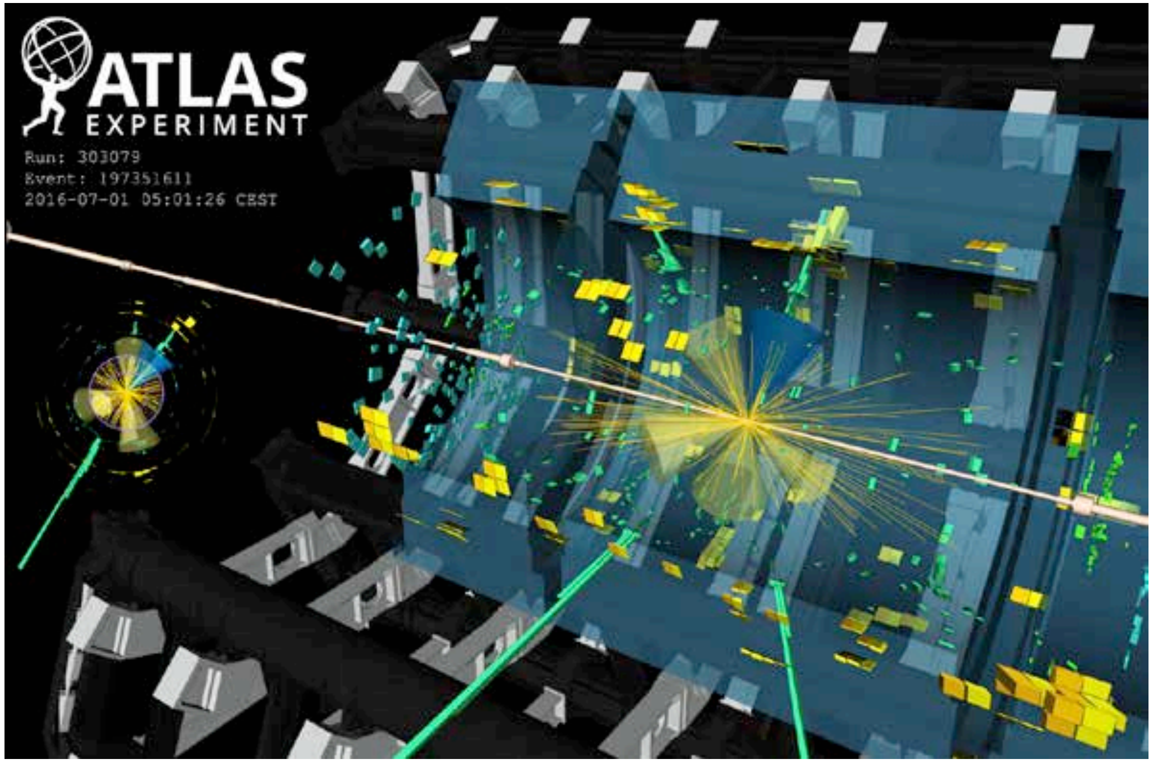
Latest Results from the LHC and Prospects for HL-LHC



Karl Jakobs
University of Freiburg / Germany

Joint Kavli IPMU – ICEPP Symposium, 18th June 2018

Latest Results from the LHC and Prospects for HL-LHC

- Status of LHC Data Taking in Run 2
- A summary of recent results from the LHC
  Where do we stand? Focus on Higgs boson physics
- Prospects for HL-LHC
  With focus on Higgs boson physics

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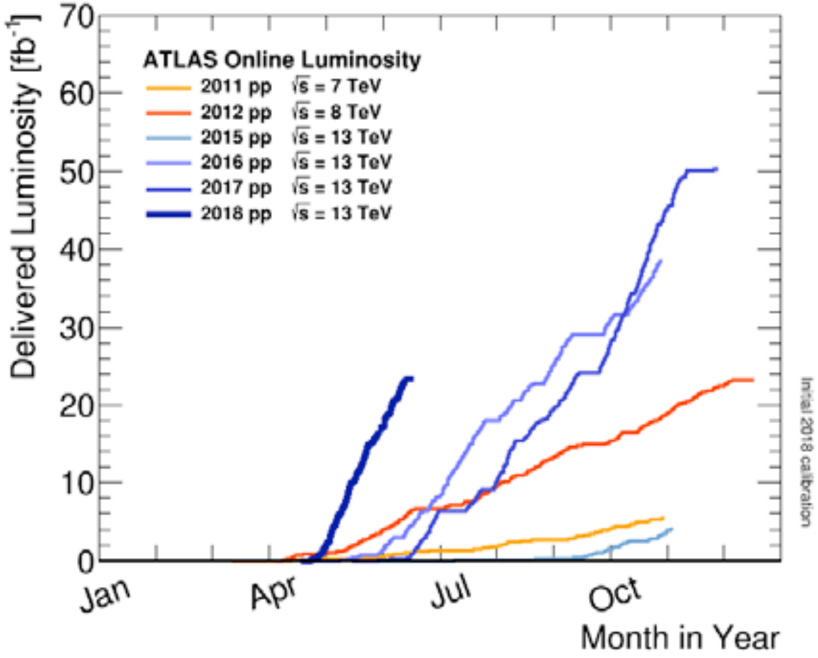
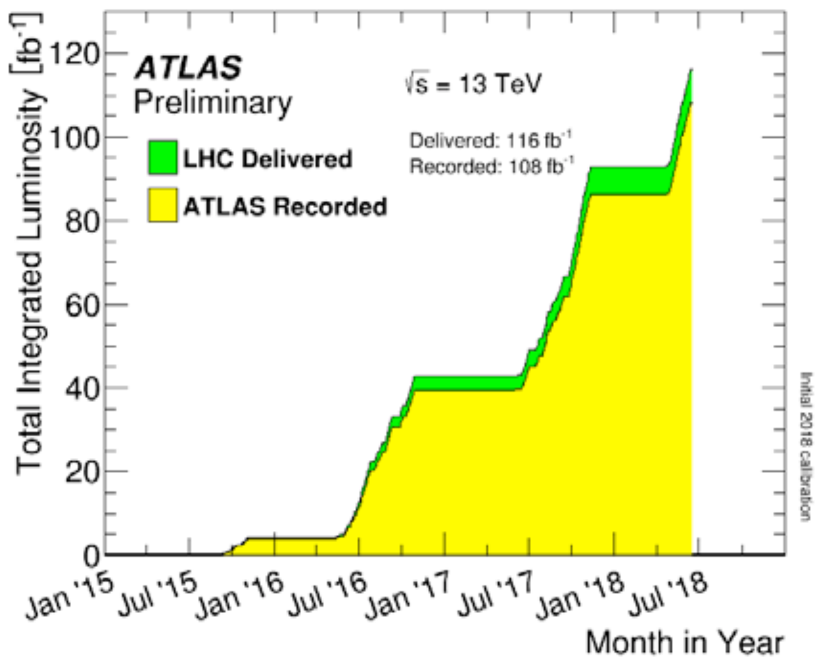
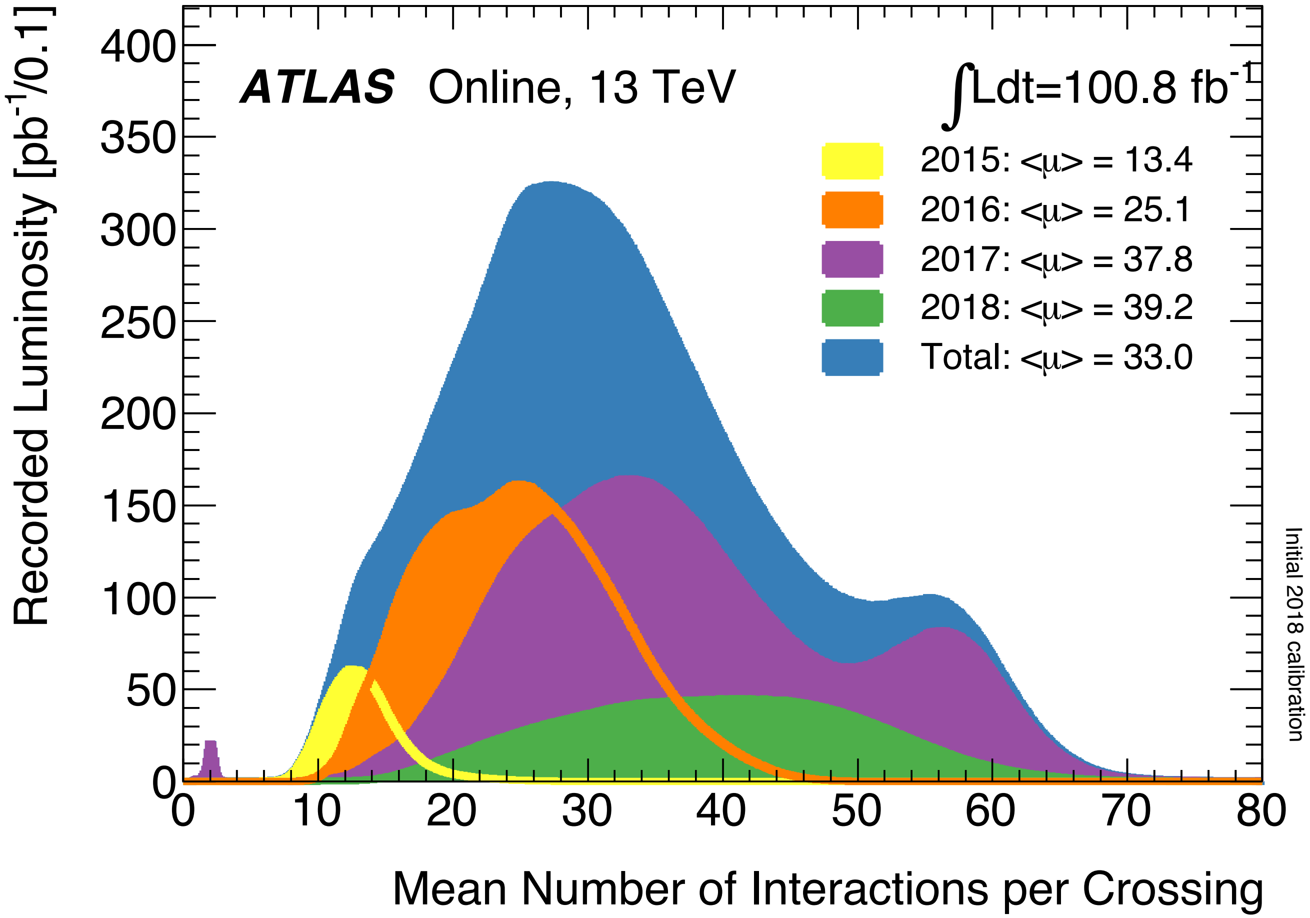
Data taking in Run 2



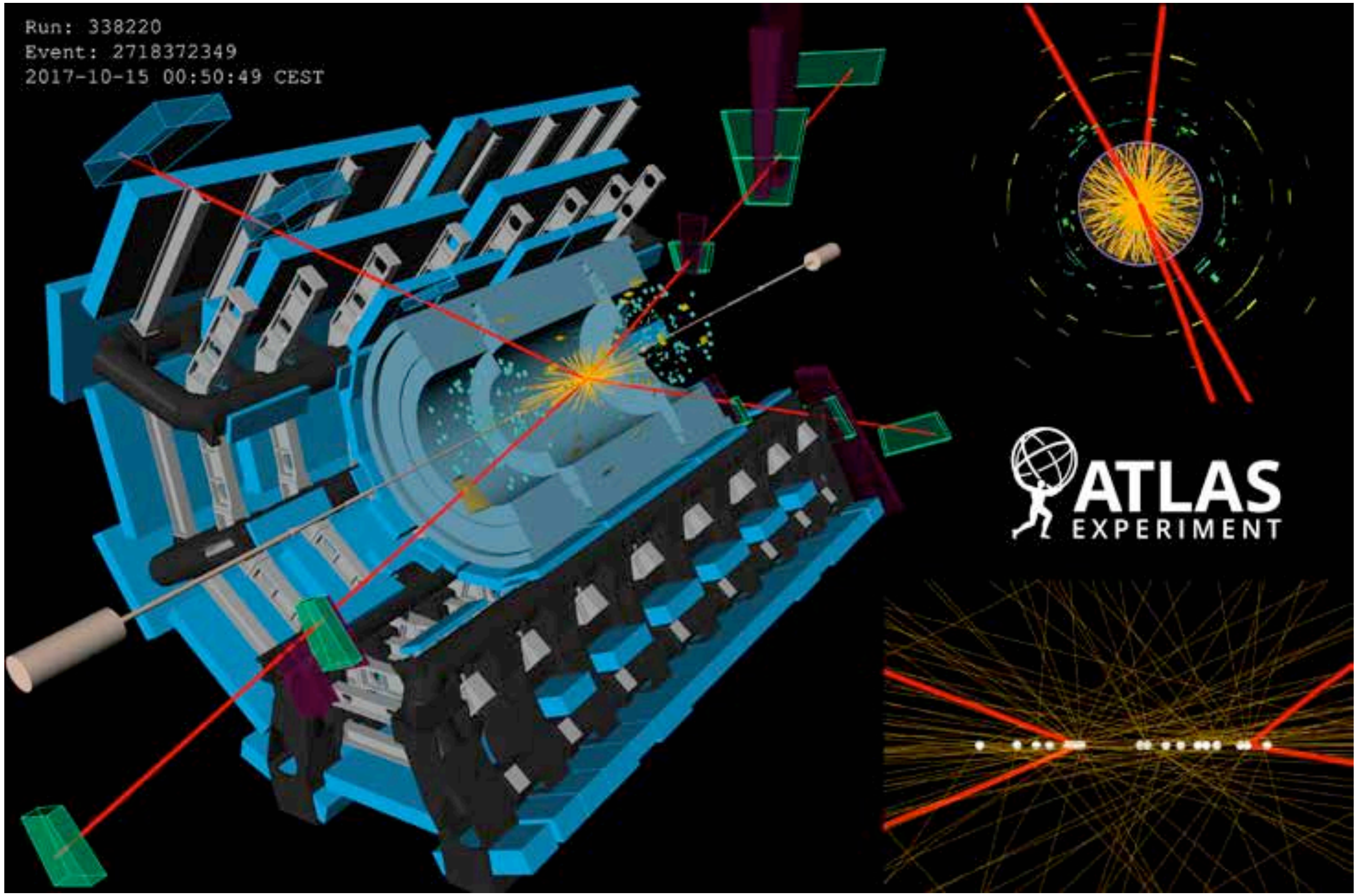


- *Excellent performance of the accelerator and of the experiments*
- *The ATLAS and CMS experiments have recorded >100 fb^{-1} in Run 2 ($\sqrt{s}$ = 13 TeV); High data taking efficiency*
- *Stiff luminosity slope in 2018, better running conditions than in 2017 (no luminosity levelling necessary)*

Data taking in Run 2



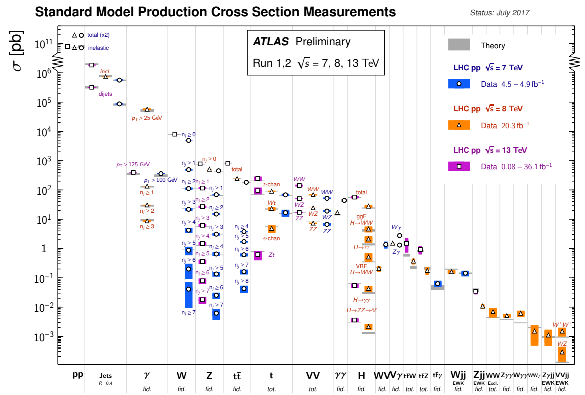
Pileup in 2017



A clear event with four identified muons, however, from two independent har scattering events in the same bunch crossing (see z-vertex reconstruction)

The Physics Messages from the LHC
- a summary from the first 8 years-

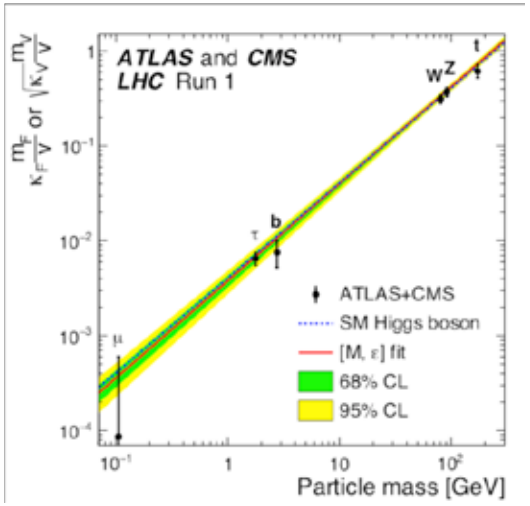
(i) The Standard Model has been tested at the highest energies



High LHC intensities (excellent machine and detectors)
→ rarer and rarer processes are being explored

(ii) A Higgs boson has been discovered (2012)

The properties of the discovered Higgs boson are in agreement with the predictions of the Standard Model
-within the present uncertainties-

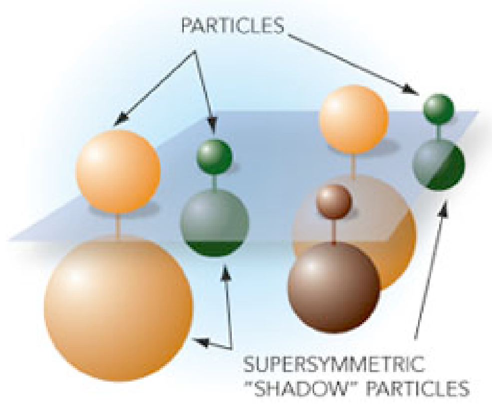


(iii) No Physics Beyond the Standard Model has been discovered (yet)

The mission of the LHC for the next decade (HL-LHC)

(i) Continue the direct searches for Physics Beyond the Standard Model at the highest energies

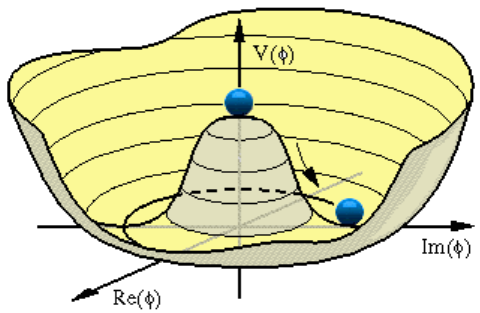
→ Address more complex scenarios



(ii) Exploration of the Higgs sector

- Does the discovered Higgs particle have the properties as predicted in the Standard Model? (higher precision, access to rare decay modes)

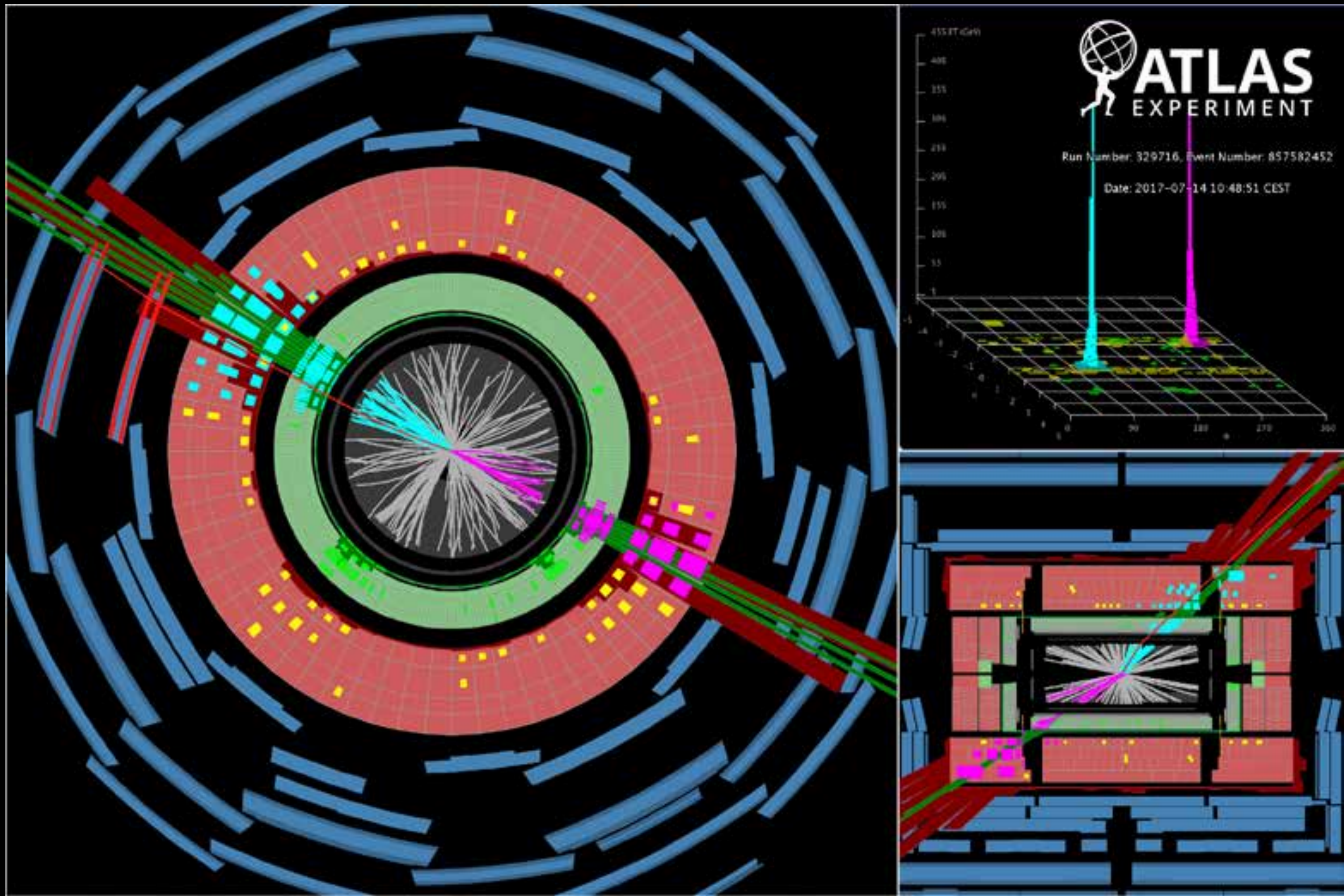
- Investigation of the Higgs boson self-coupling
  → Higgs boson potential



(iii) Precision Measurements

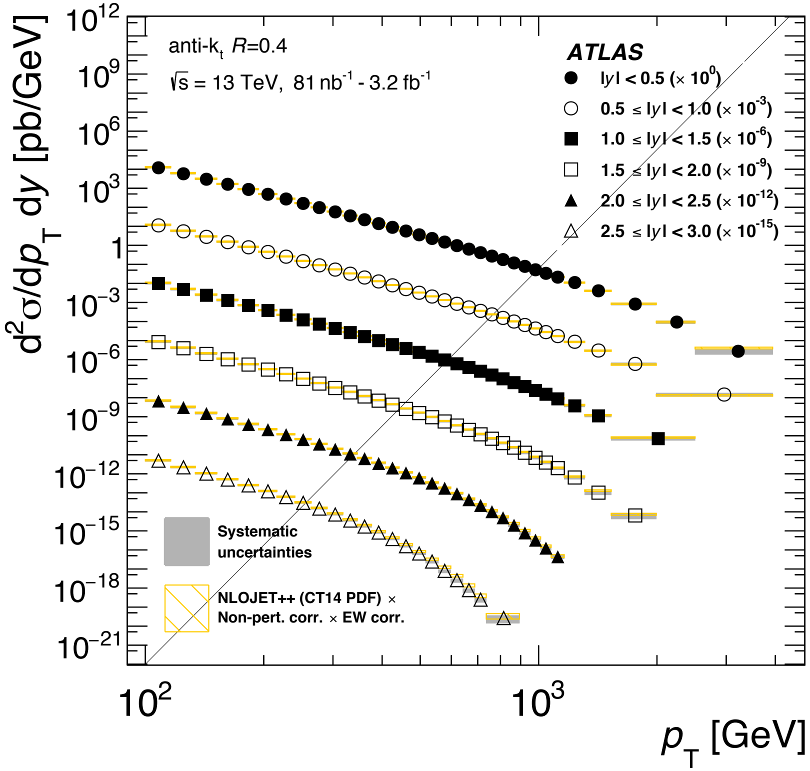
- Precision measurements of Standard Model processes and parameters
- Measurement of rare processes

Summary of recent results from the LHC

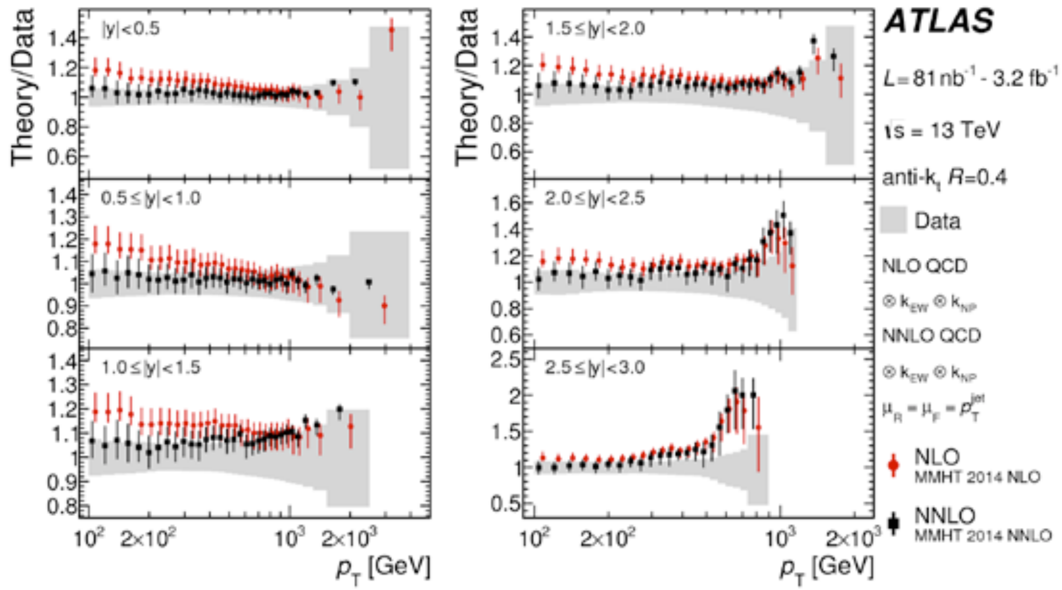


Di-jet event with the highest di-jet invariant mass of m_{jj} = 9.3 TeV recorded during 2017

Double differential jet production cross sections, as a function of p_T and rapidity y (full 2015 data set, √s = 13 TeV)



JHEP 05 (2018) 195



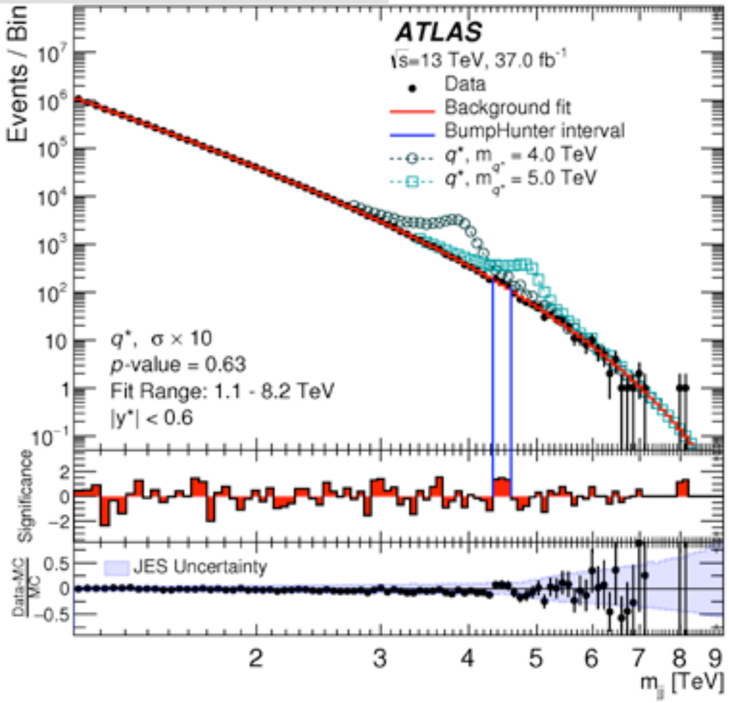
- Also at the highest energies explored so far, the data are well described by NLO perturbative QCD calculations (NLOJet++)

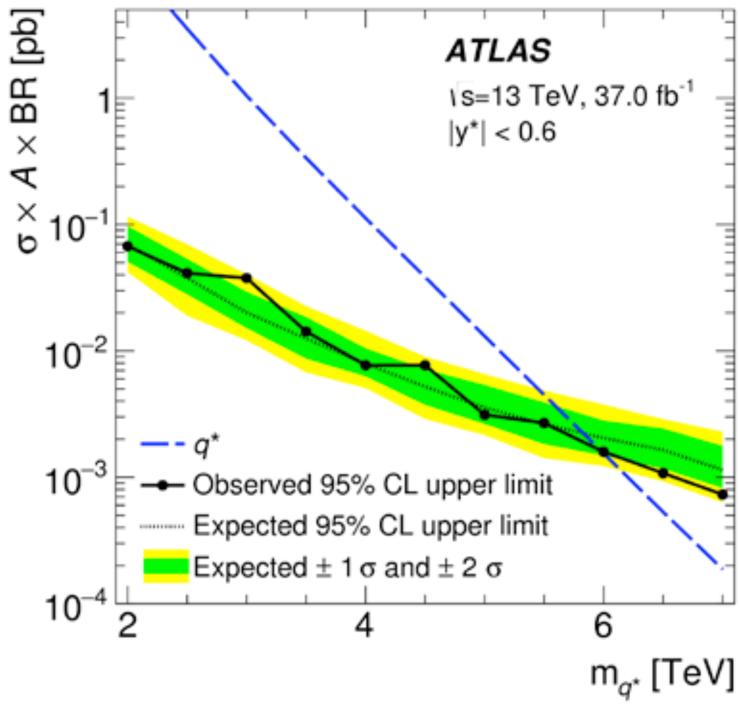
- Latest comparisons to NNLO predictions (NNLOJet) [J. Currie, N. Glover, T. Pieres, Phys. Rev. Lett. 118 (2017)]
  → improved agreement, however, scale dependent

Search for new phenomena in di-jet events

- First publication on complete Run-2 (2015+2016) dataset: 37.0 fb^{-1} at $\sqrt{s}$ = 13 TeV

Phys. Rev. D96 (2017) 052004

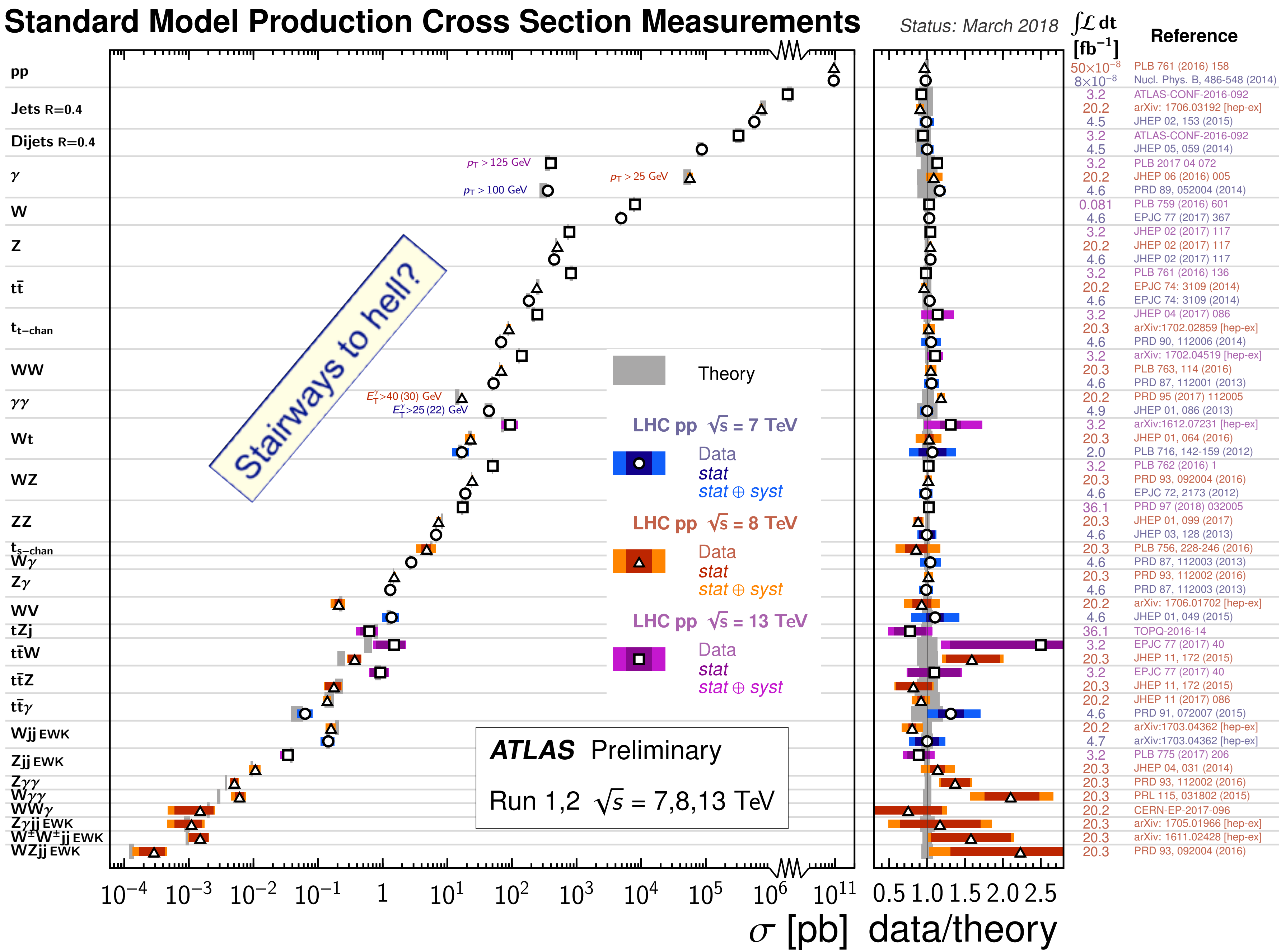




- 95% CL exclusion limits:

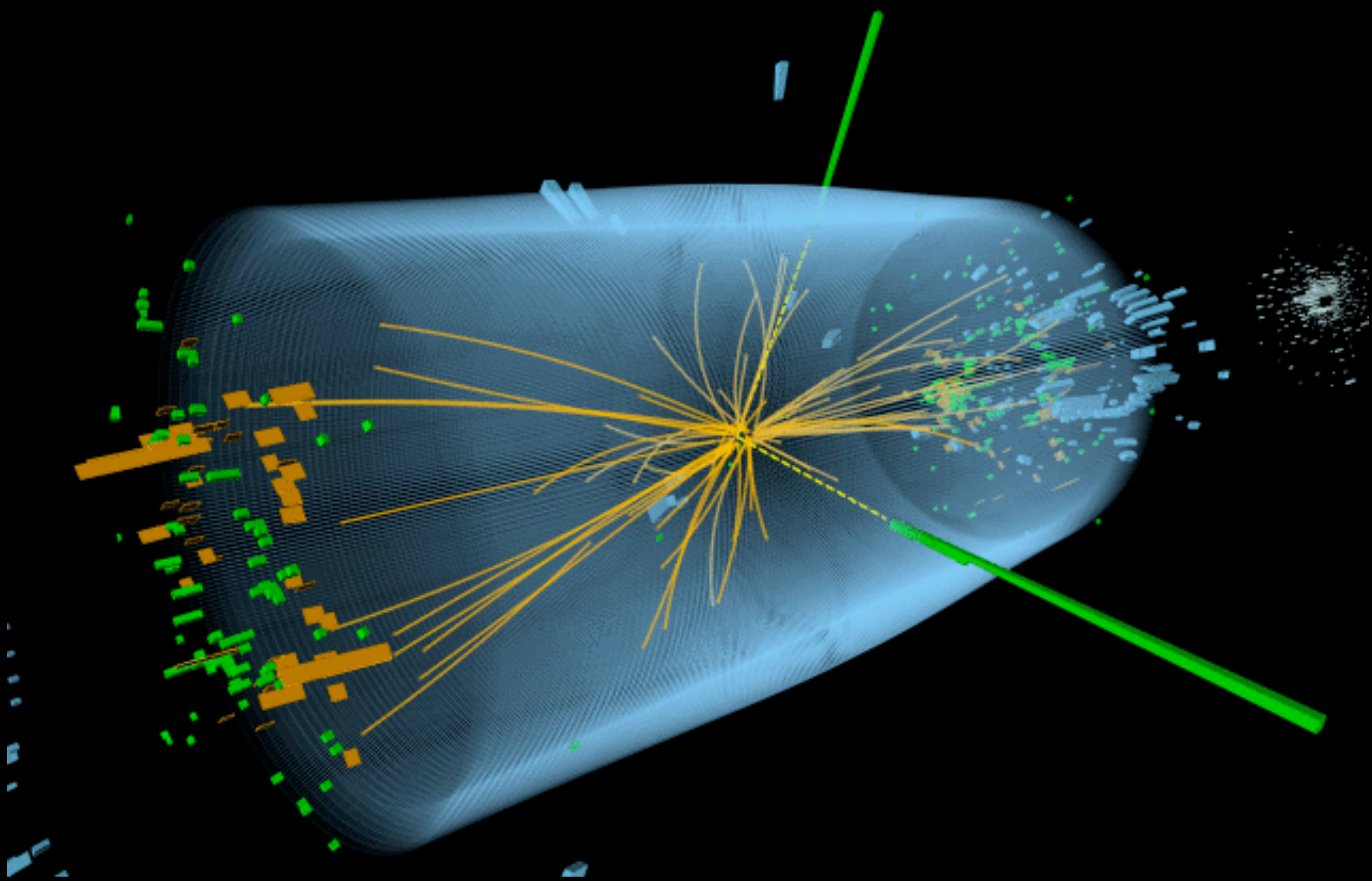
Excited quarks	m_{q*} > 6.0 TeV	(5.8 TeV exp.)*
Add. gauge bosons:	$m_{W'}$ > 3.6 TeV	(3.7 TeV exp.)
Quantum Black Holes:	m_{BH} > 8.9 TeV	(8.9 TeV exp.)
Contact Interactions:	Λ > 13.1 TeV (η_{LL} = +1)	
	Λ > 21.8 TeV (η_{LL} = -1)	

*pre-LHC limit on excited quarks from the Tevatron: 0.87 TeV



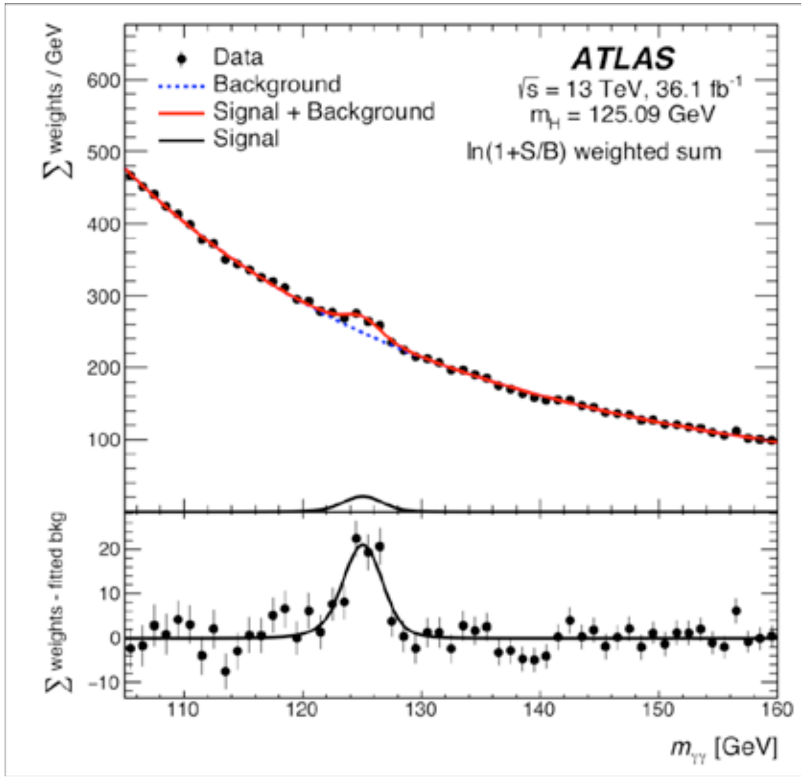
Huge progress also on the theoretical side: (N)NLO QCD / el.weak corrections

Status of Higgs Boson measurements

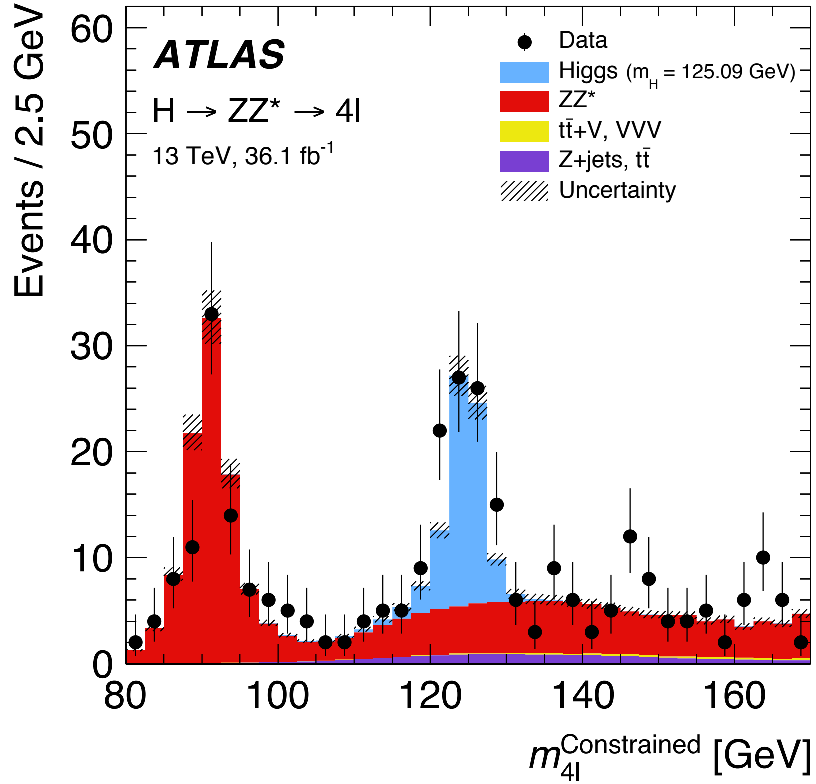


Results of Searches for H → γγ and H → ZZ* → 4l at 13 TeV

arXiv:1802.04146 (2018)



JHEP 03 (2018) 095

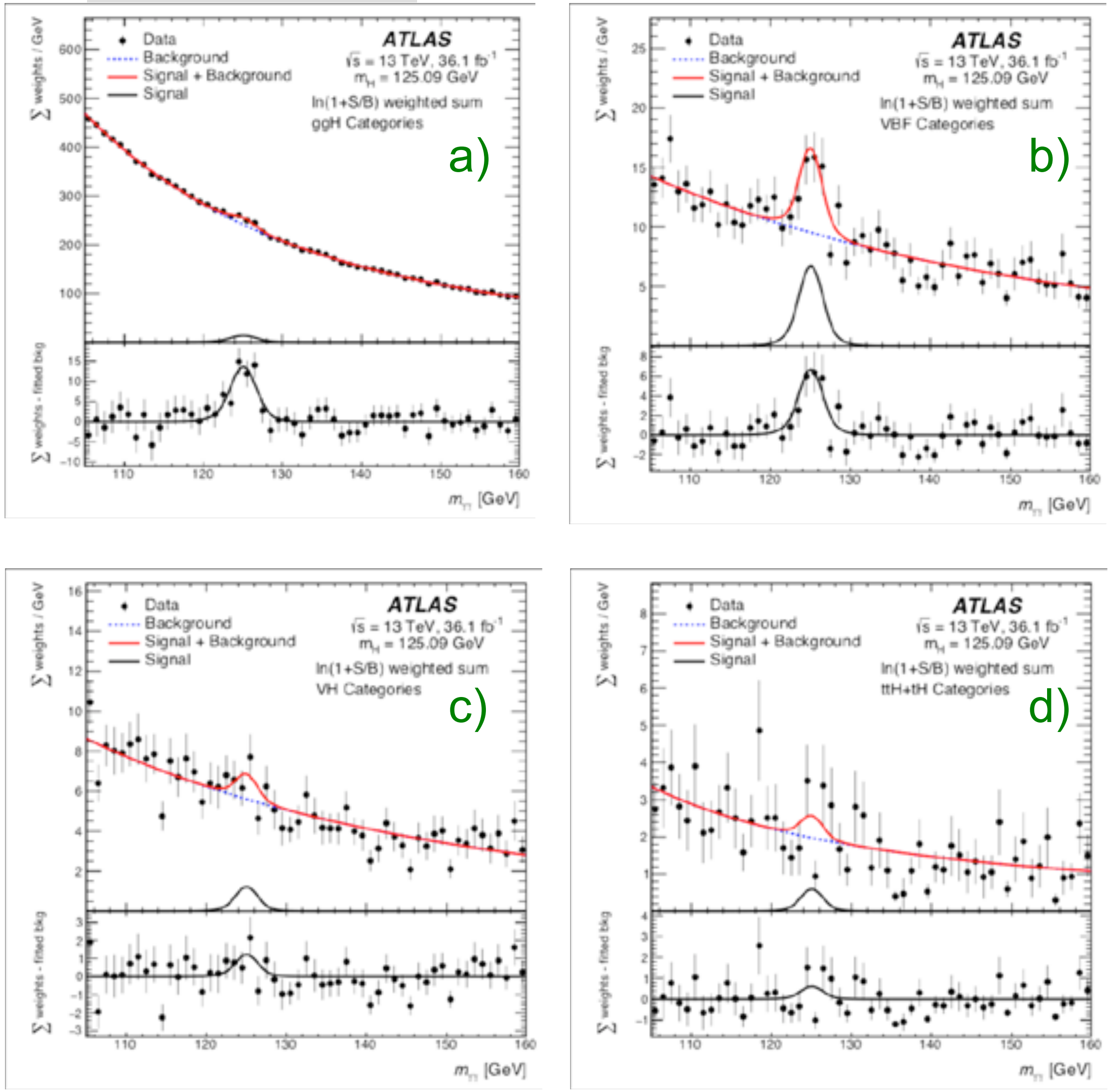


- Impressive signals in these high-resolution bosonic decay channels
  (Data collected during 2015 and 2016 in Run 2 at 13 TeV)

- Observation with a significance of > 5σ in each channel

H → γγ signals for various categories

arXiv:1802.04146 (2018)



a) untagged categories
   (expected to be dominated by gluon fusion)

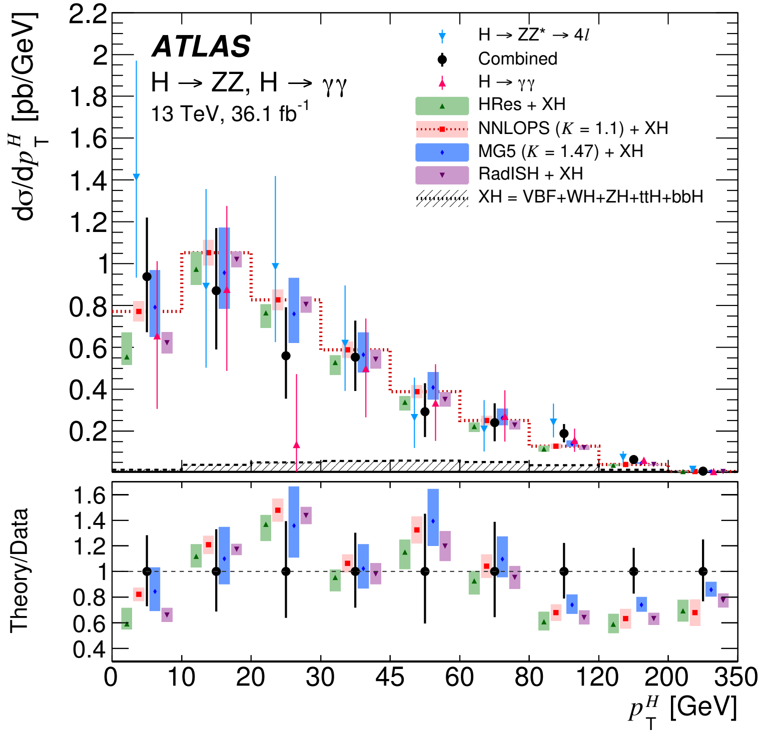
b) VBF categories
   (tag-jet configuration, $\Delta\eta$, m_{jj})

c) VH categories
   (one-lepton, E_T^{miss}, low-mass di-jets)

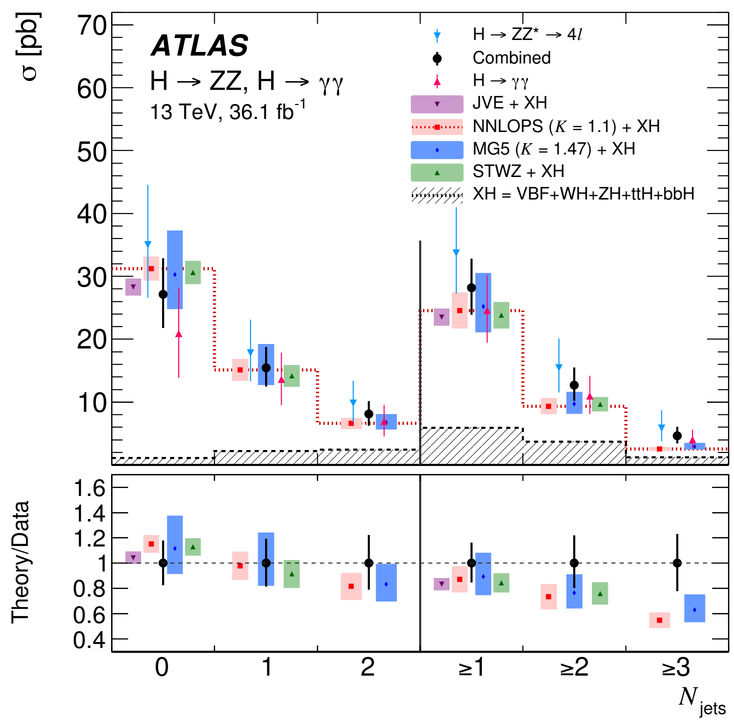
d) ttH categories
   (lepton, jets, b-jet(s))

Differential cross-section measurements

arXiv:1805.10197



arXiv:1805.10197

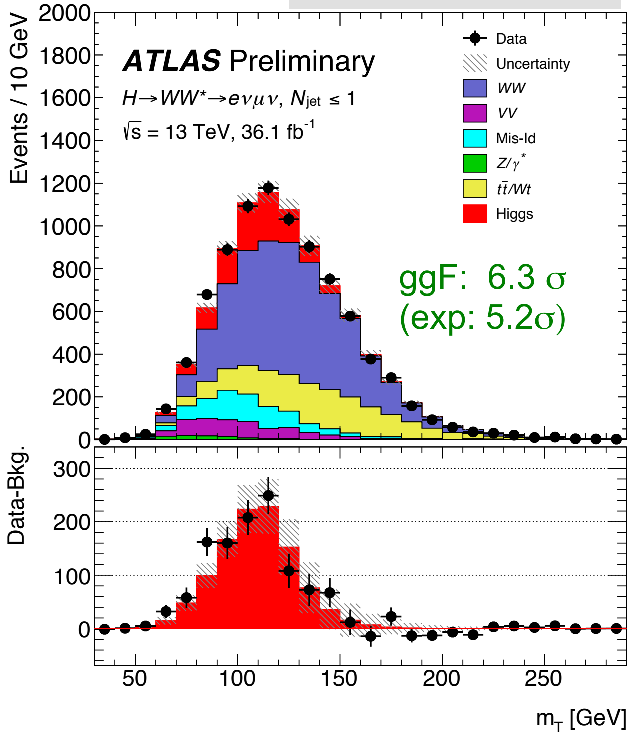


- Data are well described by theoretical calculations (within large uncertainties)
- Such measurements will become important ingredients for future measurements of Higgs boson parameters (Effective Field Theories)

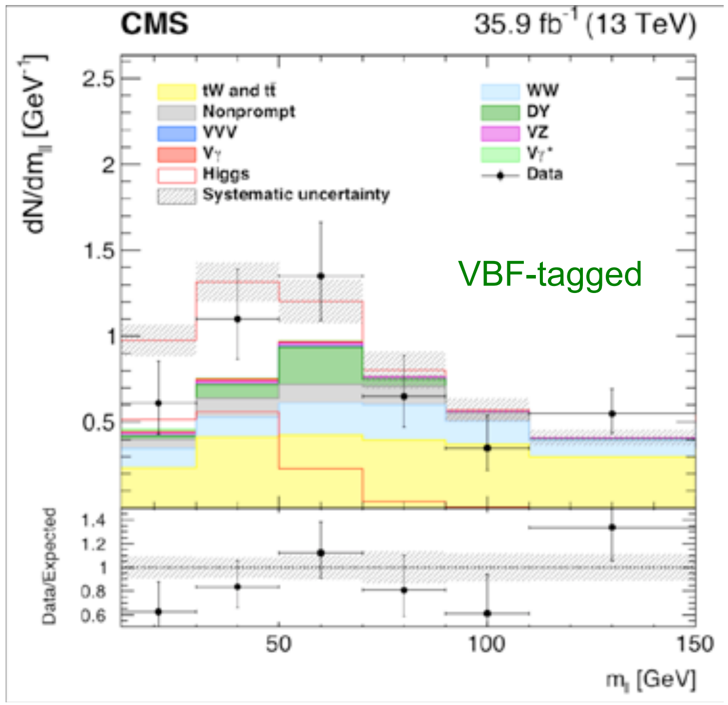
$H \rightarrow WW^* \rightarrow \ell\nu\ \ell\nu$ signal

- Large branching fraction, however, also severe backgrounds (no mass peak, due to neutrinos)
- → Rely on lepton/jet kinematics (→ transverse mass M_T, di-lepton invariant mass $m_{\ell\ell}$, $\theta_{\ell\ell}$)

ATLAS-CONF-2018-004



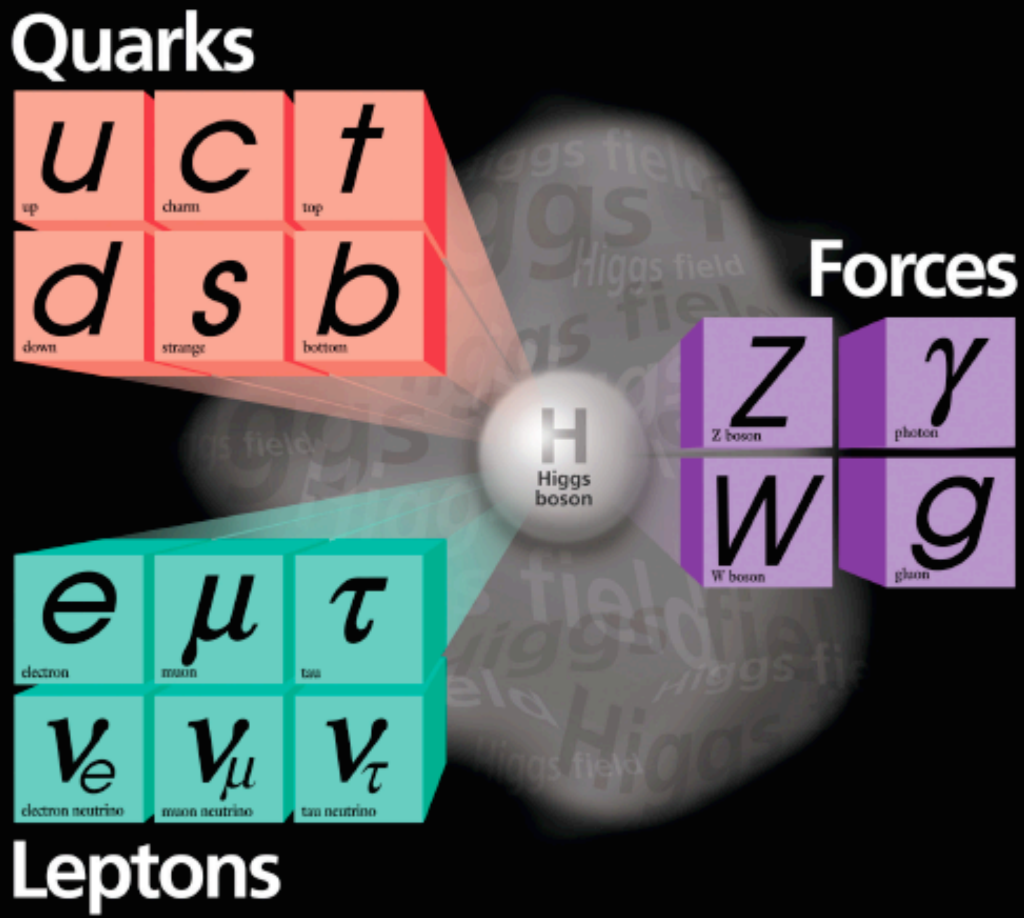
arXiv:1806.05246



- Very significant excesses visible in the "transverse mass" and $m_{\ell\ell}$ distributions

ATLAS: gluon fusion 6.3σ observed (5.2σ expected)
CMS: total 9.1σ observed (7.1σ expected)

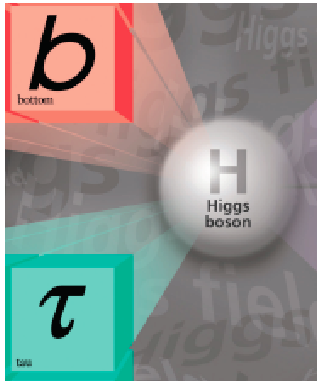
Couplings to fermions?



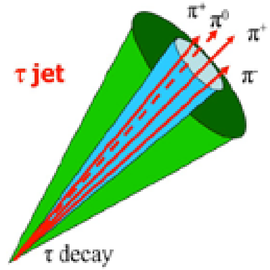
Couplings to bosons well established in Run 1 and nicely confirmed in Run 2

Search for H → ττ and H → bb decays, and ttH production

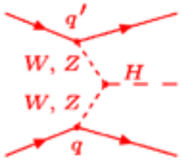
Couplings to quarks and leptons ?



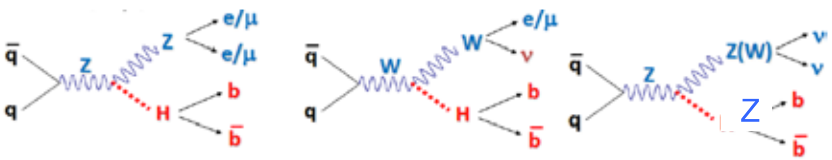
- Search for H → ττ and H → bb decays;
- Challenging signatures due to jets (bb decays) or significant fraction of hadronic tau decays



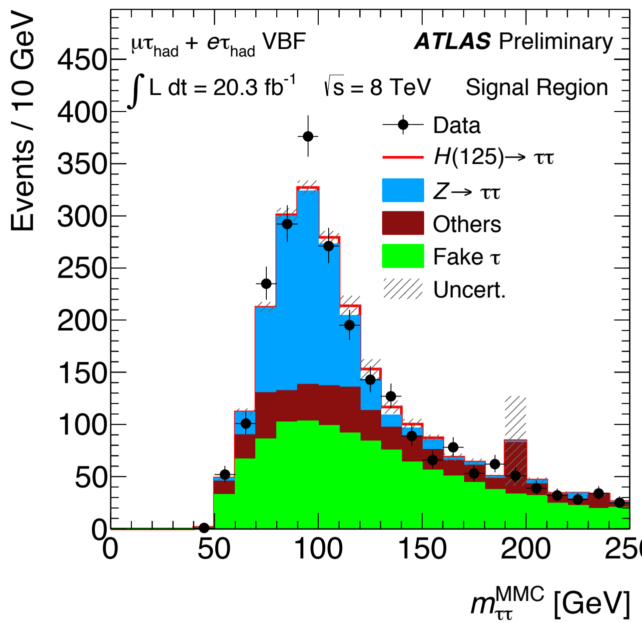
- Vector boson fusion mode essential for H → ττ decays



- Associated production WH, ZH modes have to be used for H → bb decays

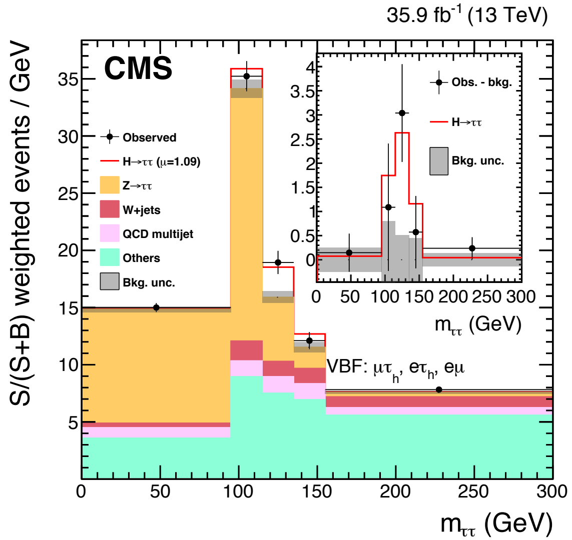


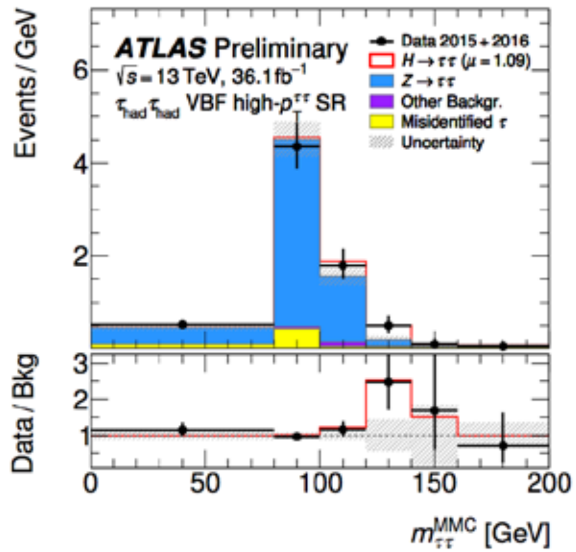
- Exploitation of multivariate analyses



Couplings to Fermions: H → ττ

- Search for H → ττ with ττ decaying in eμ, $\mu\tau_h$, $e\tau_h$ and $\tau_h\tau_h$
- Largest background from Z→ ττ and hadronic multi-jet events
- Search in categories aiming at ggH and VBF production



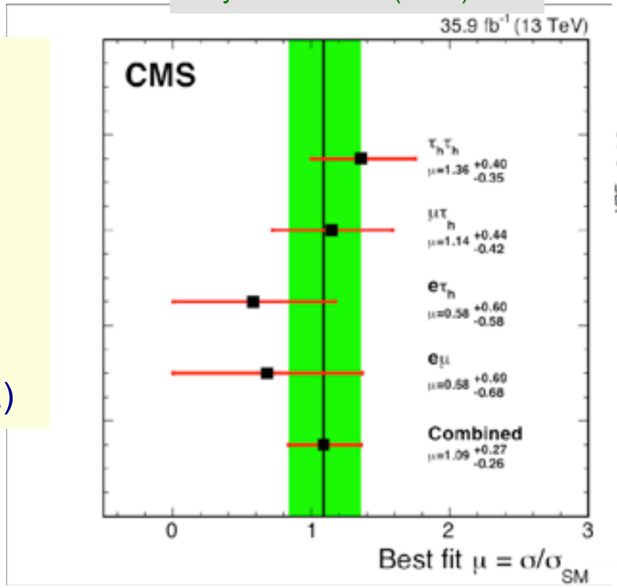


Phys. Lett. B779 (2018) 283

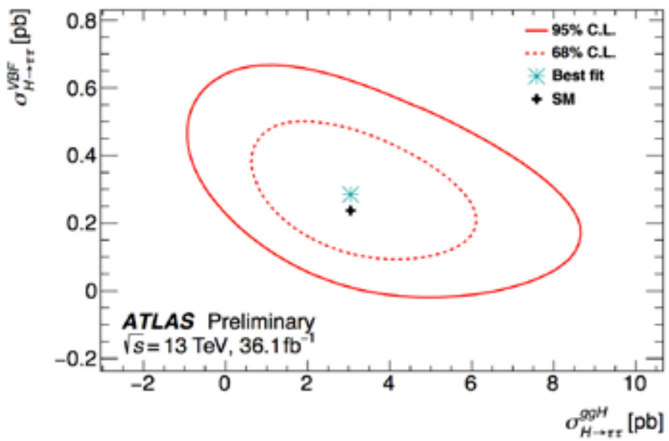
Observation of H → ττ

Significance:

CMS: 5.9σ
ATLAS: 6.4σ
(combination of Run-1 and Run-2 data)

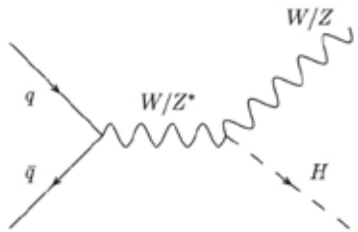


ATLAS-CONF-2018-021



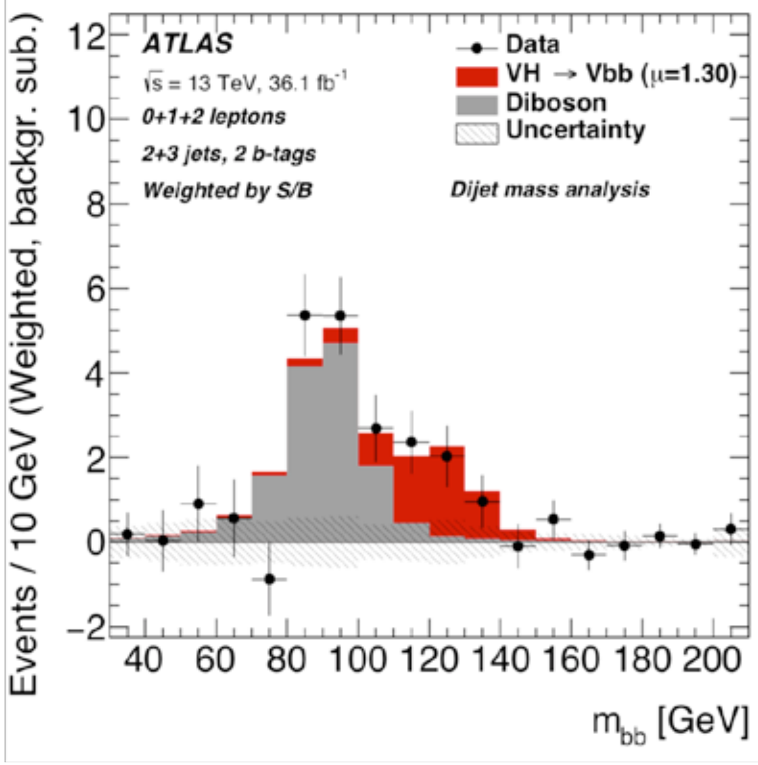
Search for H → bb decays

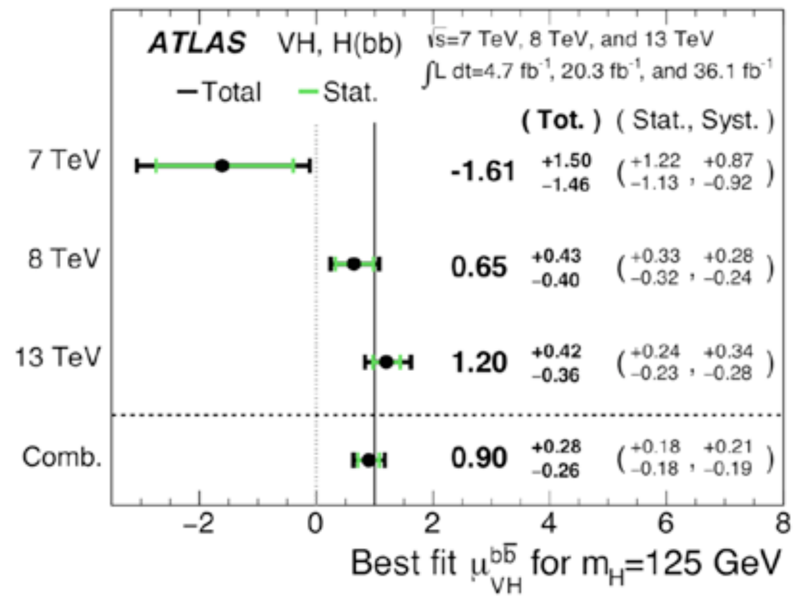
- H→bb mode dominates Higgs decays (BR~58%)
- Most sensitive channel exploits VH, H→bb (V=W/Z)
- Combined ATLAS+CMS significance 2.6σ (3.7σ expected) from LHC Run-1



- Combination of Z and W final states characterised by lepton multiplicity:
  (2-lepton (Z→ℓℓ), 1-lepton (W→ℓν), and
  0-lepton (Z→νν))

JHEP 12 (2017) 024

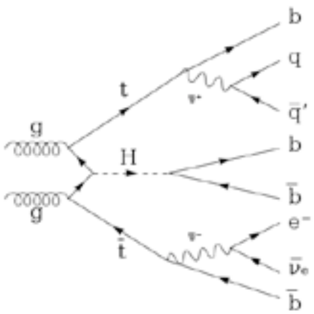




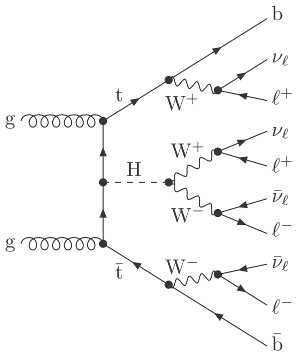
Combination of result with ATLAS Run-1 gives
3.6σ observed (4.0σ expected)

Search for ttH Production

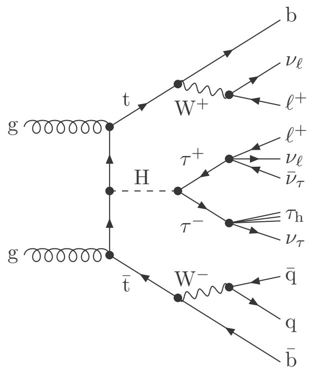
- Direct access to top-Yukawa coupling
- Rich decay topologies; final states with leptons, jets, b-jets, photons



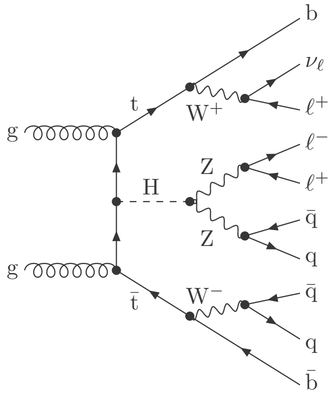
H → bb



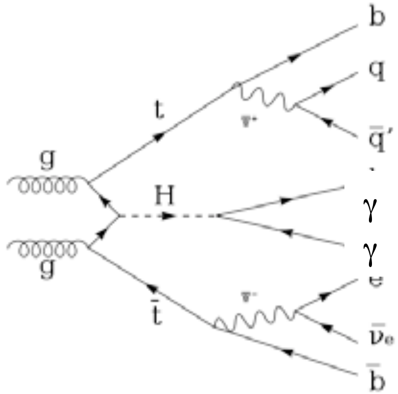
H → WW*



H → τ τ

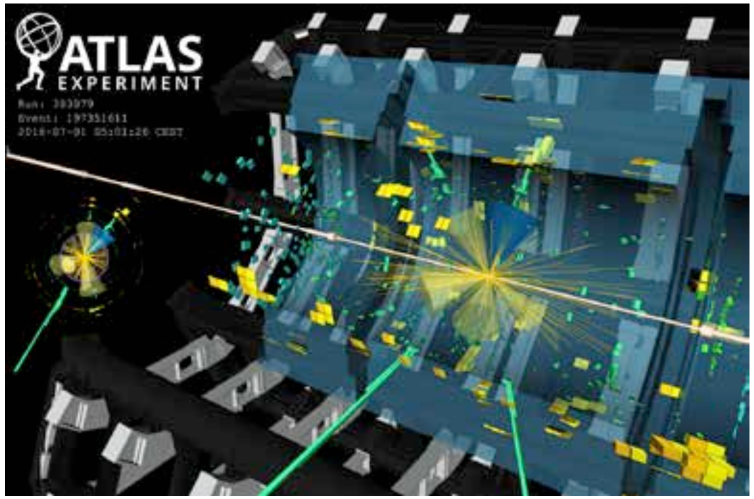


H → ZZ



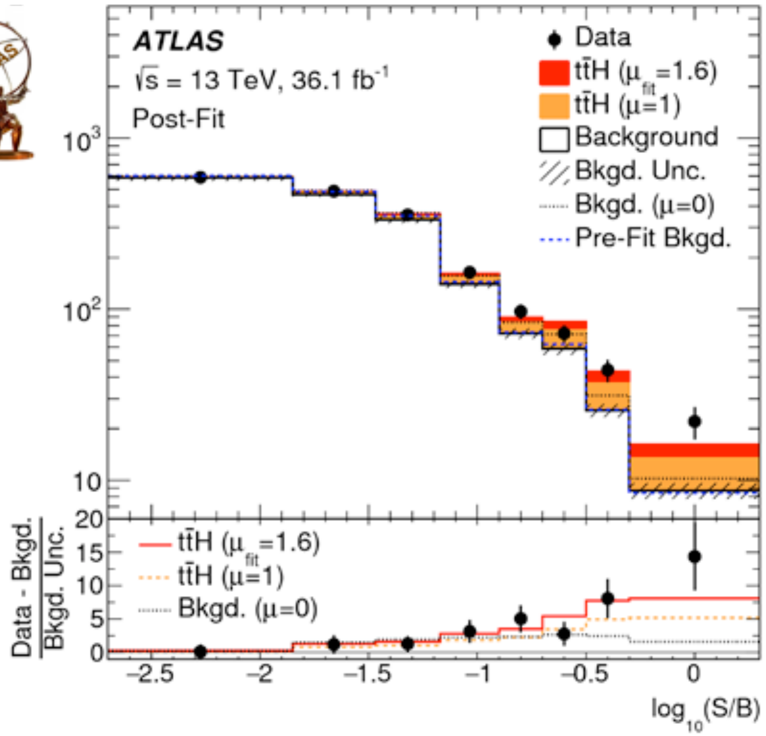
H → γ γ

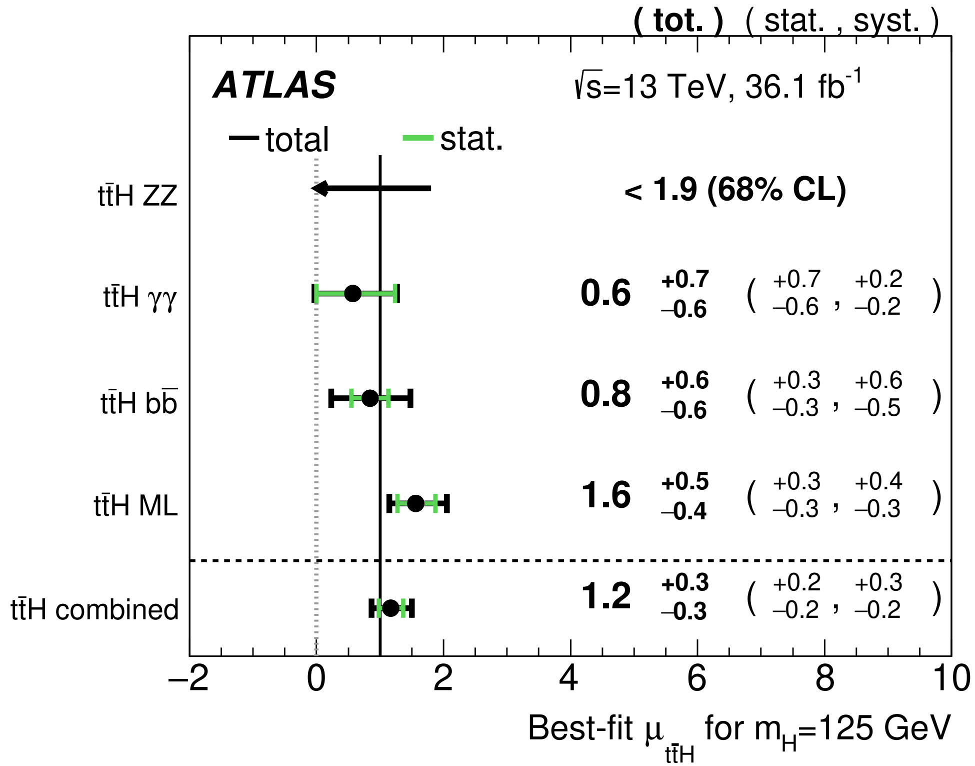
multi-lepton channels (ML)



Evidence for ttH production

arXiv:1712.08891, Phys. Rev. D97 (2018) 072003



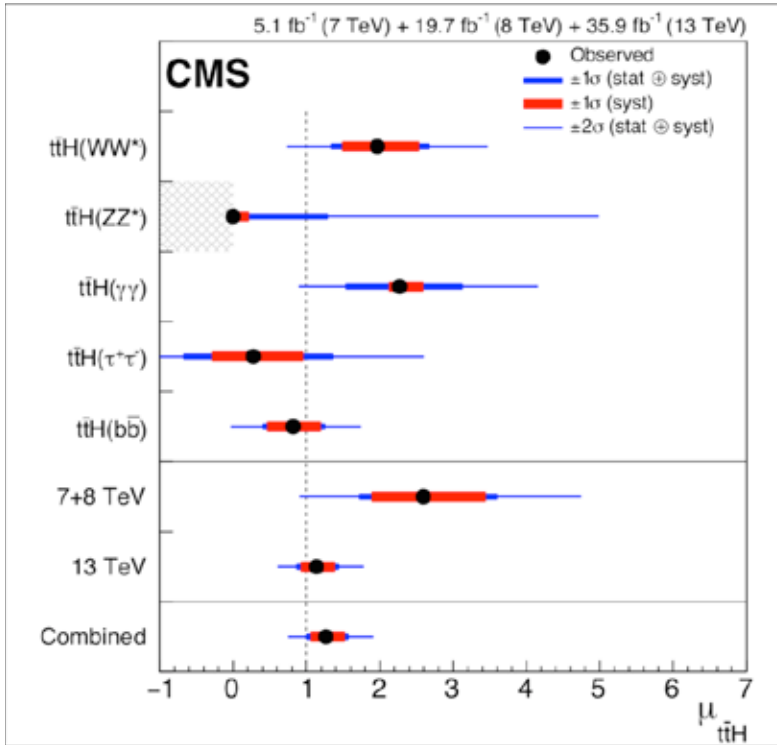


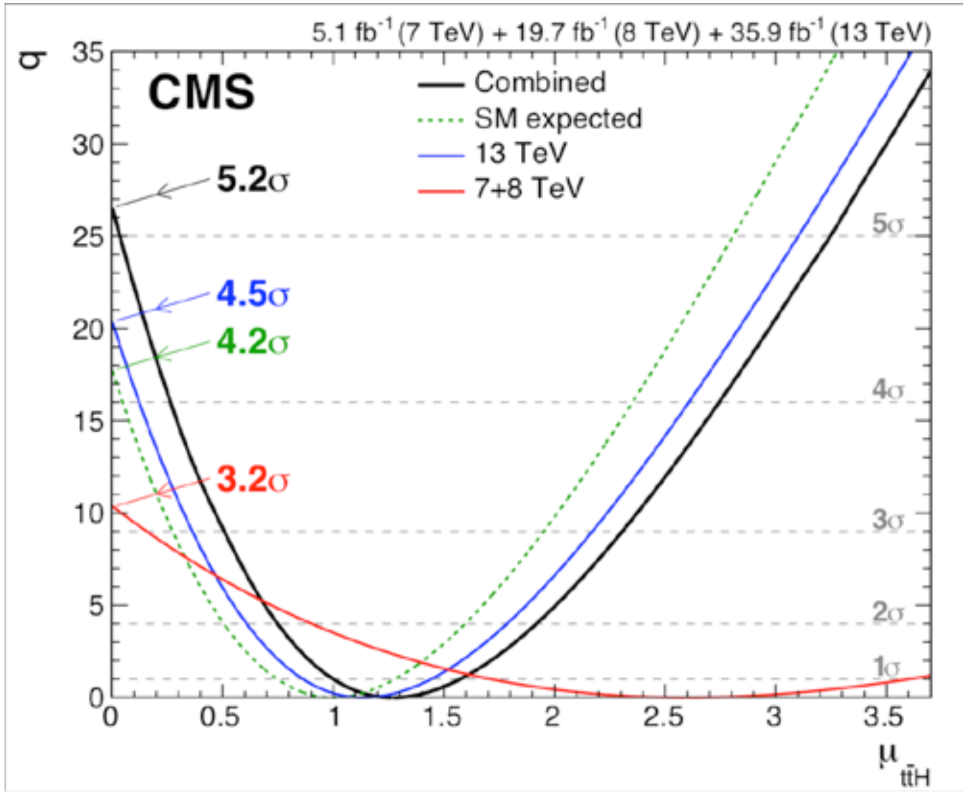
- Combination of all channels leads to 4.2σ observed (3.8σ expected) (Phys. Rev. D97 (2018) 072003)
  In addition, Run-1 sensitivity of 2.7σ observed (1.8σ expected) (JHEP08 (2016) 045)

- Measured production and decay rates consistent with SM expectation

Observation of ttH production

Phys. Rev. Lett. 120 (2018) 231801





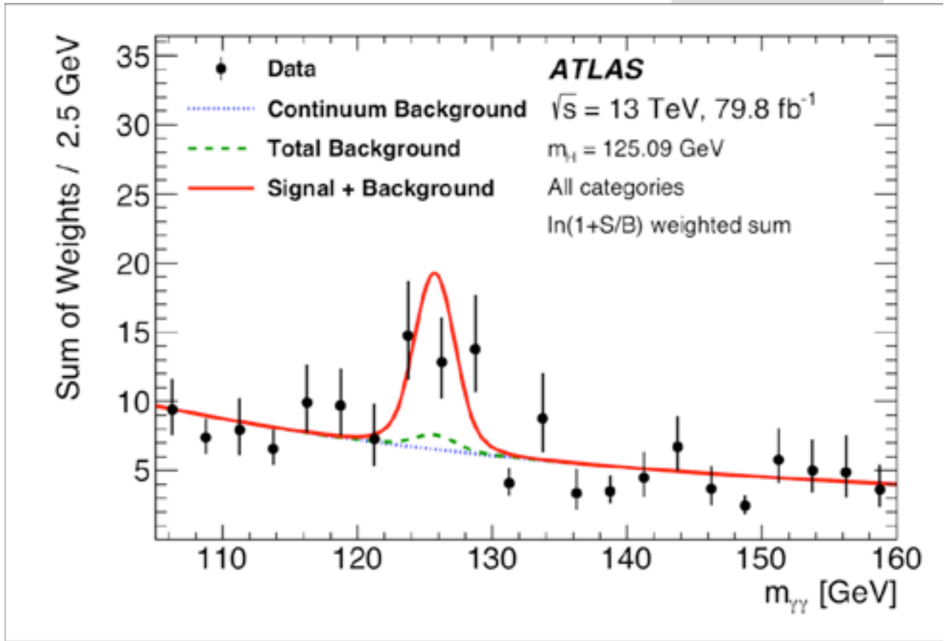
Observation of ttH production:
(combination of Run-1 and Run-2 data)

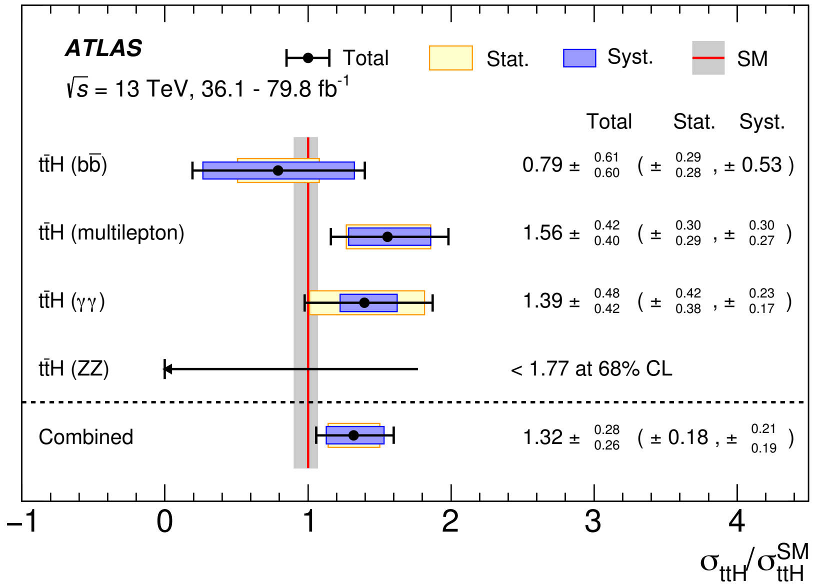
$\mu = 1.26^{+0.31}_{-0.26}$

Significance: 5.2σ (obs.), 4.2σ (exp.)

Including the 2017 data for H→ γγ and H → ZZ*

arXiv:1806.00425





Higgs signal appears in
γγ final states

Observation of ttH production with larger significance

$\mu = 1.32\ ^{+0.28}_{-0.26}$

Significance: 6.3σ (obs.), 5.1σ (exp.)
(Run-1 + Run-2 data)

Combined ATLAS & CMS Higgs analysis — Run-1 legacy

ATLAS & CMS Run-1 combination of Higgs coupling measurements

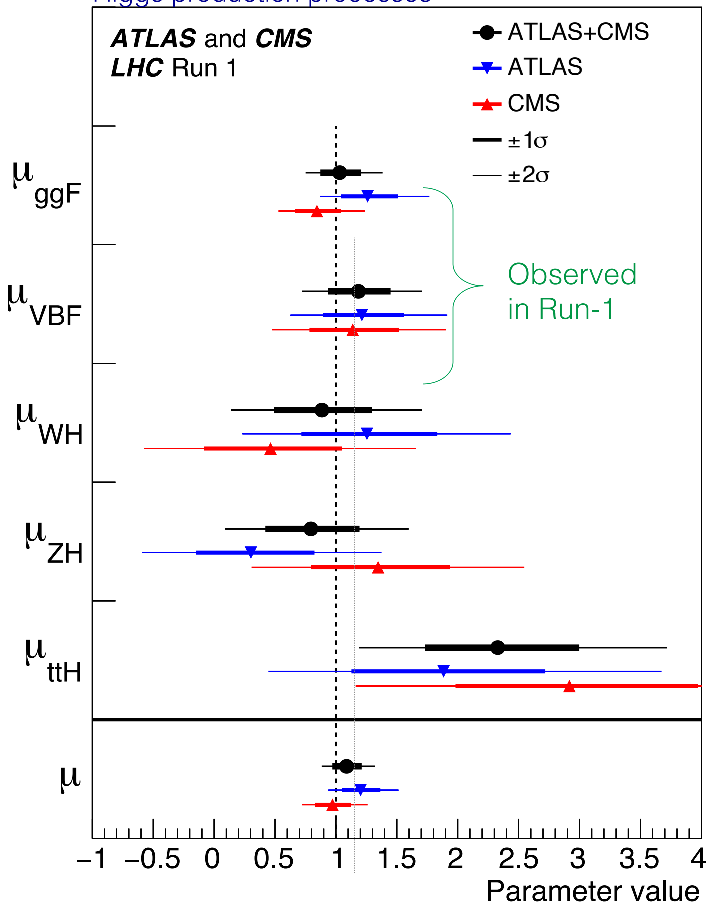
[arXiV:1606.02266]

Agreement among experiments

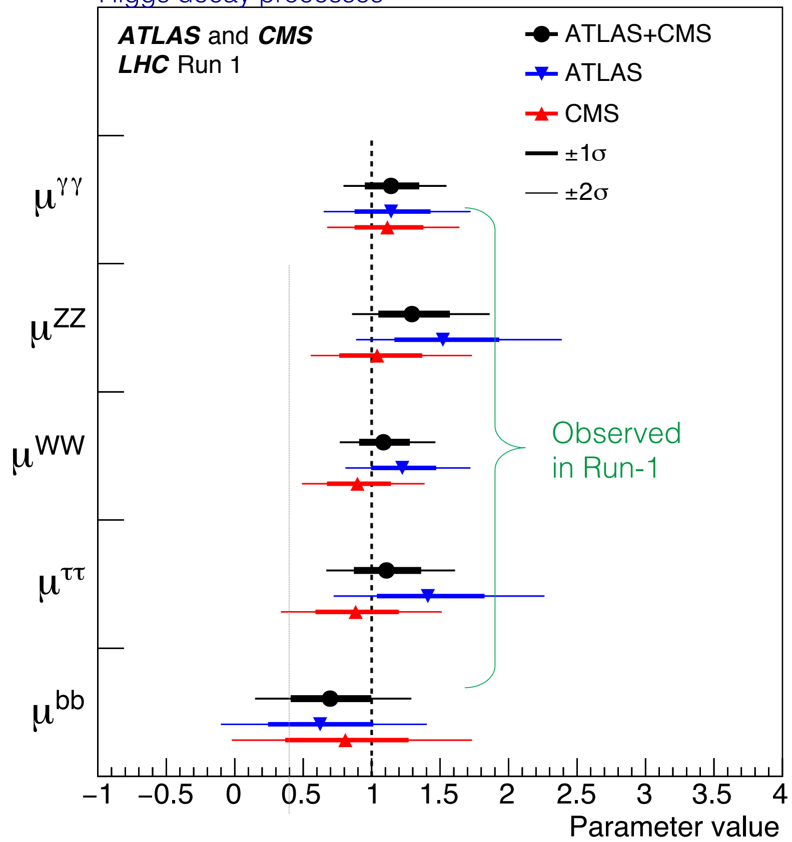
Overall signal strength (Run-1): μ = 1.09 ± 0.11 (A & C)

Run-2: 1.17 ± 0.10 (CMS, all channels, 0.06 stat/syst/sig),
1.09 ± 0.12 (ATLAS, ZZ* + γγ)

Higgs production processes

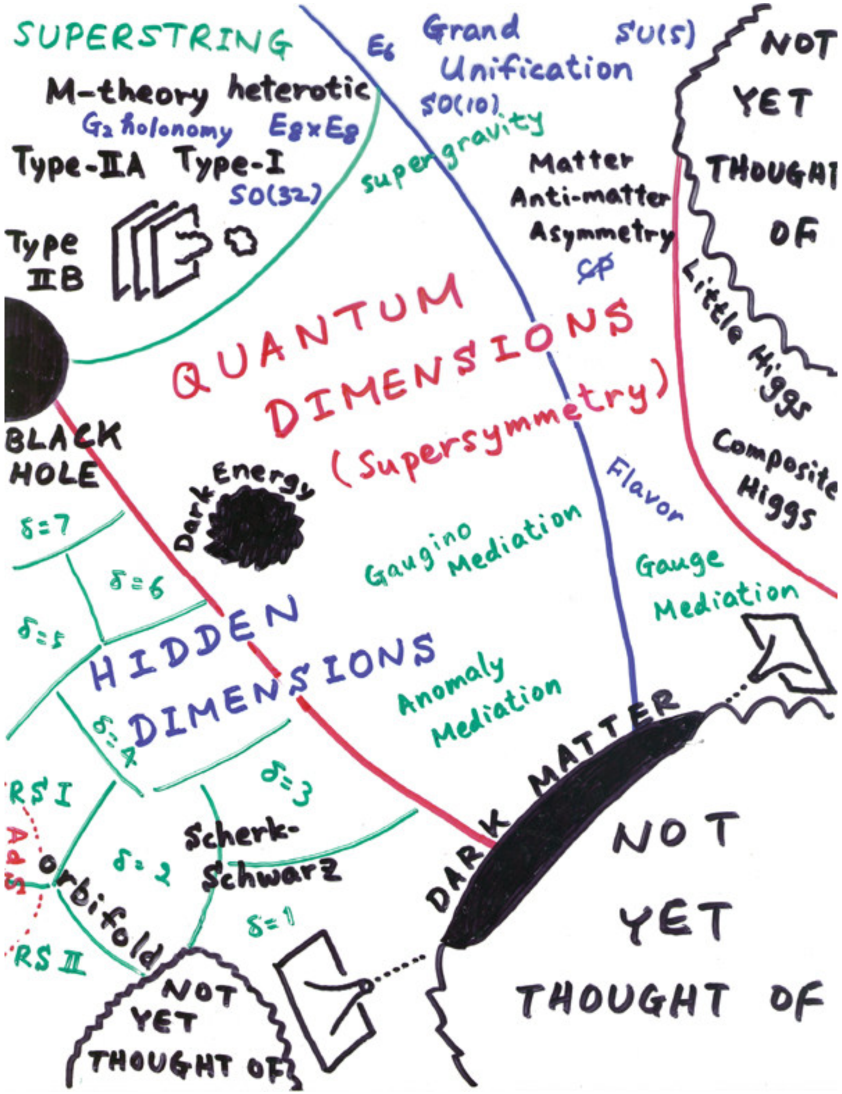


Higgs decay processes



Note that the least model-dependent observables at the LHC are **ratios of couplings**

Search for Physics beyond the Standard Model



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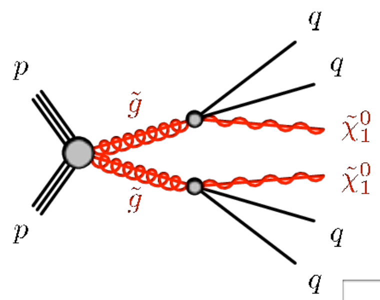
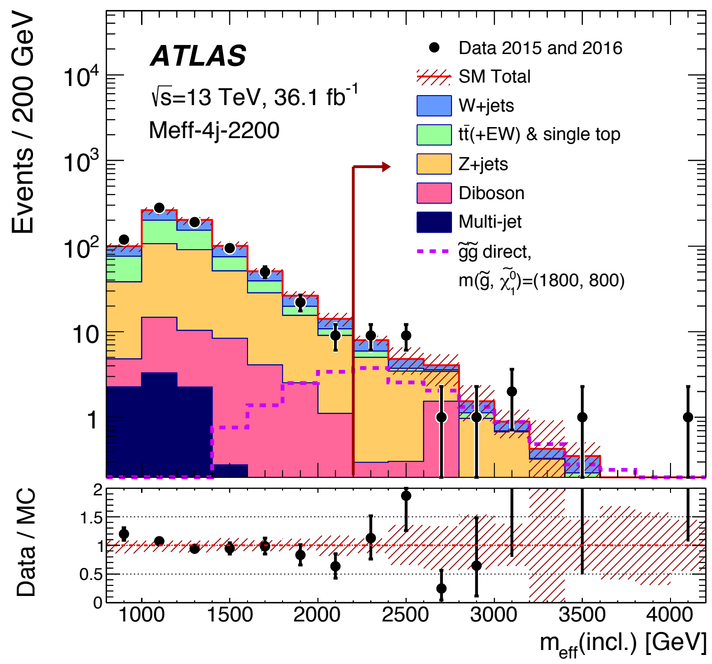
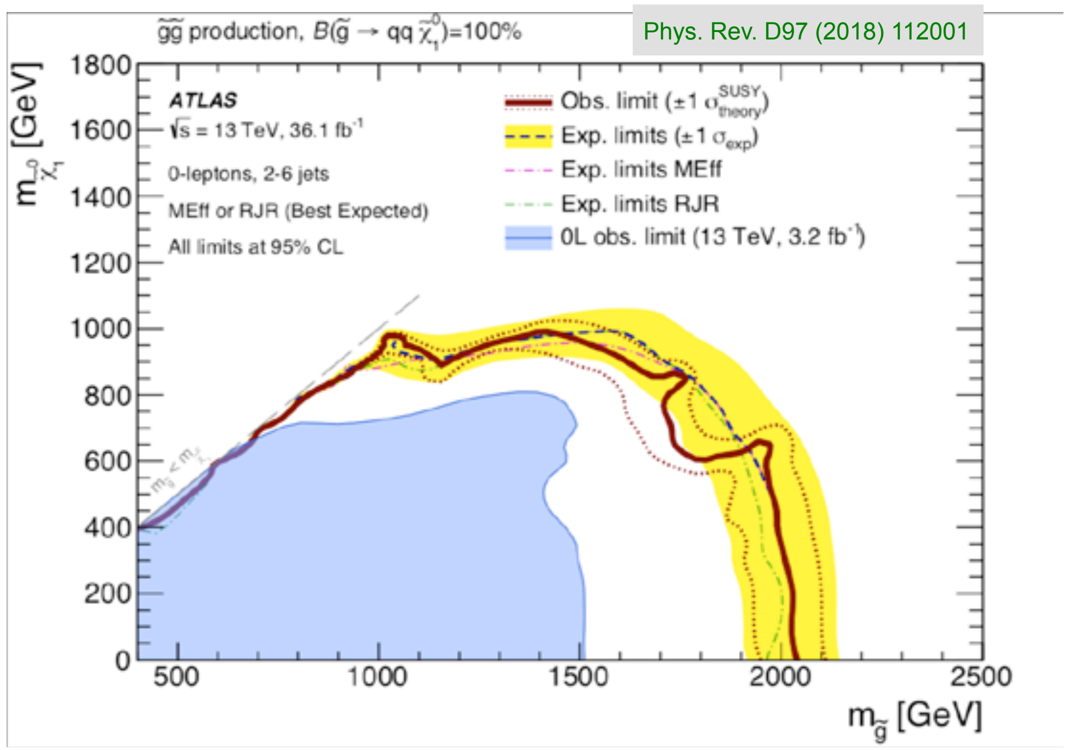
Search for Supersymmetry

-Important new results with complete 2015-2016 dataset-



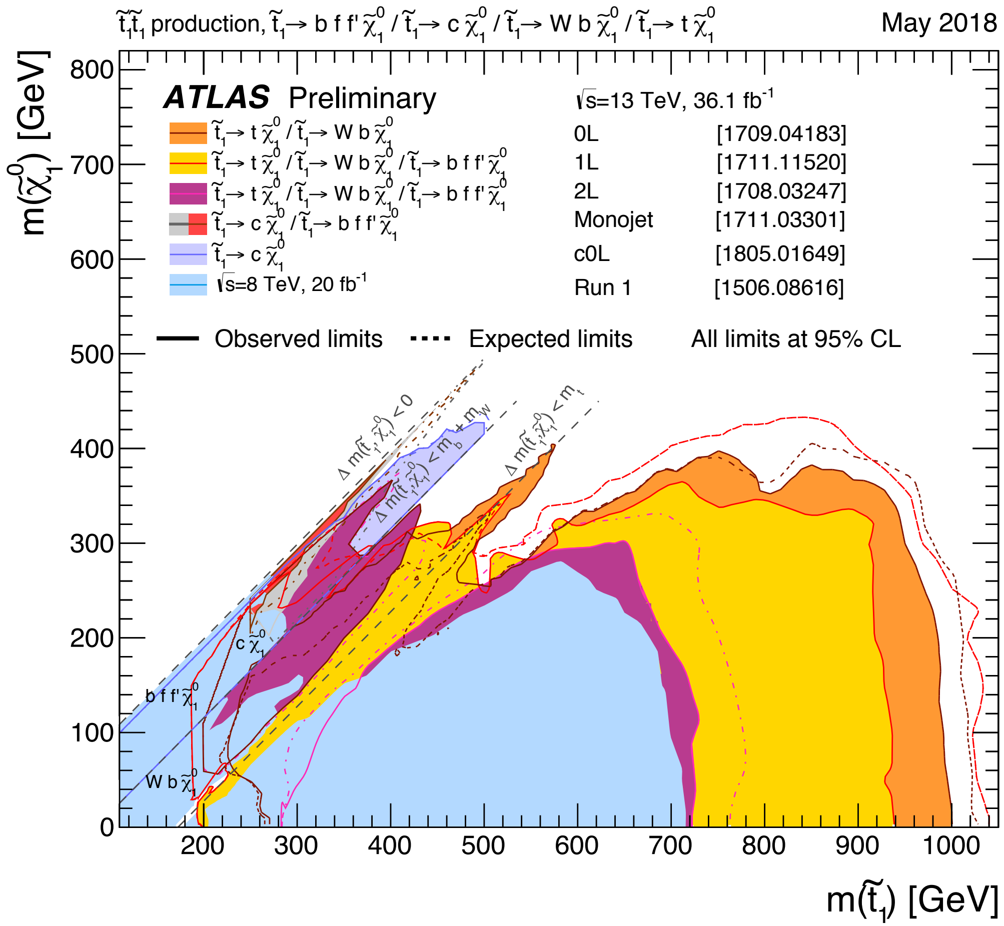




Data well described by expectations from SM processes

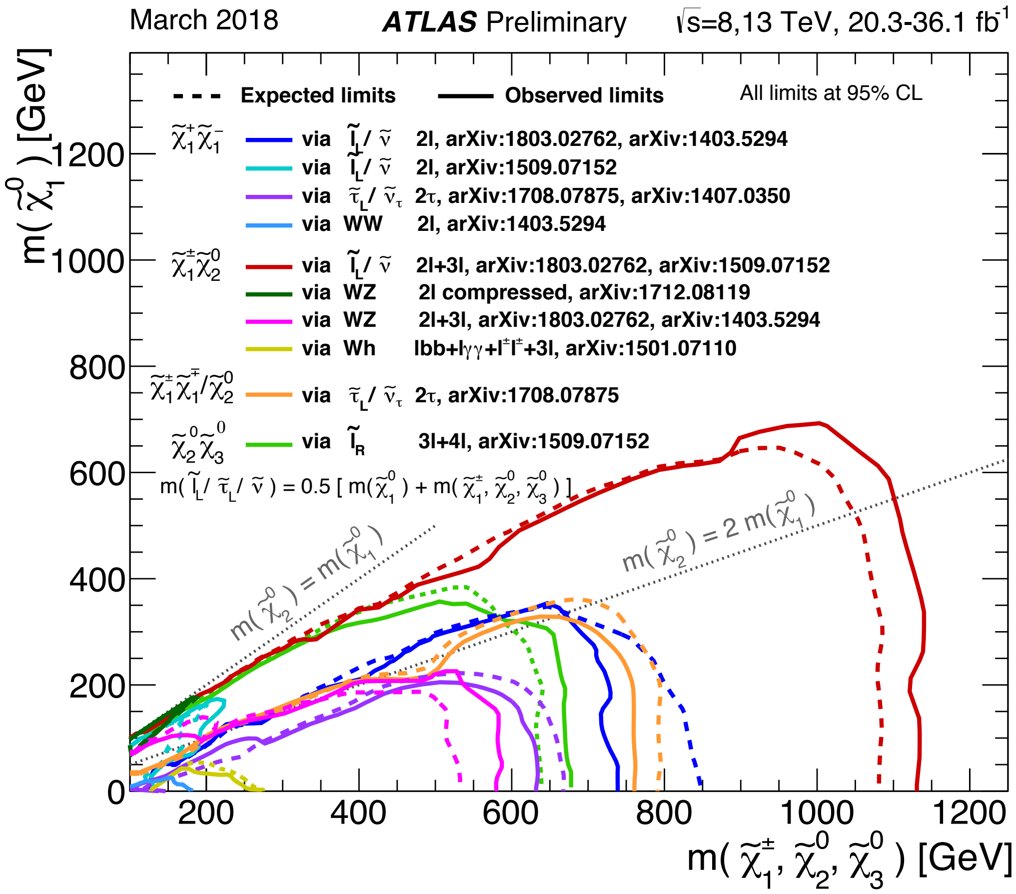
Gluino mass limit beyond 2 TeV, $m(\chi^0) = 0$

Results on dedicated searches for stop quarks



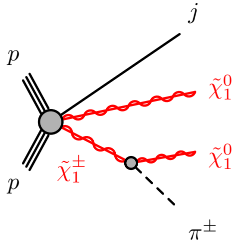
- Weaker mass limits for partners of the top quark (lower production rate, tt background)
- However, significant progress, with mass limits ~1 TeV (light neutralinos), including coverage for complex decay scenarios

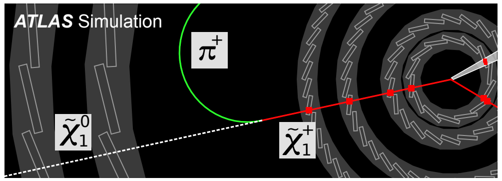
Results on electroweak SUSY production

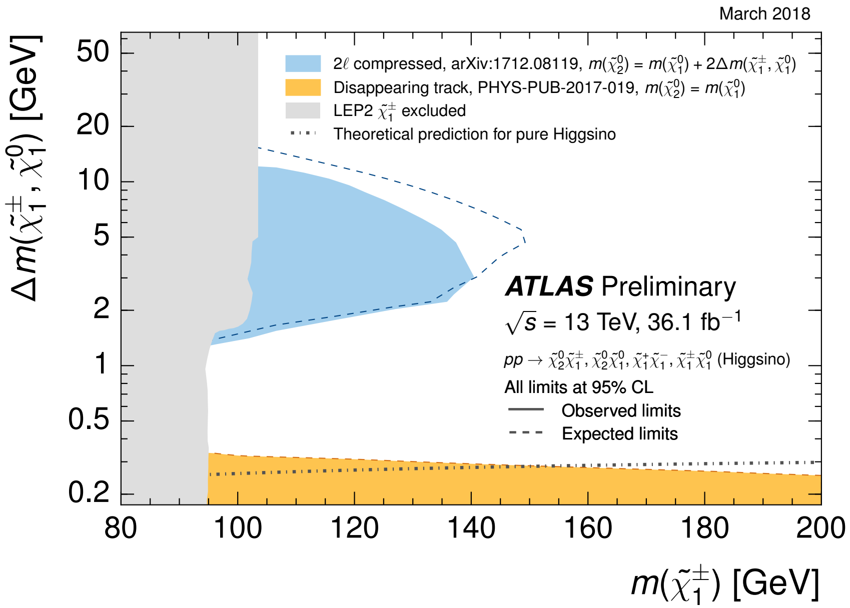


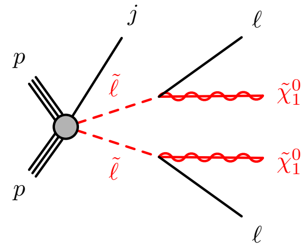
The 95% CL exclusion limits on $\chi_1^+\chi_1^-$, $\chi_1^\pm\chi_2^0$ and $\chi_2^0\,\chi_3^0$ production with either SM-boson-mediated or ℓ-mediated decays, as a function of the $\chi_1^\pm$, χ_2^0 and χ_1^0 masses. The production cross-section is for pure wino $\chi_1^+\chi_1^-$ and $\chi_1^\pm\chi_2^0$, and pure higgsino $\chi_2^0\chi_3^0$.

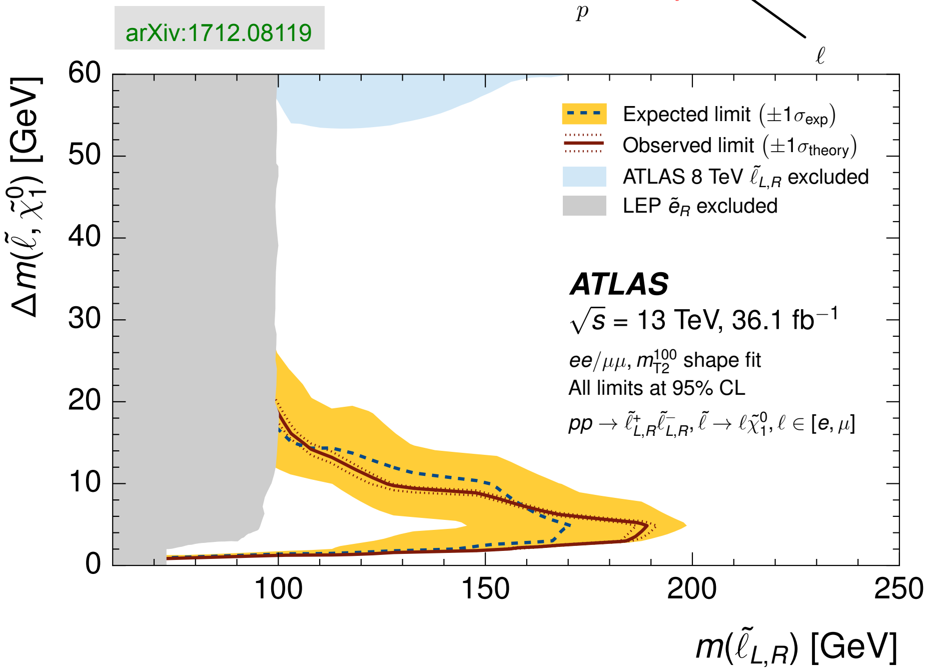
Electroweak SUSY sensitivity beyond LEP limits











Interesting limits for electroweak SUSY production with compressed mass states
(left): First direct Higgsino constraints from ATLAS (combination of several analyses)

(right): Exclusion of slepton masses up to 190 GeV

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2017

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 37.0)\ \text{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

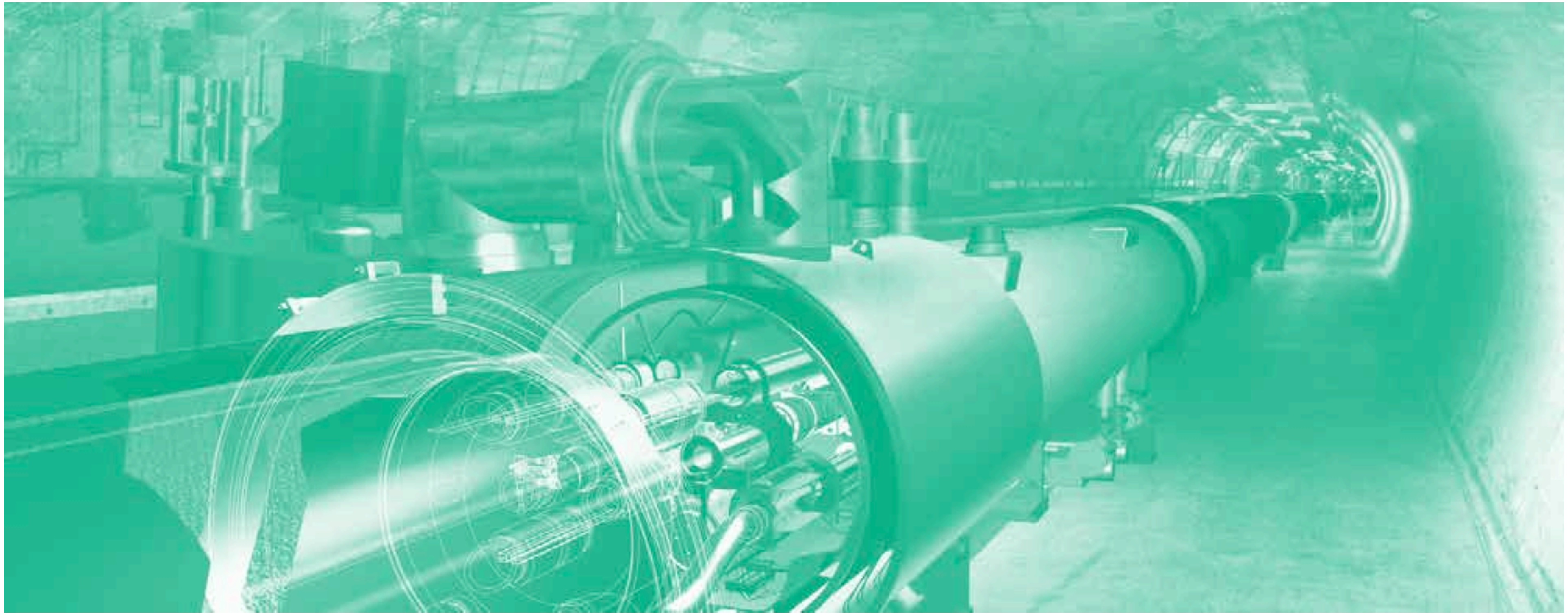
	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\text{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	$0\ e, \mu$	$1-4$ j	Yes	36.1	M_D 7.75 TeV	$n = 2$	ATLAS-CONF-2017-060
	ADD non-resonant $\gamma\gamma$	$2\ \gamma$	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	CERN-EP-2017-132
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09217
	ADD BH high $\sum p_T$	$\geq 1\ e, \mu$	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	$2\ \gamma$	–	–	36.7	G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	CERN-EP-2017-132
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	$1\ e, \mu$	1 J	Yes	36.1	G_{KK} mass 1.75 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2017-051
	2UED / RPP	$1\ e, \mu$	≥ 2 b, ≥ 3 j	Yes	13.2	KK mass 1.6 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	ATLAS-CONF-2016-104
Gauge bosons	SSM $Z' \to \ell\ell$	$2\ e, \mu$	–	–	36.1	Z' mass 4.5 TeV		ATLAS-CONF-2017-027
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	36.1	Z' mass 2.4 TeV		ATLAS-CONF-2017-050
	Leptophobic $Z' \to bb$	–	2 b	–	3.2	Z' mass 1.5 TeV		1603.08791
	Leptophobic $Z' \to tt$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	3.2	Z' mass 2.0 TeV	$\Gamma/m = 3\%$	ATLAS-CONF-2016-014
	SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	36.1	W' mass 5.1 TeV		1706.04786
	HVT $V' \to WV \to qqqq$ model B	$0\ e, \mu$	2 J	–	36.7	V' mass 3.5 TeV	$g_V = 3$	CERN-EP-2017-147
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	ATLAS-CONF-2017-055
	LRSM $W'_R \to tb$	$1\ e, \mu$	2 b, 0-1 j	Yes	20.3	W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \to tb$	$0\ e, \mu$	≥ 1 b, 1 J	–	20.3	W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV η_{LL}^-		1703.09217
	CI $\ell\ell qq$	$2\ e, \mu$	–	–	36.1	Λ 40.1 TeV η_{LL}^-		ATLAS-CONF-2017-027
	CI $uutt$	2(SS)/$\geq 3\ e,\mu$	≥ 1 b, ≥ 1 j	Yes	20.3	Λ 4.9 TeV	$\lvert C_{RR} \rvert = 1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	$0\ e, \mu$	$1-4$ j	Yes	36.1	m_{med} 1.5 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 400$ GeV	ATLAS-CONF-2017-060
	Vector mediator (Dirac DM)	$0\ e, \mu$, $1\ \gamma$	≤ 1 j	Yes	36.1	m_{med} 1.2 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 480$ GeV	1704.03848
	$VV\chi\chi$ EFT (Dirac DM)	$0\ e, \mu$	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	$2\ e$	≥ 2 j	–	3.2	LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	$2\ \mu$	≥ 2 j	–	3.2	LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	$1\ e, \mu$	≥ 1 b, ≥ 3 j	Yes	20.3	LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht + X$	0 or $1\ e, \mu$	≥ 2 b, ≥ 3 j	Yes	13.2	T mass 1.2 TeV	$\mathcal{B}(T \to Ht) = 1$	ATLAS-CONF-2016-104
	VLQ $TT \to Zt + X$	$1\ e, \mu$	≥ 1 b, ≥ 3 j	Yes	36.1	T mass 1.16 TeV	$\mathcal{B}(T \to Zt) = 1$	1705.10751
	VLQ $TT \to Wb + X$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	36.1	T mass 1.35 TeV	$\mathcal{B}(T \to Wb) = 1$	CERN-EP-2017-094
	VLQ $BB \to Hb + X$	$1\ e, \mu$	≥ 2 b, ≥ 3 j	Yes	20.3	B mass 700 GeV	$\mathcal{B}(B \to Hb) = 1$	1505.04306
	VLQ $BB \to Zb + X$	2/$\geq 3\ e, \mu$	$\geq 2/\geq 1$ b	–	20.3	B mass 790 GeV	$\mathcal{B}(B \to Zb) = 1$	1409.5500
	VLQ $BB \to Wt + X$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	36.1	B mass 1.25 TeV	$\mathcal{B}(B \to Wt) = 1$	CERN-EP-2017-094
	VLQ $QQ \to WqWq$	$1\ e, \mu$	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	37.0	q^* mass 6.0 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1703.09127
	Excited quark $q^* \to q\gamma$	$1\ \gamma$	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	CERN-EP-2017-148
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	13.3	b^* mass 2.3 TeV		ATLAS-CONF-2016-060
	Excited quark $b^* \to Wt$	1 or $2\ e, \mu$	1 b, 2-0 j	Yes	20.3	b^* mass 1.5 TeV	$f_g = f_L = f_R = 1$	1510.02664
	Excited lepton ℓ^*	$3\ e, \mu$	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	$3\ e, \mu, \tau$	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LRSM Majorana ν	$2\ e, \mu$	2 j	–	20.3	N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	ATLAS-CONF-2017-053
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	$3\ e, \mu, \tau$	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Monotop (non-res prod)	$1\ e, \mu$	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{\text{non-res}} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass 785 GeV	DY production, $\lvert q \rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass 1.34 TeV	DY production, $\lvert g \rvert = 1 g_D$, spin 1/2	1509.08059

$\sqrt{s} = 8$ TeV (green bars) $\sqrt{s} = 13$ TeV (yellow bars)

Mass scale [TeV]: 10^{-1}, 1, 10

*Only a selection of the available mass limits on new states or phenomena is shown.

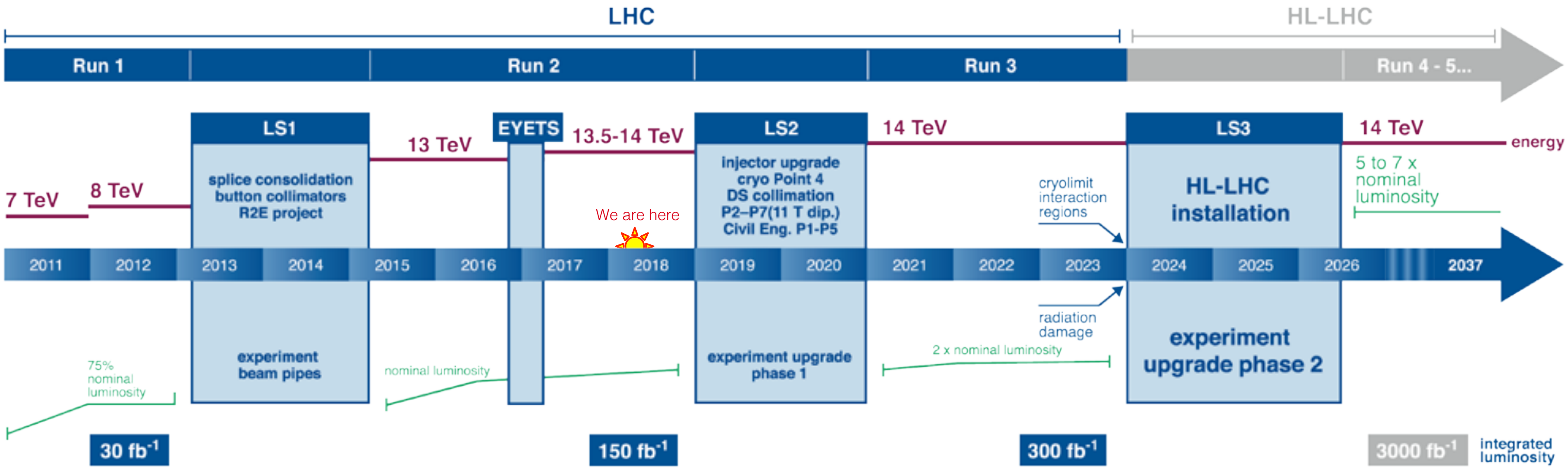
†Small-radius (large-radius) jets are denoted by the letter j (J).



The next steps

Phase-II:
The High-Luminosity LHC

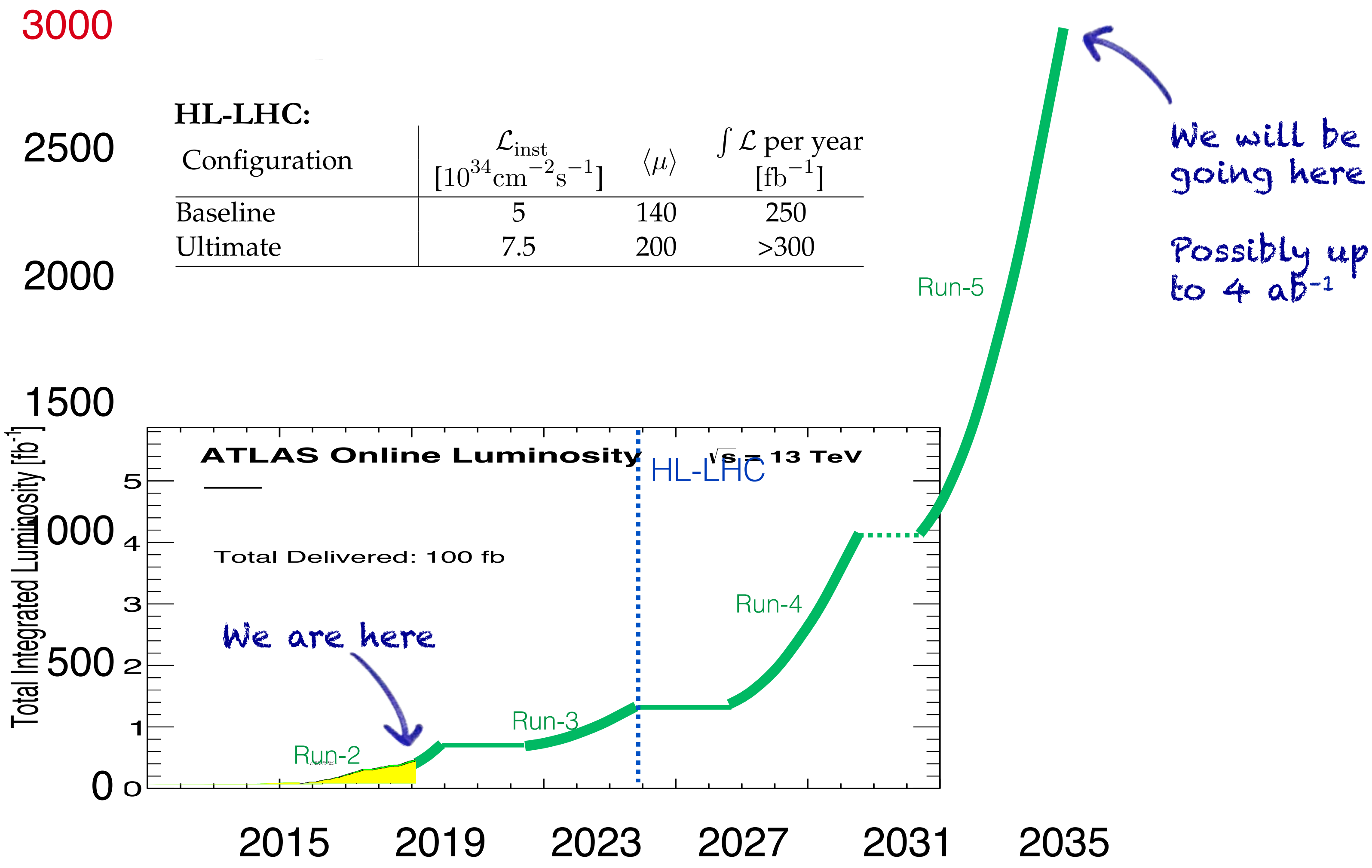
LHC / HL-LHC Plan



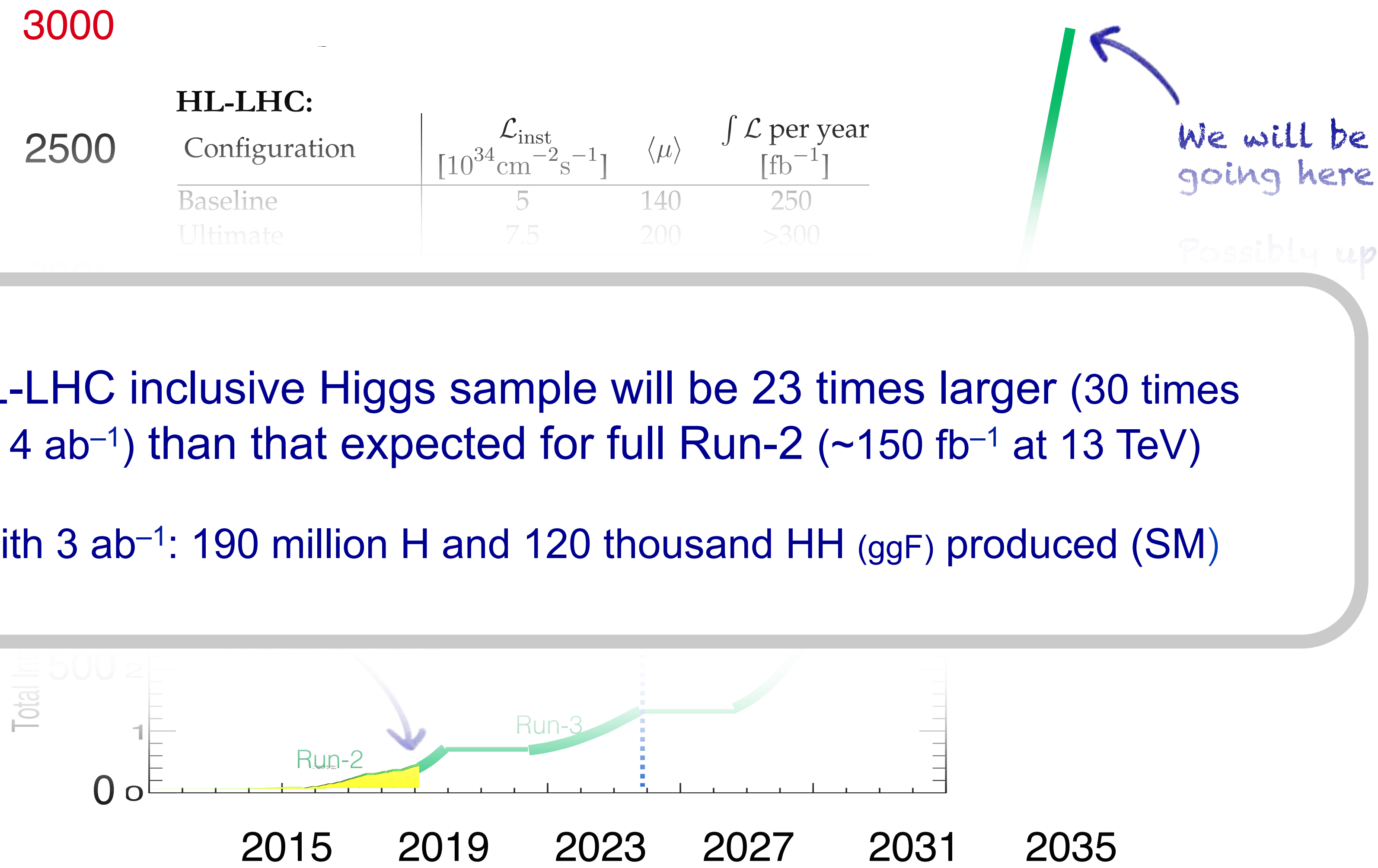
Expected integrated luminosity of LHC and HL-LHC

HL-LHC:

Configuration	$\mathcal{L}_{inst}$ $[10^{34}cm^{-2}s^{-1}]$	$\langle\mu\rangle$	$\int\mathcal{L}$ per year $[fb^{-1}]$
Baseline	5	140	250
Ultimate	7.5	200	>300



Expected integrated luminosity of LHC and HL-LHC

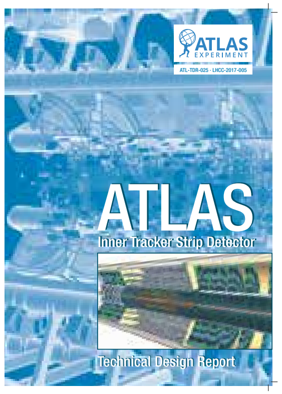


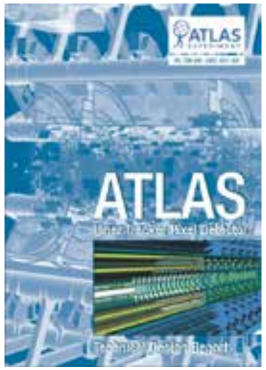
HL-LHC inclusive Higgs sample will be 23 times larger (30 times for 4 ab^{-1}) than that expected for full Run-2 (~150 fb^{-1} at 13 TeV)

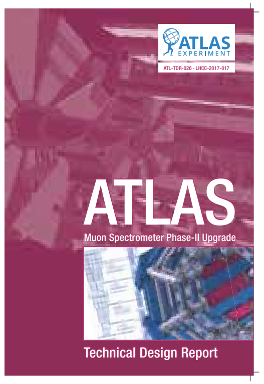
With 3 ab^{-1}: 190 million H and 120 thousand HH (ggF) produced (SM)

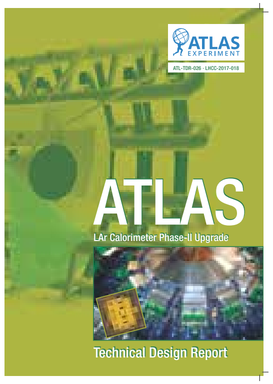
Status of Phase-II
Detector Upgrade Technical Design Reports (TDR)

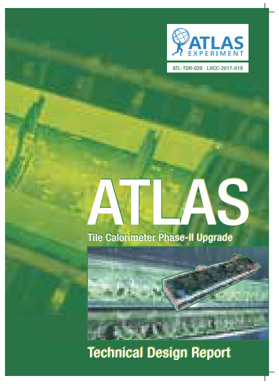
All six TDRs of the ATLAS Phase-II Upgrade programme have been presented by ATLAS, reviewed and approved by the LHCC and UCG, and finally approved by the CERN Research Board

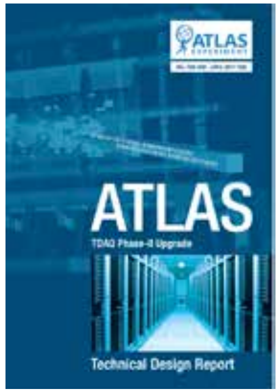








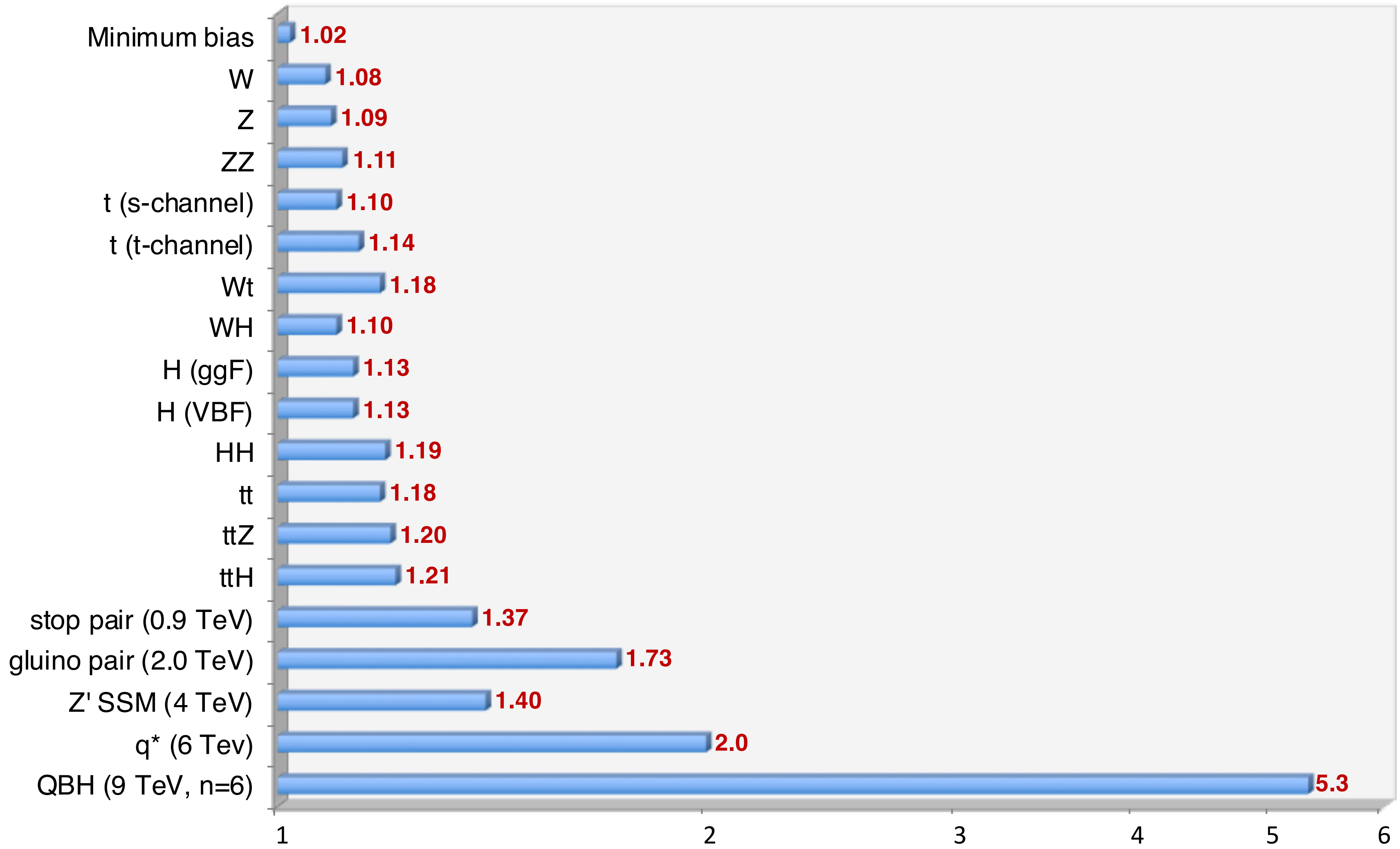




Silicon Strip + Pixel tracker Muon system Calorimeters TDAQ

… but also a huge amount of work ahead of us..

14 TeV / 13 TeV cross-section ratios



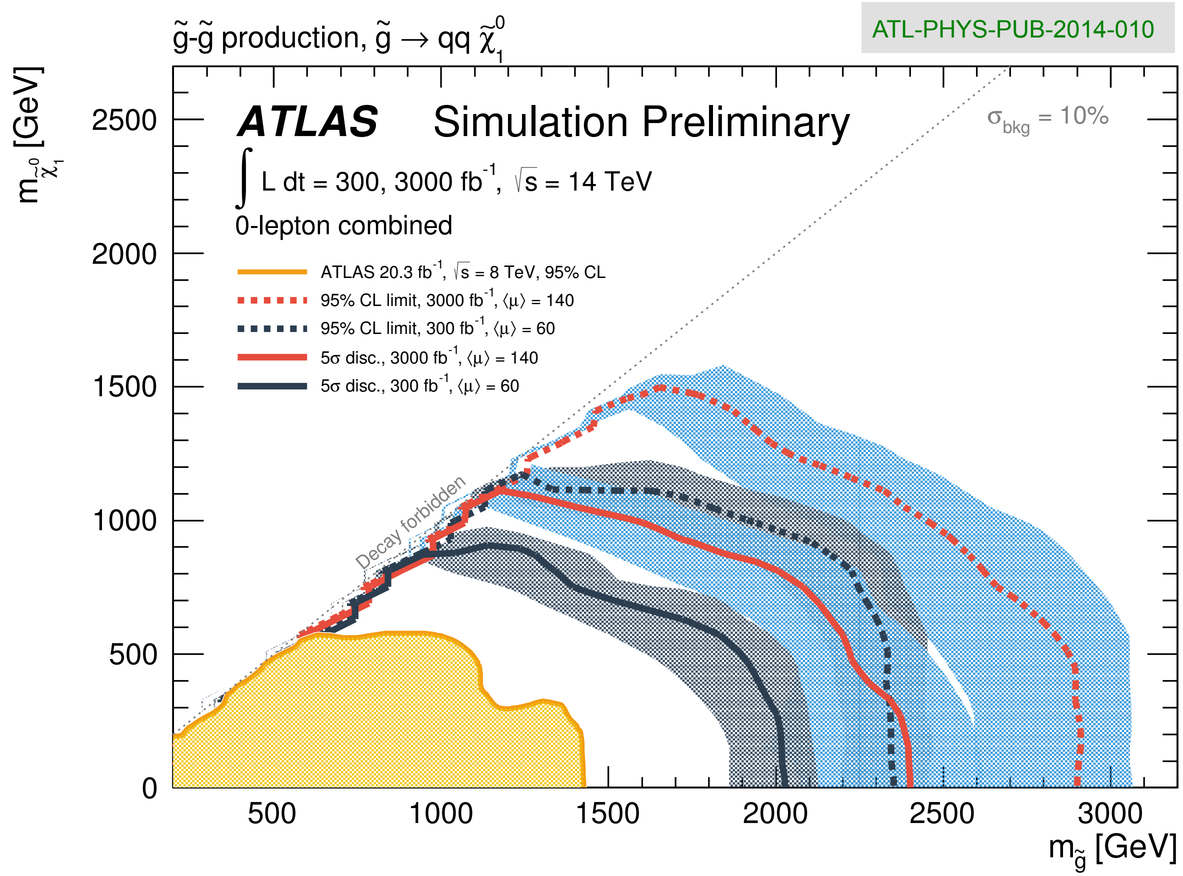
Methodology of HL-LHC studies

- The experiments use full or parameterised fast simulation tuned to full simulation of upgraded detectors, together with overlaid pileup and simplified analyses to explore HL-LHC reach

- Alternatively, current full analyses are extrapolated to HL-LHC energy and conditions

  - In both cases bold assumptions on evolution of theoretical uncertainties made
  - Both methods suffer from caveats. **Many studies are conservative**
  - Most of the studies shown here will be updated for the **HL-LHC Yellow report; under preparation, will appear by end of this year**
  - All studies shown here for 3 ab^{-1} and assuming 200 or 140 pileup events on average per bunch crossing

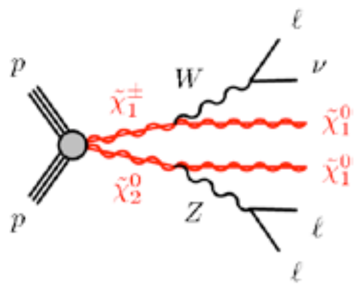
Prospects for standard SUSY searches

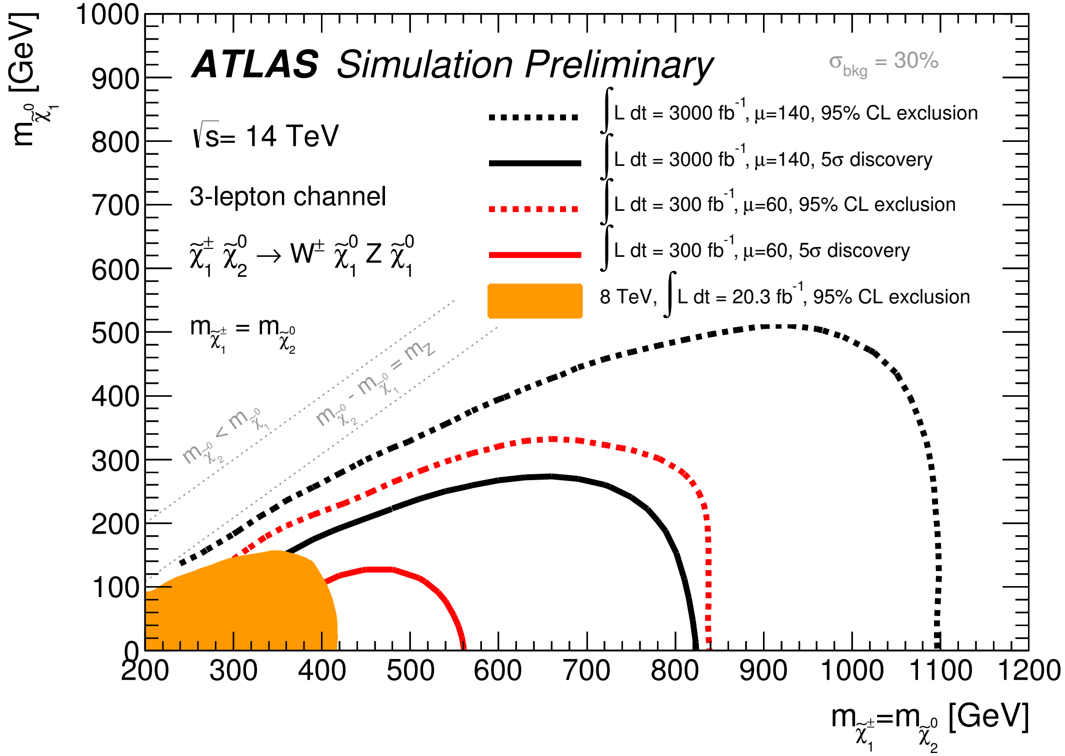


HL-LHC 95% C.L. exclusion limits for gluinos up to ~ 3 TeV

Prospects for standard SUSY searches (cont.)

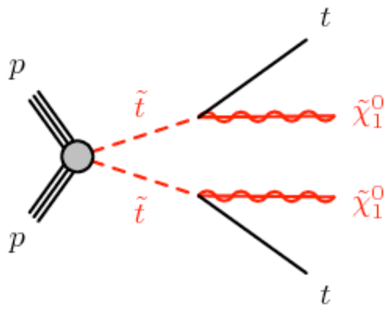
ATL-PHYS-PUB-2014-010

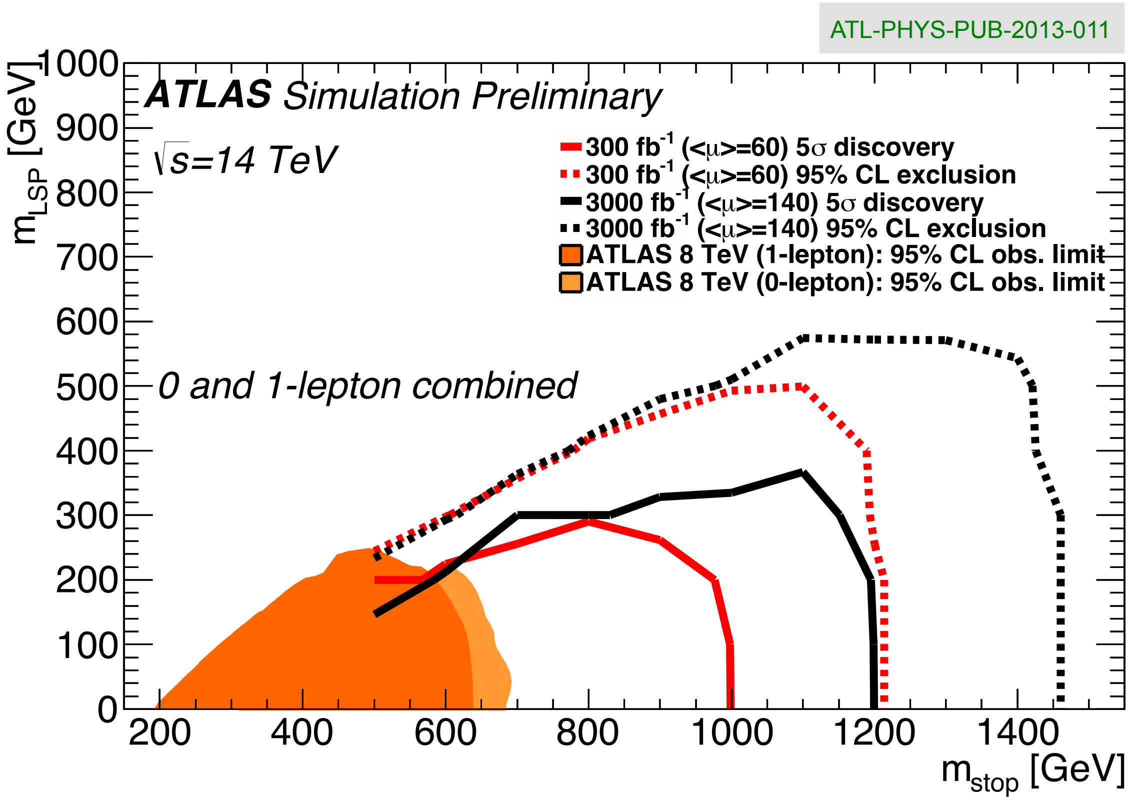




HL-LHC 95% C.L. exclusion limits for charginos / neutralinos up to ~ 1.1 TeV

Prospects for standard SUSY searches (cont.)





HL-LHC 95% C.L. exclusion limits for stops up to ~ 1.5 TeV

Higgs physics programme at the LHC in a nutshell

Higgs boson properties:

- Mass (well known), width (through interference measurements)
- Spin (0^+ established), CP (odd admixture possible) — not discussed today

Rare Higgs boson decays:

- Observation of $H \rightarrow \mu\mu$, $H \rightarrow Z\gamma$, HH production (constraint on Higgs boson self coupling)
- Search for very rare (e.g., $H \rightarrow M\gamma$, $M=J/\psi$, ϕ, ρ), difficult ($H \rightarrow cc$) or anomalous decays (invisible or new particles, or flavour violating)

Higgs boson couplings:

- Study of Higgs boson production and anomalous couplings by differential cross-section measurements
- Global and partially global coupling fits: experiments moving from "kappa" interpretation to EFT

New physics in Higgs boson production or other scalar states:

- Search for anomalous FCNC through top decays, Higgs production via SUSY cascades, etc.
- Search for additional scalar particles

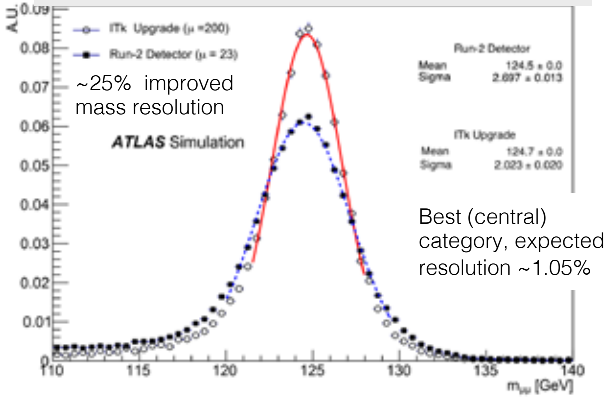
Coupling to 2nd generation: Higgs decay to H → μμ (BR: 0.022% in SM)

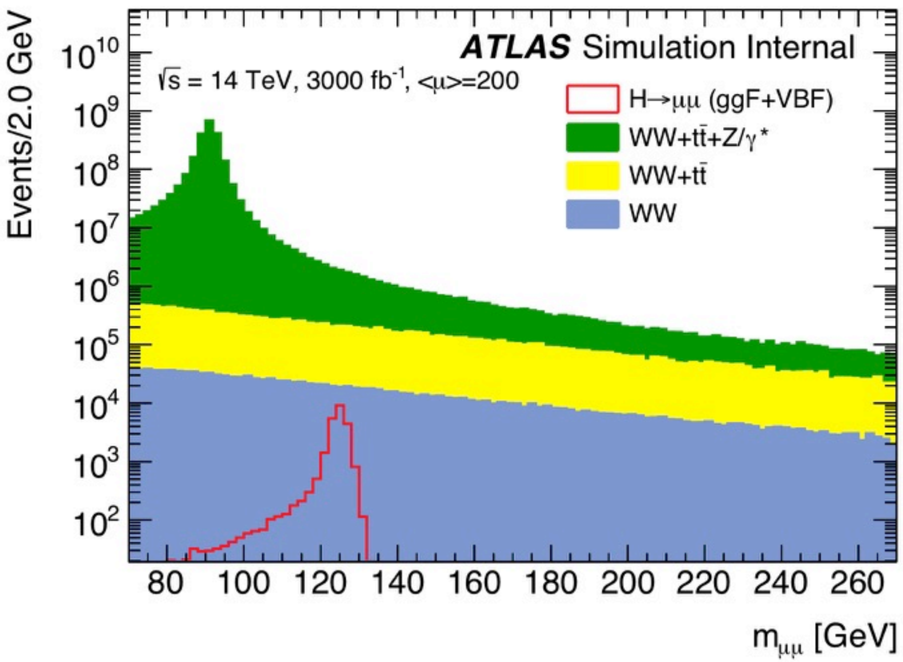
Upgraded detectors feature improved di-muon mass resolution

→ Cross-section times branching fraction measurement to ~13% (ATLAS), 10% (CMS) precision for 3 ab^{-1}

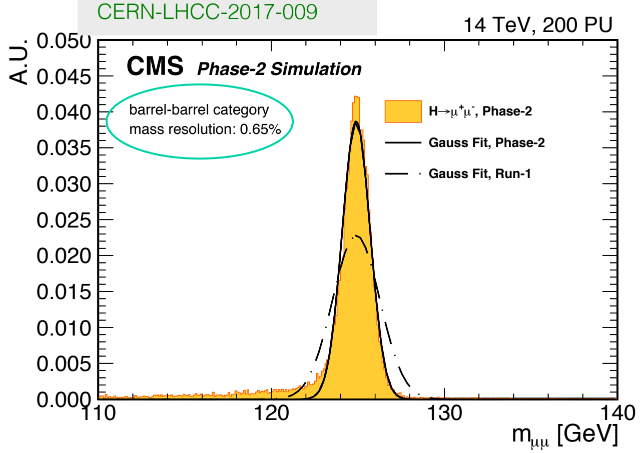
Challenging data-driven Drell-Yan background determination

ATLAS ITk Strip TDR: CERN-LHCC-2017-005





CMS Tracker TDR:
CERN-LHCC-2017-009



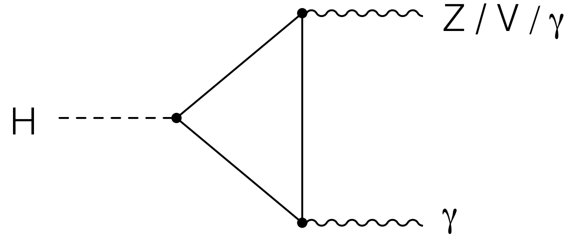
Rare loop decay to H → Zγ (BR: 0.15% in SM, 0.010% with Z → ee, μμ)

Large background from Z production with radiative photons

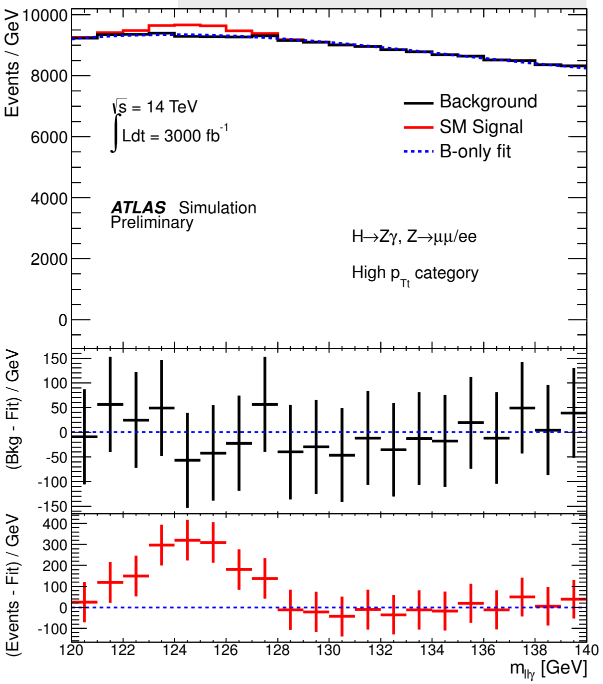
Observation with combined ATLAS & CMS dataset expected with 3 ab^{-1}

Combined statistical precision of about 15% on cross-section

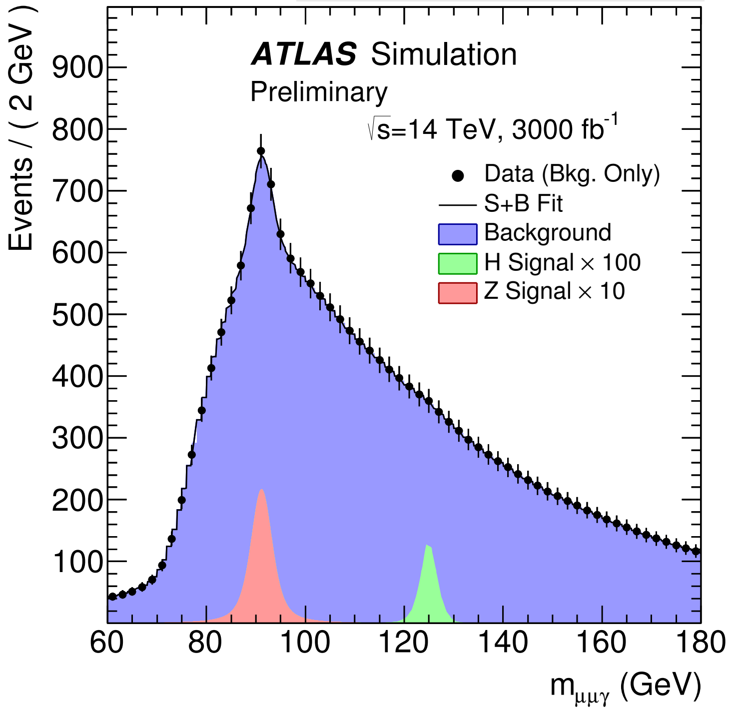
Challenging data-driven background determination



ATLAS ATL-PHYS PUB-2014-006



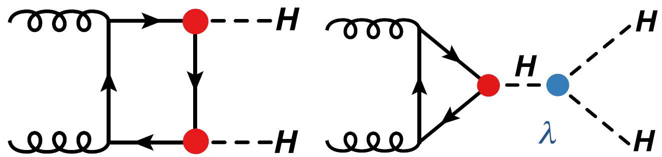
ATLAS ATL-PHYS PUB-2015-043



Also searches for, eg, H → J/ψ γ with expected sensitivity of 15 times SM prediction (BR: 2.9 10^{-6})

Di-Higgs boson production

HH cross section predicted to 40 ± 2 fb at 14 TeV,
i.e., >1000 times smaller than for single Higgs production

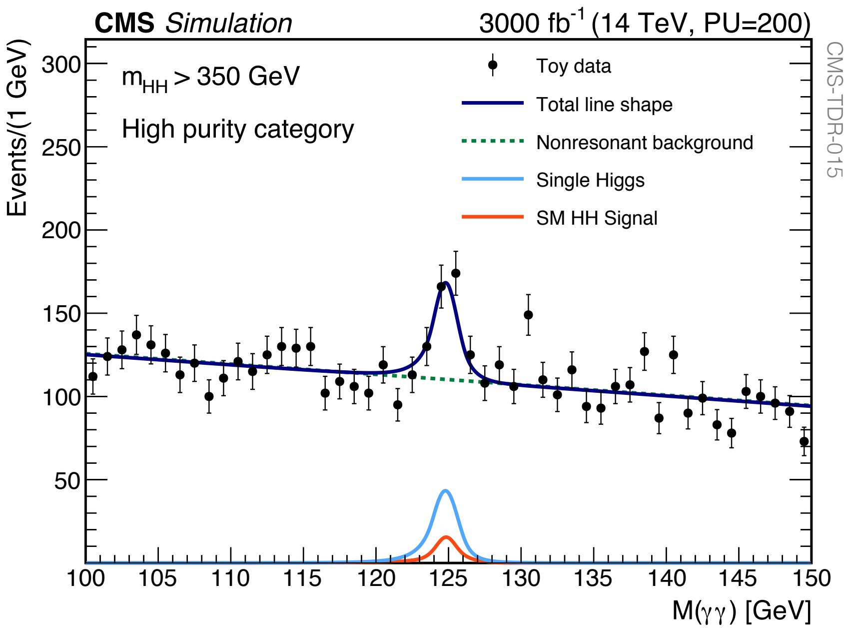


Sophisticated analyses needed, room for innovation;
Extrapolation uncertainty in continuum background prediction

Best channels: bbγγ (BR = 0.26%), bbττ (7.3%), bbbb (33%), bbWW, 25% → combination

Currently (36 fb^{-1} at 13 TeV) for bbγγ: μ_{HH} < 19 (17_{exp}) [CMS, using LO signal simulation, some effect on acceptance]

Projection to HL-LHC (bbγγ, 2017): ~1.5σ significance, CMS combines w/ bbττ in HL-LHC TP (2015): 1.9σ



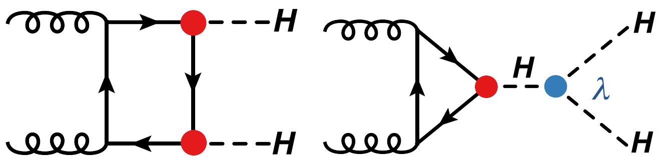
It is not yet established which of the three main channels will be best

The bbbb channel strongly depends on the lowest jet p_T trigger threshold and on top background modelling

Combining ATLAS and CMS in all channels, hoping for analysis improvements, and including new channels may give 3σ HH sensitivity with 3 ab^{-1}

Constraints on Higgs trilinear self coupling λ_{HHH}

Constraint on λ_{HHH} by simulating NLO MC HH samples for different λ_{HHH} values. Effects on total HH cross section and acceptance

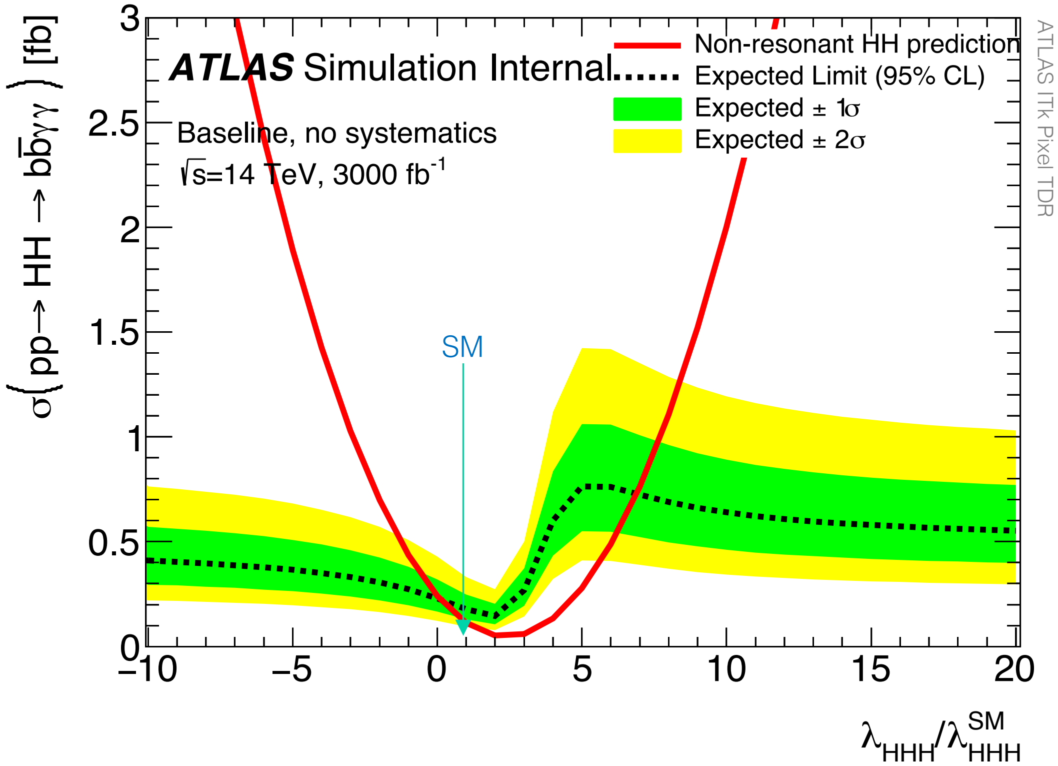


LO diagrams contributing with negative interference to SM HH production

Box diagram dominates inclusive production

Sensitivity to H self coupling rises at low m_{HH}

Projection to HL-LHC (bbγγ, 2017)



95% CL limit: $0.2 < \lambda / \lambda_{SM} < 6.9$ (bbγγ)

These analyses use only inclusive rates. Fitting differential variables such as m_{HH}, $p_{T,H}$ close to threshold should allow to improve the constraint on λ (but hard for bbbb channel, so : bbγγ and bbττ might be best for λ)

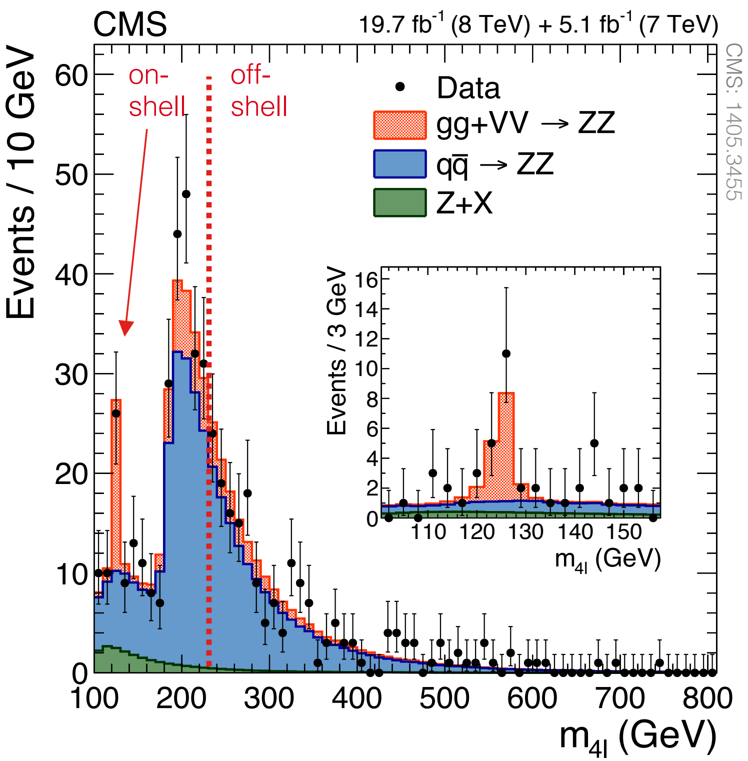
[See, e.g., 1607.07441]

λ_{HHH} also affects single-H production at NLO through internal H loops
→ Complementary information from differential H cross-section measurements

Off-shell coupling measurement

Both CMS and ATLAS have constrained the Higgs off-shell coupling and through this obtained upper limits on the Higgs total width Γ_H. Current limit Γ_H < 22 MeV at 95% CL ($\Gamma_{H,SM}$ = 4.1 MeV).

The method uses the independence of off-shell cross section on Γ_H and relies on identical on-shell and off-shell Higgs couplings. One can then determine Γ_H from measurements of $\mu_{\text{off-shell}}$ and $\mu_{\text{on-shell}}$



$$\mu_{\text{off-shell}}(\hat{s}) \equiv \frac{\sigma^{gg\to H^*\to VV}_{\text{off-shell}}(\hat{s})}{\sigma^{gg\to H^*\to VV}_{\text{off-shell, SM}}(\hat{s})} = \kappa^2_{g,\text{off-shell}}(\hat{s}) \cdot \kappa^2_{V,\text{off-shell}}(\hat{s})$$

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

With L_2 = 3000 fb^{-1}, one may find:

$$\mu^{(L2)}_{\text{off-shell}} = 1.00^{+0.43}_{-0.50}\ \text{(stat+sys)}$$

$$\Gamma^{(L2)}_H = 4.2^{+1.5}_{-2.1}\ \text{MeV (stat+sys)}$$

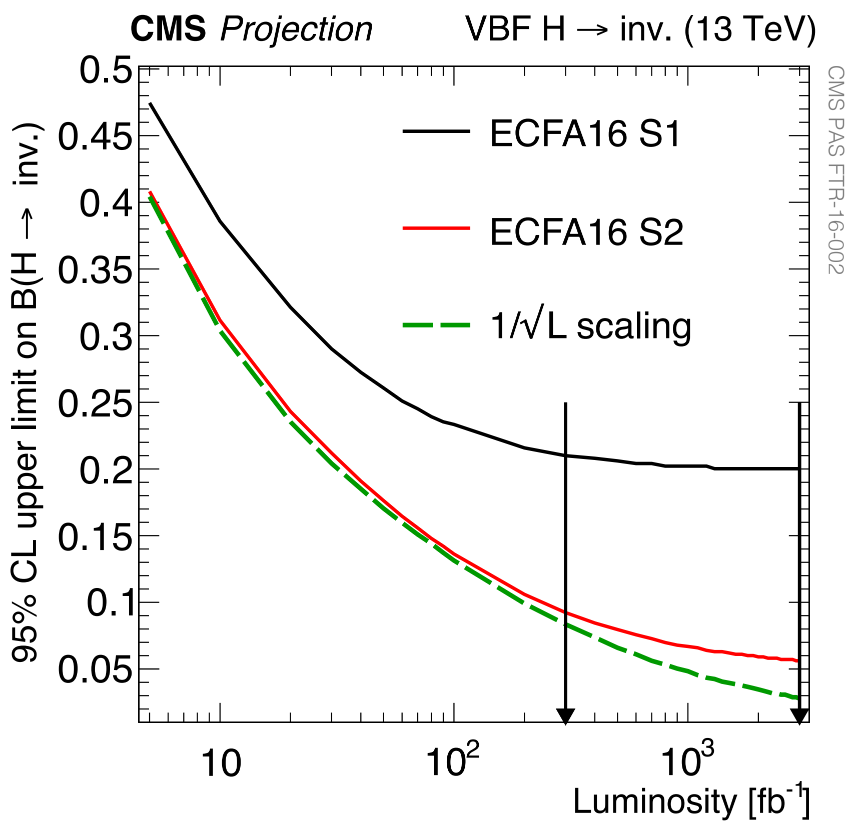
ATLAS: ATL-PHYS-PUB-2015-024

Large theory uncertainty (~30%) from gg → ZZ

Constraints on invisible Higgs boson decays

If dark matter (DM) is a thermal relic of the early universe and it is light enough so the Higgs can decay to it, it leads to invisible Higgs decays

Such decays can be detected through Higgs VBF, ZH or ISR-jet production, or in a model-dependent way through the coupling fit (e.g., assuming SM couplings to SM particles)



Best limit of ~3% on H → invisible branching fraction at 3 ab^{-1}
(reminder: current limit: 24%)

However, systematics limited, so difficult extrapolation

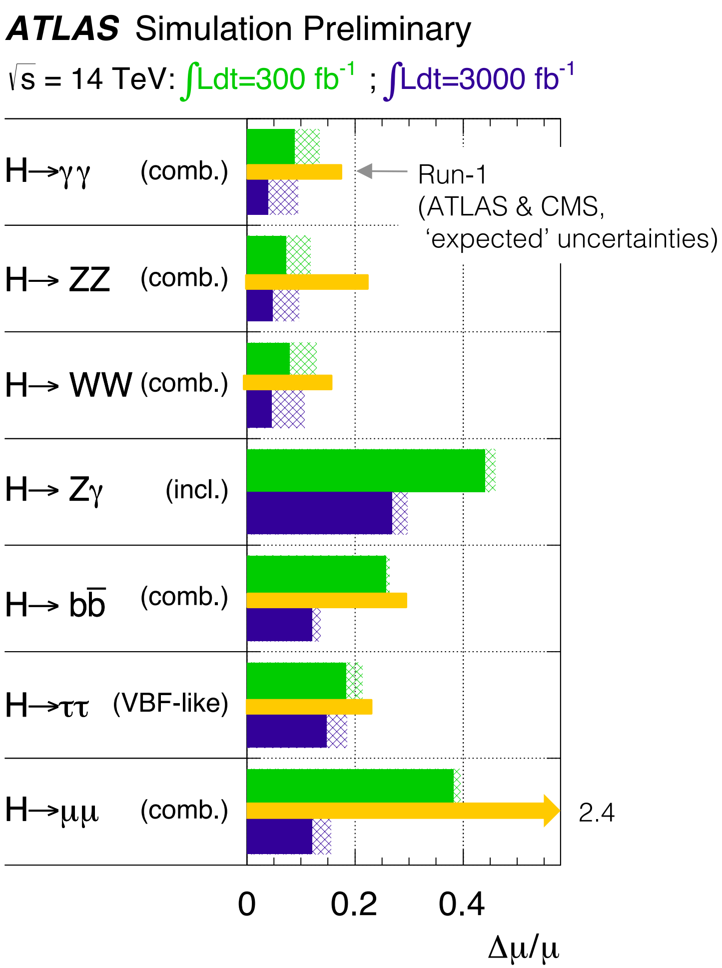
An extrapolation of the combined coupling fit under SM hypothesis gives
H → invisible limits of 9%
(13% when including theory uncertainties)

ATL-PHYS-PUB-2014-017

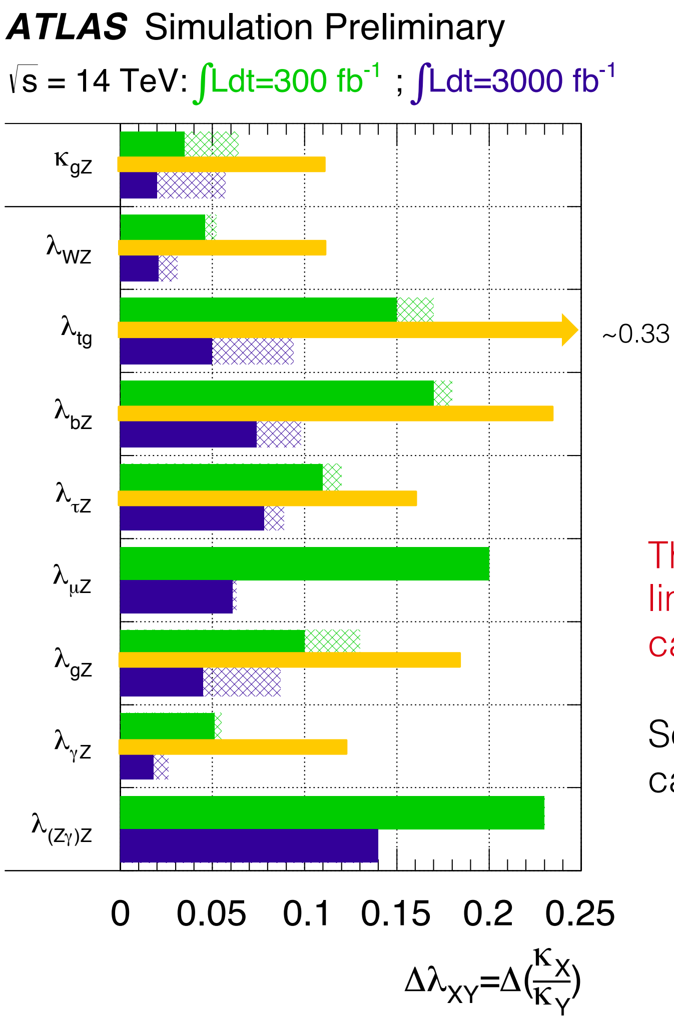
Higgs boson couplings — ATLAS (Status 2014)

Higgs signal strengths (left) and ratios of coupling modifiers (right), compared to current precision (orange)

Conservative extrapolation: does not include improved detector design, large theoretical uncertainties, simplified analyses



4–5% for main channels, 10~20% on rare modes



Theory uncertainty limiting in several cases

Some uncertainties cancel in ratios

Conclusions

- The LHC and the experiments (ATLAS, CMS, LHCb, and ALICE) challenge the validity of the Standard Model at the high-energy frontier with ever increasing precision
- In order to exploit the full potential of the LHC, massive upgrades are needed for the accelerators and the experiments
- The HL-LHC will make a strong impact on Higgs property measurements. It has sensitivity to discover rare Higgs decays to μμ and Zγ, and to study couplings to bosons and third generation fermions to a few percent precision
- Di-Higgs production can likely be seen, but a significant measurement of Higgs self-coupling seems beyond reach. However, important constraints can be obtained.
- Higgs measurements in conjunction with other SM sectors such as diboson and top will allow to obtain coherent information in the framework of EFT or model extensions of the SM.
- Precision measurements in the SM sector will contribute to these constraints