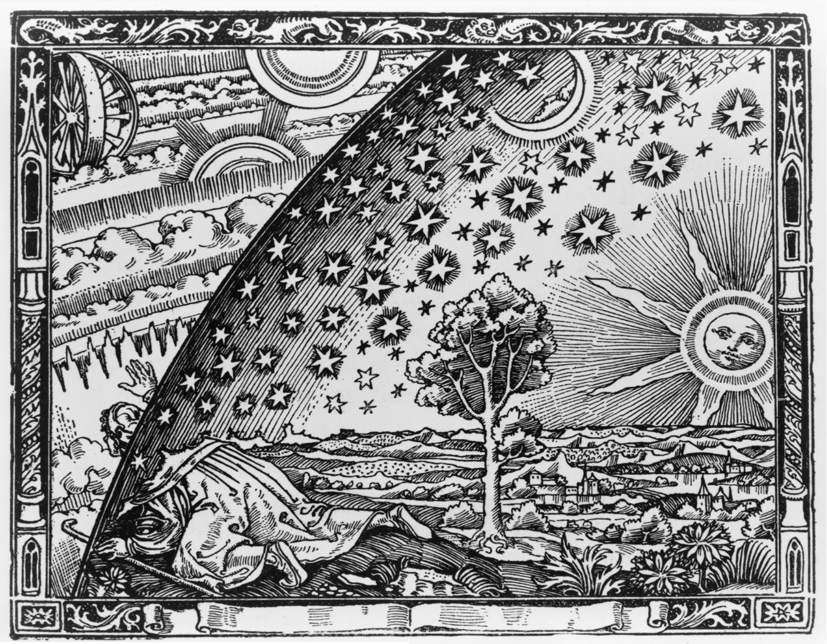
To the Higgs and beyond

Hamburg International Summer School
14 – 25 July 2025



Katharina Behr

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

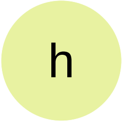
CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

ATLAS EXPERIMENT

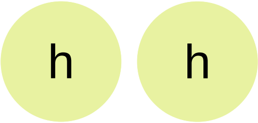
DESY.

Outline

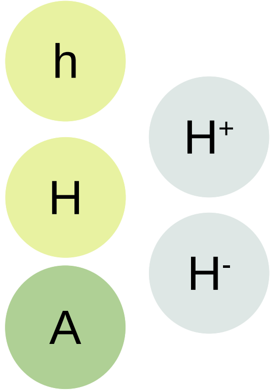
- **Part 1: The vacuum is not empty**
  - The Higgs boson in the Standard Model
  - Characterization of the Higgs boson since its discovery

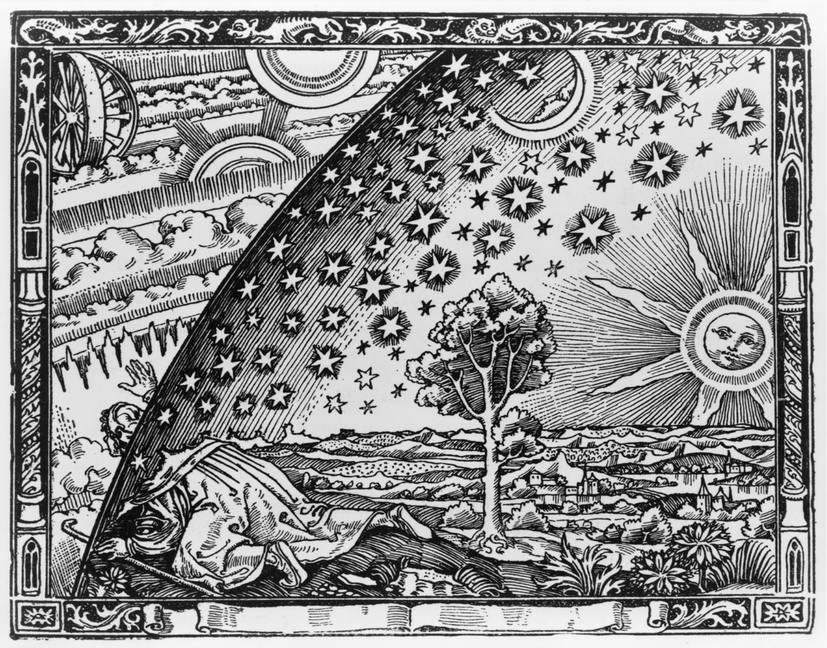


- **Part 2: What is the fingerprint of the vacuum?**
  - Unravelling the Higgs potential
  - Higgs boson pair production
  - Extra: Triple Higgs production
  - Outlook: the future of the LHC and beyond



- **Part 3: Is there even more to the vacuum?**
  - Extended Higgs sectors
  - Extra: news from the ttbar threshold
  - Long-lived particles and the Higgs





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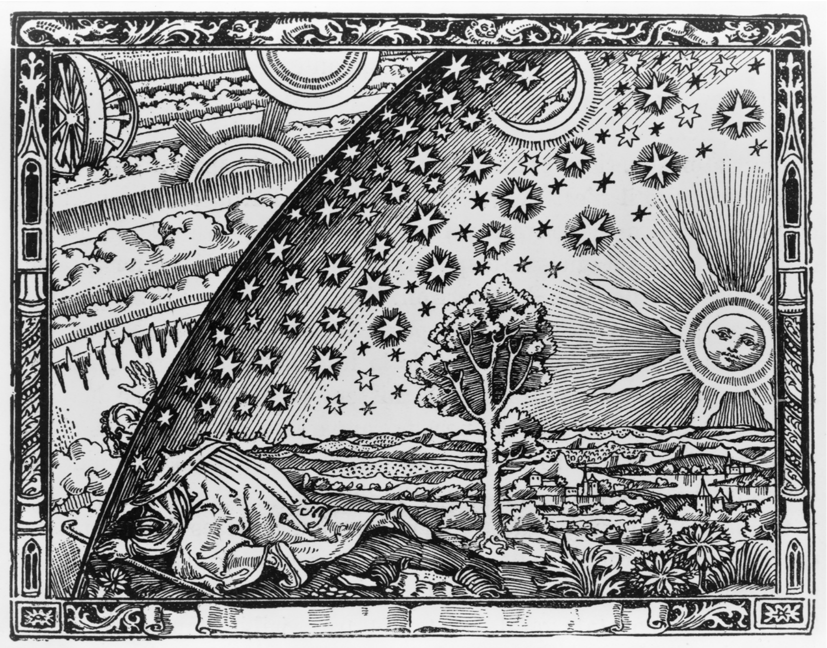
h H A H^+ H^-



Many questions, many possible answers!

Open questions in the SM:

Unification of all forces?

Gravity?

Hierarchy problem?

Nature of DM?

Matter-antimatter imbalance?

Strong CP problem?

Flavour anomalies?

Muon g-2?

...

Beyond SM theories:

Composite Higgs

Axions

Leptoquarks

Extended Higgs sector

Supersymmetry

Extra dimensions

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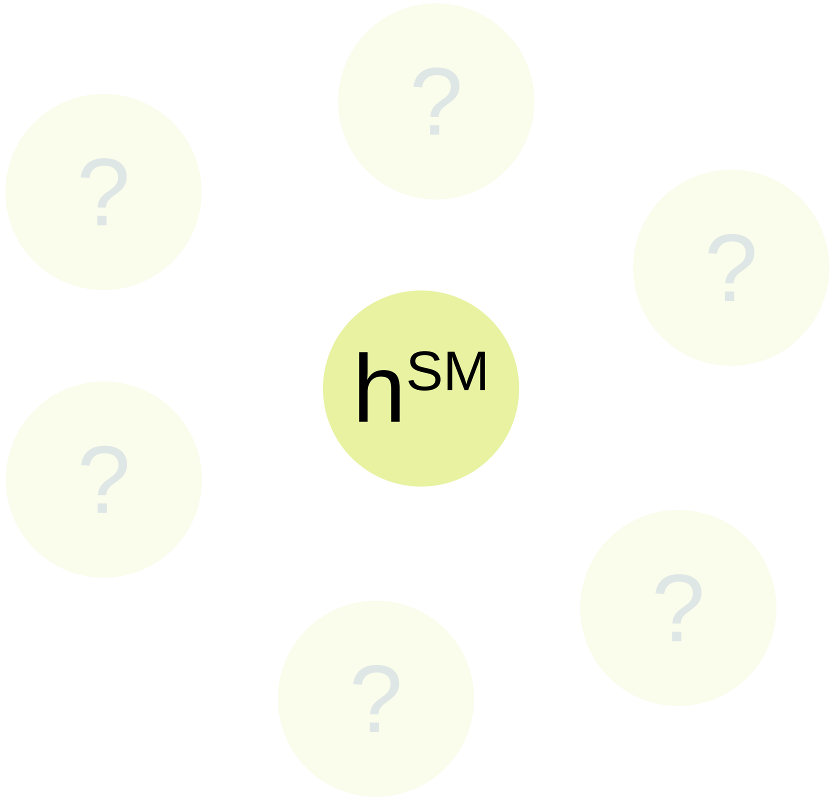
Why look for more Higgs bosons?

> Supersymmetry: predicts a second Higgs doublet

> Axion DM models: require at least one more Higgs doublet or Higgs triplet

> Additional sources of CP violation in the Higgs sector: possible with another Higgs doublet



The 125 GeV Higgs boson could just be the first of its kind.

Constraints from existing measurements (1)

> Higgs sector cannot be extended arbitrarily…

> … need to ensure that BSM theory predictions do not contradict existing measurements

> ρ parameter constraints

- ρ depends on structure of Higgs sector
  - ρ = 1 in SM
  - Value confirmed in measurements
- BSM model with multiple Higgs doublets:
- For example: *SU(2)* doublets with Y = ± 1
  - Yields ρ = 1!

$$\rho = \frac{M_W^2}{M_Z^2 \cos^2 \theta_W}$$

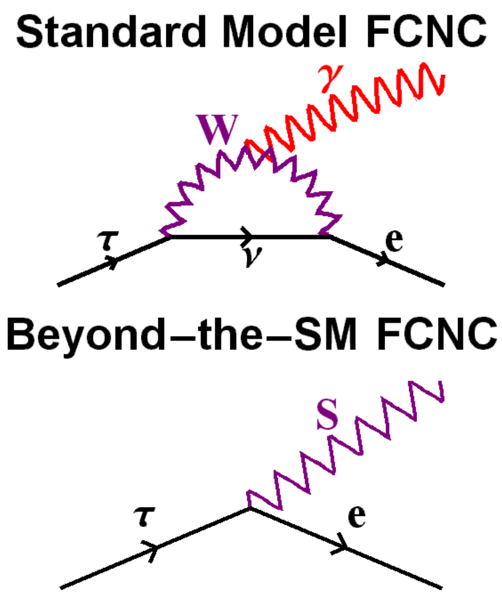
$$\rho = \frac{\sum_{i=1}^{n} \left[I_i(I_i+1) - \frac{1}{4} Y_i^2 \right] v_i}{\sum_{i=1}^{n} \frac{1}{2} Y_i^2 v_i}$$

$$I(I+1) = \frac{3}{4} Y^2$$

Constraints from existing measurements (2)

- Higgs sector cannot be extended arbitrarily…
- … need to ensure that BSM theory predictions do not contradict existing measurements

- ρ parameter constraints
- Constraints flavour changing neutral currents
  - FCNCs are absent in the SM at tree-level
  - Never observed in precision measurements
  - Extended Higgs sectors must not introduce (significant) FCNCs



Constraints from existing measurements (3)

- Higgs sector cannot be extended arbitrarily…
- … need to ensure that BSM theory predictions do not contradict existing measurements

- ρ parameter constraints
- Constraints flavour changing neutral currents
- Unitarity constraints
  - Amplitudes for self-scattering of longitudinal vector bosons must not violate unitarity
  - SM Higgs sector regularises these scattering amplitudes

$$V_L V_L \rightarrow V_L V_L$$

Two-Higgs-Doublet Models (2HDMs)

- Two complex scalar SU(2) doublets with $Y = +1$
- Focus on CP conserving case with softly broken Z^2 symmetry
- Most general scalar potential

More details in this nice lecture by M. Muhlleitner [link]

$$
\begin{aligned}
V &= m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 \left(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1 \right) + \frac{\lambda_1}{2} \left(\Phi_1^\dagger \Phi_1 \right)^2 + \frac{\lambda_2}{2} \left(\Phi_2^\dagger \Phi_2 \right)^2 \\
&\quad + \lambda_3 \Phi_1^\dagger \Phi_1 \Phi_2^\dagger \Phi_2 + \lambda_4 \Phi_1^\dagger \Phi_2 \Phi_2^\dagger \Phi_1 + \frac{\lambda_5}{2} \left[\left(\Phi_1^\dagger \Phi_2 \right)^2 + \left(\Phi_2^\dagger \Phi_1 \right)^2 \right] ,
\end{aligned}
$$

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> 8 real parameters: m_{11}, m_{22}, m_{12}, λ_1, λ_2, λ_3, λ_4, λ_5

> 2 VEVs:

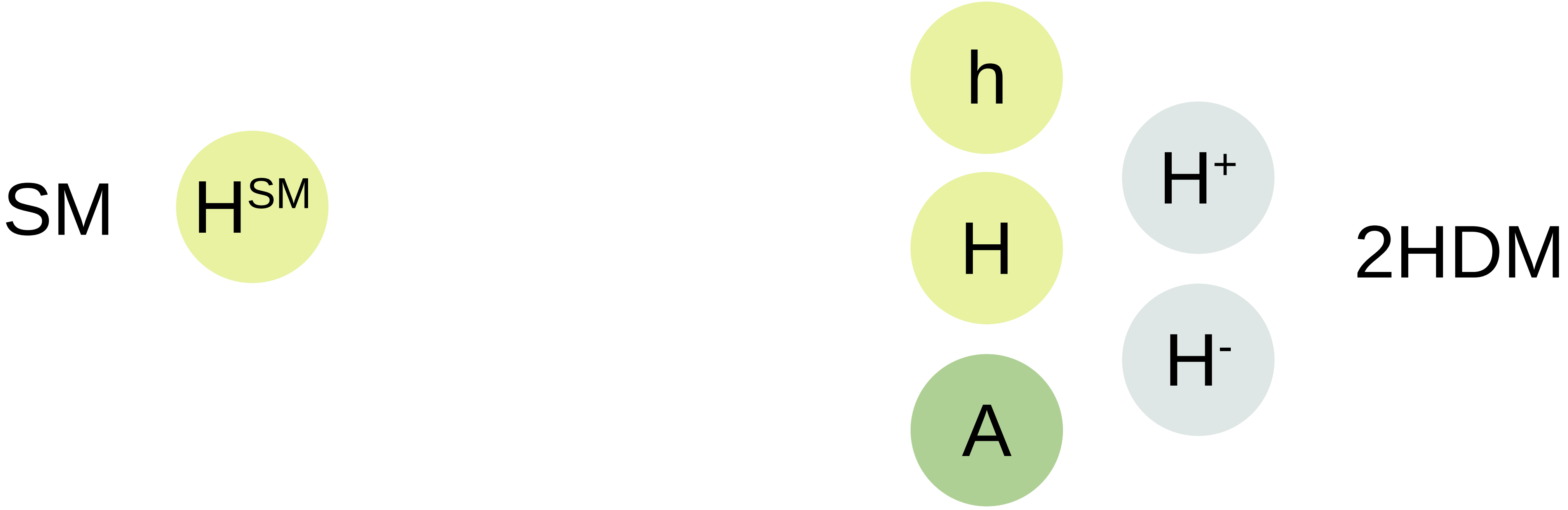
$$\langle \Phi_1 \rangle = \begin{pmatrix} 0 \\ \frac{v_1}{\sqrt{2}} \end{pmatrix} \quad \text{and} \quad \langle \Phi_2 \rangle = \begin{pmatrix} 0 \\ \frac{v_2}{\sqrt{2}} \end{pmatrix}$$

2HDM: particle content

- 8 real fields
- 3 fields provide longitudinal degrees of freedom for *W, Z*
- 5 Higgs fields after EWSB:

  2 scalars, 1 pseudoscalar, 2 charged

$$\Phi_a = \begin{pmatrix} \phi_a^+ \\ \frac{v_a + \rho_a + i\eta_a}{\sqrt{2}} \end{pmatrix} , \qquad a = 1, 2$$



2HDM: parameters

> 8 real parameters: m_{11}, m_{22}, m_{12}, λ_1, λ_2, λ_3, λ_4, λ_5

> Re-parameterise potential in terms of 8 “physical” parameters:

- m_h, m_H, m_A, $m_{H\pm}$, $\tan\beta$, $\cos(\beta-\alpha)$, M_{12}

$$\tan\beta = \frac{v_2}{v_1}$$

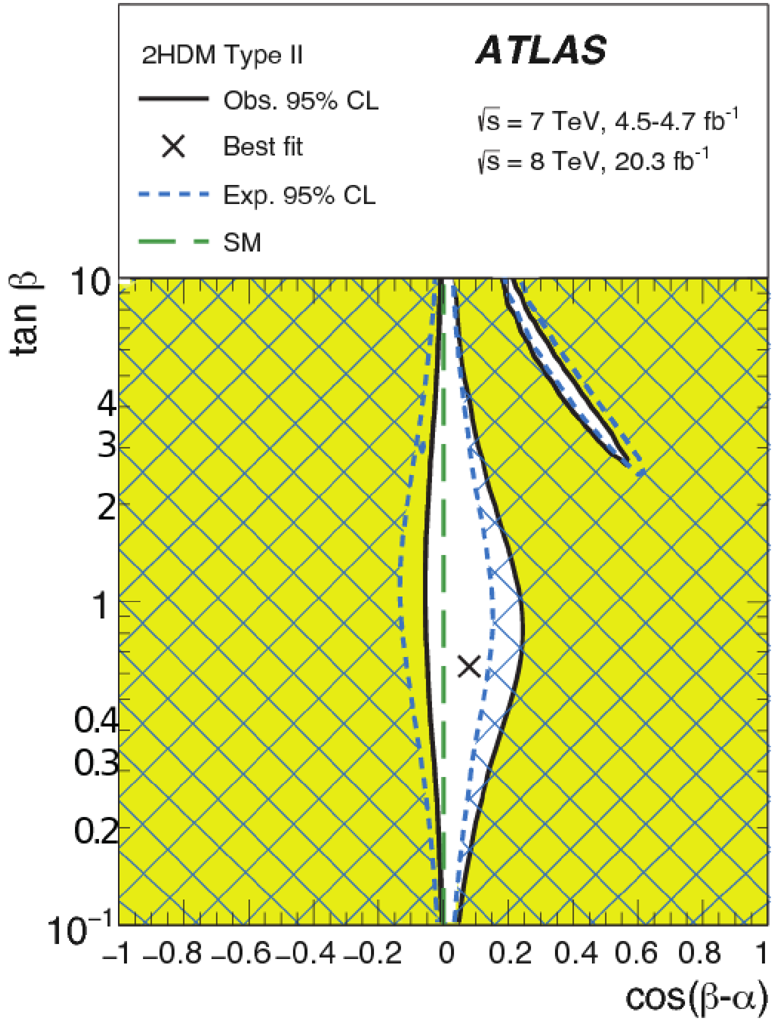
H-h mixing angle

Scale of soft Z^2 symmetry breaking

2HDM: parameters

- Constraints from precision measurements of 125 GeV boson
  - Couplings to fermions and limits on invisible decays
- Alignment limit $\cos(\beta-\alpha) = 0$ favoured
  - Assume lighter scalar h is the 125 GeV boson with SM couplings

$$h = H^{SM}$$



2HDM: Yukawa structure

> No FCNC → each type of fermion couples to only one of the doublets (Z^2 symmetry)

> Four Yukawa coupling scenarios:

Model	Up quarks	Down quarks	Leptons
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

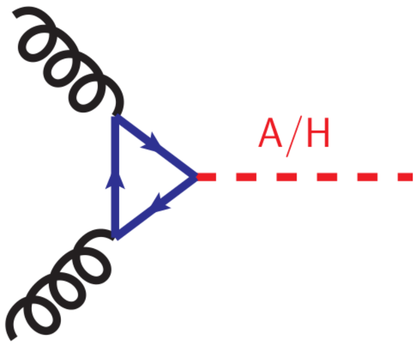
SUSY models

> Type-II 2HDM:

- Up quark coupling ~ 1/tanβ
- Down quark / lepton coupling: tanβ

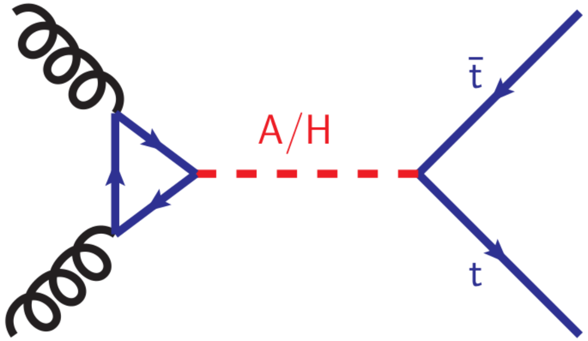
Searching for extra neutral Higgs bosons

> Dominant production: loop induced gluon fusion



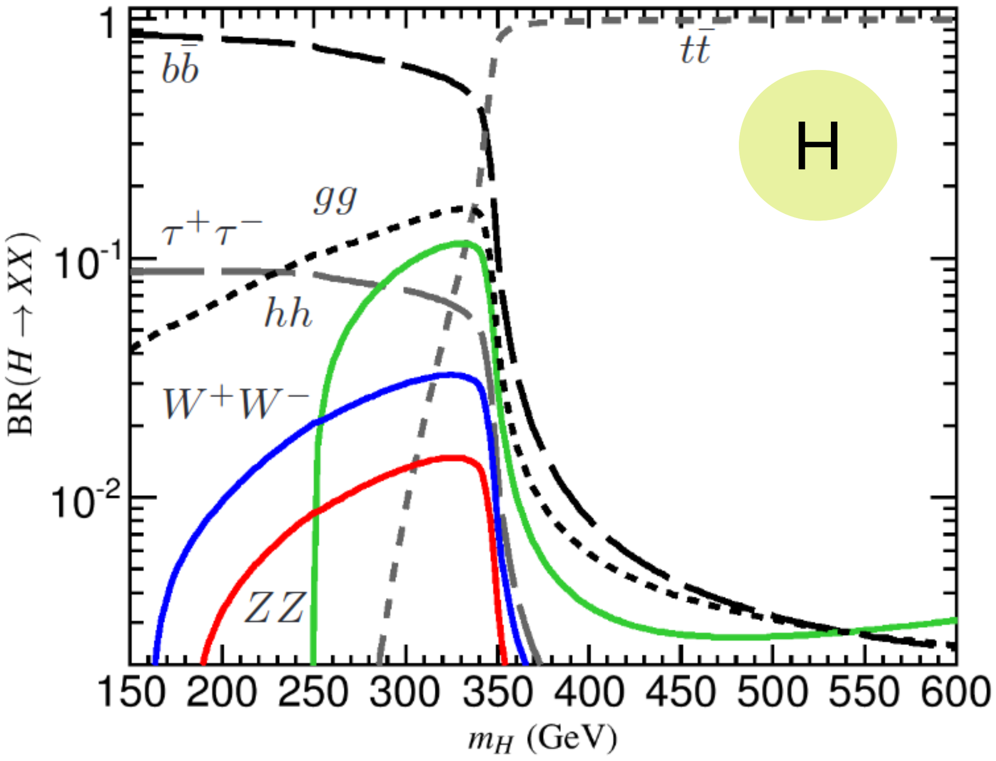
Searching for extra neutral Higgs bosons

- Dominant production: loop induced gluon fusion
- Decay modes depend on: $m_{A/H}$, tanβ



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

tanβ = 1.5, cos(β-α) = 0.01



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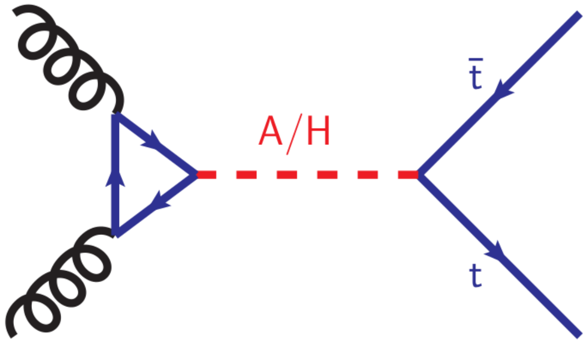

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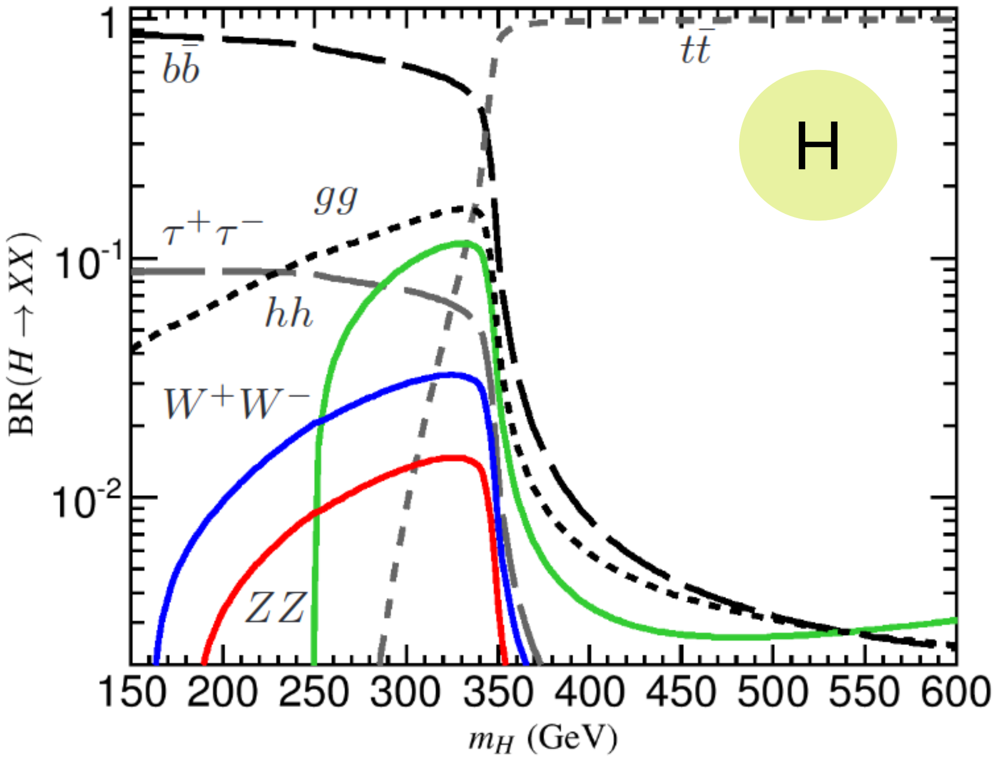
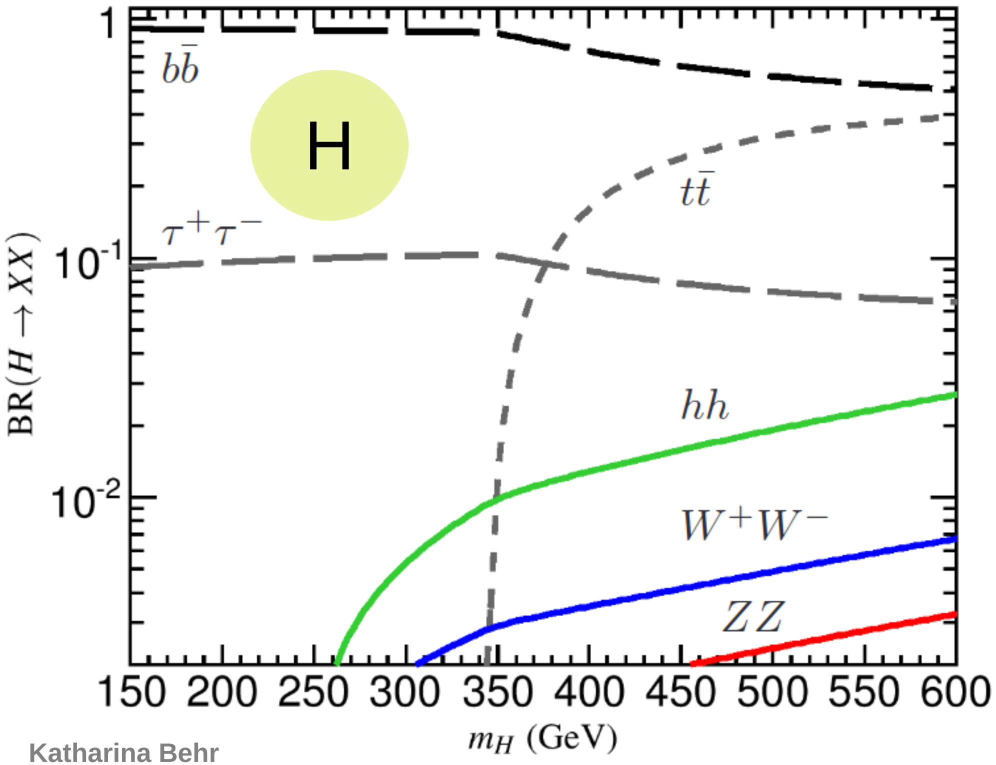


tanβ = 7, cos(β-α) = 0.01

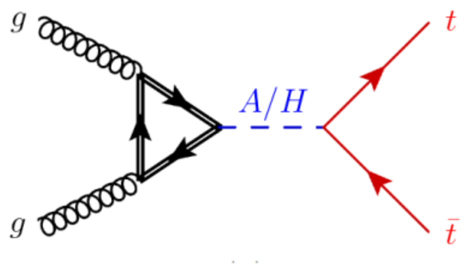


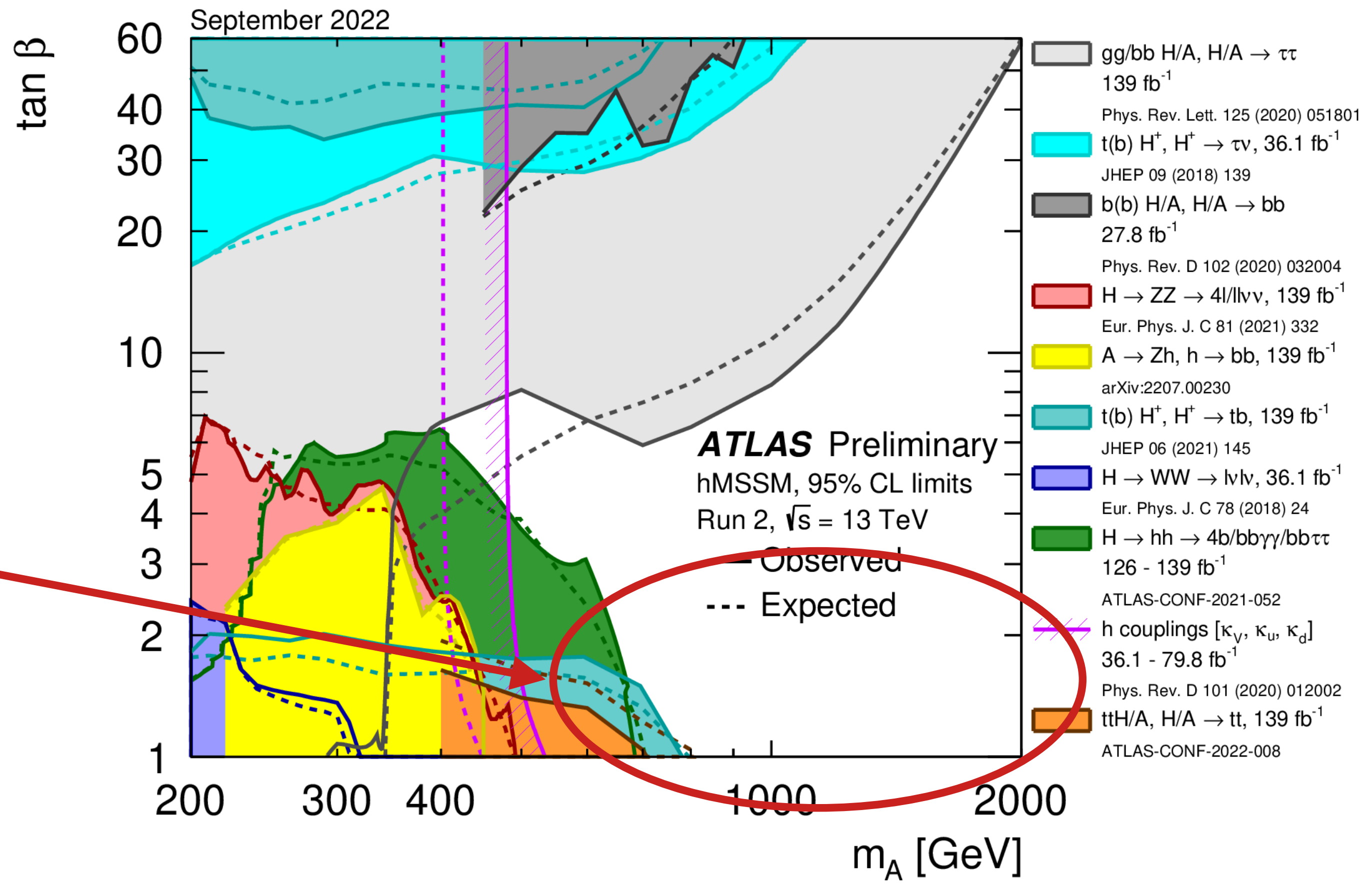
Example: hMSSM

- 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 $\tan\beta$:

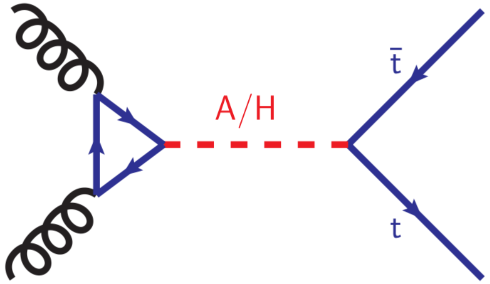
Preferential A/H coupling to ttbar!





The challenge: interference

- Why is the search in the high-mass, low-tanβ region so complicated?
- Signal: loop induced resonant production of heavy scalar H or pseudoscalar A from gluons
  - Similar to SM Higgs production but $m_{A/H} > 2*m_{top}$



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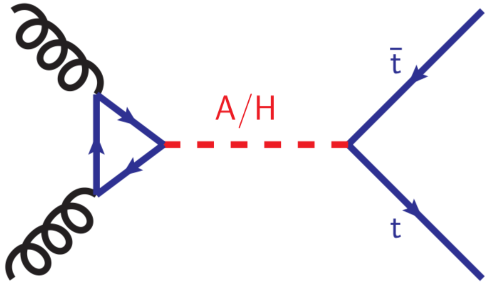

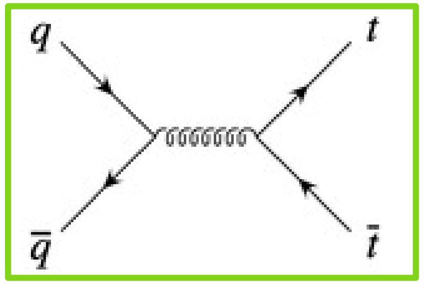

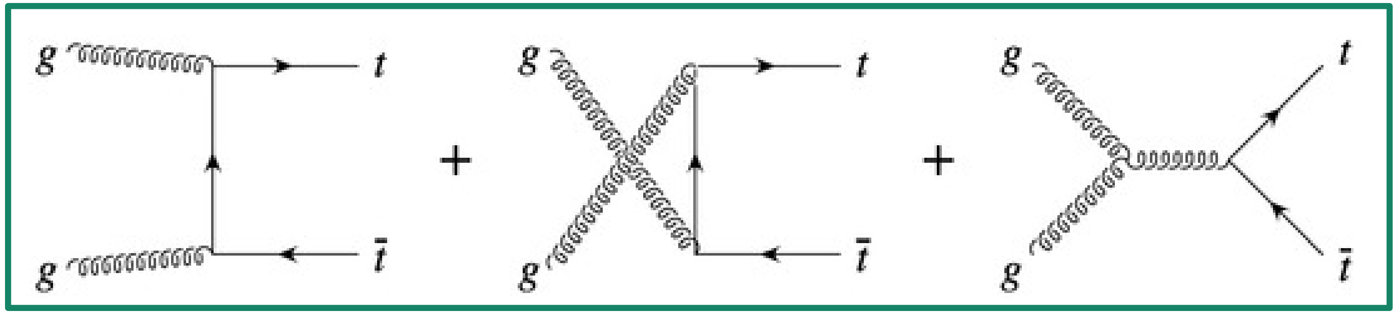

80% gg-initiated
20% qq-initiated

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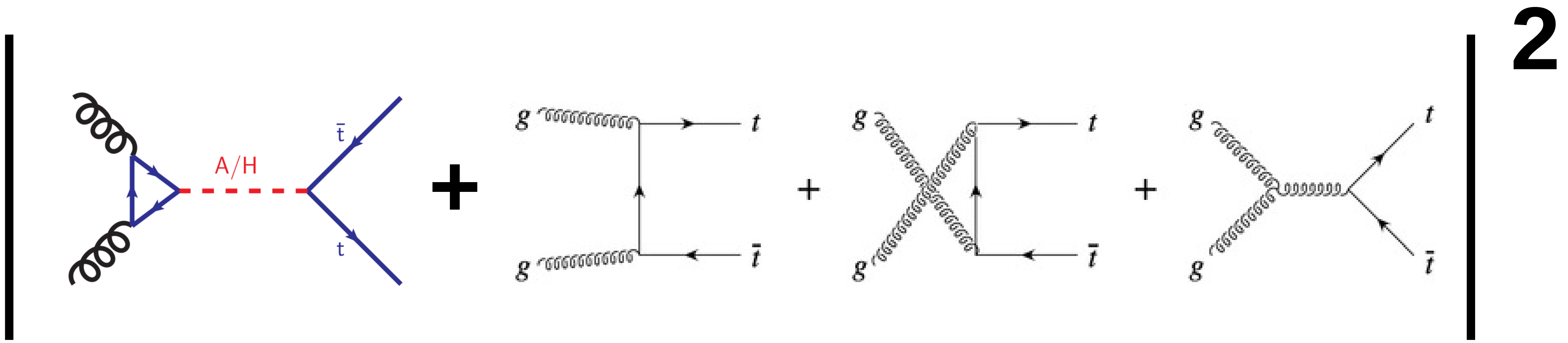
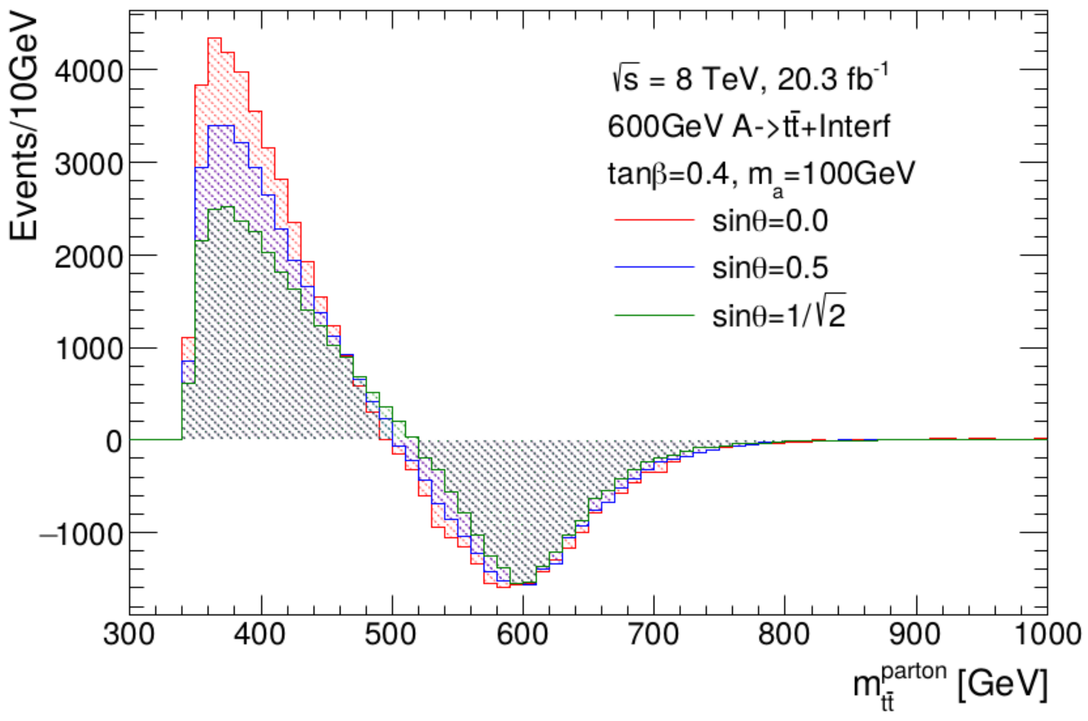


The challenge: interference

- **Many challenges** compared to bump hunts
  - Interference pattern highly model dependent → many simulations needed!



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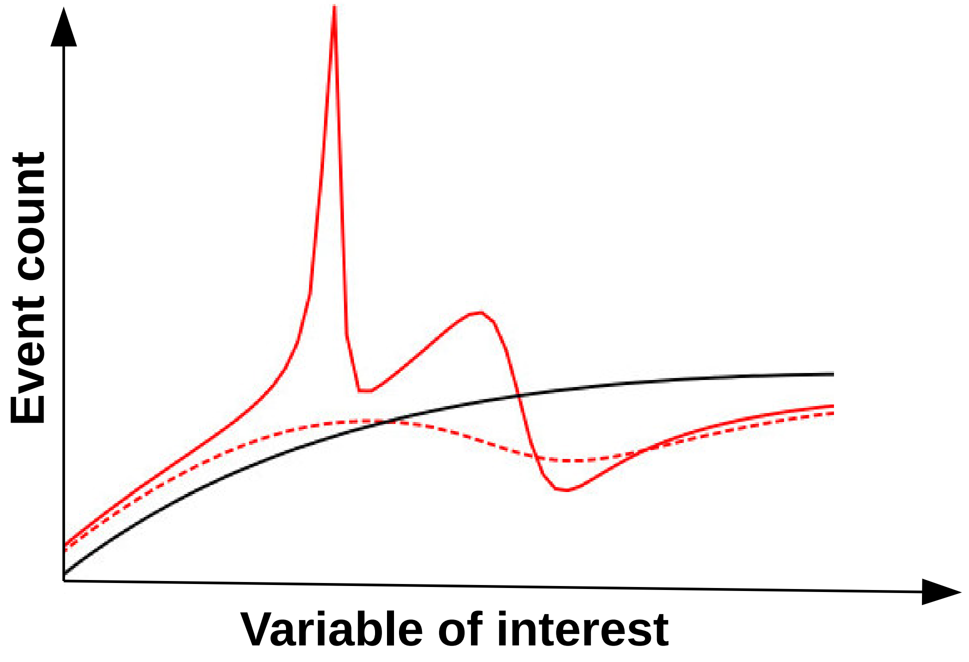

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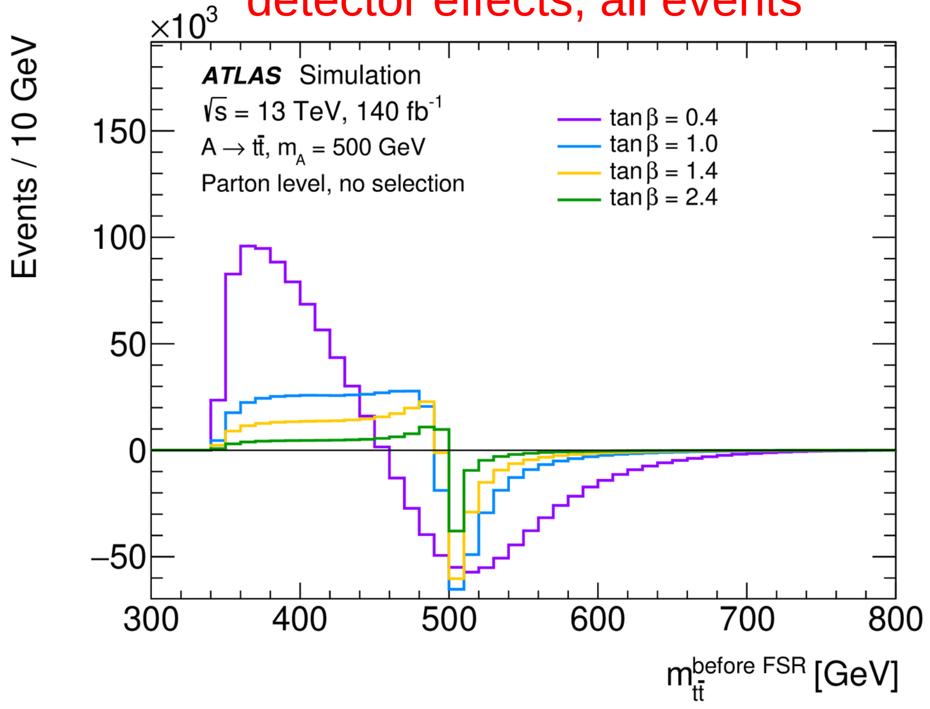
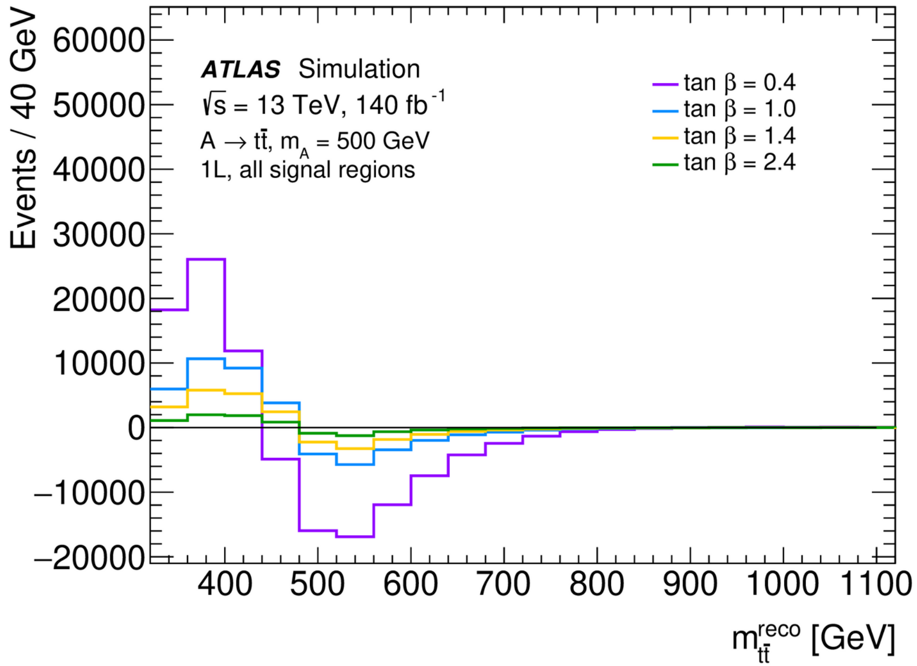
  - Detector effects “wash out” details of pattern

Simulated pattern without detector effects, all events

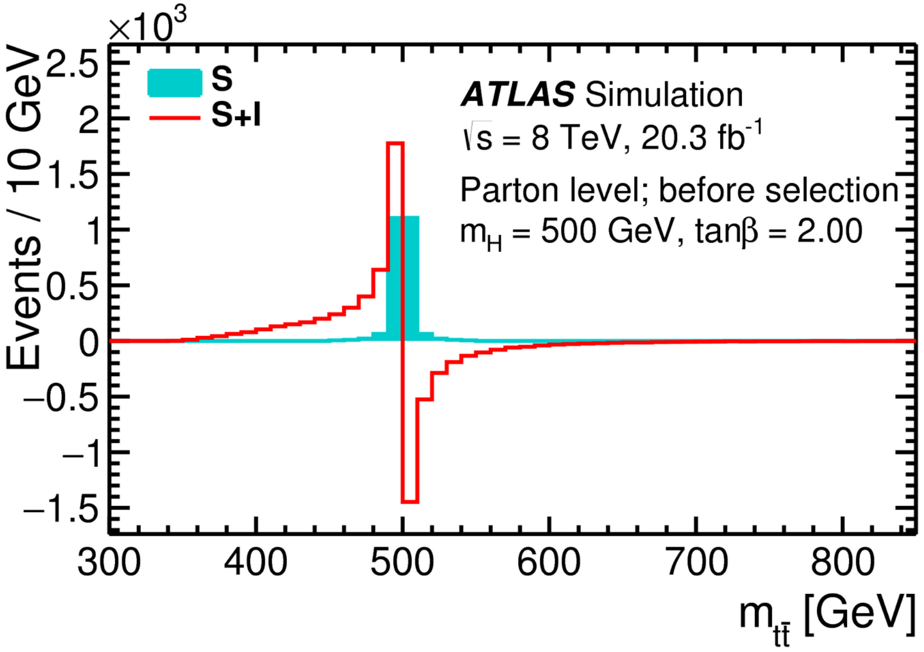


Simulated pattern with detector effects, signal region



The challenge: interference

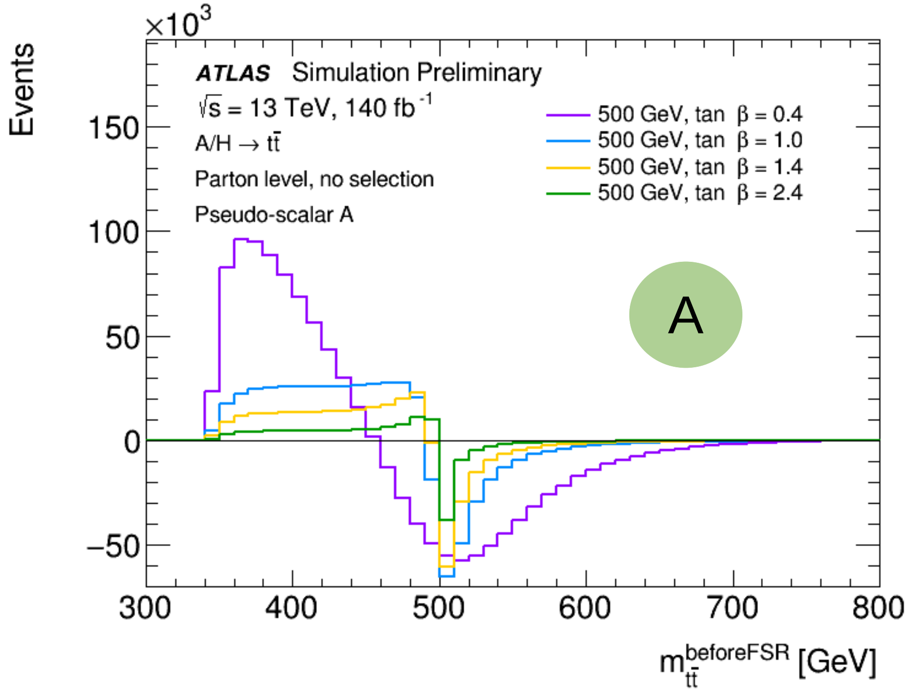
- **Many challenges** compared to bump hunts
  - Interference pattern highly model dependent → many simulations needed!
  - Very complex patterns, especially if there is more than one new particle
  - Detector effects “wash out” details of pattern
  - Risk to miss narrow patterns
    - Peak and dip in the same bin cancel out
  - Statistical interpretation
  - ...

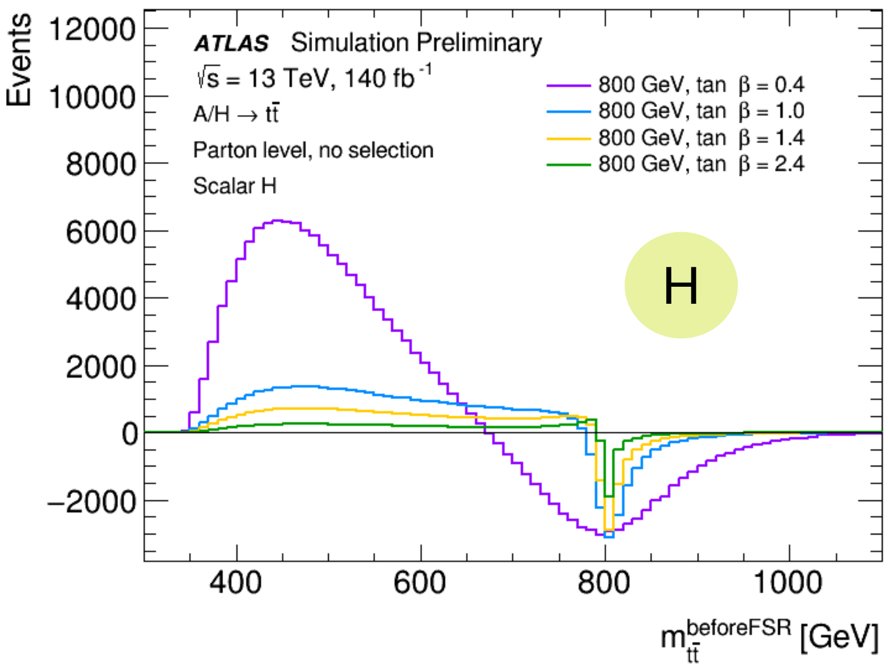


The advantage: interference

> Strong model dependence of interference pattern allows to characterise potential new particle(s)

→ Fingerprint that carries information about particle properties





Larger tanβ

↓

Smaller total width

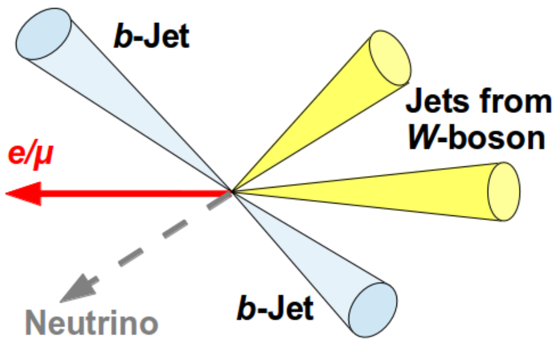
↓

Narrower pattern

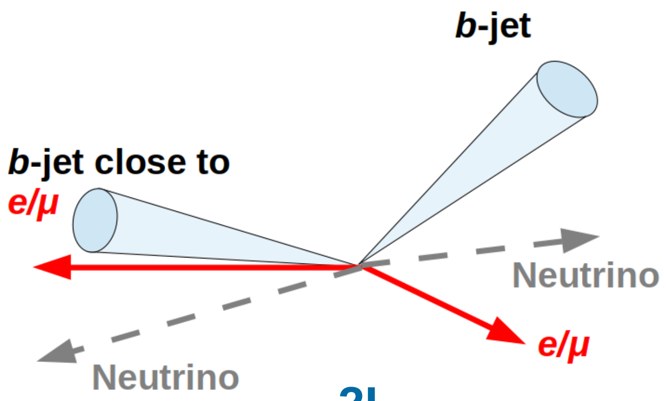
Search strategy

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

$t \to Wb$



1L Resolved

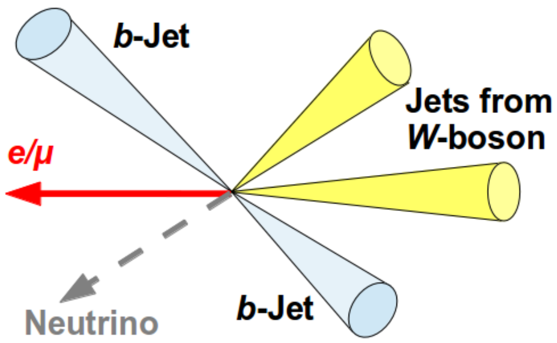


2L

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}

$t \to Wb$



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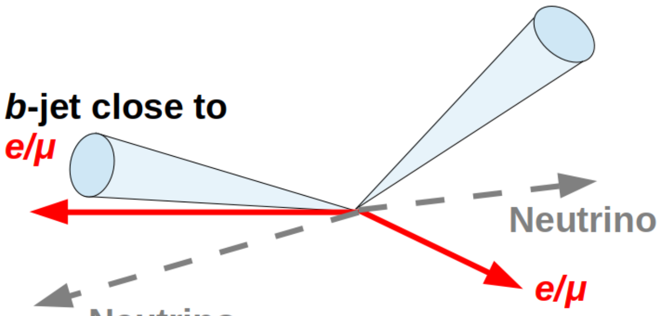

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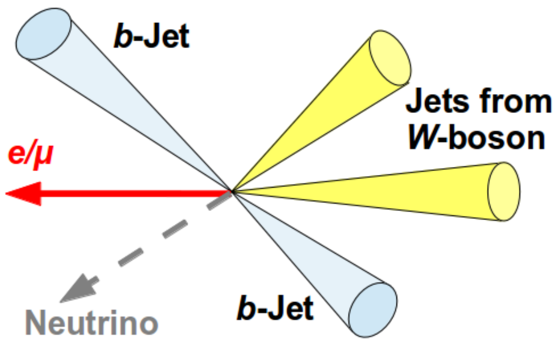
- **2L channel**: m_{llbb} as proxy for m_{ttbar}
- **1L channel**: reconstruct full ttbar system, m_{ttbar}
  - Resolved: small-*R* jets assigned via χ^2 algorithm, ==1 or ≥ 2 *b*-tagged



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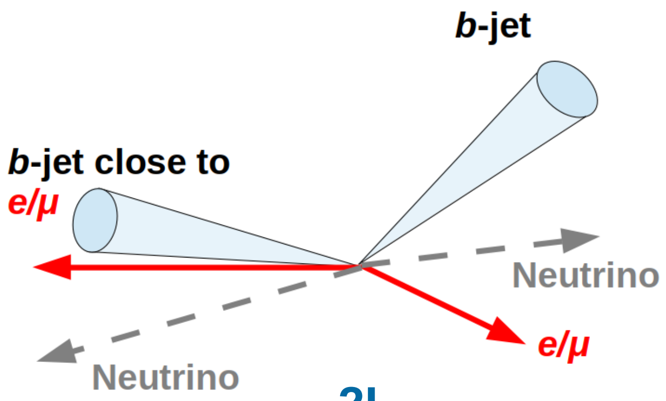

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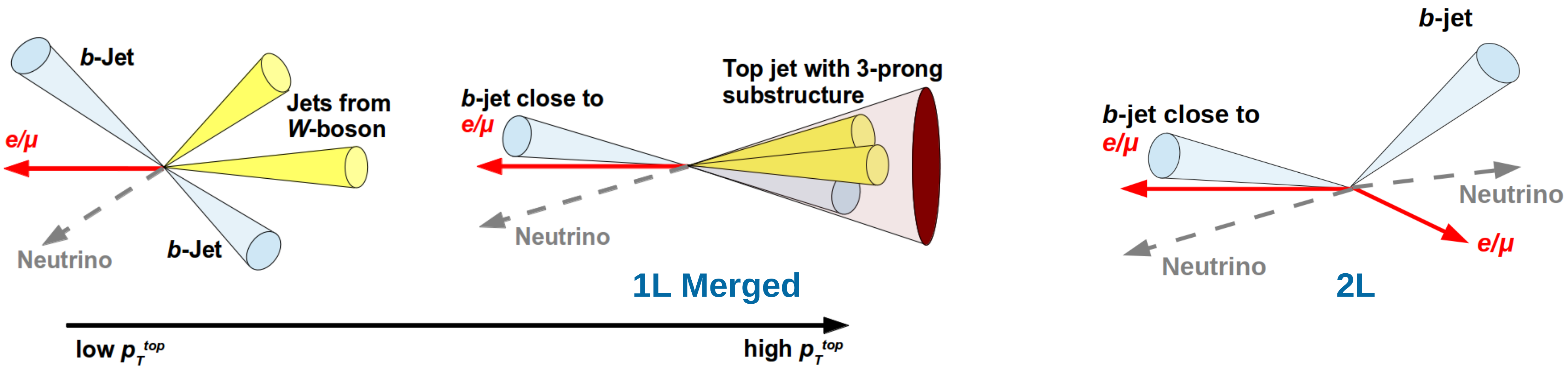
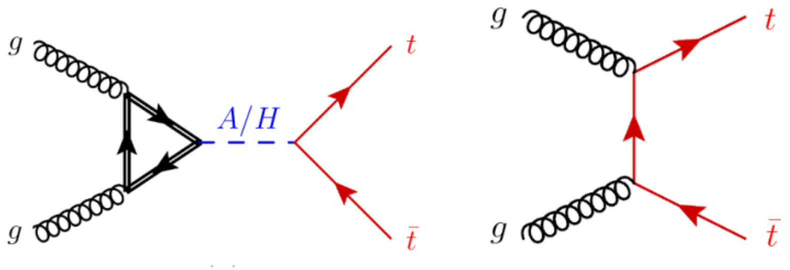
> **1L channel**: reconstruct full ttbar system, m_{ttbar}

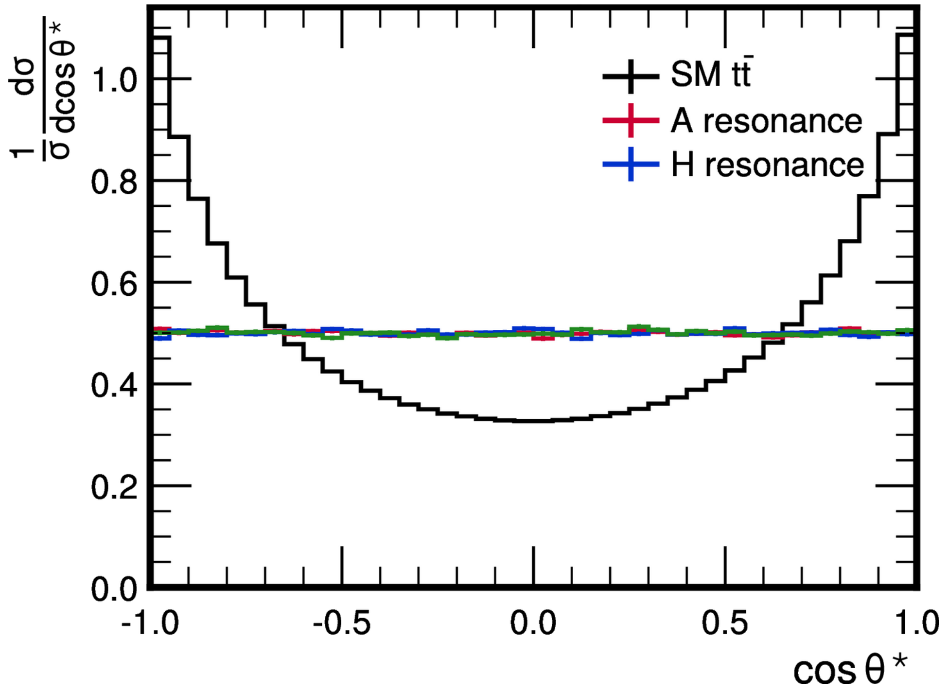
- Resolved: small-*R* jets assigned via χ^2 algorithm, ==1 or ≥ 2 *b*-tagged
- Merged: large-*R* jet to reconstruct hadronic top-quark decay

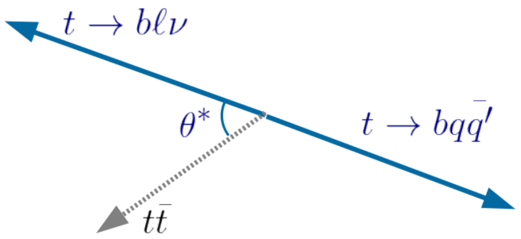


It’s all about spins!

- Signal: s-channel production in pure spin-singlet state (isotropy!)
- Background: a mixture of production modes and spin states
- Angular variables to distinguish between signal and background







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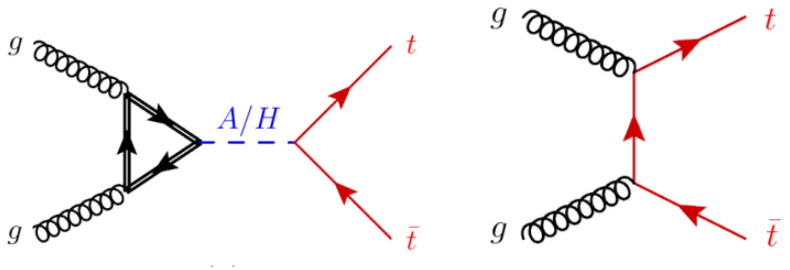
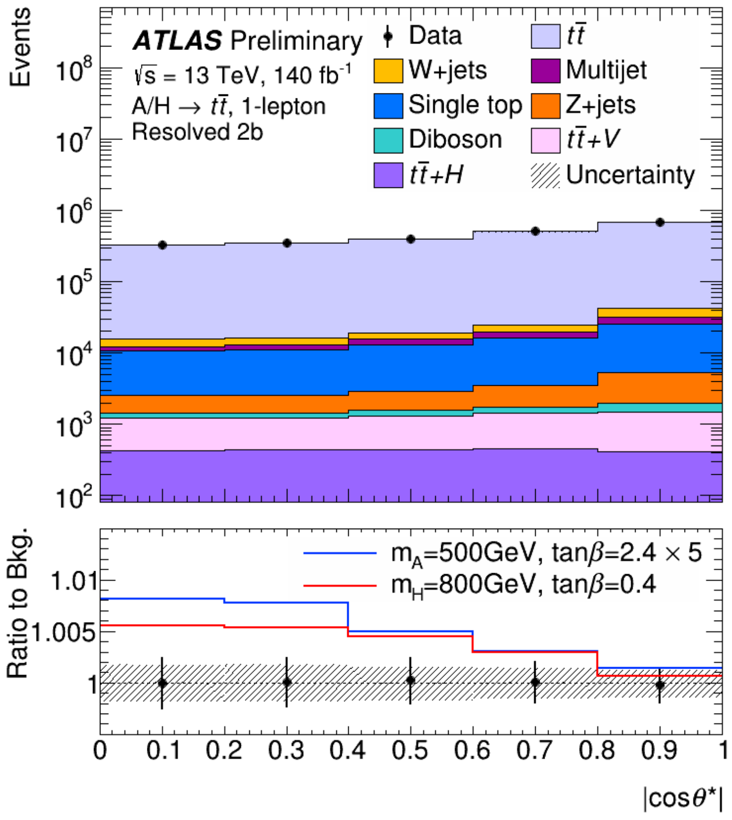
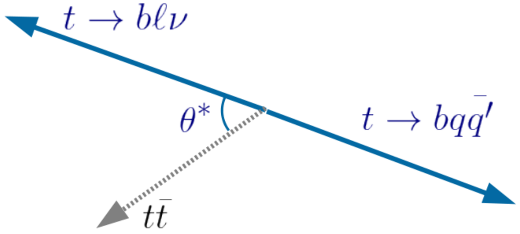


1L Resolved



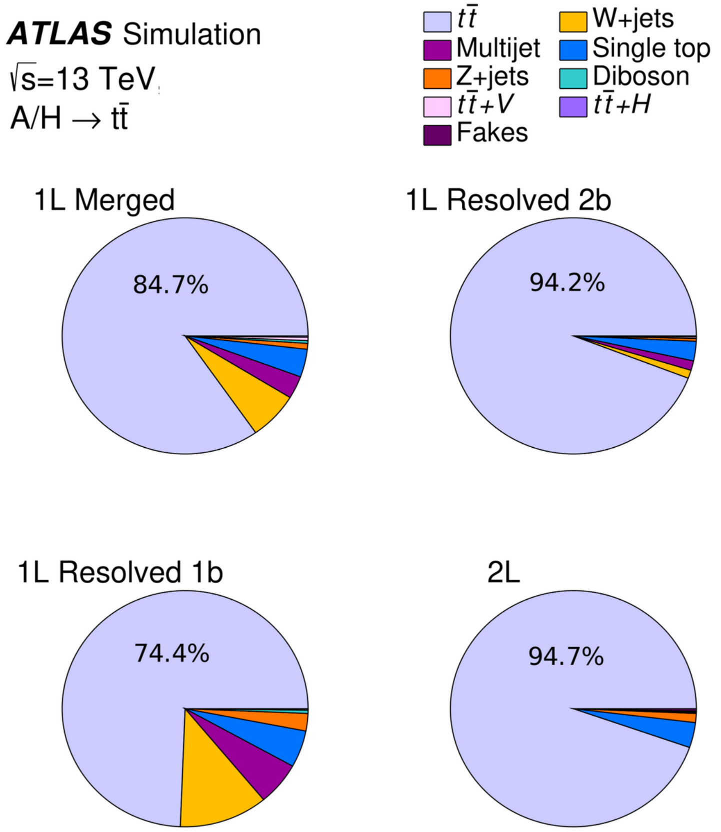


Background processes

- Dominant and irreducible background from SM ttbar production

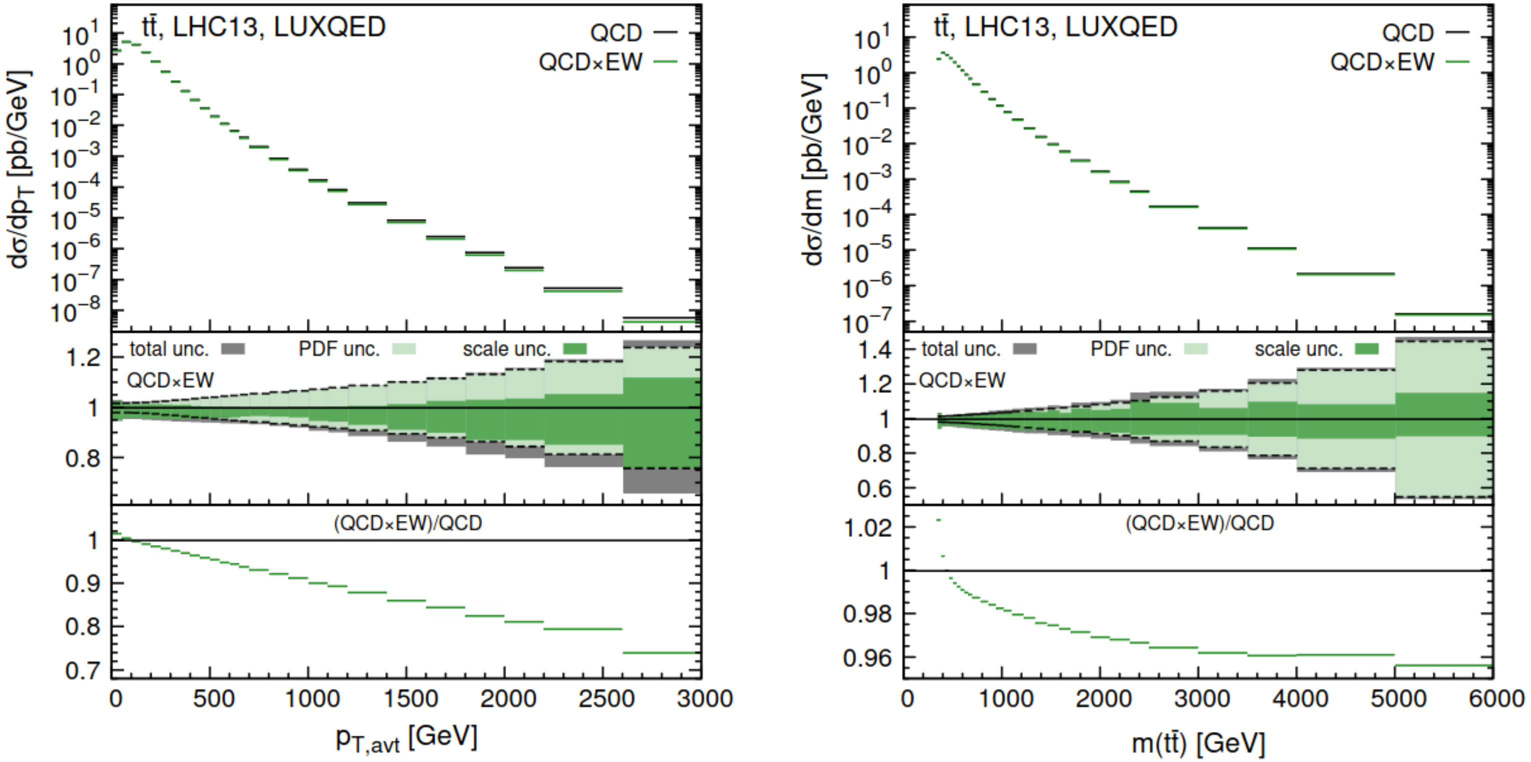
16 signal regions after angular binning

(regions shown here not split into angular bins for simplicity)



Background processes

> Dominant and irreducible background from SM ttbar production
  - Correct NLO Powheg+Pythia MC to NNLO-QCD+NLO-EW
  - Via iterative reweighting in m(ttbar), p_T(t), p_T(tbar)



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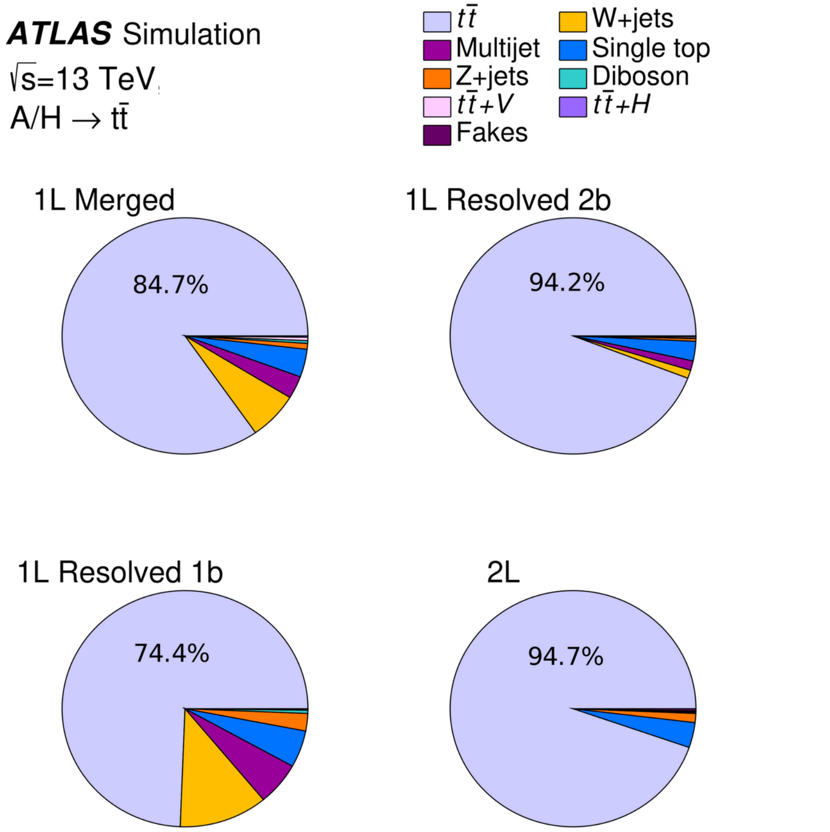


Statistical analysis without interference

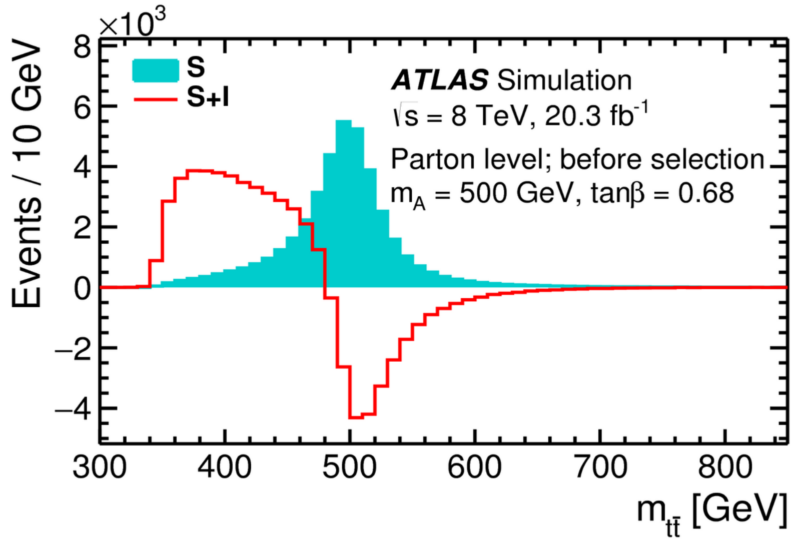
- Simple likelihood parameterisation in terms of signal strength

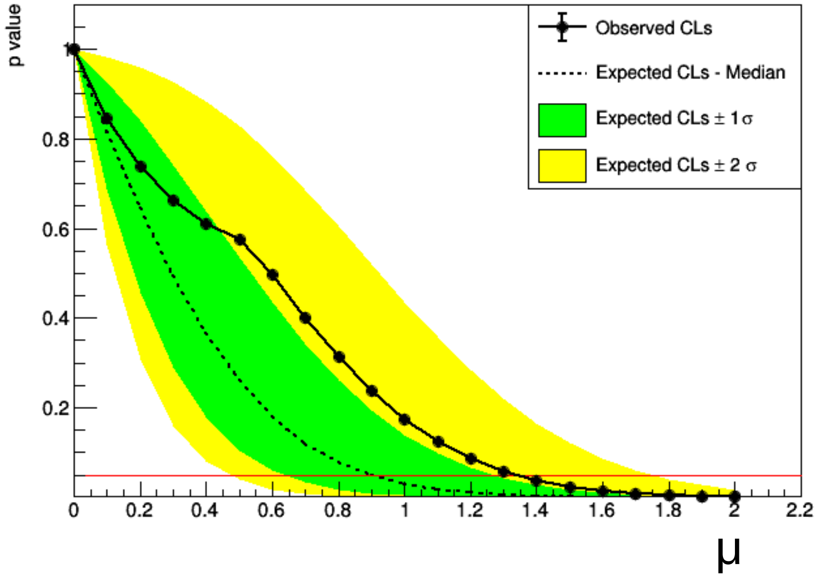
$$\mu \cdot S \qquad\qquad + B$$

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

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

- p-value scan to determine upper limits on μ





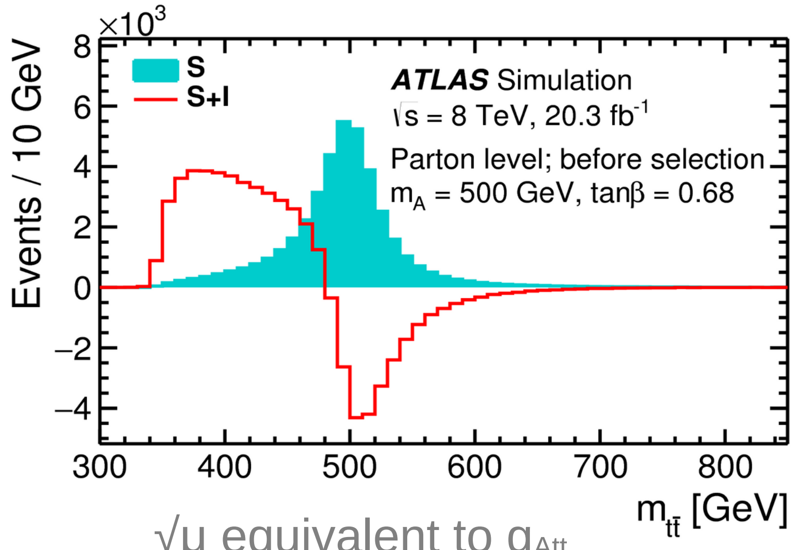
Statistical analysis with interference

> Extend likelihood to include interference term

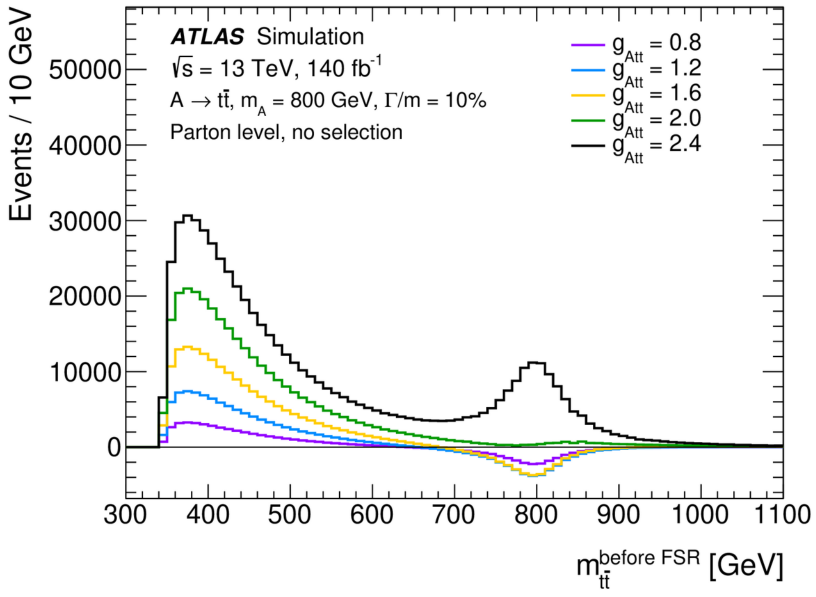
$$\mu \cdot S + \sqrt{\mu} \cdot I + B = (\mu - \sqrt{\mu}) \cdot S + \sqrt{\mu} \cdot (S + I) + B$$

> Quadratic dependence on POI = √μ

- Interference shape changes with POI



√μ equivalent to g_{Att}



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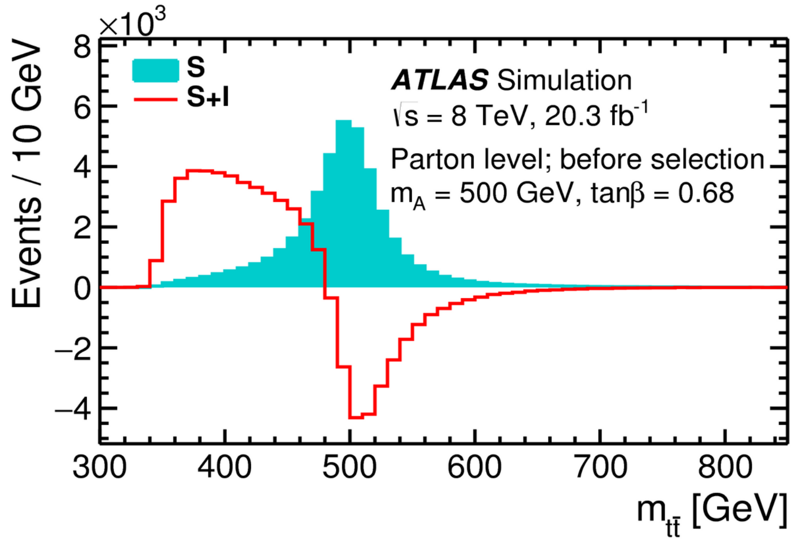
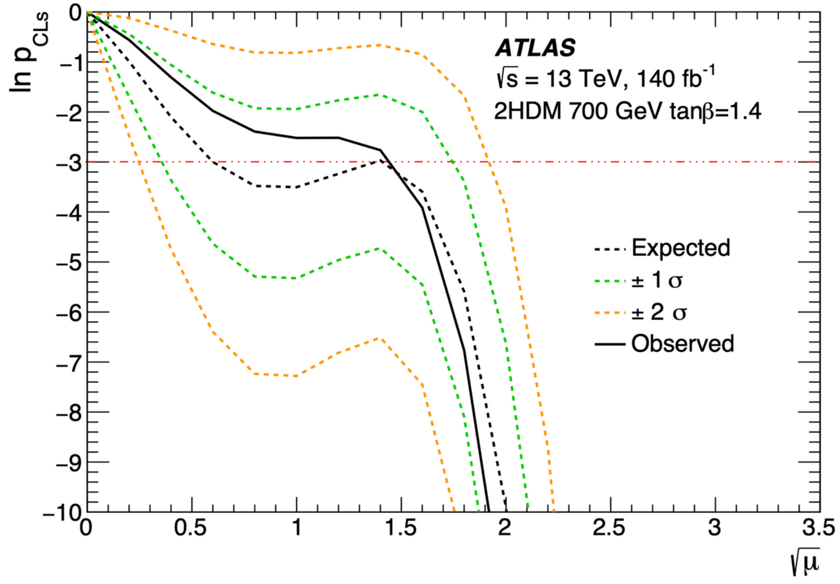


> Quadratic dependence on POI = √μ

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



Search stage

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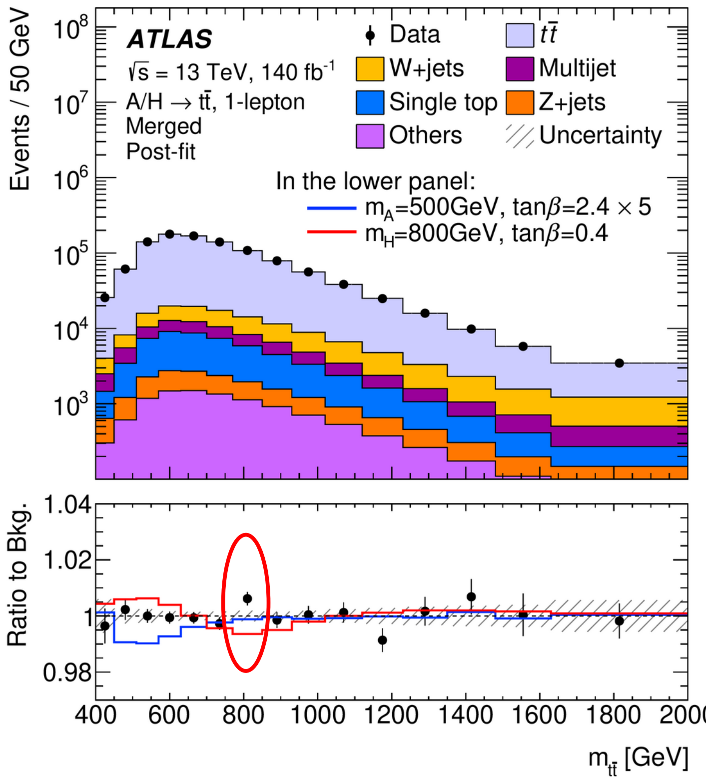
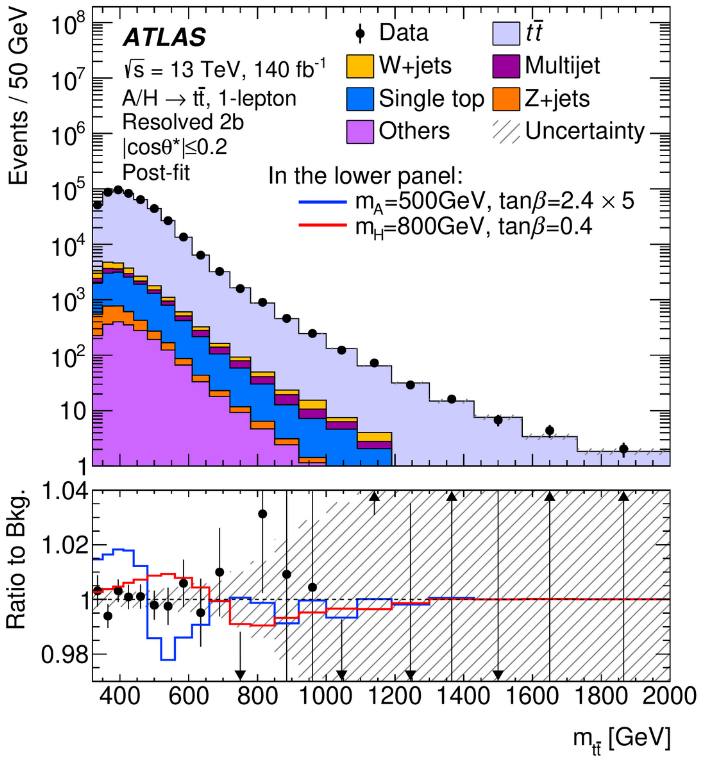
- Tested agreement between data and S+I+B hypotheses with masses [400,1400] GeV and widths [1,40]%
- Most significant deviation from SM-only (2.3σ local): m_A = 800 GeV, Γ_A/m_A = 10% and $\sqrt{\mu}$ = 4.0

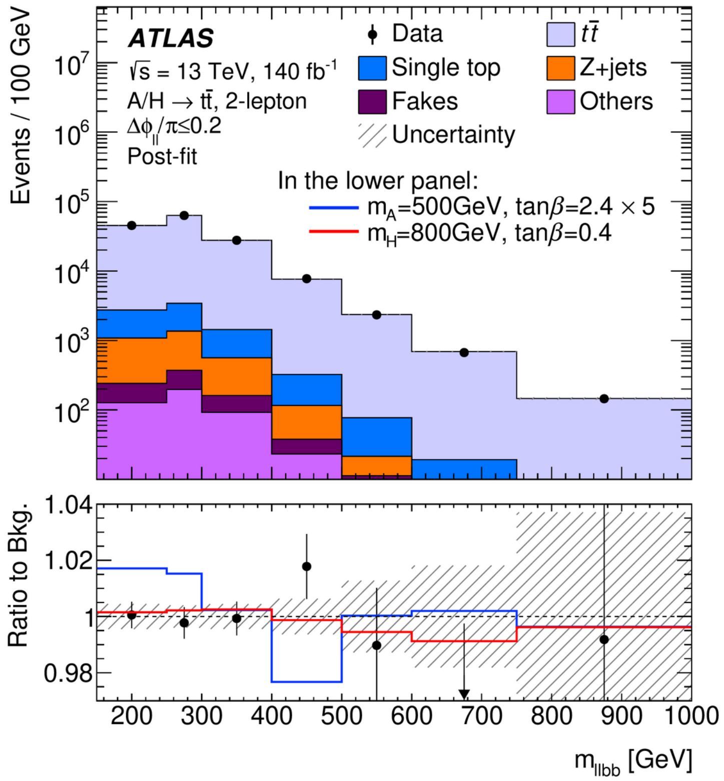
1L Merged



1L Resolved 2b



2L



Constraints on relevant benchmark models: hMSSM

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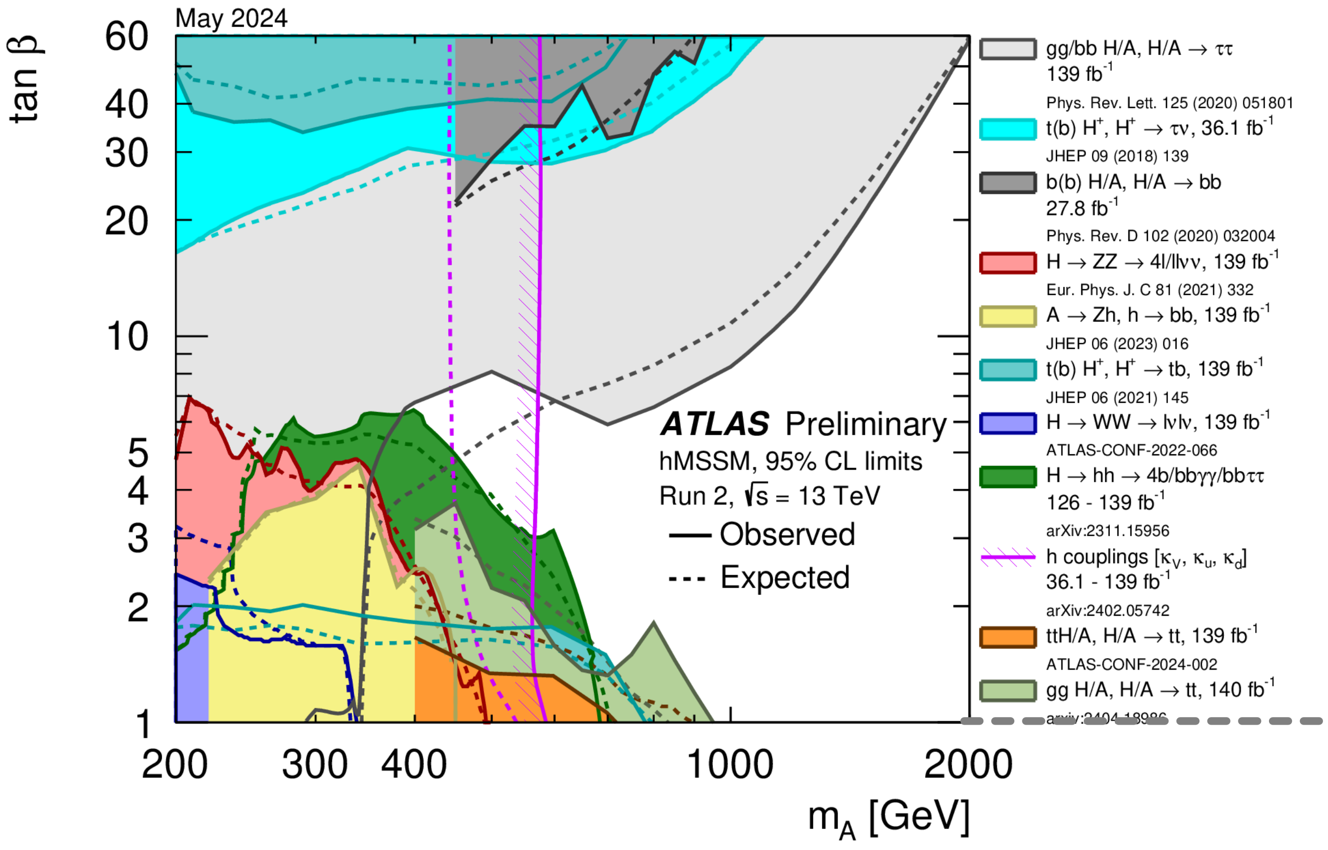
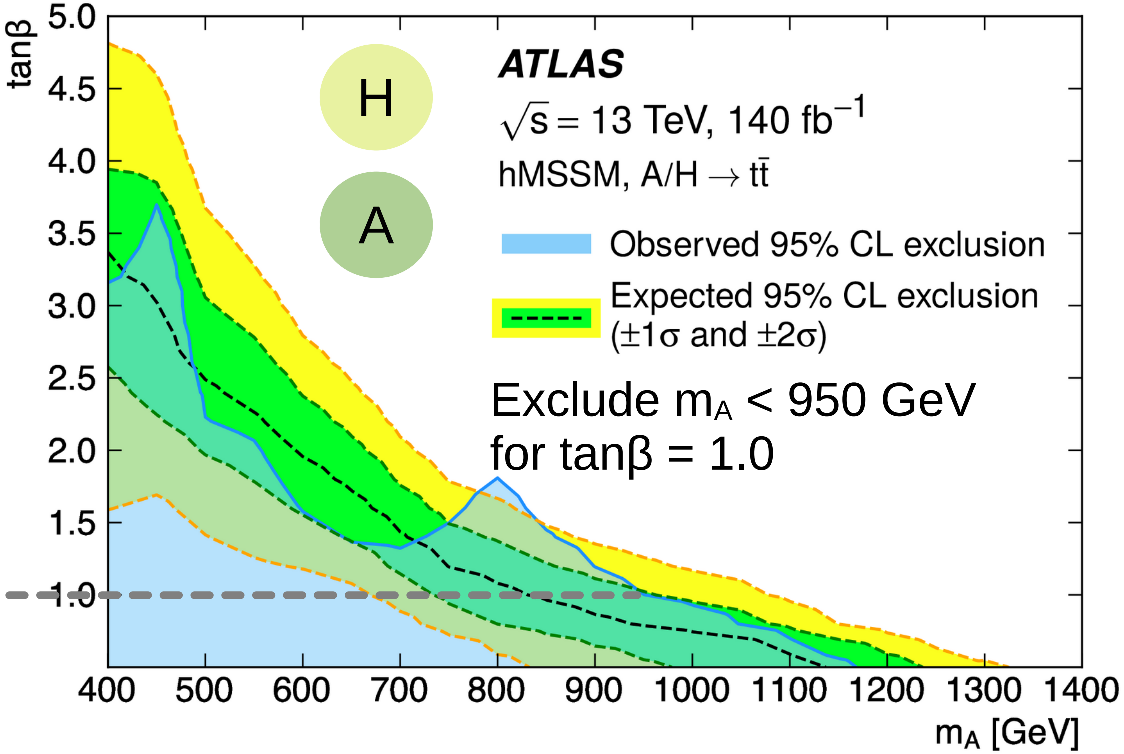
> Strongest constraints on m_A at lowest value of $\tan\beta = 1.0$



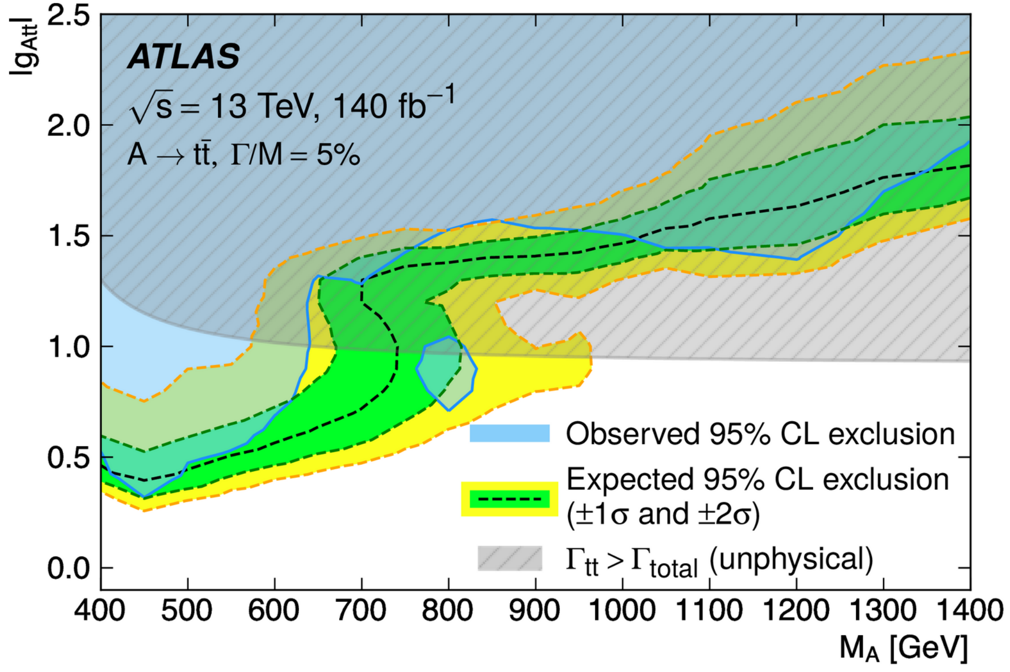


$m_A \sim m_H$

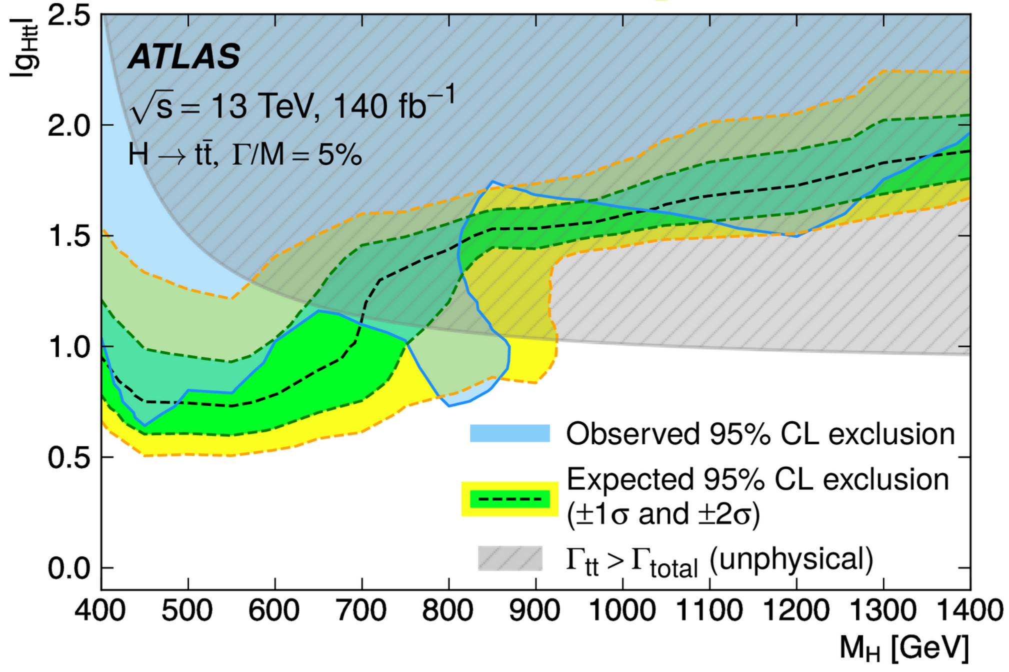
Coupling constraints for a single (pseudo)scalar

- Upper limit on coupling to top quarks for a fixed width
- “Island” due to local minima in likelihood scan

Pseudoscalar A

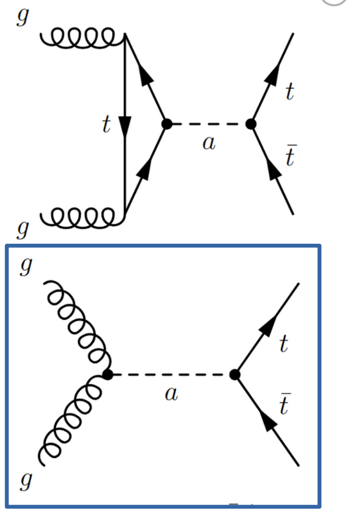


Scalar H



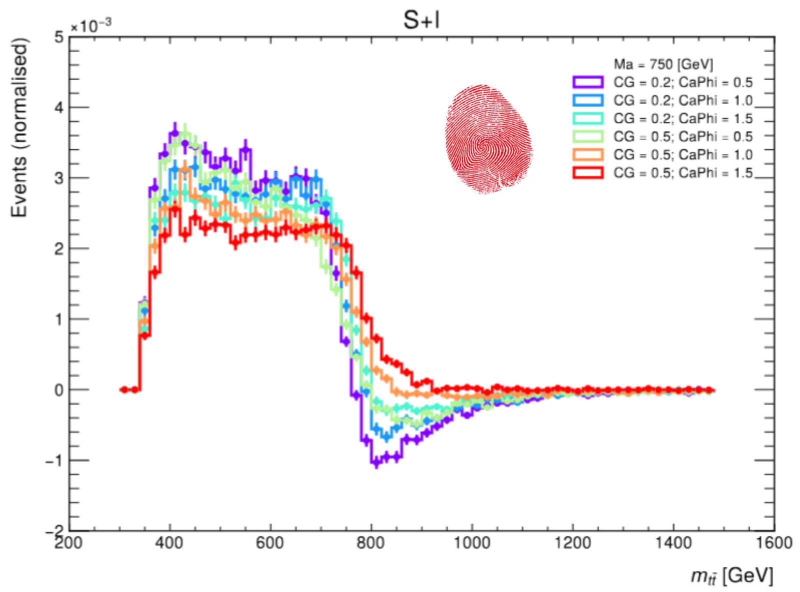
Extra: ALPs coupling to top quarks

- 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!

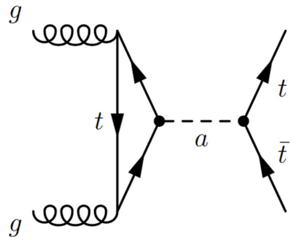
M. Rodrigues, KB



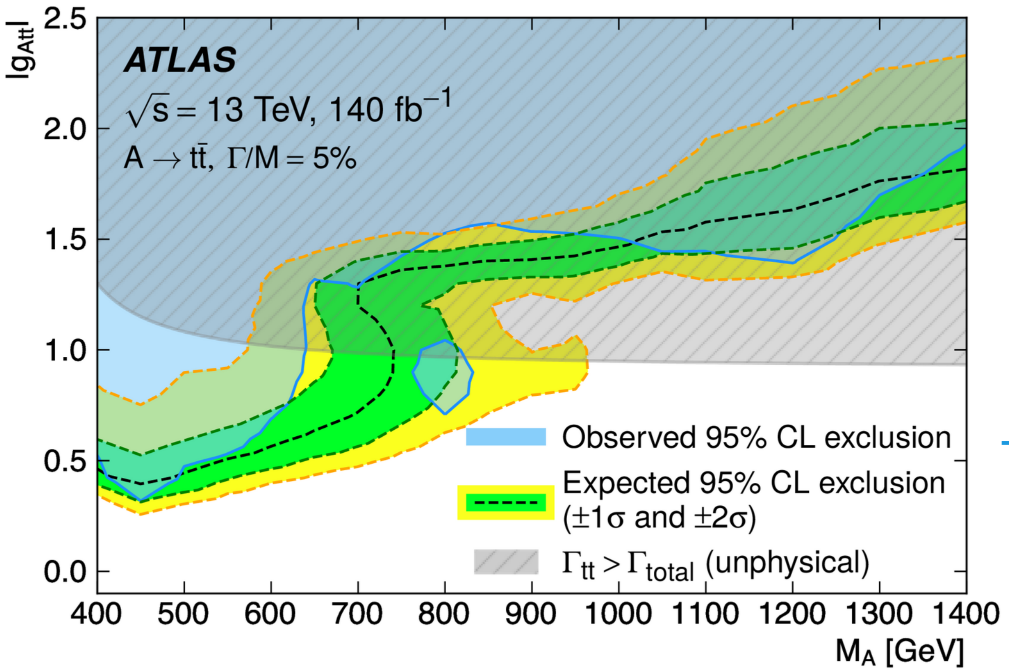
Related work:
Jeppe et al: DESY-24-059
Carra et al: PRD 104 (2021) 9, 092005

Extra: ALPs coupling to top quarks

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

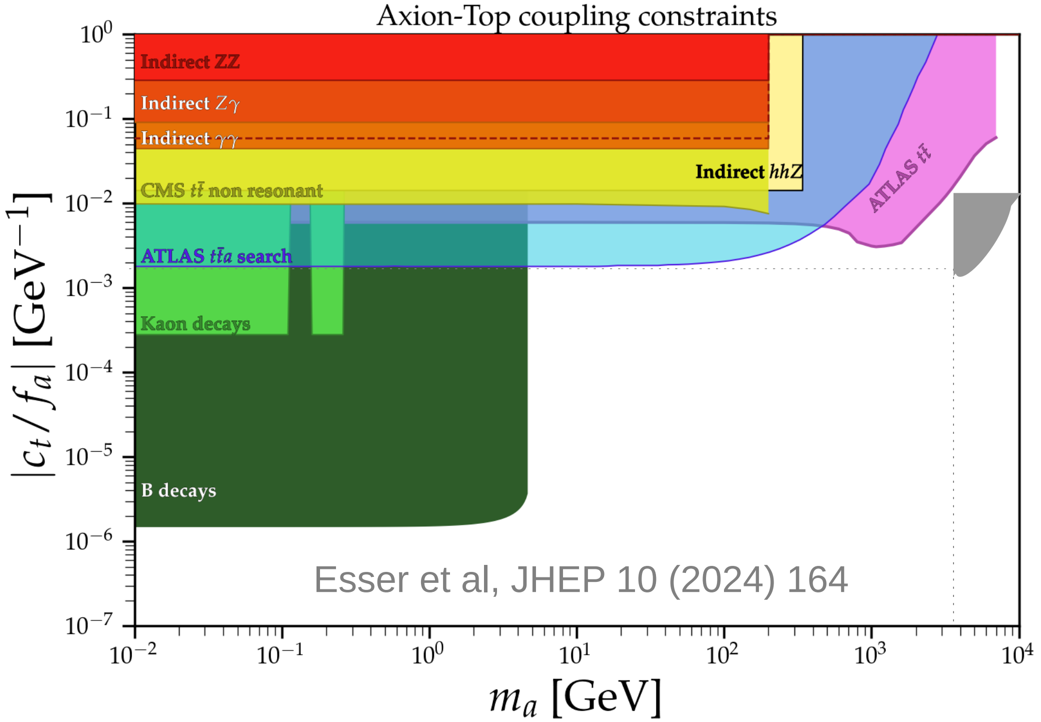


Fixed pseudoscalar width



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

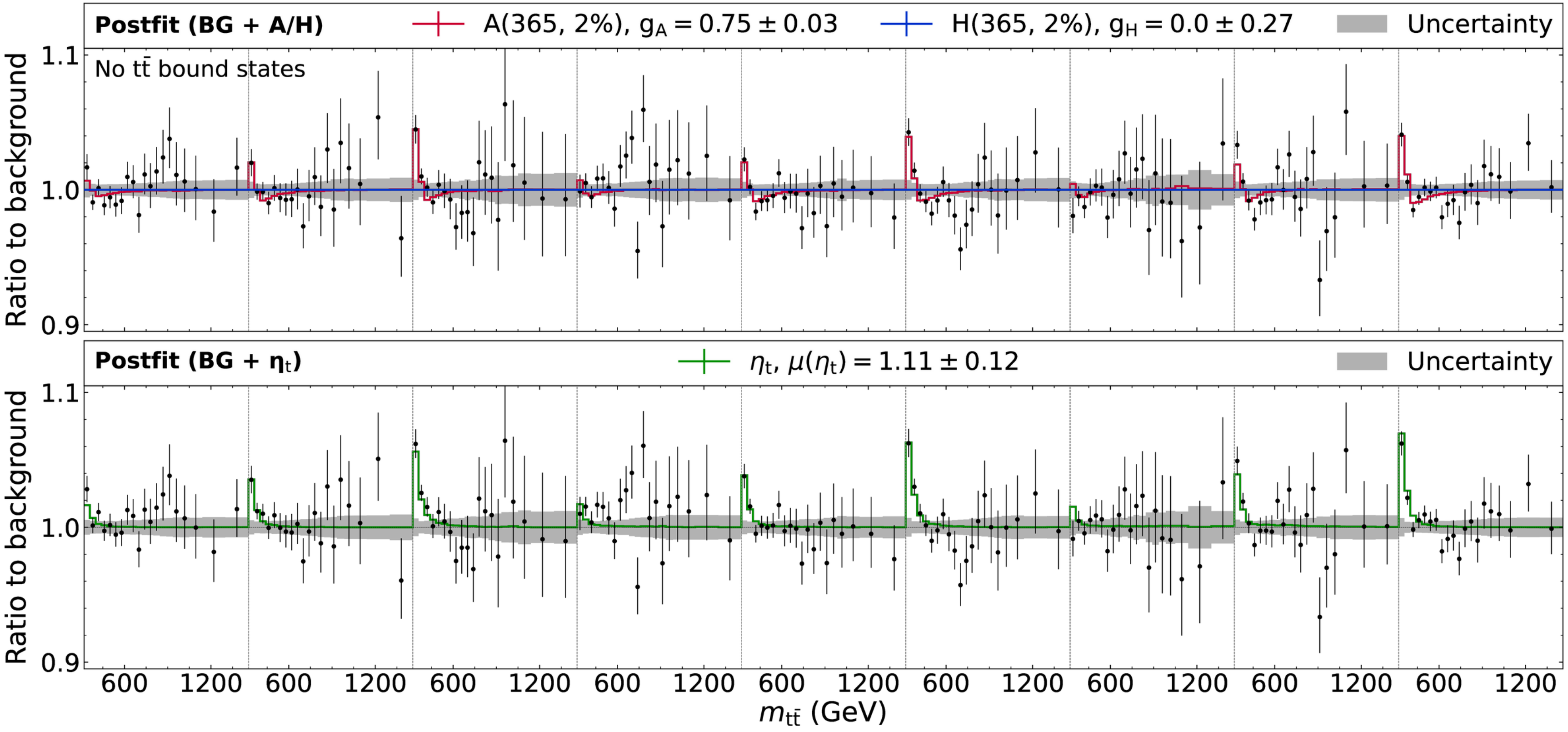
Width depends on m_a and c_t

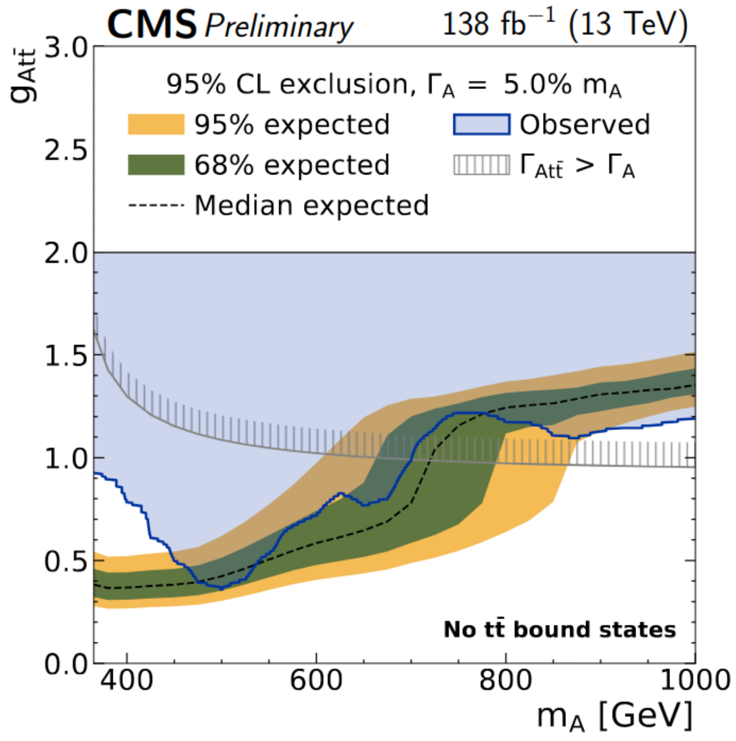


Esser et al, JHEP 10 (2024) 164

A little twist ...

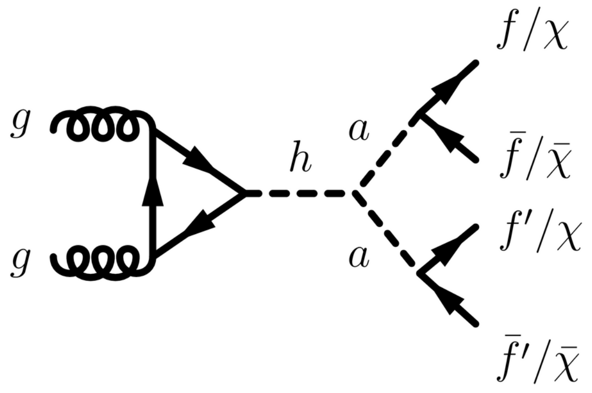
- Similar analysis by CMS but more optimised for low-m_{tt} than high-m_{tt} region
- Observe > 5σ deviation of the data from the prediction in the ttbar threshold region (m_{tt} < 400 GeV)





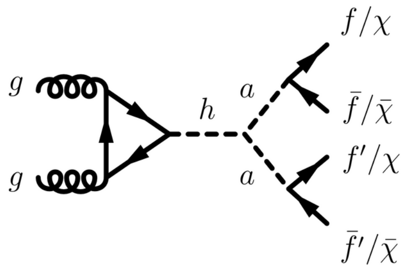
What if extra bosons are light?

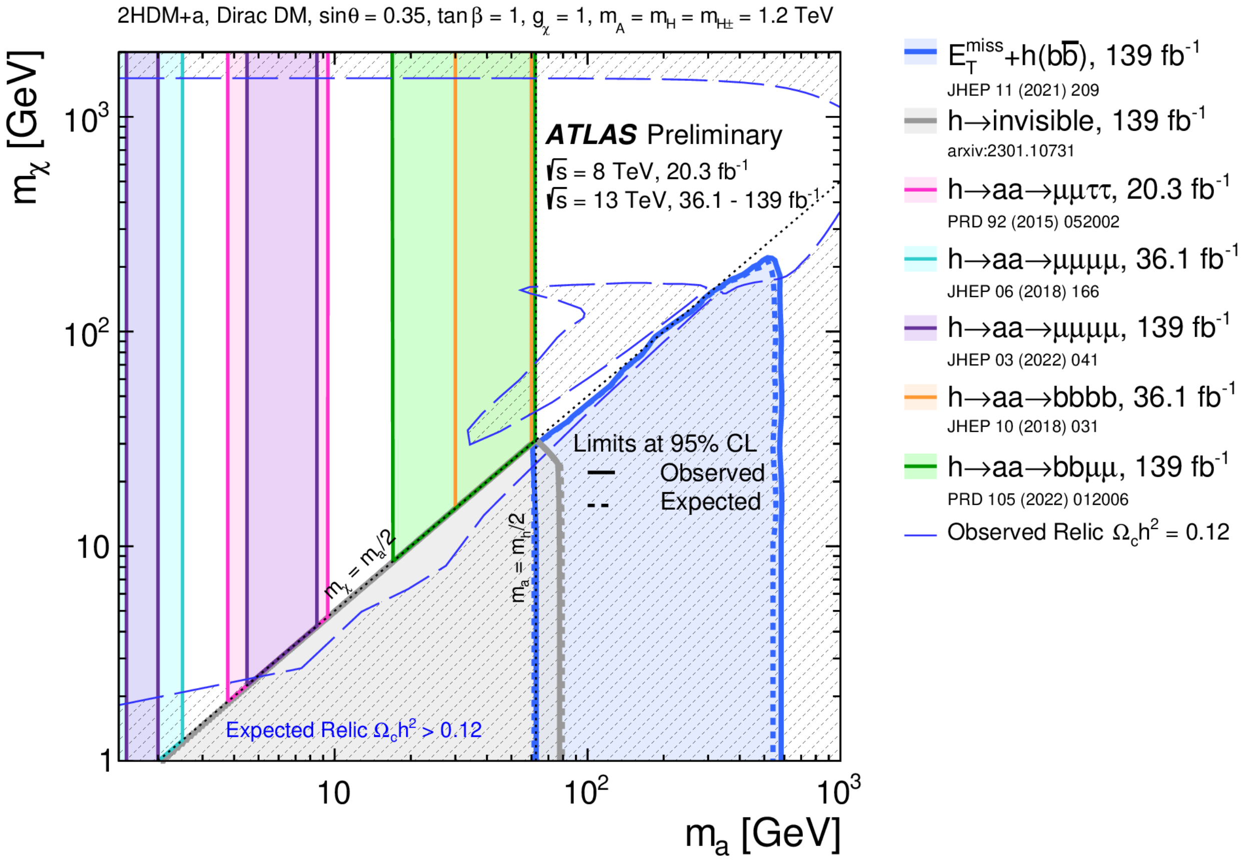
- New (pseudo)scalar states with mass < 125 GeV constrained but not excluded by LEP etc.
- Motivation especially for light pseudoscalars:
  - Extended Higgs sector models
  - ALPs
- Exotic Higgs decays: $h_{125} \rightarrow aa$
- Detector signatures depend on
  - Mass m_a ($\rightarrow$ Yukawa coupling to SM fermions)
    - $h_{125} \rightarrow aa \rightarrow 4b$
    - $h_{125} \rightarrow aa \rightarrow 4\mu$
    - …
  - Couplings to BSM particles, e.g. DM
    - $h_{125} \rightarrow aa \rightarrow 4b$
  - Lifetime of *a*
  - …



Example: pseudoscalar mediator to DM

Simplified model





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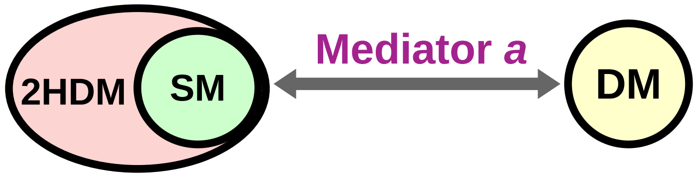
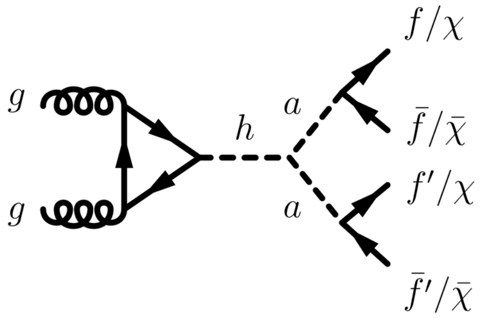
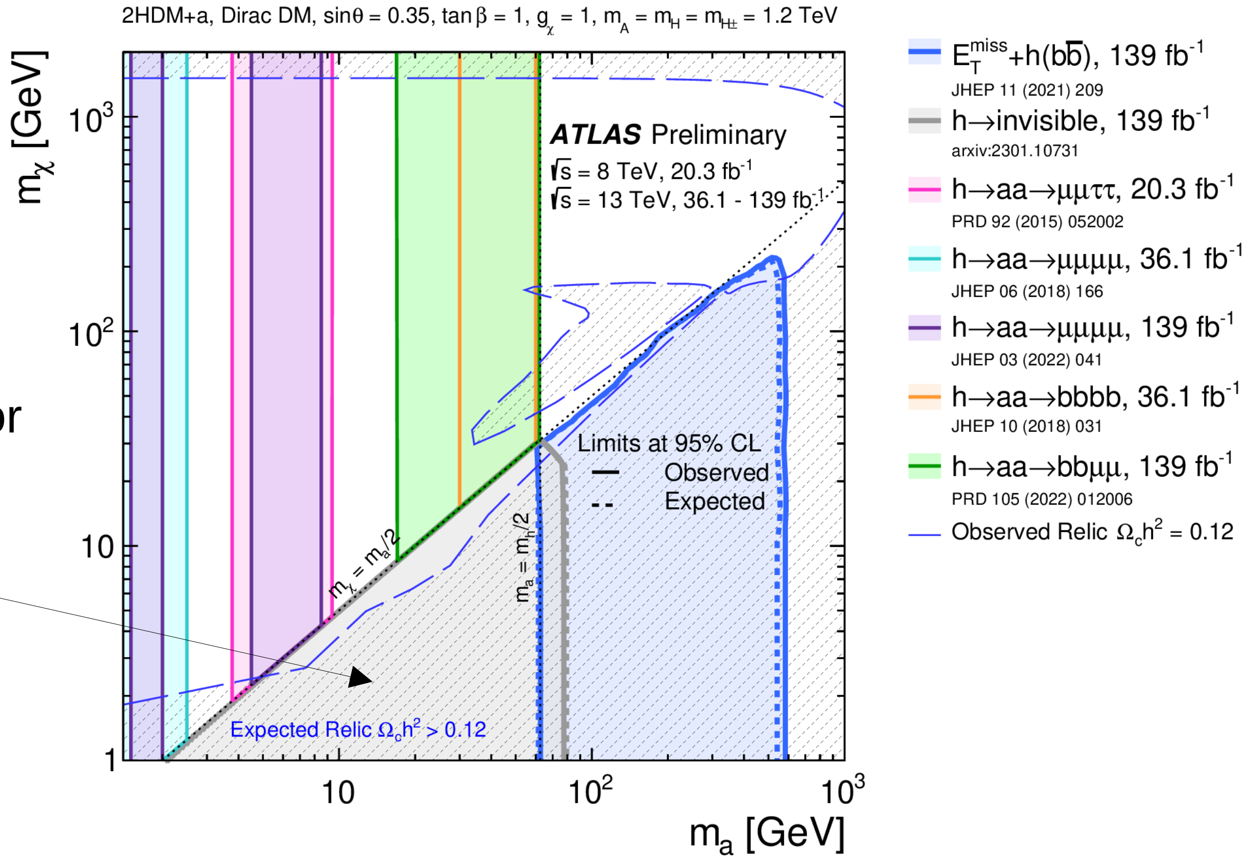


Extended model:
2HDM+*a*



Invisible mediator decays to DM



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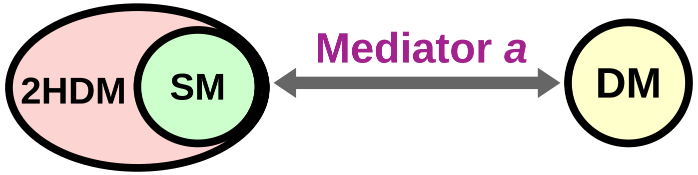

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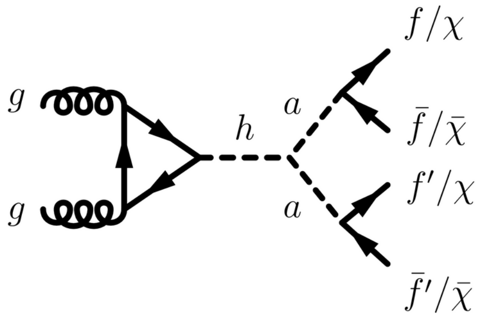

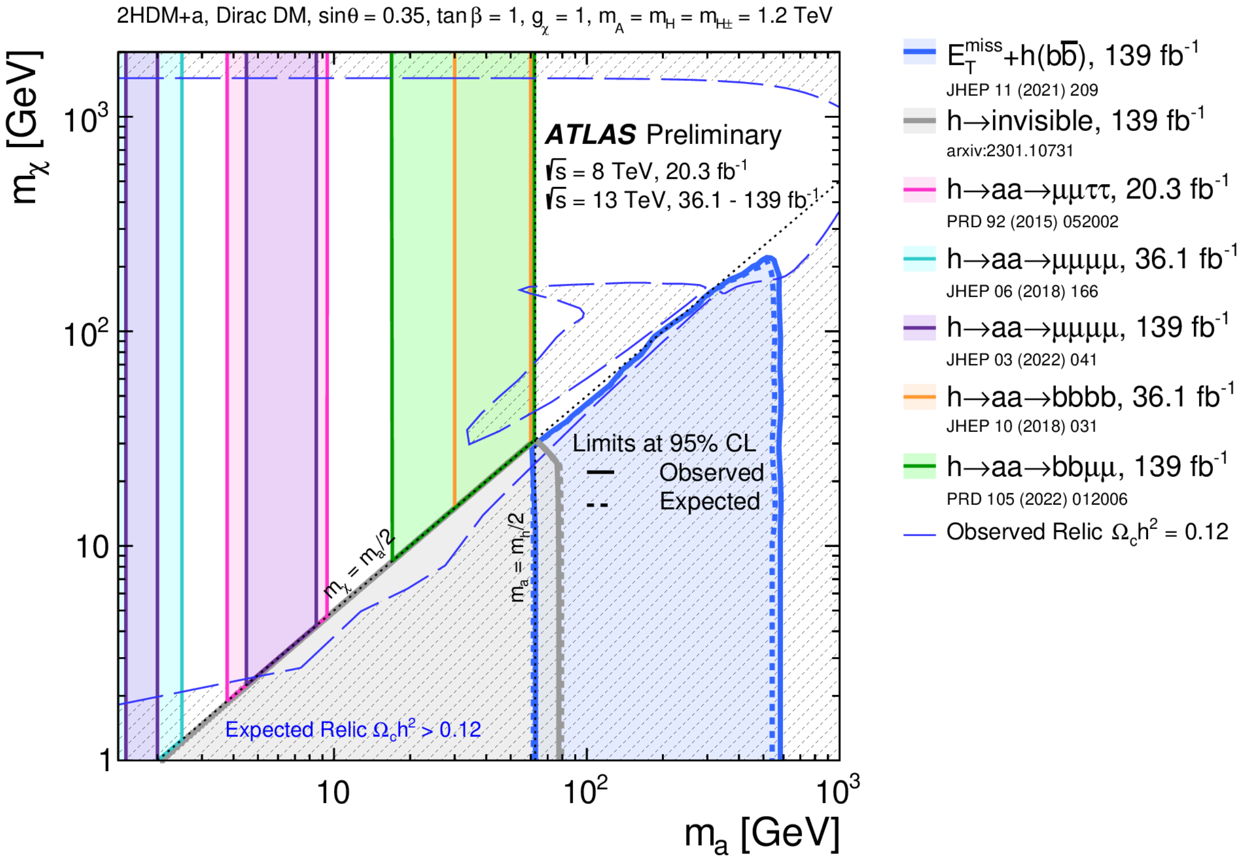

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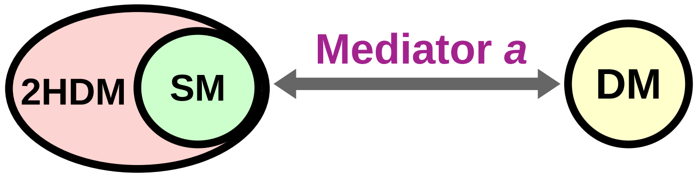
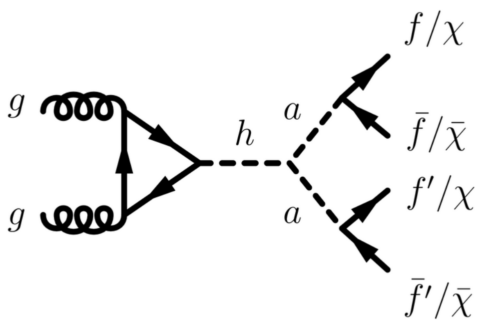
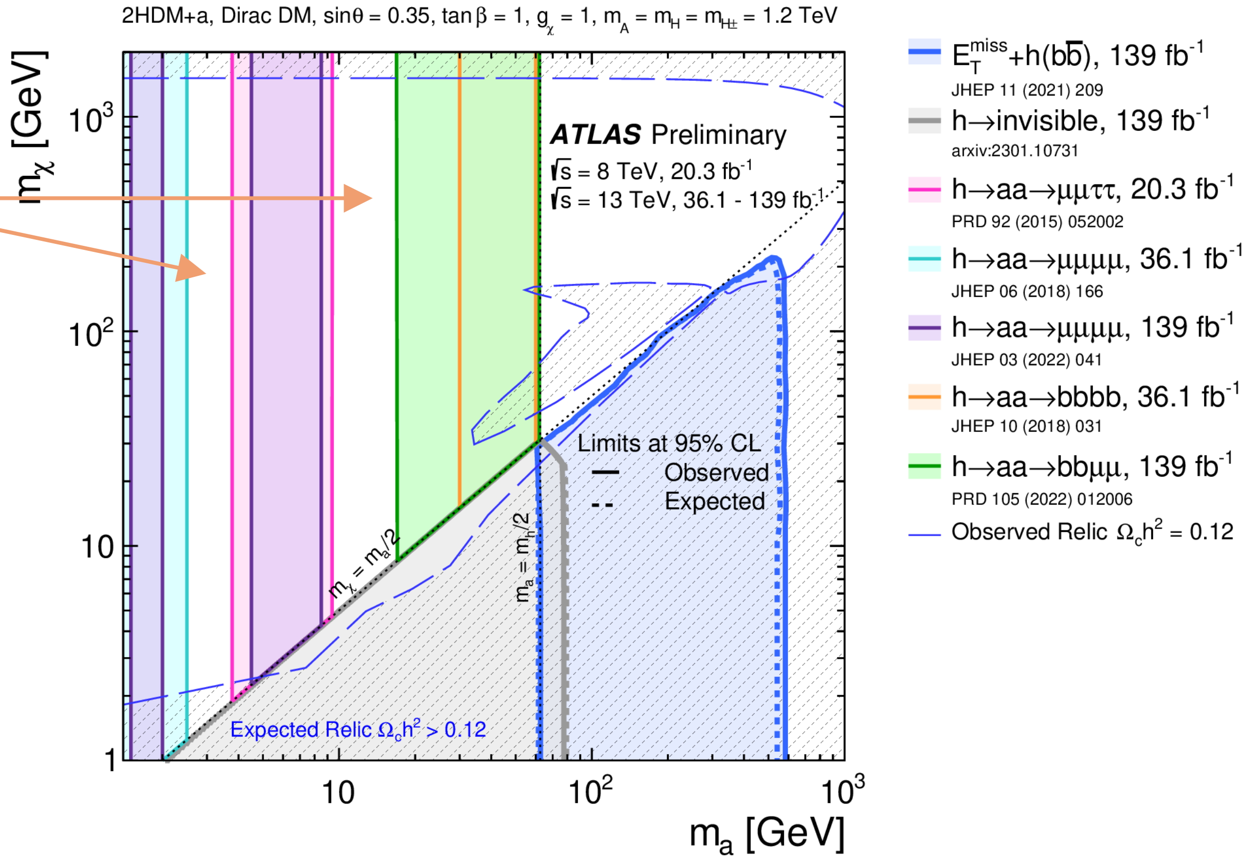


Extended model:
2HDM+*a*

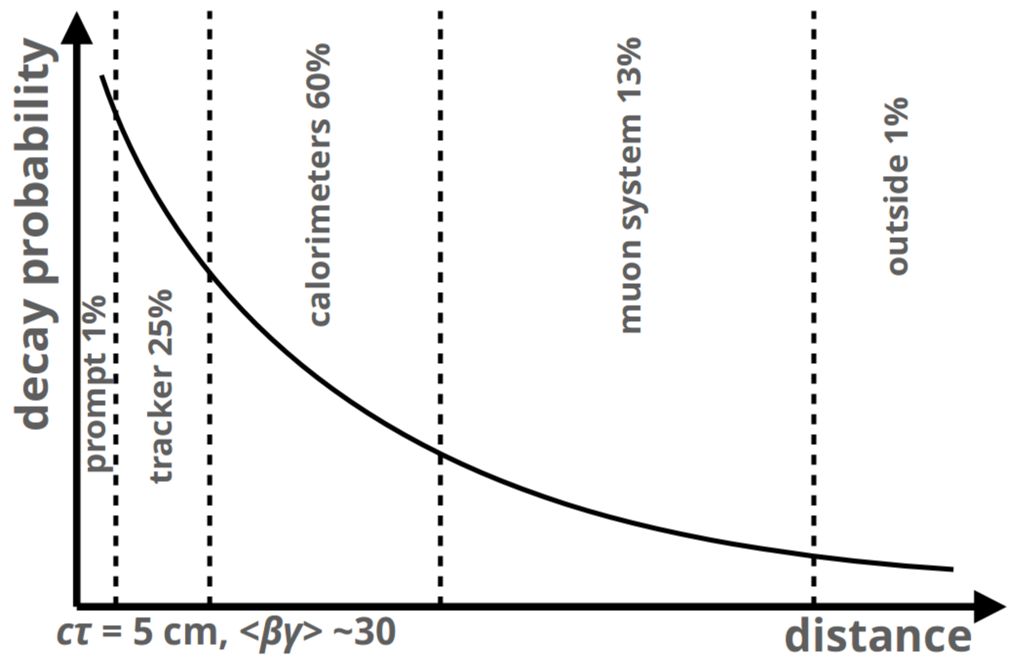
J/Psi and Upsilon resonances
→ resonant background, difficult to model, large uncertainties

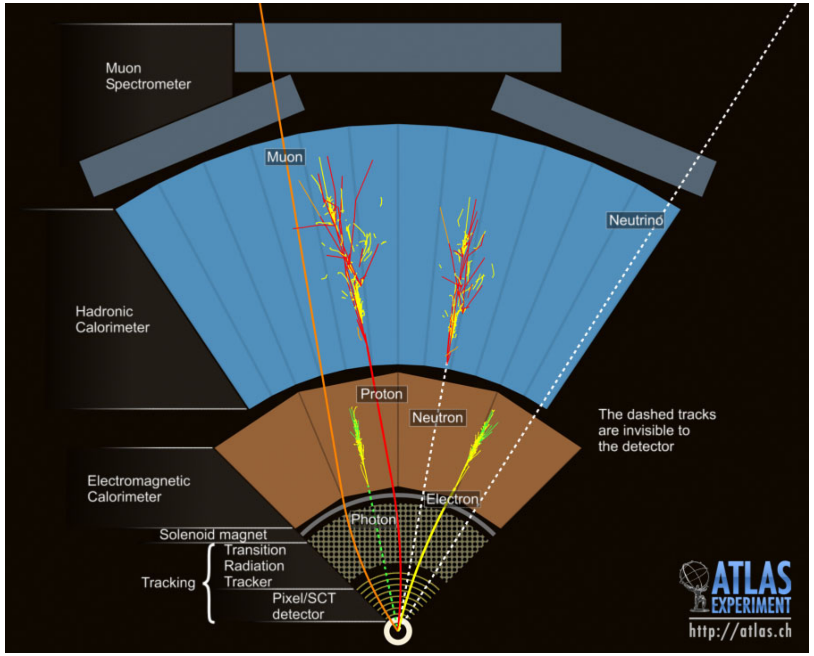




Long-lived particles

- Exotic decay products (a, S, ...) of the Higgs could be long-lived
- Proper lifetime cτ of order mm to m → decay not at interaction point but inside detector volume
- Wealth of possible detector signatures: displaced tracks, trackless jets, displaced muons, …
  - Not captured by standard particle identification algorithms!





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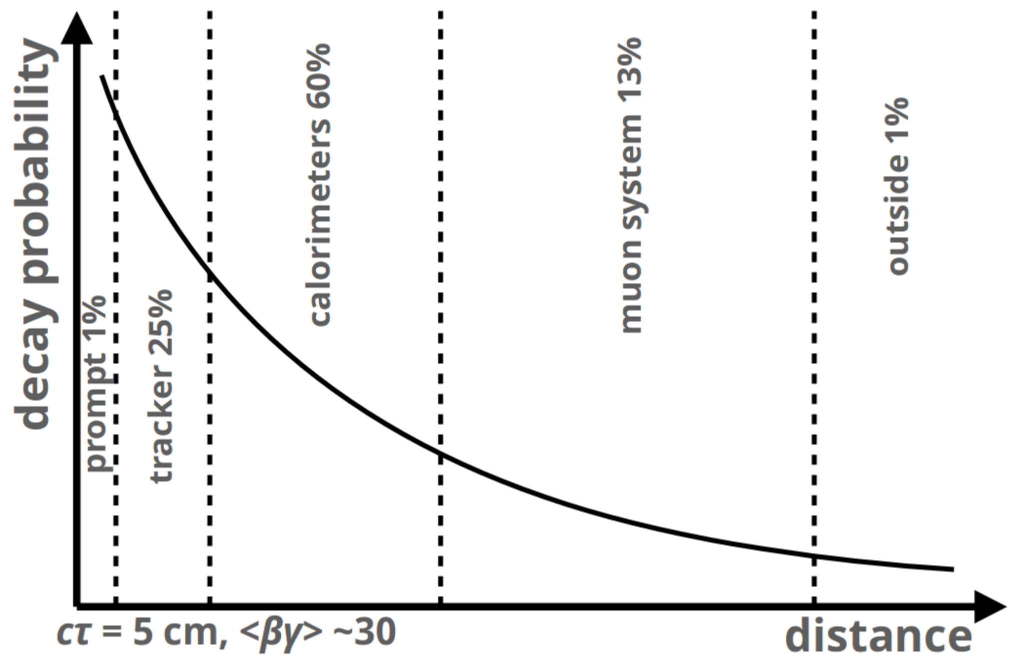

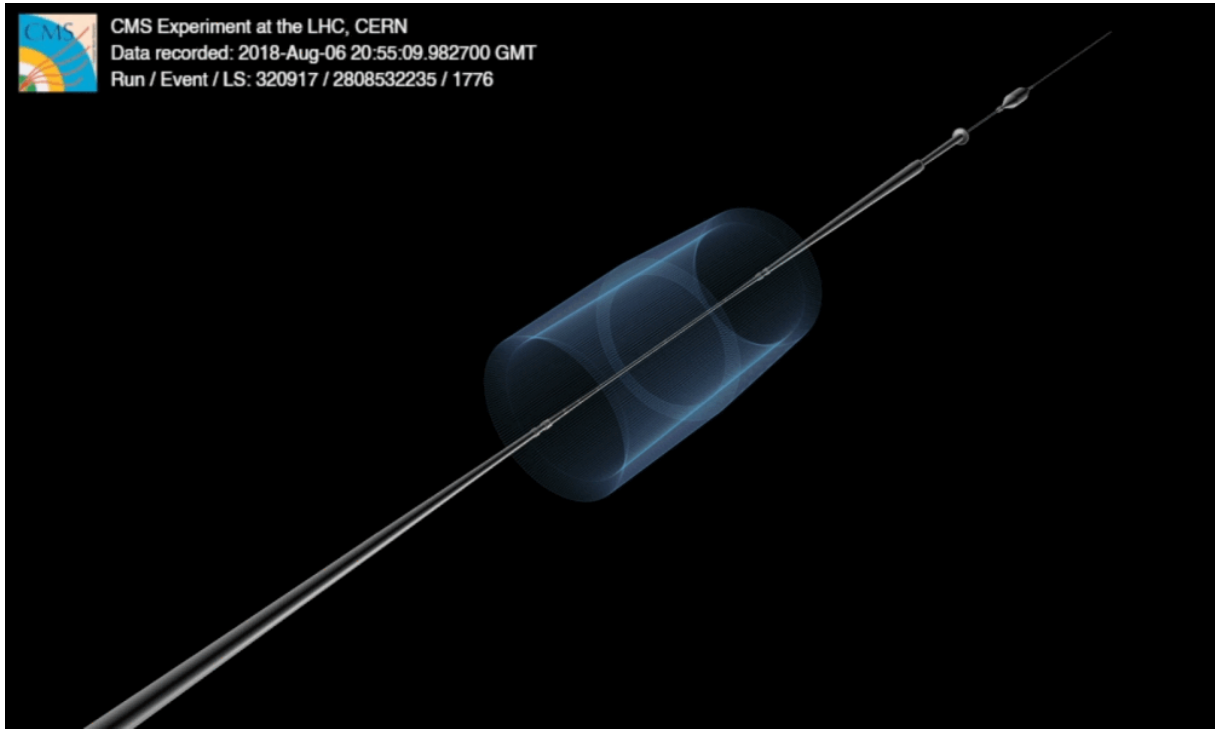

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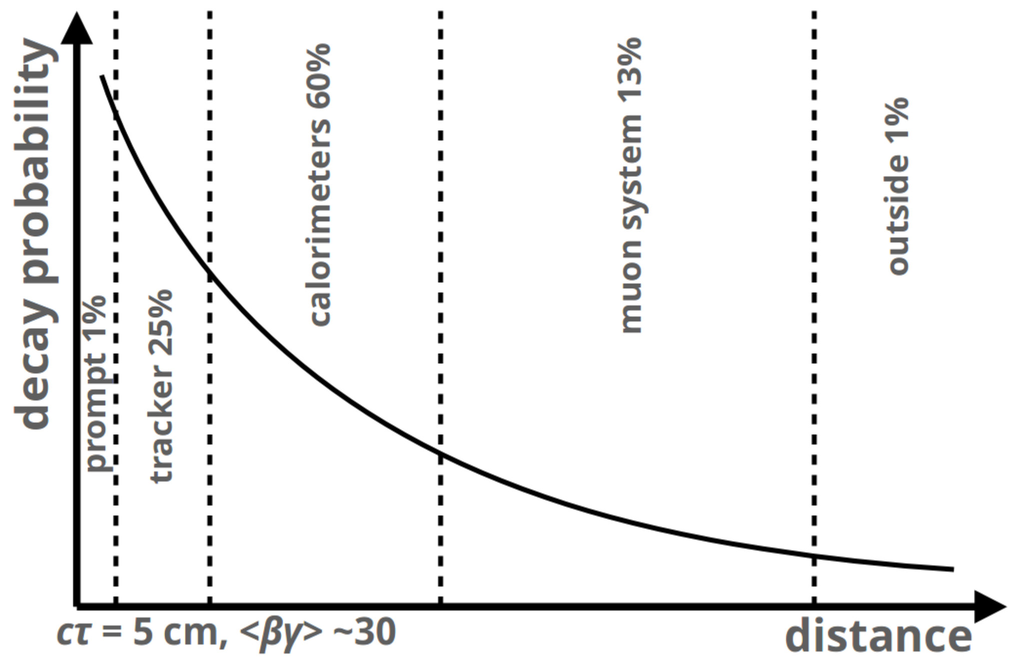
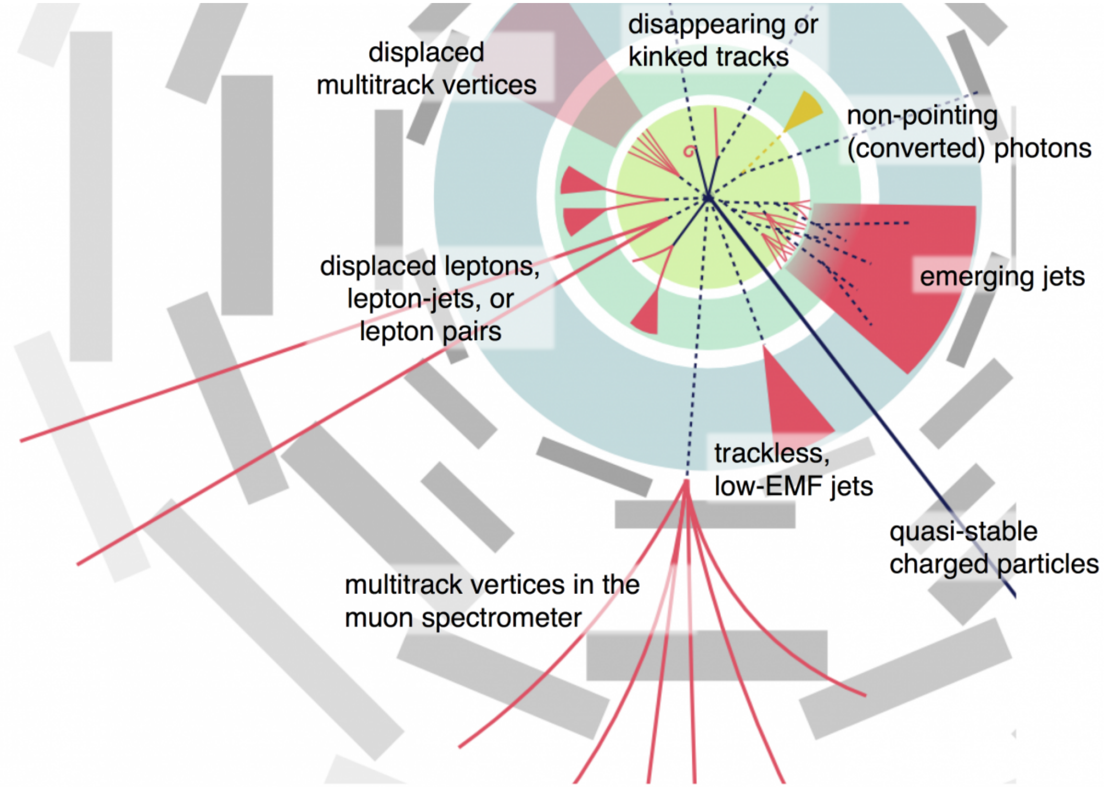


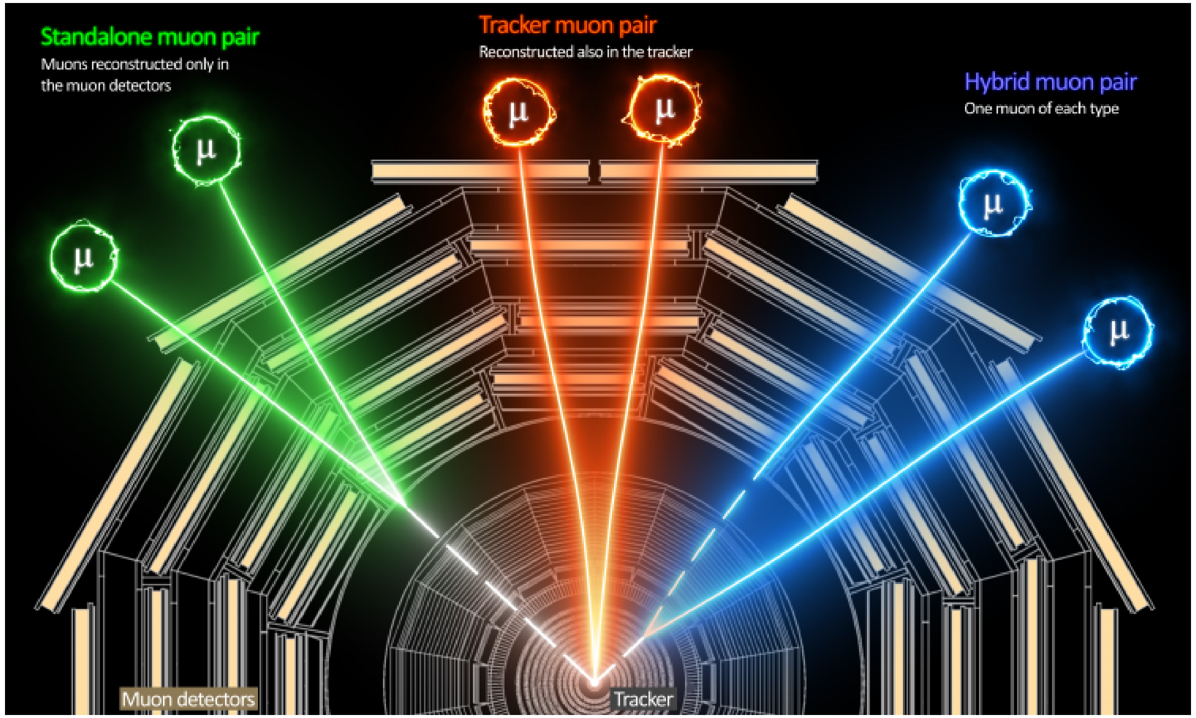


Example: displaced muon pairs

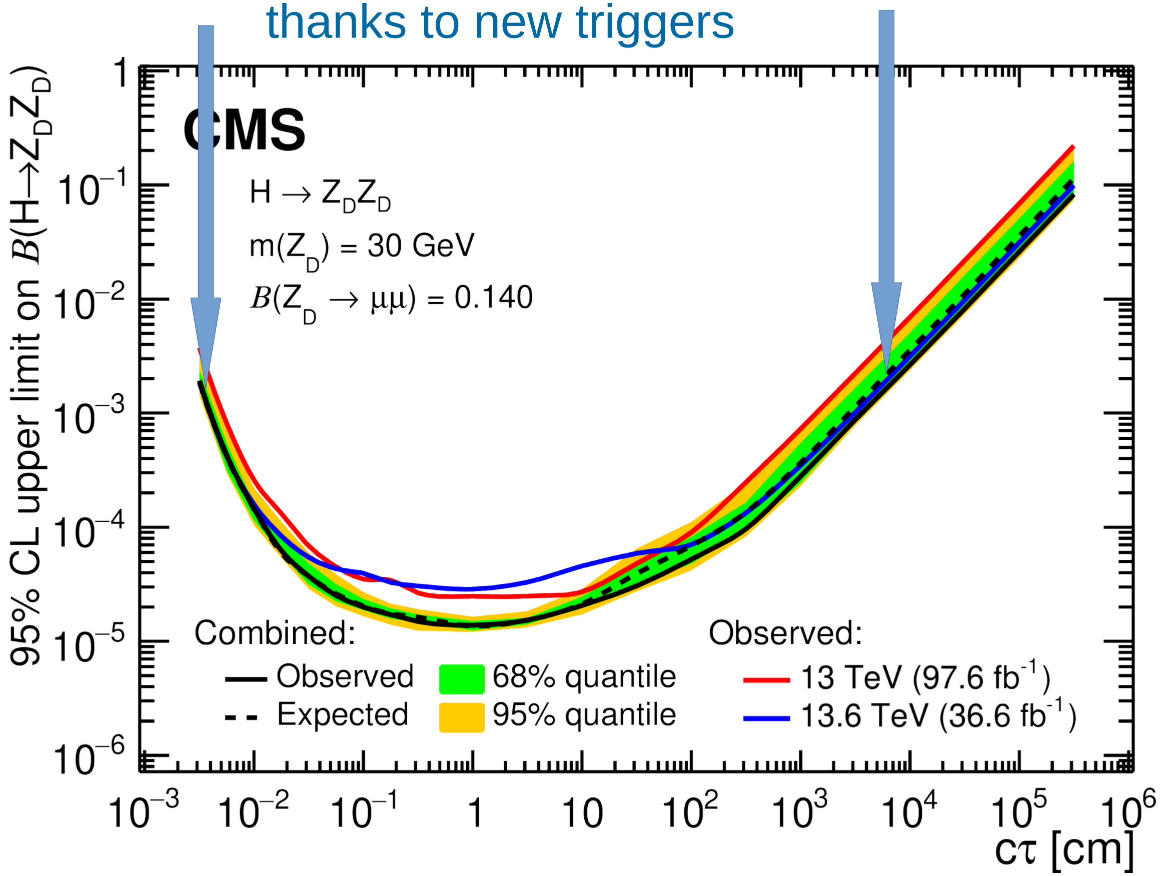
> Exotic Higgs decay to a pair of long-lived dark photons: $h \rightarrow Z_D Z_D \rightarrow \mu\mu\ \mu\mu$

> Implemented novel triggers targeting displaced muon pairs + other offline analysis techniques

> Significant sensitivity boost across lifetime range

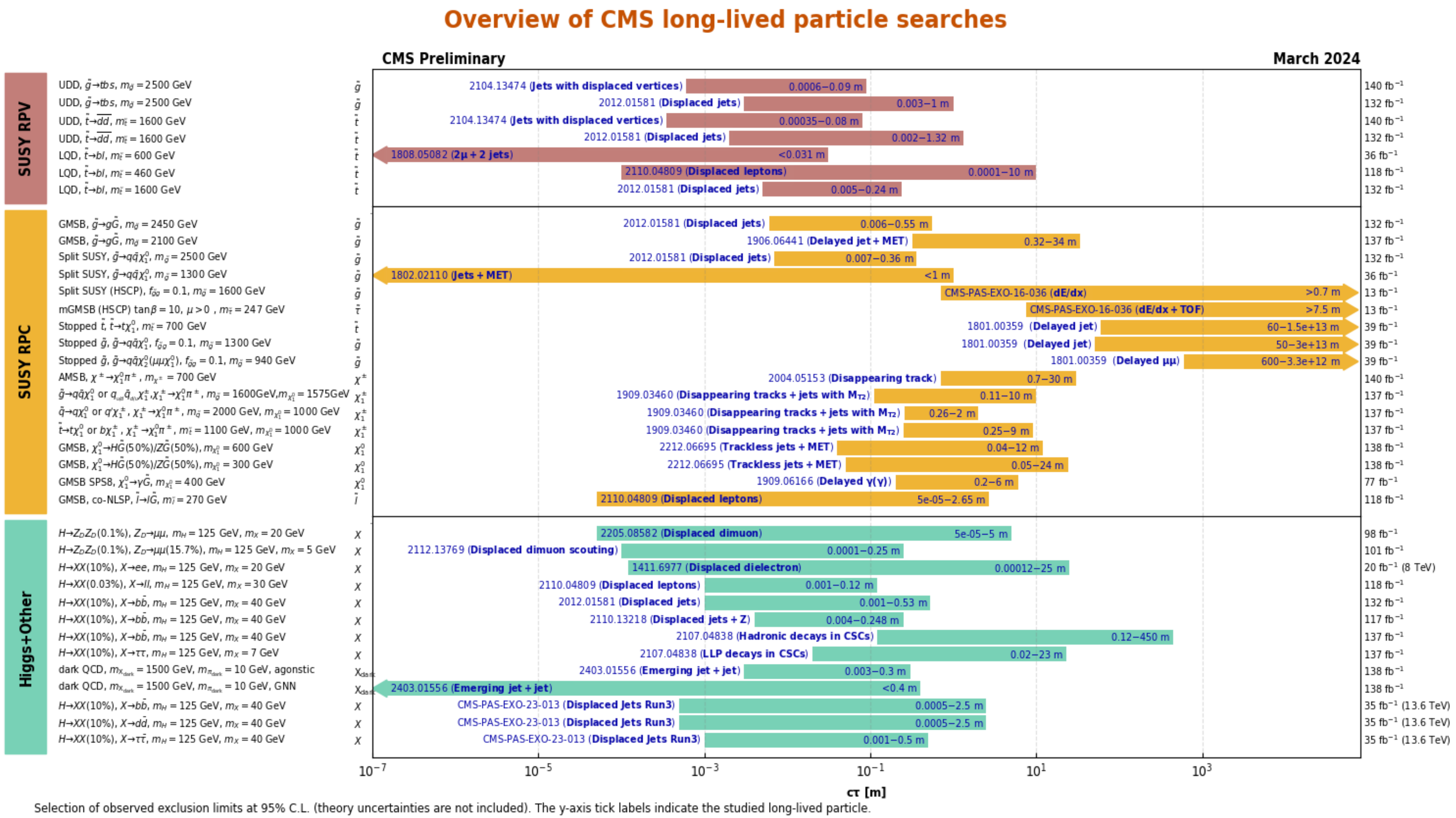


Enhanced sensitivity with Run-3 thanks to new triggers

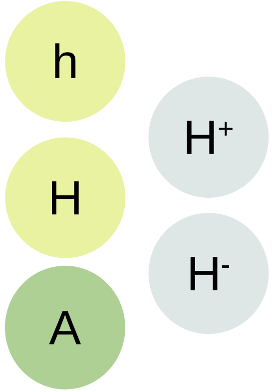


Impressive lifetime coverage

> Probing lifetimes/decay lengths from O(μm) to O(10m)



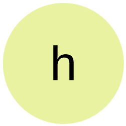
Higgs Part 3: Summary



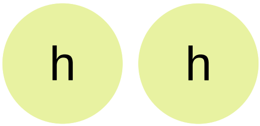
- Extended Higgs sectors part of many well-motivated extensions of the SM
- Broad experimental programme to search for extra Higgs bosons
  - Different production modes (gg-fusion, exotic Higgs decays)
  - Different decay modes
- Decays to top quarks particularly challenging due to interference
  - Excess seen at ttbar threshold … see bonus lecture!

Overall summary

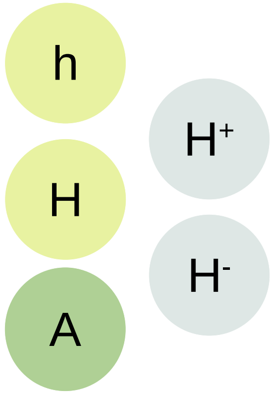
- **Part 1: The vacuum is not empty**
  - Significant progress in characterising the Higgs boson
  - Measurements in agreement with SM within current uncertainties → much room for BSM physics



- **Part 2: What is the fingerprint of the vacuum?**
  - Unprecedented constraints on self-couplings from hh searches on LHC Run-2 data
  - Algorithm improvements via AI crucial



- **Part 3: Is there even more to the vacuum?**
  - Broad search programme for new states
  - Exciting news from ttbar threshold
  - Plethora of little explored unusual signatures



BONUS SLIDES

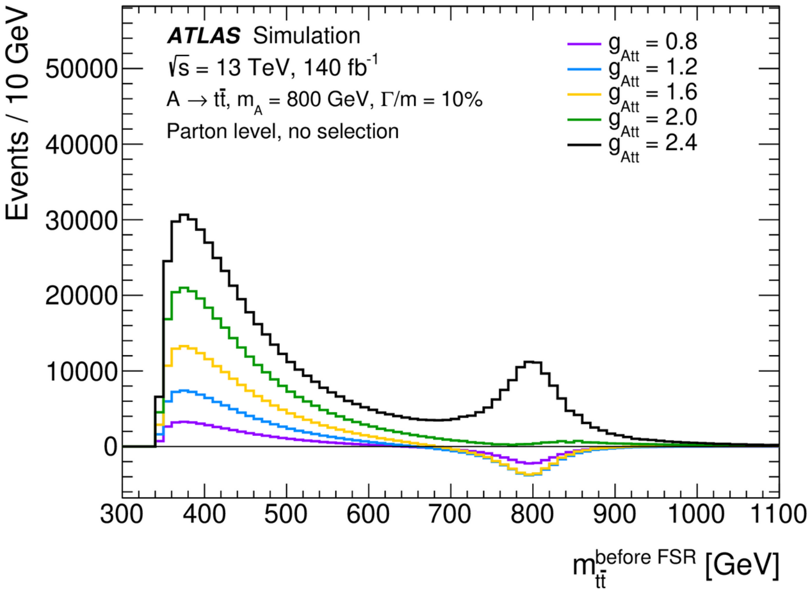
Choice of test statistic

> 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

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

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

Systematic uncertainties (ATLAS)

- 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 with interference

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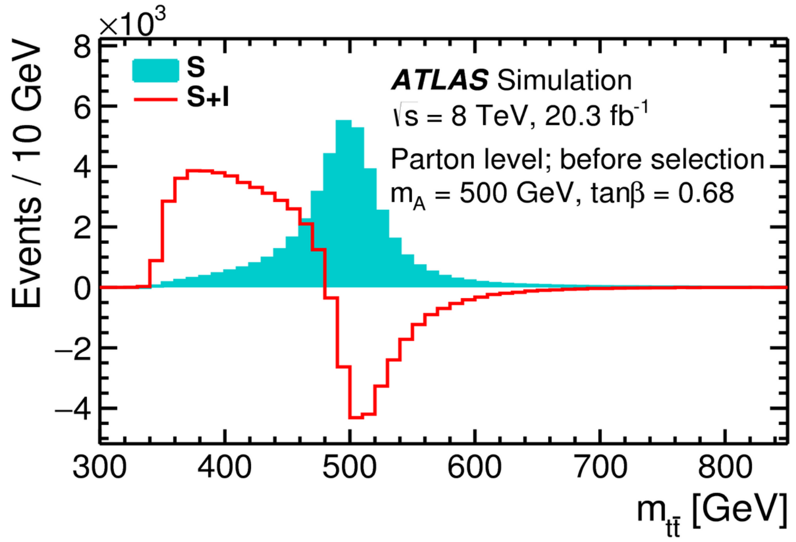
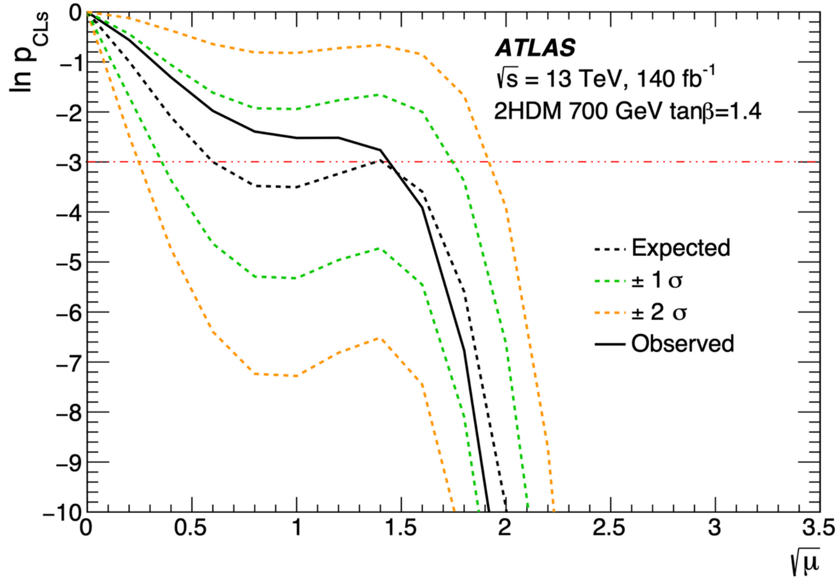
- Extend likelihood to include interference term

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

- 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





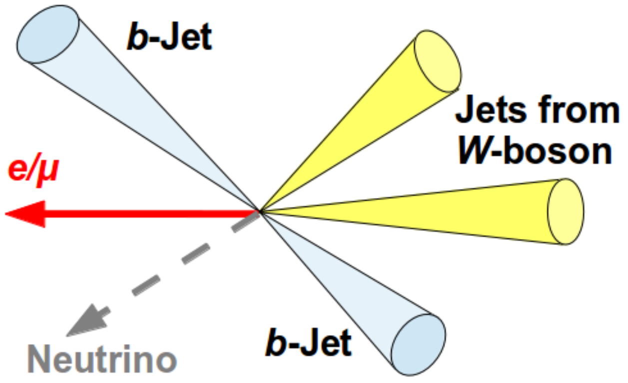
1L Resolved

> Require ≥ 4 jets, ≥ 1 b-jet

> Reconstruct full ttbar system:

- Neutrino 4-vector from W-mass constraint
- Assignment of jets based on χ^2 minimisation

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



1L Merged

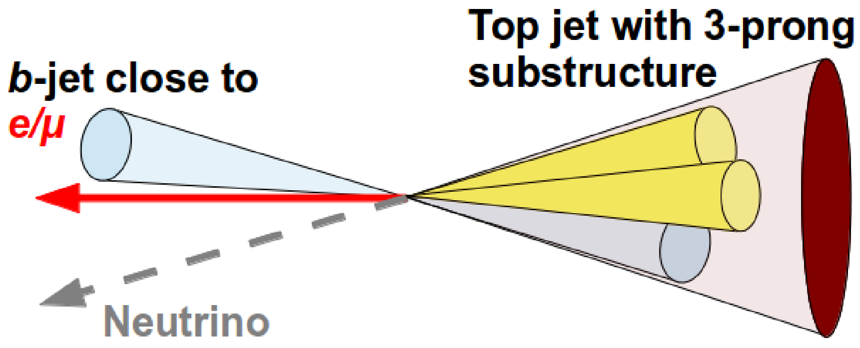
> Top candidate jet:
  - Variable-R jet (R_{max} = 1.5) optimised for intermediate top boosts (m_{ttbar} ~ 1 TeV)
  - Jet radius shrinks with jet p_T
  - Jet size automatically adapts to boost of top quark

> 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

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

(ρ = 600 GeV)



Differences in background modelling

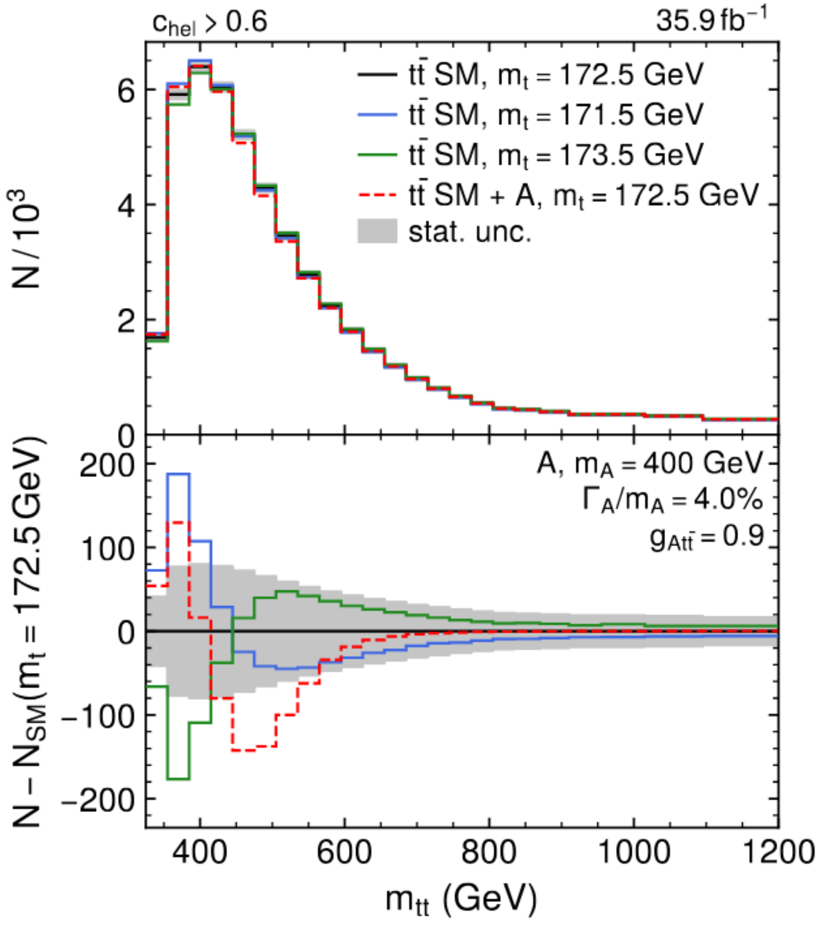
> Reweighting from NLO Powheg+Pythia to NNLO-QCD+NLO-EW

> 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

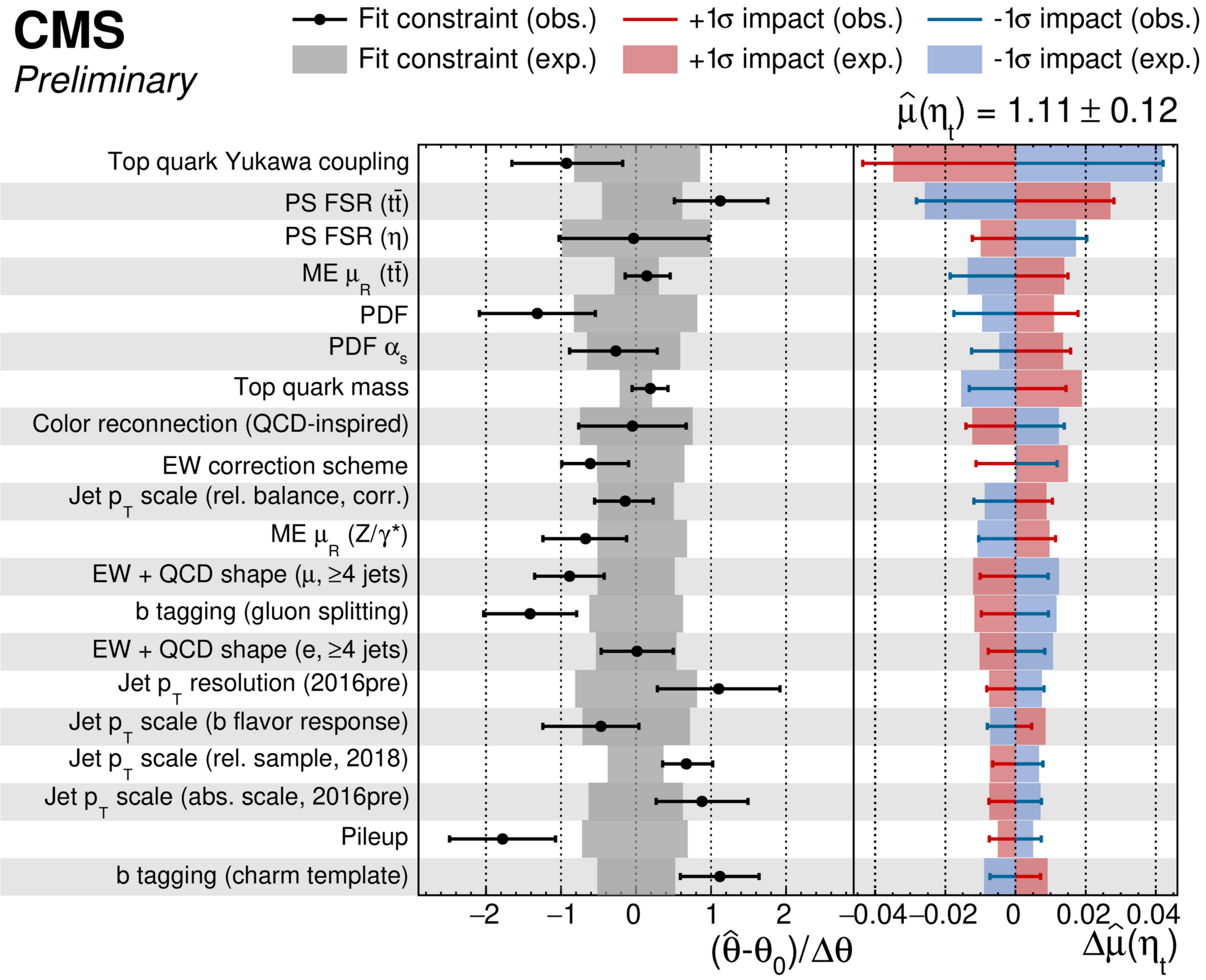
- Not included in ATLAS model, not provided by Mitov et al.
- Leading for CMS

> 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} ?

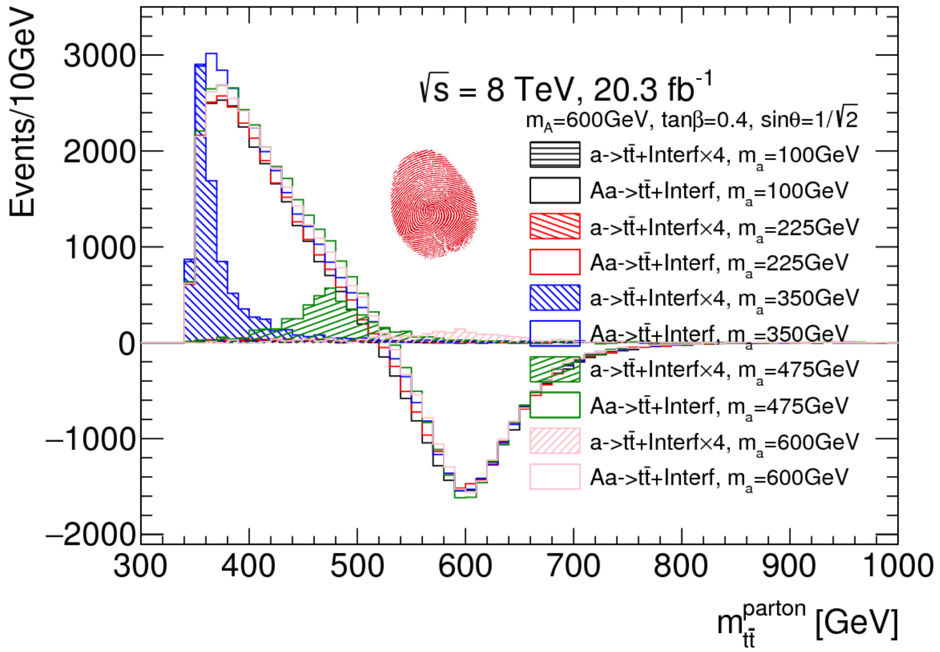


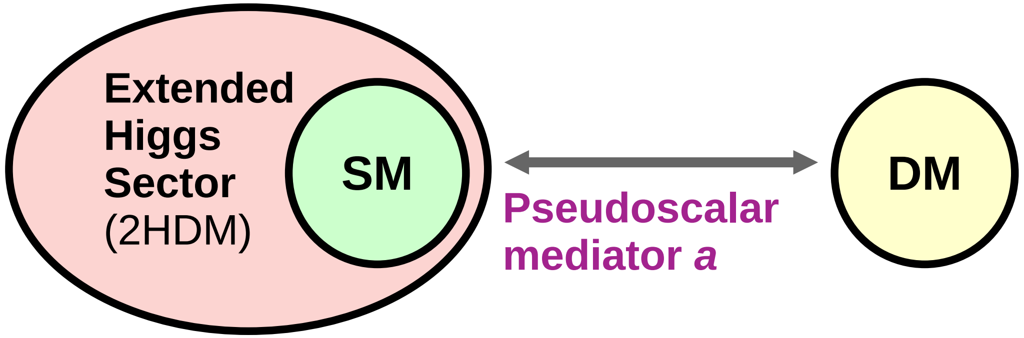
Dark matter interpretations: 2HDM+a

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





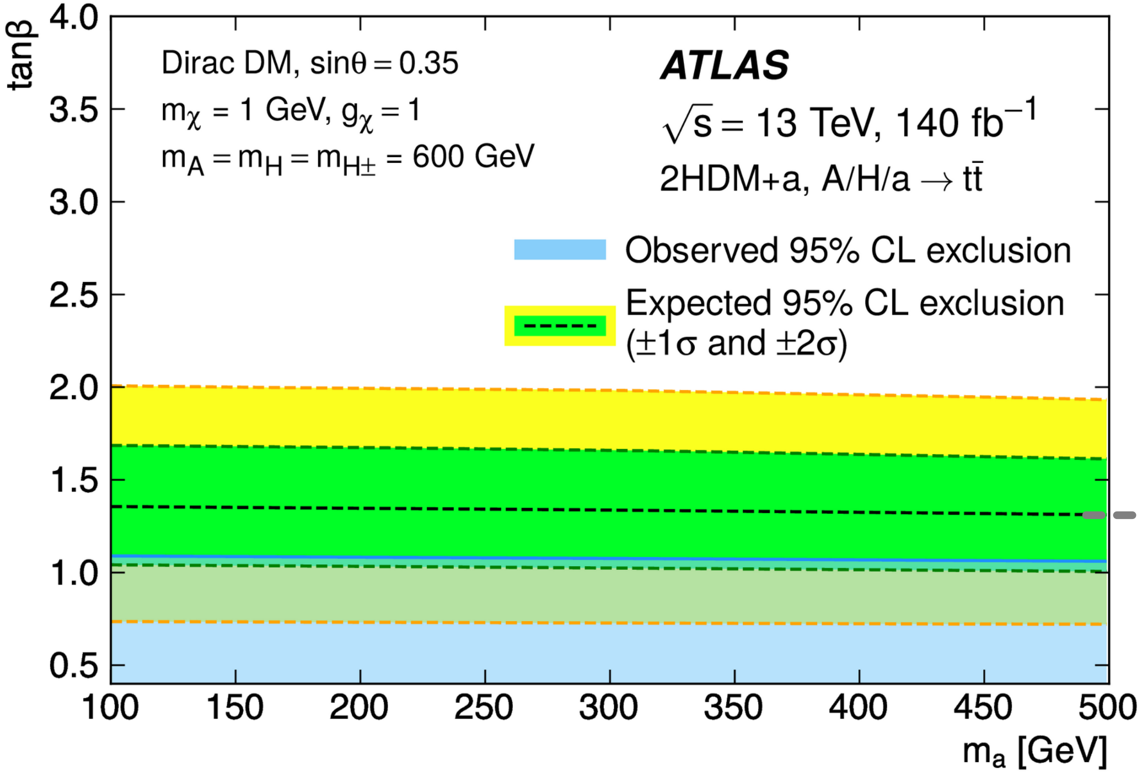
LHC Dark Matter Working Group: Phys. Dark Univ. 27 (2020) 100351

Bauer, Haisch, Kahlhoefer: JHEP05(2017) 138

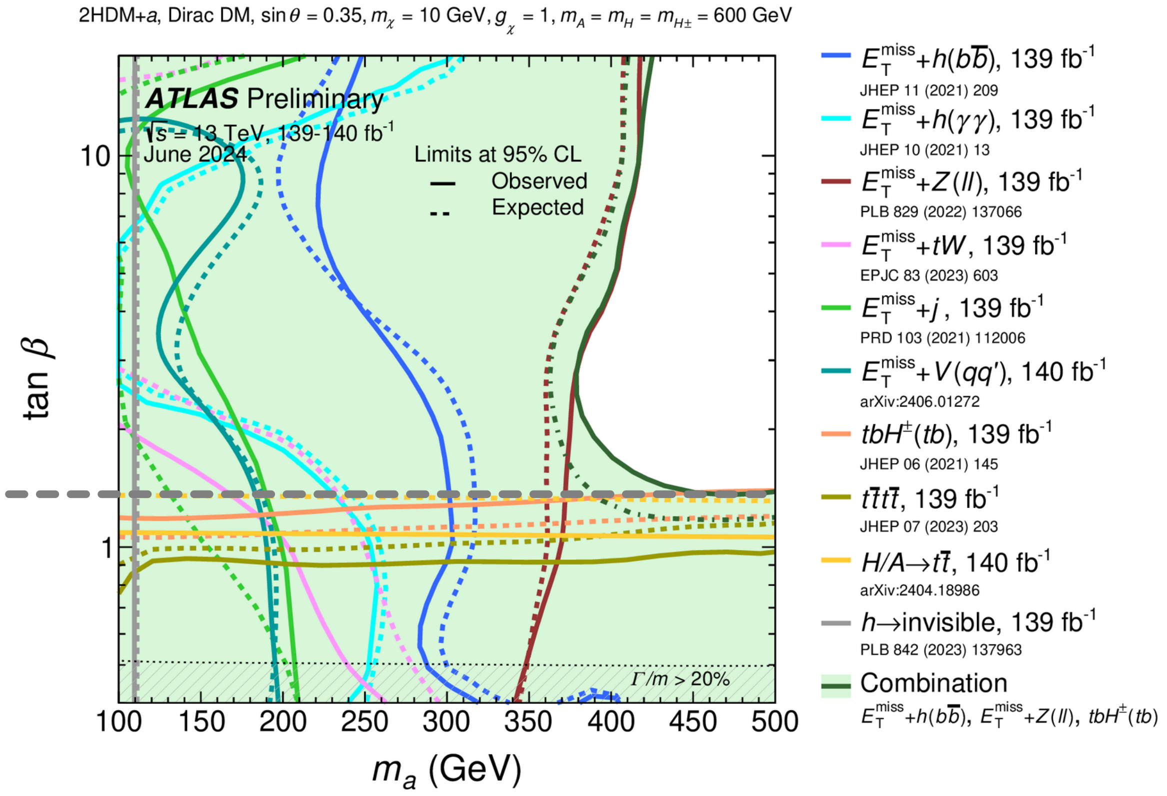
Dark matter interpretations: 2HDM+a

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

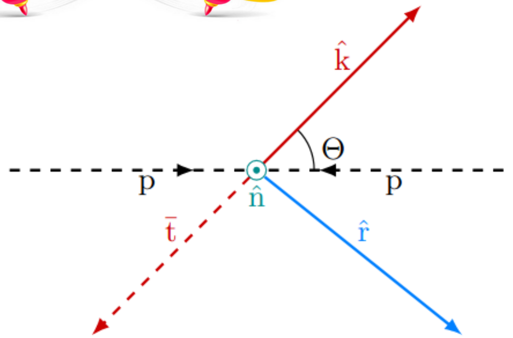


Key differences with ATLAS

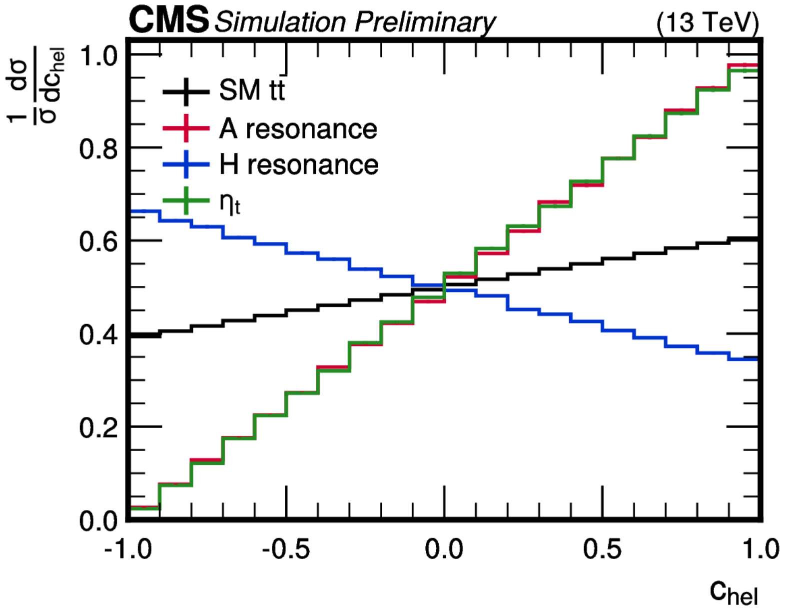
> Spin correlation variables sensitive to degree of entanglement in 2L channel

- 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