UNIVERSITÄT BONN
Rheinische
Friedrich-Wilhelms-
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SM Higgs Rare Processes

Tatjana Lenz

SUSY 2018, Barcelona

on behalf of ATLAS and CMS

ATLAS EXPERIMENT

CMS

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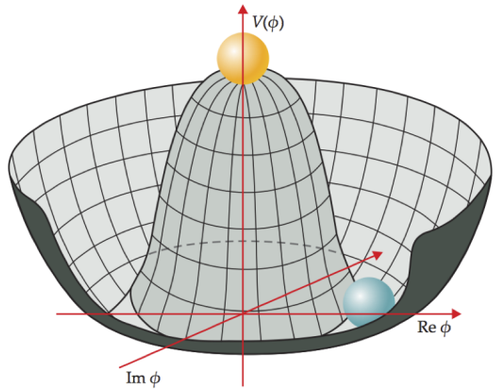
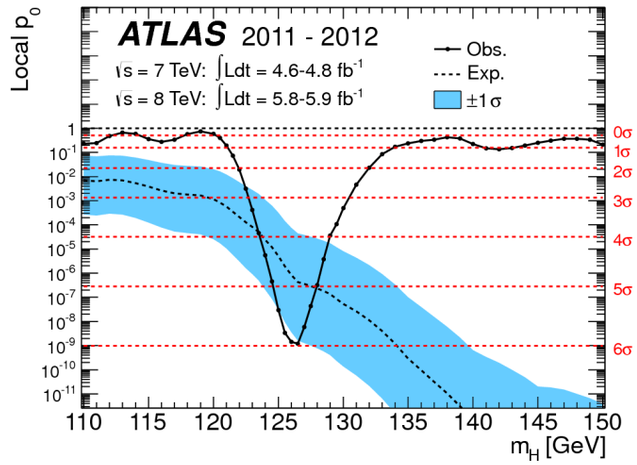
Why Study the Higgs Boson?

Unique role in the SM

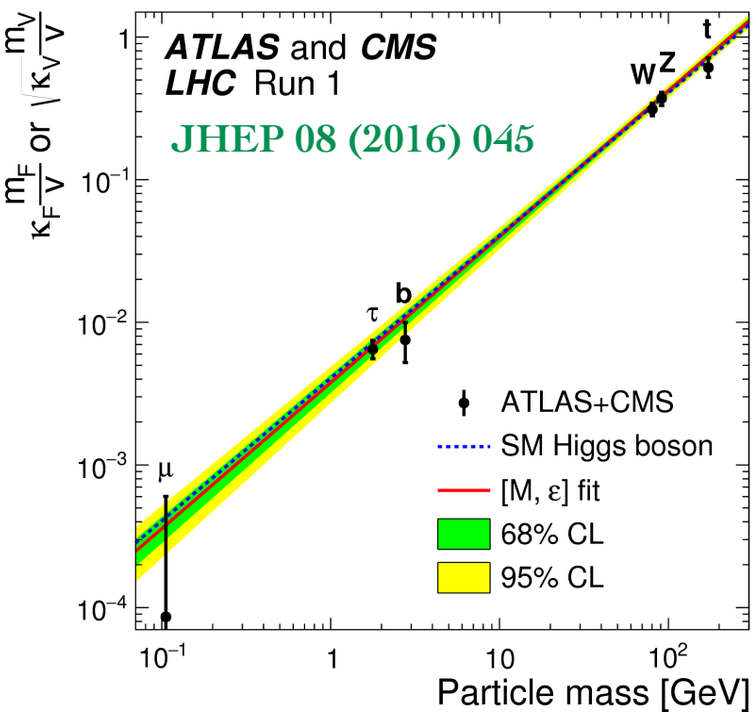
- only elementary scalar
- only field with a non-zero vev
- masses of particles via Higgs couplings





Open questions:

- the SM Higgs boson?
- responsible for masses of all particles?
- produced via top quark loops or BSM particles?
- and many other



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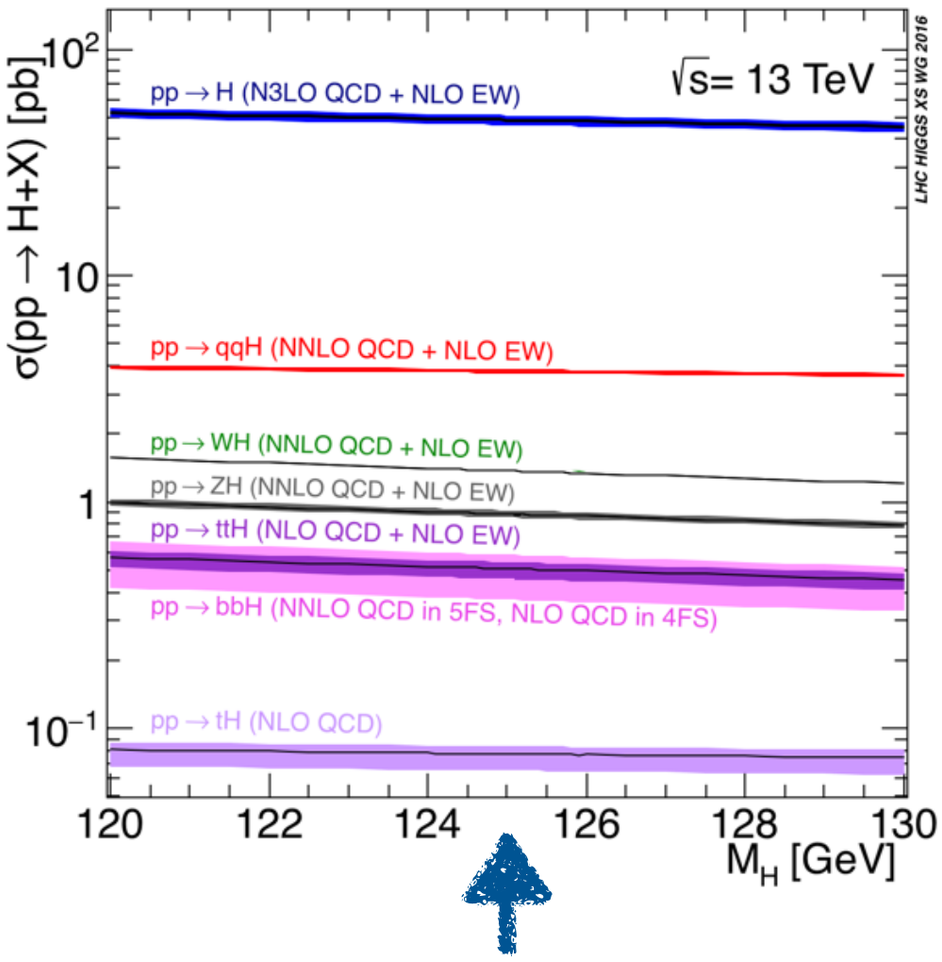
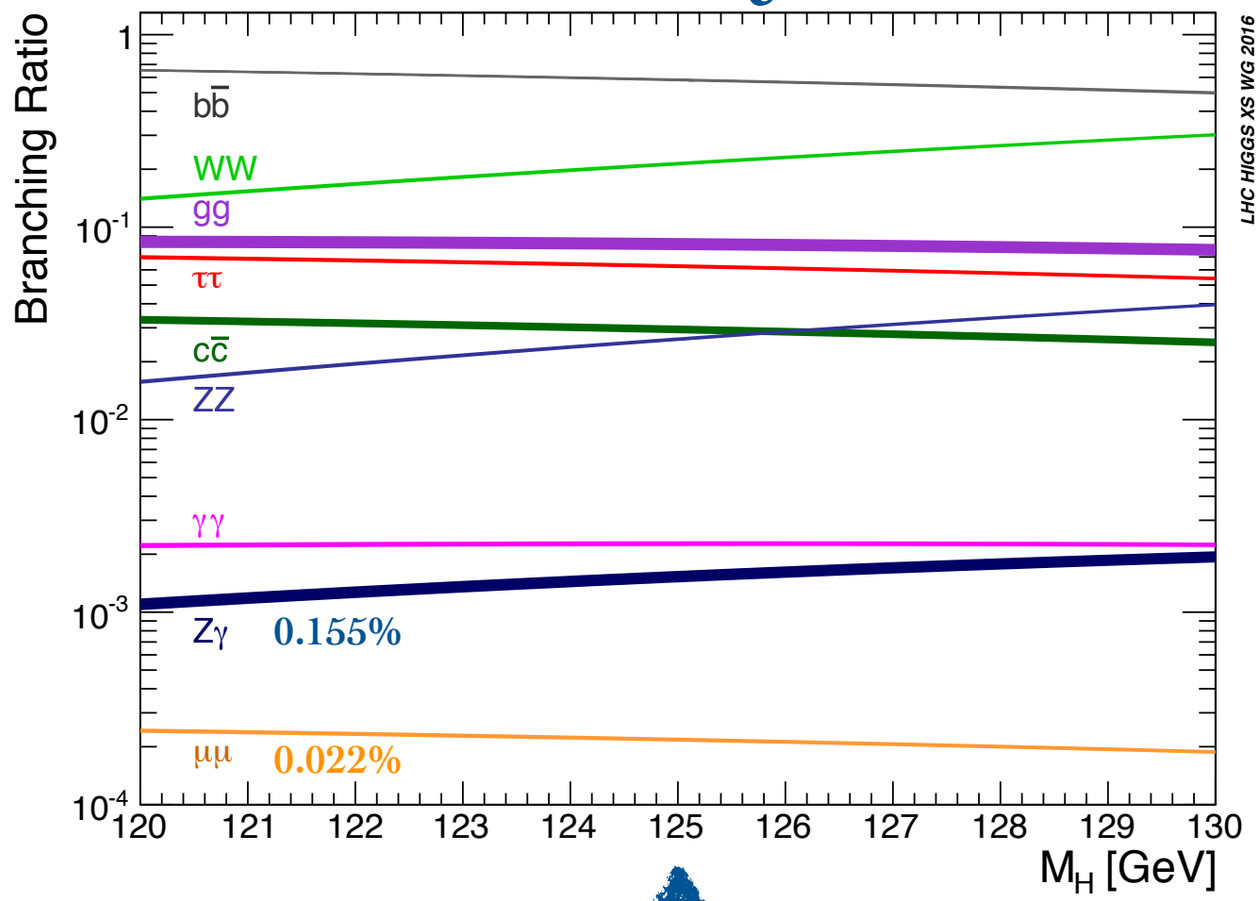
Higgs Boson Portrait

Production



Decay

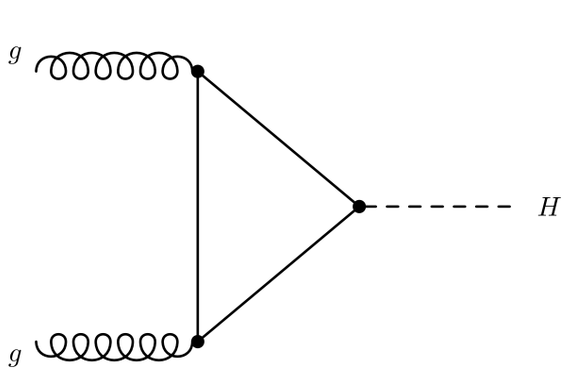


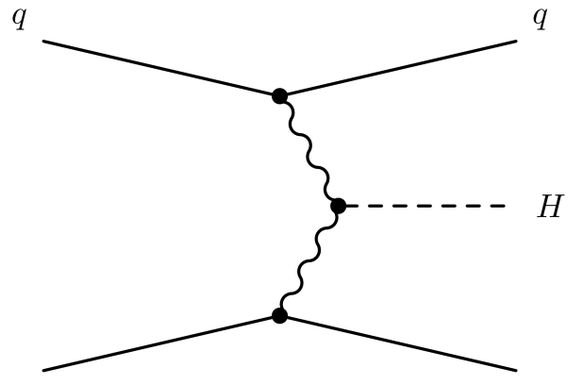
$gg \to H$ @ 86%

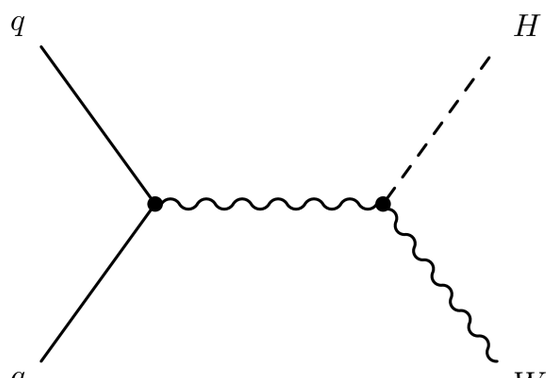
qqH @ 7%

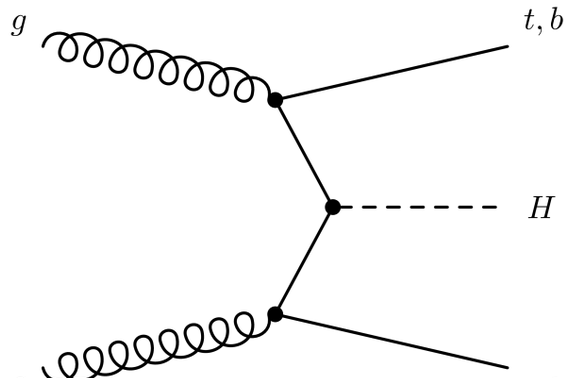
VH @ 5%

ttH @ 0.6%









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Higgs Boson Properties

Well-known properties:

- observation of all bosonic and ττ, bb fermionic couplings
- observation of VBF, ttH, VH ← new!!!
- (differential) cross section measurements
- couplings, spin and CP measurements
- precise measurement of H mass

SM-like Higgs boson!?

Topics of this Talk:

- Higgs rare decays
  - μμ, Z/γ, meson +γ, invisible
- Di-Higgs production

can deviate from the SM predictions and be enhanced as predicted in several BSM models

Rare Decays

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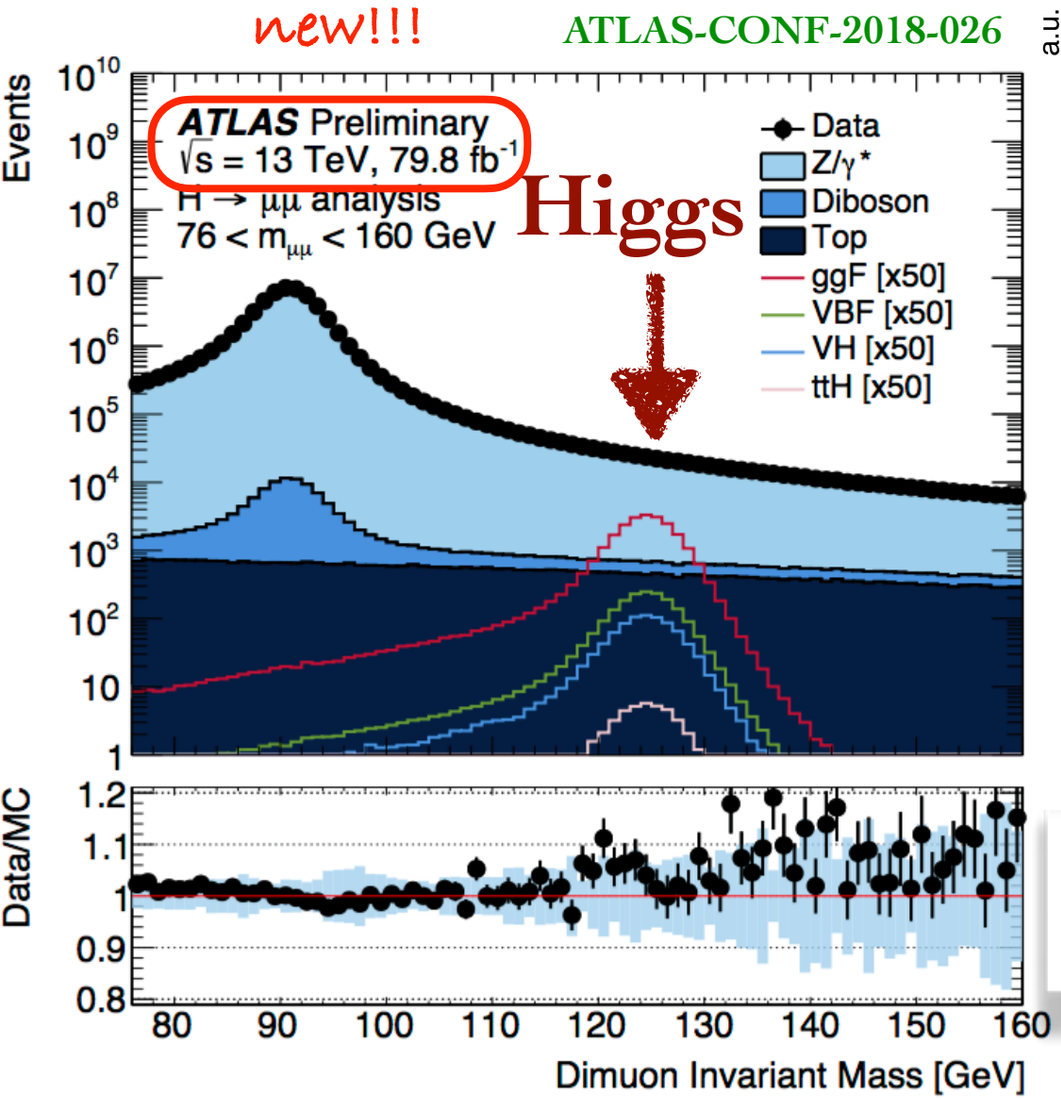
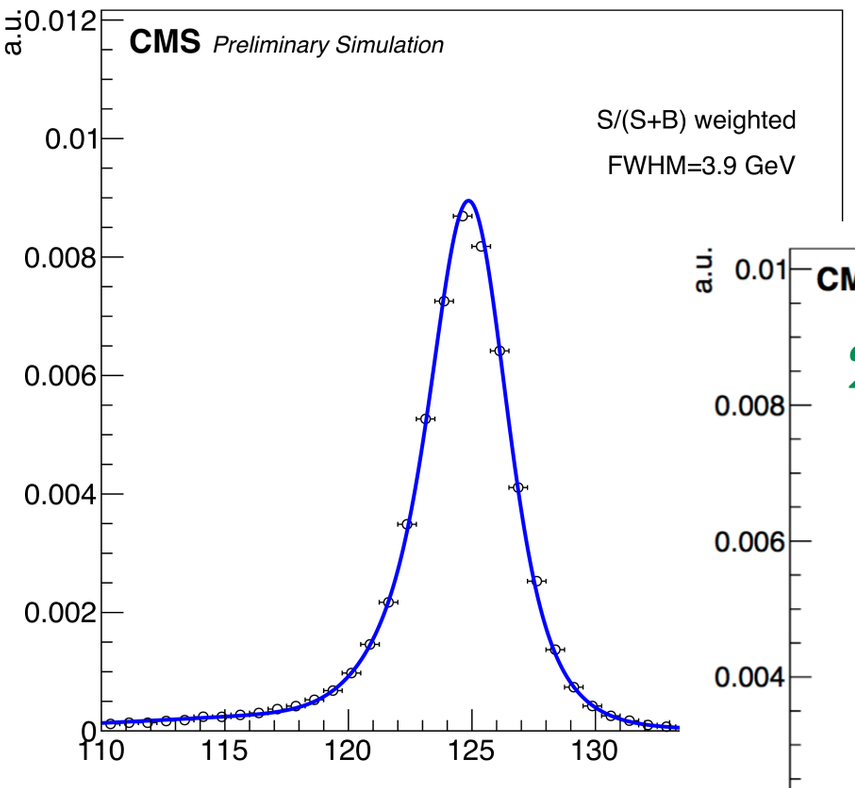
Muon Yukawa Coupling

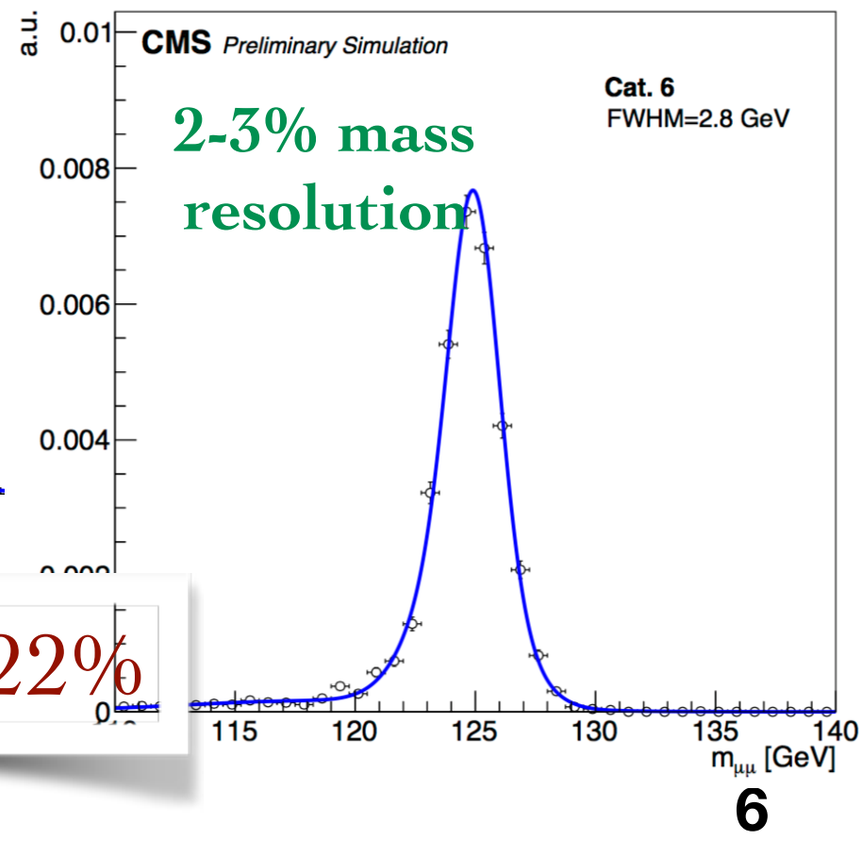
- most sensitive channel to observe coupling to the second generation
- small but narrow signal on a huge but smooth Drell-Yan background
  => requires excellent di-muon mass resolution

new!!! ATLAS-CONF-2018-026





CMS HIG-17-019



BR(H->μμ)=0.022%

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Analysis Strategy

- require 2 isolated opposite sign muons, veto b-jets
- categorise events based on S-B separation and muon p_T resolution
- signal and background described by analytic functions
- fit di-muon mass distribution in all categories

ATLAS

- BDT to separate in ***VBF tight***, ***VBF loose*** and ***ggF*** categories
- ggF category split in 6 sub-categories by muon η and di-muon pT

CMS

- BDT to separate signal and background
- 15 categories based on BDT score and largest |η| of two muons

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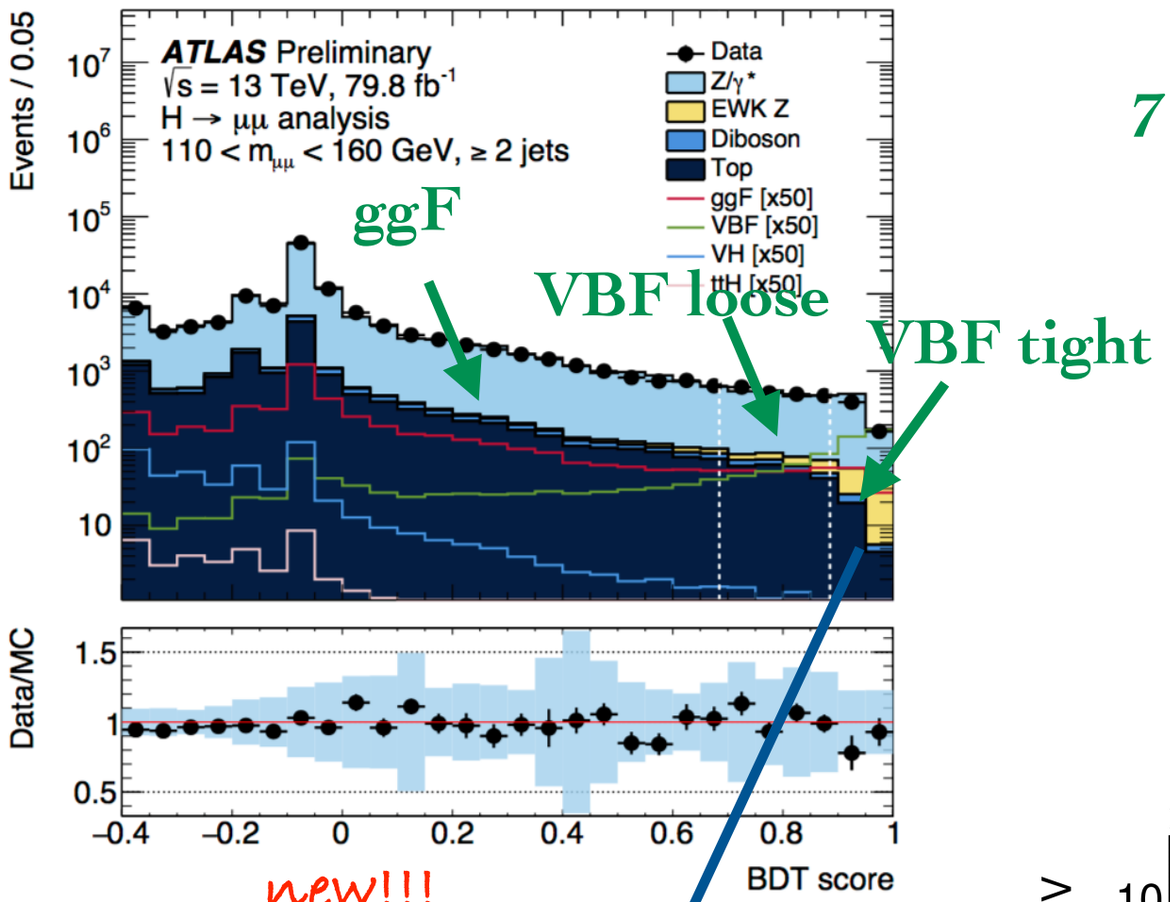
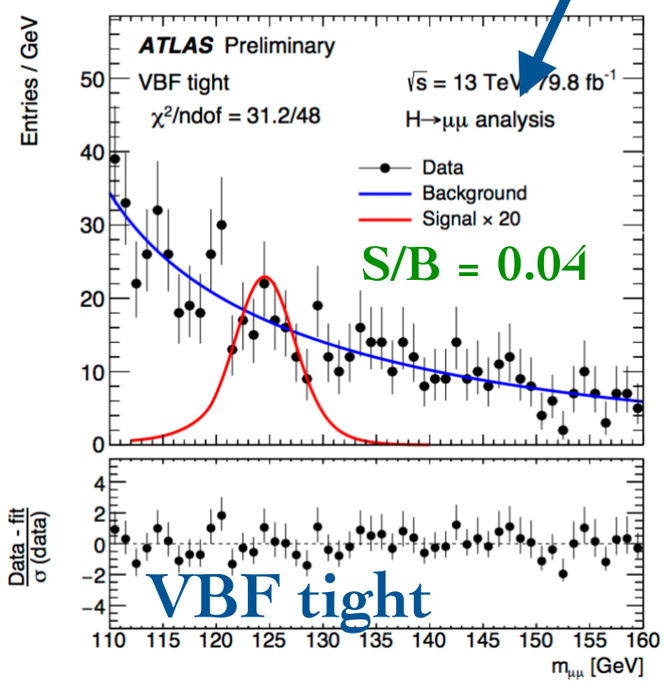
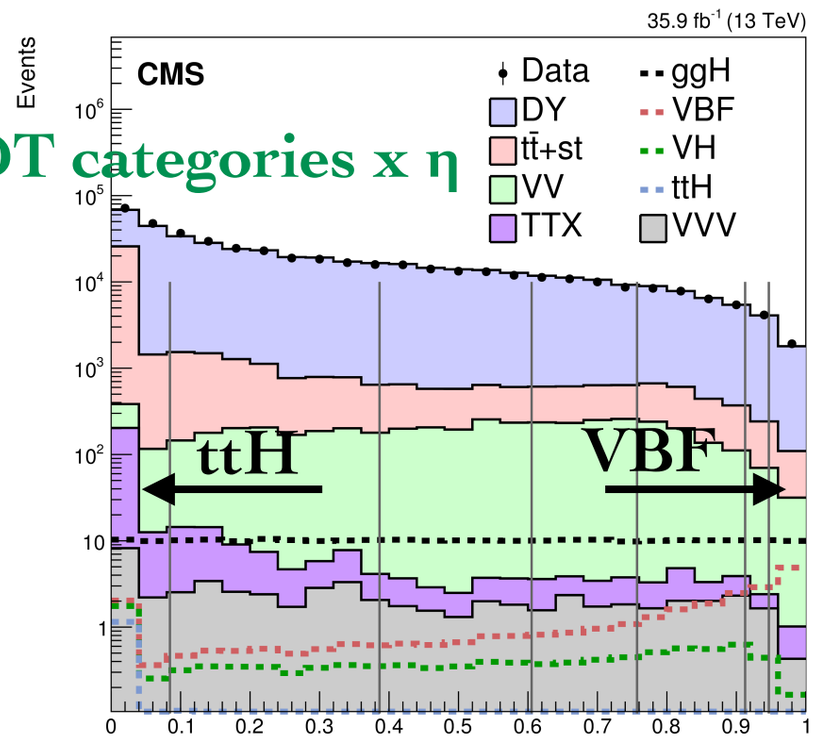
Distributions

ATLAS-CONF-2018-026

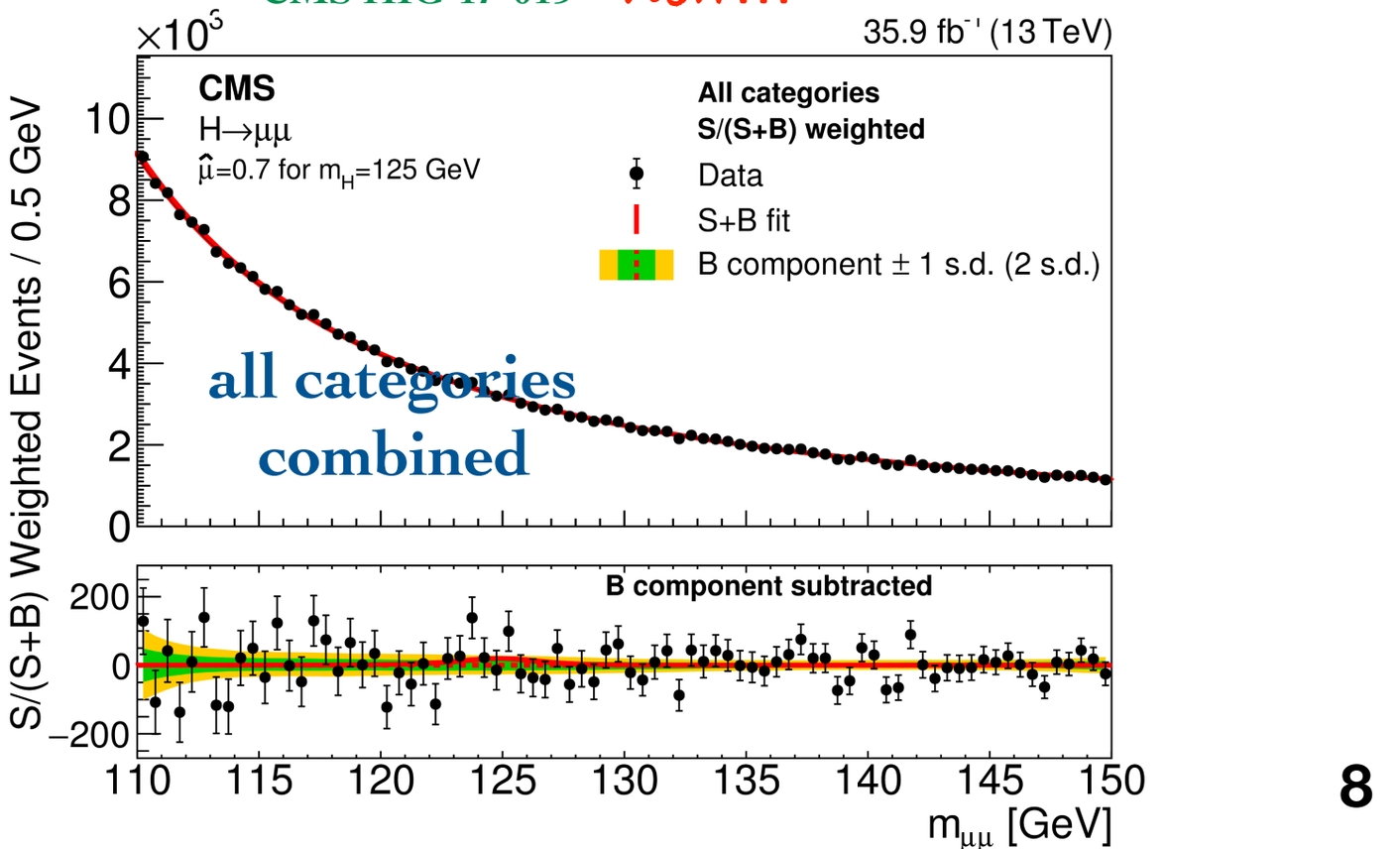




7 BDT categories x η



CMS HIG-17-019 new!!!



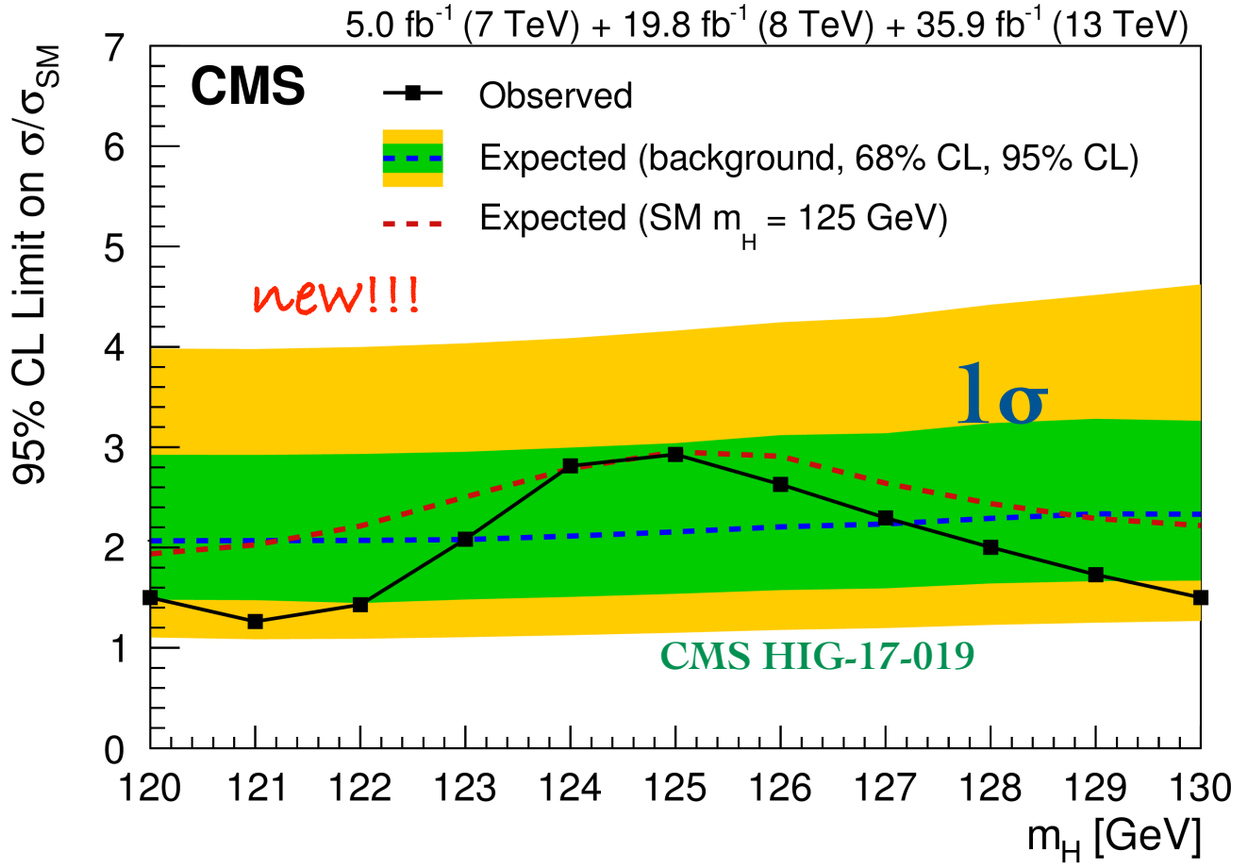
Results

ATLAS

- obs (exp) upper limit on signal strength
  $\mu < 2.1$ (2.0) at 95% CL (80/fb @ 13 TeV) new!!!

CMS

- obs (exp) upper limit on signal strength
  $\mu < 2.92$ (2.16) at 95% CL (61/fb @ 7/8/13 TeV)



Approaching SM sensitivity with Run-3 data (300/fb)
Observation at HL-LHC (3000/fb)

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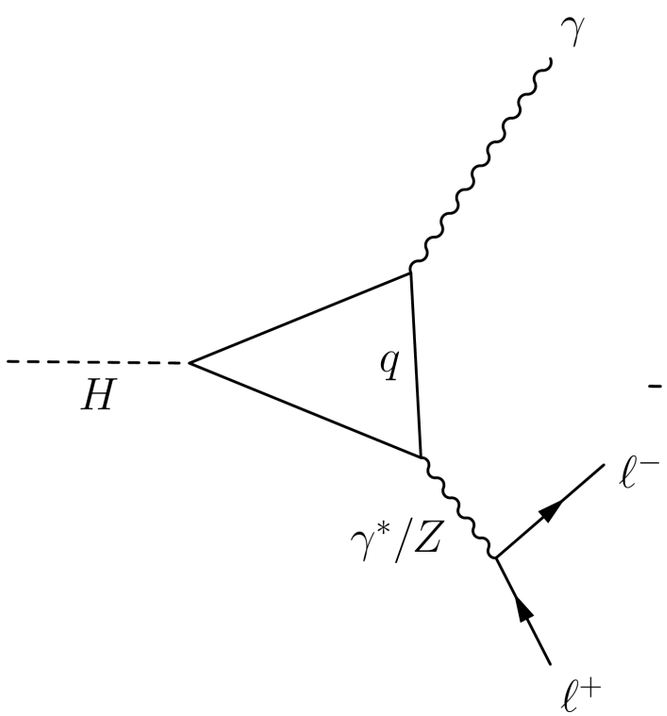
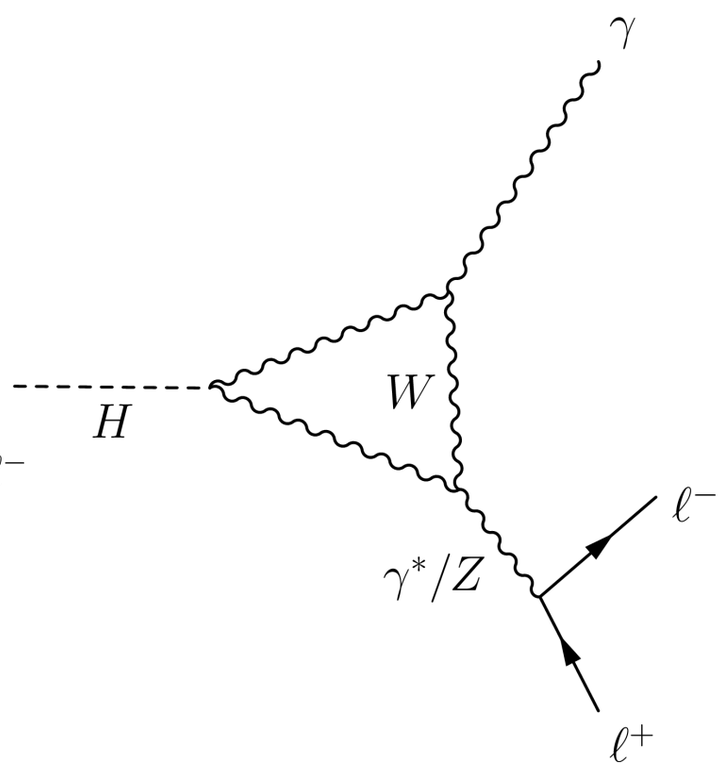
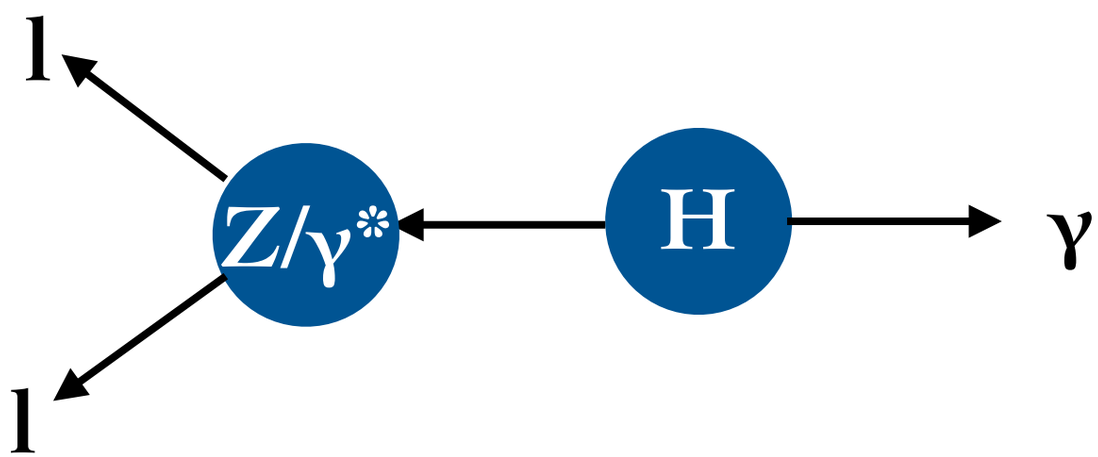
Higgs Boson to Z/γ* + γ

- similar to H -> γγ
  - loop-induced process, sensitive to new physics
- search performed in leptonic channels: eeγ or μμγ
- H -> γ*γ irreducible and interfere with Zγ
  - separate by a requirement on the dilepton mass
- signal extracted by fitting the m(llγ) spectrum
  - tiny peak above a falling background





BR(H->Z+γ)=0.115%



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Analysis Strategy

- same flavour, opposite-charge leptons and a photon
- multiple event categories to enhance signal sensitivity

ATLAS

- m(ll) > 45 GeV for Z(->ee/μμ)γ
- kinematic fit to improve the invariant Z mass resolution
- Z->μμ events corrected for collinear FSR

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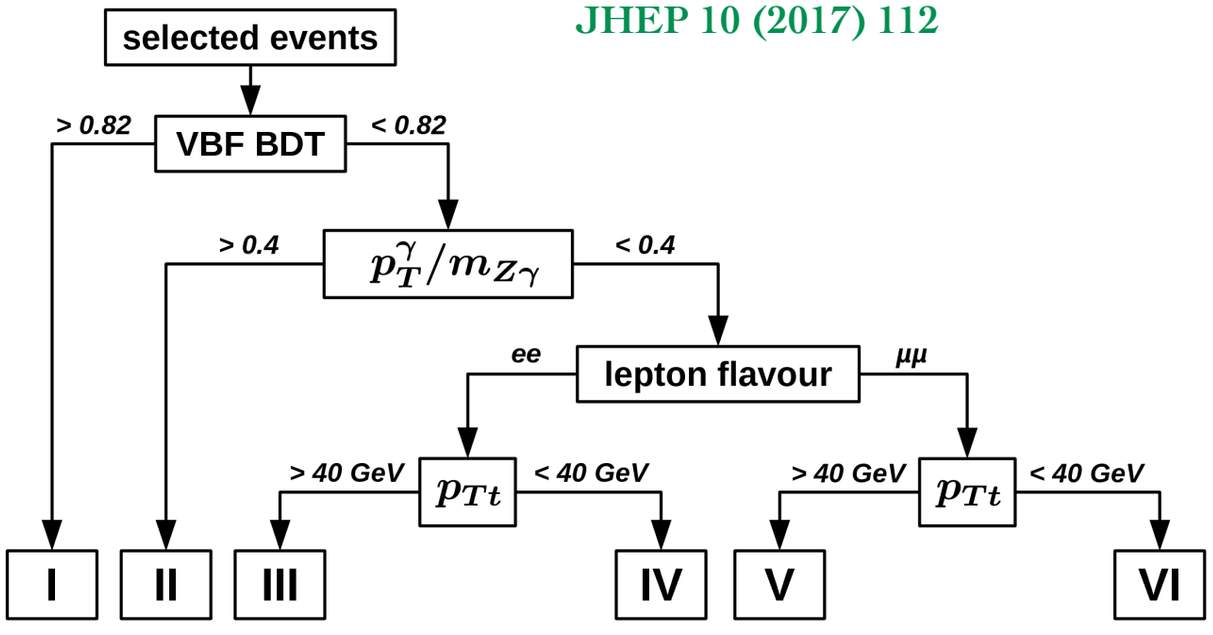

CMS

- m(ll) > 50 GeV for Z(->ee/μμ)γ
- m(ll) < 50 GeV for γ*(->μμ)γ
- high m(ll) categories:
  - VBF
  - VH
  - boosted
  - untagged based on e, μ, γ energy resolution
- low m(ll) categories:
  - VBF
  - untagged based on γ energy resolution

CMS-HIG-17-007

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Distributions

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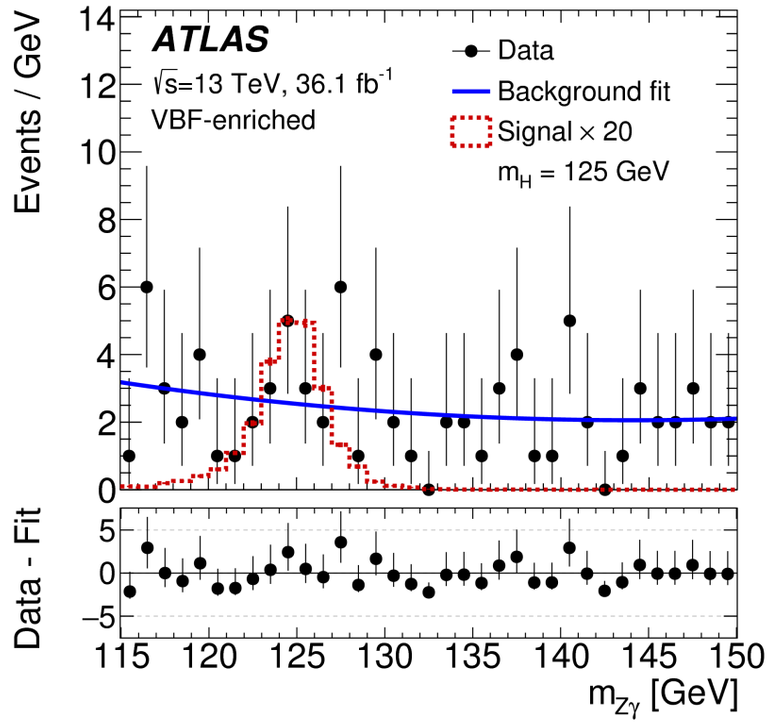

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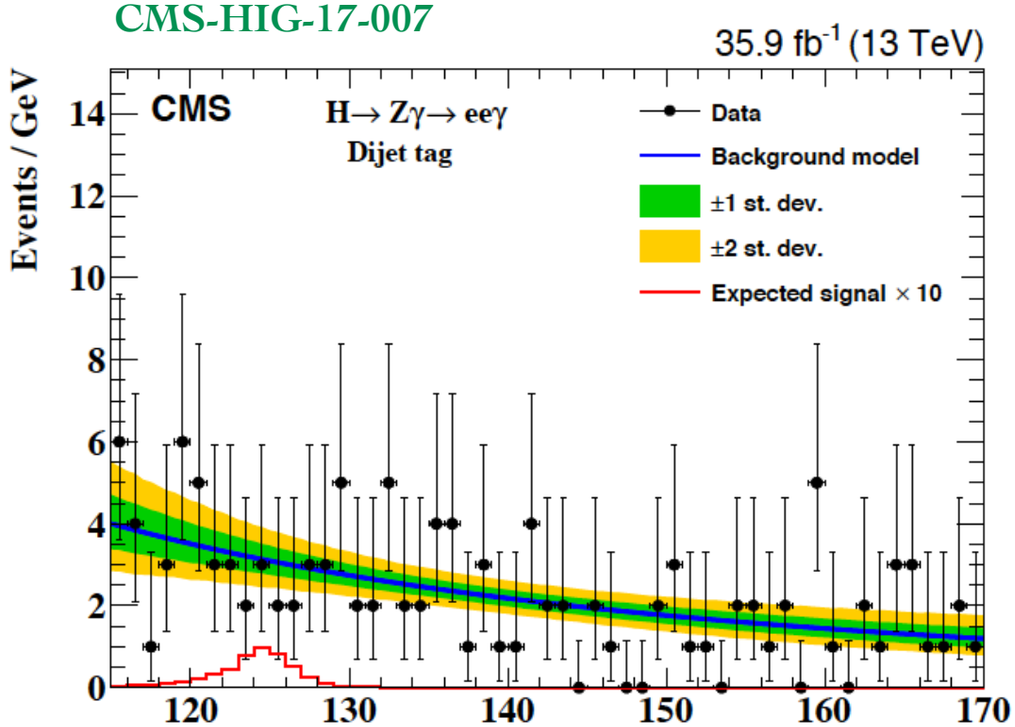

Background fit functions vary per category

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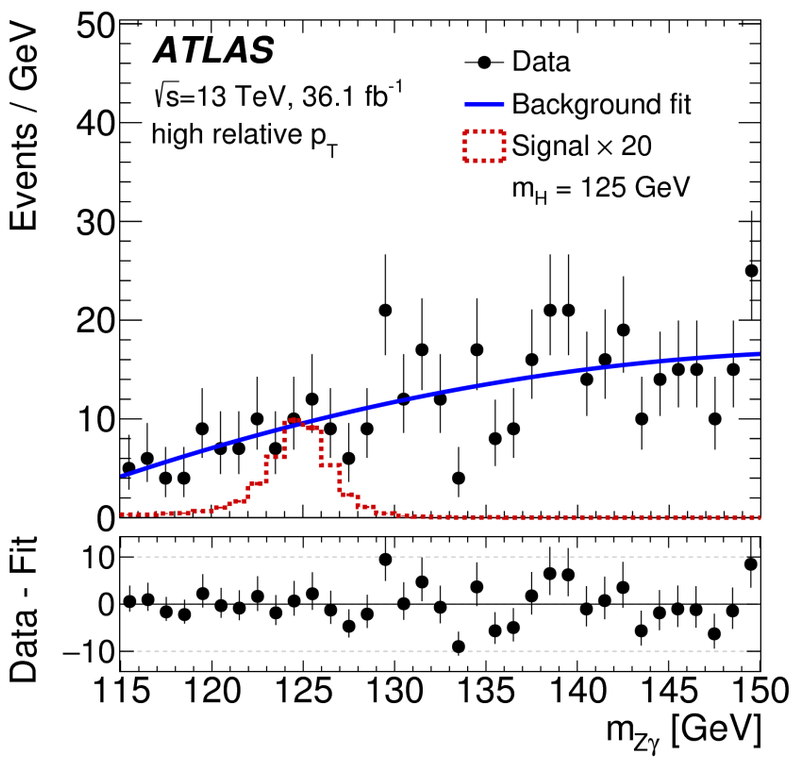

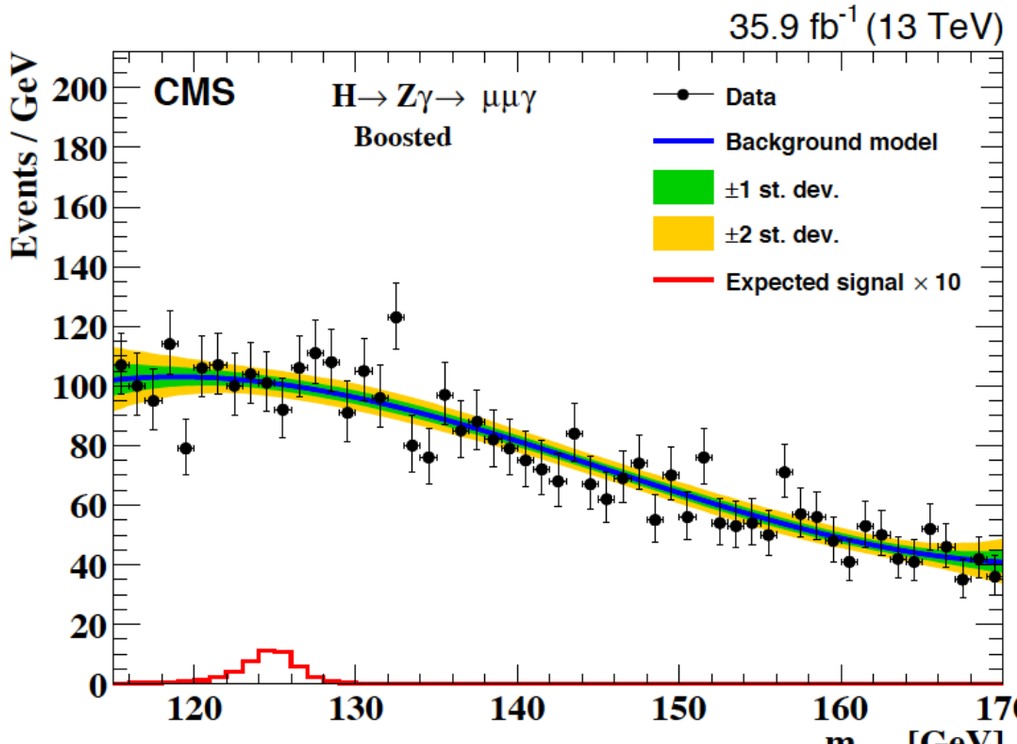

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Results

ATLAS

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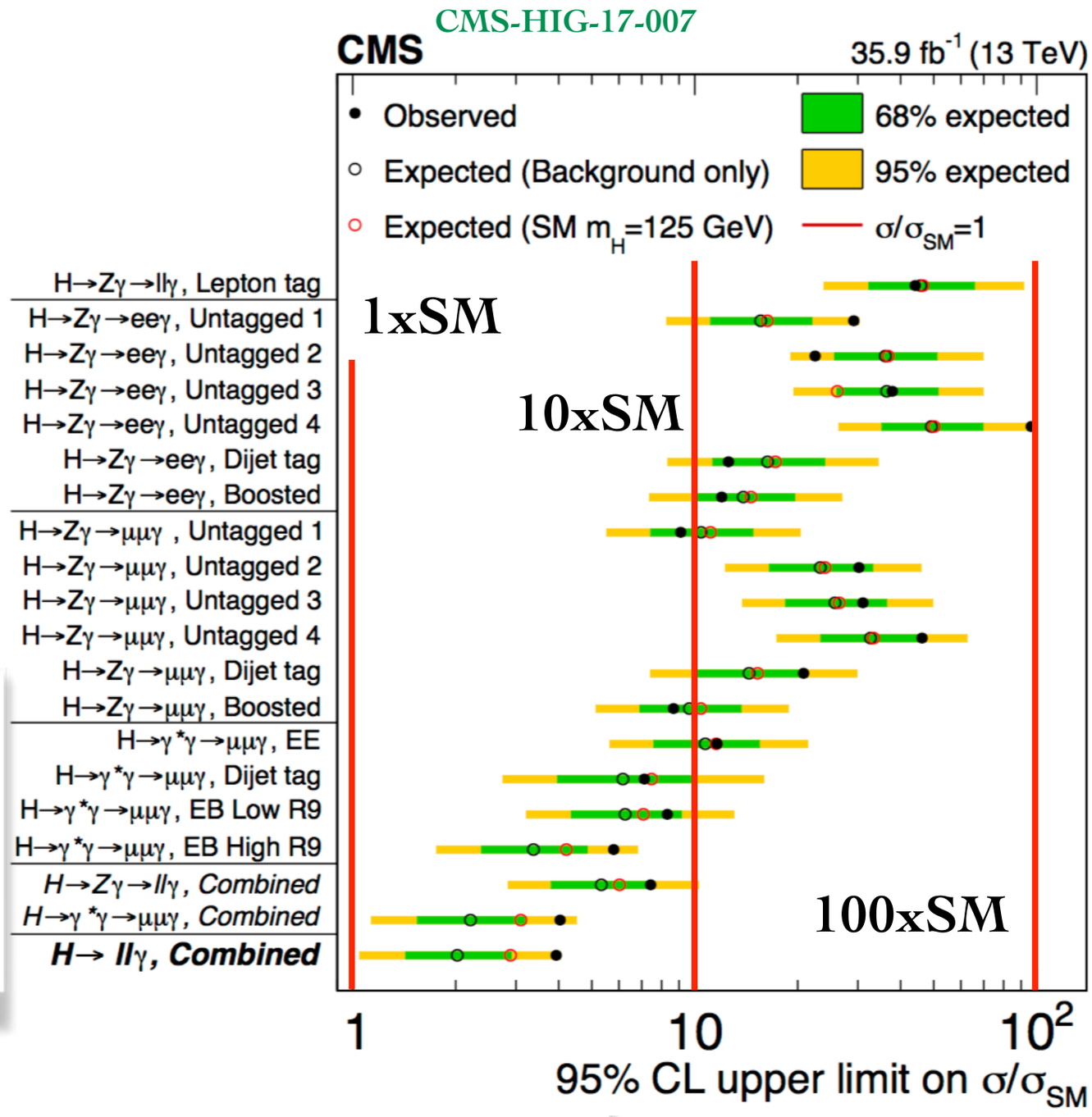
obs (exp)
BR(H->Zγ) < 6.6(4.4)xSM

CMS

obs (exp)
BR(H->Zγ) < 8.0(5.8)xSM
BR(H->γ*γ) < 4.0(2.2)xSM

CMS-HIG-17-007



HL-LHC to reach the SM sensitivity

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Higgs Boson to Meson + γ

- test **light (u,d,s) quark couplings** to SM Higgs:

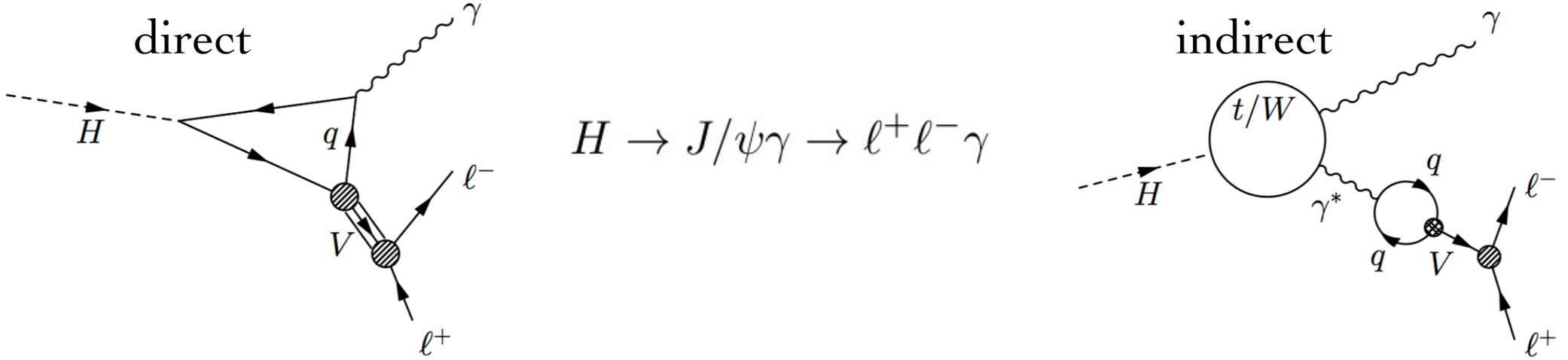
$$\mathcal{BR}(H \to \rho\gamma) = 1.7 \cdot 10^{-5}$$

$$\mathcal{BR}(H \to \phi\gamma) = 2.3 \cdot 10^{-6}$$

- test **bottom and charm quark couplings** to SM Higgs:

$$\mathcal{BR}(H \to J/\psi\gamma) = 2.8 \cdot 10^{-6}$$

$$\mathcal{BR}(H \to \Upsilon(1S, 2S, 3S)\gamma) = (6.1, 2.0, 2.4) \cdot 10^{-10}$$



- search for enhanced Higgs couplings
- triggers and background estimate techniques from B-physics

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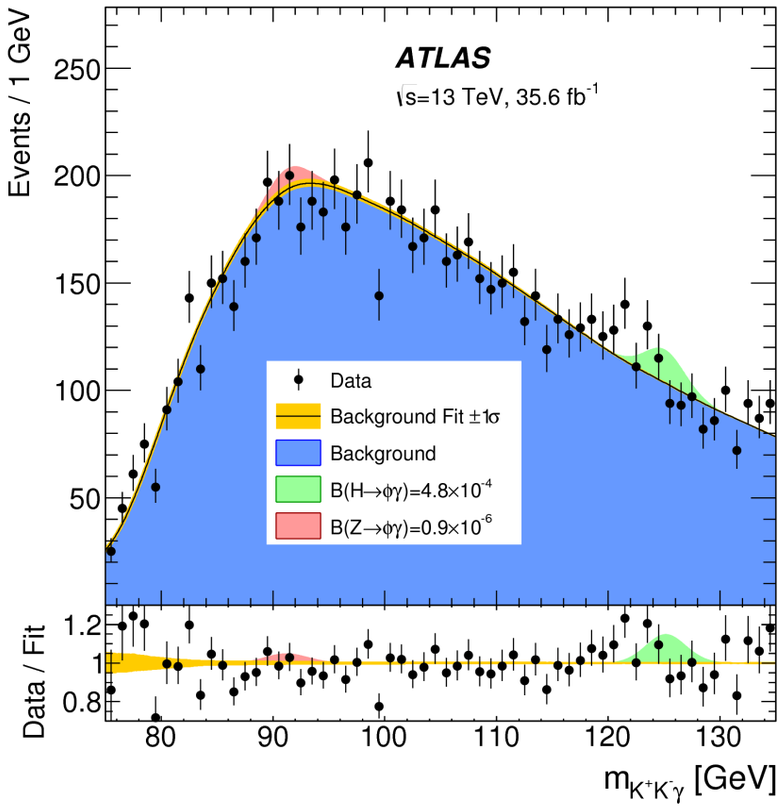
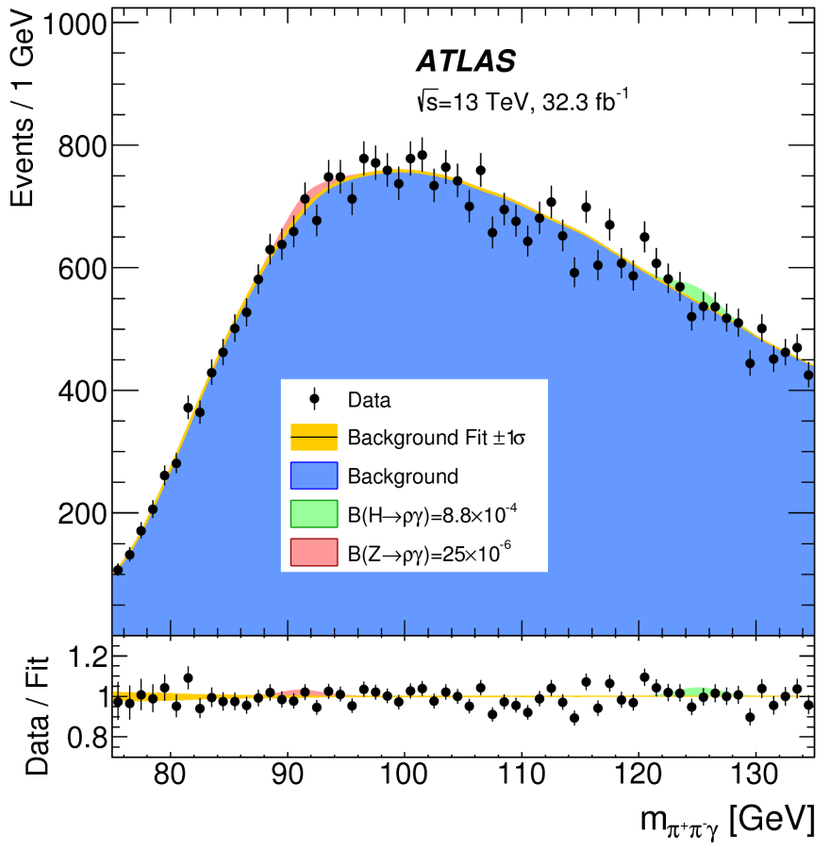
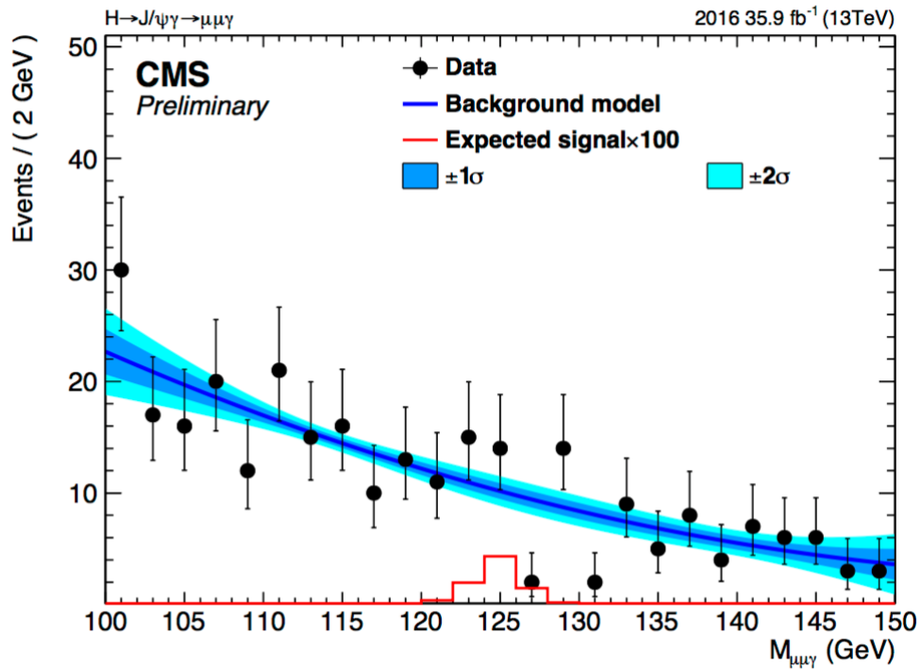
Results

HIGG-2016-13





CMS-SMP-17-012



$\mathcal{BR}$ Limit (95%)	ATLAS Observed
$\mathcal{BR}(H \to \phi\gamma)[10^{-4}]$	4.8 (52× SM)
$\mathcal{BR}(H \to \rho\gamma)[10^{-4}]$	8.8 (208× SM)
$\mathcal{BR}(H \to J/\psi\gamma)[10^{-3}]$	1.5 (536× SM)
$\mathcal{BR}(H \to \Upsilon(1S,2S,3S)\gamma)[10^{-6}]$	1.3,1.9,1.3

Run-2

Run-1

CMS Observed
Run-2
220xSM

stronger limits on charm coupling from H->cc

HIGG-2017-01

difficult at LHC …

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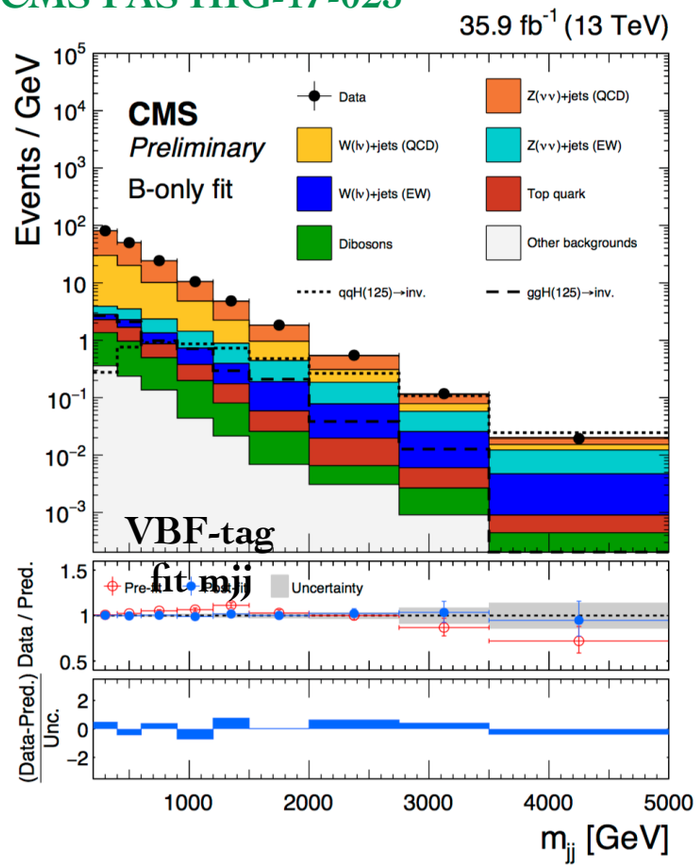
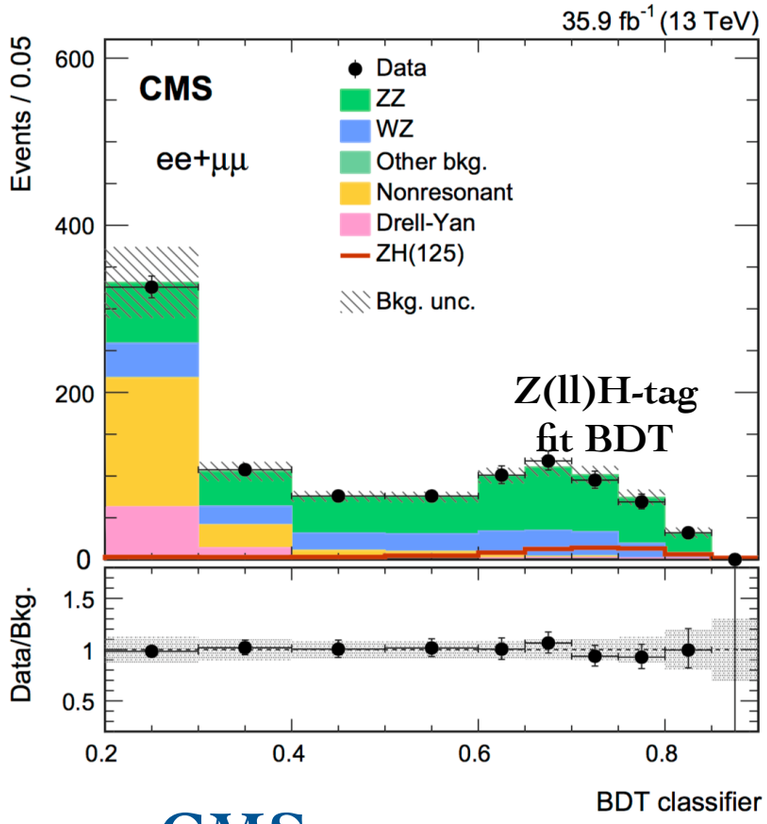
Higgs Boson to νν

- SM decays to invisible particles via H->ZZ*->4ν (BR~0.1%)
- plenty of room for couplings to a new hidden dark sector

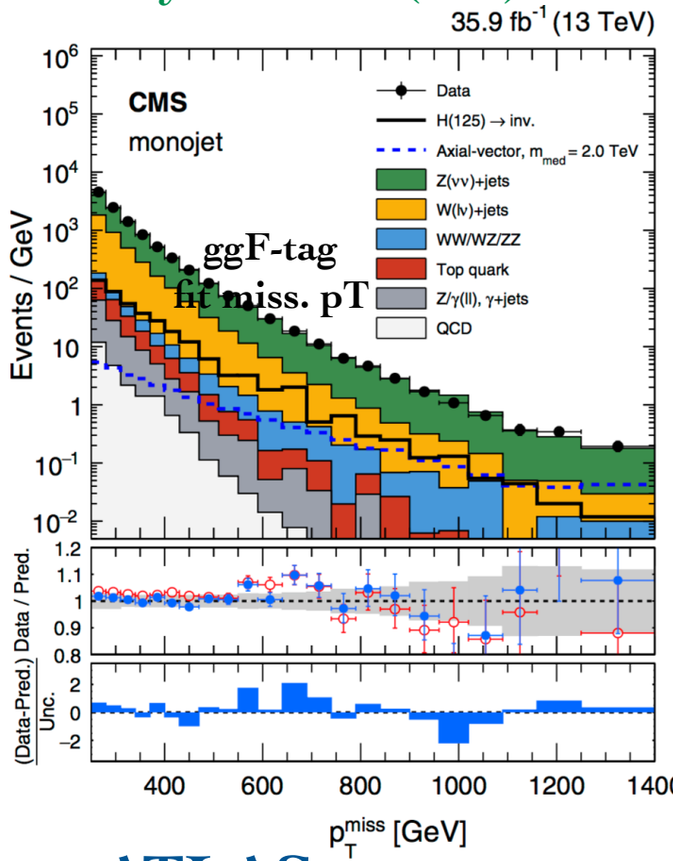
CMS PAS HIG-17-023



Eur. Phys. J. C 78 (2018) 291



Phys. Rev. D 97 (2018) 092005



CMS

VBF-tag: < 28 (21) %
VH-tag, V -> ll: < 40 (42) %
VH-tag, V -> qq: < 50 (48) %
ggF-tag: < 64 (58) %

combined: < 24 (18) %

ATLAS

Run 2 ZH: < 67 (39) %

Run 1 VBF+VH: < 25 (27) %

PLB 776 (2017) 318

JHEP11(2015)206

95% CL on BR(H-> inv): Obs (Exp)

indirect from couplings measurement: < 22% (measured μ = 1.17)

Higgs Self-Coupling

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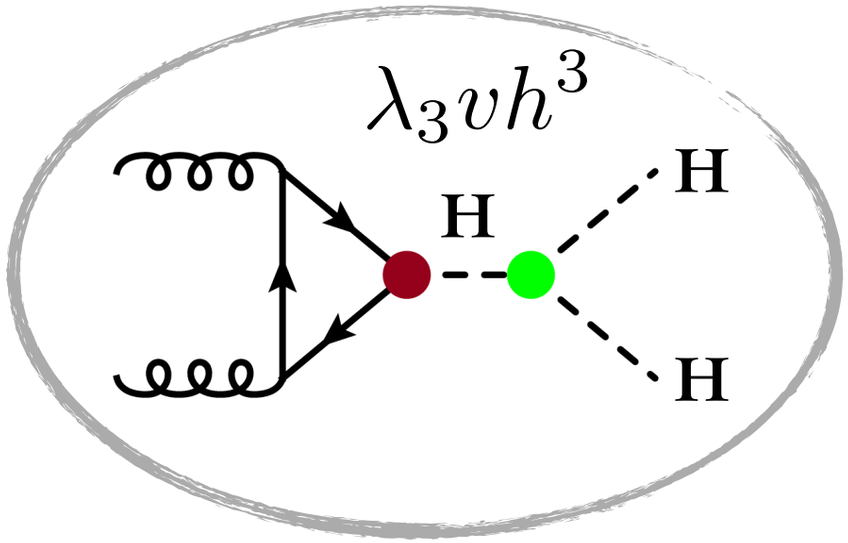
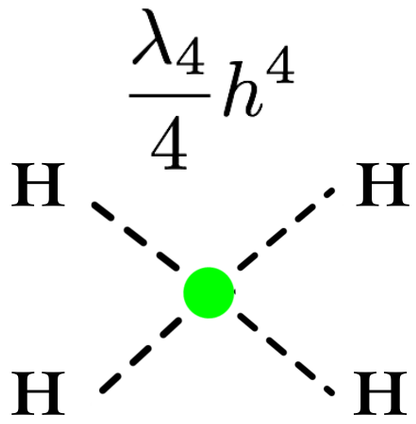
Higgs Self-Coupling

- **HH production** allows a direct test of Higgs potential and Higgs self-coupling

$$V(h) = \frac{m_h^2}{2}h^2 + \lambda_3 v h^3 + \frac{\lambda_4}{4}h^4 \qquad \text{SM: } \lambda_3 = \lambda_4 = \lambda = \frac{m_h^2}{2v^2}$$





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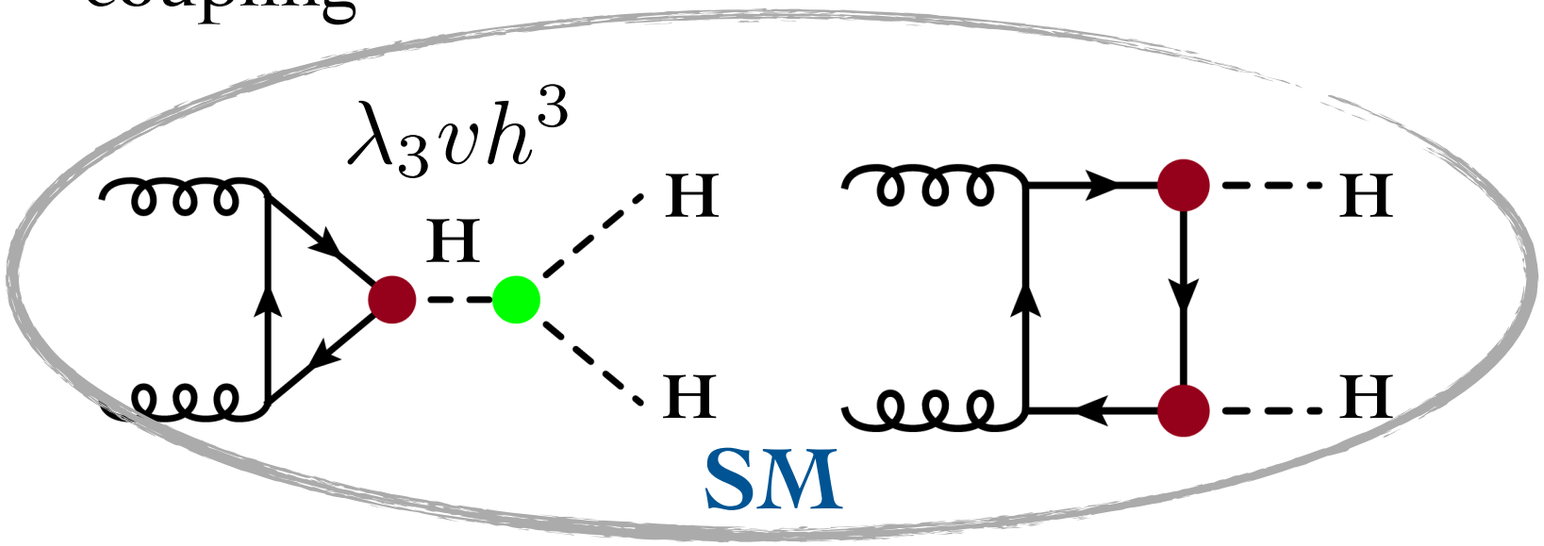
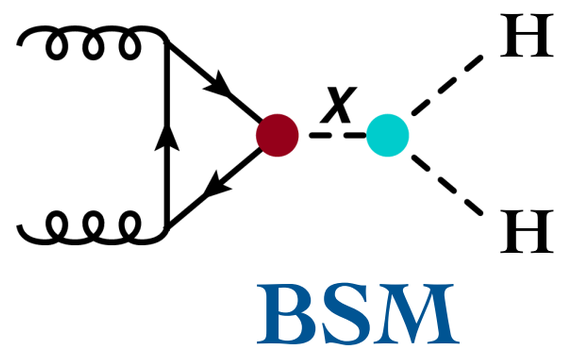
Higgs Self-Coupling

- **HH production** allows a direct test of Higgs potential and Higgs self-coupling





- **SM HH production** cross section 1000 times smaller than pp → H
  - two diagrams with **destructive interference**
- **BSM** can lead to enhancement in the HH production
  - **non-resonant** production due to modified λ, new vertices or new particles in the loop
  - **resonant** production modes: KK gravitons, H in 2HDM, new scalar singlets, cross sections up to O(pb)

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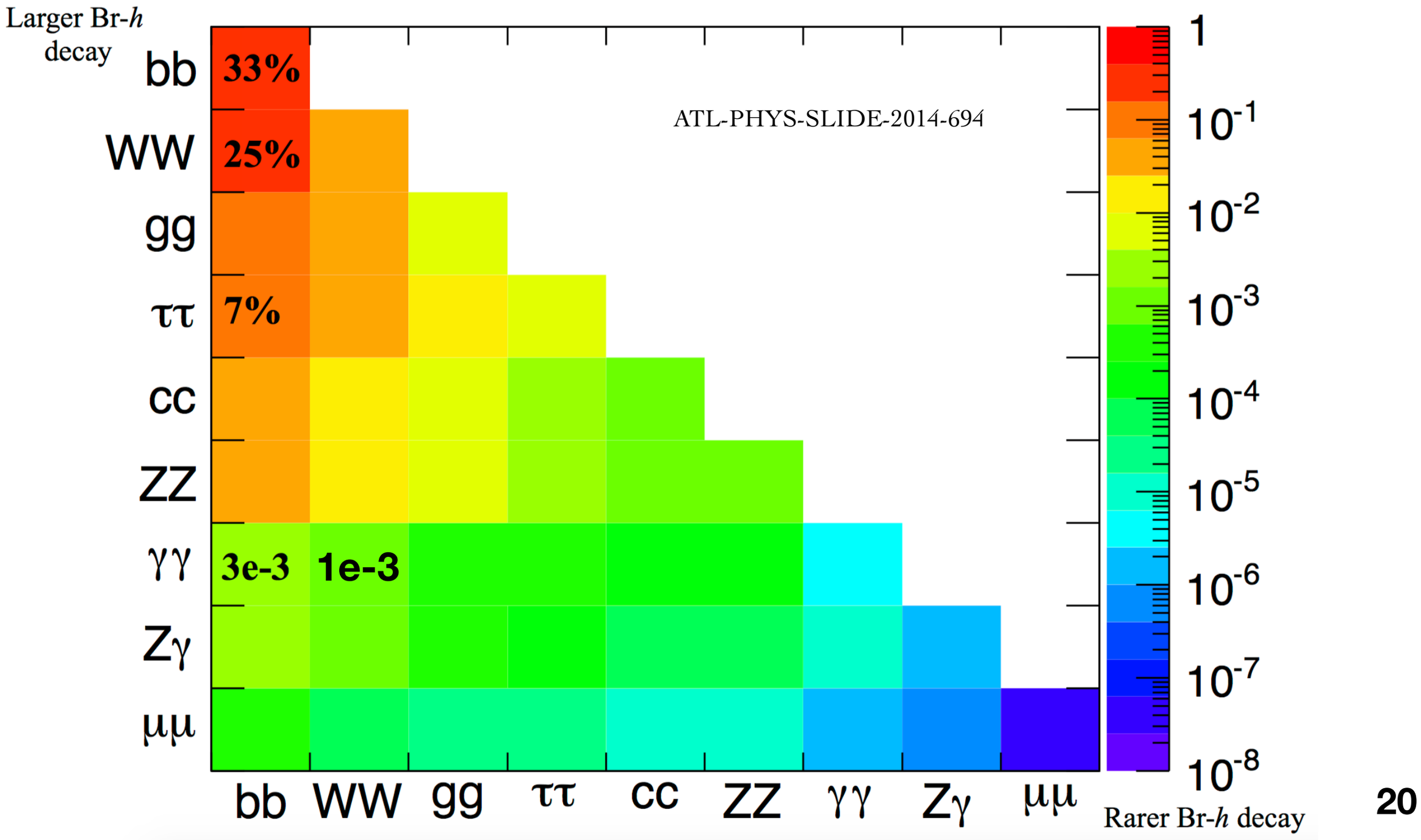
HH Decay Modes

most promising channels at LHC: 4b, bbττ and bbγγ



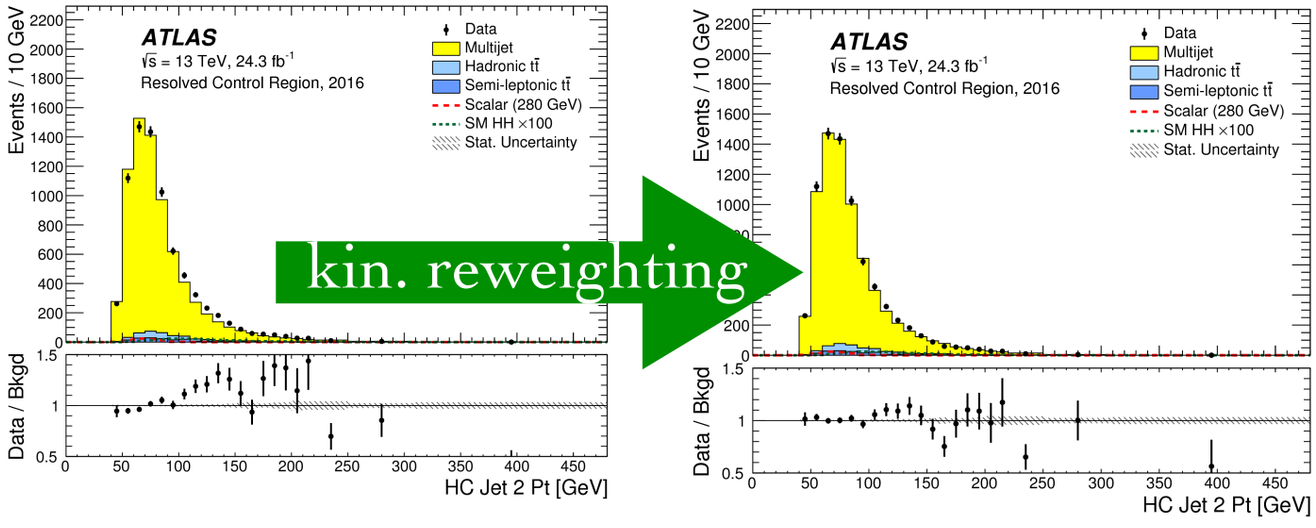
HH 4b

- key element: excellent b-tagging to reconstruct 4 b-jets
- main background: multijets
- Higgs candidates are 2 di-b-jet pairs with the smallest mass difference

ATLAS

- take from data in 4-jet, 2-btag signal region and reweight comparing 2-btag and 4-btag distributions in the sideband region

arXiv:1804.06174



CMS

- BDT to separate signal and bkg
- hemisphere mixing technique on data events with 4 b-jets to provide samples for BDT training and application

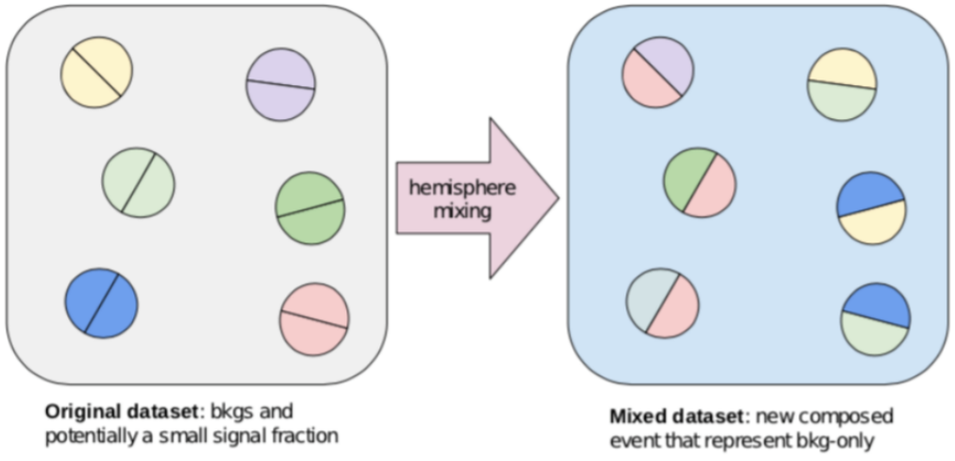


fig. from C. Vernieri

- modelling is validated using 4b-mass sidebands

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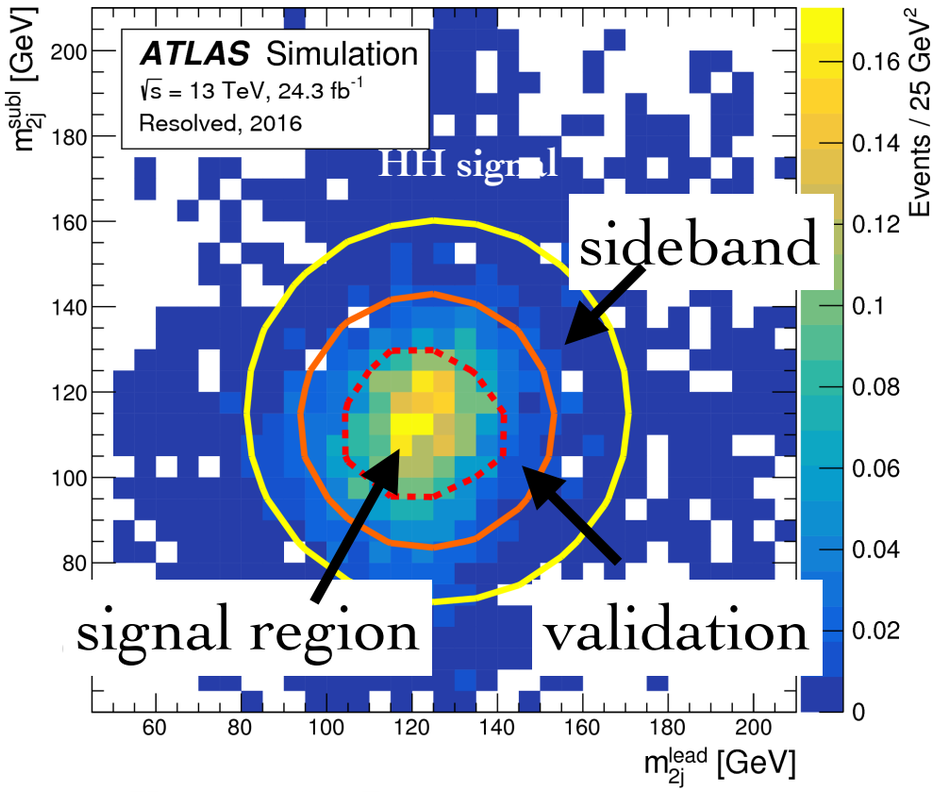
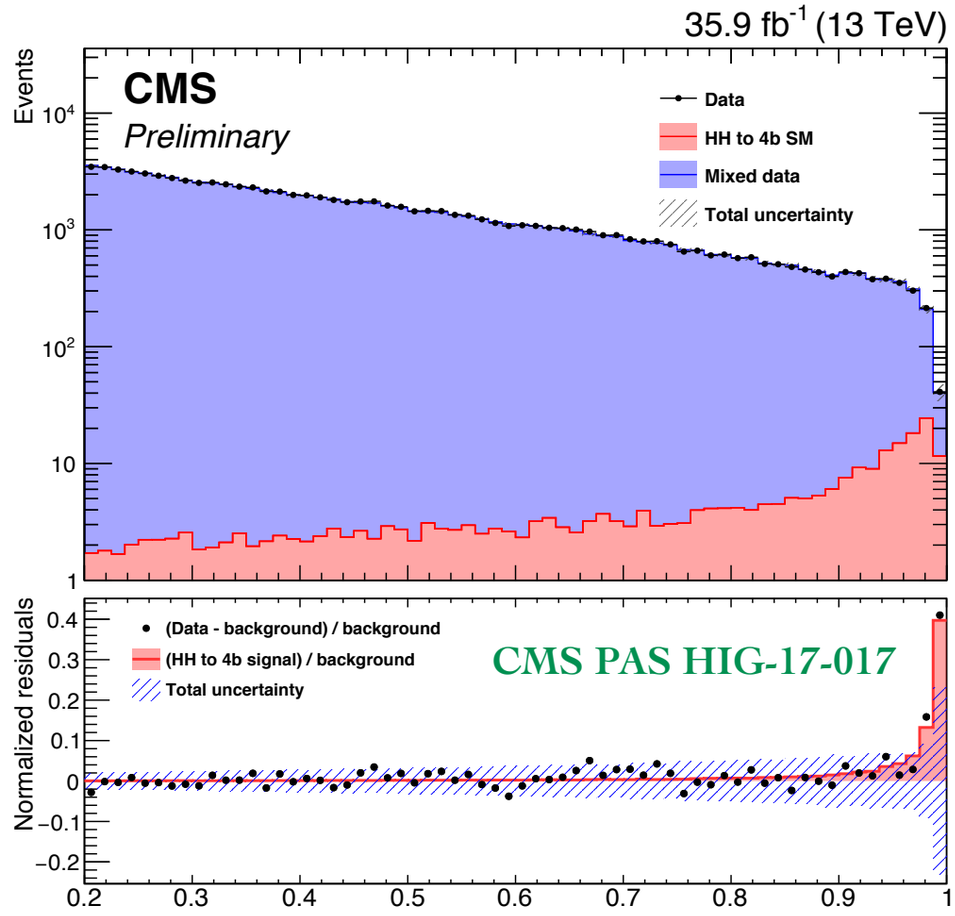
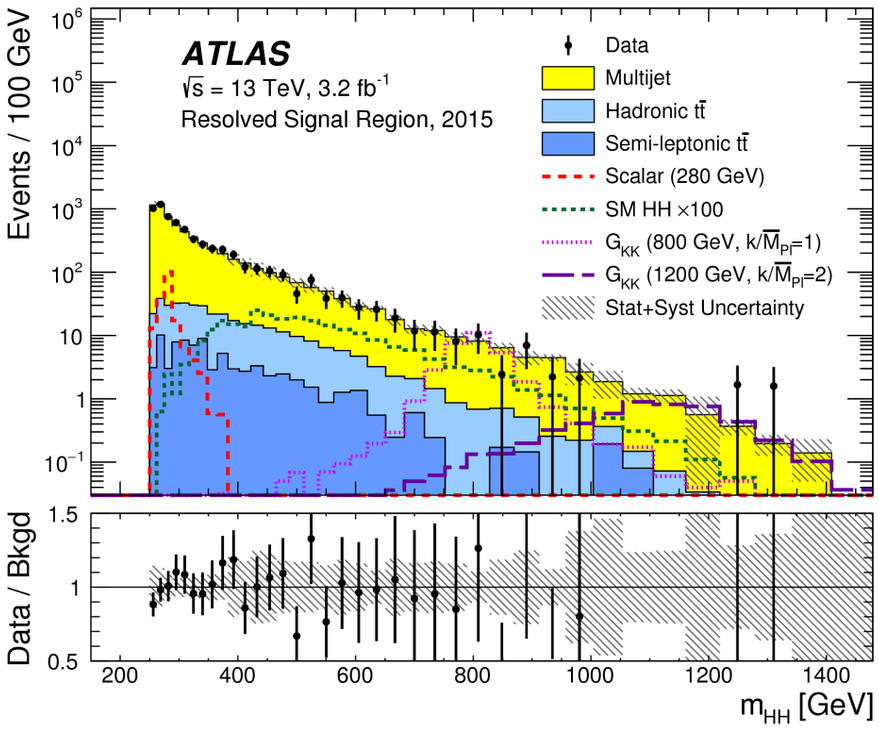
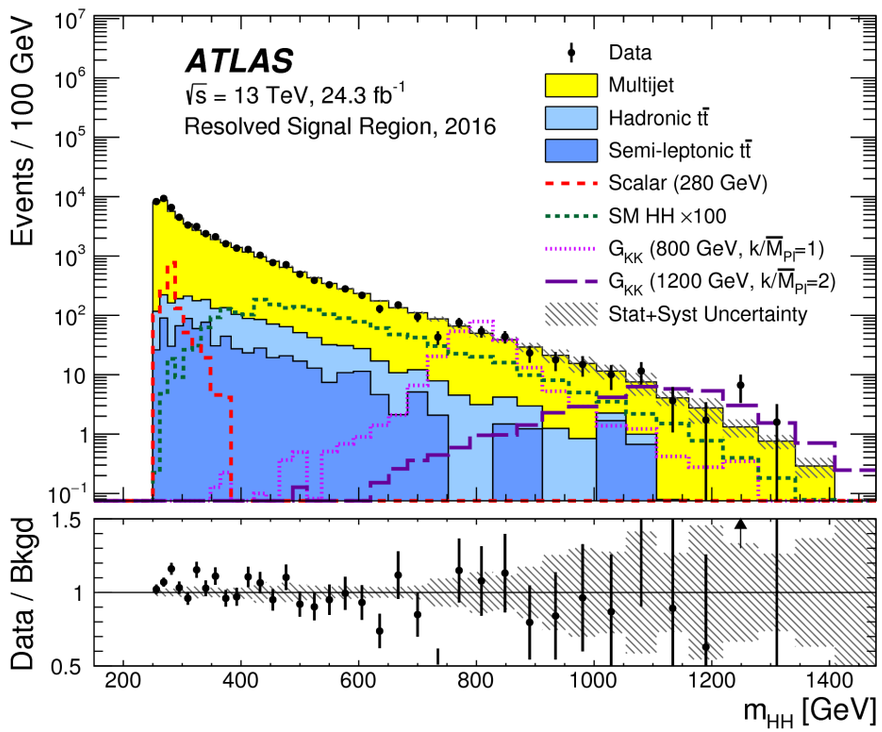
Distributions



arXiv:1804.06174







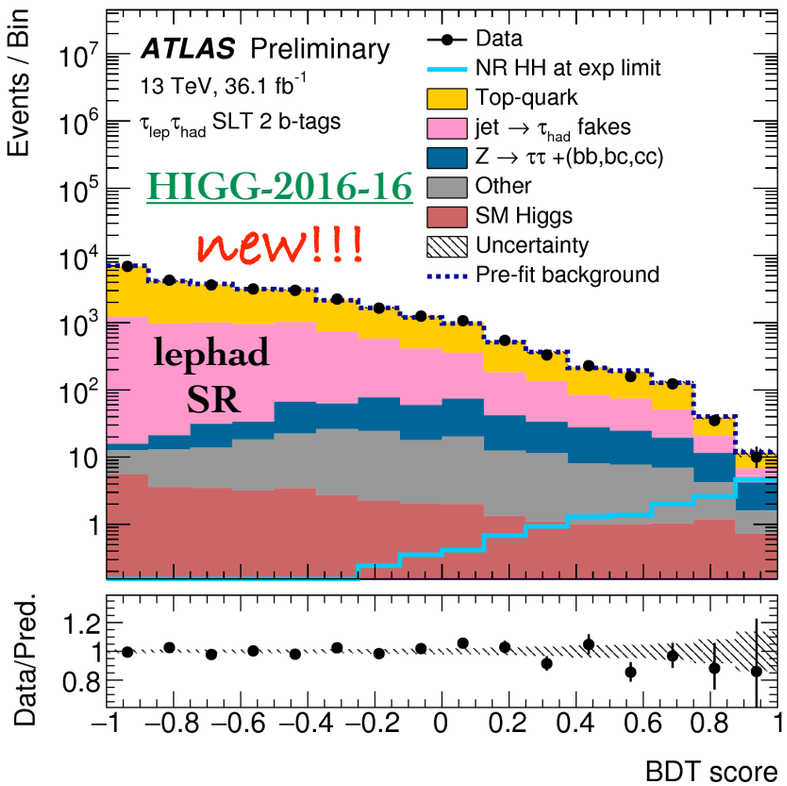
exp limit
ATLAS 21xSM
CMS 37xSM

HH bbττ

- signature: $\tau_{lep}\,\tau_{had}$ or $\tau_{had}\,\tau_{had}$ and 2 b-jets

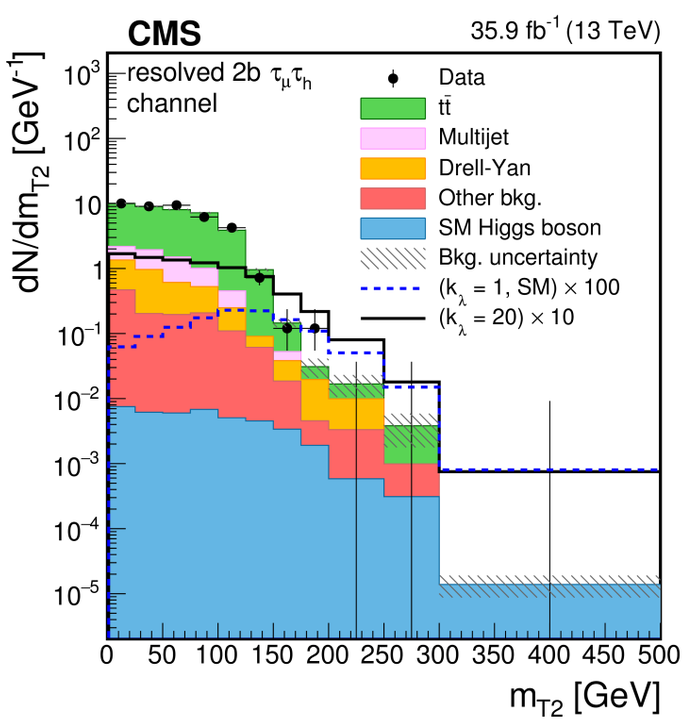
ATLAS

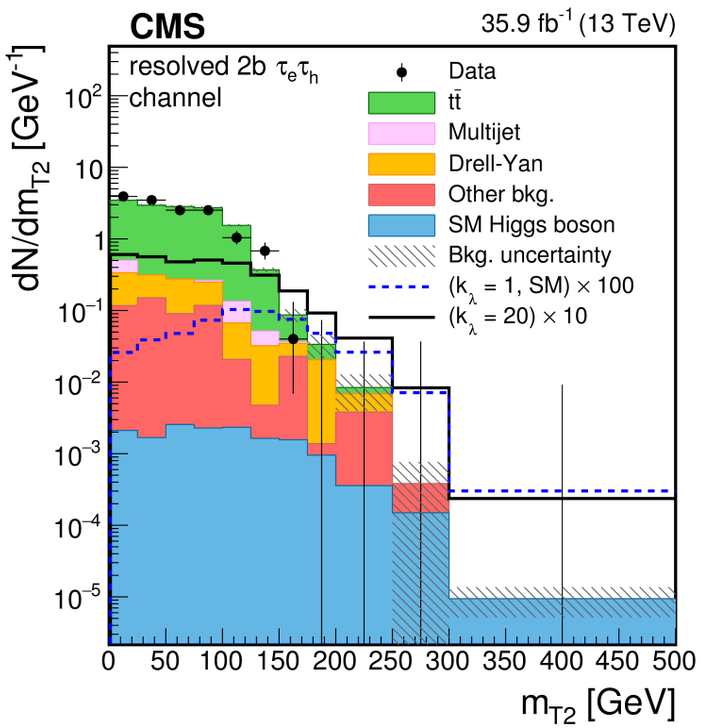
- BDT to separate signal and bkg
- fit BDT score in signal region (preselection + 2 b-tagged jets)



CMS

- define signal region by some cuts
- 2 and 1 b-tags
- lephad channel use BDT to suppress tt bkg
- fit m_{T2} in the signal region





PLB 788 (2018) 101

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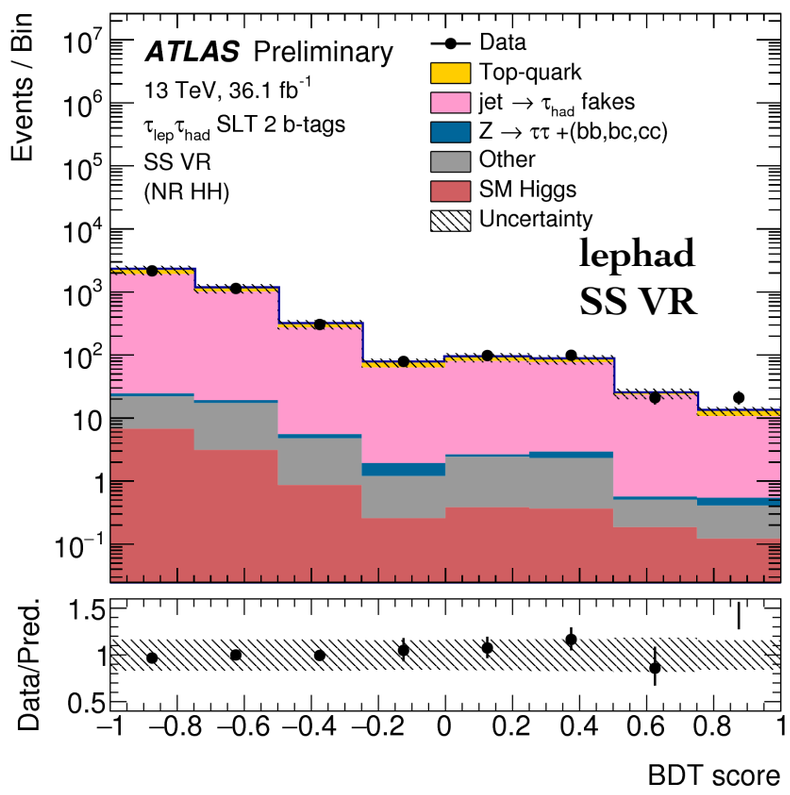
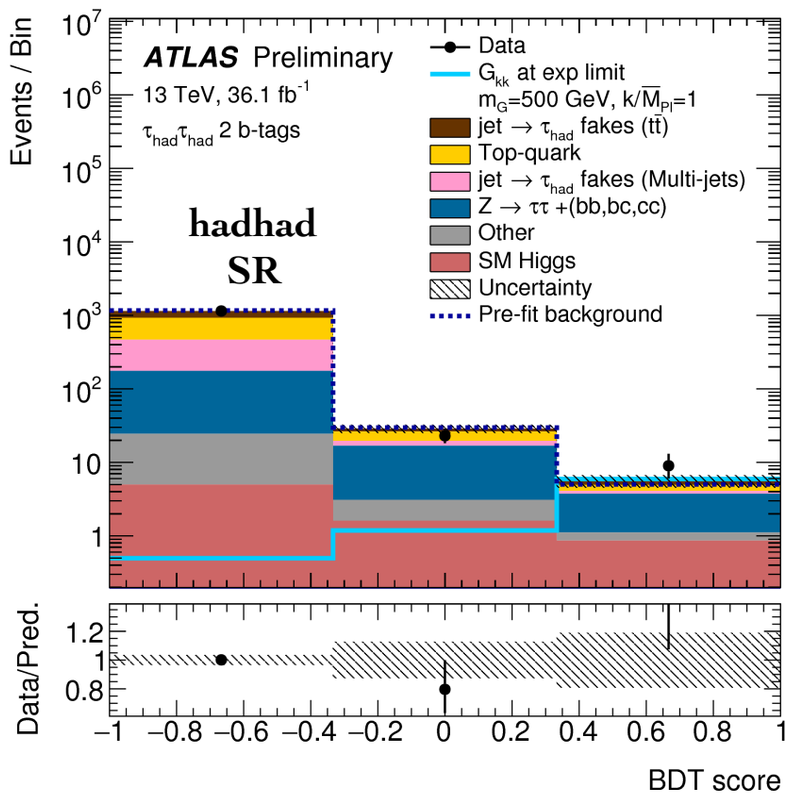
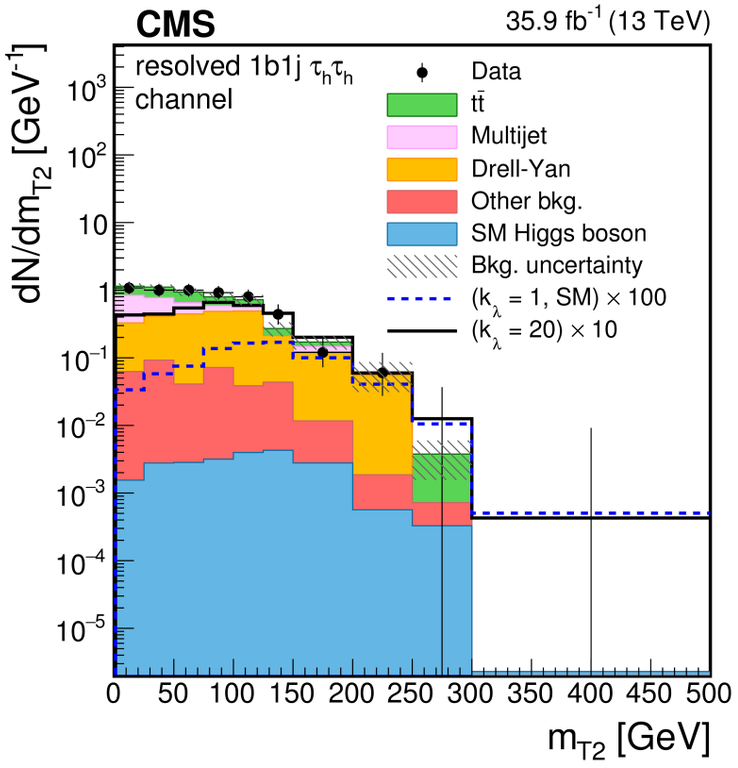
Distributions

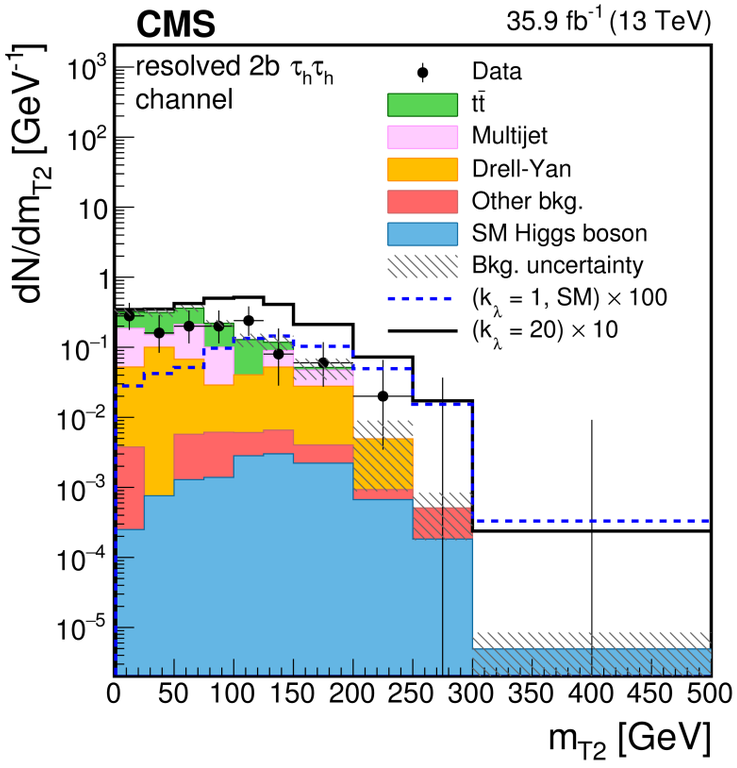
HIGG-2016-16





PLB 788 (2018) 101





exp limit
ATLAS 13xSM
CMS 25xSM

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HH bbγγ

- small BR but clean signature: 2 photons + 2 b-jets

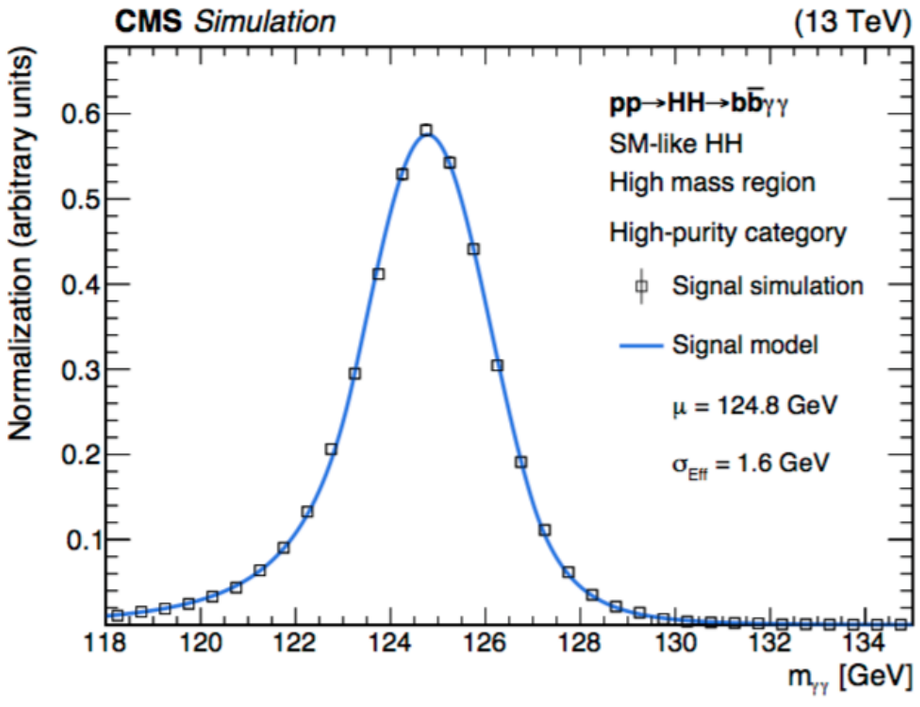
ATLAS

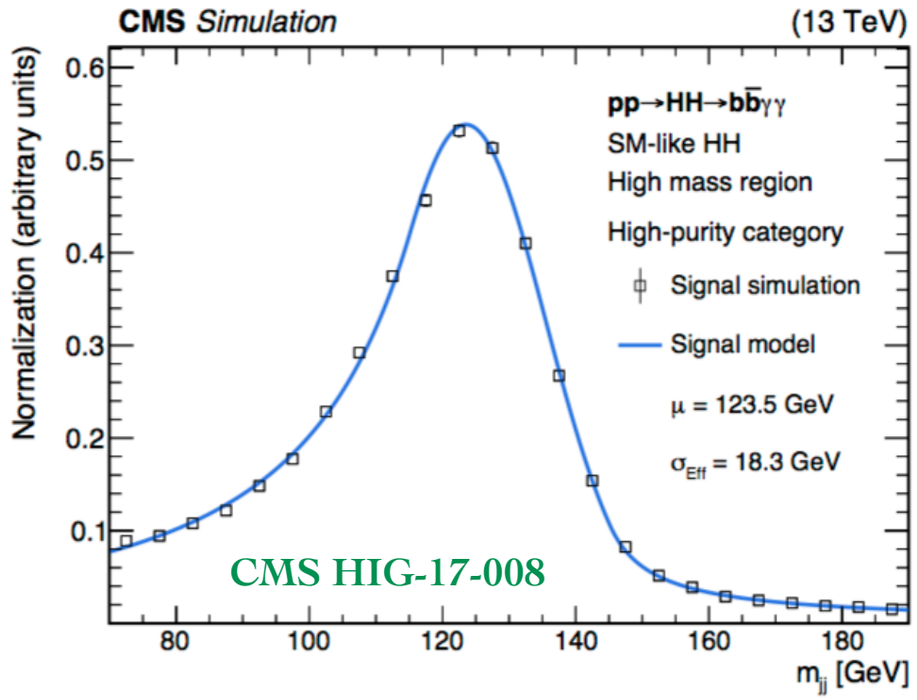
- 1 b-tag region is used as well: second non-b-tagged jet chosen using a BDT
- fit to $m_{\gamma\gamma}$

CMS

- events split in low and high m_{HH} categories
- 2 MVAs to categorise events
- fit to m_{jj} and $m_{\gamma\gamma}$

- signal modelled by Gaussian core and power-law tails
- bkg modelled by a parametrised form obtained from a fit to data





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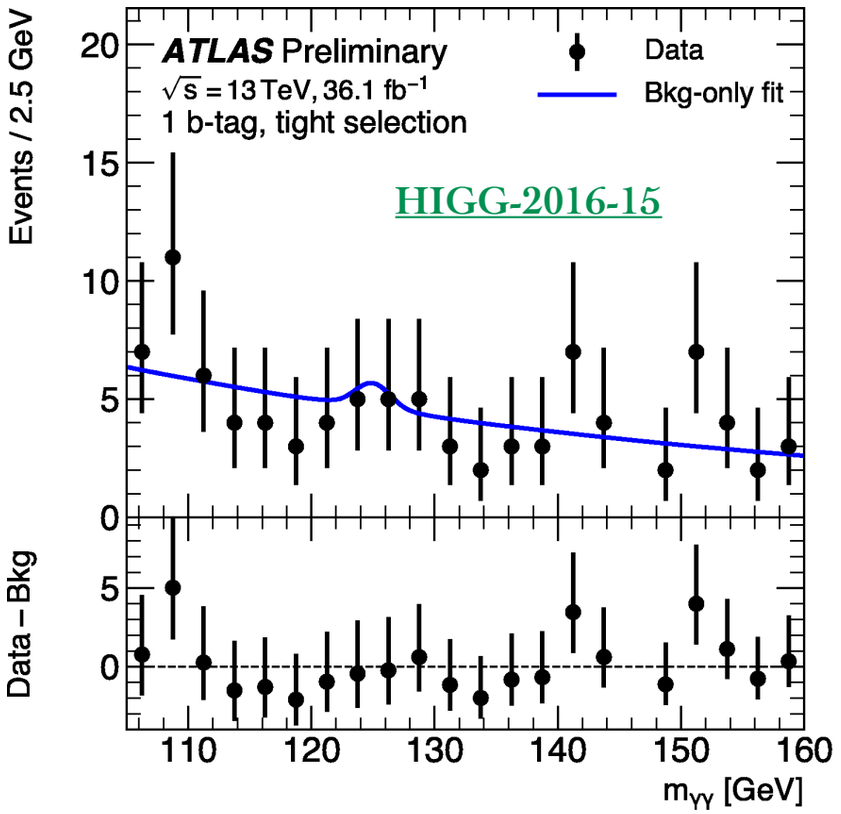
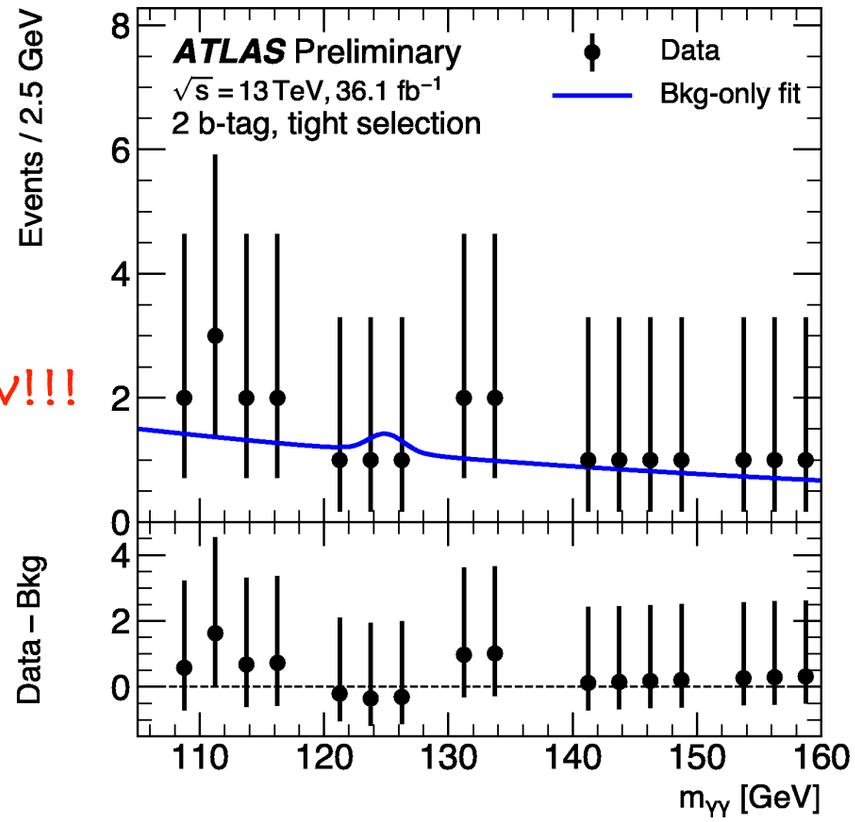
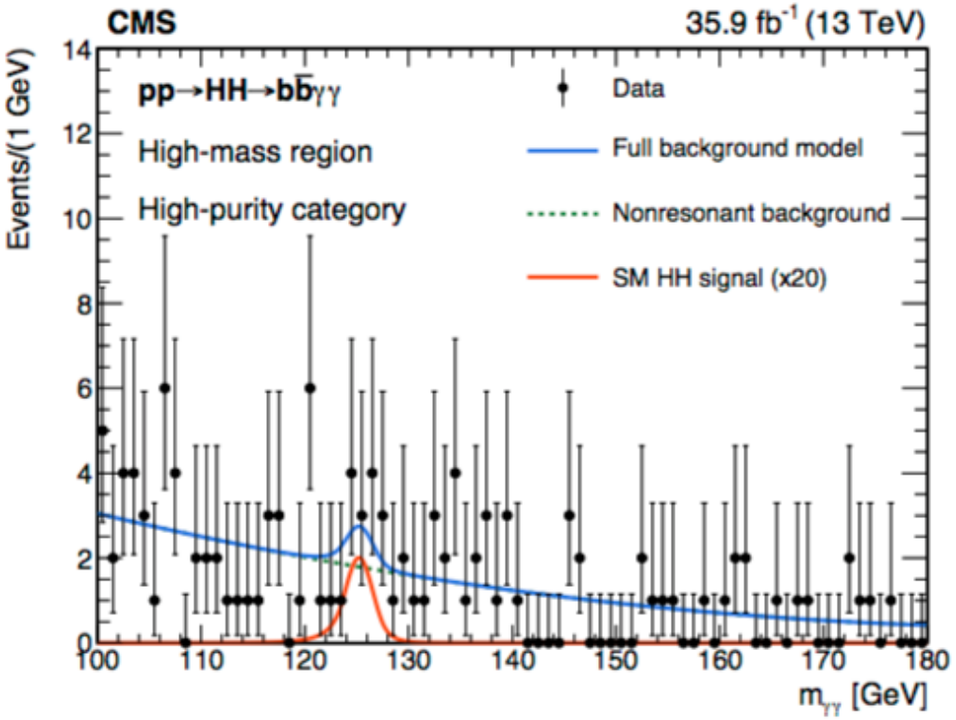
Distributions

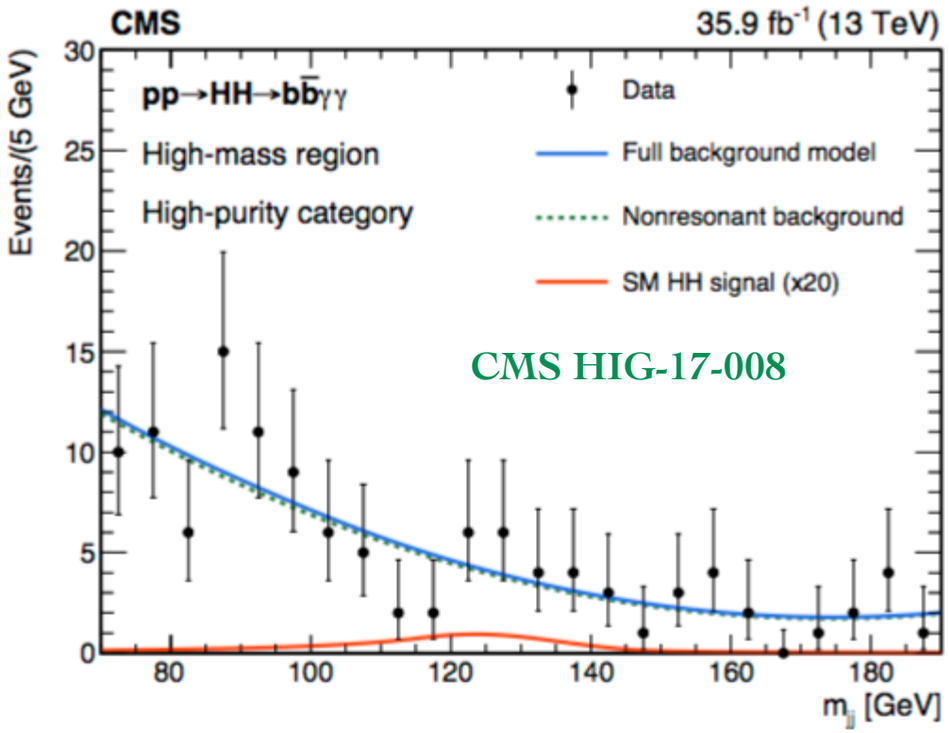


new!!!



exp limit
ATLAS 28xSM
CMS 24xSM





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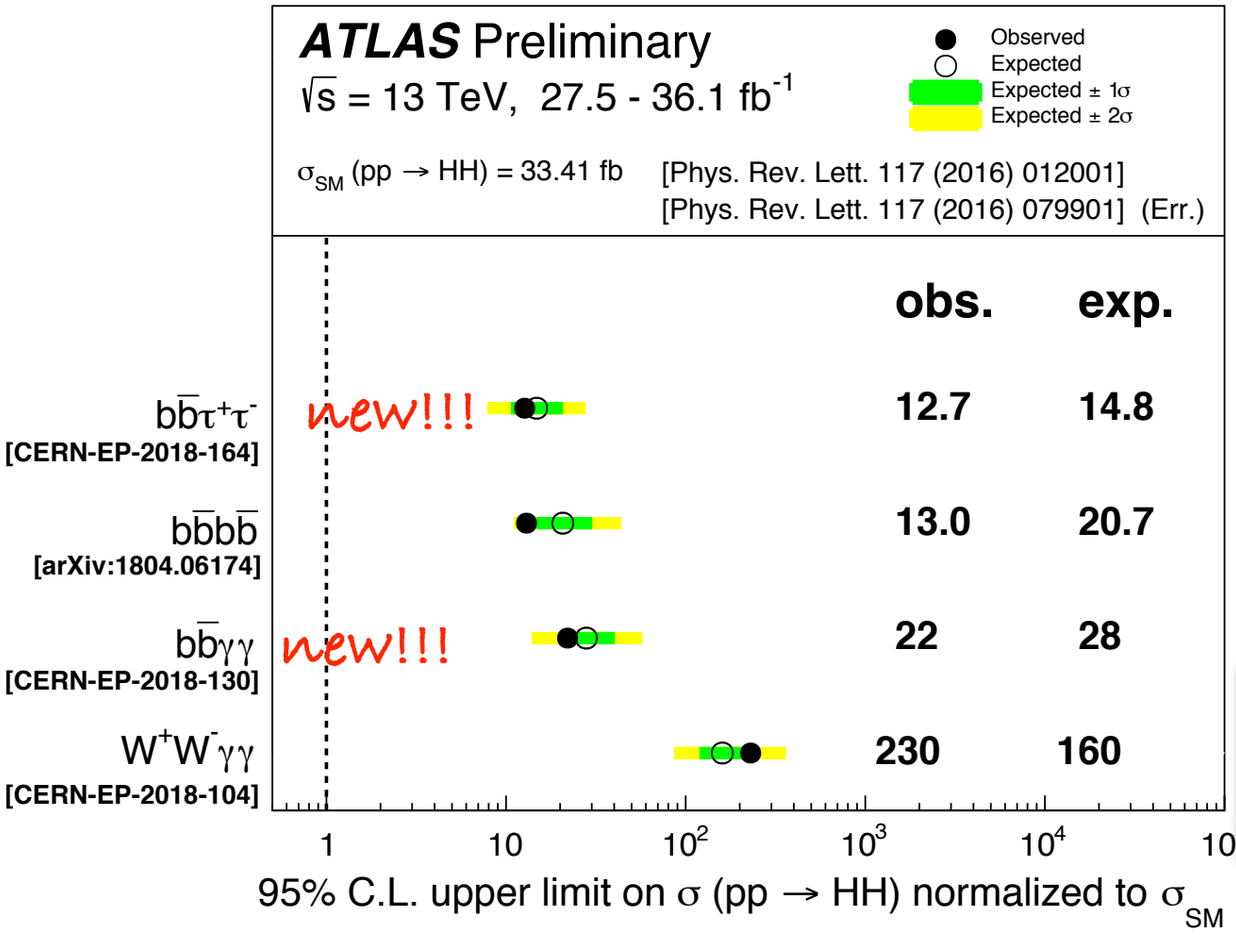
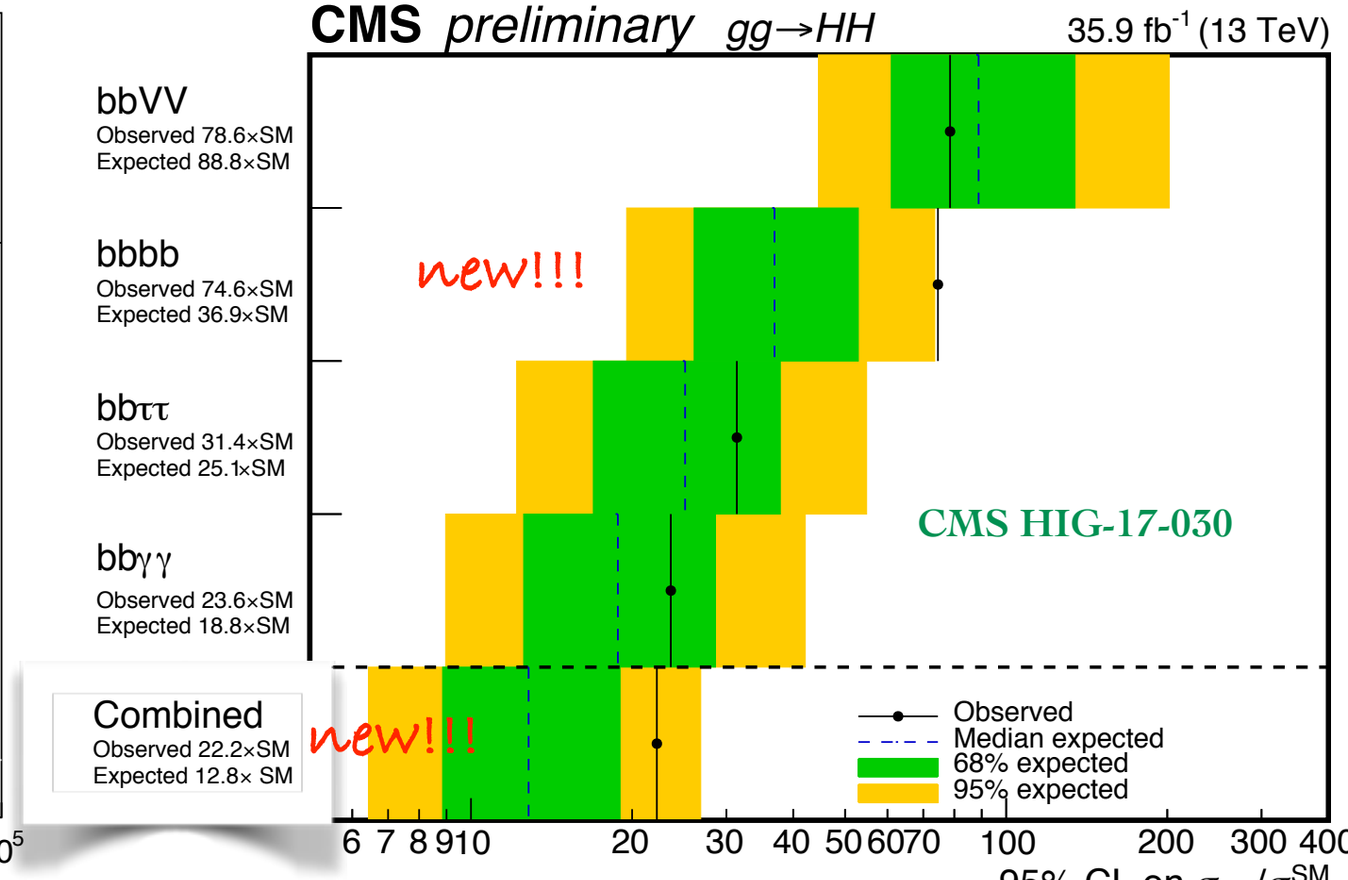
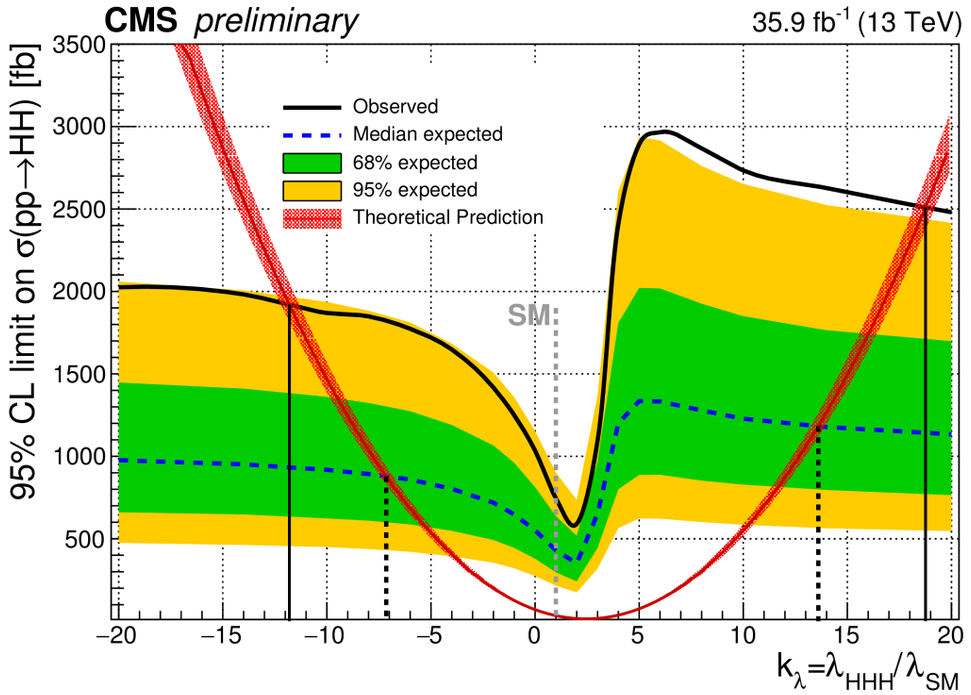
SM HH Results





upper limit on HH: approaching 10 x SM



Conclusions

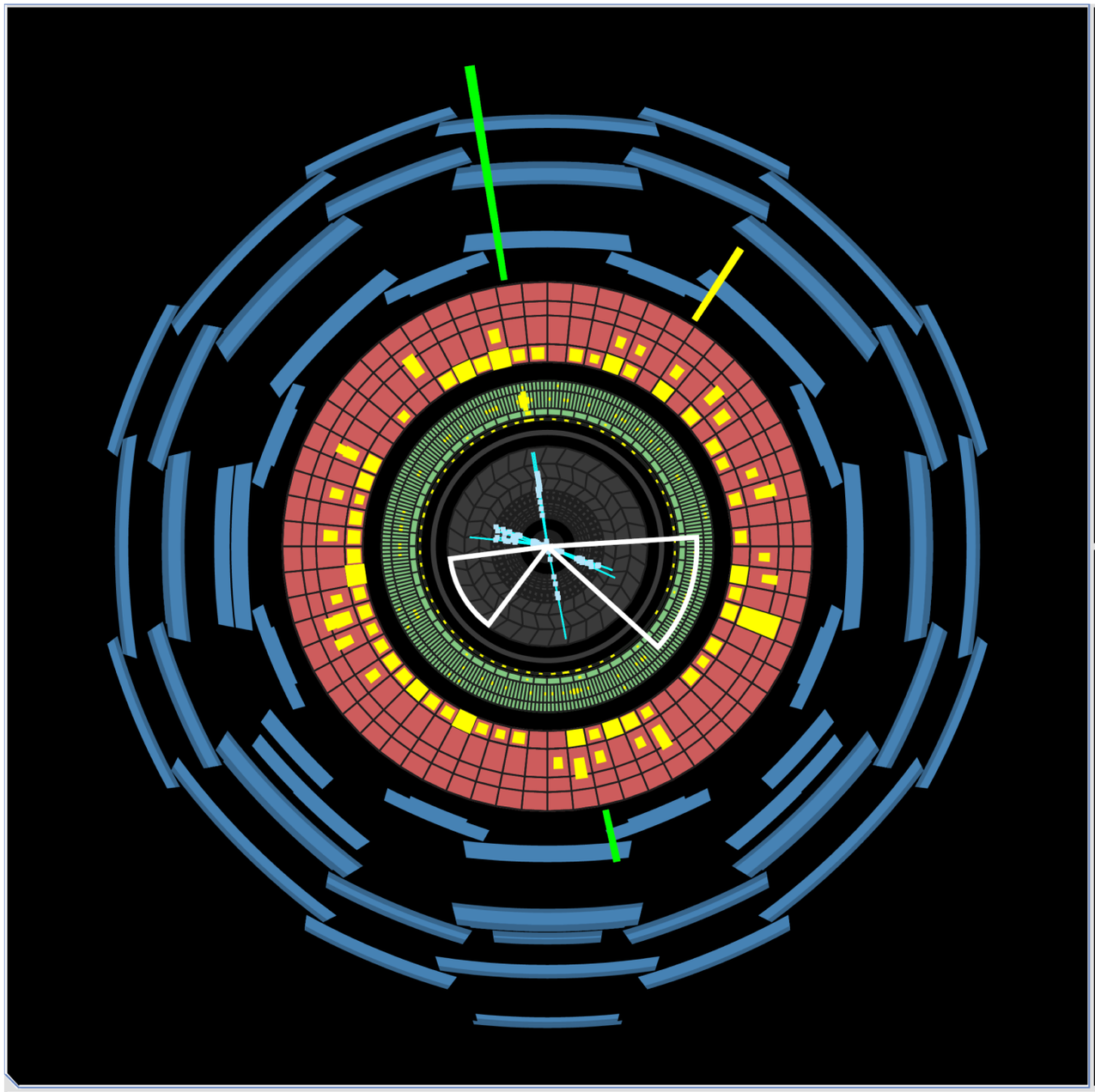
- presented searches for rare Higgs boson decays and di-Higgs production
  - rare decays: μμ, Z/γ, meson +γ, invisible
  - HH-production
  - new results on individual channels and combinations
    - ATLAS: H->μμ, HH->bbττ, HH->bbγγ
    - CMS: HH->4b and combination

- all results consistent with SM expectation

- searches for rare processes become interesting
  - could approach SM sensitivity with Run-3 / HL-LHC

- limits on BSM models already now

BACKUP



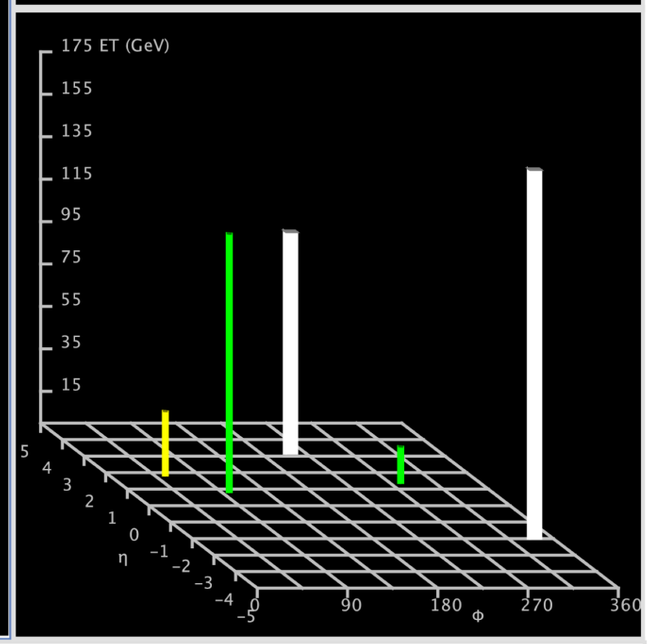
H -> Zγ -> eeγ

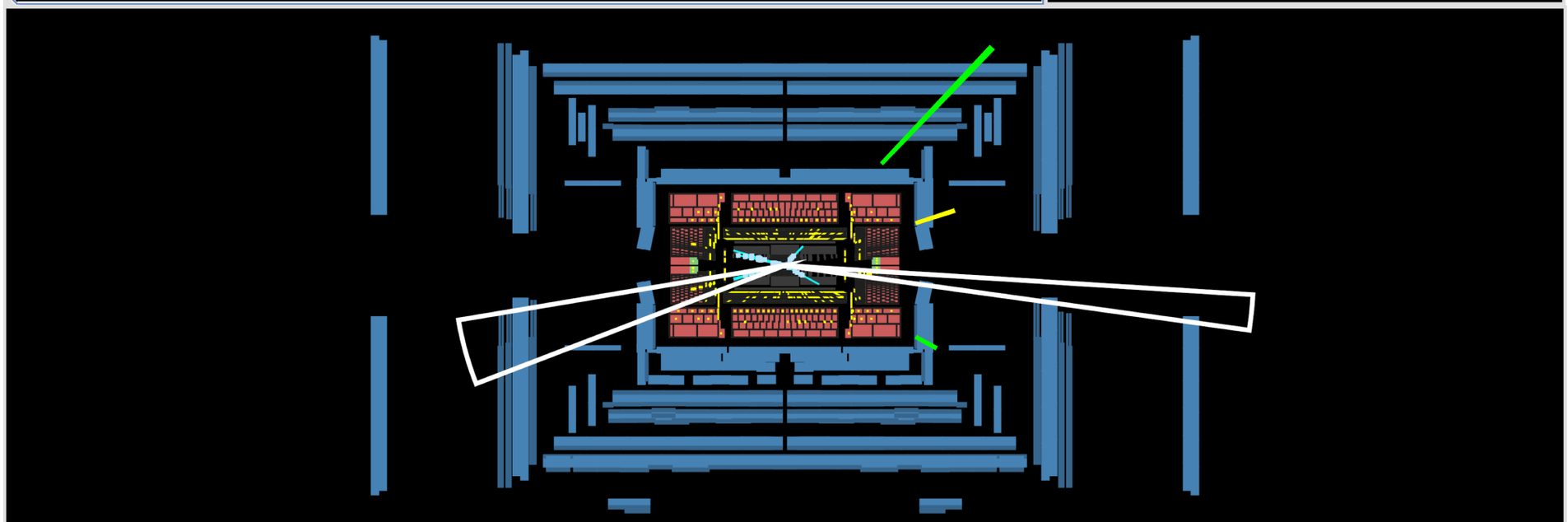
ATLAS EXPERIMENT

Run Number: 307259, Event Number: 996436752

Date: 2016-08-26 16:54:08 UTC

JHEP 10 (2017) 112





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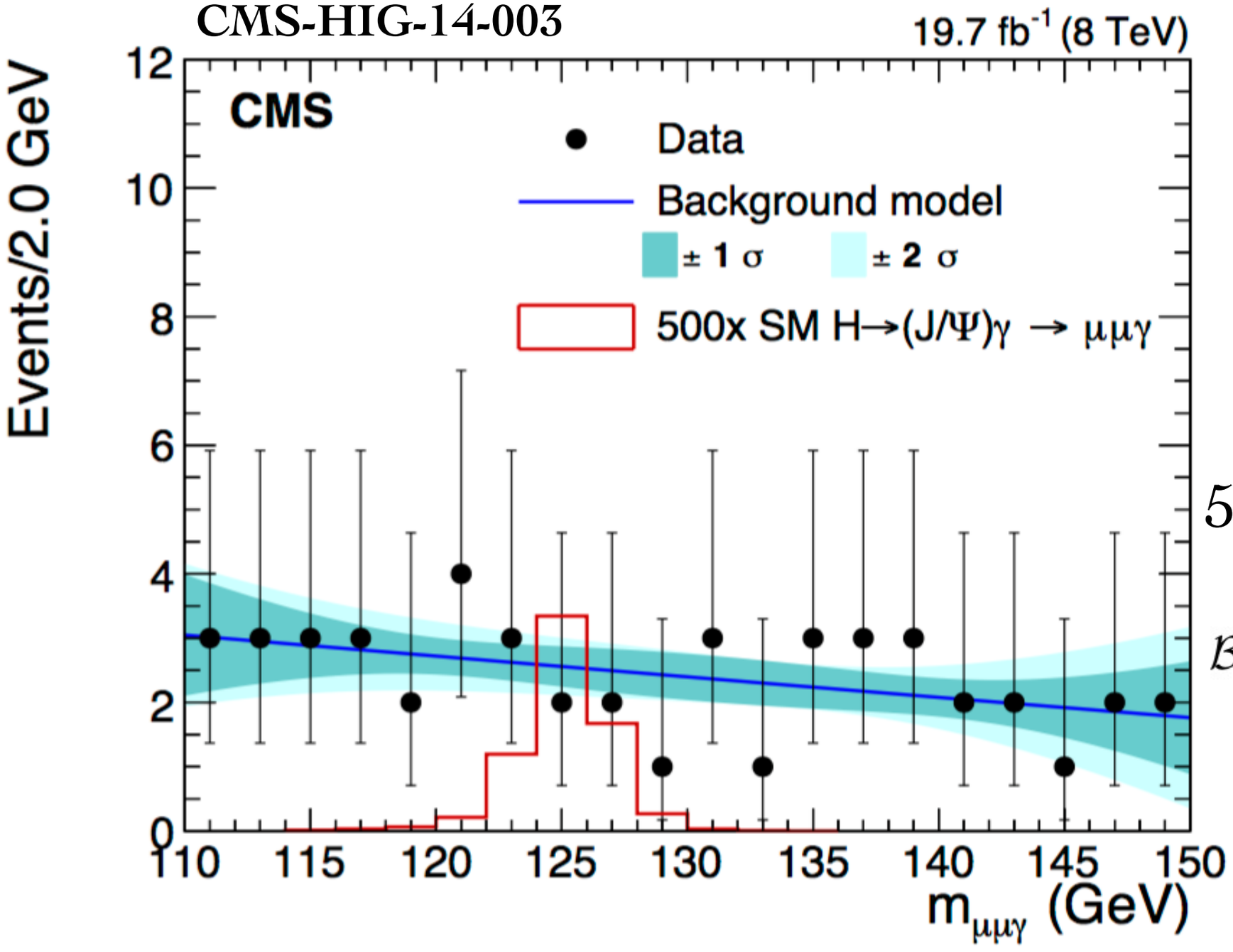
Higgs to meson + γ

CMS-HIG-14-003



Run-1 obs. result:
540 x SM prediction

$$\mathcal{BR}(H \to J/\psi\gamma) < 1.5 \cdot 10^{-3}$$

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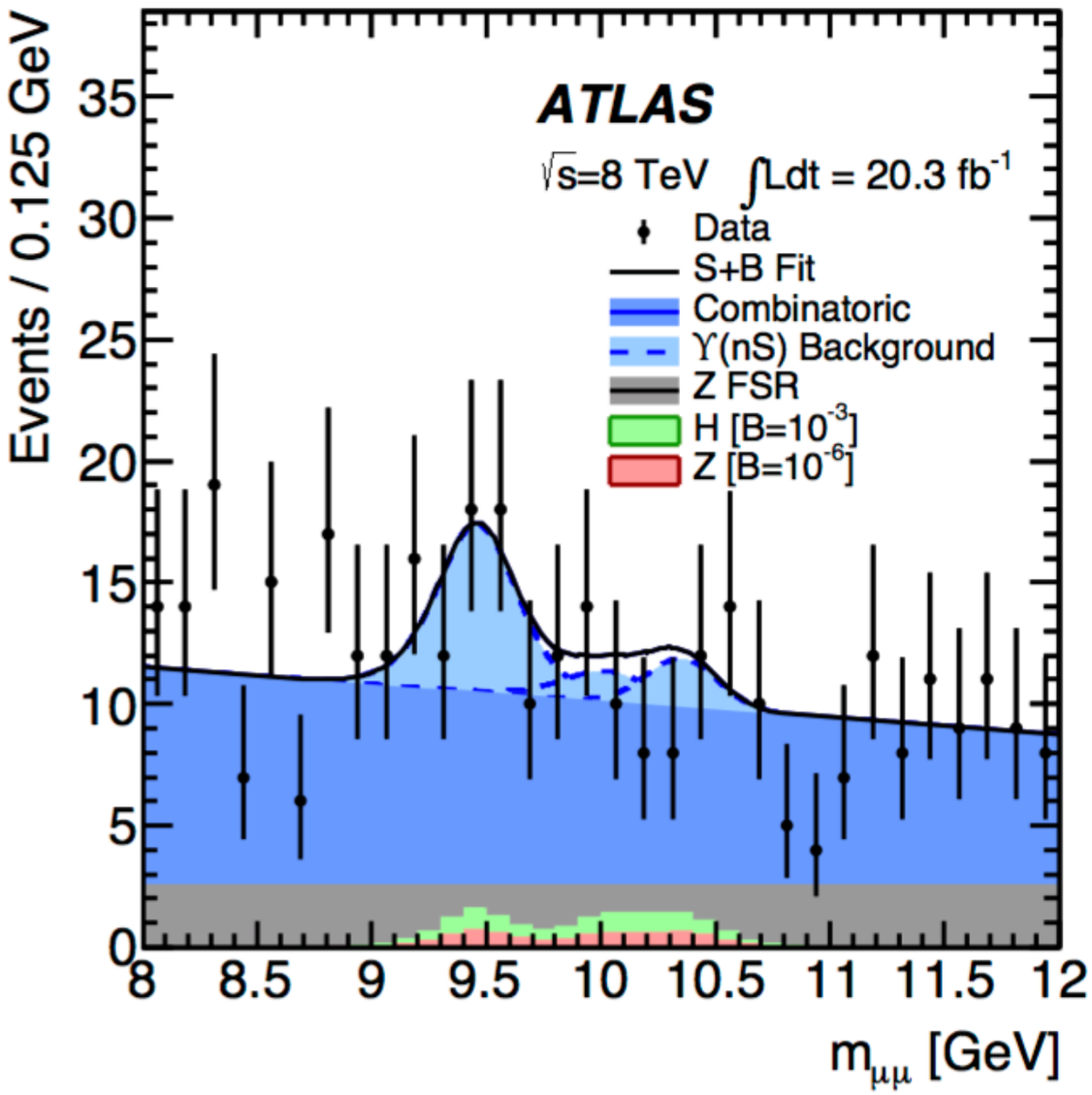
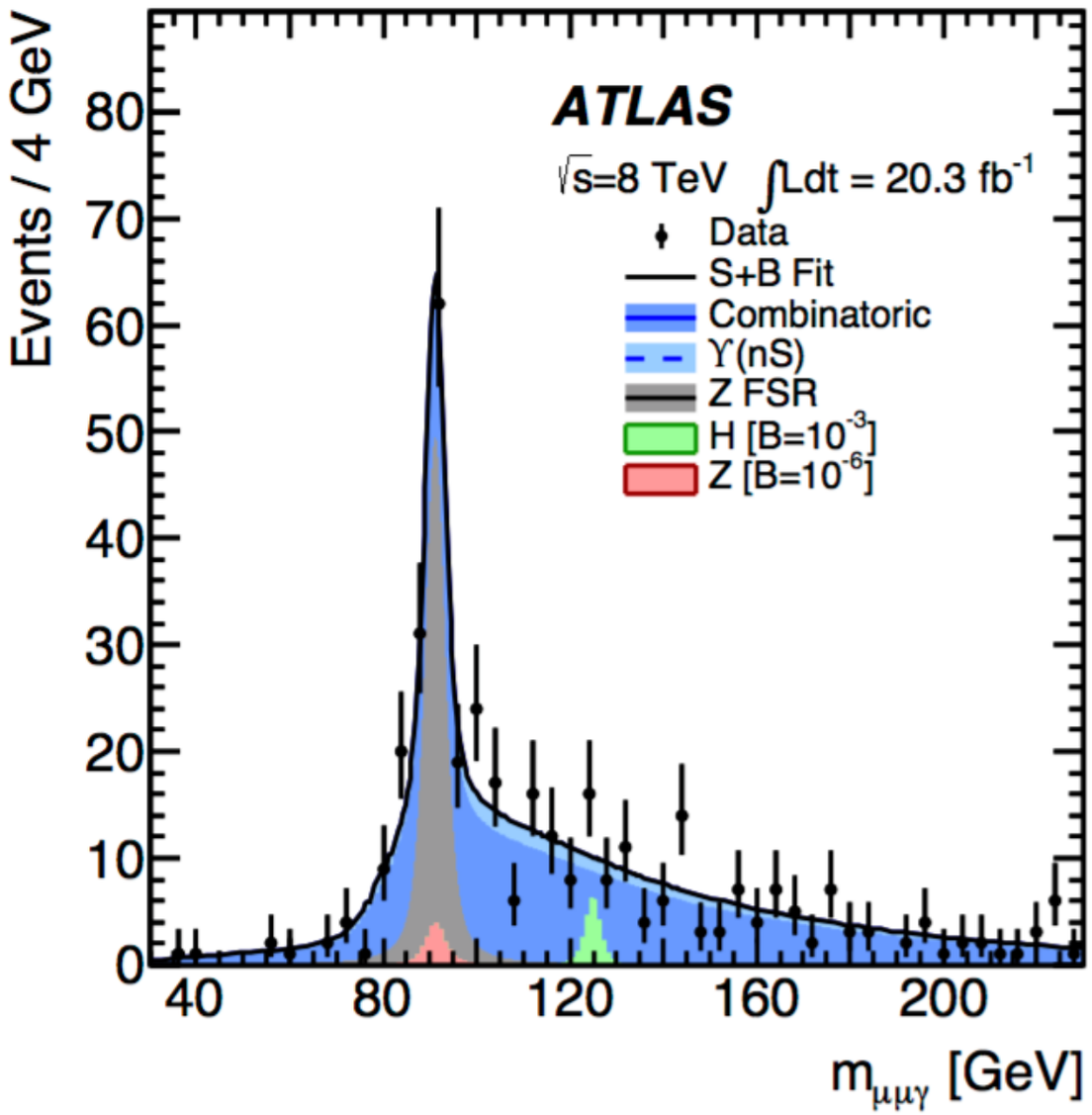
Higgs to meson + γ

arXiv:1501.03276





- unbinned max. likelihood fit to extract upper 95% CL limit
  - 540 x SM for J/ψ
  - > 10.000 x SM for Y(1S,2S,3S)γ

Title