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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Outline

- Introduction
- Event selections and categorization
- Signal and background modeling
- Results
- Summary
- Backups

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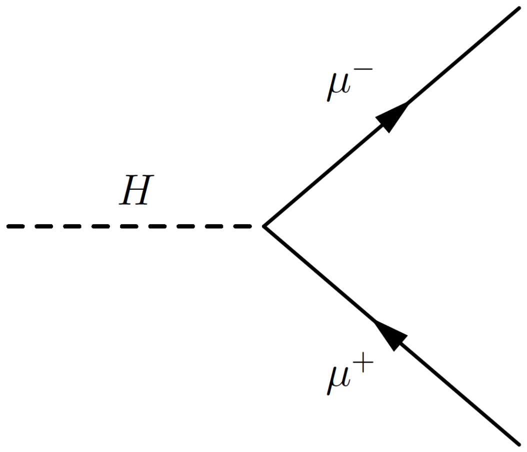
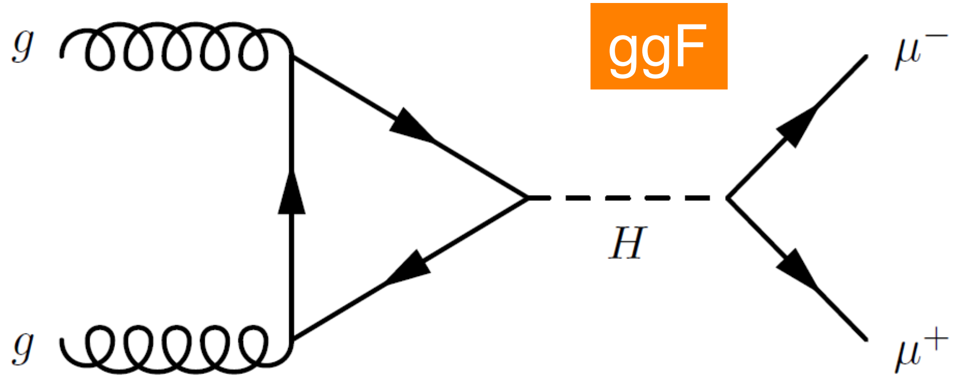
Introduction – why H→$\mu\mu$?

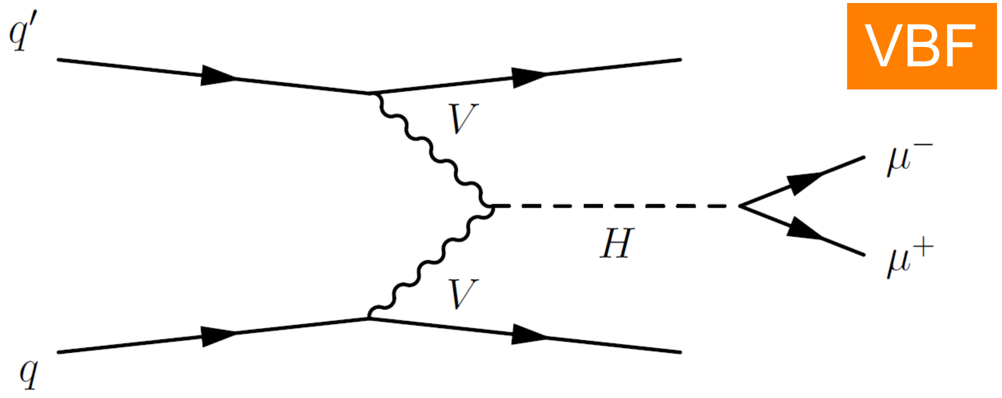
- Standard Model Higgs boson first discovered in 2012.
- Interactions between the Higgs boson and the third generation charged fermions (H→$\tau\tau$/bb, ttH) have been observed.
- Are there also interactions between the Higgs boson and the other generation fermions (2^{nd}: μ/c, 1^{st}: e)?
  - Predicted by Standard Model
  - Not yet observed (only upper limits set)
- The search of H→$\mu\mu$ decay is crucial for measuring the **Higgs coupling to second generation fermions**!



Introduction – our signals

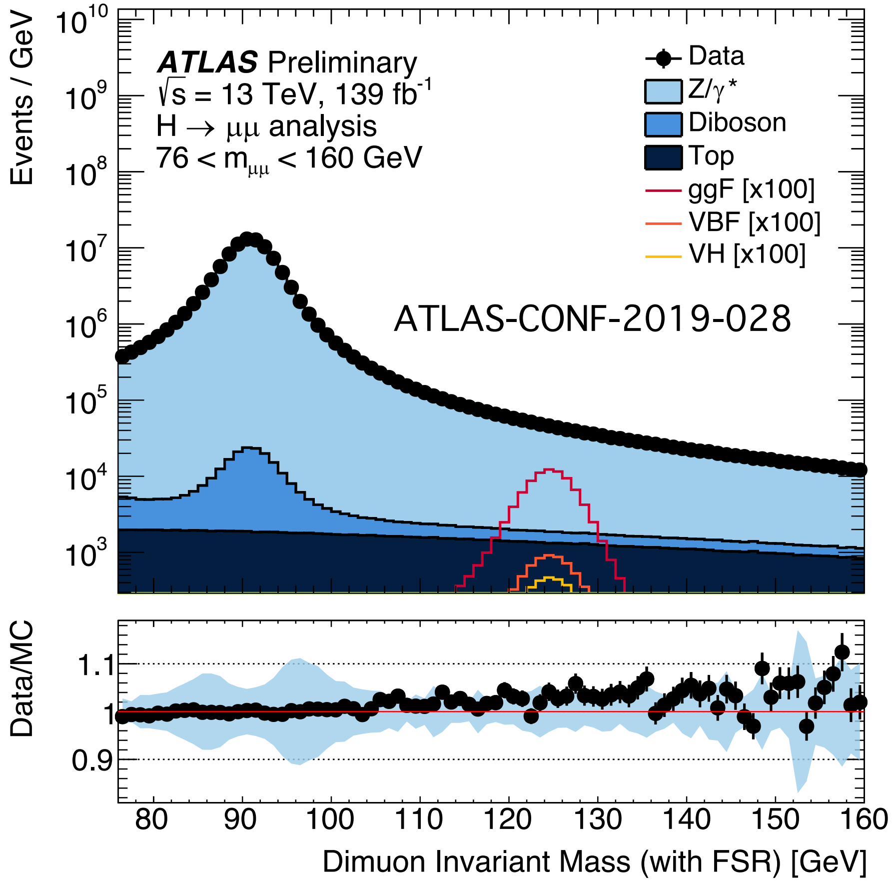
- What do we search for?
  - Two isolated muons with opposite charges (decayed from Higgs)
  - Focus on the two major Higgs production modes: gluon-gluon fusion (ggF) and vector boson fusion (VBF)
  - Other production modes (ttH and VH) also considered





Introduction – our background

- What are the backgrounds?
  - The major background (> 90%) is the **Drell-Yan (DY) process** ($Z/\gamma^* \rightarrow \mu\mu$)
  - Also contributions from tops and diboson events.



- Major challenge: low branching ratio ($\sim 10^{-4}$) and large background => **signal/background ratio < 0.1%**
  - Hard to find the signal (requires good separation between signal and background)
  - Result can be easily biased from the background mismodeling

Introduction – the progress

- Previous preliminary ATLAS limits with 80 fb^{-1} of 13 TeV pp collisions: σ*BR < 2.2xSM (ATLAS-CONF-2018-026)
- **New** preliminary result with full Run2 data (**139 fb^{-1}**) released in EPS-HEP 2019. (EPS Talk, Public note: ATLAS-CONF-2019-028)
  - 75% more data, as well as refined analysis techniques:
    - Optimized BDT-based event categorization
    - Better background modeling
    - FSR recovery to improve the signal mass resolution
  - Sensitivity improved by **~50%** (~half from higher statistics, half from optimization)

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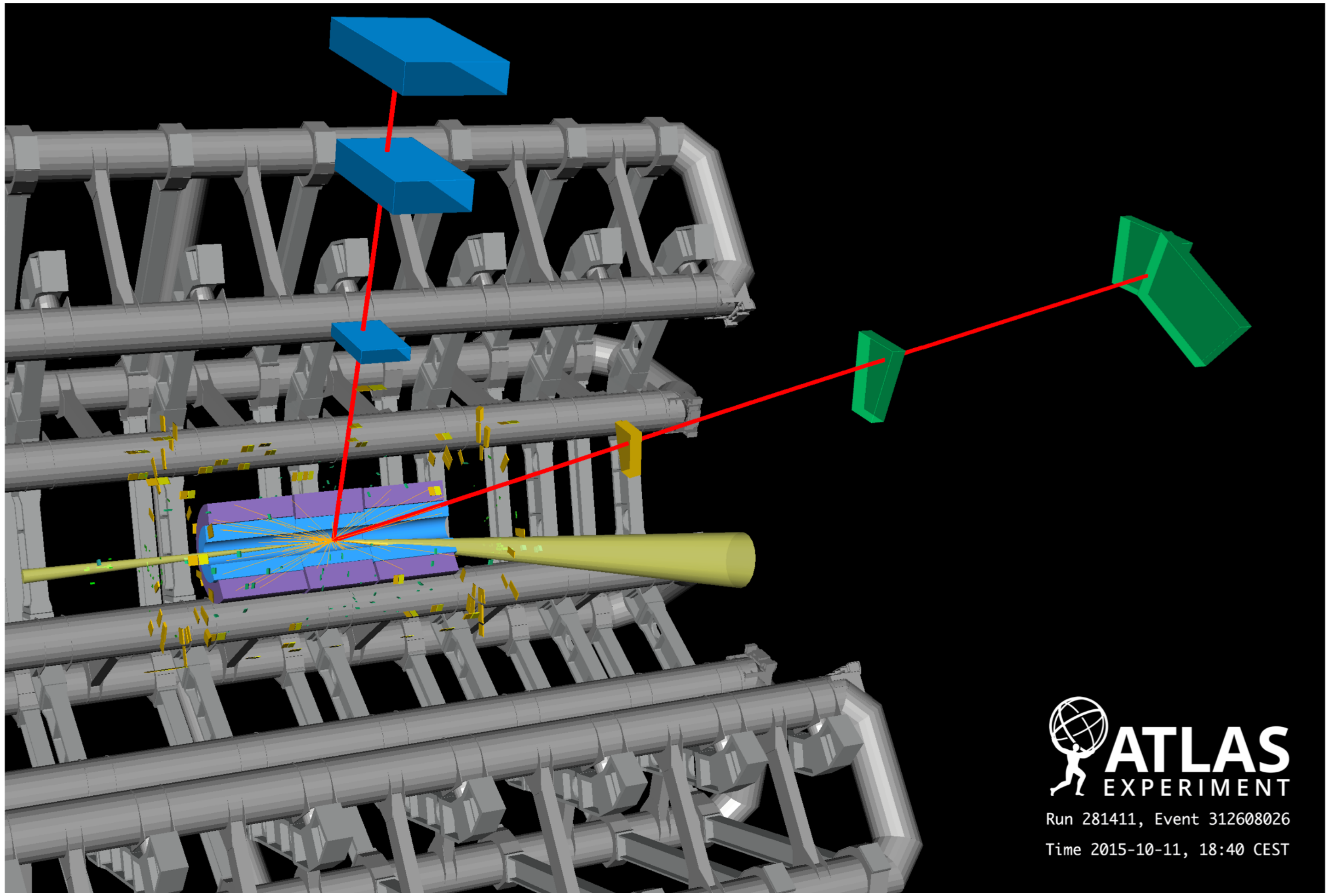
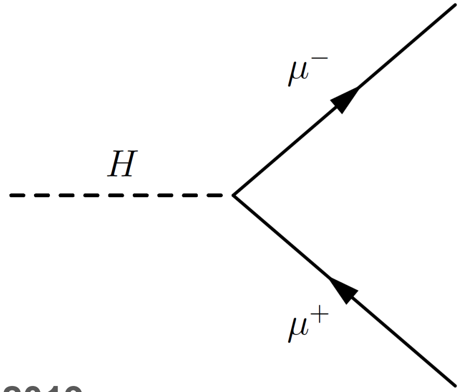
Event selections

- Single-muon triggers
- Two opposite-sign muons
- Veto events with b-tagged jets
- $110 < m_{\mu\mu} < 160$ GeV

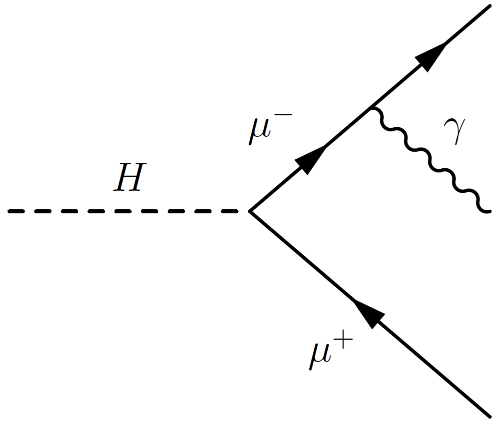


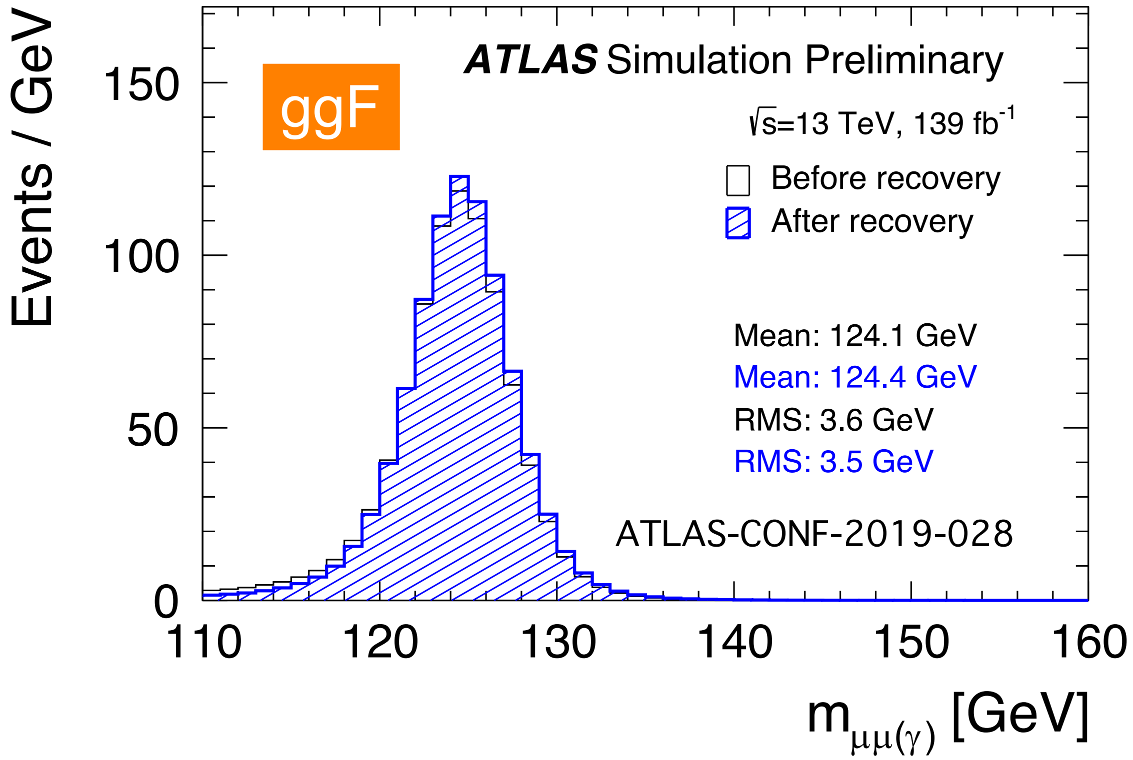


- ~2.5M events in data (mostly Drell-Yan)
- ~860 signal events expected (ε~60%)

FSR recovery

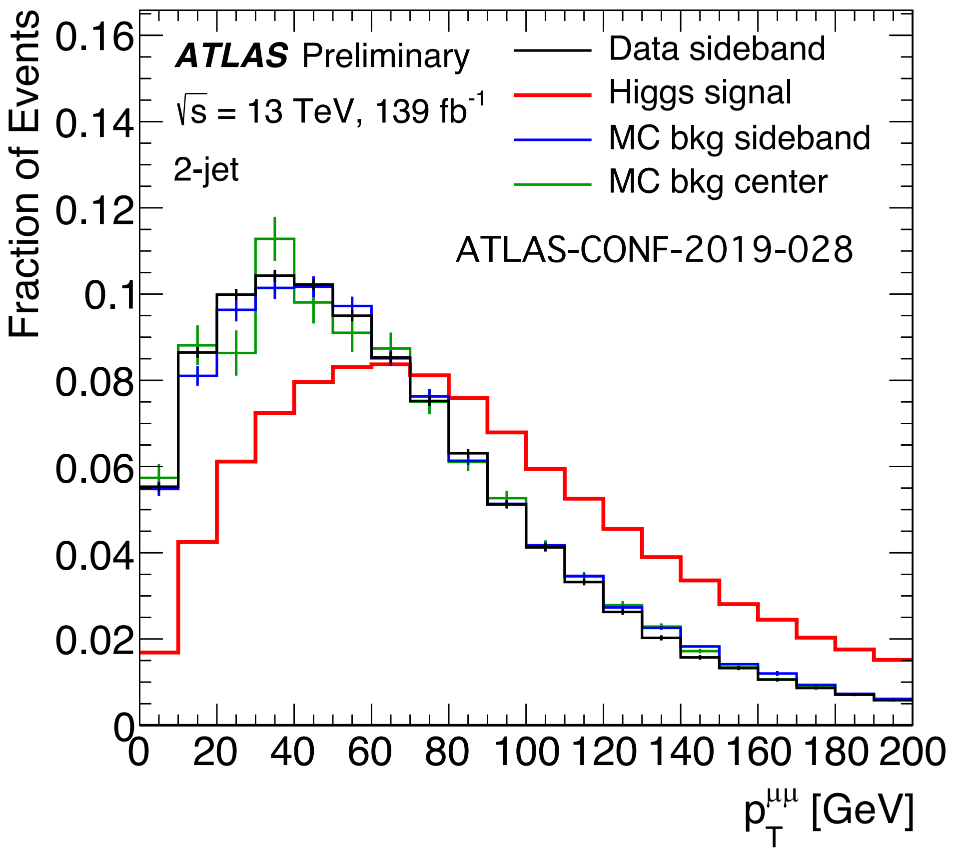
- Muon may lose a significant amount of energy due to the QED final state radiation (FSR).
- Including photon in the $m_{\mu\mu}$ calculation can improve the signal reconstruction => achieve better sensitivity
- Signal $m_{\mu\mu}$ width reduced by **~3%** (better resolution!)





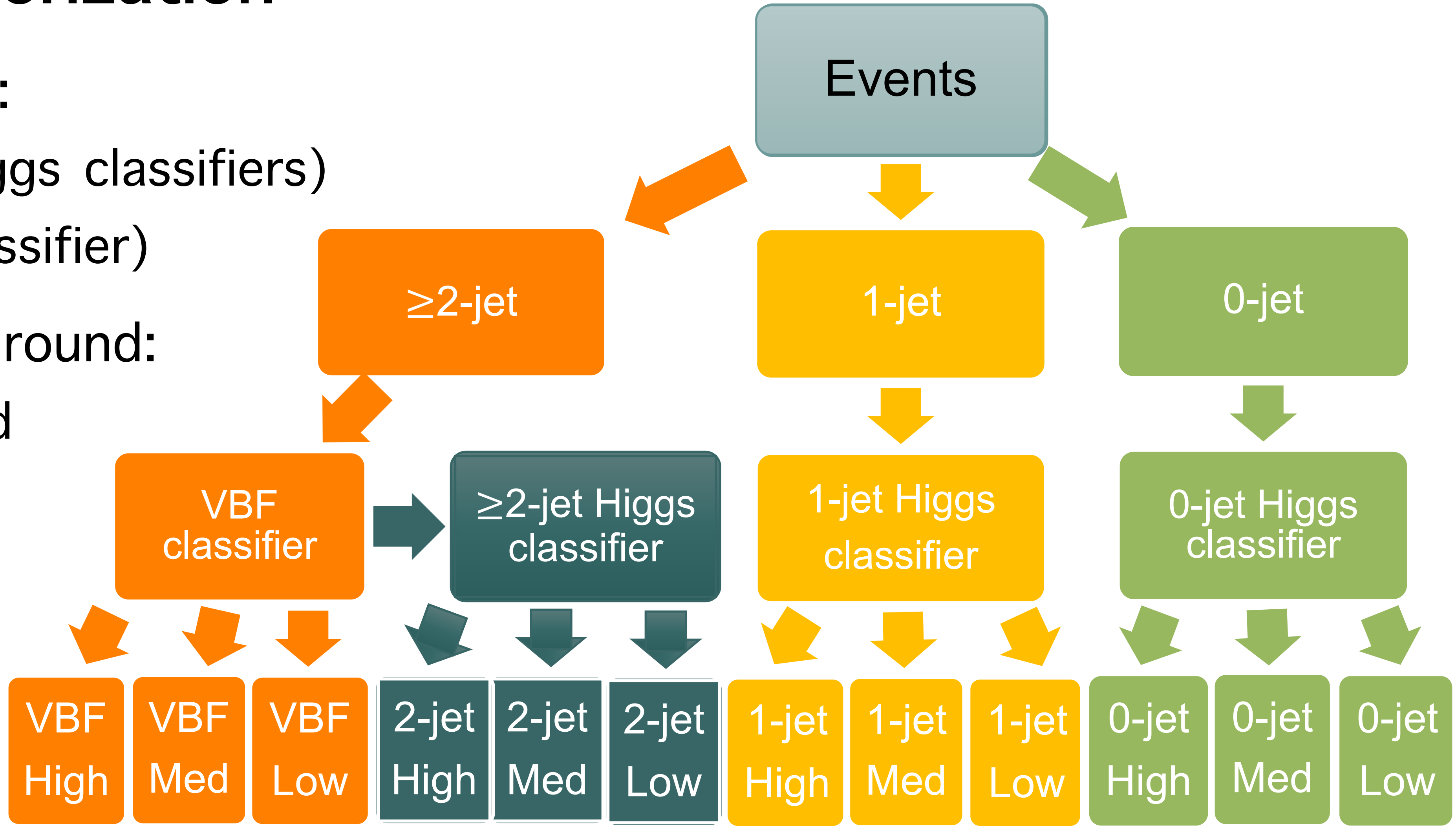
Event categorization

- How do we distinguish signals from such a huge background?
- Exploit the kinematic differences using boosted decision trees (BDT)
- BDT inputs:
  kinematic variables of dimuon system and leading jets, and E_T^{miss}
- Categorize the events based on BDT scores
- Each category has different S/B ratio => enhance sensitivity!



Event categorization

- Training signal:
  - VBF+ggF (Higgs classifiers)
  - VBF (VBF classifier)
- Training background:
  - data sideband

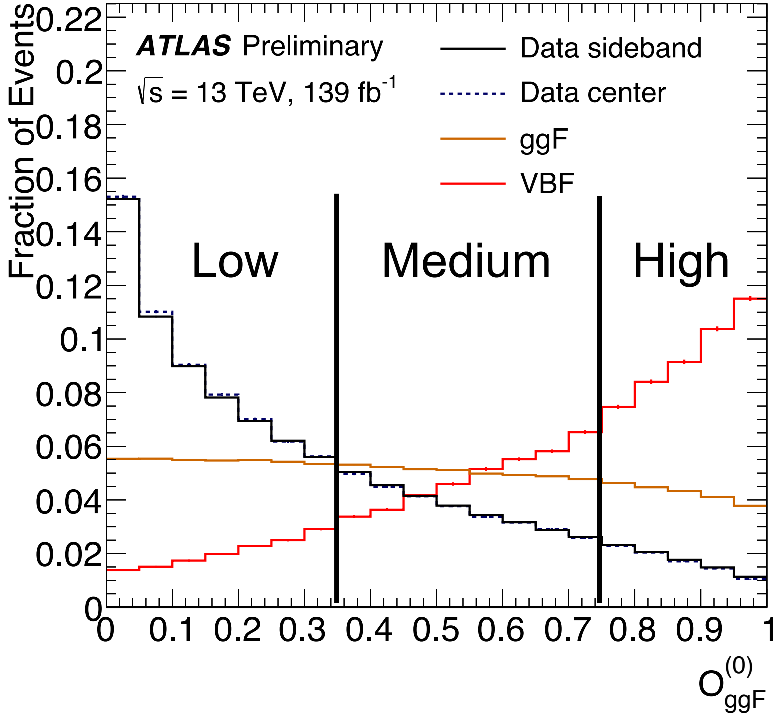


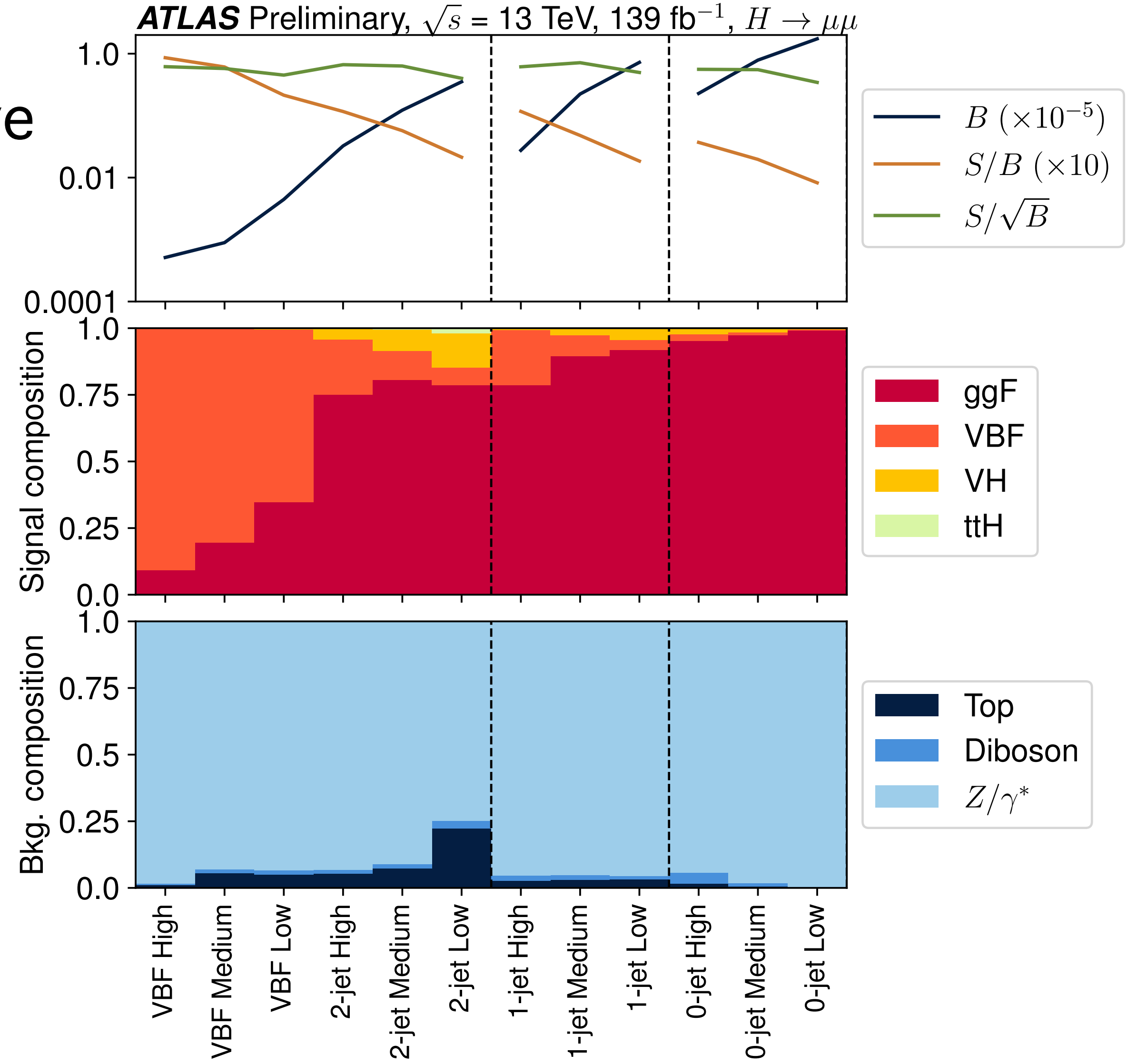
In total **12 categories**

Event categorization

ATLAS-CONF-2019-028

- Very different S/B ratio between categories; VBF-High most sensitive
- Mainly VBF events in the VBF categories





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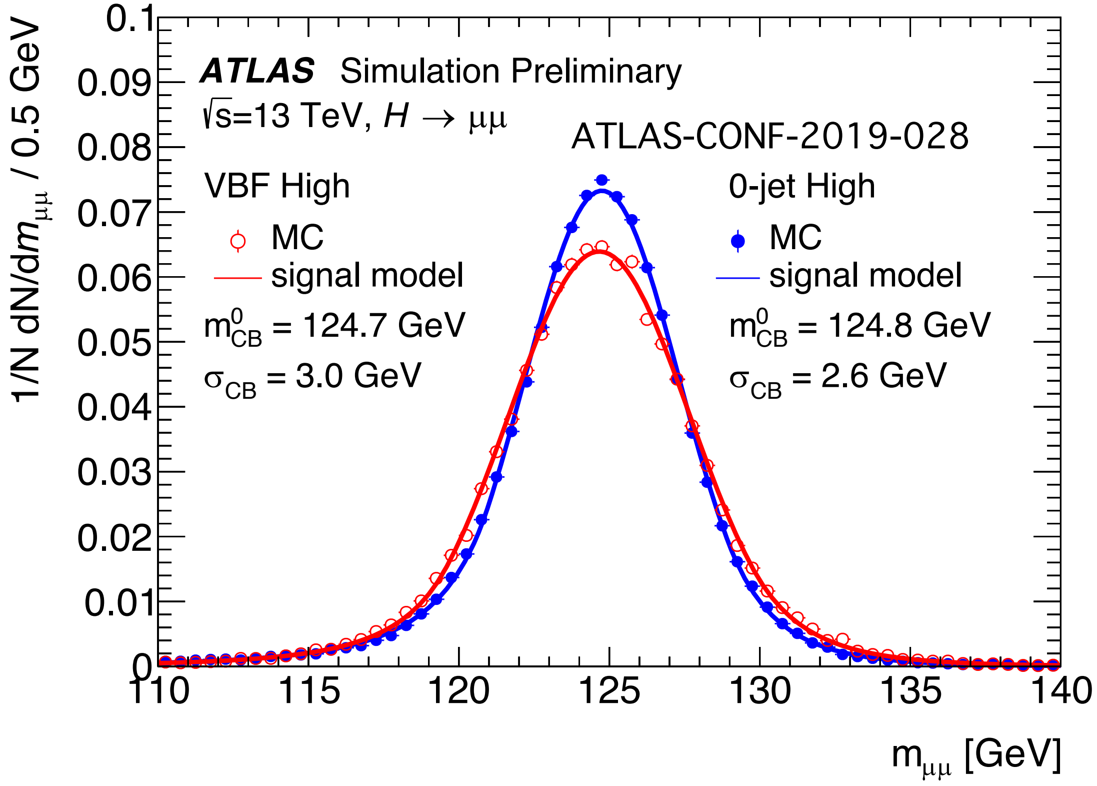
Signal and background Modeling

- Strategy:
  - Analytical functions (describing the signals and background) fit to **$m_{\mu\mu}$ distribution of data)**
  - Signal and background yields to be determined through the fit

Signal modeling

- A double-sided Crystal Ball function (Gaussian + power-law tails) is used to describe the signal shape in each category
- Parameters determined from simulation data for each category
- Main systematics:
  - μ momentum scale and resolution
  - Missing higher order QCD correction
  - Underlying event and parton showering

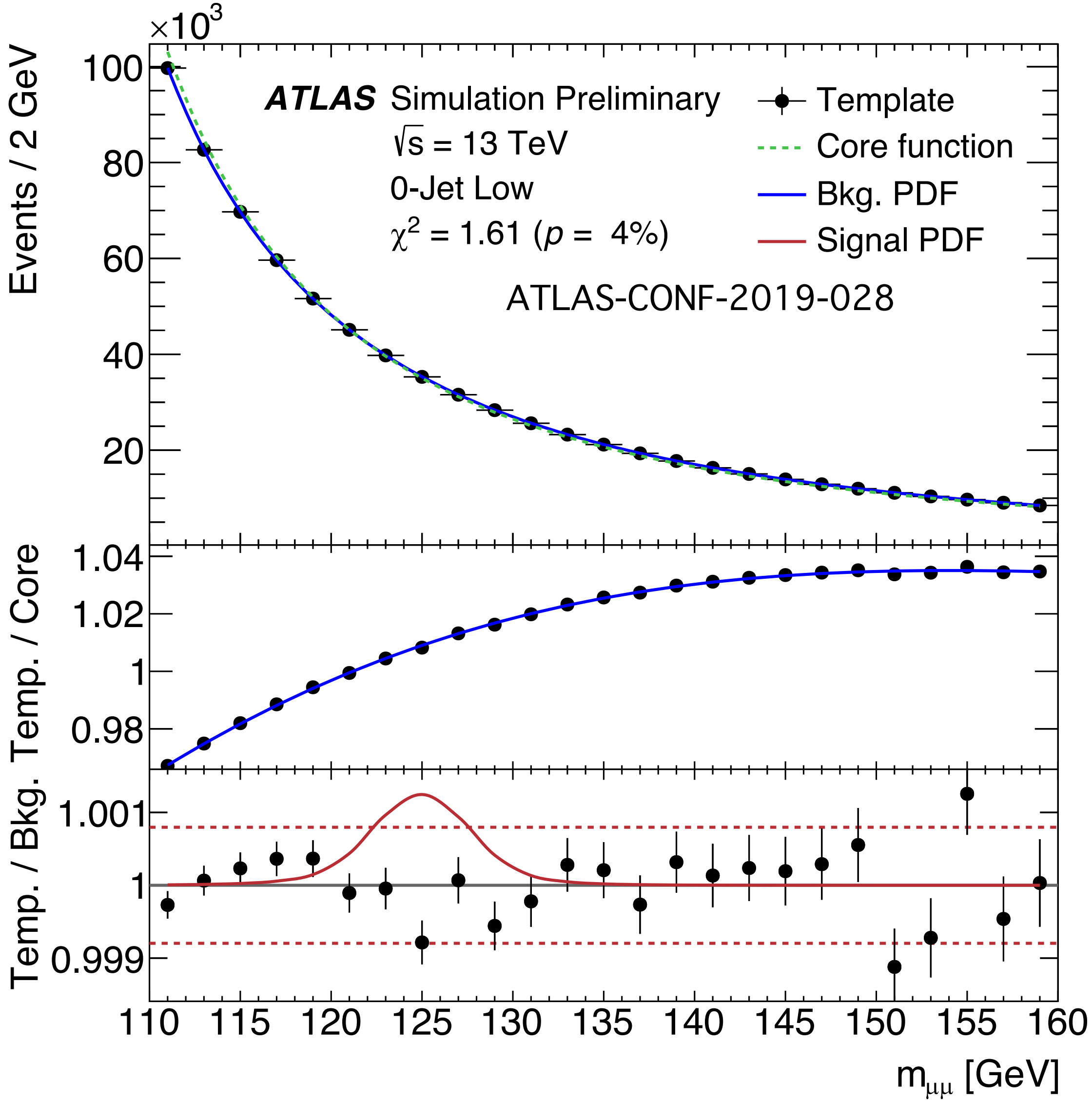


Background modeling

- Major challenges:
  - Very low S/B ratio
  - DY process has very steep slope at low mass (near Z peak)
- Solution: use a core×empirical to model the background shape
  - Core function: fully rigid physics motivated line shape to cope with the non-trivial shape in the mass spectrum
    - LO DY line-shape convolved with muon resolution
  - Empirical function: fully flexible functions to absorb the mismodeling from the core function
    - Power-law or Epoly functions (different in each category)

Background modeling

- Selected functions have to pass the fit quality criteria:
  - Signal bias |S| < 20% of fit uncertainty on S in S+B fit to background-only template
- |S| in each category is then used as the background modeling systematic



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Results

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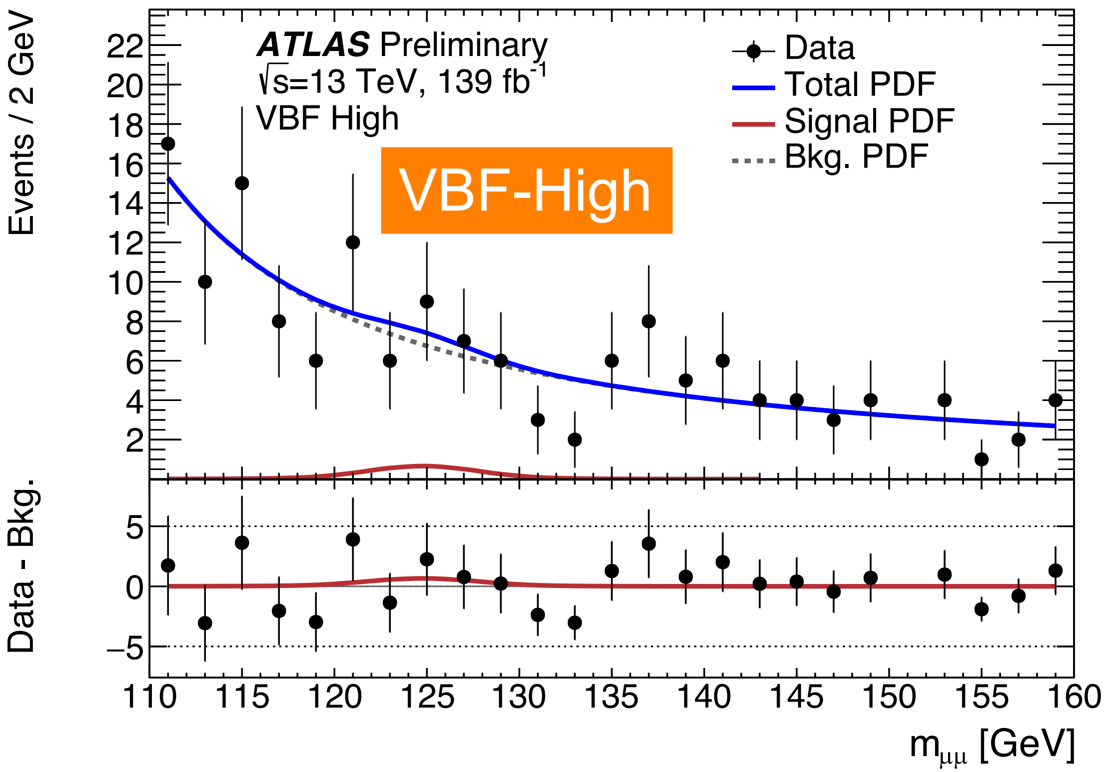

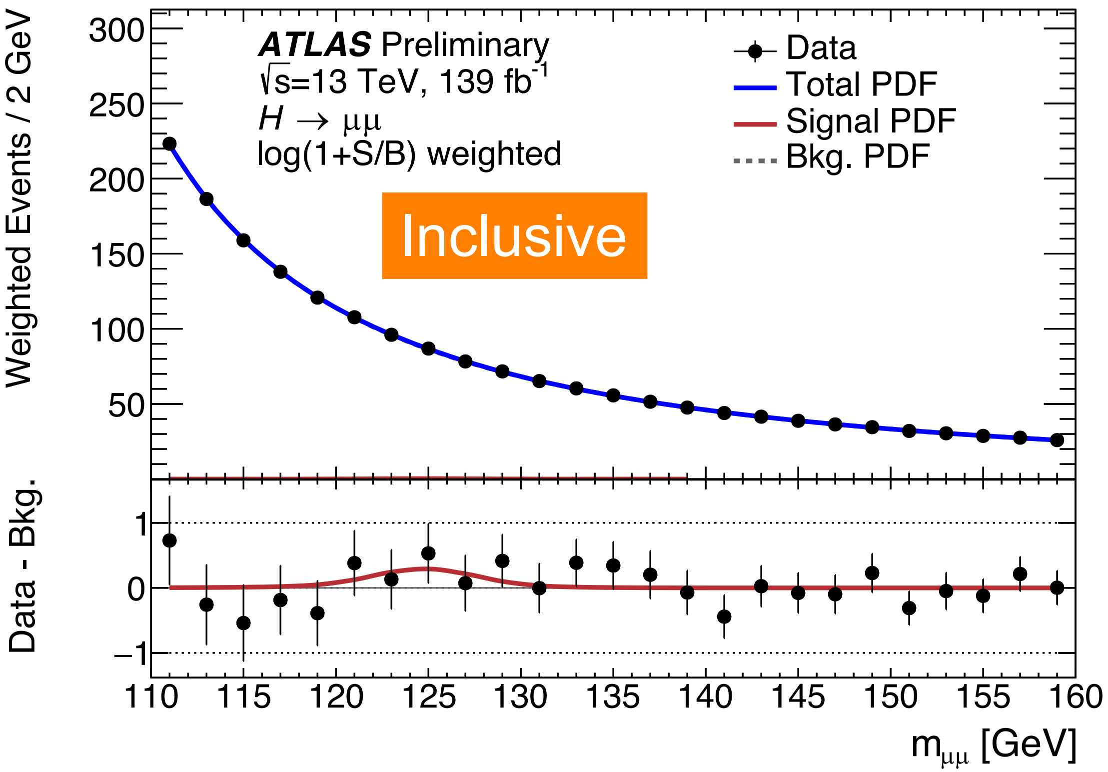

- Perform a simultaneous maximum likelihood fit to the $m_{\mu\mu}$ distributions in 12 categories

Results

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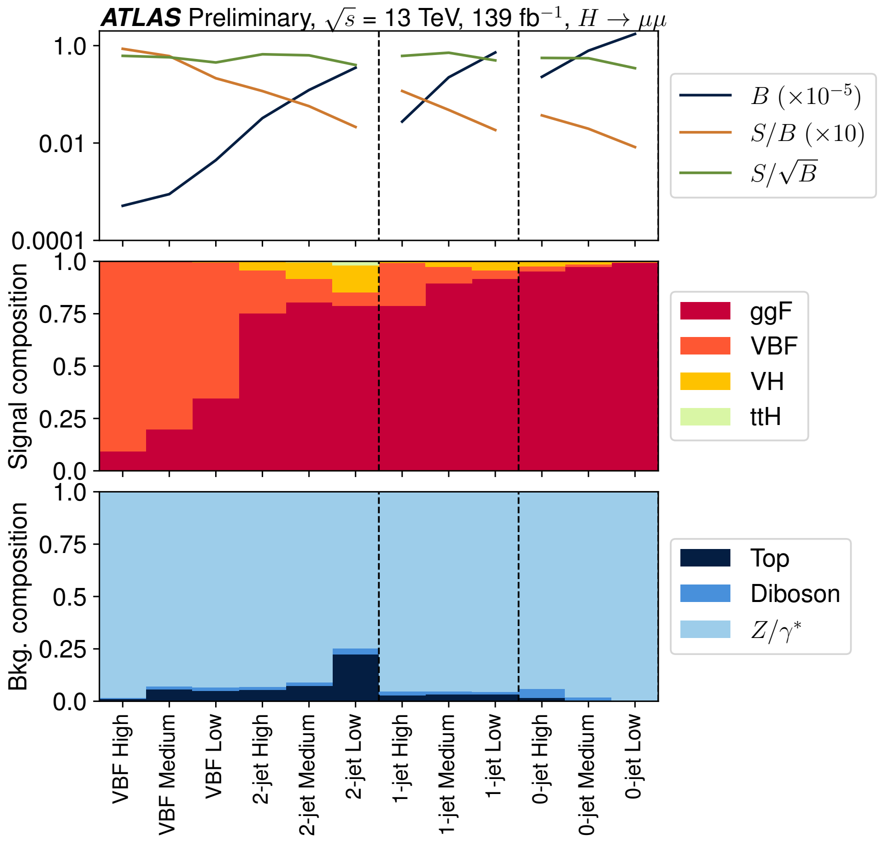
Category	Data	S_{SM}	S	B	$S/\sqrt{B}$	S/B [%]
VBF High	40	4.5	2.3	34	0.39	6.6
VBF Medium	109	5.5	2.8	100	0.28	2.8
VBF Low	450	9.6	4.9	420	0.24	1.2
2-jet High	3400	38	19	3440	0.33	0.6
2-jet Medium	13938	70	35	13910	0.30	0.3
2-jet Low	40747	75	38	40860	0.19	0.1
1-jet High	2885	32	16	2830	0.31	0.6
1-jet Medium	24919	107	54	24890	0.35	0.2
1-jet Low	77482	134	68	77670	0.24	0.1
0-jet High	24777	85	43	24740	0.27	0.2
0-jet Medium	85281	155	79	85000	0.27	0.1
0-jet Low	180478	144	73	180000	0.17	<0.1



- Signal and background yields determined by the fit

Results

	Observed	Expected
Significance	0.8σ	1.5σ
Fitted signal strength μ	0.5±0.7	1.0±0.7
Upper limit @ 95% CL	1.7 x SM	**1.3 x SM** (assuming no $H\to\mu\mu$) **2.2 x SM** (assuming $H\to\mu\mu$)

- No significant excess has been observed
- Results statistically limited

Summary

- H→$\mu\mu$ decay channel provides the best opportunity for probing the interactions between Higgs boson and the second generation fermions.
- ATLAS measured H→$\mu\mu$ decay with full Run2 data (139 fb^{-1}); sensitivity increased by **~50%** (wrt previous iteration) due to the increased data and better analysis techniques
- Observed significance is **0.8σ**, while 1.5σ is expected.
- The fitted signal strength μ = 0.5 ± 0.7 (currently compatible with both μ=1 and μ=0 assumptions)
- Looking forward the future results!

Backup slides

Mass distribution of the events with FSR