

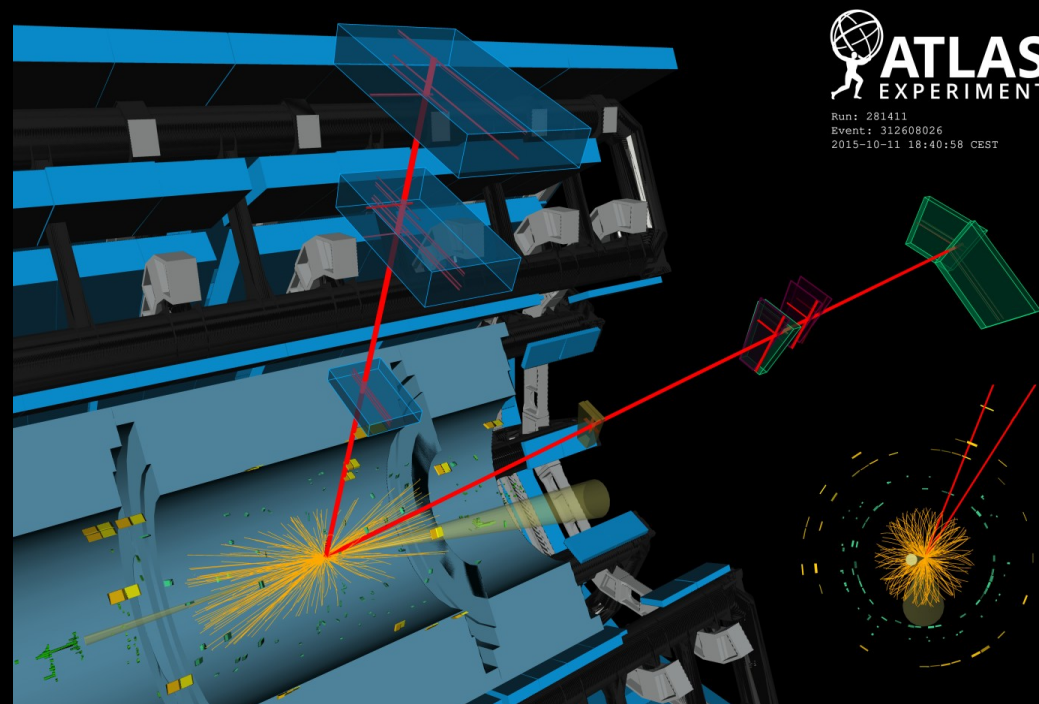
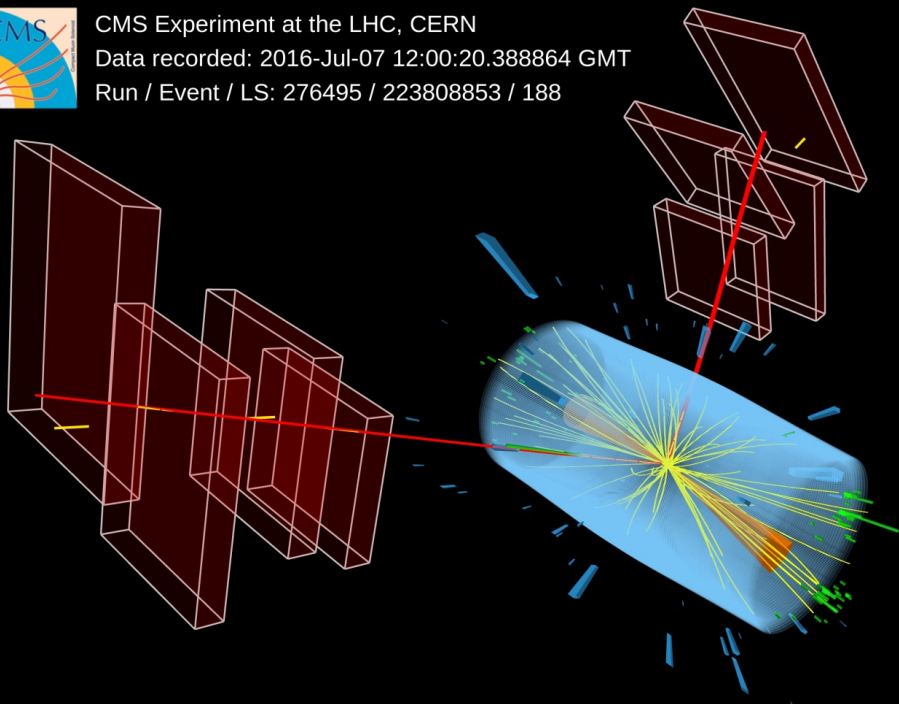
# Search for rare SM decay of the Higgs boson at the LHC



CMS Experiment at the LHC, CERN

Data recorded: 2016-Jul-07 12:00:20.388864 GMT

Run / Event / LS: 276495 / 223808853 / 188



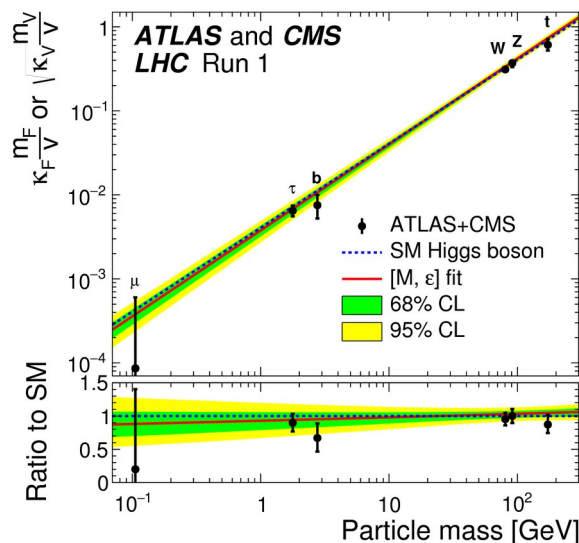
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2015-10-11 18:40:58 CEST

**Silvio Donato** (INFN Pisa)  
on behalf of the ATLAS and CMS Collaborations

- Introduction
- **Higgs  $\rightarrow \mu\mu$**
- Higgs  $\rightarrow \ell\ell\gamma$ 
  - **Low  $\ell\ell$  mass ( $H \rightarrow \gamma^*(\ell\ell)\gamma$ )**
  - **High  $\ell\ell$  mass ( $H \rightarrow Z(\ell\ell)\gamma$ )**
- Higgs  $\rightarrow$  charm quarks
  - Higgs  $\rightarrow J/\psi \gamma$ .
- Conclusions

Recent results (<1y)

- The Higgs boson has been observed decaying to
  - massive vector bosons (Z, W) and photons,
  - third-generation charged fermions (b,  $\tau$ ),
    - coupling to top quark has also been observed.
- The interaction to the 1<sup>st</sup> and 2<sup>nd</sup> gen fermions not observed yet.
- Small deviations from the SM expectation might reveal the presence of new physics,
  - rare decays could be modified by new physics interactions.



Decay	BR
H $\rightarrow$ $\gamma\gamma$	0.23%
H $\rightarrow$ ZZ	2.7%
H $\rightarrow$ WW	21.6 %
H $\rightarrow$ $\tau\tau$	6.3 %
H $\rightarrow$ bb	58 %
H $\rightarrow$ $\mu\mu$	0.022 %
H $\rightarrow$ Z $\gamma$	0.155 %
H $\rightarrow$ cc	2.90 %
H $\rightarrow$ gg	8.56 %

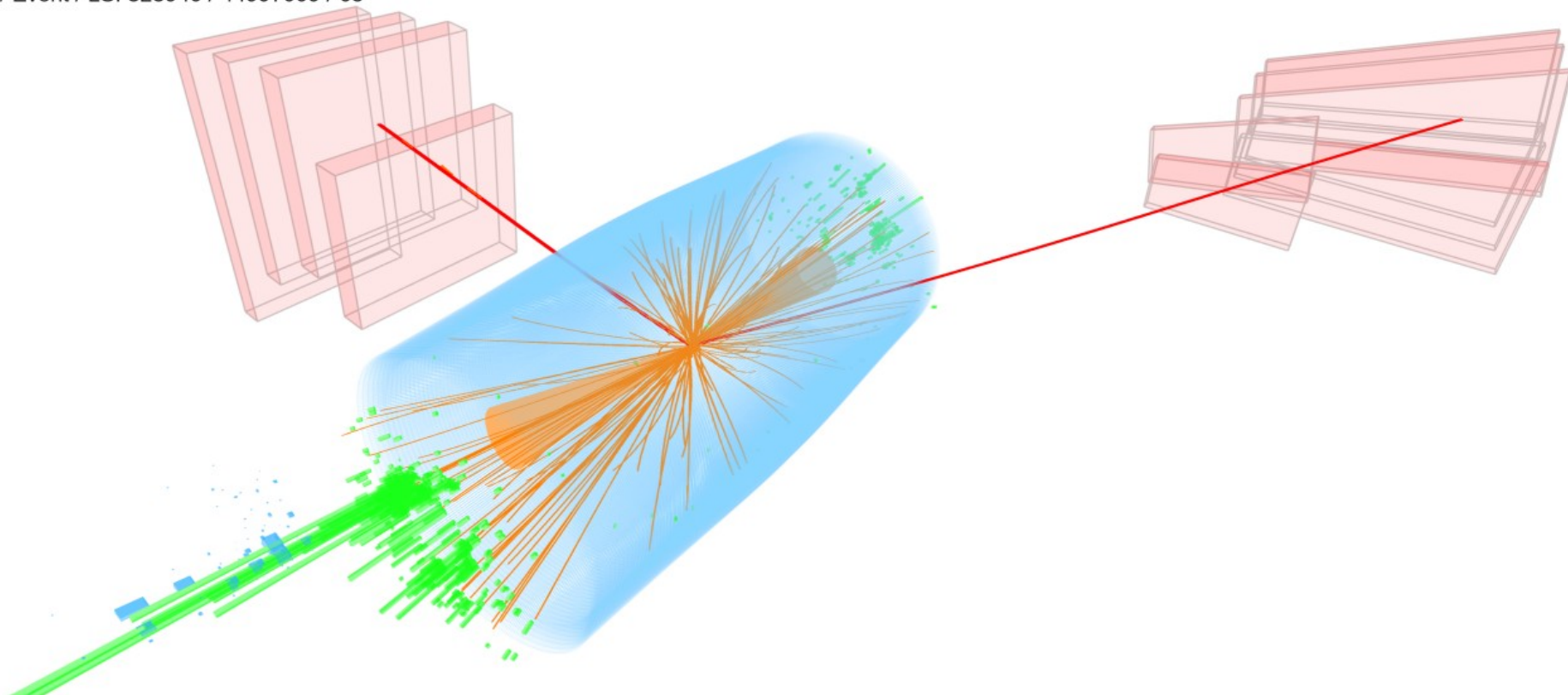
# Higgs $\rightarrow$ $\mu\mu$



CMS Experiment at the LHC, CERN

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Run / Event / LS: 323940 / 44997009 / 65



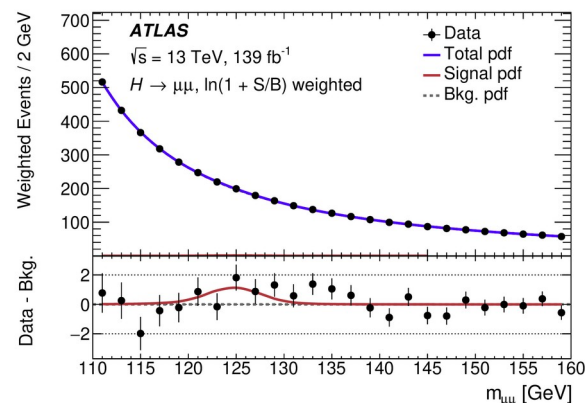
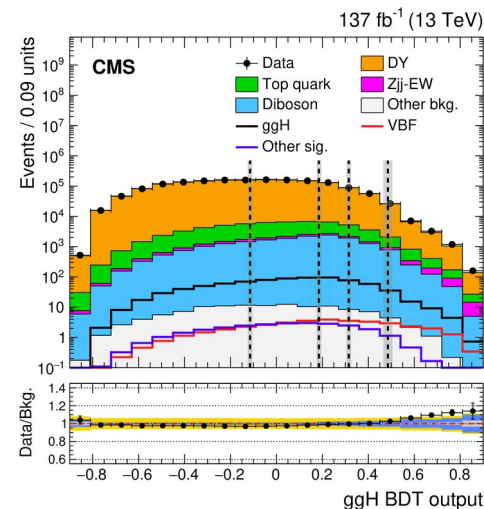
# Higgs $\rightarrow \mu\mu$

- Both analyses divided by the **production modes**:

- VBF (no b jets, no additional leptons, VBF selection),
- ggH (no b jets, no additional leptons, VBF veto),
- WH (no b jets, 1 additional leptons),
- ZH (no b jets, 2 additional leptons),
- Leptonic ttH ( $\geq 1$  b jets, 1 add. leptons),
- Hadronic ttH ( $\geq 1$  b jets, 2 add. leptons). [CMS only]

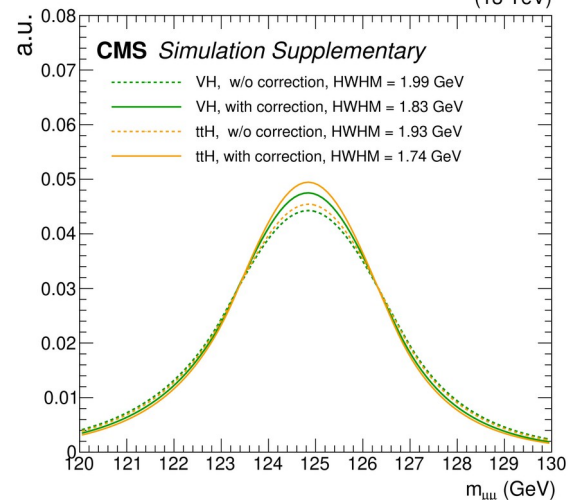
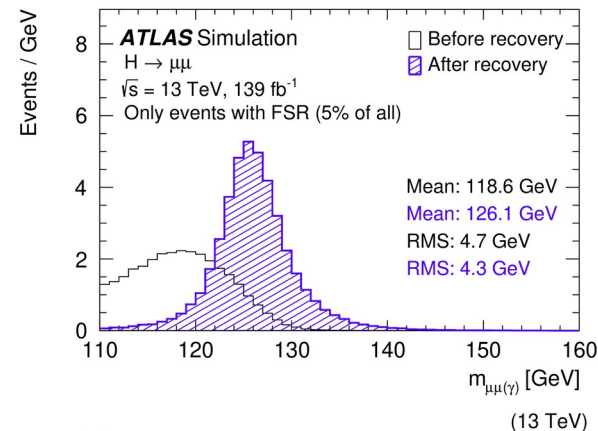
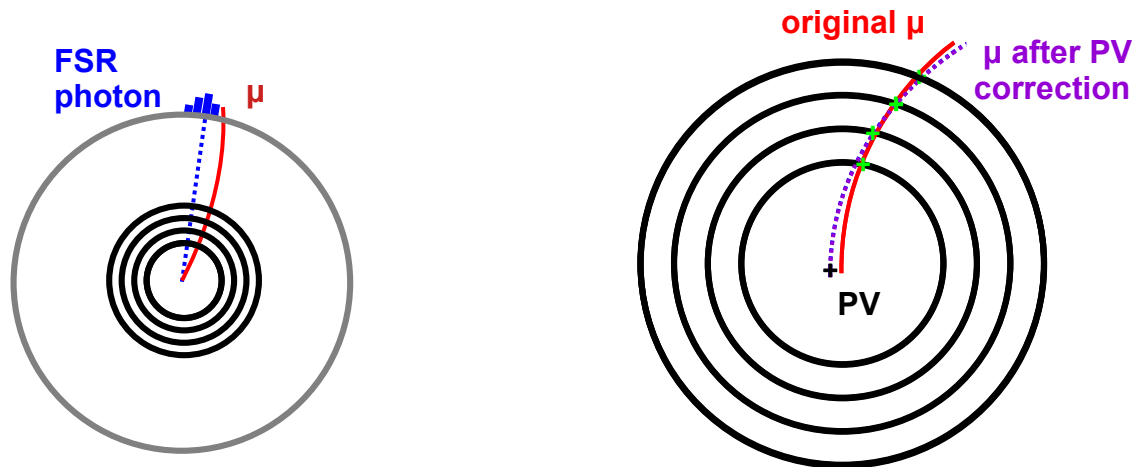
- A **multivariate** discriminator is trained in each region.

- categories with different signal **purity**,
- **fit** the Higgs boson peak **dimuon mass**.



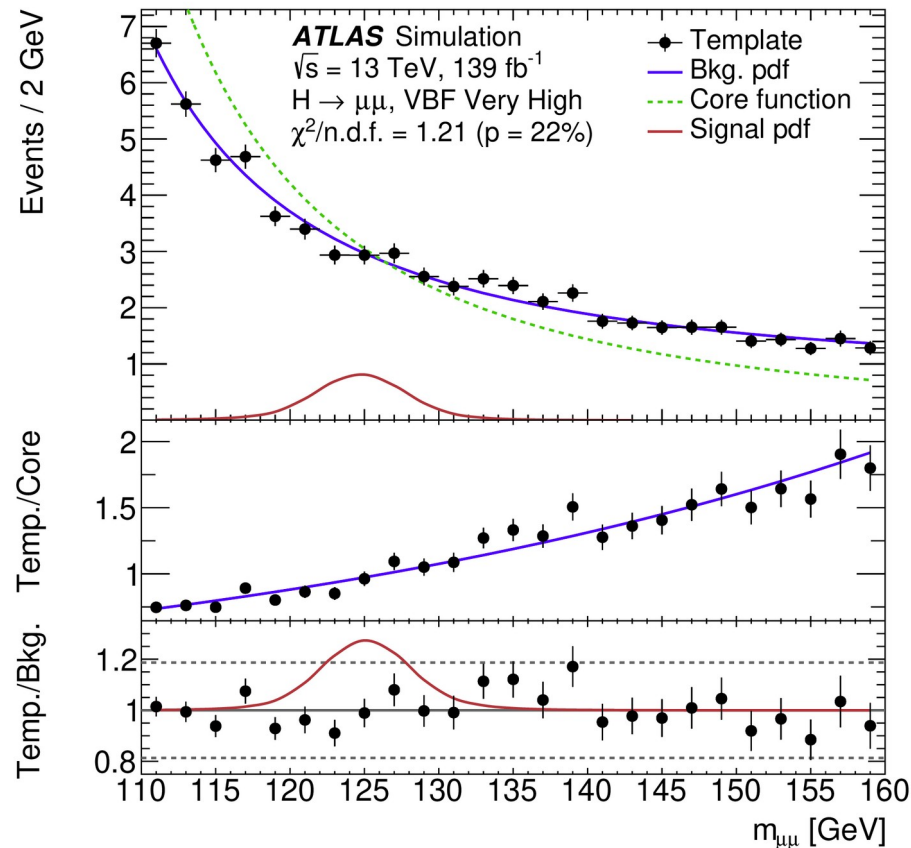
# Higgs $\rightarrow \mu\mu$

- **Final state radiation (FSR) energy recovery:**
  - $p_T$  **resolution** improvement (3%),
  - signal **efficiency** increase (2%).
- Muon track fitted using **primary vertex**,
  - $p_T$  **resolution** improvement (3 – 10 %).



# Higgs $\rightarrow \mu\mu$

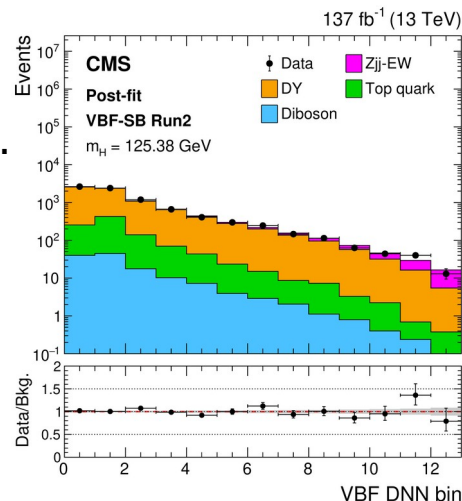
- Background model:  
“core” function x “empirical” function.
- **Core function:**
  - common to all the categories;
  - based on theory to model the  $Z/\gamma \rightarrow \gamma\gamma$  line-shape.
- **Empirical function:**
  - specific to each category;
  - Chebyshev polynomial [CMS] or power-law functions/exponentials of poly [ATLAS].
- Thorough **bias studies:**
  - based on fitting MC simulations [ATLAS]
    - alternative MC generators used as a cross-check
    - 20 billions of (fast) simulated events;
  - pseudo-experiments generated with alternative functions [CMS].
- Less free parameters  $\rightarrow$  improved sensitivity  $\sim$ **10%**



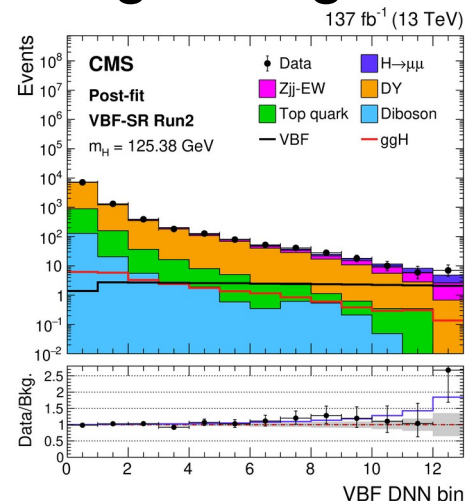
- **Simulation-based** analysis in **VBF** category [**CMS**]:

- signal extracted by fitting a **DNN** discriminator including  $m_{\mu\mu}$  in
  - signal region: [ $m_{\mu\mu}=115-135$  GeV],
  - side band: [ $m_{\mu\mu}=110-115$  &  $135-150$  GeV].
- side-band DNN obtained using  $m_{\mu\mu} = 125$  GeV;
- background estimated using simulation templates;
- expected sensitivity: **+20%**.

## Side band



## Signal region

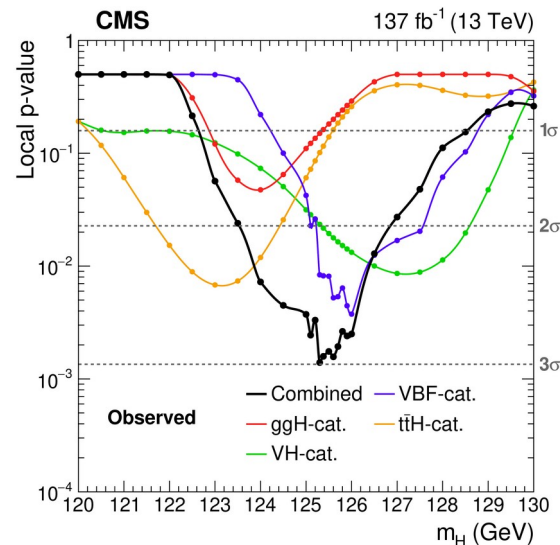
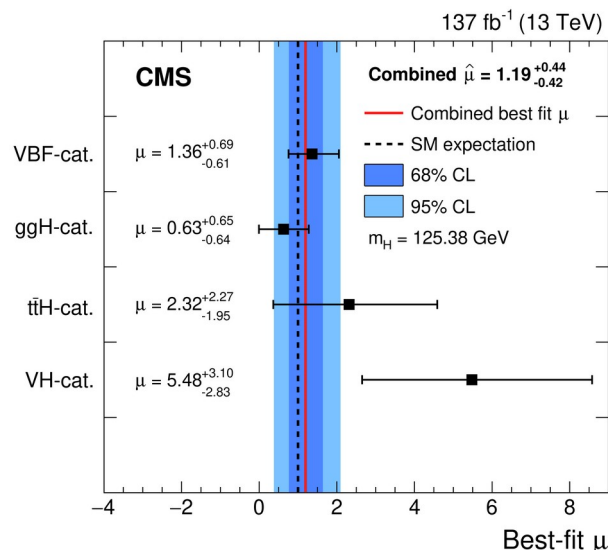
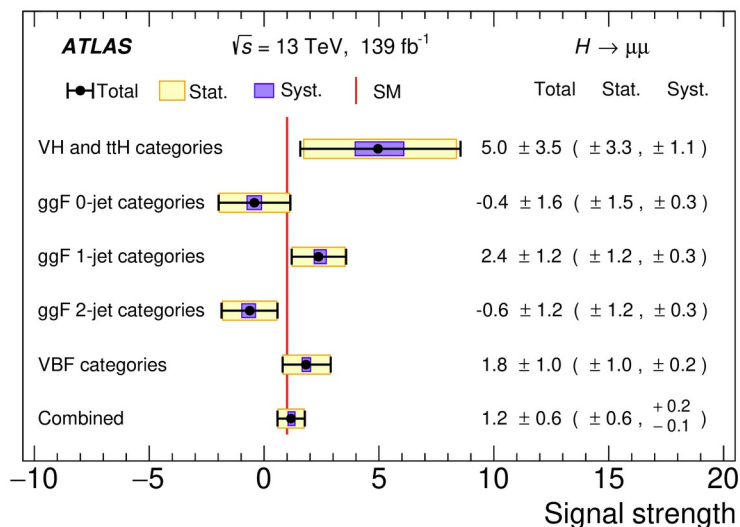


- **ATLAS** decided to use a data-driven analysis which is independent from the background MC models/systematics.



# Higgs $\rightarrow \mu\mu$

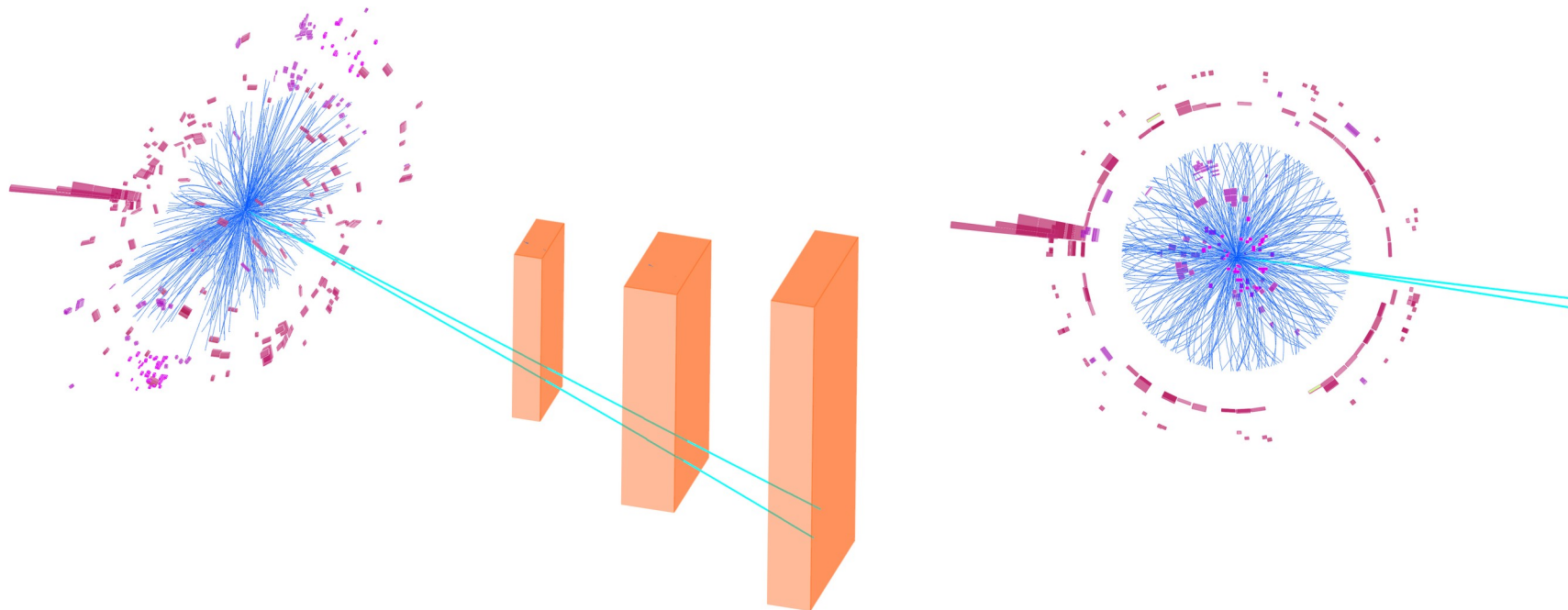
- Results:
  - CMS:  $\mu = 1.19 \pm 0.40$  (stat)  $\pm 0.15$  (syst)  $\rightarrow$  **p-value:  $3.0\sigma$  ( $2.5\sigma$  exp.);**
  - ATLAS:  $\mu = 1.2 \pm 0.6$  (stat)  $^{+0.2}_{-0.1}$  (syst)  $\rightarrow$  **p-value:  $2.0\sigma$  ( $1.7\sigma$  exp.).**
- The uncertainty is statistically dominated.



# Higgs $\rightarrow \gamma^*(\ell\ell)\gamma$

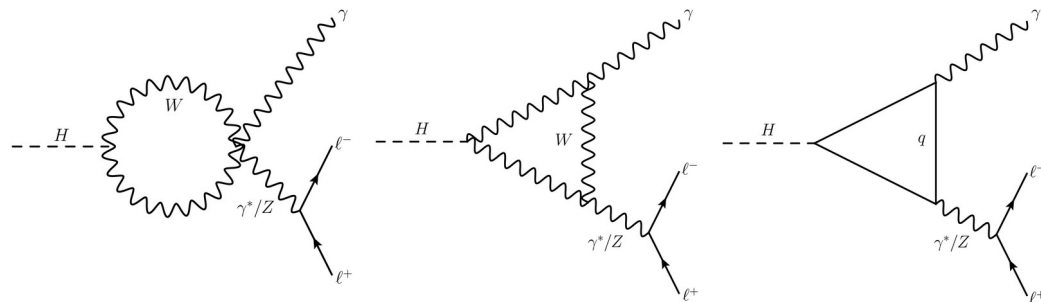


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# Higgs $\rightarrow \gamma^*(\ell\ell)\gamma$

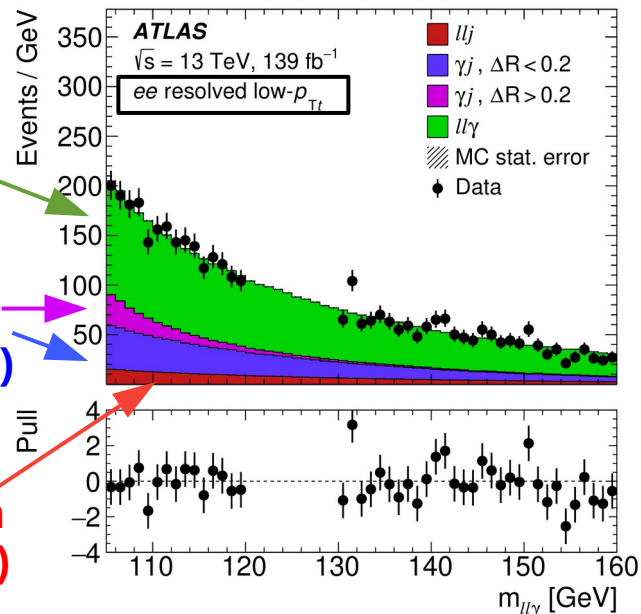
- Search for  $H \rightarrow \ell\ell\gamma$ 
  - $\ell$  = electron or muon.
- Low-mass  $\ell\ell$  ( $m_{\ell\ell} < 30$  GeV)
  - dominated by  $\gamma^* \rightarrow \ell\ell$ .
- Nine analysis categories:
  - [ $\mu\mu$ , ee-resolved, ee-merged] x
  - [VBF-enriched, high  $p_{T\ell}$ , low  $p_{T\ell}$ ].
- **Backgrounds:**
  - Irreducible **non-resonant**  $\ell\ell\gamma$  bkg;
  - **Resonant**  $H \rightarrow \gamma\gamma$ , with  $\gamma \rightarrow ee$  conv. (<7%, only in  $H \rightarrow ee\gamma$  channel).



$\ell\ell\gamma$  from simulation

$j\gamma$  from control region (misid. jet  $\rightarrow \ell$ )

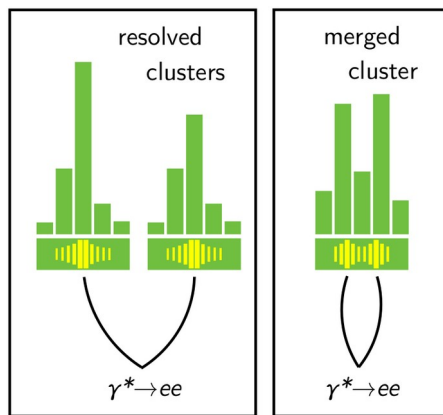
$\ell\ell j$  from control region (misid jet  $\rightarrow \gamma$ )



# Higgs $\rightarrow \gamma^*(\ell\ell)\gamma$

- Merged-ee challenging:

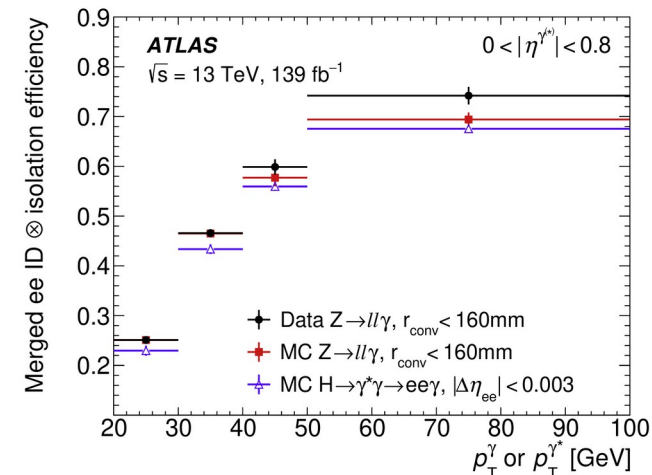
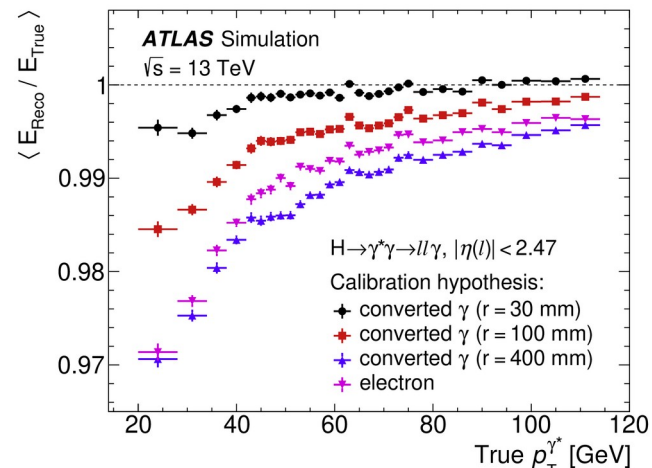
- background from  $\gamma \rightarrow ee$  conversion;
- dedicated trigger;
- special reconstruction.



- Calibrated using the hypothesis of a converted  $\gamma$  ( $r = 3$  cm).

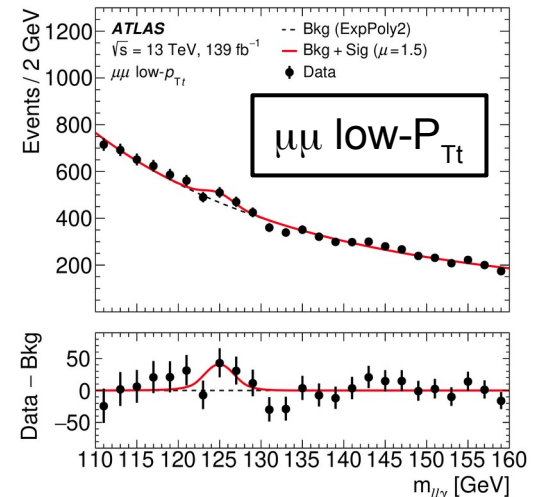
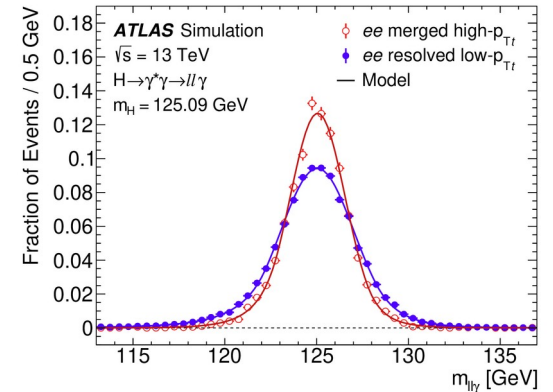
- Reconstruction and ID efficiency from data:  $Z(\ell\ell) +$  converted  $\gamma$  with  $r_{\text{conv}} < 16$  cm.

- Further minor corrections are based on MC.



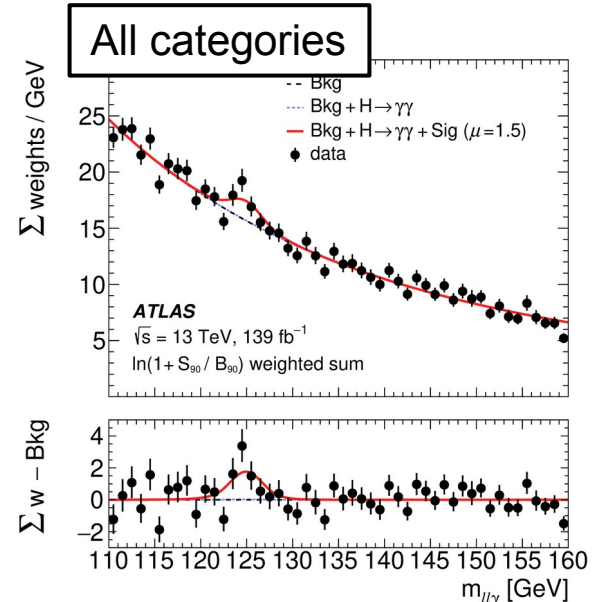
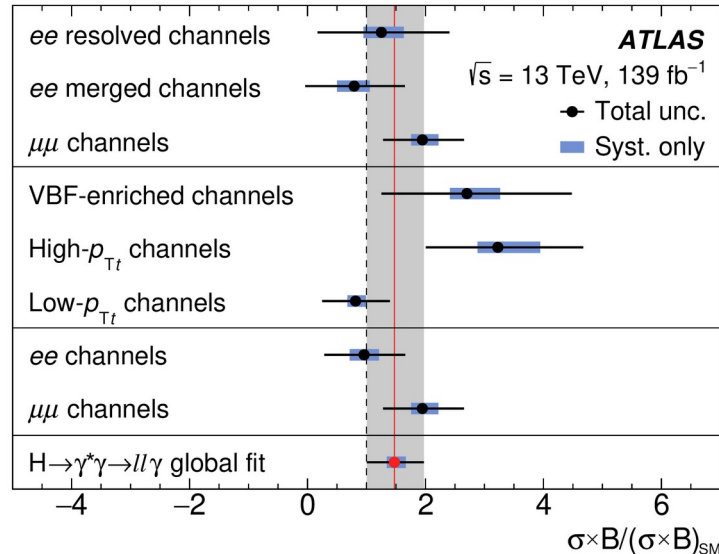
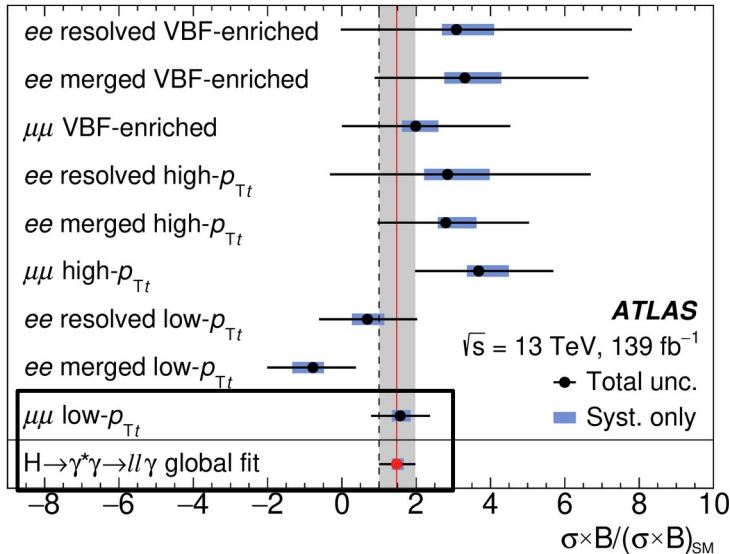
# Higgs $\rightarrow \gamma^*(\ell\ell)\gamma$

- The fit is performed using **analytic functions** for both signal and background based on templates.
  - double-sided **Crystal Ball** function for signal,
  - (second order) exponential or power law for **background**.
- Analytic function chosen and tested using templates
  - Large  $\ell\ell\gamma$  simulated bkg sample using a **parameterisation** of the object efficiency instead of full simulation.

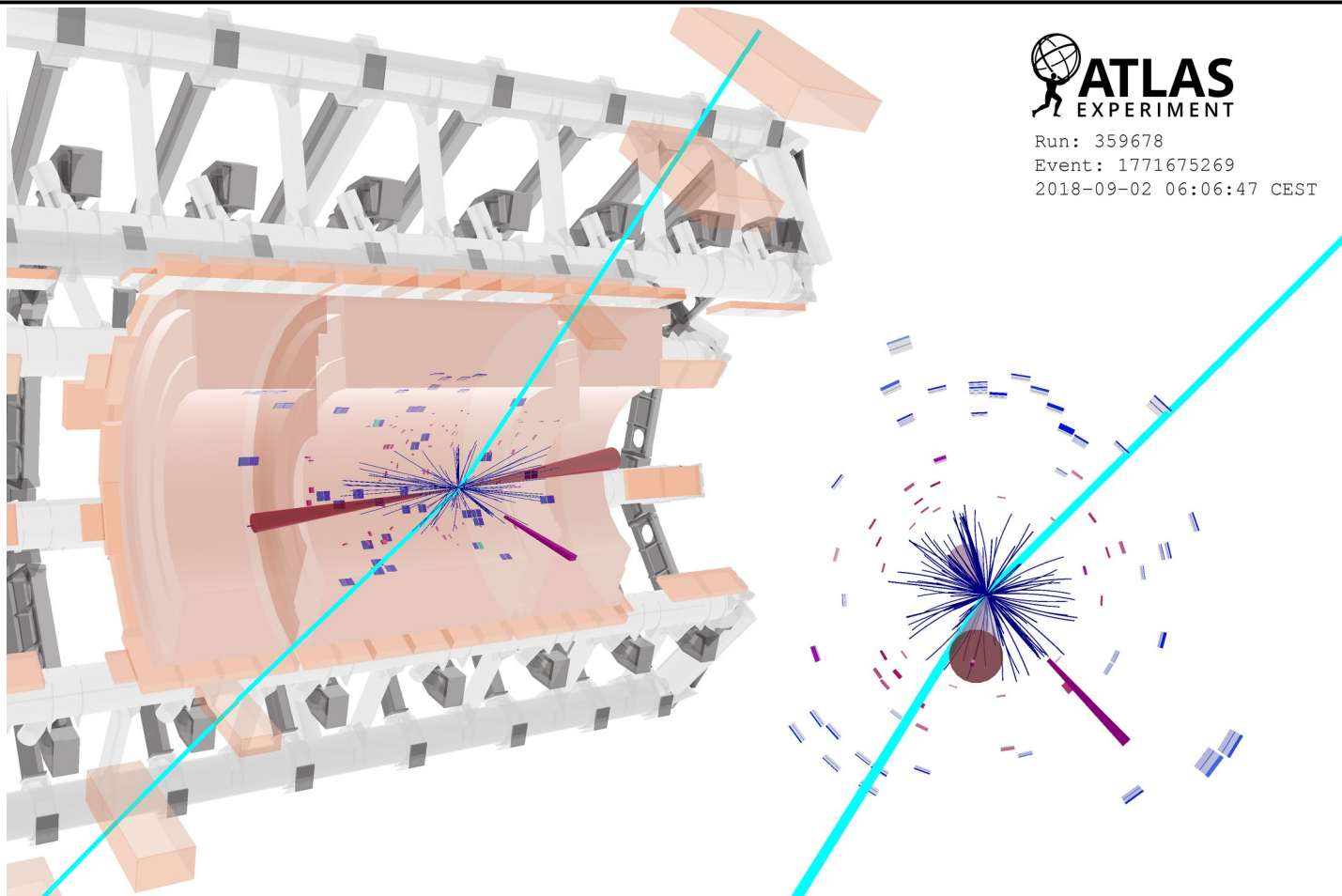


# Higgs $\rightarrow \gamma^*(\ell\ell)\gamma$

- Simultaneous fit of 9 categories:  $\mu = 1.5 \pm 0.5$  (stat.)  $\pm_{-0.1}^{0.2}$  (syst.).
- Cross section:  $8.7 \pm 2.7$  (stat.)  $\pm_{-0.6}^{0.7}$  (syst.) fb.
- **Observed** (expected) significance:  **$3.2\sigma$**  ( $2.1\sigma$ ).



# Higgs $\rightarrow$ Z( $\ell\ell$ ) $\gamma$



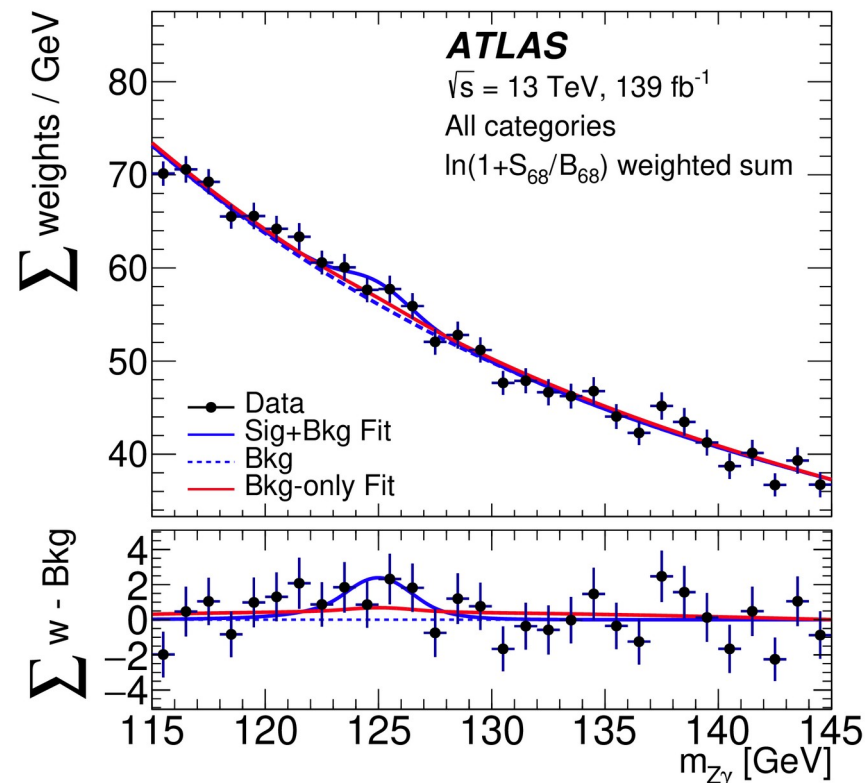
# Higgs $\rightarrow$ $Z(\ell\ell)\gamma$

- Similar to the low mass  $\ell\ell\gamma$  analysis,  $\ell$  = electrons or muons.
- Divided in six **categories** with different purity using a BDT:
  - **VBF (using BDT)**, high-relative  $p_T$  ( $p_T/m_{Z\gamma} > 0.4$ ), [high/low  $p_{T\ell}$ ]  $\times$  [ $\mu\mu$ ,  $ee$ ].
- **Background** non resonant  $Z(\ell\ell)\gamma$ , small contribution of  $Z(\ell\ell) + \text{jets}$
- Signal extracted fitting  $m_{Z\gamma}$  using **analytic function** for signal (double-sided crystal ball) and background based on templates.
- **Signal template**: from simulation,
- **Background template**: from simulation ( $Z\gamma$ , main background) and from control region ( $Zj$ ).
- Invariant mass resolution:
  - +3% recovering the energy from the **FSR**;
  - +14% using the **kinematic fit** for the Z boson mass (+10% for muons).

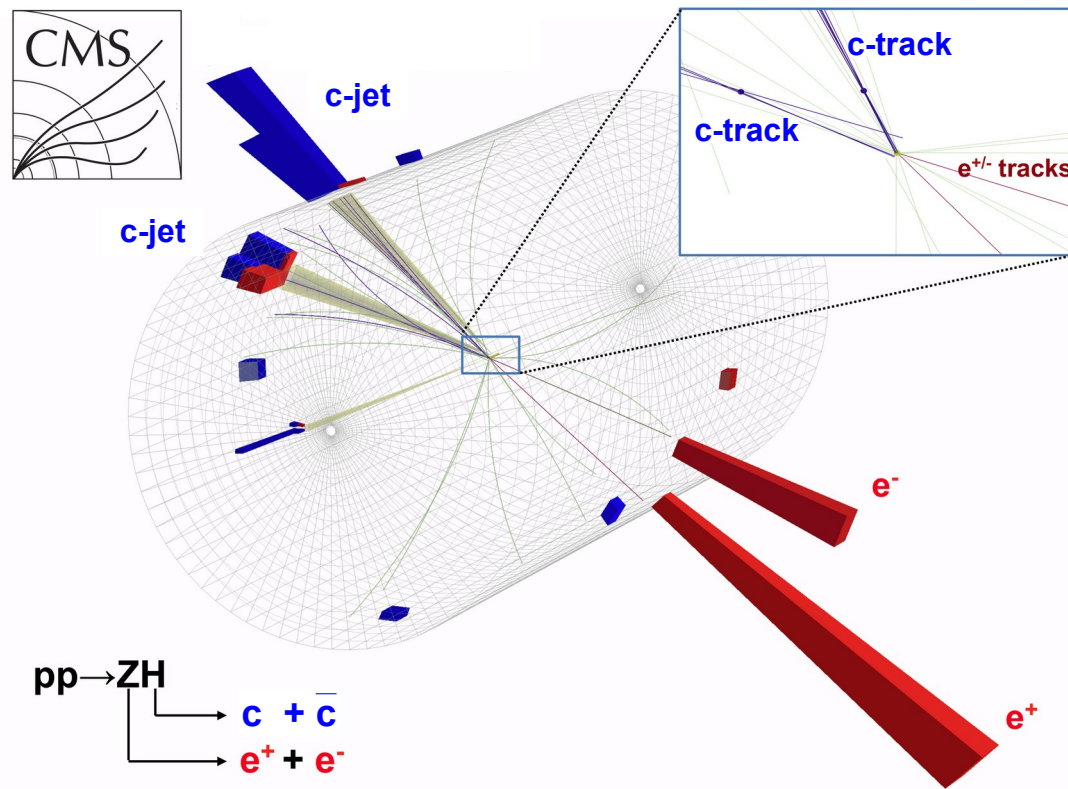


# Higgs $\rightarrow$ Z( $\ell\ell$ ) $\gamma$

- Full Run-2 result (ATLAS):
  - $\mu = 2.0 \pm 0.9$  (stat.)  $^{+0.4}_{-0.3}$  (syst.);
  - $2.2\sigma$  observed ( $1.2\sigma$  expected).
- CMS result (2016 only)
  - Z( $\ell\ell$ ) $\gamma$  +  $\gamma^*(\ell\ell)\gamma$  combination,
  - 95% CL upper limit:  
 $\mu < 3.9$  ( $\mu < 2.0$  exp.)

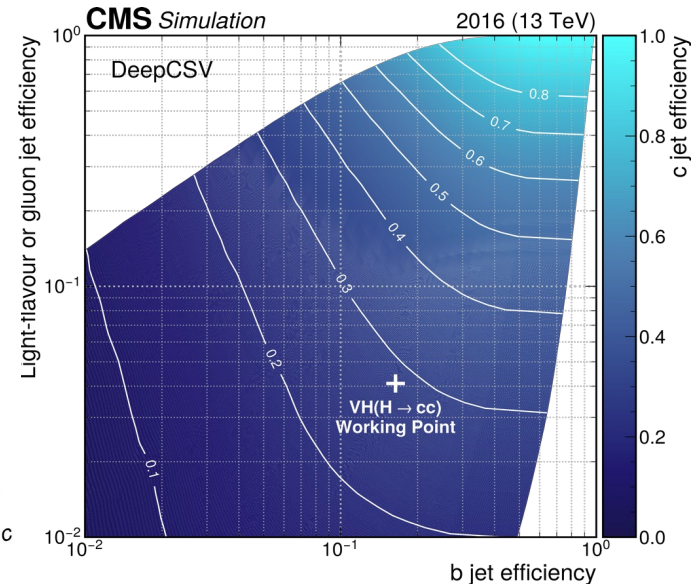
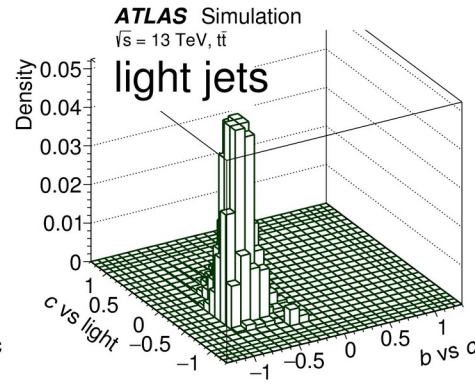
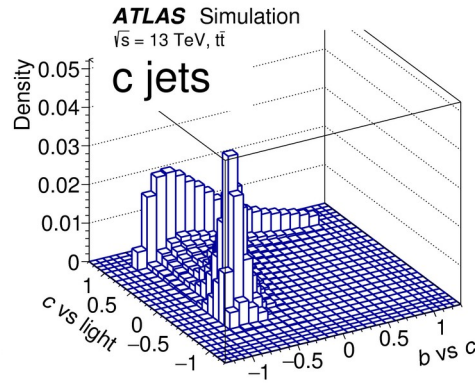
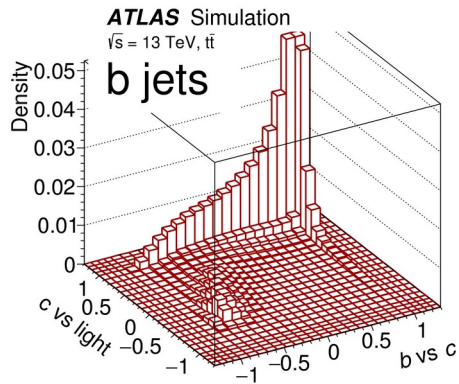


# Higgs $\rightarrow$ cc



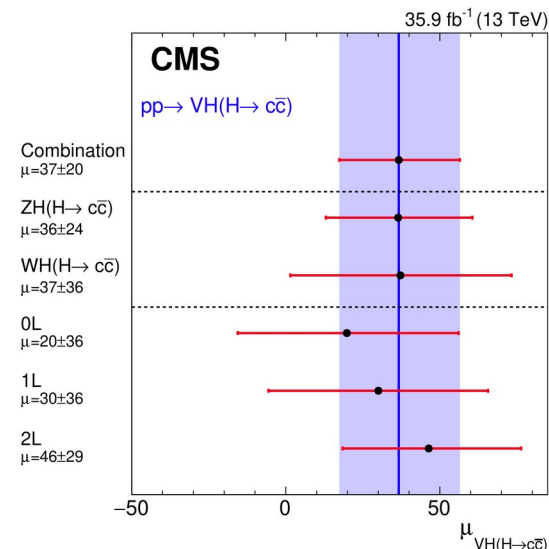
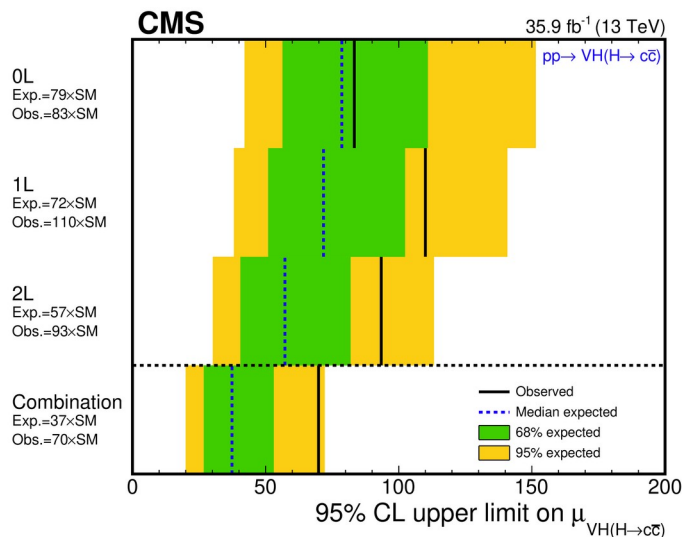
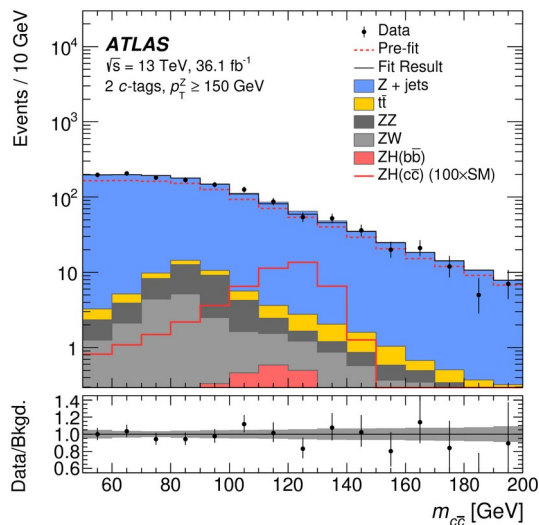
# Higgs $\rightarrow$ cc

- The  $H \rightarrow cc$  has been searched in the VH ch., similarly to **VH(bb)**.
  - First analysis by **ATLAS**, fit  $m_{cc}$  distribution in the resolved **Z( $\ell\ell$ )H(cc)** cat.
  - More recent analysis by **CMS** including both the resolved and merged H(cc);
    - signal extraction based on a BDT (**resolved** cat.) and on  $m_{SD}$  (**merged** cat.).
    - explores all the categories **Z( $\ell\ell$ )/W( $\ell\nu$ )/Z( $\nu\nu$ )H(cc)**,
  - **c-tagger** is a key ingredient.



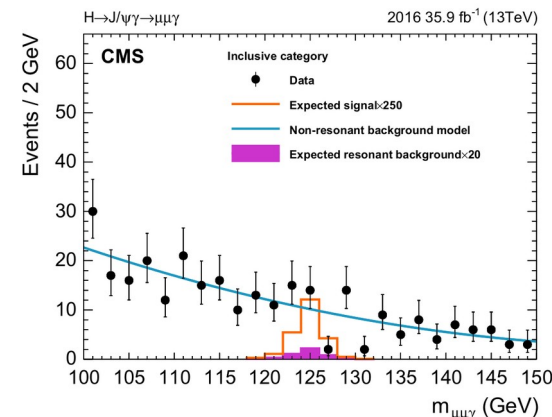
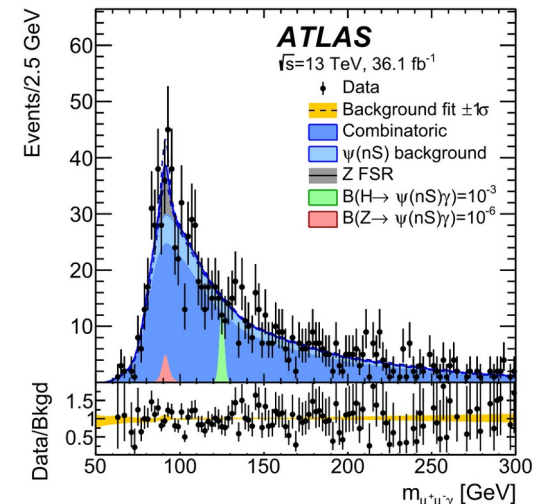
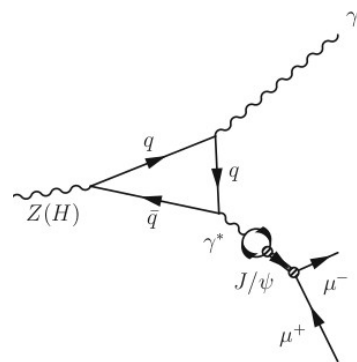
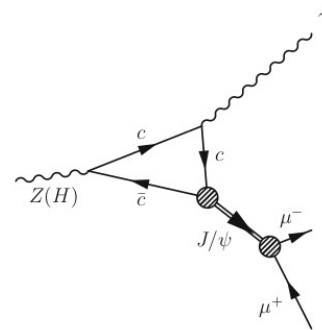
# Higgs $\rightarrow$ cc

- Results based on **2016 data** (36 fb<sup>-1</sup>):
  - **ATLAS**:  $\mu = -69 \pm 101$   $\rightarrow$  95% CL UL:  $\mu < 110$  (150 exp.)
  - **CMS**:  $\mu = 37 \pm 17$  (stat)  $_{-9}^{+11}$ (syst)  $\rightarrow$  95% CL UL:  $\mu < 70$  (37 exp.)
- Large improvements expected in Run-2 legacy analyses.



# Higgs $\rightarrow$ $J/\psi$ $\gamma$

- A further way to probe the coupling of the Higgs boson to c quark is the rare decay  $H \rightarrow J/\psi \gamma$ 
  - $B_{SM}(H \rightarrow J/\psi \gamma) = 3.0 \pm 0.2 \cdot 10^{-6}$ .
- The 95% CL upper limits:
  - ATLAS:  $BR < 3.5 \cdot 10^{-4}$  ( $3.0 \cdot 10^{-4}$  exp.)
  - CMS:  $BR < 7.6 \cdot 10^{-4}$  ( $5.2 \cdot 10^{-4}$  exp.)
- ATLAS set similar limits also for  $\psi(2s)$ ,  $\psi(3s)$ ,  $Y(ns)$



- A  $3\sigma$ -evidence for  $H \rightarrow \mu\mu$  and for  $H \rightarrow \gamma^*(\ell\ell)\gamma$  have been reported by CMS and ATLAS, respectively,
  - large improvement have been obtained wrt the previous analyses.
- Further improvements will be obtained with Run-3 data, and finally with HL-LHC data.
- We are probing the Higgs boson decays at the level of  $10^{-4}$  !
  - No significant deviation from the SM prediction has been found, so far...

