Search for the Higgs boson decay to a pair of muons

with 139 fb^{-1} at the ATLAS detector at the LHC

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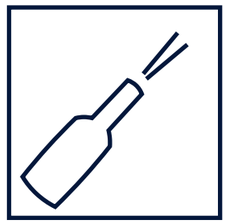
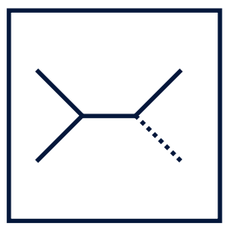
on behalf of the ATLAS Collaboration

Higgs Hunting
July 31, 2019
Paris, France

Motivation



Higgs discovery in 2012 a major triumph of the Standard Model



Observed in main production modes and many decay channels

H->μμ has sensitivity to coupling to second generation fermions

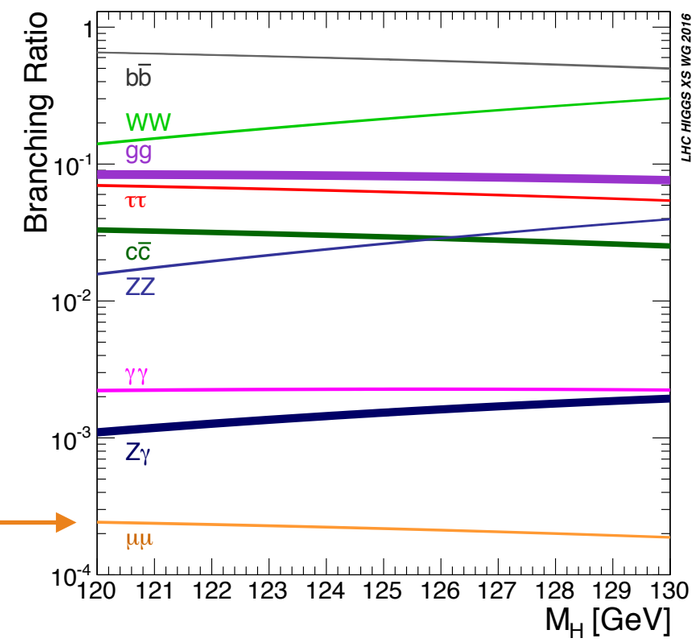
This talk: H->μμ with full Run 2 ATLAS dataset

ATLAS-CONF-2019-028

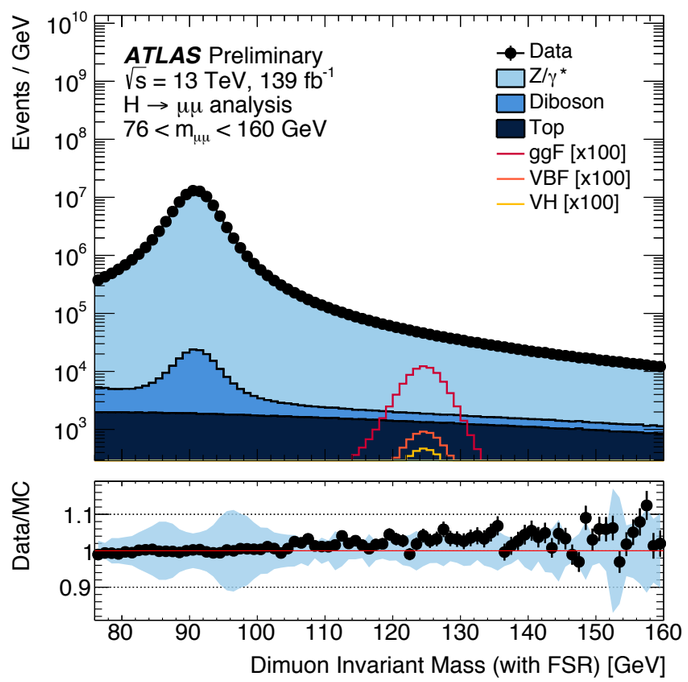
Key difficulty

small
signal
yield

(~1300 expected events
before selection in 139 fb^{-1})



large
DY
background



very small S/B

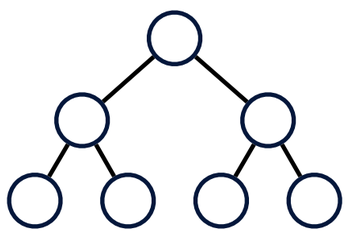
(~1/500 inclusive)

-> keep as much signal as possible
-> require excellent background modelling

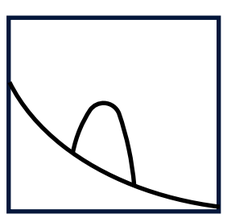
Top figure from CERN Yellow Report 4, bottom from ATLAS-CONF-2019-028

Strategy

Loose muon and event selection



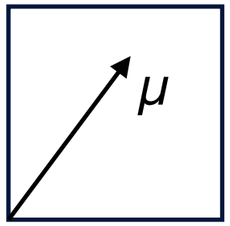
Fully-multivariate categorisation to maximise sensitivity



Fit the dimuon invariant mass in data

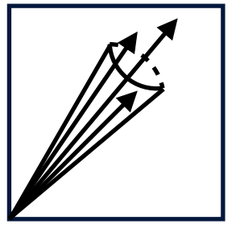
Object and Event Selection

MUON



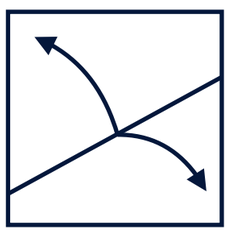
Loose quality muons
Loose isolation
$|\eta| < 2.7$, $p_T > 15$ GeV

JET



$|\eta| < 4.5$, $p_T > 25$ (30) GeV for $|\eta| < 2.4$ (otherwise)
pileup reduction cuts
loosest b-tagging (for the veto)

EVENT



Loosest unprescaled single-μ triggers
2 opposite charge muons, lead muon $p_T > 27$ GeV
Veto events with b-tagged jet(s)
Recover FSR to improve mass resolution

Categorisation

jet channel	XGBoost discriminant(s)
0-jet	Higgs classifier (3 categories)
1-jet	Higgs classifier (3 categories)
≥ 2-jet	VBF clf. (3 categ.), if not VBF: Higgs clf. (3 categ.)

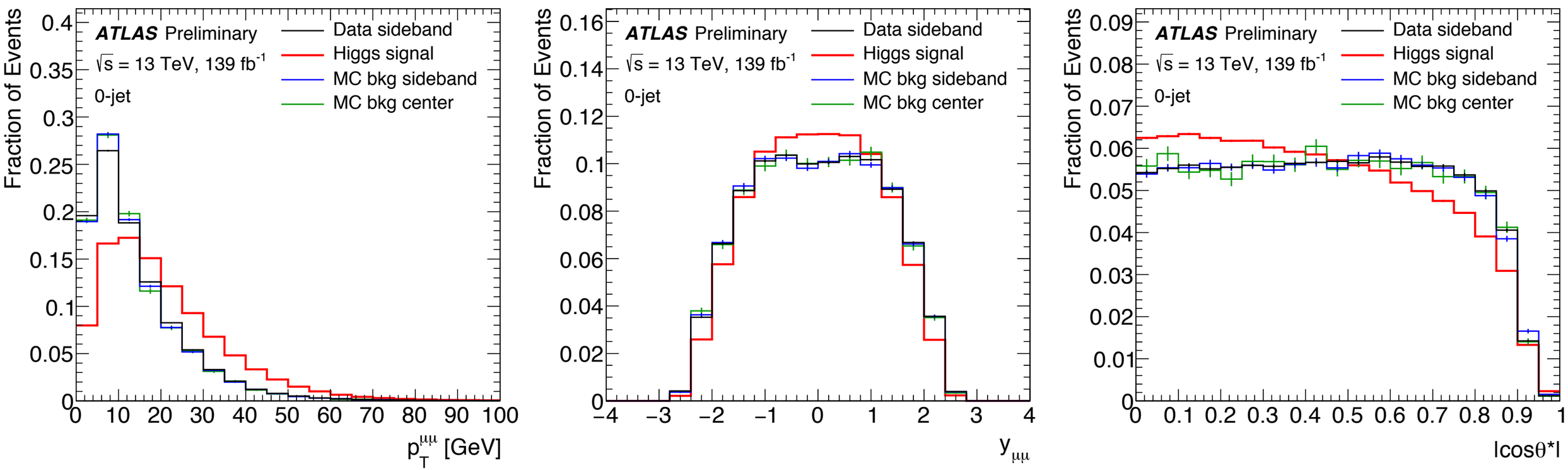
Higgs classifier: ggF + VBF signal MC trained against data sidebands*

VBF classifier: VBF signal MC trained against data sidebands

*data sidebands: 2015-2018, $m_{\mu\mu} \in [110, 120] \cup [130, 180]$ GeV

Training variables

jet channel	Training variables
0-jet	$p_T^{\mu\mu}$, $Y_{\mu\mu}$, $\lvert\cos(\theta^*)\rvert$
1-jet	0-jet variables + p_T^{j1}, η_{j1}, $\Delta\phi_{j1,\mu\mu}$
≥ 2-jet	1-jet variables + p_T^{j2}, η_{j2}, $\Delta\phi_{j2,\mu\mu}$, p_T^{jj}, Y_{jj}, $\Delta\phi_{jj,\mu\mu}$, m_{jj}, MET



Figures from ATLAS-CONF-2019-028

Categorisation summary

S = # signal events
B = # background events
(both mμμ ∈ [120, 130] GeV)

Signal composition

Background composition

Category boundaries determined by optimising the number counting significance

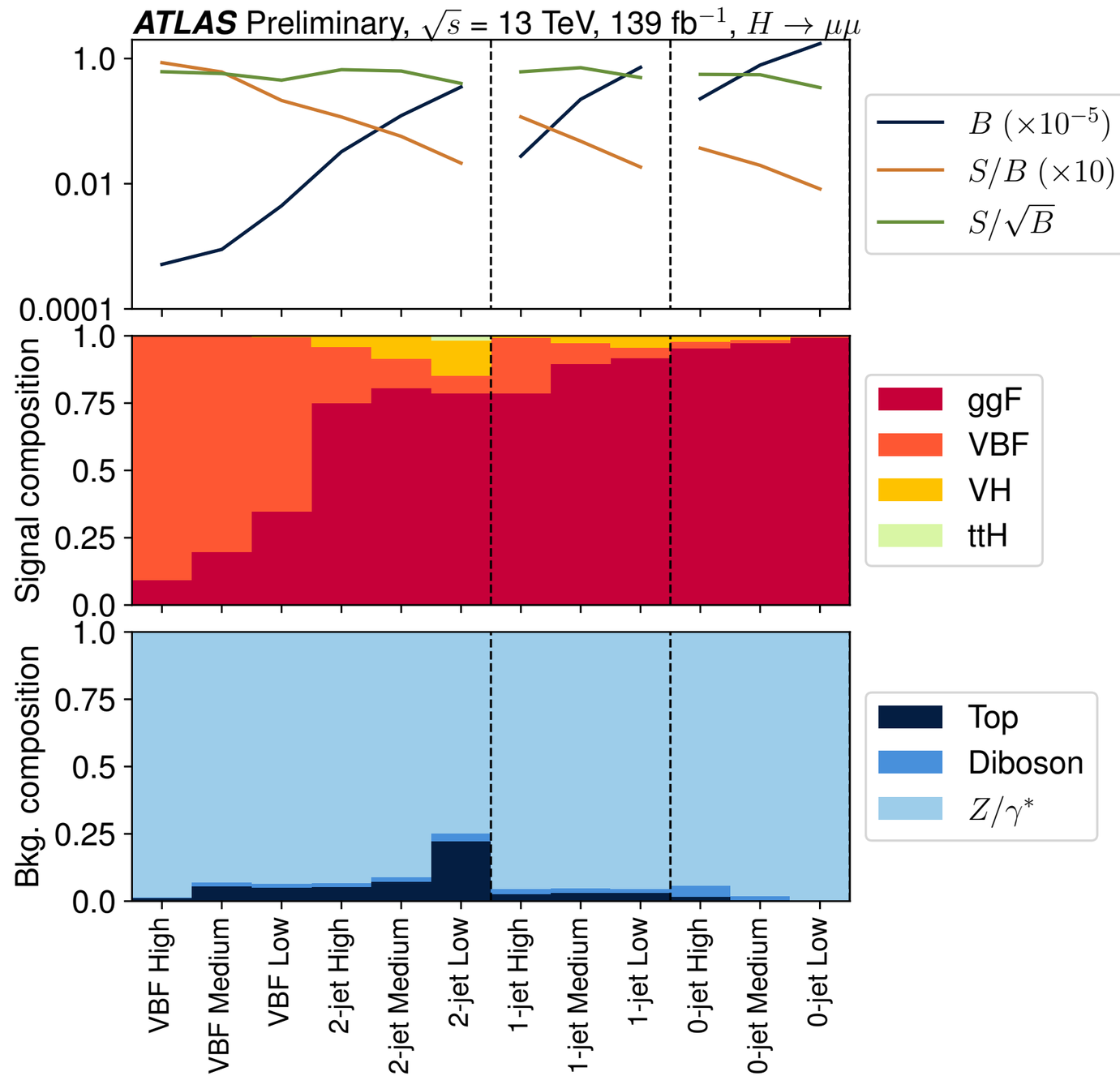
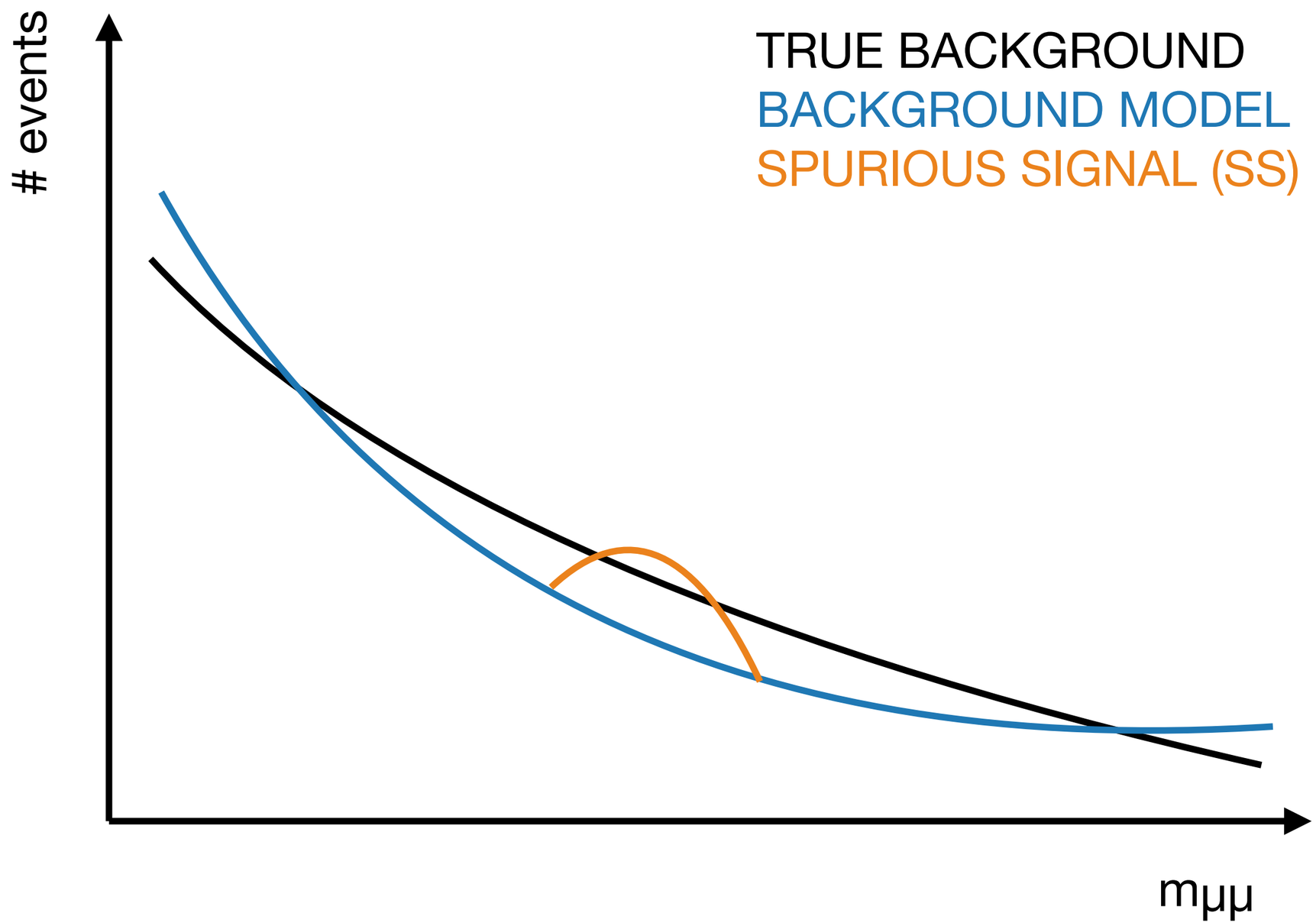
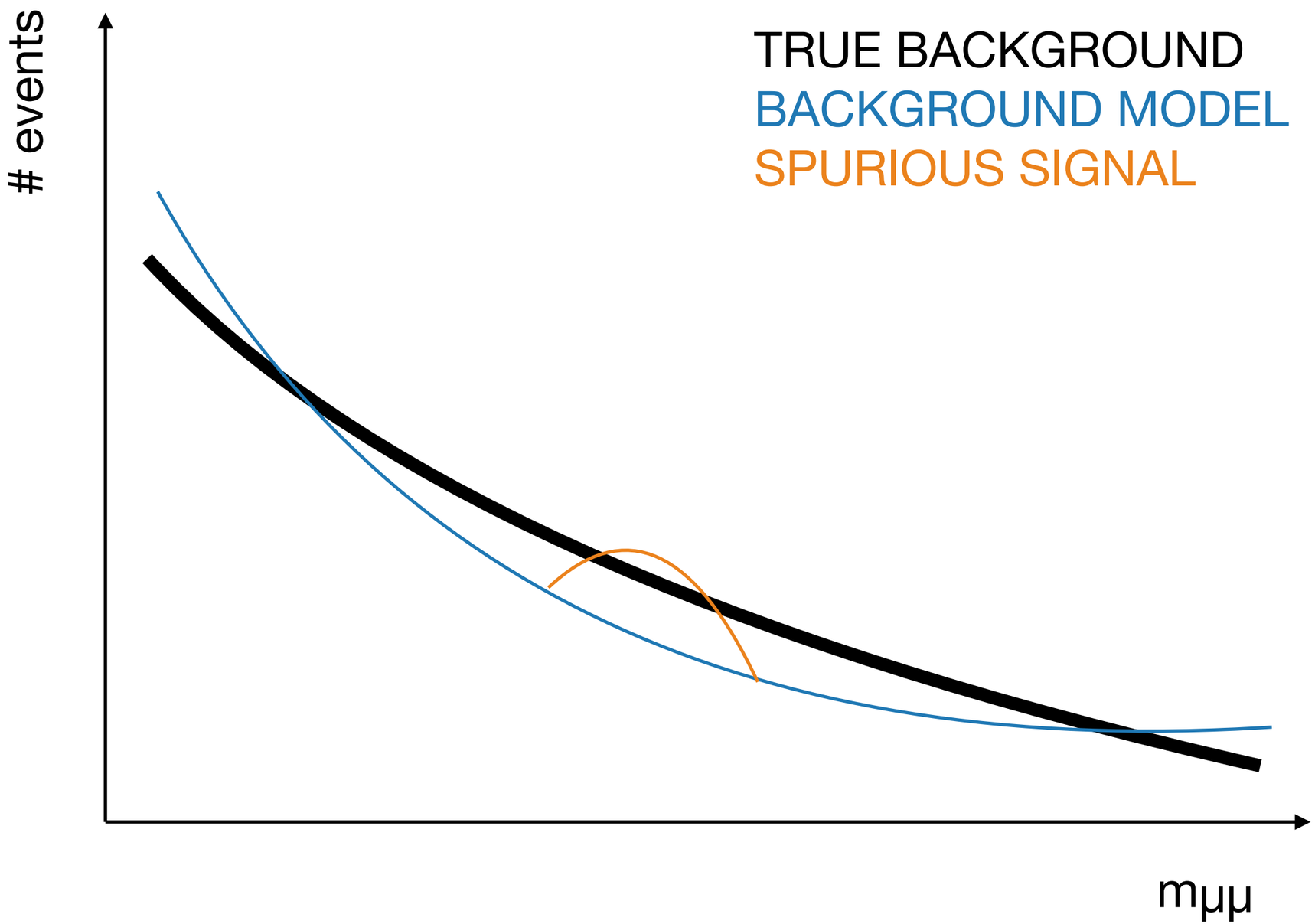


Figure from ATLAS-CONF-2019-028

Background modelling: key challenge



“TRUE BACKGROUND”



“TRUE BACKGROUND”

Very high-statistics MC needed to validate the background model.
Dedicated **fast DY simulation with parametrised response.**

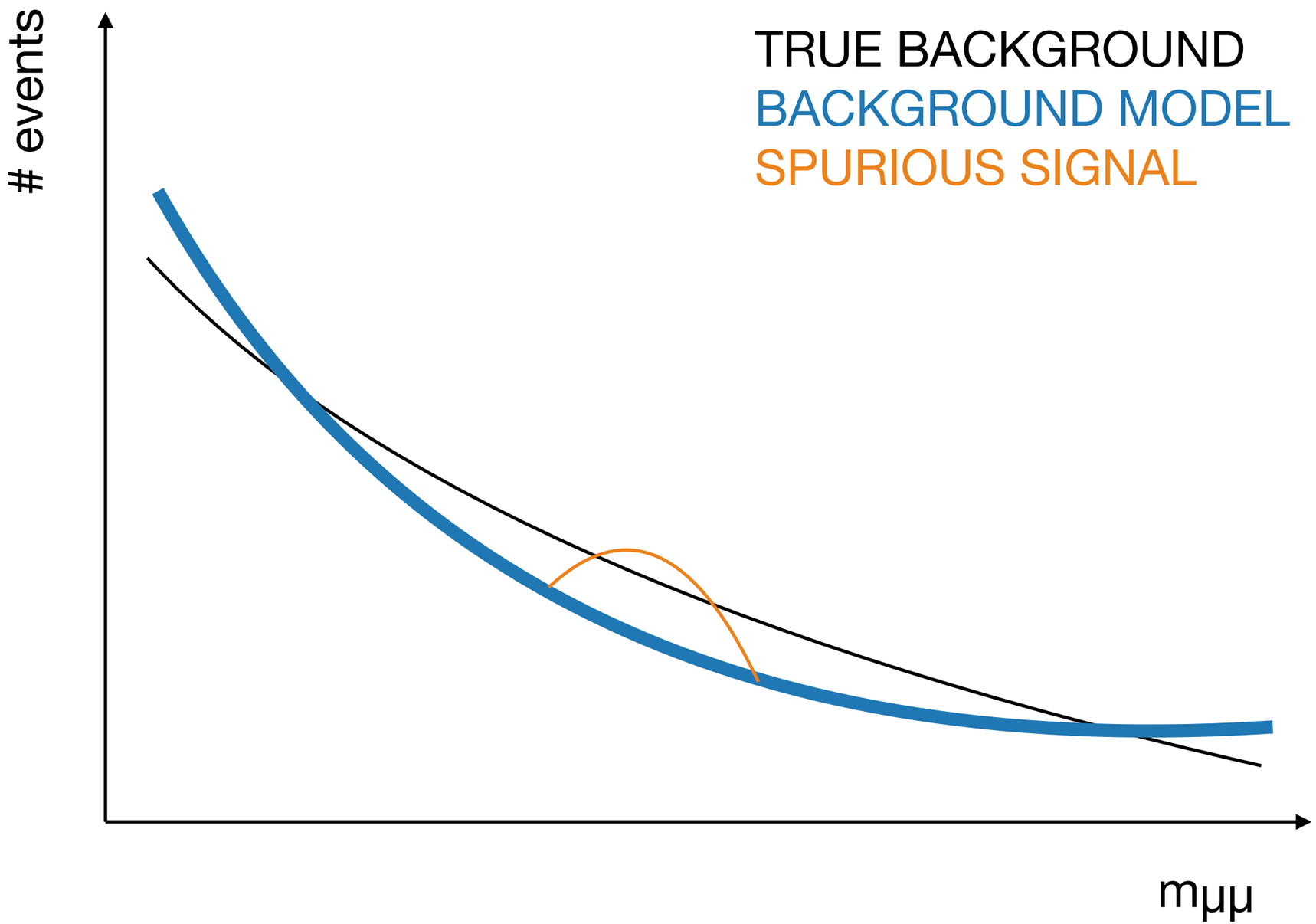
Event generation (DY only)
NLO Powheg (0 and 1 jet) and LO Alpgen (2 jet) fast event generation (~100 ab^{-1})

Muon corrections
Parametrised smearing for p_T, derived from full-sim.
Reco+ID, isolation, impact parameter efficiencies derived from full-sim.
Trigger efficiencies from measurements in data.

+ Jet p_T corrections + FSR resolution + Pileup jet overlay + MET smearing

Normalisation adjusted to data.

BACKGROUND MODEL



BACKGROUND MODEL

$PDF_{bkg}(m_{\mu\mu})$ = **Rigid core** x **Empirical function**

<u>Common to all categories</u>

<u>Rigid, physics-inspired shape.</u>
Analytic LO 2→2 Drell-Yan lineshape, convolved to model muon resolution.

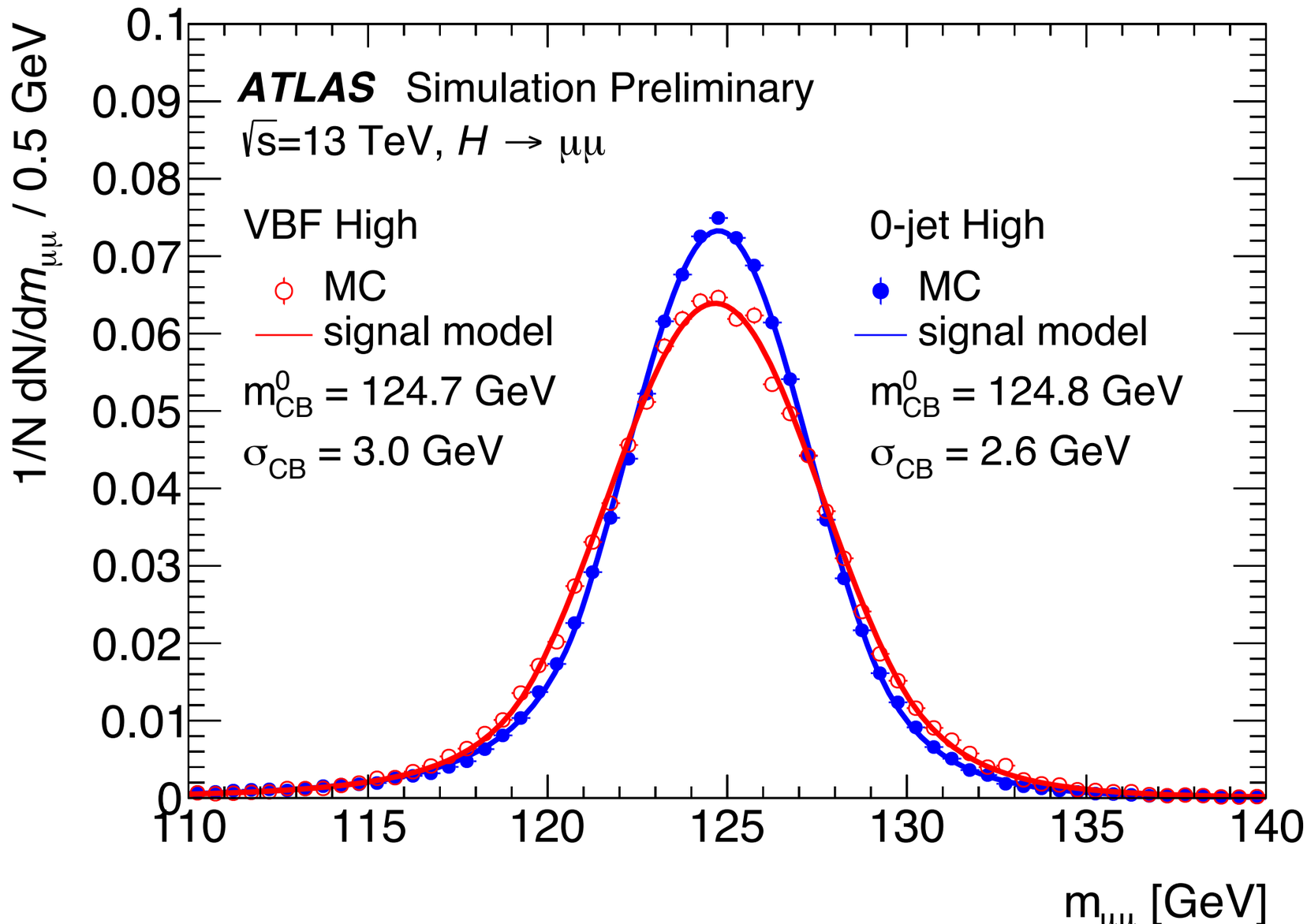
<u>Different in each category*</u>

<u>Flexible analytical function.</u>
Models remaining part of the spectrum.

*Selection procedure outlined in the backup

SIGNAL MODEL

Double-sided Crystal Ball function



FSR tail recovered

Figure from ATLAS-CONF-2019-028

Example fit to data (VBF High)

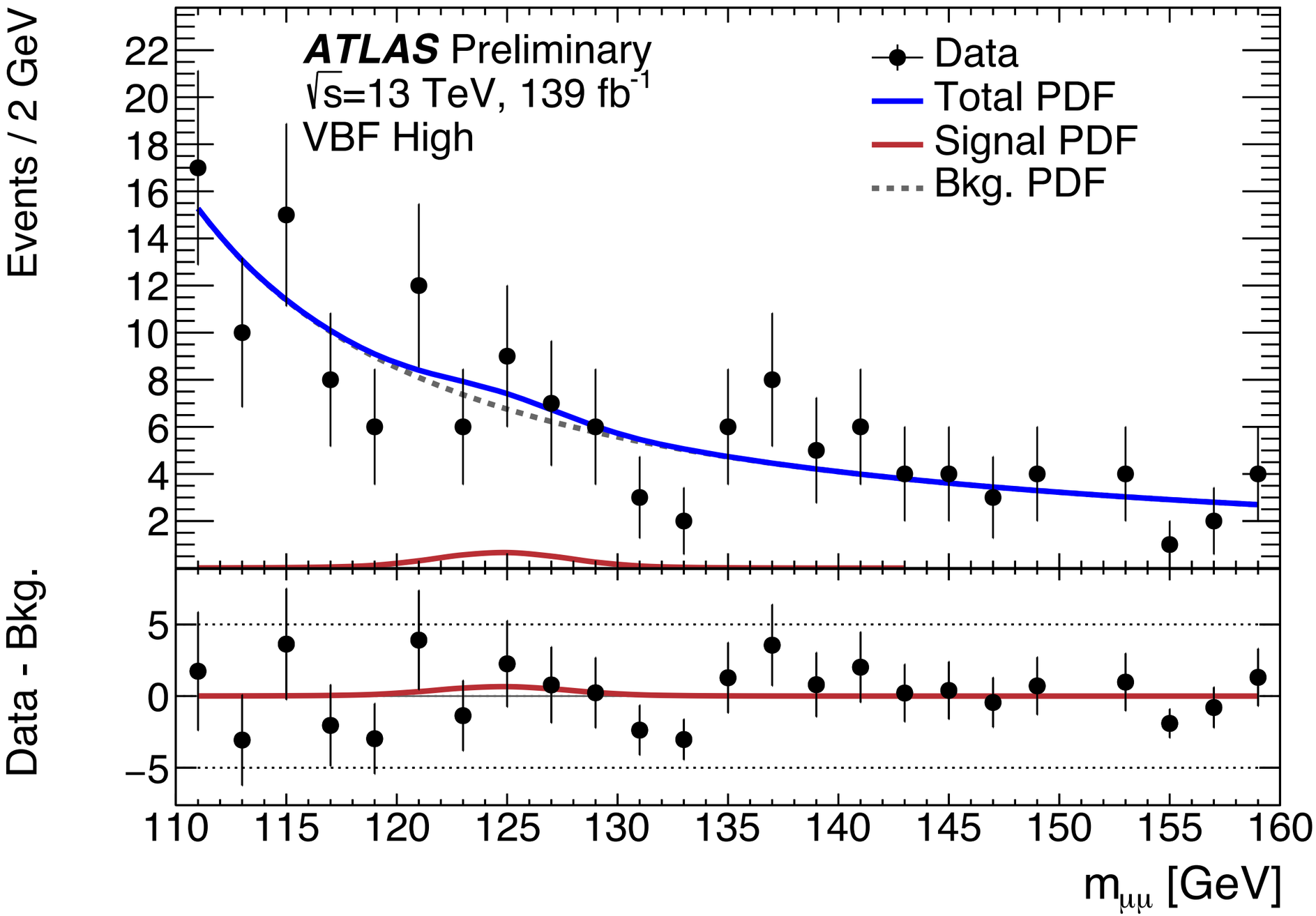


Figure from ATLAS-CONF-2019-028

Uncertainties

Statistics dominated analysis (~0.7)
Systematics ~0.1

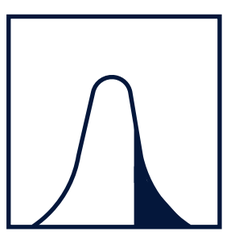
} Uncertainty on signal strength

Systematic uncertainties sources:

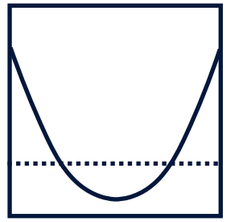
1) Spurious signal (background mismodelling)
2) Signal acceptance (theoretical and experimental)

Results

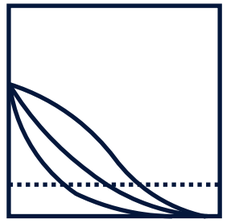
~50% improvement w.r.t. previous ATLAS result



Significance **0.8σ** (1.5σ expected)

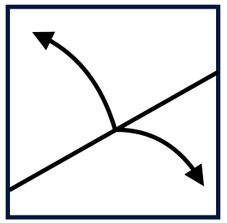


Measurement **μ = 0.5 ± 0.7**

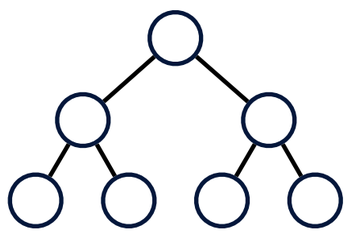


Limit (95% CL) **1.7×SM** (1.3 expected B-only, 2.2 SM S+B)

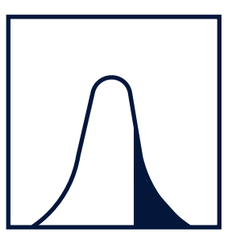
Summary



Search for SM Higgs boson decay to muon pairs



Loose muon and event selection
Optimised multivariate categorisation
Improved background modelling



0.8σ (1.5σ expected)

Thank you!

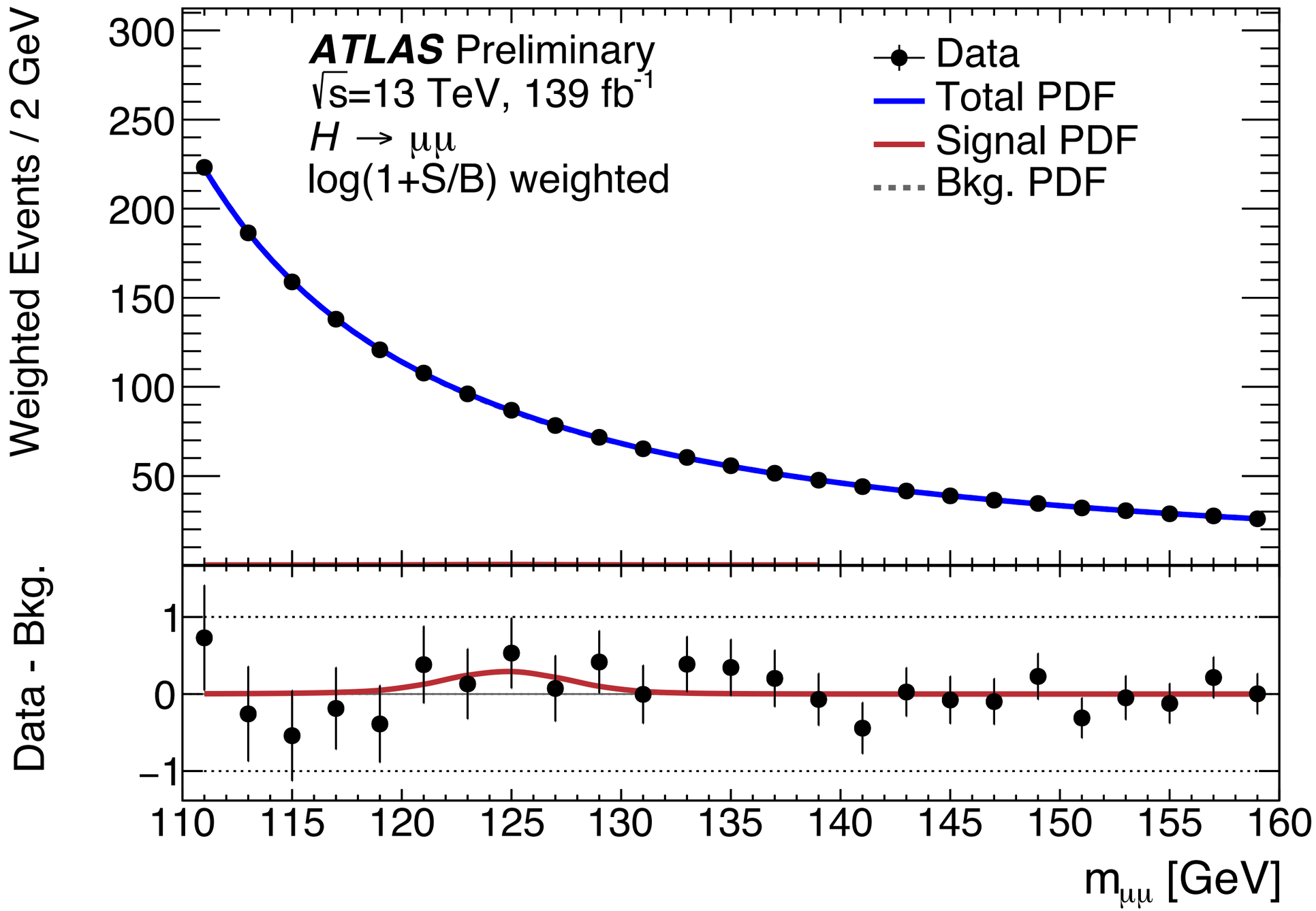
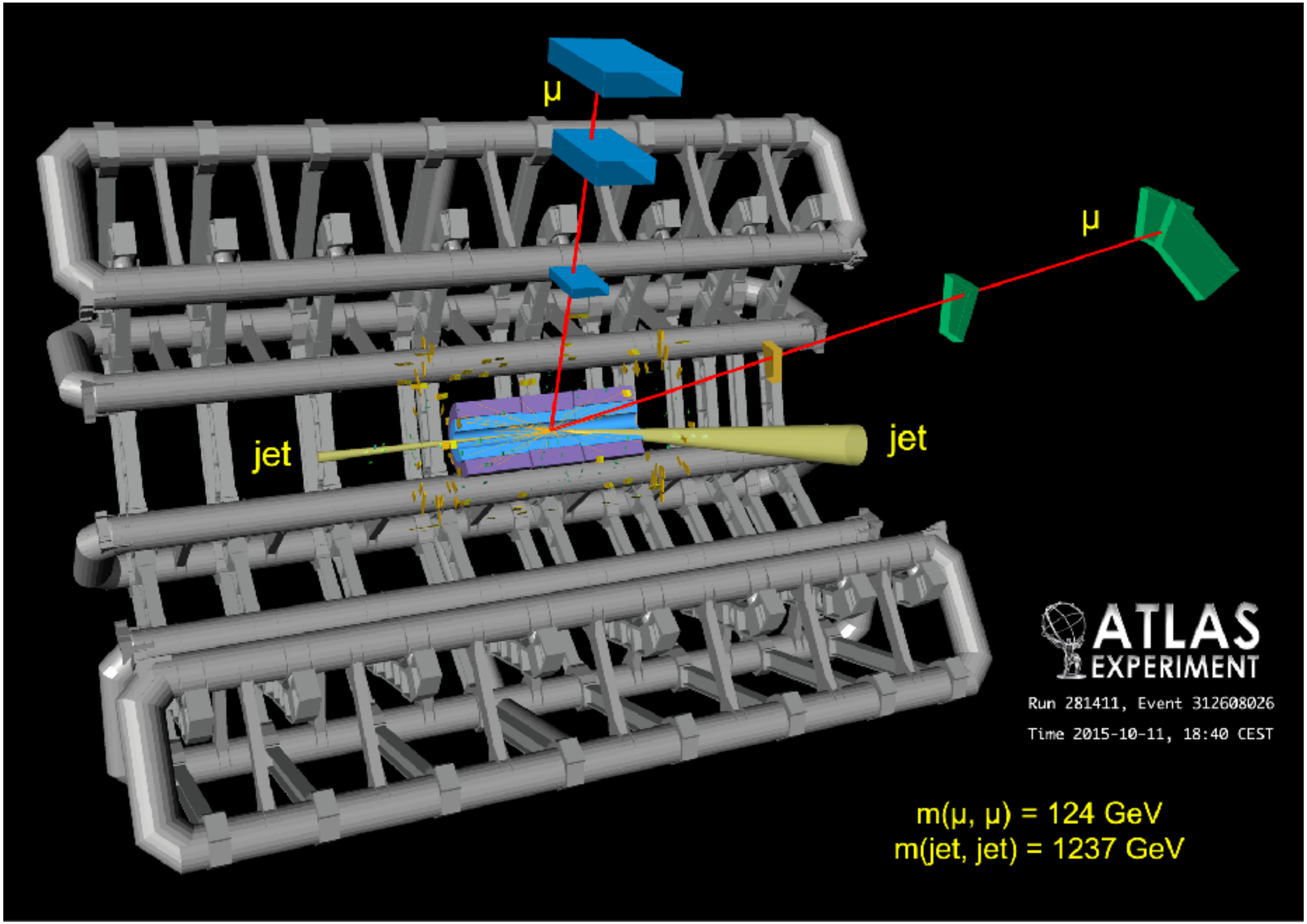


Figure from ATLAS-CONF-2019-028

BONUS

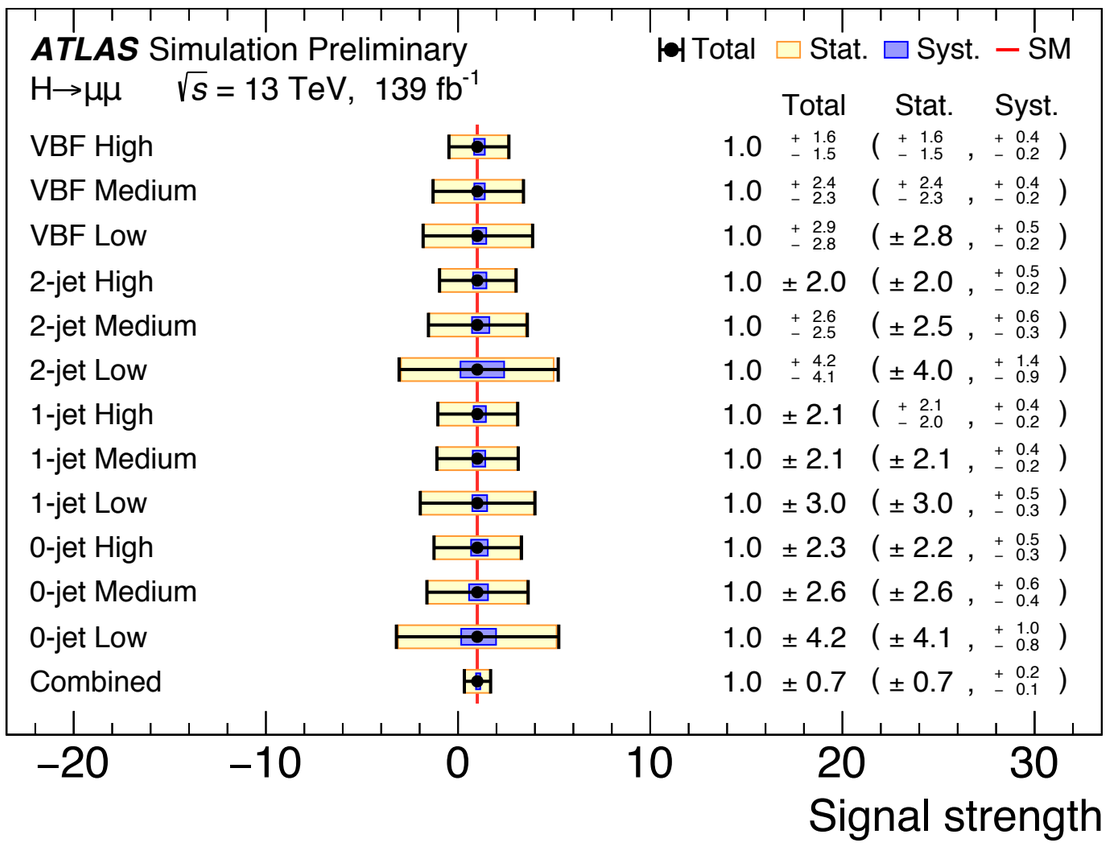
Event Display



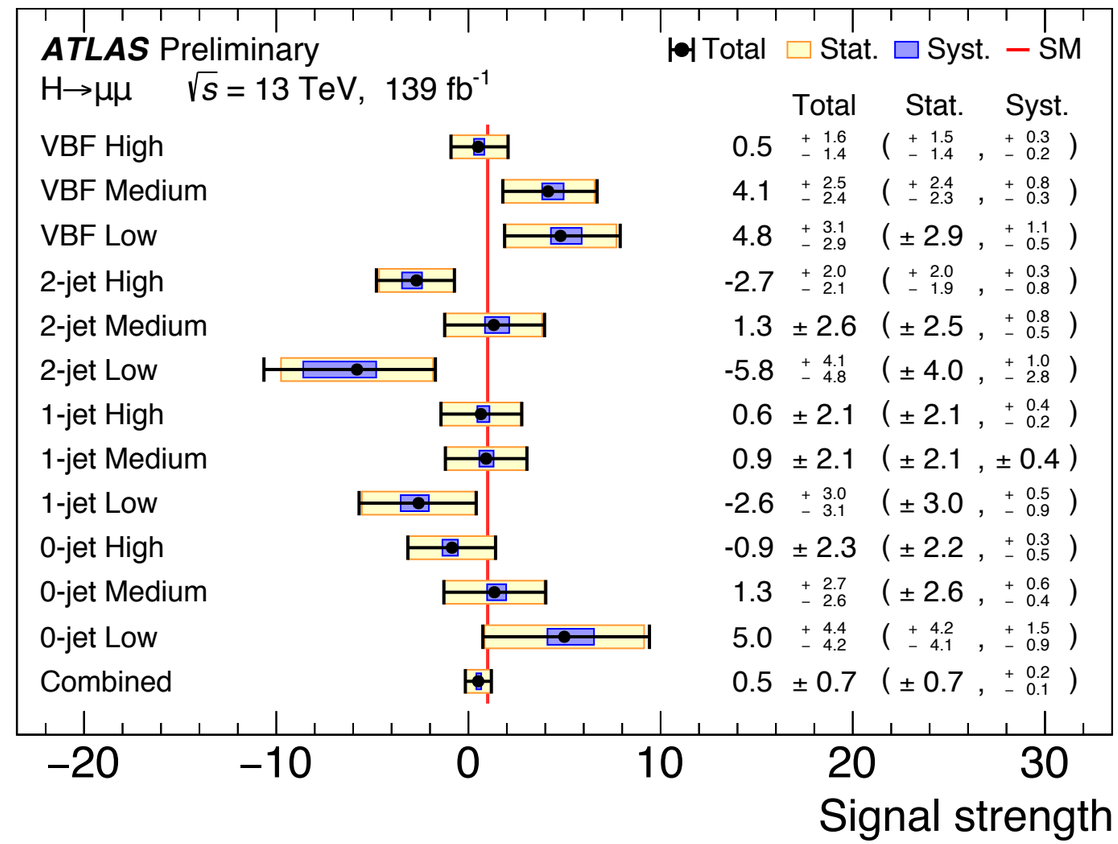
From ATLAS Public Event Displays

Observed Summary

Expected



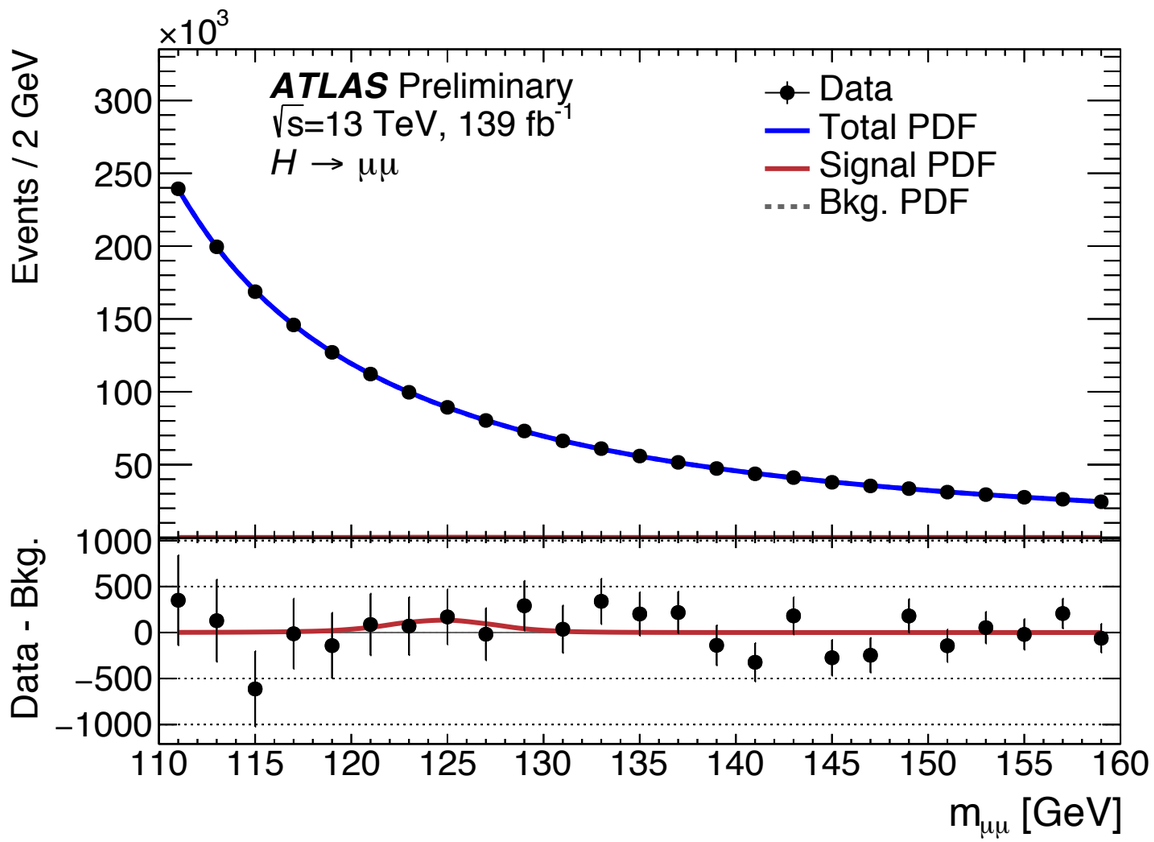
Observed



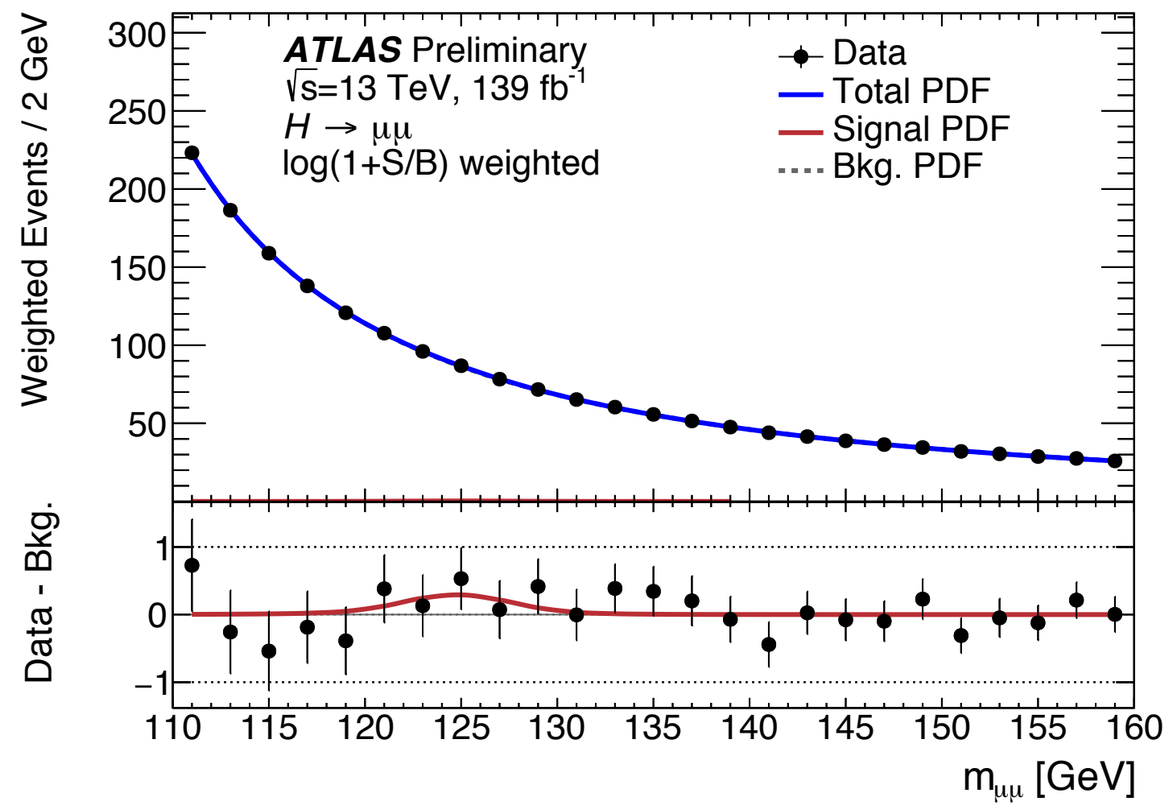
Figures from ATLAS-CONF-2019-028

Summary

Unweighted



Weighted

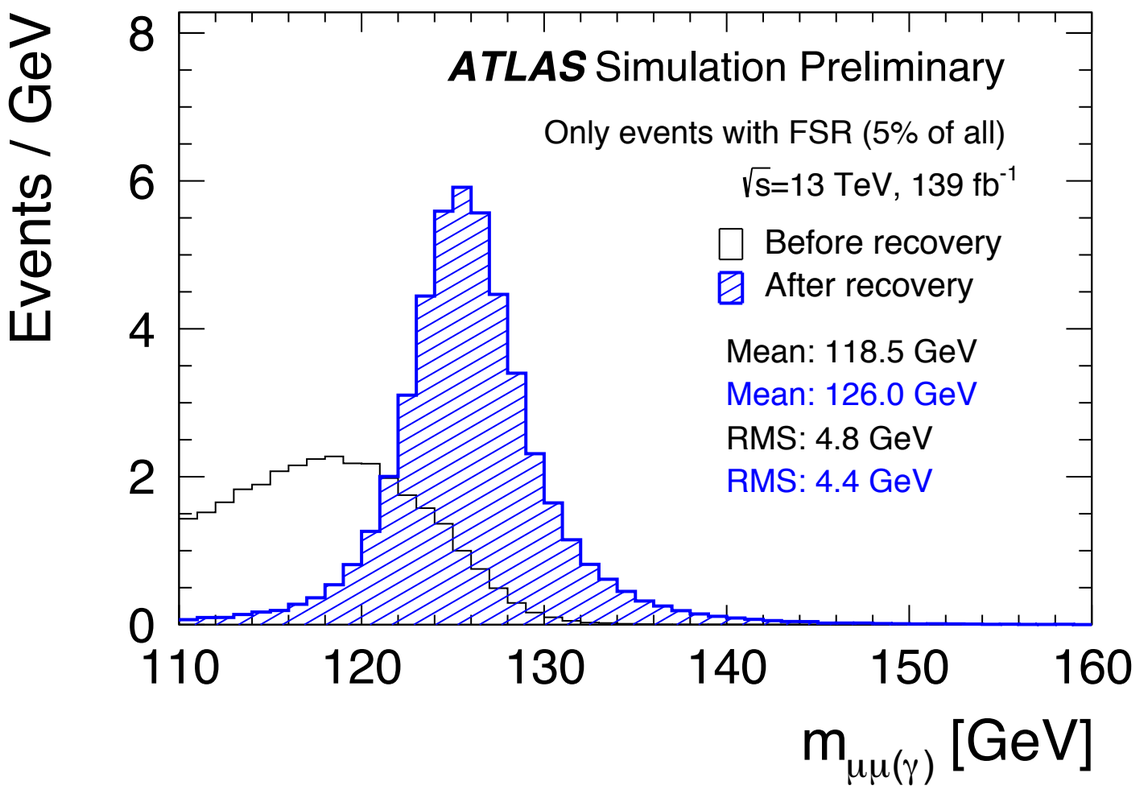


Figures from ATLAS-CONF-2019-028

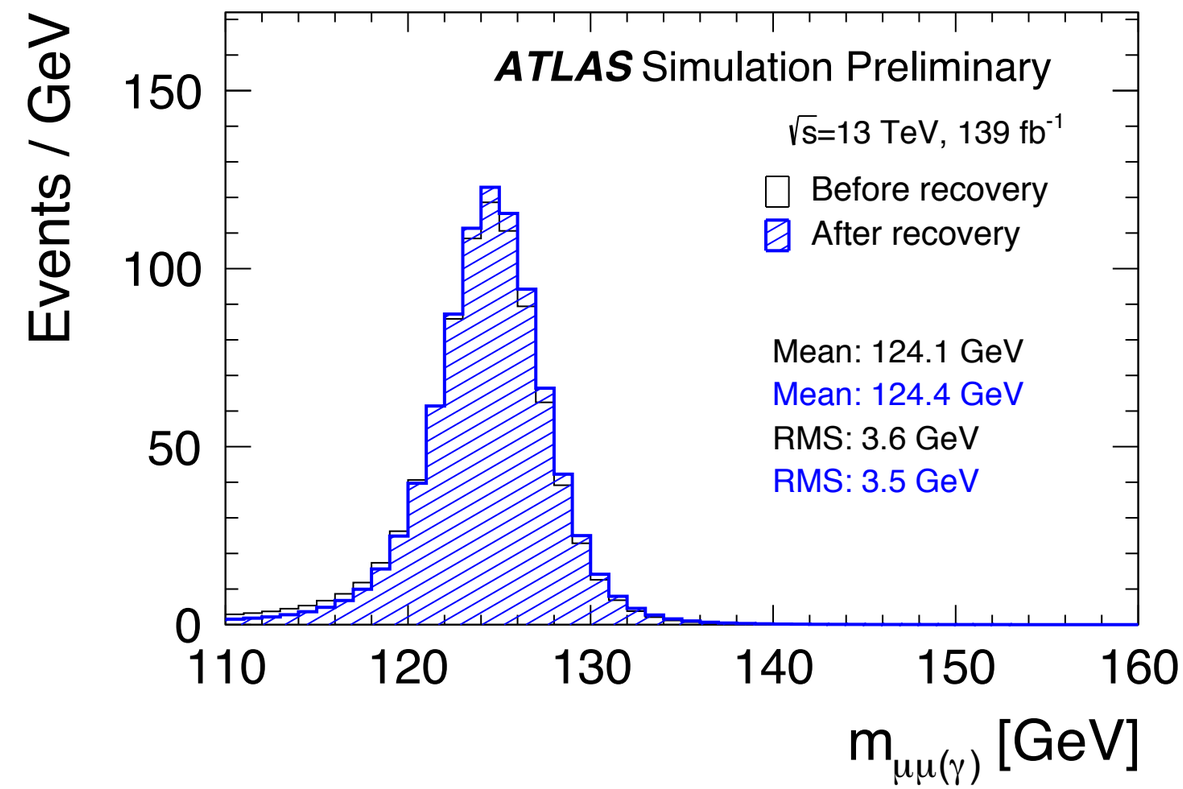
Final state radiation

Muons can lose energy via radiating a photon:
-> adding the photon to mμμ calculation improves resolution

Only events with FSR



All events



Figures from ATLAS-CONF-2019-028

Selected empirical functions

Category	Empirical Function	max(SS/ δS)[%]	max(SS/S_{SM})[%]
VBF High	Power0	10.6	14.7
VBF Medium	Epoly2	0.51	1.3
VBF Low	Power1	3.6	7.5
2-jet High	Epoly2	8.7	16.3
2-jet Medium	Epoly4	1.2	3.9
2-jet Low	Epoly3	-8.2	-33.2
1-jet High	Power1	6.1	12.1
1-jet Medium	Epoly3	-8.1	-19.8
1-jet Low	Epoly3	-2.5	-5.8
0-jet High	Power1	14.6	26.5
0-jet Medium	Epoly3	-11.6	-39.0
0-jet Low	Epoly3	-18.5	-74.2

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

Tables from ATLAS-CONF-2019-028

Category yields

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

Table from ATLAS-CONF-2019-028

Background model selection

For each category:

A) Re-weight the fast MC to data sidebands:

1. 1st order polynomial in VBF categories
2. 2nd order polynomial in Higgs categories

} Both adjust normalisation

B) Pick the **Empirical function** based on these criteria:

1. Goodness of B-only fits: P(χ2) > 1%
    1. Data sidebands
    2. Full-sim MC: DY (Sherpa), top, diboson
    3. Re-weighted fast MC
2. SS/σ_S < 20%
    1. SS is the spurious signal (maximum over [120, 130] GeV range) obtained in S+B fits to re-weighted fast MC
    2. σ_S is the statistical uncertainty on the extracted signal at 139fb^{-1}
3. Smallest number of parameters
4. Smallest SS value

Full Object Selection

1) <u>Muons</u>
   - Loose muon Working Point
   - FixedCutPflowLoose isolation
   - pT > 15 GeV
   - |eta| < 2.7
   - impact parameters: $|d_0$ significance$|$ < 3.0, $|z_0 \sin(\theta)|$ < 0.5 mm

2) <u>Jets</u>
   - Antikt4TopoEM algorithm
   - |eta| < 4.5
   - pT > 25 GeV for |eta| < 2.4
   - pT > 30 GeV for 2.4 < |eta| < 4.5
   - JetVertexTagging > 0.59 for (pT < 60 GeV && |eta| < 2.4)
   - fJVT < 0.5 forward region
   - pass MV2c10 60% WP for (|eta| < 2.5 && pT > 20 GeV). Only used for the b-veto purpose.

3) <u>Electrons (only used for overlap removal)</u>
   - *Medium* likelihood, pT > 7 GeV, |eta| < 2.47 excluding the crack region
   - *Loose* isolation
   - impact parameters: $|d_0$ significance$|$ < 3.0, $|z_0 \sin(\theta)|$ < 0.5 mm

Full Event Selection

- Pass GRL and event cleaning for data
- Pass lowest unprescaled single muon trigger
- Trigger matching
- Two opposite sign muons
- Lead muon pT > 27 GeV
- Subleading muon pT > 15 GeV
- Veto events with a b-jet