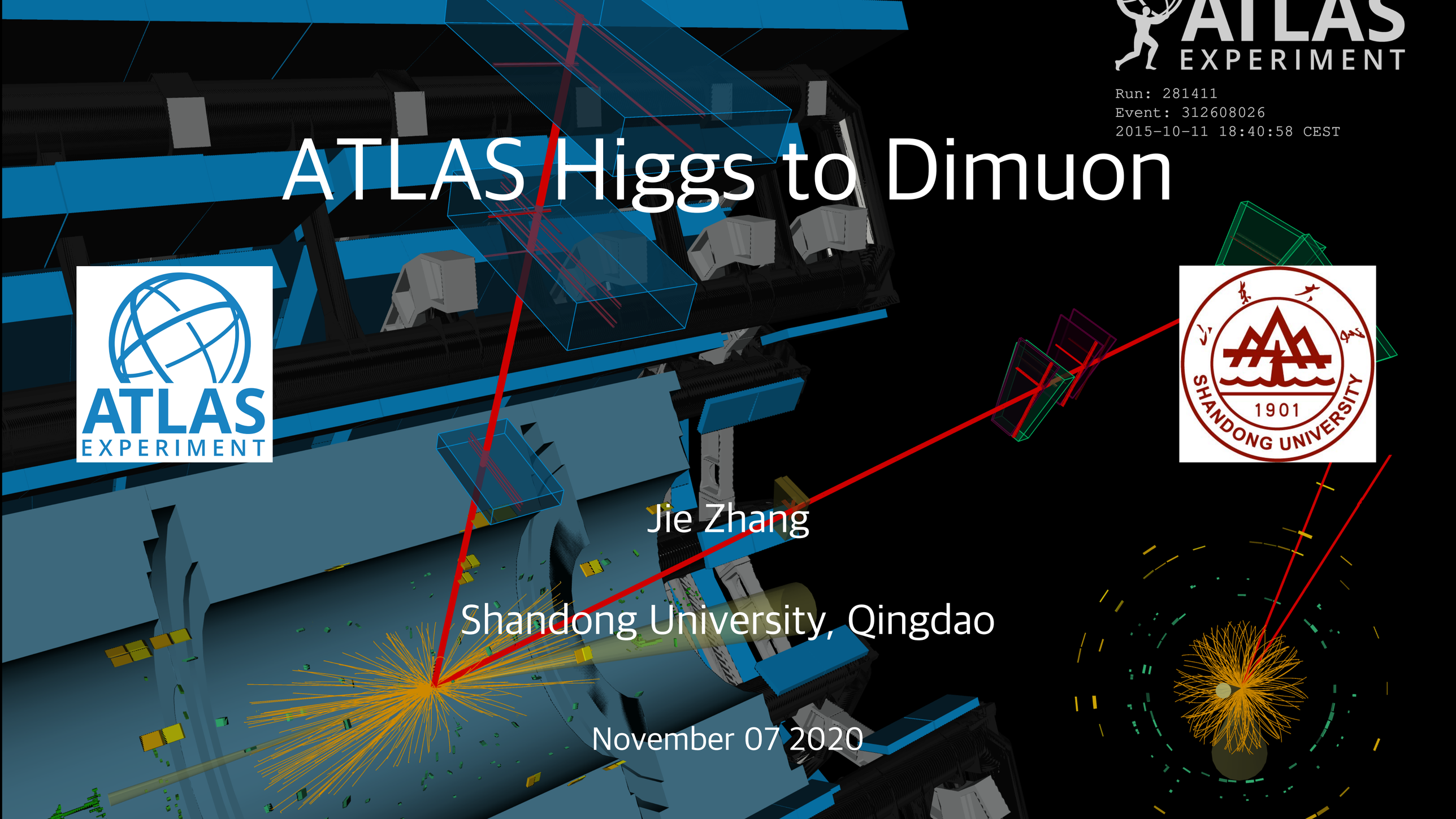


ATLAS Higgs to Dimuon

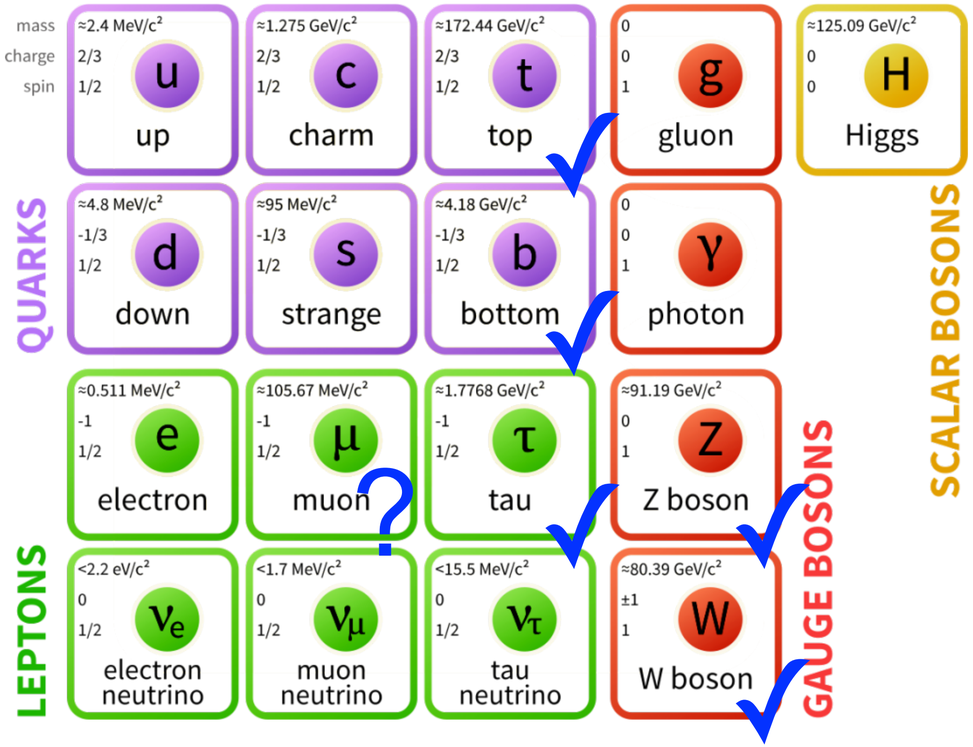
Jie Zhang

Shandong University, Qingdao

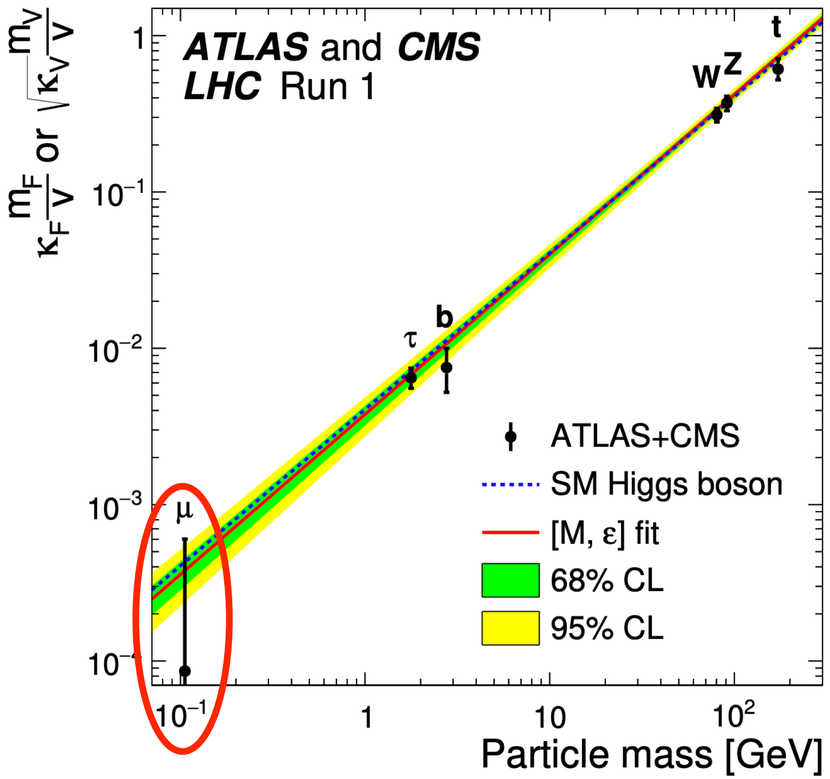
November 07 2020

The Coupling between the Higgs Boson and the Muon

- The Higgs boson only couples with the elementary massive particles.

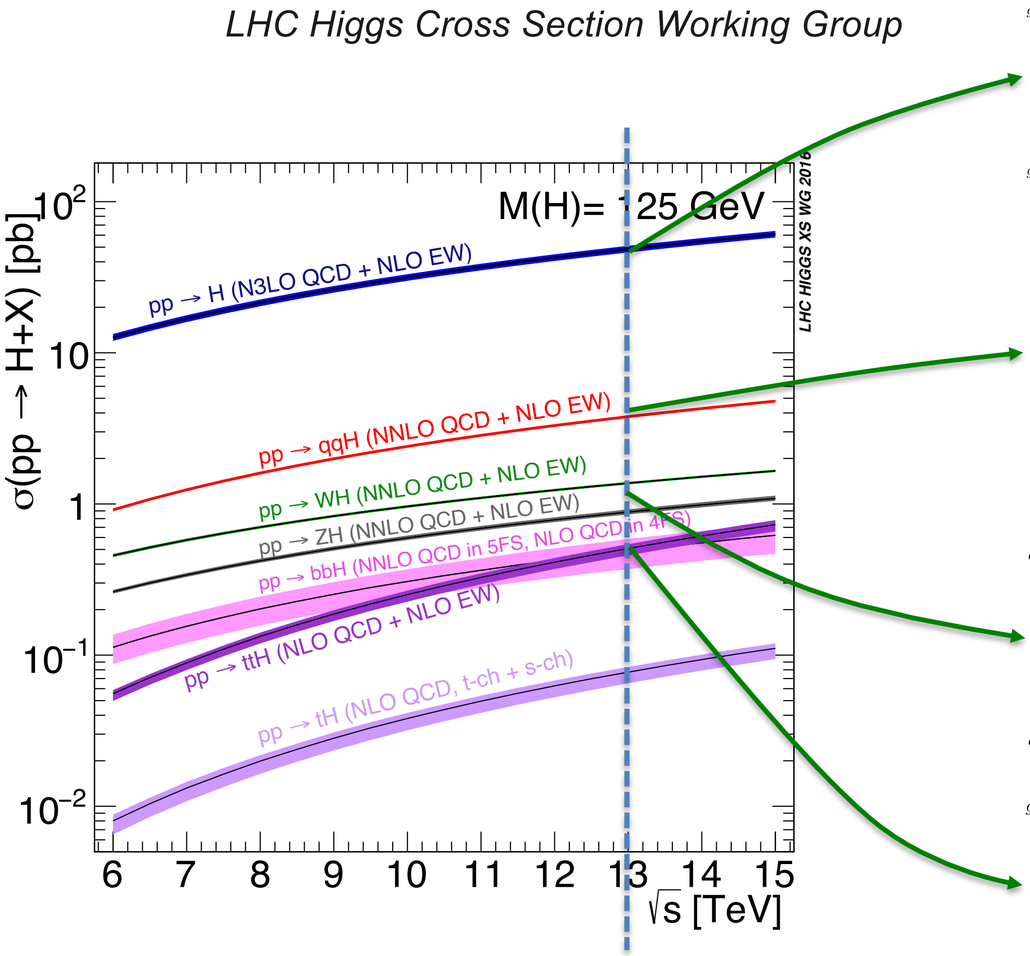


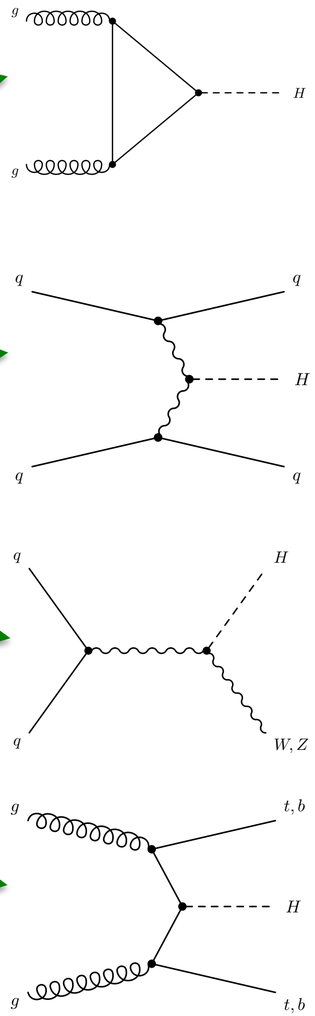
JHEP 08 (2016) 045

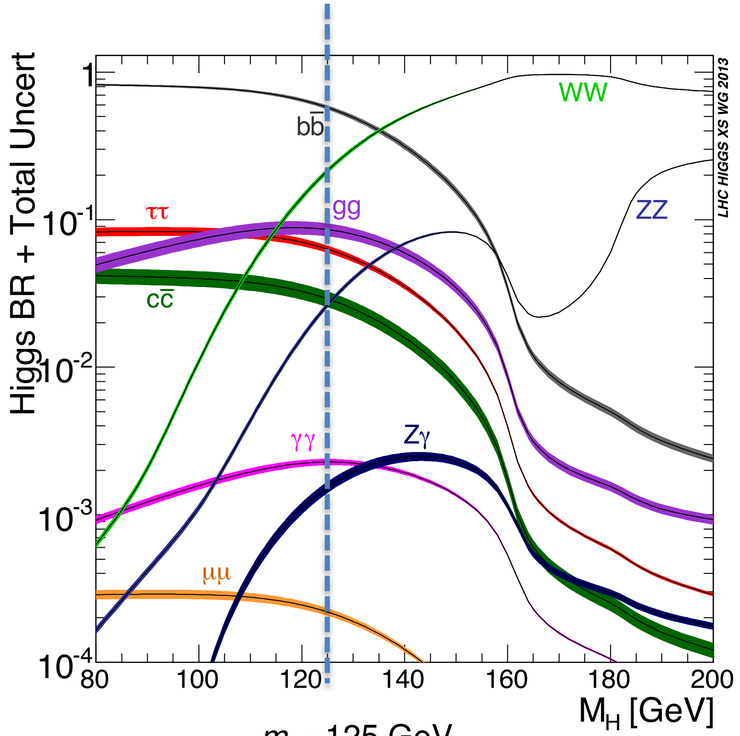


- In the right plot, only the coupling between the Higgs boson and the muon have not been observed.
- The H → μμ decay is a unique channel to explore the Higgs boson coupling to the second generation of fermions.

The Production and Decay Modes of the Higgs Boson at the LHC







m_H=125 GeV

Higgs decays	**BR** [%]
$H \to bb$	57.8
$H \to WW$	21.4
$H \to gg$	8.19
$H \to \tau\tau$	6.27
$H \to ZZ$	2.62
$H \to cc$	2.89
$H \to \gamma\gamma$	0.227
$H \to Z\gamma$	0.153
$H \to \mu\mu$	0.022

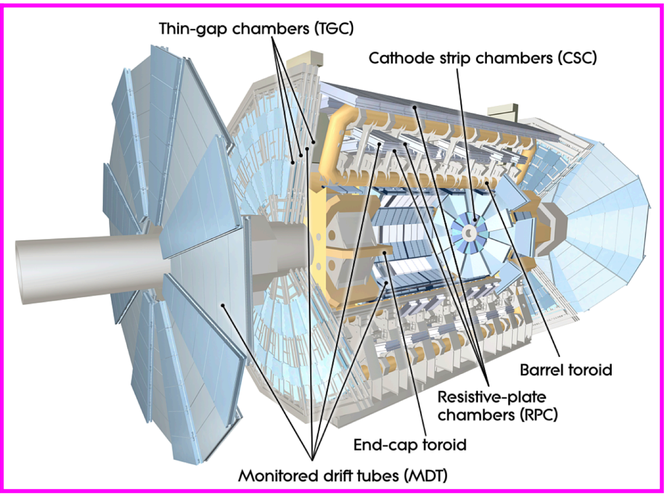
With 140 fb^{-1}, about 7M ggF events,

520K VBF, 350K VH events and 70K ttH events

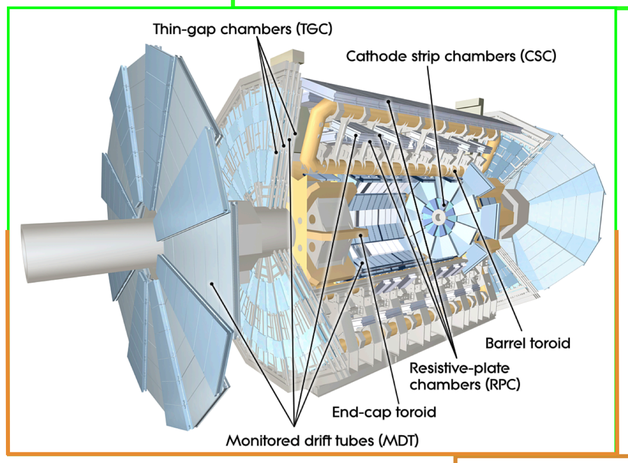
ATLAS Detector

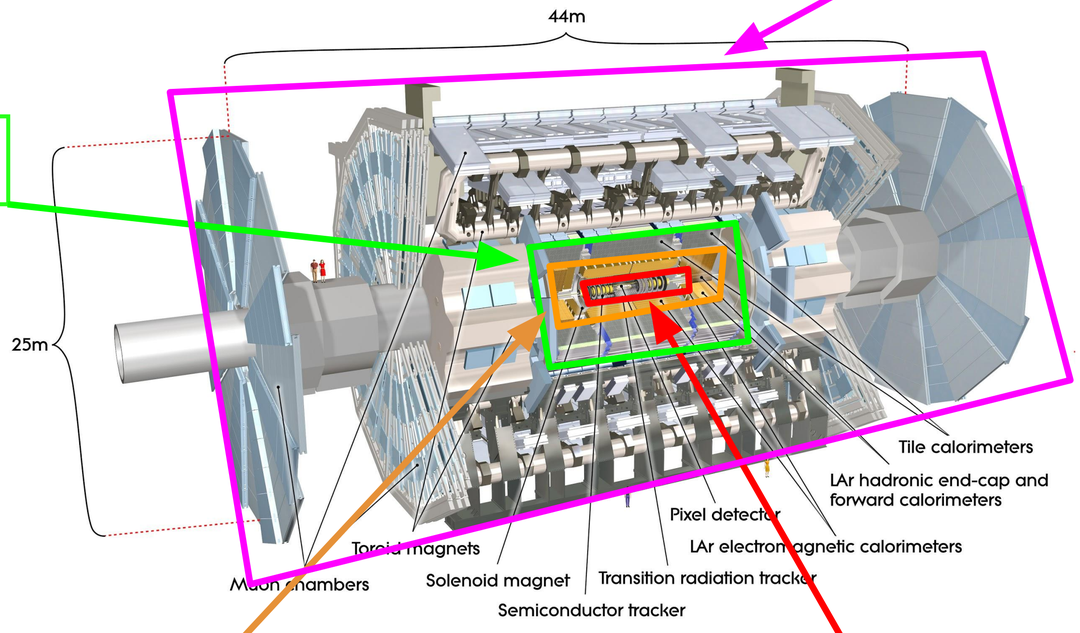
- Diameter $25m$, Length $44m$
- Overall weight 7000 *tonnes*

Muon Spectrometer
- Tracking for $|\eta| < 2.7$
- Barrel ($|\eta| < 1.05$) and two endcap sections
- Three superconducting air-core toroids
  - Bending integral of 2.5 Tm in barrel
  - Bending integral up to 6 Tm in the end-caps



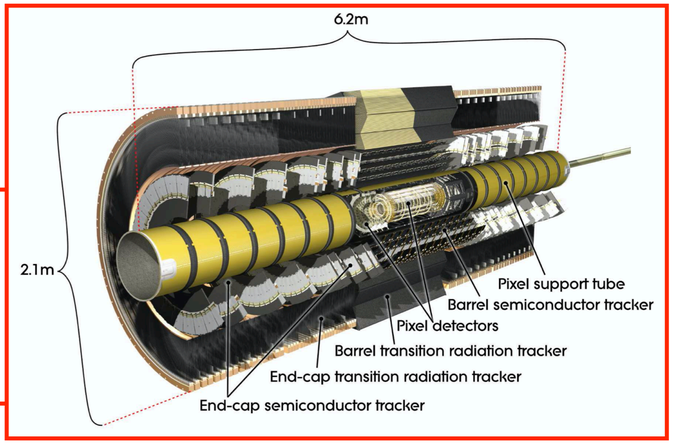
Hadronic Calorimeter
- Iron and scintillator tiles for $|\eta| < 1.5$





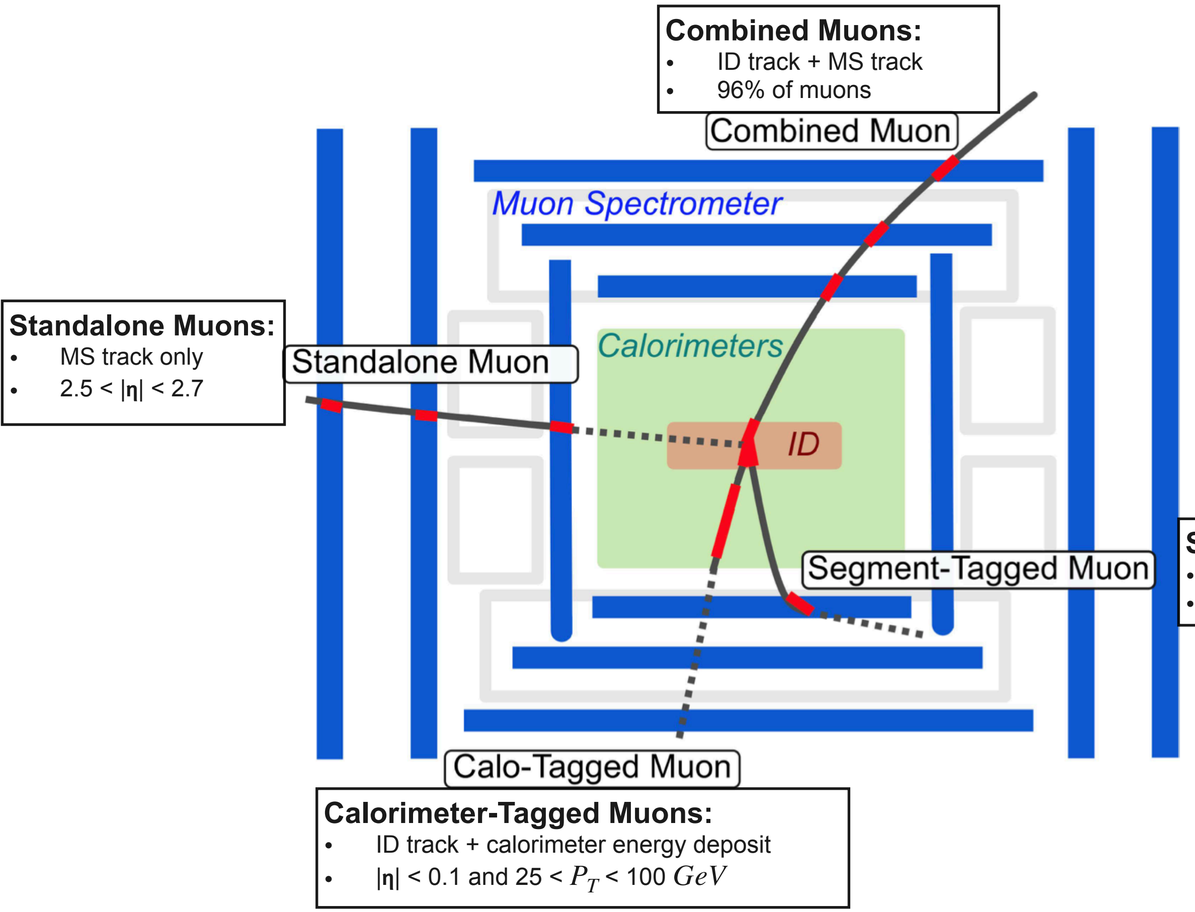
Electromagnetic Calorimeter
- Electromagnetic:
  - Sampling liquid-argon (LAr) calorimeter
  - $|\eta| < 3.2$

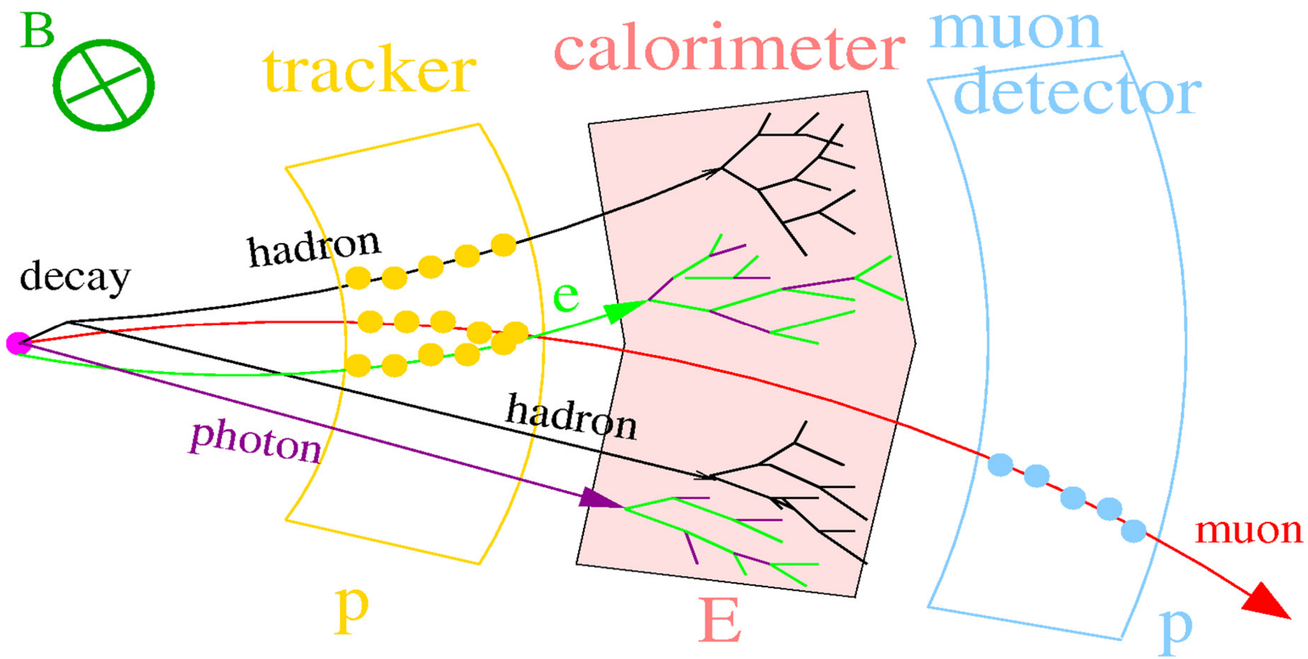
Inner Detector
- Technologies:
  - Silicon Pixel $|\eta| < 2.5$ (Insertable B Layer (LBL) added during LS1
  - Semi-Conductor Tracker (SCT) $|\eta| < 2.5$
  - Transition Radiation Tracker (TRT) $|\eta| < 2.0$
- 2T axial magnetic field for momentum measurements



ATLAS Muon

- Muon is the minimum ionizing particle
- The mass of muon is 105.6 MeV/c^2





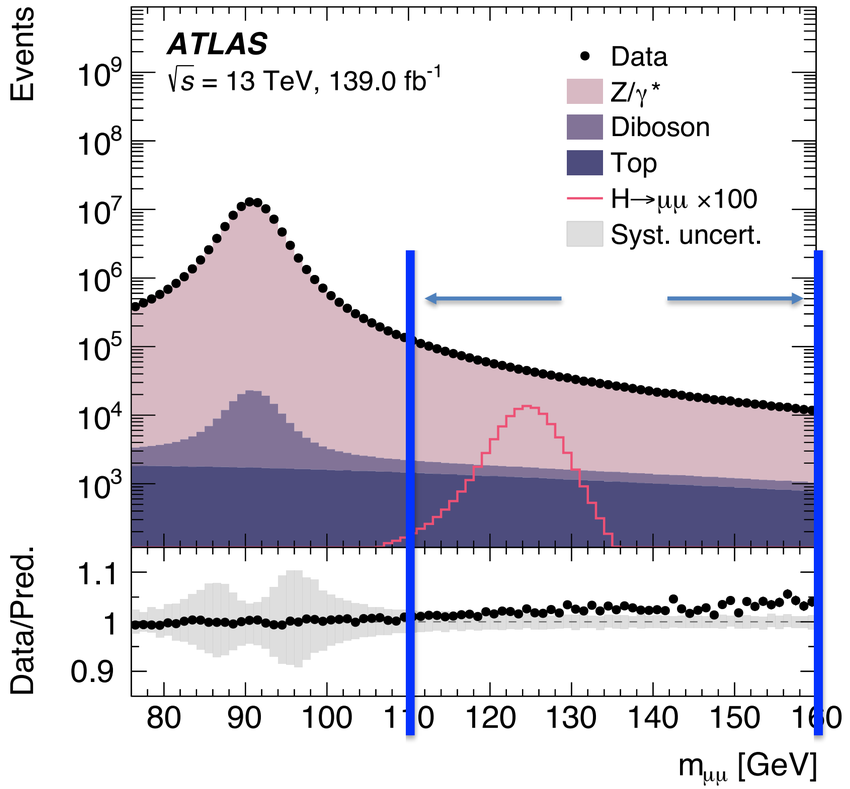
- Muon leaves a track in the Inner Tracker
- Muon leaves very little energy in the Calorimeter
- Muon leaves a track in the Muon Spectrometer

Analysis Strategy

- Signal has good $m_{\mu\mu}$ resolution. Background $m_{\mu\mu}$ is smooth.
- Use analytic functions to model signal and Background.
- Fully data-driven method.

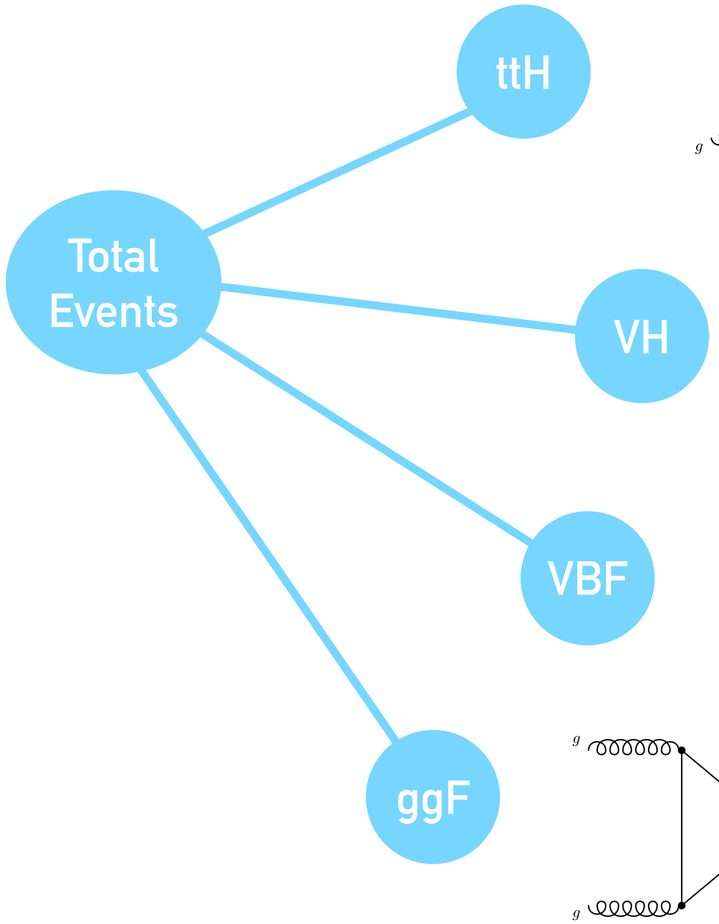
- ggF, VBF, VH and ttH signal processes are considered.
- Dominant background is Drell-Yan process.

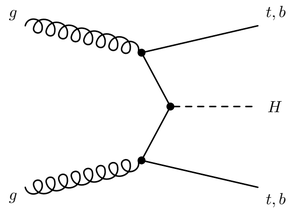
arXiv: 2007.07830



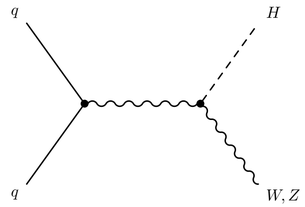
Event Categorization

- The category selections targeting the different Higgs Boson production modes are made in a specific exclusive order.

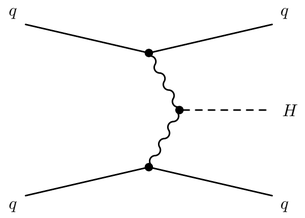




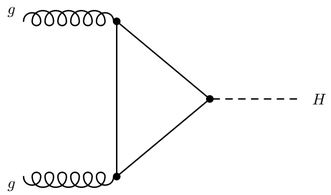
- 3/4 leptons
- At least one b-tagged jet



- 3/4 leptons
- No b-tagged jet



- 2 leptons
- No b-tagged jet

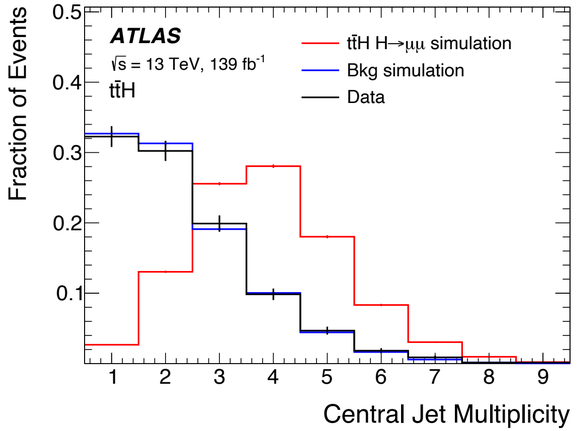


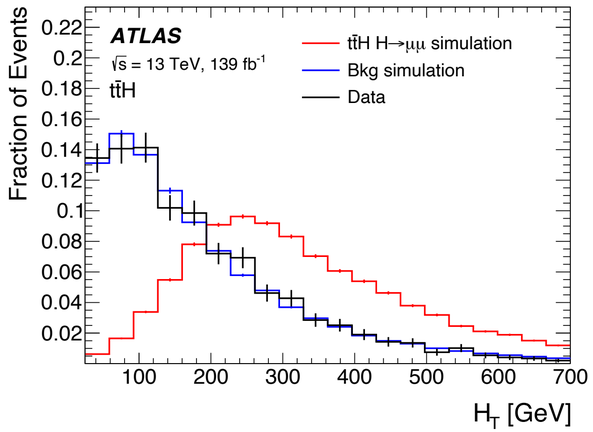
- 2 leptons
- No b-tagged jet

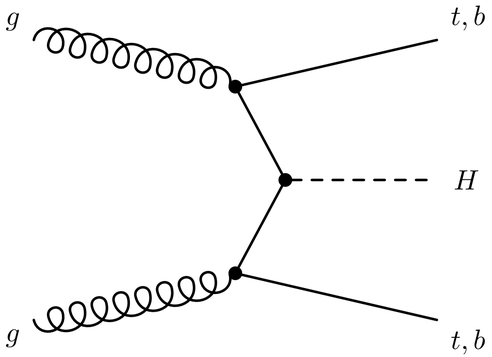
ttH Category

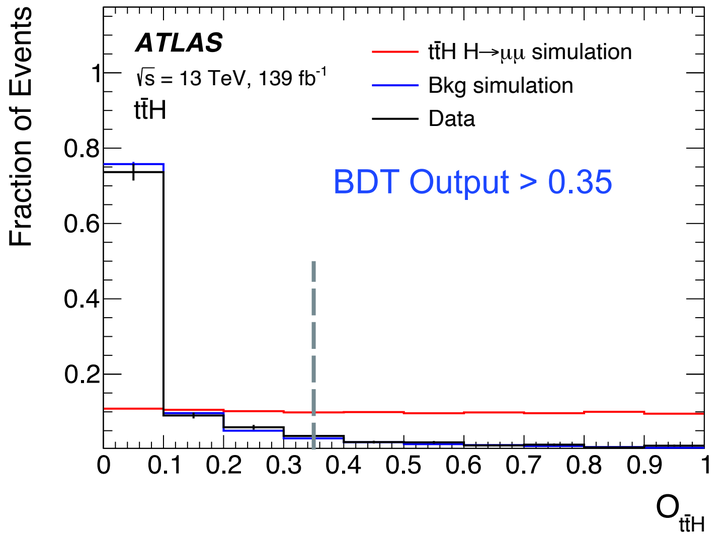
- Use BDT (implemented in XGBoost package) to further suppress backgrounds
- Leading two muons as H → μμ
- 12 variables are used for the BDT
- Main background is ttZ. Expected signal: 1.2 events

arXiv: 2007.07830

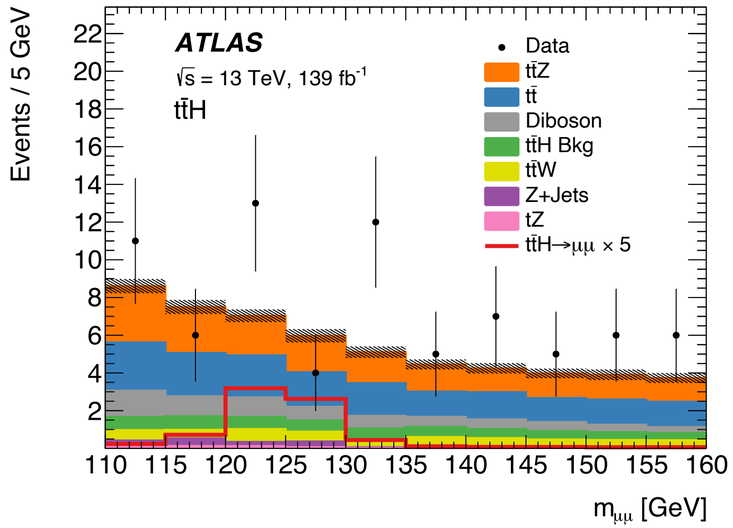








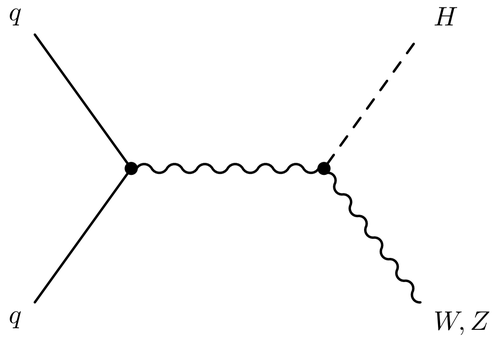
After BDT selection

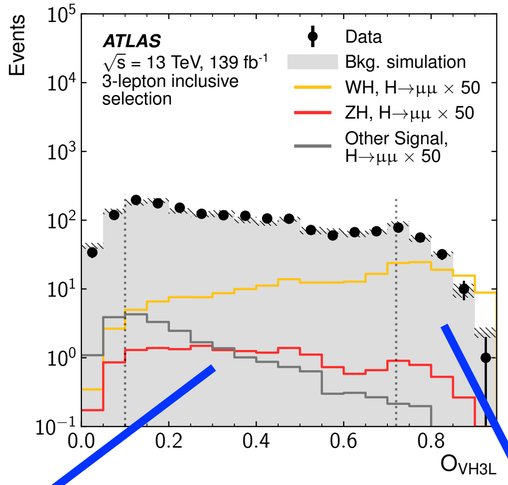


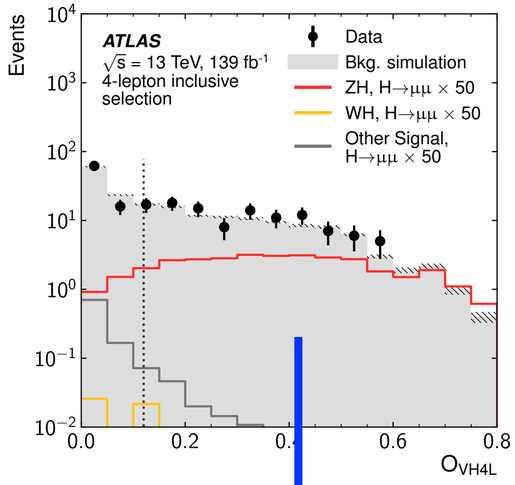
VH Categories

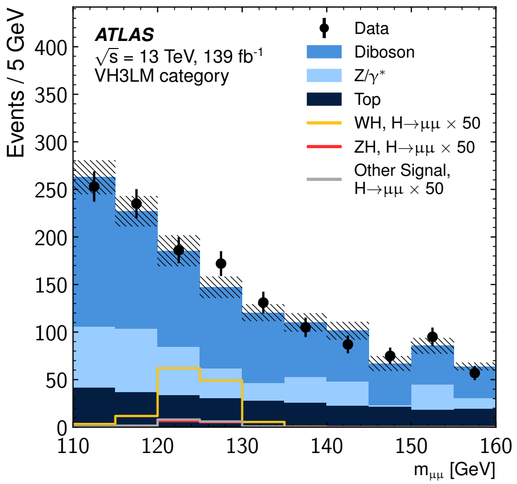
- WH/ZH, (H → μμ). Expected signal: 4.7 events
- Two BDTs: one BDT for 3 lepton (8 variables) and another BDT for 4 lepton (7 variables)
- Main background: Diboson

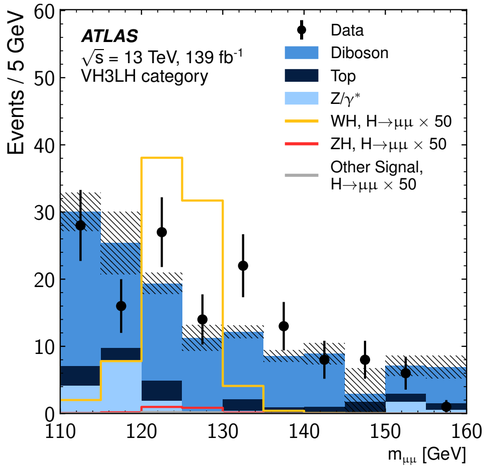
arXiv: 2007.07830

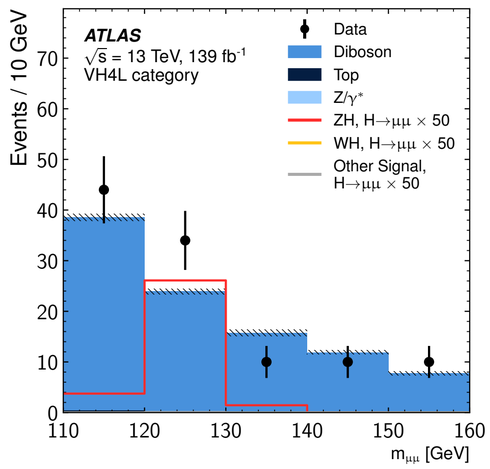






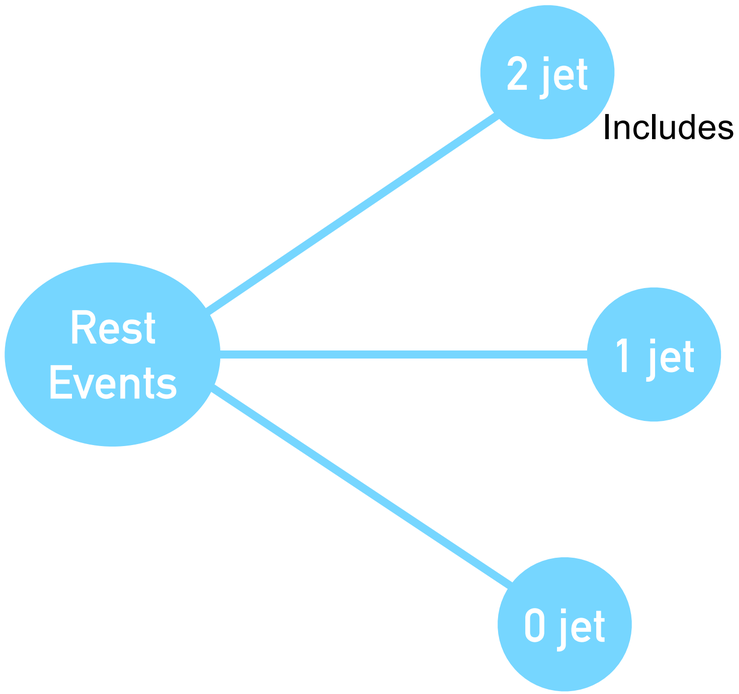




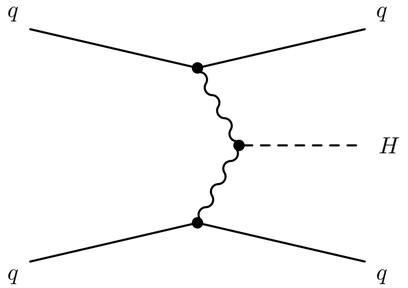


VBF and ggF Categories

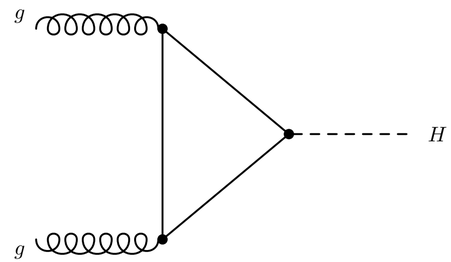
arXiv: 2007.07830



Includes events with 2 or more jets.

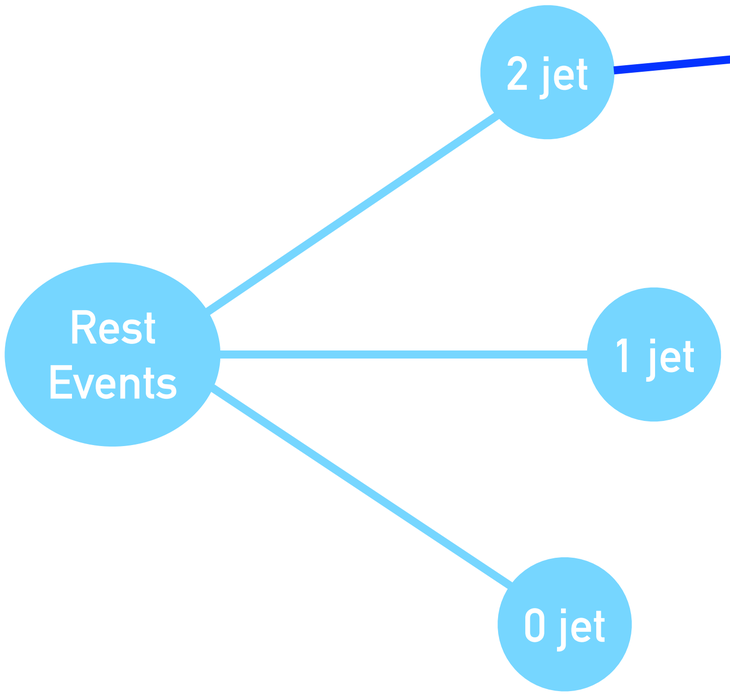


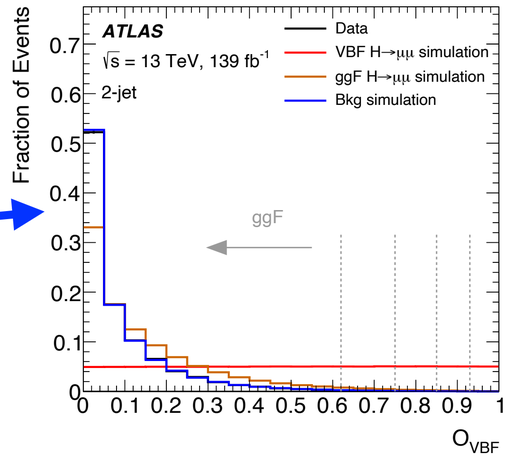
ggF



VBF

VBF and ggF Categories

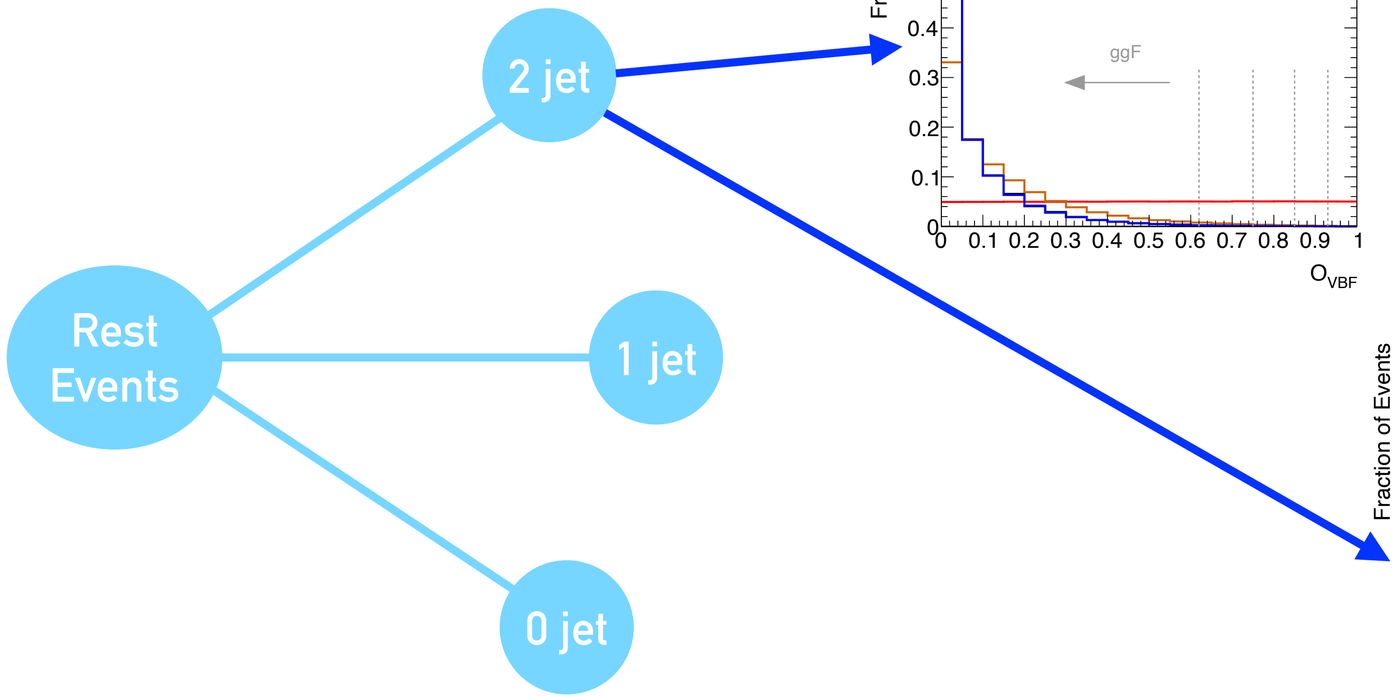


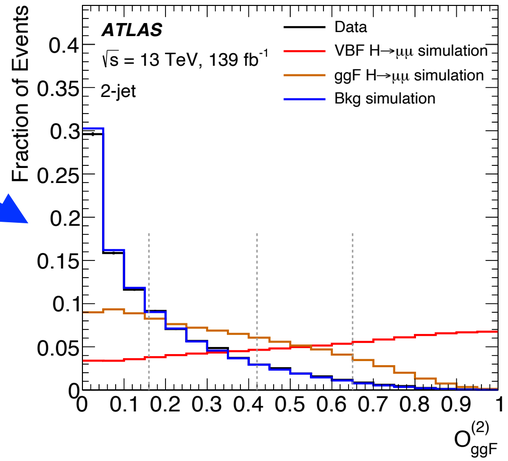


arXiv: 2007.07830

VBF and ggF Categories

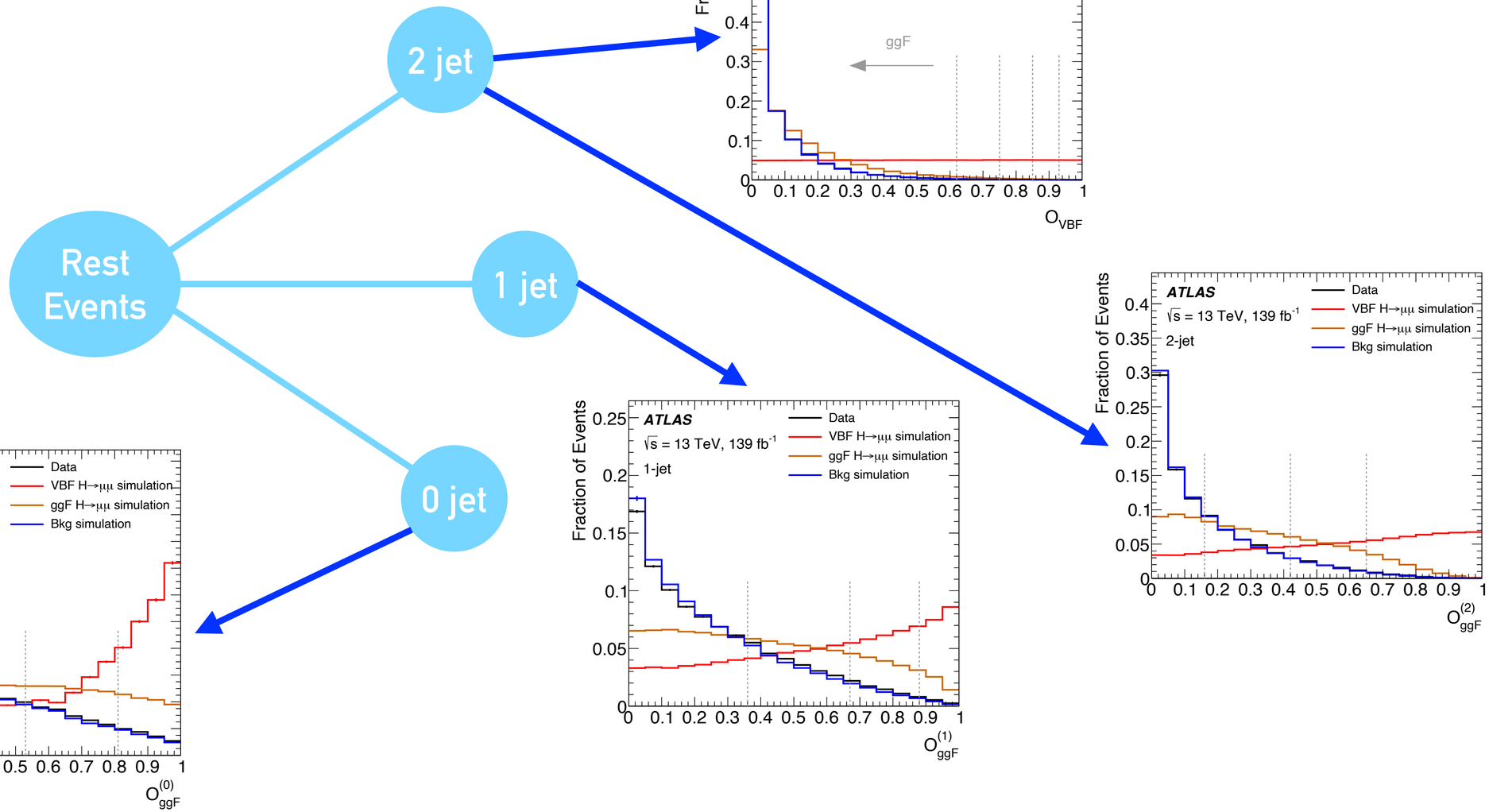
arXiv: 2007.07830





VBF and ggF Categories

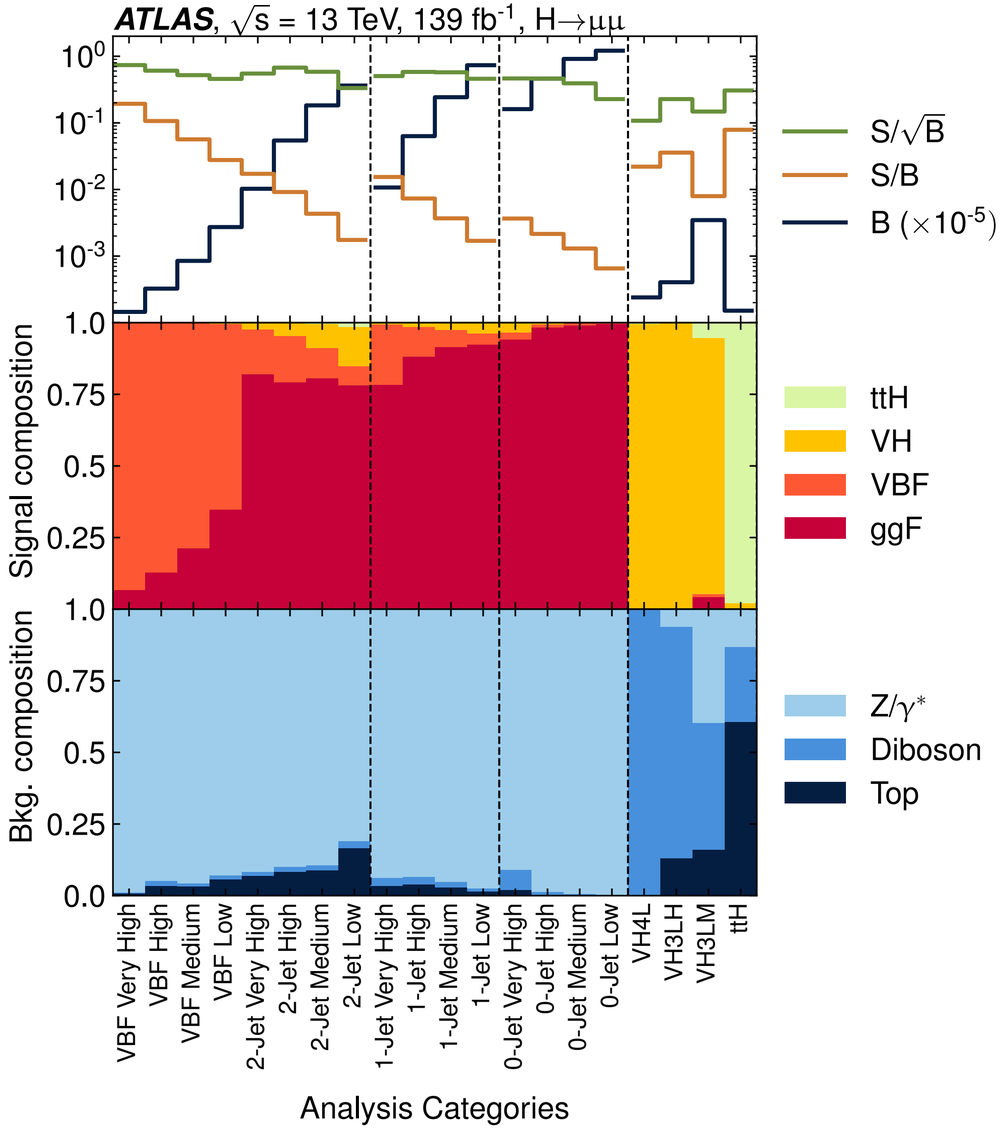
arXiv: 2007.07830



Event Categorization

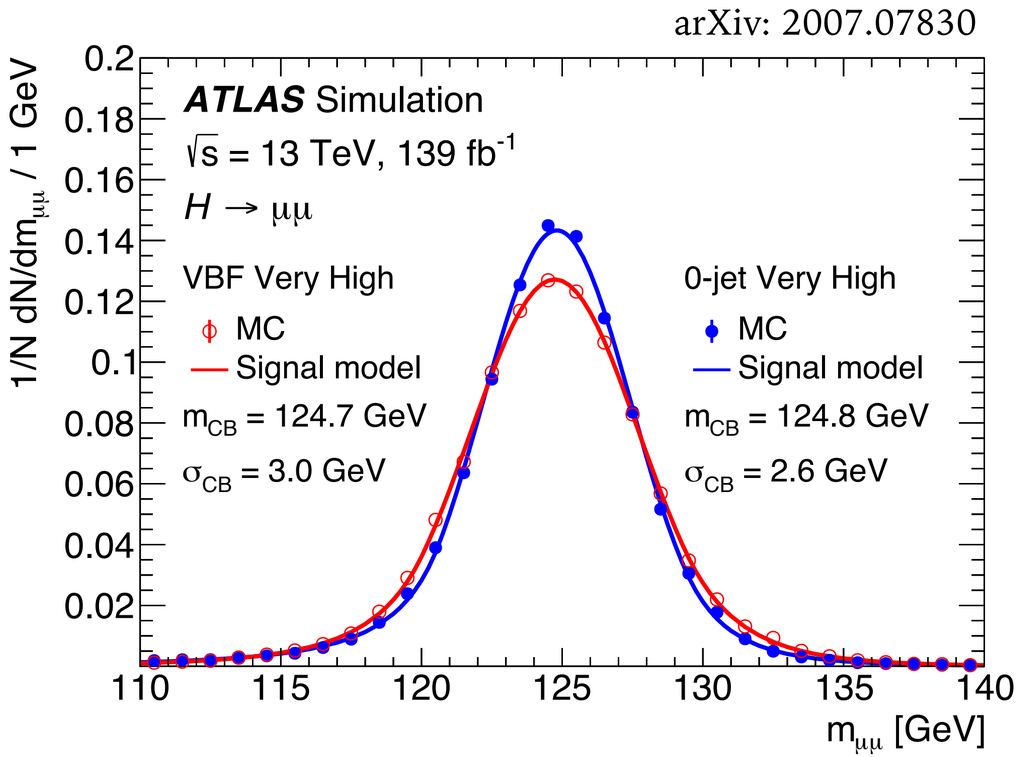
- 20 categories in total

arXiv: 2007.07830



Signal Modeling

- Double-sided Crystal-Ball function is used to model the signal shape, which is described by a Gaussian core of distribution and two asymmetric exponential tails as below:



$$f_{DCB}(m_{\mu\mu}) = \begin{cases} \exp\left[-\left(\frac{m_{\mu\mu}-M_{CB}}{\sigma_{CB}}\right)^2/2\right] & \text{if } \alpha_{low} \le \frac{m_{\mu\mu}-M_{CB}}{\sigma_{CB}} \le \alpha_{high} \\ \frac{\exp\left[-\alpha_{low}^2/2\right]}{\left[\frac{\alpha_{low}}{n_{low}}\left(\frac{n_{low}}{\alpha_{low}} - \alpha_{low} + \frac{m_{\mu\mu}-M_{CB}}{\sigma_{CB}}\right)\right]^{n_{low}}} & \text{if } \frac{m_{\mu\mu}-M_{CB}}{\sigma_{CB}} \le \alpha_{low} \\ \frac{\exp\left[-\alpha_{high}^2/2\right]}{\left[\frac{\alpha_{high}}{n_{high}}\left(\frac{n_{high}}{\alpha_{high}} - \alpha_{high} + \frac{m_{\mu\mu}-M_{CB}}{\sigma_{CB}}\right)\right]^{n_{high}}} & \text{if } \frac{m_{\mu\mu}-M_{CB}}{\sigma_{CB}} \ge \alpha_{high} \end{cases}$$

- M_{CB}: mean value of the DCB function
- σ_{CB}: width of the DCB function
- α_{low}: threshold for the left low-end tail
- α_{high}: threshold for the right low-end tail
- n_{low}: power in the left low-end tail
- n_{high}: power in the right low-end tail

Background Modeling

- Proposed model with two components: [fix] x [floating]

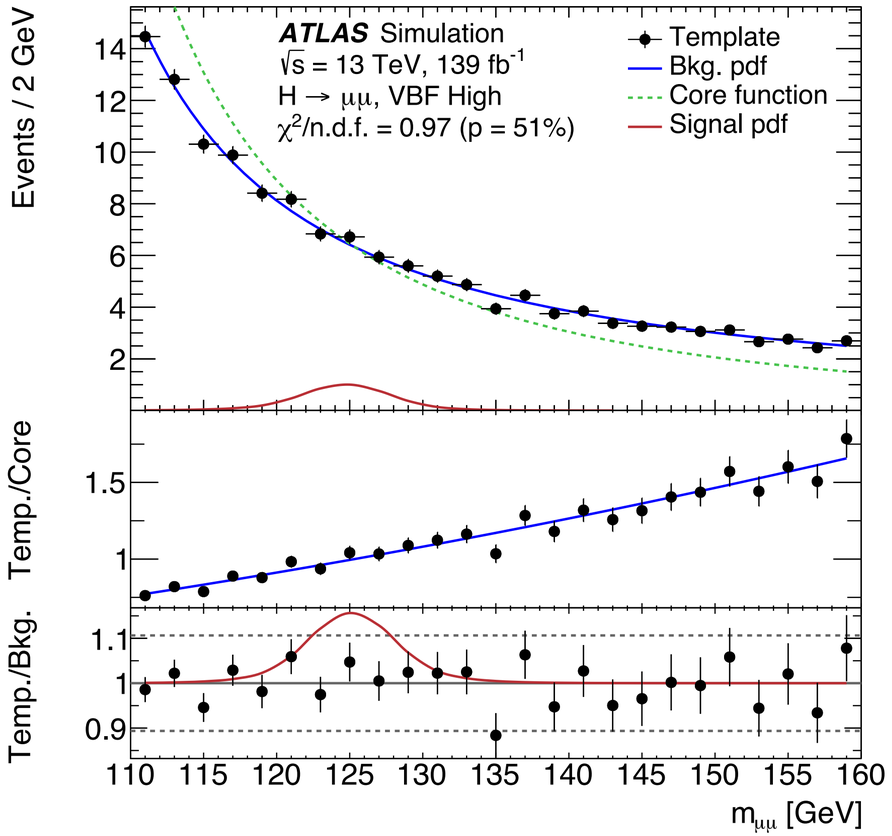
arXiv: 2007.07830

  - Fixed part (physics motivated): LO 2 → 2 Drell-Yan analytic lineshape
    - $m_{\mu\mu}$ resolution effect included by smearing with Gaussian
  - Floating part: **Chosen with high-stat DY fast simulated sample**

Category	Empirical Function
VBF Very High	Epoly1
VBF High	Power0
VBF Medium	Power0
VBF Low	Power0
2-jet Very High	Power1
2-jet High	Epoly2
2-jet Medium	Power1
2-jet Low	Epoly3
1-jet Very High	Epoly2
1-jet High	Epoly2
1-jet Medium	Power1
1-jet Low	Power1
0-jet Very High	Power1
0-jet High	Power1
0-jet Medium	Power1
0-jet Low	Epoly3
VH4L	Power1
VH3LH	Epoly2
VH3LM	Epoly3
$t\bar{t}H$	Power0

Function	Expression
PowerN	$m_{\mu\mu}^{(a_0+a_1 m_{\mu\mu}+a_2 m_{\mu\mu}^2+\ldots+a_N m_{\mu\mu}^N)}$
EpolyN	$\exp(a_1 m_{\mu\mu} + a_2 m_{\mu\mu}^2 + \ldots + a_N m_{\mu\mu}^N)$

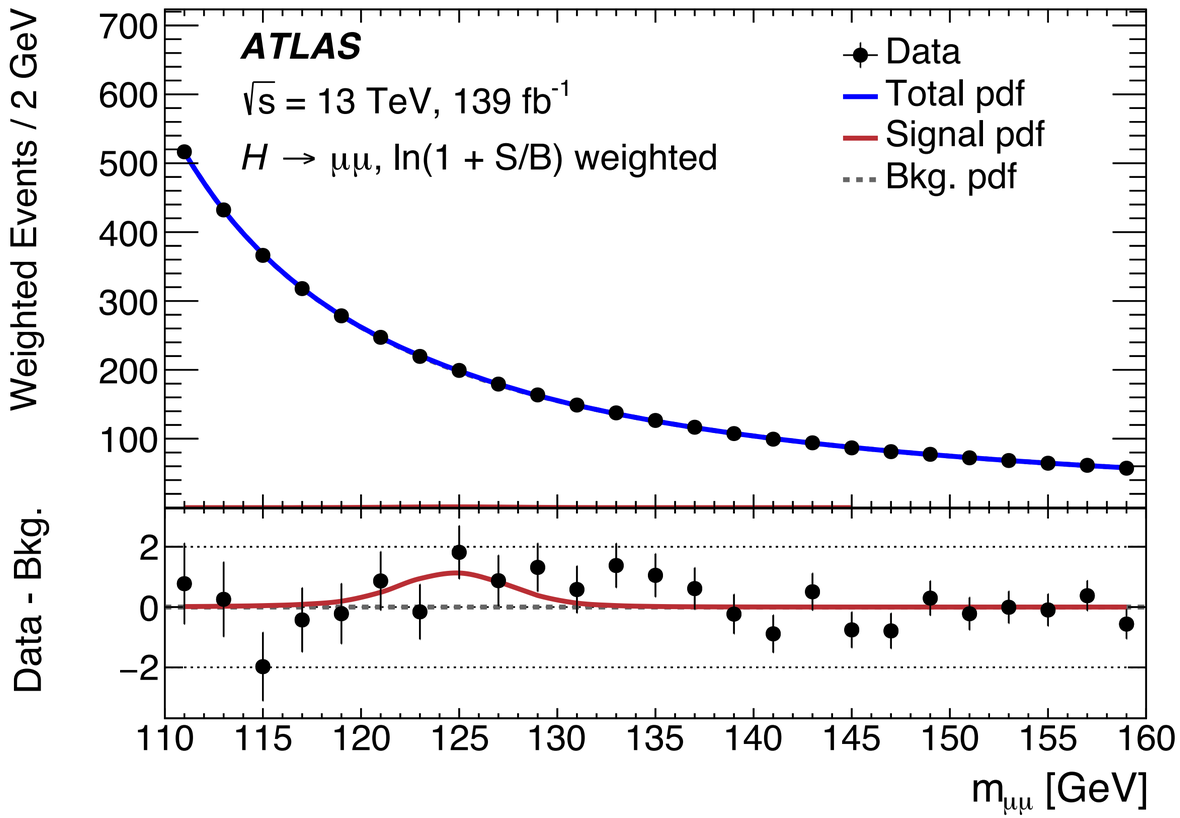
Simultaneously fit with 20 categories to extract signal strength



Results

Statistical Results

arXiv: 2007.07830



Significance: 2.0σ (1.7σ expected)

Best fit: μ = 1.2 ± 0.6

Data statistics: ±0.58

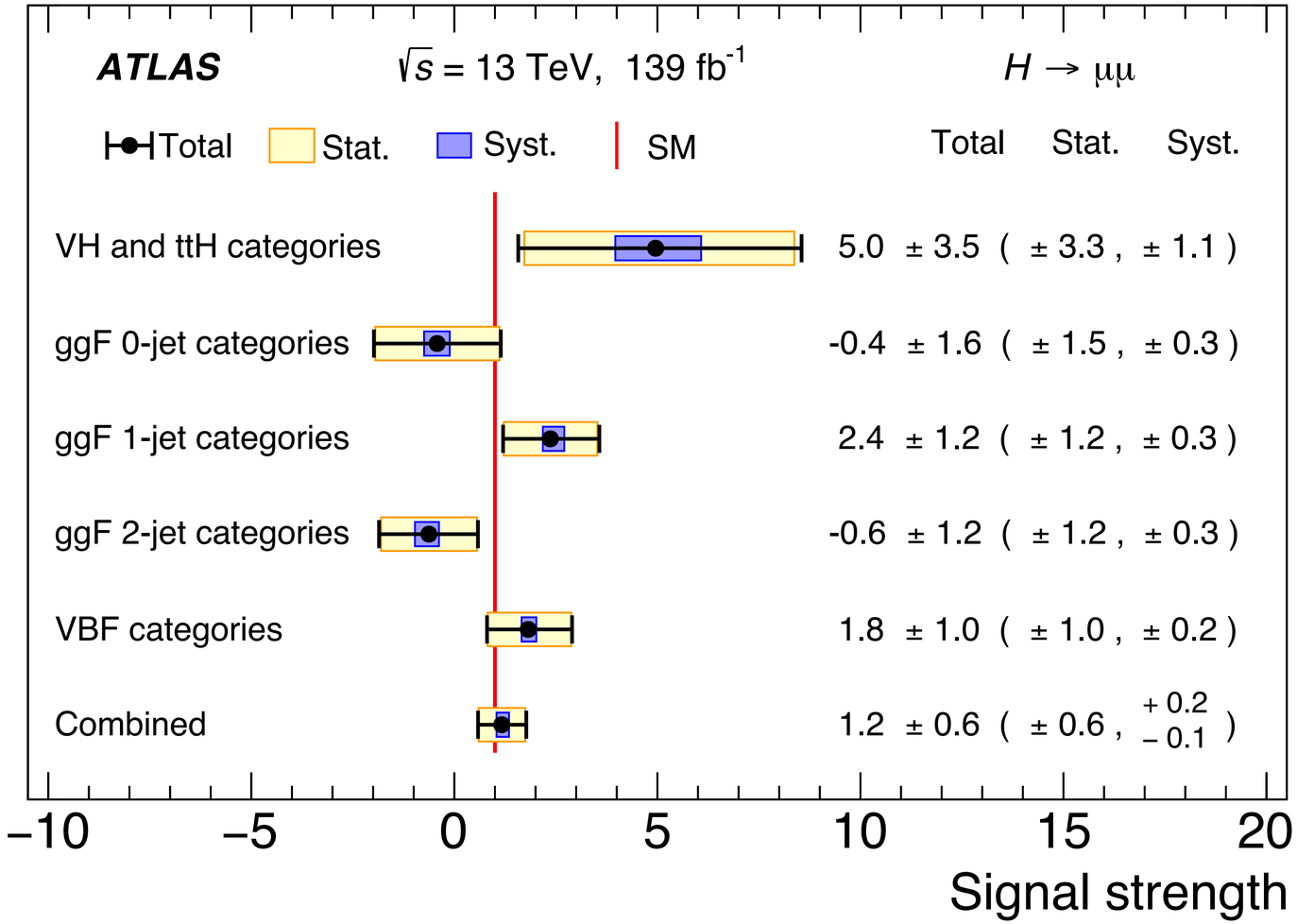
Signal theory syst.: +0.13 -0.08

Signal experimental syst.: +0.07 -0.03

Spurious signal syst.: ±0.10

Signal Strength in Different Categories

arXiv: 2007.07830



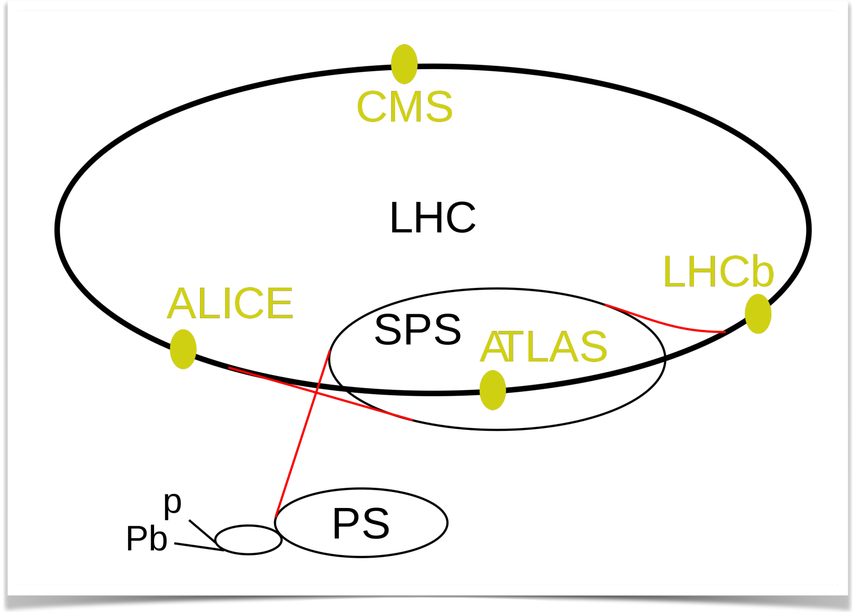
Summary

- H → μμ is used to probe the Higgs coupling to second generation fermions. arXiv: 2007.07830
- H → μμ search with full Run2 data. Observed significance: 2.0**σ** (1.7**σ** expected).
- Best-fit combined signal strength: μ = 1.2 ± 0.6.

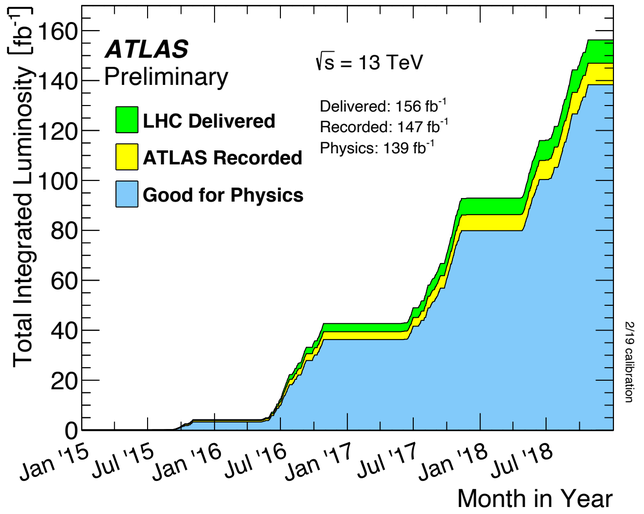
- Outlook:
  - Need more data to understand the coupling between Higgs boson and muons.
  - LHC Run3 will start from Feb 2022.

Backup

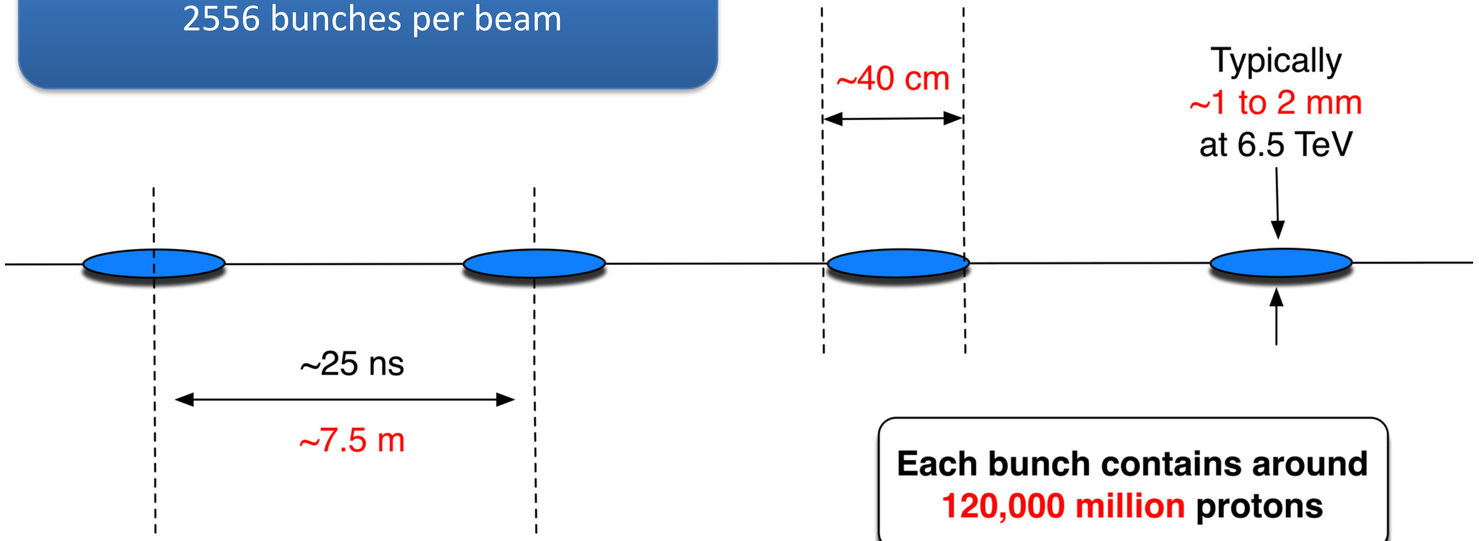
Large Hadron Collider (LHC) Run2



- 2 beams travel in opposite directions, and intersect at four points which is where the particle collisions take place
- each proton beam at full intensity will consist of 2808 bunches
- each bunch will contain 115 billion protons at the start of nominal fill
- the time interval between bunches is 25 ns
- 40 million collisions per second



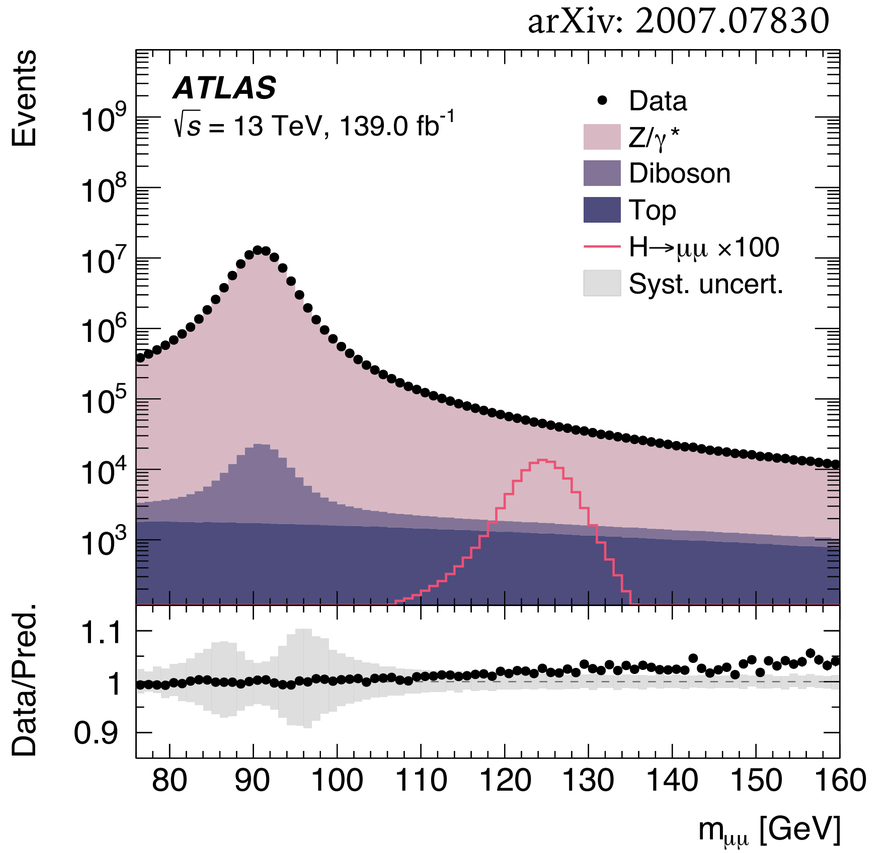
In 2017 the LHC is operating with 2556 bunches per beam



Each bunch contains around 120,000 million protons

Higgs to μμ

- The Higgs cross section at 13 TeV is about 55 pb. With 140 fb^{-1} data, ~8 million Higgs boson have been produced.
- 1540 of them decay to μμ.

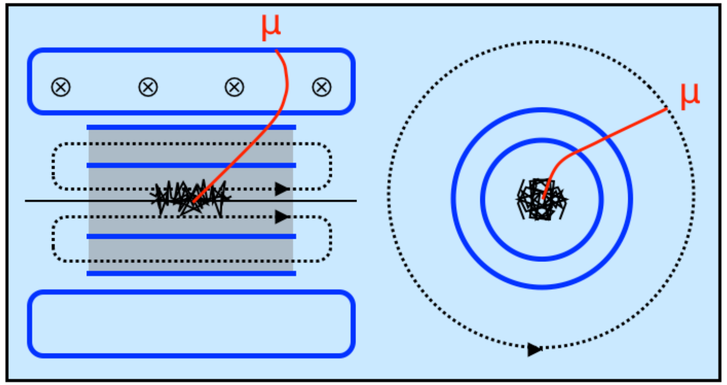


- Why it is so difficult to find H → μμ ?
  - Low branching ratio
  - Large irreducible background

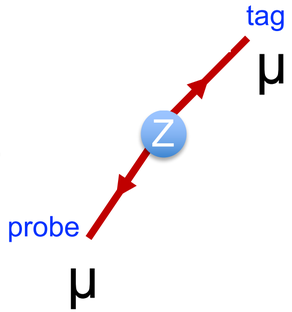
  ➡ signal/background ratio typically at 0.1% level
    - Hard to find signal (requires good separation between signal and background)
    - Result can be easily biased from background mismodeling

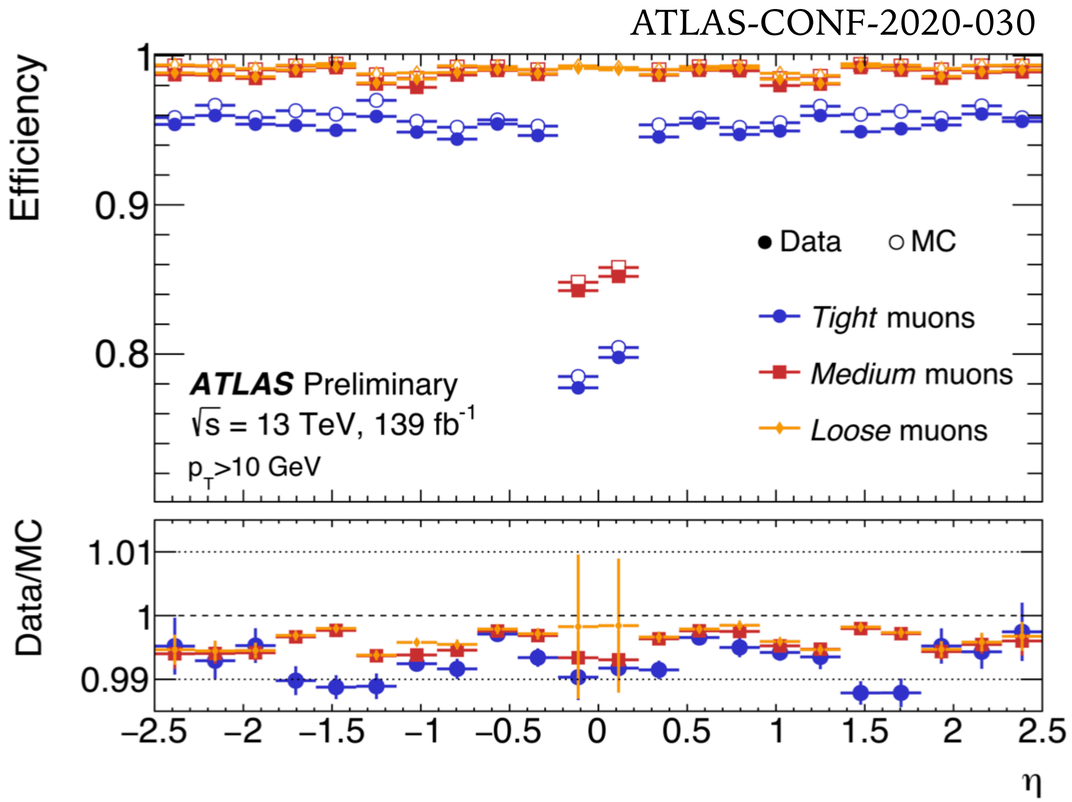
Reconstruction and Calibration in the Muon Spectrometer

- Reconstruction:
  - In the x-y plane, muon's track is a straight line



- Calibration:
  - Use the Z → μμ samples

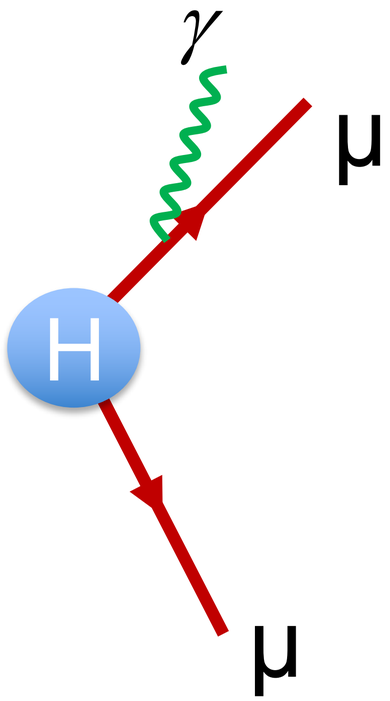


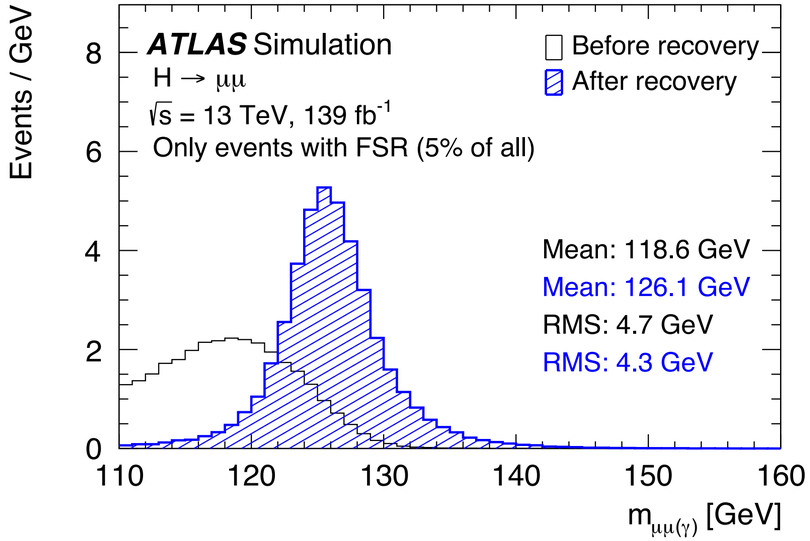


  - Within the ID acceptance |η| < 2.5, the *Medium working point* accepts only CB muons.
  - The *Loose* selection working point accepts all the muons passing the *Medium WP*. In addition, it includes CT and ST muons in the range |η| < 0.1.

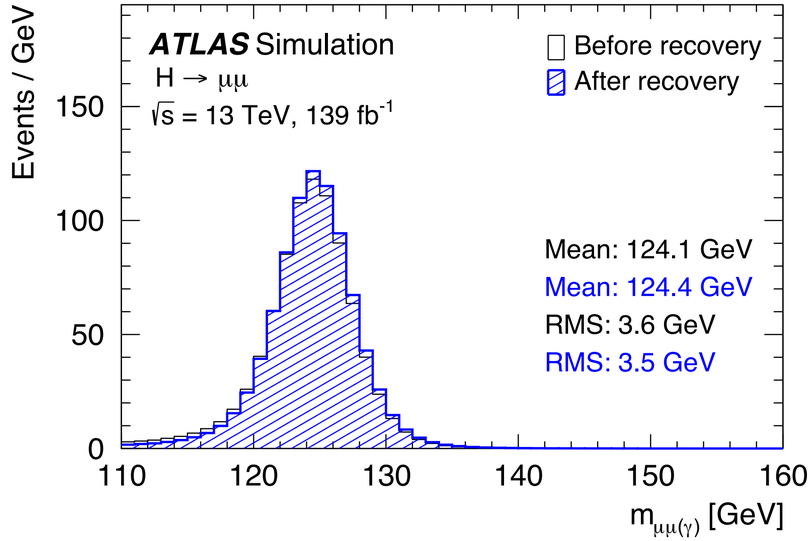
Muon QED Final State Radiation

- Add FSR photon to $m_{\mu\mu}$ calculation to improve the $m_{\mu\mu}$ resolution





arXiv: 2007.07830



- The FSR recovery leads to a narrower mass distributions and decreases the peak RMS by around 3%.

Event Yields

- Events within $m_{\mu\mu}$ = 120-130 GeV

arXiv: 2007.07830

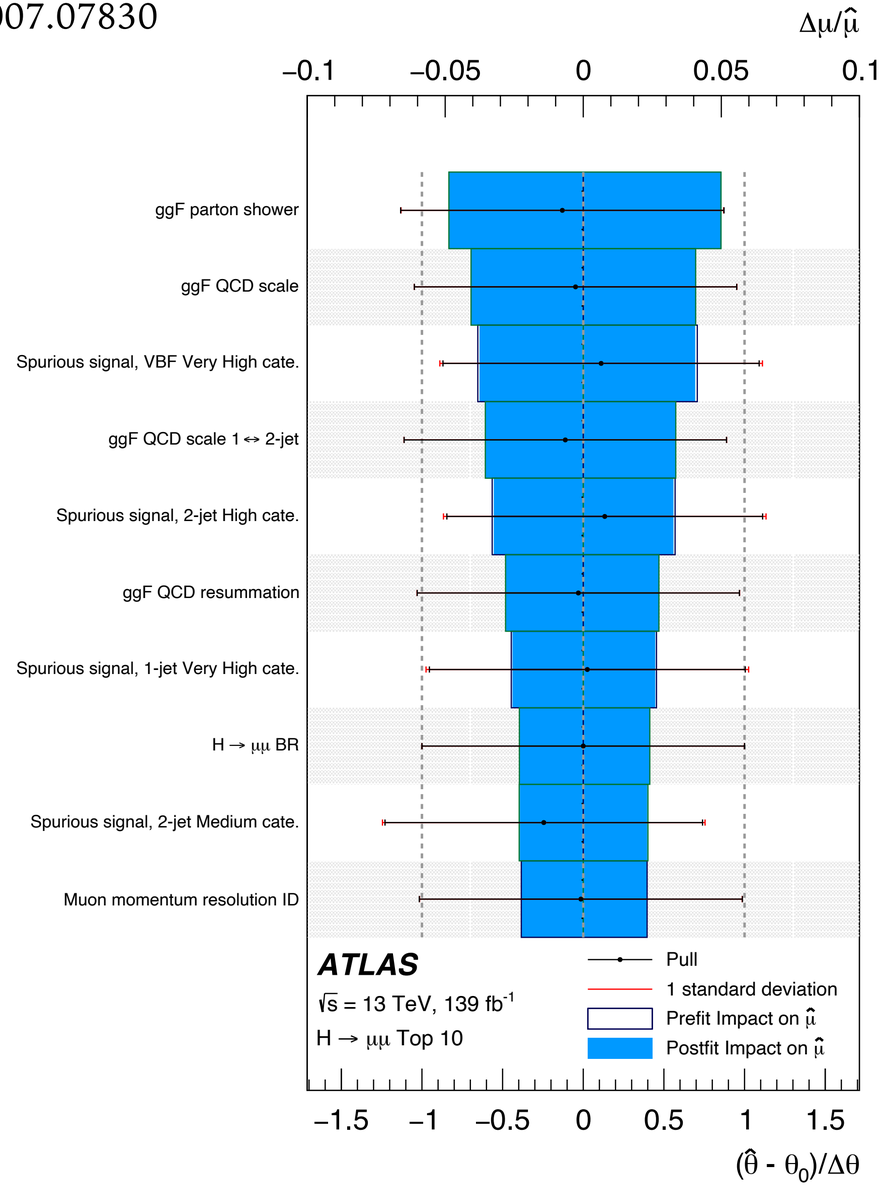
Category	Data	S_{SM}	S	B	$S/\sqrt{B}$	S/B [%]	σ [GeV]
VBF Very High	15	2.81 ± 0.27	3.3 ± 1.7	14.5 ± 2.1	0.86	22.6	3.0
VBF High	39	3.46 ± 0.36	4.0 ± 2.1	32.5 ± 2.9	0.71	12.4	3.0
VBF Medium	112	4.8 ± 0.5	5.6 ± 2.8	85 ± 4	0.61	6.6	2.9
VBF Low	284	7.5 ± 0.9	9 ± 4	273 ± 8	0.53	3.2	3.0
2-jet Very High	1030	17.6 ± 3.3	21 ± 10	1024 ± 22	0.63	2.0	3.1
2-jet High	5433	50 ± 8	58 ± 30	5440 ± 50	0.77	1.0	2.9
2-jet Medium	18 311	79 ± 15	90 ± 50	$18\,320 \pm 90$	0.66	0.5	2.9
2-jet Low	36 409	63 ± 17	70 ± 40	$36\,340 \pm 140$	0.37	0.2	2.9
1-jet Very High	1097	16.5 ± 2.4	19 ± 10	1071 ± 22	0.59	1.8	2.9
1-jet High	6413	46 ± 7	54 ± 28	6320 ± 50	0.69	0.9	2.8
1-jet Medium	24 576	90 ± 11	100 ± 50	$24\,290 \pm 100$	0.67	0.4	2.7
1-jet Low	73 459	125 ± 17	150 ± 70	$73\,480 \pm 190$	0.53	0.2	2.8
0-jet Very High	15 986	59 ± 11	70 ± 40	$16\,090 \pm 90$	0.55	0.4	2.6
0-jet High	46 523	99 ± 13	120 ± 60	$46\,190 \pm 150$	0.54	0.3	2.6
0-jet Medium	91 392	119 ± 14	140 ± 70	$91\,310 \pm 210$	0.46	0.2	2.7
0-jet Low	121 354	79 ± 10	90 ± 50	$121\,310 \pm 280$	0.26	0.1	2.7
VH4L	34	0.53 ± 0.05	0.6 ± 0.3	24 ± 4	0.13	2.6	2.9
VH3LH	41	1.45 ± 0.14	1.7 ± 0.9	41 ± 5	0.27	4.2	3.1
VH3LM	358	2.76 ± 0.24	3.2 ± 1.6	347 ± 15	0.17	0.9	3.0
$t\bar{t}H$	17	1.19 ± 0.13	1.4 ± 0.7	15.1 ± 2.2	0.36	9.2	3.2

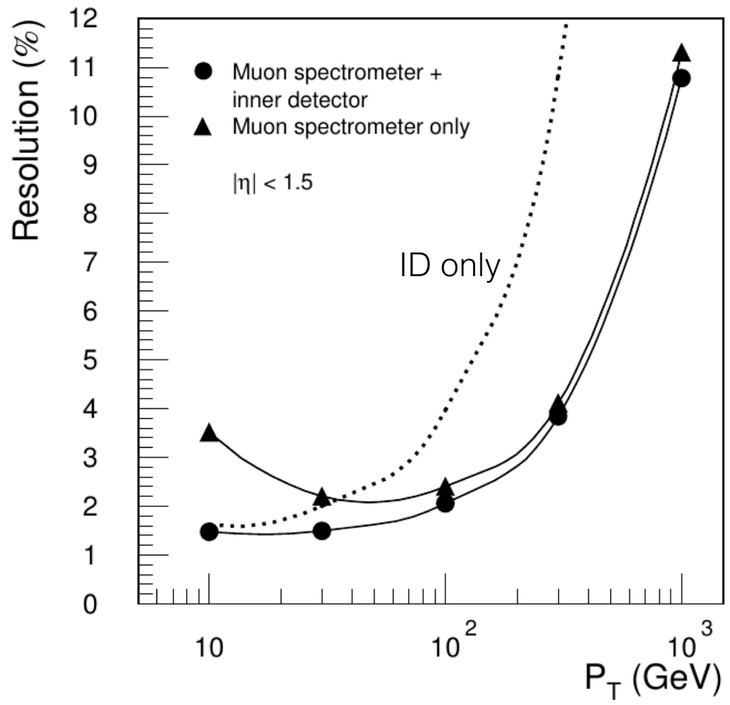
Systematic Uncertainties

arXiv: 2007.07830

Main systematic uncertainties

- Theory uncertainty on signal cross-section
- Experimental uncertainties on muon selection efficiency
- Spurious signal systematic per category due to background fit



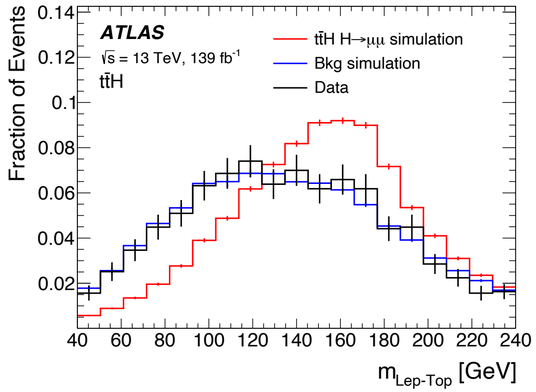


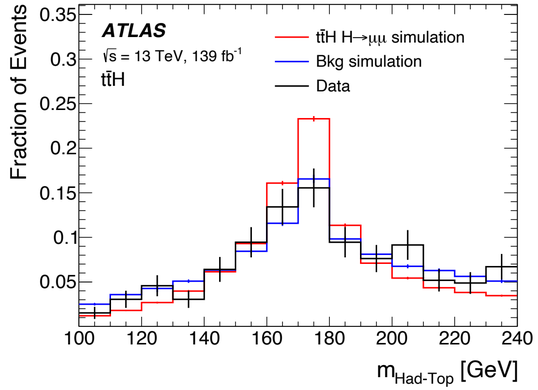
- Most H → μμ signal have muon P_T between 50 GeV and 100 GeV
- Sensitivity to signal is proportional to the $1/\sqrt{\sigma}$

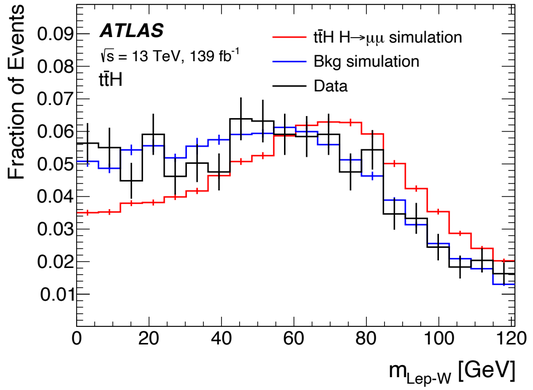
$$\frac{S}{\sqrt{B}} \sim \frac{1}{\sqrt{\sigma}}$$

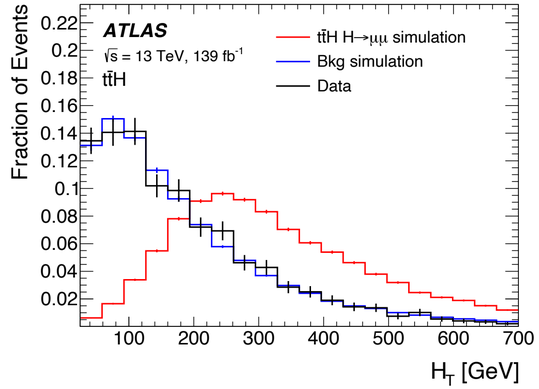
Improving the dimuon mass resolution is the key to find H → μμ signal at LHC

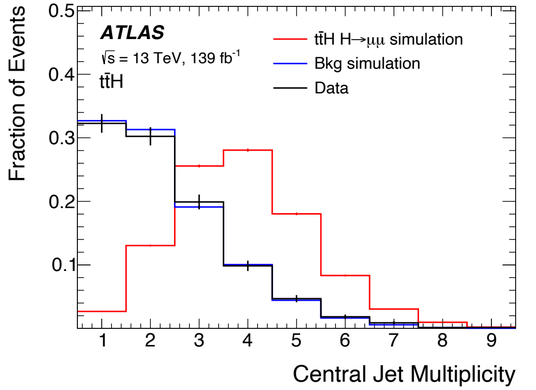
ttH BDT Training Variables

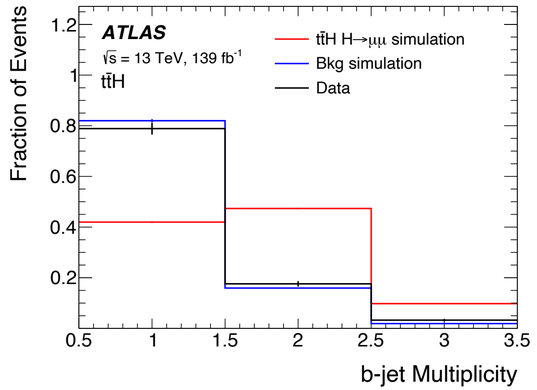


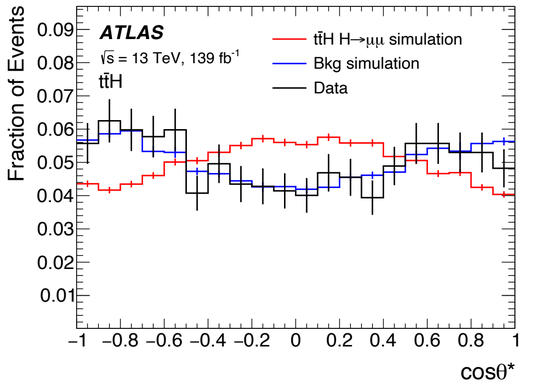


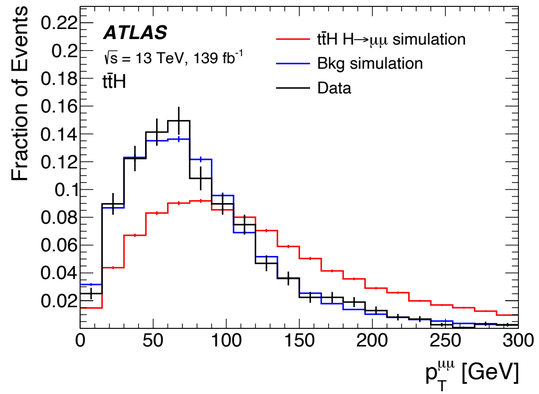


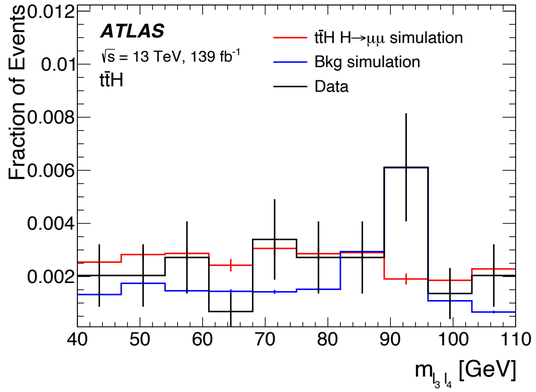


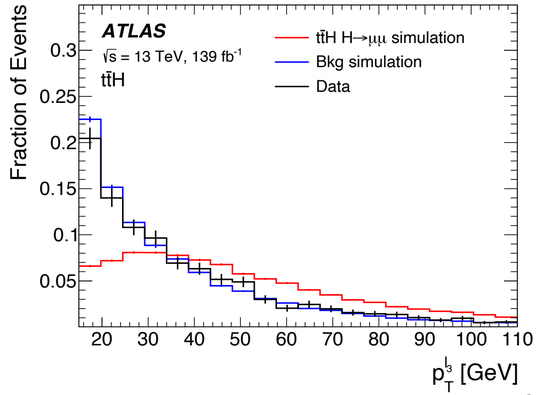


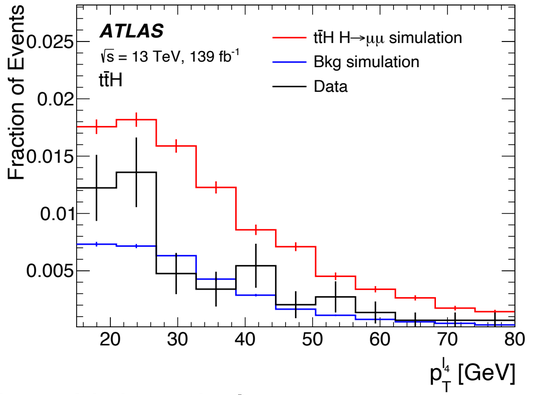


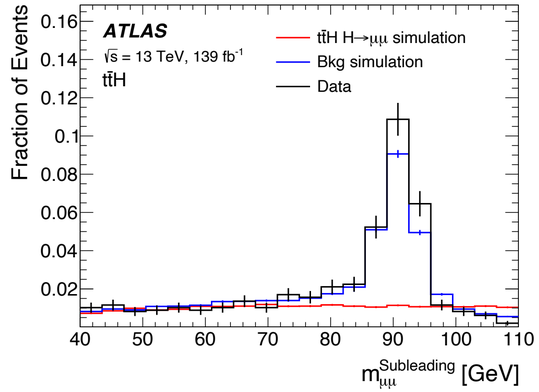




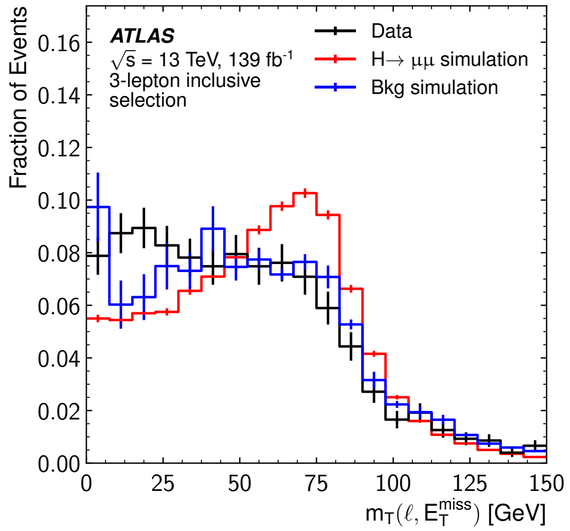


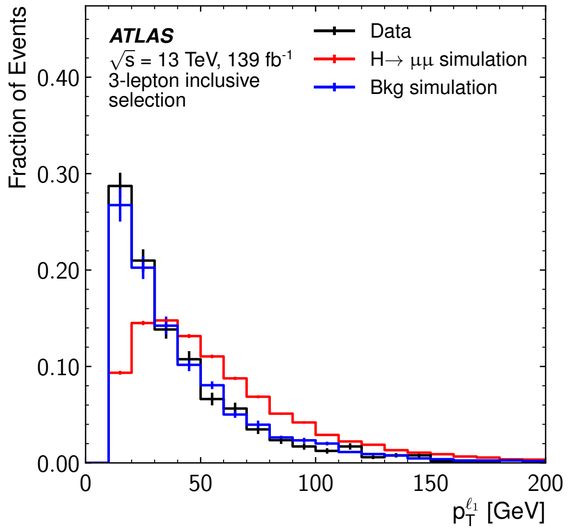


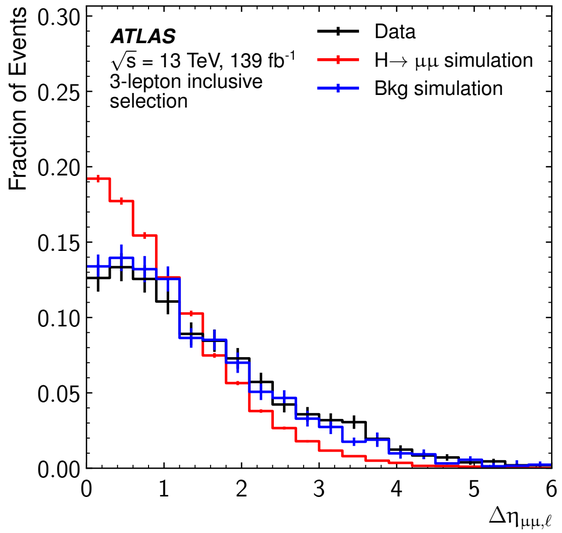


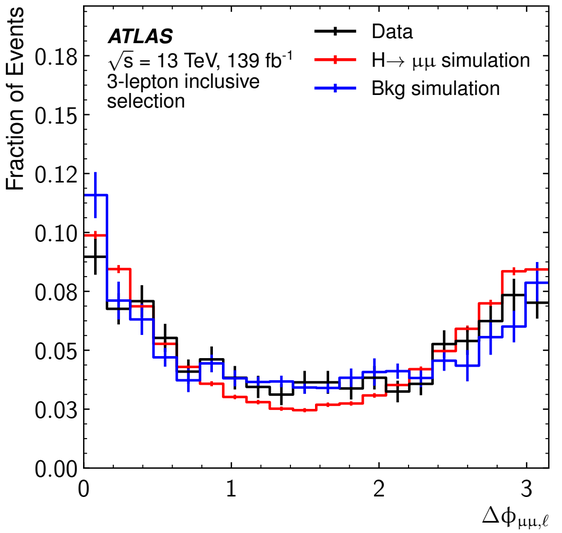


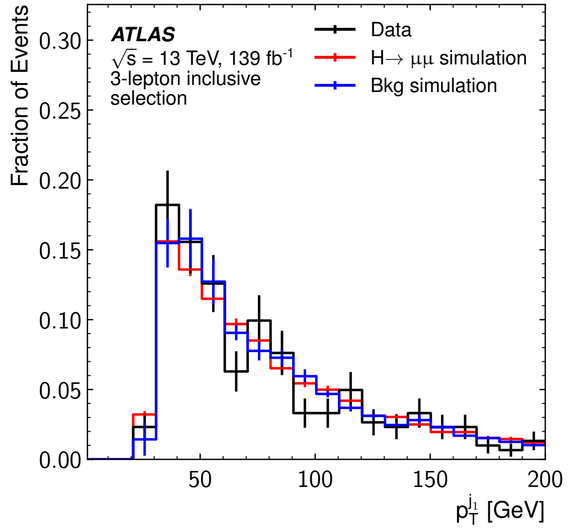
VH 3-lepton BDT Training Variables

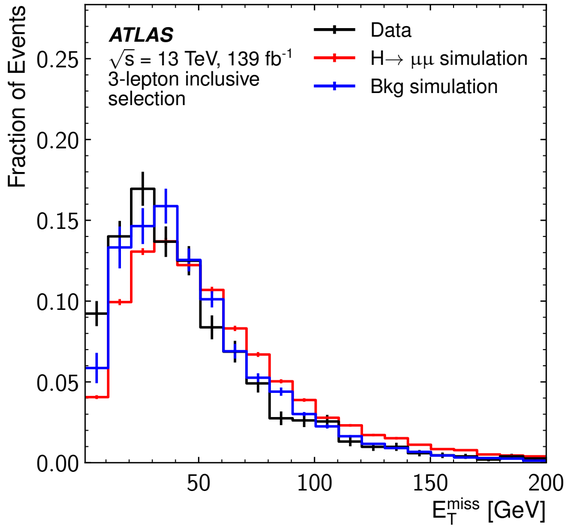


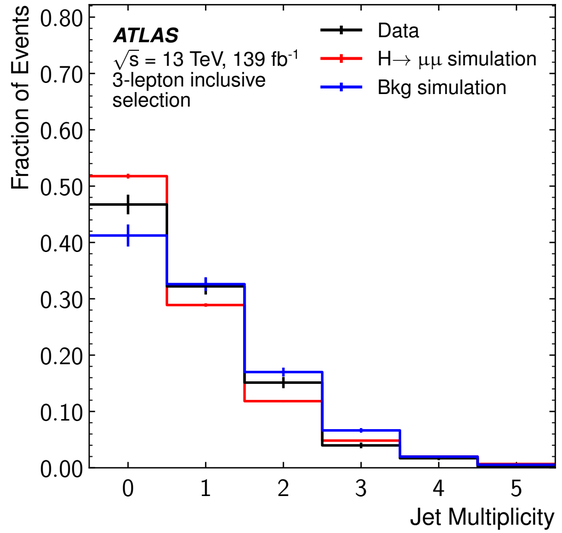


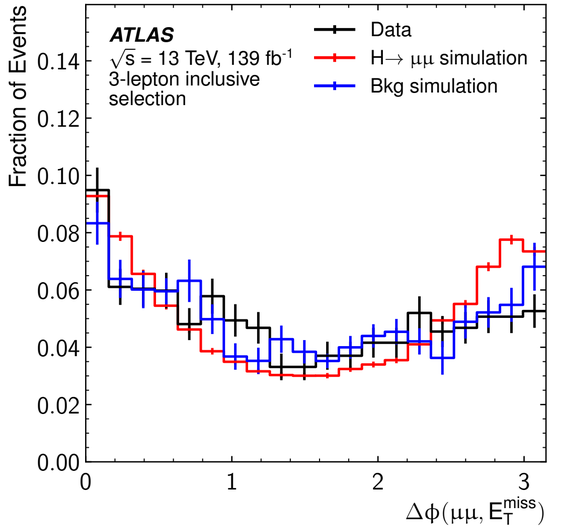




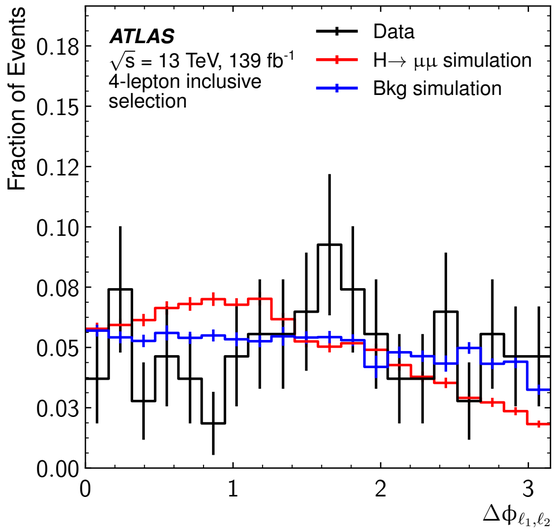


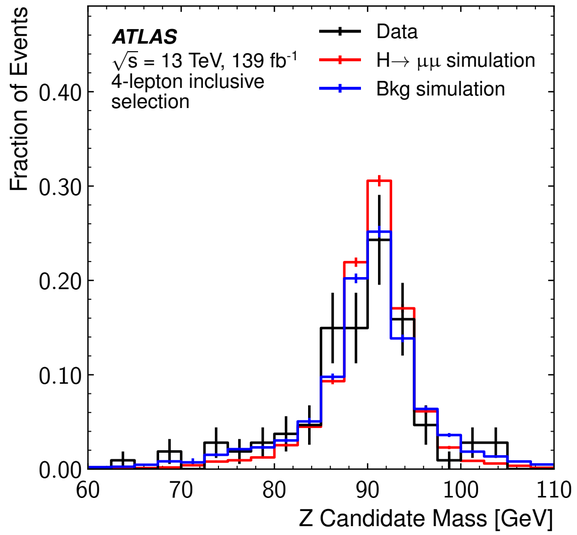


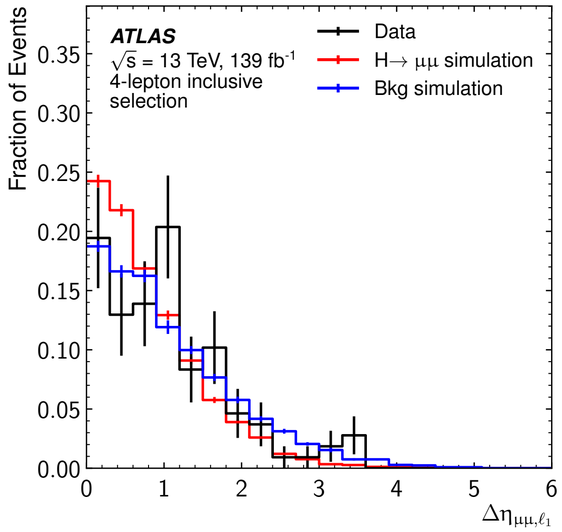


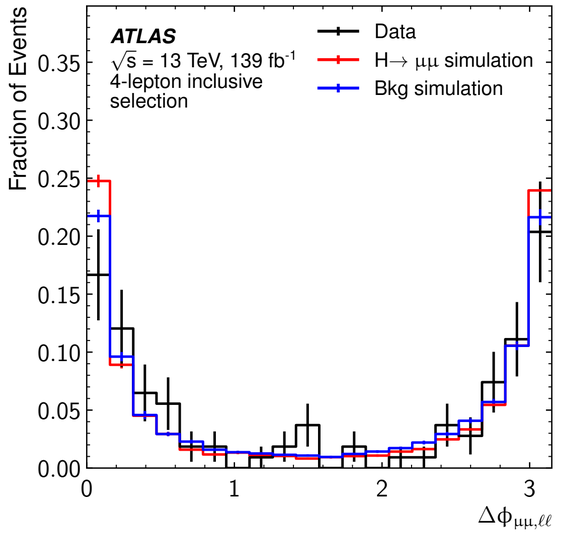


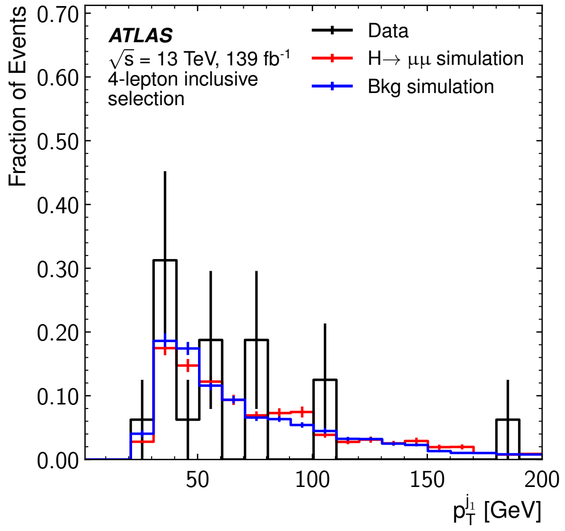
VH 4-lepton BDT Training Variables

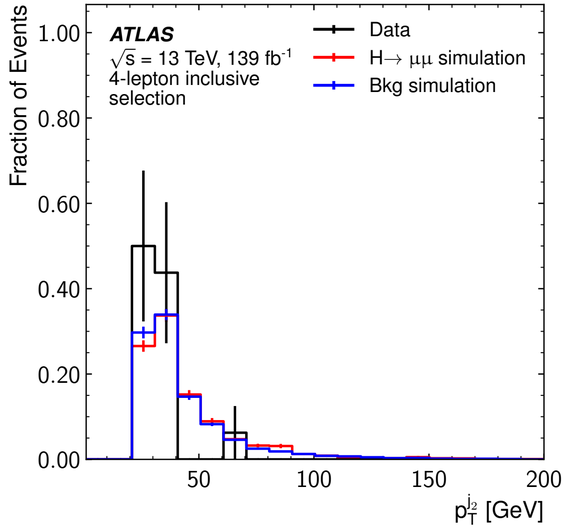


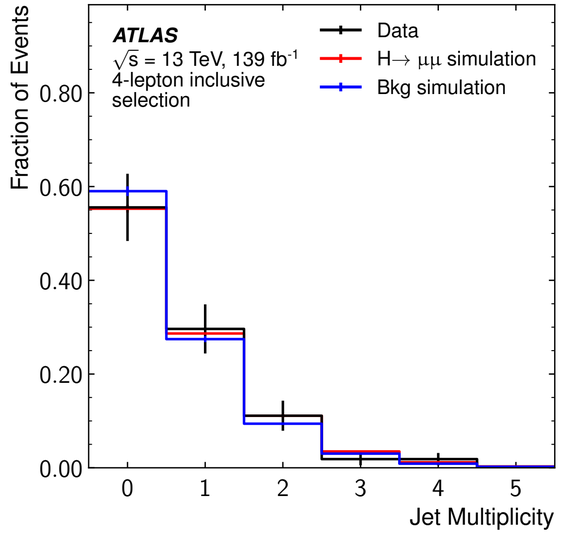




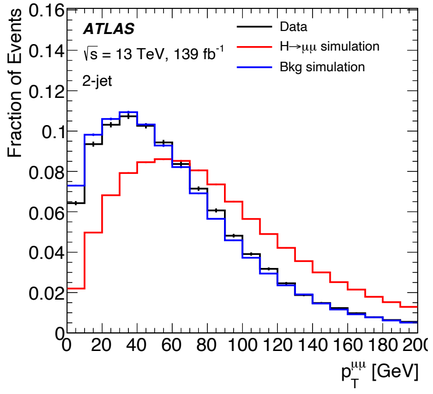


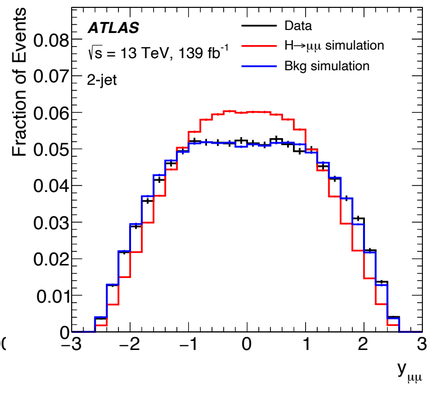


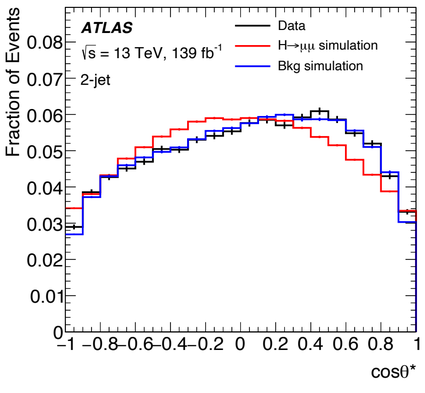


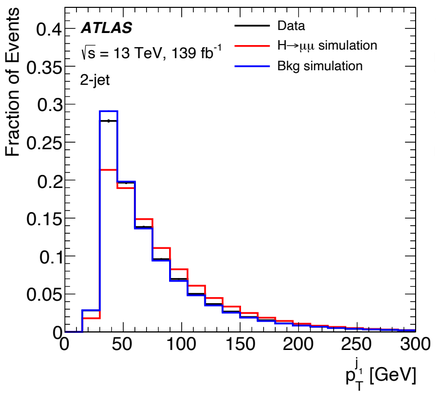


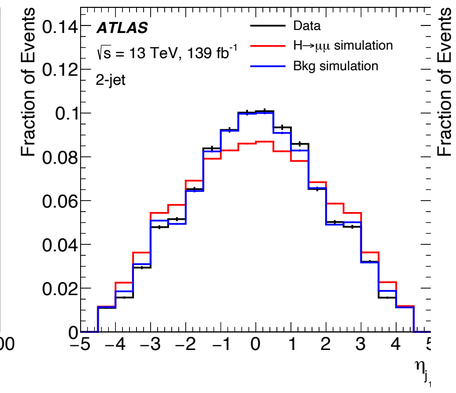
2-jet BDT Training Variables

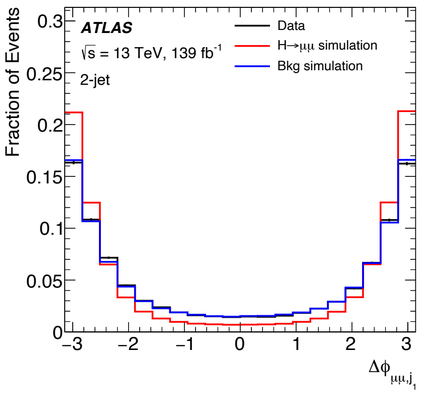


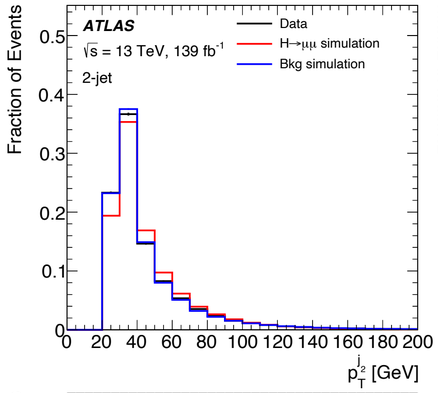


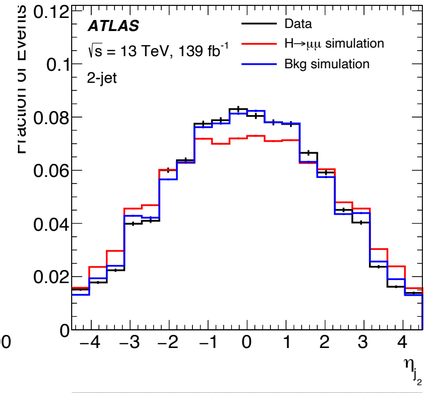


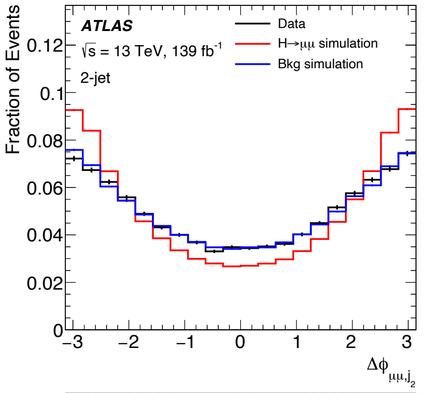


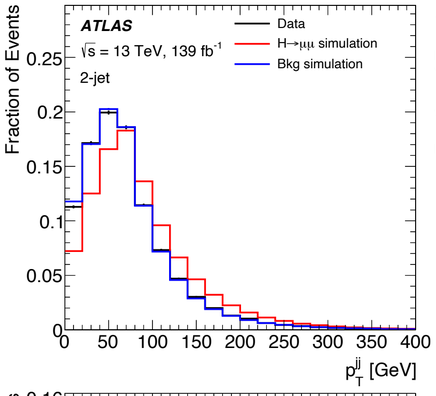


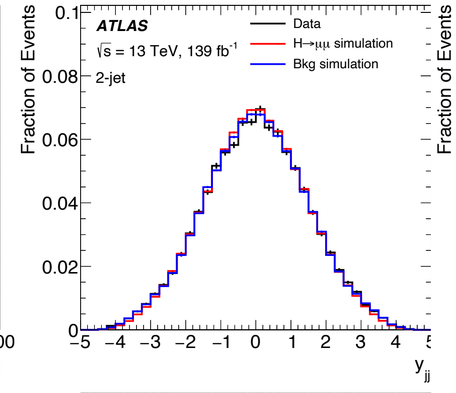


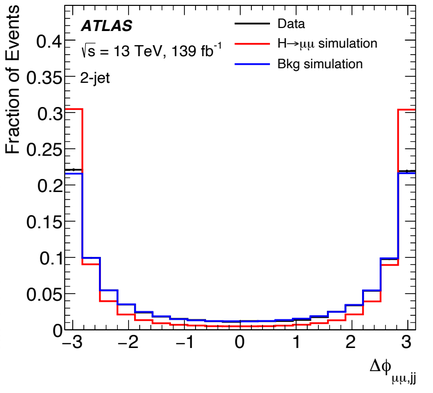


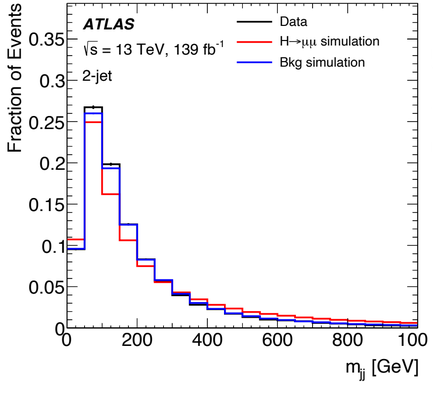


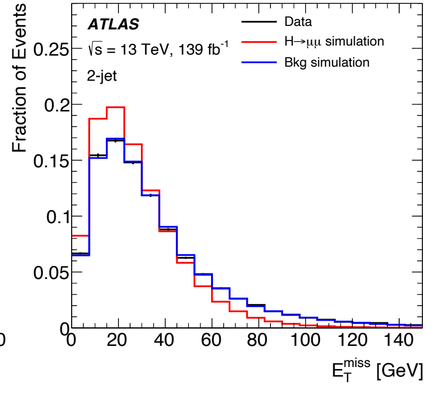


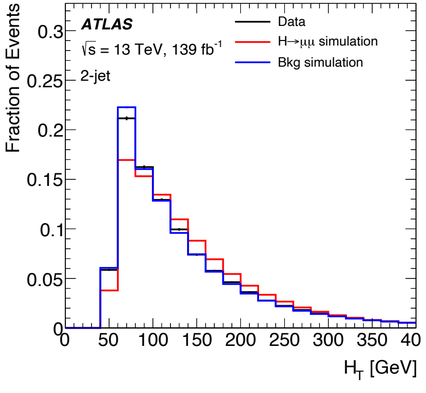


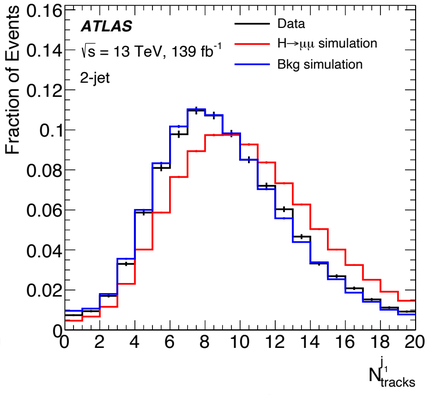


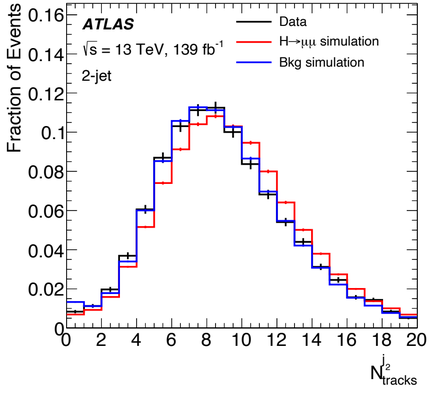




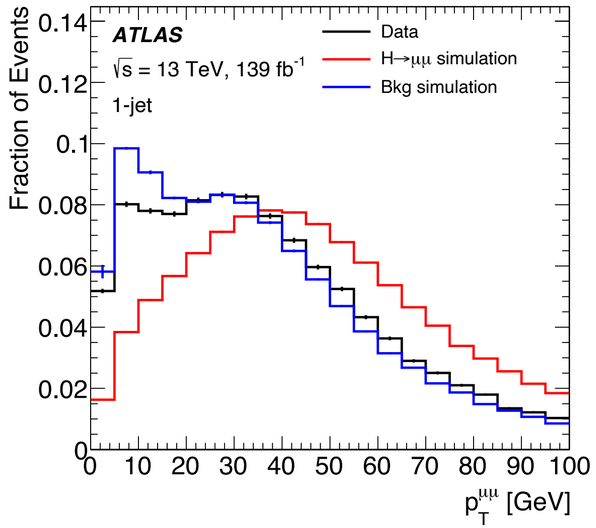


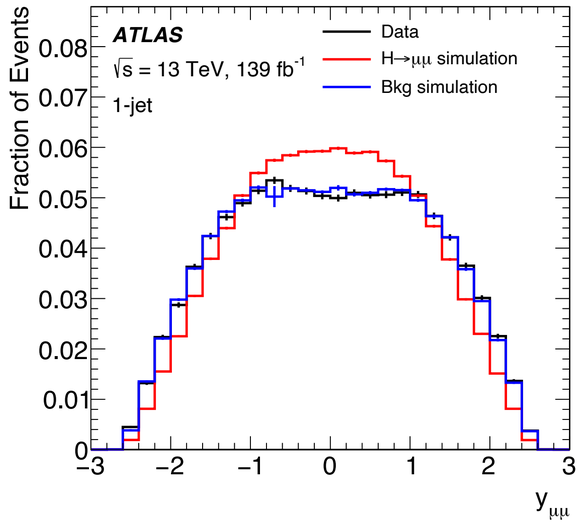


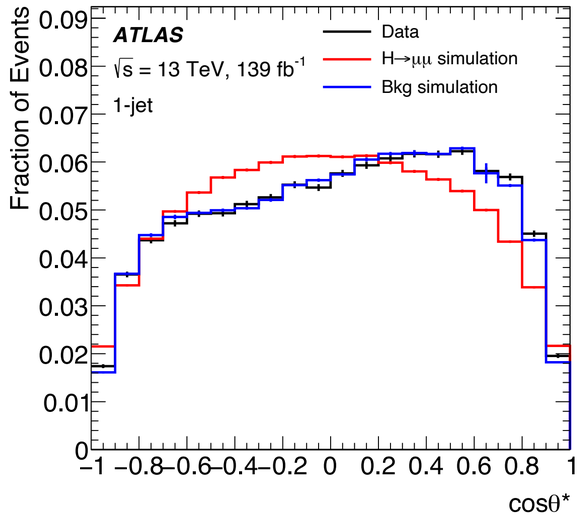


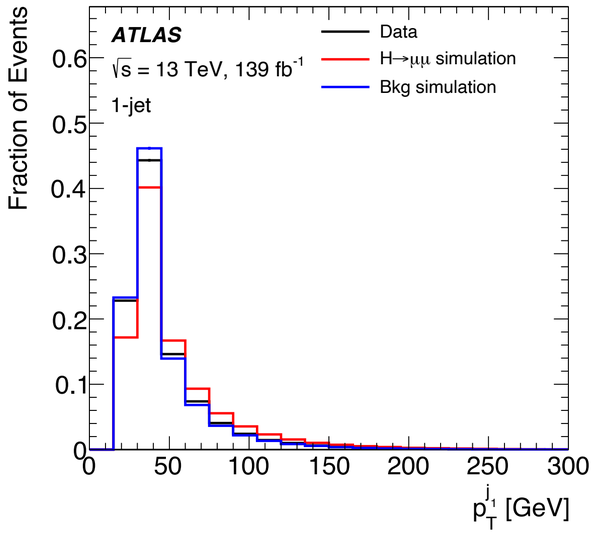


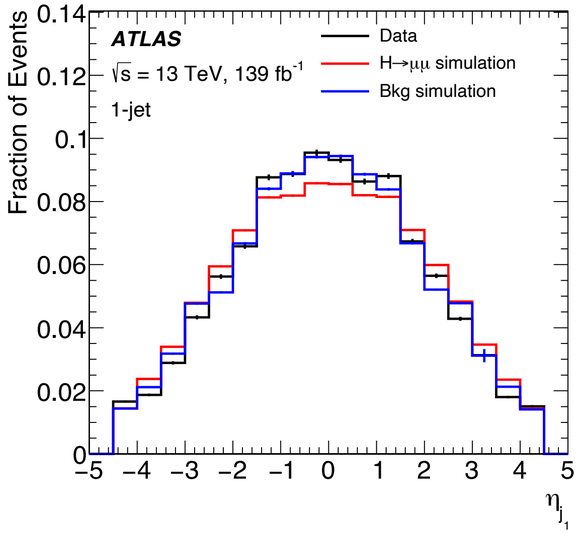
1-jet BDT Training Variables

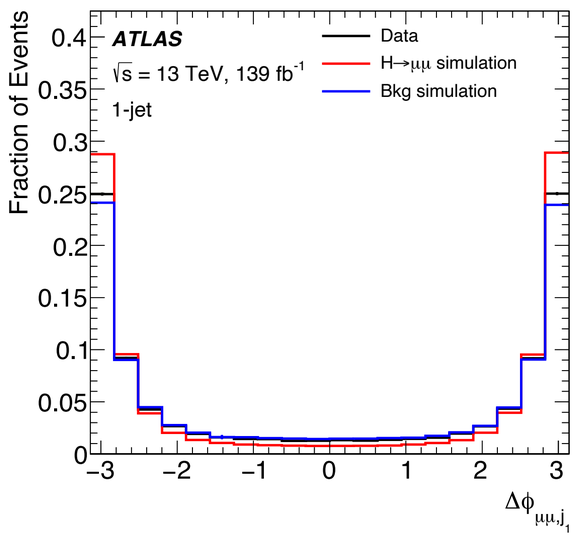


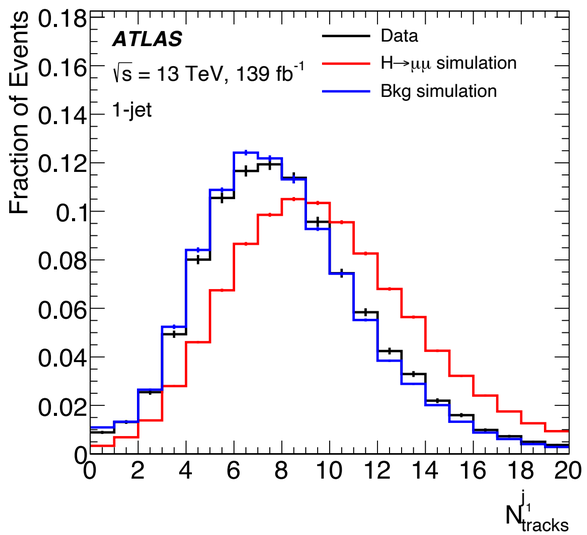




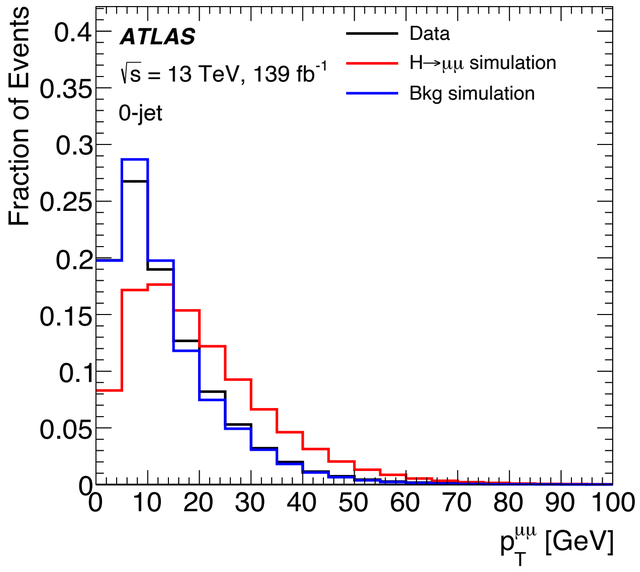


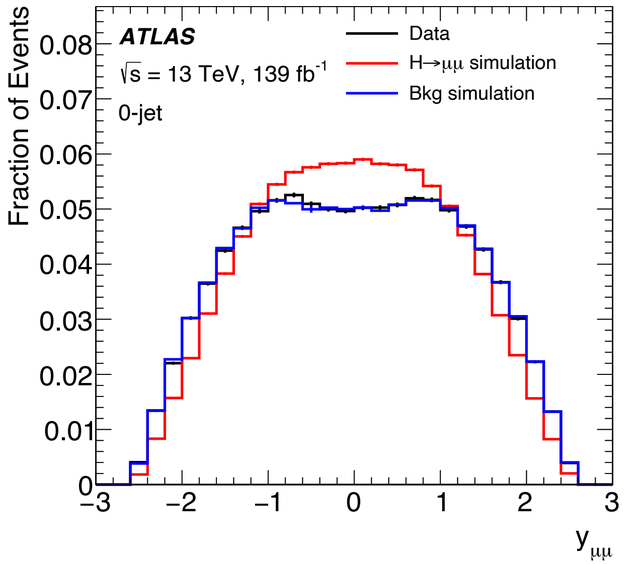


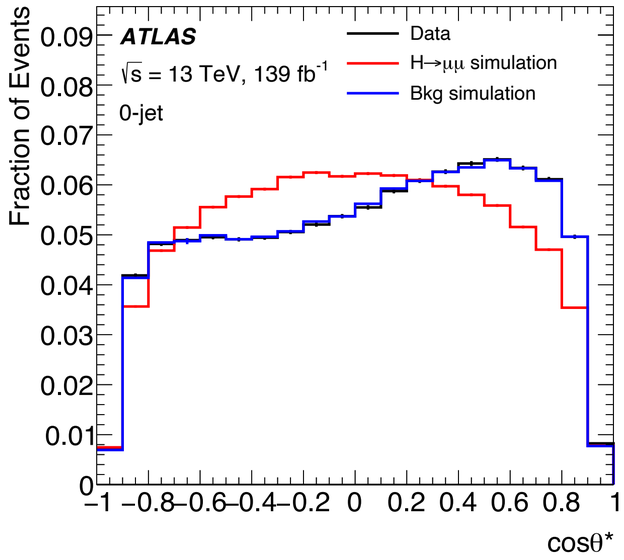




0-jet BDT Training Variables







Signal plus Background fits with μ = 1.2