Latest Higgs results from ATLAS

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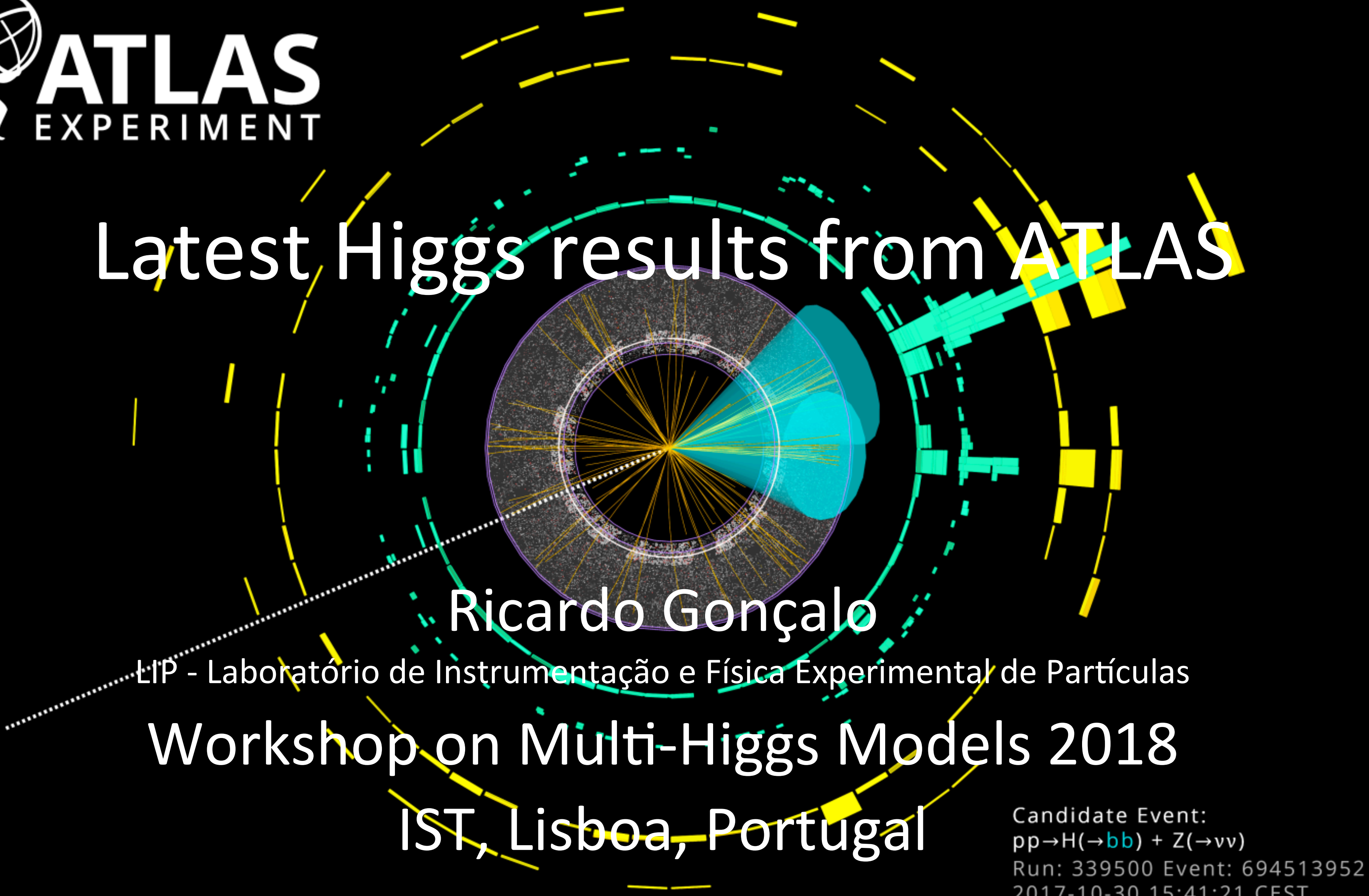
LIP - Laboratório de Instrumentação e Física Experimental de Partículas

Workshop on Multi-Higgs Models 2018

IST, Lisboa, Portugal



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COMPETE 2020

PORTUGAL 2020

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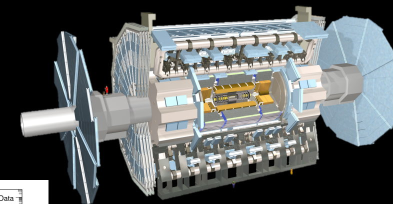
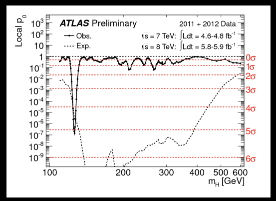
Outlook

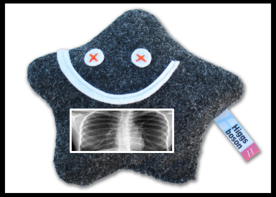
ATLAS and the LHC



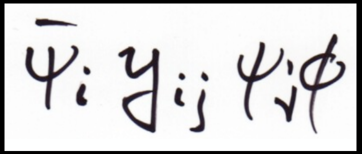
The Run 1 legacy



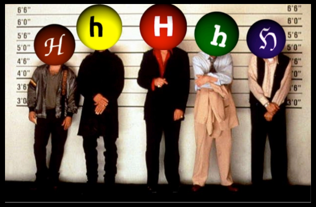
Probing the 125 GeV Higgs



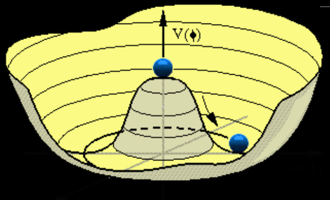
Probing the Yukawa sector



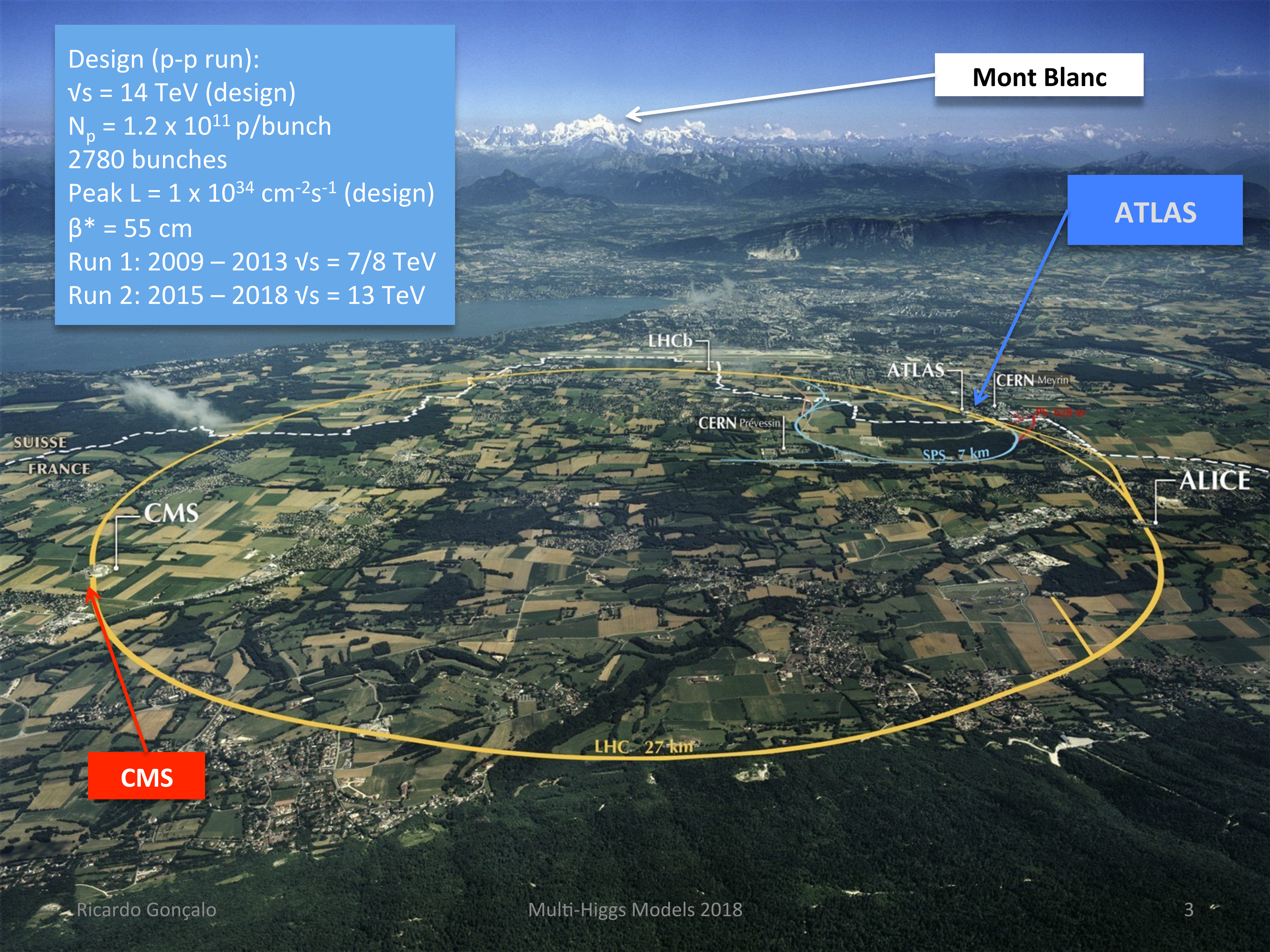
Searching wider



The long run: di-Higgs

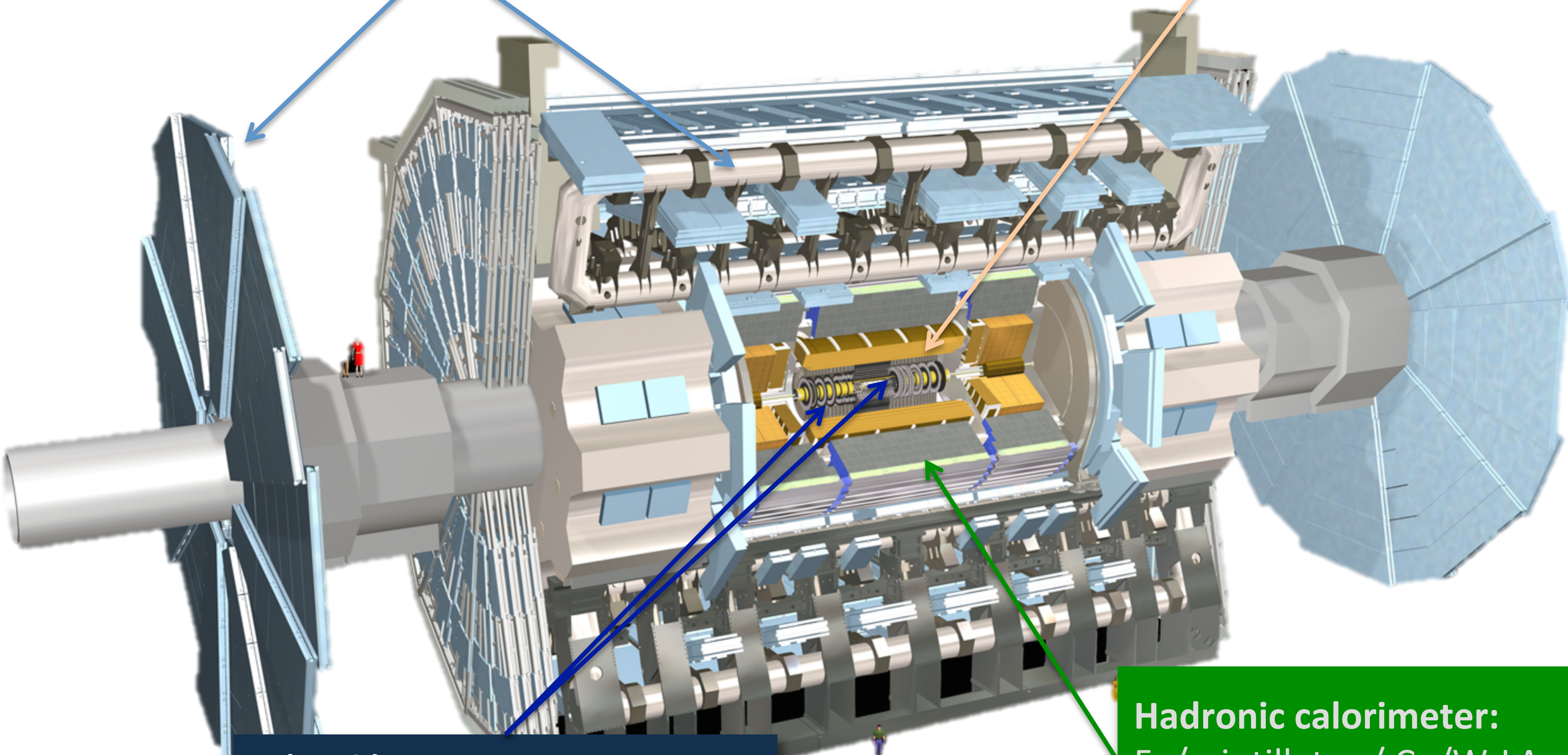


Design (p-p run):
$\sqrt{s}$ = 14 TeV (design)
$N_p = 1.2 \times 10^{11}$ p/bunch
2780 bunches
Peak L = 1×10^{34} $cm^{-2}s^{-1}$ (design)
β^* = 55 cm
Run 1: 2009 – 2013 $\sqrt{s}$ = 7/8 TeV
Run 2: 2015 – 2018 $\sqrt{s}$ = 13 TeV



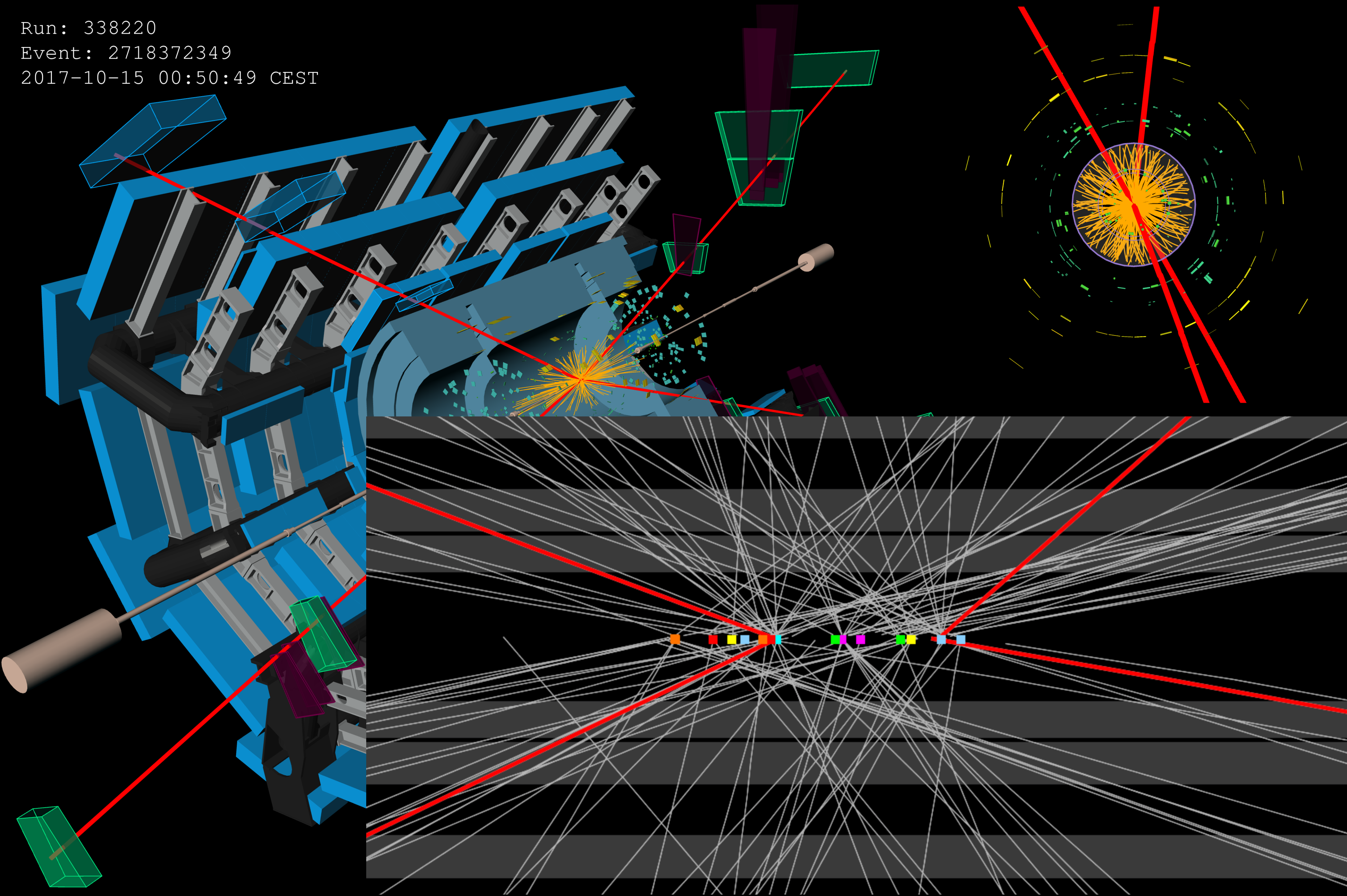
Muon Spectrometer: $|\eta| < 2.7$
Air-core toroid + gas-based muon chambers
σ/p_T = 2% @ 50GeV to 10% @ 1TeV (ID+MS)

EM calorimeter: $|\eta| < 2.5$ (3.2)
Pb-LAr accordion sampling
$\sigma/E = 10\%/\sqrt{E} \oplus 0.7\%$



Solenoid: B = 2 T
Inner Tracker: $|\eta| < 2.5$
Si pixels/strips and Trans. Rad. Det.
$\sigma/p_T = 0.05\%\ p_T\,(\text{GeV}) \oplus 1\%$

Hadronic calorimeter:
Fe/scintillator / Cu/W-LAr
$\sigma/E_{jet} = 50\%/\sqrt{E} \oplus 3\%$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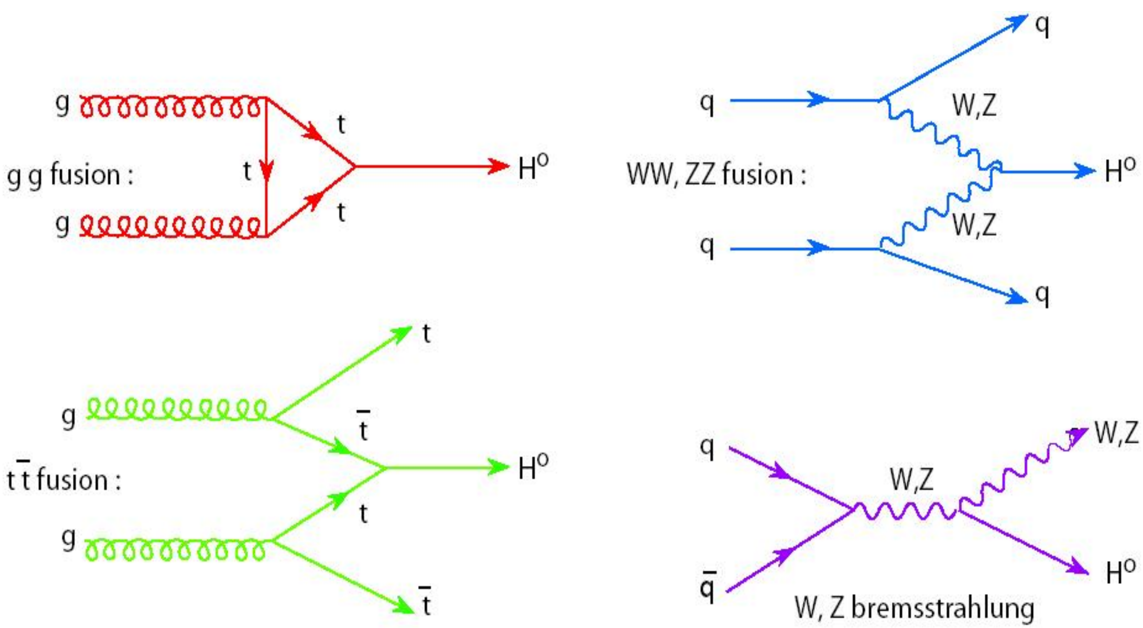
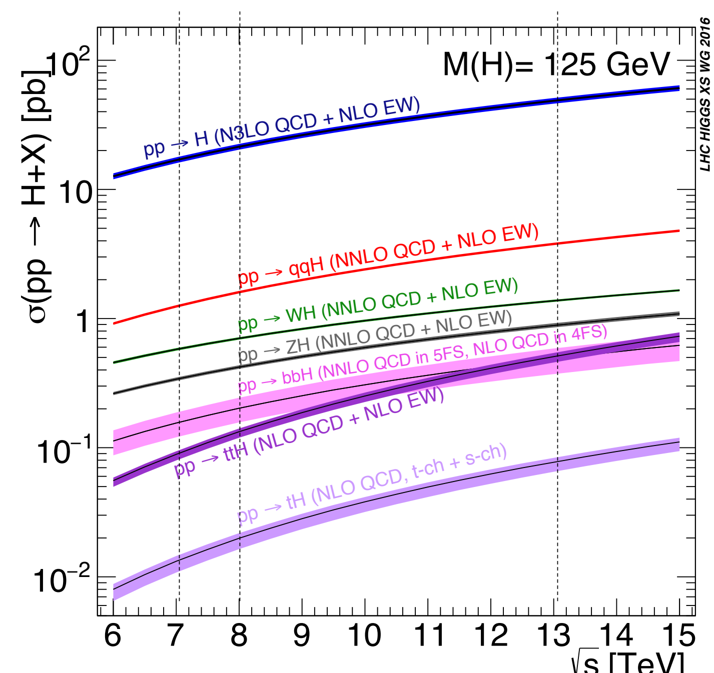
Higgs @ the LHC

- Many different production and decay mechanisms
  - Span 3 orders of magnitude in cross section and branching ratio
  - Some very clean decays with low BR (γγ, 4l)
  - Other very difficult with higher rates (bb, WW, ττ,...)
- Access Higgs properties through combination of different channels
- Enormous amount of progress since discovery 6 years ago!





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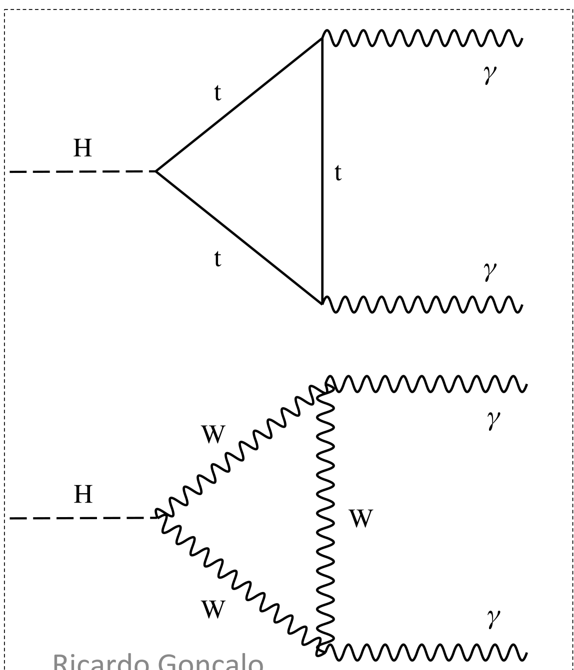
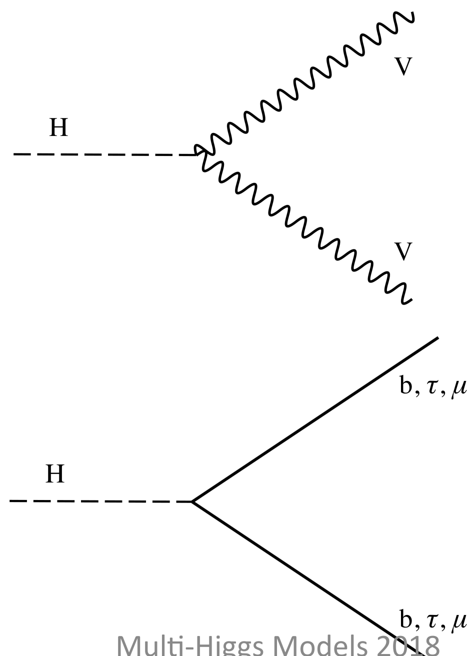
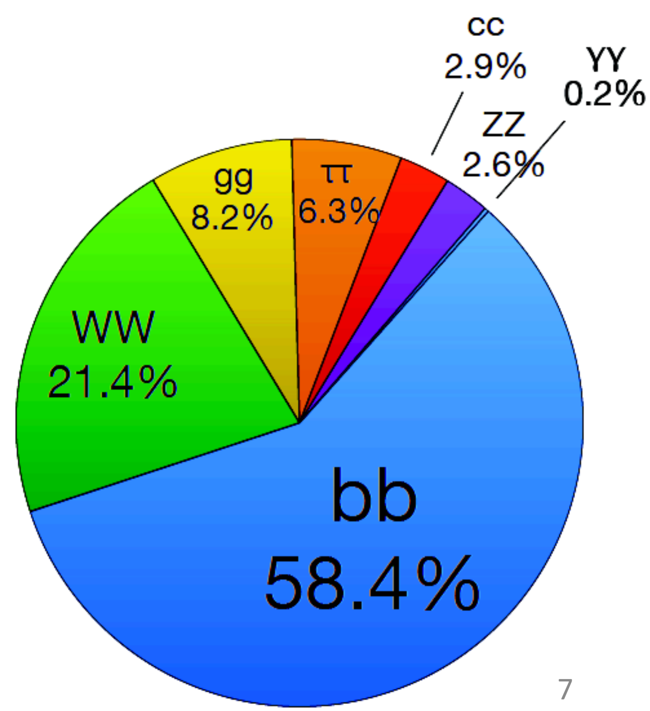
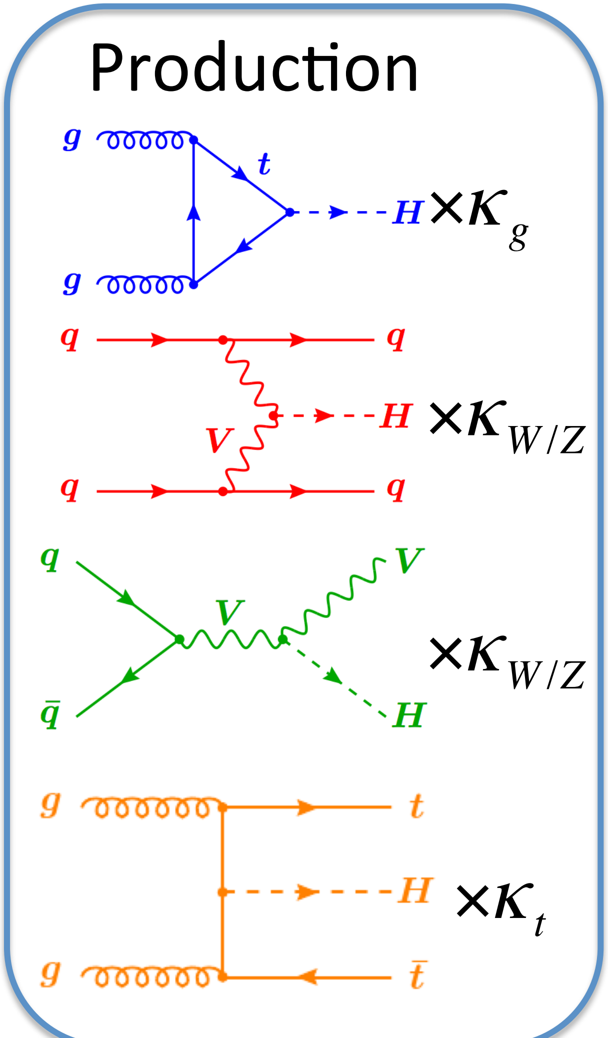






$$\kappa_i^2 = \sigma_i / \sigma_i^{SM} \qquad \kappa_f^2 = \Gamma_f / \Gamma_f^{SM} \qquad \mu = \frac{(\sigma \cdot BR)^{Obs.}}{(\sigma \cdot BR)^{SM}} = \kappa_i^2 \cdot \kappa_f^2$$



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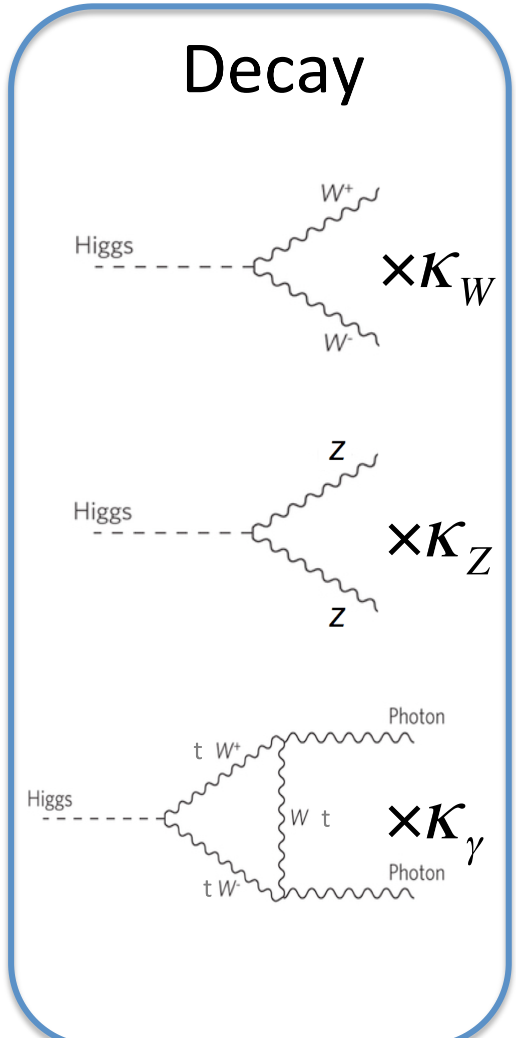
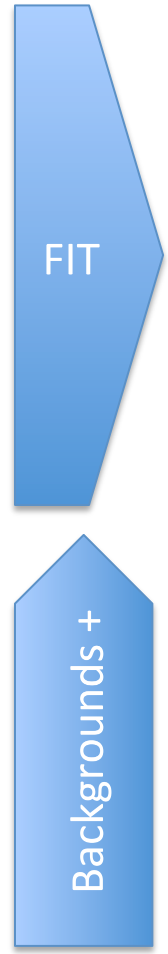
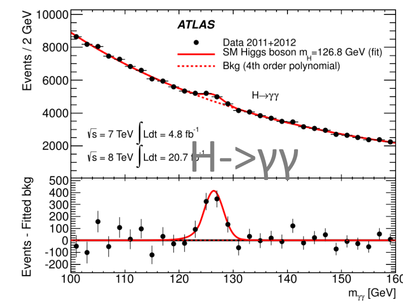
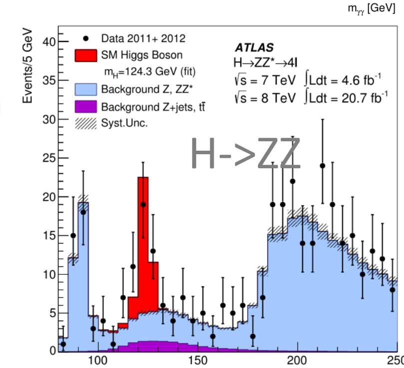
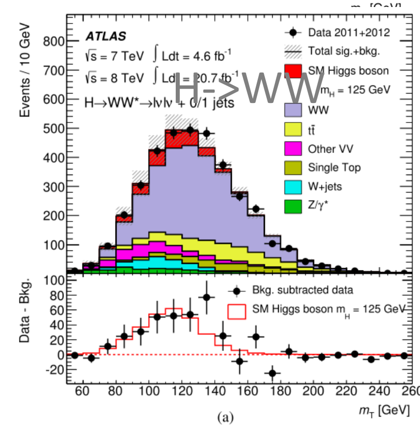
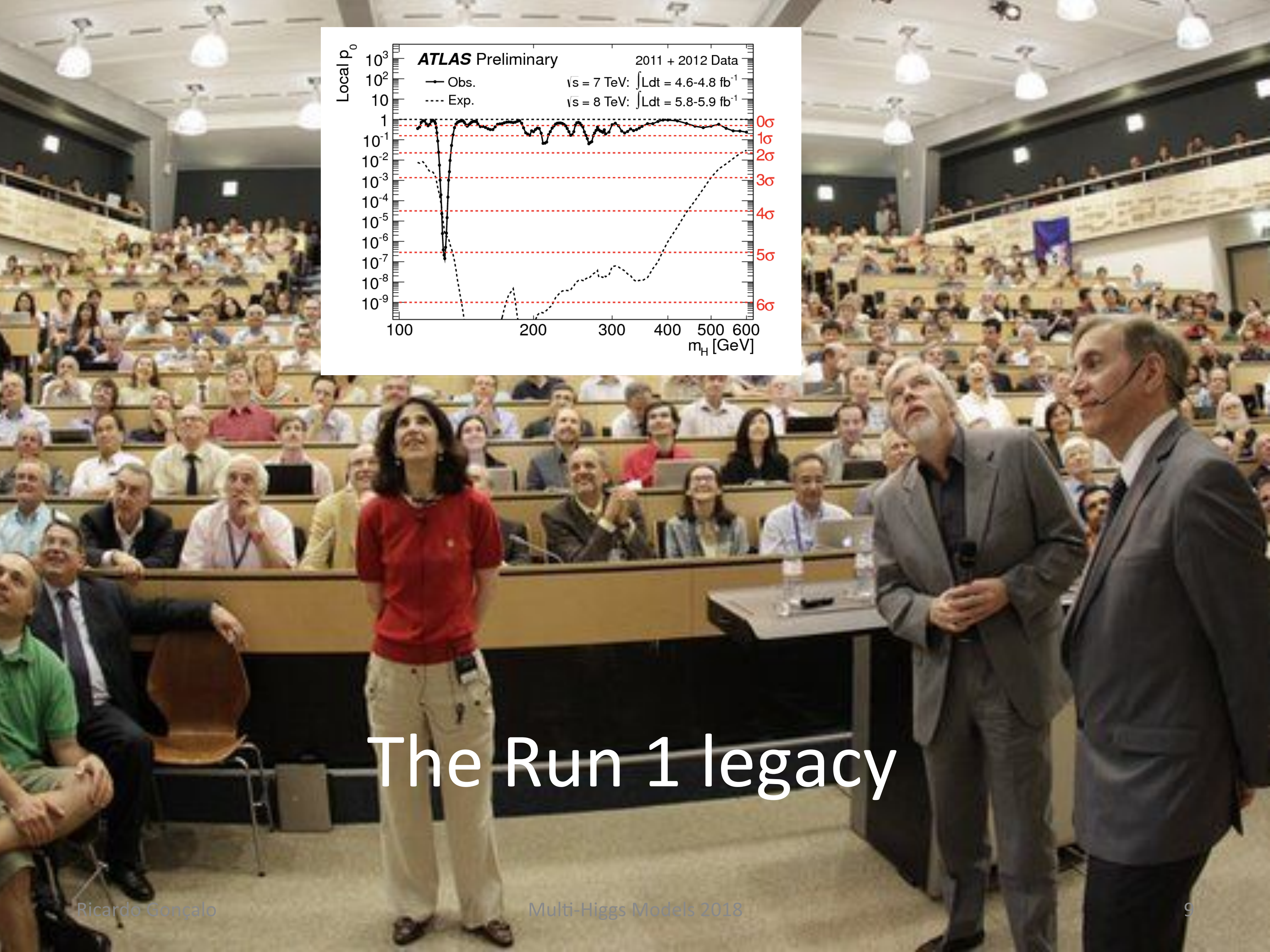












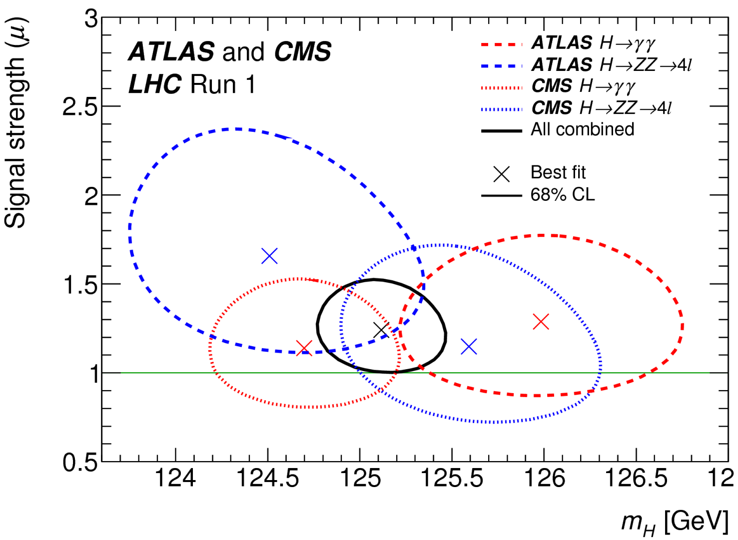
The Run 1 legacy

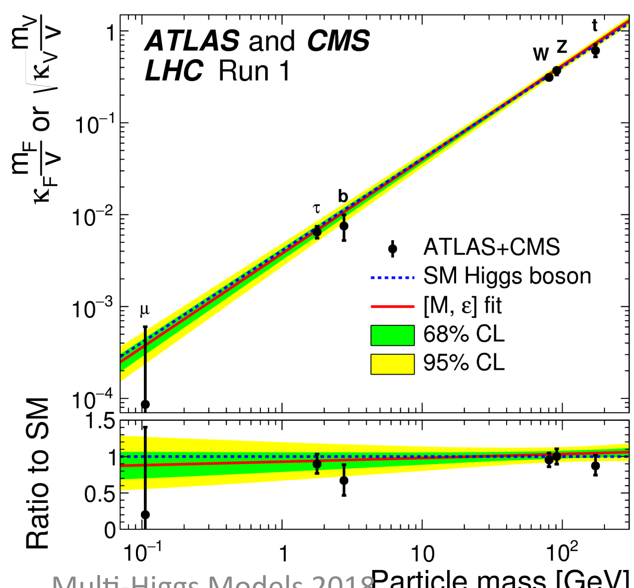
Phys. Rev. Lett. 114 (2015) 191803
JHEP 08 (2016) 045

The Run 1 legacy

- Mass – Higgs mass measured with 0.2% accuracy:
  - **m_H = 125.09 ± 0.21 (stat.) ± 0.11 (scale) ± 0.02 (other) ± 0.01 (theory) GeV**
- Couplings:
  - ggF with H → ZZ,γγ,WW **observed** by individual experiments
  - VBF and H → ττ observed with **>5σ** significance by ATLAS+CMS combination
  - ttH, VH production and H → bb **not observed** during Run1
- Couplings **compatible with SM**:
  - Signal strength: $\mu_{VBF+VH}/\mu_{ggF+ttH} = 1.06^{+0.35}_{-0.27}$
  - Coupling modifiers broadly consistent with SM but large uncertainty

$\mu = (\sigma \times BR)_{Obs} / (\sigma \times BR)_{SM}$





Significance (σ)		
Prod.	Obs.	Expect.
VBF	5.4	4.7
VH	3.5	4.2
ttH	4.4	2.0
Decay	Obs.	Expect.
H→ττ	5.5	5.0
H→bb	2.6	3.7

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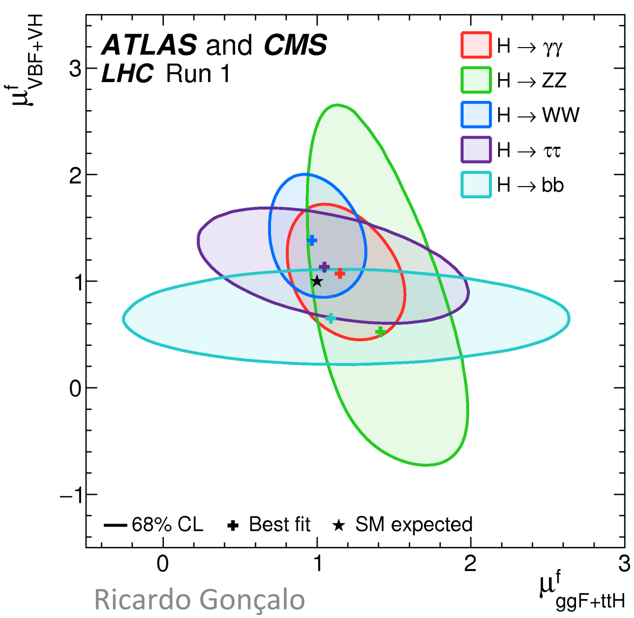

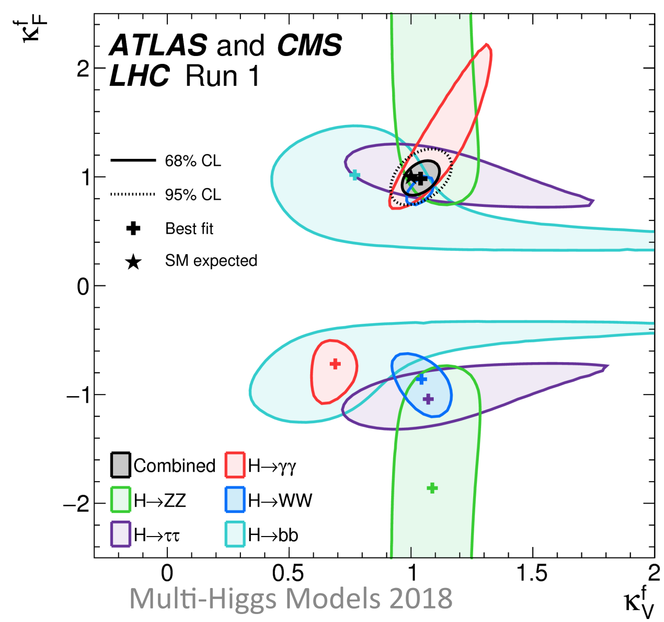

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Probing the 125 GeV Higgs

arXiv:1806.00242 [hep-ex]/Phys.Lett. B 784 (2018) 345–366

Higgs boson mass

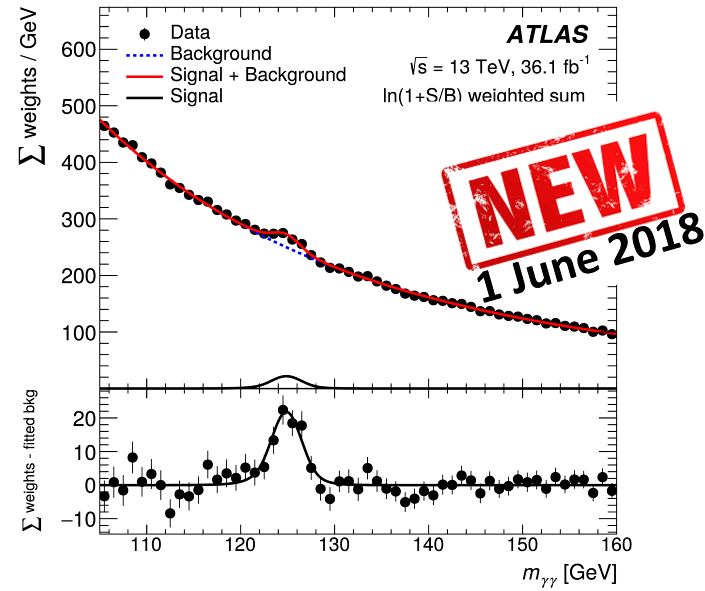
- Mass measurement from CMS H→ZZ*→4l:

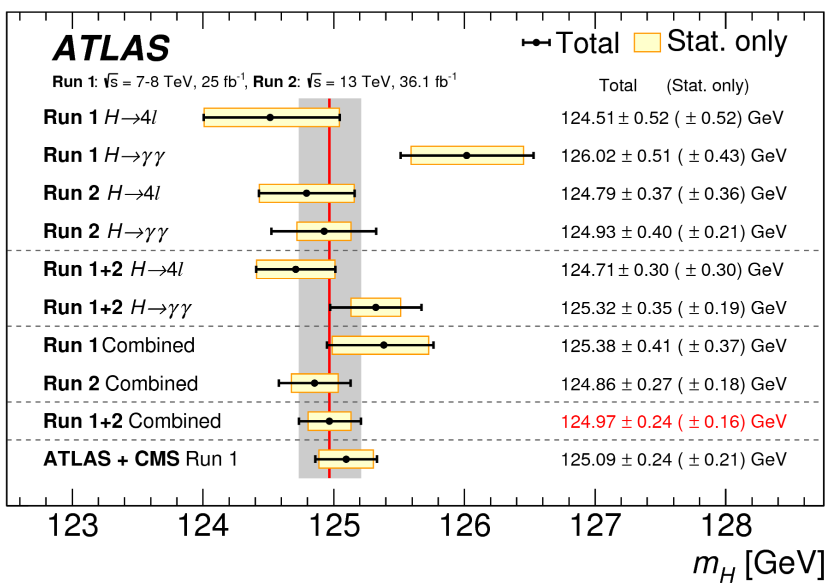
  m_H^{ZZ*}= 125.26 ± 0.20 (stat) ± 0.08 (syst) GeV
- New Measurements from ATLAS

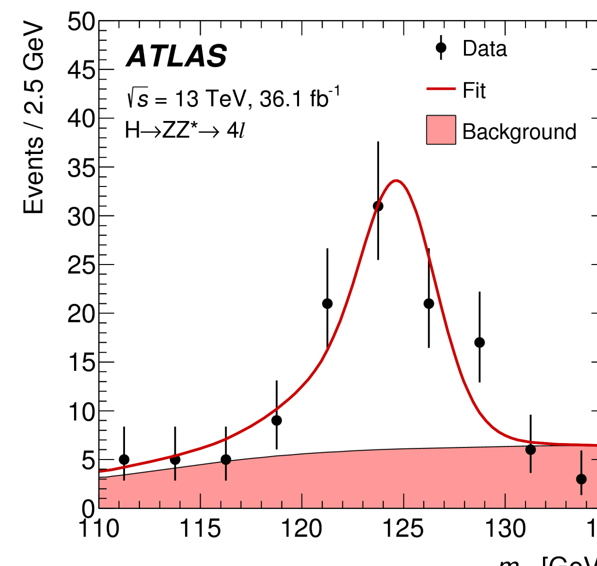
  H→ γγ: $m_H^{\gamma\gamma}$ = 124.93 ± 0.40 GeV

  H→ZZ*→4l: m_H^{ZZ*} = 124.79 ± 0.37 GeV
- Run 1+2 combination from ATLAS:

  m_H = 124.97 ± 0.19 (stat) ± 0.13 (syst.) GeV







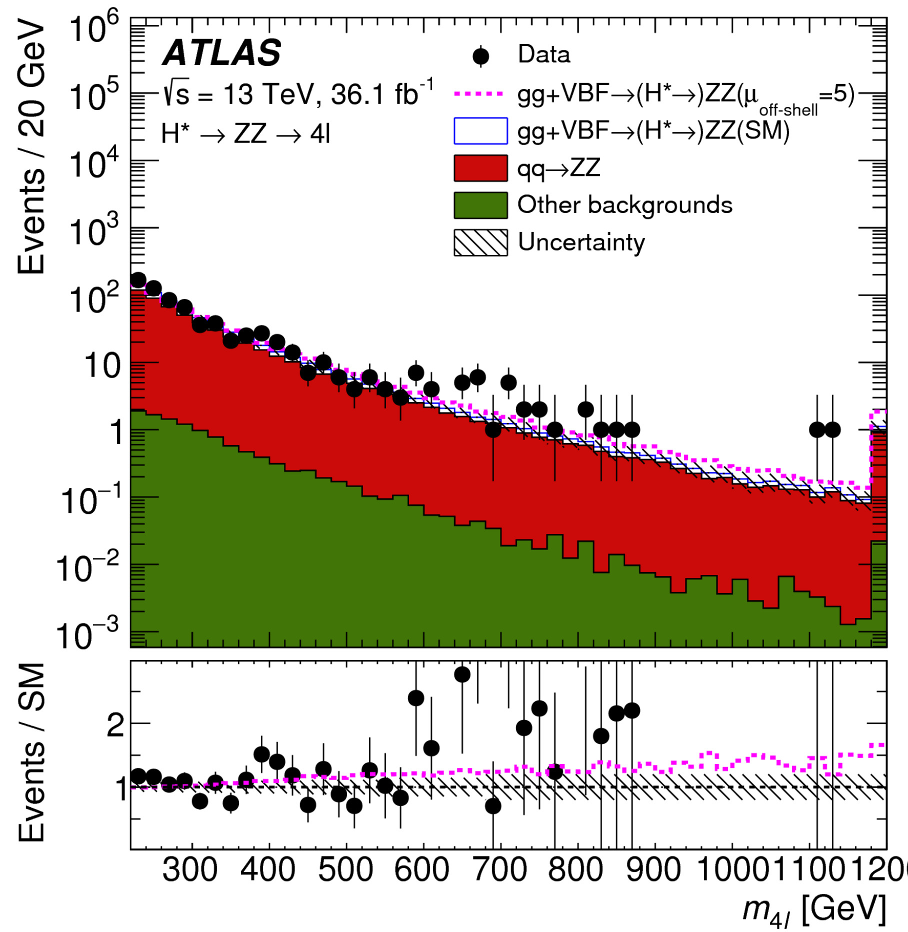
NEW
2 Aug 2018

Higgs boson width

- SM Higgs width Γ_H~4.1 MeV
  - Too small to be measured directly
  - Best direct limit from CMS:
    - Γ_H < 1.1GeV @ 95% CL
- Off-shell Higgs production sensitive(*) to Γ_H

$$\frac{\mu_{\mathrm{off-shell}}}{\mu_{\mathrm{on-shell}}} = \frac{\kappa^2_{\mathrm{g,off-shell}} \cdot \kappa^2_{\mathrm{Z,off-shell}}}{\kappa^2_{\mathrm{g,on-shell}} \cdot \kappa^2_{\mathrm{Z,on-shell}}} \frac{\Gamma_H}{\Gamma_H^{SM}}$$

- ATLAS measurement:
  - **pp→H→ZZ→4l** and ZZ→2l2ν
  - **m(H) > 2 m(Z)**
  - 36.1 fb^{-1} of 13 TeV data
  - Observed (expected) limit:
    - Γ_H < 14.4 (15.2) MeV



(*) Assume interference term with $gg \to ZZ$ proportional to $\kappa_{g,\text{off-shell}} \cdot \kappa_{Z,\text{off-shell}}$

Higgs boson cross sections

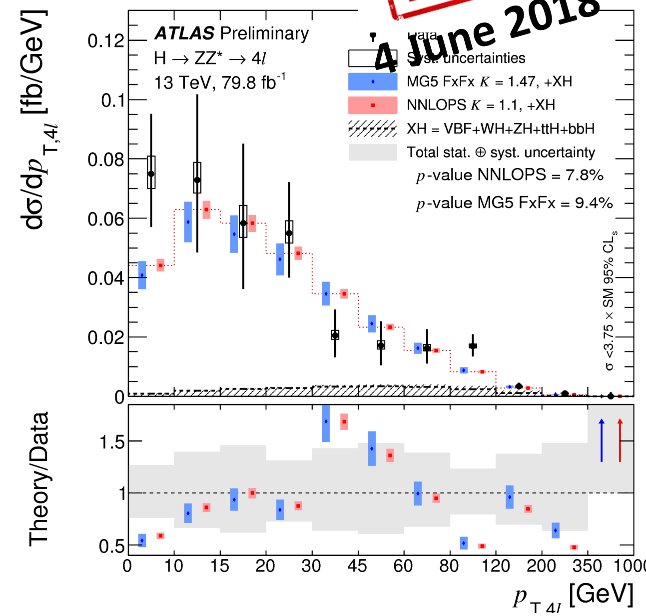
NEW

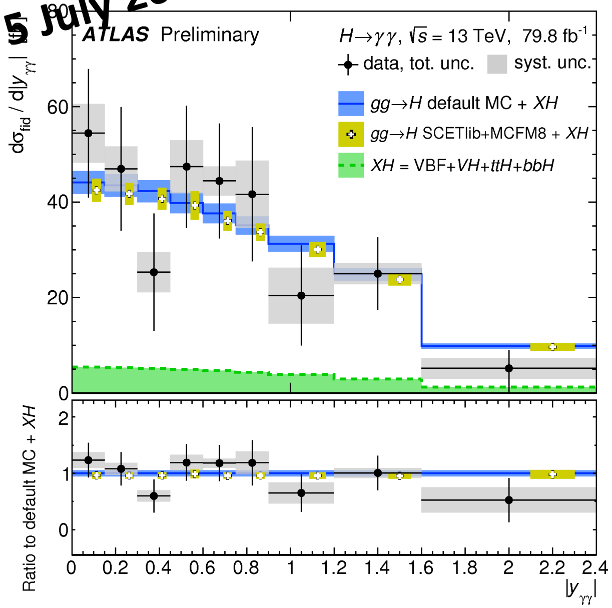
4 June 2018

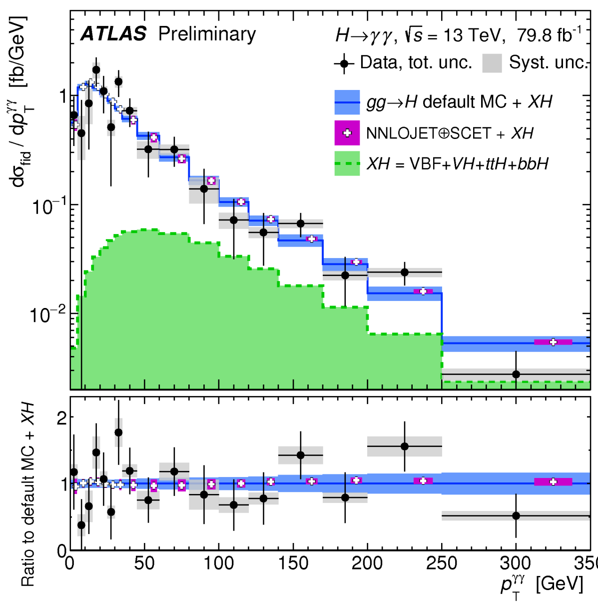
- Reached a new phase in the exploration of the Higgs sector!
- Differential cross sections:
  - Higgs p_T sensitive to new physics in gluon-fusion loop
  - Number of jets sensitive to modeling of radiation and different production modes

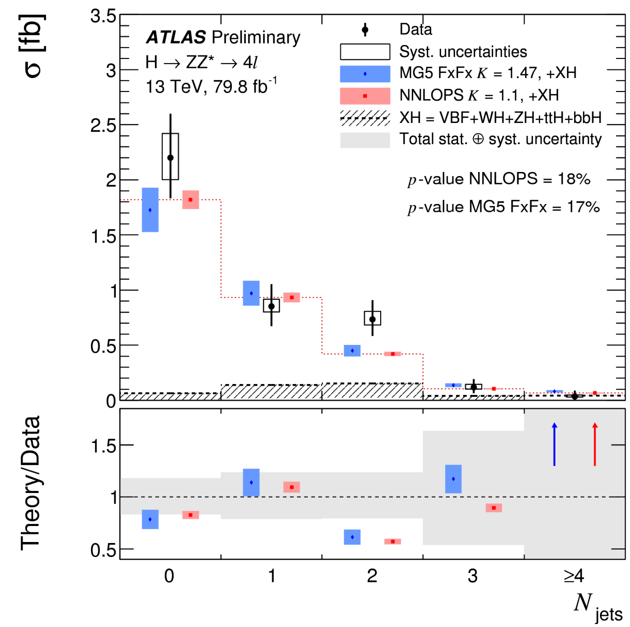
NEW

5 July 2018



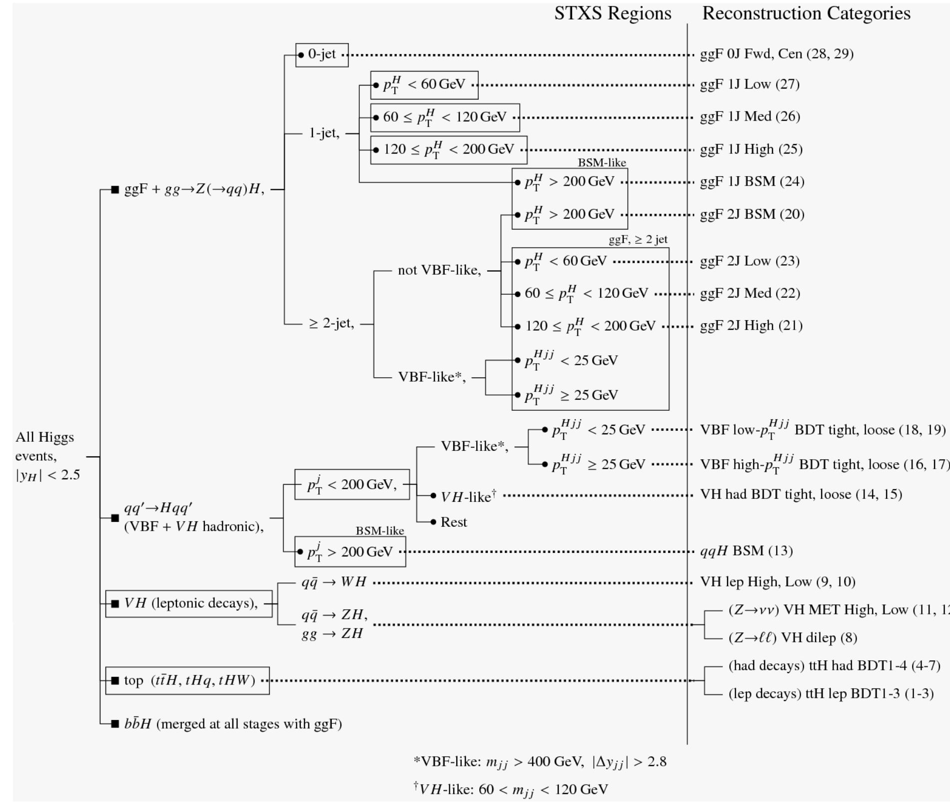


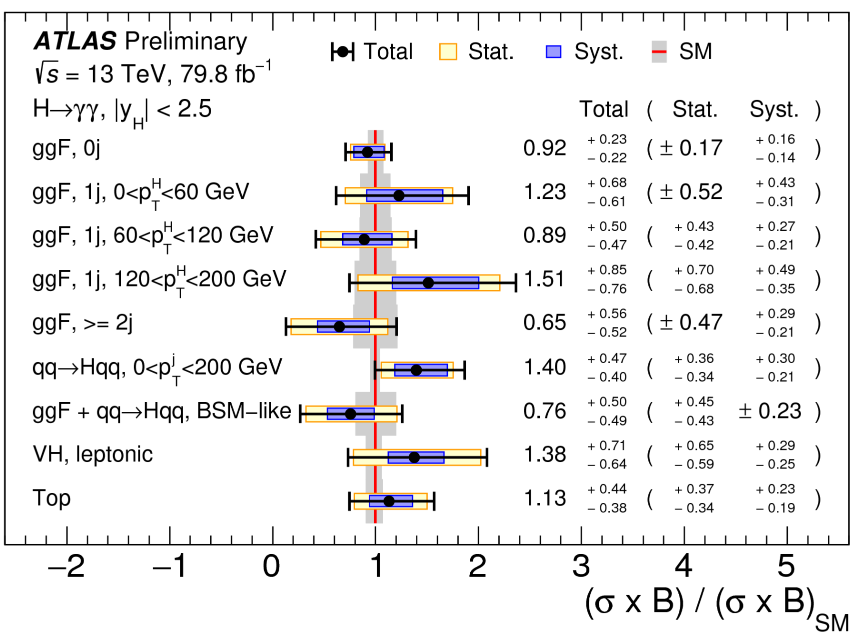


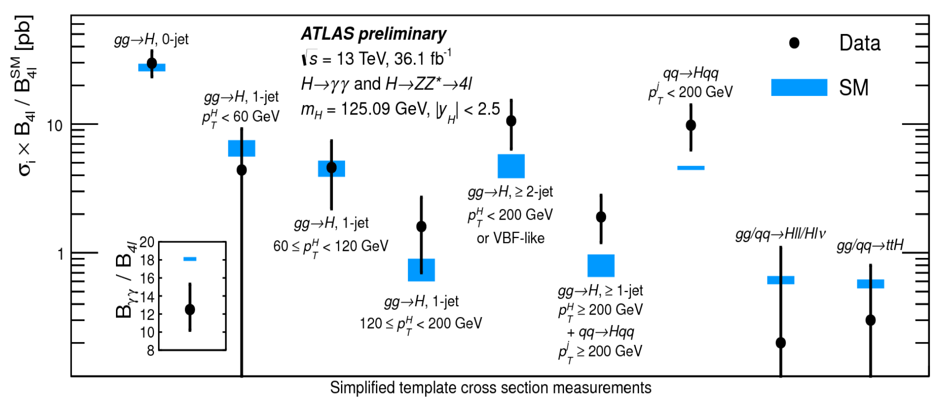


NEW
5 July 2018

- Simplified template cross sections (STXS):
  - Independent, simple fiducial region definitions for each Higgs production mode
  - Common for ATLAS, CMS and theory
  - Good balance between experimental precision and theory uncertainty

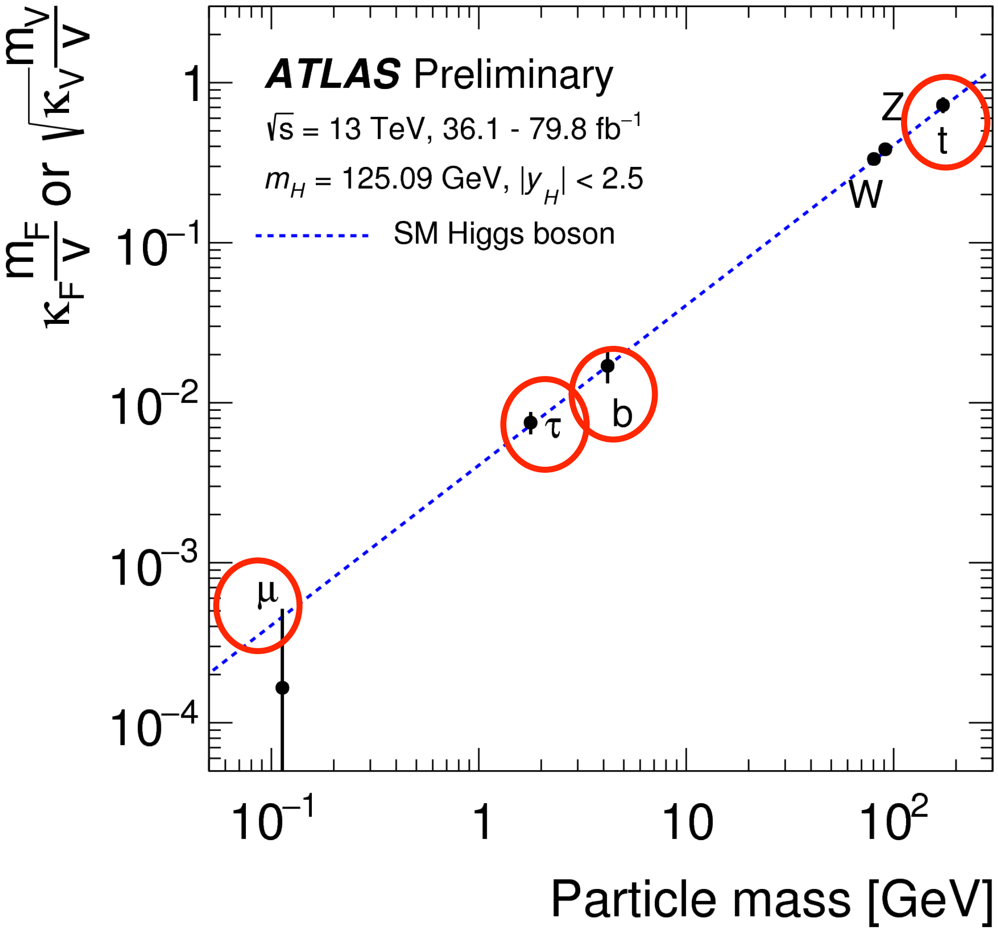






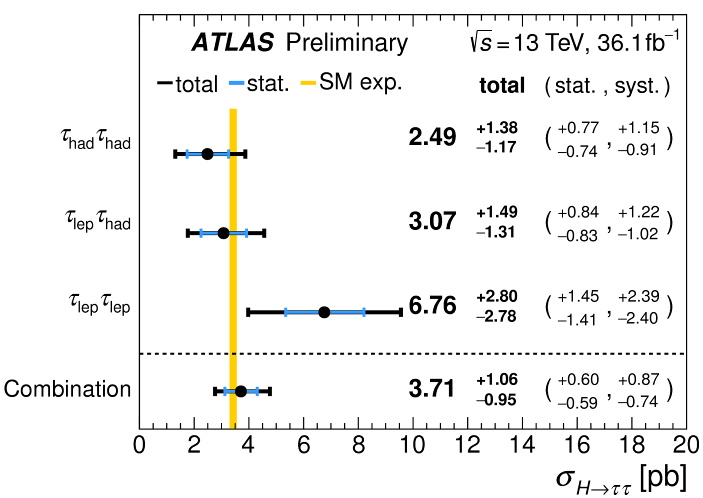
Models 2018

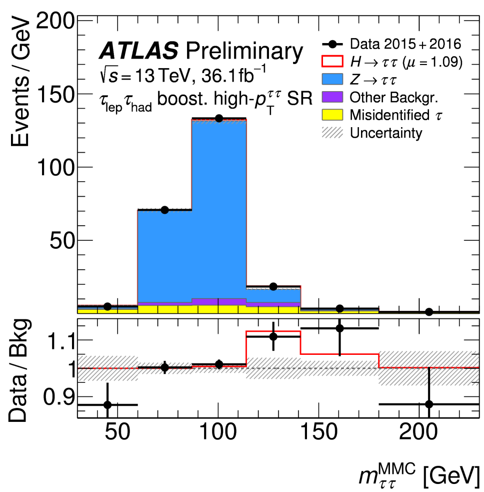
Exploring the Yukawa sector

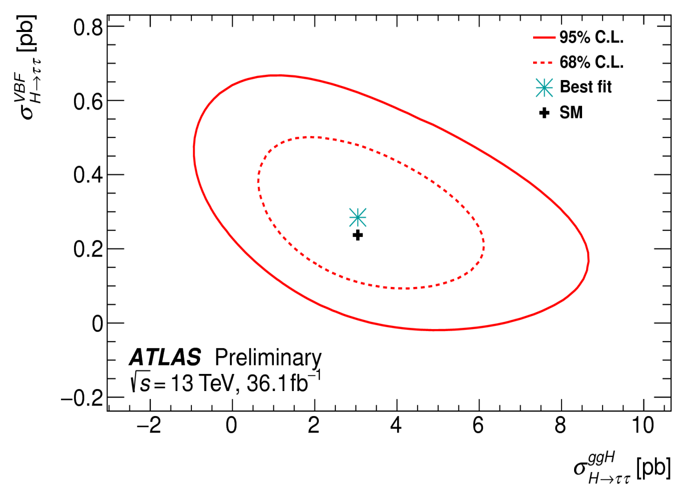


Observation of H→ττ

- Combine all final: $\tau_{had}\tau_{had}$, $\tau_{lep}\tau_{had}$, $\tau_{lep}\tau_{lep}$
- Categories targeting boosted Higgs (mostly ggF) and VBF (additional jets)
- Dominant backgrounds from $Z\rightarrow\tau\tau$ and jets faking taus
- Cut-based analysis using fit to $m_{\tau\tau}$ distribution in 13 signal regions
- Largest uncertainties: data and MC statistics, signal modelling and jets
- Cross section measurement (13 TeV):
- σ^{ggF} = 3.0 ± 1.0 (stat.) $^{+1.6}_{-1.2}$ (syst.) pb; σ^{VBF} = 0.28 ± 0.09 (stat.) ± 0.10 (syst.) pb
- Significance:
  - 36 fb^{-1} of 13 TeV data: 4.4 σ observed; 4.1 σ expected
  - Combining with 7 and 8 TeV data: 6.4 σ observed; 5.4 σ expected





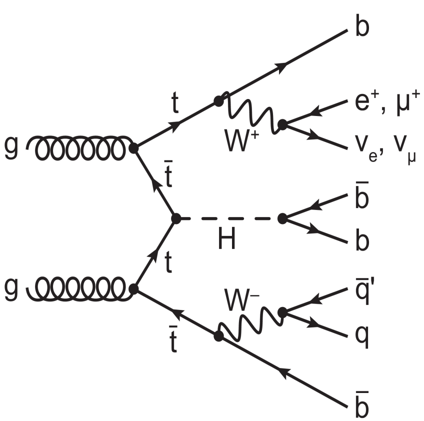


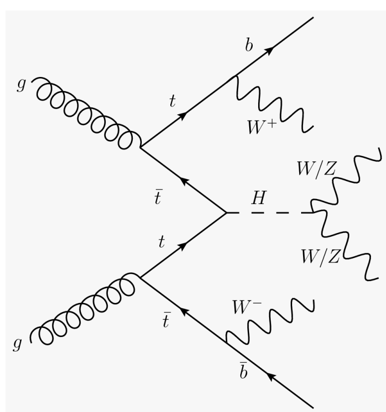
Observation of ttH production

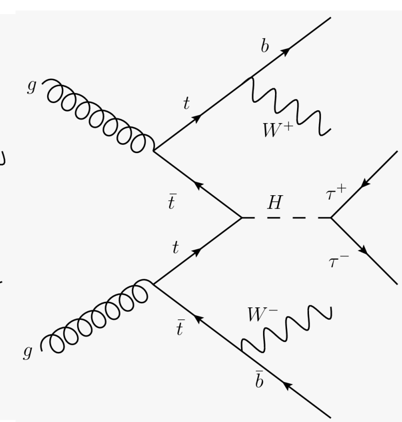
- **Direct** access to top Yukawa coupling
- Experimental tour-de-force!
  - Complex final states
  - Large irreducible backgrounds
  - Small cross sections: O(0.5)pb @ 13 TeV

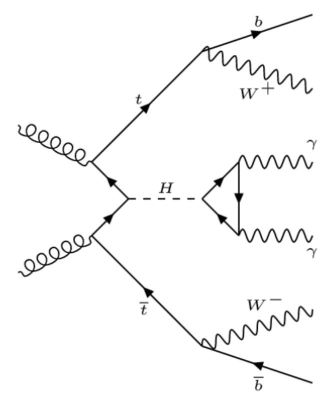
1 June 2018

- Use all available final states:
  - **H→bb**: high stats but low purity BR≈58%, S/B≈1-6%
  - **Multileptons:** H→$\tau\tau$, H→WW*, H→ZZ* BR = 30%, S/B=4-34%
  - **H→$\gamma\gamma$**: clean but low stats BR = 0.23%, S/B=5-200%
  - **H→ZZ*→4lep**: clean but very low stats BR = 0.01%, S/B=50-500%





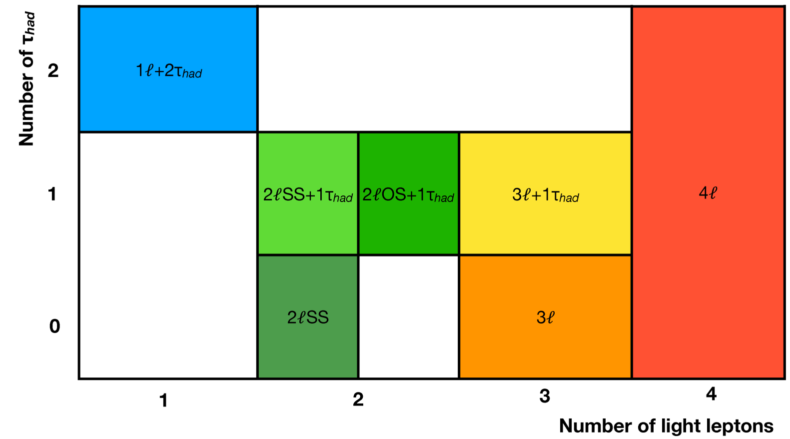




ttH observation: bb and Multileptons

ttH(H→leptons)

- Sensitive to: H→$\tau\tau$, H→WW* and H→ZZ*
- Backgrounds: ttW/ttZ, non-prompt leptons and jets faking taus
- Main uncertainties: signal modelling, jet energy scale and non-prompt lepton estimate
- 4.1σ observed; 2.8σ expected

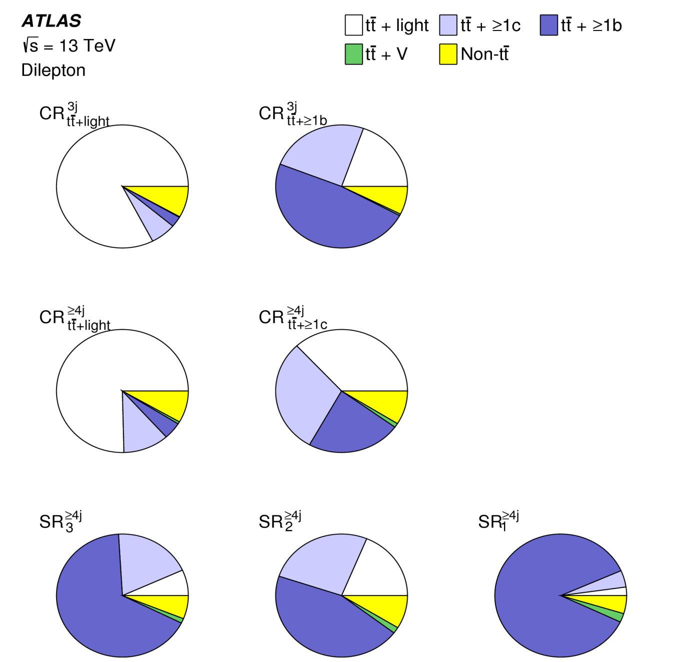


ttH(H→bb):

- Profit from large H→bb branching ratio (58.4%)
- But challenging final state: large ttbb irreducible background, theory uncertainties, combinatorics...
- Main uncertainties: tt+heavy flavours, b tagging, jet calibration
- ATLAS: 1.2σ observed; 1.6σ expected

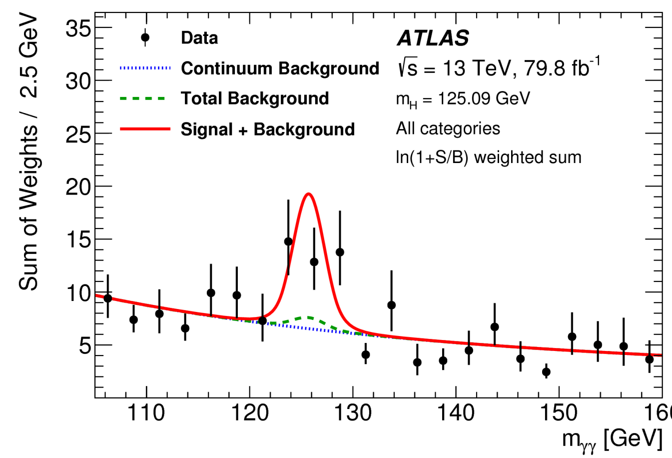
For **both** channels:

- Intensive use of dedicated machine learning (NN, BDT) and matrix element methods: suppress fake leptons, reconstruct events, flavour tagging, and enhance S/B



ttH(H→γγ) and Combination

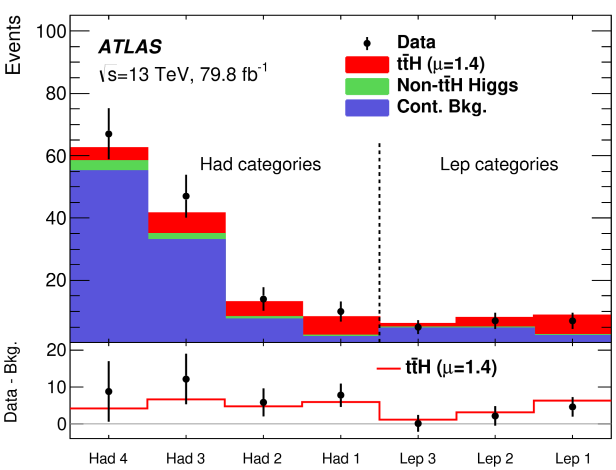
- ttH(H→$\gamma\gamma$):
  - New signal categories from BDT discriminant
  - **Sensitivity increased by 50%**

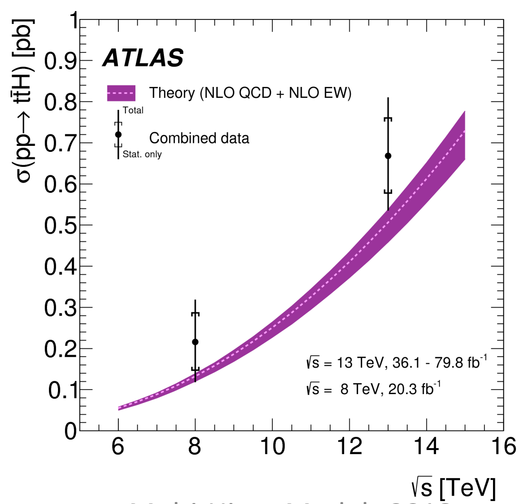


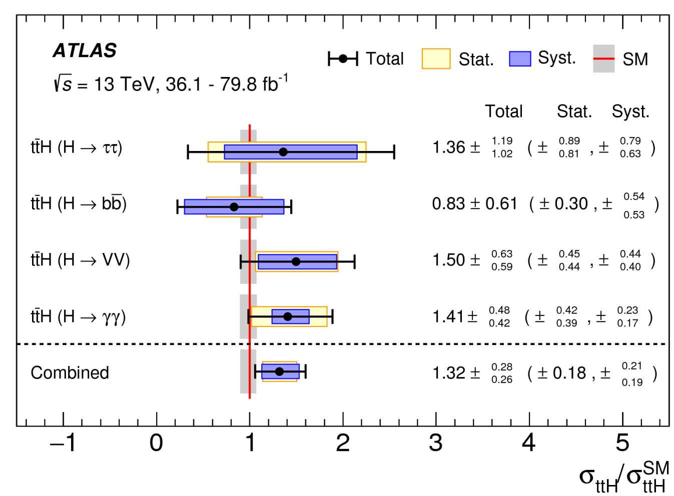
ttH combination: ttH(H→leptons + H→bb + H→γγ)

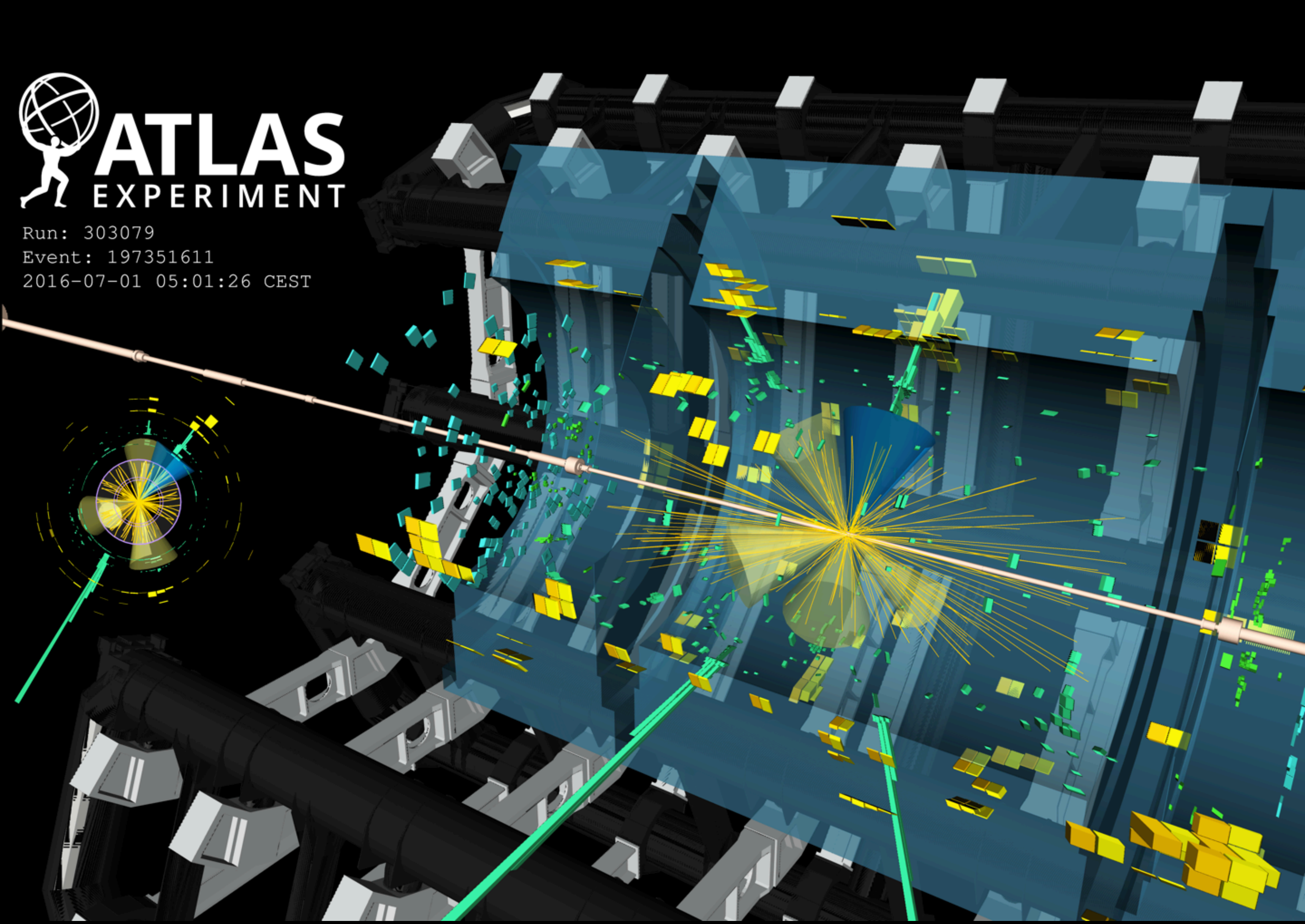
- Run 2 data from 2015+2016+2017 ($\gamma\gamma$/ZZ): 79.8 fb^{-1}
  - 5.2 σ observed, 4.9 σ expected
- Adding Run 1: 6.3 σ observed, 5.1 σ expected
- Measured production cross section at 13 TeV:

  670 ± 90 (stat.) +110–100 (syst.) fb



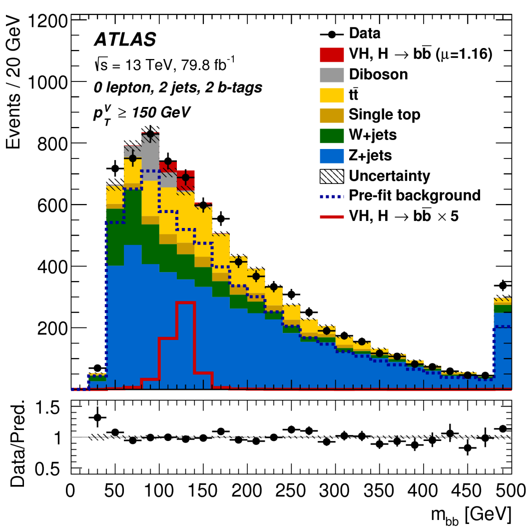


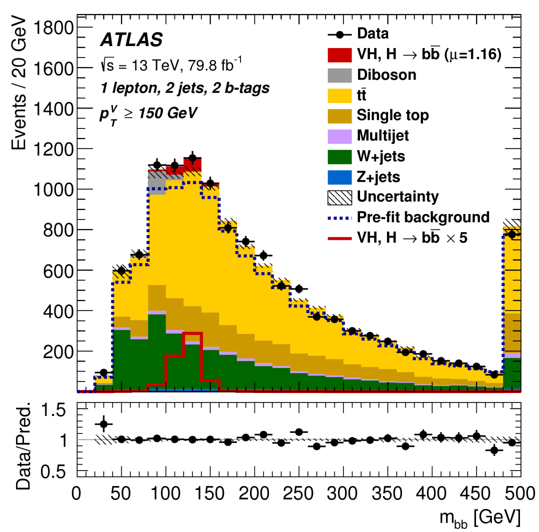


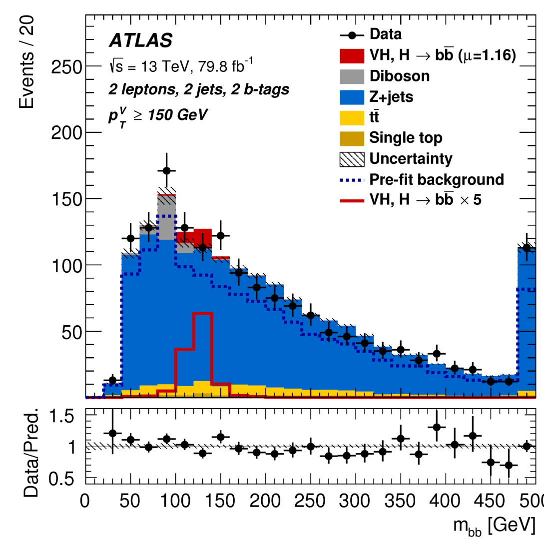

ATLAS
EXPERIMENT
Run: 303079
Event: 197351611
2016-07-01 05:01:26 CEST

Observation of H→bb

- See **CERN seminar last week**! (https://indico.cern.ch/event/750541/)
- Largest branching fraction (58.4%) but huge background from heavy flavour production
- Must use associated production: WH/ZH
  - Require 2 b jets + 0 (Z→$\nu\nu$), 1 (W→$\ell\nu$) or 2 (Z→$\ell\ell$) leptons
- Largest backgrounds:
  - Z+heavy flavour (0- and 2-lepton) and tt (1-lepton)
  - Irreducible background from VZ with Z→bb

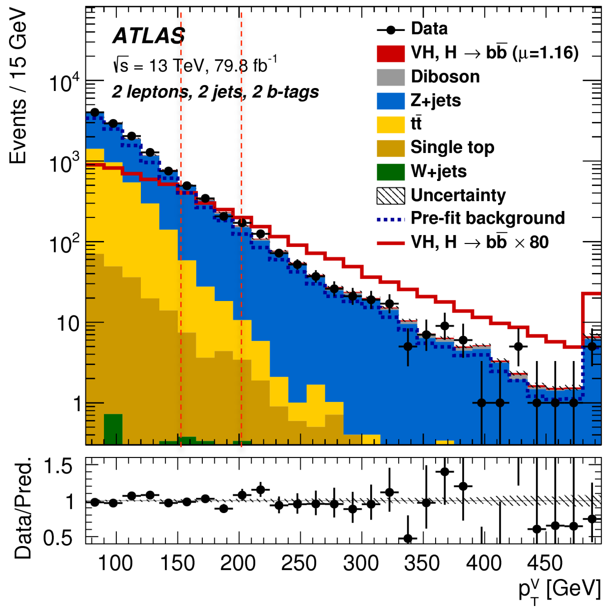




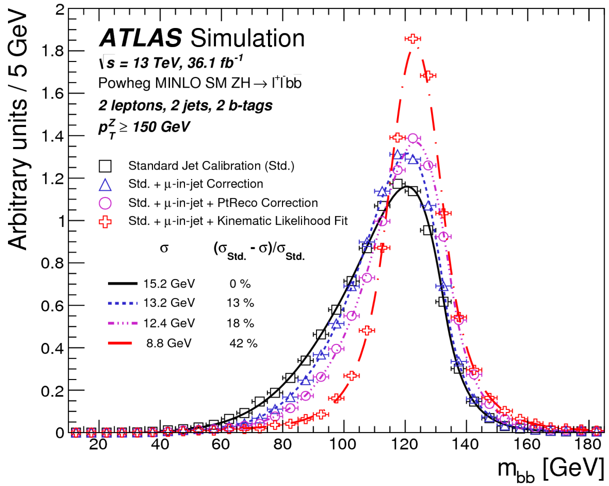


Observation of H→bb

- Harder p_T spectrum for signal than backgrounds
  - Go to high p_T to improve S/B
- Use for event categories:
  - $75 < p_T^V < 150$ GeV (2ℓ only)
  - $150 < p_T^V < 200$ GeV
  - $p_T^V > 200$ GeV

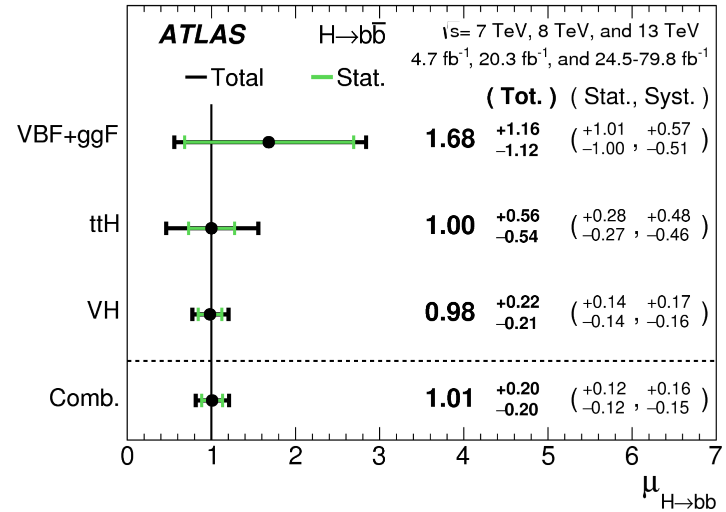


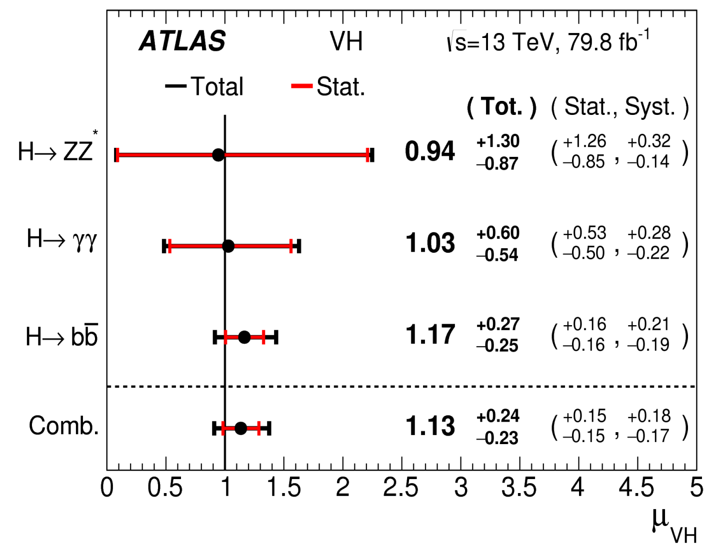
- Main discriminant variables m_{bb}, p_T^V and ΔR_{bb}
  - m_{bb} resolution extremely important!

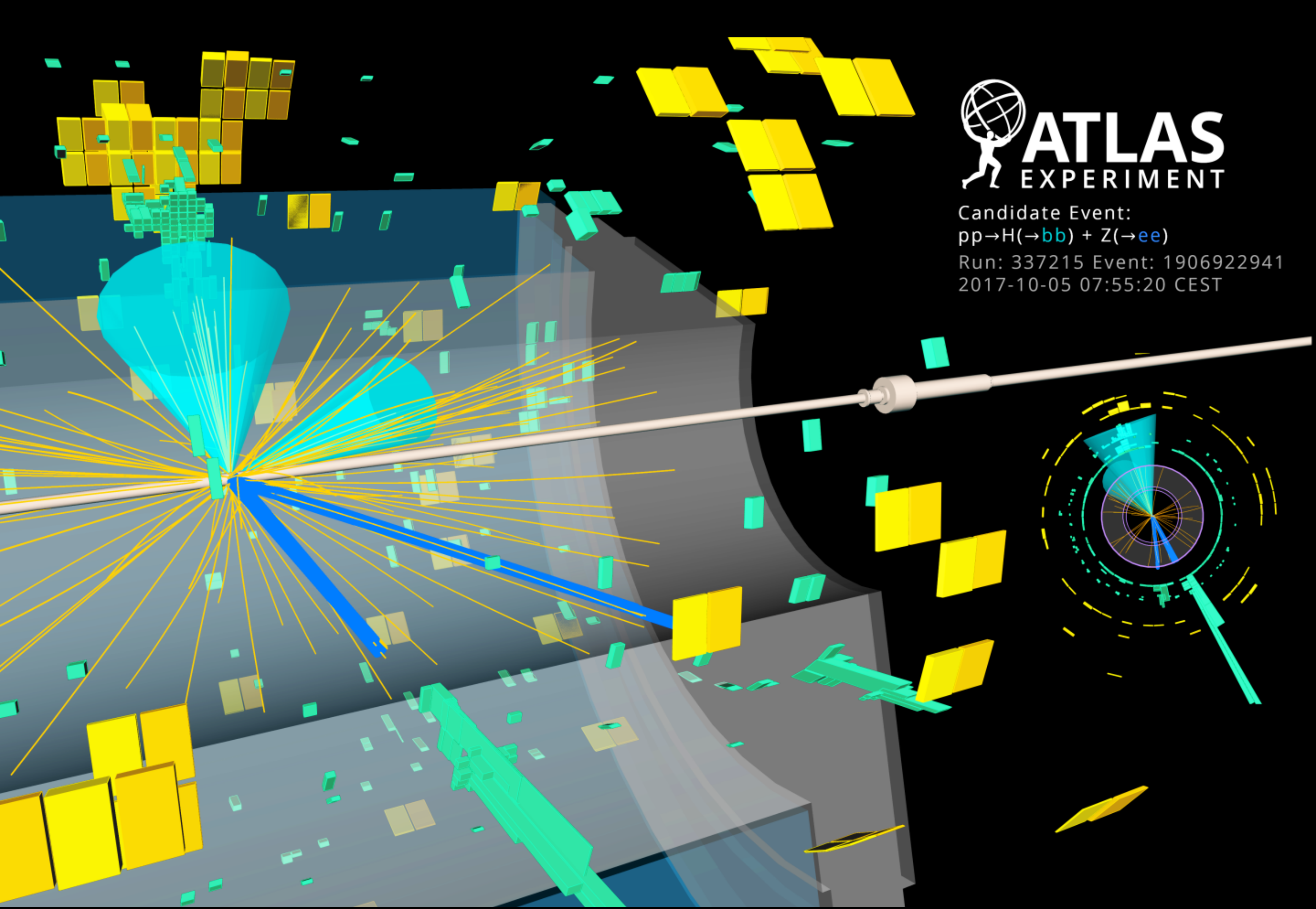


Observation of H→bb

- Run 2:
  - Observed (expected) of 4.9σ (4.3σ)
- Adding Run 1:
  - Observed (expected) of 4.9σ (5.1σ)
- Adding ttH and VBF:
  - Observed (expected) of 5.4σ (5.5σ)
  - **Observation of H→bb decays**
- Adding H→ZZ and H→γγ:
  - Observed (expected) of 5.3σ (4.8σ)
  - **Observation of VH production**





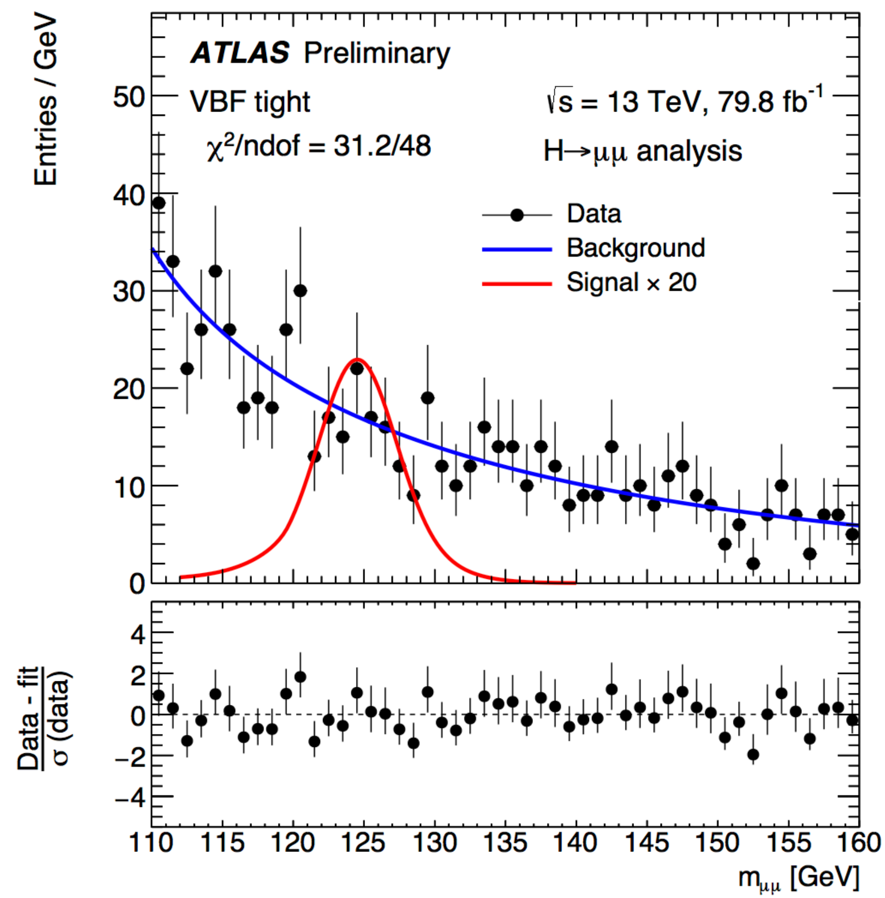

ATLAS
EXPERIMENT
Candidate Event:
pp→H(→bb) + Z(→ee)
Run: 337215 Event: 1906922941
2017-10-05 07:55:20 CEST

2nd generation Yukawa: H→μμ

NEW

2 July 2018

- Easy to trigger on, but very rare
- Used 80 fb^{-1} of 13 TeV data
- Event categories based on muon η, $p_T^{\mu\mu}$, and VBF (BDT)
- Search peak in $m_{\mu\mu}$
- Background from sidebands à la H→γγ analysis
- 95% CL limits:
  2.1 (obs), 2.0 (exp)
- **Getting close to SM sensitivity!**



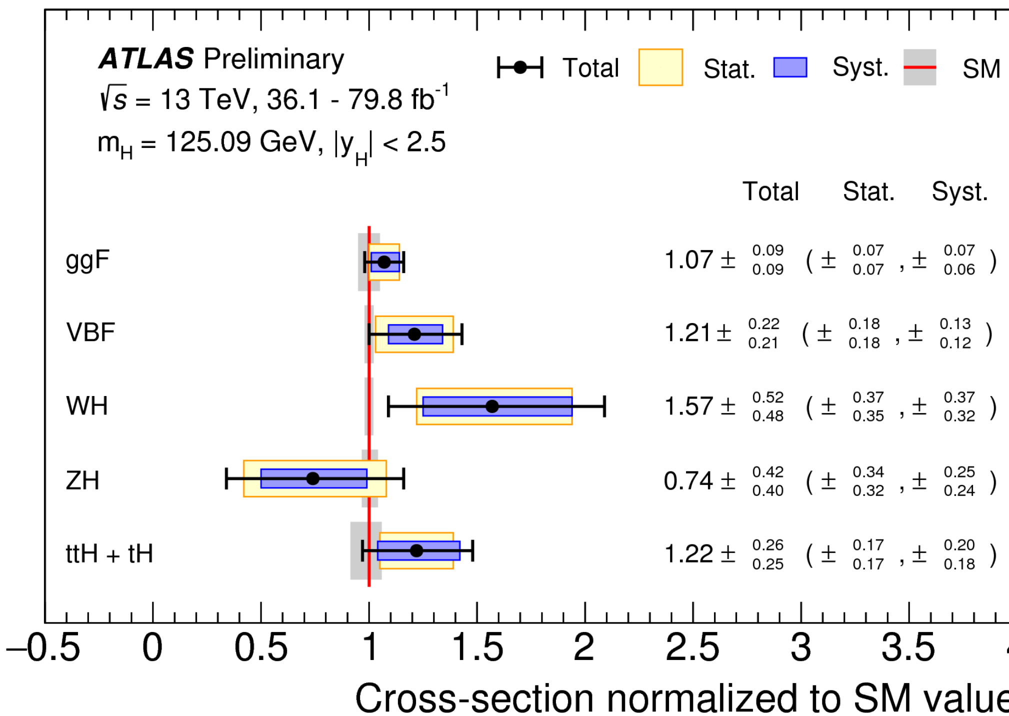
ATLAS-CONF-2018-031

Combination

NEW
7 July 2018

- Combined γγ, ZZ, WW,ττ, μμ and bb (incl. ttH+tH modes)
  - Up to 79.8 fb^{-1} of $\sqrt{s}$ = 13 TeV data
- Combination yields VBF significance 6.5σ (5.3σ expected) **from ATLAS alone**
- Main production modes (ggF, VBF, VH, ttH) have all been observed!!
- Good agreement with SM predictions
- Overall signal strength:

  $\mu = 1.13^{+0.09}_{-0.08}$
- Quantified space for undetectable decays or modified BR (e.g. BSM H→cc)
  - $B_{BSM} < 0.13$ at 95% CL.(*)

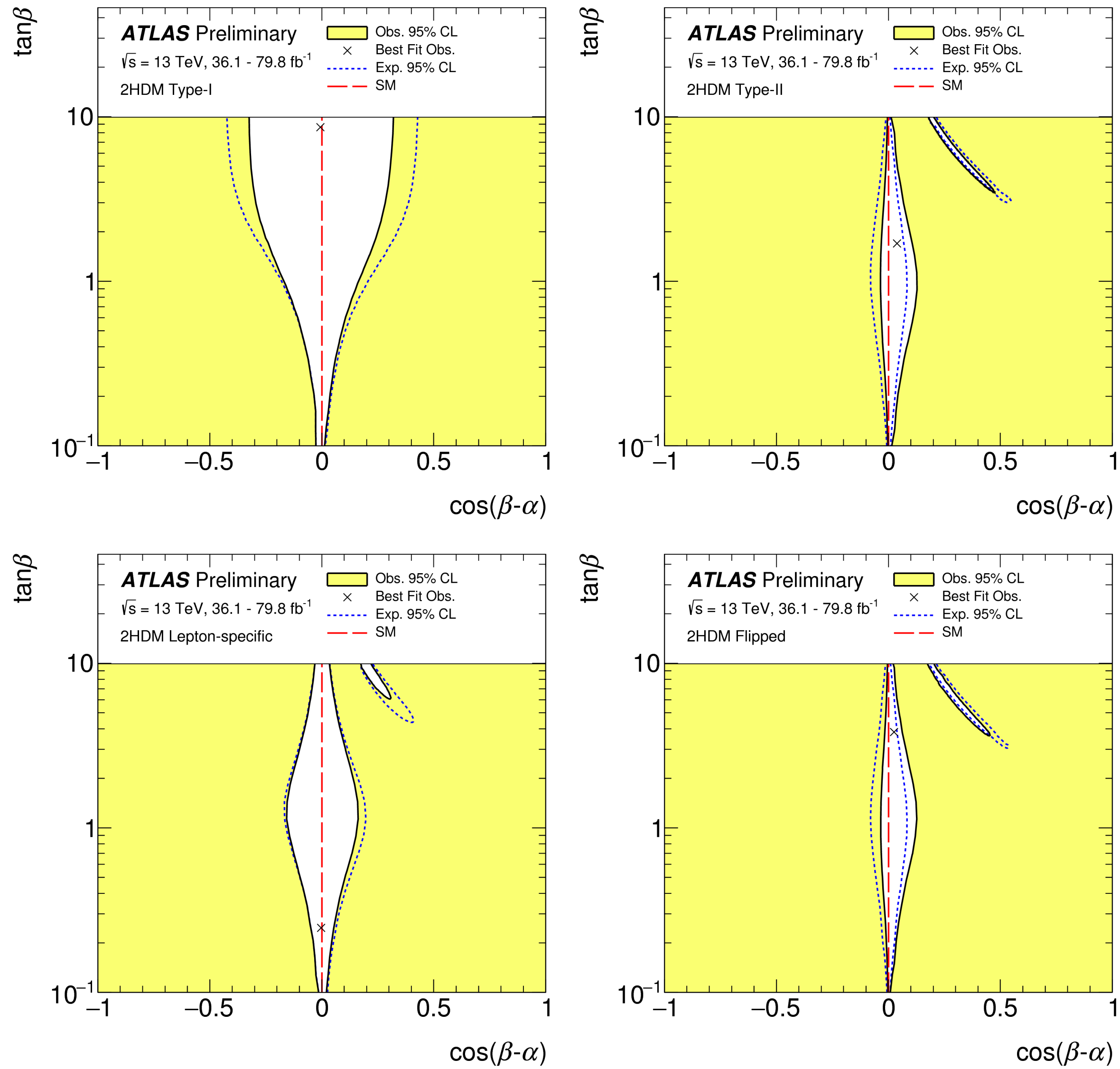


(*) In determination of κ_g and κ_γ - assumption dependent

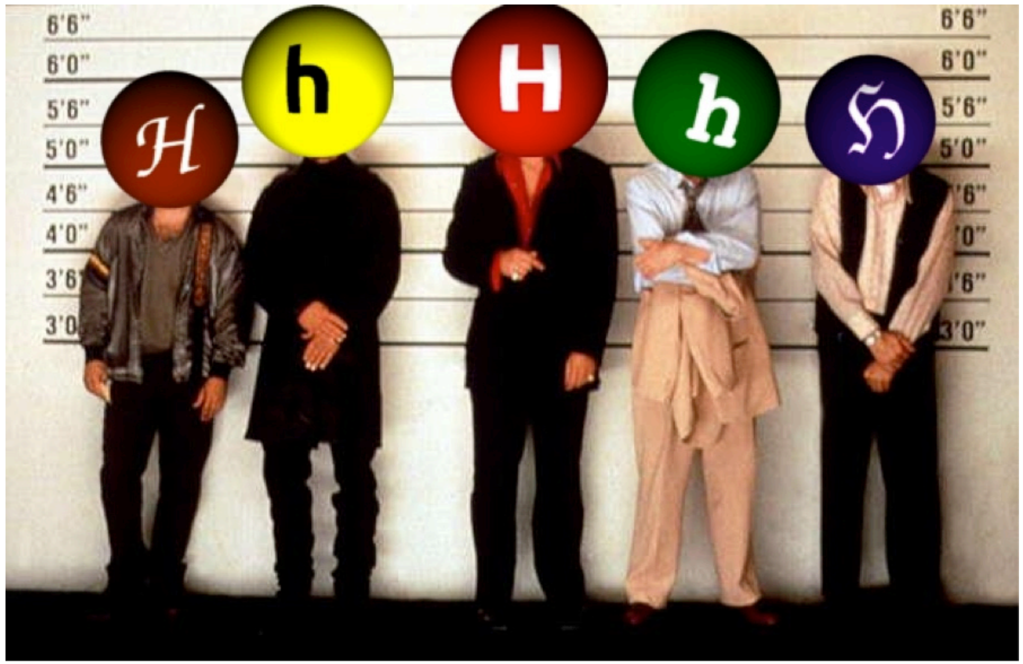
ATLAS-CONF-2018-031

Implications for 2HDM

- H(125) assumed to be light CP-even neutral scalar *h* in 2HDM
- *h* production and decay same as for SM Higgs boson



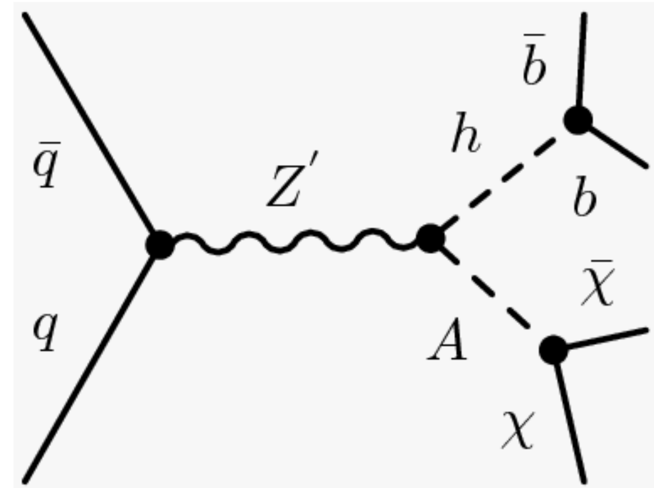
Casting a wider net



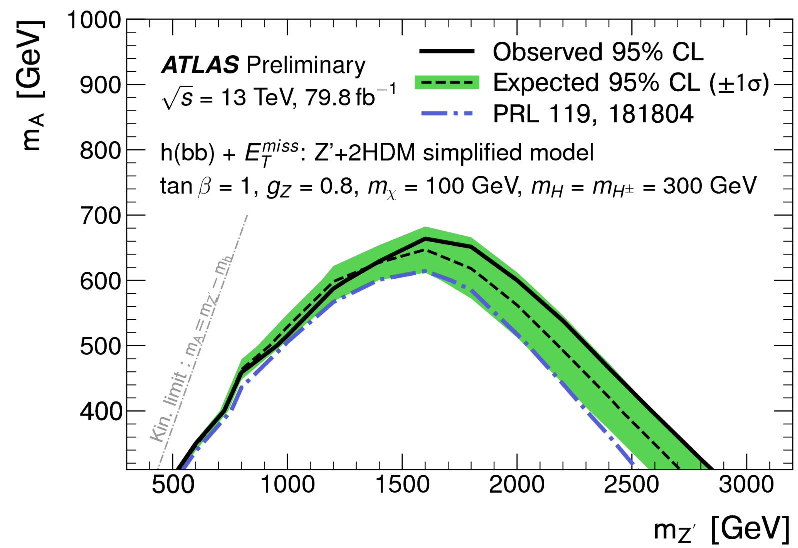
NEW
25 July 2018

Higgs + Dark Matter

- Used 79.8 fb^{-1} of 13 TeV data
  - High E_T^{miss} (>150GeV) and b-tagging to suppress backgrounds
  - Reconstruct b-jets as 2 small jets or merged variable-radius (VR) track jets



- Signal benchmark: Type-II 2HDM + $U(1)_{Z'}$ symmetry (Z'-2HDM)
- Main backgrounds: tt, W/Z+jets
- Excluded region in $m_A - m_{Z'}$ plane

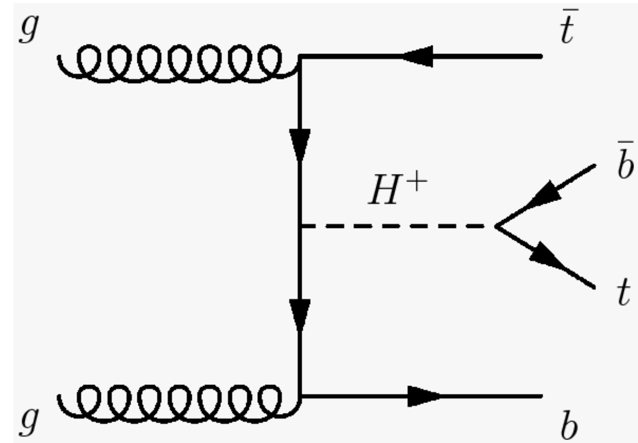


NEW
10 Aug 2018

arXiv:1808.03599

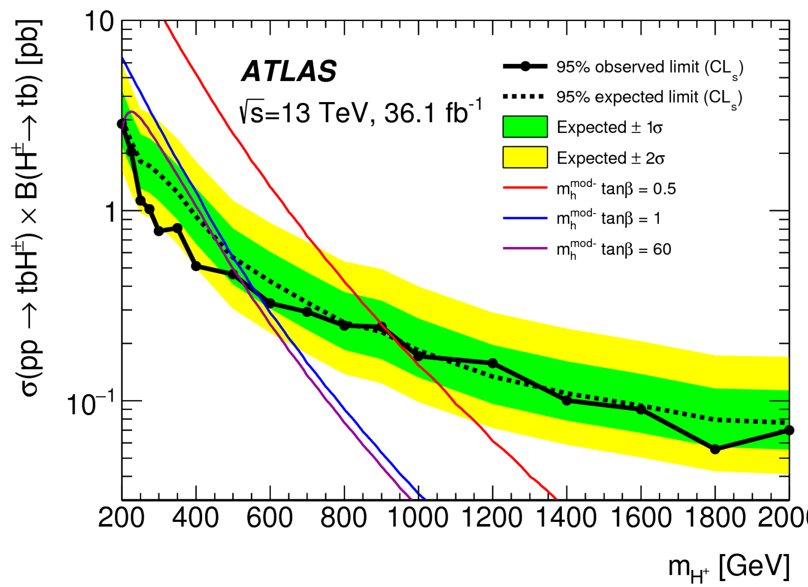
Charged Higgs: $H^+ \rightarrow tb$

- Explored single-lepton and dilepton tt final states
  - In range m_{H+}: 200 – 2000 GeV
- 36.1 fb^{-1} of 13 TeV data



- Events categories: N_{jets} and $N_{b\text{-}tags}$
  - Allow to constrain backgrounds in simultaneous fit

- BDTs trained in signal regions
  - Separate signal and background for 18 mass points
  - Matrix method used in single-lepton channel



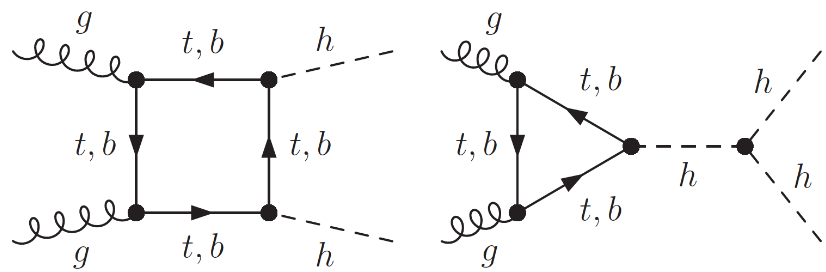
- Extracted limits on σ x BR and on m_{H+} - tan β plane for two MSSM scenarios

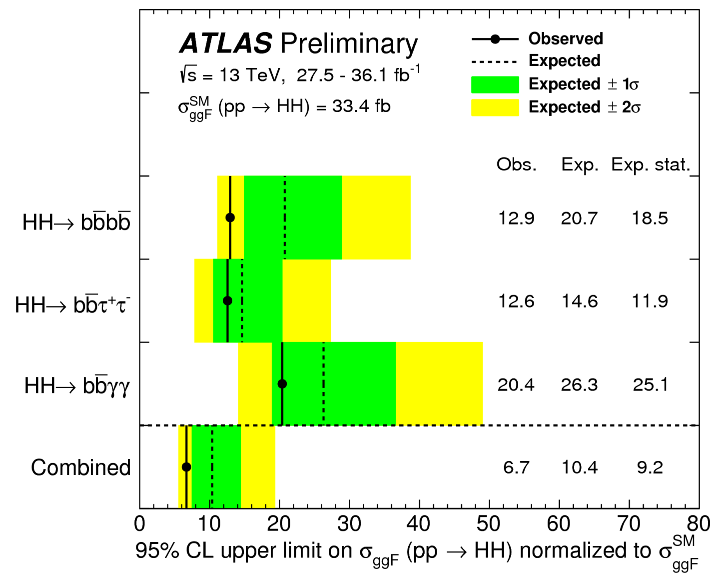
NEW
7 July 2018
4 Sep 2018

Triple Higgs coupling

- The triple Higgs coupling λ_{HHH} can be probed through di-Higgs production
- Very suppressed in SM!
  - Negative interference between LO diagrams
  - Cross section 1500x less than ggF
- Wide range of decay BR and channel purity
- bbττ analysis:
  - Used 36 fb^{-1} of 13 TeV data
  - Final state BR(bbττ)=7%
  - Non-Resonant 95% CL limit:
    μ < 12.7 observed (14.8 expexcted)
- Combination: at ≈10 x SM sensitivity – with 3% of the HL-LHC luminosity analyzed

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$$

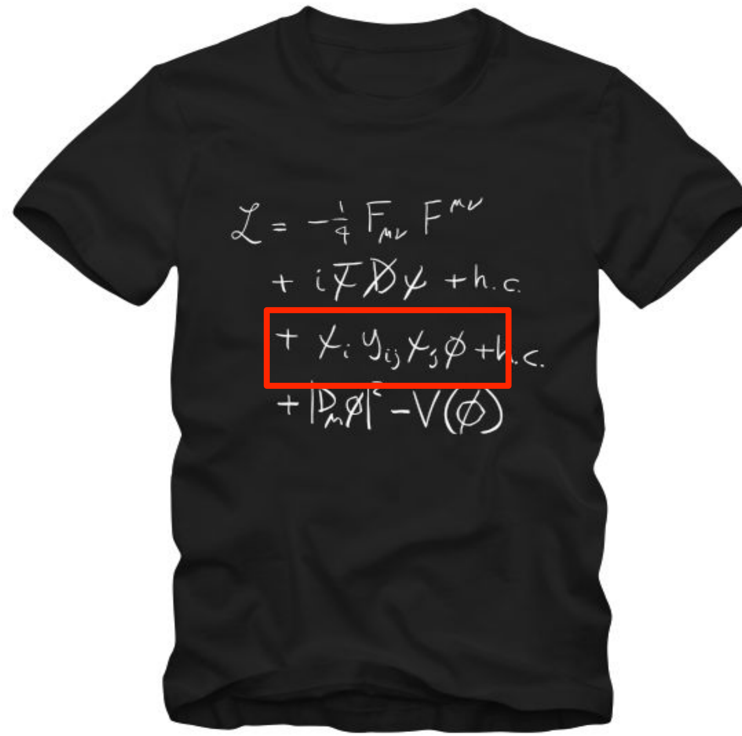




Di-Higgs combination plot here

Summary

- Another milestone was crossed last week by ATLAS and CMS with the H→bb observation
- Main production modes (ggF, VBF, VH, ttH) have all been observed!!
- The Higgs sector continues to look SM-like
- **But!**
- We know there is new physics out there!
- We have only collected ≈130 fb^{-1} of 3000 fb^{-1} of 13 TeV data expected at the HL-LHC
- We have a strong programme of precision measurements and searches for new Higgs states and decays



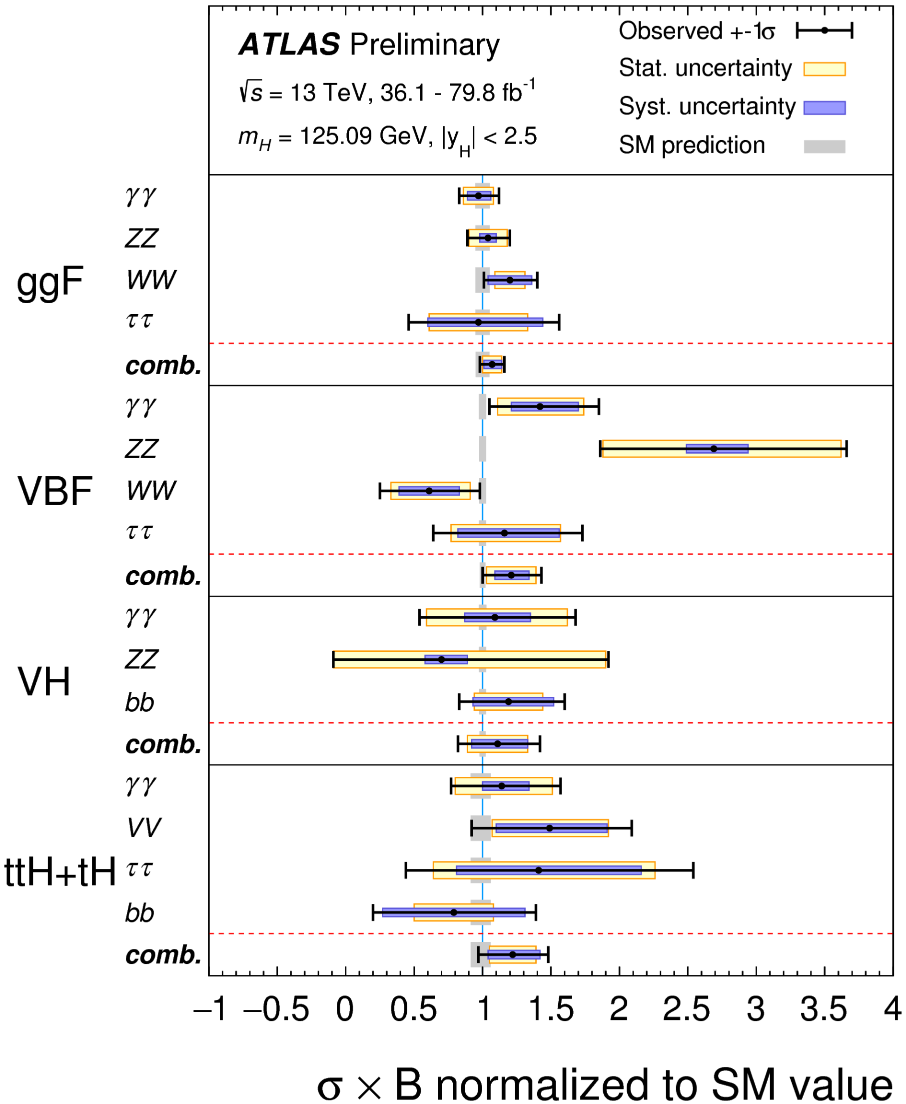
Overall highlight from the past year (very personal bias!):
"The >5σ observations of ttH and H → ττ, independently by ATLAS and CMS, firmly establish the existence of a new kind of fundamental interaction, Yukawa interactions."
Gavin Salam (LHCP'18)

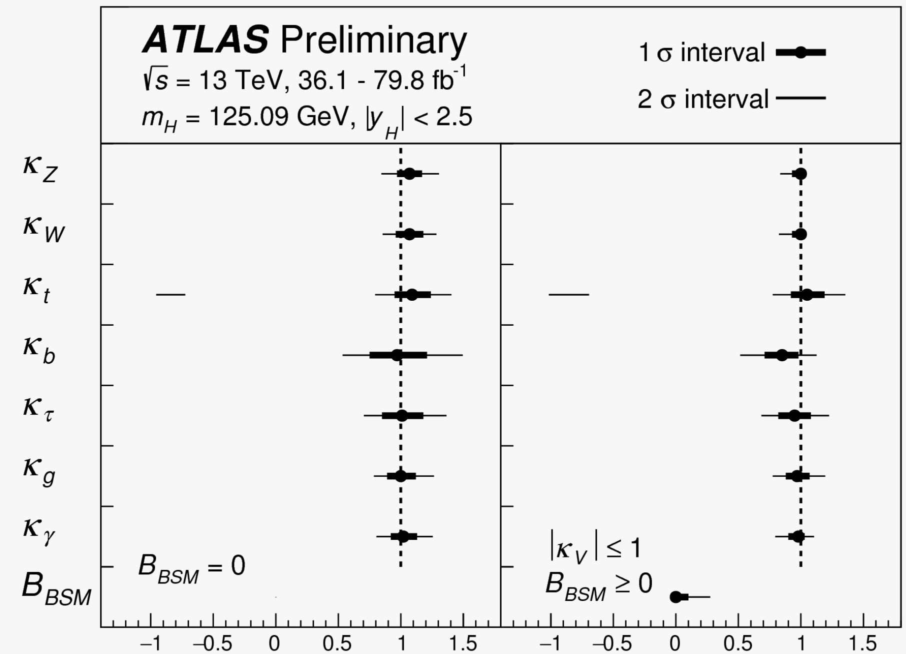
See here for more: [ATLAS Public results page]

Bonus slides

- a

More on Combination





a Higgs boson at a mass of 125 GeV [10, 11], the expected natural width of the SM Higgs boson is $\Gamma_H^{\mathrm{SM}} \sim 4.1$ MeV [12]. However, above 125 GeV off-shell production of the Higgs boson has a substantial cross section at the LHC [13–16], due to the increased phase space as the vector bosons ($V = W, Z$) and top quark decay products become on-shell with the increasing energy scale. This provides an opportunity to study the Higgs boson properties at higher energy scales. Off-shell production can provide sensitivity to new physics that alters the interactions between the Higgs boson and other fundamental particles in the high-mass region [17–24].

The measured off-shell event yield from gluon–gluon fusion (ggF) production normalised to the SM prediction, where this ratio is referred to as the signal strength $\mu_{\text{off-shell}}$, can be expressed as

$$\mu_{\text{off-shell}} = \frac{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell}}}{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell,SM}}} = \kappa^2_{g,\text{off-shell}} \cdot \kappa^2_{Z,\text{off-shell}},$$

where $\sigma^{gg\to H^*\to ZZ}_{\text{off-shell}}$ is the cross section of the off-shell Higgs boson production via ggF with subsequent decay into a ZZ pair, and $\kappa_{g,\text{off-shell}}$ and $\kappa_{Z,\text{off-shell}}$ are the off-shell coupling modifiers relative to the SM predictions associated with the $gg \to H^*$ production and the $H^* \to ZZ$ decay, respectively. The off-shell Higgs boson signal cannot be treated independently of the $gg \to ZZ$ background, as sizeable negative interference effects appear [13]. The interference term is assumed to be proportional to $\sqrt{\mu_{\text{off-shell}}} = \kappa_{g,\text{off-shell}} \cdot \kappa_{Z,\text{off-shell}}$. Similarly, $\mu_{\text{on-shell}}$ for the on-shell Higgs boson production via ggF is given by:

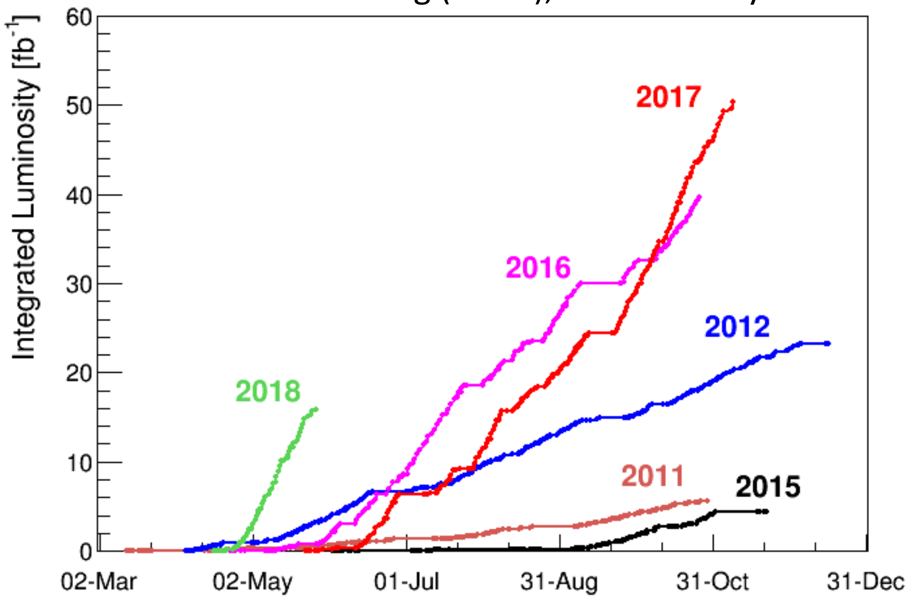
$$\mu_{\text{on-shell}} = \frac{\sigma^{gg\to H\to ZZ^*}_{\text{on-shell}}}{\sigma^{gg\to H\to ZZ^*}_{\text{on-shell,SM}}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{Z,\text{on-shell}}}{\Gamma_H/\Gamma_H^{\mathrm{SM}}},$$

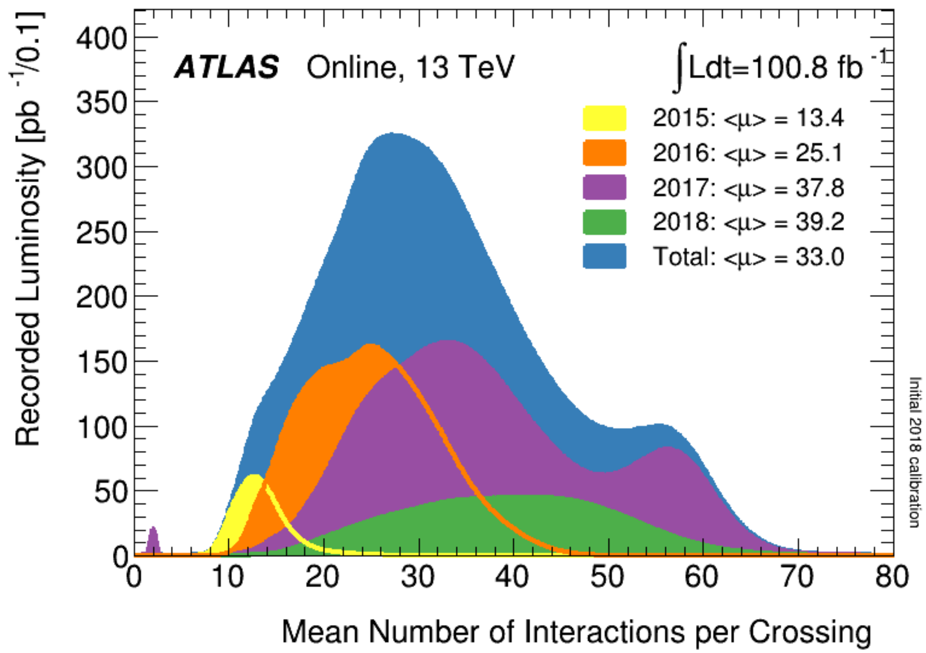
which depends on the Higgs boson total width Γ_H. A measurement of the relative off-shell and on-shell event yields, $\mu_{\text{off-shell}}/\mu_{\text{on-shell}}$, provides direct information about Γ_H, if one assumes identical on-shell and off-shell Higgs boson coupling modifiers [15, 25]. The above formalism describing the ratio of

ATLAS, CMS and the LHC

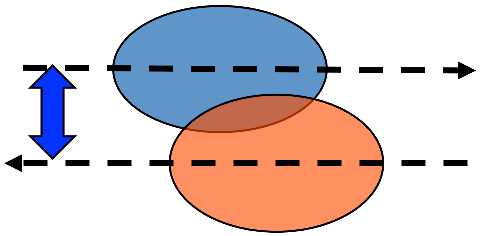
- Run 1: 2009 – 2013; ≈ 5 fb^{-1} at $\sqrt{s}$ = 7 and ≈ 20 fb^{-1} at 8 TeV per experiment
- Run 2: 2013 – 2018; expect > 150 fb^{-1} at $\sqrt{s}$ = 13 TeV by the end of run
- Instantaneous luminosity of **2 x 10^{34} $cm^{-2}s^{-1}$** in 2017 (2x design!)
- Downside is pileup => experimental challenge!
  - Multiple vertices, large occupancy, degraded reconstruction resolution, etc
  - LHC breaking new ground to go around this: leveling!

R. Steerenberg (CERN), LHCC 30 May 2018

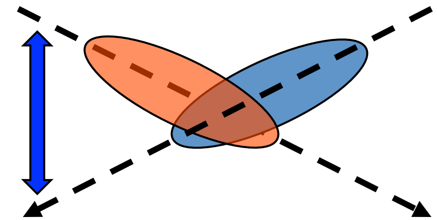




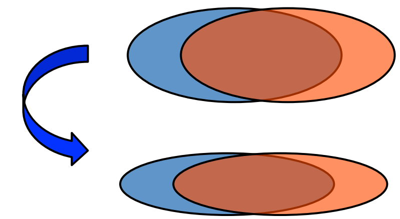
Leveling by beam offset



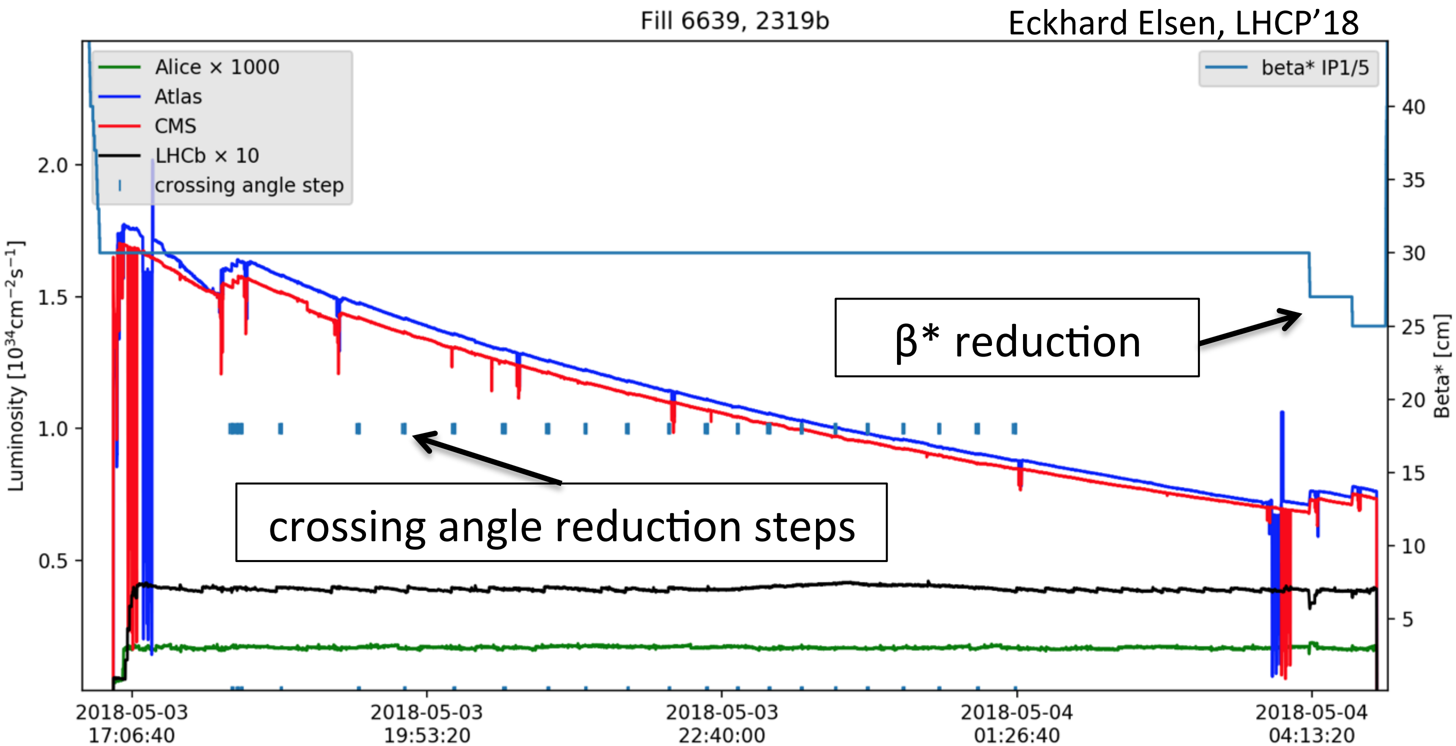
Anti-leveling: crossing angle



Anti-leveling: β* reduction



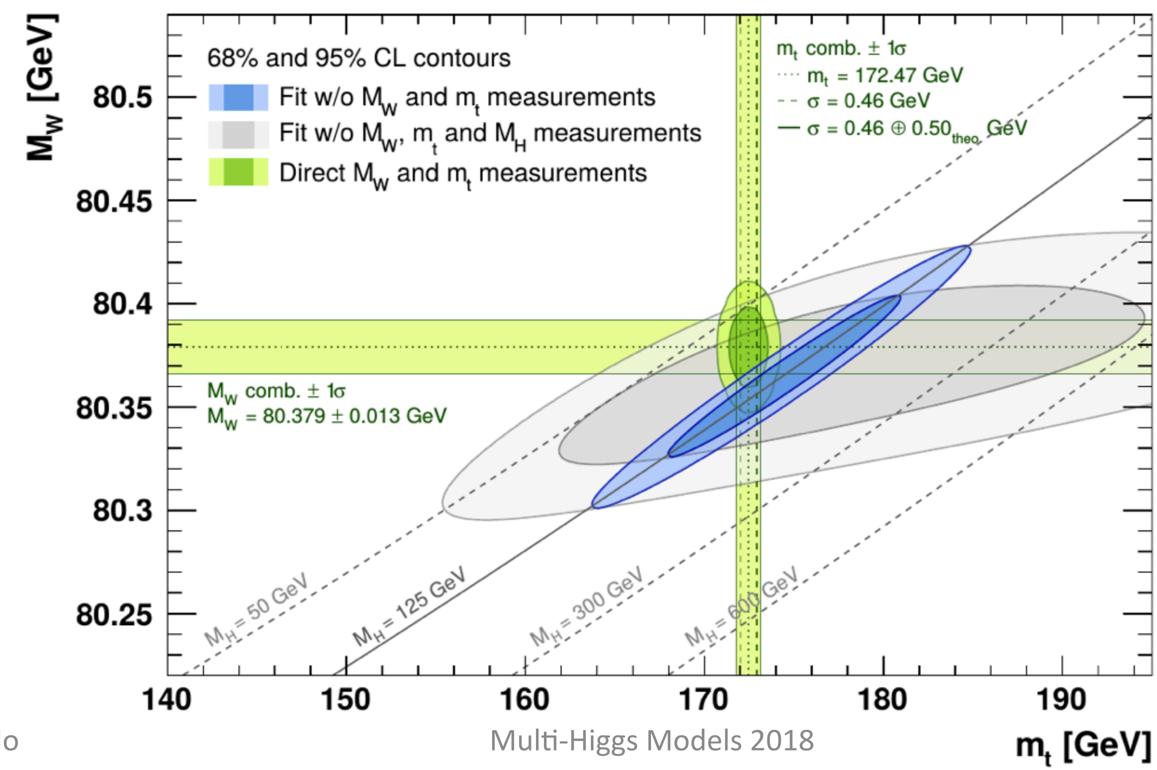
Eckhard Elsen, LHCP’18



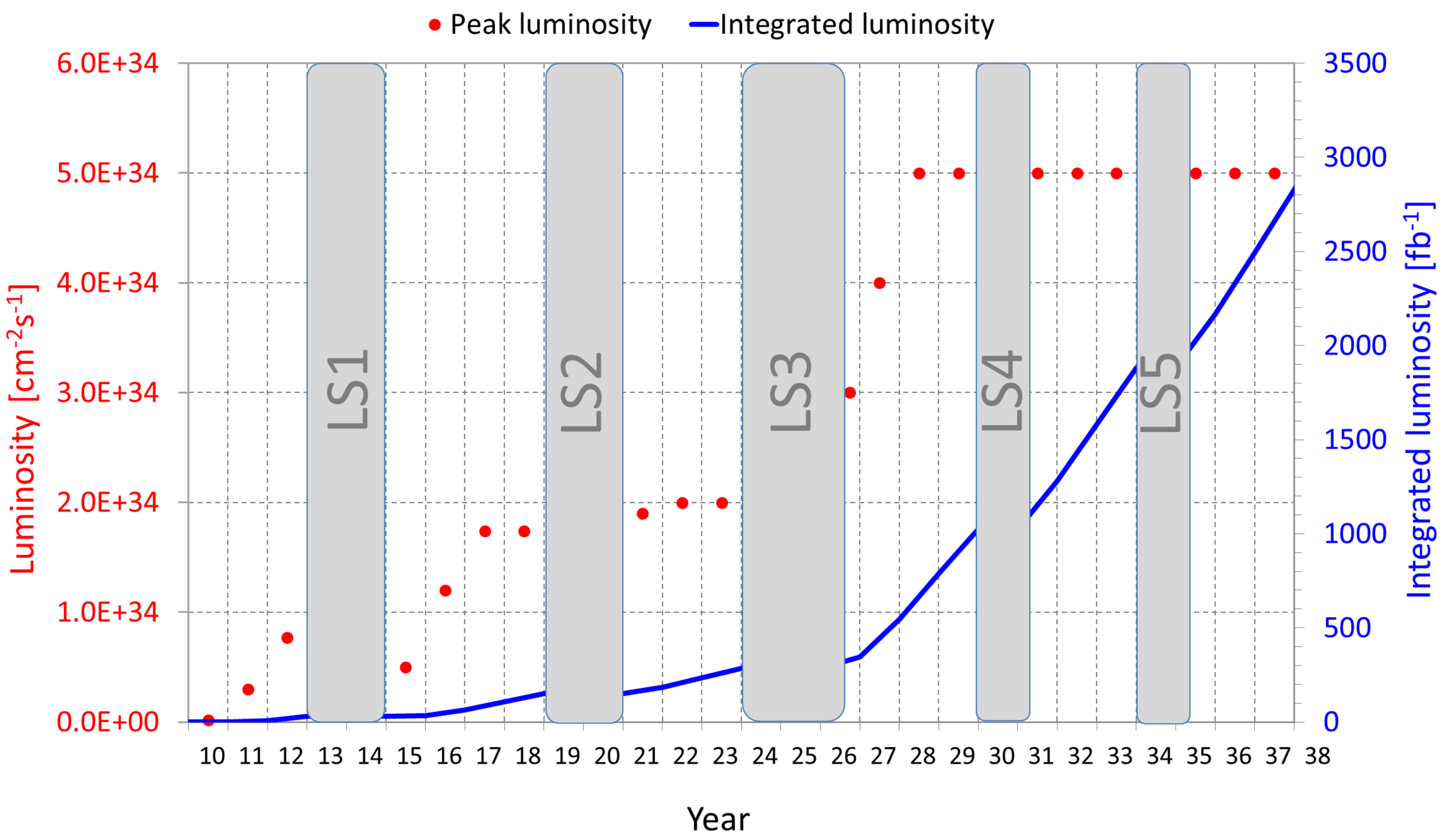
Exploring the electroweak scale

- Precision measurements of m_W, m_t, m_H are stringent tests of the SM at the EW scale
  - E.g. excluding measured m_H, global EW fit gives m_H = 90 ± 21 GeV (1.7 σ tension) driven in part by m_{top}

arXiv:1803.01853

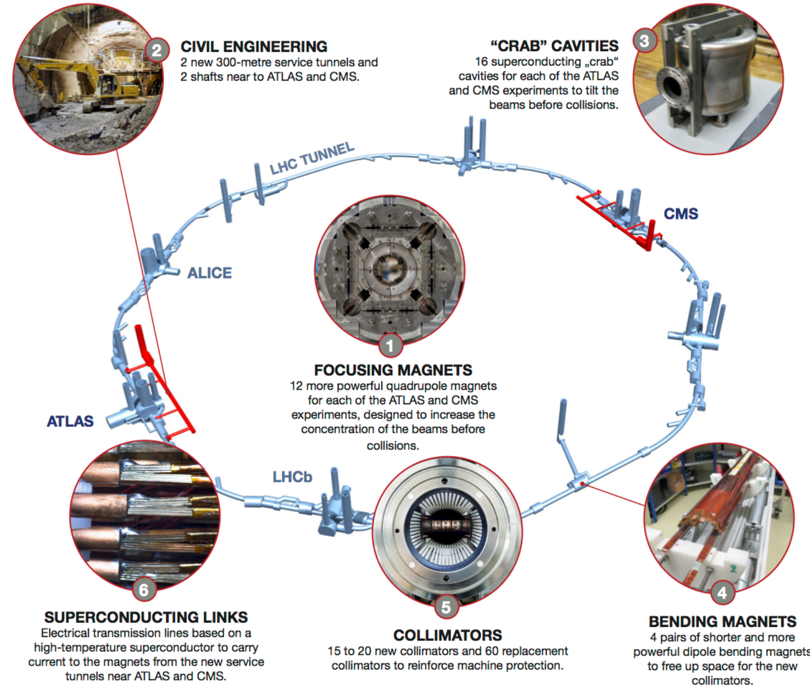


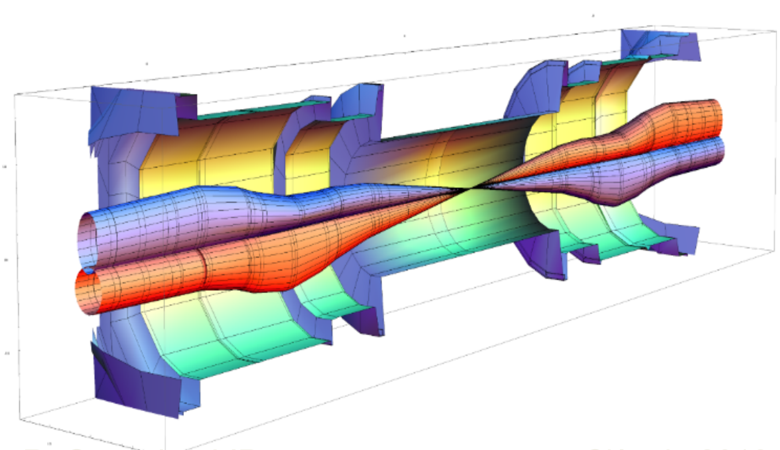
LHC and HL-LHC timeline

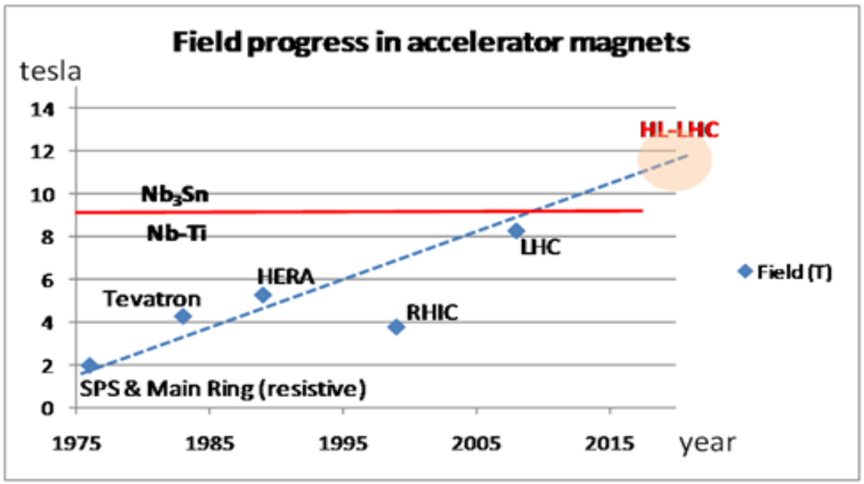


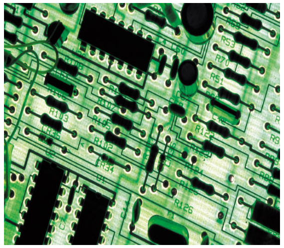
LHC Upgrades

- Development of a new generation of superconducting magnets with higher critical field (Nb_3Sn):
  - 13.5 T instead of 8 T (LHC, NbTi)
- Desenvolvimento de “crab cavities”
- Aumentam eficiência das colisões
- Colimadores, conectores, eng. civil, etc

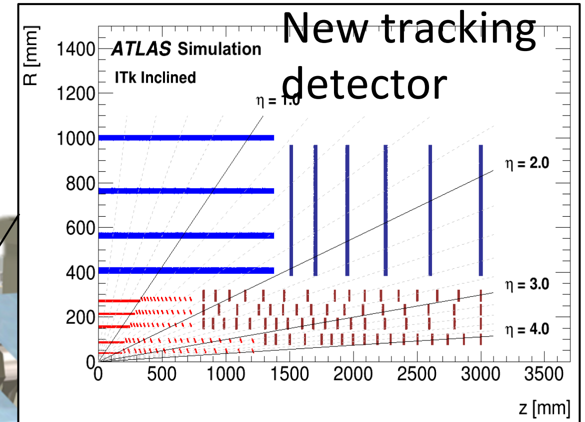




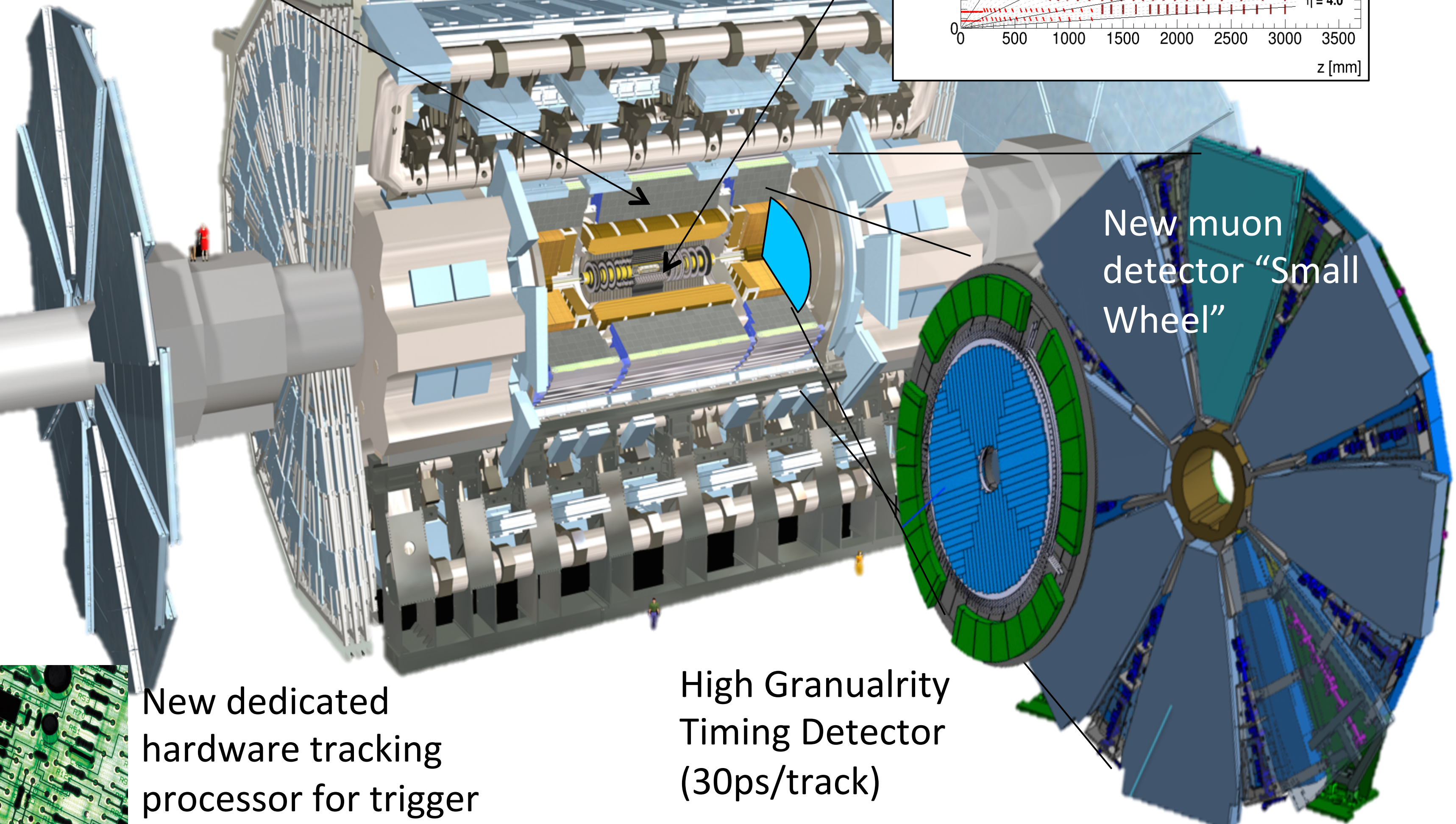




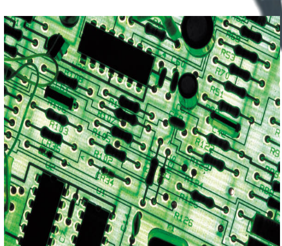
Calorimeter: new DAQ electronics, HV sources and gap scintillators



New tracking detector



New muon detector “Small Wheel”



New dedicated hardware tracking processor for trigger

High Granualrity Timing Detector (30ps/track)