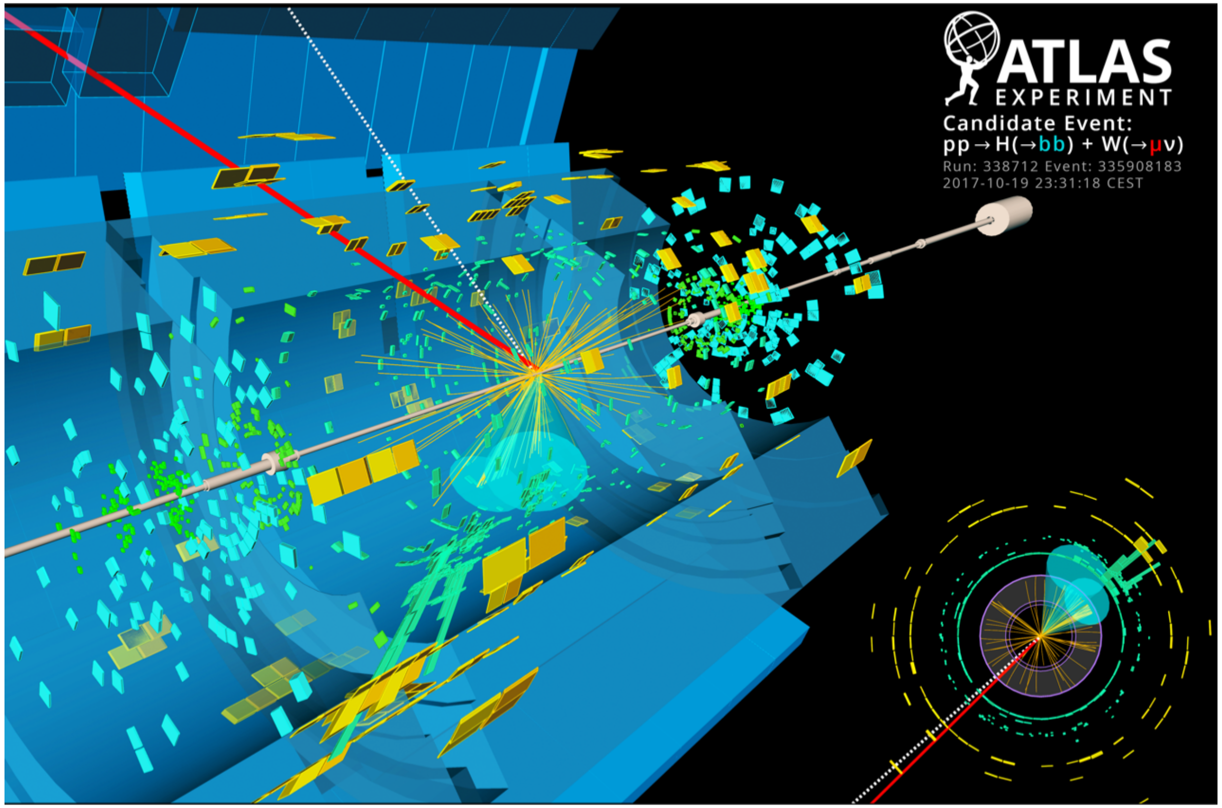
Physics at the LHC



Karl Jakobs
University of Freiburg / Germany

Humboldt Forum, Kitzbühel, 24th June 2019

Physics at the LHC

- Data Taking at the LHC

- Physics highlights
  - Standard Model processes and parameters
  - Higgs boson physics
  - Search for Supersymmetry
  - Dark Matter

- Plans for the High Luminosity LHC (HL-LHC)

Karl Jakobs
University of Freiburg / Germany

Humboldt Forum, Kitzbühel, 24th June 2019

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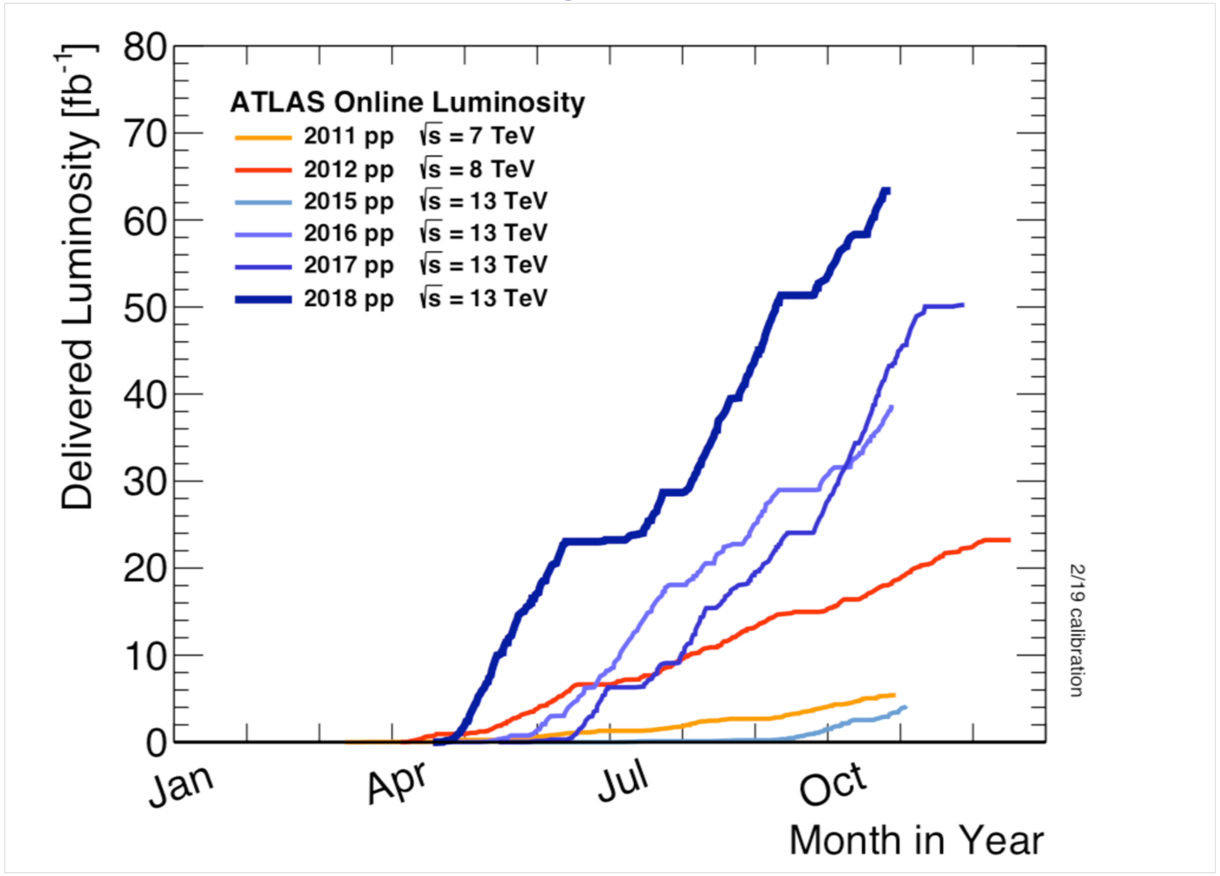
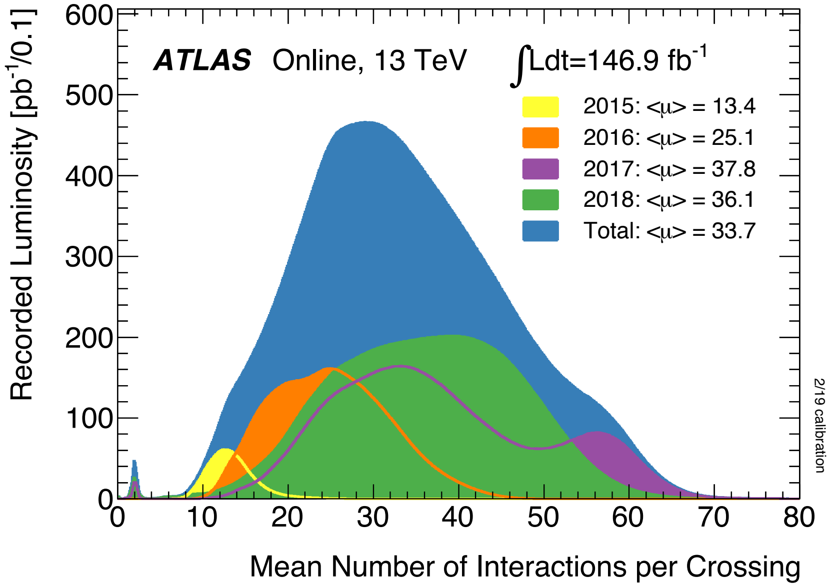
Data taking at the LHC

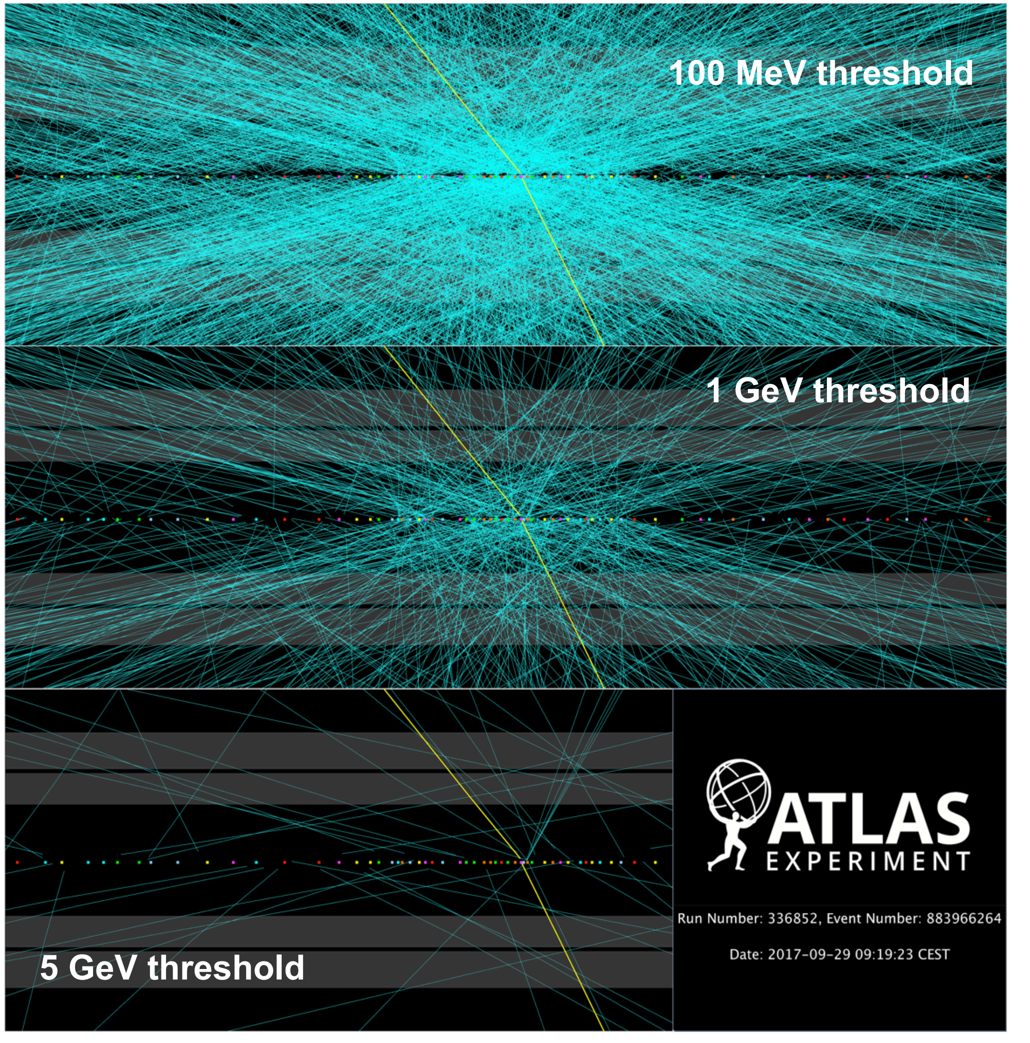


- Run 1: 2010 – 2012 $\sqrt{s}$ = 7 / 8 TeV L_{int} = 28 fb^{-1} delivered
  Run 2: 2015 – 2018 $\sqrt{s}$ = 13 TeV L_{int} = 156 fb^{-1} delivered

- Excellent performance of the accelerator and of the experiments
  The goal of 150 fb^{-1} (in Run 1 + Run 2) has been clearly surpassed

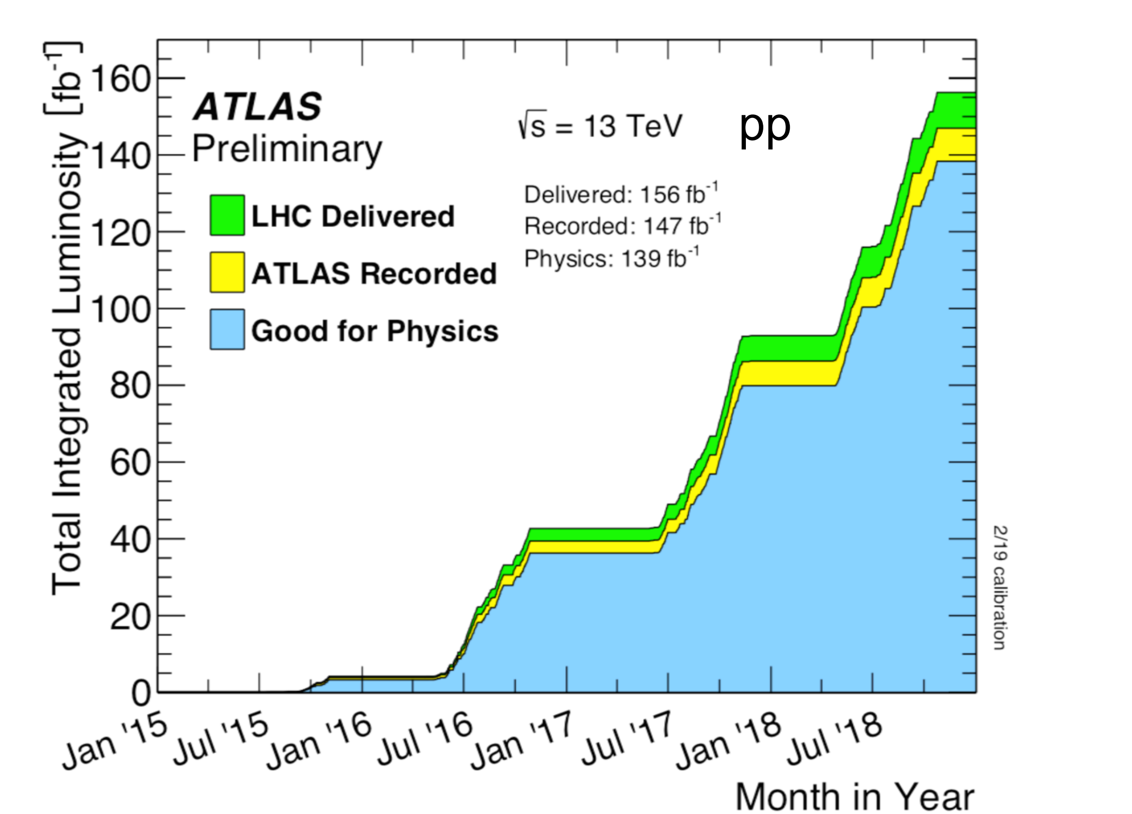
Data taking at the LHC (cont.)





Z→ $\mu\mu$ candidate with 65 additional reconstructed vertices!

Data taking in Run 2



In Run 2 (2015 – 2018):

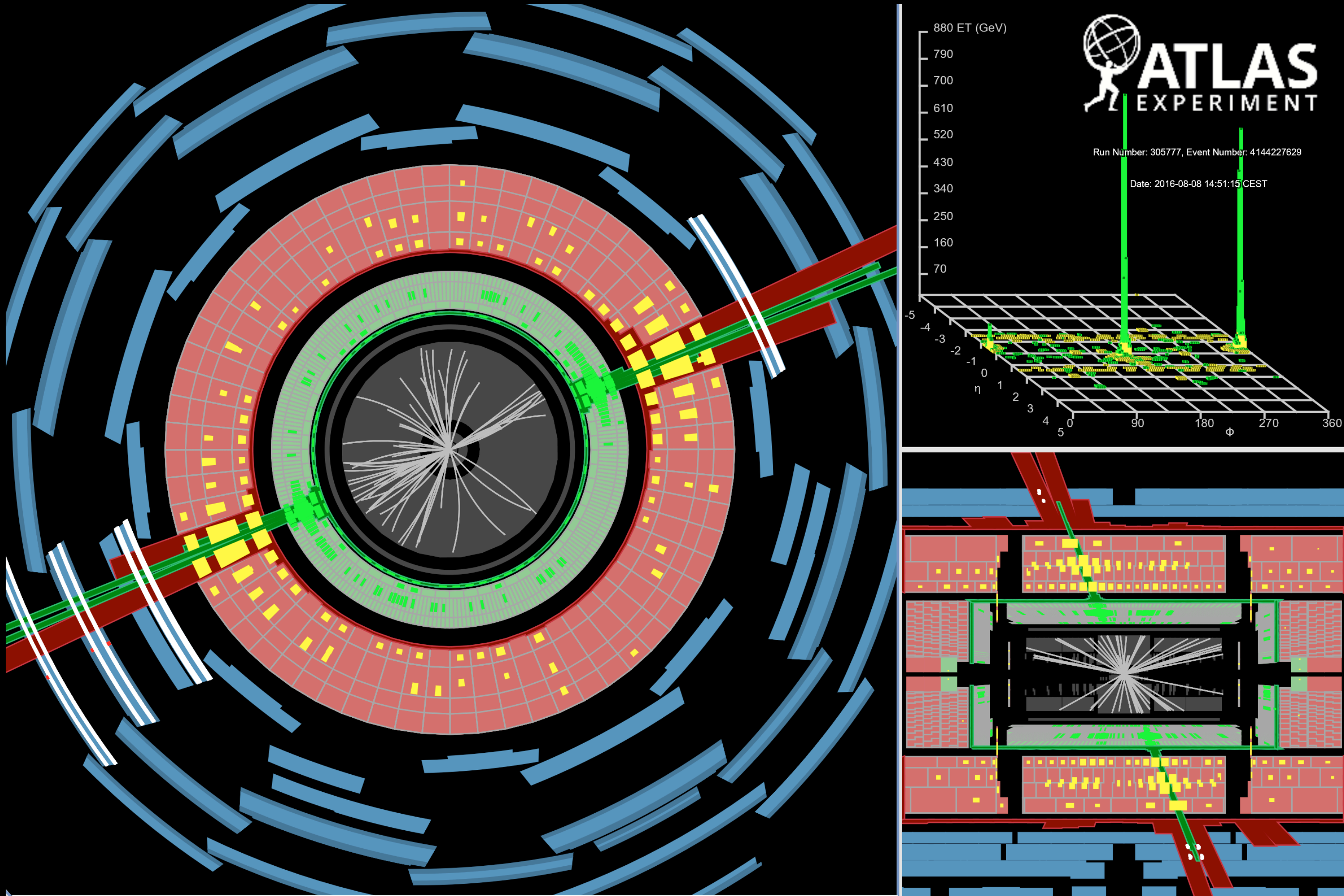
Delivered: 156 fb^{-1}

Recorded: 147 fb^{-1}
(Data taking efficiency 94.2%)

Good for Physics: 139 fb^{-1}
(Efficiency 94.6%, → high data quality)

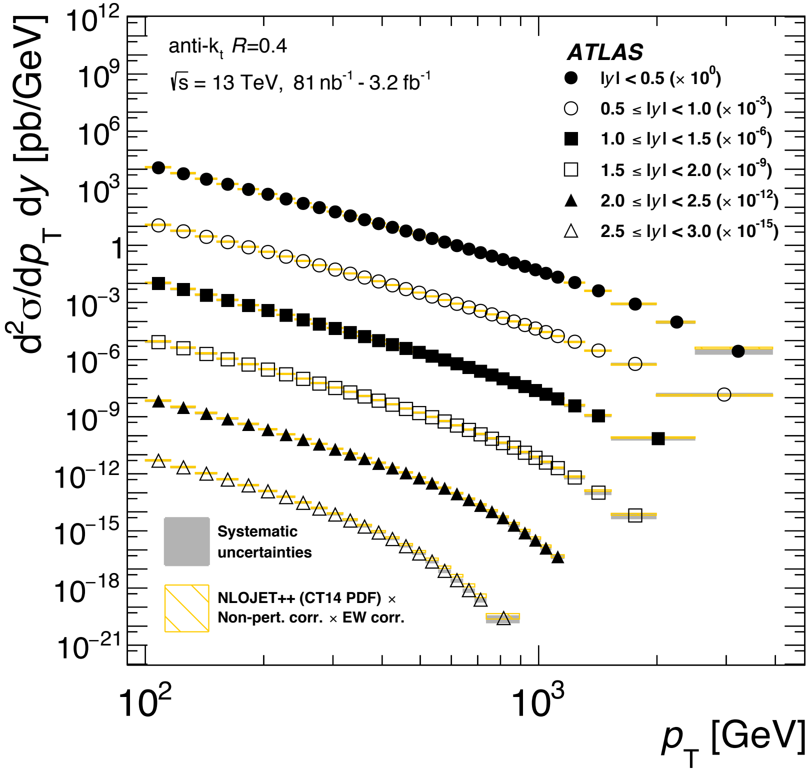
- Excellent performance as well of the ATLAS and CMS experiments
  High data-taking efficiency and high data quality
- Timely analyses → some results shown here use the complete Run-2 dataset

Summary of recent results from the LHC

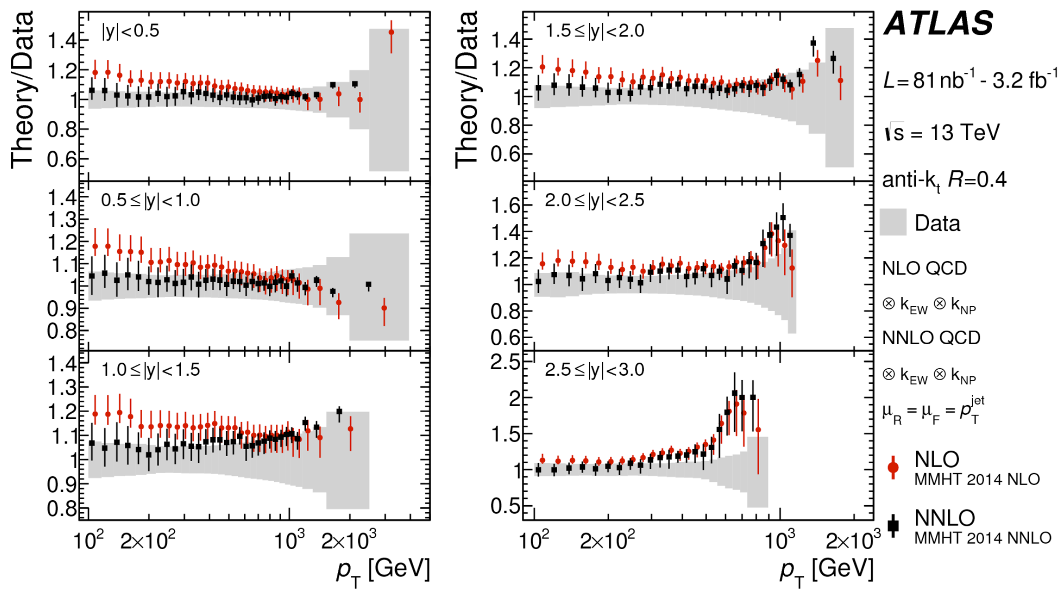


Di-jet event with the highest di-jet invariant mass of m_{jj} = 8.02 TeV recorded during 2016

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



JHEP 05 (2018) 195



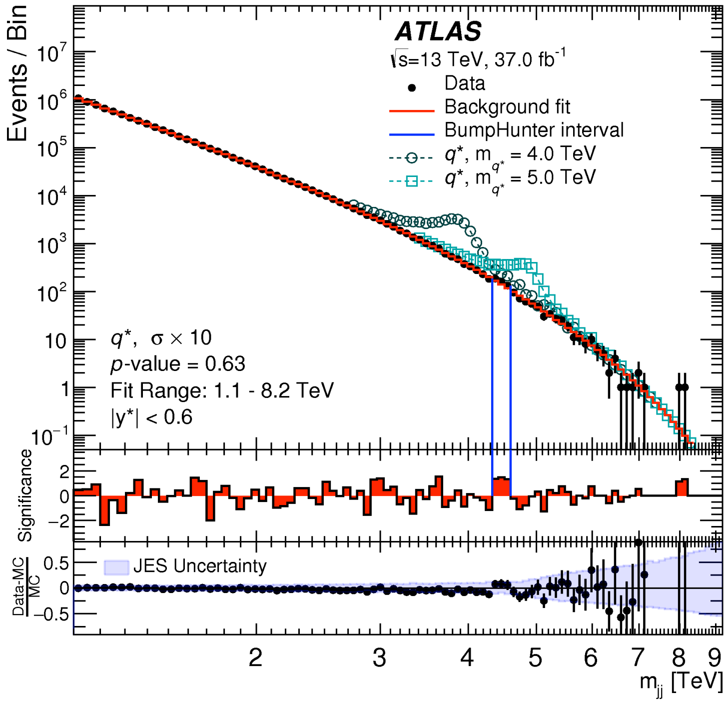
- Also at the highest energies explored so far, the data are well described by NLO perturbative QCD calculations (NLOJet++)

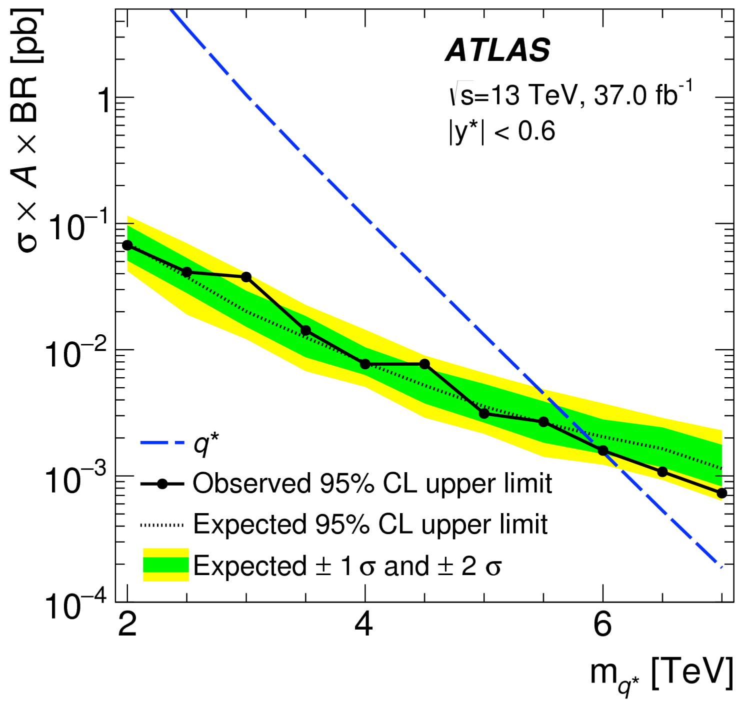
- Latest comparisons to NNLO predictions (NNLOJet) [J. Currie, N. Glover, T. Pieres, Phys. Rev. Lett. 118 (2017)]
→ improved agreement, however, scale dependent

Search for new phenomena in di-jet events

- Publication on 2015+2016 data: 37.0 fb^{-1} at $\sqrt{s}$ = 13 TeV

Phys. Rev. D96 (2017) 052004





- 95% CL exclusion limits:

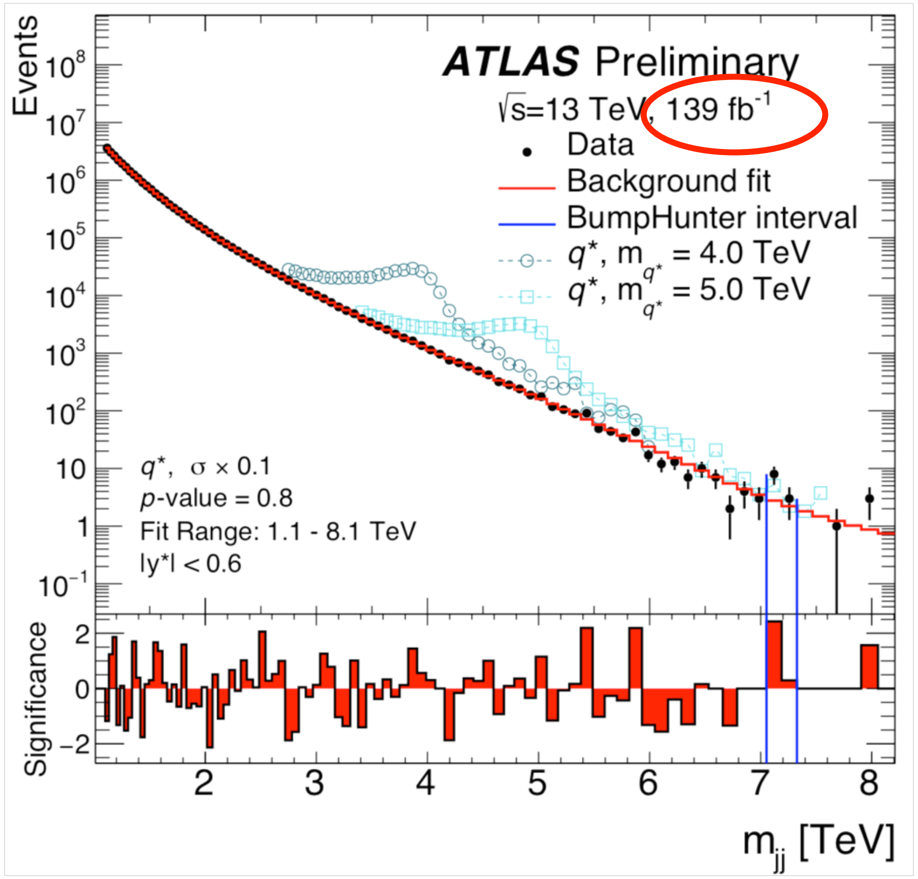
Excited quarks	m_{q^*} > 6.0 TeV	(5.8 TeV exp.)*
Add. gauge bosons:	$m_{W'}$ > 3.6 TeV	(3.7 TeV exp.)
Quantum Black Holes:	m_{BH} > 8.9 TeV	(8.9 TeV exp.)
Contact Interactions:	Λ > 13.1 TeV (η_{LL} = +1)	
	Λ > 21.8 TeV (η_{LL} = -1)	

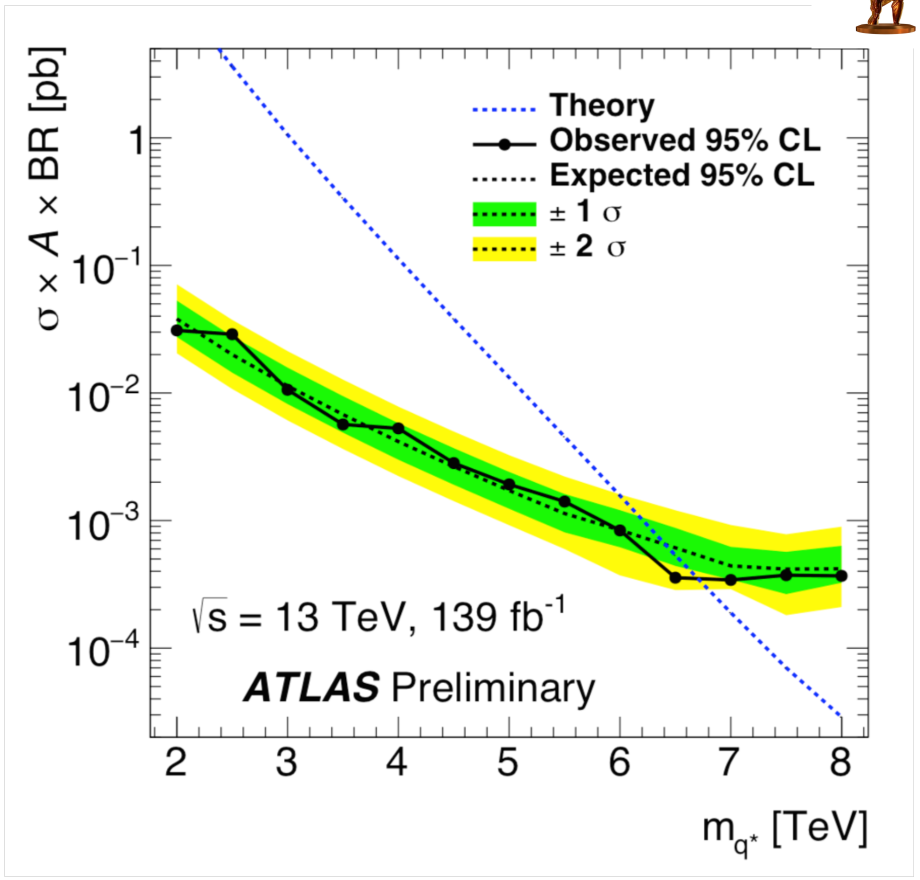
*pre-LHC limit on excited quarks from the Tevatron: 0.87 TeV

Search for new phenomena in di-jet events

- Prel. result based on complete Run-2 (2015-2018) dataset: 139 fb^{-1} at $\sqrt{s}$ = 13 TeV

ATLAS-CONF-2019-007



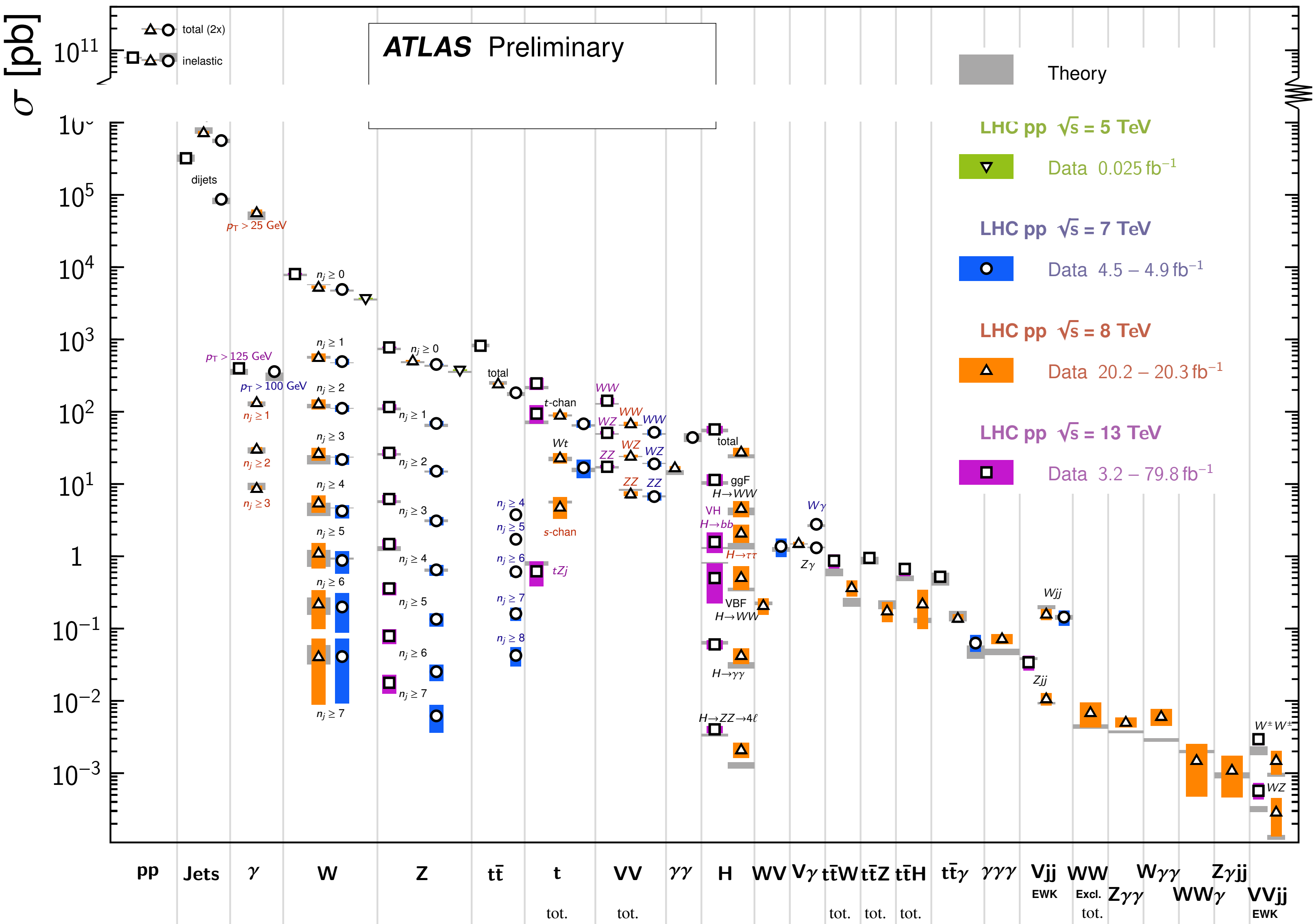


- 95% CL exclusion limits: Excited quarks

36 fb^{-1}	m_{q^*} > 6.0 TeV	(5.8 TeV exp.)
139 fb^{-1}	m_{q^*} > 6.7 TeV	(6.4 TeV exp.)

Standard Model Production Cross Section Measurements

Status: March 2019



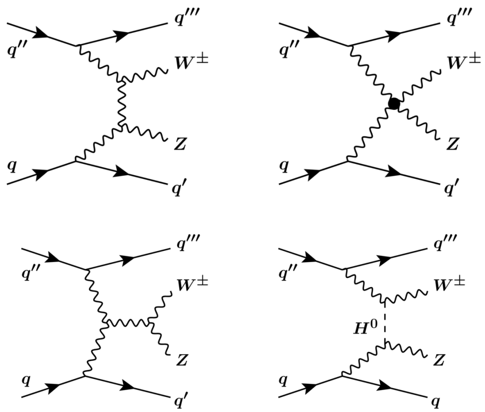
Huge progress also on the theoretical side: (N)NLO QCD / el.weak corrections

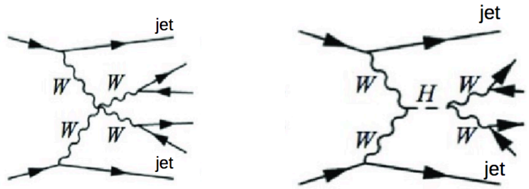
LHC for theorists: “Long and Hard Calculations”

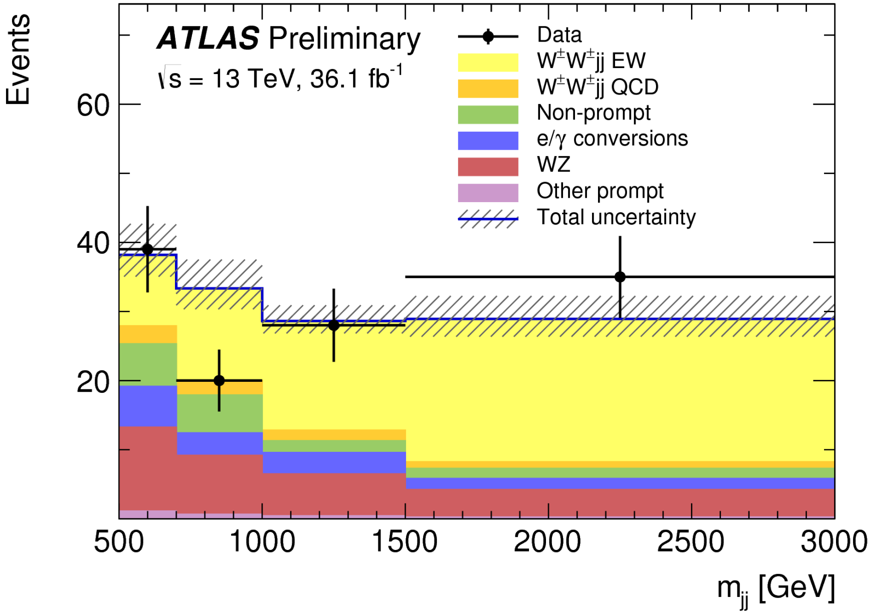
Vector boson scattering

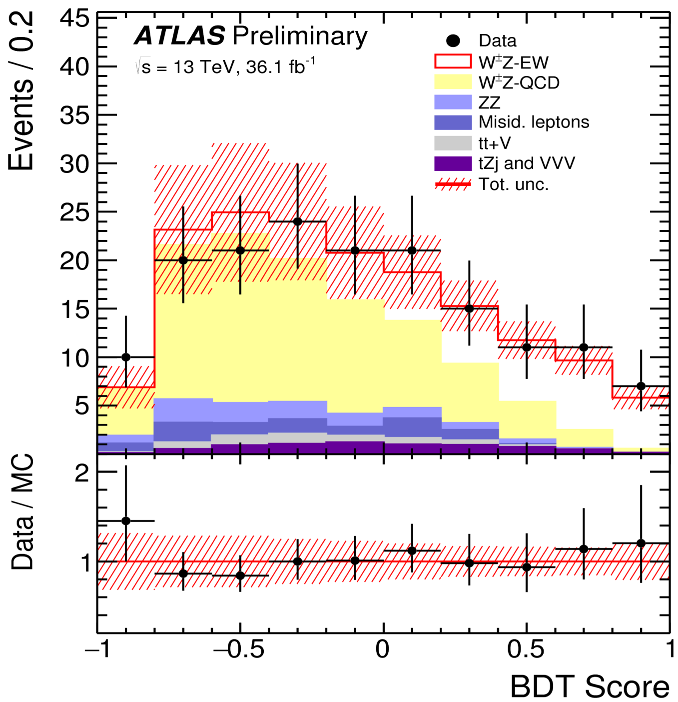
EW same-charge WW+jj 6.9σ (4.6σ) obs (exp)
ATLAS-CONF-2018-030

EW WZ+jj production 5.6σ (3.3σ) obs (exp)
ATLAS-CONF-2018-033

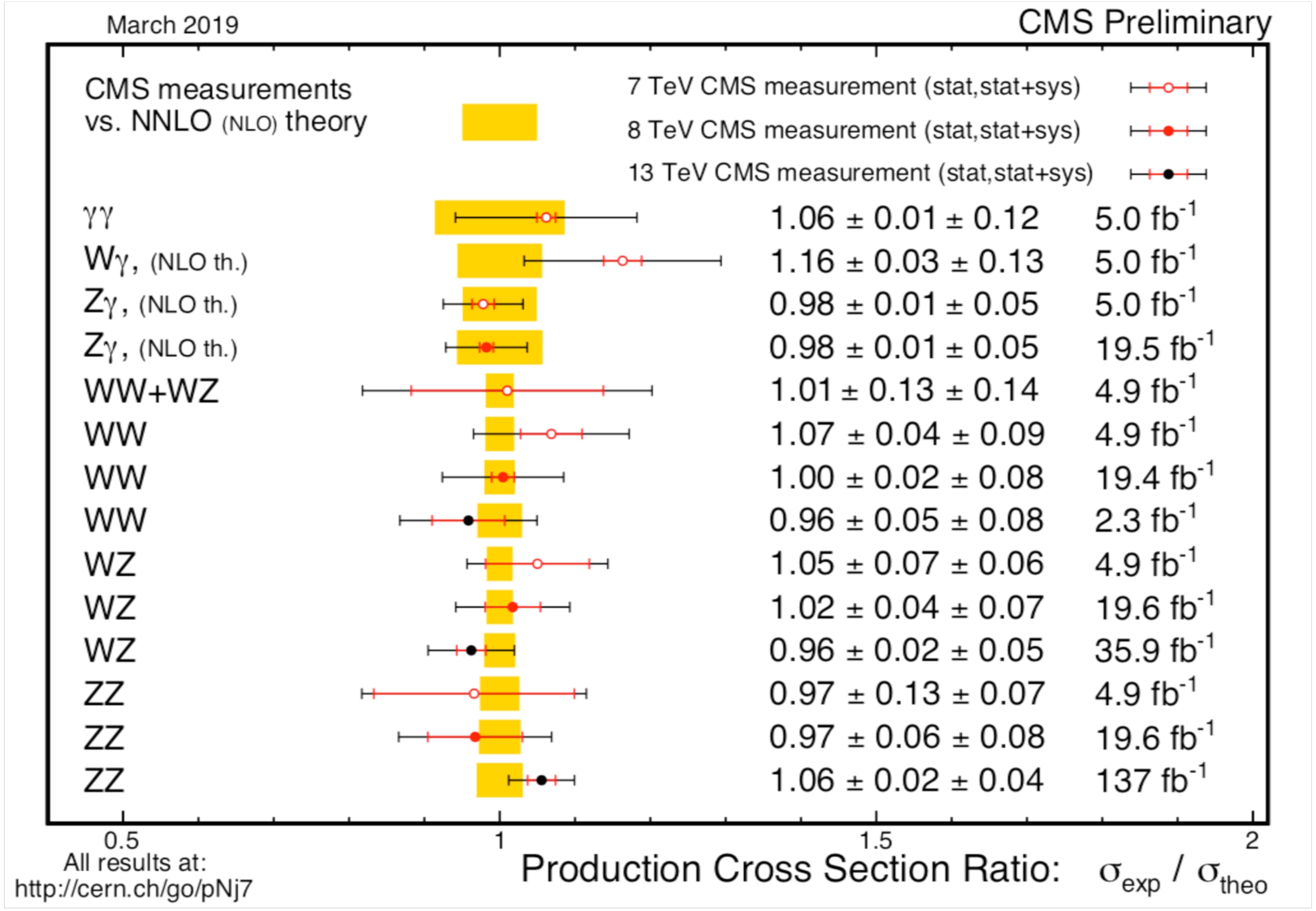






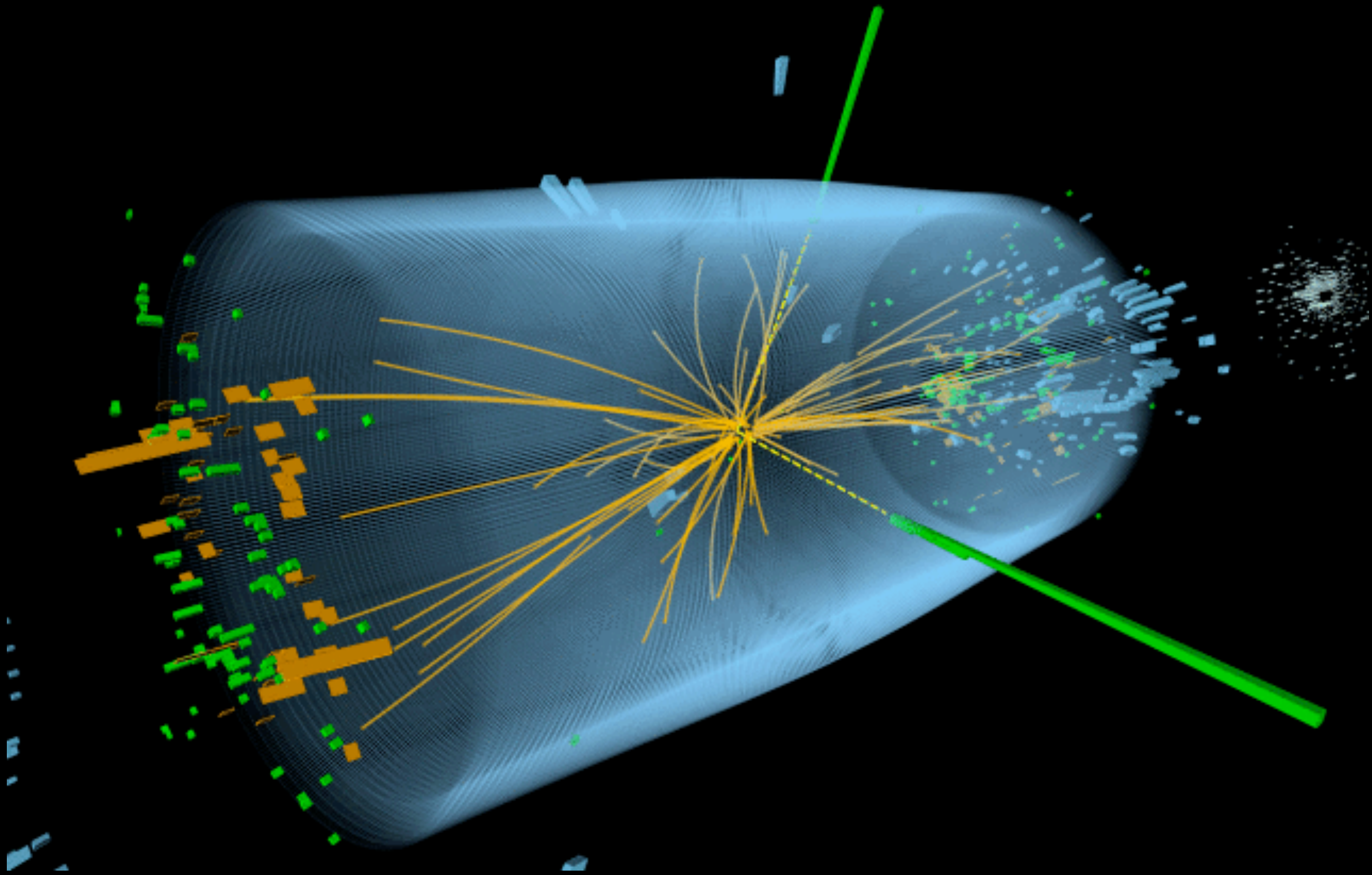


Cross-sections for di-boson production



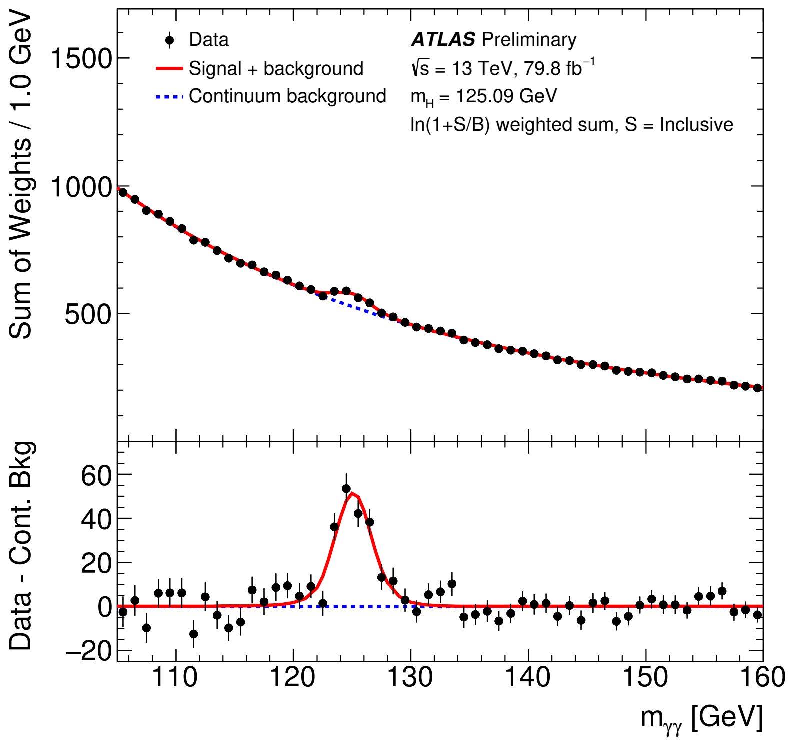
Di-boson cross-section ratios: exp. measurement / theoretical predictions (SM)
(Theory predictions have been updated to the latest NNLO calculations where available)

Status of Higgs Boson measurements

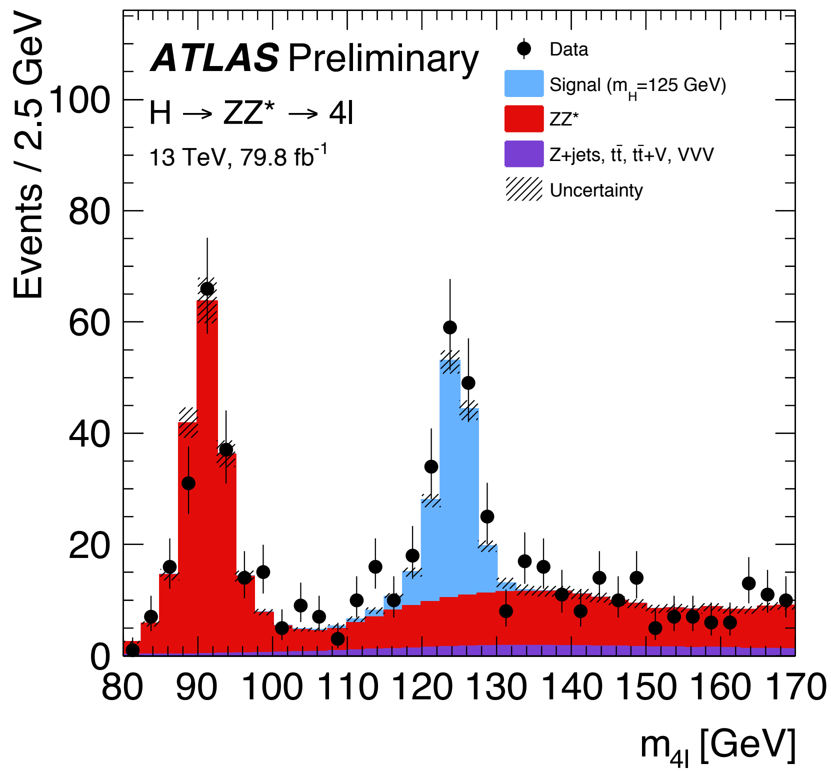


Results of Searches for H → γγ and H → ZZ* → 4ℓ at 13 TeV

ATLAS-CONF-2018-028



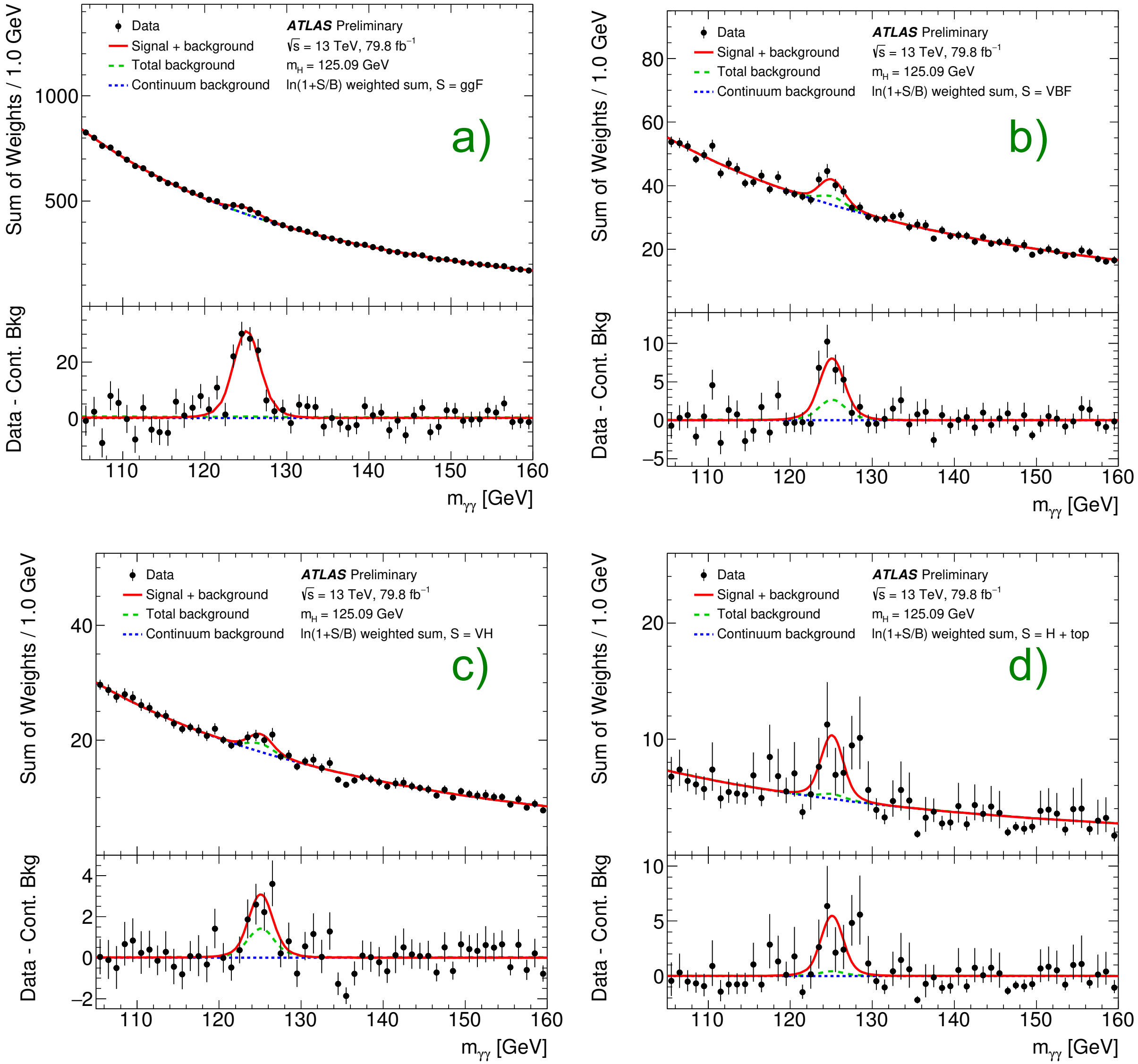
ATLAS-CONF-2018-018



- Impressive signals in these high-resolution bosonic decay channels
  (Data collected form 2015 to 2017 in Run 2 at 13 TeV)
- Observation with a significance of > 5σ in each channel

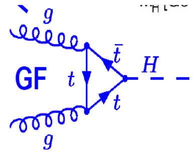
H → γγ signals for various categories

ATLAS-CONF-2018-028



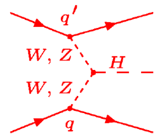
a) untagged categories

(expected to be dominated by gluon fusion)



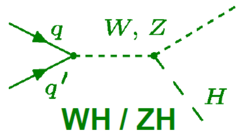
b) VBF categories

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



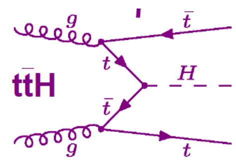
c) VH categories

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



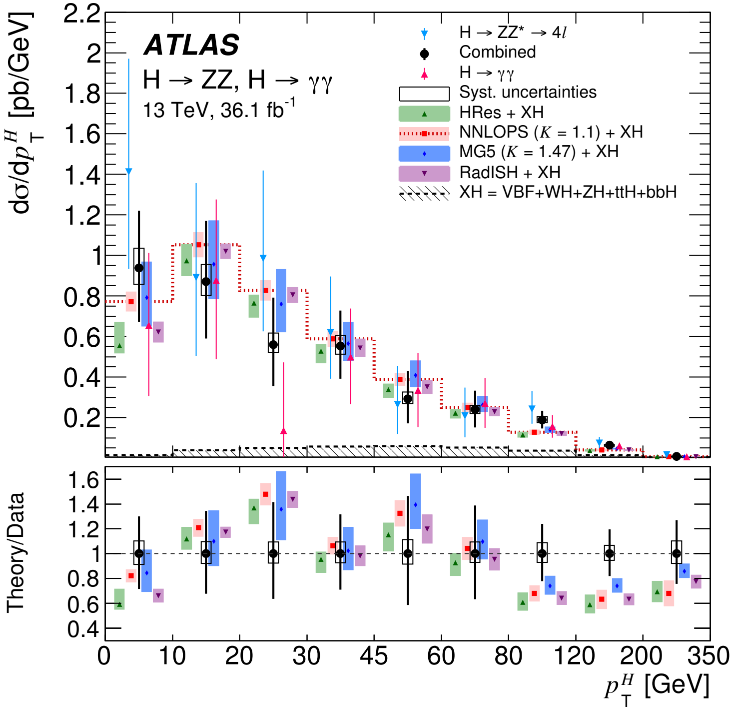
d) ttH categories

(lepton, jets, b-jet(s))

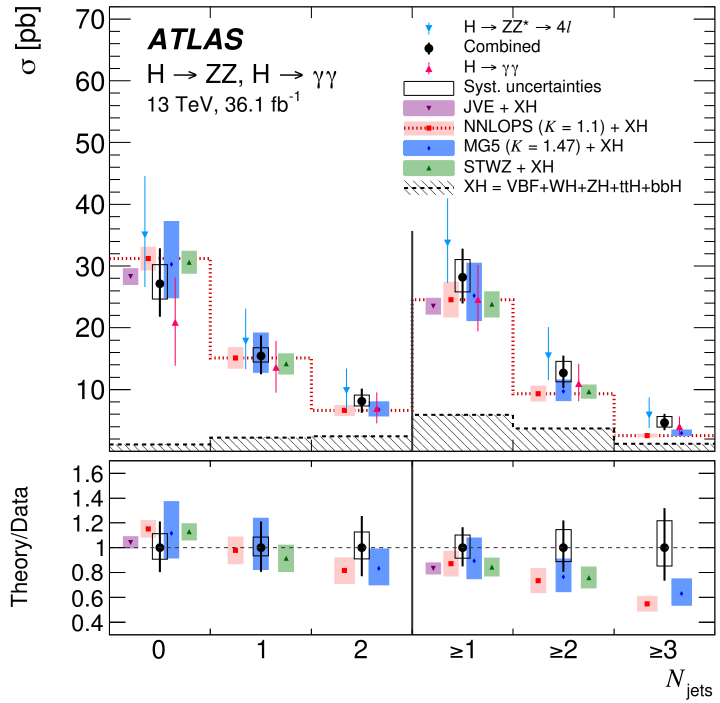


Differential cross-section measurements

Phys. Lett. B786 (2018) 114



Phys. Lett. B786 (2018) 114

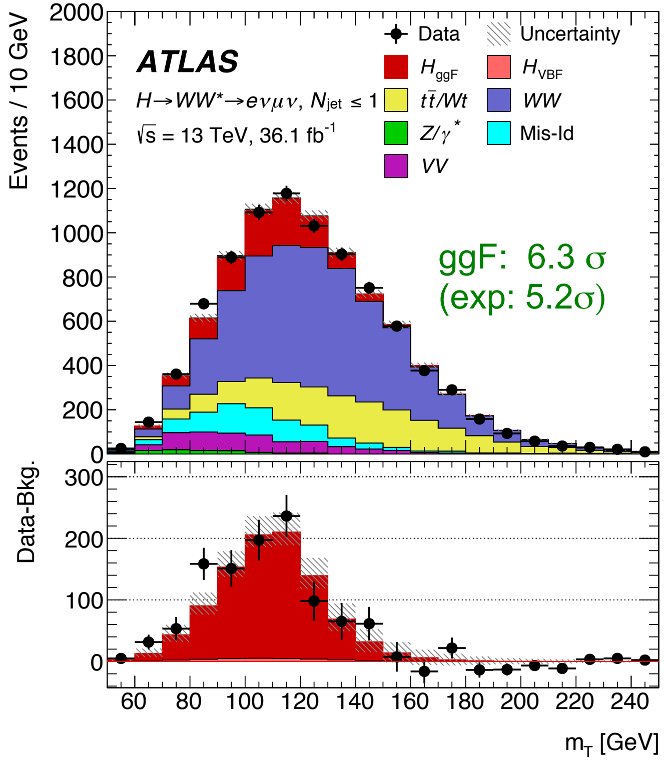


- Data are well described by theoretical calculations (within large uncertainties)
- Such measurements will become important ingredients for future measurements of Higgs boson parameters (Effective Field Theories)

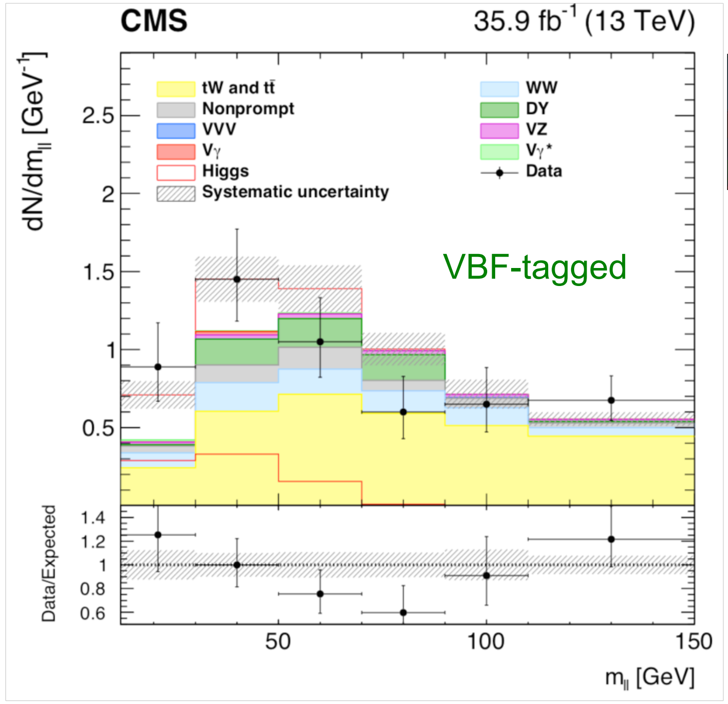
H → WW* → ℓν ℓν signal

- 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 $m_{\ell\ell}$, $\theta_{\ell\ell}$)

Phys. Lett. B789 (2019) 508



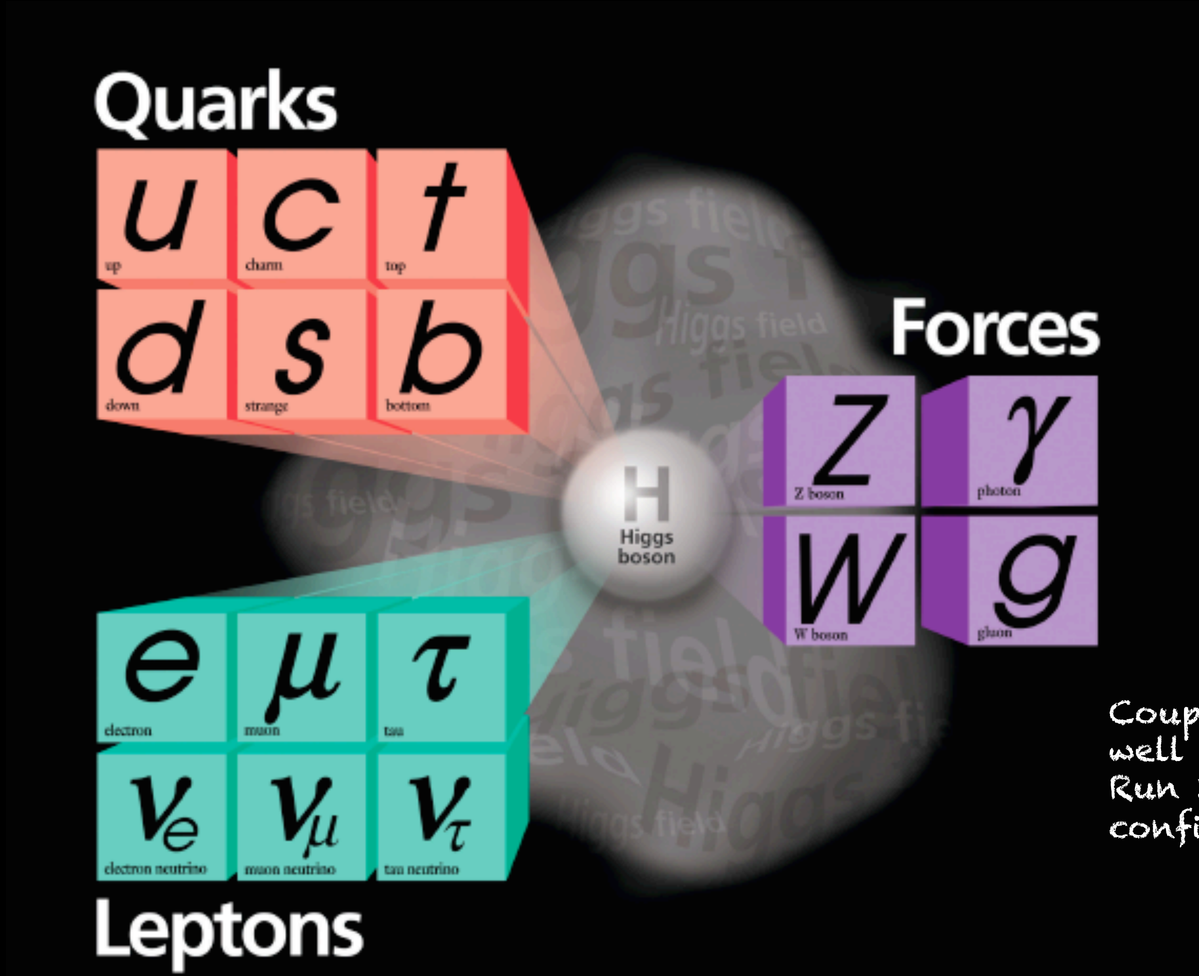
Phys. Lett. B791 (2019) 96



- 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?

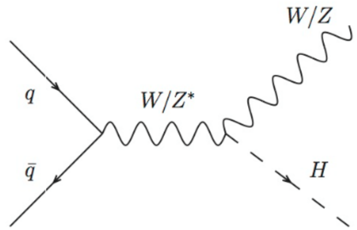


Couplings to bosons well established in Run 1 and nicely confirmed in Run 2

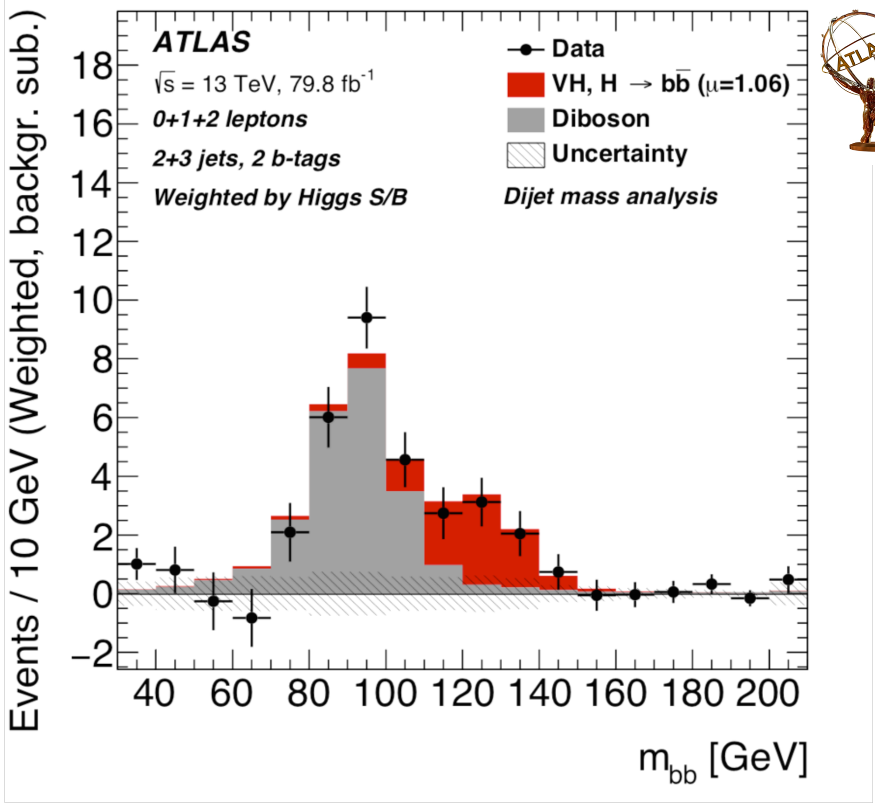
Search for H → ττ and H → bb decays, and ttH production

Observation of H → bb decays

- H→bb mode dominates Higgs decays (BR~58%)
- Most sensitive channel exploits VH, H→bb (V=W/Z)



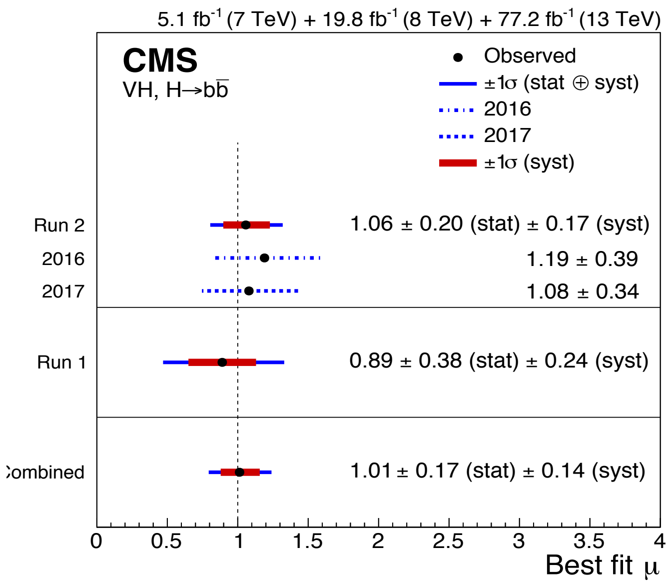
Phys. Lett. B786 (2018) 59



- Combination of Z and W final states characterised by lepton multiplicity:

(2-lepton (Z→ℓℓ), 1-lepton (W→ℓν), and
0-lepton (Z→νν))

Phys. Rev. Lett. 121 (2018) 121801



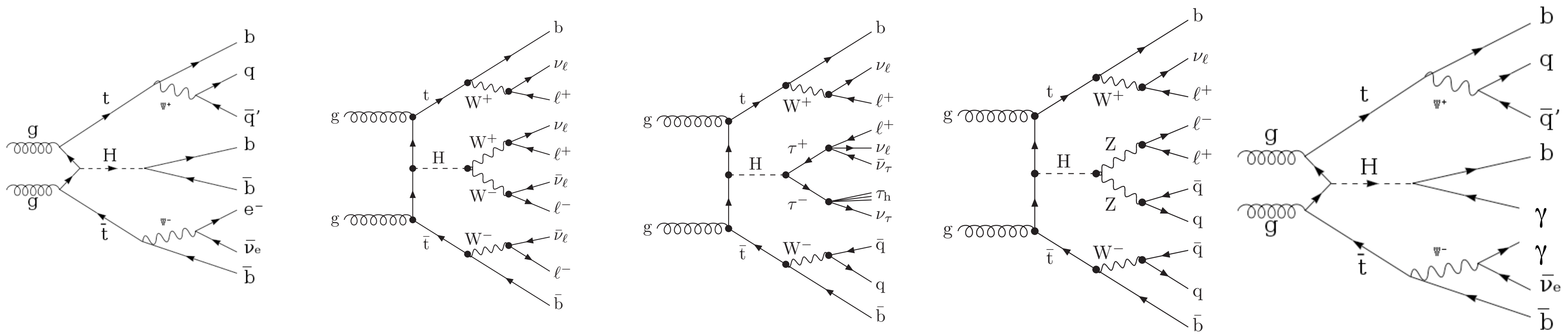
$\mu = \sigma_{meas} / \sigma_{SM}$

Published on the same day
(24th Aug 2018)

Combination with ATLAS Run-1 results
→ **5.4σ observed (5.5σ expected)**

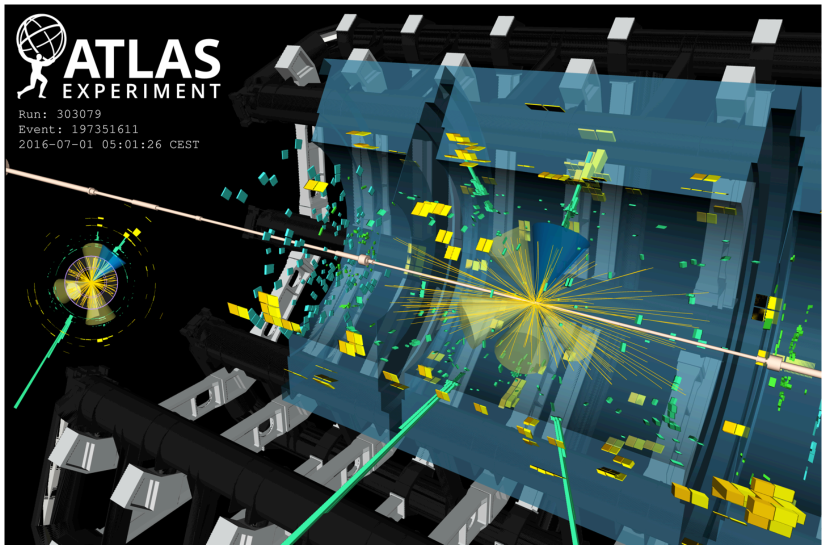
Search for ttH Production

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



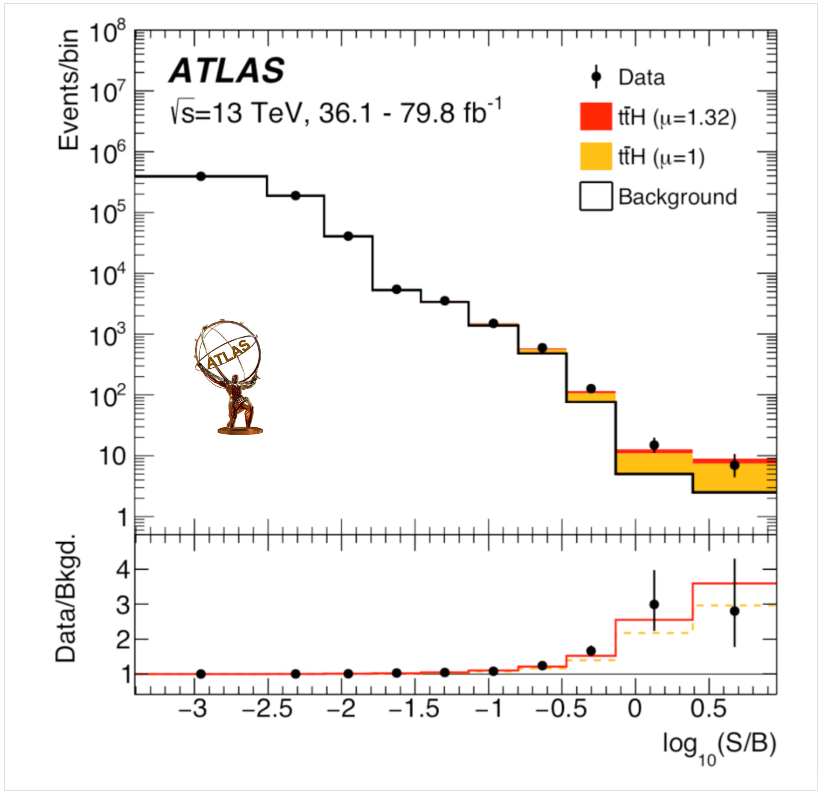
H → bb   H → WW*   H → τ τ   H → ZZ   H → γ γ

multi-lepton channels (ML)

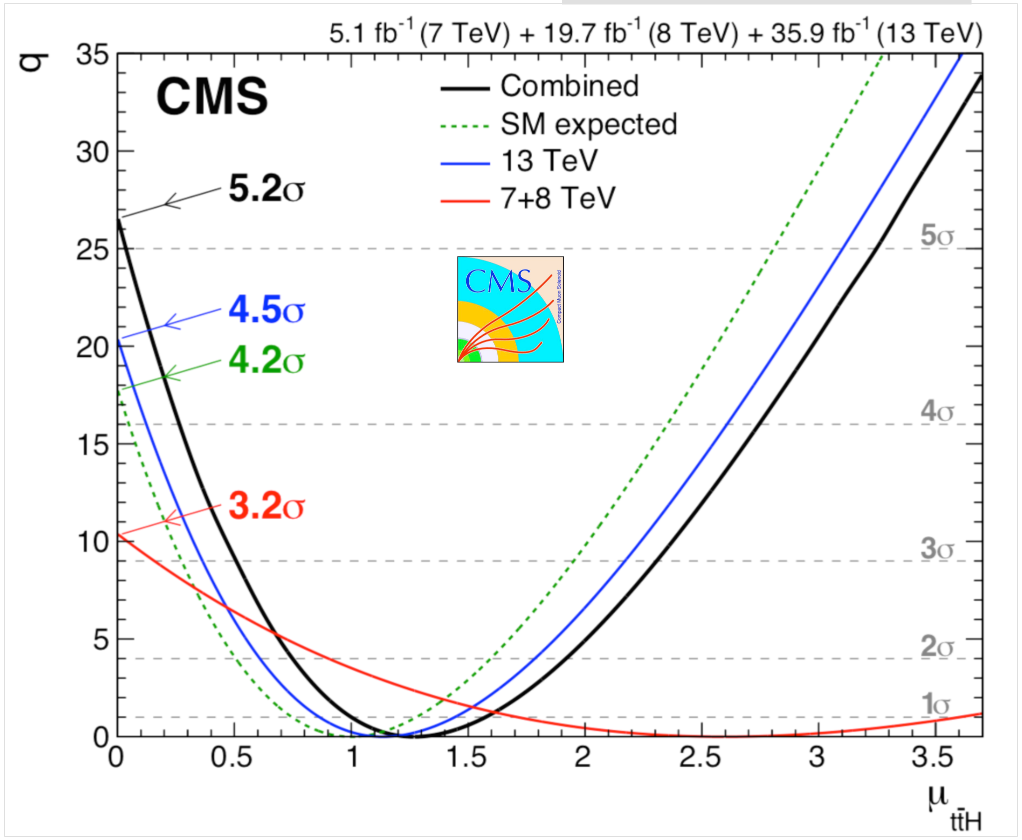


Observation of ttH production

Phys. Lett. B784 (2018) 173



Phys. Rev. Lett. 120 (2018) 231801



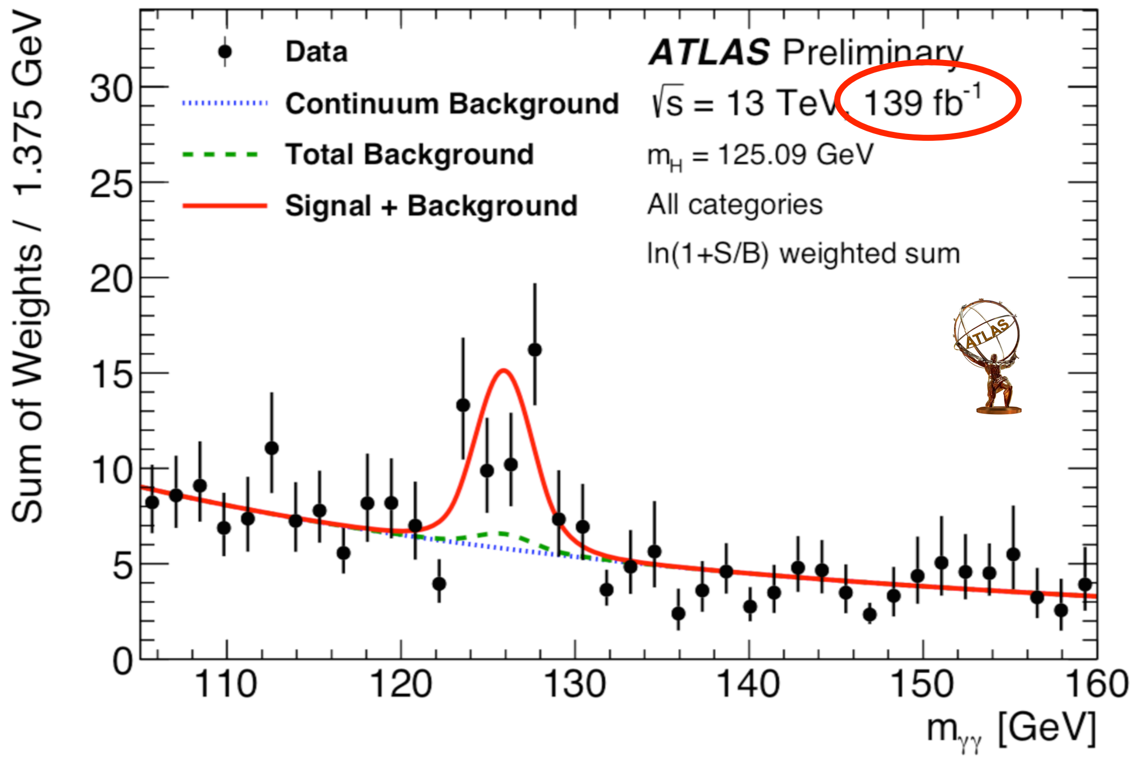
- **Combination of all channels** leads to observation of ttH production in both experiments (2018)
- Measured production and decay rates consistent with SM expectation

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

μ = 1.26

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

Including the 2018 data for H→ $\gamma\gamma$



Higgs signal appears in ttH production with decays into $\gamma\gamma$

- Observed significance: 4.9σ (4.2σ exp.)
- Signal strength consistent with SM expectation: $\mu_{t\bar{t}H} = 1.38\,^{+0.33}_{-0.31}\,(\text{stat.})\,^{+0.13}_{-0.11}\,(\text{exp.})\,^{+0.22}_{-0.14}\,(\text{theo.})$

Combined ATLAS & CMS Higgs analysis — Run-1 legacy

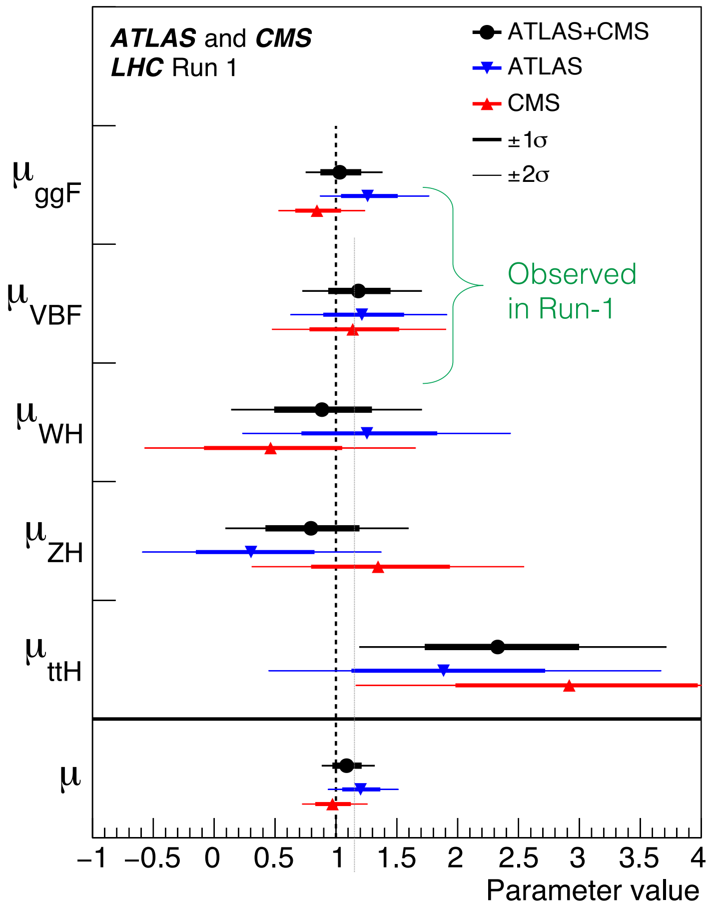
ATLAS & CMS Run-1 combination of Higgs boson coupling measurements

JHEP 08 (2016) 045

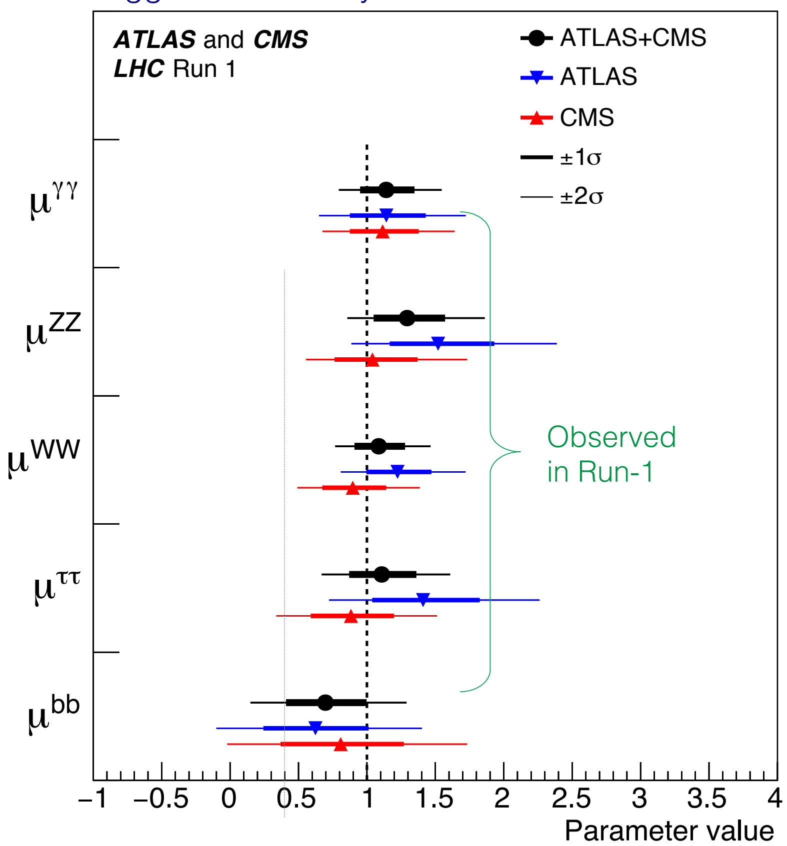
Agreement among experiments

Overall signal strength (Run 1): **μ = 1.09 ± 0.11 (ATLAS + CMS)**

Higgs boson production



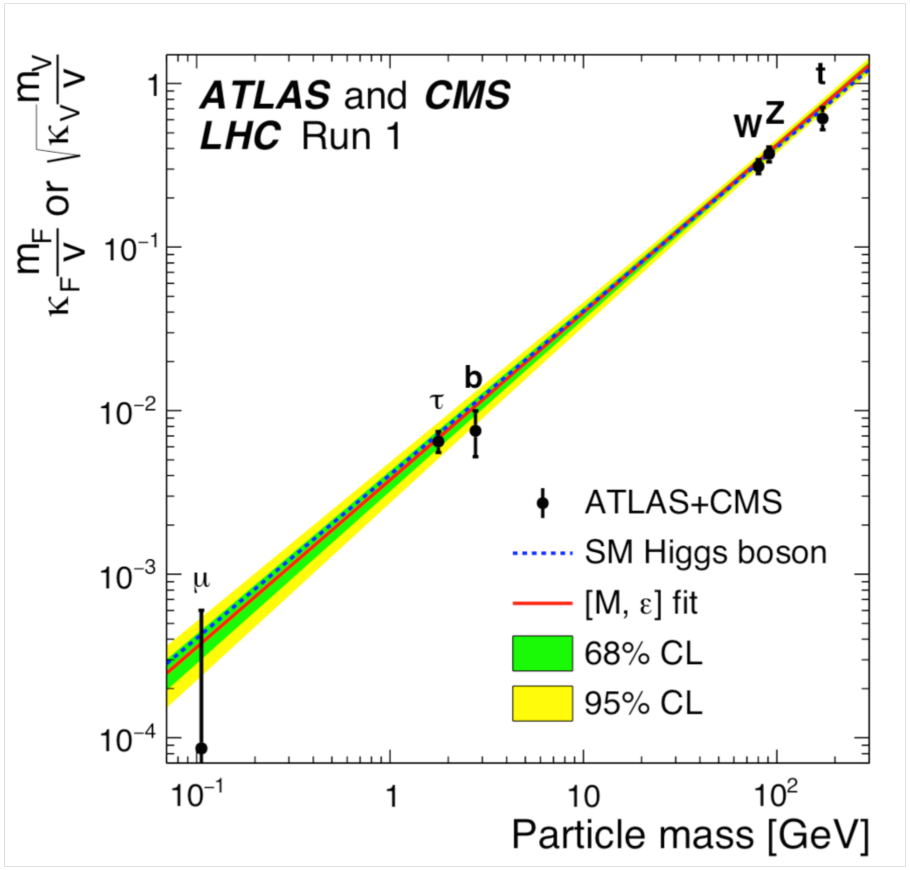
Higgs boson decays

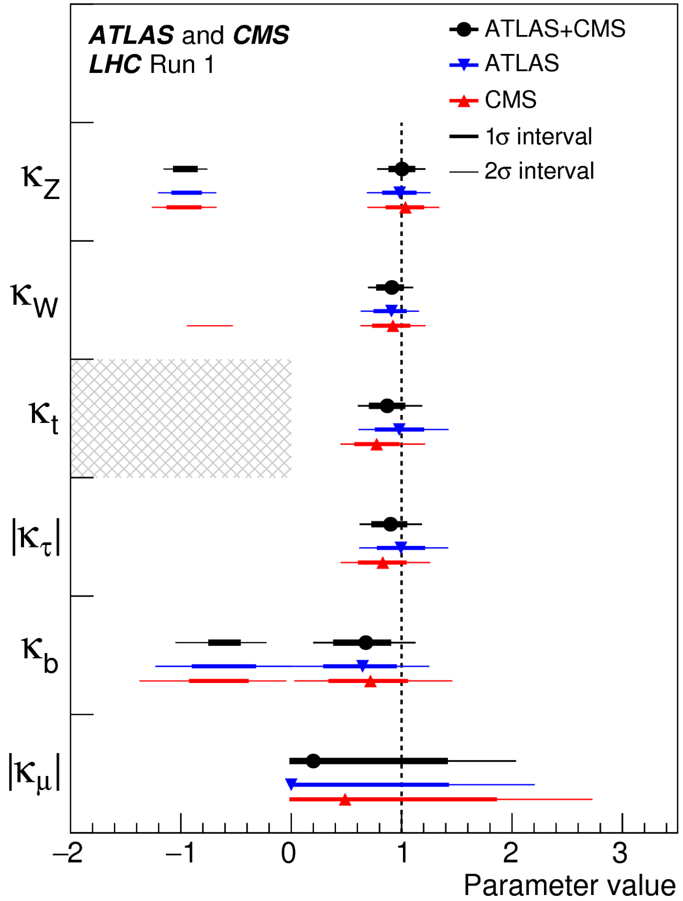


Note that the least model-dependent observables at the LHC are ratios of couplings

Higgs boson properties

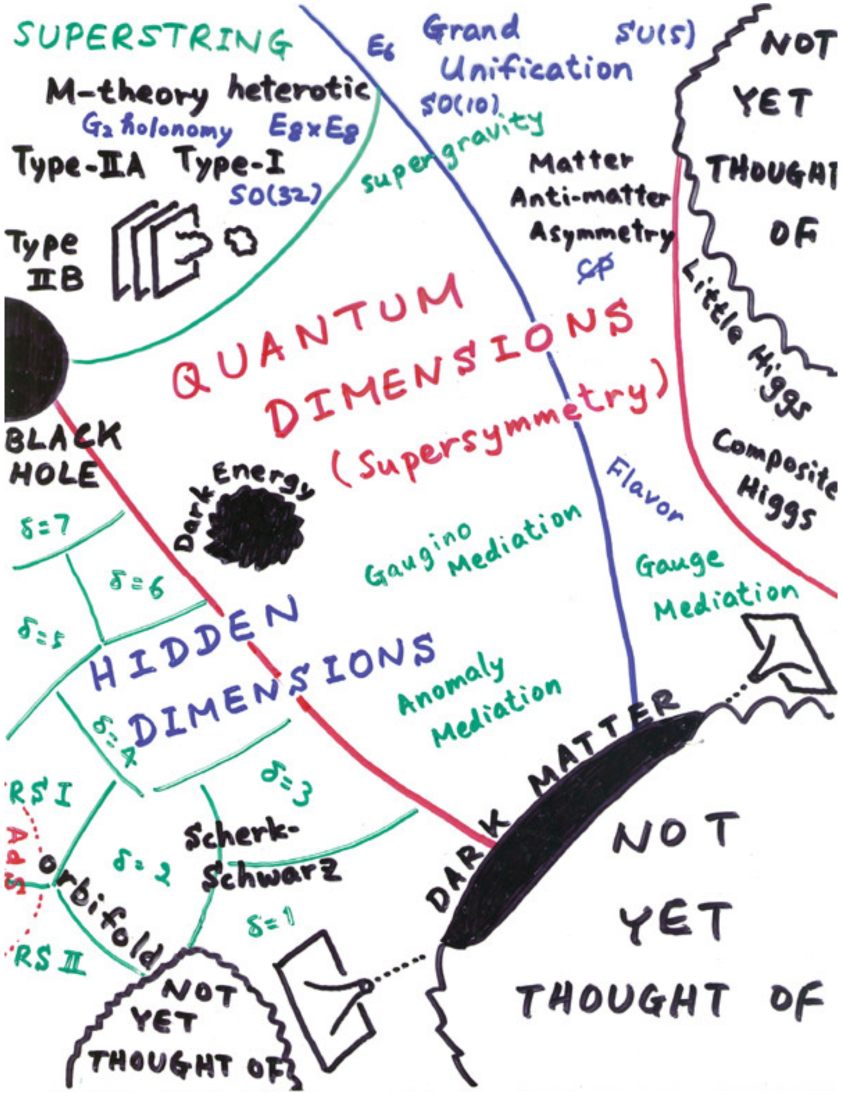
Coupling modifieres
SM: $\kappa = 1$





So far, all measured properties are in agreement with the expectations from the Standard Model, however, precision has to be increased
→ access to rare decay modes, higher precision, Higgs boson self-coupling

Search for Physics beyond the Standard Model



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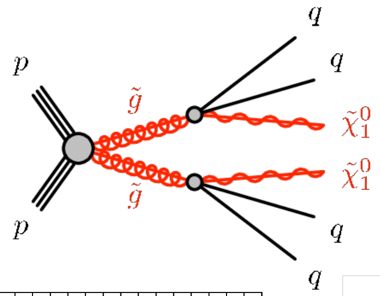
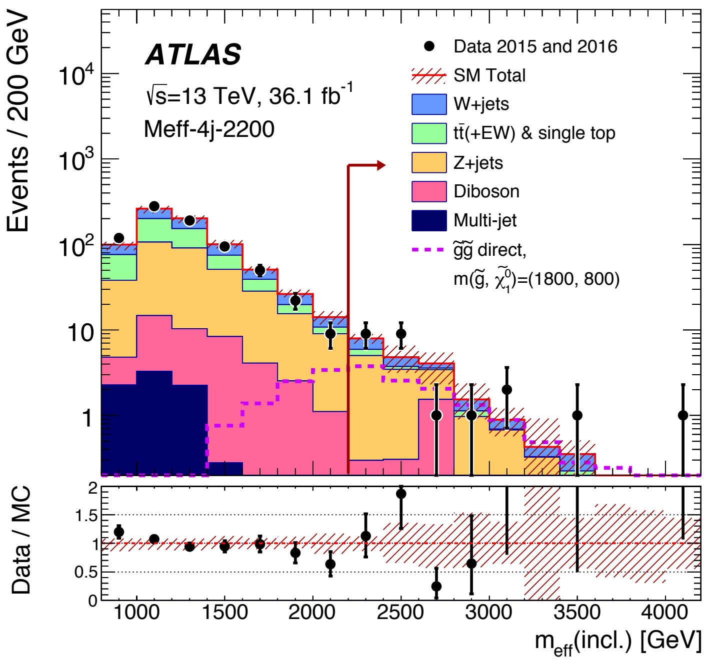
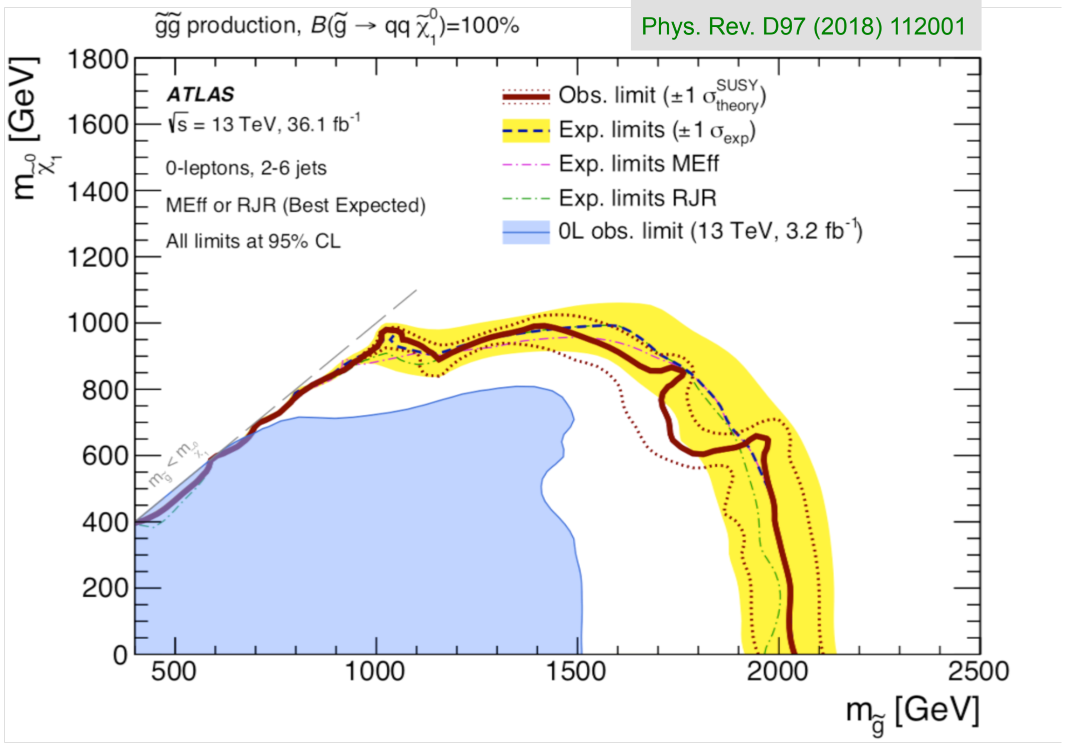
Search for Supersymmetry

-Results are already partially based on the complete Run-2 dataset-





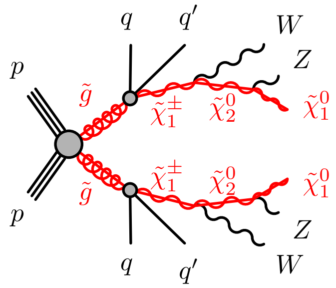
m_{eff} = scalar sum of momenta of all final state objects



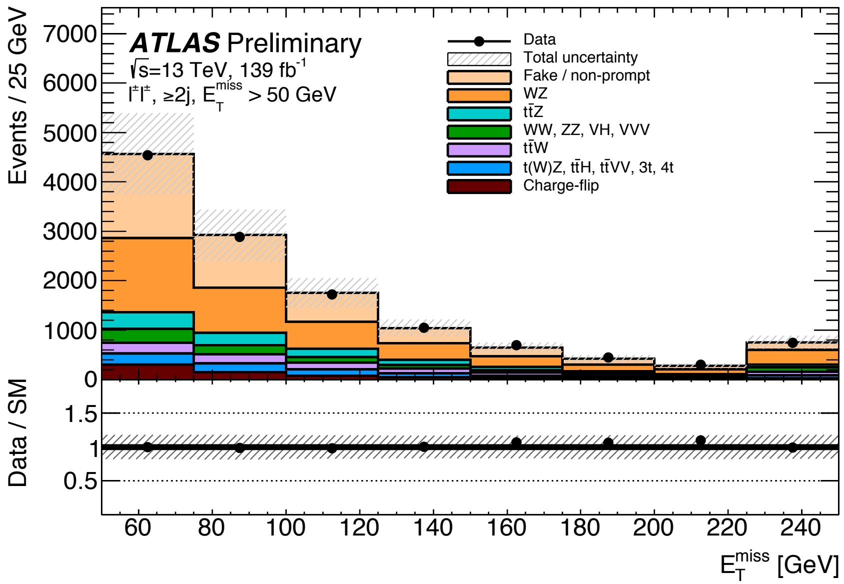
Gluino mass limit beyond 2 TeV, $m(\chi^0) = 0$

Data well described by expectations from SM processes

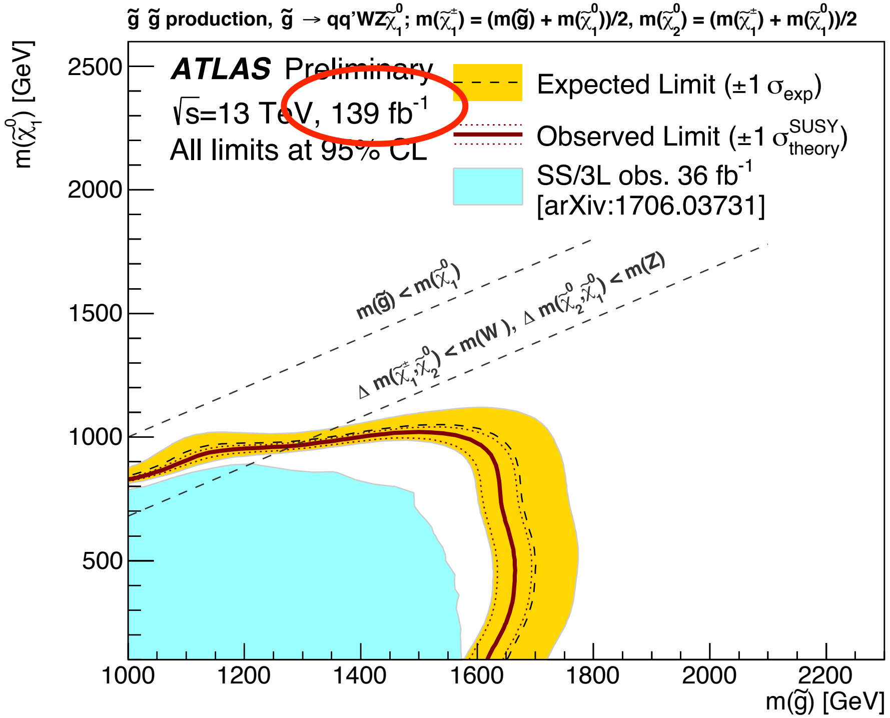
Gluino searches in final states with leptons



ATLAS-CONF-2019-015



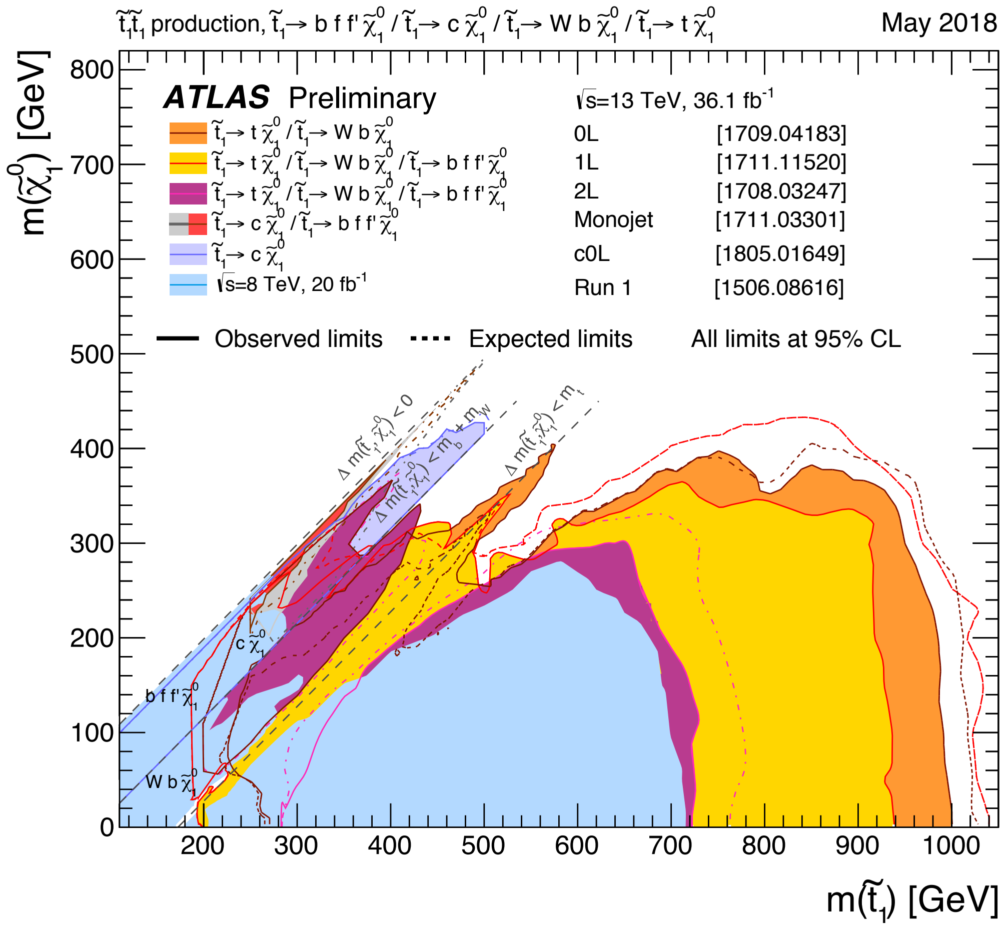
(E_T^{miss} in events with 2 same-sign leptons,+ 2 jets)



Data well described by expectations from SM processes

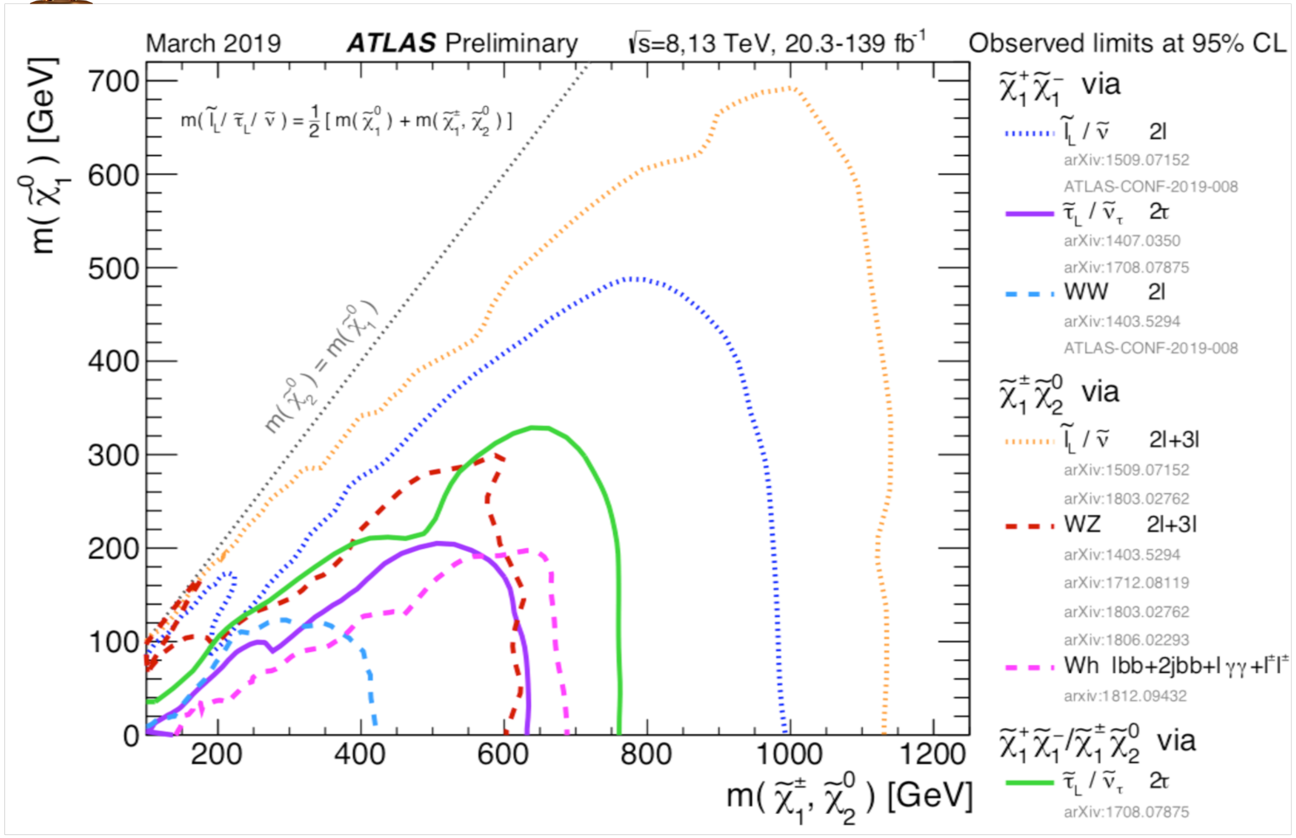
Gluino mass limit beyond 1.6 TeV, $m(\chi^0) = 0$

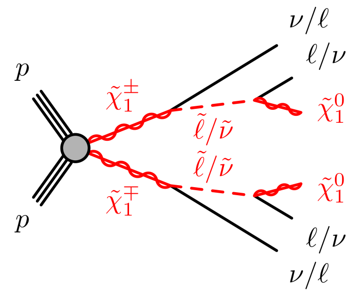
Results on dedicated searches for stop quarks

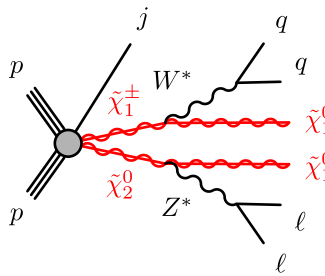


- Weaker mass limits for partners of the top quark (lower production rate, tt background)
- However, significant progress, with mass limits ~1 TeV (light neutralinos), including coverage for complex decay scenarios

Results on electroweak SUSY production

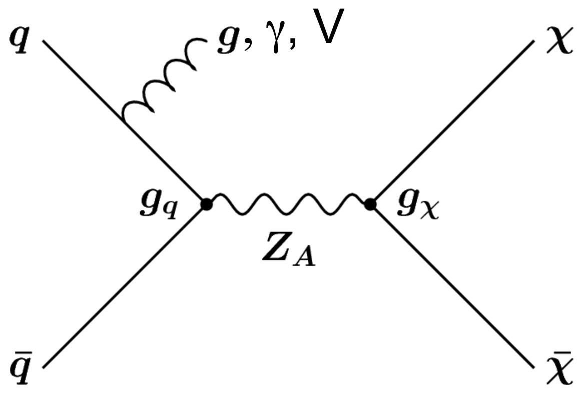






The 95% CL exclusion limits on $\chi_1^+\chi_1^-$ and $\chi_1^\pm\chi_2^0$ production with either SM-boson-mediated or ℓ-mediated decays, as a function of the $\chi_1^\pm$, χ_2^0 and χ_1^0 masses. The production cross-section is for pure wino $\chi_1^+\chi_1^-$ and $\chi_1^\pm\chi_2^0$. Each individual exclusion contour represents a union of the excluded regions of one or more analyses.

Searches for Dark Matter particles (using signatures with large E_T^{miss})



- Mono-jet
- Mono-photon
- Mono-W or mono-Z
- Mono Higgs (H → bb)
- Mono-top

Example: mono-jet search, E_T^{miss} spectrum

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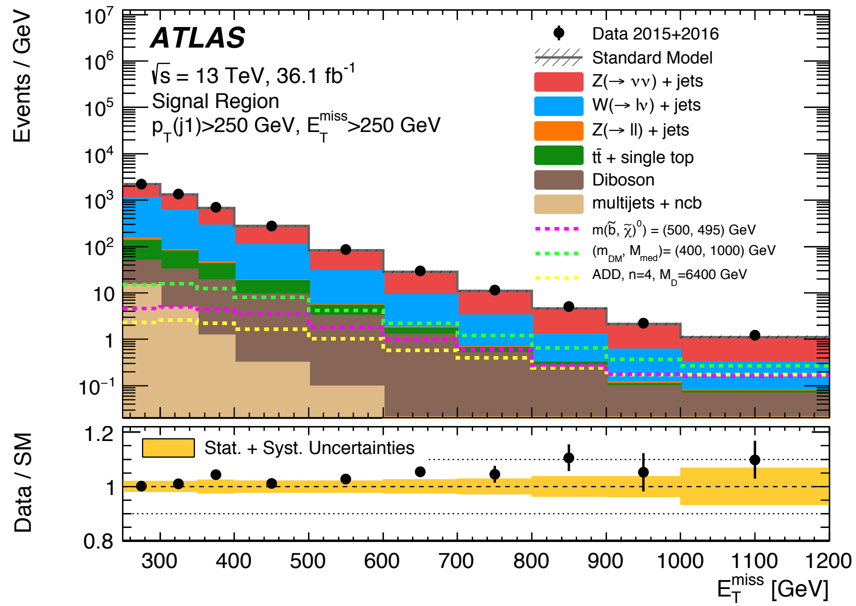
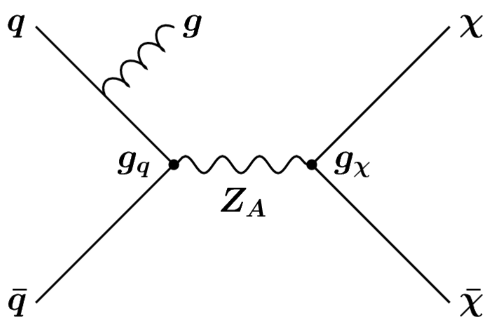
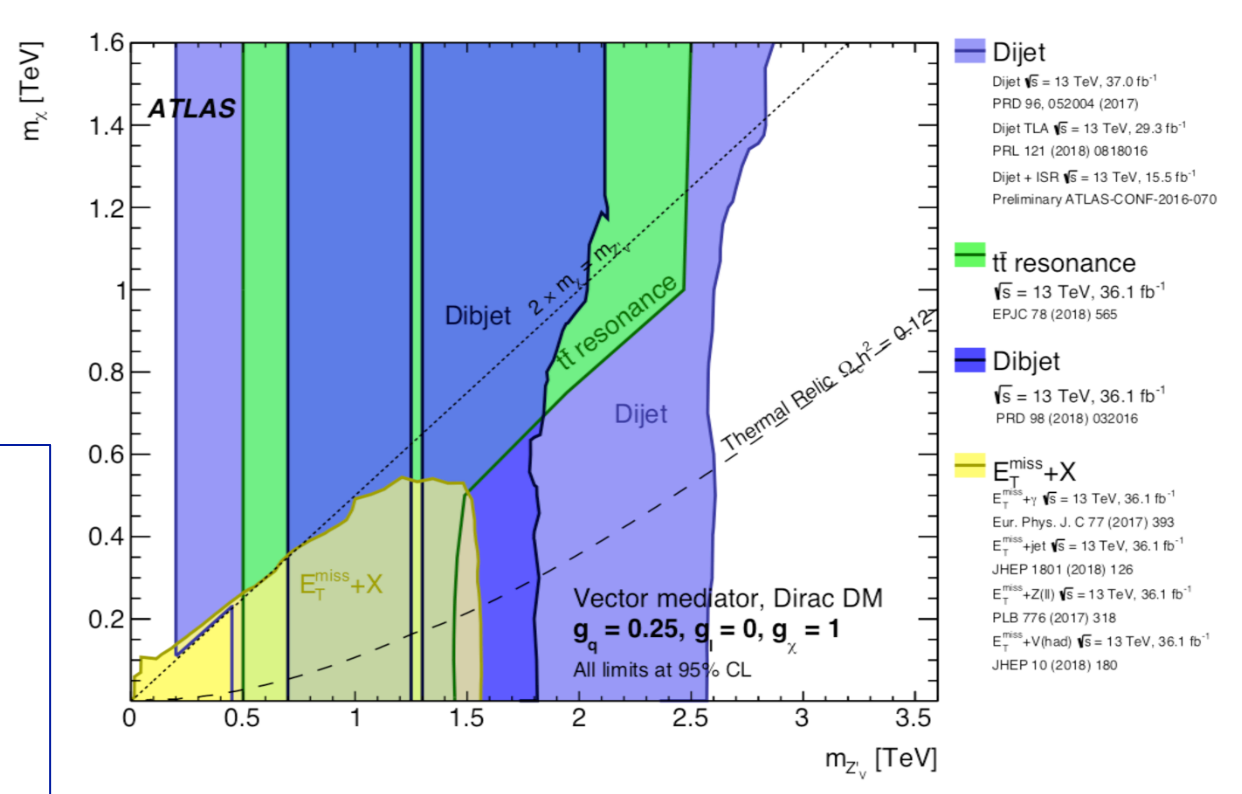


Data are in good agreement with the expectations from Standard Model processes

(applies to all mono-X searches)

Interpretation on searches for Dark Matter:





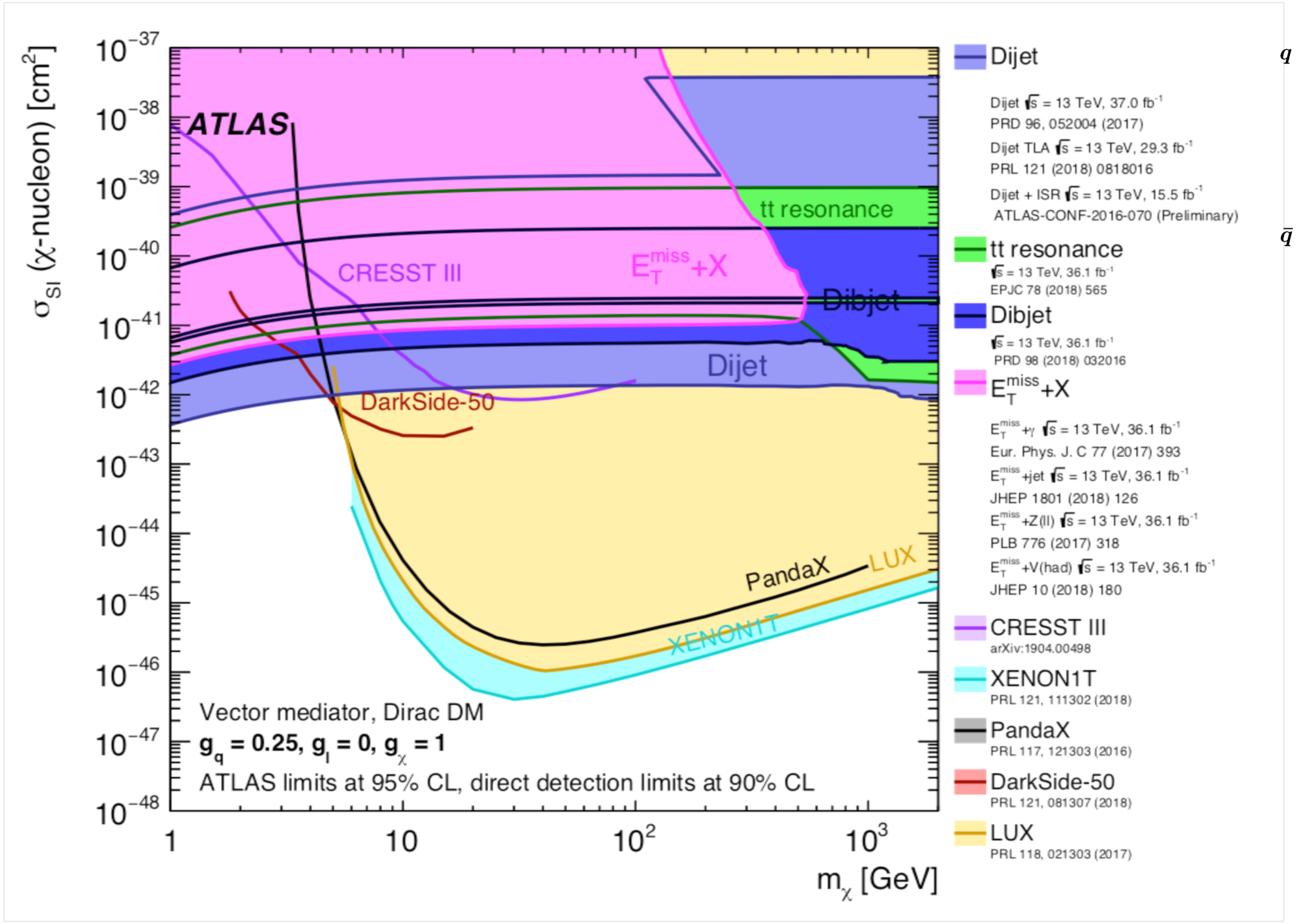
Model assumptions:

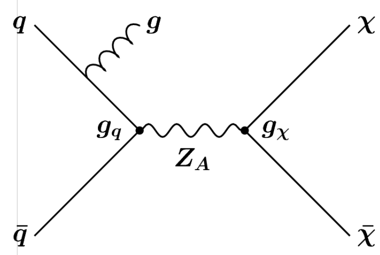
- neutral, spin-1 particle acts as mediator
- DM assumed to be Dirac fermion

- Five parameters:
  - Mass of mediator
  - Mass of DM particle
  - g_q: flavour-universal coupling of Z' boson to all quarks
  - g_l : coupling to all lepton-flavours
  - g_X: coupling to DM

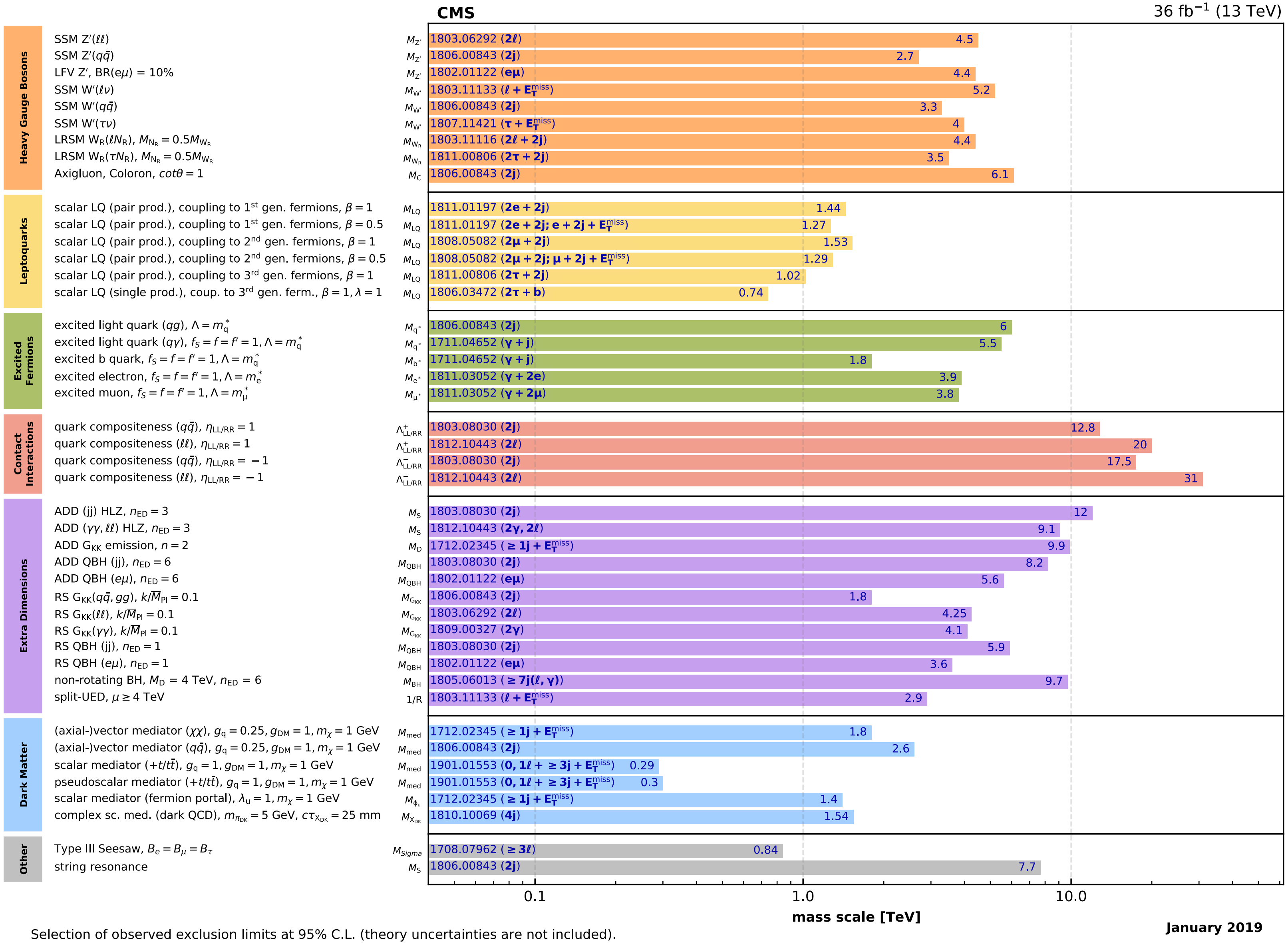
Sensitivity via searches for resonances and events with large E_T^{miss}

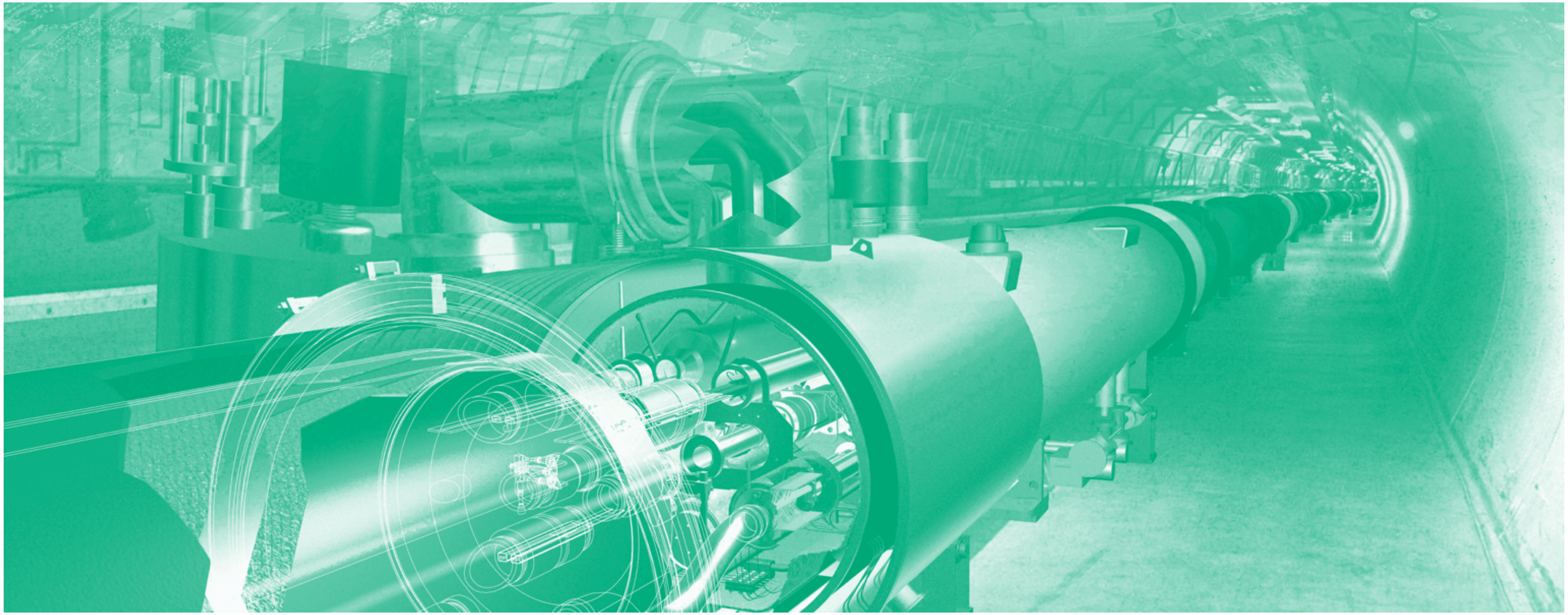
Interpretation on searches for Dark Matter:





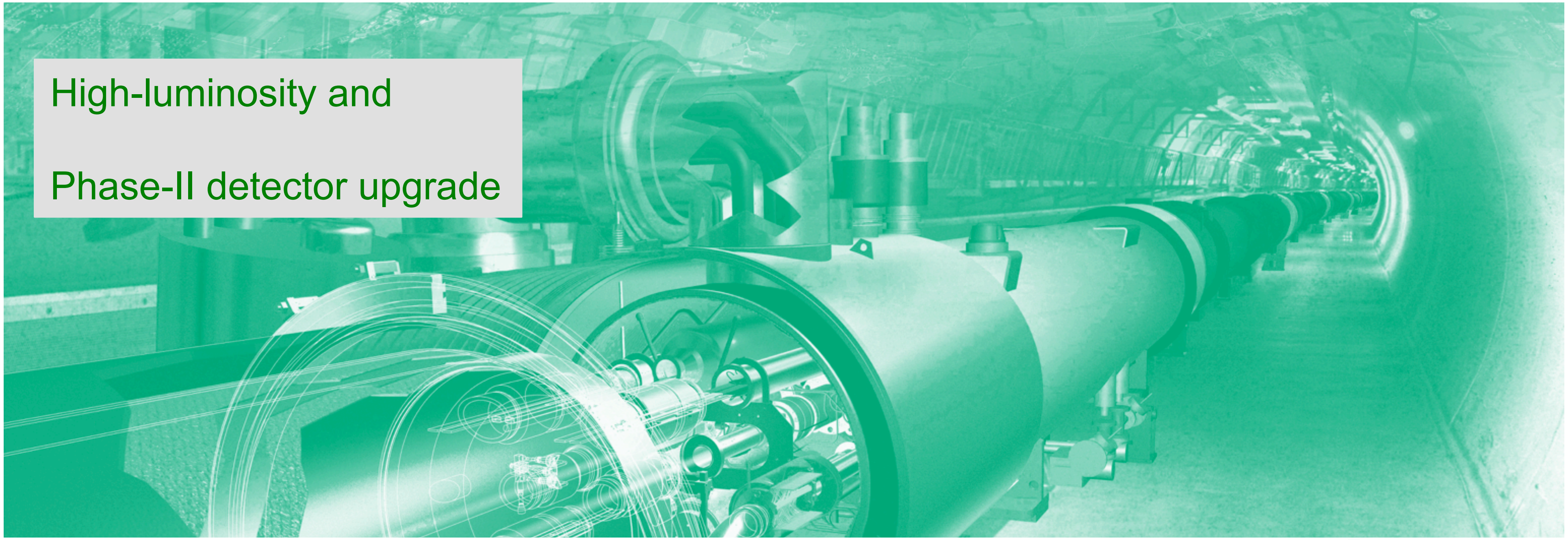
Summary of Results on Searches for other BSM physics



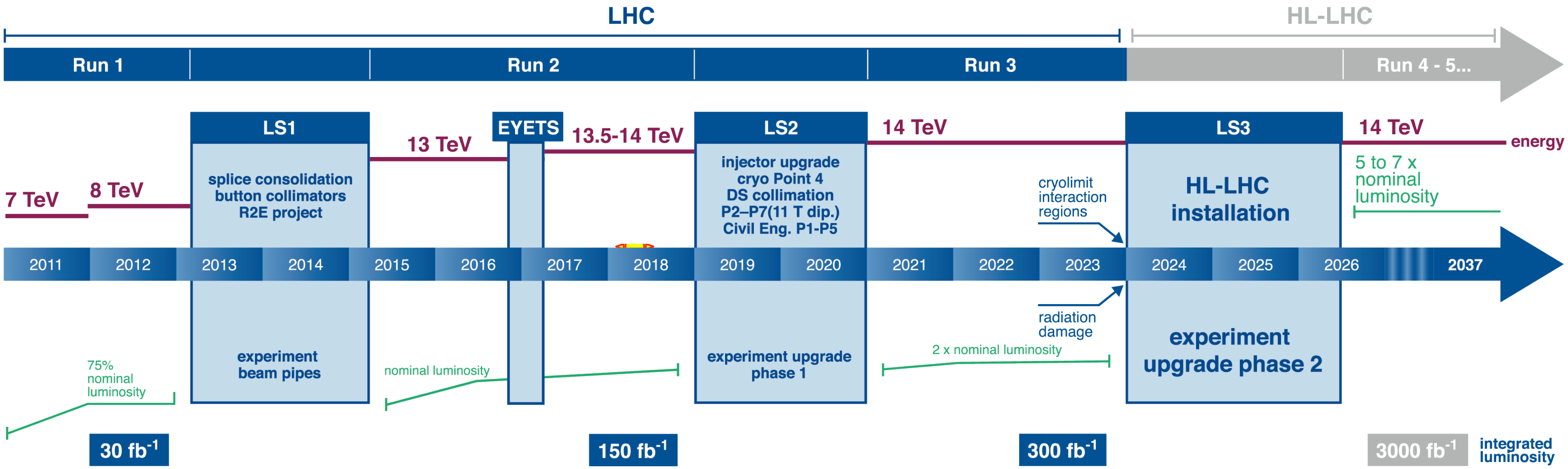


The next steps

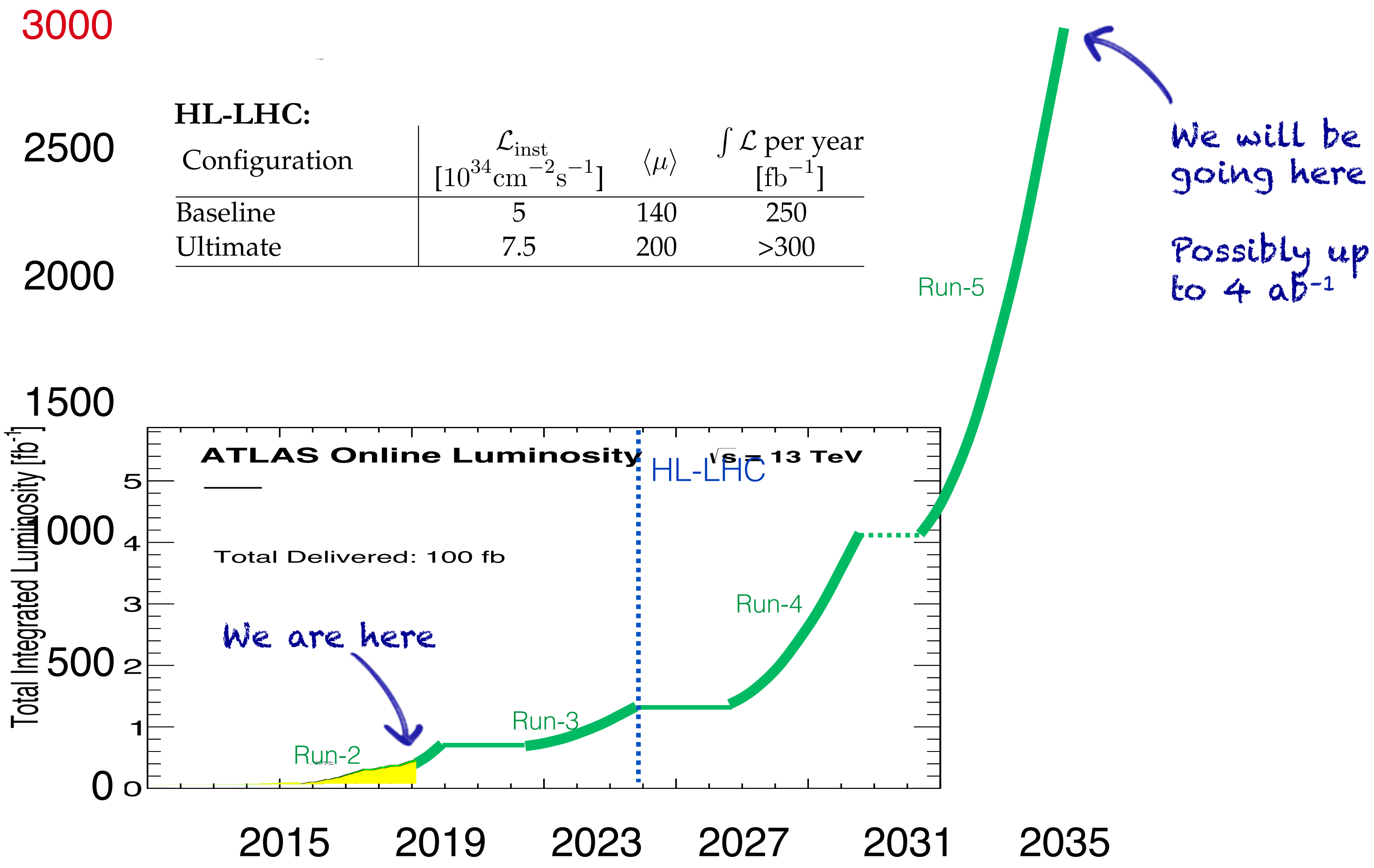
High-luminosity and Phase-II detector upgrade



LHC / HL-LHC Plan



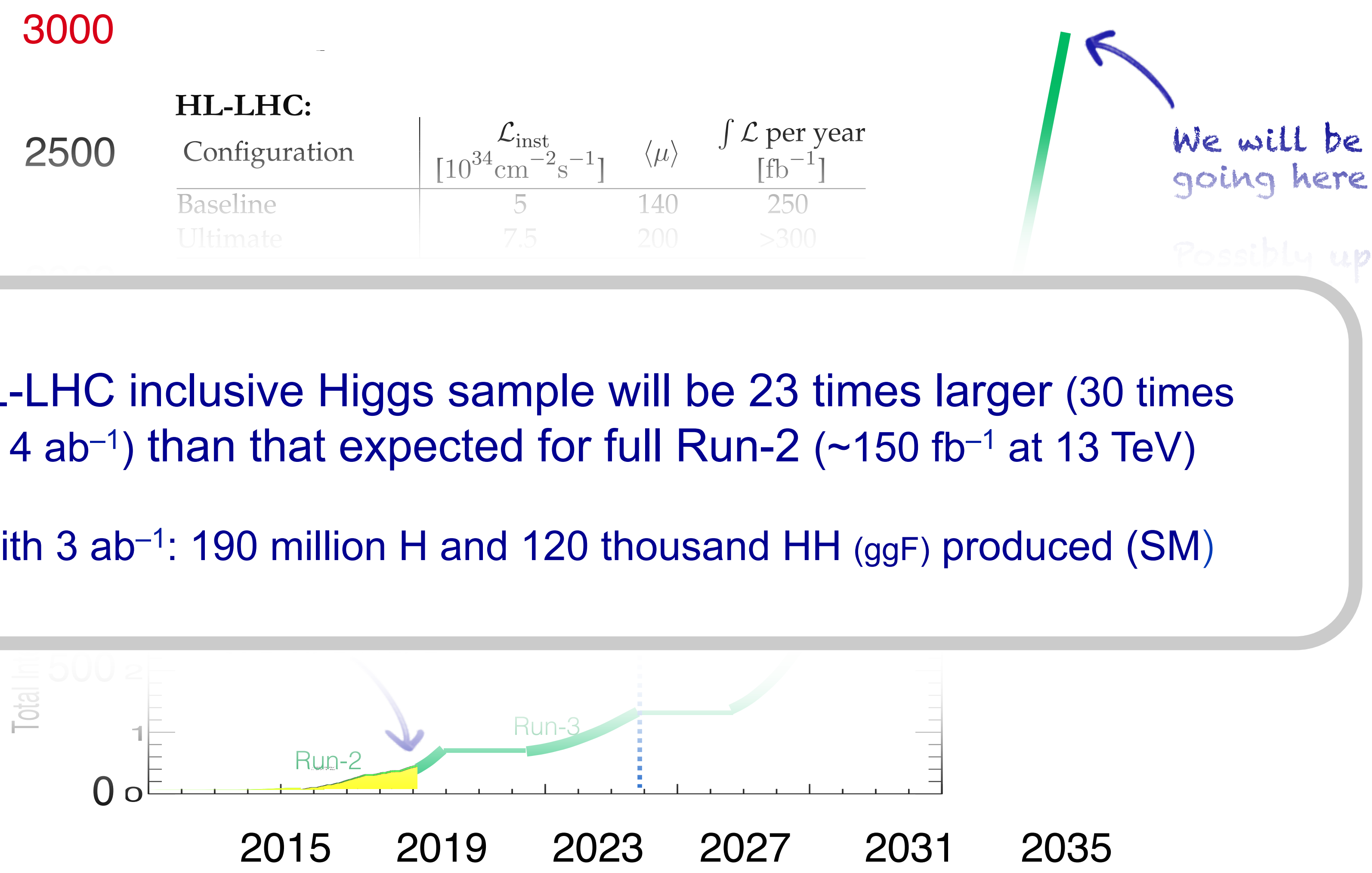
Expected integrated luminosity of LHC and HL-LHC



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



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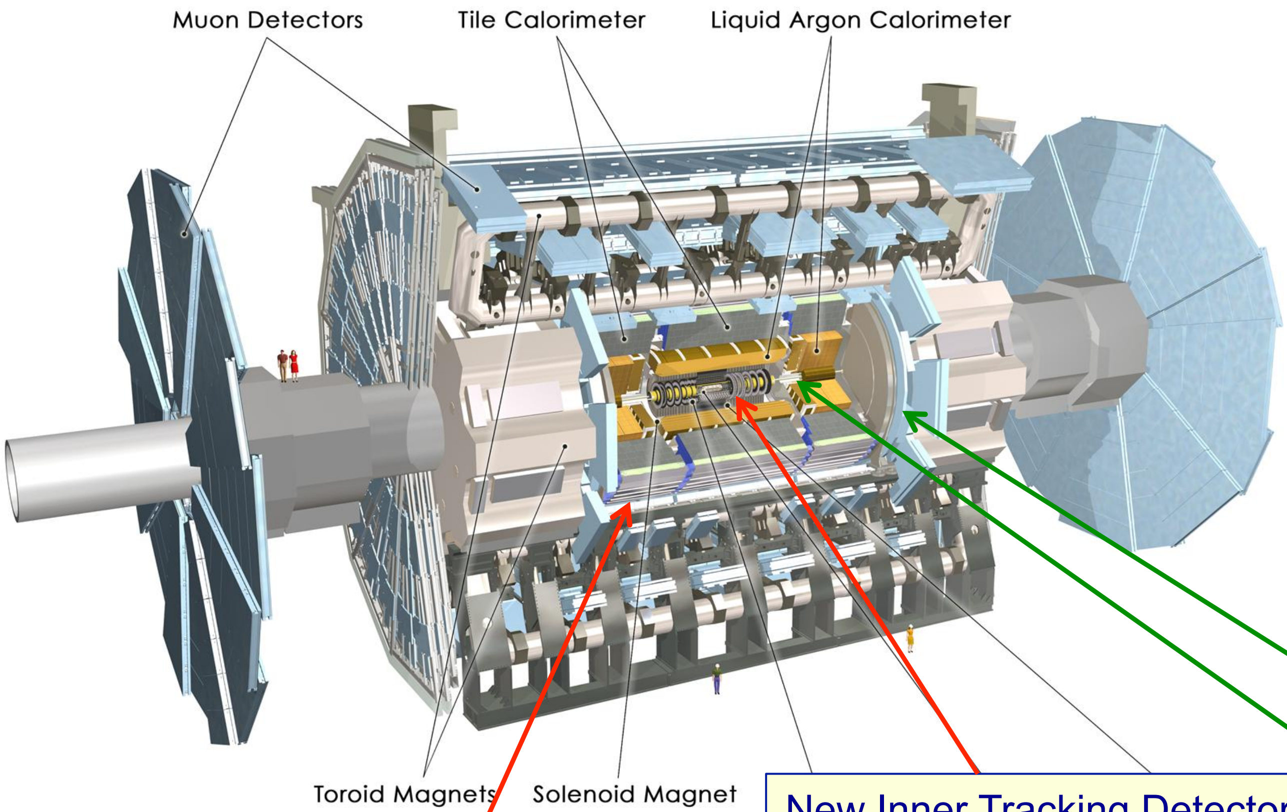
Baseline	5	140	250
Ultimate	7.5	200	>300

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)

ATLAS Phase-II Upgrade



Upgraded Trigger and Data Acquisition System:

- L0: 1 MHz
- Improved High-Level Trigger

Electronics Upgrade :

- LAr Calorimeter
- Tile Calorimeter
- Muon system

New Inner Tracking Detector (all silicon tracker, up to $|\eta| = 4$)

New muon chambers in the inner barrel region

Options:
- High granularity timing detector (forward region)
- High-η muon tagger

Conclusions

- With the operation of the LHC at the highest energies, particle physics has entered a new era;
  Superb performance of the LHC and the experiments

- The Standard Model is challenged at the high-energy frontier with ever increasing precision

- Higgs boson:
  - Within present uncertainties, its properties are in agreement with the predictions of the Standard Model
  - We moved from the discovery to the measurement phase;
  - The Higgs boson might be a portal to *New Physics* (precision required)

- So far no signals from New Physics

- Future direction: HL-LHC
  Exploration of the Higgs sector and continuation of direct searches