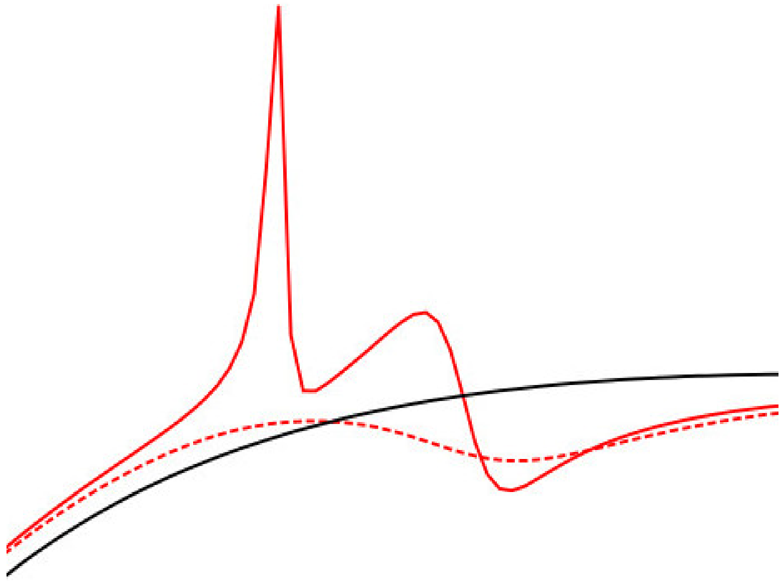
# Searching for the fingerprints of new phenomena with top quarks



**Dr. Katharina Behr**

KIT Particle Physics Colloquium

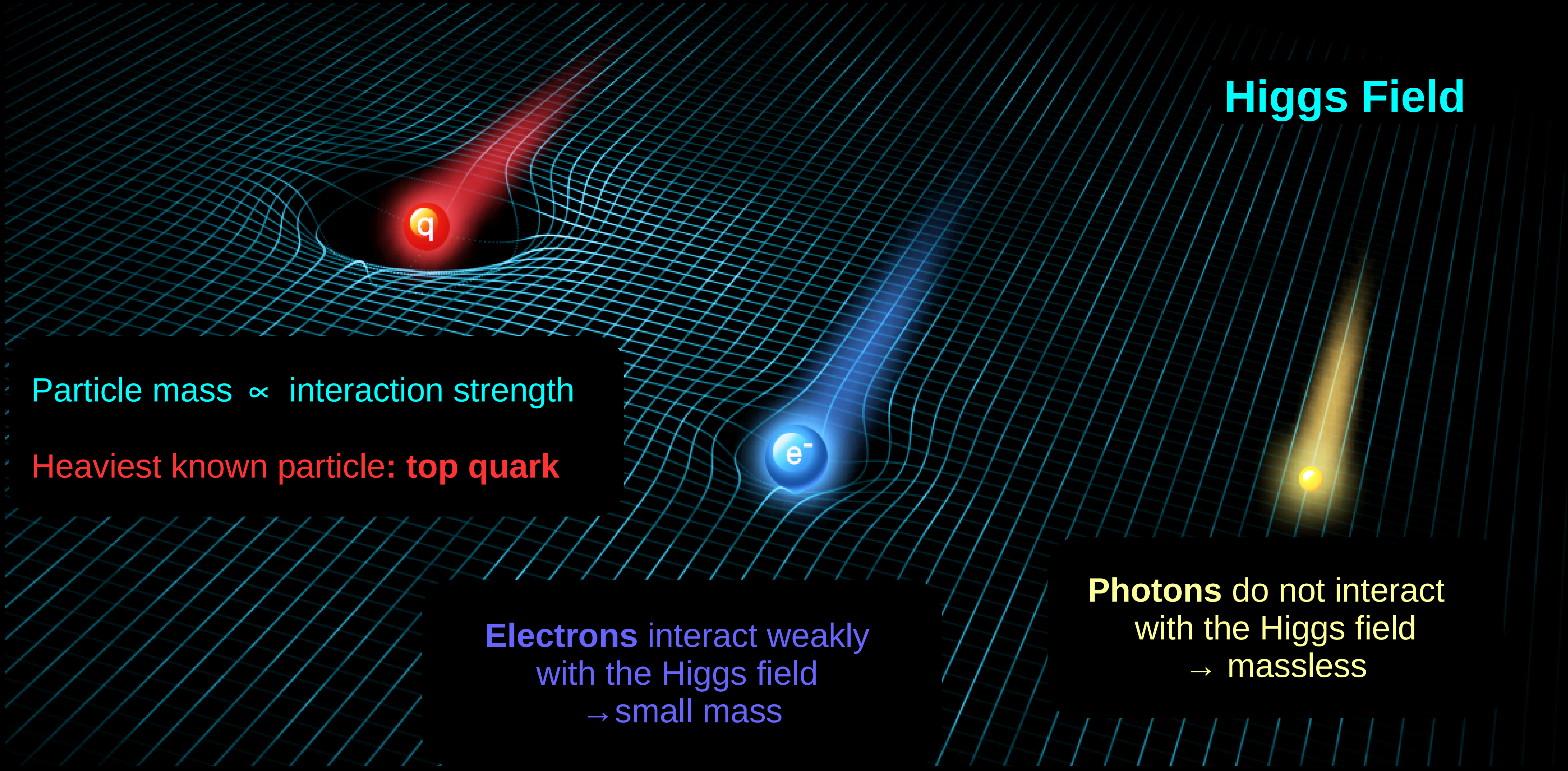
23 January 2025

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

ATLAS EXPERIMENT

DESY.

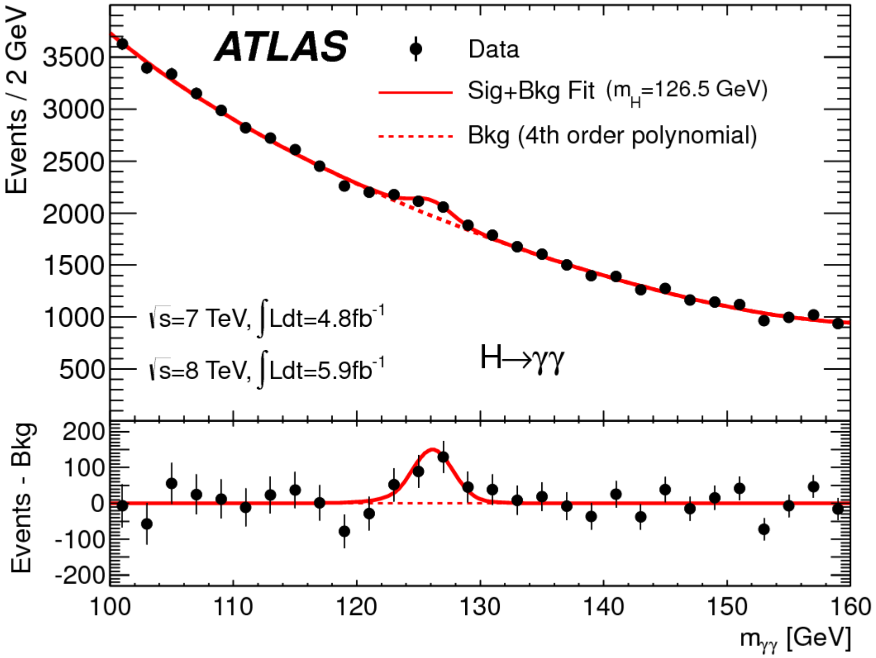


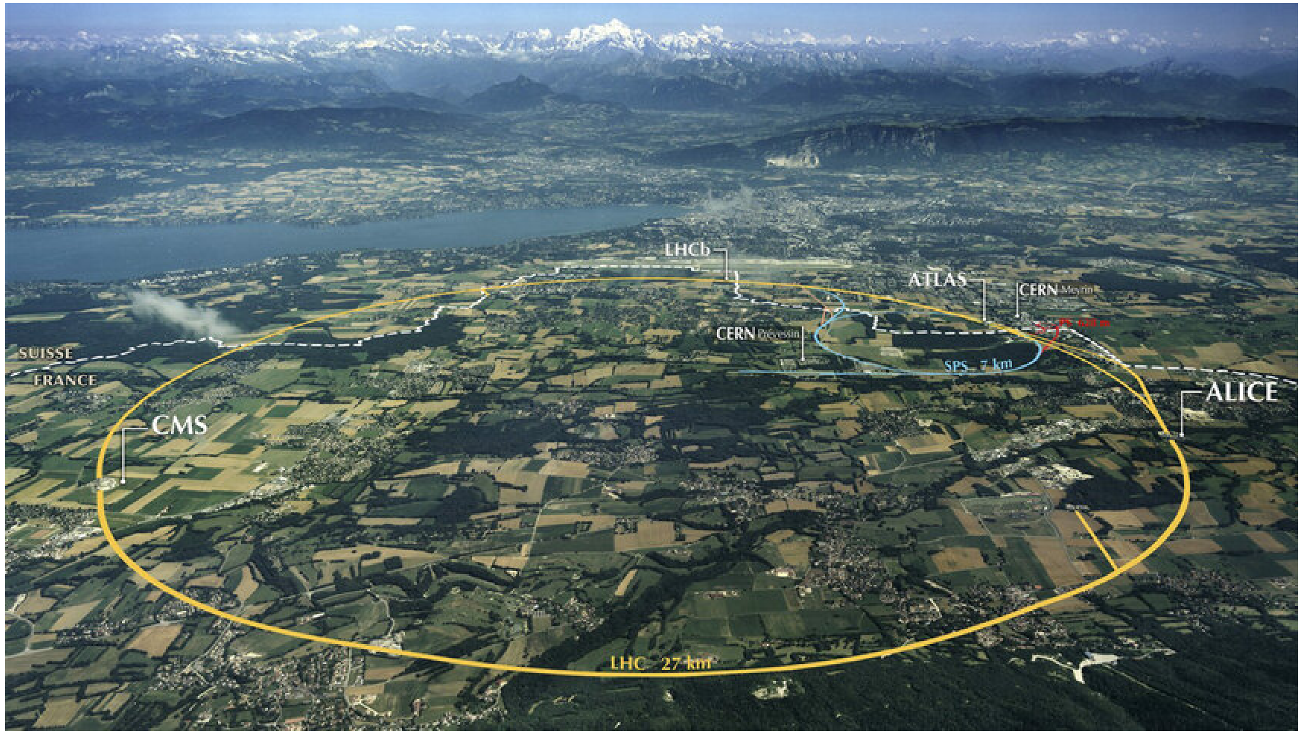

Artistic view of the Higgs field.
Image credit: beyondsciencetv.com

# The discovery of a Higgs boson...

> … by the ATLAS and CMS experiments at the LHC in 2012.

Observation in γγ channel

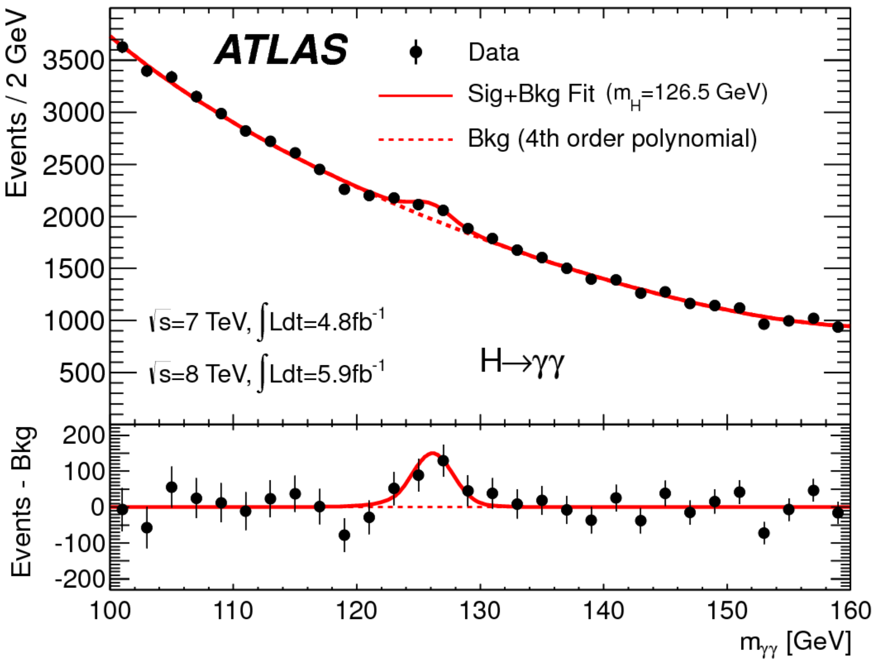


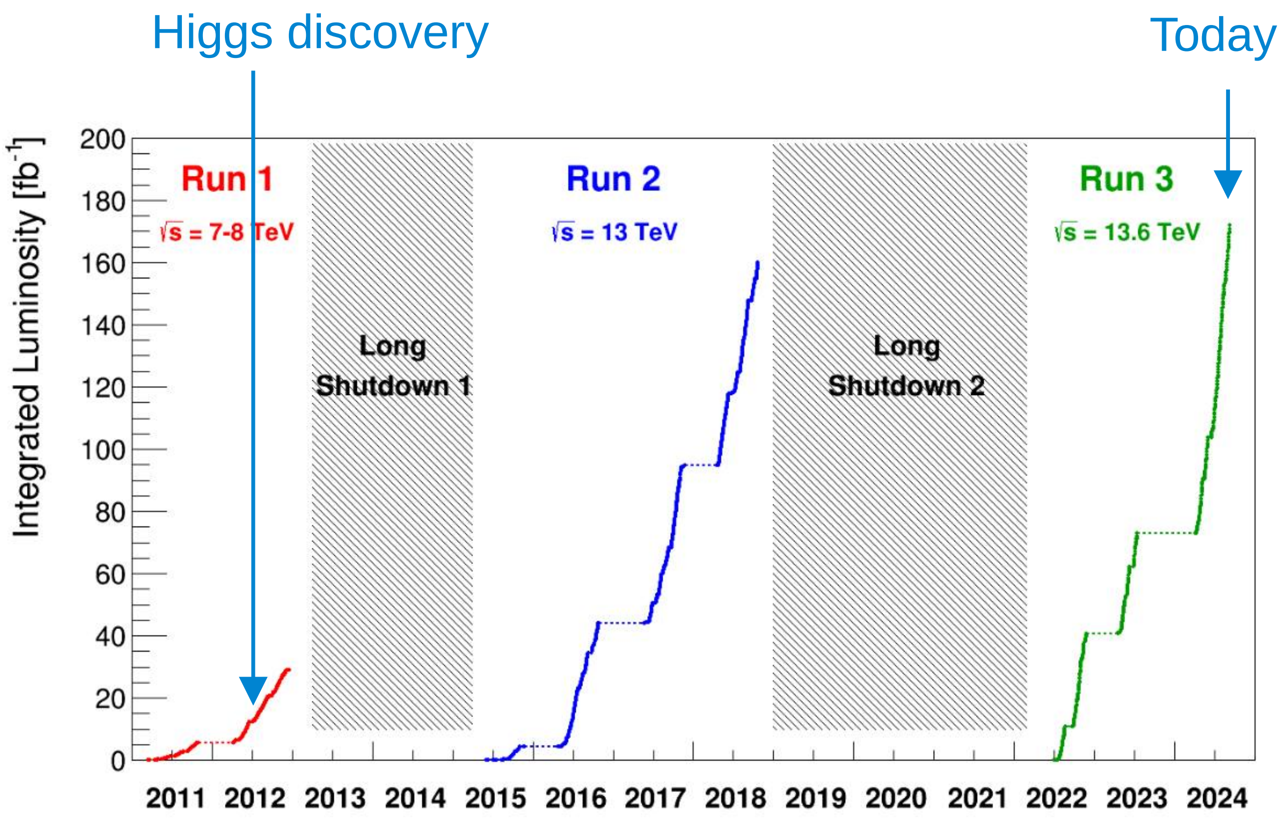



# The discovery of a Higgs boson...

- … by the ATLAS and CMS experiments at the LHC in 2012.
- Only a fraction of LHC Run-1 data: ~10 $fb^{-1}$ of data at $\sqrt{s}$ = 7 TeV and 8 TeV

Observation in γγ channel

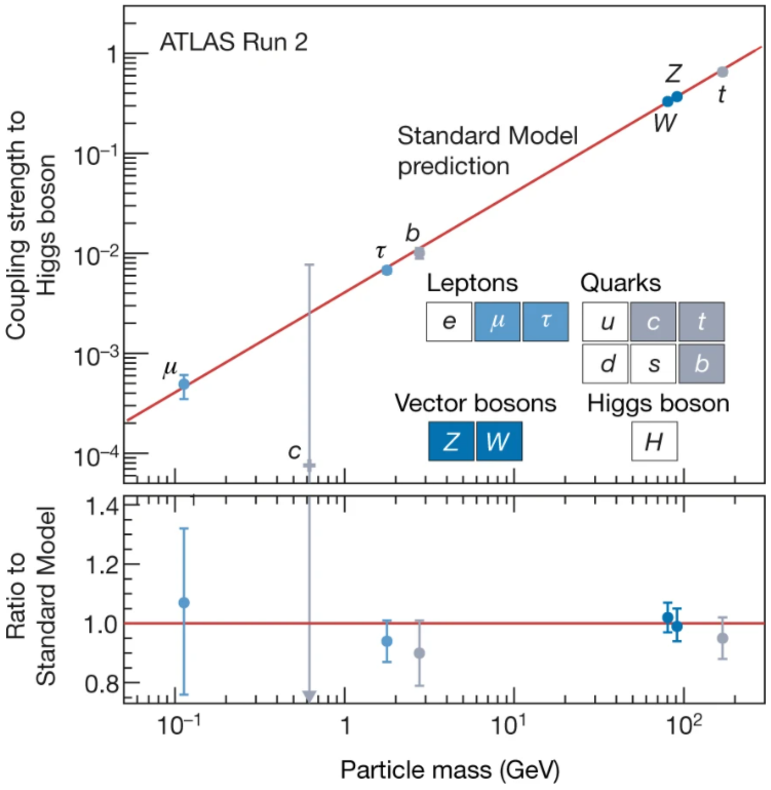


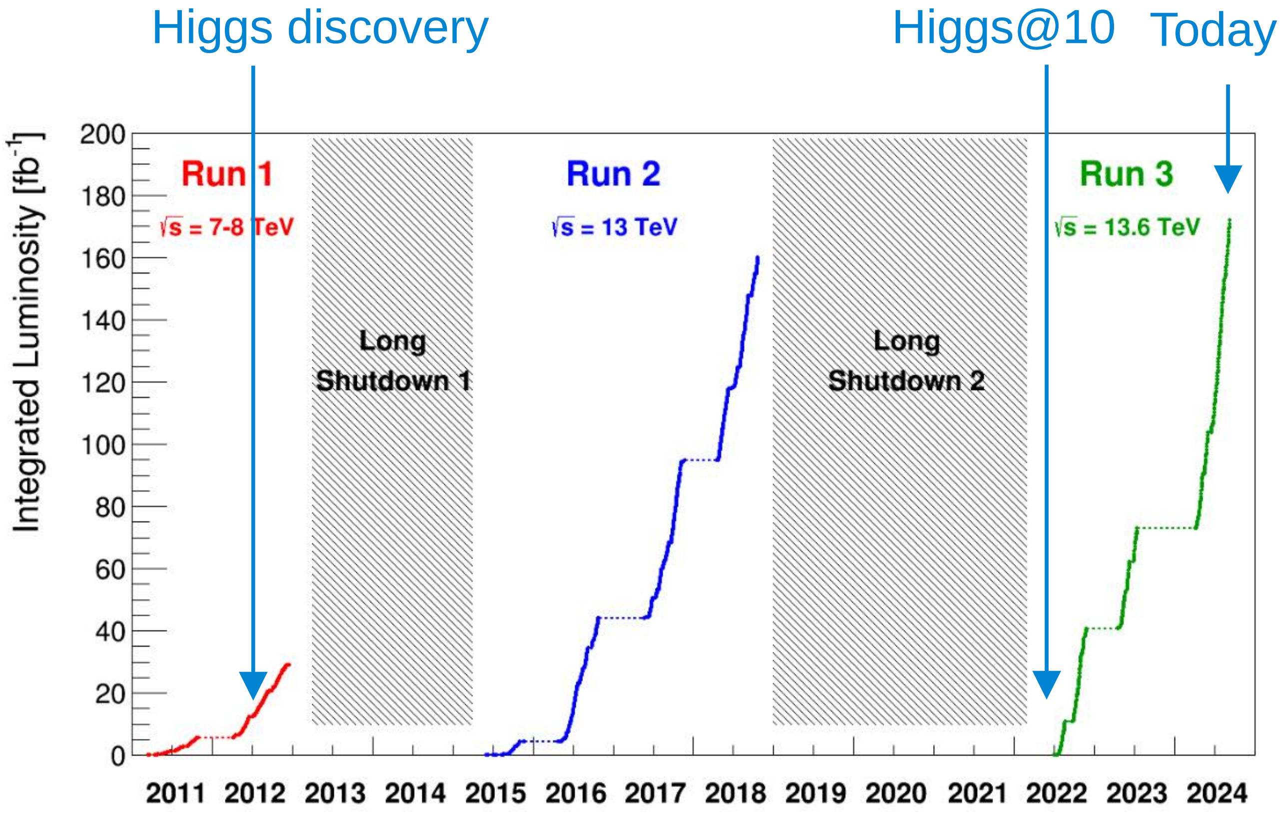



# … what we have learned in the 12 years since ...

> Tremendous progress made in precisely measuring the properties of this Higgs boson
  - Mass, width, CP properties, …
  - Production cross-sections and couplings to SM particles
  - Observation of production and decay modes

Nature 6075 2-59 (2022)



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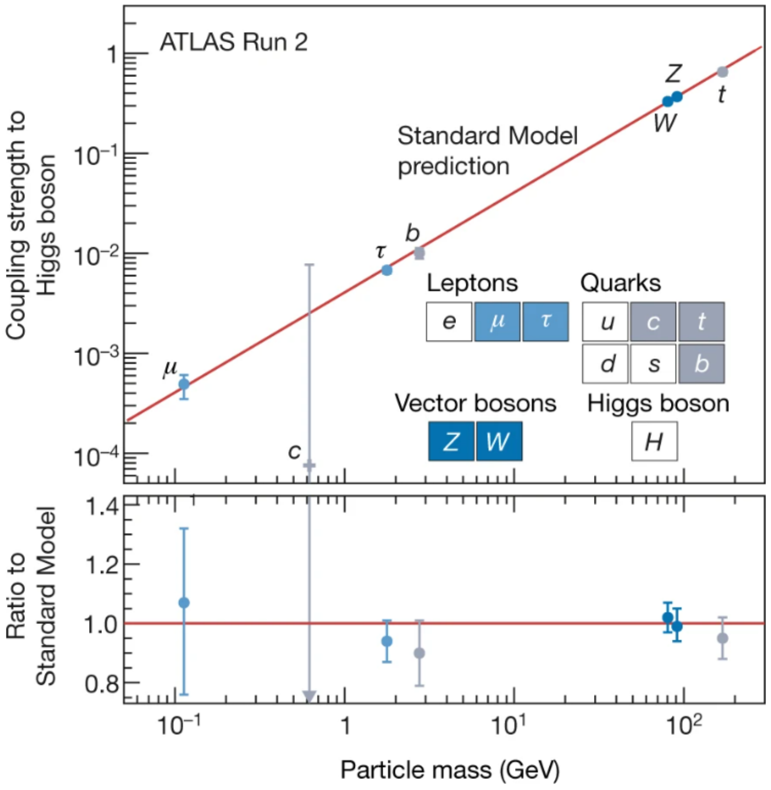
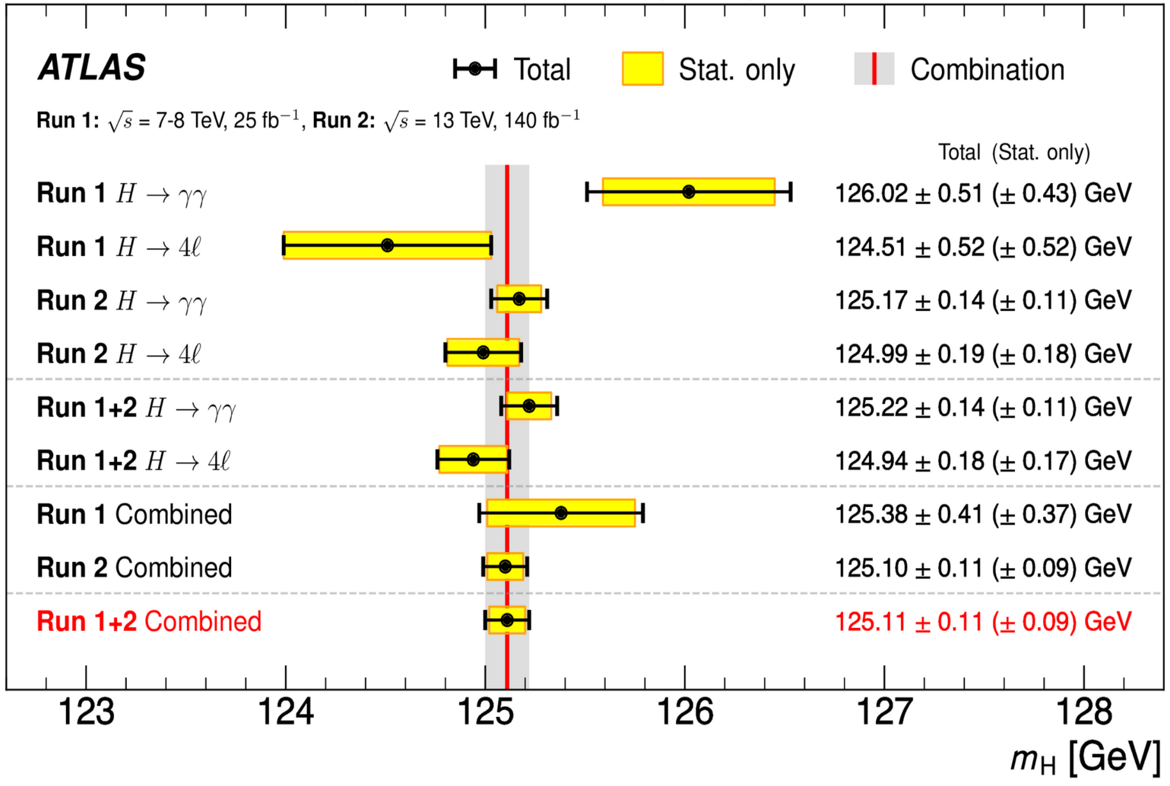
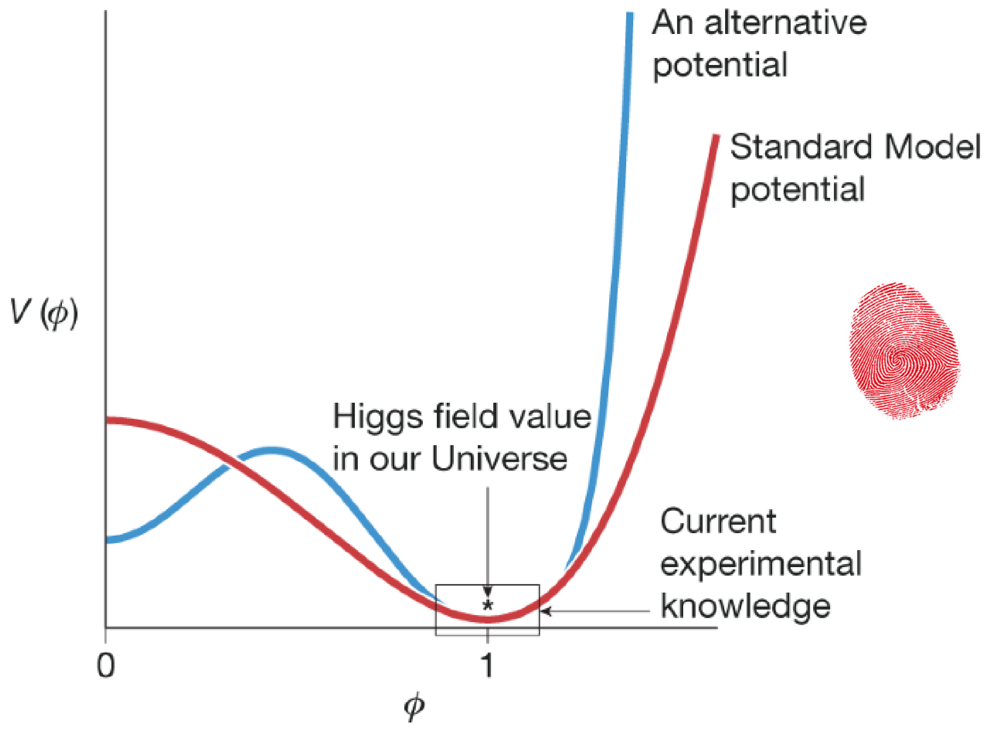



Phys. Rev. Lett. 131 (2023) 251802



# … and what we have yet to discover!

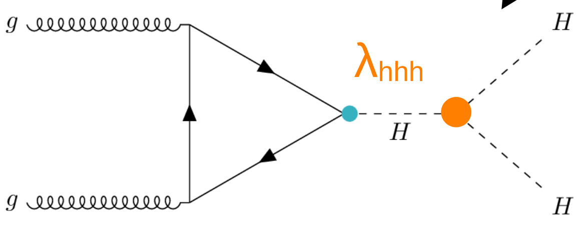
Full shape of the Higgs potential?

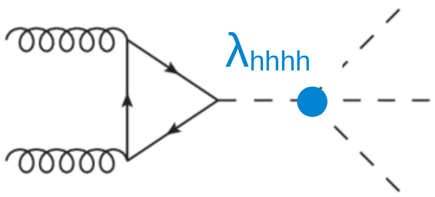


# … and what we have yet to discover!

- SM: full shape accessible via Higgs self couplings

$$V_{SM} = 1/2\, m_h^2\, h^2 + v\, \lambda_{hhh}\, h^3 + \lambda_{hhhh}\, h^4 + \ldots$$

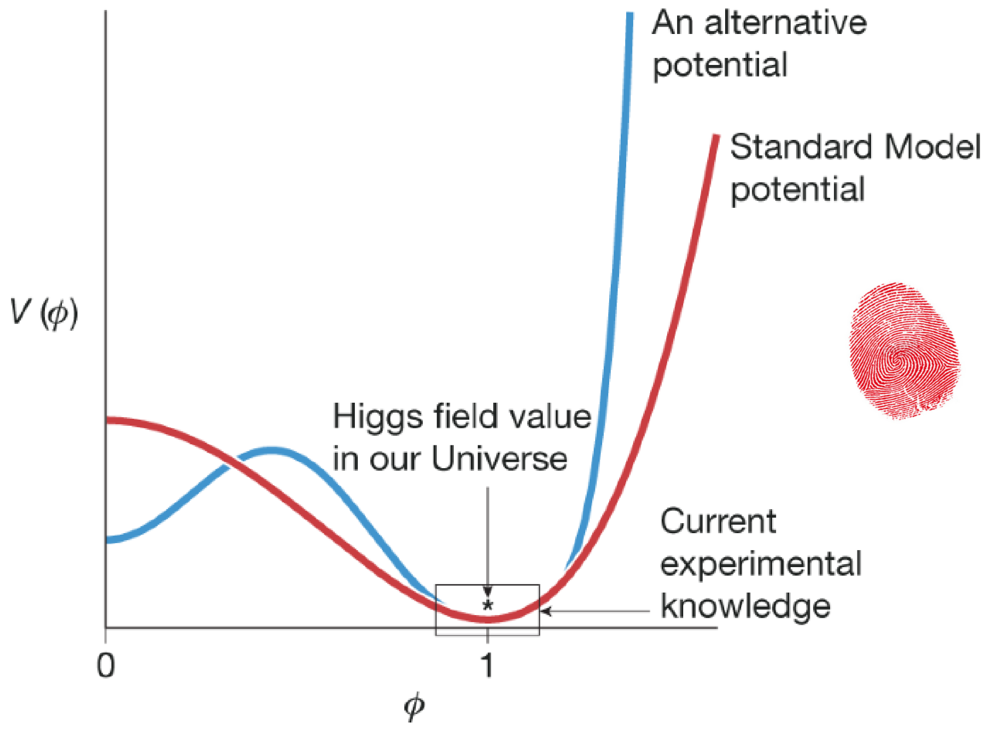



$$\lambda_{hhh}^{SM} = 3m_h^2/v$$

$$\lambda_{hhhh}^{SM} = \lambda_{hhh}^{SM}/v$$

Full shape of the Higgs potential?



# … and what we have yet to discover!

> BSM: many different shapes possible

> Smoking-gun hints of extended Higgs sectors:

- Deviation of self-coupling from SM value
- Presence of extra Higgs bosons

E.g. extra scalar singlet

$$V = V_{SM} + v\,\lambda_{hhH}\,h^2H + v\,\lambda_{HHH}\,H^3 + \ldots$$

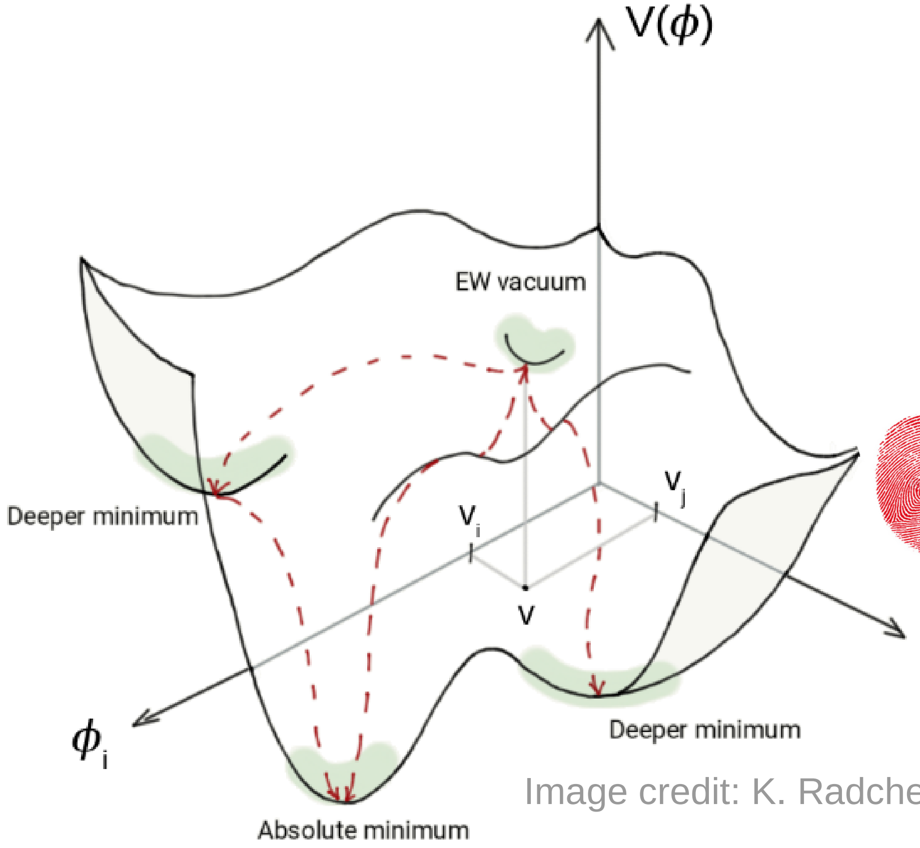
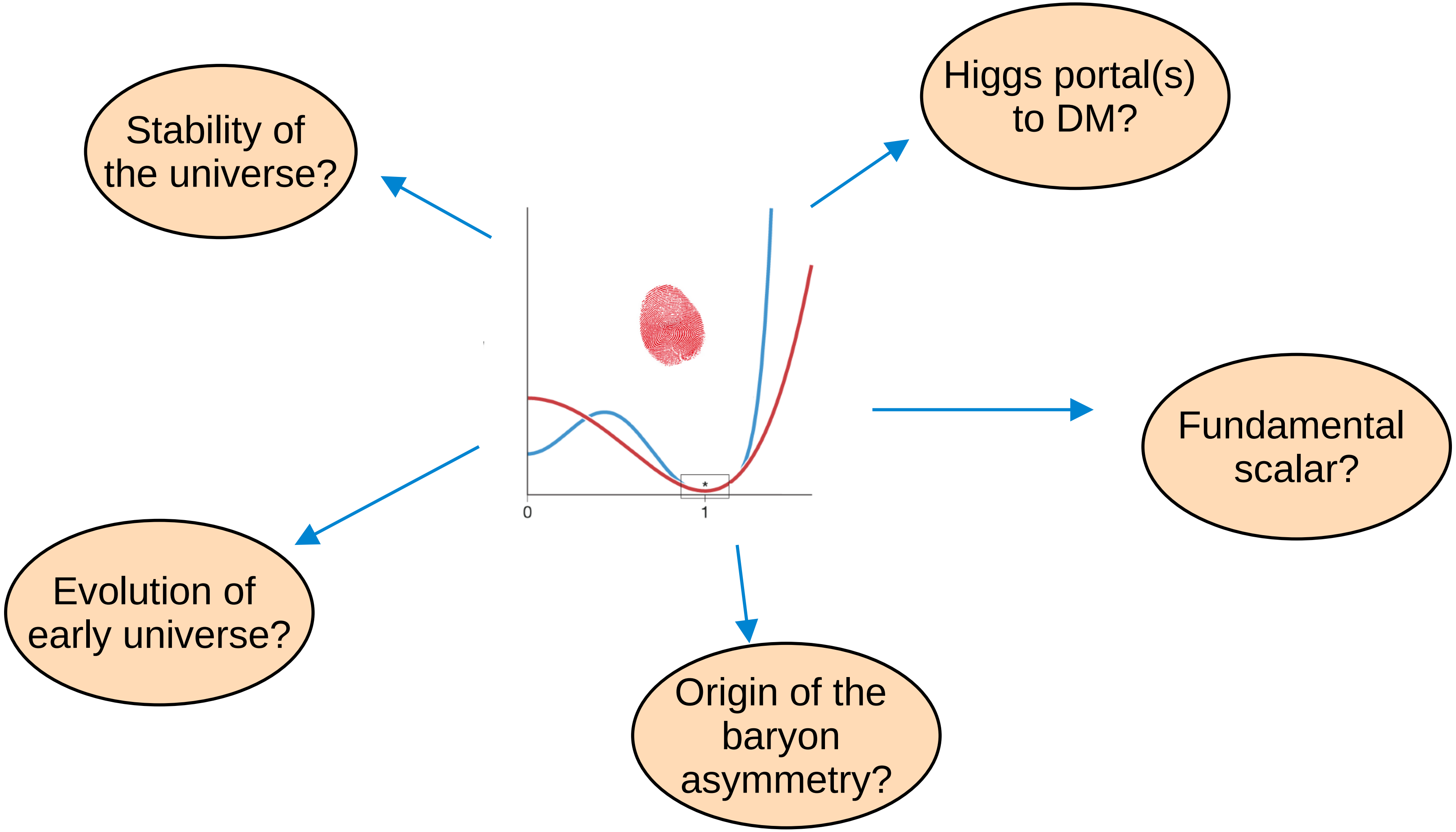



Image credit: K. Radchenko

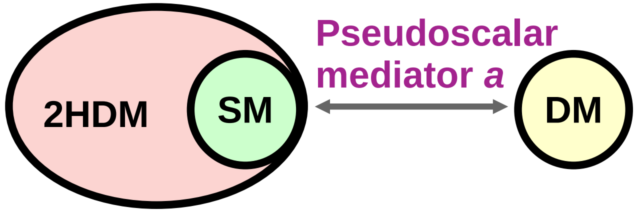
# Why care about the full potential?

- Higgs potential may provide answers to many key open questions in particle physics

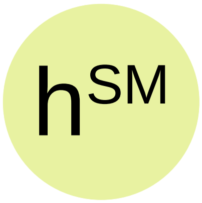


# Extended Higgs sector models

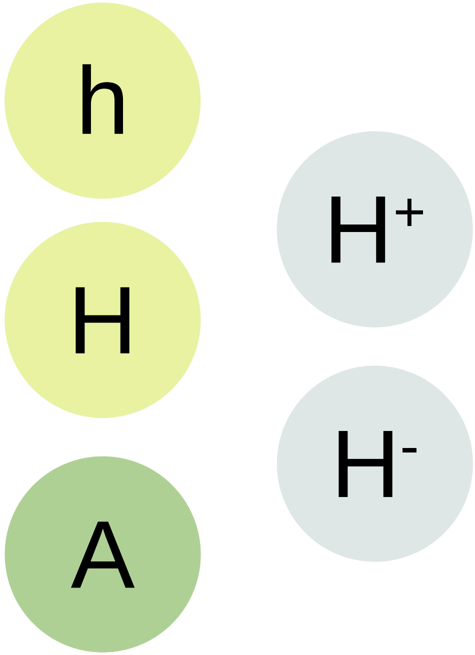
- Supersymmetry: requires a second Higgs doublet
- Axion DM models: require at least one more Higgs doublet or Higgs triplet
- WIMP DM models with an extended Higgs sector (2HDM+a)
- Additional sources of CP violation in the Higgs sector: possible with another Higgs doublet
- ...




SM




The 125 GeV Higgs boson could well be the first of its kind!

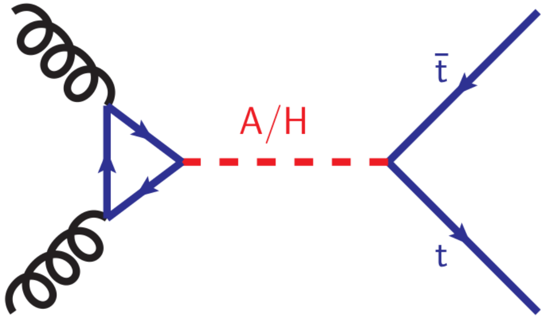



2HDM

with CP conserving potential

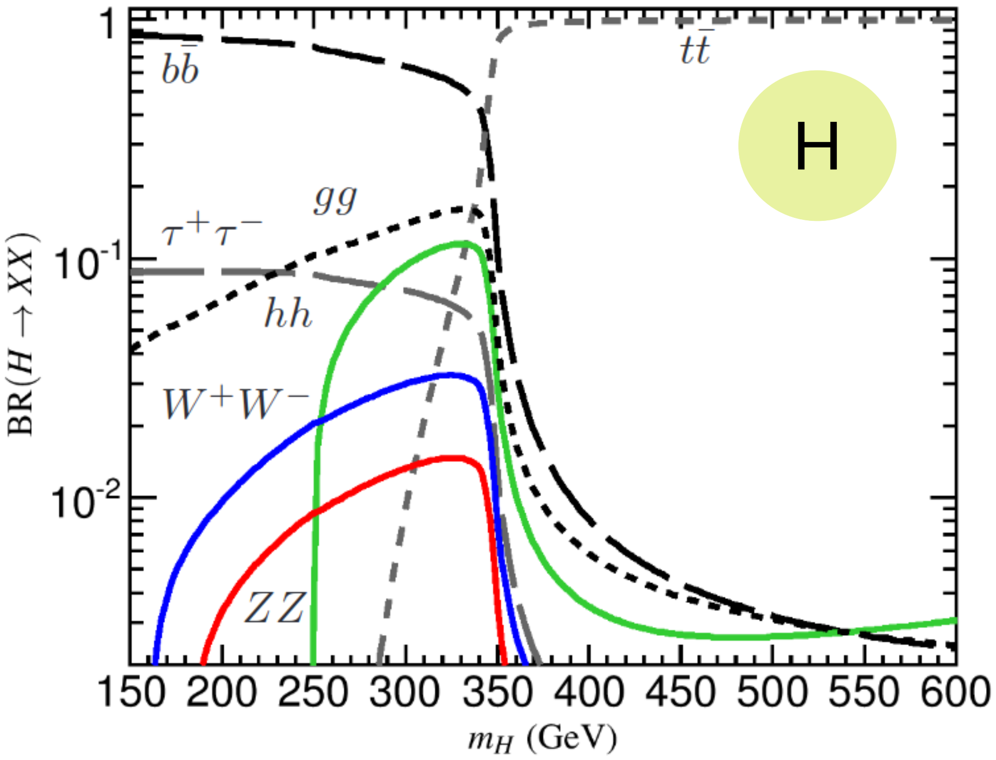
# Type-II 2HDM: neutral Higgs bosons

- Dominant production: loop induced gluon fusion
- Other production and decay modes depend on: $m_{A/H}$, $\tan\beta = v_2/v_1$

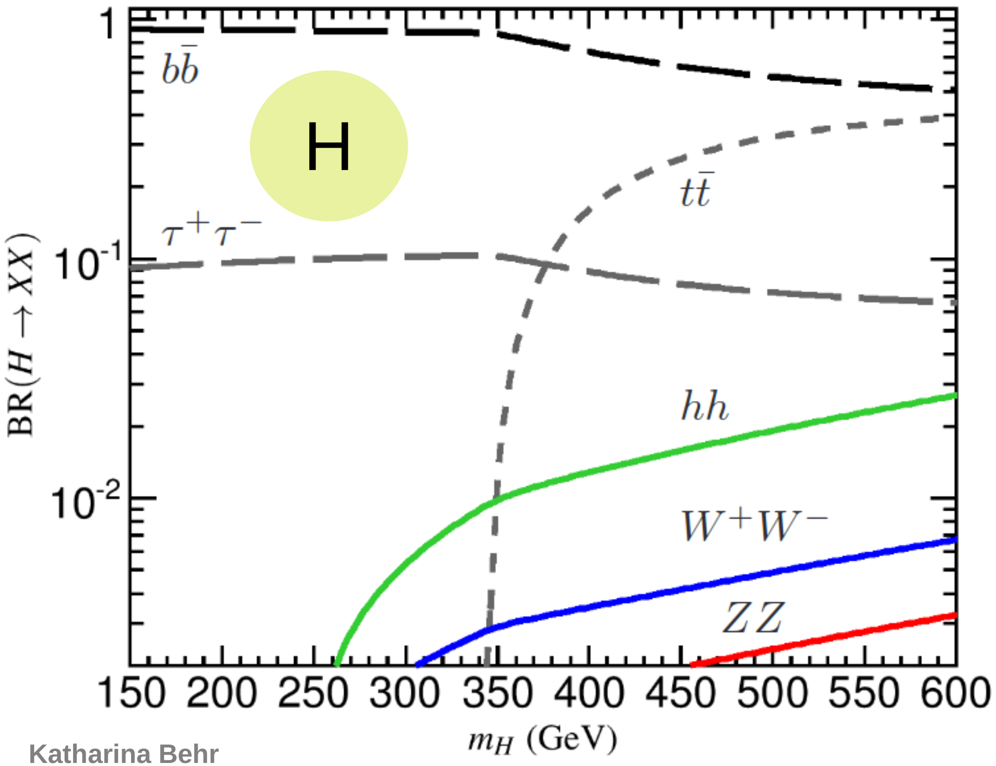



$g_{up} \sim 1/\tan\beta$
$g_{dw,lep} \sim \tan\beta$

tanβ = 1.5, cos(β-α) = 0.01




tanβ = 7, cos(β-α) = 0.01



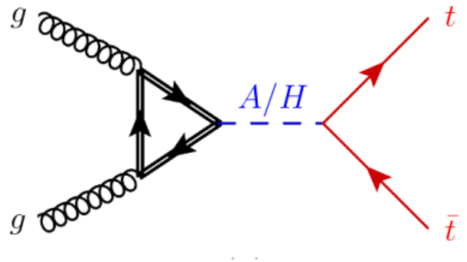
# Example: hMSSM

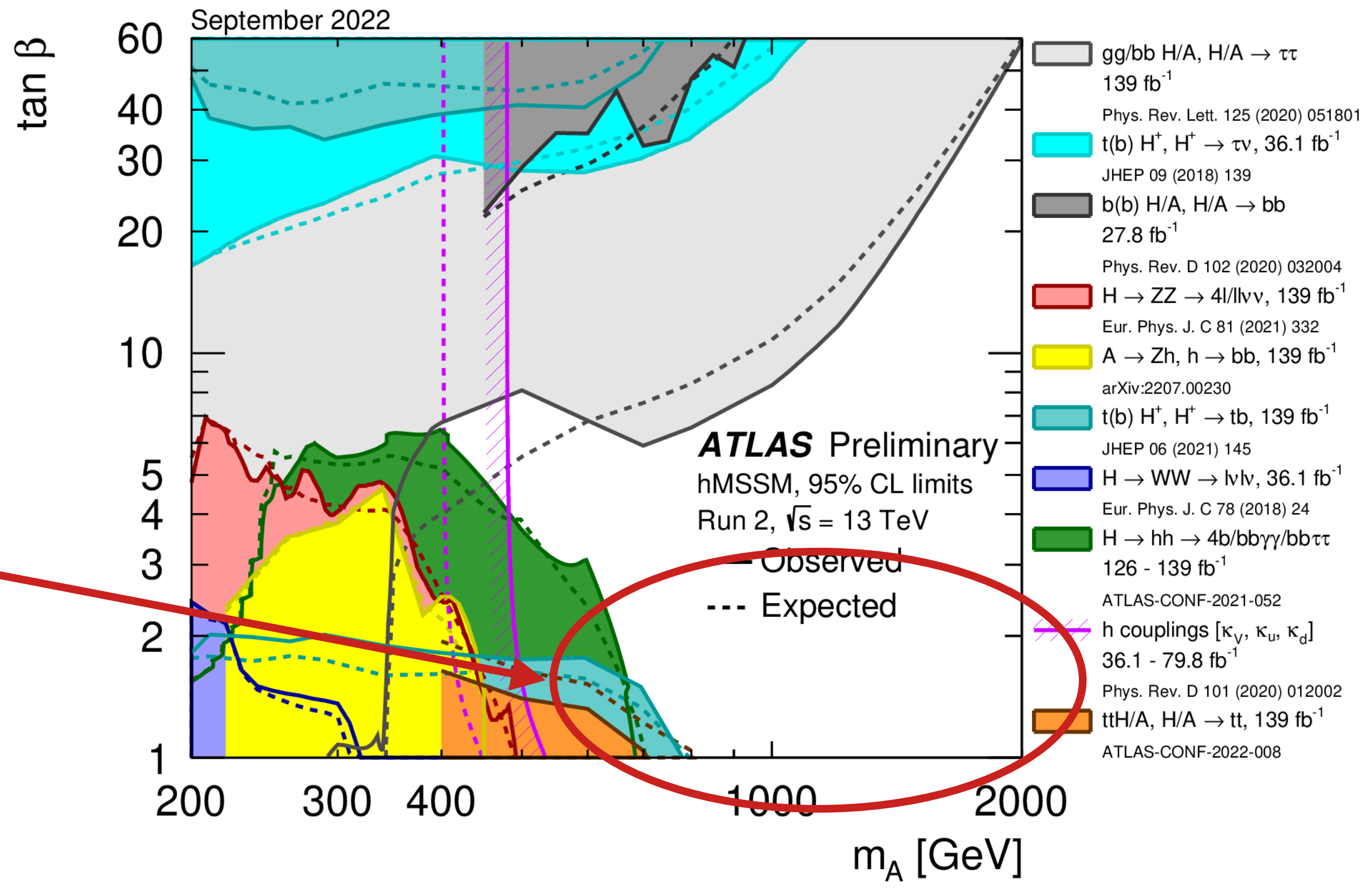
> Minimal supersymmetric model
  - Higgs-sector: type-II 2HDM
  - SUSY particles assumed to be heavy

> Only 2 free parameters: $m_A$, $\tan\beta$

Main uncovered region at high $m_A$, low $\tan\beta$:

Preferential A/H coupling to ttbar!

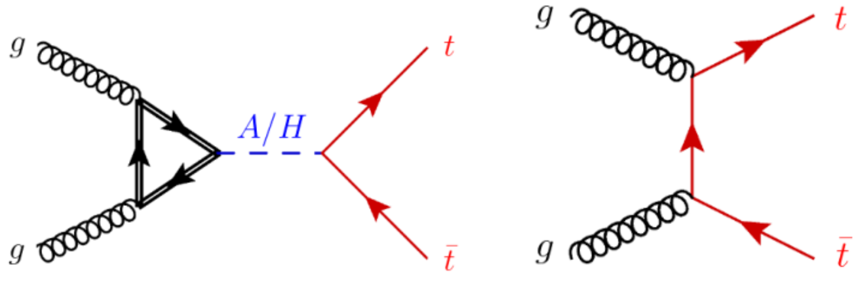


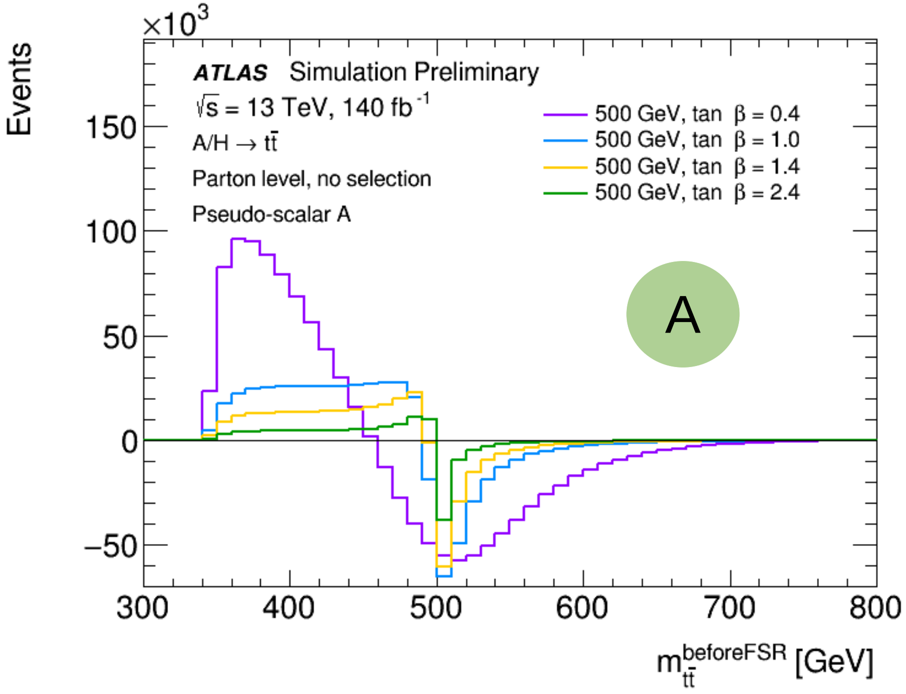
# Signal-background interference

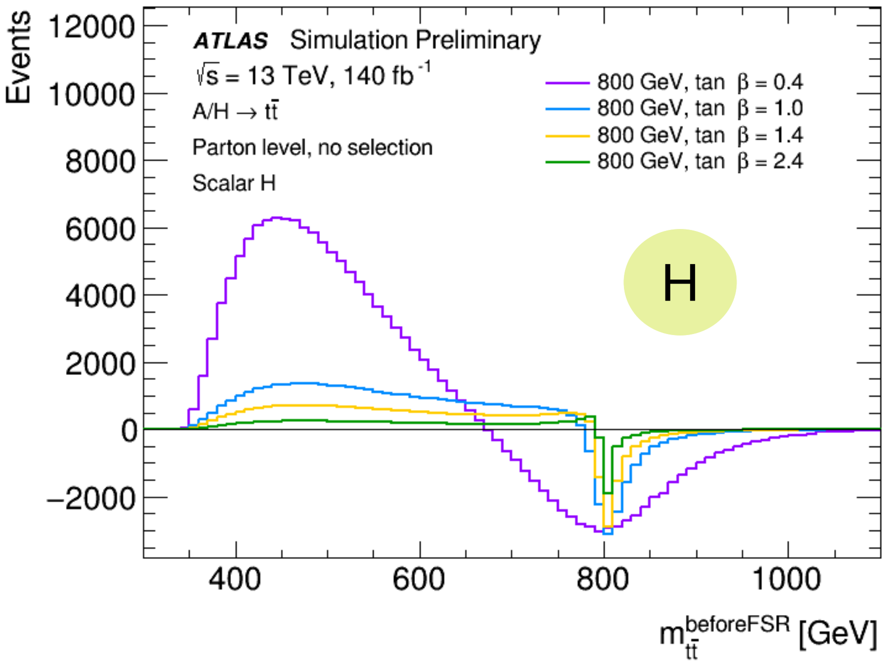


- Strong interference between signal process and irreducible background from SM ttbar production
- Interference pattern strongly dependent on signal parameters (model dependence!)




S+I component modelled with MadGraph at LO
+ k-factors for NLO cross-section




Larger tanβ

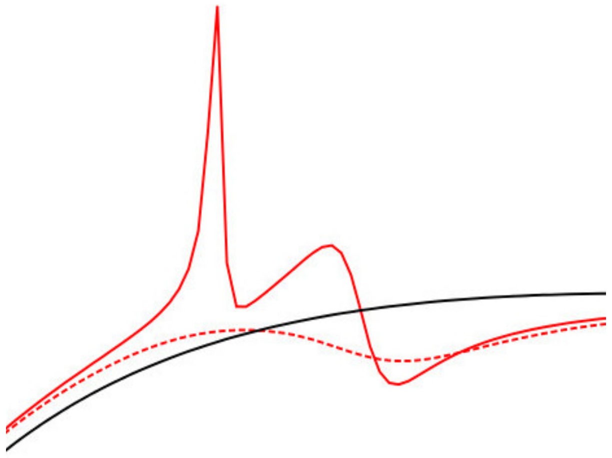
↓

Smaller total width

↓

Narrower pattern

**ATLAS result:** JHEP 08 (2024) 013

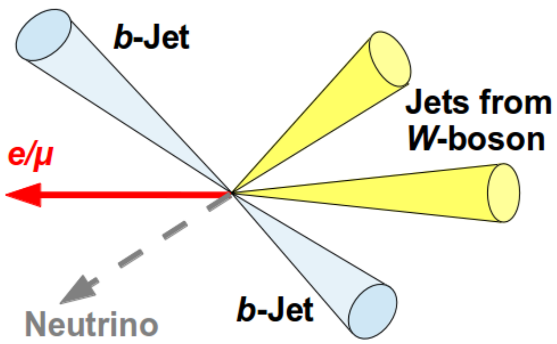


# Search strategy

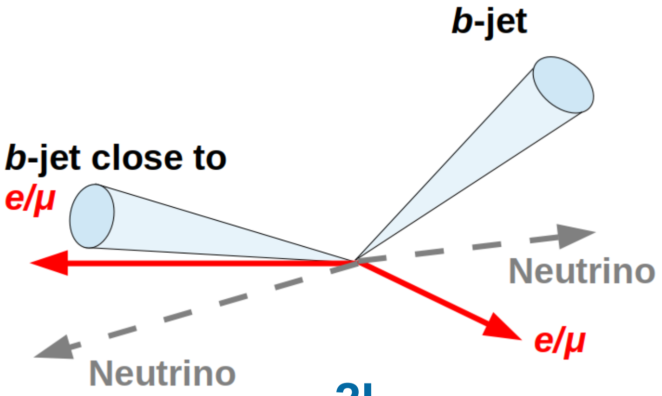


> Two orthogonal sets of regions: 1L (e or μ) + 2L ($e^+e^-$, eμ, $\mu^+\mu^-$)

$t \rightarrow Wb$




1L Resolved



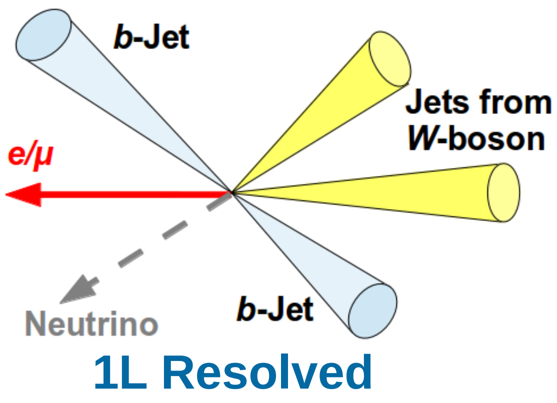

2L

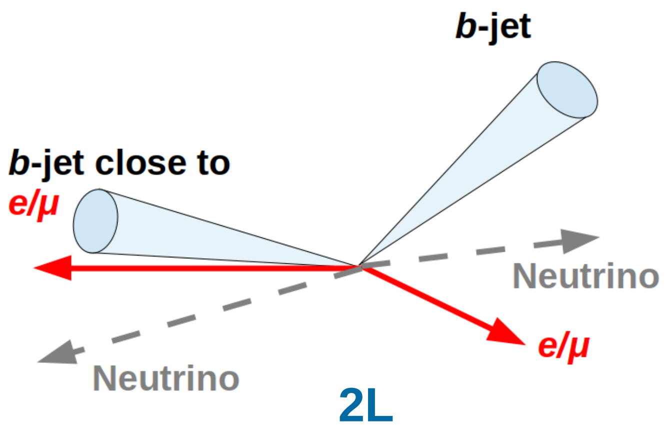
# Search strategy



- Two orthogonal sets of regions: 1L (e or μ) + 2L ($e^+e^-$, eμ, $\mu^+\mu^-$)
- **2L channel**: $m_{llbb}$ as proxy for $m_{ttbar}$

$t \rightarrow Wb$



# Search strategy

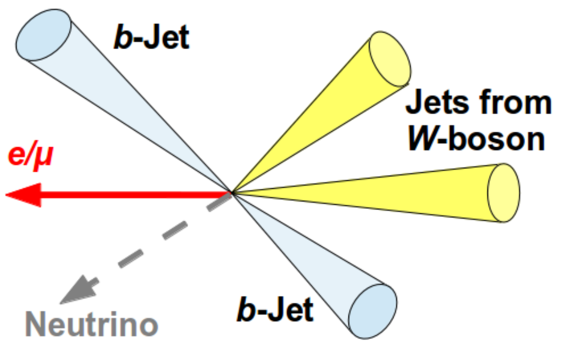
$t \rightarrow Wb$

> Two orthogonal sets of regions: 1L (e or μ) + 2L ($e^+e^-$, eμ, $\mu^+\mu^-$)

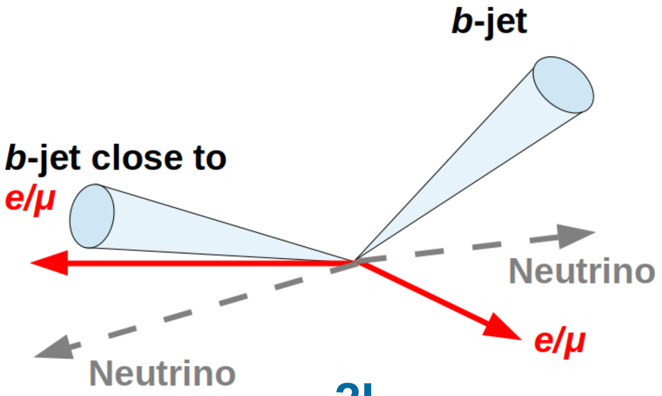
> **2L channel**: $m_{llbb}$ as proxy for $m_{ttbar}$

> **1L channel**: reconstruct full ttbar system, $m_{ttbar}$

- Resolved: small-*R* jets assigned via $\chi^2$ algorithm, ==1 or ≥ 2 *b*-tagged




1L Resolved




2L

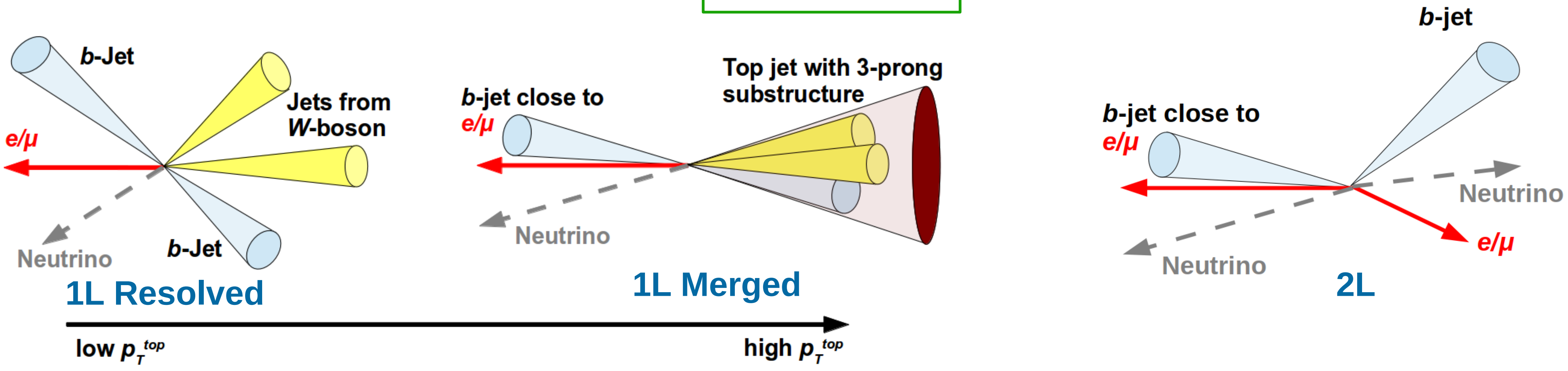
# Search strategy

$t \rightarrow Wb$

- Two orthogonal sets of regions: 1L (e or μ) + 2L ($e^+e^-$, eμ, $\mu^+\mu^-$)
- **2L channel**: $m_{llbb}$ as proxy for $m_{ttbar}$
- **1L channel**: reconstruct full ttbar system, $m_{ttbar}$
  - Resolved: small-*R* jets assigned via $\chi^2$ algorithm, ==1 or ≥ 2 *b*-tagged
  - Merged: large variable-*R* jet ($R_{max}$ = 1.5) optimised for intermediate top boosts ($m_{ttbar}$ ~ 1 TeV)

$$R_{\mathrm{eff,i}}(p_T) = \frac{\rho}{p_{T,i}}$$

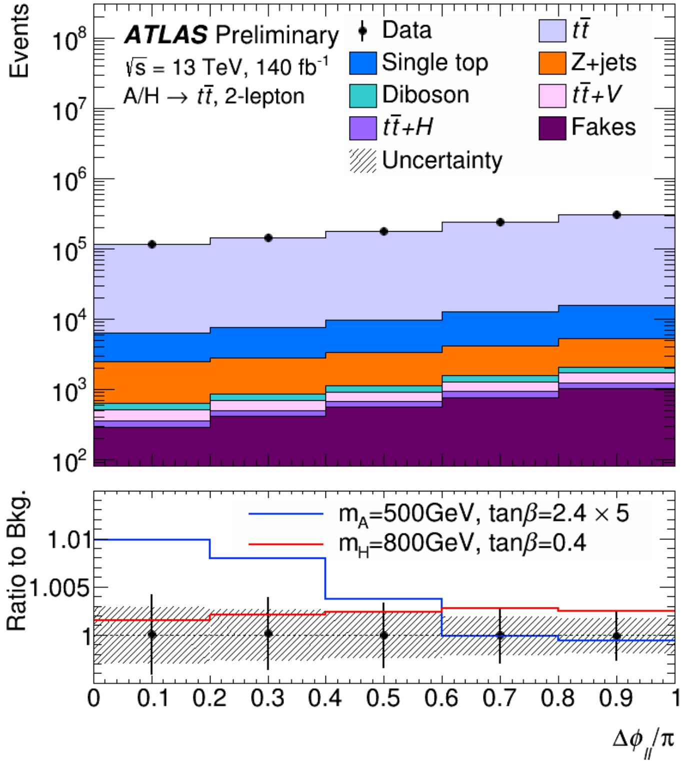
(ρ = 600 GeV)

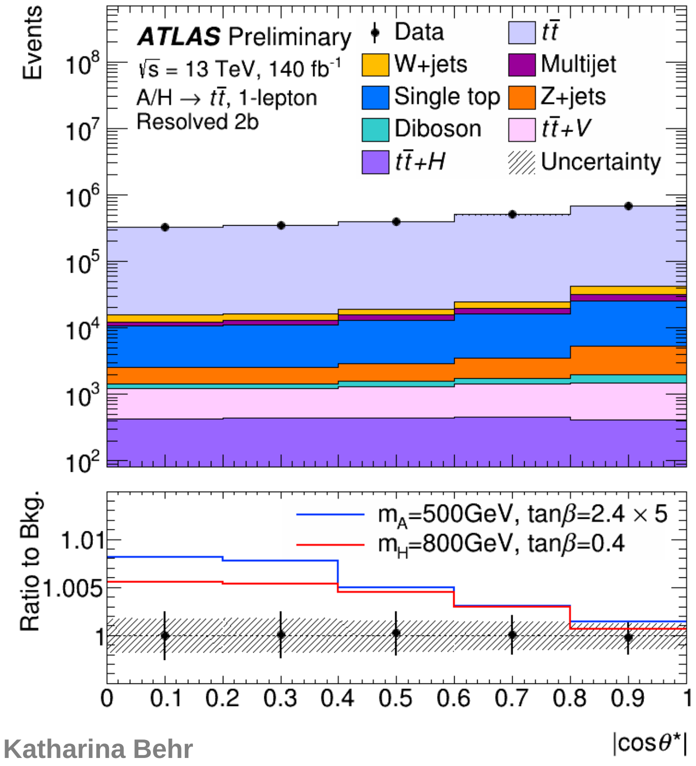


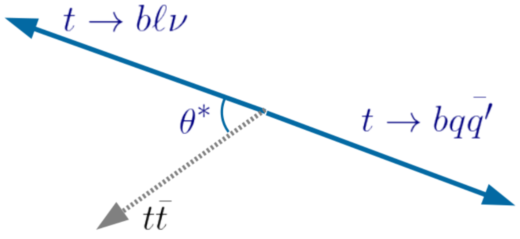
# Event categories



> Split resolved signal regions into bins of angular variables sensitive to spin state of the ttbar system
  - 1L: cosθ*, 2L: Δφ(ll)
> Improved signal-background discrimination, sensitivity improved ~20%
> Additional discrimination between scalar and pseudoscalars



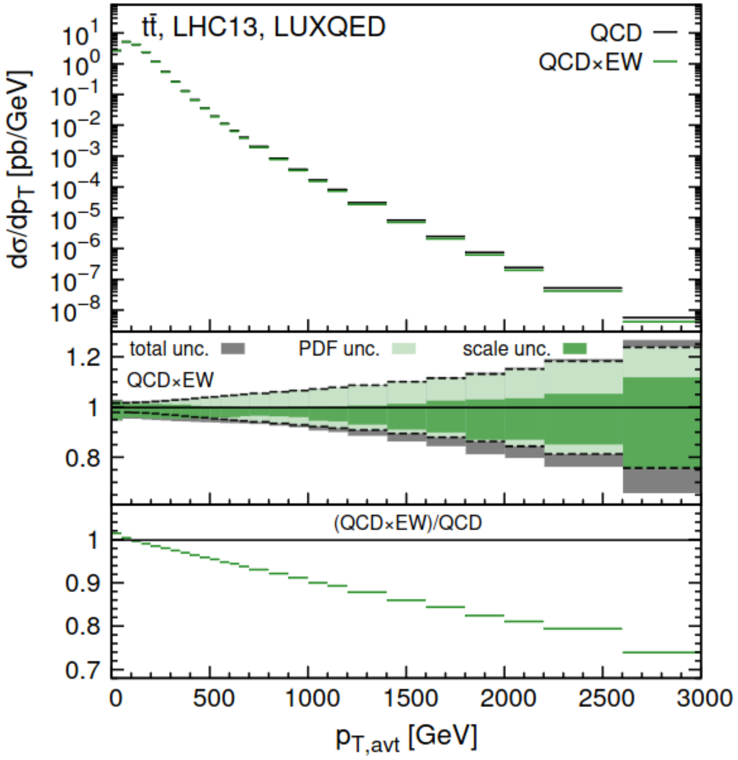



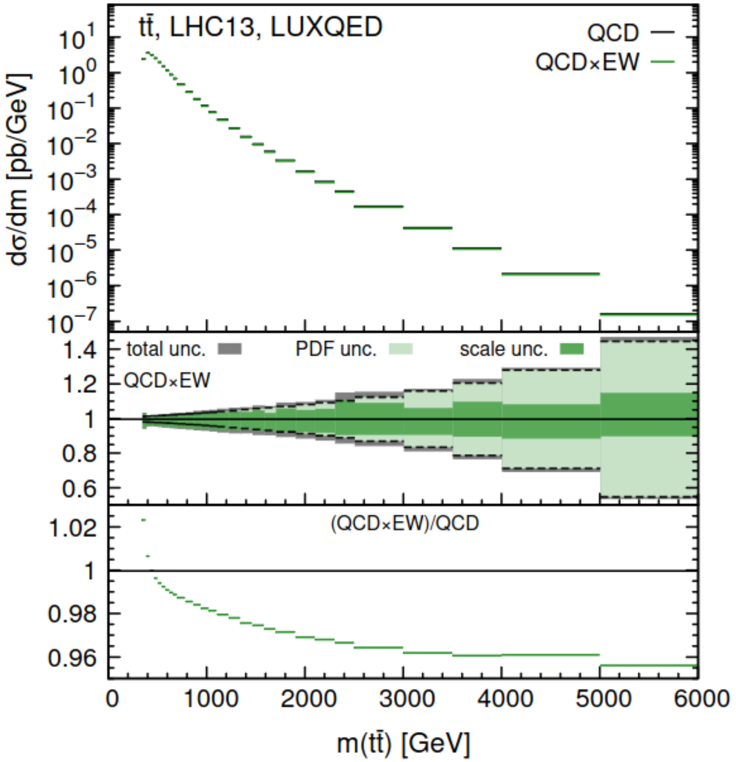
# Background processes

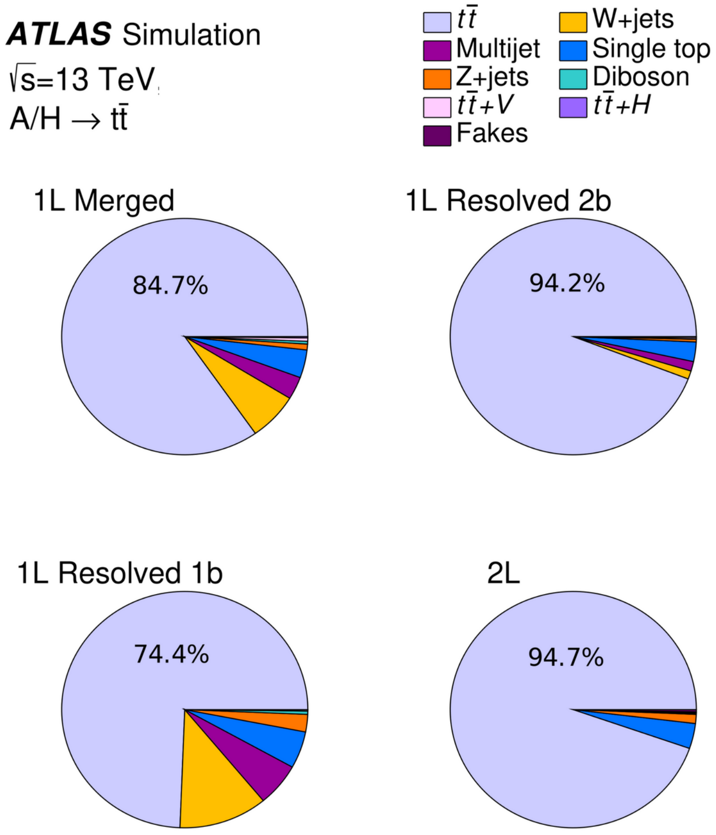


> Dominant and irreducible background from SM ttbar production

- Correct NLO Powheg+Pythia MC to NNLO-QCD+NLO-EW [M. Czakon et al., JHEP 10 (2017) 186]
- Via iterative reweighting in m(ttbar), $p_T$(t), $p_T$(tbar)



# Systematic uncertainties

- Largest sources of uncertainty: SM ttbar modelling
- tt NNLO includes:
  - Uncertainties in reweighting
  - Scale and PDF uncertainties on calculation
  - Uncertainty on EW component from comparison of NN vs LUX PDFs
- tt lineshape: comparison with MadSpin
- tt PS: Pythia vs Herwig
- $m_{top}$: ± 0.76 GeV

| Uncertainty component | Fractional contribution [%] $m_A$ = 800 GeV, $\tan\beta$ = 0.4 | Fractional contribution [%] $m_A = m_H$ = 500 GeV, $\tan\beta$ = 2.0 |
|---|---|---|
| **Experimental** | **30** | **42** |
| Small-$R$ jets (JER, JES) | 22 | 29 |
| Large-$VR$ jets | 11 | 20 |
| Flavour tagging | 13 | 17 |
| Leptons | 4 | 5 |
| Other ($E_T^{miss}$, luminosity, pile-up, JVT) | 10 | 14 |
| **Modelling: SM $t\bar{t}$ and signal** | **91** | **79** |
| $t\bar{t}$ NNLO | 49 | 28 |
| $t\bar{t}$ lineshape | 27 | 29 |
| $t\bar{t}$ ME-PS ($p_T^{hard}$) | 36 | 30 |
| $t\bar{t}$ ME-PS ($h_{damp}$) | 41 | 25 |
| $t\bar{t}$ ISR& FSR | 9 | 13 |
| $t\bar{t}$ PS | 29 | 41 |
| $t\bar{t}$ cross-section | 21 | 31 |
| $t\bar{t}$ Scales & PDF | 21 | 16 |
| $m_t$ | 6 | 4 |
| Signal | 19 | 9 |
| **Modelling: other** | **41** | **16** |
| $W$+jets | 11 | 8 |
| $Z$+jets | 1 | 2 |
| Multijet | 27 | 10 |
| Fakes | <1 | 1 |
| Other bkg. | 29 | 10 |
| **MC statistics** | **18** | **26** |
| **Total systematic uncertainty** | **±100** | **±100** |
| **Total statistical uncertainty** | **< 1** | **< 1** |

# Statistical analysis without interference



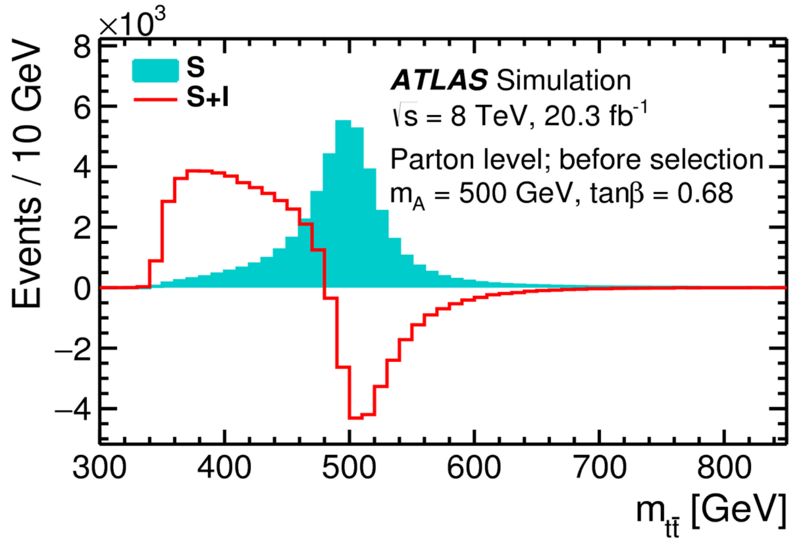
- Simple likelihood parameterisation in terms of signal strength

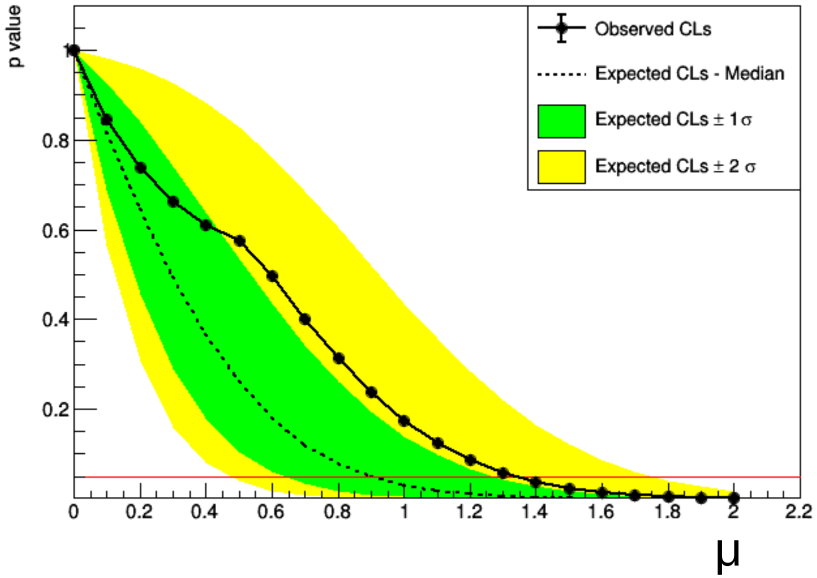
$$\mu \cdot S \qquad + B$$

- Linear dependence on POI = μ
- Standard LHC profile likelihood test statistic

$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{\boldsymbol{\theta}}}(\mu))}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})}$$

- p-value scan to determine upper limits on μ



# Statistical analysis with interference

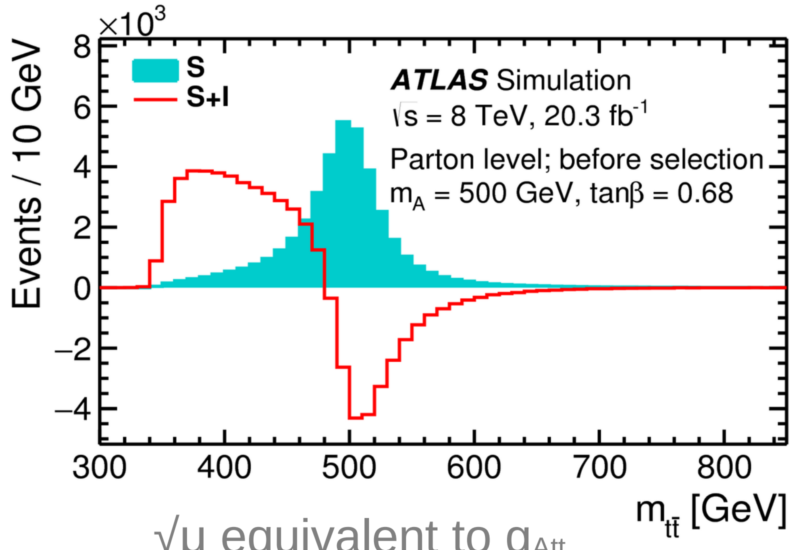


> Extend likelihood to include interference term

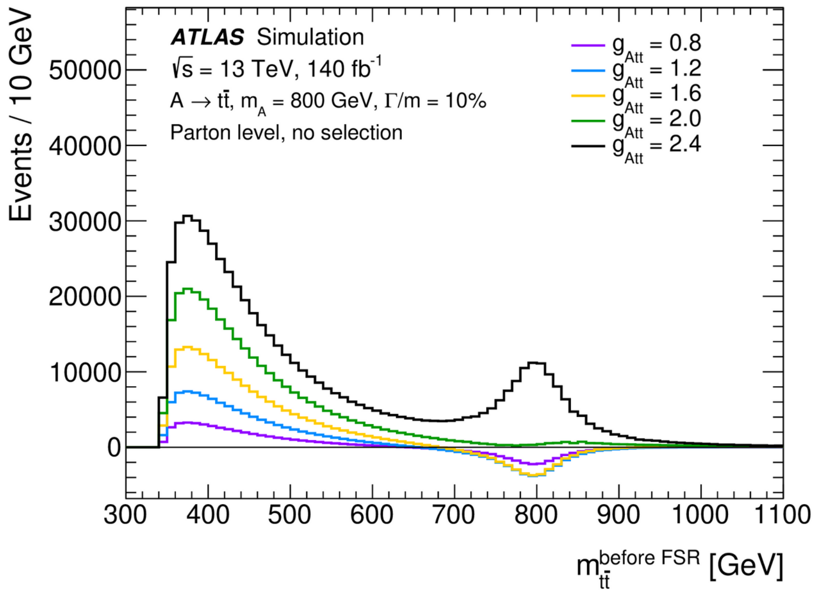
$$\mu \cdot S + \sqrt{\mu} \cdot I + B = (\mu - \sqrt{\mu}) \cdot S + \sqrt{\mu} \cdot (S + I) + B$$

> Quadratic dependence on POI = √μ

- Interference shape changes with POI




√μ equivalent to $g_{Att}$



# Statistical analysis with interference

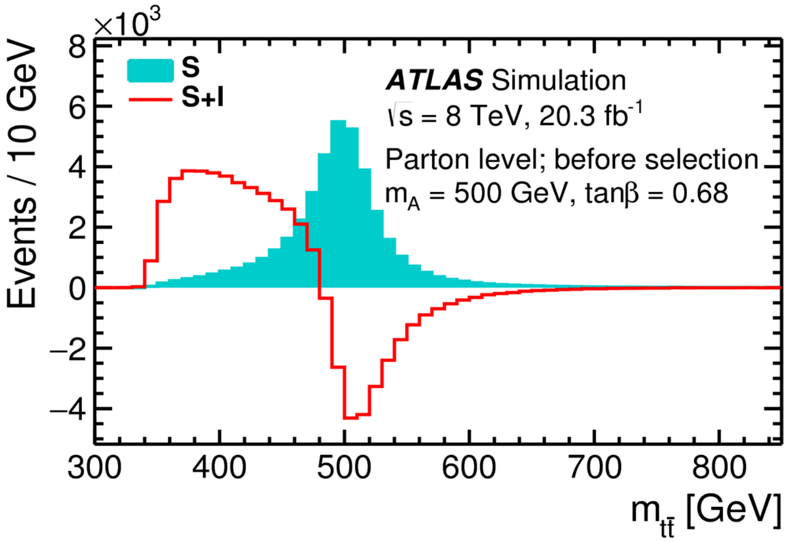


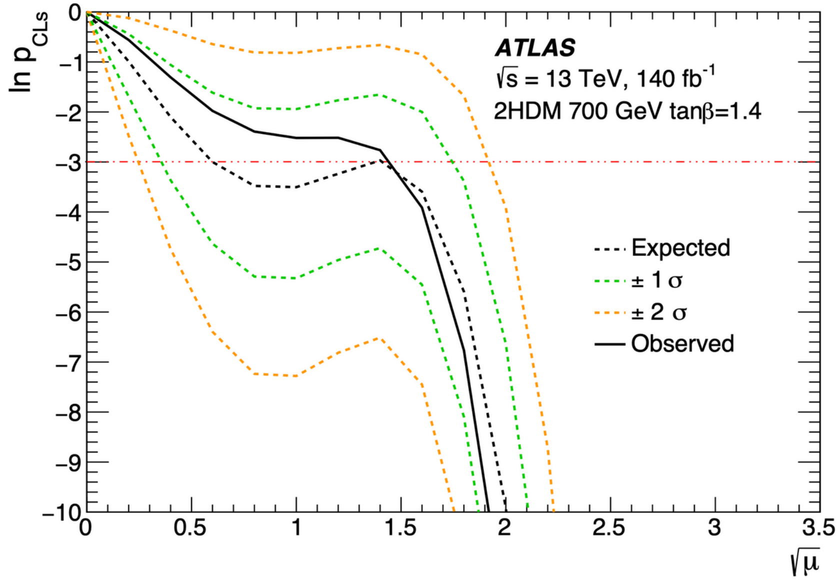
> Extend likelihood to include interference term

$$\mu \cdot S + \sqrt{\mu} \cdot I + B = (\mu - \sqrt{\mu}) \cdot S + \sqrt{\mu} \cdot (S + I) + B$$

> Quadratic dependence on POI = √μ

- Interference shape changes with POI
- Local minima can appear in CLs scan
- Upper limits not well defined!



# Statistical analysis with interference



> Extend likelihood to include interference term

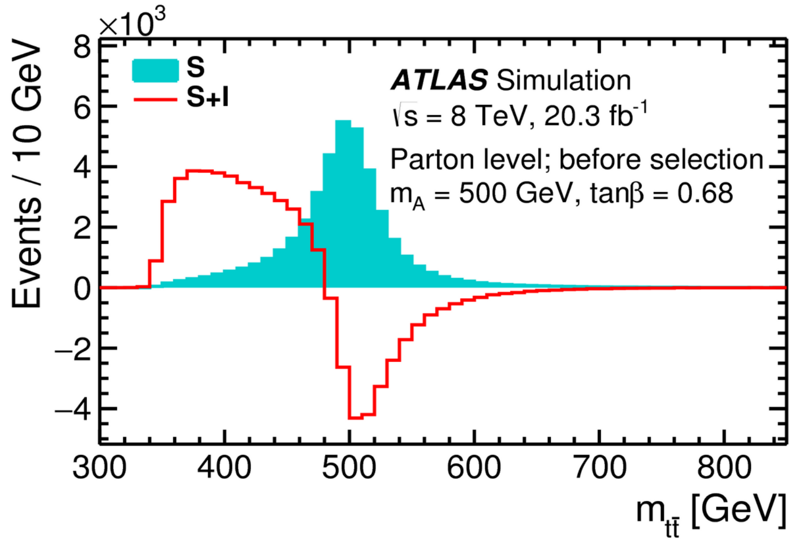
$$\mu \cdot S + \sqrt{\mu} \cdot I + B = (\mu - \sqrt{\mu}) \cdot S + \sqrt{\mu} \cdot (S + I) + B$$

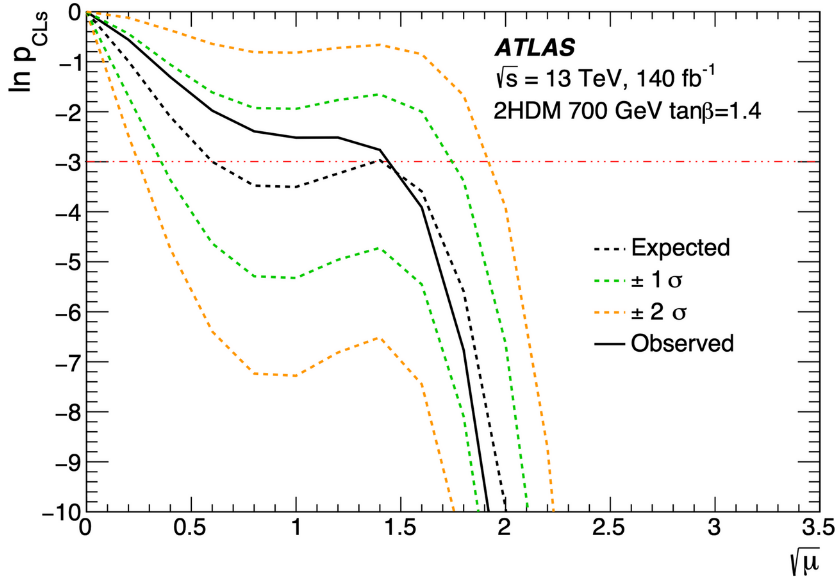
> Quadratic dependence on POI = √μ

- Interference shape changes with POI
- Local minima can appear in CLs scan
- Upper limits not well defined!

> Requires going beyond common statistical approaches

- Choice of appropriate test statistic
- Interpolation between signal hypotheses
- Correct limit band calculation
  - New baseline in ATLAS StatAnalysis (on cvmfs)
- Treatment of histograms with negative yields



# Choice of test statistic

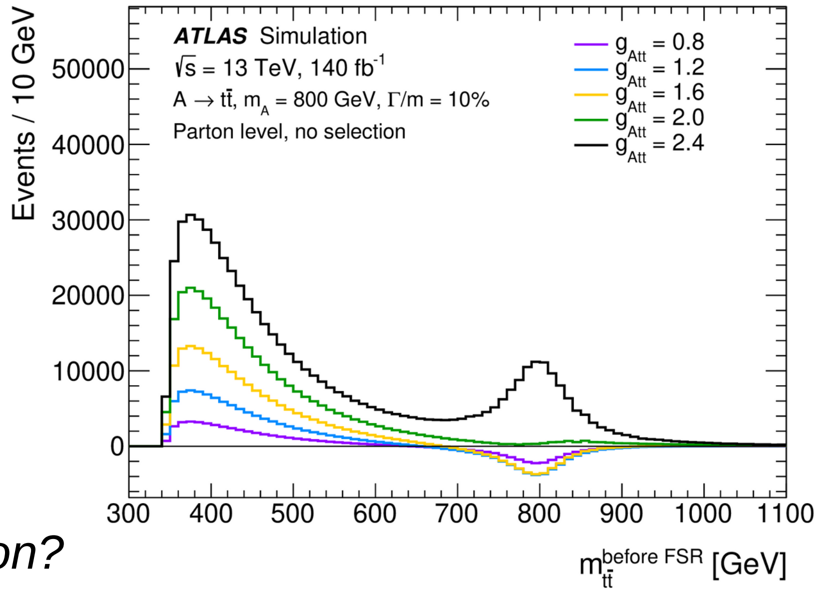


> Search stage:

- *Should we reject SM in favour of (any) BSM hypothesis?*
- Test agreement of data with range of interference patterns
- Consider all possible values of POI

$$q_0 = -2\ln \frac{\mathcal{L}(0, \hat{\hat{\theta}}_0)}{\mathcal{L}(\hat{\sqrt{\mu}}, \hat{\theta}_{\hat{\sqrt{\mu}}})}$$

√μ equivalent to $g_{Att}$




> Exclusion stage:

- *Should we reject the BSM hypothesis (μ=1) under consideration?*
- Test (dis)agreement of data with specific interference pattern of tested signal hypothesis

$$q_{1,0} = -2\ln \frac{\mathcal{L}(1, \hat{\hat{\theta}}_1)}{\mathcal{L}(0, \hat{\hat{\theta}}_0)}$$

$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{\boldsymbol{\theta}}}(\mu))}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})}$$

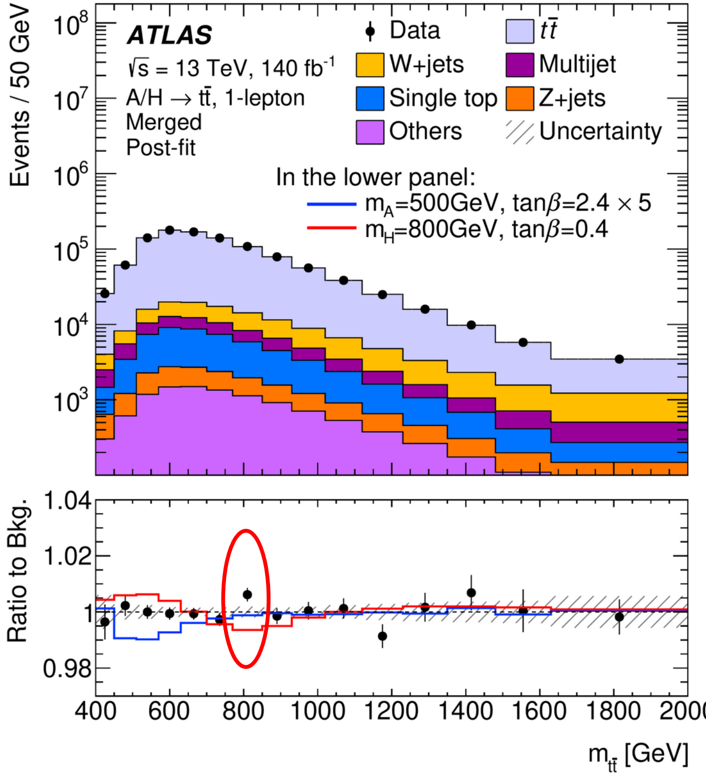
# Search stage

JHEP 08 (2024) 013

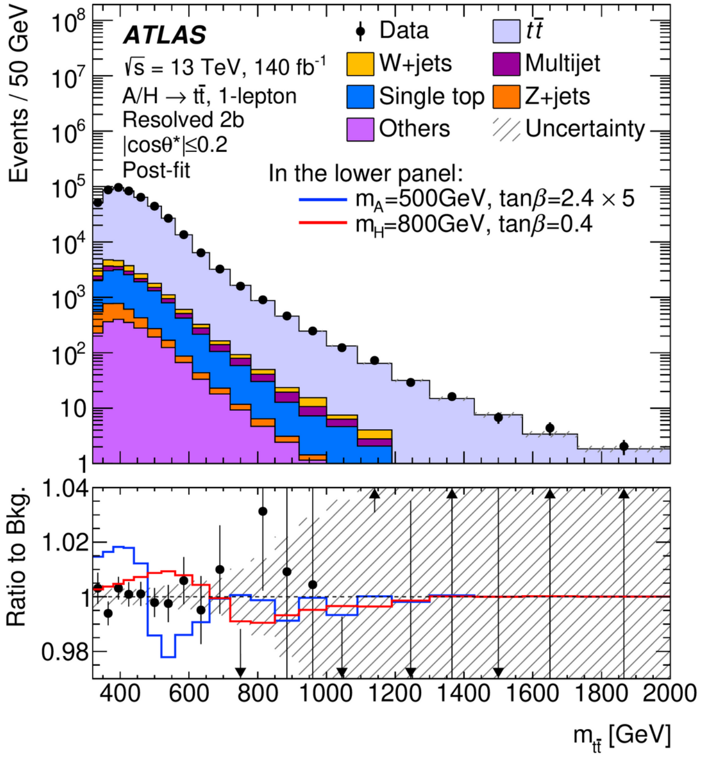
$$q_0 = \frac{\mathcal{L}(0,\hat{\hat{\theta}}_0)}{\mathcal{L}(\hat{\sqrt{\mu}},\hat{\theta}_{\hat{\sqrt{\mu}}})}$$

> Tested agreement between data and S+I+B hypotheses with masses [400,1400] GeV and widths [1,40]%
- Most significant deviation from SM-only (2.3σ local): $m_A$ = 800 GeV, $\Gamma_A/m_A$ = 10% and $\sqrt{\mu}$ = 4.0
- Driven by narrow upward fluctuation around 800 GeV in merged region

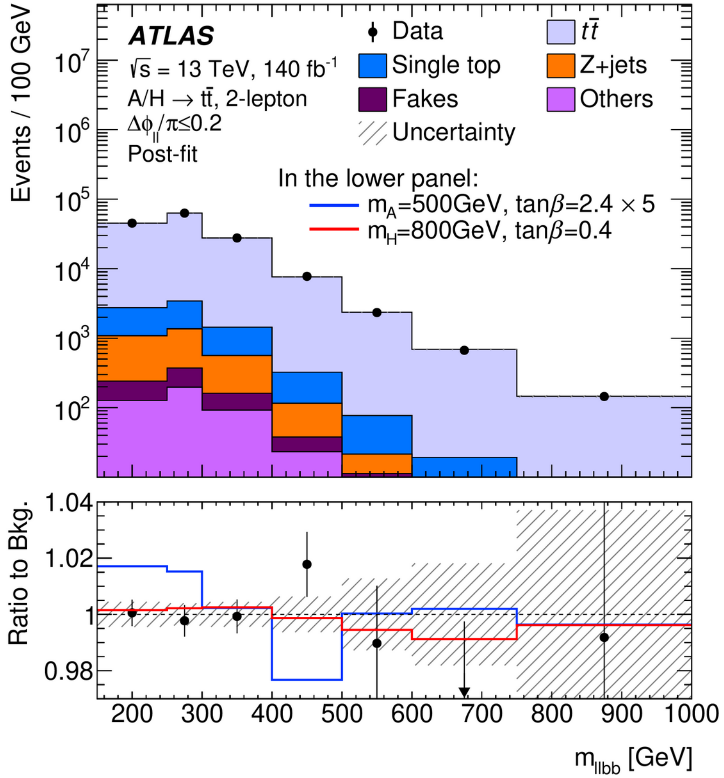
1L Merged




1L Resolved 2b

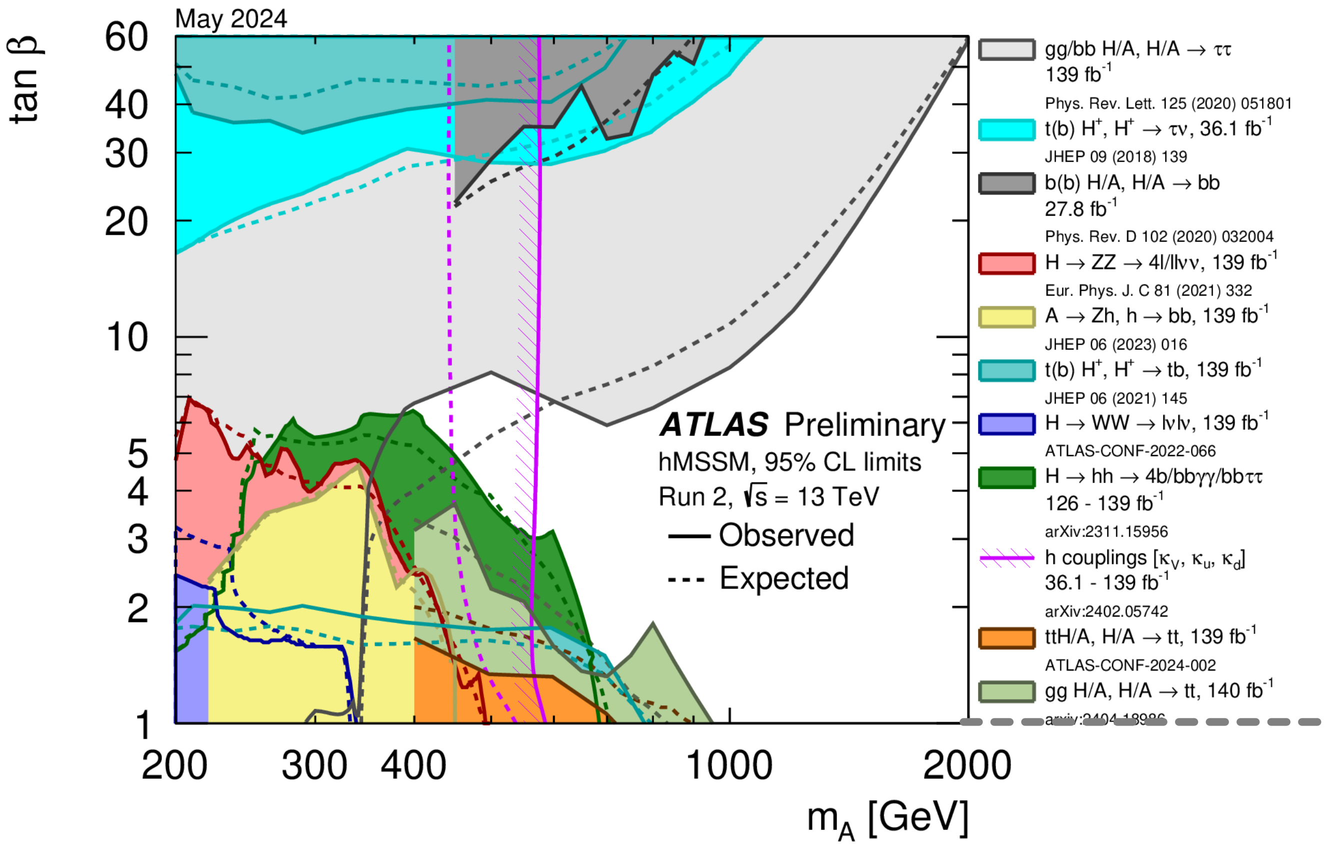


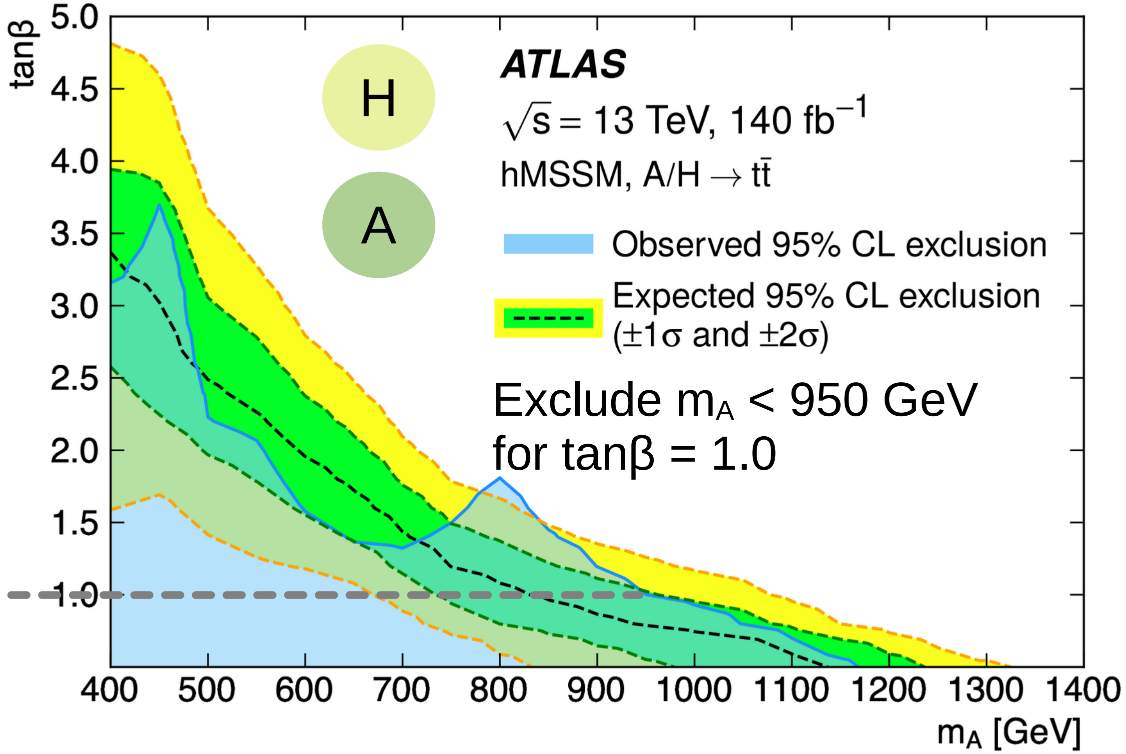

2L



# Constraints on relevant benchmark models: hMSSM

> Strongest constraints on $m_A$ at lowest value of tanβ = 1.0



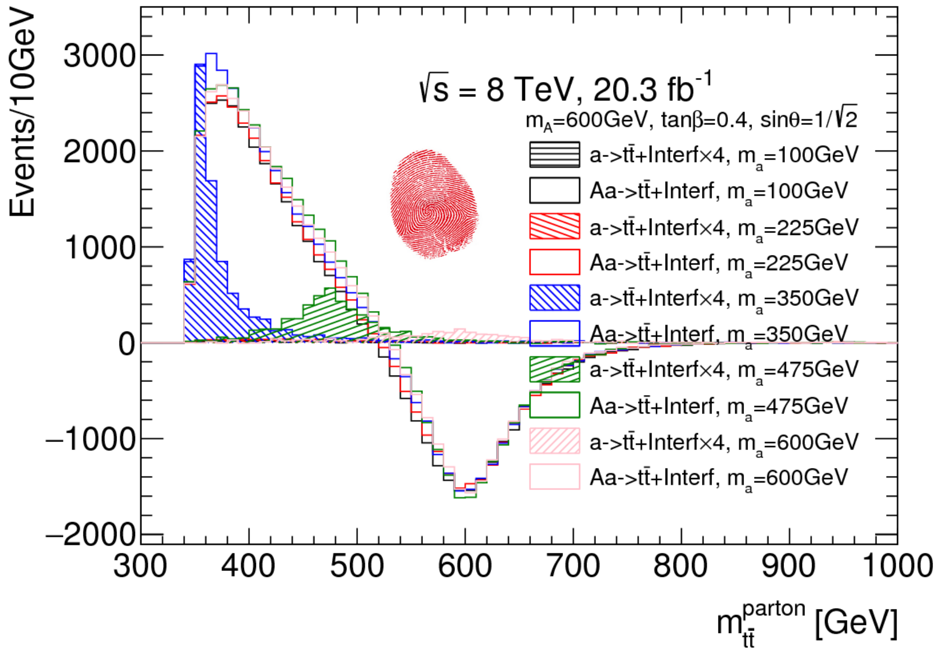

$m_A \sim m_H$

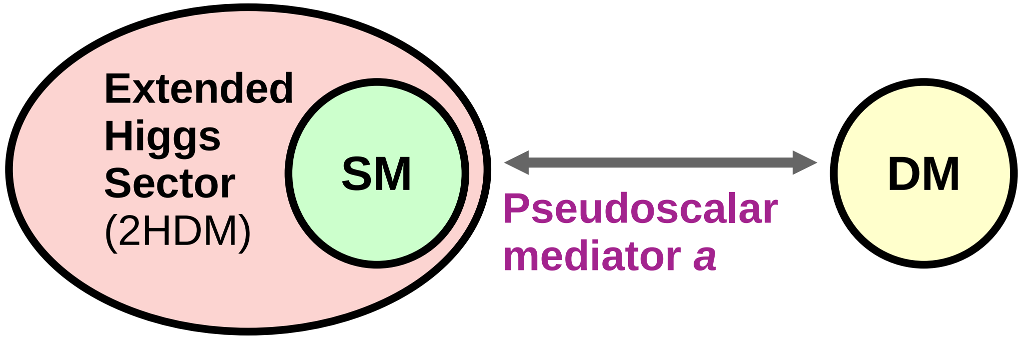
# Dark matter interpretations: 2HDM+a

JHEP 08 (2024) 013

- Minimal, UV-complete extension of simplified models
- First DM interpretation of an interference search
- First search considering interference patterns due to mixing of two pseudo-scalars

PhD thesis Y. Chen + LHCDMWG




**LHC Dark Matter Working Group**: Phys. Dark Univ. 27 (2020) 100351

**Bauer, Haisch, Kahlhoefer:** JHEP05(2017) 138

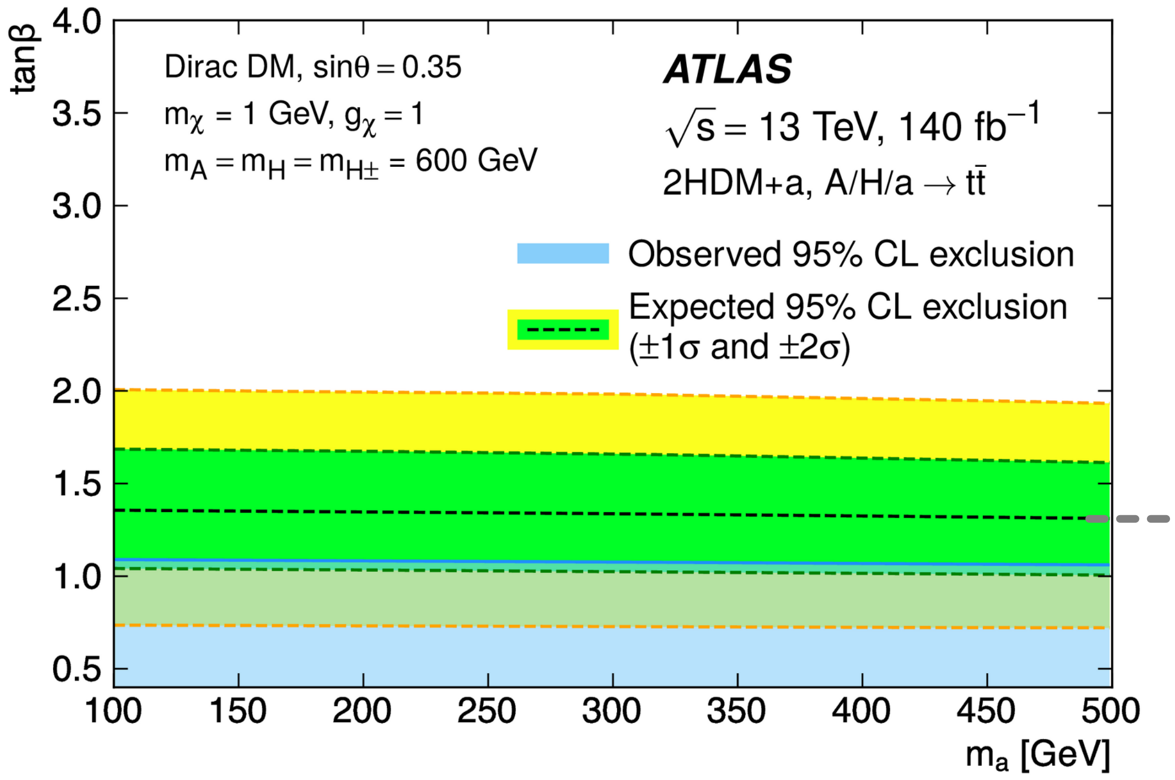
# Dark matter interpretations: 2HDM+a

JHEP 08 (2024) 013

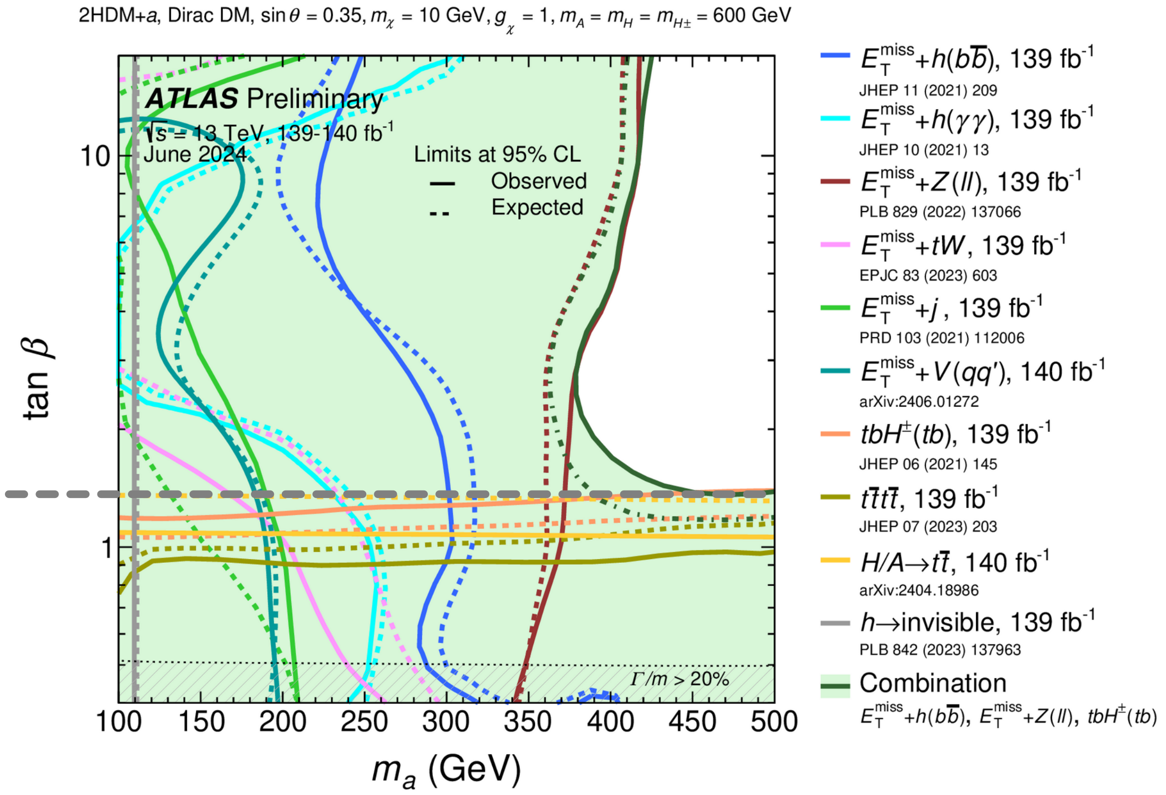
> Benchmark scenario 3a in LHC DM WG recommendations

> Leading expected exclusion at high mediator mass

> Observed exclusion slightly weaker than $H^+(tb)$ result due to downward fluctuation




Science Bulletin 69 (2024) 3005

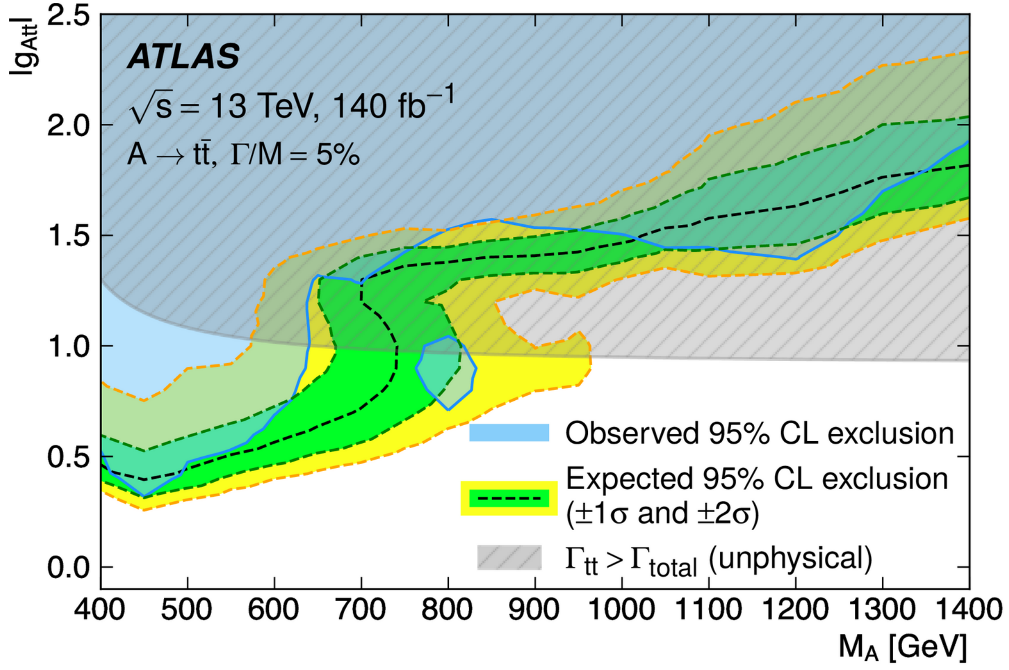


# Coupling constraints for a single (pseudo)scalar

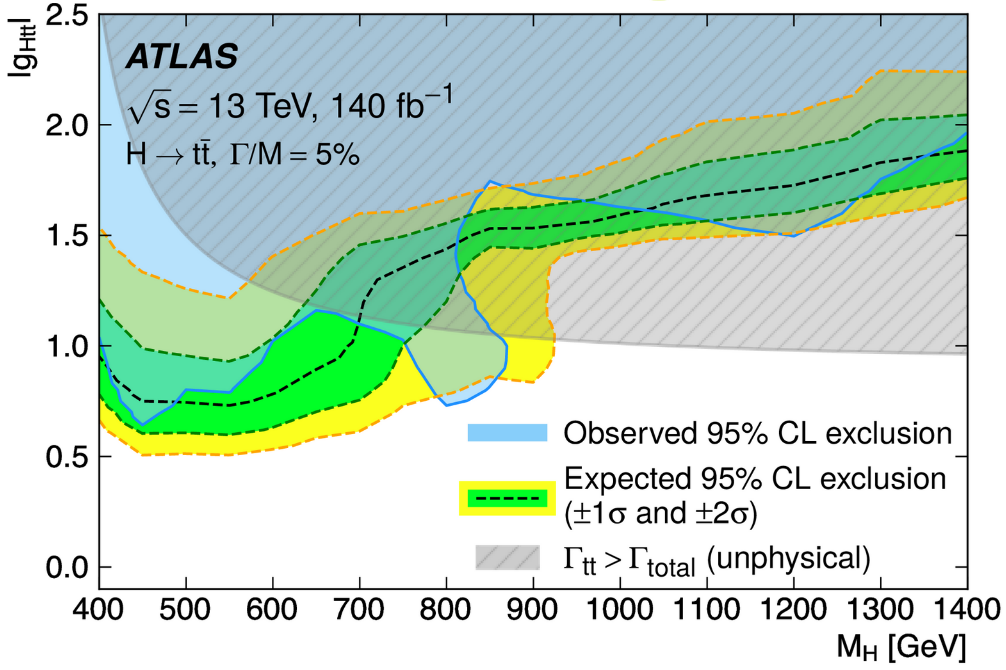
> Upper limit on coupling to top quarks for a fixed width

> "Island" due to local minima in likelihood scan

Pseudoscalar A




Scalar H

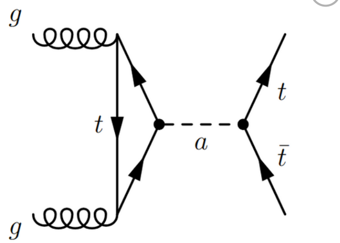


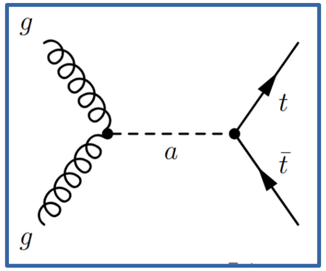
# Extra: ALPs coupling to top quarks

> Interference searches sensitive to axion-like particles (ALPs) at the GeV scale

> Key difference compared to heavy Higgs bosons: direct gluon coupling!

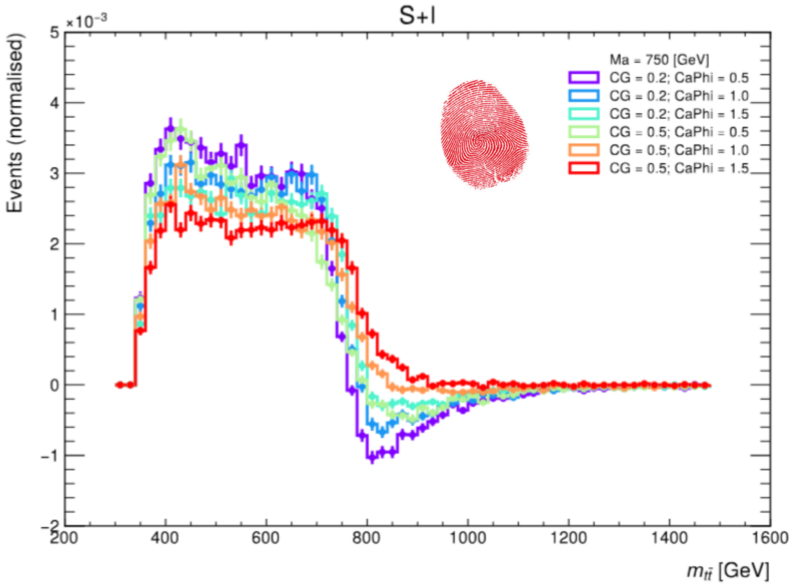
  - Different interference pattern!




Unique for ALPs!

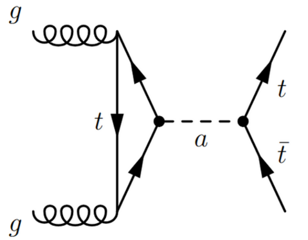
M. Rodrigues, KB



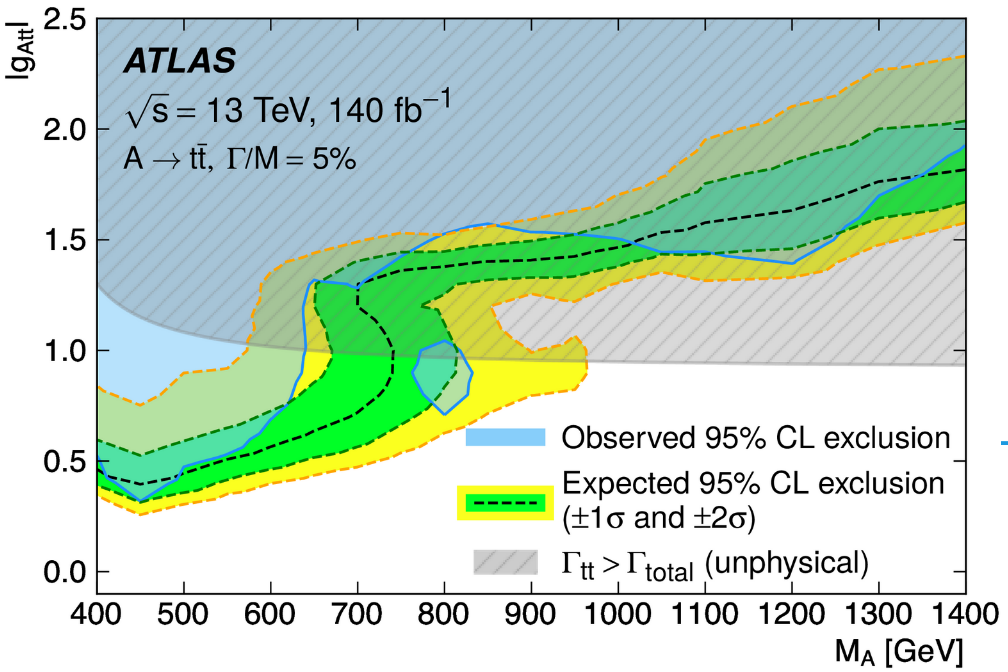

Related work:
Jeppe et al: DESY-24-059
Carra et al: PRD 104 (2021) 9, 092005

# Extra: ALPs coupling to top quarks

- Assume $c_G = 0$
- Constraints from heavy-Higgs search directly translate to constraints on $c_t$

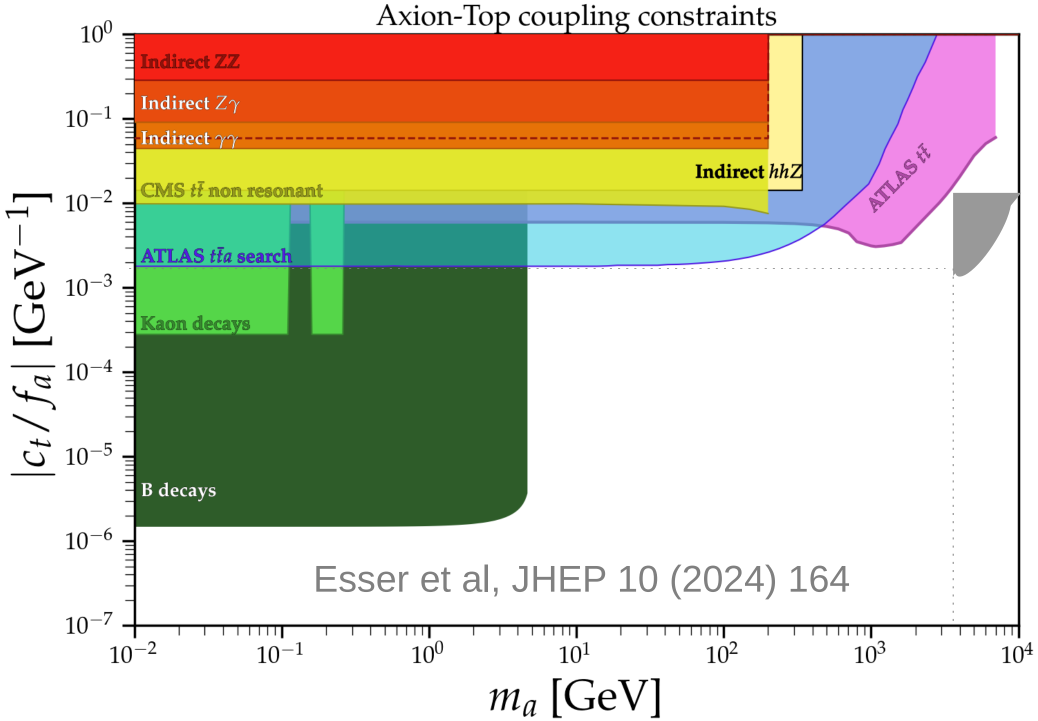



Fixed pseudoscalar width



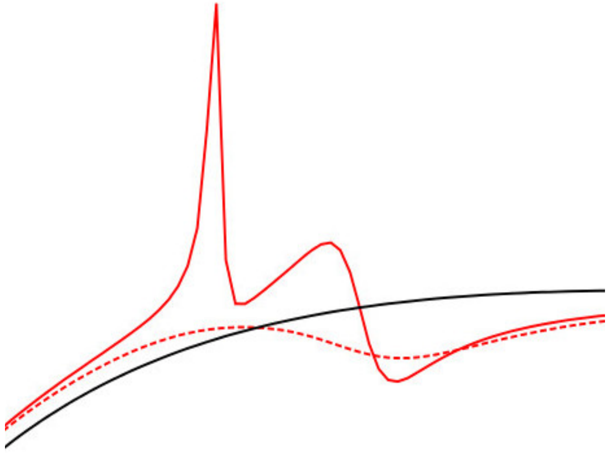

$g_{Att}/v = c_t/f_a$

Width depends on $m_a$ and $c_t$




Esser et al, JHEP 10 (2024) 164

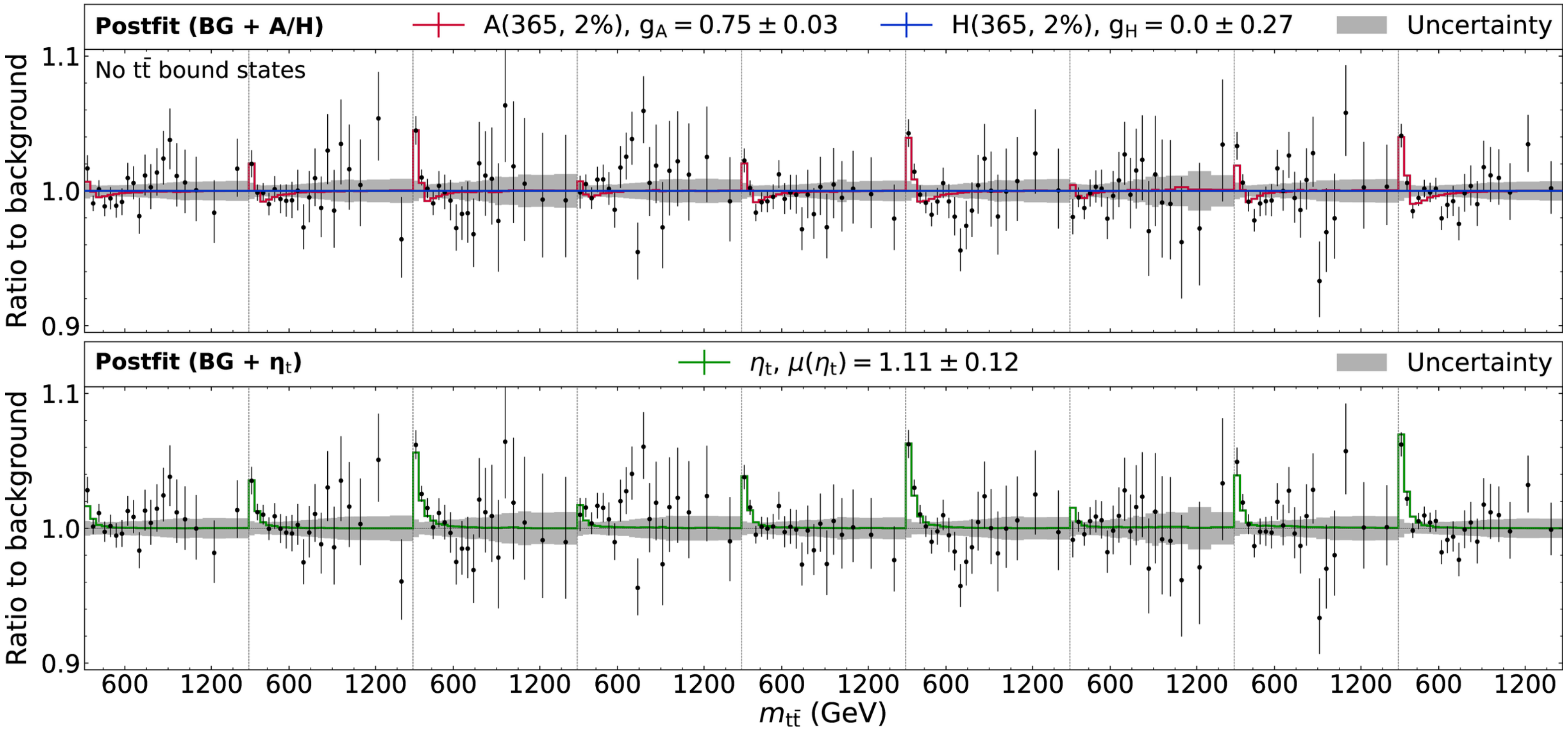
## **CMS preliminary result:** CMS-PAS-HIG-22-013

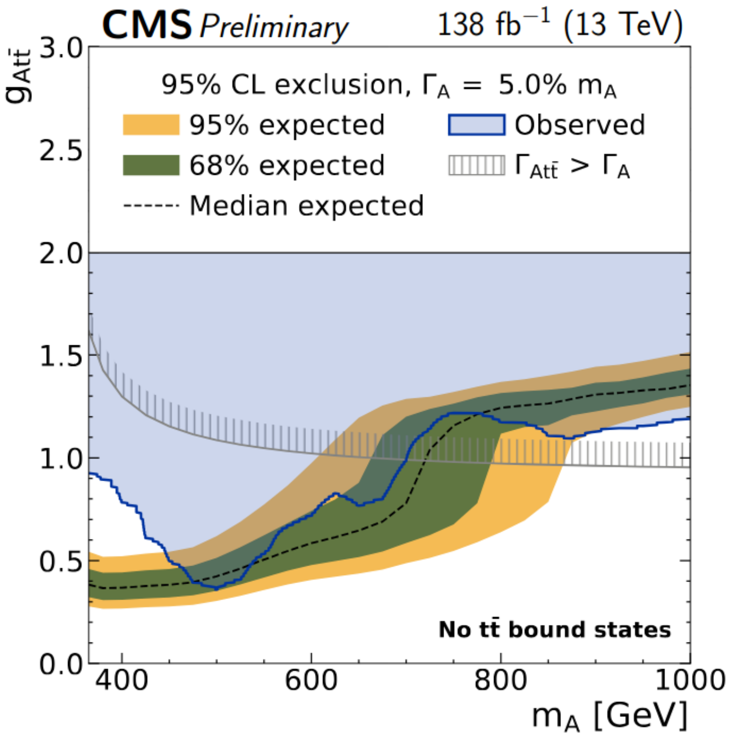


# In a nutshell



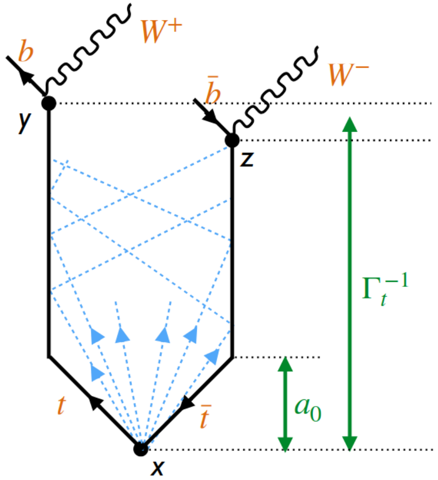
- Equivalent interference search on CMS Run-2 dataset
- Observe > 5σ deviation of the data from the prediction in the ttbar threshold region ($m_{tt}$ < 400 GeV)
  - Consistent with presence of ttbar quasi-bound state ("toponium")
  - Consistent also with narrow pseudoscalar state with $m_A$ = 365 GeV

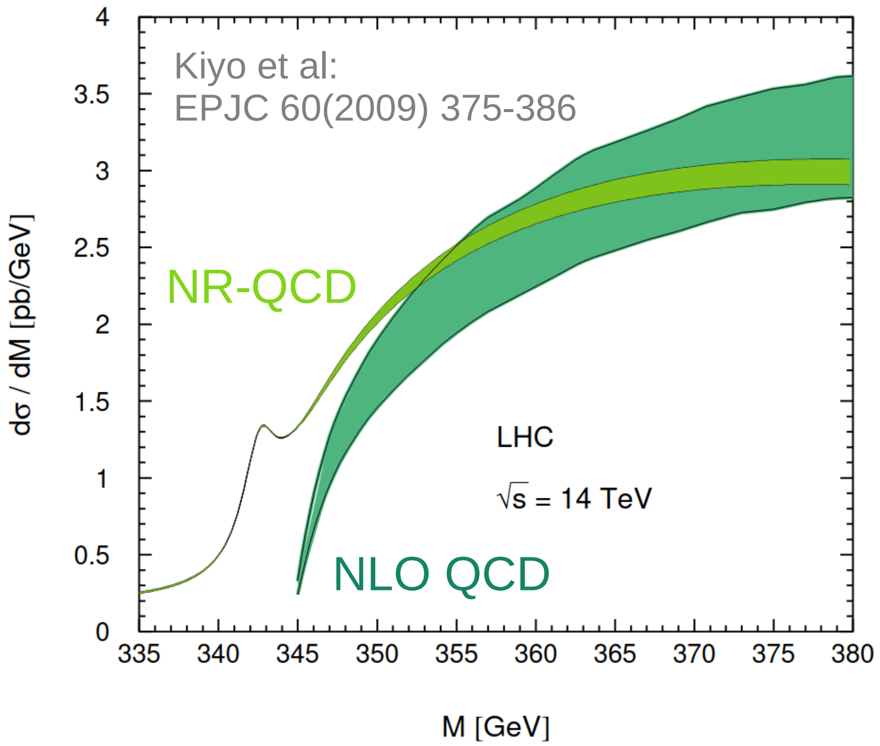


# Toponium – a ttbar quasi-bound state

- Formation of ttbar quasi-bound state below ttbar threshold
  - Plane wave packet propagating until the QCD potential barrier
    - Scale: the Bohr radius $a_0$
  - Oscillation between the barrier until the system decay
    - Scale: $\Gamma_t^{-1}$
    - Possible gluon exchange before decay
  - Off-shell top or anti-top at decay
- Described by non-relativistic QCD (NR-QCD)
- Approximated as pure-S pseudoscalar resonance $\eta_t$
  - m = 343 GeV and Γ/m = 7 GeV

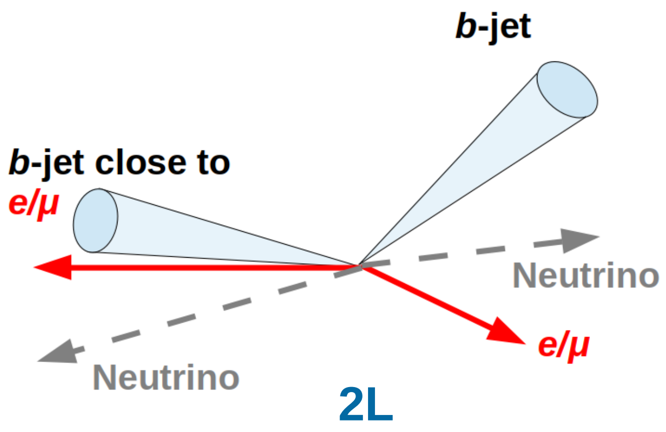


# CMS strategy

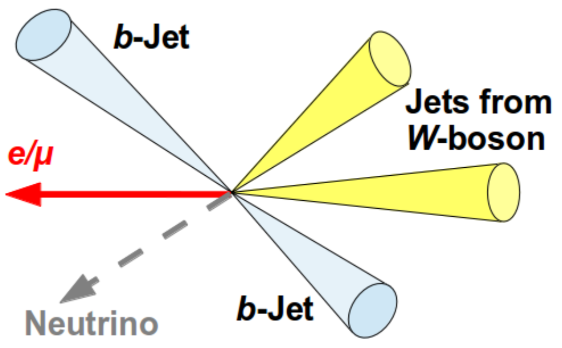


- Two orthogonal sets of regions: 1L (e or μ) + 2L ($e^+e^-$, eμ, $\mu^+\mu^-$)
- **2L channel** [leading sensitivity for toponium → lowest $m_{ttbar}$]
  - Analytic reconstruct of $m_{ttbar}$
    - Assumptions: all $p_T^{miss}$ from νν, tops on-shell, *W* bosons on-shell
    - Assign *b*-jets using likelihood, based on $m_{lb}$
    - Finite detector resolution: repeat reconstruction 100 times with randomly smeared inputs, take weighted average

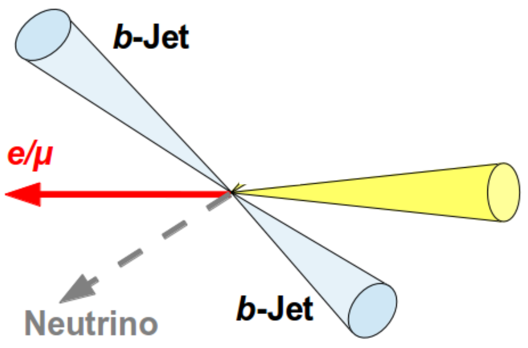


# CMS strategy

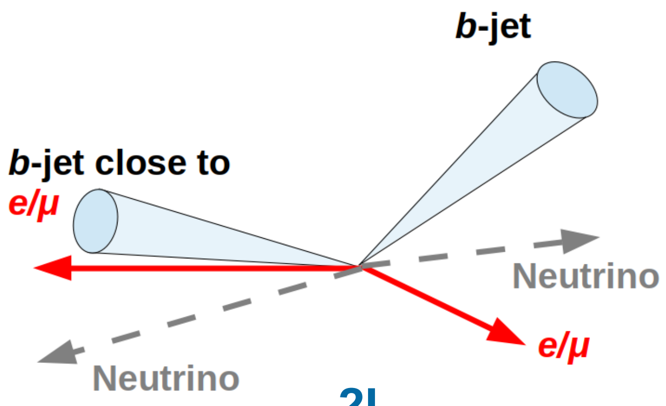
- Two orthogonal sets of regions: 1L (e or μ) + 2L ($e^+e^-$, eμ, $\mu^+\mu^-$)
- **2L channel** [leading sensitivity for toponium → lowest $m_{ttbar}$]
  - Analytic reconstruct of $m_{ttbar}$
- **1L channel**
  - Resolved topology: ≥4 small-*R* jets, ==2 *b*-tags
  - "Merged" topology: ==3 jets, ==2 *b*-tags
  - Reconstruct $m_{ttbar}$: via $\chi^2$ algorithm




**1L, ≥4 jets**




**1L, ==3 jets**

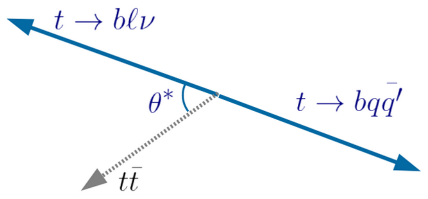


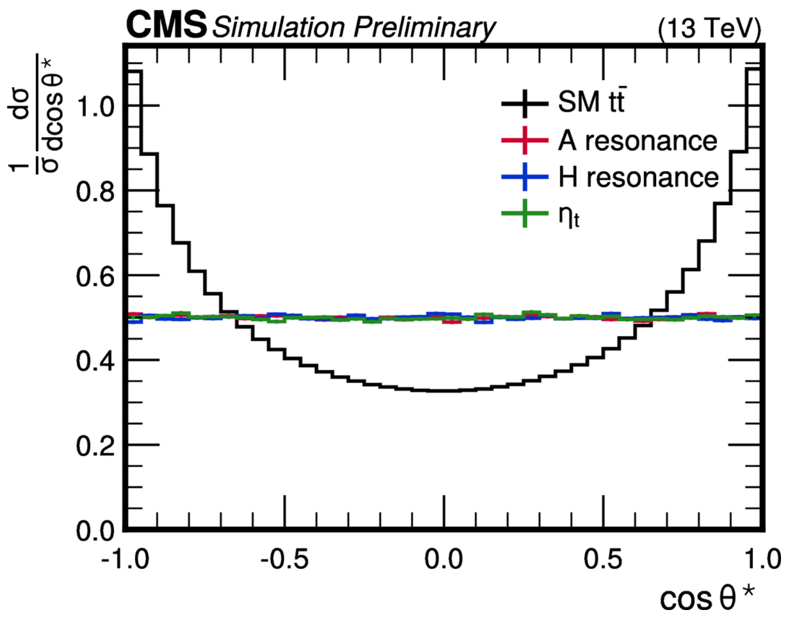

**2L**

# CMS: angular variables

> Split 1L and 2L regions into bins of angular variables sensitive to spin state of the ttbar system

- 1L: $\cos\theta^*$



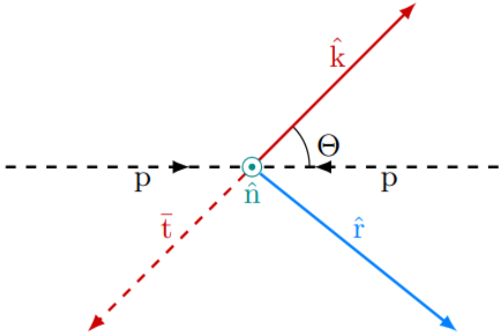
# CMS: angular variables

CMS-PAS-HIG-22-013

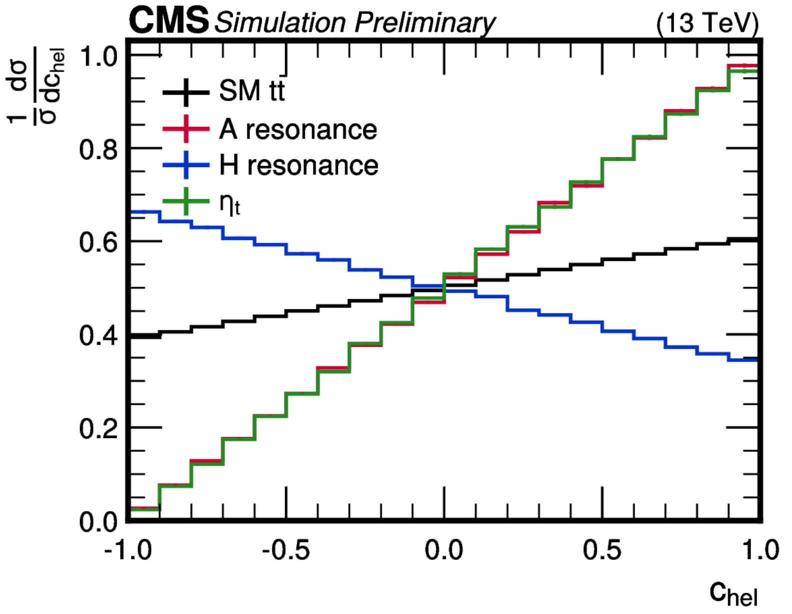
> Split 1L and 2L regions into bins of angular variables sensitive to spin state of the ttbar system

- 1L: $\cos\theta^*$
- 2L: $c_{hel}$, $c_{han}$

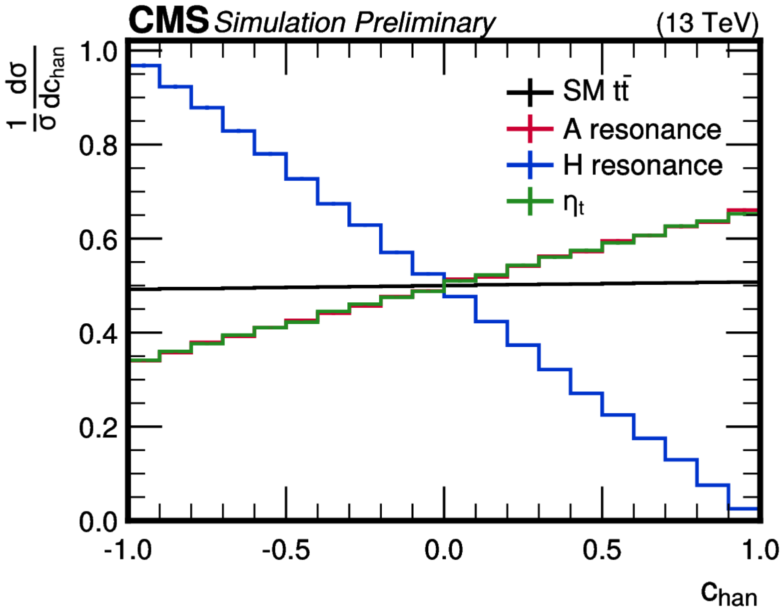
$$c_{\text{hel}} = -(\hat{\ell}^+)_k(\hat{\ell}^-)_k - (\hat{\ell}^+)_r(\hat{\ell}^-)_r - (\hat{\ell}^+)_n(\hat{\ell}^-)_n$$
$$c_{\text{han}} = +(\hat{\ell}^+)_k(\hat{\ell}^-)_k - (\hat{\ell}^+)_r(\hat{\ell}^-)_r - (\hat{\ell}^+)_n(\hat{\ell}^-)_n$$

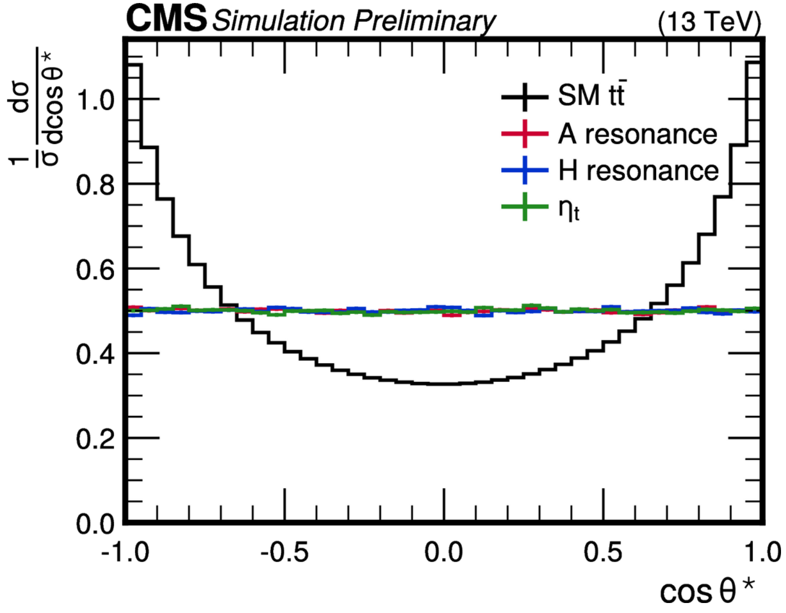



Enhances sensitivity to pseudoscalar




Enhances sensitivity to scalar



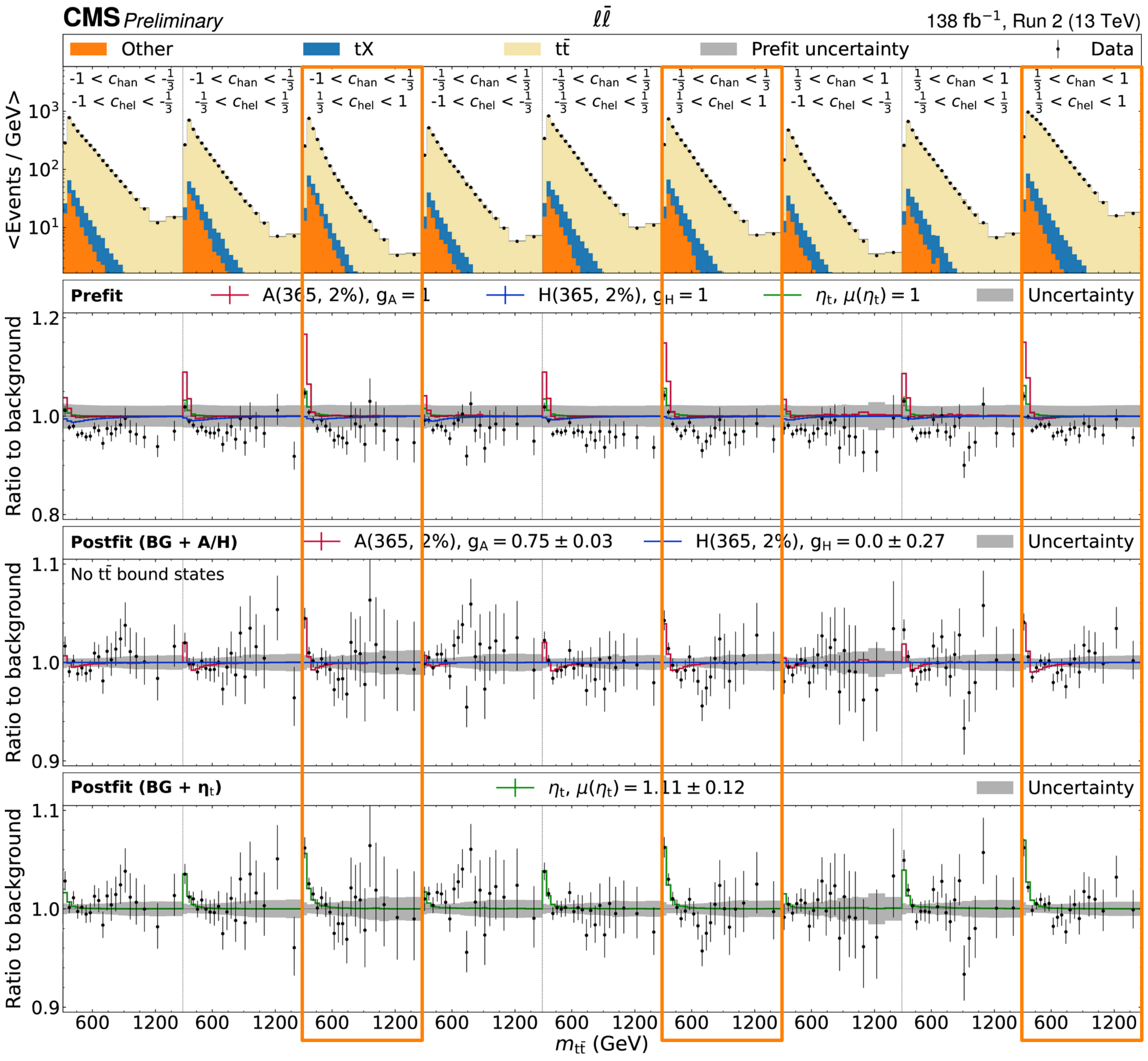



# CMS 2L signal regions



Binned in $c_{hel}$ and $c_{han}$

High $c_{hel}$ bins most sensitive to pseudoscalar states



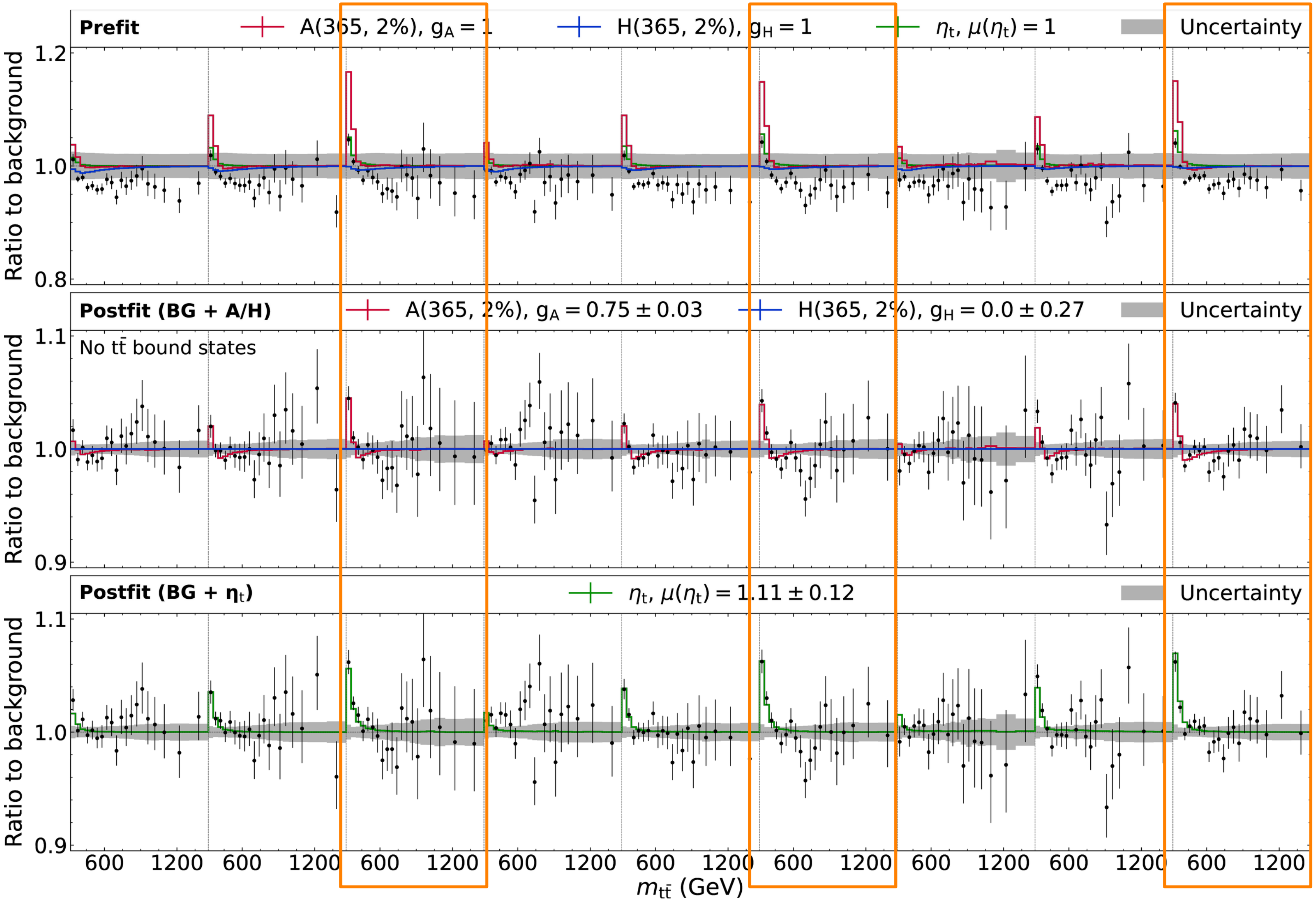
# CMS 2L signal regions



Prefit

BSM pseudoscalar:
A+I+B

Toponium:
η+B



# Differences in background modelling

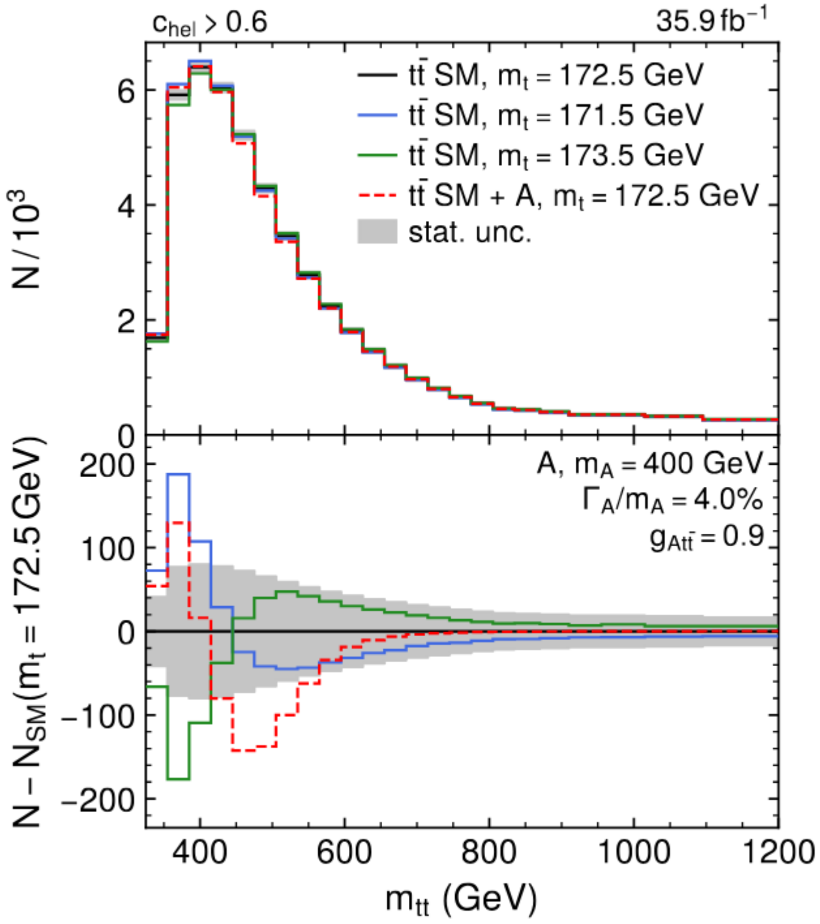
> Reweighting from NLO Powheg+Pythia to NNLO-QCD+NLO-EW

> CMS:

- Double differential reweighting in $m_{tt}$ and $\cos\theta^*_t$
- Calculated with HATHOR and MATRIX
- $m_t$ = 172.5 GeV

> ATLAS: $m_t$ = 173.3 GeV

Anuar et al, arxiv:2404.19014



# Differences in treatment of systematic uncertainties

> Top Yukawa coupling

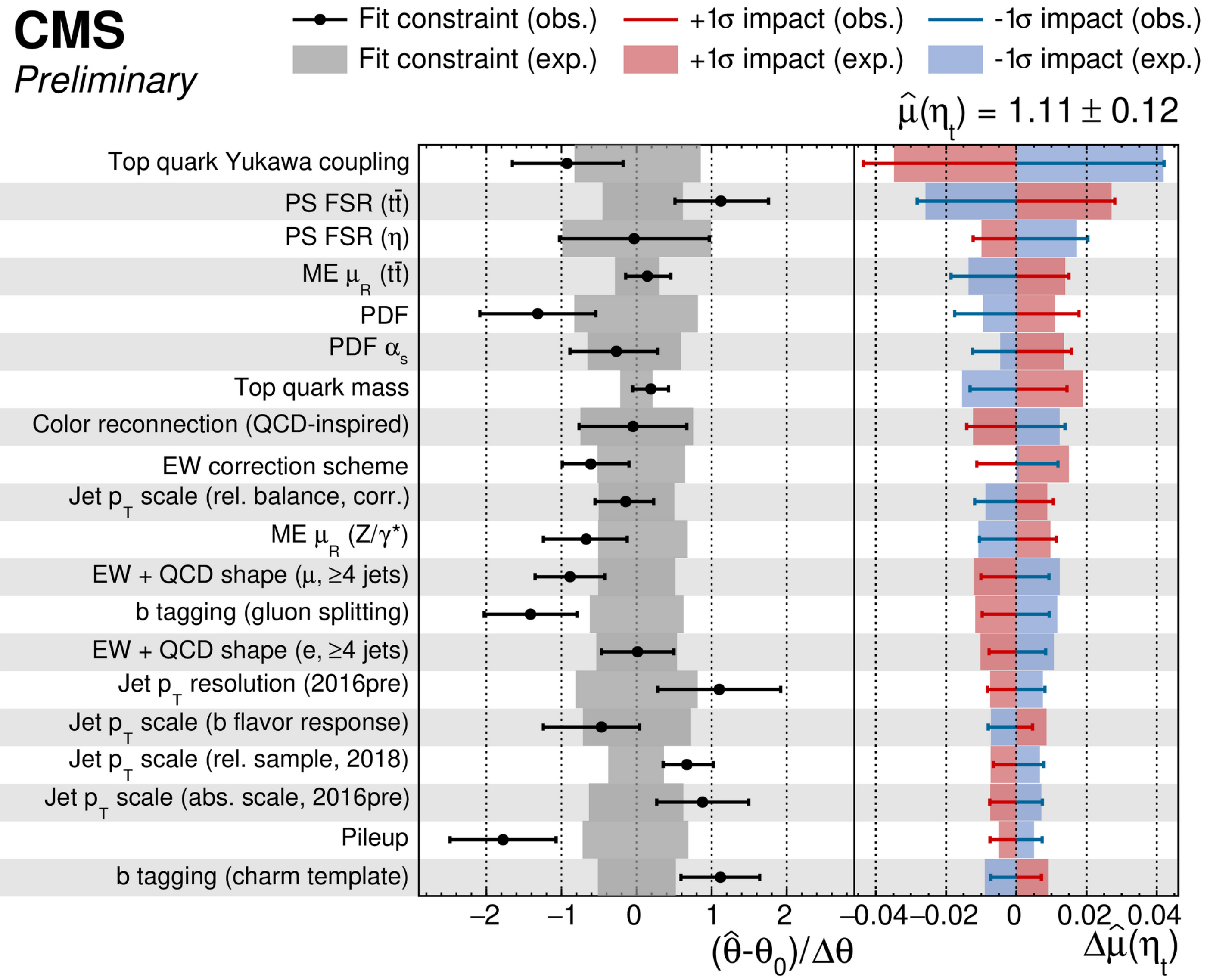
- Not included in ATLAS model, not provided by Mitov et al.
- Leading for CMS

> Top mass uncertainty

- Heavily constrained and high ranking for CMS
- Not the case for ATLAS

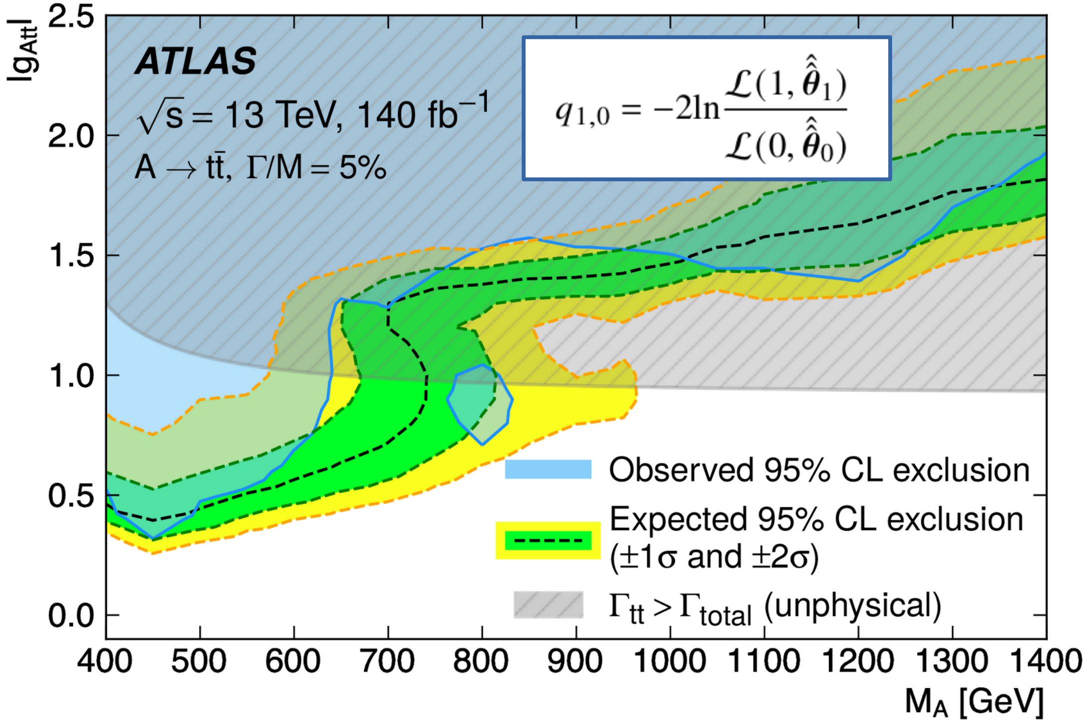
> Parton shower (Pythia8 vs Herwig7)

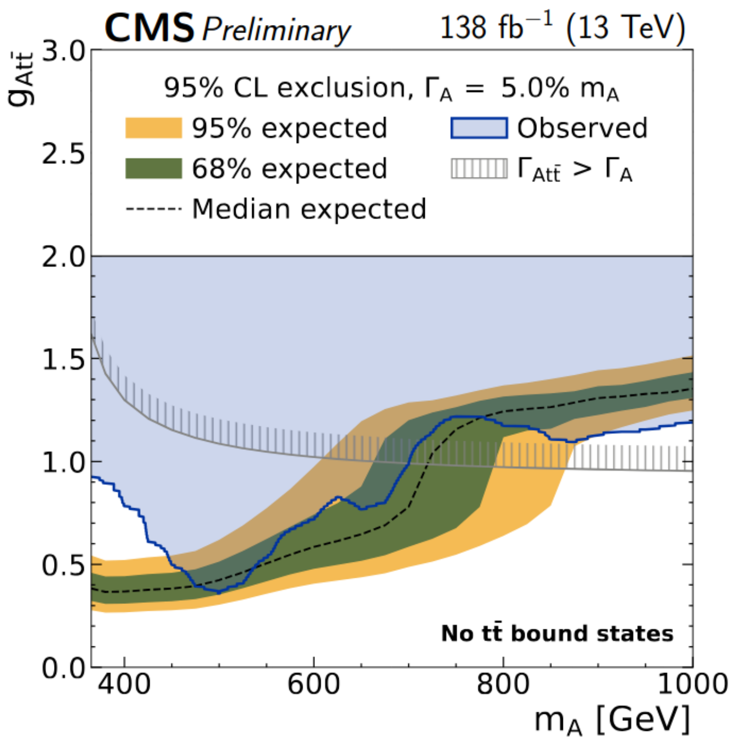
- Major uncertainty for ATLAS: high-ranking, pulled, and constrained
- Small impact for CMS (internal studies)
- Impact reduced by use of $c_{hel}$ and $c_{han}$ ?



# Comparison with ATLAS result: sensitivity

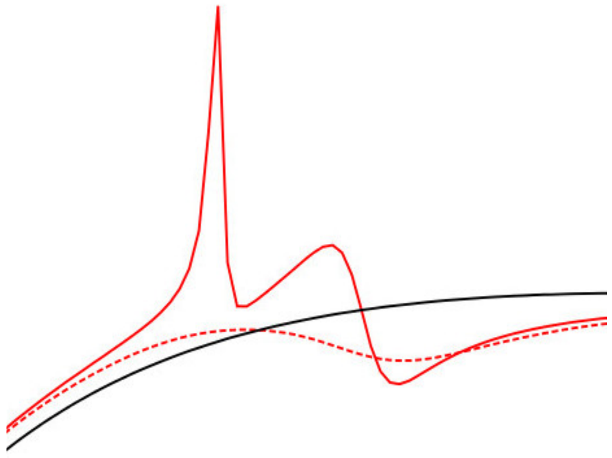
- Note 1: CMS choice of standard profile-likelihood test statistics leads to slightly over-optimistic constraints for them as they compare to global minimum instead of μ=0
- Note 2: Islands in exclusion contour due to local minima in $CL_s$ scan

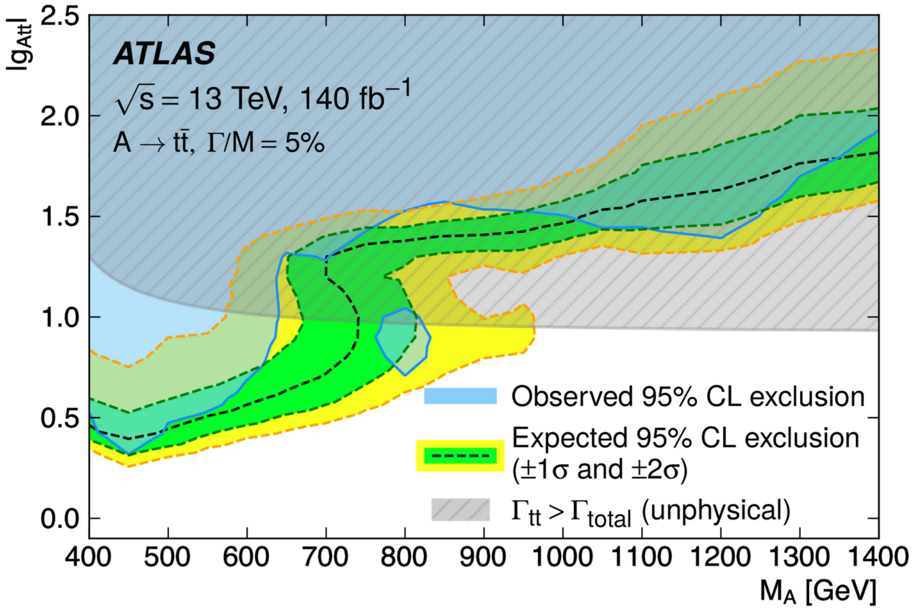


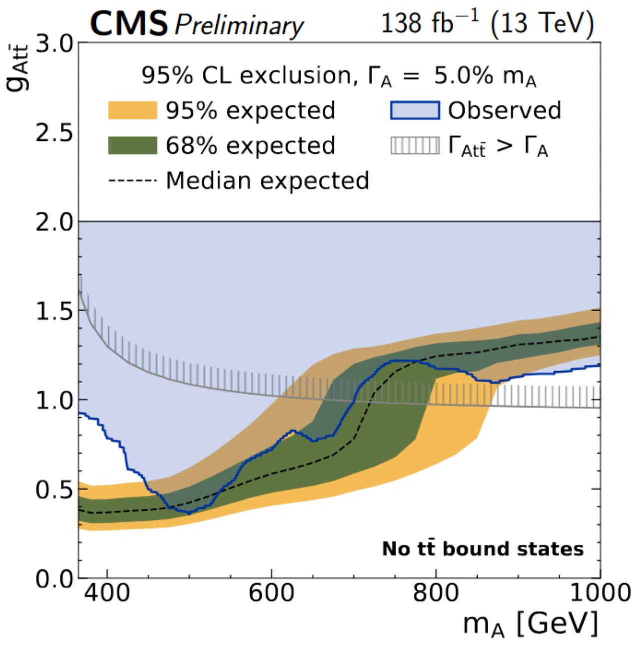



# Summary

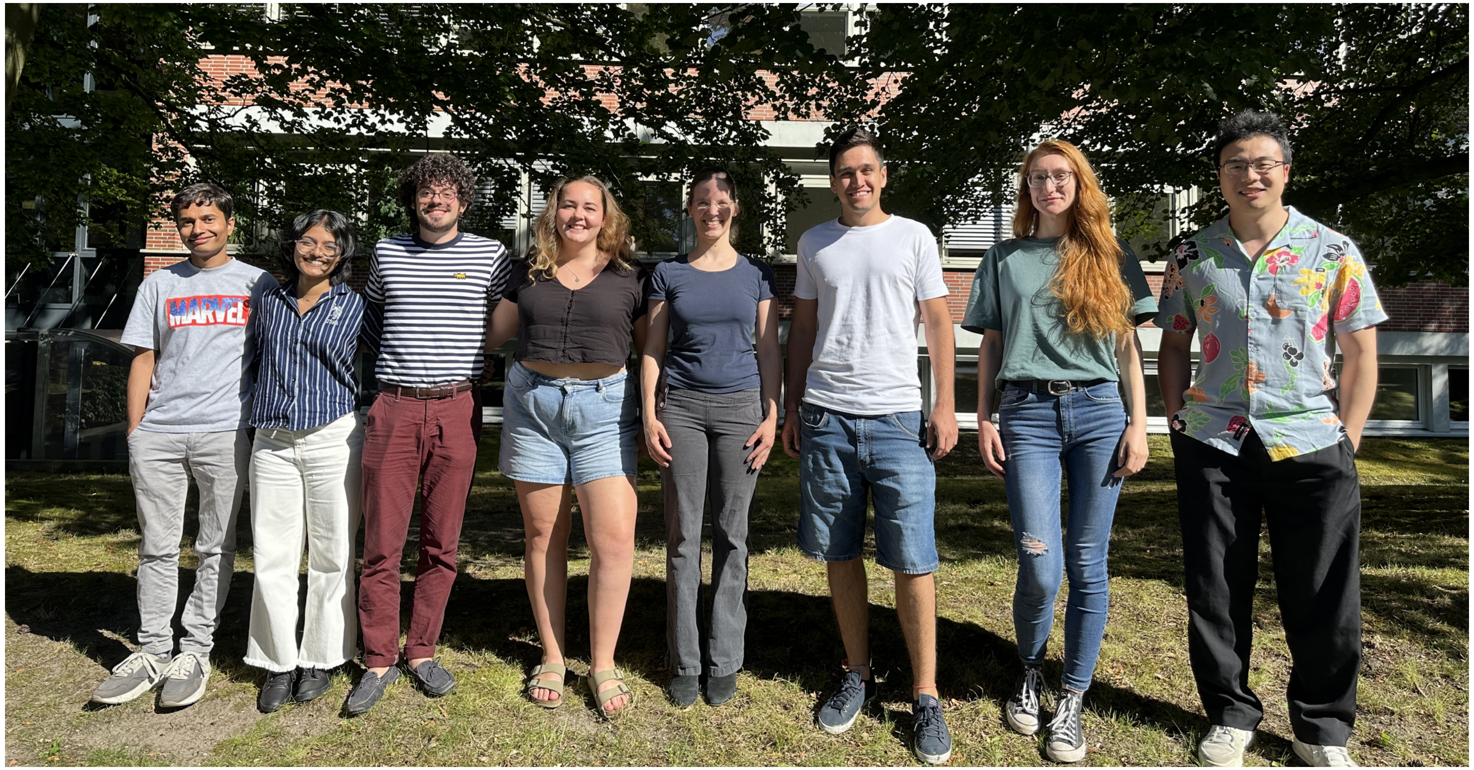
- Interference searches in ttbar final states open up exciting regions of (B)SM parameter space
- Developed suite of novel technical and statistical tools addressing interference patterns
- First constraints beyond 1 TeV and on DM models provided by ATLAS
- Threshold excess observed by CMS – toponium?
- Investigations are on-going...





# Thank you!

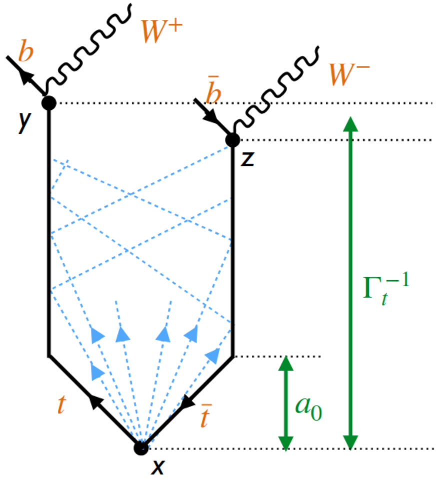


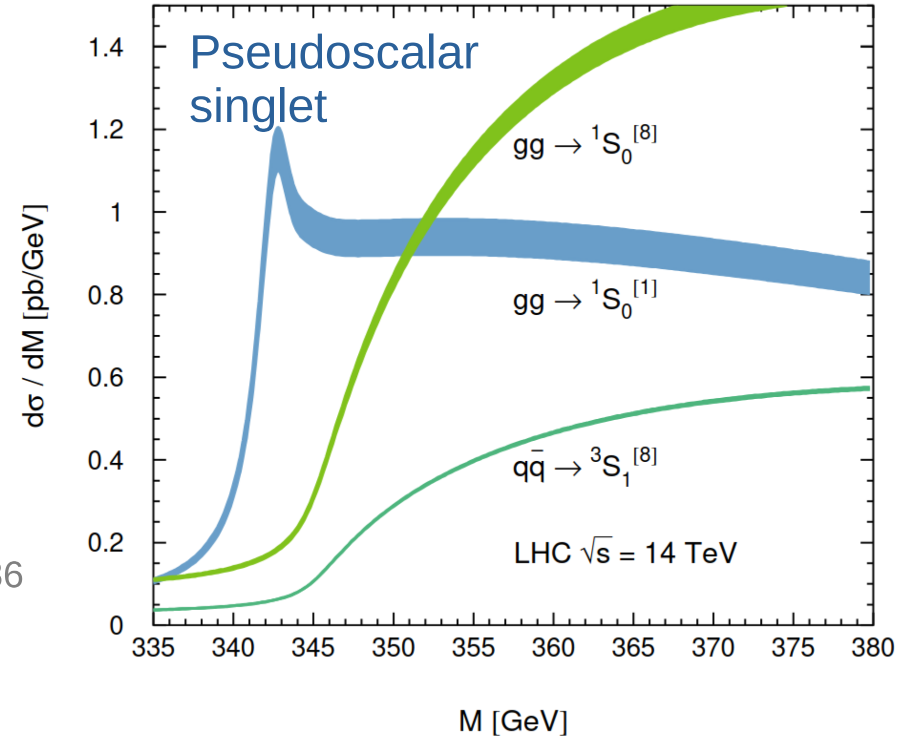

Helmholtz Young Investigator Group “Fingerprints of the Vacuum”
Contact: **Dr. Katharina Behr** (katharina.behr@desy.de)

# Extra Material

# Toponium – modelling

- Simplified model used in CMS result
  - Based on work by C. Severi
  - Pseudoscalar resonance $\eta_t$ with m = 343 GeV and Γ/m = 7 GeV
- General consensus that this is too simplistic
  - Toponium is NOT an s-channel resonance
  - Missing octet contributions
  - Concerns regarding modeling of off-shell top quarks
- More complete model by B. Fuks [arXiv:2411.18962]
  - Under study by ATLAS and CMS

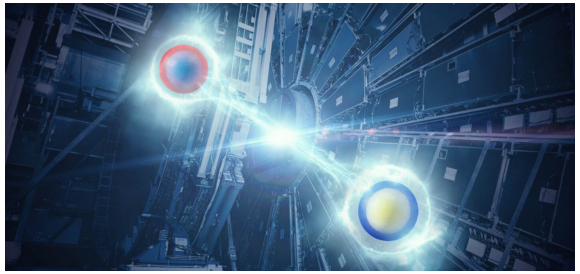


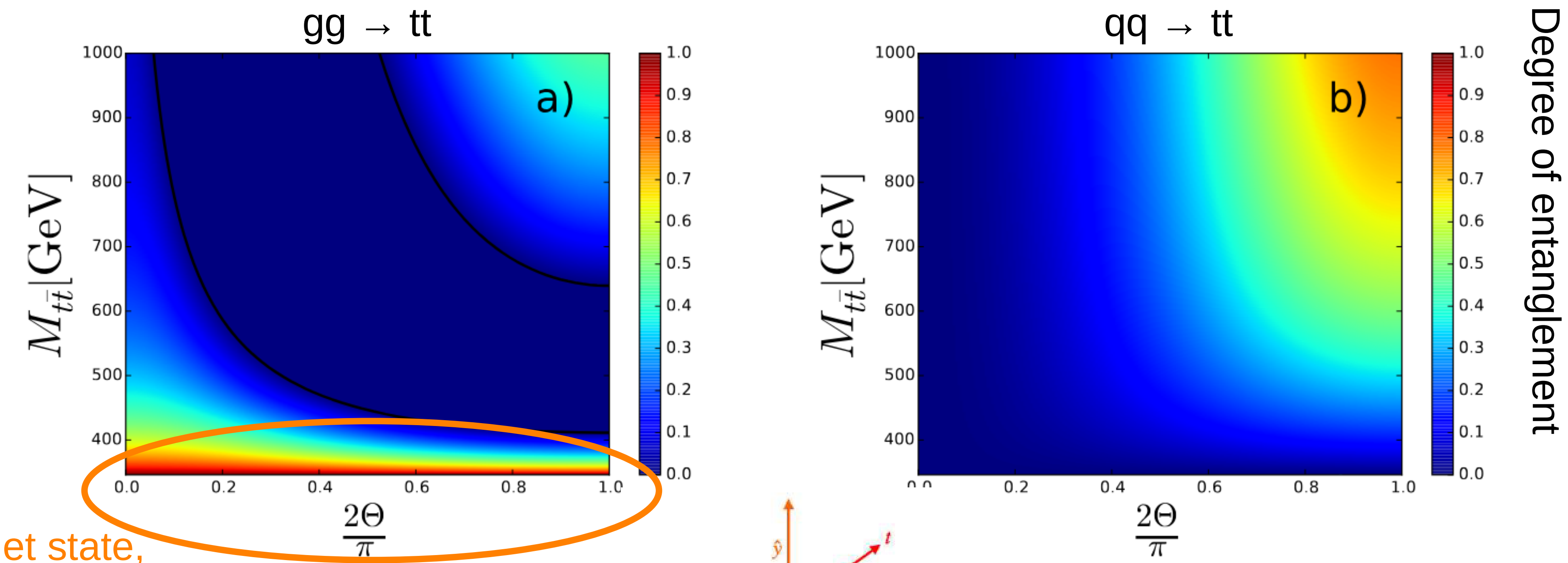




Kiyo et al:
EPJC 60(2009) 375-386

# Aside: entanglement measurements close to threshold

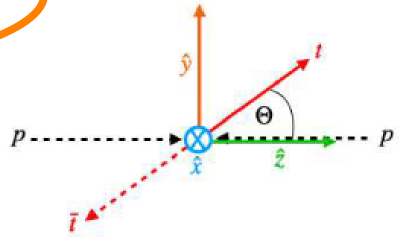
- Threshold region sensitive to entanglement between top and antitop
- Top – antitop system = two qubit system
- Maximal entanglement in spin-singlet state for gg → tt at threshold





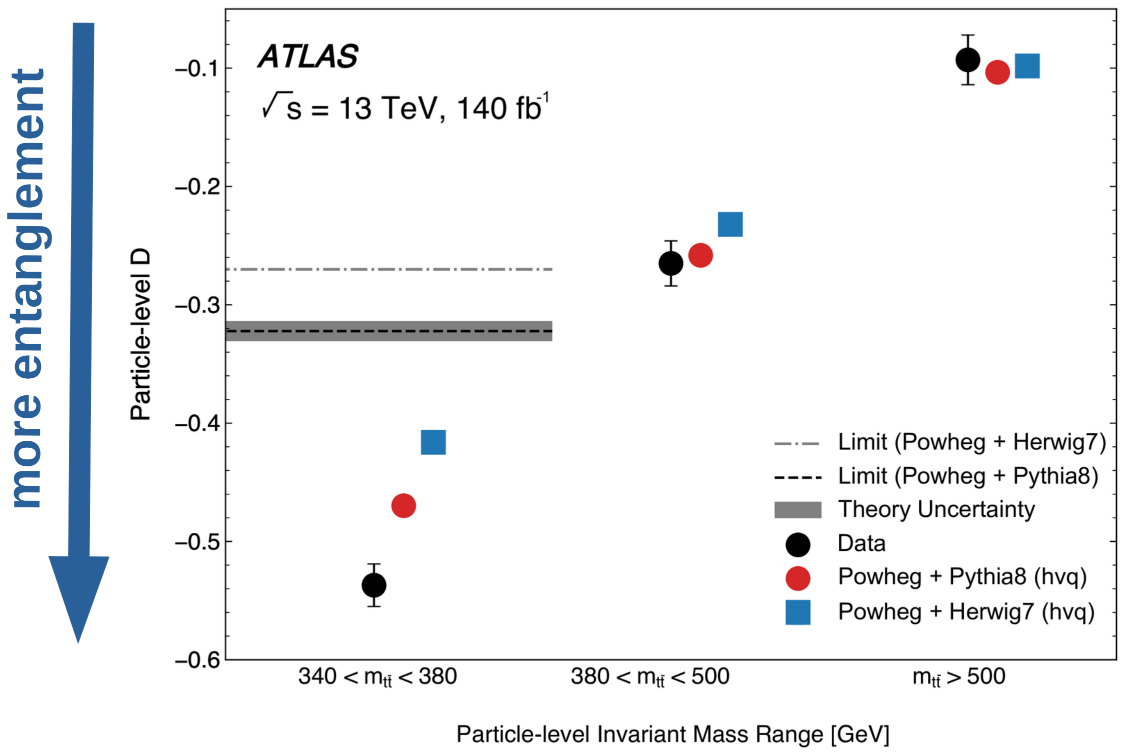

Pure spin singlet state, maximally entangled, time-like separation

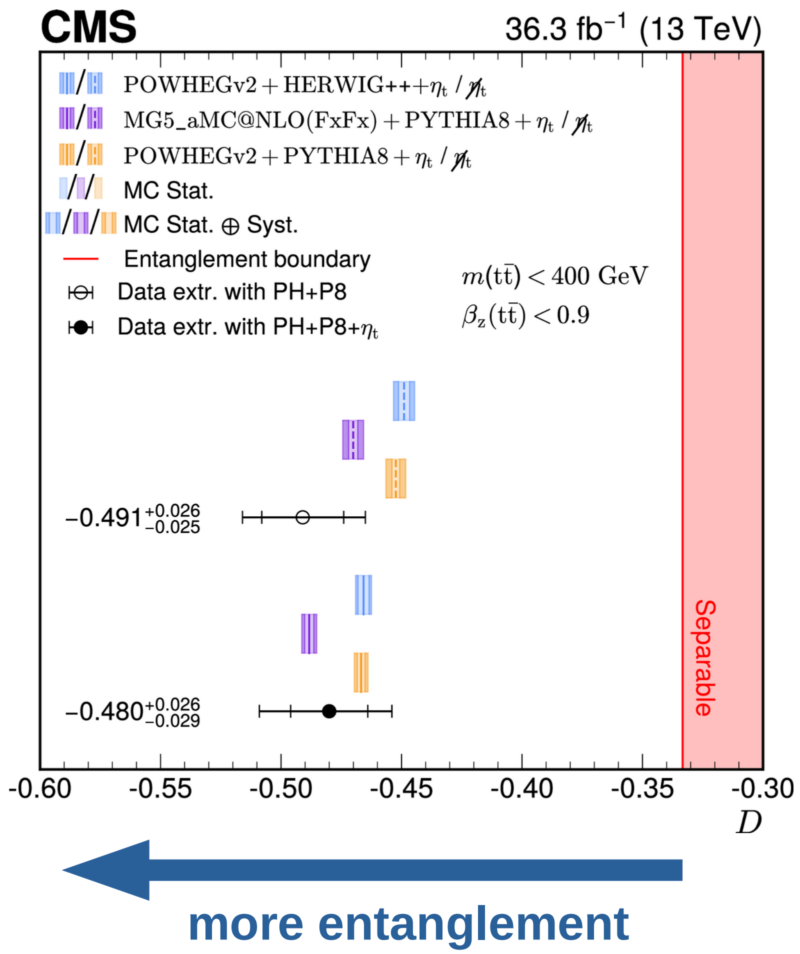
$$\frac{|\uparrow_{\hat{n}}\downarrow_{\hat{n}}\rangle + |\downarrow_{\hat{n}}\uparrow_{\hat{n}}\rangle}{\sqrt{2}}$$



# Aside: entanglement measurements close to threshold

- Entanglement observed by both ATLAS and CMS close to threshold in 2L channel
- Addition of toponium model improves agreeement between data and expectation for CMS



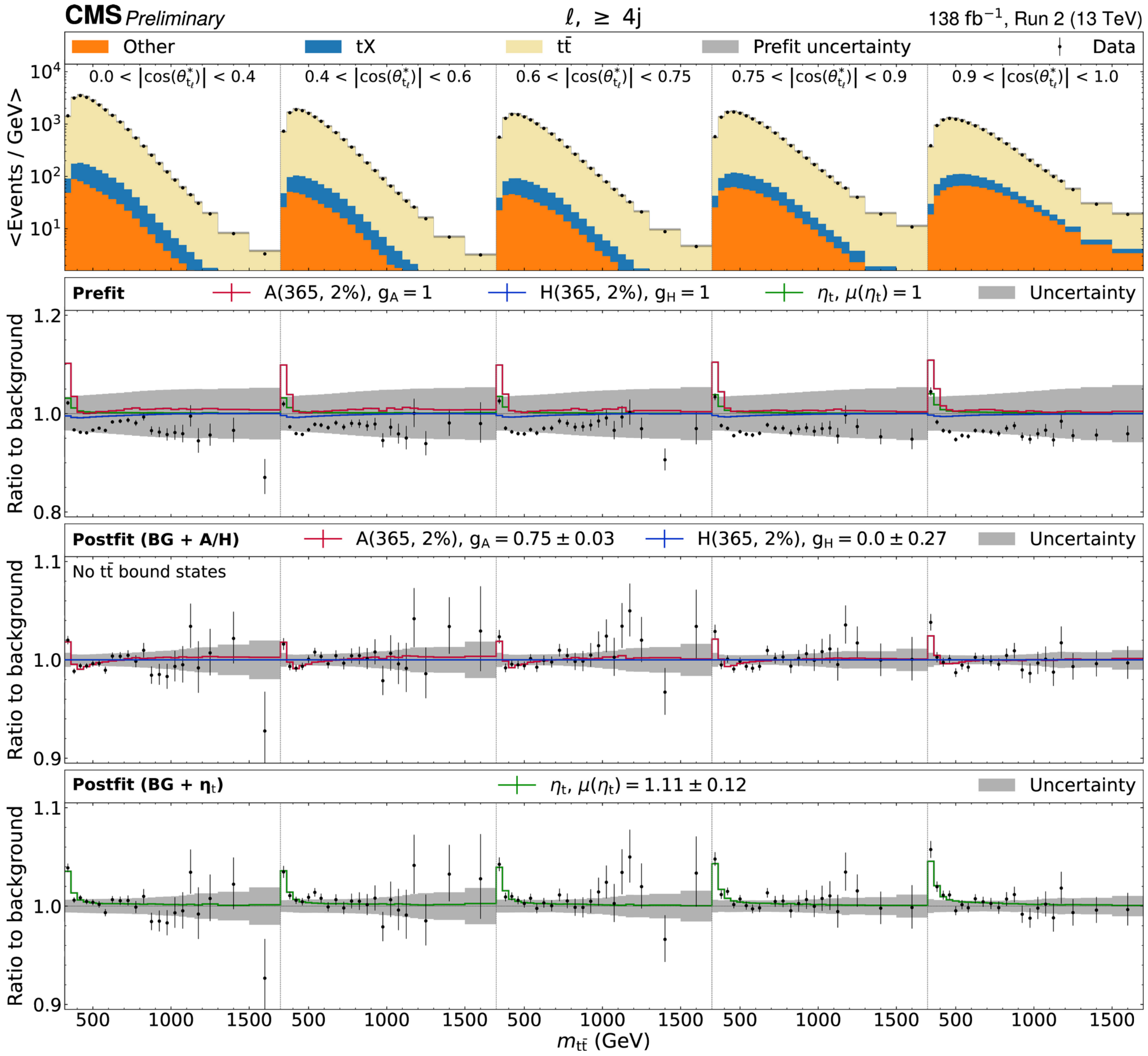



# CMS 1L signal regions



Binned in cosθ*

Post-fit excess less pronounced but clearly visible

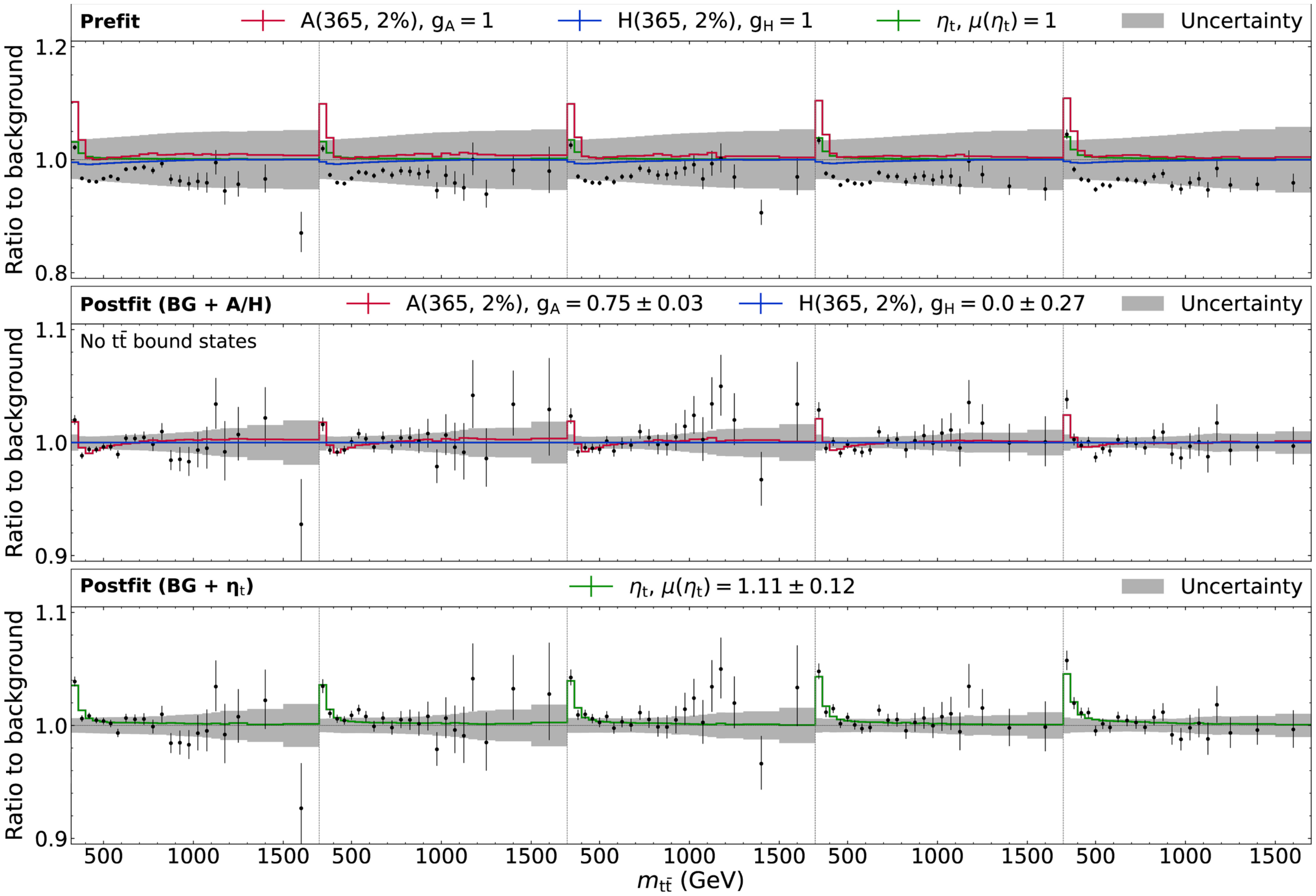


# CMS 1L signal regions

CMS-PAS-HIG-22-013

Binned in cosθ*

Post-fit excess less pronounced but clearly visible



# ATLAS 1L signal regions (pre-fit)

> Pre-fit excess in data in lowest $m_{tt}$ bins for all resolved signal regions and deficit in high $m_{tt}$ tails

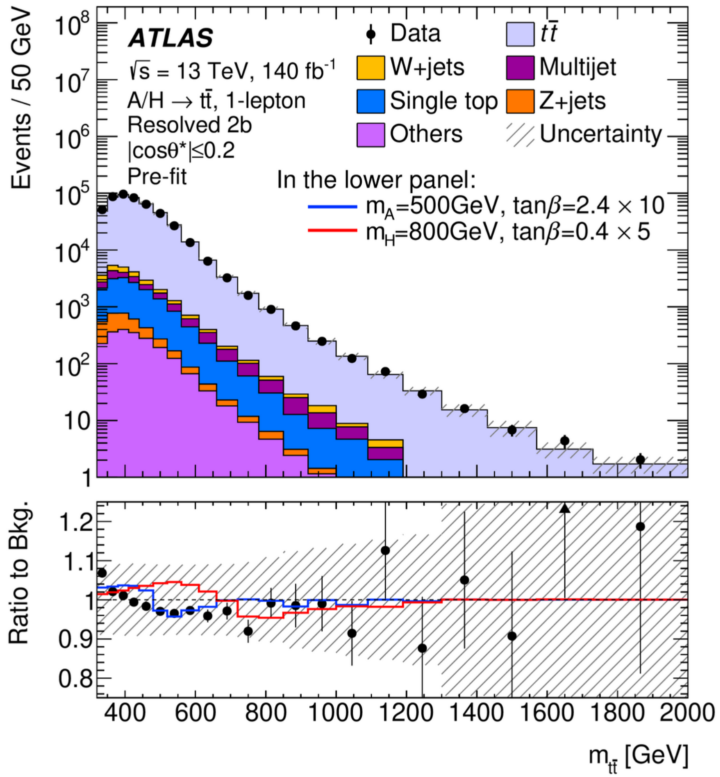
- Similar to what CMS observes pre-fit

> Probe same kinematic range as CMS

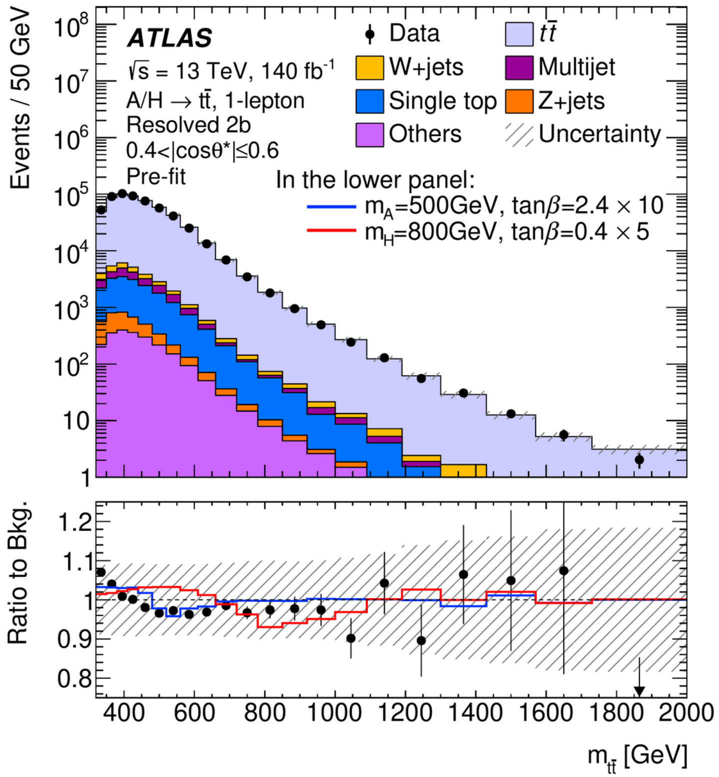
- Binning: 320, 350, 380, 410, 440, …

**Comparison with CMS**: 320, 360, 400, 440, ...

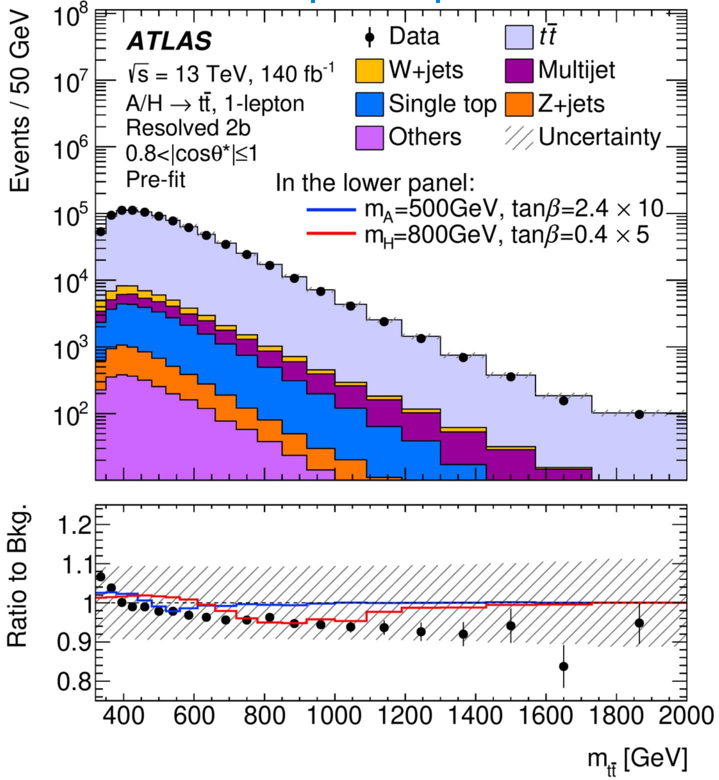
$|\cos\theta^*| < 0.2$




$0.4 < |\cos\theta^*| < 0.6$



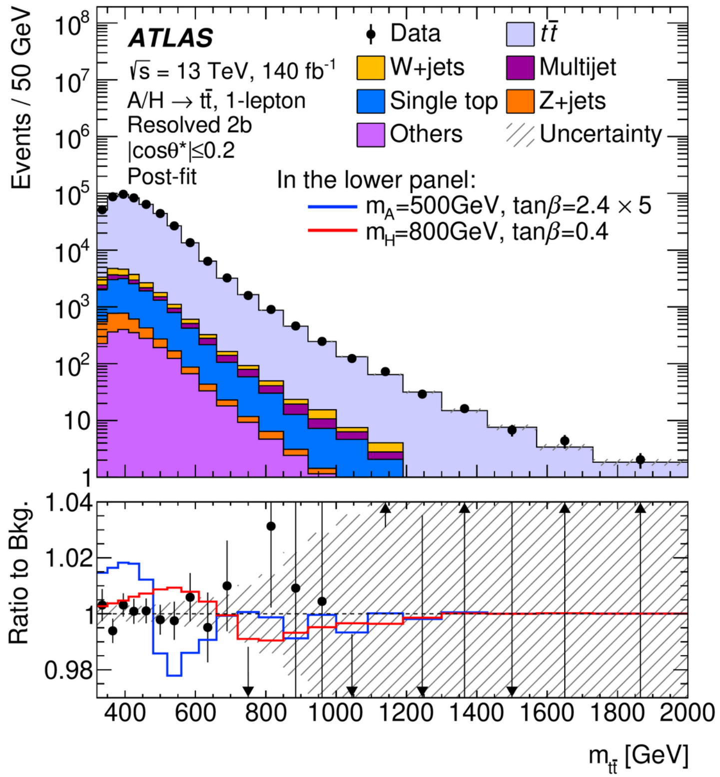

$0.8 < |\cos\theta^*| < 1.0$



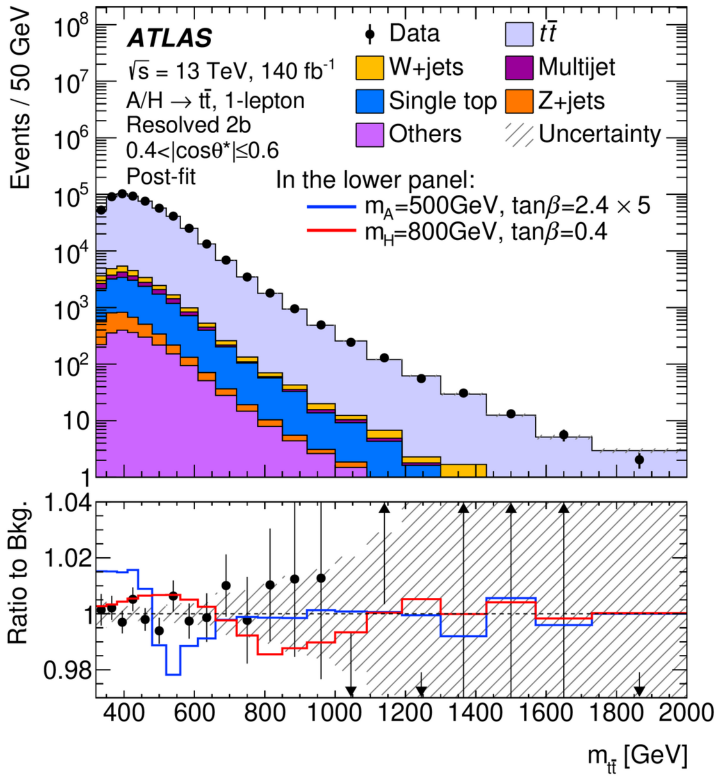
# ATLAS 1L signal regions (post-fit)

- Good post-fit agreement between data and prediction in all Resolved 2b signal regions
- Fit can accommodate pre-fit excess within uncertainties

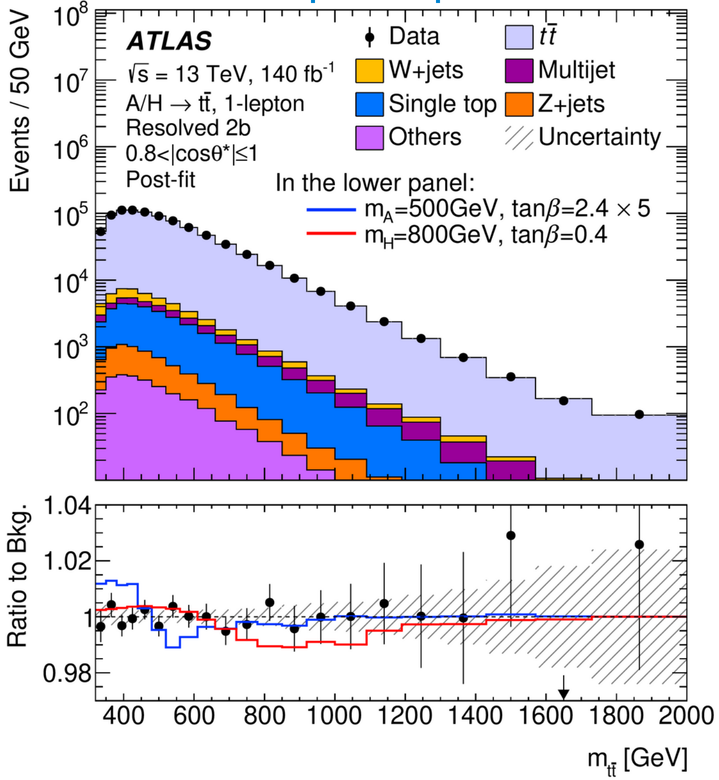
$|\cos\theta^*| < 0.2$




$0.4 < |\cos\theta^*| < 0.6$




$0.8 < |\cos\theta^*| < 1.0$

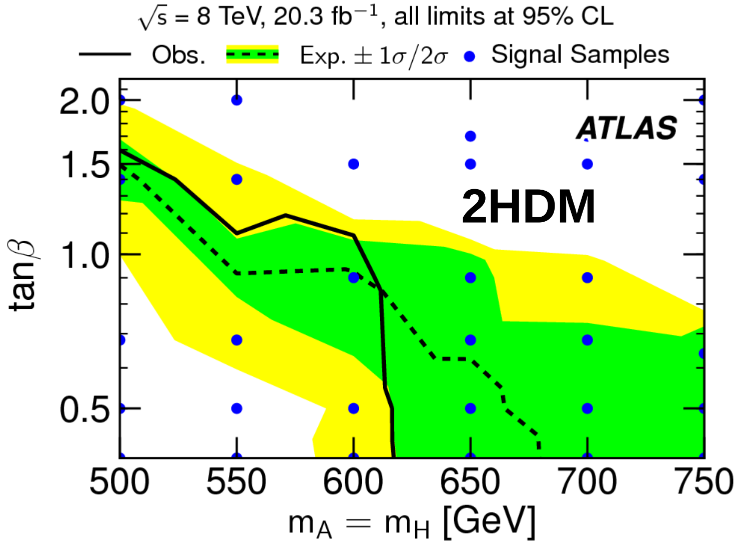


# Context

> Previous ATLAS search on 8 TeV data in the 1L channel

- First LHC search to account for interference effects
- Interpreted in type-II 2HDM

Phys. Rev. Lett. 119 (2017) 191803




> Improvements compared to ATLAS 8 TeV search:

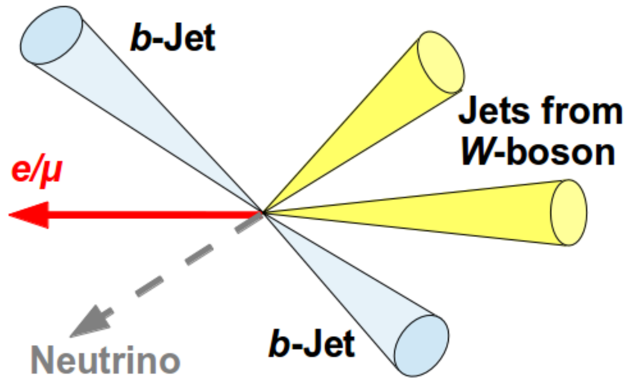
- Statistical combination of 1L and 2L channels
- SR targeting merged hadronic top decays
- Reweight SM ttbar background to NNLO-QCD+NLO-EW
- Improved statistical treatment
- Wider variety of benchmark models:
  hMSSM, 2HDM+a, model-agnostic interpretation

# 1L Resolved

- Require ≥ 4 jets, ≥ 1 b-jet
- Reconstruct full ttbar system:
  - Neutrino 4-vector from W-mass constraint
  - Assignment of jets based on $\chi^2$ minimisation

$$\chi^2 = \left[\frac{m_{jj} - m_W}{\sigma_W}\right]^2 + \left[\frac{(m_{jjb} - m_{jj}) - m_{t_h-W}}{\sigma_{t_h-W}}\right]^2 + \left[\frac{m_{jl\nu} - m_{t_l}}{\sigma_{t_l}}\right]^2 + \left[\frac{(p_{T,jjb} - p_{T,jl\nu}) - (p_{T,t_h} - p_{T,t_l})}{\sigma_{\mathrm{diff}\, p_T}}\right]^2$$

- Scale jet 4-vectors for hadronic decay to match W- and top-mass requirements
  - Improves $m_{ttbar}$ resolution by around 12%

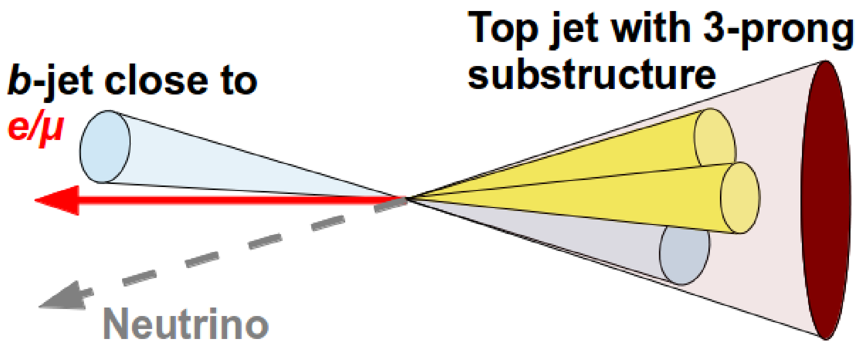


# 1L Merged

> Top candidate jet:
  - Leading large variable-R jet ($R_{max}$ = 1.5, $R_{min}$ = 0.4, ρ = 600 GeV) with $p_T$ > 200 GeV, m > 100 GeV
  - Reclustered from R=0.4 jets
  - Optimised for semi-merged and merged regimes in the $m_{ttbar}$ range [500,1500] GeV

> Leptonic top b-candidate jet: ≥ 1 small-R jet well separated from top candidate jet

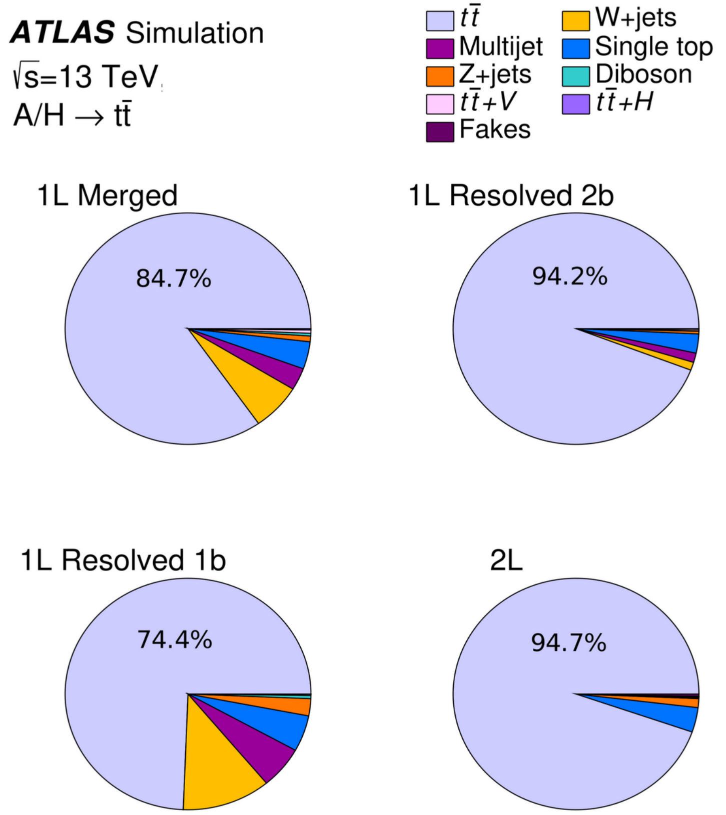
> Reconstruct full ttbar system:
  - Neutrino 4-vector from W-mass constraint
  - Selected lepton
  - Leptonic top b-candidate
  - Top candidate jet



# Background processes

> Dominant and irreducible background from SM ttbar production
  - Correct NLO Powheg+Pythia MC to NNLO-QCD+NLO-EW [M. Czakon et al., JHEP 10 (2017) 186]
  - Via iterative reweighting in m(ttbar), $p_T$(t), $p_T$(tbar)

> Smaller backgrounds
  - Wt production
  - Multijet (1L) → fully data-driven (Matrix Method)
  - W+jets (1L) → norm. corrections (charge-asymmetry method)
  - Z+jets (2L) → m(llbb) reweighting from CR
  - ttbar+V/h
  - Diboson
  - Fakes (2L)



# Systematic uncertainties

> Largest sources of uncertainty: SM ttbar modelling

**Comparison with CMS**:

- Top Yukawa coupling uncertainty on higher-order prediction their highest-ranking one for toponium fit
  - Not considered by ATLAS as not available in theory prediction
- Top-mass uncertainty of ±1 GeV but constrained to ~200 MeV

| Uncertainty component | Fractional contribution [%] $m_A = 800$ GeV $\tan\beta = 0.4$ | Fractional contribution [%] $m_A = m_H = 500$ GeV $\tan\beta = 2.0$ |
|---|---|---|
| **Experimental** | **30** | **42** |
| Small-$R$ jets (JER, JES) | 22 | 29 |
| Large-$VR$ jets | 11 | 20 |
| Flavour tagging | 13 | 17 |
| Leptons | 4 | 5 |
| Other ($E_T^{miss}$, luminosity, pile-up, JVT) | 10 | 14 |
| **Modelling: SM $t\bar{t}$ and signal** | **91** | **79** |
| $t\bar{t}$ NNLO | 49 | 28 |
| $t\bar{t}$ lineshape | 27 | 29 |
| $t\bar{t}$ ME-PS ($p_T^{hard}$) | 36 | 30 |
| $t\bar{t}$ ME-PS ($h_{damp}$) | 41 | 25 |
| $t\bar{t}$ ISR& FSR | 9 | 13 |
| $t\bar{t}$ PS | 29 | 41 |
| $t\bar{t}$ cross-section | 21 | 31 |
| $t\bar{t}$ Scales & PDF | 21 | 16 |
| $m_t$ | 6 | 4 |
| Signal | 19 | 9 |
| **Modelling: other** | **41** | **16** |
| $W$+jets | 11 | 8 |
| $Z$+jets | 1 | 2 |
| Multijet | 27 | 10 |
| Fakes | <1 | 1 |
| Other bkg. | 29 | 10 |
| **MC statistics** | **18** | **26** |
| **Total systematic uncertainty** | **±100** | **±100** |
| **Total statistical uncertainty** | **< 1** | **< 1** |

# Uncertainty correlation scheme

> Experimental uncertainties fully correlated between regions and samples

> Modeling uncertainties uncorrelated between samples

- Except $m_{top}$ uncertainty, which is correlated between S, S+I, and B samples

> Modeling uncertainties correlated across regions with the following exceptions:

- Uncorrelated between all 11+5 regions:
  - tt ME-PS ($p_{T,hard}$), tt ME-PS ($h_{damp}$), tt PS
- Uncorrelated between Resolved and Merged regions of 1L channel and the 2L channel but correlated across angular bins
  - tt cross-section, tt scales, tt ISR&FSR

> Various alternative correlation schemes were tested, no significant impact on sensitivity

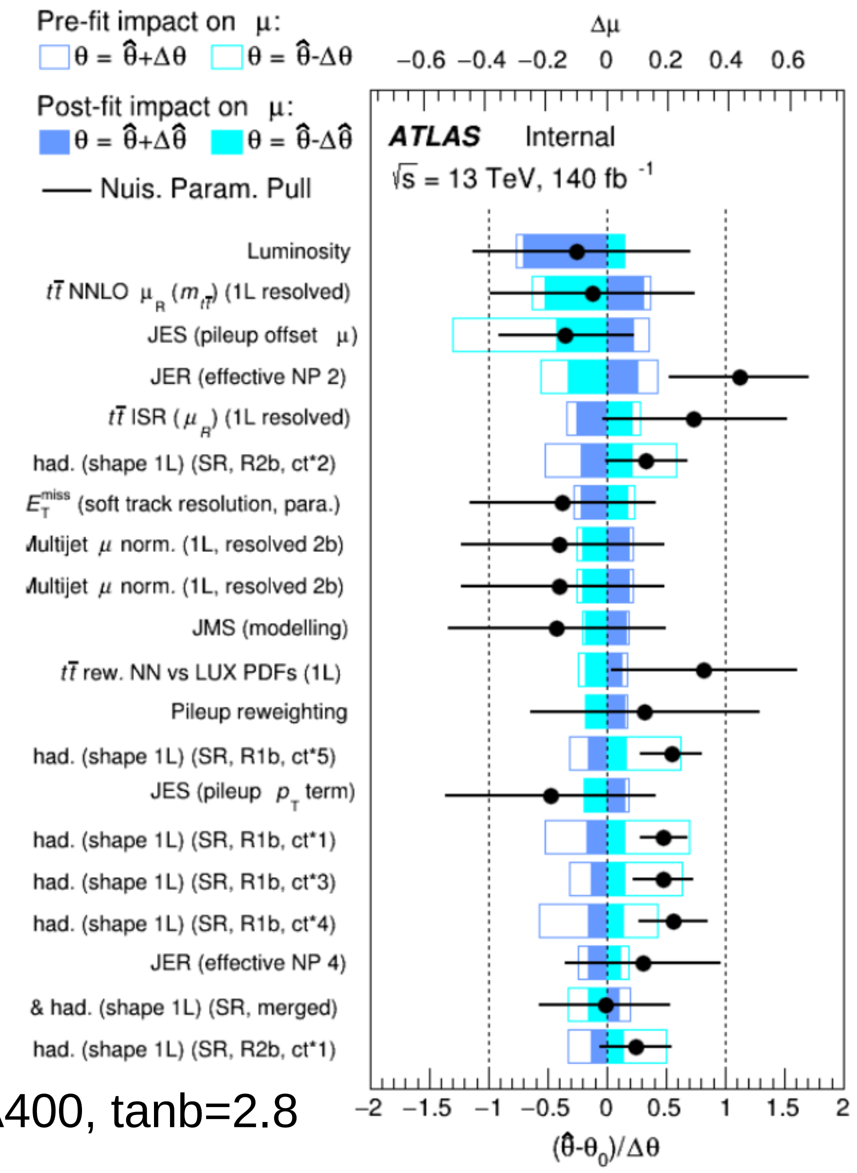
- Including partial correlation

**Comparison with CMS**:

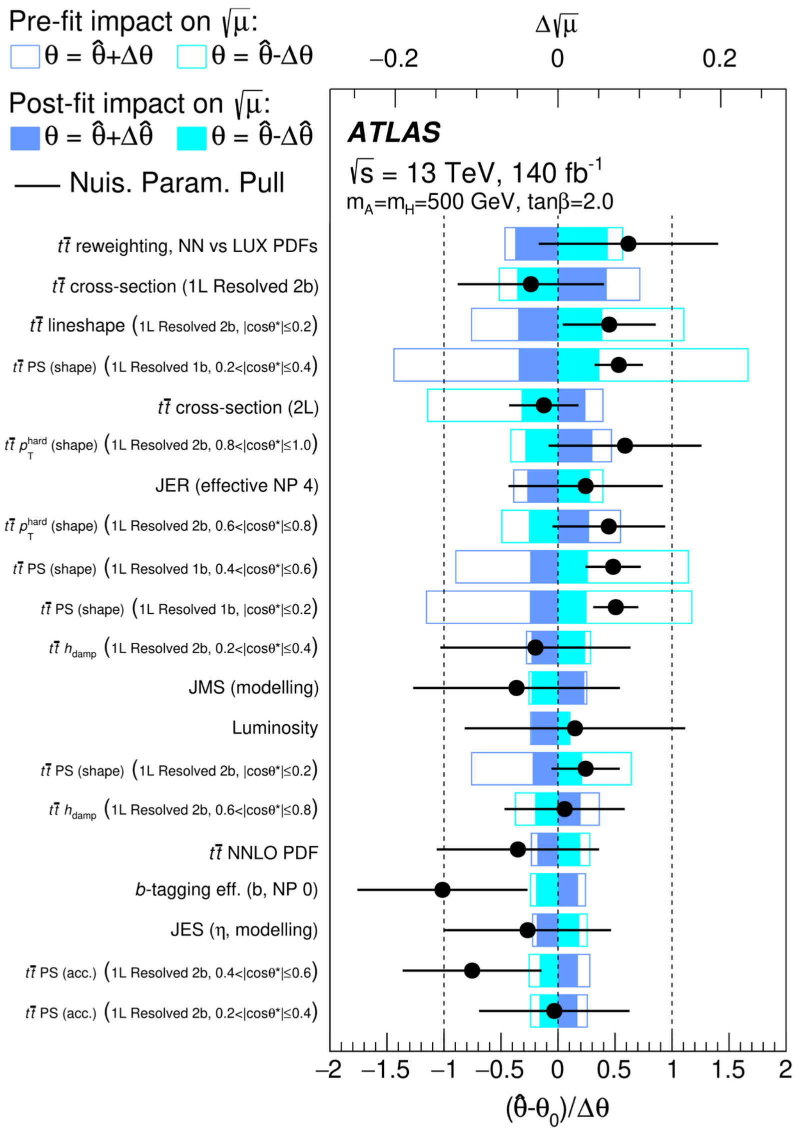
> Correlate most modeling uncertainties across SRs

# Nuisance parameter ranking

- Strongest constraint on tt PS
  → consistent with other ATLAS Top analyses
- $m_{top}$ does not rank highly, nor strongly constrained




A400, tanb=2.8

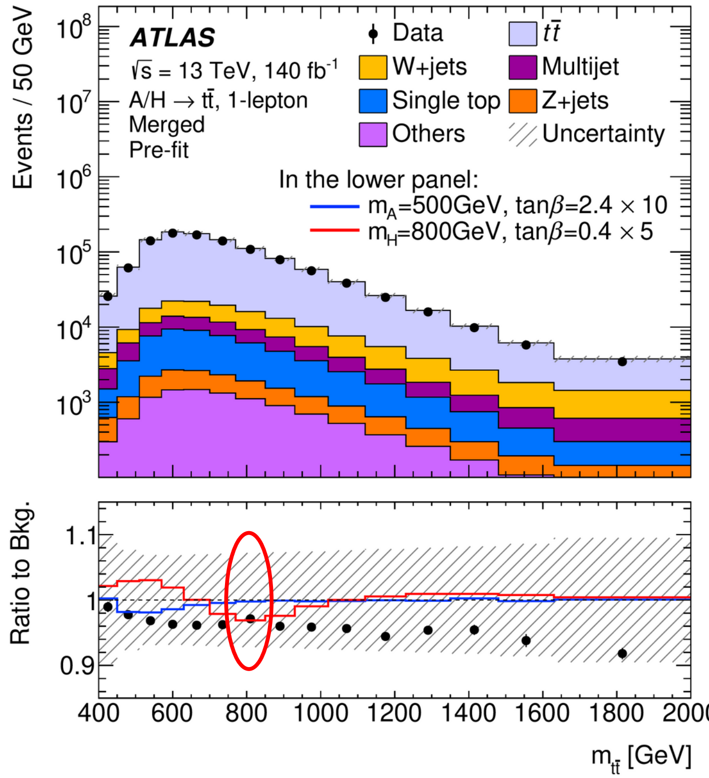


# Search stage (pre-fit)

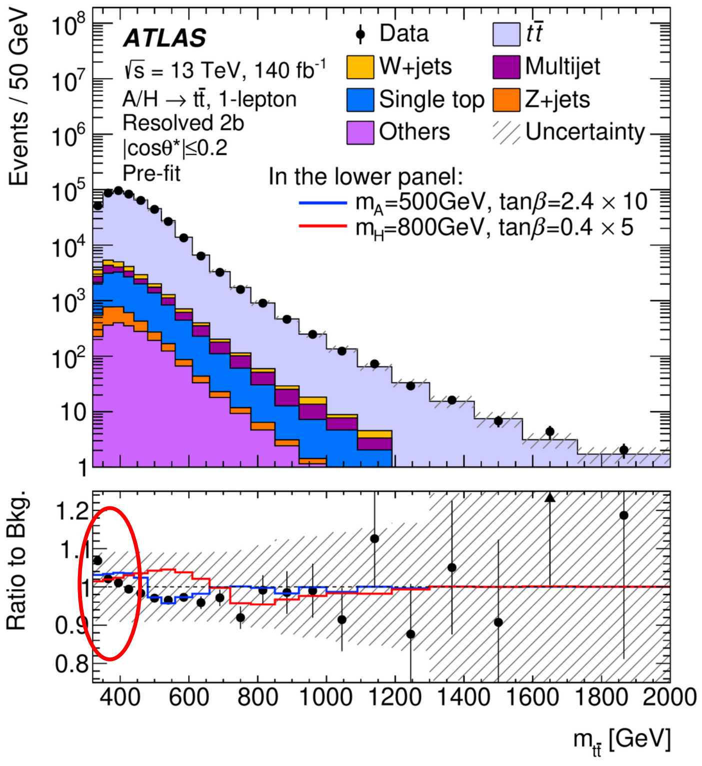
$$q_0 = \frac{\mathcal{L}(0,\hat{\hat{\theta}}_0)}{\mathcal{L}(\hat{\sqrt{\mu}},\hat{\theta}_{\hat{\sqrt{\mu}}})}$$

> Pre-fit excess in data in lowest $m_{tt}$ bins for all resolved signal regions

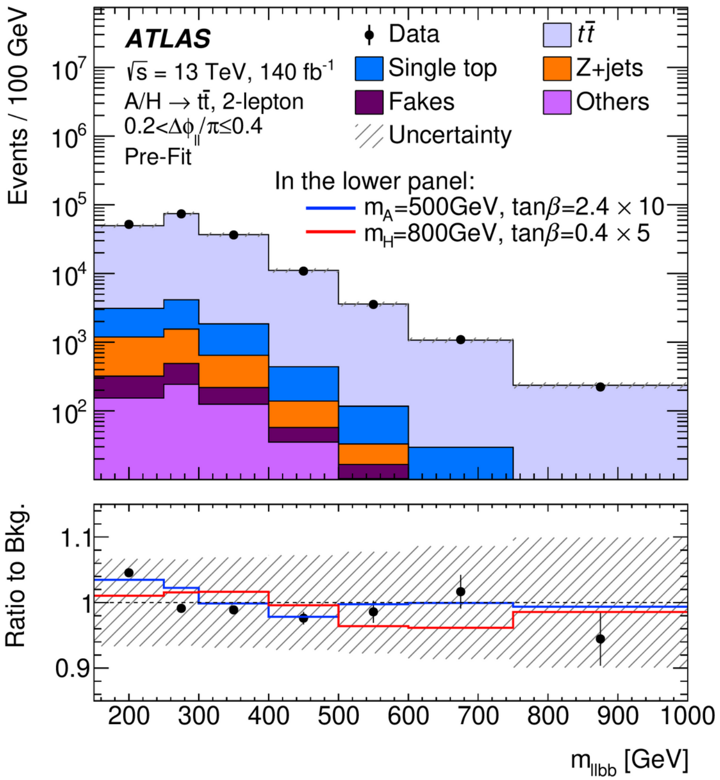
1L Merged




1L Resolved 2b




2L



# Limit band calculation (1)

> Contour method (previous ATLAS default)

- Determine dataset $A_N$ representative of the Nσ fluctuation of test statistics under b-only hypothesis
- $A_N$ is dataset with $\mu=\mu_N$ where $\mu_N$ solves the equation: $q_{\mu N} = N^2$
- Here $q_\mu$ is the normal LHC profile likelihood test statistic
- Unique solution if likelihood linear in μ
- If not, can lead to nonphysical crossing of the exclusion contours (1σ and 2σ bands or median)

> Band method

- Independent of choice of test statistic
- Edges of 1σ (2σ) bands indicate range of signal hypotheses that would be excluded under the background-only hypothesis in 68% (95%) of equivalent searches (intuitive Frequentist approach)
- Find value $r_1^N$ of test statistics $r_1$ related to the probability of the N-th Gaussian normile:

$$P\left(r_1 > r_1^N \middle| \mathrm{alt}\right) = 1 - \Phi(N)$$

# Limit band calculation (2)

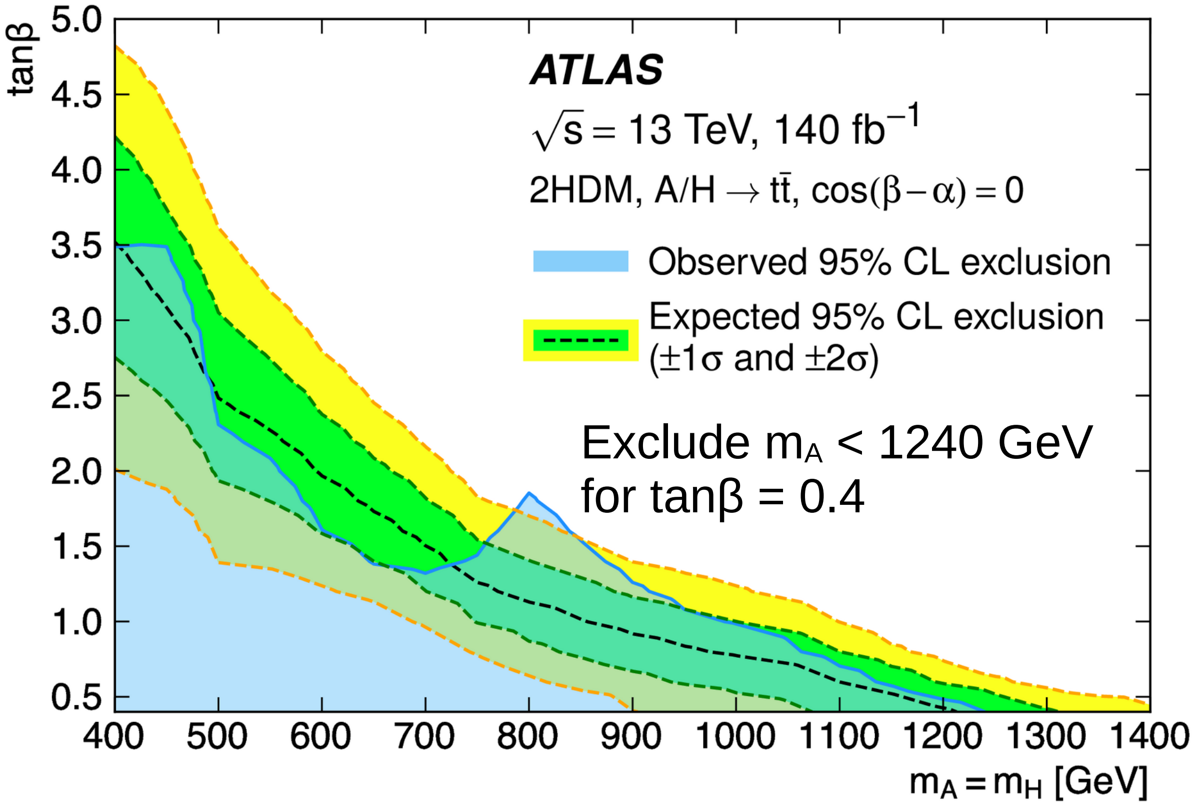
> Example how to calculate limit bands for given signal hypothesis

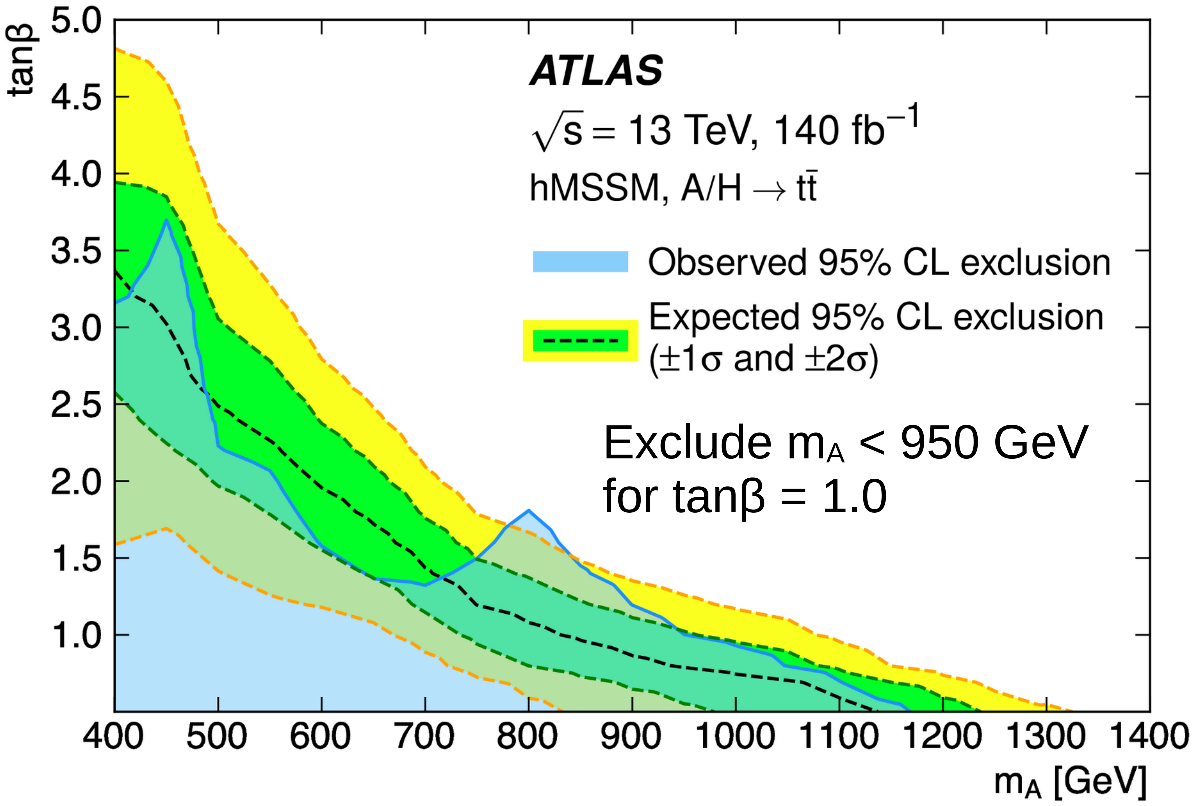
```
# Setup StatAnalysis
export ATLAS_LOCAL_ROOT_BASE=/cvmfs/atlas.cern.ch/repo/ATLASLocalRootBase
source ${ATLAS_LOCAL_ROOT_BASE}/user/atlasLocalSetup.sh
asetup StatAnalysis,0.2,latest
import ROOT

# Assume you run on existing workspace
muName = "mu"      # name of the signal strength parameter
mu_test = 3      # signal strength to test
modelName = "simPdf" # name of the top-level pdf in the workspace
dsName = "obsData"   # name of observed data dataset in the workspace

w = ROOT.xRooNode("workspace.root")
nll = w[modelName].nll(dsName)
hp = nll.hypoPoint(muName,mu_test,0) # assuming here that 0 = bkg-only signal strength
hp.pCLs_asymp( nSigma ) # replace nSigma with 0 to get expected, +1 to get +1 sigma, etc etc ...
                                          # returns a pair of numbers, first is pValue, second is uncert on the pValue
```

# Exclusion regions: 2HDM and hMSSM

$$q_{1,0} = -2\ln\frac{\mathcal{L}(1,\hat{\hat{\theta}}_1)}{\mathcal{L}(0,\hat{\hat{\theta}}_0)}$$

- Strongest mass exclusion at low tanβ to date
- Significant improvement in tanβ exclusion at 400 GeV compared to previous interference searches
  - Up to 3.5 (3.16) in the 2HDM (hMSSM)



# The ATLAS Detector