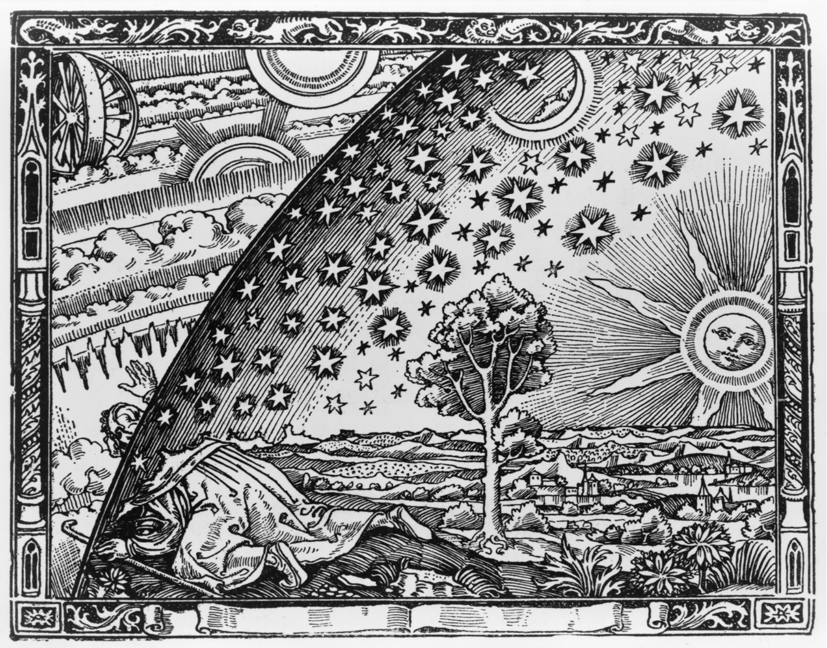
To the Higgs and beyond

Quantum Universe Days
17 – 19 February 2025



Katharina Behr

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

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

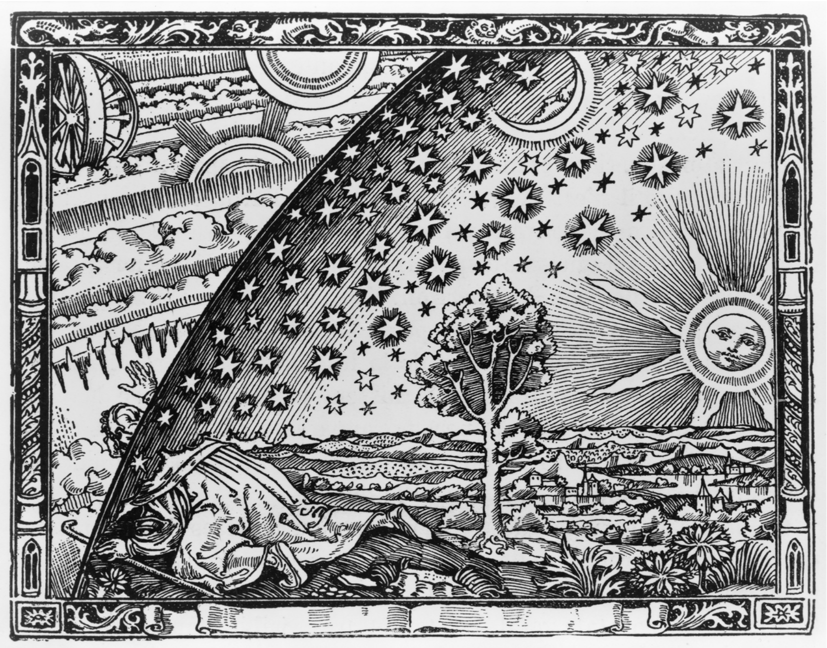
h

- **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

h h

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

h H^+ H H^- A



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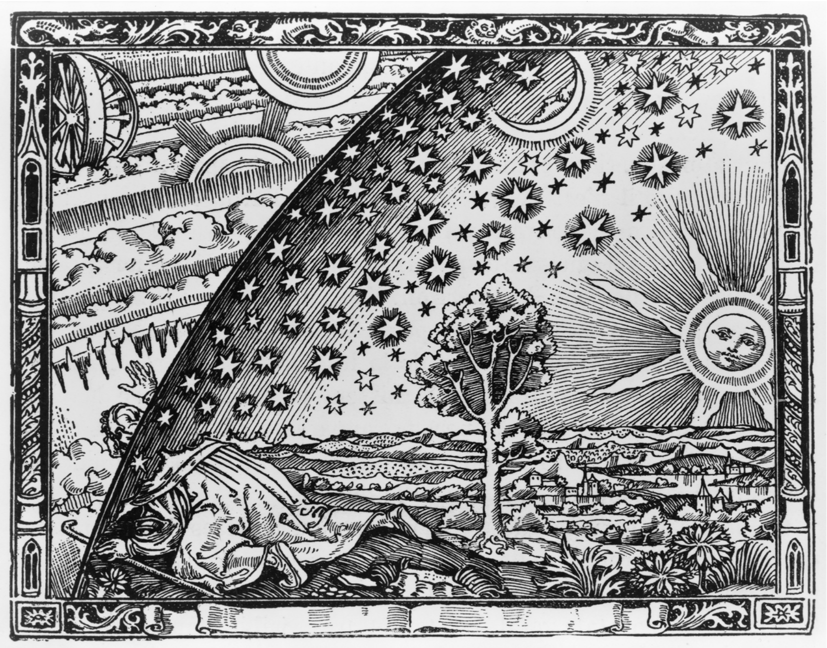

Many questions, many possible answers!

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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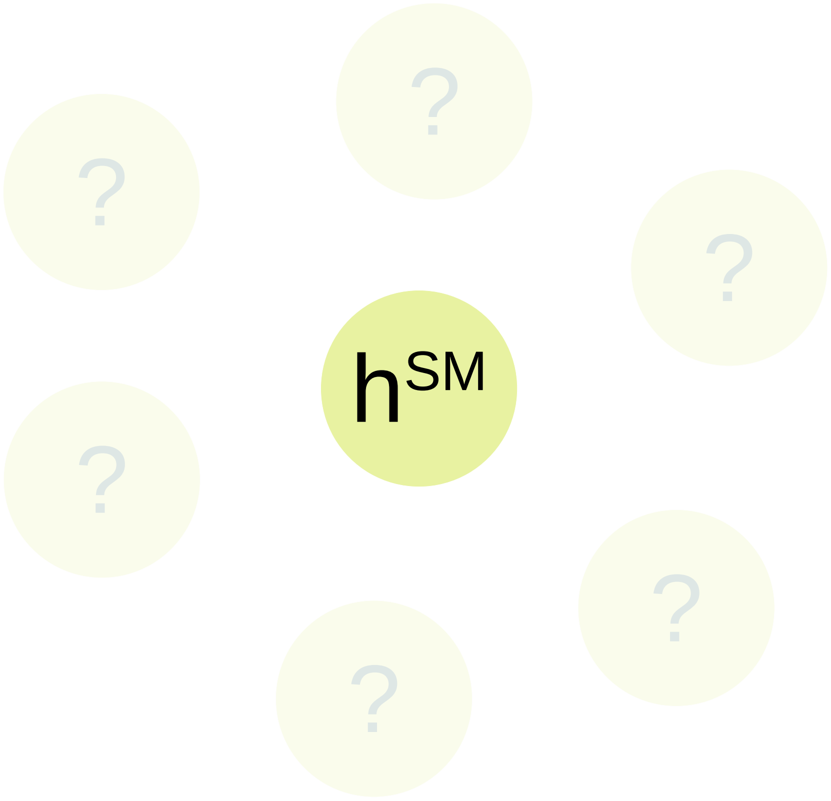
Why look for more Higgs bosons?

- 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

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

  - BSM model with multiple Higgs doublets:

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

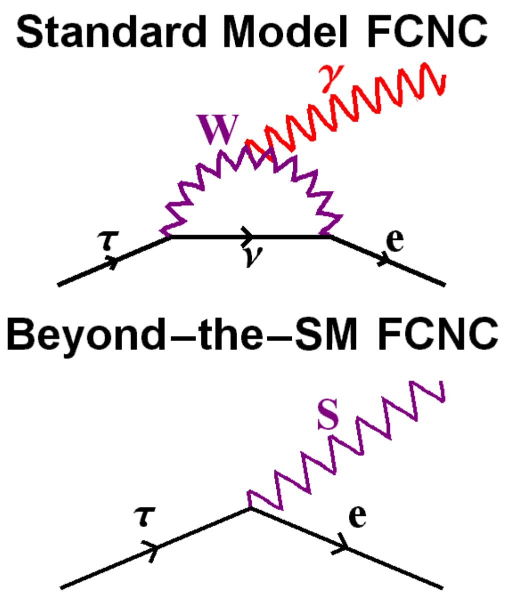
  - For example: *SU(2)* doublets with Y = ± 1
    - Yields ρ = 1!

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

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

$$\boxed{V_L V_L \to V_L V_L}$$

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]

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

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\end{aligned}
$$

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

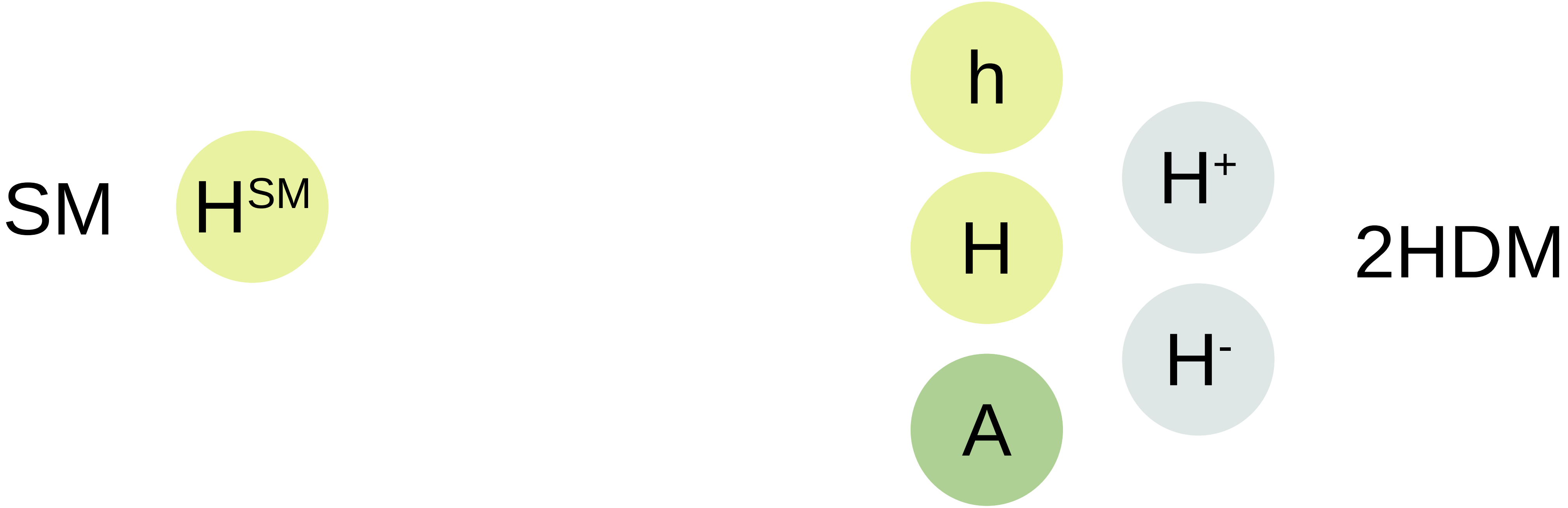
$$
\langle \Phi_1 \rangle = \begin{pmatrix} 0 \\ \frac{v_1}{\sqrt{2}} \end{pmatrix} \quad \text{and} \quad \langle \Phi_2 \rangle = \begin{pmatrix} 0 \\ \frac{v_2}{\sqrt{2}} \end{pmatrix}
$$

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}

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

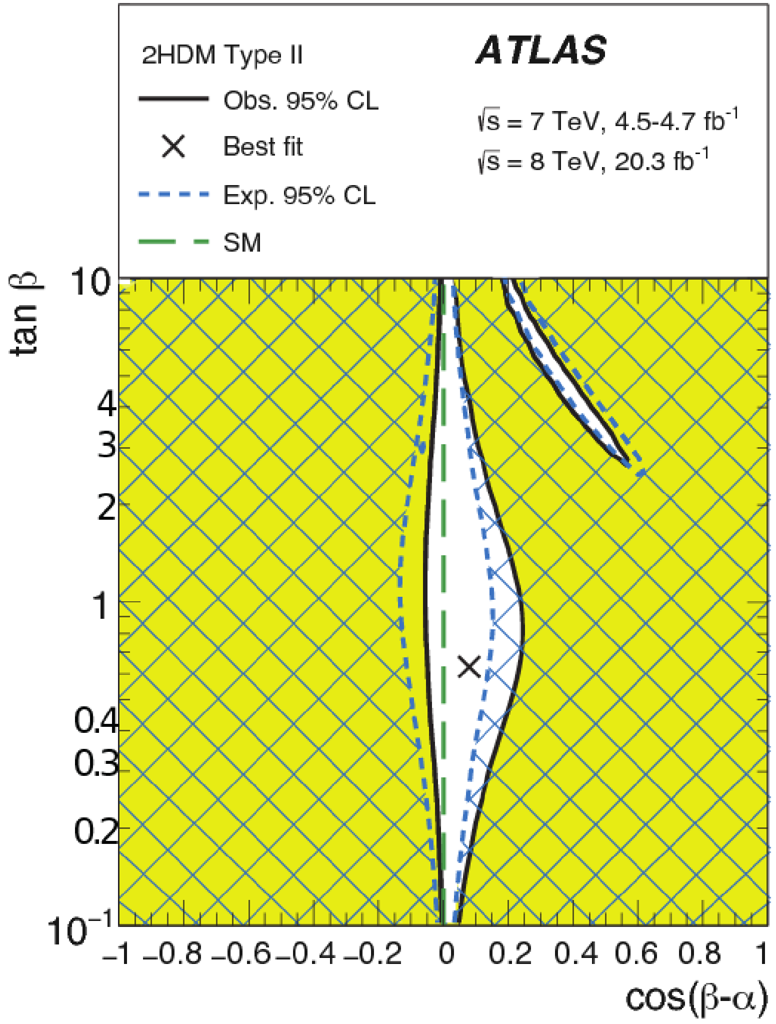
H-h mixing angle

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
  – See Monday's lecture
> Alignment limit $\cos(\beta-\alpha) = 0$ favoured
  – Assume lighter scalar h is the 125 GeV boson 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:

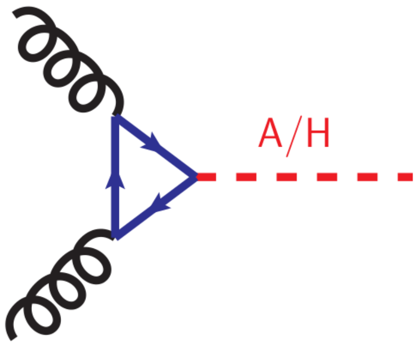
Model	Up quarks	Down quarks	Leptons
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

SUSY models

- Type-II 2HDM:
  - Up quark coupling ~ $1/\tan\beta$
  - Down quark / lepton coupling: $\tan\beta$

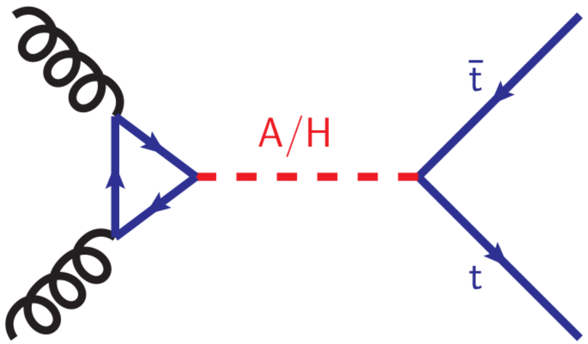
Searching for extra neutral Higgs bosons

- Dominant production: loop induced gluon fusion



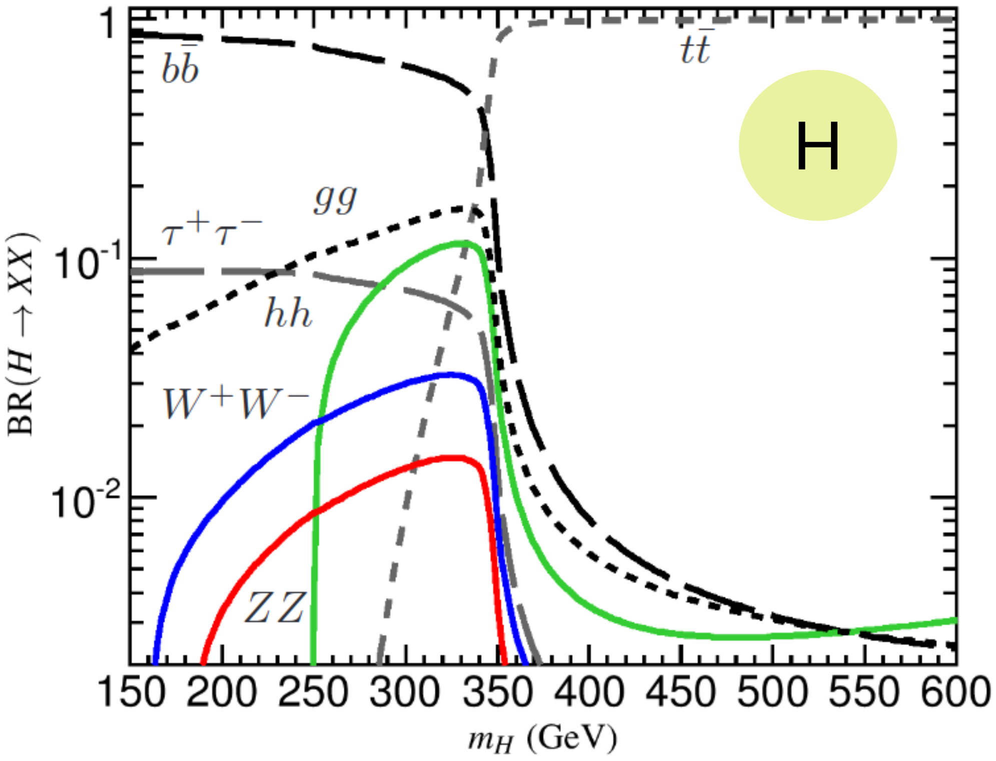
Searching for extra neutral Higgs bosons

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



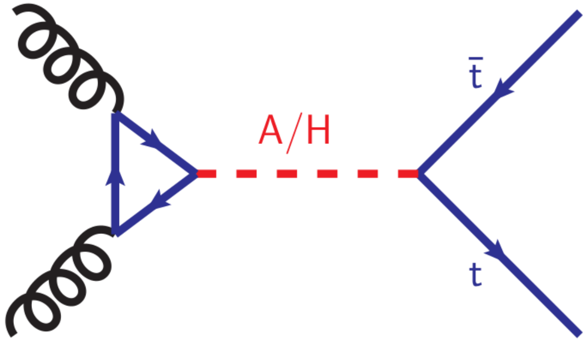
g_{up} ~ 1/tanβ
$g_{dw,lep}$ ~ tanβ

tanβ = 1.5, cos(β-α) = 0.01



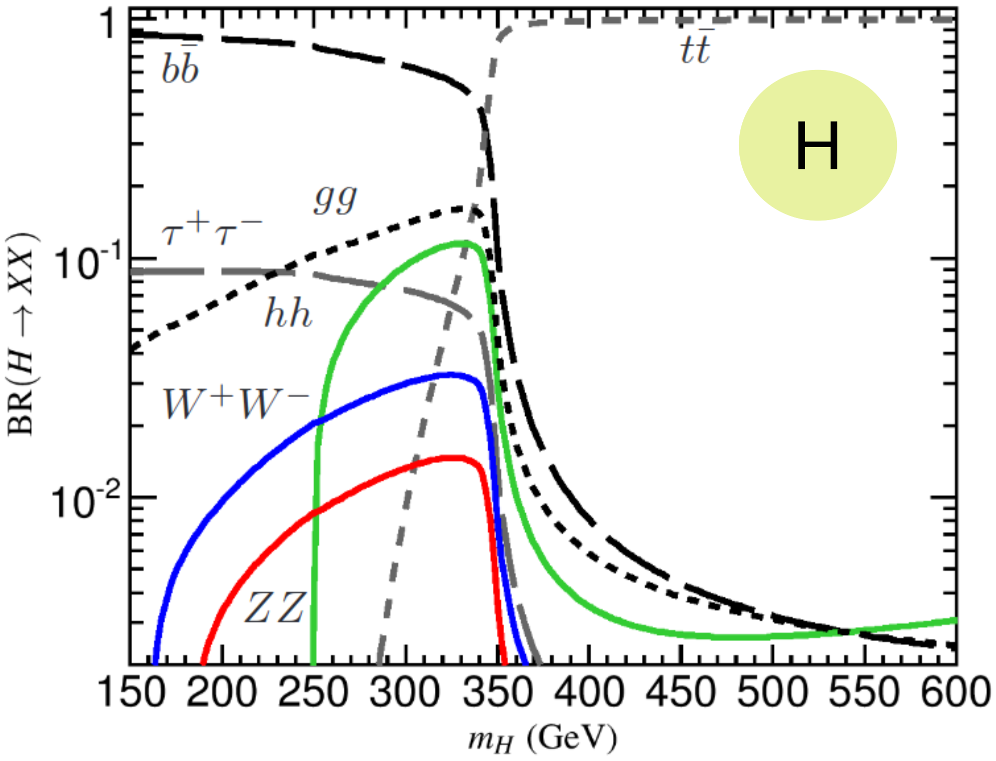
Searching for extra neutral Higgs bosons

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

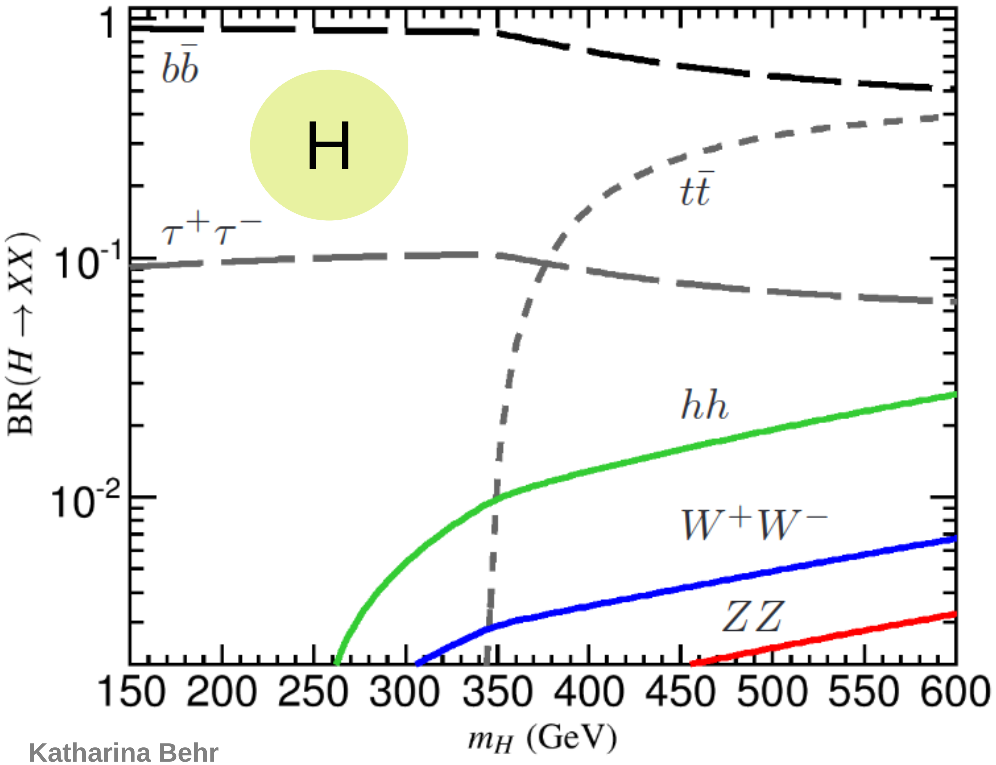


$g_{up} \sim 1/\tan\beta$
$g_{dw,lep} \sim \tan\beta$

tanβ = 1.5, cos(β-α) = 0.01



tanβ = 7, cos(β-α) = 0.01

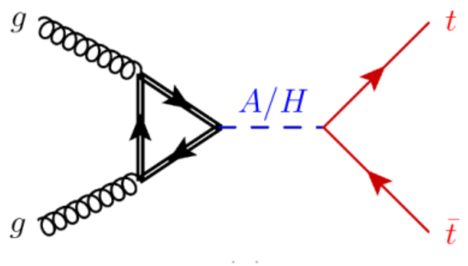


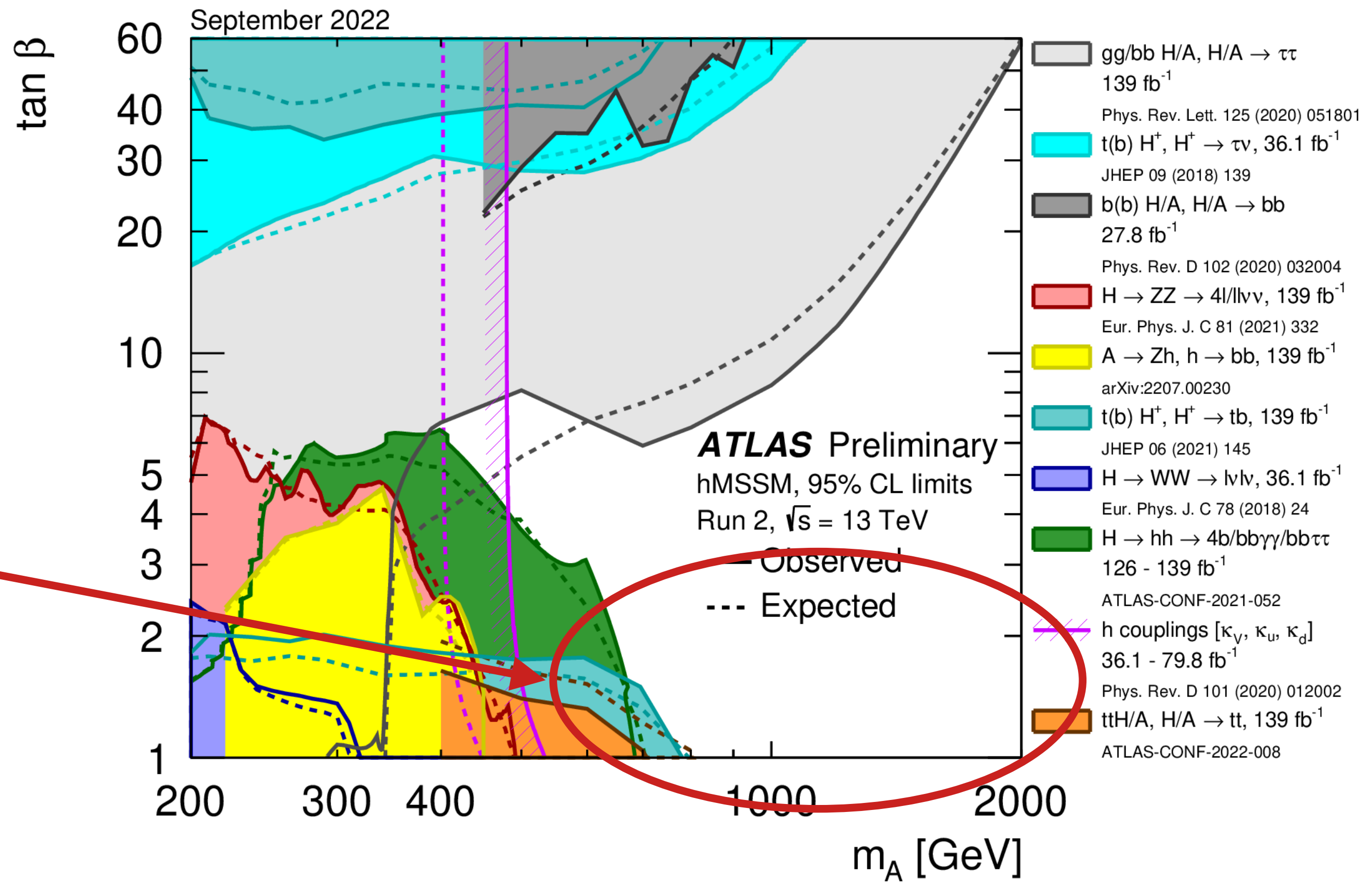
Example: hMSSM

- 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 $\tan\beta$:

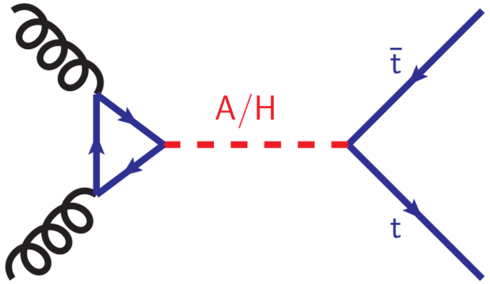
Preferential A/H coupling to ttbar!





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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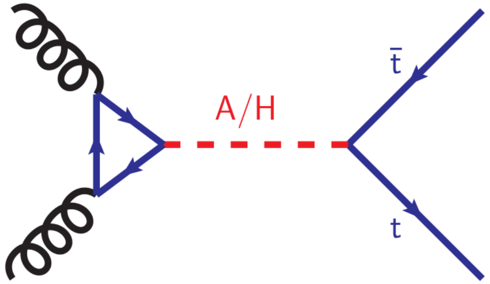

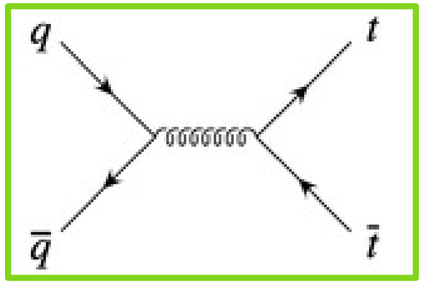

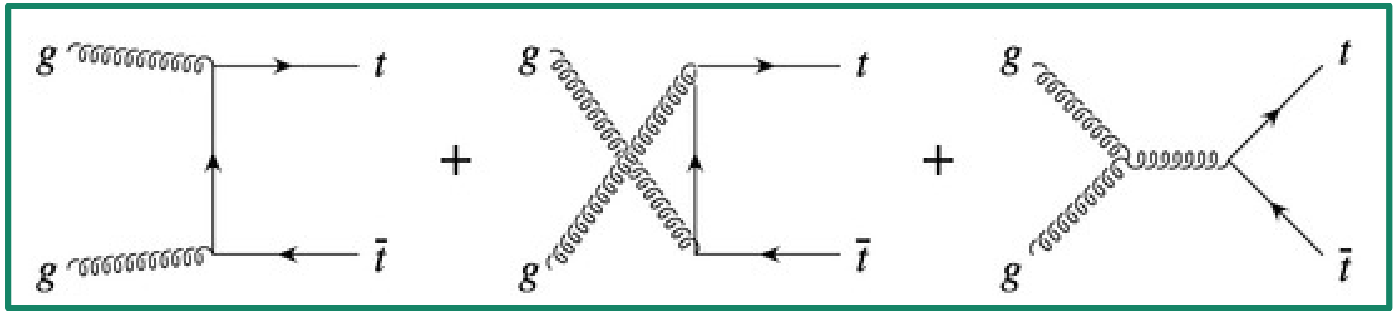

80% gg-initiated
20% qq-initiated

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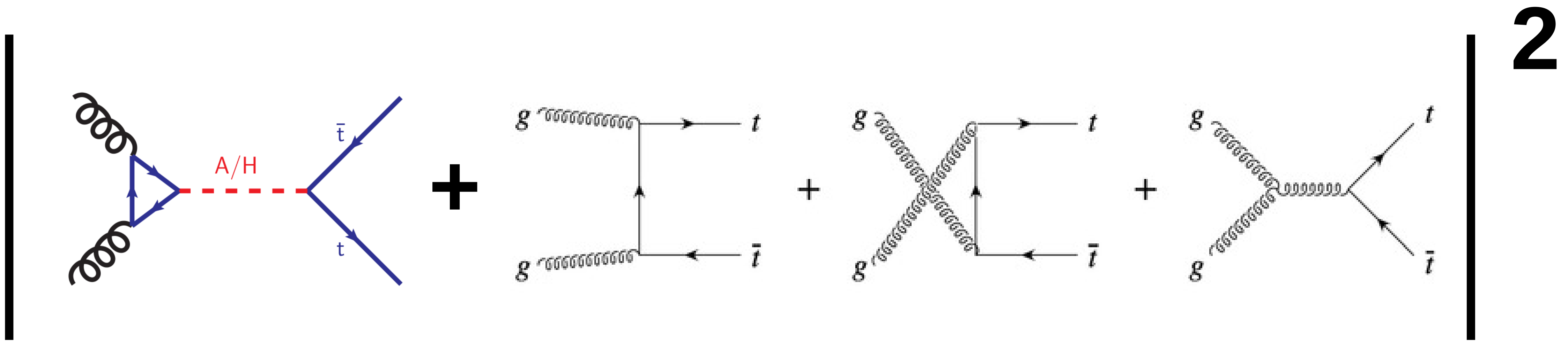
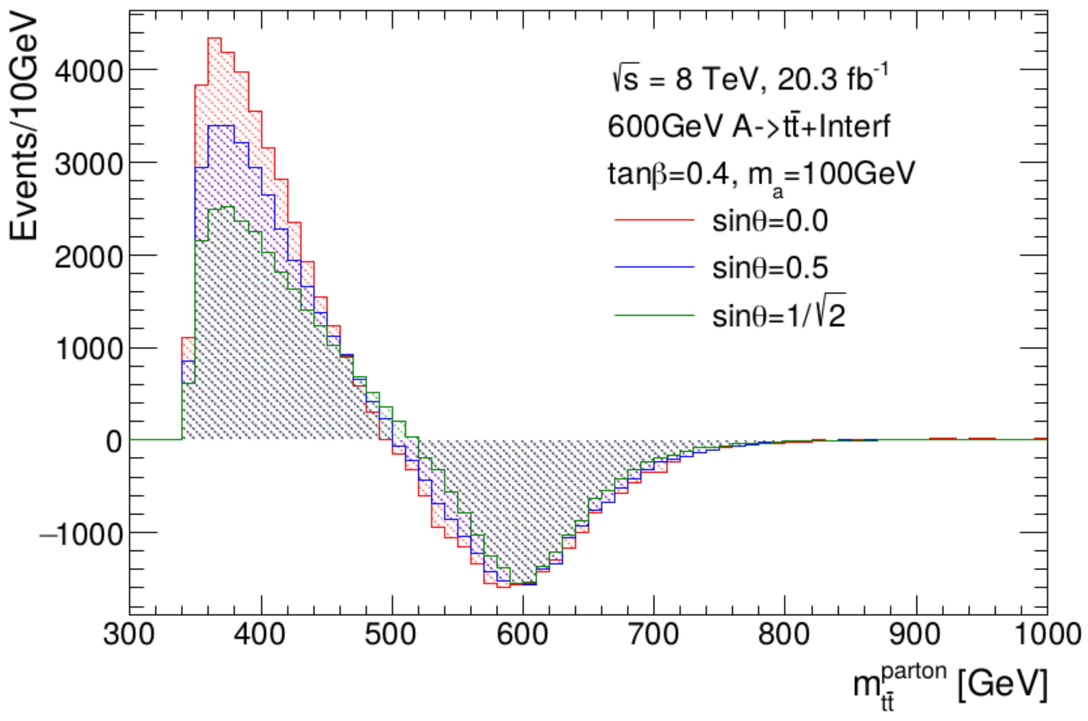


The challenge: interference

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



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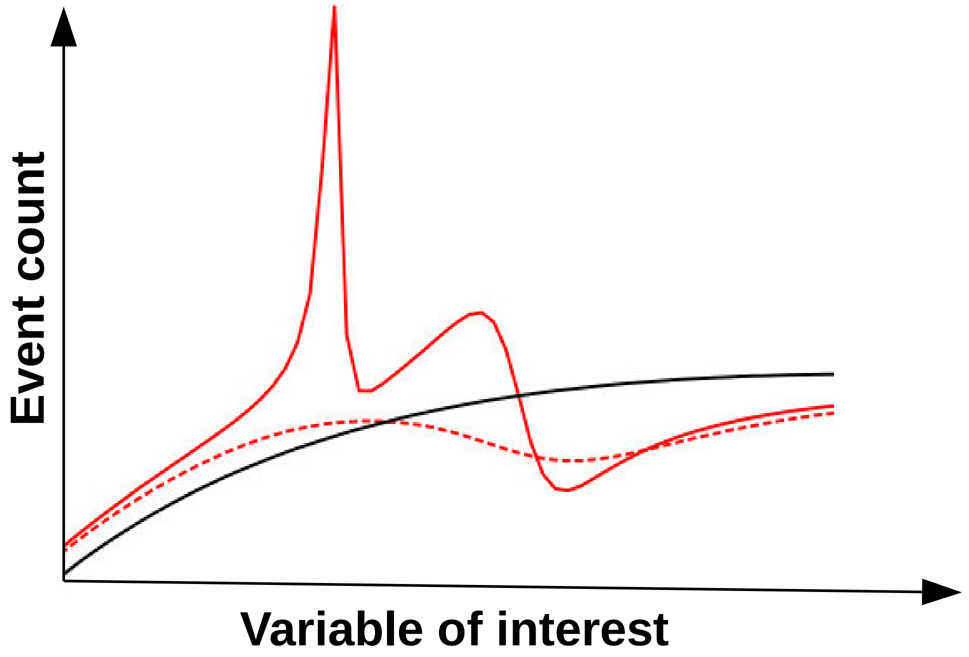

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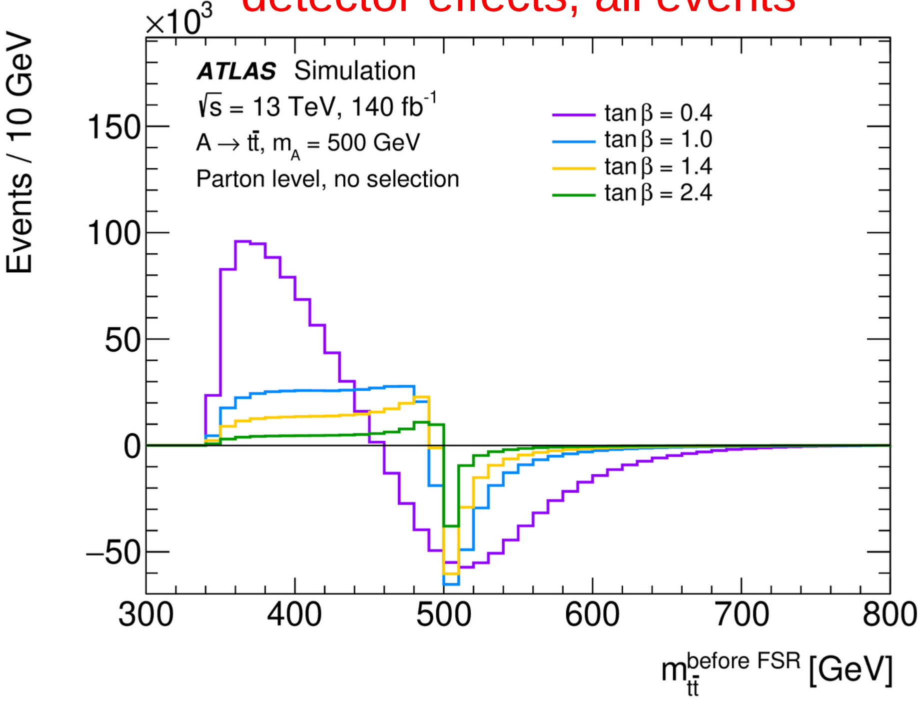
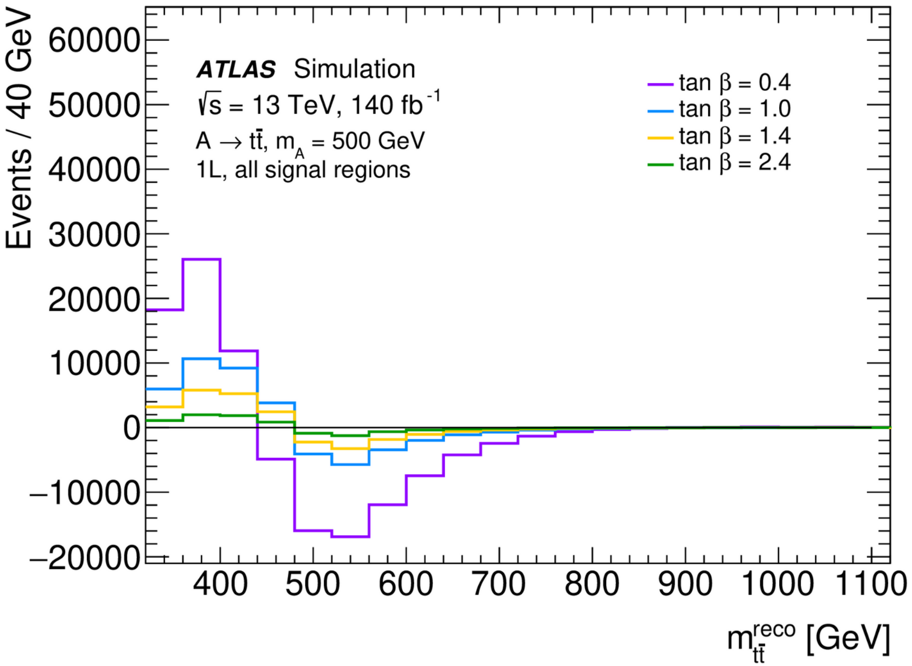
  - Very complex patterns, especially if there is more than one new particle
  - Detector effects “wash out” details of pattern

Simulated pattern without detector effects, all events

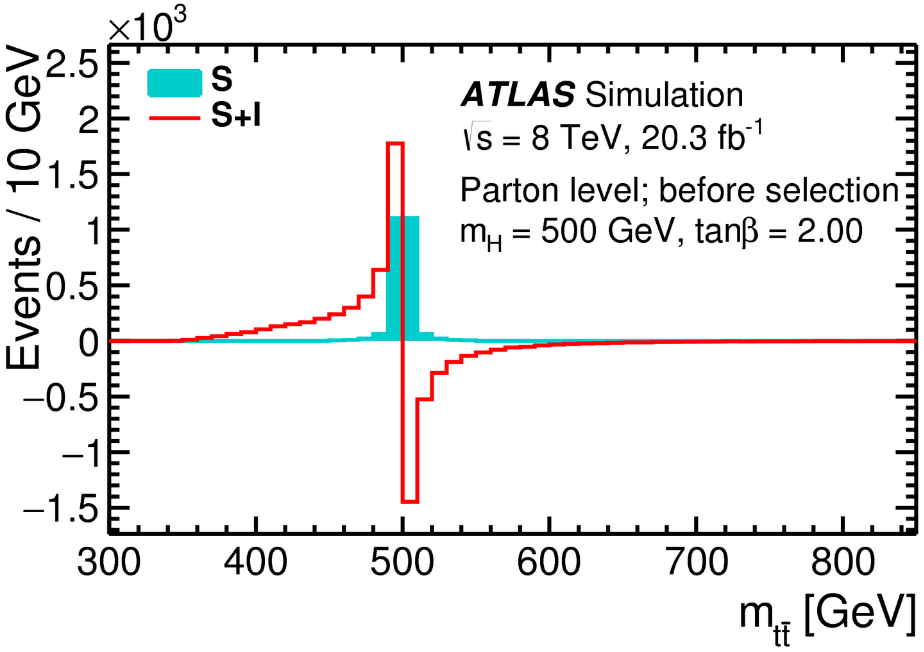


Simulated pattern with detector effects, signal region



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
  - ...

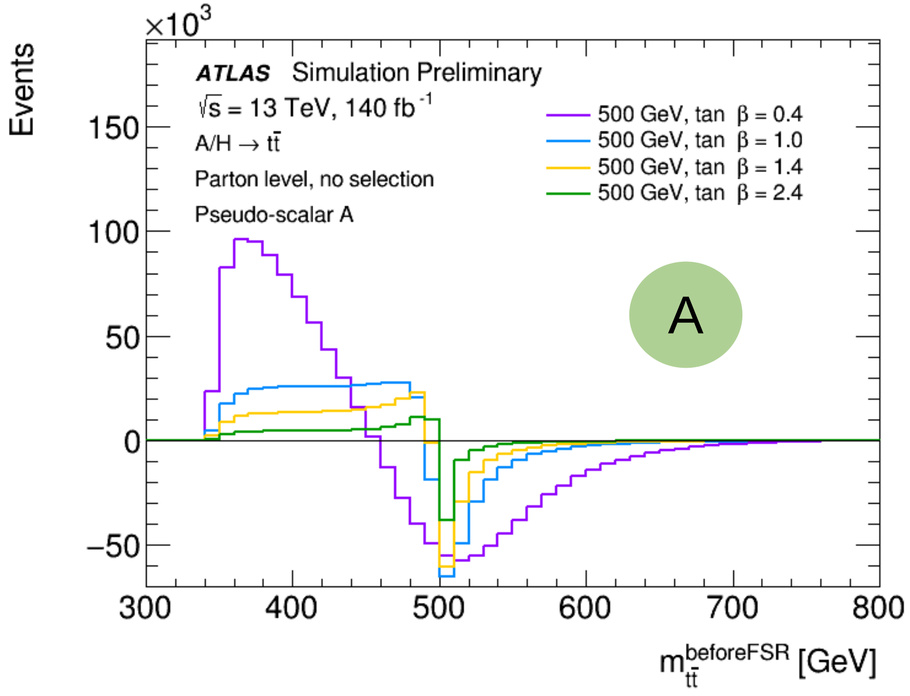


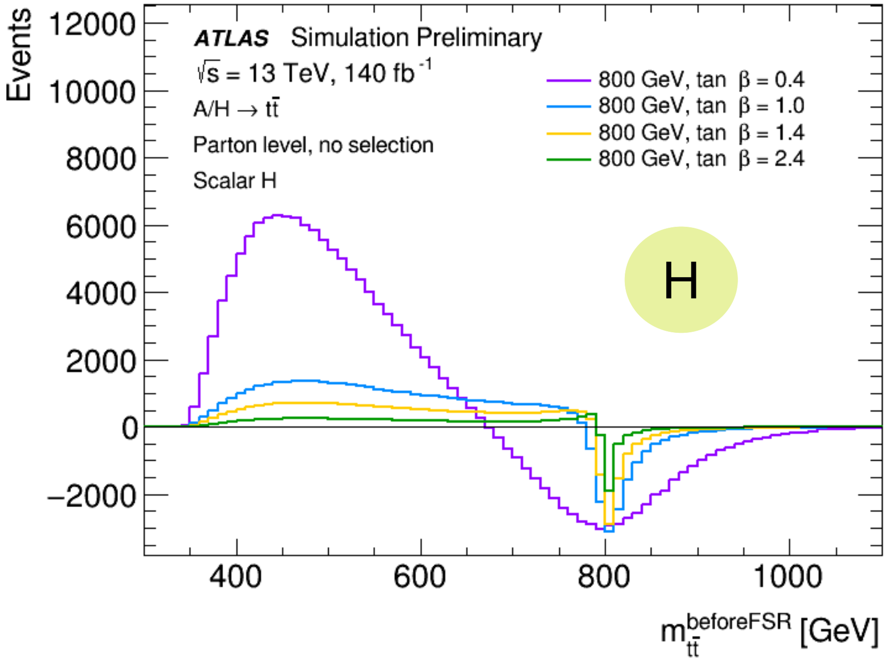
The advantage: interference

JHEP 08 (2024) 013

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

→ Fingerprint that carries information about particle properties





Larger tanβ

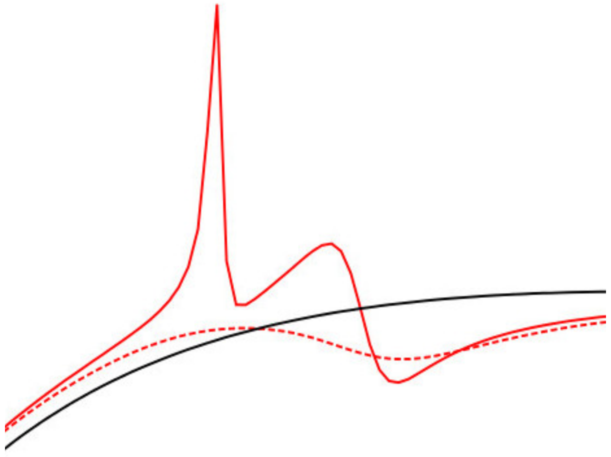
↓

Smaller total width

↓

Narrower pattern

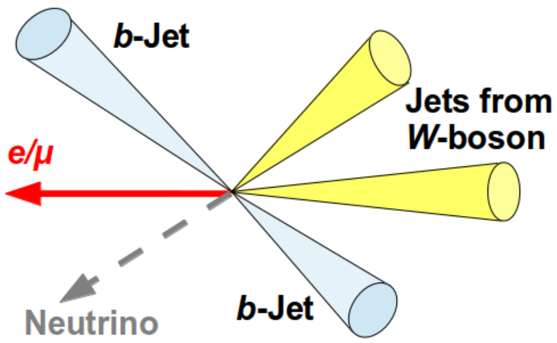
ATLAS result: JHEP 08 (2024) 013



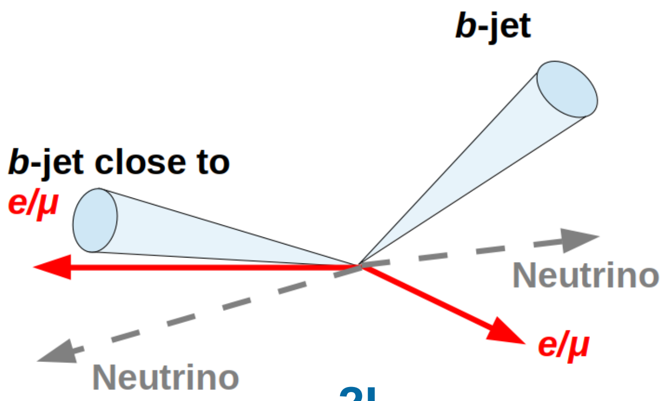
Search strategy (ATLAS)

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

$\boxed{t \to Wb}$



1L Resolved



2L

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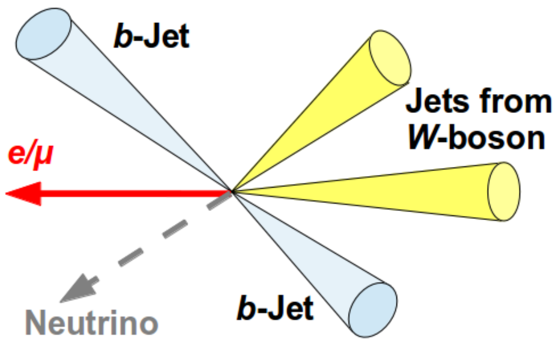

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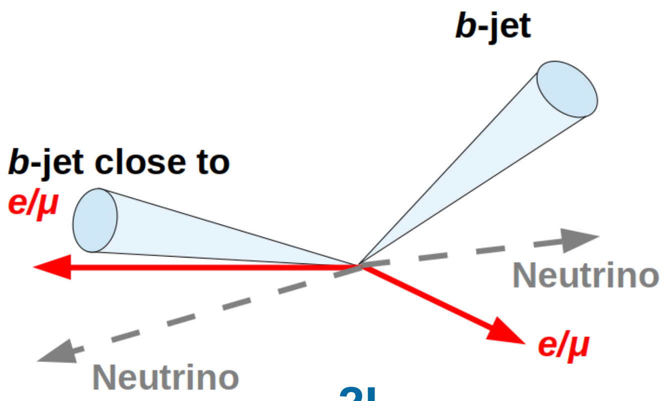

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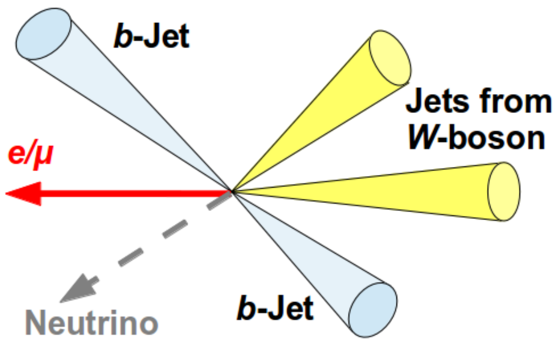
  - Resolved: small-*R* jets assigned via χ^2 algorithm, ==1 or ≥ 2 *b*-tagged



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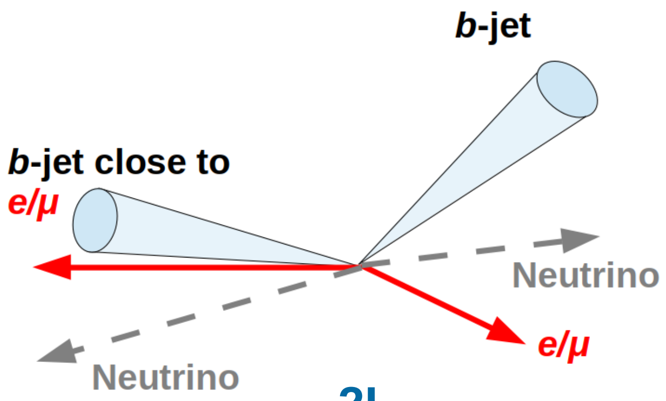

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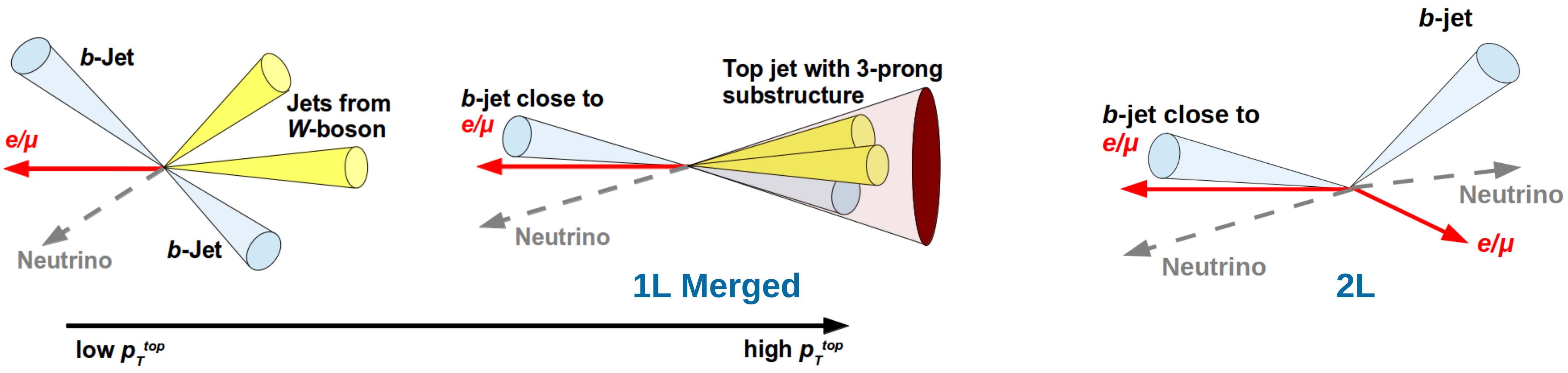
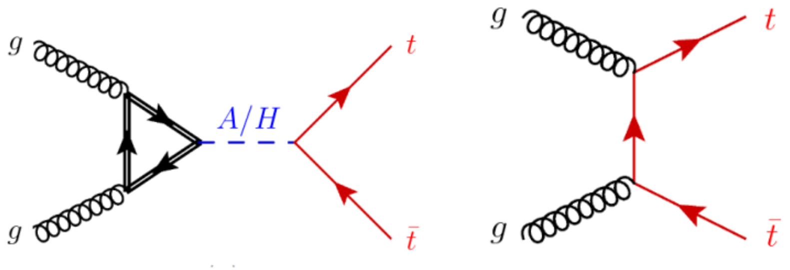
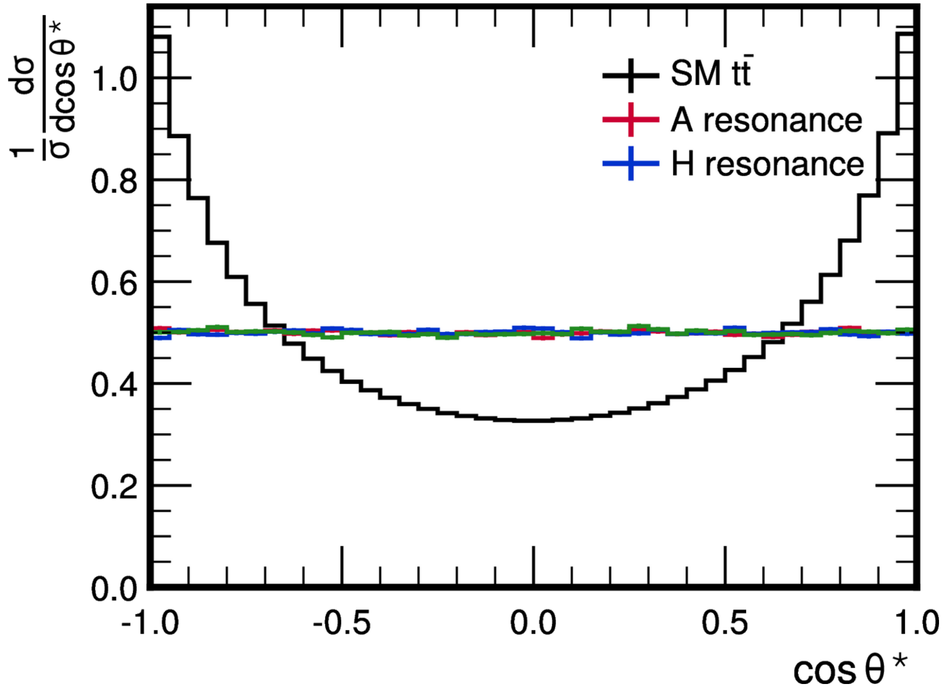
  - Resolved: small-*R* jets assigned via χ^2 algorithm, ==1 or ≥ 2 *b*-tagged
  - Merged: large-*R* jet to reconstruct hadronic top-quark decay

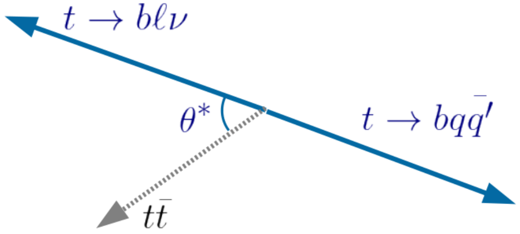


It’s all about spins!

- 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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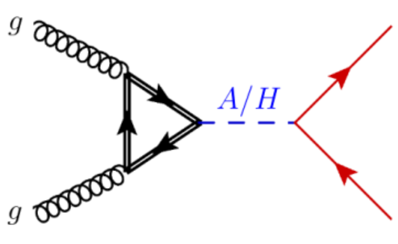

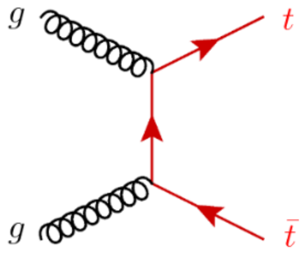

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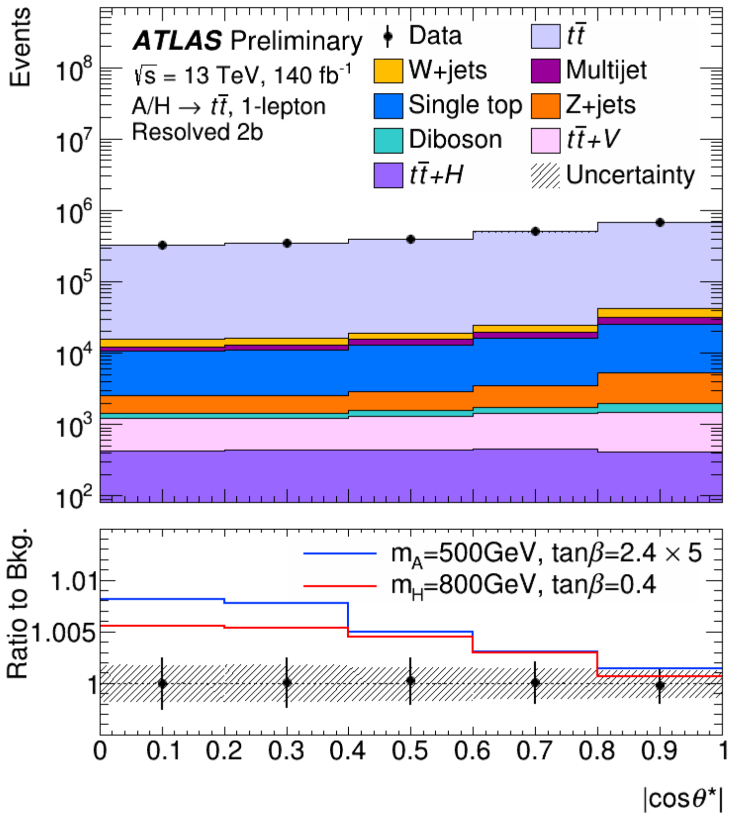

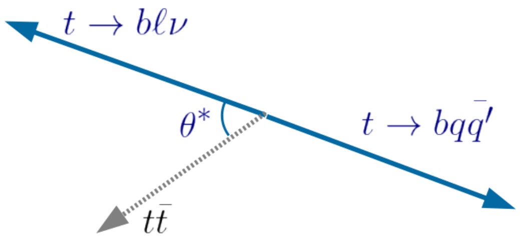

It's all about spins!

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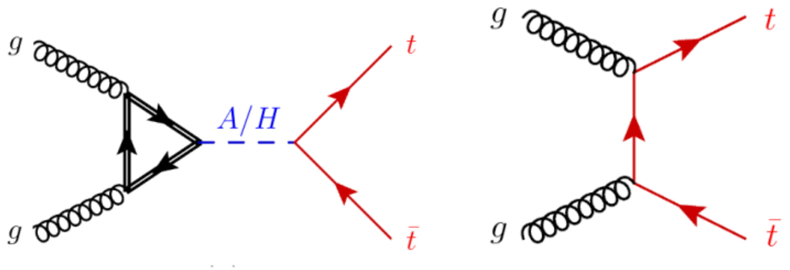
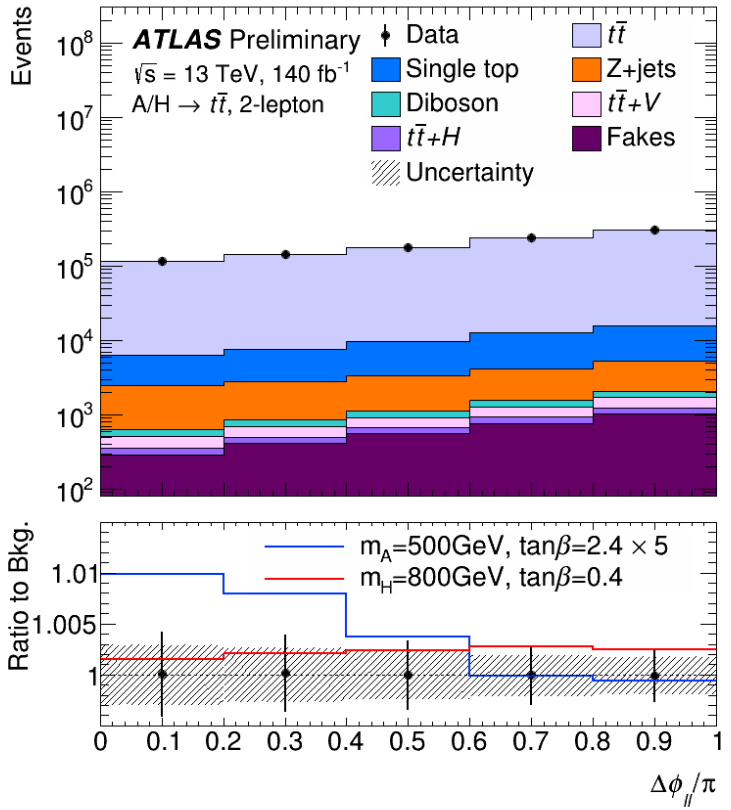
> Signal: s-channel production in pure spin-singlet state (isotropy!)

> Background: a mixture of production modes and spin states

> Angular variables to distinguish between signal and background



2L

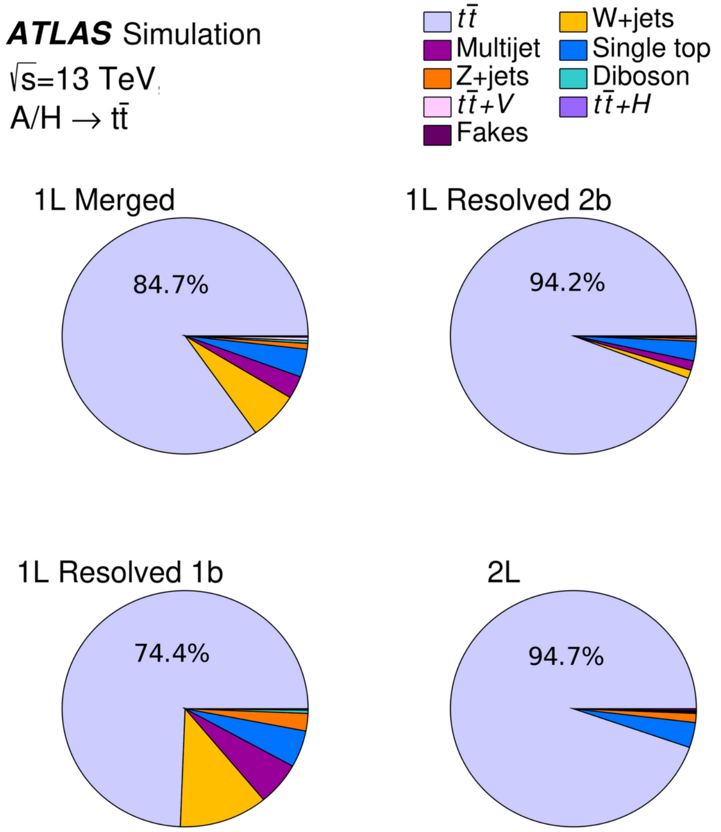


Azimuthal angle between leptons from tops
→ additional discrimination between A and H!

Background processes

> Dominant and irreducible background from SM ttbar production

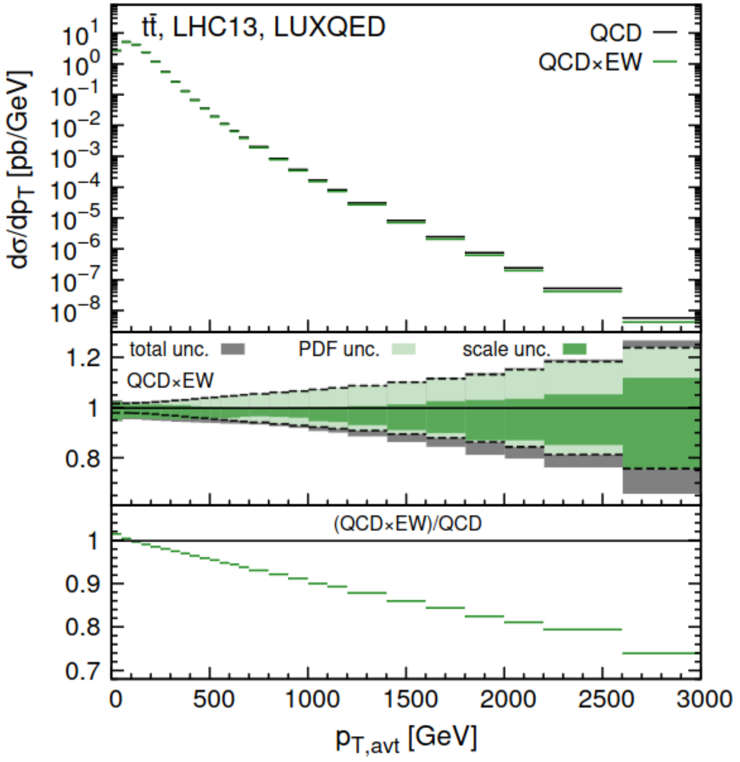
16 signal regions after angular binning
(regions shown here not split into angular bins for simplicity)

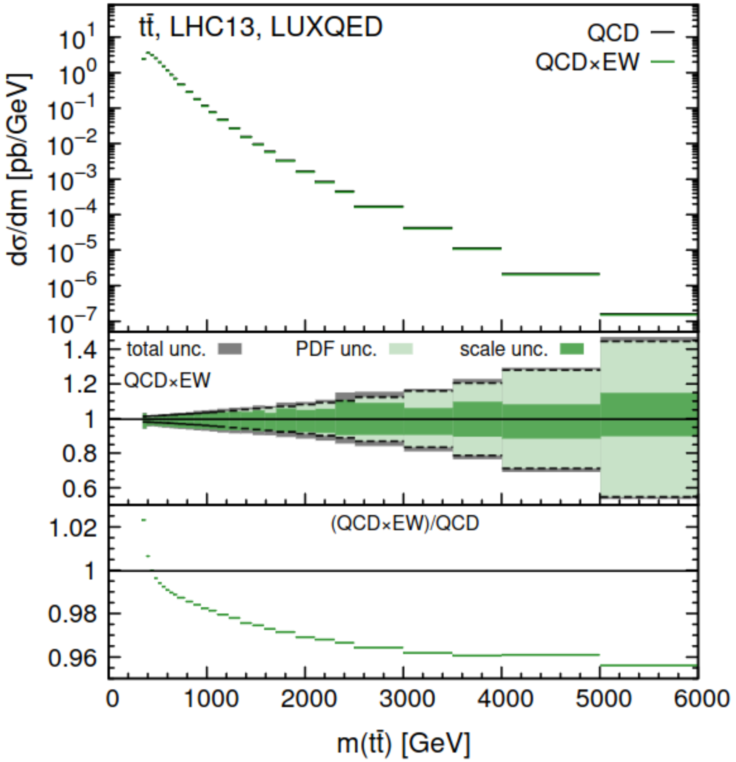


Background processes

> Dominant and irreducible background from SM ttbar production

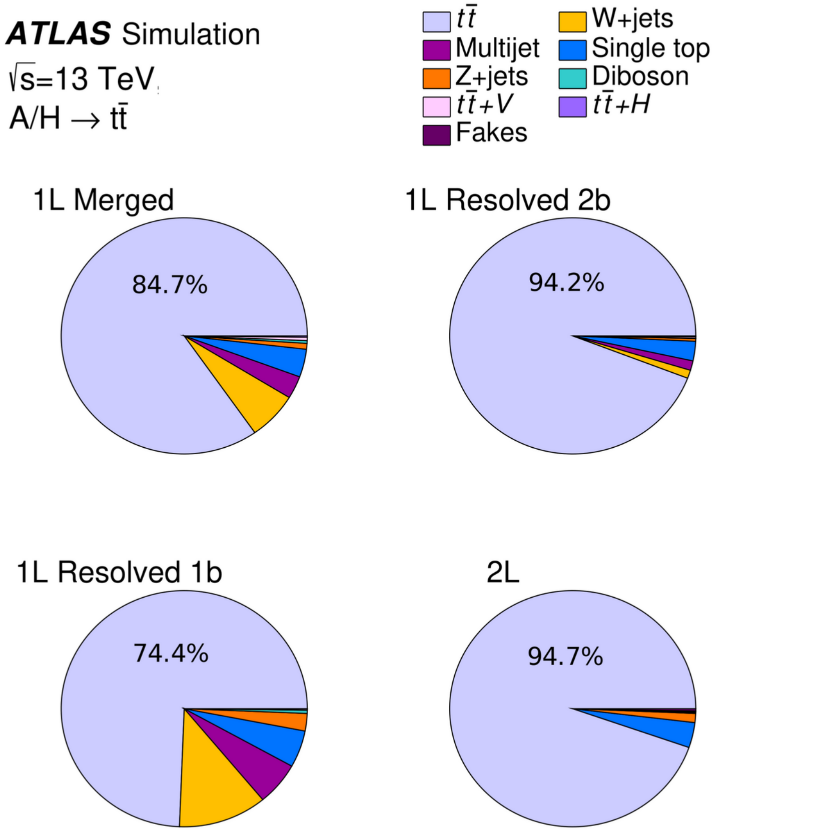
- Correct NLO Powheg+Pythia MC to NNLO-QCD+NLO-EW
- Via iterative reweighting in m(ttbar), p_T(t), p_T(tbar)





16 signal regions after angular binning

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



Statistical analysis without interference

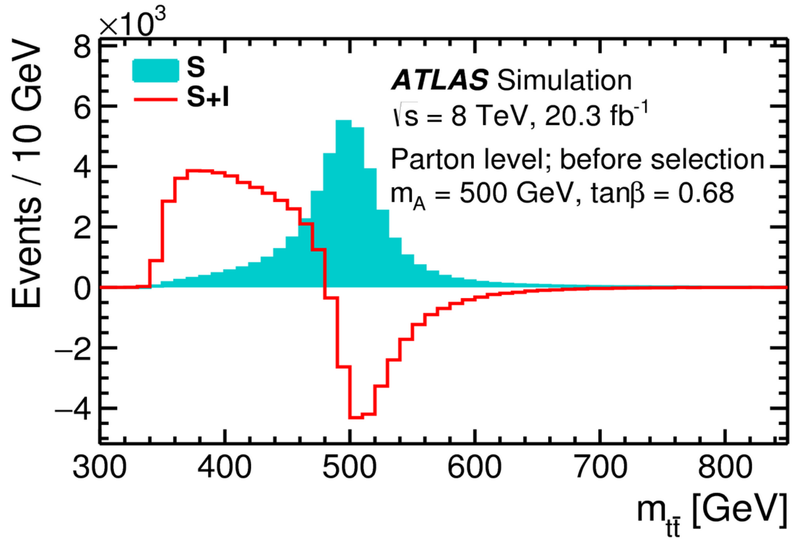
- Simple likelihood parameterisation in terms of signal strength

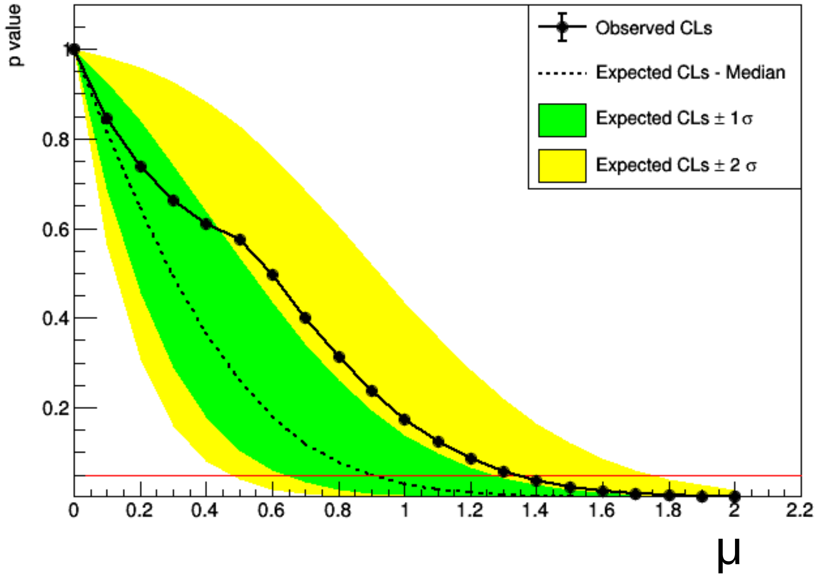
$$\boxed{\mu \cdot S \qquad\qquad + B}$$

- 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





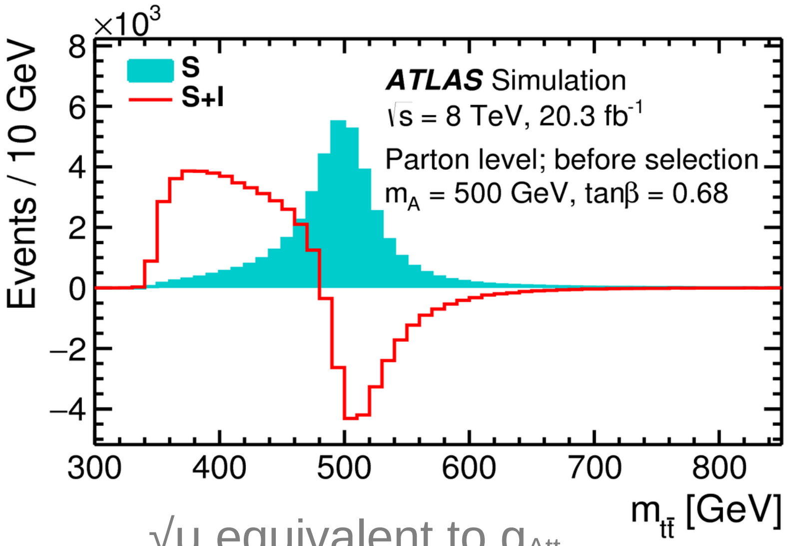
Statistical analysis with interference

> Extend likelihood to include interference term

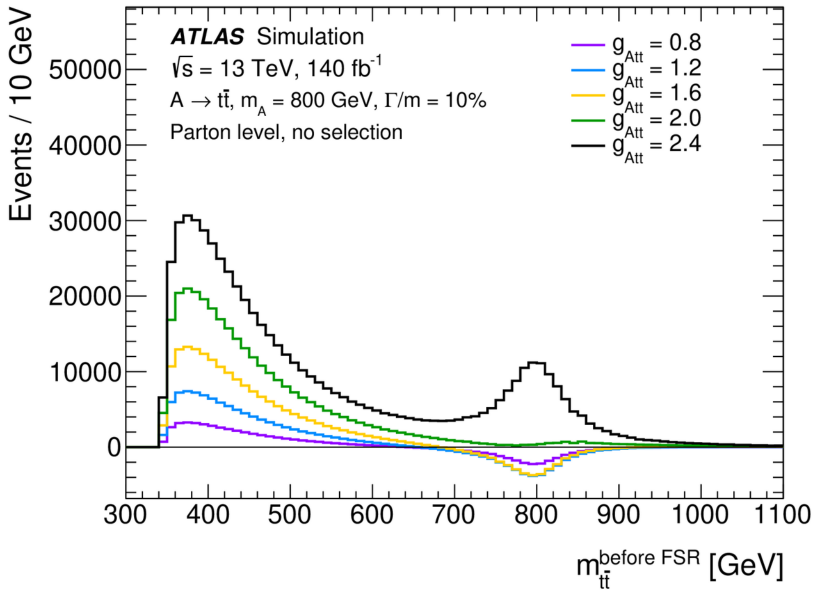
$$\mu \cdot S + \sqrt{\mu} \cdot I + B = (\mu - \sqrt{\mu}) \cdot \boxed{S} + \sqrt{\mu} \cdot \boxed{(S + I)} + B$$

> Quadratic dependence on POI = √μ

- Interference shape changes with POI



√μ equivalent to g_{Att}



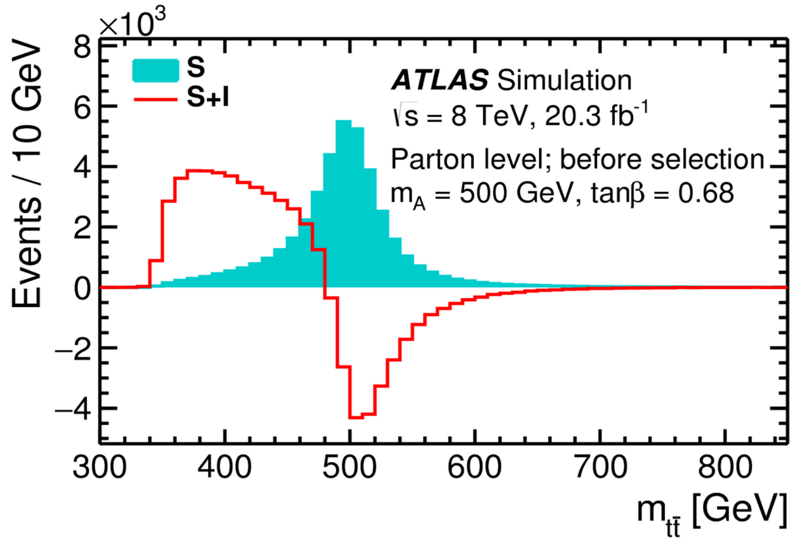
Statistical analysis with interference

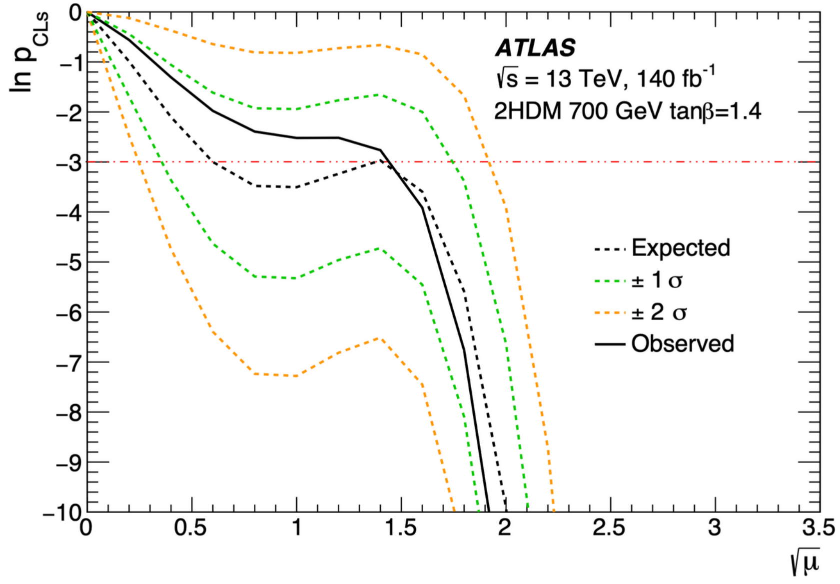
> Extend likelihood to include interference term

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

> Quadratic dependence on POI = √μ

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





Search stage

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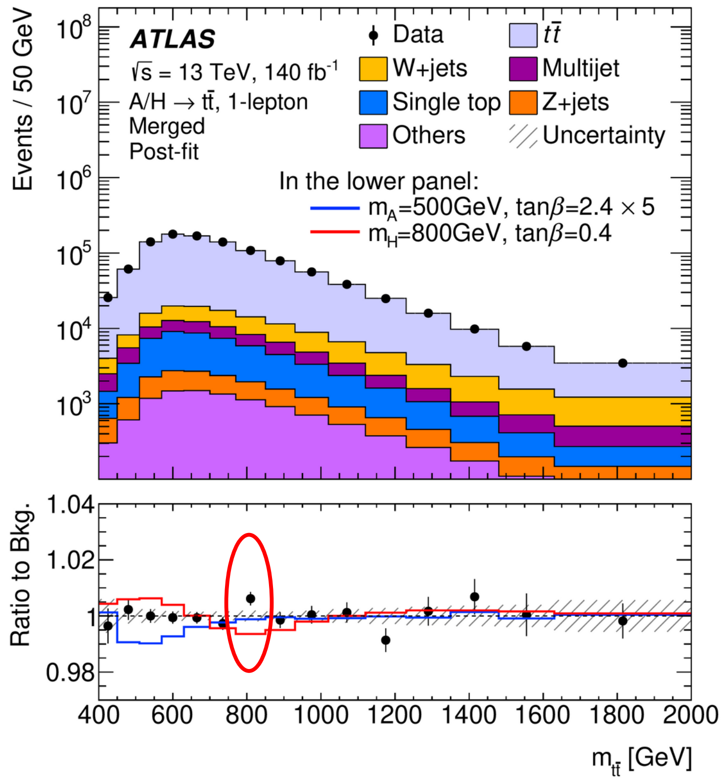
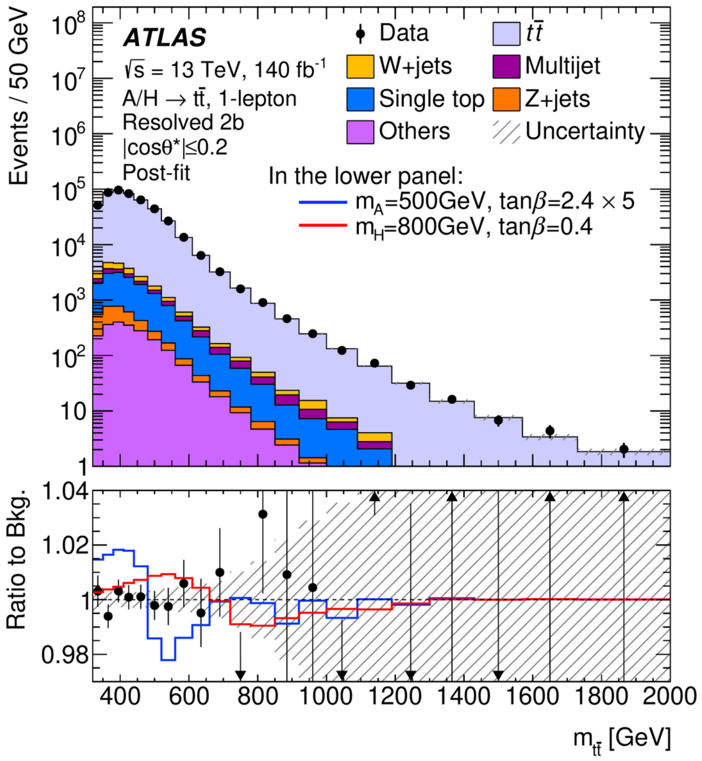
> Tested agreement between data and S+I+B hypotheses with masses [400,1400] GeV and widths [1,40]%

> Most significant deviation from SM-only (2.3σ local): m_A = 800 GeV, Γ_A/m_A = 10% and $\sqrt{\mu}$ = 4.0

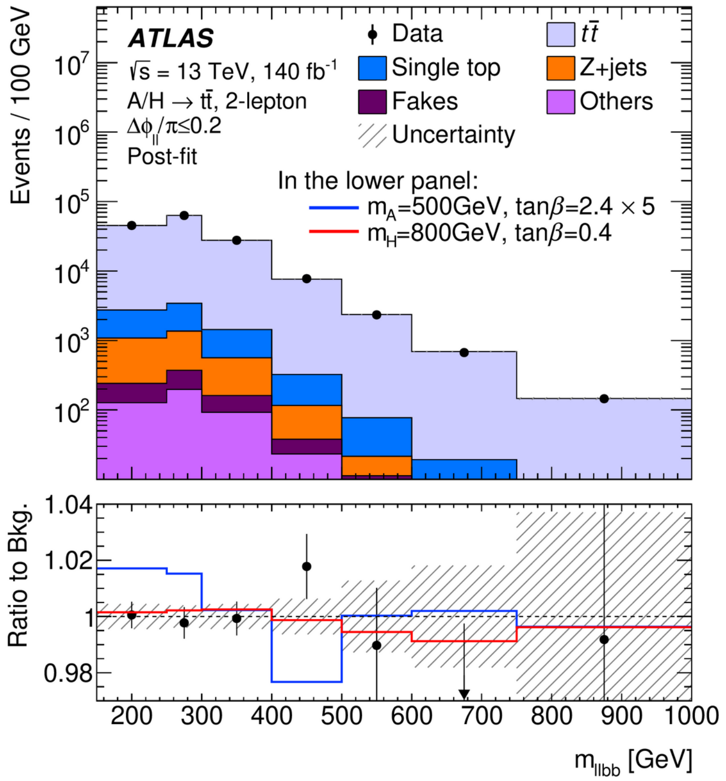
1L Merged



1L Resolved 2b



2L



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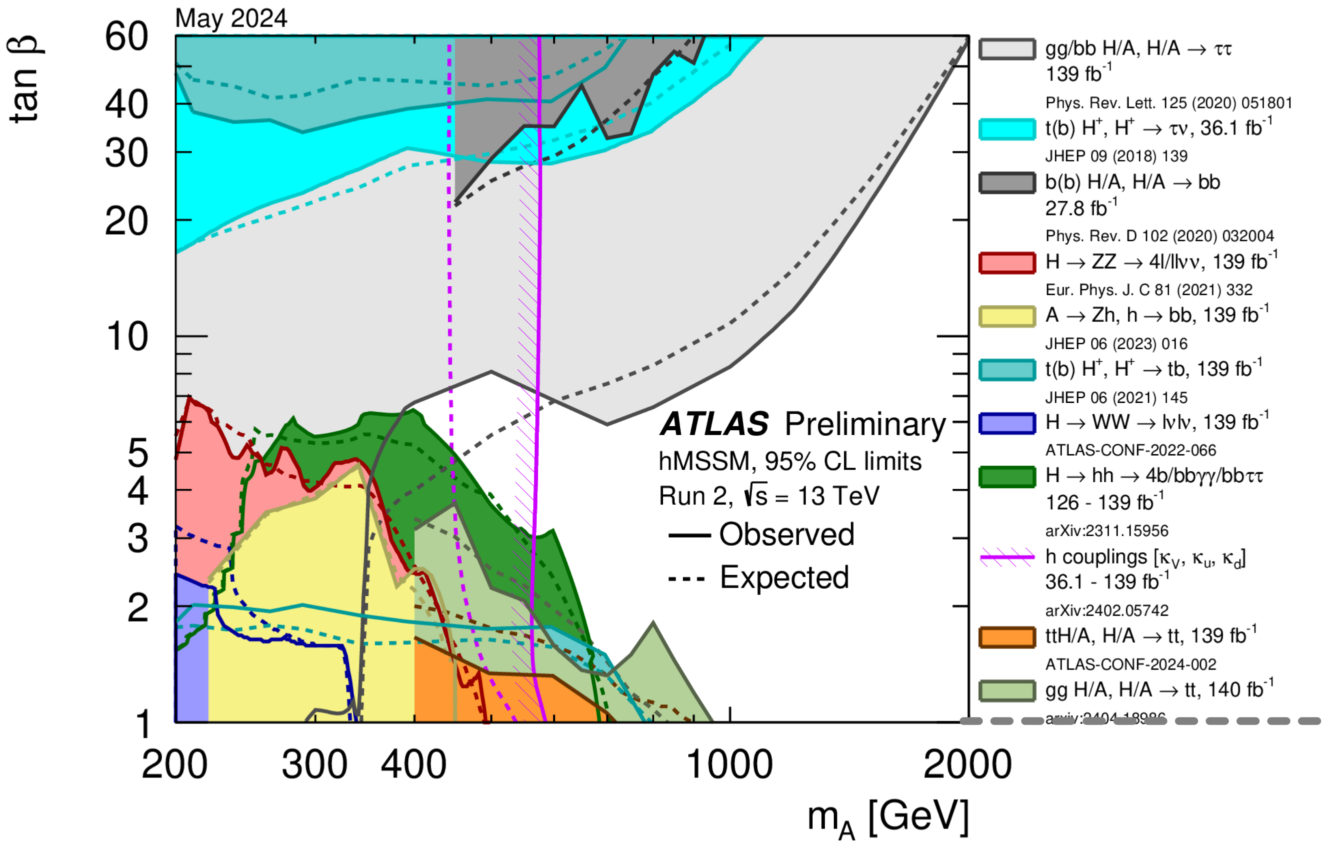
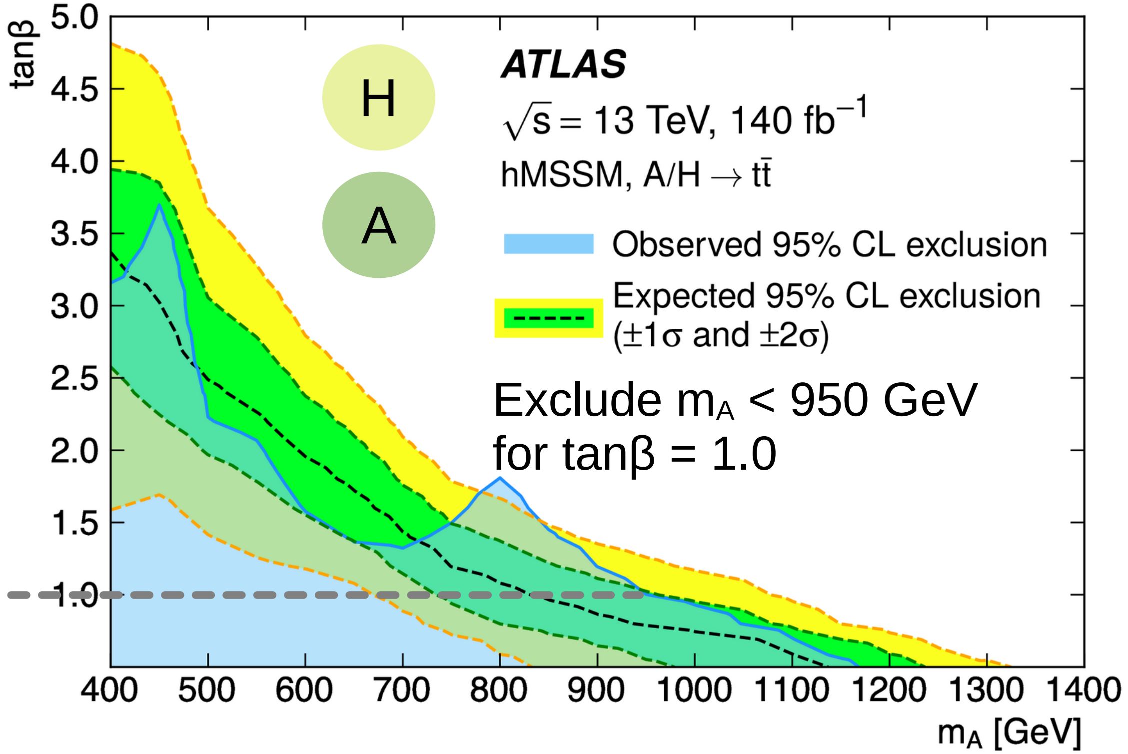
Constraints on relevant benchmark models: hMSSM

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



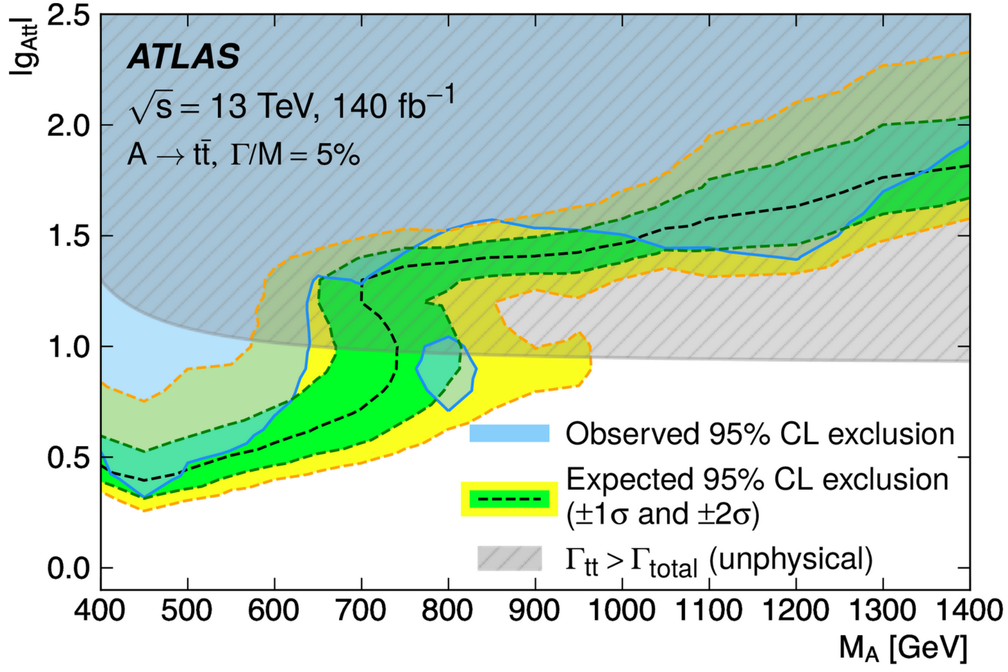


$m_A \sim m_H$

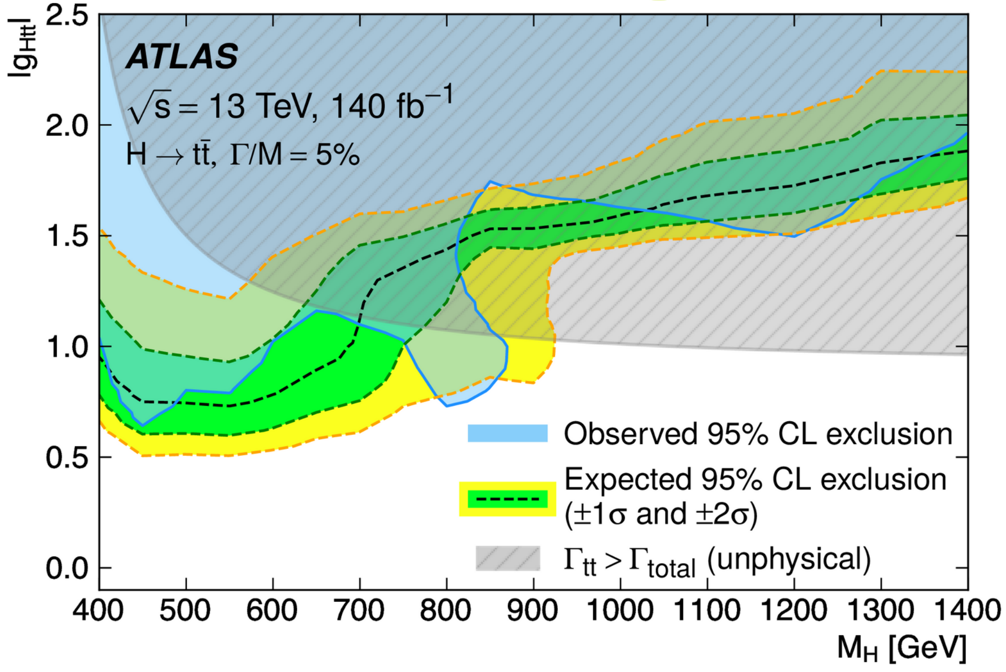
Coupling constraints for a single (pseudo)scalar

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

Pseudoscalar A

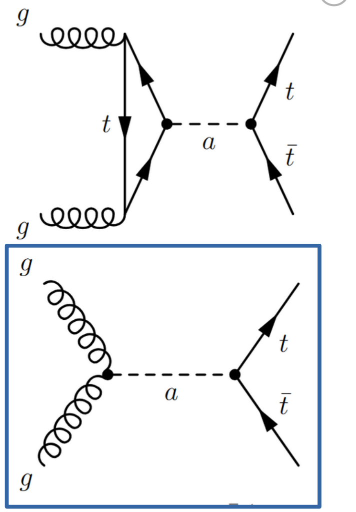


Scalar H



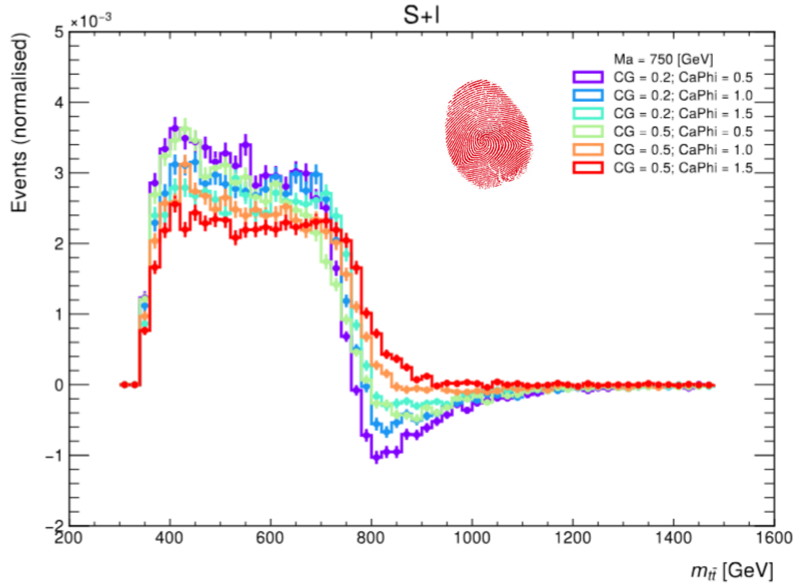
Extra: ALPs coupling to top quarks

- 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!

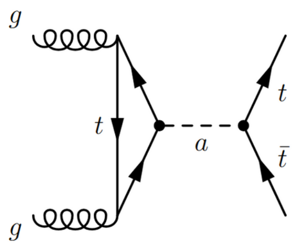
M. Rodrigues, KB



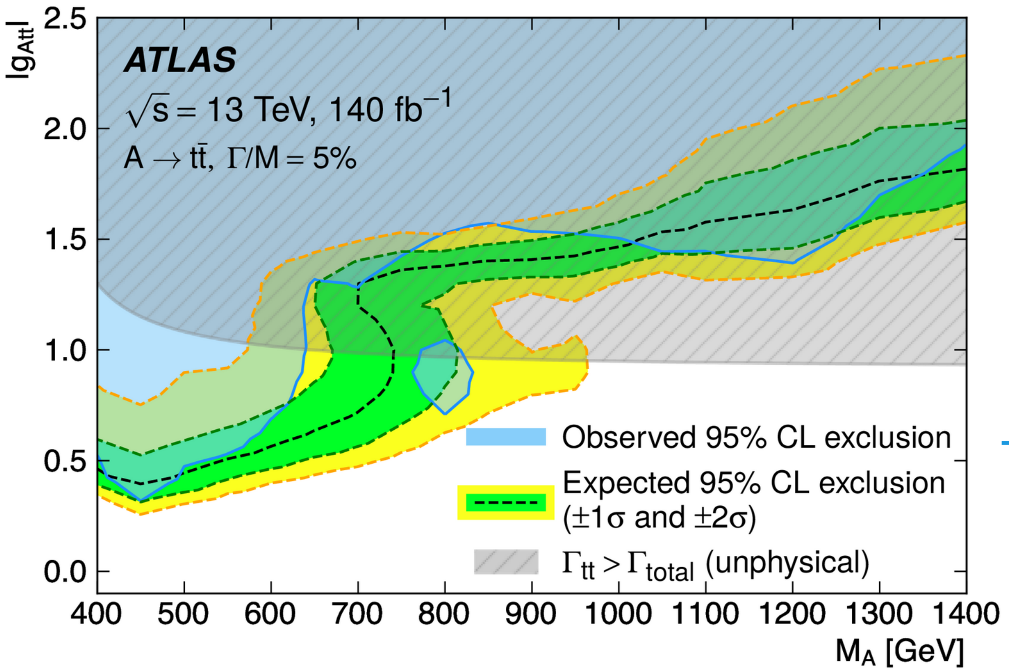
Related work:
Jeppe et al: DESY-24-059
Carra et al: PRD 104 (2021) 9, 092005

Extra: ALPs coupling to top quarks

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

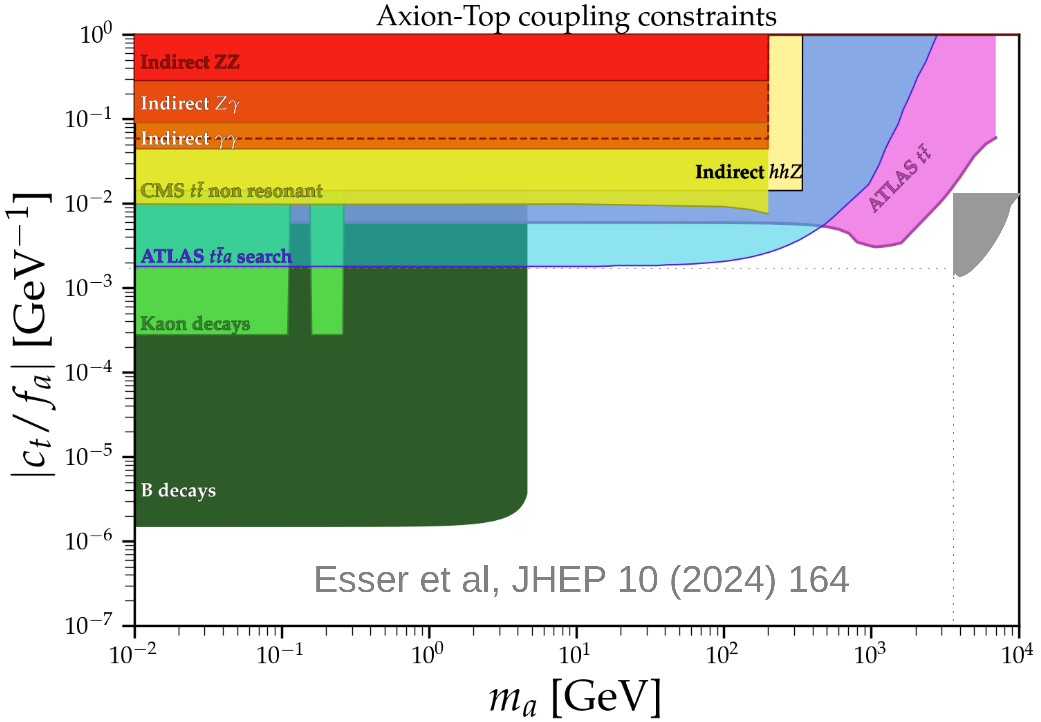


Fixed pseudoscalar width

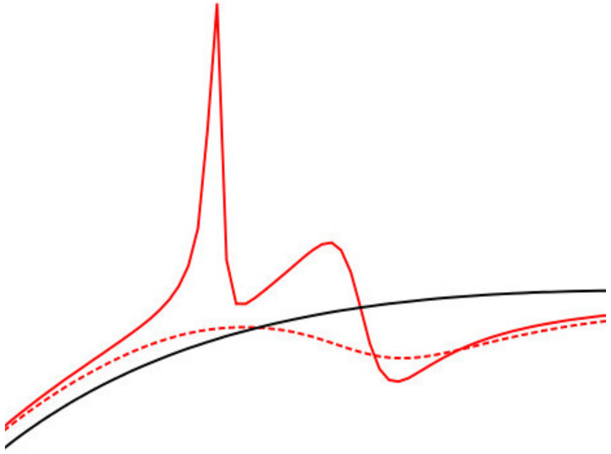


$g_{Att}/v = c_t/f_a$

Width depends on m_a and c_t



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

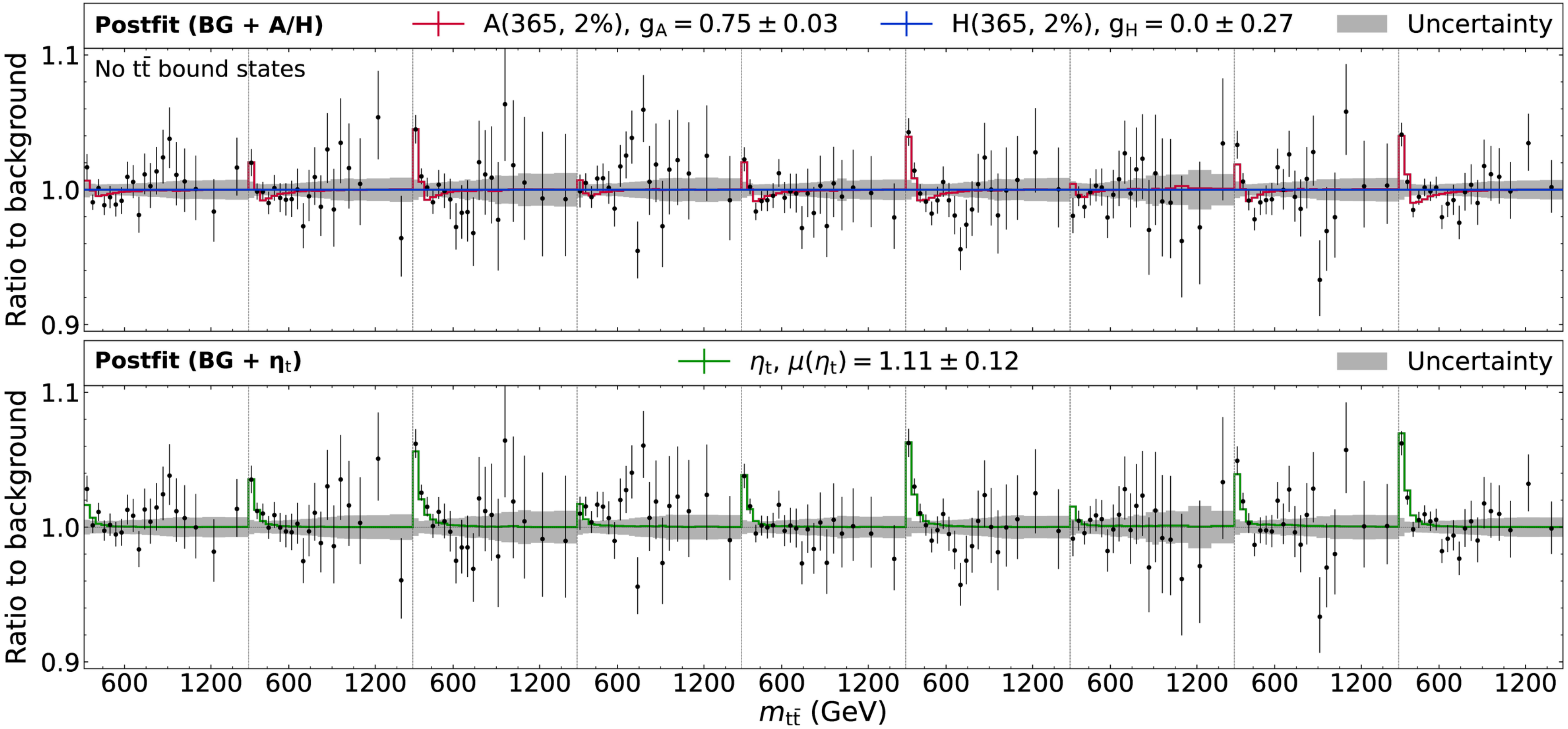


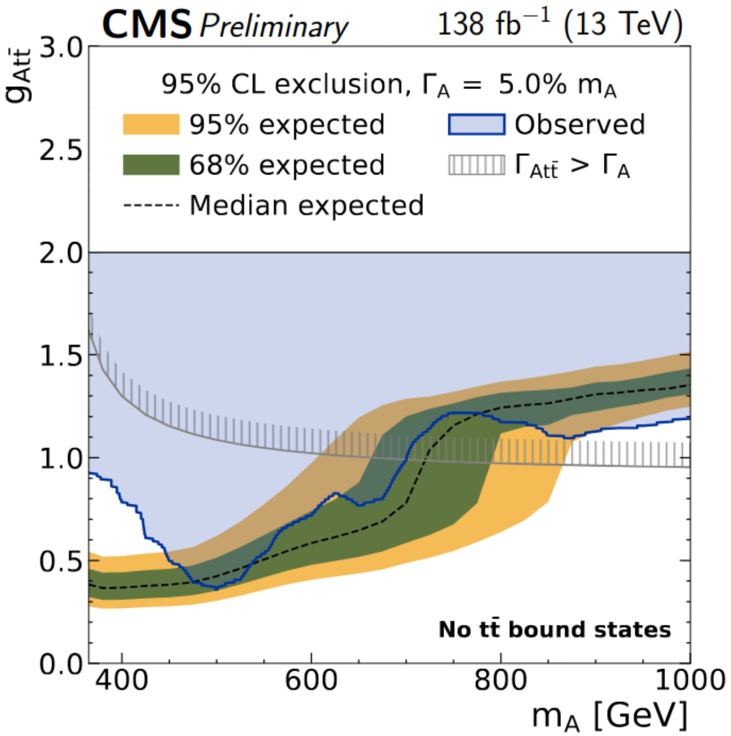
In a nutshell

CMS-PAS-HIG-22-013

> 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



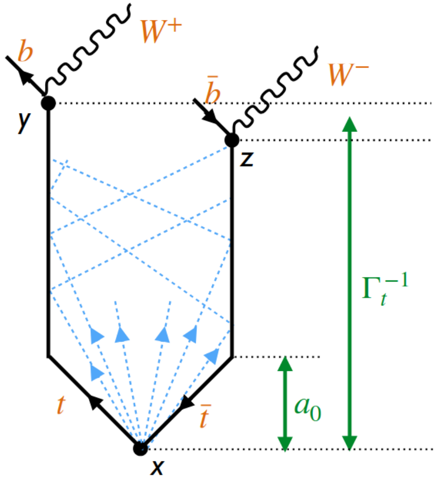


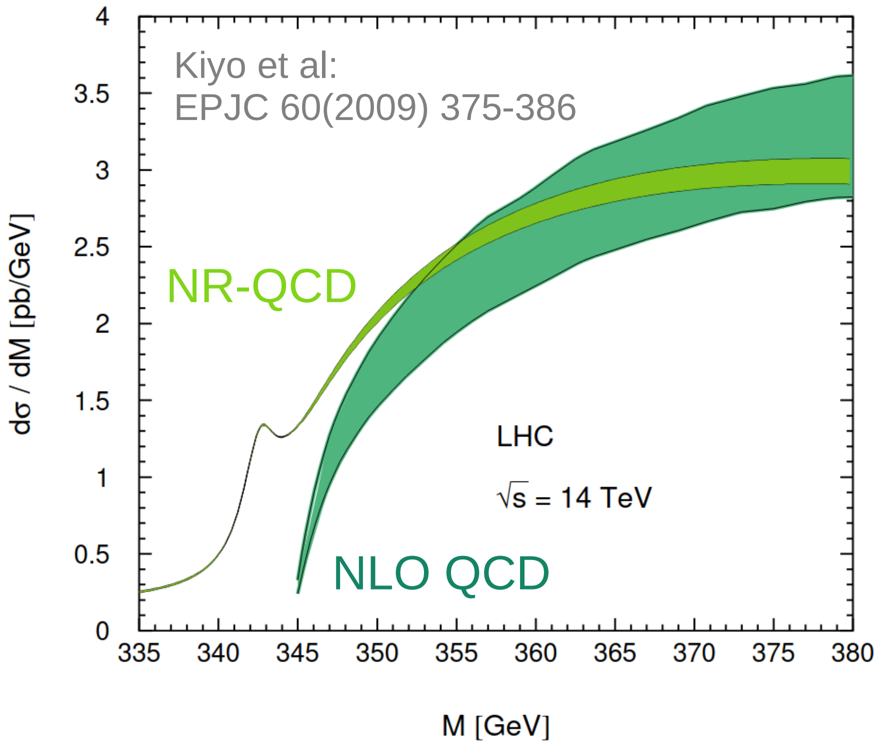
Toponium – a ttbar quasi-bound state

> 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: Γ_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 η_t
  - m = 343 GeV and Γ/m = 7 GeV





Key differences with ATLAS

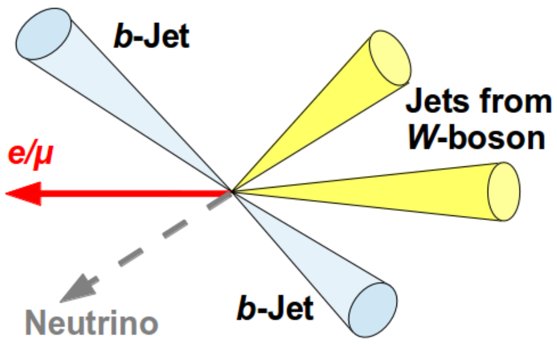
> Two orthogonal sets of regions: 1L (e or μ) + 2L (e^+e^-, eμ, $\mu^+\mu^-$)

> **2L channel**

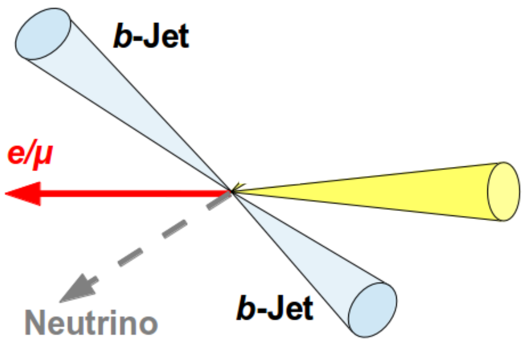
- Analytic reconstruct of m_{ttbar}

> **1L channel**

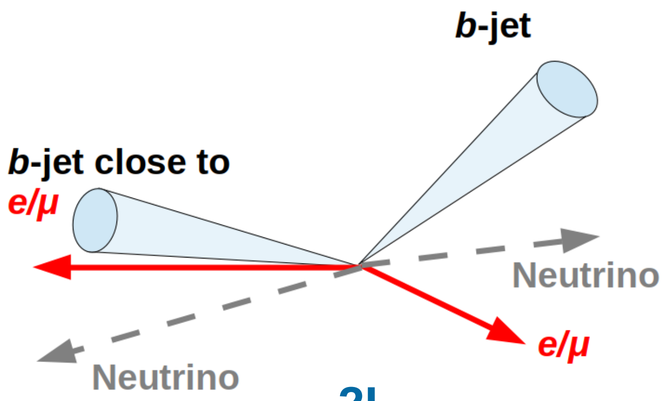
- Resolved topology: ≥4 small-*R* jets, ==2 *b*-tags
- "Merged" topology: ==3 jets, ==2 *b*-tags
- Reconstruct m_{ttbar}: via χ^2 algorithm



1L, ≥4 jets



1L, ==3 jets



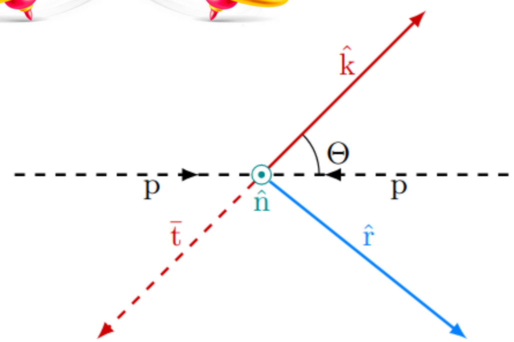
2L

Key differences with ATLAS

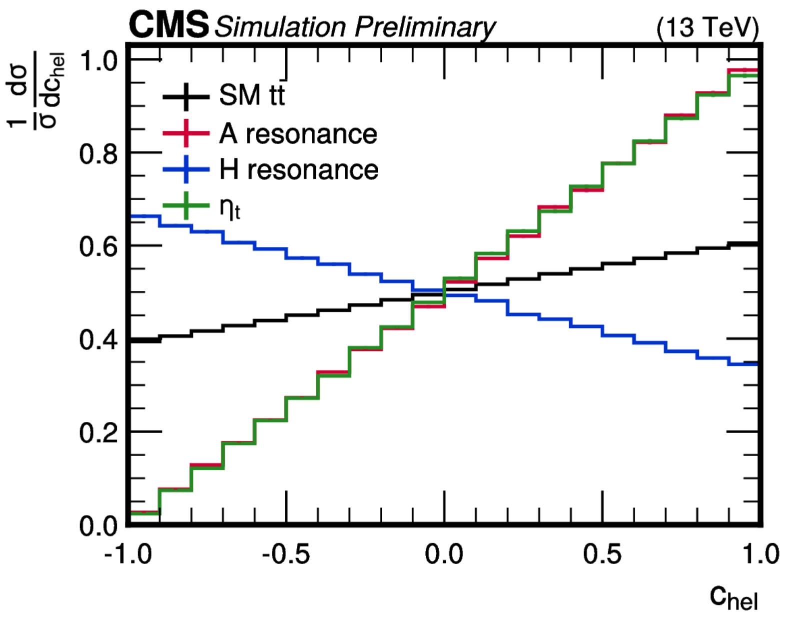
> Spin correlation variables sensitive to degree of entanglement in 2L channel

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

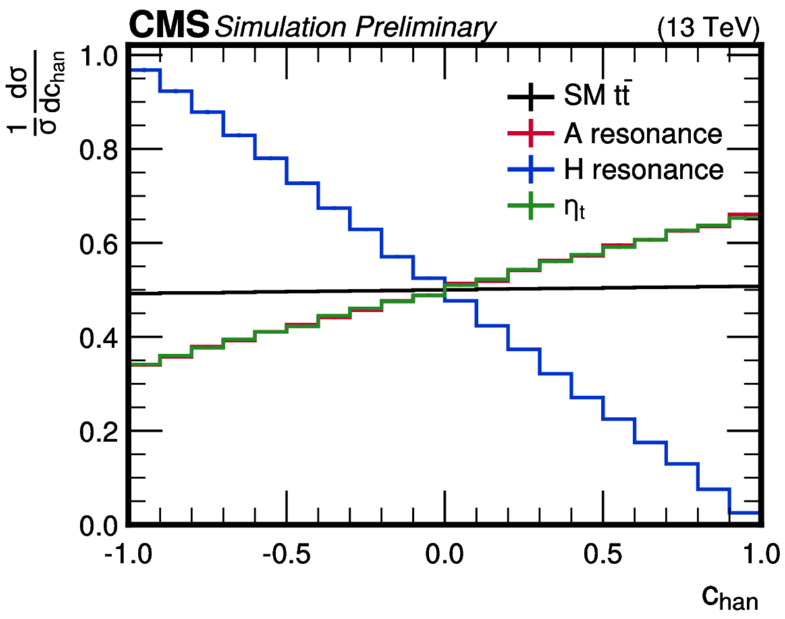
$$c_{\rm hel} = -(\hat{\ell}^+)_k(\hat{\ell}^-)_k - (\hat{\ell}^+)_r(\hat{\ell}^-)_r - (\hat{\ell}^+)_n(\hat{\ell}^-)_n$$
$$c_{\rm han} = +(\hat{\ell}^+)_k(\hat{\ell}^-)_k - (\hat{\ell}^+)_r(\hat{\ell}^-)_r - (\hat{\ell}^+)_n(\hat{\ell}^-)_n$$

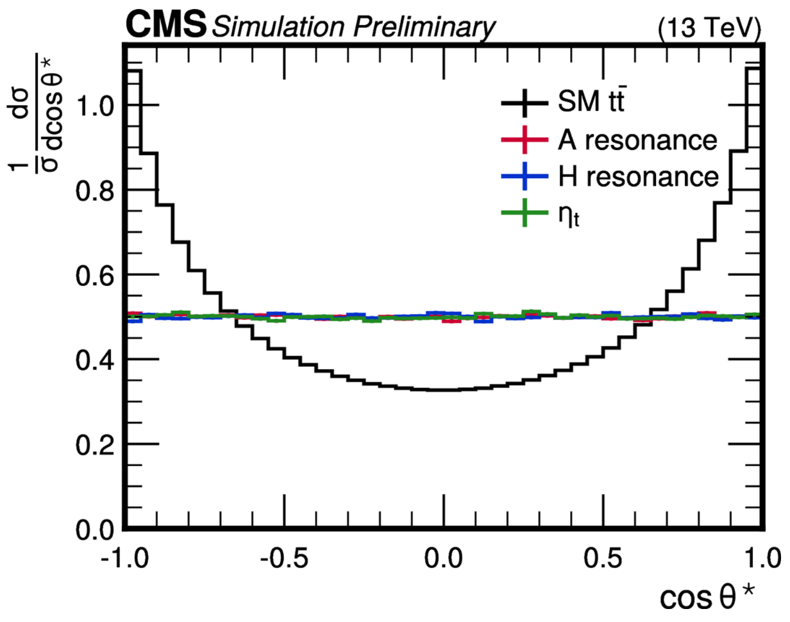


Enhances sensitivity to pseudoscalar



Enhances sensitivity to scalar



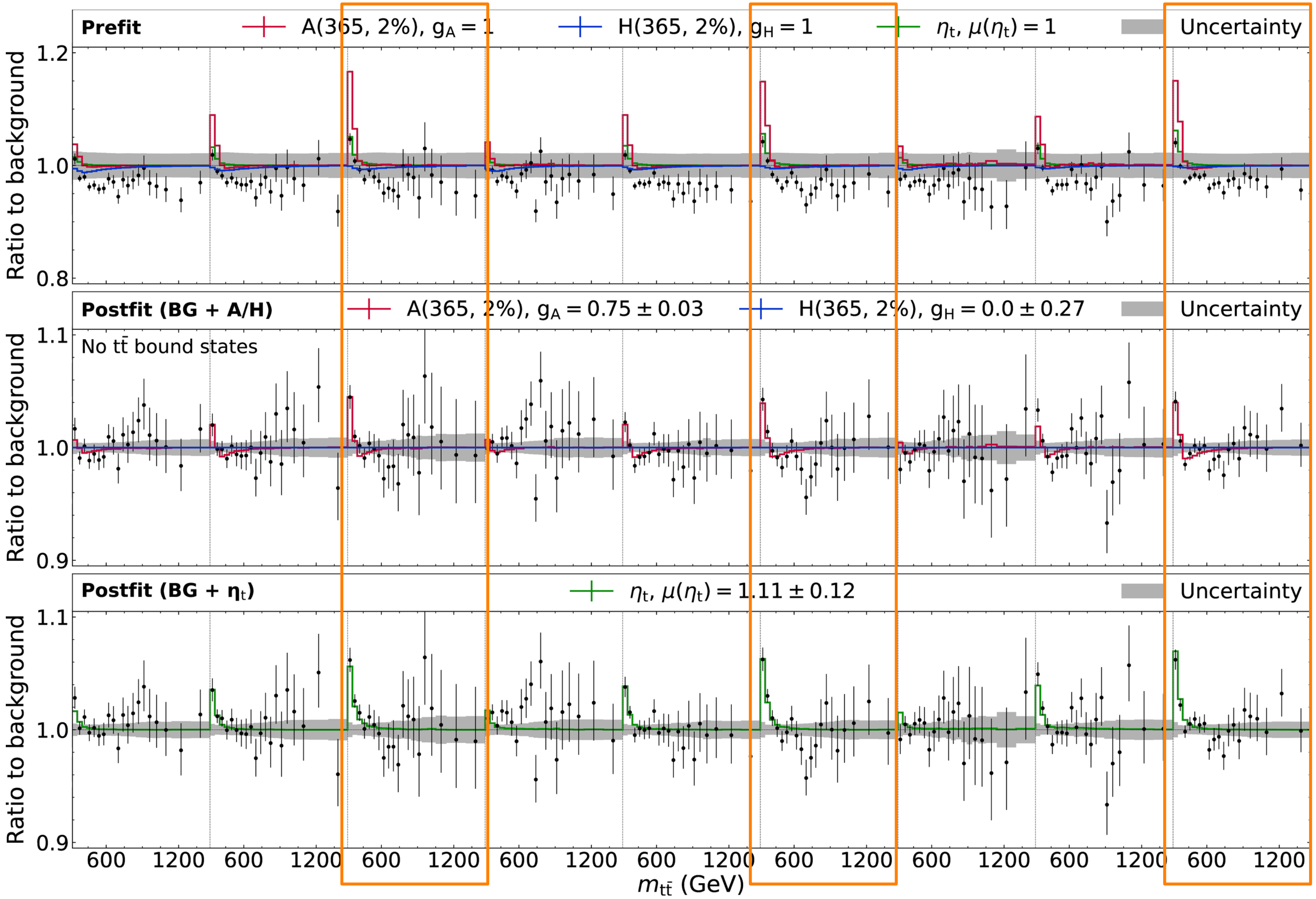


CMS 2L signal regions

Prefit

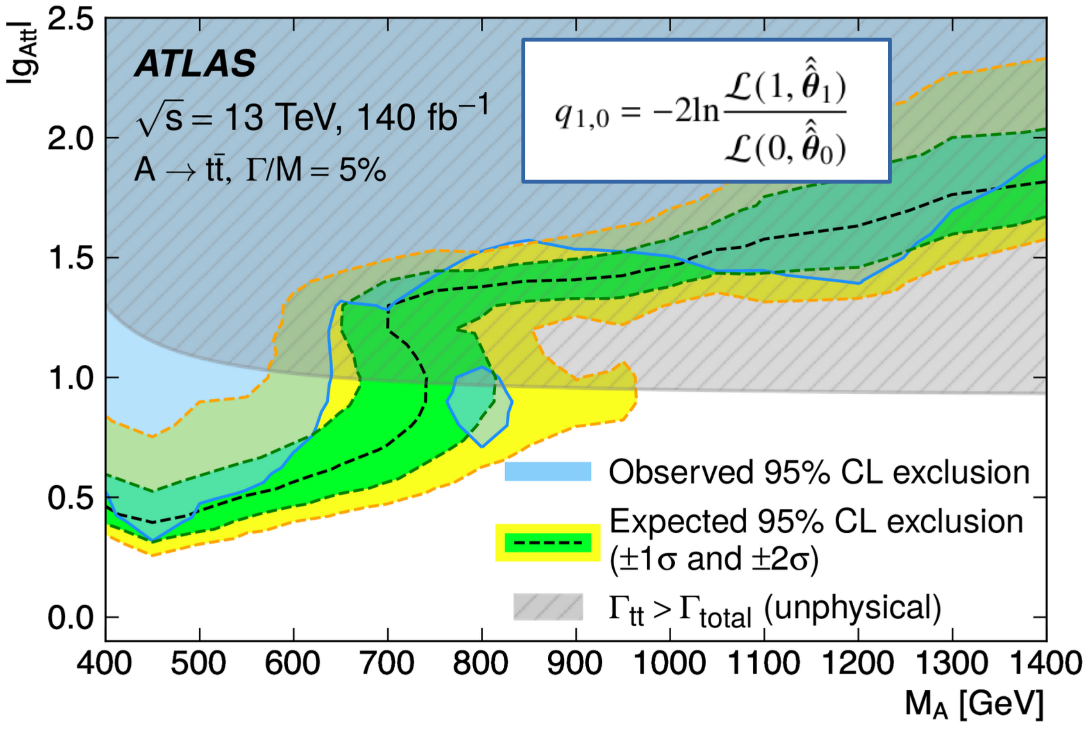
BSM pseudoscalar:
A+I+B

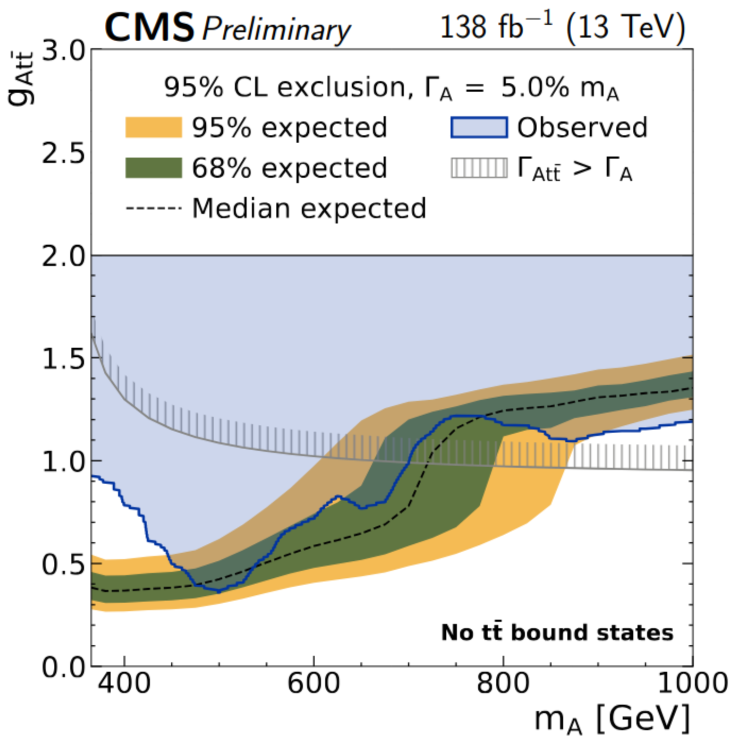
Toponium:
η+B



Sensitivity comparison

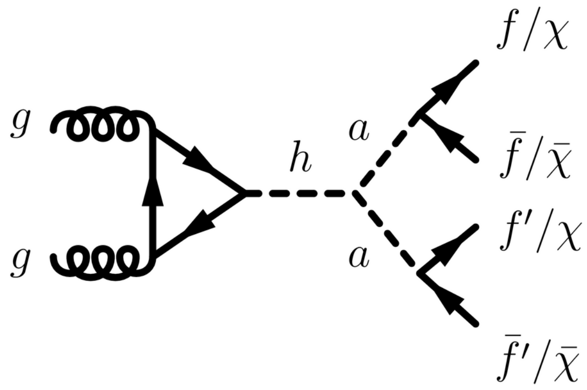
- Same expected sensitivity at low mass
  - Despite differences in region definition, background modelling, systematic uncertainties, ...
- Observed results differ notably
  - Investigations on-going...





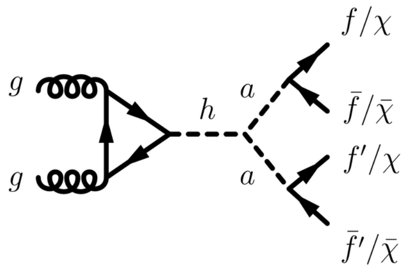
What if extra bosons are light?

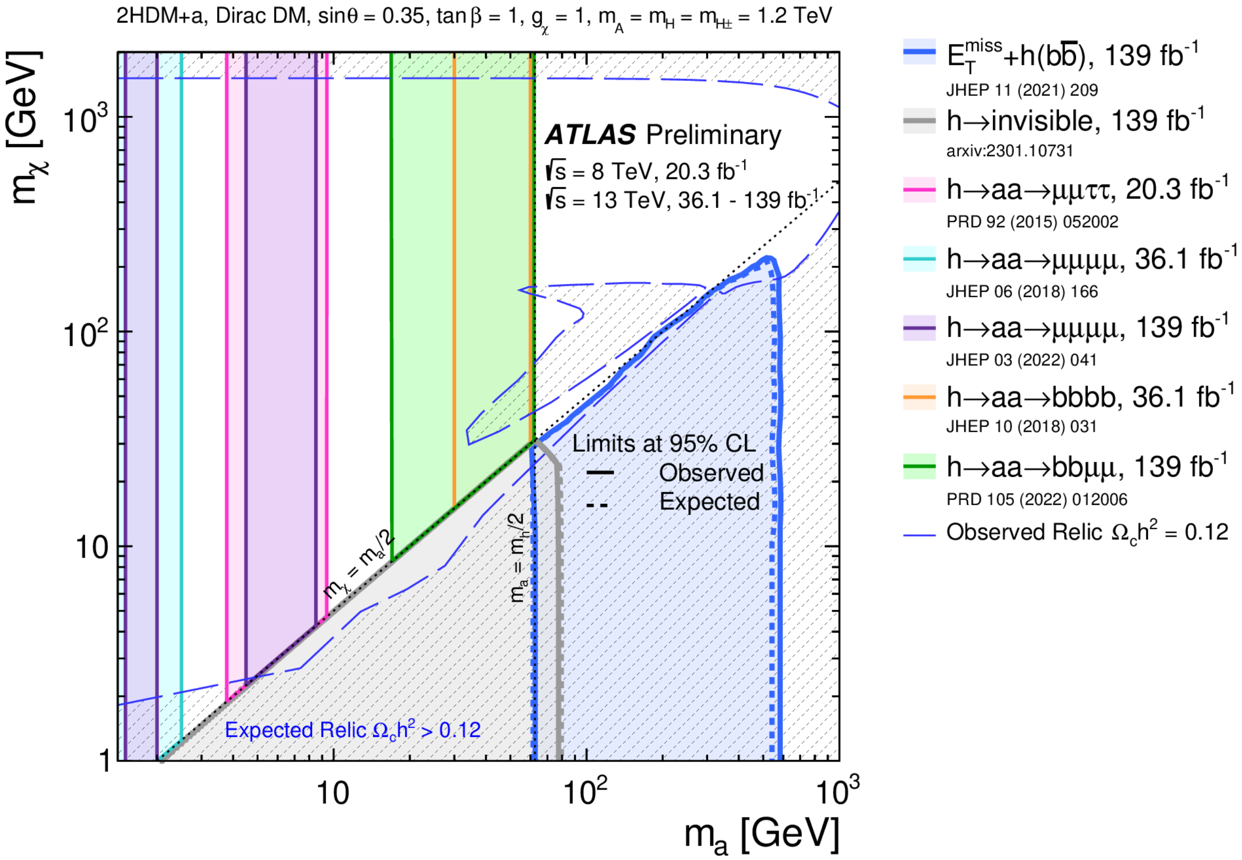
- New (pseudo)scalar states with mass < 125 GeV constrained but not excluded by LEP etc.
- Motivation especially for light pseudoscalars:
  - Extended Higgs sector models
  - ALPs
- Exotic Higgs decays: $h_{125} \rightarrow aa$
- Detector signatures depend on
  - Mass m_a (→ Yukawa coupling to SM fermions)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



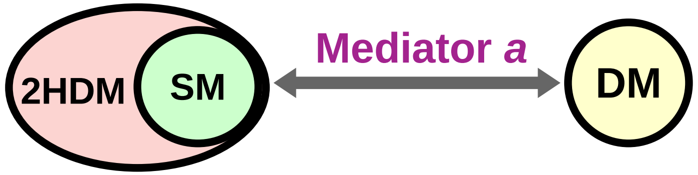
Example: pseudoscalar mediator to DM

Simplified model

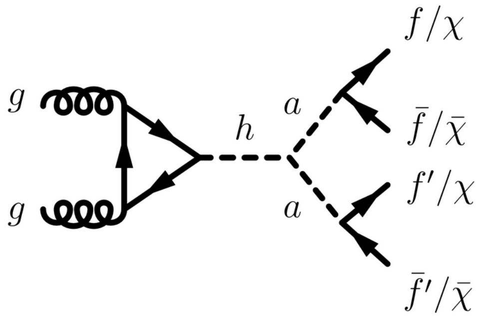




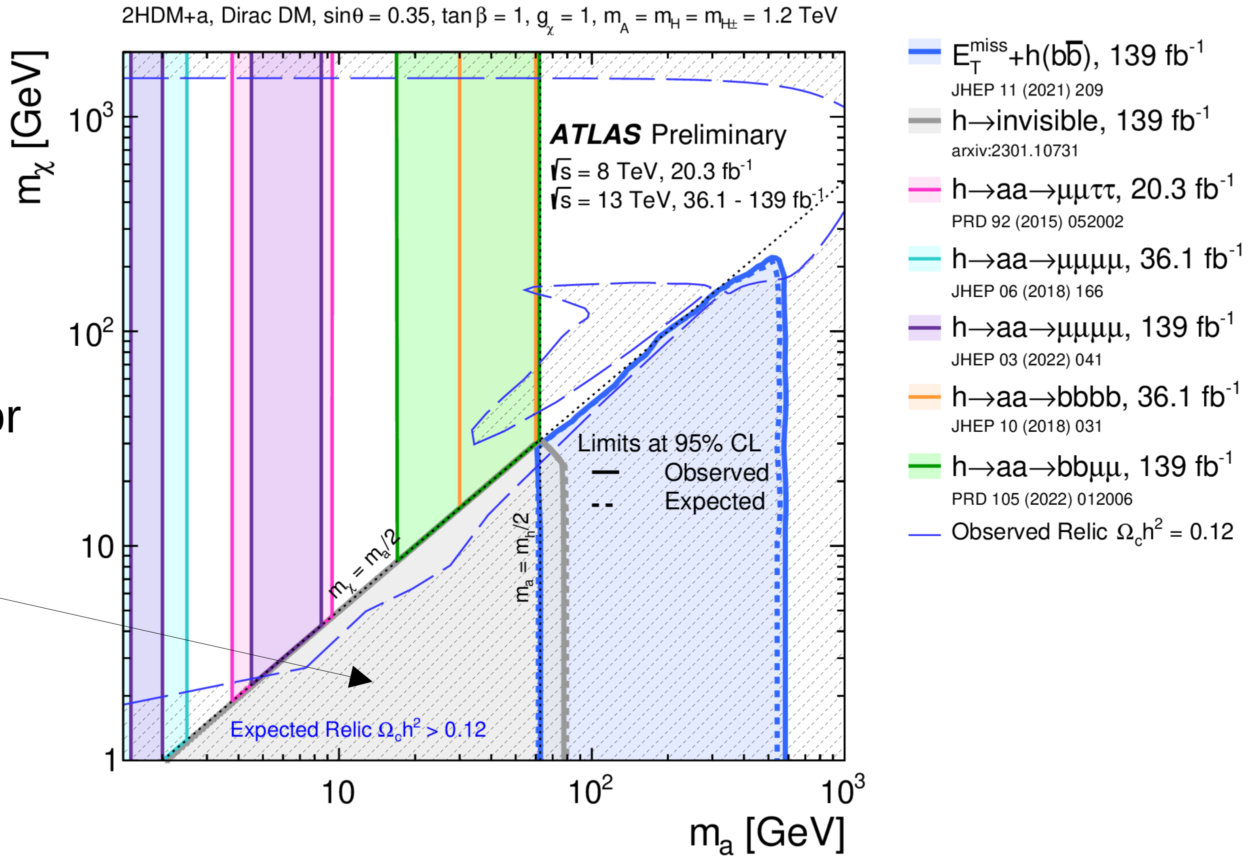
Example: pseudoscalar mediator to DM



Extended model:
2HDM+*a*



Invisible mediator decays to DM



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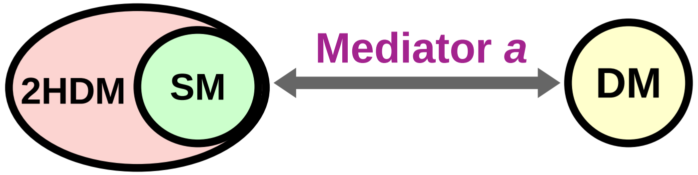
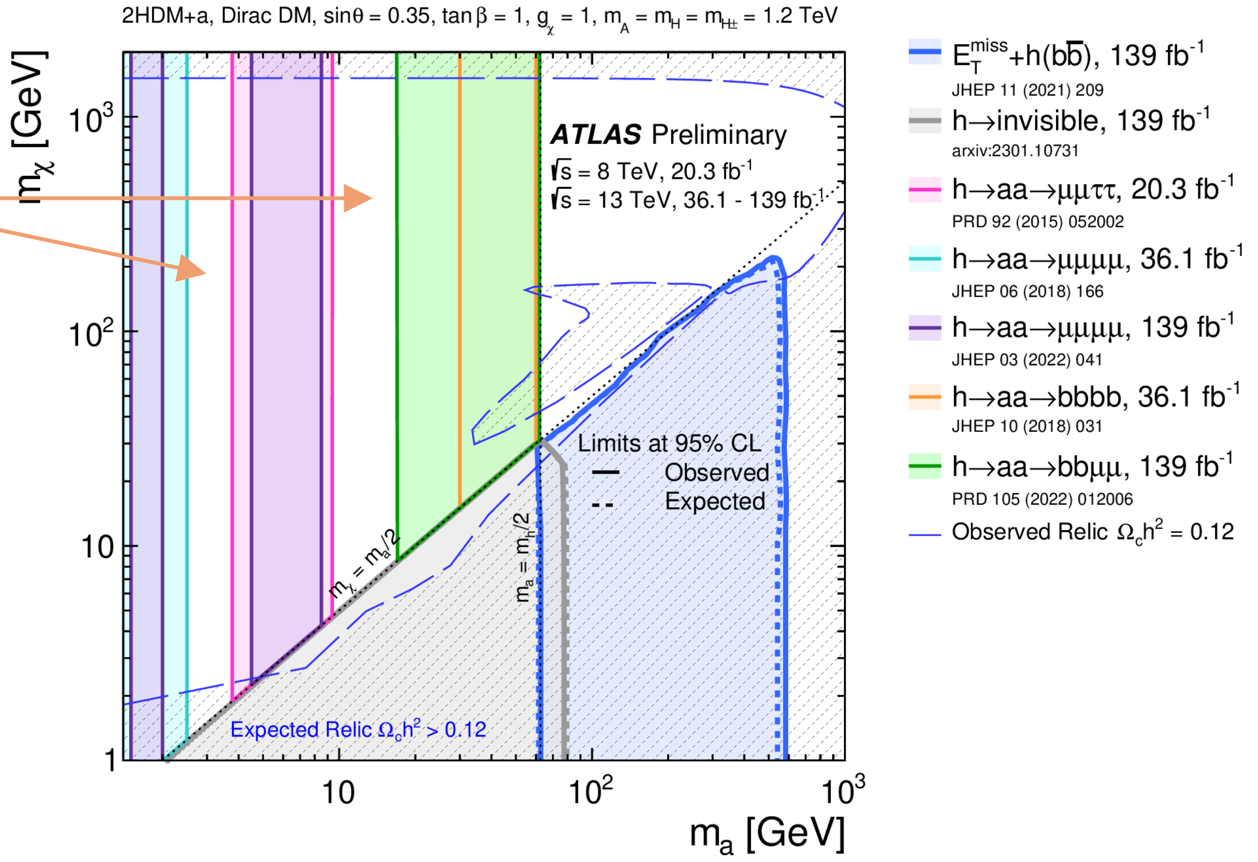
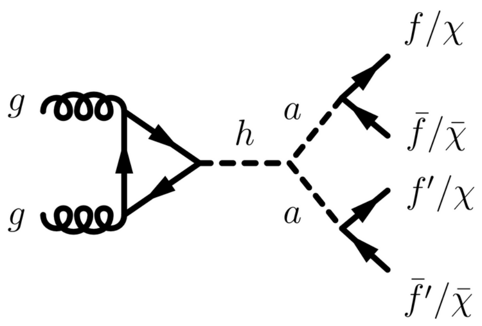


Extended model:
2HDM+*a*

Quiz question:
What about those unprobed regions for masses ~3 GeV and ~10 GeV?





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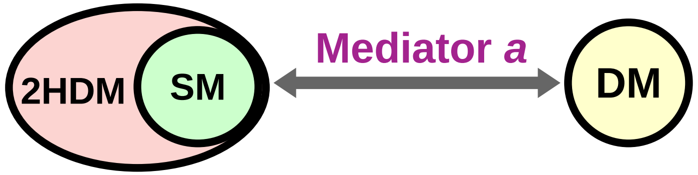
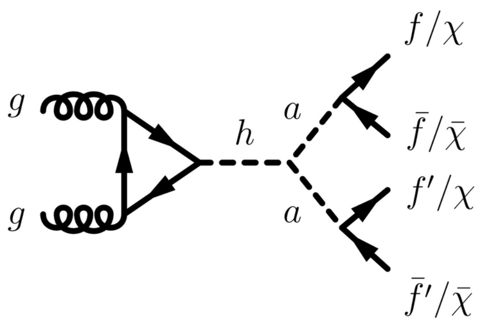
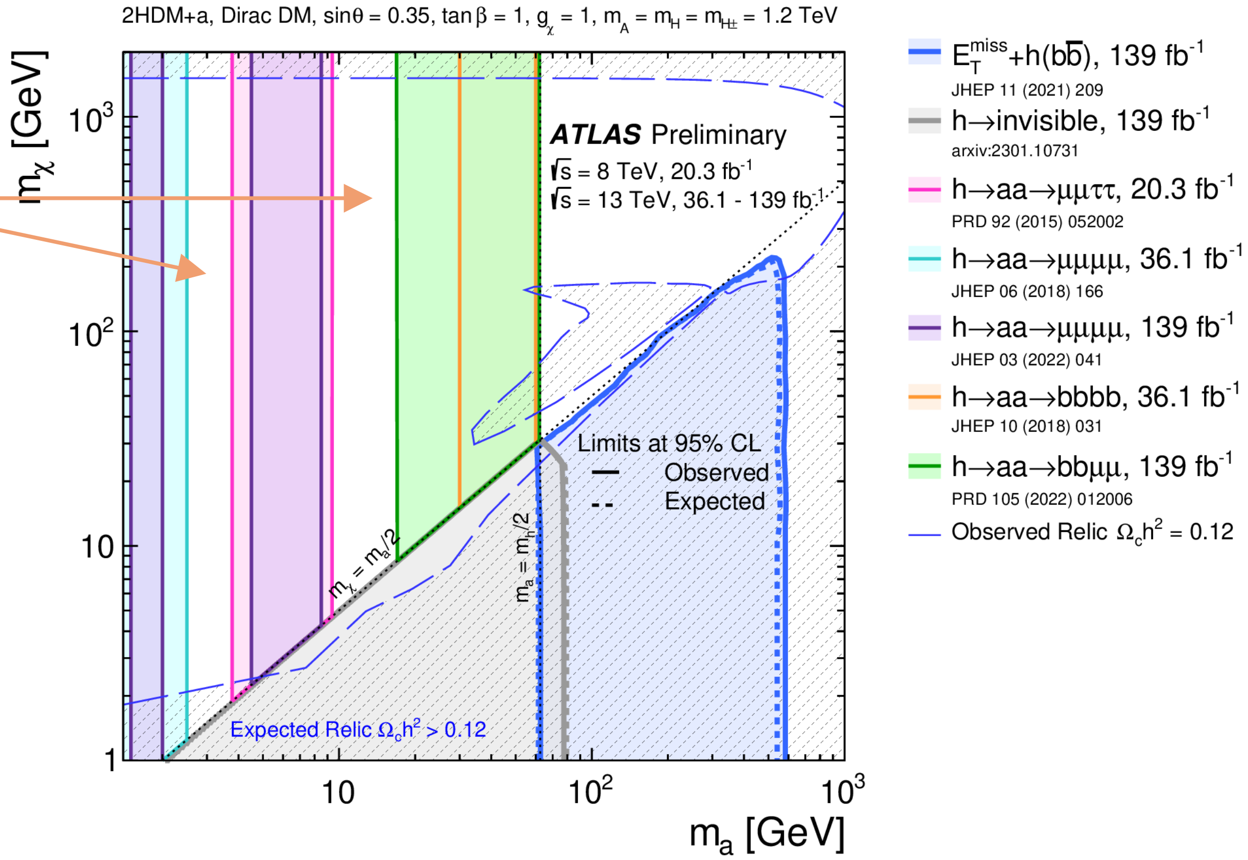


Extended model:
2HDM+*a*

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





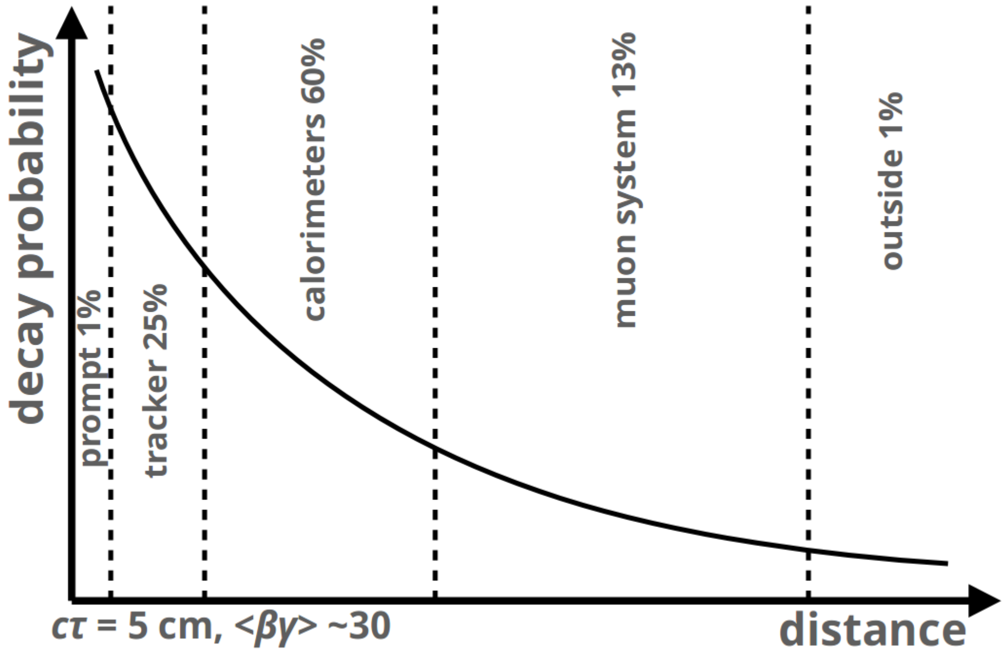
Long-lived particles

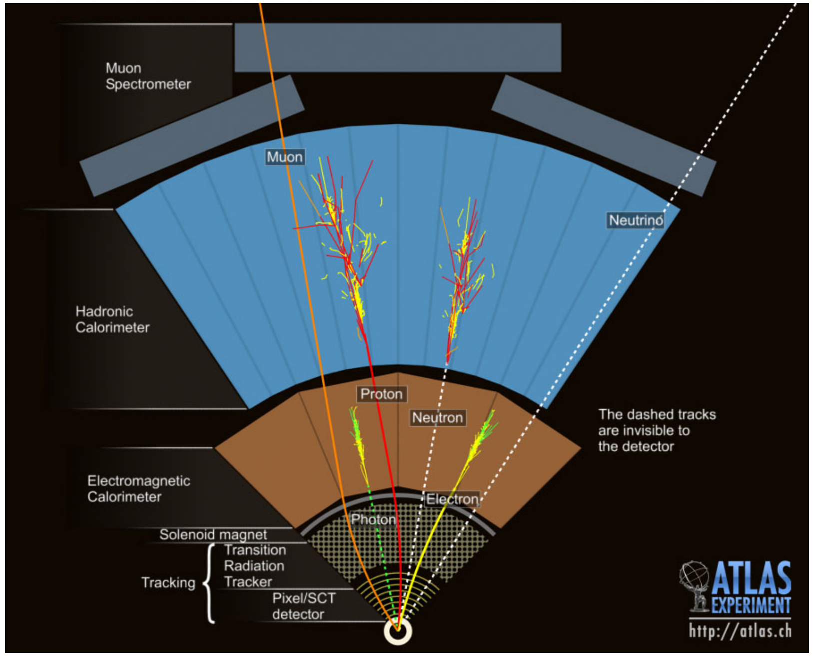
> Exotic decay products (a, S, ...) of the Higgs could be long-lived

> 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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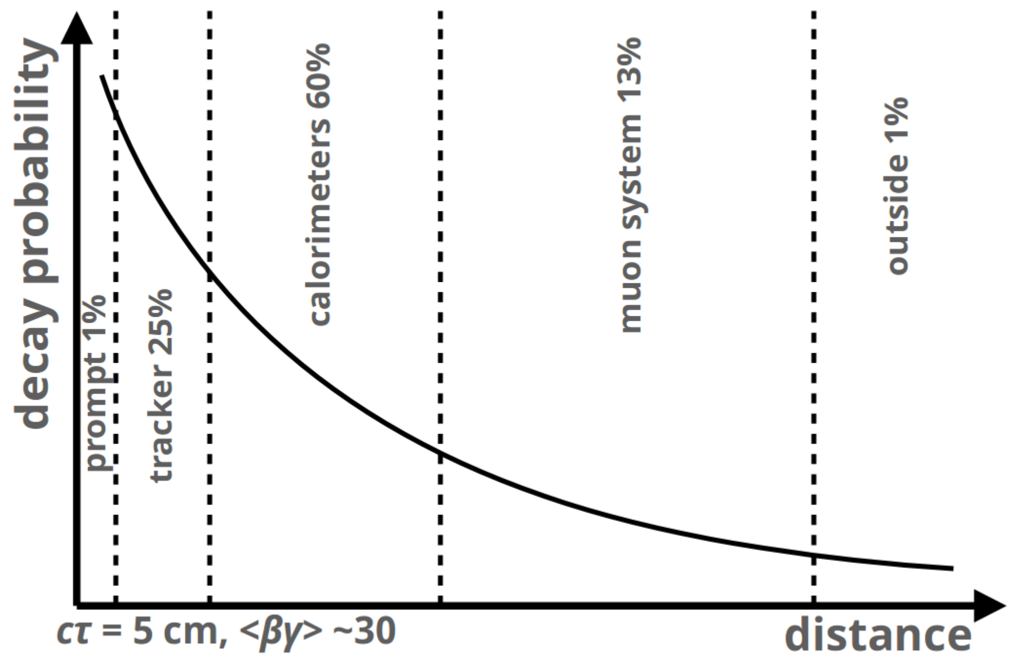

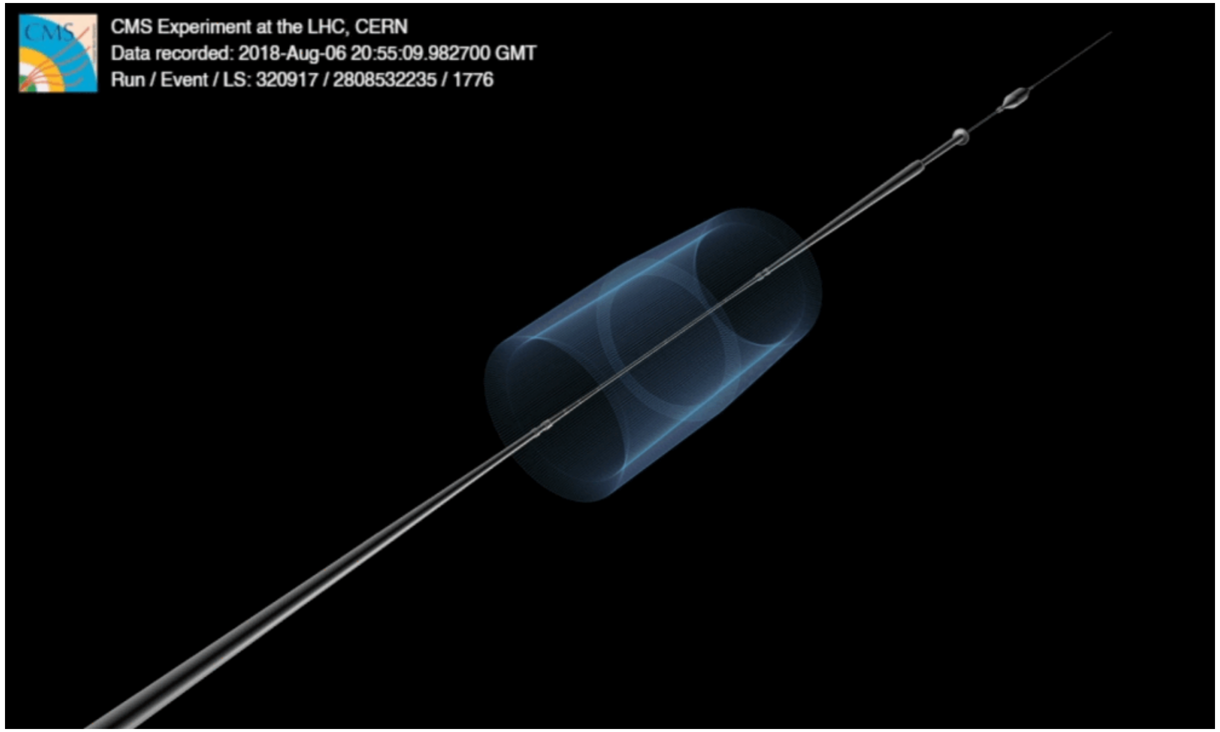

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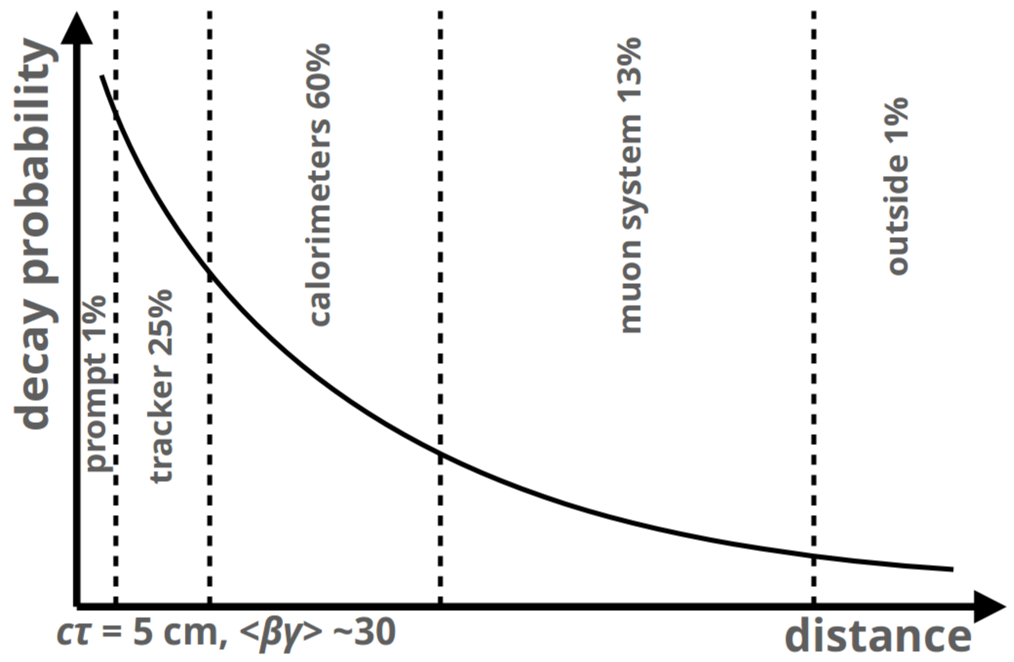
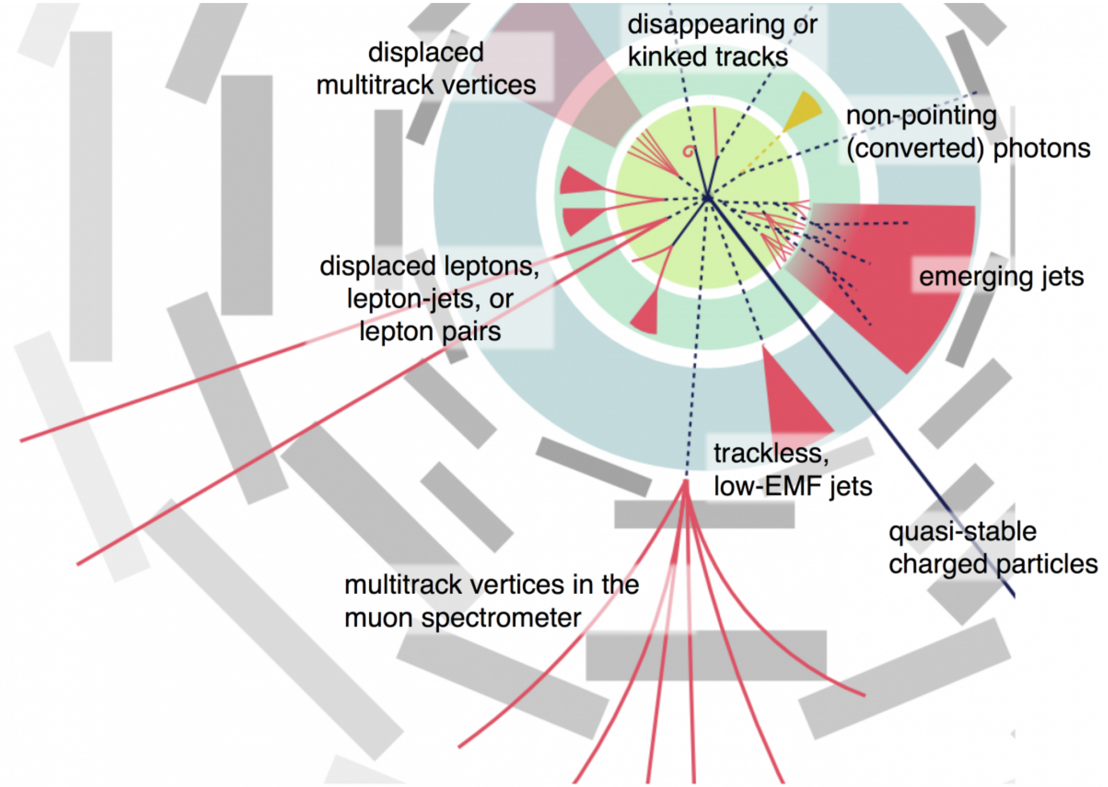
> Wealth of possible detector signatures: displaced tracks, trackless jets, displaced muons, …

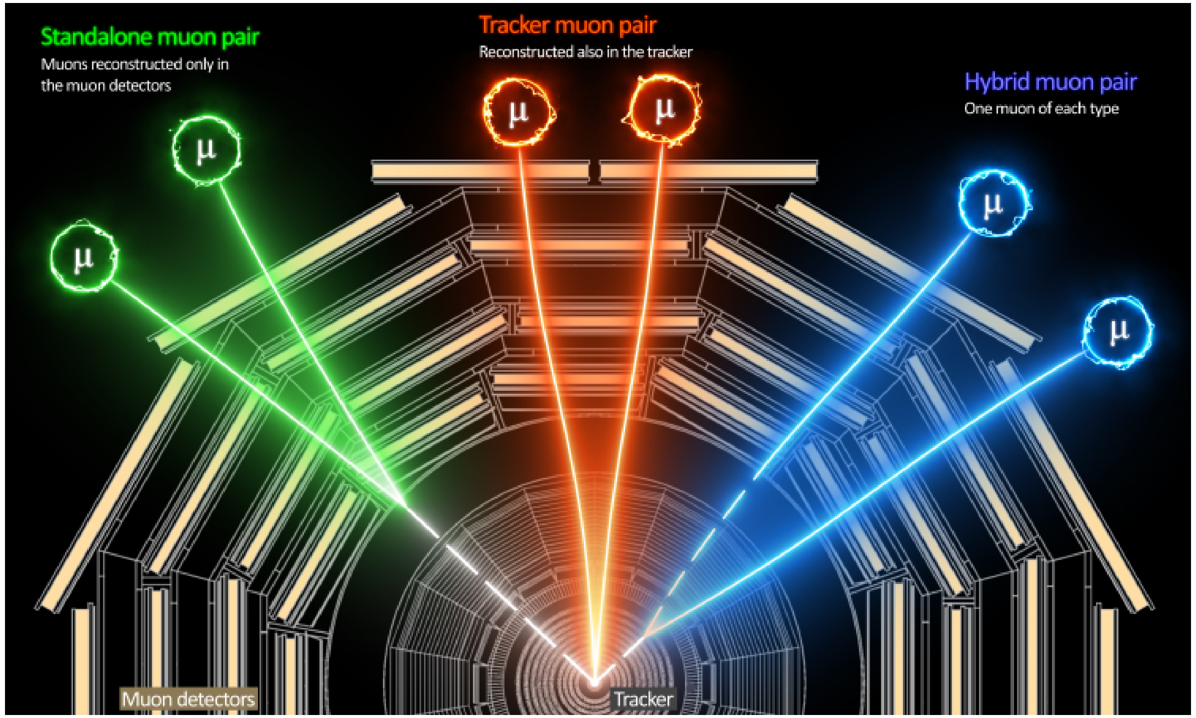
- Not captured by standard particle identification algorithms!



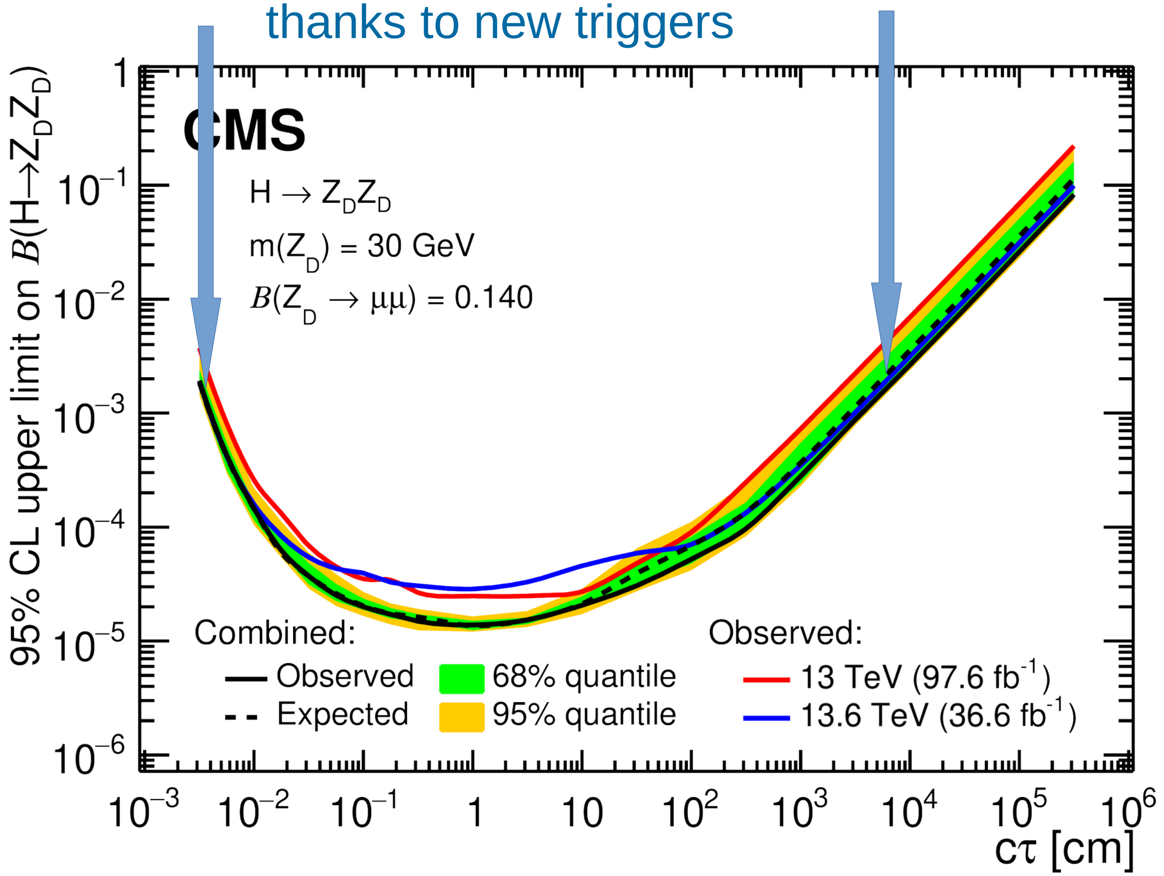


Example: displaced muon pairs

- 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

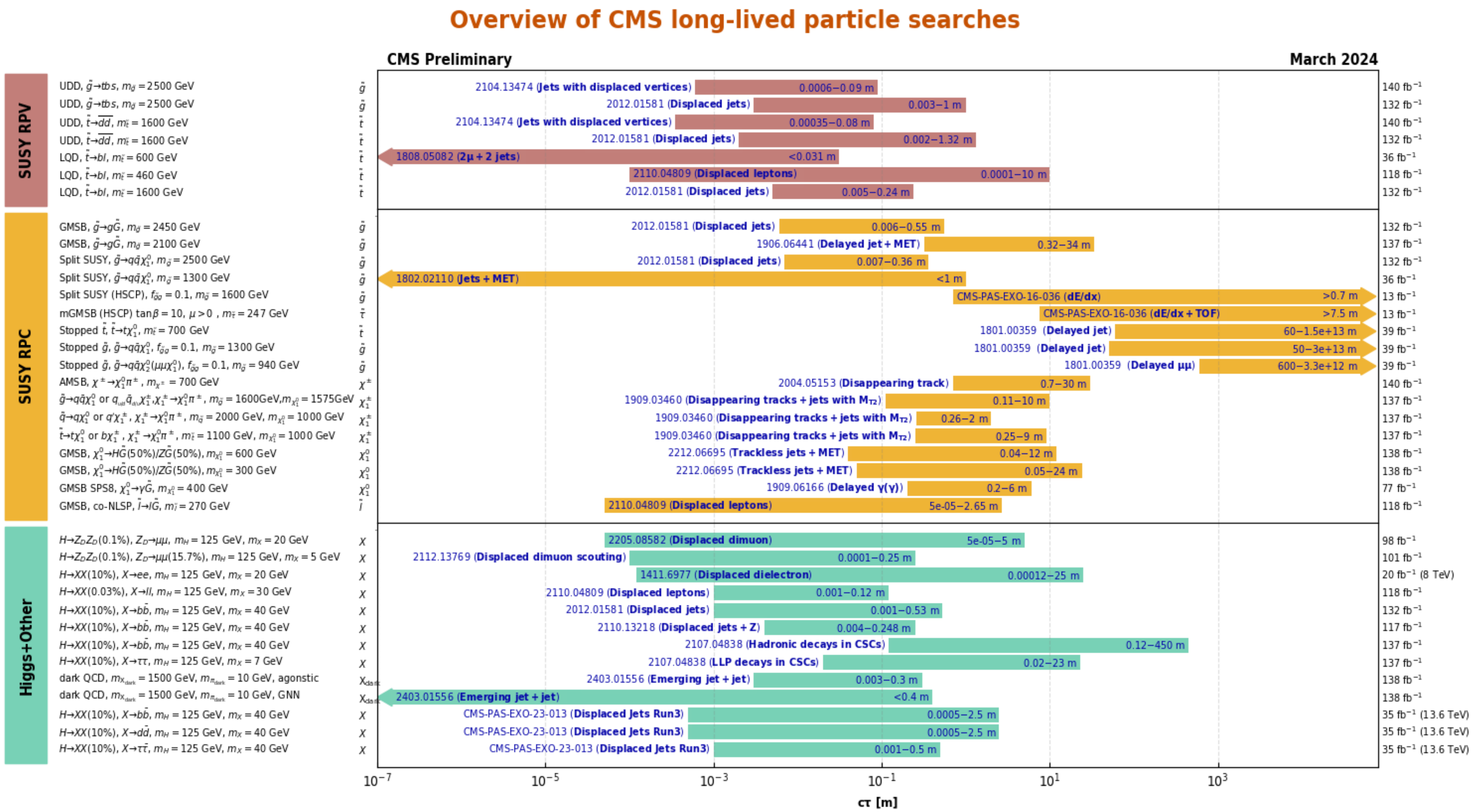


Enhanced sensitivity with Run-3 thanks to new triggers



Impressive lifetime coverage

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



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

Higgs Part 3: Summary

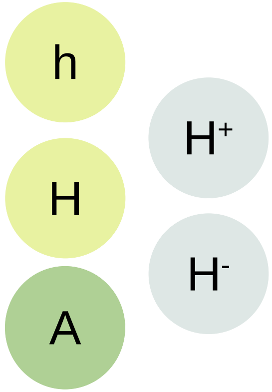
> Extended Higgs sectors part of many well-motivated extensions of the SM

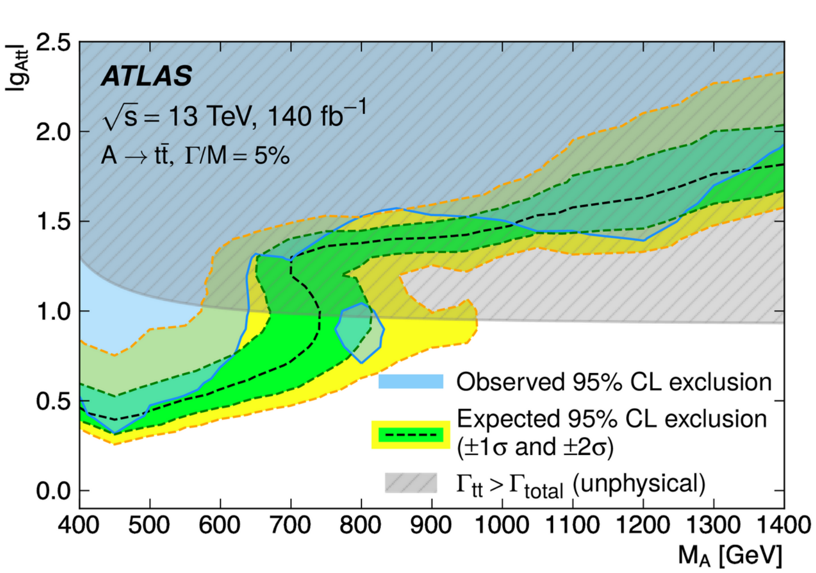
> Broad experimental programme to search for extra Higgs bosons

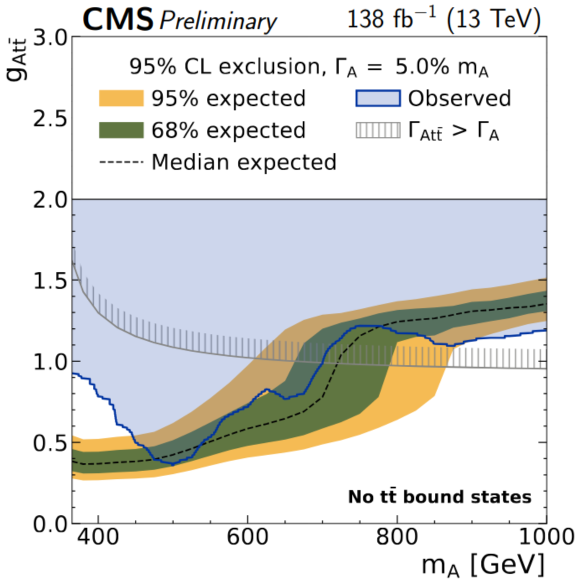
- Different production modes (gg-fusion, exotic Higgs decays)
- Different decay modes

> Decays to top quarks particularly challenging due to interference

- Excess seen by CMS Collaboration at ttbar threshold … under investigation

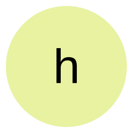






Overall summary

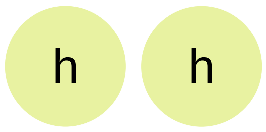
> **Part 1: The vacuum is not empty**



- Significant progress in characterising the Higgs boson
- Measurements in agreement with SM within current uncertainties → much room for BSM physics

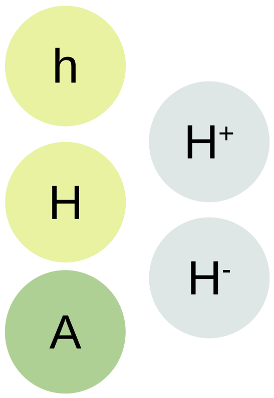
> **Part 2: What is the fingerprint of the vacuum?**

- 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



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

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  - 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

YOUR contributions could be crucial to our understanding of the vacuum!

BONUS SLIDES

Choice of test statistic

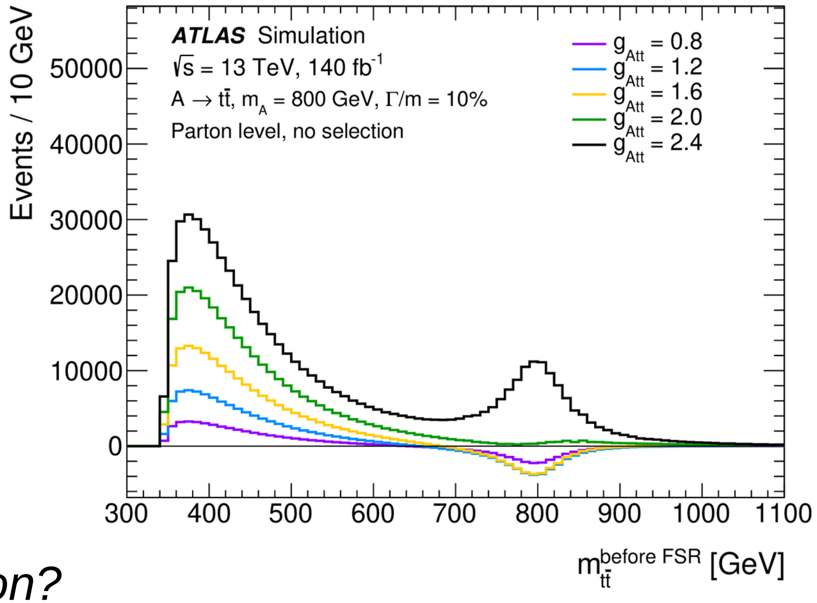
JHEP 08 (2024) 013

> 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

> Extend likelihood to include interference term

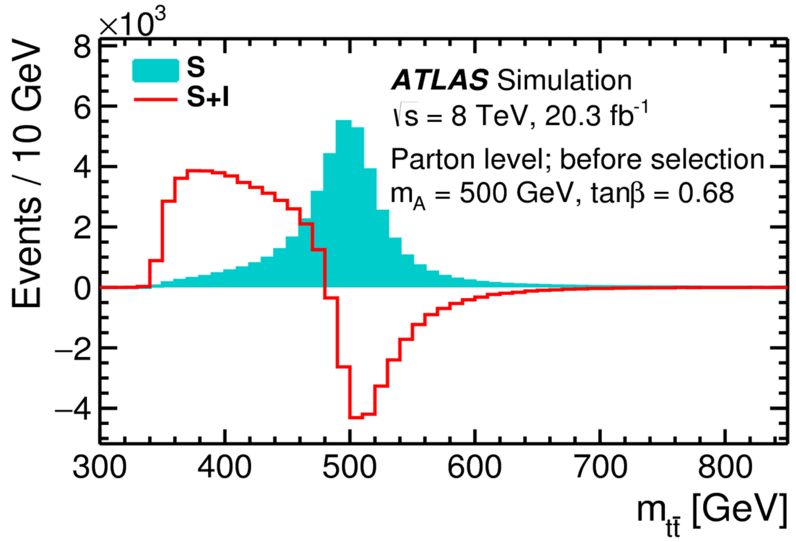
$$\mu \cdot S + \sqrt{\mu} \cdot I + B = (\mu - \sqrt{\mu}) \cdot \boxed{S} + \sqrt{\mu} \cdot \boxed{(S + I)} + B$$

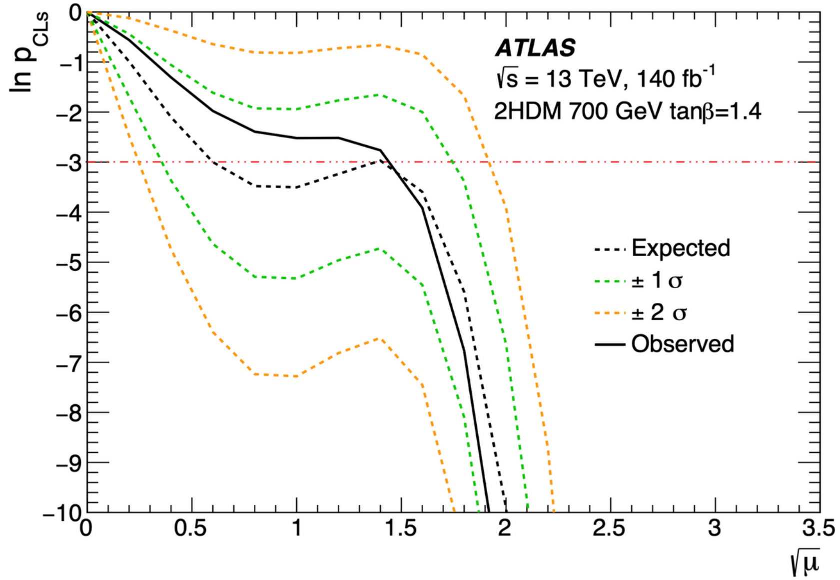
> Quadratic dependence on POI = √μ

- 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

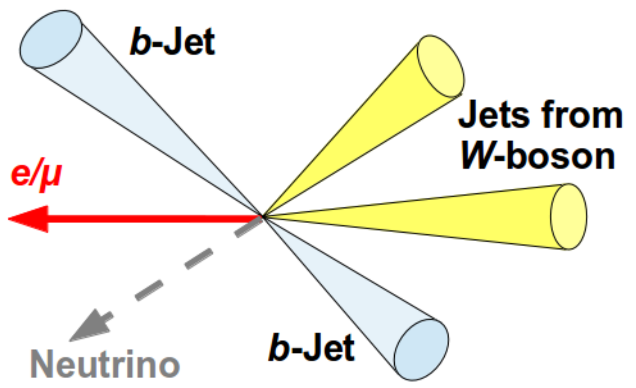




1L Resolved

- 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

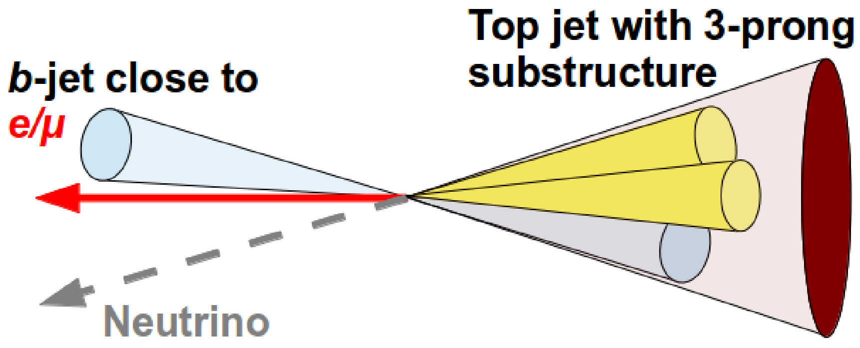
> Leptonic top b-candidate jet: ≥ 1 small-R jet well separated from top candidate jet

> Reconstruct full ttbar system:

- Neutrino 4-vector from W-mass constraint
- Selected lepton
- Leptonic top b-candidate
- Top candidate jet

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

(ρ = 600 GeV)



Differences in background modelling

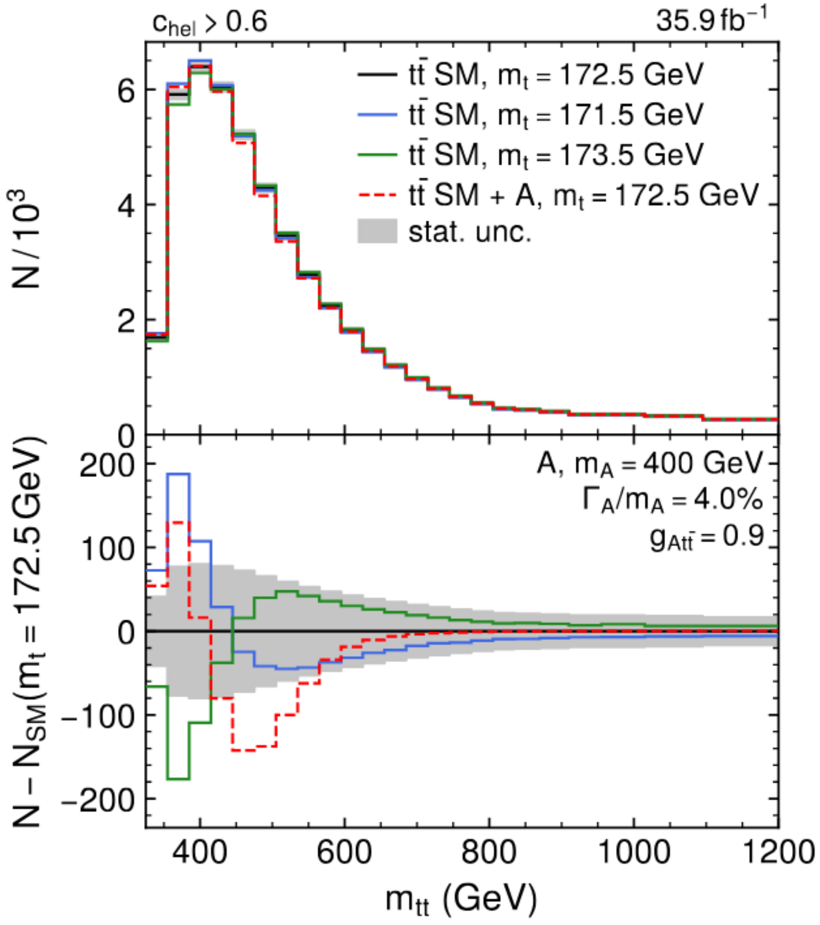
> Reweighting from NLO Powheg+Pythia to NNLO-QCD+NLO-EW

> 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

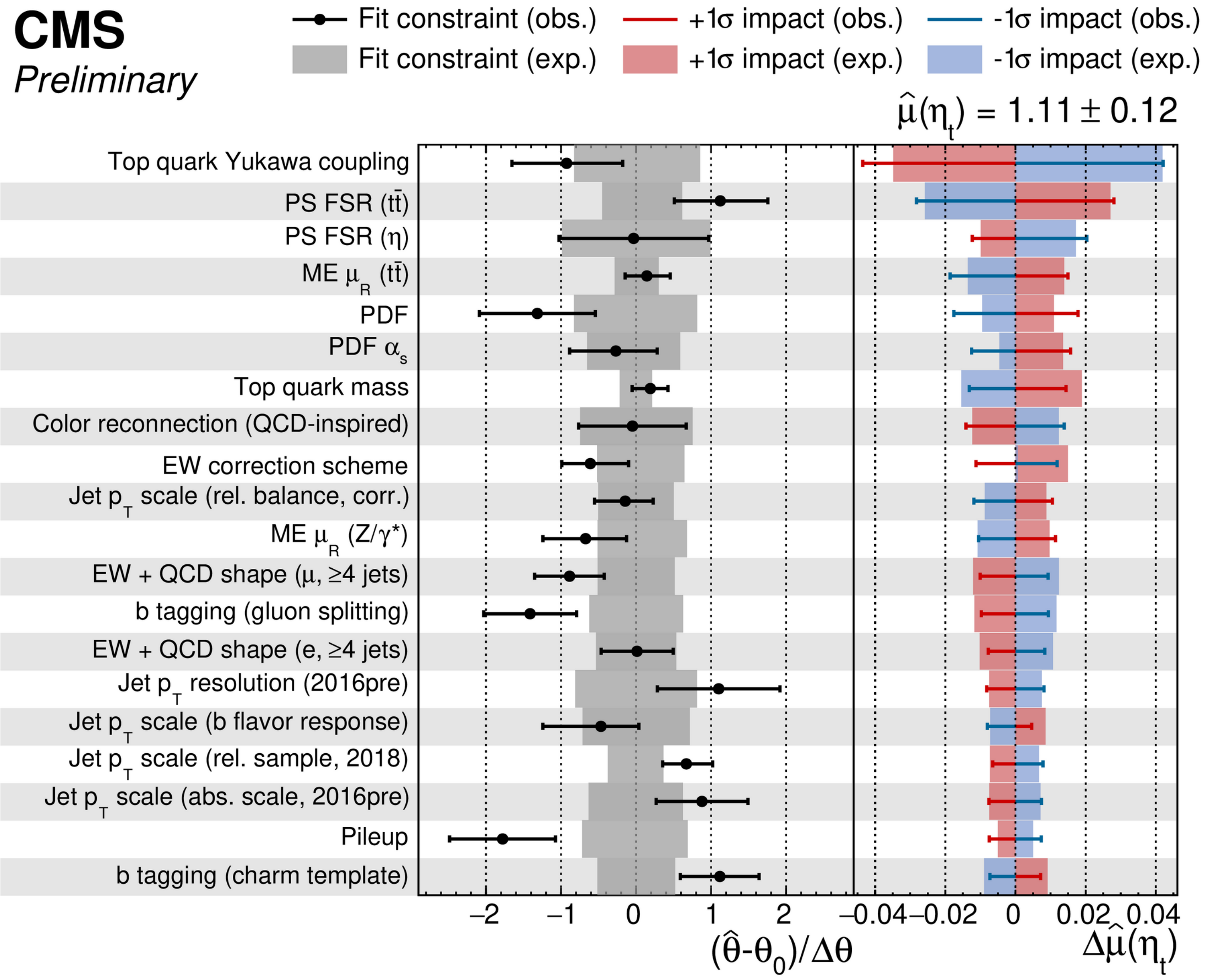


Differences in treatment of systematic uncertainties

> 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} ?

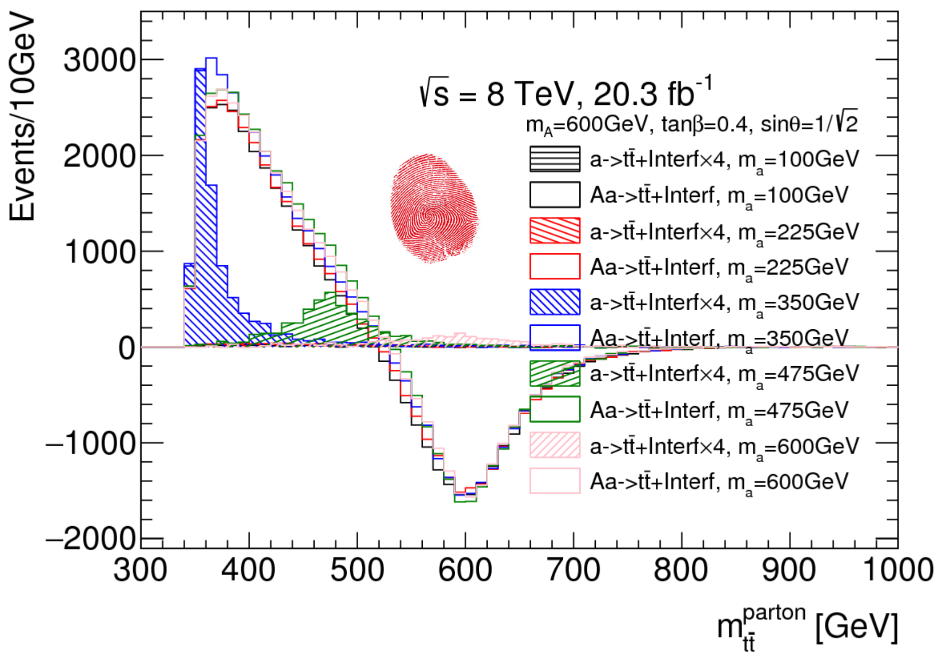


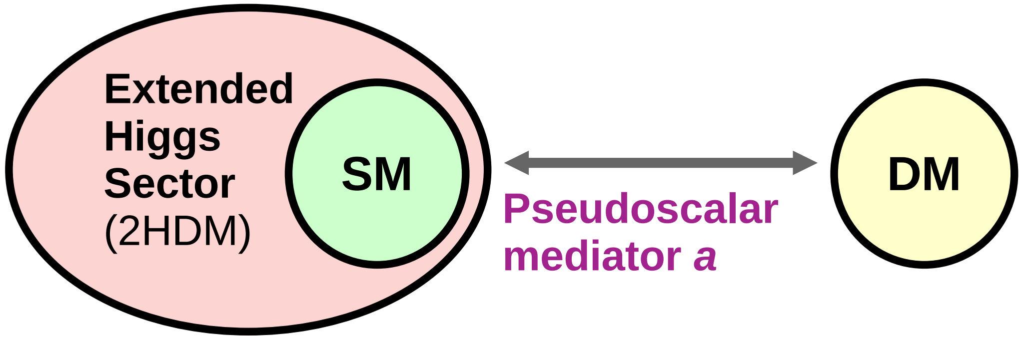
Dark matter interpretations: 2HDM+a

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





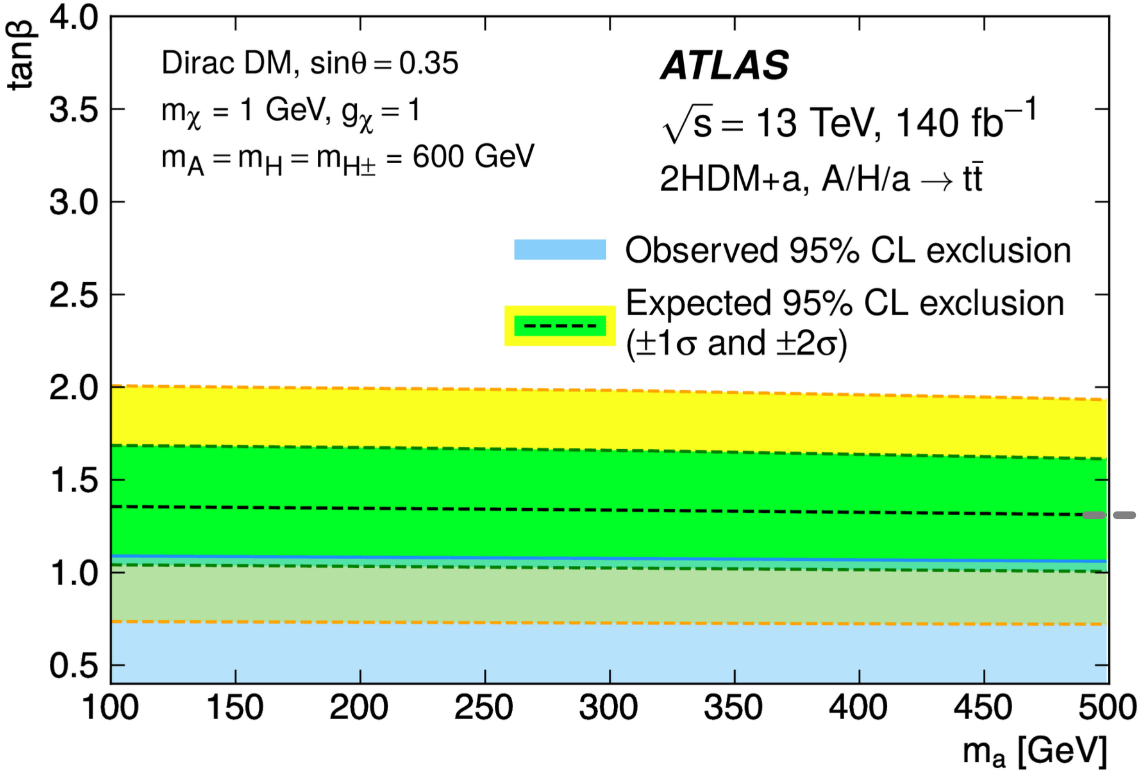
LHC Dark Matter Working Group: Phys. Dark Univ. 27 (2020) 100351

Bauer, Haisch, Kahlhoefer: JHEP05(2017) 138

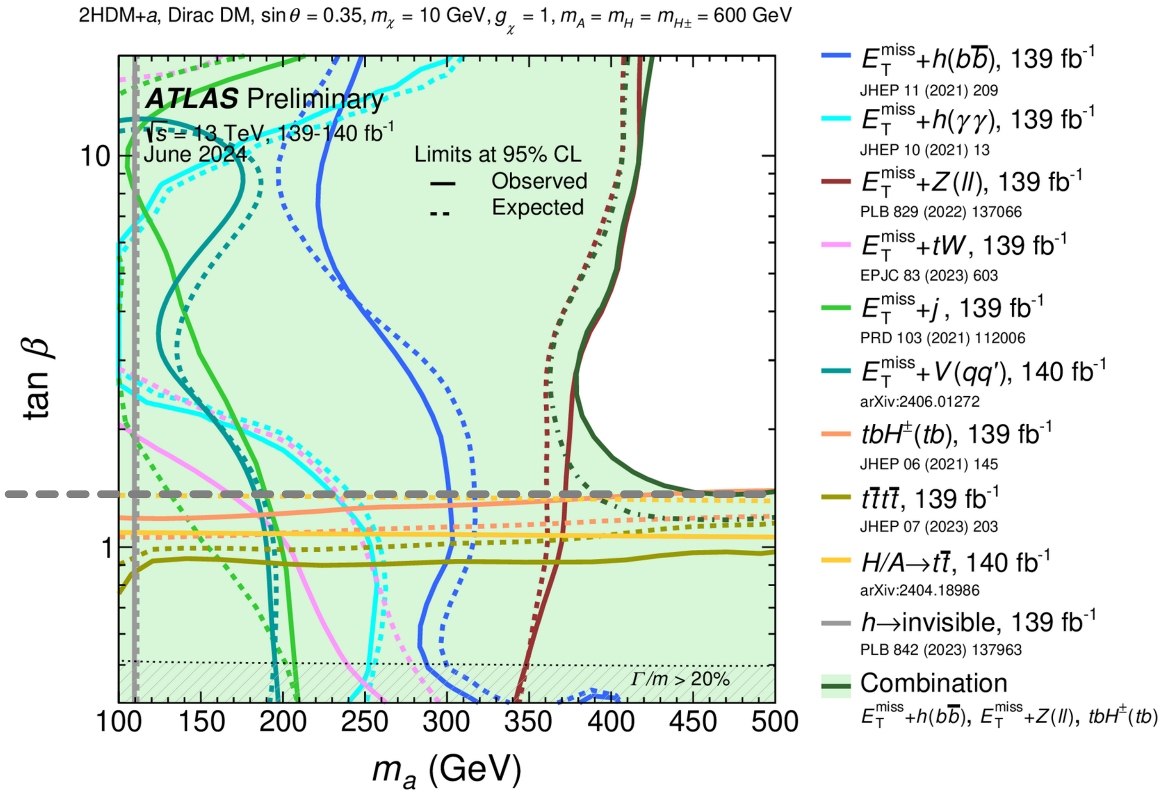
Dark matter interpretations: 2HDM+a

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



The LHC today

- LHC Page 1: https://op-webtools.web.cern.ch/vistar/vistars.php
- Collisions at new record energy of 13.6 TeV started on 5th July!

Matter-antimatter imbalance

- Equal amounts of matter and antimatter created in the Big Bang (B=0)
- Observable universe completely dominated by matter (B>0)
- What caused this imbalance?

- **Sakharov conditions**
  1. Baryon number violating processes
  2. C and CP violation
  3. Processes out of thermal equilibrium

- Possible in the SM and BSM models
  - E.g. supersymmetry
- Not observed yet
  - Proton decay would be the smoking gun

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  2. C and CP violation
  3. Processes out of thermal equilibrium

Conditions met in SM e.g. during EWSB

The strong CP problem (1)

> QCD can in principle violate CP (assuming all quarks are massive)

> Example of a Yang-Mills theory with a single massive quark

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \boxed{\theta\frac{g^2}{32\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu}} + \bar{\psi}(i\gamma^\mu D_\mu - \boxed{me^{i\theta'\gamma_5}})\psi.$$

Potentially CP violating, unless $\theta = -\theta'$
→ fine-tuning!

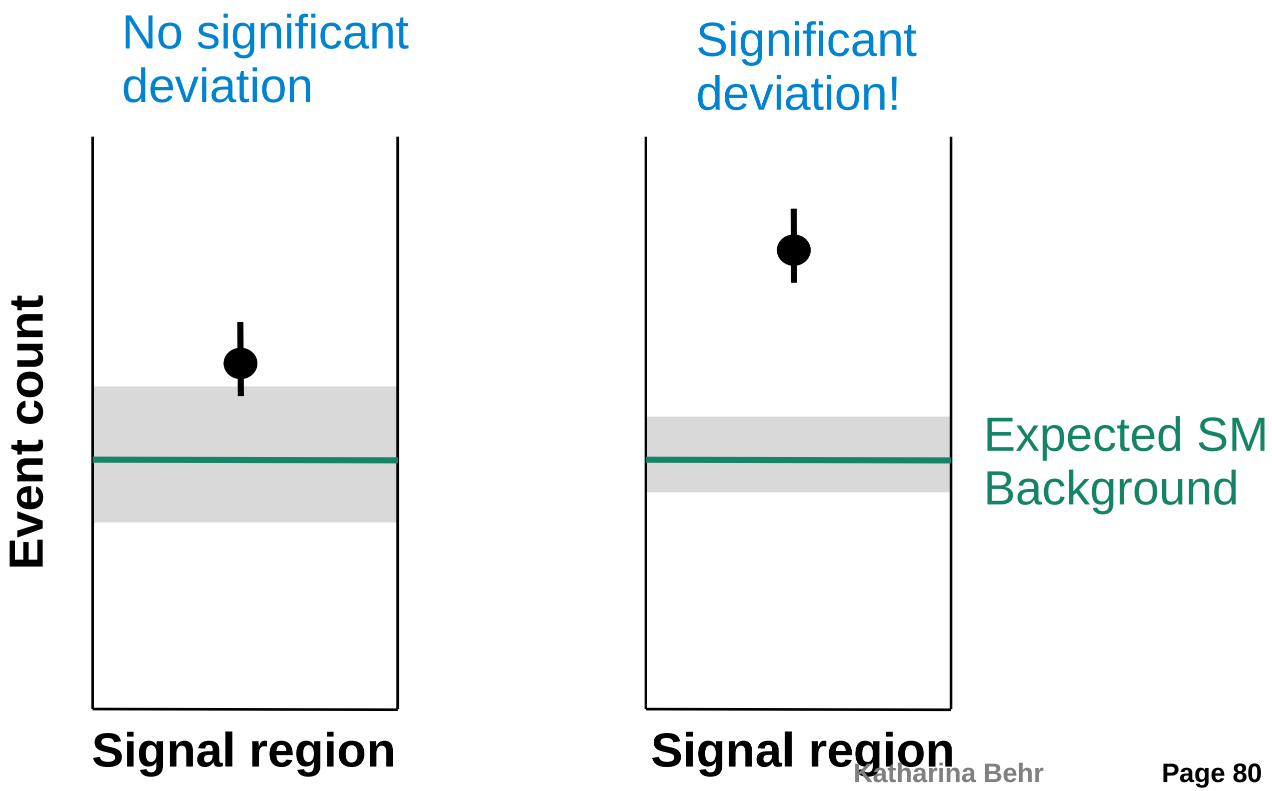
> Strong CP violation in SM QCD (6 massive quarks) via equivalent phase θ^*

> Would imply non-zero neutron electric dipole moment: $d_N = (5.2\ 10^{-16}\ e\ \mathrm{cm})\ \theta^*$

> Measurements constrain dipole moment to $|d_N| < 10^{-26}\ e$ cm → $\theta^* < 10^{-10}$ → fine-tuning!

Cut-and-count method

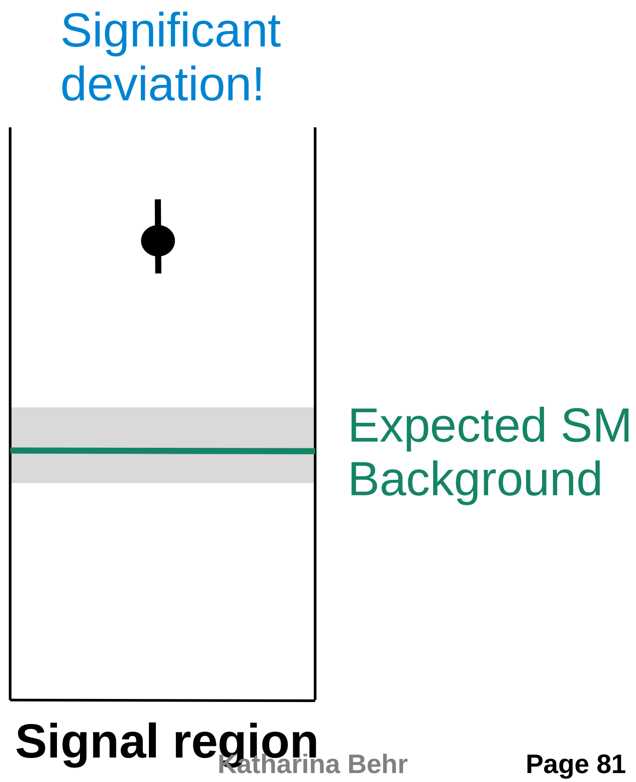
- Select (**cut**) events that you expect to be consistent with signal (signal region)
- **Count** data events in signal region and compare with number of expected SM events
- Calculate significance of deviation from SM prediction (accounting for uncertainties)



Cut-and-count method

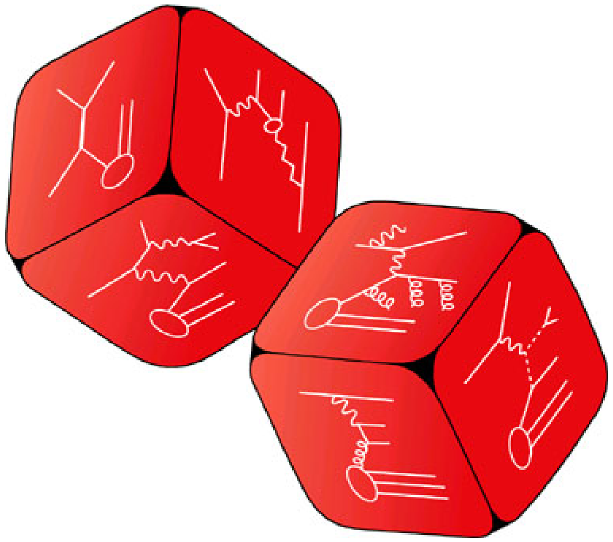
- Select (**cut**) events that you expect to be consistent with signal (signal region)
- **Count** data events in signal region and compare with number of expected SM events
- Calculate significance of deviation from SM prediction (accounting for uncertainties)

- **Advantage**: suited for low-stat regions, model agnostic
- **Disadvantage**: single bin → vulnerable to fluctuations → less sensitive



Monte Carlo event generators in a nutshell

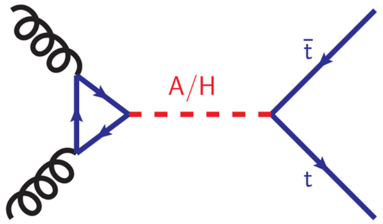
- Quantum nature of elementary particle interactions: non-deterministic
  - Given initial state can lead to different final states with different probabilities
- **Idea:**
  - Calculate probability distribution for a given process (or sub-processes)
  - Random sampling to generate events with particle kinematics according to these distributions



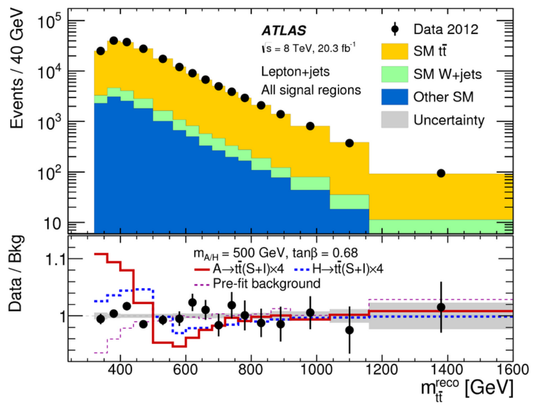
Experimental Techniques

Experimental analysis step by step

> Pick and study a signal of interest

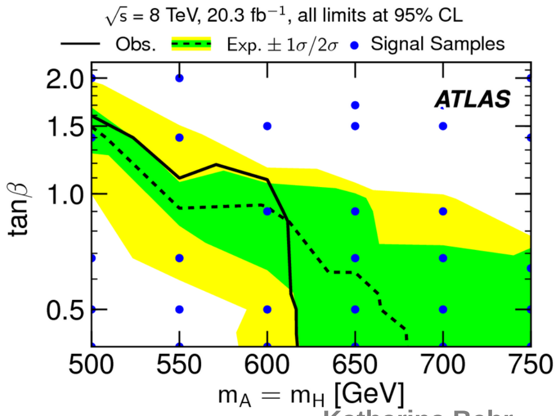


> Select subset of events enriched in signal (signal region)



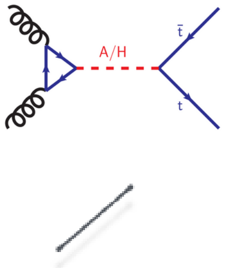
> Estimate backgrounds and systematic uncertainties

> Test agreement between SM prediction and data



How to search for BSM signals?

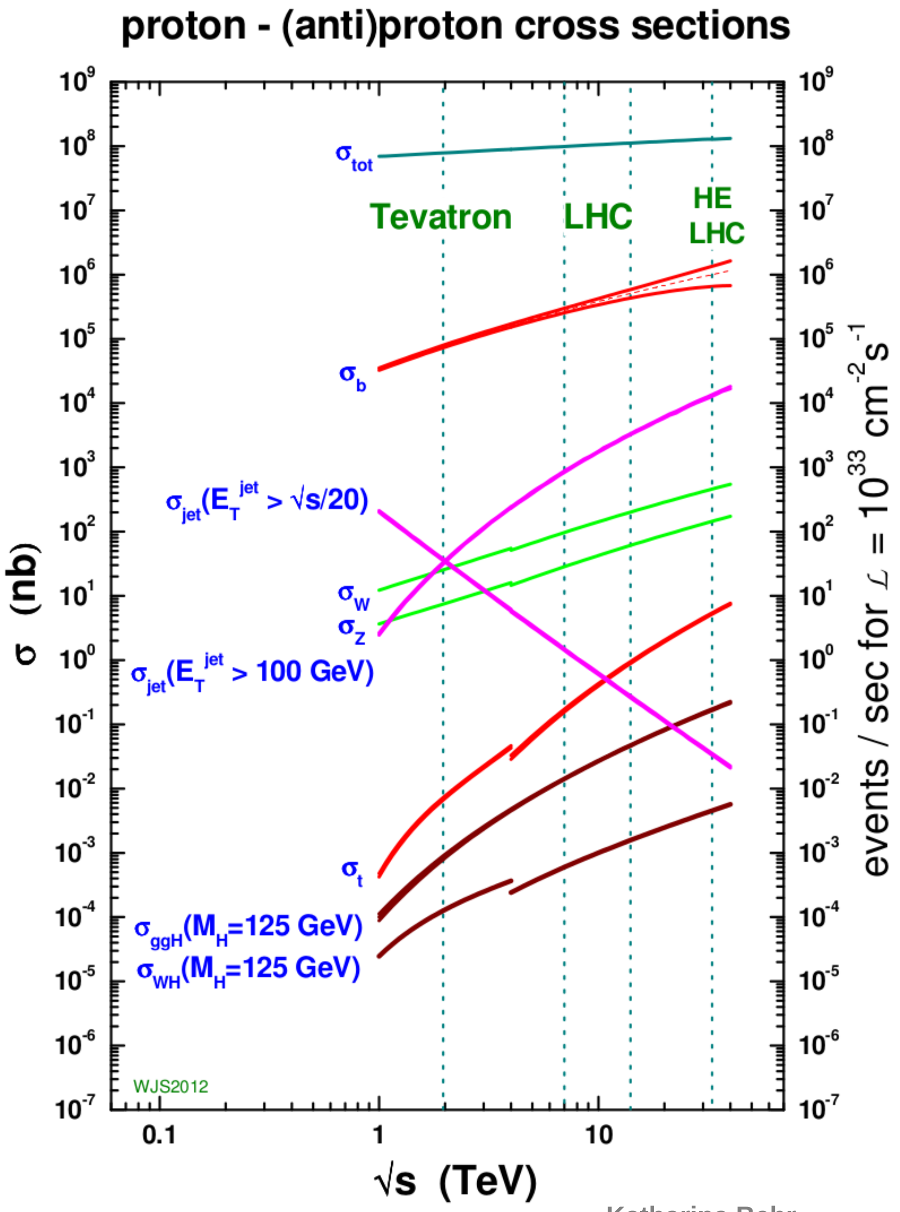
> Isolate small signal from huge dataset



Signal
(a.k.a. the needle)

Background
(a.k.a. the haystack)
(...it's meant to be a haystack)

T.G. McCarthy



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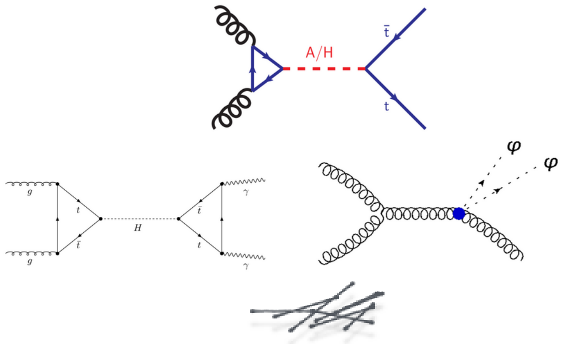
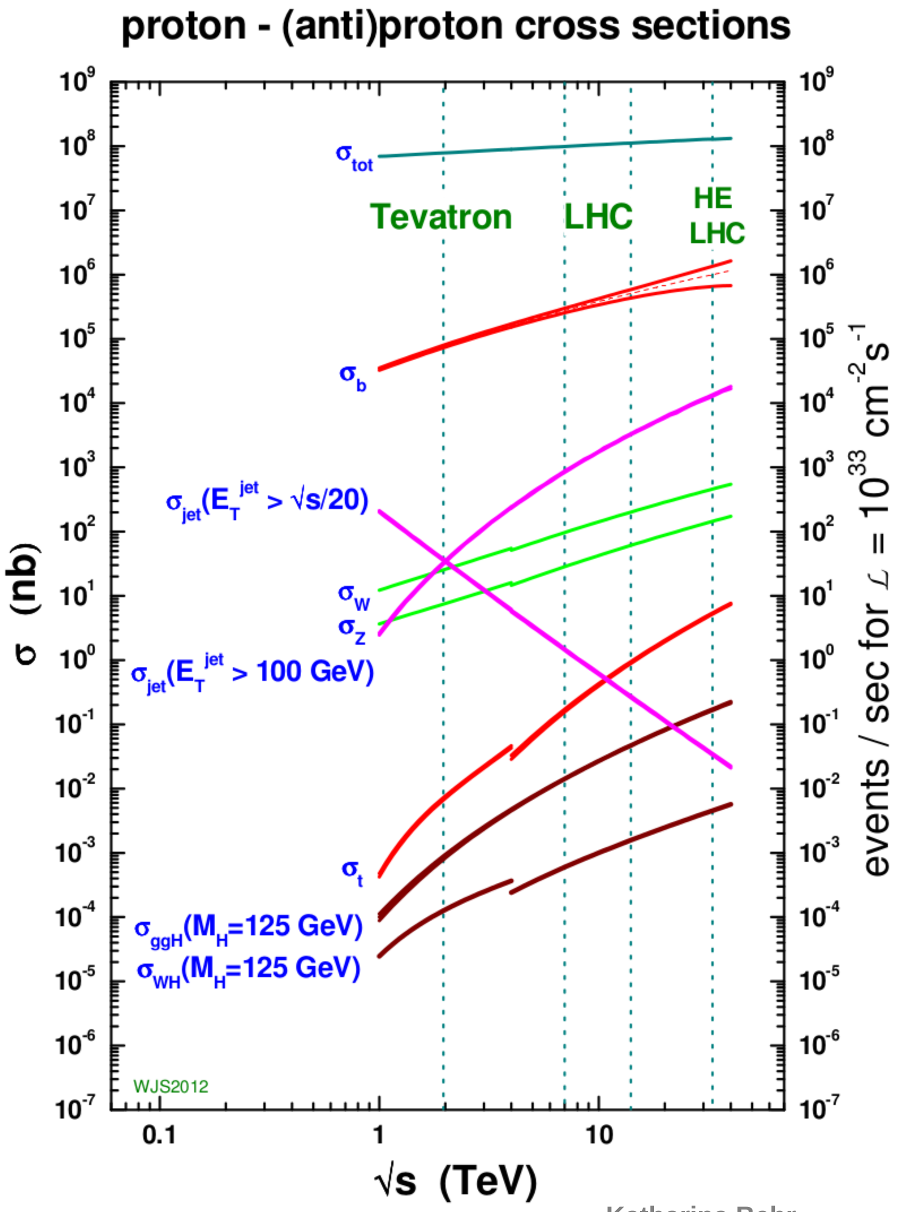


Signal
(several needles)

Backgrounds
(several different types of haystacks)
(will all be blended together into a big mess)

T.G. McCarthy

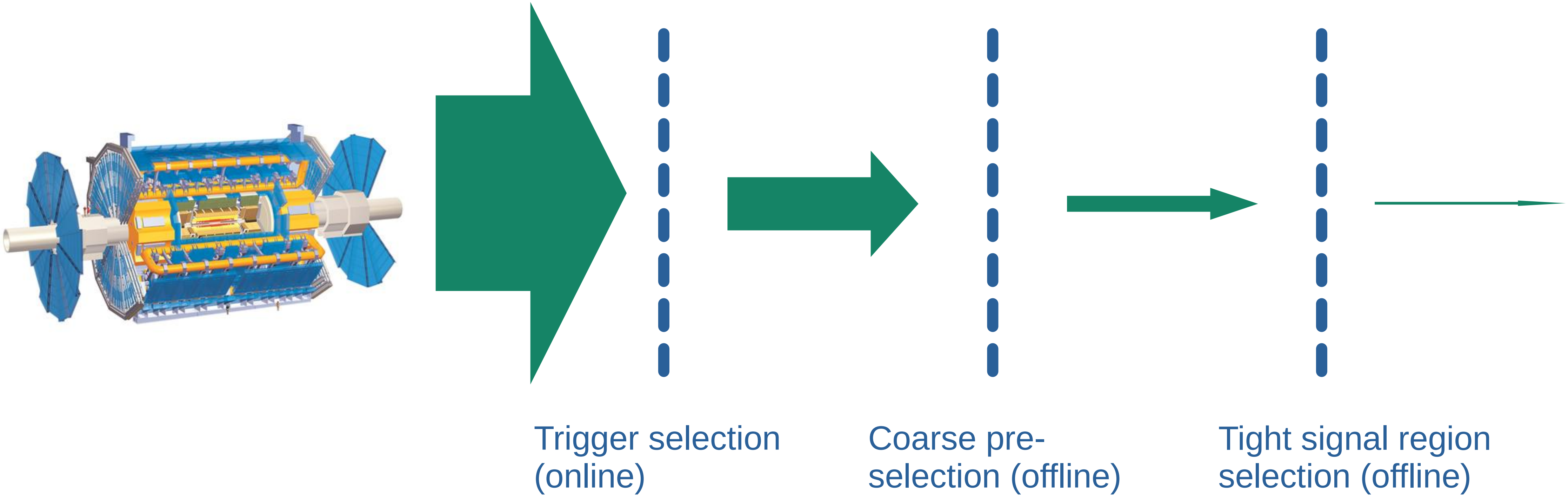


Select signal-like events

> Define criteria that characterise chosen signal in detector

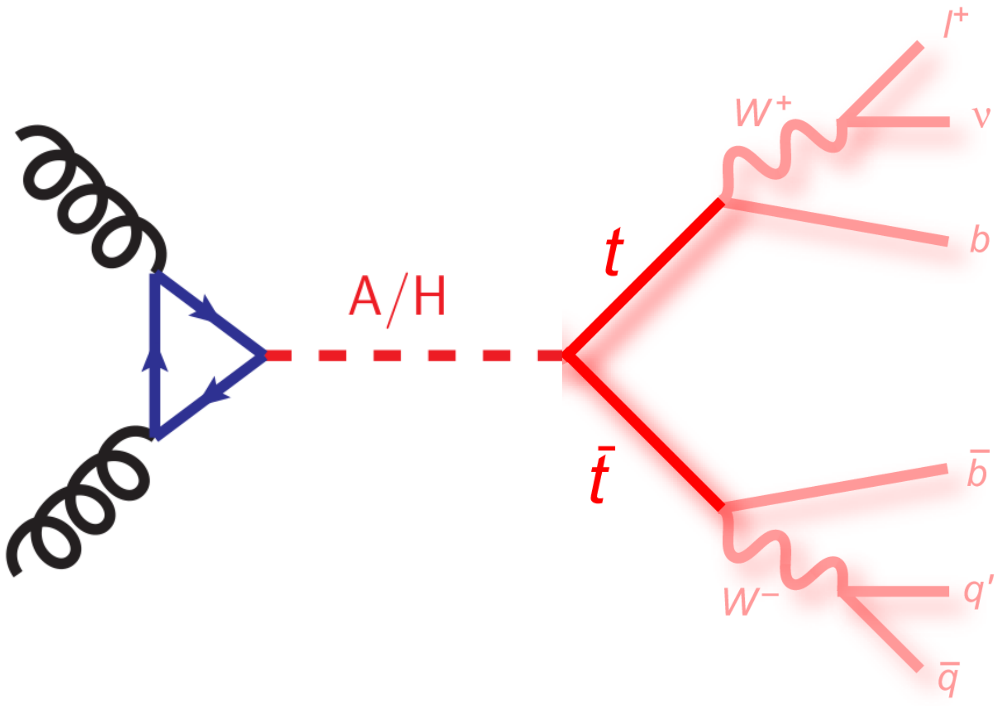
> Apply selection criteria to reduce background

> Signal-enriched region (signal region)



Exercise

- Define a signal region for semi-leptonic ttbar decay
- For simplicity assume that charged lepton is an electron or muon



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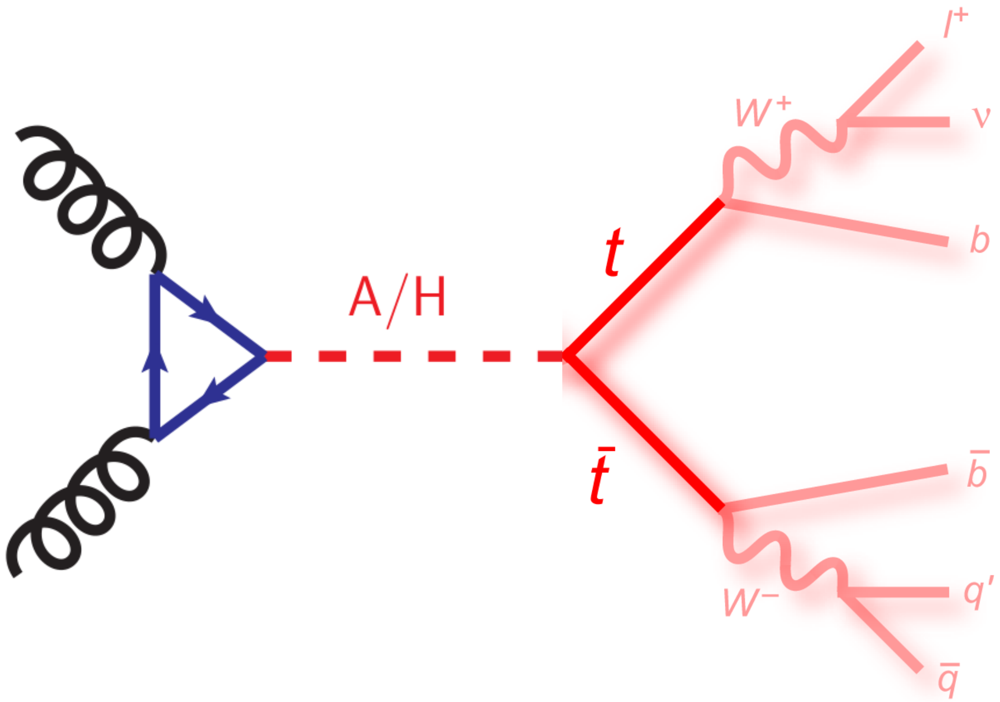
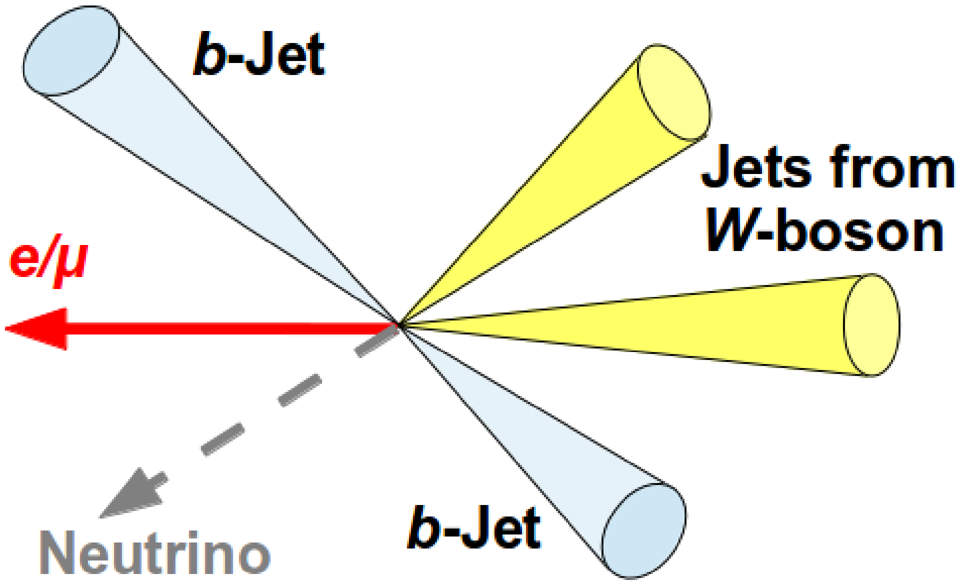


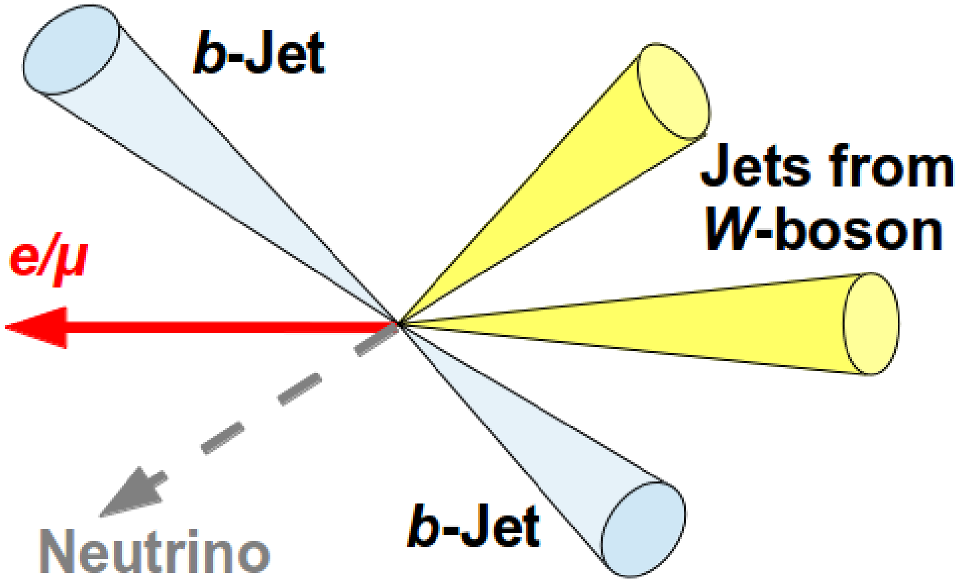


Exercise: Solution

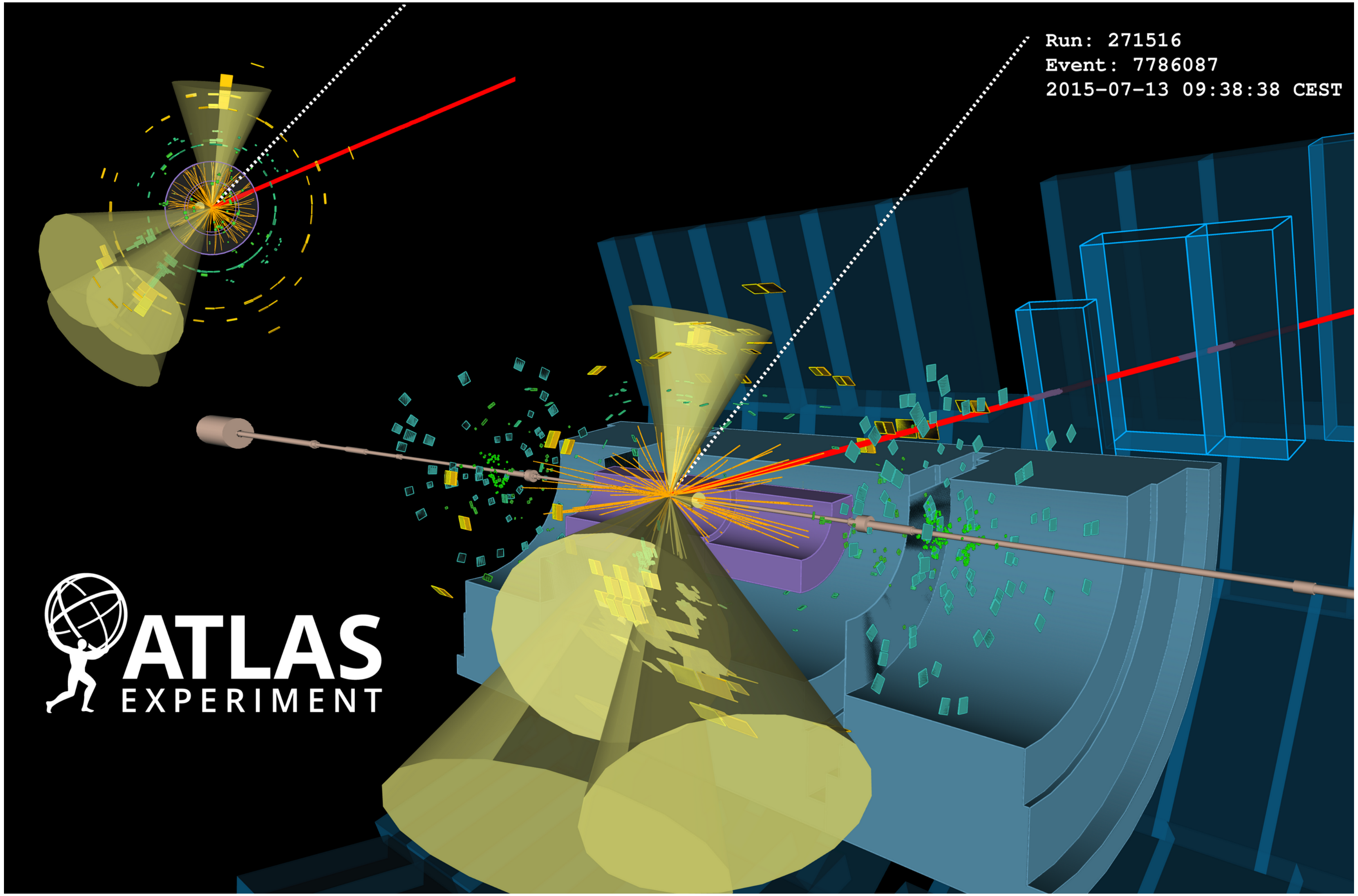
- > Exactly 1 electron or muon
- > Missing energy (from the neutrino)
- > At least 4 jets

- > Bonus 1: 2 jets identified as b-jets

- > Bonus 2:
  - Combined mass of 2 jets = W mass
  - Combined mass of 3 jets = top mass

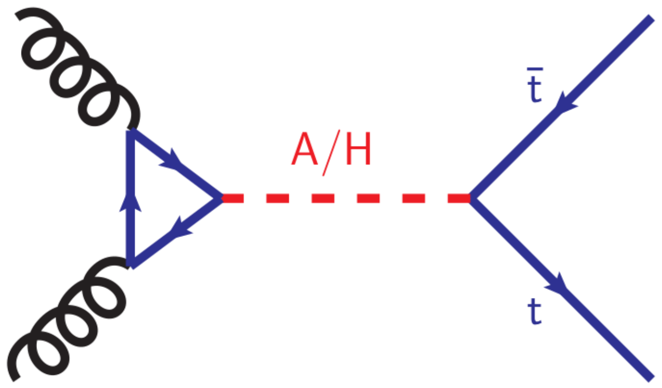


Exercise: Solution

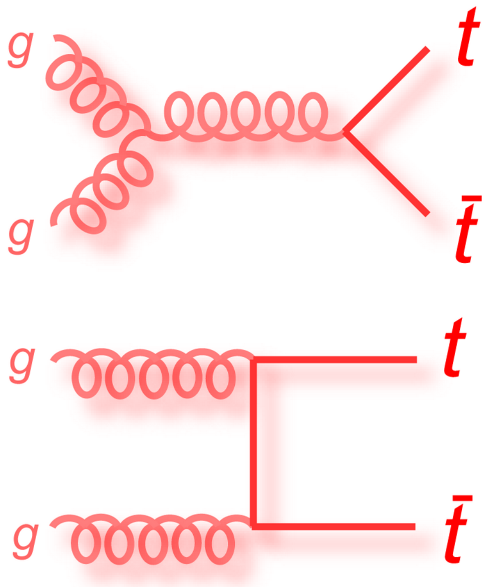


Signal vs backgrounds

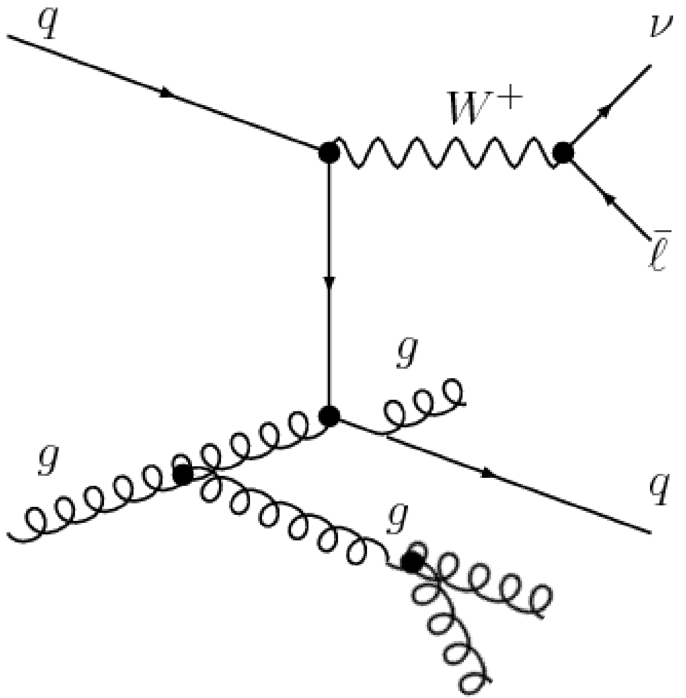
Signal



SM ttbar production
Irreducible background



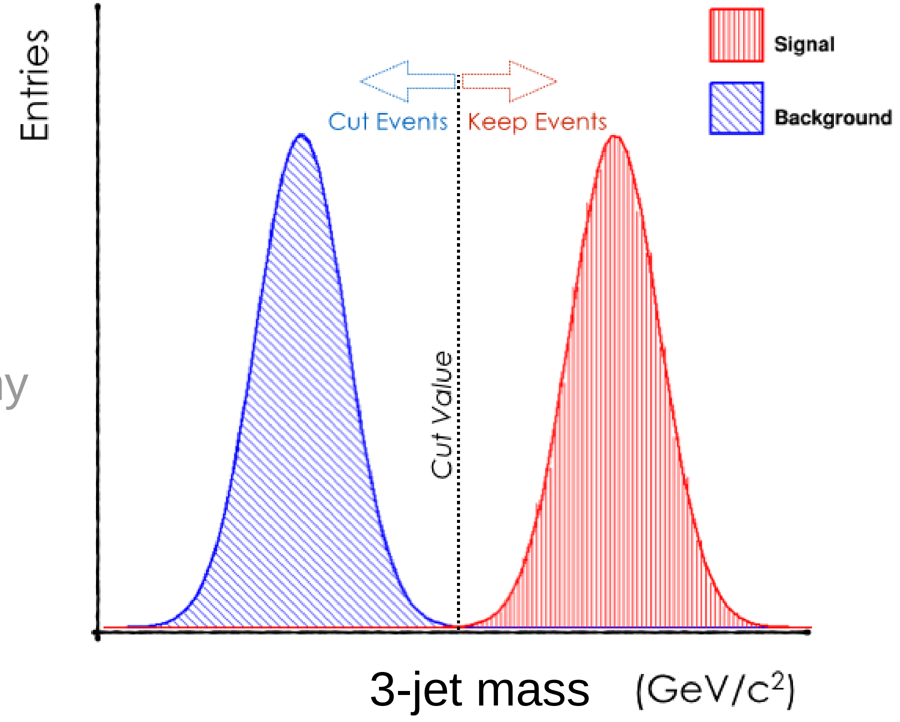
SM W+jets production
Reducible background



Signal region definition

- Apply selection criteria (cuts) to reduce background
- Signal-enriched region (signal region)
- Additional cuts based on differences in kinematic distributions

T.G. McCarthy



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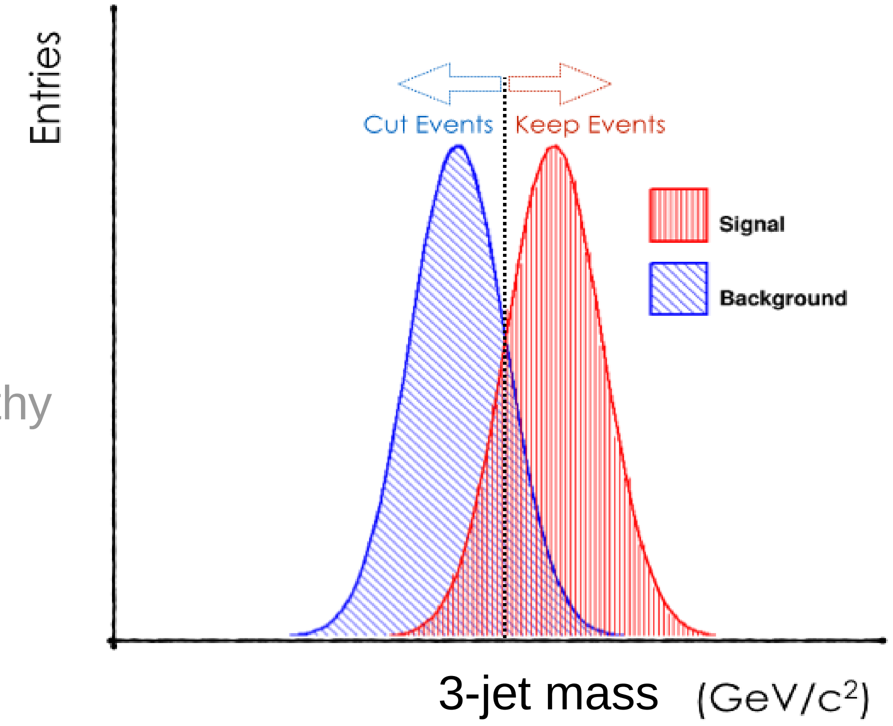

T.G. McCarthy

Signal region definition

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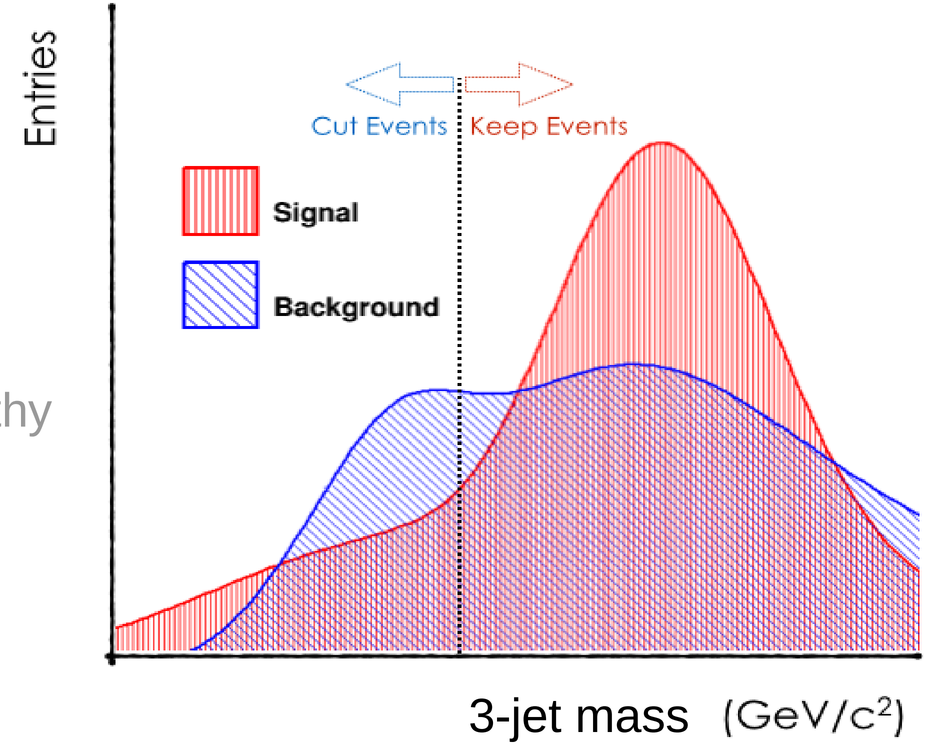
- Additional cuts based on differences in kinematic distributions

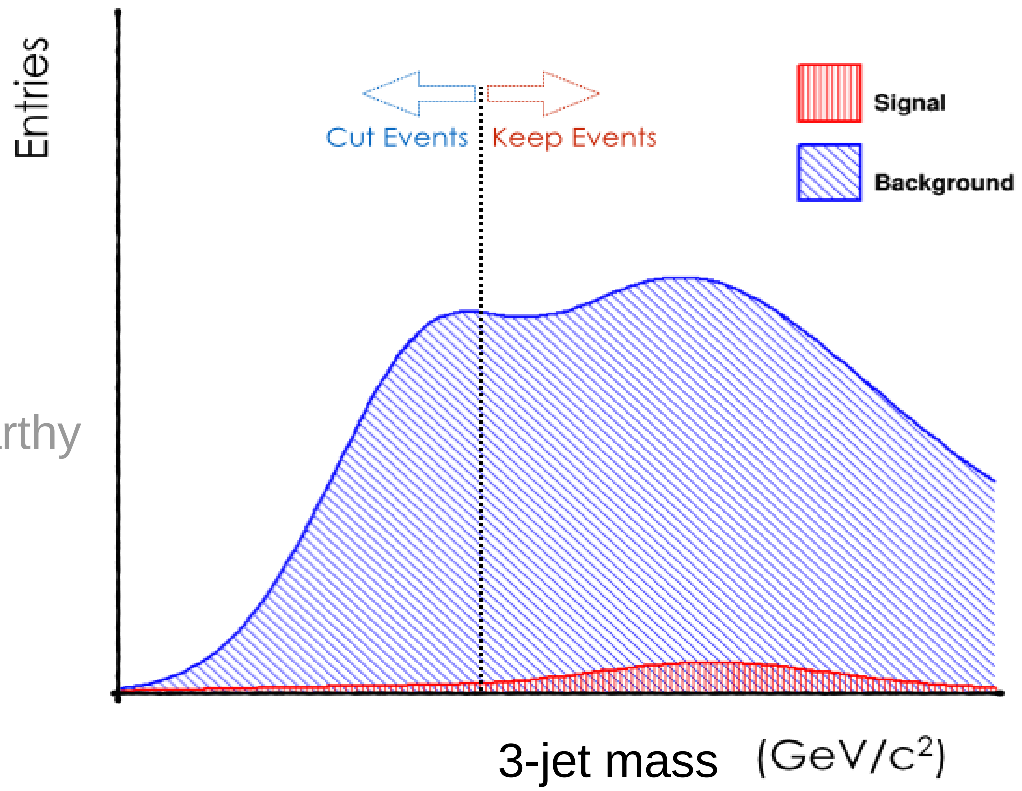
T.G. McCarthy



Signal region definition

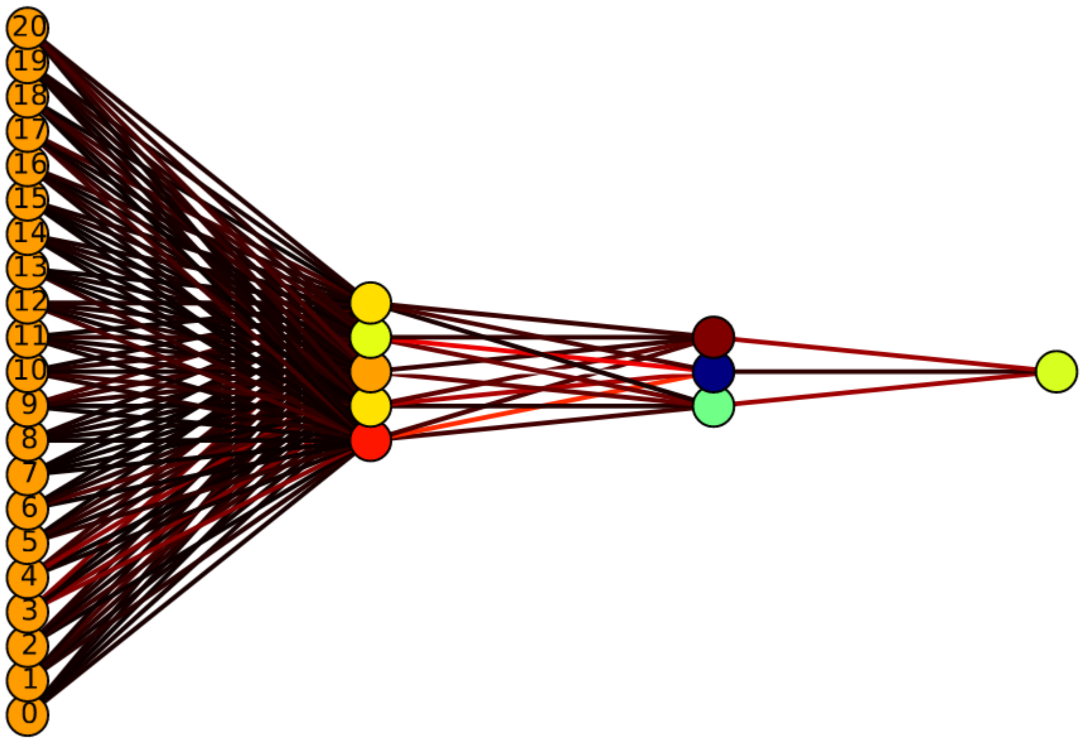
- Apply selection criteria (cuts) to reduce background
- Signal-enriched region (signal region)
- Additional cuts based on differences in kinematic distributions

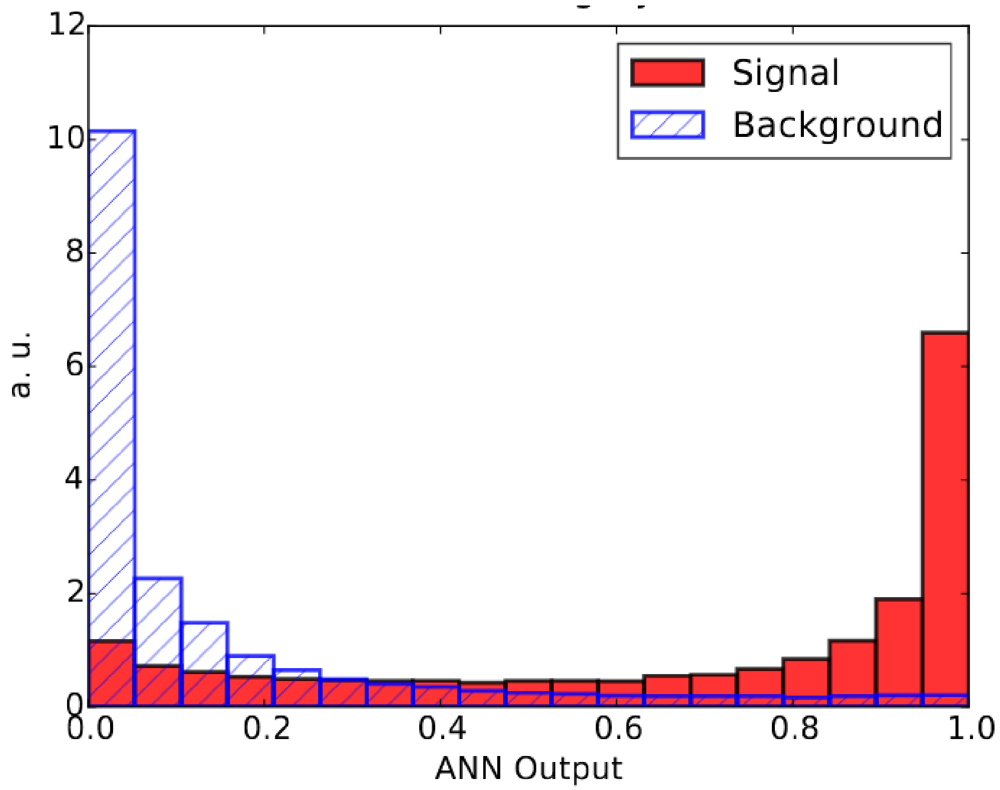
T.G. McCarthy



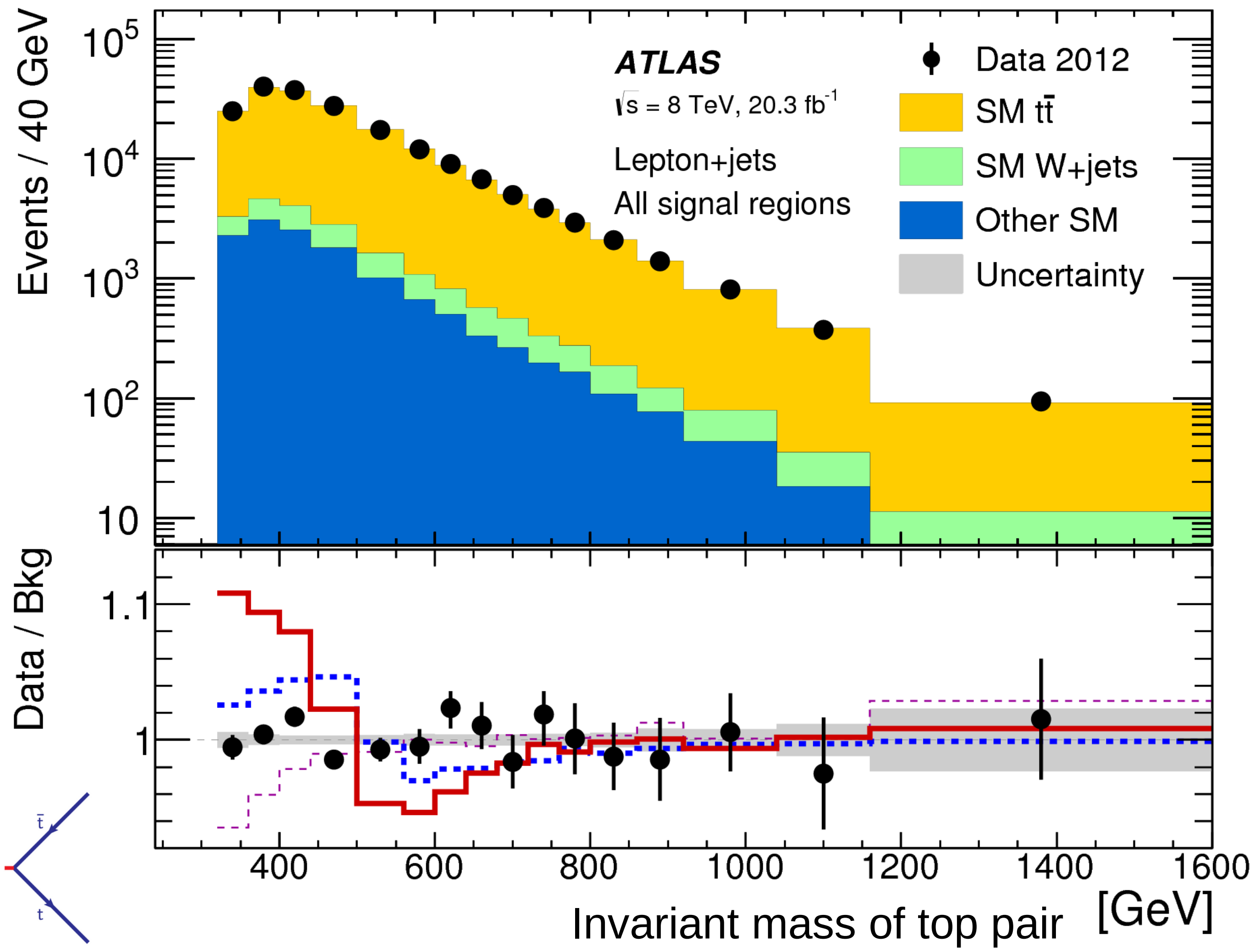
Signal region definition

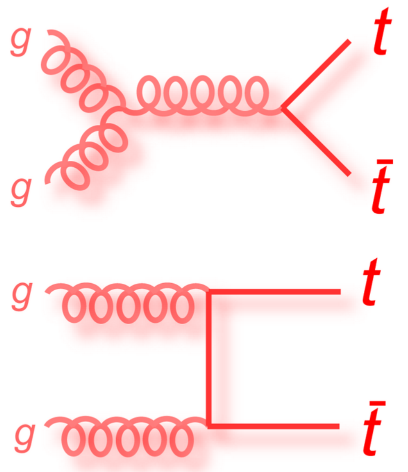
> Can refine signal regions using machine-learning algorithms
  - Exploit small differences in various kinematic variables
  - Exploit correlations

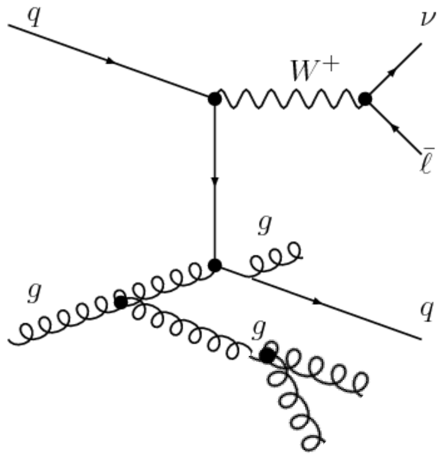


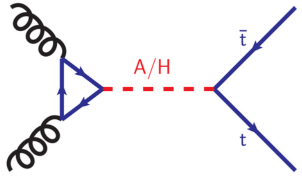


A final signal region







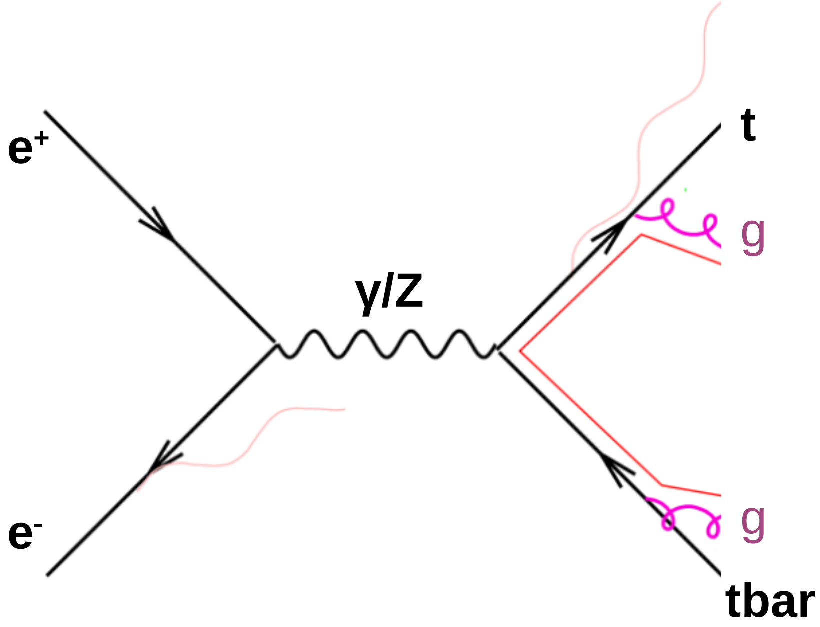


Event simulation

- Simulate possible signals based on theoretical models
  - Optimise sensitivity of searches
- Simulate background processes
  - Compare predictions to data and look for deviations
  - Some background processes can be simulated very accurately…
  - … others not (see data-driven estimates later)
- Estimate systematic uncertainties
  - Create different background predictions within experimental uncertainties
  - E.g. top mass known with ±1 GeV uncertainty
    - → Simulate top quark pair production for m_{top}(central) and m_{top}(central)±1 GeV

Simulation step by step

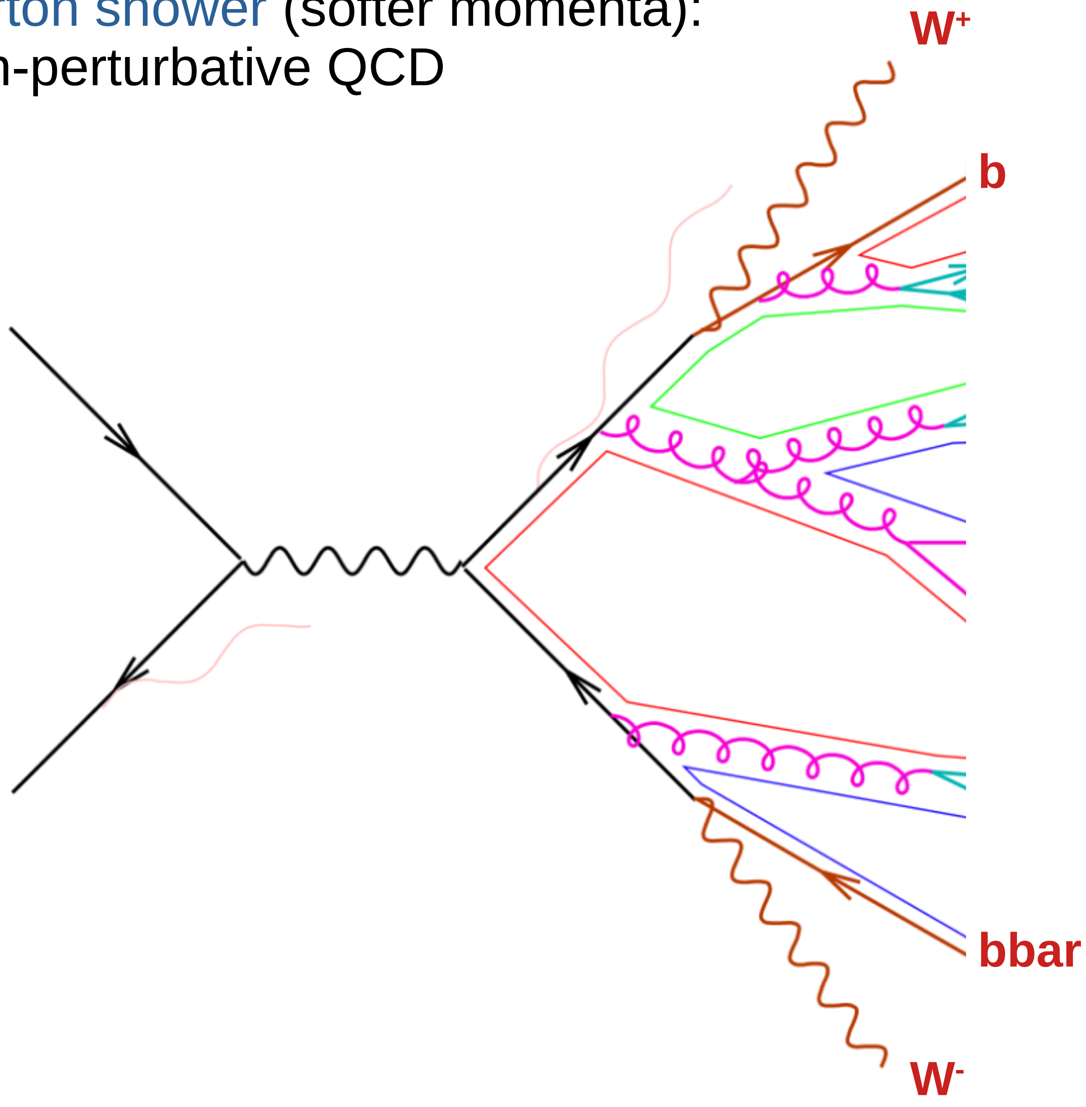
- Hard processes (large momentum transfers): perturbative QCD



- hard scattering
- (QED) initial/final state radiation

Simulation step by step

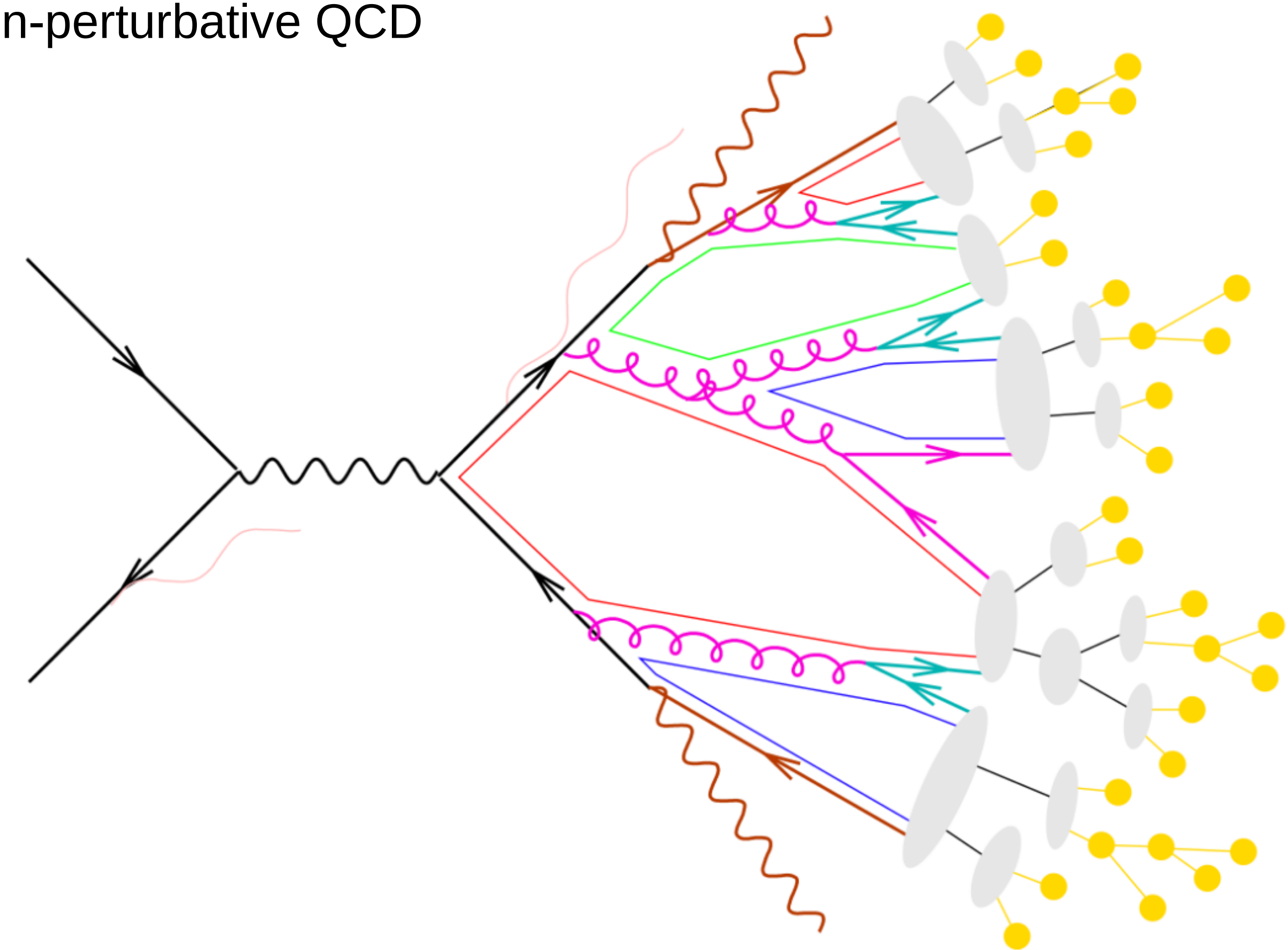
> Parton shower (softer momenta): non-perturbative QCD



- hard scattering
- (QED) initial/final state radiation
- partonic decays, e.g. $t \rightarrow bW$
- parton shower evolution
- nonperturbative gluon splitting

Simulation step by step

> Hadronisation (soft, low energy): non-perturbative QCD



- hard scattering
- (QED) initial/final state radiation
- partonic decays, e.g. $t \rightarrow bW$
- parton shower evolution
- nonperturbative gluon splitting
- colour singlets
- colourless clusters
- cluster fission
- cluster $\rightarrow$ hadrons
- hadronic decays

Think outside the (black)box!

> Many different event generators available for HEP/LHC

  – Choice depends on process, required precision, …

    • E.g. matrix-element generators: MadGraph, Powheg

    • E.g. matrix-element + parton-shower generators: Pythia, Herwig

  – Important to understand differences and subtleties to not treat them as blackboxes!

Think outside the (black)box!

“[…] remember that the programs ***do not represent a dead collection of established truths****, but rather one of many possible approaches to the problem of multiparticle production in high-energy physics, at the frontline of current research.* ***Be critical!****”*

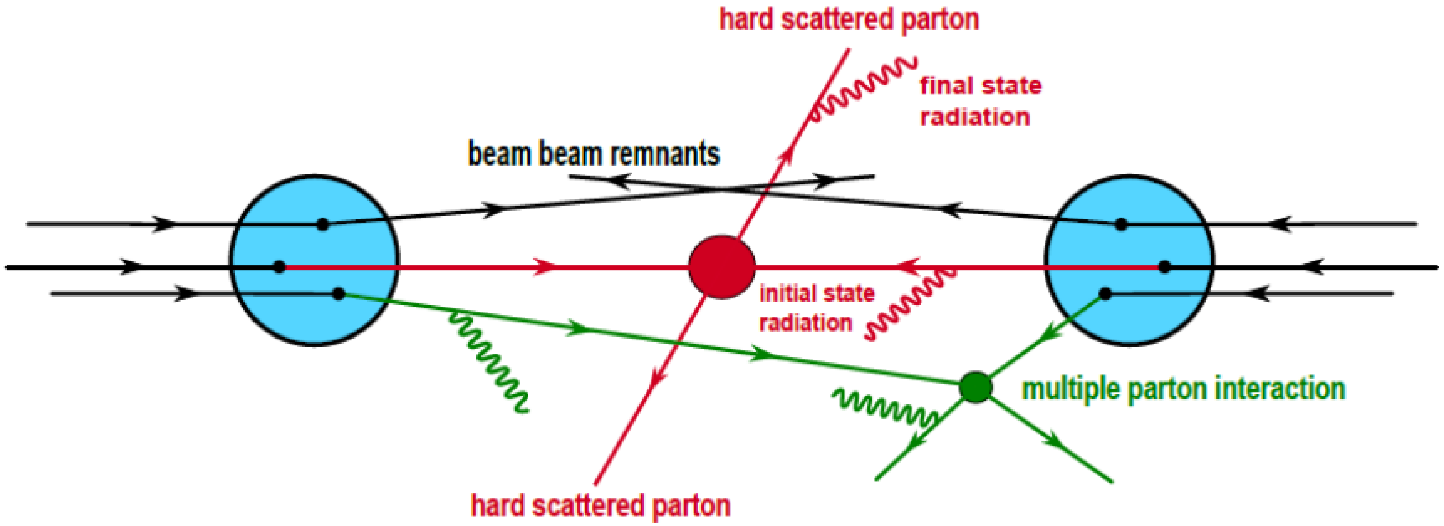
From the manual of the Pythia5 MC generator

Further aspects

- Simulate interactions of (collider) stable particle with detector material
  - Geant4, Delphes, ...

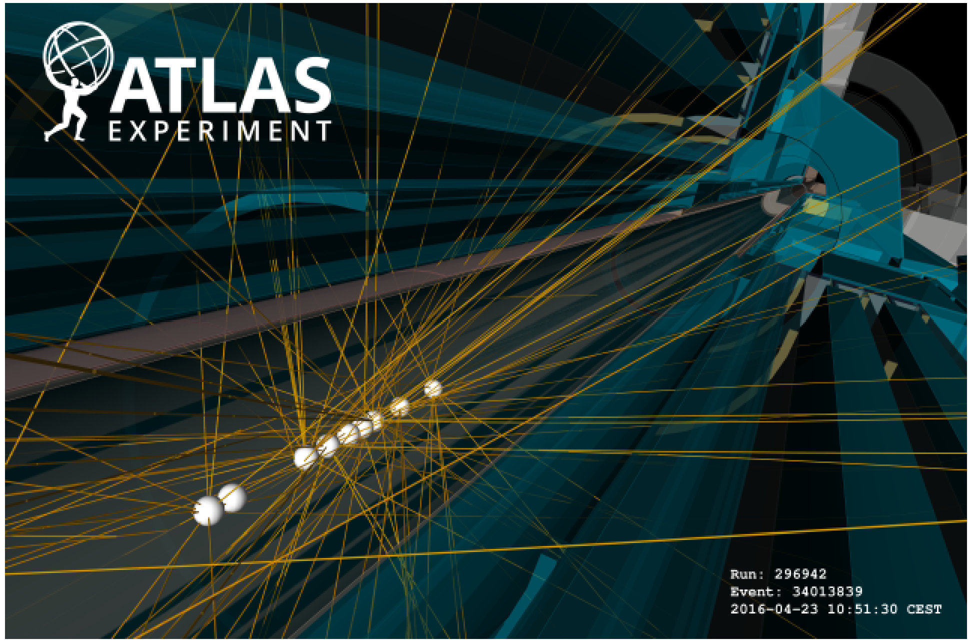
Further aspects

- Simulate interactions of (collider) stable particle with detector material
  - Geant4, Delphes, …
- Specifically for hadron colliders (LHC, Tevatron, …):
  - **Underlying Event**: simulate interactions of additional partons within same two protons



Further aspects

- Simulate interactions of (collider) stable particle with detector material
  - Geant4, Delphes, …
- Specifically for hadron colliders (LHC, Tevatron, …):
  - **Underlying Event**: simulate interactions of additional partons within same two protons
  - **Pile-up**: simulate interactions of additional protons in the same bunch crossing



- Further reading:

  lecture by M. Seymour and M. Marx [link]

Estimating background processes from data

> Simulation not always feasible for estimating background processes
  - Instrumental backgrounds (related to detector effects)
    - Jets with high EM component faking electrons
    - Backgrounds from detector noise
    - …
  - Processes with large cross-section that would require large MC statistics
    - Mostly multijets at the LHC
  - Known modeling limitations
    - Missing higher-order processes
    - …

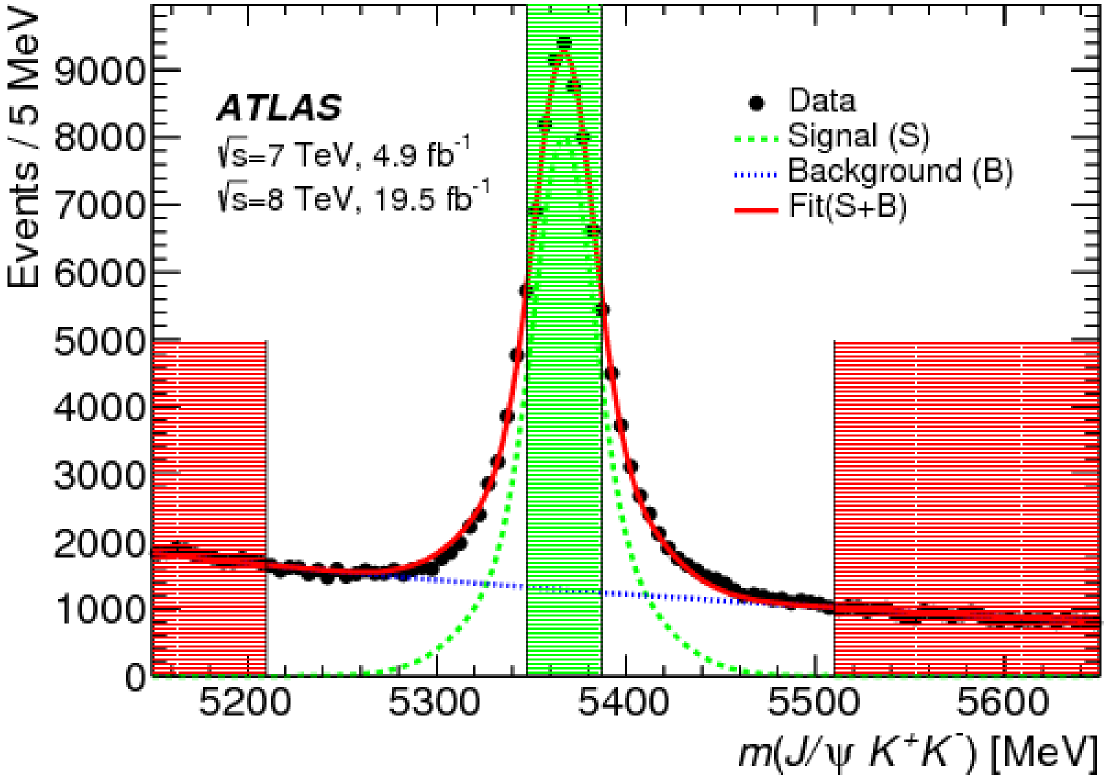
> Use fully data-driven estimates or data-driven corrections

Sidebands

> Assume known signal region (= location in the spectrum)

> Fit background in sidebands (= adjoining parts of the spectrum, signal depleted)

> Extrapolate to signal region

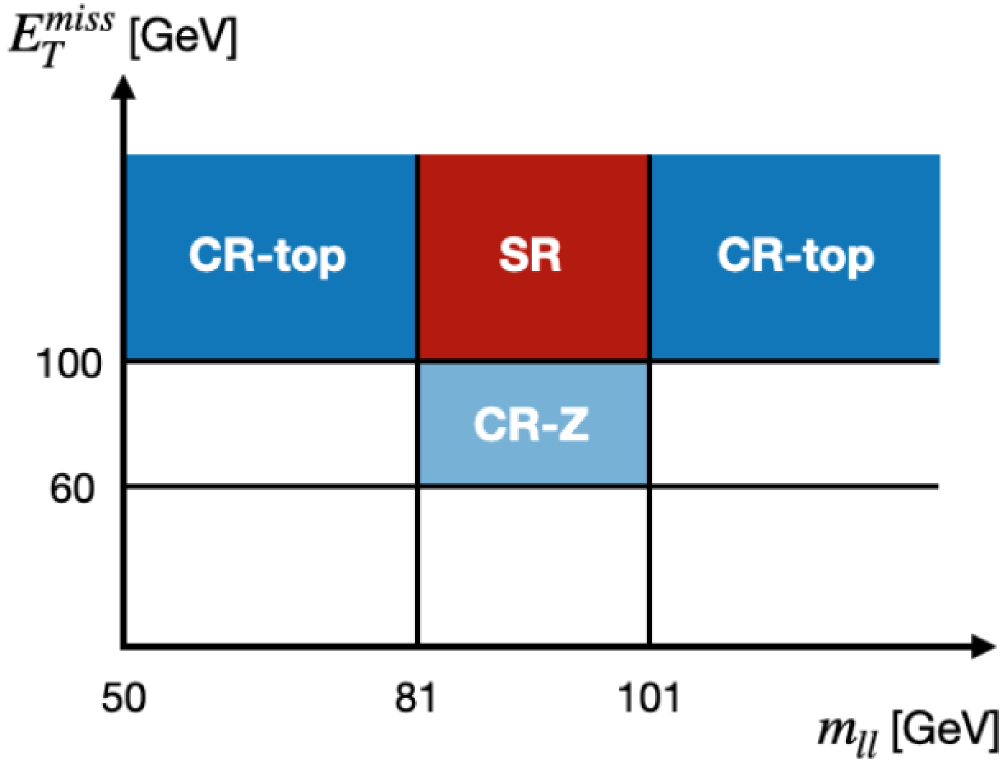


Control Regions

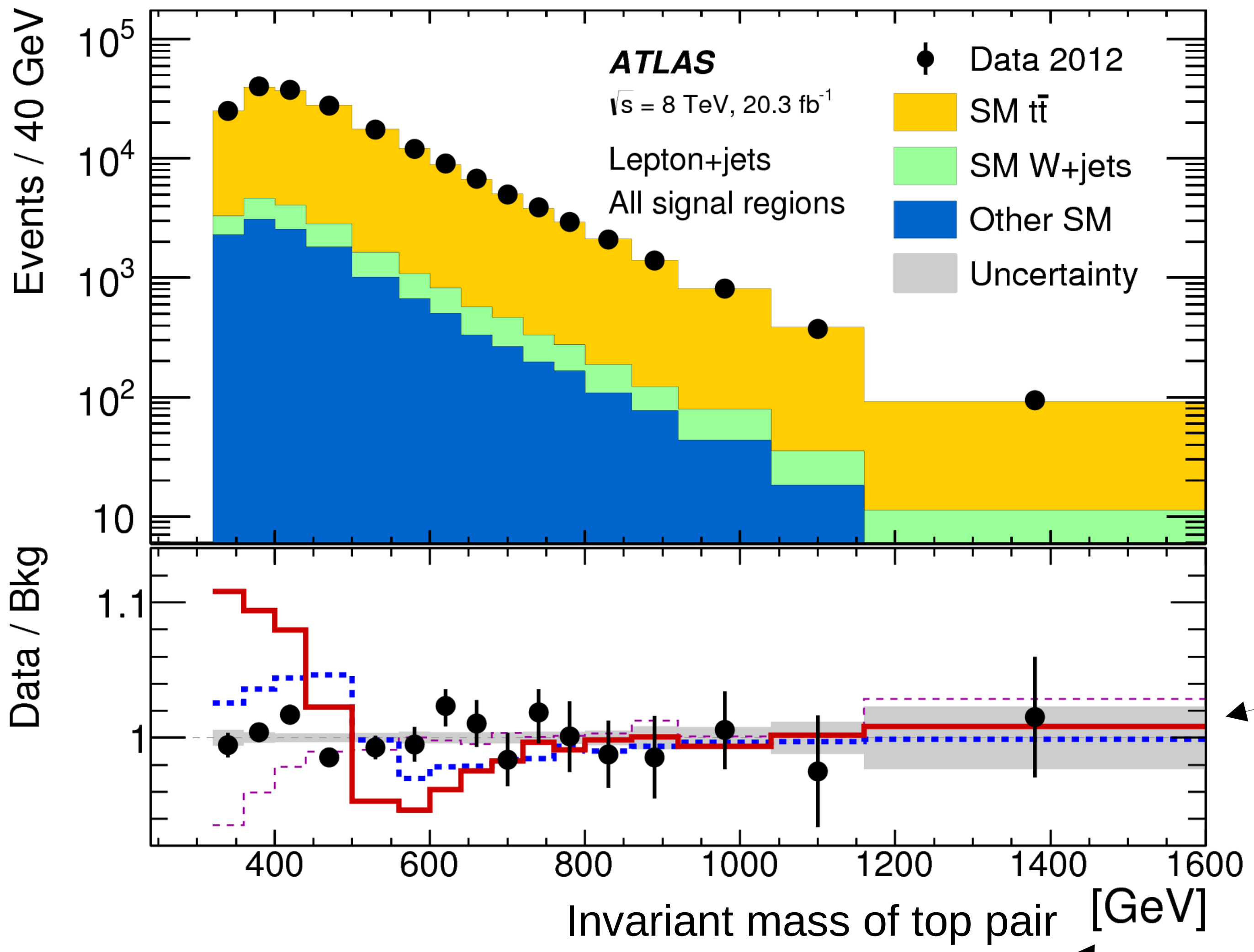
> Same idea as with sidebands but using a modified selection to define a control region
  - Orthogonal to signal region, signal depleted

> Must be carefully designed to
  - Be signal depleted
  - Be enriched in background of interest
  - Close enough to SR to avoid biases
  - ...

Signal signature: $Z(\rightarrow ll) + E_T^{miss}$ + bbar



A final signal region

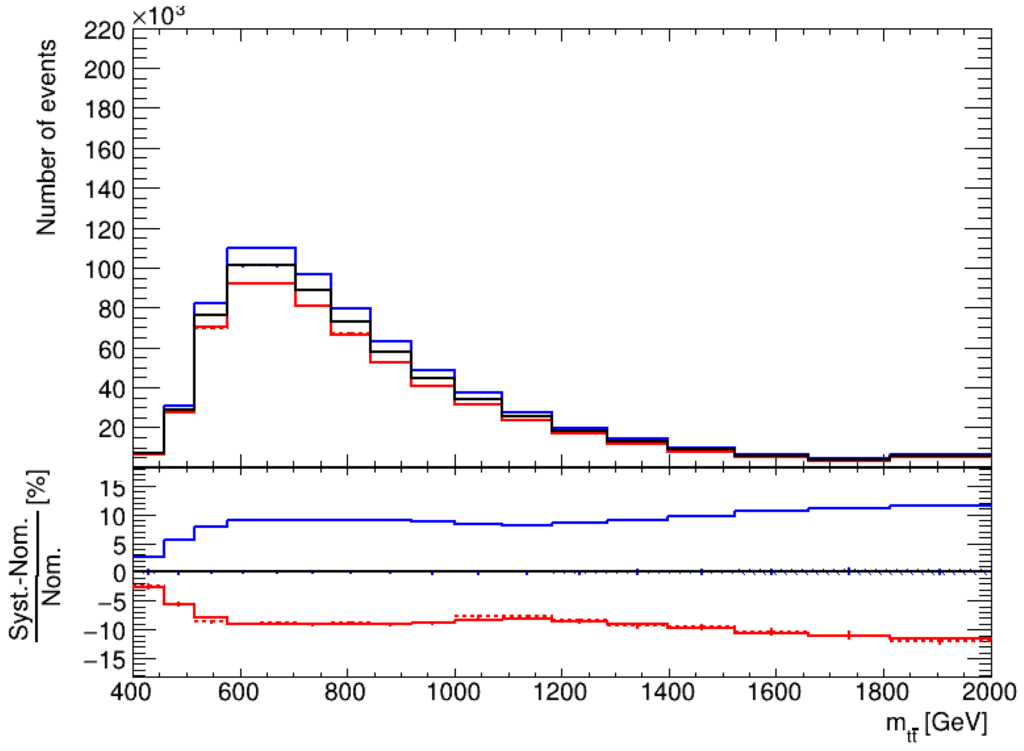


Systematic and statistical uncertainties

Variable of interest

Systematic uncertainties

- Various different sources:
  - Modeling uncertainties, e.g. unknown higher-order corrections
  - Experimental uncertainties, e.g. uncertainties on electron energy measurement
- Propagate to final spectrum
- Uncertainties degrade sensitivity to signal



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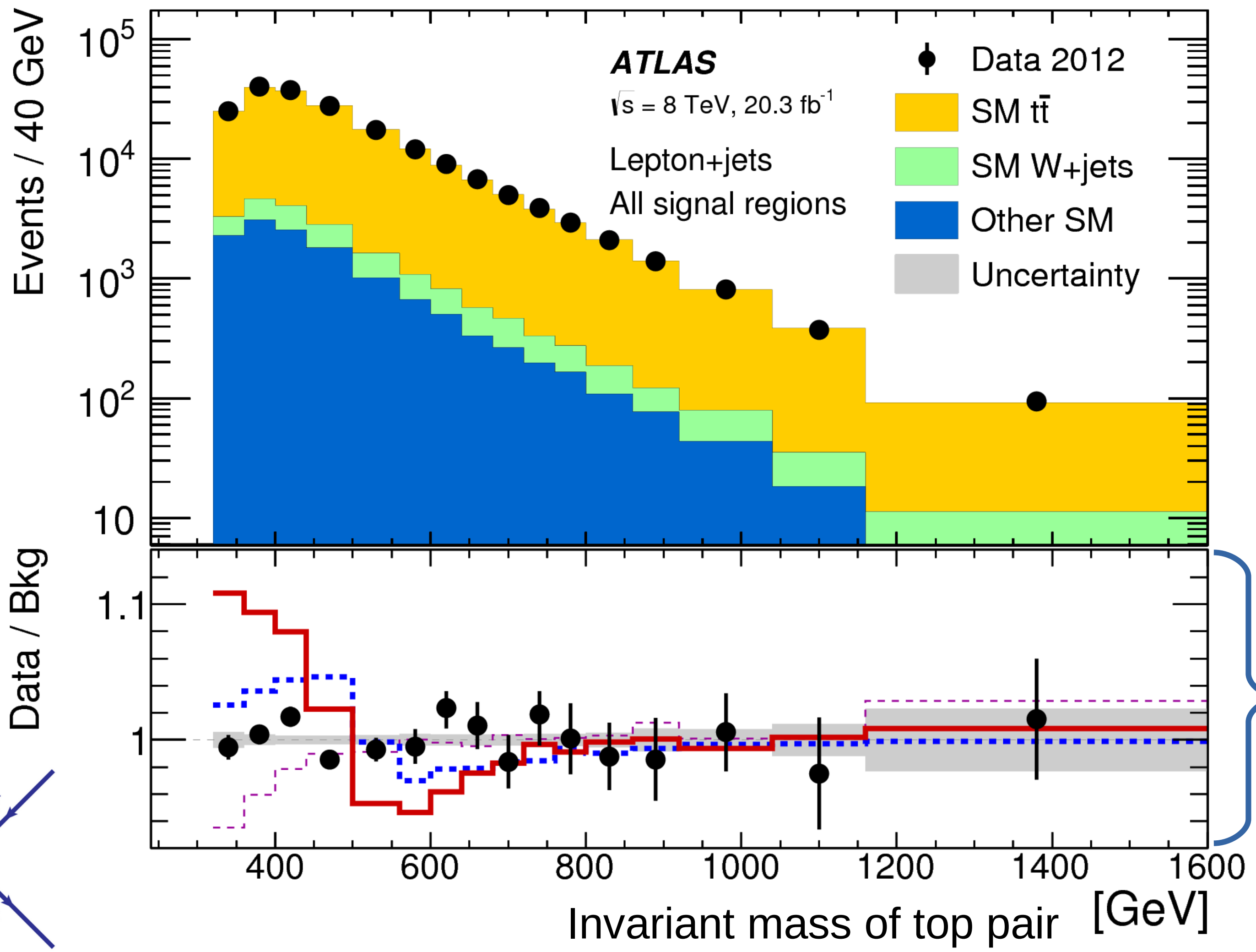
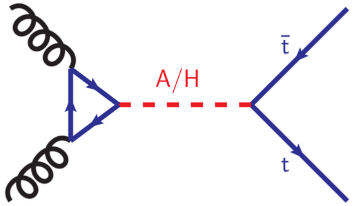


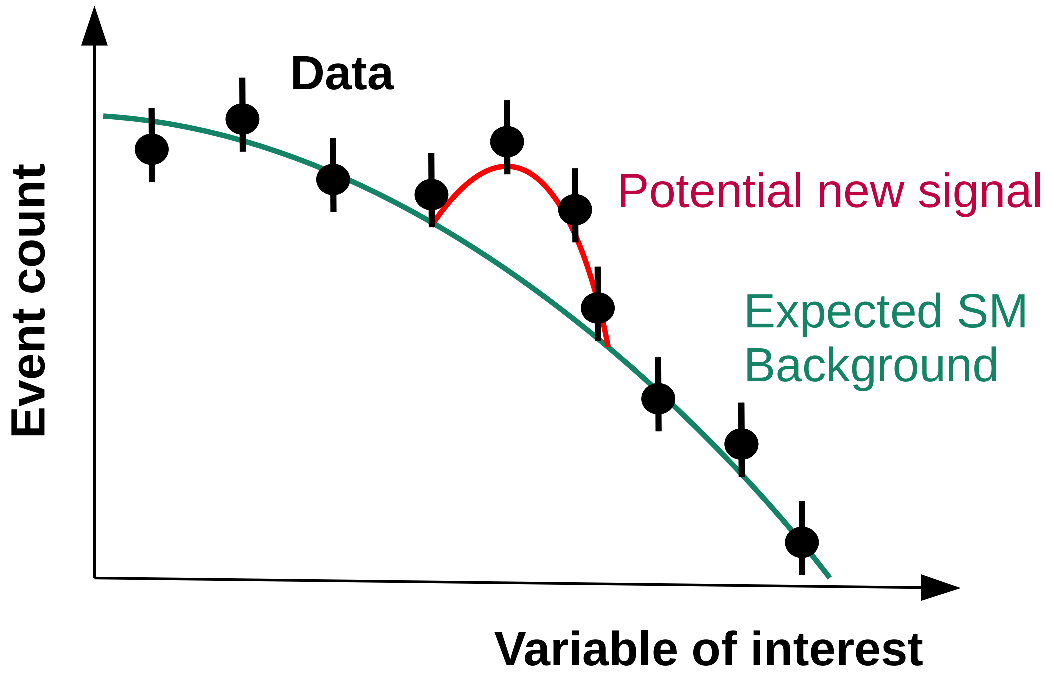


What type of deviation are we looking for?

What are we looking for?

> Most generally put: we search for a significant deviation from the SM prediction

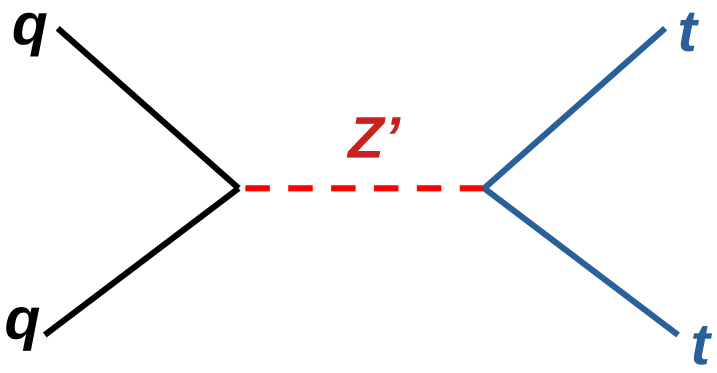
> Different search strategies
  - Cut-and-count method
  - Bump hunt
  - Tail hunt
  - ...

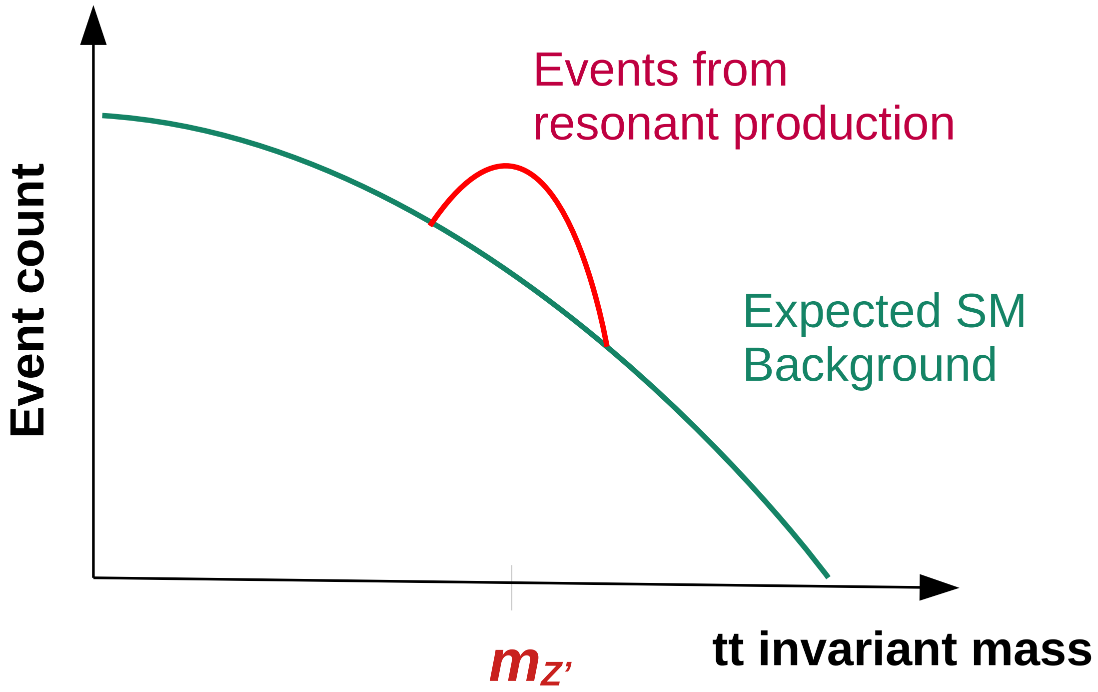


> Each comes with its own set of advantages/disadvantages!

Bump Hunting

> Search for a localised deviation in the distribution of a variable of interest
  - Typically: invariant mass

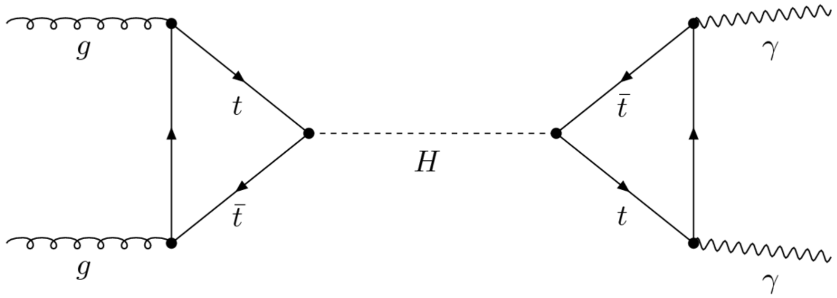


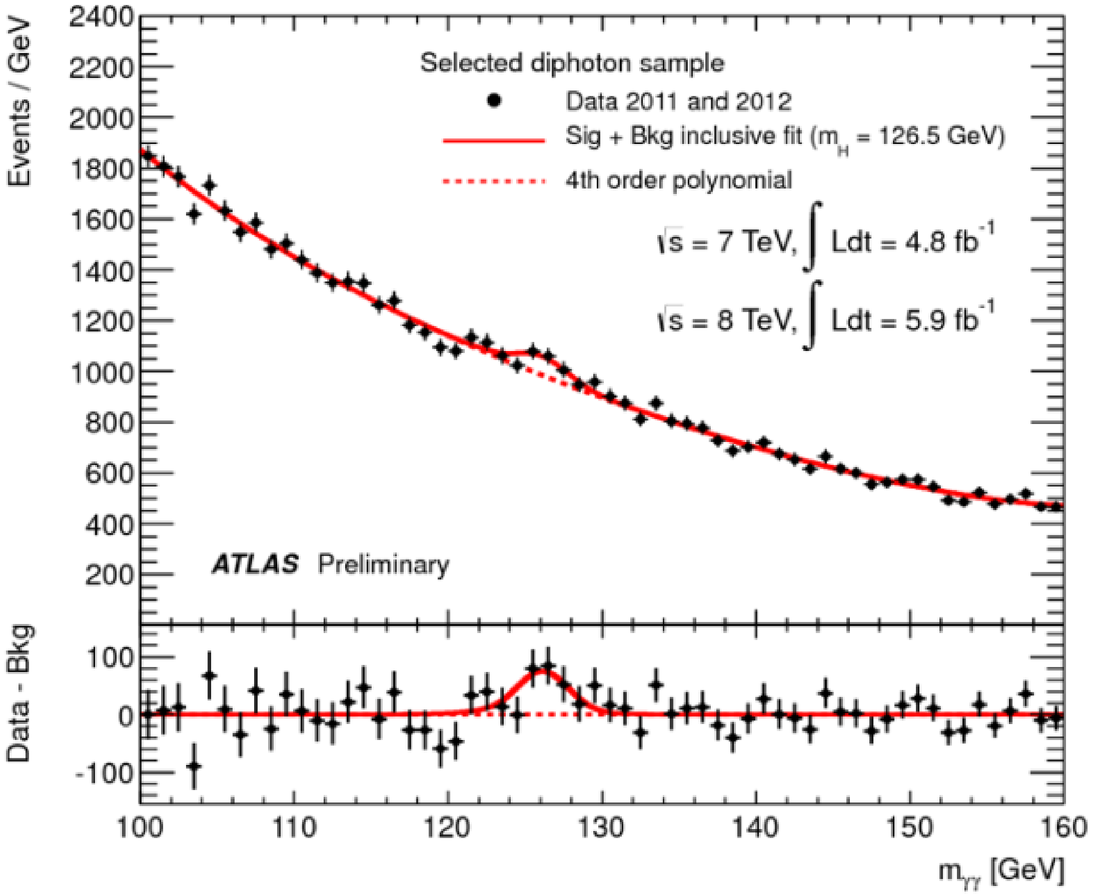


Bump Hunting

> Search for a localised deviation in the distribution of a variable of interest
  – Typically: invariant mass

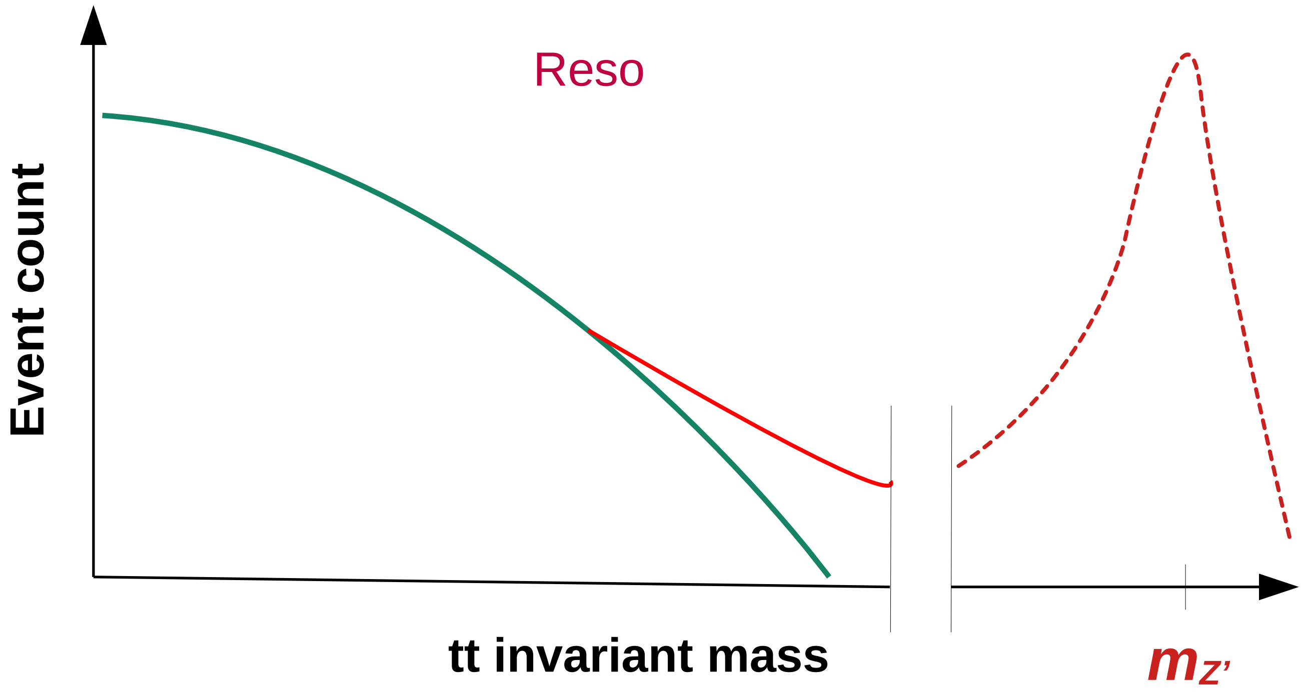
> Most recent successful example:
  – Higgs boson discovery (2012, CERN)





Tail Hunting

- Search for a tail enhancement in the distribution of a variable of interest
- Typical examples:
  - Resonances beyond reach of the LHC



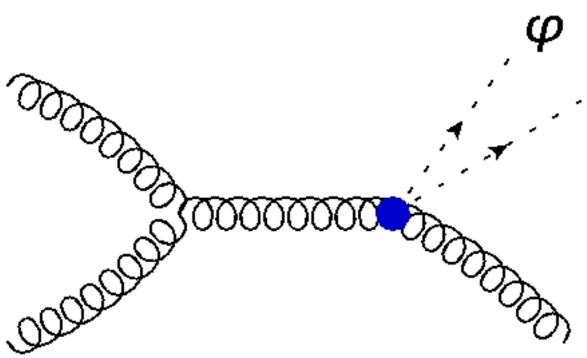
Tail Hunting

> Search for a tail enhancement in the distribution of a variable of interest

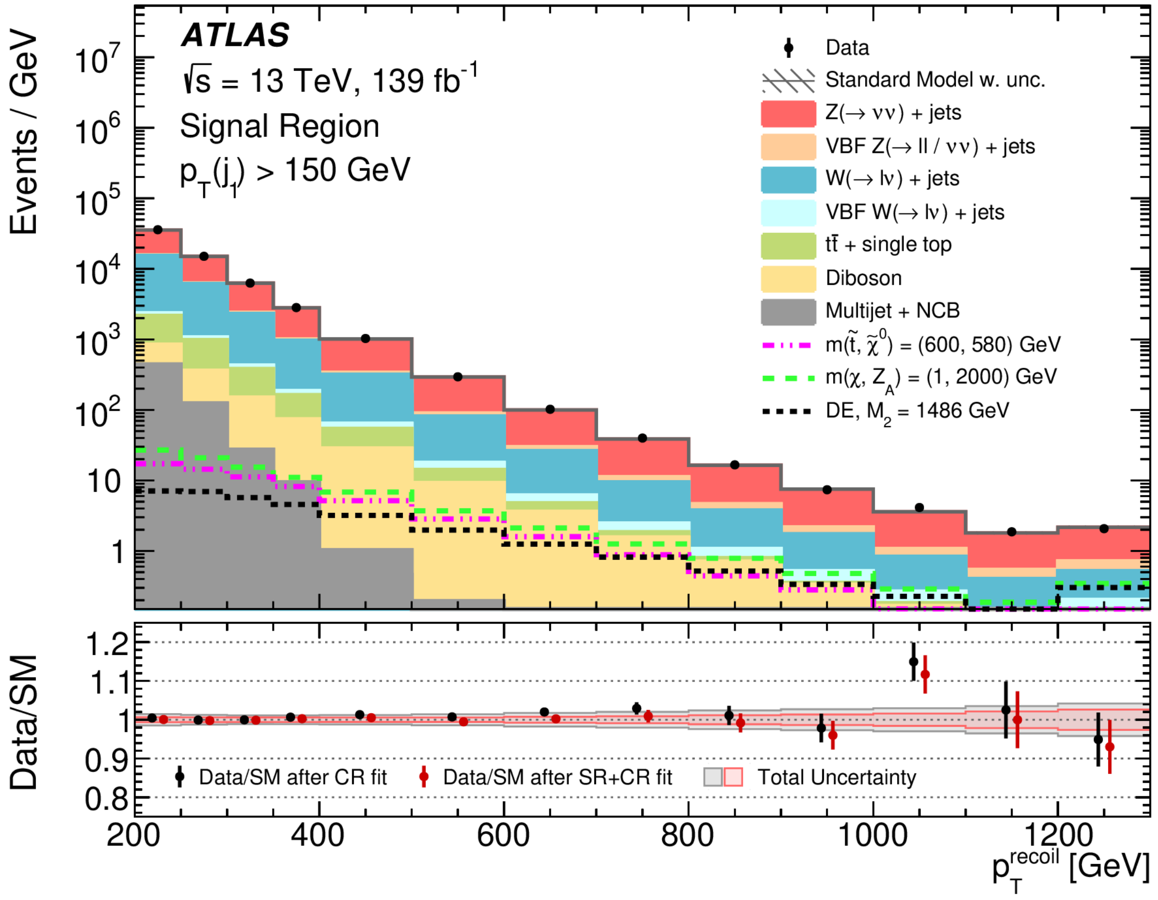
> Typical examples:

- Resonances beyond reach of the LHC
- Non-resonant production of new particles
  - E.g. dark matter or dark energy

Non-interacting scalar dark energy particles, → missing energy



Recoiling gluon, leading to single visible jet



Tail Hunting

> Search for a tail enhancement in the distribution of a variable of interest

> Typical examples:

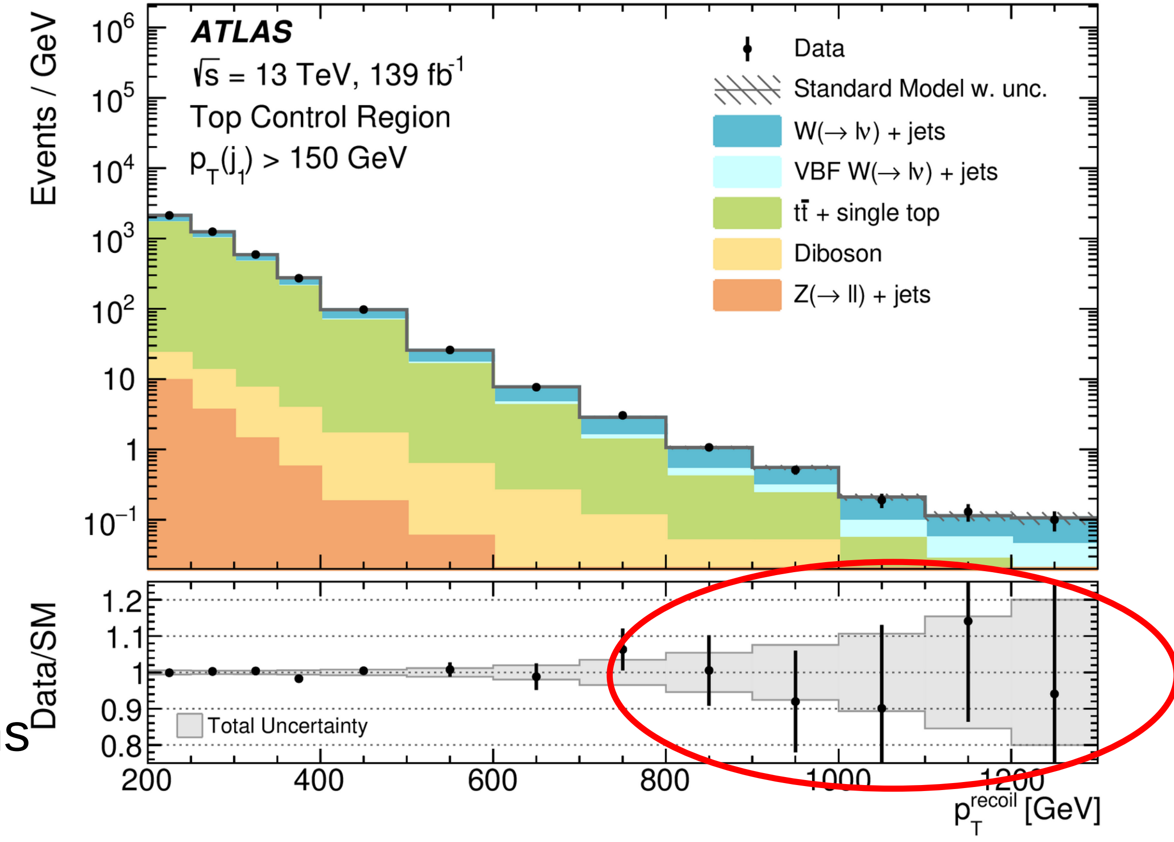
  – Resonances beyond reach of the LHC
  – Non-resonant production of new particles

> **Advantages**:

  – Sensitive to processes that cannot be identified by bump hunts

> **Disadvantages**:

  – Tails of distributions suffer from low statistics
  – Often sizeable systematic uncertainties
    • E.g. due to missing higher-order calculations



What if new particles are less obvious to spot?

> Bump hunt assumes “signal sitting on top of background”: **S** **+** **B** $= |s|^2 + |b|^2$

What if new particles are less obvious to spot?

- Bump hunt assumes “signal sitting on top of background”: **S** **+** **B** = $|s|^2 + |b|^2$
- Quantum mechanics: two processes with same initial and same final state will interfere!
  - $|s + b|^2 = |s|^2 + 2\,\mathrm{Re}(s\, b) + |b|^2$ = **S** **+** **I** **+** **B** → **Interference!!**

What if new particles are less obvious to spot?

- Bump hunt assumes "signal sitting on top of background": **S** + **B** = $|s|^2 + |b|^2$
- Quantum mechanics: two processes with same initial and same final state will interfere!
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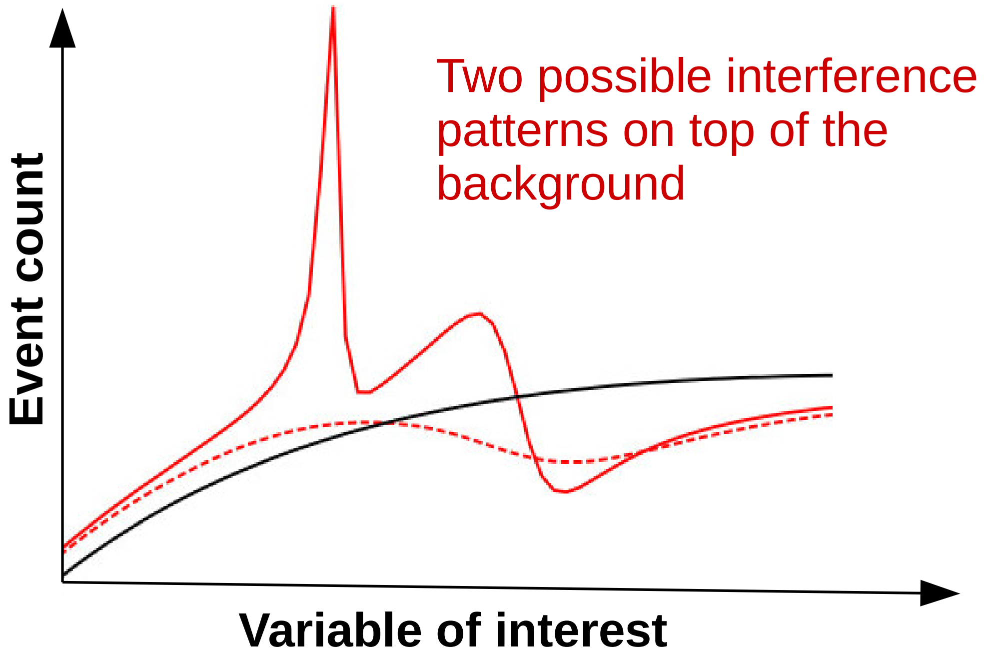
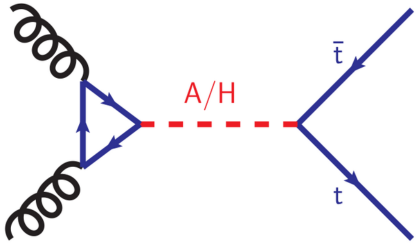
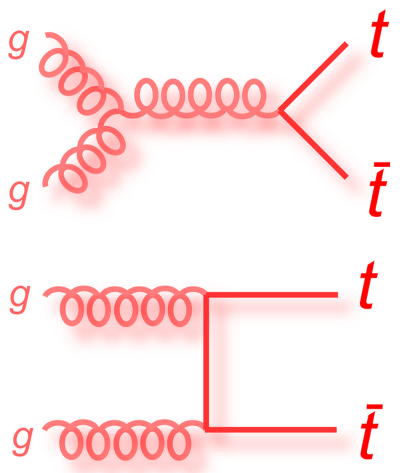
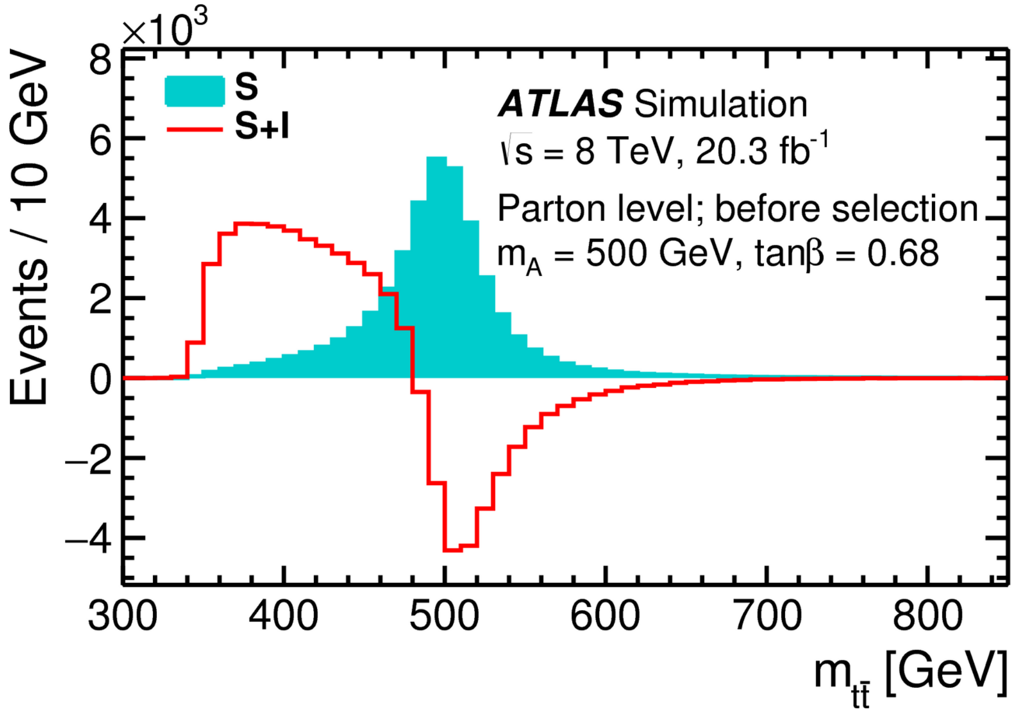


Beyond Bump Hunts

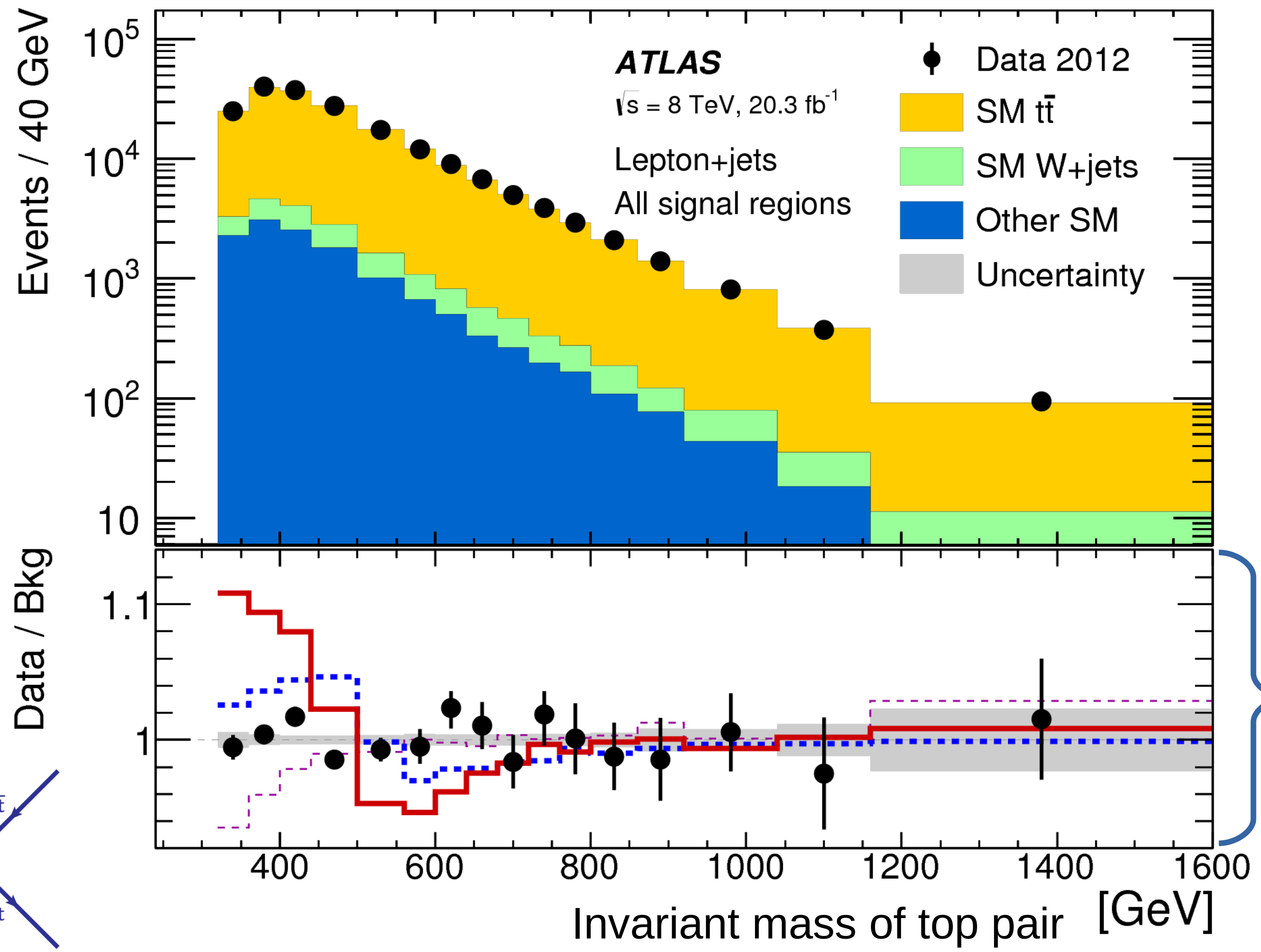
- Prominent example: decay of a heavy Higgs boson A/H to a top-antitop quark pair
- Need cutting edge methods → on-going research @ DESY



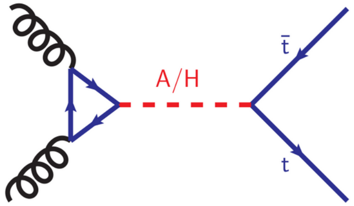




A final signal region



Need to quantify agreement between data and SM prediction

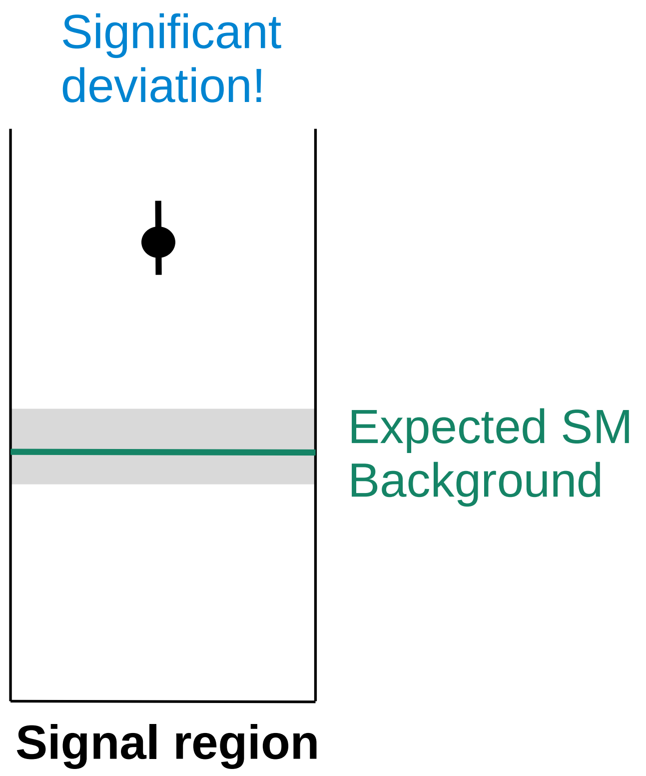


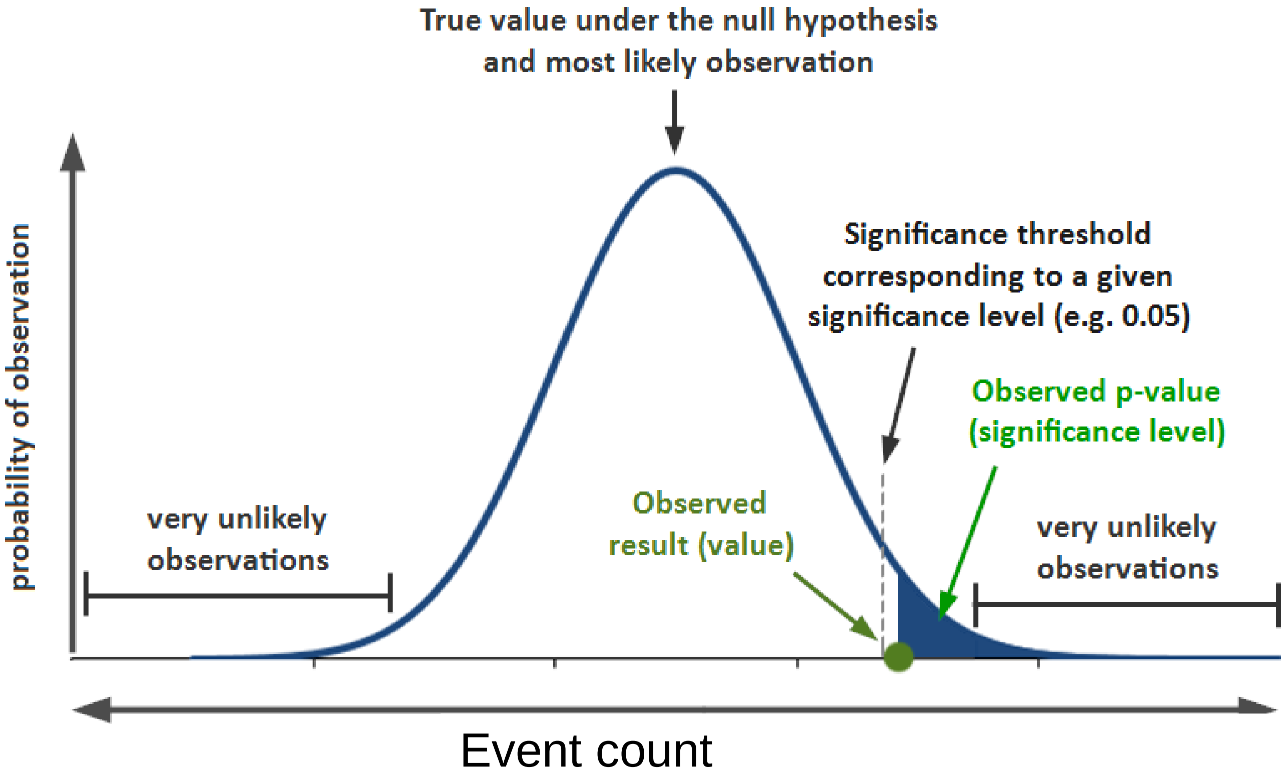
Statistical analysis

- Two statistical analysis stages in BSM searches:
  - Quantify agreement between data and SM prediction (*“Any interesting deviation?”*)
  - Quantify (dis)agreement between data and BSM hypothesis (*“limit setting”*)

Step 1: quantify agreement with SM prediction

- Null hypothesis H_0: SM only, no BSM
- **p-value**: probability that H_0 produces deviation at least as extreme as the one observed
- Simple example: cut-and-count





Step 1: quantify agreement with SM prediction

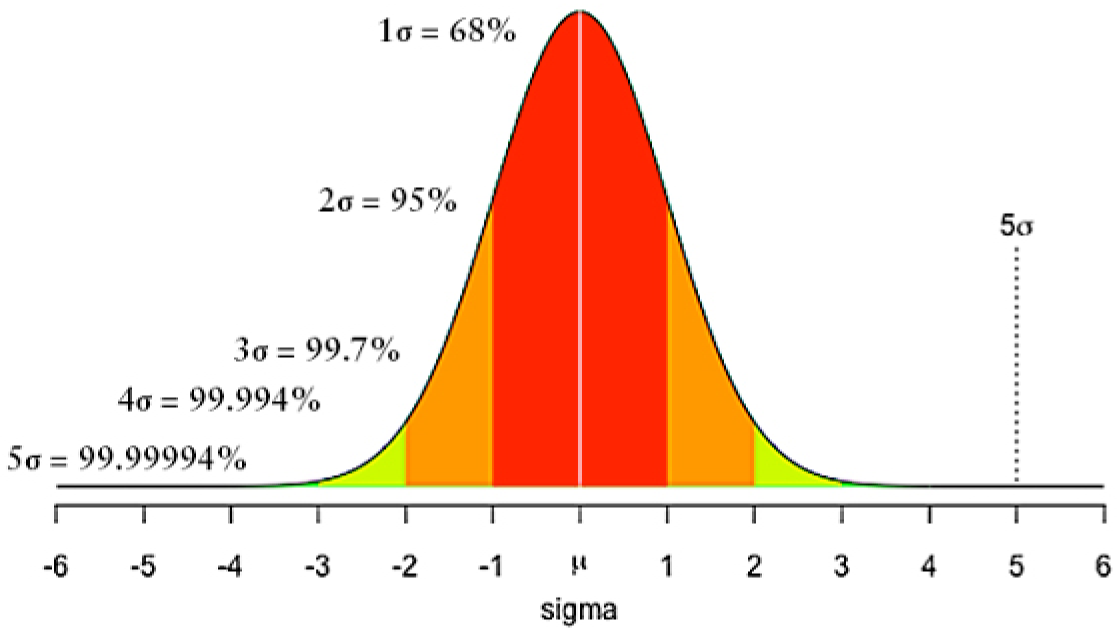
> Null hypothesis H_0: SM only, no BSM

> **p-value**: probability that H_0 produces deviation at least as extreme as the one observed

> Or quote **significance** instead:

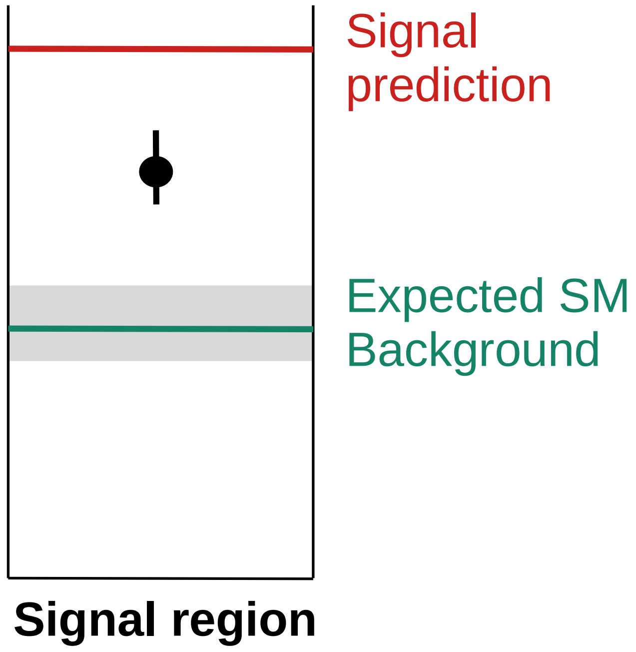
$$\boxed{Z = \Phi^{-1}(1-p)}$$

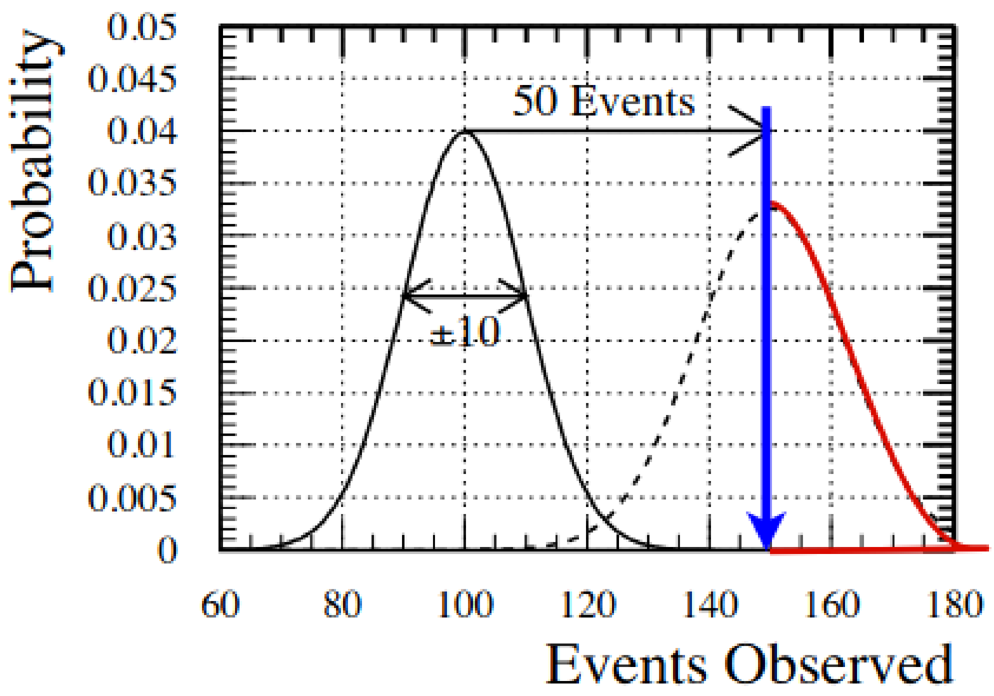
> where Φ^{-1} is inverse of cumulative Gaussian



Step 2: Quantify agreement with BSM hypothesis H_1

- If excess was found: test agreement with BSM … and open the champagne ;)
- If no excess was found: test degree to which H_1 is excluded by data (limit setting)



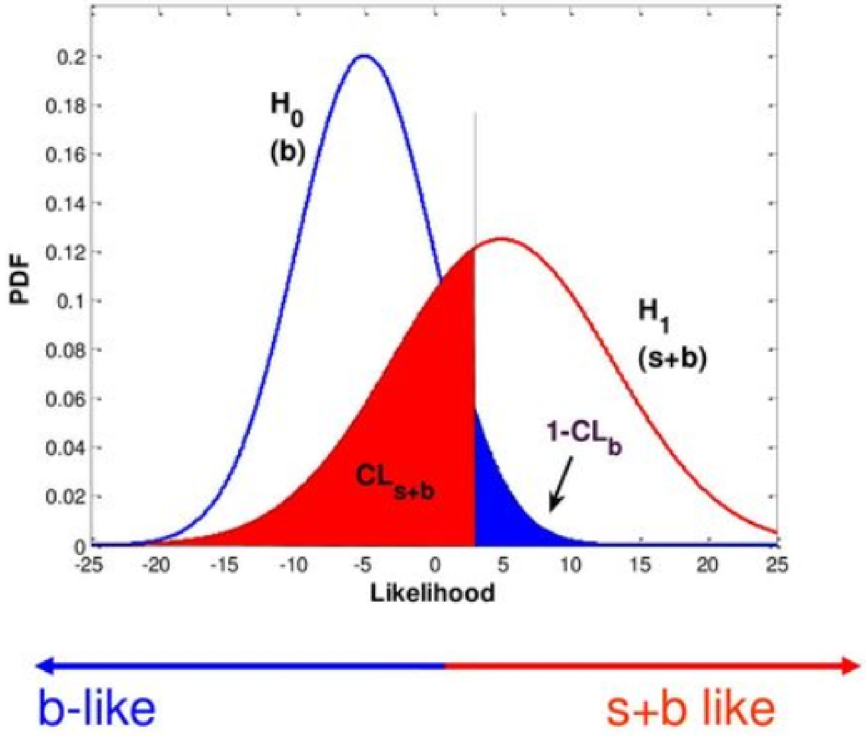


Step 2: Quantify agreement with BSM hypothesis H_1

> Usually, setup is more complicated: many bins, many signal regions

> Construct a likelihood function that quantifies data/MC agreement in all bins

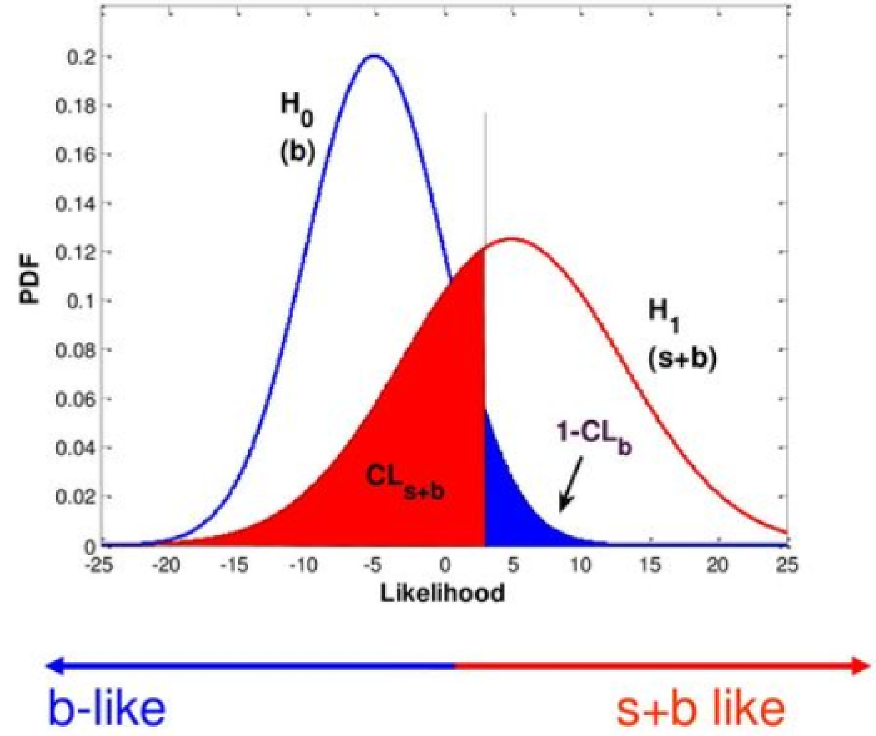
$$L(D|\mu,\boldsymbol{\theta}) = \underbrace{\prod_{j=1}^{M}\prod_{i=1}^{N}\mathrm{Pois}(n_{i,j}|\mu,\boldsymbol{\theta})}_{\text{Poisson terms}} \cdot \underbrace{\prod_{\mathrm{NP}} f(\theta^{(\mathrm{NP})})}_{\text{Constraint terms}}$$



Further reading:
Lecture by G. Cowan [link]

Step 2: Quantify agreement with BSM hypothesis H_1

- CL(s+b) – probability to falsely reject signal because it is too similar to background
- Confidence level
  - H_1 excluded at 95% CL if $CL(s+b) < 0.05$

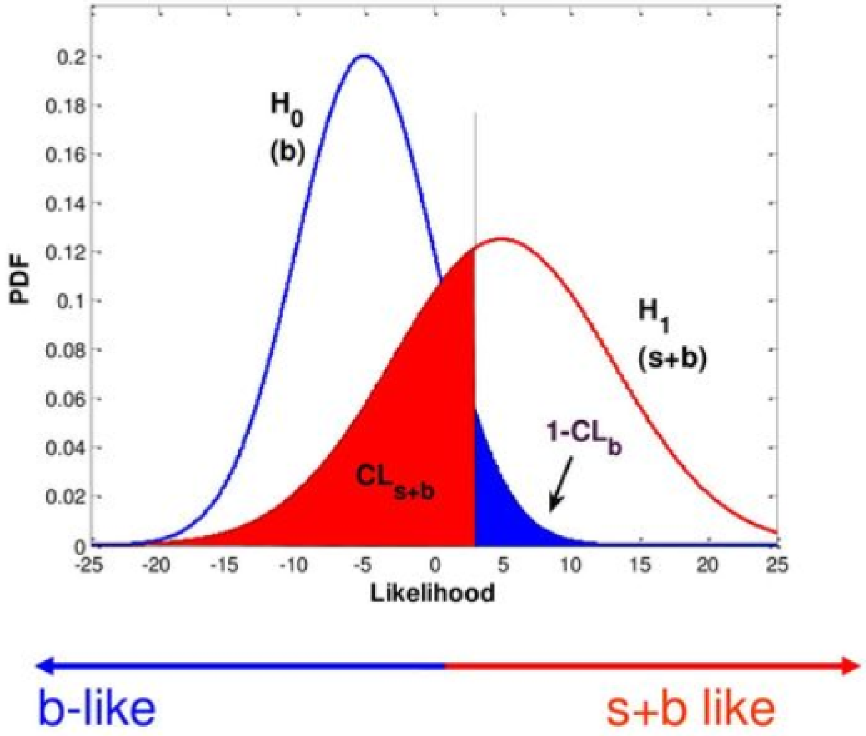


Step 2: Quantify agreement with BSM hypothesis H_1

> Problem:
  - Danger to falsely reject H_1 even if separation between H_1 and H_0 is poor, i.e. sensitivity to H_1 is low

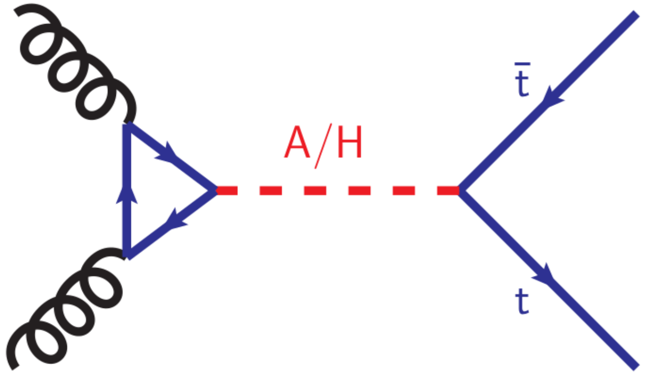
> Solution:
  - CL(s) = CL(s+b)/[1-CL(b)]

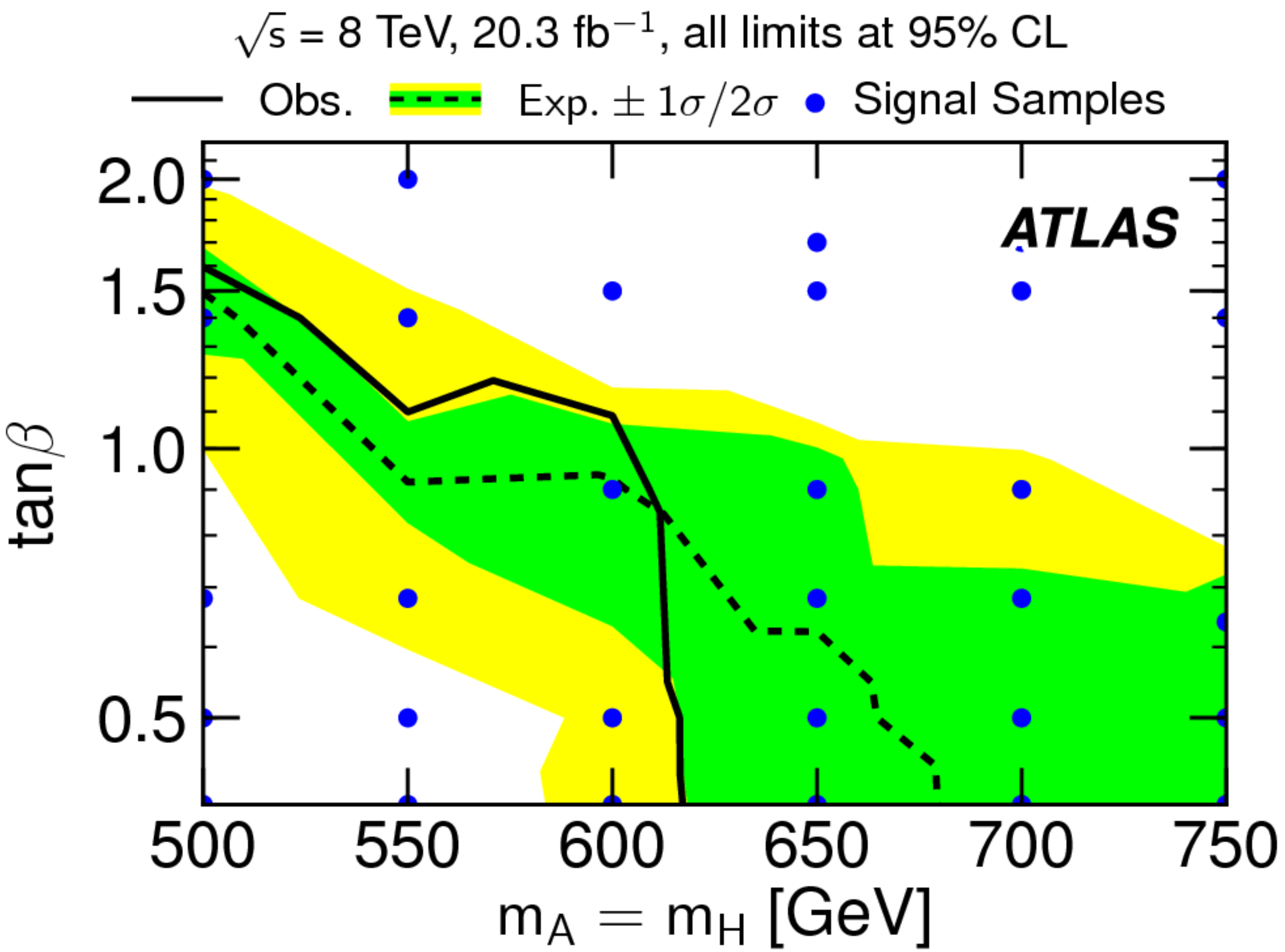
> Confidence level
  - H_1 excluded at 95% CL if CL(s) < 0.05



A final result

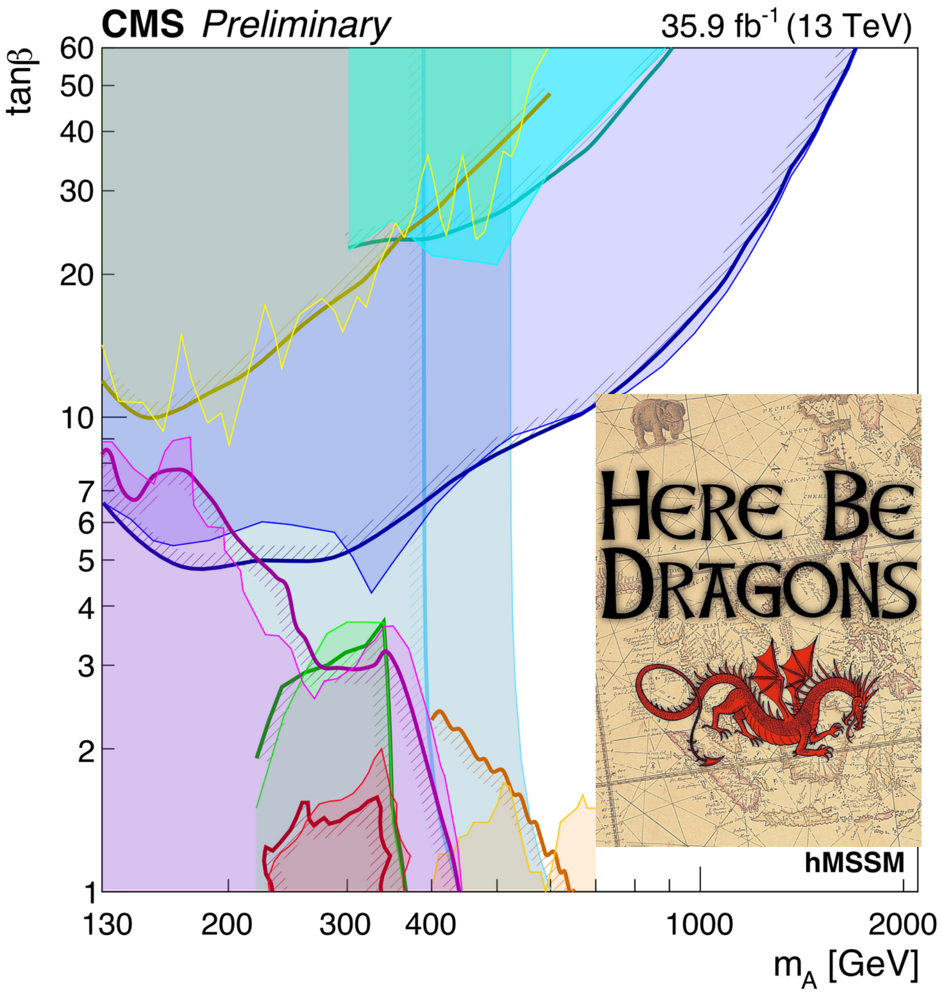
> The famous “Brazilian” plot, showing observed and expected exclusion limits with error bands





Where do we stand?

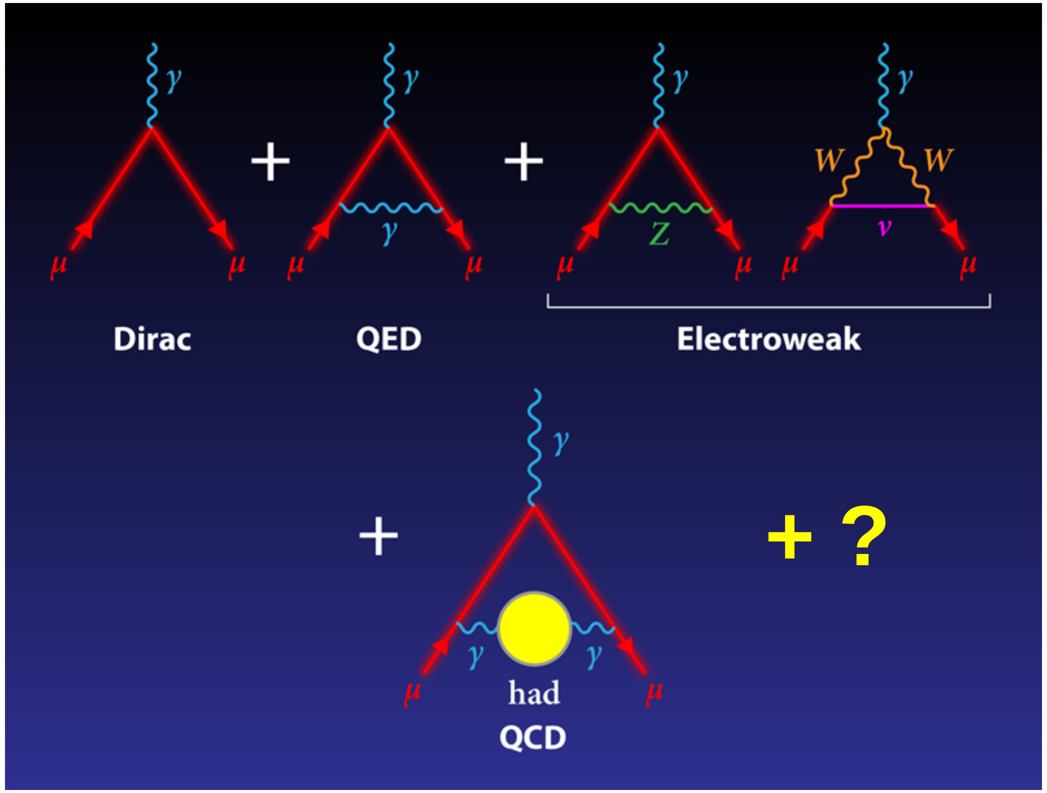
- No significant (5σ) deviation from the SM observed so far.
- Results constrain BSM models…
- … and point to uncharted territory!



Muon g-2 (1)

- Anomalous magnetic moment of the muon in analogy to that of the electron

$$\boxed{\vec{\mu} = g\,\frac{q}{2m}\,\vec{S}}$$



- Loop quantum corrections: $g \neq 2$
- Anomalous magnetic moment: $a = (g\text{-}2)/2$
- Sensitive to large range of possible quantum corrections, including possible BSM contributions

Muon g-2 (2)

- Storage ring with polarised muons in magnetic field → measure precession frequency
- Measurements at BNL (2004) first revealed tension with SM of 2.6σ significance
- Confirmed by new Fermilab measurement (2021) at 4.2σ combined significance
  - More data is being taken and analysed