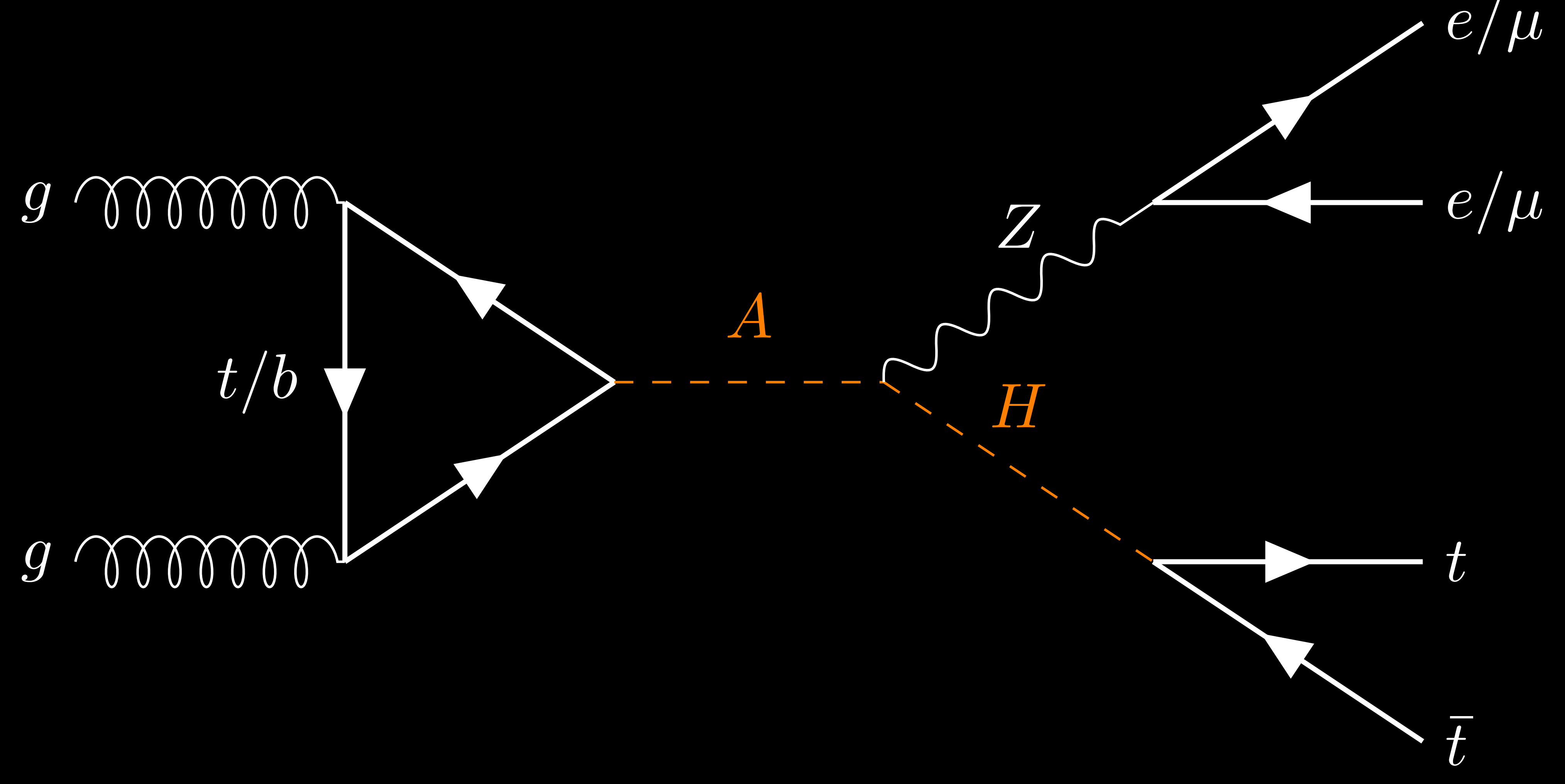
Search for $A \to ZH \to \ell\ell t\bar{t}$ at $\sqrt{s} = 13 TeV$ with the ATLAS detector

RTG Fall workshop



Roman Küsters

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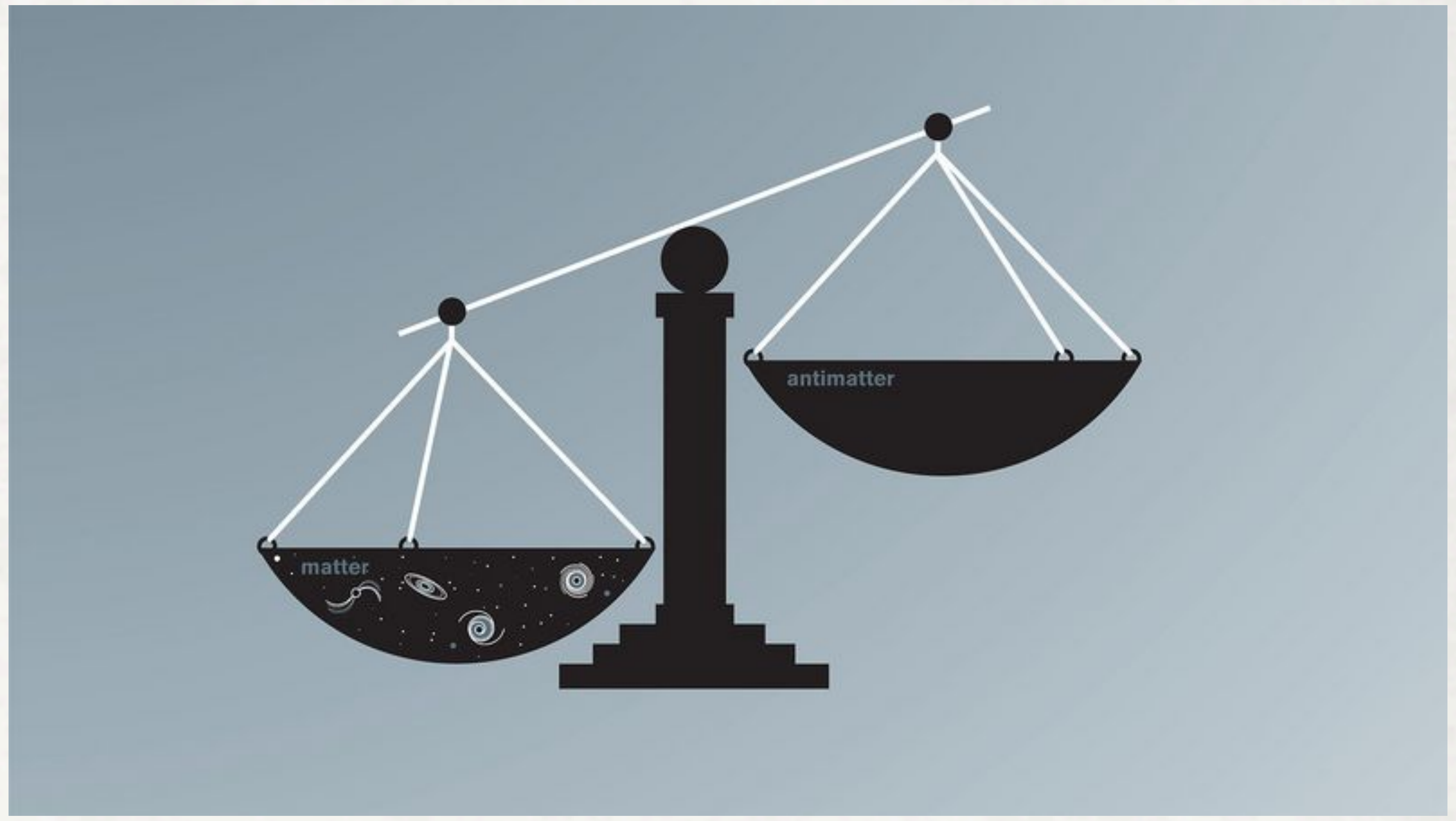
Emmy Noether-Programm

DFG Deutsche Forschungsgemeinschaft

UNI FREIBURG

Motivation



link

Observe huge matter-antimatter asymmetry in universe

Where is matter-antimatter asymmetry originating from?

conditions for Baryogenesis formulated in 1967 by Andrei Sakharov

➡3 Sakharov Conditions

1. **C/CP violation**
2. **baryon number violation**
3. **interactions out of equilibrium**

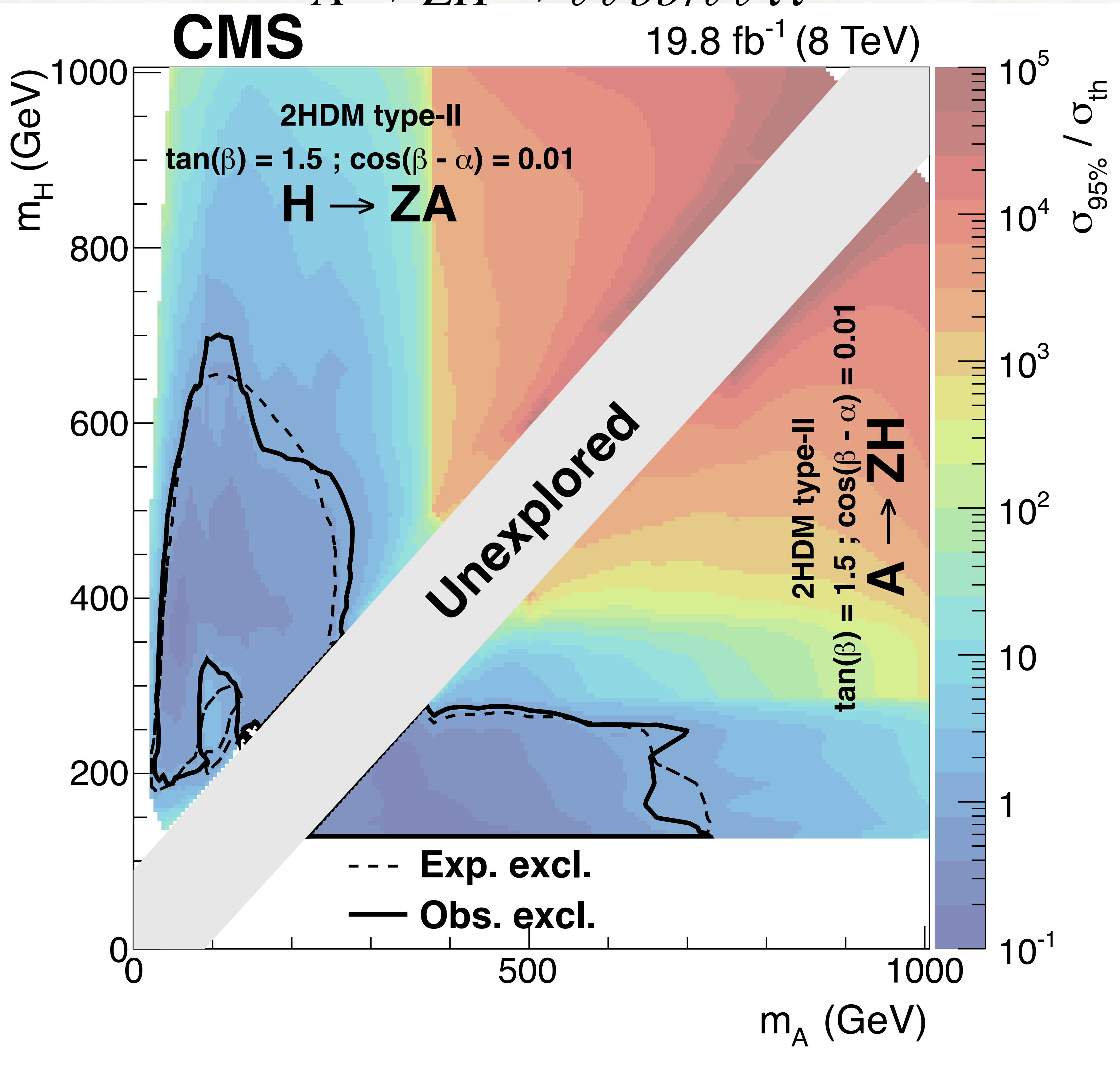
} Standard Model does not fulfil all of these conditions

⇒Baryogenesis requires new physics!

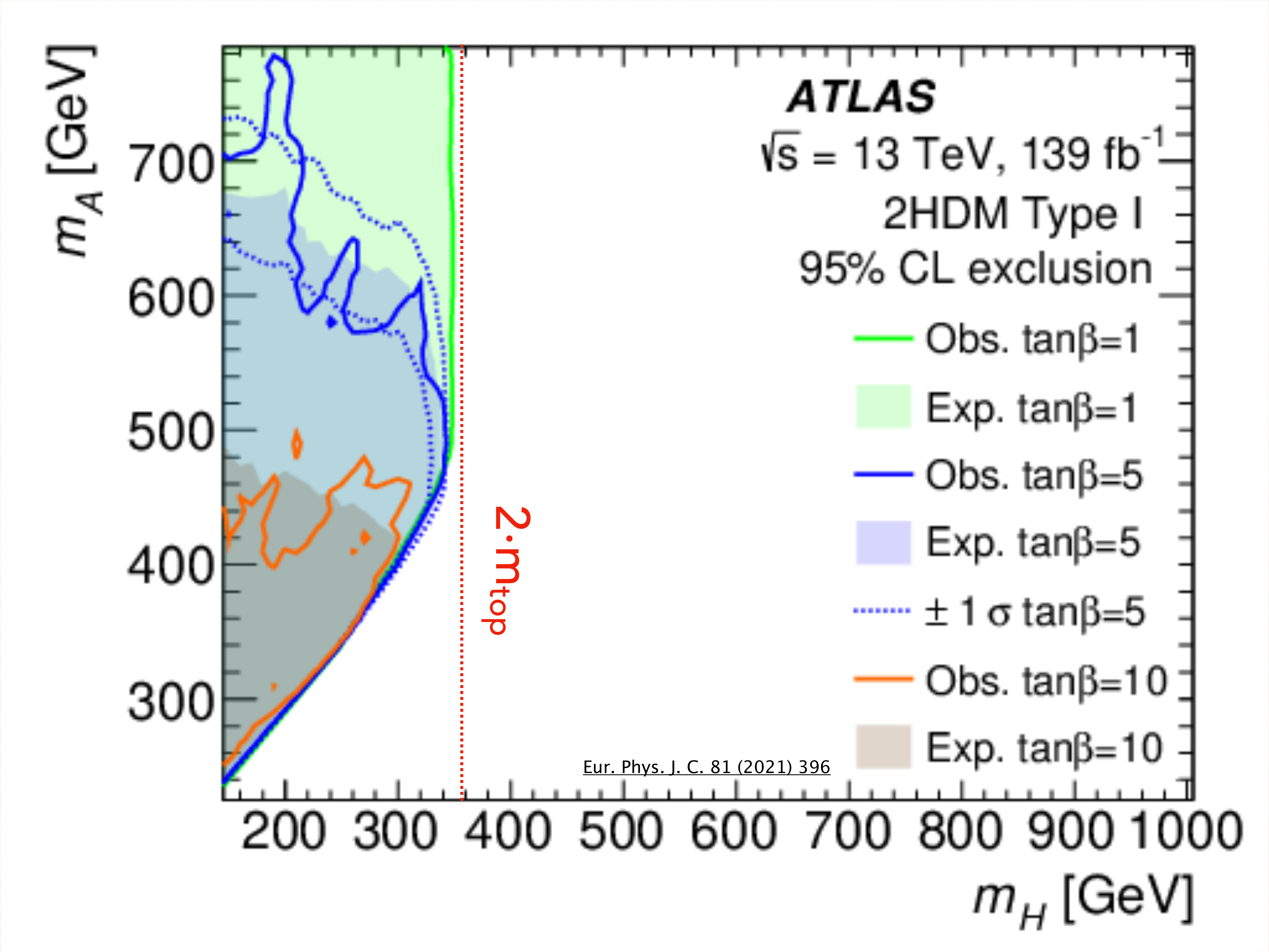
Current status

- neither CMS nor ATLAS have probed regions of m_H > 350 GeV
- current Analysis should be able to extend this region

$A \rightarrow ZH \rightarrow \ell\ell b\bar{b}/\ell\ell\tau\tau$



$A \rightarrow ZH \rightarrow \ell\ell b\bar{b}$



2HDM's as a solution to Baryogenesis

2HDM: Two Higgs Doublet Model

- one of the simplest extensions of standard model: addition of a second Higgs doublet

⇒8 fields, **BUT** 3 fields are absorbed by EWSB for electroweak interactions

⇒in total 5 physical Higgs bosons:

- 2 neutral CP even bosons (H, h)
- 1 neutral CP odd boson (A)
- 2 charged bosons ($H^{\pm}$)

choose h to be m_h = 125 GeV

2HDM can fulfil Sakharov conditions!!!

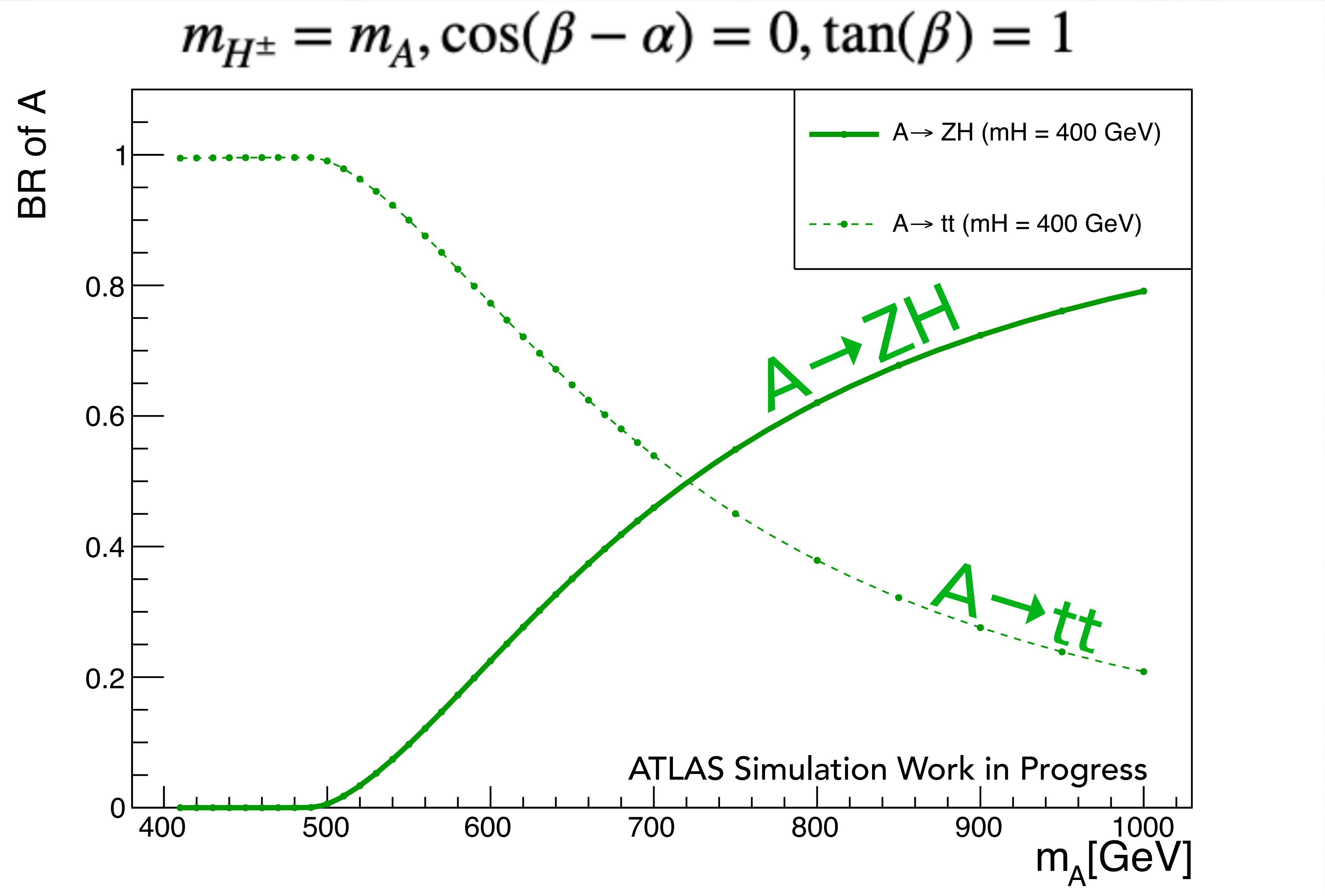
Aim of this Analysis:

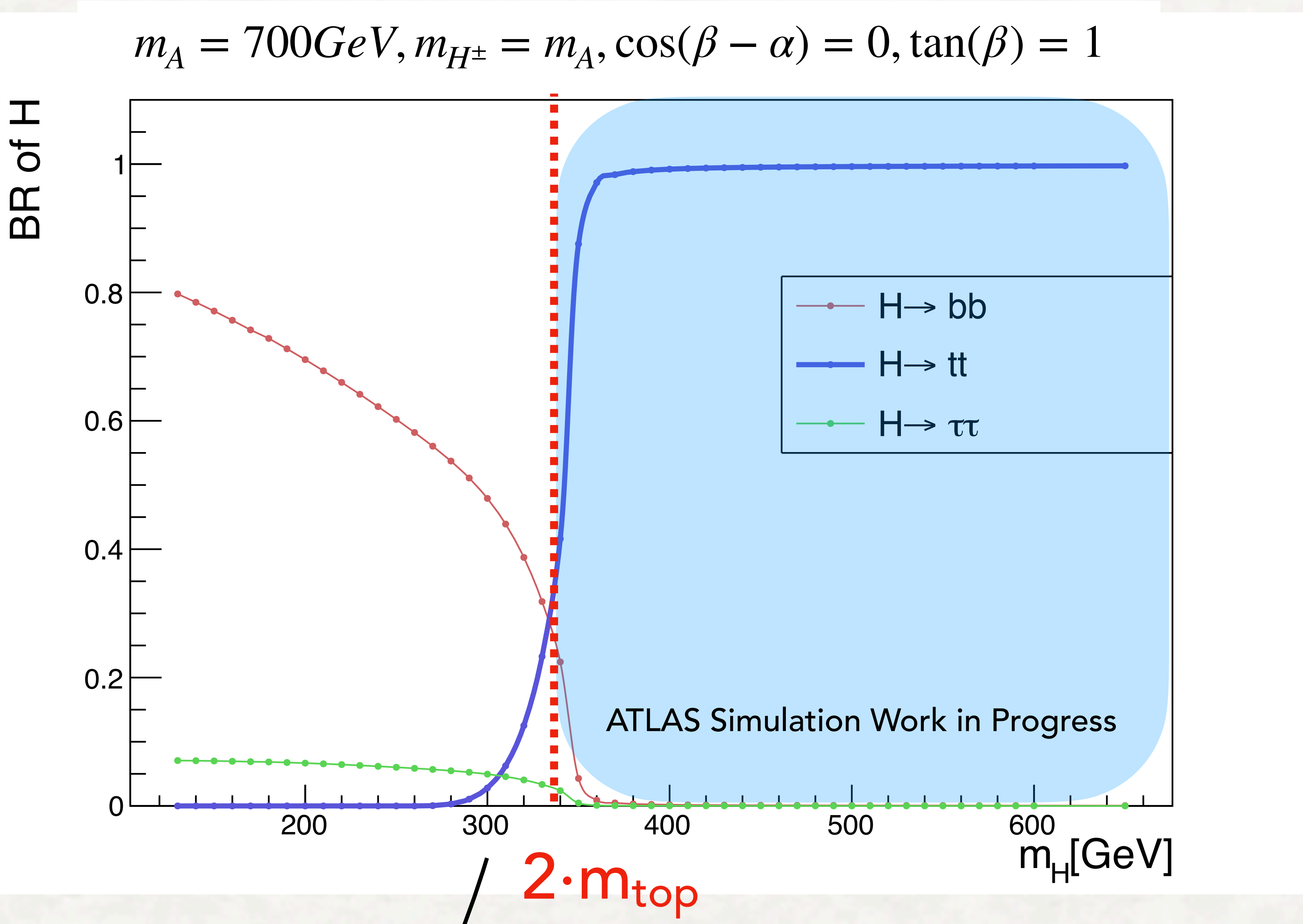
➡ Search for heavy scalars with large mass splitting

➡ extend mass region to m_H > 350 GeV

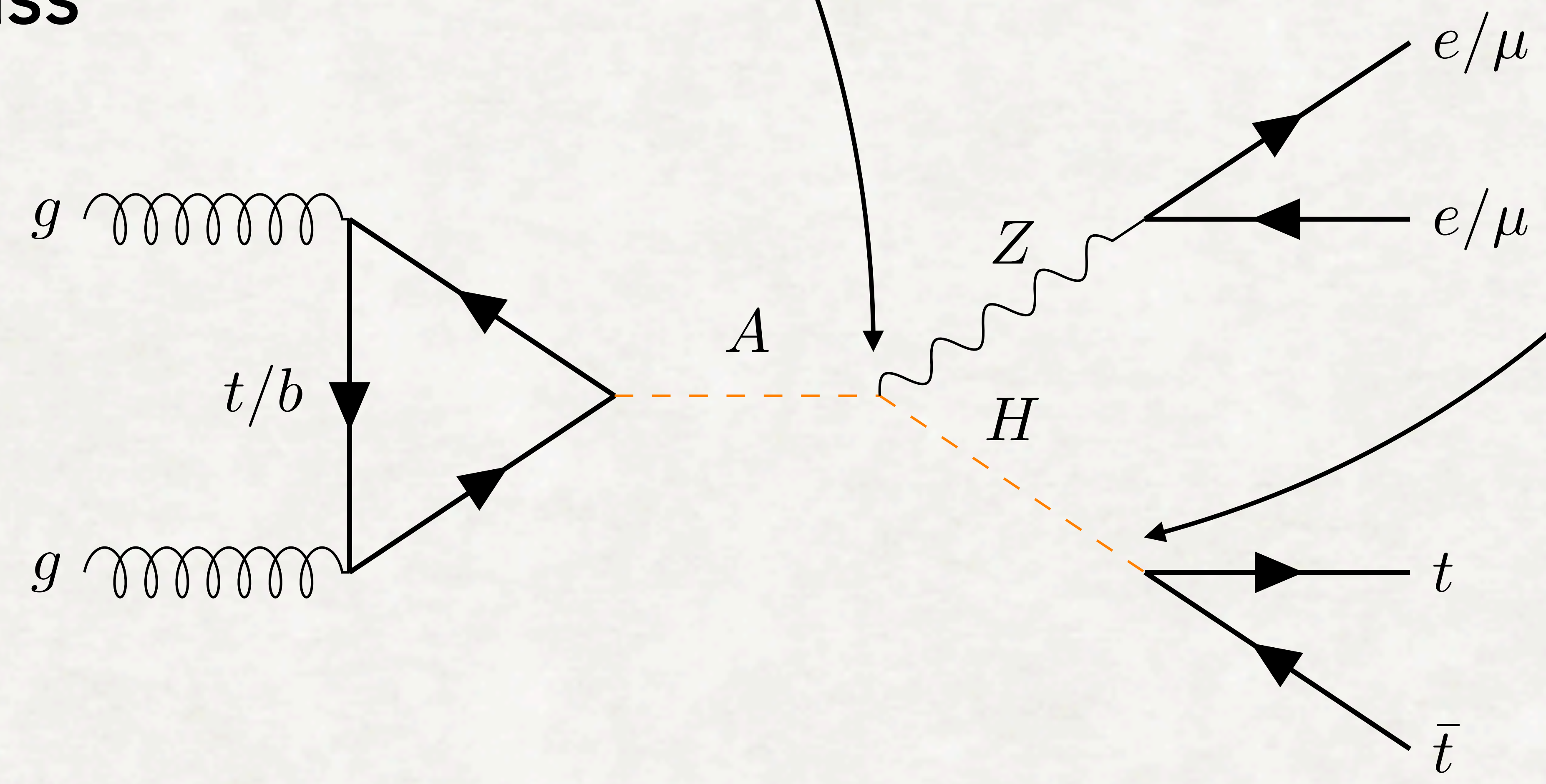
2HDM can lead to Baryogenesis if $m_A >> m_H$

Branching Ratios of A & H:





$A \to ZH$ dominant for large mass splitting ($m_A > m_H$ +vev)

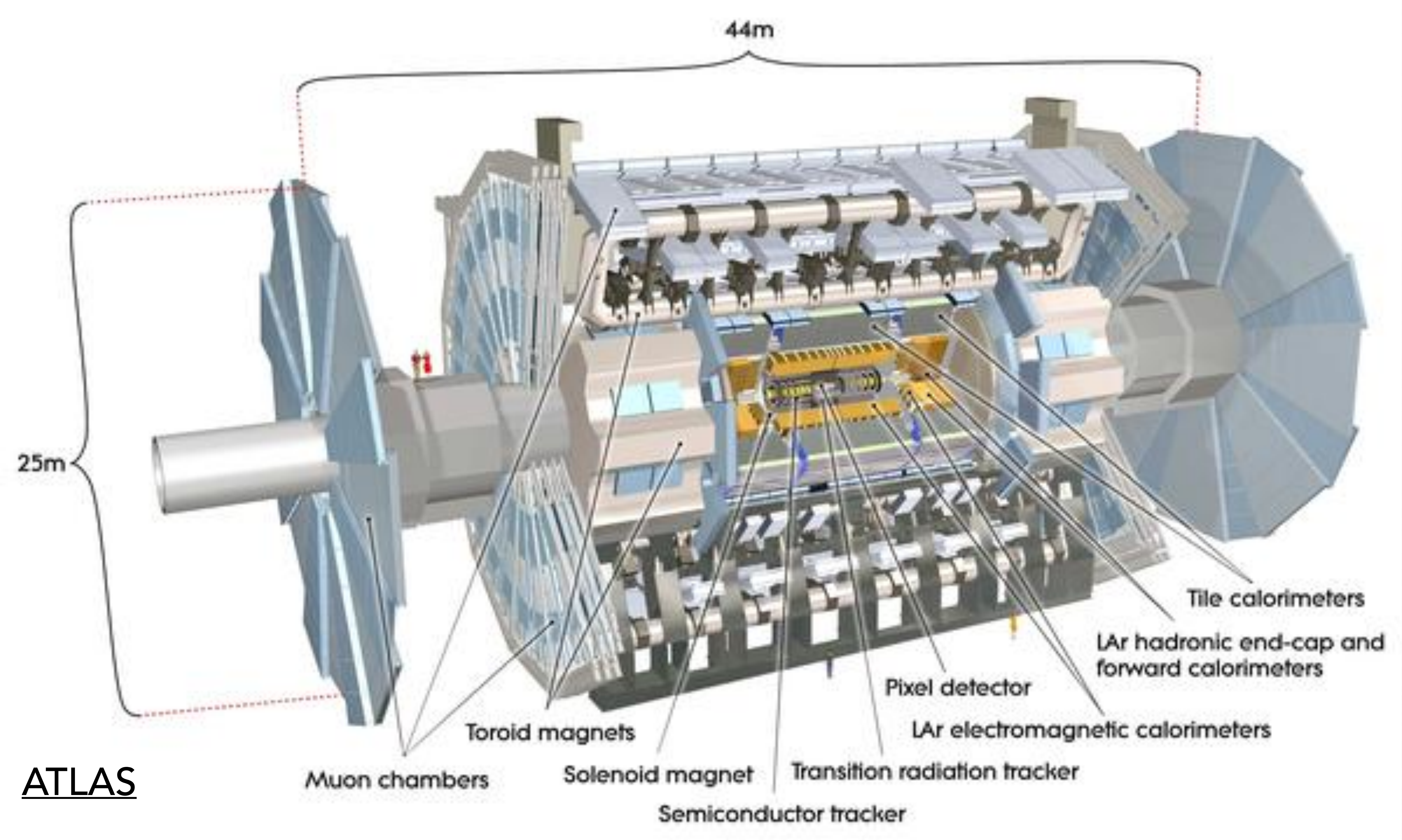


H → $t\bar{t}$ dominant for m_H > 350 GeV (ca 2*m_{top})

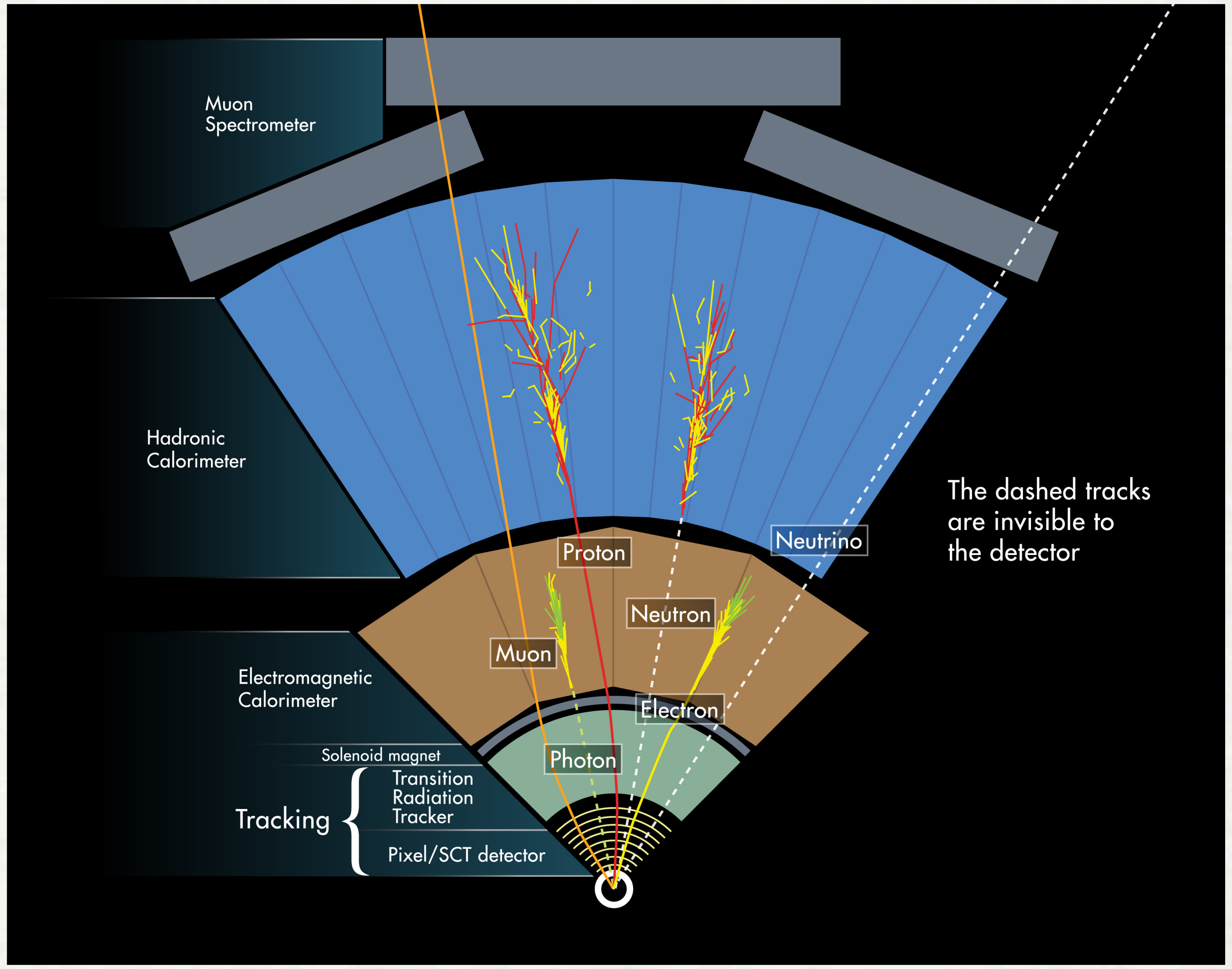
The ATLAS Detector

A Toroidal LHC ApparatuS

- multi purpose detector
- 1 of 4 major experiments at LHC



ATLAS



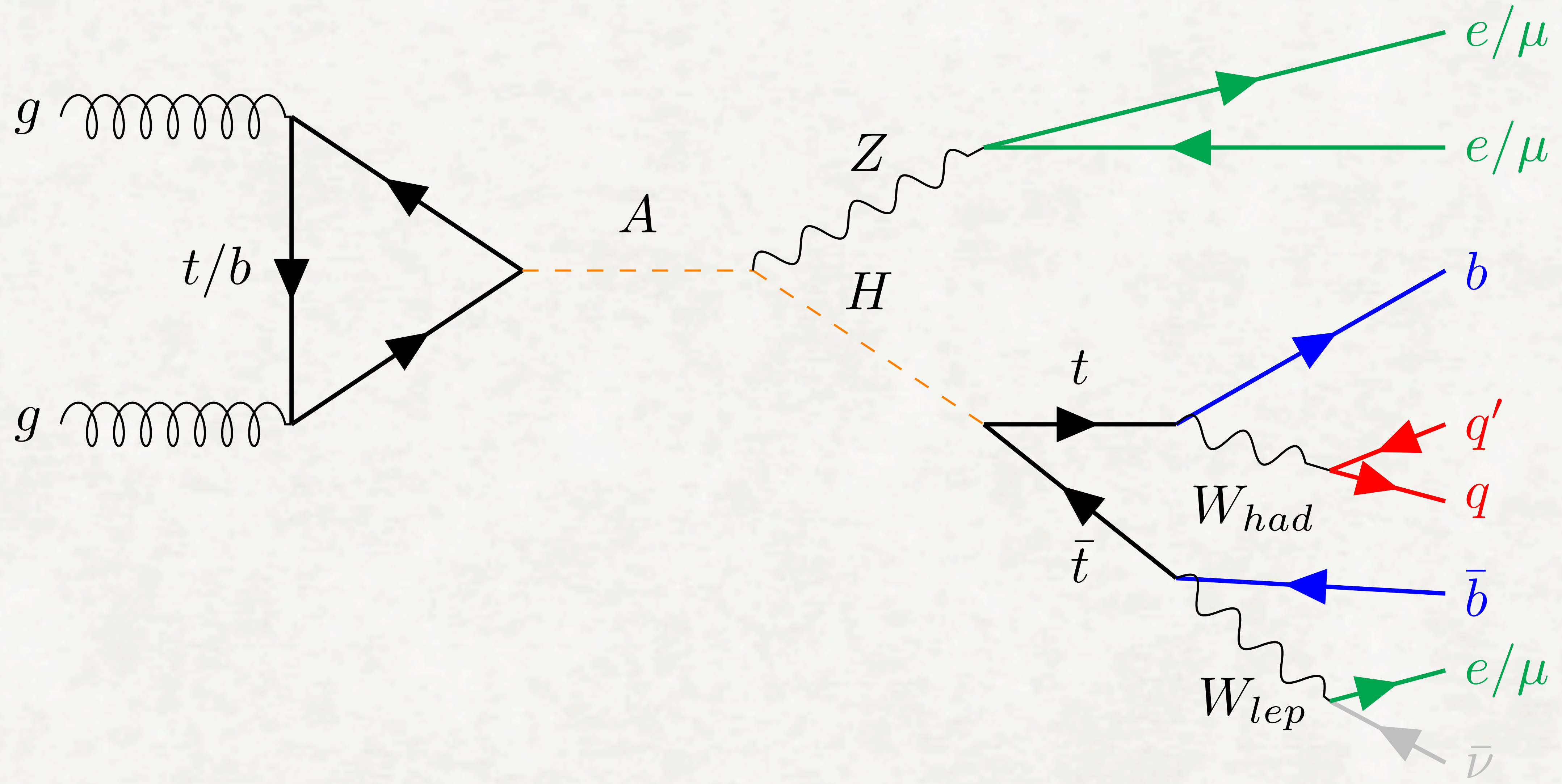
CDS

4 main components

- Tracking: Charged particles
- Calorimeter:
  - Electromagnet: Electrons & Photons
  - Hadronic: Hadrons
- Muon Spectrometer: Muons

Selection & Reconstruction

- Z Boson: decay to 2 leptons of **opposite charge, same flavour**
- 1 top: hadronic decay->1 b-jet + 2 **jets**
- 1 top: leptonic decay->1 **lepton** + 1 **b-jet** + 1 **neutrino**



⇒**≥4 jets, exactly 2 b-jets, exactly 3 leptons**

Z-Boson reconstruction:

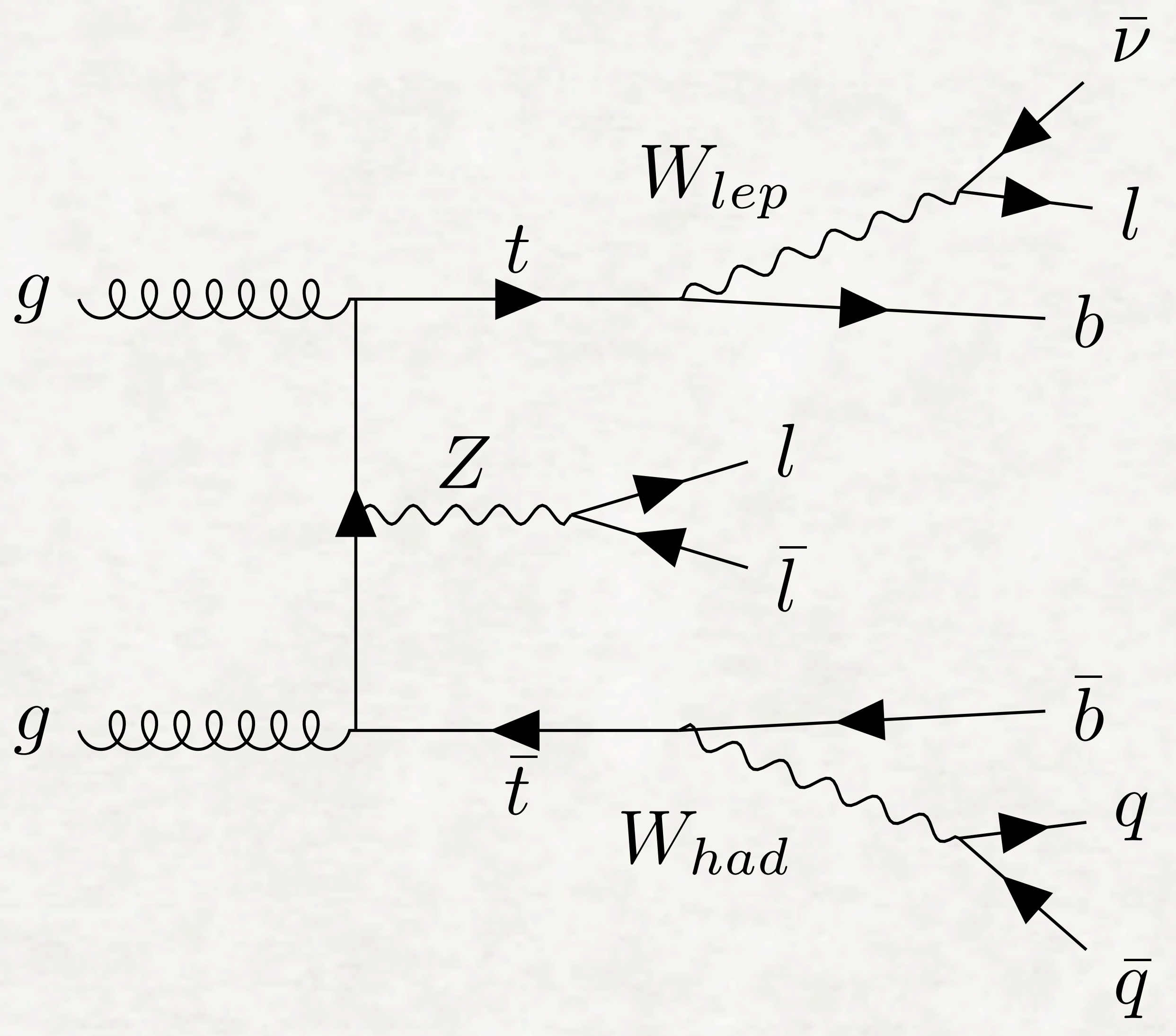
- oppositely charged leptons
- same flavour leptons
- select pair with mass closest to m_Z

$t\bar{t}$ reconstruction ("Pseudotop"):

leptonic top $t \rightarrow l + \nu + b$	**hadronic top** $t \rightarrow q + q' + b$
• lepton not from Z • b-jet with min dR to this lepton	• 2 light jets with mass closest to m_W • remaining b-jet

Main Backgrounds

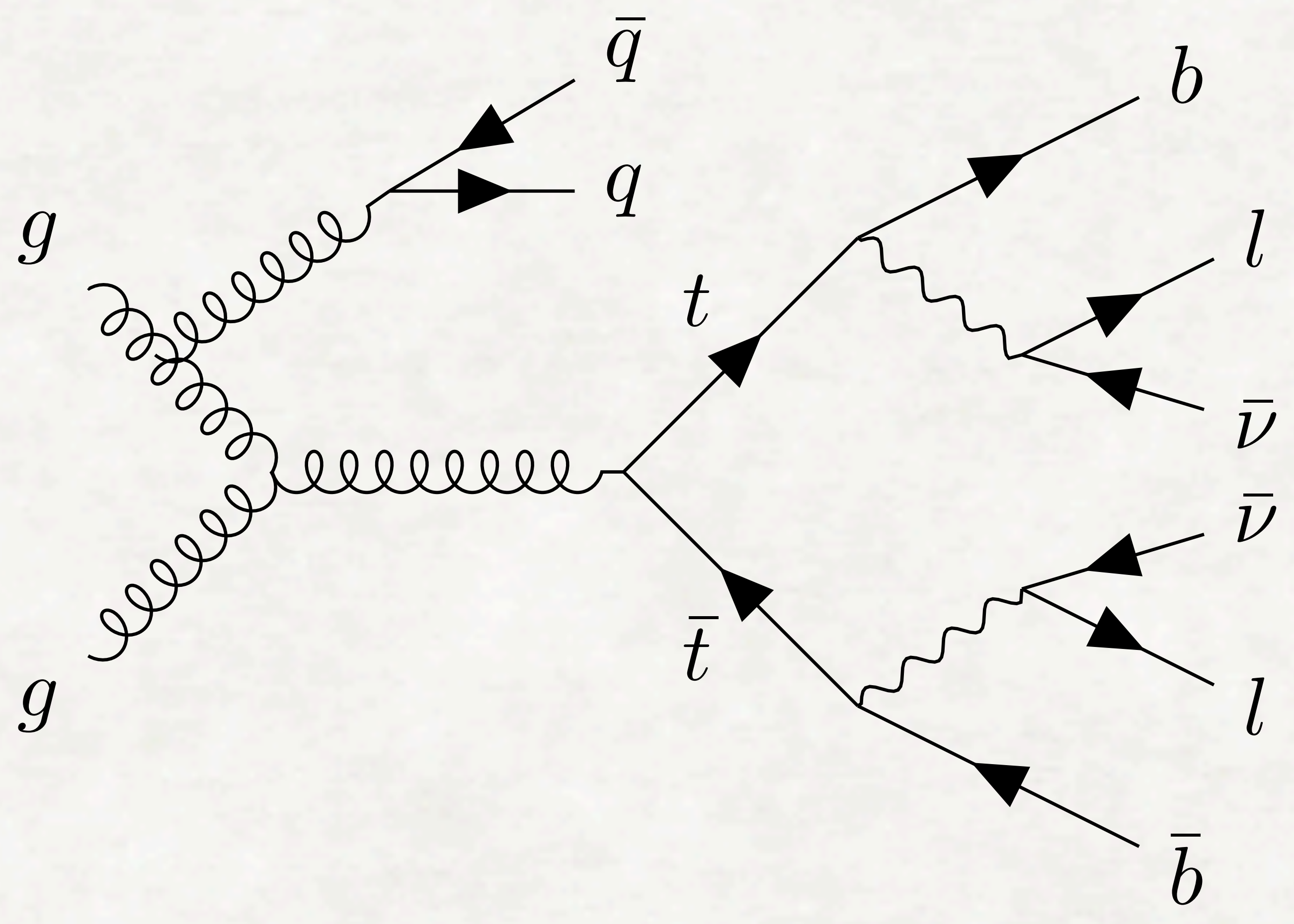
ttZ



- irreducible
- softer leptons, different topology

- No resonance in m_{VH} expected

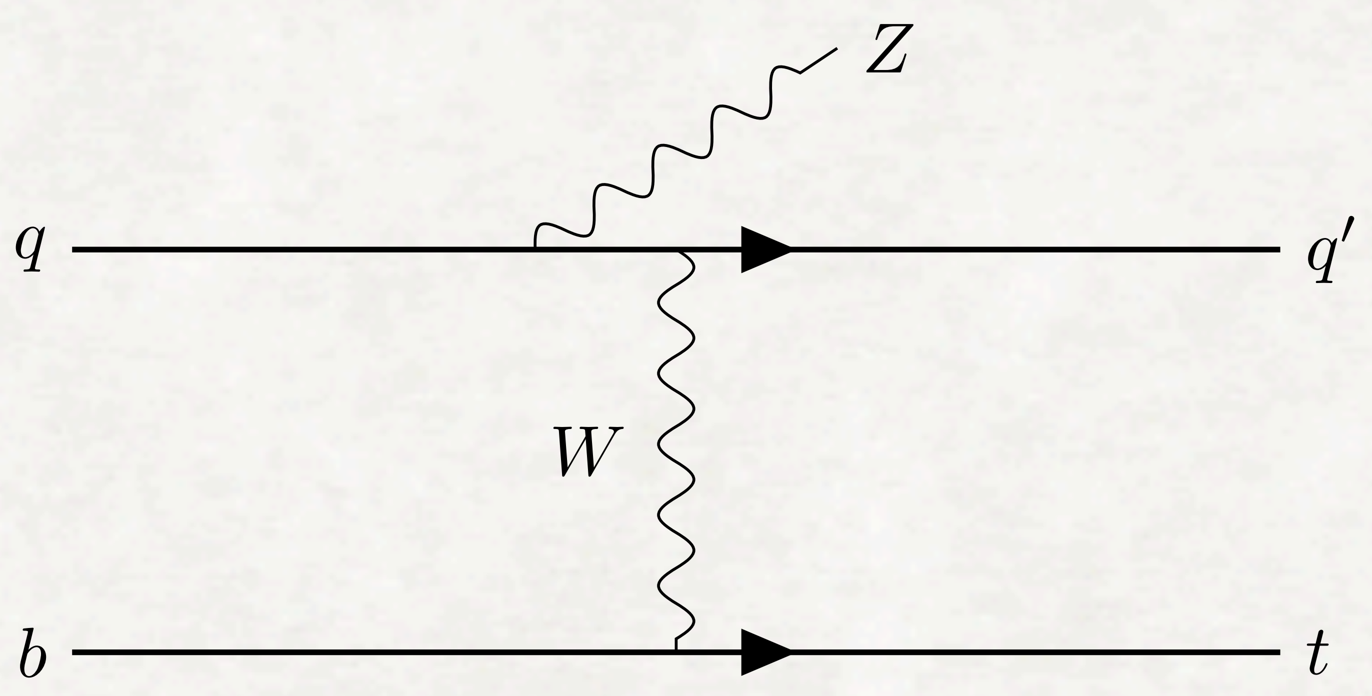
tt+fake lepton



- low misidentification rate, but high cross section
- $m_{jj} \neq m_W$, $m_{ll} \neq m_Z$
- fake lepton: misidentified jets or non prompt leptons

- No resonance in m_Z expected

single top + Vector boson

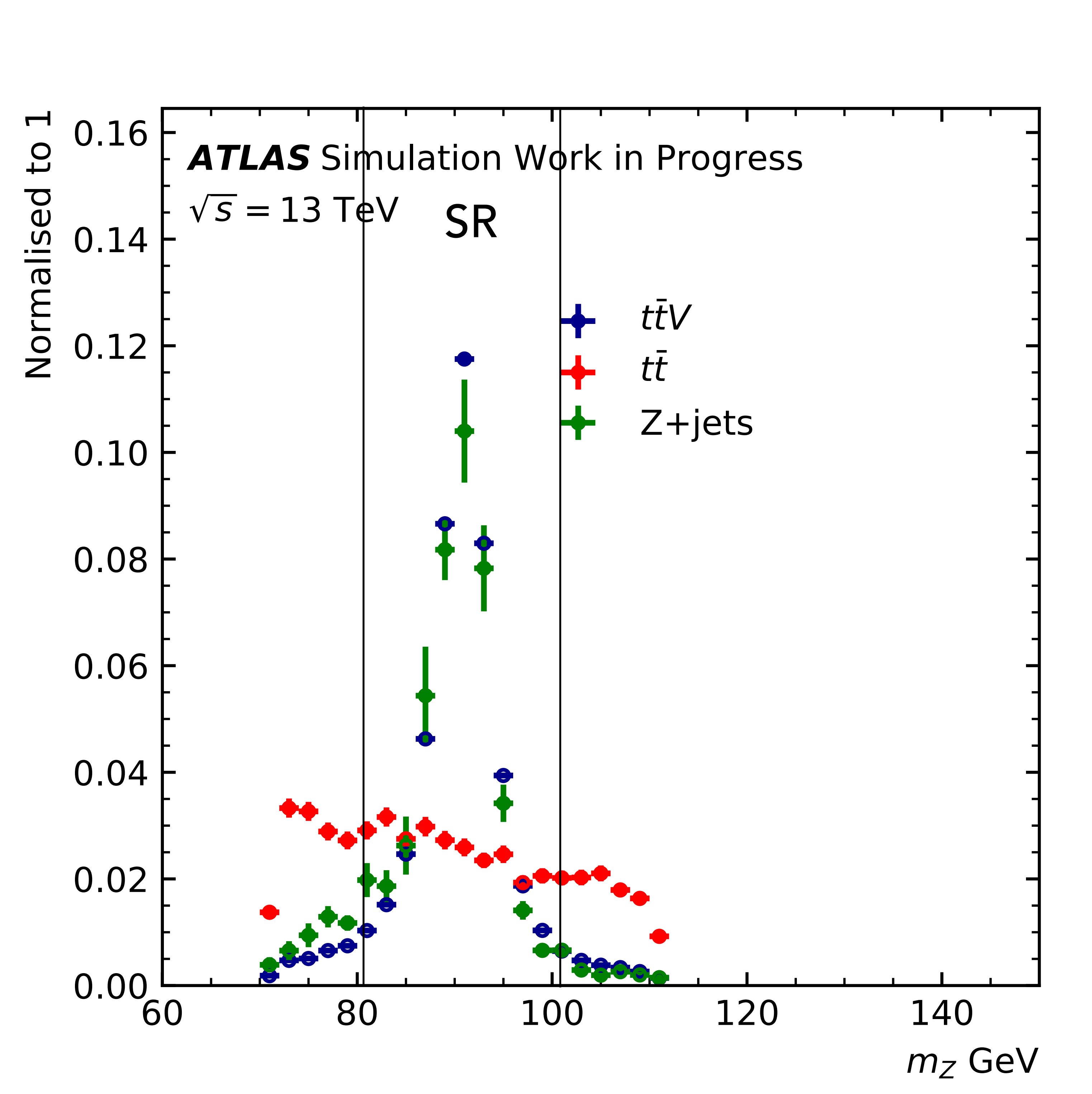


- third dominant background

- no resonance expected in m_{VH}

Event Selection (Signal Region)

	Signal Region	Control Regions
Trigger	single-lepton-trigger	
$N_{\text{b-jets}}$	$= 2$	
N_{jets}	≥ 4	
N_{Leptons}	$= 3$	
b-tag Working Point	77% btag working point	
Jet optimisations	Muon in jet correction	
η (H) in ZH restframe	value is m_A/m_H dependent	
p_T l1	27 [GeV]	
Lepton optimisations	at least 1 OSSF lepton pair	no OSSF lepton pair
p_T l2/l3	13/13 [GeV]	7/7 [Gev]
m_Z window cut	$\|m_{ll} - m_Z\| < 10$ GeV	$\|m_{ll} - m_Z\| < 20$ GeV



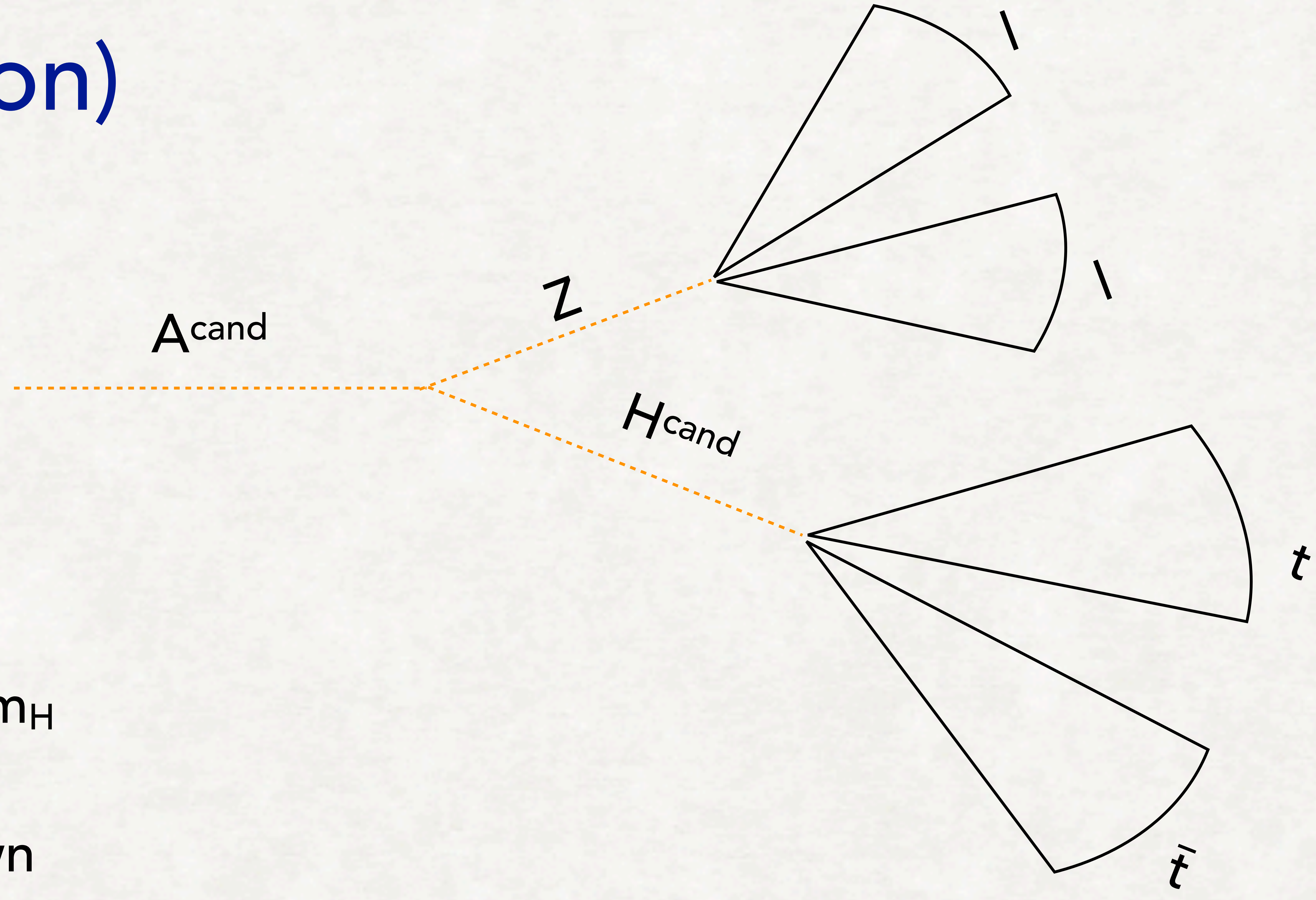
cuts have been optimised to maximise significance

Event Selection (Signal Region)

- 2 resonances expected
  - m_H^{cand}
  - m_A^{cand}
- 2 dim scan

- converting into 1D problem with rebinning of m_H
  - testing different mass hypotheses for mH
  - rescaling of m_H , since m_H hypothesis is known
- look for resonance in m_A or Δm in bins of m_H

➡if signal is present, expect resonance in m_A , m_H & m_A - m_H



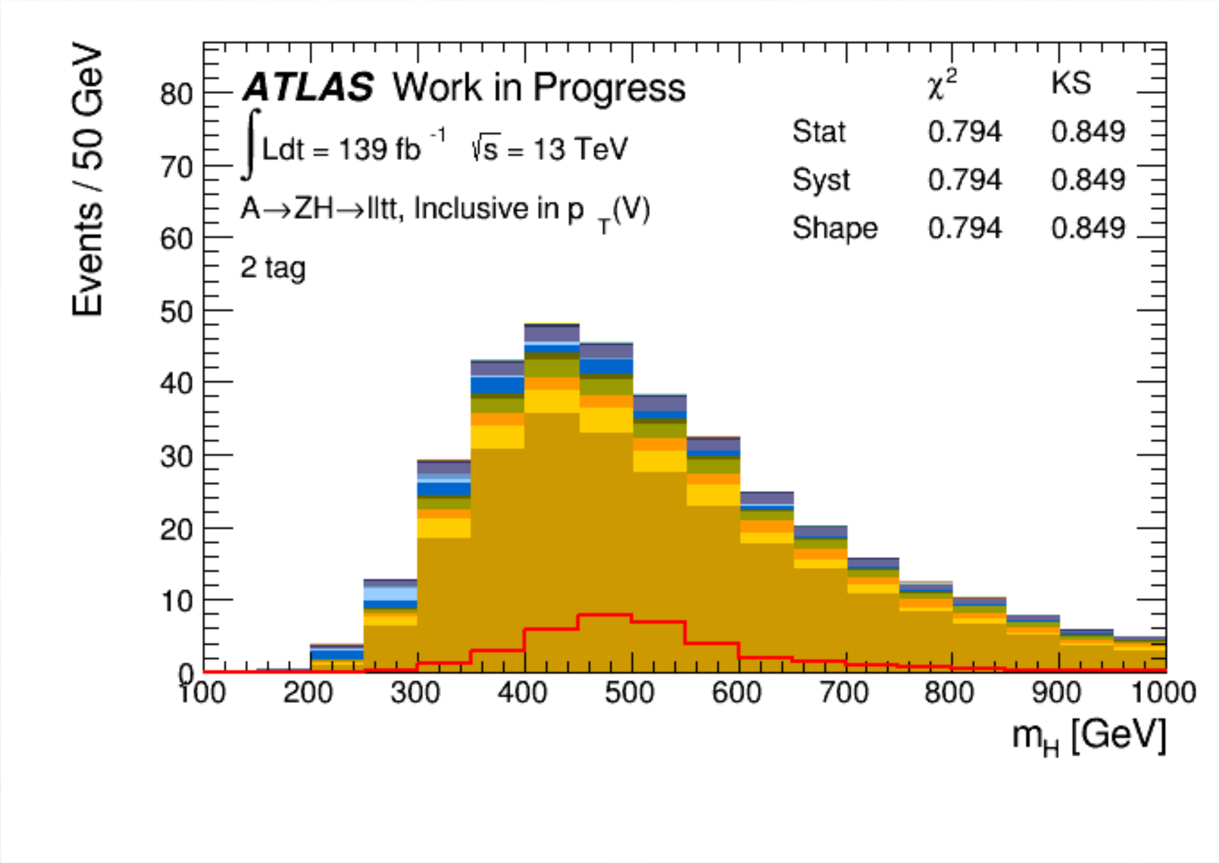
$m_H^{cand} = m_{t\bar{t}}$

$m_A^{cand} = m_{t\bar{t}Z}$

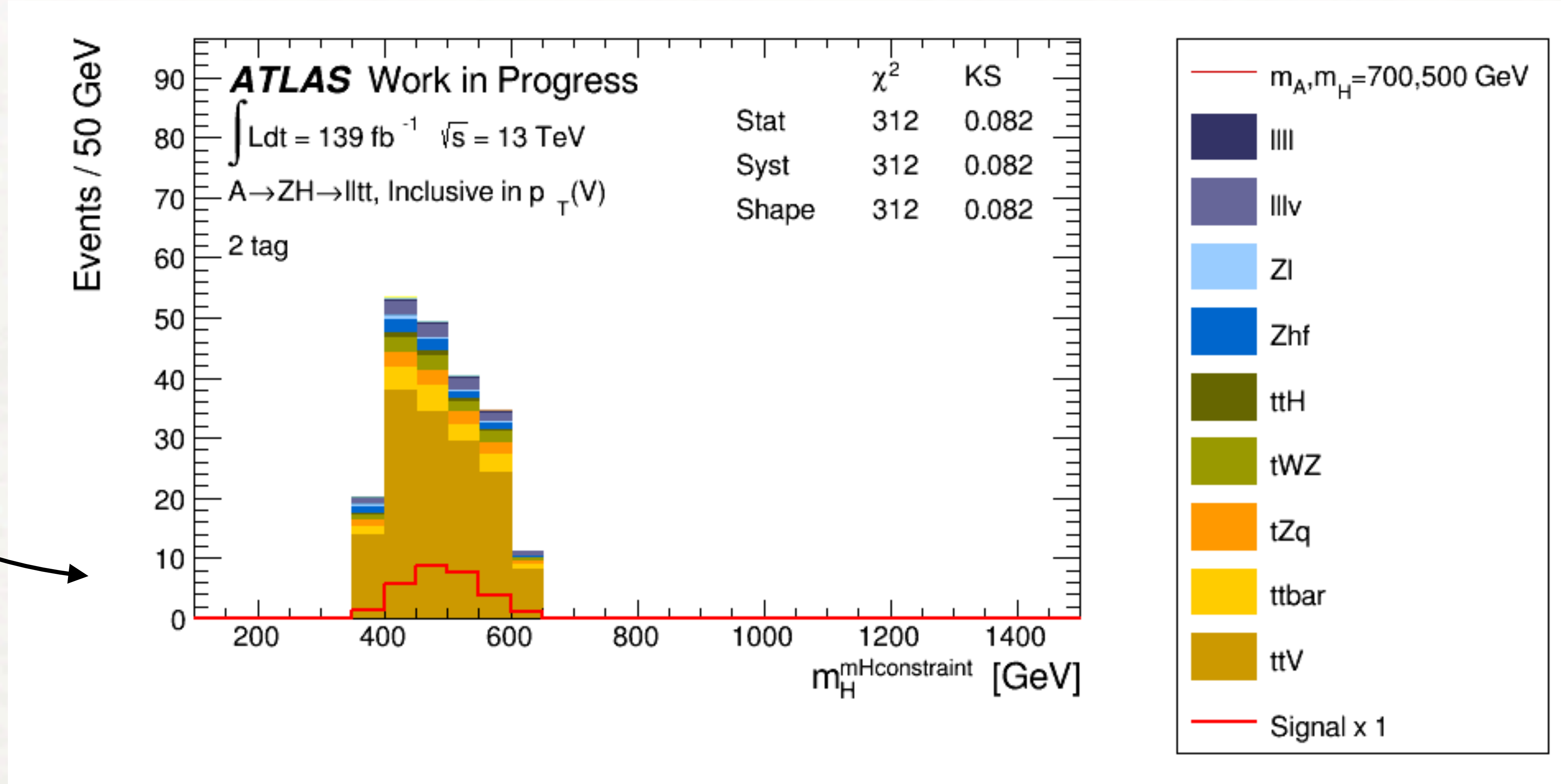
further information: arXiv:1807.07734

Rescaling of m_H

before mH window cut



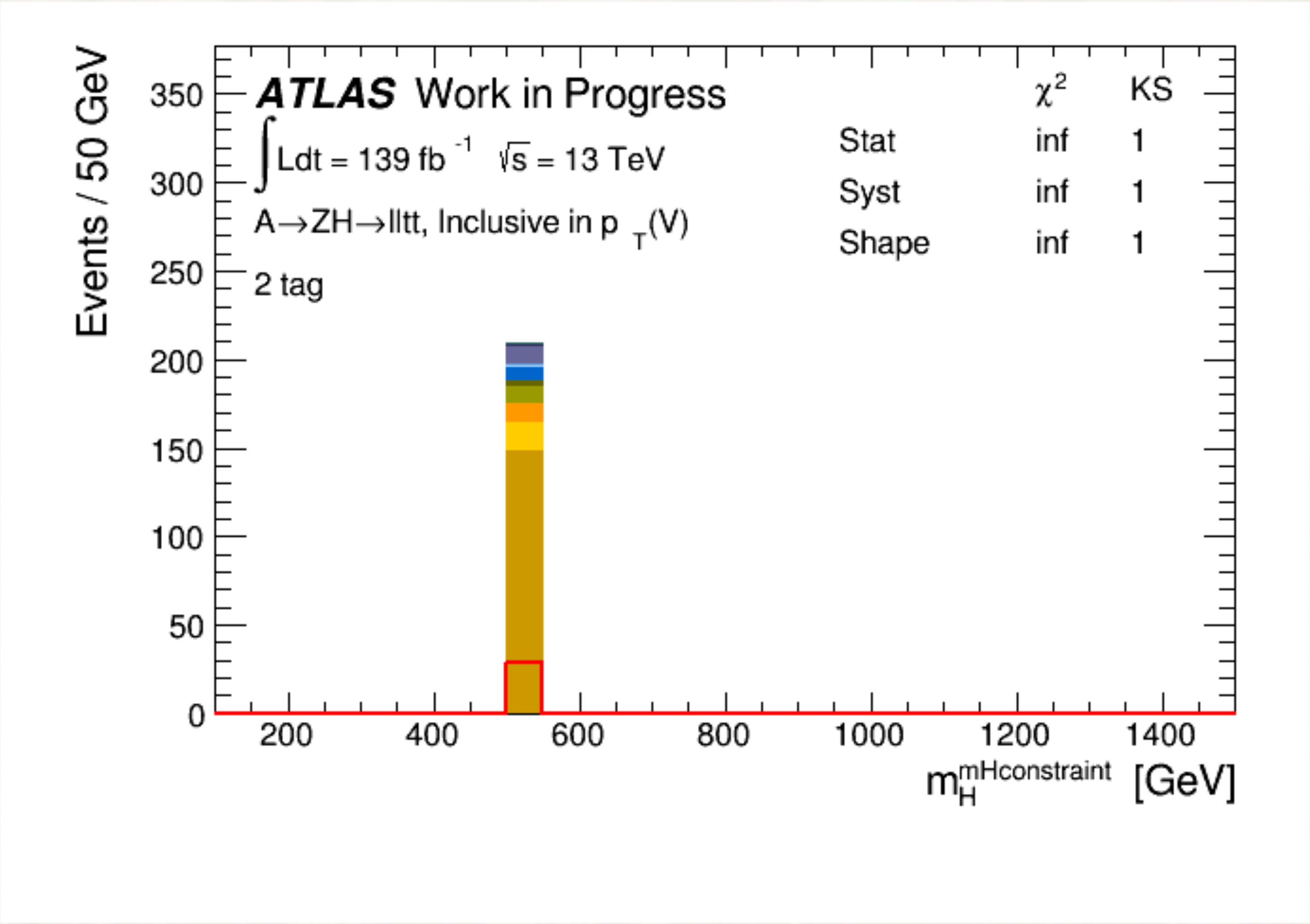
after mH window cut



rescale Lorentz vector of H_{cand} to match m_H hypothesis

$p(t_{1,2}) \rightarrow p(t_{1,2}) \cdot m_{H\ hypo} / m_{t\bar{t}}$

after mH rescaling

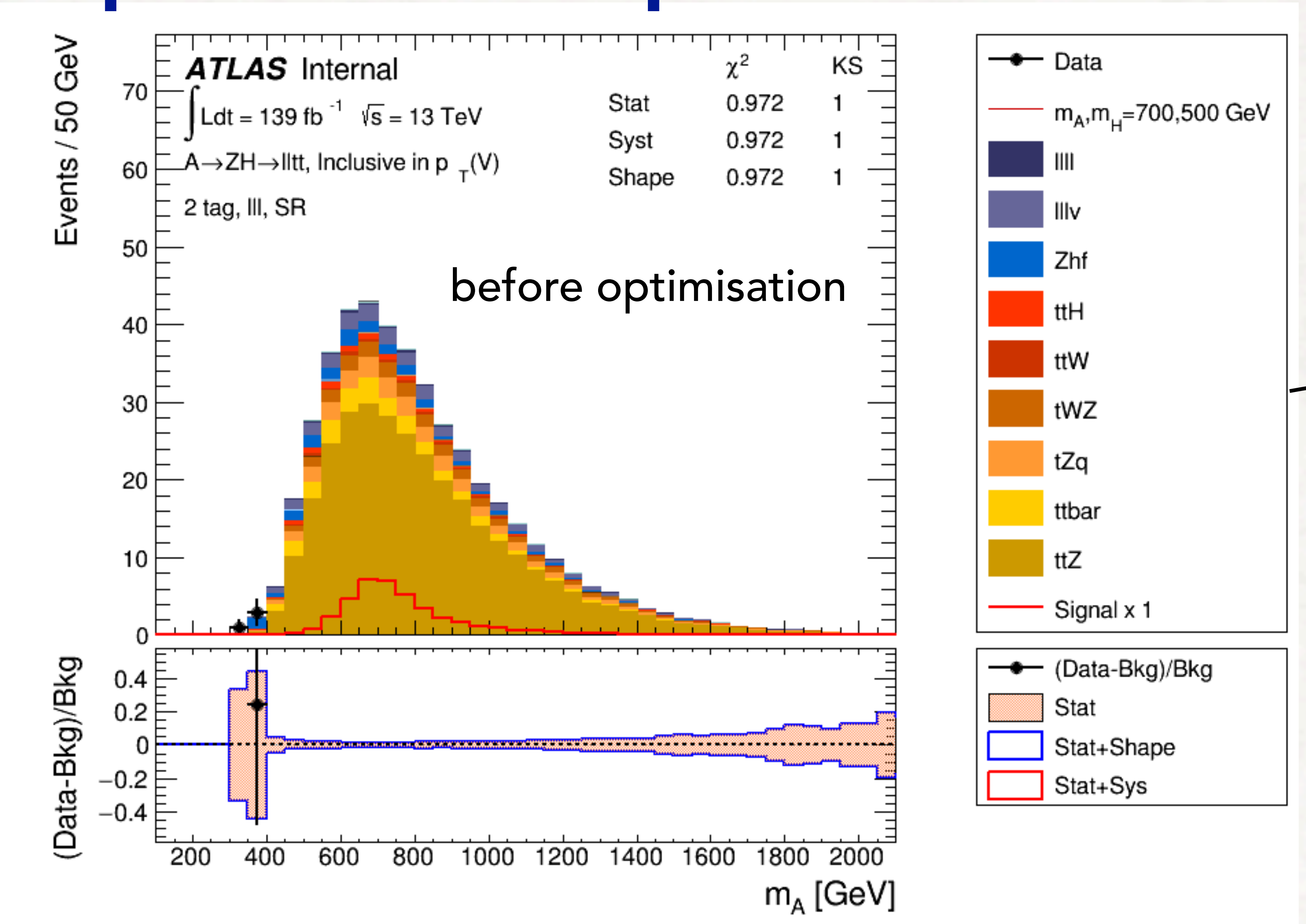


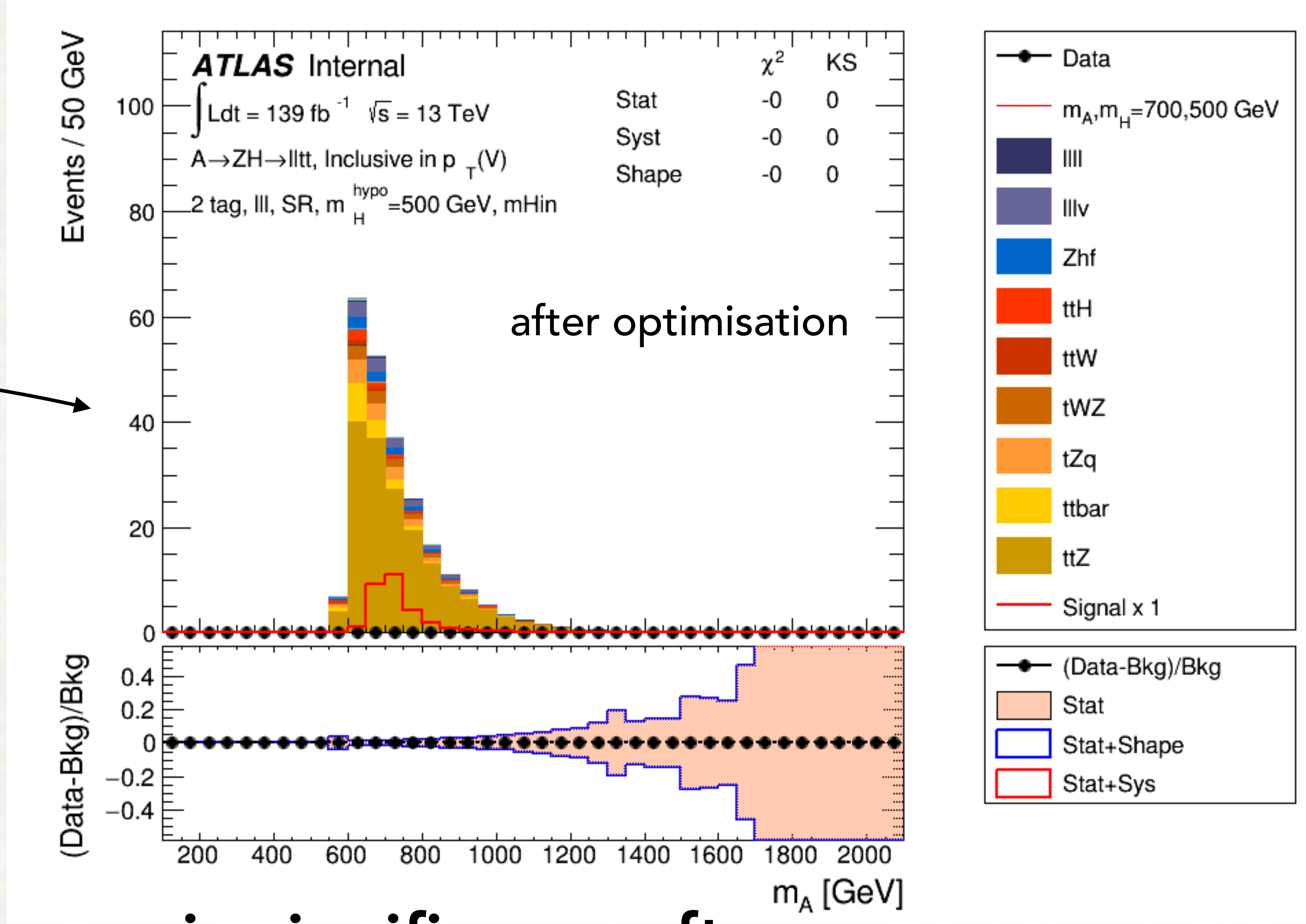
apply window cut on m_H

$$|m_H^{cand} - m_H^{hypo}| < \begin{cases} 1.5 \cdot \sigma(m_{reco}) & \text{if } m_H^{hypo} < 500 \text{ GeV} \\ 2.0 \cdot \sigma(m_{reco}) & \text{if } m_H^{hypo} \geq 500 \text{ GeV} \end{cases}$$

⇒ use m_A - m_H in bins of m_H

Impact of Optimisation



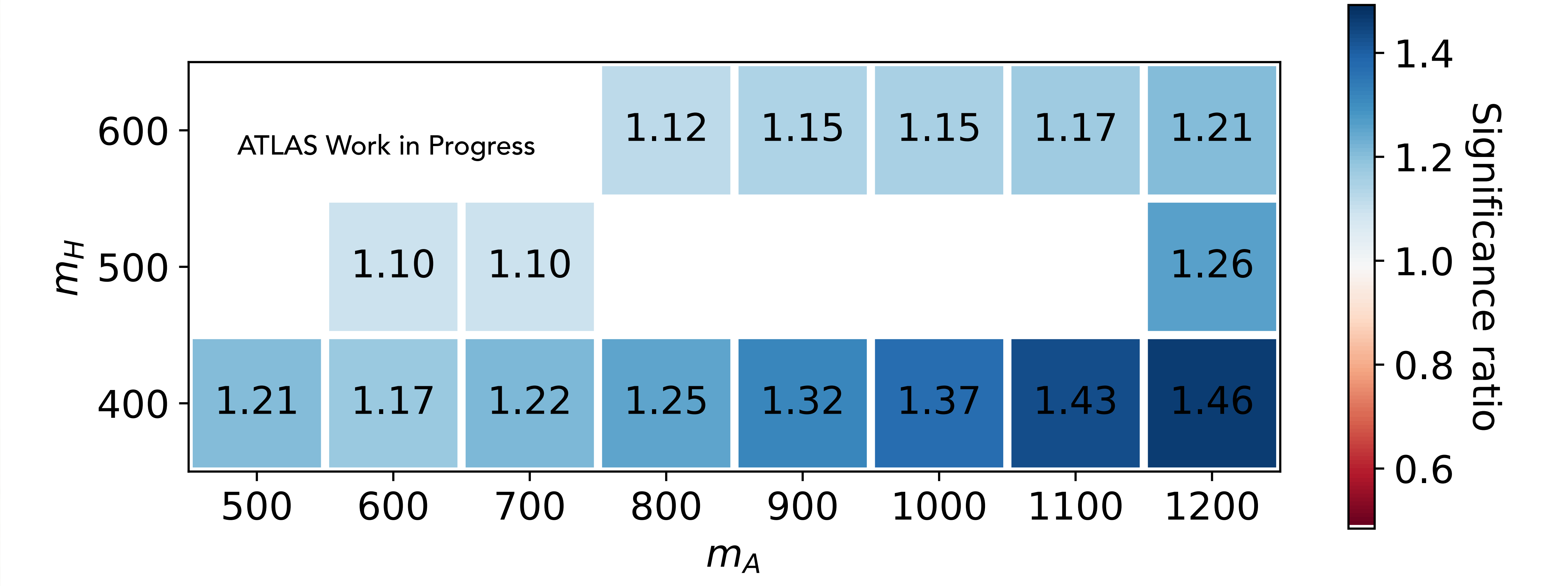


- significance calculated for variable $m_A - m_H$
- Asymptotic log-likelihood ratio formula

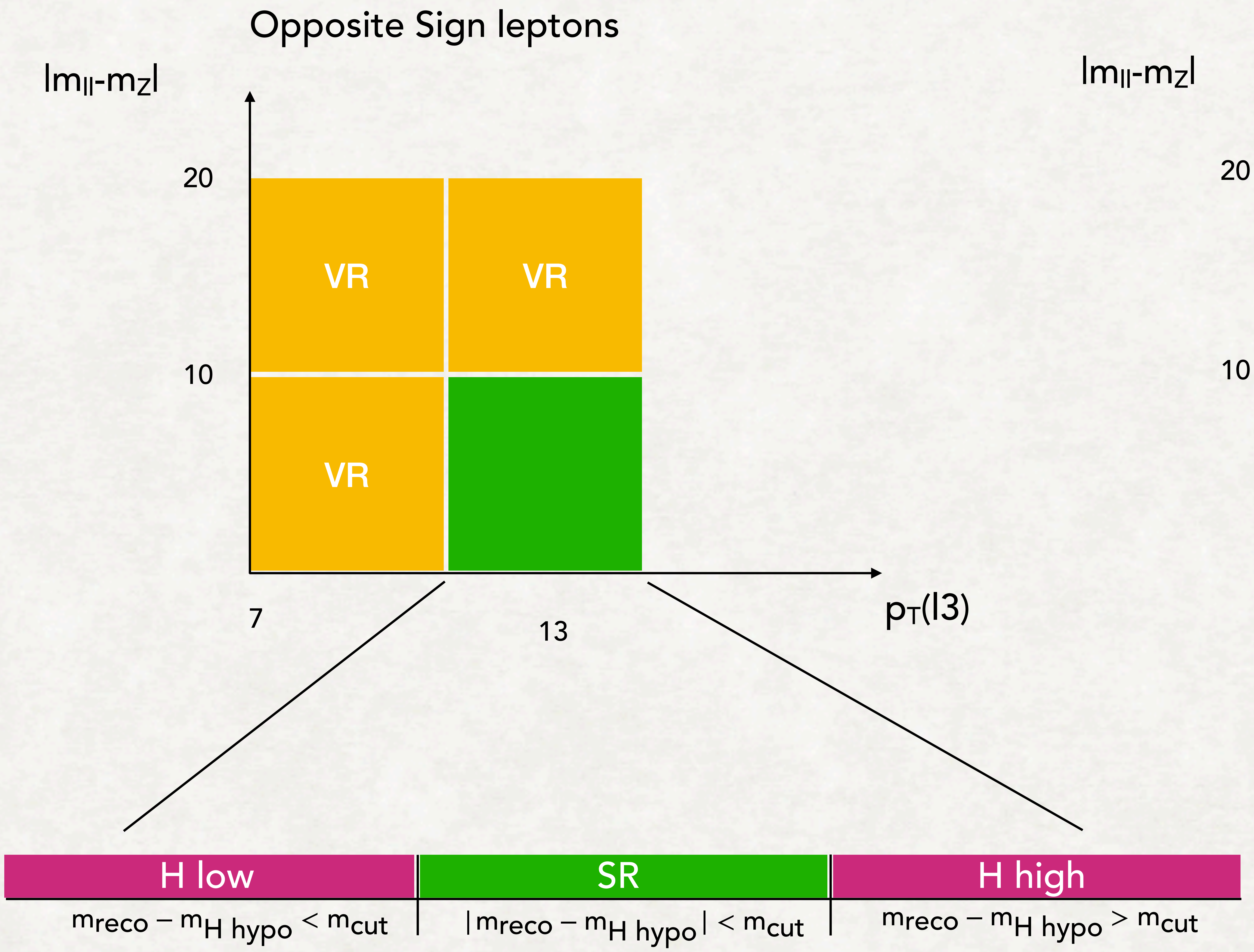
$$\rightarrow S = \sqrt{\sum_{i=0}^{n=N_{bins}} \left(2[(s_i + b_i)\ln(1 + \frac{s_i}{b_i}) - s_i] \right)^2}$$

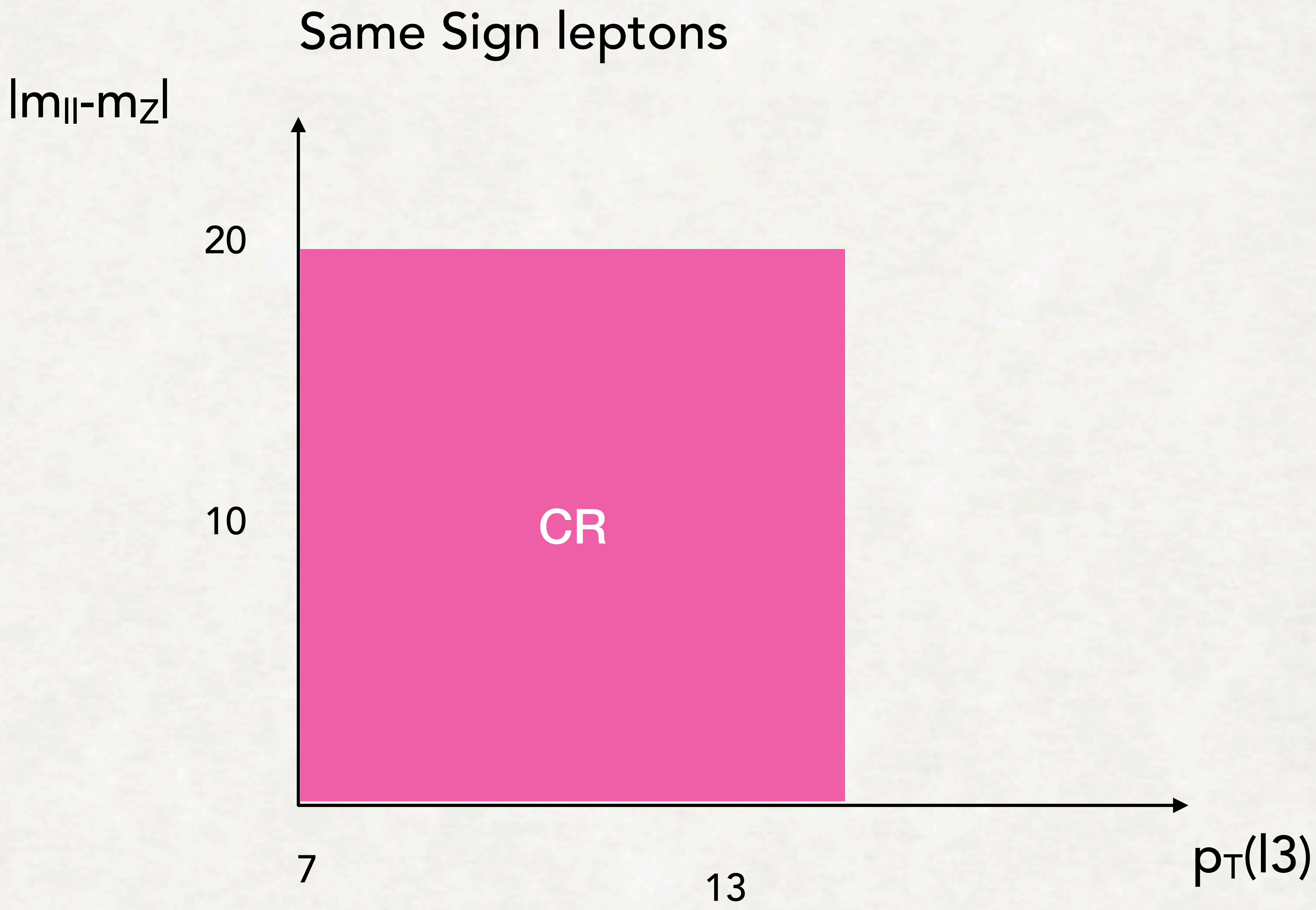
- significance ratio = $\frac{\text{significance after cut}}{\text{significance before cut}}$

large increase in significance after optimisation



Signal/Control & Validation Regions





- Regions are orthogonal to each other

Fit procedure & setup

- perform a simultaneous binned profile likelihood fit to
  - extract parameter of interest μ
  - constraint backgrounds

- regions are orthogonal to each other

Control Region (unblinded) ⟷ fit simultaneously ⟷ **Signal Region** (blinded so far) → apply constraints in etc → **Validation Region** (unblinded)

Control Region

- no/small signal contribution
- used for further constraints on different systematic uncertainties
  - especially ttbar

Signal Region

- Region of Interest, most signal
- get final parameters from a fit to this region

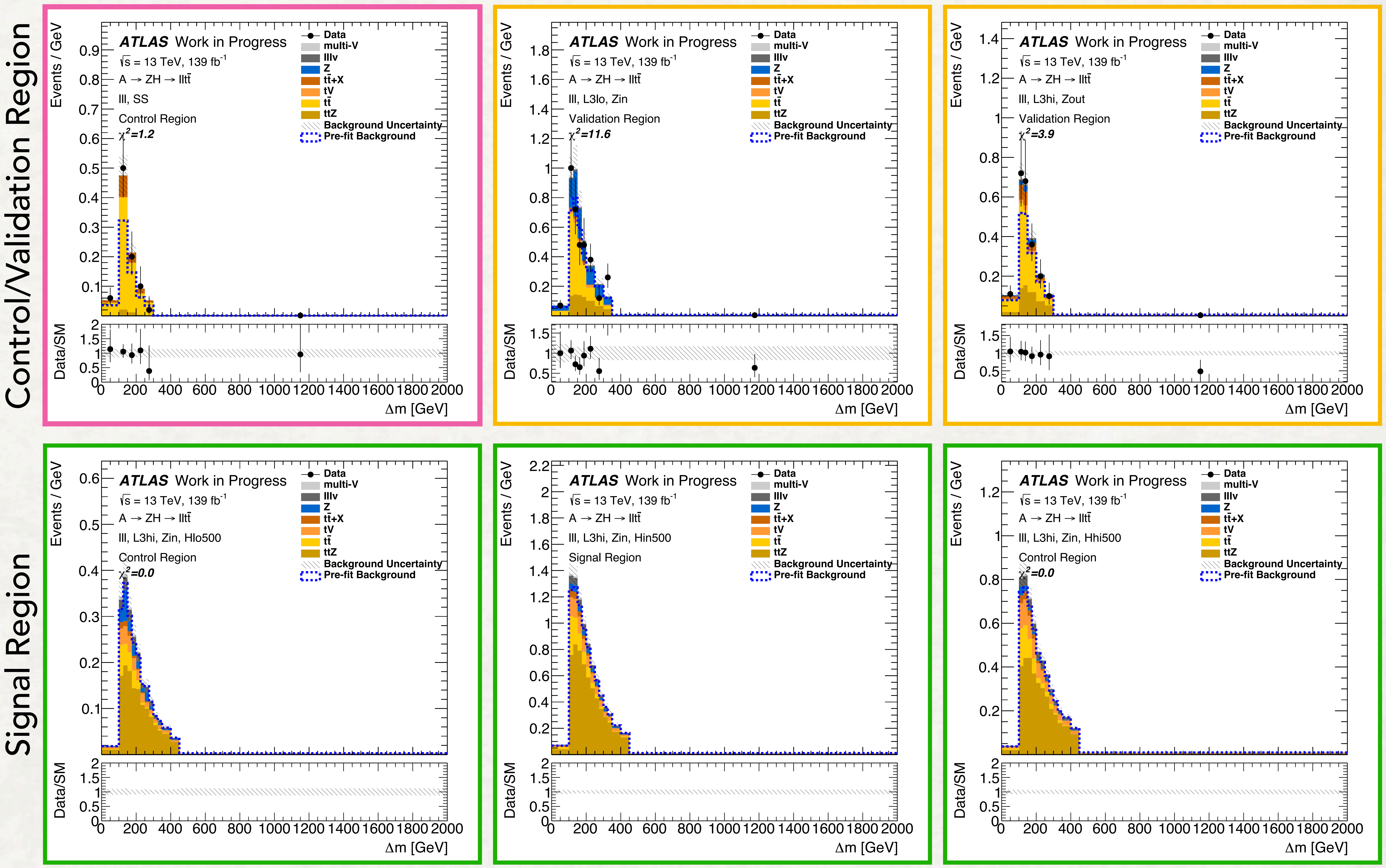
Validation Region

- Validate Results/Fit Parameters in these regions
- Apply constraints obtained from Fit to this region
- compare shapes of data & MonteCarlo Backgrounds

Results

- Fit to Asimov data:
    - data is sum of all background MonteCarlo samples
- Fit describes CR & VR

- Constrains of background normalisation are applied
- validate impact of shape uncertainties



✓ no shape mismodelling can be seen in Control & Validation Region

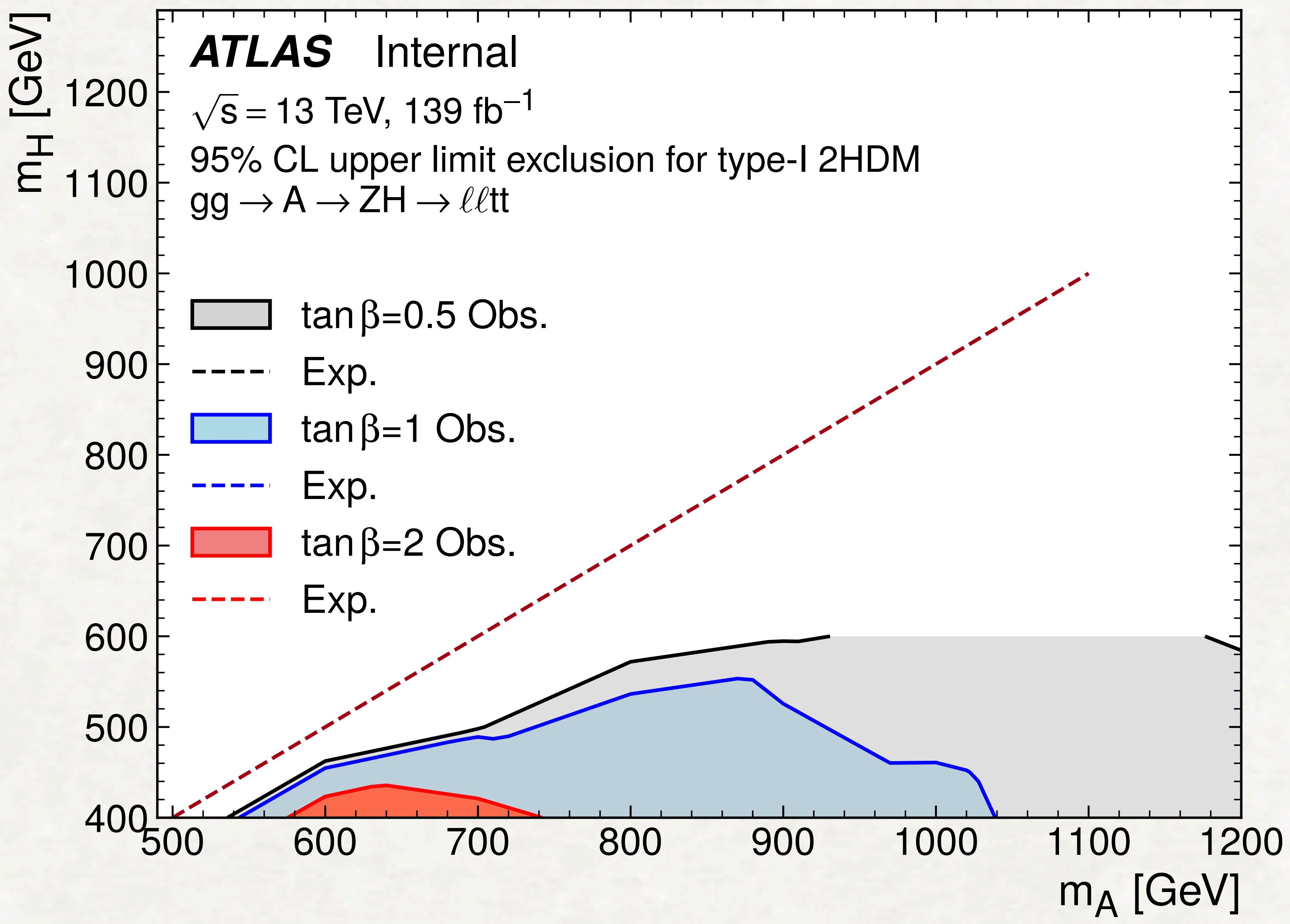
Summary & Future Steps

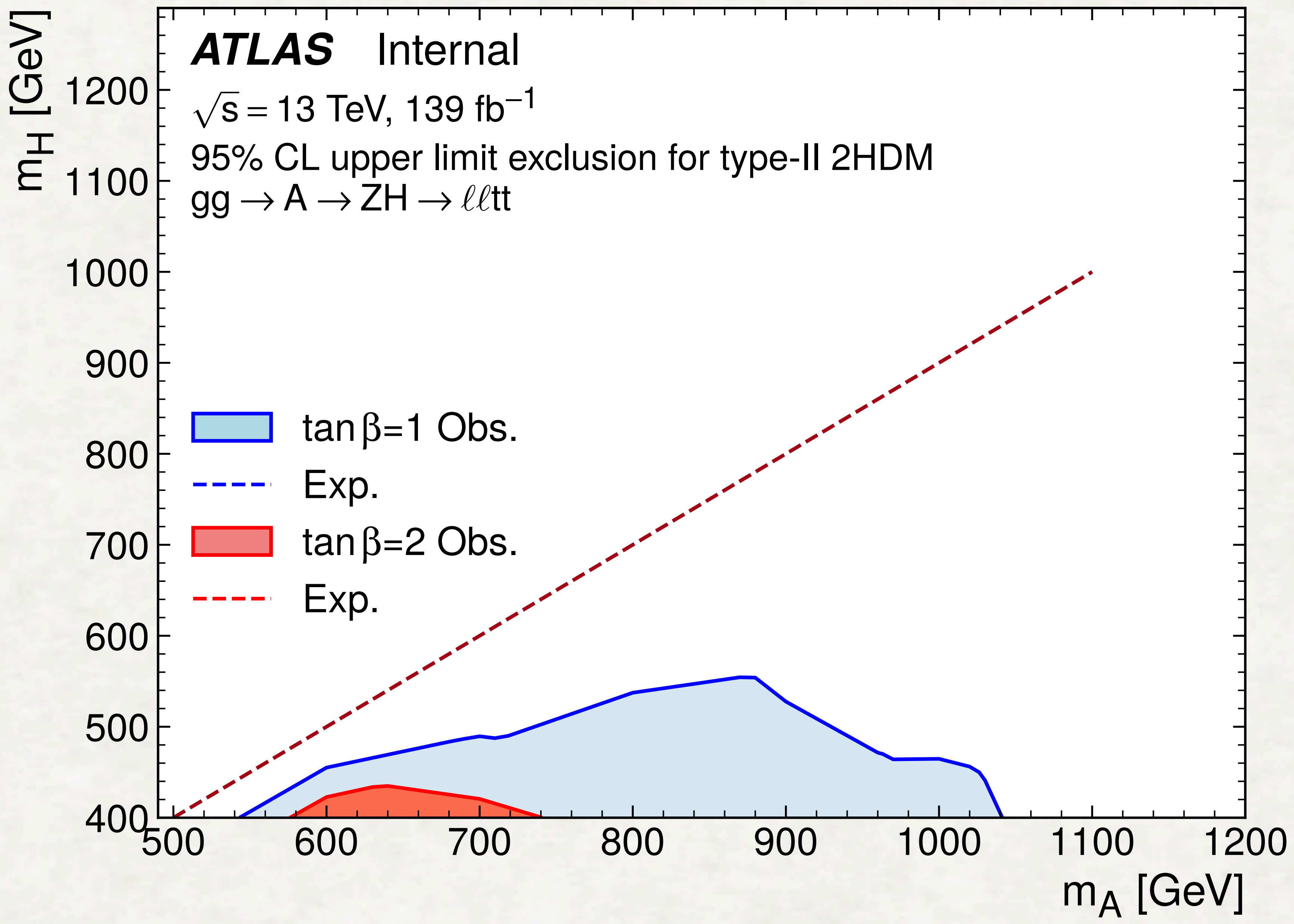
Done so far

- optimised selection
- included systematic uncertainties
- optimised fit setup

Future Steps:

- optimize binning in Signal region
- unblind the analysis
- obtain upper limits on cross section for different signal hypotheses

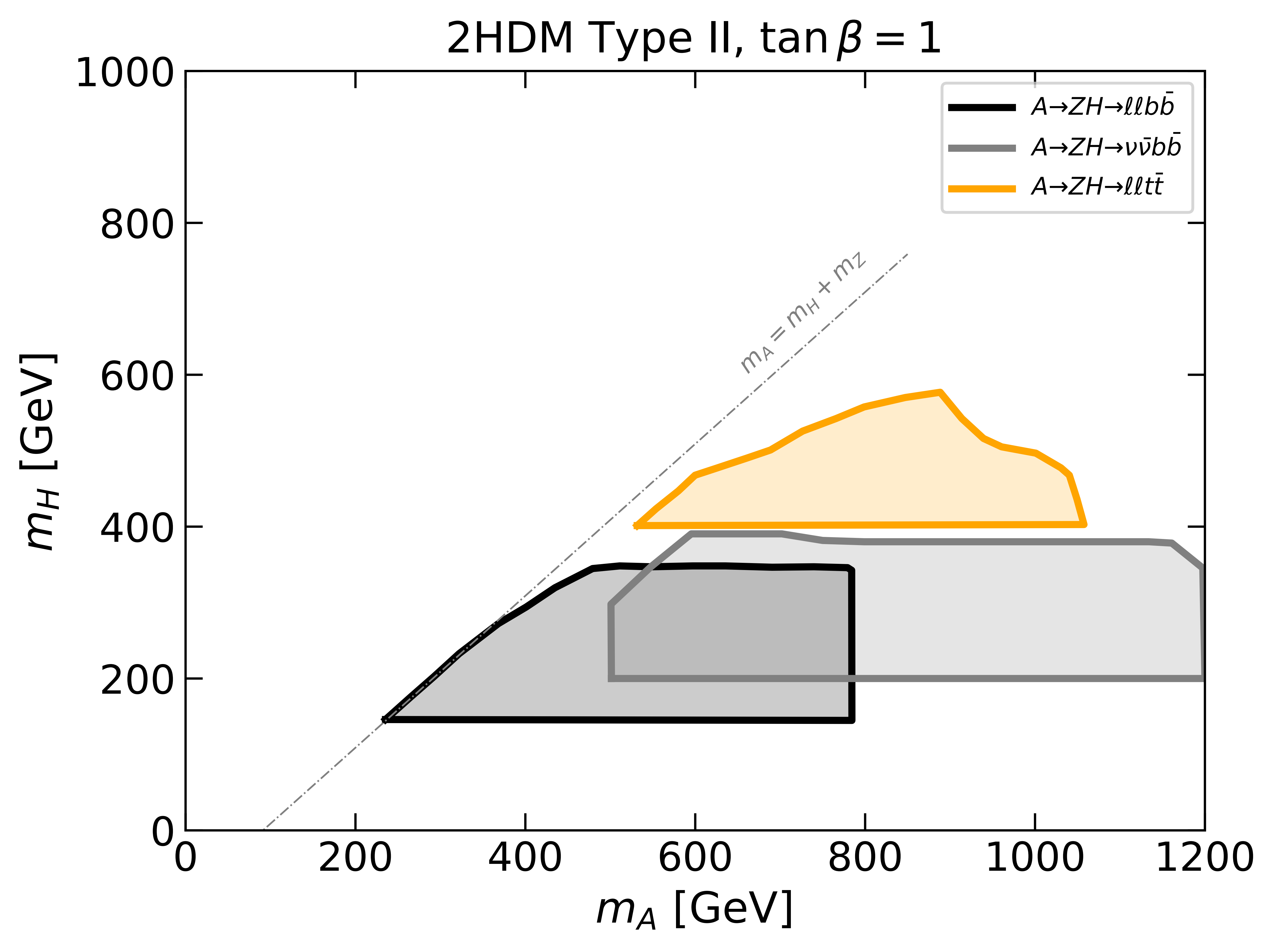




Outlook

test if signal is present, otherwise:

- put upper limits on $\sigma(A \to ZH \to \ell\ell t\bar{t})$
- extend exclusion regions to higher mass regions



probe phase space so far unexplored with the LHC

— for a bridge between Particle Physics and Cosmology —

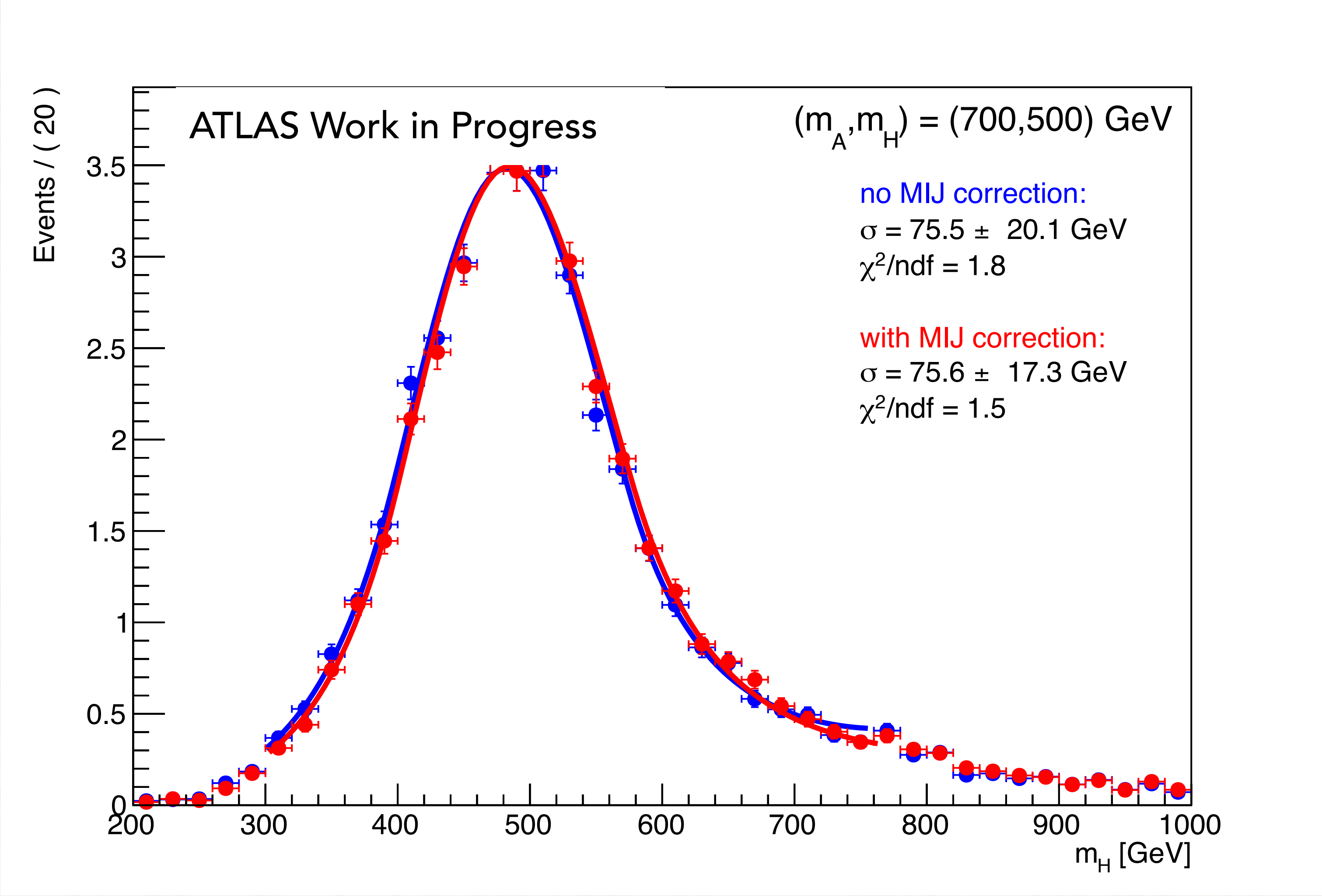
Back Up

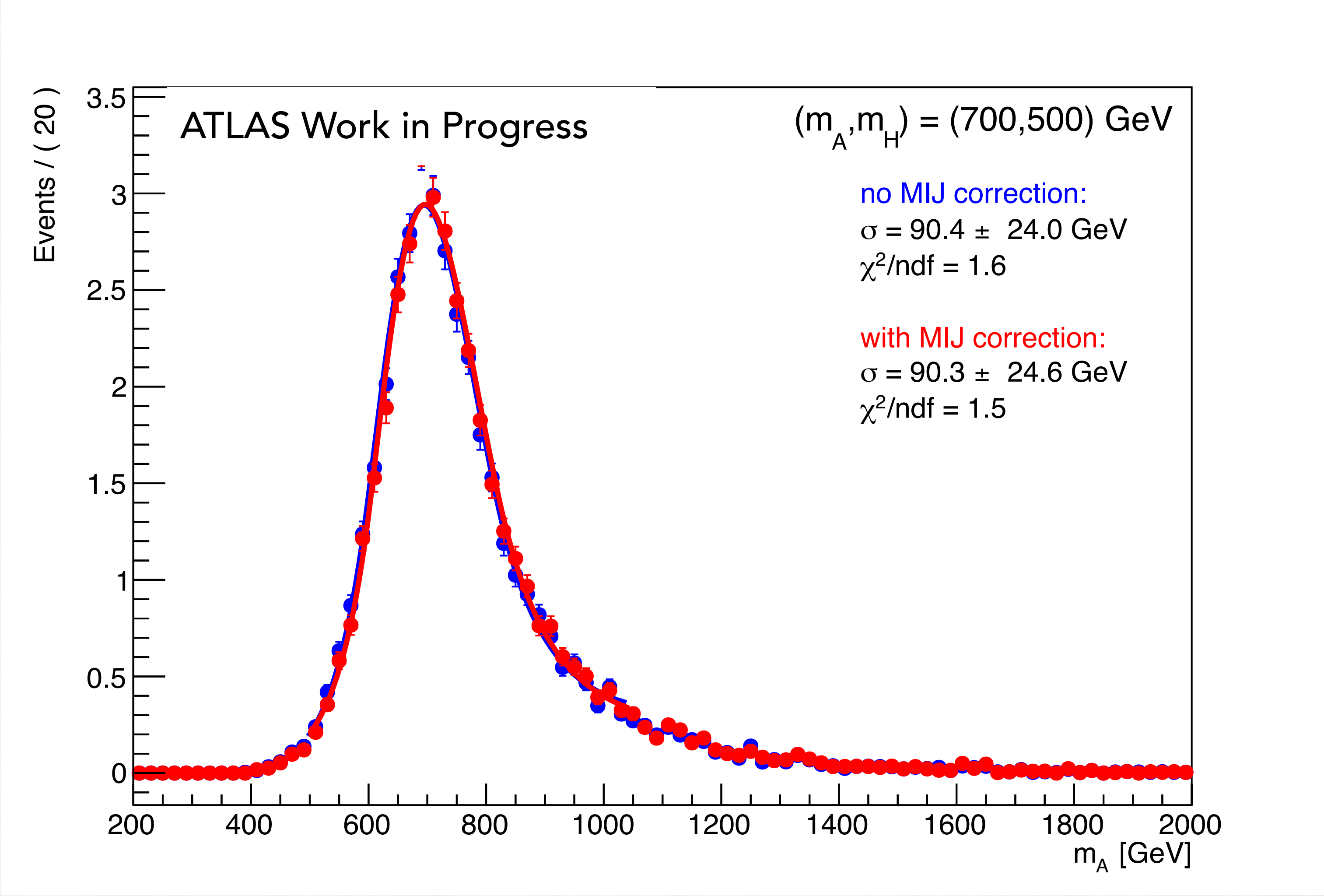
Muon in Jet correction

b-jets contain leptonic decaying B-hadrons

➡lower response in calorimeter due to neutrinos and muons

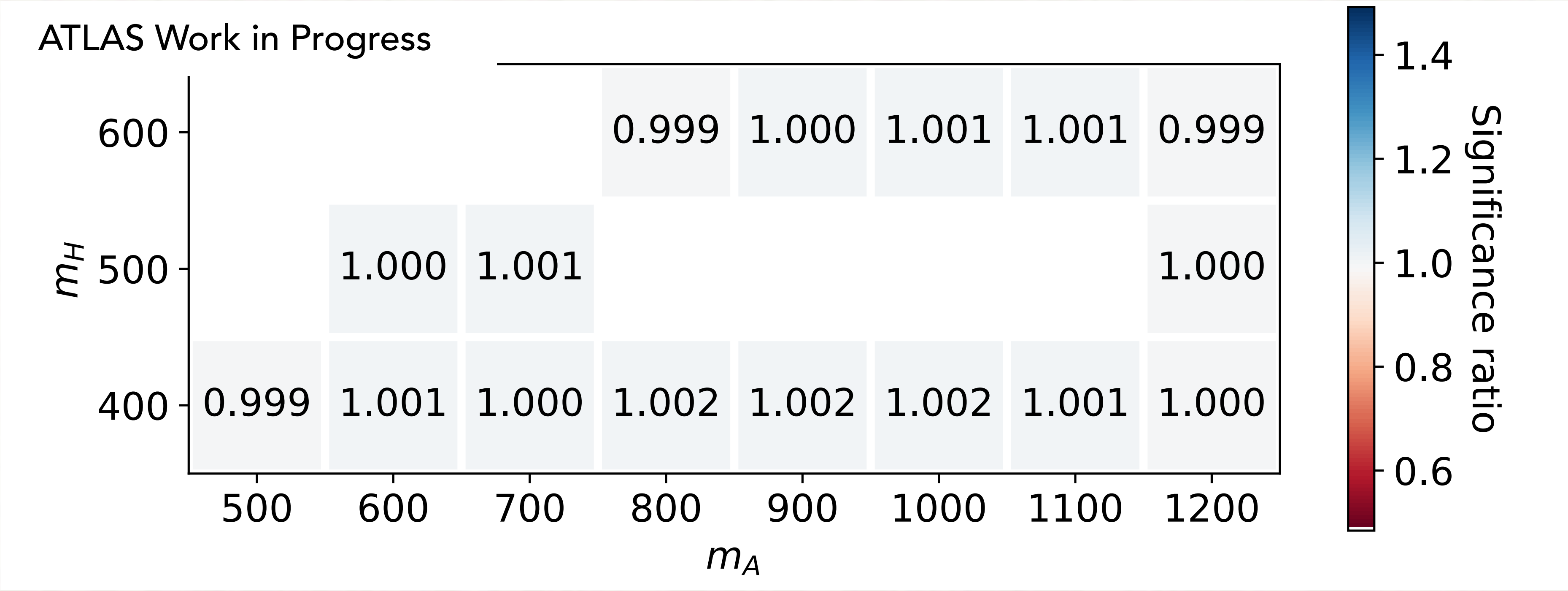
➡add 4 momentum of muon closest to b-jet axis to momentum of b-jet



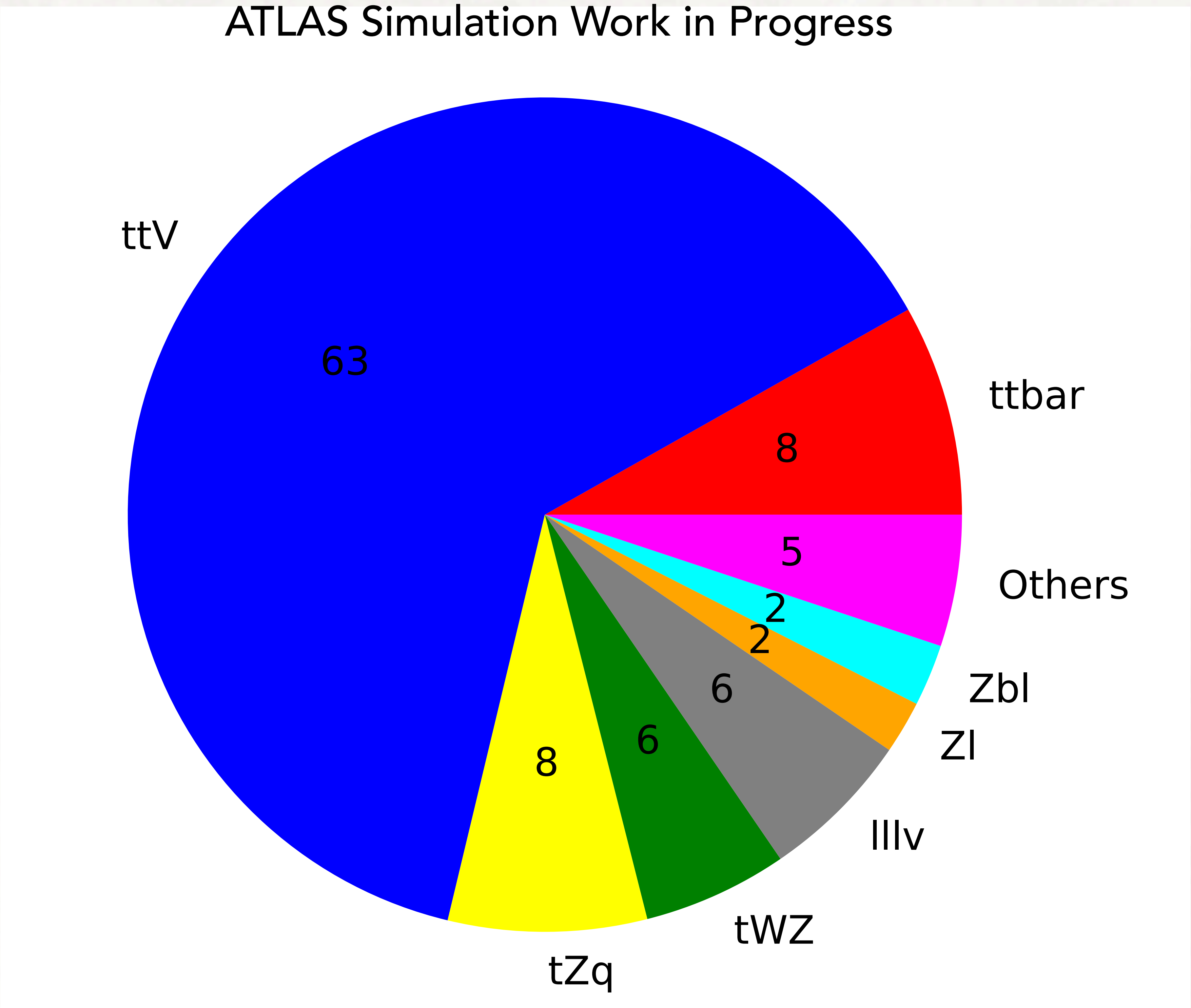


⇒no big change in resolution and significance between

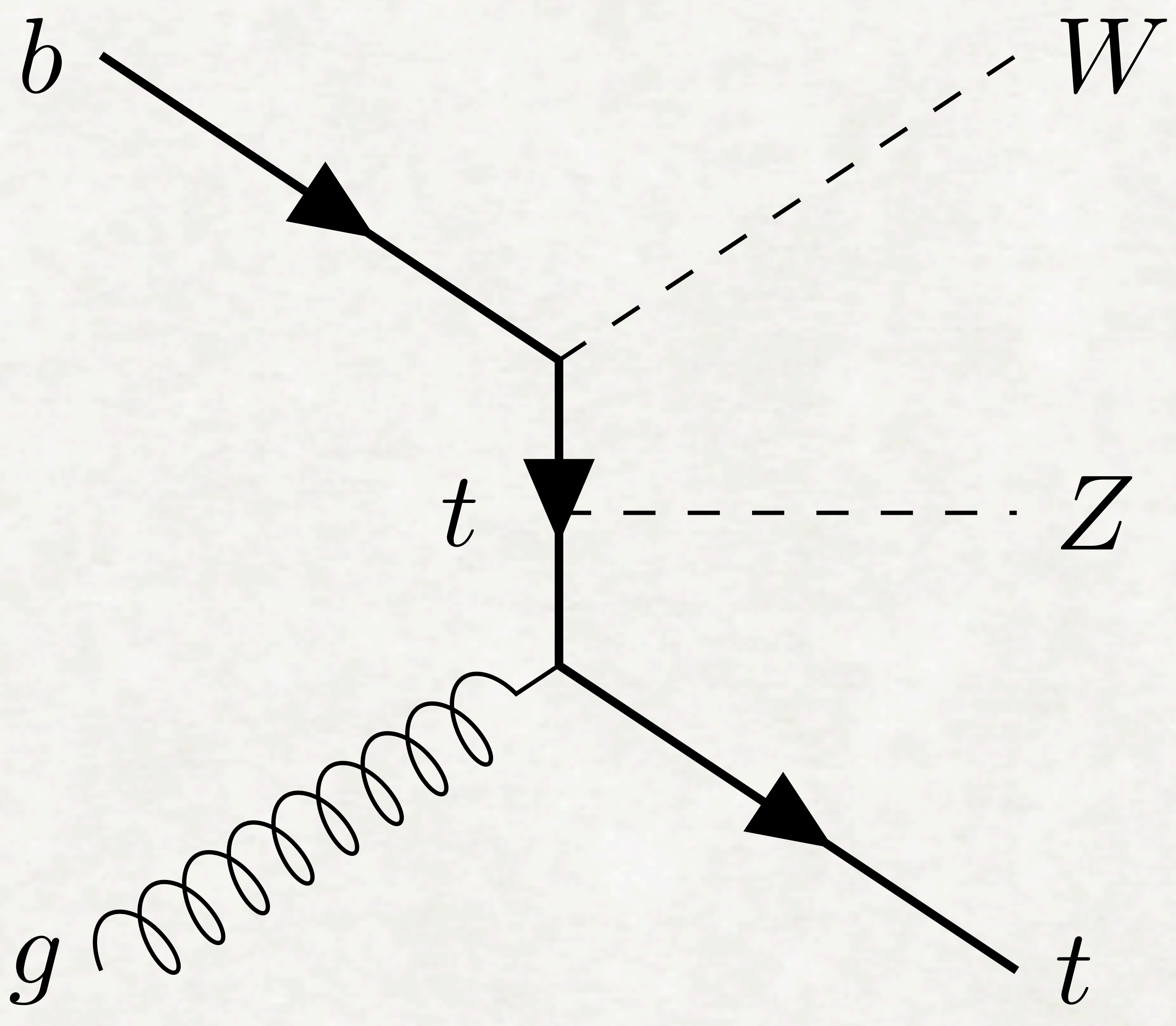
- MIJ correction
- no MIJ correction



Background composition



tWZ



Systematic uncertainties

Theoretical Uncertainties

different sources of theoretical uncertainties affecting MC modelling:

- missing higher orders in matrix elements
- parton shower/hadronisation uncertainties
- uncertainties from PDFs and α_s
- etc…

normalisation uncertainties

- uncertainty applied to samples where normalisation is not floating
- estimated by comparing nominal events to alternative samples

shape uncertainties

- uncertainties on shape of fit variable
- estimated by comp shape of fit variable to alternative samples

acceptance uncertainties:

- alteration of shape of observables used to separate fit regions
  - induce normalisation/acceptance differences

Experimental Uncertainties

- arising from reconstruction of obejcts
- impact of experimental uncertainties smaller than impact of theoretical uncertainties
- have influence on yields of backgrounds and shape of fit discriminant

Event Selection (Validation Regions)

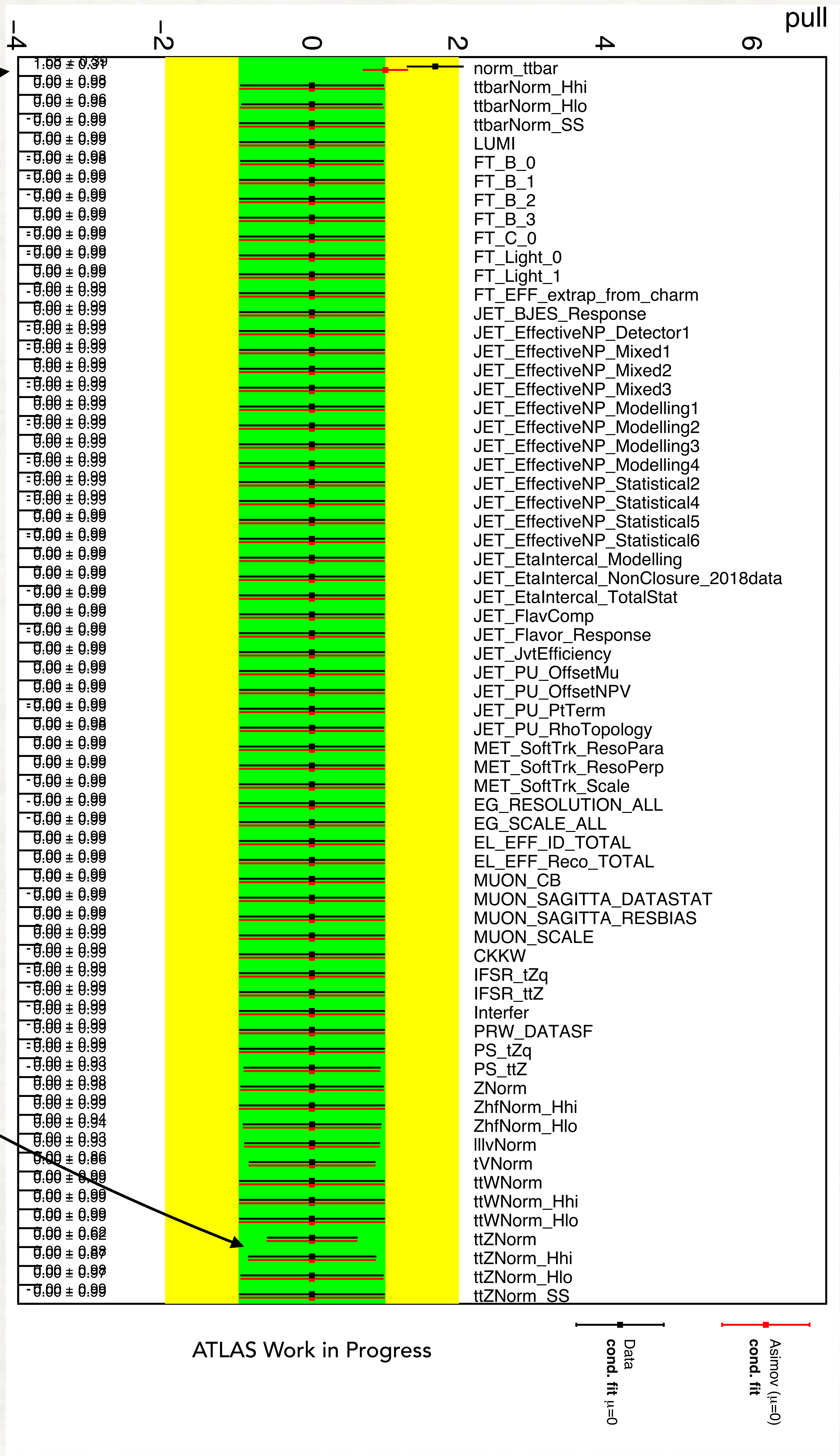
- Regions of Control, Signal & Validation are orthogonal to each other
- assuring that no signal is given in Control and Validation regions

	p_T l3 high, Z out	p_T l3 low, Z in	Signal Region	Control Region
previous cuts	Identical			
Lepton optimisation	at least 1 OSSF			no OSSF
p_T l1/l2/l3	27/13/13 [GeV]	27/7/7 - 27/13/13 [Gev]	27/13/13 [GeV]	27/7/7 [GeV]
m_Z window cut	10 GeV $< \|m_{ll} - m_Z\| <$ 20 GeV	$\|m_{ll} - m_Z\| <$ 10 GeV	$\|m_{ll} - m_Z\| <$ 10 GeV	$\|m_{ll} - m_Z\| <$ 20 GeV

Pull Plots

underestimating ttbar
➡apply scale factor of 1.683 to ttbar
➡calculated from a control Region only fit

- zero pulls observed for nuisance parameters
- expected for fit to pseudodata
- some Nuisance Parameter are overconstrained



Fit procedure & setup

Profile Likelihood Fit:

- shape analysis, based on distributions of continous variables
- Parameter of interest: Signal Strength: $\mu = \frac{\sigma_{meas}}{\sigma_{theory}}$

$$\mathscr{L}(n, \theta^0 \,|\, \mu, \theta) = \text{Pois}\,(n \,|\, \mu S + B) \left[\prod_{b \in \text{bins}}^{n} \frac{\mu \nu_b^{\text{sig}} + \nu_b^{\text{bkg}}}{\mu S + B} \right] \left[\prod_{j \in \text{systs}} \mathscr{G}(\theta_j^0 \,|\, \theta_j, \Delta\theta) \right]$$

- use profile likelihood fit
- fit MC templates of various background contributions to dat

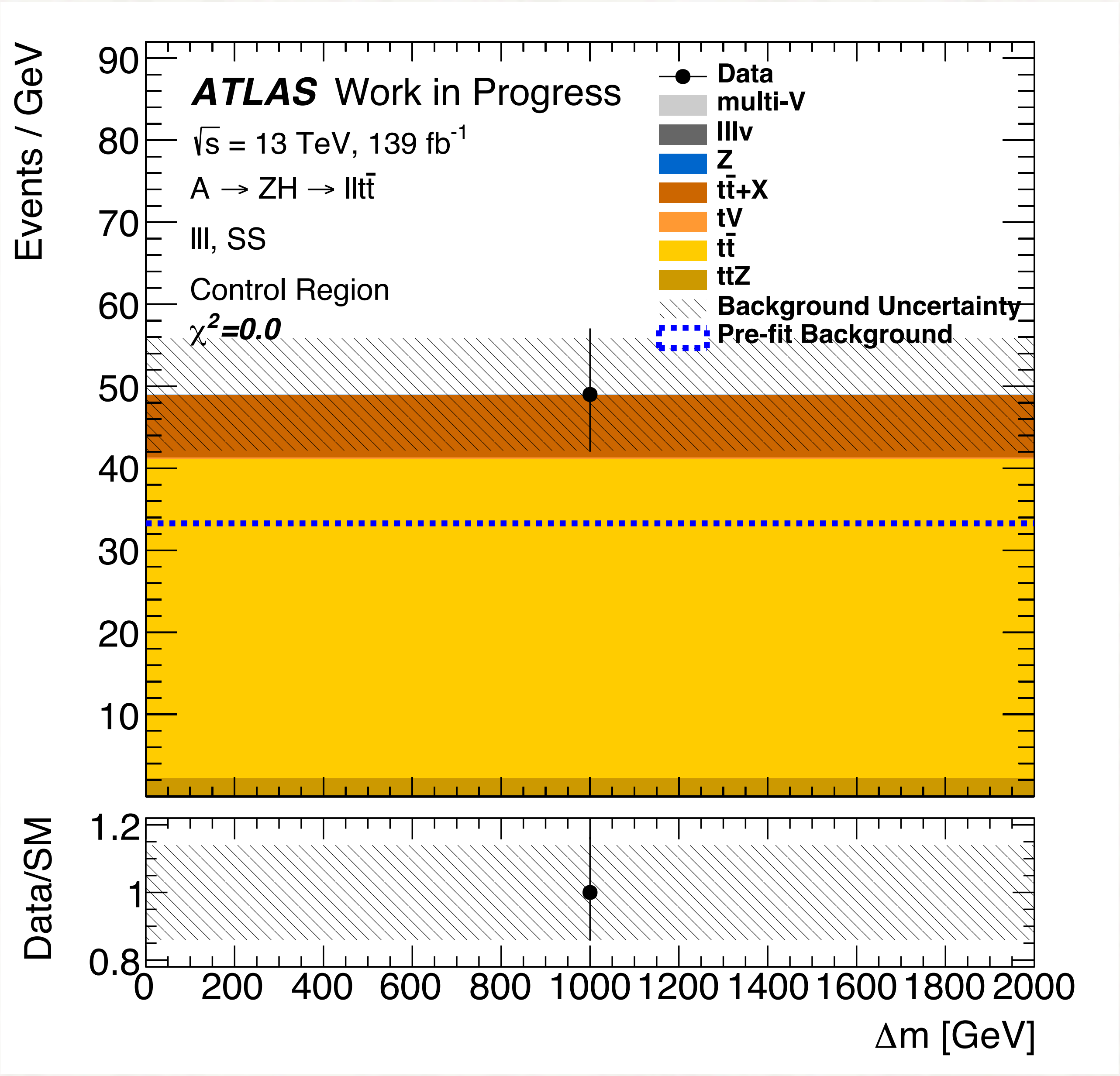
- blinded in Signal region to avoid bias
- fit to Pseudodata in signal region ($\mu = 0$)

Optimised setup of fit in different aspects

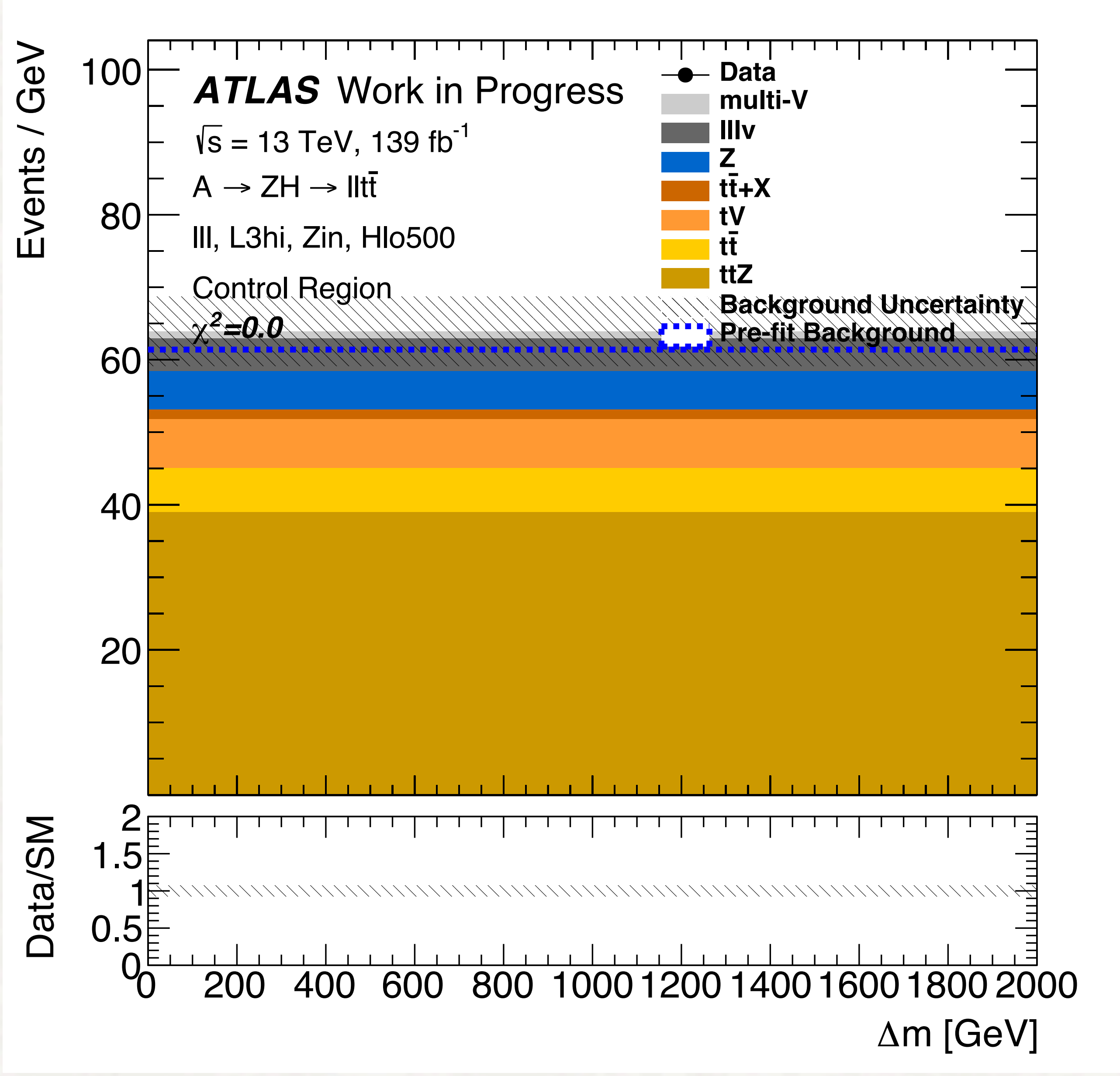
- use sideband regions with 1 bin as additional control re
- use SameSign as Control Region in Fit - but unblinded
- p_T (l3) high - Z out and p_T (l3) low - Z in are used as valic

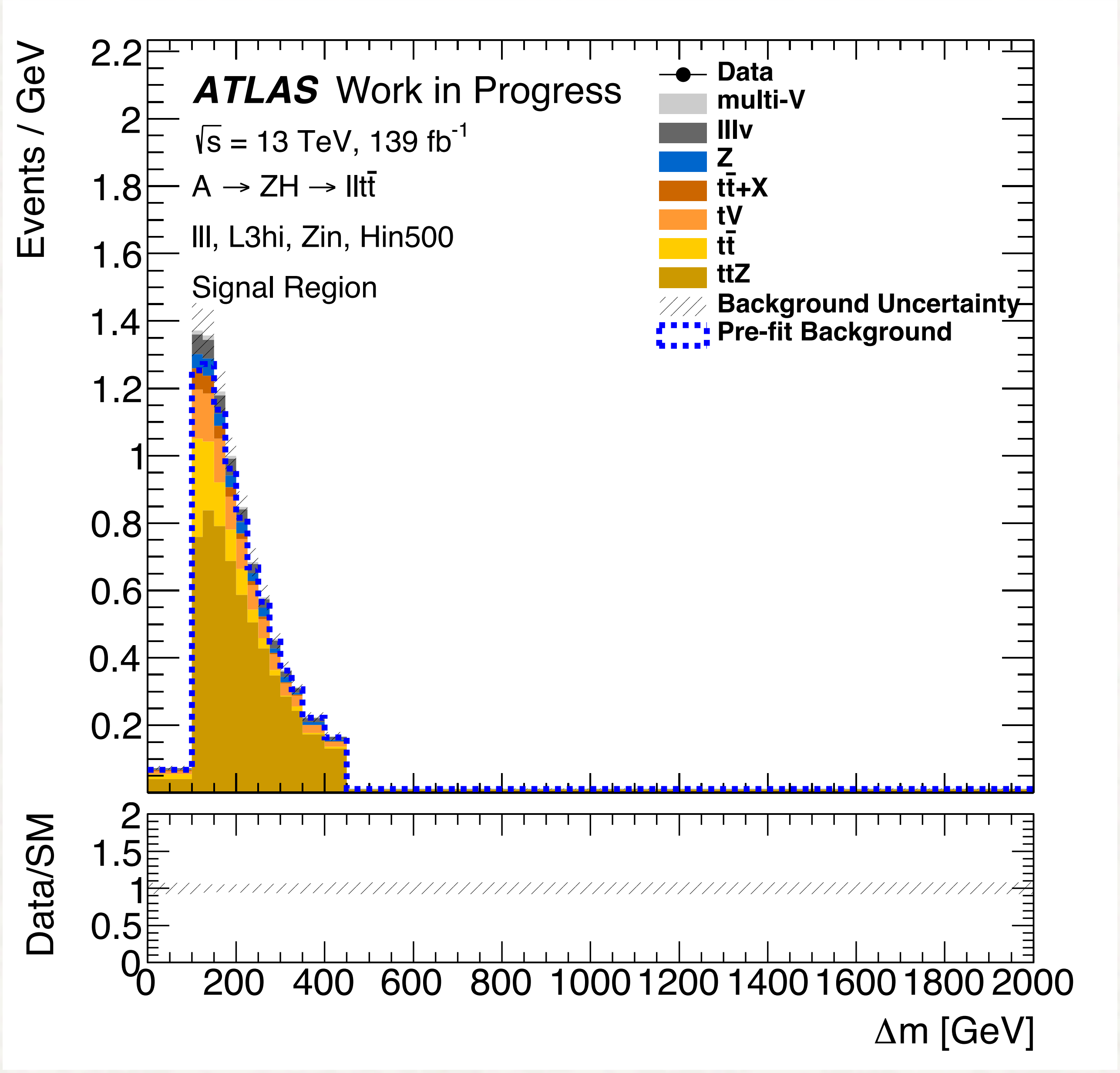
Fit setup (m_A =700 GeV, m_H = 500GeV)

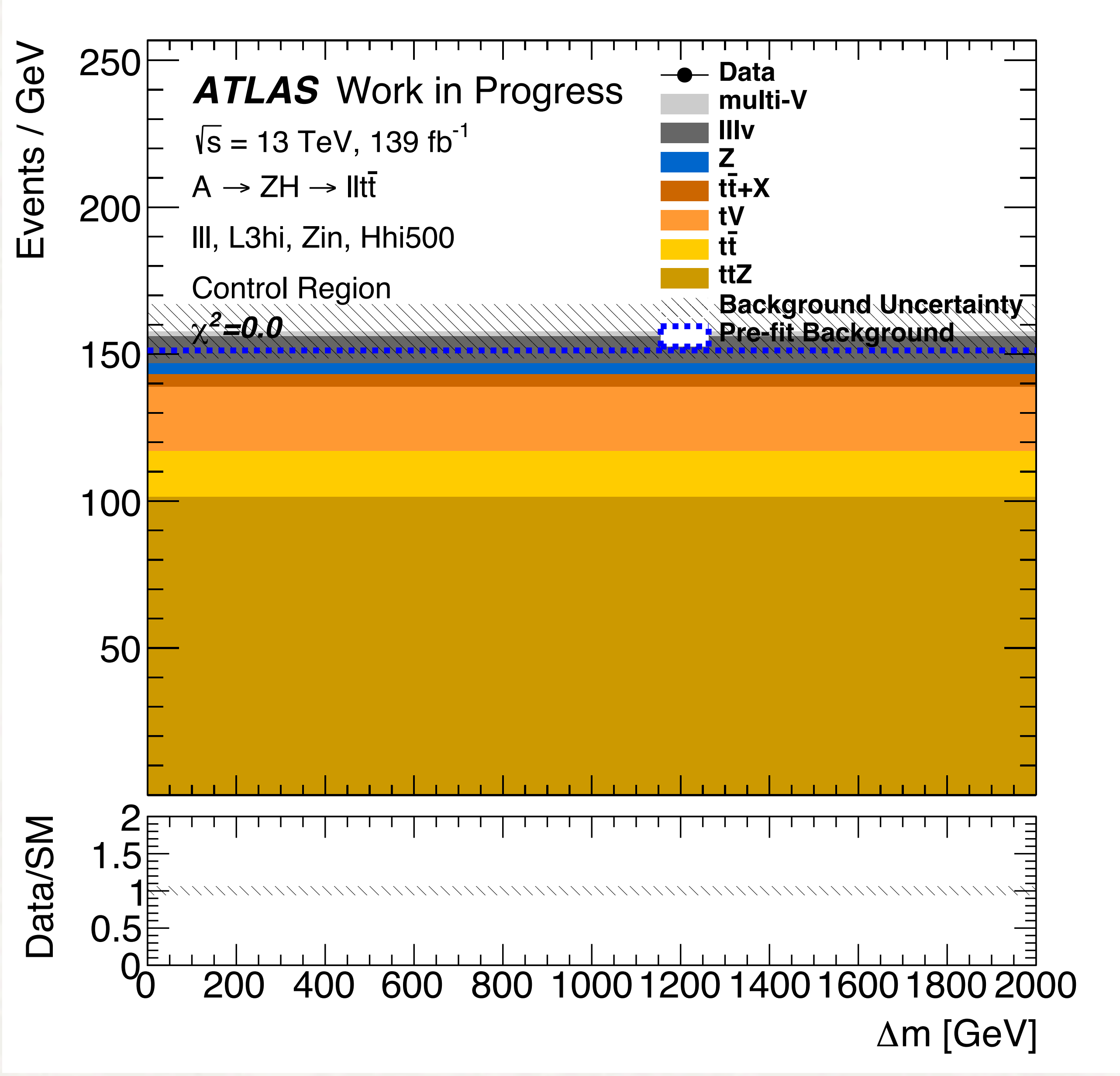
- Results of fit shown
- no shapes of Control Regions are used in Fit
- Same Sign is only unblinded region in fit



unblinded







blinded

pTl3 high, Zout