Search for new resonances in ttbar final states with the ATLAS detector

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ttbar heavy resonances

- Benchmark models (2HDM)
- Search in lepton + jets channel
  - Strategy
  - Selection
  - mtt reconstruction
- Impact of detector resolution
  - Jet rescaling method

Introduction

- Several Beyond-the-SM (BSM) theories seeking to solve a variety of open questions in SM:
  - Neutrino mass
  - Mass spectrum of the particles
  - Inclusion of gravitation
  - Hierarchy problem, ...

- BSM theories predict new heavy particles which could couple strongly with the top quark

Benchmark models

- Searches for new particles in ttbar final states
  - Warped extra-dimensions (Randall-Sundrum):
    - Kaluza-Klein gluon **(g_{kk})**
    - KK Bulk-RS graviton **(G_{kk})**
  - Top-color model (TC):
    - Leptophobic TC heavy **Z' boson**
  - 2 Higgs Doublet Model (2HDM):
    - 4 scalars and 1 pseudo-scalar:

Benchmark models

- Searches for new particles in ttbar final states
  - Warped extra-dimensions (Randall-Sundrum):
    - Kaluza-Klein gluon **(g_{kk})**
      spin-1, width: 10-40% **(broad resonance)**
    - KK Bulk-RS graviton **(G_{kk})**
      spin-2, width: 3-6%
  - Top-color model (TC):
    - Leptophobic TC heavy **Z' boson**
      spin-1, width: 1.2% **(narrow resonance)**
  - 2 Higgs Doublet Model (2HDM):
    - 4 scalars and 1 pseudo-scalar:
      spin-0, width: from ~0% until 100%

Width have an impact
in the potential discovery!

Top quark pairs

- **Top quark decays before hadronizing**

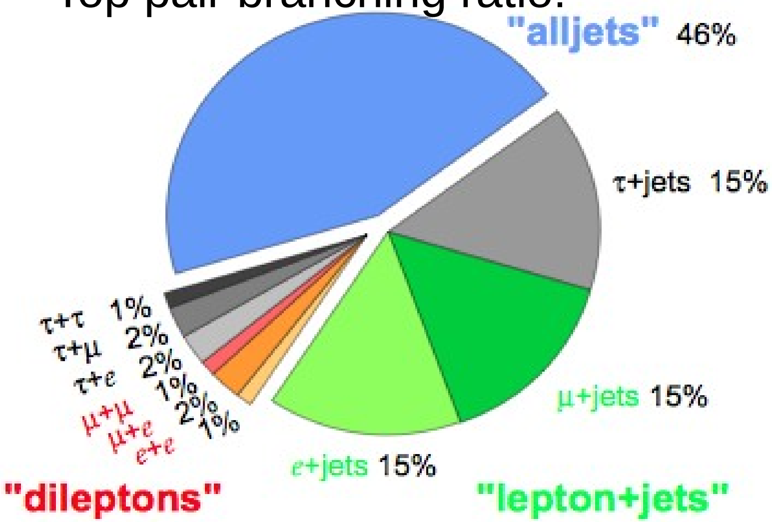
  BR(t $\longrightarrow$ bW^+) ~ 100%

(a) (b)

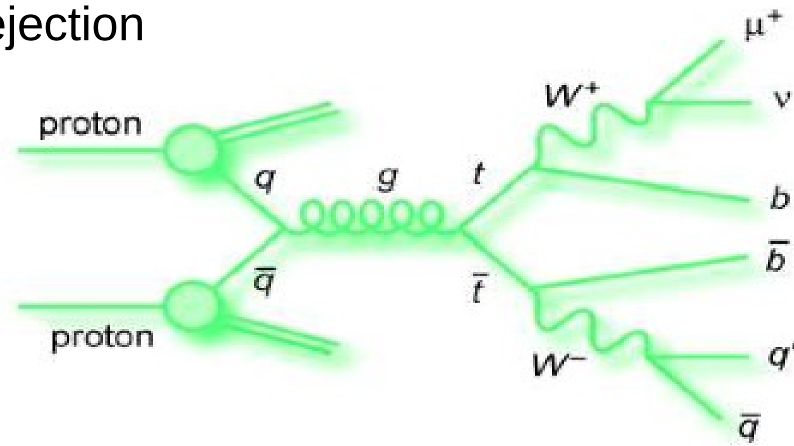
- At the LHC, top pair production (LO) at 8 TeV.
  - **80% Gluon fusion**: (a) and (b)
  - **20% quark-antiquark annihilation:** (c)

(c)

- Top pair branching ratio:

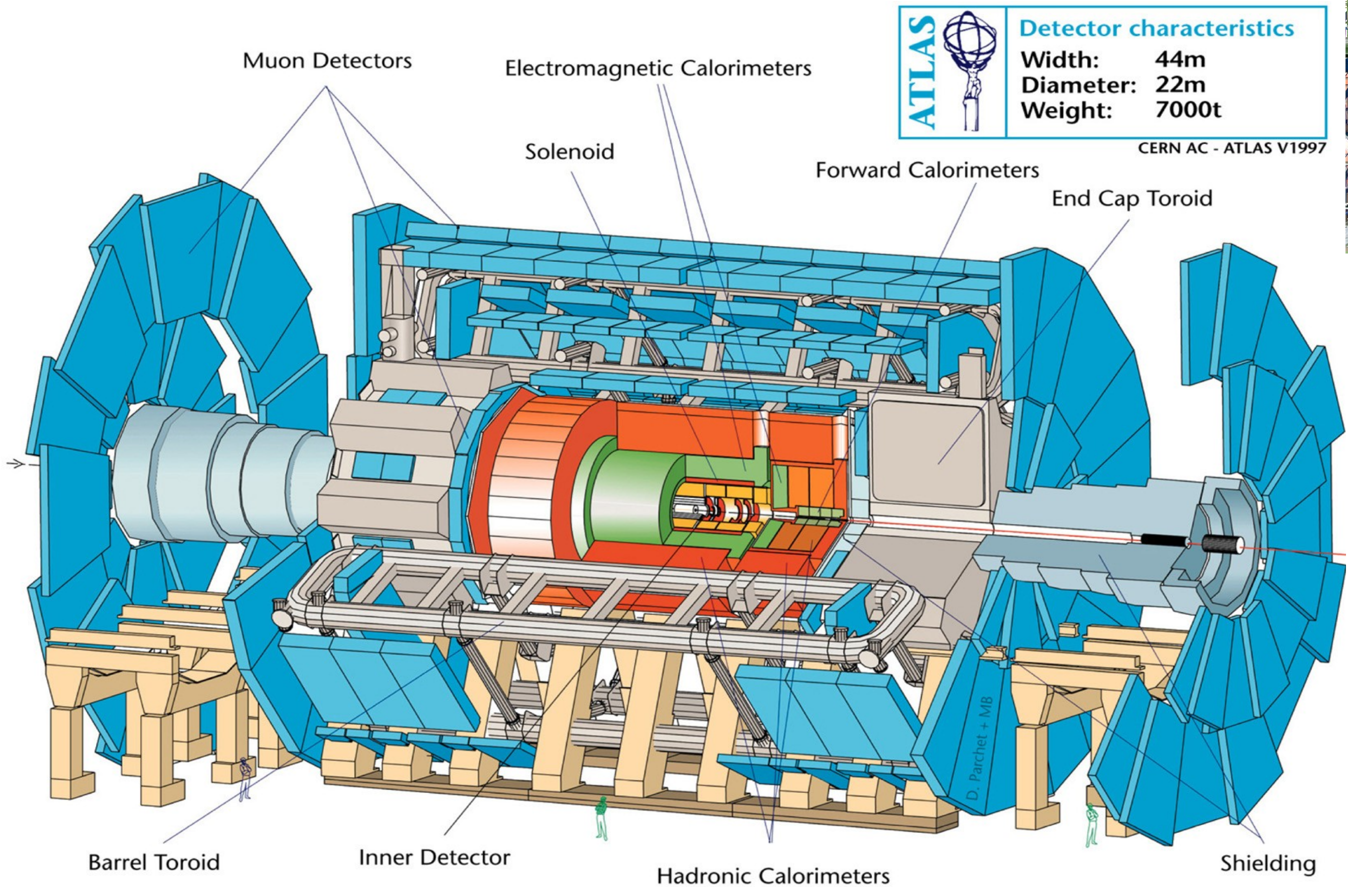


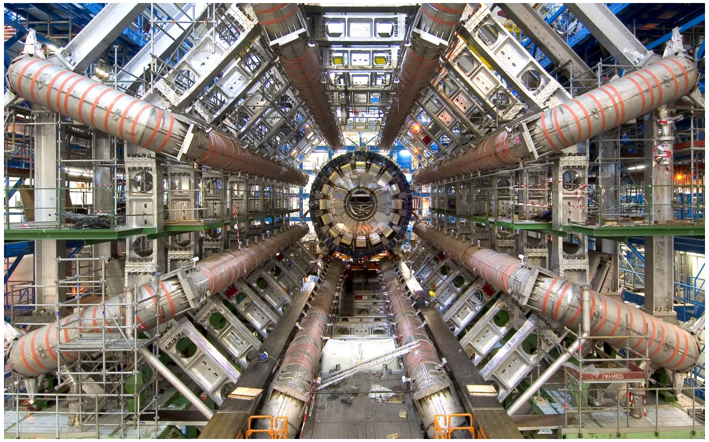
- Search for new physics in the Lepton + jets channel: Best balance between the BR and background rejection

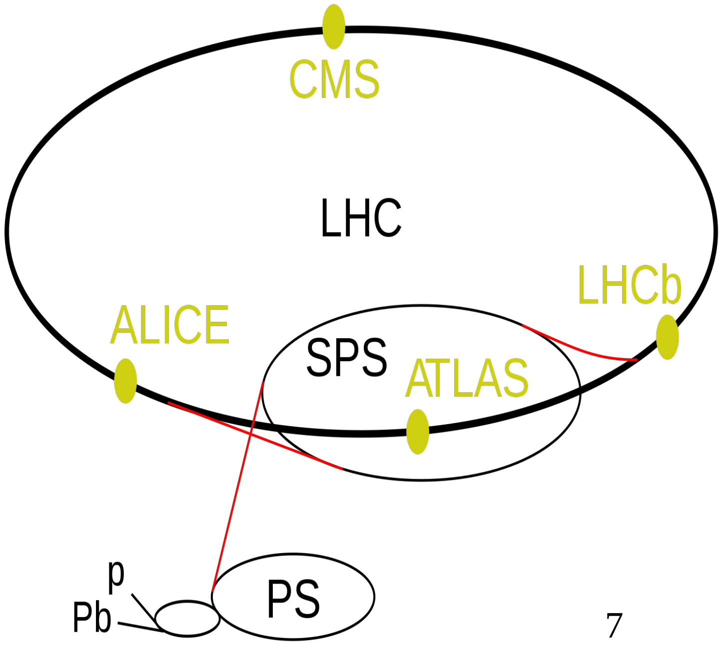


Experimental setup

The ATLAS detector



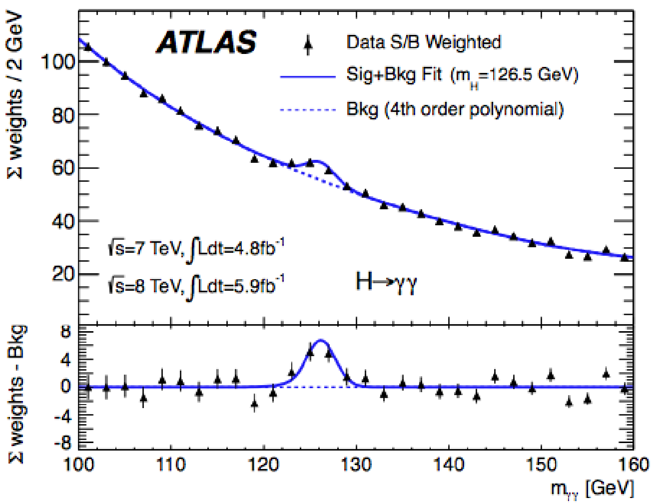


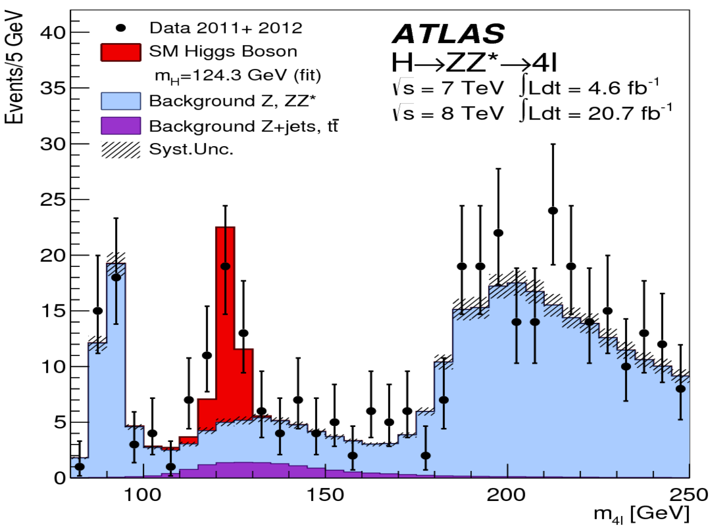


Two Higgs doubles model (2HDM)

2HDM motivation

- Discovery of a SM Higgs-like particle at LHC: $m_h \sim 125$ GeV





- Further investigations into the scalar sector
  - It may have richer structure
- Two-Higgs doublet are the simplest extension in the scalar sector of SM

2HDM: Scalar sector

- Two identical SU(2) doublets scalar fields Φ_1 and Φ_2

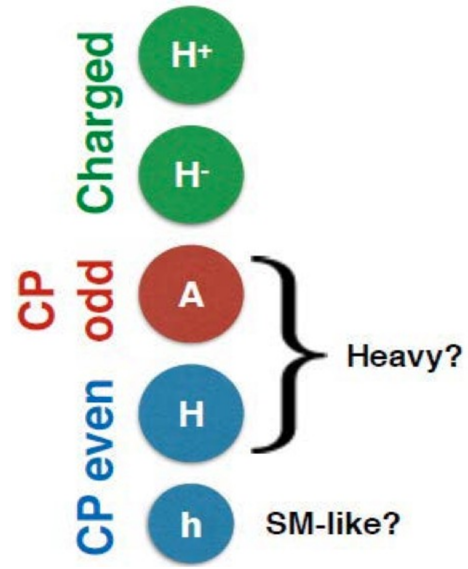
- Most general scalar potential invariant under electroweak symmetry (tree-level)

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

- 8 degrees of freedom → 3 correspond to the W, Z bosons masses

- The other 5 are manifested as physical particles

- Free parameters of the model:
  - tanβ: ratio between the two vev's
  - α: mixing angle of CP-even fields
  - Masses of the new particles



2HDMs: Types

- 4 types of 2HDM: different coupling to fermions

Type	u_R	d_R	e_R
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

$\sim$ MSSM

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$\sim$ MSSM

- Couplings with SM particles modified by factors $g_{\Phi,\bar{q}/V,qV}$ depending of α and β

Φ	$g_{\Phi\bar{u}u}$		$g_{\Phi\bar{d}d}$		$g_{\Phi VV}$
	Type I	Type II	Type I	Type II	Type I/II
h	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\beta-\alpha)$
H	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos(\beta-\alpha)$
A	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\tan\beta$	0

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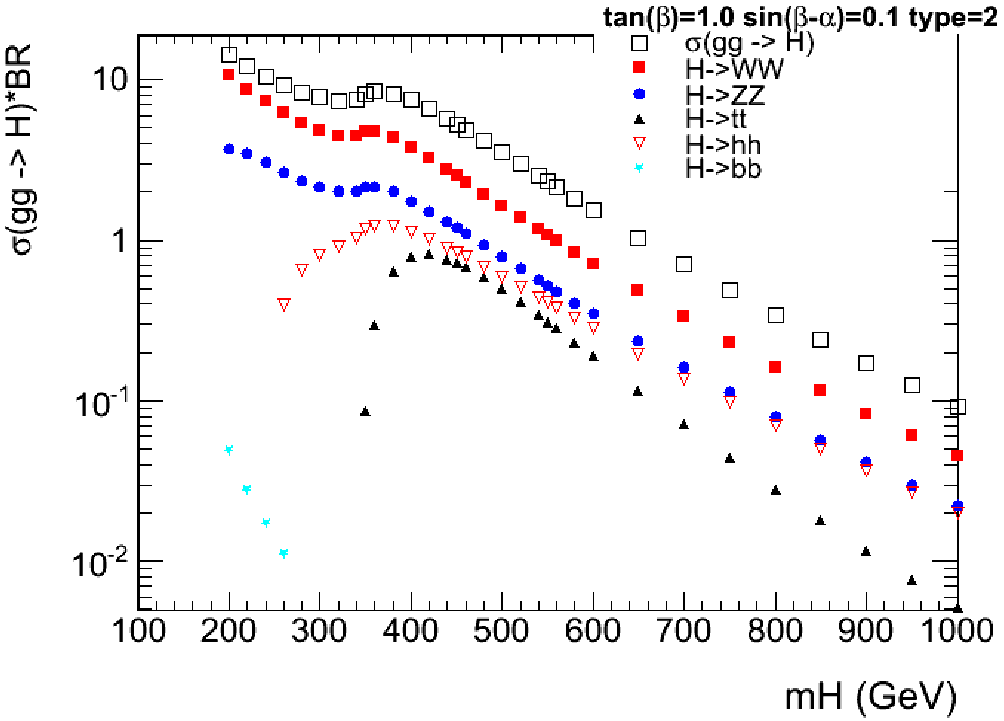
$\sim$ MSSM

- $|\sin(\beta - \alpha)| = 1$ $\rightarrow$ h scalar looks like SM Higgs boson

$$H^{SM} = h * sin(\beta - \alpha) + H * cos(\beta - \alpha)$$

2HDMs: Type II



- $\tan\beta$ = 1.0 and $\sin(\beta-\alpha)$ = 0.1
- WW and ZZ channels are dominant wrt ttbar
- Couplings: top quark, b quark and vector boson

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	Type I	Type II	Type I	Type II	Type I/II
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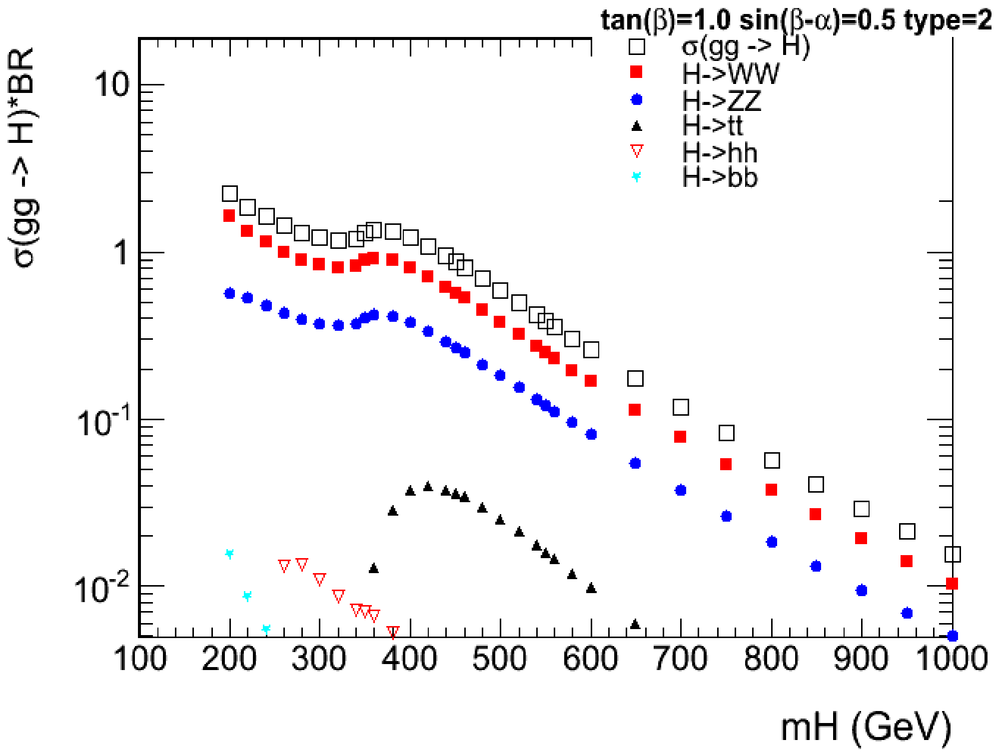

- tanβ = 1.0 and sin(β-α) = 0.5
- WW and ZZ channels are dominant
  → Coupling with top quark is weaker
- Couplings: top quark, b quark and vector boson

Φ	$g_{\Phi\bar{u}u}$		$g_{\Phi\bar{d}d}$		$g_{\Phi VV}$
	Type I	Type II	Type I	Type II	Type I/II
h	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\beta-\alpha)$
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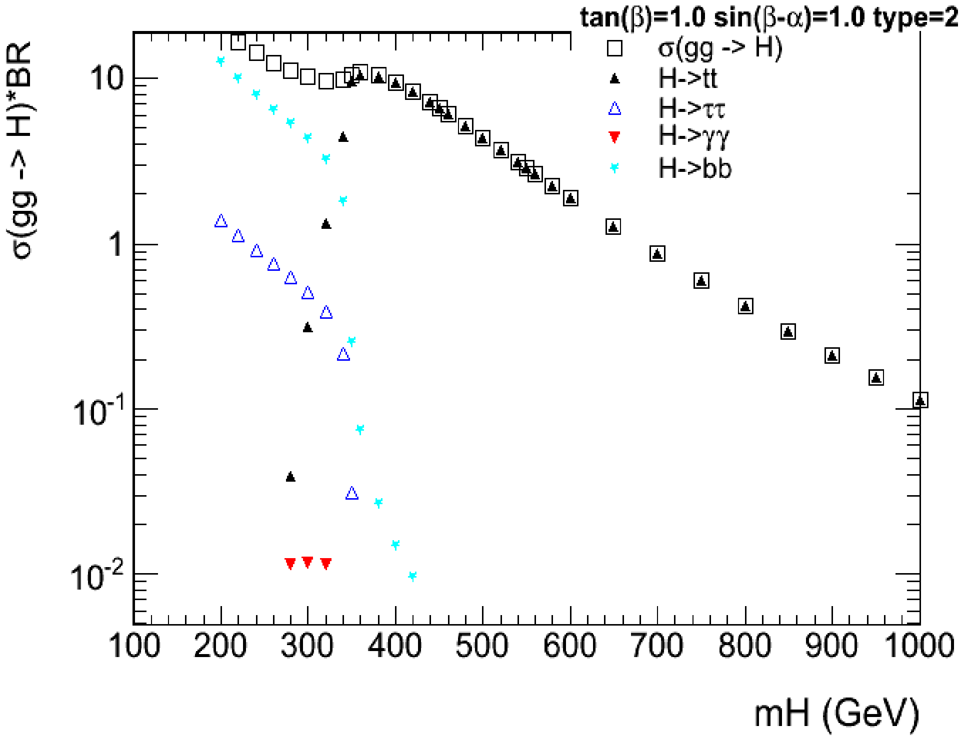

- tanβ = 1.0 and sin(β-α) = 1.0
- SM-like limit
- ttbar channel is dominant

  → Coupling W, Z vanish

- Couplings: top quark, b quark and vector boson

Φ	$g_{\Phi\bar{u}u}$		$g_{\Phi\bar{d}d}$		$g_{\Phi VV}$
	Type I	Type II	Type I	Type II	Type I/II
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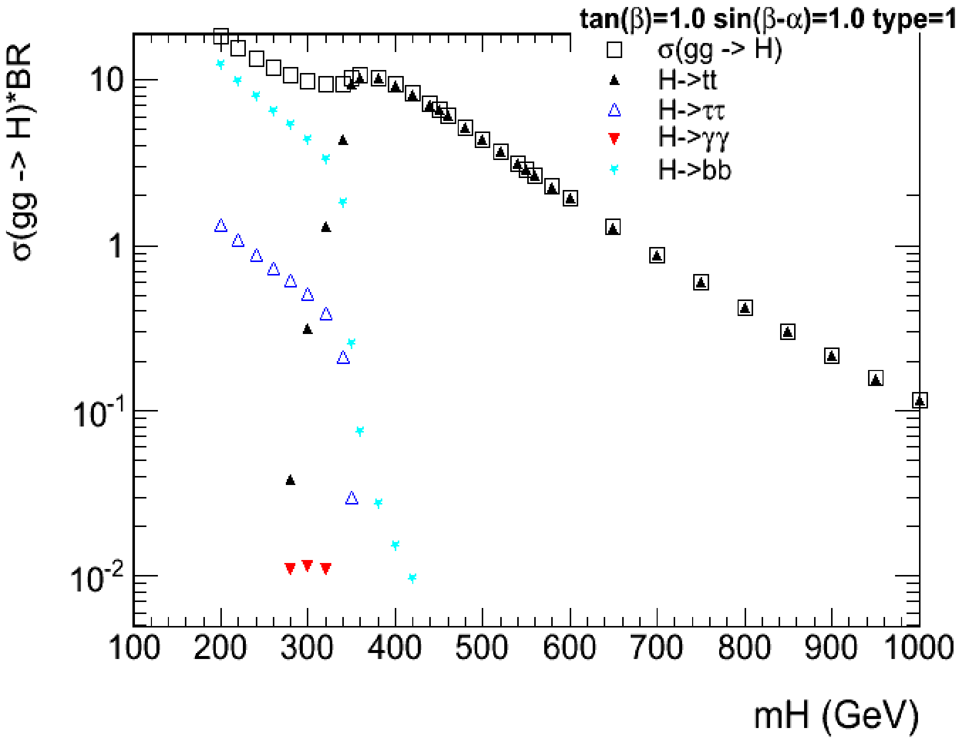
2HDMs: Type I



- $\tan\beta = 1.0$ and $\sin(\beta-\alpha) = 1.0$
- SM-like limit
- Same couplings with u-type quraks than Type I
  - $\rightarrow$ ttbar channel is dominant
- Couplings: top quark, b quark and vector boson

Φ	$g_{\Phi\bar{u}u}$		$g_{\Phi\bar{d}d}$		$g_{\Phi VV}$
	Type I	Type II	Type I	Type II	Type I/II
h	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\beta-\alpha)$
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ttbar resonances
in the lepton+jets channel

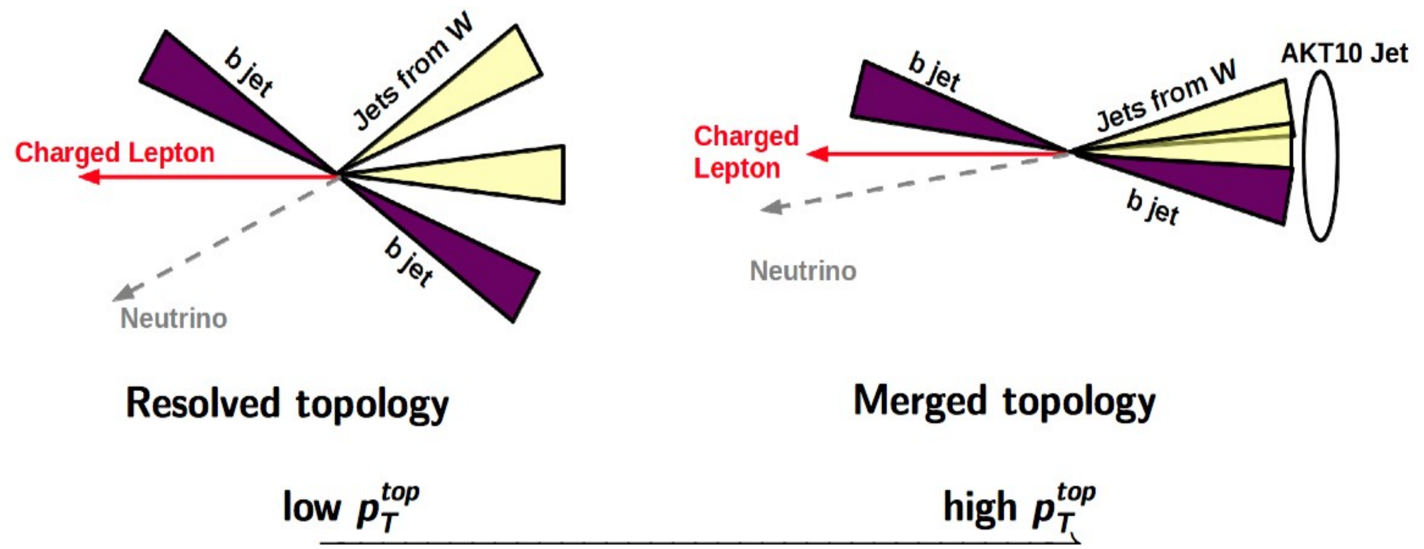
Strategy

- Top-antitop events selected in e/mu + jets channels
- Two types of jets topology: resolved and boosted
- Invariant mass of ttbar candidates are reconstructed
- Background estimation
- Invariant mass spectrum is searched for local excesses/deficits
- Limits are set in the cross-section*BR if no significant excesses/deficits
- Cross-section*BR limits translated into bounds on the allowed mass for new particles

Event selection

- **Common selection:**
  - Exactly 1 lepton (e or μ) in the acceptance of the detector
  - MET > 20 GeV
  - MTW (transverse mass computed using MET and lepton four-momentum)
    - MET + MTW > 60 GeV

- **Boosted selection:**
  - ≥ 1 small-R jet
  - ≥ 1 large-R jet
  - ≥ 1 b-tagged small-R jet



- **Resolved selection:**
  - Fail boosted selection
  - ≥ 4 small-R jets
  - ≥ 1 b-tagged small-R jet
  - **$\log_{10}\chi^2 < 0.9$**

Neutrino's reconstruction

- Neutrinos do not interact with the detector material

  → inferred from the total transverse momentum balance

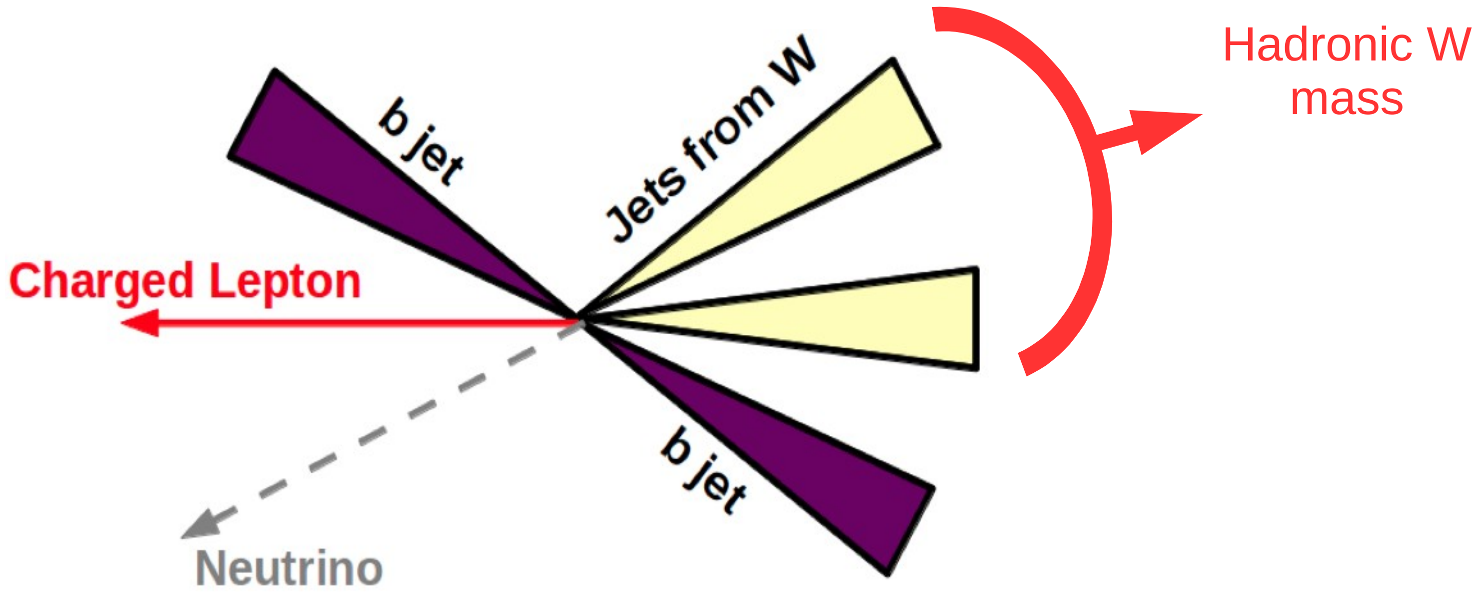
- **Neutrino's momentum**: transverse component from MET
  - Longitudinal component of the momentum is unknown (pZ)
  - pZ computed imposing an on-shell W mass constrain: lepton + MET system
  - Quadratic equation for pZ:
    - Real solutions:
      - Smallest pZ
    - Non-real solutions:
      - MET is rescaled and rotated applying the minimum variation necessary to find one real solution

      → <u>Imperfect resolution on MET is the most likely explanation for non-real solutions to pZ equation</u>

$$p_{z,\nu}^{\pm} = \frac{\mu p_{z,l}}{p_{\mathrm{T},l}} \pm \sqrt{\frac{\mu^2 p_{z,l}^2}{p_{\mathrm{T},l}^4} - \frac{E_l^2 p_{\mathrm{T},\nu}^2 - \mu^2}{p_{\mathrm{T},l}^2}}.$$

Event reconstruction

- **Chi2 minimization:** algorithm used to select the right jet combination to reconstruct mtt



1

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

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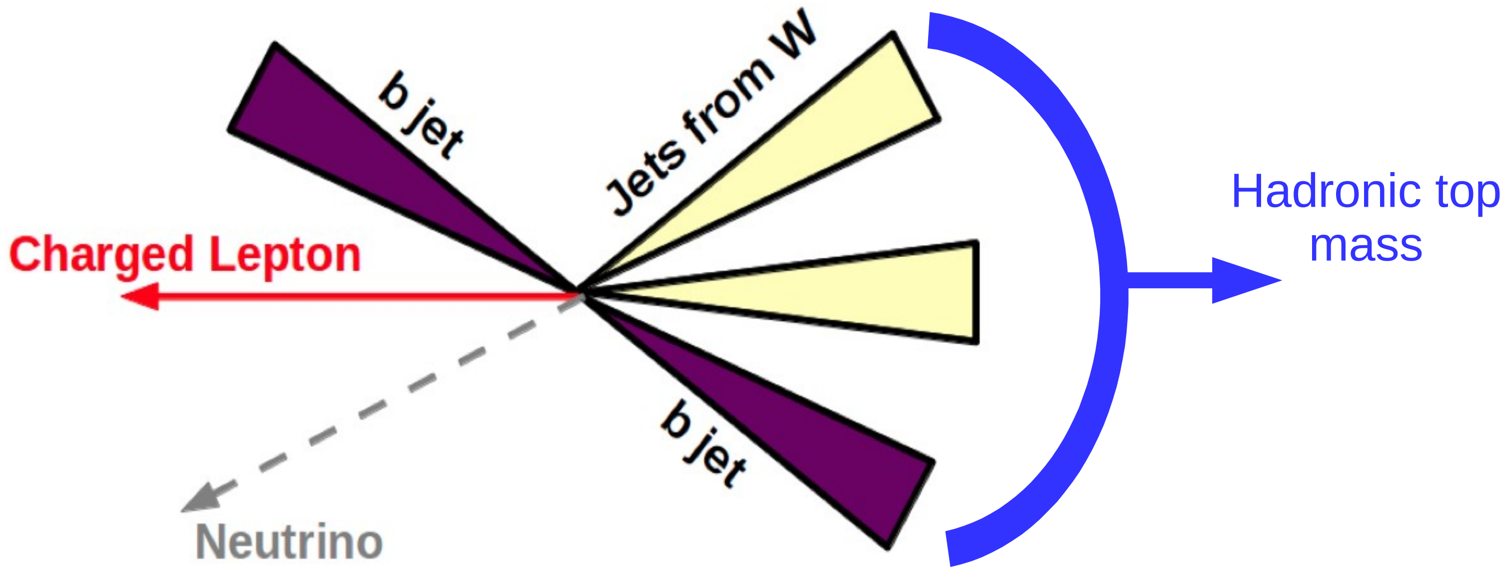

2

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

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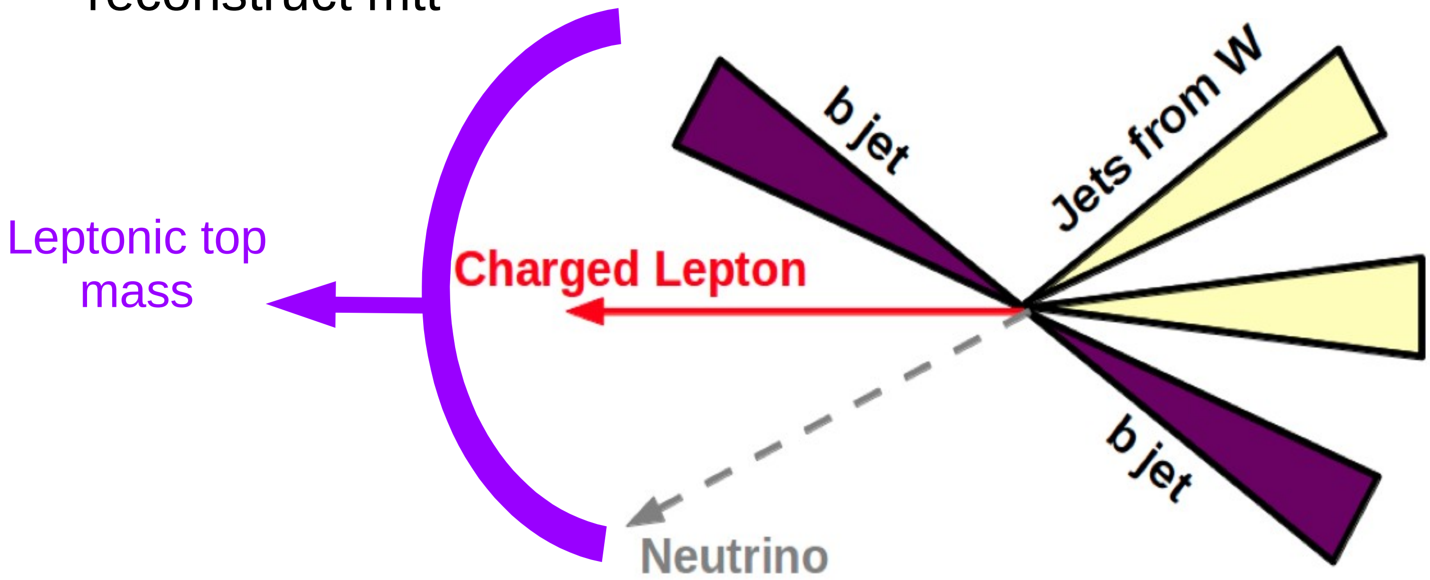

3

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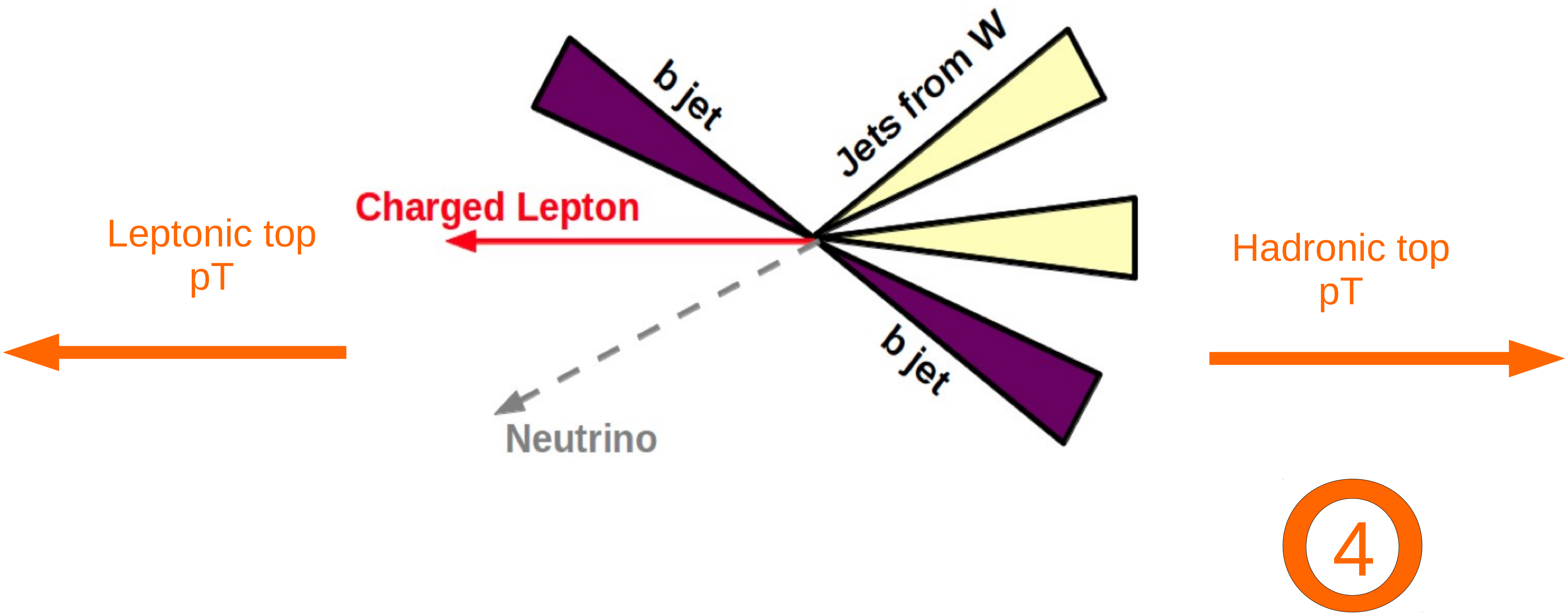

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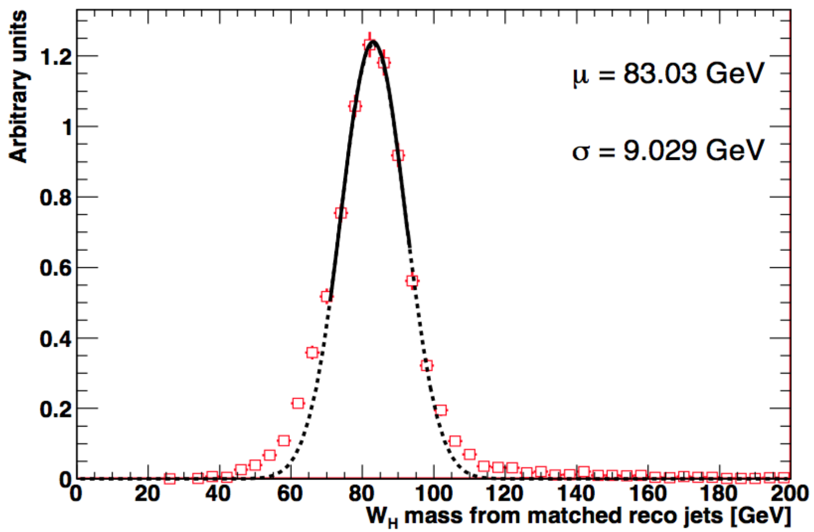
- All possible jet permutation are tried
  - Only the permutation with lowest chi2 are used

- Constrains determined from the reconstructed objets matched to the partons



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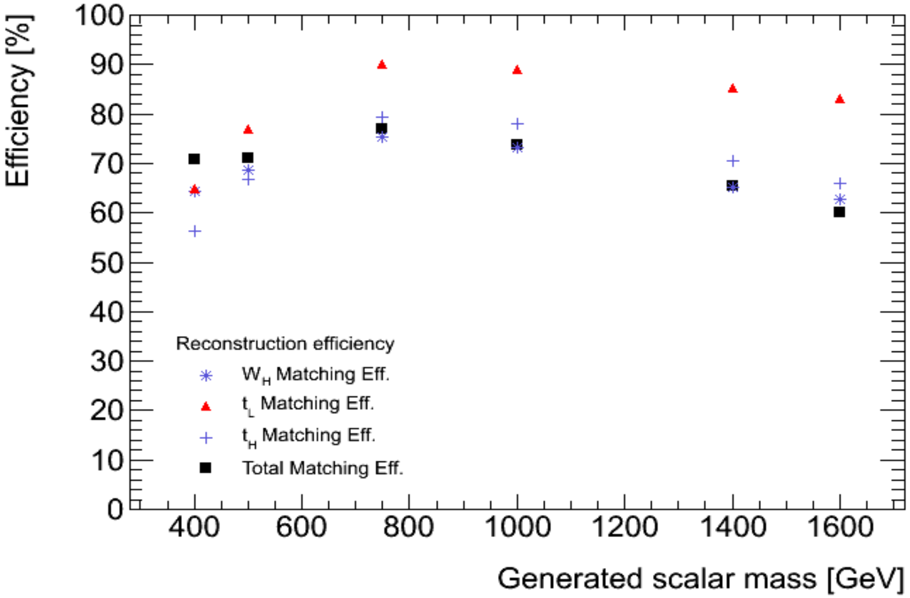
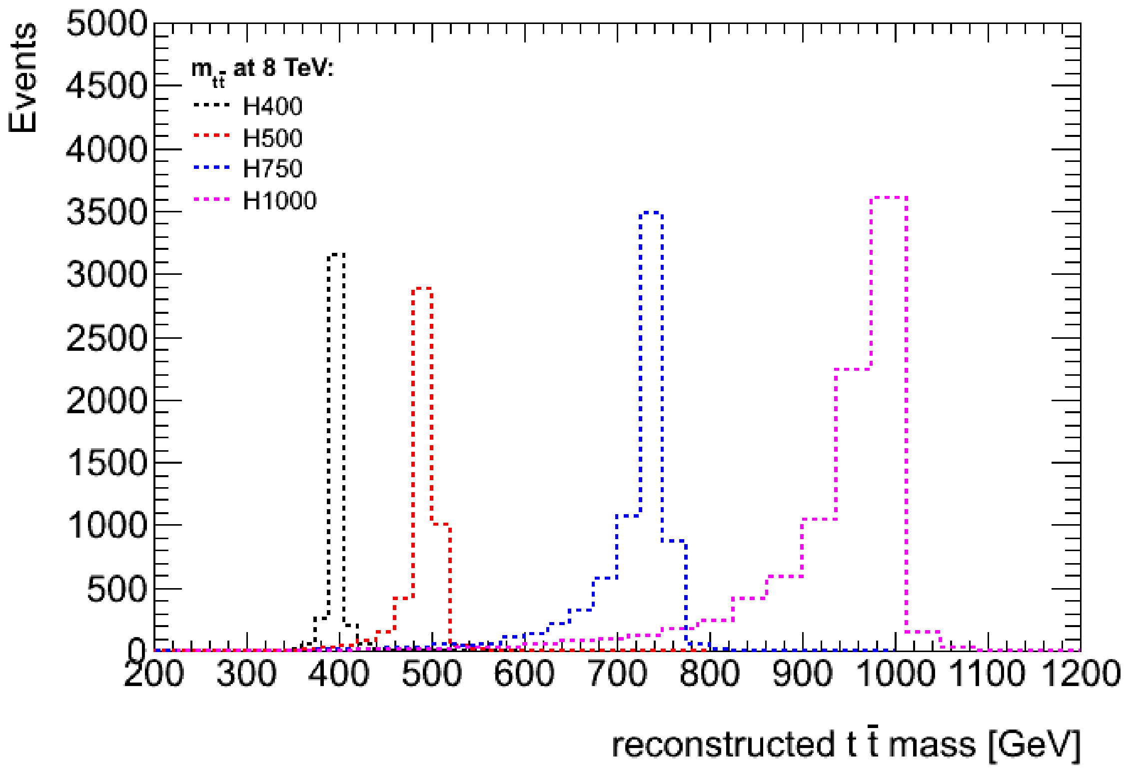
- Chi2 performance: The algorithm selects the correct combination ~70% of the reconstructible events



mtt reconstruction

- Invariant mass of the ttbar pair is the discriminant variable
- ttbar pair is build by summing up the four momentum of jets, lepton and neutrino
- Reconstruction of mtt for the signal of benchmark models considered at different generated mass

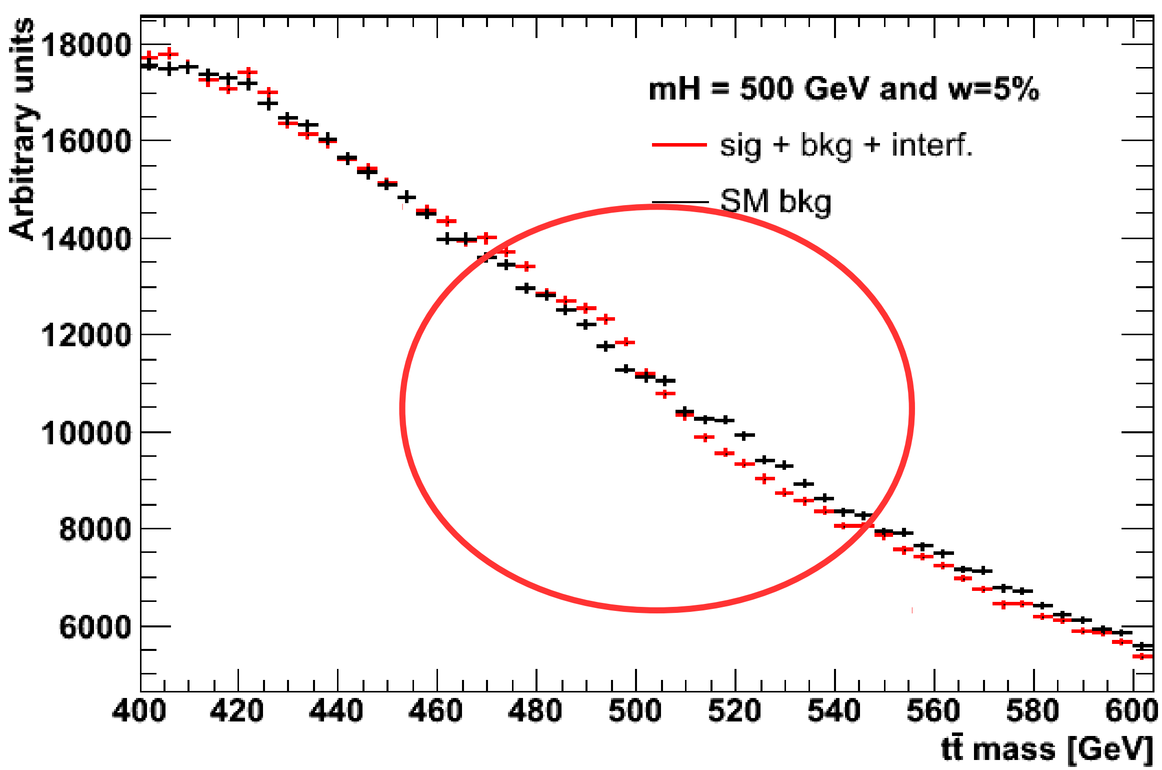


Impact of the detector resolution in the search for 2HDM signal into ttbar

2 HDM signal into $\bar{t}t$

- Decay channel: $H/A \rightarrow t\,\bar{t}$
- Signal have same initial/final states than the SM bkg
  - Interference (peak/dip structure)

H signal + interference



Smearing

- Detector smearing as a tool for phenomenology
  - Useful to understand the limitations induced by detectors on an theoretical well motivated analysis
  - Smearing techniques can help to produce rough estimates
- Detector resolution: assuming a gaussian impact
  - ~8% of the reconstructed mass for the ATLAS detector
  - Convolution of the mtt spectra with a gaussian of 8% width
    - σ/μ is interpreted as the detector resolution

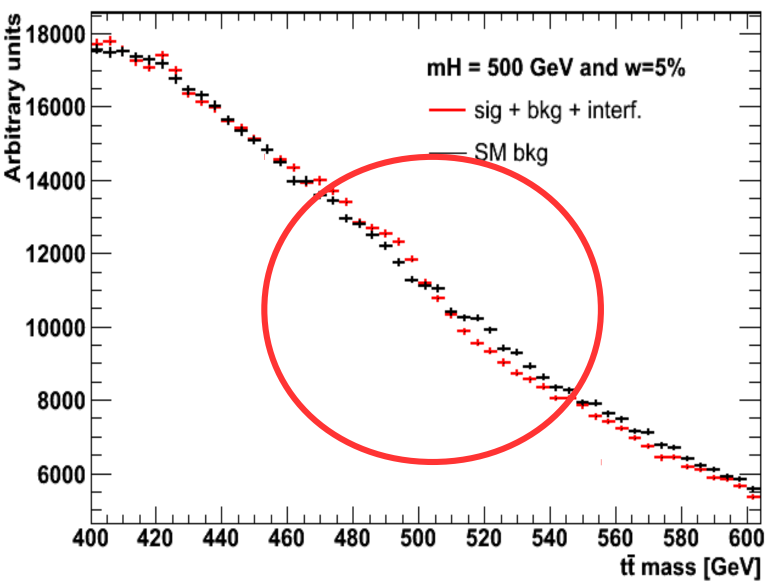
Impact of detector resolution

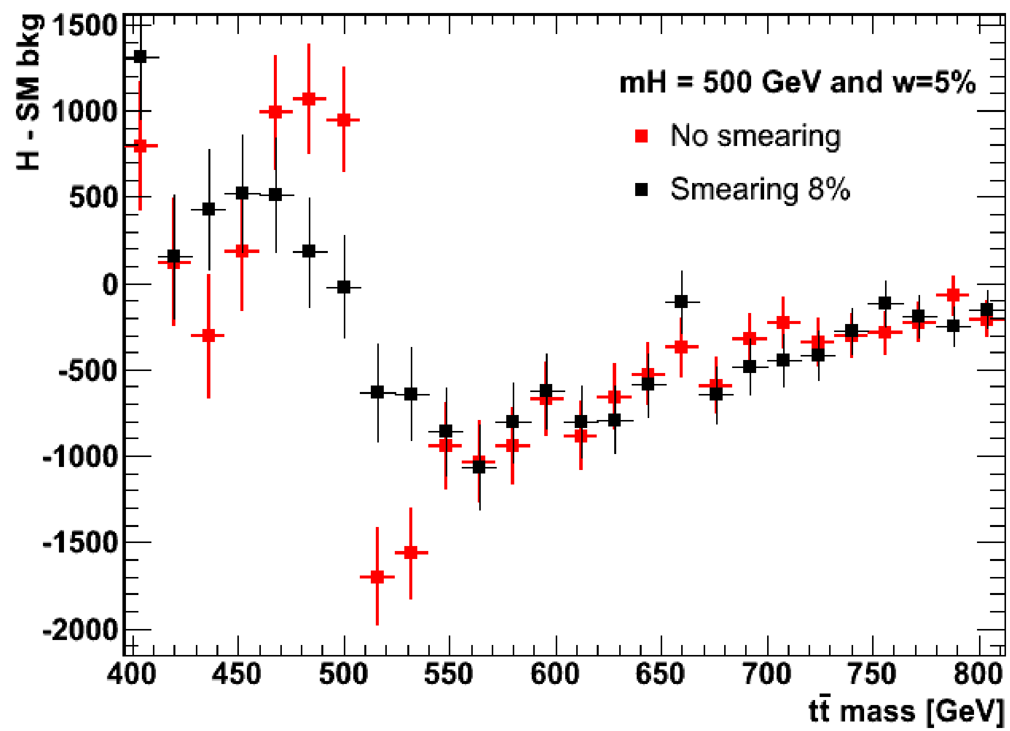
- The smearing will help to check the impact of the resolution of ATLAS on the scalar signal w/ interference

  Loss of sensitivity → Signal more difficult to detect

- Improving the mtt resolution to balance the detector resolution:

  → Let use the information of the ttbar system

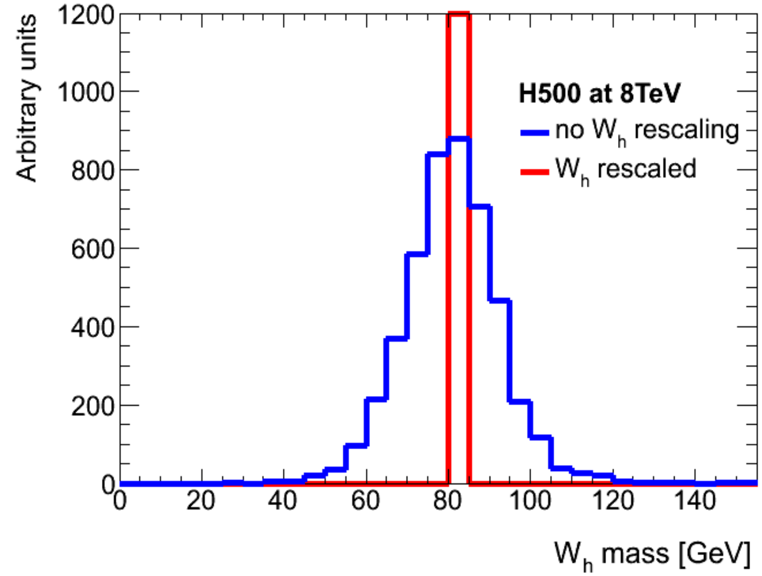


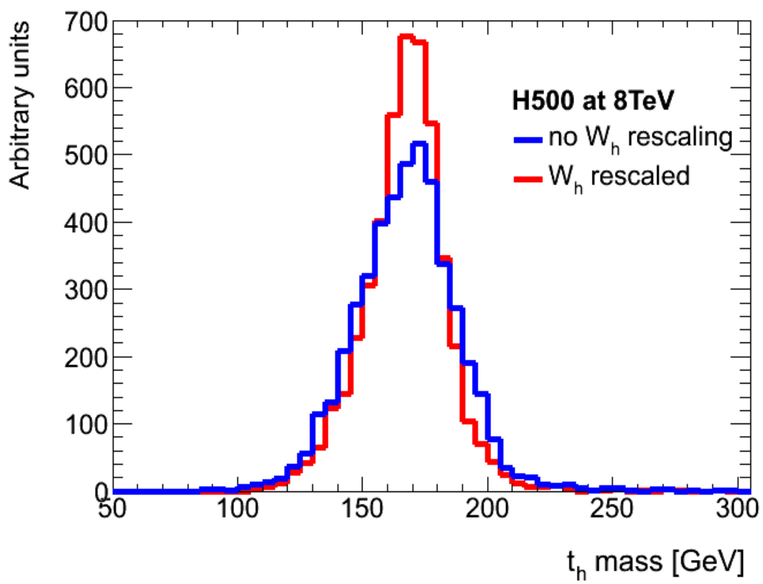


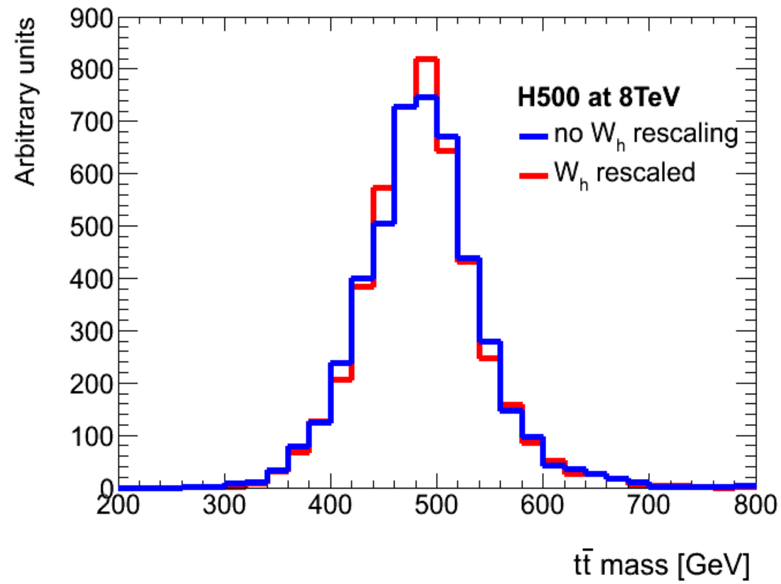
Jet rescaling

Rescaling the jets from W_h

- Considering reconstructible events
- Rescale the jets 4-momentum ($\mathbf{J_1} + \mathbf{J_2}$) to get the Mw value at the PDG
  - $M_W = 80.4$ GeV
  - $k^2(\mathbf{J_1} + \mathbf{J_2})^2 = (M_W)^2$
- Top mass and mtt resolutions are improved

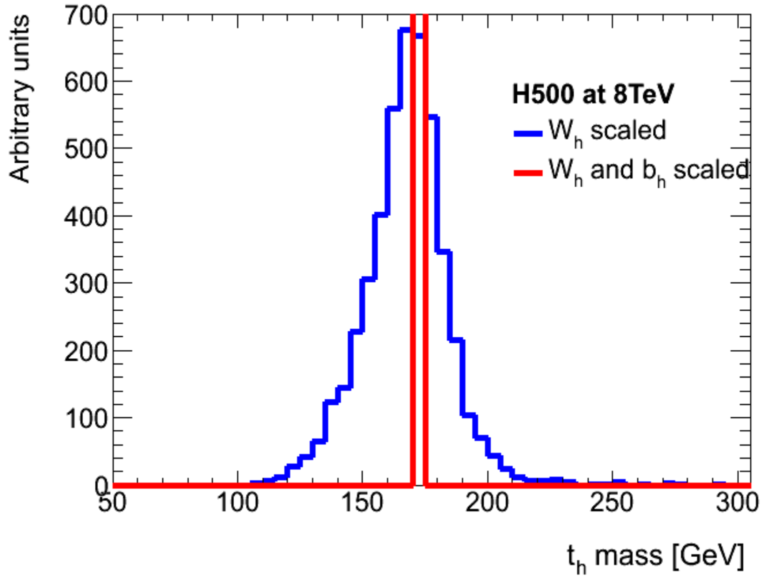


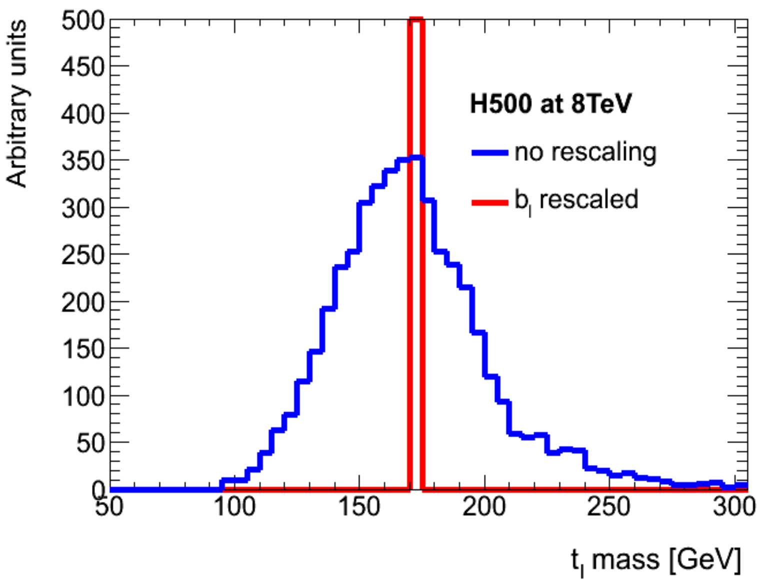


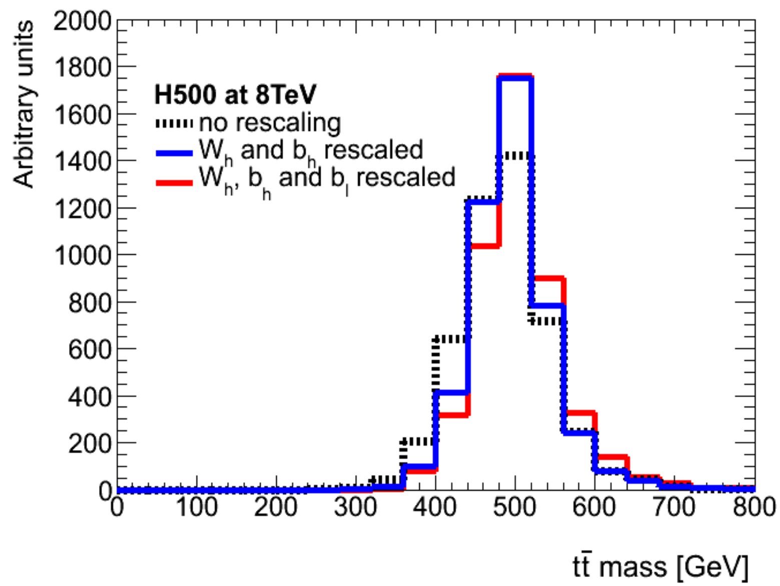


Rescaling the b-jets

- Rescale the b-jet 4-momentum:
  - Constraining the top mass (M_{top} = 172.5 GeV)
- The jet rescaling absorbs the uncertainties on the mass reconstruction
- Improvement on the mtt resolution



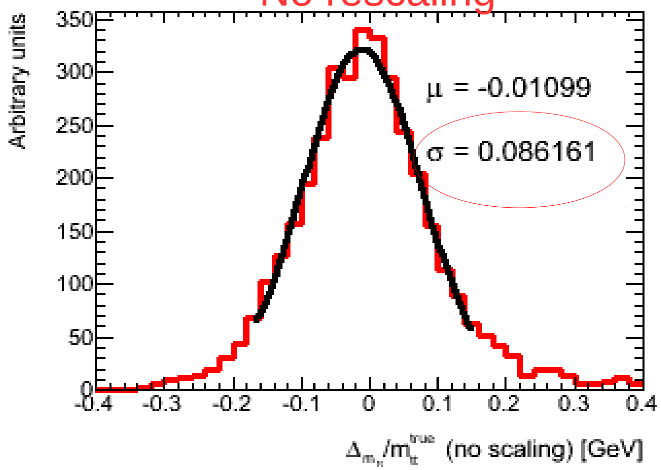




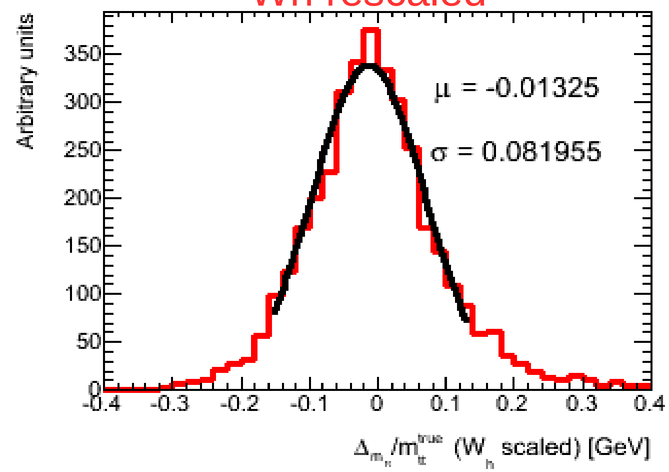
Improvement of mtt resolution

- Relative mass difference: $\frac{\Delta_{m_{tt}}}{m_{tt}^{true}} = \frac{m_{t\bar{t}}^{reco} - m_{t\bar{t}}^{true}}{m_{t\bar{t}}^{true}}$
- Gaussian fit to extract the mass resolution

No rescaling

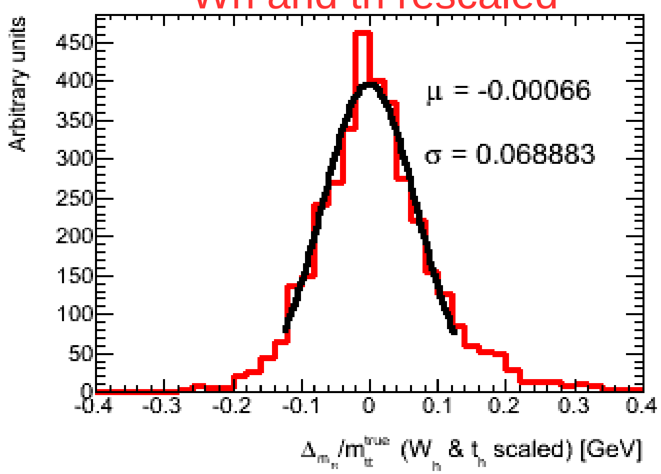


Wh rescaled

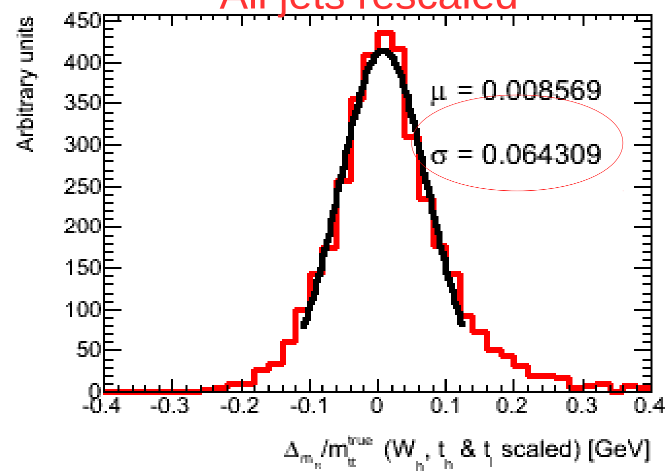


H 500 GeV

Wh and th rescaled

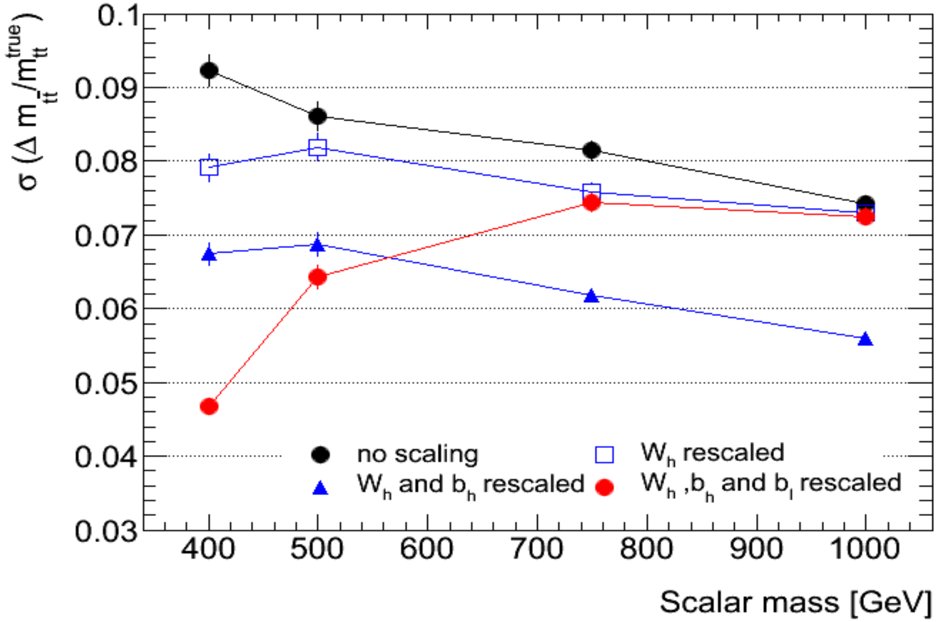


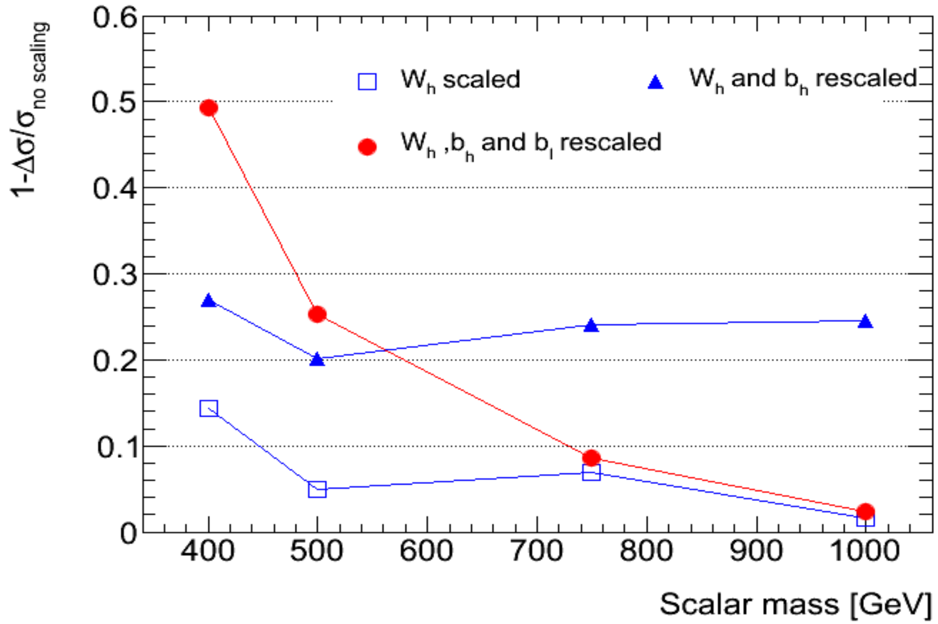
All jets rescaled



mtt resolution vs scalar mass (assuming perfect reconstruction)

- σ(mtt diff rel) for all the mass points:
  - Low mass: improvement after each rescaling
  - High mass: degradation after the rescaling of the leptonic top
  - Uncertainty in the MET direction has large impact at high mass



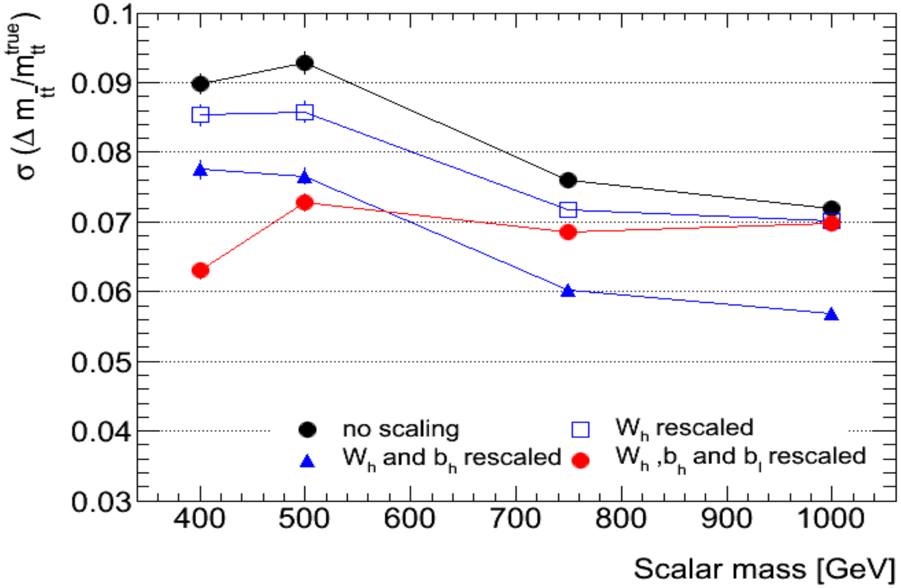


- Improvement wrt the no-rescaling case

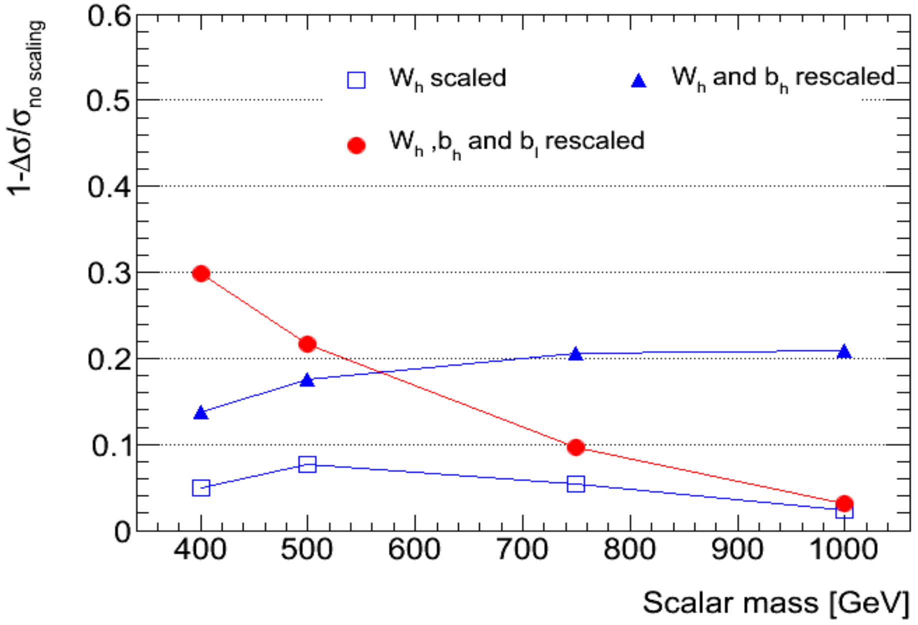
$$1 - \frac{\sigma_{Cal} - \sigma_{noCal}}{\sigma_{noCal}}$$

- ~25% improvement after W_h and b_h rescaling

mtt resolution vs scalar mass (χ^2 algorithm)



- Same tendency using the standard reconstruction algorithm
  - High mass: degradation after the rescaling of the leptonic top



- ~20% improvement after W_h and b_h rescaling
- Reasonable considering the improvement in the ideal case

Conclusion

- ttbar decay mode for the scalar signal is dominant in a region of the parameters space

- Improving the mass resolution will help to balance the impact of the detector resolution

Rescaling of W_h and b_h:

- ➔ ~25% in the assuming perfect reconstruction
- ➔ ~20% using the chi2 minimization

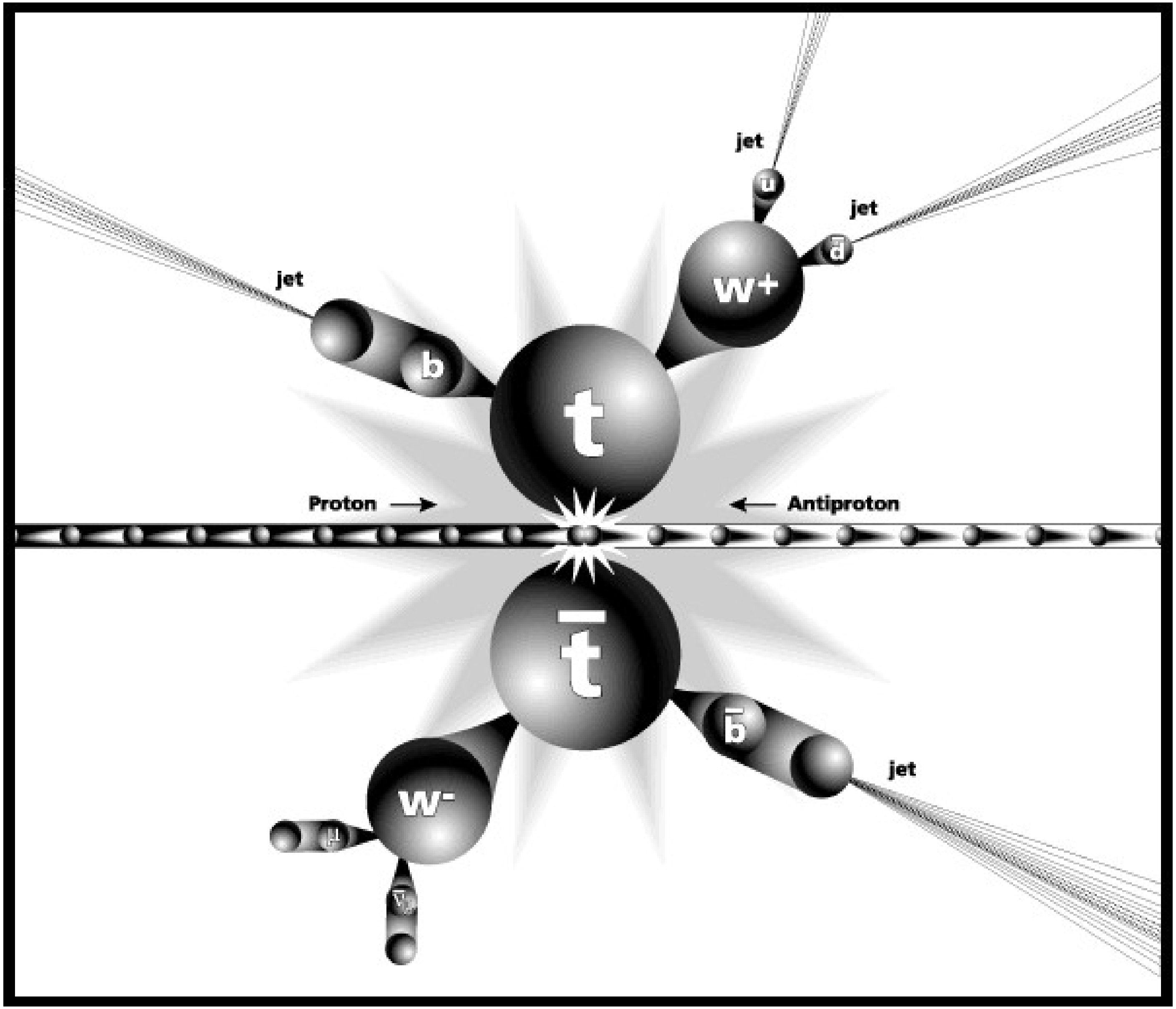
- The calibration of the bl degrades the m_{tt} resolution (investigations ongoing)

  Bad energy/direction resolutions of MET

- **Next prospect:** Rescaling the large-R jet for the boosted topology

  This study will be used in the search for tt resonance at 13 TeV

Back up



Various BSM models predict resonances in the $m_{t\bar{t}}$ spectrum

Warped extra-dimensions (Randall-Sundrum)

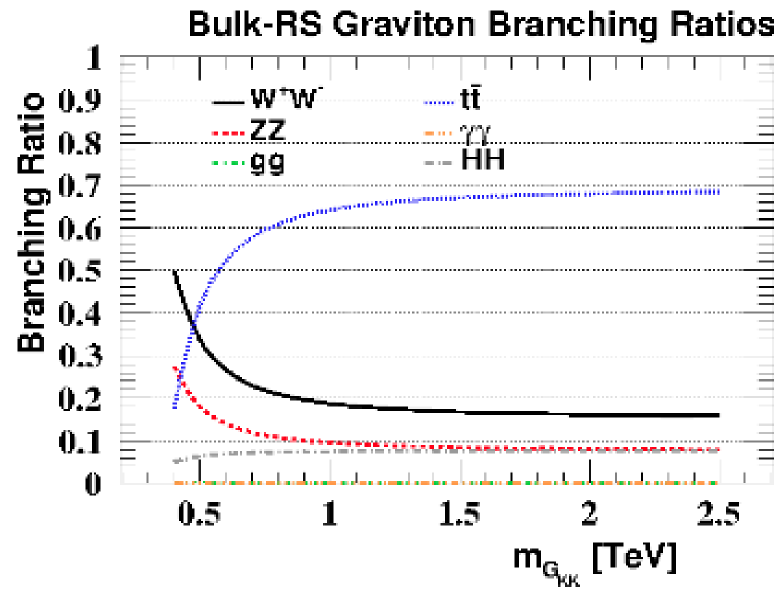
- **Kaluza-Klein (KK) gluon (g_{KK})**
  Spin-1, width: 10–40%
- **KK/Bulk-RS graviton (G_{KK})**
  Spin-2, width: 3–6%

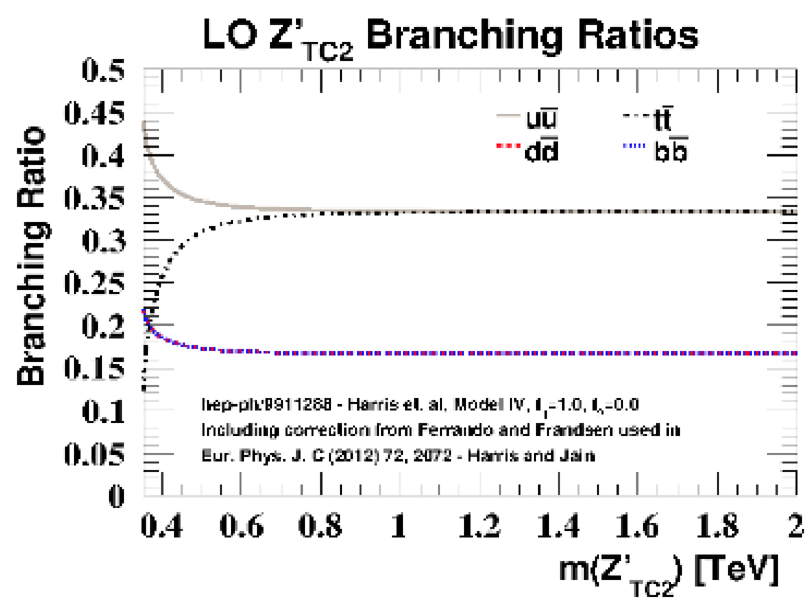
Top-colour (TC) model:

- **Leptophobic TC Z' boson (Z′)**
  Spin-1, width: 1.2%

Searches in all decay channels:

- All-hadronic
- 1 lepton+jets
- (Dileptonic)

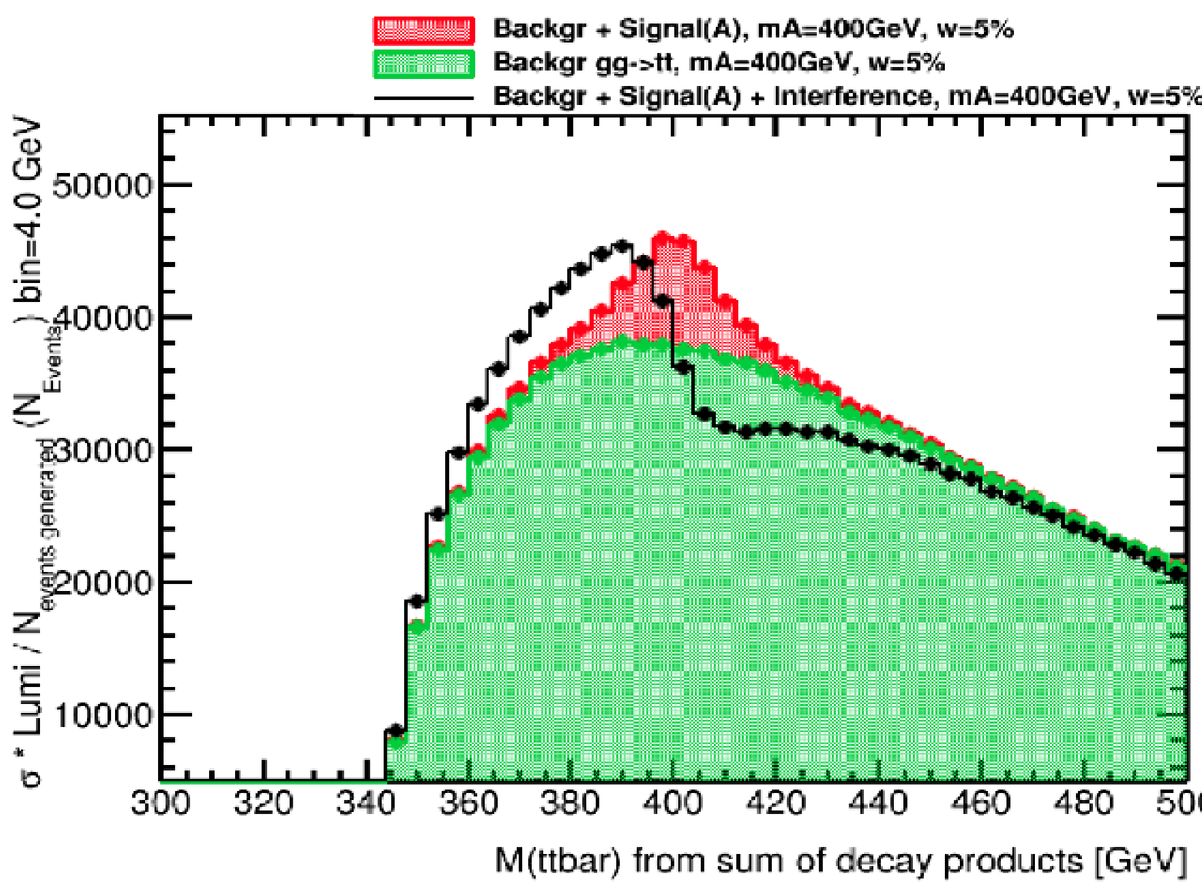




2 HDM signal into $\bar{t}t$

- Decay channel: $H/A \rightarrow t\,\bar{t}$
- Signal have same initial/final states than the SM bkg
  - Interference (peak/dip structure)

- $m_{t\,\bar{t}}$ at truth level:
  - SM bkg
  - Signal + bkg
  - Signal + bkg + interference



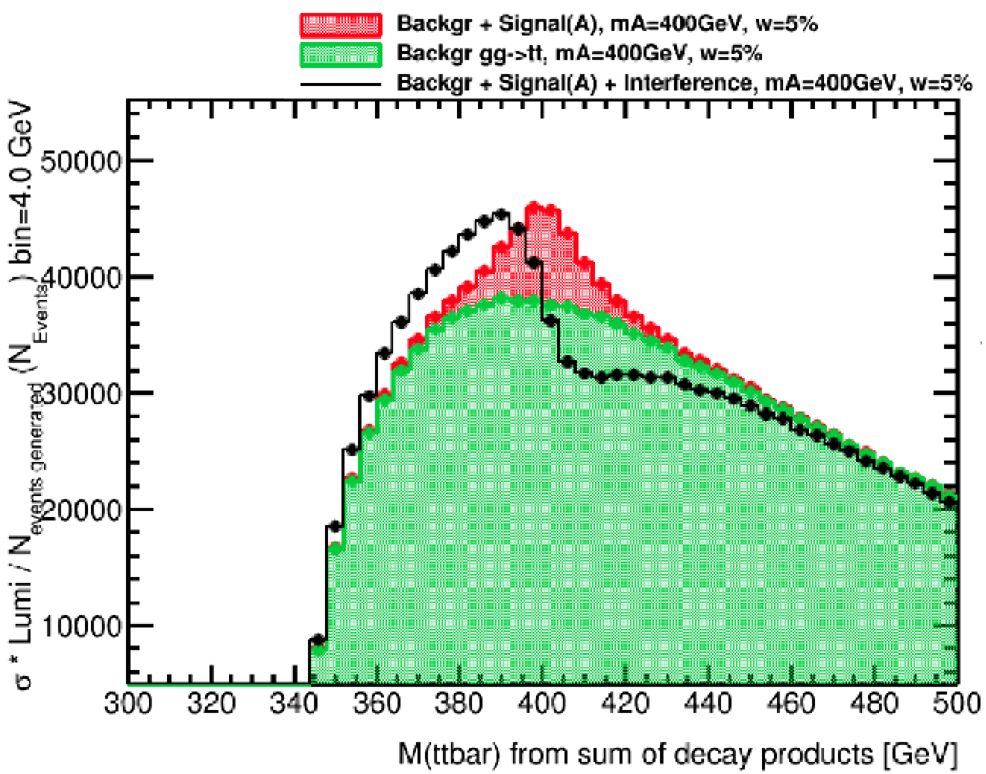
2 HDM signal into $t\bar{t}$

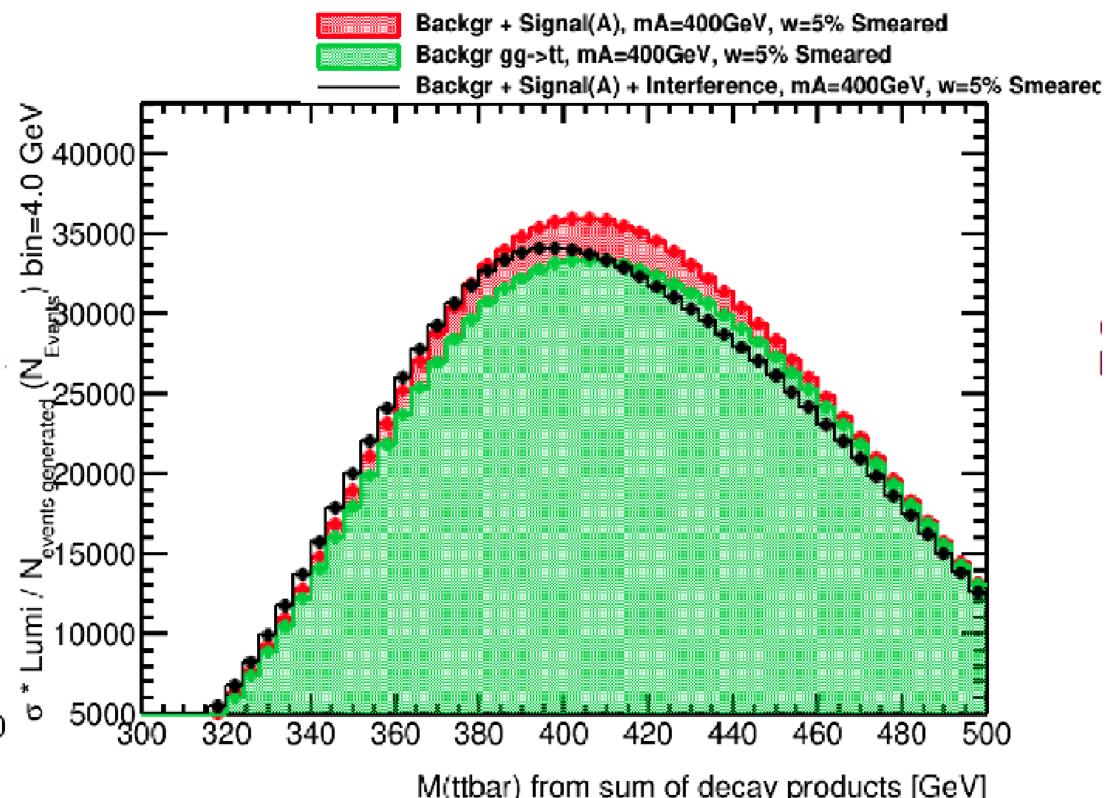
- Impact of the detector resolution (Smearing by 8%)

  Loss of sensitivity $\longrightarrow$ Signal more difficult to detect

- Improving the mtt resolution to balance the detector resolution:

  $\rightarrow$ Jet Rescaling





2HDMs: Types

- 4 types of 2HDM: different coupling to fermions

Type	u_R	d_R	e_R
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

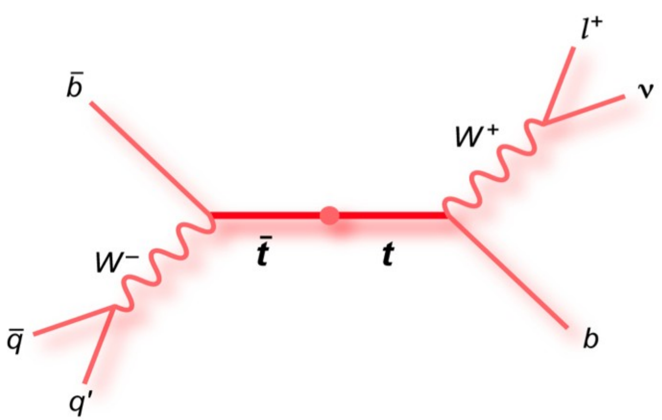
- $|\sin(\beta - \alpha)| = 1$ → h scalar looks like SM Higgs boson

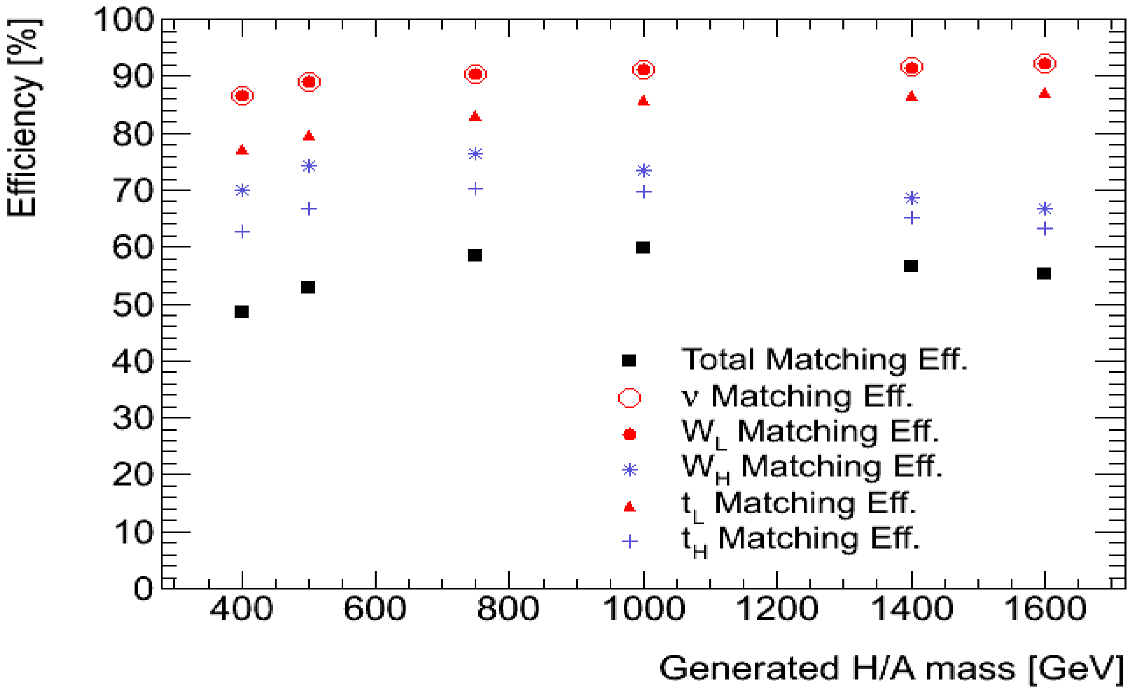
$$H^{SM} = h * sin(\beta - \alpha) + H * cos(\beta - \alpha)$$

Φ	$g_{\Phi\bar{u}u}$		$g_{\Phi\bar{d}d}$		$g_{\Phi VV}$
	Type I	Type II	Type I	Type II	Type I/II
$\boxed{h}$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\boxed{\sin(\beta-\alpha)}$
H	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos(\beta-\alpha)$
A	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\tan\beta$	0

Event reconstruction

- Reconstructible events
  - Partons matched to the physics objects
  - Perfect reconstruction assumption
- Efficiencies of the reconstructible events
  - Between 50% and 60% after the matching of all the objects

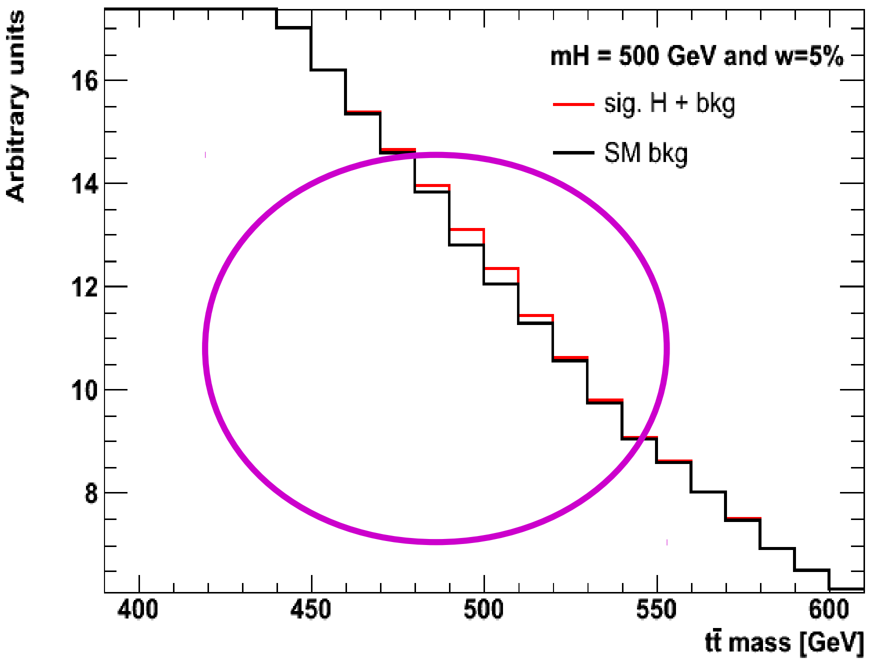




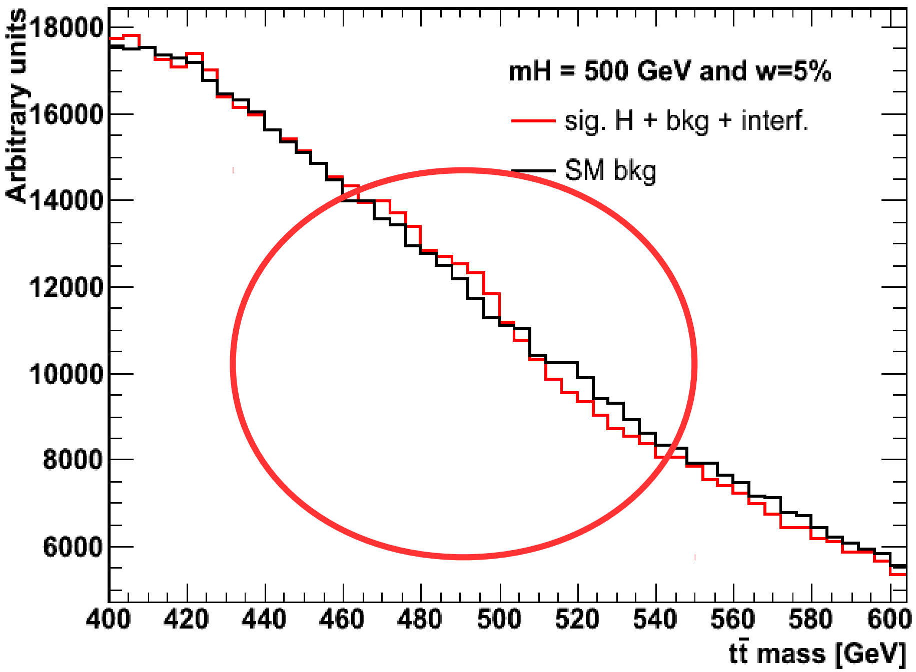
2 HDM signal into $t\bar{t}$

- Decay channel: $H/A \rightarrow t\,\bar{t}$
- Signal have same initial/final states than the SM bkg
  - Interference (peak/dip structure)

H signal



H signal + interference



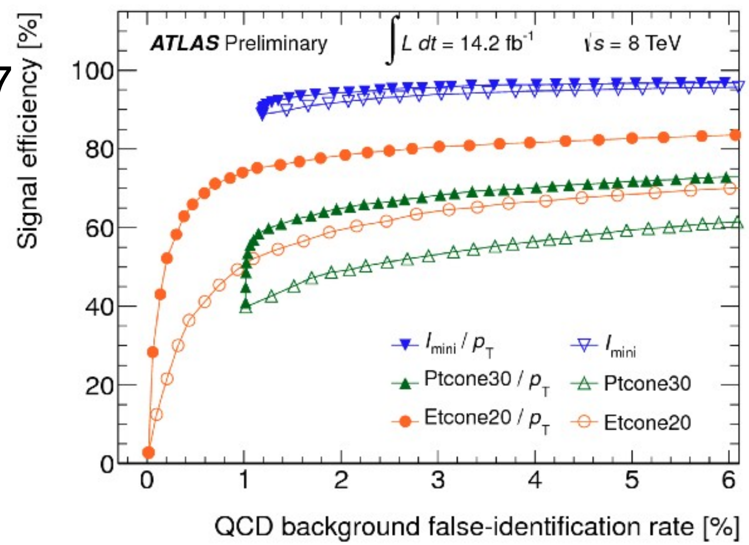
Lepton+jet channel: Physics objects

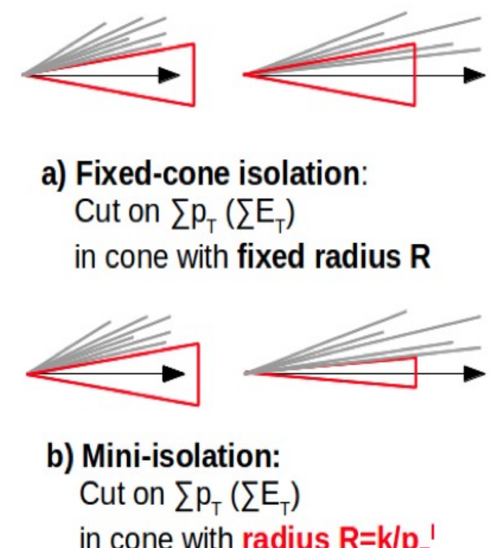
- Only considered electron/muon in the final state

- Mini-isolation: [Σ pT of tracks within a variable cone size]/pT
  - Stable performance with efficiency close to 100%

- **Electrons**:
  - ET > 25 GeV and |η| < 2.47
  - MI10 < 0.05

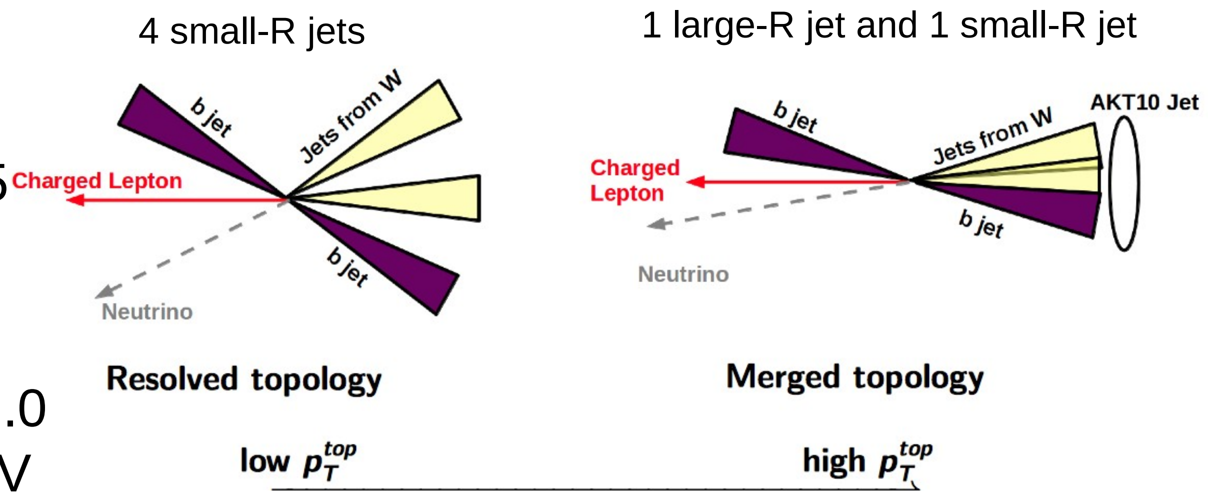
- **Muons**:
  - pT > 25 GeV and |η| < 2.0
  - MI10 < 0.05





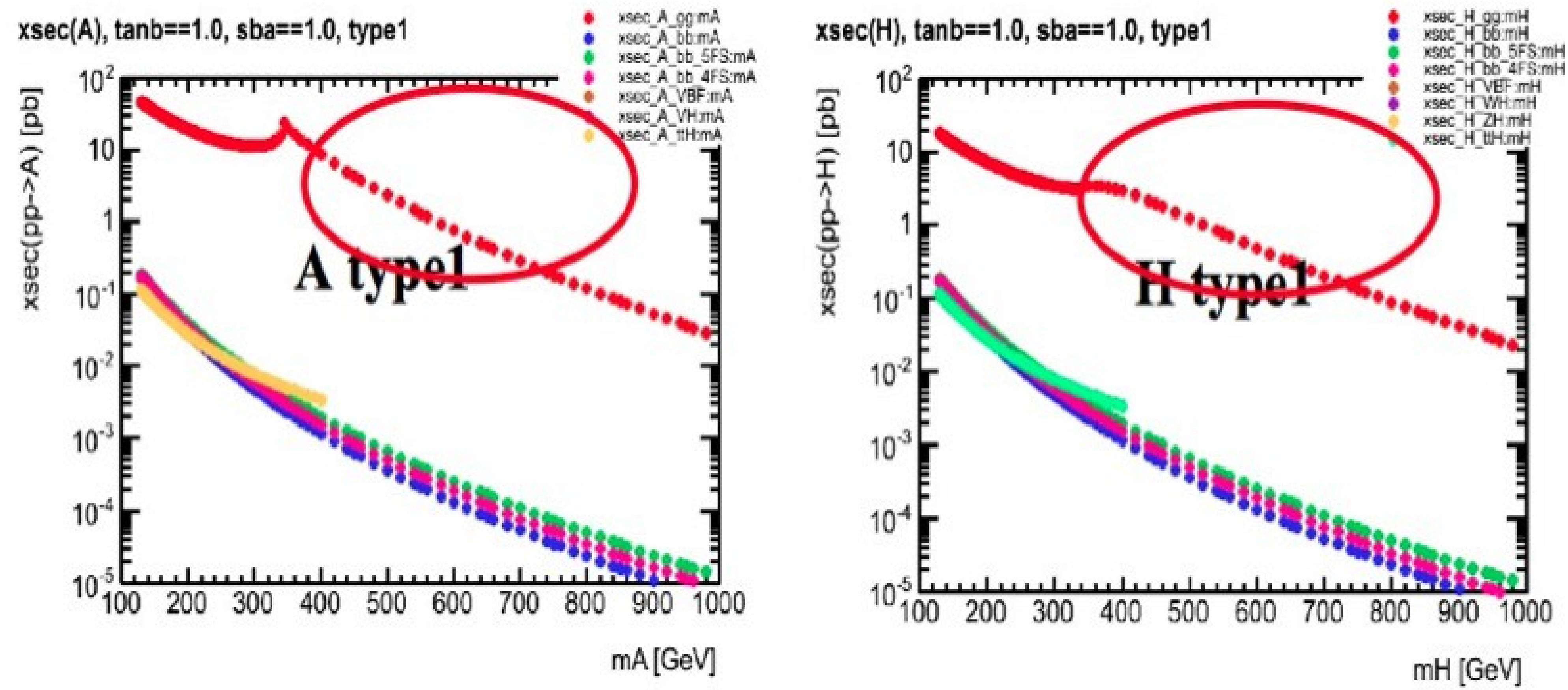
Lepton+jet channel: Physics objects

- **Jets:**
  - <u>Small-R jets:</u>
    Anti-kt algorithm, R=0.4
    $p_T > 25$ GeV and $| \eta | < 2.5$
  - <u>Large-R jets:</u>
    Anti-kt algorithm, R=1.0
    $p_T > 300$ GeV and $| \eta | < 2.0$
    $M > 100$ GeV, $d_{12} > 40$ GeV



- **B-tagging is applied to small-R jets**

2HDM production mode



- Gluon fusion ($gg \to A/H$) is the dominant channel