Odd Higgs, Even Higgs: A View from the Top

Reinhild Yvonne Peters

The University of Manchester

UK Research and Innovation

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European Research Council
Established by the European Commission

The Goal

- Goal: understand the most fundamental building blocks of nature and their interactions

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- Particle Physics: The Standard Model (SM) of Particle Physics!
  - Discovery of a Higgs in 2012: Standard Model technically complete

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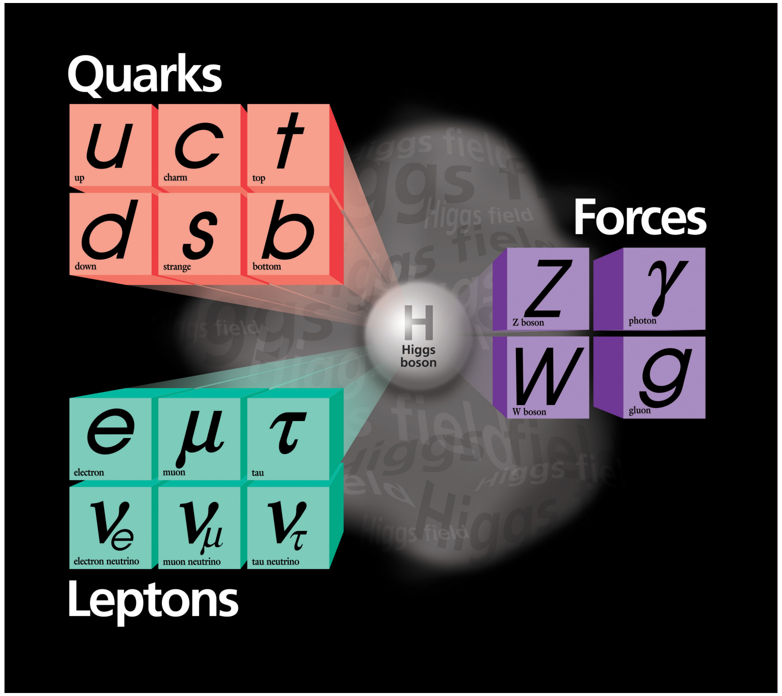
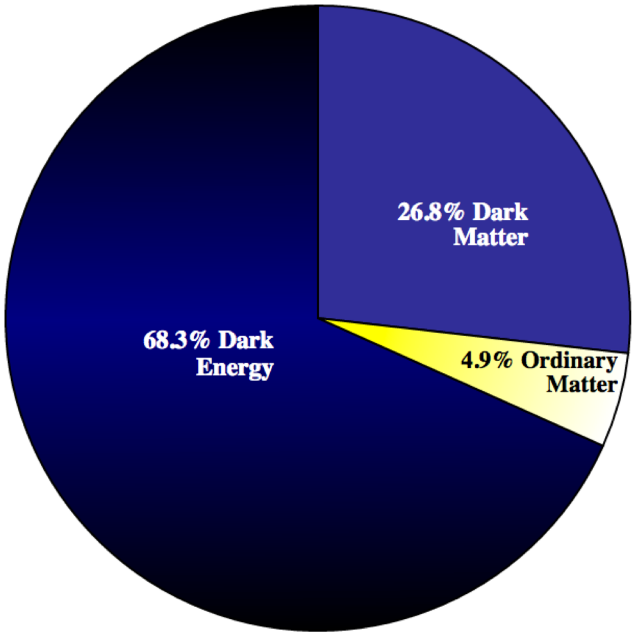


!

New Physics?

- We know: Standard model can not be the whole story
- For example:
  - What is dark matter? And dark energy?



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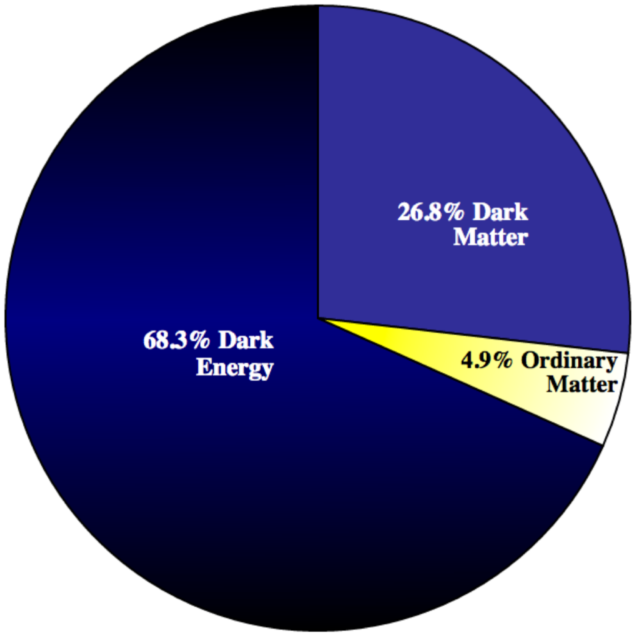
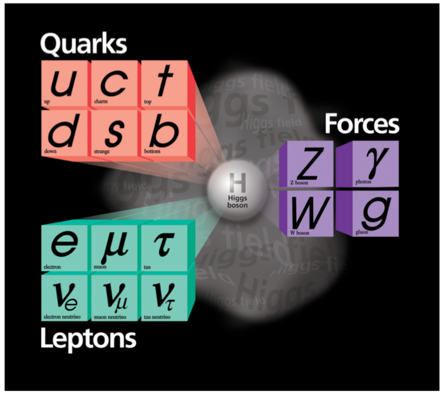
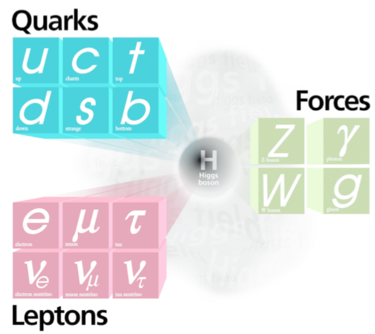


Early Universe:





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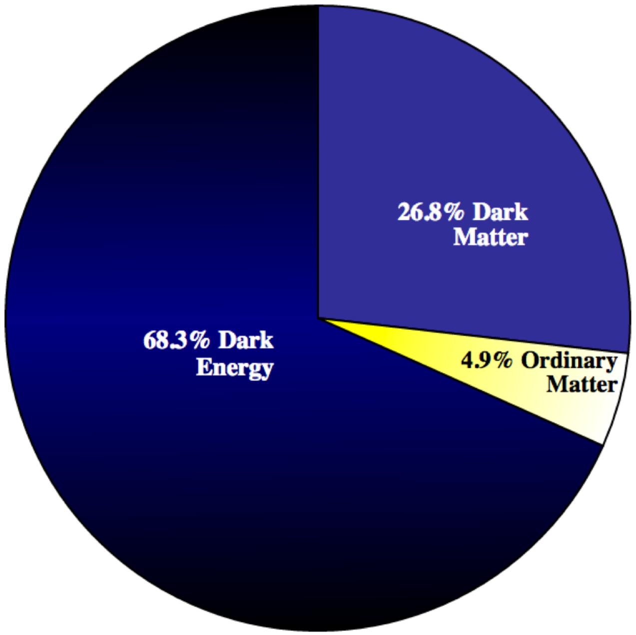

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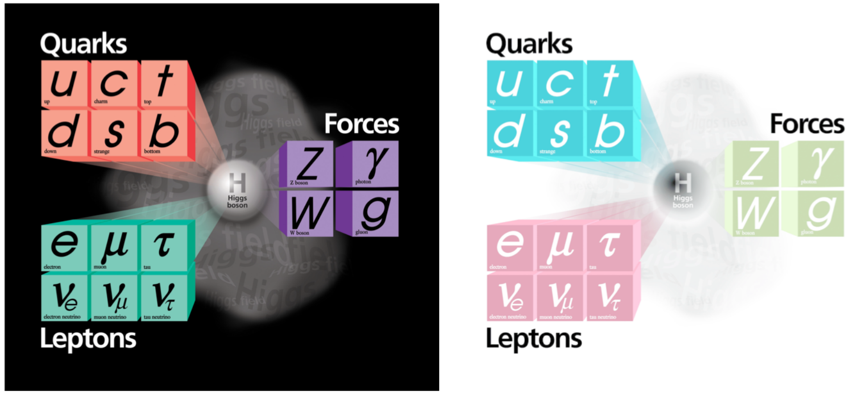
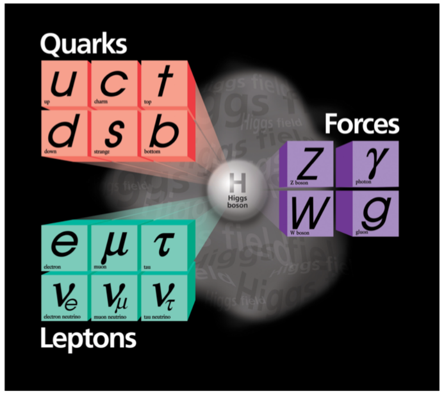


Our Universe today:

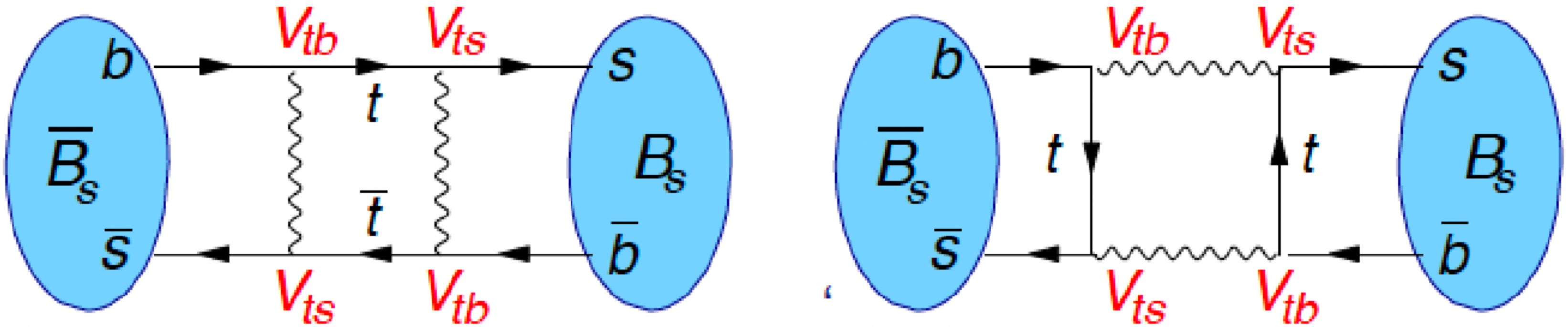


Explanation requires **CP violation!**

(CP=charge parity transformation; Sakharov conditions)

CP Violation

- CP violation: Known in the SM in the quark sector
  - Kaons, B and most recently in charm hadrons



- BUT: not enough!
  - Required: baryon-anti-baryon fraction of about ~$6x10^{-10}$ (WMAP)
  - Quark sector: too small by about 10^{-16}

→ where is the rest?

Searches for CP Violation

- Many searches for CP violation ongoing
  - For example, at LHCb to fully explore the quark sector
- So far less explored areas of particular interest:
  Neutrino and Higgs sector

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- Neutrino sector:
  - Possible CP-violating phase in PNMS matrix

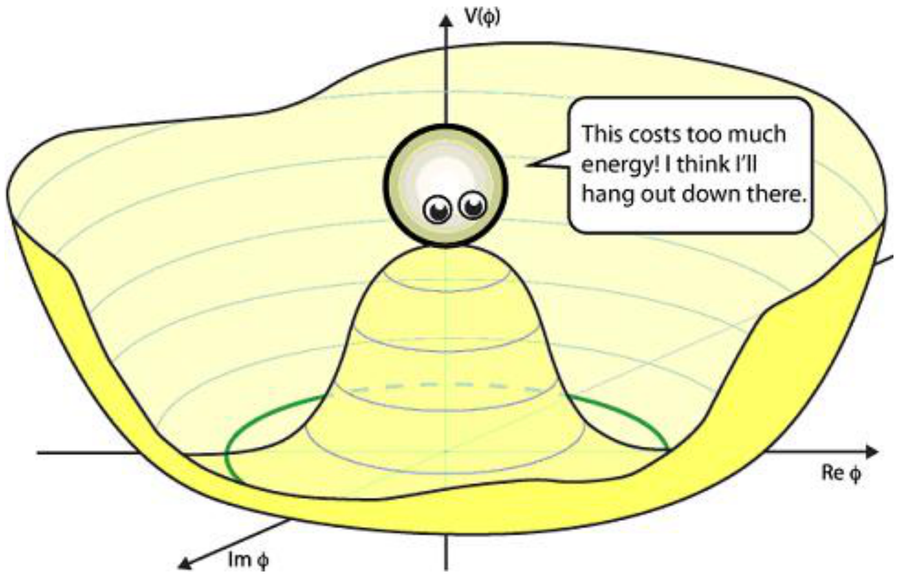
$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}\, e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13}\, e^{i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

  - Aim of upcoming experiments like DUNE to probe for CP violation in neutrino sector

- Higgs sector: most recently discovered fundamental particle
  - Lots of room for unknowns!

The Higgs

- Higgs field: gives mass to W & Z bosons
  - “Mexican Hat Potential”
- Higgs Boson: Only known fundamental scalar (spin 0) particle
- **CP-even** in SM
- Discovered in 2012 by ATLAS & CMS



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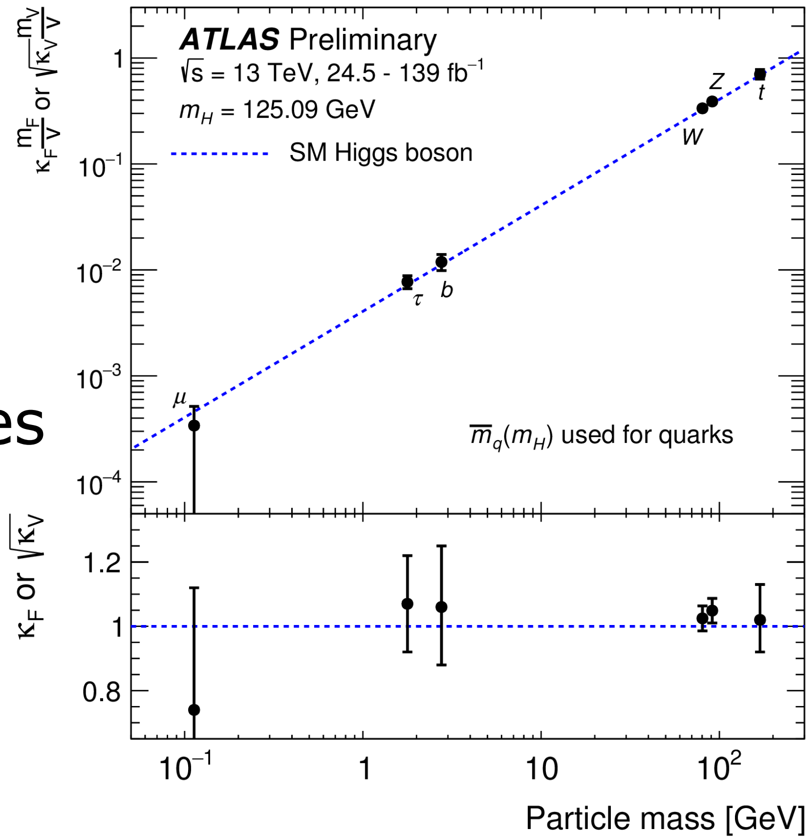
- Coupling depends on mass of particles
  - Coupling of about 1 to **top quark**
  - Special role of the top quark for electroweak symmetry breaking?



ATLAS-CONF-2019-005

The Top Quark

- Heaviest known elementary particle!
  - About 172.5 GeV = 3.07×10^{-22} grams
    - More than 1 million times more heavy than electrons!
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  - Quarks always occur in bound states (like protons)
  - Top quark decays faster than the binding time
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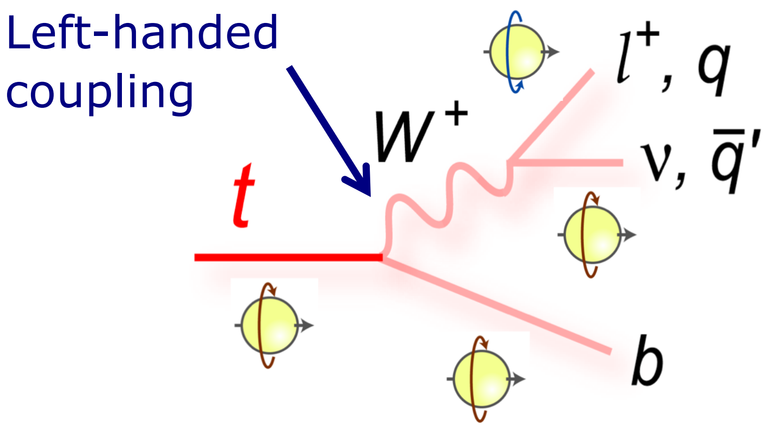
- Top quarks do not exist in our every-day nature
  - Need to be produced at colliders with high energies

The Top-Higgs Connection

- Relation of top and Higgs: insight into coupling properties and CP-properties of the Higgs
- CP violation requires CP-odd admixture
- Top-Higgs:
  - Highest coupling → deviation from 1 would indicate new physics
  - Short lifetime: spin information transferred to decay products → access **CP information** of Higgs



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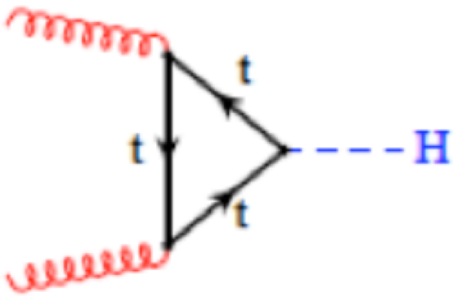
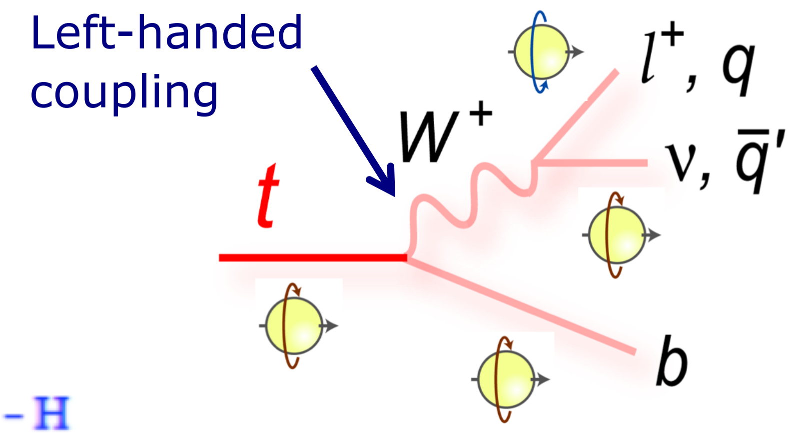
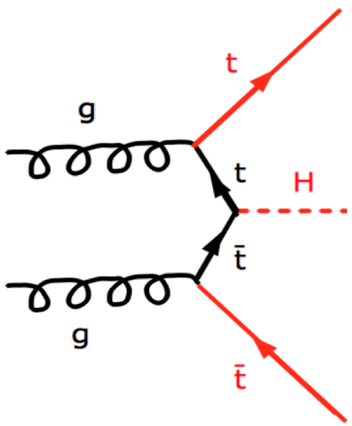
- Which processes?
  - The “obvious” loops (indirect)
    - But: model-dependent!

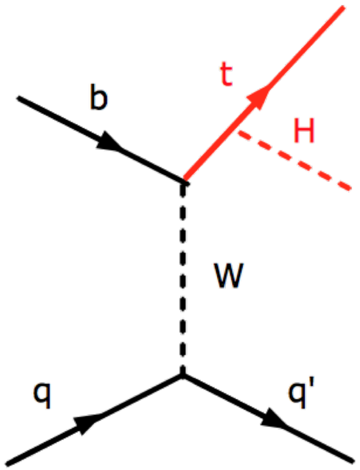


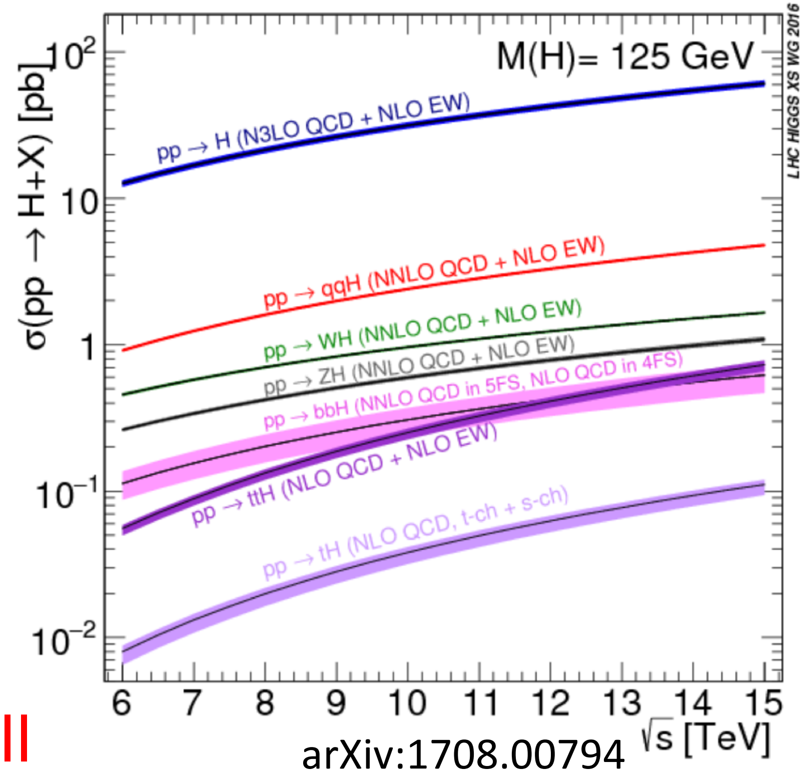


$t\bar{t}H$ and tH

- Direct access to top-Higgs Yukawa: $t\bar{t}H$ and tH
- tH: also access to sign of Yukawa coupling
  - Due to interference







arXiv:1708.00794

- Challenge: SM cross sections very small
  - NLO $t\bar{t}H$: $\sigma(ttH) = 507^{+35}_{-50}$ fb
  - NLO tHq: $\sigma(tHq)_{\mathrm{NLO}} = 74.25^{+6.5}_{-14.9}$ (QCD scale + FS) $\pm$ 3.7 (PDF+α_s) fb

arXiv:1610.07922

Top-Higgs Yukawa and CP

- Effect of CP on Lagrangian:

$$\mathcal{L}_{t\bar{t}H} = -\kappa_t' y_t \phi \bar{\psi}_t (\cos\alpha + i\gamma_5 \sin\alpha)\psi_t$$

- Parameters:
  - y_t: Yukawa coupling
  - κ_t': coupling modifier
  - α: CP-mixing angle
  - ϕ: Higgs field
  - ψ_t: top quark spinor field
  - $\boldsymbol{\gamma}_5$: Dirac matrix

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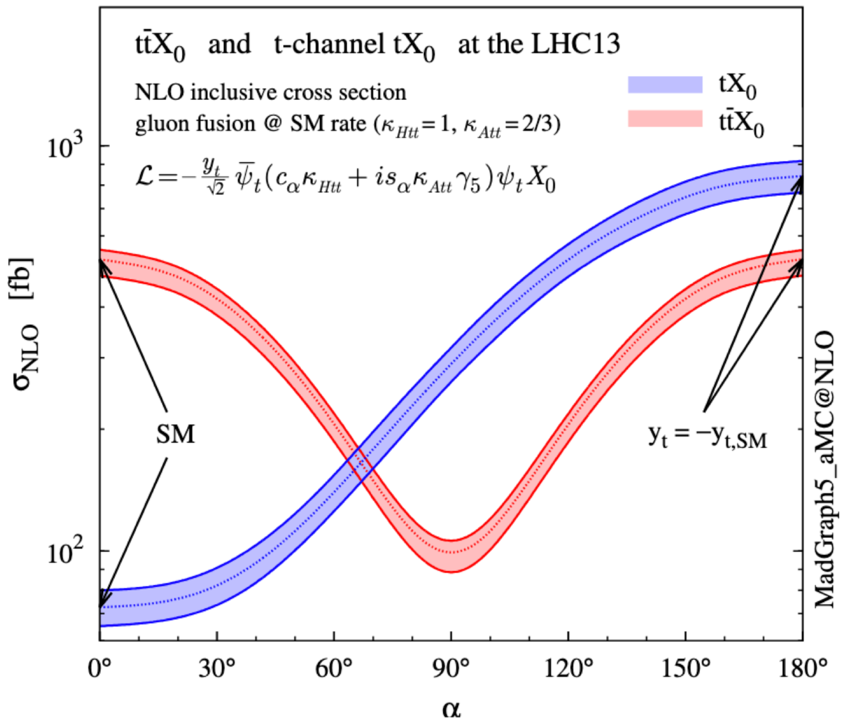


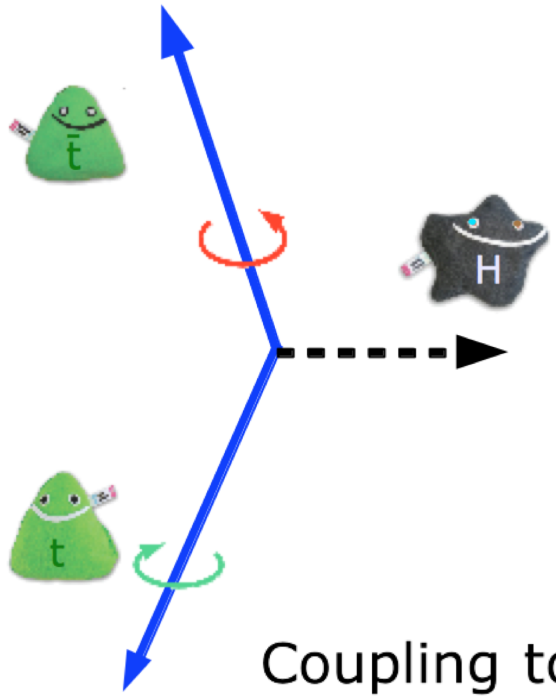
Eur. Phys. J. C **75**, 267 (2015)

- Inclusive cross section sensitive to CP odd admixtures
- Extra sensitivity: use strength of sensitive observables

CP odd versus even?

- Higgs: spin 0
- Top: fermions → spin 1/2

CP even:



Coupling to
same helicity $t\bar{t}$

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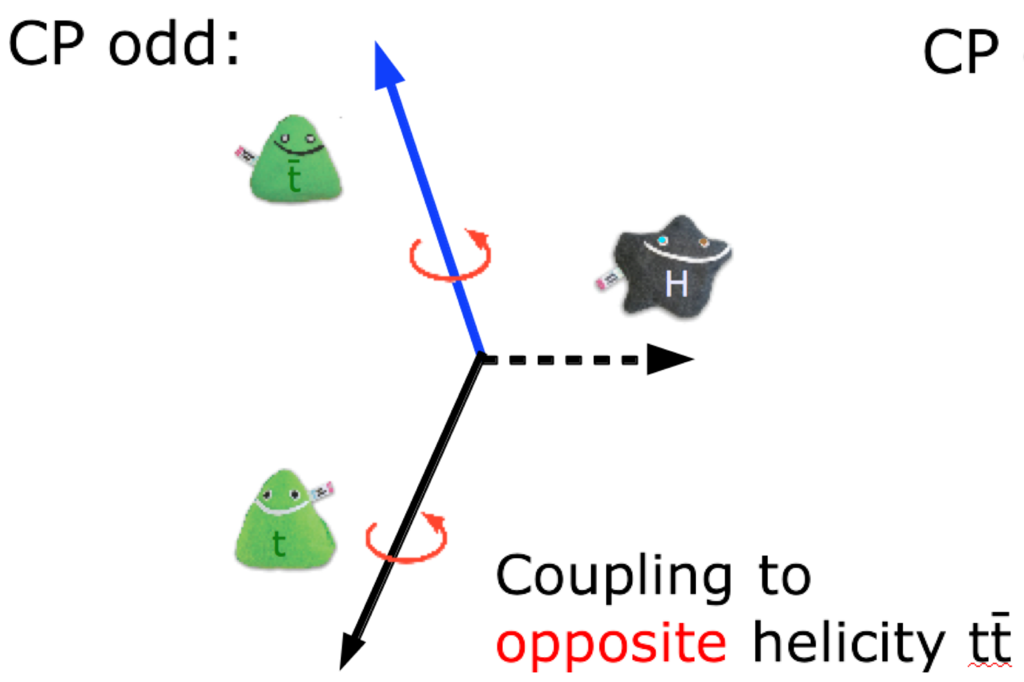

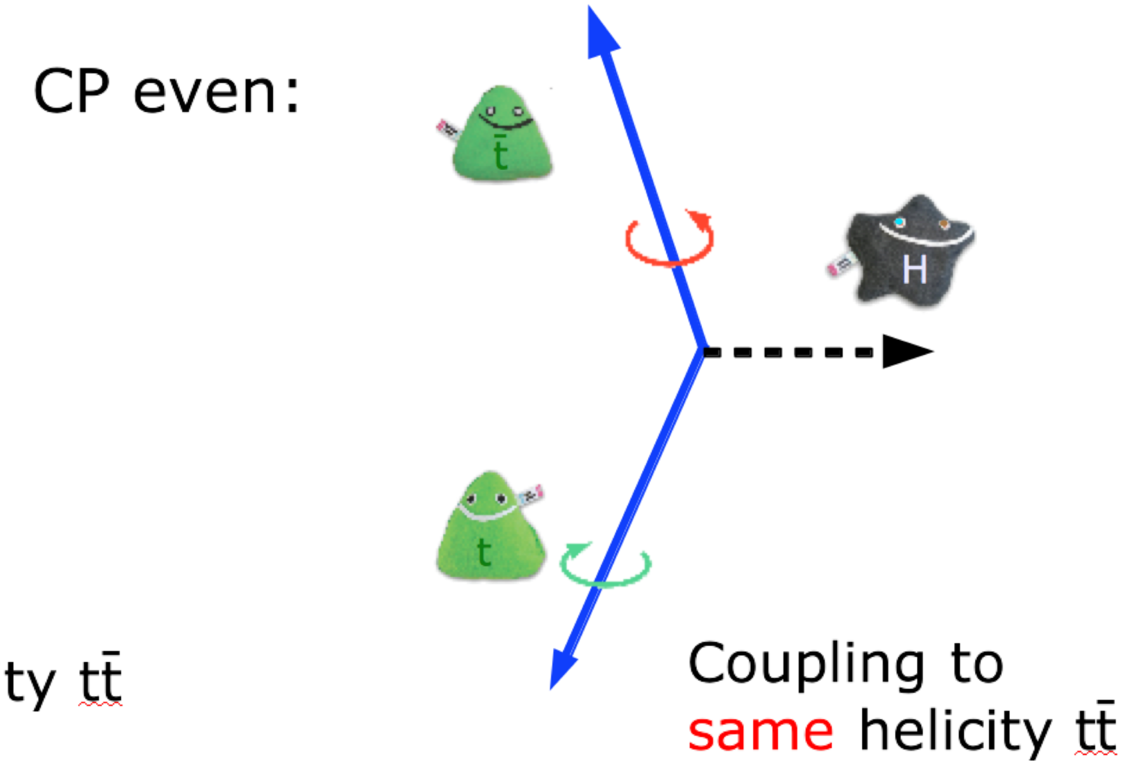

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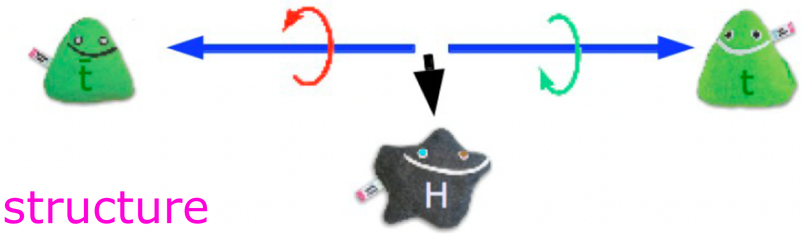
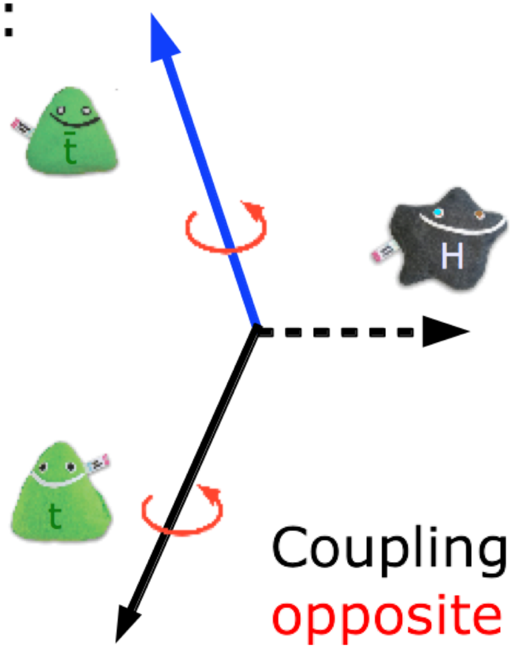


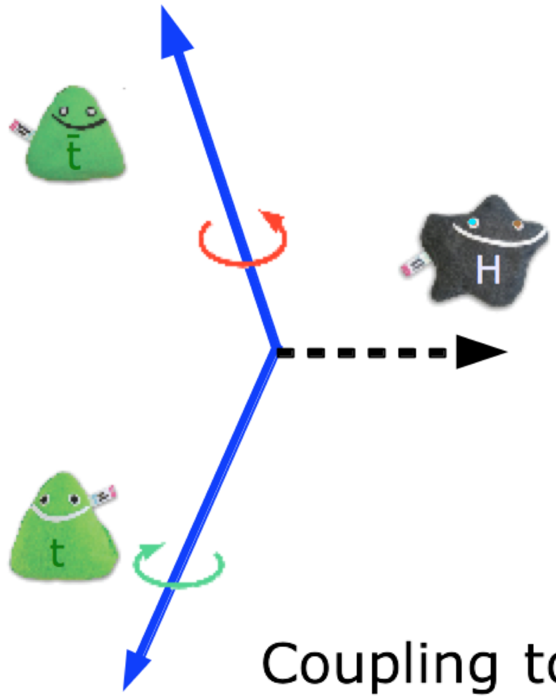
Observables sensitive to spin structure provide extra CP information!

CP odd:



Coupling to **opposite** helicity $t\bar{t}$

CP even:

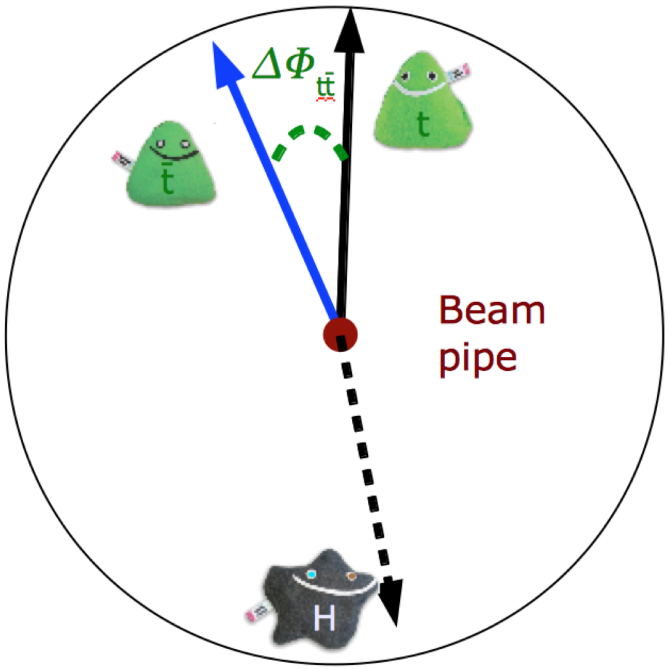


Coupling to **same** helicity $t\bar{t}$

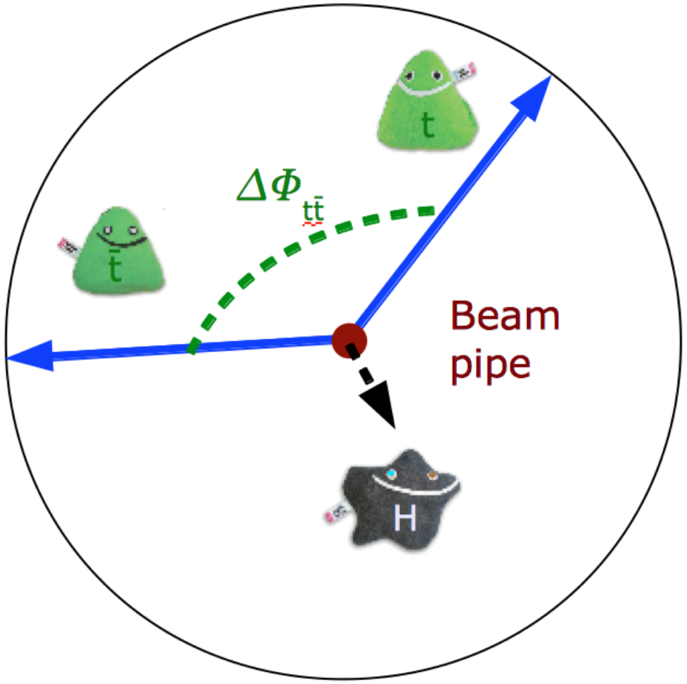
CP odd versus even?

- Observables sensitive to spin structure provide extra CP information!
- Example angular difference between top-quarks

CP odd:



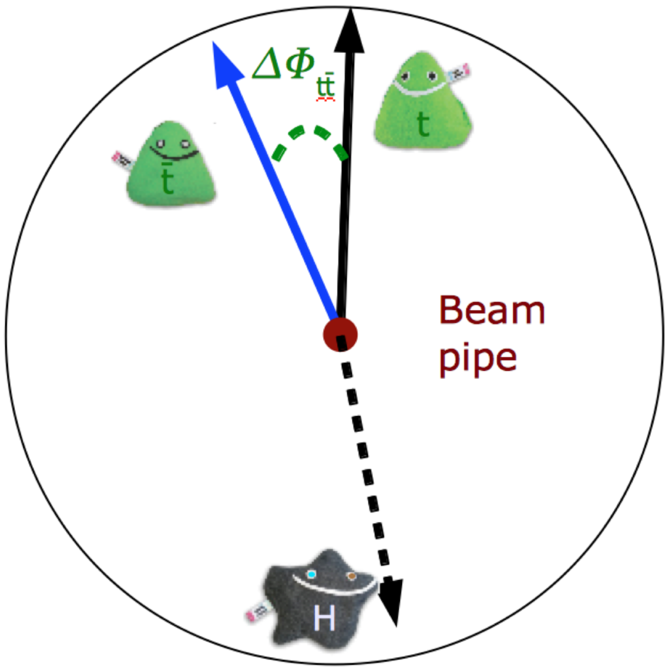
CP even:



CP odd versus even?

- Observables sensitive to spin structure provide extra CP information!
- Example angular difference between top-quarks
- Experimental measurements: explore cross sections and observables in tH and $t\bar{t}H$

CP odd:



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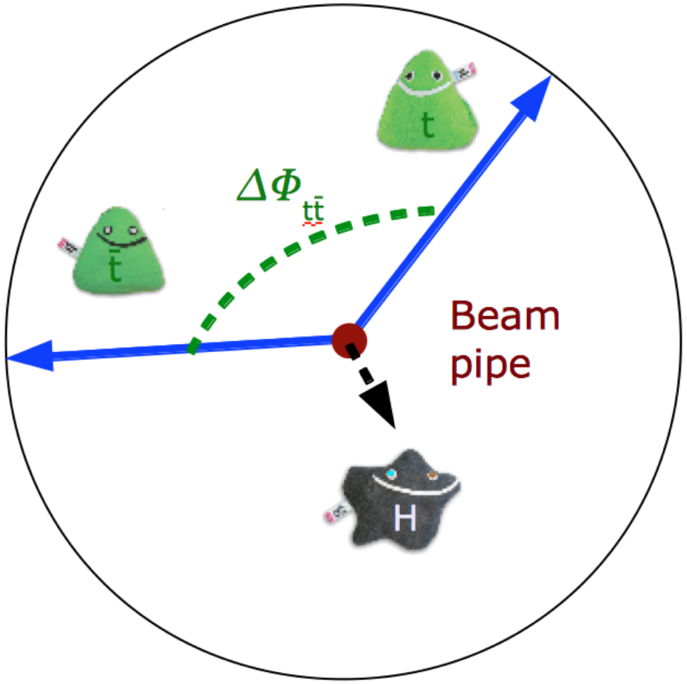
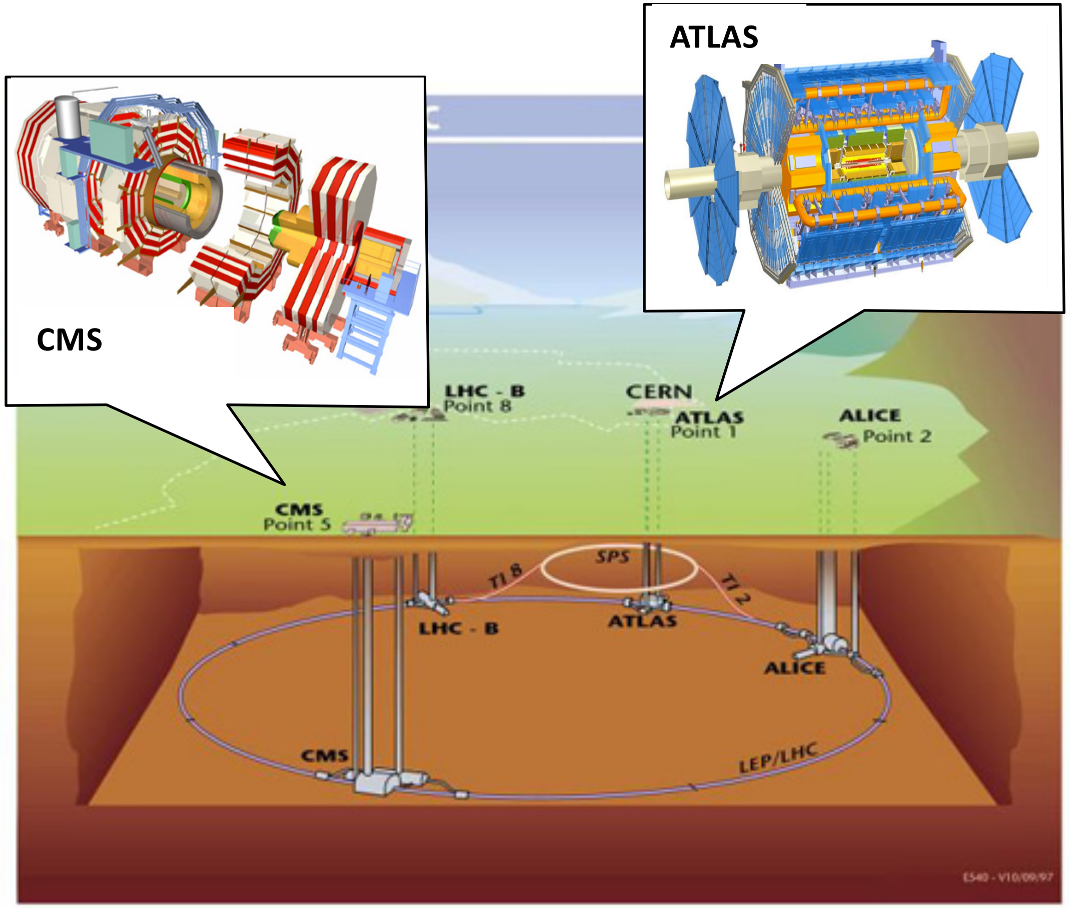


Required Tools

- 1. Somewhere to produce $t\bar{t}H$ and tH processes:
  the LHC

LHC: The highest Energies

- LHC: Start 2009
  - Energies like 10^{-13} - 10^{-14} seconds after big-bang!
  - Currently: 13.6 TeV
- Some LHC key data:
  - 27km ring
  - ~100m underground
  - 1232 dipole magnets to keep protons in their orbit
  - Further magnets for focusing
- Magnets get cooled to 1.9 Kelvin (-271.25 Celsius)
  → colder than outer space (2.7 Kelvin)
  → the LHC is the coolest ring in the universe!



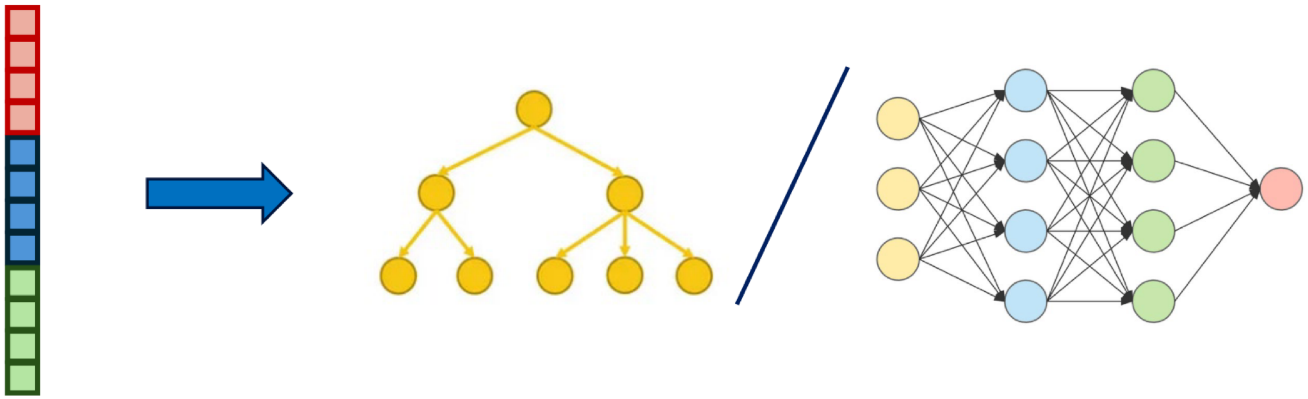
Required Tools

- 1. Somewhere to produce $t\bar{t}H$ and tH processes: the LHC
- 2. Something to enhance signal over background:
  - Machine Learning

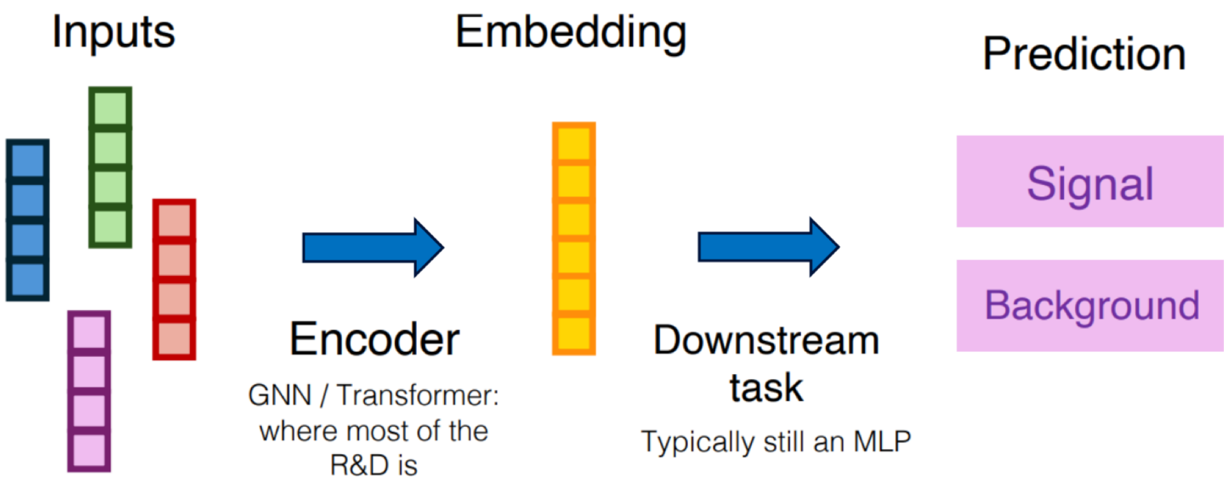
Machine Learning

- Techniques to optimize event classification, object predictions, …
- Deep learning with one input feature vector
  - BDTs
  - NNs

    …



- Deep learning with set of feature vectors as distinct objects
  - Transformers
  - GNNs
  - …



Required Tools

- 1. Somewhere to produce $t\bar{t}H$ and tH processes: the LHC
- 2. Something to enhance signal over background:
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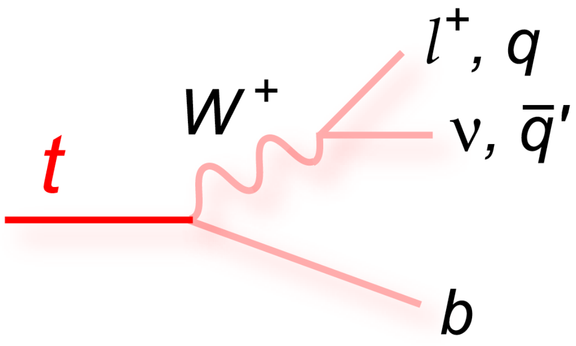
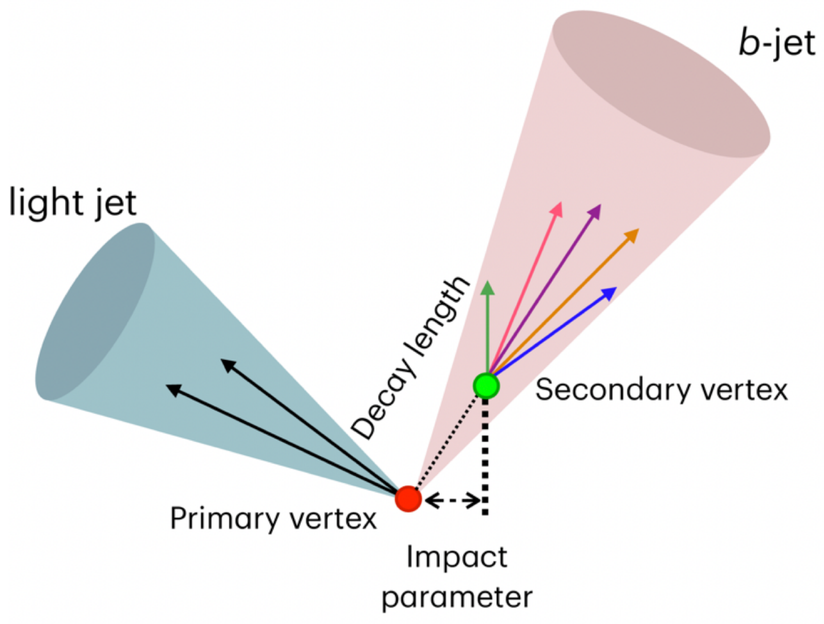
  - b-tagging



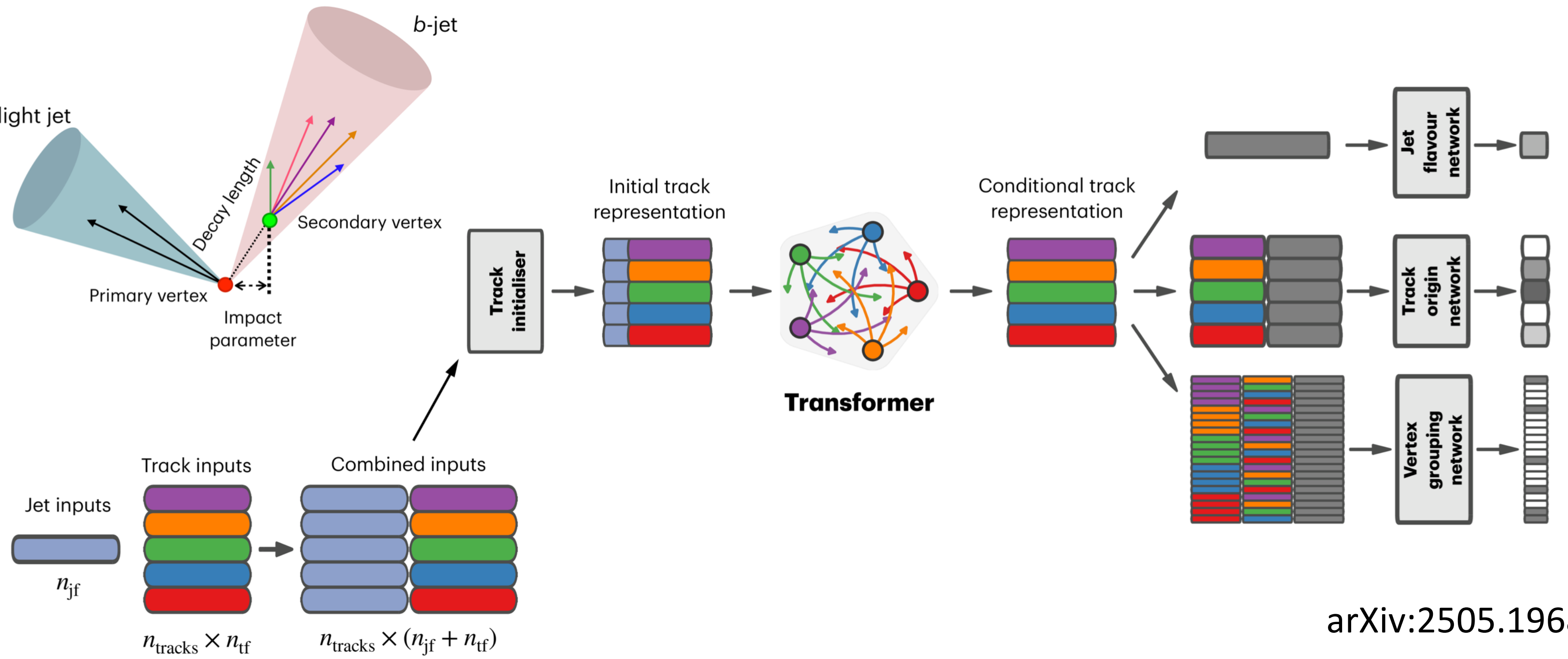
B-Tagging

- Important tool to increase purity of processes with top quarks
- b-hadron: travels some millimeters before it decays
  - Displaces tracks, secondary vertices



B-Tagging

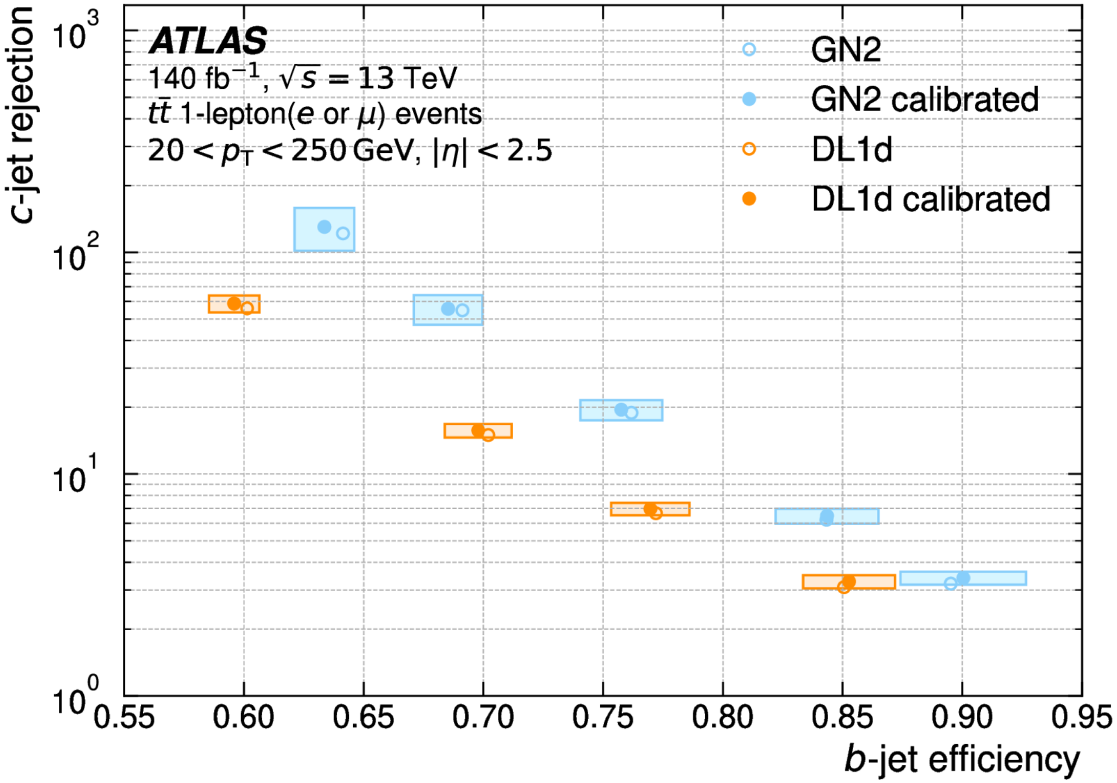
- Important tool to increase purity of processes with top quarks
- b-hadron: travels some millimeters before it decays
  - Displaces tracks, secondary vertices
- Use of sophisticated tools, for example transformer



arXiv:2505.19689

B-Tagging

- Latest b-tagger: GN2
- Very good identification of b-jets
- Differentiation between b-jets and c-jets
  - Important for some spin-related analyses, $H \rightarrow c\bar{c}$ analyses, …



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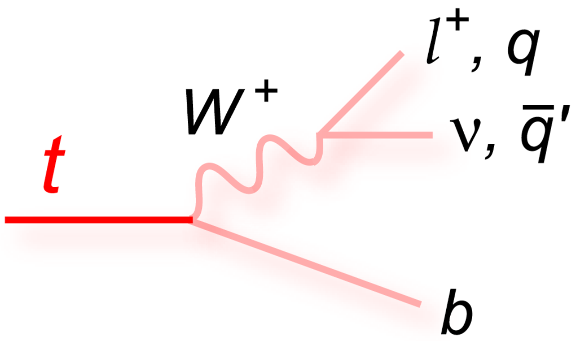
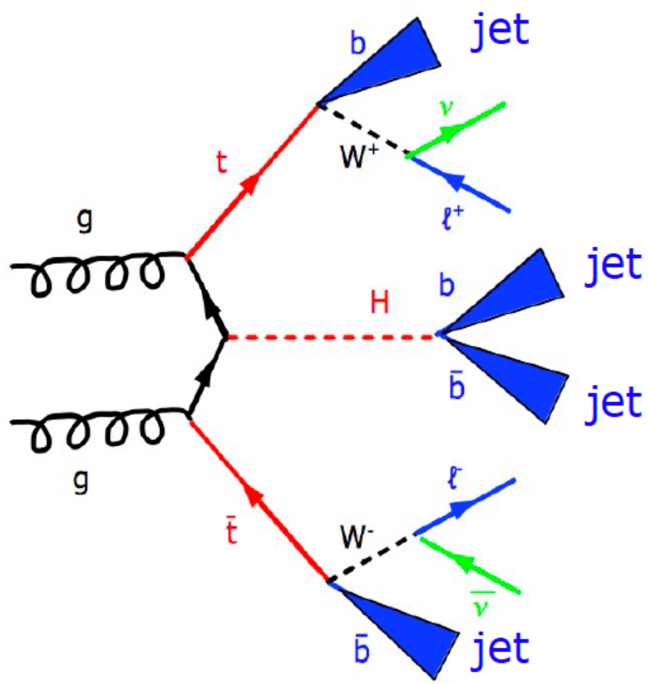
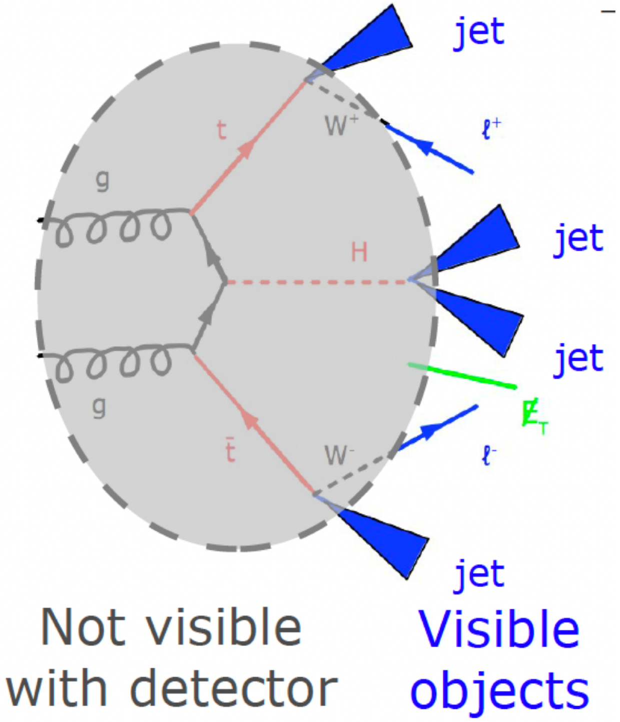


- 3. Something to reconstruct sensitive observables: event reconstruction



Event Reconstruction

- Goal: reconstruct Higgs/Top 4-vectors
- Detector: only final state objects can be reconstructed
  - Object pairings unknown
  - Neutrinos not detected



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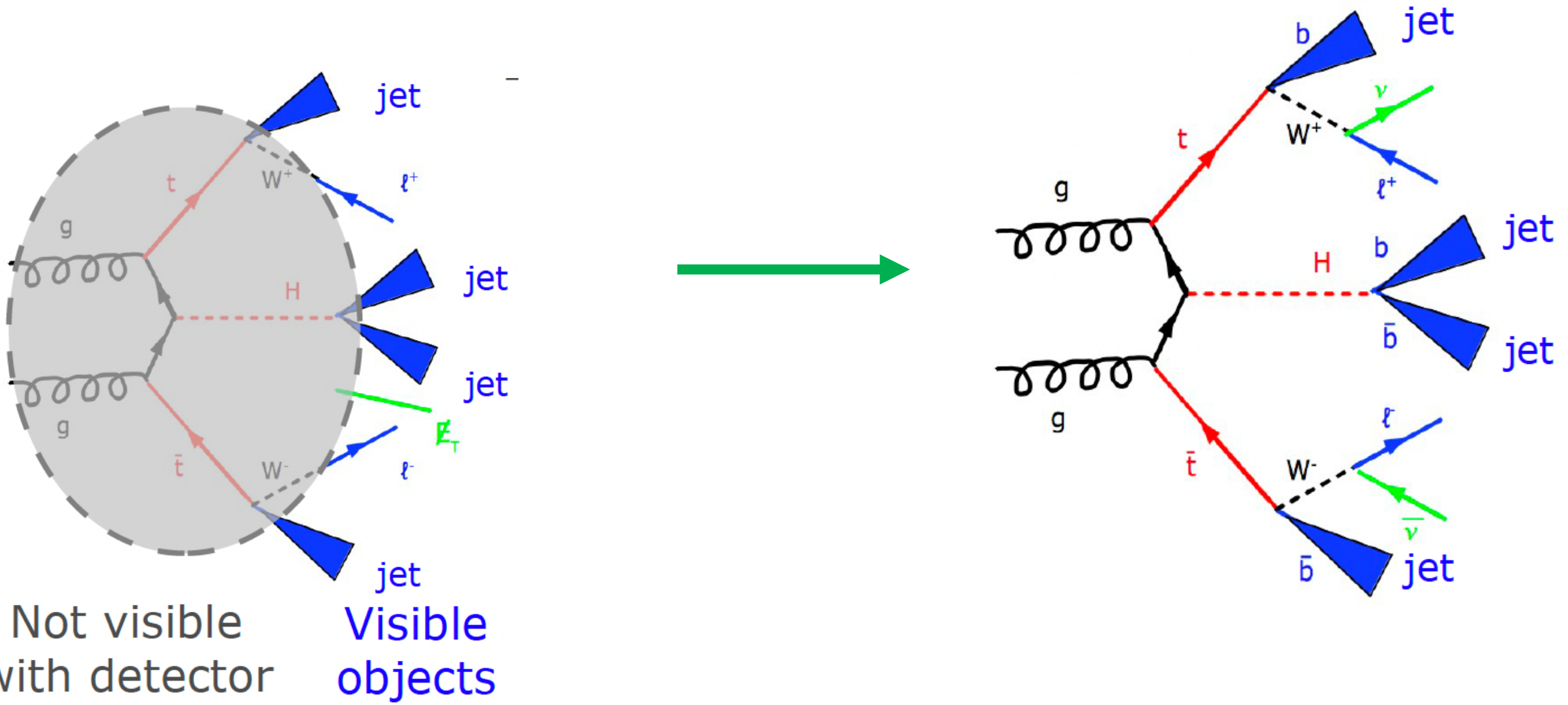

Event Reconstruction

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- Detector: only final state objects can be reconstructed
  - Object pairings unknown
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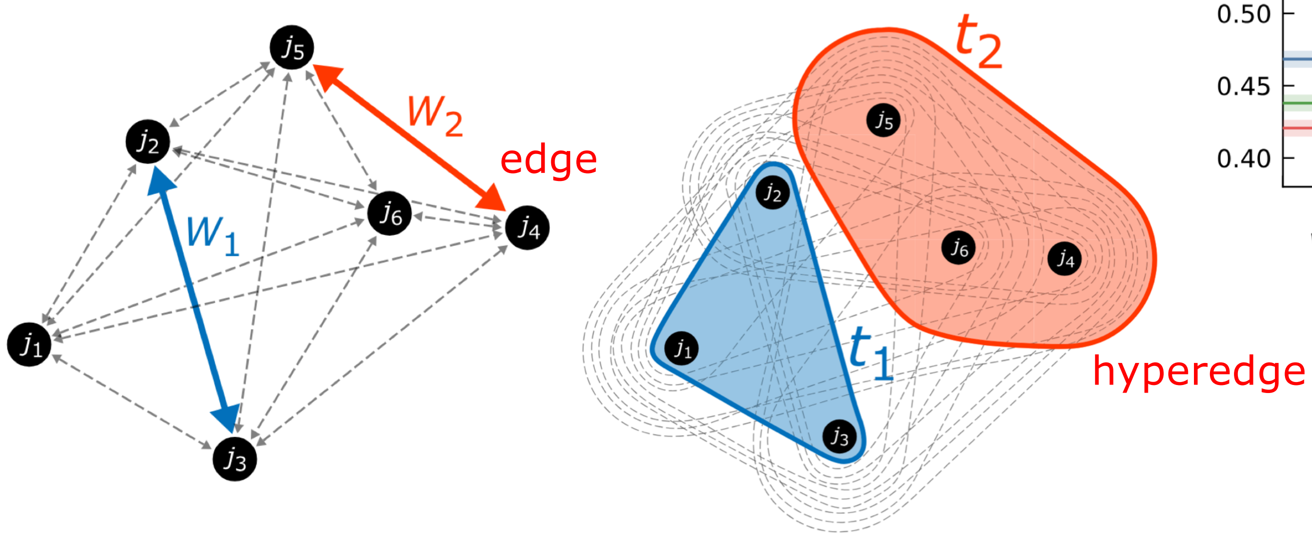
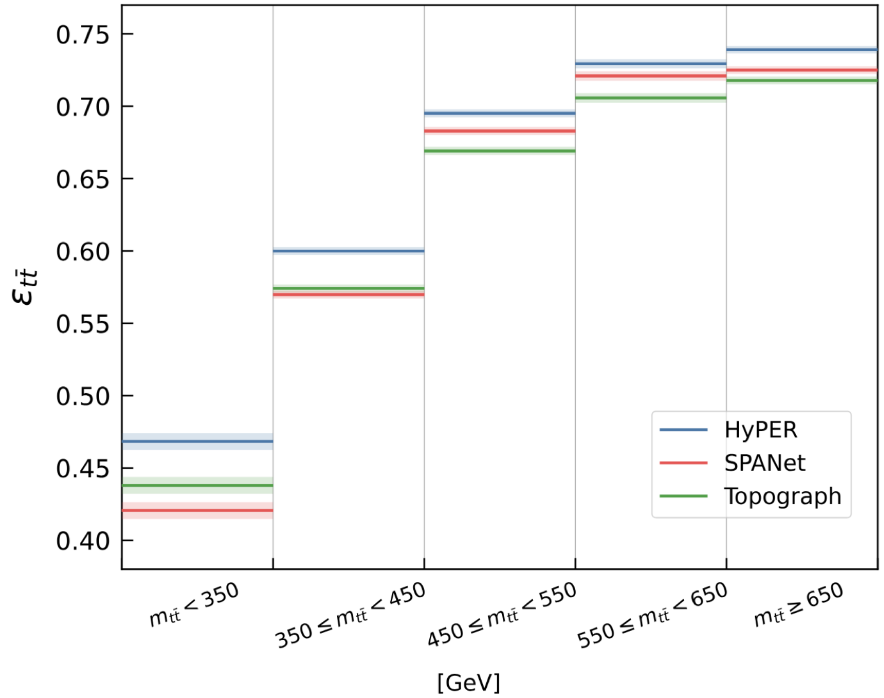
- Various tools on the market
  - For example GNN-based HyPER for object pairing
    - Performance in $t\bar{t}$: best on the market





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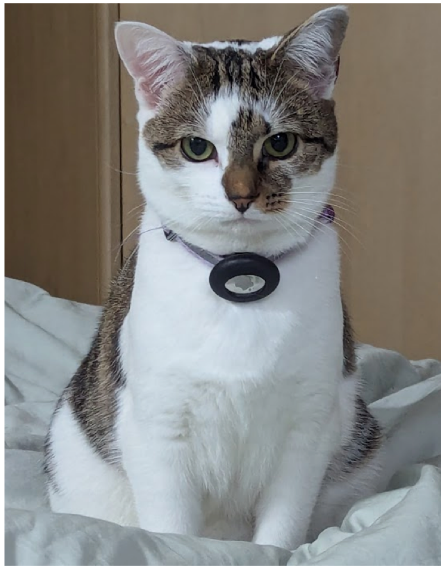
Analysis Strategy

Step 1: choose process and final state



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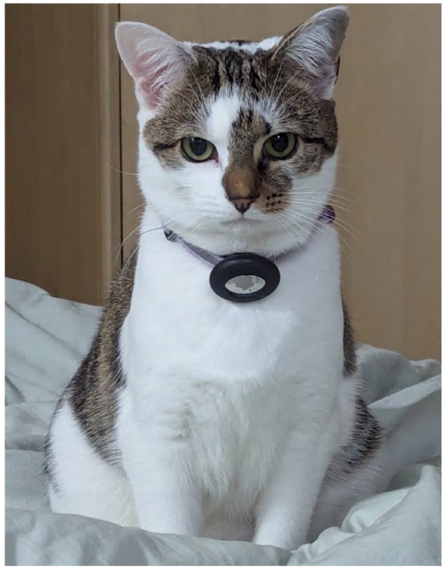

Step 2: Model backgrounds and enhance signal fraction

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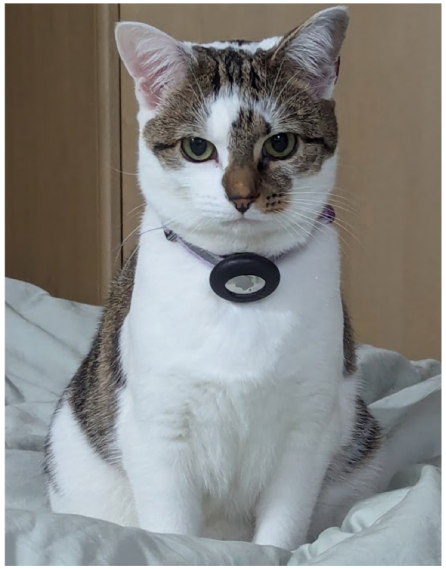
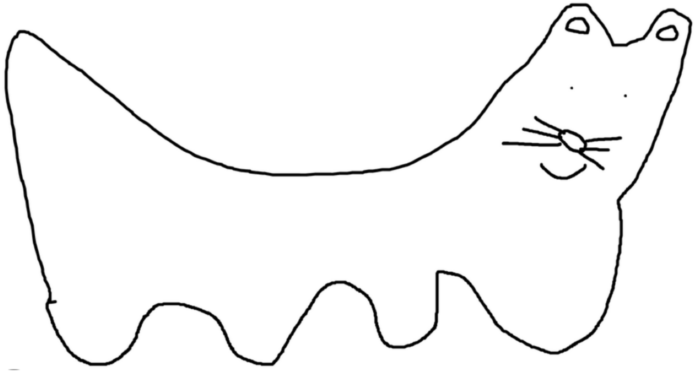


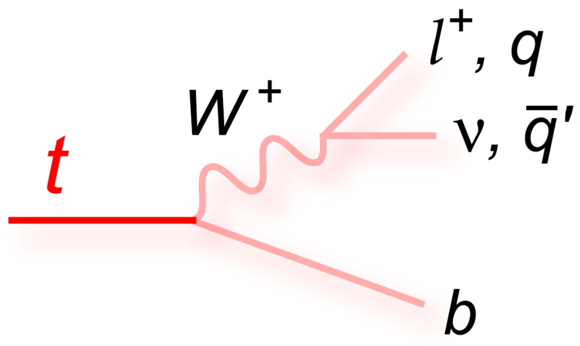
Step 2: Model backgrounds and
enhance signal fraction

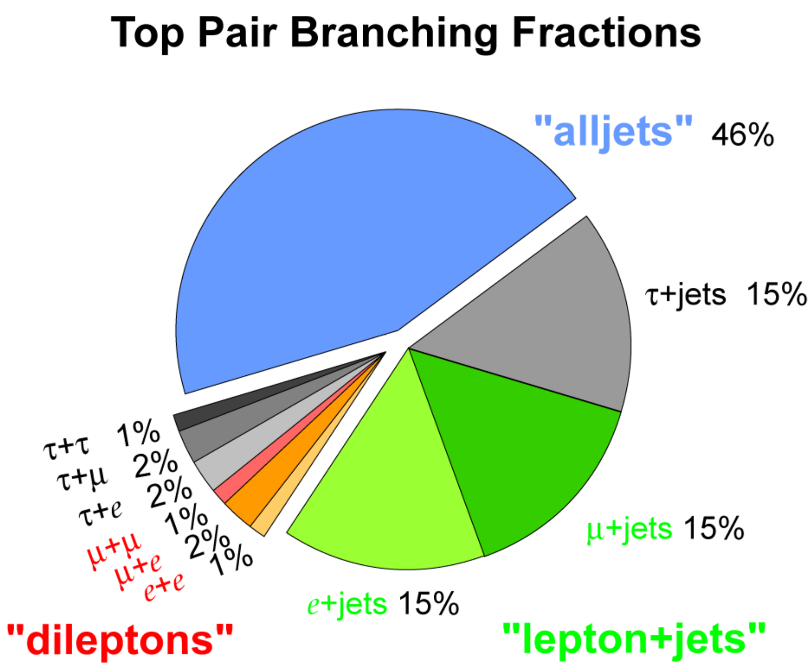
Step 3: Fit to
observables; set limits



Choice of Final States

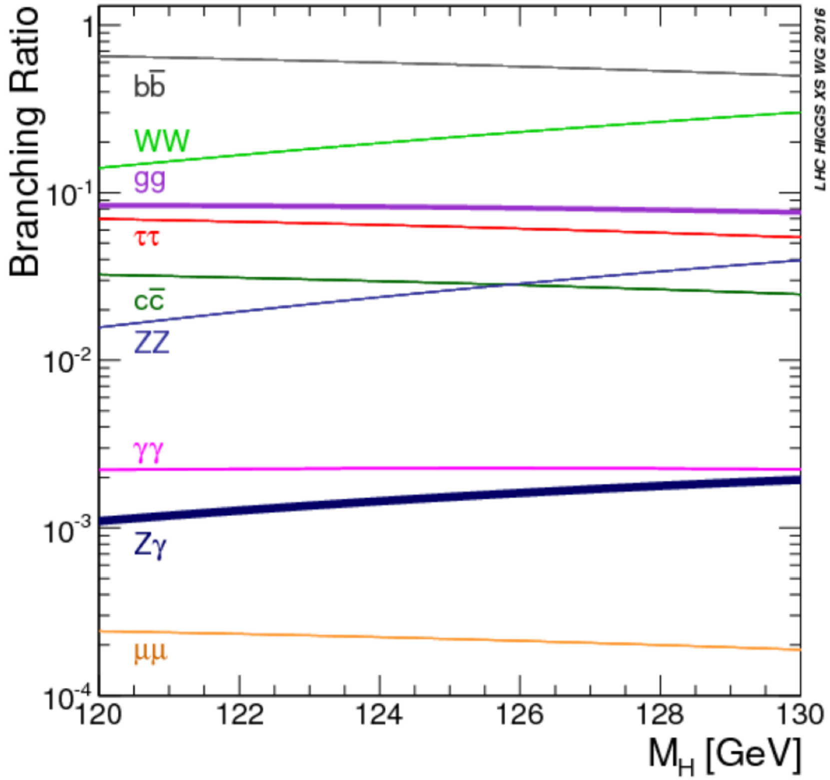
- Balance of sizable signal and manageable background
- $t\bar{t}$ pair: top decay leptonically or hadronically
  - Determines dominant backgrounds





Choice of Final States

- Balance of sizable signal and manageable background
- $t\bar{t}$ pair: top decay leptonically or hadronically
  - Determines dominant backgrounds
- Main processes analysed so far:
  - $t\bar{t}H$ with $H \rightarrow \gamma\gamma$
    - Pro: very clean signal
    - Con: small Higgs branching fraction
  - $t\bar{t}H$ with $H \rightarrow W^+W^-$ and $\tau^+\tau^-$
    - Pro: decent Higgs branching fractions, manageable background
    - Con: CP violating effects more likely expected in coupling to fermions
  - $t\bar{t}H$ with $H \rightarrow b\bar{b}$
    - Pro: Largest Higgs branching fraction, extra motivation for 3rd generation fermion couplings in new physics models, e.g. maximally symmetric 2HDMs
    - Con: large background from $t\bar{t}b\bar{b}$



$t\bar{t}H$, $H\rightarrow\gamma\gamma$ in ATLAS

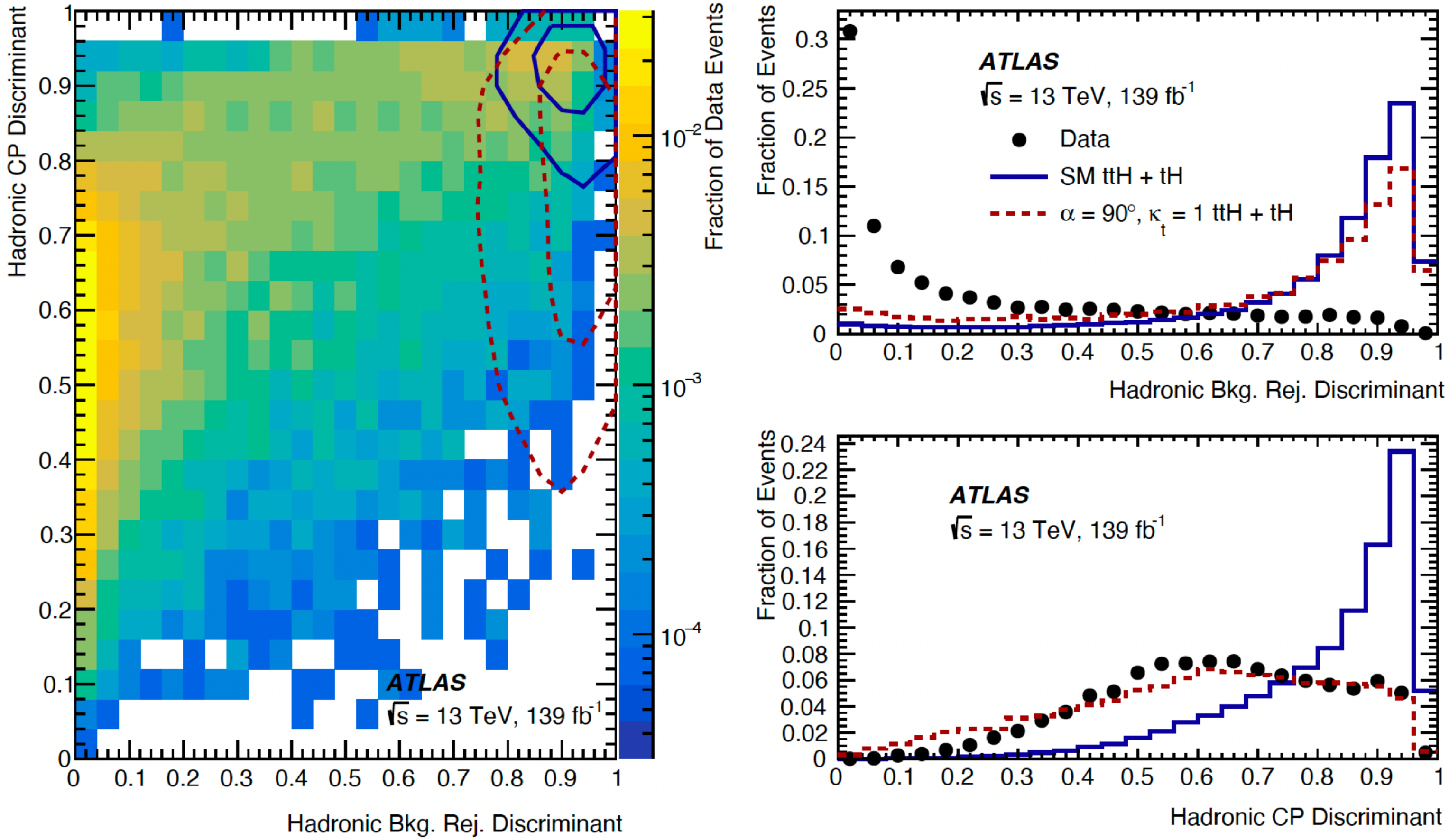
- Signal enrichment: require two isolated photons
  - Separation of $t\bar{t}$ decays into leptonic (>0 leptons) and hadronic (0 leptons)
  - $m_{\gamma\gamma}$ close to Higgs mass
- Reconstruction of top quark candidates using "Top Reco BDT"
  - Identification of top candidates
- 2D BDT by training two independent BDTs:
  - BDT to separate signal from background
  - BDT to separate CP-even from CP-odd $t\bar{t}H$ and tH
    - Use of kinematic and angular observables as input

Phys. Rev. Lett. 125 (2020) 061802

$t\bar{t}H$, $H\rightarrow\gamma\gamma$ in ATLAS

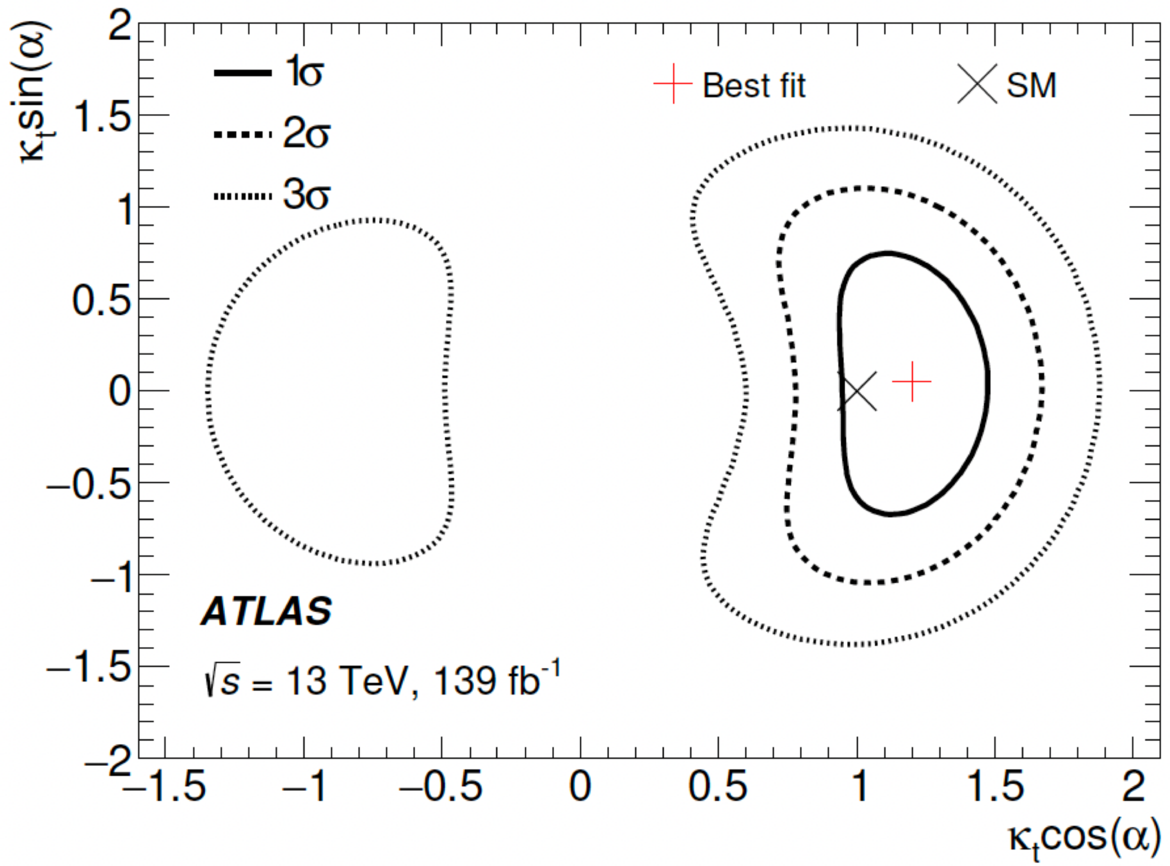
- Separate 2D BDT space into 20 categories
  - After removing low values in background BDT
- Fit of $m_{\gamma\gamma}$ in all categories

Phys. Rev. Lett. 125 (2020) 061802



$t\bar{t}H$, $H\rightarrow\gamma\gamma$ in ATLAS

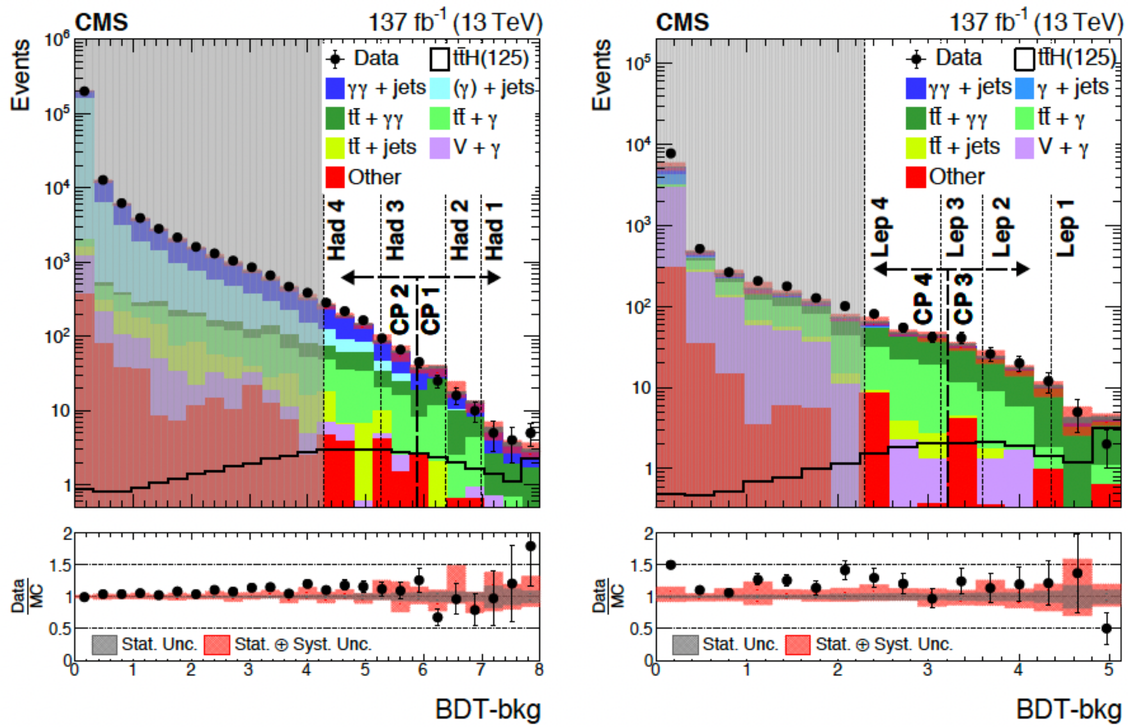
Result: exclusion of pure CP-odd coupling at 3.9 σ @95%CL



Phys. Rev. Lett. 125 (2020) 061802

$t\bar{t}H$, $H\rightarrow\gamma\gamma$ in CMS

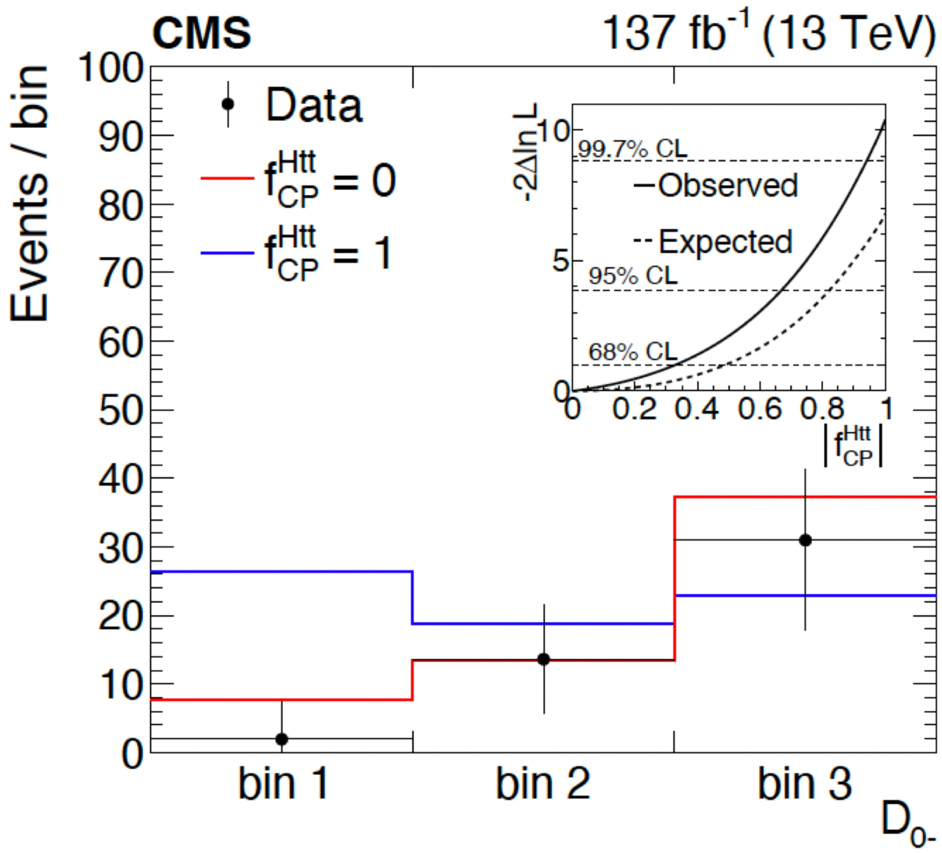
- Signal enrichment: require two isolated photons
  - Separation of $t\bar{t}$ decays into leptonic (>0 leptons) and hadronic (0 leptons)
- Training of BDT to separate $t\bar{t}H$ from background
- Training of CP-odd versus CP-even BDT in 4 categories
  - Using kinematic variables and b-tagging scores
  - Split into 3 bins
- Fit of $m_{\gamma\gamma}$ in all categories



Phys. Rev. Lett. 125, 061801 (2020)

$t\bar{t}H$, $H\to\gamma\gamma$ in CMS

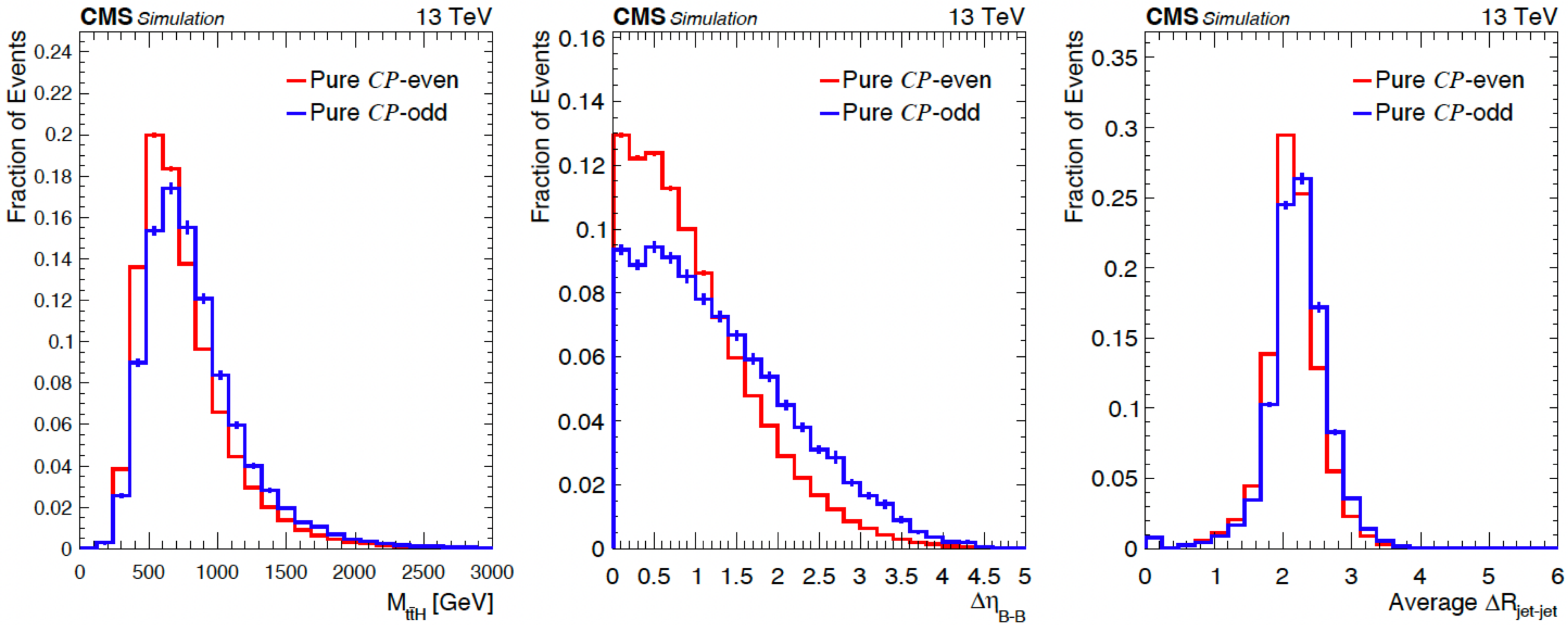
Result: exclusion of pure CP-odd coupling at 3.2 σ @95%CL



Phys. Rev. Lett. 125, 061801 (2020)

$t\bar{t}H$ multilepton in CMS

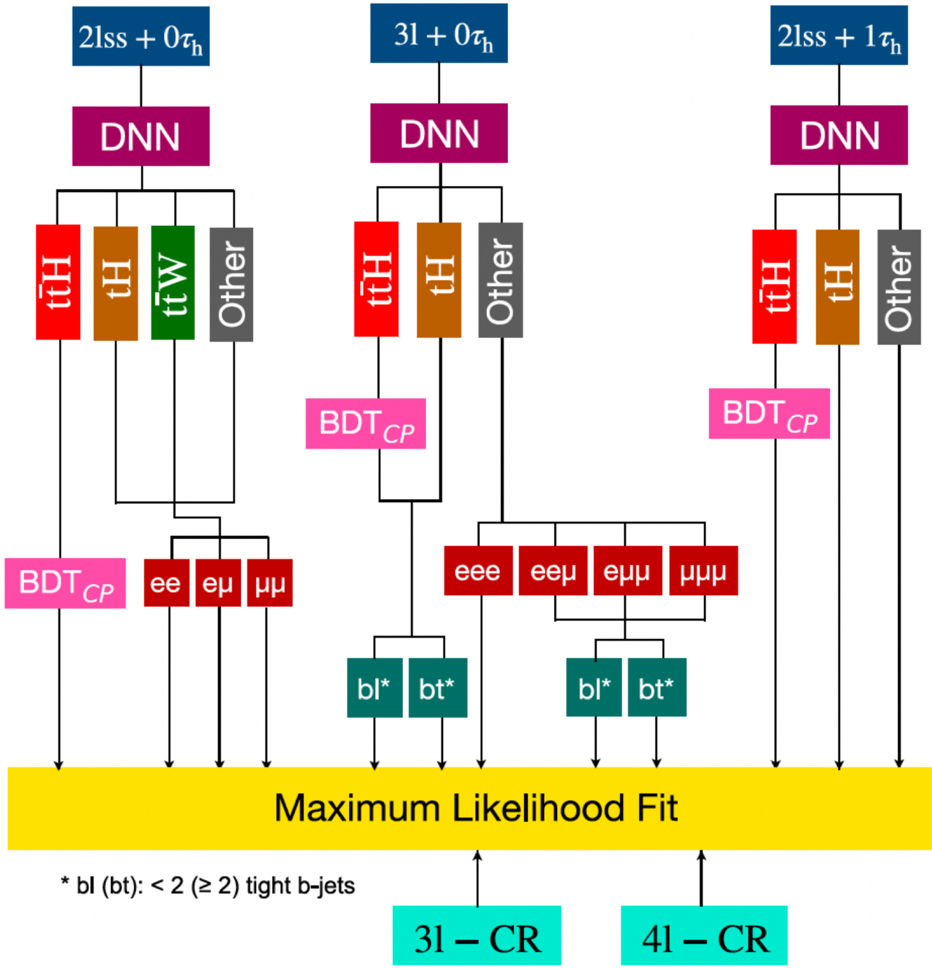
- $H \to VV$ and $\tau\tau$ decays
- Categorization:2 same-sign leptons + 0 or 1τ; 3 leptons + 0τ
- Multivariate methods for $t\bar{t}H$ & tH signal versus background
- CP-sensitive BDT trained in each channel



JHEP 07 (2023) 092

$t\bar{t}H$ multilepton in CMS

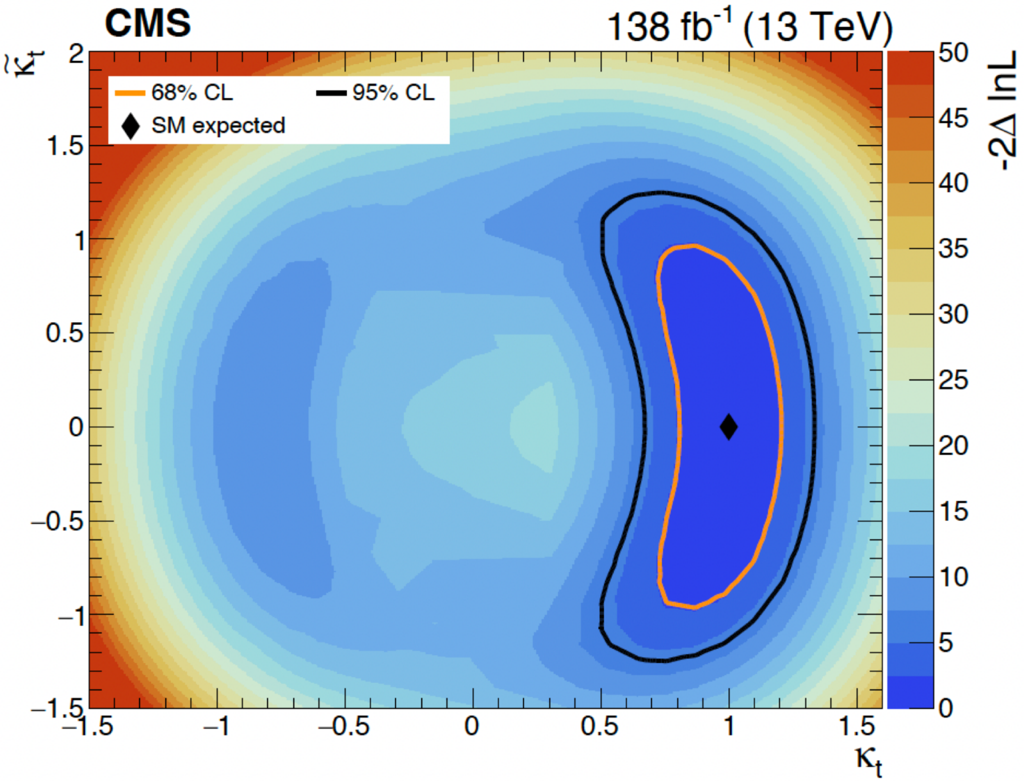
- Likelihood fit over various categories



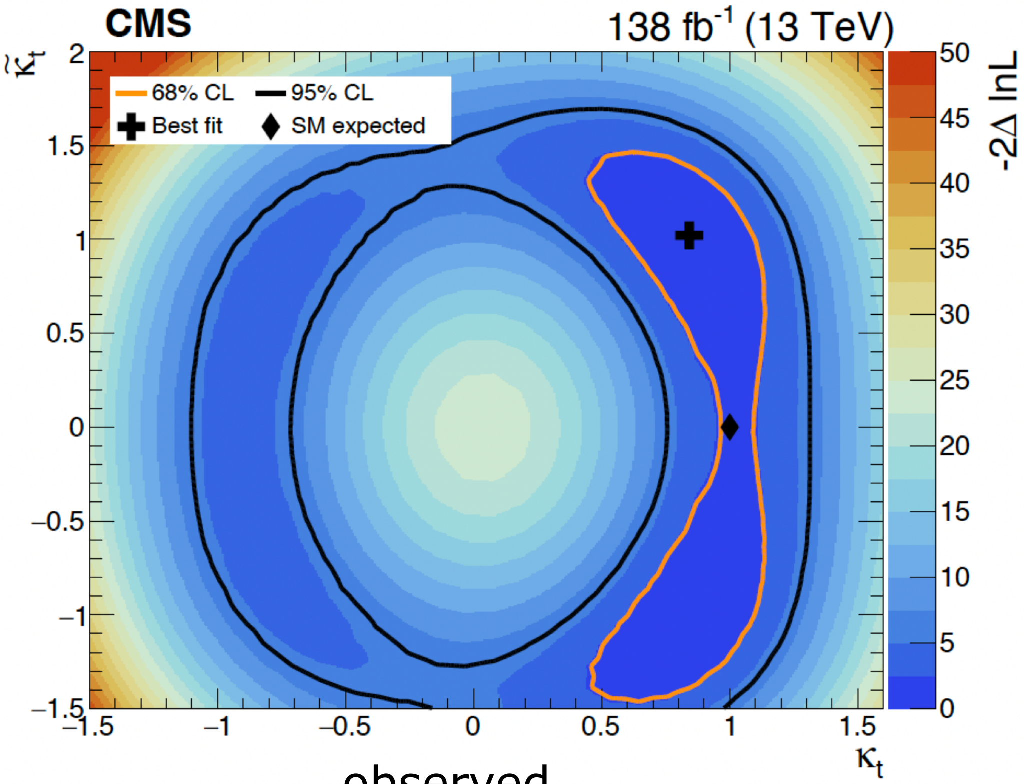
JHEP 07 (2023) 092

$t\bar{t}H$ multilepton in CMS

- Result: Exclusion of pure CP-odd Higgs with 2σ at 95% CL



predicted

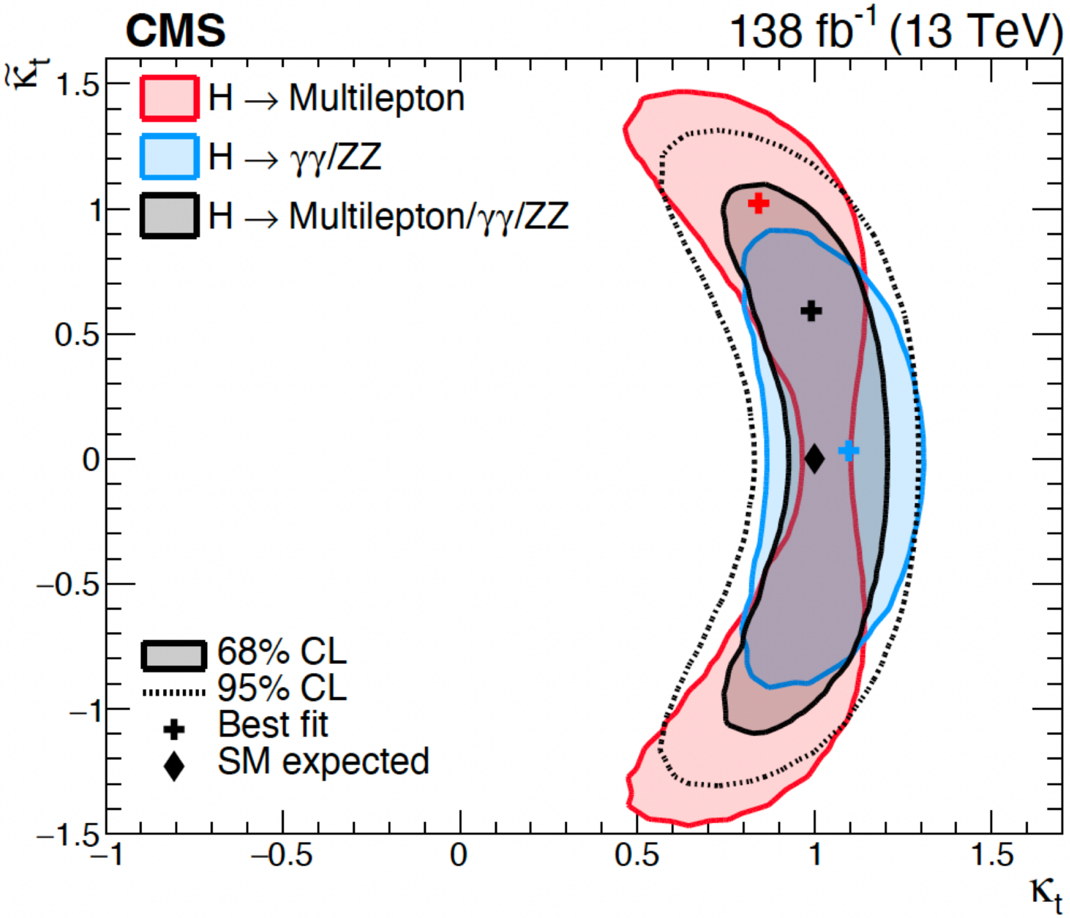


observed

JHEP 07 (2023) 092

$t\bar{t}H$ in CMS combined

- Result: exclusion of pure CP-odd with 3.7σ at 95% CL



JHEP 07 (2023) 092

$t\bar{t}H$, $H\rightarrow b\bar{b}$ in ATLAS

- Channels: $t\bar{t}H$ with 1 and 2 leptons + boosted region
- Signal enrichment using reconstruction and classification BDTs
  - Reconstruction BDT: assign jets to Higgs or top decay
    - Used as input to classification BDT & to construct CP-sensitive observables
  - Classification BDT: separate $t\bar{t}H$ signal versus backgrounds
- CP-sensitive observables:
  - L+jets:

$$b_2 = \frac{(\vec{p}_1 \times \hat{z}) \cdot (\vec{p}_2 \times \hat{z})}{|\vec{p}_1||\vec{p}_2|} \qquad \propto d\phi_{t\bar{t}}$$

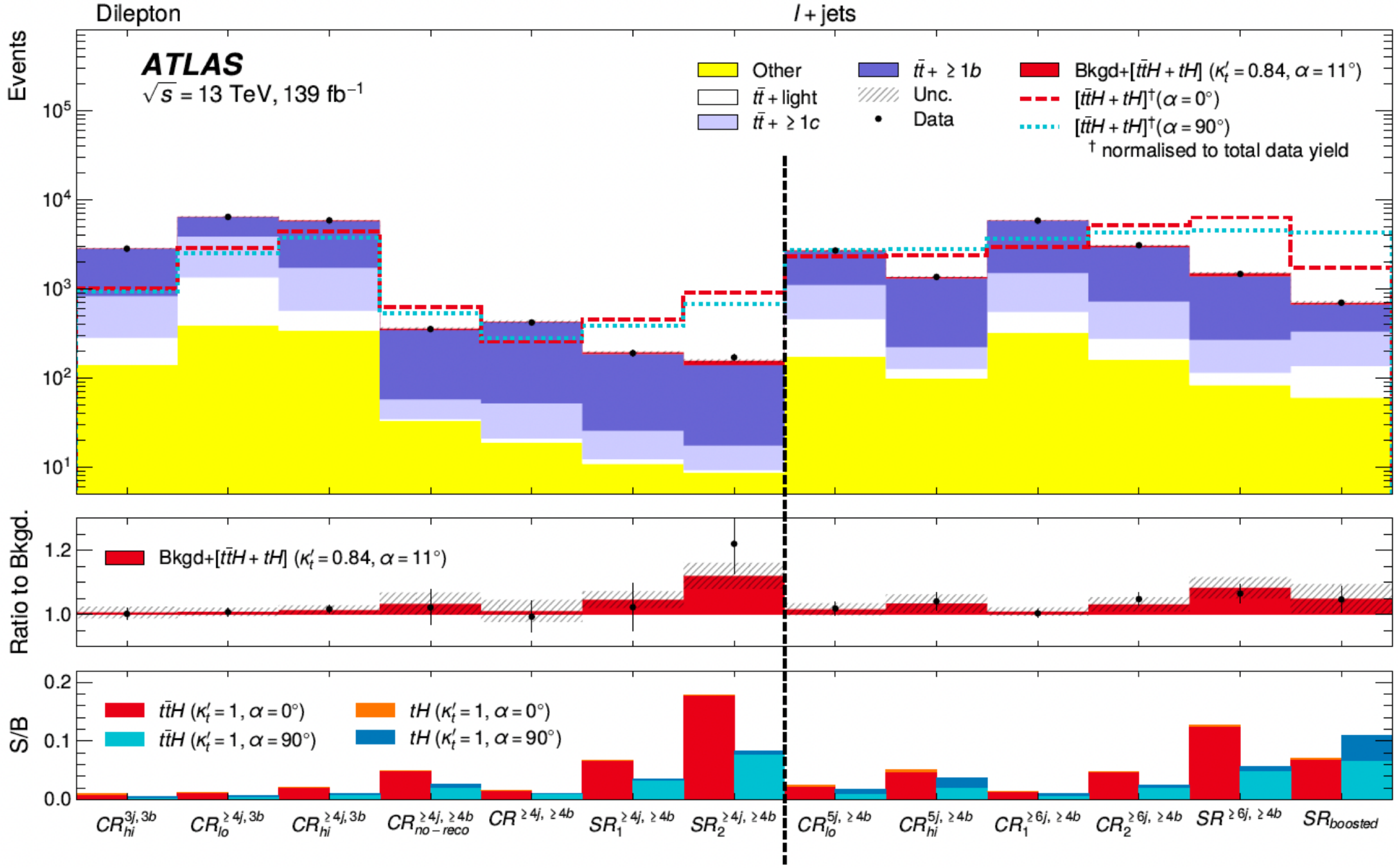
  - Dilepton:

$$b_4 = \frac{(\vec{p}_1 \cdot \hat{z})(\vec{p}_2 \cdot \hat{z})}{|\vec{p}_1||\vec{p}_2|}$$

p_1, p_2: momenta of top quarks
z: direction of beam axis

$t\bar{t}H$, $H\rightarrow b\bar{b}$ in ATLAS

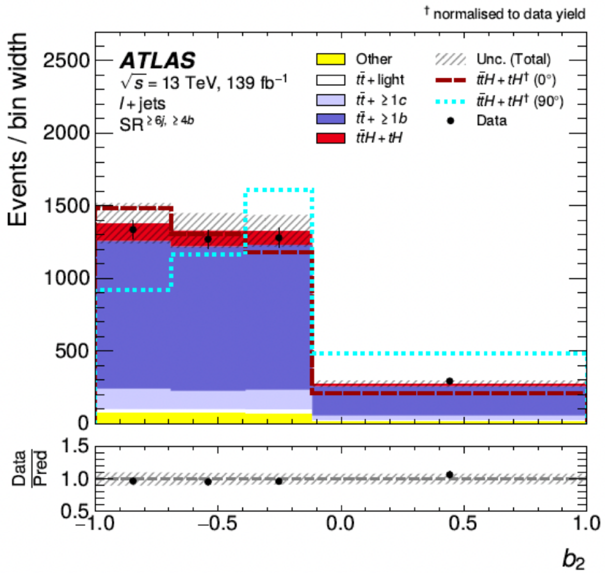
- Separation into regions
- Fit over all regions

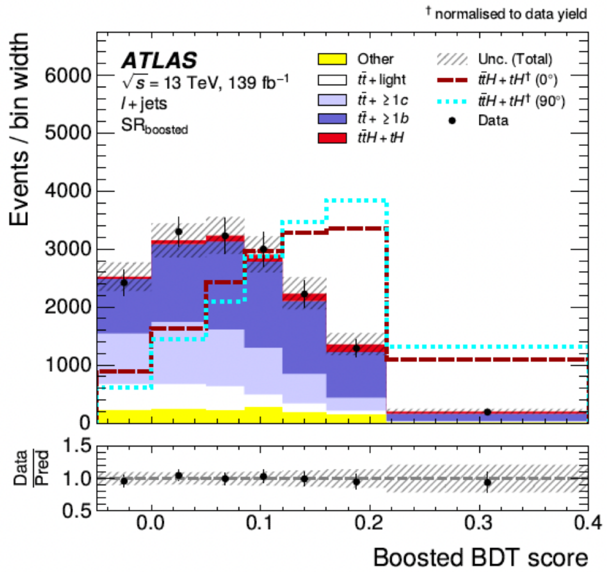


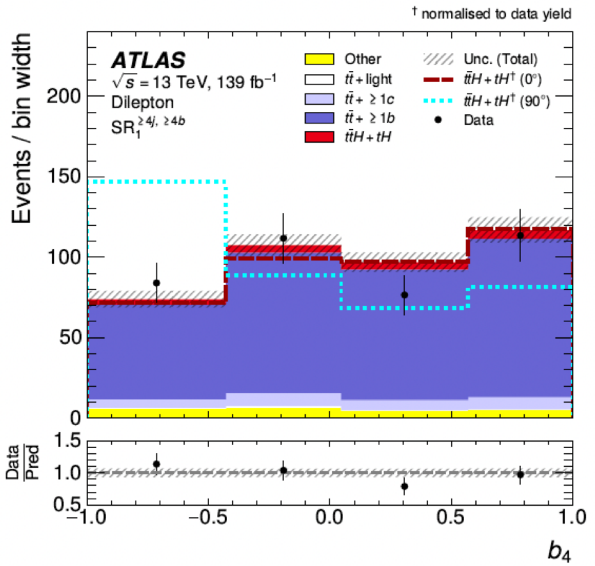
Phys. Lett. B. 849 (2024) 138469

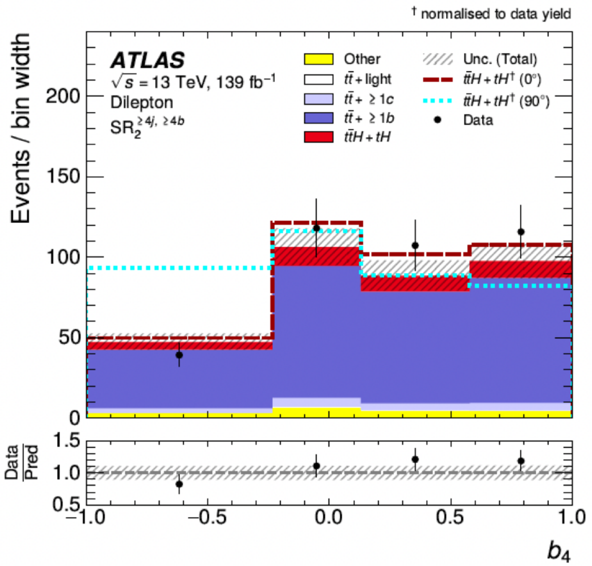
$t\bar{t}H$, $H \to b\bar{b}$ in ATLAS

- Fit over CP-sensitive observables





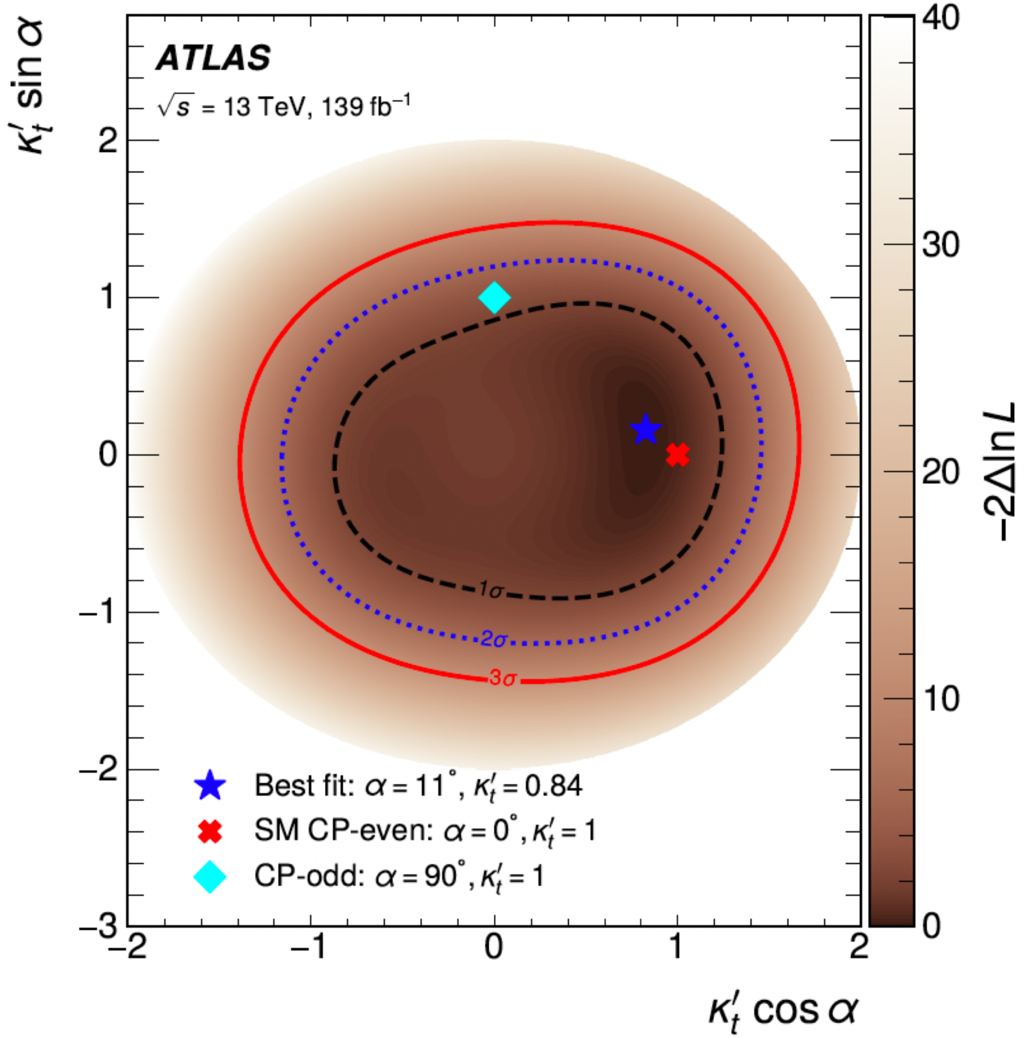




Phys. Lett. B. 849 (2024) 138469

$t\bar{t}H$, $H \to b\bar{b}$ in ATLAS

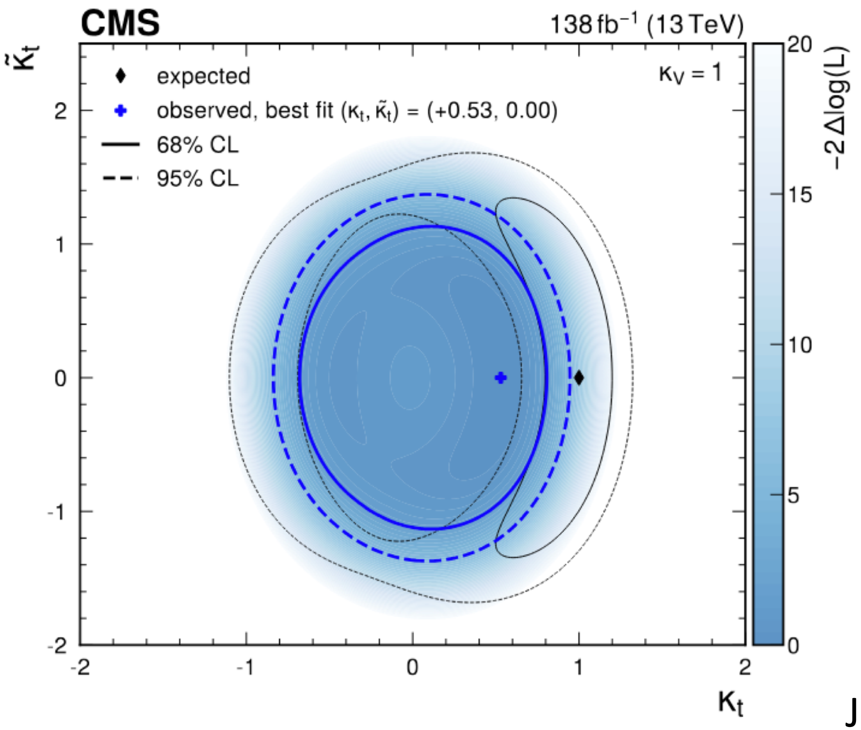
- Result: $\alpha = 11^{+52°}_{-73}$



Phys. Lett. B. 849 (2024) 138469

$t\bar{t}H$, $H \to b\bar{b}$ in CMS

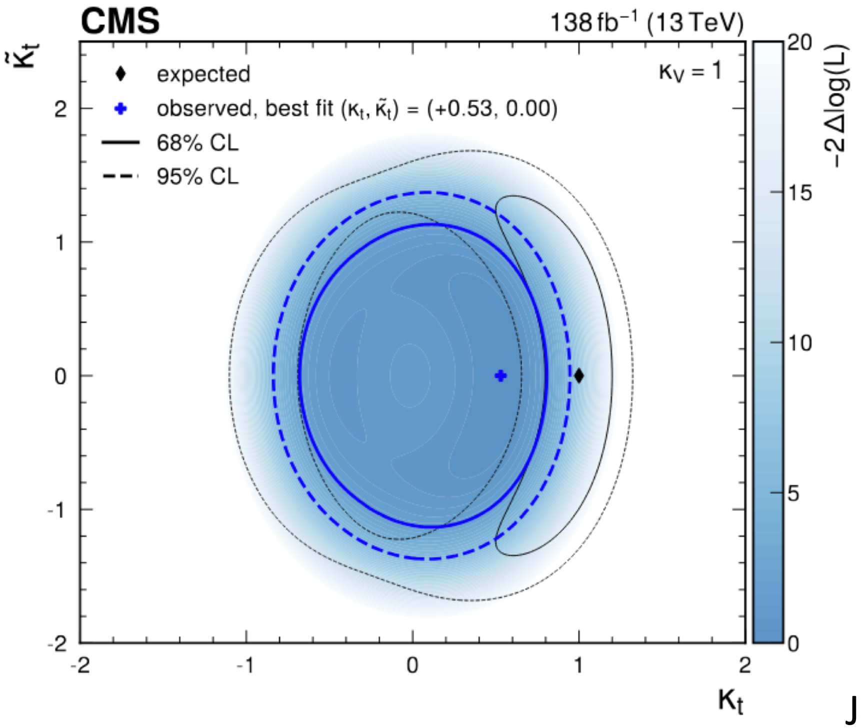
- Measurement of $t\bar{t}H$ and tH cross section
- Not dedicated measurement of CP structure, but interpretation in terms of CP structure

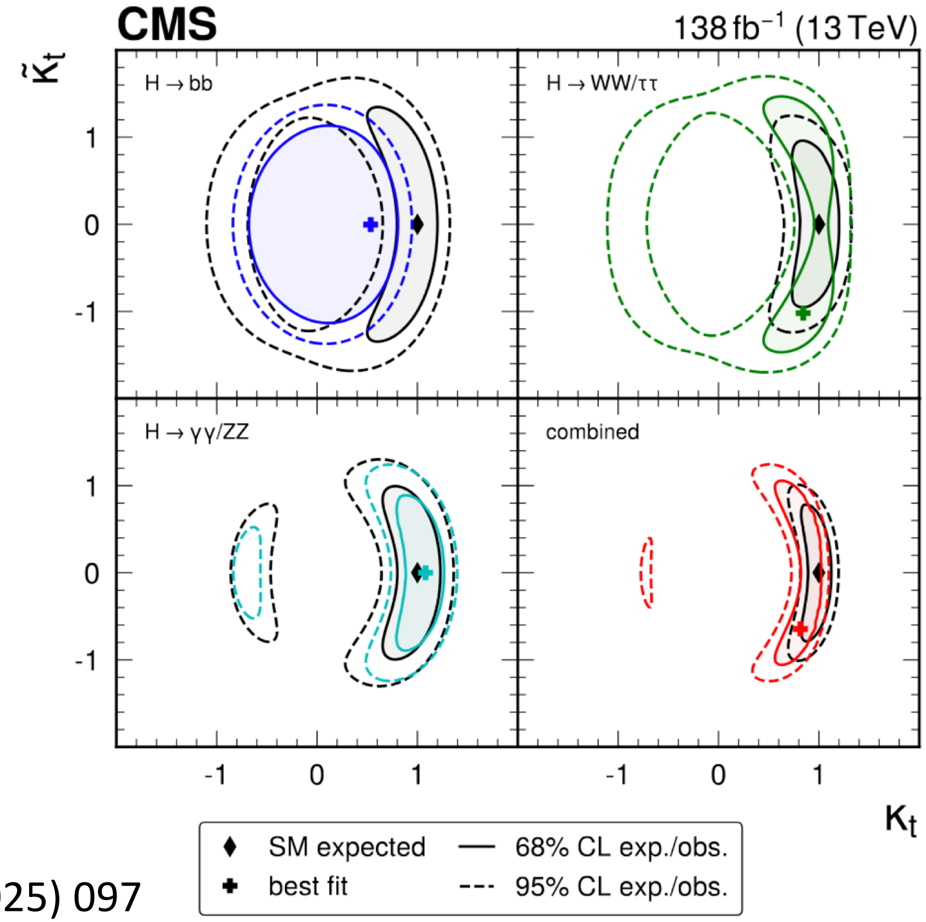


JHEP 02 (2025) 097

$t\bar{t}H$, $H \rightarrow b\bar{b}$ in CMS

- Measurement of $t\bar{t}H$ and tH cross section
- Not dedicated measurement of CP structure, but interpretation in terms of CP structure
- Combination with other channels: $\alpha < 67^\circ$ at 95% CL





JHEP 02 (2025) 097

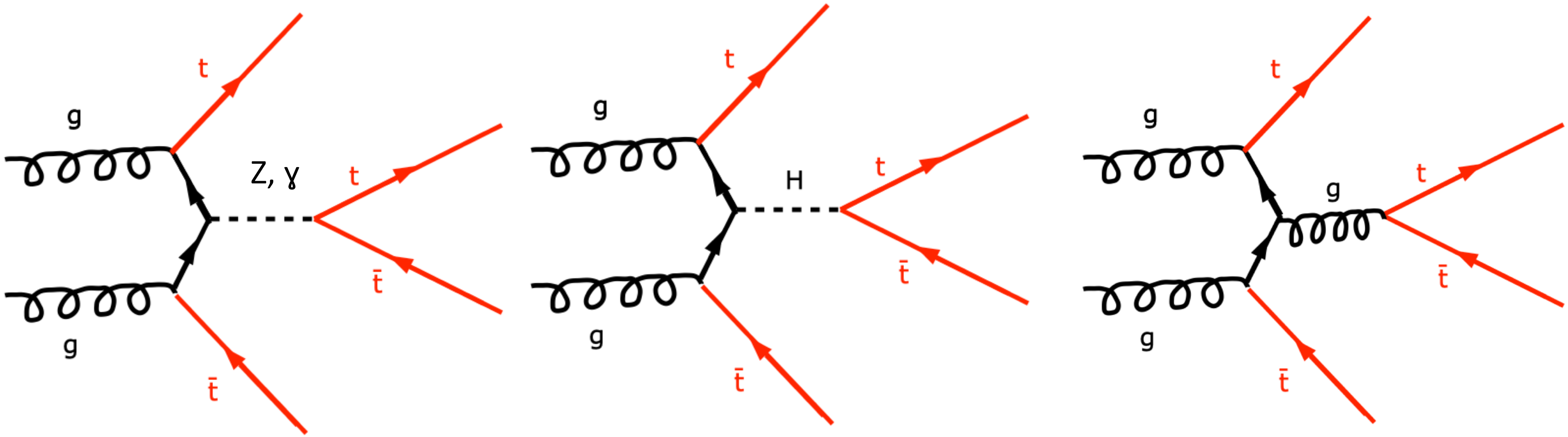
tH in ATLAS

New exciting ATLAS result coming out soon! (~ weeks)

Stay Tuned!

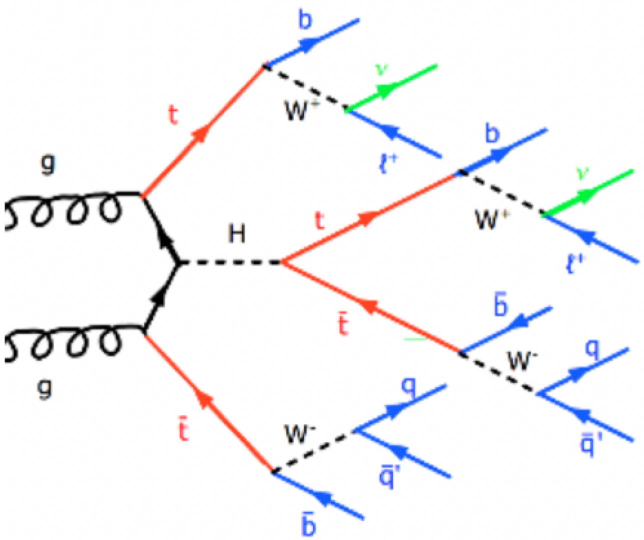
4 Tops

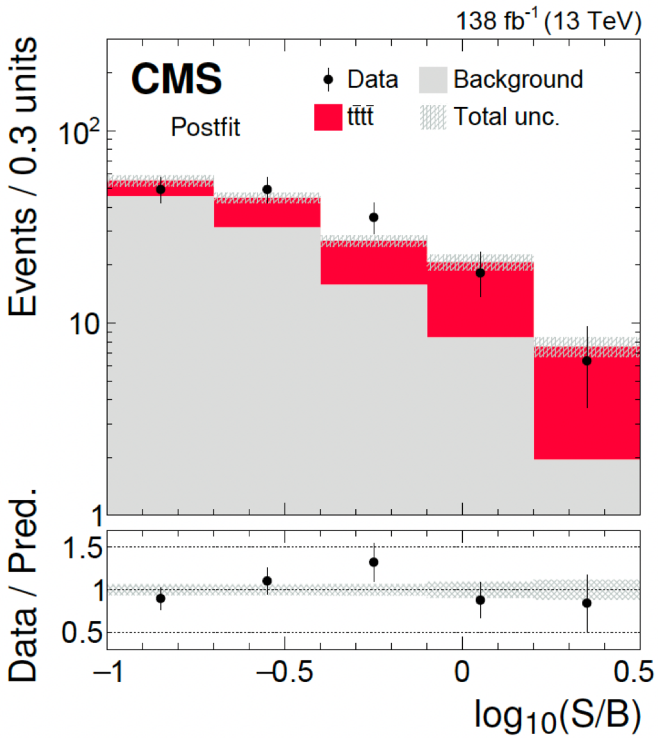
- $t\bar{t}t\bar{t}$: Rare process (12fb)
  - involving all SM interactions
  - Enhanced cross section in many BSM scenarios
- Sensitive to magnitude and CP properties of top-Higgs Yukawa coupling
  - Independent of Higgs decay



4Top in CMS

- Channels: same-sign dilepton and multilepton
  - Smaller branching fractions, but also smaller backgrounds
- Use of BDTs in different channels to enhance signal discrimination

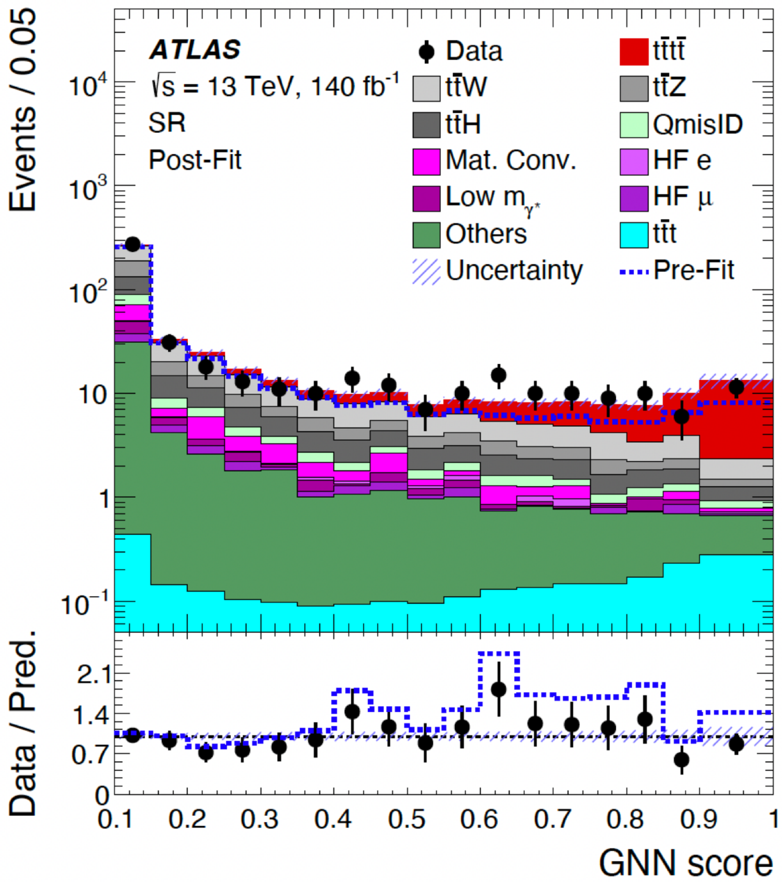




Phys. Lett. B 847 (2023) 138290

4Top in ATLAS

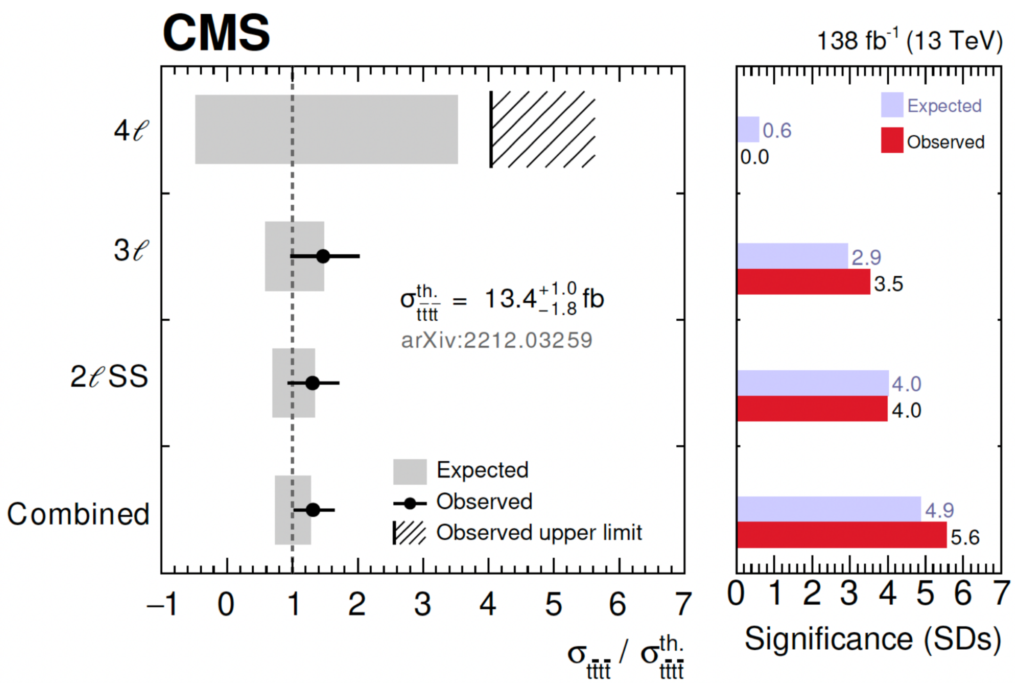
- Same channels as CMS
- Use of GNN for signal/background discrimination



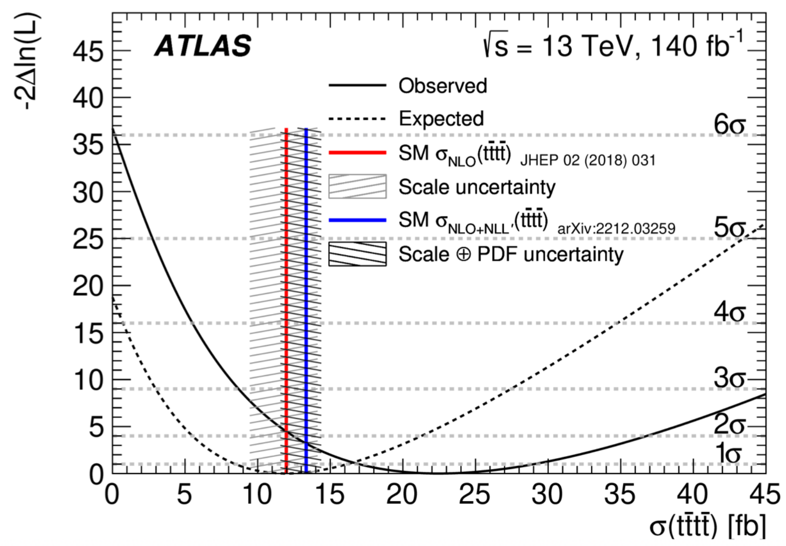
Eur. Phys. J. C 83 (2023) 496

4Top Observation!

- First observation of 4top production by ATLAS & CMS!
- SM prediction: 12.0±2.4fb



Phys. Lett. B 847 (2023) 138290



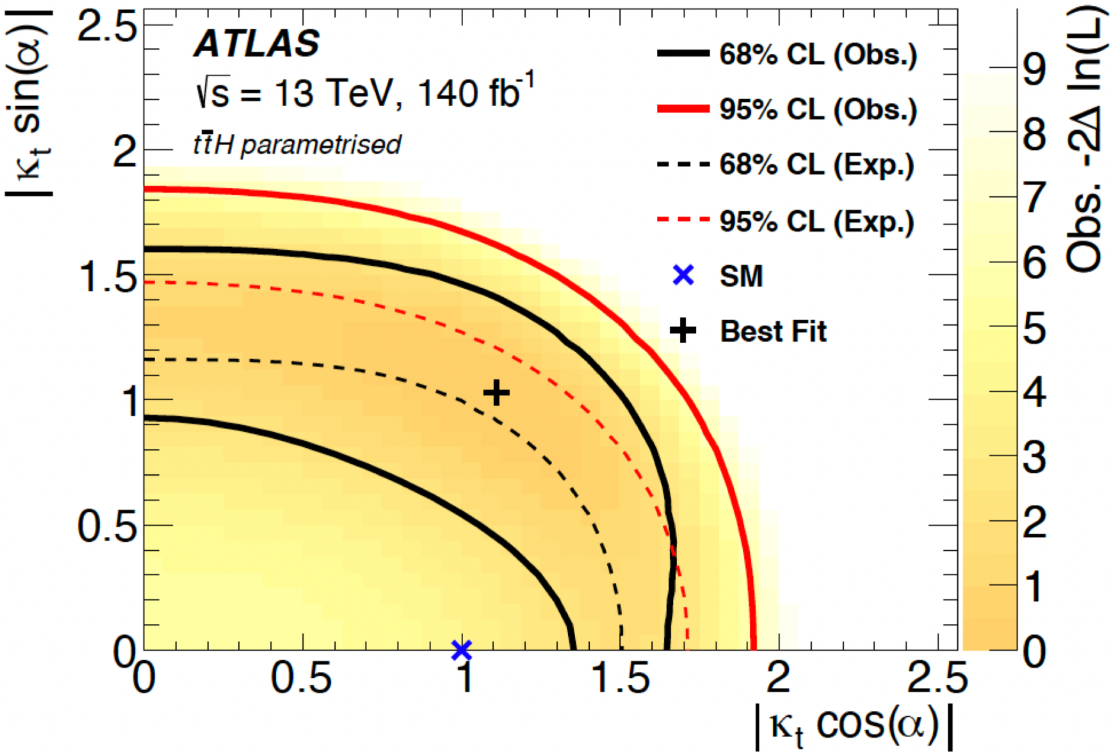
$$\sigma_{t\bar{t}t\bar{t}} = 22.5^{+4.7}_{-4.3}(\text{stat})\ ^{+4.6}_{-3.4}(\text{syst})\ \text{fb} = 22.5\ ^{+6.6}_{-5.5}\ \text{fb}$$

Eur. Phys. J. C 83 (2023) 496

- Observed cross sections larger than SM prediction
  - Intriguing: Statistics or physics beyond the standard model?

4Top and Top-Higgs

- ~10% of 4top process due to Higgs interaction
- Can interpret cross section in terms of Yukawa coupling and CP
  - Less stringent limits, but independent of non-top Higgs decay model



Eur. Phys. J. C 83 (2023) 496

CP violation in Top-Higgs: The Future

- Many avenues proposed by theorists for further improvements
  - Optimised variables
  - Machine learning

Boosting probes of CP violation in the top Yukawa coupling with Deep Learning
arXiv:2405.16499

Machine Learning the Higgs-Top CP Phase
arXiv:2110.07635

Constraining the $\mathcal{CP}$ structure of Higgs-fermion couplings with a global LHC fit, the electron EDM and baryogenesis
arXiv:2211.00845

Constraining $\mathcal{CP}$-violation in the Higgs–top-quark interaction using machine-learning-based inference
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Determining the CP Property of $ht\bar{t}$ Coupling via a Novel Jet Substructure Observable
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arXiv:2211.00845

- Various other searches sensitive to CP
  - Direct searches: 2HDM searches
    - CP-odd Higgs bosons
  - Indirect approach: EFT

CP, top-Higgs and EFT

- Assuming new physics at much higher energies: effective field theory approach
  - Model independent
- SMEFT:

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{d>4} \sum_{i}^{N_d} \frac{C_i O_i^{(d)}}{\Lambda^{d-4}}$$

C: Wilson coefficient
O: operator
Λ: scale

- Contribution to physical observables X

$$X_{\mathrm{SMEFT}} = X_{\mathrm{SM}} + \sum_i \frac{C_i}{\Lambda^2} X_i^{\mathrm{int}} + \sum_{ij} \frac{C_i C_j}{\Lambda^4} X_{ij}^{\mathrm{quad}} + \mathcal{O}(\Lambda^{-4})$$

From interference with SM

- Total cross section: CP-even observable; sensitive to CP-odd coupling at quadratic order

CP, top-Higgs and EFT

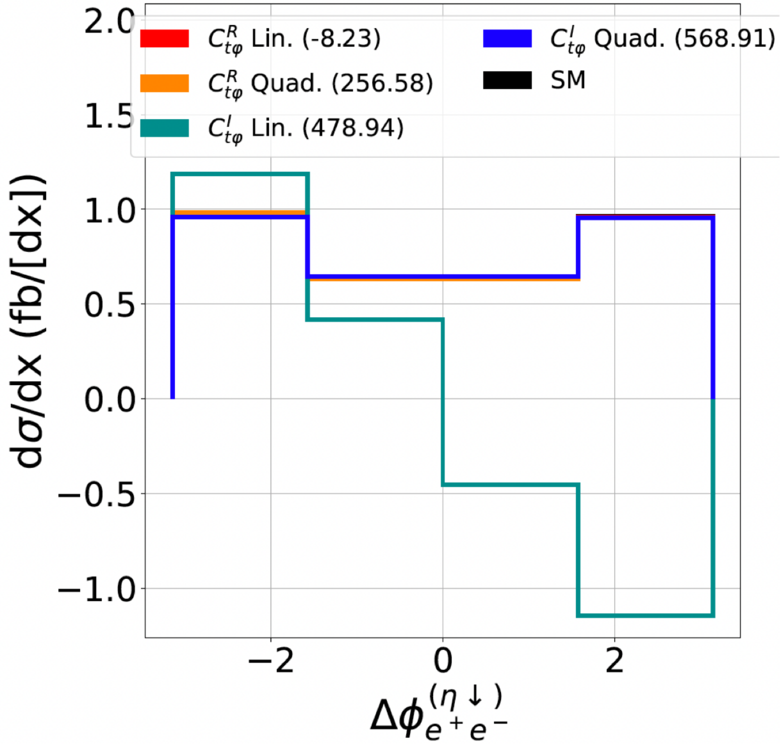
- Construction of CP-sensitive CP-odd observables for $t\bar{t}H$ and tH
  - Sensitive to CP-odd couplings at linear order

- EFT operators related to CP structure:

$$\mathcal{L}_{h\bar{t}t} = -\frac{m_t}{v}\bar{t}(\kappa\cos\alpha + i\gamma_5\kappa\sin\alpha)th,$$

$$\kappa\cos\alpha = 1 - \frac{3v^3}{2\sqrt{2}\,m_t}\frac{C_{t\varphi}}{\Lambda^2}, \quad \kappa\sin\alpha = -\frac{3v^3}{2\sqrt{2}\,m_t}\frac{C^I_{t\varphi}}{\Lambda^2}.$$

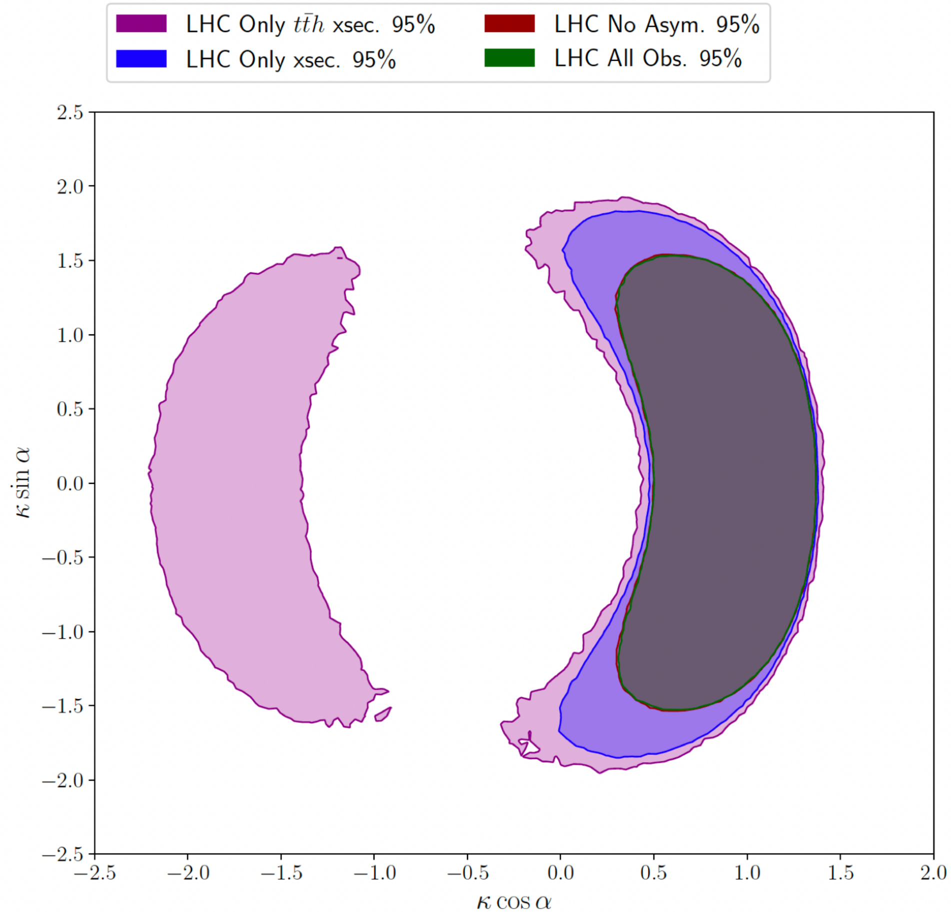
  - $C_{t\varphi}$: related to operator between top and Higgs field



V. Mirales, YP, E. Vryonidou, J. Winter, arXiv:2412.10309

CP, top-Higgs and EFT

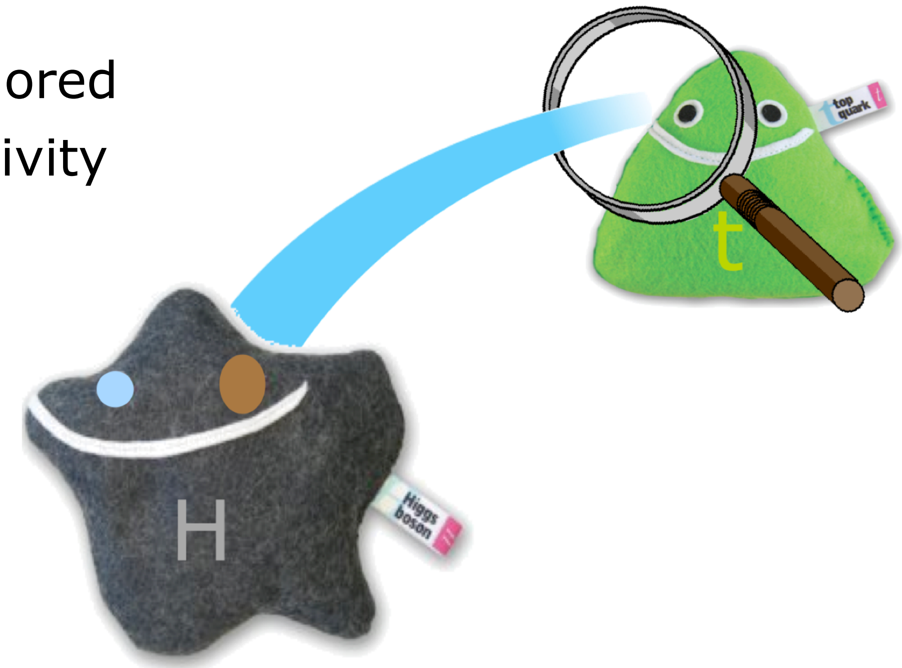
- Assuming 300 fb^{-1}
- tH input needed to resolve degeneracy



V. Mirales, YP, E. Vryonidou, J. Winter, arXiv:2412.10309

Summary

- Top-Higgs joined the hunt for CP violation!
- Main processes: $t\bar{t}H$ and tH
  - With extra insight from 4top processes
- ATLAS & CMS: exclusion of pure CP-odd top-Higgs coupling
  - But: CP violation only requires admixture of CP-odd Higgs
- The future is bright
  - New LHC data (Run 3) set still to be explored
  - Various ideas for improvements of sensitivity



BACKUP

4Top Observation ATLAS

Uncertainty source	$\Delta\sigma$ [fb]		$\Delta\sigma/\sigma$[%]	
Signal modelling				
$t\bar{t}t\bar{t}$ generator choice	+3.7	−2.7	+17	−12
$t\bar{t}t\bar{t}$ parton shower model	+1.6	−1.0	+7	−4
Other $t\bar{t}t\bar{t}$ modelling	+0.8	−0.5	+4	−2
Background modelling				
$t\bar{t}H$+jets modelling	+0.9	−0.7	+4	−3
$t\bar{t}W$+jets modelling	+0.8	−0.8	+4	−3
$t\bar{t}Z$+jets modelling	+0.5	−0.4	+2	−2
Other background modelling	+0.5	−0.4	+2	−2
Non-prompt leptons modelling	+0.4	−0.3	+2	−2
$t\bar{t}t$ modelling	+0.3	−0.2	+1	−1
Charge misassignment	+0.1	−0.1	+0	−0
Instrumental				
Jet flavour tagging (b-jets)	+1.1	−0.8	+5	−4
Jet uncertainties	+1.1	−0.7	+5	−3
Jet flavour tagging (light-flavour jets)	+0.9	−0.6	+4	−3
Jet flavour tagging (c-jets)	+0.5	−0.4	+2	−2
Simulation sample size	+0.4	−0.3	+2	−1
Other experimental uncertainties	+0.4	−0.3	+2	−1
Luminosity	+0.2	−0.2	+1	−1
Total systematic uncertainty	+4.6	−3.4	+20	−16
Statistical				
Intrinsic statistical uncertainty	+4.2	−3.9	+19	−17
$t\bar{t}W$+jets normalisation and scaling factors	+1.2	−1.1	+6	−5
Non-prompt leptons normalisation (HF, Mat. Conv., Low m_{γ^*})	+0.4	−0.3	+2	−1
Total statistical uncertainty	+4.7	−4.3	+21	−19
Total uncertainty	+6.6	−5.5	+29	−25

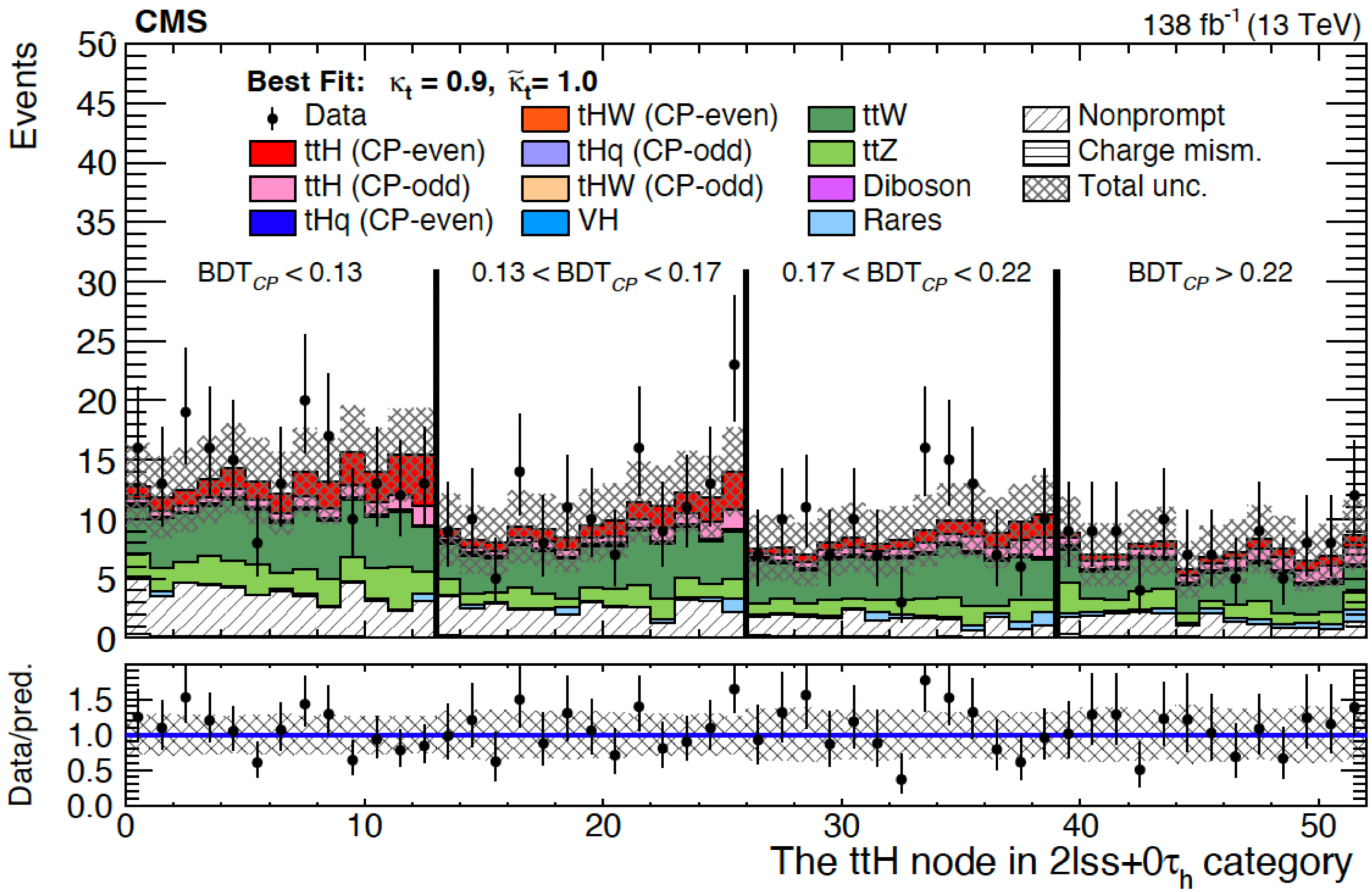
ttH, H to bb ATLAS

Region		Dilepton				ℓ+jets			
		$\mathrm{TR}^{\geq 4j,\geq 4b}$	$\mathrm{CR}^{\geq 4j,3b}_{\mathrm{hi}}$	$\mathrm{CR}^{\geq 4j,3b}_{\mathrm{lo}}$	$\mathrm{CR}^{3j,3b}_{\mathrm{hi}}$	$\mathrm{TR}^{\geq 6j,\geq 4b}$	$\mathrm{CR}^{5j,\geq 4b}_{\mathrm{hi}}$	$\mathrm{CR}^{5j,\geq 4b}_{\mathrm{lo}}$	$\mathrm{TR}_{\mathrm{boosted}}$
N_{jets}		≥ 4			$= 3$	≥ 6	$= 5$		≥ 4
$N_{b\text{-tag}}$	@85%	–				≥ 4			
	@77%	–				–			$\geq 2^{\dagger}$
	@70%	≥ 4	$= 3$			≥ 4			–
	@60%	–	$= 3$	< 3	$= 3$	–	≥ 4	< 4	–
$N_{\mathrm{boosted\ cand.}}$		–				0			≥ 1
Fit observable		–	Yield			–	$\Delta R^{\mathrm{avg}}_{bb}$		–

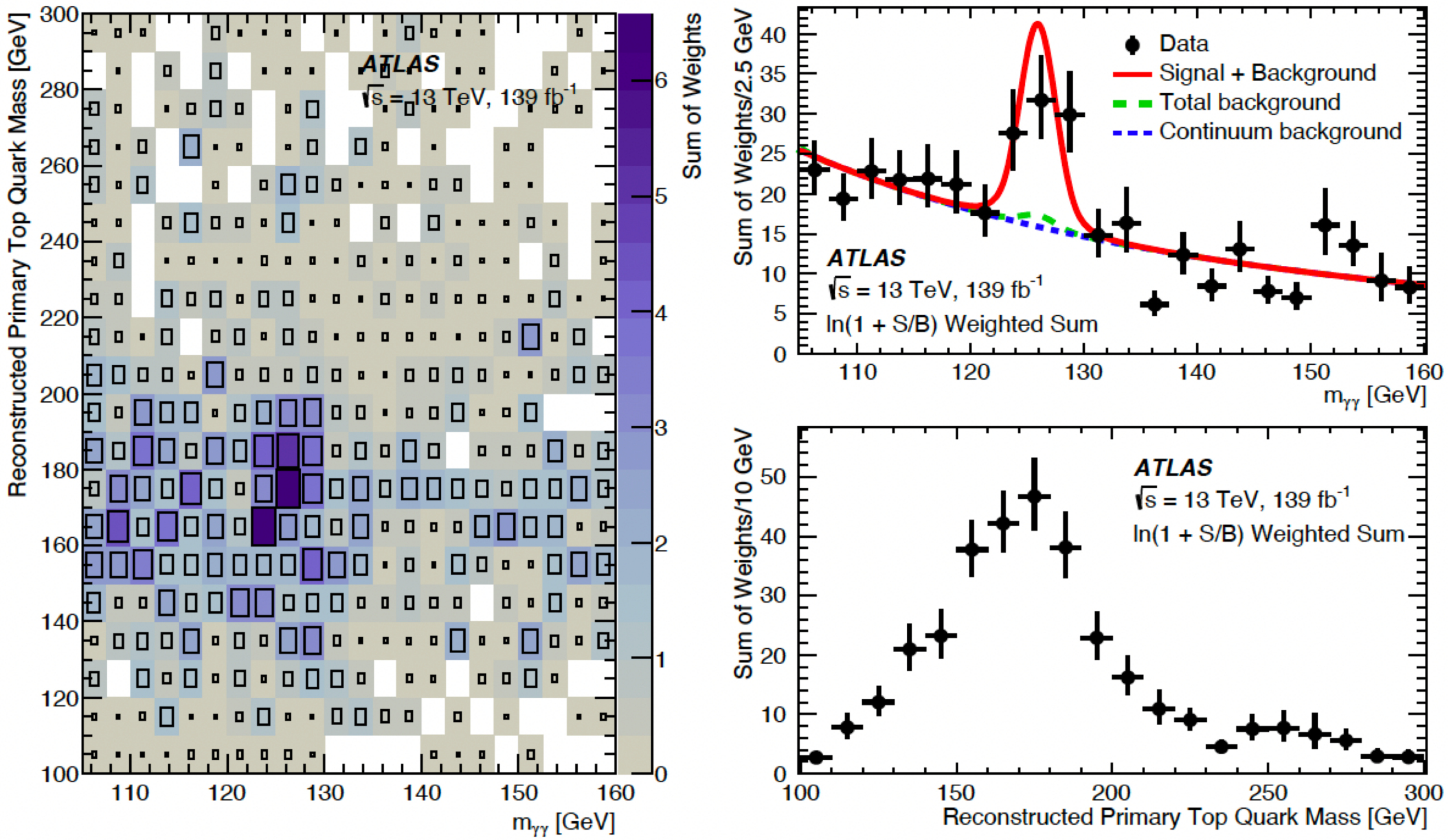
For tH and tWH: interference between diagrams with
CP-even and CP-odd $t-H$ and SM $W-H$ couplings are considered by parametrising the signal yield in each analysis bin (fitted to simulated samples)

$$N_{tH}(\kappa_t', \alpha) = A\kappa_t'^2 c_\alpha^2 + B\kappa_t'^2 s_\alpha^2 + C\kappa_t' c_\alpha + D\kappa_t' s_\alpha + E\kappa_t'^2 c_\alpha s_\alpha + F$$

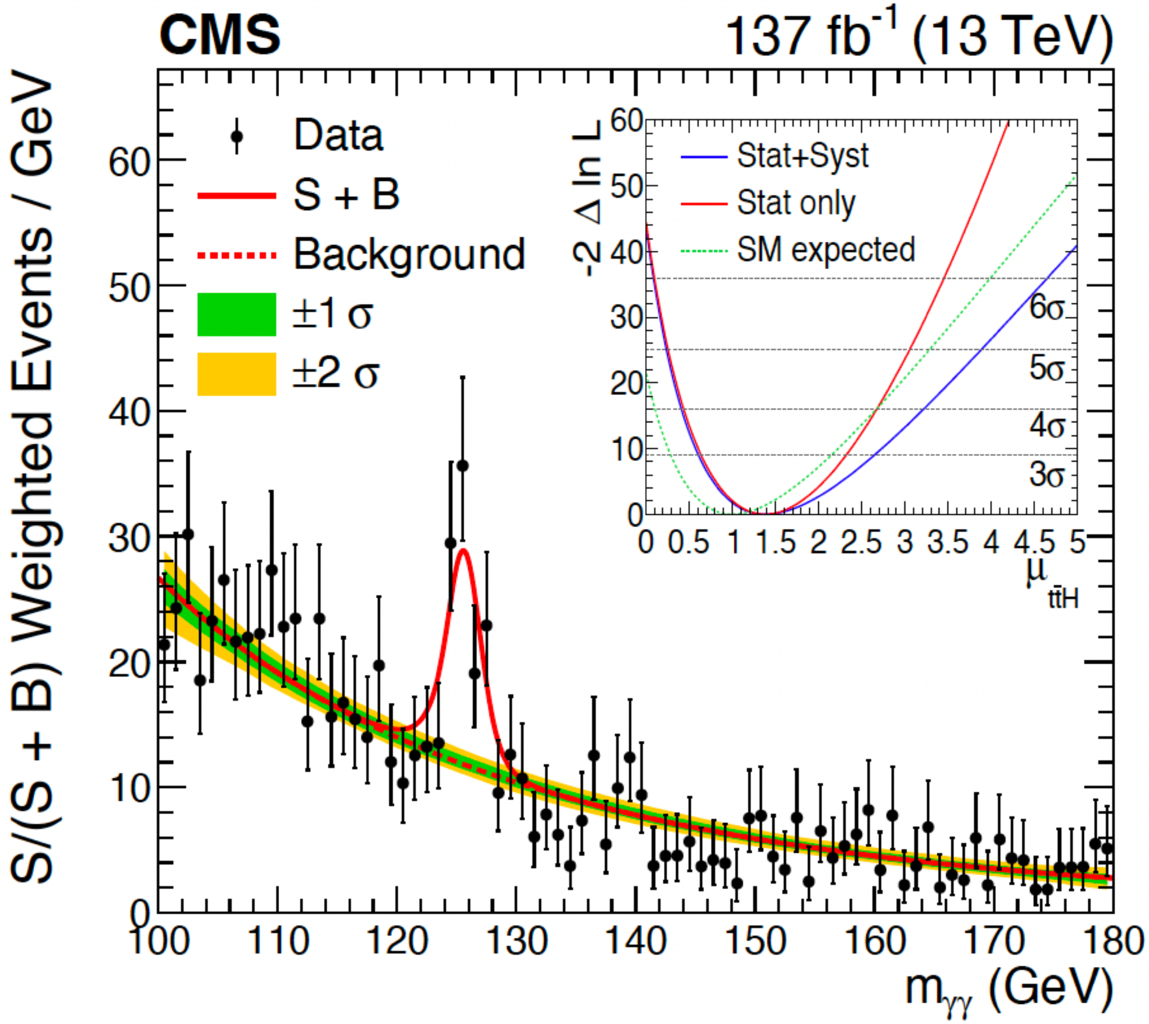
ttH, multilepton, CMS



ttH, H to gamma gamma ATLAS



ttH, H to gamma gamma CMS



HyPER

- Edges, nodes and HyPER structure

$$\mathbf{x}_i^{(0)} = (p_{Ti}, \eta_i, \phi_i, E_i, b\text{-tag}_i),$$
$$\mathbf{e}_{j\to i}^{(0)} = \mathbf{e}_{ij}^{(0)} = (\Delta\eta_{ij}, \Delta\phi_{ij}, \Delta R_{ij}, M_{ij}),$$
$$\mathbf{u}^{(0)} = (N_{\text{jets}}, N_{b\text{-tagged}}),$$