KMI2017
International Symposium

Review on the LHC Run2 results

KMI2017, 5th-7th January 2017

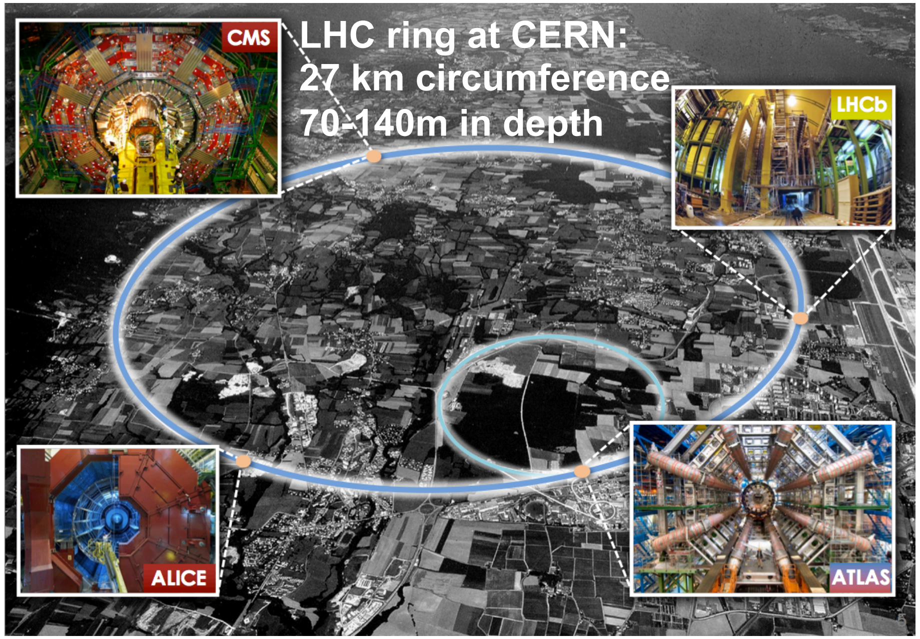
Yu Nakahama (KMI, Nagoya University)

Outline of this talk

- Introduction to LHC and the ATLAS Run2 experiment
- Review of physics results
  - Standard Model measurements
  - Higgs physics
  - Searches for New Physics phenomena; Exotics, SUSY
- Summary

Large Hadron Collider

- LHC is an energy-frontier collider at CERN, delivering proton-proton collision events
  - to two multi-purpose detectors; ATLAS and CMS
  - to dedicated detectors; LHCb for B-physics studies and ALICE for heavy-ion studies



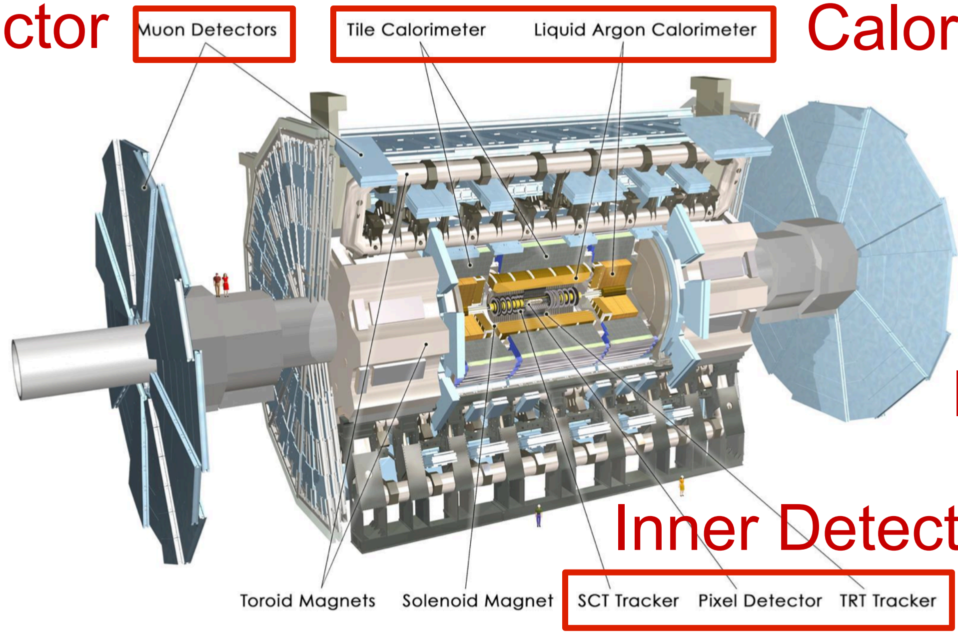
- Recent history and future
  - LHC Run1 (2009-2012) with p-p collisions at $\sqrt{s}$ = 7-8 TeV
  - Currently in a high-energy phase at $\sqrt{s}$ = 13-14 TeV, Run2 (2015-2018), followed by a bit higher luminosity phase Run3 (2021-2023)
    - I review recent physics highlights in this talk
  - For future, high-luminosity LHC (2026-) and FCC (far beyond) is planned
    - B. Petersen will present the future physics program
    - M. Tomoto will present muon trigger upgrade (KMI's contribution)

The ATLAS experiment

- The ATLAS detector is a multi-purpose detector that can directly explore energy scale from O(10) GeV to O(10) TeV

Muon Detector

Calorimeter



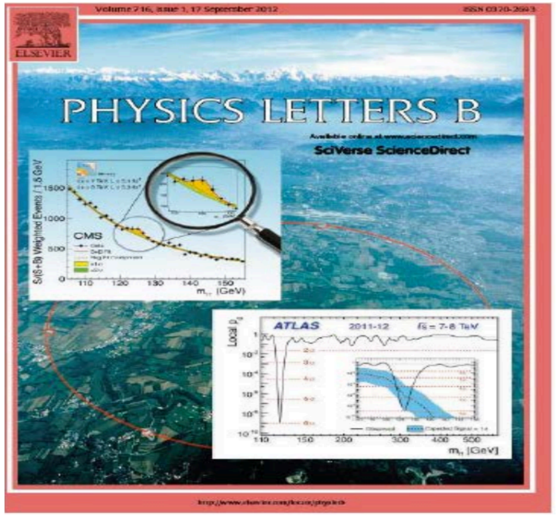
Inner Detector

+ Trigger and Data acquisition system

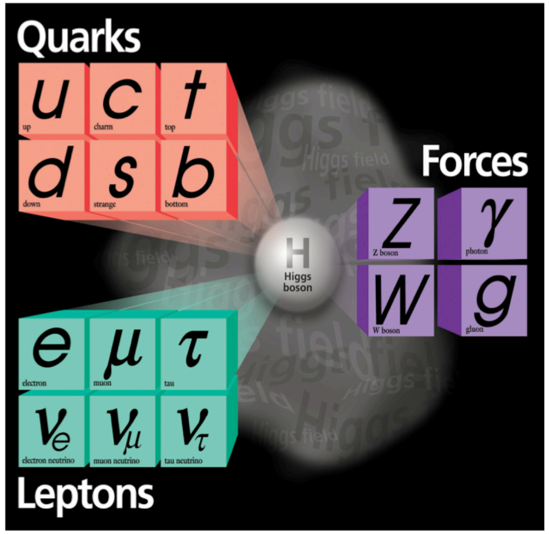
- The ATLAS experiment has around 2900 collaborators from 180 institutions across 38 countries
- KMI has been contributing to ATLAS
  - with primary focuses on “Muon Detector and Trigger system”, as well as on “Top physics and New Physics searches”

Physics highlights with the Run1 dataset

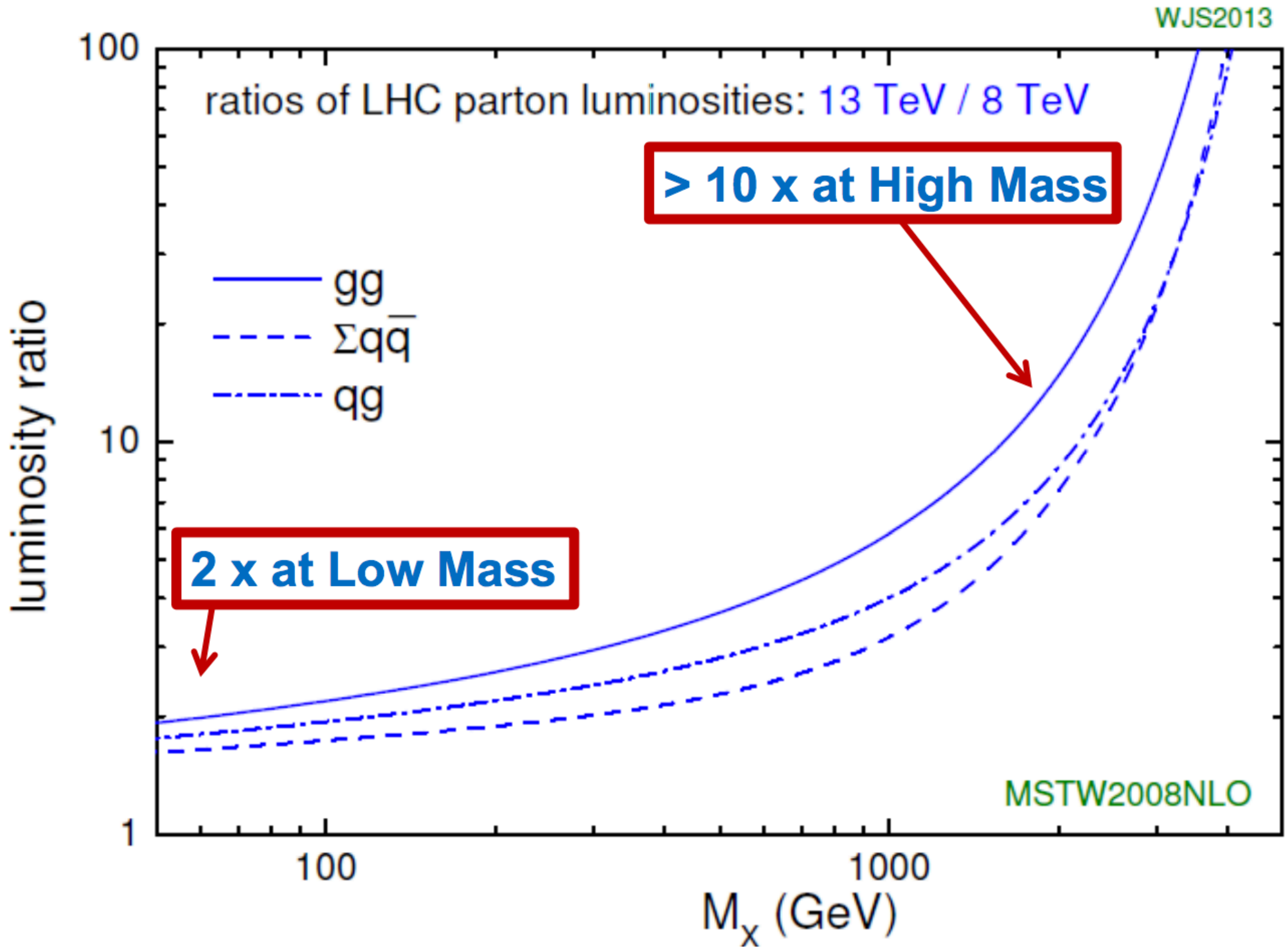
- Higgs discovery
  - Higgs-like particle discovery was announced on July 4th 2012 - Phys. Lett. B 716 (2012) 1-29
  - March 2013: key papers on particle properties. New particle declared as "a Higgs boson"
  - Citation for the 2013 Nobel Prize in Physics



- Deep and broad range of experimental results, all beautifully fitting in the Standard Model framework of elementary particle physics

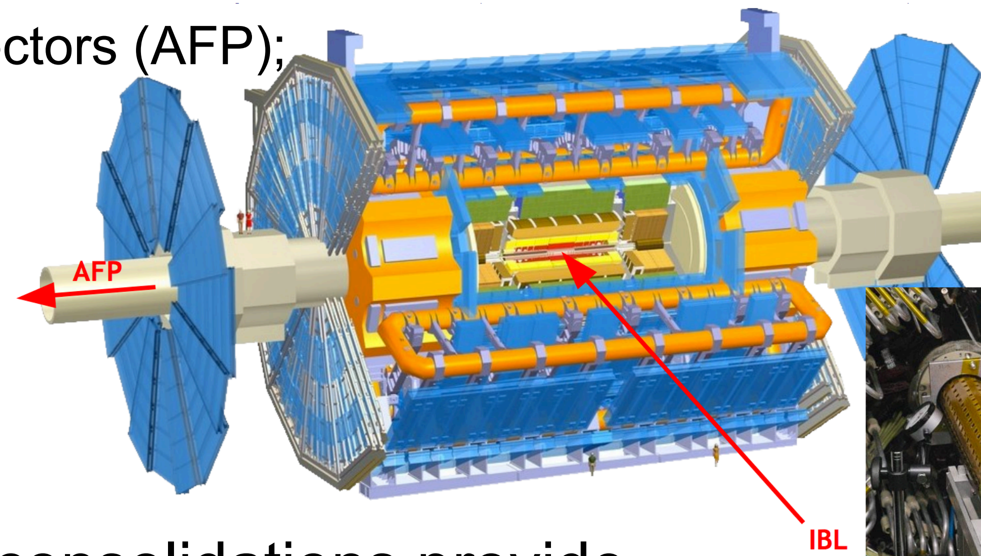


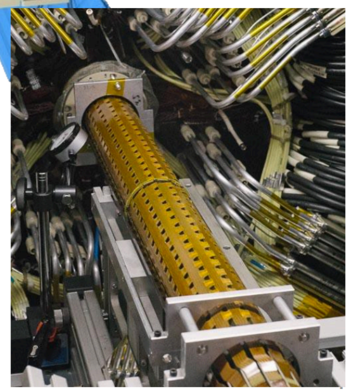
$\sqrt{s}$ = 13 TeV: parton luminosity increase



ATLAS in Run2

- Primary physics focuses
  - on New Physics searches using early datasets and
  - on measurements of Higgs properties using higher-statistics datasets
- New detectors installed
  - Innermost pixel layer (IBL); 3.4cm from the interaction point
  - Forward proton detectors (AFP); 210m from IP





- In addition, various consolidations provide improved running at high luminosities and rates

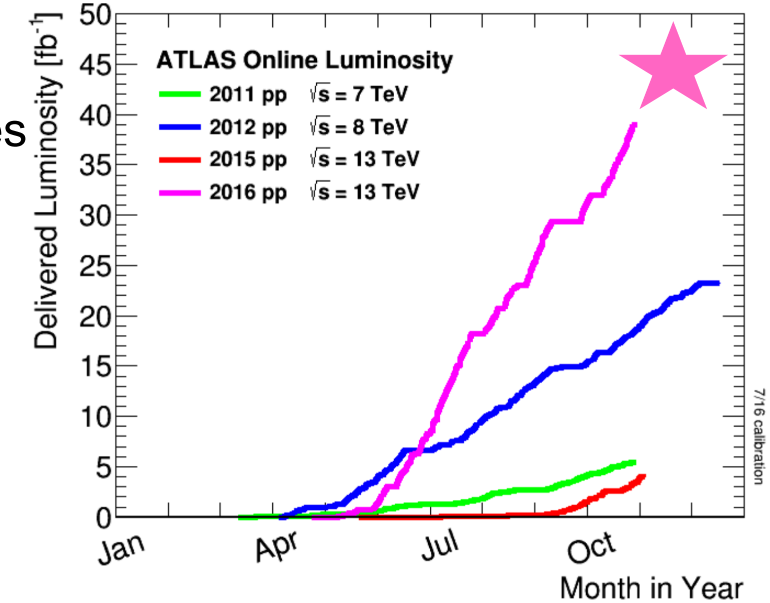
ATLAS data taking in 2016

- The 2016 pp data taking lasted until 26th October
  - Set a record in peak luminosity: 1.4e34
  - Total dataset recorded ~36 fb^{-1} with excellent data quality; >90% of data collected usable for analyses

Operations in the ATLAS control room

  - 2016 was an extremely productive year, comparing with previous years

Delivered luminosities to ATLAS (per year)



Trigger challenge in high luminosities

- Critical contribution from KMI, including menu-coordination role

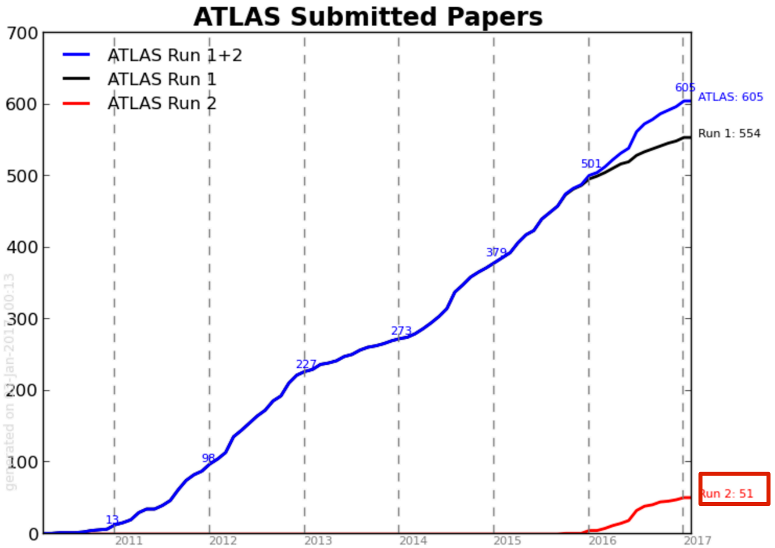
- Designed and operated a complex list of trigger selections to meet varied physics, monitoring and performance requirements
  - Typically ~2000 active trigger selections, driven by the priorities in the ATLAS physics program
  - Stable primary triggers
  - Peak output rate at Level-1; 90kHz
  - Ave. output rate at High Level to storage; 1.0kHz
  - → meeting detector operation and DAQ requirements

Main primary trigger	Trigger thresholds at HLT [GeV]
single leptons	Isolated μ, p_T > 26
	Isolated e, E_T > 26
E_T^{miss}	> 110 (in MHT, jet-based)
single jet	p_T > 380
single photon	E_T > 140
di-muon for B-phys	$p_T(\mu_1, \mu_2)$> 6, 6 + topological/mass cuts
di-tau	$p_T(\tau_1, \tau_2)$> 35, 25+jet requirement at L1
di-photon	$p_T(\gamma_1, \gamma_2)$> 35, 25

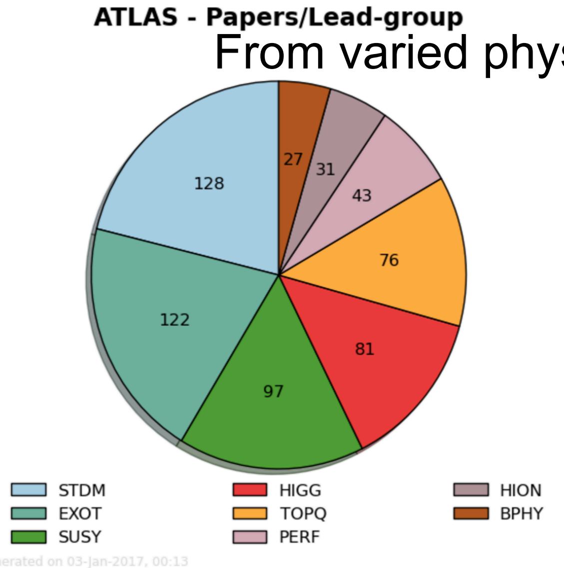
  - Trigger menu for the rest of Run2 is being prepared for 2e34

Physics Results

- ATLAS has submitted 605 papers in total
  - including 51 papers using Run2 dataset



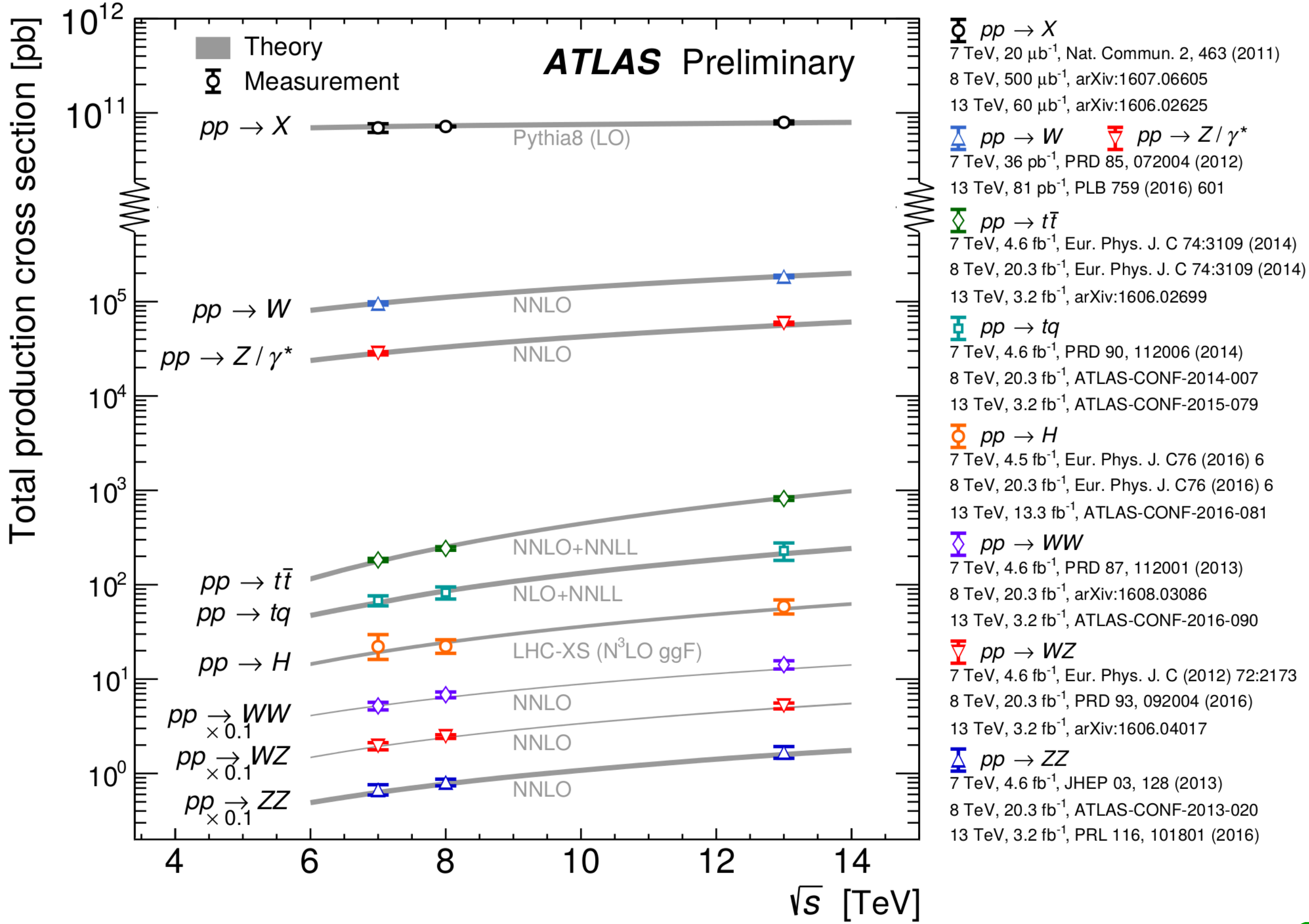
From varied physics areas



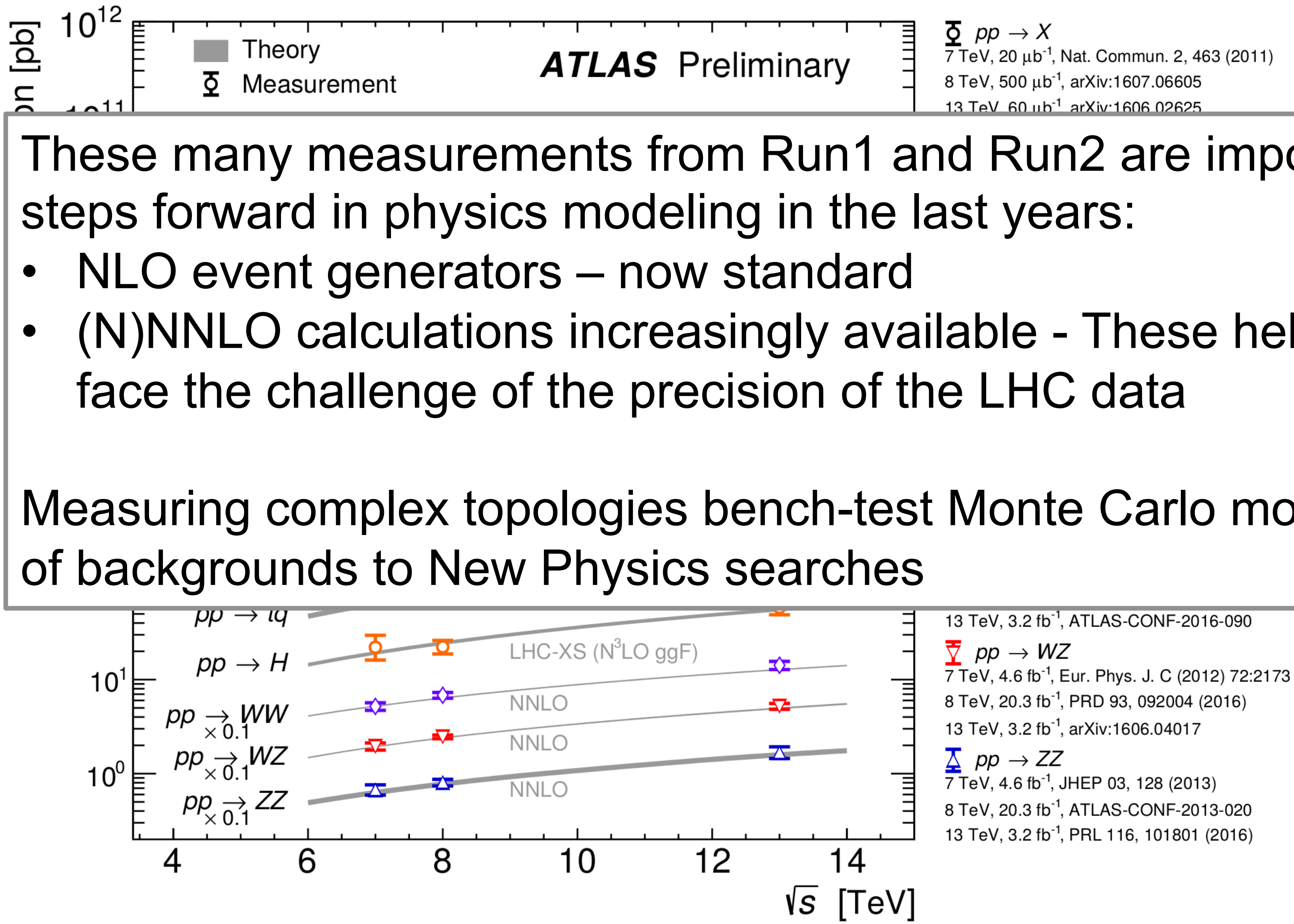
  - the full list here: https://twiki.cern.ch/twiki/bin/view/AtlasPublic
- Following slides review a few selected highlights, mostly using 13 fb^{-1} dataset, collected up to 2016 summer
  - Disclaimer; Topics here are driven by the priorities in the Run2 ATLAS physics program, by my tastes, as well as by the KMI's contributions
  - Apologies if your favorite topics are not covered

- Measurements

Inclusive cross-section measurements: broad range



Inclusive cross-section measurements: broad range

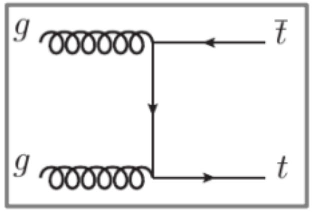


These many measurements from Run1 and Run2 are important steps forward in physics modeling in the last years:

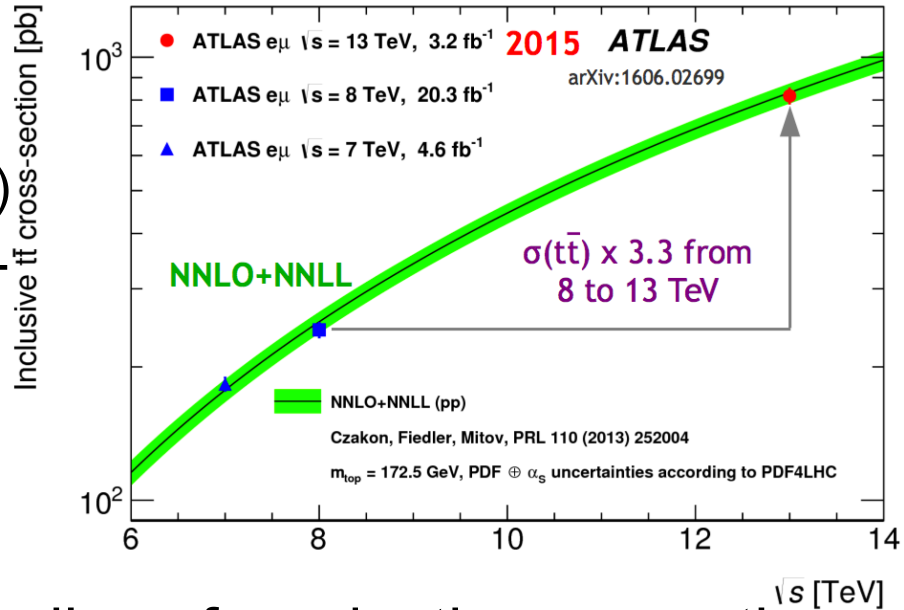
- NLO event generators – now standard
- (N)NNLO calculations increasingly available - These help to face the challenge of the precision of the LHC data

Measuring complex topologies bench-test Monte Carlo models of backgrounds to New Physics searches

ttbar cross-section measurements



- Nagoya's contributions since early Run1
- Precise measurements of inclusive ttbar cross-sections
  - Precisions ±(3.9-4.4)% (7-13 TeV) is better than theory NNLO+NNLL predictions (~5%)

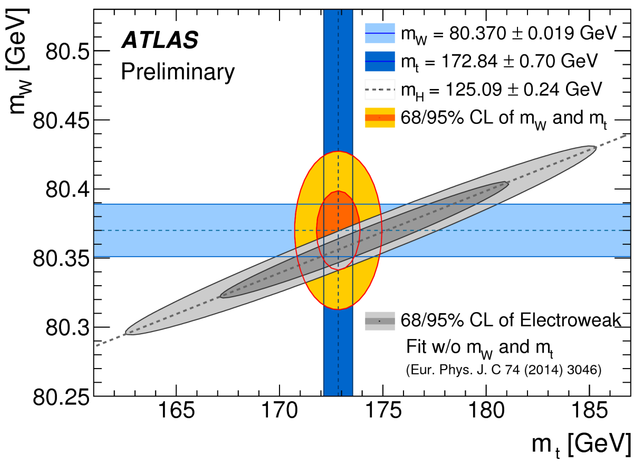


- High statistics allow detailed studies of production properties
  - e.g. differential cross-section measurements (Check poster by K. Kawade, the Nagoya ex-member)

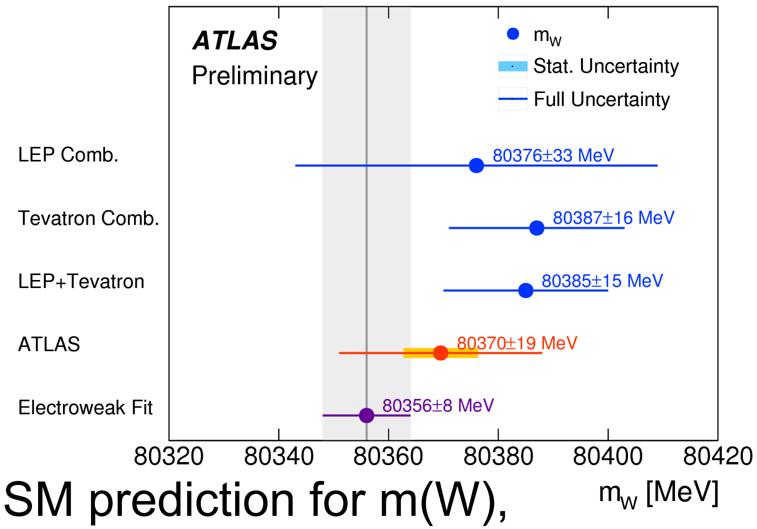
W-boson mass measurement

ATLAS-CONF-2016-113

- Precise measurement is motivated for a consistency test of the SM and a probe of BSM physics – yet with slow progress
- After long/huge efforts, the first ATLAS result using the 7 TeV dataset was released in Dec 2016
  - m(W)= 80.370 ± 0.019 GeV, a competitive measurement, dominated by physics modeling uncertainties as expected
  - Consistency tests of the SM



SM prediction for m(W) vs m(t), assuming m(H) = 125.09 ± 0.24 GeV



SM prediction for m(W), assuming m(H) = 125.09 ± 0.24 GeV
m(t) = 172.84 ± 0.70 GeV

- Understanding the 125 GeV Higgs

Physics of the 125 GeV Higgs

- Higgs discovery opened the door on the scalar sector
- In Run1 we measured:
  - Its spin-parity, and its mass precisely (±0.2%)
  - Production via gluon-fusion, vector-boson fusion, and with a W or Z
  - The decays to $\gamma\gamma$, WW, ZZ, and the fermionic decay to $\tau\tau$

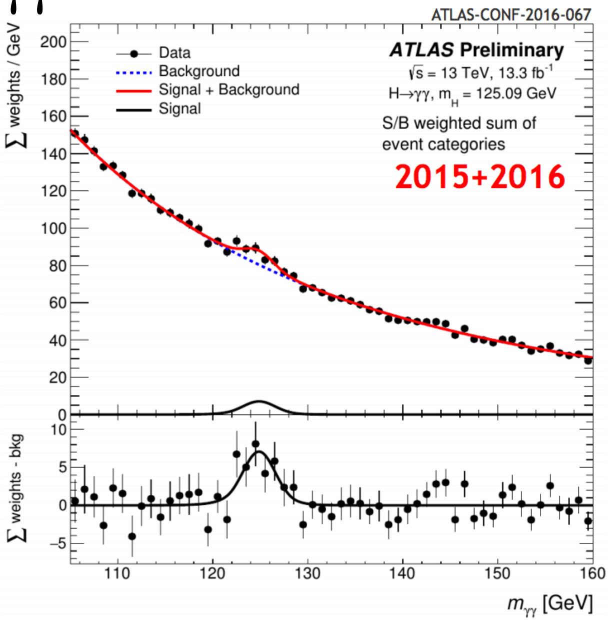
→ These proved true the BEH mechanism to break gauge symmetry

→ However, apart from the mass, none of these measurements are yet very precise and leave room for significant deviations. Also, important modes are still unseen (bb, ttH, $\mu\mu$, Zγ, HH)

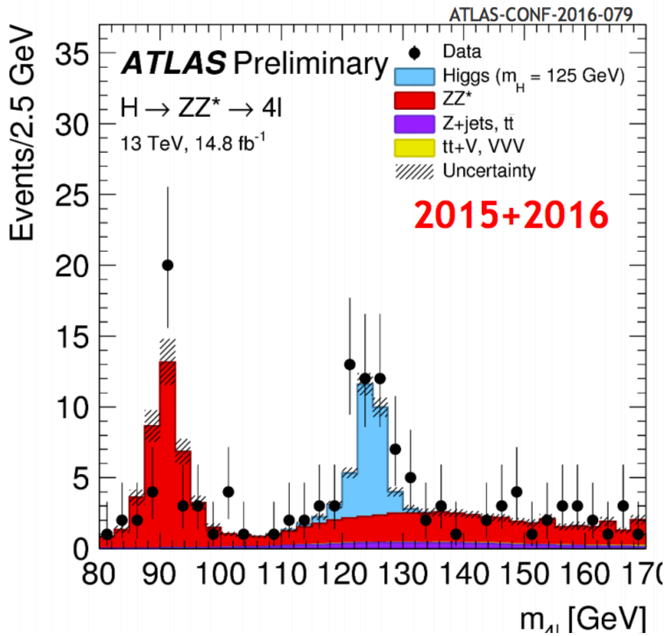
- Run2 priorities:
  - Establish and measure at 13 TeV
  - Search for ttH production to probe ttH coupling directly
  - Search for H→bb decays
  - Search for rare decays
  - Refine measurements of couplings, mass, etc
  - Expand use of H as a tool to find New Physics

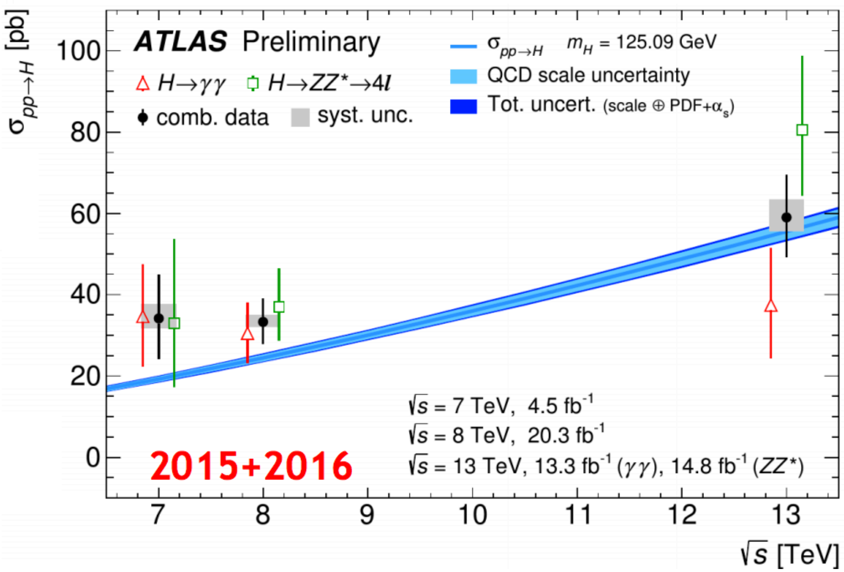
Clear Higgs observation at 13 TeV in bosonic channels

$H\rightarrow\gamma\gamma$



$H\rightarrow 4\ell$





Combining γγ+4ℓ channels

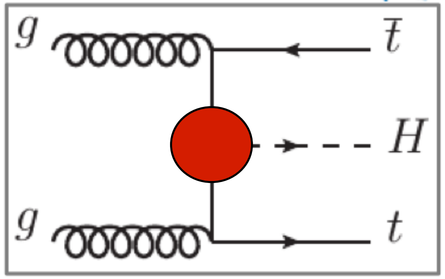
σ(pp→H+X, 13 TeV)= $59.0^{+9.7}_{-9.2}$ (stat.) $^{+4.4}_{-3.5}$ (syst.) pb

SM prediction $55.5^{+2.4}_{-3.4}$ pb

Overall significance at 13 TeV ~10σ

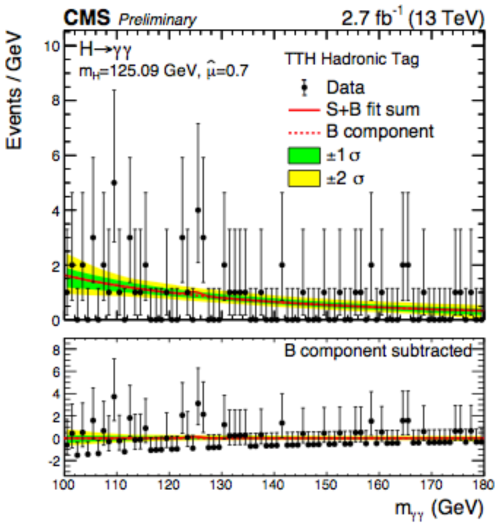
First search for ttH production at 13 TeV by CMS

- Direct measurement of Higgs-top coupling
- CMS showed preliminary results for ttH in all major Higgs decay channels: γγ, multi-lep, bb



- *Highly* complex analyses, huge effort to get these done so quickly after data taking (already by Moriond 2016)

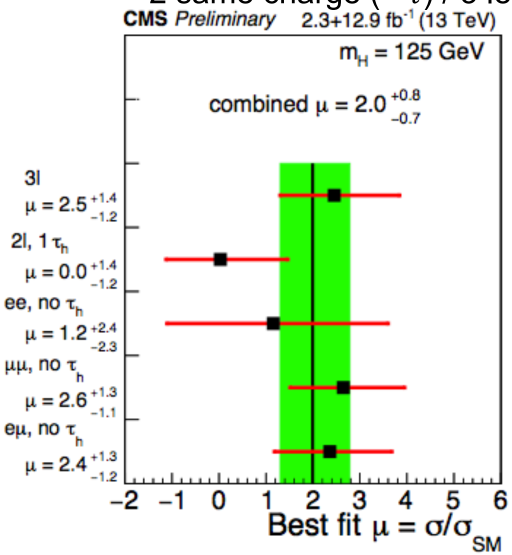
H → γγ,
tt → 0 & 1 leptons



$\mu = 3.8\,^{+4.5}_{-3.6}$

CMS-PAS HIG-15-005

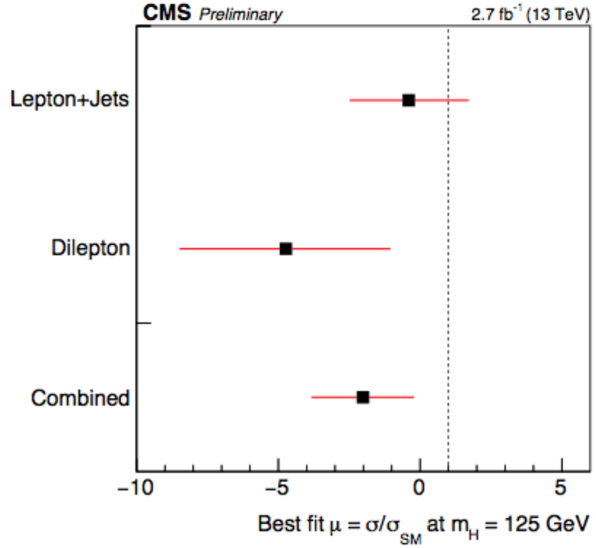
ttH → multi-leptons
2 same charge (+ τ) / 3 leptons



$\mu = 2.0\,^{+0.8}_{-0.7}$

CMS-PAS-HIG-16-022

H → bb
tt → 1 & 2 leptons

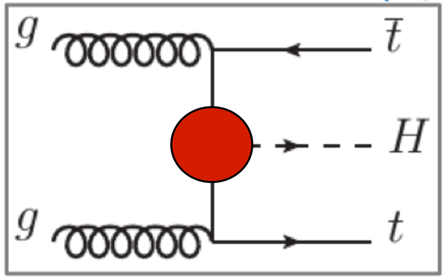


$\mu = -2.0 \pm 1.8 < 2.6$ (95% CL)

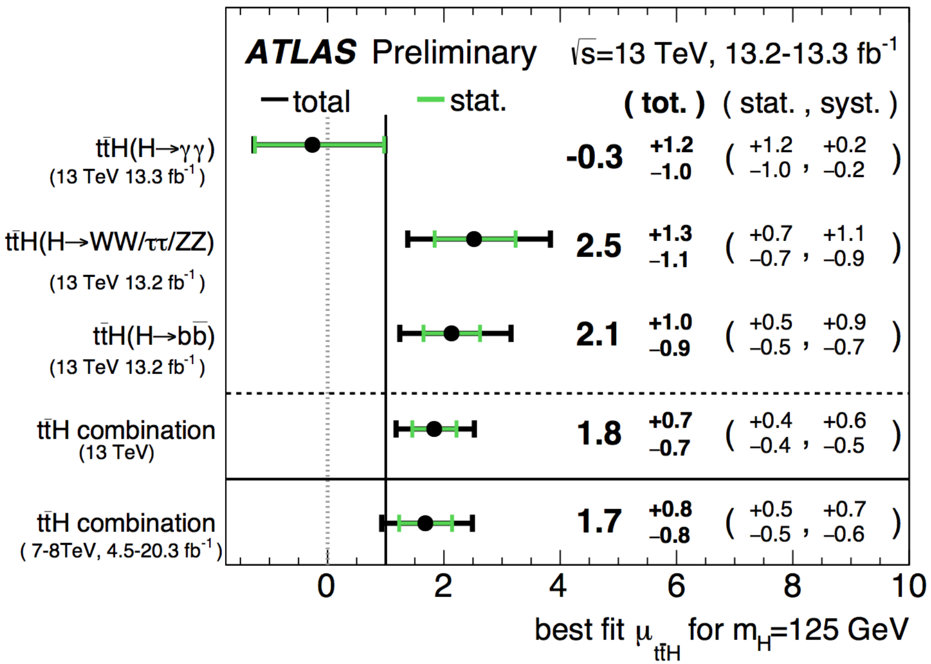
CMS-PAS HIG-16-004

First search for ttH production at 13 TeV by ATLAS

- Direct measurement of Higgs-top coupling
- ATLAS showed preliminary results for ttH in all major channels and their combination at ICHEP 2016



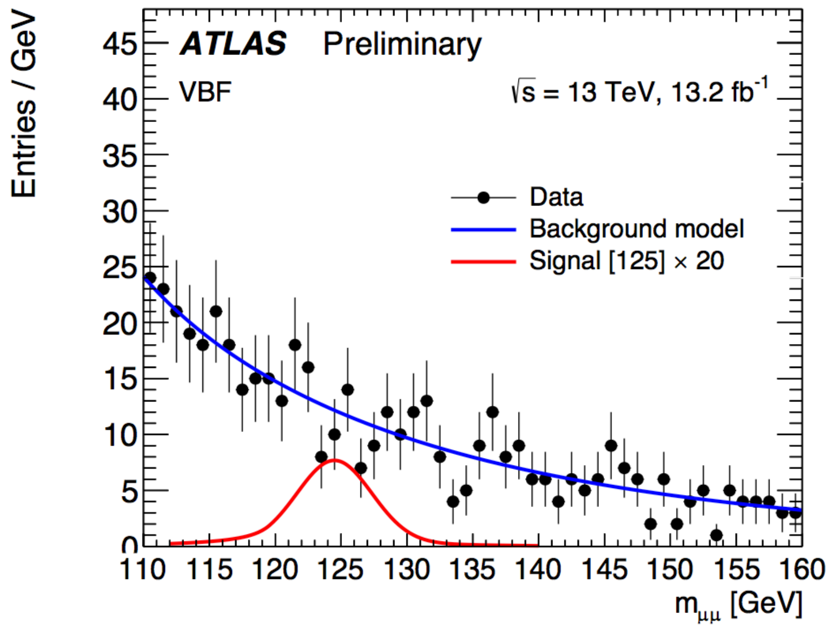
Individual channels and combination

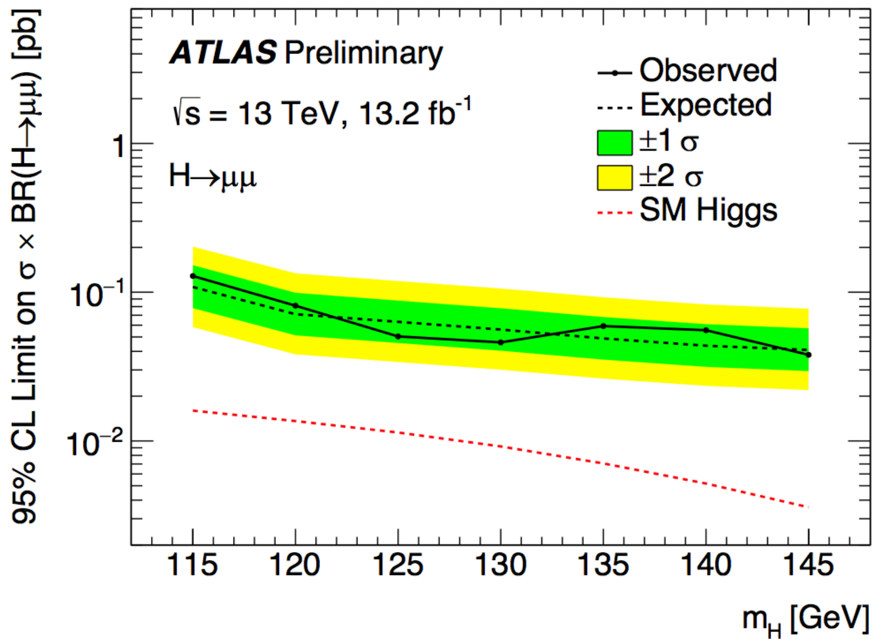


→ Observed significance 2.8σ (expect 1.8σ, improved sensitivity over Run1)

Searches for rare Higgs decays e.g. H→μμ

- Beyond SM reach at present, but could have New Physics contributions?
  - Strongly resolution dependent, improve sensitivity by categorising events (low/high *p* , central/forward, VBF)
  - Obs limit: 4.4 times SM. Needs ~300 fb^{-1} data to reach SM (Run3)

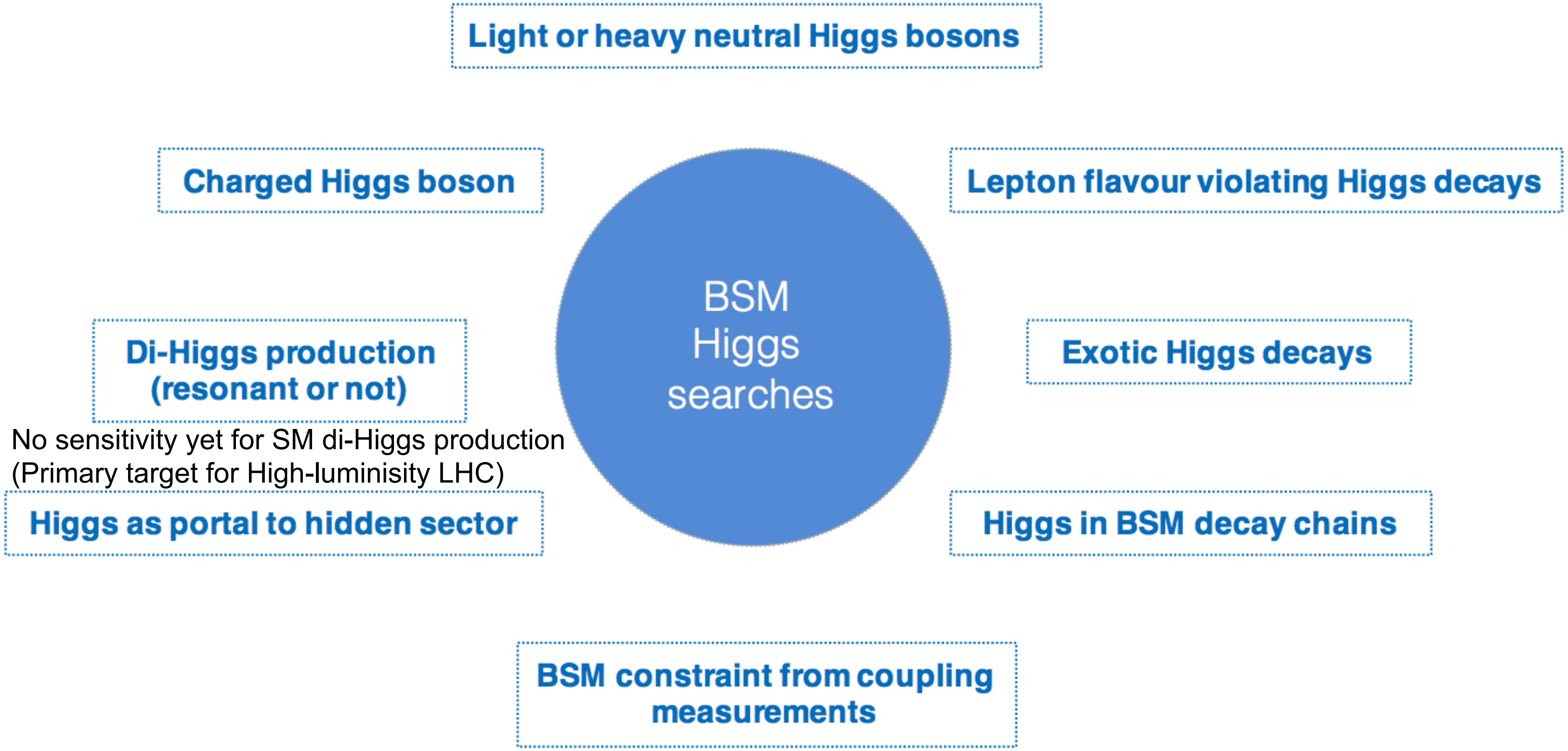




  - Can already exclude universal Higgs coupling to fermions
    - Would have observed H→μμ, if same BR as H→ττ

Beyond the Standard Model Higgs physics

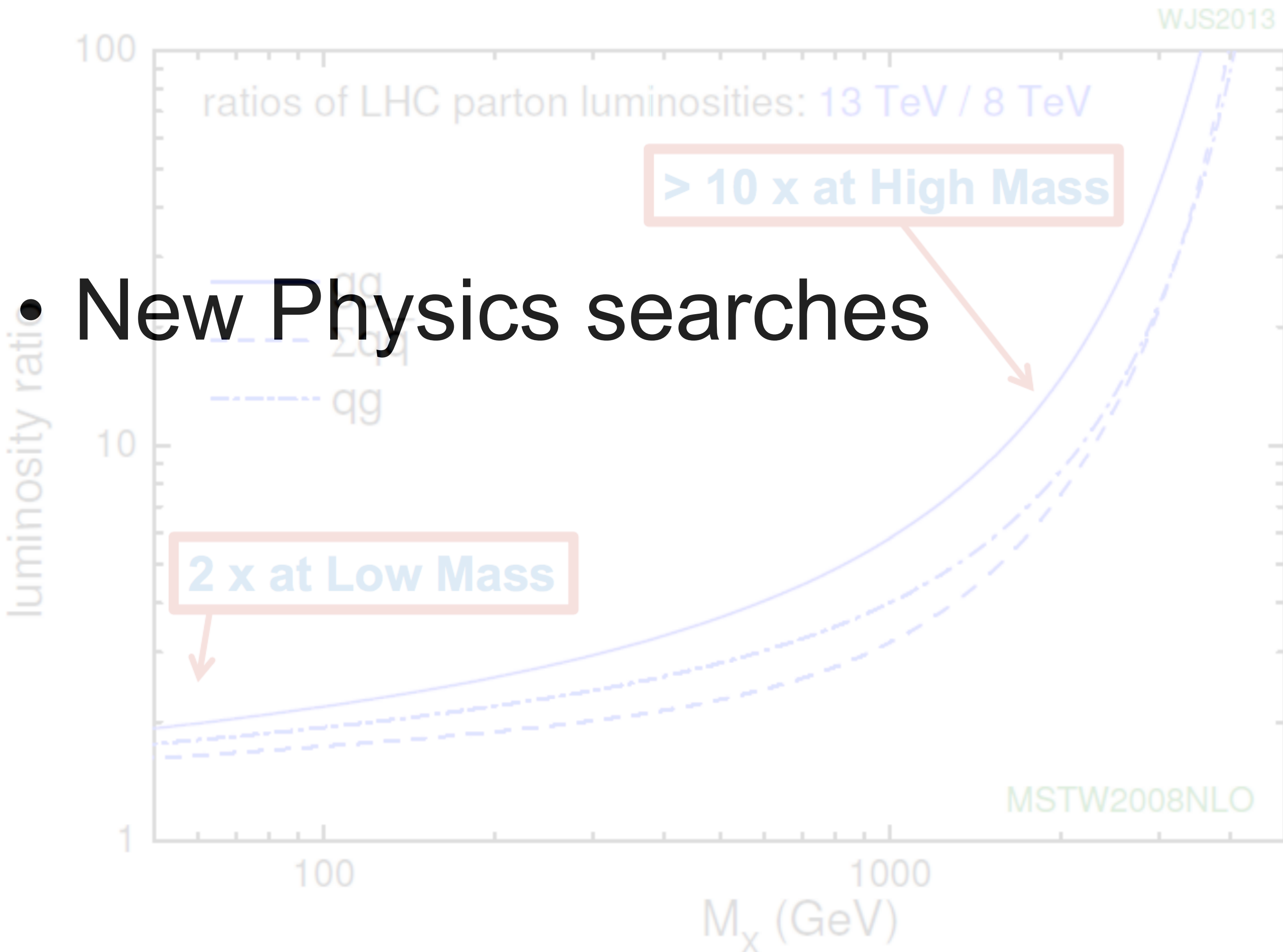
- Higgs sector may be non-minimal and/or Higgs boson may couple to New Physics
- Diverse search program is in place;



No deviations from SM found in any of these searches

Taken from: Thibault Guillemin @ SEARCH 2016

- New Physics searches



New Physics searches in Run2

- Broad search program
  - from inclusive surveys of basic event topologies
  - to dedicated searches ruling out corners of phase space
- Major extension of reach compared to Run1
- All results shown here include 2016 data
- They probe well into the TeV, even multi-TeV, mass scale range

Exploring Exotics

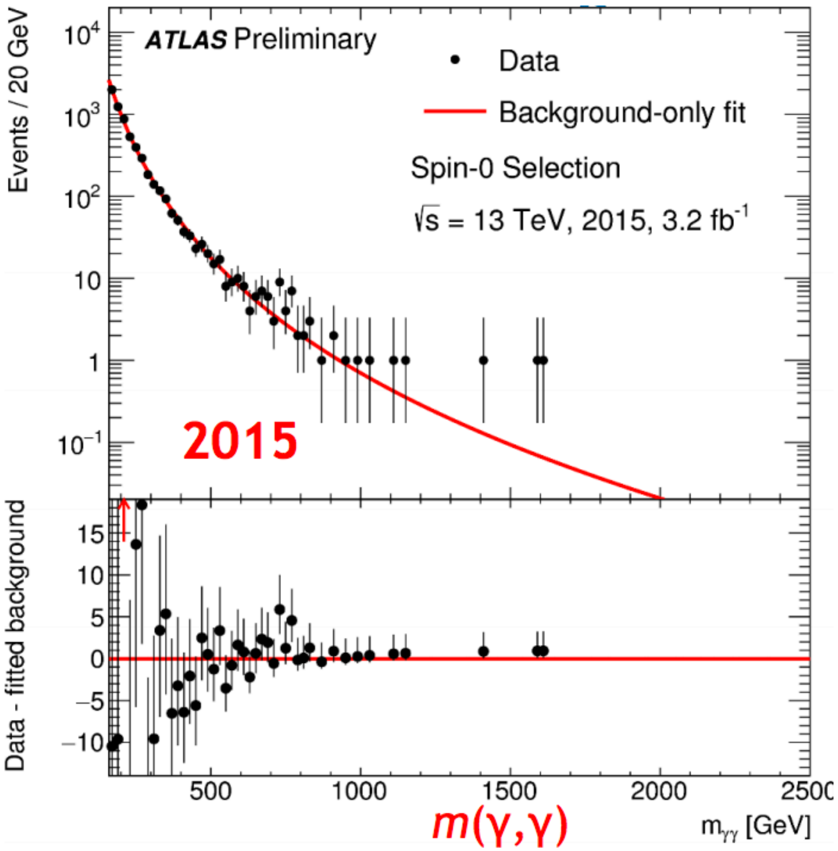
- **Guiding physics models**
  - Technicolor
  - Warped Extra Dimensions
  - Grand Unified Theories
  - Heavy Vector Triplet
  - Quantum Black H…es
  - Hidden valley
  - Contact Interac… Compositeness
  - Exited Fermions
  - Leptoquarks
  - …

- One model with different signatures
- One signature probing various models

- **Signatures**
  - Di-lepton / di-jet / di-b-jet resonances (Z’, W’, ...)
  - Di-boson resonances
    - WZ,ZZ,Wγ,Zγ
    - Multi-jet resonances
    - tb,Ht,Zt,Zb (Z’,W’,T,B,...)
  - …cesses in high tails (non …sonances)
  - Long lived particles
  - Large missing energy
  - …

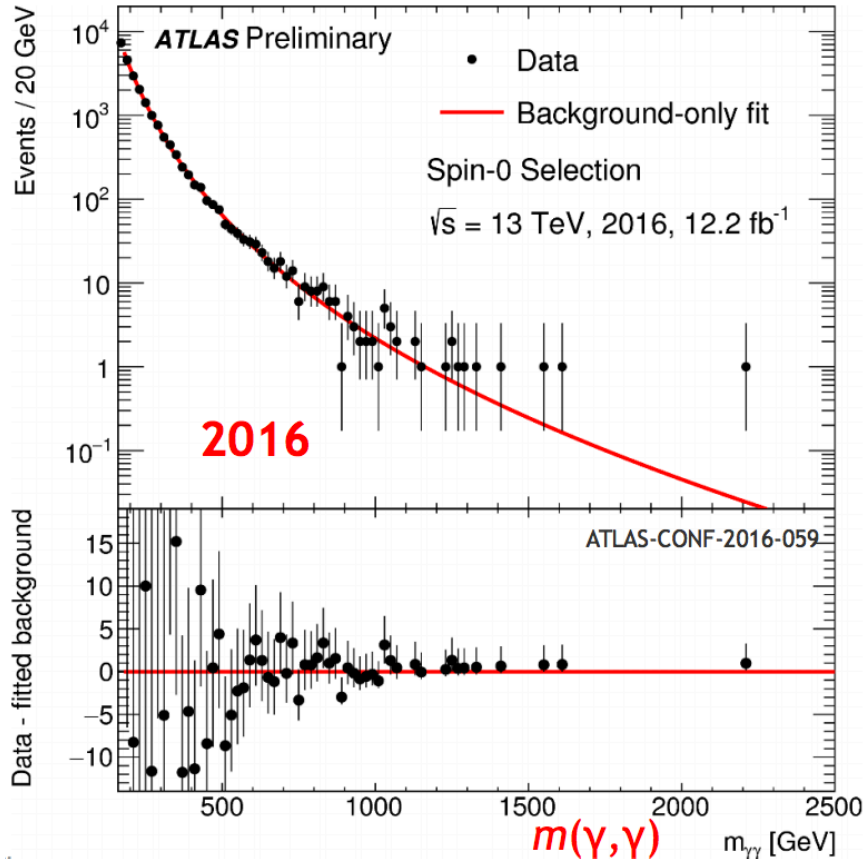
→ Search as broad and general as possible (signatures, masses, rates) covering physics without guiding models

Di-photon searches



2015 ATLAS data: localised excess seen

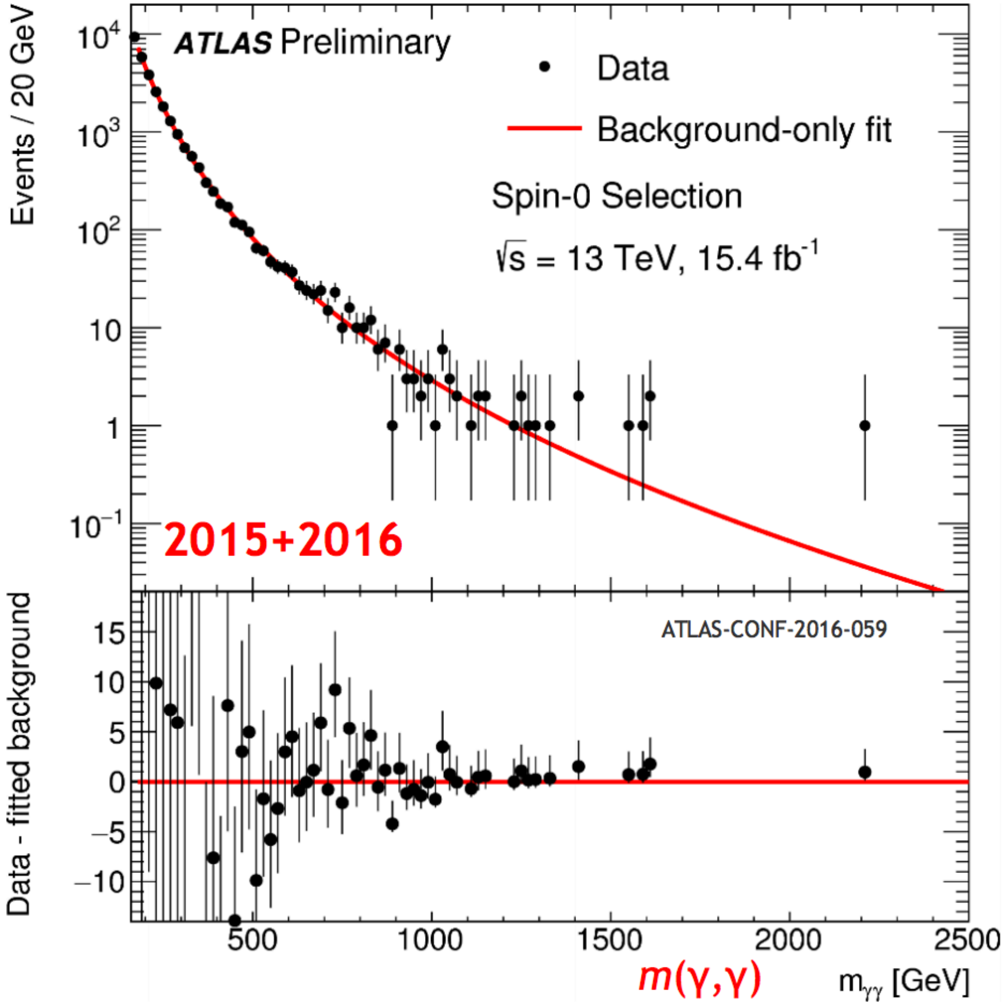
- 2.1σ global (3.9σ local) significance at 750 GeV (spin-0 search), width ~50 GeV



2016 data: no clustering around 730-750 GeV, and 3.8x more data

- 2016 data consistent with 2015 at 2.7σ
- Appears that the 2015 excess was a statistical fluctuation

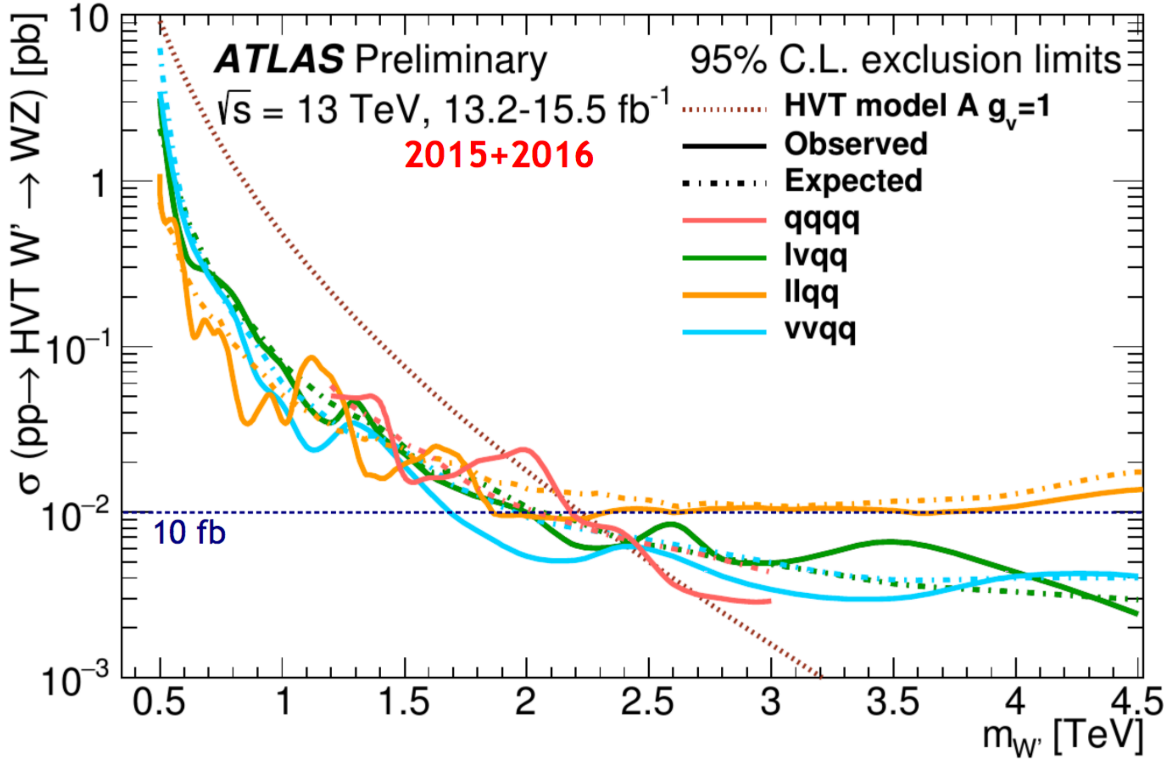
Finally with 2015+2016 data



- Small excess at 710 GeV (Γ/m~10%)
- Local significance 1.4σ, global <1σ

Massive di-boson searches

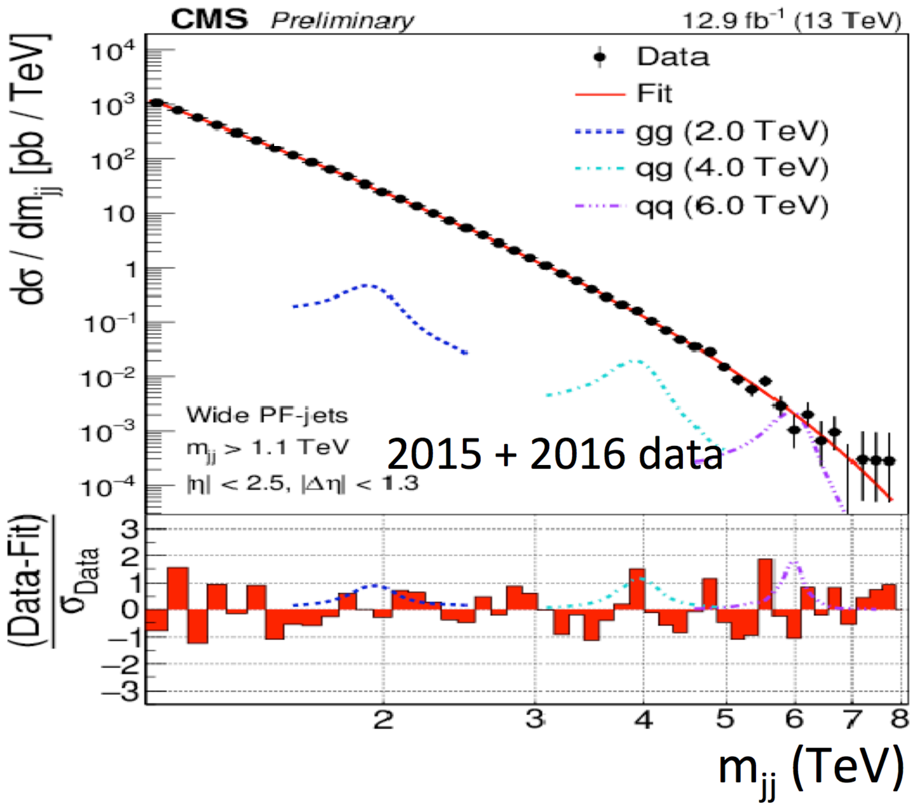
- Search for resonant di-boson production
  - Boosted (“fat jet”) selections vital at high-p_T
  - Explored many channels with 2016 data

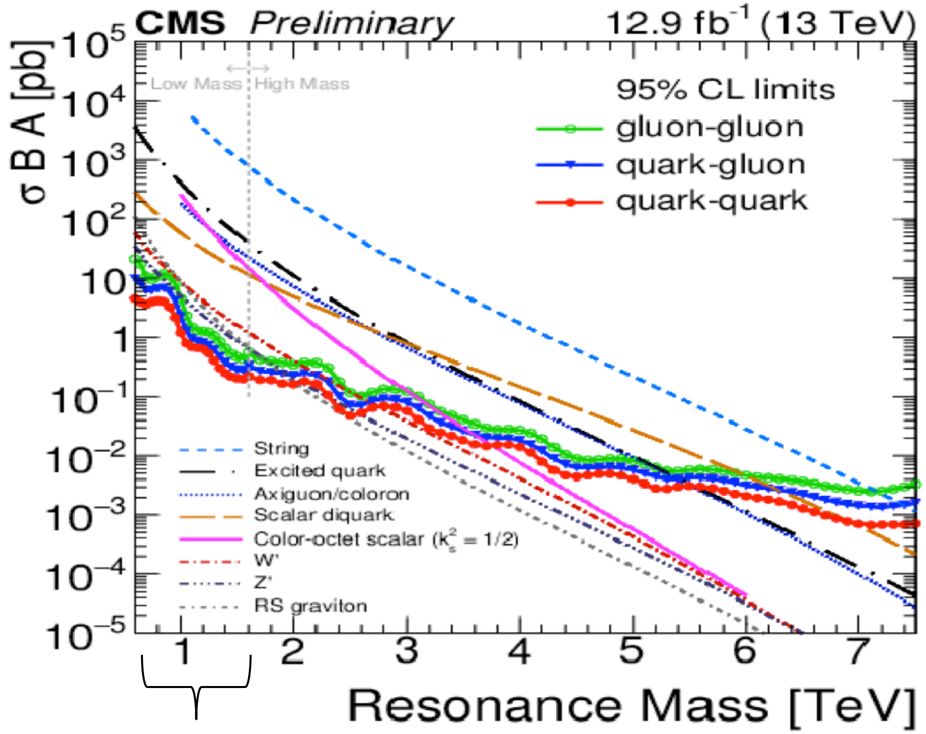


  - Overlaying limits from all WZ searches – no persistent excesses, in contrary to the Run1 excesses

Di-jet searches

- Search for New Physics in di-jet mass spectrum; bump hunter
  - Di-jet: qq, qg, gg (high mass > ~1 TeV). High priority in early Run2
  - Sensitivity based on signal shapes including large low mass tails

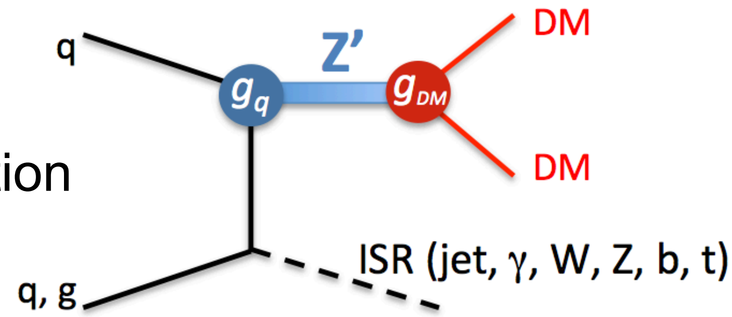




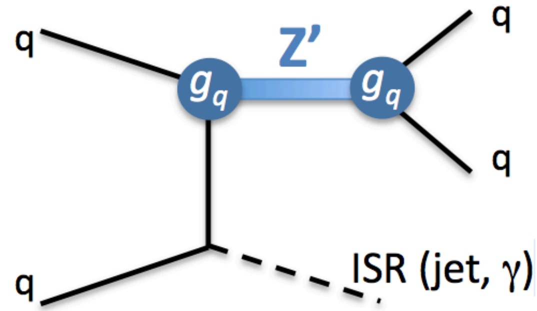
For low-mass search, a dedicated trigger technique “data scouting at trigger level” allowed lower threshold by keeping partial info. and online calibration

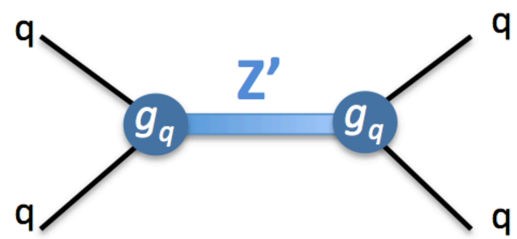
Di-jet searches: Dark Matter Interpretation

- Complementary to mono-(jet, γ, W, Z, b, t, H, ...) searches
  - Tag DM pair (E_T^{miss}) via Initial state radiation
  - Mediator (Z') mixing with Z, H

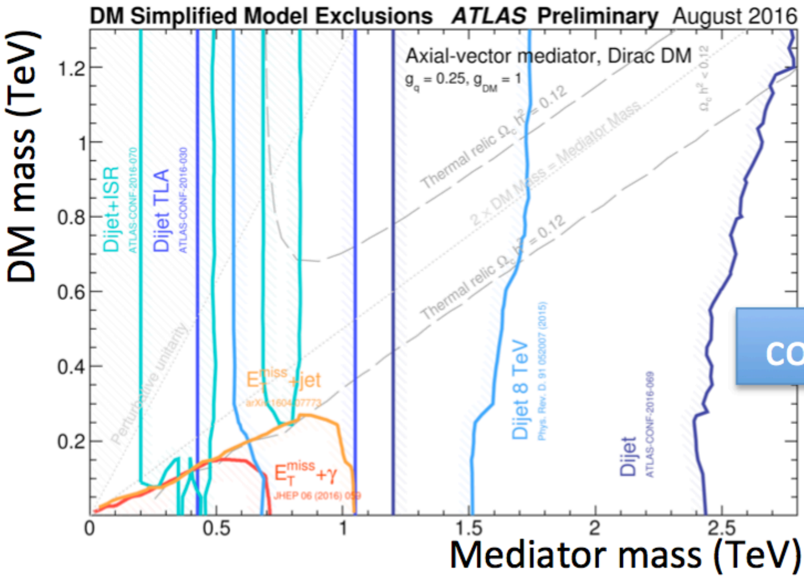


- Mediator (Z')
  - Couples to quarks(g_q) and DM(g_{DM})
  - Dijet searches cover a broad mediator mass range
  - DM interpretation of Z' searches

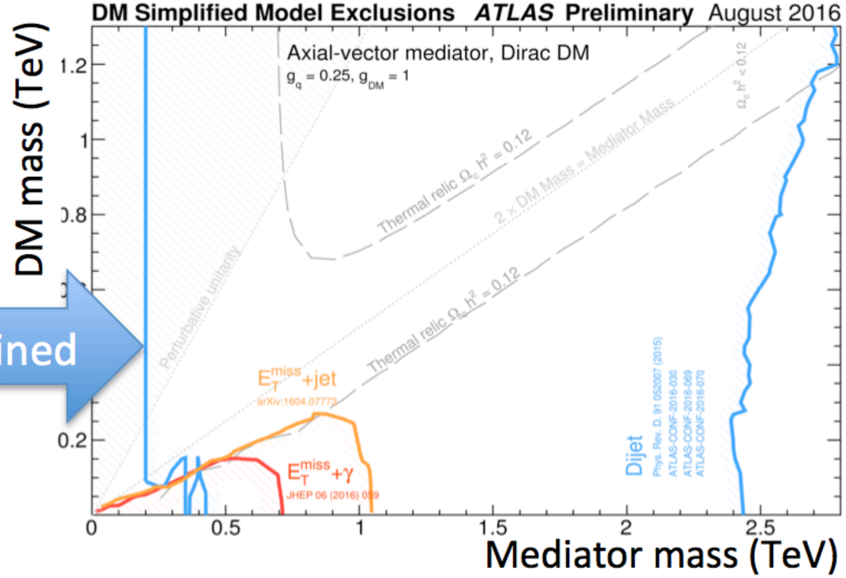




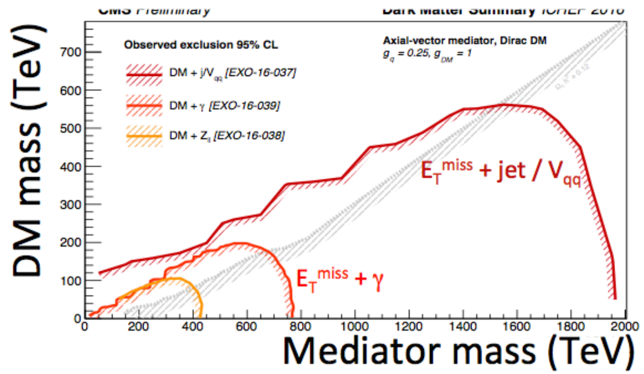
Di-jet searches: Dark Matter Interpretation



combined



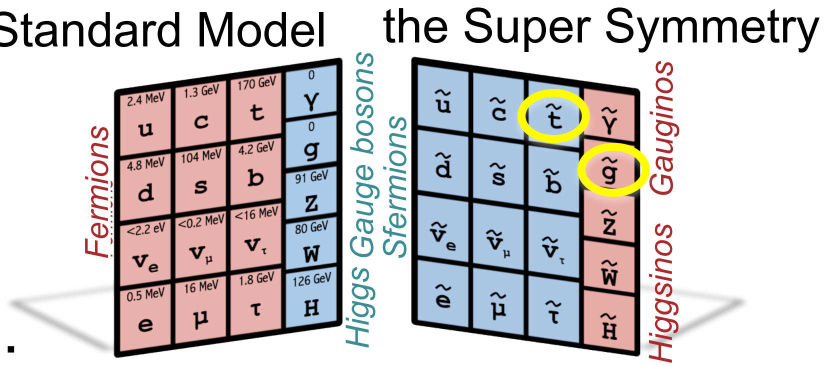
$g_q = 0.25, g_{DM} = 1$



- Complementary to mono-X searches; cover a broad mediator mass range – Results highly depend on choice of coupling parameters ($L = g_q \gamma^\mu q \, Z'_\mu$)

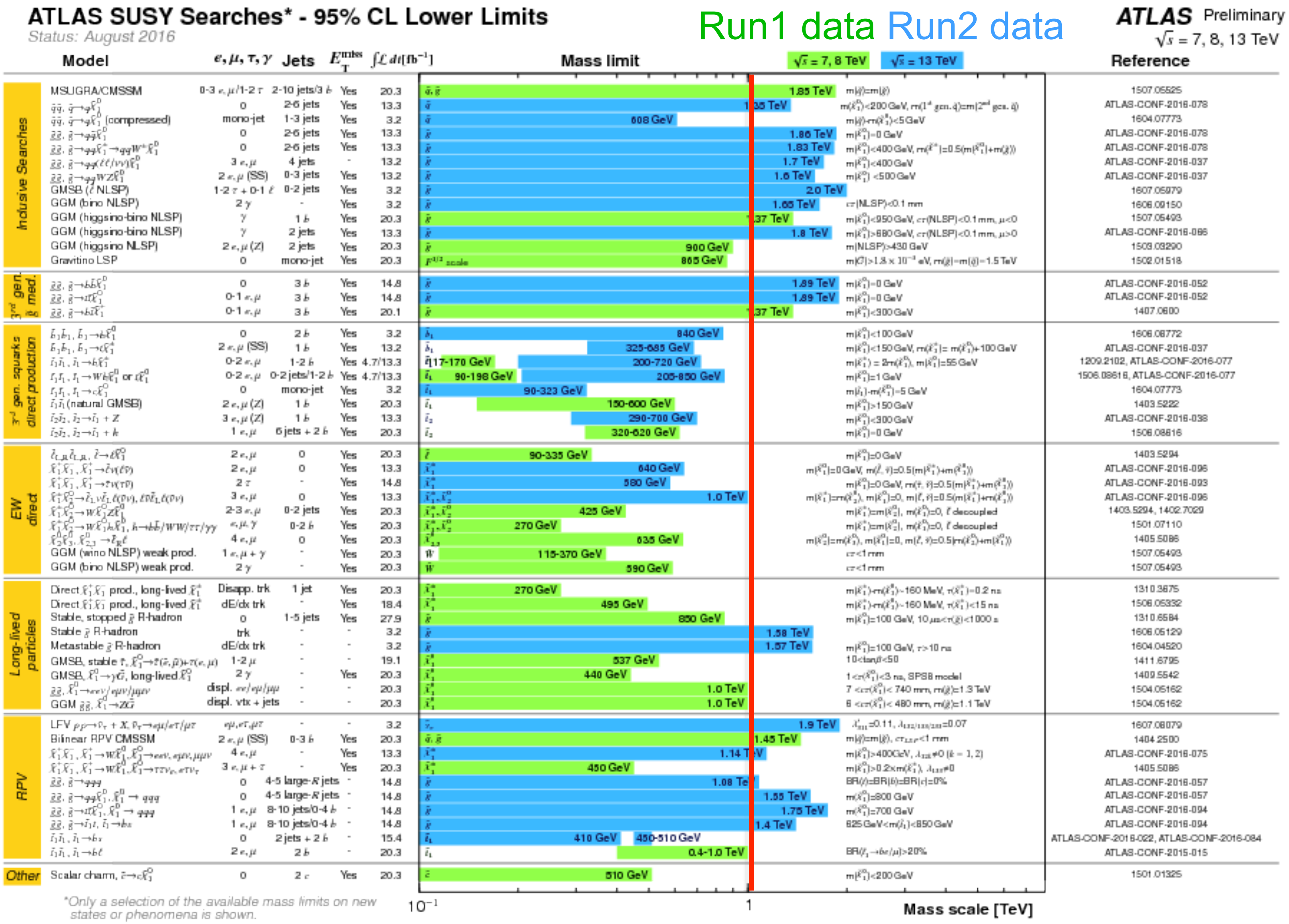
SUSY searches

- The case for SUSY is well known
  - Natural Dark Matter candidate in *neutralino1*
  - Can solve the fine-tuning problem – if *t~ and g~* are light

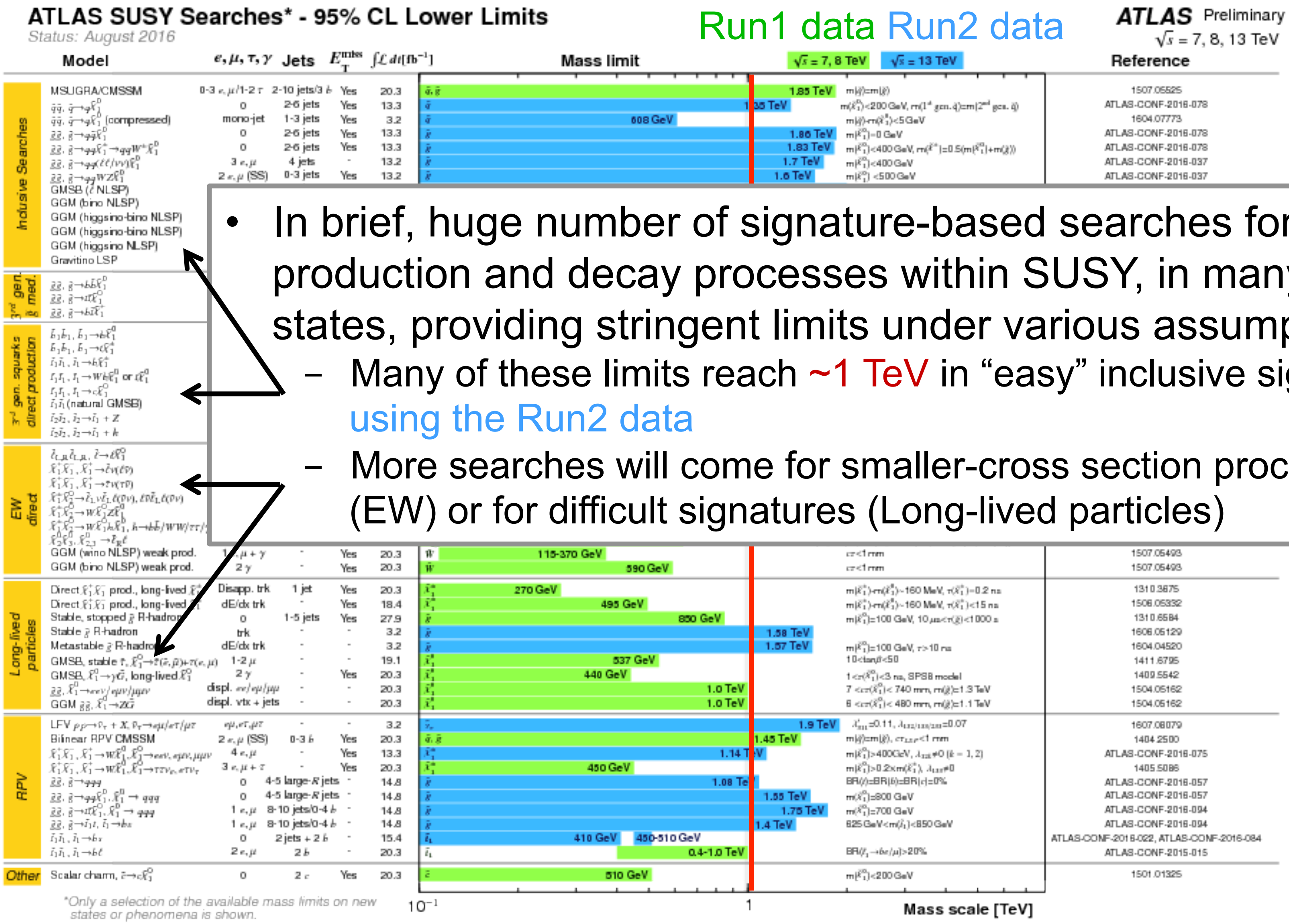


- In Run1 we identified:
  - m(*g~*)>1.4TeV for low-mass *neutralino1*
  - m(*t~*)>700GeV if m(*neutralino1*)<100GeV
- Run2 priorities:
  - Extend mass reach according to √s increase
  - Fill “kinematic holes” where particles are soft
  - “Leave no stone unturned” e.g. displaced decays from long-lived particles

SUSY search results



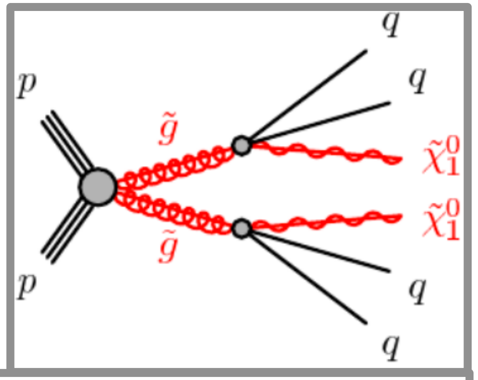
SUSY search results

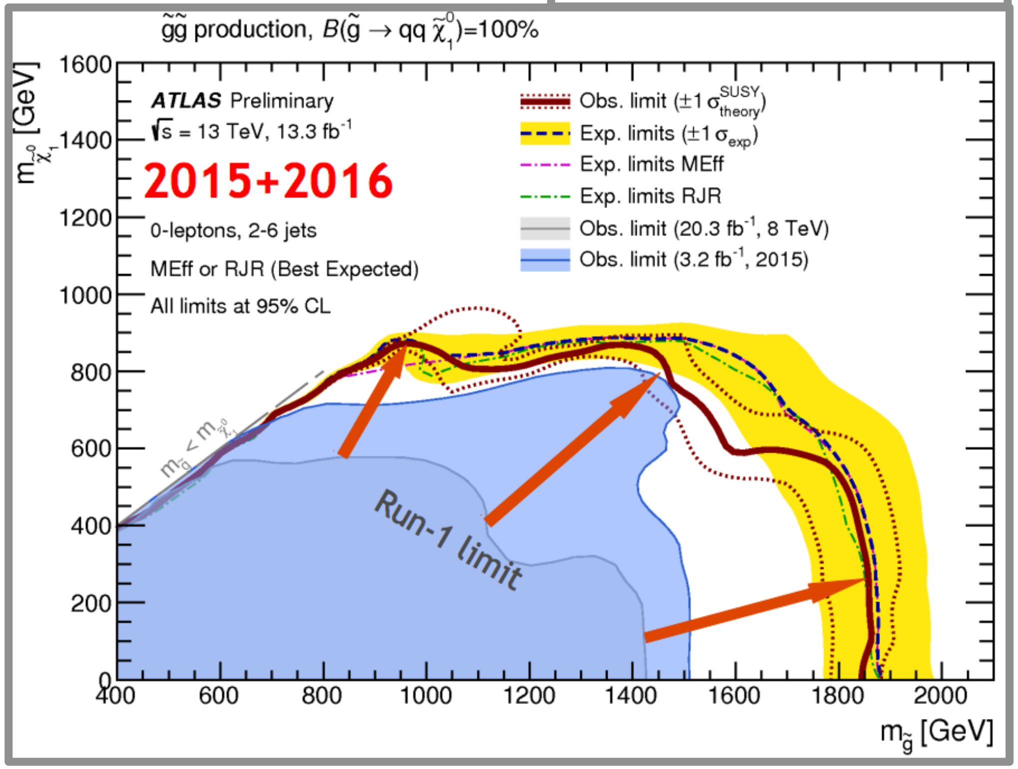


- In brief, huge number of signature-based searches for various production and decay processes within SUSY, in many final states, providing stringent limits under various assumptions;
  - Many of these limits reach ~1 TeV in “easy” inclusive signatures using the Run2 data
  - More searches will come for smaller-cross section processes (EW) or for difficult signatures (Long-lived particles)

Example: g~/q~ search with jets+E_T^{miss}

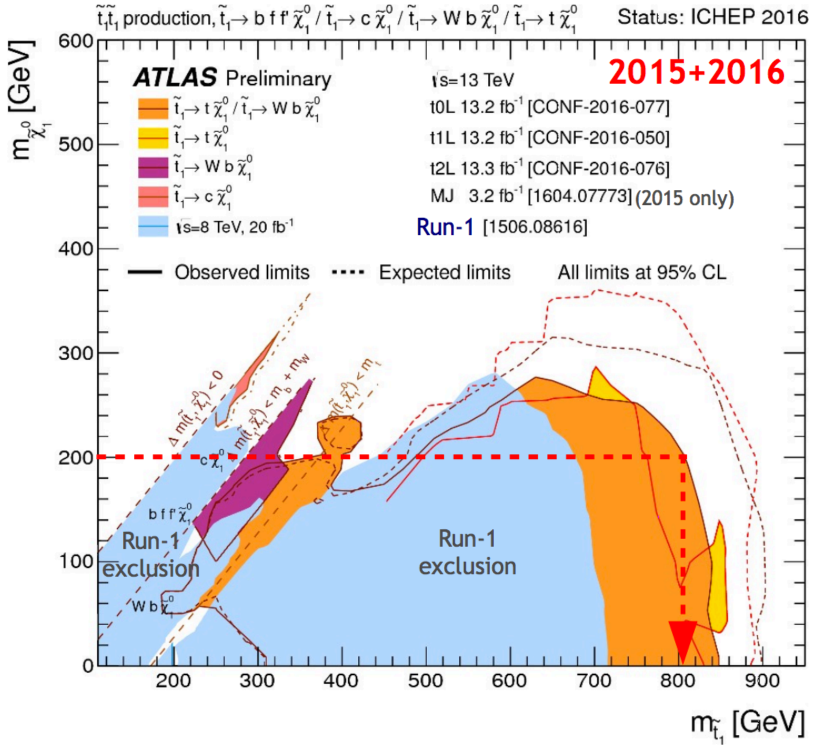
- Event selection: require 2-6 jets and veto isolated leptons
  - Sensitive to g~ and q~ production
  - High priority in early Run2
- Total of 30 signal regions to cover various mass spectra
  - No significant excesses in any signal region overall
  - For small m(neutralino1) exclusion reach extended m(g~) < 1.4 TeV (Run1)
    → < 1.86 TeV (2015+16)
  - Check details in poster by Y. Sano (a Nagoya PhD student)





t~ search summary

- Search for top squark pair productions
  - Explored many channels with 2016 data



For m(neutralino1) < 200 GeV, m(t~) < 800 GeV excluded except in rather small regions

  - Developing dedicated searches for such compressed spectra
    → Check details in poster by K. Onogi (a Nagoya PhD student)

Conclusion

- The LHC is performing extremely well
- A broad range of LHC Run2 results using early 2016 dataset
  - Starting precise measurements of H(125) at 13 TeV
    - Concluding on the Standard Model ttH sensitivity
  - 13 TeV in Run2 brings significant increase in sensitivity, shaping the search program in 2015 and early 2016
    - The limits set significantly extend the Run1 results, thus further constraining various models. No significant excesses, though some ~3σ effects as expected. More data will tell which, if any, will remain
    - The search program is moving toward more challenging signatures and scenarios
- Expecting exciting future
  - New results with ~40 fb^{-1} in early spring of 2017
  - Data analysed so far: a small fraction of total Run2 (100 fb^{-1})

- Backup slides

pMSSM scans

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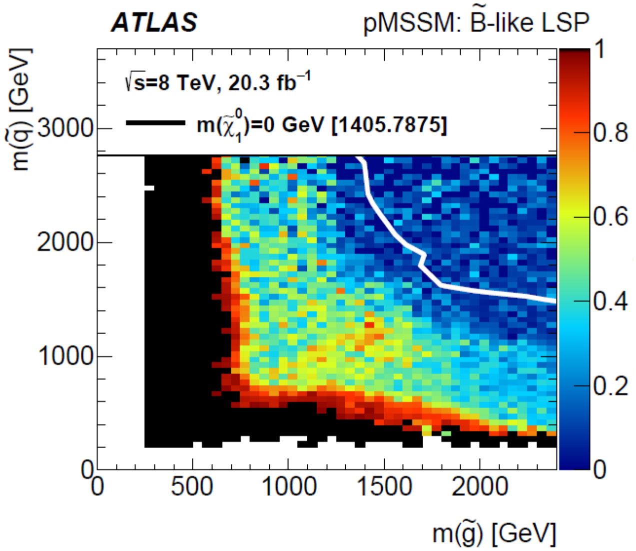
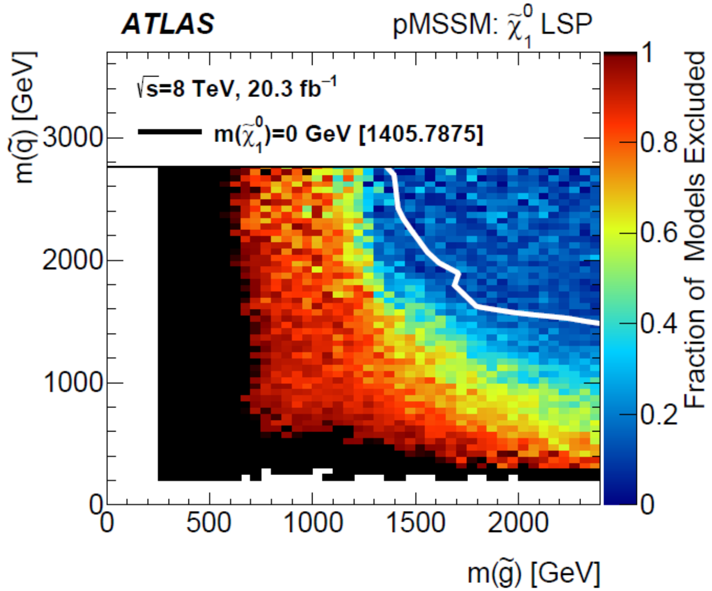
- LHC: simplified model → BR=1 (even for cascade decays)
- setting limits on various pMSSM using all ATLAS search results in Run1
  - Good coverage of pMSSM, dependence on LSP nature (via signatures)





  - Similar scan will be repeated with results using the Run2 full dataset