Search for the Higgs boson decaying to a pair of muons in pp collisions at 13 TeV with the ATLAS detector

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H→μμ

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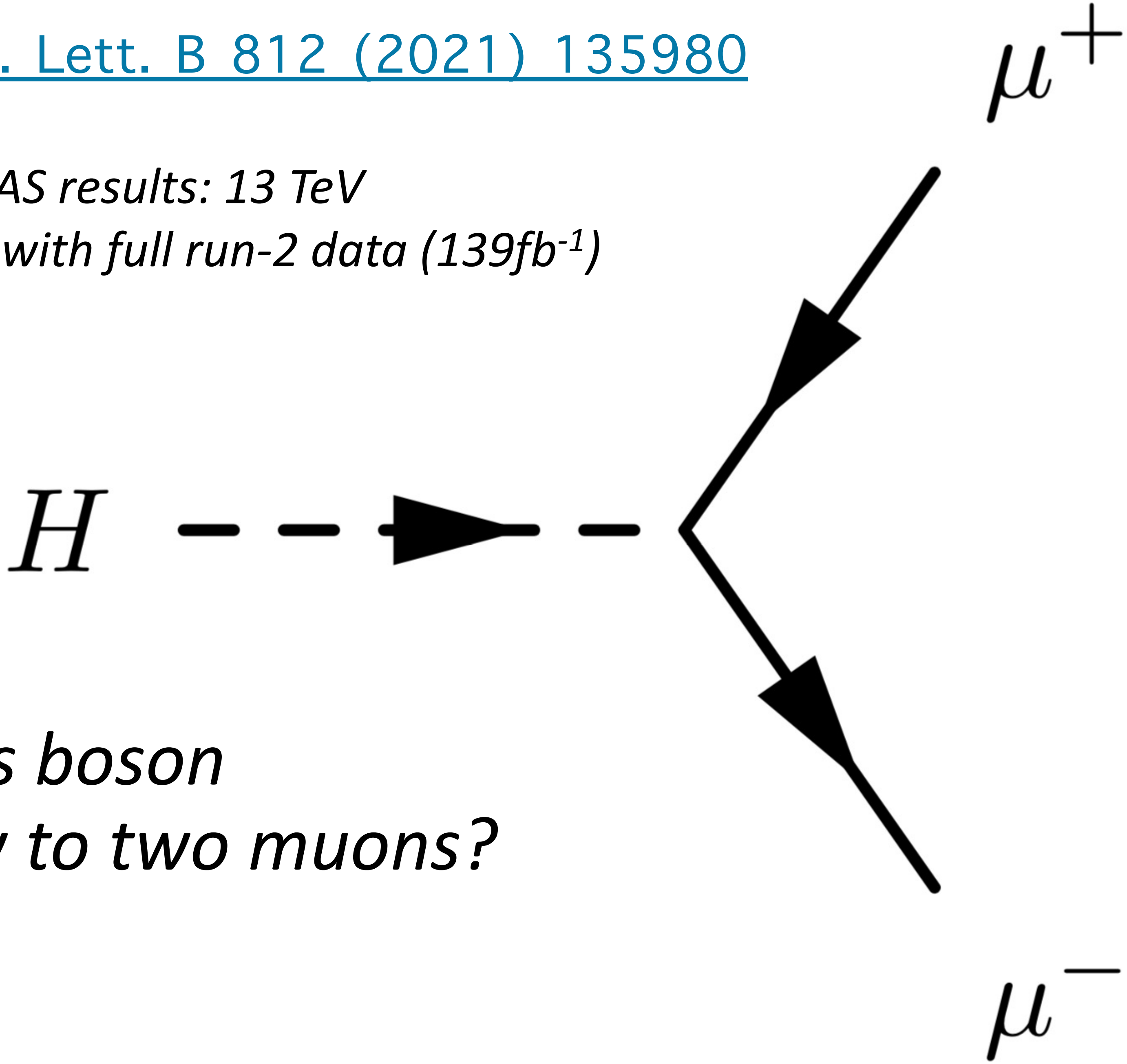
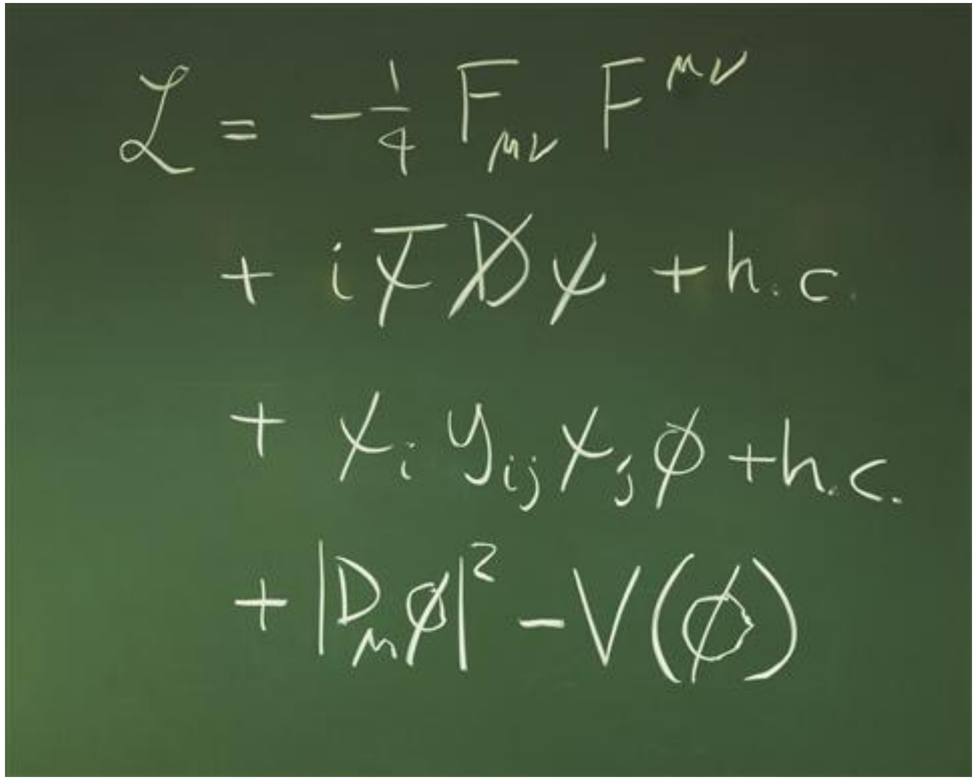
ATLAS results: 13 TeV
with full run-2 data (139fb^{-1})

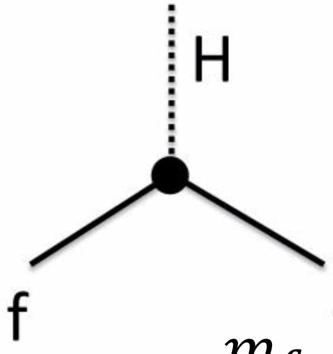


Does Higgs boson
decay to two muons?

H→$\mu\mu$

- Predicted by SM via Yukawa coupling, but…
  - SM is not perfect (various experimental results can’t be explained, e.g. DM, flavor hierarchy of fermion mass, muon g-2, etc)
  - BSM often modify Higgs coupling to muons
  - Experiments only observed Higgs coupling to 3rd-generation fermions (H→$\tau\tau$/bb, ttH), while no observation of Higgs coupling to 2nd-generation fermions yet
- H→$\mu\mu$ search has become the next milestone in the LHC programs!

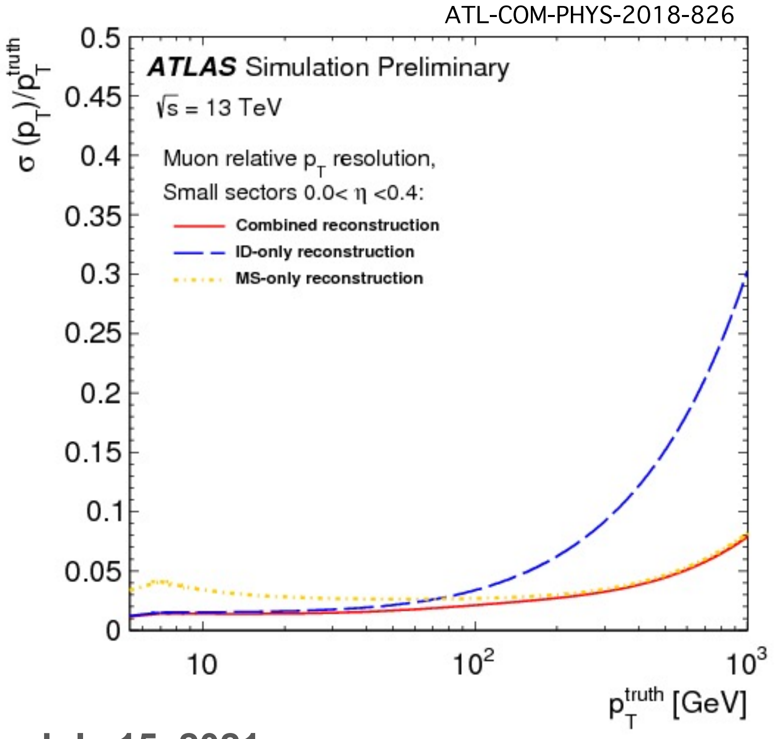




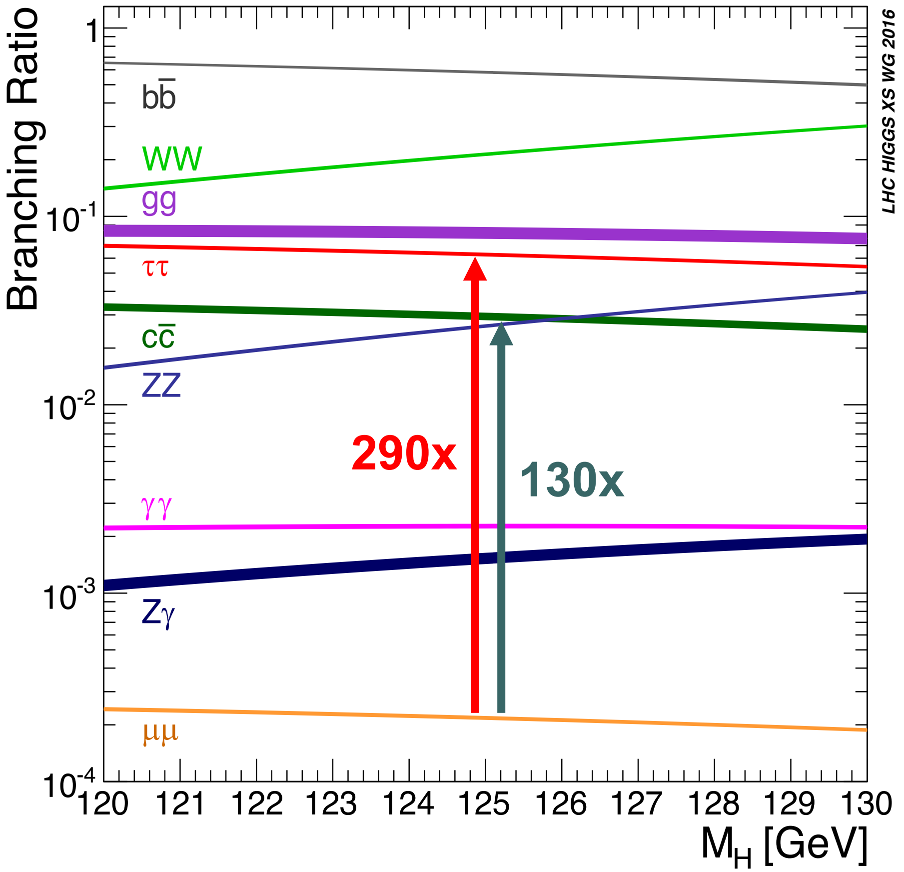
$$g_{Hf\bar{f}} = \frac{m_f}{v}$$

H→$\mu\mu$

- Very small branching ratio ~ 2×10^{-4} = 1/290×Br(H→$\tau\tau$) = 1/130×Br(H→cc)
- Large background (mainly Drell-Yan)
- Good muon reconstruction and resolution



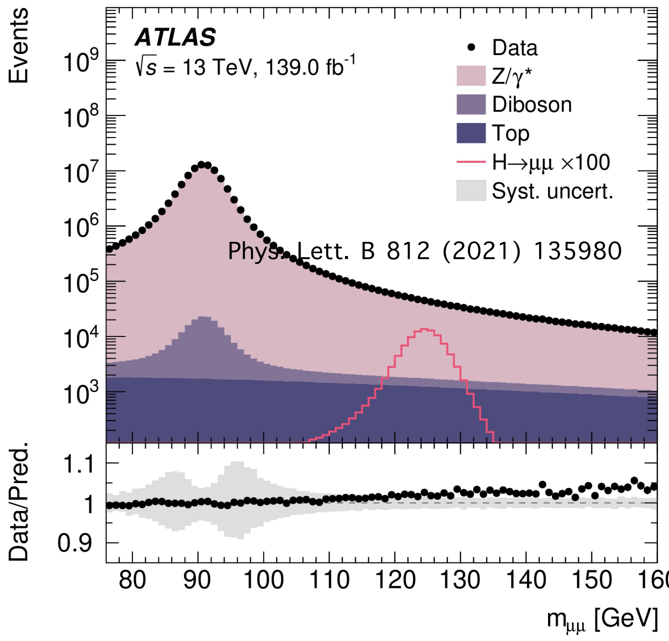
- Low systematic uncertainties



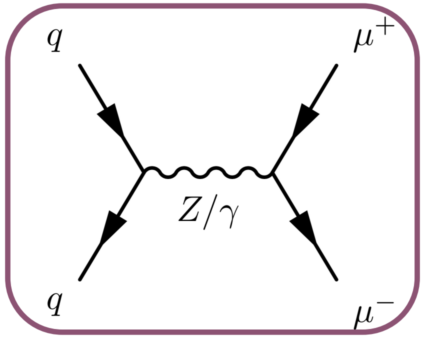
- H→$\mu\mu$ currently provides the best opportunity for probing the Higgs coupling to 2nd-generation fermions

Background

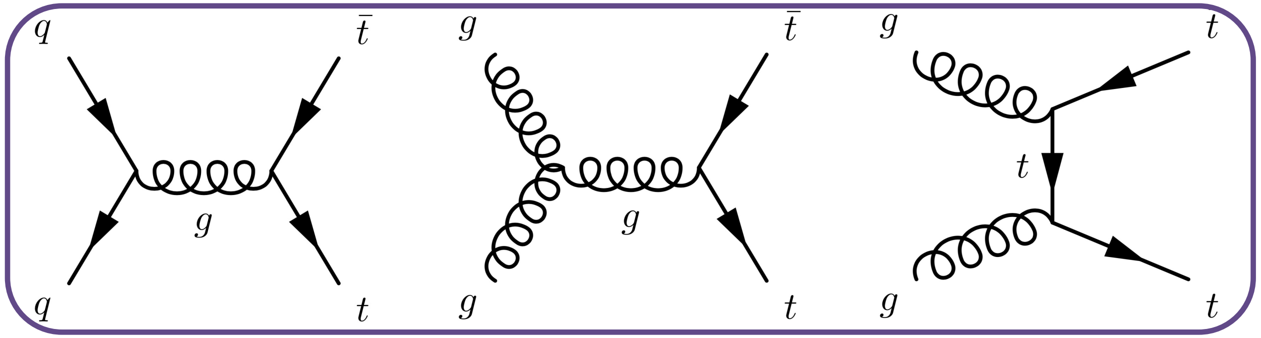
- Main background: Drell-Yan process (>90%)
- $t\bar{t}$ and diboson become important in VH/ttH phase space



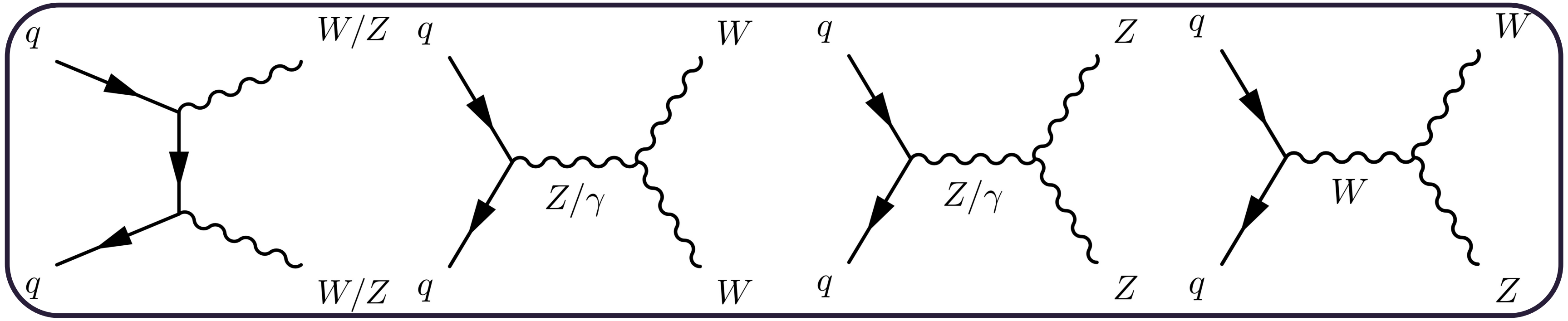
DY



$t\bar{t}$



Diboson



- *Major challenge: very small S/B (< 0.1%)*
  - Hard to find signals (requires good separation between signals and background)
  - Result easily biased by background mismodeling (requires careful background modeling procedure)

Outline

- BDT-based event categorization
- Signal and background modeling
- Results

Event selection

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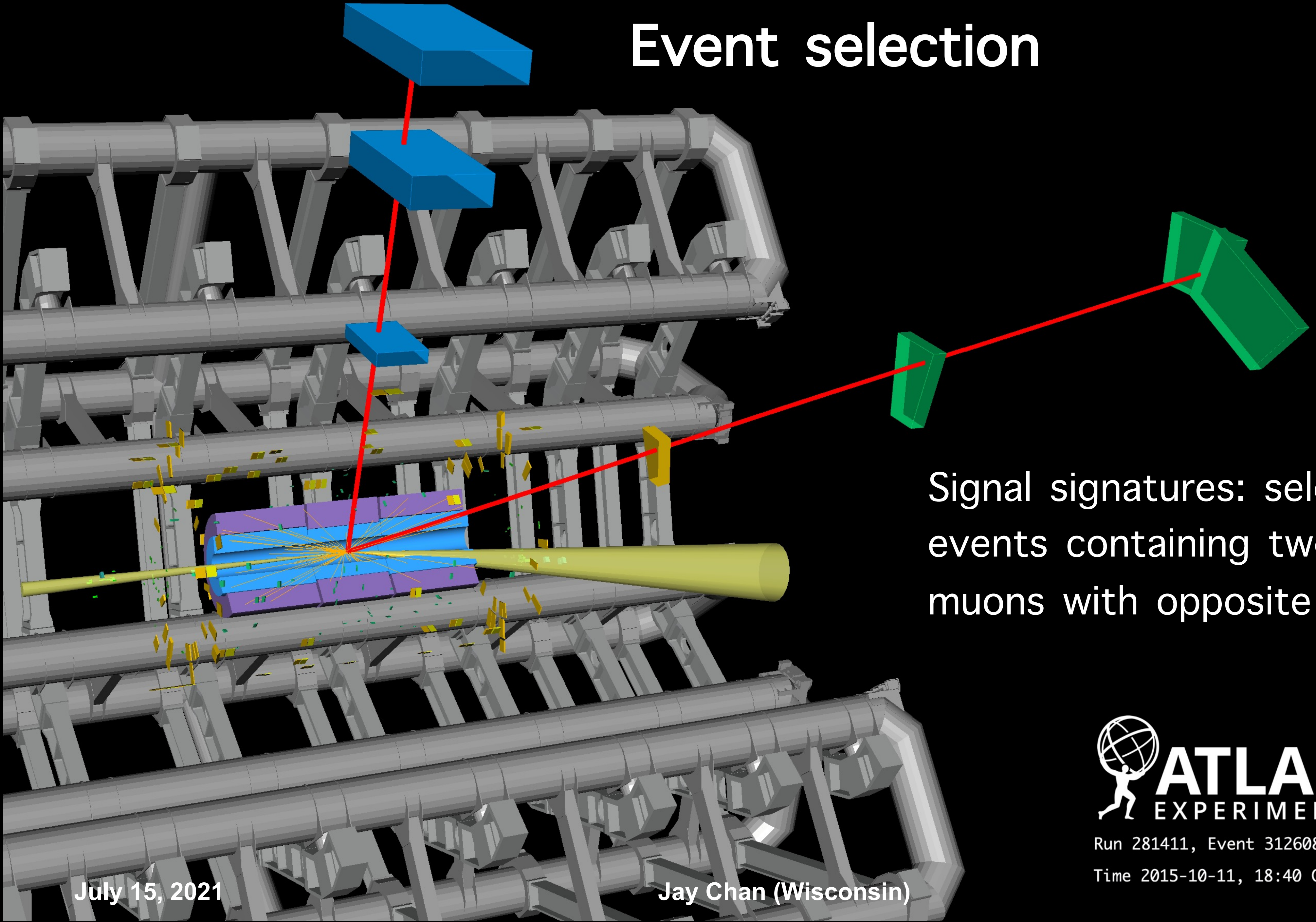


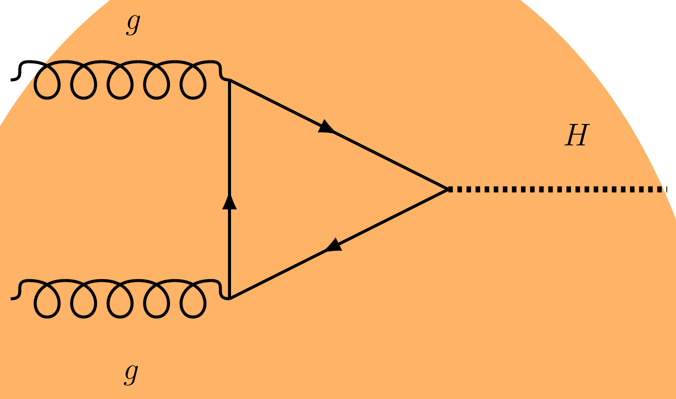
Signal signatures: select events containing two isolated muons with opposite charges

ATLAS EXPERIMENT

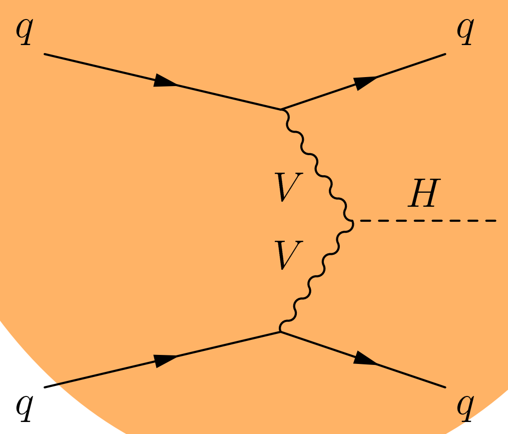
Run 281411, Event 312608026

Time 2015-10-11, 18:40 CEST

Production driven categorization



VBF+ggF channel
Rest events



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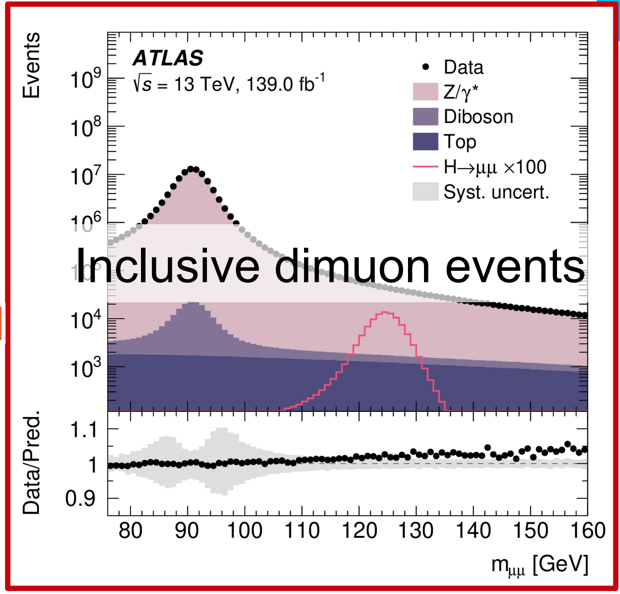
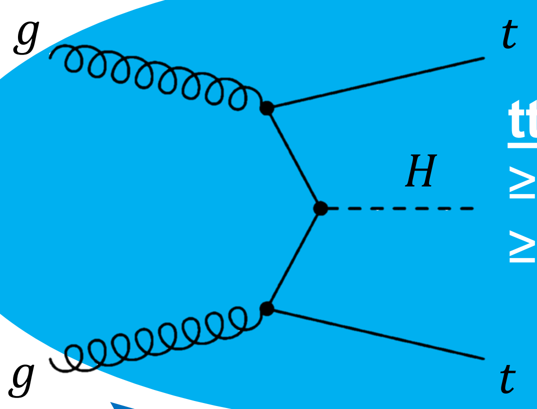
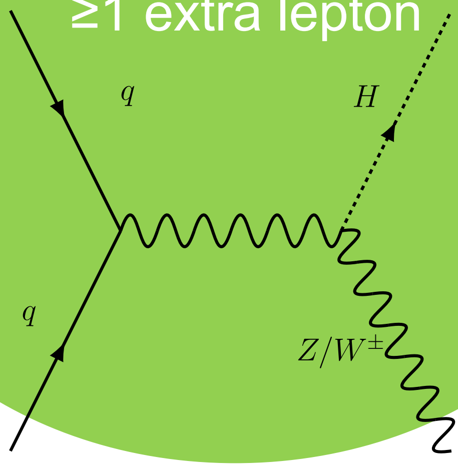




ttH channel
≥1 b-jets
≥1 extra lepton

VH channel
0 b-jets
≥1 extra lepton



3 production-mode channels

➔**Further split to 20 categories by BDTs**

BDT classifier

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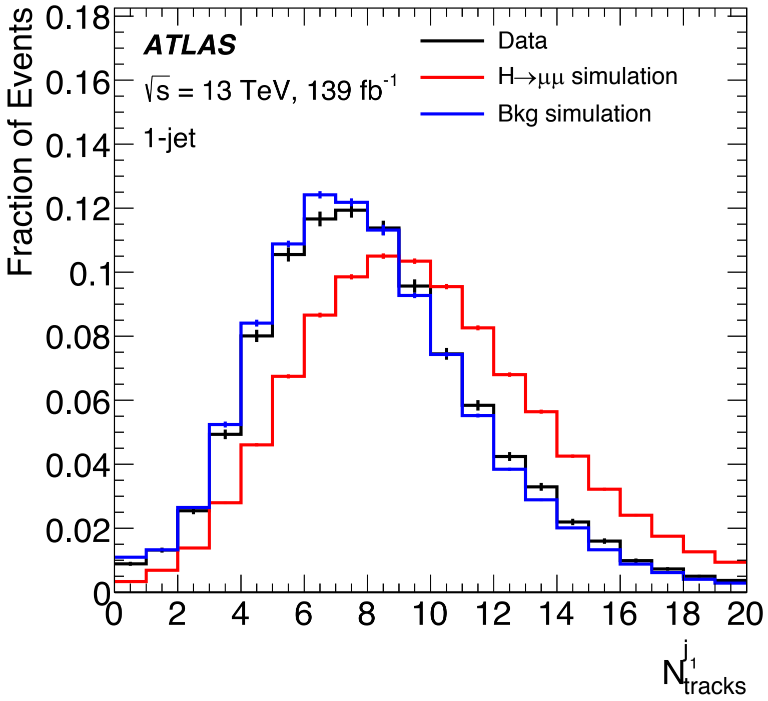

- Dedicated BDTs are trained for different production modes and phase space
  - Key to further separate the signal from background
  - Mainly employ kinematic variables of di-jet system, jets, etc
- Also utilize number of tracks inside the two leading jets – useful to distinguish quark/gluon jets and VBF events

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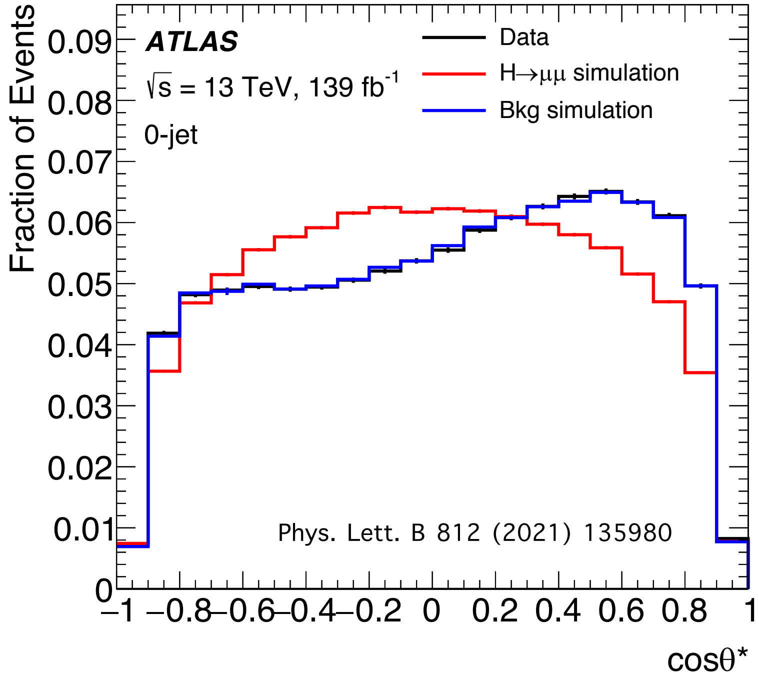
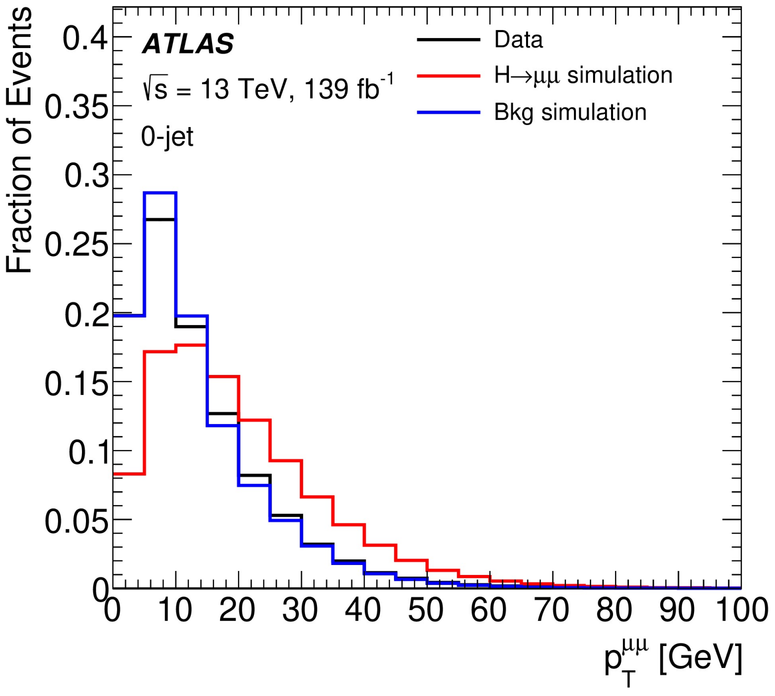
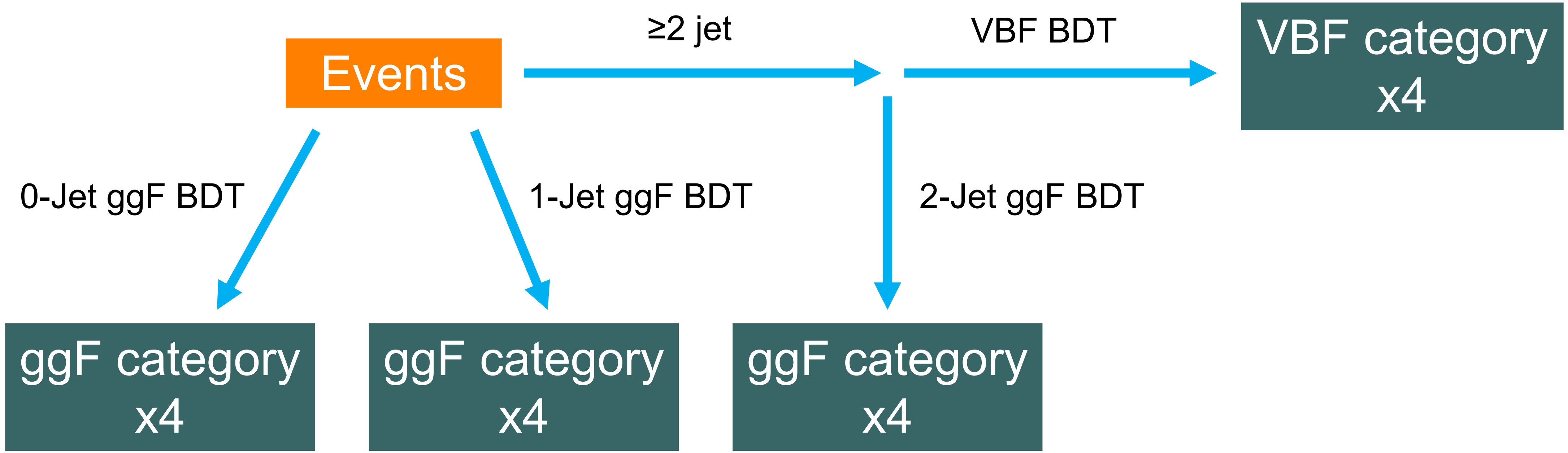




BDT categorization for ggF/VBF categories



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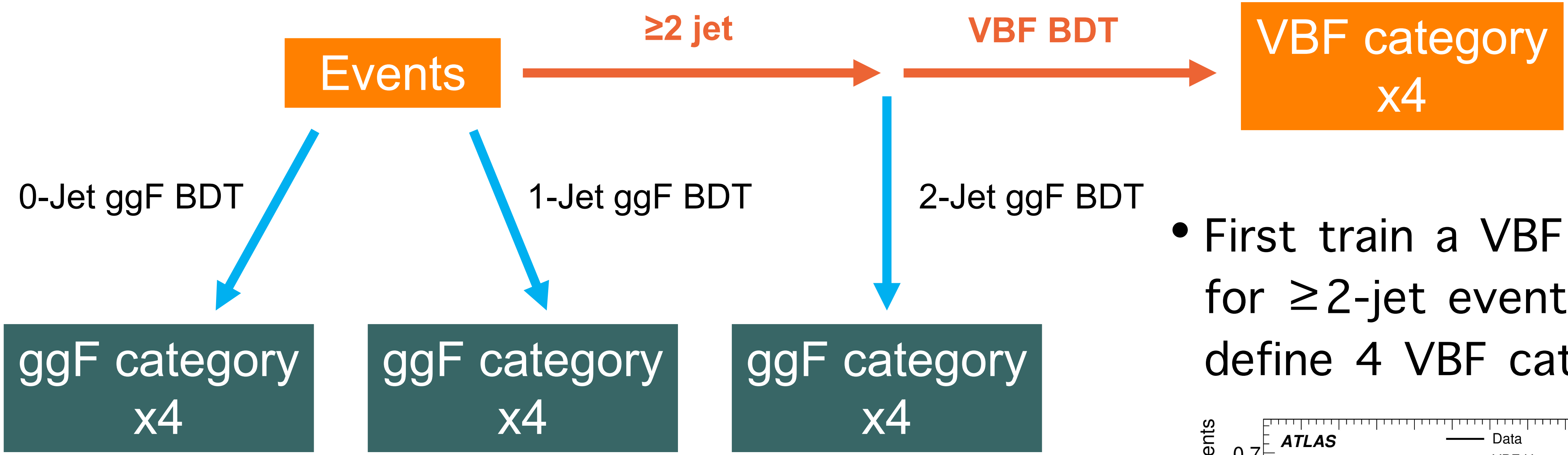
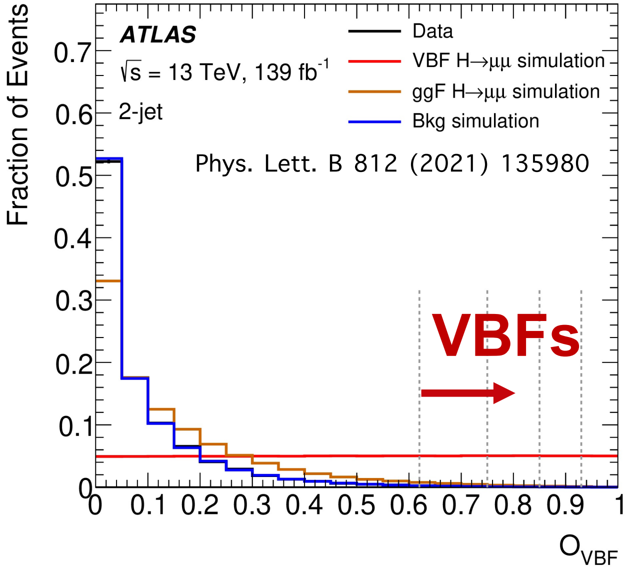
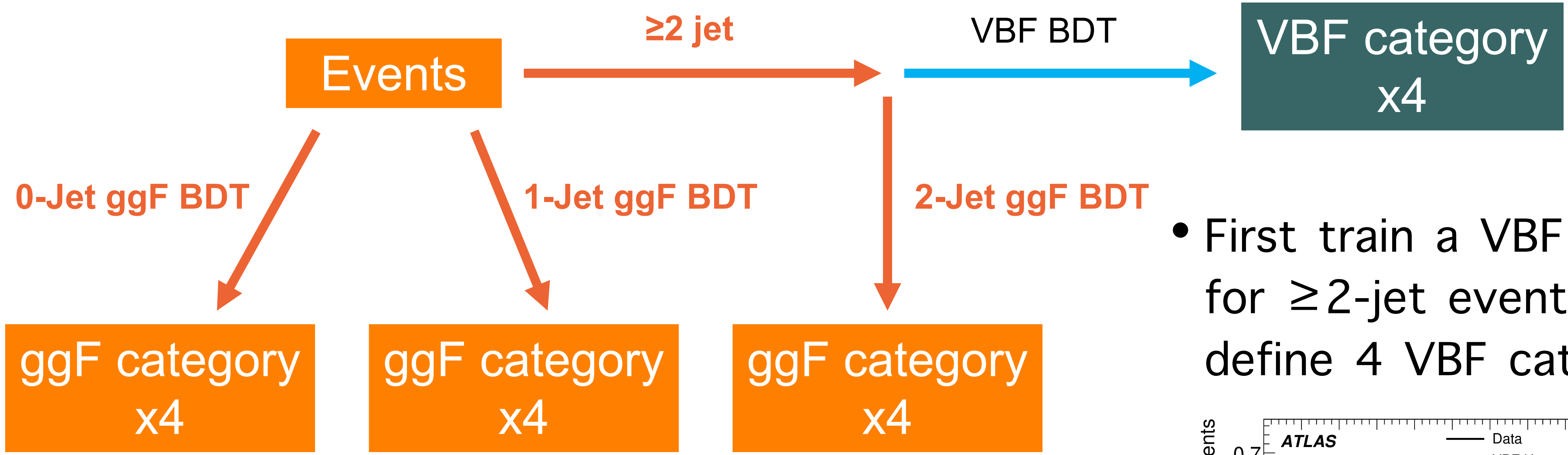


- First train a VBF BDT for ≥2-jet events and define 4 VBF categories



BDT categorization for ggF/VBF categories



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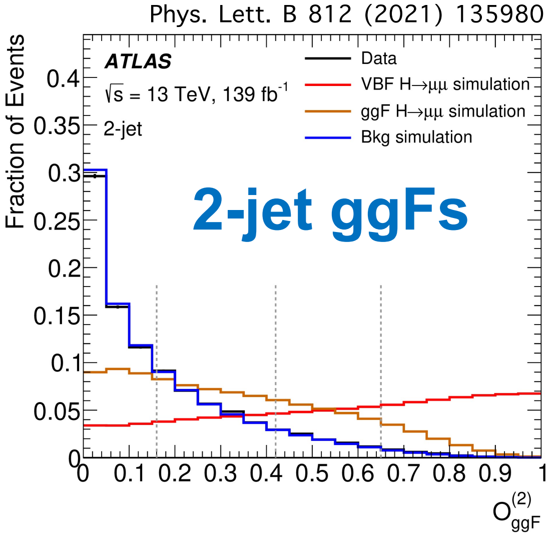
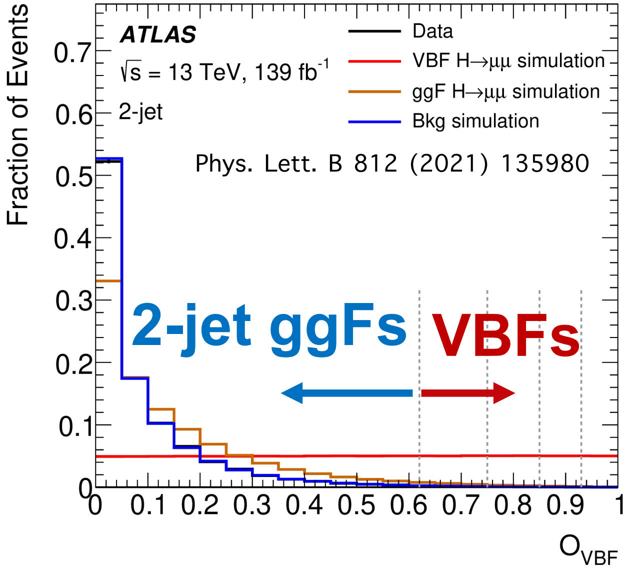
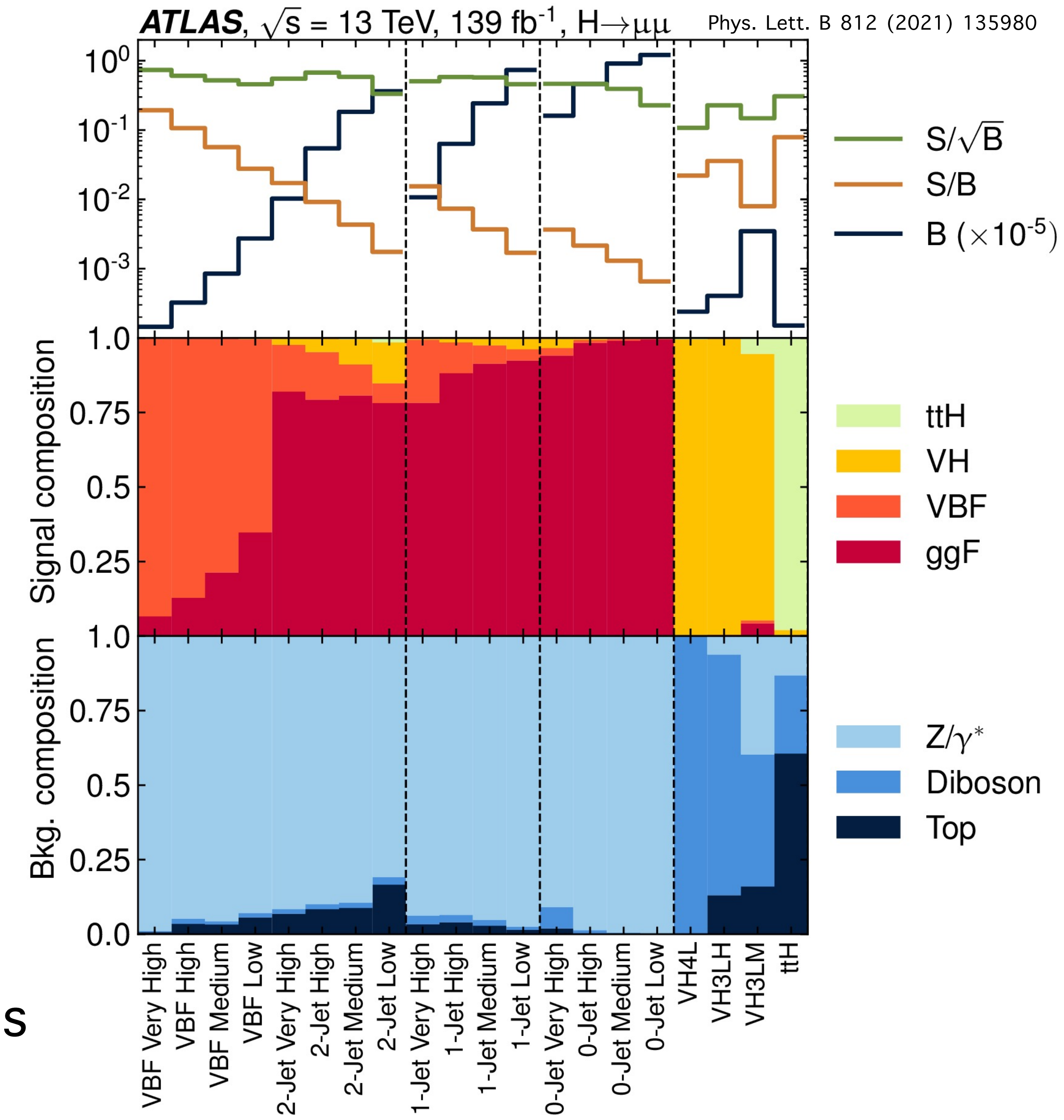


- Rest of the events sorted by 0-Jet/1-Jet/≥2-Jet ggF BDT into 4 ggF categories each (12 ggF categories in total)



Summary of categories

Category	ggF	VBF	WH	ZH	$t\bar{t}H$
VBF Very High	6.6%	93.3%	0.0%	0.0%	0.0%
VBF High	12.8%	87.1%	0.0%	0.0%	0.0%
VBF Medium	21.3%	78.5%	0.1%	0.1%	0.0%
VBF Low	34.8%	64.8%	0.2%	0.2%	0.0%
2-jet Very High	82.0%	15.7%	1.2%	1.0%	0.2%
2-jet High	79.3%	16.0%	2.7%	1.8%	0.3%
2-jet Medium	80.7%	10.4%	5.4%	3.0%	0.5%
2-jet Low	78.2%	6.6%	8.8%	4.9%	1.5%
1-jet Very High	78.2%	21.2%	0.3%	0.3%	0.0%
1-jet High	88.2%	10.4%	0.9%	0.6%	0.0%
1-jet Medium	91.4%	6.1%	1.6%	0.9%	0.0%
1-jet Low	92.4%	3.8%	2.6%	1.2%	0.0%
0-jet Very High	94.1%	2.5%	1.4%	2.0%	0.0%
0-jet High	98.3%	1.0%	0.4%	0.3%	0.0%
0-jet Medium	99.1%	0.6%	0.2%	0.1%	0.0%
0-jet Low	99.5%	0.3%	0.1%	0.1%	0.0%
VH4L	0.0%	0.0%	0.1%	99.5%	0.4%
VH3LH	0.3%	0.1%	96.9%	2.6%	0.1%
VH3LM	4.2%	1.0%	80.8%	8.6%	5.3%
$t\bar{t}H$	0.1%	0.0%	1.5%	0.4%	98.0%



- **20 categories** in total
- Different Higgs production modes are well separated

Outline

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Signal modeling

- Signal shape (also background) modeled with **analytical functions**
  - Often asymmetric in the $m_{\mu\mu}$ spectrum due to the detector resolution effect
- Parametrized with a **double-sided Crystal Ball function** (Gaussian + power-law tails) for each category using full-simulation MC signal samples
  - Gaussian width varies between 2.6 and 3.2 GeV (much larger than natural width ~4 MeV!)

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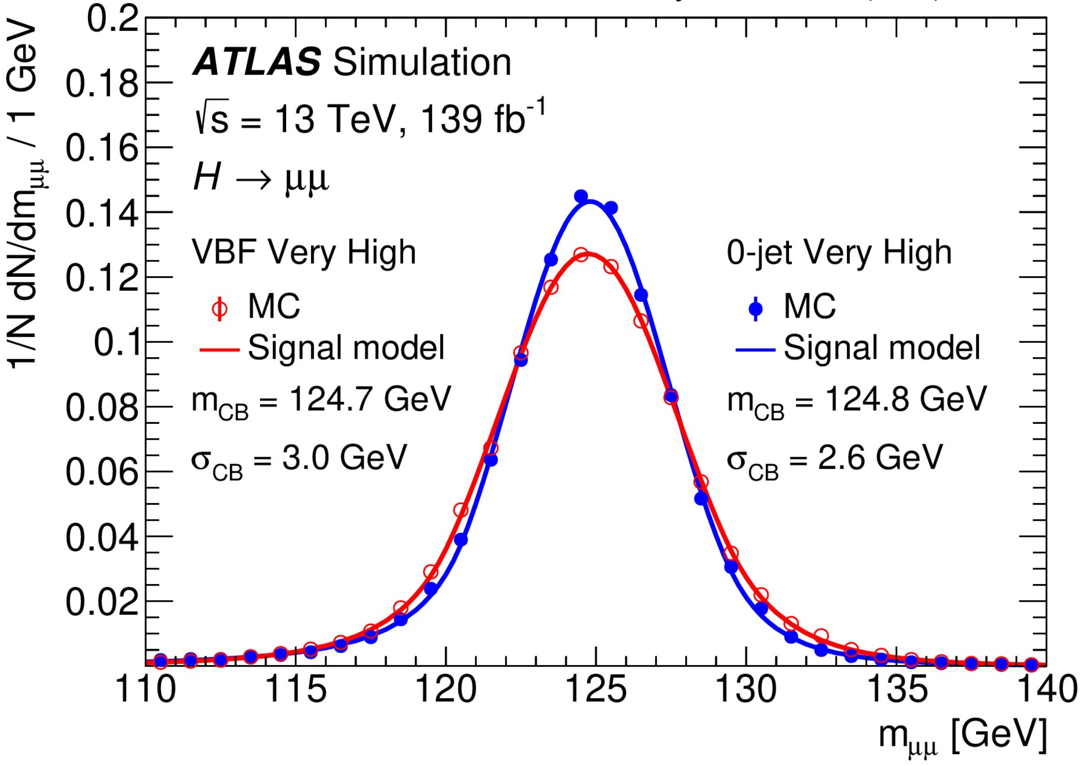
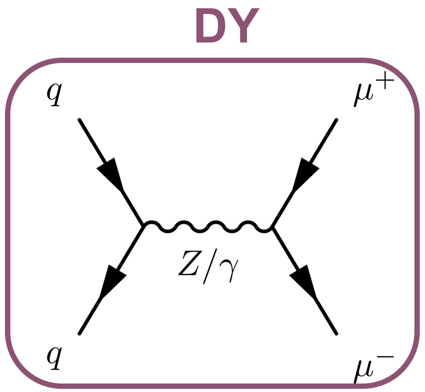


- Main systematic uncertainties:
  - μ momentum scale and resolution
  - Missing higher order QCD correction
  - Underlying event and parton showering

Background modeling



- Major challenge due to the very low S/B ratio
- Mainly focus on the non-trivial shape of the DY $m_{\mu\mu}$ spectrum: model with (Core) × (Empirical)
  - Core function: LO DY line-shape convolved with the Gaussian muon resolution function
    - All parameters are fixed
  - Empirical function: Power-law or Epoly functions (different in each category)
    - With free parameters to absorb the mismodeling from the core function
- Function choices are selected based on spurious signal test procedure with high statistics simulation

Spurious signal test

- Evaluate the background modeling bias by performing a S+B fit to the simulation background
  - Resulting S is the "spurious signal" (SS)
- Selected functions must pass the fit quality criteria:
  - **SS < 20%** of expected statistical uncertainty in data
  - χ^2 p-value > 1% for B-only fits to simulation background and data sideband

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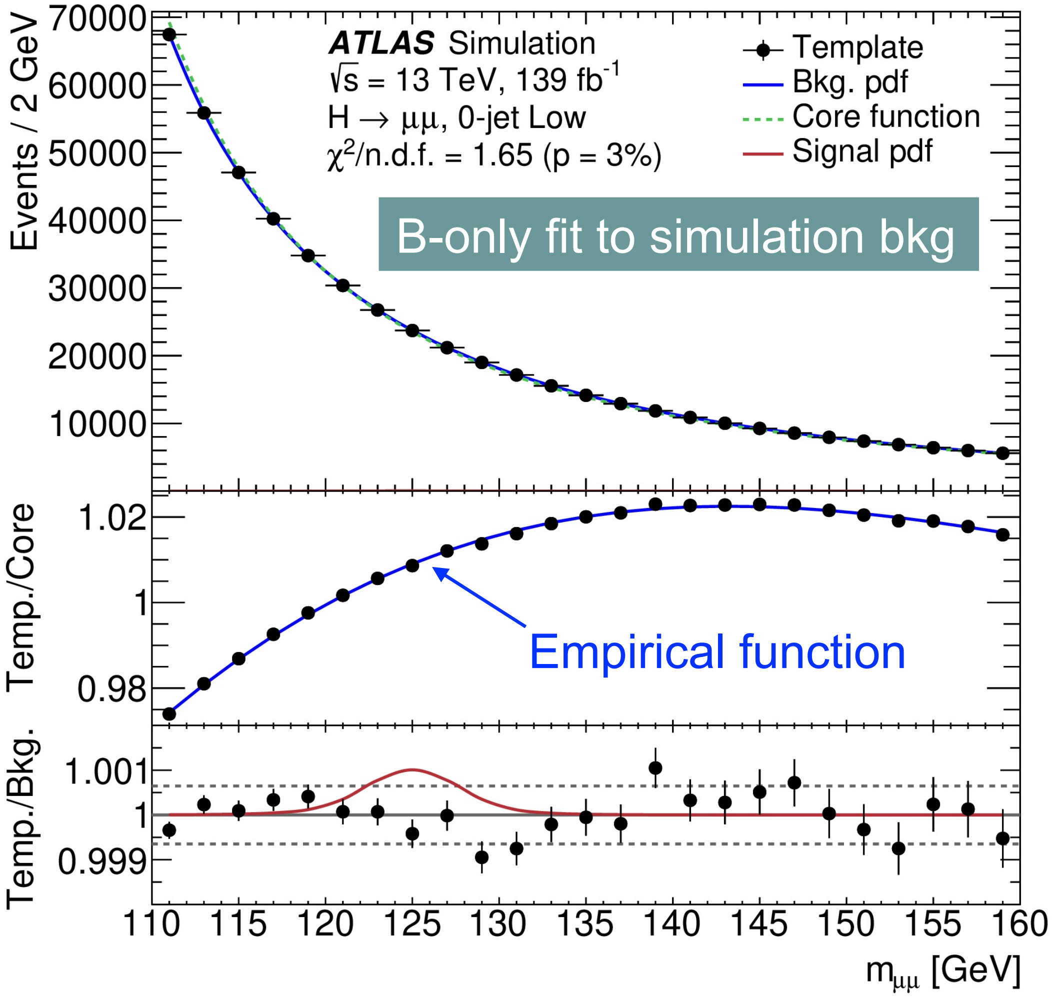

- Eventually SS in each category is taken as a background modeling uncertainty

Outline

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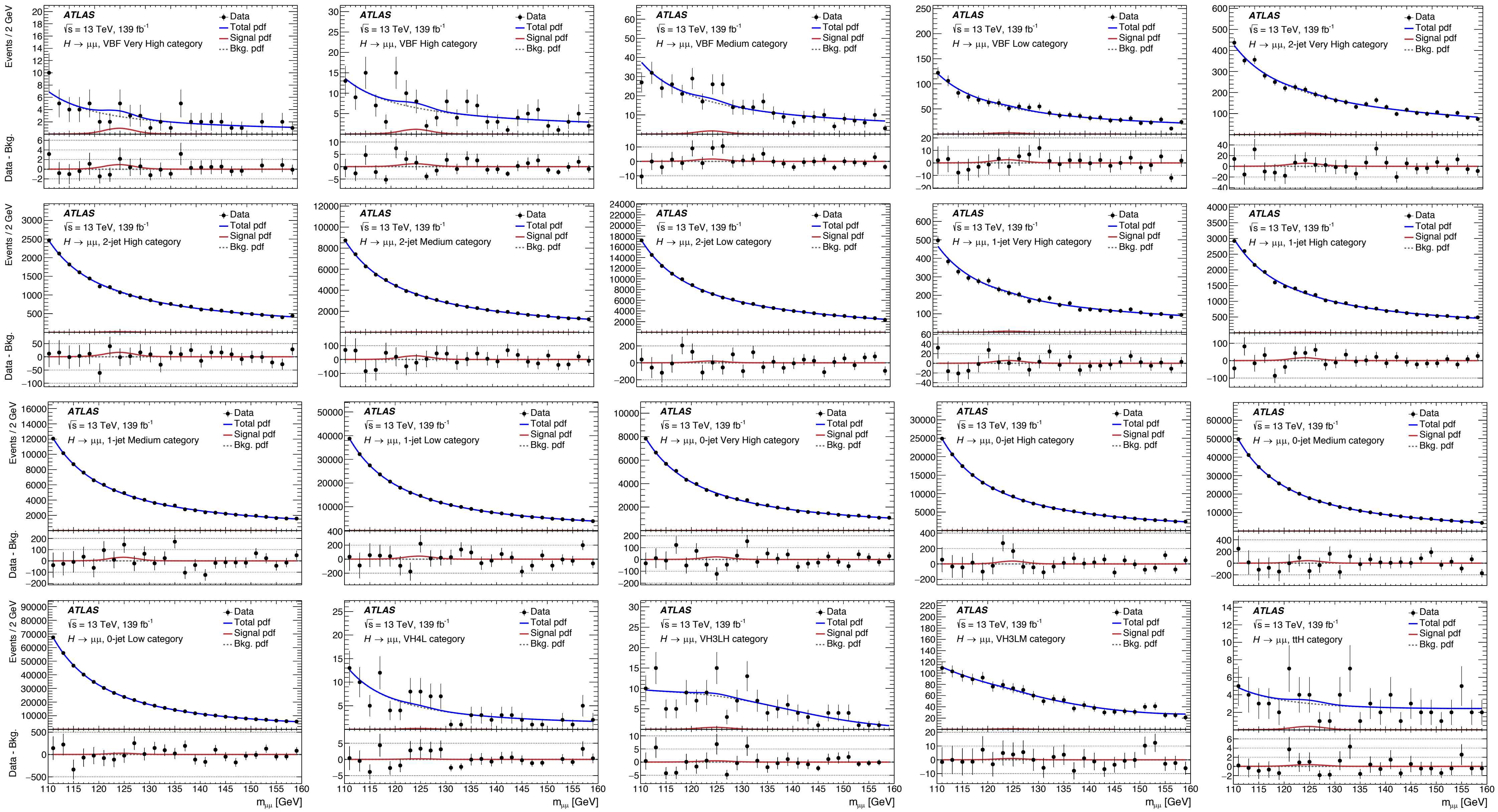
Observed dimuon mass spectrum

- Fit to the $m_{\mu\mu}$ spectrum in data in all 20 categories simultaneously



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Observed dimuon mass spectrum

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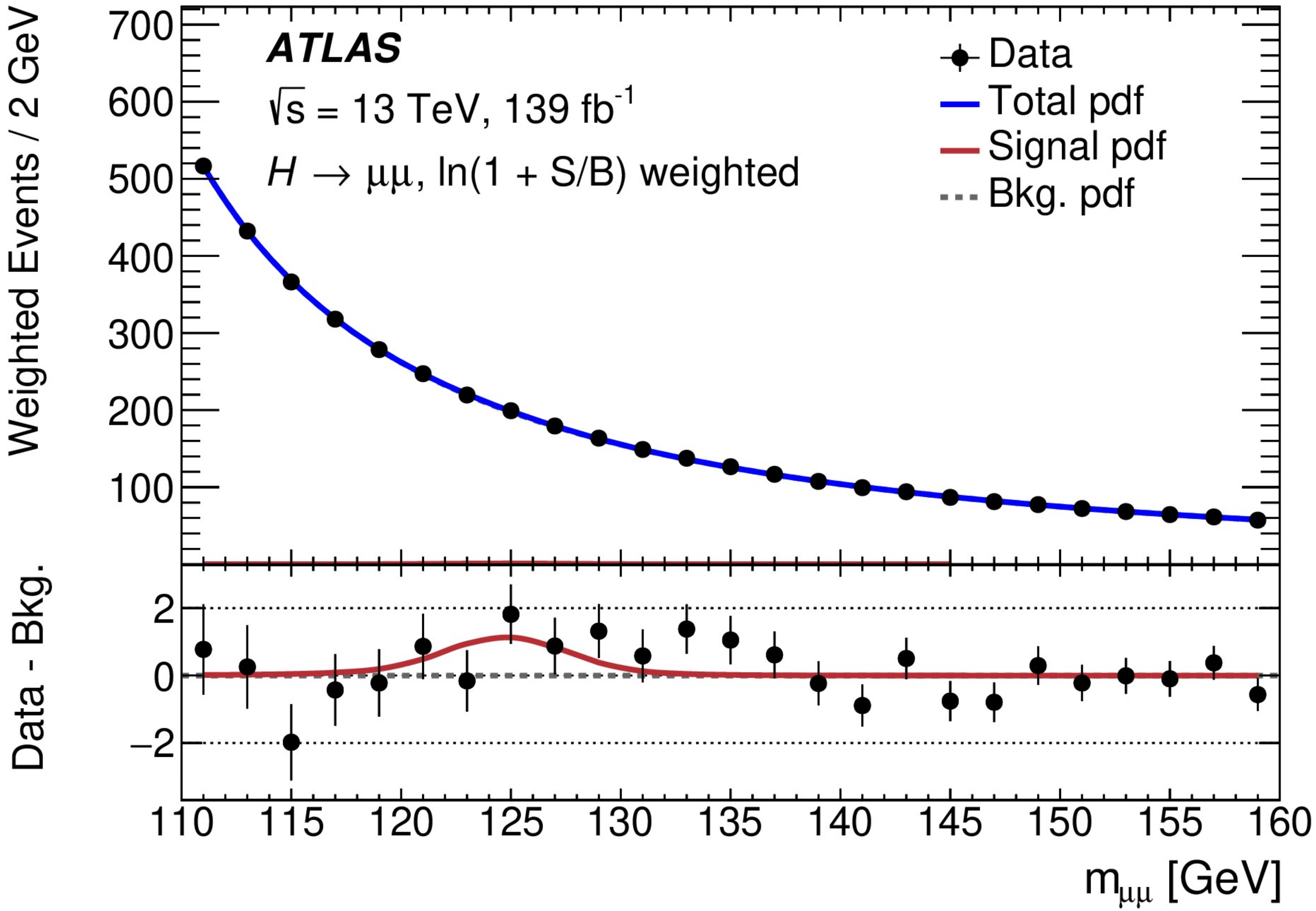

- Sum of events from all 20 categories
- Events and pdfs are weighted by ln(1+S/B) in each category to reflect the sensitivity after the categorization

Signal strength, significance and upper limit

- Signal strength (observed signal yield / SM prediction):

  $1.2 \pm 0.6\ (\pm\ 0.6(\text{stat.})\ ^{+0.2}_{-0.1}(\text{syst.}))$

- Significance against no H→μμ signal hypothesis:

  2.0σ observed, 1.7σ expected

- Observed upper limit @ 95% CL:
  - $Br(H\rightarrow\mu\mu) < 4.7\times10^{-4} = 2.2\times SM$
  - 2.0×SM expected (W/ H→μμ signal)
  - 1.1×SM expected (W/O H→μμ signal)

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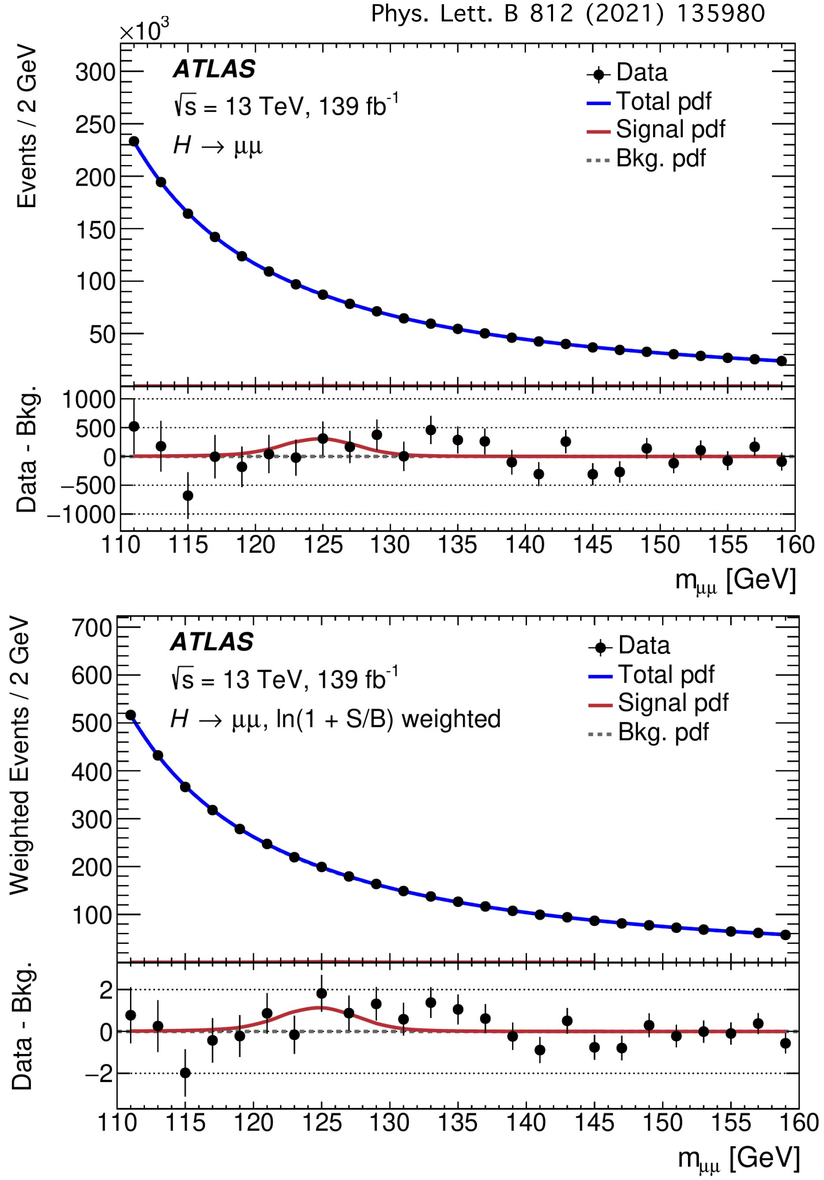

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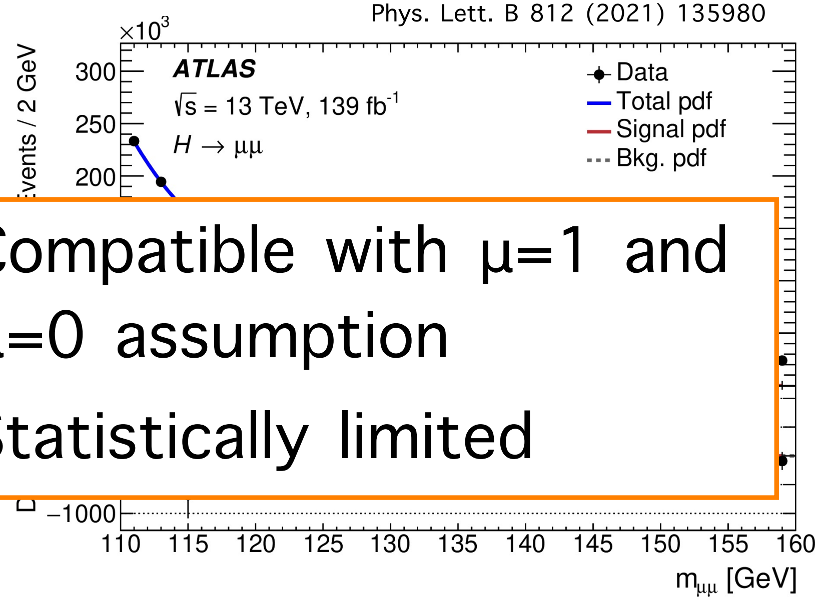
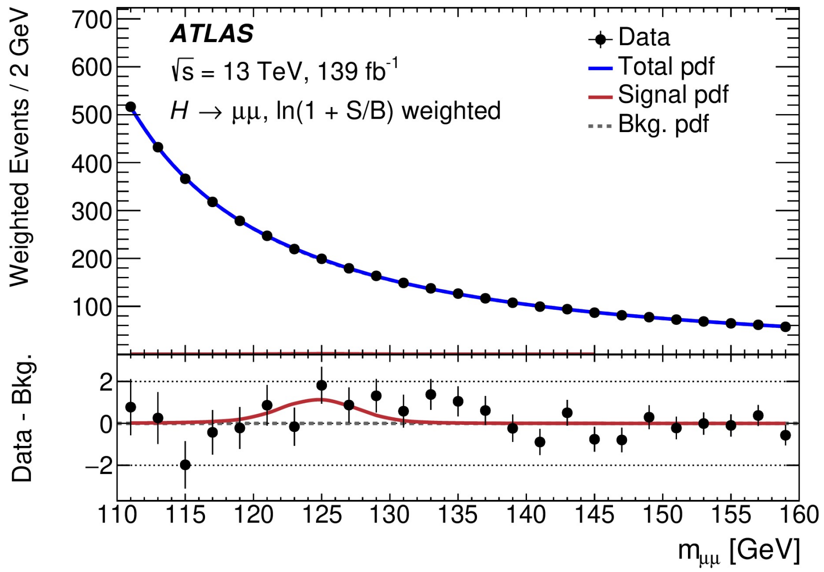


- Compatible with μ=1 and μ=0 assumption
- Statistically limited



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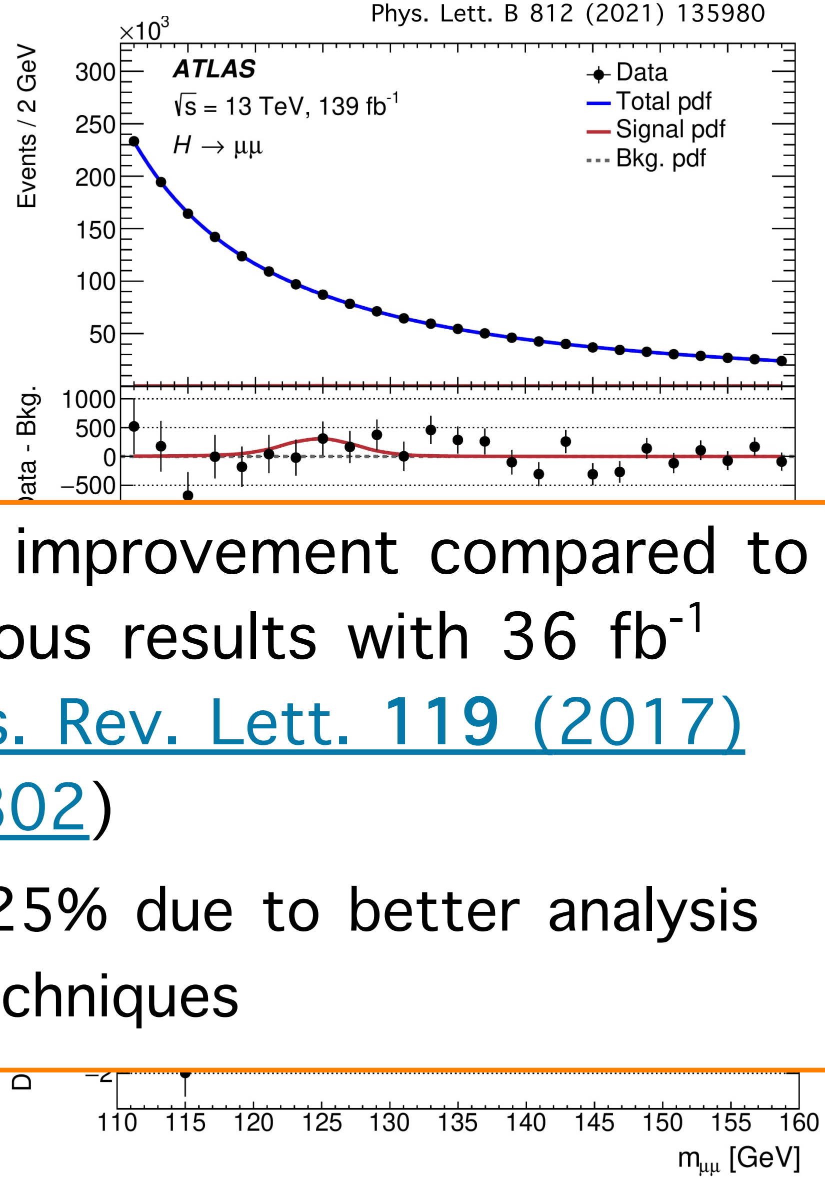

- ~2.5 improvement compared to previous results with 36 fb^{-1} (Phys. Rev. Lett. **119** (2017) 051802)
  - ~25% due to better analysis techniques

Signal strength, significance and upper limit

- Signal strength (observed signal yield / SM prediction):
  - $1.2 \pm 0.6\ (\pm 0.6(\text{stat.})\ ^{+0.2}_{-0.1}(\text{syst.}))$
- Significance against no $H\to\mu\mu$ signal hypothesis:
  - 2.0σ observed, 1.7σ expected
- Observed upper limit @ 95% CL:
  - $Br(H\to\mu\mu) < 4.7\times10^{-4} = 2.2\times SM$
  - $2.0\times SM$ expected (W/ $H\to\mu\mu$ signal)
  - $1.1\times SM$ expected (W/O $H\to\mu\mu$ signal)

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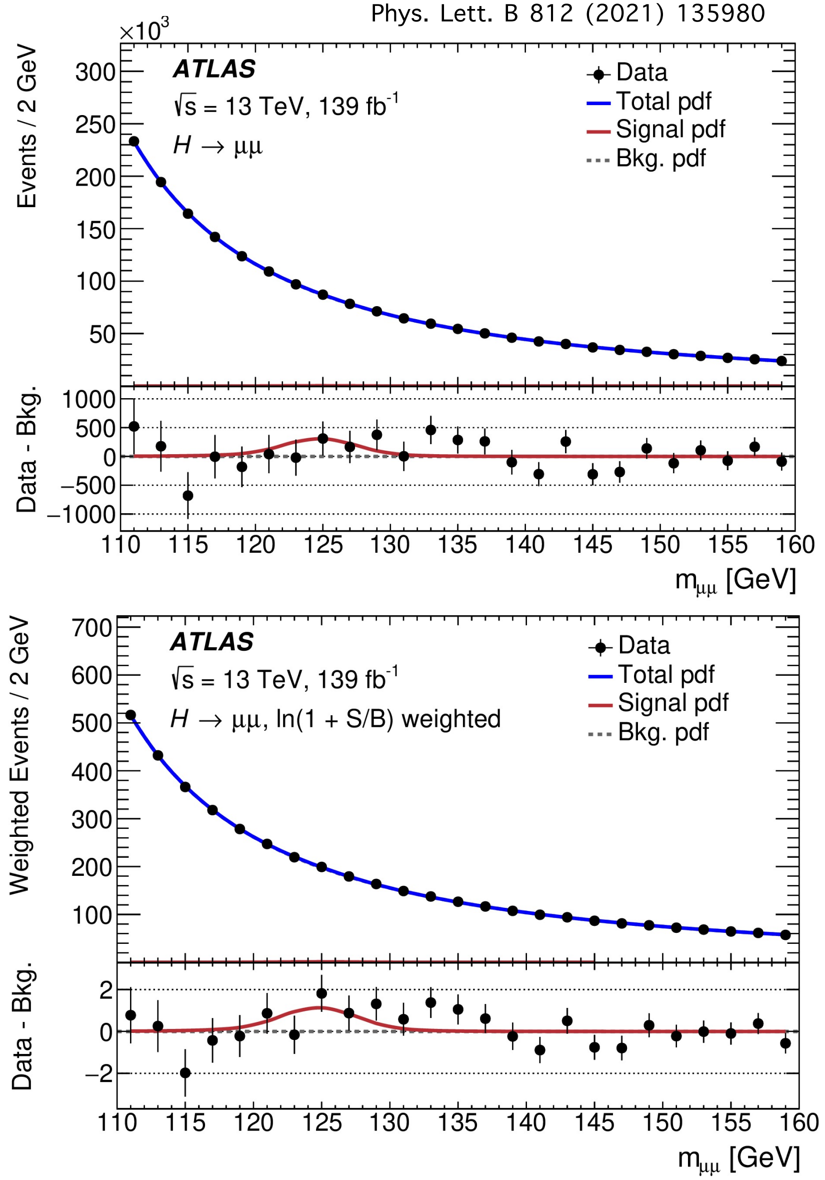


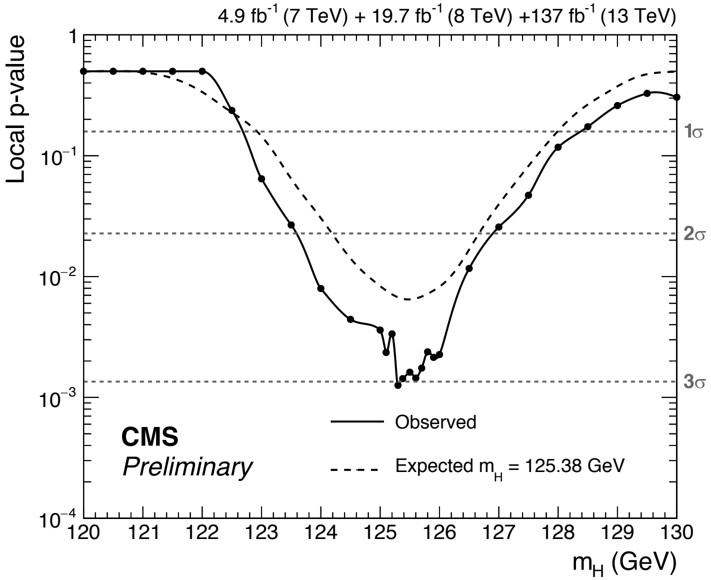
Conclusion

- $H \to \mu\mu$ decay channel provides the best opportunity for probing the interactions between Higgs boson and the second-generation fermions.
- ATLAS measured $H \to \mu\mu$ decay with full Run2 data (139 fb^{-1})
  - Observed significance is **2.0σ (1.7σ expected)**
  - Signal strength is **1.2 ± 0.6 (wrt SM)**
  - $Br(H \to \mu\mu) < 4.7 \times 10^{-4}$ (@ 95 CL) = $2.2 \times$SM
- Results currently compatible with Standard Model prediction and statistically limited
  - Looking forward to future results with more data!

Backup slides

Outlook

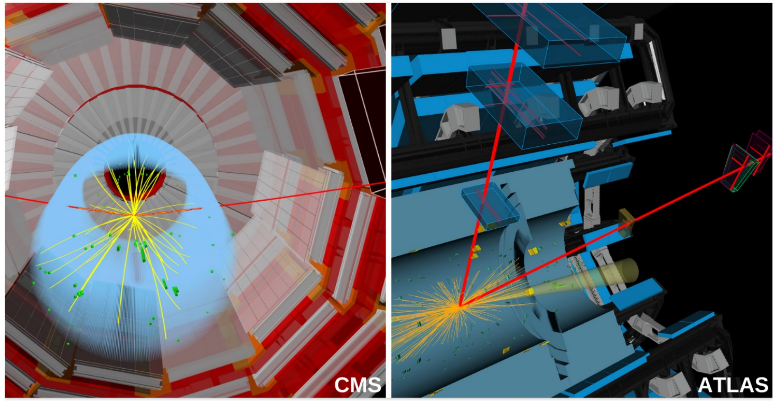
- CMS has observed **3σ** significance for $H \to \mu\mu$ with LHC full run-2 data
  - A simple combination between **ATLAS** and **CMS** is $\sqrt{2.0^2 + 3.0^2} = 3.6\sigma$ (assuming no correlation between two experiments)



CERN experiments announce first indications of a rare Higgs boson process

The ATLAS and CMS experiments at CERN have announced new results which show that the Higgs boson decays into two muons

3 AUGUST, 2020



Candidate event displays of a Higgs boson decaying into two muons as recorded by CMS (left) and ATLAS (right). (Image: CERN)

Geneva. At the 40th ICHEP conference, the ATLAS and CMS experiments announced new results which show that the Higgs boson decays into two muons. The muon is a heavier copy of the electron, one of the elementary particles that constitute the matter content of the Universe. While electrons are classified as a first-generation

- Expected integrated luminosity with LHC run-3: ~300 fb-1
  - Data statistics increased ~2 times
  - Sensitivity increased $\sim\sqrt{2}$ ~1.4
  - Possibility of reaching 5σ observation!

Projection based on current expected significance

- ATLAS (CMS) expected 1.7σ (2.5σ) significance for H→μμ with LHC full run-2 data
  - A simple combination between ATLAS and CMS is $\sqrt{1.7^2 + 2.5^2} = 3.0\sigma$ (assuming no correlation between two experiments)
- Expected integrated luminosity with LHC run-3: ~300 fb-1
  - Data statistics increased ~2 times
  - Sensitivity increased by $\sim\sqrt{2}$ ~1.4
  - Expected significance = 3σ × 1.4 = 4.2σ

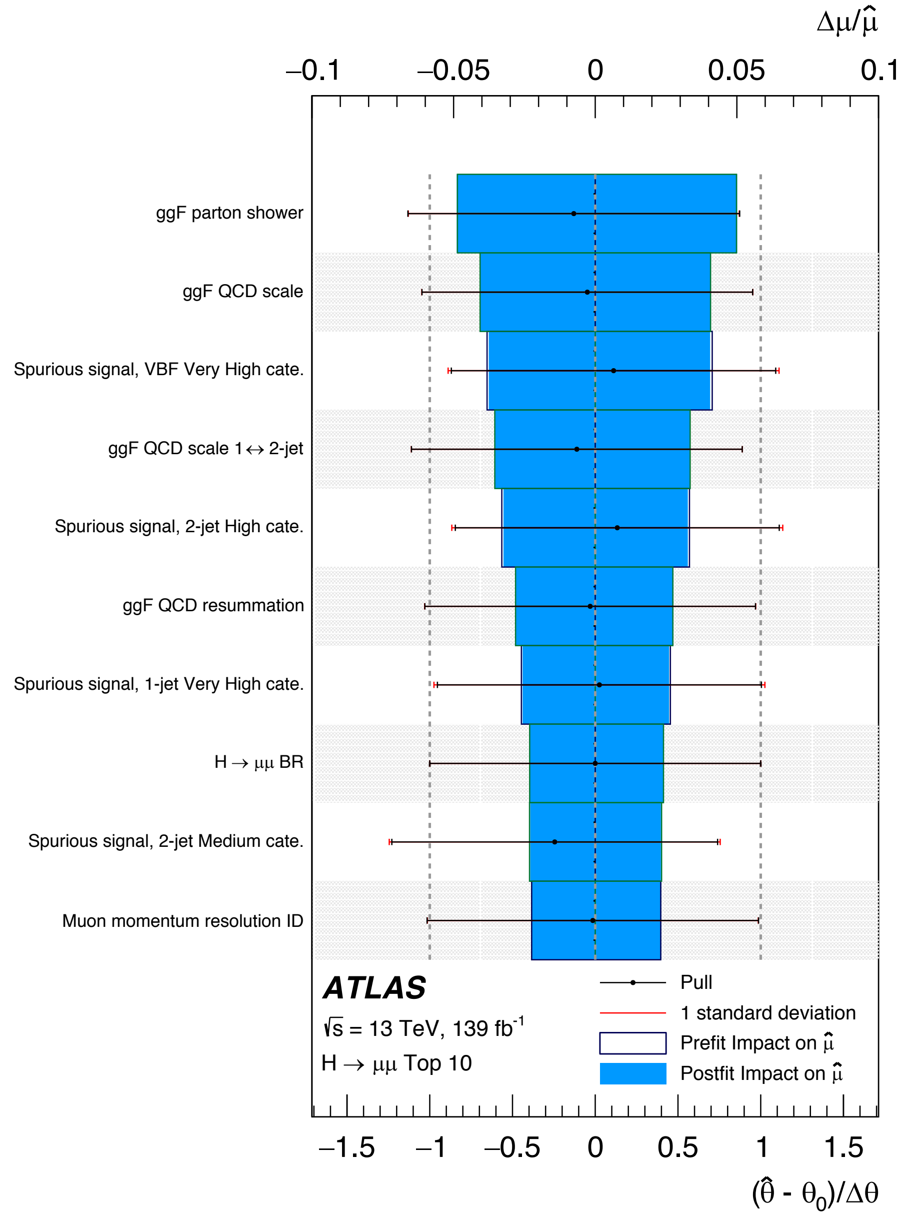
Fitted signal and background yields in each category

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

List of systematic uncertainties

- Theoretical effects
  - Missing higher-order QCD corrections
  - Parton distribution functions
  - Underlying events and hadronization
  - Higgs decay branching ratio and cross-section
- Experimental effects
  - muon reconstruction and identification efficiencies
  - Trigger efficiency
  - Isolation and impact parameter requirements
  - Muon momentum scale and resolution
  - MET calculation
  - b-tagging efficiency
  - Number of tracks associated with jets
  - Pile-up modelling
  - Electron reconstruction and identification efficiency
  - Jet reconstruction efficiency, energy scale and resolution

Impacts of systematic uncertainties



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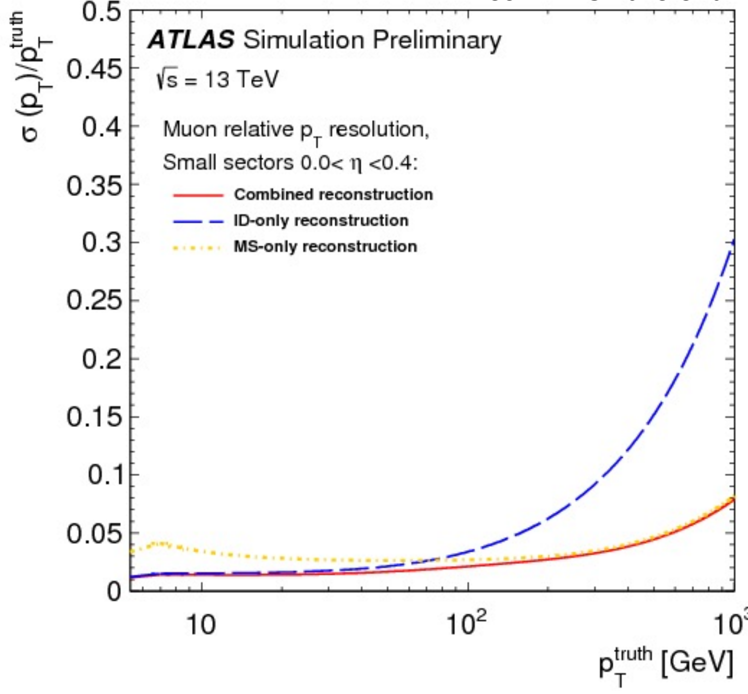
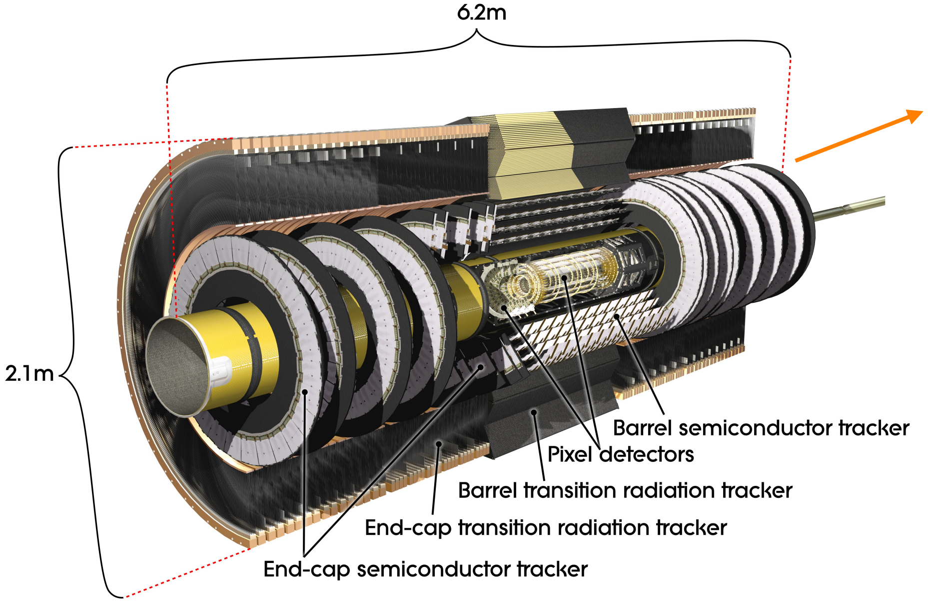
Muon reconstruction

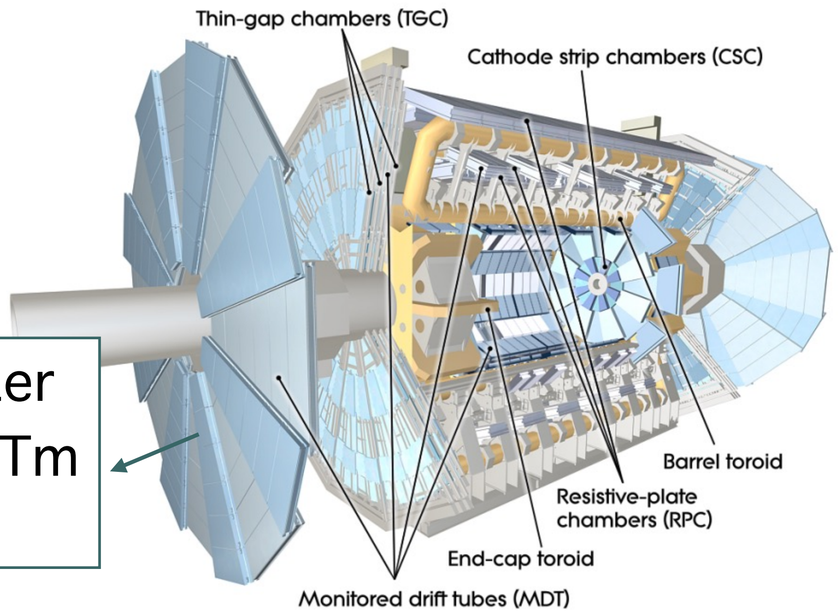
- Muons are mainly reconstructed from inner detector and muon spectrometer
- Muon momentum resolution is mostly limited by inner detector in the $H \to \mu\mu$ kinematic phase space (p^T_μ < 60 GeV)
  - Resolution typically at 1~2%





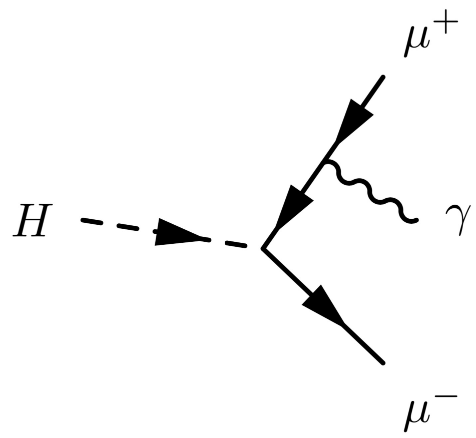
Inner detector
- B = 2T
- |η| < 2.5

Muon spectrometer
- $\int B \times dl$ = 1~7.5Tm
- |η| < 2.7

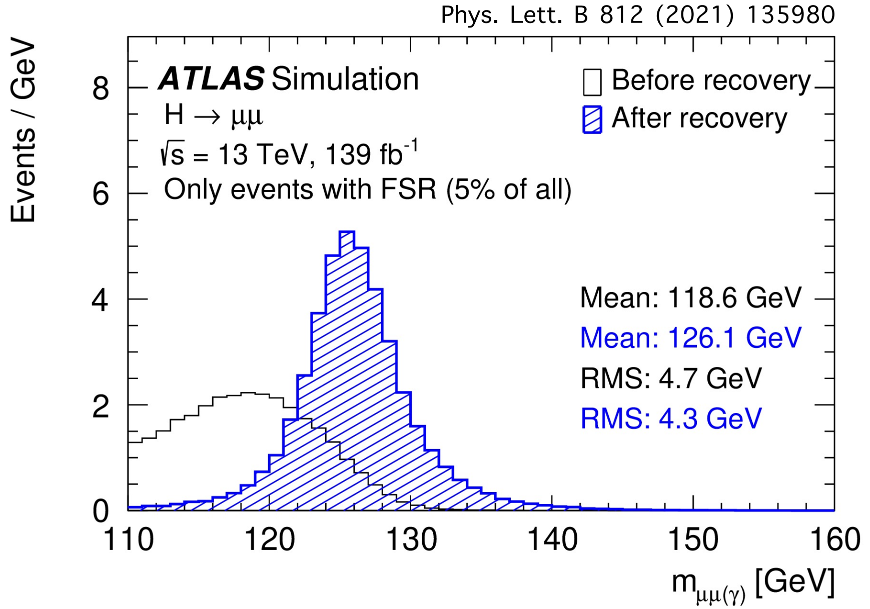


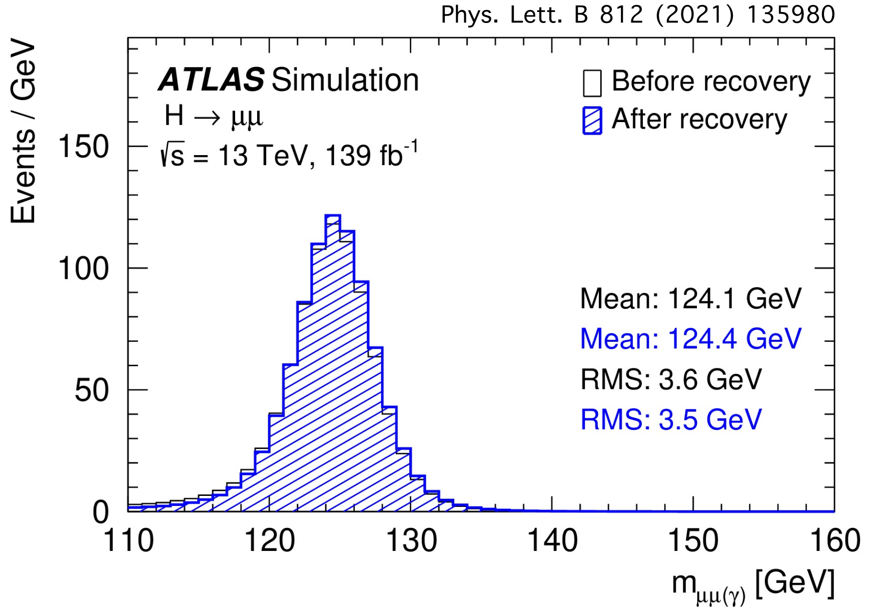
Final State Radiation recovery

- Muon may lose a significant amount of energy due to QED final state radiation



- Include up to 1 final state photon for each event in $m_{\mu\mu}$ calculation to improve signal reconstruction
  - $\Delta R(\gamma,\mu) < 0.2$
  - p_T^{γ} threshold increases linearly with $\Delta R(\gamma,\mu)$ from 3 to 8 GeV to supress pile-up background
- $m_{\mu\mu}$ resolution improved by **~3%**





Dimuon event selections

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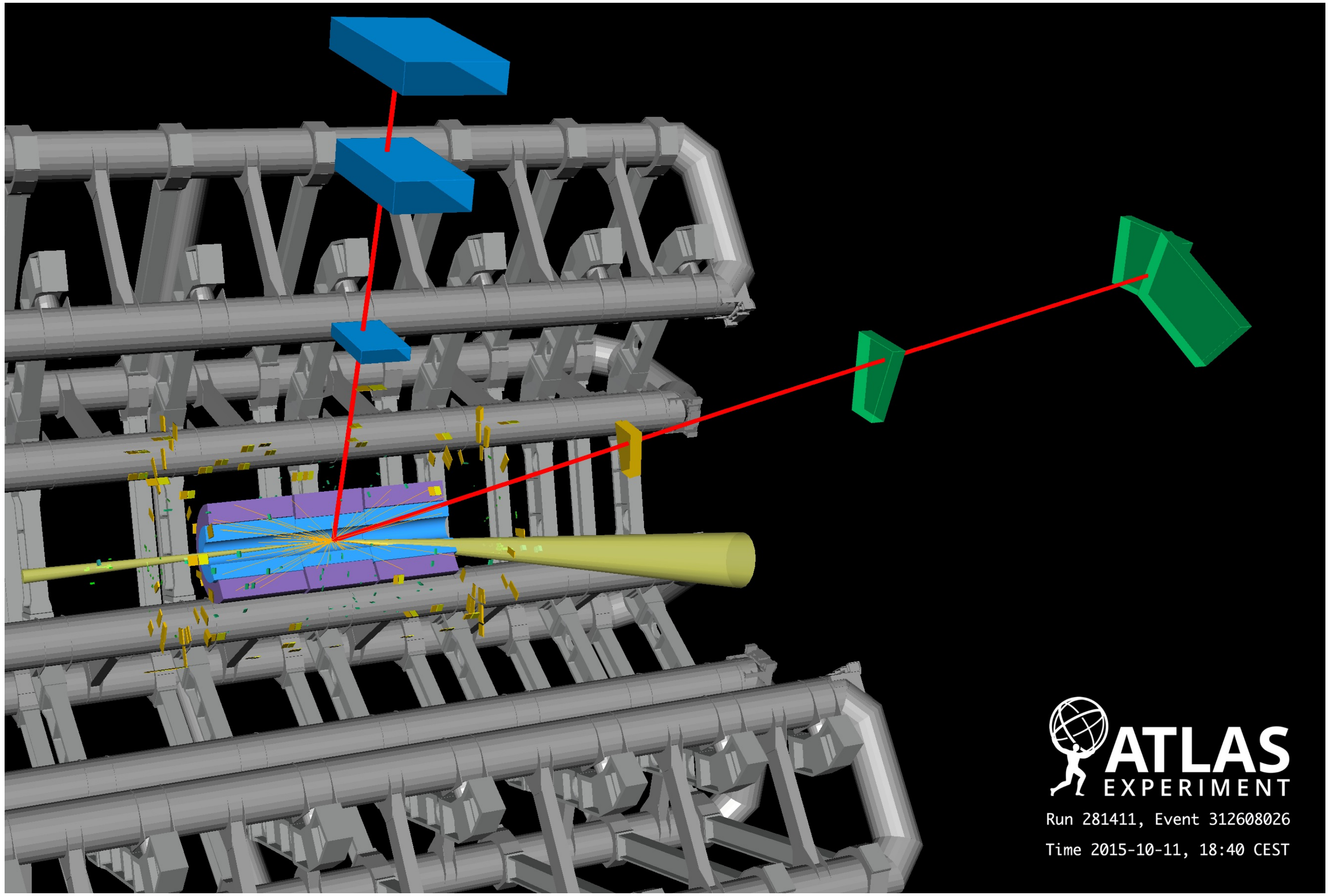
- Passing single-muon triggers
- Having two muons with opposite charges
- Muon p_T > 6 GeV
- Muon η < 2.7
- Passing loose muon identification criteria based on particle tracks
- Passing isolation requirement to suppress hadronic activities

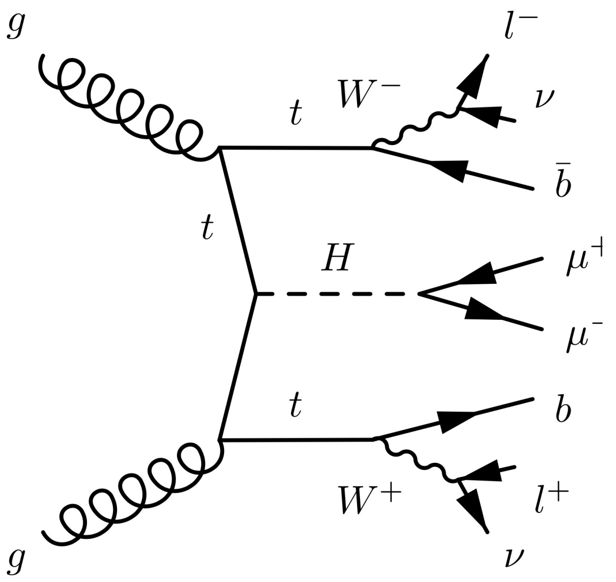


- Further selections for different Higgs production phase spaces

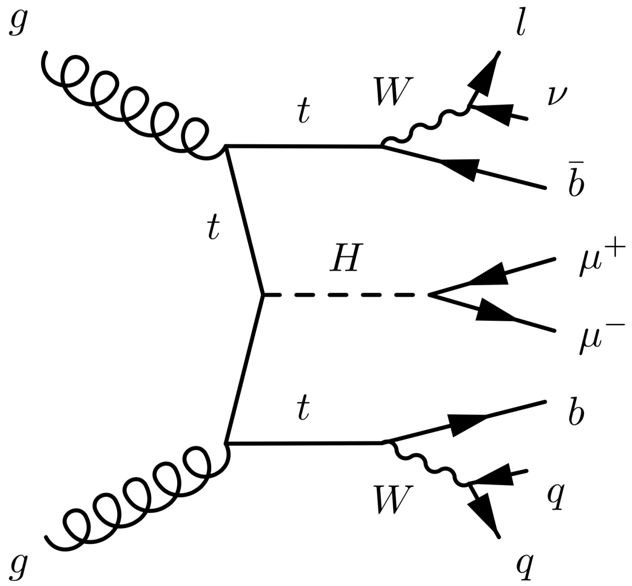
ttH category

- Target leptonic and semi-leptonic decays from $t\bar{t}$
  - Require at least 1 additional lepton (μ/e) and at least 1 b-jet
  - Leading (sub-leading) muon p_T > 27 (15) GeV

Leptonic



Semi-leptonic



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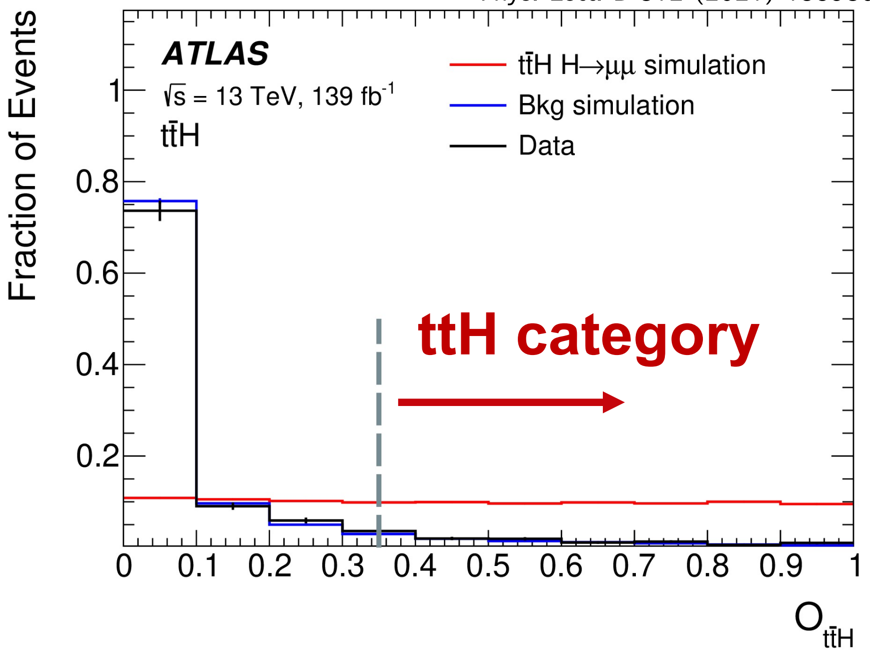
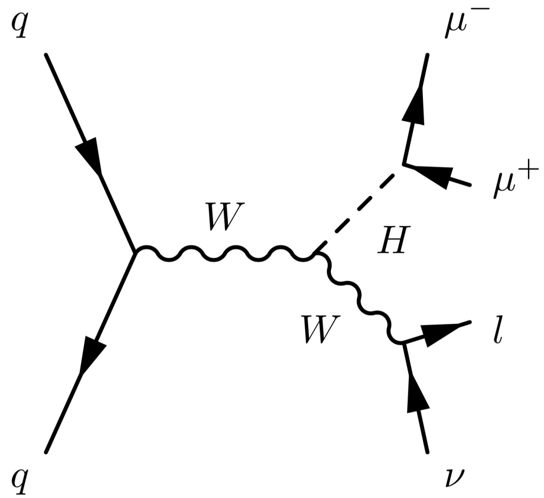
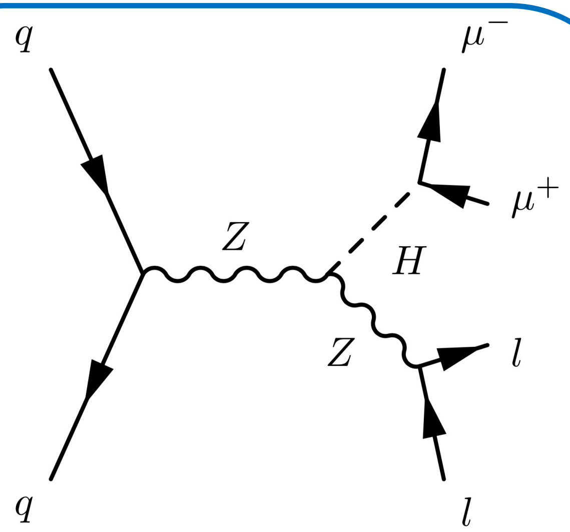


- BDT model trained to distinguish ttH signal against SM background with 12 event kinematic variables
- The ultimate ttH category is defined with BDT output ($O_{t\bar{t}H}$) > 0.35

VH categories



- 3-lepton channel targets WH production in leptonic decay
  - Exactly 3 leptons
  - No b-jet and no Z candidate*
  - Leptons p_T > 27, 10, 10(15) GeV for μ(e)



- 4-lepton channel targets ZH production in leptonic decay
  - > 4 leptons
  - No b-jet and < 2 Z candidates*
  - Leptons p_T > 27, 15, 8, 6 GeV

- Dedicated muon pairing if more than 2 muons
  - Two muons are paired to form the Higgs candidate by minimizing the χ^2 difference between reconstructed and expected mass values of the Higgs and W/Z bosons

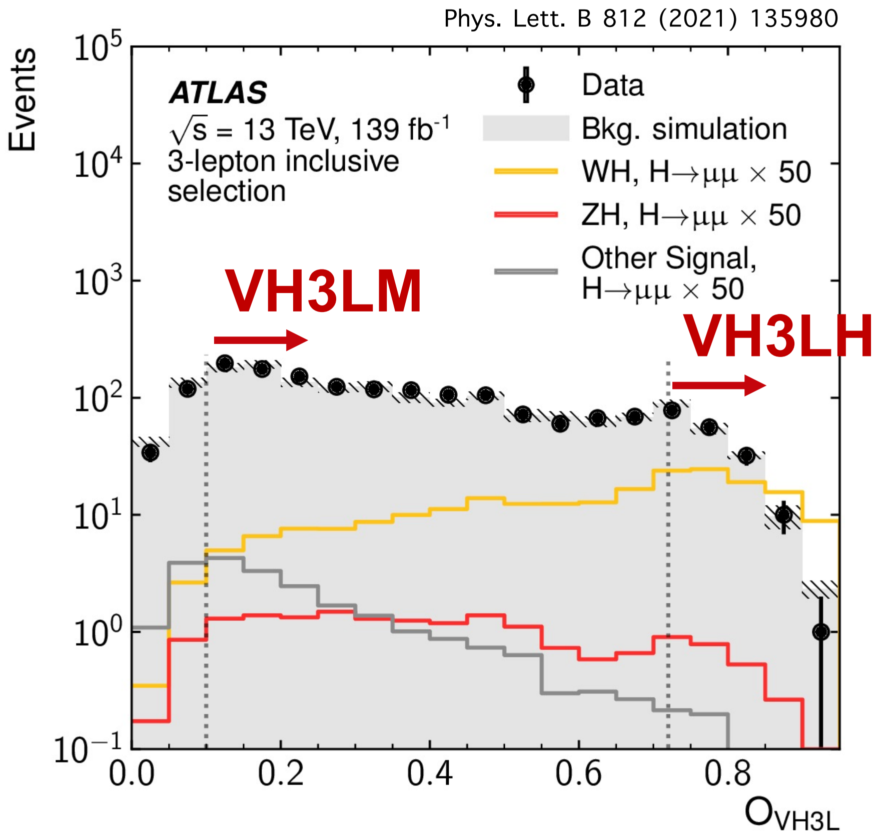
$$\chi^2 \equiv \left(\frac{m_H^{reco.} - m_H^{exp.}}{\sigma_H}\right)^2 + \left(\frac{m_{W/Z}^{reco.} - m_{W/Z}^{exp.}}{\sigma_{W/Z}}\right)^2$$

$\sigma_{H(W)(Z)}$ is the expected mass resolution of H(W)(Z)

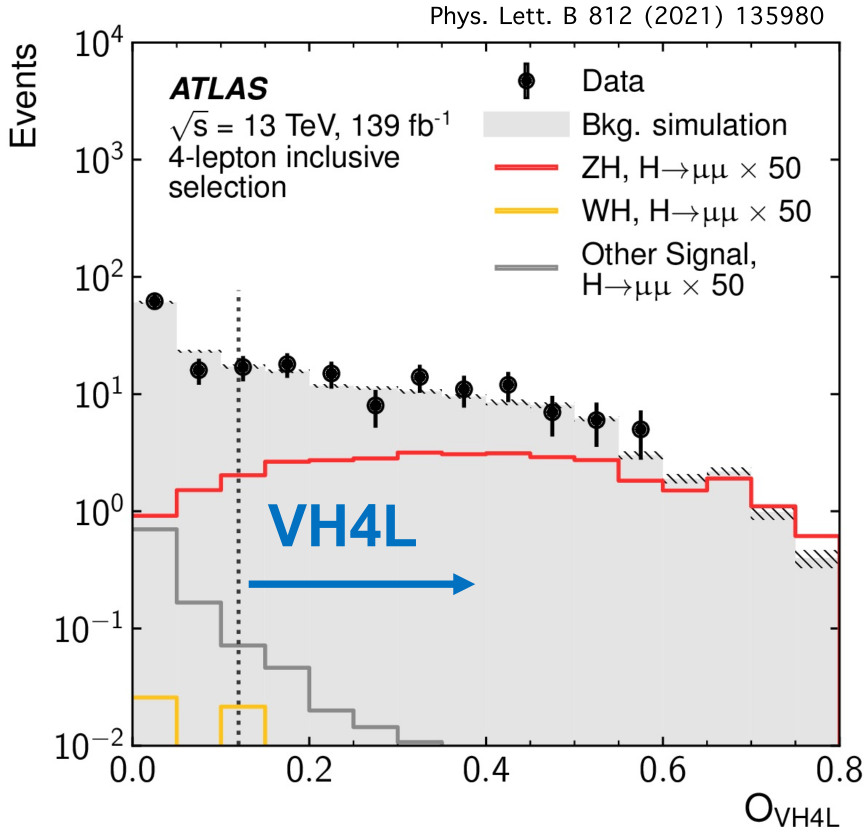
- 97(93)% correct pairing for 3μ(>4μ) cases

* Z = dimuon with $m_{\mu\mu}$ = 80-105 GeV

BDT for VH categories



- 2 BDTs trained for 3-lepton and 4-lepton channels
- Ultimate VH4L category defined by a BDT cut
- 3-lepton channel split to 2 sub-categories by BDT



- 8 variables used to train the BDT for 3-lepton channel
- WH as training signal and SM background as training background

- 7 variables used to train the BDT for 4-lepton channel
- ZH as training signal and SM background as training background

BDT training variables

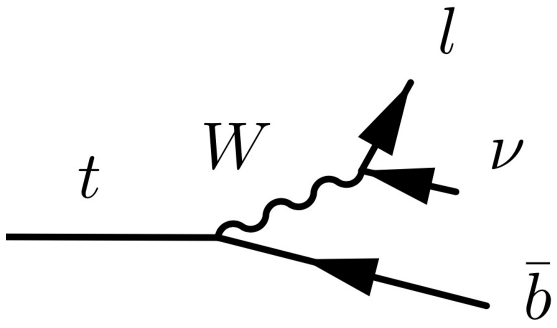
- **ttH:**
  - $\cos\theta^*$, $p_{T(\mu\mu)}$, $p_{T(l3)}$, $p_{T(l4)}$, $m_{leptonic\ top}$, $m_{leptonic\ W}$, $m_{hadronic\ top}$, $m_{(l3,l4)}$, $m_{(\mu3,\ \mu^*)}$, $N_{central\ jet}$, N_{bjet}, H_T,

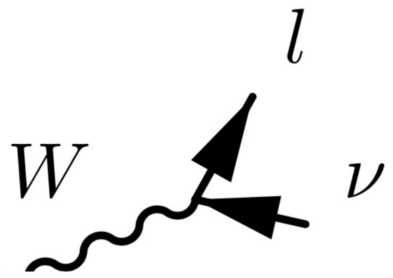
μ*=opposite charge muon from Higgs candidate

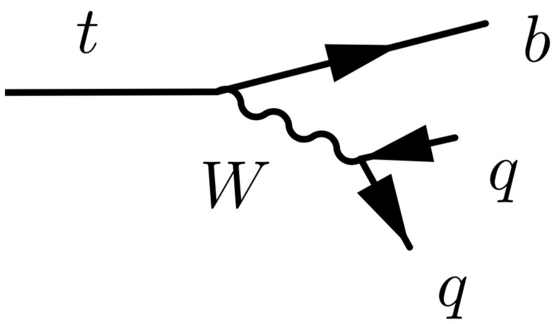
- **VH3L:**
  - $m_{leptonic\ W}$, $p_{T(l3)}$, $\Delta\Phi_{(l3,\ H)}$, $\Delta\eta_{(l3,\ H)}$, $p_{T(j1)}$, MET, $\Delta\Phi_{(MET,\ H)}$, n_j
- **VH4L:**
  - $p_{T(j1)}$, $p_{T(j2)}$, n_j, $\Delta\Phi_{l3,\ l4}$, $\Delta\Phi_{Z,\ H}$, $\Delta\eta_{Z,\ H}$, m_Z
- **ggF/VBF:**
  - $\cos\theta^*$, $p_{T(\mu\mu)}$, $Y_{\mu\mu}$, $p_{T(j1)}$, η_{j1}, $\Delta\Phi_{j1,\ \mu\mu}$, $N_{track}^{j_1}$, $p_{T(j2)}$, η_{j2}, $\Delta\Phi_{j2,\ \mu\mu}$, $p_{T(jj)}$, Y_{jj}, $\Delta\Phi_{jj,\ \mu\mu}$, m_{jj}, MET, H_T, $N_{track}^{j_2}$

Note: $n_j \geq 1$ $n_j \geq 2$

Variable definition







- $m_{\text{leptonic top}}$: transverse mass of the 3rd lepton, MET and b-jet
- $m_{\text{leptonic W}}$: transverse mass of the lepton and MET
- $m_{\text{hadronic top}}$: invariant mass of q, q, b

- $\cos\theta^*$: lepton decay angle in the Collins–Soper frame

$$\cos\theta^* = \frac{2(p_1^+ p_2^- - p_1^- p_2^+)}{\sqrt{m_{\ell\ell}^2 (m_{\ell\ell}^2 + p_{\mathrm{T},\ell\ell}^2)}} \frac{p_{Z,\ell\ell}}{|p_{Z,\ell\ell}|}$$

$H \rightarrow \mu\mu$ object preselection

Muons	Electrons	Jets
• Loose working point • FixedCutPflowLoose isolation • pT > 6 GeV • $\lvert\eta\rvert < 2.7$ • Impact parameters: $\lvert$d0 significance$\rvert$ < 3.0 $\lvert$Z0 sinθ$\rvert$ < 0.5 mm	• Medium likelihood working point • FCLoose isolation • PT > 7 GeV • $\lvert\eta\rvert < 2.47$ (excluding crack region $1.37 < \lvert\eta\rvert < 1.52$) • Impact parameters: $\lvert$d0 significance$\rvert$ < 5.0 $\lvert$Z0 sinθ$\rvert$ < 0.5 mm	• Antikt4PFlowEM algorithm • PT > 25 GeV for $\lvert\eta\rvert < 2.4$ PT > 30 GeV for $2.4 < \lvert\eta\rvert < 4.5$ • JVT > 0.59 for $\lvert\eta\rvert < 2.4$ and 20 < pT < 120 JVT > 0.11 for $2.4 < \lvert\eta\rvert < 2.5$ and 20 < pT < 120 • b-tagging: MV2c10 60% working point for ggF/VBF MV2c10 85% working point for VH/ttH

H→μμ event selections

- GRL and event cleaning for data
- Trigger and trigger matching:
  - 2015: HLT_mu20_iloose_L1MU15 or HLT_mu50
  - 2016/17/18: HLT_mu26_ivarmedium or HLT_mu50

Exclusive categories with highest priority on the right

ggF/VBF	VH 3lep	VH 4lep	ttH
• Exactly 2 opposite charge muons • Leading (subleading) muon pT > 27 (15) GeV • b-jet veto (60%) • No ttH, no VH	• Exactly 3 leptons • At least 1 oppositely-charged muon pair • b-jet veto (85%) • $N_Z = 0$ • Leptons pT > 27, 10, 10(15) GeV for μ(e)	• At least 4 leptons • At least 1 oppositely-charged muon pair • b-jet veto (85%) • $N_Z < 2$ • Leptons pT > 27, 15, 8 ,6 GeV	• 1 oppositely-charged muon pair • Leading (subleading) muon pT > 27 (15) GeV • 1 additional μ/e with pT > 15 GeV • $N_{bjet} \geq 1$ (85%)