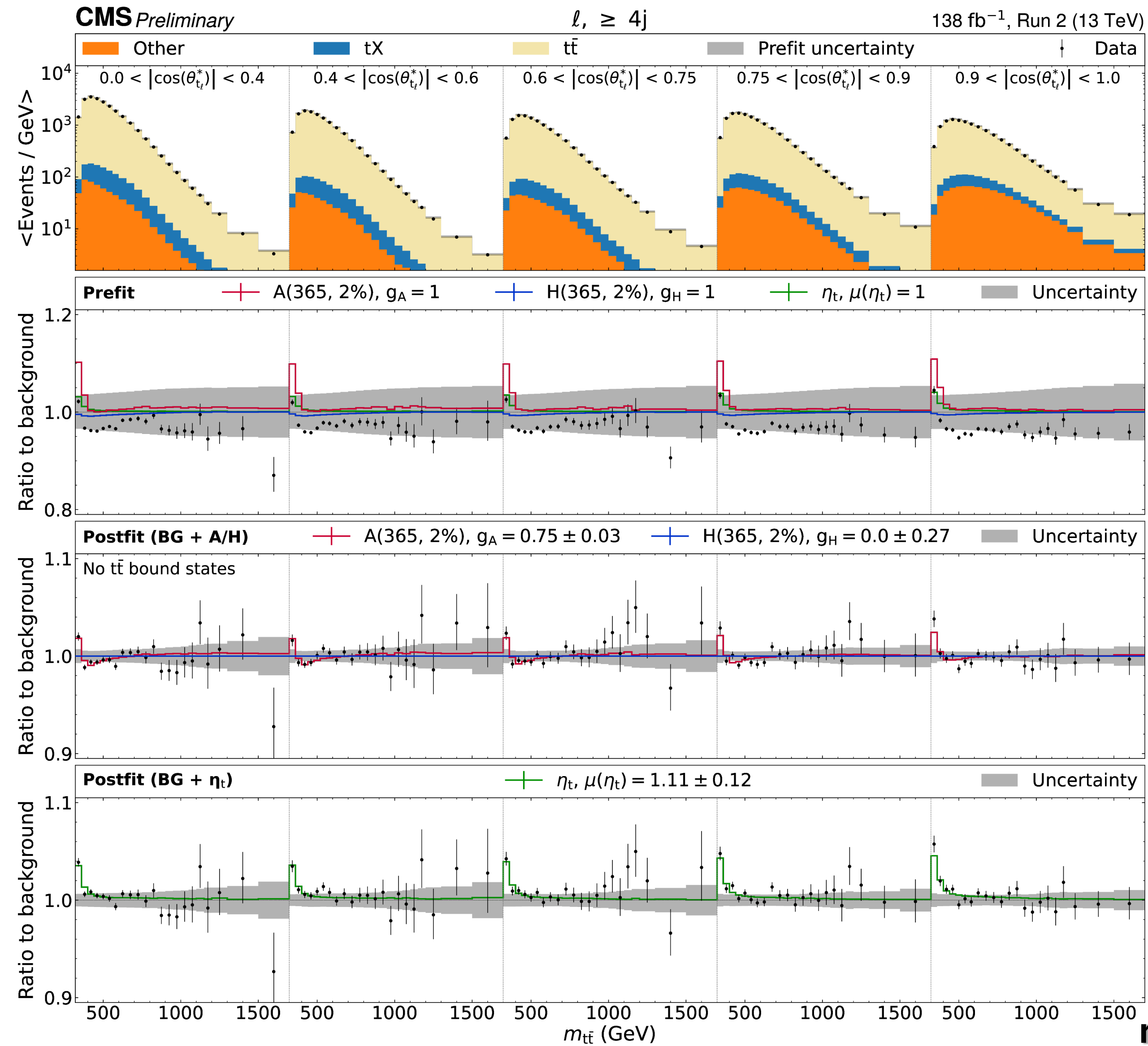
- 3 or more jets

Results – Lepton+3jets



→ similar features,
but less pronounced

Results – Lepton+ ≥ 4 jets



→ similar features

List of systematic uncertainties

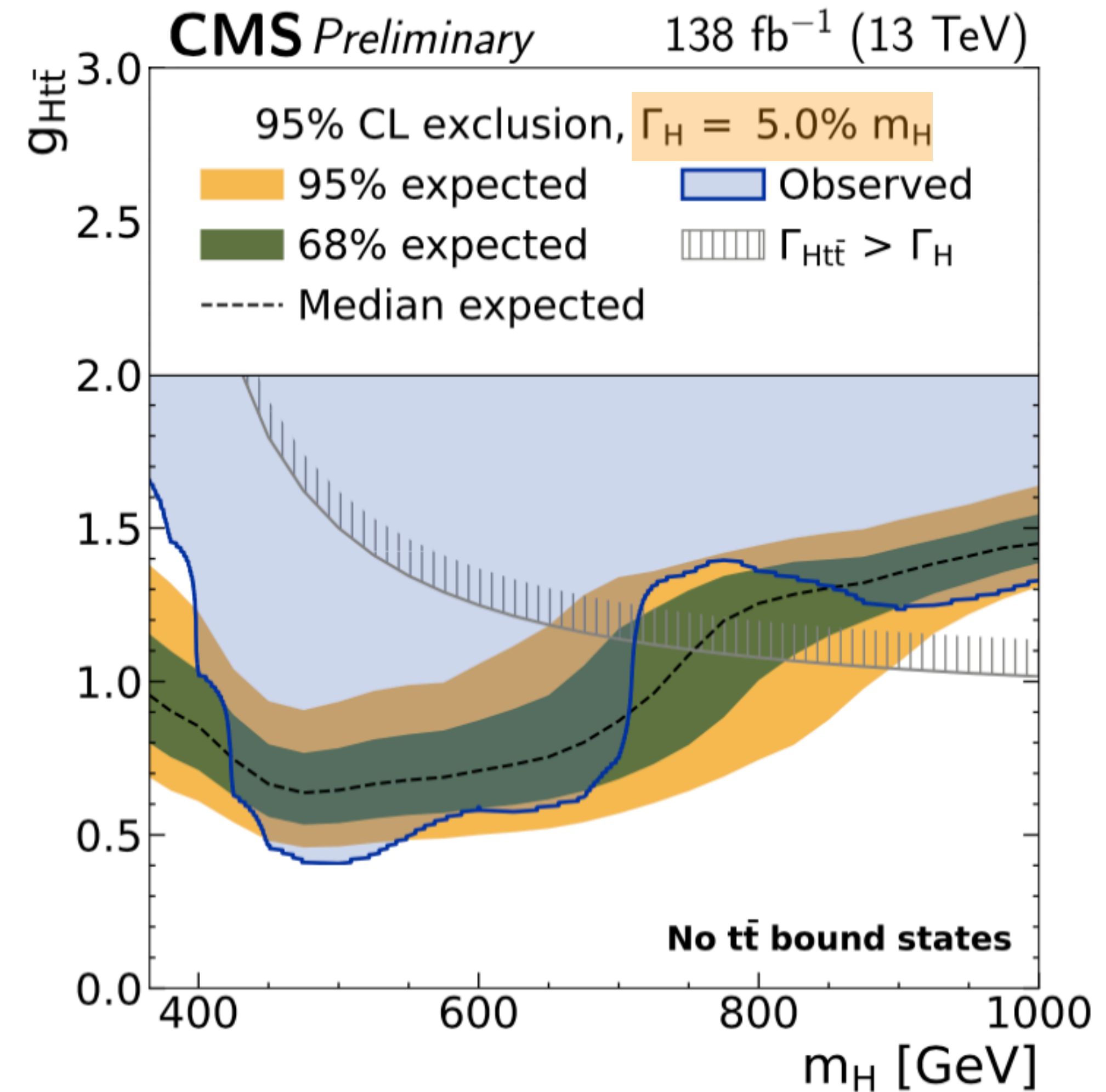
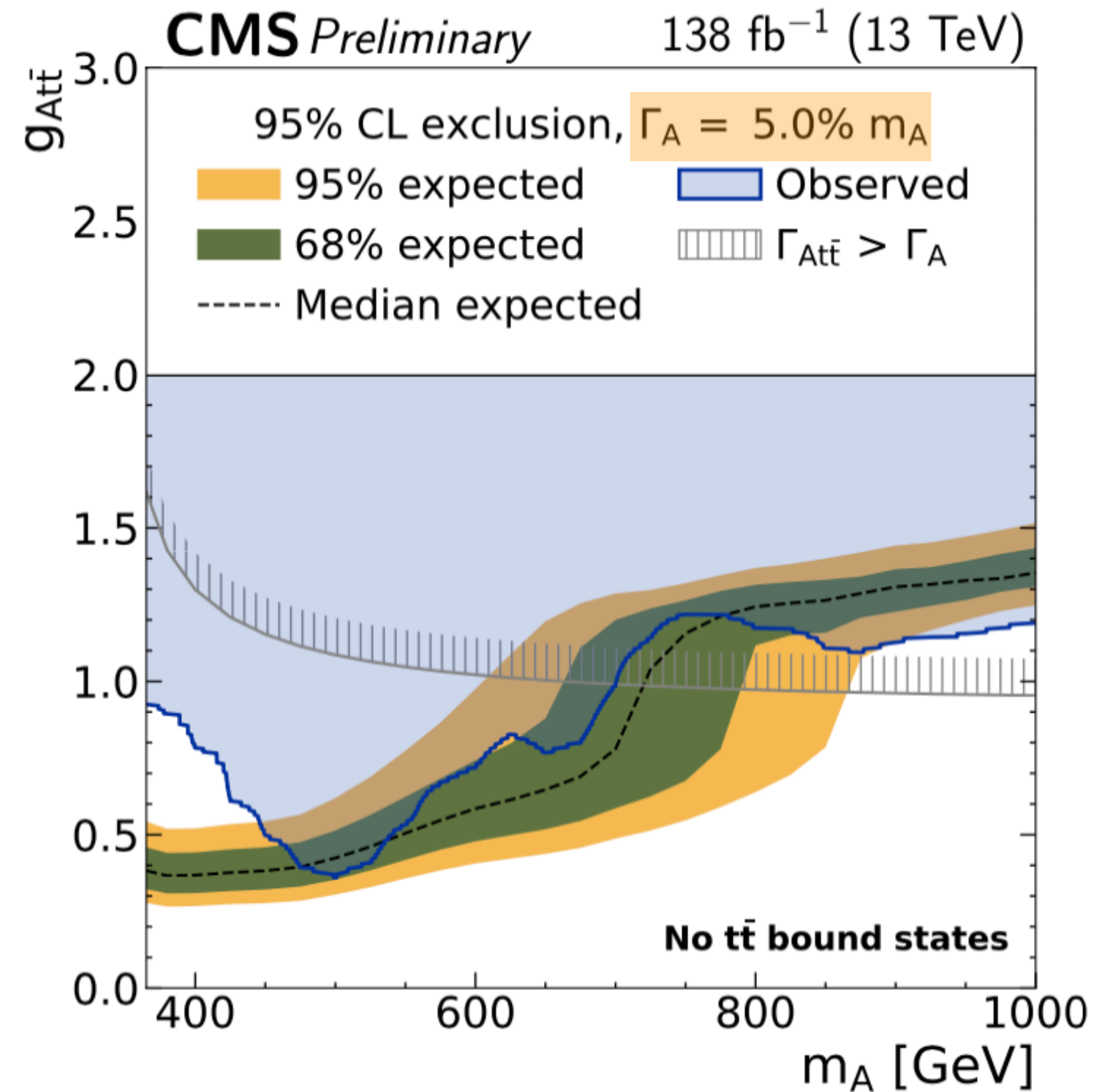
Experimental

- Jet energy corrections - split into 11 subsources
- Jet energy resolution
- Unclustered p_{miss}^T (uncorrelated between years)
- Luminosity – correlated and decorrelated parts between years
- Pileup
- Trigger efficiencies (separate for $\ell\ell$ / 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 ($\ell\ell$)

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: $\pm 1\text{GeV}$ (interpolated from $\pm 3\text{GeV}$)
 - 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



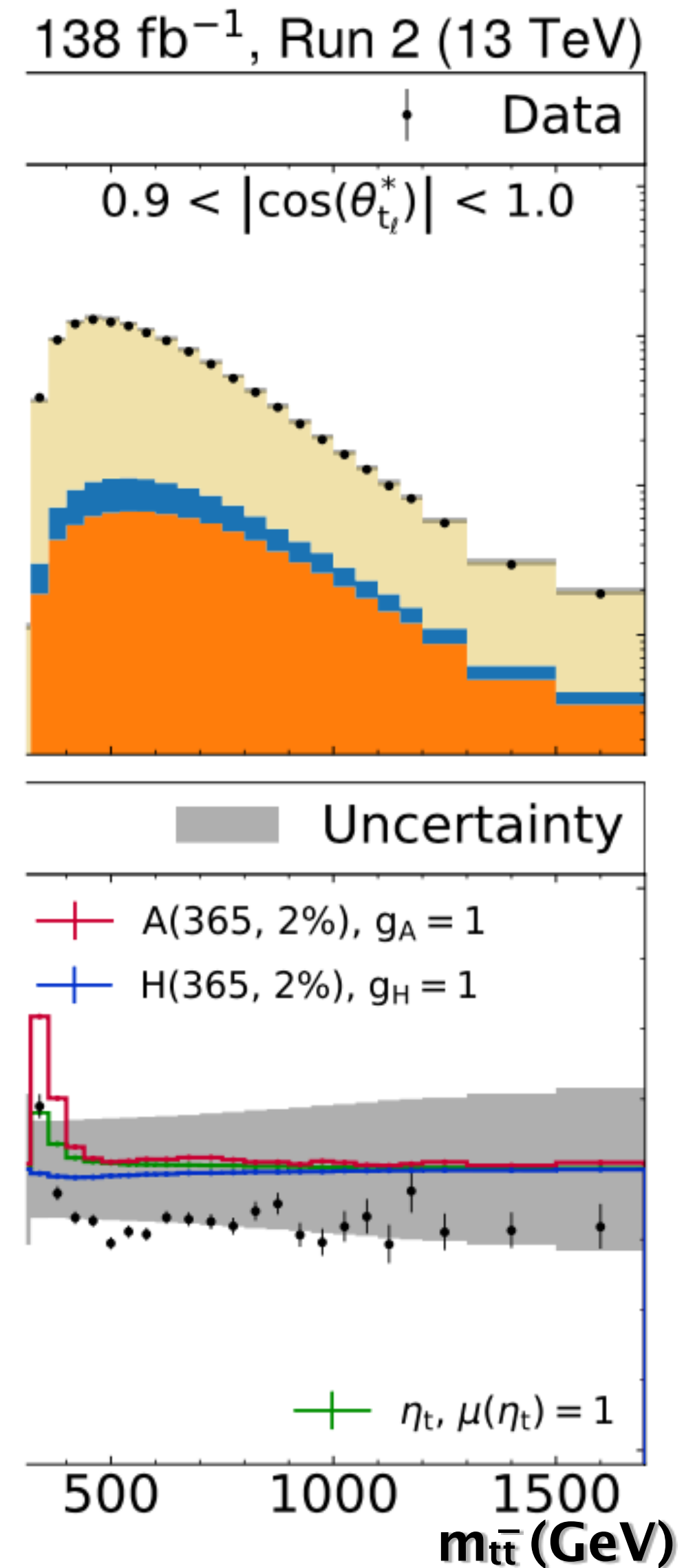
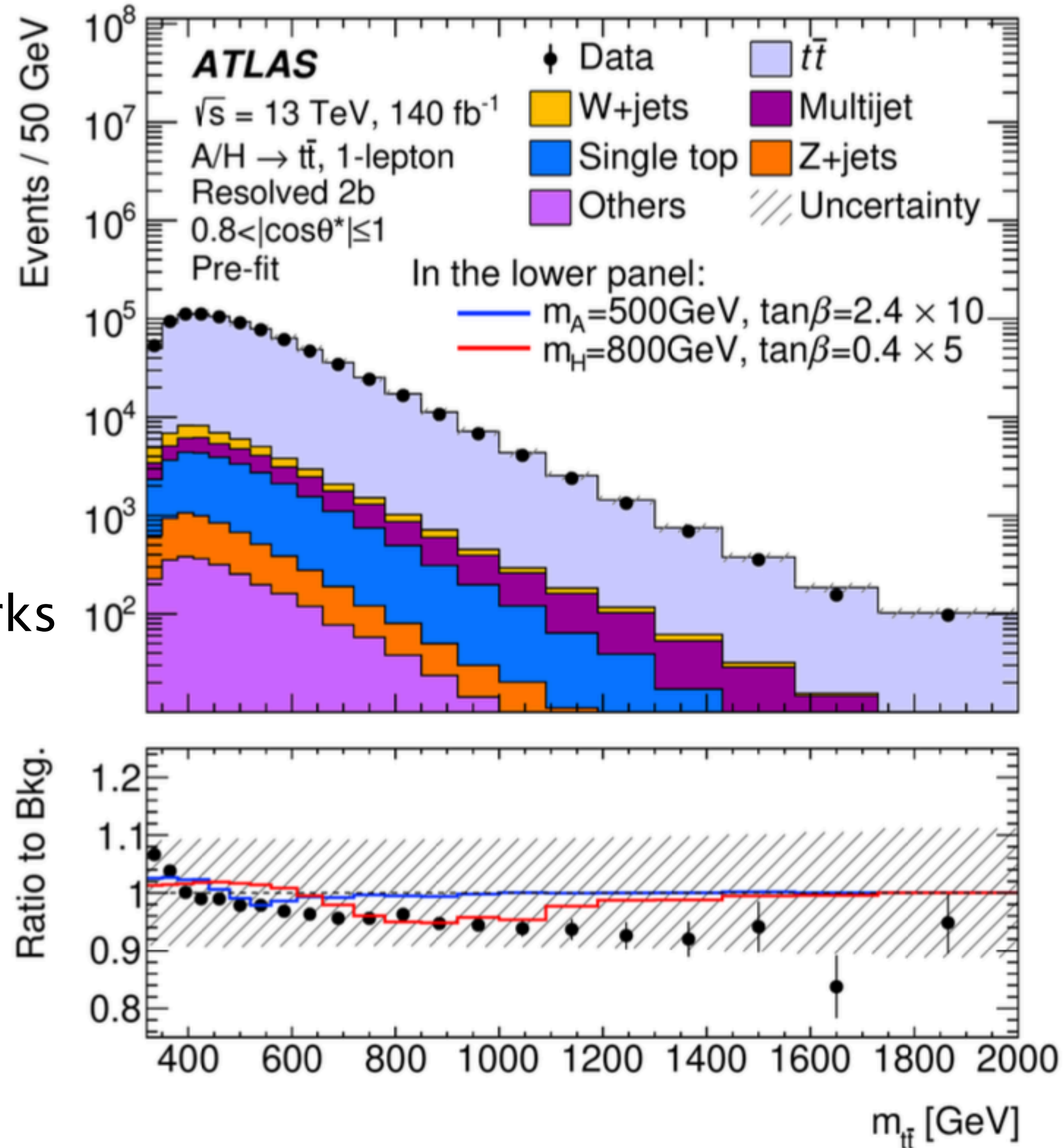
→ excess at low $m_{t\bar{t}}$ is reflected at low A/H masses, but stronger for pseudoscalar A

Comparison with ATLAS – prefit

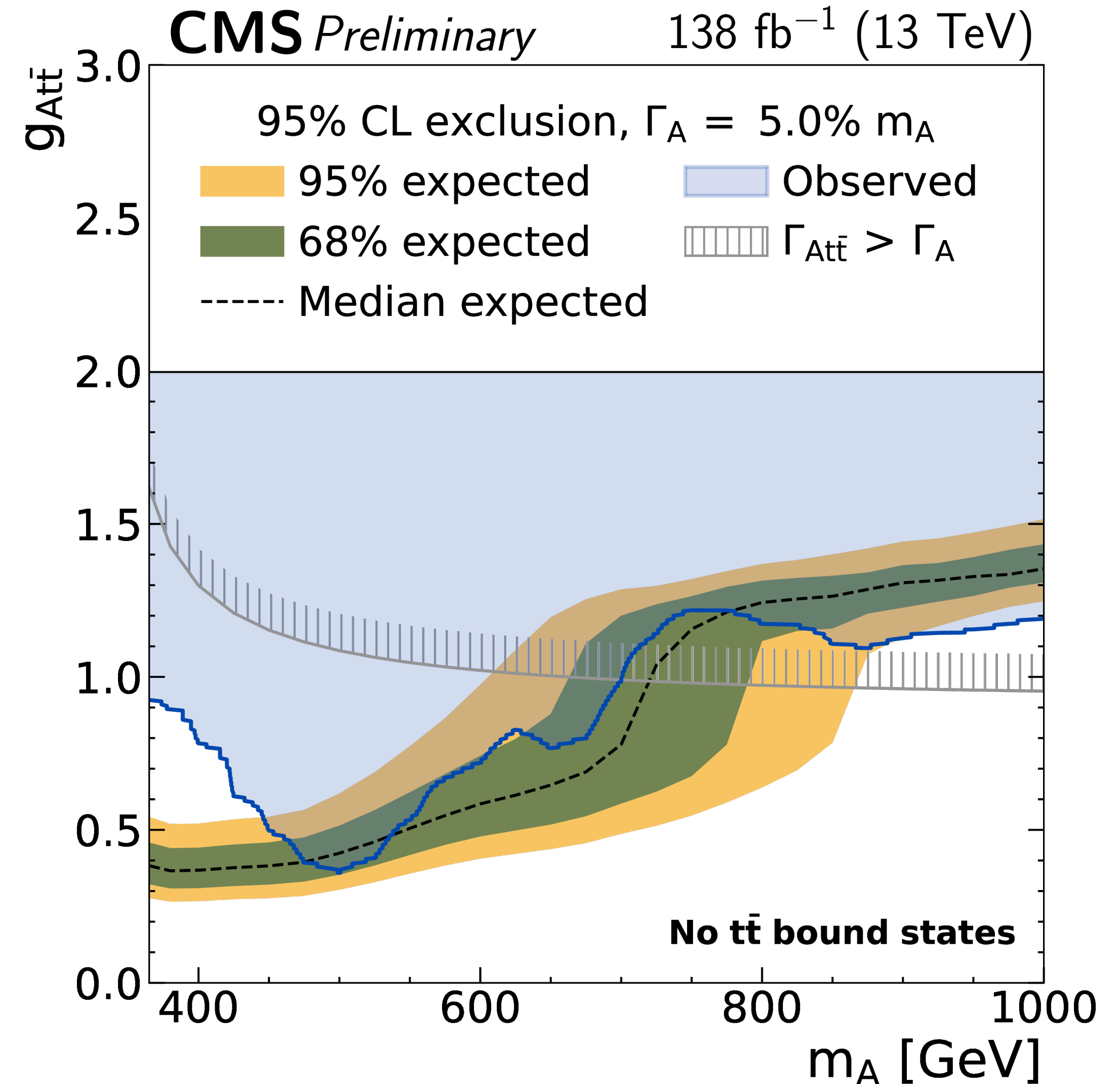
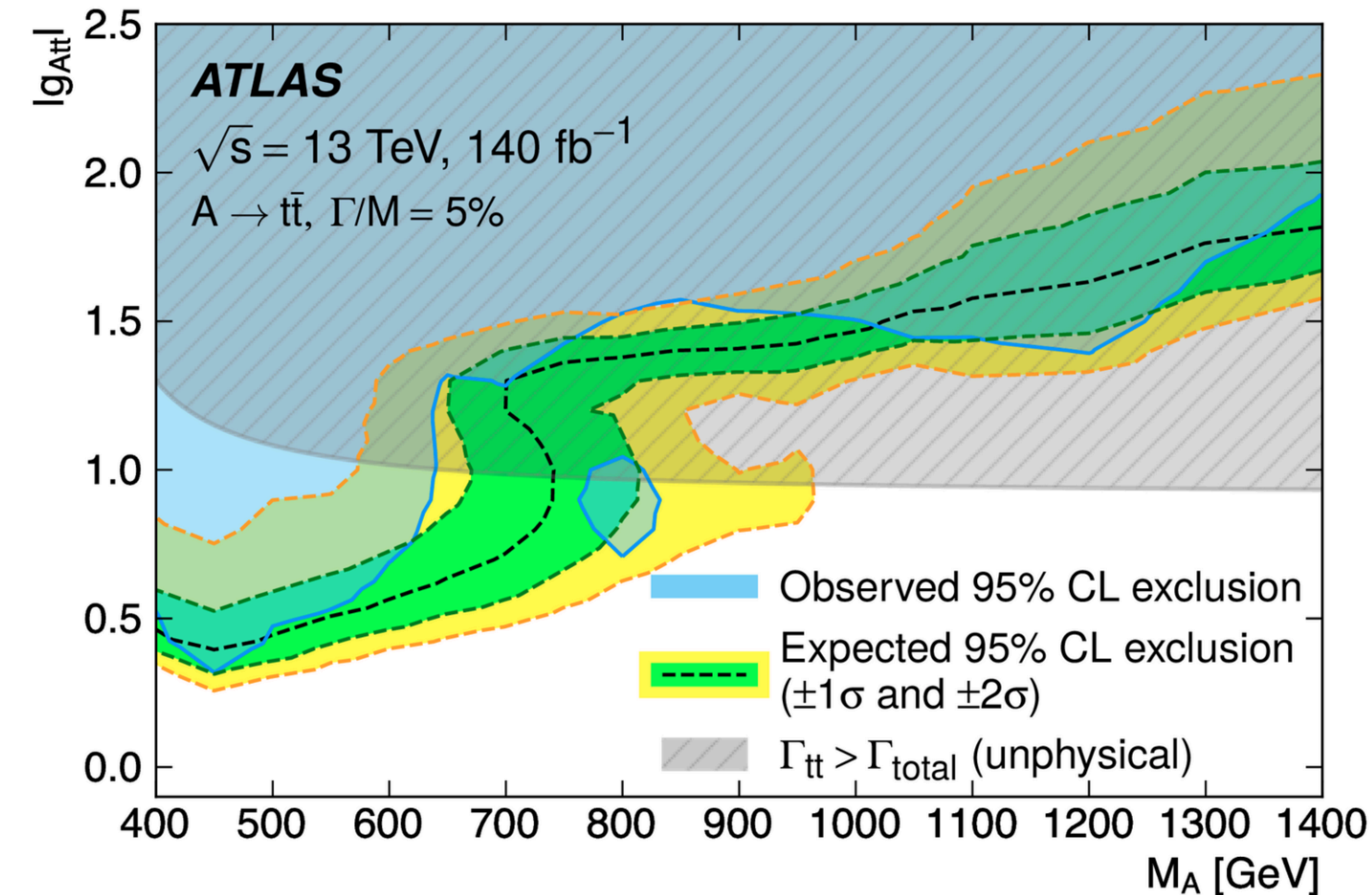
- $1\ell, 2b, \geq 4$ jets category for both ATLAS and CMS
- compare pre-fit distributions
- e.g. look at high $|\cos\theta^*|$:

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

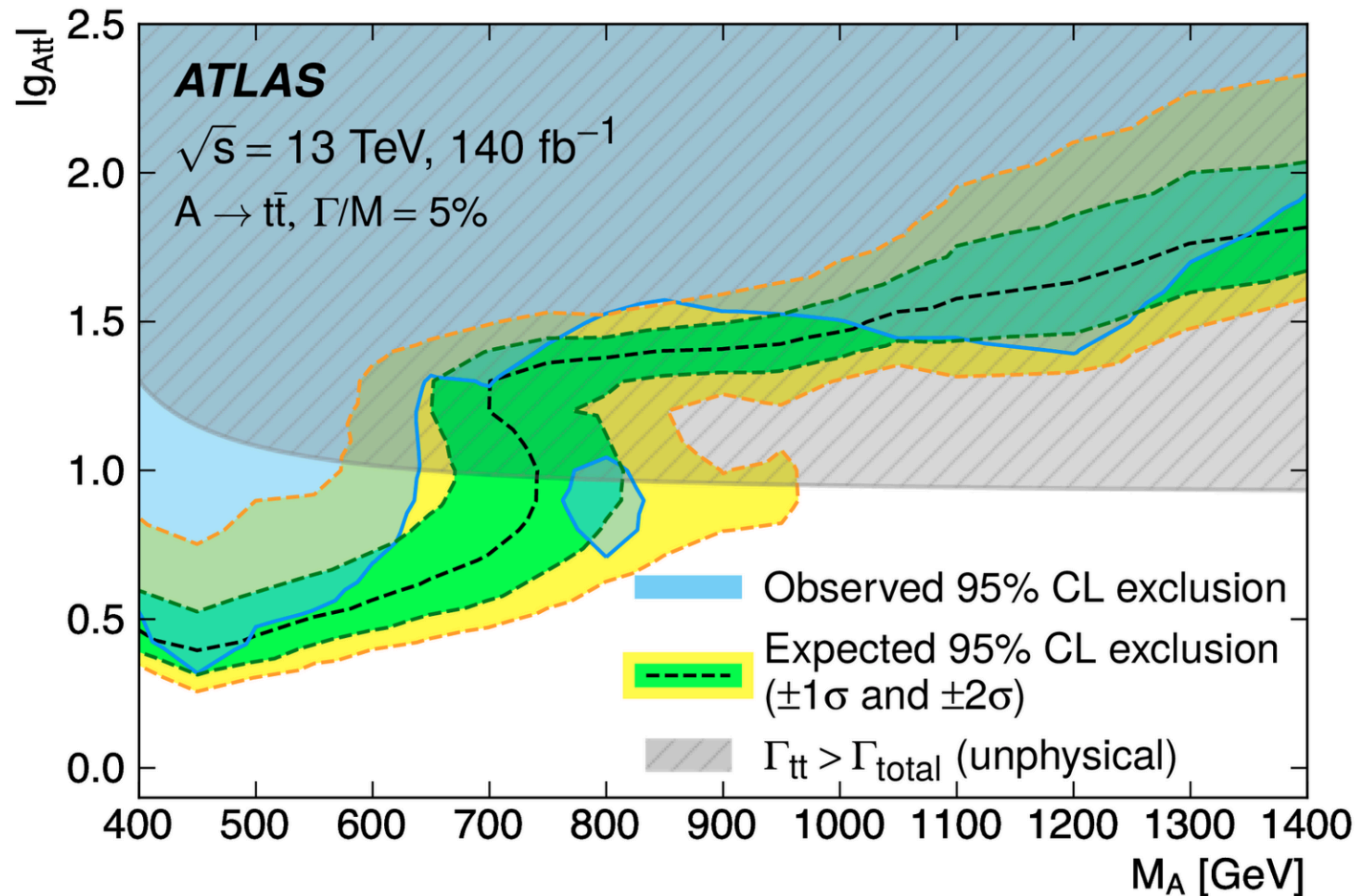
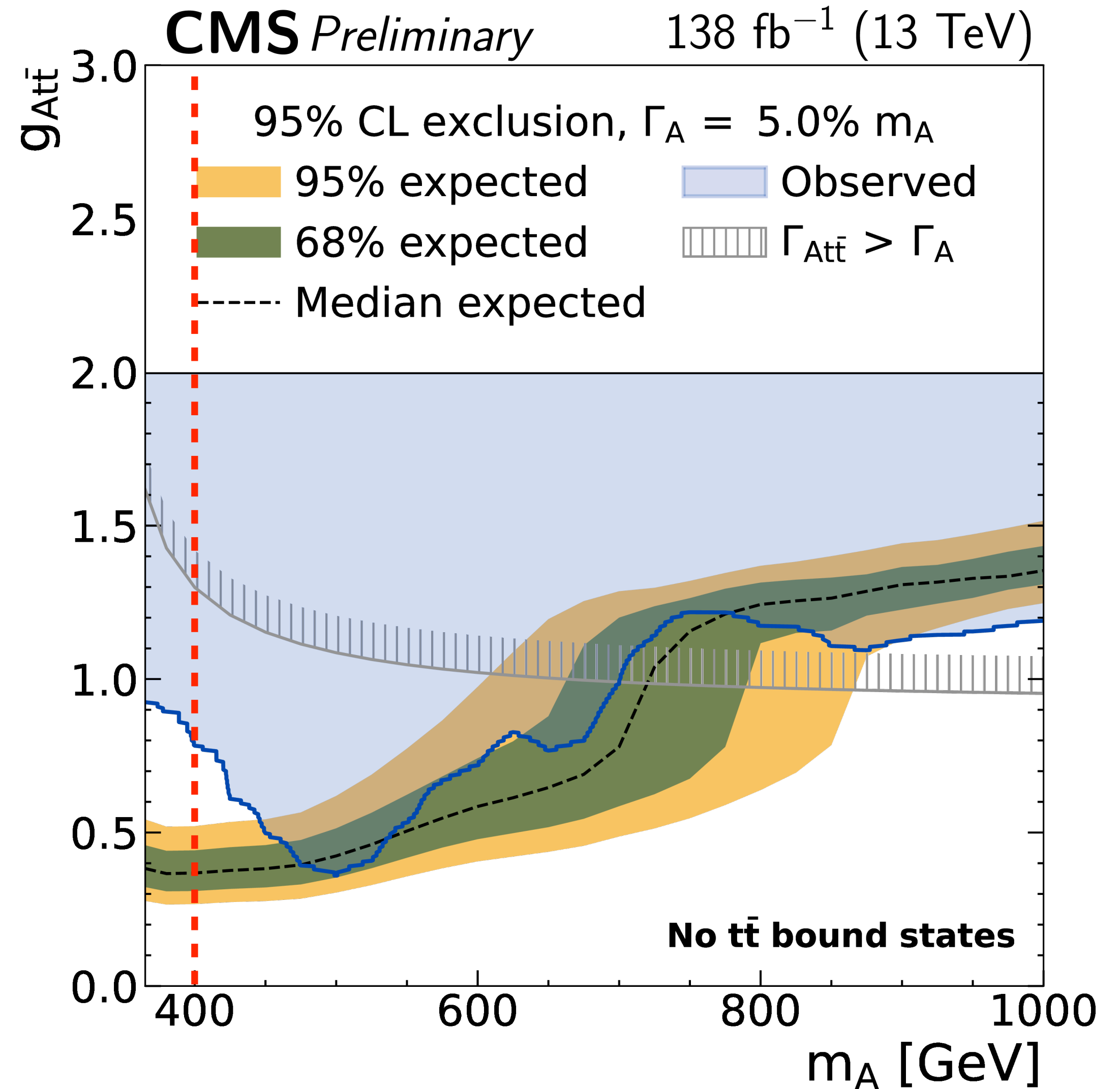
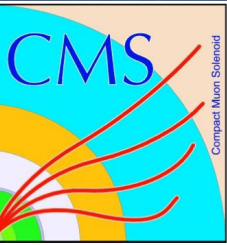
- for dilepton difficult to compare
 - ATLAS does not reconstruct top quarks
 - different variables: $m_{\ell\ell bb}$ vs. $\Delta\varphi_{\ell\ell}$



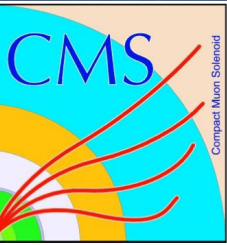
Comparison with ATLAS – limits, combined



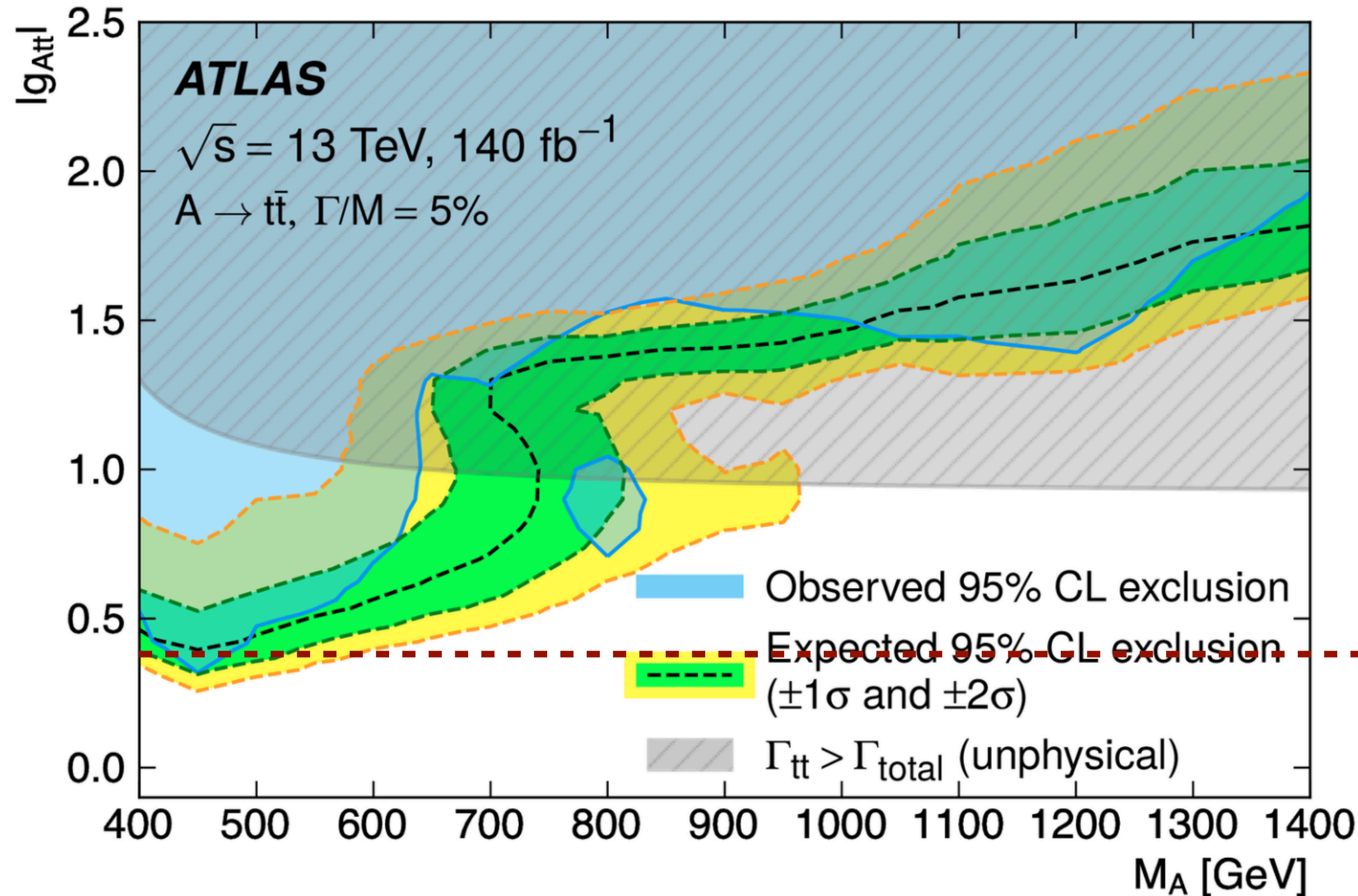
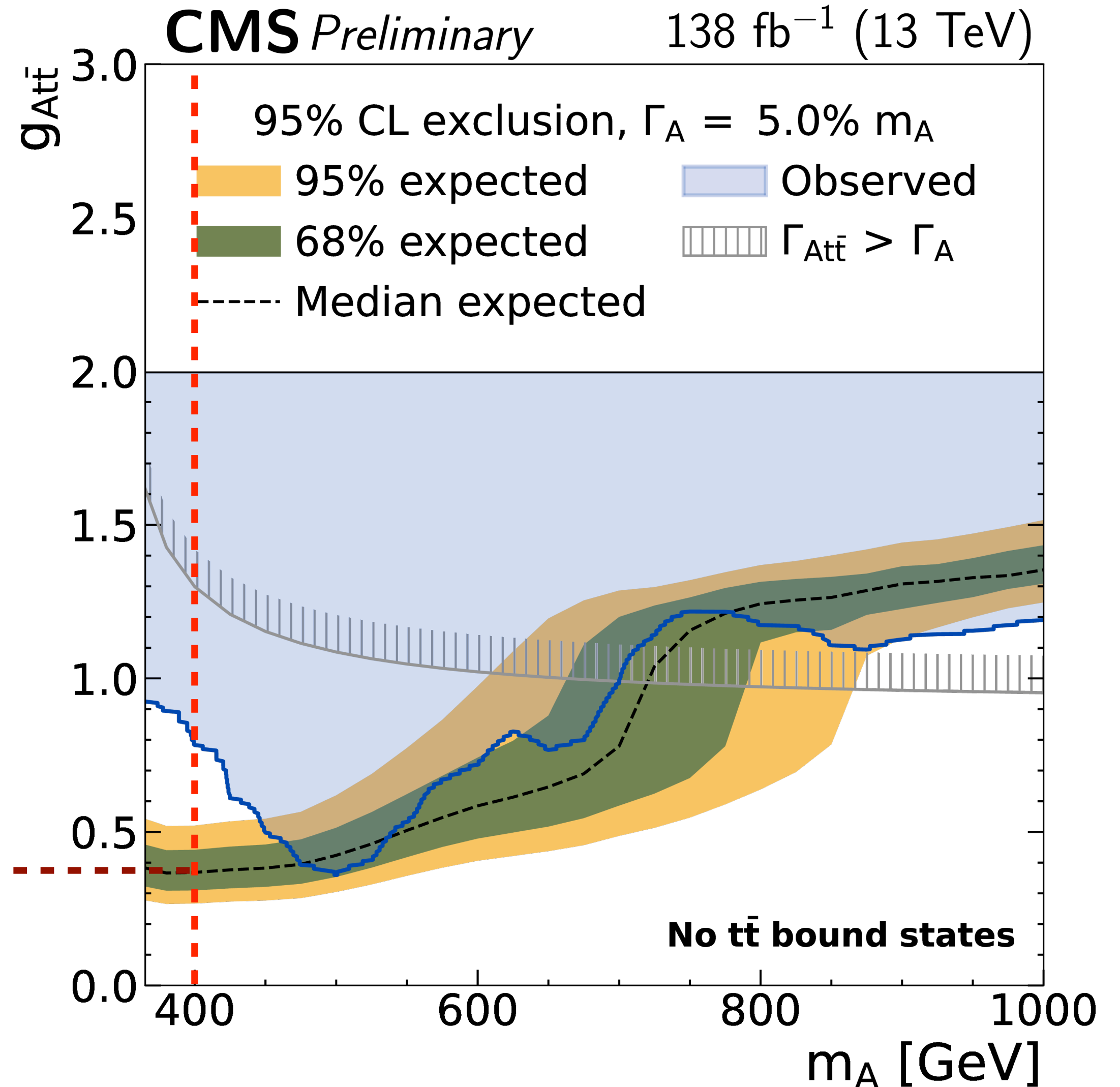
Comparison with ATLAS – limits, combined



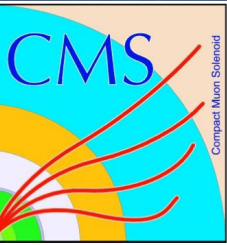
Comparison with ATLAS – limits, combined



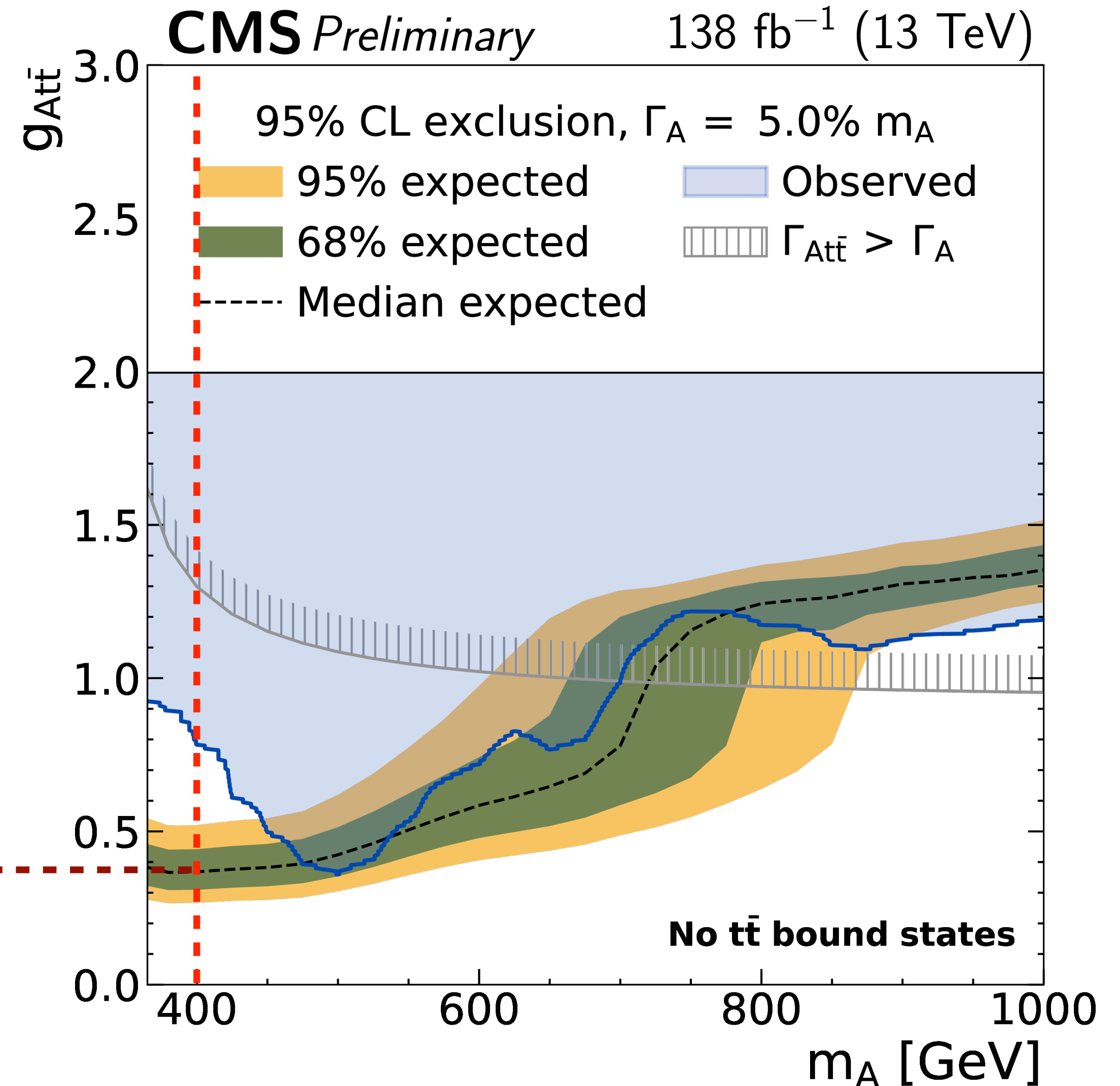
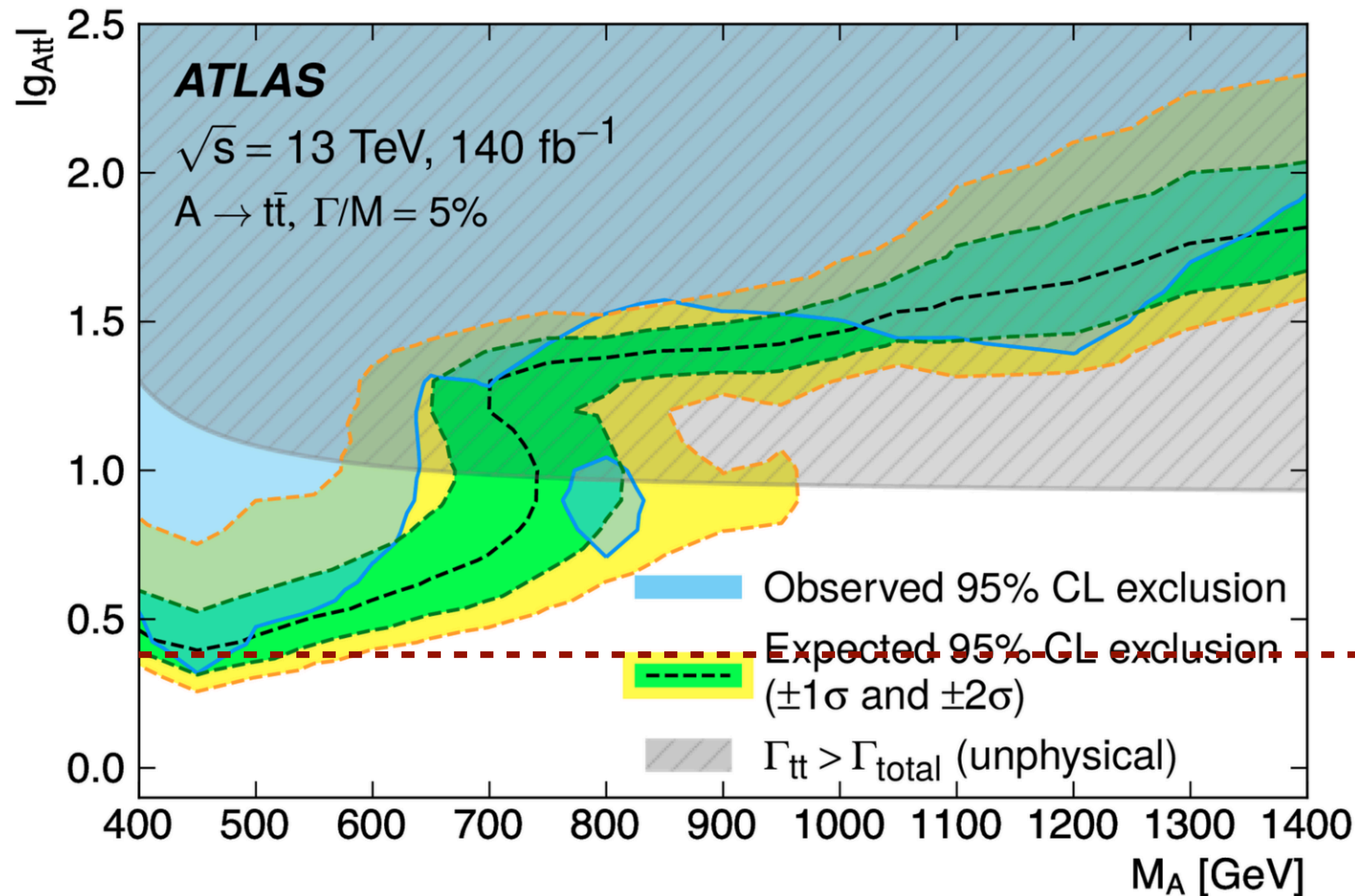
→ similar expected limits



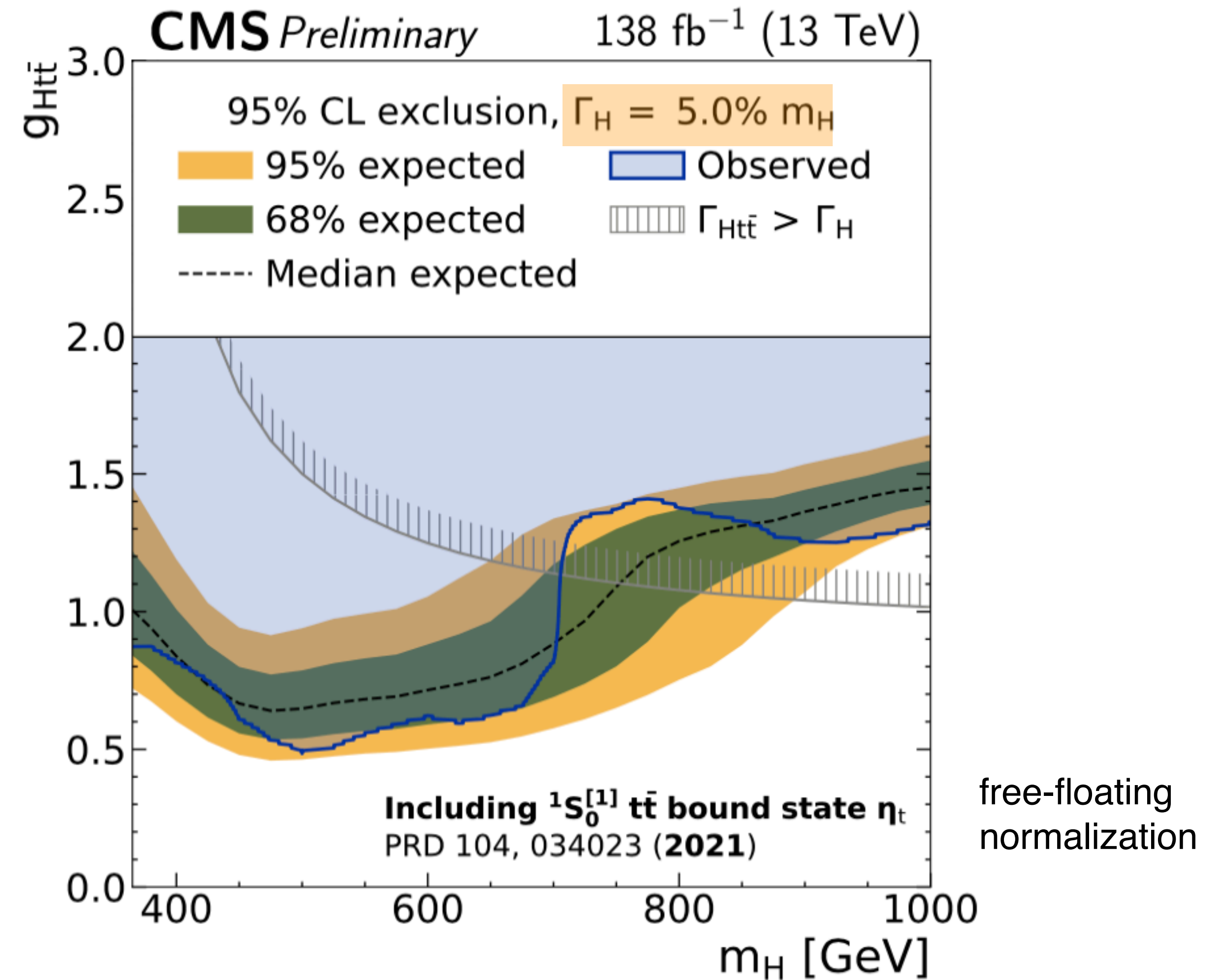
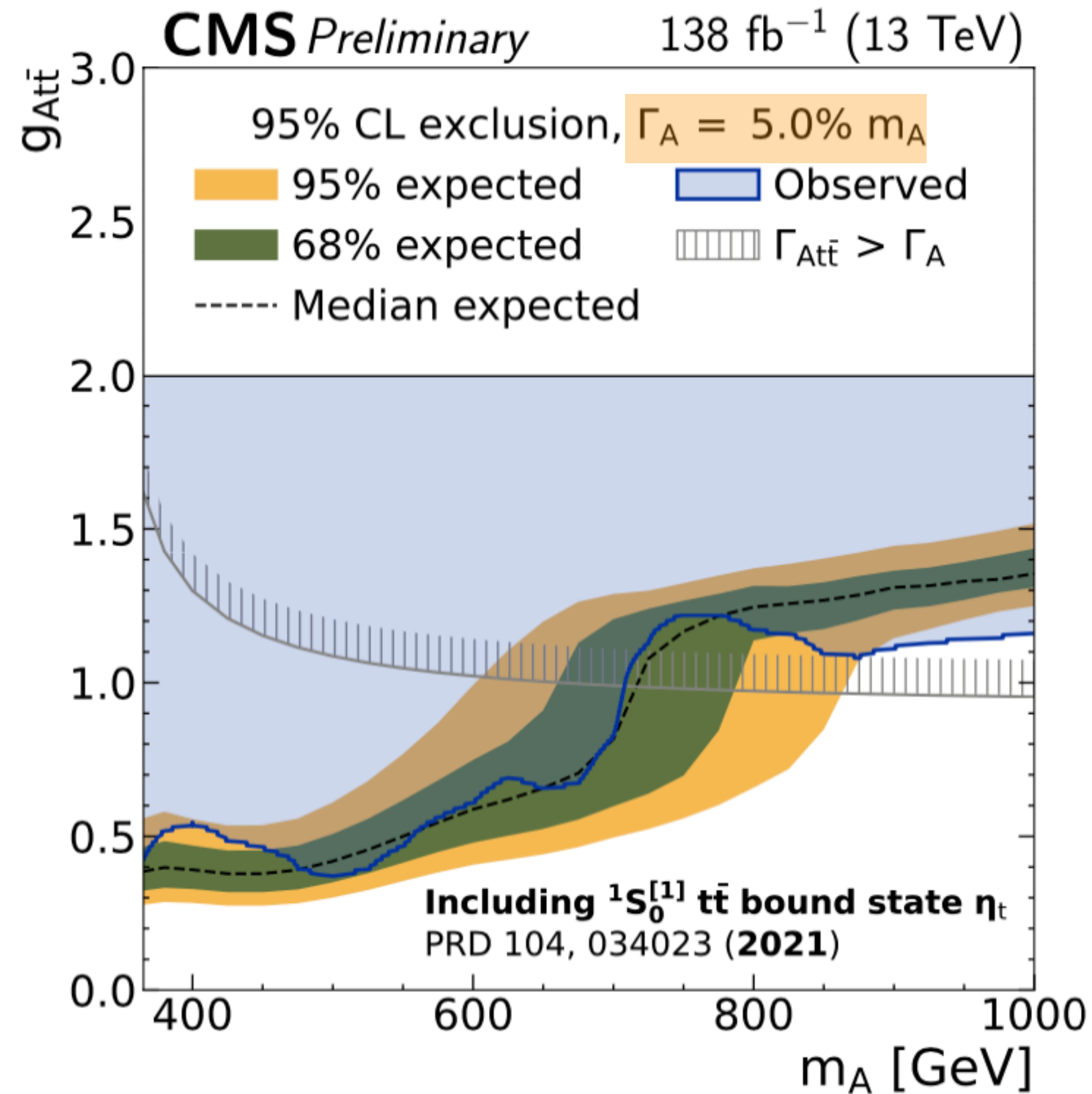
Comparison with ATLAS – limits, combined



- similar expected limits
- but no excess in ATLAS postfit
- we are comparing...



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



- since η_T looks similar as pseudoscalar A, no surprise that excess is no longer present
- most stringent limits to date!

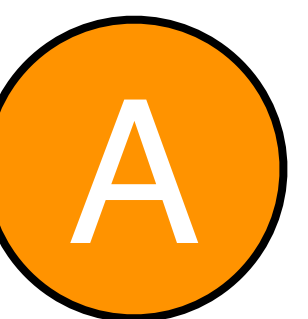
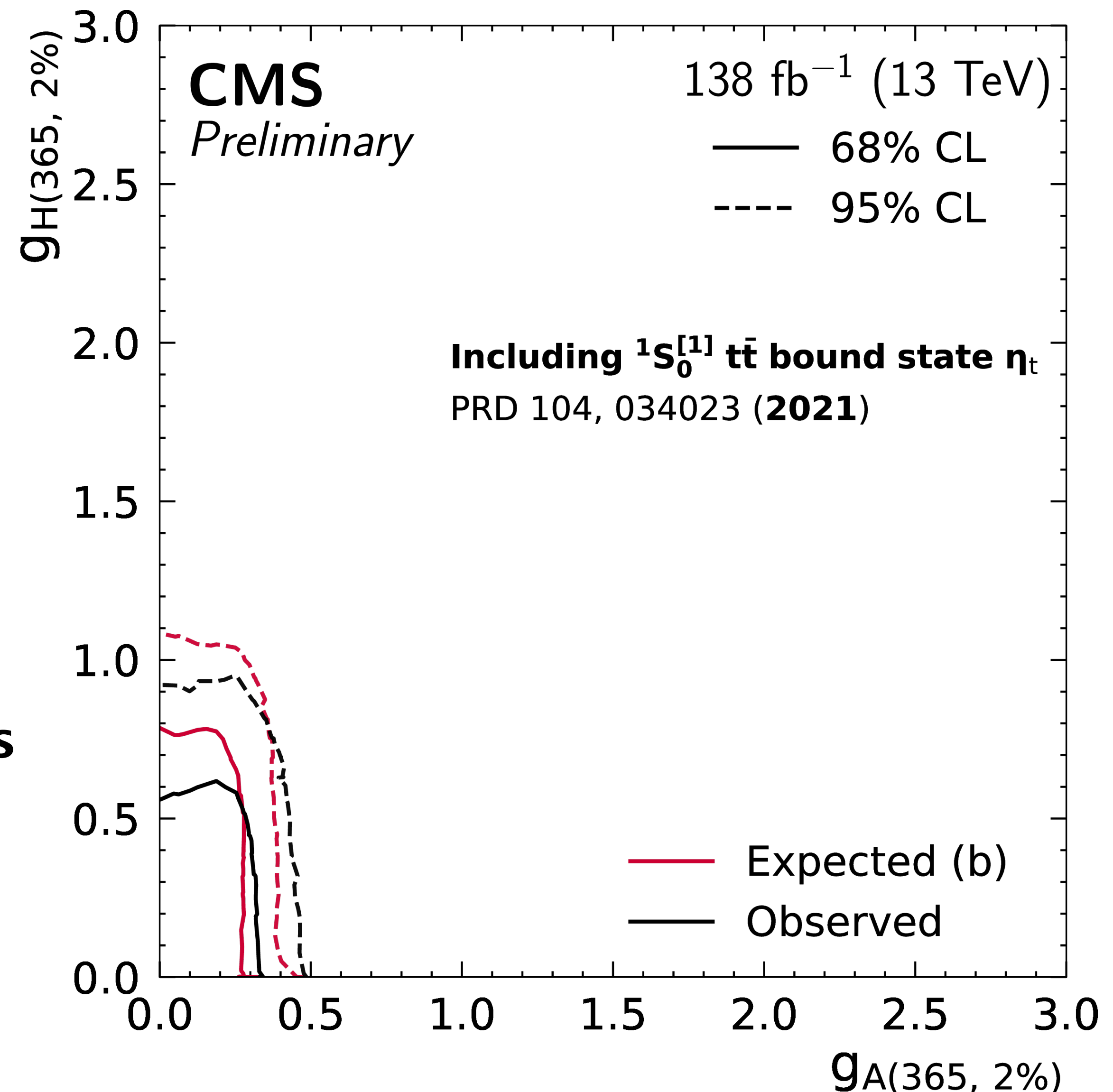
Search for A and H simultaneously



BSM models (e.g. 2HDM) often predict
simultaneous 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

List of MC generators

Process	QCD order	ME Generator
$t\bar{t}$	NLO	POWHEG v2 (hvg)
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

$$\frac{(R_{in/out}^{\geq 1b})_{data}}{(R_{in/out}^{\geq 1b})_{MC}} = \frac{(R_{in/out}^{0b})_{data}}{(R_{in/out}^{0b})_{MC}} \quad \longrightarrow \quad SF = \frac{(N_{out}^{\geq 1b})_{data}}{(N_{out}^{\geq 1b})_{MC}} = \frac{(N_{in}^{\geq 1b})_{data}}{(N_{in}^{\geq 1b})_{MC}} \frac{(R_{in/out}^{0b})_{MC}}{(R_{in/out}^{0b})_{data}}.$$

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

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

$$\sigma^{\text{rew.}} = \overset{\text{Powheg}}{\sigma_{\text{NLO QCD}}^{\text{LO EW}}} \times \overset{\text{Hathor}}{\frac{\sigma_{\text{LO QCD}}^{\text{NLO EW}}}{\sigma_{\text{LO QCD}}^{\text{LO EW}}}}$$

- Alternate choice: additive

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

- Difference treated as systematic uncertainty

Experimental Systematic uncertainties

A binned profile maximum likelihood fit [94–97], implemented in COMBINE [98], is performed to evaluate the compatibility of the observed data with the predictions and to obtain a best fit estimate of the cross section of the η_t and/or χ_t contributions. A three-dimensional (3D) template built from $m_{t\bar{t}}$, c_{hel} , and c_{han} is used as the fitted distribution. Various sources of uncertainty affect the 3D template and are implemented as nuisance parameters in the fit, capable of changing both the rate and the shape of the templates. Experimental uncertainties related to trigger, electron identification [33], muon identification [34], and b tagging (separately for b/c and u/d/s/g jets) [43] efficiencies, as well as to pileup reweighting, are evaluated by varying the corresponding corrections to the simulation by their uncertainties. Uncertainties in the jet p_T scale and resolution [38], as well as an additional uncertainty in the p_T^{miss} contribution from detector deposits not clustered into jets [39], are evaluated by varying the jet p_T and p_T^{miss} directly. Additional nuisance parameters are assigned for an inefficiency caused by the gradual shift in the timing of the ECAL trigger inputs [32], and for the uncertainty of 1.6% in the integrated luminosity measurement [99–101] that affects the normalization of all simulated processes. Besides experimental effects, several theoretical uncertainties related to the modeling of the signal and background processes are considered, as described below.

Theoretical Systematic uncertainties

First, we consider theoretical uncertainties in the FO pQCD prediction of $t\bar{t}$ production. The NLO EW correction depends on the value of the top quark Yukawa coupling y_t . The leading y_t dependence is quadratic, originating from the interference of diagrams containing a virtual Higgs boson with LO pQCD diagrams. A shape uncertainty of $+11/-12\%$ in y_t around the nominal value of the SM prediction is evaluated, conservatively using the uncertainty from the measurement reported in Ref. [102]. Following Ref. [65], the difference between the multiplicative and additive application schemes when combining the NLO EW corrections with the NNLO pQCD corrections of about 1–2% is taken as an additional uncertainty. We treat the multiplicative application scheme as the nominal EW correction and the additive application scheme as the $+1\sigma$ shift of this uncertainty. Relative to the nominal template, the -1σ shift has the same magnitude and opposite sign as the $+1\sigma$ shift. All other uncertainties encoding the difference between nominal and alternative modeling choices are implemented similarly. The uncertainty in m_t is considered by shifting its value in simulation by $\pm 1\text{ GeV}$ [103]. We have checked that the exact range of the m_t uncertainty does not influence the conclusions of this work. The values of μ_R and μ_F in the ME calculation are varied independently up and down by a factor of 2. The effects of the m_t , μ_R , and μ_F variations on the shape of the 3D template are considered at NLO accuracy, whereas the effects on the overall normalization are taken from the NNLO+NNLL calculation [58, 104]. The scales used to evaluate the strong coupling constant α_s in the PS simulation of ISR and FSR are varied independently by a factor of 2 in each direction. Uncertainties in the underlying event tune are estimated by varying the CP5 parameters [49]. Two uncertainties are considered for the color reconnection model, with one based on the “QCD-inspired” model [105], and the other by switching on the early resonance decay option in PYTHIA [106]. The uncertainty in the ME-PS matching scale is evaluated by varying the POWHEG parameter h_{damp} , which controls the radiation of additional high- p_T jets.

Theoretical Systematic uncertainties

The nominal value of h_{damp} and the considered variations are $1.58^{+0.66}_{-0.59} m_t$ [107]. The uncertainty from the PDF choice is evaluated by reweighting the simulated $t\bar{t}$ events using 100 replicas of the NNPDF3.1 PDF set, and taking the base variation with the largest eigenvalue as obtained from a principal component analysis in the space of the final 3D templates. The uncertainty in the value of α_s in the PDF set is used as a second independent PDF uncertainty.

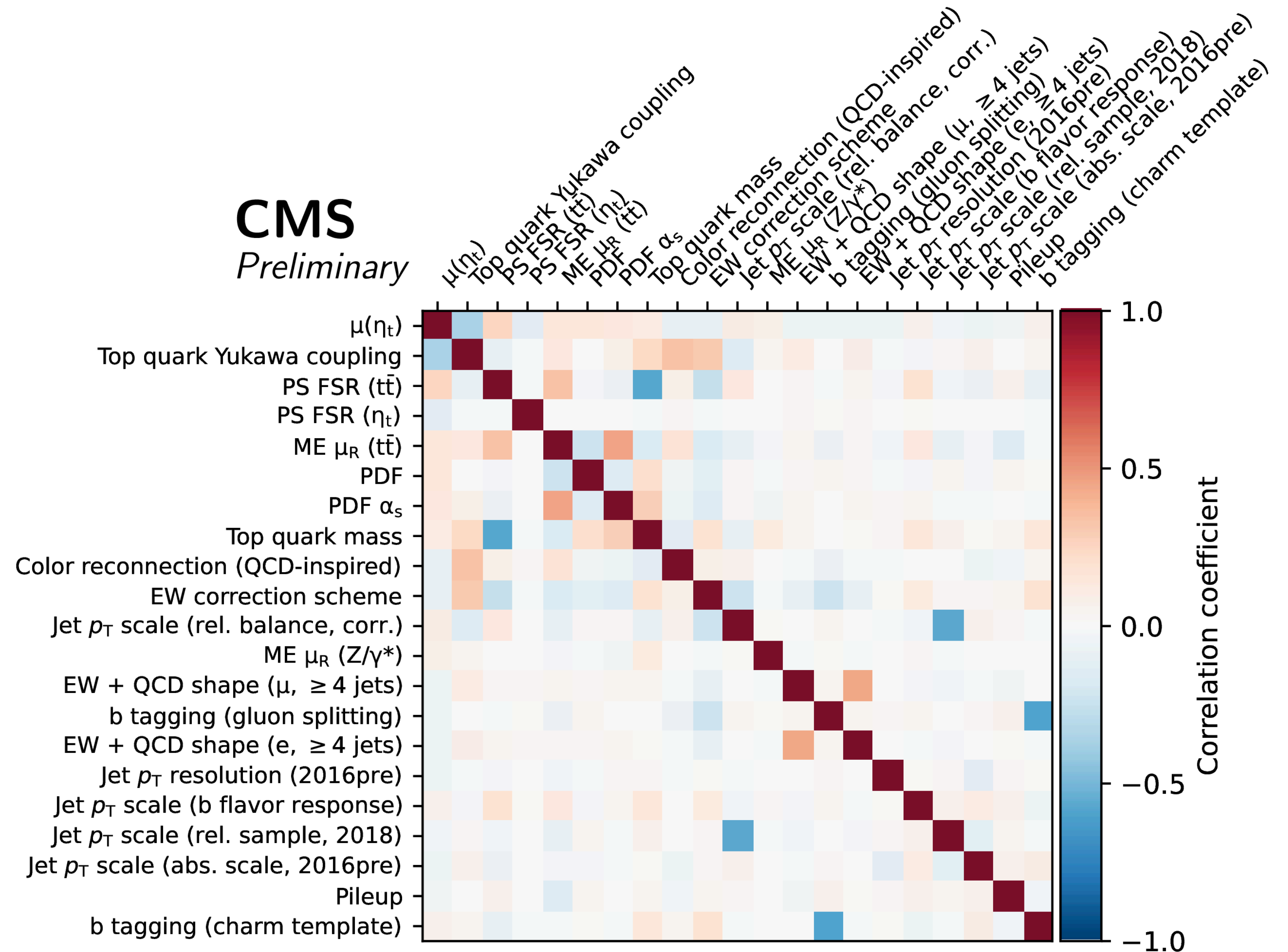
The choice of ME event generator for the $t\bar{t}$ FO pQCD prediction is validated through a comparison of the nominal $t\bar{t}+tW$ FO pQCD prediction with the alternative prediction obtained with `bb4l`, which includes off-shell contributions to the $b\bar{b}\ell^+\ell^-\nu\bar{\nu}$ final state. The difference between the two predictions is assigned as an additional uncertainty. Similarly, the comparison of the nominal $t\bar{t}$ FO pQCD prediction with the alternative generator setup using HERWIG is used to assign an additional uncertainty for the choice of the parton shower program.

The uncertainties due to μ_F , ISR, and FSR scales in the η_t and χ_t simulations are evaluated by independently varying them up and down by a factor of 2. Since the employed model uses effective η_t and χ_t production via a contact interaction with no dependence on α_s , variations of μ_R have no effect. The uncertainty in m_t is considered by varying its value in simulation by ± 1 GeV, and is treated as fully correlated with the m_t variation in the FO pQCD $t\bar{t}$ prediction. Other theoretical uncertainties in the η_t and χ_t simulations, such as the PDF variations, are found to be small compared to the already considered effects and are thus neglected.

The μ_R , μ_F , ISR, and FSR scale uncertainties are also independently considered for the Z/γ^* and tX processes. Normalization uncertainties for the non- $t\bar{t}$ background processes are assigned based on the precision of relevant cross section measurements [108–113], resulting in large uncertainties than those of the corresponding theoretical computations.

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, $e\mu$, $\mu\mu$
Electron identification (2)	shape	all	ej, ee, $e\mu$
Muon identification (10)	shape	all	μj , $e\mu$, $\mu\mu$
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.	$t\bar{t}V$	$\ell\bar{\ell}$
Z/γ^* normalization	norm.	Z/γ^*	$\ell\bar{\ell}$
Diboson normalization	norm.	Diboson	$\ell\bar{\ell}$
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 $p_T > 15 \text{ GeV}$ 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 $\pm 3 \text{ GeV}$, 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 $1.58^{+0.66}_{-0.59} m_t$ [96]. The uncertainty arising from the choice of the PDF set is evaluated by reweighting the simulated $t\bar{t}$ 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.

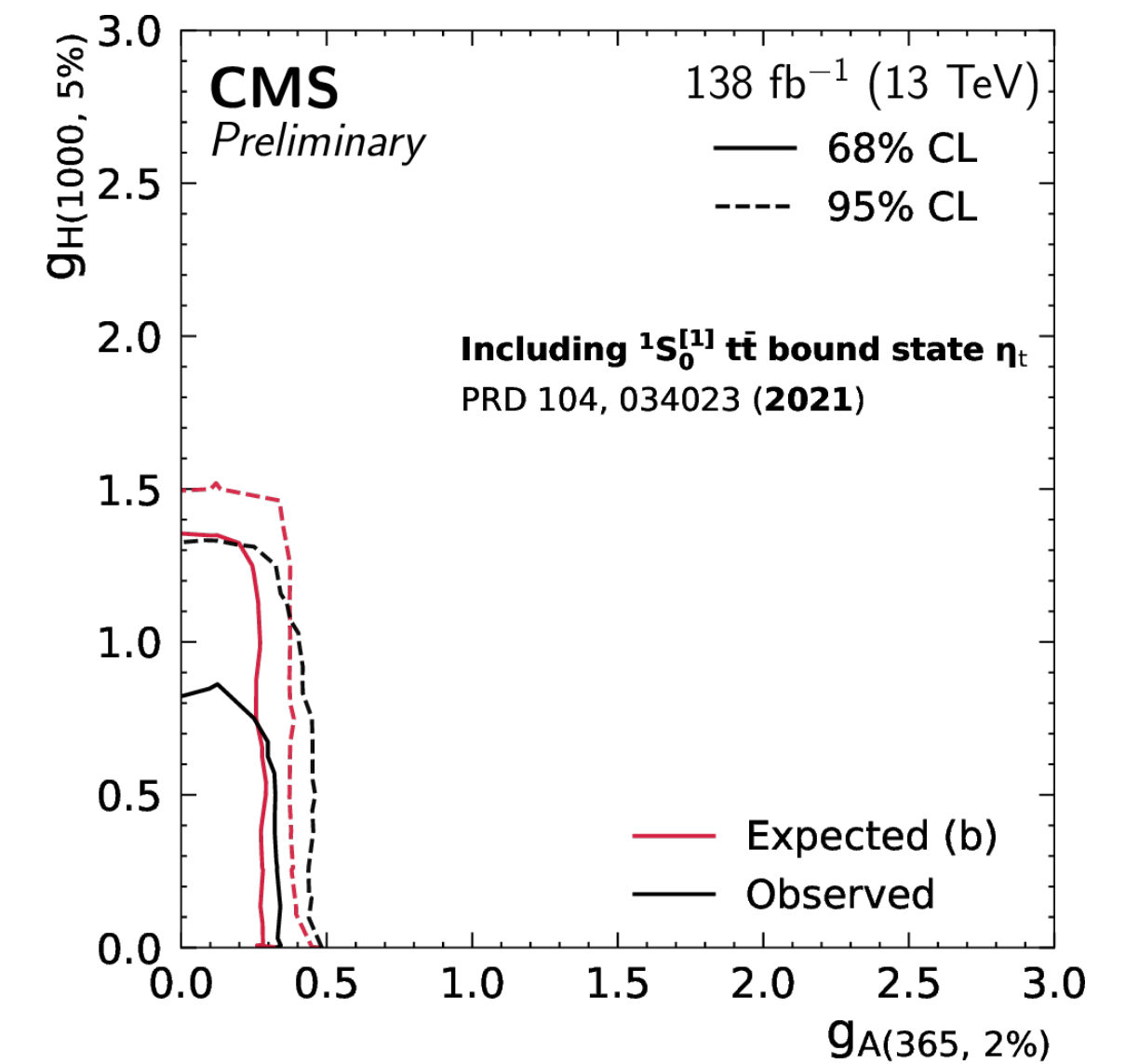
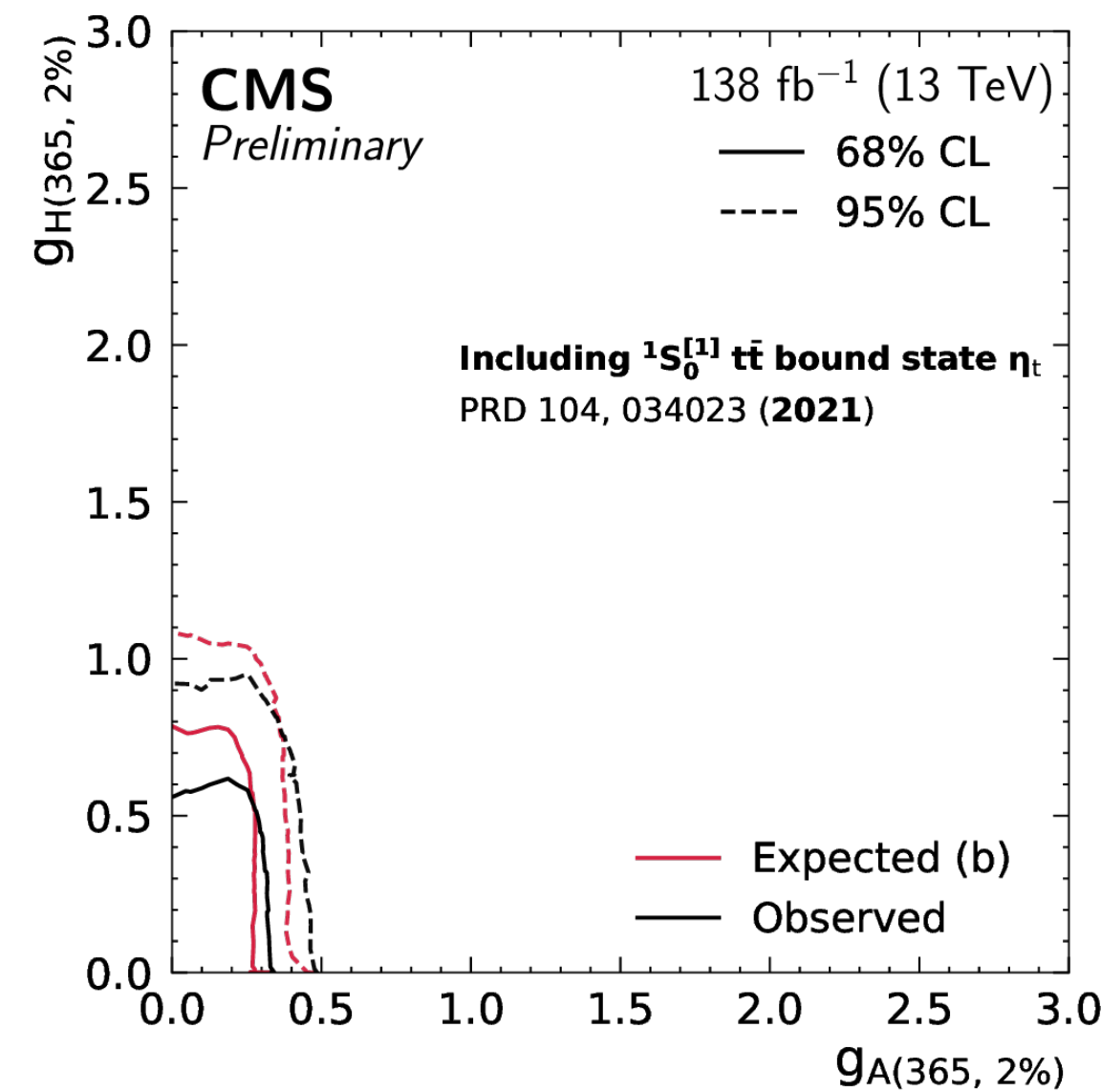
The expected yields for most of the non- $t\bar{t}$ background processes are derived using theoretical predictions for the cross sections at NLO or higher accuracy. The uncertainties assumed in the normalization of these processes are conservative and always exceed those of the corresponding theoretical 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 $t\bar{t}$ and single top quark subtraction are considered separately for each channel and era. In the $\ell\bar{\ell}$ channels, the uncertainty in the $t\bar{t}V$ 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 $t\bar{t}$ 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 $t\bar{t}$ background become dominant.

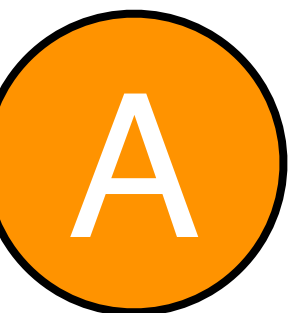
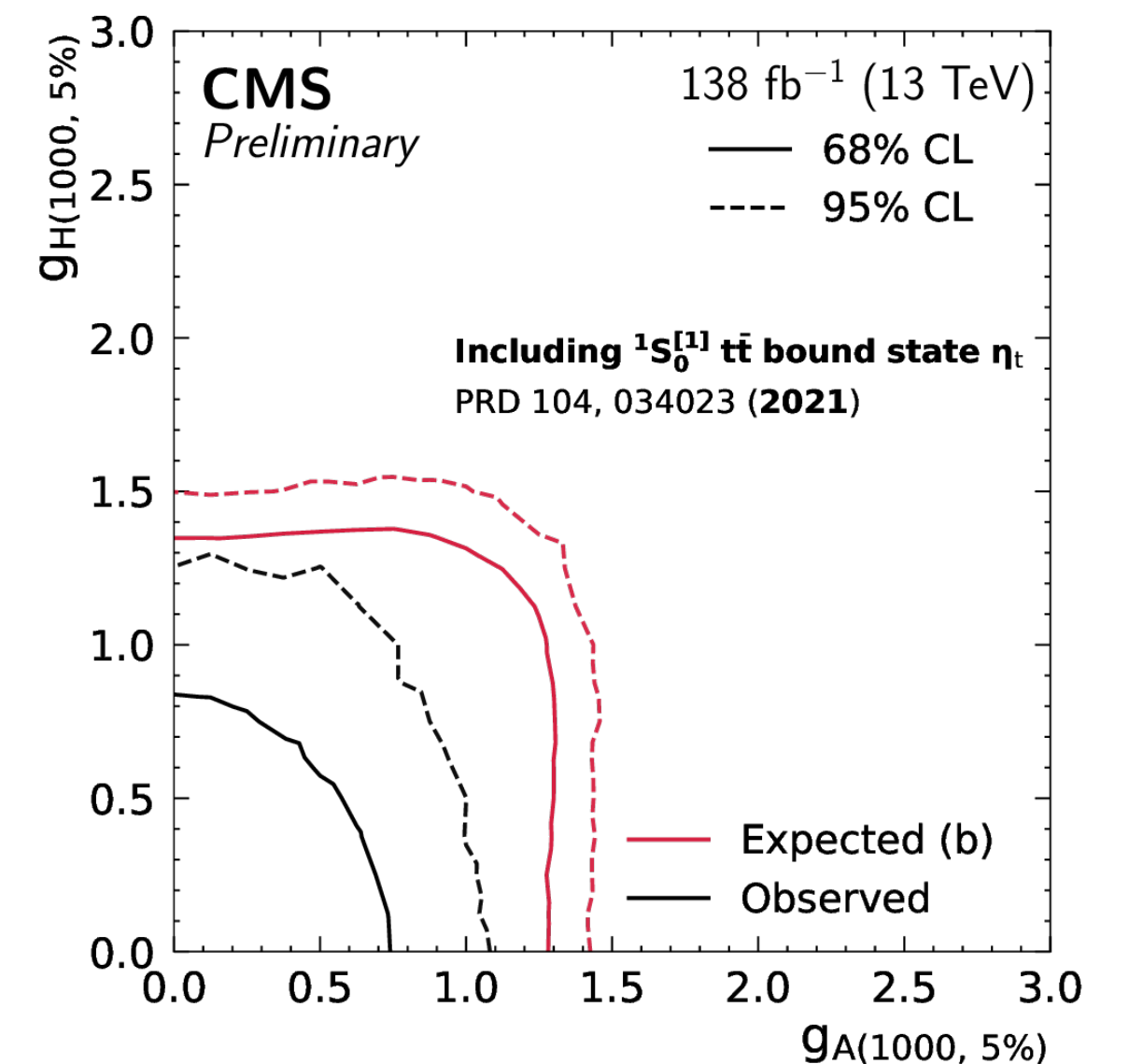
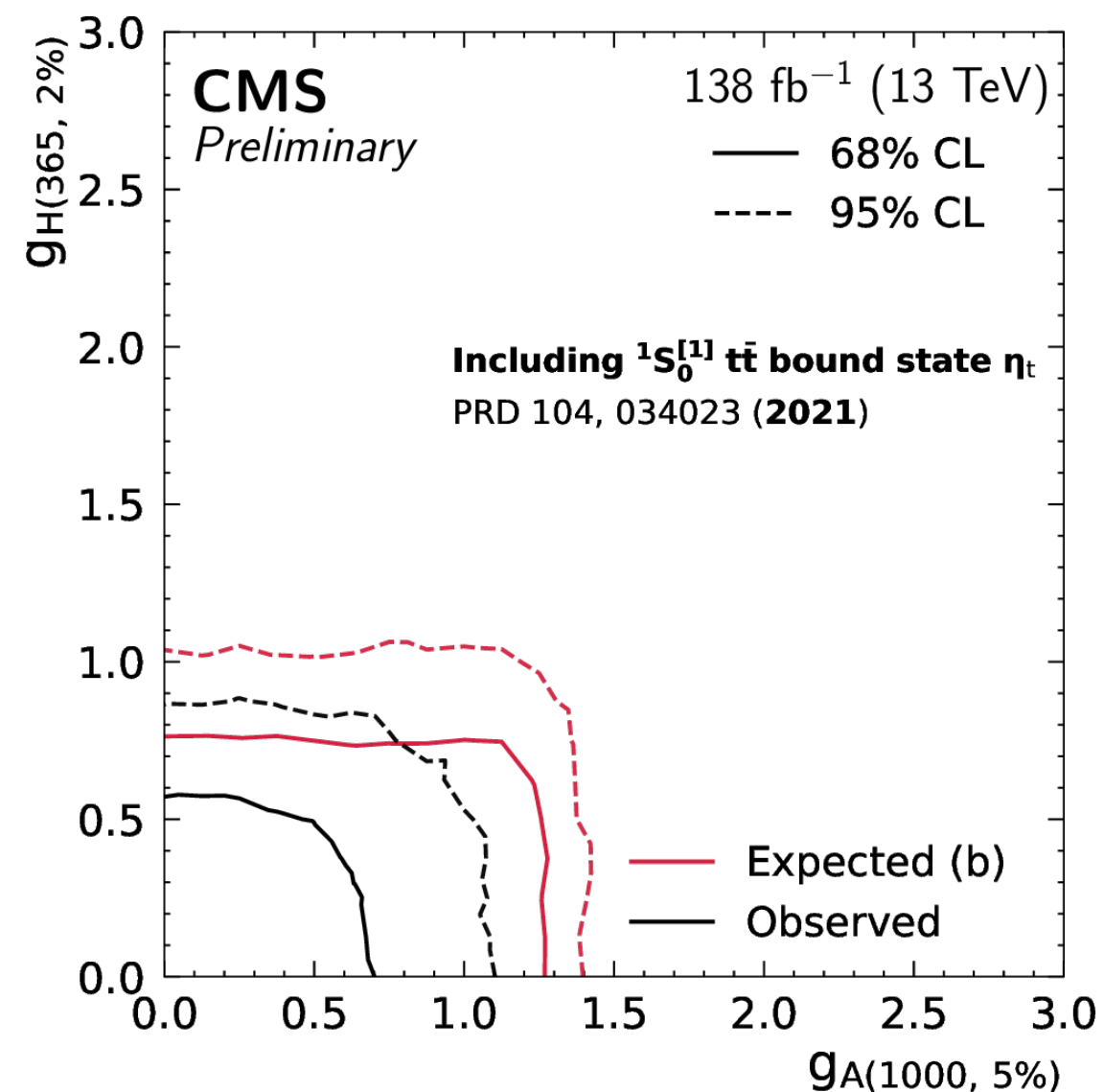
Search for A and H simultaneously: more scenarios



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

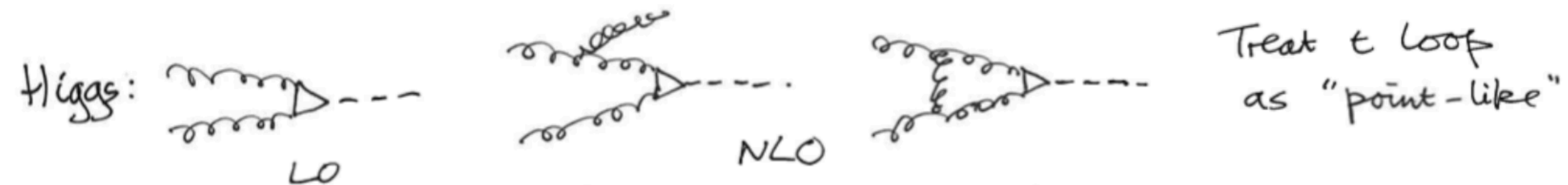
- model-independent exclusion contours for A vs H couplings to top quarks with numerical Feldman-Cousings method

→ **stringent limits**

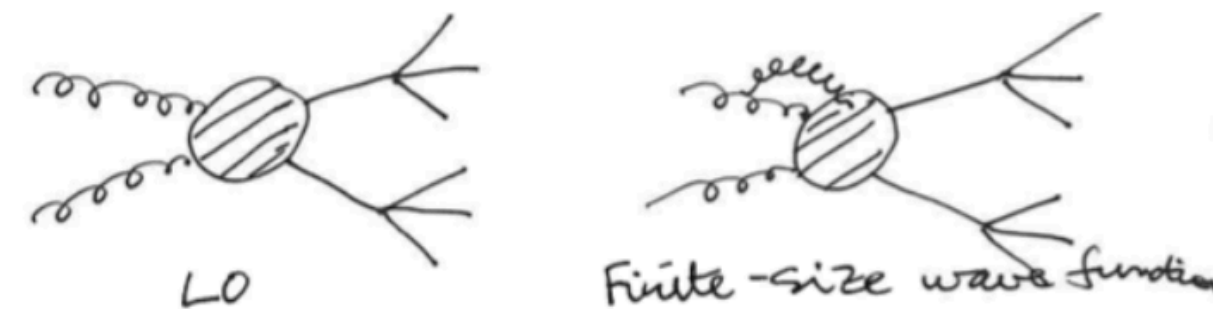


Toponium production at the LHC

More complicated than Higgs production:



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

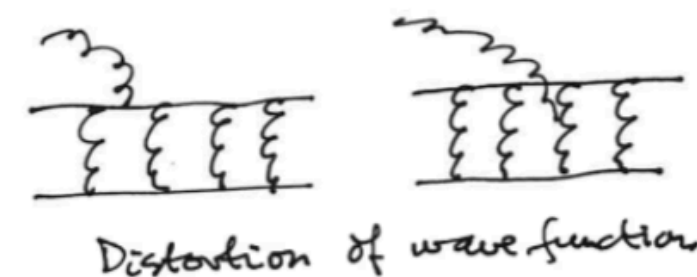


Sommerfeld enhancement of cross section close to $t\bar{t}$ threshold

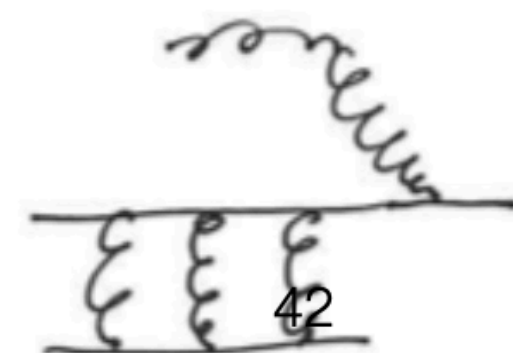
$$\text{blob} = \sum \overline{\psi\psi} \dots \psi\psi$$

Sommerfeld enhancement

Distorted by gluon interactions

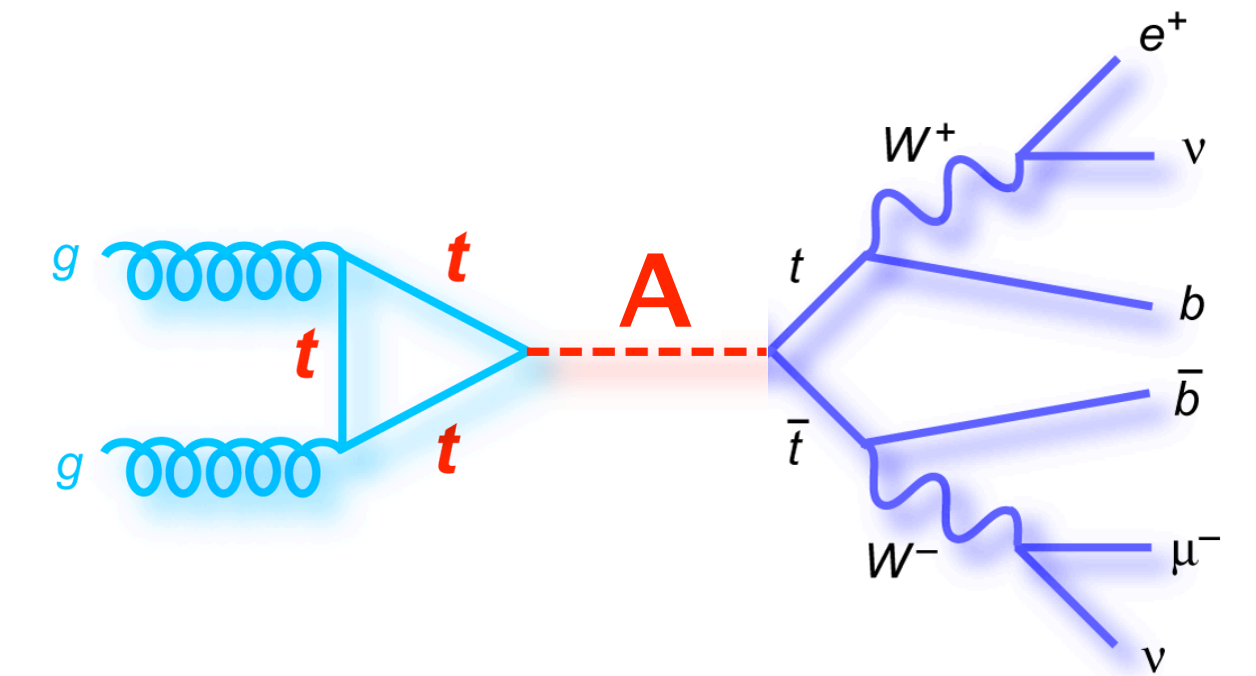
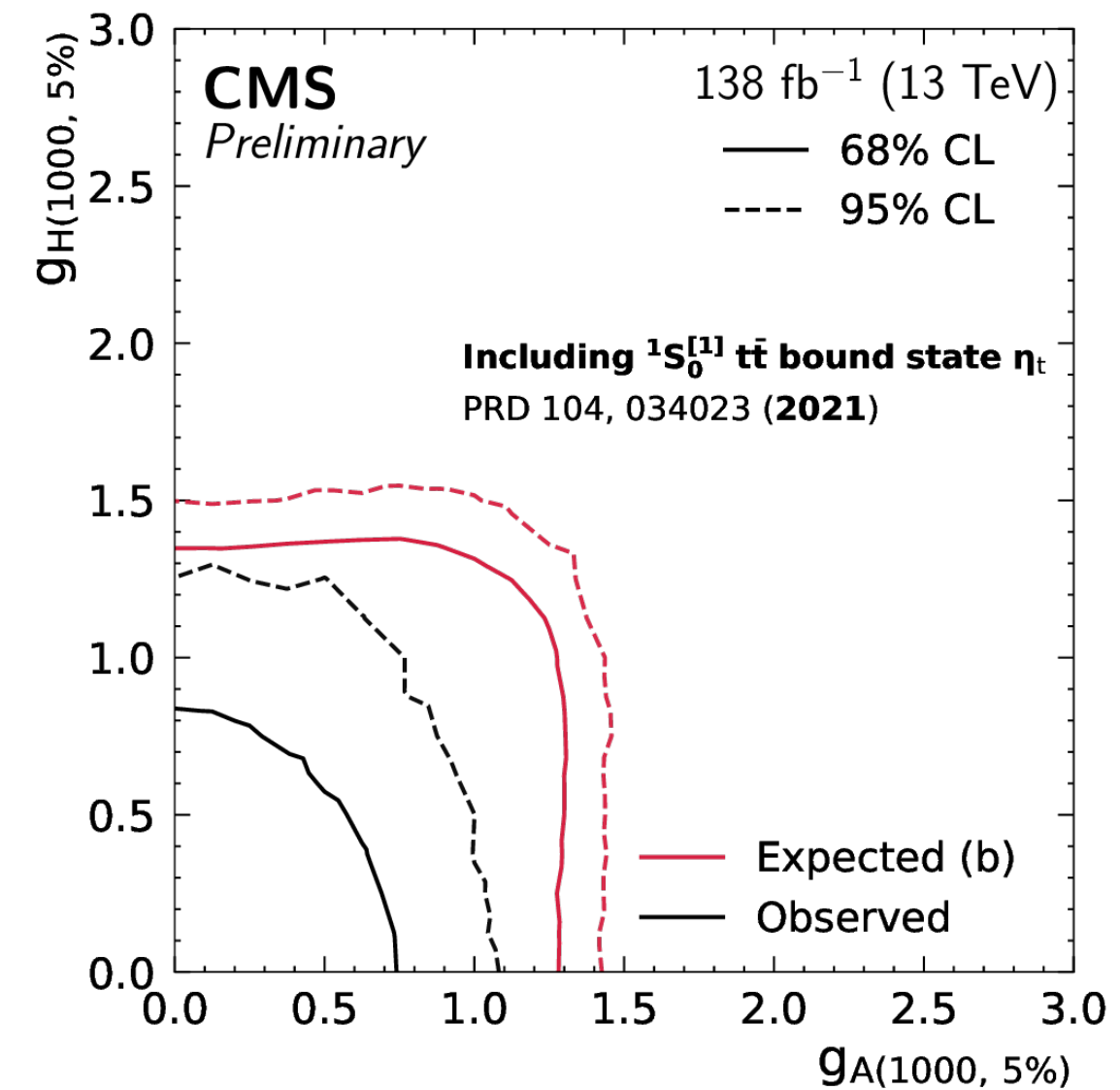
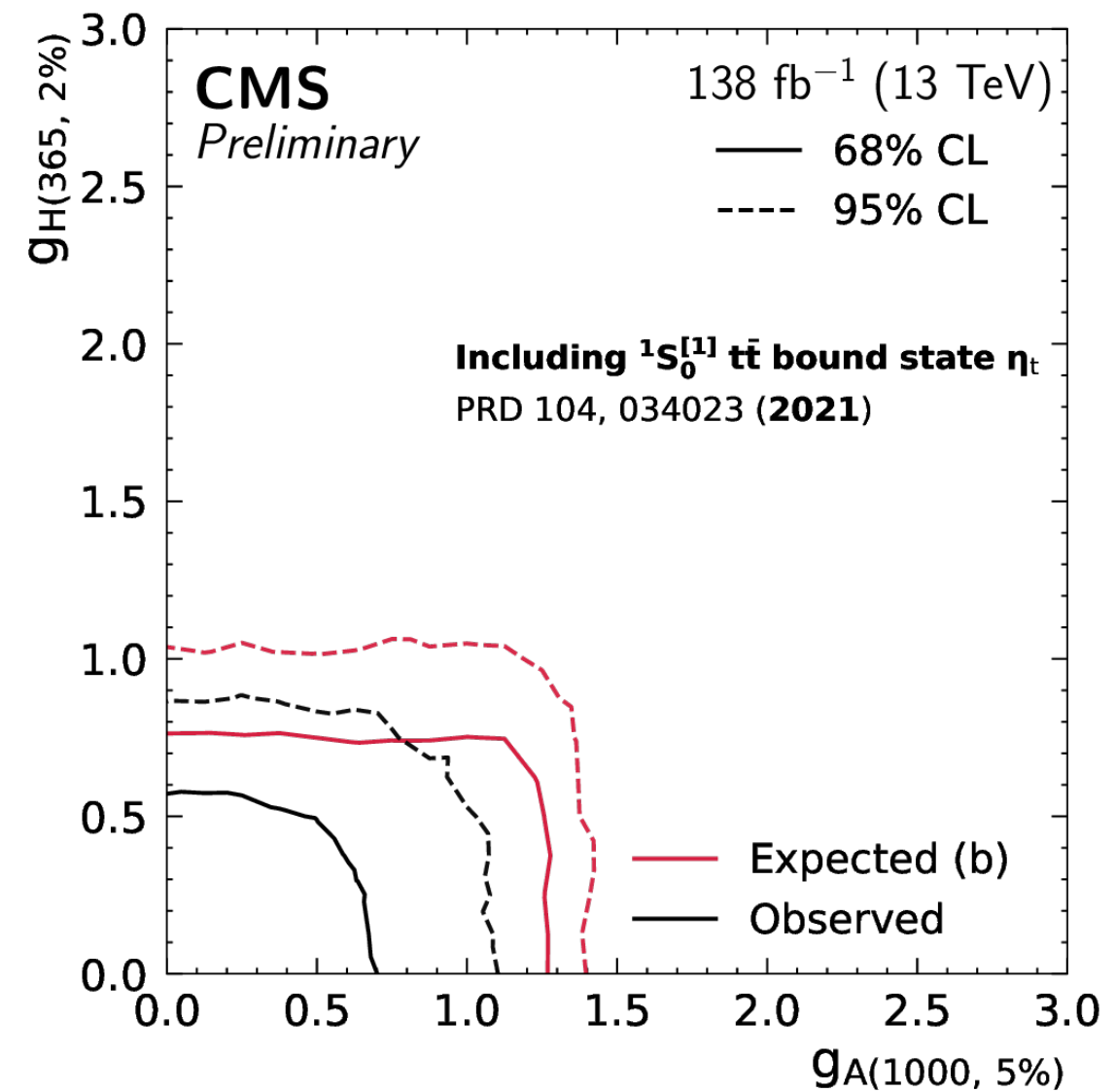
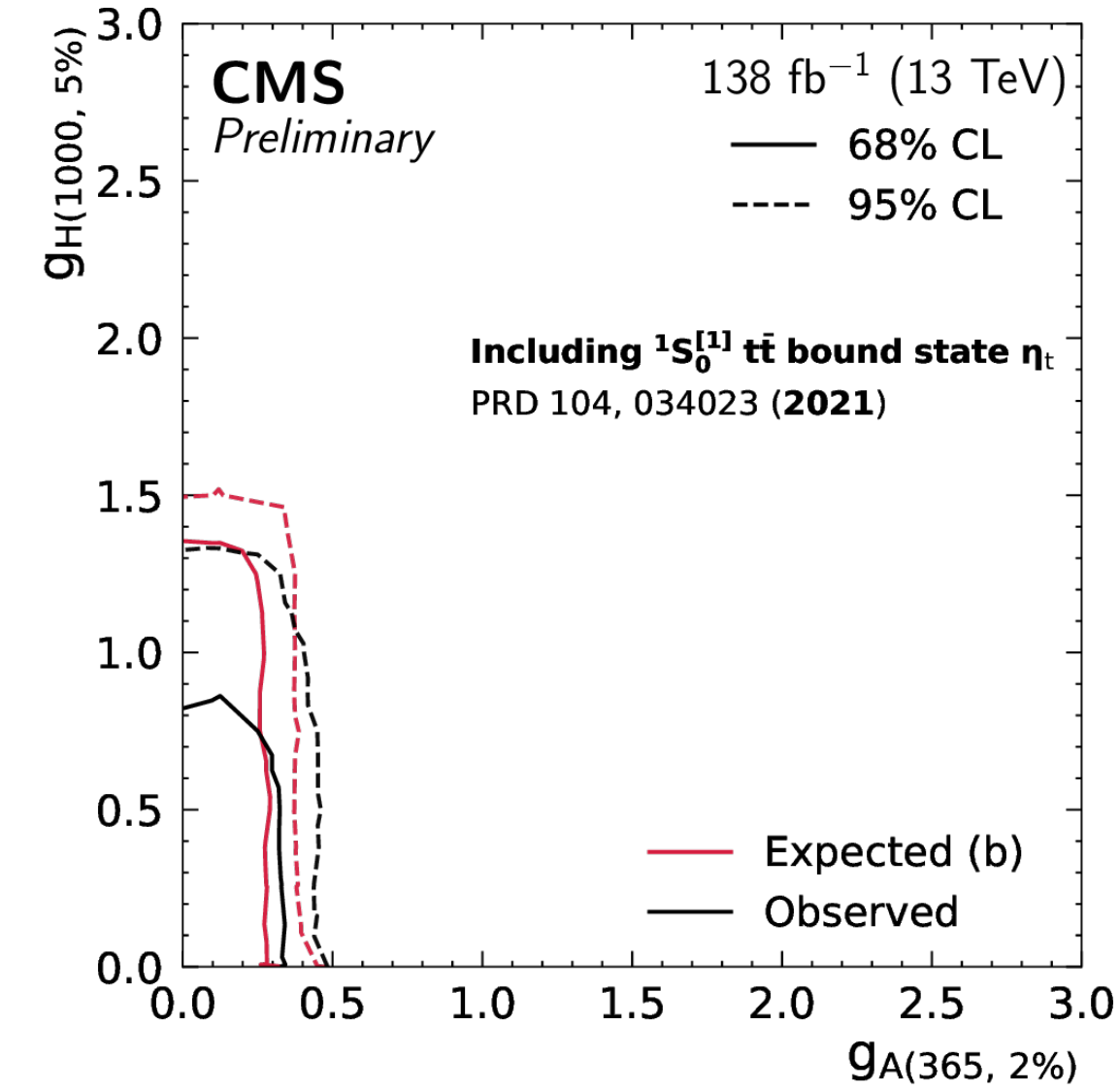
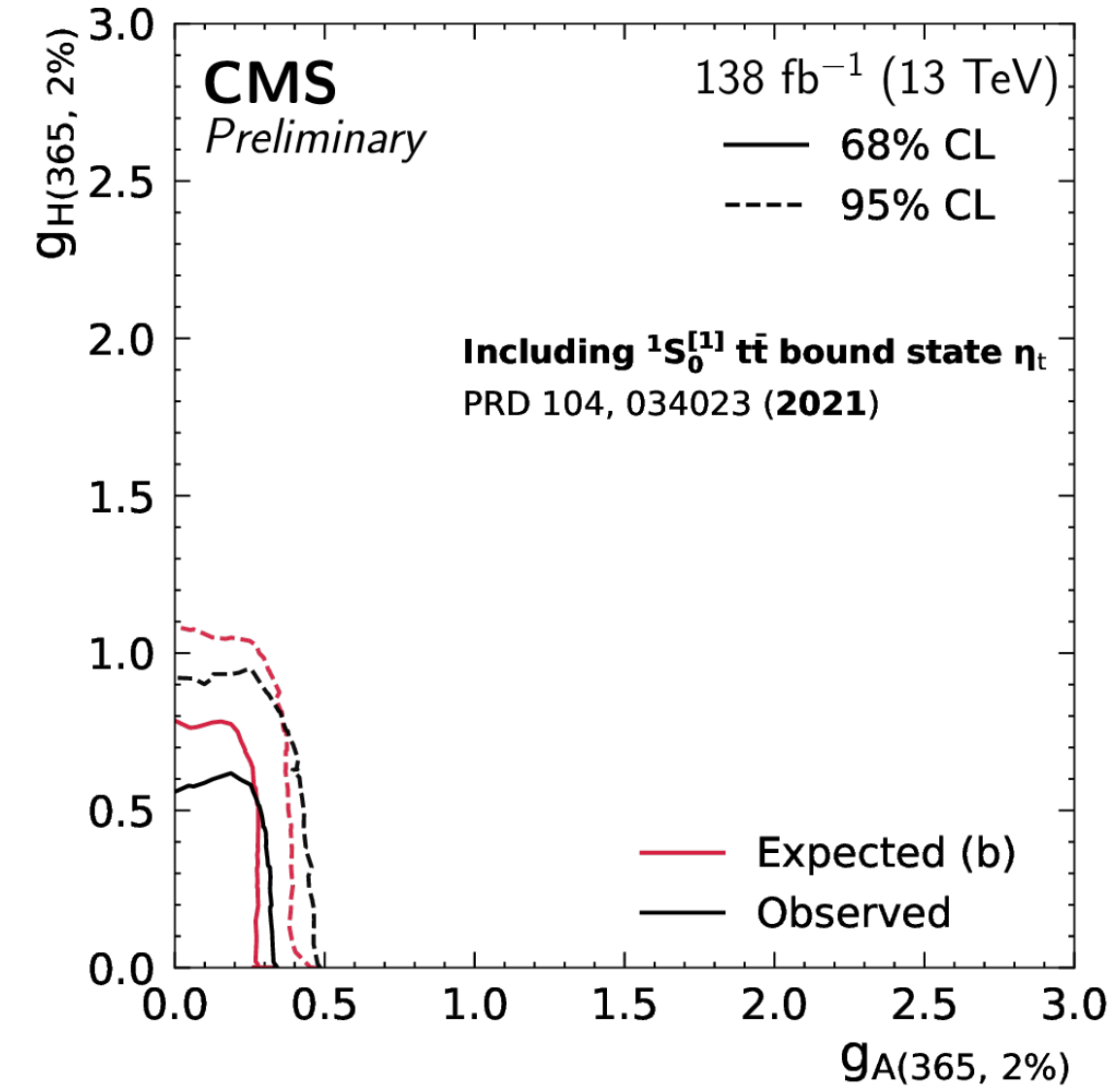
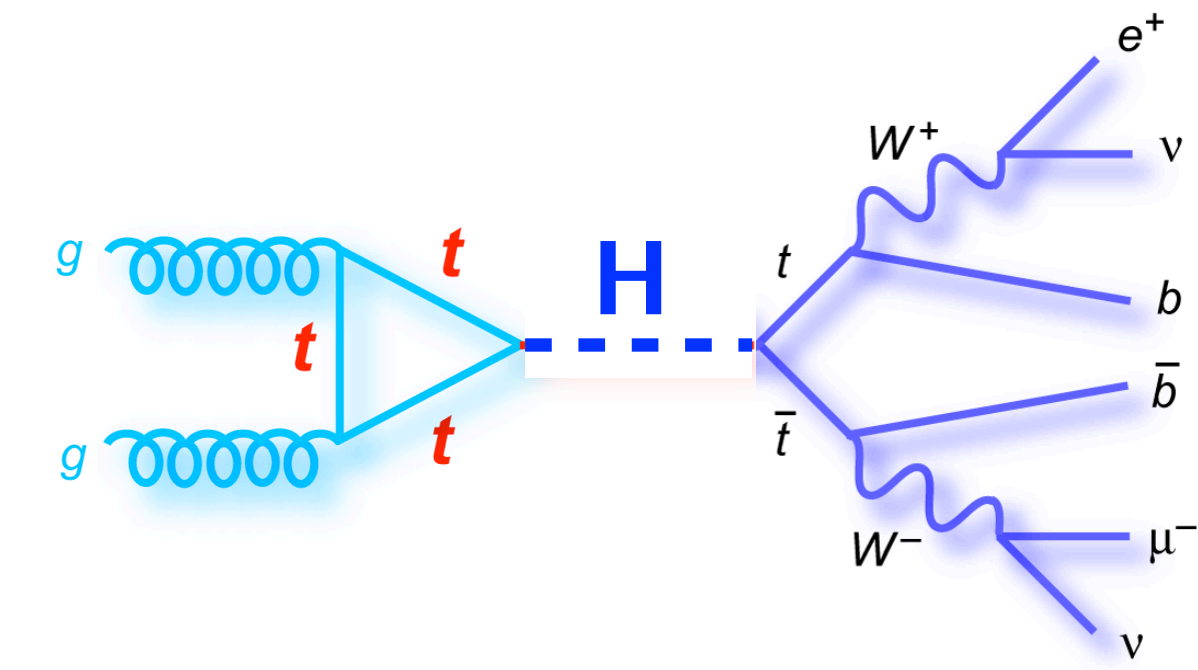


$t\bar{t}$ off-shell, unstable, gluon interactions



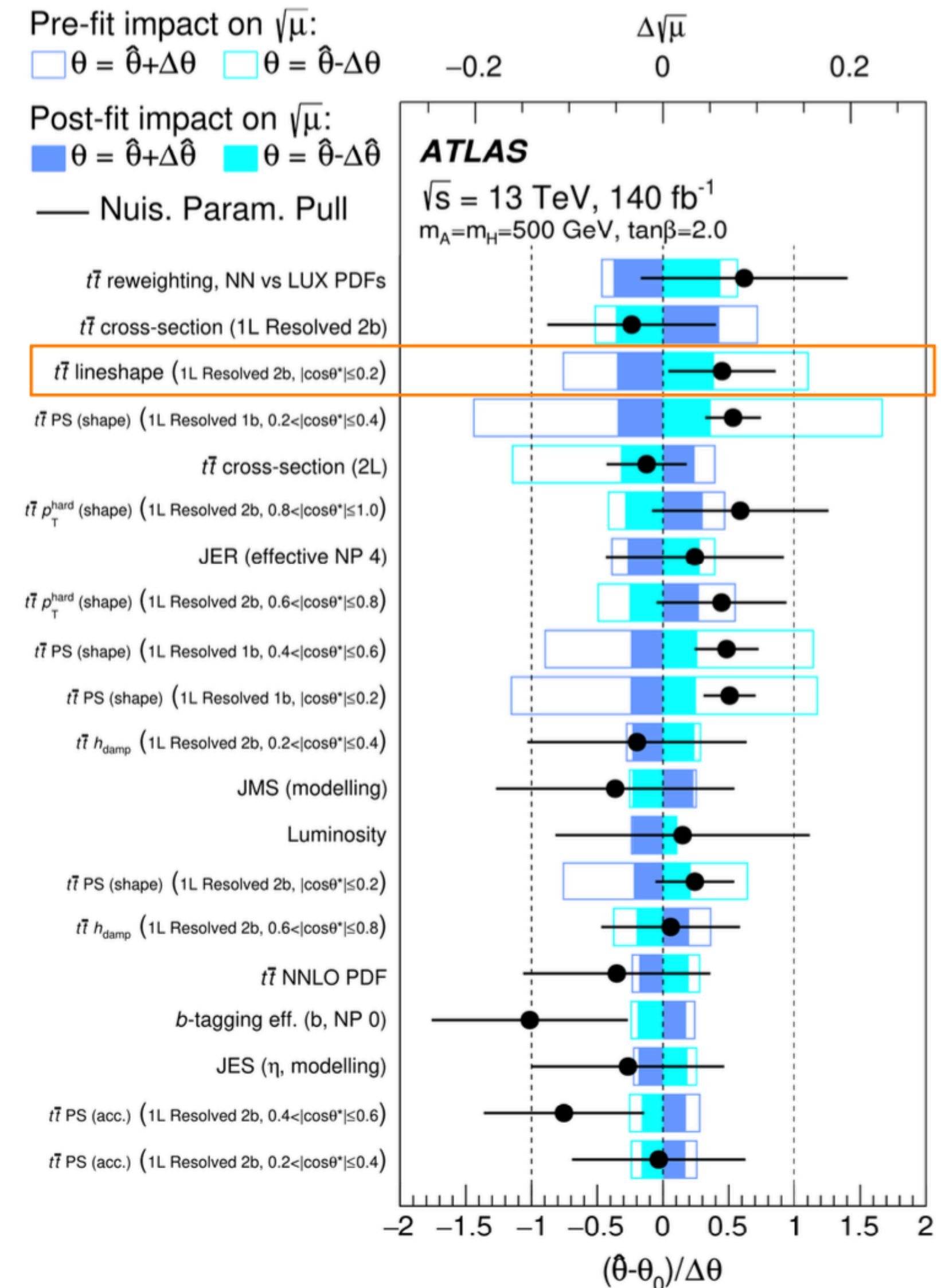
John Ellis

Results of A+H interpretation – Combination

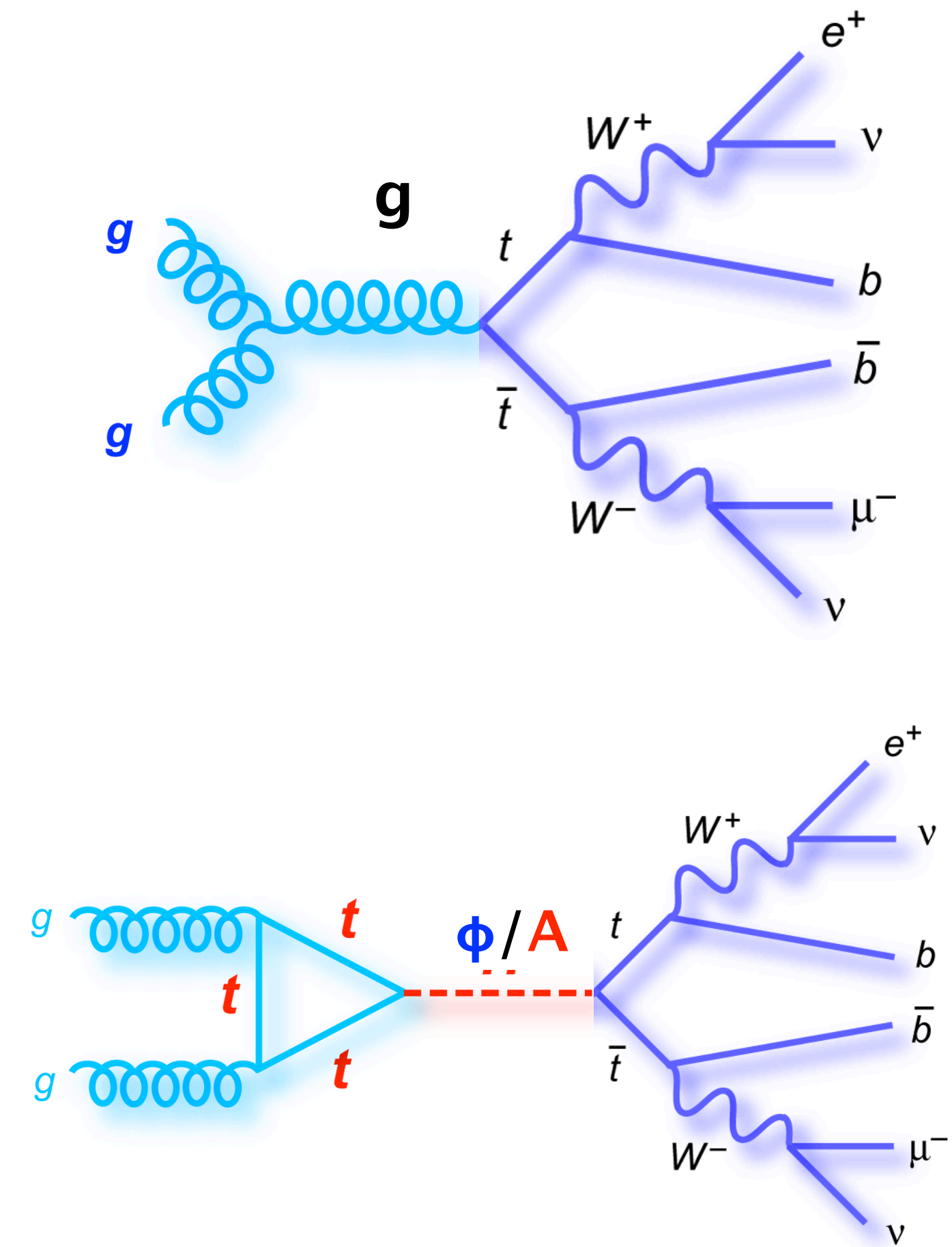
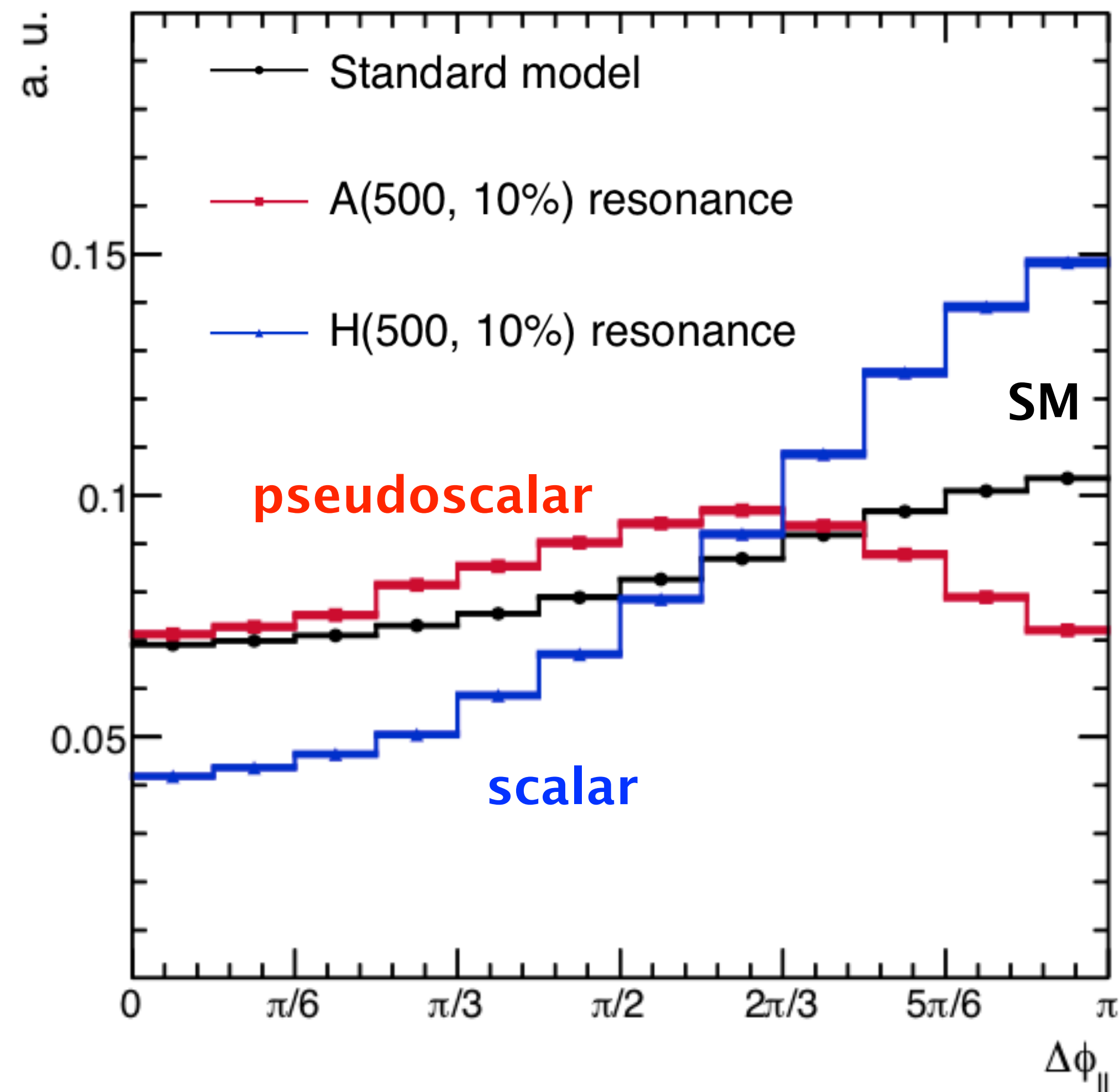
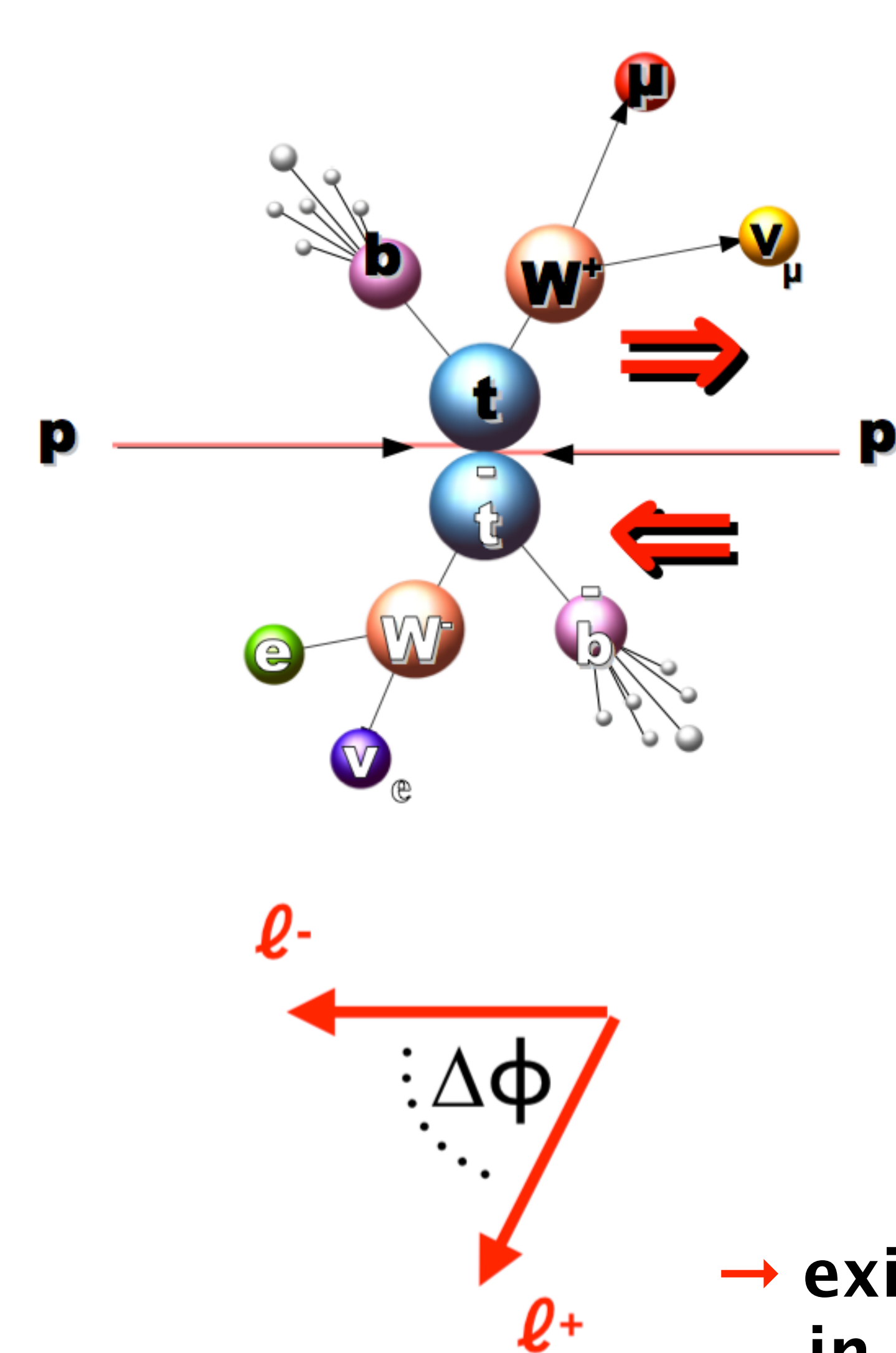


ATLAS uncertainties

- 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 $\cos\theta^* / \Delta\phi_{\ell\ell}$
 - CMS: modeling uncertainties fully correlated
- Impact plot: e.g. lineshape has high impact and is pulled

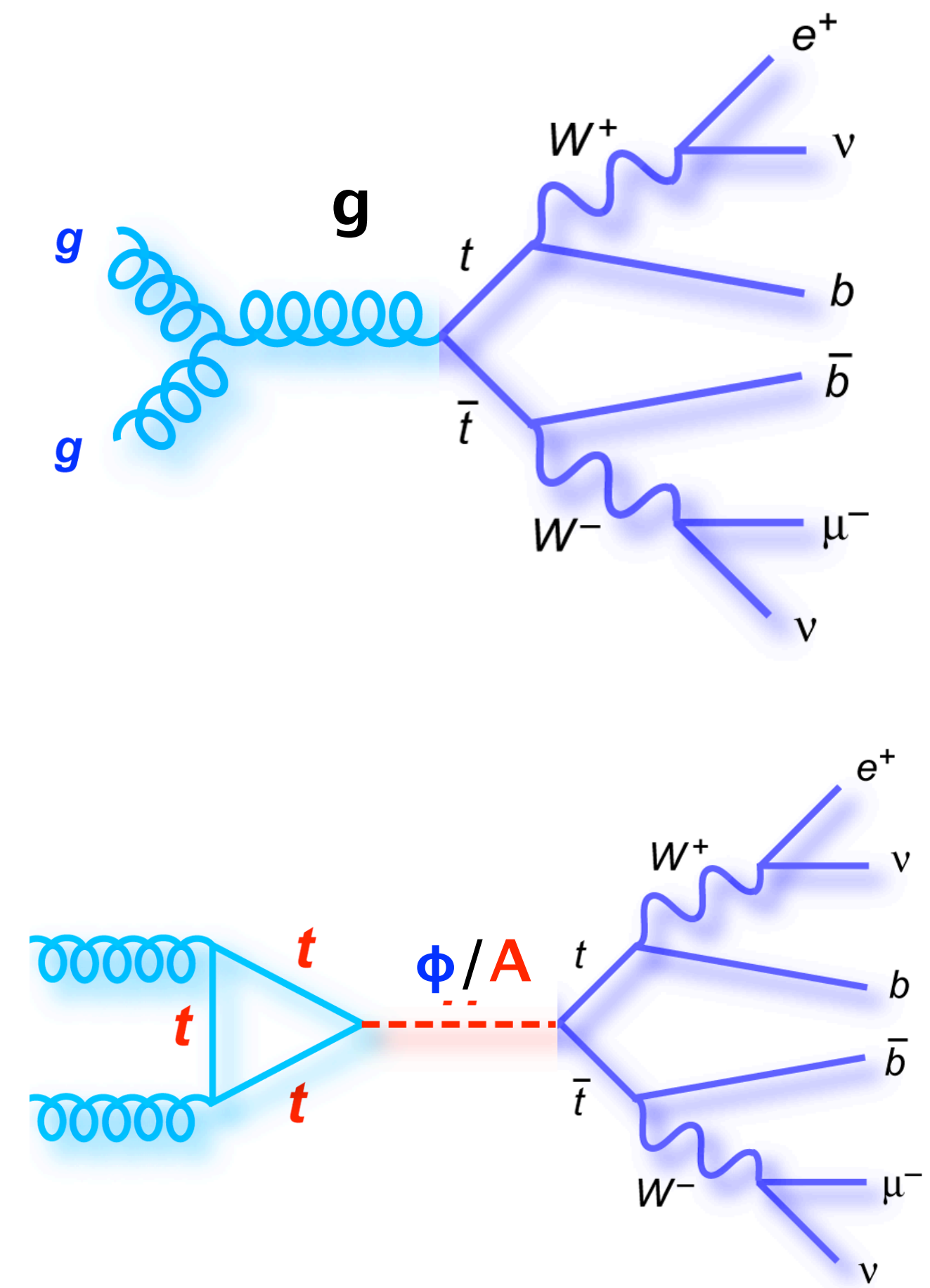
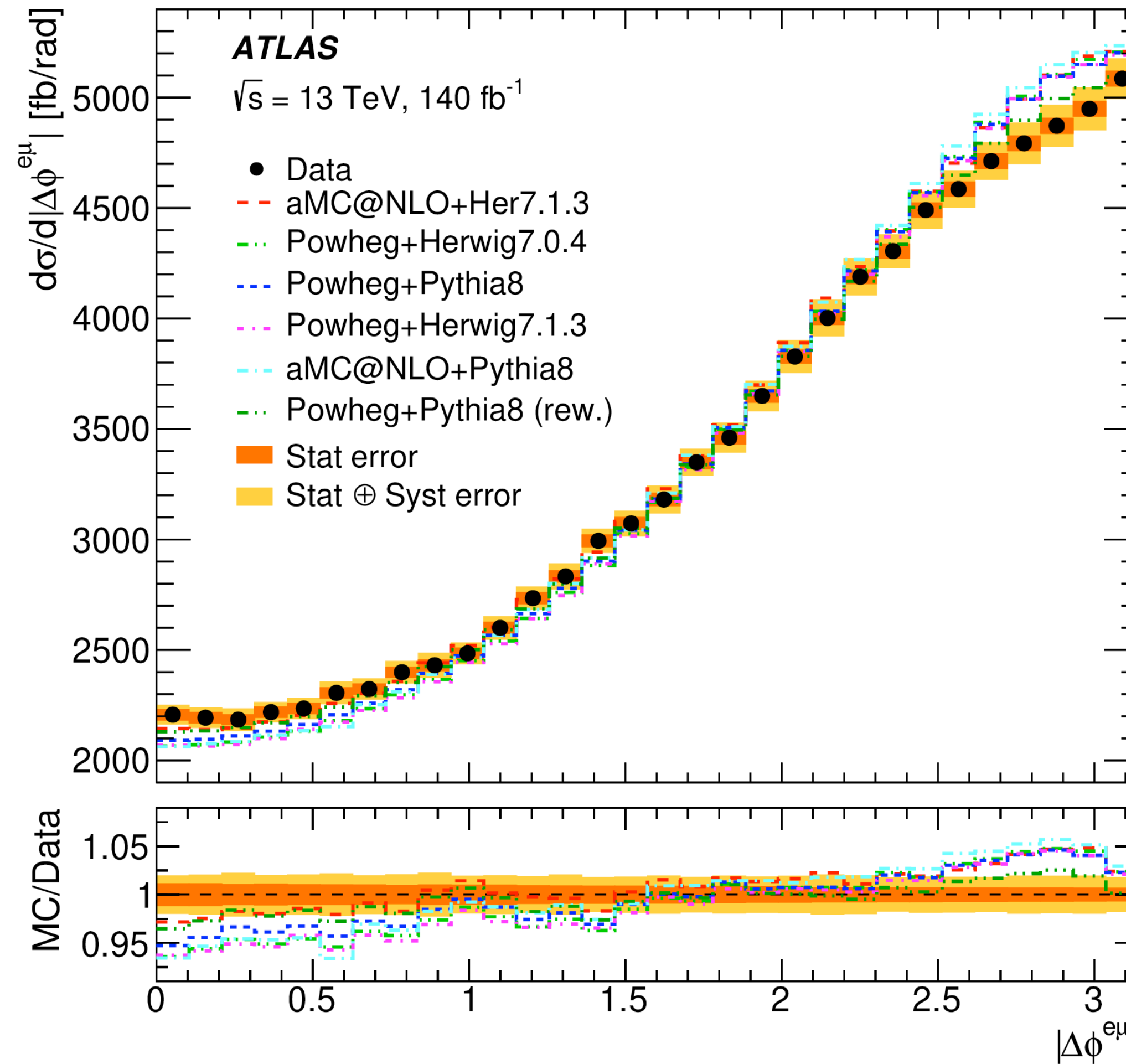
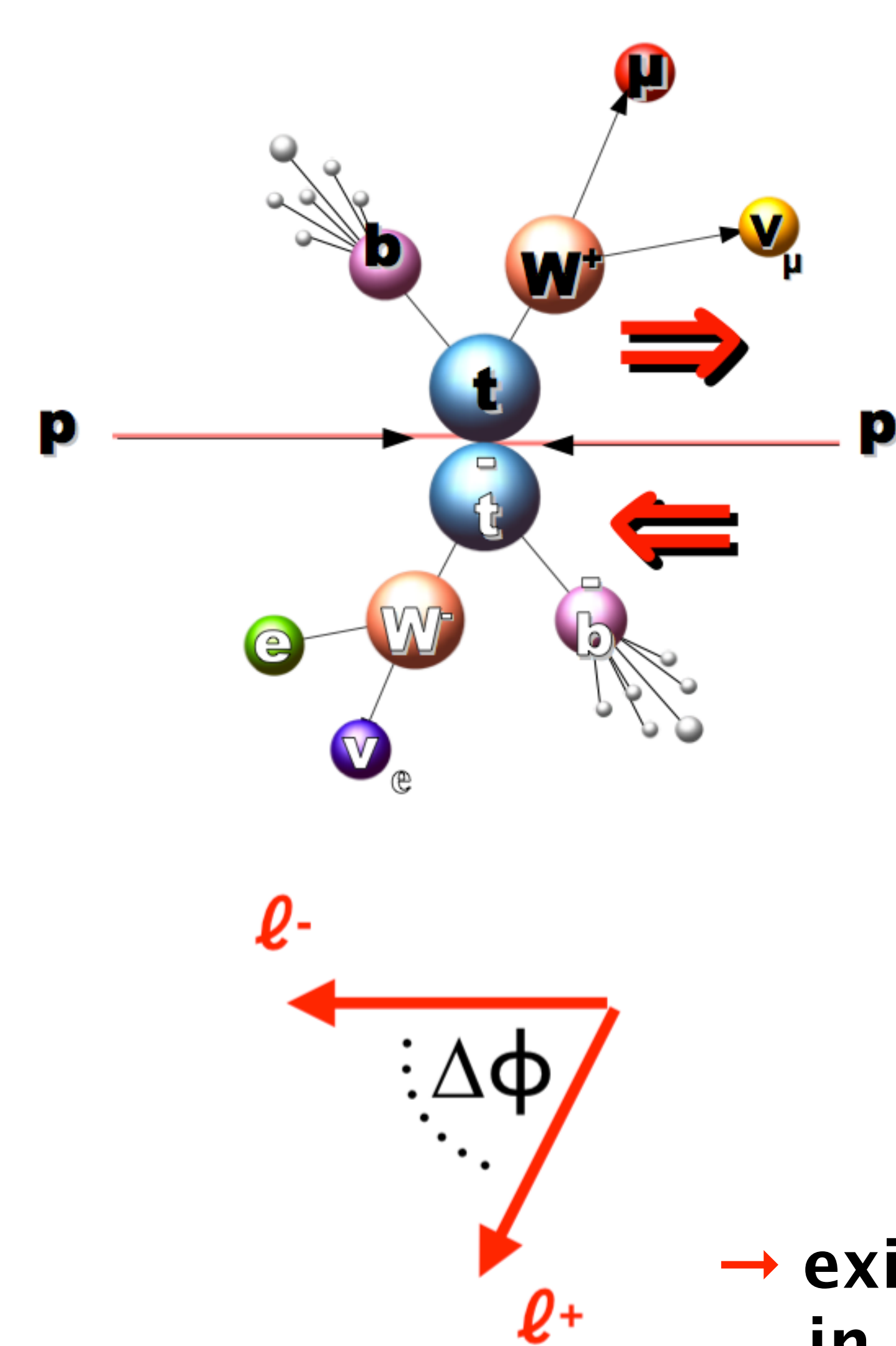


Top-Antitop Quark Spin Correlation



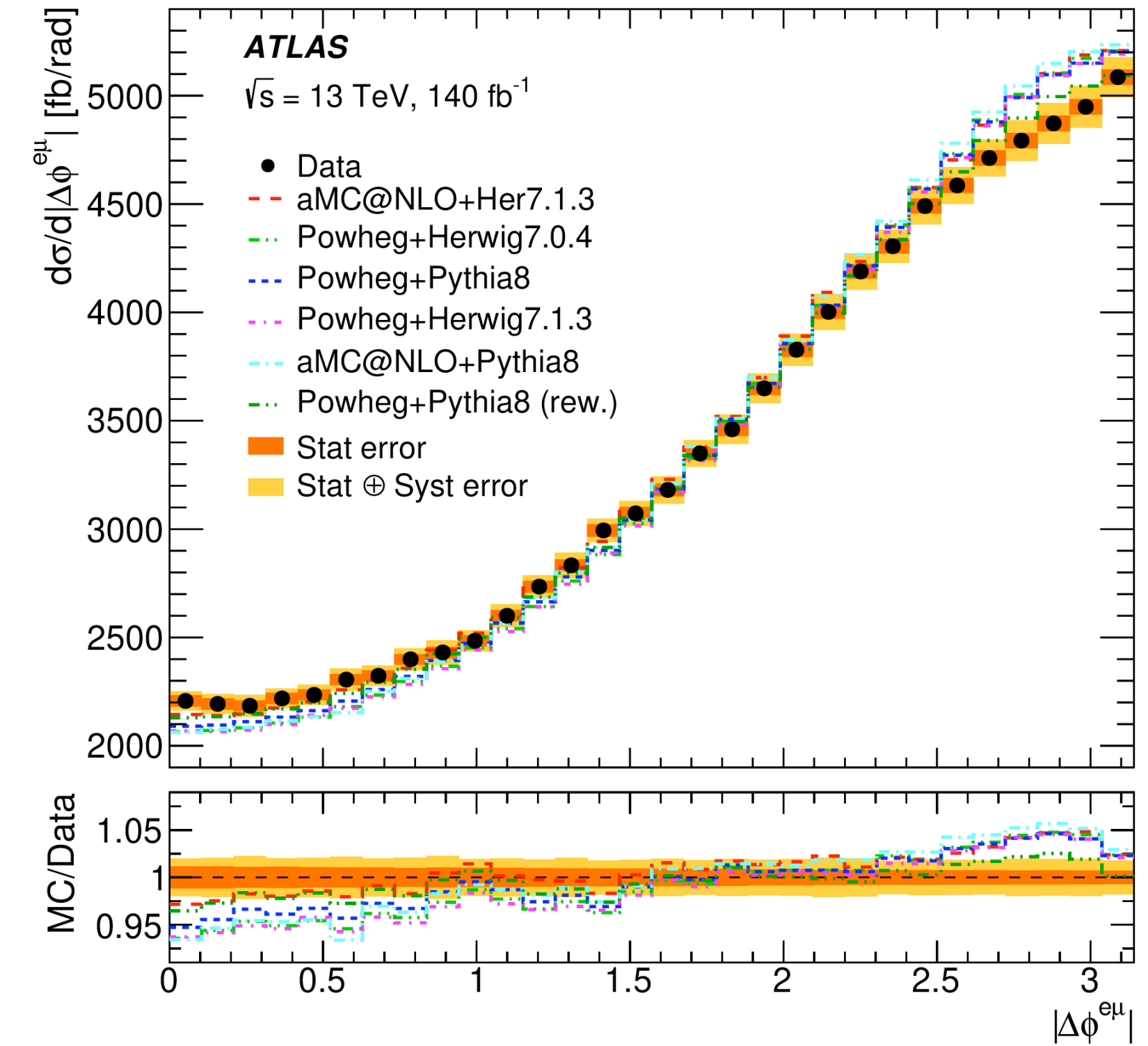
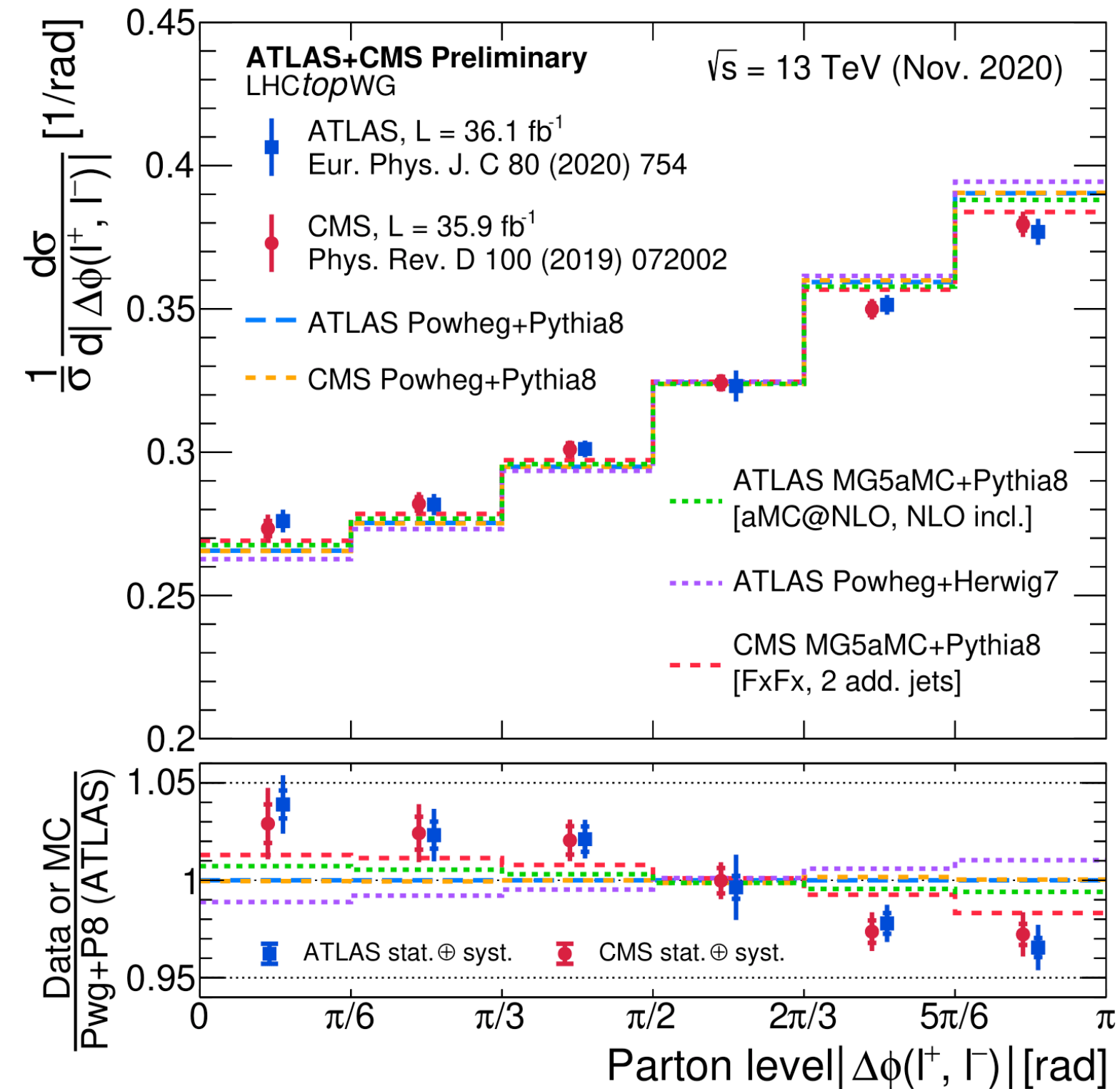
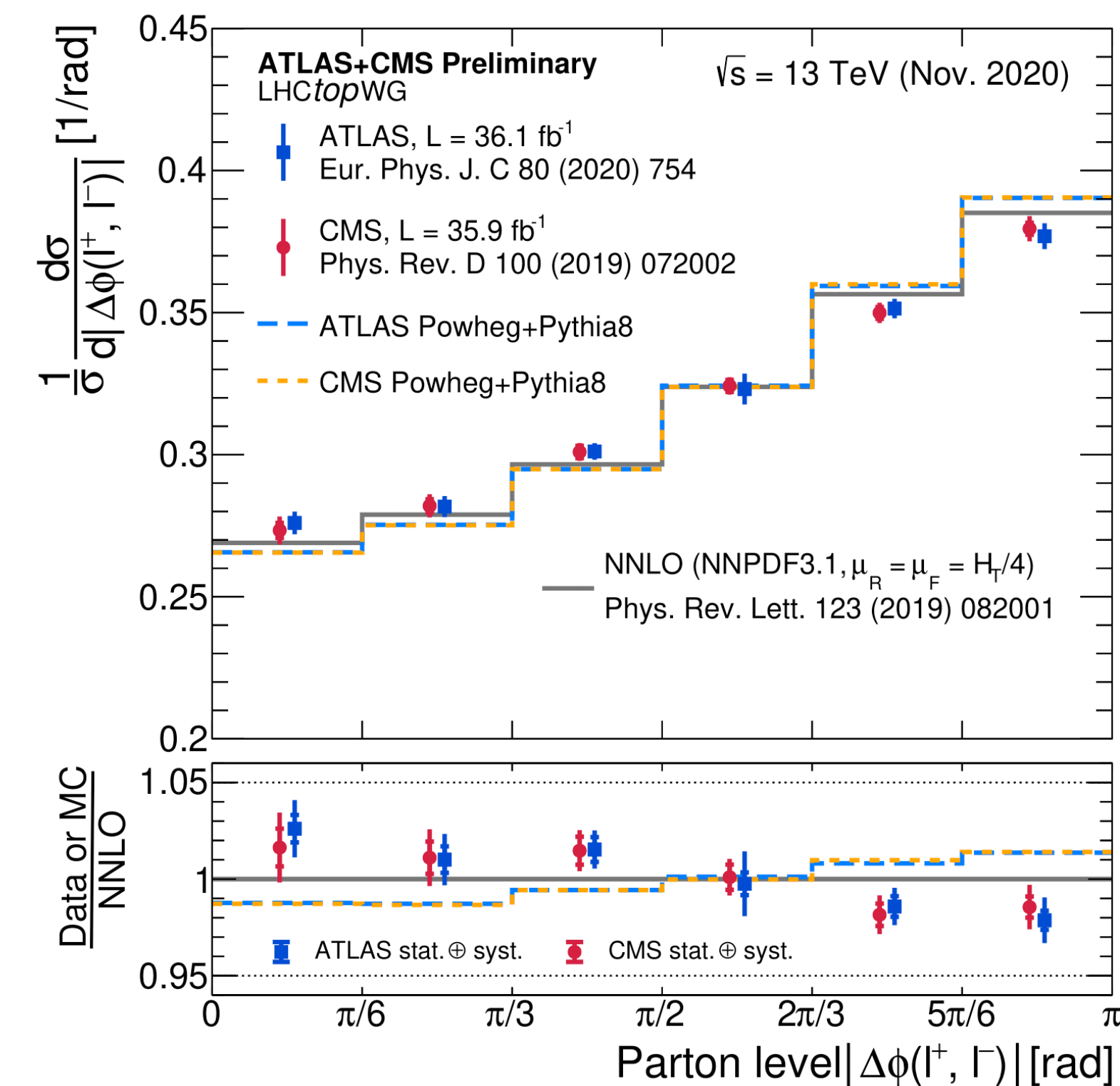
→ existence of a pseudoscalar would lead to flatter distribution in data corresponding to stronger spin correlation

Top-Antitop Quark Spin Correlation



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

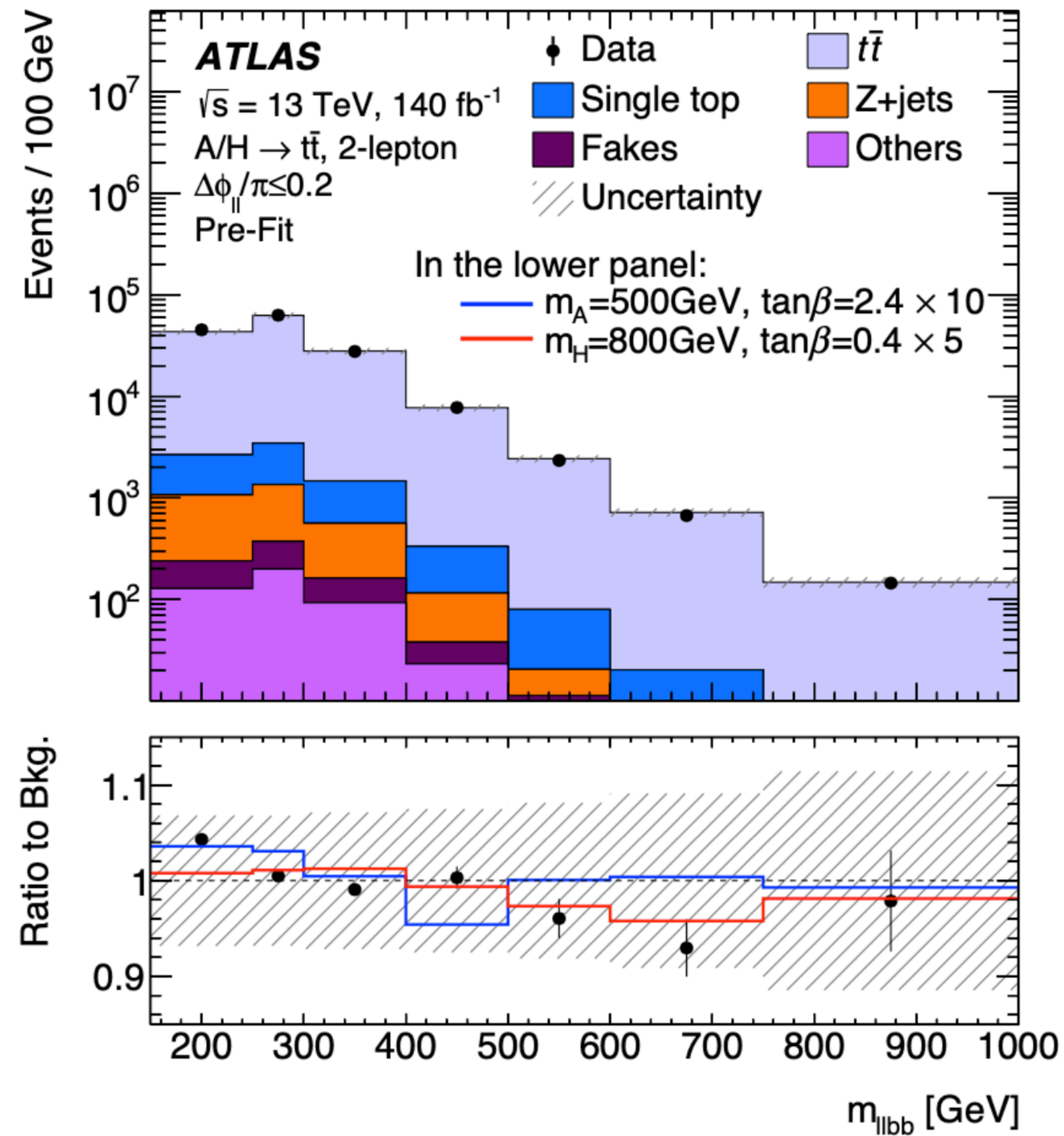
Azimuthal Angle between Leptons in Lab System



→ difficult to model

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

ATLAS Dilepton prefit



ATLAS Dilepton postfit

