LHC physics results and prospects

Takanori Kono (Ochanomizu Univesity)
on behalf of the ATLAS and CMS Collaborations

Asian Linear Collider Workshop
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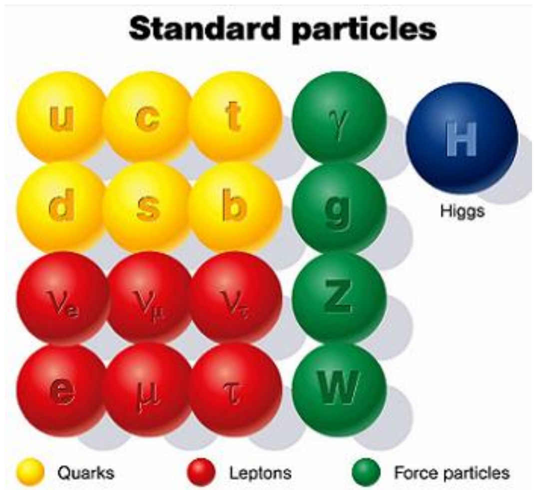
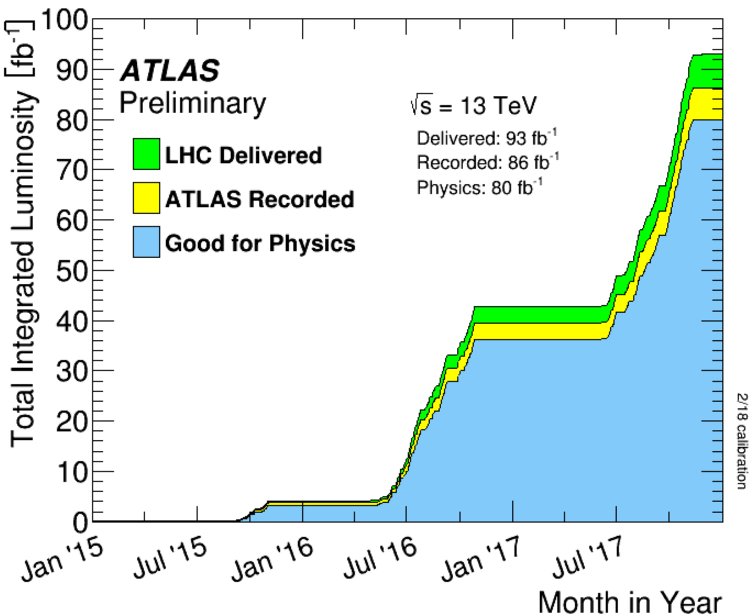
お茶の水女子大学
Ochanomizu University

ATLAS EXPERIMENT

CMS

Particle physics and LHC





- All elements of the Standard Model (SM) are confirmed and SM continues to describe observations successfully

Mysteries of the SM

- Flavor structure, mass hierarchy
- Symmetry between quarks and leptons
- Origin of the electroweak (EW) symmetry breaking (EWSB)

Unexplained phenomena

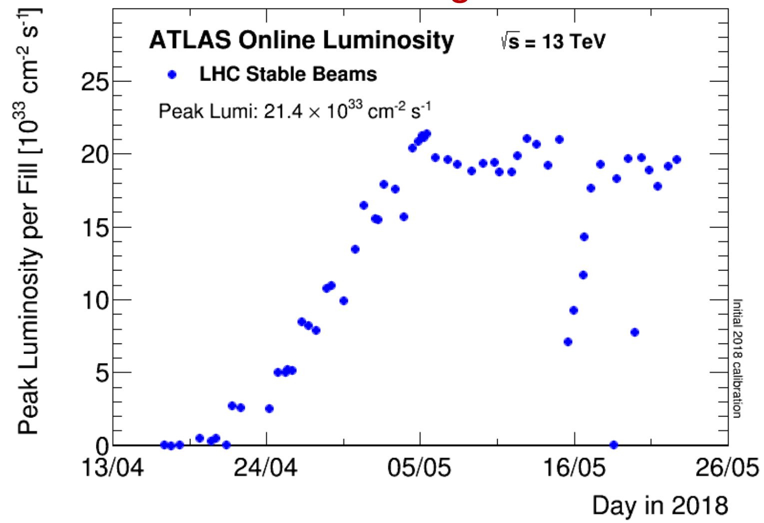
- Gravity is not included in SM
- Dark matter, dark energy

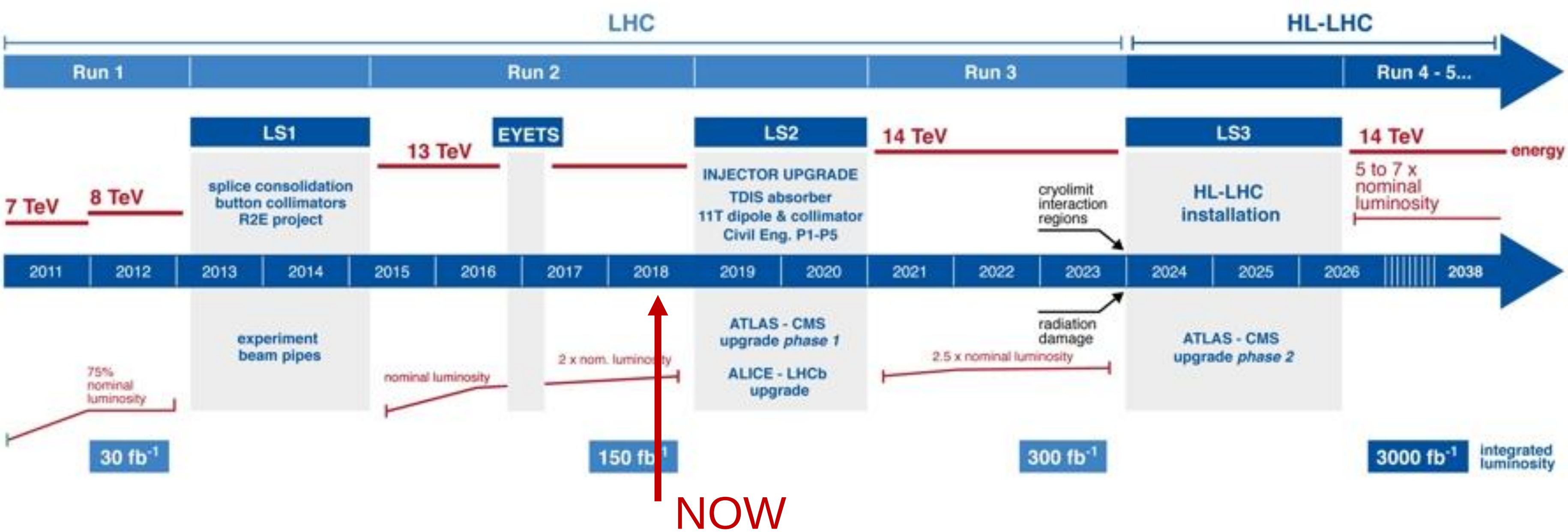
- Deepen understanding of the SM by precision measurements
- Search for new physics

LHC Upgrade

- Run-2 (end of 2018)
  - $\sqrt{s} = 13$ TeV, 150 fb^{-1}
- Run-3 (2021 – 2023)
  - $\sqrt{s} = 14$ TeV, 300 fb^{-1}
- High-Luminosity LHC (2026 – 2036?)
  - $\sqrt{s} = 14$ TeV, 3,000 fb^{-1}

2018 data-taking has started!





Physics cases at the LHC

SM (incl. top) measurements

- Inclusive and differential cross sections
- Mass, coupling
- Anomalous gauge couplings
- Top quark properties and interactions

Higgs particle and EWSB

- Mass, width, spin, parity, …
- Cross sections
- Couplings to other particles
- Heavy Higgs searches

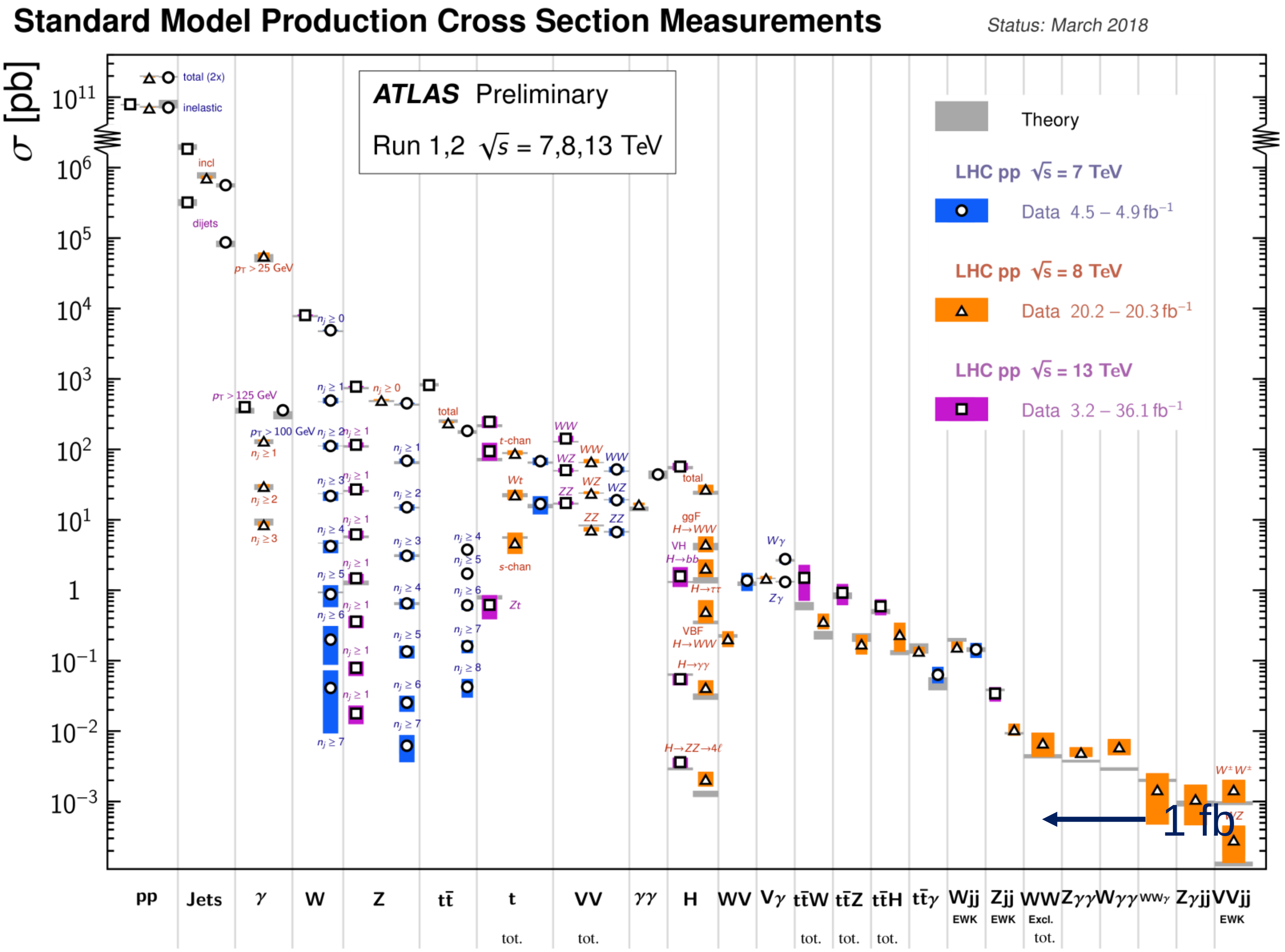
Flavor physics

- B-hadron properties
- CP violation
- Rare decays
- Flavor structure with top

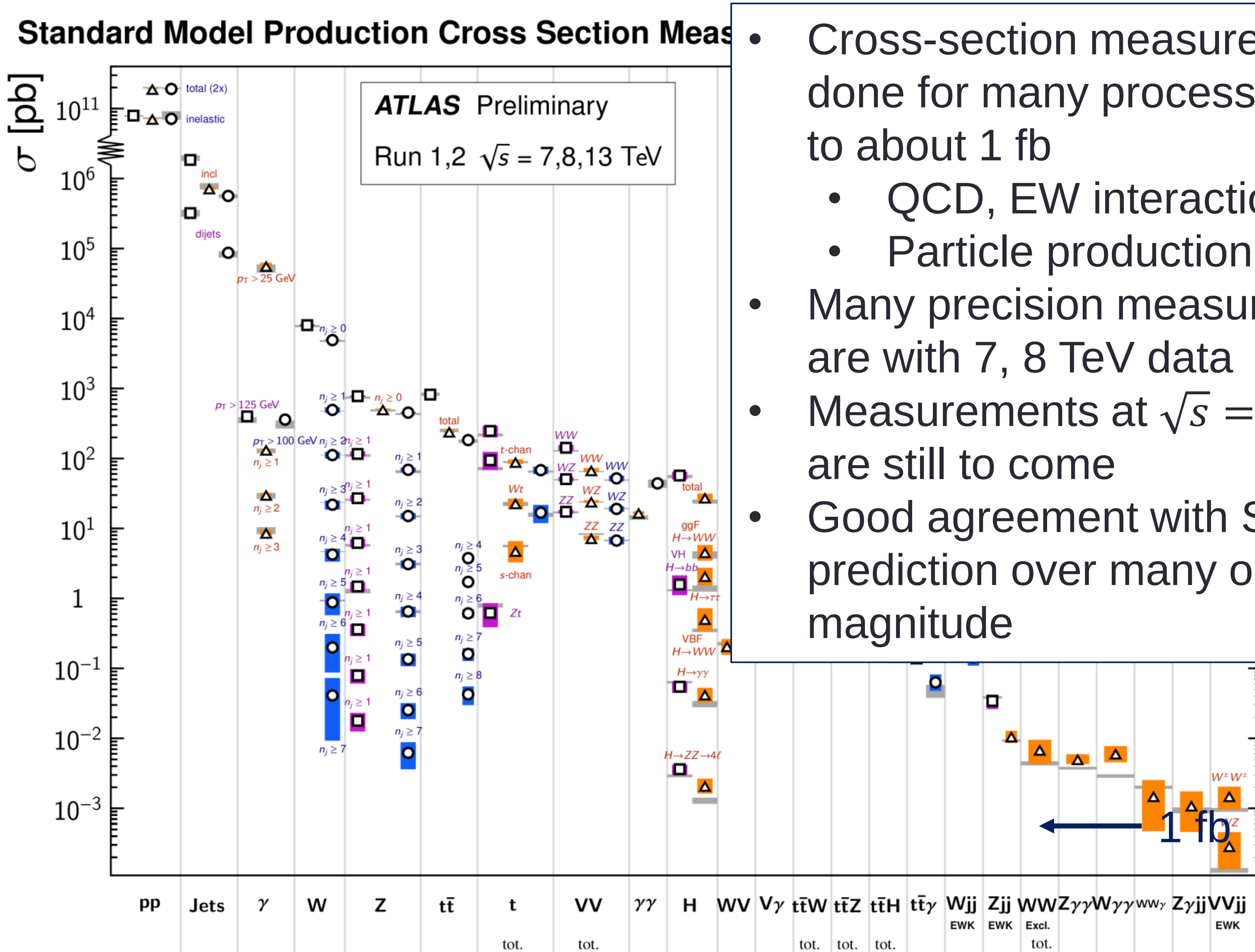
SUSY and BSM searches

- Direct search of new particles
- SUSY, dark matter candidate etc.
- Resonance or non-resonance

Standard model summary plot



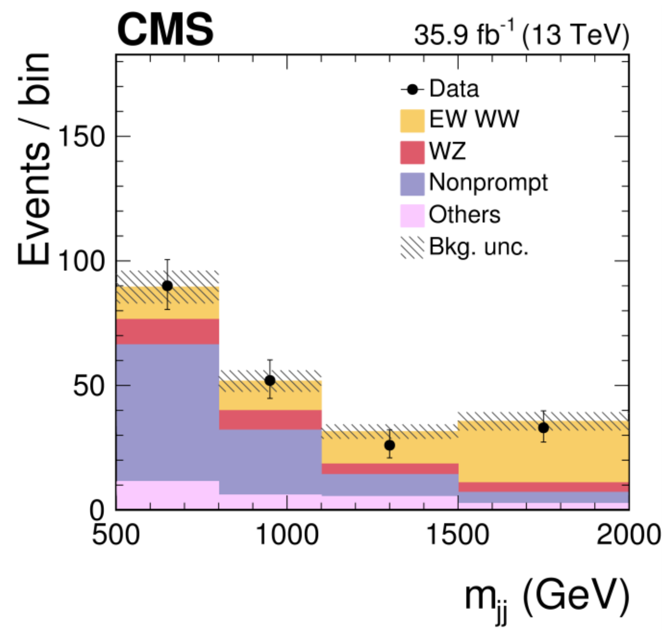
Standard model summary plot

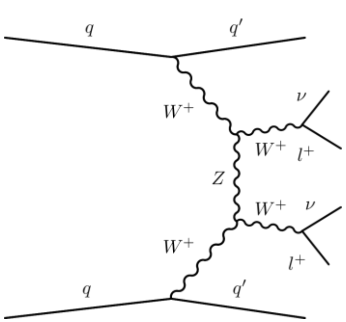


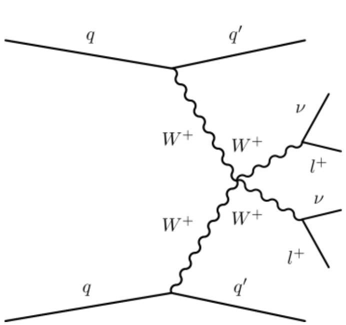
- Cross-section measurements are done for many processes, down to about 1 fb
  - QCD, EW interactions
  - Particle production
- Many precision measurements are with 7, 8 TeV data
- Measurements at $\sqrt{s} = 13$ TeV are still to come
- Good agreement with SM prediction over many orders of magnitude

EW production of same-sign W pairs

- EW production of vector boson pairs (Vector Boson Scattering, VBS) probes the triple/quartic gauge interactions
- CMS observation at 5.5σ
- Limits on the coefficients of dimension-8 effective operators
- Limits on the s_H parameter for the Doubly charged Higgs in the framework of Georgi-Machacek model of Higgs triplet
  - $s_H > 0.18\ (0.44)$ for $m_{H^\pm} = 200\ (1{,}000)$ GeV



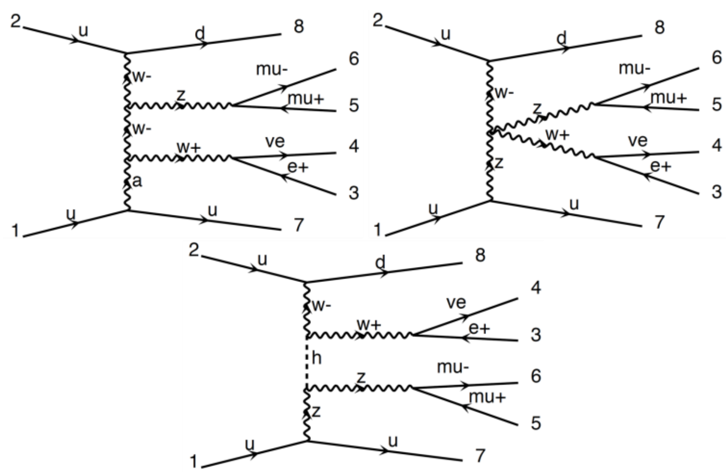




	Observed limits (TeV $^{-4}$)	Expected limits (TeV $^{-4}$)	Previously observed limits (TeV $^{-4}$)
f_{S0}/Λ^4	[−7.7, 7.7]	[−7.0, 7.2]	[−38, 40] , [11]
f_{S1}/Λ^4	[−21.6, 21.8]	[−19.9, 20.2]	[−118, 120] , [11]
f_{M0}/Λ^4	[−6.0, 5.9]	[−5.6, 5.5]	[−4.6, 4.6] , [36]
f_{M1}/Λ^4	[−8.7, 9.1]	[−7.9, 8.5]	[−17, 17] , [36]
f_{M6}/Λ^4	[−11.9, 11.8]	[−11.1, 11.0]	[−65, 63] , [11]
f_{M7}/Λ^4	[−13.3, 12.9]	[−12.4, 11.8]	[−70, 66] , [11]
f_{T0}/Λ^4	[−0.62, 0.65]	[−0.58, 0.61]	[−0.46, 0.44] , [37]
f_{T1}/Λ^4	[−0.28, 0.31]	[−0.26, 0.29]	[−0.61, 0.61] , [37]
f_{T2}/Λ^4	[−0.89, 1.02]	[−0.80, 0.95]	[−1.2, 1.2] , [37]

Phys. Rev. Lett. 120 (2018) 081801

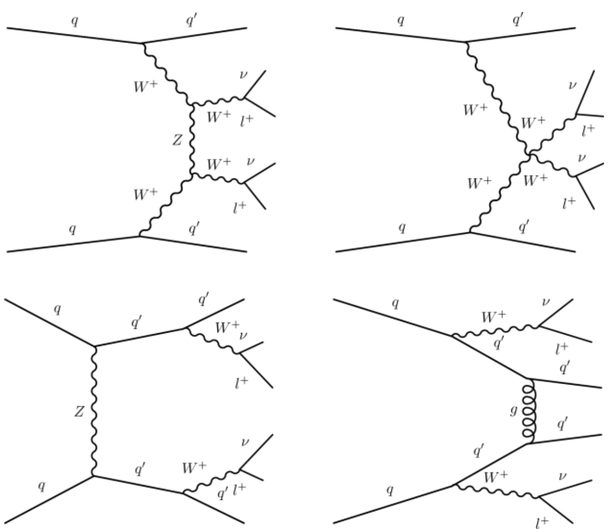
Prospects of same-sign WW at HL-LHC

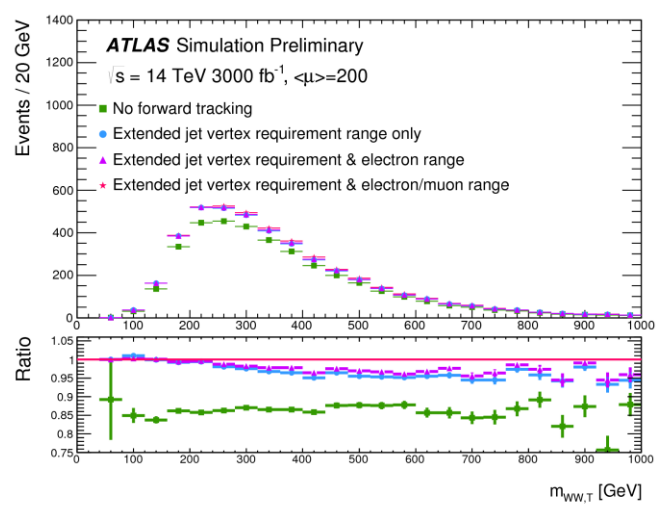


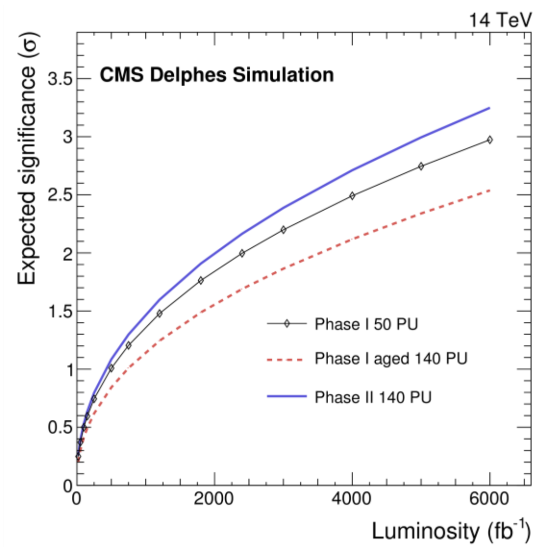
ATL-PHYS-PUB-2017-023

CMS-PAS-SMP-14-008

- Same-sign WW VBS
  - Expected uncertainty of the cross is about 5% at HL-LHC
  - Longitudinal WW component can be extracted using sensitive variables, e.g. $\Delta\phi_{jj}, p_T^{\mathrm{lepton}}$
- WZ VBS is more difficult



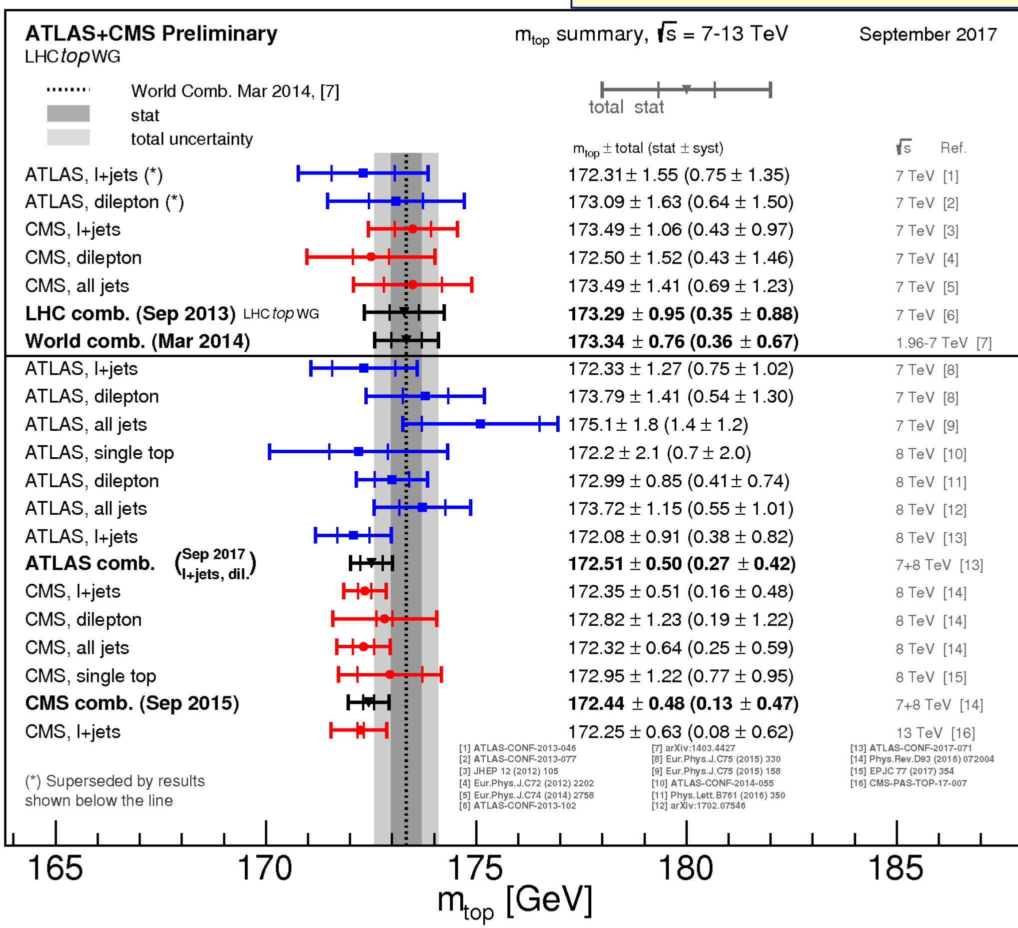


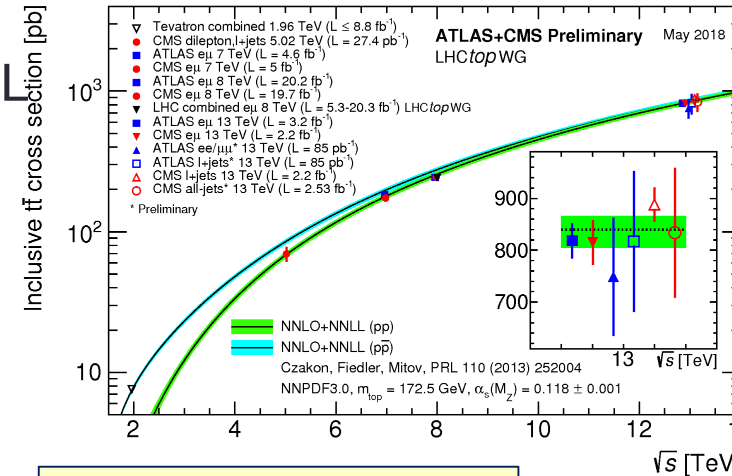


Top mass and cross sections

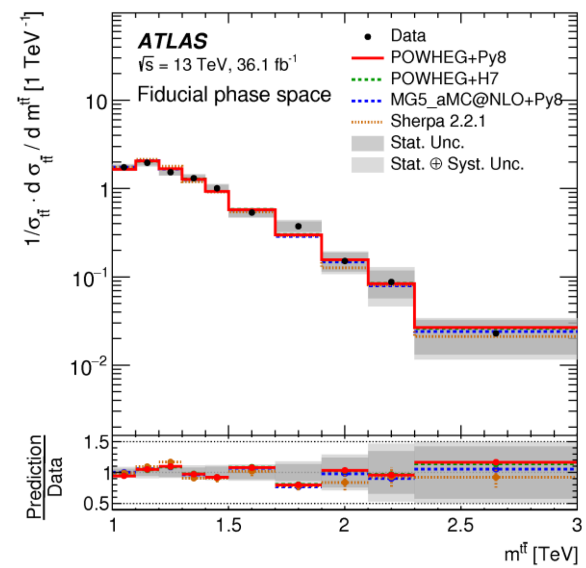
- $m_t = 173.34 \pm 0.76$ (world average)
- Cross section well described by NNLO+NNLL QCD calculation

LHC Top working group



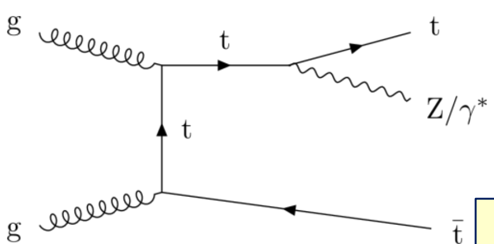


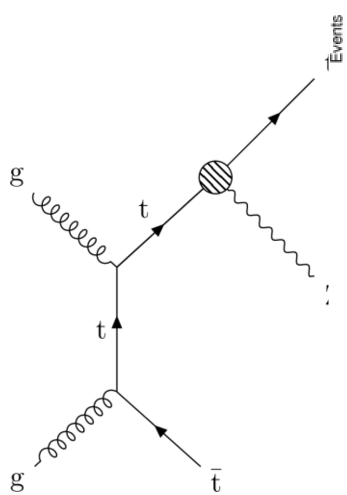
ATLAS-TOPQ-2016-09

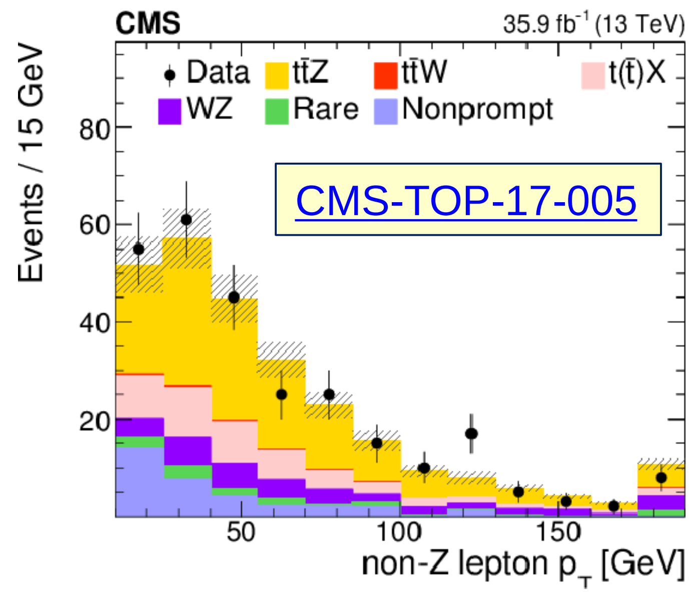


$t\bar{t}Z$ and $t\bar{t}W$ cross sections

- Interesting final state to investigate as extensions of SM may alter the couplings to top or EW gauge bosons
- Within the SM, it probes the top neutral current interaction







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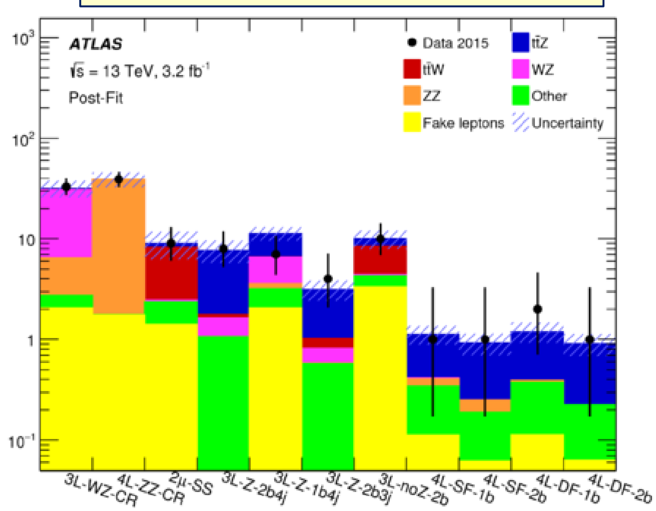
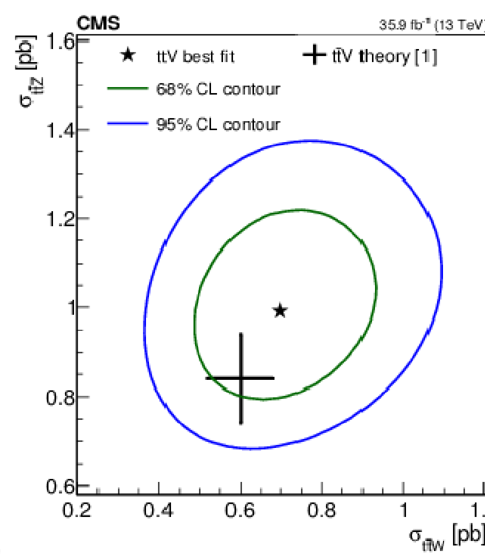
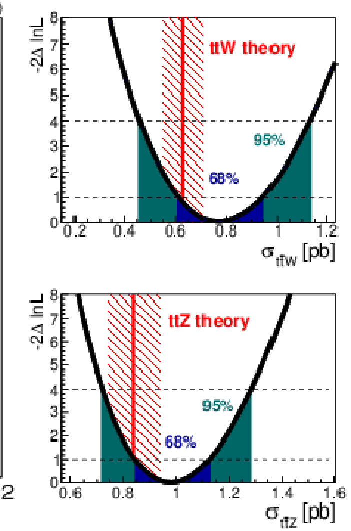
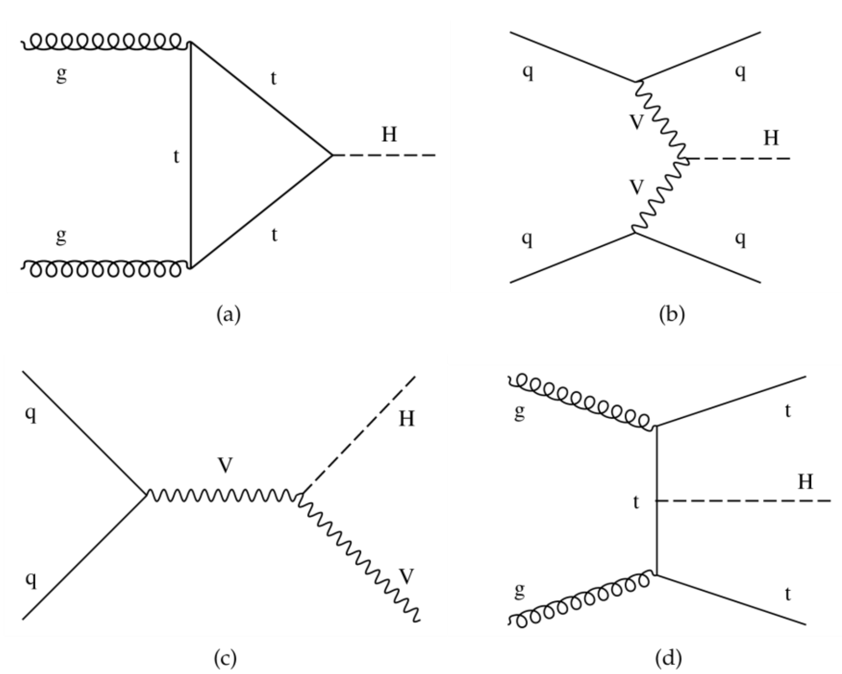






Higgs production and decay

Production processes



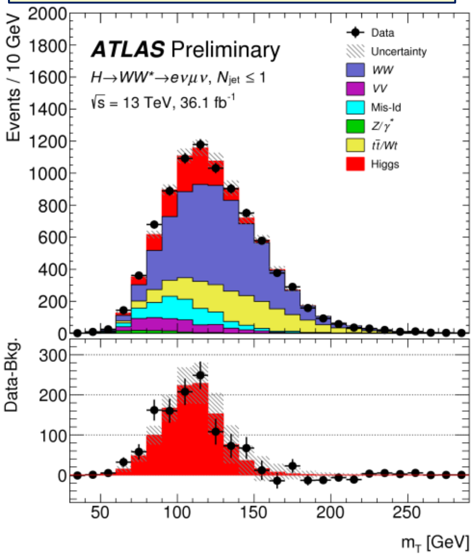
Decay mode	Branching ratio (%)
$b\bar{b}$ (*)	58.4
WW	21.4
(gg)	8.19
$\tau\tau$	6.27
$(c\bar{c})$	2.89
ZZ	2.62
$\gamma\gamma$	0.227

- ( ): No observation for these decay modes
- (*) Evidence at 3.5σ (ATLAS), 3.8σ(CMS)

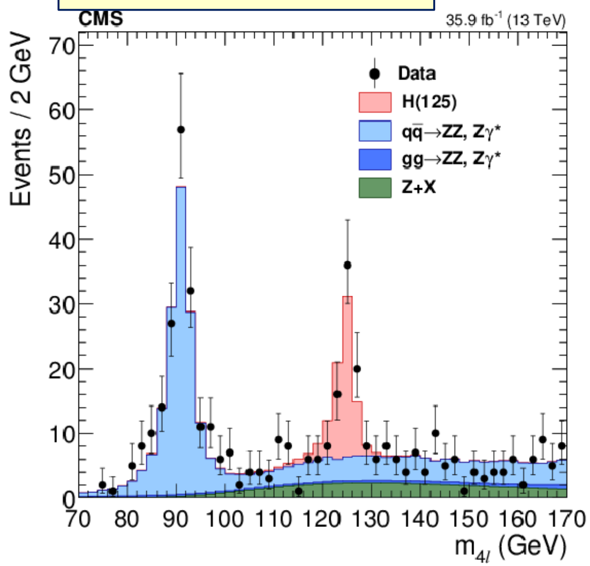
- Gluon-gluon fusion (ggF) process has the largest cross section followed by vector boson fusion (VBF), WH/ZH associated production
- $t\bar{t}H$ is useful to probe top-Higgs coupling

Higgs observations $(WW, ZZ, \gamma\gamma, \tau\tau, b\bar{b})$

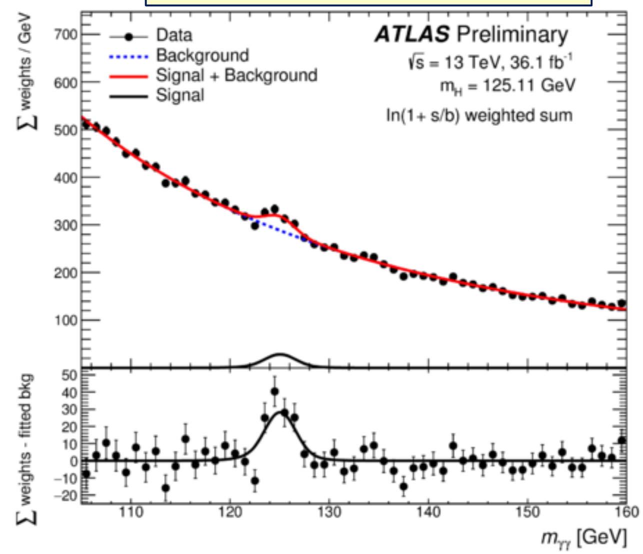
ATLAS-CONF-2018-004



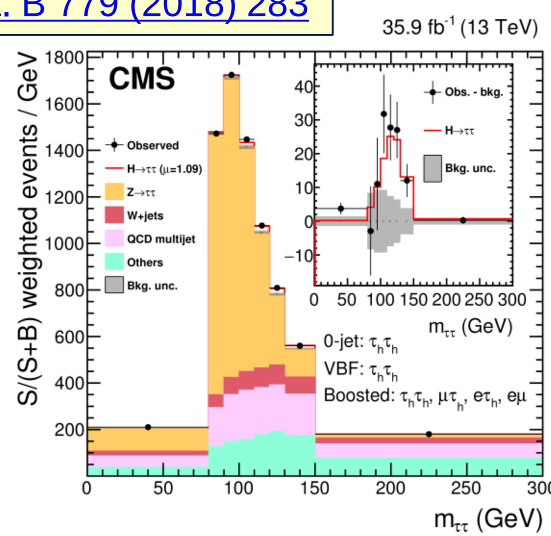
JHEP 11 (2017) 047



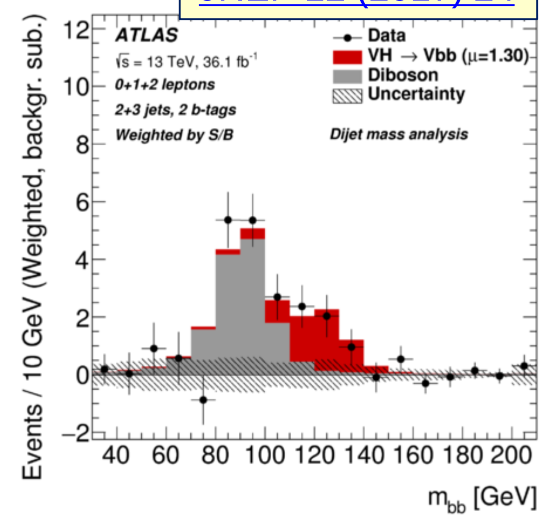
ATLAS-CONF-2017-046



Phys. Lett. B 779 (2018) 283

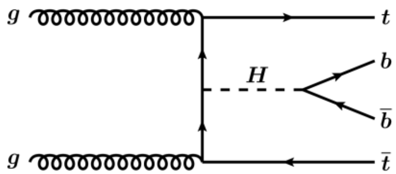


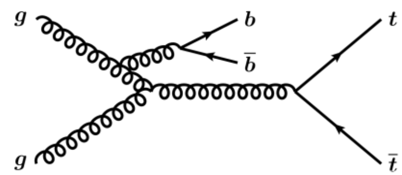
JHEP 12 (2017) 24



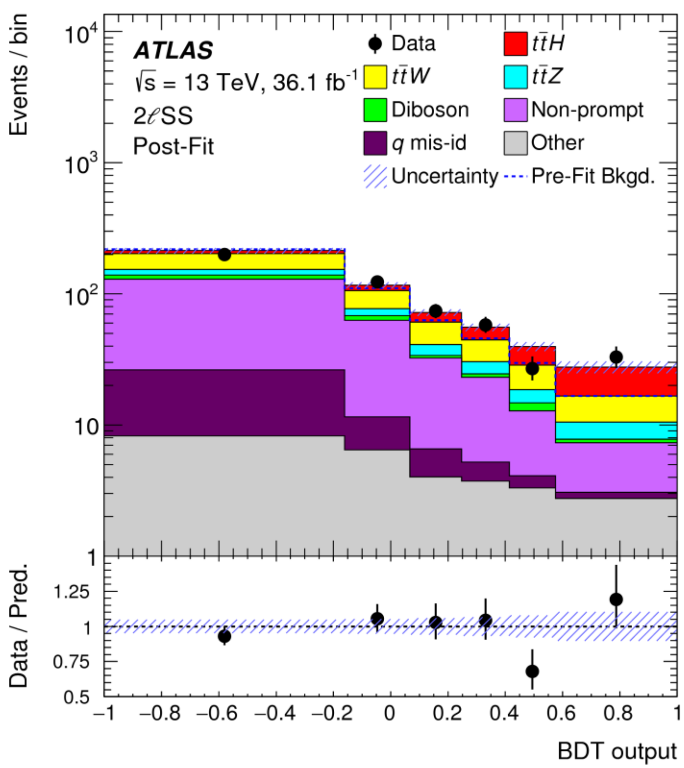
- Higgs boson is observed in many decay modes as predicted by the SM
- Observation in $WW, ZZ, \gamma\gamma$ channels at Run-1
- $\tau\tau$ and $b\bar{b}$ at Run-2

$t\bar{t}H$

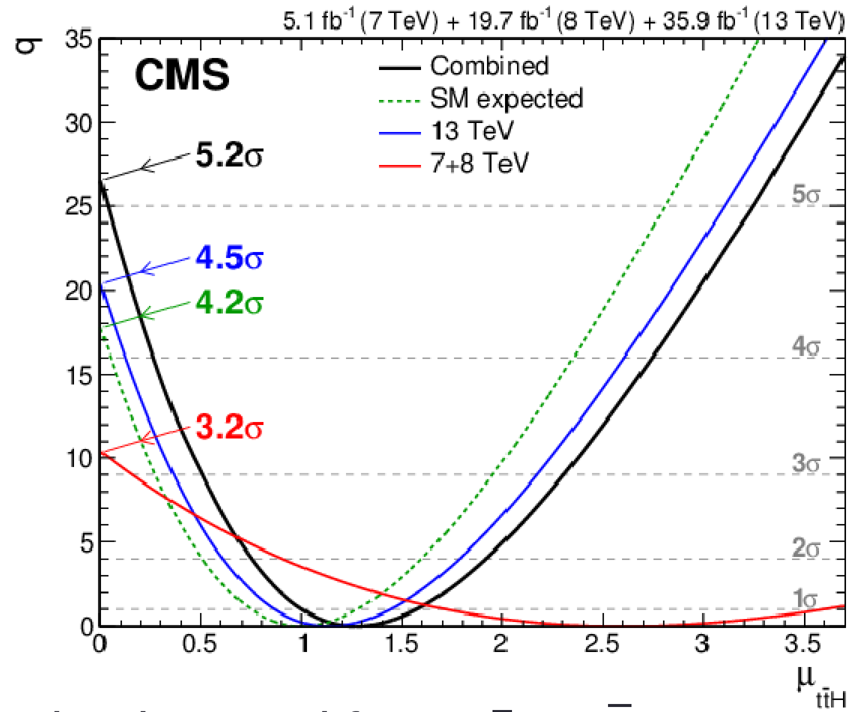




Phys. Rev. D97 (2018) 072003

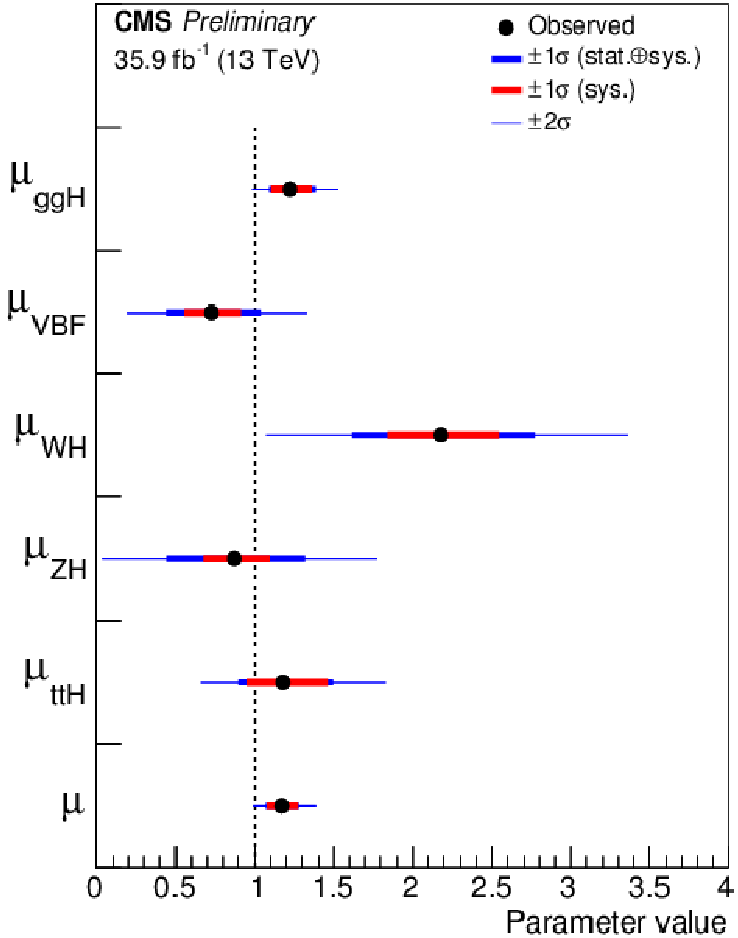


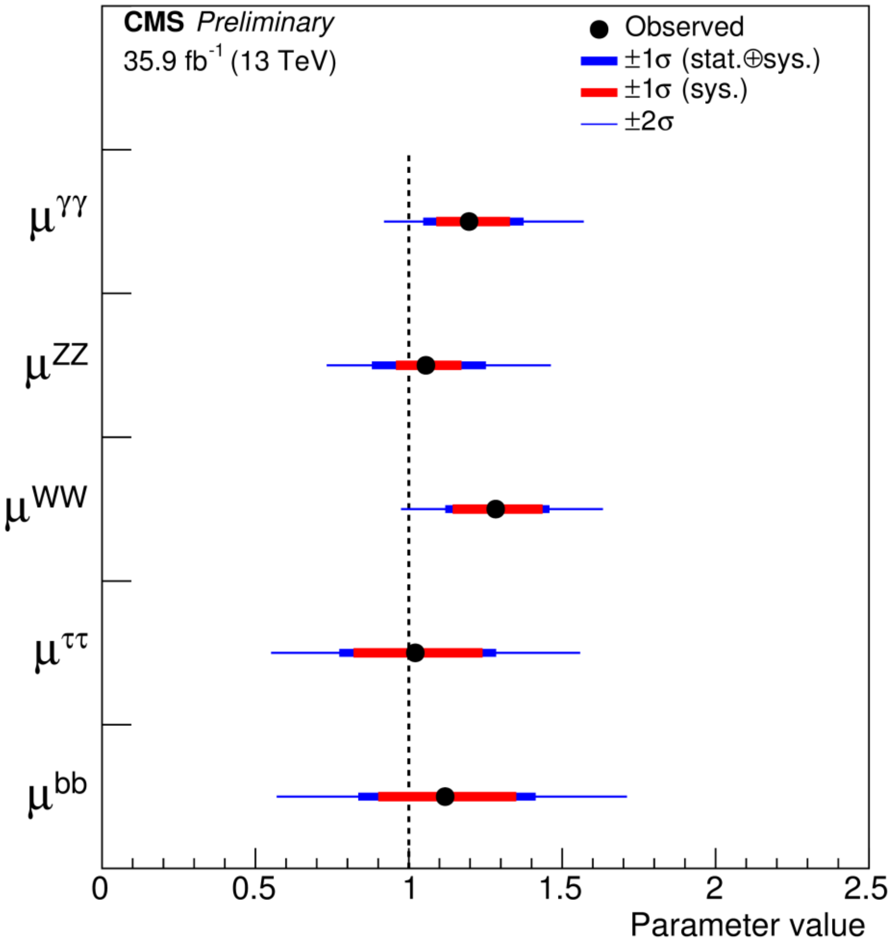
CMS-HIG-2017-35



- Large background from $t\bar{t} + b\bar{b}$
- ATLAS (only Run-2 data):
  - $\sigma_{t\bar{t}H} = 790^{+230}_{-210}$ fb, 4.2σ (3.8σ) observed (expected) significance
- CMS: Observation with at 5.2σ
  - Run-1 and Run-2 combined

Signal strengths at production and decay





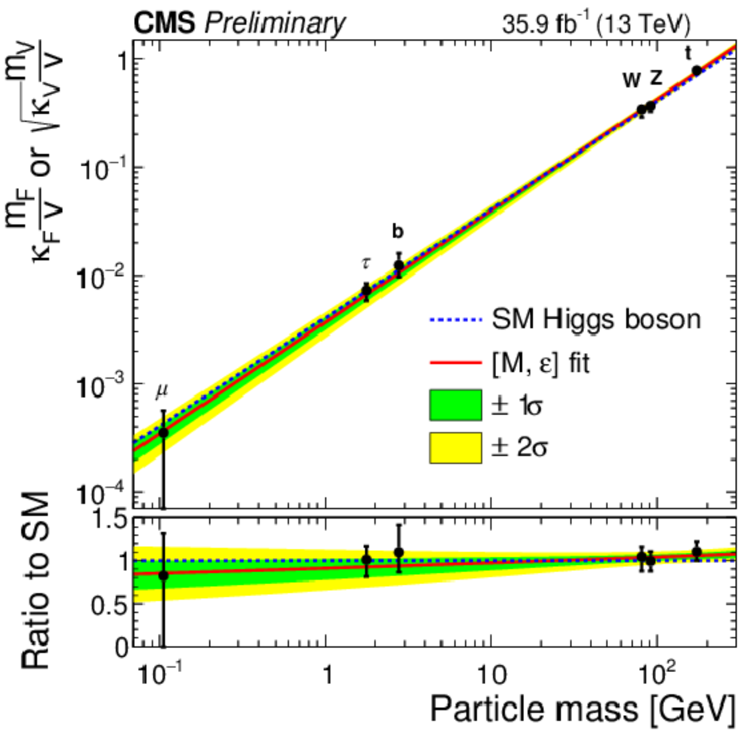
CMS-PAS-HIG-17-031

- Limited by systematics in several channels
- Similar results are also available from ATLAS (ATLAS-CONF-2017-047)

Higgs mass and coupling

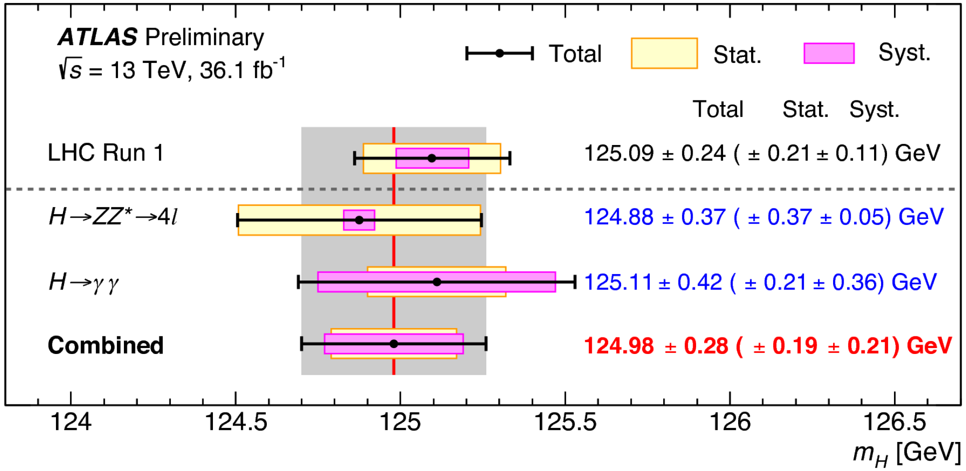
- Coupling measurements
  - About 10～20% uncertainties
  - Consistent with the SM Higgs boson

CMS-PAS-HIG-17-031



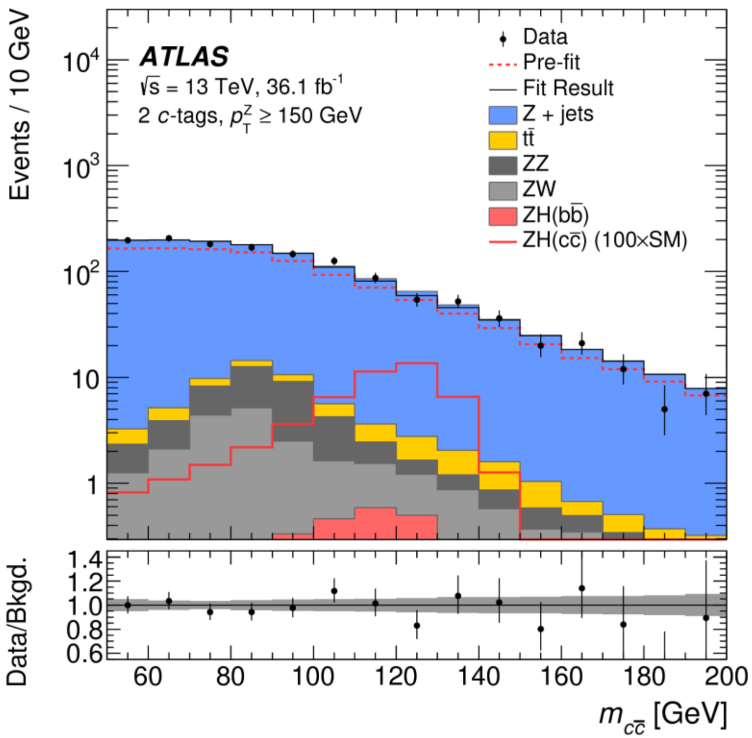
- Mass (precision of 0.2%)
  - $m_H = 124.98 \pm 0.24$ GeV (ATLAS)
  - $m_H = 125.26 \pm 0.21$ GeV (CMS)

ATLAS-CONF-2017-046 (ATLAS)
JHEP 11 (2017) 047 (CMS)



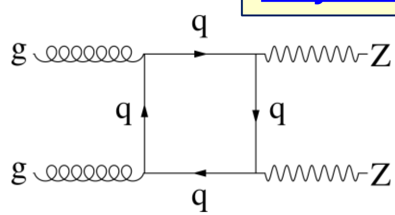
$H \rightarrow c\bar{c}$ and total width

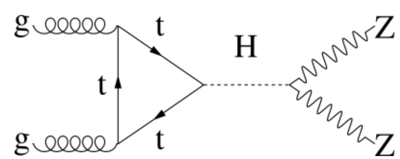
Phys. Rev. Lett. 120 (2018) 211802

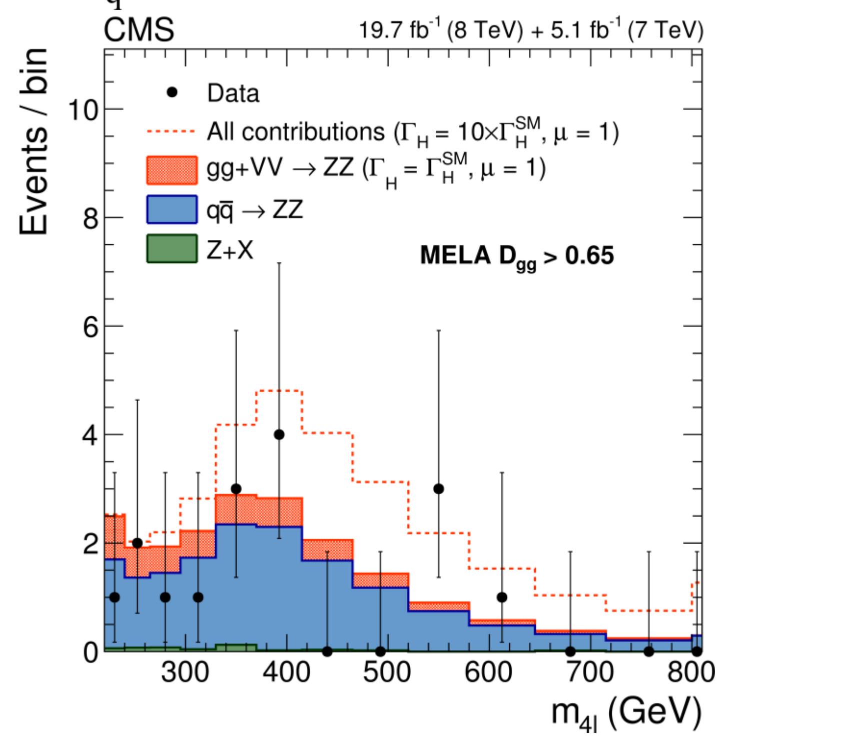


- Upper limit on $\sigma(pp \rightarrow ZH) \cdot Br(H \rightarrow c\bar{c})$
  - 2.7 $(3.9^{+2.1}_{-1.1})$ pb at 95% CL
- SM value: 26 fb

Phys. Lett. B 736 (2014) 64-85





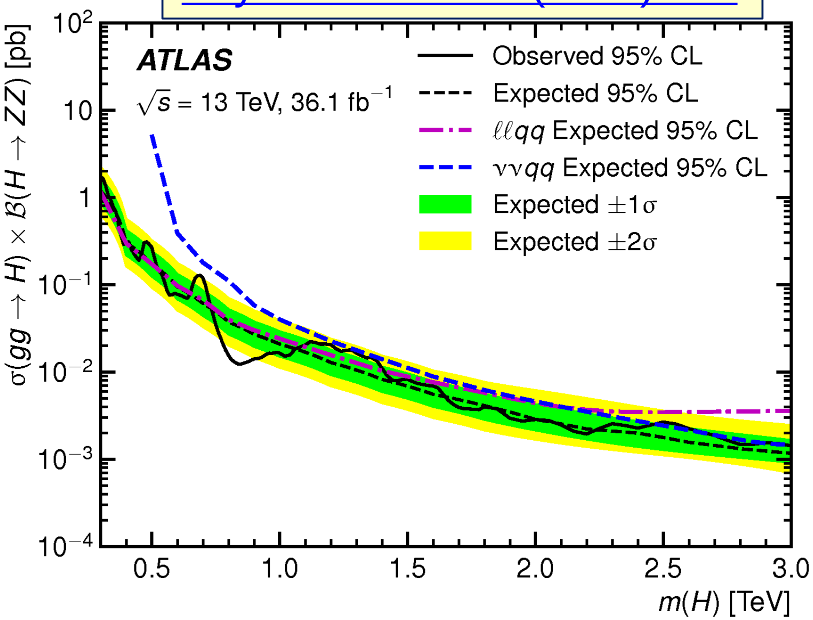


- $\Gamma_H < 22$ MeV at 95% CL. 5.4 times the SM expectation with $m_H = 125.6$ MeV

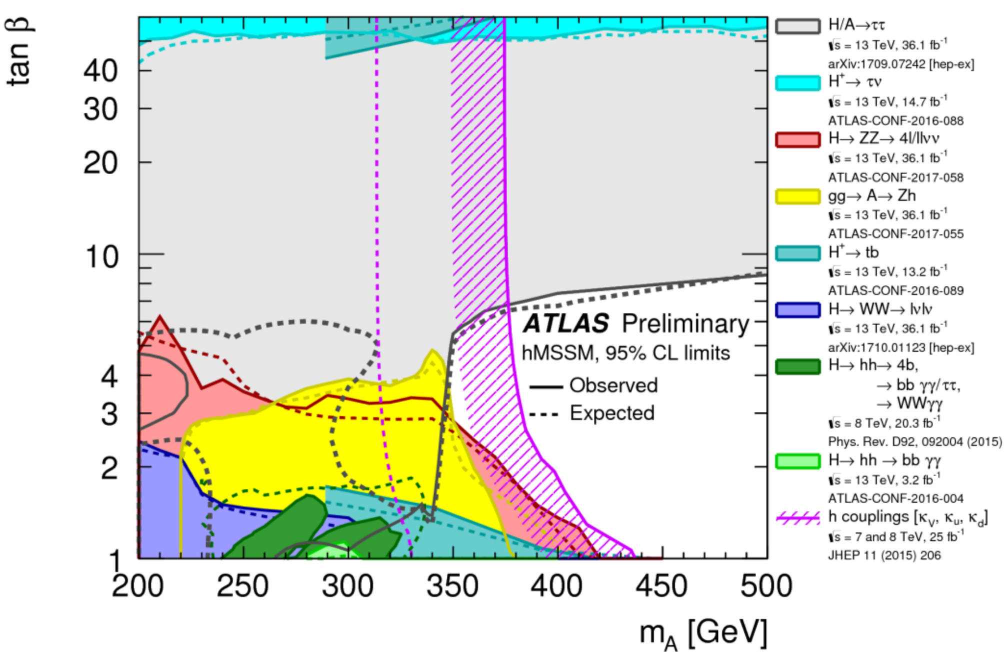
BSM Higgs

- There could be more than one Higgs boson in extensions of the SM
  - 5 Higgs bosons $(h, H, A, H^{\pm})$ in two Higgs doublet model
- Search channels
  - $H^{+} \rightarrow \tau\nu, t\bar{b}$, $H \rightarrow ZZ, WW, \tau\tau, hh, aa, t\bar{t}, \gamma\gamma$, $A \rightarrow Zh$
  - No signal found and limits are set in the hMSSM or general 2HDM
  - Interpretation of results in the context of hMSSM for many analyses. Other interpretations are tried as well, e.g. $\mathrm{H} \rightarrow t\bar{t}$, $A \rightarrow Zh$

Phys. Lett. B. 777 (2017) 091

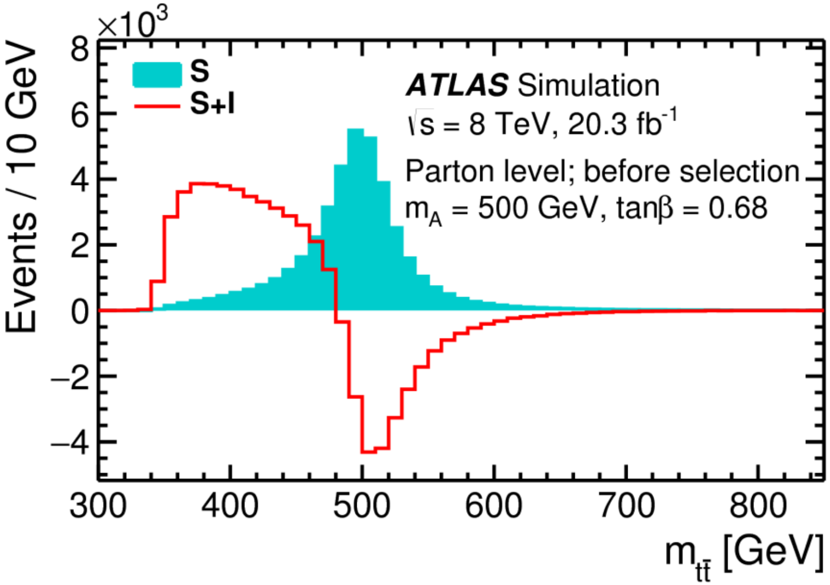


Limits in the context of hMSSM

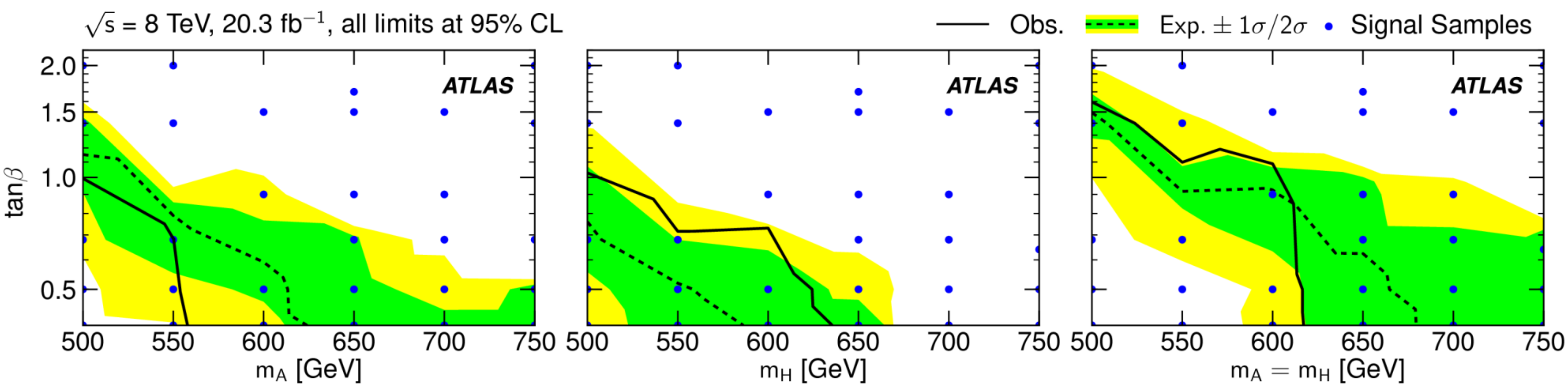


BSM Higgs : $A/H \to t\bar{t}$

Phys. Rev. Lett. 119 (2017) 191803

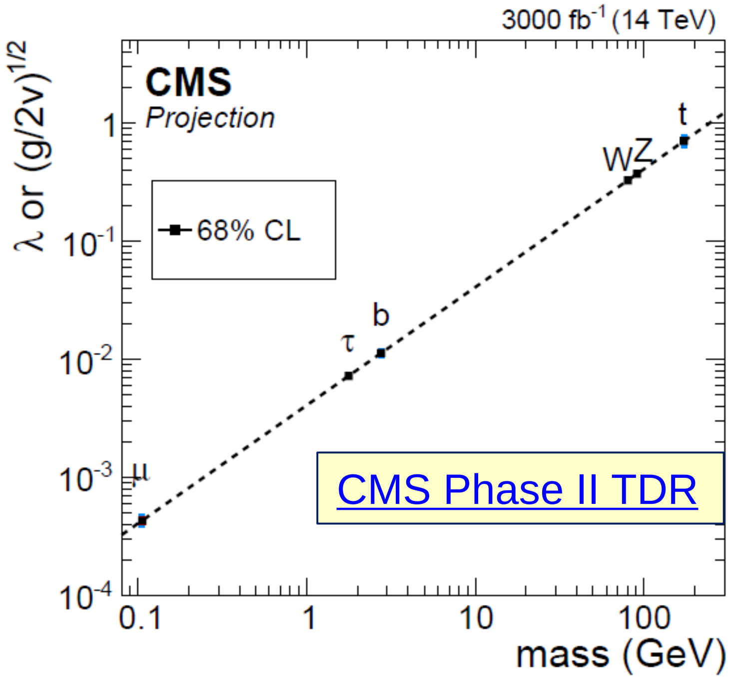


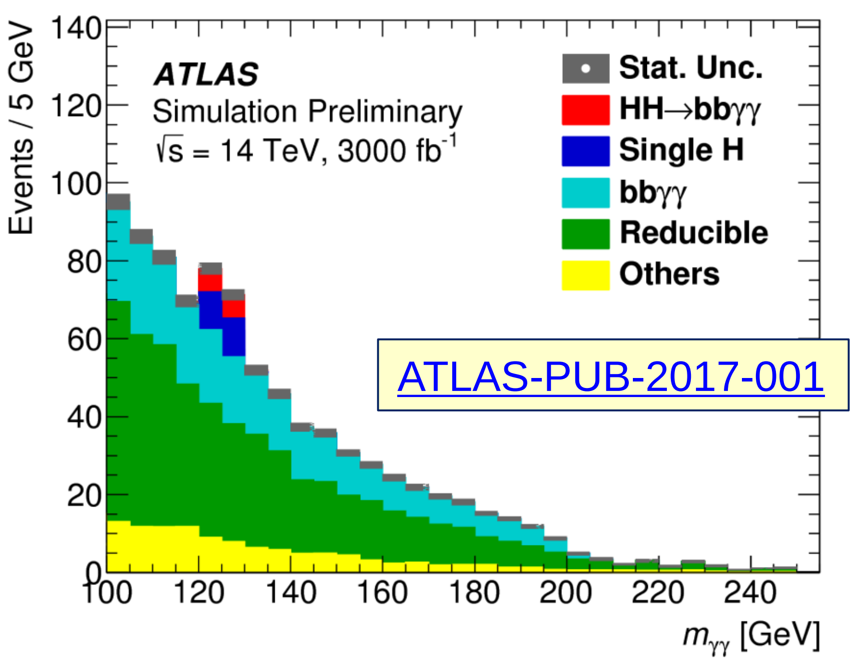
- Heavy Higgs A/H decaying into $t\bar{t}$
  - Dominant at $m_{A/H} > 500$ GeV
  - Enhanced at low $\tan\beta$ (<3)
- Interference with SM $gg \to t\bar{t}$
  - Distortion of the peak to peak-dip structure
- Excludes low-$\tan\beta$ regions for for various mass values



Higgs prospects at HL-LHC

- Percent level uncertainty for couplings (currently 10~20%)
- $\Gamma_H = 4.2^{+1.5}_{-2.1}$ MeV from the interference between on/off-shell production (ATLAS-PUB-2015-024)
- Expect 7σ observation of $H \to \mu\mu$ (CMS-PAS-FTR-16-002)
  - Only 2nd generation fermion accessible at the LHC
- Di-Higgs production (most promising channel is $HH \to b\bar{b}\gamma\gamma$)
  - $-0.8 < \lambda/\lambda_{SM} < 7.7$ (ATLAS-PUB-2017-001)



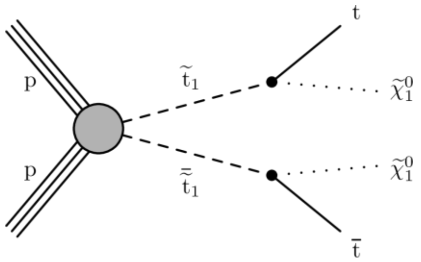


BSM searches

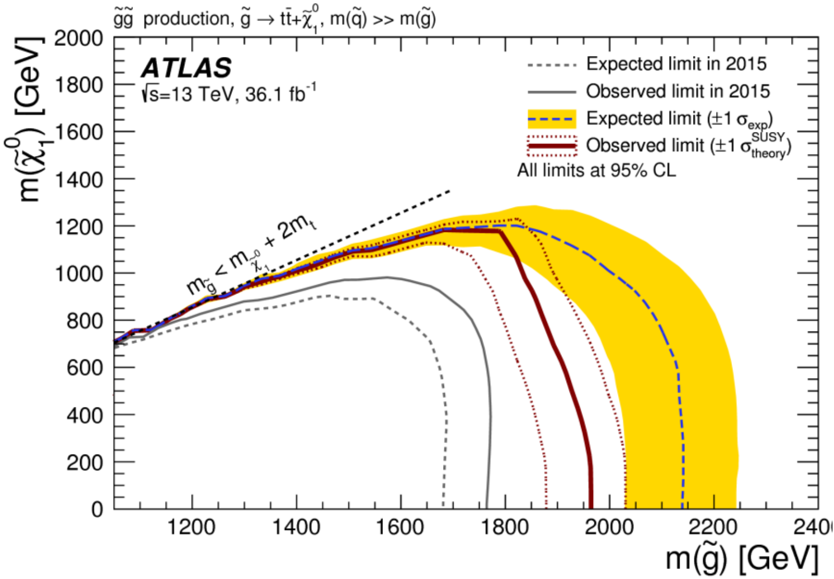
SUSY strong production

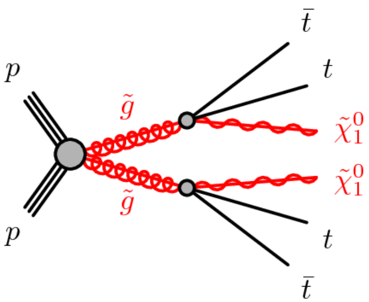
- Many analyses are done in various production and decay modes
- Gluino mass below ~2 TeV are excluded
- Stop mass
  - $m(\tilde{t}) < 420$ GeV for mass degeneracy with the lightest neutralino
  - $m(\tilde{t}) < 700$ GeV otherwise

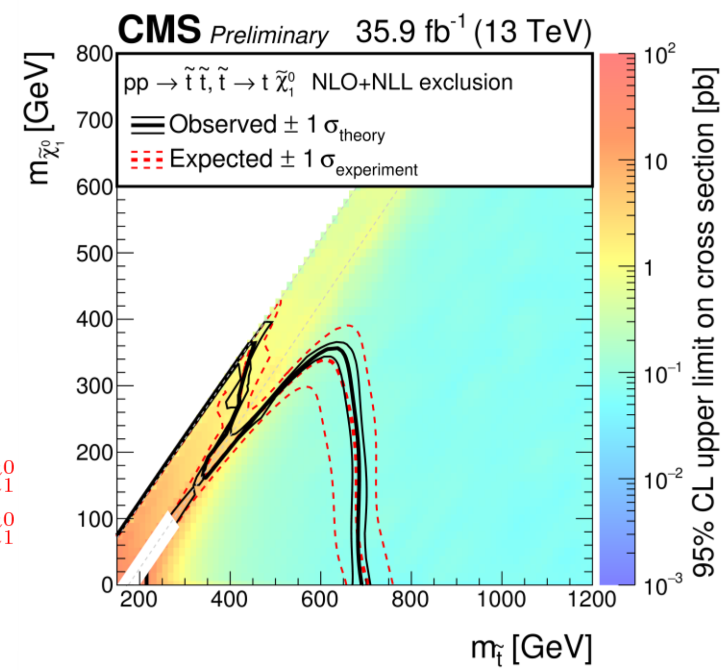
[CMS-PAS-SUS-17-010]



[ATLAS-SUSY-2016-10]

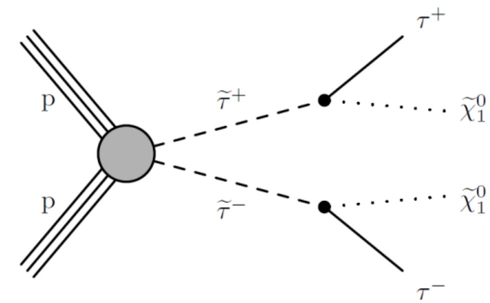




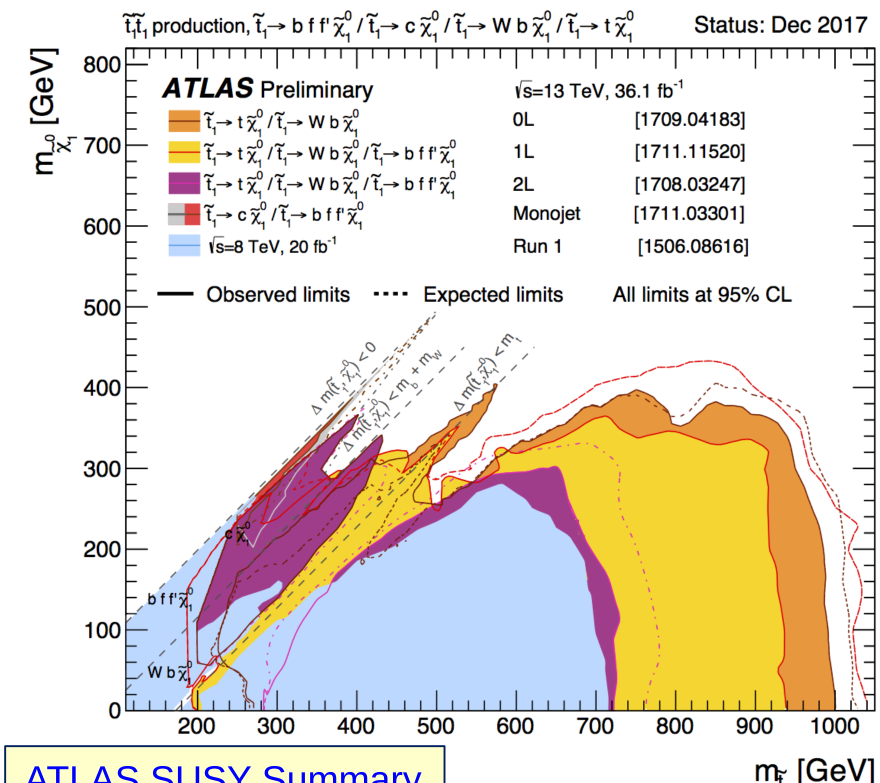


Limits for 3rd generation SUSY particle

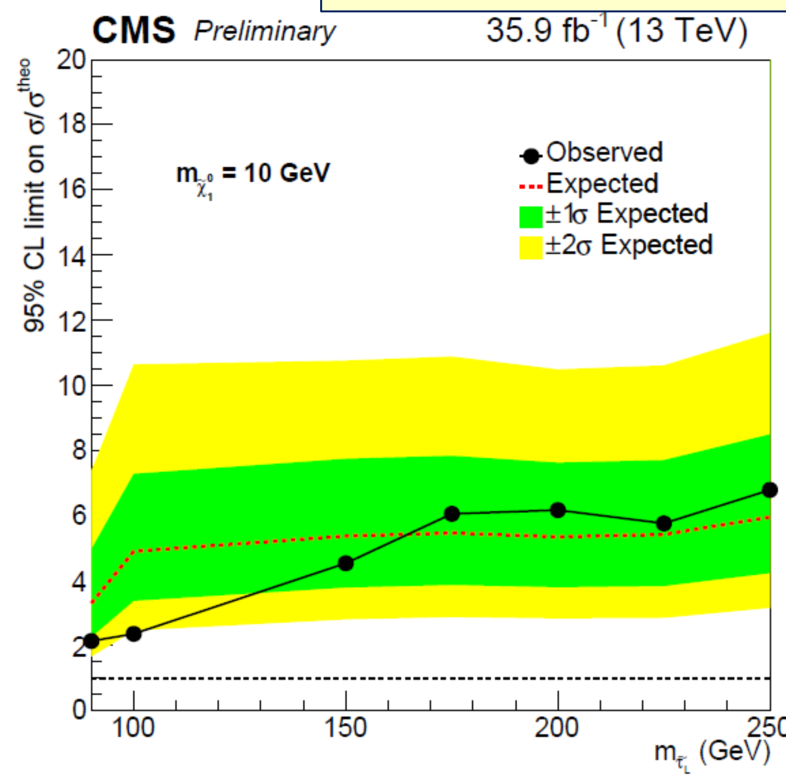
- Top squarks are searched for in various final states
- Low p_T object selection to explore compressed scenarios
  - Small $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0)$ → soft decay products
- Direct $\tilde{\tau}$ production → no sensitivity yet



CMS-PAS-SUS-17-002

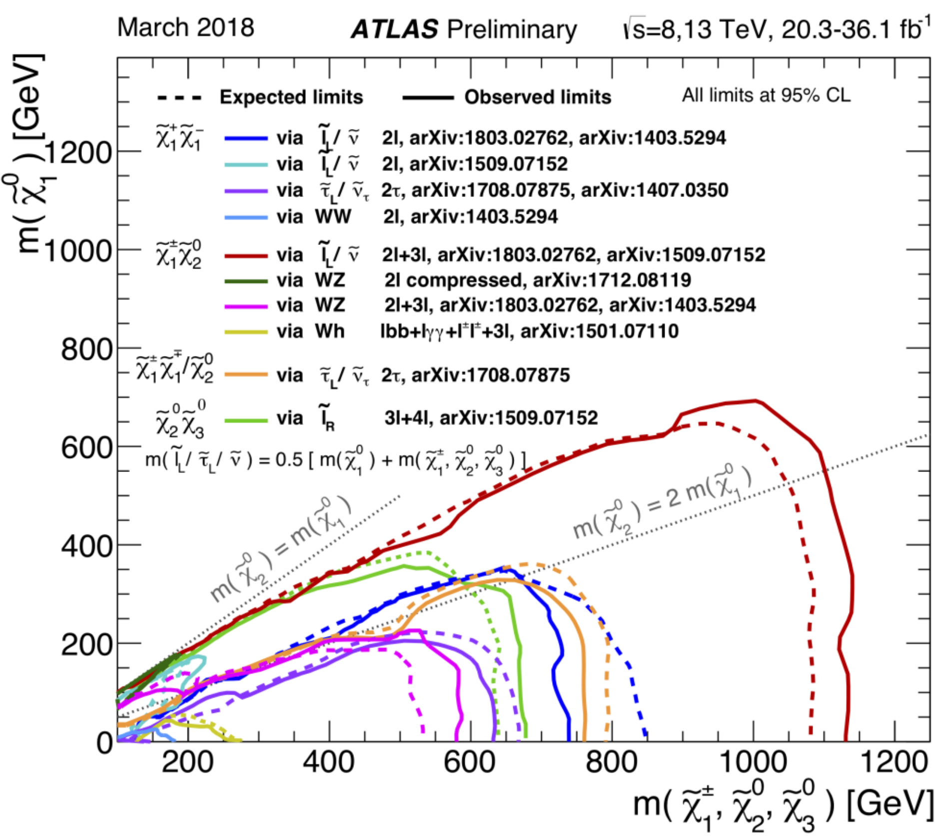


ATLAS SUSY Summary

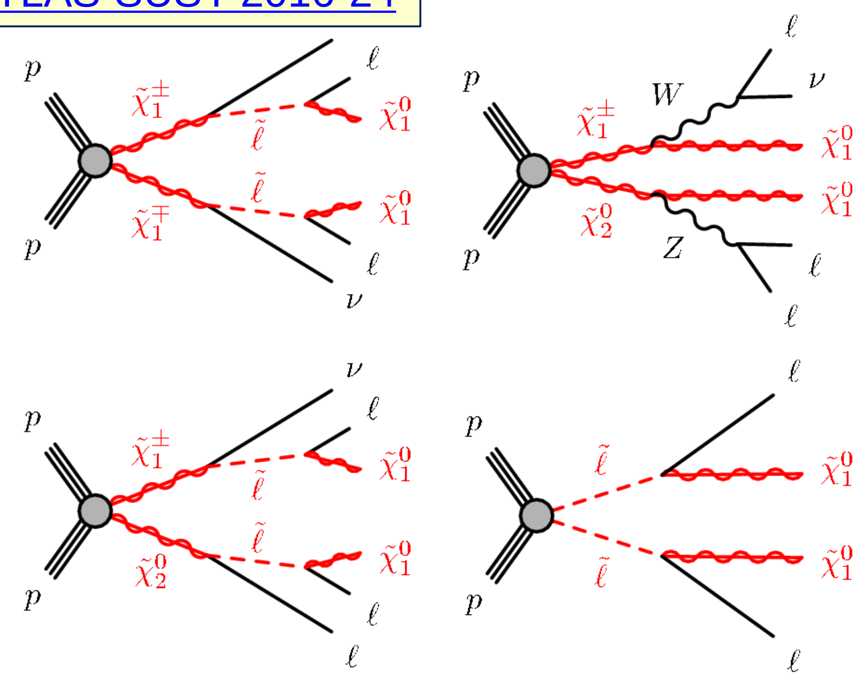


SUSY EW

- Searches for the production of $\tilde{\chi}^{\pm}_{1,2}$, $\tilde{\chi}^{0}_{2}$, $\tilde{l}^{\pm}$ which decays into $\tilde{\chi}^{0}_{1}$ and leptons
- For mass-degenerate chargino and neutralinos, masses up to 1,100 GeV are excluded for $m(\tilde{\chi}^{0}_{1})$<550 GeV, but depends heavily on the scenario
- Very little exclusion for direct chargino production, and none for direct stau production



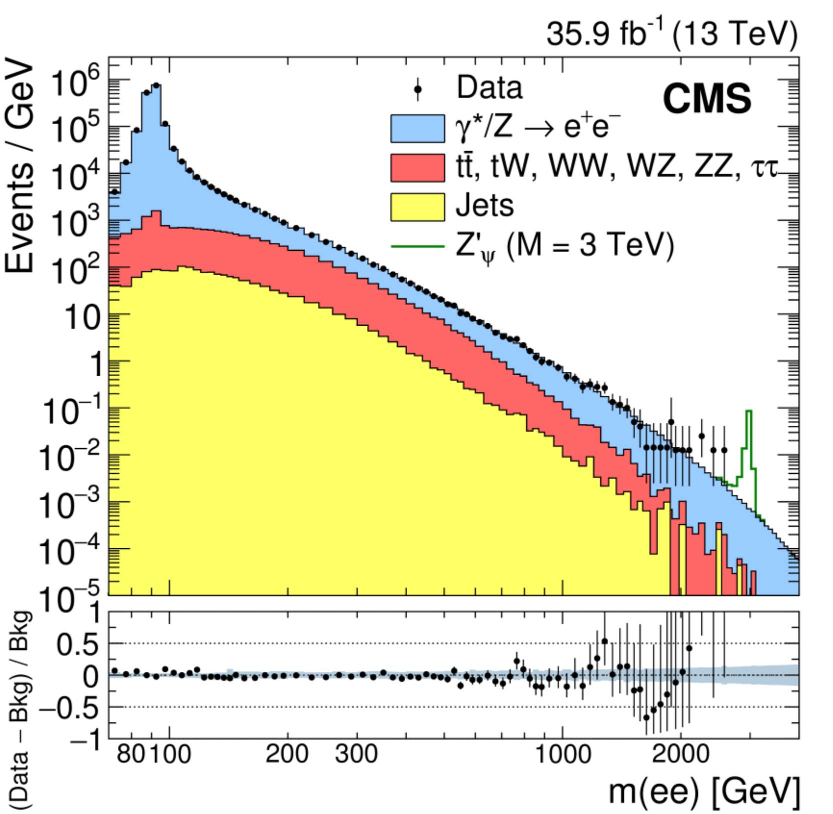
ATLAS-SUSY-2016-24

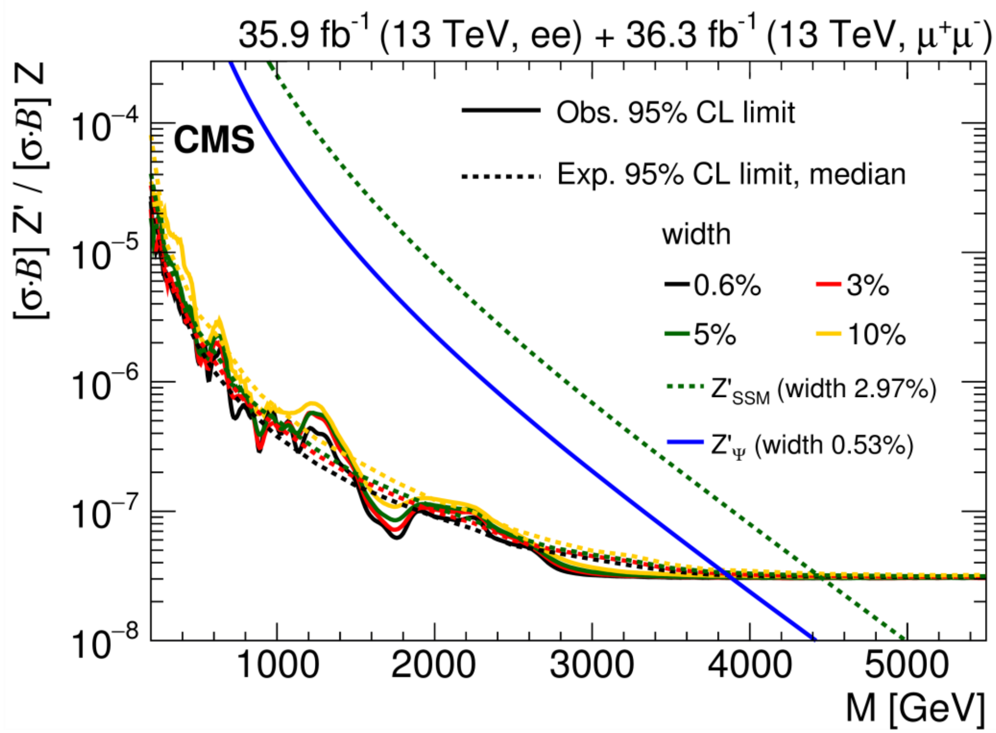


Dilepton resonances

- Search for a resonance in the dilepton invariant mass spectrum
- So far, no deviation from the SM is observed by ATLAS and CMS
- Extend the Z'_{SSM} limit from 4.5 TeV to 4.7 TeV

CMS-EXO-16-047

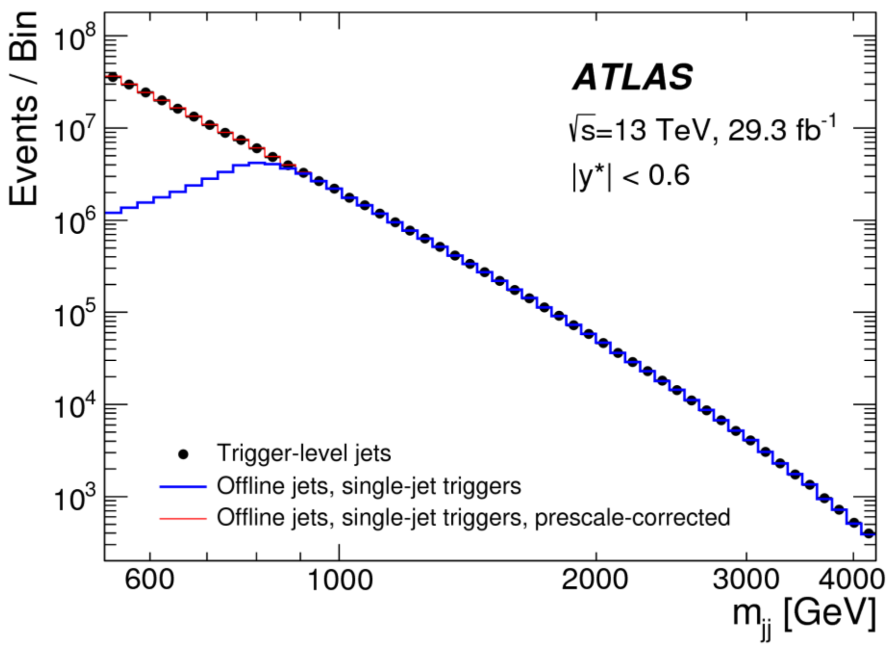


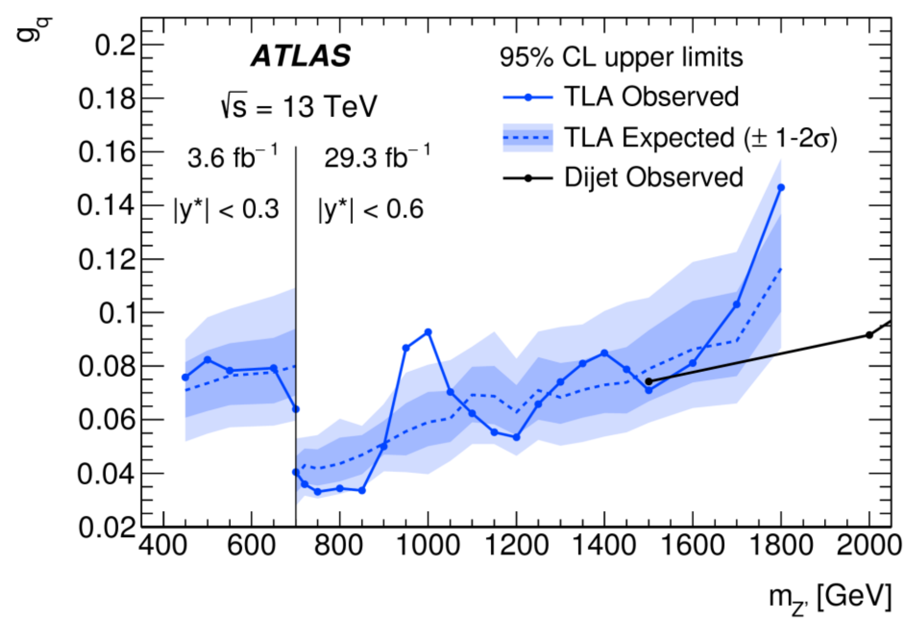


Dijet resonances

ATLAS-EXOT-2016-20

- Dijet search with trigger level analysis
  - Aim for low-mass resonances with small coupling (e.g. leptophobic Z')
  - Low mass objects ($m_{jj} < 1$ TeV) are usually not triggered
  - One could use trigger-level objects to analyze and save minimum data at high rate
    - Only jet four momenta and calorimeter variables
- Limits on the Z' coupling (g_q) is set against $m_{Z'}$ for 450<$m_{Z'}$<1800 GeV





Non-resonance searches

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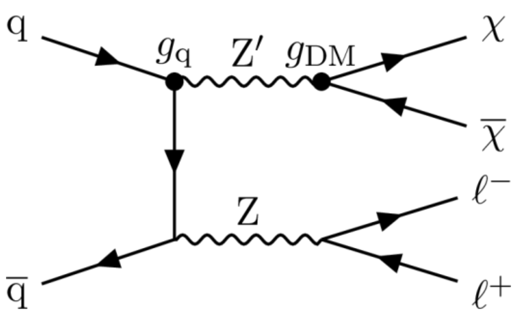
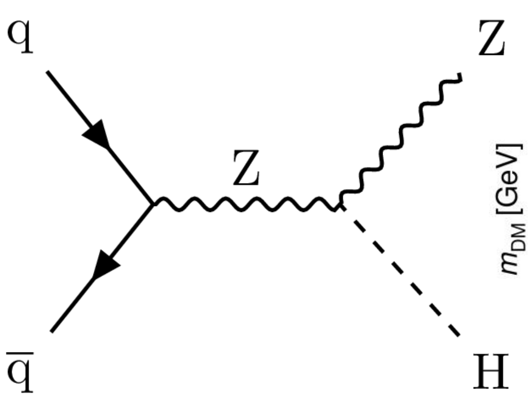
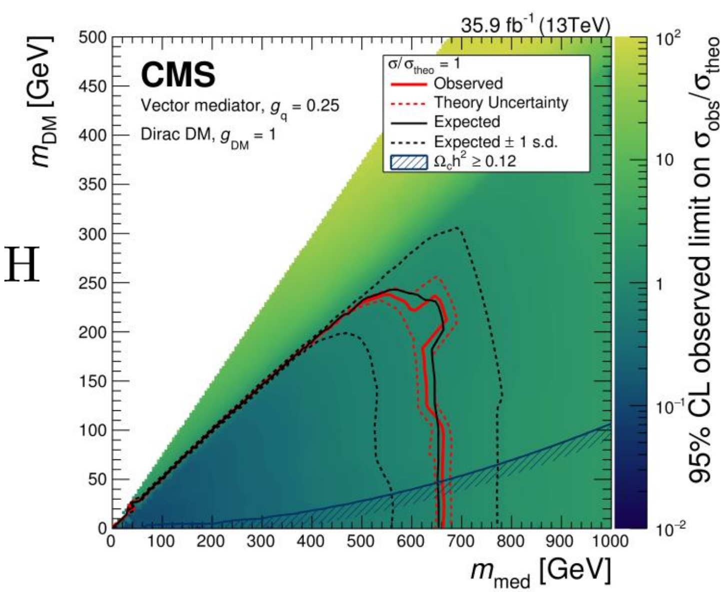
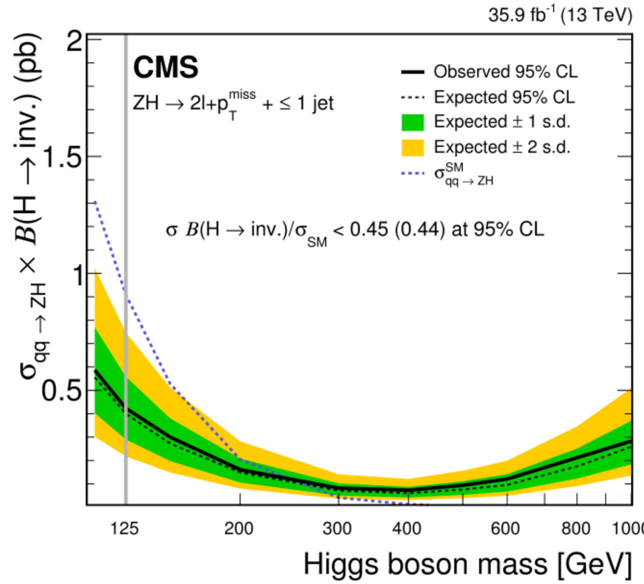


- Mono-Z search
  - A generic search for dark matter candidates
  - χ: dark matter candidate
  - Z': A messenger particle which couples to both SM and the dark sector
  - Final state: Two leptons from Z + E_T^{miss}
- Many other mono-X searches are also performed

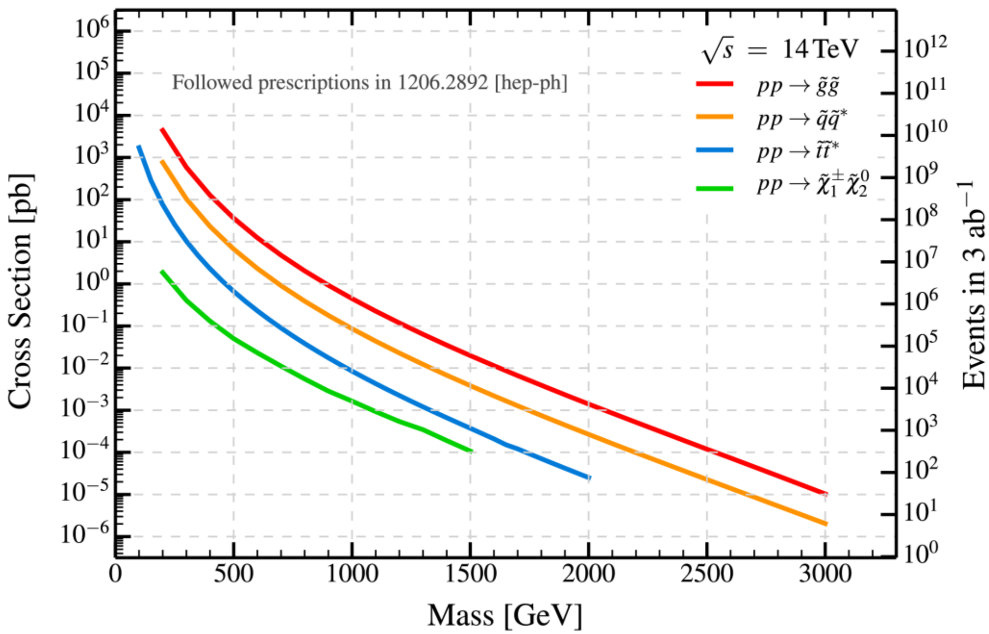


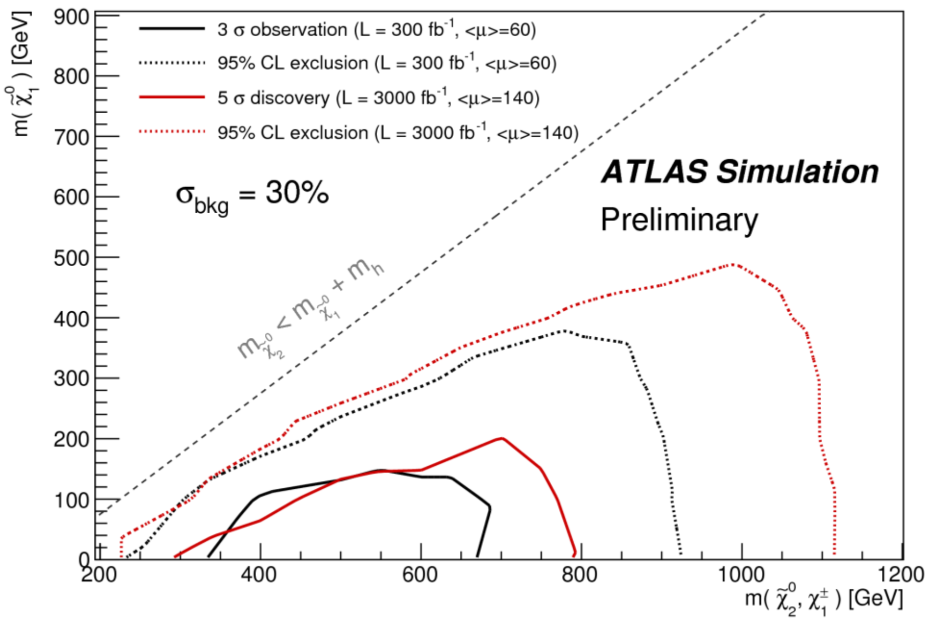




SUSY prospects

ATL-PHYS-PUB-2015-032

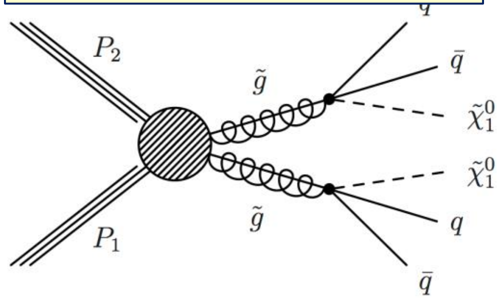




- Currently, exclusion of squarks and gluino masses go up to ~2 TeV
- Limits on gauginos and slepton masses are lower (500 – 1,000 GeV)
  - More data will extend the reach for these particles significantly
  - Exclusion limit: $m_\chi < 900\ (1{,}100)$ GeV with 300 (3,000) fb^{-1}

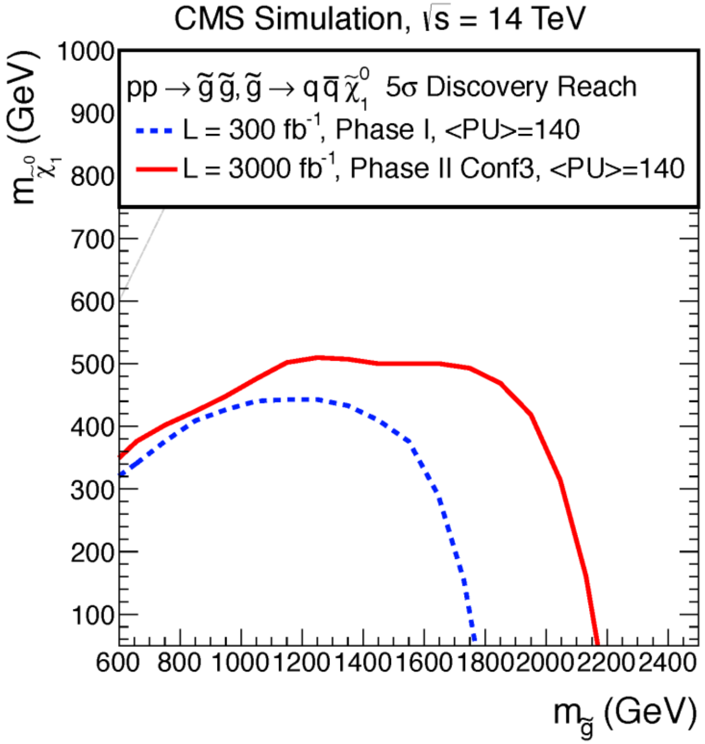
Prospects for gluinos

[CMS-PAS-FTR-13-014]

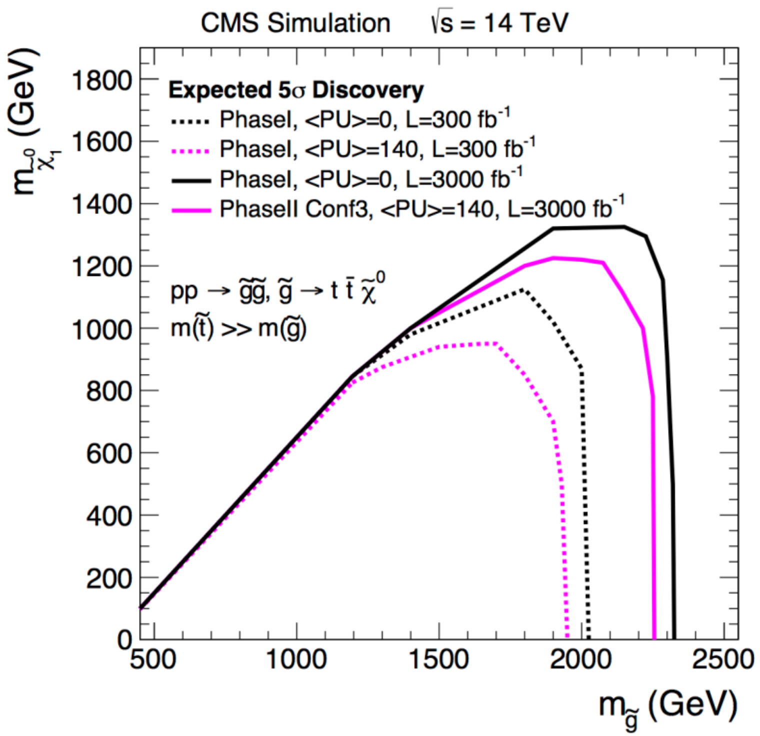


- Large production cross section
- Gluino masses up to 2.2 (1.8) TeV and LSP mass up to 500 (400) GeV can be discovered with 3,000 (300) fb^{-1}

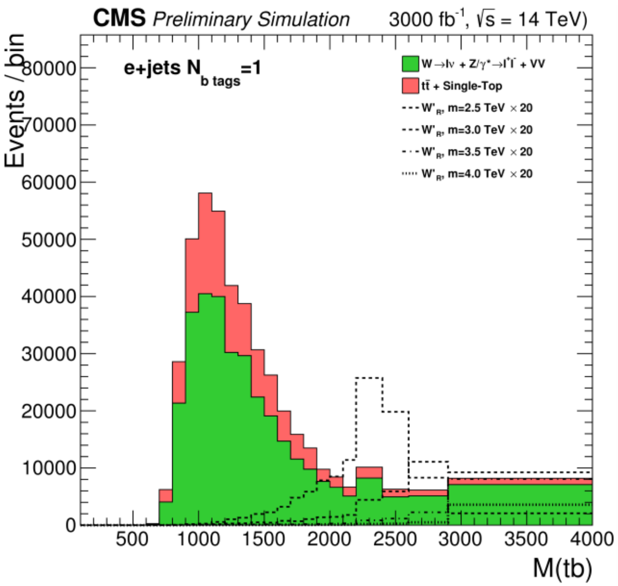
$\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$: Multijet, E_T^{miss}



- In case gluino decays preferentially to top
  - $\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$: Multijet, E_T^{miss}, 1-lepton

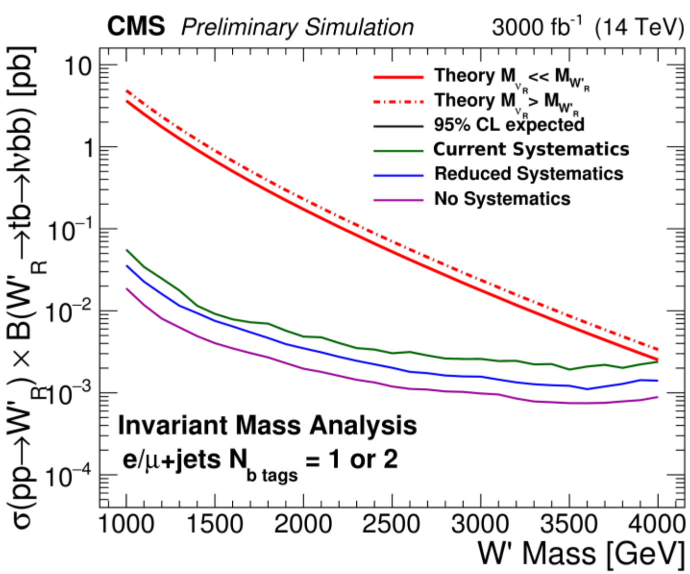


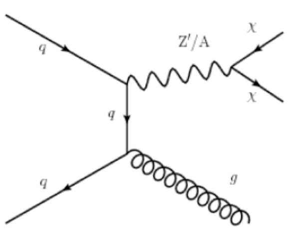
Prospects for new particles

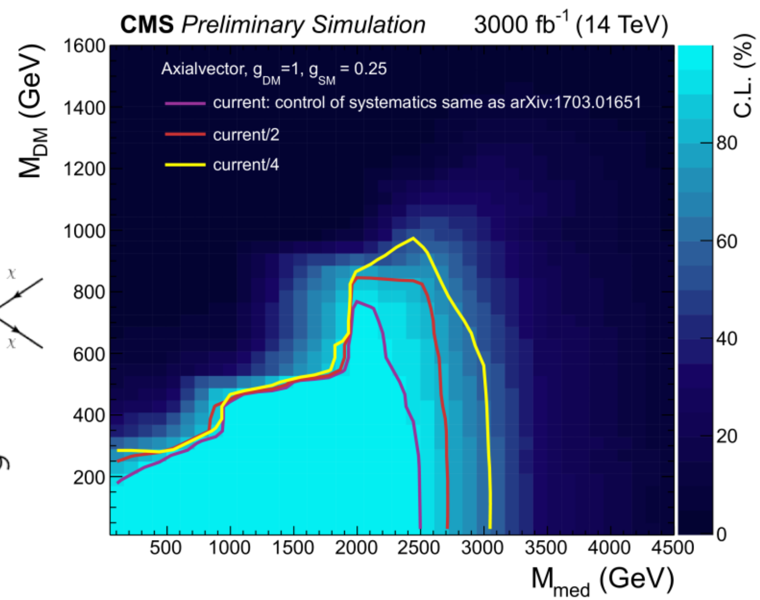


- Extrapolation from the Run-2 analyses
- $W_R' \rightarrow tb$, Z' search
  - Exclusion up to 4 TeV
- Mono-jet search for DM candidate
  - For an axial-vector (AV) and pseudoscalar (PS) mediator, mediator mass up to 3 TeV (900 GeV) can be excluded

CMS-PAS-FTR-16-005







Conclusion

- LHC provides a unique opportunity to investigate a wide variety of SM processes
  - QCD and EW processes, gauge couplings, top and Higgs properties, etc.
    - Precision measurements are also used to probe anomalous interactions
  - Higgs boson observation ($WW, ZZ, \gamma\gamma, \tau\tau$) and evidence ($b\bar{b}$)
    - Signal strengths are consistent with SM Higgs
    - HL-LHC will improve the precision of couplings to percent level
- Many direct searches for BSM physics are pursued
  - Resonance and non-resonance searches
  - Still no hint of new physics
  - HL-LHC will extend the reach above 1 TeV for gaugino masses and multi TeV masses for various resonances