Search for Higgs boson pair production with the ATLAS detector at the LHC

Thesis defence,

Jakob Novak

Jožef Stefan Institute

University *of Ljubljana*
Faculty *of Mathematics and Physics*

ATLAS EXPERIMENT

Outline

Part I: High energy physics at the LHC

- Standard Model and electroweak symmetry breaking
- The Large Hadron Collider
- The ATLAS experiment:
  - Experimental setup
  - Event reconstruction

Part II: Resolved di-Higgs 1-lepton search:

- SM di-Higgs hypothesis and SH hypothesis
- Experimental signature
- Machine learning approach
- Fake lepton background estimation
- Statistical analysis and results

Standard Model

Standard Model is the most accurate description of particle physics, i.e. **high energy physics** (GeV - TeV)

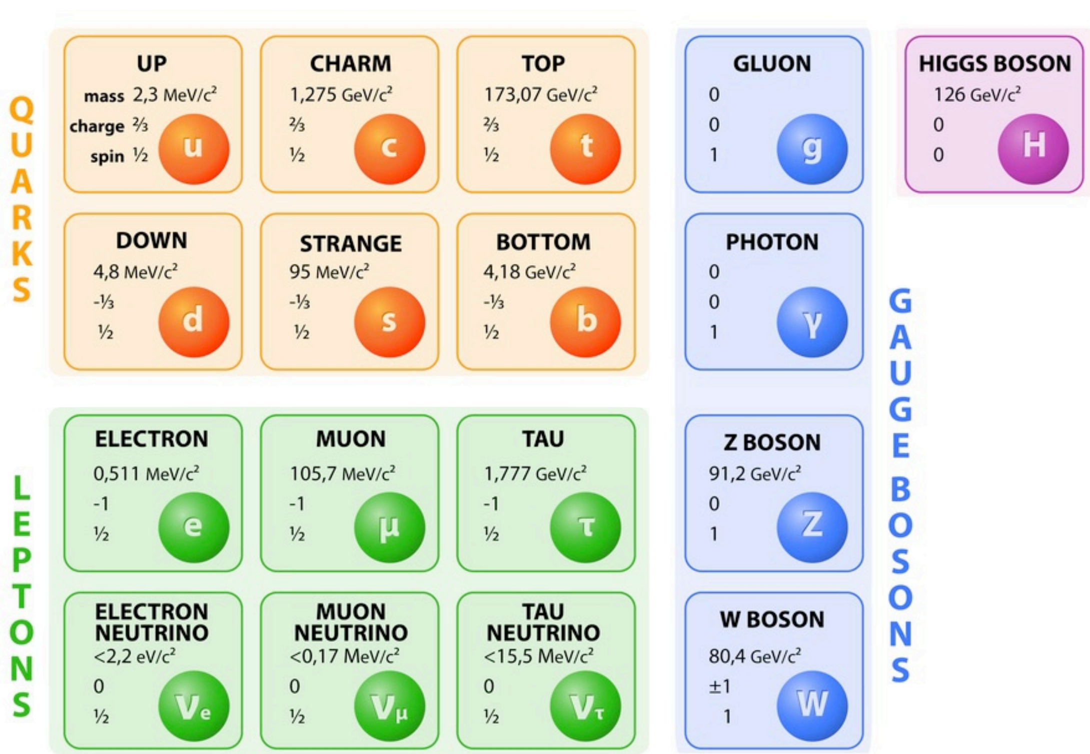
Shortcomings:

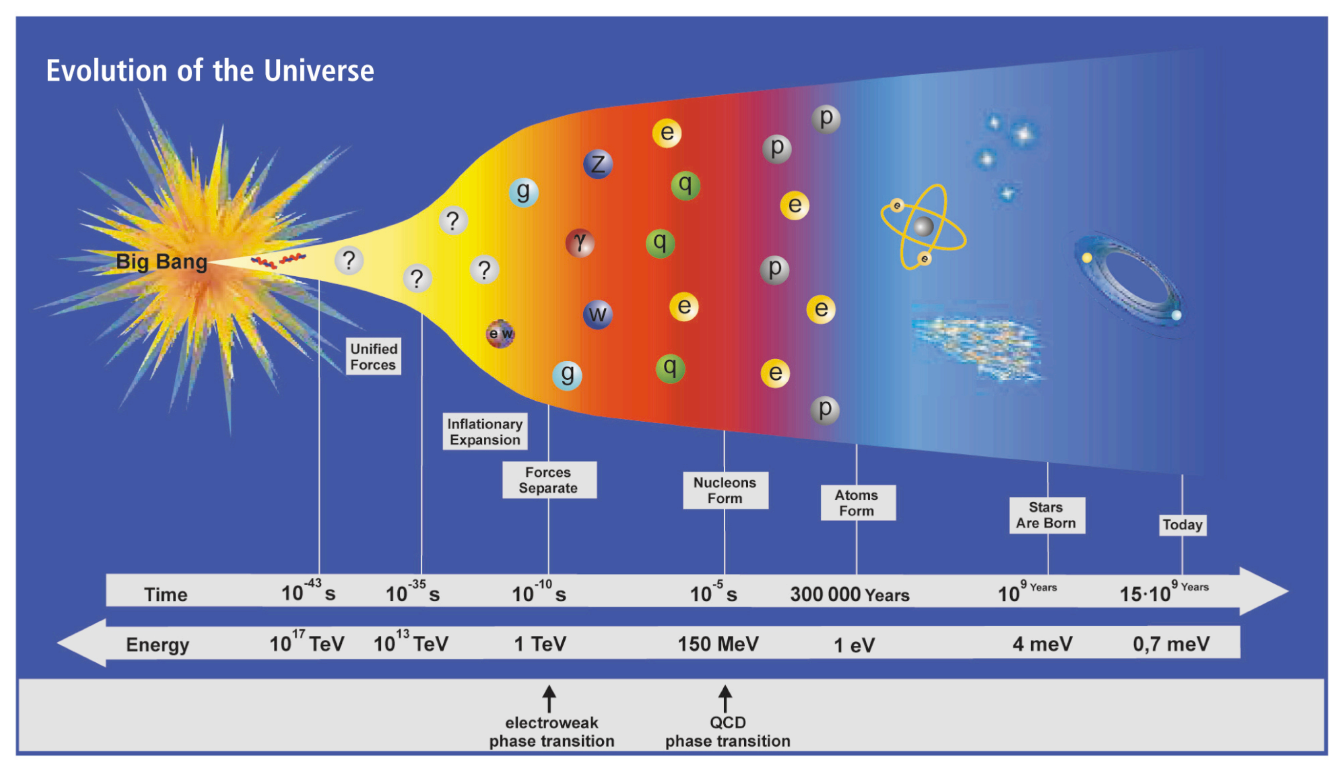
- Mismatch with the low-energy phenomena (gravity, dark matter, dark energy)
- Hierarchy problem

Standard Model provides a basis for understanding of the **early universe**

Shortcomings:

- What triggers inflation?
- Matter-anti-matter asymmetry



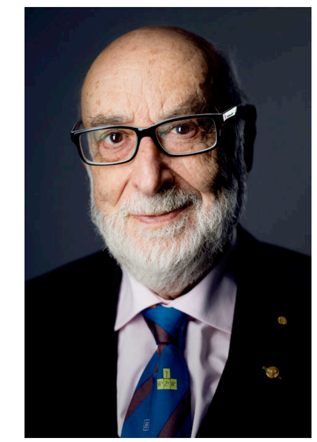


EW symmetry breaking

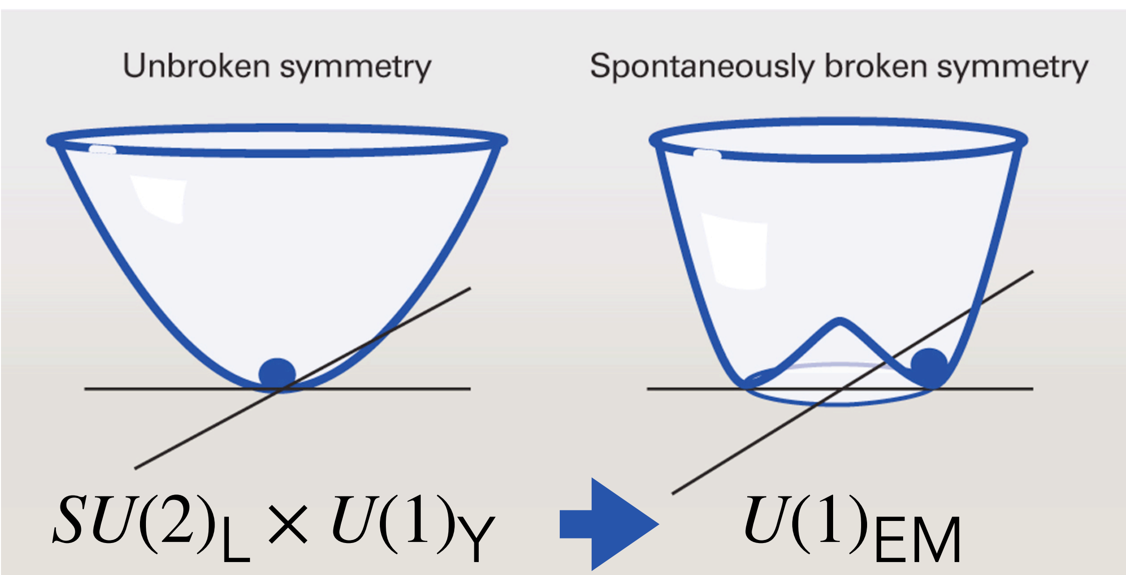
EWSB mechanism proposed in 1964

Nobel prize awarded to Higgs and Englert after Higgs boson discovery by the ATLAS and CMS experiment

P. Higgs



F. Englert



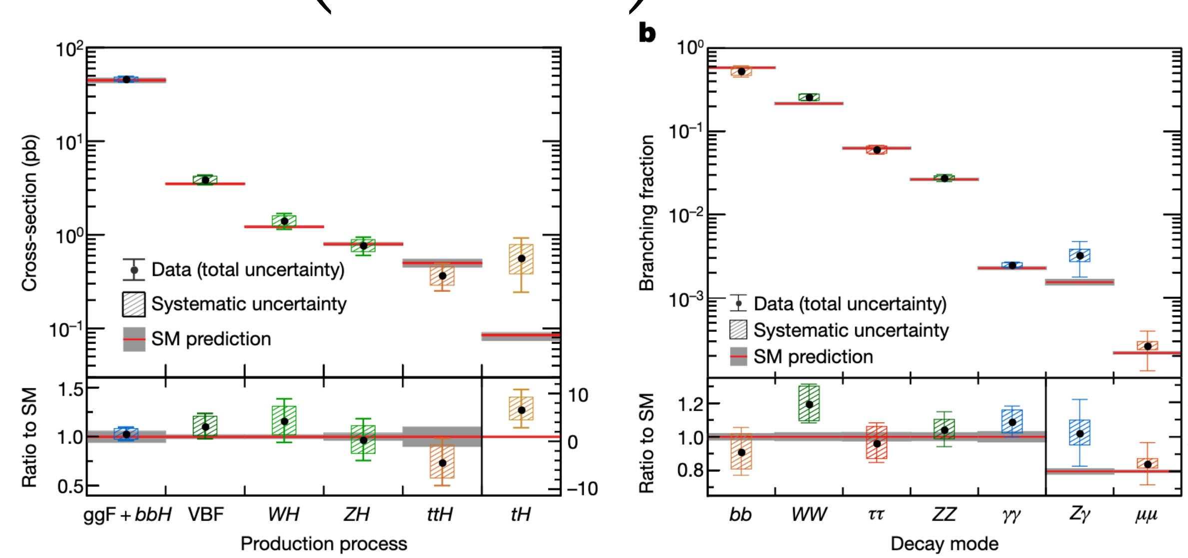
Higgs field (Φ) potential is characterised by a degenerate vacuum at $\Phi \neq 0$:

$$V(\Phi) = \lambda \left(\Phi^\dagger \Phi - \frac{v^2}{2} \right)^2, \quad SU(2)_L \text{ dublet}$$

Weak bosons and fermions acquire mass

SM provides a compact but not exclusive experimentally congruent description

Better understanding of the EW sector is needed



https://www.science.org/doi/10.1126/science.337.6100.1289

The Large Hadron Collider

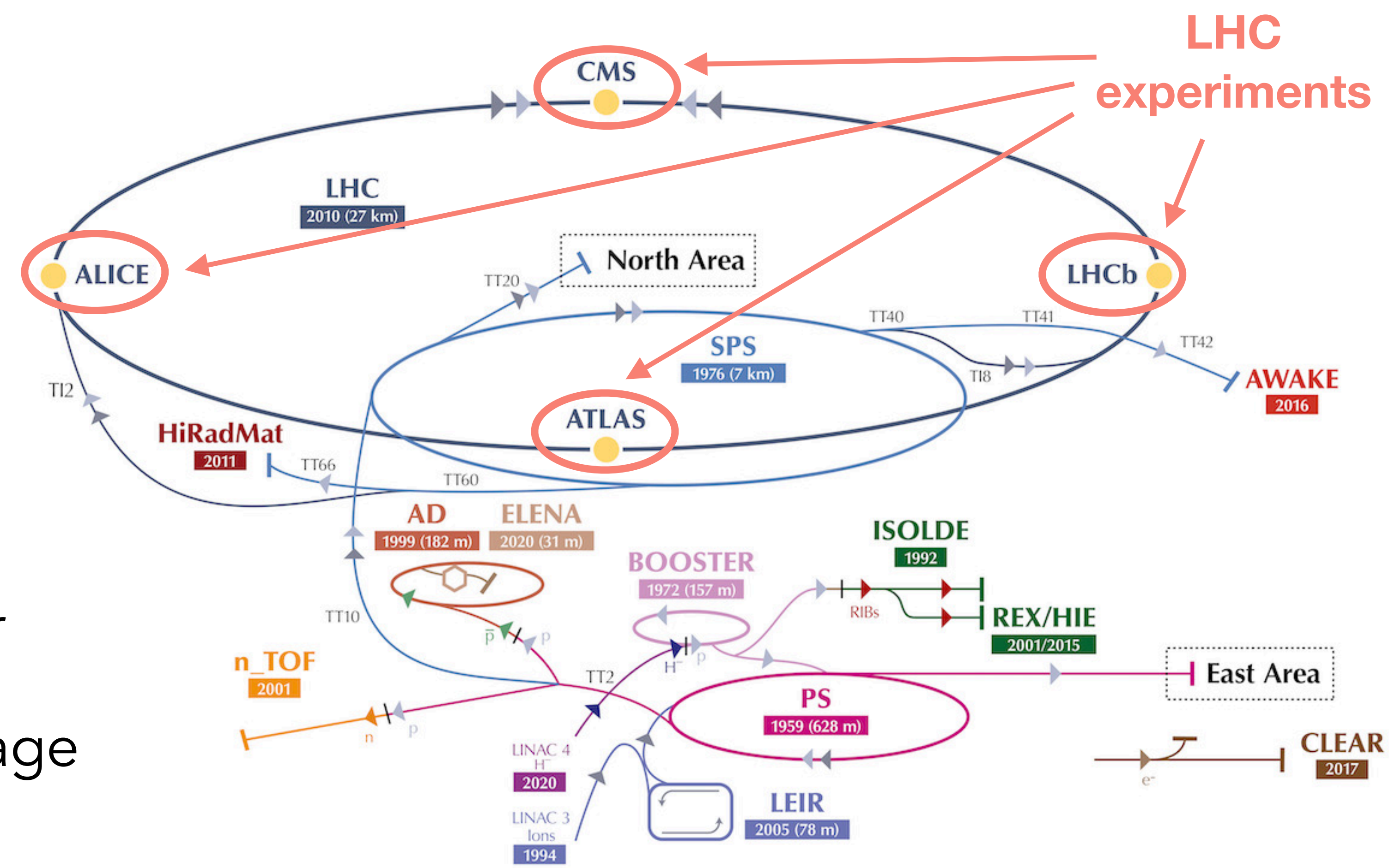
The Large Hadron Collider (LHC) is currently the most powerful particle accelerator in the world

Final stage of the CERN accelerator chain at France - Switzerland border

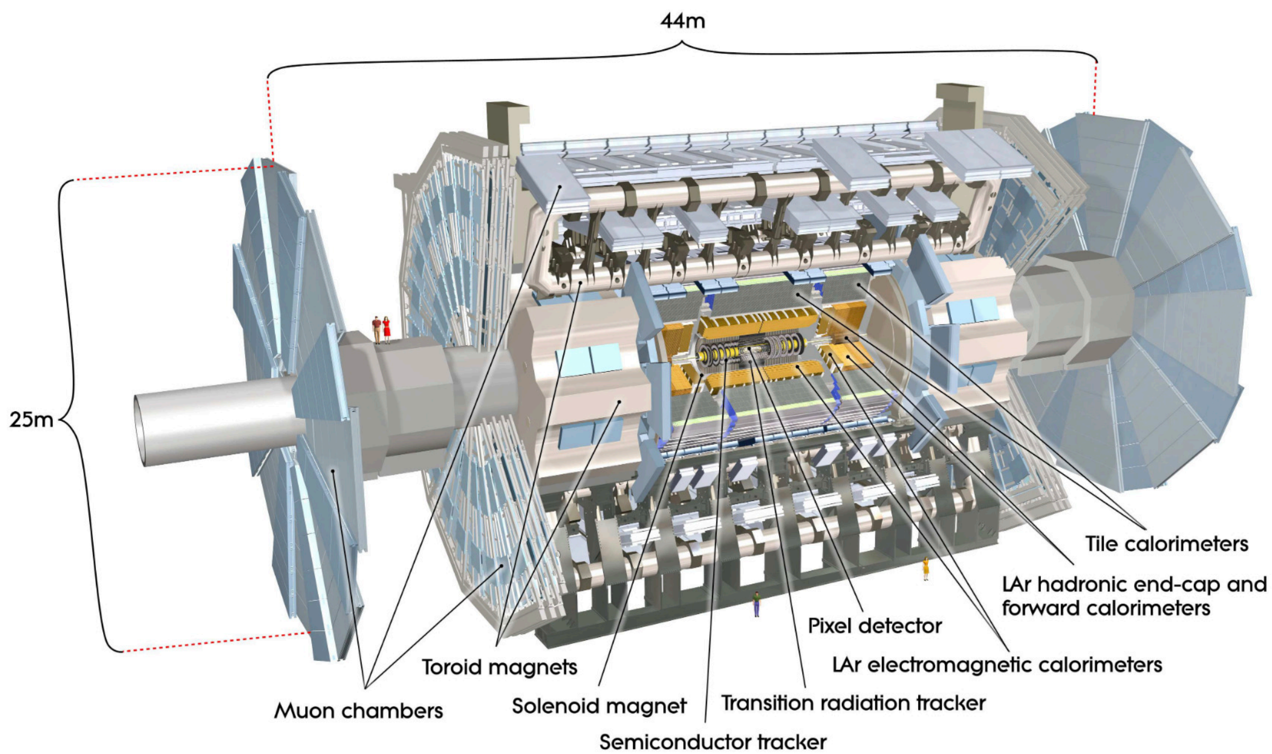
26.7 km circumference, 100 m average depth

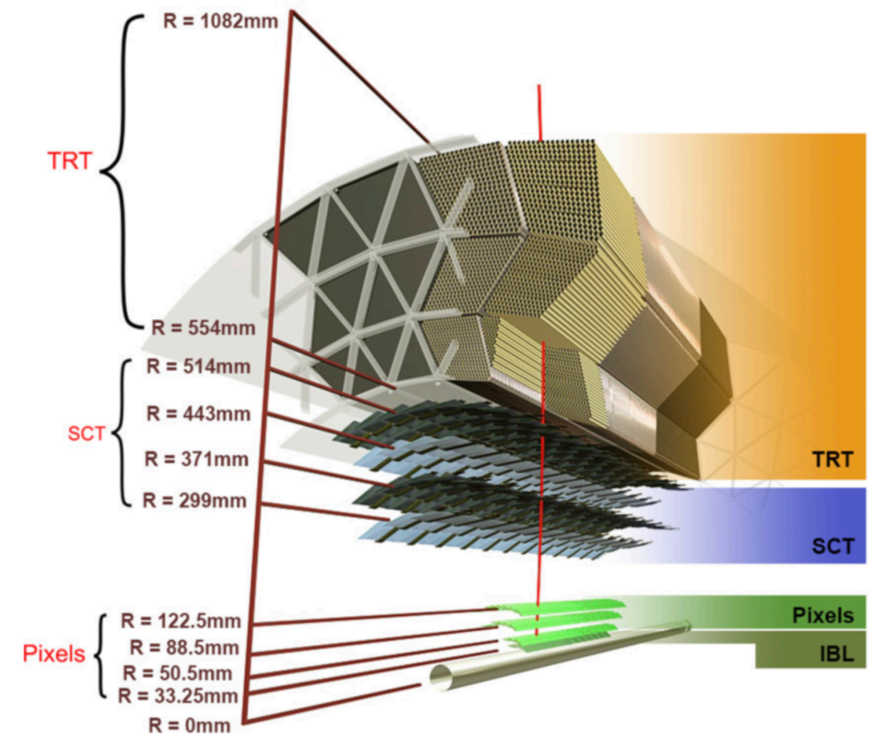
Accelerator of protons and heavy ions

Delivered cca. 6×10^{16} collisions with energies up to 13.6 TeV



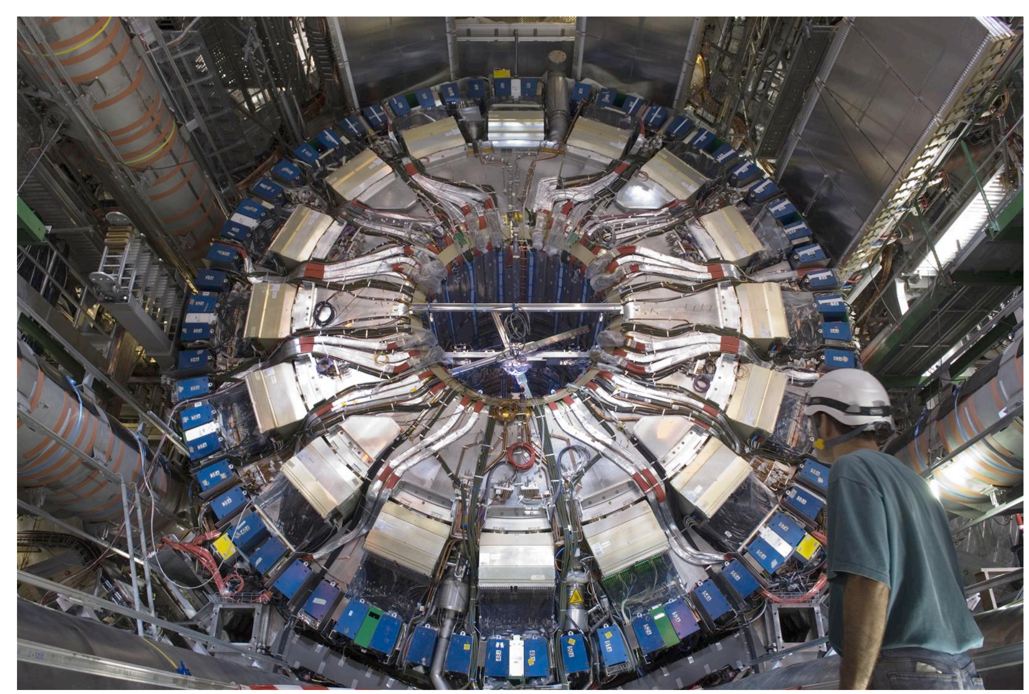
The ATLAS Detector





The ATLAS detector is a general purpose device consisting of several subsystems:

- Inner Detector (Pixel, SCT, TRT)
- Electromagnetic calorimeter and Hadronic (Tile and LAr) calorimeter
- Muon spectrometer
- Central solenoid and toroid magnets
- Two-level trigger



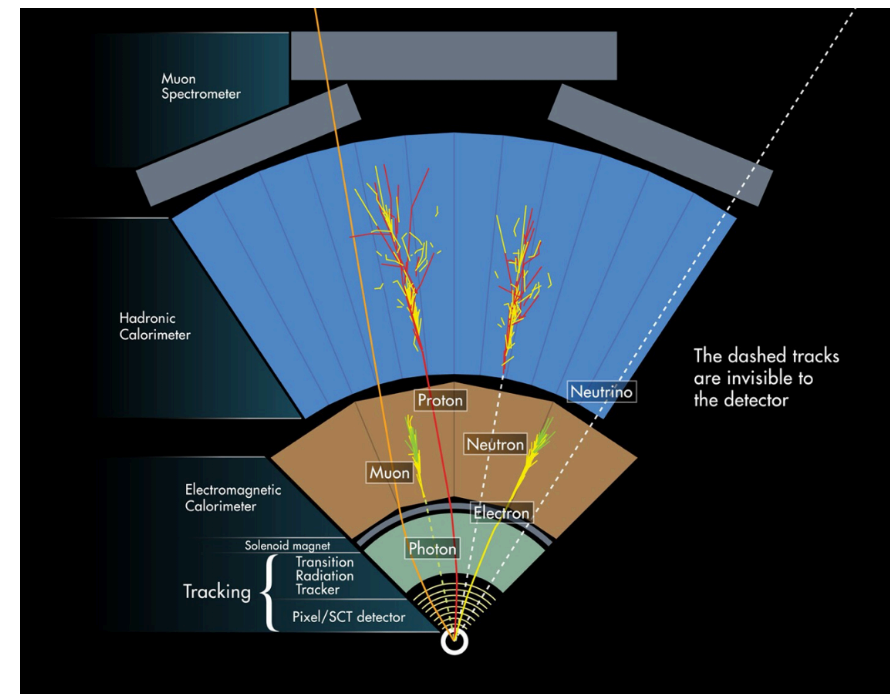
Event reconstruction

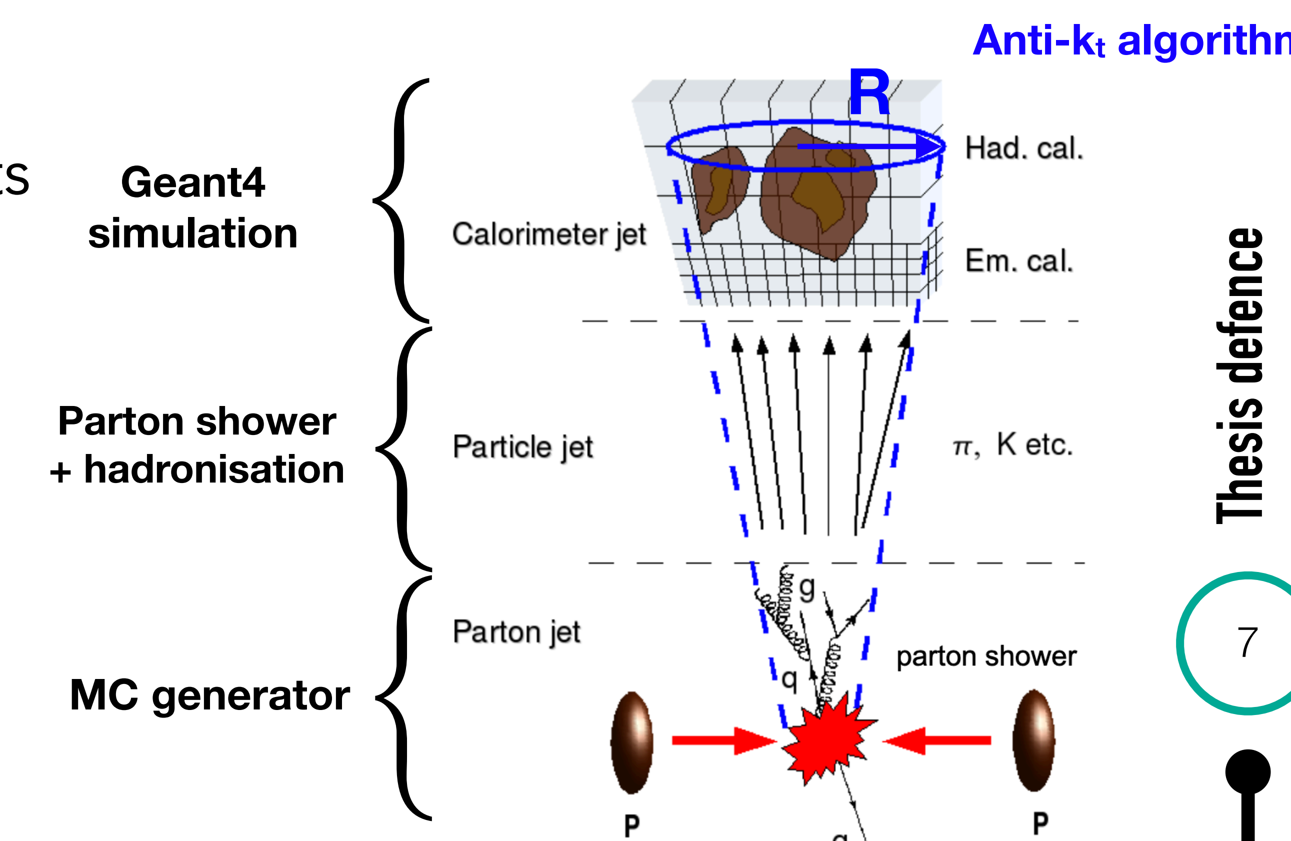
ID tracks, topo-clusters from the calorimeters and MS segments are used to build high-level objects

High level objects ↔ hard interaction products:

- Electrons: tracks + EM topo-clusters
- Photons: EM topo-clusters
- Jets: EM+HAD topo-clusters and tracks
- Muons: tracks + MS segments
- Hadronic taus: more collimated than jets
- Missing transverse momentum

B-tagging: jets with tracks matched to secondary vertices from B-meson decays





Part II:
Resolved di-Higgs 1-lepton search

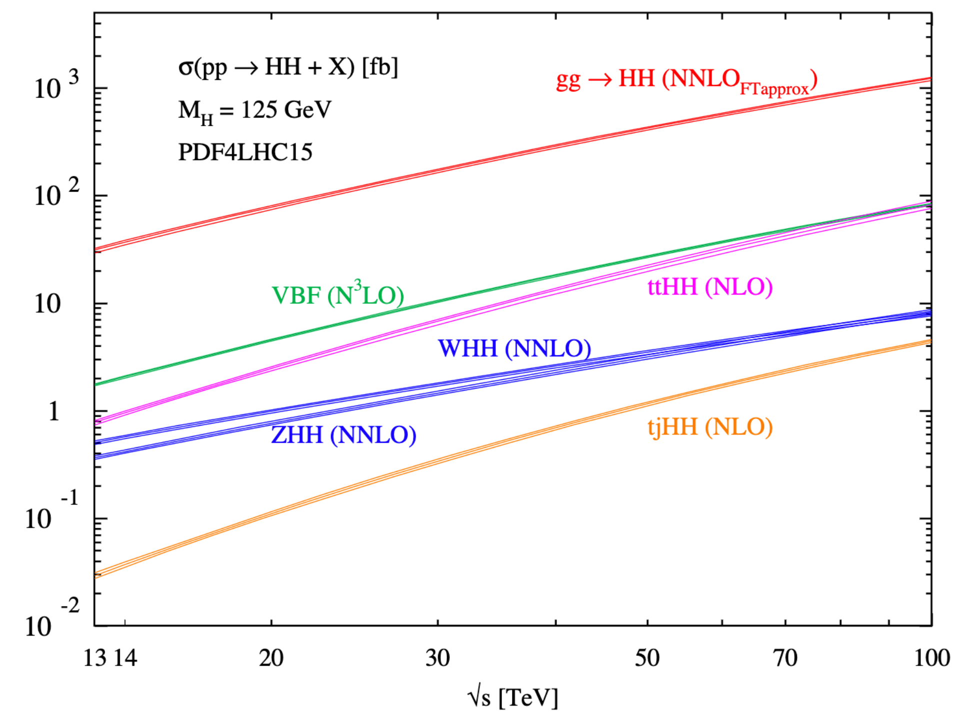
Di-Higgs signal

Non-resonant Higgs pair production (di-Higgs) is a probe to measure Higgs potential, more precisely tri-linear Higgs self-coupling (λ_3)

SM consistency check: $\lambda_{3,SM} = m_H^2/2v$

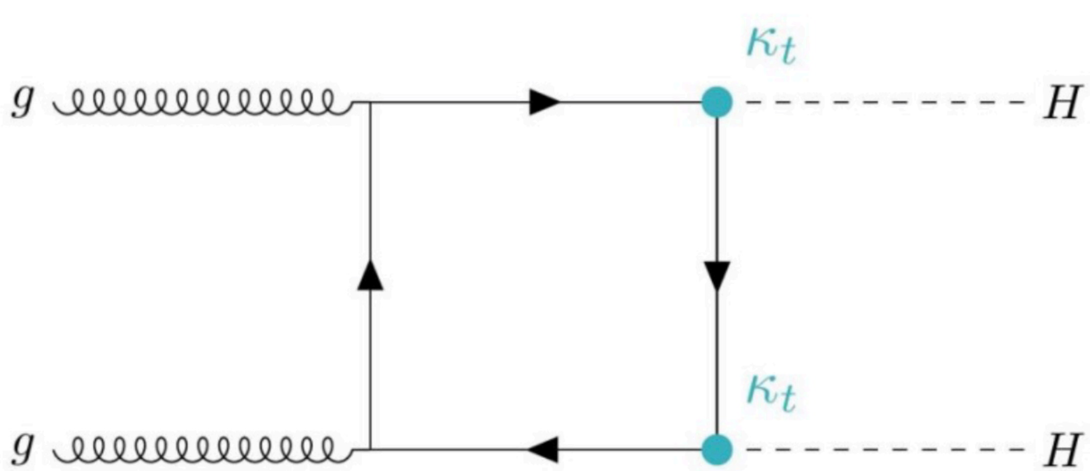
Gluon fusion is the dominant production mode $\sigma_{ggF}(13\text{ TeV}) = 30.5$ fb, VBF sub-leading

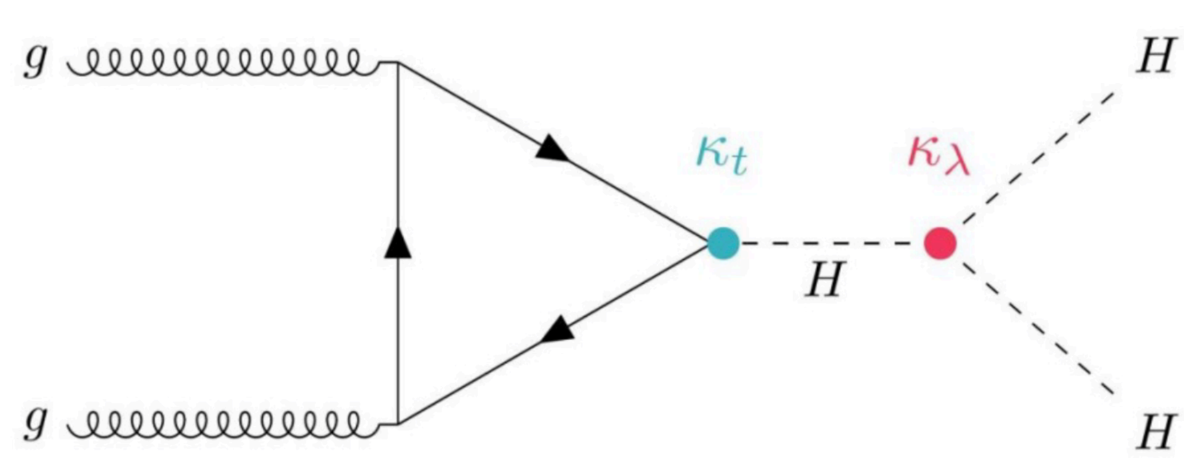
Any deviations from the SM Higgs potential could result in an enhanced di-Higgs production rate



$$V(h) = \frac{1}{2}m_h^2 h^2 + \lambda v h^3 + \frac{\lambda}{4}h^4$$

mass term — tri-linear self-coupling — quartic self-coupling





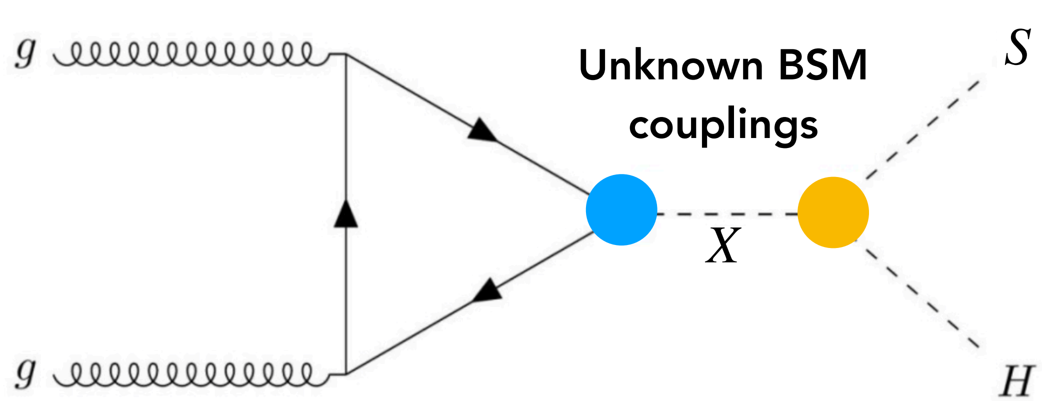
SH hypothesis

Extensions of the EW sector provide baryogenesis and inflatons

They are characterised by the presence of additional scalar resonances

Special interest of this work are asymmetric decays: $X \to SH$

X is a CP-even scalar and S is a Higgs-like scalar with $m_X > m_S > m_H$

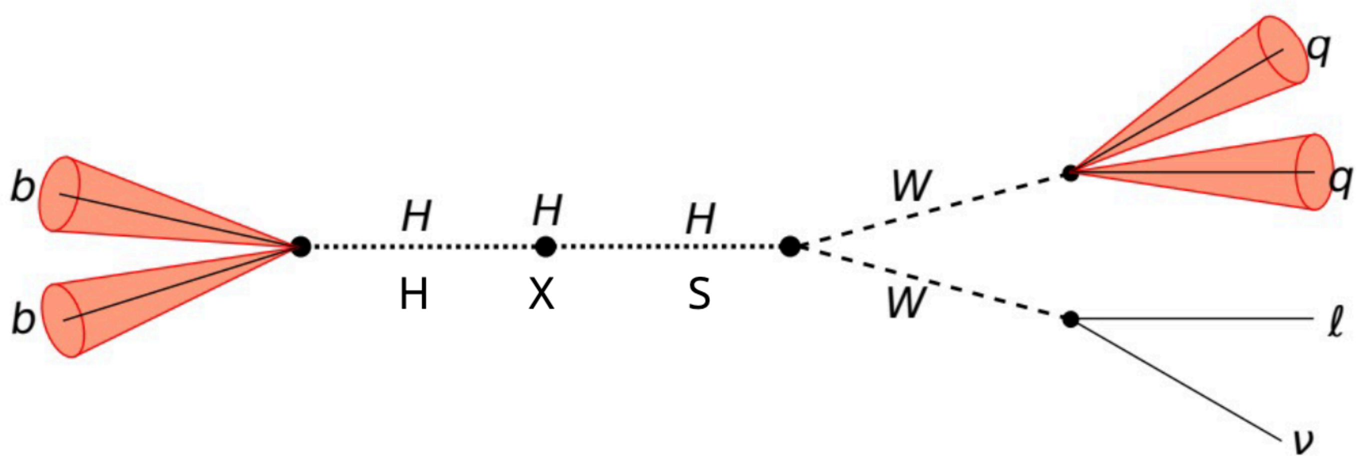


Various BSM theories predict such decay chains, such as NMSSM and C2HDM (more examples in the backup)

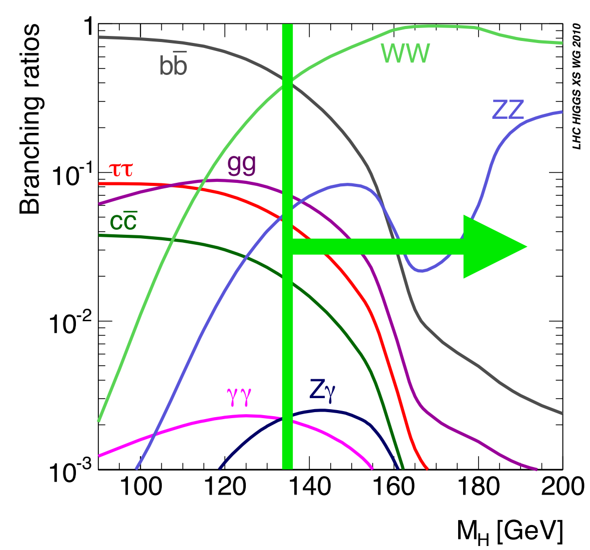
SH Mass hypotheses
Unit = GeV

m_X \ m_S	170	240	400	550	750	1000	1500	2000	2500
350	✅								
500	✅	✅							
750	✅	✅	✅	✅					
1000	✅	✅	✅	✅	✅				
1500	✅	✅	✅	✅	✅	✅			
2000	✅	✅	✅	✅	✅	✅	✅		
2500	✅	✅	✅	✅	✅	✅	✅	✅	
3000	✅	✅	✅	✅	✅	✅	✅	✅	✅

Single-lepton channel



	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%



Single-lepton channel is a trade-off between the branching ratio and clean experimental signature

$\sigma(HH \to bbWW^* \to bbql\nu) \sim 2.3\ fb$

Preselection:

- Lepton or MET trigger
- Exactly one lepton
- Exactly 2 b-tagged jets
- At least 2 light jets
- Tau veto and LRJ veto (SH)

Irreducible background:

- $t\bar{t}$, W+jets, single-top
- Estimated using MC

Reducible background:

- Fake (jets) and non-prompt leptons
- Data-driven estimation

Machine learning

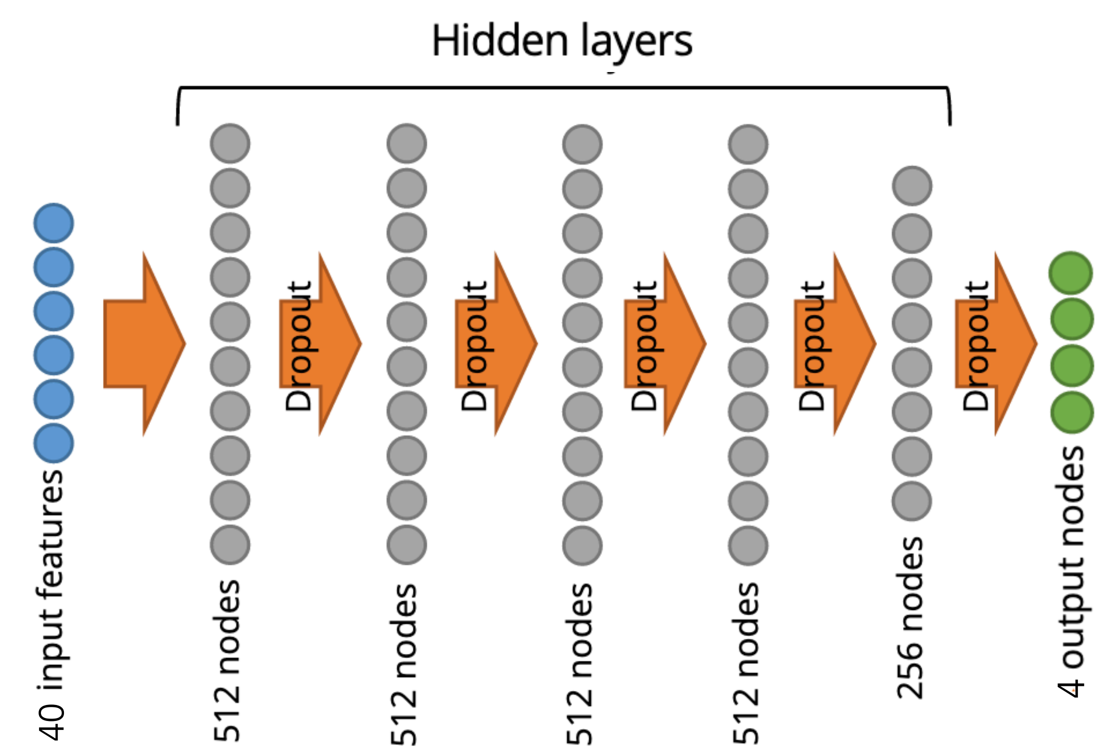
Multi-class DNN (Keras+TensorFlow) with 4 output scores: p_{signal}, p_{ttbar}, p_{Wjets}, p_{Stop}

40 input features,
5 hidden layers,
dropuout rate 0.5

$$d_{\text{signal}} = \log\left(\frac{p_{\text{signal}}}{1 - p_{\text{signal}}}\right)$$

5-fold cross-validation, 20% test set

6 mass point groups defined for the SH training

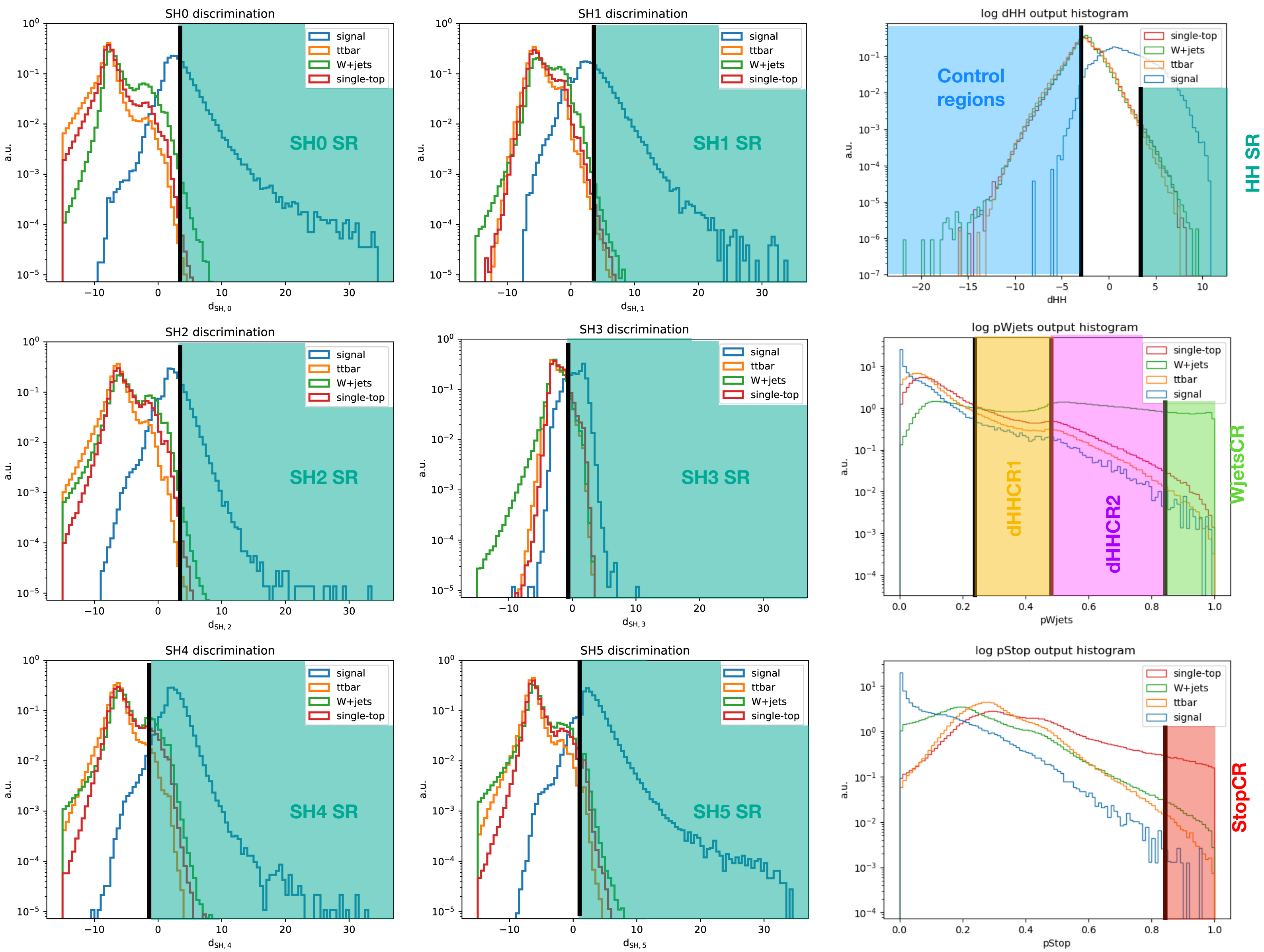


m_X \ m_S	170 GeV	240 GeV	400 GeV	550 GeV	750 GeV	1 TeV	1.5 TeV	2 TeV	2.5 TeV
350 GeV	0.49								
500 GeV	0.34	0.48							
750 GeV	0.23	0.32	0.53	0.73					
1 TeV	0.17	0.24	0.40	0.55	0.75				
1.5 TeV	0.11	0.16	0.27	0.37	0.50	0.67			
2 TeV	0.08	0.12	0.20	0.27	0.37	0.50	0.75		
2.5 TeV	0.07	0.10	0.16	0.22	0.30	0.40	0.60	0.80	
3 TeV	0.06	0.08	0.13	0.18	0.25	0.33	0.50	0.67	0.83

Ratio m_S/m_X

SH0
SH1
SH2
SH3
SH4
SH5

Analysis regions



4 control regions

- dHHCR1: $t\bar{t}$ normalization
- dHHCR2: W+jets and fakes normalization (electron/muon split)
- WjetsCR: W+jets normalization
- StopCR: single-top normalization

7 signal and 7 validation regions

Analysis	VR	SR
HH	$d_{HH} > -3$, $\log(T) \leq 4^*$	$d_{HH} > 1$, $\log(T) > 4$
SH0	$-2 < d0_{SH} < 2$	$d0_{SH} > 3$
SH1	$-2 < d1_{SH} < 2$	$d1_{SH} > 3$
SH2	$-4 < d2_{SH} < 2$	$d2_{SH} > 3$
SH3	$-7 < d3_{SH} < -4$	$d3_{SH} > -1$
SH4	$-4 < d4_{SH} < -2$	$d4_{SH} > -1$
SH5	$-3 < d5_{SH} < 0$	$d5_{SH} > 1$

* T stands for Topness, defined in backup

CR	dHHCR1	dHHCR2	WjetsCR	StopCR
p_{Wjets}	$0.24 < p_{Wjets} < 0.48$	$0.48 < p_{Wjets} < 0.85$	$p_{Wjets} > 0.85$	-
p_{Stop}	-	-	-	$p_{Stop} > 0.85$
d_{HH}	$d_{HH} < -3$	$d_{HH} < -3$	$d_{HH} < -3$	$d_{HH} < -3$

Fake-factor method

Tight and loose leptons are defined based on the ID, isolation and tracking requirement

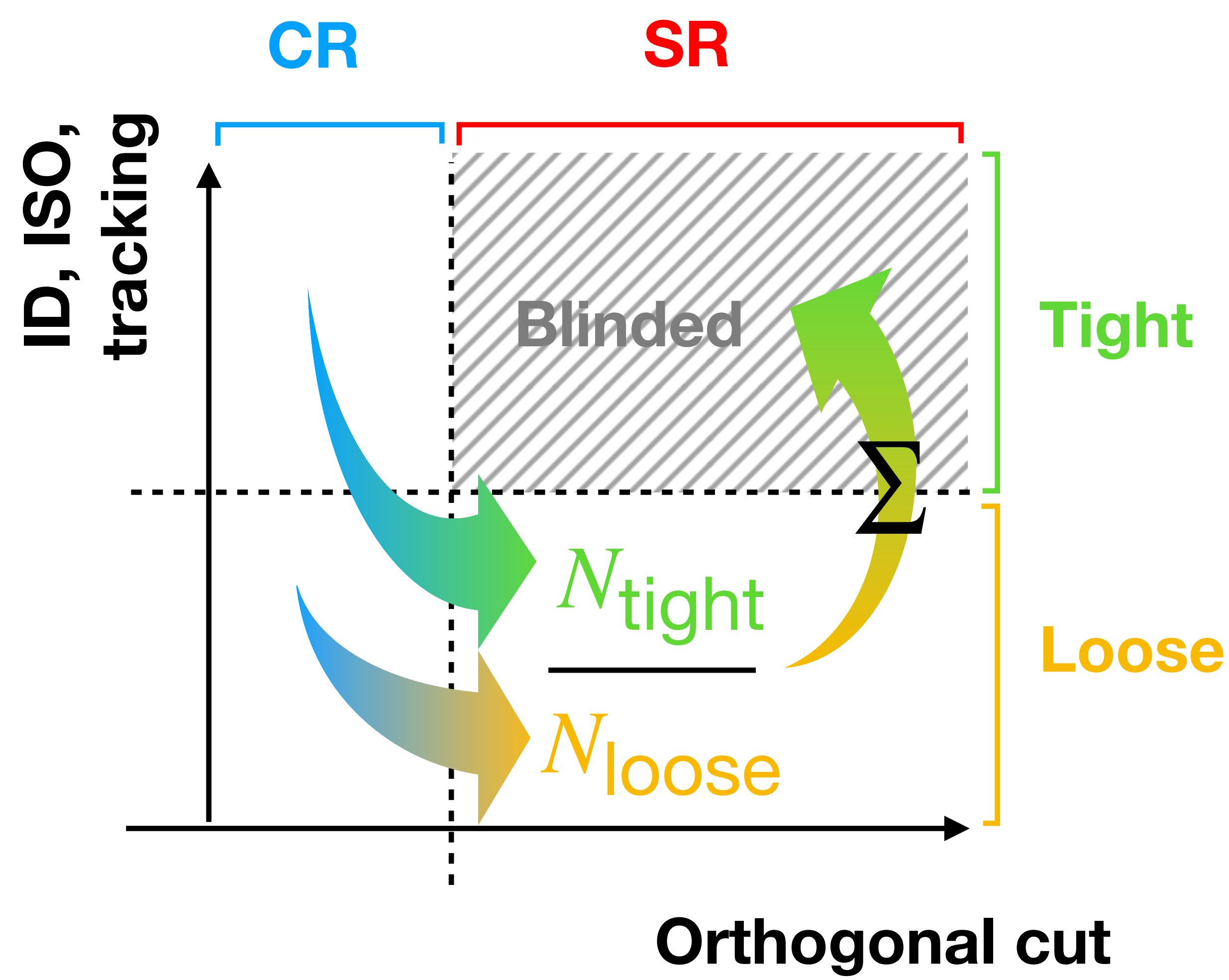
Fake-factor measured in the CR:

$$F(p_T, \eta) = \frac{N_{\text{tight}}(p_T, \eta)}{N_{\text{loose}}(p_T, \eta)}$$

Fake-factors applied to loose SR leptons, prompt contributions subtracted:

$$N_{SR} = \left[\sum_{i \in L} F_i\right]_{\text{data}} - \left[\sum_{i \in L} F_i\right]_{\text{prompt}}$$

Di-lepton (tag and probe) region with 1 b-tag jet and 3 light jets used as CR



Two sets of fake-factors derived:

- Trigger-matched (tag) lepton fake-factors used in lepton trigger SR
- The other (probe) lepton used in MET trigger SR

Statistical analysis

Hypothesis testing is performed using **profile likelihood fit** and **CL_s method** (RooFit framework)

Statistical uncertainty of the data, statistical uncertainty of the MC and **systematic uncertainties** are taken into account

CRs and SRs are fit simultaneously, multi-bin fit in SRs, split per trigger and lepton flavour

Separate fit for HH signal and each of the SH mass points:

- 182 free parameters for HH
- 210-224 free parameters for SH

Theoretical uncertainties:

- Cross-section uncertainties
- Modelling (PDF, scale, ME+PS matching, PS modelling, PS tune)

Detector uncertainties:

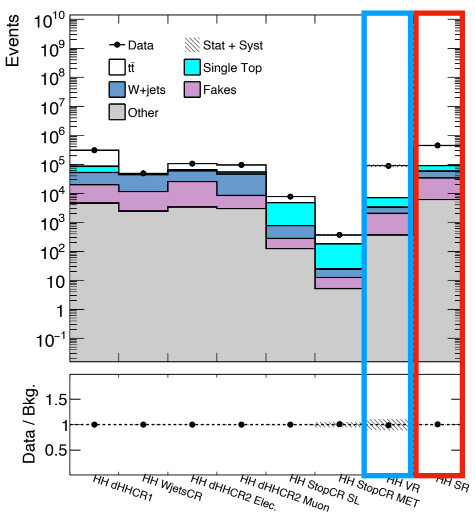
- Luminosity and pile-up
- Electron and muon reco, ISO, ID, trigger and TTVA (muon-only)
- JES, JER, JVT, Jet flavour comp
- Flavour tagging
- Tau, MET and LRJ

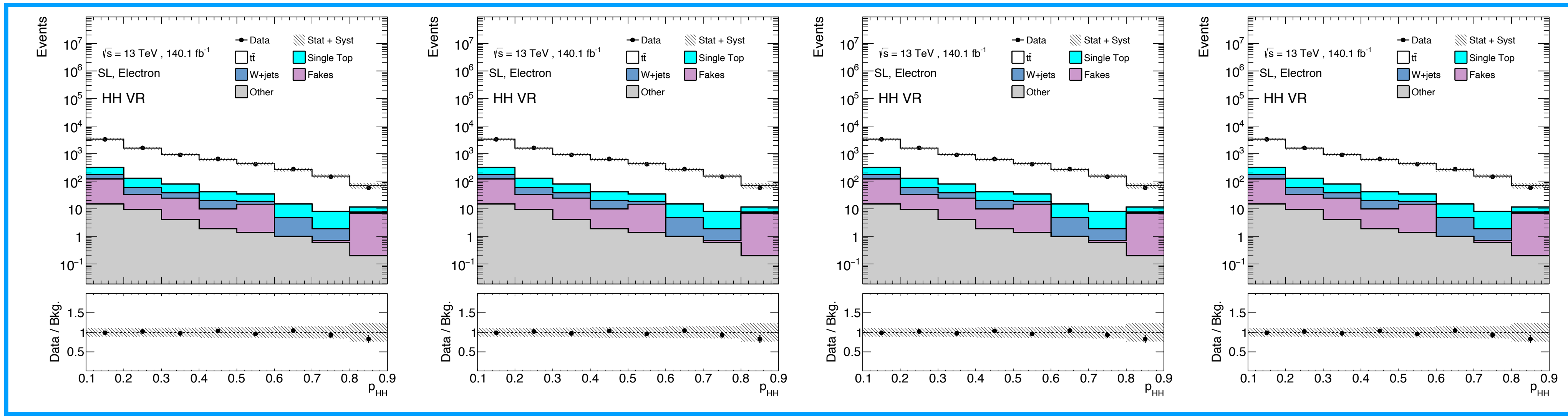
Fakes uncertainties:

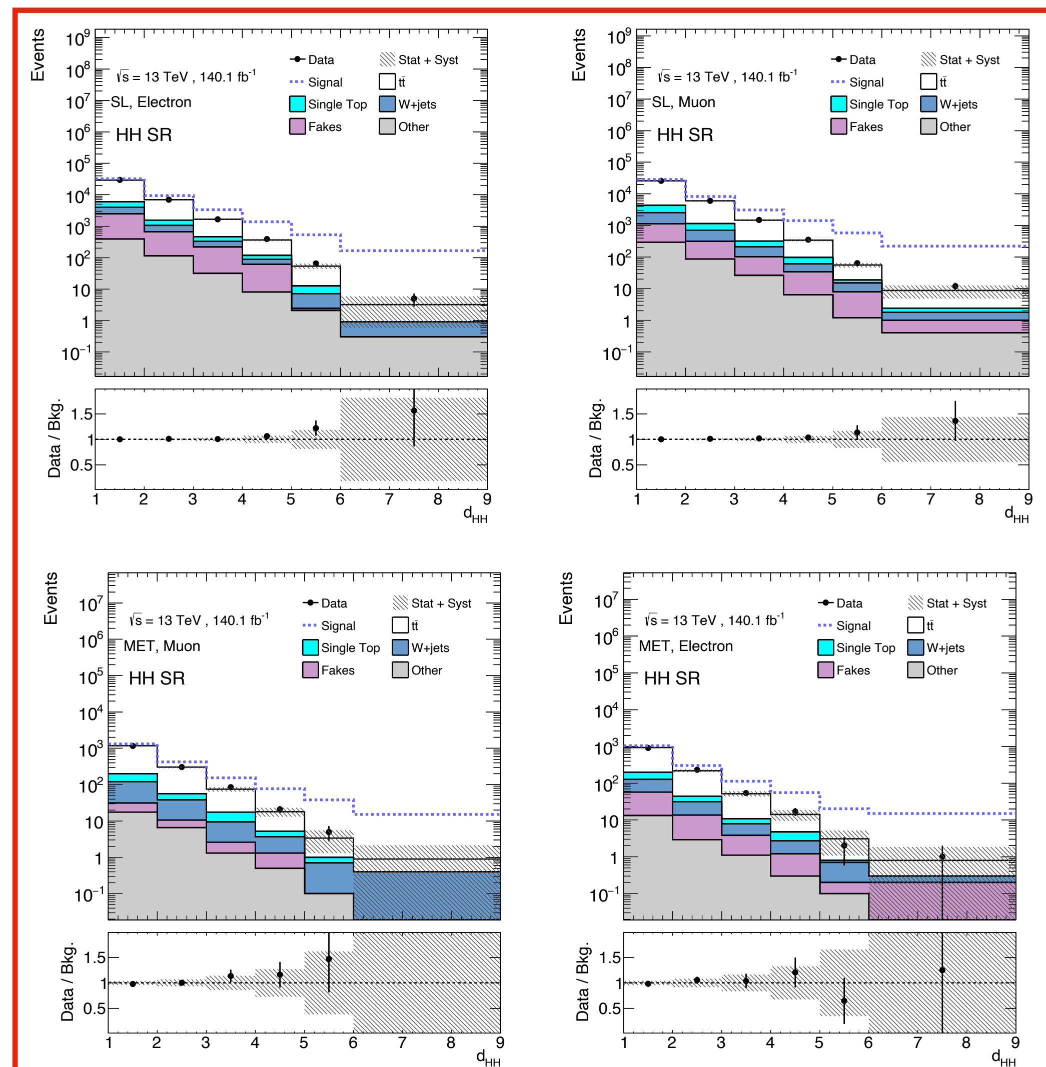
- FF extrapolation and statistical uncertainty, MC normalisation

$$L(N \mid \mu, \boldsymbol{\tau}, \boldsymbol{\alpha}, \boldsymbol{\gamma}) = \Pi_{i=1}^{m} P_i(N_i \mid \mu, \boldsymbol{\tau}, \boldsymbol{\alpha}, \boldsymbol{\gamma}) \cdot G(\gamma_i \mid 1, \sigma_{\overline{N}_i}) \cdot \Pi_{j=1}^{n} G(\alpha_j \mid 0, 1)$$

HH search result



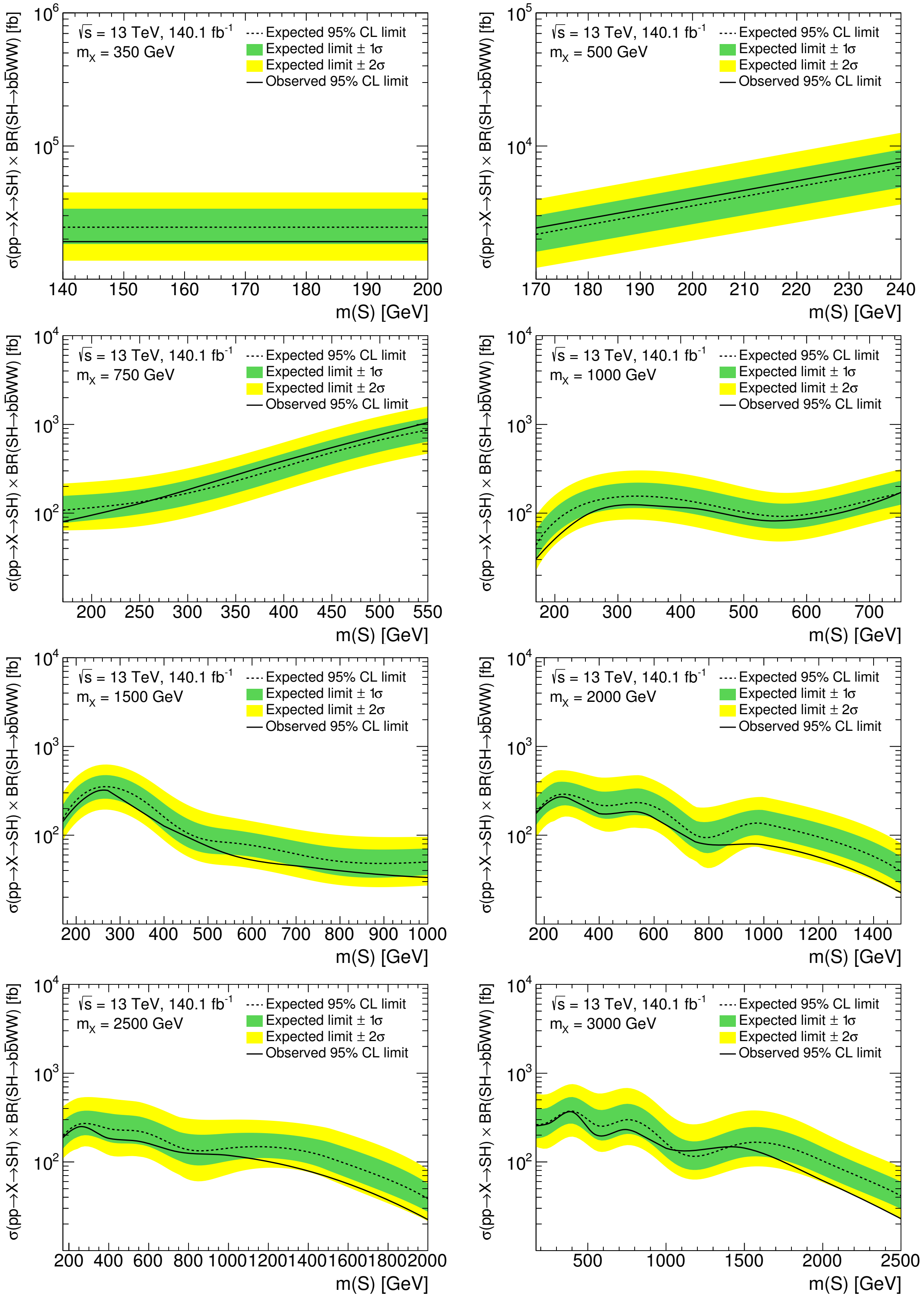




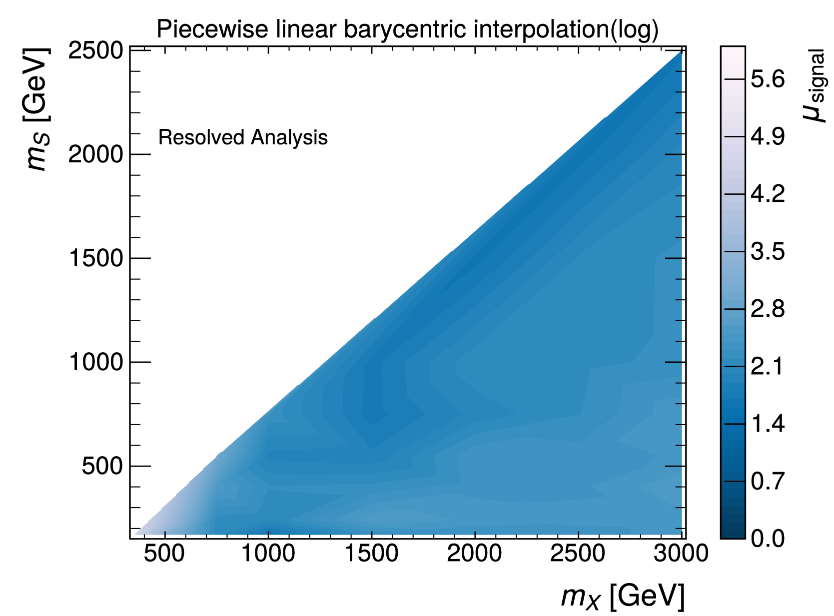
Good agreement is observed in analysis VRs and no significant excess above the background prediction in analysis SRs has been found

95% CL expected (observed) upper limit on the HH production cross-section has been set: $24.8^{+14.0}_{-8.0}$ (44.7) times the SM prediction

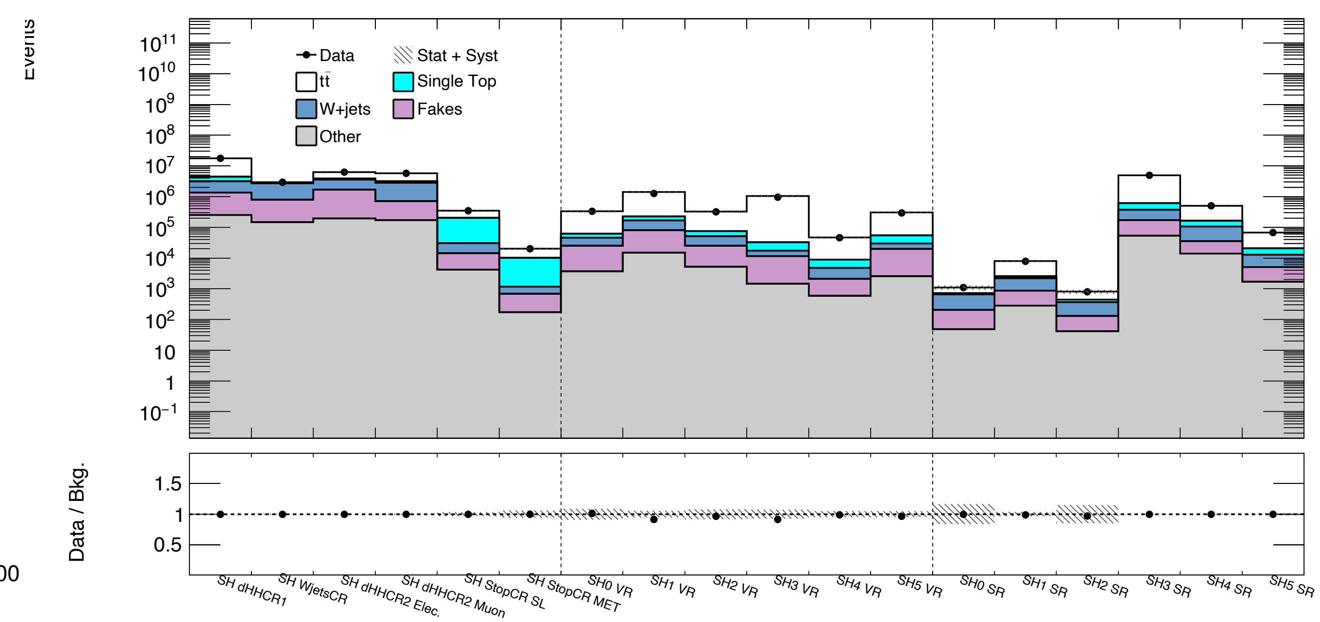
SH search result



Good agreement in analysis VRs is observed and no significant excess above the background prediction in analysis SRs has been found



95% CL expected (observed) upper limit on the SH production cross-section have been derived



Conclusions & discussion

The first search for the non-resonant Higgs production in the resolved single-lepton final state on the full Run 2 (140.1 ifb) data has been carried out

The previous result has been improved from 300 × σ_{SM} to 25 × σ_{SM} (no impact on statistical combination)

The first model independent SH search has been carried out in the resolved single-lepton channel

SH result competitive in m_X = 750 - 1500 GeV, currently the most sensitive measurement for m_X > 1500 GeV and $m_S \lesssim m_X$

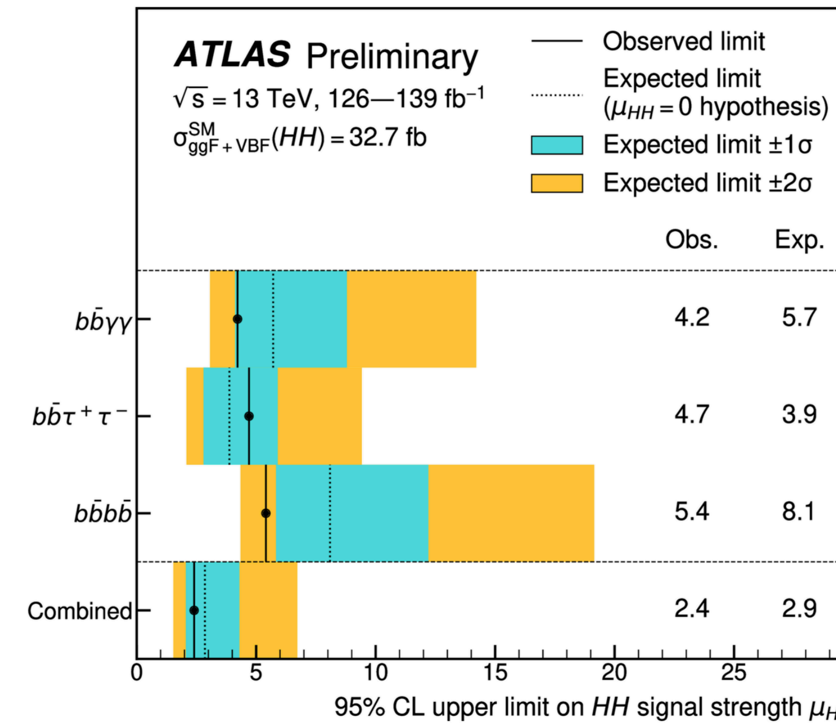
2× 6×

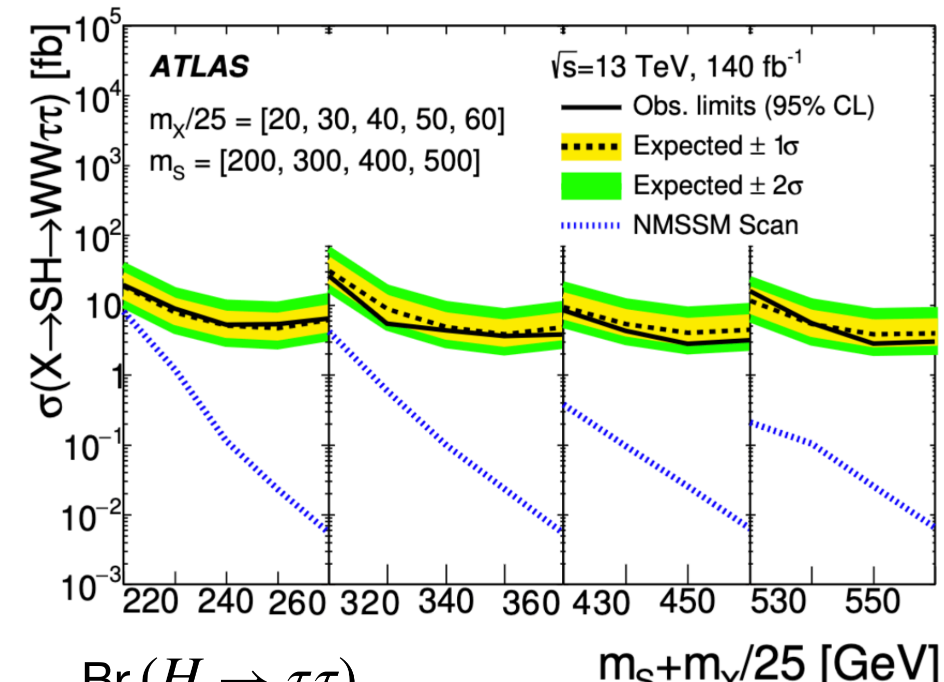
$$300 \times \sigma_{SM} \longrightarrow 150 \times \sigma_{SM} \longrightarrow 25 \times \sigma_{SM}$$

36.1 ifb

Luminosity increase

Analysis optimization





$$\frac{\mathrm{Br}\,(H \to \tau\tau)}{\mathrm{Br}\,(H \to bb)} = 0.107$$

Thesis defence

Backup slides

Data analysis workflow

Motivation: confirm or reject a hypothesis

- Hypothesis → signal process

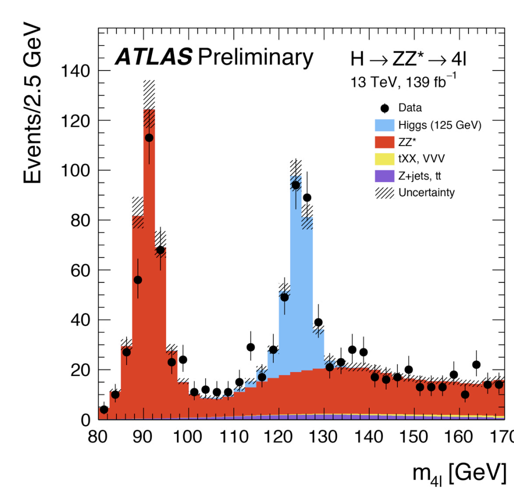
Signal and backgrounds are modelled with MC generator and detector simulation

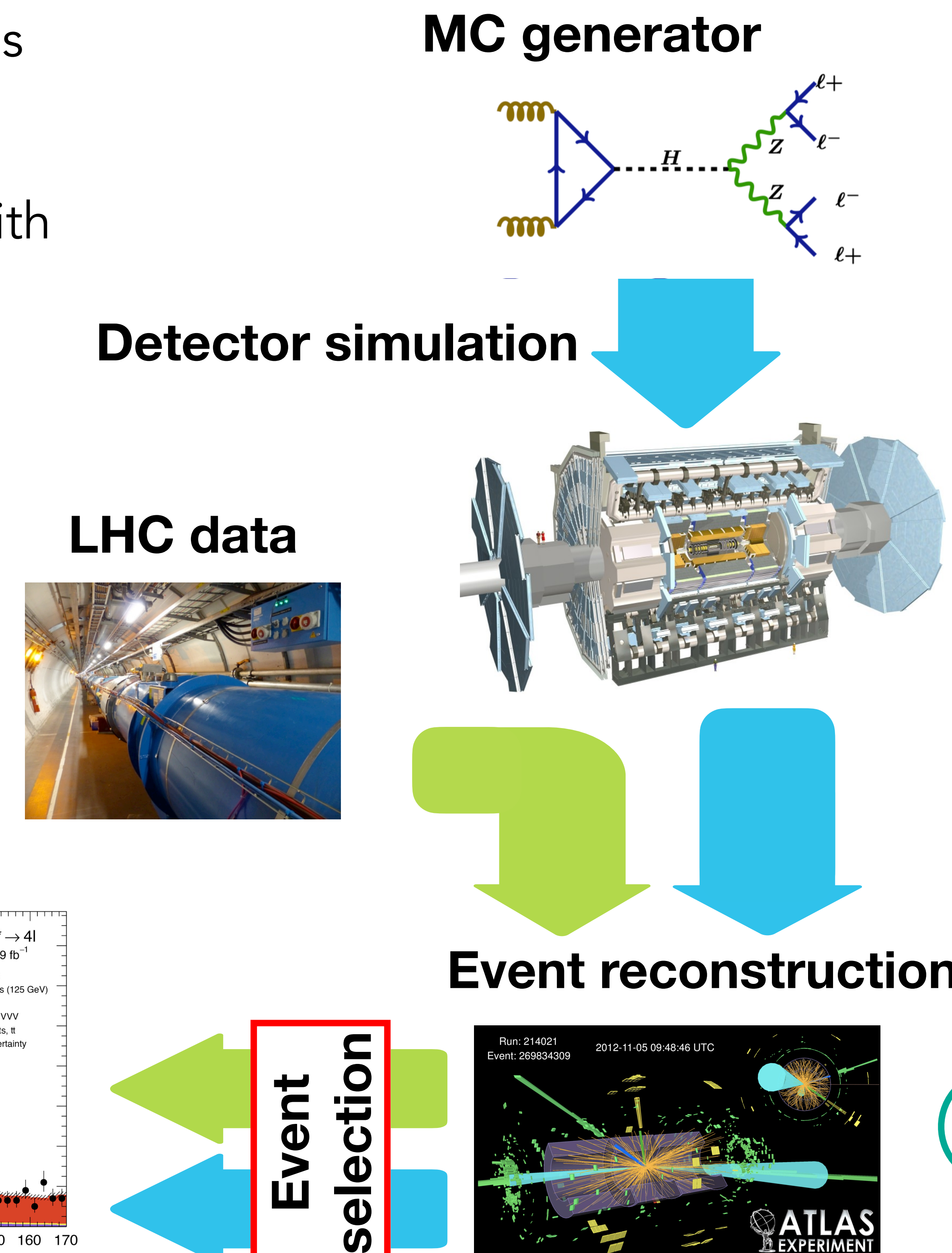
MC events can be processed in the same way as the data:

- Reconstruction: from detector readout to physics quantities
- Event selection: high signal purity region
- Statistical analysis

90 PB of data recorded in one year of operation of the LHC experiments

Simulation of billions of events





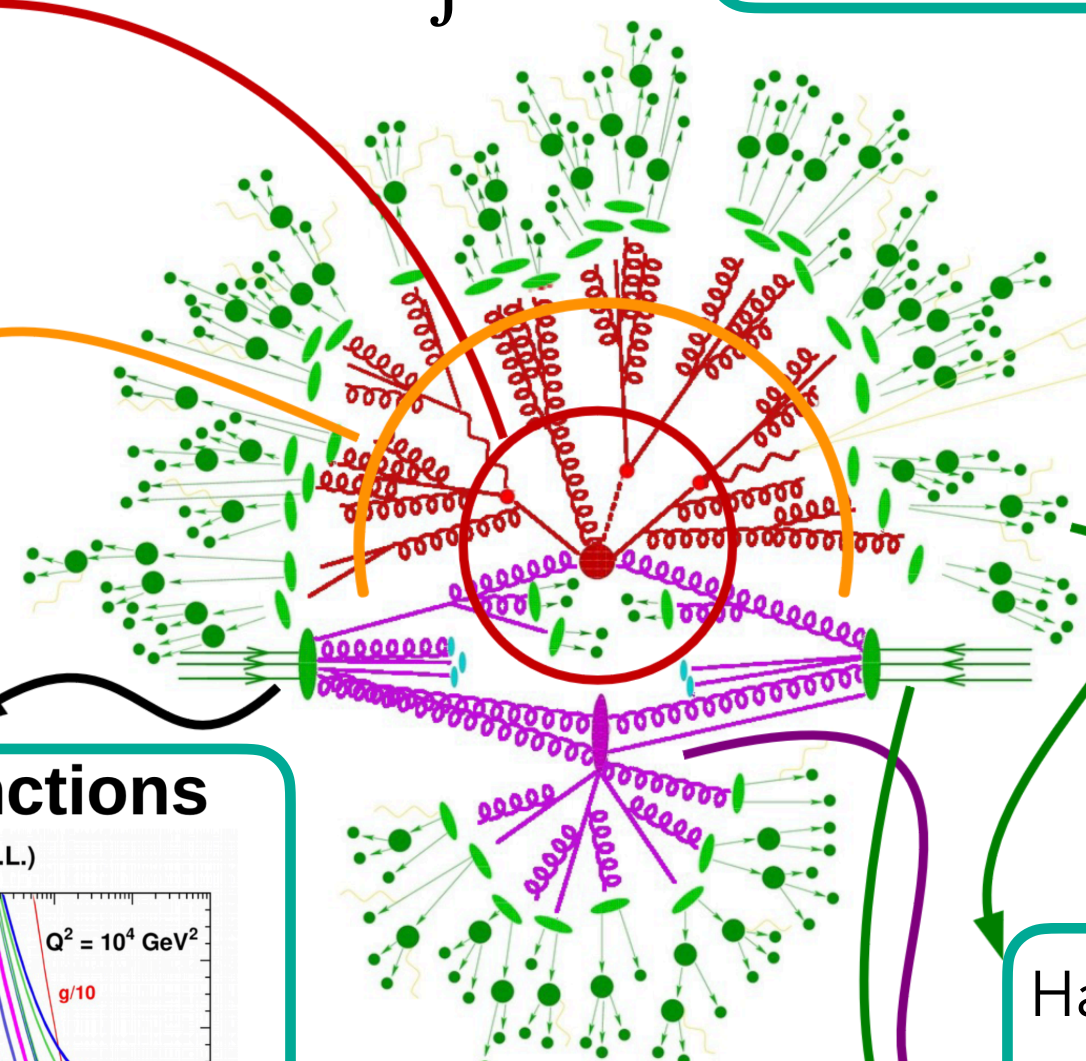
MC simulation

Perturbative QCD

$$\sigma_{pp\to X} = \int \mathrm{d}x_a \, \mathrm{d}x_b \, f_a(x_a, \mu_F) f_b(x_b, \mu_F) \, \sigma_{ab\to X}(x_a, x_b)$$

Hard interaction
- Fixed order (Powheg, aMC@NLO, …)

Parton shower
- Initial state
- Final state



Detector response

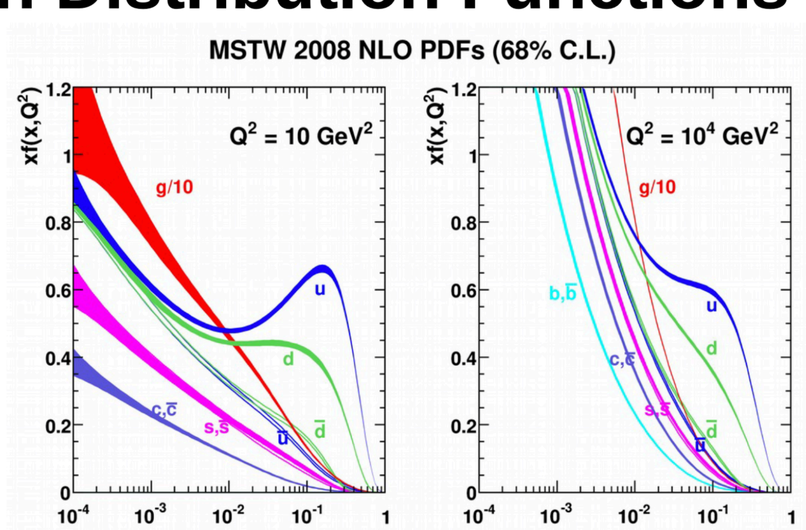
Geant4 simulation

Digitisation (pile-up, readout electronics, …)

Non-perturbative QCD

- Hadronisation
- Beam remnants
- Primordial k_t

Parton Distribution Functions (PDF)



Slide adapted from the talk by Stefano Camarda

SH theoretical models

Complex two-Higgs doublet:

- Most general CP-violating two Higgs doublet model, softly-broken $\mathbb{Z}_2$ symmetry
- Scalar sector – 3 spin-0 mass states, (hi with no definite CP) + charged Higgs.

Next-to-minimal supersymmetric SM:

- The standard SUSY two Higgs doublets + complex superfield
- NMSSM Higgs sector - 3 neutral CP-even, 2 neutral CP-odd and 2 charged Higgs bosons
- CP-conserving

Two-Higgs doublet + complex scalar:

- The additional singlet enters the neutral Higgs sector and mix with both CP-even and CP-odd sectors

Next-to-minimal two-Higgs doublet:

- CP-conserving 2HDM extended by a real scalar singlet field
- Scalar sector – 3 CP-even states, 2 CP-odd neutral scalars + charged scalars
- Charged and pseudoscalar remain unchanged w.r.t. 2HDM

Higgsness & Topness

- Higgsness and Topness had old sigma values from truth distributions in last iterations.
  New values from fits on reco distributions were not applied in the code by mistake
- Updated also the definition of Higgsness variable adding the $H \to bb$ information, increasing the separation power:

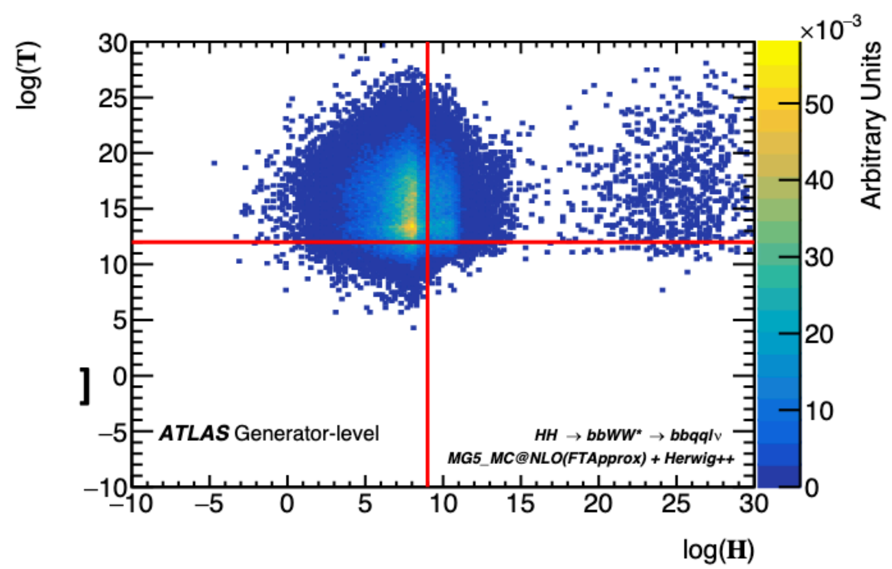
$$H = \min_{p_z^\nu}\left[\frac{\left(m_{bb}^2 - m_H^2\right)^2}{\sigma_{Hbb}^4} + \frac{\left(m_{l\nu qq}^2 - m_H^2\right)^2}{\sigma_{HWW}^4} + \min\left(\frac{\left(m_{l\nu}^2 - m_W^2\right)^2}{\sigma_W^4} + \frac{\left(m_{qq}^2 - m_{W^*_{peak}}^2\right)^2}{\sigma_{W^*}^4}, \frac{\left(m_{qq}^2 - m_W^2\right)^2}{\sigma_W^4} + \frac{\left(m_{l\nu}^2 - m_{W^*_{peak}}^2\right)^2}{\sigma_{W^*}^4}\right)\right]$$

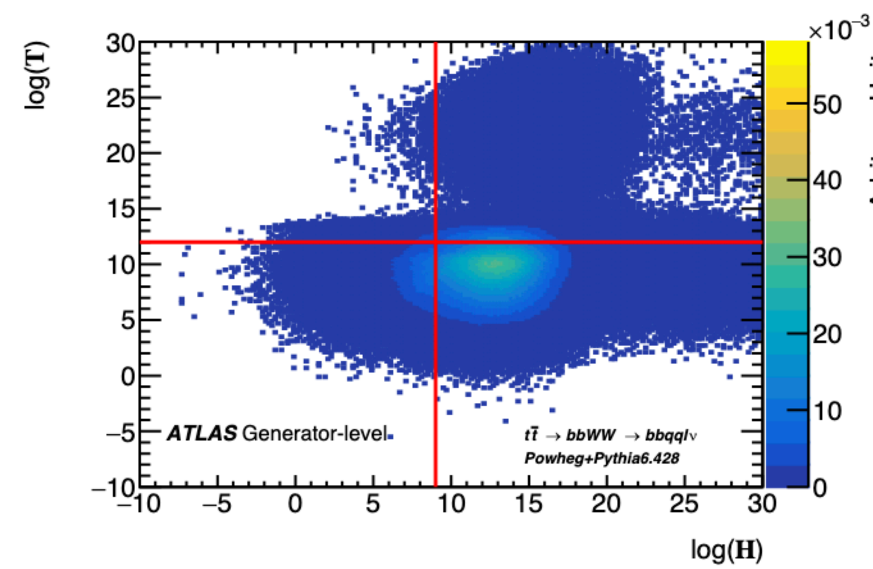
new

- Updated sigmas applied and DNN retrained, as Higgsness and Topness are input features:
  - $\sigma_{top} = 30\ GeV$
  - $\sigma_W = 15\ GeV$
  - $\sigma_{W^*} = 18\ GeV$
  - $\sigma_{Hbb} = 16\ GeV$
  - $\sigma_{HWW} = 21\ GeV$

In this case obtained from a scan optimising the separation of the Higgsness variable using the Jeffrey's distance variable:

$$Jeffrey's\ distance = \sum_k \left|\sqrt{s_k} - \sqrt{b_k}\right|^2$$



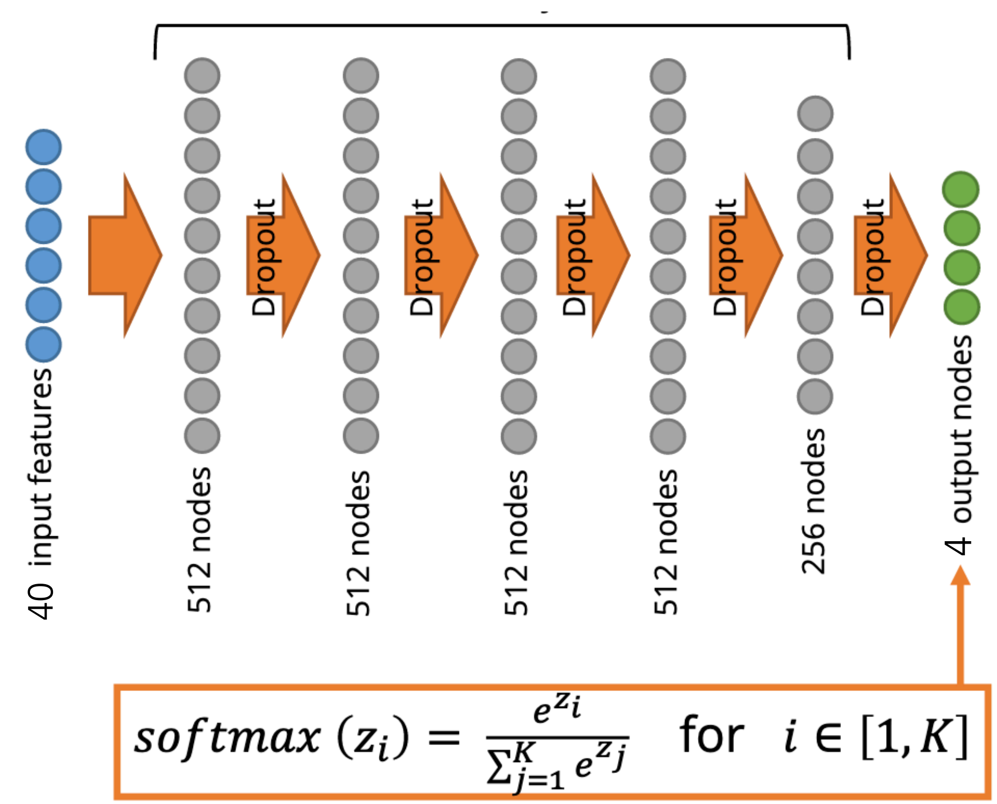


[ATL-PHYS-PUB-2019-040]

- Updated also the cut on Topness to build the dHHTopnessVR consequently to have $< 1\%$ of the signal, as in the previous definition of the region. Updated cut is now: $\boldsymbol{log(T) < 4}$ (was < 10)

DNN classifier

- DNN model trained with signal (separately for HH and SH), $t\bar{t}$, single-top and W+jets
- The choice of the neural network topology and activation was made keeping the highest test accuracy
- Multiclass DNN architecture: 5 hidden layers (4x512+256 nodes), ReLu activation function, 4 output scores, interpreted as probabilities for the four processes
- Dropout rate = 0.5 between each layer
- Batch size = 64, Adam optimizer (lr=0.0001)
- 40 features used in the classifier:



- m, p_T, η, ϕ, charge of the lepton
- p_T, η, ϕ of the 2 b-jets
- p_T, η, ϕ of the 3 leading light jets
- Higgsness, Topness
- MET, ϕ_{MET}, N_j
- $\Delta\phi^{max}_{MET,b}$, $\Delta\phi^{min}_{MET,b}$
- $m_{T\ell\nu}$, $\Delta\phi_{\ell\nu}$
- $\Delta R^{min}_{\ell j}$, $\Delta R^{max}_{\ell j}$
- m_{bb}, $\Delta\phi_{bb}$, ΔR_{bb}
- m_{TWW}, m_{THH}
- $\Delta R^{min}_{\ell b}$, $\Delta R^{max}_{\ell b}$
- Loglttbar, Logldihiggs