Highlights of H→ff at the LHC

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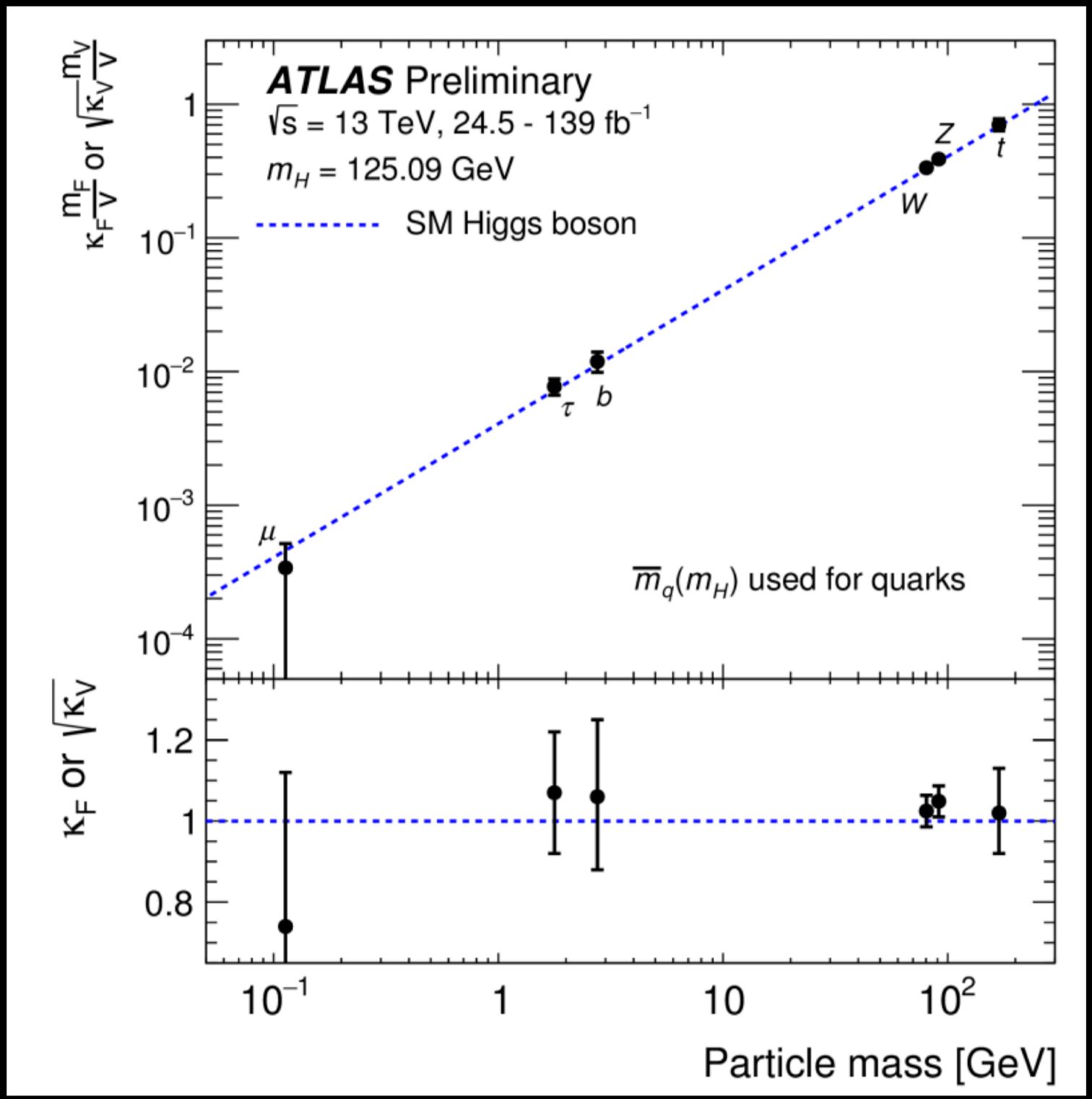
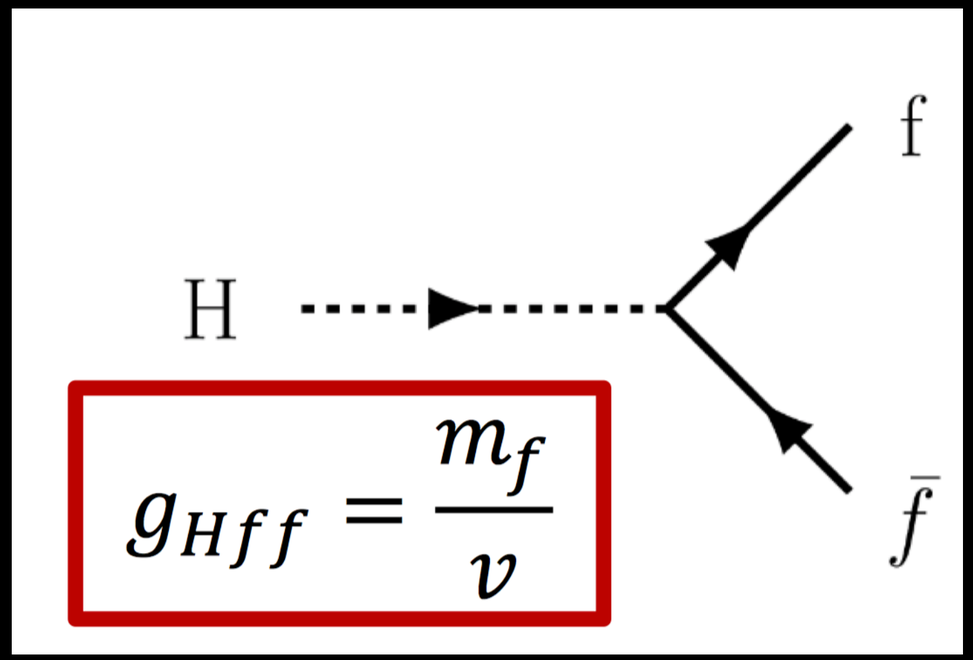
on behalf of the ATLAS and CMS collaboration

Higgs coupling to fermions

- **Higgs coupling to fermions via ad-hoc Yukawa couplings**
- **Proportional to fermion mass**

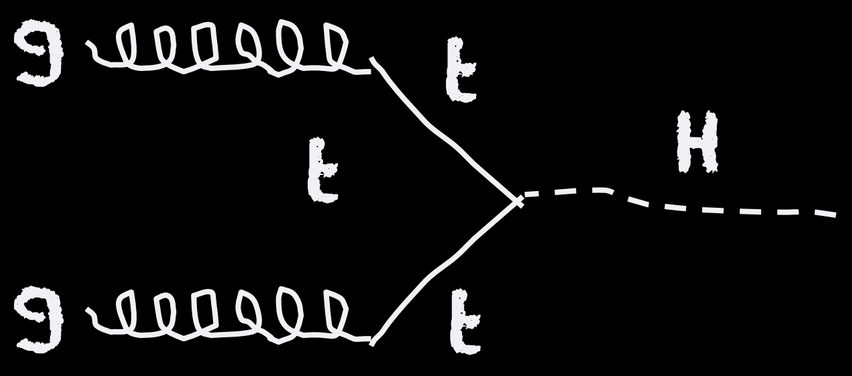




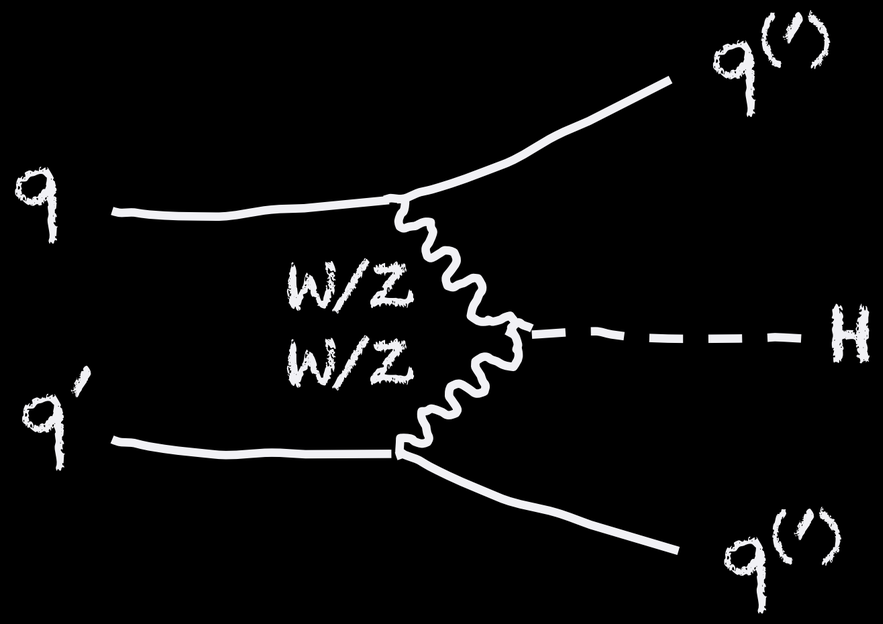
Higgs production at LHC

At the LHC, the Higgs boson is dominantly produced via gluon fusion for $\sigma_{H,total}$ = 56 pb at $\sqrt{s}$ = 13 TeV for m_H = 125 GeV

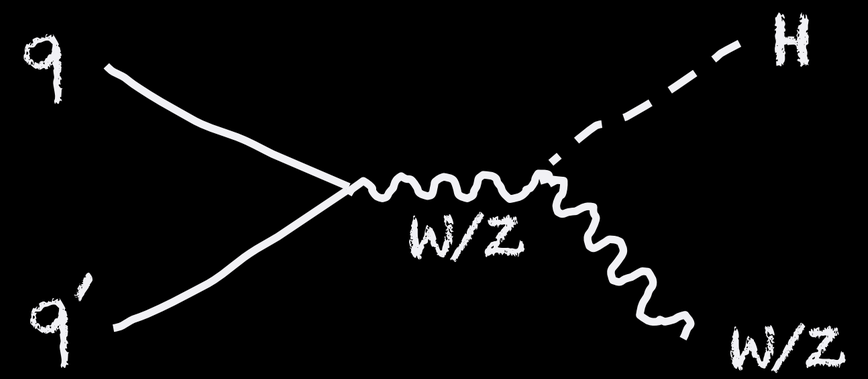
gluon fusion $\sigma_{H,ggF}$ ~ 49 pb



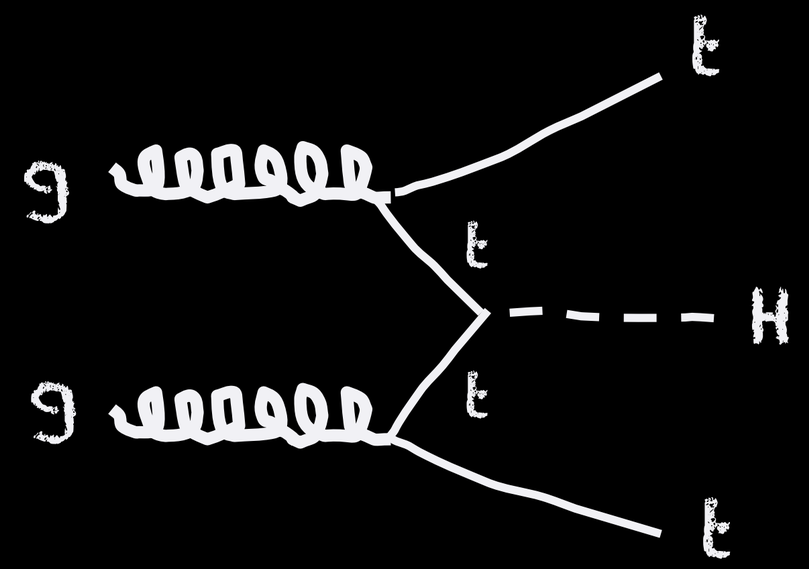
Vector Boson Fusion : VBF
(σ_{VBF} ~ 3.8 pb)



Higgs-strahlung
($\sigma_{W/Z+H}$ ~ 1.4/0.9 pb):

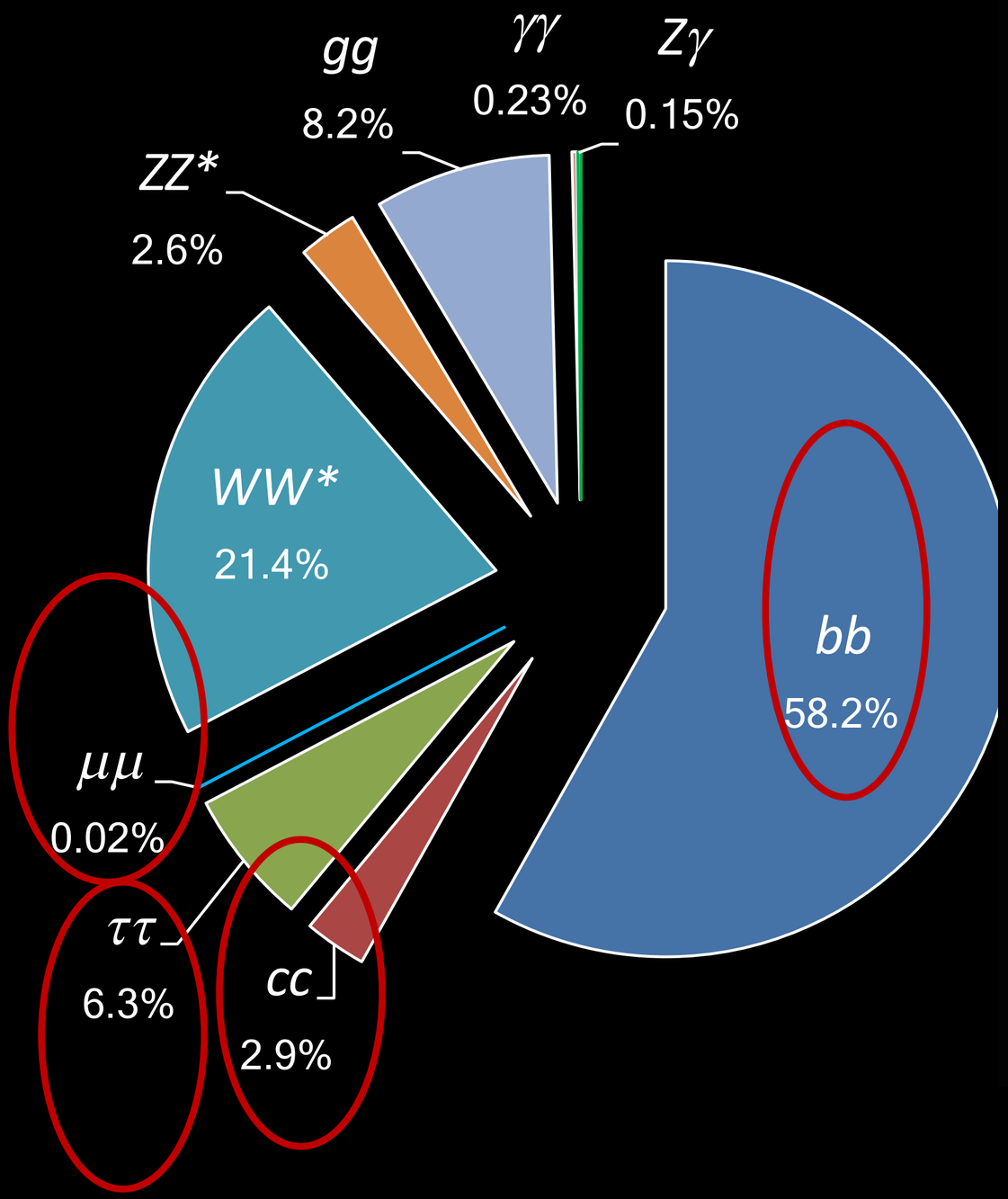


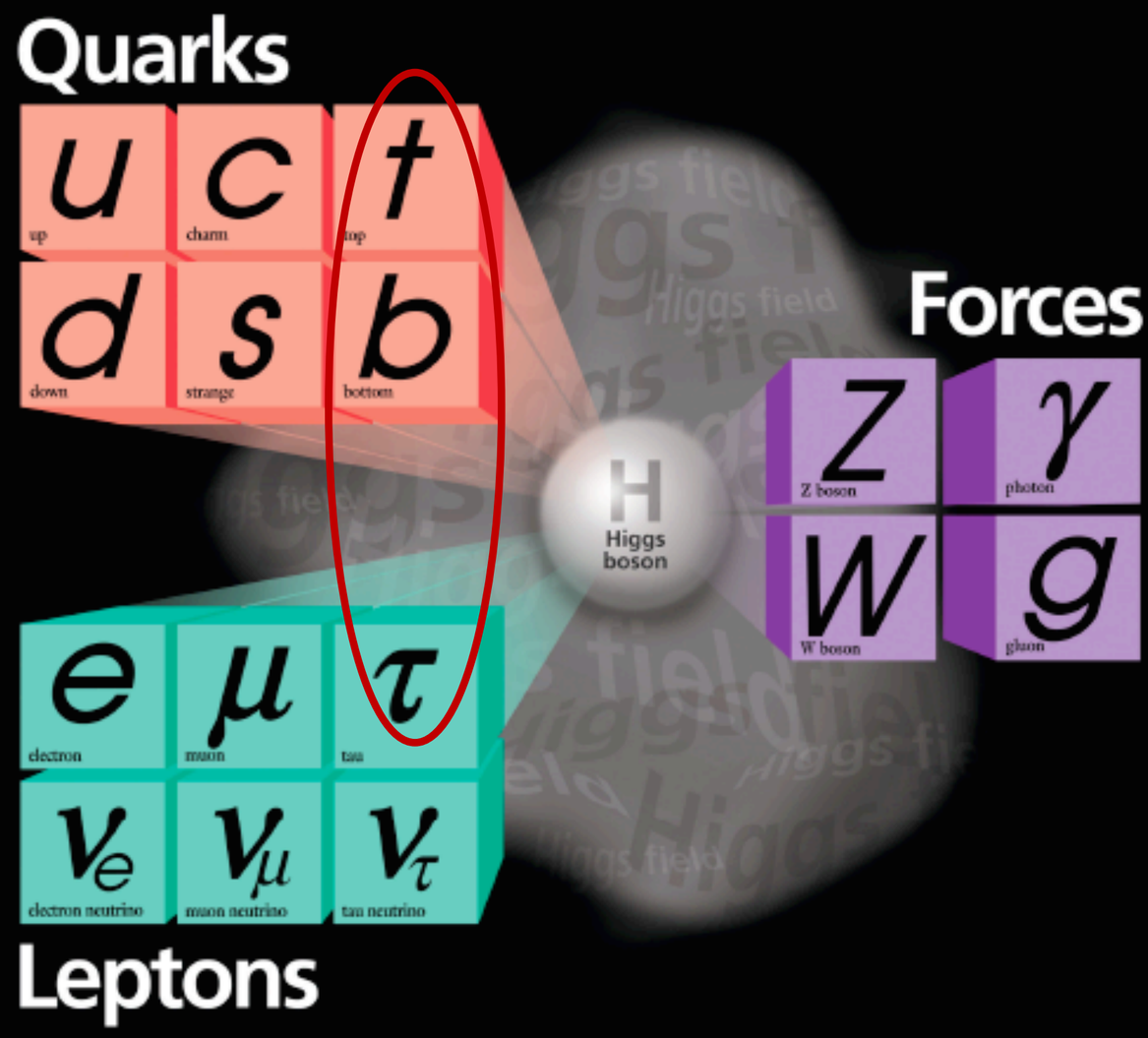
"ttH" production
(σ_{ttH} ~ σ_{bbH} ~ 0.5 pb)



Higgs decay model

- **H→bb (BR~58%): Higgs dominant decay mode, observed in 2018**
- **H→ττ (BR~6.3%): Observed in run 1**
- **H→cc (BR~3%): Probe Higgs coupling to 2nd generation quark**
- **H→μμ (BR~0.02%): Probe Higgs coupling to 2nd generation lepton**

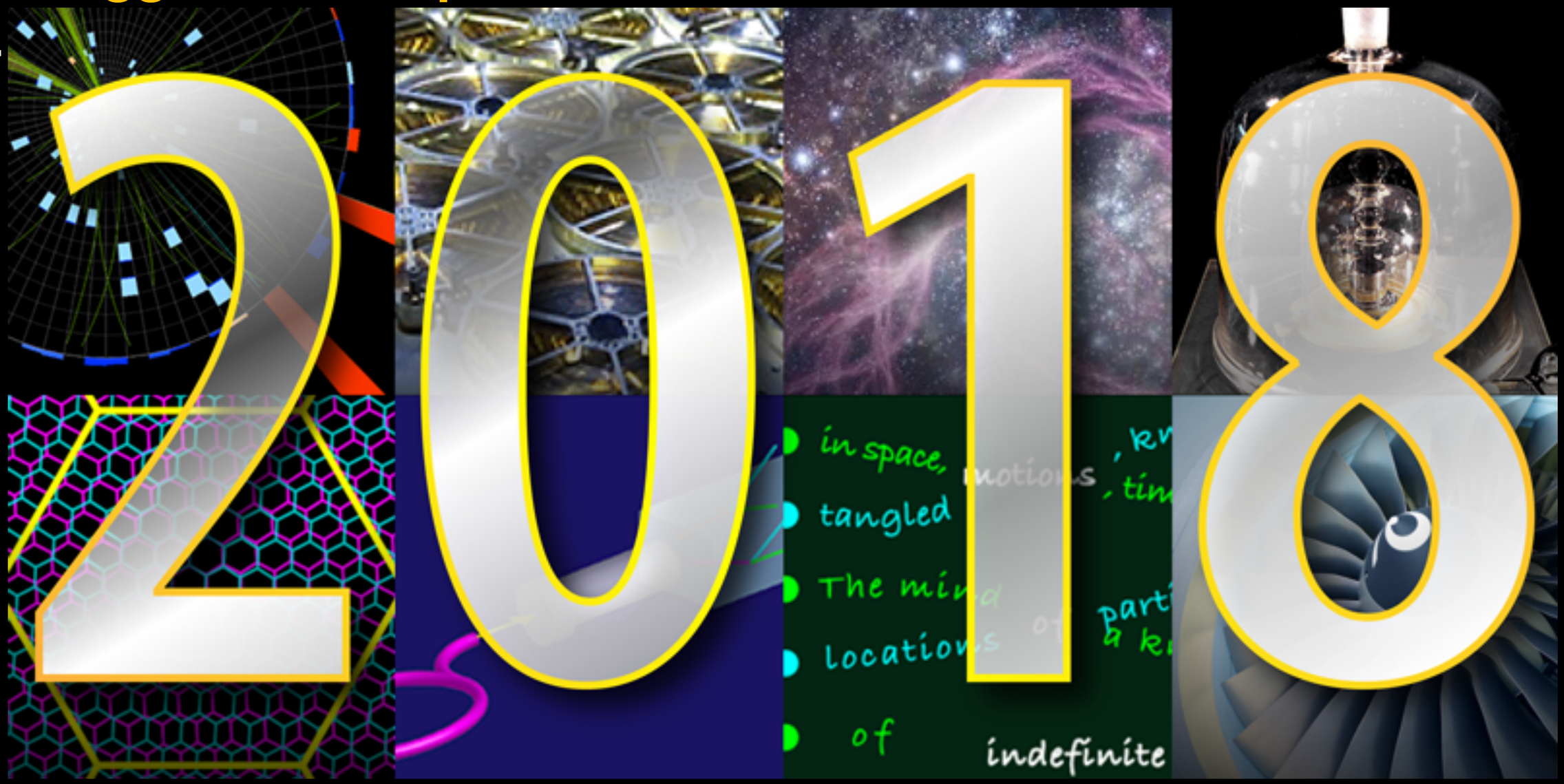




APS highlight 2018:
ttH and H →bb observation

Top 10 highlight 2018 in American physics Society(APS)

- **Graphene: A New Superconductor**
- **The Higgs Shows up with the Heaviest Quarks**
- ….

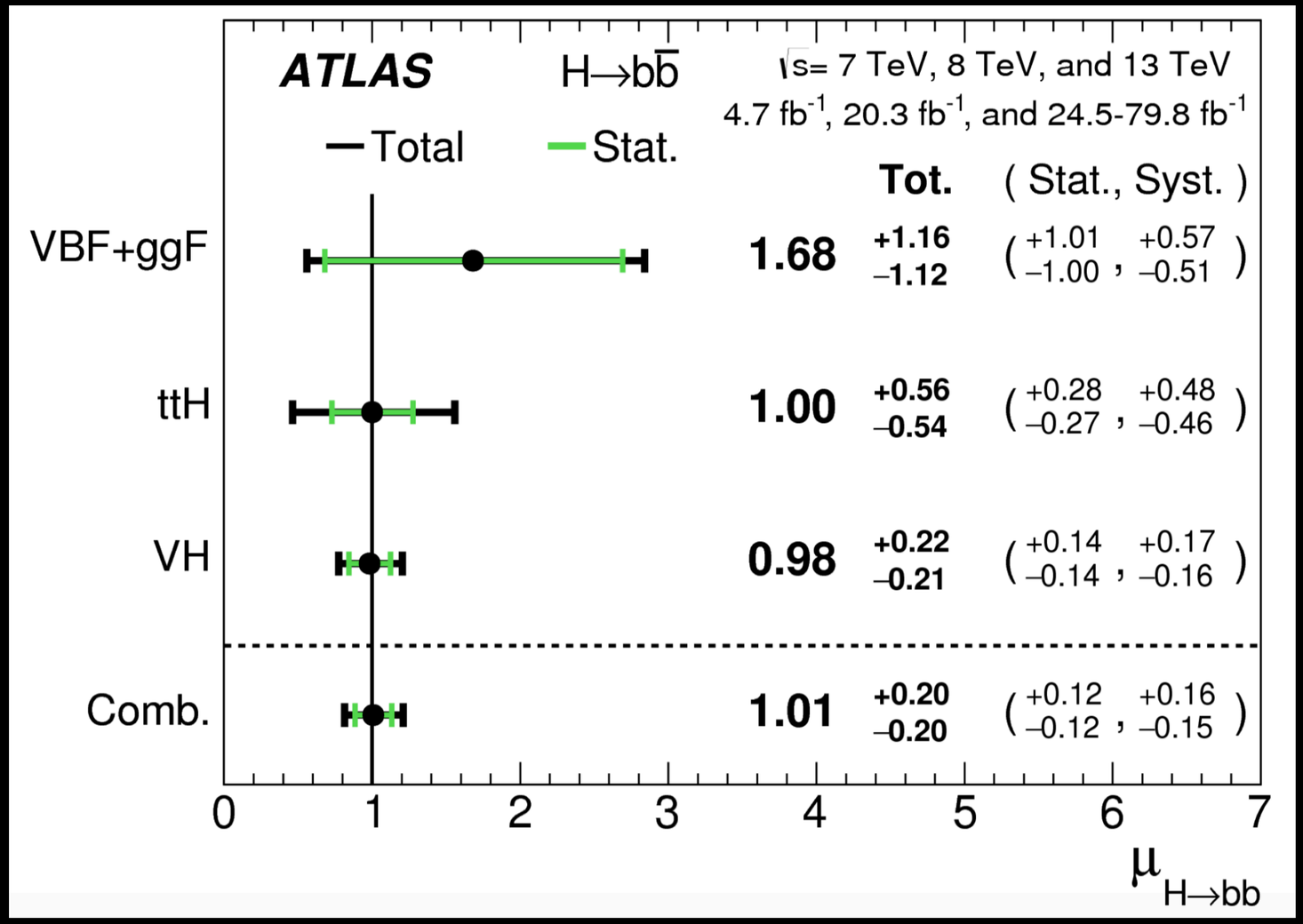


https://physics.aps.org/articles/v11/129

ttH observation will be covered in the talk by Haifeng

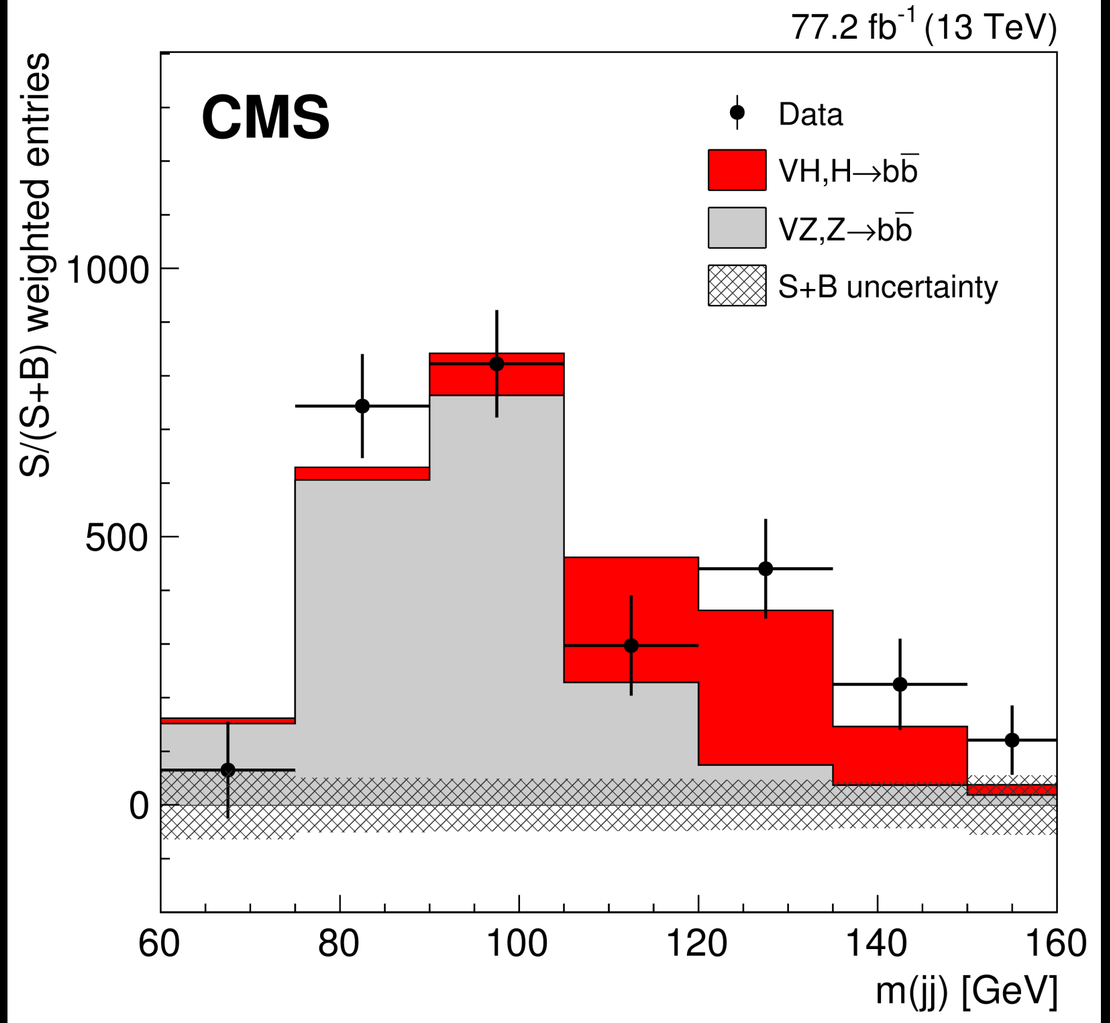
H →bb observation

- **H->bb study Started at LEP, developed in Tevatron, found at LHC**
- **H->bb observation in 2018 by ATLAS and CMS**
- **Top 10 highlight 2018 in American physics Society(APS)**



VBF+ggF+ttH+VH combined
5.4σ obs (5.5σ exp.)

PLB 786 (2018) 59

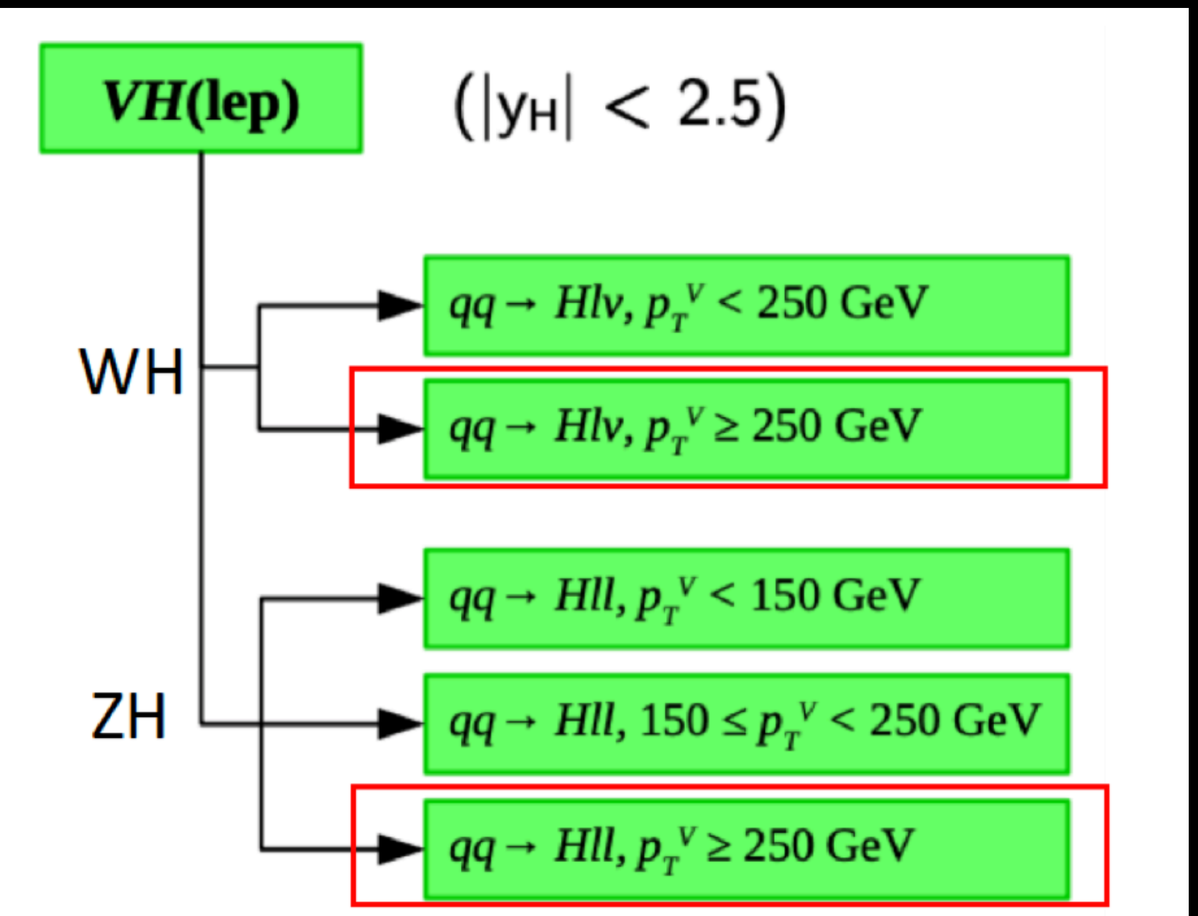


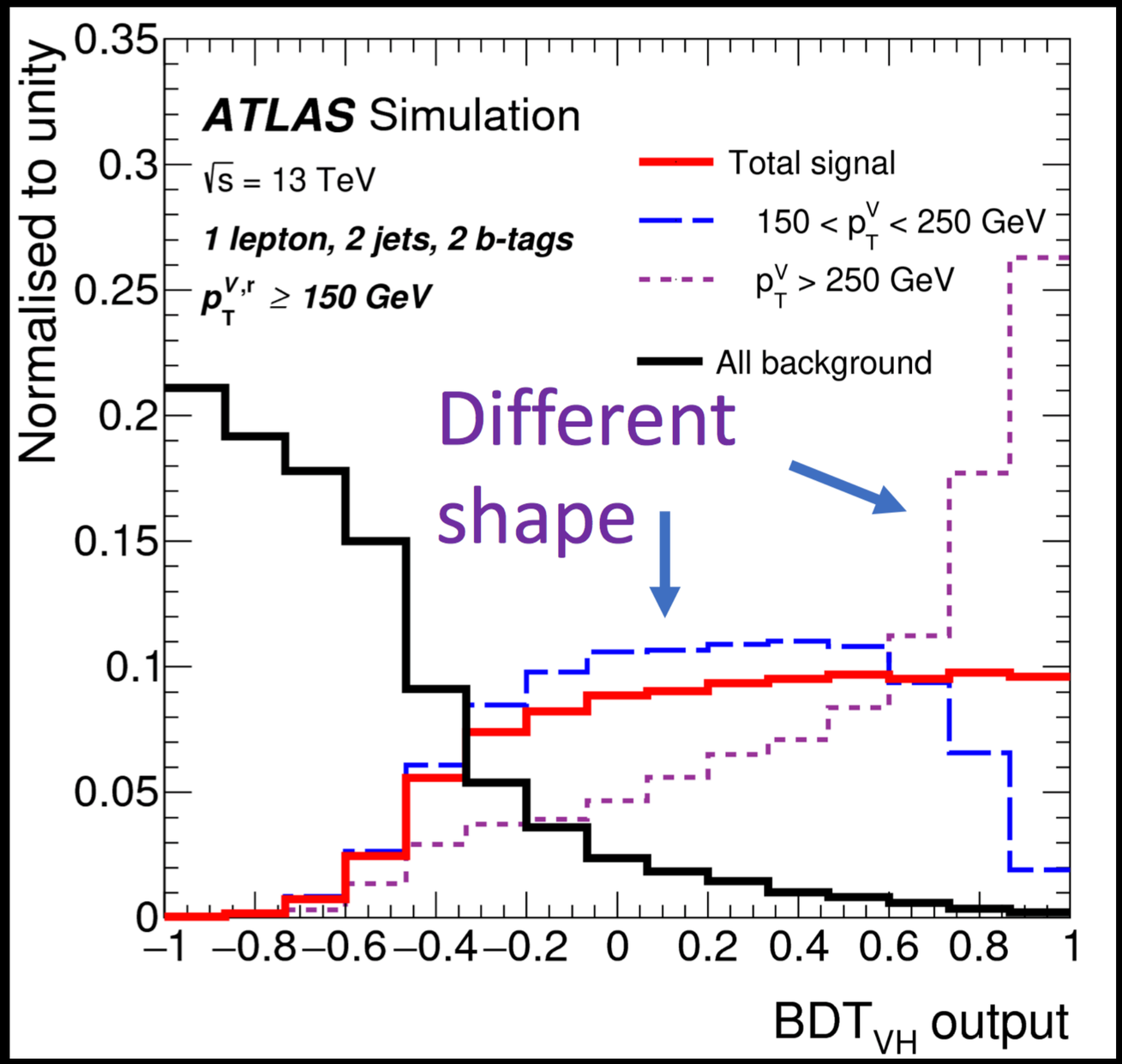
VBF+ggF+ttH+VH combined
5.6σ obs (5.5σ exp.)

Phys. Rev. Lett. 121 (2018) 121801

H→bb simplified template cross section

- **Motivation:** **Extract more information from limited data**
- **Strategy:**
  - **Divided by production modes and by $p_T V$ regions**
  - **Sensitivity provided by BDT shapes**

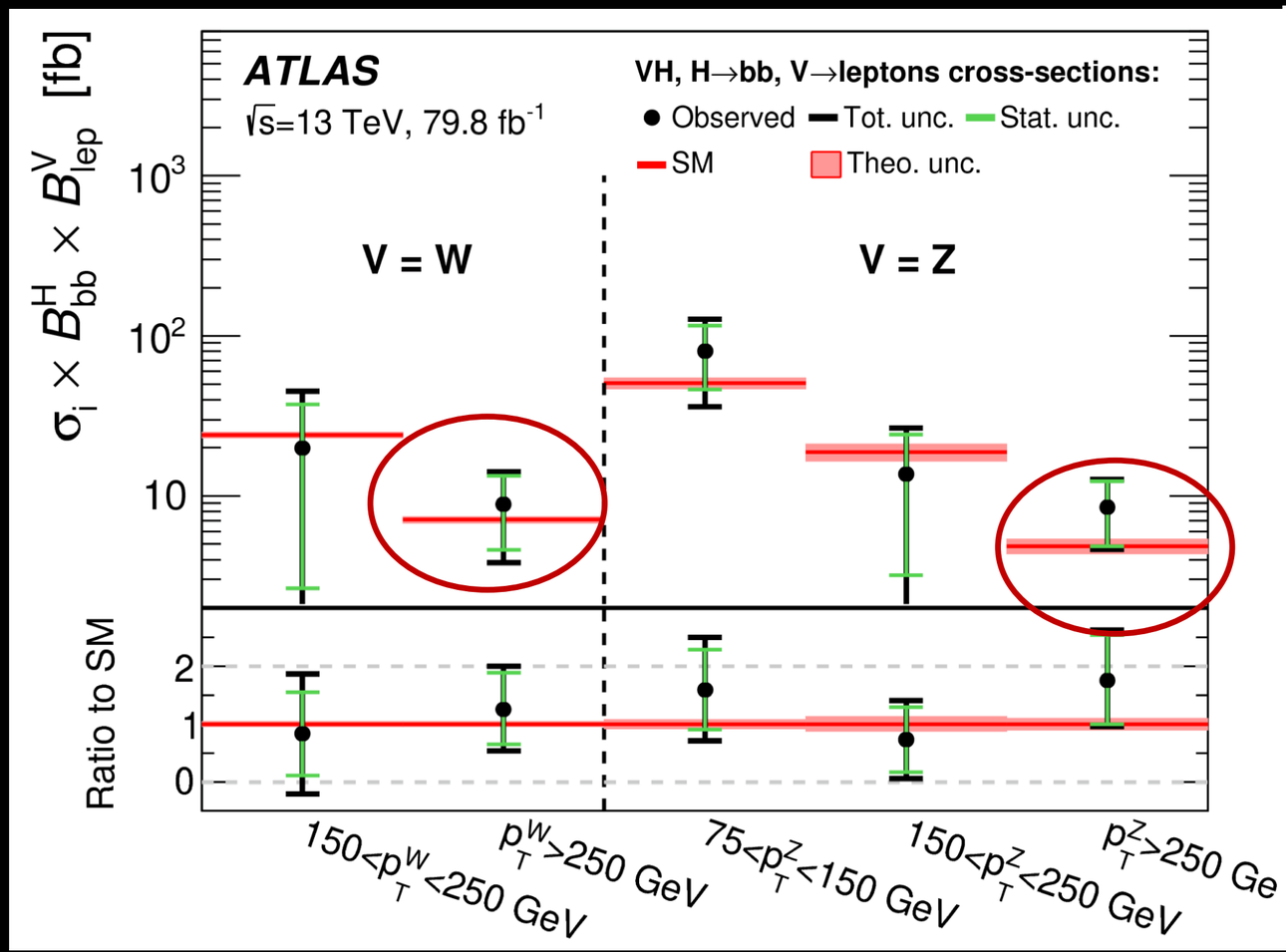


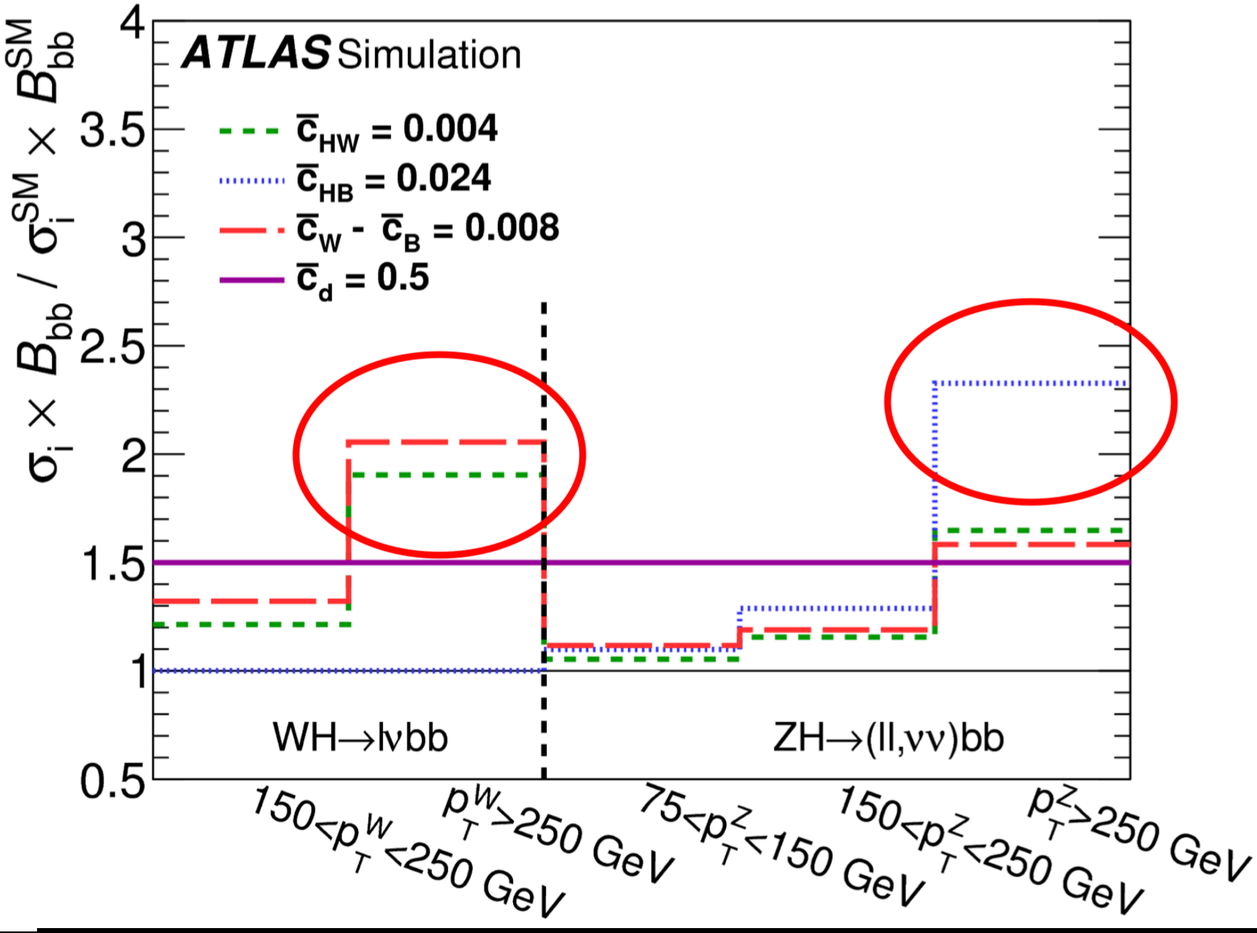


JHEP 05 (2019) 141

H→bb simplified template cross section

- **Strategy: Divided by production mode and by $p_T V$ regions**
- **Highlight: high pT bins are more sensitivity to BSM physics**





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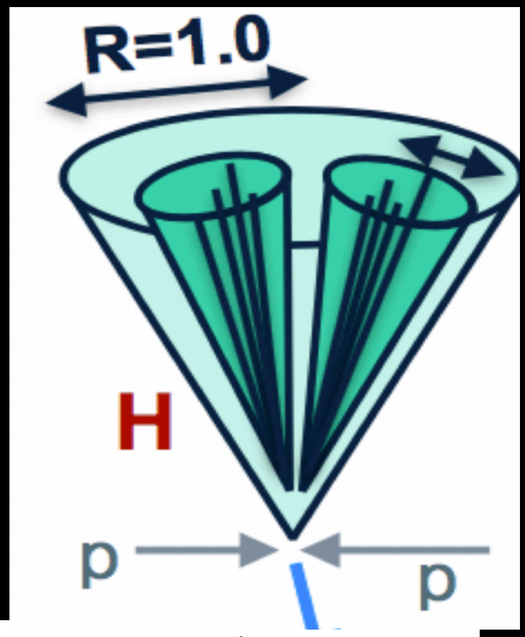
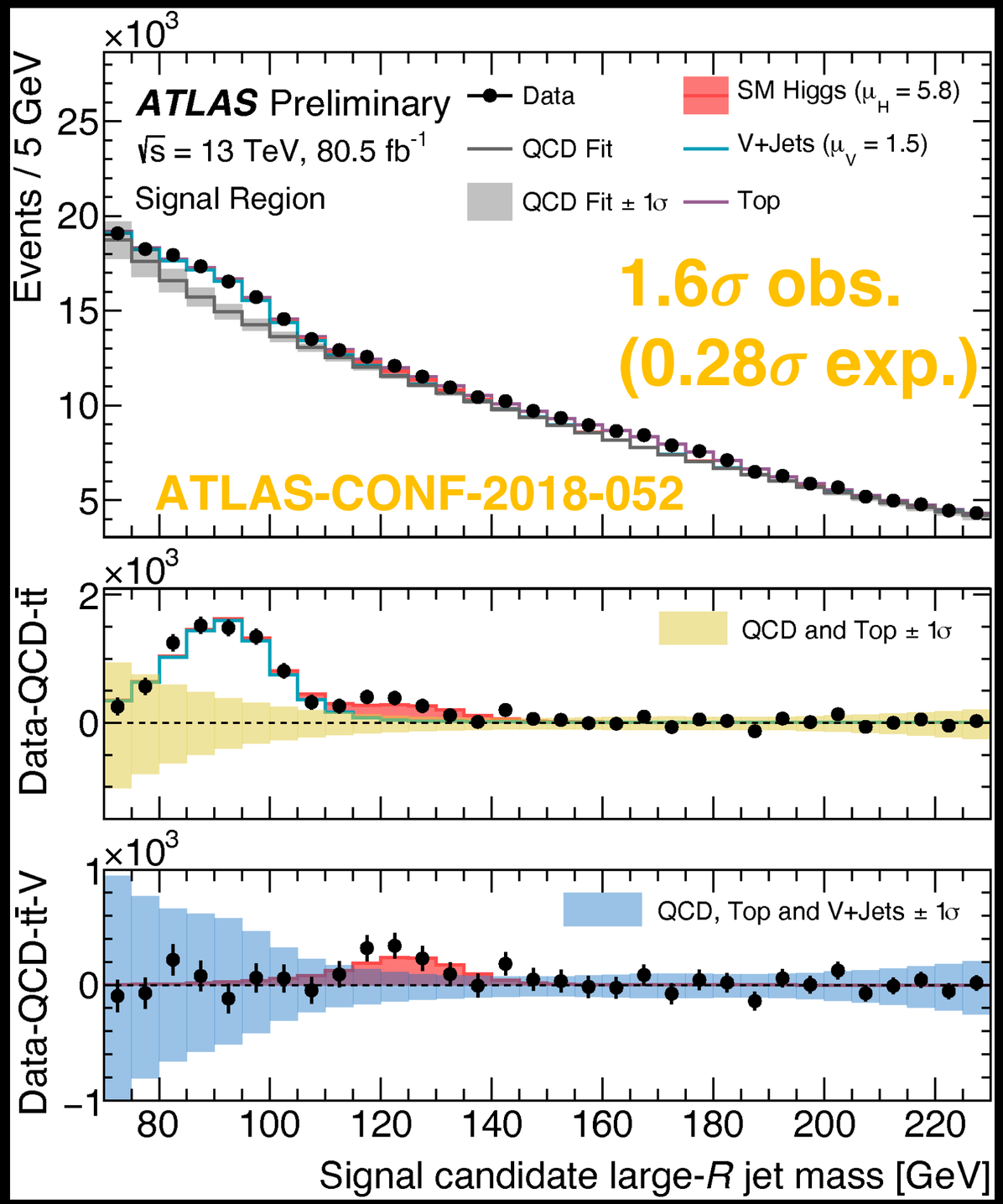
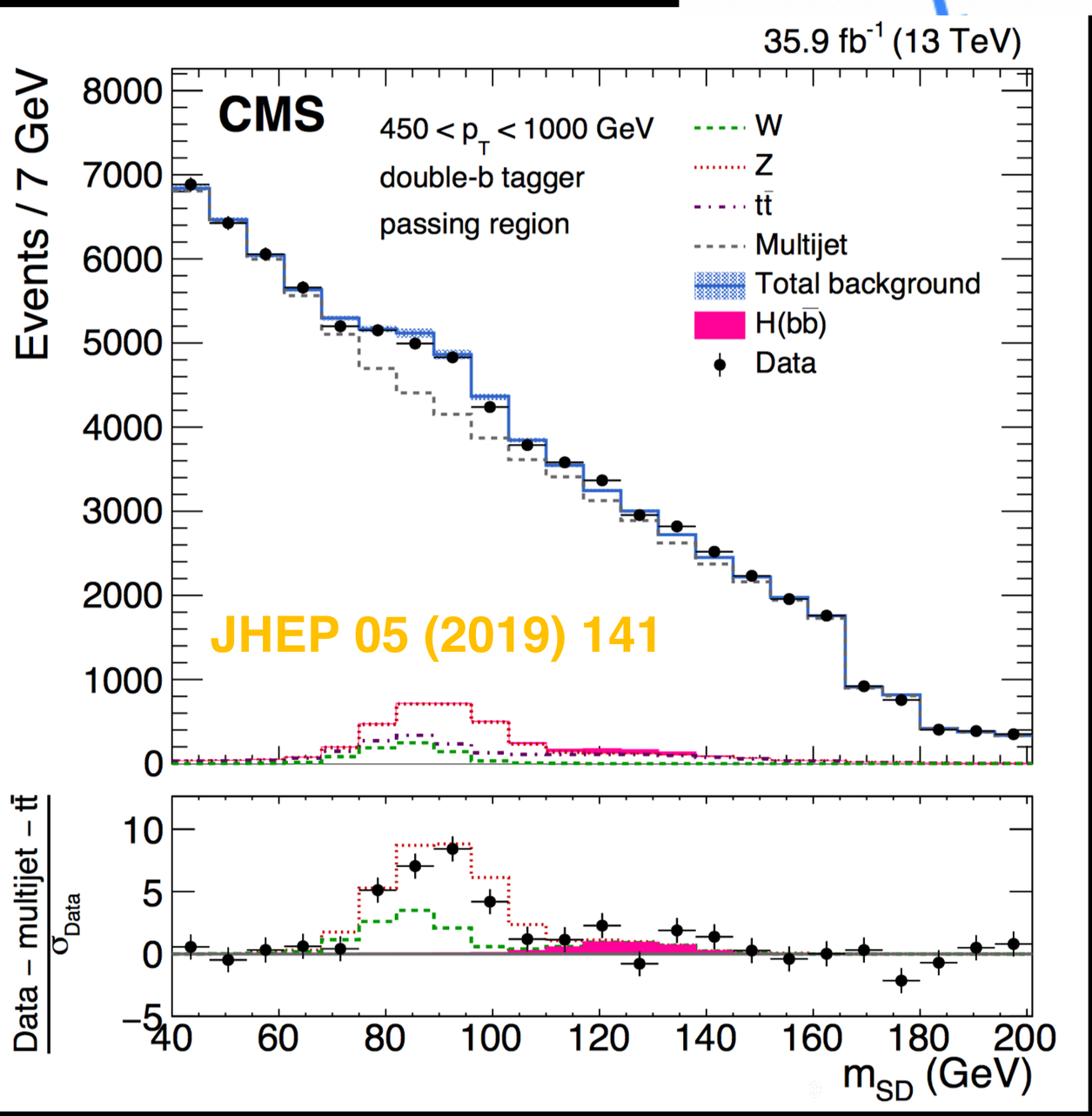
H→bb :boosted $gg \rightarrow Hj$

- **Boosted analysis: 2 large-R jets**
- **2 b-tagged track jets in one large R-jet**
- **Higgs candidate p_T > ~480 GeV**

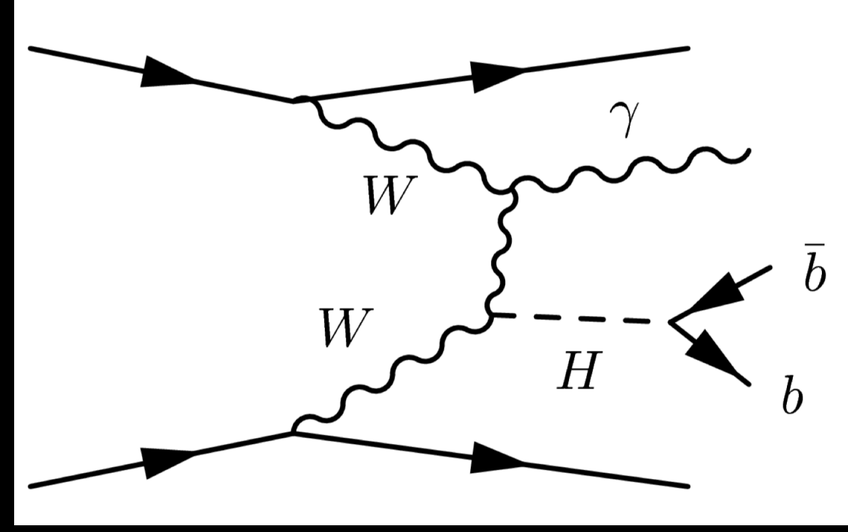




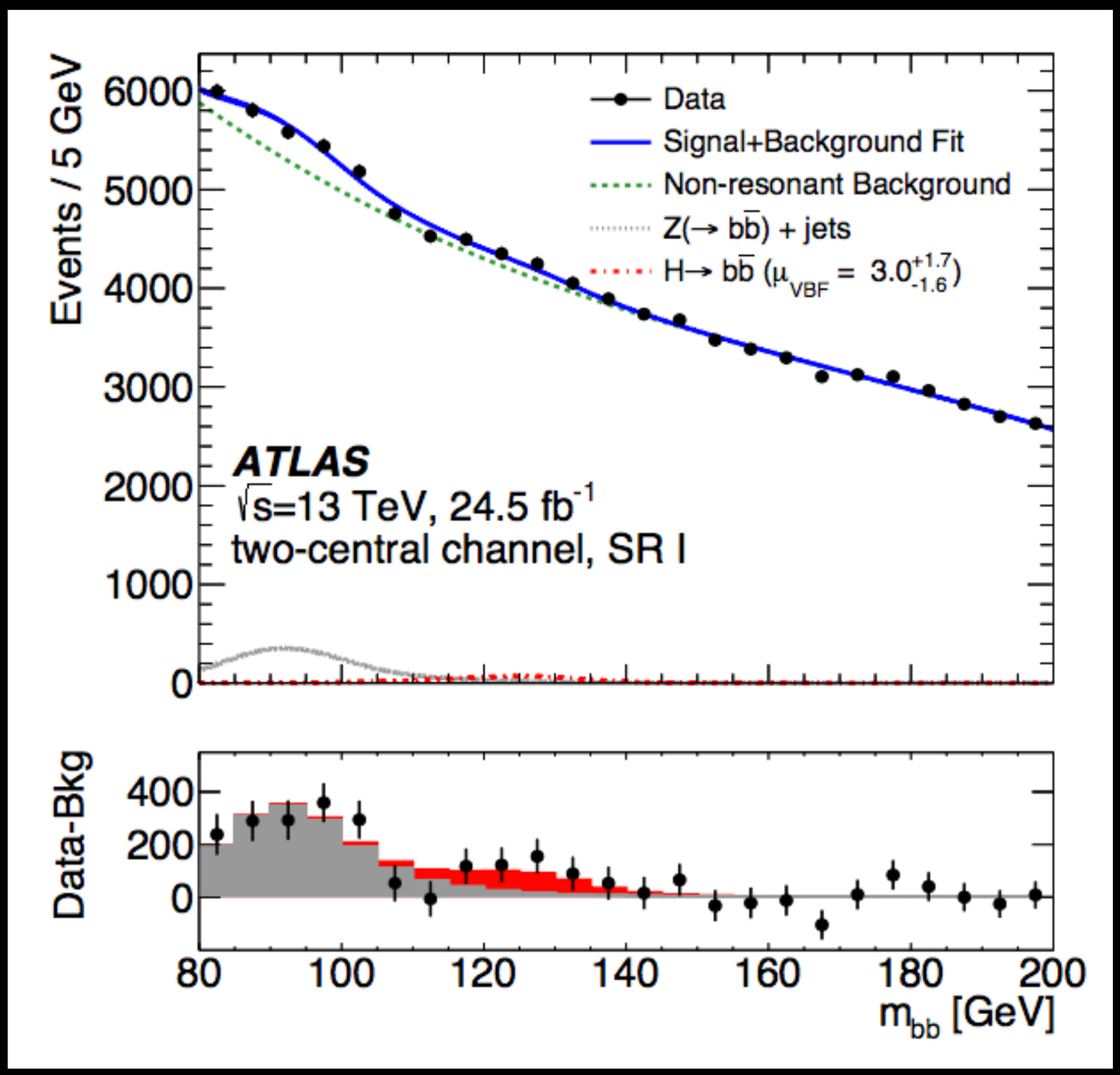


VBF H→bb analysis

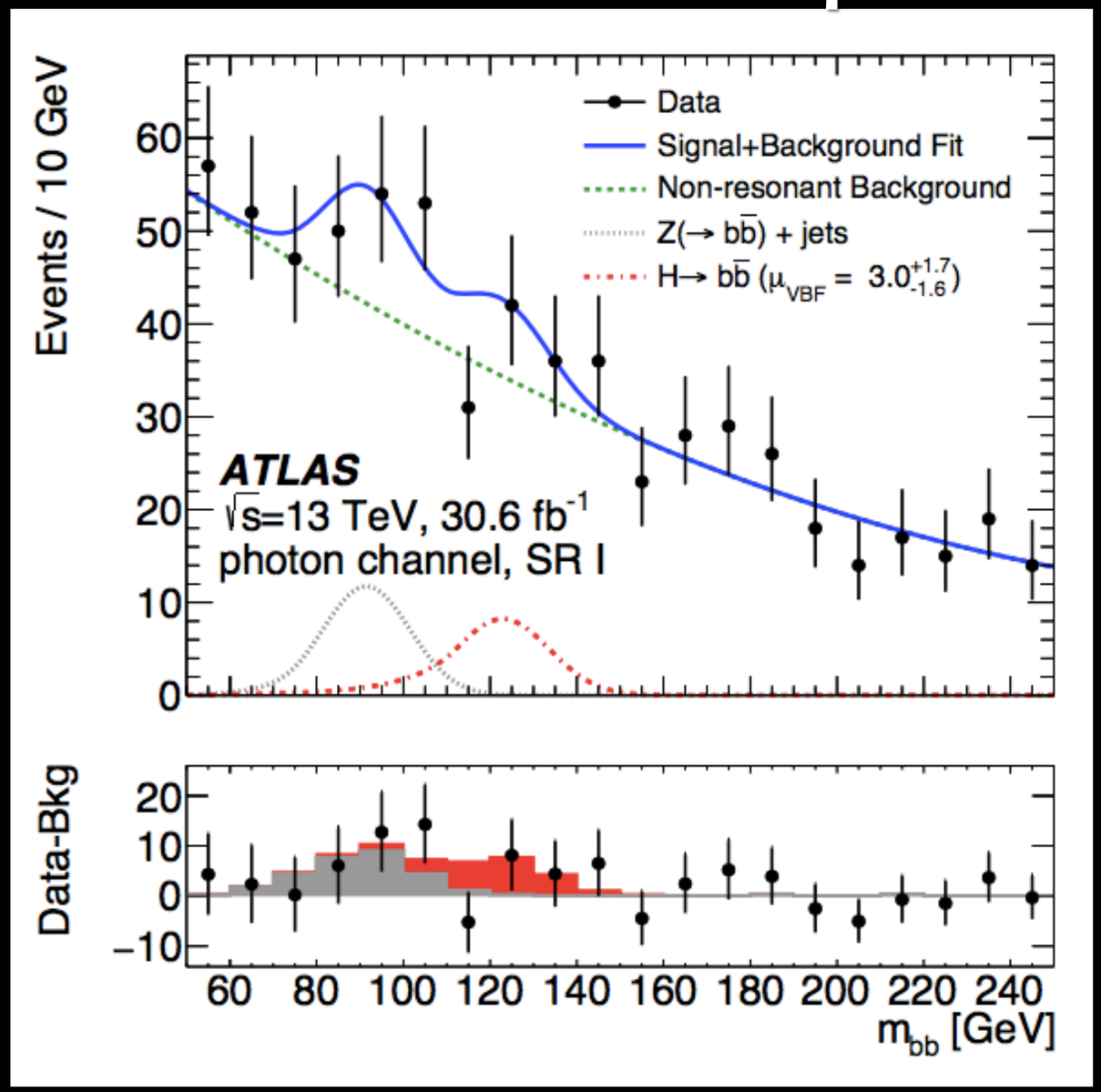
- **Inclusive VBF: 2 b jets + 2 VBF jets**
- **VBF+ γ : 2 b jets + 2 VBF jets+ +γ**
- **Photon channel is more sensitive**
- **Significance: 1.9σ obs. (0.7σ exp.)**



VBF H→bb



VBF H→bb+γ



Phys. Rev. D 98 (2018) 052003

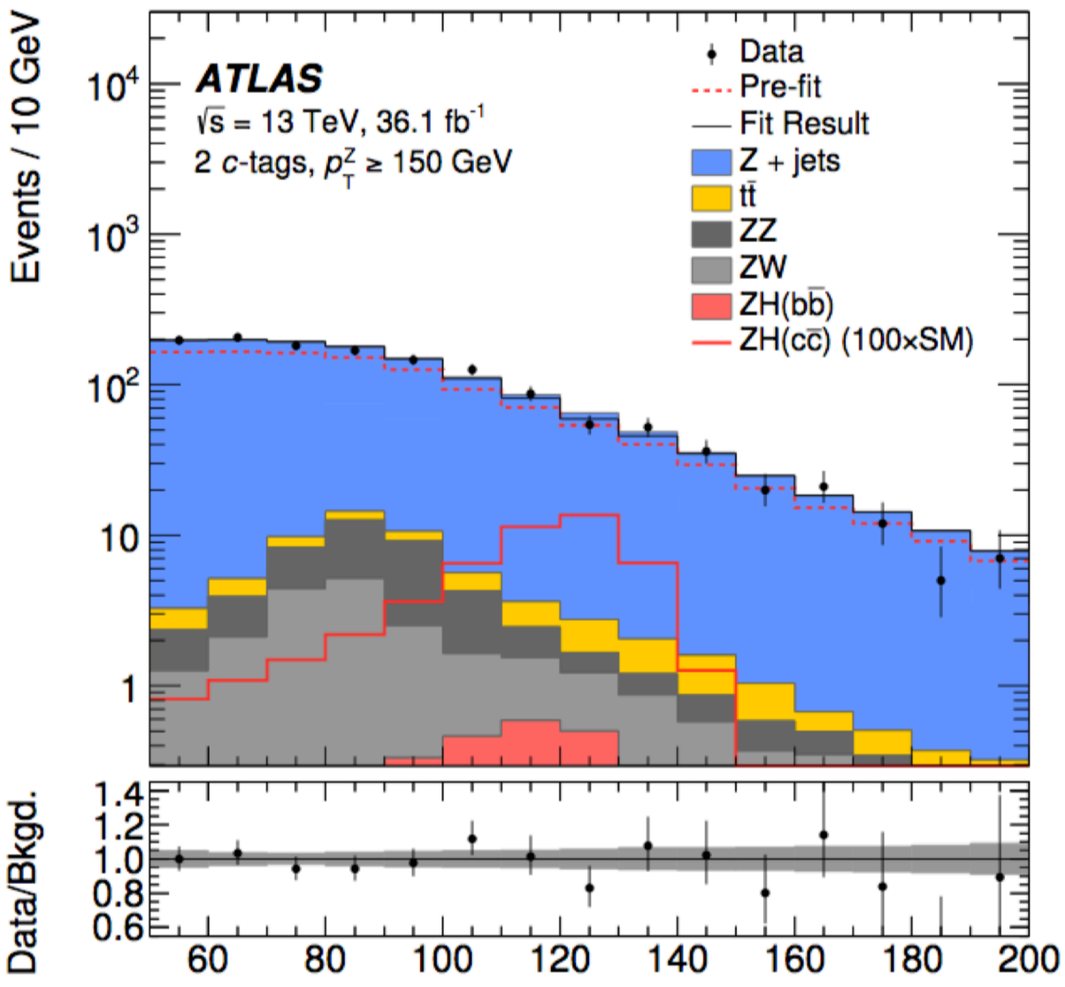
H→cc

- **Challenge:**
  - Charm quark tagging (20~40% efficiency)
  - large background rate from light quarks and b quarks

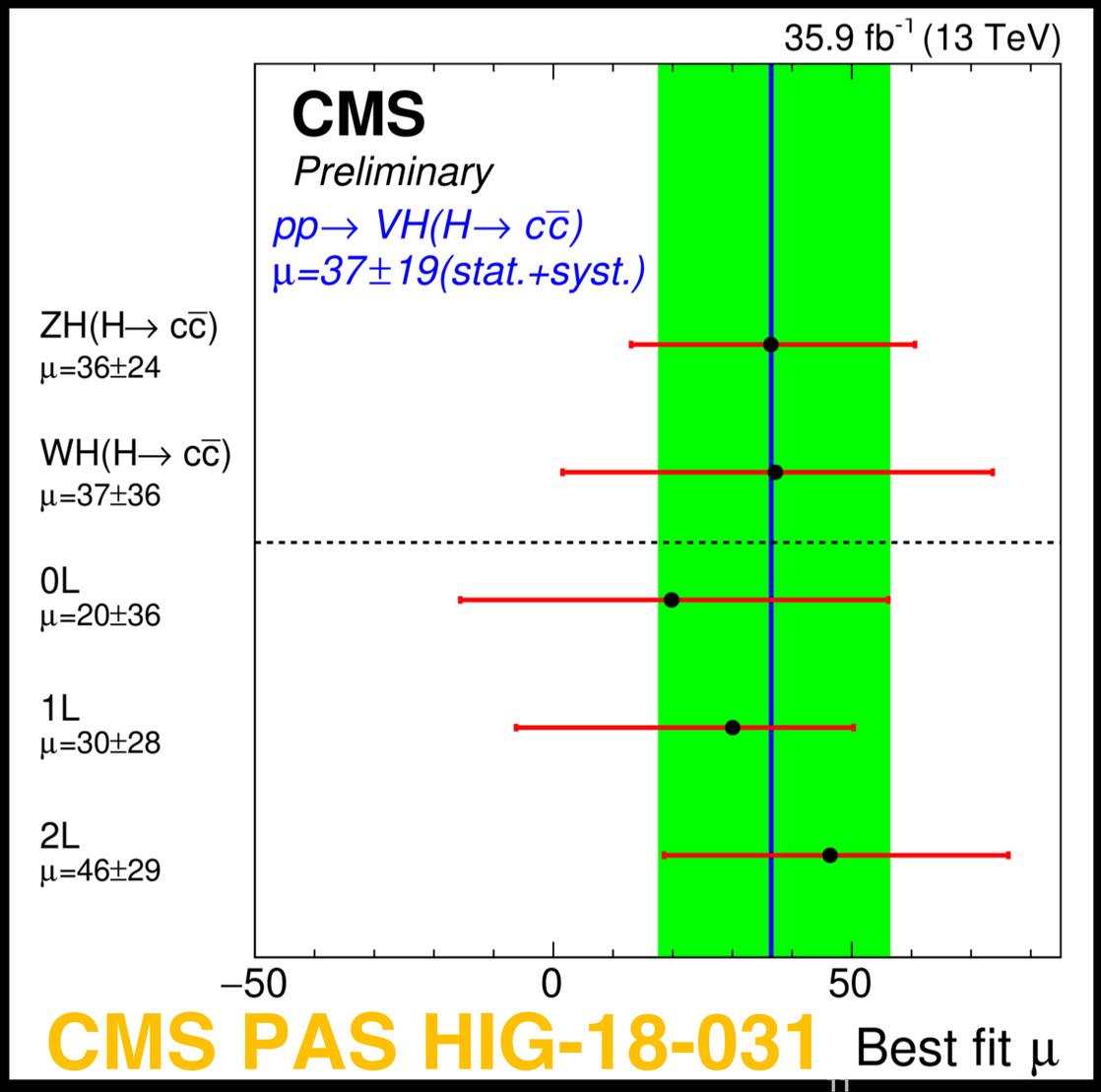
	Dataset	obs. (exp.) limits
ATLAS	Run 2	< 110 (150)x SM
CMS	Run2	< 70 (37) x SM

SM predicted: H→cc (BR~3%)

Search for Higgs coupling to 2nd generation quarks



PRL 120 (2018) 211802



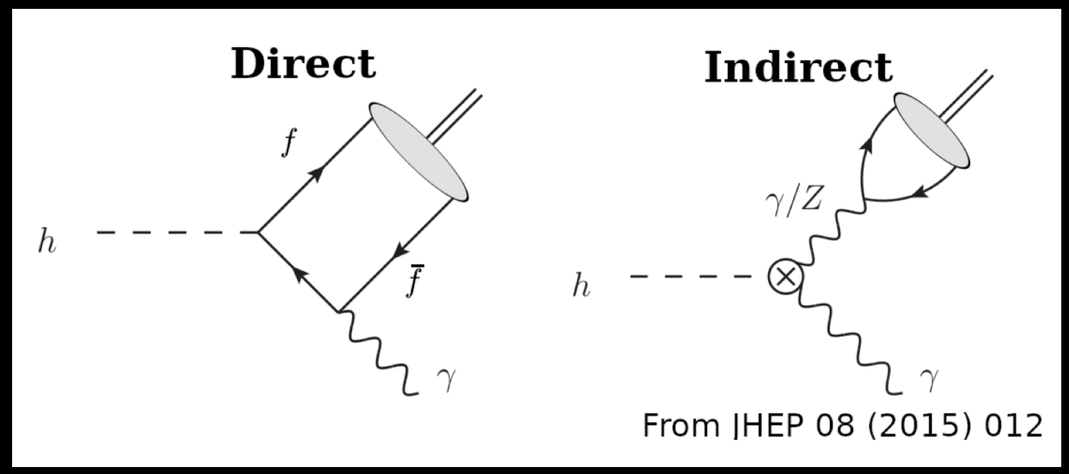
CMS PAS HIG-18-031

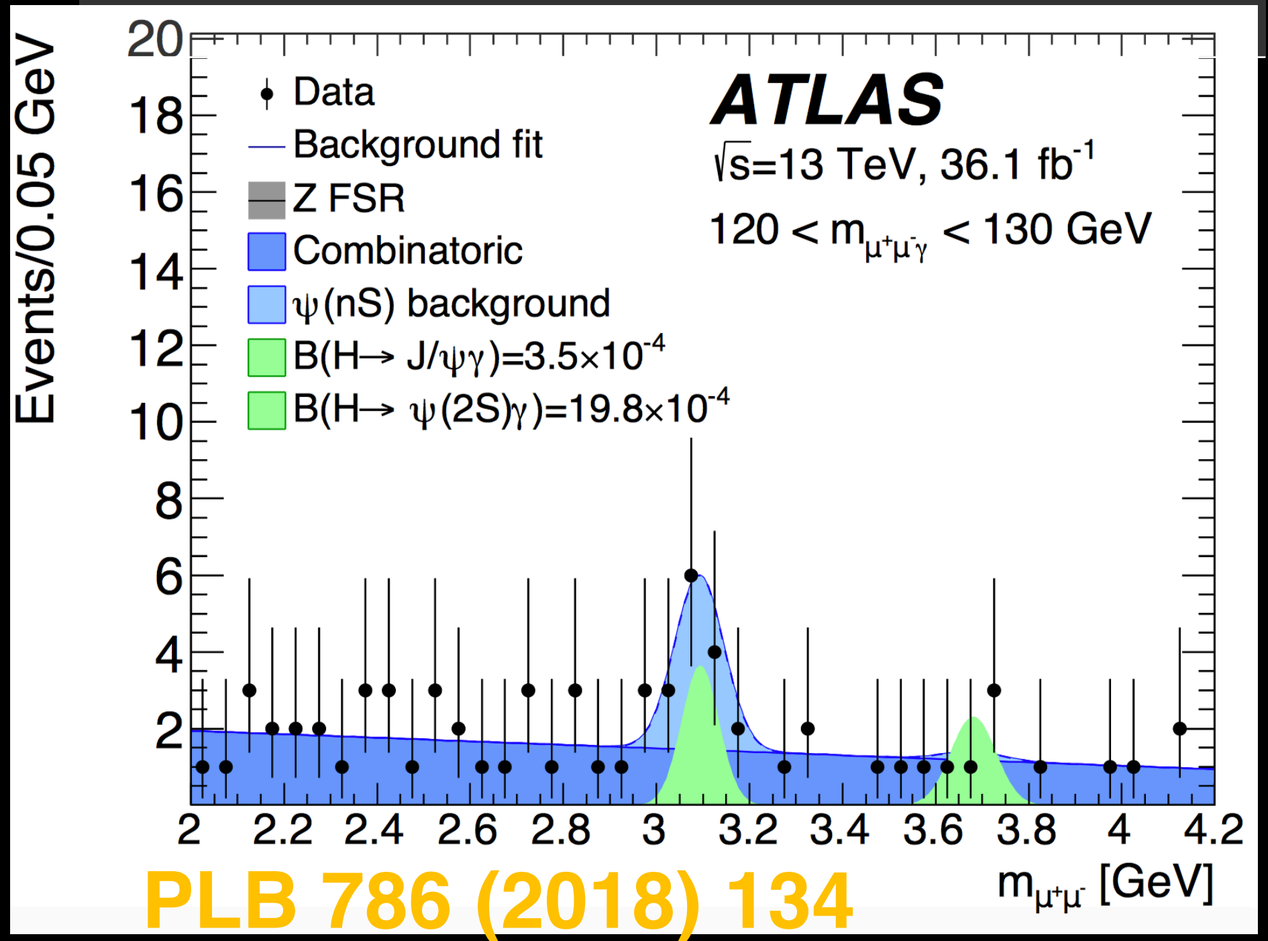
H→cc : meson+ γ

Exclusive decays to γ and vector-meson

- **direct contribution sensitive to c-quark Yukawa**
- **however indirect contribution dominant**

	obs. (exp.) upper limits on BRs
ATLAS	3.5(3.0) ×10^{-4}
CMS	7.6(5.2) ×10^{-4}
SM pred.	3.0×10^{-6}





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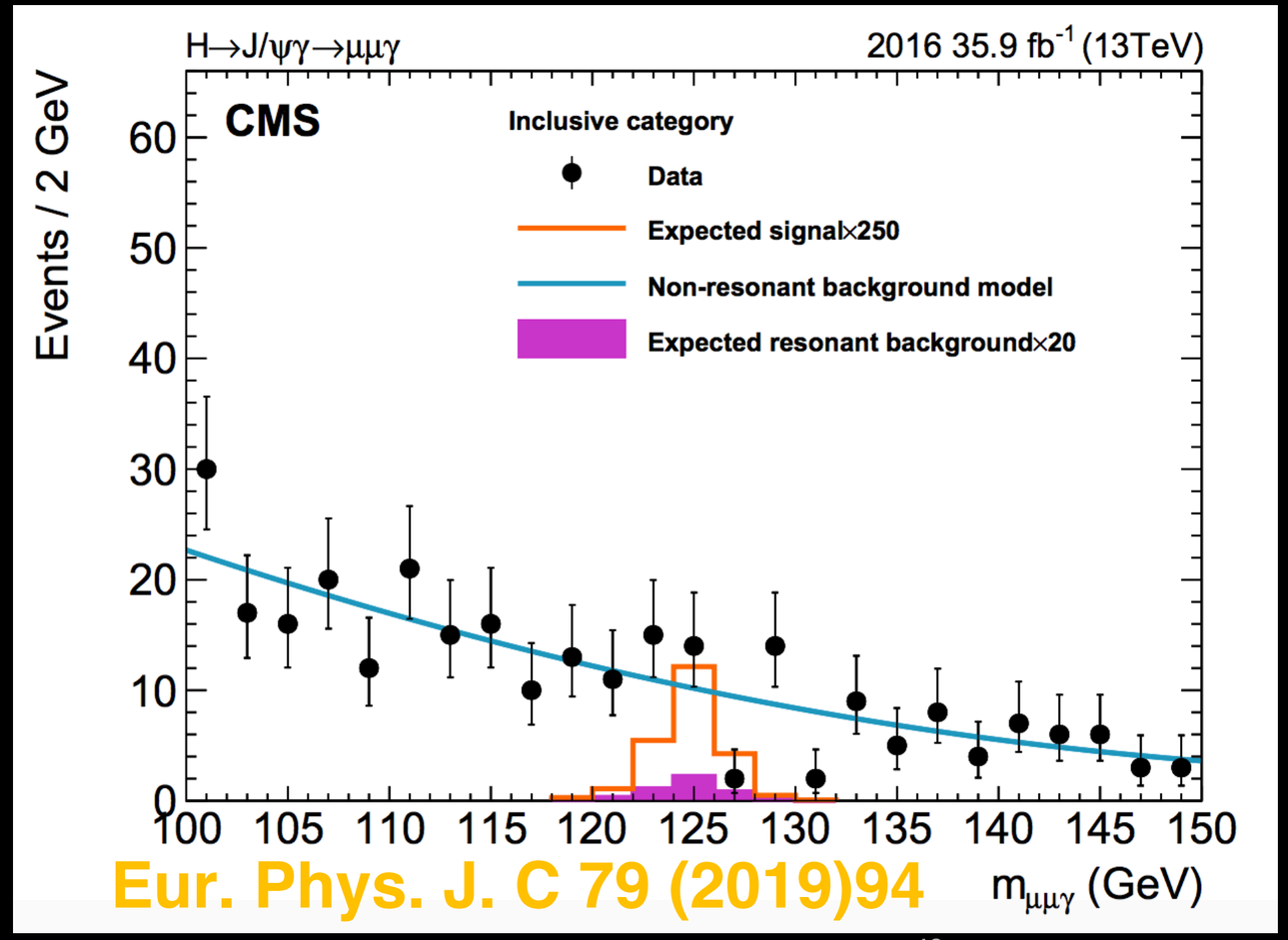
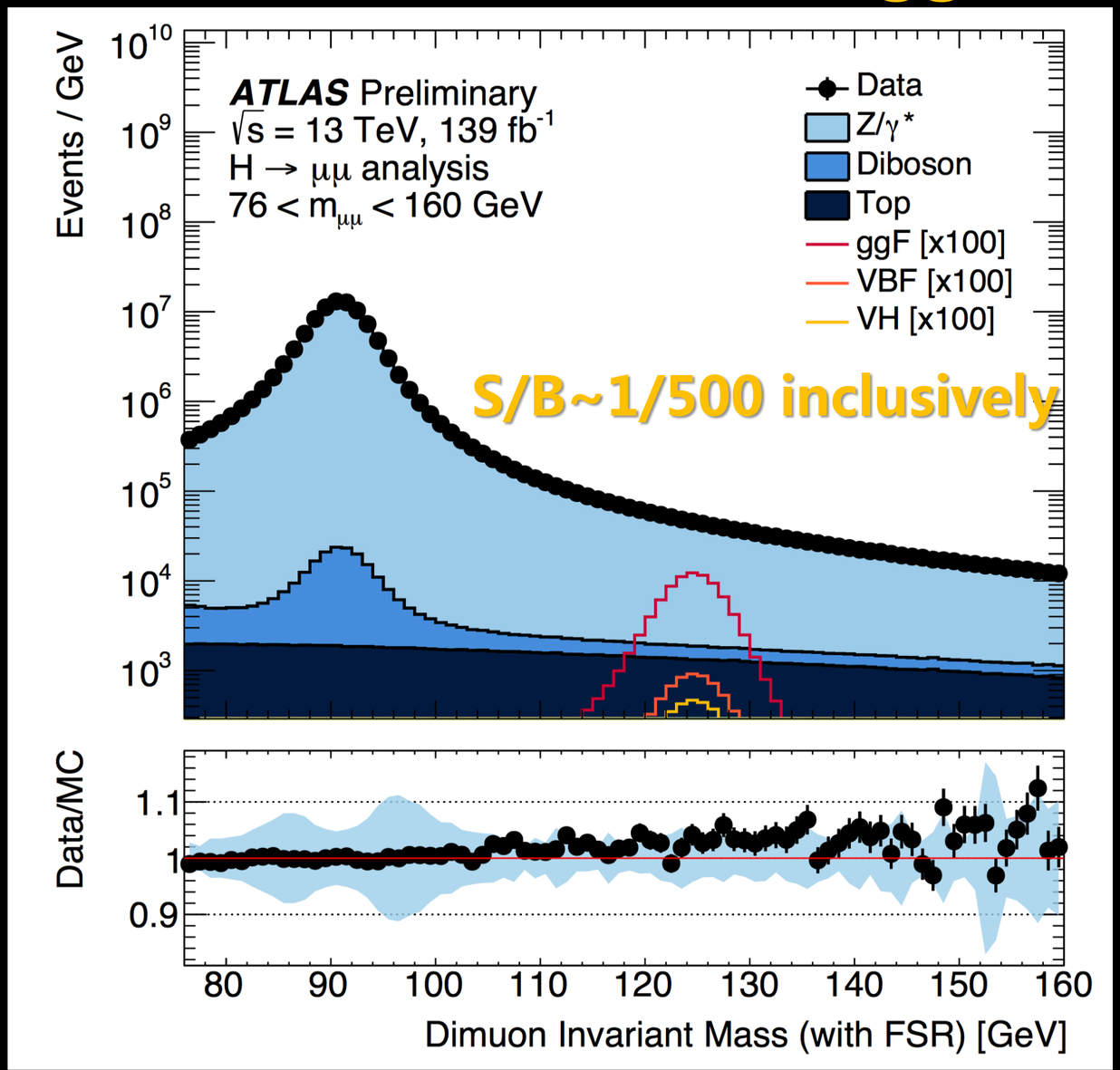


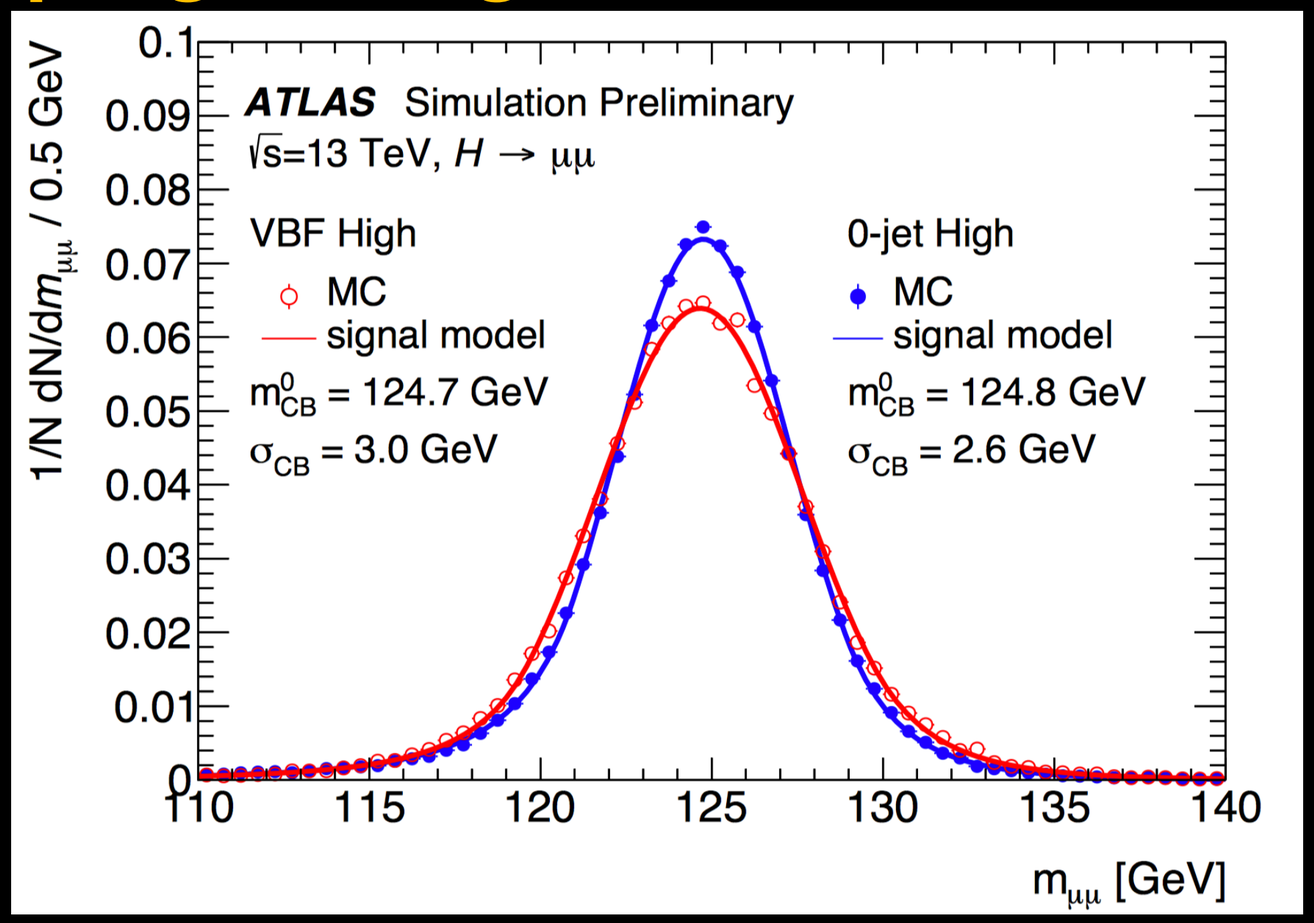
Eur. Phys. J. C 79 (2019)94

H→μμ

- **Challenge:**
  - Very small branching ratio B(H → $\mu^+\mu^-$) = 2.2 × 10^{-4}
  - large background rate from Drell–Yan Z/γ ∗ → $\mu^+\mu^-$
- **Strategy**
  - Multivariate categorisation to maximise sensitivity
  - Higgs production via ggF and VBF in exclusive selections with ≥ 2, = 1, = 0 jets

Search for Evidence of Higgs coupling to 2nd generation fermions



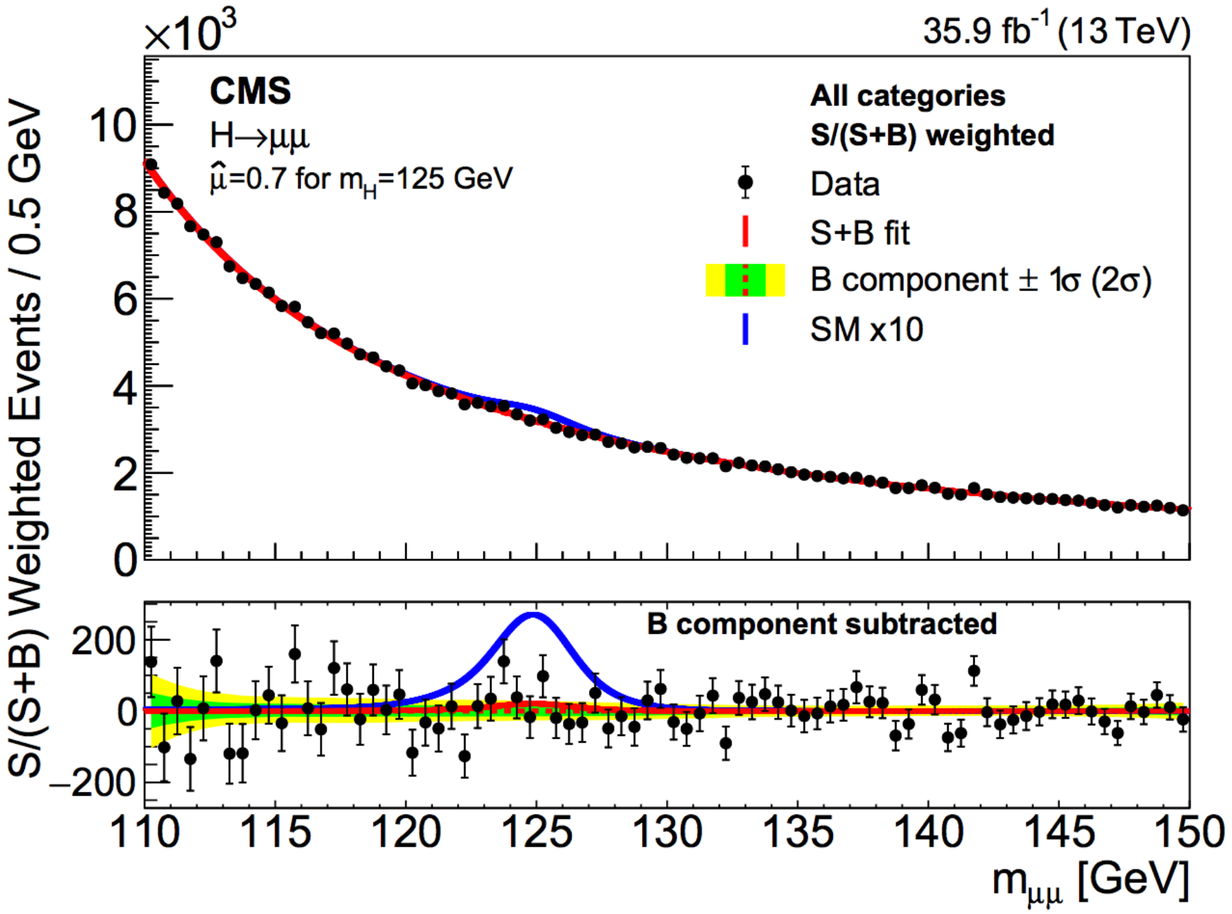


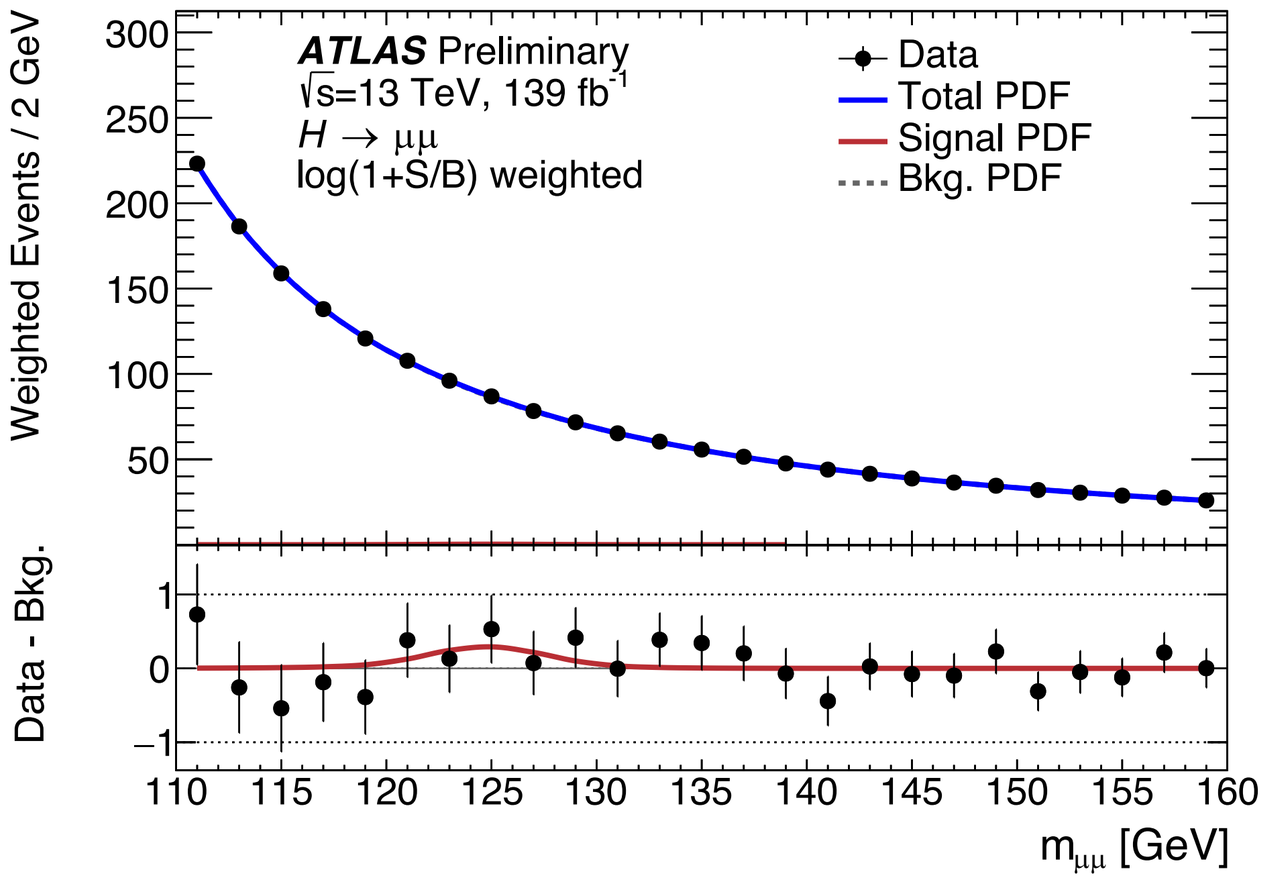
ATLAS-CONF-2019-028

H→μμ

	Data luminosity	obs. (exp.) upper limits	obs. (exp.) Significance
ATLAS	Run 2 (139 fb^{-1})	1.7 (1.3) × SM	0.8σ(1.5σ)
CMS	Run 1+2 (35.9 fb^{-1})	2.92 (2.16) × SM	0.9σ(1.0σ)

Simultaneous S + B fit in all categories



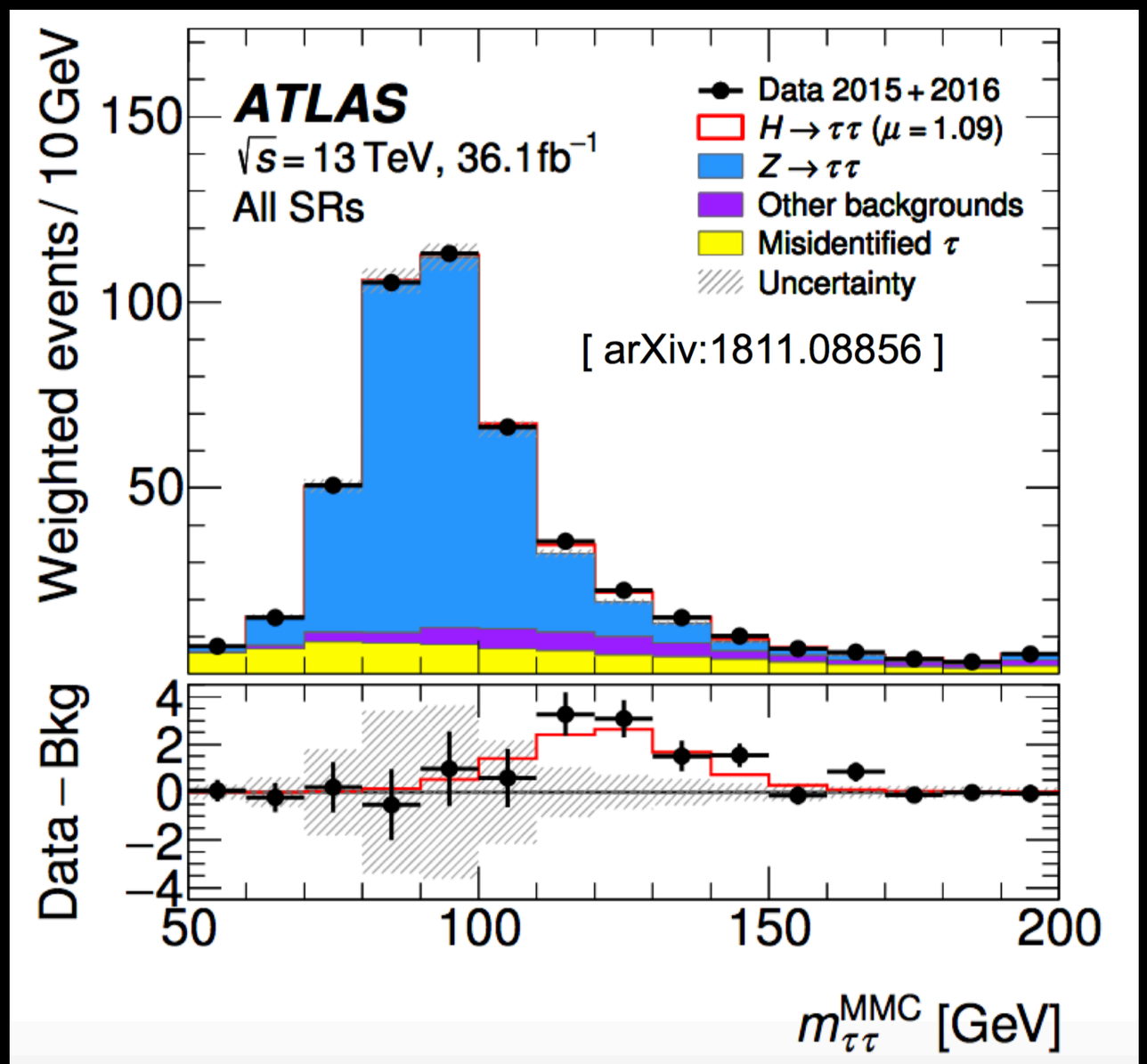


Phys. Rev. Lett. 122 (2019) 021801 ATLAS-CONF-2019-028

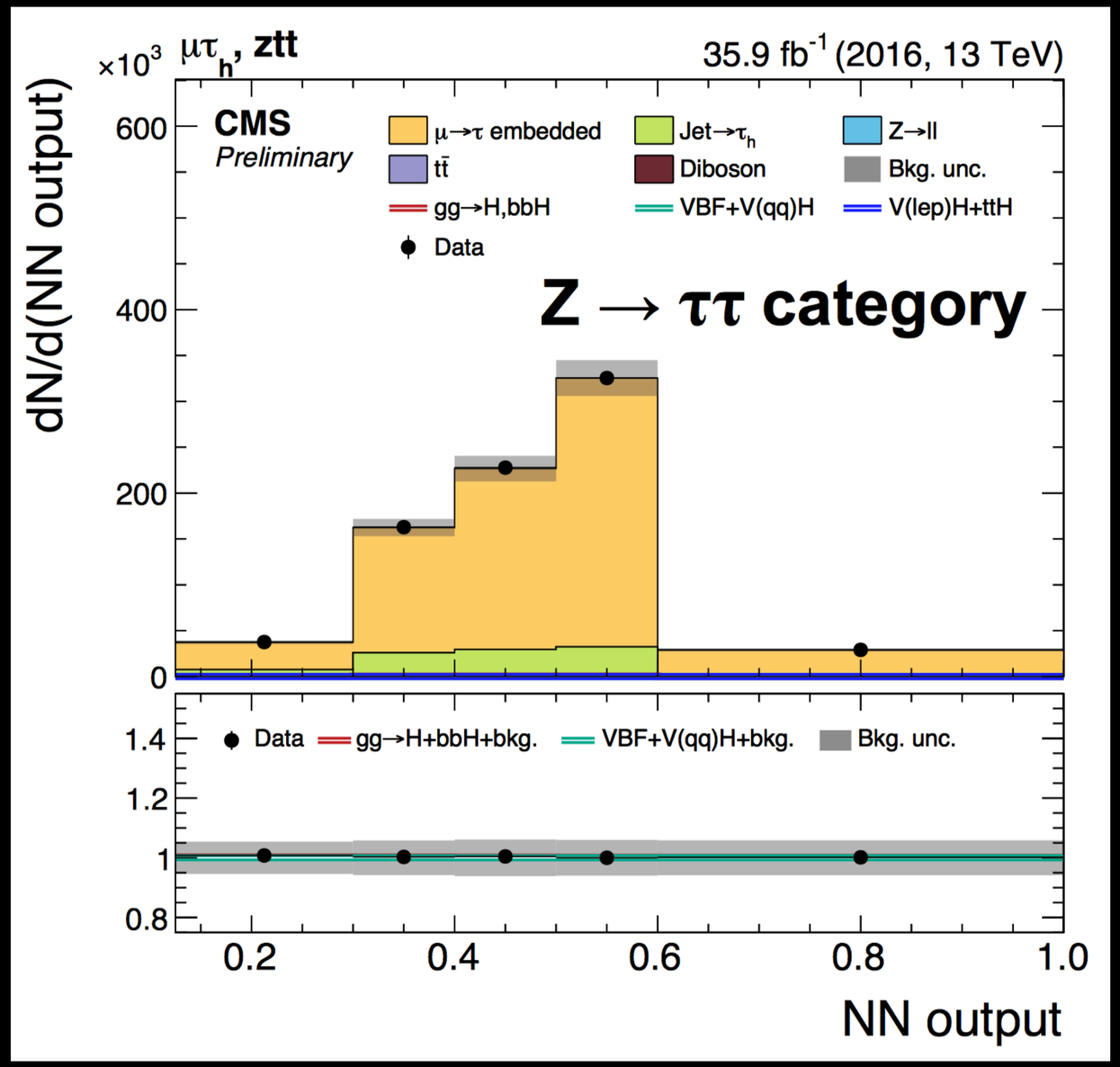
H→ττ

- **Challenge:**
  - large background Z →ττ background and jets faking taus
- **Strategy**
- CMS used τ-embedding with Z →μμ data (improve Z →ττ modelling)
- 90 % of total background estimated from data

di-τ mass m^{MMC}



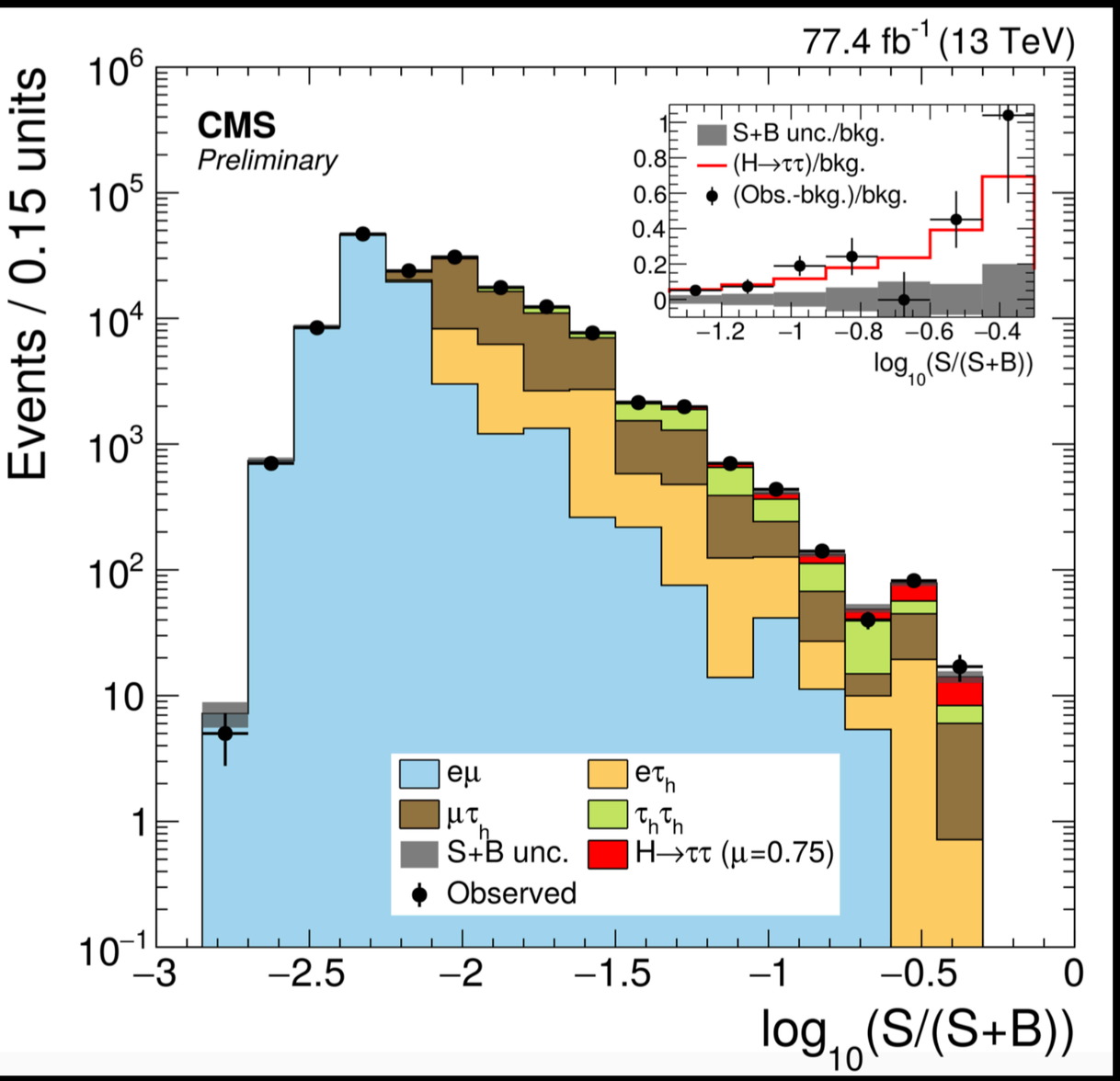
Z →ττ control region

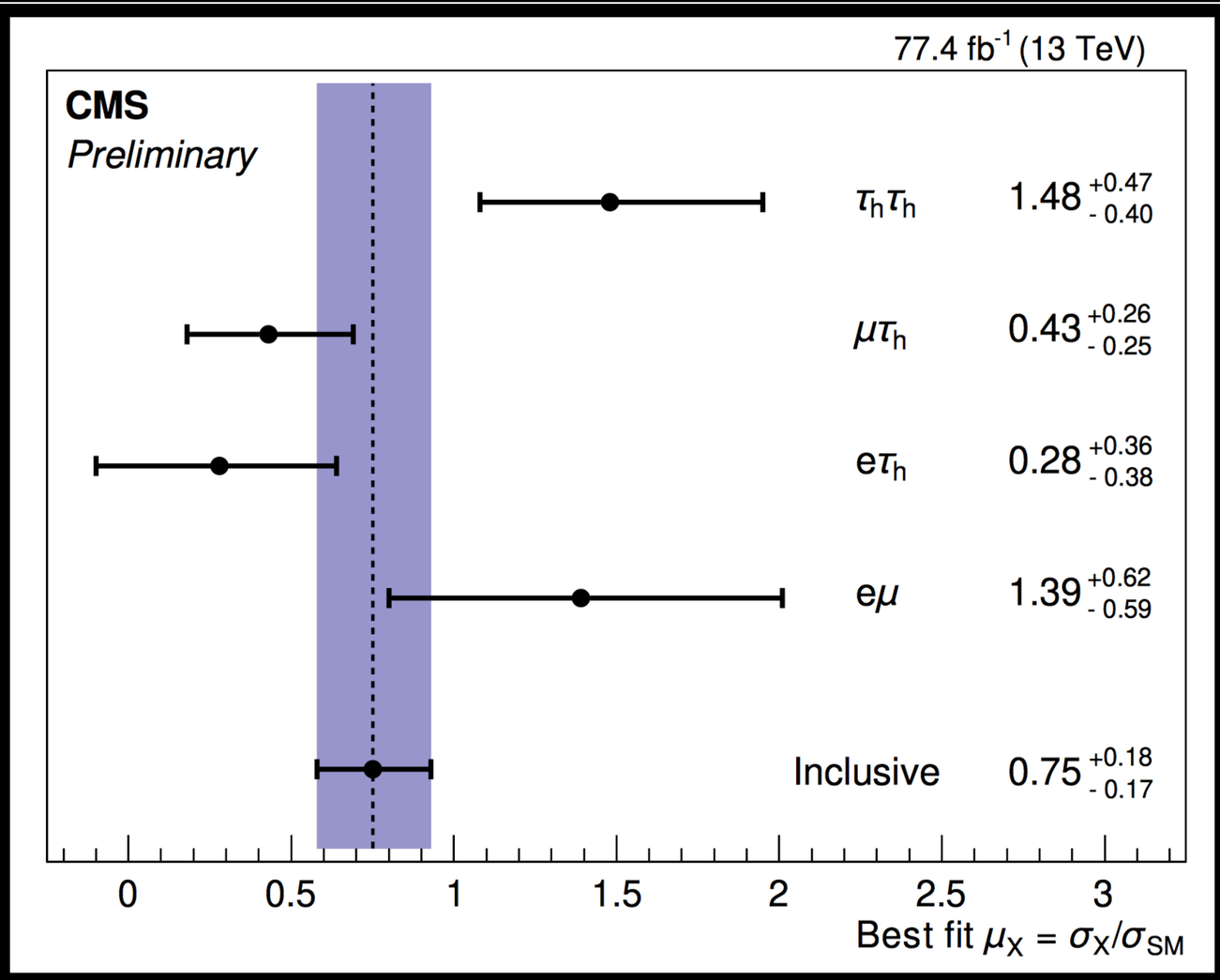


Phys. Rev. D 99, 072001 (2019)

H→ττ

ATLAS	obs. (exp.) Significance	CMS	obs. (exp.) Significance
Run 2(36.1fb^{-1})	4.4σ(4.1σ)	Run 2(77.4fb^{-1})	4.7σ(6.6σ)
Run1+Run2	6.4σ(5.4σ)	Run1+Run2(35.9fb^{-1})	5.9σ(5.9σ)



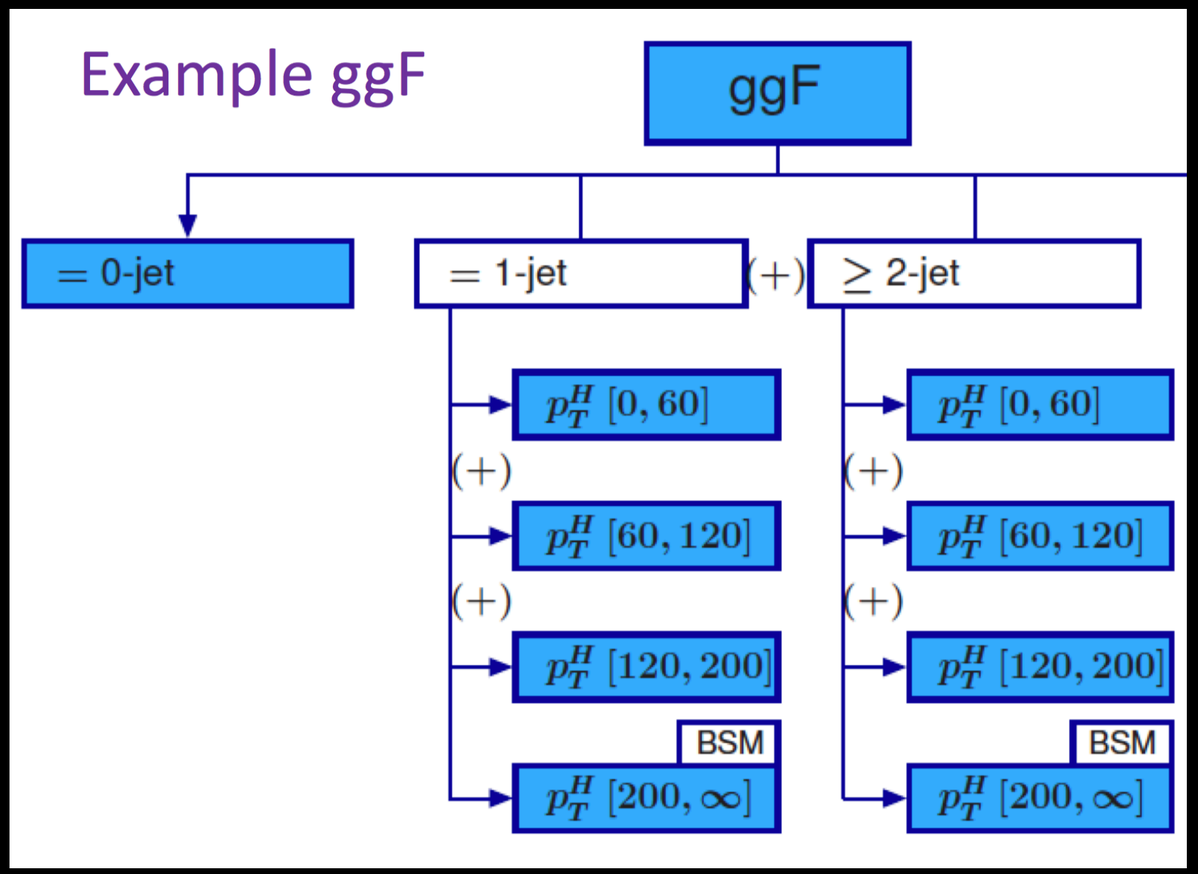


CMS PAS HIG-18-032

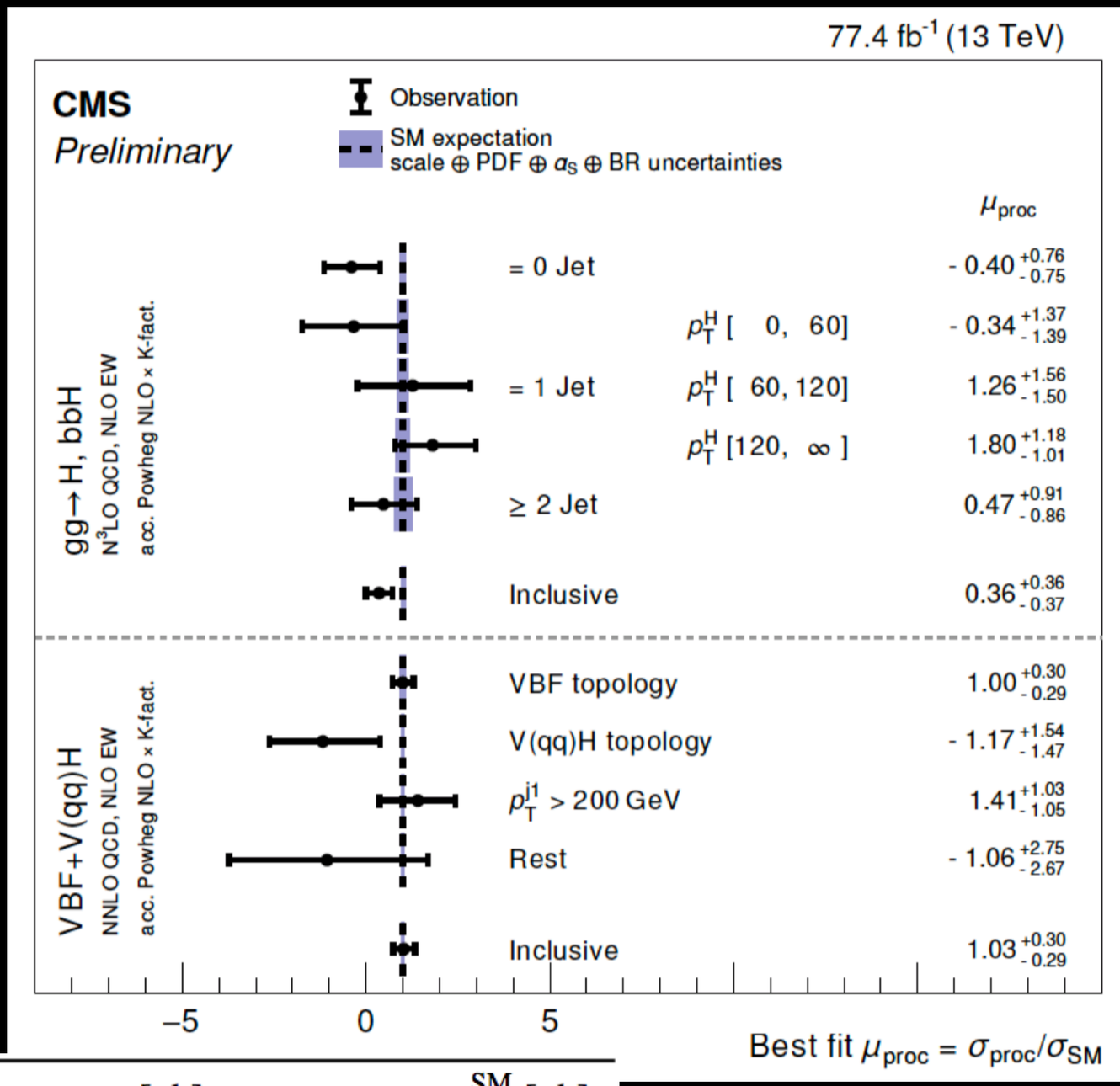
H→ττ simplified template cross section(STXS)

Simplified template cross section(STXS)

- Dividing phase space into bins
- By production modes
- By number of jets, $p_T(H)$, m_{jj}



CMS H→ττ STXS



ATLAS H→ττ STXS

Process	Particle-level selection	σ [pb]	σ^{SM} [pb]
ggF	$N_{jets} \geq 1$, $60 < p_T^H < 120$ GeV, $\lvert y_H \rvert < 2.5$	1.79 ± 0.53 (stat.)± 0.74 (syst.)	0.40 ± 0.05
ggF	$N_{jets} \geq 1$, $p_T^H > 120$ GeV, $\lvert y_H \rvert < 2.5$	0.12 ± 0.05 (stat.)± 0.05 (syst.)	0.14 ± 0.03
VBF	$\lvert y_H \rvert < 2.5$	0.25 ± 0.08 (stat.)± 0.08 (syst.)	0.22 ± 0.01

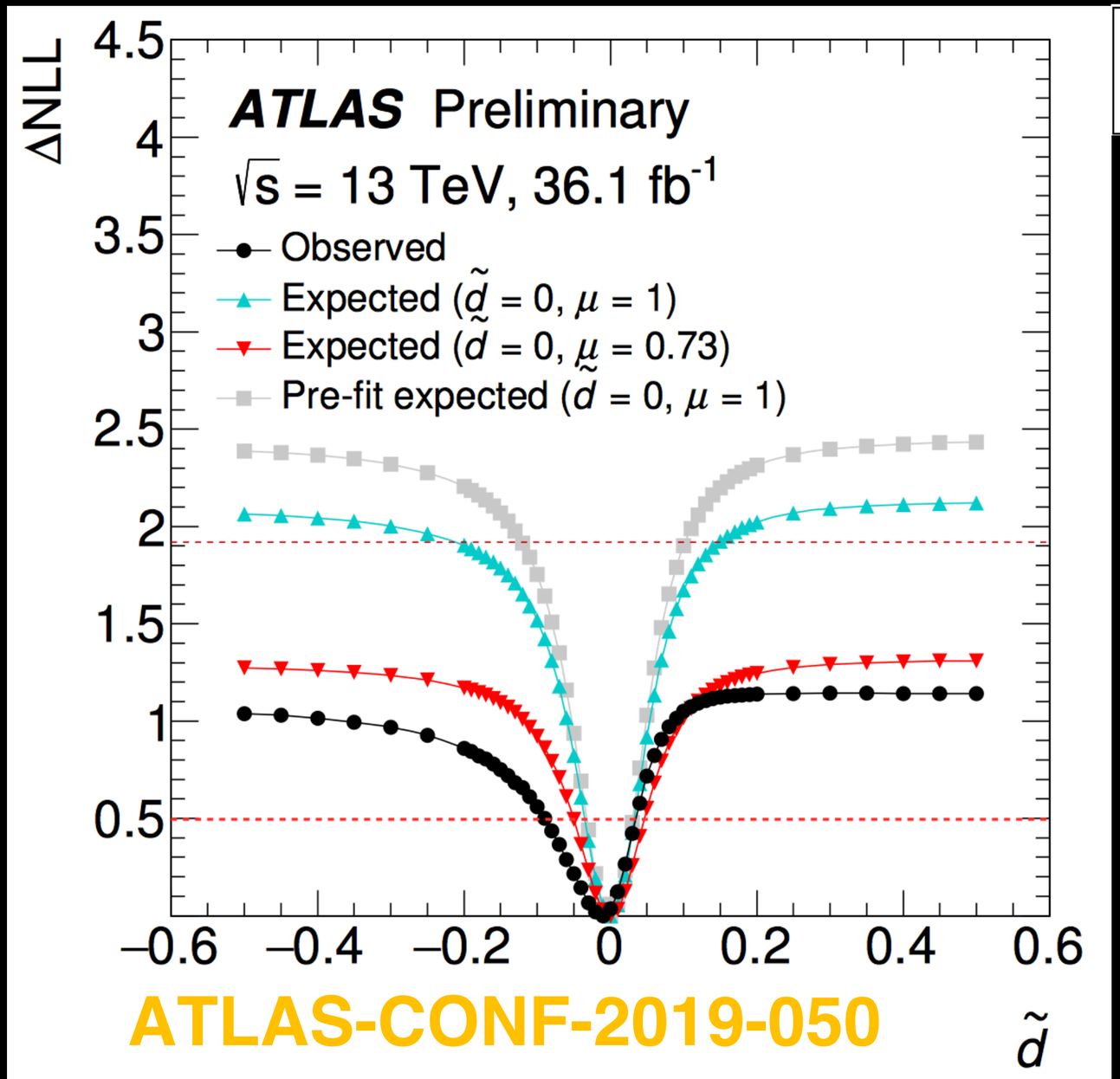
H→ττ : Test of CP Invariance

- **Motivation:**
  - **Observed baryon asymmetry in the universe → CP violation**
  - **Any CP violation in Higgs section ?**
  - **Construct CP sensitive Optimal observable (OO)**

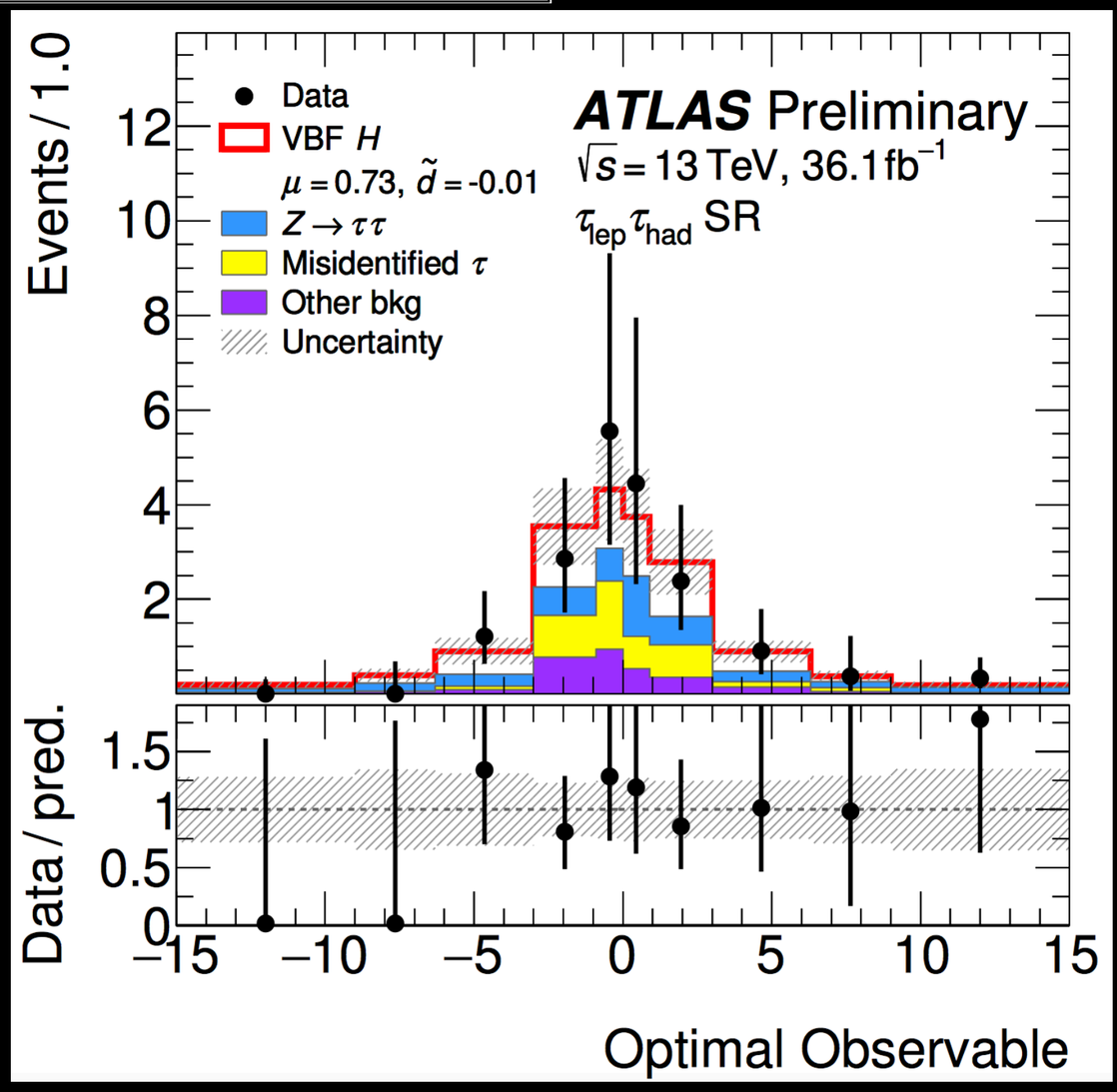
$$|\mathcal{M}|^2 = \underbrace{|\mathcal{M}_{\text{SM}}|^2}_{\text{CP-even}} + \underbrace{\tilde{d}\cdot 2\text{Re}\left(\mathcal{M}^*_{\text{SM}}\,\mathcal{M}_{\text{CP-odd}}\right)}_{\text{CP-odd (source of CP violation)}} + \underbrace{\tilde{d}^2\cdot|\mathcal{M}_{\text{CP-odd}}|^2}_{\text{CP-even}}$$

$$OO = \frac{2\text{Re}(\mathcal{M}^*_{\text{SM}}\mathcal{M}_{\text{CP-odd}})}{|\mathcal{M}_{\text{SM}}|^2}$$

	⟨OO⟩
$\tau_{lep}\tau_{lep}$ SF	-0.54 ± 0.72
$\tau_{lep}\tau_{lep}$ DF	0.71 ± 0.81
$\tau_{lep}\tau_{had}$	0.74 ± 0.78
$\tau_{had}\tau_{had}$	-1.13 ± 0.65



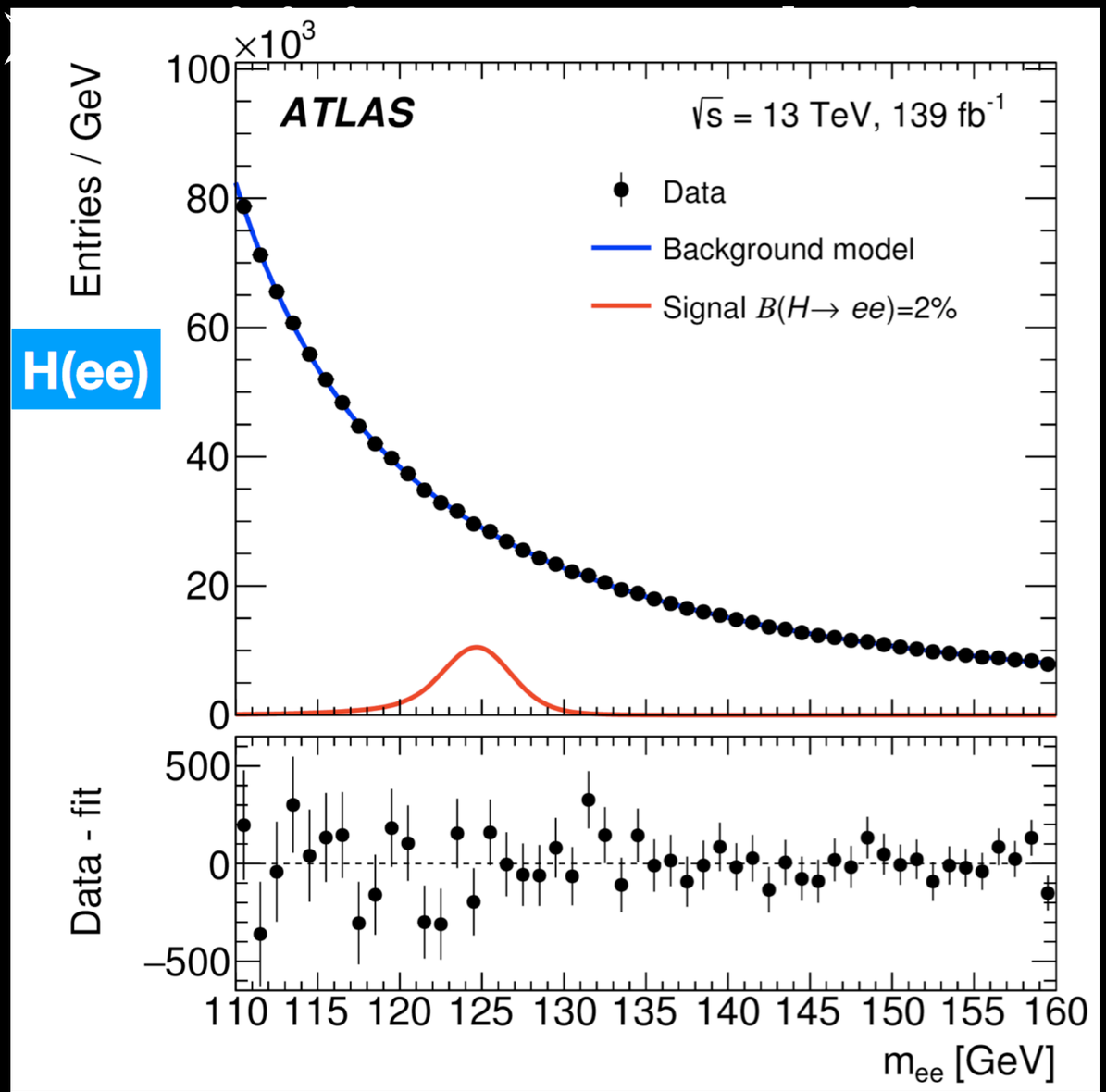
ATLAS-CONF-2019-050

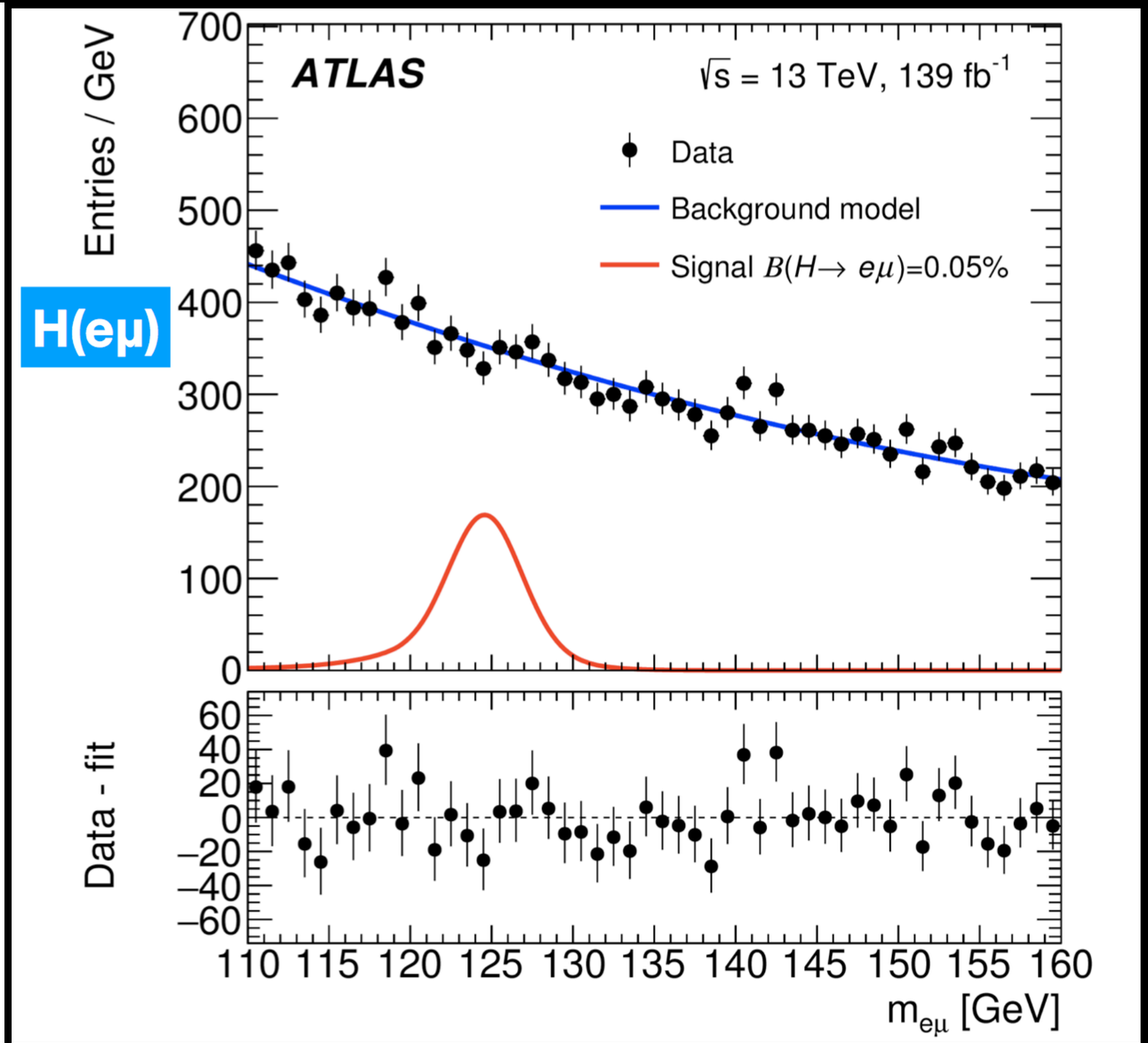


H→ee

	H→ee branching ratio obs. (exp.) upper limits	**H→eμ** branching ratio obs. (exp.) upper limits
ATLAS	3.6 (3.5) ×10^{-4}	6.1 (5.8) ×10^{-5}
CMS	0.0019	3.5 ×10^{-4}

➢ **H→ee Branching ratio: SM expectation ~5·10^{-9}**

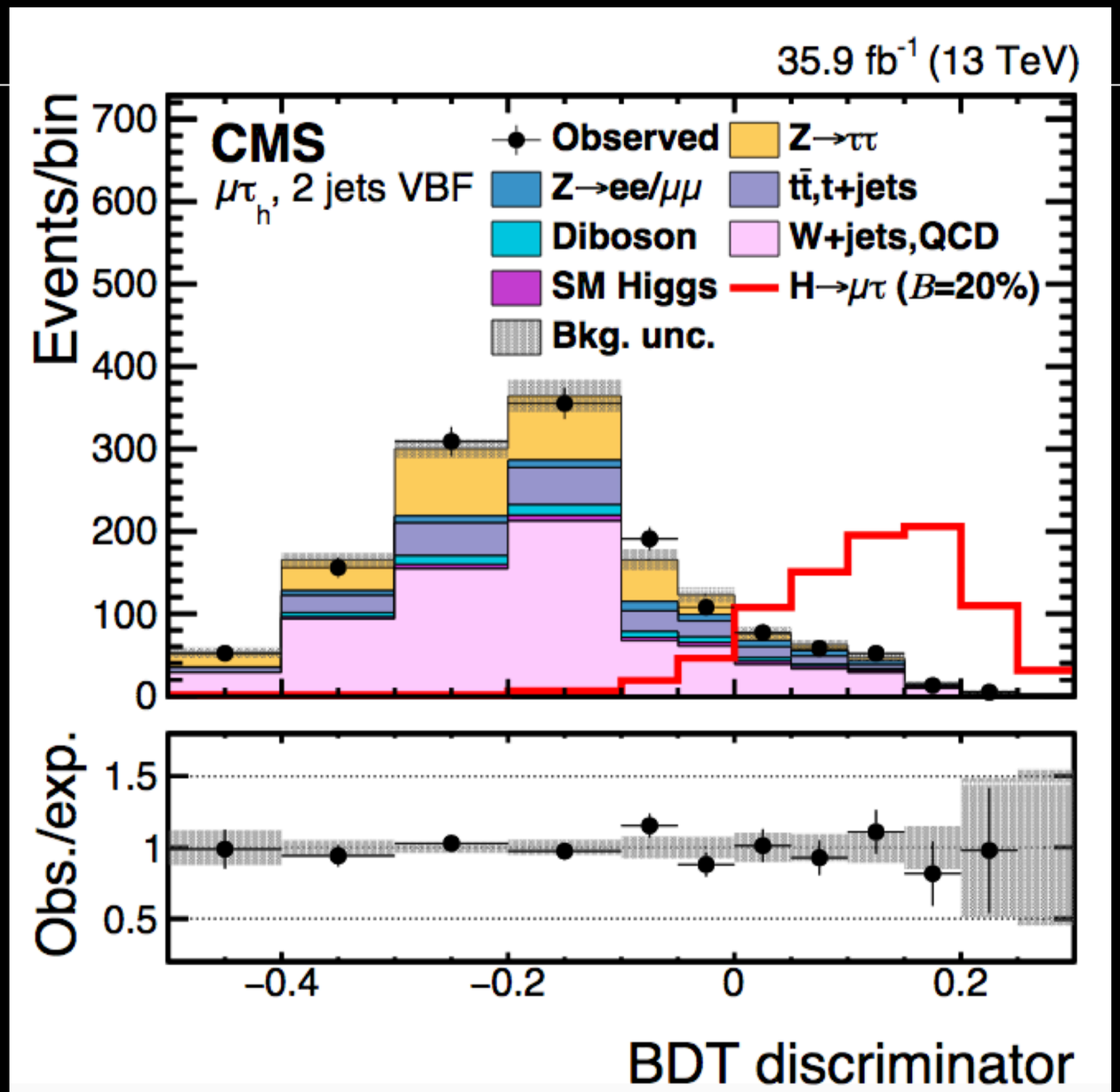




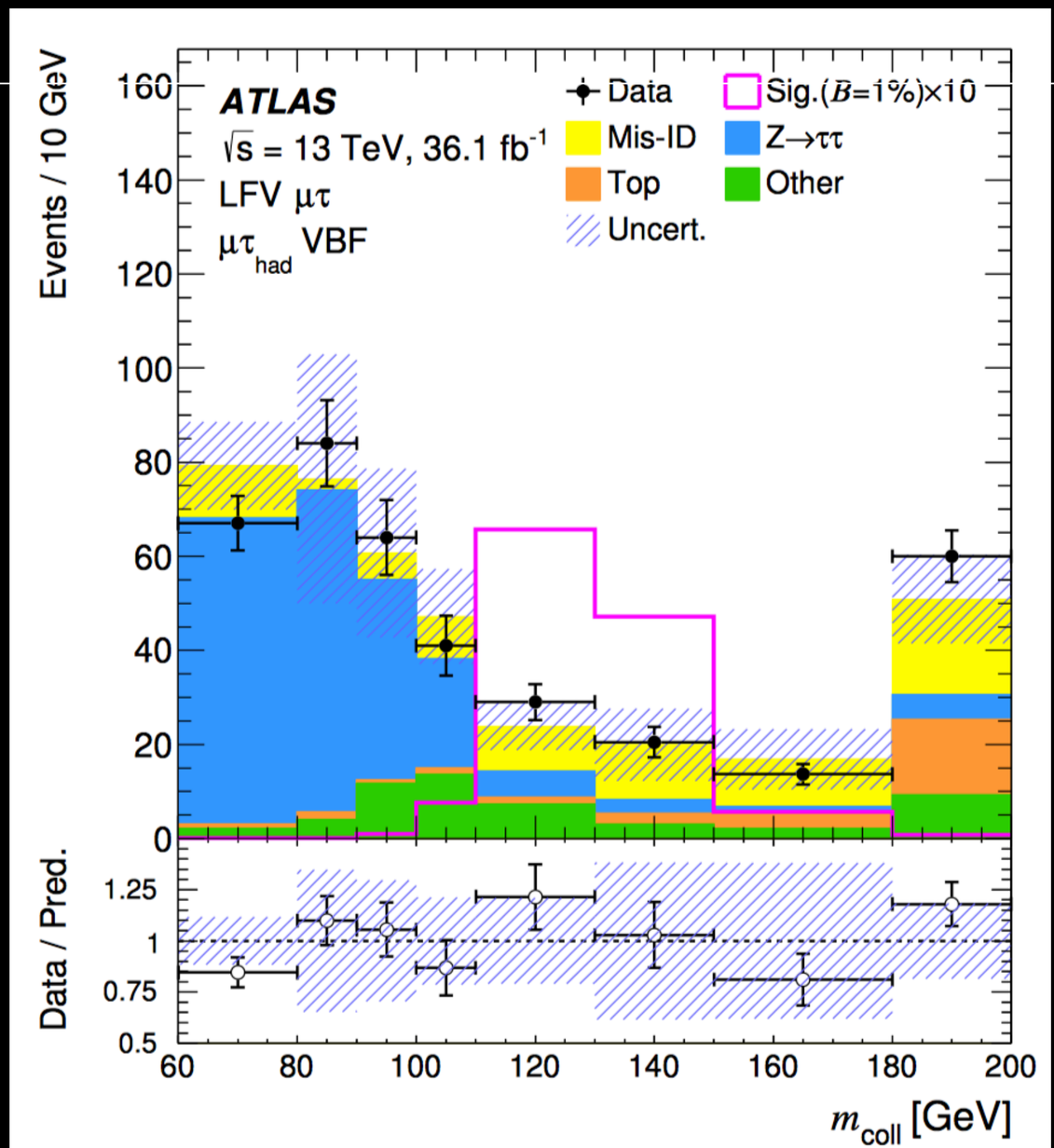
CMS:PLB 744 (2015) 184 **ATLAS:HIGG-2018-58**

H→eτ/μτ lepton flavor violation

	Dataset	H→eτ branching ratio obs. (exp.) upper limits	H→μτ branching ratio obs. (exp.) upper limits
ATLAS	Run 2	0.47%(0.34%)	0.28%(0.37%)
CMS	Run 2	0.61%(0.37%)	0.25%(0.25%)



JHEP 06 (2018) 001



CERN-EP-2019-126

Summary

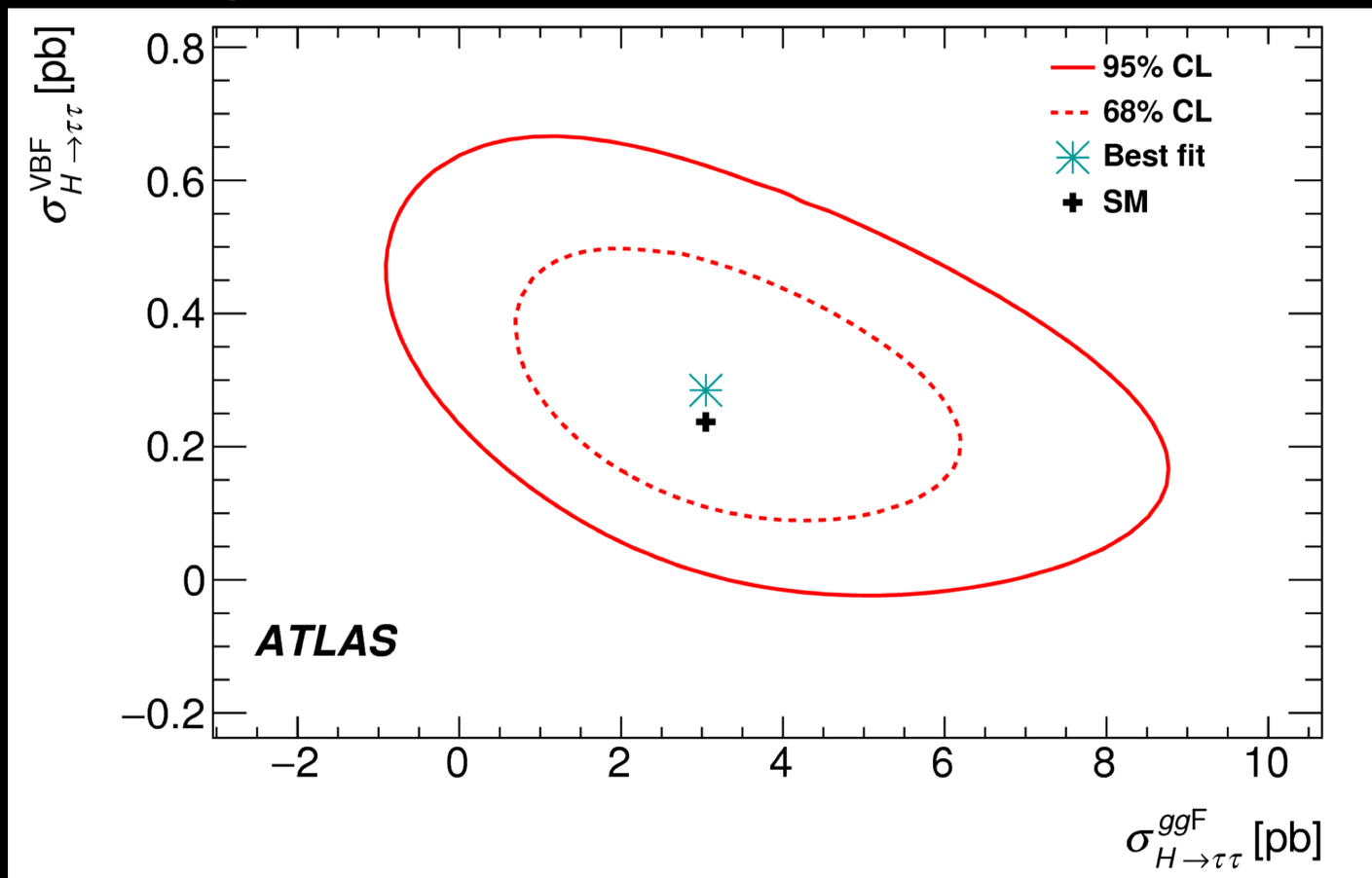
- **Observation of Higgs coupling to top and b-quarks in 2018**
  - **Top 10 Physics highlight in 2018 by American Physics Society.**

- **First measurements of H→ττ/bb in kinematic bins (STXS)**
  - **Complementary measurements to $H \rightarrow bosons$**

- **Access to 2nd generation fermions is approaching**
  - **H→μμ : remarkable sensitivity achieved (~1σ)**
  - **H→cc : more work needed on c jet tagging**

H→ττ

- **Highlight:**
  - **Measurements split by production mode**
  - **Test the consistentency with SM**
  - **Agree with SM within 2σ**



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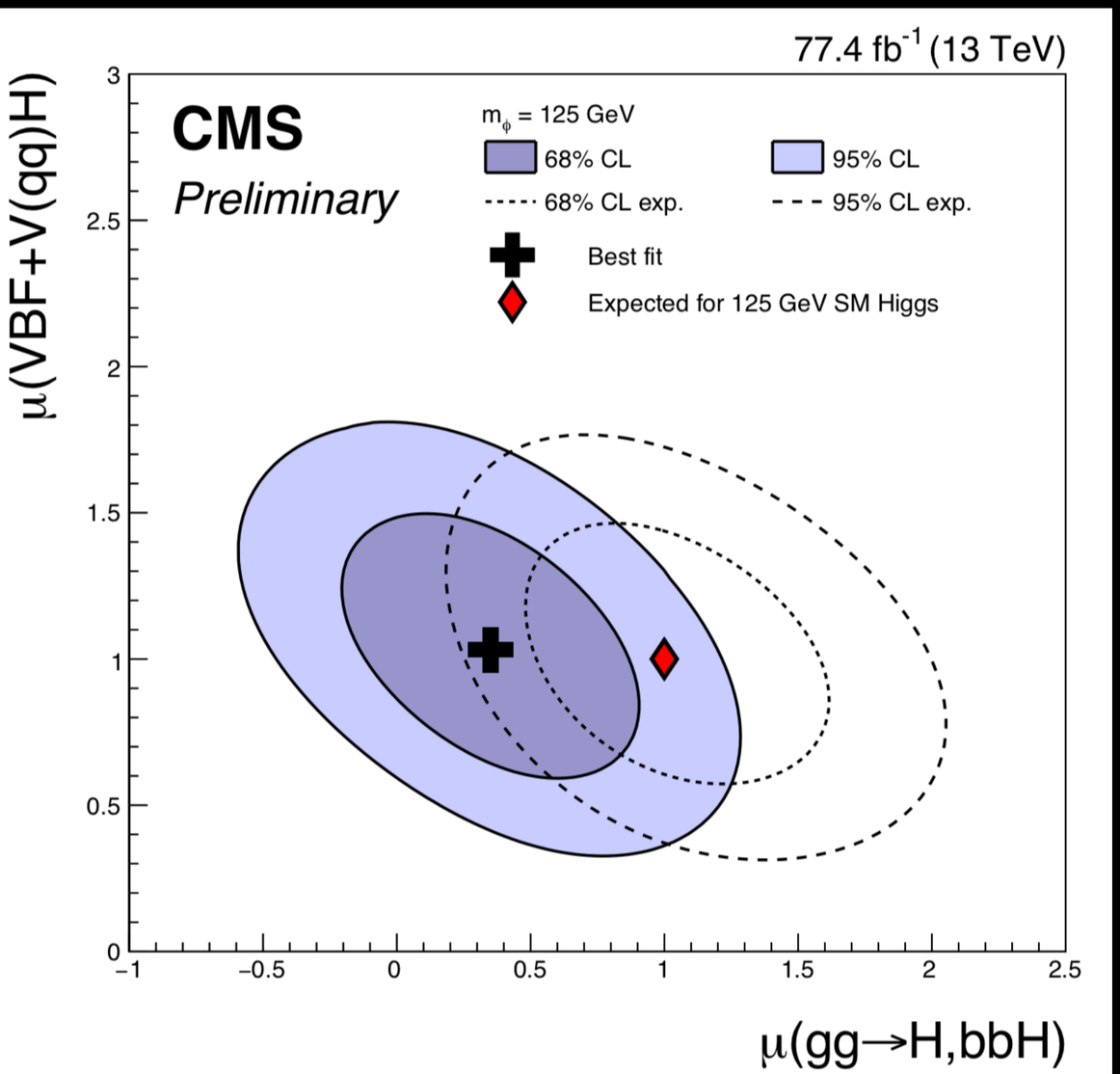
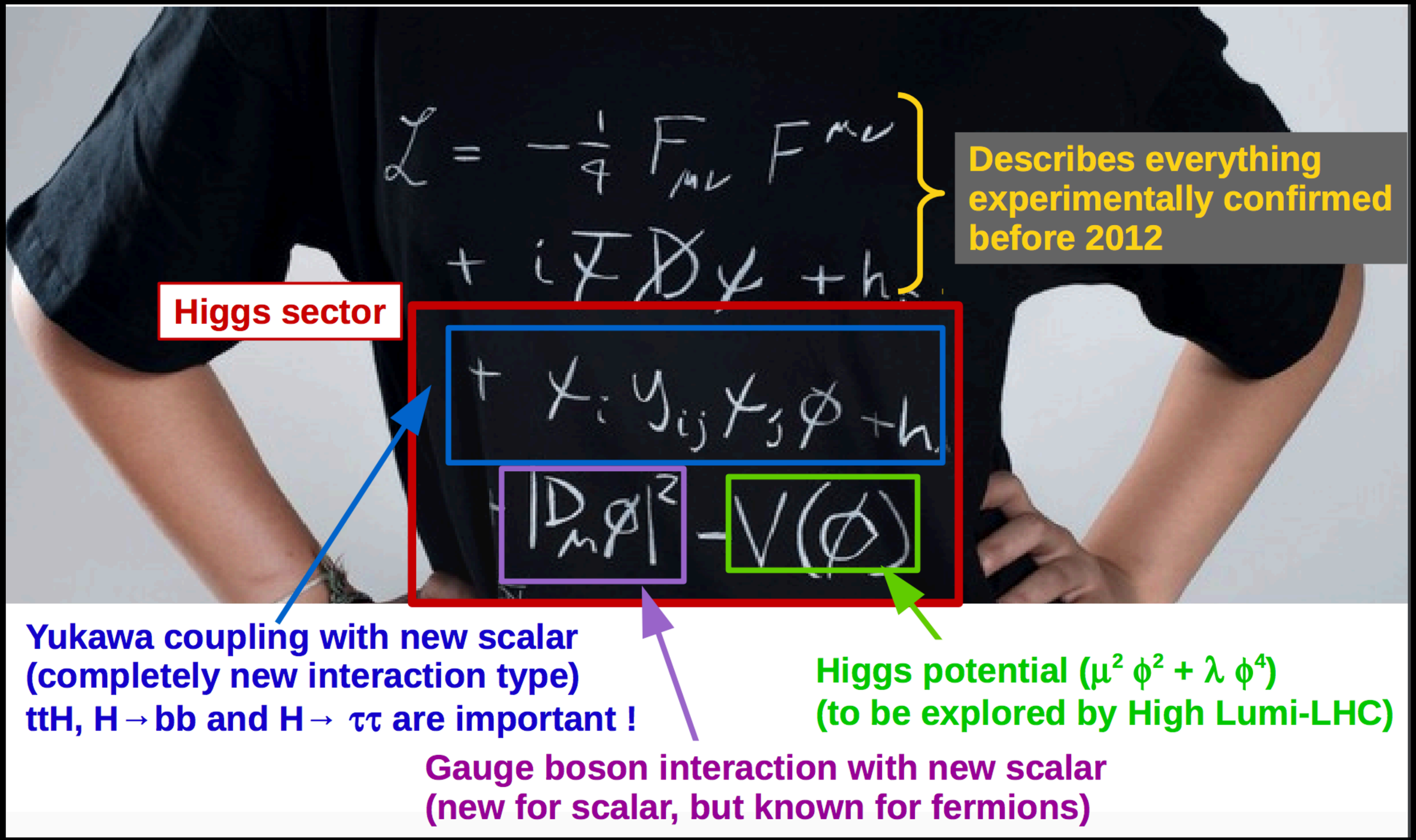
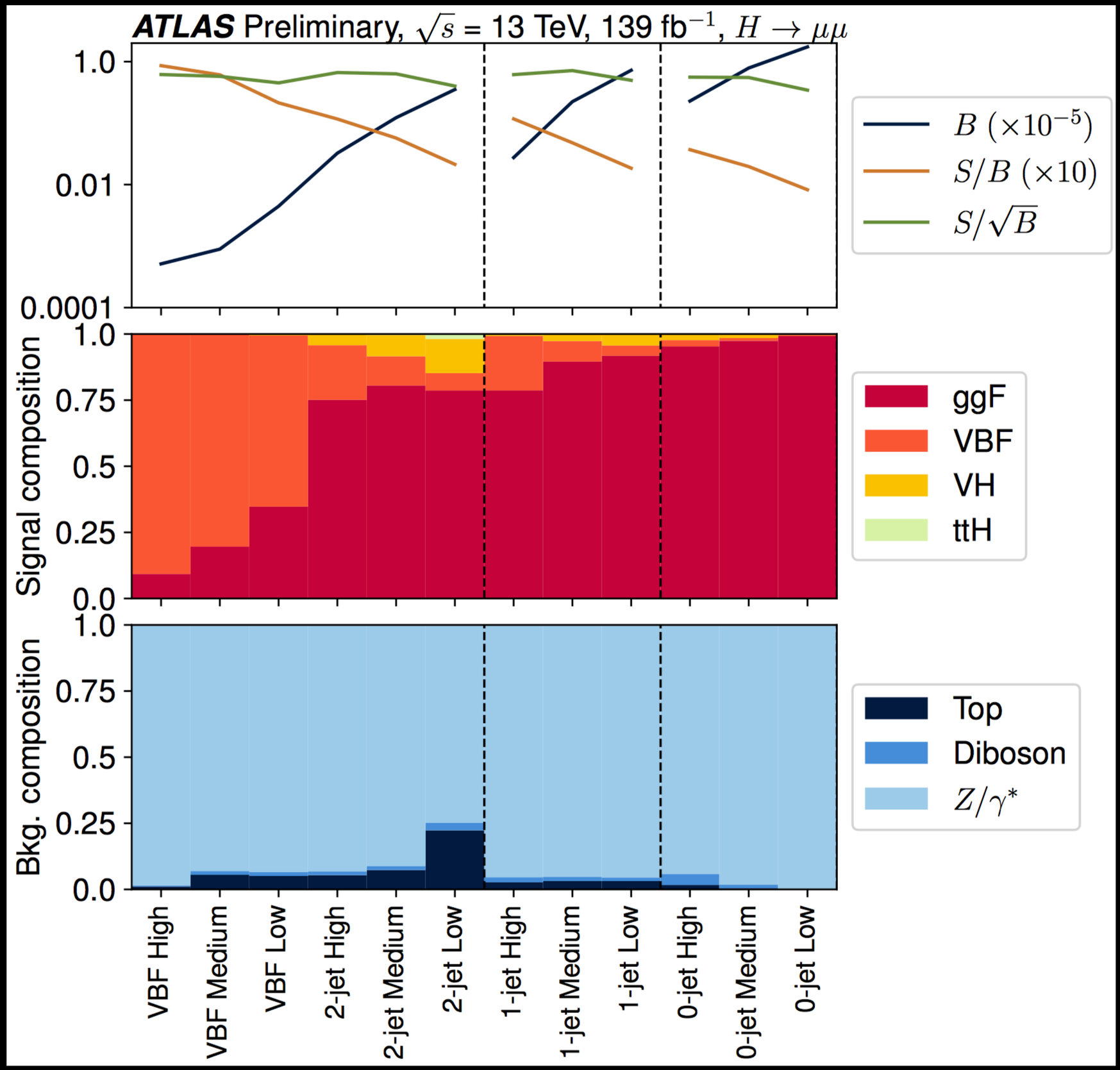


CMS PAS HIG-18-032


$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i \bar{\psi} \not{D} \psi + h.$
$+ x_i y_{ij} x_j \phi + h.$
$|D_\mu \phi|^2 - V(\phi)$
Describes everything experimentally confirmed before 2012
Higgs sector
Yukawa coupling with new scalar
(completely new interaction type)
ttH, H→bb and H→ ττ are important !
Higgs potential ($\mu^2 \phi^2 + \lambda \phi^4$)
(to be explored by High Lumi-LHC)
Gauge boson interaction with new scalar
(new for scalar, but known for fermions)

H→μμ category



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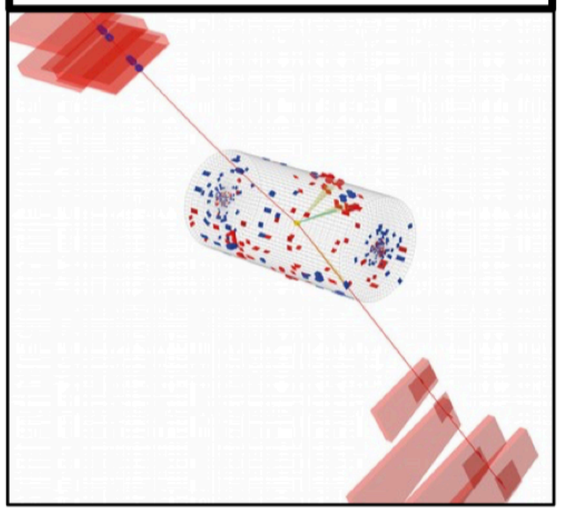
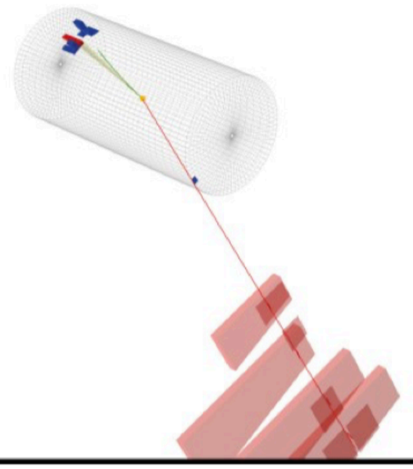
$Z \to \mu\mu$ Selection

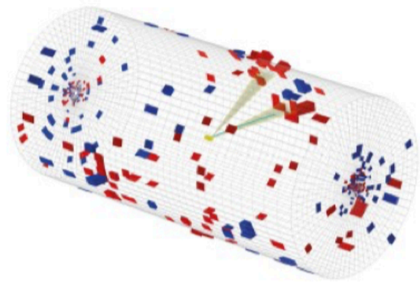


$Z \to \tau\tau$ Simulation



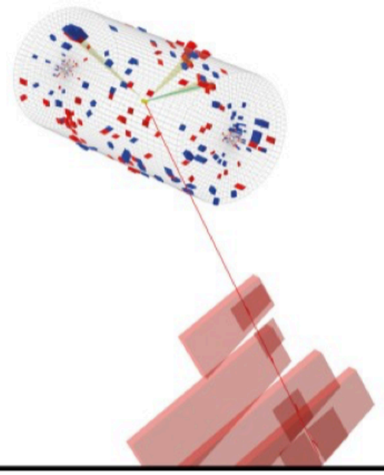
Simulate τ leptons with same kinematic properties as muons.

$Z \to \mu\mu$ Cleaning



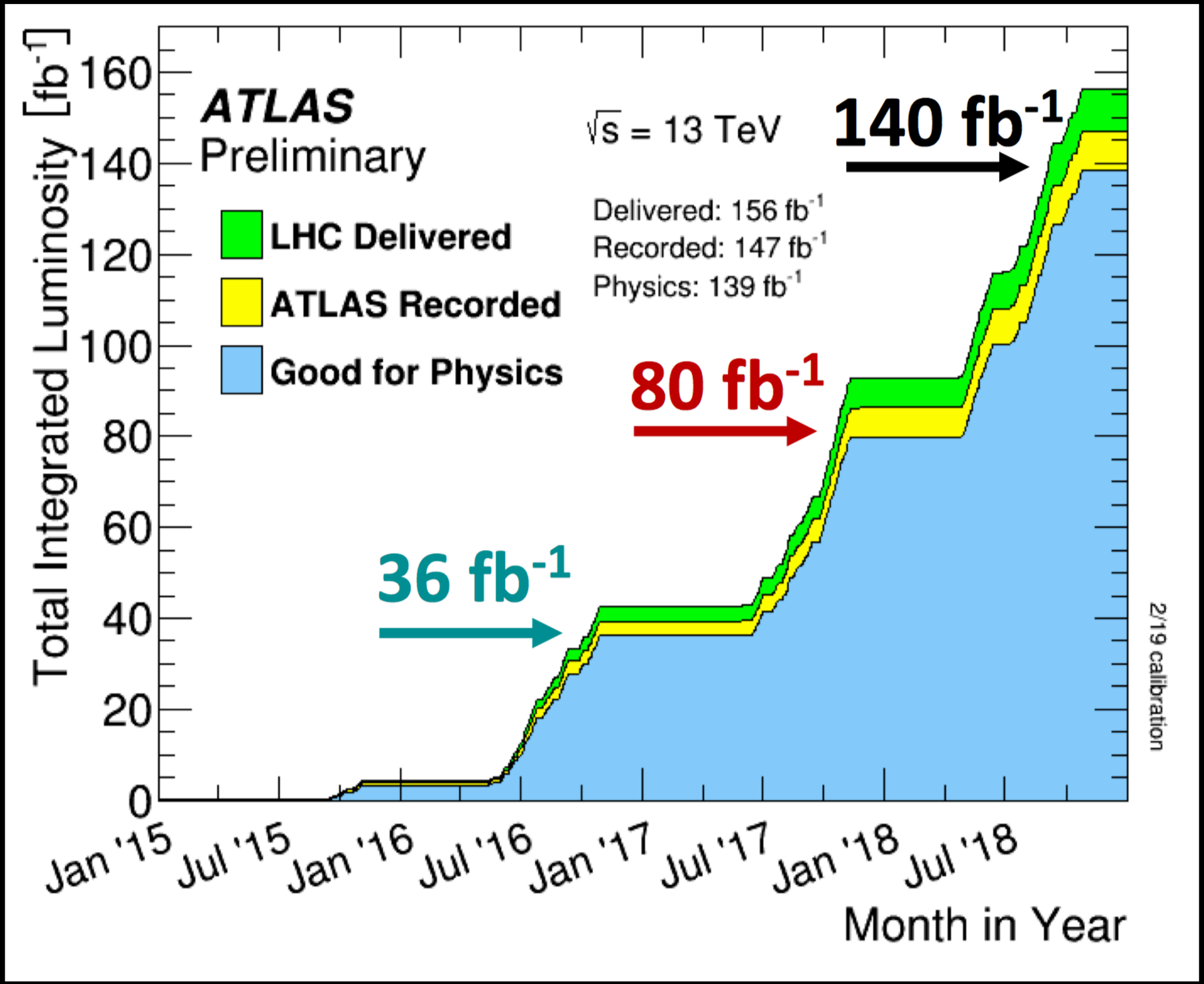
Remove energy deposits from muons.

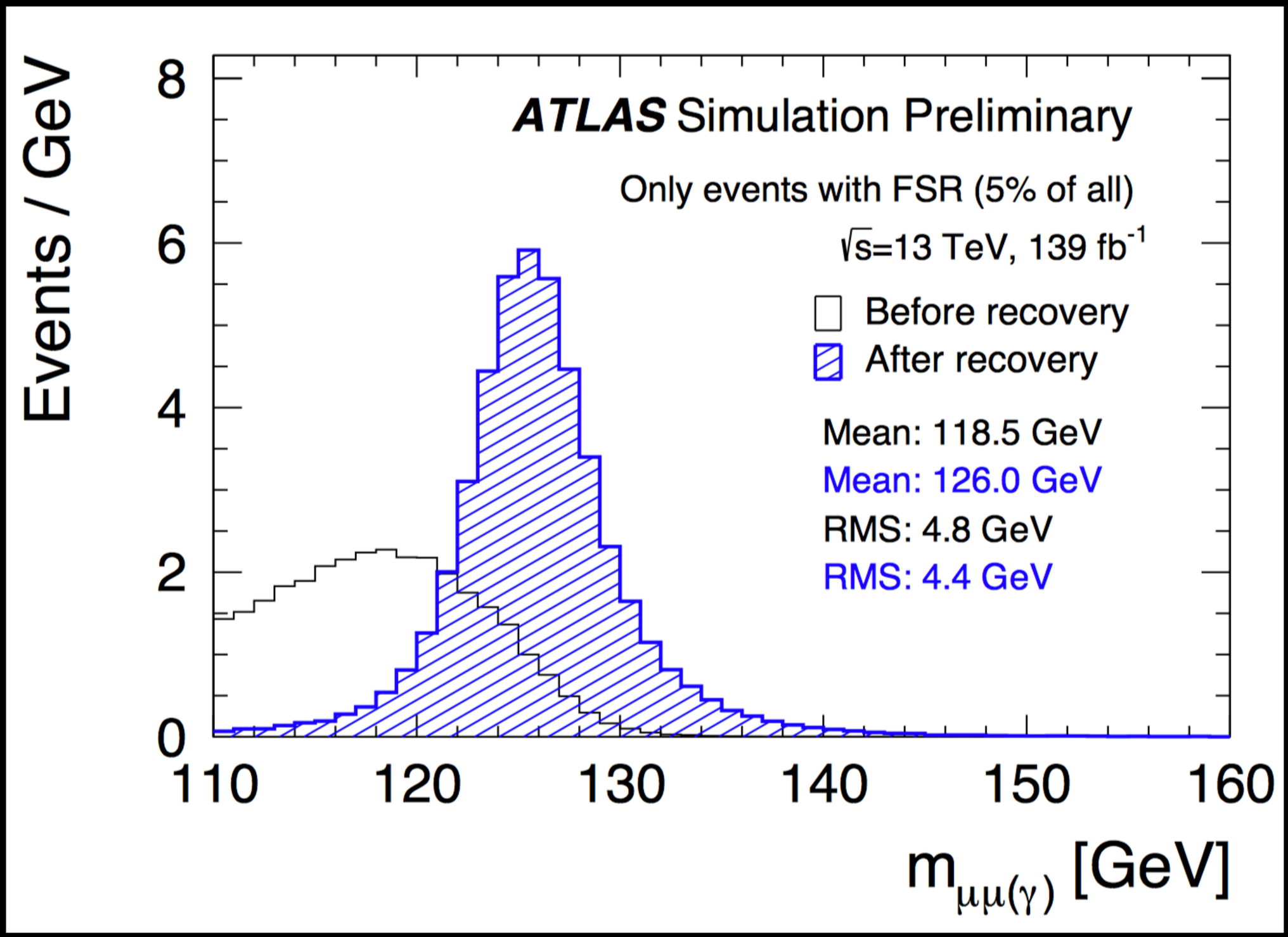
$Z \to \tau\tau$ Hybrid



Merge simulated and cleaned event.

Proton-proton collision dataset




ATLAS Simulation Preliminary
Only events with FSR (5% of all)
√s=13 TeV, 139 fb-1
Before recovery
After recovery
Mean: 118.5 GeV
Mean: 126.0 GeV
RMS: 4.8 GeV
RMS: 4.4 GeV
Events / GeV
0
2
4
6
8
110
120
130
140
150
160
mμμ(γ) [GeV]

Road map for H→bb discovery

- **Started in LEP era, developed in Tevatron, found at LHC**
- **H->bb observation in 2018 by ATLAS and CMS**
- **Top 10 highlight 2018 in American physics Society(APS)**