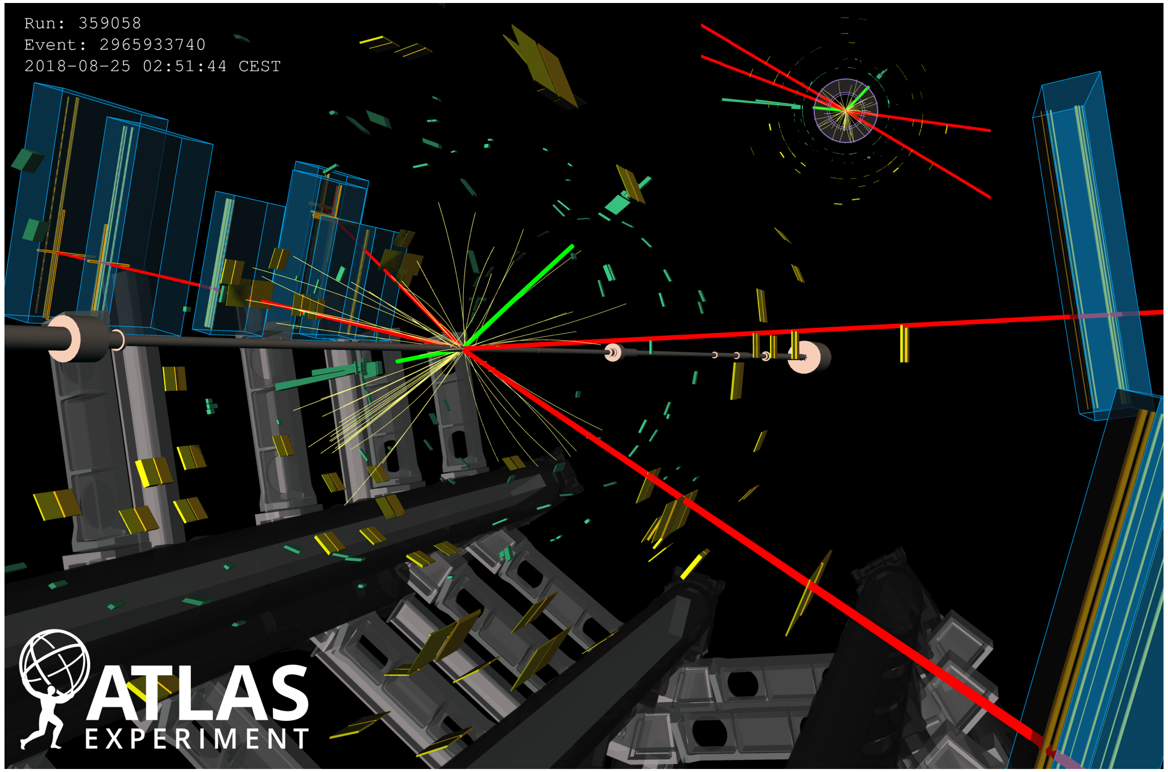
Physics at the LHC

- Where do we stand? Prospects for HL-LHC -



Karl Jakobs
University of Freiburg / Germany

XXV IFT Christmas Workshop, Madrid,
12th December 2019

Physics at the LHC
- Where do we stand? Prospects for HL-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)

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Physics at the LHC

- Where do we stand? Prospects for HL-LHC -

A few preliminary remarks on this talk:

- Focus on latest results and full Run-2 data analyses
- ATLAS heavy – mostly due to convenience (apologies for this!): in most cases there are equivalent results from CMS

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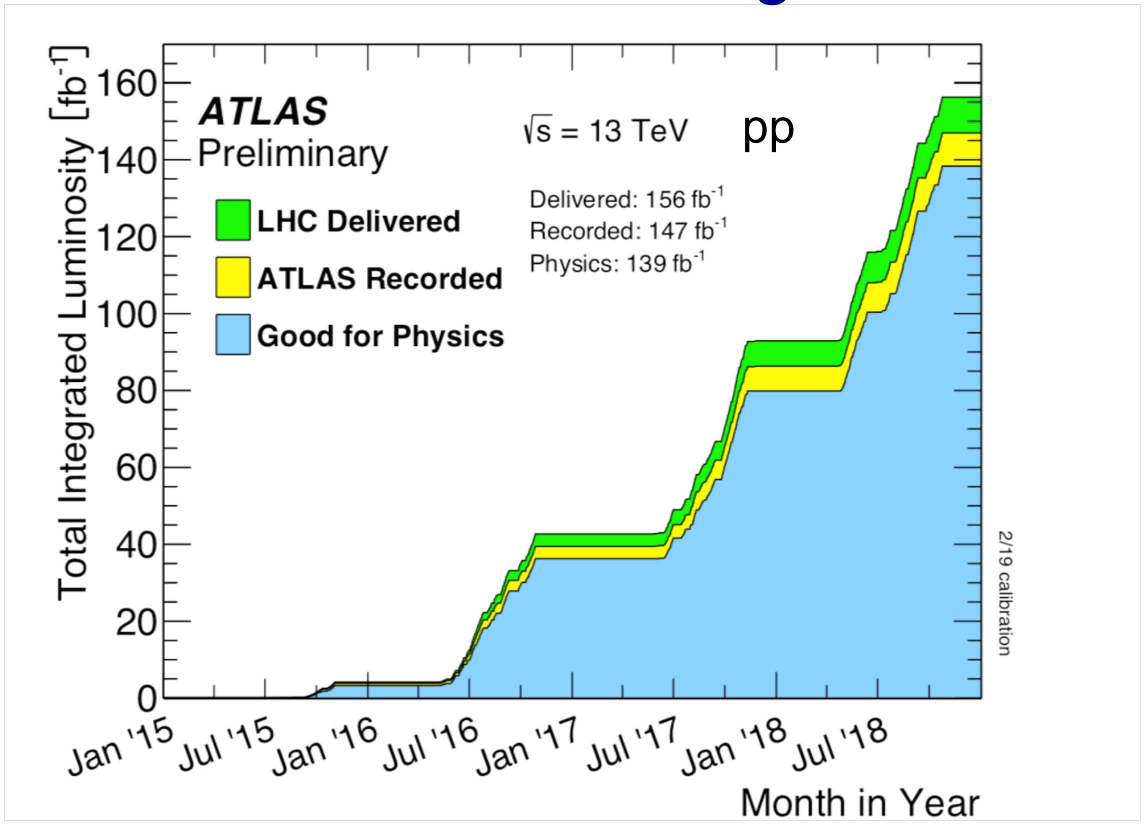
Data taking at the LHC in Run 2



In Run 2 (2015 – 2018):

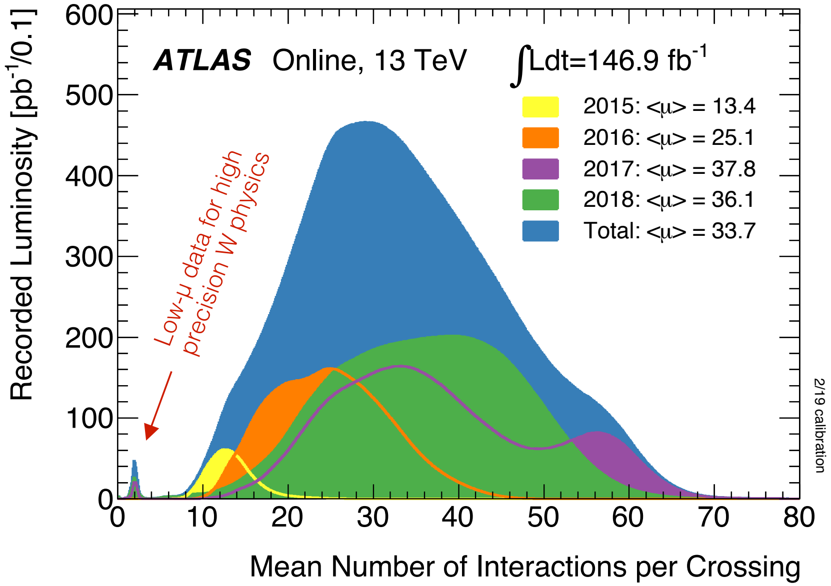
Delivered: 156 fb^{-1}

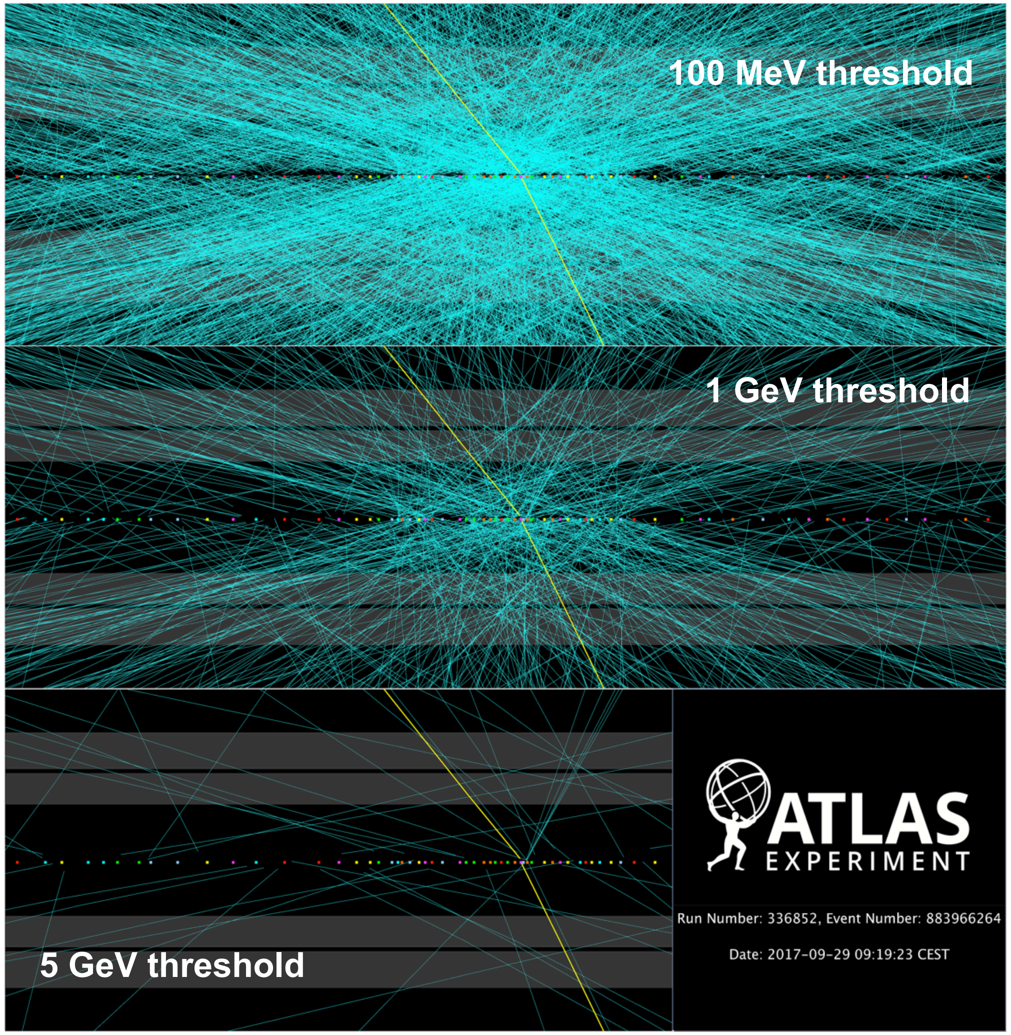
Recorded: 147 fb^{-1}
(Data taking efficiency 94.2%)

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

- Excellent performance of the accelerator and the ATLAS and CMS experiments
  High data-taking efficiency and high data quality
- Integrated luminosity in Run 2 measured with a precision of ±1.7% [ATLAS-CONF-2019-021]
- Timely analyses → Many results based on the complete Run-2 dataset

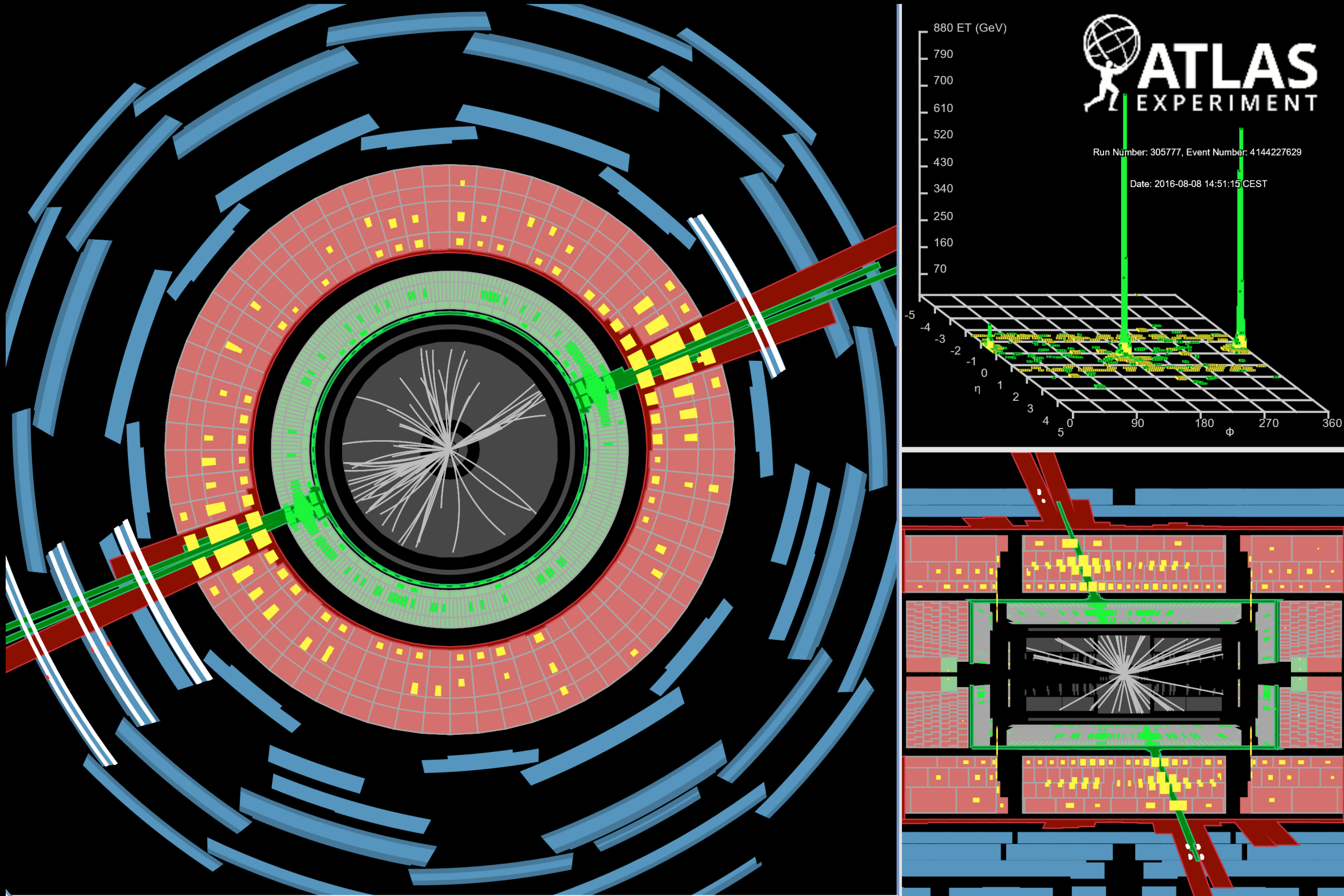
Data taking at the LHC in Run 2 (cont.)





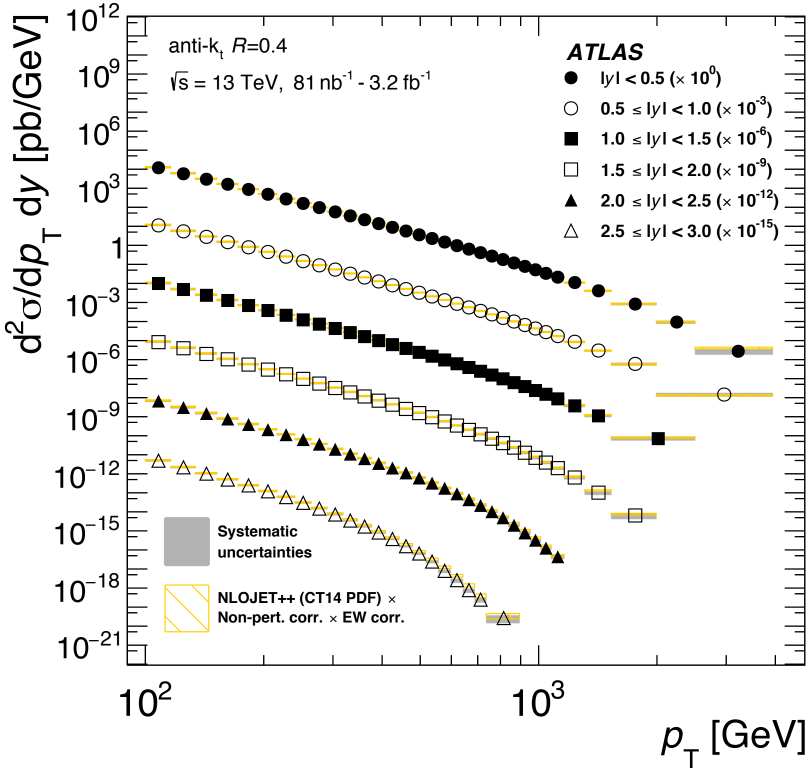
Z→ $\mu\mu$ candidate with 65 additional reconstructed vertices!

Summary of recent results from the LHC

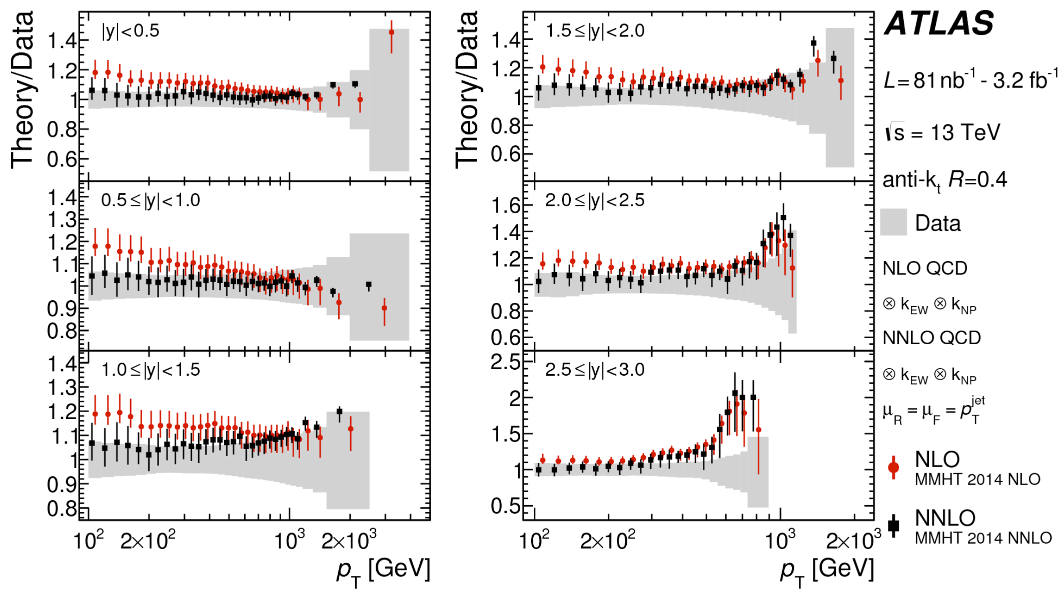


Di-jet event with the highest di-jet invariant mass of m_{jj} = 8.02 TeV recorded during 2016

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

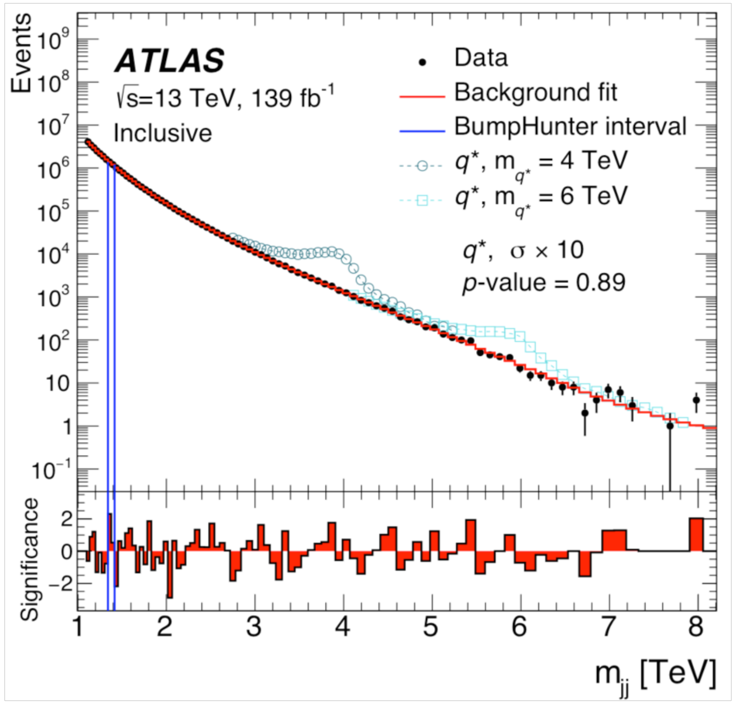


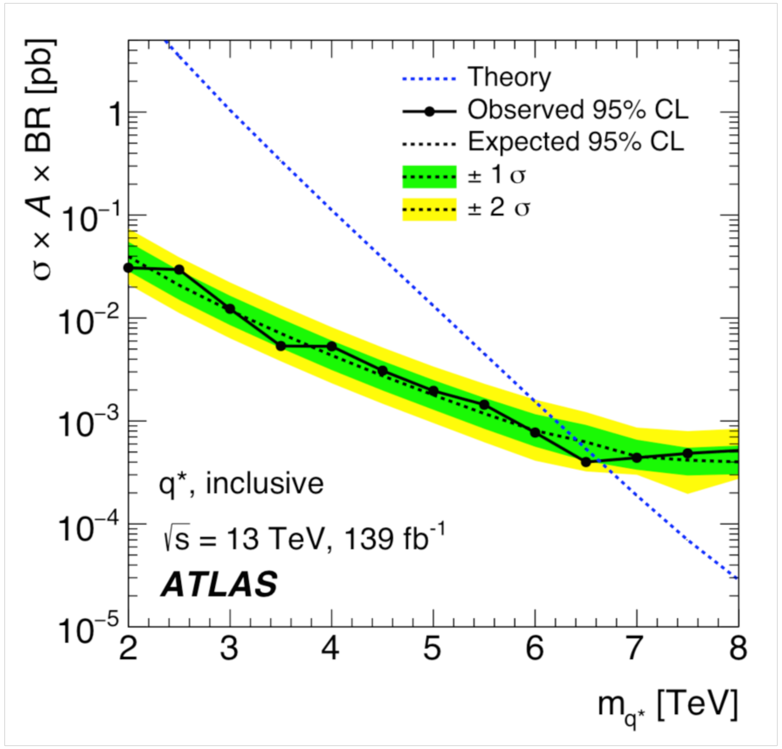
- Also at the highest energies explored so far, the data are well described by NLO perturbative QCD calculations (NLOJet++)
- Latest comparisons to NNLO predictions (NNLOJet) [J. Currie, N. Glover, T. Pieres, Phys. Rev. Lett. 118 (2017)]
  → improved agreement, however, scale dependent

Search for new phenomena in di-jet events

- Results based on Run-2 data (2015 – 2018): 139.0 fb^{-1} at $\sqrt{s}$ = 13 TeV

arXiv: 1910.08447





- 95% CL exclusion limits:

Excited quarks	m_{q^*} > 6.7 TeV	(6.4 TeV exp.)*
Add. gauge bosons:	$m_{W'}$ > 4.0 TeV	(4.2 TeV exp.)
Quantum Black Holes:	m_{BH} > 9.4 TeV	(9.4 TeV exp.)
Contact Interactions:	Λ > 13.1 TeV (η_{LL} = +1)	
	Λ > 21.8 TeV (η_{LL} = -1)	

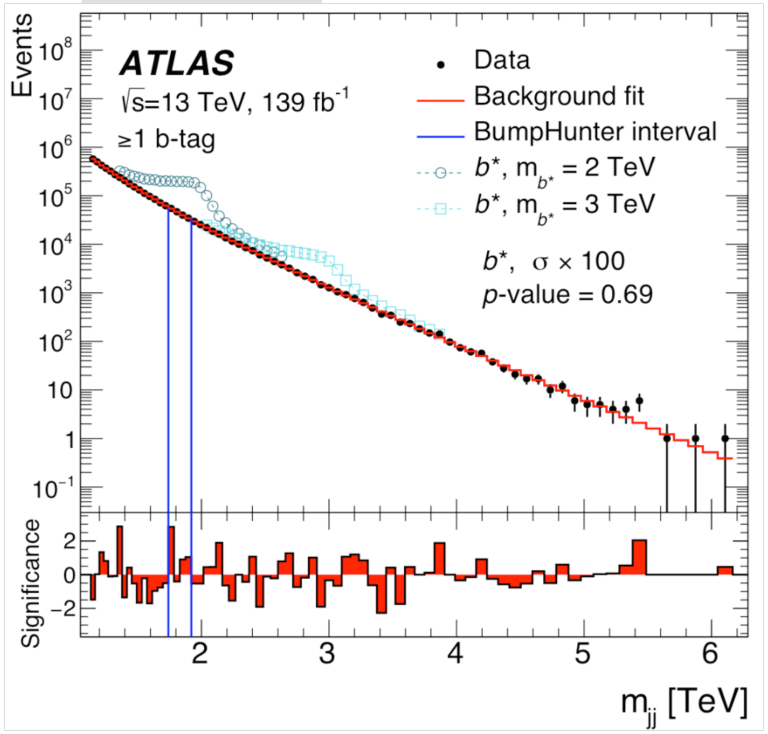
Phys. Rev. D96 (2017) 052004, 36 fb^{-1}

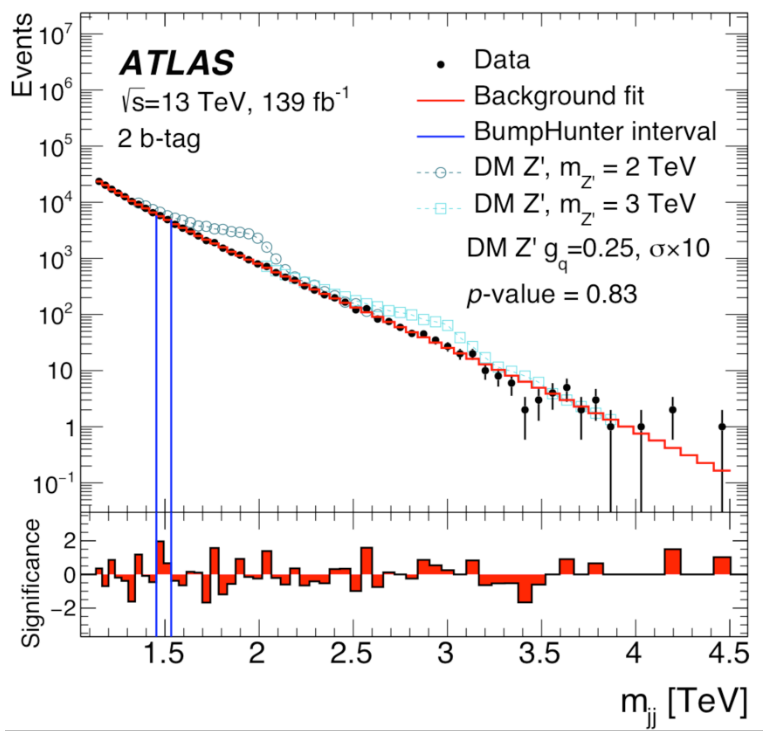
*pre-LHC limit on excited quarks from the Tevatron: 0.87 TeV

Search for new phenomena in **b-jet events**

- Results based on Run-2 data (2015 – 2018): 139.0 fb^{-1} at $\sqrt{s}$ = 13 TeV

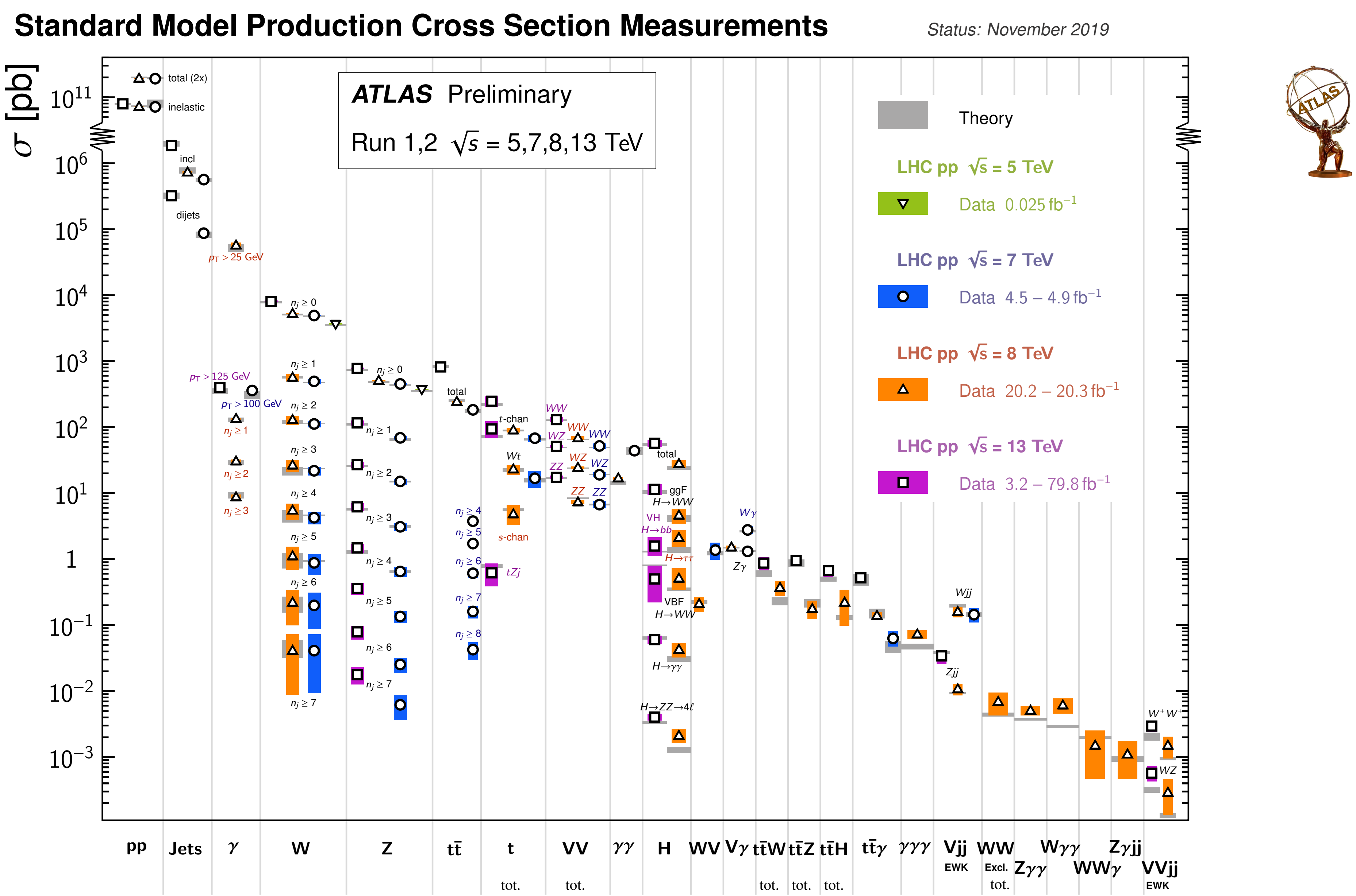
arXiv: 1910.08447





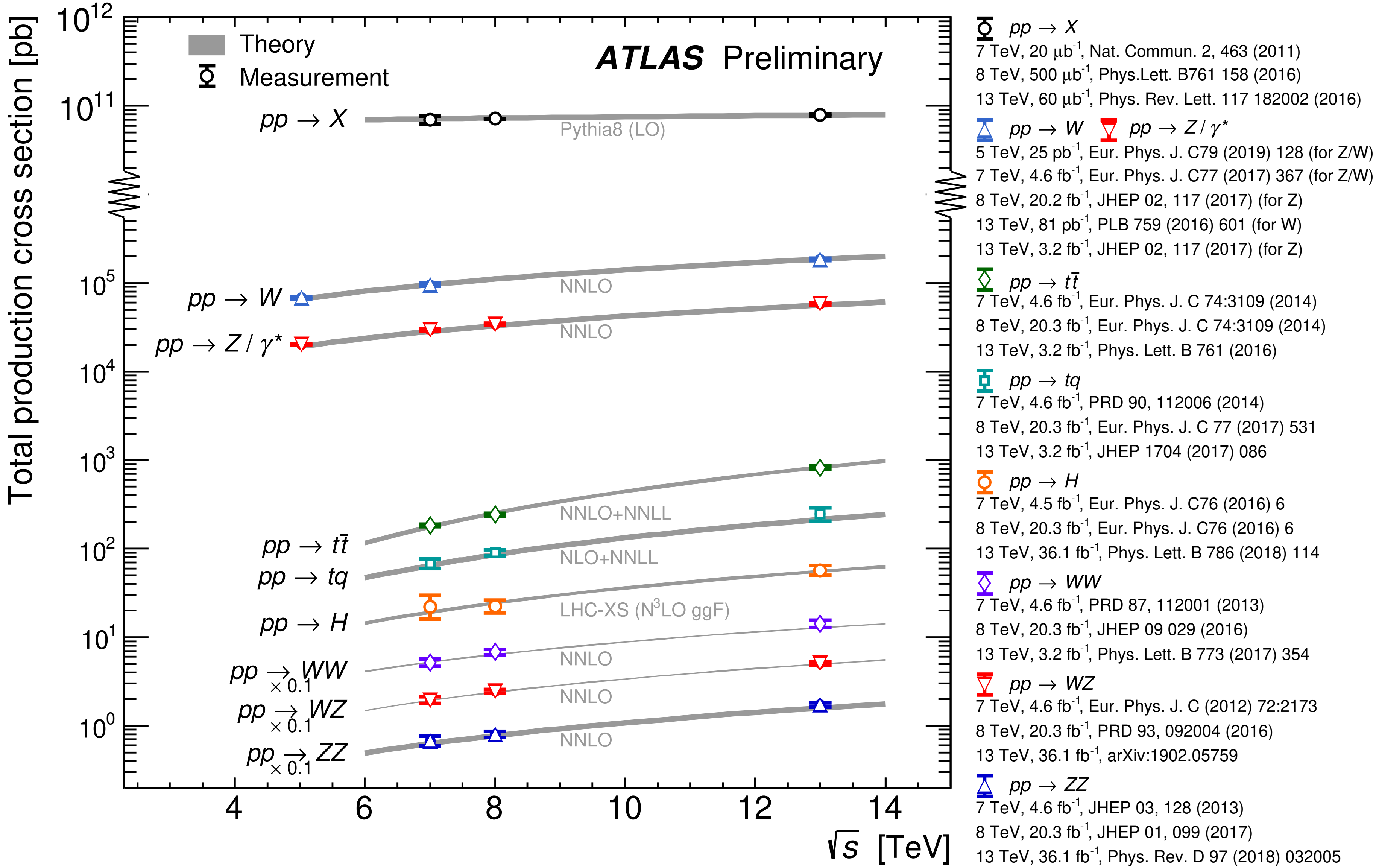
Interpretation in terms of excited b* quarks and dark matter mediators:

		95% C.L. lower signal mass limit observed	expected
$1b$	b^*	3.2 TeV	3.1 TeV
$2b$	DM mediator Z' $g_q = 0.20$	2.8 TeV	2.8 TeV
	DM mediator Z', $g_q = 0.25$	2.9 TeV	3.0 TeV
	SSM Z',	2.7 TeV	2.7 TeV
	graviton, $k/\overline{M}_{PL} = 0.2$	2.8 TeV	2.9 TeV



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

LHC for theorists: “Long and Hard Calculations”

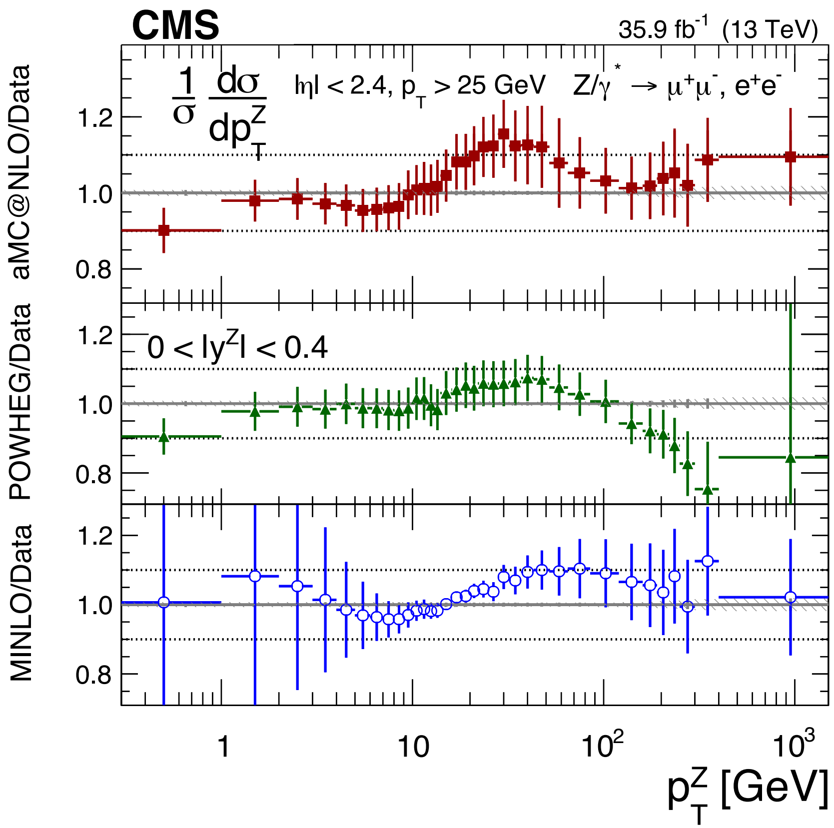

Total production cross section [pb]
Theory
Measurement
ATLAS Preliminary
pp → X
Pythia8 (LO)
pp → W
pp → Z / γ*
NNLO
NNLO
pp → tt̄
pp → tq
pp → H
pp → WW ×0.1
pp → WZ ×0.1
pp → ZZ ×0.1
NNLO+NNLL
NLO+NNLL
LHC-XS (N3LO ggF)
NNLO
NNLO
NNLO
√s [TeV]
pp → X
7 TeV, 20 μb-1, Nat. Commun. 2, 463 (2011)
8 TeV, 500 μb-1, Phys.Lett. B761 158 (2016)
13 TeV, 60 μb-1, Phys. Rev. Lett. 117 182002 (2016)
pp → W pp → Z / γ*
5 TeV, 25 pb-1, Eur. Phys. J. C79 (2019) 128 (for Z/W)
7 TeV, 4.6 fb-1, Eur. Phys. J. C77 (2017) 367 (for Z/W)
8 TeV, 20.2 fb-1, JHEP 02, 117 (2017) (for Z)
13 TeV, 81 pb-1, PLB 759 (2016) 601 (for W)
13 TeV, 3.2 fb-1, JHEP 02, 117 (2017) (for Z)
pp → tt̄
7 TeV, 4.6 fb-1, Eur. Phys. J. C 74:3109 (2014)
8 TeV, 20.3 fb-1, Eur. Phys. J. C 74:3109 (2014)
13 TeV, 3.2 fb-1, Phys. Lett. B 761 (2016)
pp → tq
7 TeV, 4.6 fb-1, PRD 90, 112006 (2014)
8 TeV, 20.3 fb-1, Eur. Phys. J. C 77 (2017) 531
13 TeV, 3.2 fb-1, JHEP 1704 (2017) 086
pp → H
7 TeV, 4.5 fb-1, Eur. Phys. J. C76 (2016) 6
8 TeV, 20.3 fb-1, Eur. Phys. J. C76 (2016) 6
13 TeV, 36.1 fb-1, Phys. Lett. B 786 (2018) 114
pp → WW
7 TeV, 4.6 fb-1, PRD 87, 112001 (2013)
8 TeV, 20.3 fb-1, JHEP 09 029 (2016)
13 TeV, 3.2 fb-1, Phys. Lett. B 773 (2017) 354
pp → WZ
7 TeV, 4.6 fb-1, Eur. Phys. J. C (2012) 72:2173
8 TeV, 20.3 fb-1, PRD 93, 092004 (2016)
13 TeV, 36.1 fb-1, arXiv:1902.05759
pp → ZZ
7 TeV, 4.6 fb-1, JHEP 03, 128 (2013)
8 TeV, 20.3 fb-1, JHEP 01, 099 (2017)
13 TeV, 36.1 fb-1, Phys. Rev. D 97 (2018) 032005

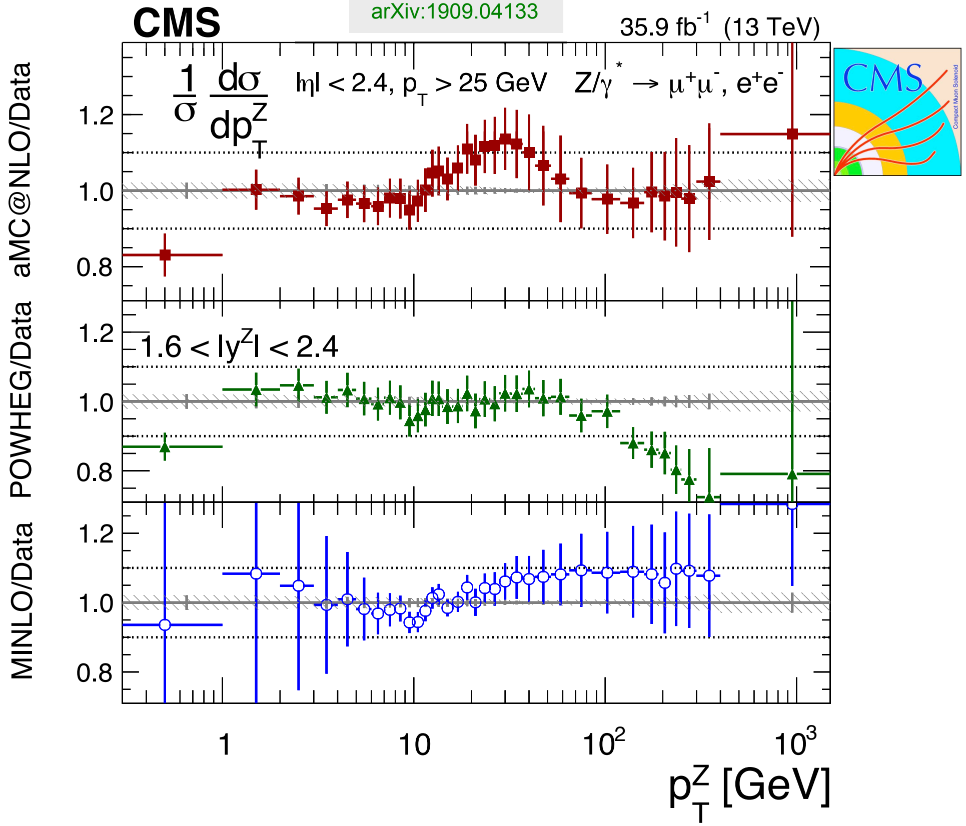
Precise measurement of **Z boson production** at √s = 13 TeV

Exploring differential measurements

- High-precision study of Z boson production at 13 TeV compared to state-of-the-art predictions

arXiv:1909.04133





Also comparisons with resummed & FO predictions. None provides fully satisfying agreement yet.

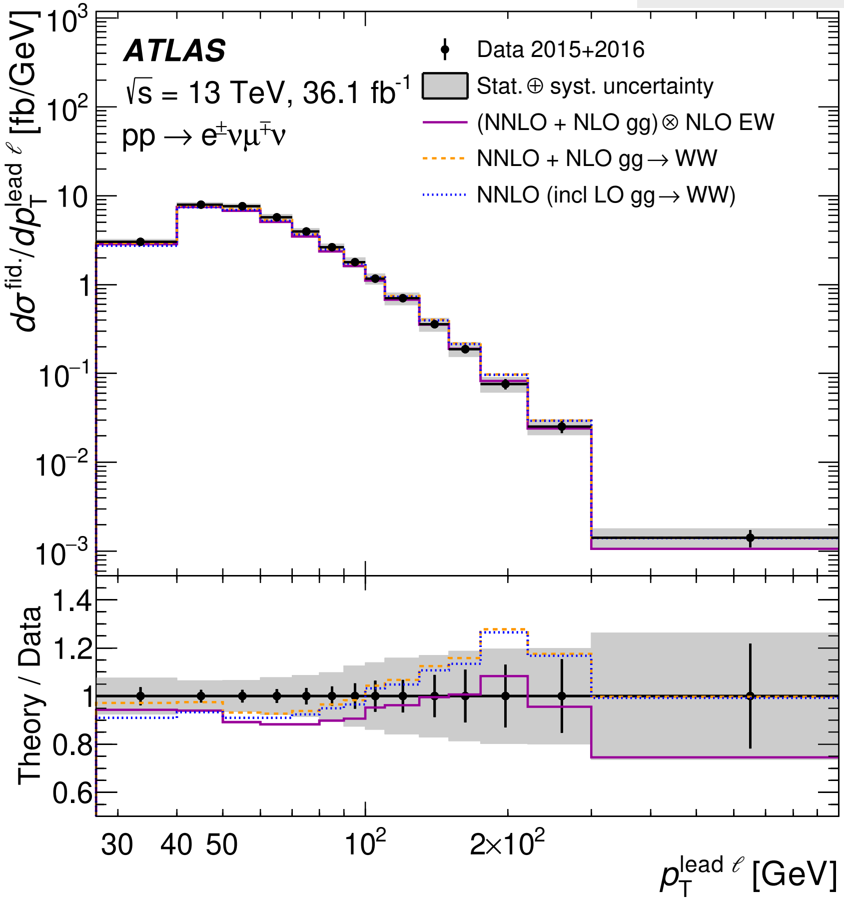
Understanding of p_T(V) spectrum and W–Z correlation important for W mass measurement

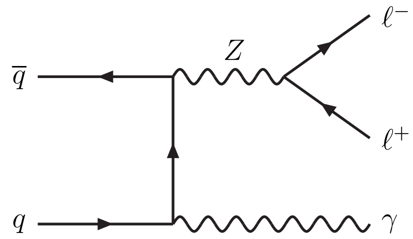
High-statistics probes of diboson production

Exploring differential measurements

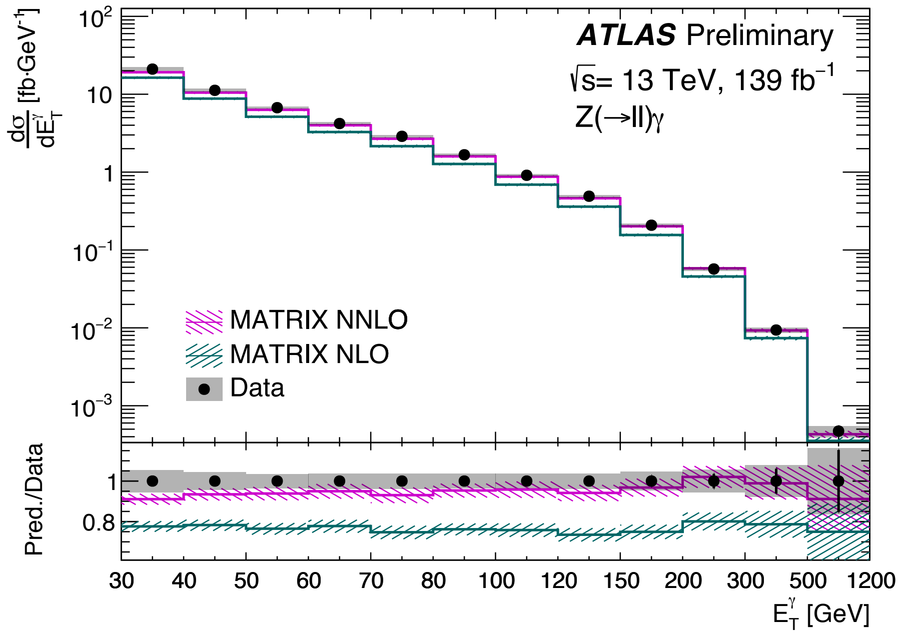
New high-precision measurements of differential W^+W^- (left) and $Z\gamma$ (right) diboson cross sections, probing the EW gauge structure of the SM and test of QCD

arXiv:1905.04242





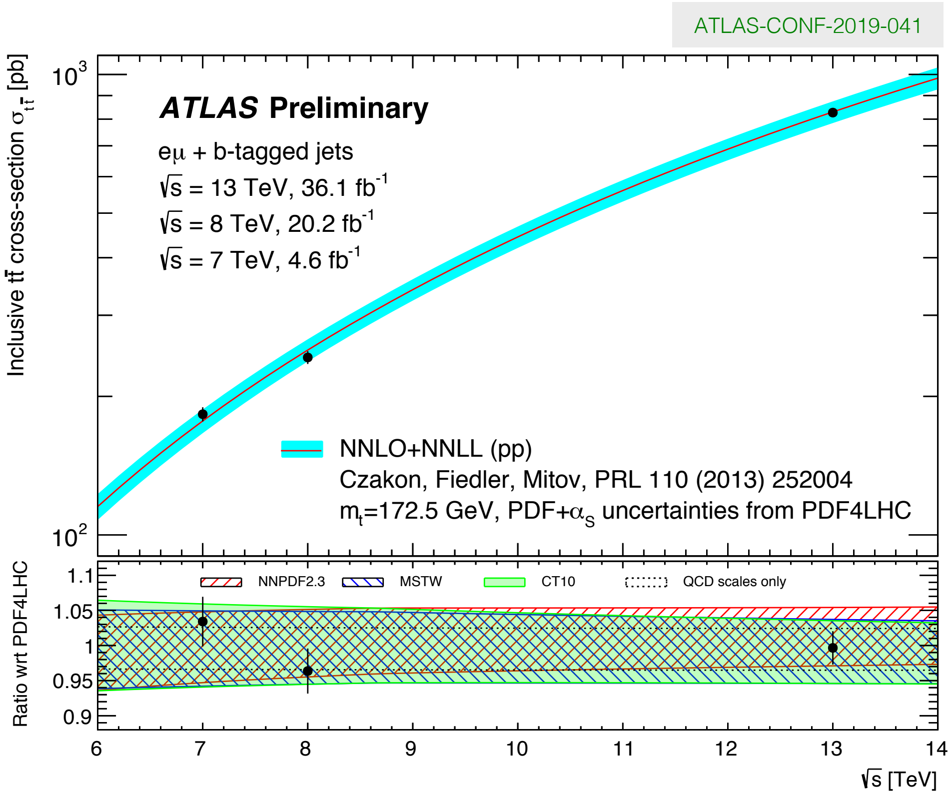
ATLAS-CONF-2019-034

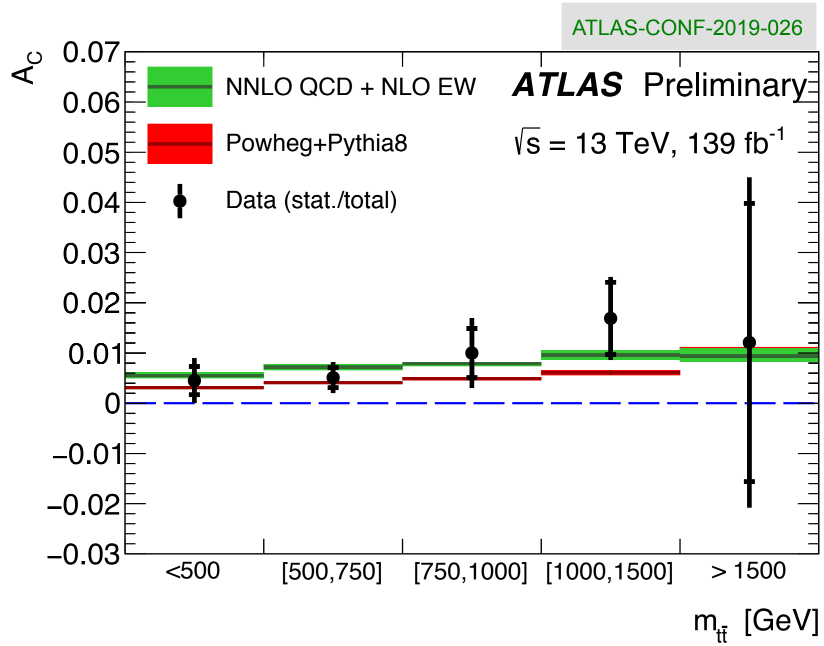


Top–antitop production measurements

Huge tt statistics at LHC allows to measure multidimensional differential cross sections

Analysis based on 36 fb^{-1} with high-precision





$\sigma(tt) = 826.4 \pm 3.6_{stat} \pm 11.5_{syst} \pm 15.7_{lumi} \pm 1.9_{beam}$ pb (2.4%)

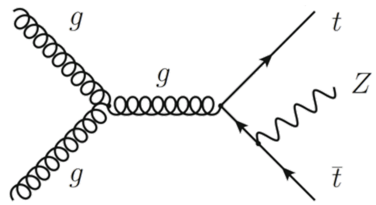
$m(t) = 173.1^{+2.0}_{-2.1}$ GeV (at pole) (1.9%)

Uncertainty dominated by PDF, QCD scale, experimental

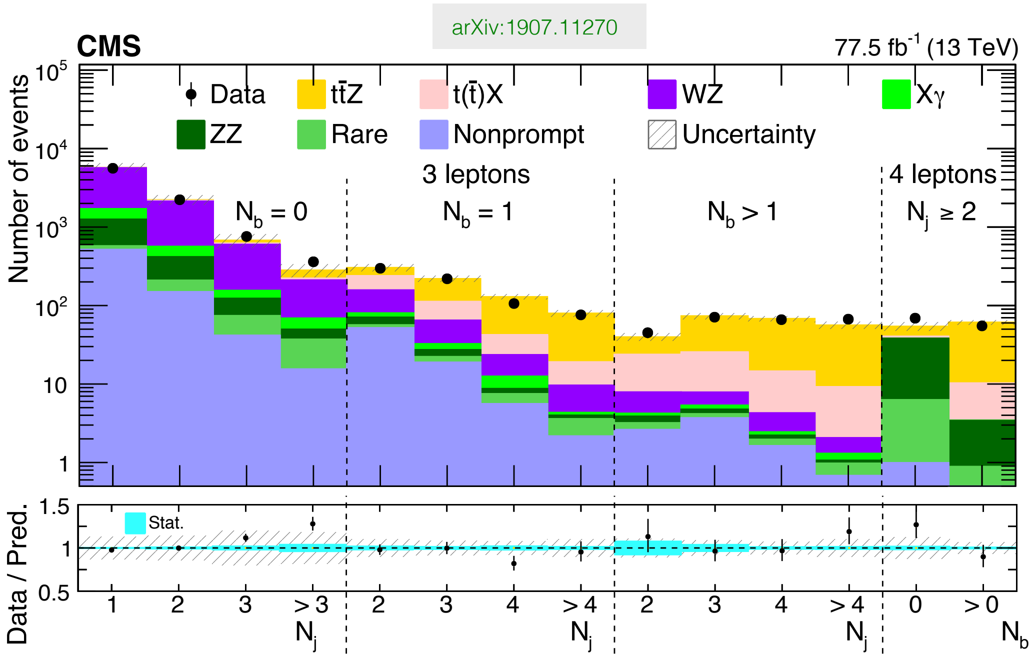
- Charge asymmetry measurement
  → non-zero at 4σ
  (first evidence at the LHC)

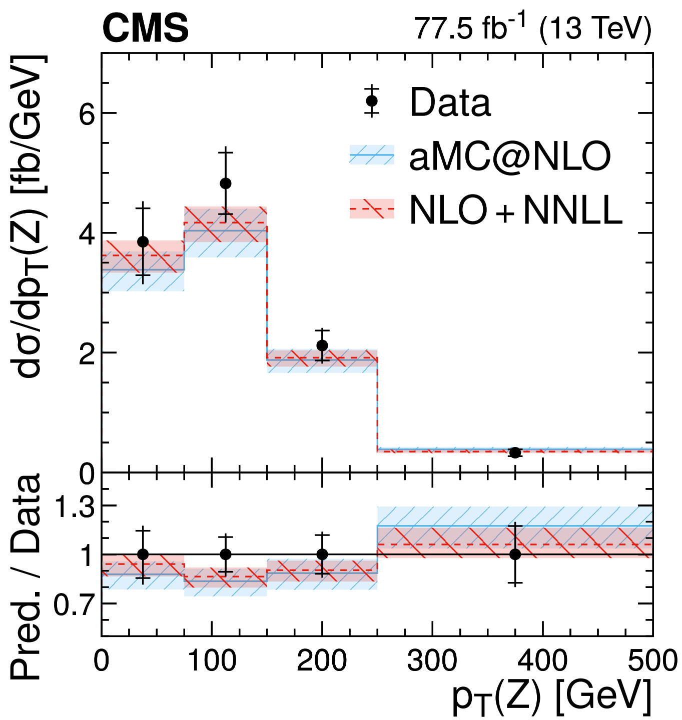
Associated production of tt with bosons

ttZ cleanest channel, allows differential cross-section measurements



- Very interesting measurement from CMS using 78 fb^{-1} in 3 and 4-lepton channels





Very clean signal regions;

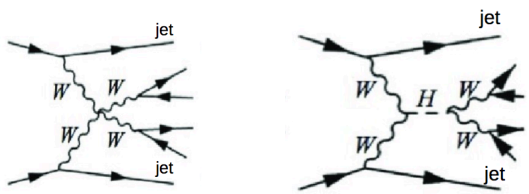
Total cross section measured: $\sigma(ttZ) = 0.95 \pm 0.05_{stat} \pm 0.06_{syst}$ pb

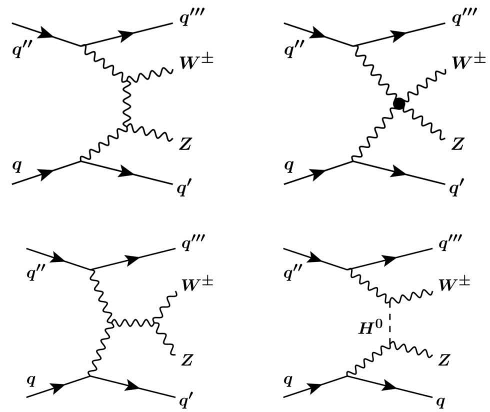
SM(NLO): 0.84 ± 0.10 pb

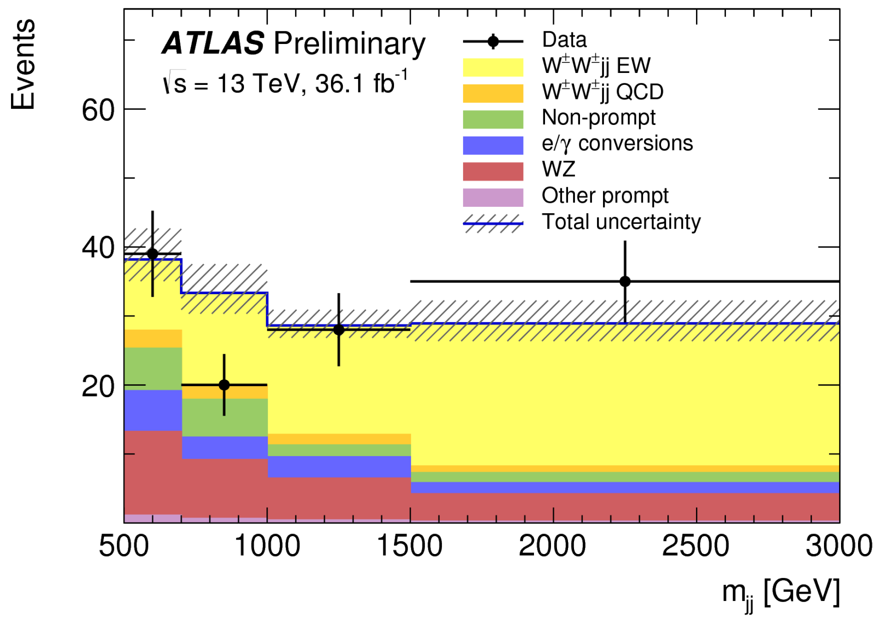
Vector boson scattering

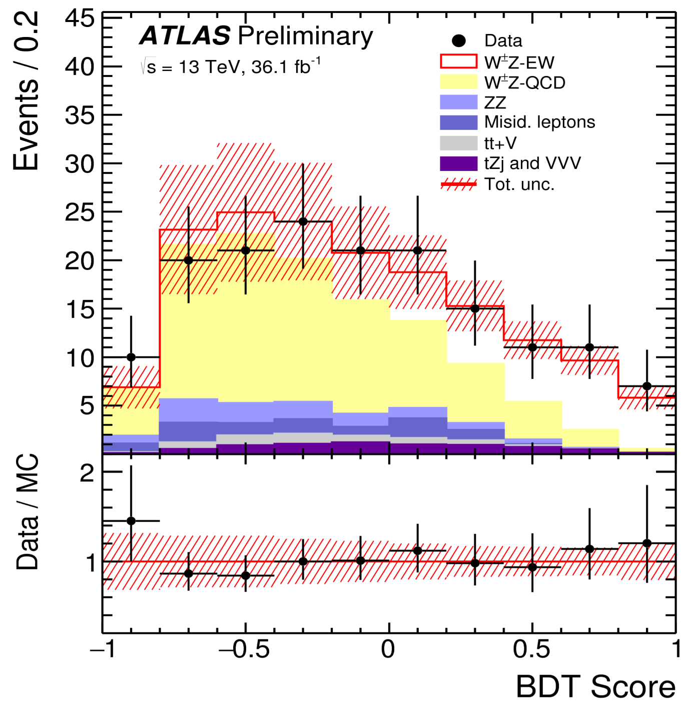
EW same-charge WW+jj 6.9σ (4.6σ) obs (exp)
[ATLAS-CONF-2018-030]()

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



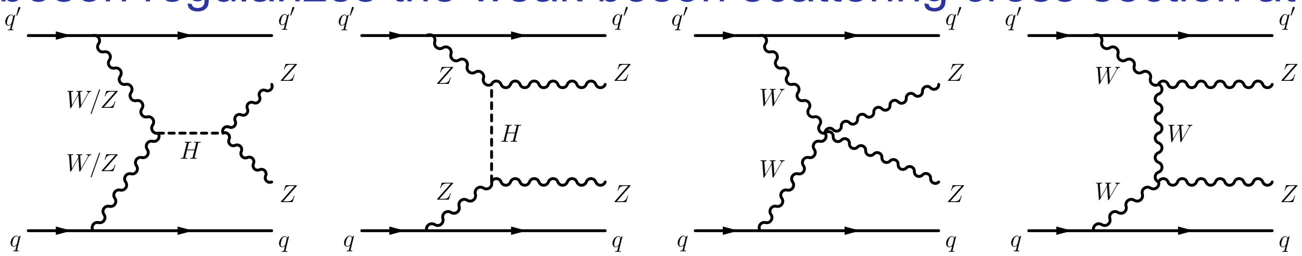






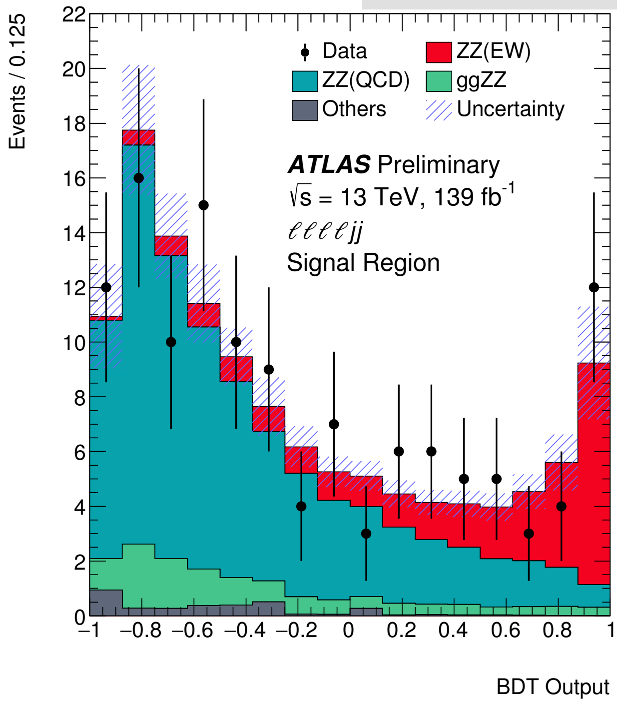
Observation of Vector Boson Scattering in ZZjj

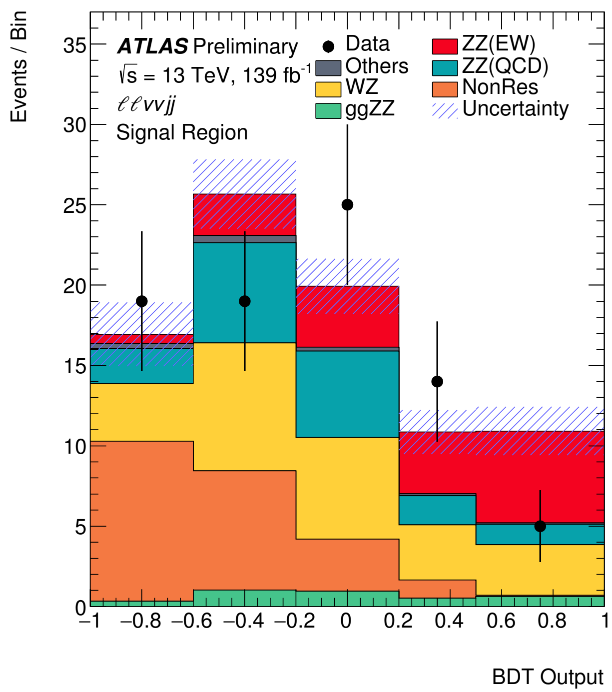
- Higgs boson regularizes the weak boson scattering cross section at high energies



- ZZjj analysis exploits decays to four charged leptons ($\ell\ell\ell\ell$) and ($\ell\ell\nu\nu$)
- Multivariate analysis to separate EW signal from backgrounds (e.g. QCD ZZ)

ATLAS-CONF-2019-033





Observed (expected) significance for EW production: 5.5σ (4.3σ)

σ_{fid}(EW) = 0.82 ± 0.21 fb

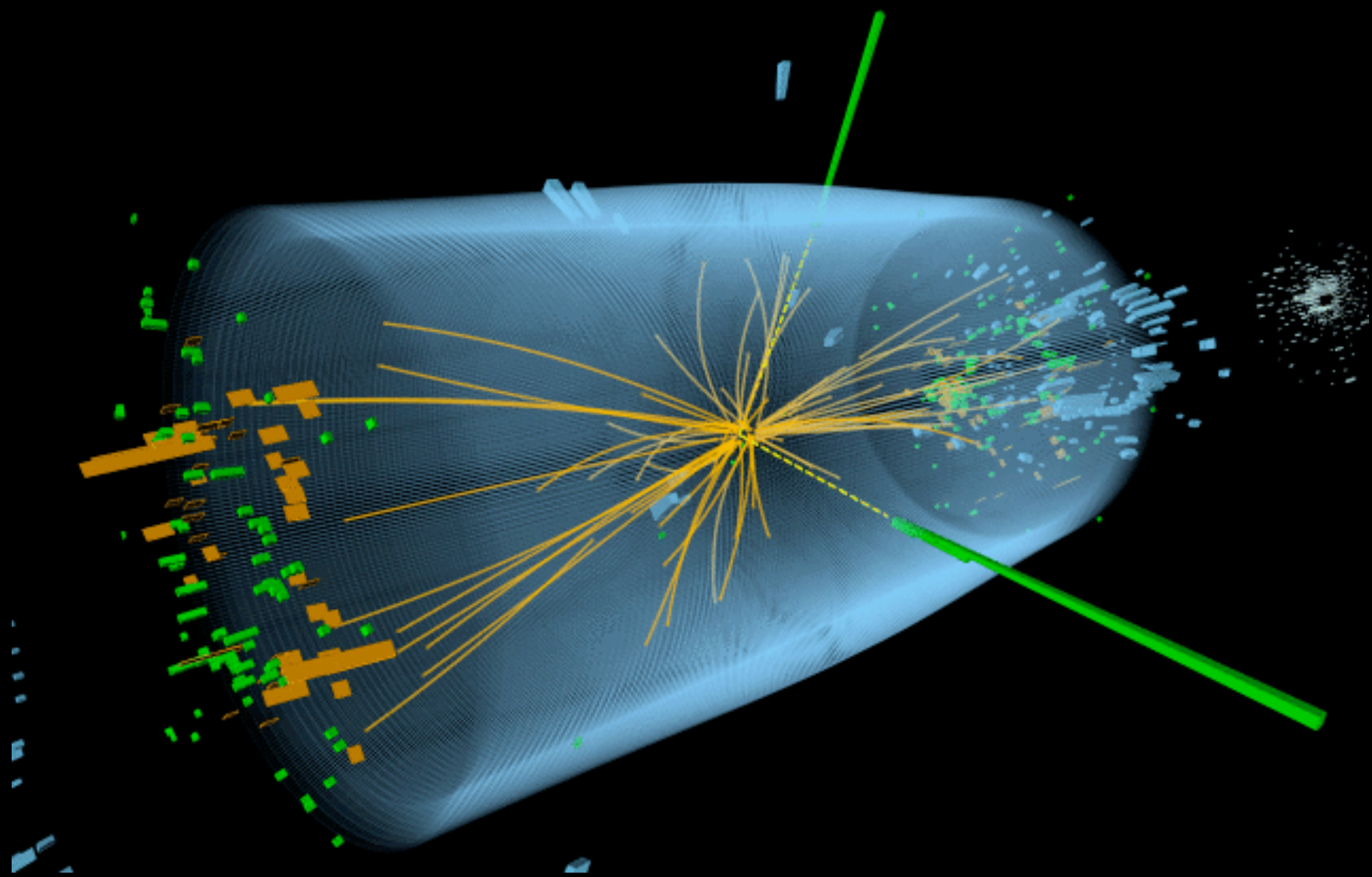
SM pred.= 0.61 ± 0.03 fb

ATLAS observed vector-boson scattering at:

- 6.9σ in WW channel
- 5.3σ in WZ channel

→ All VVjj channels have now been observed

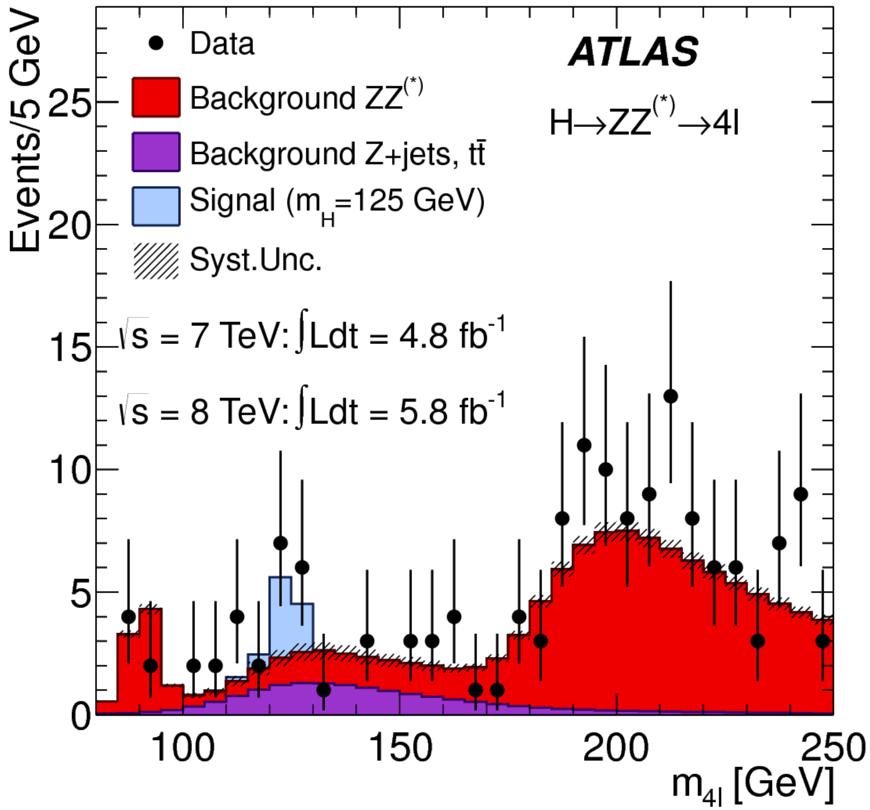
Status of Higgs Boson measurements



H → ZZ* → 4ℓ signals

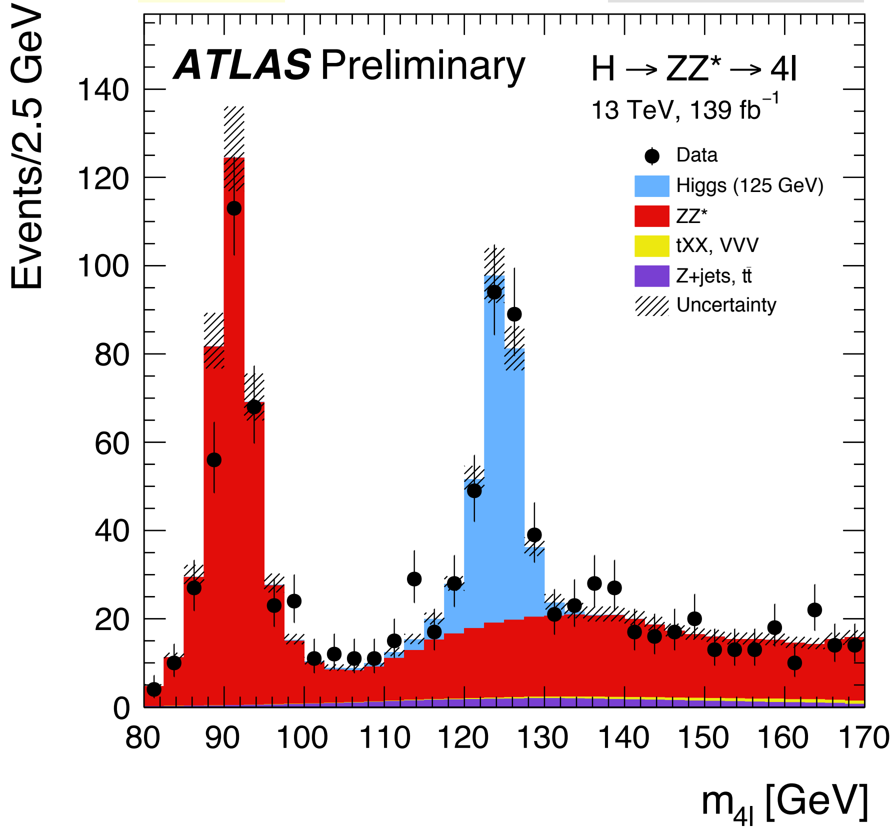
2012

Phys. Lett. B716 (2012) 1



2019

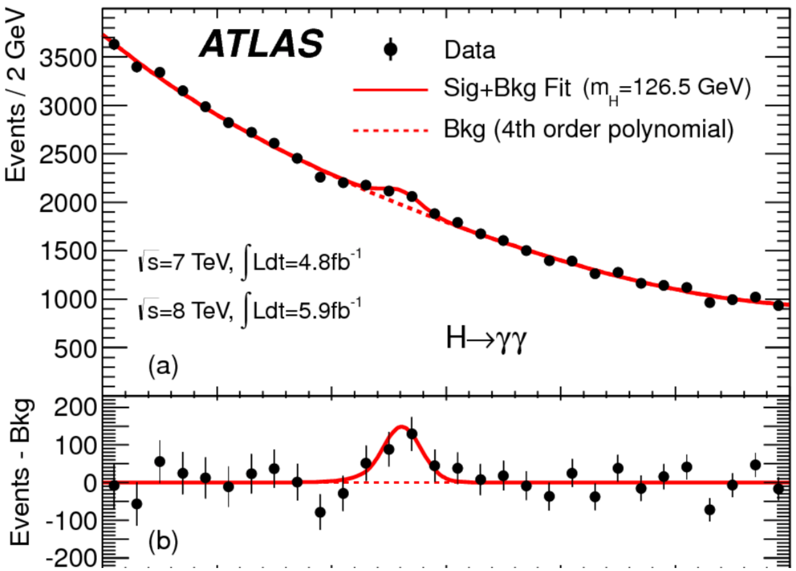
ATLAS-CONF-2019-025



Impressive progress illustrated by comparison of H → ZZ* → 4ℓ signals

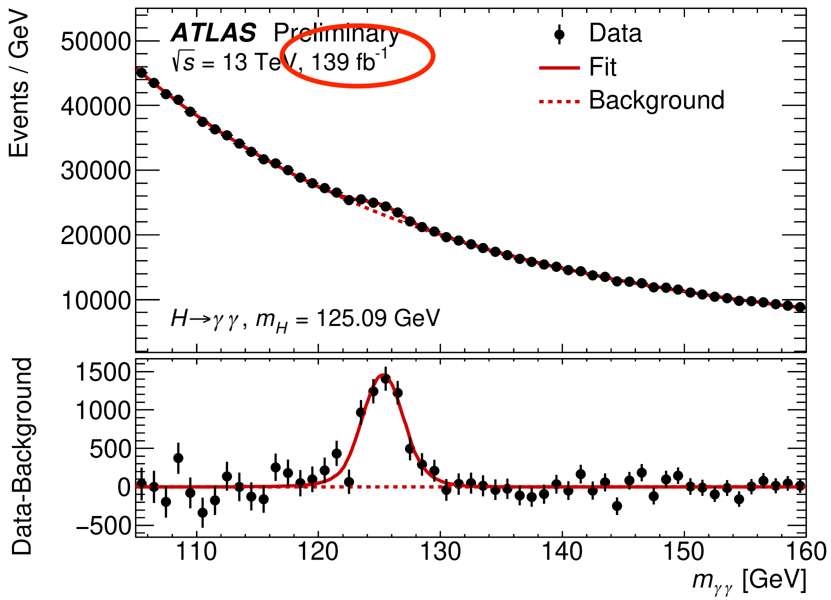
H → γγ decays

Phys. Lett. B716 (2012) 1



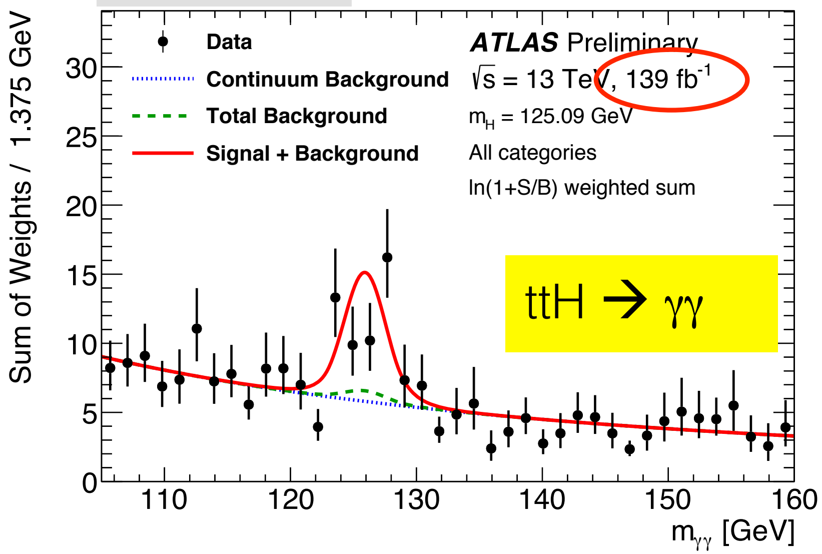
July 2012

ATLAS-CONF-2019-029



July 2019

ATLAS-CONF-2019-004

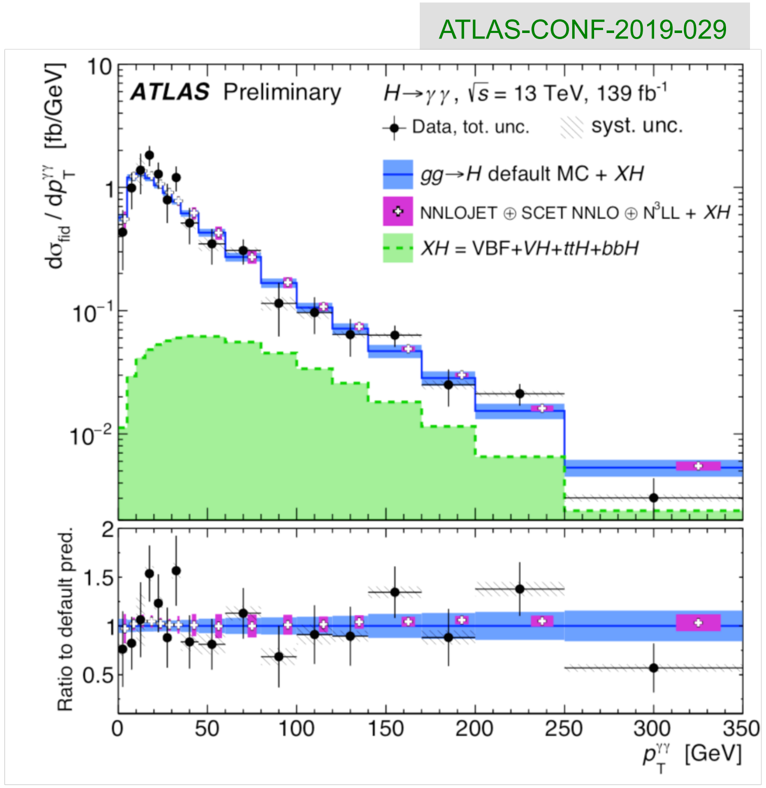


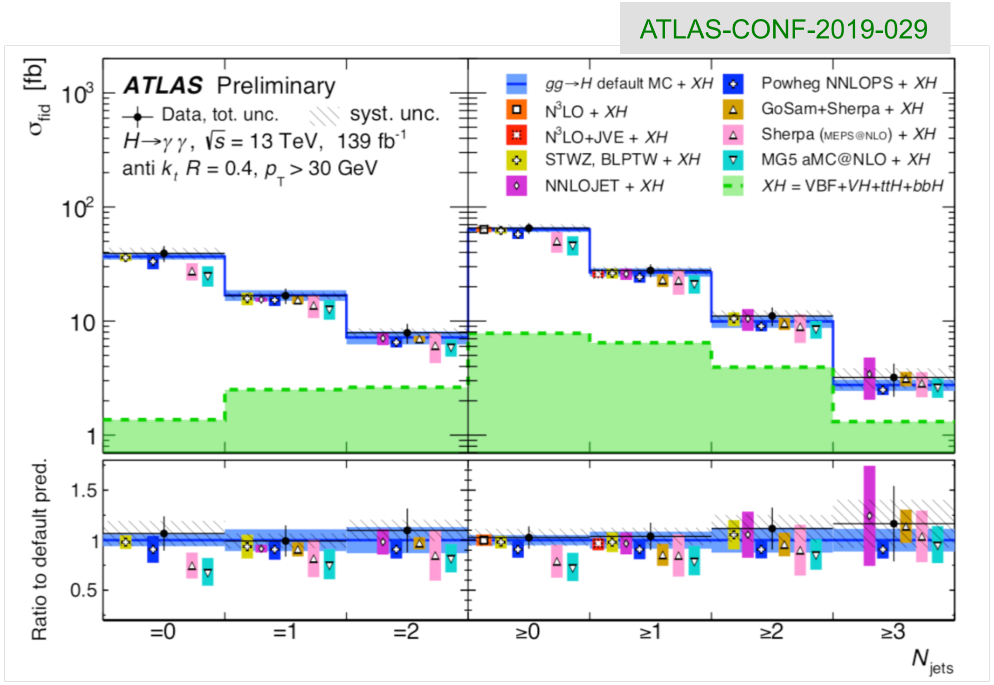
Observation of H → γγ in rare ttH production channel in 2019

4.9σ observed (4.2σ expected)

$$\mu_{t\bar{t}H} = 1.38\ ^{+0.33}_{-0.31}\ \text{(stat.)}\ ^{+0.13}_{-0.11}\ \text{(exp.)}\ ^{+0.22}_{-0.14}\ \text{(theo.)}$$

Differential H → γγ cross-section measurements



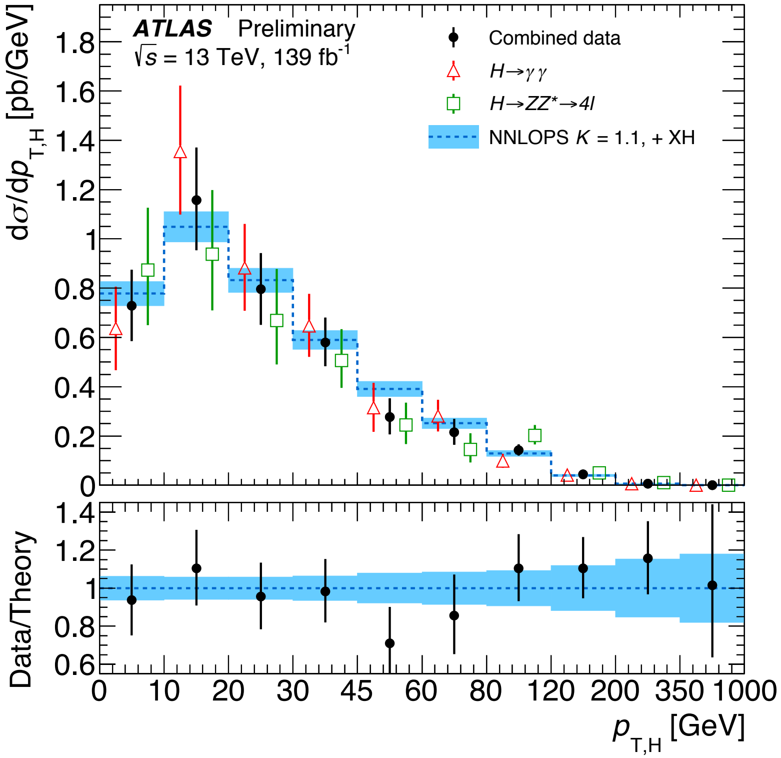


- Data are well described by theoretical calculations (within uncertainties)

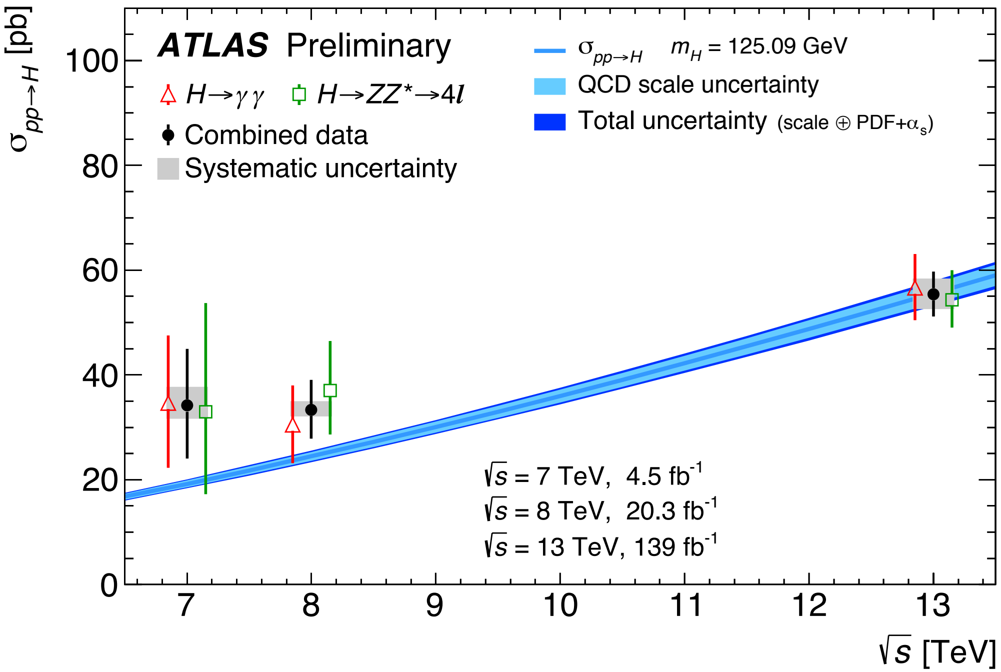
- Such measurements will become important ingredients for future measurements of Higgs boson parameters (Effective Field Theories)

Statistical combination for cross-section measurements (total and differential)

ATLAS-CONF-2019-032



ATLAS-CONF-2019-032



Combined inclusive pp → H + X cross section:

$$\sigma(pp \to H) = 56.7\,^{+6.4}_{-6.2}(\gamma\gamma),\ 54.4\,^{+5.6}_{-5.4}(4\ell),\ 55.4\,^{+4.3}_{-4.2}(\text{comb})\ \text{pb}$$

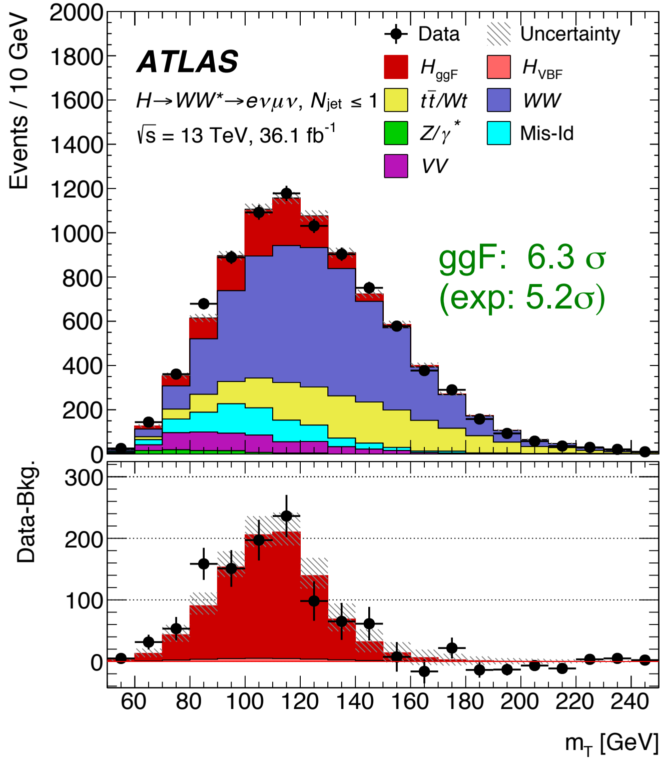
(Precision of 7.7%)

SM: 55.6 ± 2.5 pb (NLO–NNLO QCD, NLO EW)

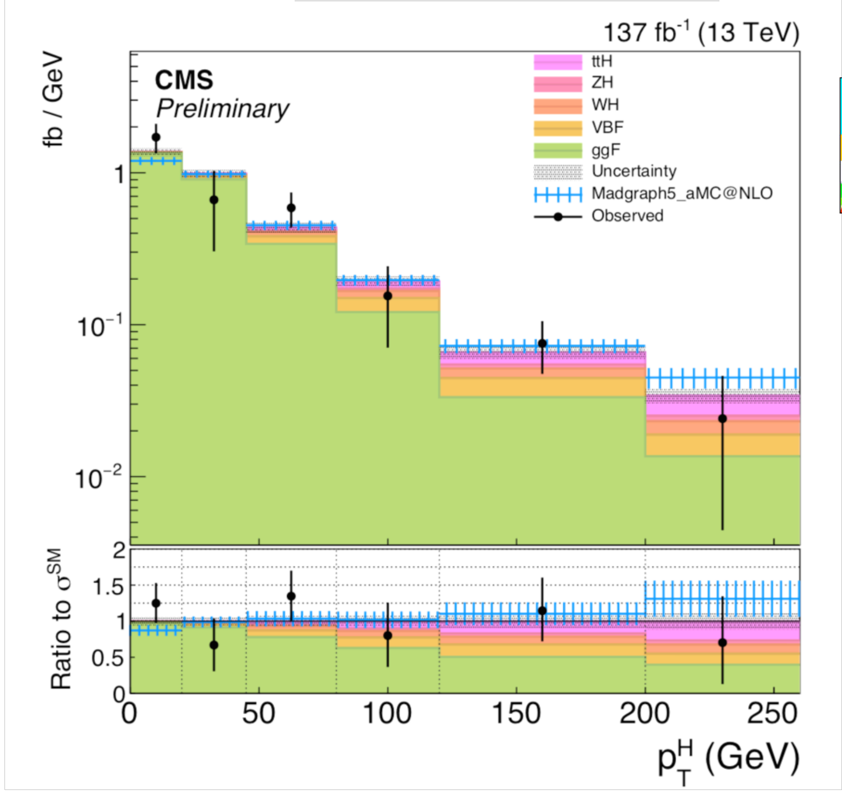
H → WW* → ℓν ℓν signal

- 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

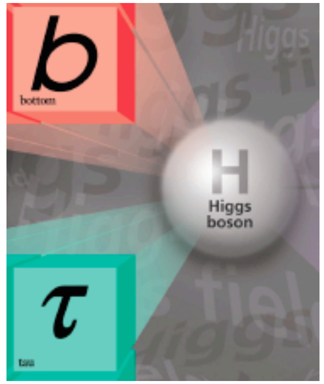


CMS-PAS-HIG-2019-002 (2019)



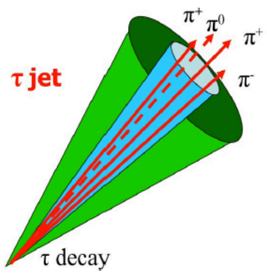
- Very significant excesses visible in the "transverse mass" and $m_{\ell\ell}$ distributions
  ATLAS: gluon fusion 6.3σ observed (5.2σ expected)
- CMS: First differential measurements with full Run-2 data

Couplings to quarks and leptons ?

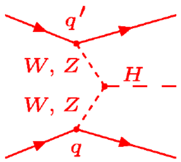


- Search for H → ττ and H → bb decays;

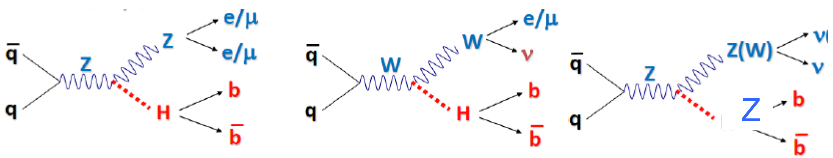
- Challenging signatures due to jets (bb decays) or significant fraction of hadronic tau decays

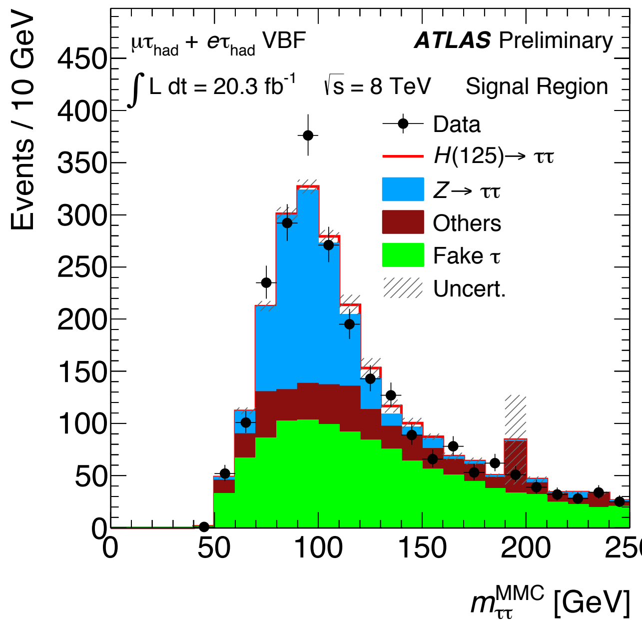


- Vector boson fusion mode essential for H → ττ decays



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

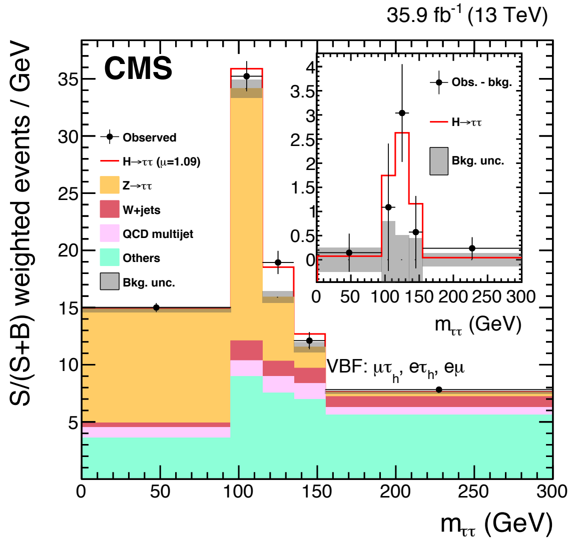


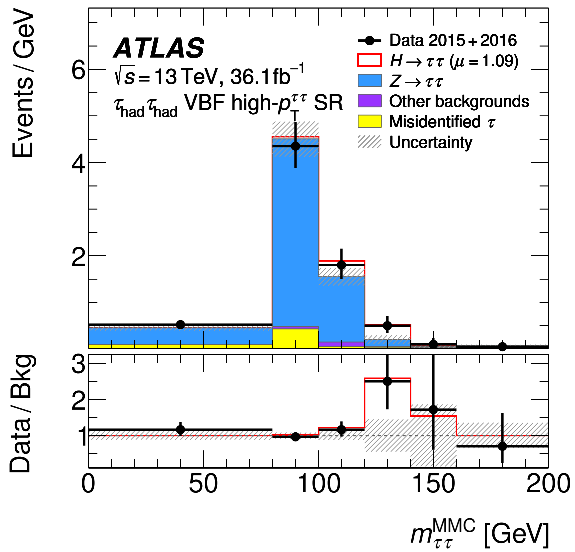


- Exploitation of multivariate analyses

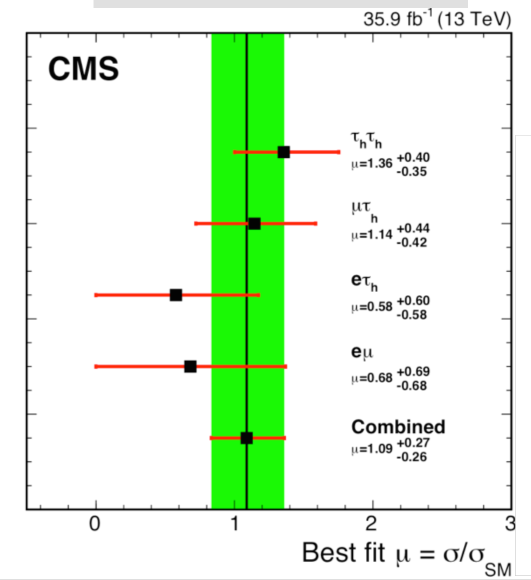
Couplings to Fermions: H → ττ

- Search for H → ττ with ττ decaying in eμ, μτ$_h$, eτ$_h$ and τ$_h$τ$_h$
- Largest background from Z→ ττ and hadronic multi-jet events
- Search in categories aiming at ggH and VBF production

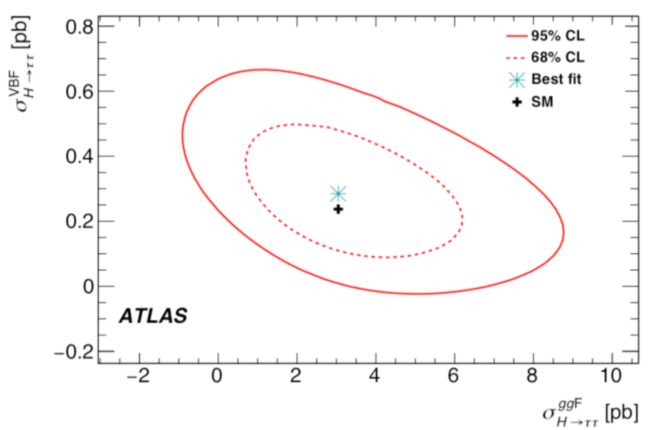




Phys. Lett. B779 (2018) 283



Phys. Rev. D99 (2019) 508



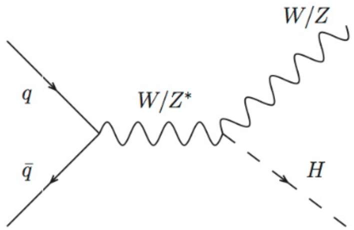
Observation of H → ττ

Significance:

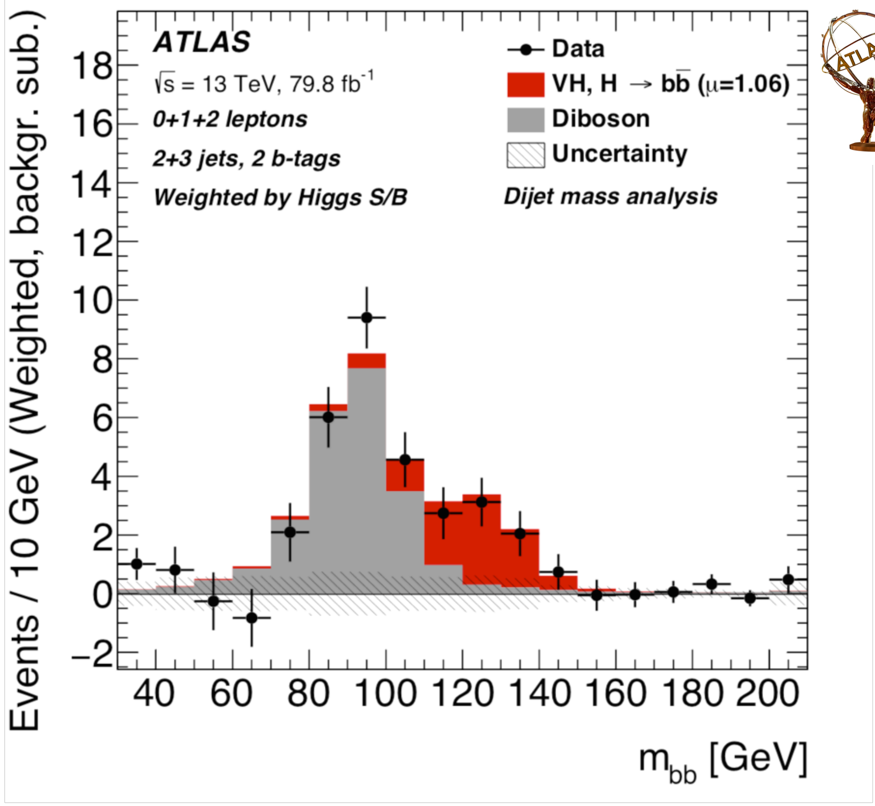
CMS: 5.9σ
ATLAS: 6.4σ
(combination of Run-1 and Run-2 data)

Observation of H → bb decays

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



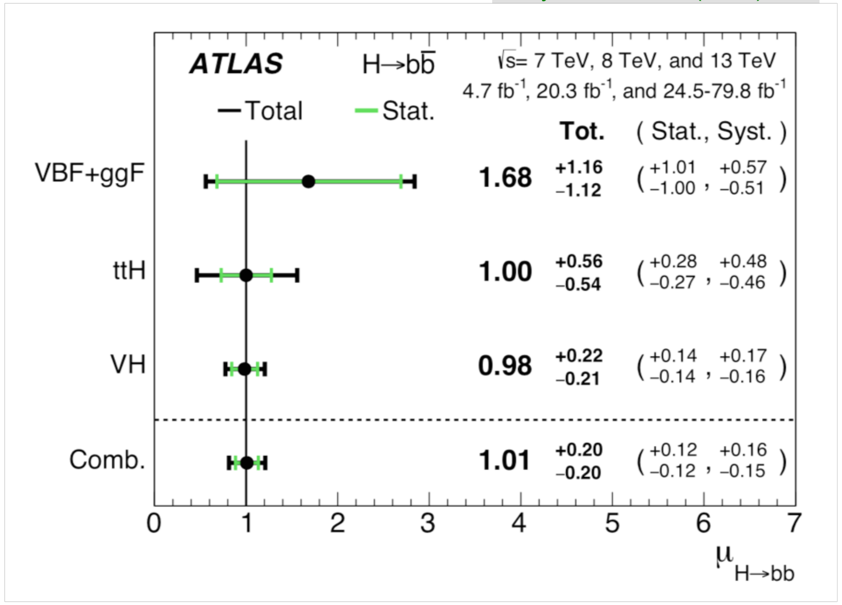
Phys. Lett. B786 (2018) 59



- 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. Lett. B786 (2018) 59

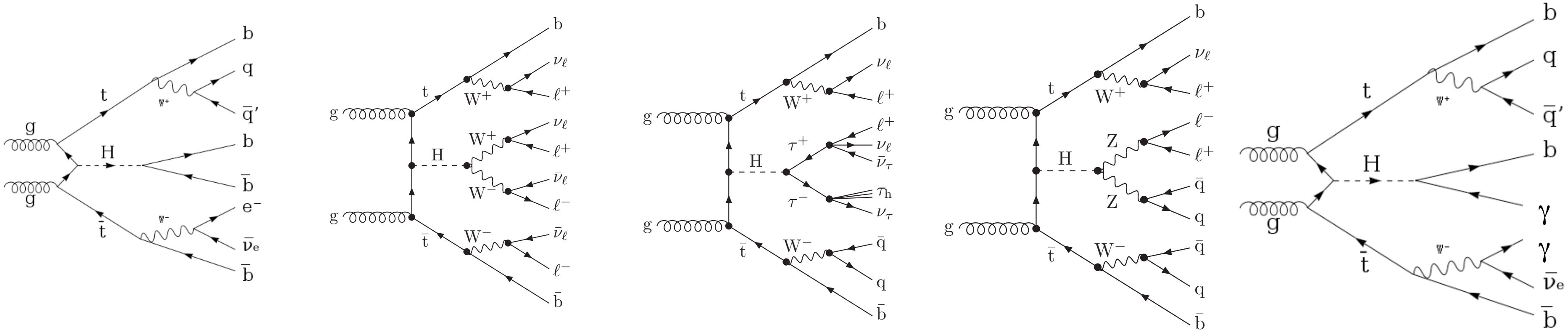


$\mu = \sigma_{meas} / \sigma_{SM}$

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

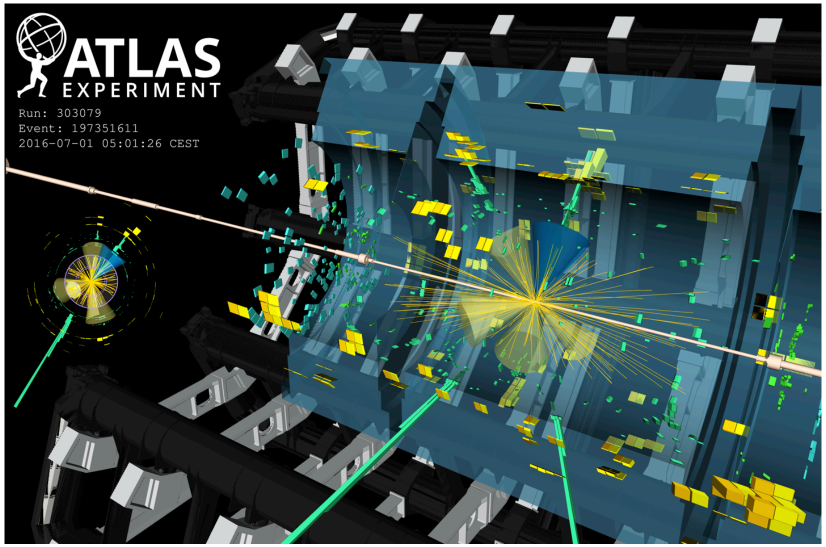
Search for ttH Production

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



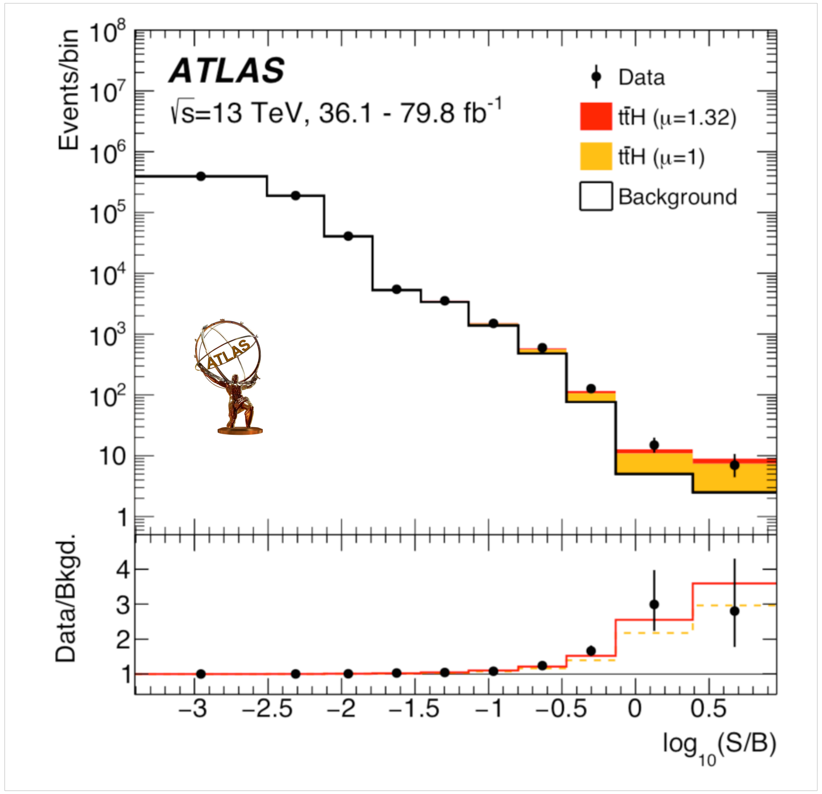
H → bb   H → WW*   H → τ τ   H → ZZ   H → γ γ

multi-lepton channels (ML)

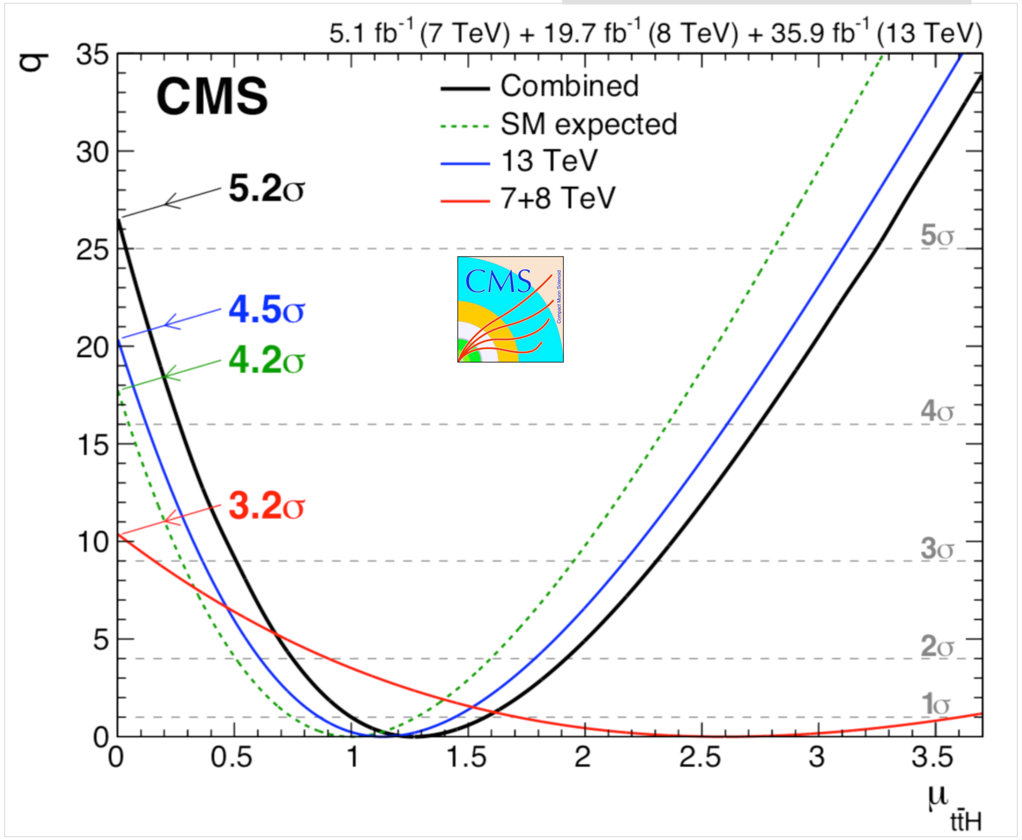


Observation of ttH production

Phys. Lett. B784 (2018) 173



Phys. Rev. Lett. 120 (2018) 231801



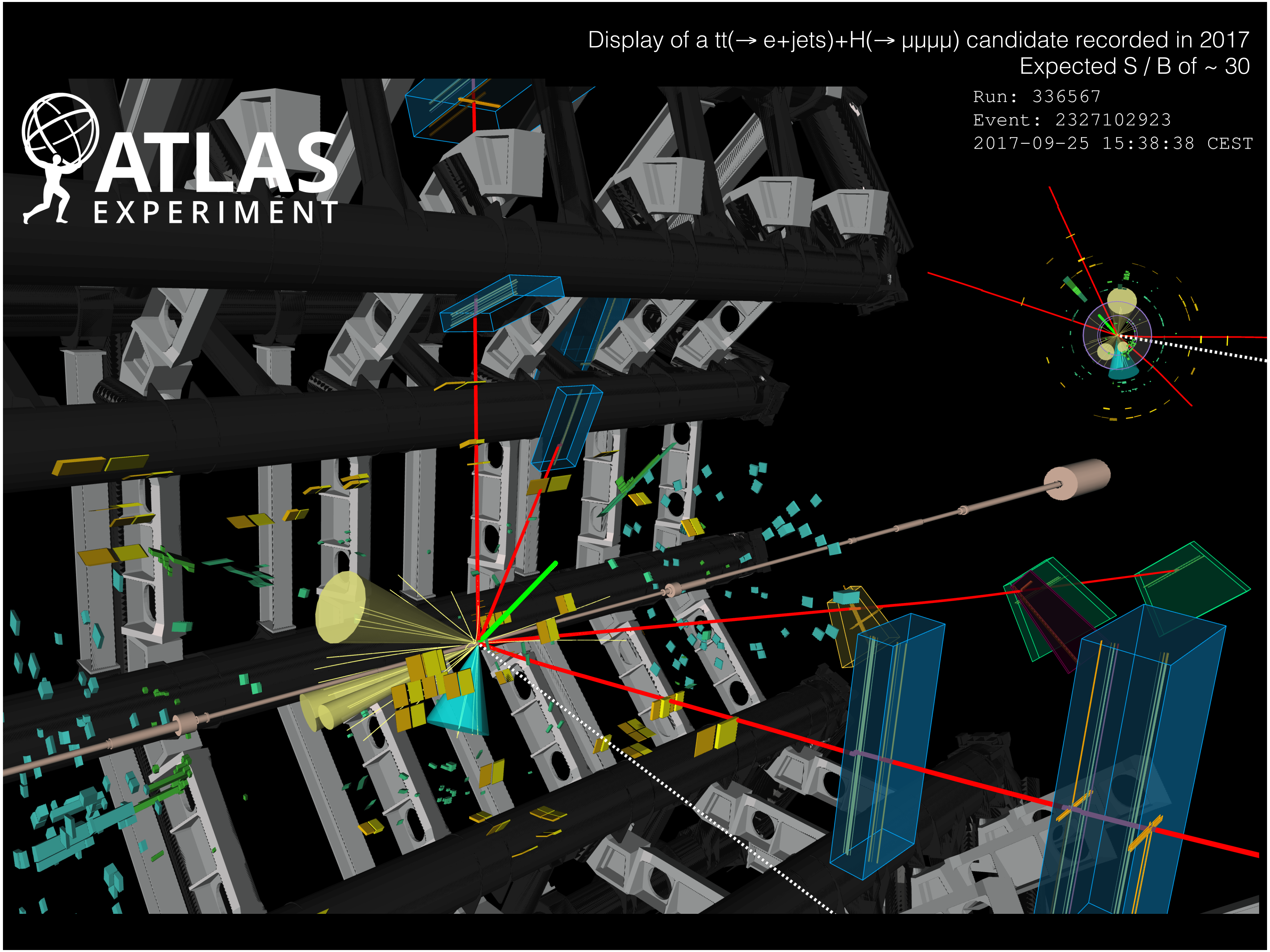
- **Combination of all channels** leads to observation of ttH production in both experiments (2018)

- Measured production and decay rates consistent with SM expectation

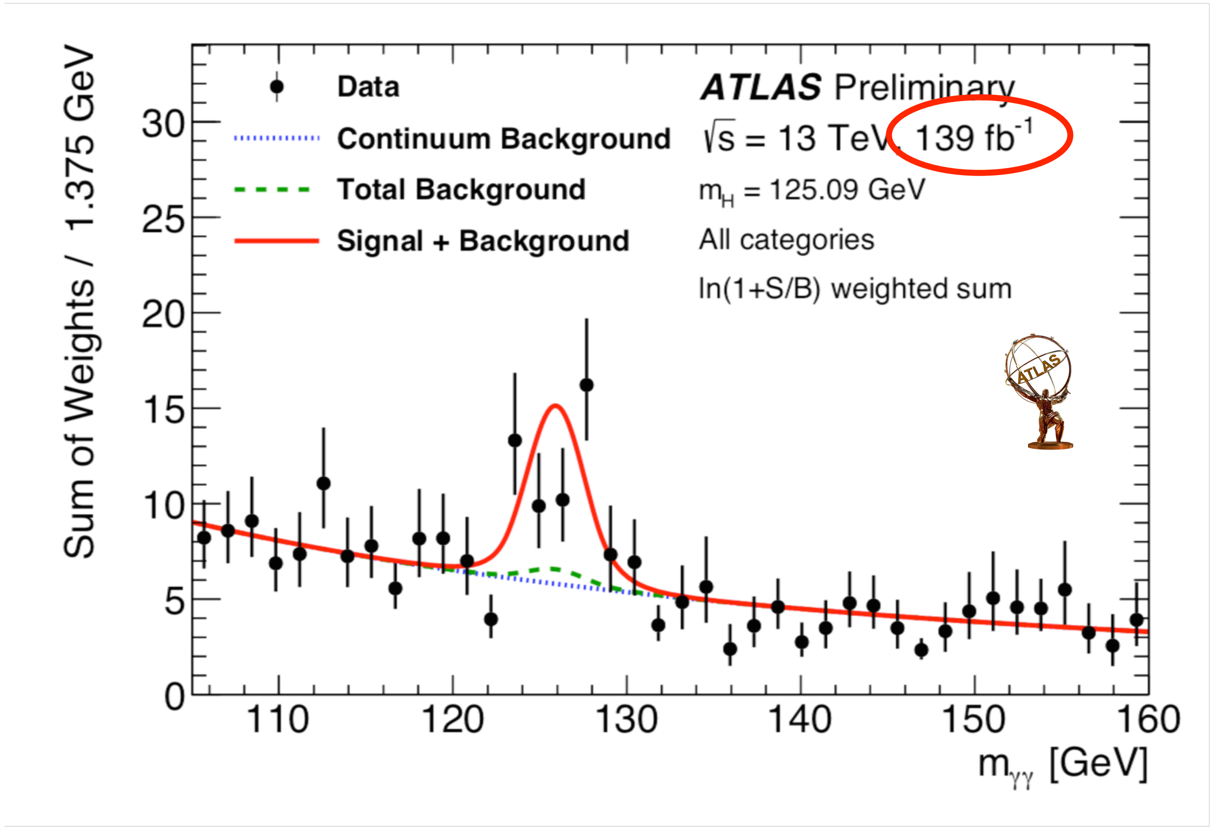
CMS observation of ttH production:
(combination of Run-1 and Run-2 data)

μ = 1.26

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


Display of a tt(→ e+jets)+H(→ μμμμ) candidate recorded in 2017
Expected S / B of ~ 30
Run: 336567
Event: 2327102923
2017-09-25 15:38:38 CEST
ATLAS
EXPERIMENT

Including the 2018 data for H→ γγ



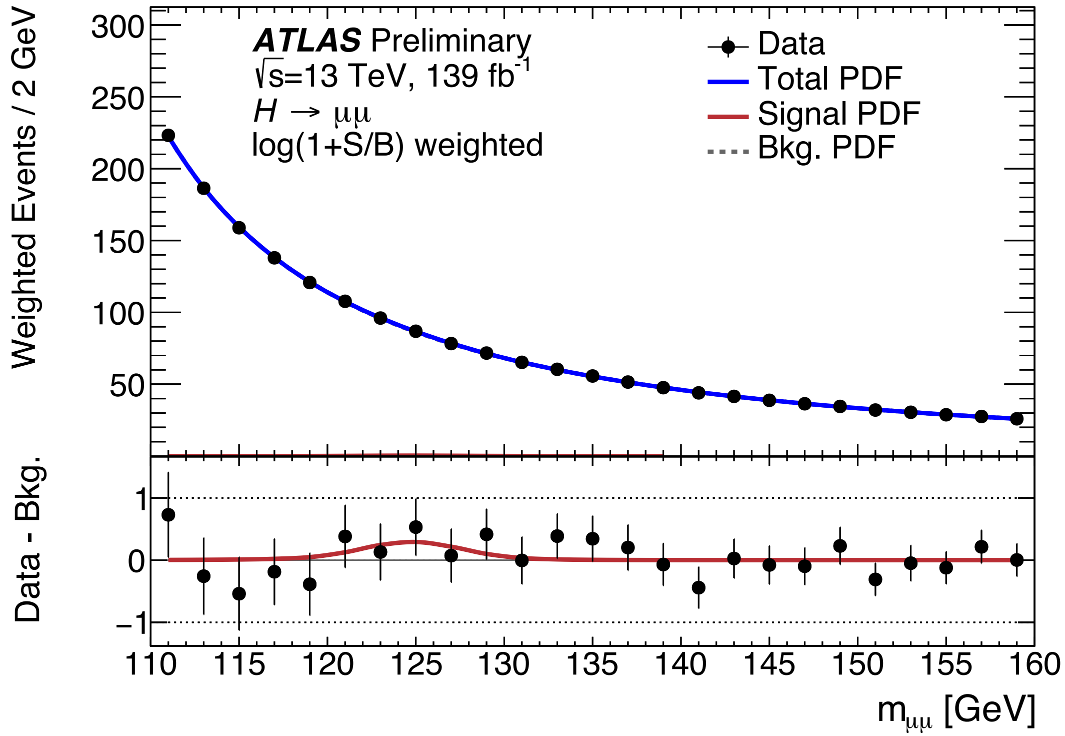
Higgs signal appears in ttH production with decays into $\gamma\gamma$

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

The next frontier: the 2nd generation H → μμ

- Challenging, due to small couplings in the SM and large backgrounds
- Perform fit using event categorization and BDTs for discrimination
- Expected sensitivity: 1.5σ, observed 0.8σ

ATLAS-CONF-2019-028



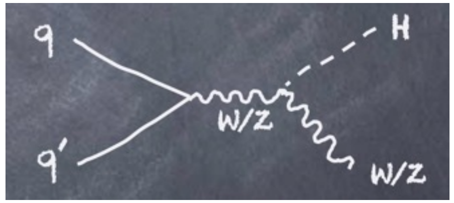
$\sigma_{obs} / \sigma_{SM} = 0.5 \pm 0.7$

Run-3 data will be important!

The next frontier: the 2nd generation   H → cc

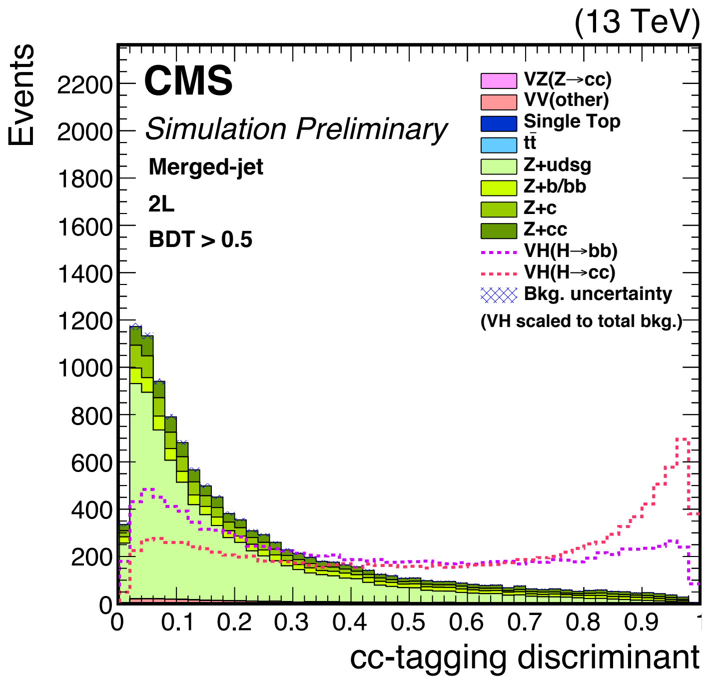
Search for VH(→ cc), new result from CMS, significantly improved over previous ATLAS limit

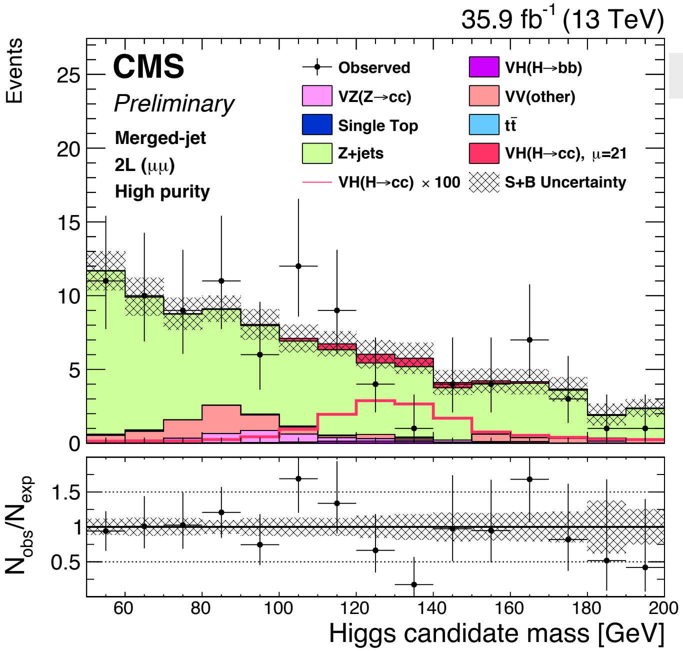
BR: 2.9% → 20 times smaller than bb, so need to worry about H → bb background



Challenging due to low cross section and need for c-tagging

- Categorisation according to charged-lepton multiplicity of V decays (0,1, 2l)
- Use and combination of of resolved (2c) and merged (1 large-R cc) jets
- Use of ML and jet substructure for tagging and classification





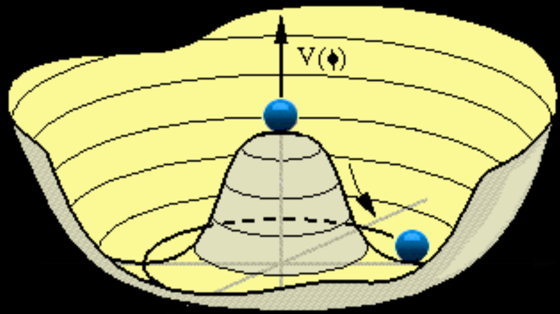
CMS-PAS-HIG-18-031

Combined 95% CL upper limit:

$\sigma \times BR / SM < 70$

(37^{+16}_{-11} expected)

Properties of the Higgs Boson



- Mass

  → Couplings to bosons and fermions

- Higgs-boson self coupling (?) → HL-LHC

Higgs boson mass

The two high-resolution channels H → ZZ* → 4ℓ and H → γγ are best suited (reconstructed mass peak, good mass resolution)

Combined results:

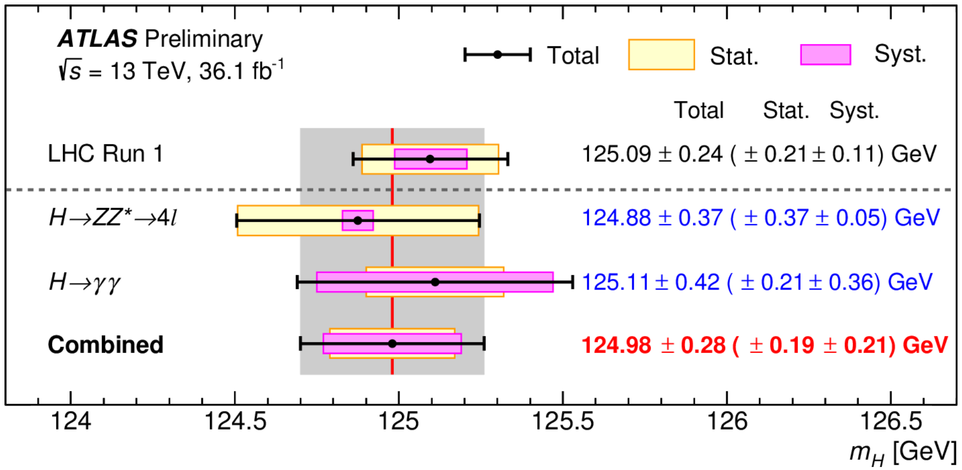
PRL 114 (2015) 191803

ATLAS + CMS: (Run 1)

m_H = 125.09 ± 0.21 (stat) ± 0.11 (syst) GeV

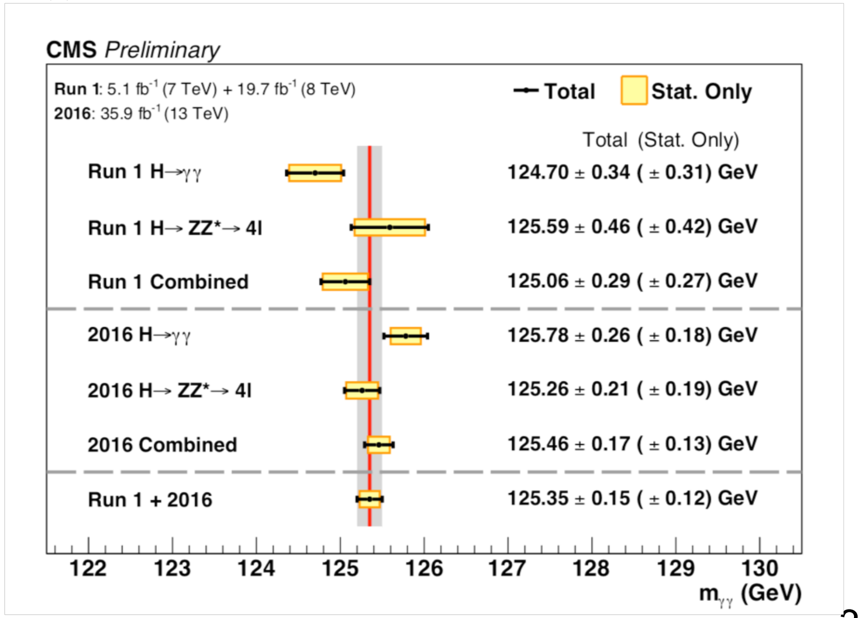
Precision of 0.2%

Updated Run-2 results:



Uncertainties:

- Statistical uncertainty still dominant
- Major systematic uncertainties: Lepton and photon energy scales and resolutions
- Theoretical uncertainties small (correlated), γγ interference effects neglected

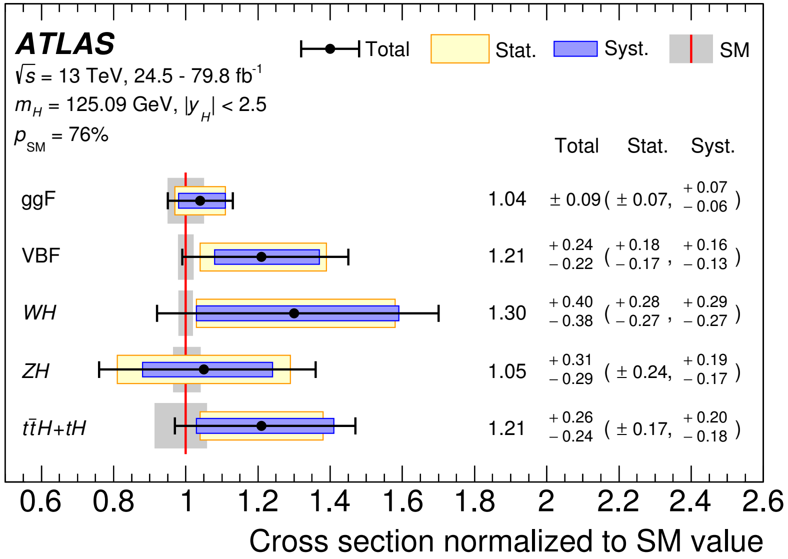


Updated Combination of Higgs boson results

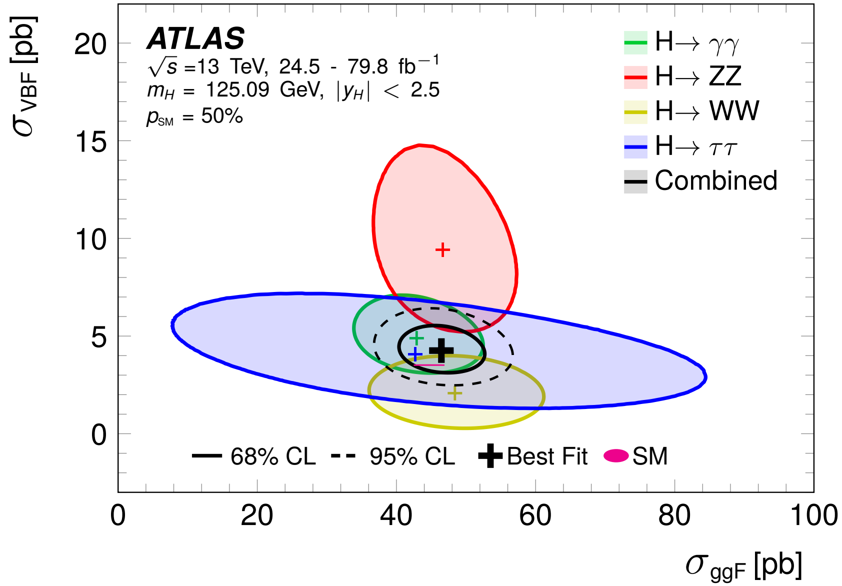
- incl. 2015 – 2017 data for some important channels-

Higgs boson production

arXiv: 1909.02845



arXiv: 1909.02845



Global signal strength: $\mu = 1.11^{+0.09}_{-0.08}$

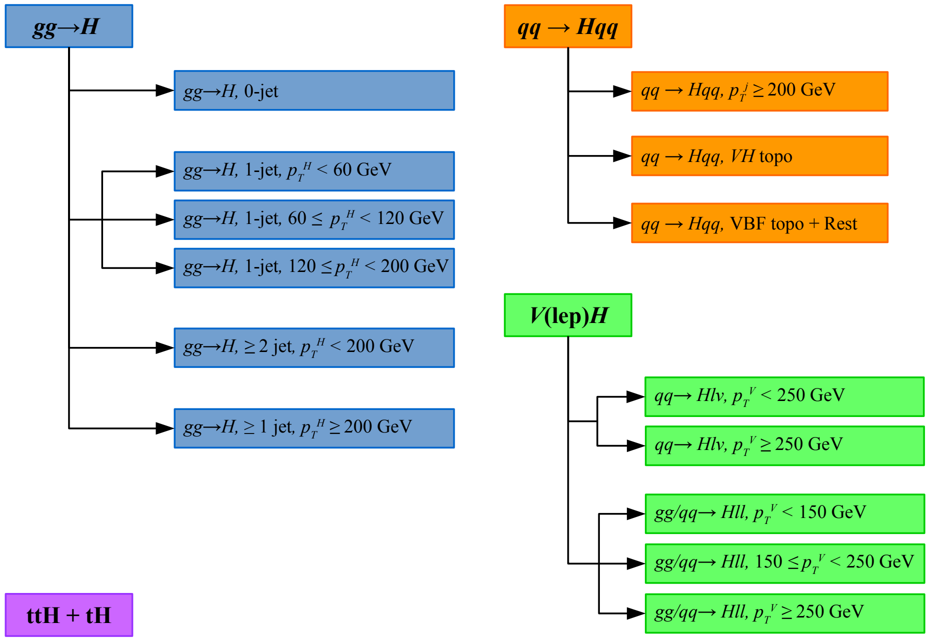
Combined significance for **vector-boson fusion production** process of 6.5σ (exp., 5.3σ)

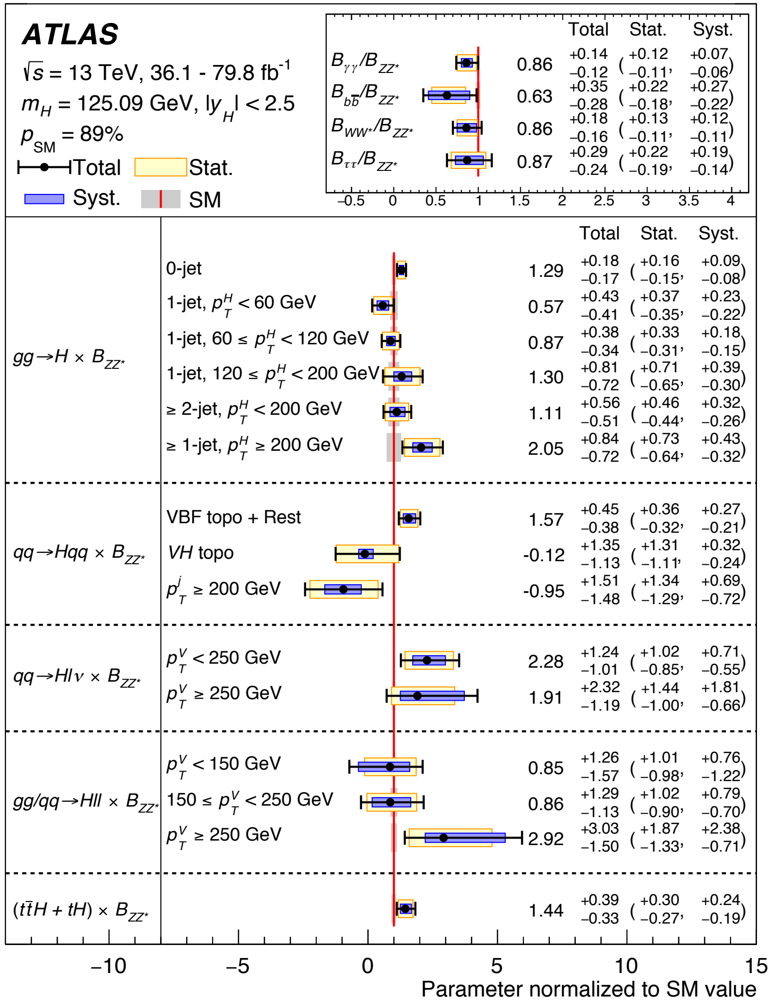
Run-1 result (ATLAS+CMS): $\mu = 1.11 \pm 0.11$

First full combination based on template cross sections (reduced theory uncertainty)

Updated Combination of Higgs boson results

arXiv: 1909.02845

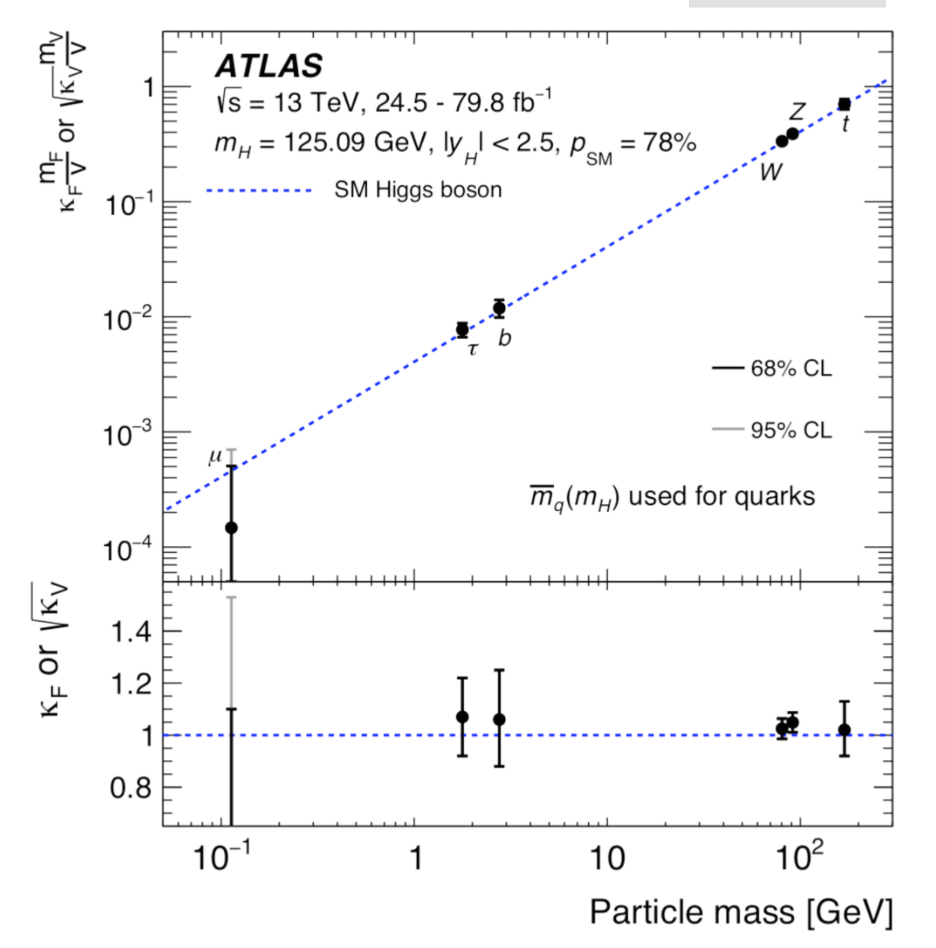




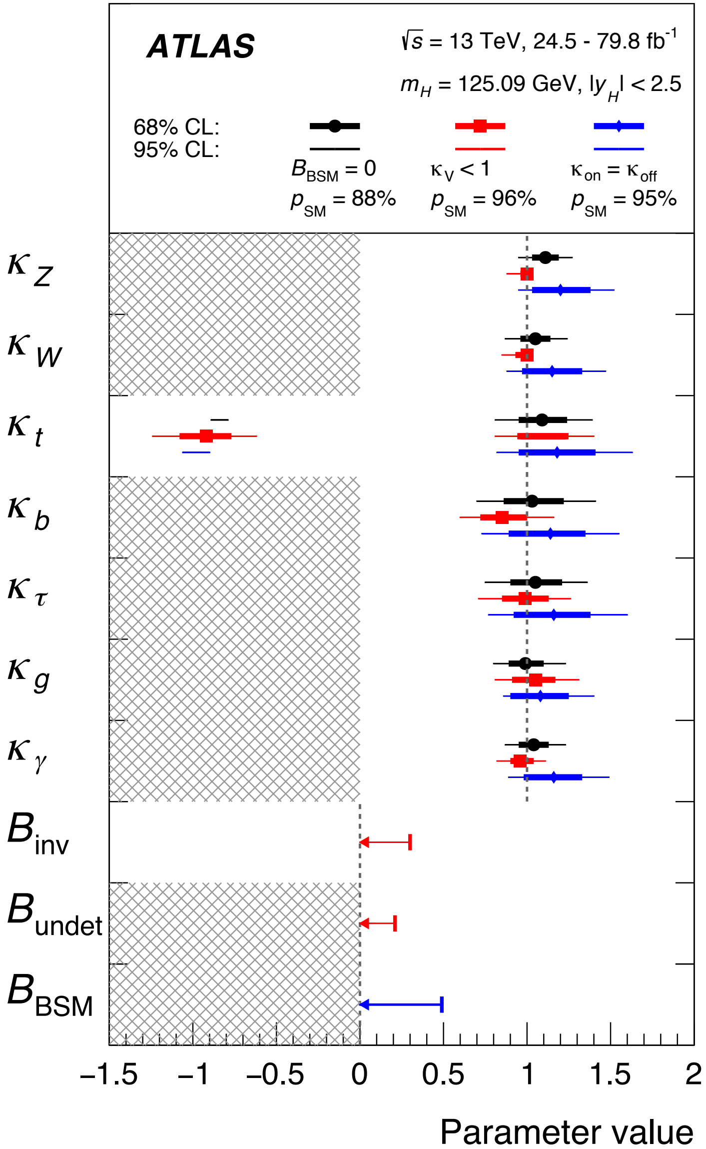
First full combination based on template cross sections (reduced theory uncertainty)

Updated Combination of Higgs boson results

arXiv: 1909.02845



arXiv: 1909.02845



First full combination based on template cross sections (reduced theory uncertainty)

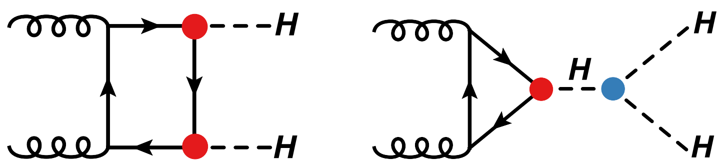
Di-Higgs boson production

HH ggF cross section predicted to 34 fb at 13 TeV,
>1000 times smaller than single Higgs production

Sophisticated analyses needed, room for innovation

Best channels: bb $\gamma\gamma$ (BR = 0.26%), bb $\tau\tau$ (7.3%), bb bb (34%)
$\rightarrow$ combination

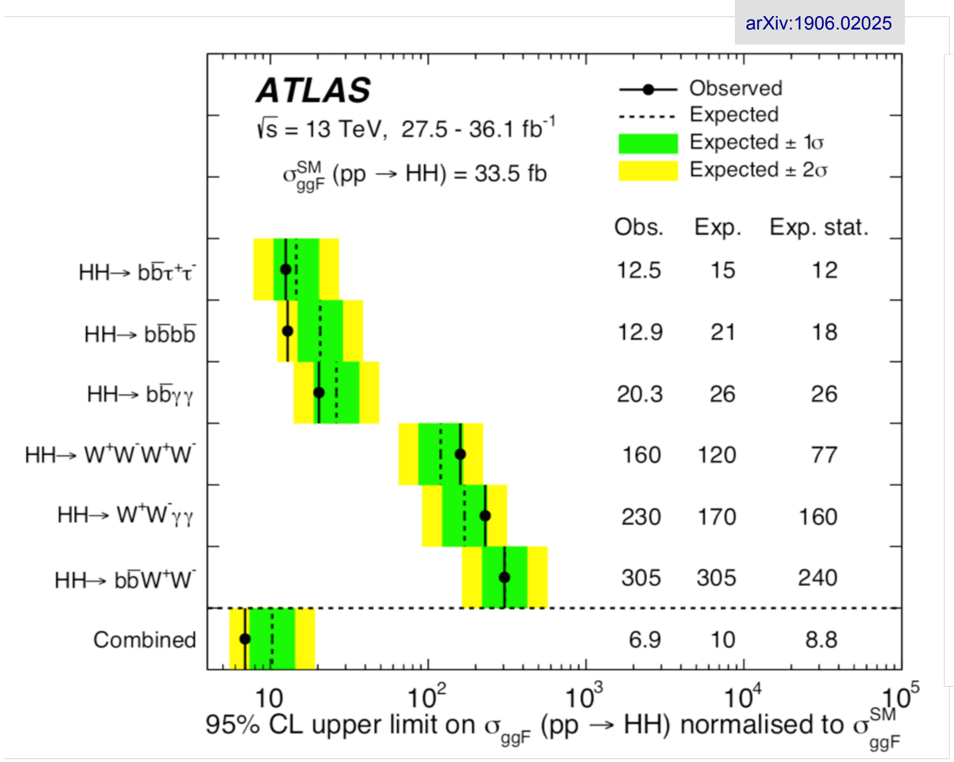
ATLAS combination using 36 fb^{-1} analyses:

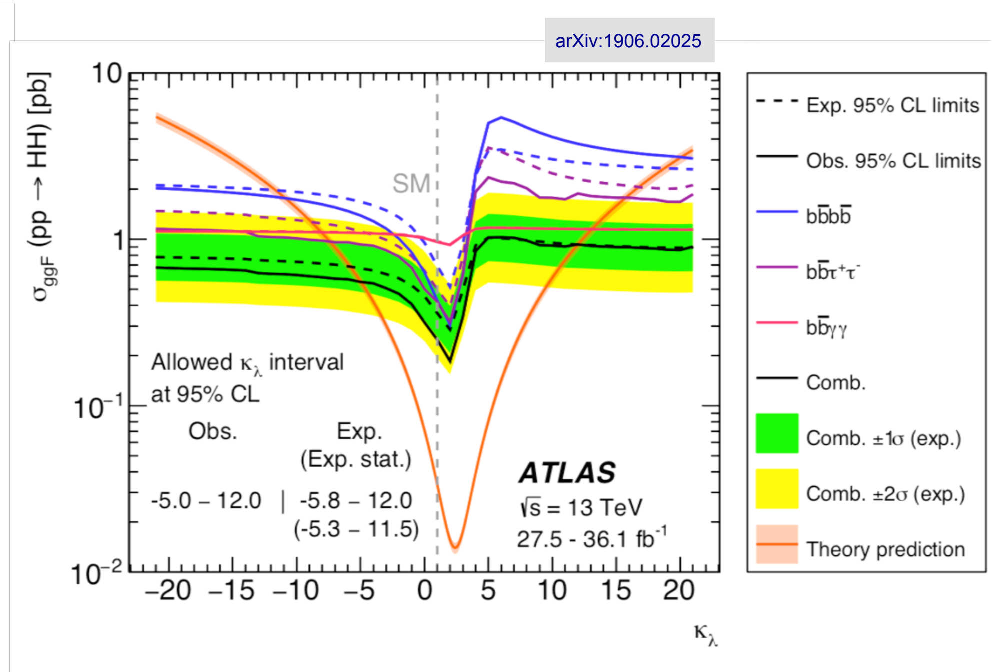


LO diagrams contributing with negative interference to SM HH production

Box diagram dominates inclusive production

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



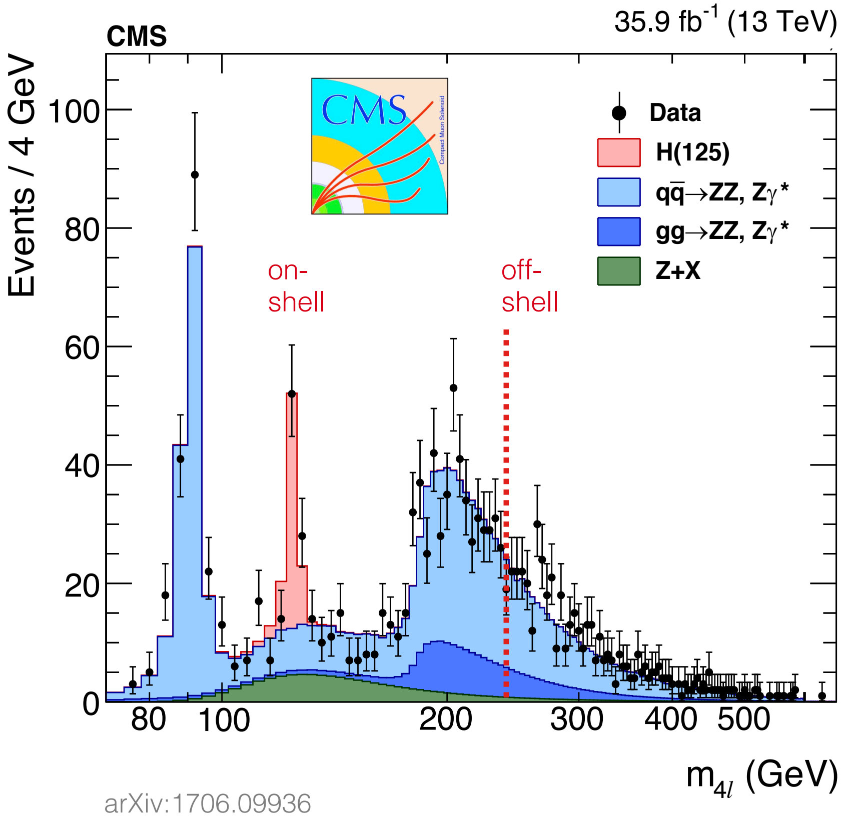


Combined fit yields 95%C.L. limits
$-5.0 < \lambda_{HHH}$ (obs.) / λ_{HHH} (SM) < 12.0

Constraints the Higgs boson width

Both CMS and ATLAS have constrained the Higgs boson off-shell coupling and through this obtained upper limits on the Higgs boson total width Γ_H.

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 $\mu_{\text{on-shell}}$



arXiv:1706.09936
(for illustration only, not the measurement reported here)

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

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

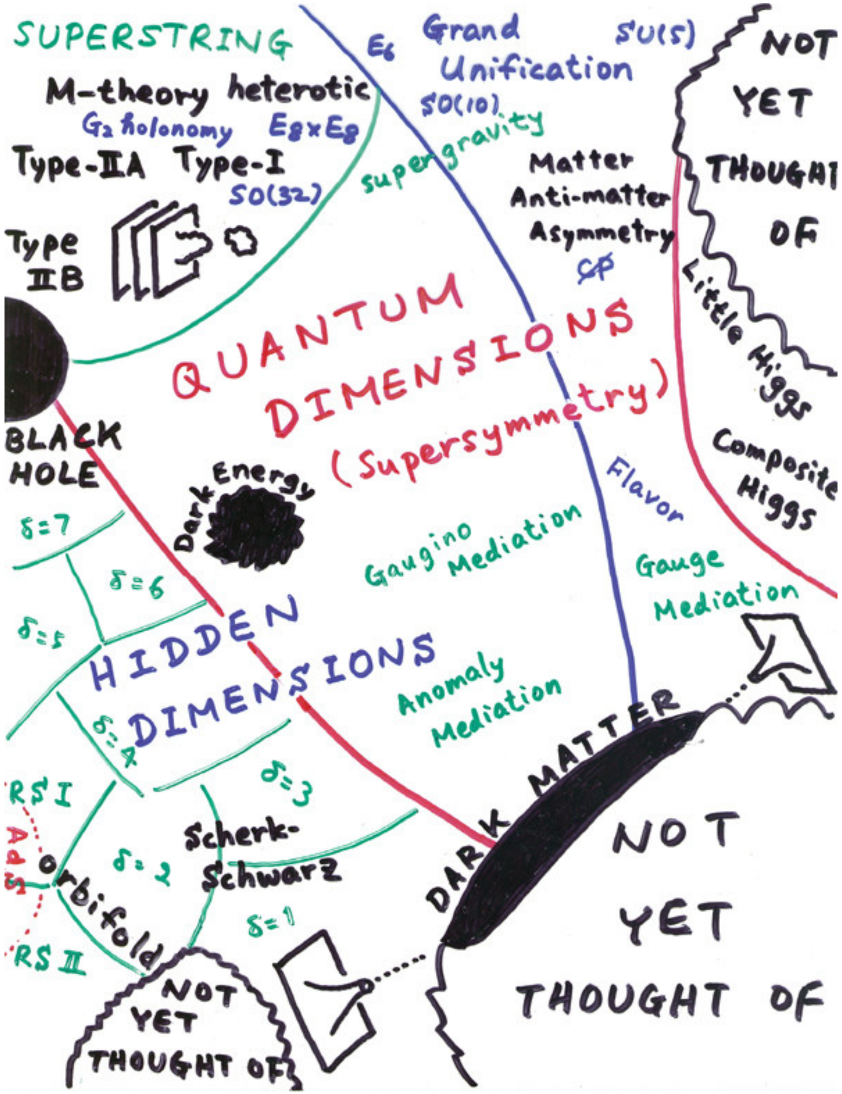
Newest result from CMS using 80 fb^{-1} and exploiting matrix element techniques to separate production modes yields: arXiv:1901.00174

$\Gamma_H < 9.2$ MeV at 95% CL ($\Gamma_{H,SM} = 4.1$ MeV)

Best fit: $\Gamma_H = 3.2\ ^{+2.8}_{-2.2}$ MeV

Theory uncertainty from gg → ZZ prediction

Search for Physics beyond the Standard Model



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SUSY: Strong production of squarks and gluinos

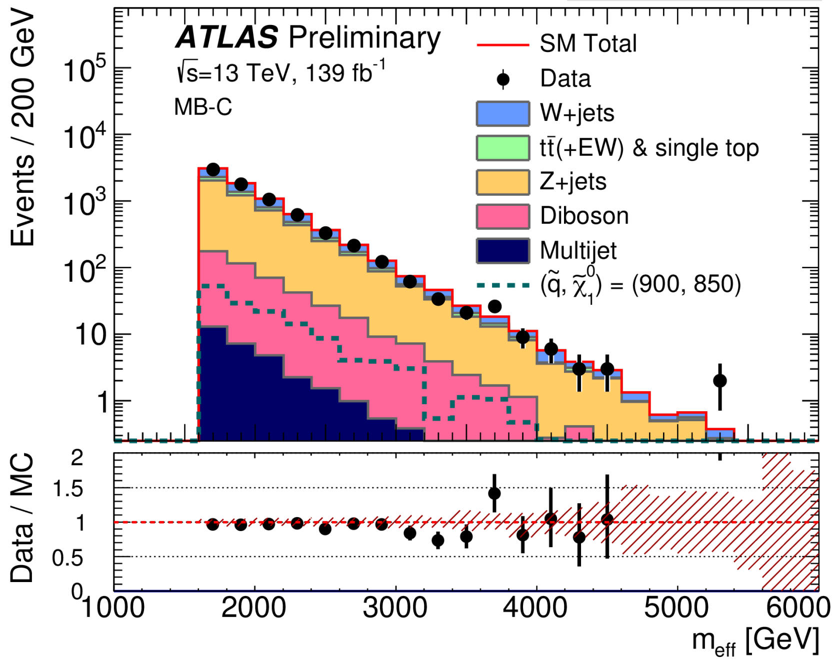
- Sensitive searches for squarks and gluinos in R-parity conserving scenarios with neutralino as LSP (no leptons)

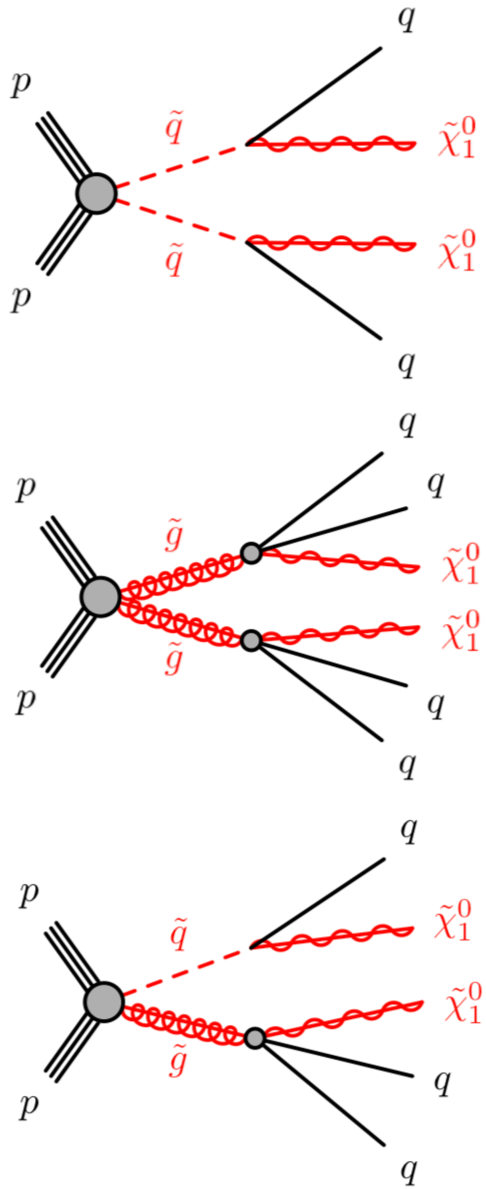
  → high mass reach

- Many different scenarios investigated with cut-based analyses and boosted decision trees

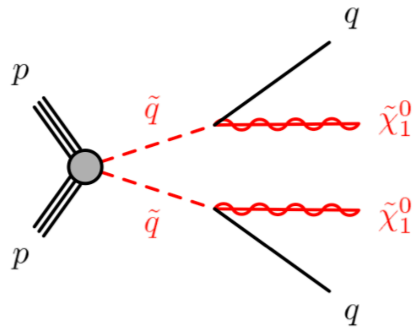
- Effective Mass variable used for some searches:
  M_{eff} = p_T sum of jets (p_T > 50 GeV) and missing p_T

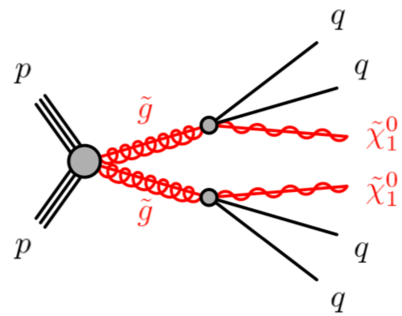
ATLAS-CONF-2019-040

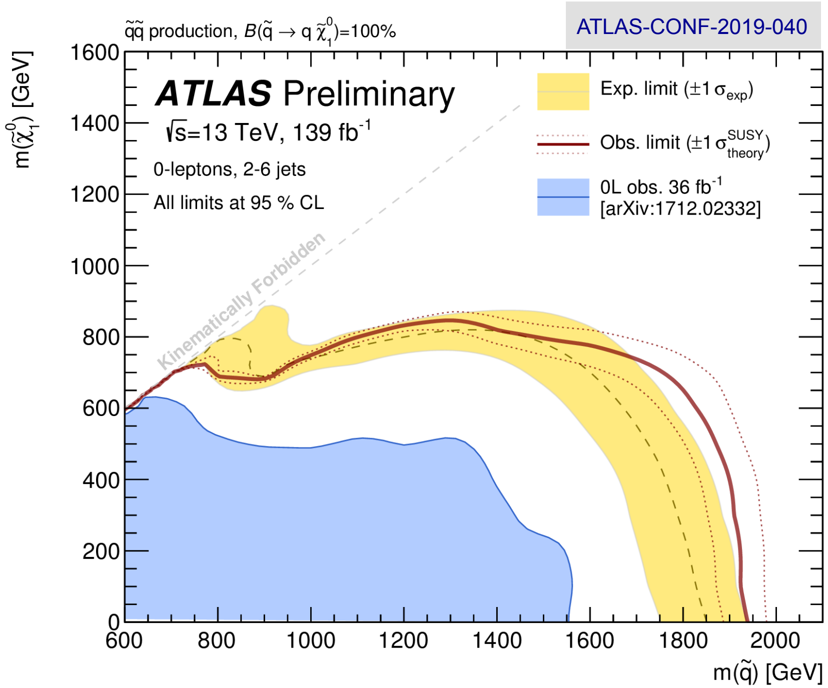


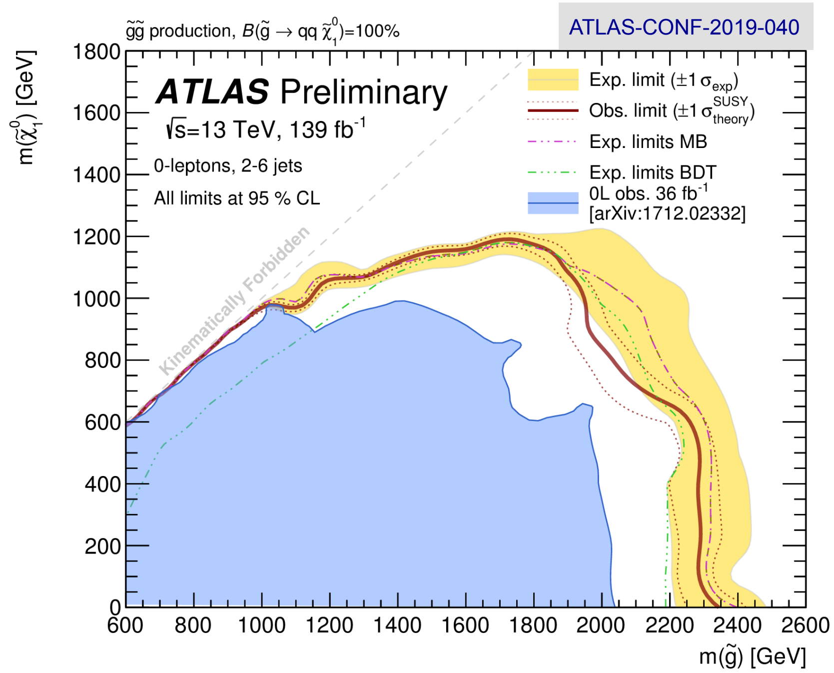


Use simplified scenarios: here squark or gluino decays to quarks and neutralino



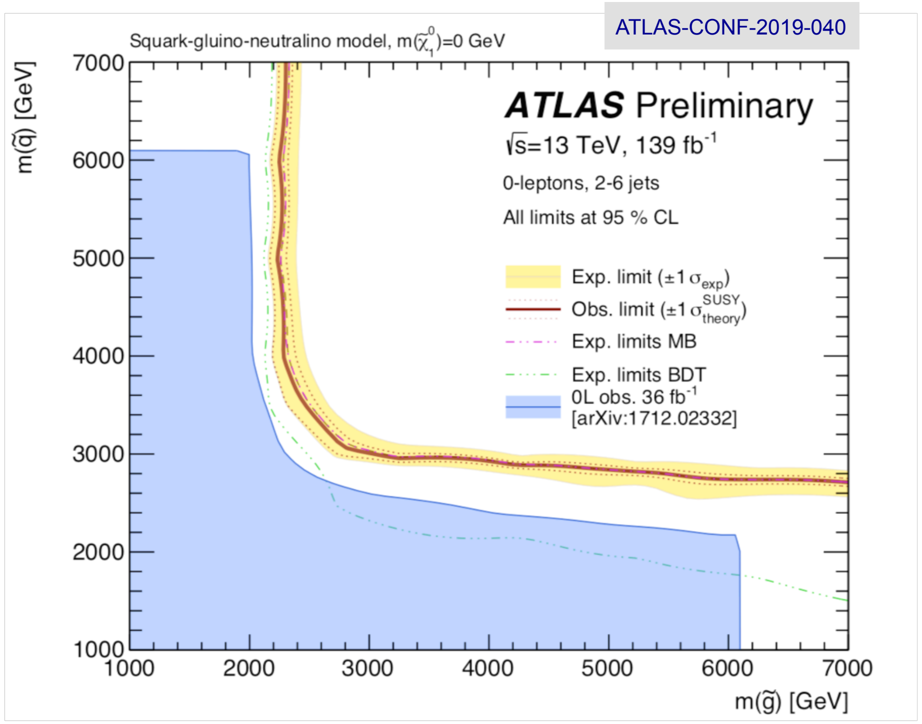


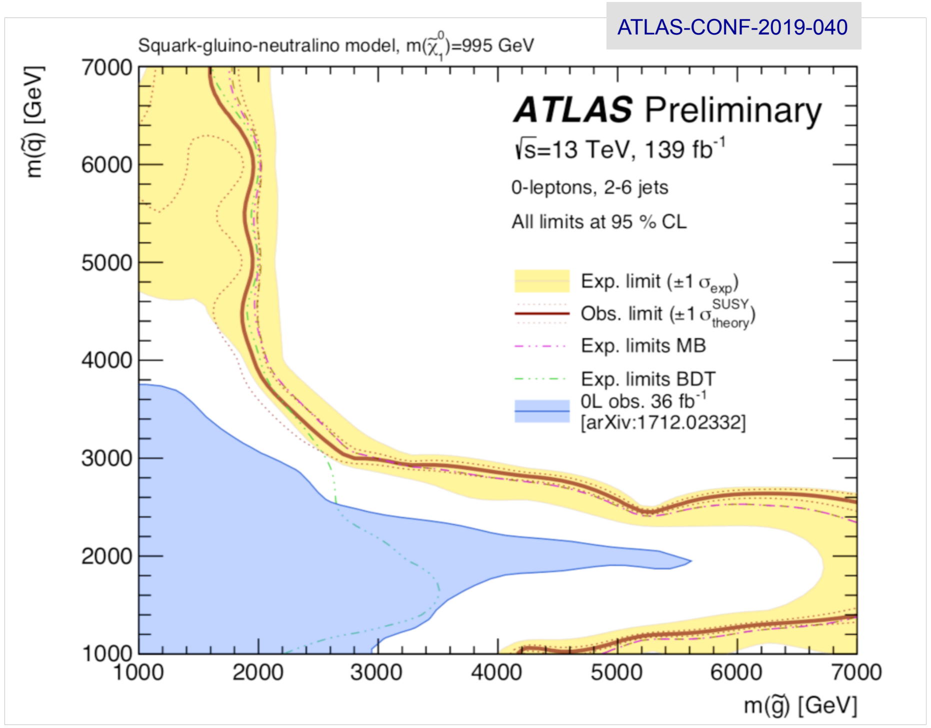




Significant improvement over previous limits;
Gluino mass limit around 2.35 TeV, $m(\chi^0) = 0$

SUSY: Strong production of squarks and gluinos
- neutralino mass dependence -

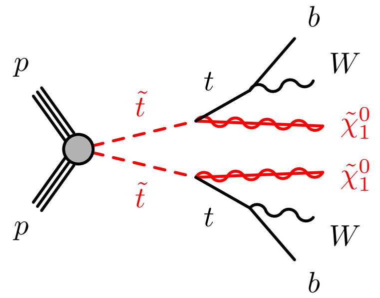


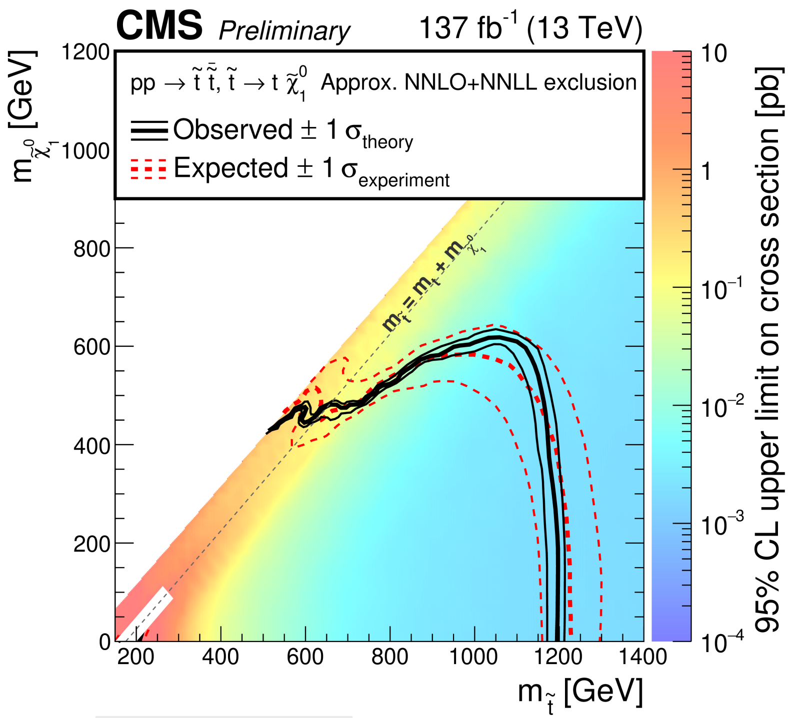


- Significant extension of mass limits with Run-2 data
- Neutralino mass has strong impact on exclusion contours

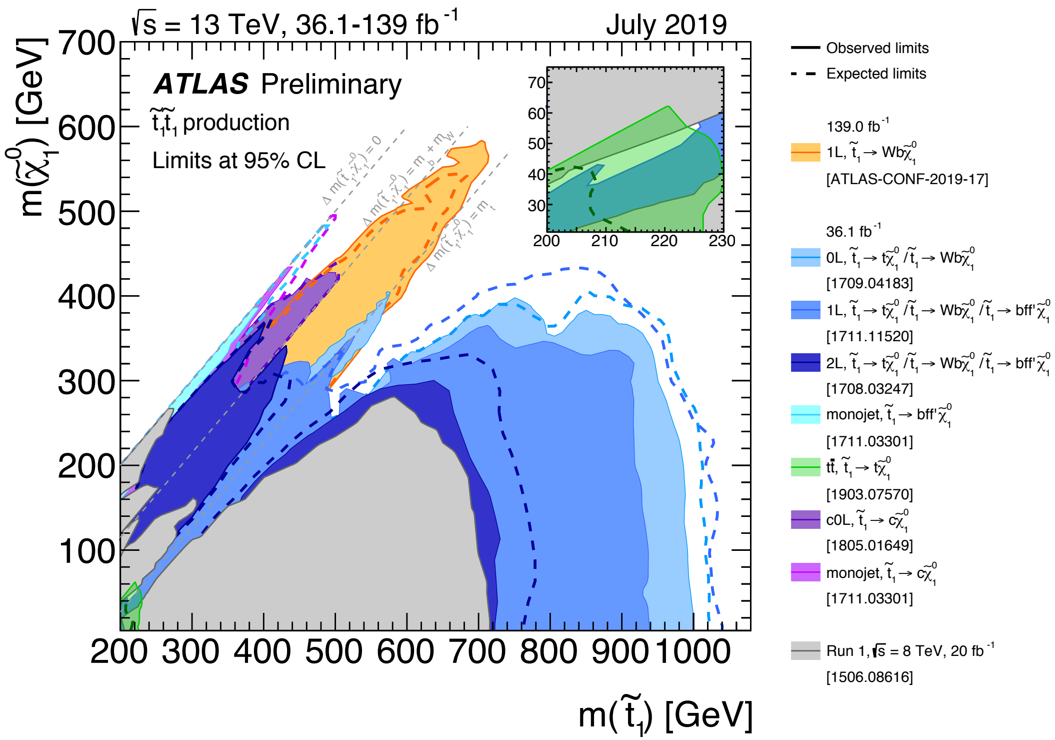
Results on dedicated searches for stop quarks

CMS: full Run-2 search for direct stop production



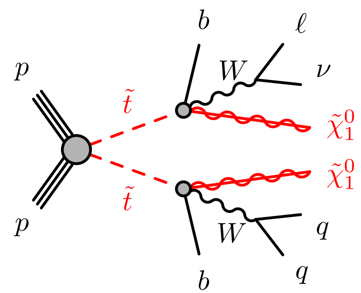


CMS-PAS-SUS-19-009

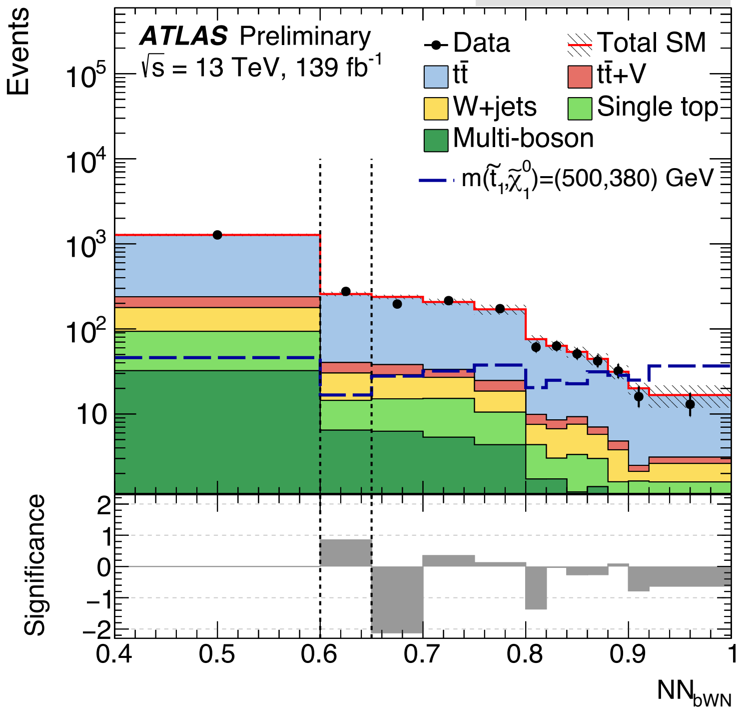


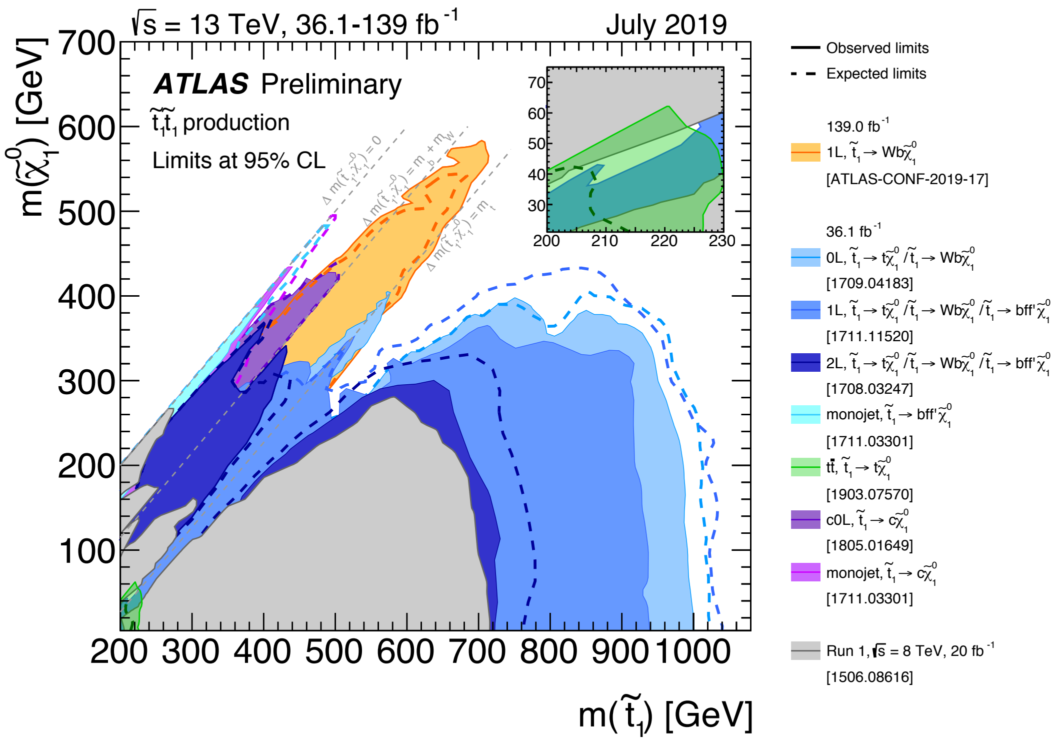
Results on dedicated searches for stop quarks

ATLAS: new stop searches address specific soft ("3-body") region of stop-pair production



ATLAS-CONF-2019-017

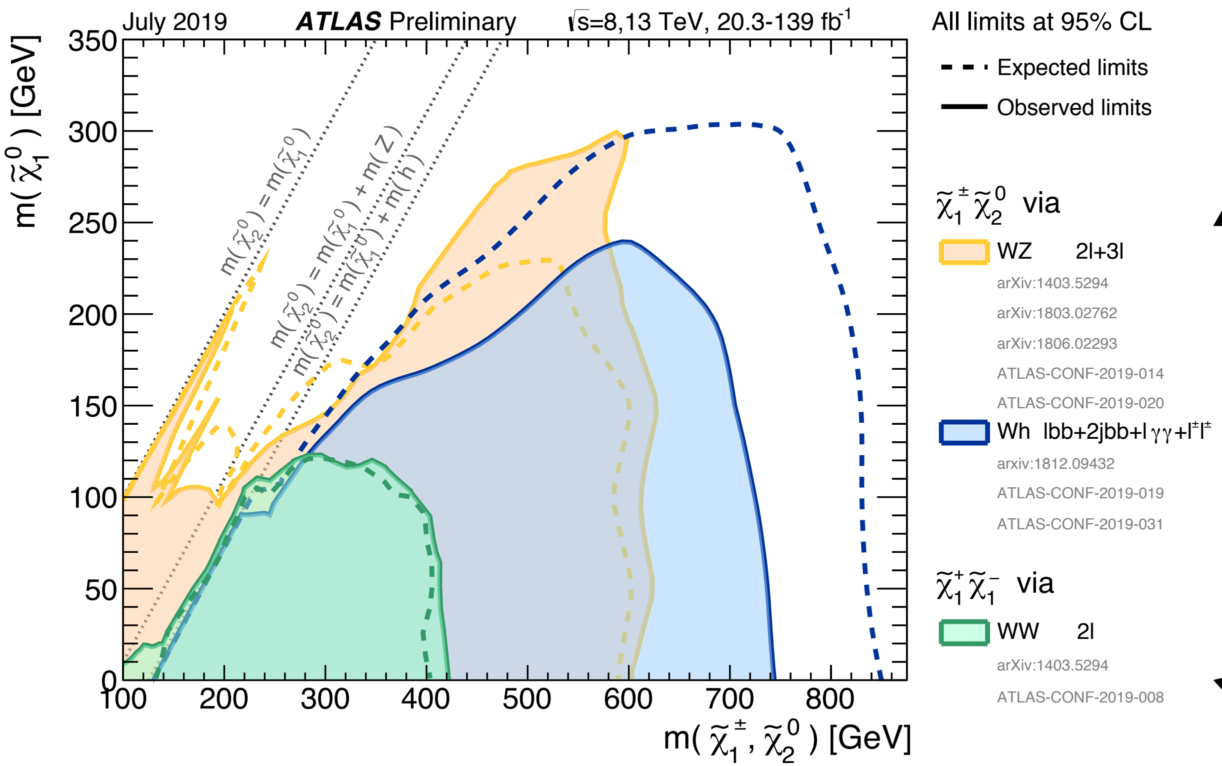


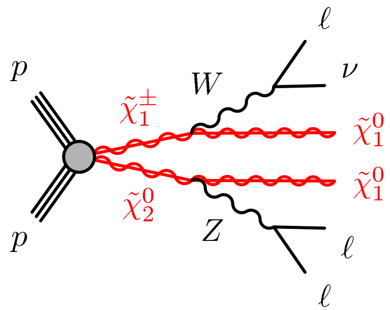


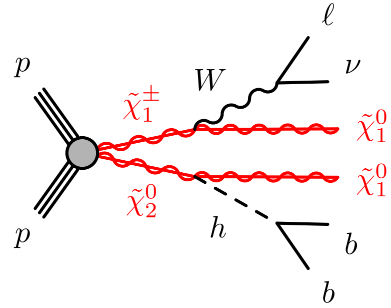
SUSY: Electroweak production

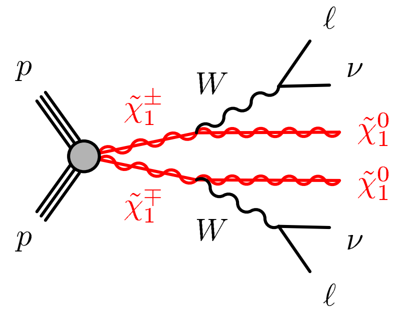
If squarks and gluinos are very heavy, then electroweak production of SUSY particles could dominate → much lower cross sections, challenging phase space to explore

Summary of some recent ATLAS SUSY EWK results with 139 fb^{-1}





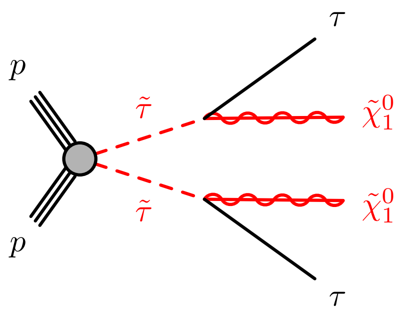




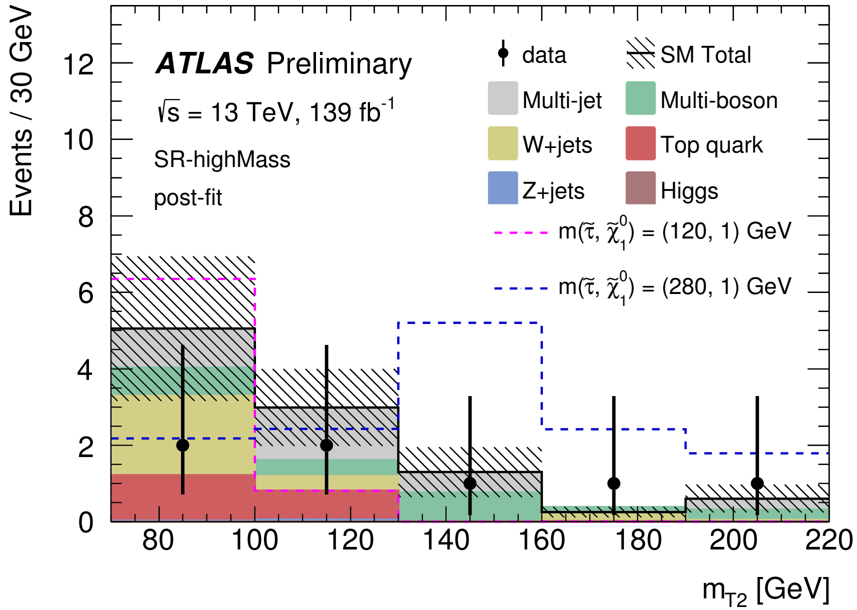
Most favourable case: electroweakino production with decays through light sleptons: exclusion reaches up to 1 TeV (not shown)

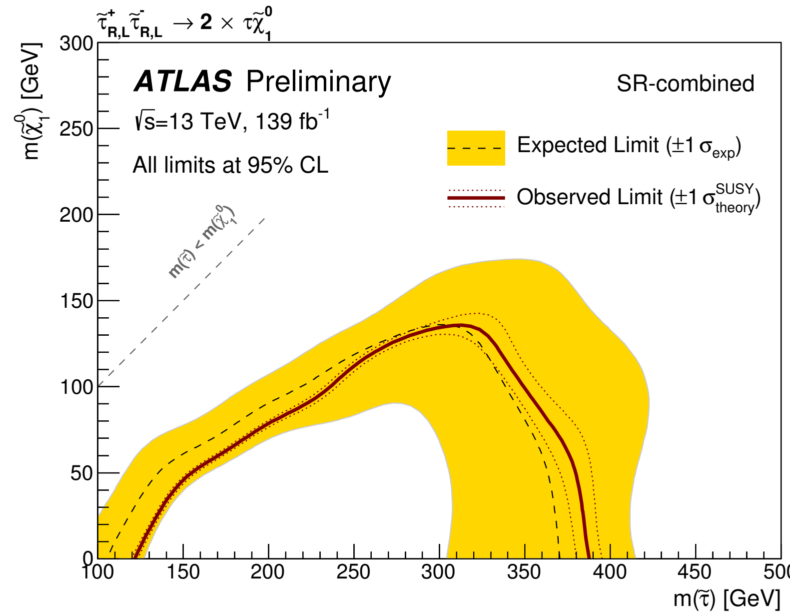
Search for stau pair production

Electroweak SUSY production,
not because it is easy …



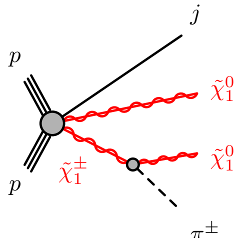
ATLAS-CONF-2019-018

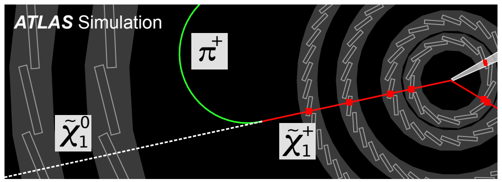


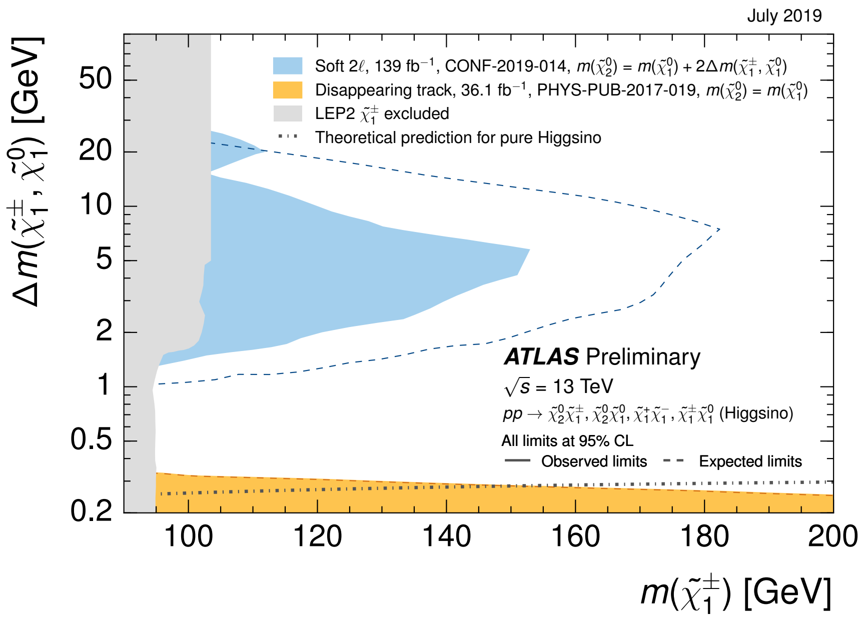


First time sensitivity achieved by ATLAS

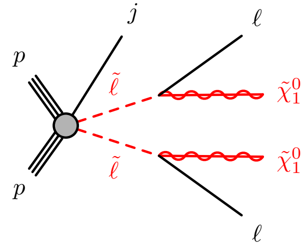
Electroweak SUSY sensitivity beyond LEP limits

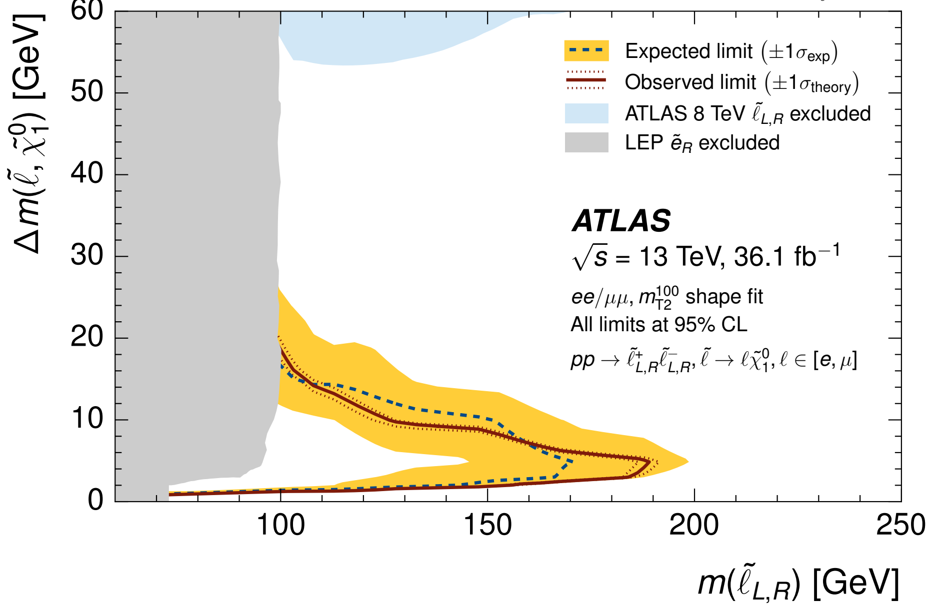






arXiv:1712.08119



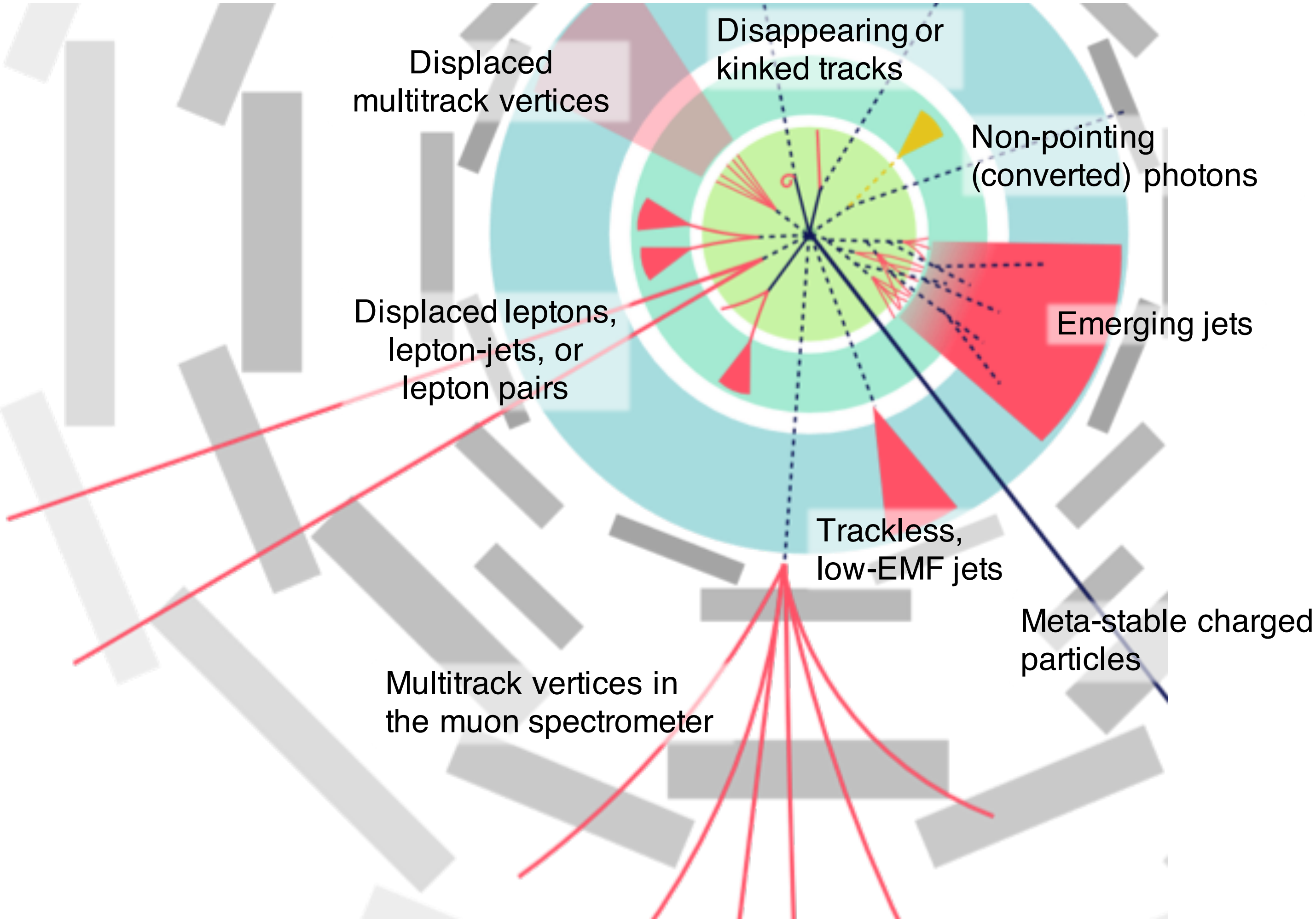


Interesting limits for electroweak SUSY production with compressed mass states
(left): First direct Higgsino constraints from ATLAS (combination of several analyses)

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

Search for Long-Lived Particles

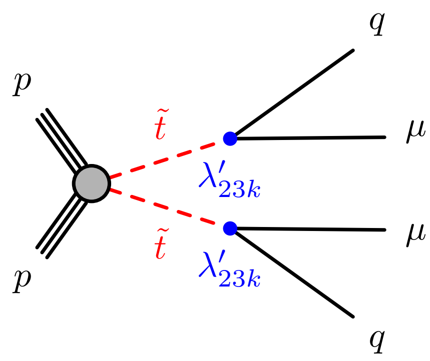
Long-lived particles can occur in case of weak couplings, small phase space (mass degeneracy), high virtuality (scale suppression)



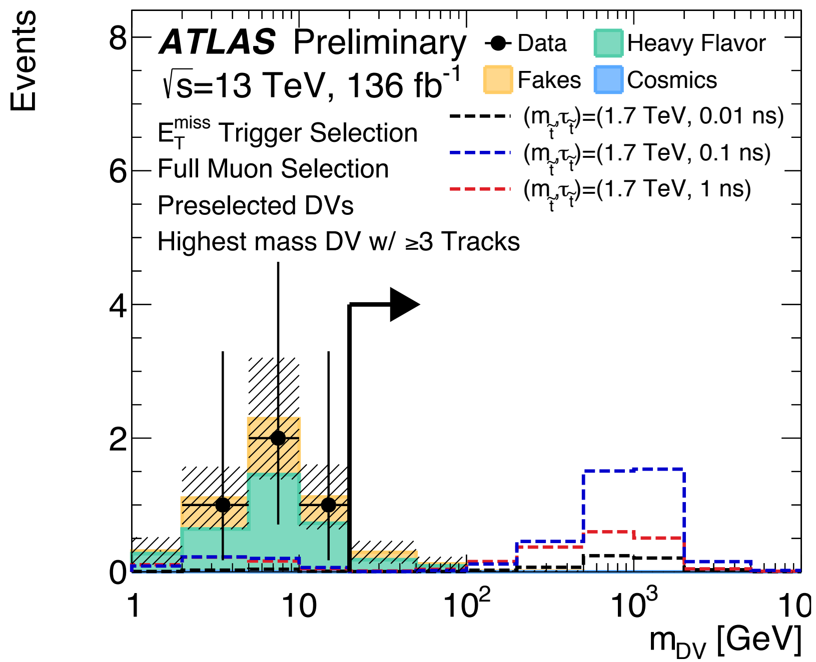
Diverse set of signatures that need to be pursued by dedicated, usually non-standard analyses, some requiring special triggers

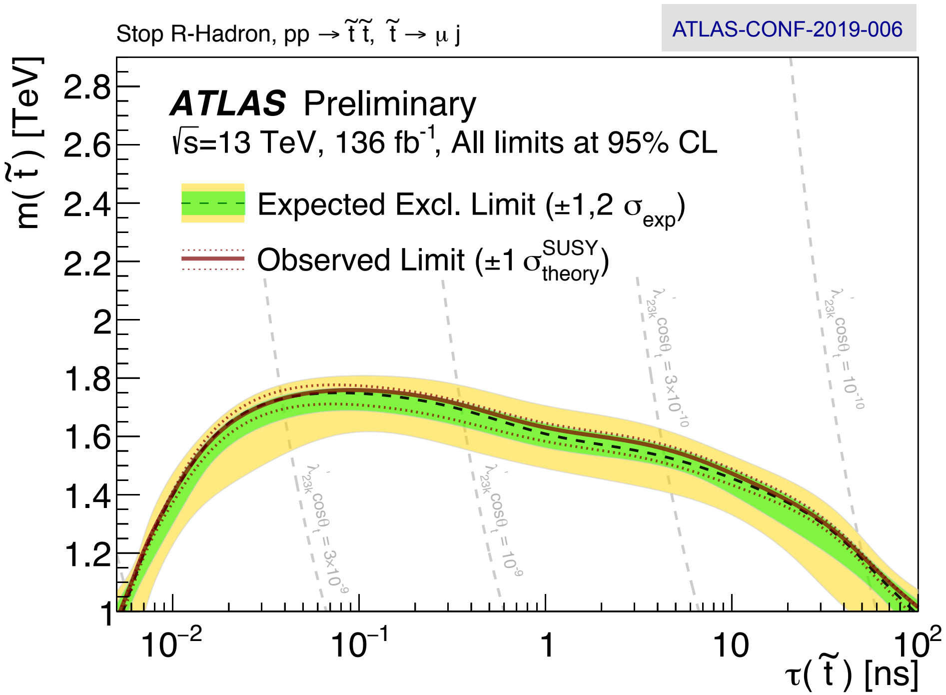
Search for a long-lived particle with displaced vertex and muon

Clean signature of large track multiplicity and vertex mass

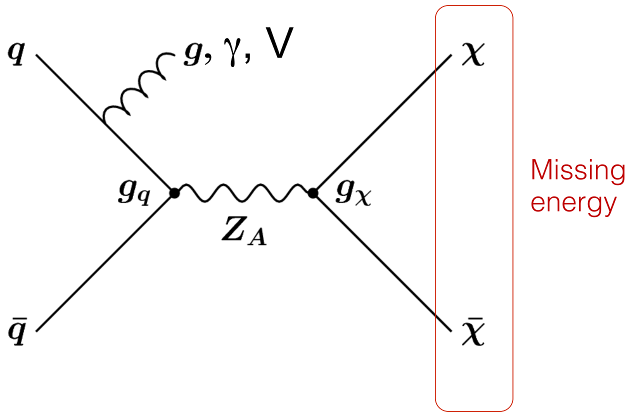


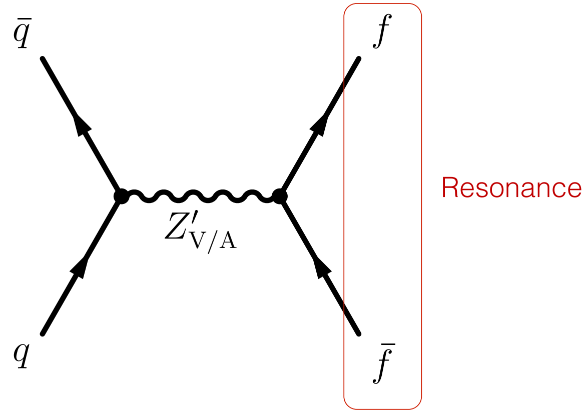
R-parity violating signature with long-lived stop





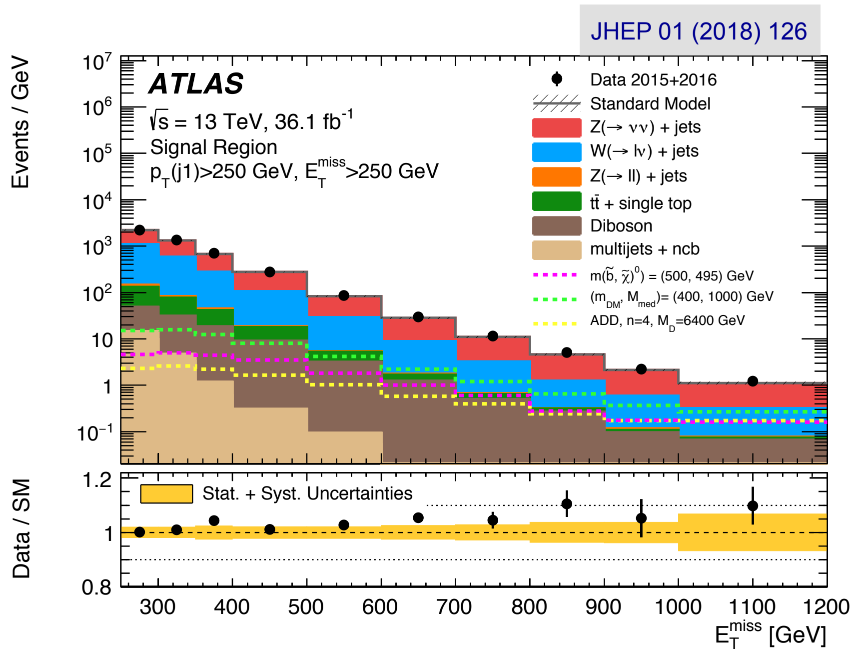
Searches for Dark Matter particles





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

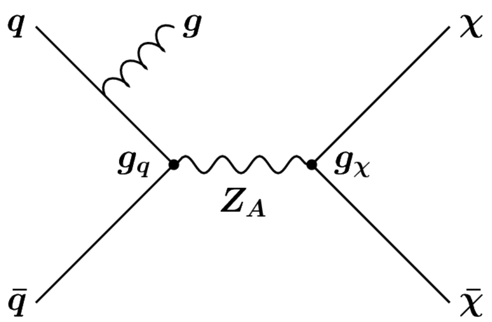
Example: mono-jet search, E_T^{miss} spectrum

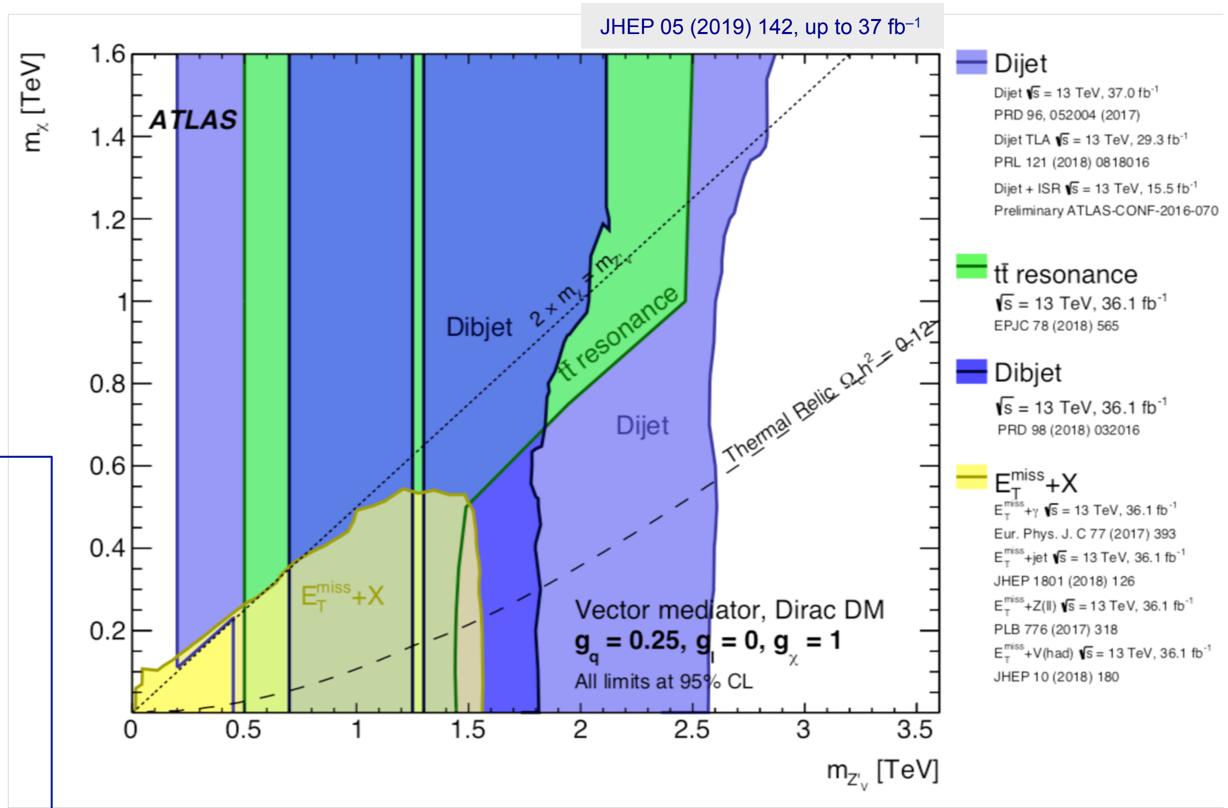


Data are in good agreement with the expectations from Standard Model processes

(applies to all mono-X searches)

Interpretation on searches for Dark Matter:





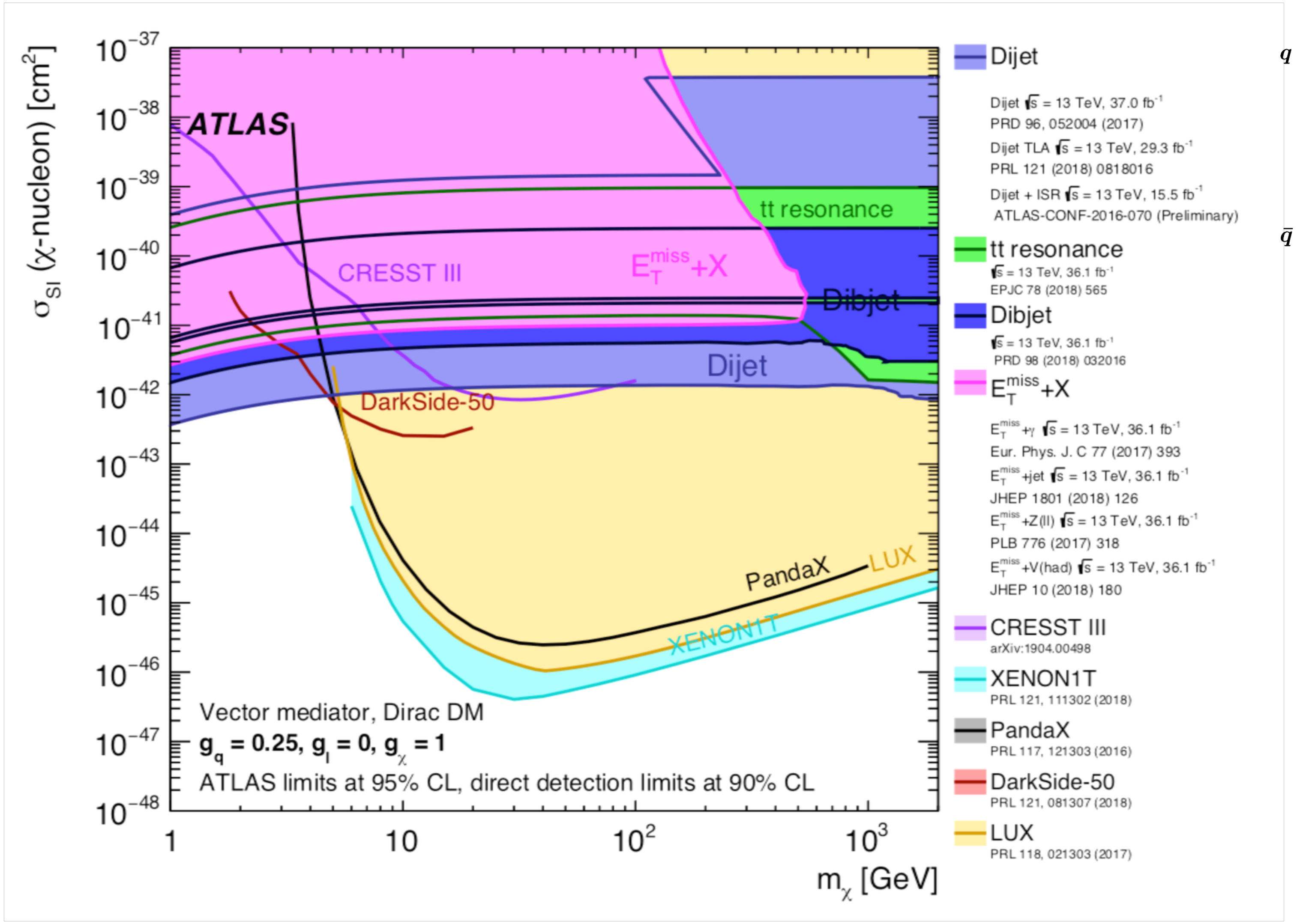
Model assumptions:

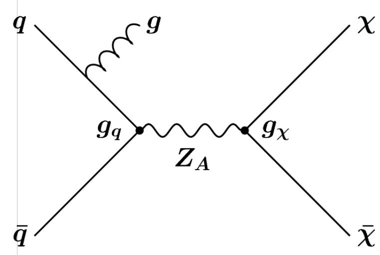
- neutral, spin-1 particle acts as mediator
- DM assumed to be Dirac fermion

- 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

ATLAS released a combination of $E_{T,}^{miss}$-based DM searches involving $E_{T,}^{miss}$ + X, X = jet, γ, W, Z, H, b(b), t(t) using large number of models and resonance searches

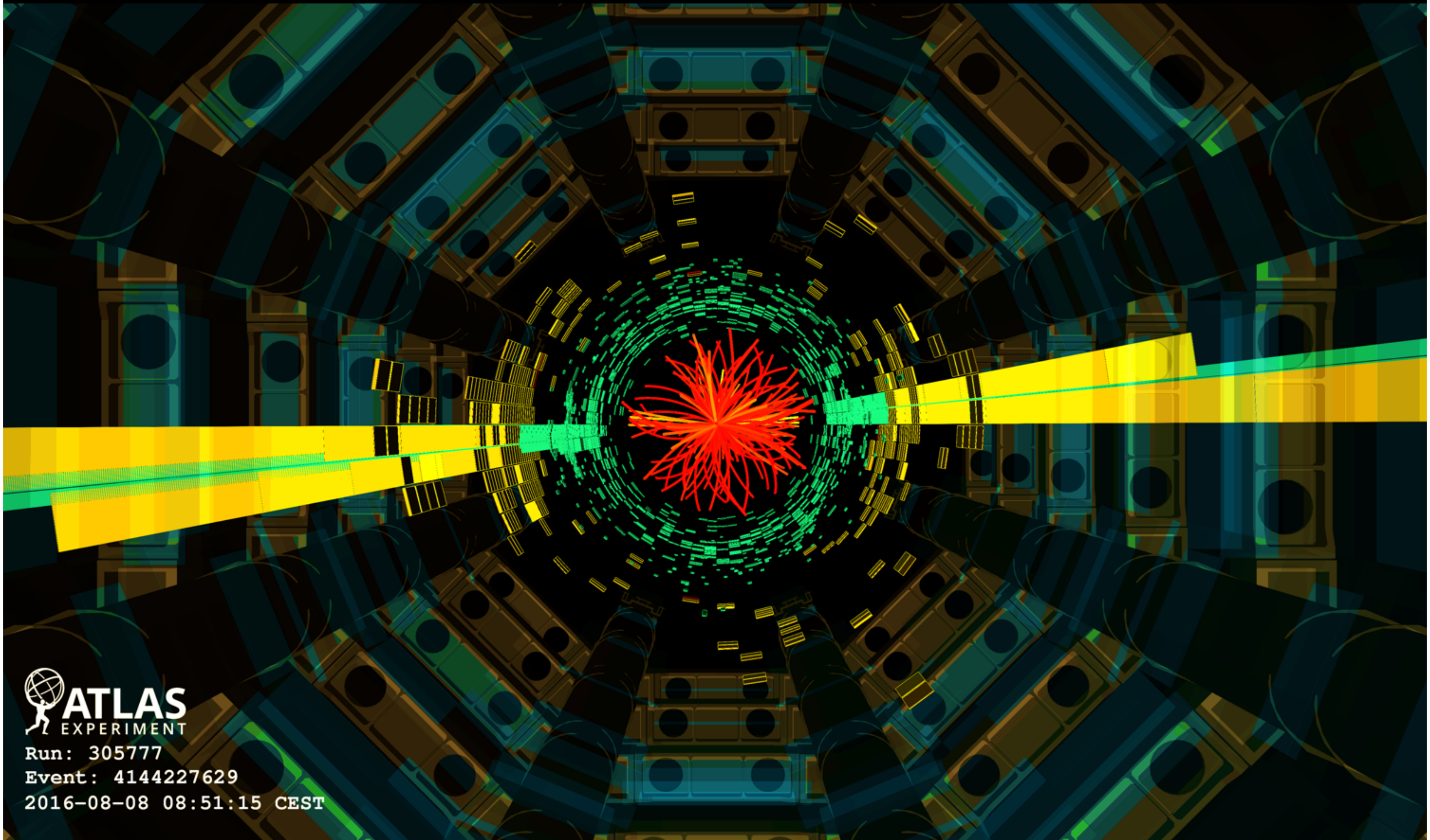
Interpretation on searches for Dark Matter:





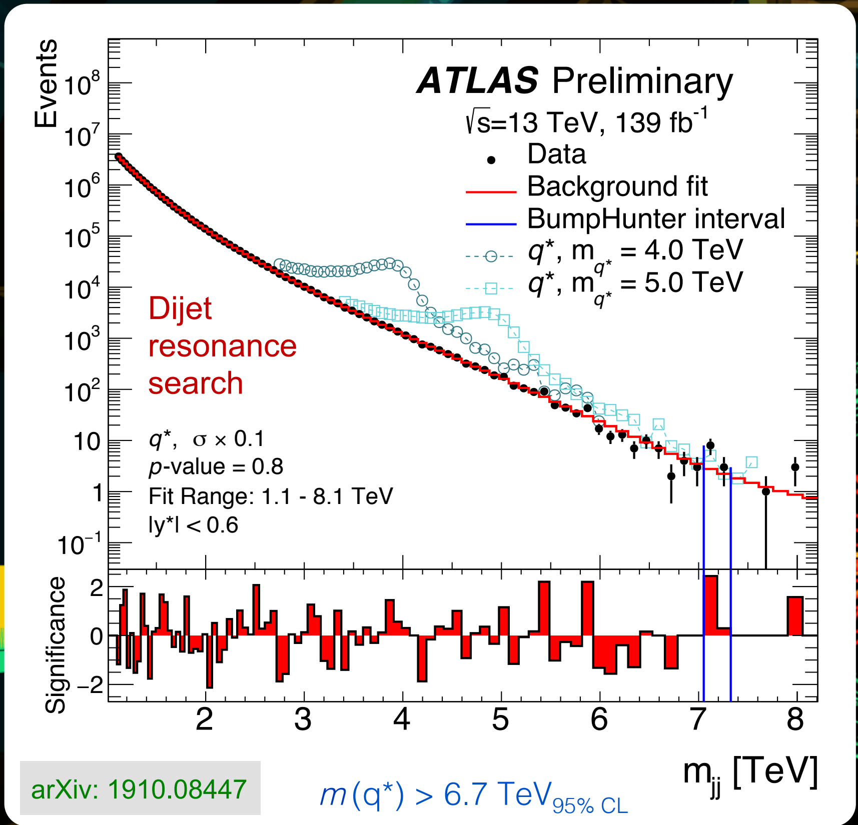
Interpretation is highly model dependent

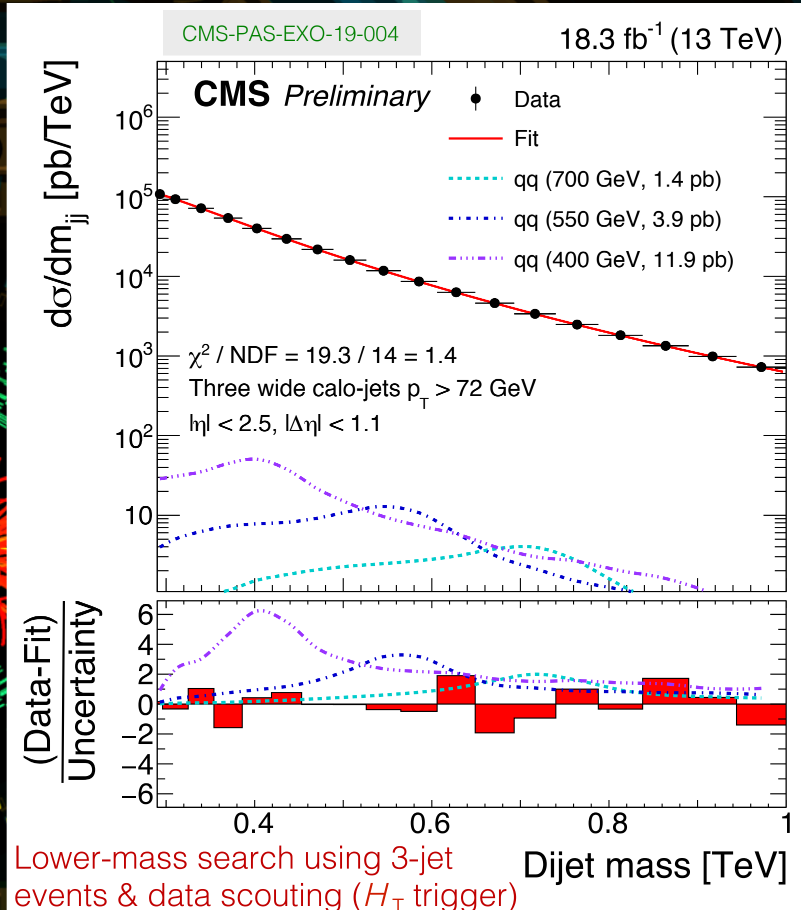
High-mass resonance searches to probe new TeV scale symmetries or forces



Highest-mass central dijet event of 8.0 TeV selected in resonance search

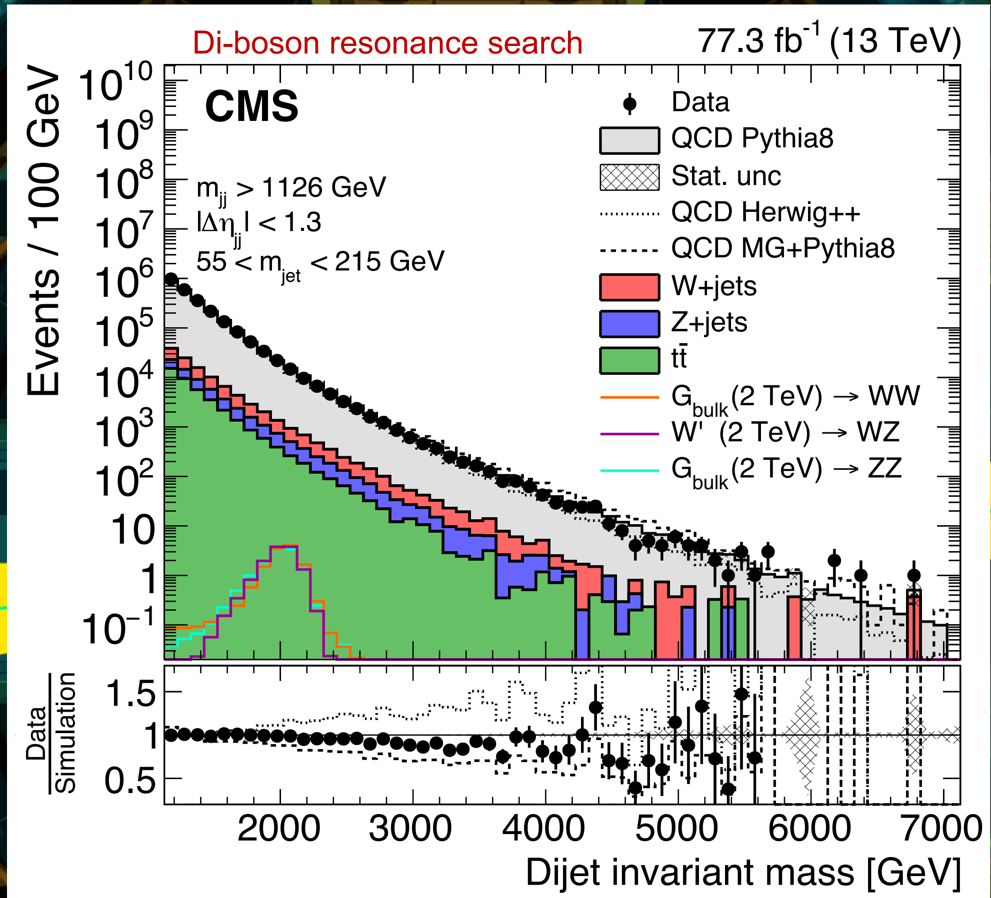
High-mass resonance searches to probe new TeV scale symmetries or forces





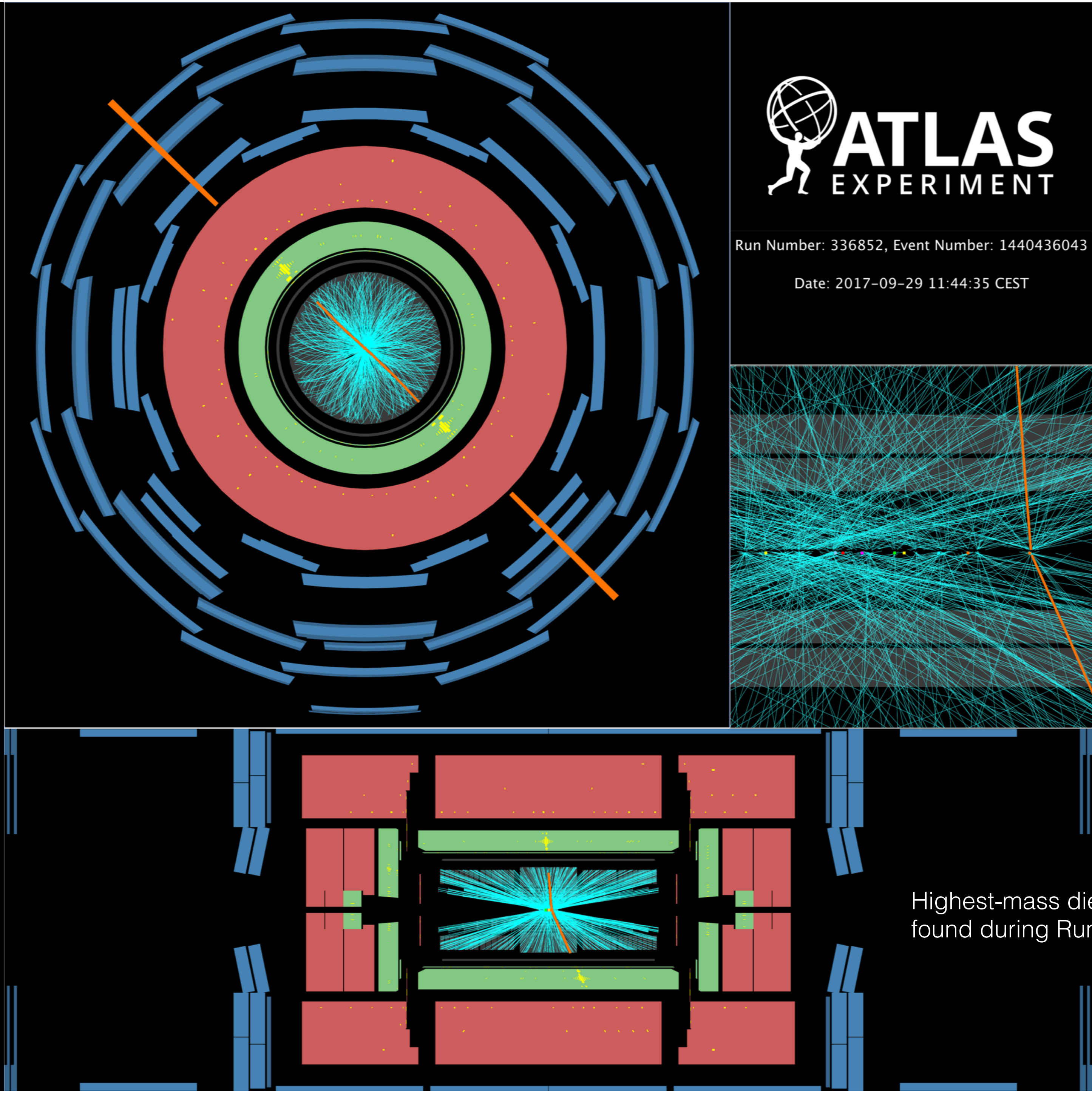
ATLAS EXPERIMENT
Run: 305777
Event: 4144227629
2016-08-08 08:51:15 CEST

High-mass resonance searches to probe new TeV scale symmetries or forces

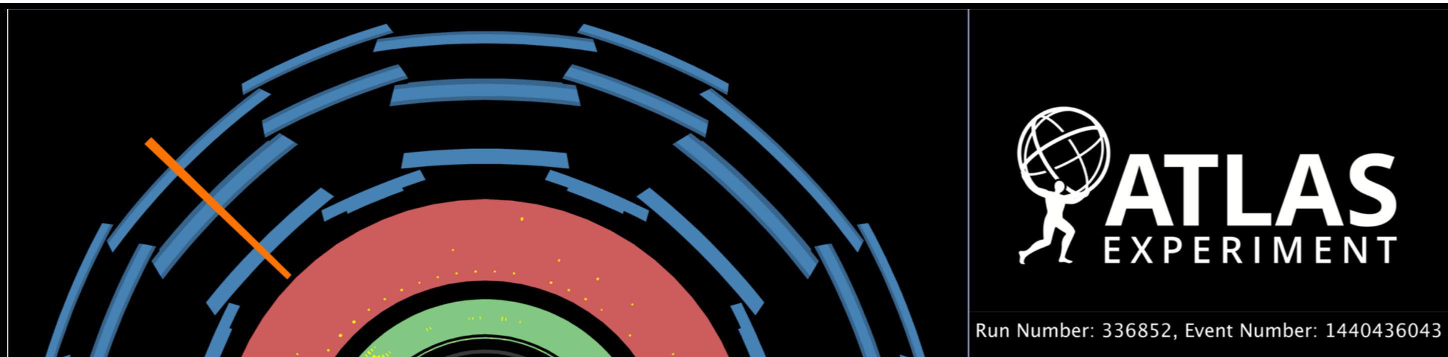


ATLAS
EXPERIMENT
Run: 305777
Event: 4144227629
2016-08-08 08:51:15 CEST

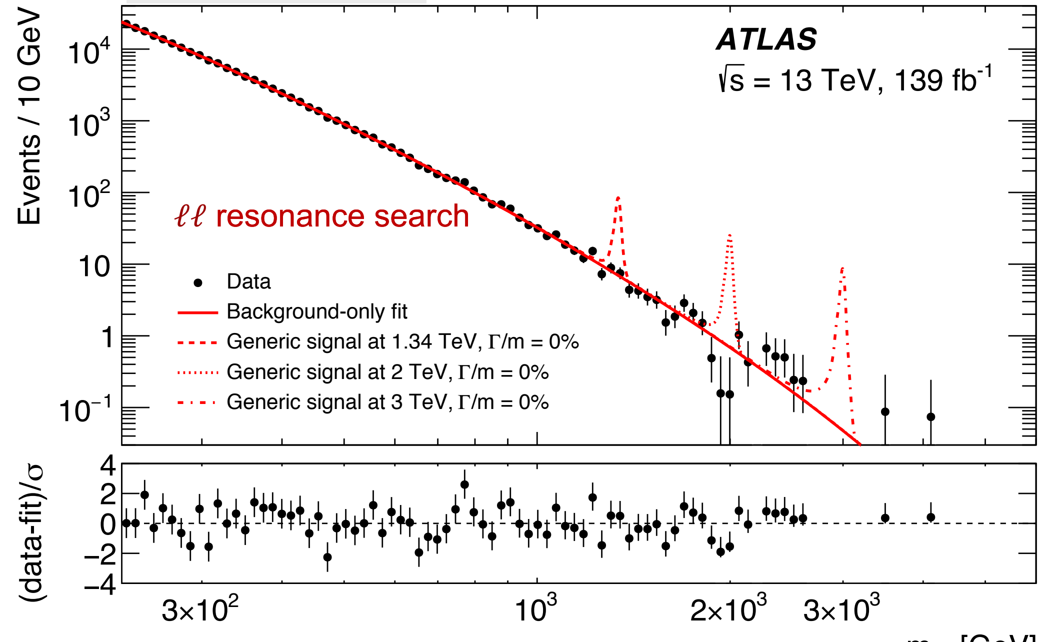
Exploit 3D likelihood fit to jet and dijet masses (30% improvement). In heavy vector triplet model, exclude Z' (W') below 3.5 (3.8) TeV



Highest-mass dielectron event found during Run-2: 4.1 TeV.

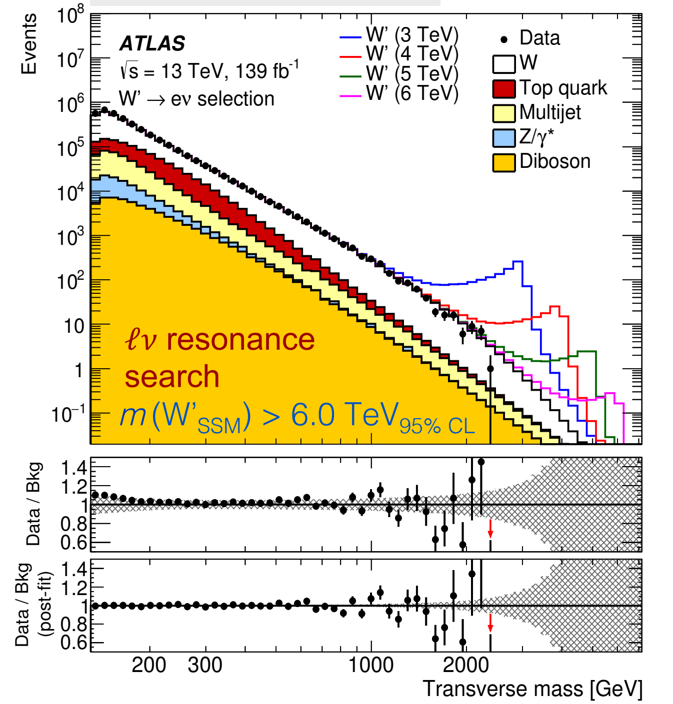


Phys. Lett. B 796 (2019) 68



$m(Z'_{SSM}) > 5.1$ TeV$_{95\%\ CL}$

Phys. Rev. D 100 (2019) 052013

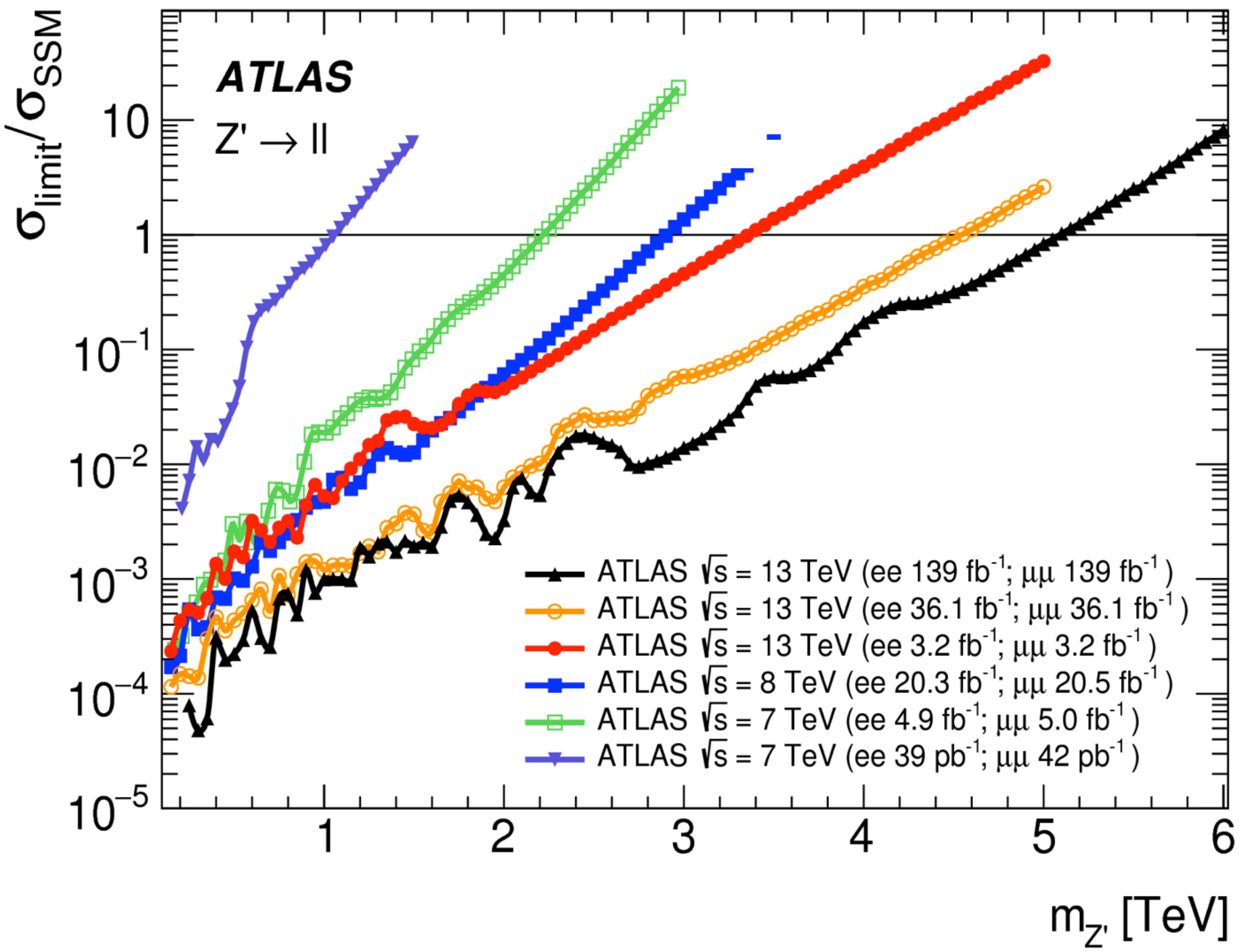


$m(W'_{SSM}) > 6.0$ TeV$_{95\%\ CL}$

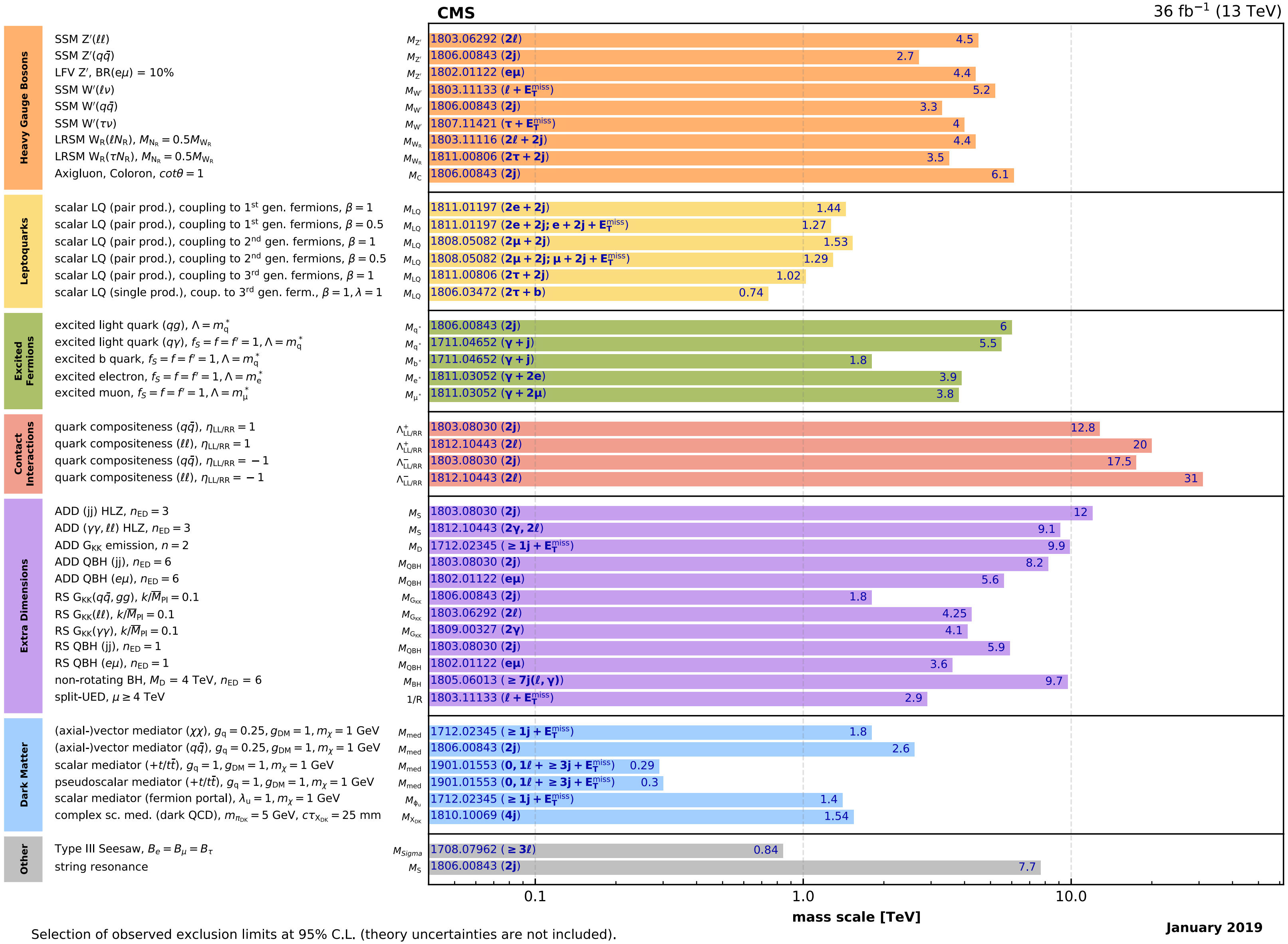
Model	Lower limits on $m_{Z'}$ [TeV]					
	ee		$\mu\mu$		$\ell\ell$	
	obs	exp	obs	exp	obs	exp
Z'_ψ	4.3	4.3	4.0	3.8	4.5	4.5
Z'_χ	4.6	4.6	4.2	4.1	4.8	4.7
Z'_{SSM}	4.9	4.9	4.5	4.4	5.1	5.0

Searches for di-lepton resonances

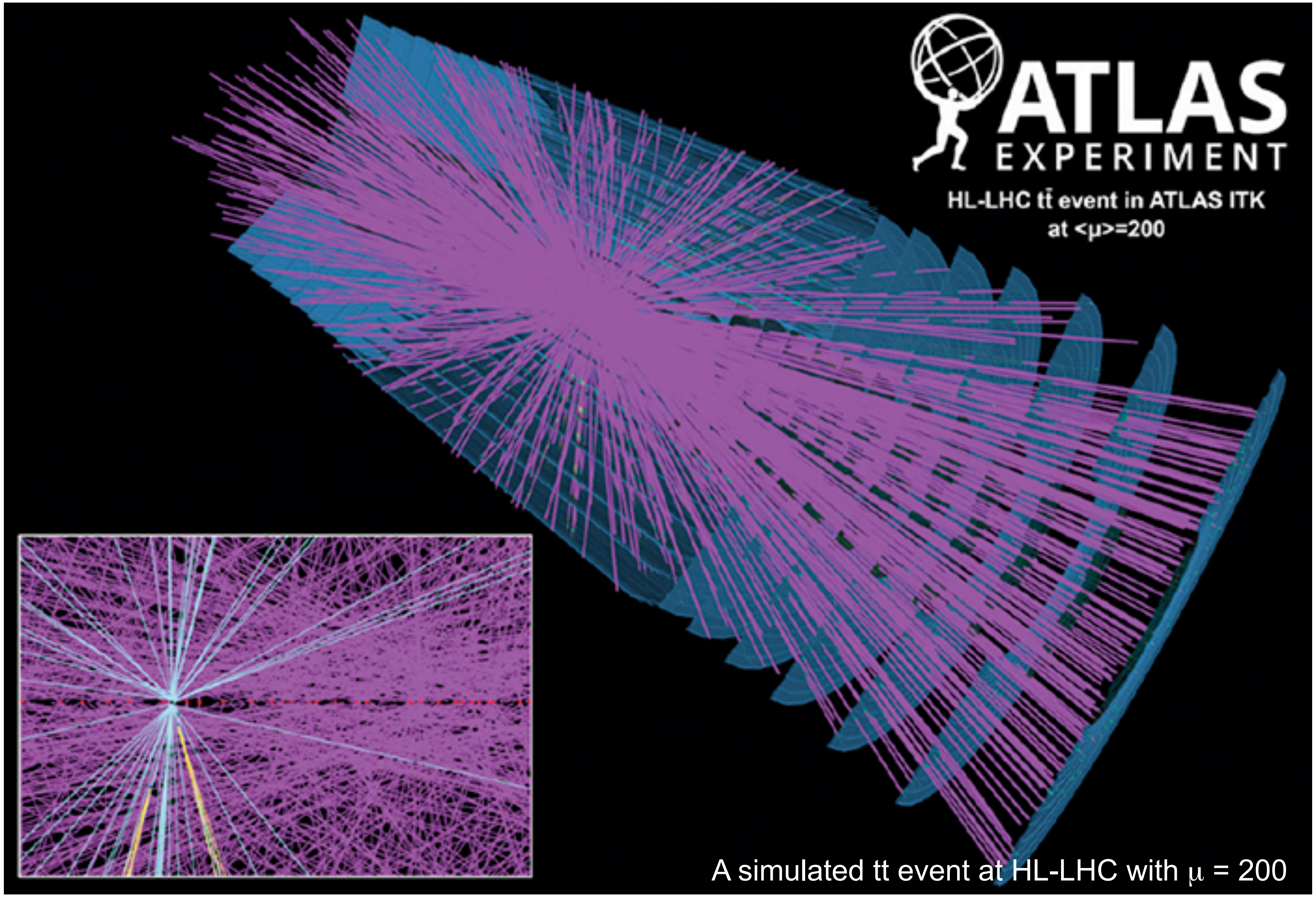
Phys. Lett. B 796 (2019) 68



Summary of Results on Searches for other BSM physics

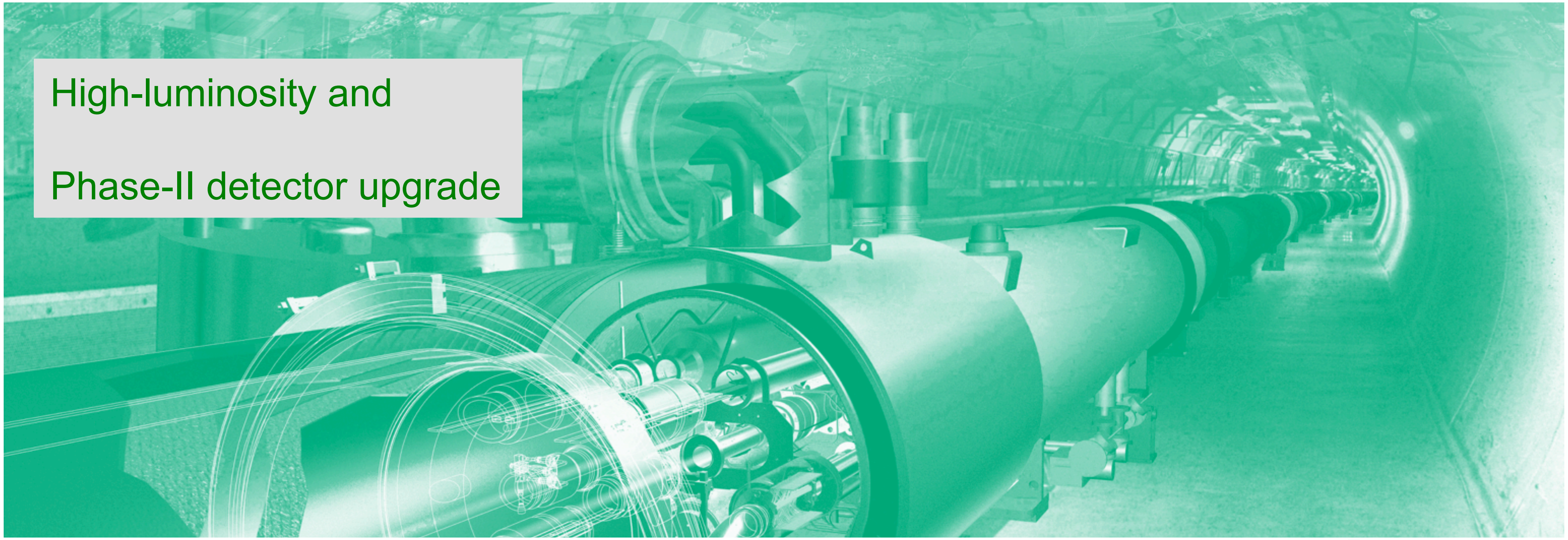


Physics at the HL-LHC

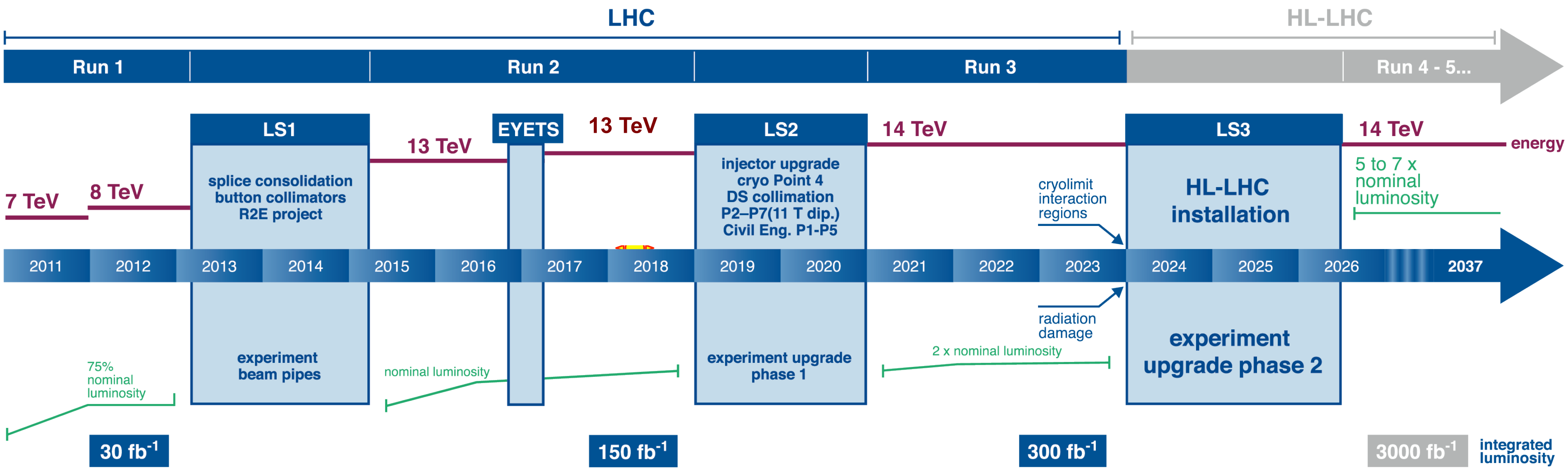


A simulated tt event at HL-LHC with μ = 200

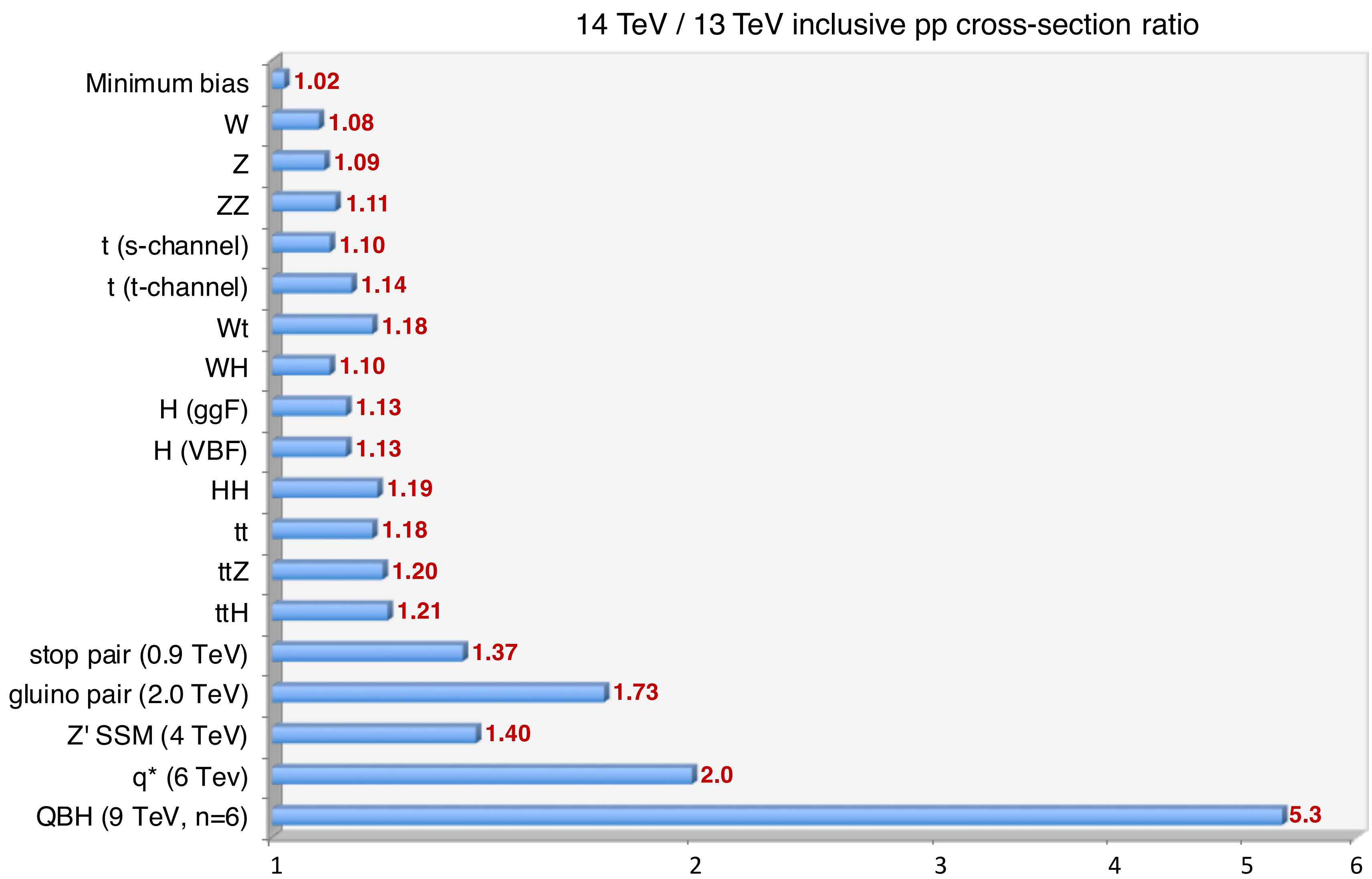
High-luminosity and Phase-II detector upgrade



LHC / HL-LHC Plan



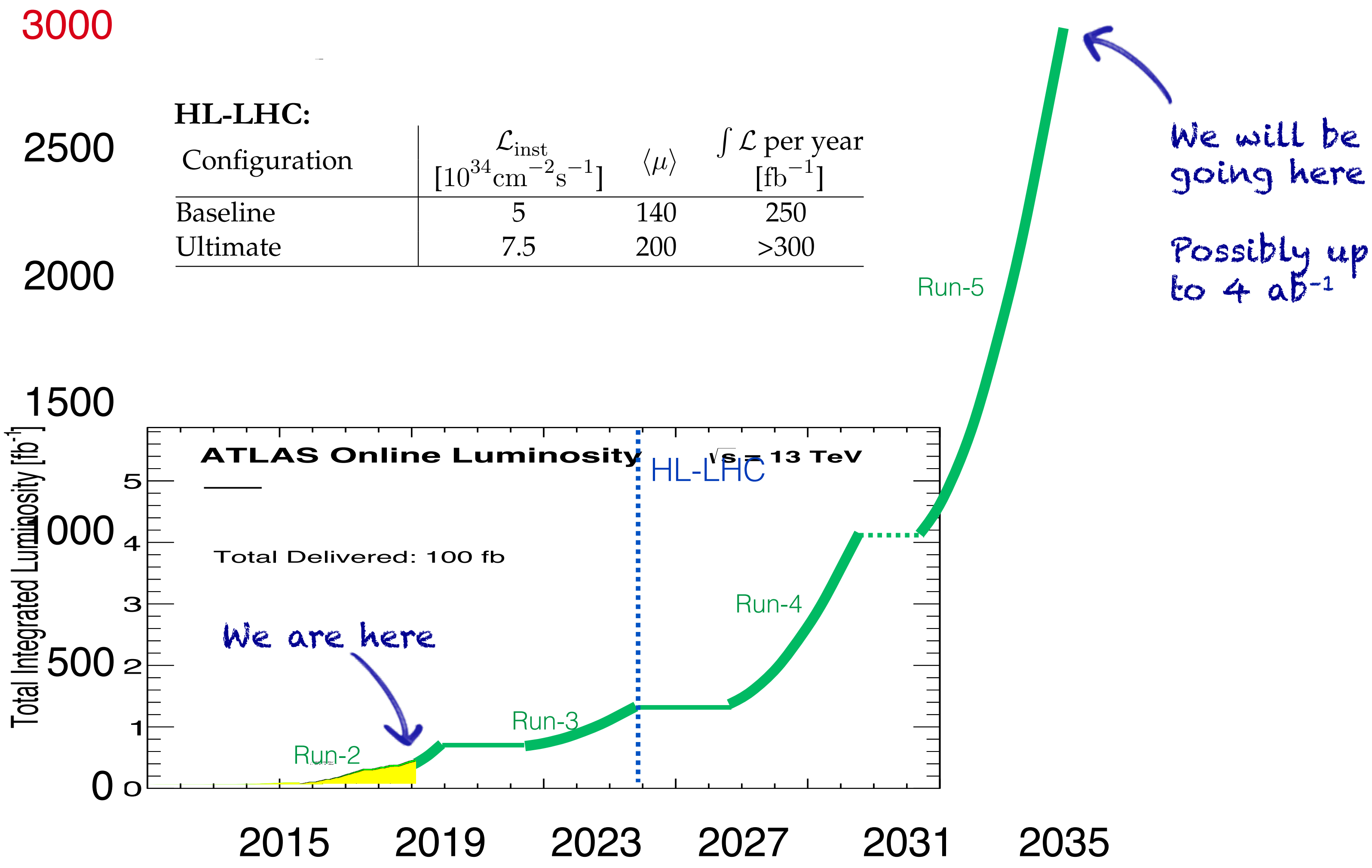
14 TeV proton–proton centre-of-mass energy



Expected integrated luminosity of LHC and HL-LHC

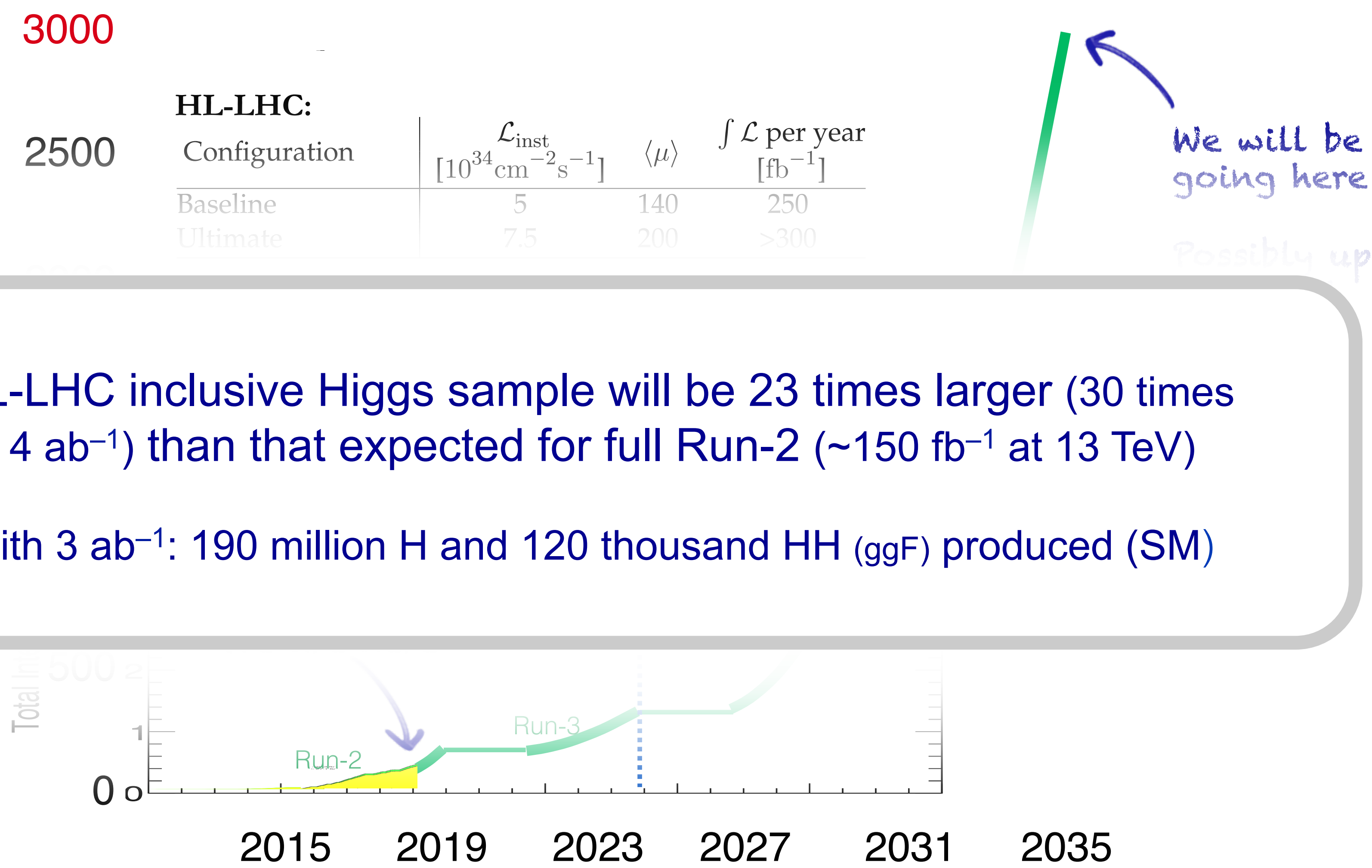
HL-LHC:

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



© P. Ferreira da Silva at Moriond EW, 2016

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)

© P. Ferreira da Silva at Moriond EW, 2016

Phase-II Detector Upgrades

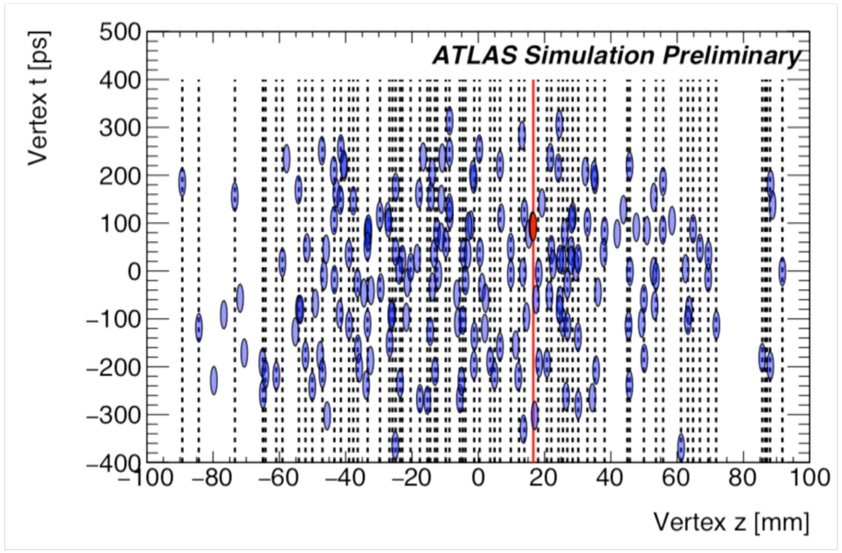
Designed to maintain current performance under high pileup (~35 → 200, L_{peak} ~ 7×10^{34} cm^{-2}s^{-1})

HL-LHC

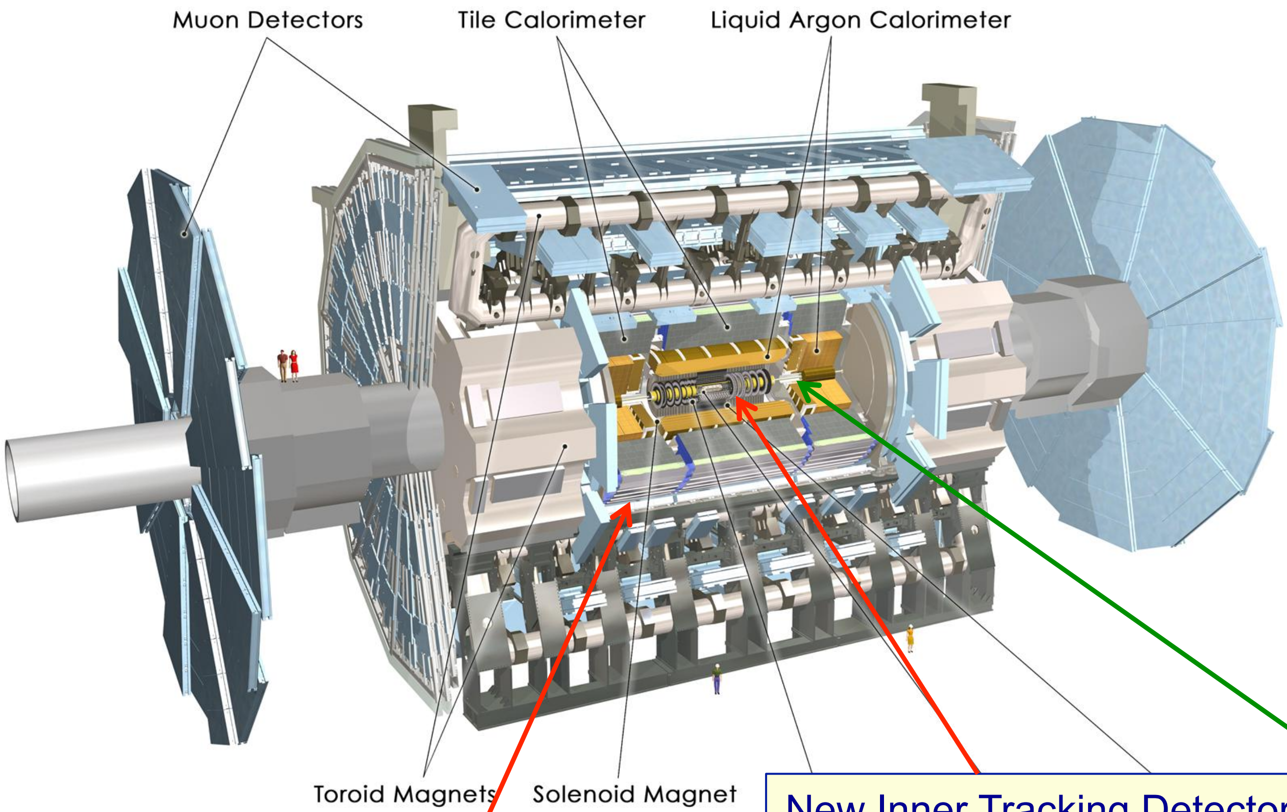
- Higgs factory for precision Higgs coupling measurements and increased rare & new physics sensitivity
- Detector upgrades required for improved pileup and radiation robustness

ATLAS and CMS developed novel detection technologies at the forefront of speed, granularity and radiation hardness

- Silicon tracking detectors with > 1B channels
- Timing detector based on fast silicon LGAD technology (30 ps timing resolution per layer)
- High granularity topological trigger and high-performance DAQ architecture
- New compute technologies: use of high-performance computing, possibly GPUs, machine learning
- ATLAS: 6 TDRs approved (1 more to come), MoUs submitted to funding agencies



ATLAS Phase-II Upgrade



Upgraded Trigger and Data Acquisition System:

- L0: at 1 MHz
  (capable of evolving to a dual-level architecture with L0 at 4 MHz)

- Improved Event Filter
  (output rate of 10 kHz, hardware tracking as co-processor)

Electronics Upgrade :
- LAr Calorimeter
- Tile Calorimeter
- Muon system

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

High granularity timing detector
(forward region)

New muon chambers
in the inner barrel region

Higgs physics programme at the HL-LHC in a nutshell

Higgs properties:

- mass (well known, expect to improve to ~33 MeV in $H \rightarrow 4\mu$), width (through interference measurements)
- spin (0^+ established), CP (odd admixture possible) — not discussed today

Rare Higgs decays:

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

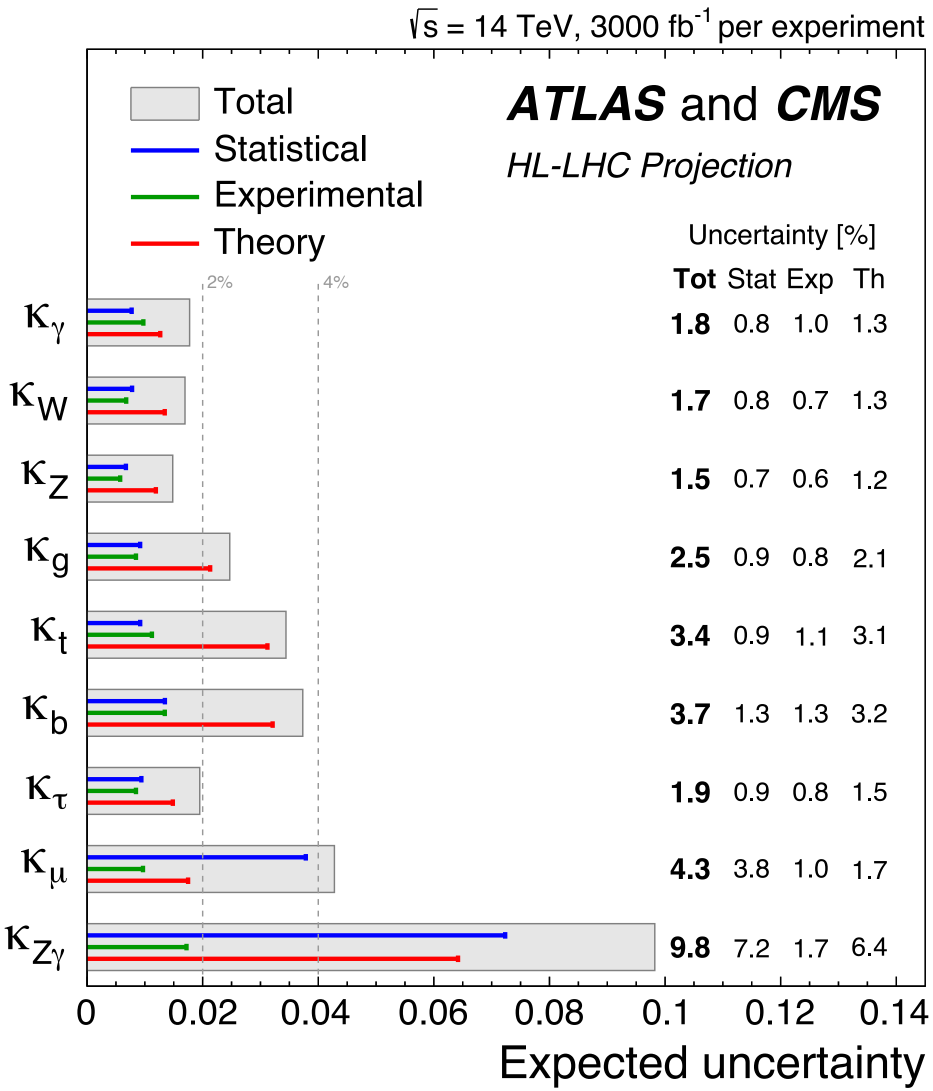
Higgs couplings:

- Study of Higgs 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 production or other scalar states

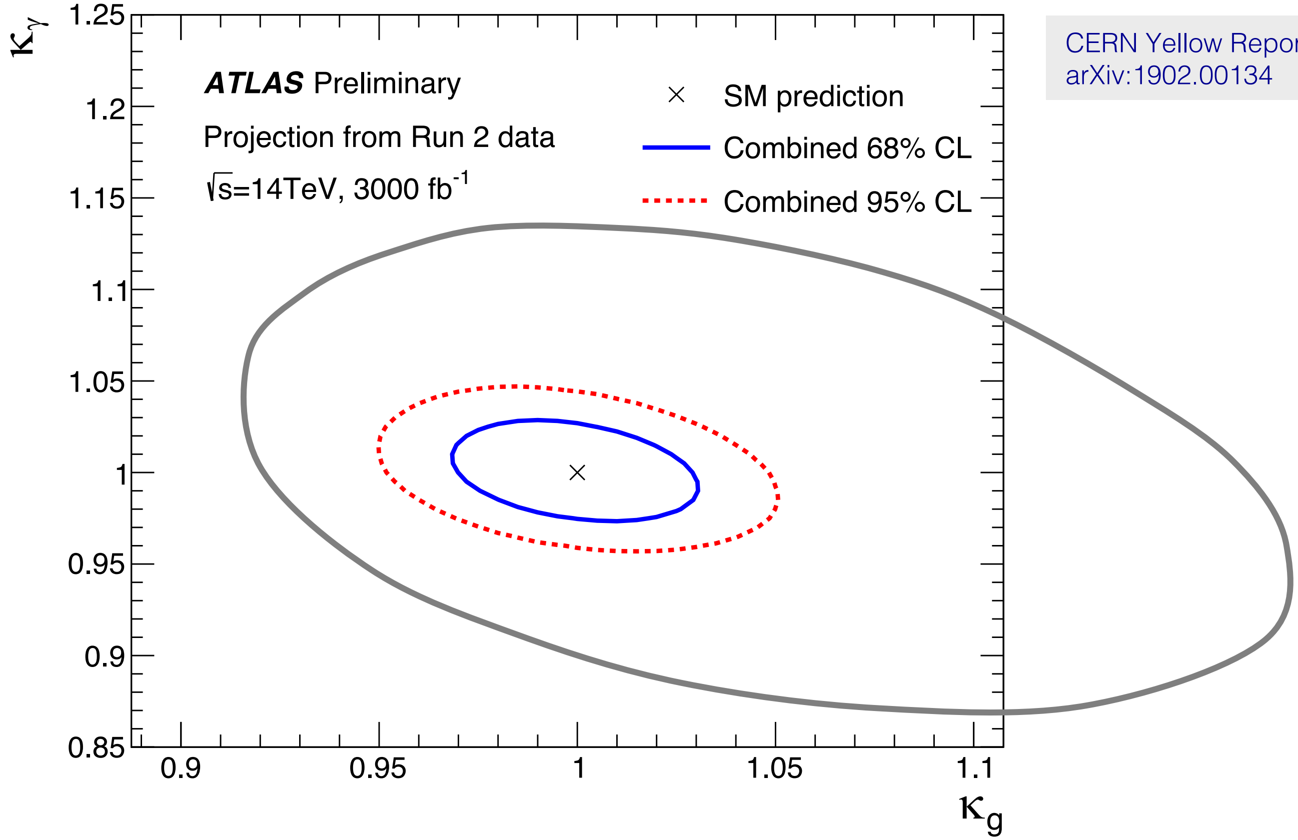
- Search for anomalous FCNC through top decays, Higgs production via SUSY cascades, etc.
- Search for additional scalar particles

Higgs Boson couplings



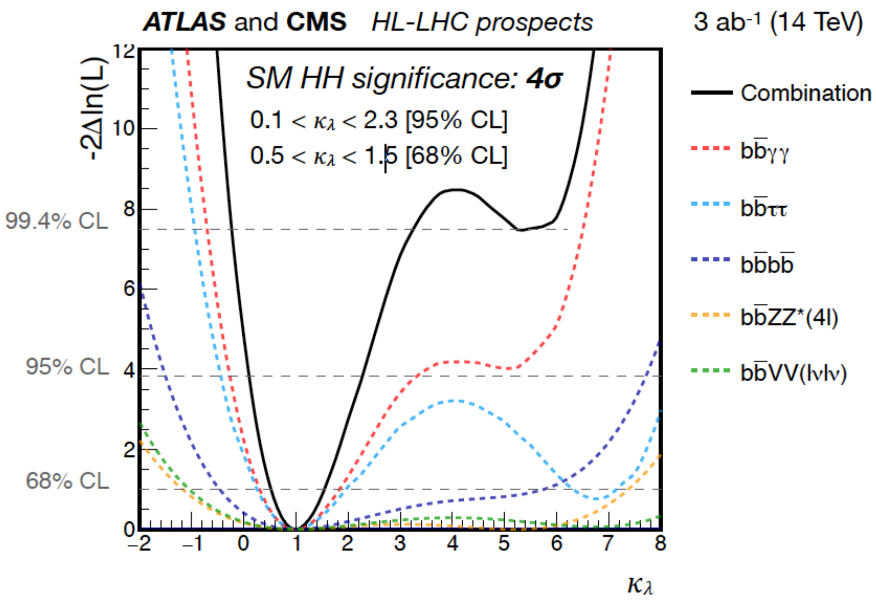
CERN Yellow Report on HL-LHC physics
arXiv:1902.00134

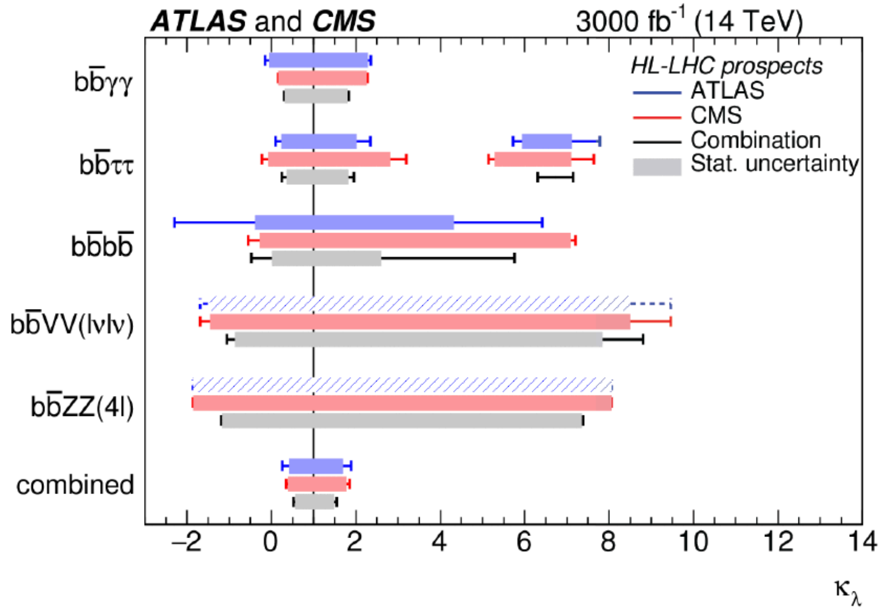
Higgs Boson couplings



CERN Yellow Report on HL-LHC physics
arXiv:1902.00134

Sensitivity on Higgs Boson self coupling





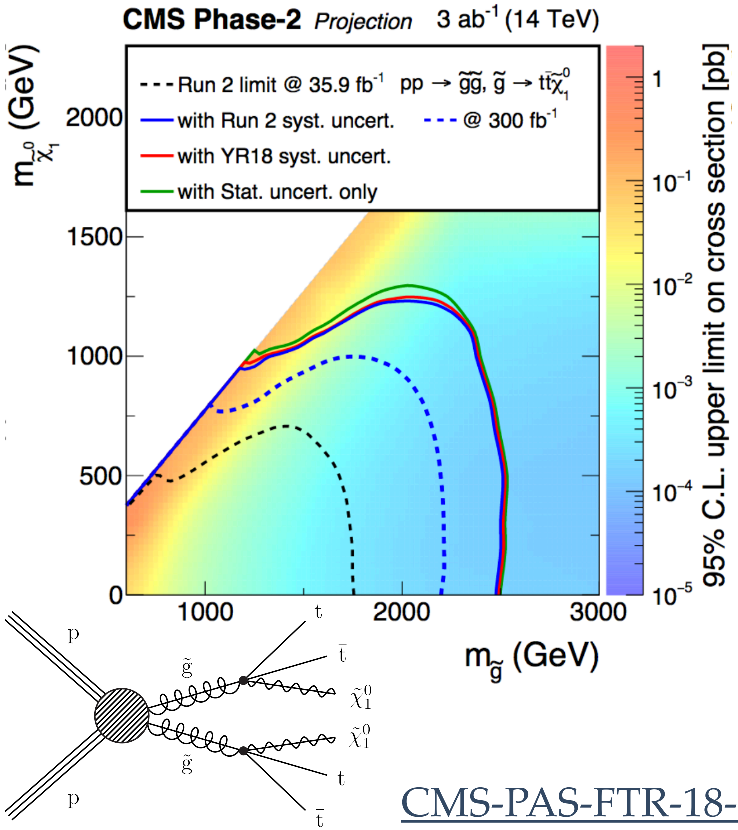
Combined ATLAS + CMS fit yields:

68% C.L. limits $0.5 < \lambda_{HHH}\,(\text{obs.}) / \lambda_{HHH}\,(\text{SM}) < 1.5$

95% C.L. limits $0.1 < \lambda_{HHH}\,(\text{obs.}) / \lambda_{HHH}\,(\text{SM}) < 2.3$

CERN Yellow Report on HL-LHC physics
arXiv:1902.00134

Sensitivity for strongly produced SUSY particles



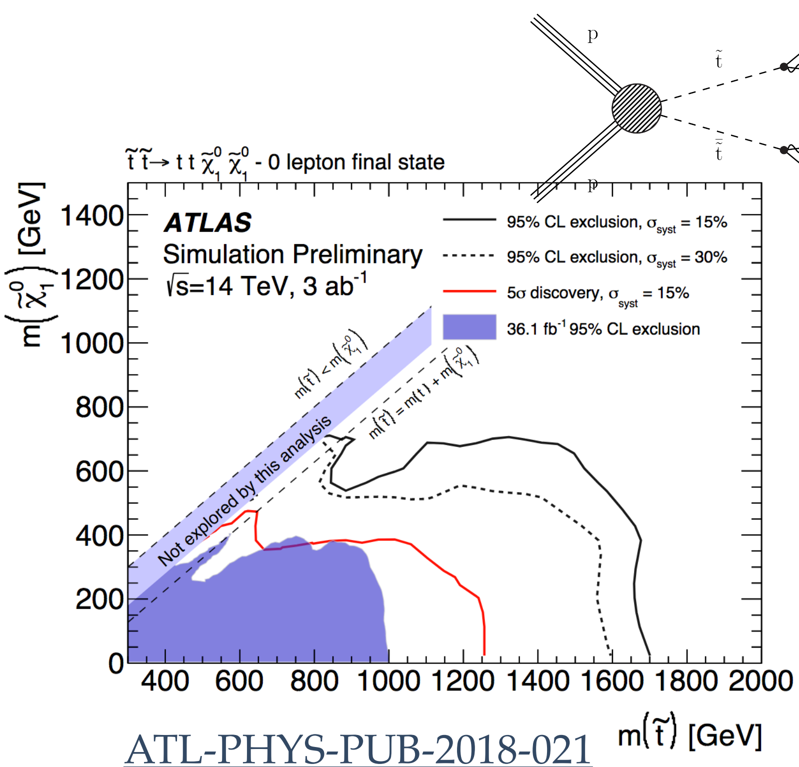
[CMS-PAS-FTR-18-037]

Results based on current analysis techniques

- S/B @ 14 TeV > S/B @ 13 TeV
- Bigger dataset allows for stricter selection criteria
- Generally reduced systematic uncertainties

Direct stop pair production analysis

- re-clusetered ("fat") jets for high mass splitting
- ISR-based selection for compressed scenario

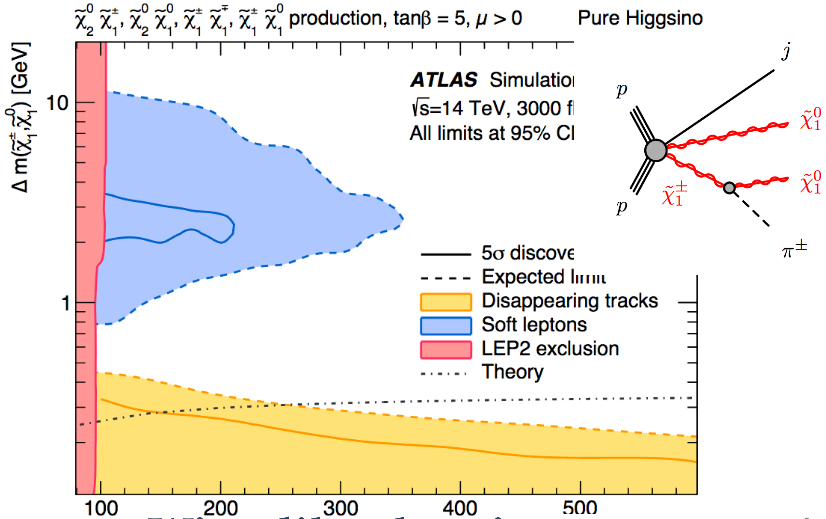


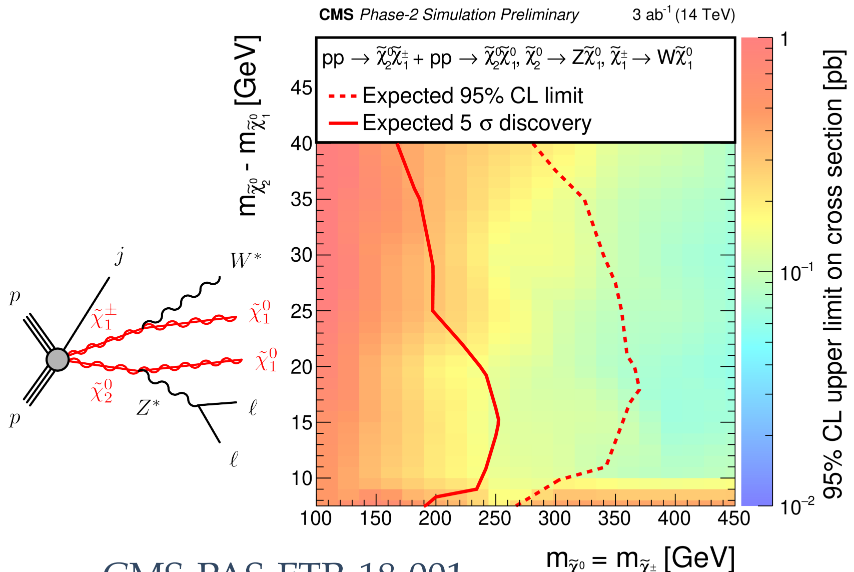
[ATL-PHYS-PUB-2018-021]

Sensitivity to el.weak SUSY production

Higgsino-like LSP (naturalness motivated)

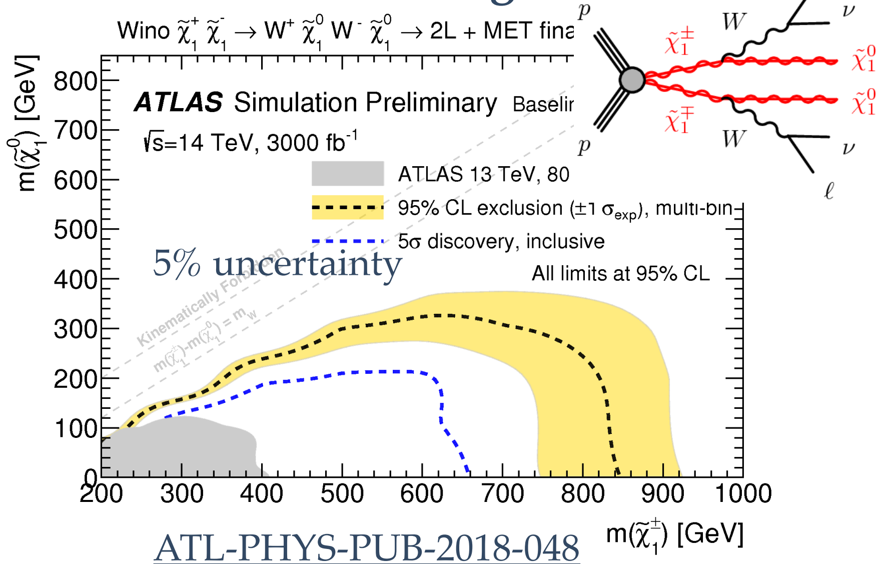
- Lightest chargino and second neutrino close in mass with LSP
  - soft objects in the final state
  - ISR-based selection
- Relies on upgrades to triggers at L1 and HLT to maintain low lepton thresholds (3-5 GeV)
- "Disappearing tracks" for even lower mass splitting





CMS-PAS-FTR-18-001

Wino-like charginos



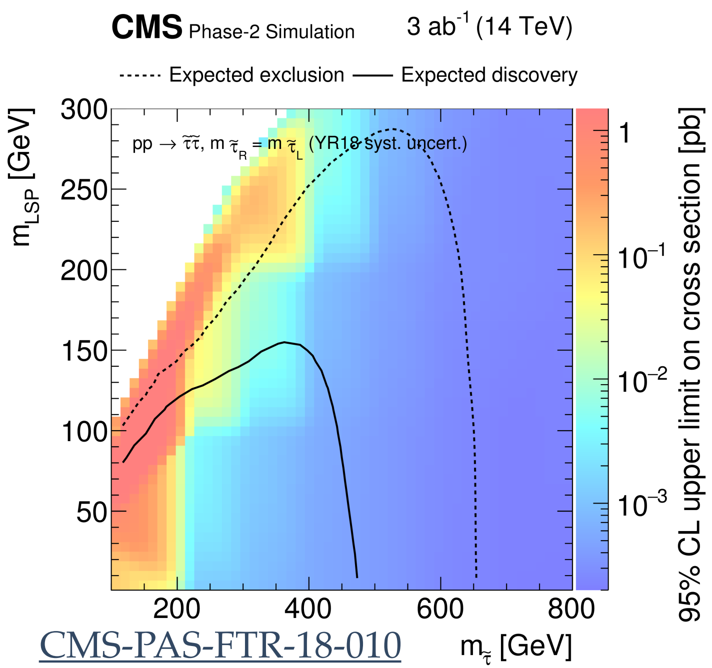
ATL-PHYS-PUB-2018-048

Sensitivity to staus

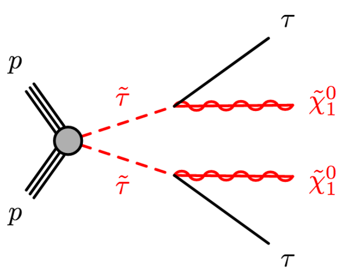
Stau as **lightest slepton** (large tanβ)

- signatures with at least one hadronically decaying tau

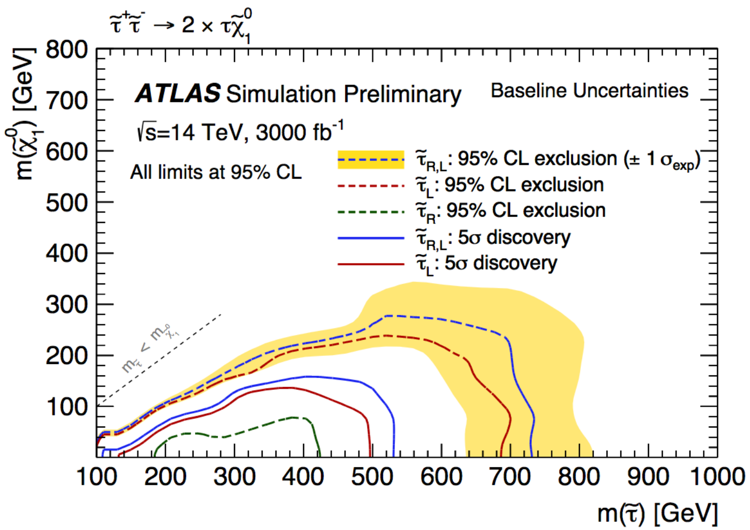
- Small cross section (<1 fb^{-1} for m(stau) > 400 GeV @ 14 TeV)
  - Large size of sample @HL-LHC important
  - Sensitivity to right-handed tau limited by cross section



CMS-PAS-FTR-18-010



ATL-PHYS-PUB-2018-048



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,
  however, more complex scenarios have to be explored with more data

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