Search for a charged Higgs ($H^{\pm}$) in the $W\,h$ ($h \rightarrow b\bar{b}$) boosted channel using multivariate methods with the ATLAS experiment

Master's Thesis Project

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10th September, 2026

FSP ATLAS
Erforschung von Universum und Materie

Content

- ❑ Introduction
- ❑ Event selection and categorisation
- ❑ Baseline analysis: deep neural network (DNN) and m_{Wh} fit

Following previous ATLAS analysis: arXiv:2411.03969

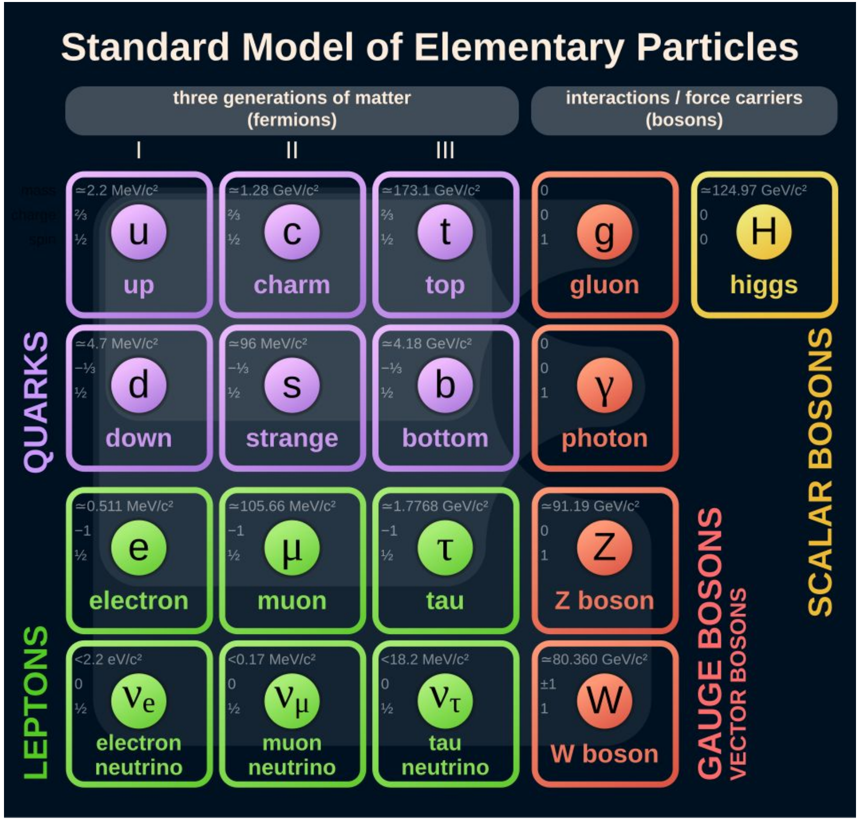
- ❑ Parameterized neural network (PNN) and fit on NN output score
- ❑ Comparison of exclusion limits on signal cross section obtained using PNN and DNN (statistics-only)

The Standard Model

- ❖ Well tested model explaining the fundamental interactions of matter.
- ❖ Incorporates special relativity and quantum mechanics.
- ❖ Valid over a huge energy range (eV to TeV).
- ❖ Last missing particle discovered in 2012 (Higgs) 

Some limitations:

- ❖ Matter-Antimatter asymmetry
- ❖ Dark Matter
- ❖ Mass-Hierarchy problem
- ❖ Gravity

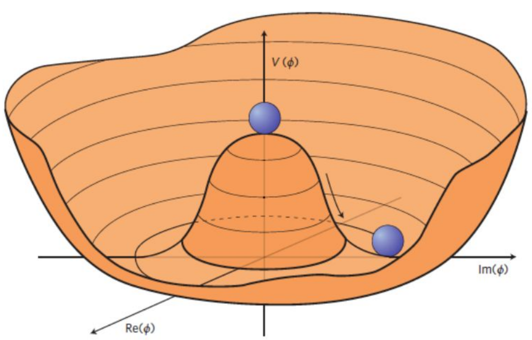


Wikimedia, Standard Model, (2016), url: https://en.wikipedia.org/wiki/File:Standard_Model_of_Elementary_Particles.svg

Higgs and extended scalers

Standard Model

One scaler $SU(2)_L$ doublet ϕ



$\mu<0$, $<\phi>\neq 0$
-> Spontaneous Symmetry breaking

$$V(\phi) = \mu^2|\phi|^2 + \lambda|\phi|^4$$

$$\phi(x) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

$$v = 246 \text{ GeV}$$

Why extend the scalar sector?

Incorporates CP-violation

Addresses Hierarchy

Connects to BSM

A simple and well motivated extension of the SM

Two doublet Higgs Model

Addition of a scalar doublet: ϕ_1 and ϕ_2

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

$$\langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1 \end{pmatrix} \qquad \langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

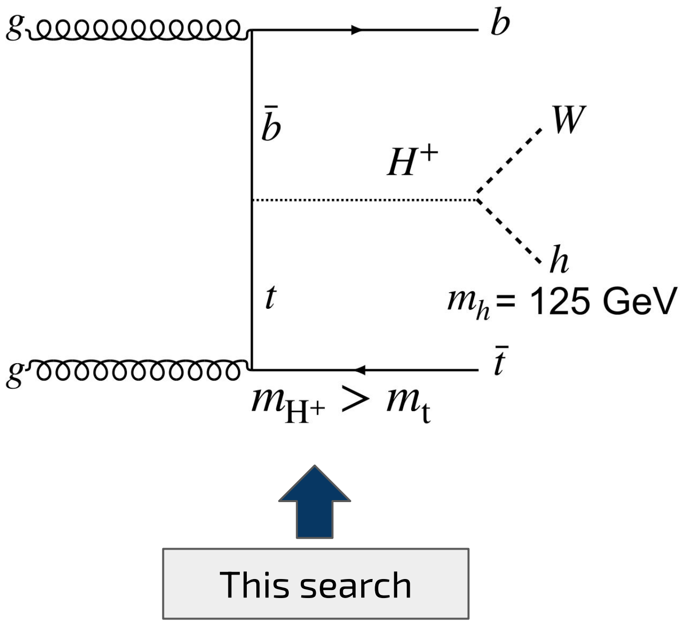
$$\tan\beta = \frac{v_2}{v_1}$$

$$\underbrace{v = \sqrt{{v_1}^2 + {v_2}^2} = 246 \text{ GeV}}_{\text{Type II considered for this analysis}}$$

2HDM and charged Higgs

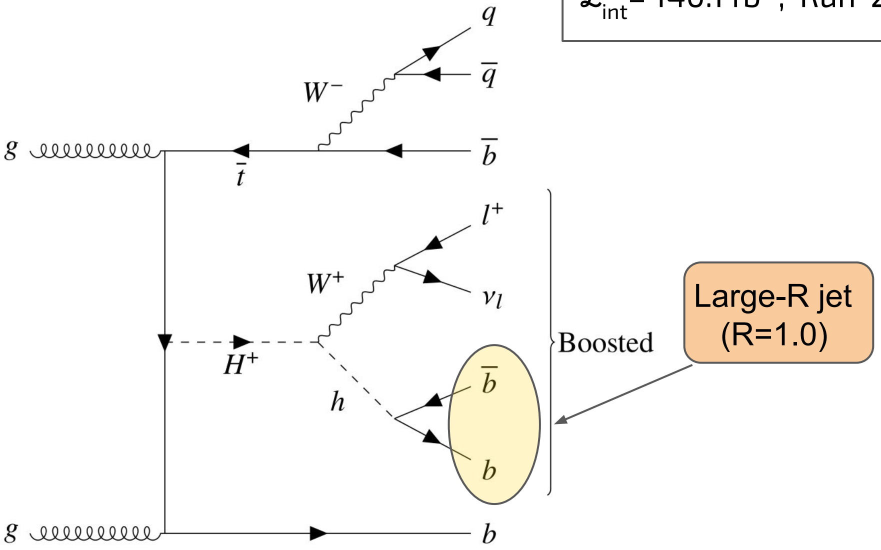
- 2HDM leading to 5 physical states after EWSB:
  - h(light),
  - H(heavy), (CP-Even)
  - A (CP-Odd)
  - **$H^{\pm}$ (charged Higgs Bosons).**

In Type II:
$tbH^{\pm}$ coupling $\propto m_b \tan\beta + m_t \cot\beta$
-> sizeable production

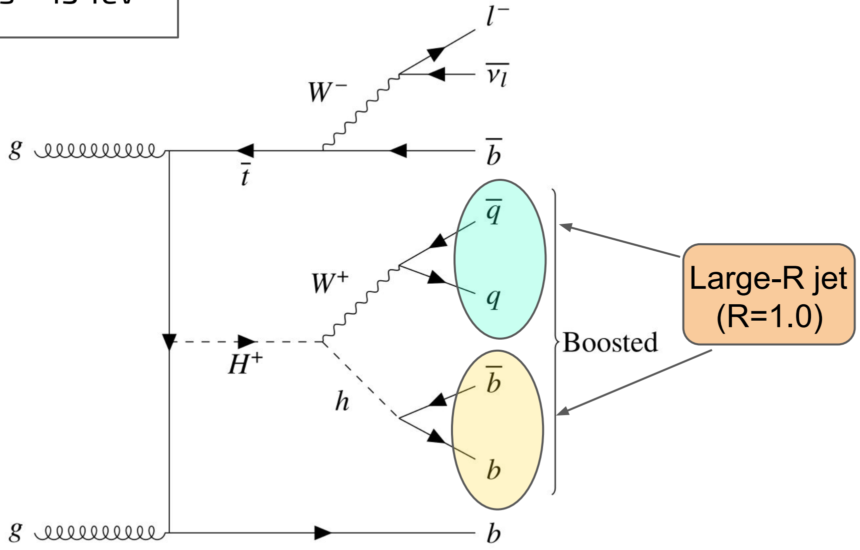


Signal Topology

$\mathcal{L}_{int}$ = 140.1 fb^{-1}, Run-2 , $\sqrt{s}$ = 13 TeV



ℓvbb channel

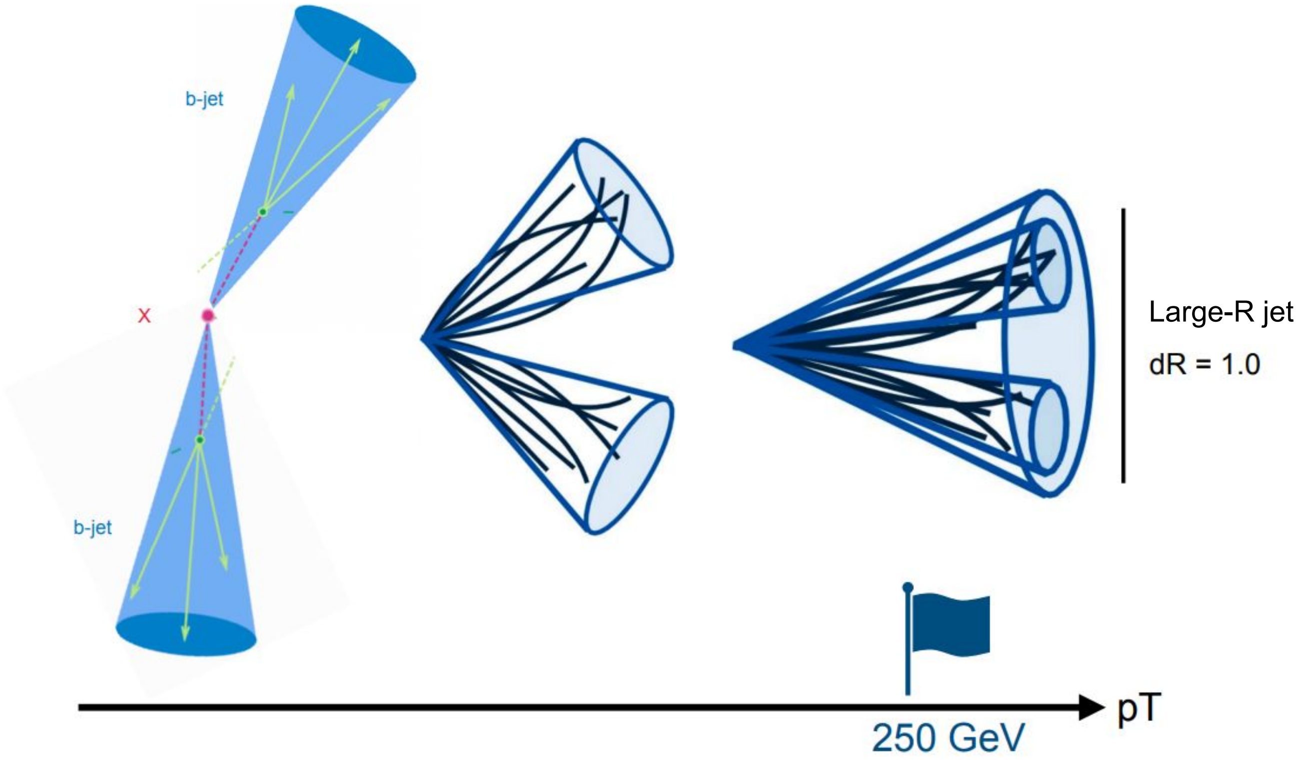


qqbb channel

Signal mass hypothesis studied : [1.2, 1.4, 1.6, 1.8, 2.0, 2.5, 3.0] TeV

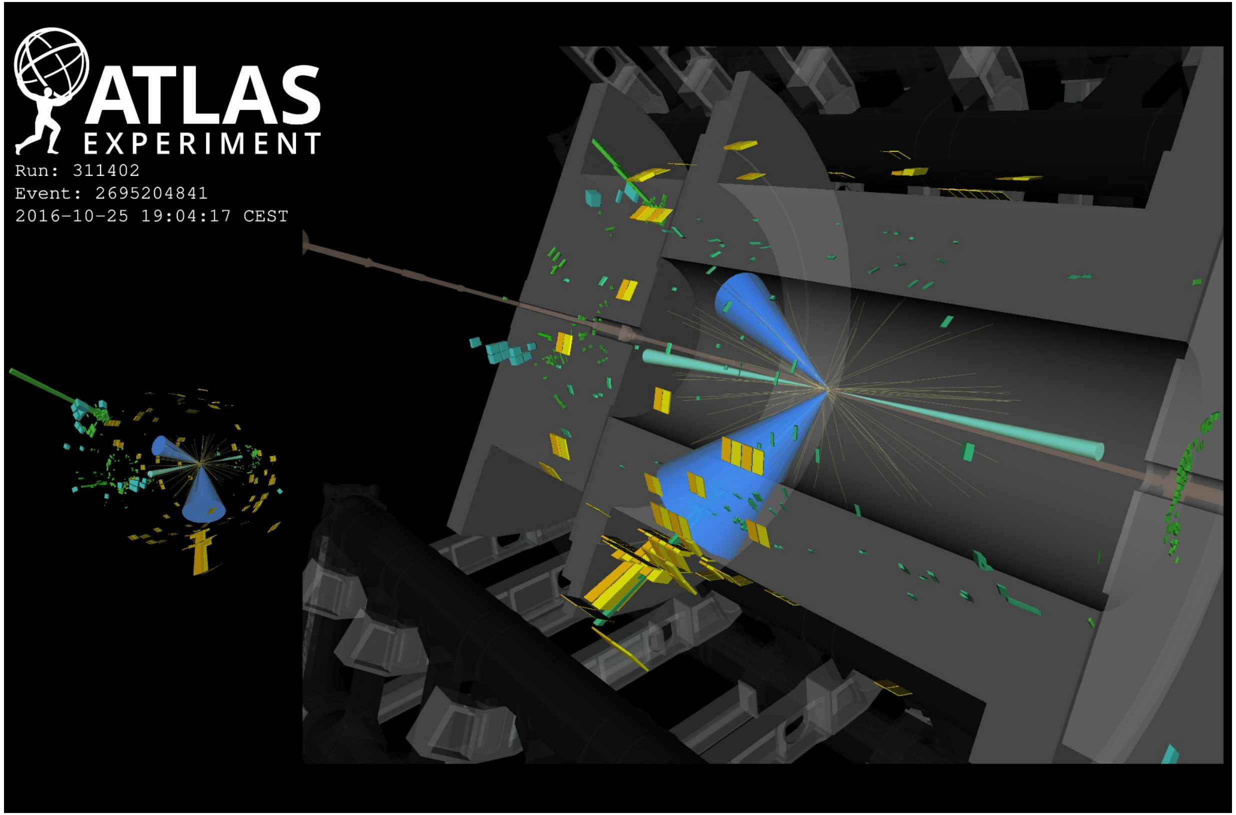
Leading backgrounds: $t\bar{t}$ + LF jets, $t\bar{t}$ + HF jets, W/Z + jets

How $h \to b\bar{b}$ actually looks like?

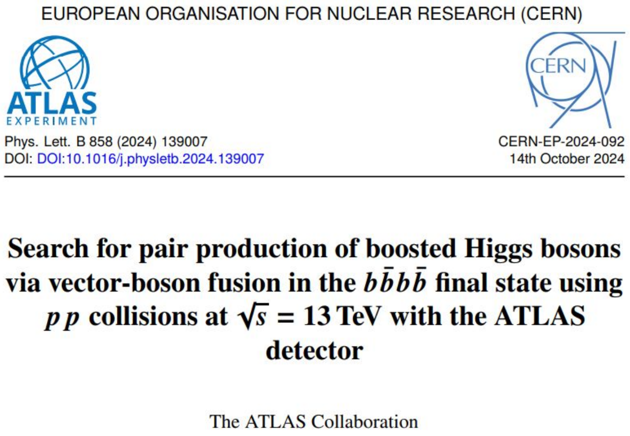


$$\Delta R \approx \frac{2m}{p_T}$$

How $h \to b\bar{b}$ actually looks like?



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2022-02/index.php



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Phys. Lett. B 858 (2024) 139007
DOI: DOI:10.1016/j.physletb.2024.139007

CERN-EP-2024-092
14th October 2024

Search for pair production of boosted Higgs bosons via vector-boson fusion in the $b\bar{b}b\bar{b}$ final state using pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration

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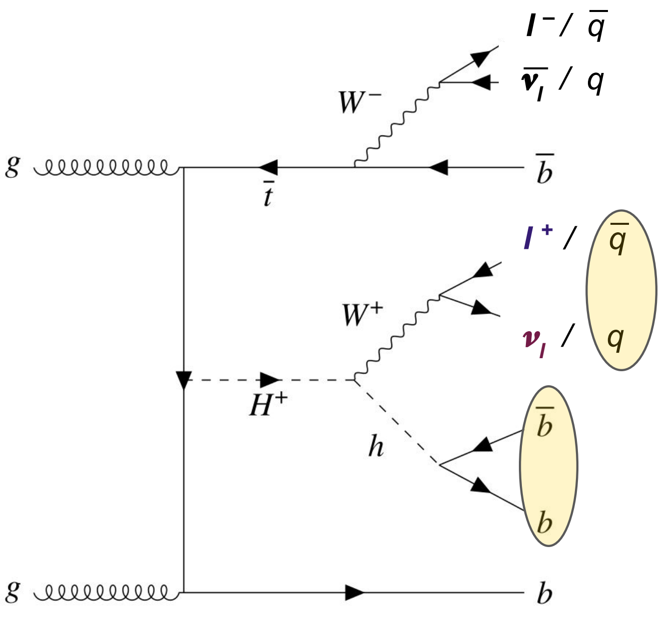
Event selection and categorization

Event Selection:

- **Trigger:** pass at least one of the single e/μ triggers.
- **Missing transverse momentum:** E_T^{miss} > 30 GeV
- **Leptons:** Exactly one e or μ with p_T > 27 GeV
- **Large-R jets** ≥ 1 (p_T≥ 250 GeV)
- **Exactly one Large-R jet** passing the **60% working point** of the **Higgs-Tagger***.
- **Overlap removal: Small-R jets** considered to be **b-tagged** if they satisfy ΔR>1.4 from the **Large-R jet**

B-tagging working point: 77%



Categorization:

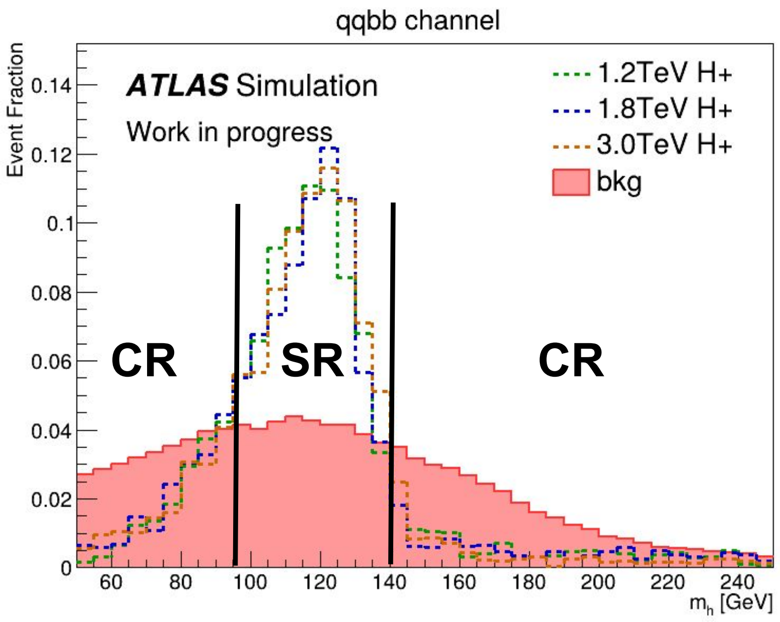
Channel	Large-R jets	W boson candidate	Higgs candidate
qqbb	**≥ 2**	***Fails $X \to b\bar{b}$ tagging 50 GeV ≤ M_J ≤ 110 GeV***	$X \to b\bar{b}$
ℓvbb	**≥ 1**	W_{lep}	$X \to b\bar{b}$

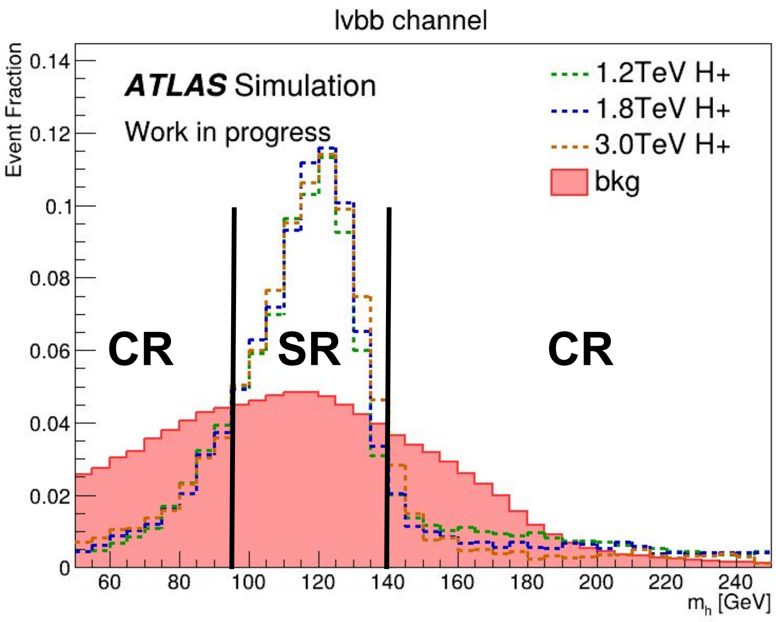
* M_J: Jet Mass

*ATL-PHYS-PUB-2020-019

Signal and Control Regions

- **Signal region**: 95 GeV ≤ m_h ≤ 140 GeV
- **Control region**:
  - **Lower sideband**: m_h < 95 GeV
  - **Higher sideband:** m_h > 140 GeV



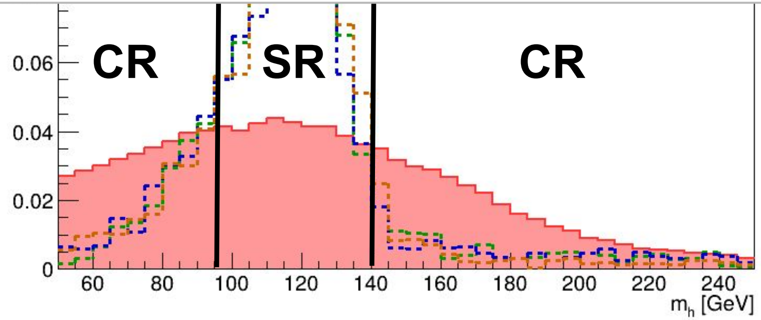


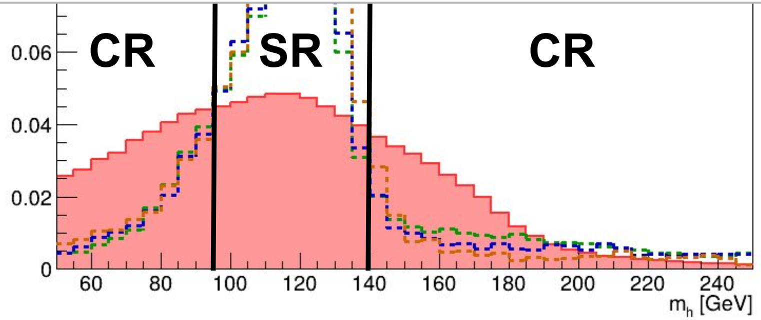
Signal and Control Regions

- **Signal region**: 95 GeV ≤ m_h ≤ 140 GeV
- **Control region**:
  - **Lower sideband**: m_h < 95 GeV
  - **Higher sideband:** m_h > 140 GeV

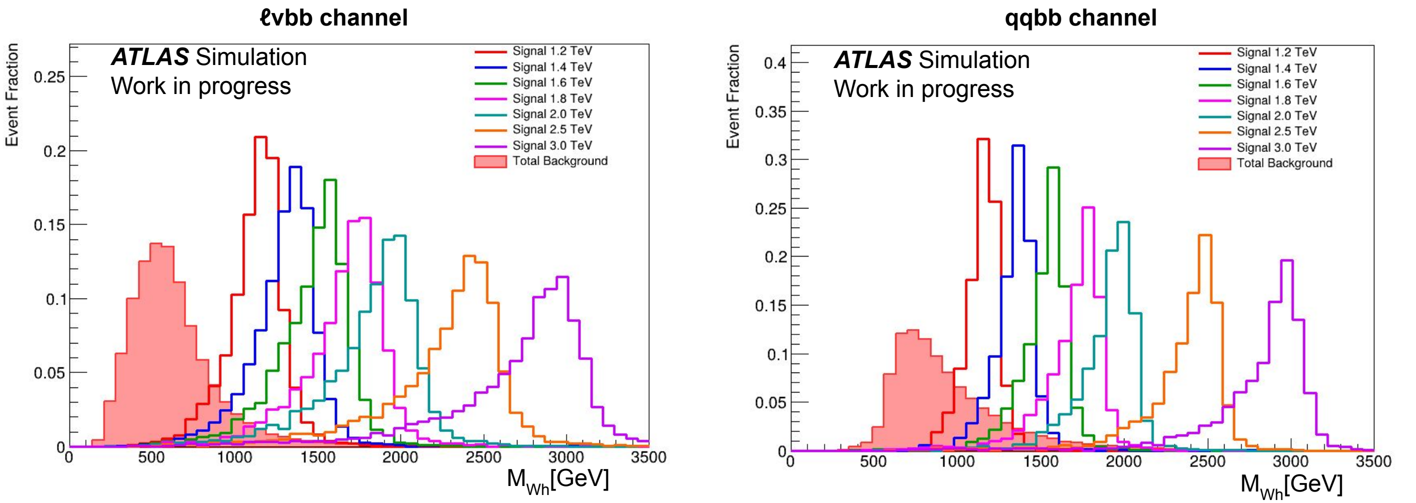
- Further division based on the number of small radius b-tagged jets outside Large-R jets.
- Additional division into two regions: **0 b-tagged, ≥1 b-tagged.**
- **Signal regions** are further divided into
  - High nn score
  - Medium nn score
  - Low nn score

  after using a DNN for event S vs B classification





M_{Wh} as a fit variable



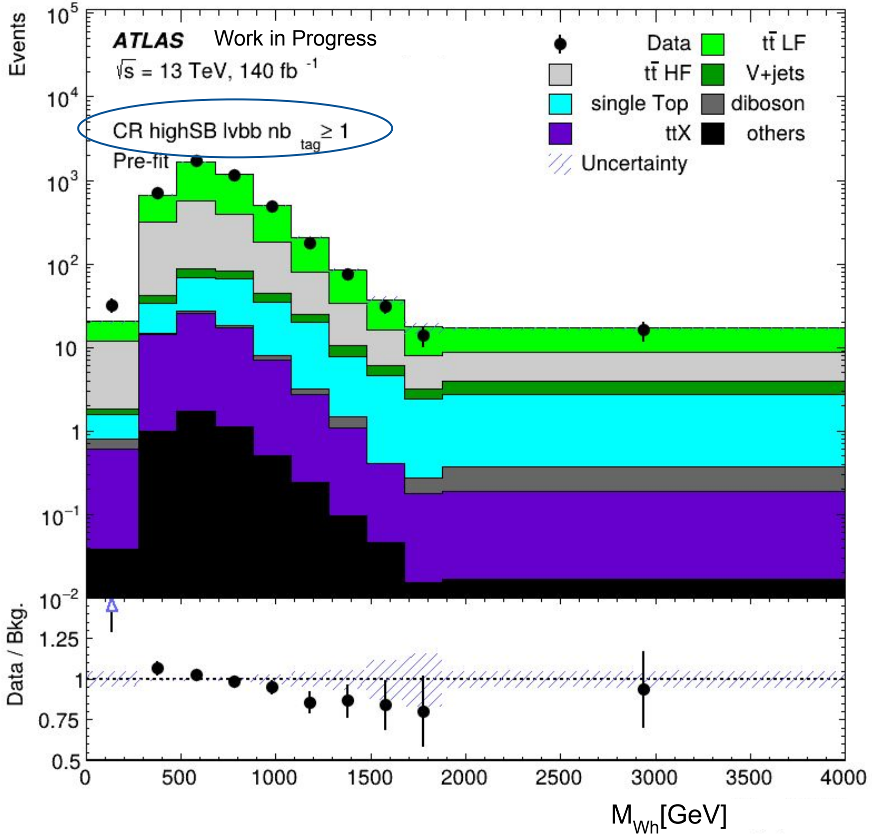
Clear separation between the signal distributions and the total background

- Normalization factors for **$t\bar{t}$ + LF, $t\bar{t}$ + HF , W/Z + jets** -> **free parameters**
- **Background-only fit to data in control regions** -> for obtaining the normalization factors.
- Simultaneous **Signal + Background blinded fit** in all **signal** and **control** regions to obtain the **signal strength parameter (μ)** and **upper limits on ($\sigma \times$ BR).**
- Both **qqbb** and **ℓvbb** channels included in the fit setup.

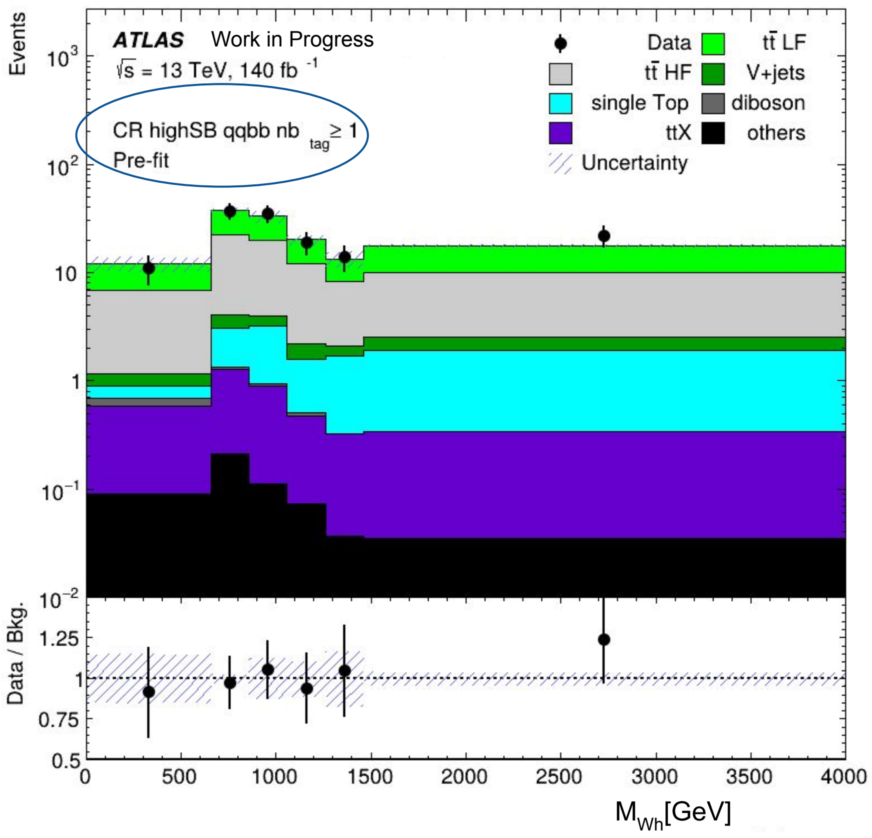
Fit Setup

M_{Wh} MC-data Agreement in CR

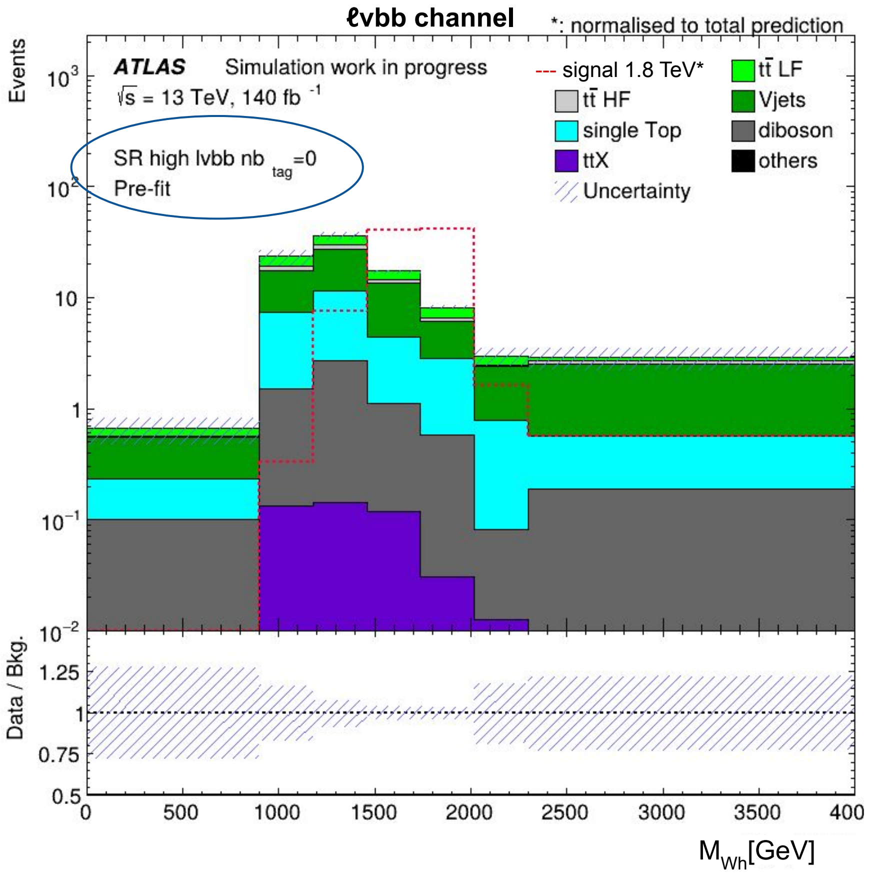
ℓvbb channel

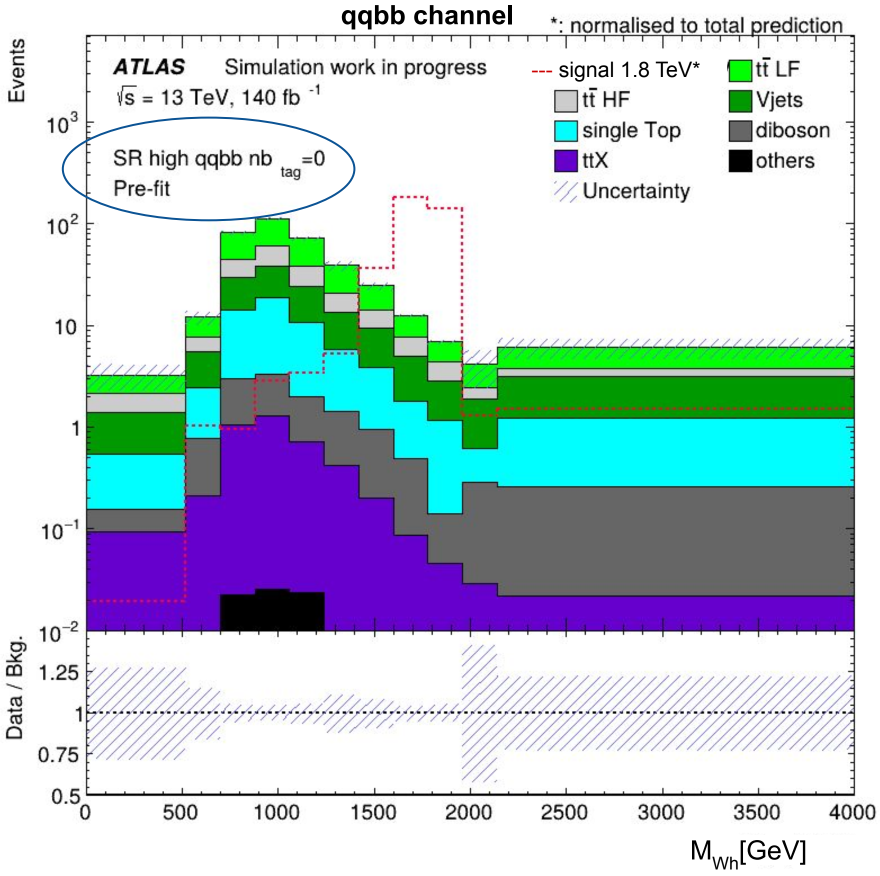


qqbb channel



M_{Wh} distribution in SR (Blinded)





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Following previous ATLAS analysis: arXiv:2411.03969

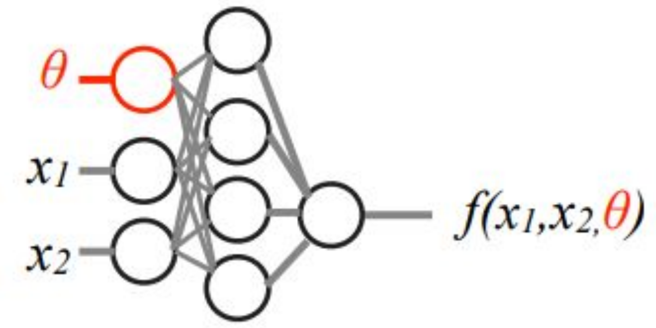
PNN for event classification

PNN for improved sensitivity

- ❖ Identical Neural network structure as DNN
- ❖ Additional input: **true $H^{\pm}$ mass** as parameter.
  Signal: True $H^{\pm}$ mass
  Background: Random $H^{\pm}$ mass from considered hypotheses
- ❖ Advantages: smooth interpolation

Two Approaches chosen:

- ❖ Trained a PNN with the same DNN setup and variables: **yielded minimal improvement (PNN 1)**
- ❖ Training a PNN with a combination of new inputs and old inputs and a more optimized network **(PNN 2)** → up-ahead



Baldi, Pierre, et al. arXiv:1601.07913 (2016).

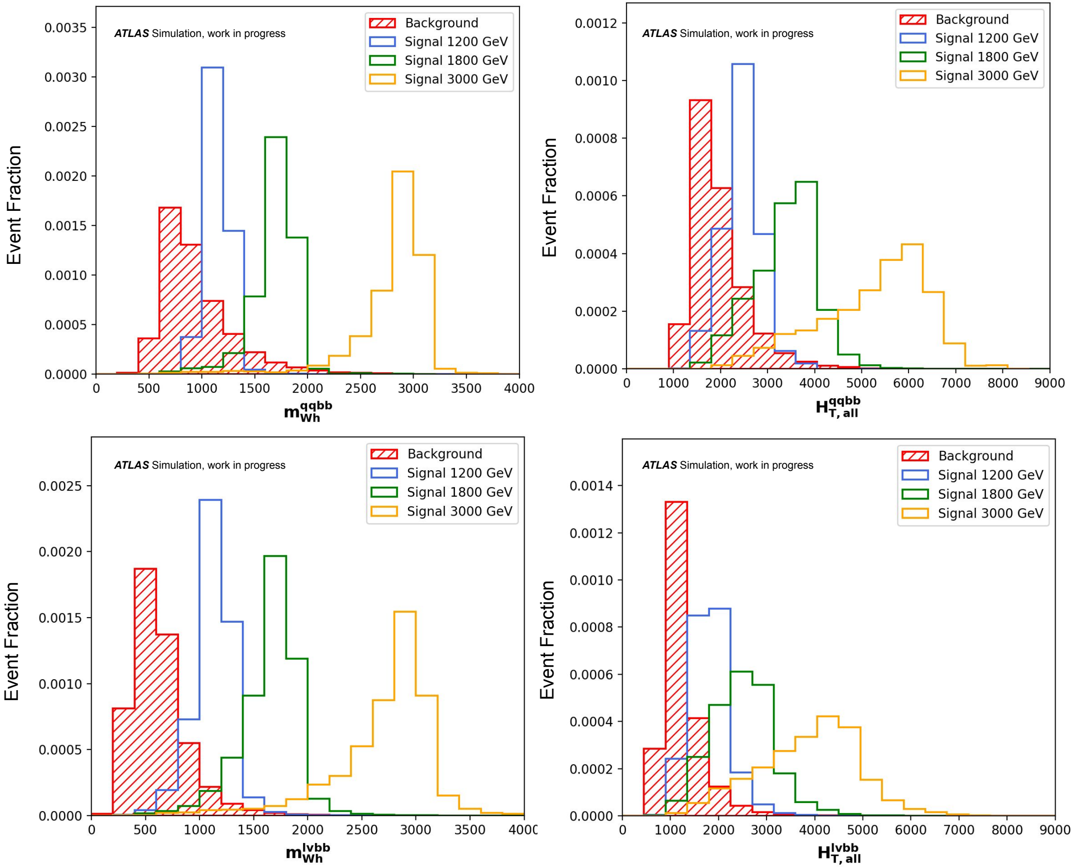
Caveat: the PNN score is mass-dependent. Therefore, both signal and background events are re-evaluated at each mass point, giving a different score distribution for each hypothesis.

PNN-2 input features and optimization

- Best input features selected using **mass-normalized permutation importance**. (More in back-up)

- **Most sensitive variable: reconstructed charged Higgs mass**

- Hyperparameter optimization done using **optuna (Bayesian optimization)** Far efficient than tedious grid and random search.



Data-MC comparison in CR (PNN-2 inputs)

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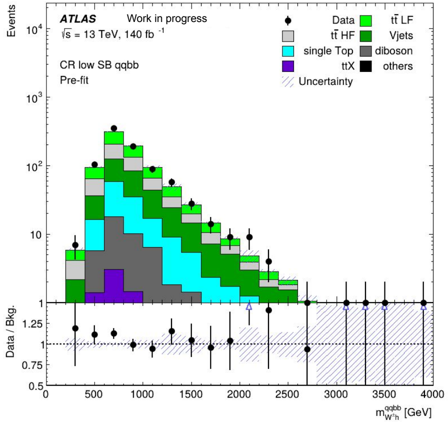
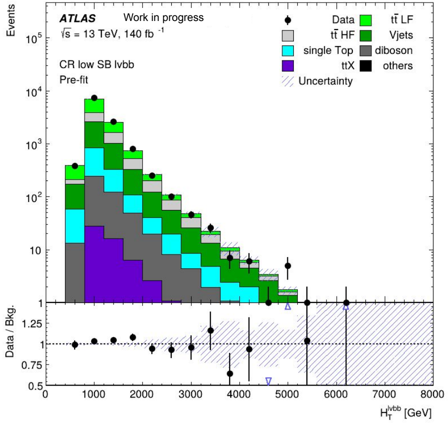
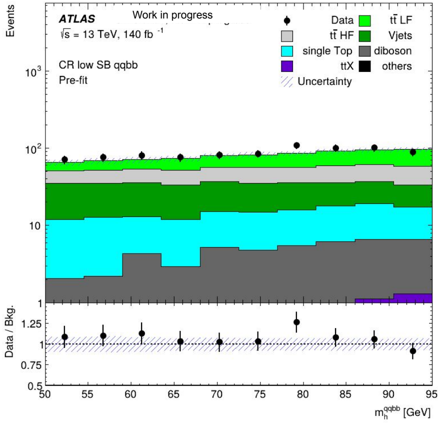
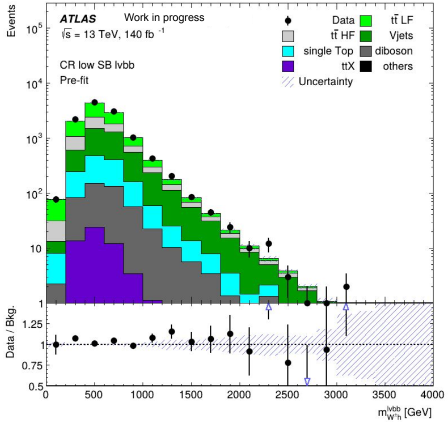
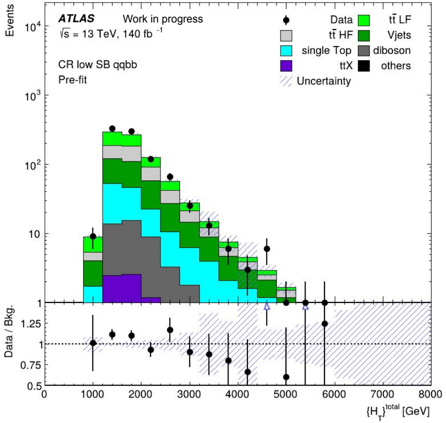
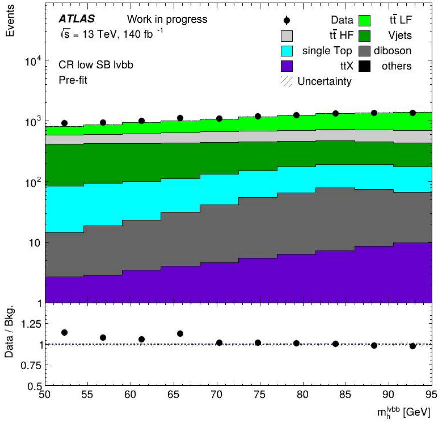
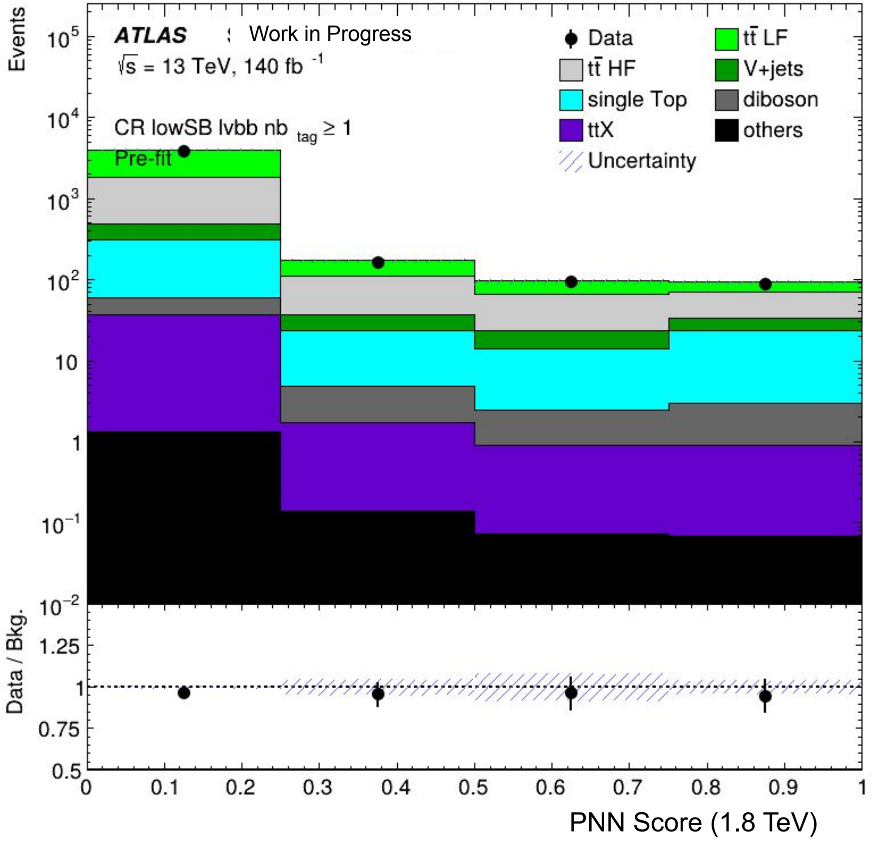
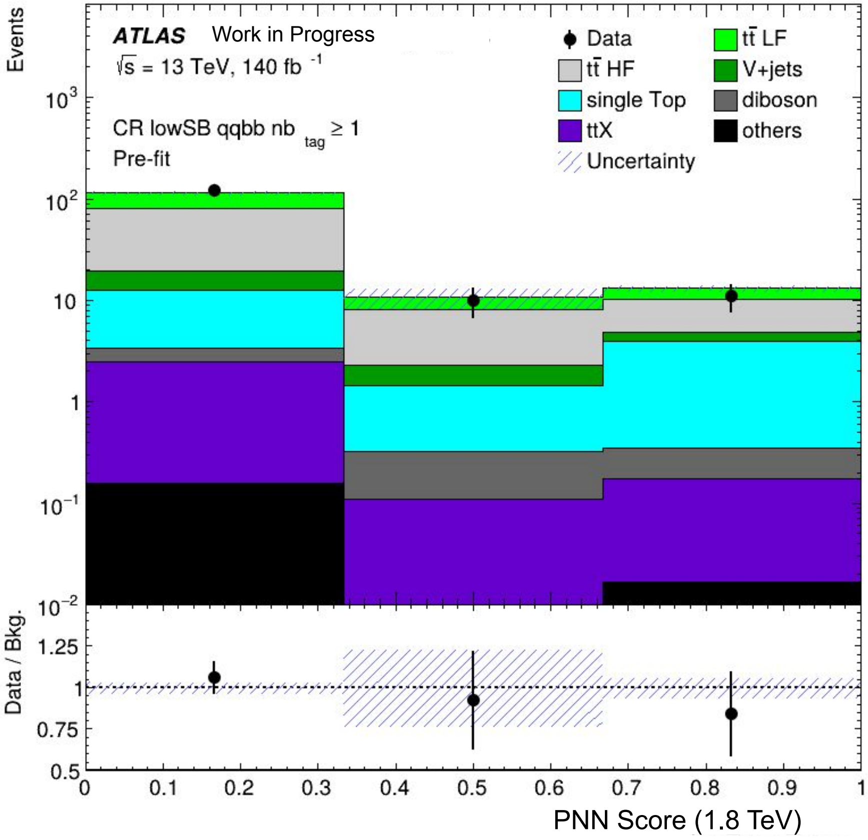
	Reconstructed m_{Wh}	$H_{T,all}$	Reconstructed m_h
qqbb			
ℓvbb			

PNN-2 score MC-data Agreement in CR

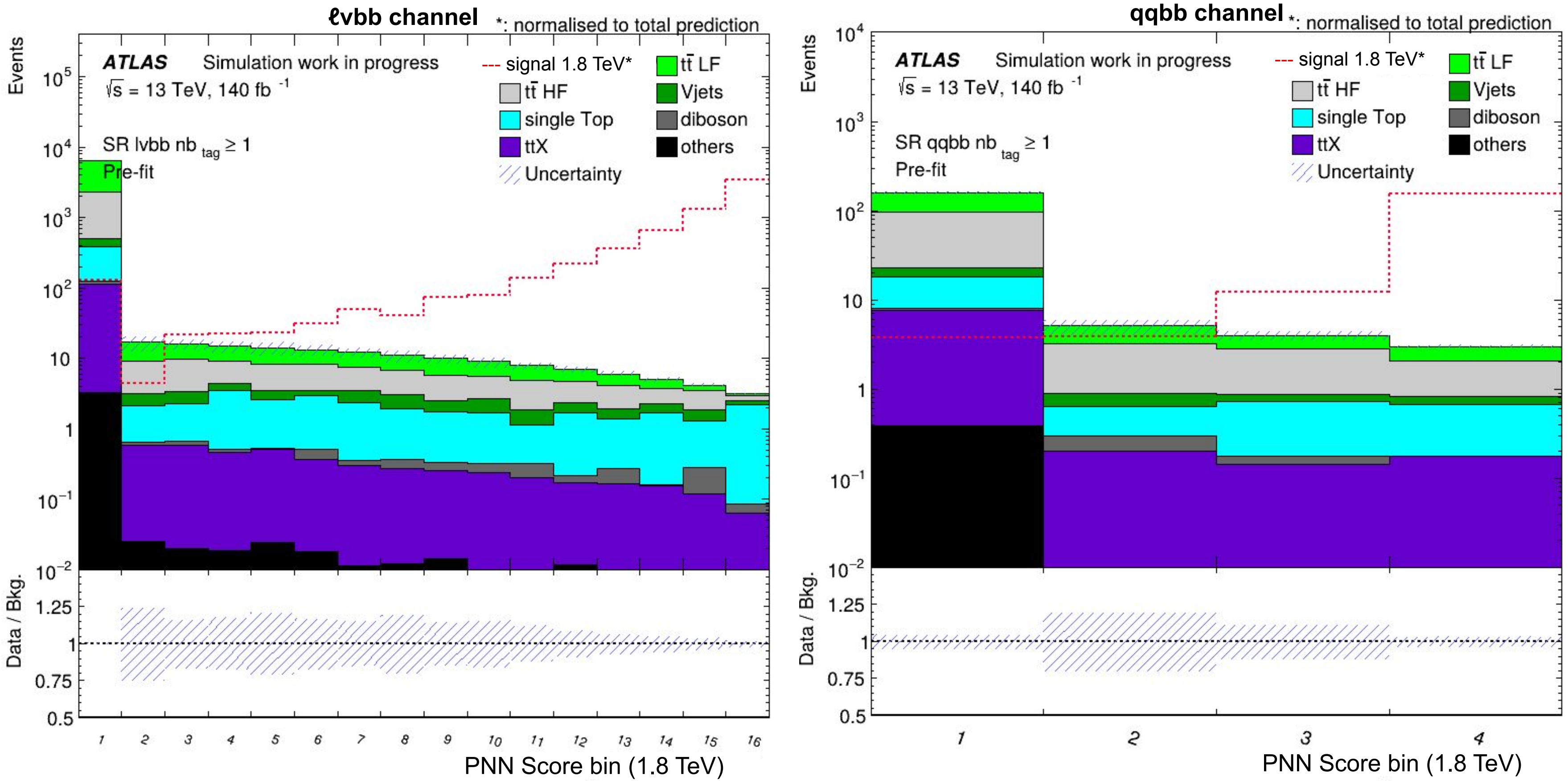
ℓvbb channel



qqbb channel



PNN-2 score distribution in SR (Blinded)



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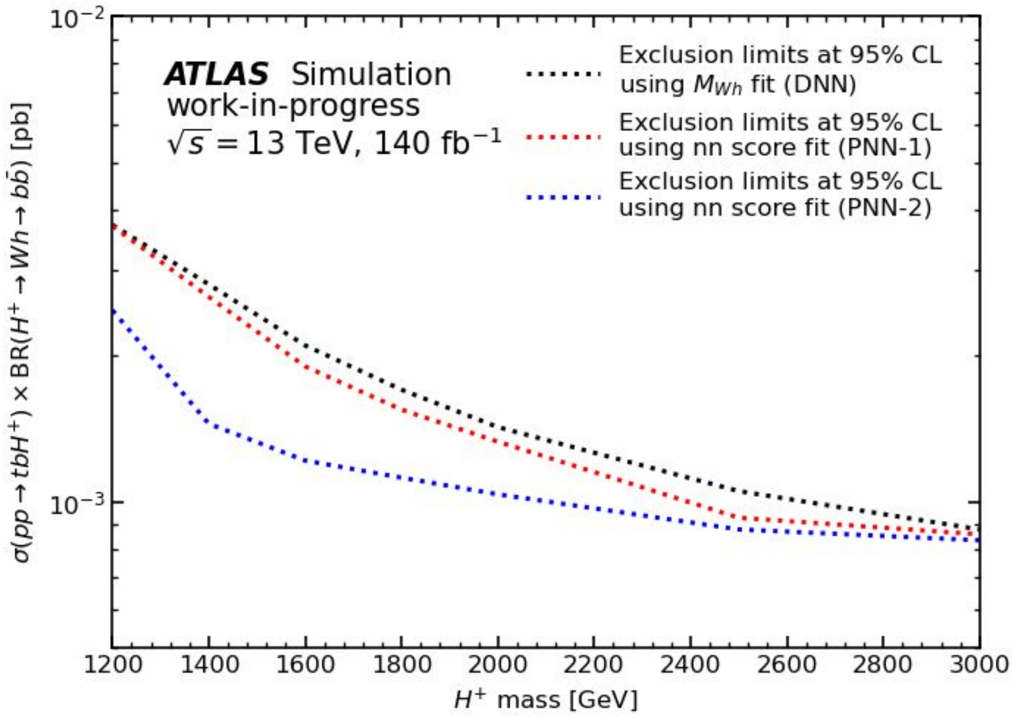
Comparison of exclusion limits

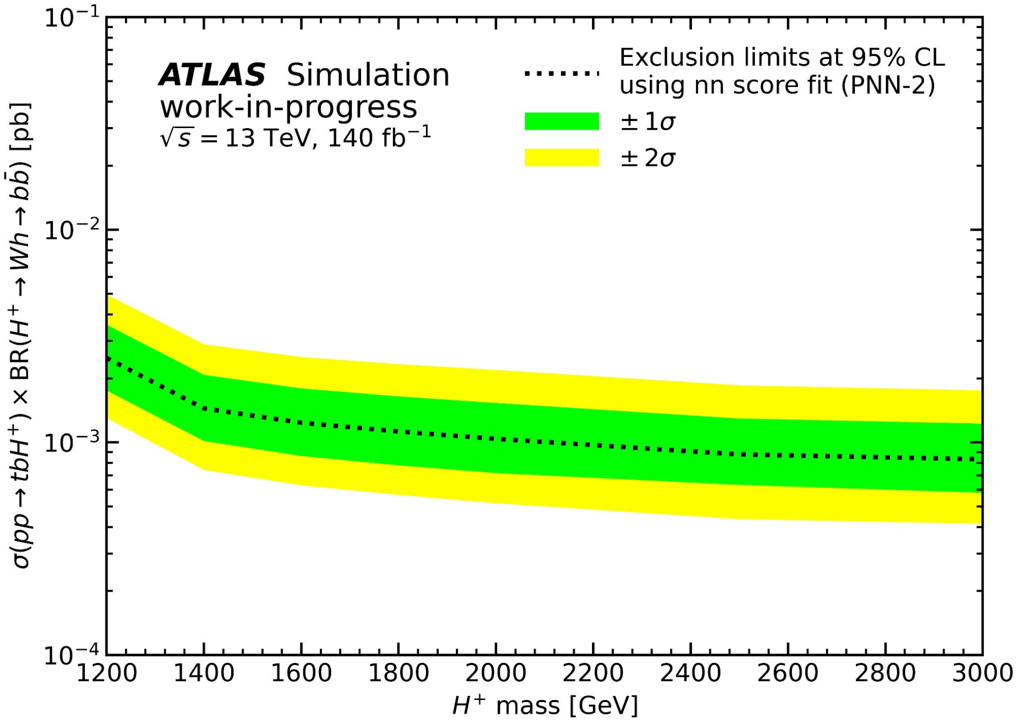
Expected Limits (Statistics-only)



- **DNN** with **M_{Wh} fit** compared to **PNN-1** and **PNN-2** with **nn score fit.**
- **Major improvement** in sensitivity using **PNN-2 with nn score fit** with: **33% (1.2 TeV)**, but only **9% (3 TeV) wrt to DNN.**
- Using **analysis sensitive variables** and fitting on the **PNN output score** improved sensitivity.
- Better exclusion limits compared to **M_{Wh} fit.**

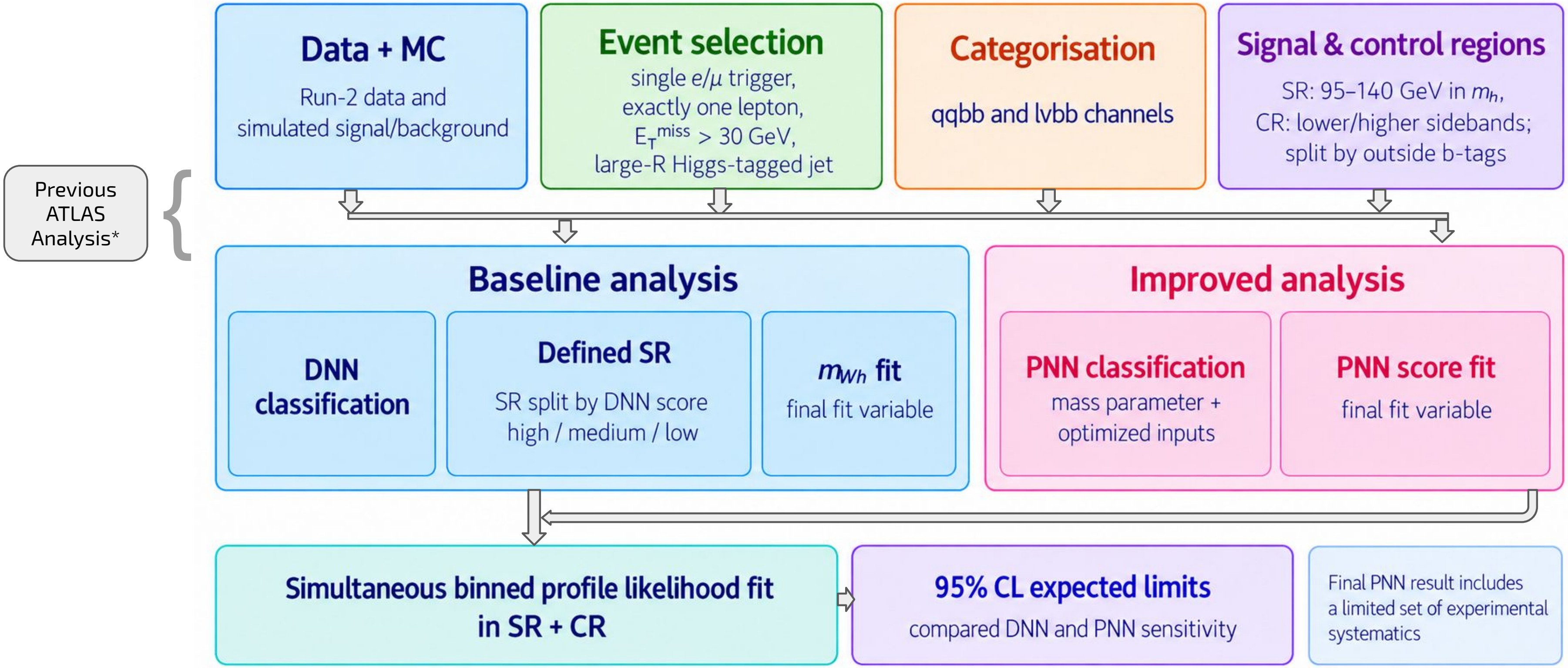
PNN-2 limits including systematics

Expected Limits



- Limited set of instrumental systematics included due to time constraint.
- **Integrated Luminosity** is the dominant one among all. N.F.s enter the fit as nuisance parameters.
- Expected limits worsen by only **0.8% at 1.2 TeV** and **0.1% at 3 TeV**.

Summary


Previous ATLAS Analysis*
Data + MC
Run-2 data and simulated signal/background
Event selection
single e/μ trigger,
exactly one lepton,
E_T^miss > 30 GeV,
large-R Higgs-tagged jet
Categorisation
qqbb and lvbb channels
Signal & control regions
SR: 95–140 GeV in m_h,
CR: lower/higher sidebands;
split by outside b-tags
Baseline analysis
DNN classification
Defined SR
SR split by DNN score
high / medium / low
m_Wh fit
final fit variable
Improved analysis
PNN classification
mass parameter +
optimized inputs
PNN score fit
final fit variable
Simultaneous binned profile likelihood fit
in SR + CR
95% CL expected limits
compared DNN and PNN sensitivity
Final PNN result includes
a limited set of experimental
systematics

Outlook

- Extend PNN-2 with the full set of relevant systematic uncertainties.

- Unblind the PNN-2 analysis and compare its performance directly with the previous ATLAS strategy.

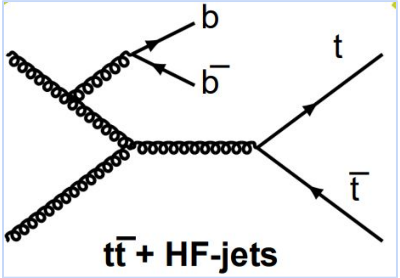
- Explore more unified multivariate approaches across both channels.

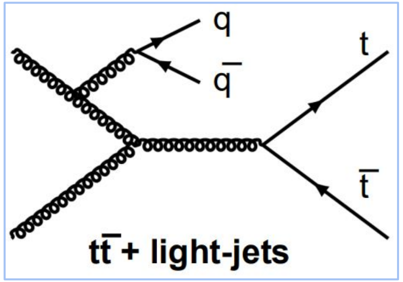
Thank you!

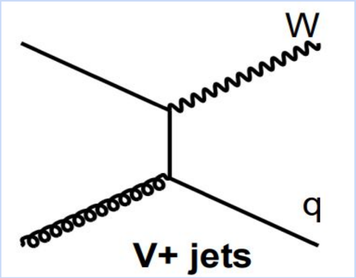
Particle physicists when their latest measurement once again confirms The Standard Model

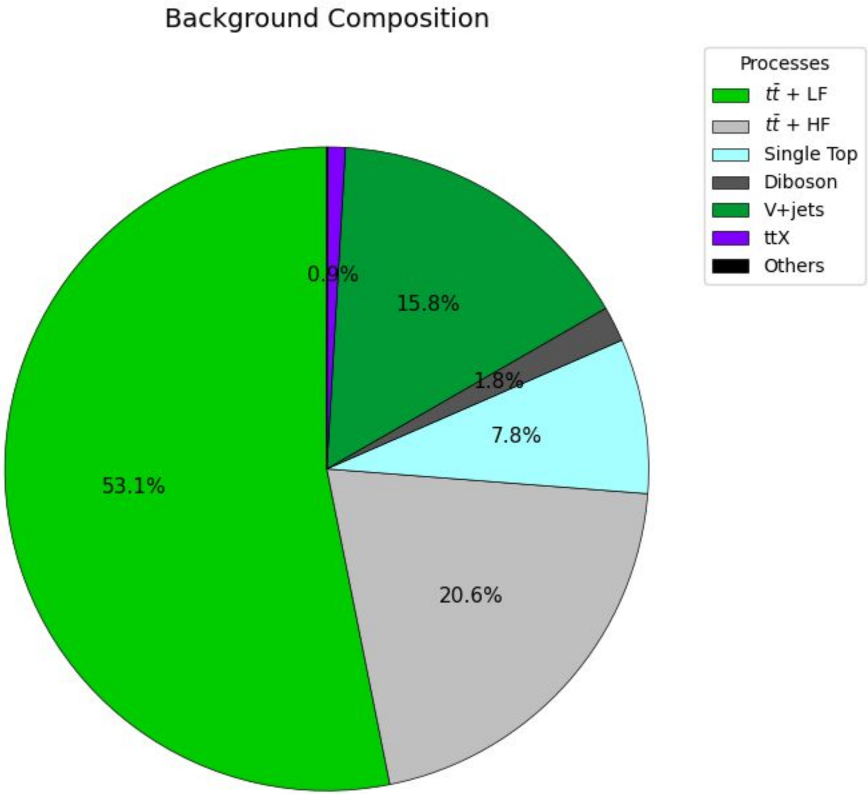
Back-up

Backgrounds









Yields after preselection and categorisation

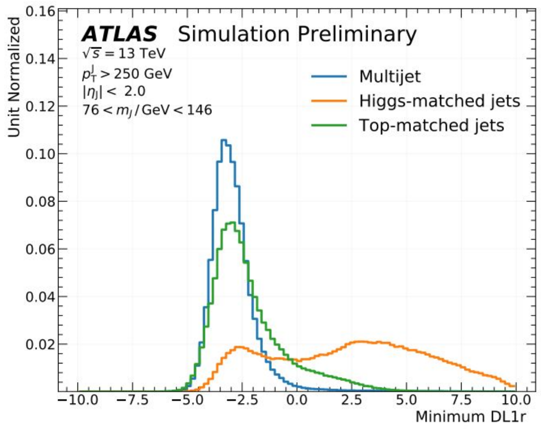
Process	qqbb weighted	$\ell\nu bb$ weighted	qqbb events	$\ell\nu bb$ events	total events
Signal 1.2 TeV	4938 ± 104	15759 ± 183	29880	94806	124686
Signal 1.4 TeV	4995 ± 103	14877 ± 175	31990	95576	127566
Signal 1.6 TeV	4059 ± 89	11159 ± 149	26063	95545	121608
Signal 1.8 TeV	5109 ± 99	13718 ± 164	33576	93854	127430
Signal 2 TeV	4863 ± 97	13134 ± 158	34188	92409	126597
Signal 2.5 TeV	4906 ± 95	12049 ± 150	34434	88119	122553
Signal 3 TeV	4672 ± 92	11527 ± 142	33757	83396	117153
V + jets	404 ± 3	5575 ± 16	336705	2215914	2552619
diboson	59 ± 2	612 ± 9	1737	22597	24334
others	2.03 ± 0.05	11.37 ± 0.11	19514	104074	123588
singletop	293 ± 6	2658 ± 19	5173	48551	53724
ttX	36.6 ± 0.3	301 ± 0.8	32308	291182	323490
ttbar + HF jets	695 ± 5	7134 ± 17	35329	358682	394011
ttbar + LF jets	1195 ± 6	18968 ± 39	243233	1383625	1626858
Total background	2683 ± 11	35260 ± 51	673999	4424625	5098624
Data	2612	34793	2612	34793	37405

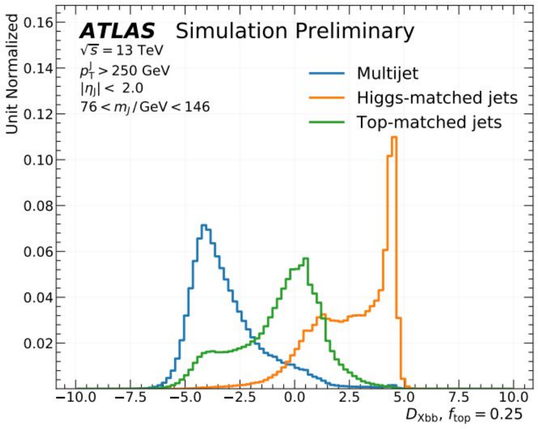
X-bb Tagger

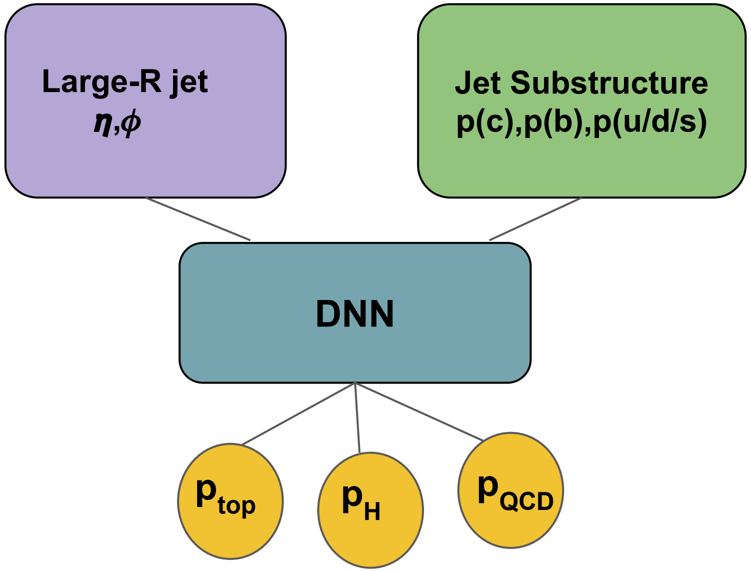
For passing 60% working point:

$$D = \ln\left(\frac{p_H}{f_{\text{top}}\, p_{\text{top}} + (1 - f_{\text{top}})\, p_{\text{QCD}}}\right) > 2.44$$

$f_{top} = 0.25$







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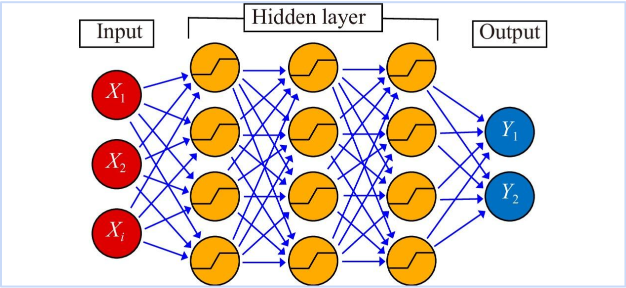
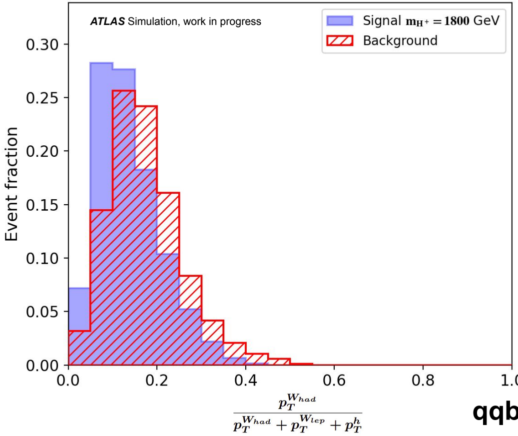
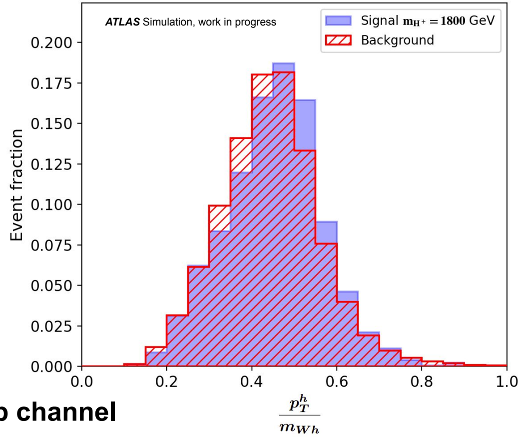
DNN for event classification

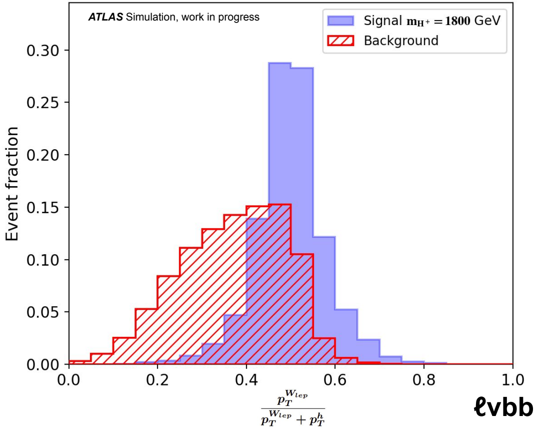


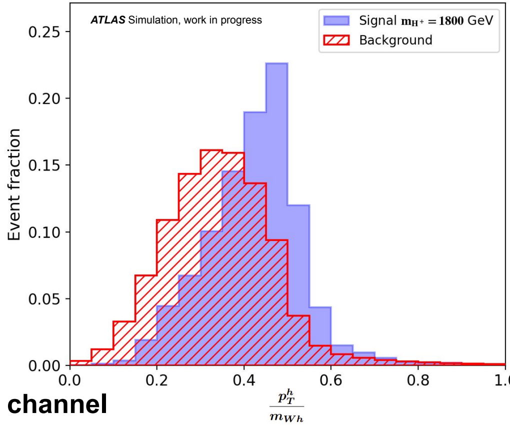
- DNN for binary classification using 3 dense layers.
- Separate networks for qqbb and ℓvbb.
- All signal mass points and background trained together.
- Use of variables for example, $p_{T,h}/m_{wh}$ and $p_{T,W}/m_{wh}$, to remove $\mathbf{H^{\pm}}$ mass dependence.
- 2-fold cross-validation using odd-even split.





qqbb channel





ℓvbb channel

Shao et al., IJMMM 31 (2024) 106-117

DNN input variables and setup

qqbb variables

$$\frac{p_T^{W_{had}}}{p_T^{W_{had}} + p_T^{W_{lep}} + p_T^h}, \quad \Delta R(\ell, W_{had}), \quad \Delta R(\ell, h), \quad \Delta\eta(h, W_{had}), \quad \Delta\phi(h, W_{had})$$

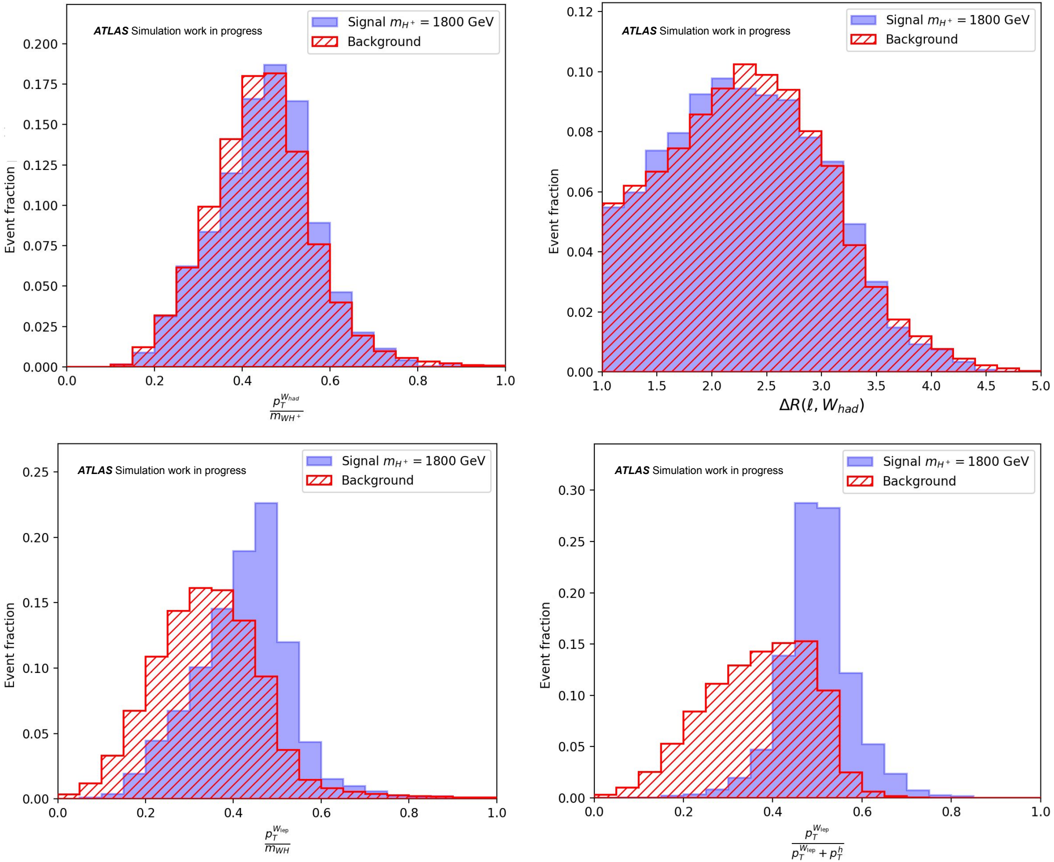
$$\frac{p_T^{W_{had}}}{m_{WH^+}}, \quad \frac{p_T^h}{m_{WH^+}}$$

$\ell\nu$bb variables

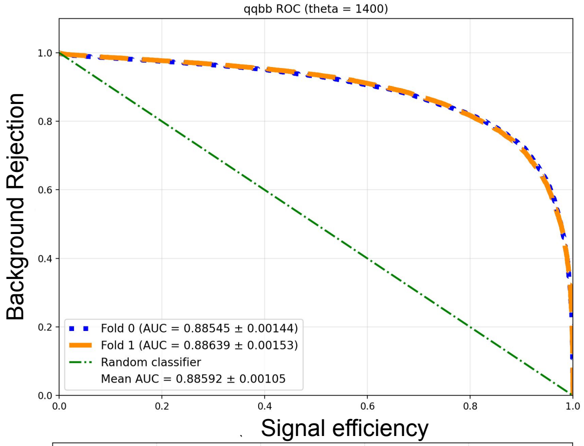
$$\frac{p_T^{W_{lep}}}{p_T^{W_{lep}} + p_T^h}, \quad m_{\text{top}}^{\text{lep}}, \quad \Delta R(\ell, h), \quad \Delta\eta(h, W_{\text{lep}}), \quad \Delta\phi(h, W_{\text{lep}})$$

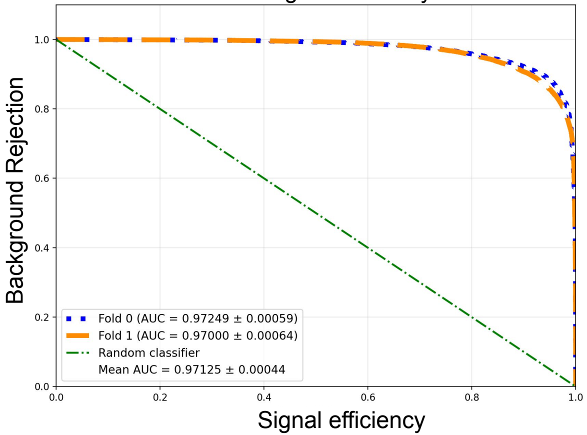
$$\frac{p_T^{W_{lep}}}{m_{WH}}, \quad \frac{p_T^h}{m_{WH}}$$

Training setup:
- Keras
- Hidden layers:
  - lvbb: 3 × 128 nodes
  - qqbb: 2 × 128 nodes
- ReLU activation + sigmoid output (binary classification)
- L2 regularisation
- Dropout
- Adam optimiser
- Batch size: 128
- Early Stopping



DNN performance



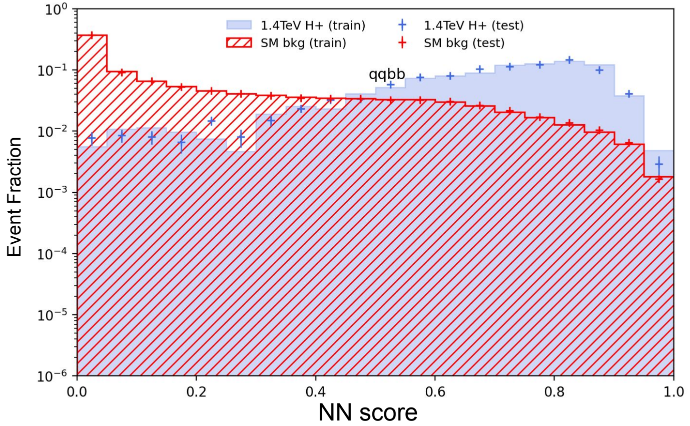


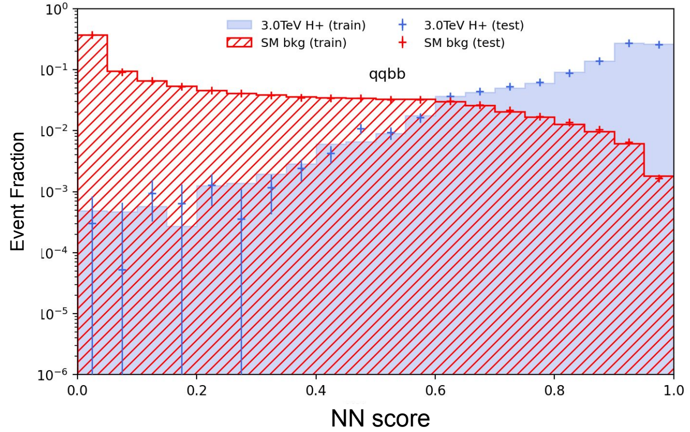
qqbb 1.4 TeV

- Performance becomes better with higher signal mass.
- Overtraining checked.

qqbb 3 TeV

Performance metric:
Area under the curve (AUC)





*AUC errors are bootstrapped errors

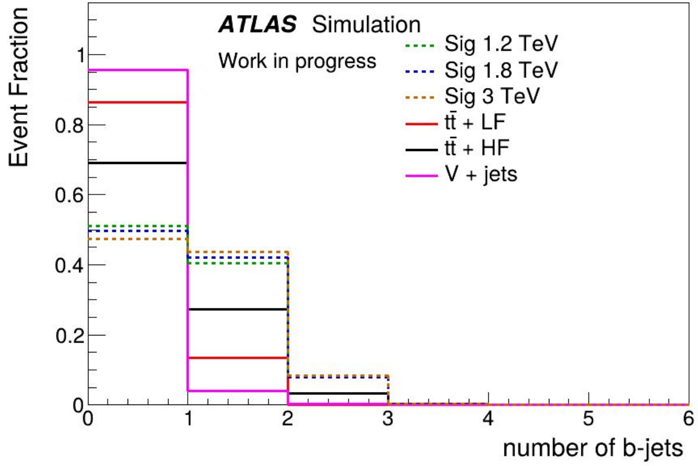
Signal and Control Regions

- ❖ Further division based on the number of small radius b-tagged jets outside Large-R jets.
- ❖ Additional division into two regions: **0 b-tagged, ≥1 b-tagged.**
- ❖ **Signal regions** are further divided into

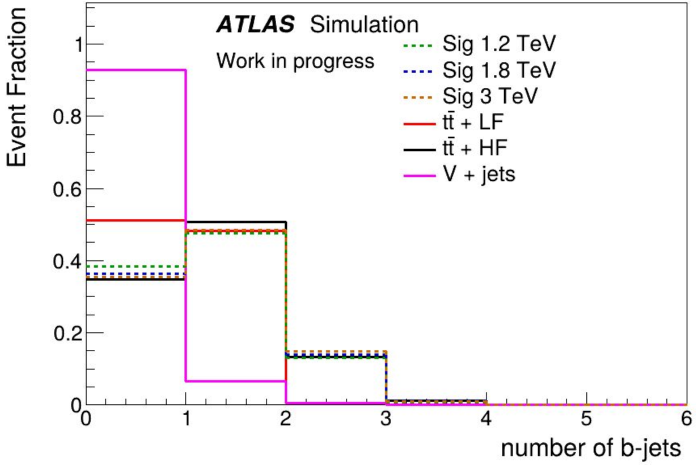
  - High nn score
  - Medium nn score
  - Low nn score

  after using a DNN for event S vs B classification

qqbb

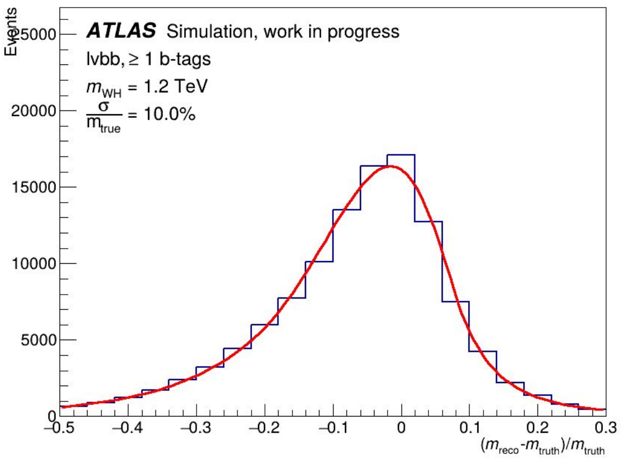


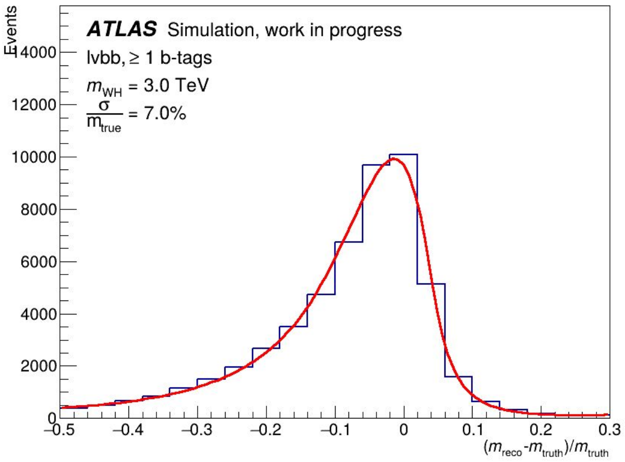
lvbb



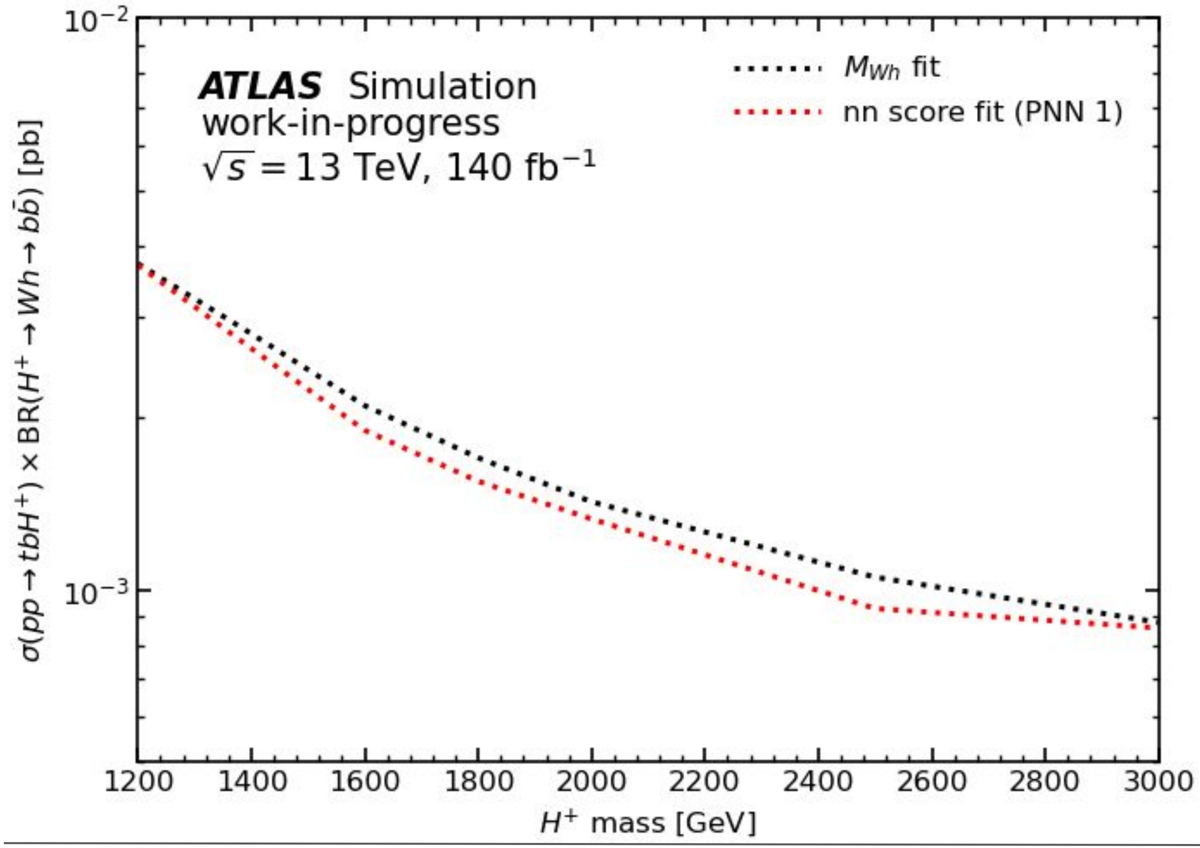
M_{Wh} Binning

- Reconstructed charged higgs mass is used for binning
- Bukin fits applied to derive relative mass resolution using FWHM.
- Made sure that each bin was not finer than the corresponding resolution.





Expected exclusion Limits (PNN 1)



- Slight improvement in sensitivity with **3%** (1.2 TeV) and **2%** (3 TeV).

PNN-2 input feature strategy

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- Proposed a large set of input variables **(30 for each Channel).**
- Permutation importance of each variable: $\Delta AUC = AUC_{Baseline} - AUC_{permuted}$
- For many low-ranked features, the ranking kept changing across mass points.
- **Normalized ΔAUC** for a feature across all features per mass point.

$$f(m,f) = \frac{\Delta \mathrm{AUC}(m,f)}{\sum_{f'} \Delta \mathrm{AUC}(m,f')} \qquad \text{with} \sum_{f} f(m,f) = 1$$

- Compared the **normalized ΔAUC** of the feature across all mass points.

Baseline AUC [1.2 TeV, 3 TeV]:

qqbb: [0.926, 0.956]
ℓνbb: [0.943, 0.971]

PNN-2 input feature strategy

- Proposed a large set of input variables **(30 for each Channel).**
- Perm
- For r ... oints.
- **Norr**
- Com

Quantity (variable: m_{H^+})	1.2 TeV	1.8 TeV	3 TeV
$\Delta\mathrm{AUC}(m, f)$	0.13	0.06	0.006
$\sum_{f'} \Delta\mathrm{AUC}(m, f')$	0.30	0.107	0.0139
$f(m, f)$	43%	56%	43%

Quantity (variable: $\eta_{W_{qq}}$)	1.2 TeV	1.8 TeV	3 TeV
$\Delta\mathrm{AUC}(m, f)$	1.9×10^{-3}	2.9×10^{-5}	5.1×10^{-7}
$\sum_{f'} \Delta\mathrm{AUC}(m, f')$	0.30	0.107	0.0139
$f(m, f)$	0.064%	0.027%	0.0037%

Baseline AUC [1.2 TeV, 3 TeV]:

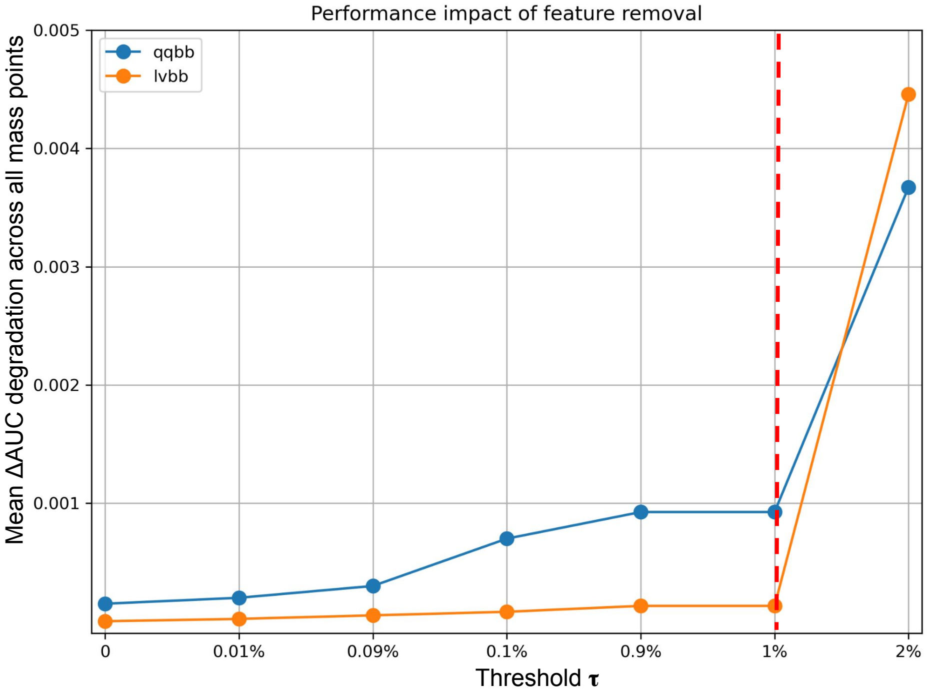
qqbb: [0.926, 0.956]
ℓνbb: [0.943, 0.971]

Threshold scan

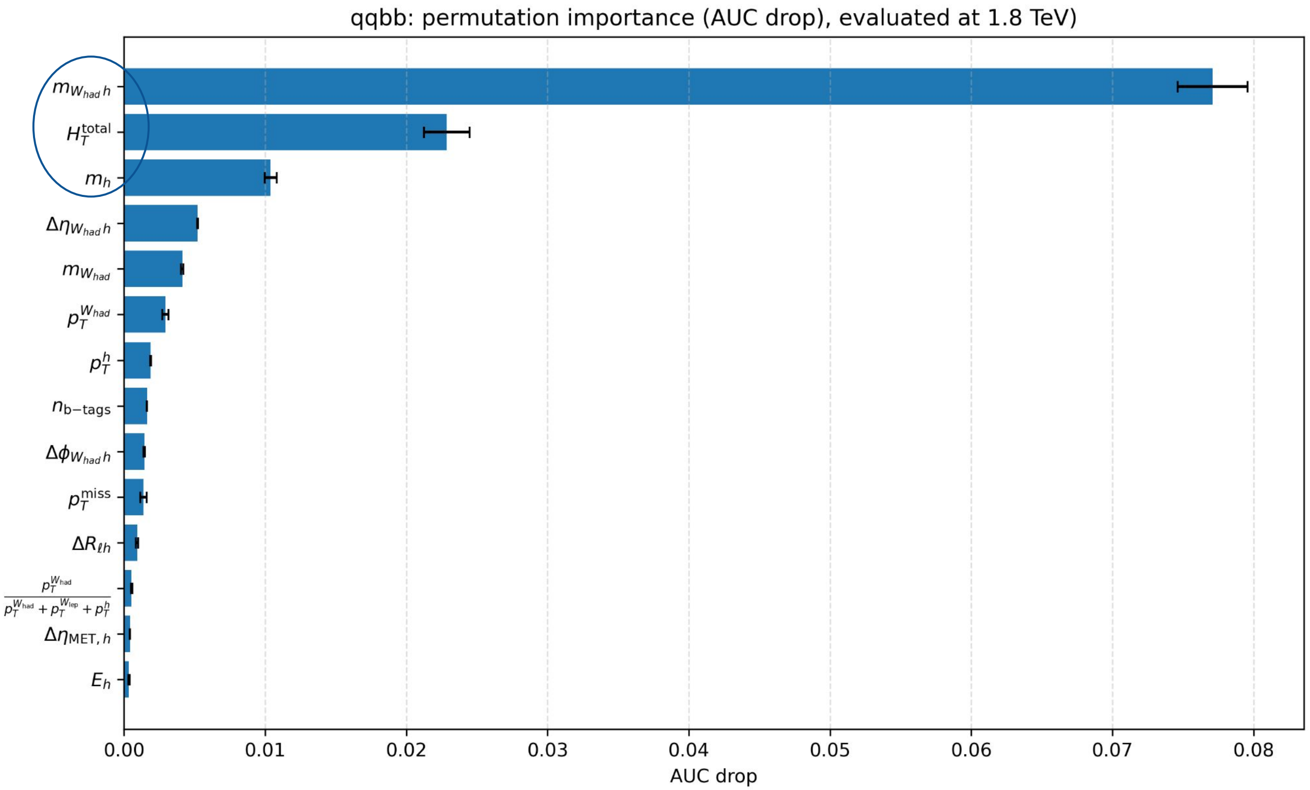
- Scanned grid of thresholds τ (normalized ΔAUC) = {0.01%, 0.09%, 0.1%, 0.9%, 1%, 2%}
- Chosen threshold = 1% (Helped getting rid of many low ranked variables)

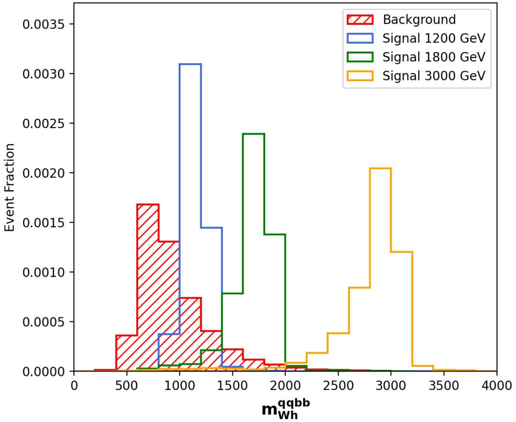
Channel	Number of features dropped
qqbb	15
$\ell\nu bb$	11

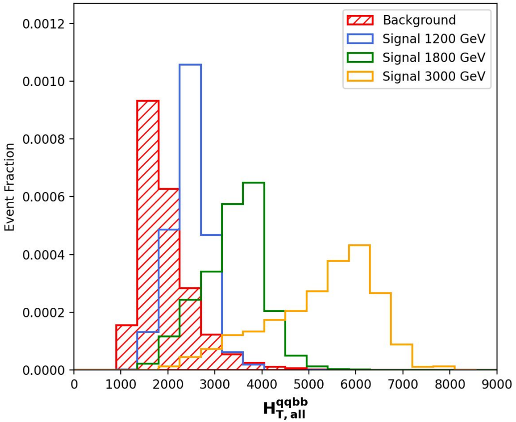
Channel	Final number of features
qqbb	14
$\ell\nu bb$	19



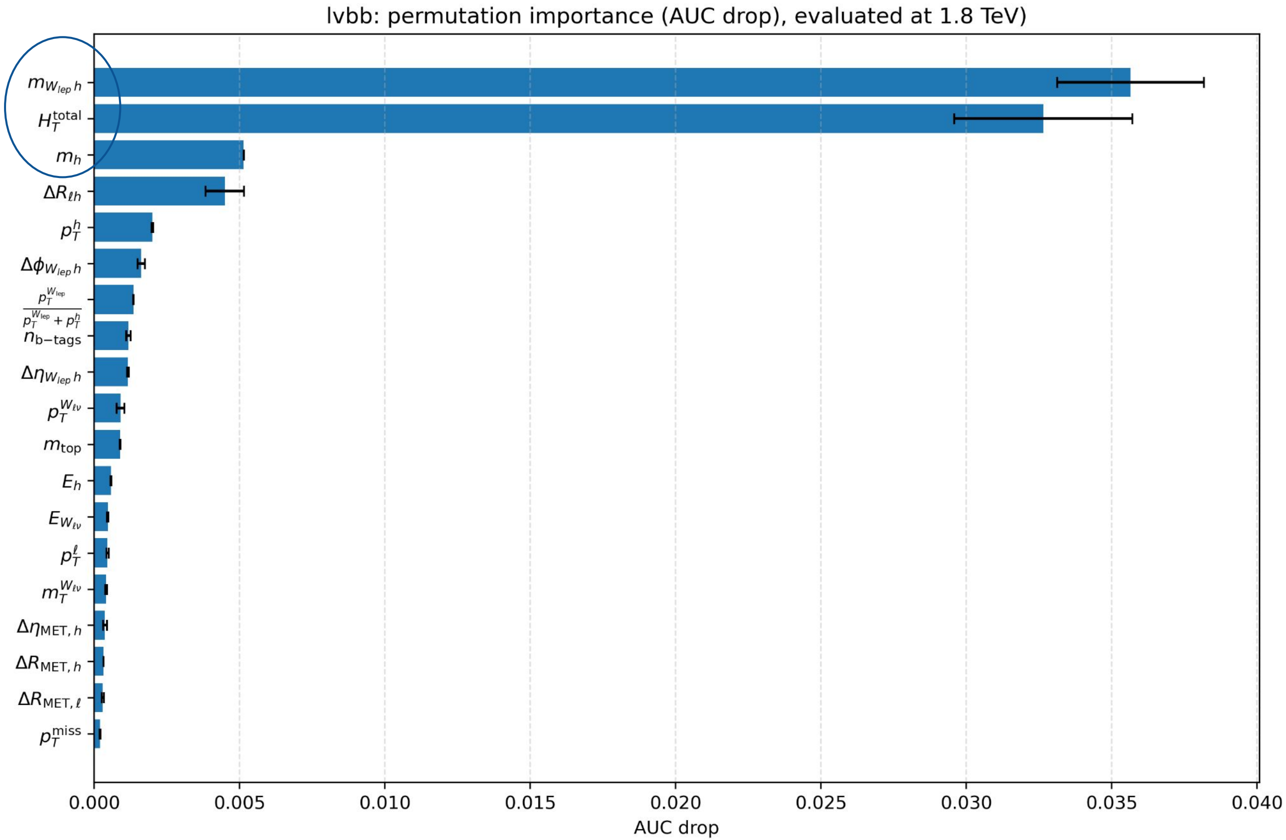
PNN-2 Feature importance (qqbb)

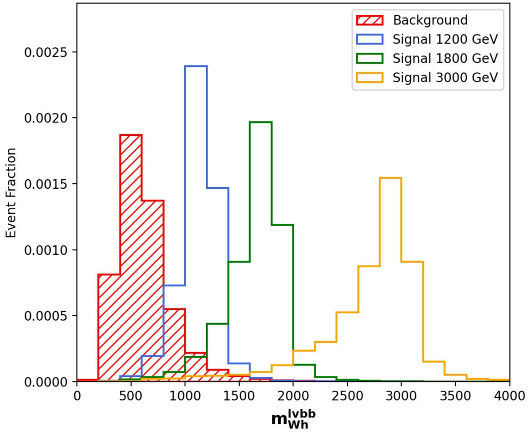


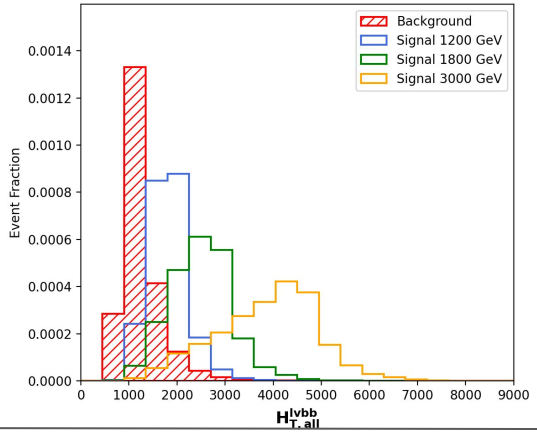




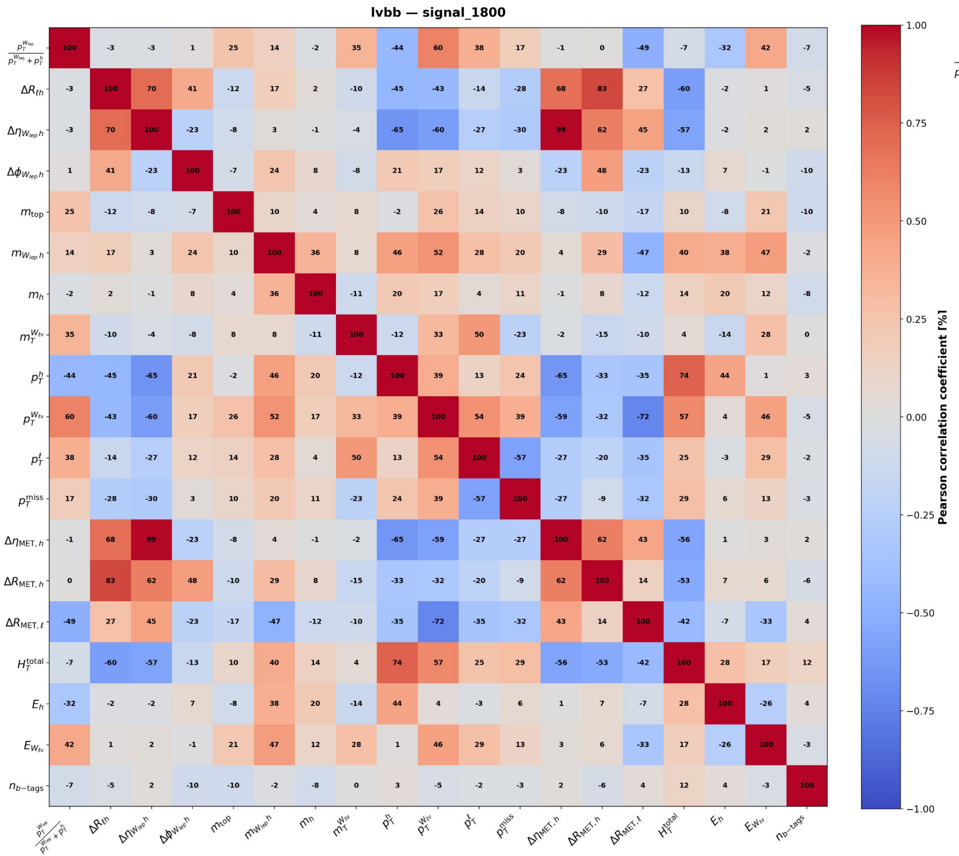
PNN-2 Feature importance (ℓvbb)

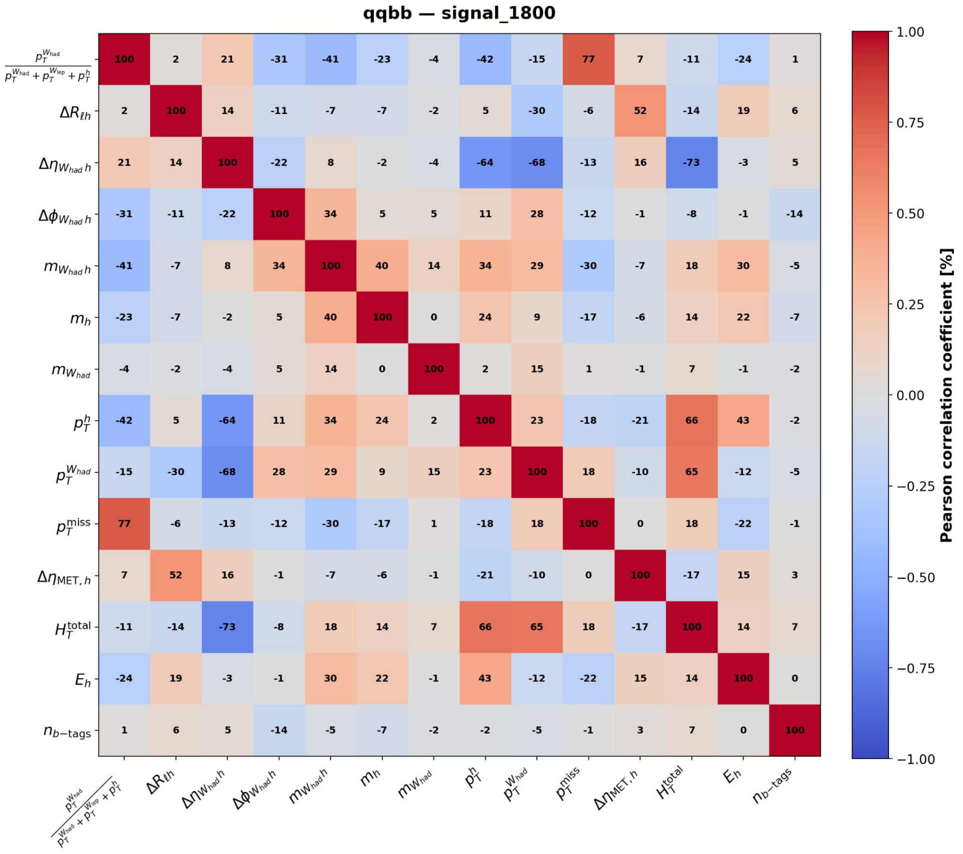






PNN-2 Correlation Matrices (1.8 TeV)





PNN-2 variables and optimized setup

qqbb variables

$$\Delta R_{\ell h},\quad \Delta\eta_{W_{had}h},\quad \Delta\phi_{W_{had}h},\quad m_{W_{had}h},\quad m_h,\quad m_{W_{had}},$$

$$p_T^h,\quad p_T^{W_{had}},\quad p_T^{\text{miss}},\quad \Delta\eta_{\text{MET},h},\quad H_T^{\text{total}},\quad E_h,\quad n_{\text{b-tags}},\quad \frac{p_T^{W_{\text{had}}}}{p_T^{W_{\text{had}}}+p_T^{W_{\text{lep}}}+p_T^h}$$

ℓνbb variables

$$\Delta R_{\ell h},\quad \Delta\eta_{W_{lep}h},\quad \Delta\phi_{W_{lep}h},\quad m_{\text{top}},\quad m_{W_{lep}h},\quad m_h,\quad m_T^{W_{\ell\nu}},$$

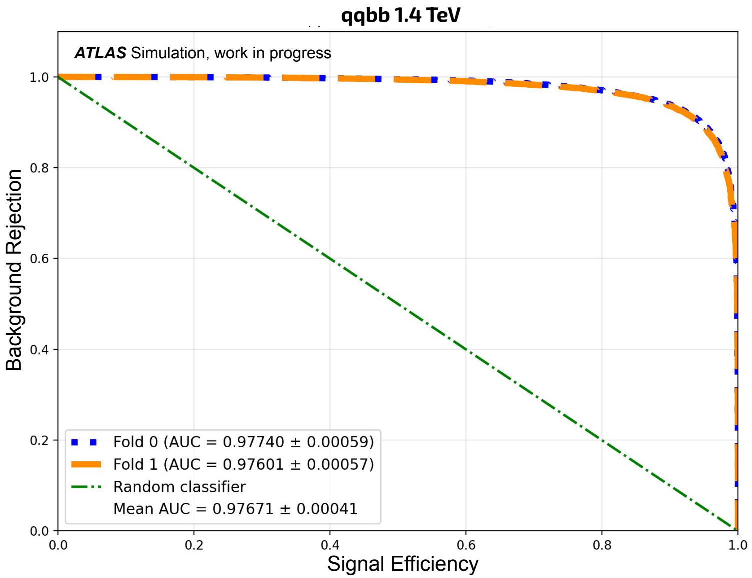
$$p_T^h,\quad p_T^{W_{\ell\nu}},\quad p_T^{\ell},\quad p_T^{\text{miss}},\quad \Delta\eta_{\text{MET},h},\quad \Delta R_{\text{MET},h},\quad \Delta R_{\text{MET},\ell},$$

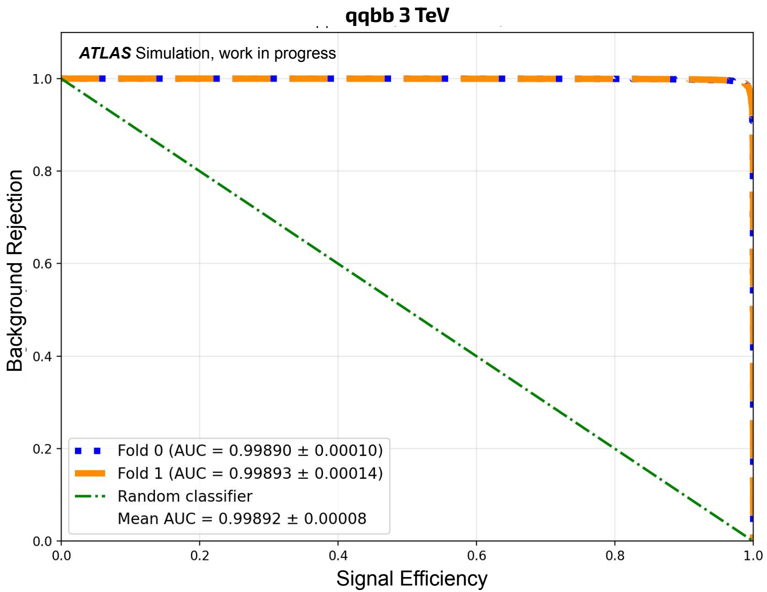
$$H_T^{\text{total}},\quad E_h,\quad E_{W_{\ell\nu}},\quad n_{\text{b-tags}},\quad \frac{p_T^{W_{\text{lep}}}}{p_T^{W_{\text{lep}}}+p_T^h},$$

- **Architecture (Best from Optuna scan)**
  - **qqbb:**
    - **4 hidden layers: 512 → 256 → 256 →256**
    - **Dropout: 0.3**
    - **L2: 0.7×10^{-6}**
    - **Learning rate: 0.0001**
    - **Batch size: 64**
    - **AUC: 0.966**

- **Architecture (Best from Optuna scan)**
  - **ℓvbb:**
    - **4 hidden layers: 512 → 256 → 256 →256**
    - **Dropout: 0.1**
    - **L2: 1.05×10^{-6}**
    - **Learning rate: 0.0001**
    - **Batch size: 64**
    - **AUC: 0.986**

PNN-2 Performance





Interpolation:

Signal mass dropped	1.8 TeV	2.5 TeV
Drop in AUC	0.0013%	0.0018%

NN Score

Basics of Statistical Analysis

$$\nu_{ir}(\mu, \boldsymbol{\theta}) = \mu\, s_{ir}(\boldsymbol{\theta}) + b_{ir}(\boldsymbol{\theta})$$

Number of signal and background events in the bin

$$\mathcal{L}(\mu, \boldsymbol{\theta}) = \prod_r \prod_i \mathrm{P}\left(n_{ir} \mid \mu\, s_{ir}(\boldsymbol{\theta}) + b_{ir}(\boldsymbol{\theta})\right) \prod_k \pi(\theta_k)$$

Likelihood function

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

Profile Likelihood ratio

$$q_\mu = -2 \ln \lambda(\mu)$$

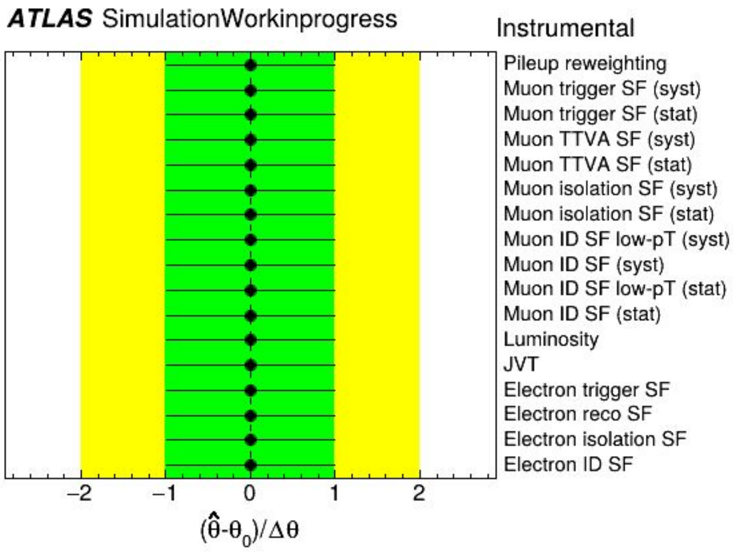
Test Statistic

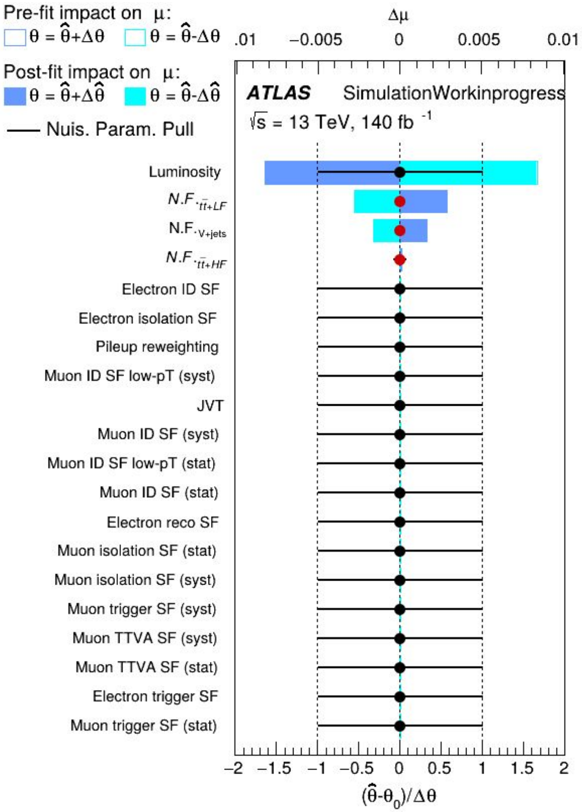
$$\mathrm{CL}_s = \frac{\mathrm{CL}_{s+b}}{1 - \mathrm{CL}_b}$$

For BSM searches, first it is tested whether the data is compatible with SM background-only hypothesis. If no significant excess is seen, no discovery is claimed. Instead and upper limit on the the allowed signal rate at 95% confidence Level excluding signal models that predict a rate above this limit

PNN-2 systematics

After S+B blinded fit





PNN-2 systematics

ATLAS SimulationWorkinprogress

	Electron ID SF	Electron isolation SF	Electron reco SF	Electron trigger SF	JVT	Luminosity	Muon ID SF (stat)	Muon ID SF low-pT (stat)	Muon ID SF (syst)	Muon ID SF low-pT (syst)	Muon isolation SF (stat)	Muon isolation SF (syst)	Muon TTVA SF (stat)	Muon TTVA SF (syst)	Muon trigger SF (stat)	Muon trigger SF (syst)	Pileup reweighting	$N.F._{V+jets}$	$N.F._{t\bar{t}+HF}$	$N.F._{t\bar{t}+LF}$	μ
Electron ID SF	100.0	-0.0	-0.0	-0.0	0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	0.0	0.0	0.0	0.0
Electron isolation SF	-0.0	100.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	0.0	0.0	0.0	0.0
Electron reco SF	-0.0	-0.0	100.0	-0.0	-0.0	-0.0	-0.0	-0.0	0.0	-0.0	0.0	-0.0	0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	0.0	-0.0
Electron trigger SF	-0.0	-0.0	-0.0	100.0	0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	0.0	0.0	0.0	0.0	0.0	0.0
JVT	0.0	-0.0	-0.0	0.0	100.0	0.0	0.0	0.0	-0.0	0.0	-0.0	0.0	-0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.0	0.0
Luminosity	-0.0	-0.0	-0.0	-0.0	0.0	100.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	0.0	-29.1	-12.1	-24.7	-54.7
Muon ID SF (stat)	-0.0	-0.0	-0.0	-0.0	0.0	-0.0	100.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	0.0	0.0	0.0	0.0	0.0	0.0
Muon ID SF low-pT (stat)	-0.0	-0.0	-0.0	-0.0	0.0	-0.0	-0.0	100.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	0.0	0.0	0.0	0.0	0.0	0.0
Muon ID SF (syst)	-0.0	-0.0	0.0	-0.0	-0.0	-0.0	-0.0	-0.0	100.0	-0.0	0.0	-0.0	0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	0.0	-0.0
Muon ID SF low-pT (syst)	-0.0	-0.0	-0.0	-0.0	0.0	-0.0	-0.0	-0.0	-0.0	100.0	-0.0	-0.0	-0.0	-0.0	-0.0	0.0	0.0	0.0	0.0	0.0	0.0
Muon isolation SF (stat)	-0.0	-0.0	0.0	-0.0	-0.0	-0.0	-0.0	-0.0	0.0	-0.0	100.0	-0.0	0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	0.0	-0.0
Muon isolation SF (syst)	-0.0	-0.0	-0.0	-0.0	0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	100.0	-0.0	-0.0	-0.0	-0.0	-0.0	0.0	0.0	0.0	0.0
Muon TTVA SF (stat)	-0.0	-0.0	0.0	-0.0	-0.0	-0.0	-0.0	-0.0	0.0	-0.0	0.0	-0.0	100.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	0.0	-0.0
Muon TTVA SF (syst)	-0.0	-0.0	-0.0	-0.0	0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	100.0	-0.0	-0.0	-0.0	0.0	0.0	0.0	0.0
Muon trigger SF (stat)	-0.0	-0.0	-0.0	-0.0	0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0
Muon trigger SF (syst)	-0.0	-0.0	-0.0	0.0	0.0	-0.0	0.0	0.0	-0.0	0.0	-0.0	-0.0	-0.0	-0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0
Pileup reweighting	-0.0	-0.0	-0.0	0.0	0.0	0.0	0.0	0.0	-0.0	0.0	-0.0	-0.0	-0.0	-0.0	0.0	0.0	100.0	0.0	0.0	-0.0	0.0
$N.F._{V+jets}$	0.0	0.0	-0.0	0.0	0.0	-29.1	0.0	0.0	-0.0	0.0	-0.0	0.0	-0.0	0.0	0.0	0.0	0.0	100.0	43.5	-47.7	10.9
$N.F._{t\bar{t}+HF}$	0.0	0.0	-0.0	0.0	0.0	-12.1	0.0	0.0	-0.0	0.0	-0.0	0.0	-0.0	0.0	0.0	0.0	0.0	43.5	100.0	-86.6	0.5
$N.F._{t\bar{t}+LF}$	0.0	0.0	0.0	0.0	-0.0	-24.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.0	-47.7	-86.6	100.0	18.8
μ	0.0	0.0	-0.0	0.0	0.0	-54.7	0.0	0.0	-0.0	0.0	-0.0	0.0	-0.0	0.0	0.0	0.0	0.0	10.9	0.5	18.8	100.0