LHC highlights in top and Higgs physics

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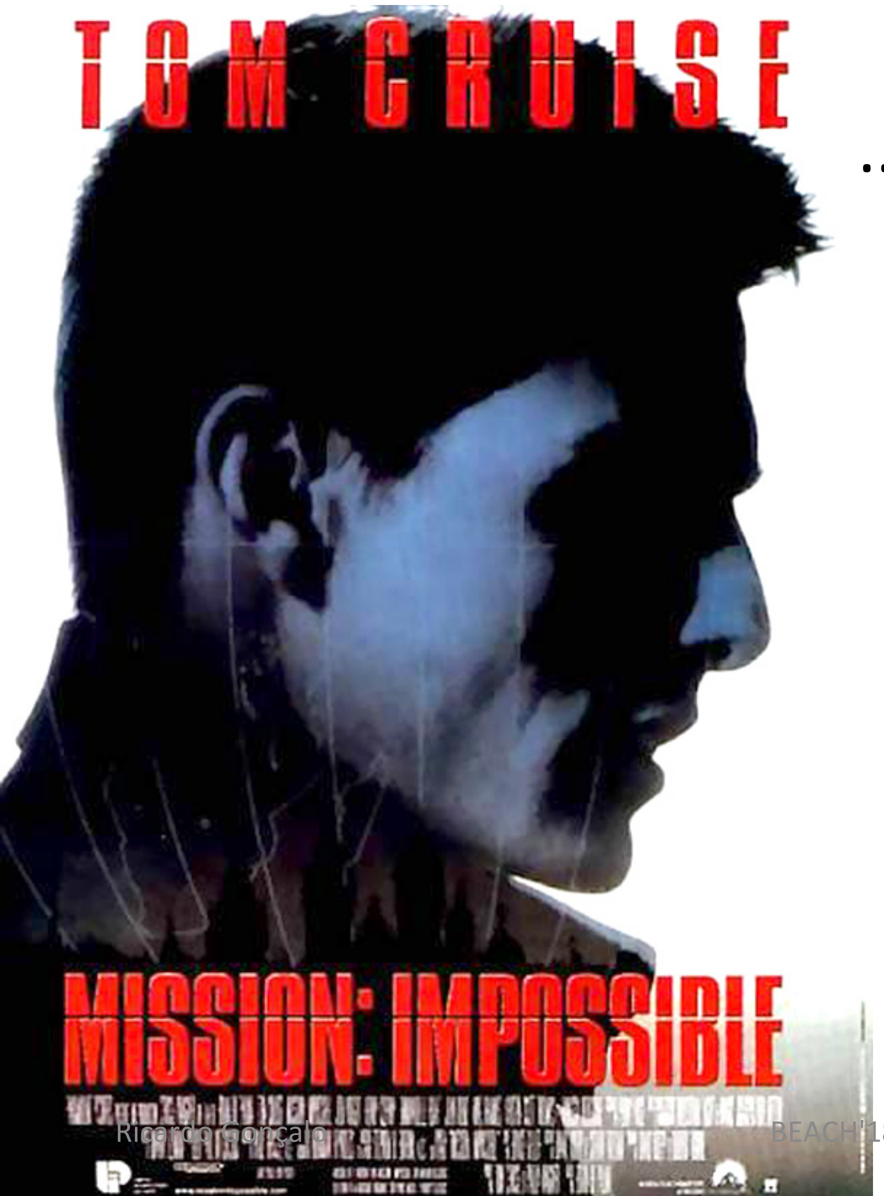
ATLAS EXPERIMENT

Outlook

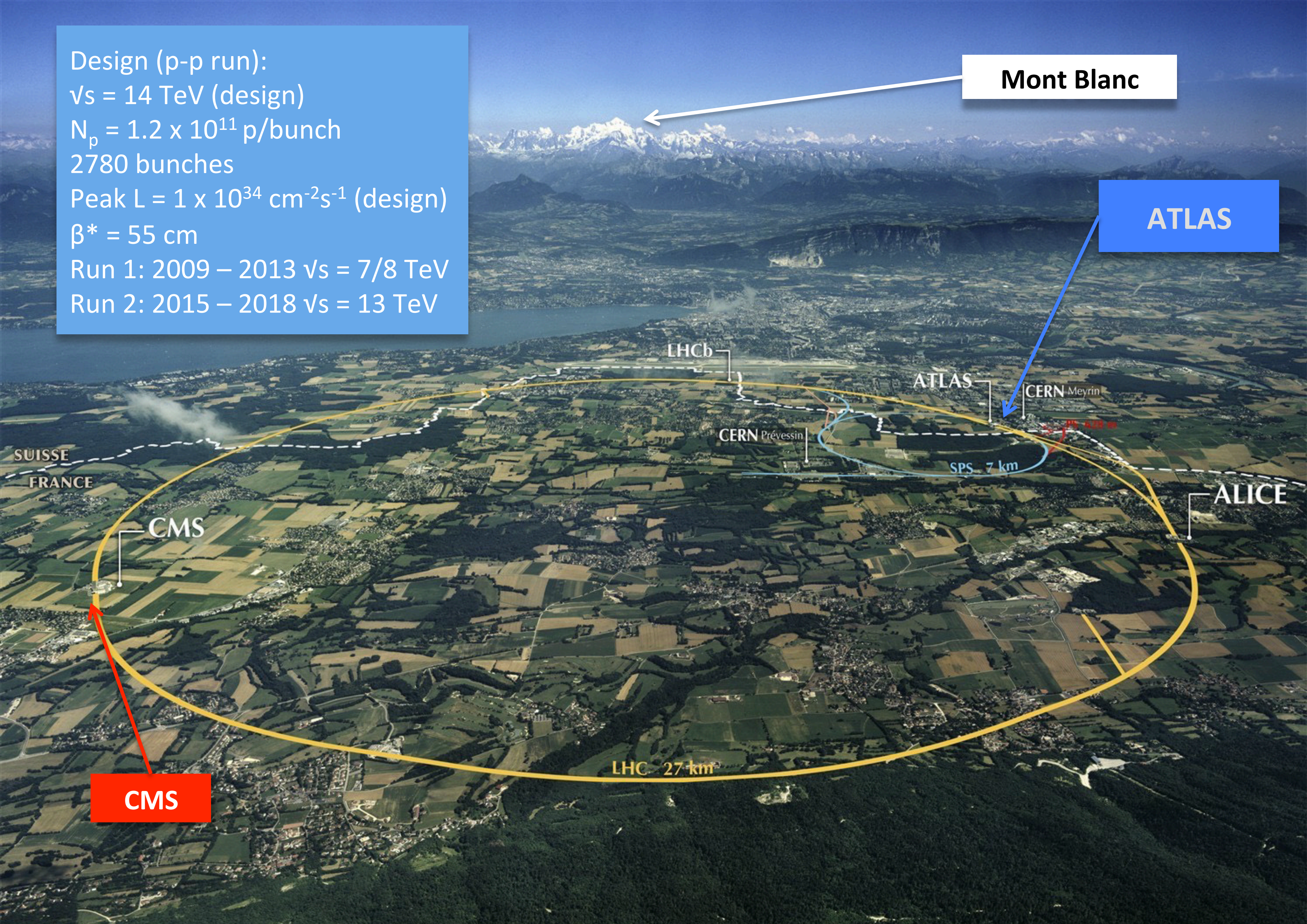


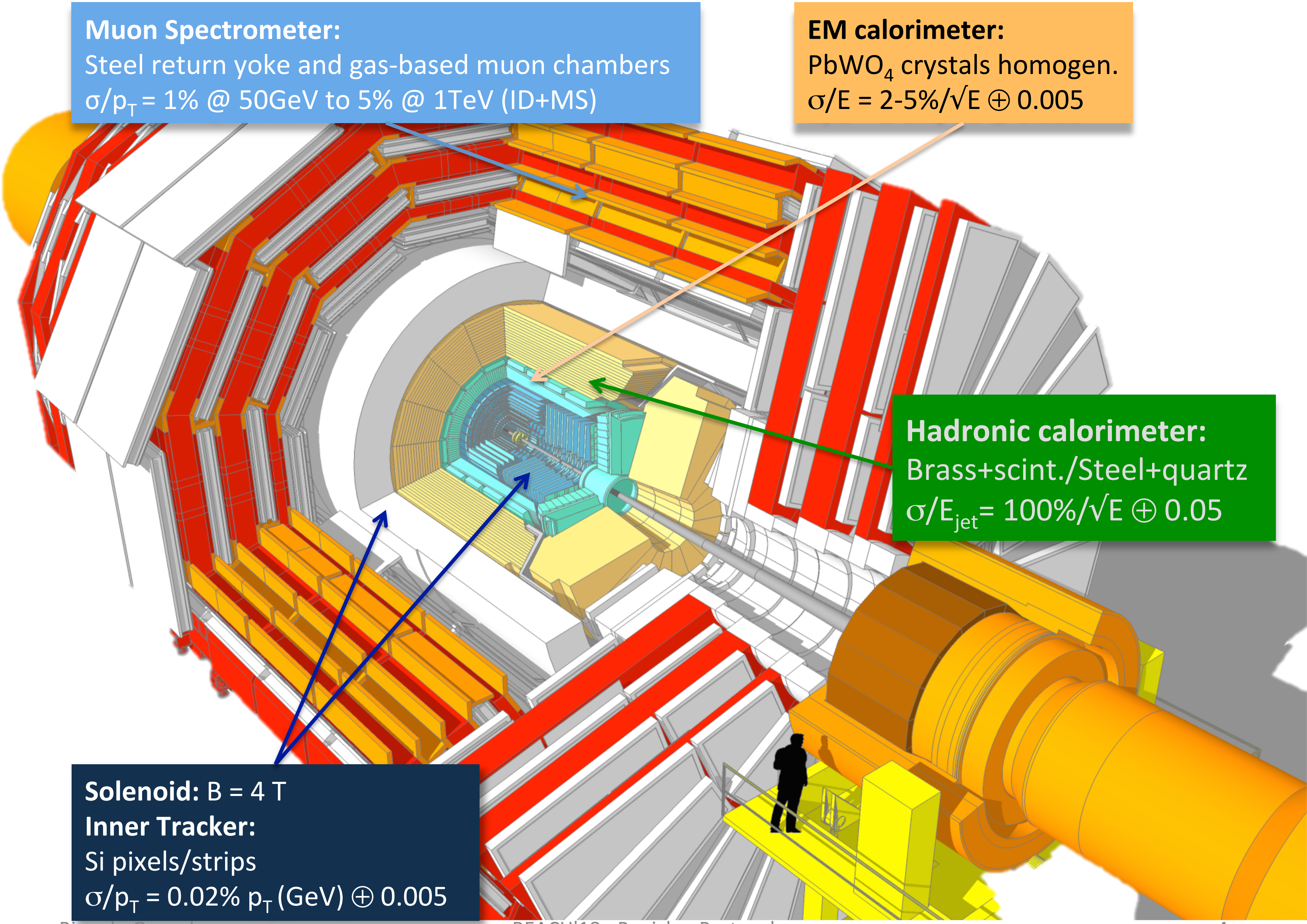
...so I'll show what I like instead ☺

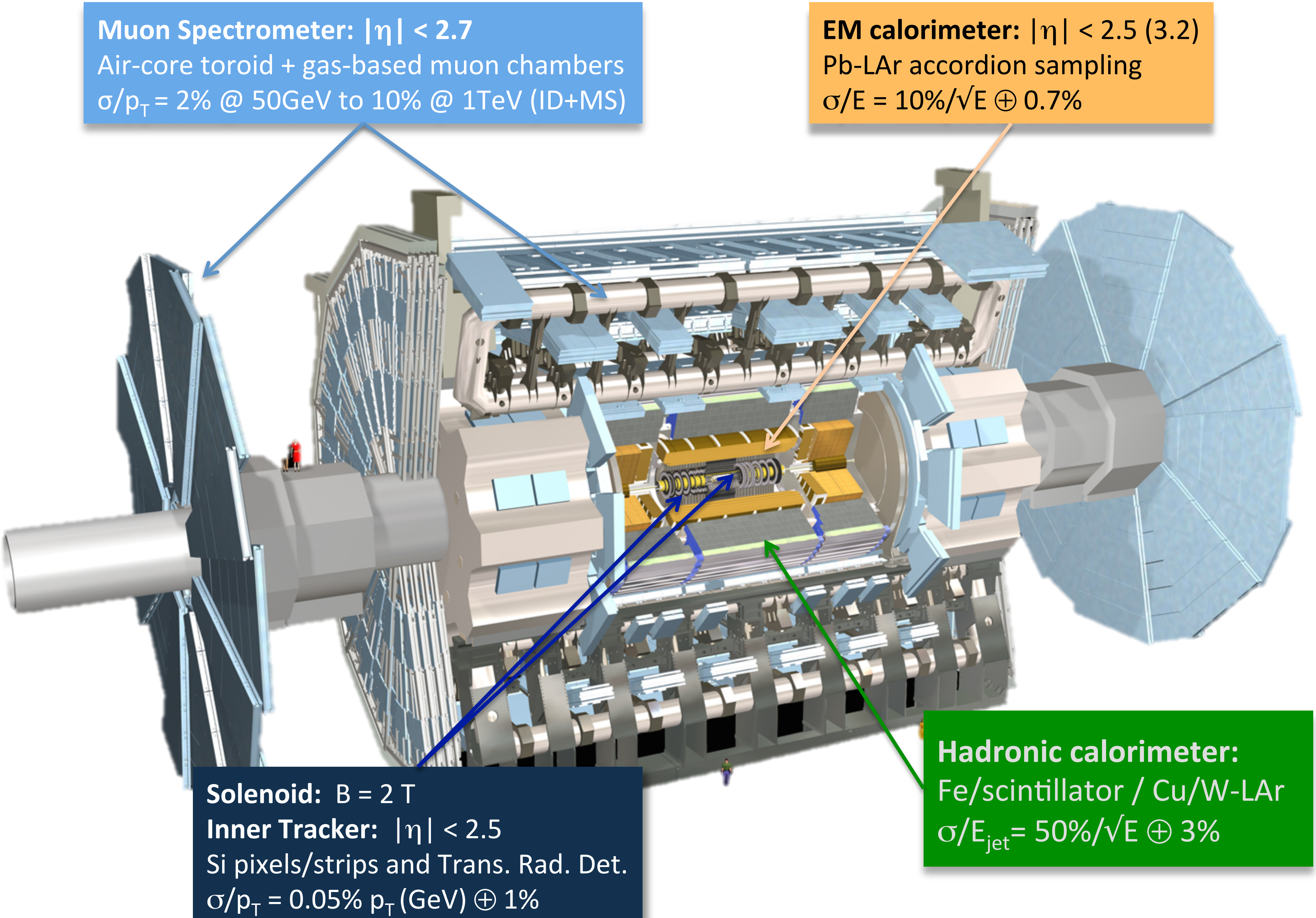
- ATLAS, CMS and the LHC
- Quick word on W mass
- Top physics
- Higgs physics

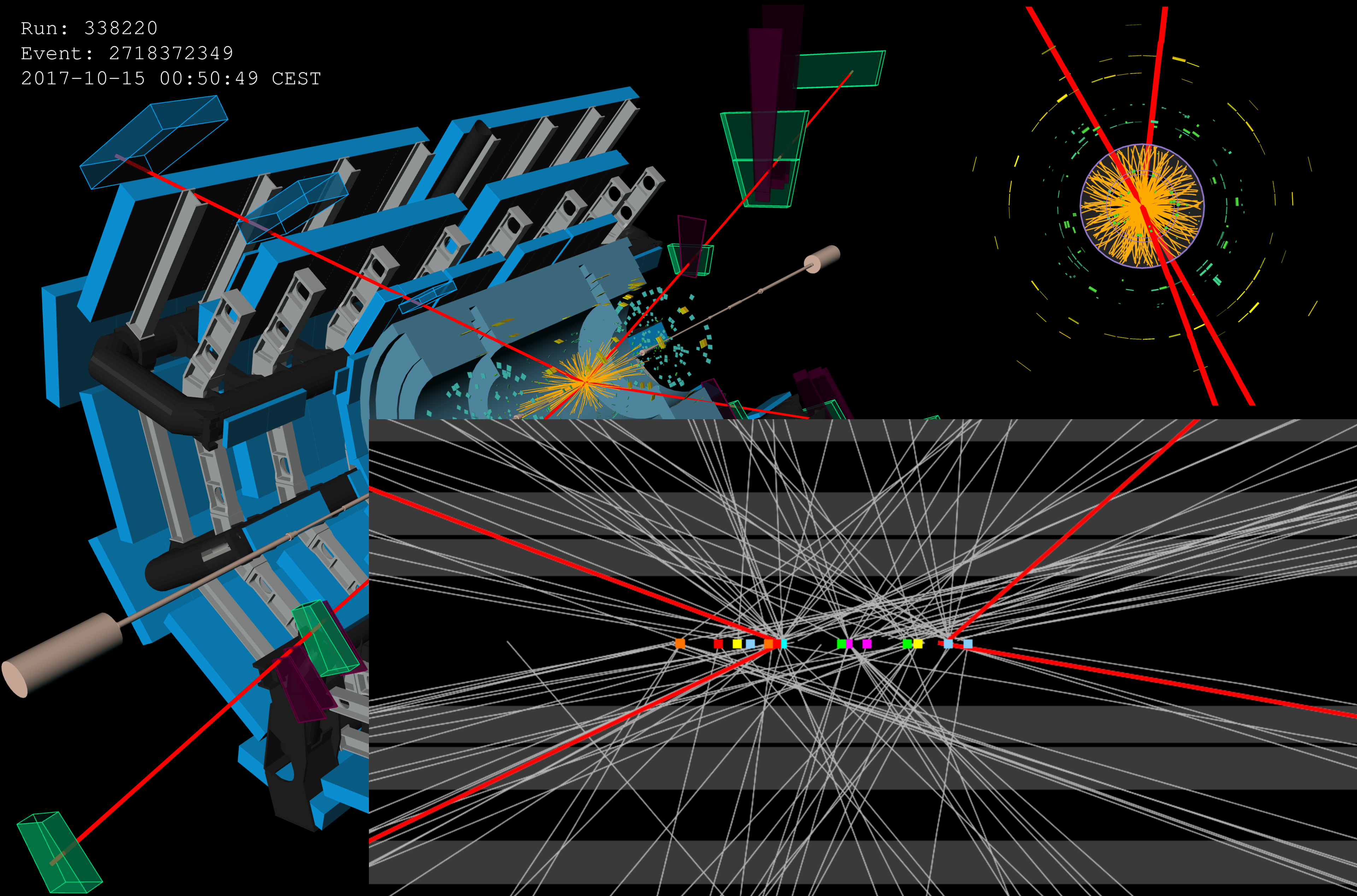
See also: next talk by Eliza Melo da Costa on Z,H decays to quarkonia

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




Muon Spectrometer:
Steel return yoke and gas-based muon chambers
σ/p_T = 1% @ 50GeV to 5% @ 1TeV (ID+MS)
EM calorimeter:
$PbWO_4$ crystals homogen.
$\sigma/E = 2\text{-}5\%/\sqrt{E} \oplus 0.005$
Hadronic calorimeter:
Brass+scint./Steel+quartz
$\sigma/E_{jet} = 100\%/\sqrt{E} \oplus 0.05$
Solenoid: B = 4 T
Inner Tracker:
Si pixels/strips
$\sigma/p_T = 0.02\%\ p_T\,(\text{GeV}) \oplus 0.005$


Muon Spectrometer: |η| < 2.7
Air-core toroid + gas-based muon chambers
σ/p_T = 2% @ 50GeV to 10% @ 1TeV (ID+MS)
EM calorimeter: |η| < 2.5 (3.2)
Pb-LAr accordion sampling
σ/E = 10%/√E ⊕ 0.7%
Hadronic calorimeter:
Fe/scintillator / Cu/W-LAr
σ/E_jet = 50%/√E ⊕ 3%
Solenoid: B = 2 T
Inner Tracker: |η| < 2.5
Si pixels/strips and Trans. Rad. Det.
σ/p_T = 0.05% p_T (GeV) ⊕ 1%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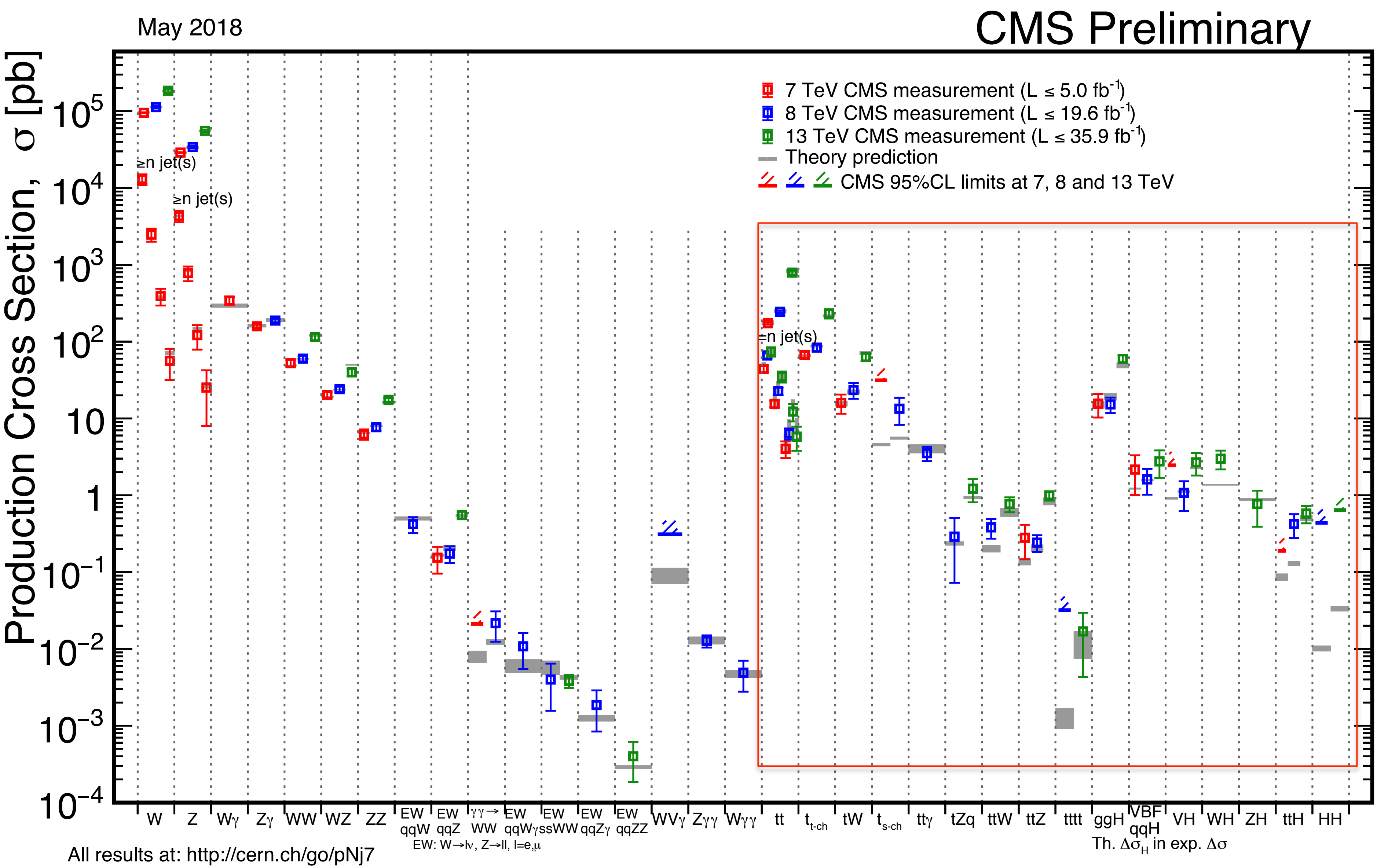
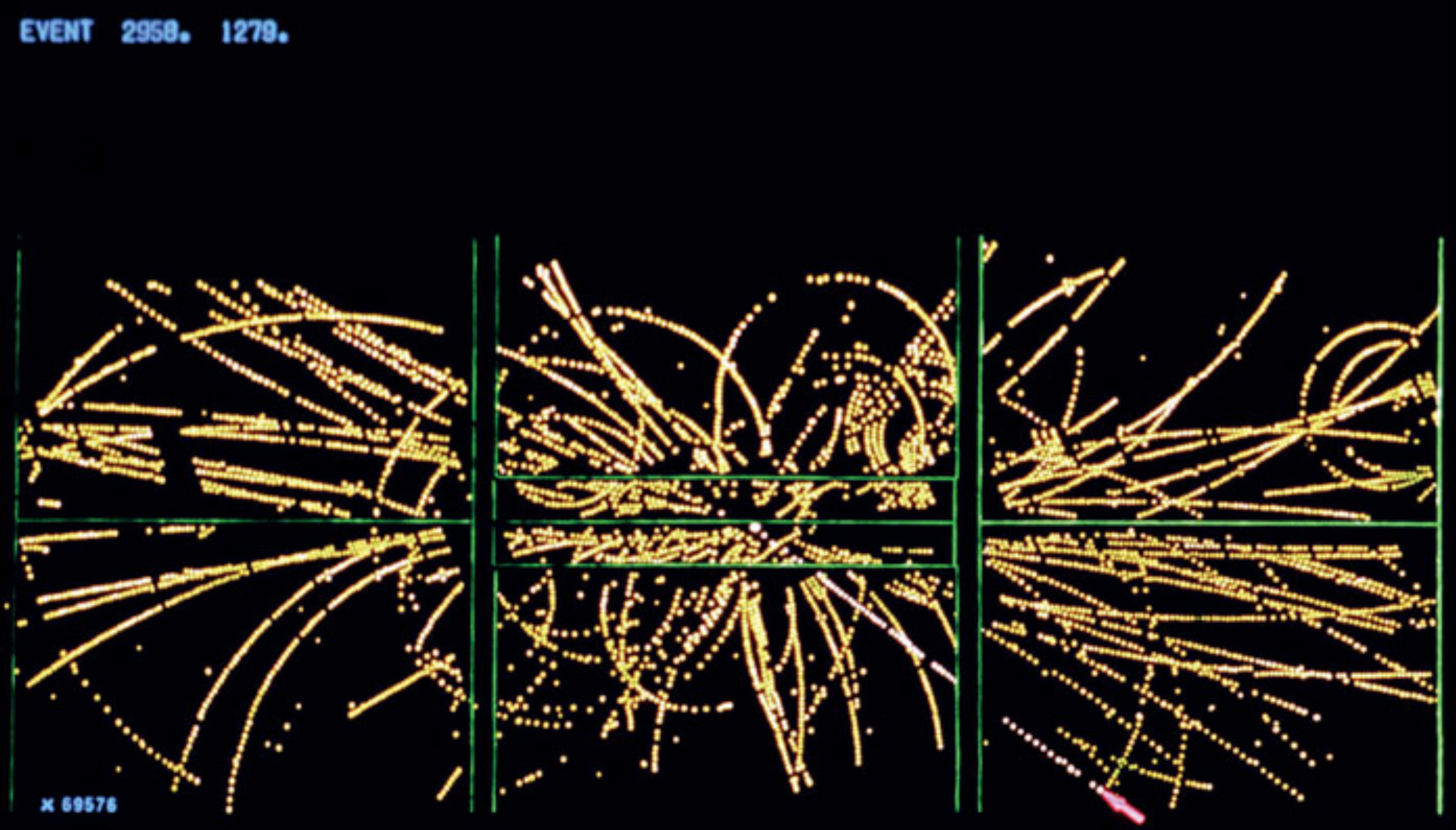

May 2018
CMS Preliminary
Production Cross Section, σ [pb]
7 TeV CMS measurement (L ≤ 5.0 fb⁻¹)
8 TeV CMS measurement (L ≤ 19.6 fb⁻¹)
13 TeV CMS measurement (L ≤ 35.9 fb⁻¹)
Theory prediction
CMS 95%CL limits at 7, 8 and 13 TeV
≥n jet(s)
W Z Wγ Zγ WW WZ ZZ EW qqW EW qqZ γγ→WW EW qqWγ EW ssWW EW qqZγ EW qqZZ WVγ Zγγ Wγγ tt t t-ch tW t s-ch ttγ tZq ttW ttZ tttt ggH VBF qqH VH WH ZH ttH HH
EW: W→lν, Z→ll, l=e,μ
Th. ΔσH in exp. Δσ
All results at: http://cern.ch/go/pNj7

W boson mass

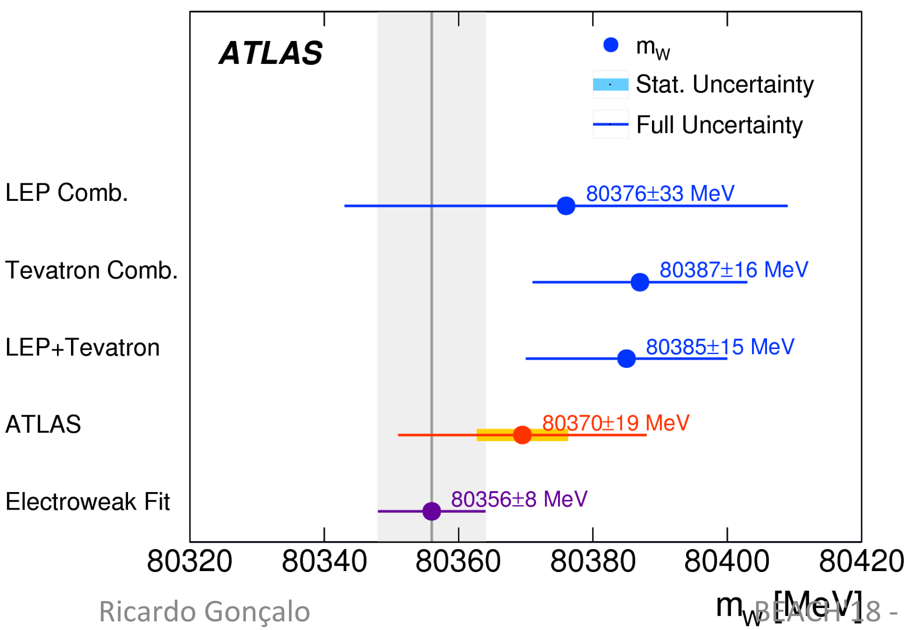


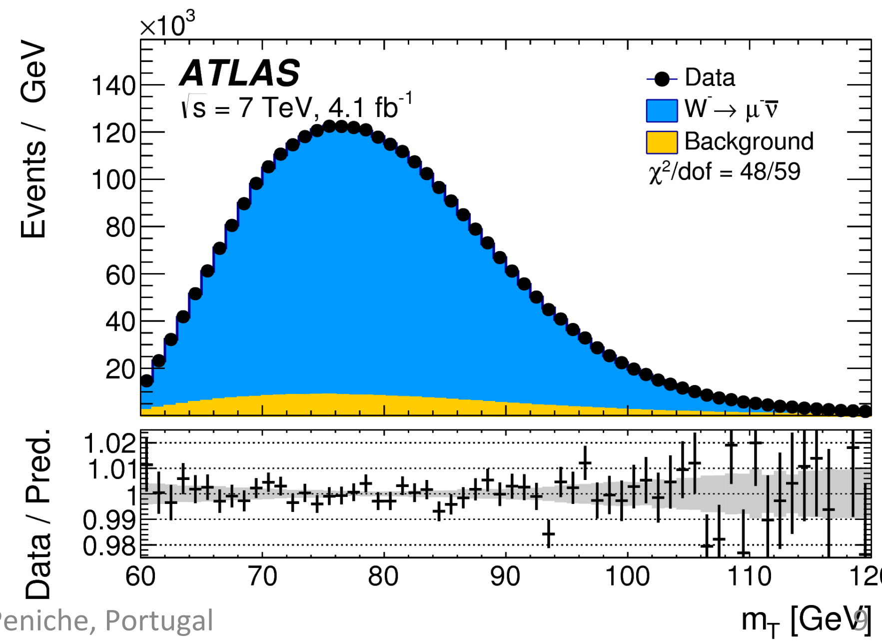
W candidate, UA1, 1982

W boson mass

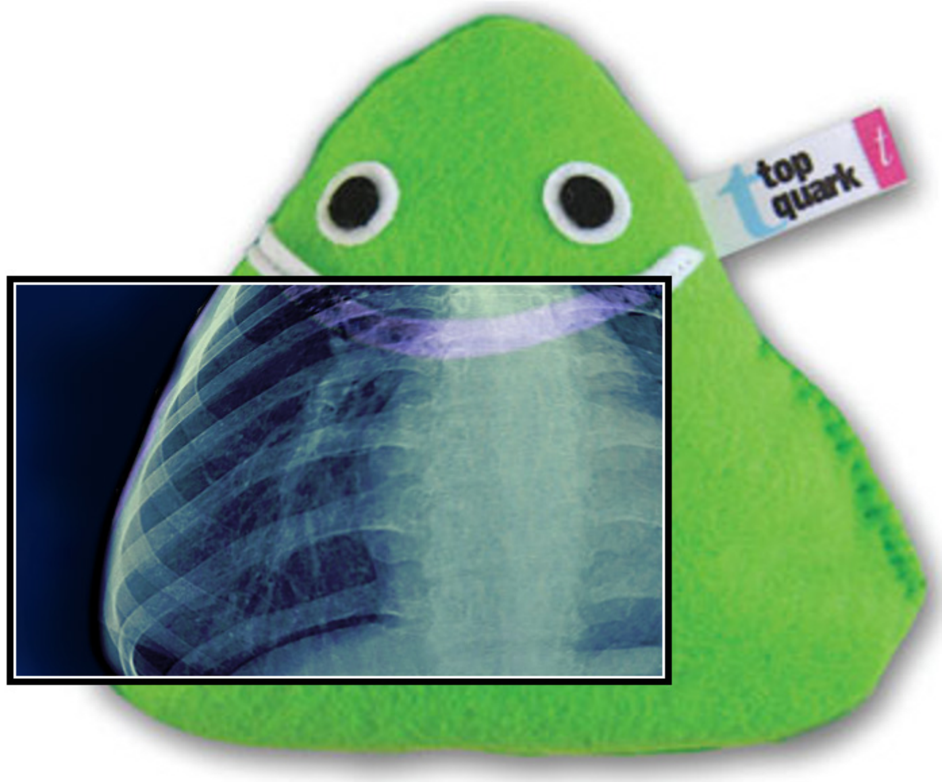
- Based on low-pileup 2011 data: $\sqrt{s}$ = 7 TeV, 4.6 fb^{-1}
- Detailed precision analysis and huge amount of work to understand detector response and modelling of kinematic quantities
- Result (0.2 per mille!) competitive with LEP and Tevatron measurements:

  m_W = 80 370 ± 7 (stat.) ± 11 syst. ± 14 modeling MeV
- To be followed up at with special low-pileup runs





Probing the top quark

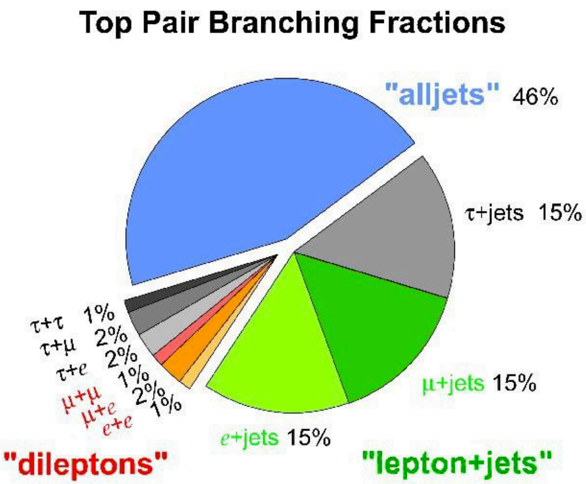


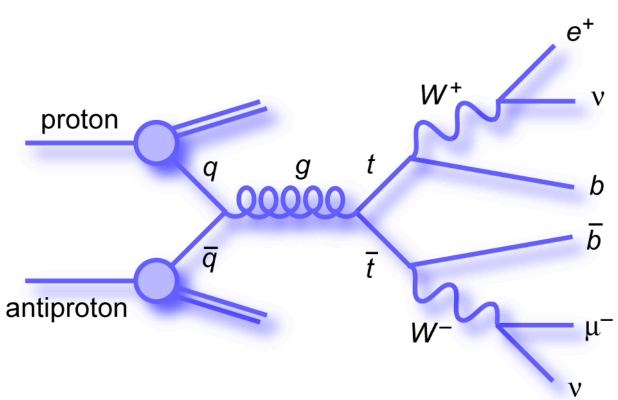
Fermilab news 8 March 2013

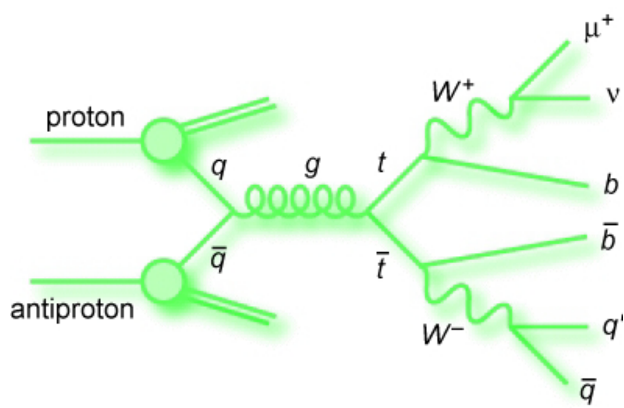
Top quarks at the LHC

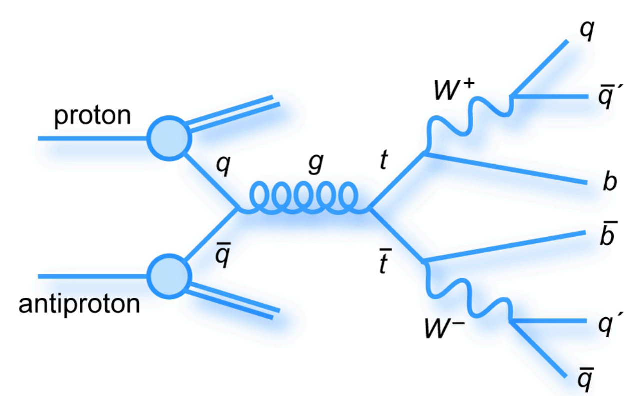
$$\underbrace{\frac{1}{m_t}}_{\substack{\text{production}\\ 10^{-27}\text{ s}}} < \underbrace{\frac{1}{\Gamma_t}}_{\substack{\text{lifetime}\\ 10^{-25}\text{ s}}} < \underbrace{\frac{1}{\Lambda_{QCD}}}_{\substack{\text{hadronization}\\ 10^{-24}\text{ s}}} < \underbrace{\frac{m_t}{\Lambda^2}}_{\substack{\text{spin-flip}\\ 10^{-21}\text{ s}}}$$

- The top is too heavy to form bound states
  - Allows observation of bare quark properties!
- Large Yukawa coupling to Higgs boson
  - Special role in EW symmetry breaking?
- top decays almost always as t→bW
  - $|V_{tb}| >> |V_{ts}| > |V_{td}|$ => BR(t→bW) ≈ 1
- The LHC is a top factory:
  - A great laboratory for top measurements
  - And background for everything else… ☺
  - Dominated by top pair from gluon fusion









What we talk about when we talk about the top mass

- The **top quark mass** is a **key parameter of the Standard Model**
  - High m_t results in/comes from Yukawa coupling close to 1
  - Results in important radiative corrections to Standard Model observables.
- **Theoretically**:
  - Beyond LO, $\mathbf{m_t}$ must be defined within a given **renormalization scheme**
  - **Pole mass** scheme: conserves m_t at all perturbation orders
  - **$\overline{\text{MS}}$ scheme**: m_t has different corrections at each order (differences of up to a few GeV!)

$$m_t^{pole} = m_t^{\overline{MS}} + \underbrace{7.557}_{\text{NLO}} + \underbrace{1.617}_{\text{NNLO}} + \underbrace{0.501}_{N^3LO} + \underbrace{0.195 \pm 0.005}_{N^4LO} \,\text{GeV}$$

- **Experimentally**:
  - **Direct measurements** sensitive to "Monte Carlo mass" $\mathbf{m_t^{MC}}$:
    - Extracted from invariant mass of decay products (yes, including jets)
    - Top mass unfolded from Monte Carlo simulation taking m_t^{MC} as input parameter
  - **Indirect measurements** sensitive to pole mass $\mathbf{m_t^{pole}}$ from observables depending on m_t
    - E.g. from σ^{meas} vs $\sigma^{theory}(\alpha_s, \mathbf{m_t}, \text{PDF}, \mu_F, \mu_R, \ldots)$
    - Measurement made in a given renormalization scheme
- **O(GeV) difference** between $\mathbf{m_t^{MC}}$ and $\mathbf{m_t^{pole}}$
  - See e.g. arXiv:1712.02796v3 [hep-ph] for an interesting discussion

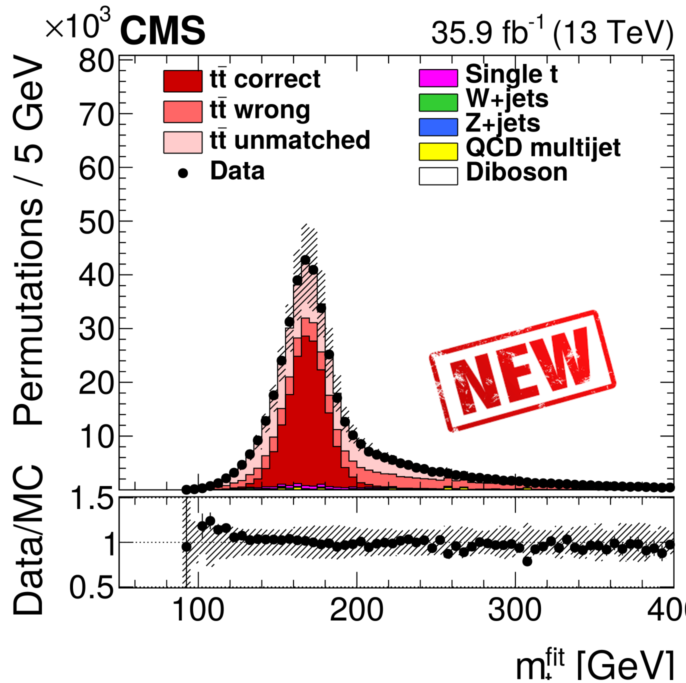
Direct m_t measurement : l+jets

- e/μ+≥4 jets (2 b-tagged)
- Kinematic fit:
  - Constraints: W mass, 2 same mass t tbar
- **CMS**: 35.9 fb^{-1} at √s = 13 TeV
  - 2D fit of m_t and m_W^{reco} ; extract JSF

  m_t = 172.25 ± 0.08 (stat+JSF) ± 0.62 (syst) GeV
- **ATLAS**: 20.2 fb^{-1} at √s = 8 TeV
  - 3D fit to: m_{top}^{reco}, m_W^{reco}, R_{bq}^{reco}
  - Extract m_t, JSF, b-JSF

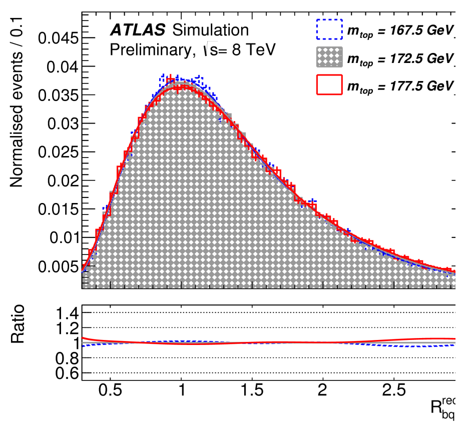
  m_t = 172.08 ± 0.39 (stat) ± 0.82 (syst) GeV
  - Adding √s = 7 TeV data:

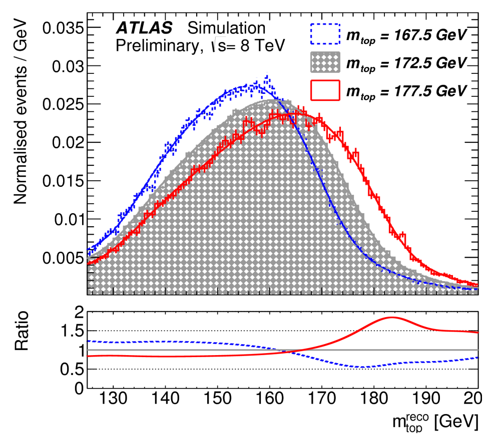
  m_t = 172.51 ± 0.27 (stat) ± 0.42 (syst) GeV

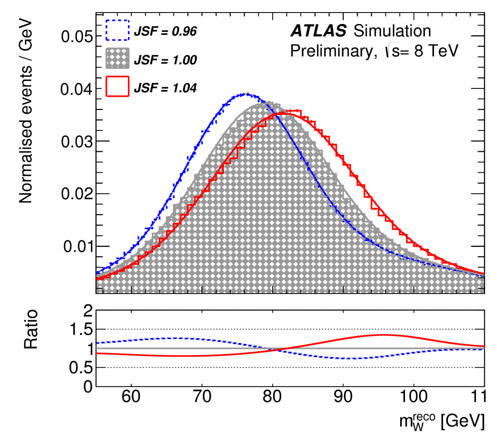


$$R_{bq}^{reco} = \frac{p_T^{b_{had}} + p_T^{b_{lep}}}{p_T^{q_1} + p_T^{q_2}}$$

(q1 and q2 light jets assigned to W)





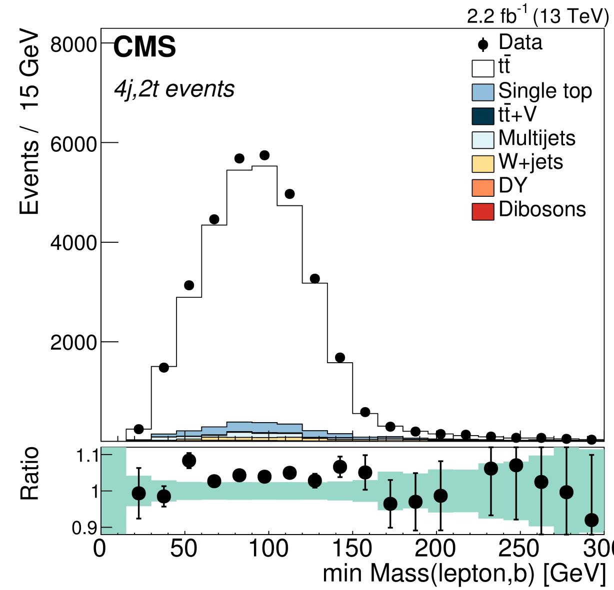


JHEP 09 (2017) 051; EPJC77 (2017) 804

Indirect m_t measurement

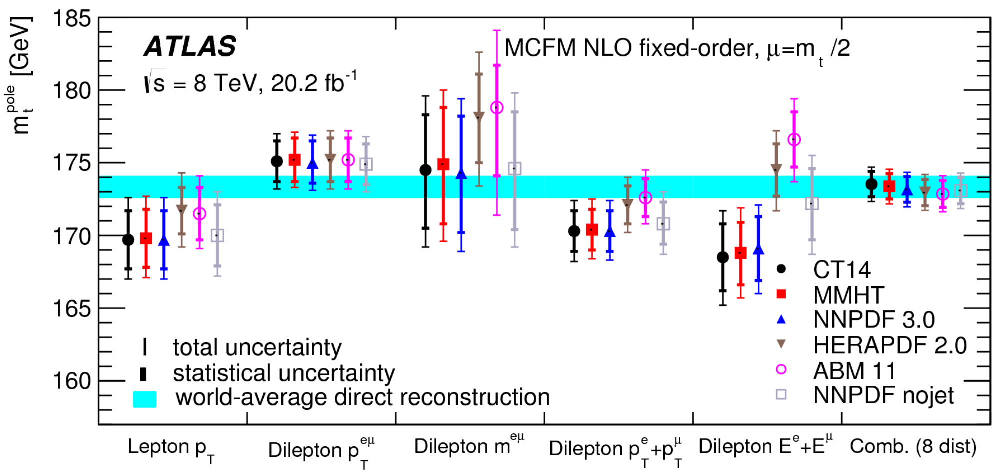
CMS: 13 TeV data, L = 2.2 fb^{-1}; lepton+jets final state

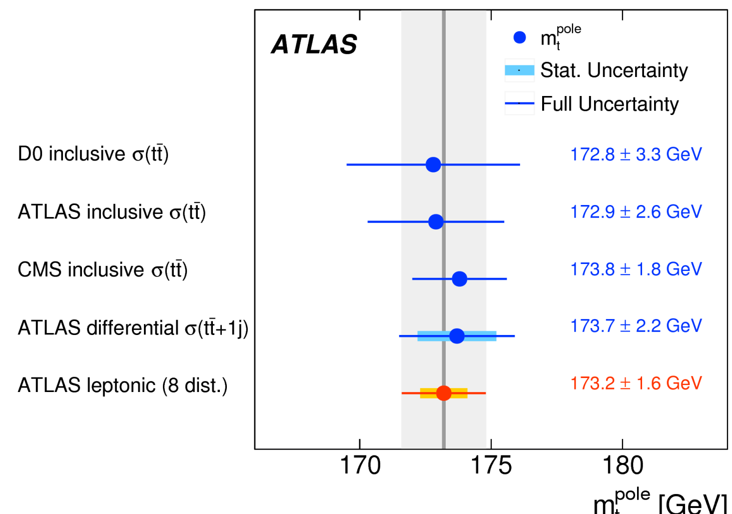
- Measure differential cross section wrt min(m_{lb}) in categories of N_{jet} and $N_{b\text{-}jet}$:
  σ = 888 ± 2 (stat) ± 27(sys) ± 20 (lumi) pb
- Extract pole mass from cross section:
  m_t^{pole} = 170.6 ± 2.7 (tot) ± 1.01 (syst.) GeV



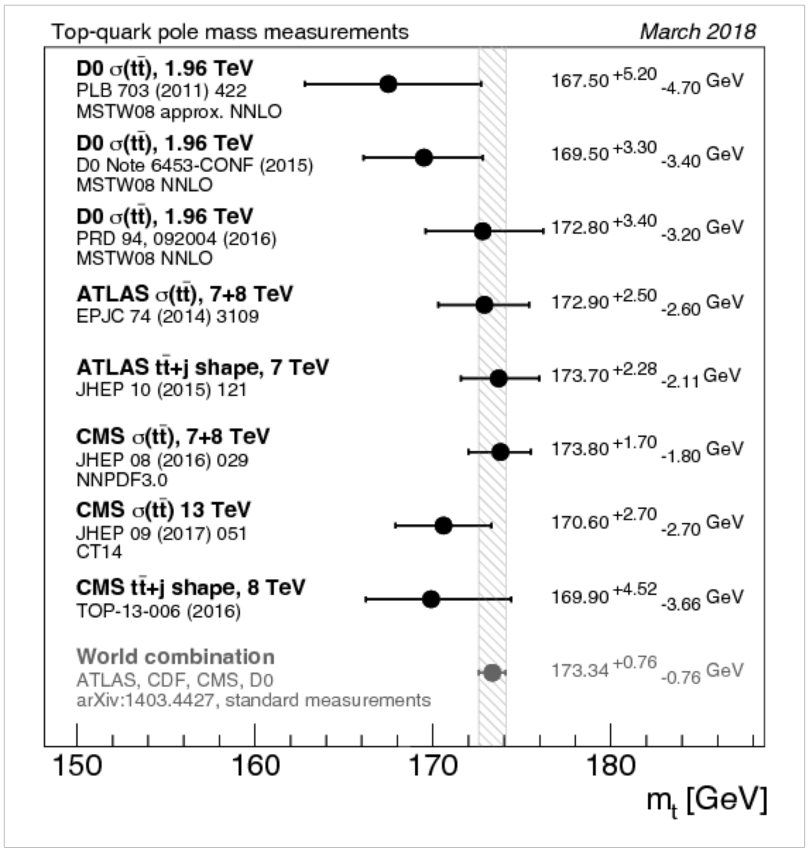
ATLAS: 8 TeV data, L = 20.2 fb^{-1}, dilepton with 1 or 2 b-jets

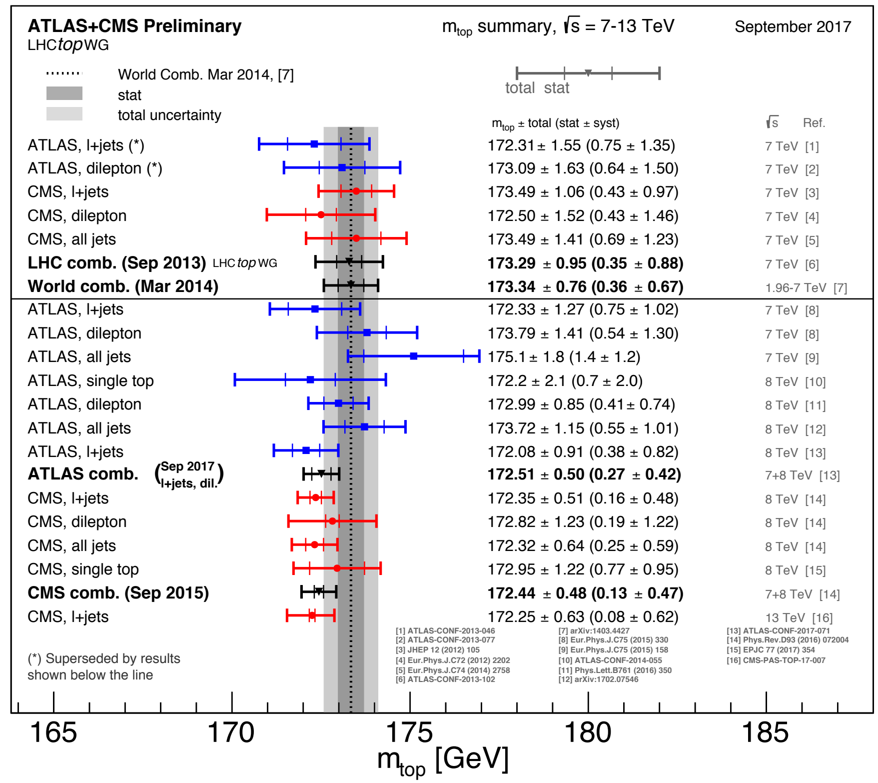
- 8 differential fiducial cross sections measured:
  p_T^l, $|\eta l|$, $p^{e\mu}$, $m^{e\mu}$, $|y^{e\mu}|$, $\Delta\phi^{e\mu}$, $p_T^e+p_T^\mu$, E^e+E^μ
- m_t^{pole} extracted from combined fit to templates or distribution moments
  – m_t^{pole}= 173.2 ± 0.9 (stat) ± 0.8 (syst) ± 1.2 (theo) GeV





m_t: the story so far

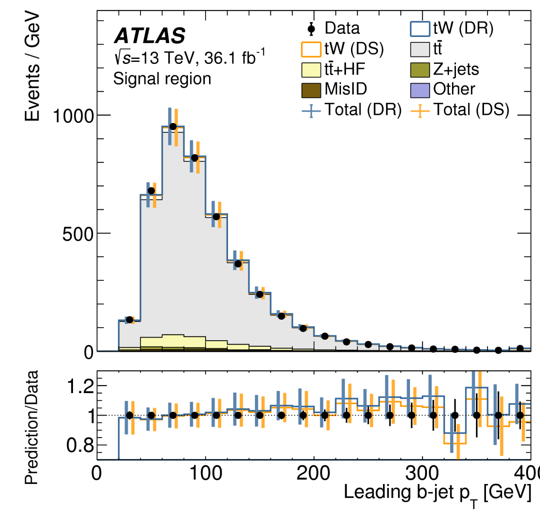


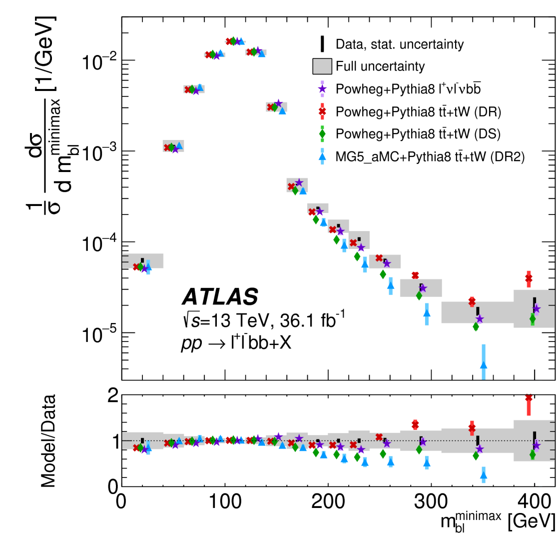


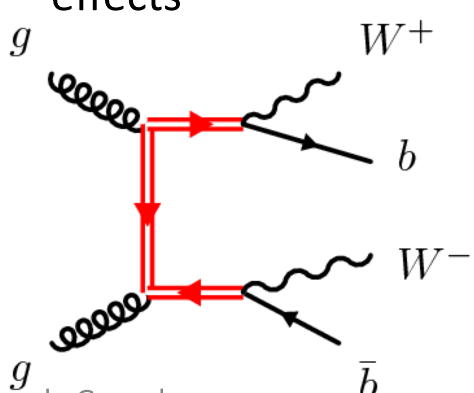
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots arXiv:1806.04667 [hep-ex]

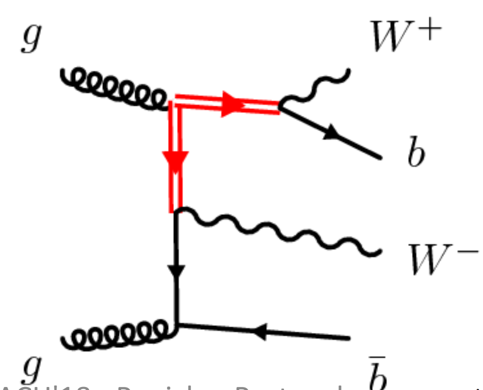
ATLAS measurement of quantum interference in single top production

- An NLO, top pair and single top (Wt) production have quantum interference
- Ad hoc treatment of the Wt and tt combination is used in most analyses:
  - **Diagram removal (DR)**: remove doubly resonant diagrams from Wtb matrix element
  - **Diagram subtraction (DS)**: subtract gauge-invariant term from Wtb matrix element
  - See review in arXiv:1607.05862 [hep-ph]
- ATLAS measured differential cross section for tt/Wt production
  - Focused on fiducial region with significant interference effects

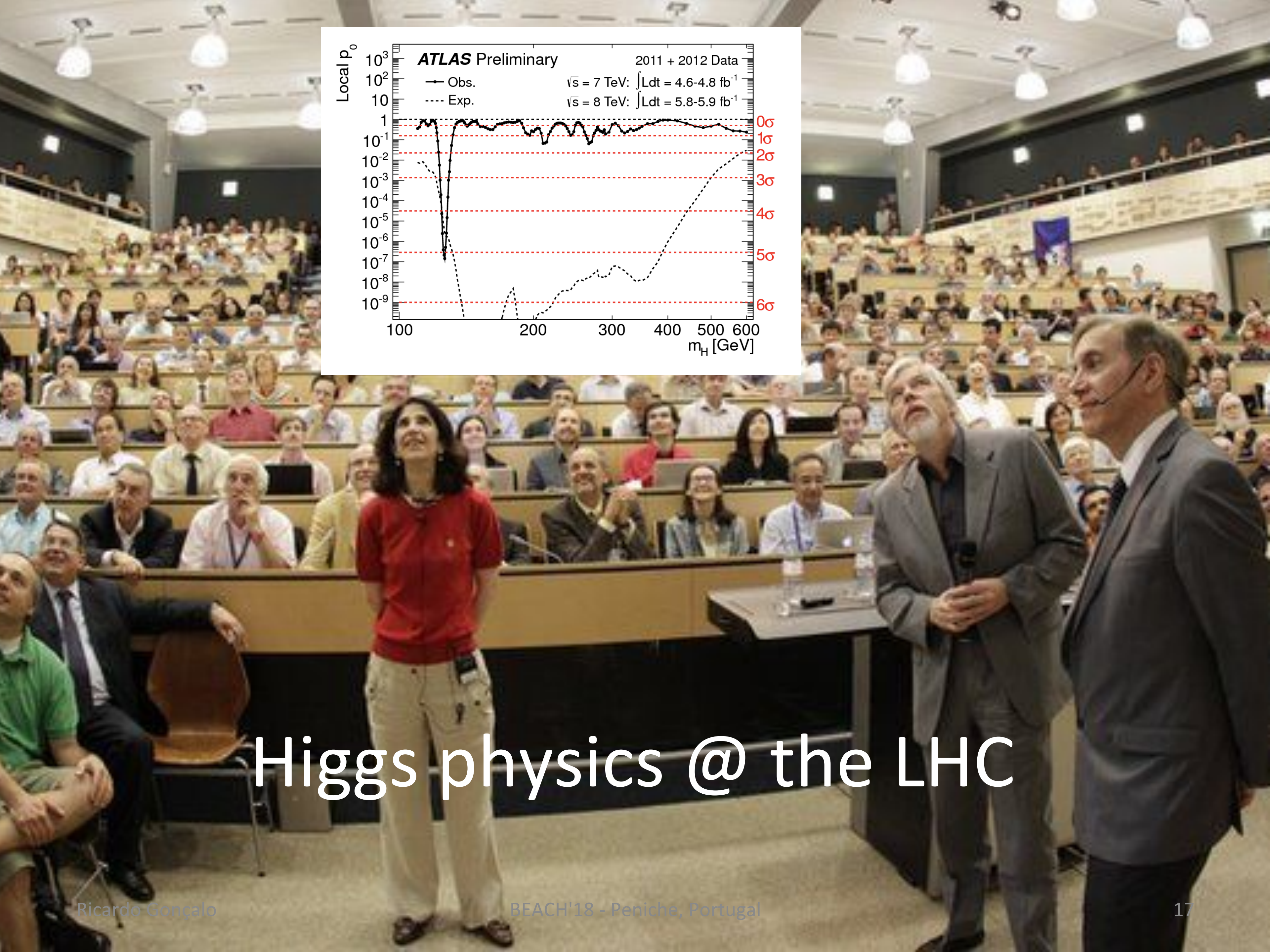








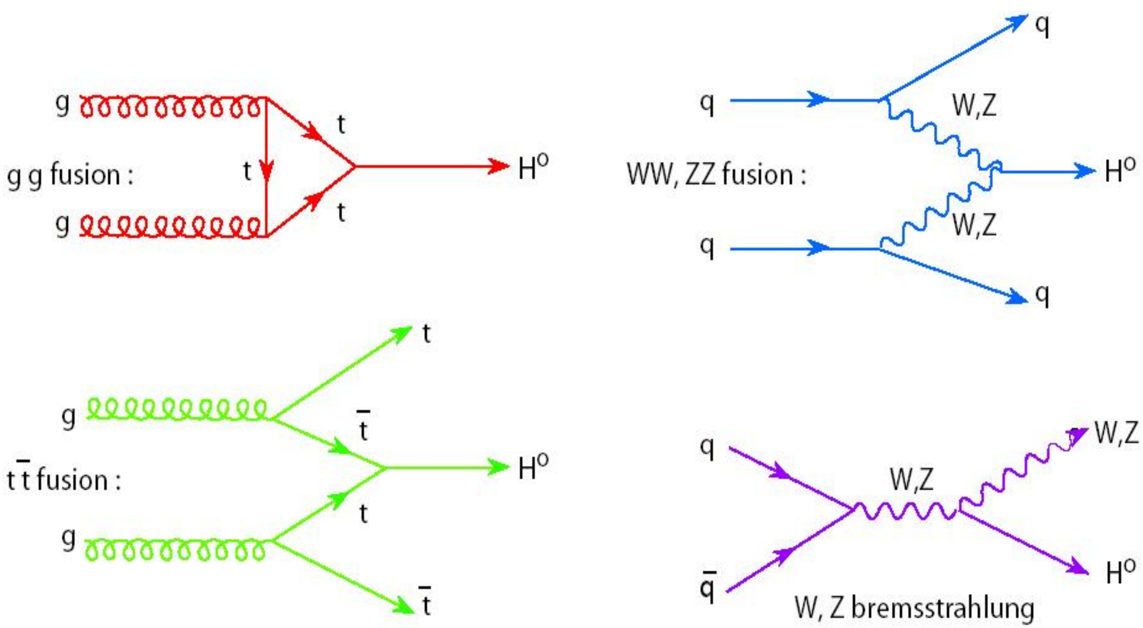
$$m_{b\ell}^{\text{minimax}} \equiv \min\{\max(m_{b_1\ell_1}, m_{b_2\ell_2}), \max(m_{b_1\ell_2}, m_{b_2\ell_1})\}$$

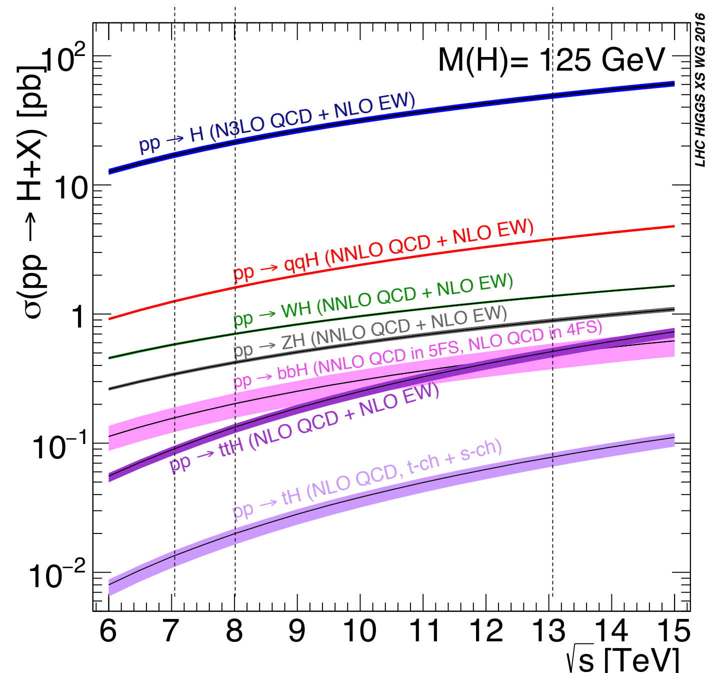


Higgs physics @ the LHC

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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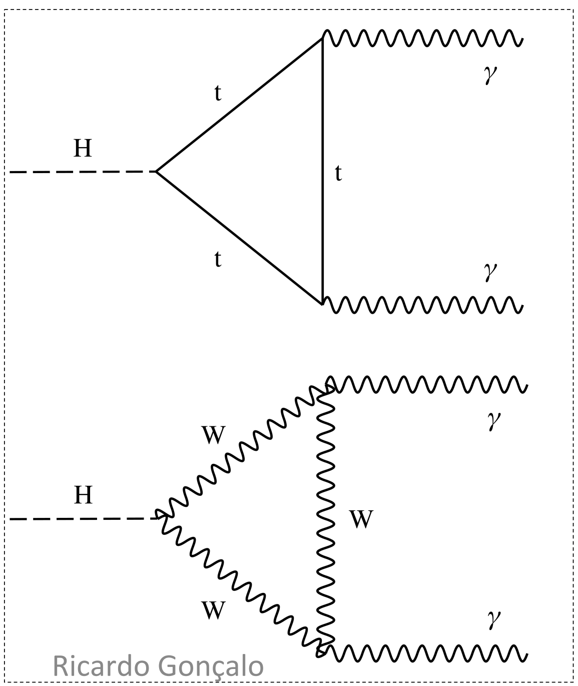
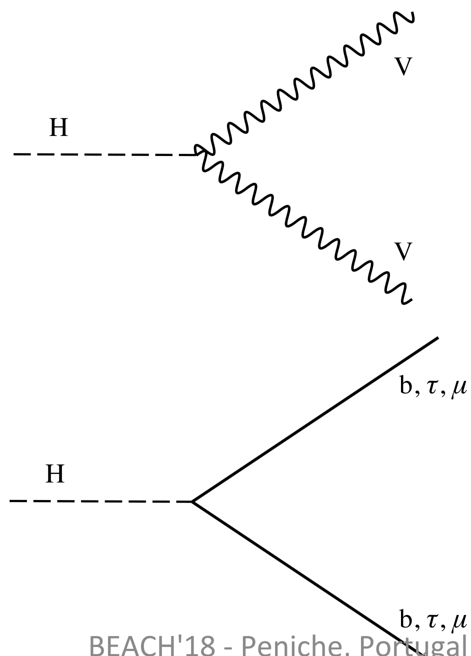
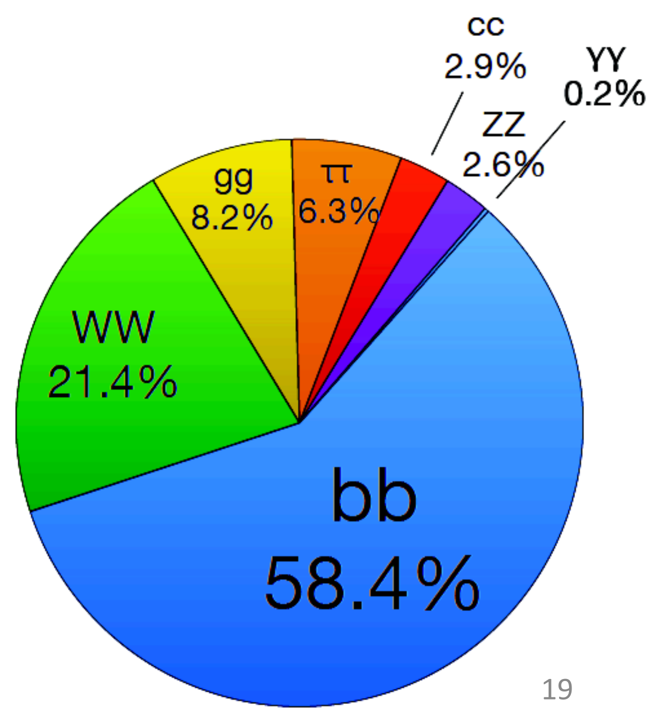
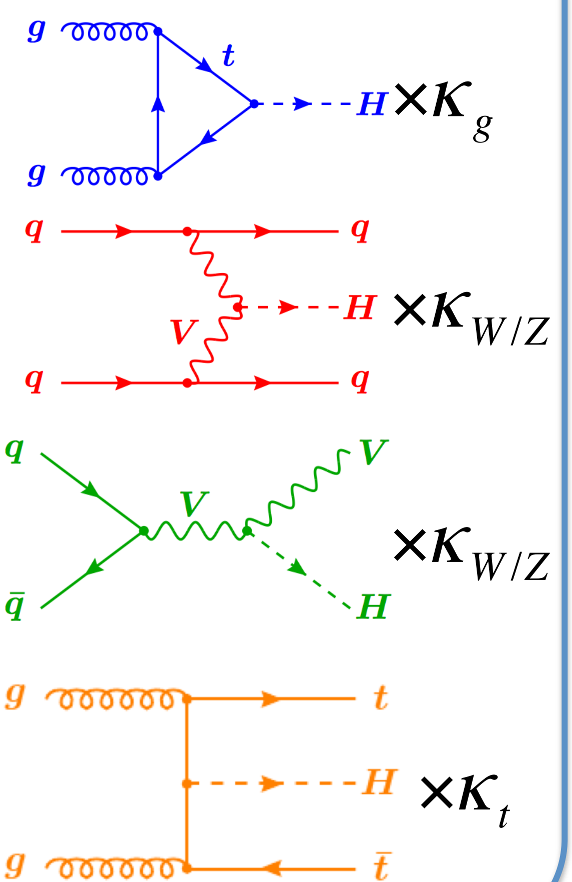






$$\kappa_i^2 = \sigma_i / \sigma_i^{SM} \qquad \kappa_f^2 = \Gamma_f / \Gamma_f^{SM} \qquad \mu = \frac{(\sigma \cdot BR)^{Obs.}}{(\sigma \cdot BR)^{SM}} = \kappa_i^2 \cdot \kappa_f^2$$

Production



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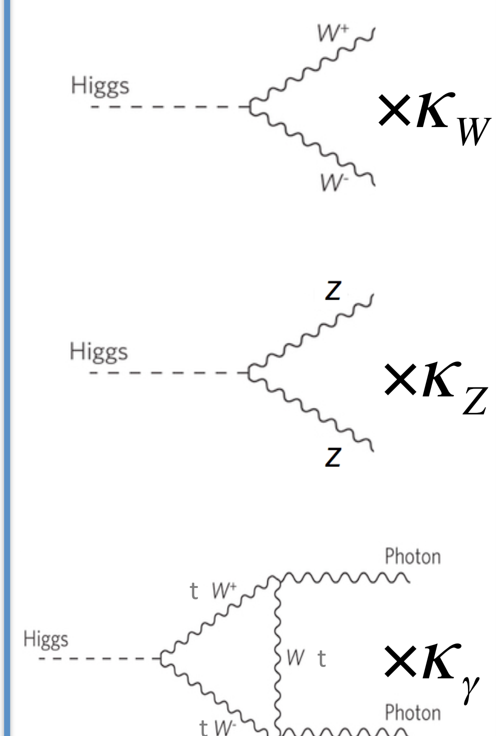
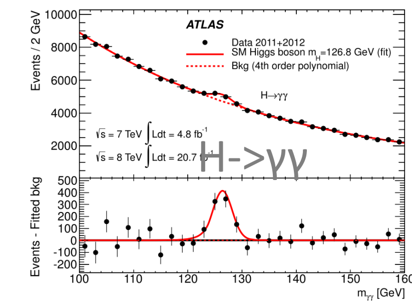
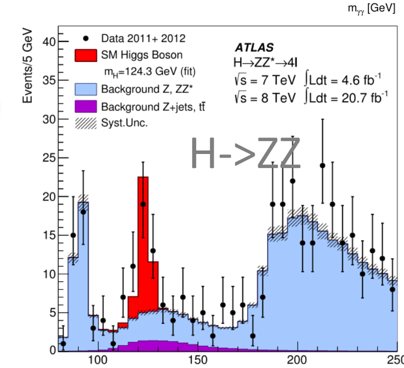
Decay

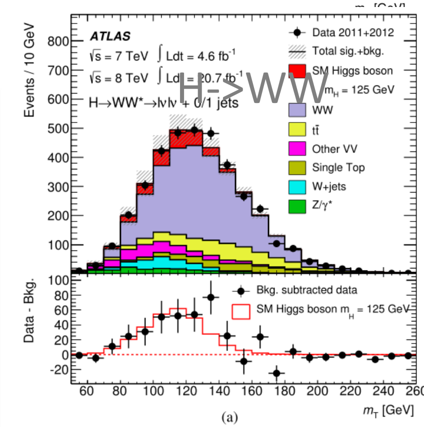


FIT

Backgrounds +





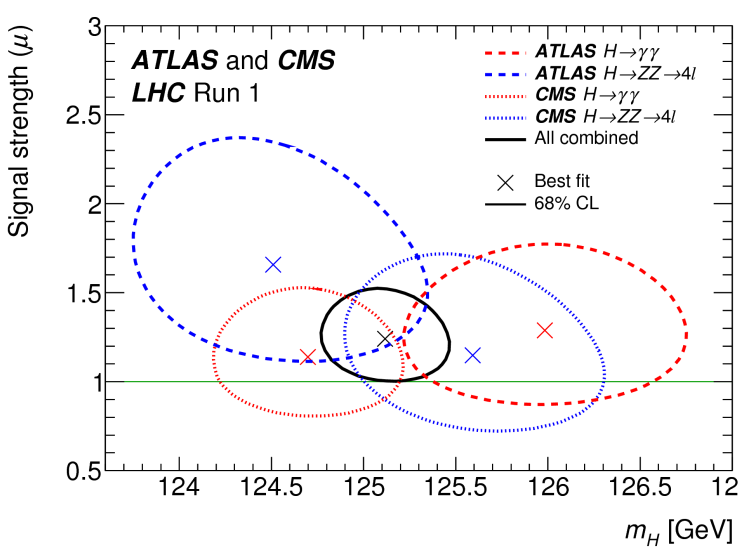


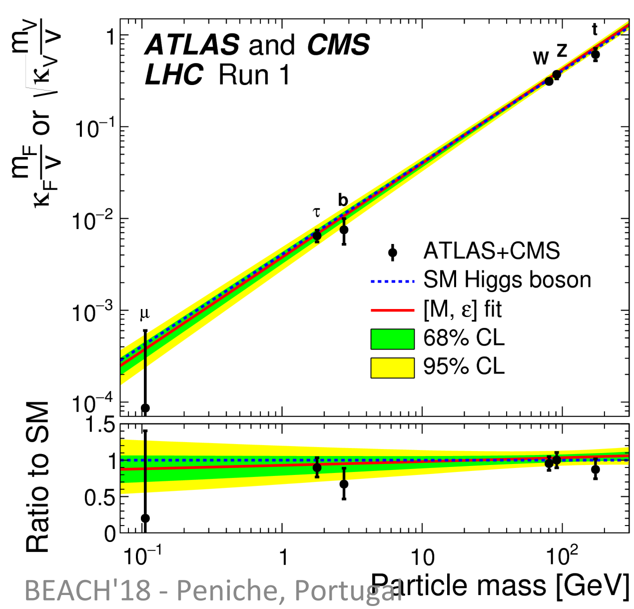
Phys. Rev. Lett. 114 (2015) 191803
JHEP 08 (2016) 045

The Run 1 legacy

- Mass – Higgs mass measured with 0.4% 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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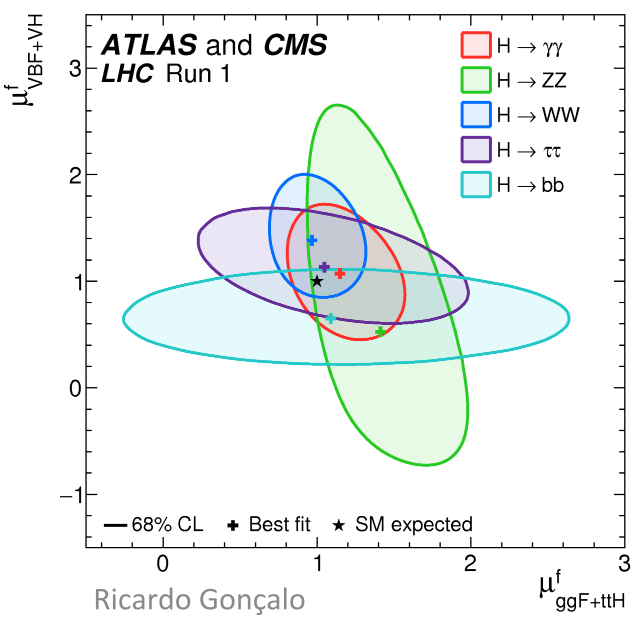

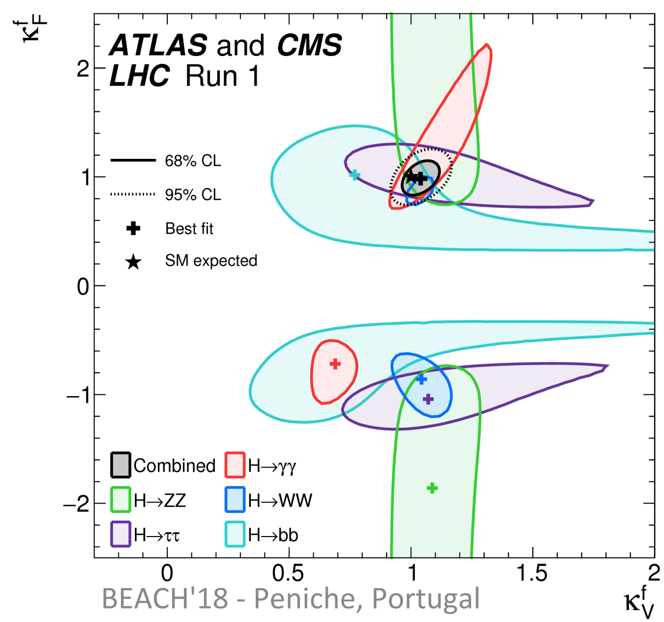

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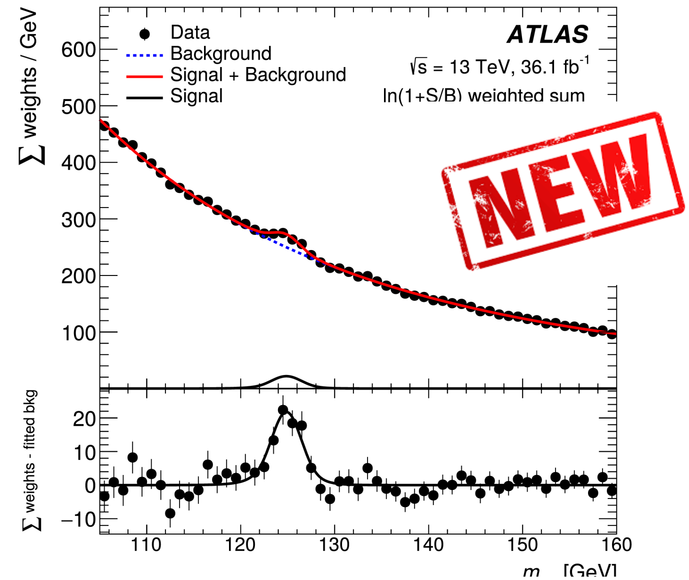
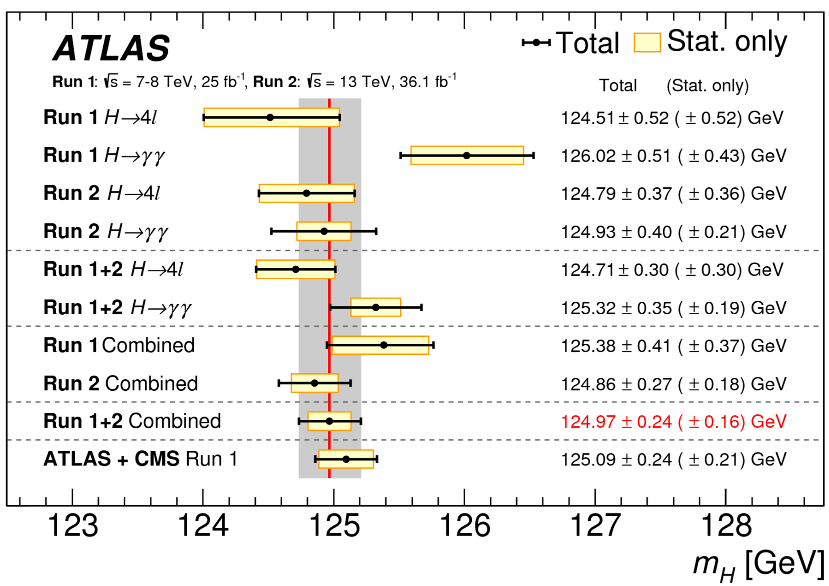
H→bb	2.6	3.7

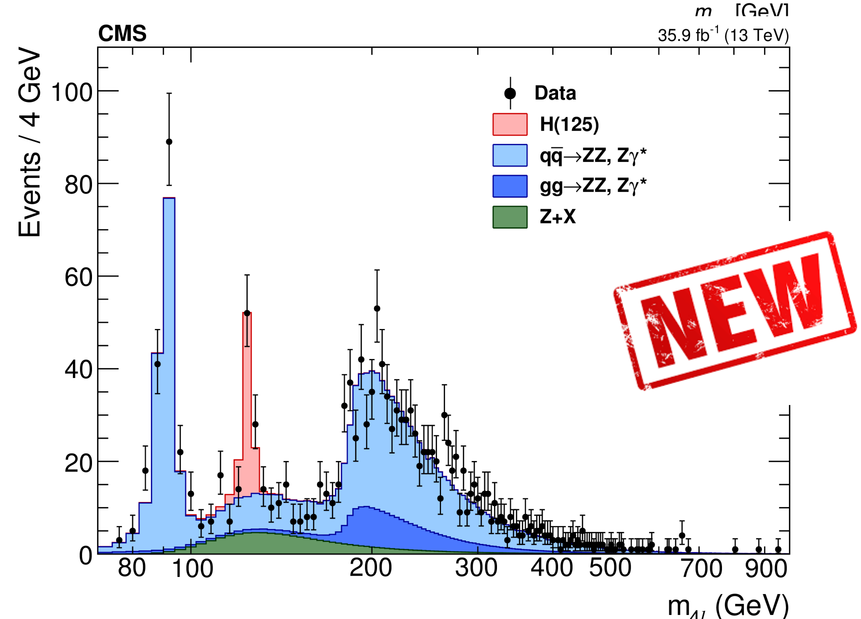
arXiv:1706.09936 [hep-ex]; arXiv:1806.00242 [hep-ex]

Run 2: Higgs boson mass

- Mass measurement from CMS H→ZZ*→4l:
  $m_H^{ZZ*} = 125.26 \pm 0.20\ (stat) \pm 0.08\ (syst)$ GeV
- New Measurements from ATLAS
  H→ γγ: $m_H^{\gamma\gamma} = 124.93 \pm 0.40$ GeV
  H→ZZ*→4l: $m_H^{ZZ*} = 124.79 \pm 0.37$ GeV
- Run 1+2 combination from ATLAS:
  $m_H = 124.97 \pm 0.19\ (stat) \pm 0.13\ (syst.)$ GeV





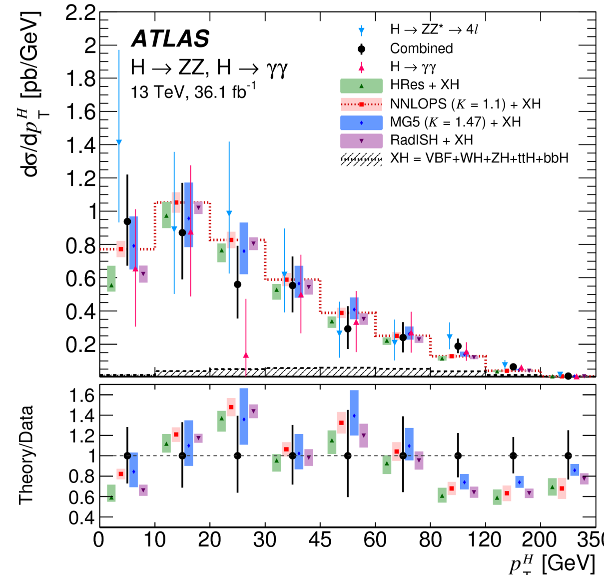


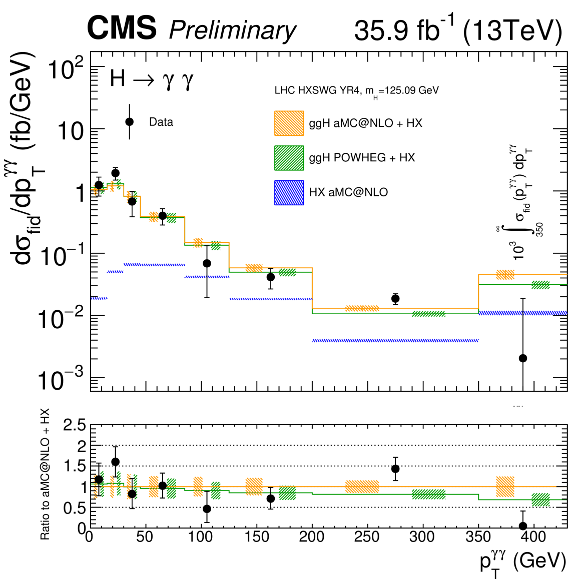
Differential Higgs boson cross sections

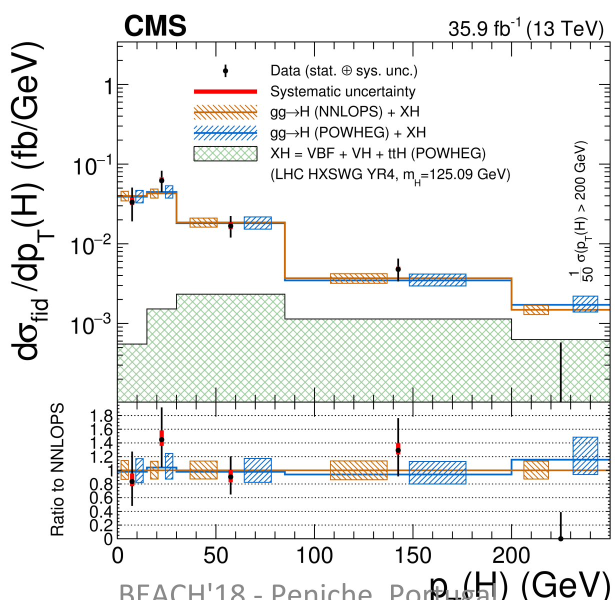
- Reached a new phase in the exploration of the Higgs sector!

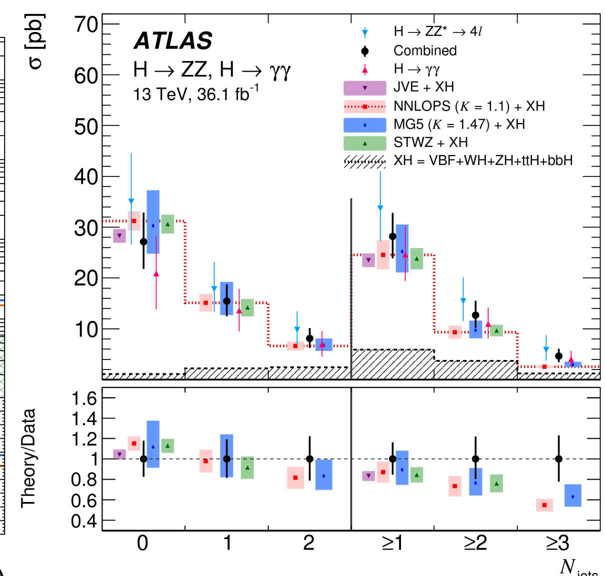
NEW

- 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



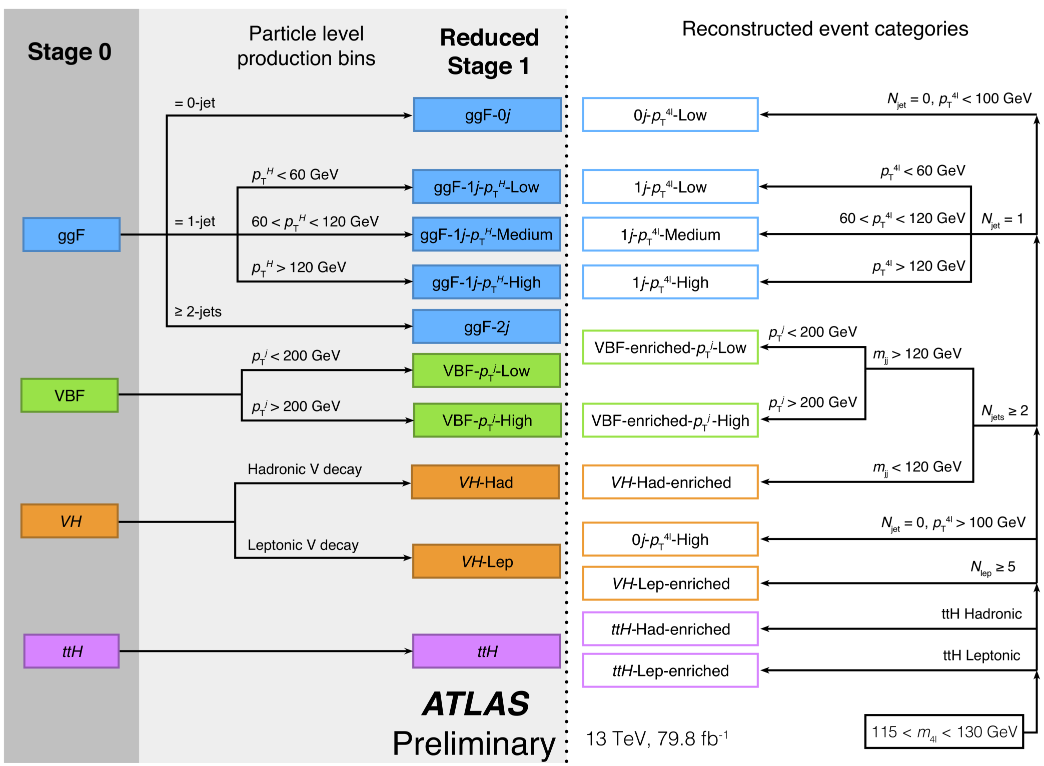


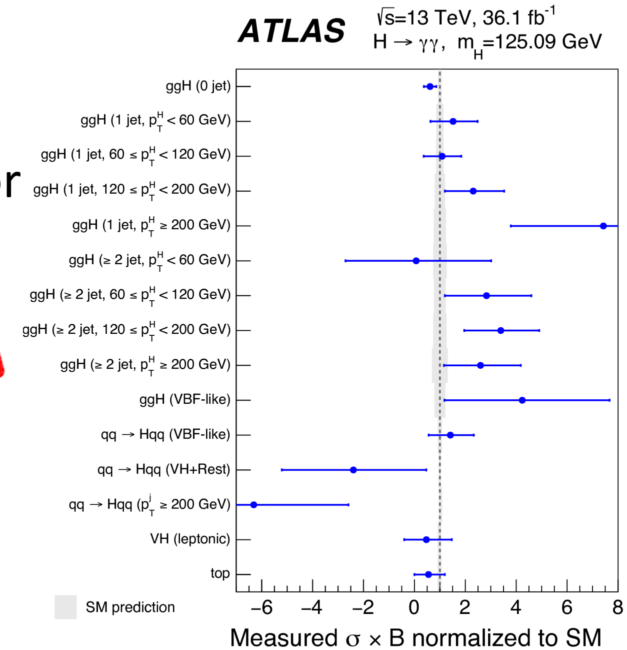


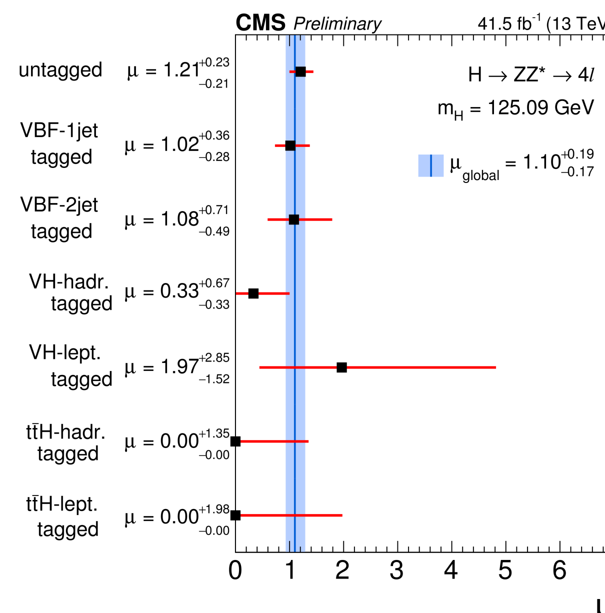


- Simplified template cross sections (STXS):
  - Independent, simple fiducial region definitions for each Higgs production mode
  - Common for ATLAS, CMS and theory
  - Good balance between experimental and theory uncertainty

NEW

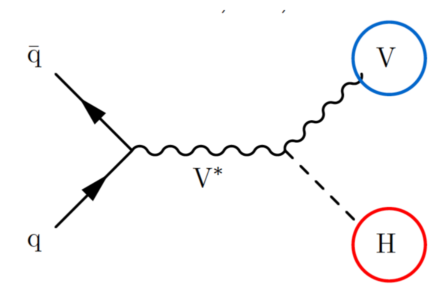




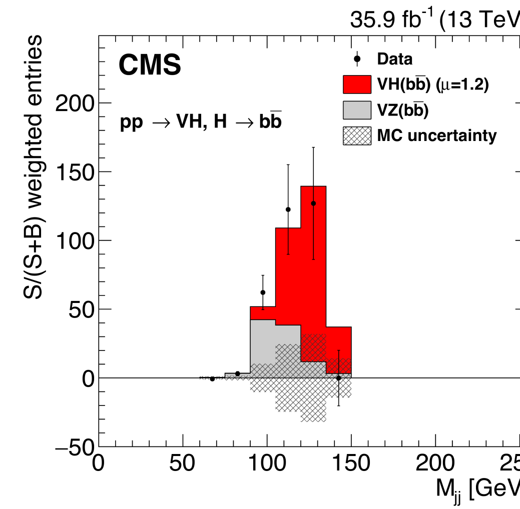


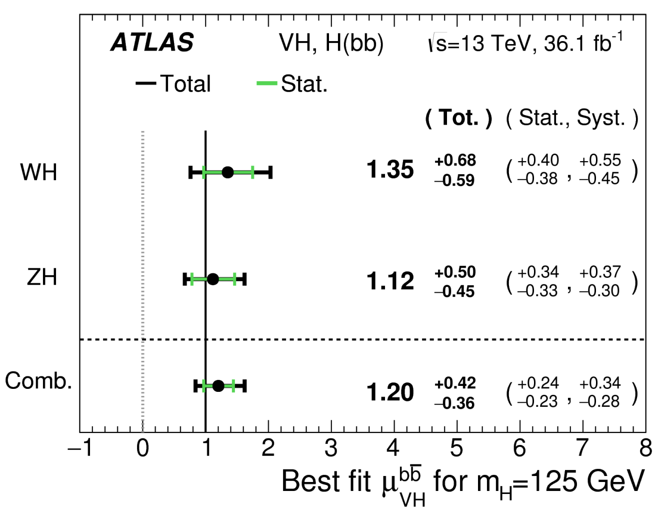
JHEP 12 (2017) 024; Phys. Lett. B 780 (2018) 501

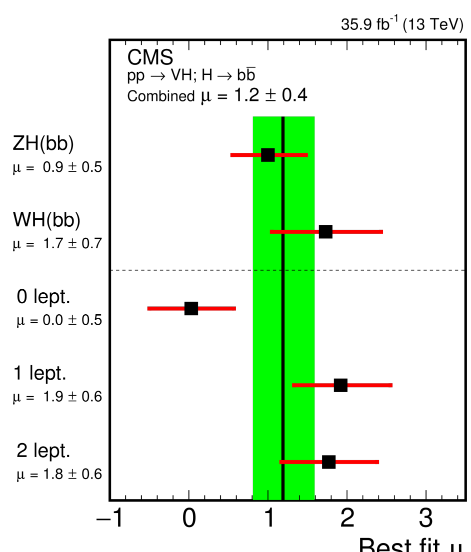
Evidence for H→bb

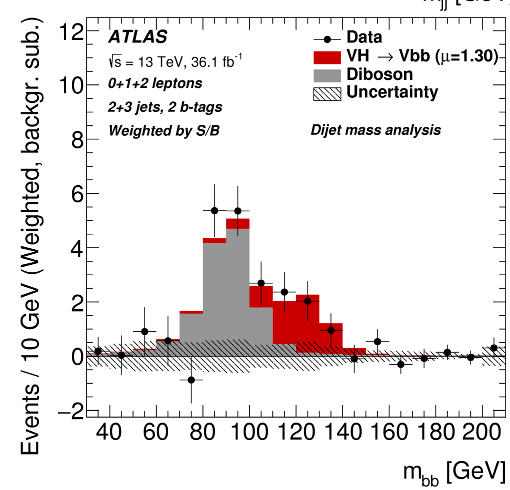


- Largest branching fraction (58.4%) but huge background from heavy flavour production
- Must use associated production: WH/ZH
  - Require 2 b jets + 0 (Z→νν), 1 (W→ℓν) or 2 (Z→ℓℓ) leptons
- Largest backgrounds:
  - Z+heavy flavour (0- and 2-lepton) and tt (1-lepton)
  - Irreducible background from VZ with Z→bb
- Significance:
  - ATLAS: observed (expected) of 3.5σ (3.0σ)
  - CMS: observed (expected) of 3.3σ (2.8σ) – 3.8σ(3.8σ) with Run 1



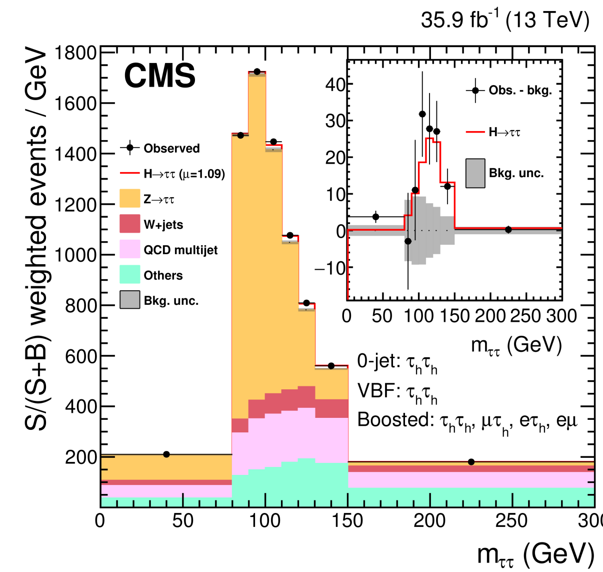


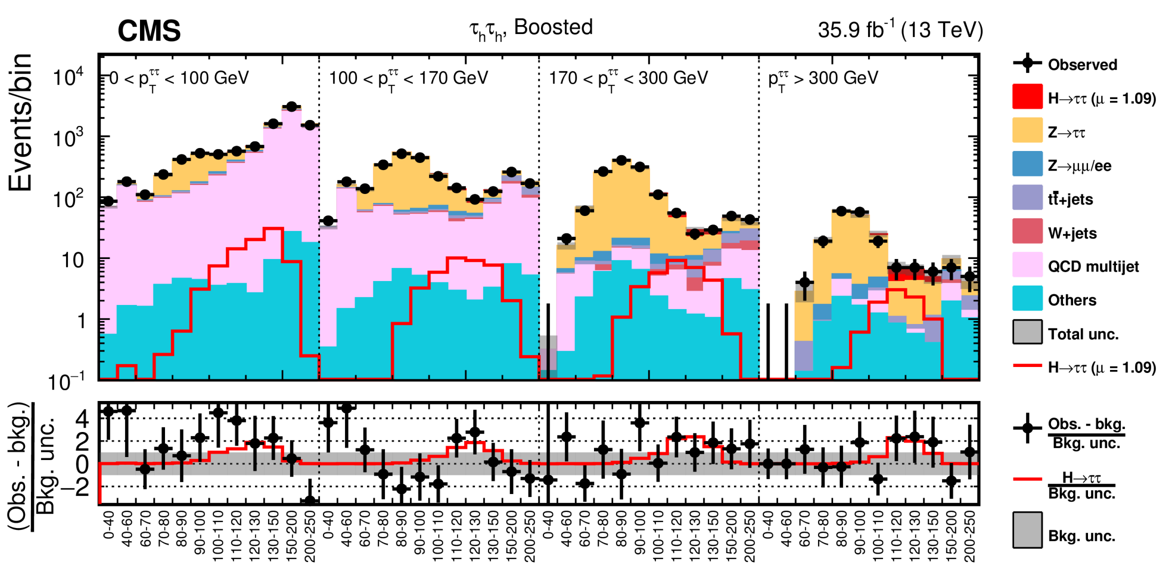


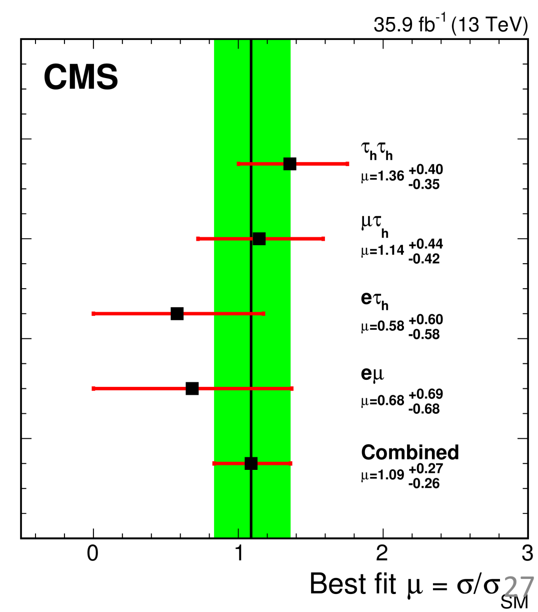


CMS observation of H→ττ

- Combine all final: $\tau_{had}\tau_{had}$, $\tau_{lep}\tau_{had}$, $\tau_{lep}\tau_{lep}$
- 3 categories: 0-jet, VBF and boosted (mostly ggF)
- 35.9 fb-1 of 13 TeV data
- 2D likelihood fit using $m_{\tau\tau}$, m_{jj} or $p_T^{\tau\tau}$
- Observed (expected) significance of 4.9σ (4.7σ)
- Combining with Run 1:
  - 36 fb-1 of 13 TeV data: 4.9 σ observed; 4.7 σ expected
  - Combining with Run 1: 5.9 σ observed; 5.9 σ expected
  - μ = 0.98 ± 0.18

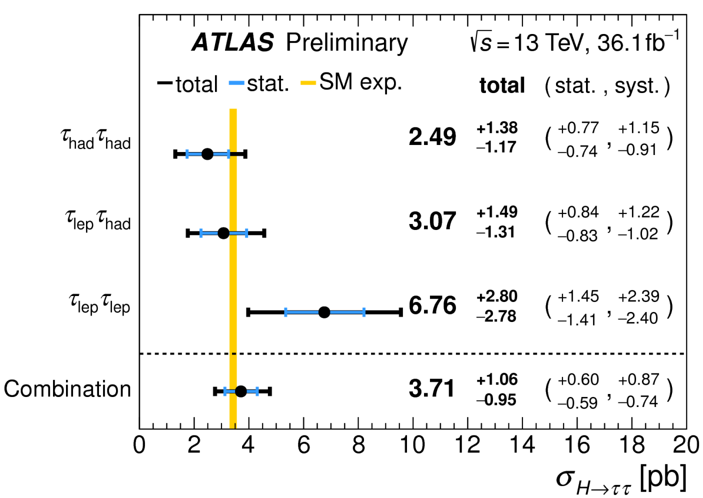


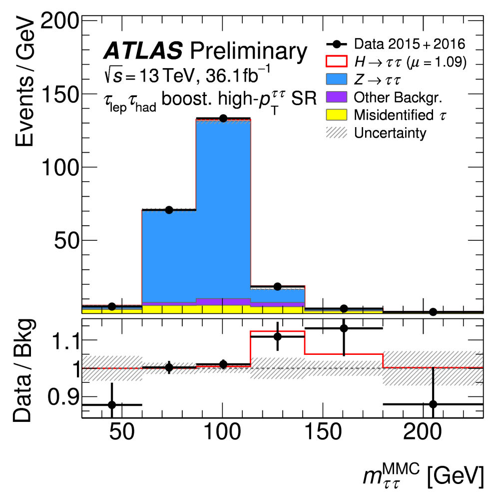


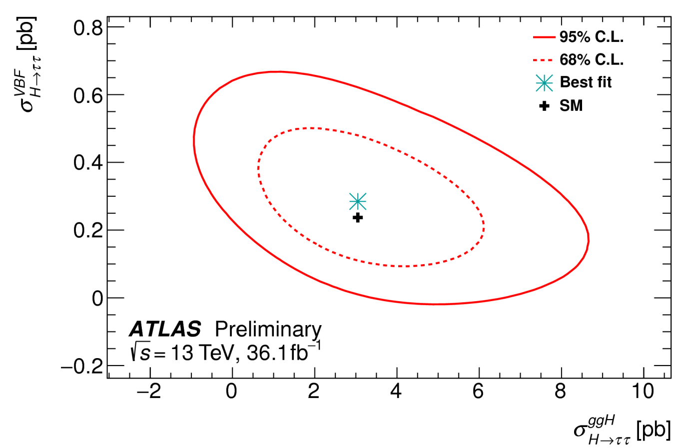


ATLAS observation of H→ττ

- 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→$\tau\tau$ 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



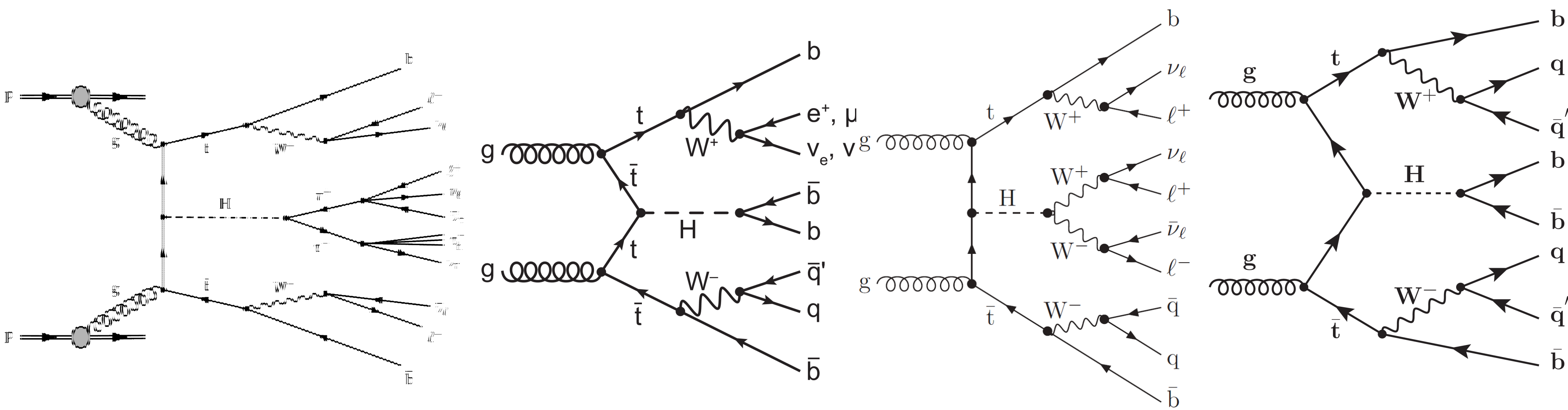




arXiv:1806.00425 [hep-ex]
arXiv:1804.02610 [hep-ex]

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
- 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%

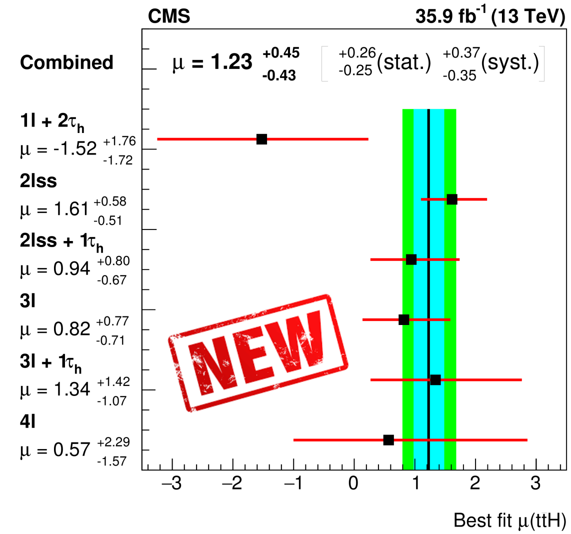


ttH(ML) Phys. Rev. D 97 (2018) 072003; arXiv:1803.05485 [hep-ex]
ttH(bb) Phys. Rev. D 97 (2018) 072016; JHEP 01 (2018) 054

ttH observation: bb and Multileptons

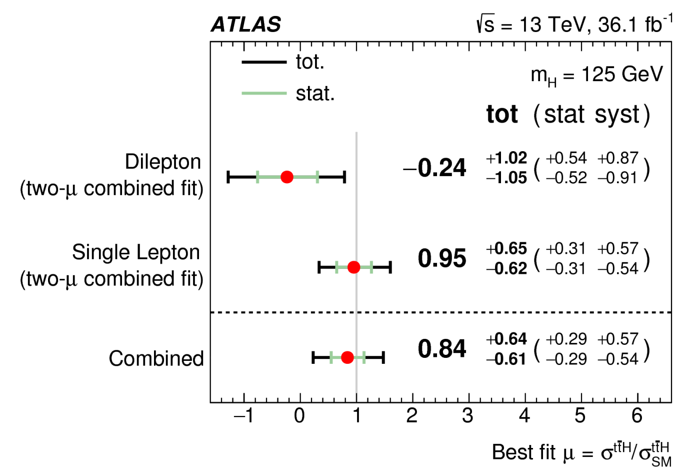
ttH(H→leptons)

- Sensitive to: H→$\tau\tau$, H→WW* and H→ZZ*
- Event categories according to number of light charged leptons and hadronic τ decays
- Backgrounds: ttW/ttZ, non-prompt leptons and jets faking taus
- Main uncertainties: signal modelling, jet energy scale and non-prompt lepton estimate
- ATLAS: 4.1σ observed; 2.8σ expected
- CMS: 3.2σ 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...
- Event categories according to number of light and b jets
- Main uncertainties: tt+heavy flavours, b tagging, jet calibration
- ATLAS: 1.2σ observed; 1.6σ expected
- CMS: 1.6σ observed; 2.2σ expected



For both channels:

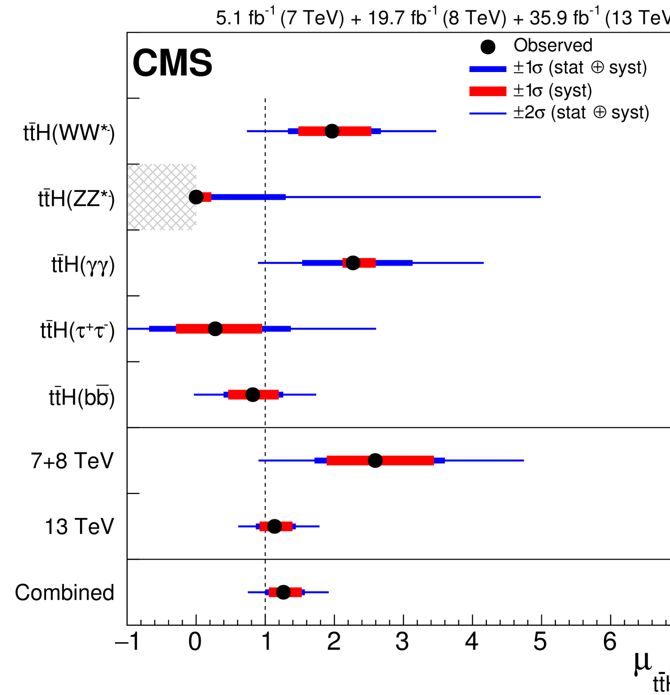
- Intensive use of dedicated machine learning (neural nets, booste decision trees) and matrix element method to discriminate agair fake leptons, reconstruct events, flavour tagging, and to enhance signal/background separation

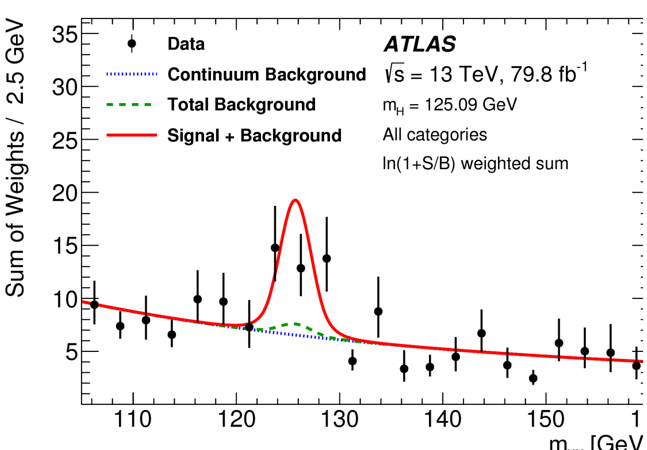
ttH observation

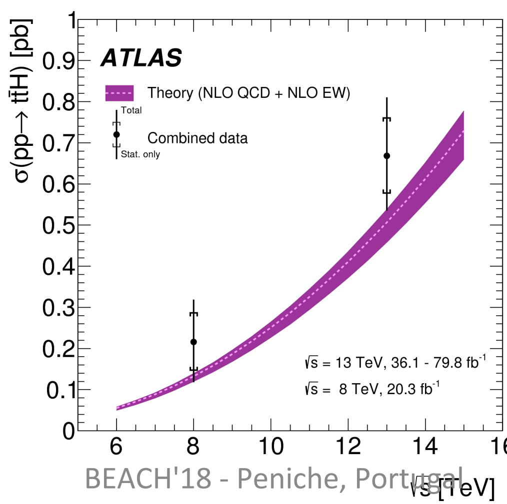
CMS:
- Combined Run 1 + 36.1 fb^{-1} Run 2:
- 5.2 σ observed, 4.2 σ expected

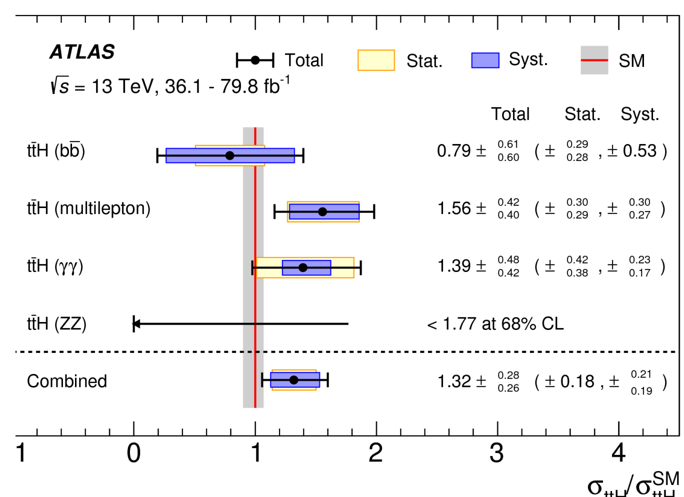
ATLAS:
- ttH(H→$\gamma\gamma$):
  - New signal categories from BDT discriminant
  - **Sensitivity increased by 50%**
- Run 2 data from 2015+2016+2017 ($\gamma\gamma$/ZZ): **79.8 fb^{-1}**
  - 5.2 σ observed, 4.9 σ expected
- Adding Run 1: 6.3 σ observed, 5.1 σ expected
- Measured production cross section at 13 TeV:

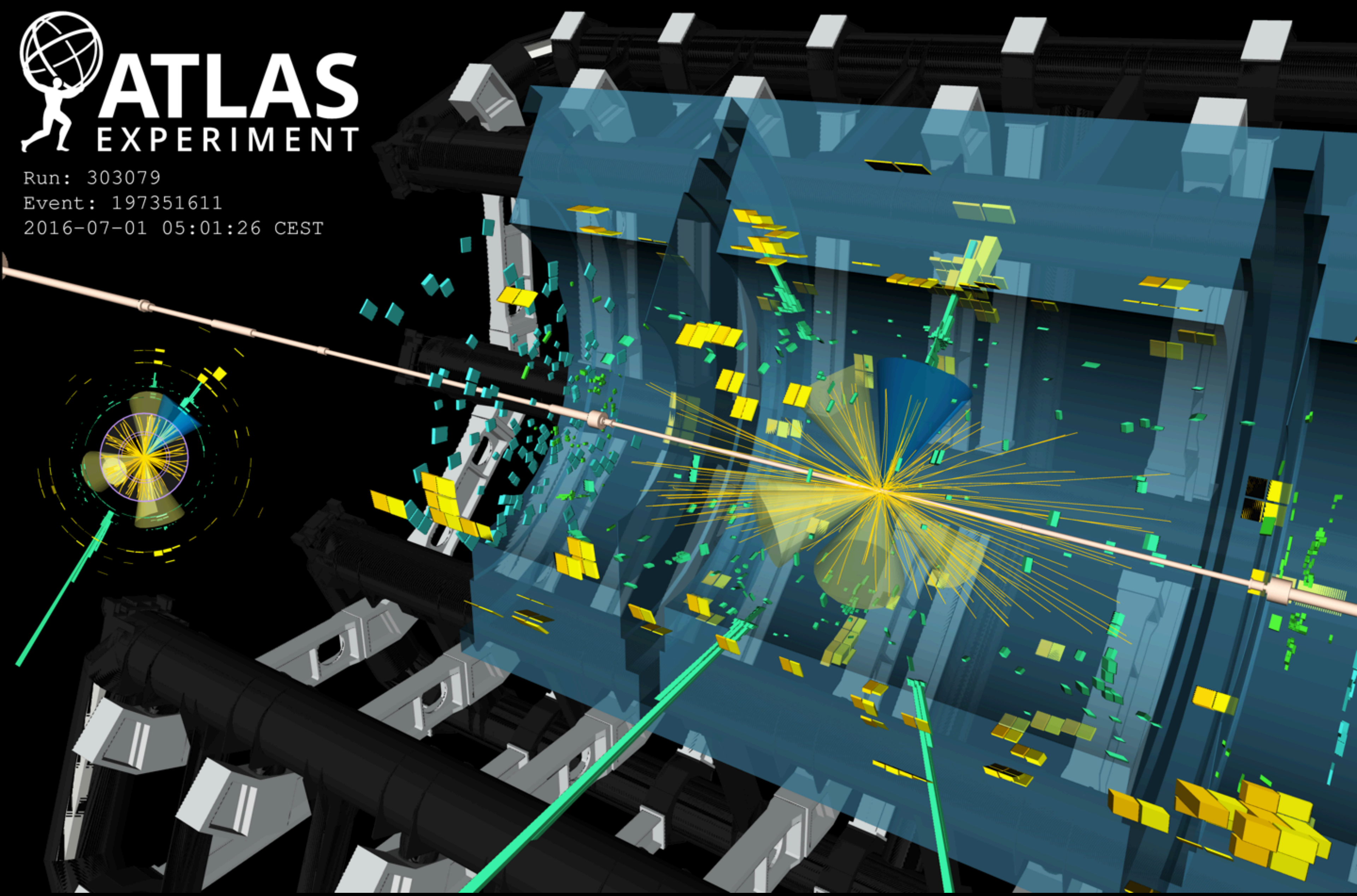
  670 ± 90 (stat.) +110–100 (syst.) fb










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

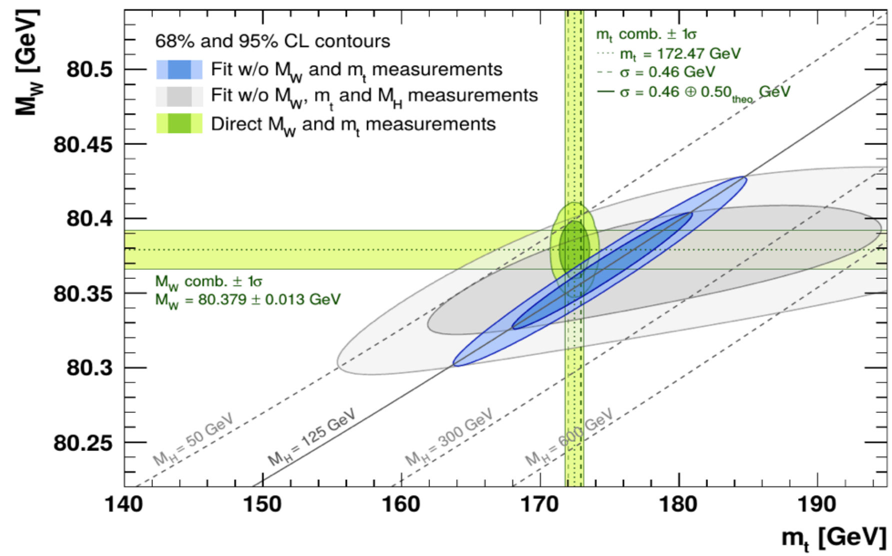
Summary

I could only show a few highlights of the ATLAS and CMS top and Higgs physics (a personal choice...)

What I have left out (LOTS!):

- Top cross section measurements, BSM, FCNC searches, etc
- Searches for 2nd generation fermion Higgs couplings, double-Higgs production, extended Higgs sector, etc
- Analysis details showing their huge sophistication
- Performance studies/improvements which make it all possible
- Projections for future LHC/HL-LHC running

arXiv:1803.01853



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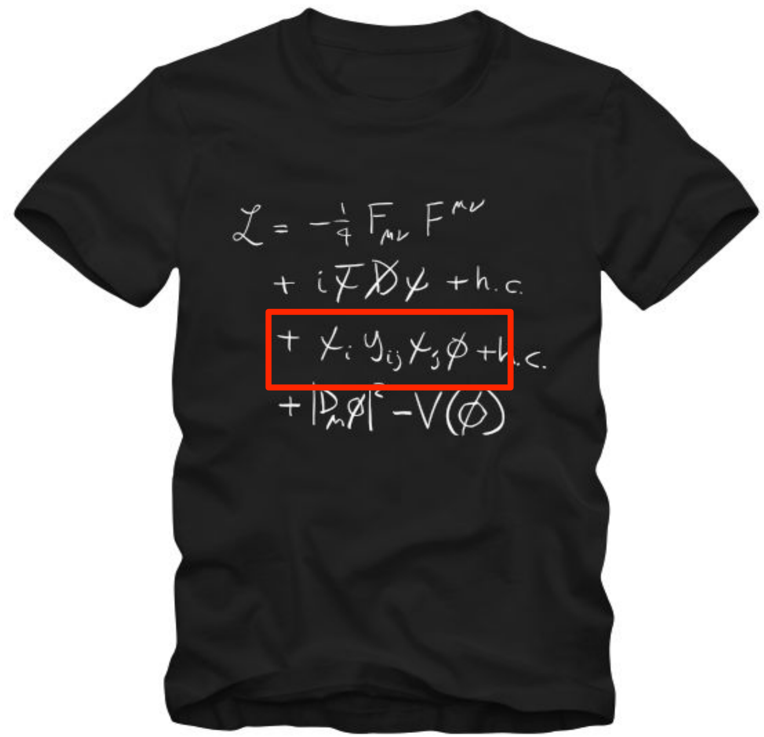


Overall highlight (personal bias):
"The >5σ observations of ttH and H → ττ, independently by ATLAS and CMS, firmly establish the existence of a new kind of fundamental interaction, Yukawa interactions."
Gavin Salam (LHCP'18)

Summary

I could only show a few highlights of the ATLAS and CMS top and Higgs physics (a personal choice...)

In conclusion:

- Higgs and top results probe deeply into our understanding of Nature
- So far, the SM holds
- So we must look closer!
- Because ~~the truth~~ New Physics is out there!

See here for more: [ATLAS Public results page]() and [CMS Publications page]()

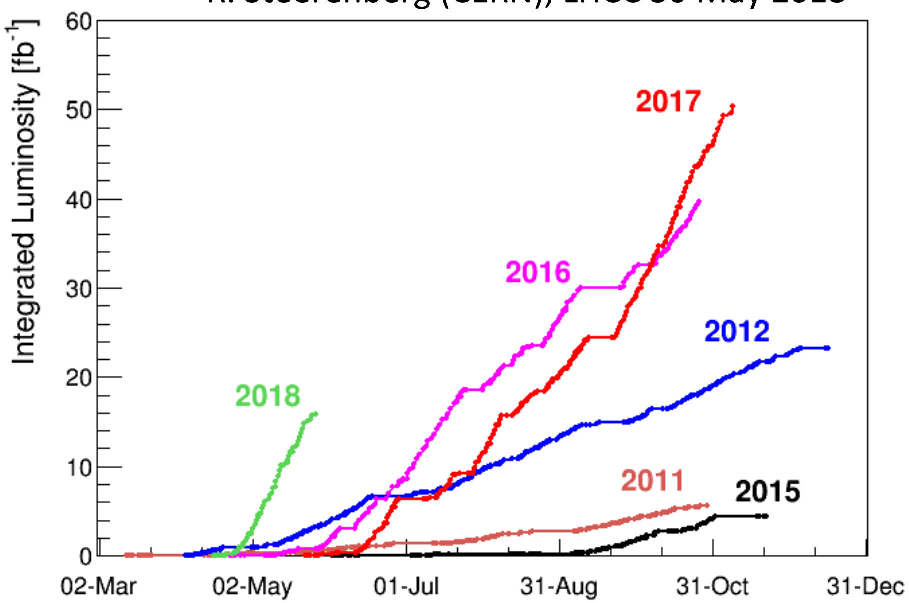
Bonus slides

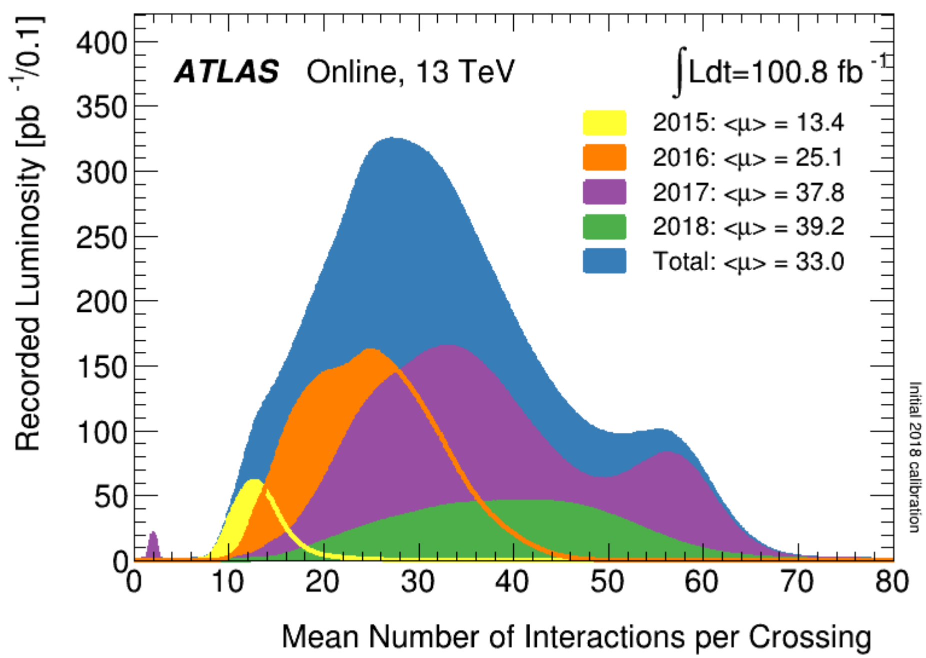
- a

ATLAS, CMS and the LHC

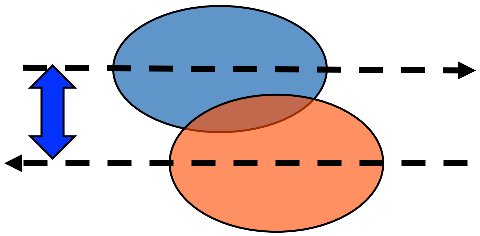
- Run 1: 2009 – 2013; ≈ 5 fb^{-1} at $\sqrt{s}$ = 7 and ≈ 20 fb^{-1} at 8 TeV per experiment
- Run 2: 2013 – 2018; expect > 150 fb^{-1} at $\sqrt{s}$ = 13 TeV by the end of run
- Instantaneous luminosity of **2 x 10^{34} $cm^{-2}s^{-1}$** in 2017 (2x design!)
- Downside is pileup => experimental challenge!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

R. Steerenberg (CERN), LHCC 30 May 2018

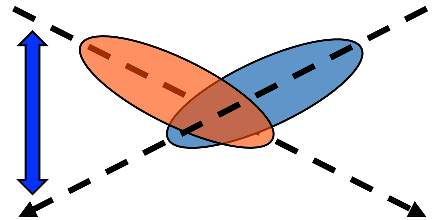




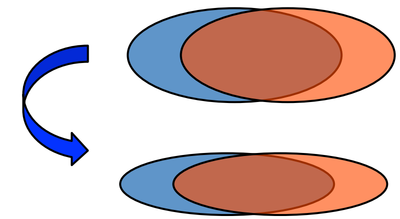
Leveling by beam offset

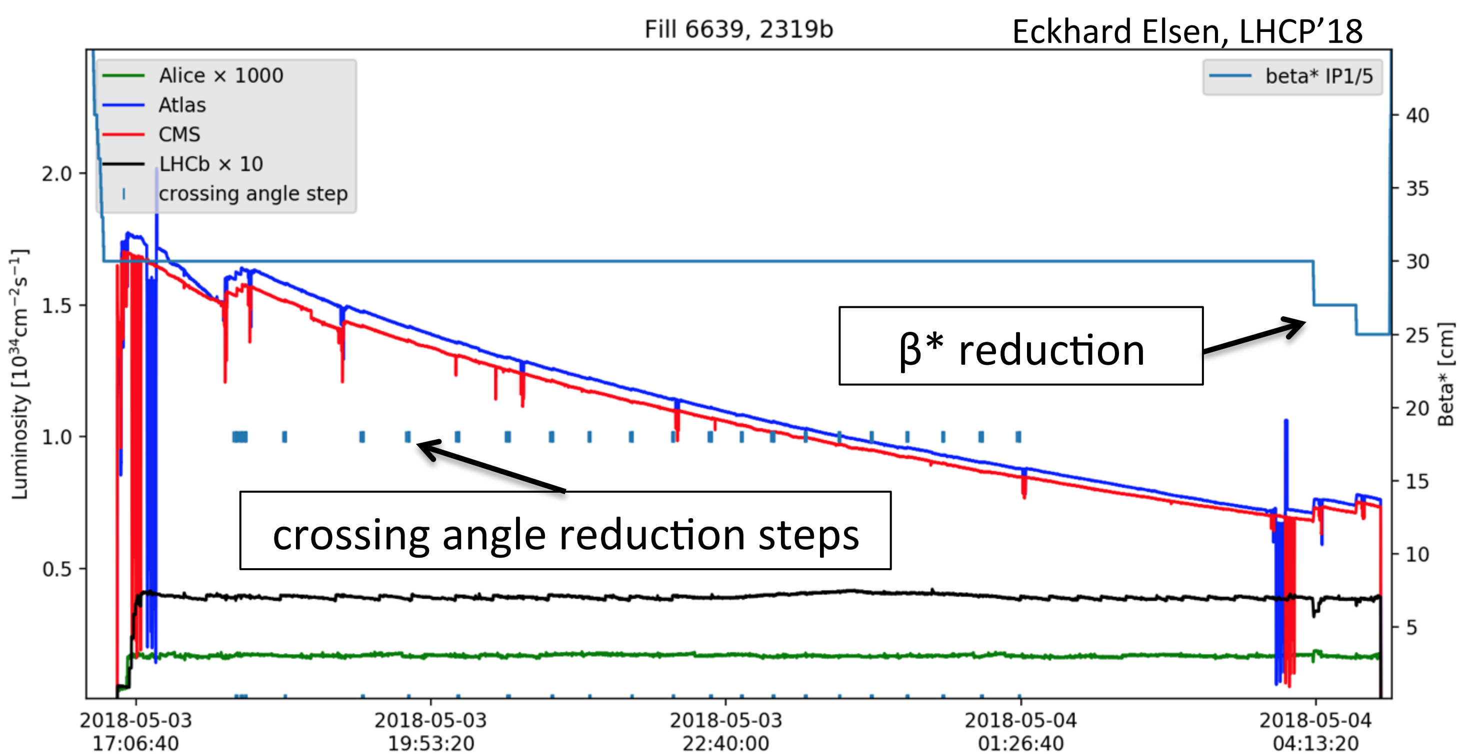


Anti-leveling: crossing angle



Anti-leveling: β* reduction

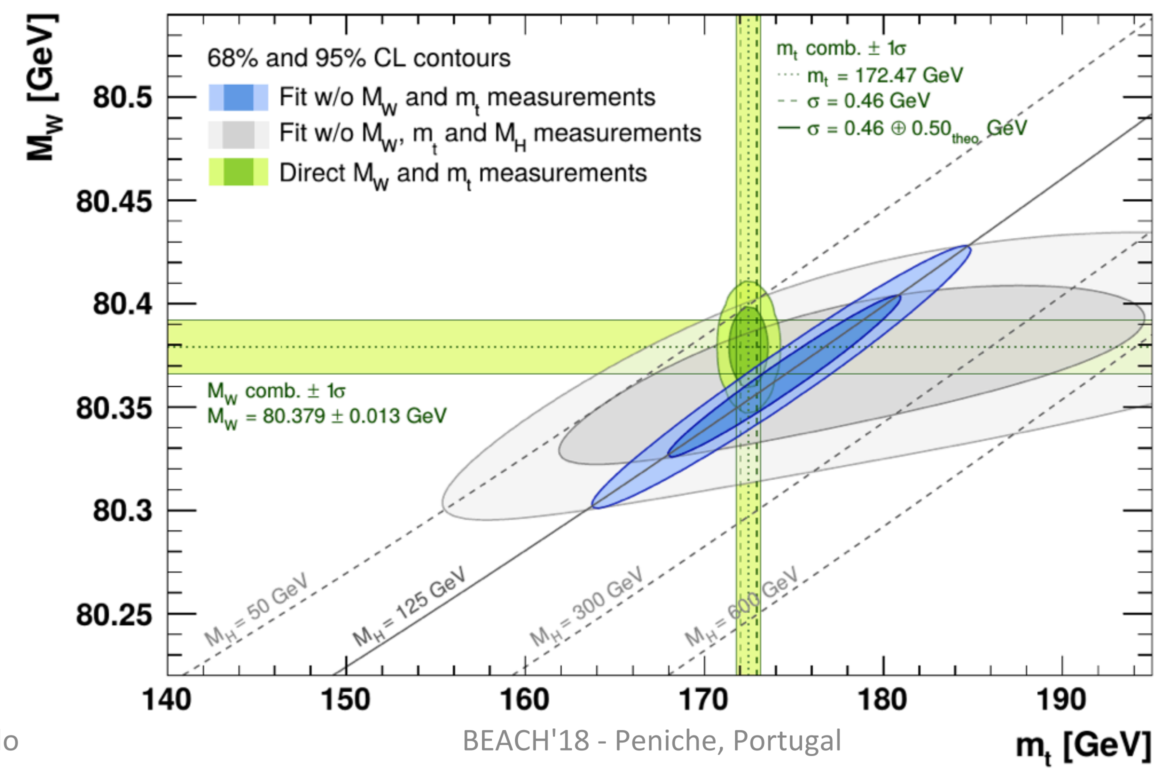




Exploring the electroweak scale

- 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 $m_H = 90 \pm 21$ GeV (1.7 σ tension) driven in part by m_{top}

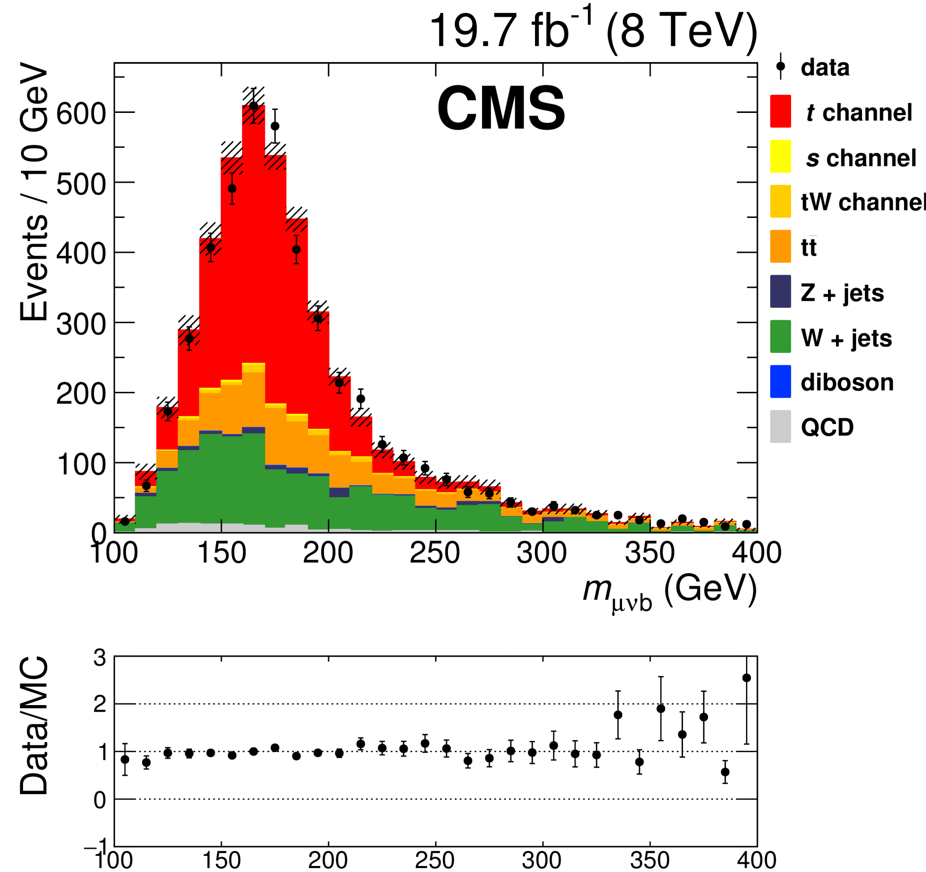
arXiv:1803.01853

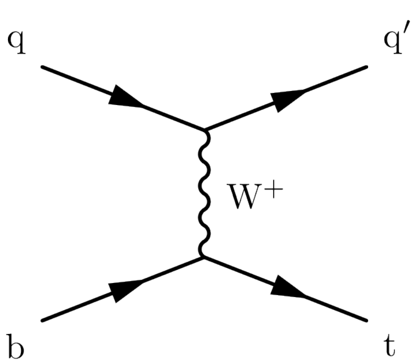


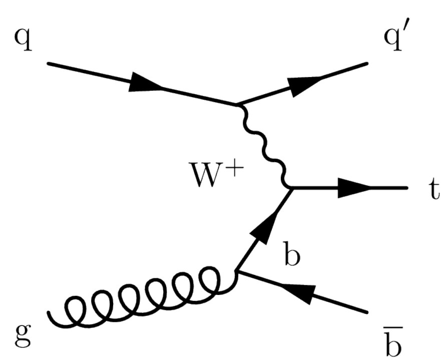
Direct m_t measurement: single top

- Focus on (electroweak) single-top production
- First measurement not in $t\bar{t}$ pair!
  - Independent sample
  - Systematic uncertainties partially uncorrelated with other channels
- $L = 19.7\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 8$ TeV
- Small xsec: $\sigma(t/\bar{t}) = 55/30$ pb
- Top reconstructed with kinematic fit assuming on-shell W

$\mathbf{m_t} = 172.95 \pm 0.77\ (\mathrm{stat})\ ^{+0.97}_{-0.93}\ (\mathrm{sys})$ GeV







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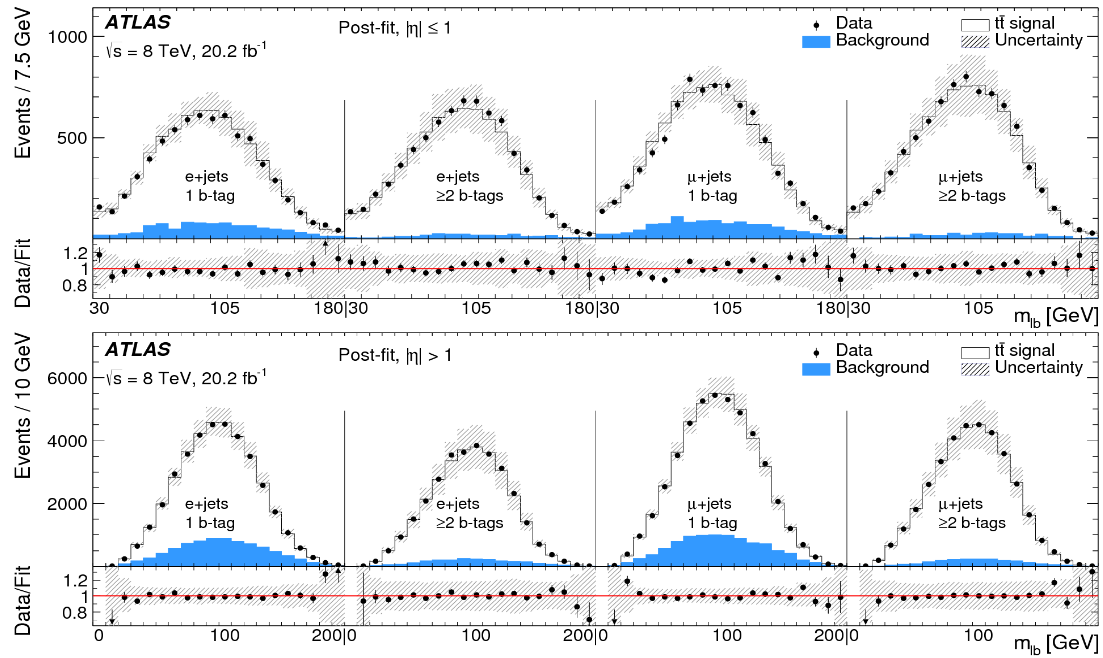
Top quark width

- NNLO calculation gives Γ_t = 1.322 GeV for m_t = 172.5 GeV
  - A clear deviation would indicate BSM physics

- Data:
  20.2 fb^{-1} at $\sqrt{s}$ = 8 TeV

- Lepton+jets $t\bar{t}$ final state
- Hadronic top reconstructed with kinematic fit

- Γ_t extracted from template fit to m_{lb} and $\Delta R_{min}(j,b)$ distributions



Coll.	Γ_t [GeV]	Ref.
D0	$2.00^{+0.47}_{-0.43}$	PRD85 (2012) 091104
CMS	1.36 ± 0.02 (stat.) $^{+0.14}_{-0.11}$	PLB736 (2014) 33
ATLAS	1.76 ± 0.33 (stat.) $^{+0.79}_{-0.68}$	EPJC78 (2018) 2, 129

LHC and HL-LHC timeline