KMI 2019
International Symposium

Status and Prospect of Physics at LHC

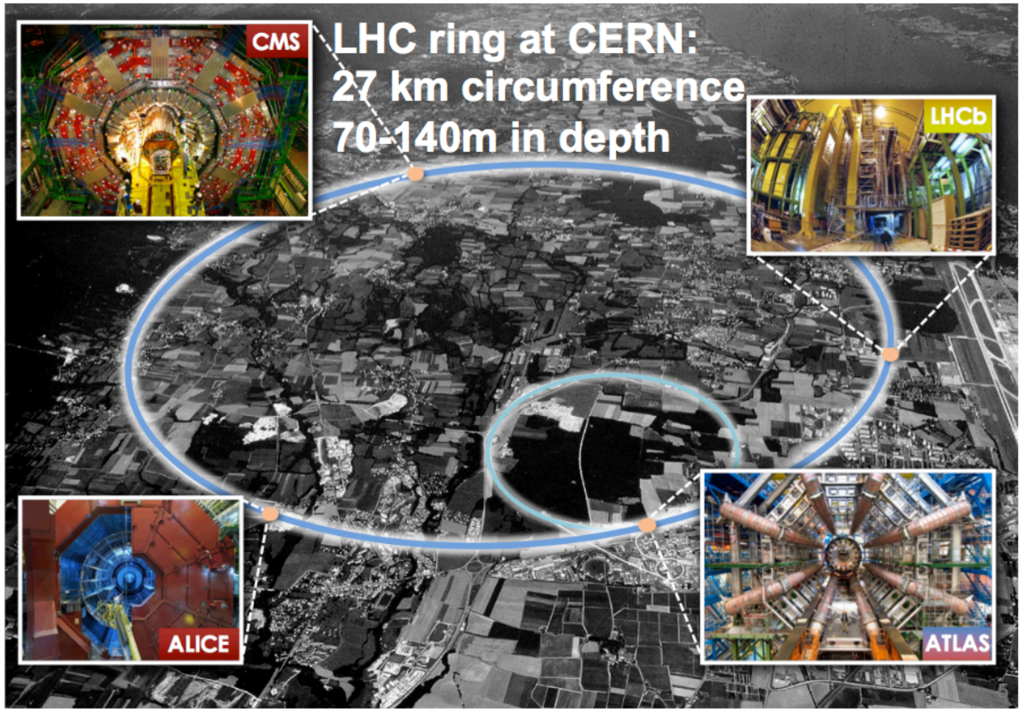
KMI2019 symposium on 18^{th}- 20^{th} February 2019

Yu Nakahama
(Nagoya University, Kobayashi-Maskawa Institute)

NAGOYA UNIVERSITY

The LHC experiment

- 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

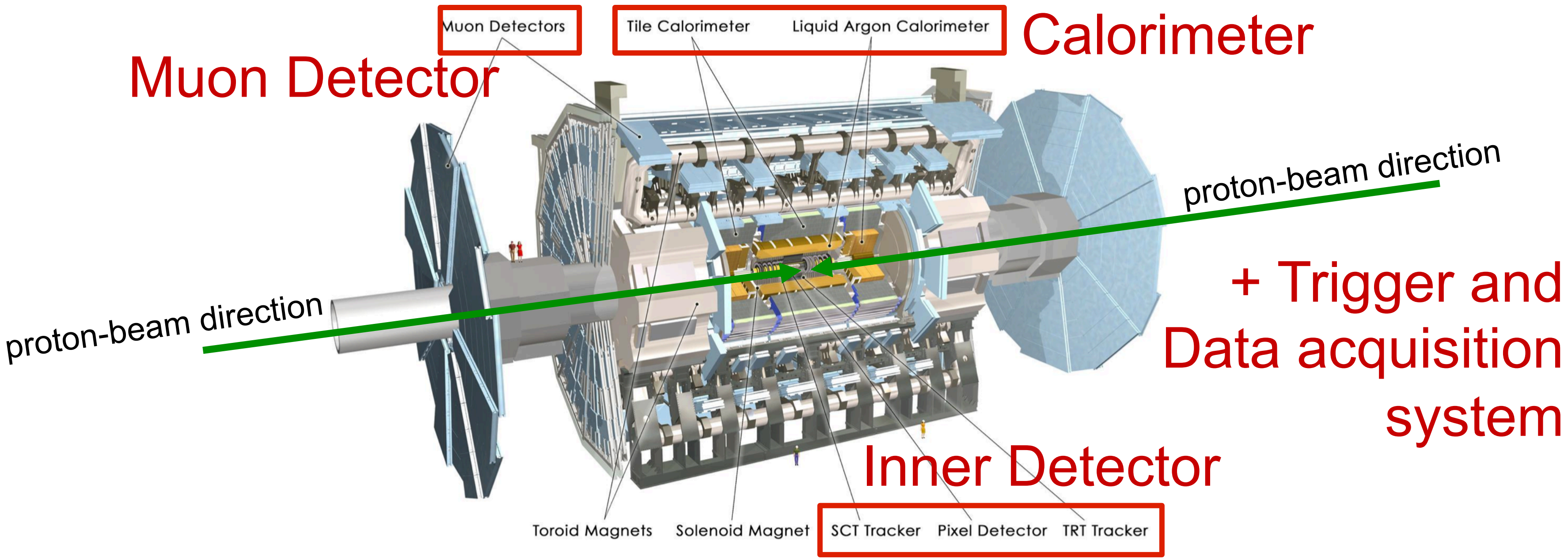


Recent history and future

- LHC Run1 (2009-2012) p-p collisions at $\sqrt{s}$ = 7-8 TeV
  - Higgs discovery in 2012
- Run2 in a high-energy phase at $\sqrt{s}$ = 13 TeV just finished (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-) planned.
  - Y. Okumura will present the future ATLAS programme.

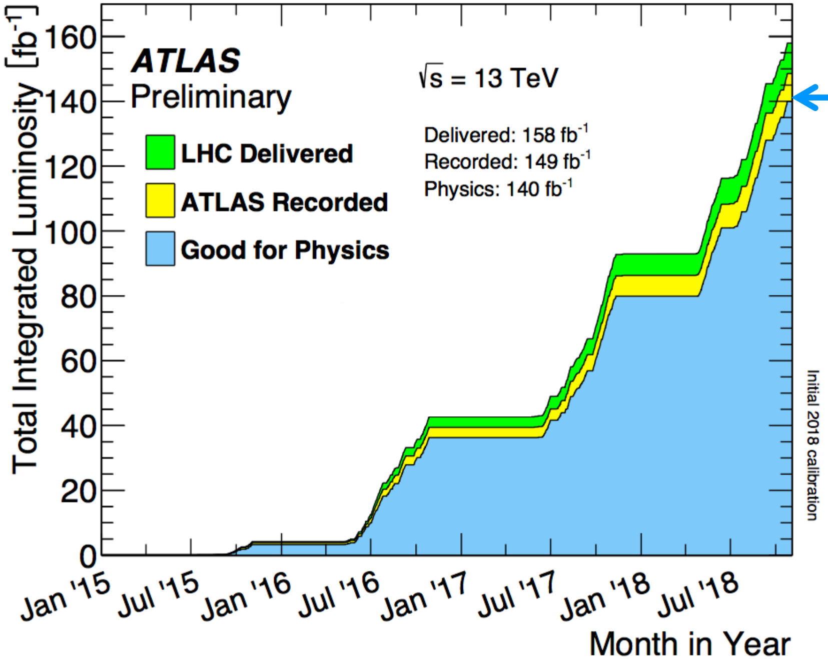
The ATLAS experiment, the KMI's contribution

- The ATLAS detector is a multi-purpose detector that can directly explore energy scale from O(1) GeV to O(10) TeV.



- ~2900 collaborators from 180 institutions across 38 countries.
- KMI has been actively contributing
  - to "Muon Detector and Trigger system" as well as to "New-Physics searches, Higgs Physics, and Top Physics".
  - Two staffs with seven students (Master 5, Doctor 2) as of now. [5M/4F]

ATLAS data taking

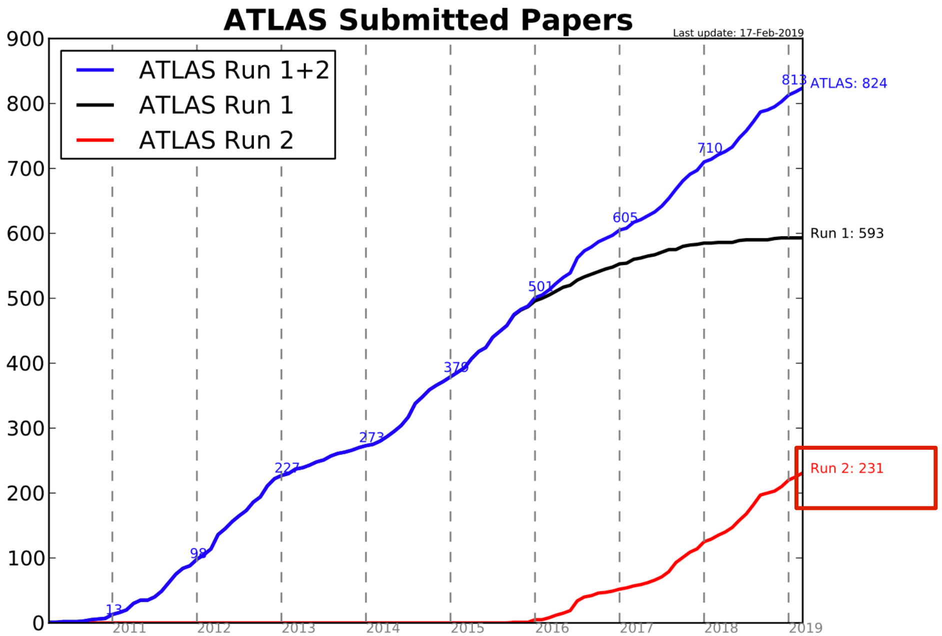


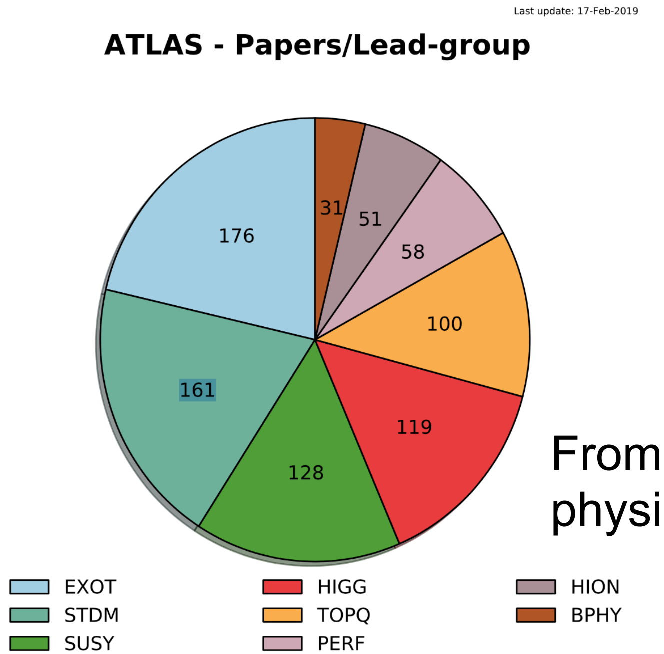
Total integrated luminosity in Run2: 140 fb^{-1} for physics

- One of major challenges at higher luminosities are in Trigger "online-event selections".
  - Critical contribution from KMI, including the menu-coordination role.
  - Designed and operated a complex list of trigger selections to meet the varied ATLAS-physics program.
    - Keep single-e/μ with ≥25 GeV, missing energy ≥200 GeV (offline)
  - Contribution to the hardware-based end-cap muon-trigger operation.

Physics Results

- ATLAS has submitted 824 papers in total
  - including 231 papers using Run2 dataset.
  - Average 7.6 papers / month.





From varied physics areas

- The full list here: https://twiki.cern.ch/twiki/bin/view/AtlasPublic

Today's talk

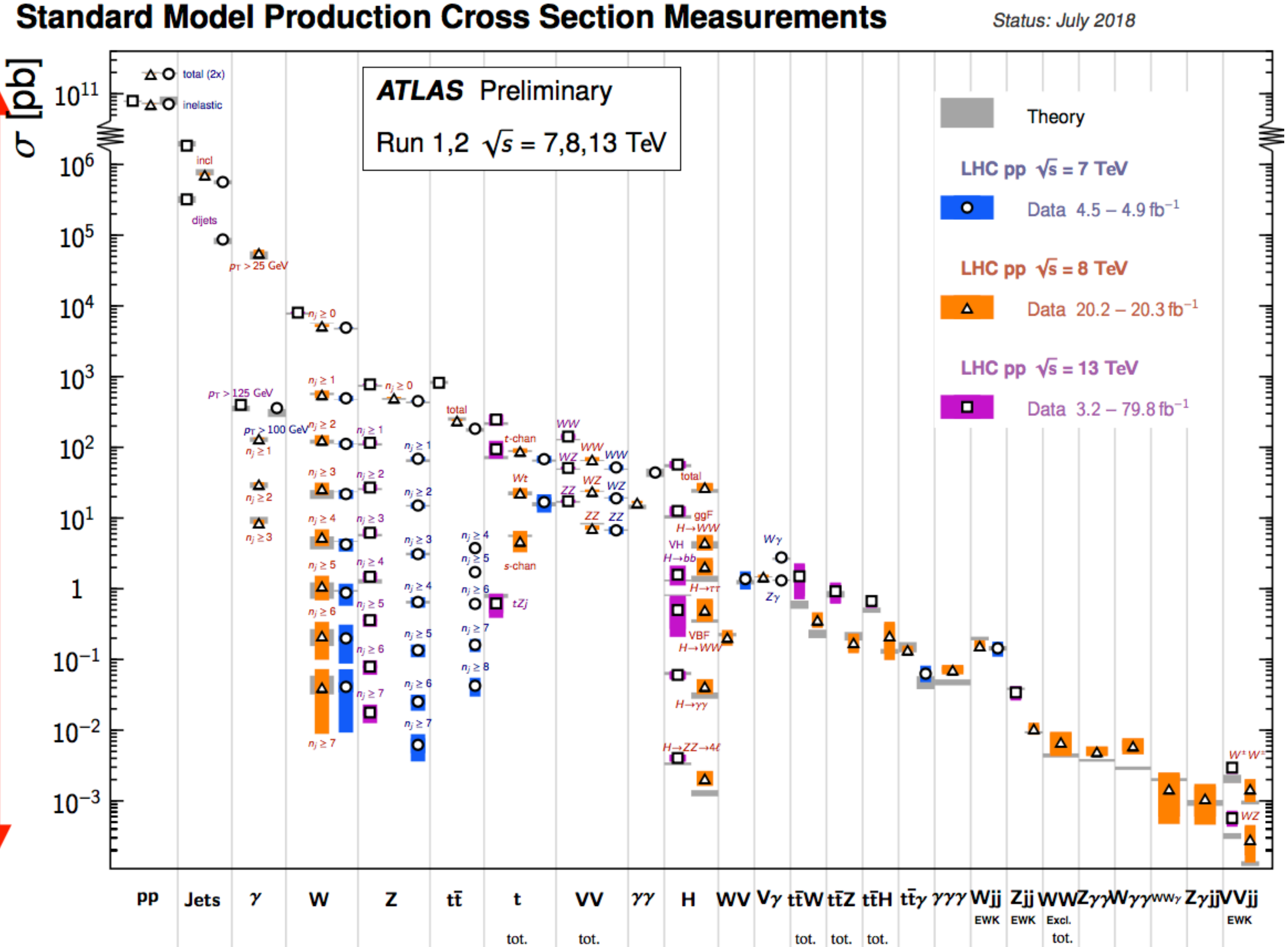
- Following slides review a few selected highlights.
  - Disclaimer: Topics here are driven by the priorities in the Run2 ATLAS physics program, by my tastes, as well as by the KMI's contributions.
  - Apologies if your favorite topics are not covered.
  - The results here use: 36 fb^{-1} (2015-16) or 80 fb^{-1} (2015-17).

- Prospect of new results with 140 fb^{-1}: to be released in a staggered way, so we will deliver results constitutively with necessary precisions and time. *"Stay tuned to us" all the time.*
  - Early search results: from 2019 spring to summer mostly
  - Precise, complex or combination analyses: in 2020-2022.

- SM Measurements

Cross-Section Summary

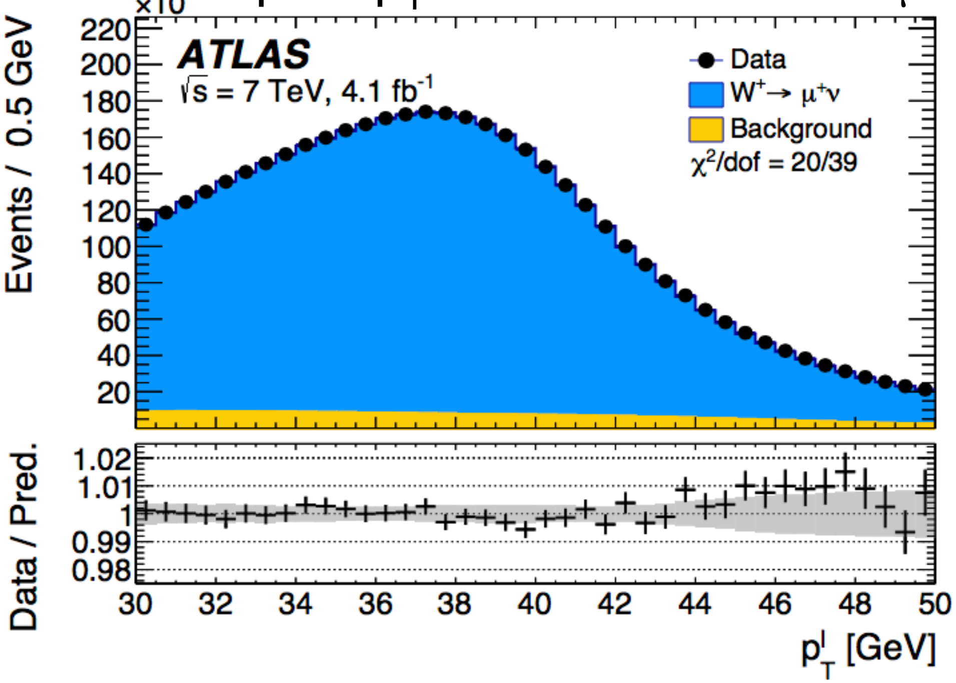
Measurements span
~14 orders of magnitude



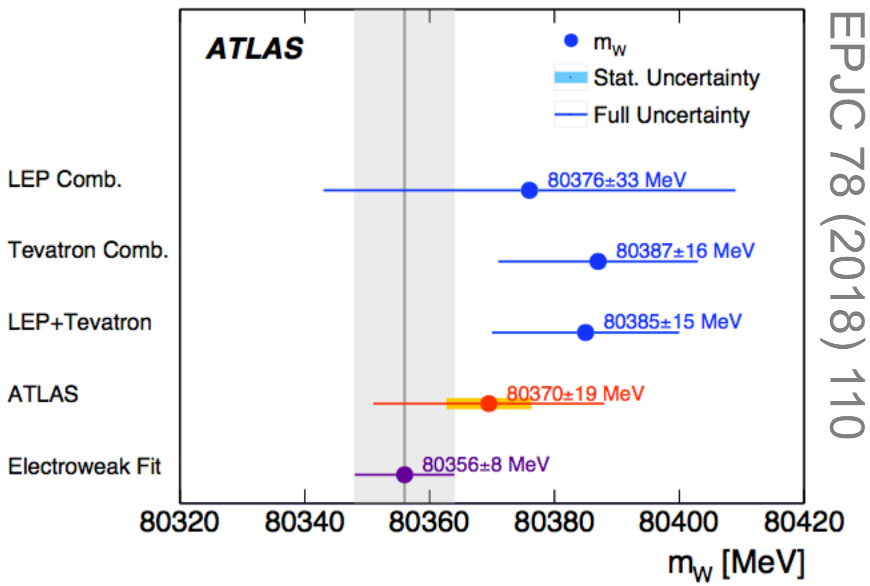
W-mass measurement

- Flagship measurement with a long-term effort: W-boson mass measurement with 7 TeV data
- Analysis: template fits to lepton p_T and m_T distributions require detailed calibration studies, and understanding of the detector.

lepton p_T distribution in $W^+ \rightarrow \mu\nu$



m_W measurements



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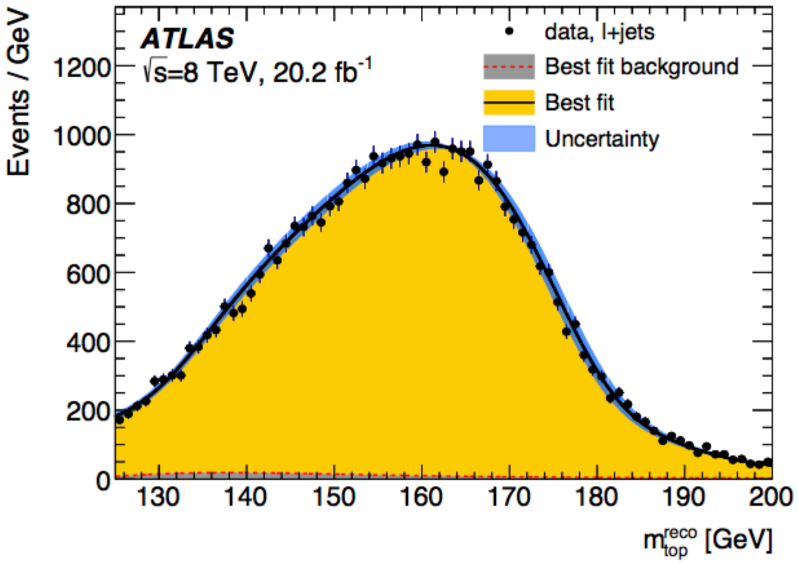
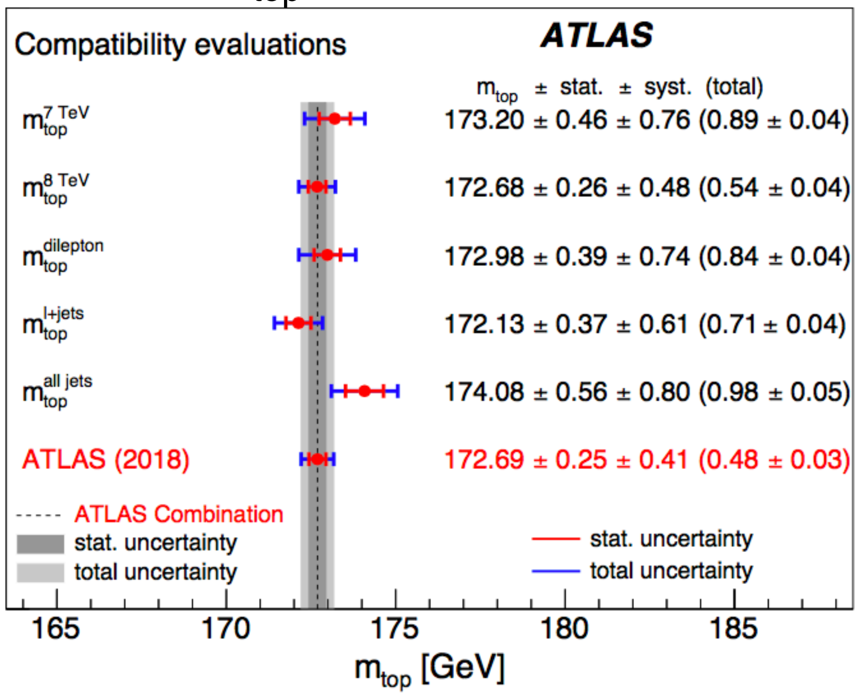
Astounding precision: 0.02%

Top-quark Precision Measurements

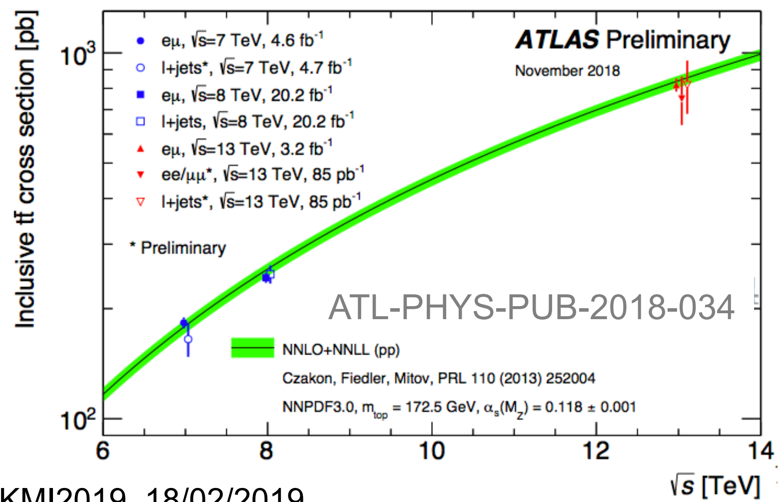
Reconstructed m_{top} distribution in lep+jets



Various m_{top} measurements



Various σ(ttbar) measurements

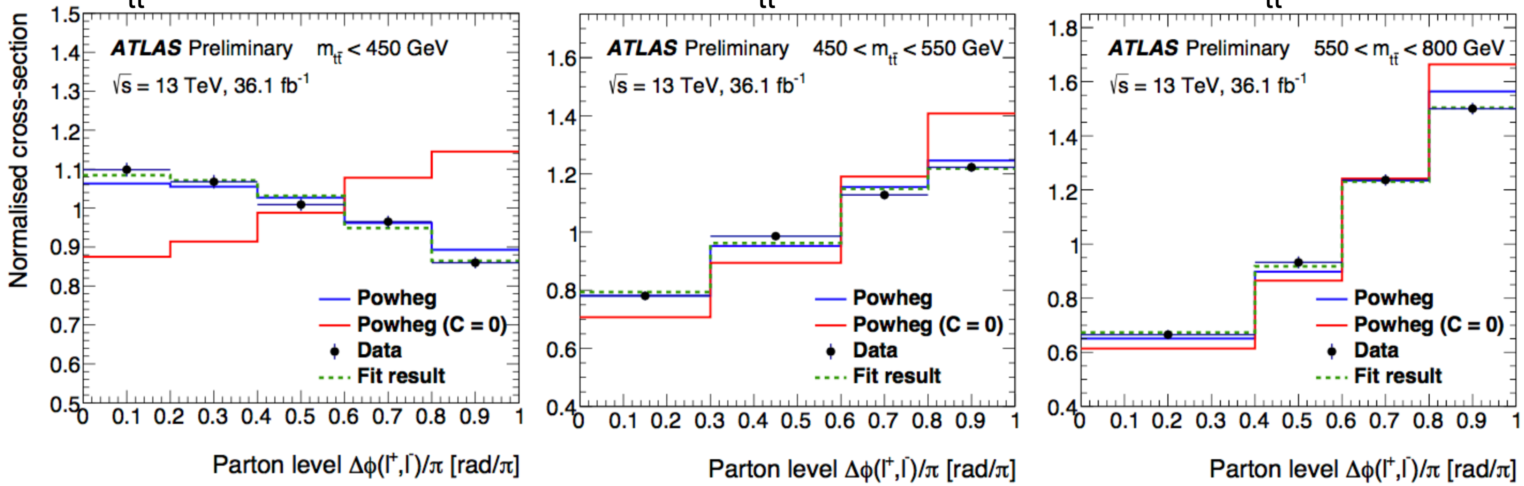


	Precision
m(top)	0.3%
σ(ttbar)	4% at 13 TeV

Spin Correlations in top-pair events

- Top quark spin transmitted directly to decay products
  - Test angular distribution of charged leptons in di-lepton events
  - Observable: azimuthal $\Delta\varphi$(l+,l-) in various m_{tt} ranges
  - Distributions unfolded to parton level to compare with prediction
  - Significant change in $\Delta\varphi$ shape from low to high m_{tt} → well modelled
- Too much spin correlations seen than SM prediction (by 3.2σ):
  - Hint of BSM effects? MC with SM-like spin correlation ON/ OFF
    Steeper distribution with OFF (C=0)
  - Due to missing NNLO correction in top decays (arXiv:1901.05407)?

m_{tt} < 450 GeV | 450 < m_{tt} < 550 GeV | 550 < m_{tt} < 800 GeV



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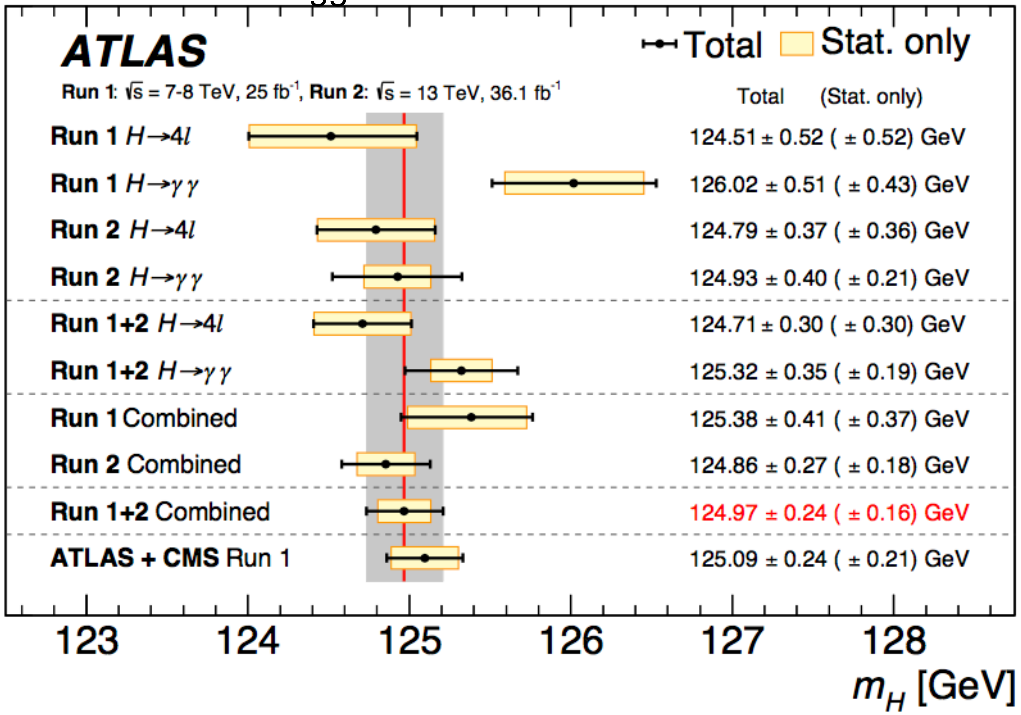
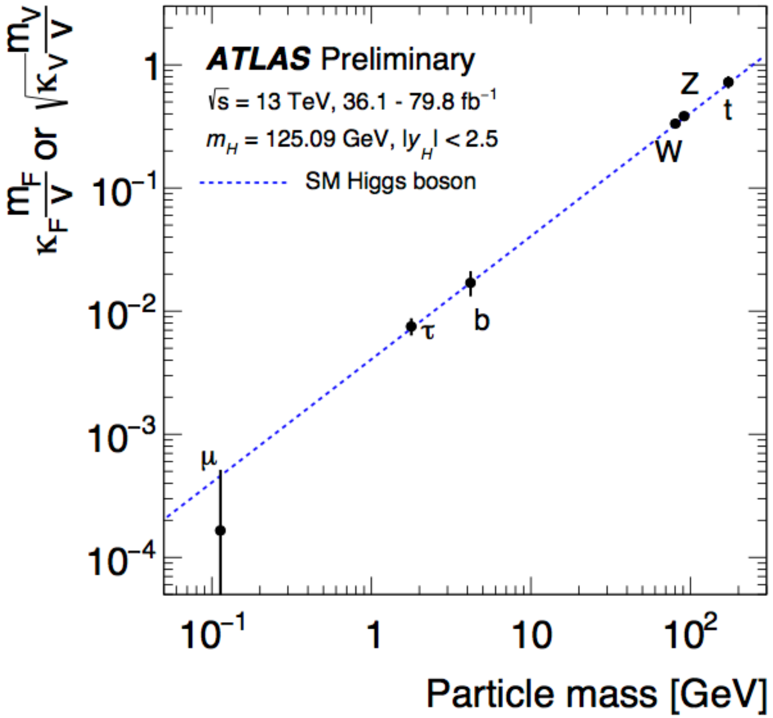
- Higgs EW Physics

Precision Higgs Physics

Various m_{Higgs} measurements

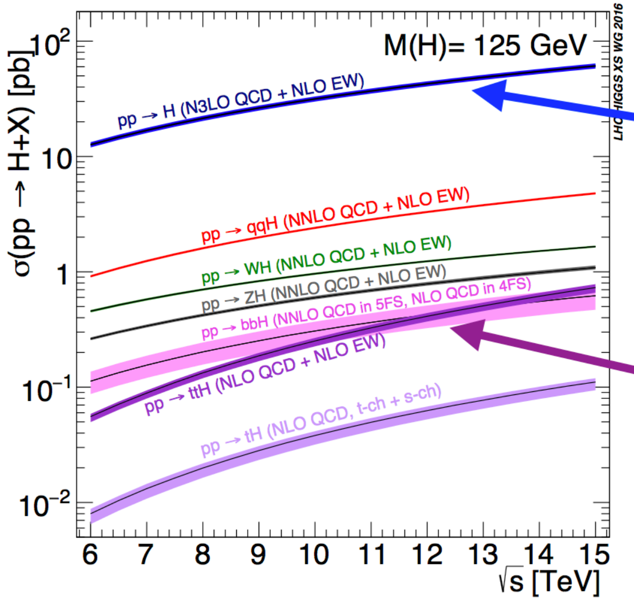


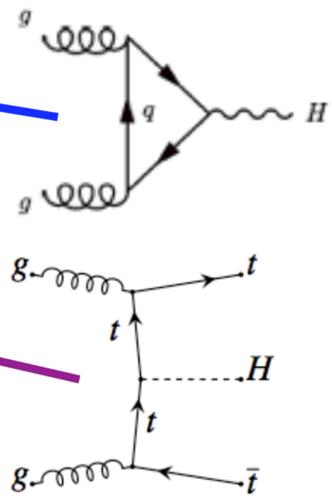
Measured Higgs-coupling vs particle mass



- Astonishing quick arrival to the precision era in Higgs physics
  - 0.2% precision on Higgs mass.
  - Numerous couplings measured/confirmed (especially to ***fermion*** sector).
  - Differential cross-sections, measurements of quantum numbers.
  - Fits to Effective Field Theory operators becoming popular.

Higgs-Top Coupling (ttH)



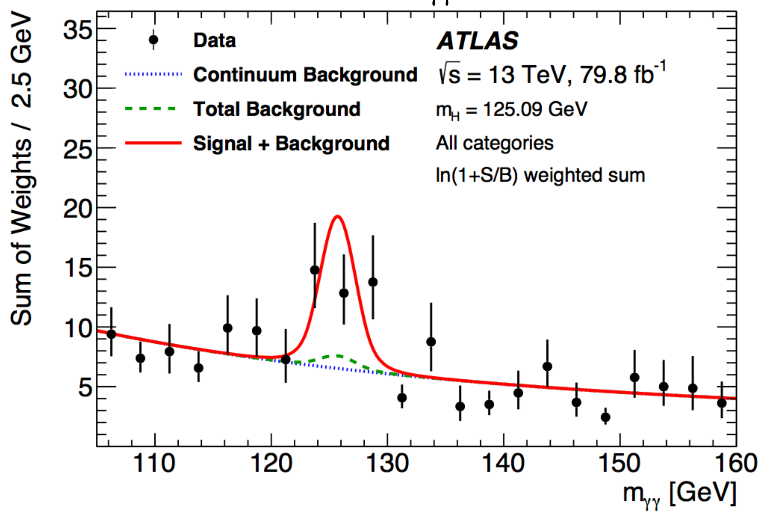


Higgs-quark couplings inferred ***indirectly*** through gluon-fusion (dominated by top quark)

Direct confirmation requires observation of ttH (or tH) process

- Higgs-Top Yukawa Coupling: y_{top} ~ 1
- All sensitive decay modes investigated:
  - γγ,
  - ZZ→4l,
  - bb,
  - multi-leptons (WW, ττ)

Reconstructed $m_{H\rightarrow\gamma\gamma}$ distribution in ttH



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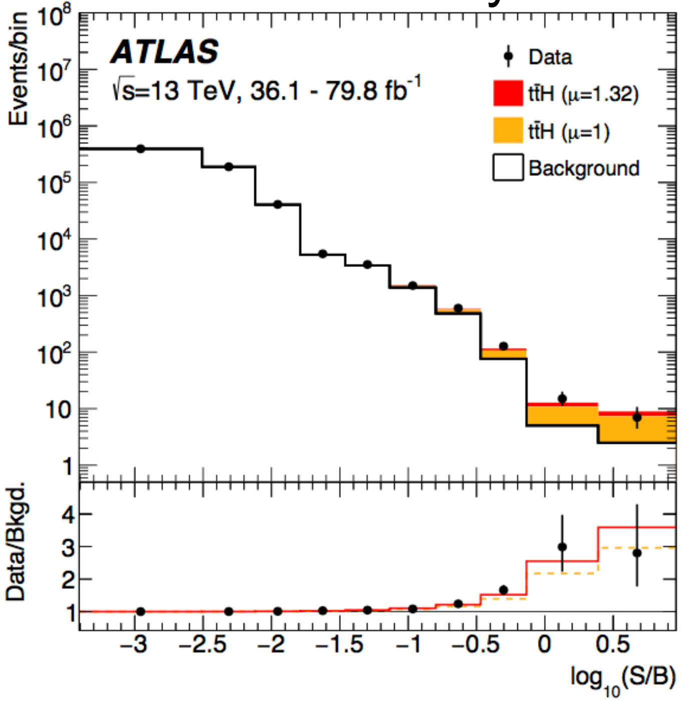
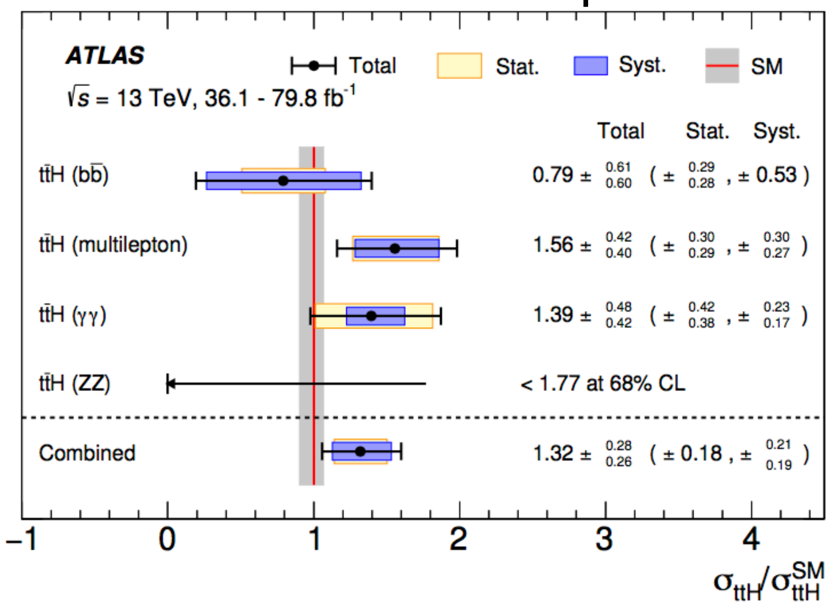
Higgs-Top Coupling (ttH)

- Extensive use of event categorization, multi-variate discriminants

Observed event yields



ttH cross section / SM prediction



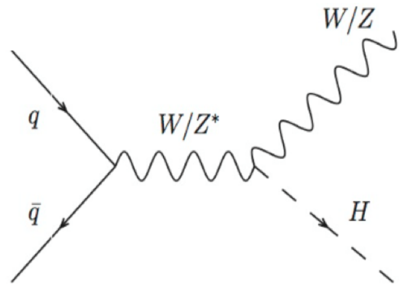
Signal significances (σ):

ATLAS	7,8 TeV	13 TeV	Comb.
Observed	2.7	5.8	6.3
Expected	1.6	4.9	5.1

Production mode firmly established, despite low cross section.

Higgs-Bottom Coupling (H→bb, VH)

- H→bb mode dominates Higgs decays (BR~58%)
  - Important to constrain (invisible)
  - Higgs width challenging QCD backgrounds
  - Most sensitive channel exploits VH(→bb), V=W/Z

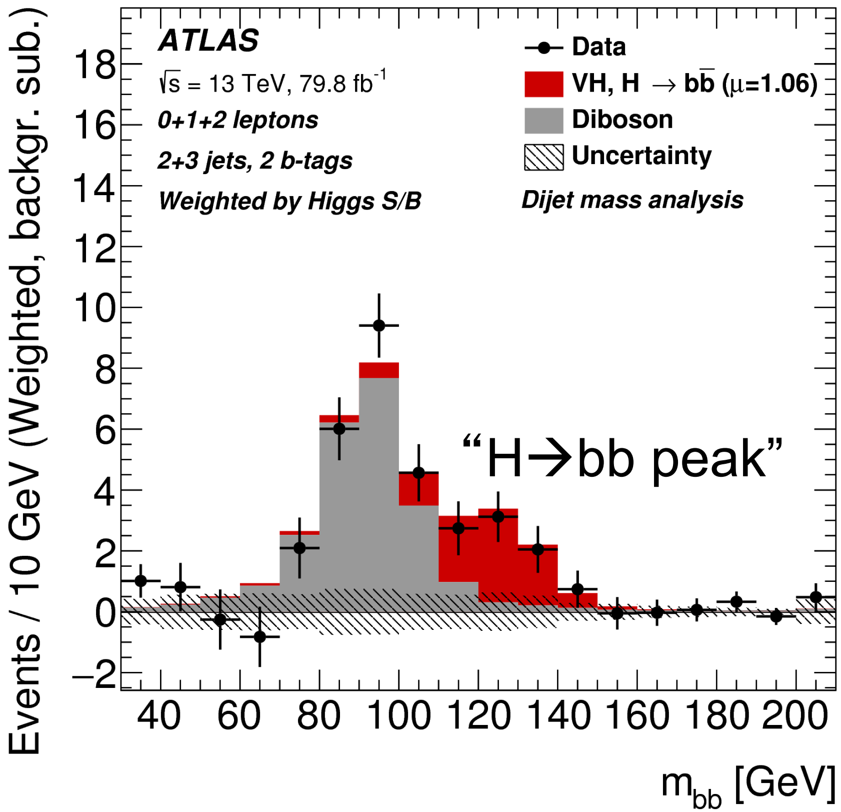


- Combine Z / W final states:
  - 2-lepton (Z→ll)
  - 1-lepton (W→lν)
  - 0-lepton (Z→νν)

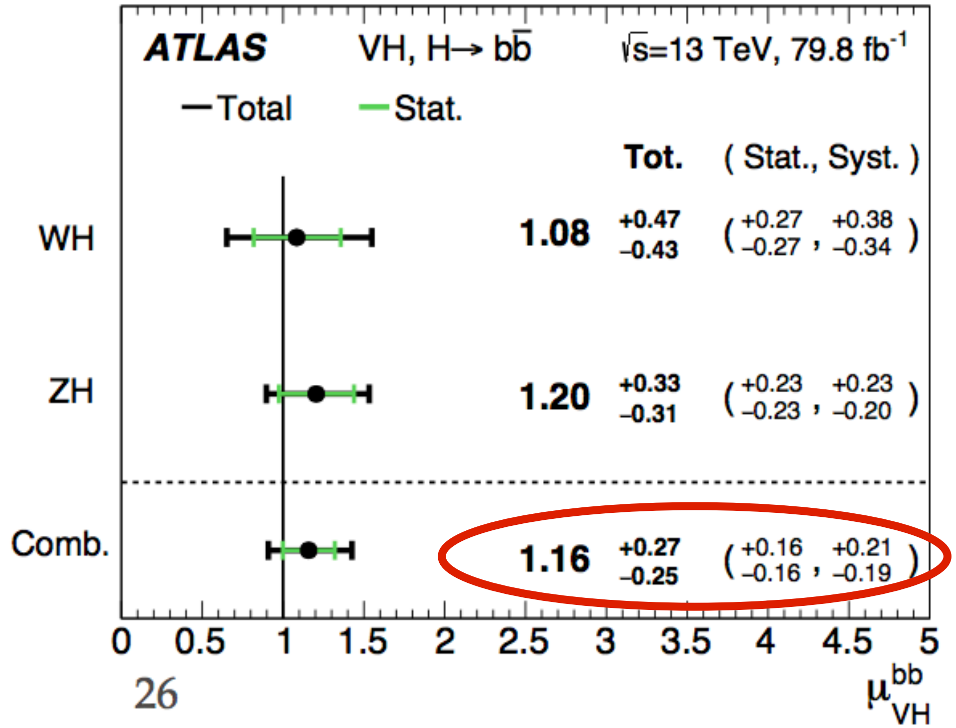
- MVA-based, cross-checked by cut-based selection in a control sample VZ(→bb)

Higgs-Bottom Coupling (H→bb, VH)

Reconstructed m_{bb} distribution from cut and count analysis



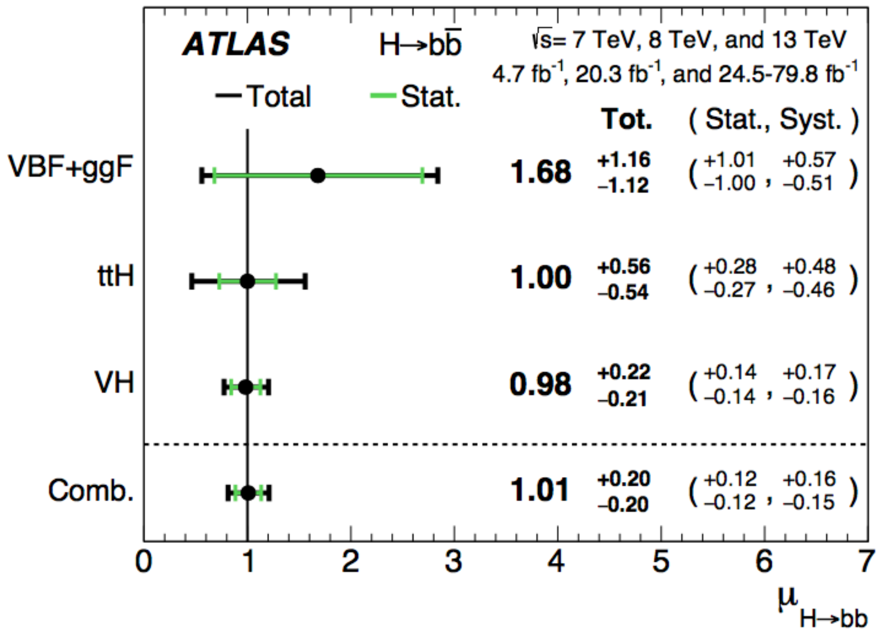
Signal strength



Significance for VH(→bb): observed **4.9σ,** expected 4.3σ.

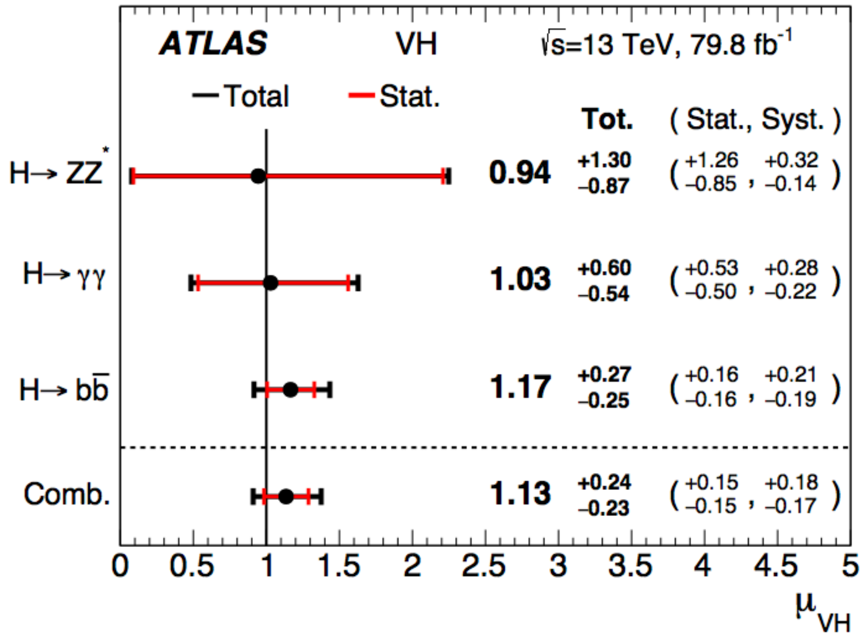
Combined H→bb and VH Results

Add analyses for more productions.



corresponds to observed **5.4σ,** expected 5.5σ.

Add analyses for H→γγ, H→ZZ decays.



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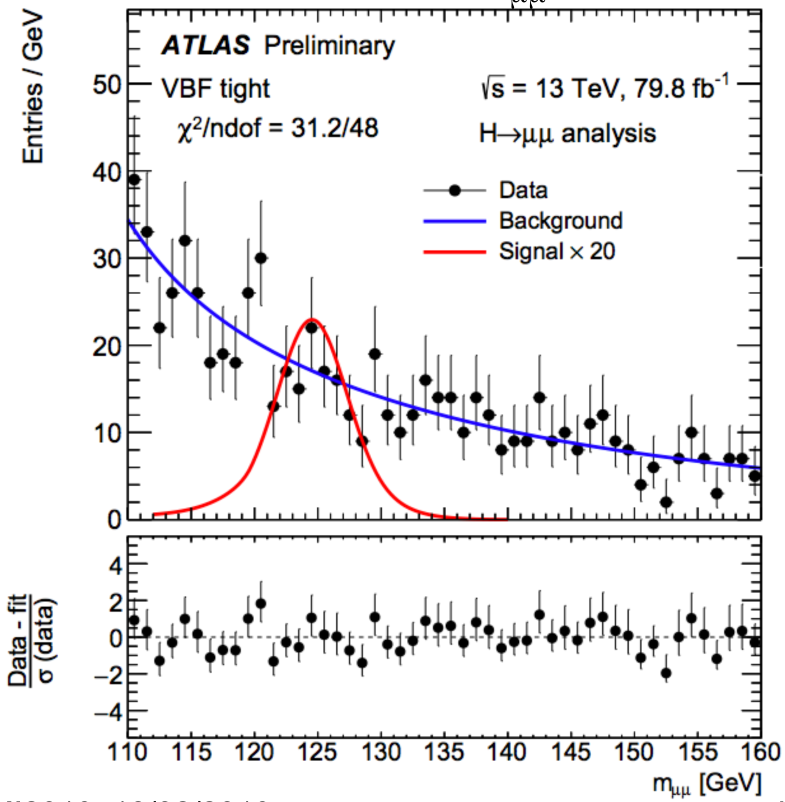
corresponds to observed **5.3σ,** expected 4.8σ.

- The H→bb decay and VH production firmly established.
- Yukawa couplings of Higgs boson to the fermion sector verified.

Rare decay: Search for H→μμ Decay

- Firm test of the Yukawa-coupling with 2nd-generation fermion. Deviation can imply “Beyond SM”.
- Strongly resolution dependent, improve sensitivity by categorizing events (low/high *p* , central/forward, VBF)

Reconstructed $m_{\mu\mu}$ distribution



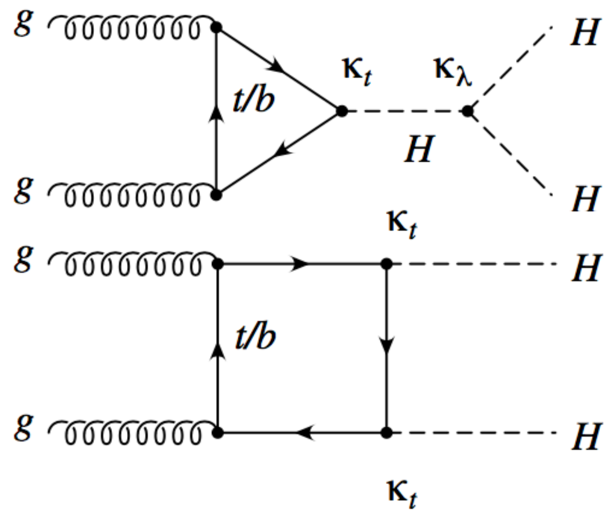
- Dominant background is from Drell-Yan process Z/γ*→μμ.

- Significance: 0.42 times SM (expected), -0.26(observed)
- Total: Observed (expected) Upper imit: 2.1 (2.0) times SM.

→KMI started contributing to the full Run-2 analysis.

Search for Higgs Pair Production

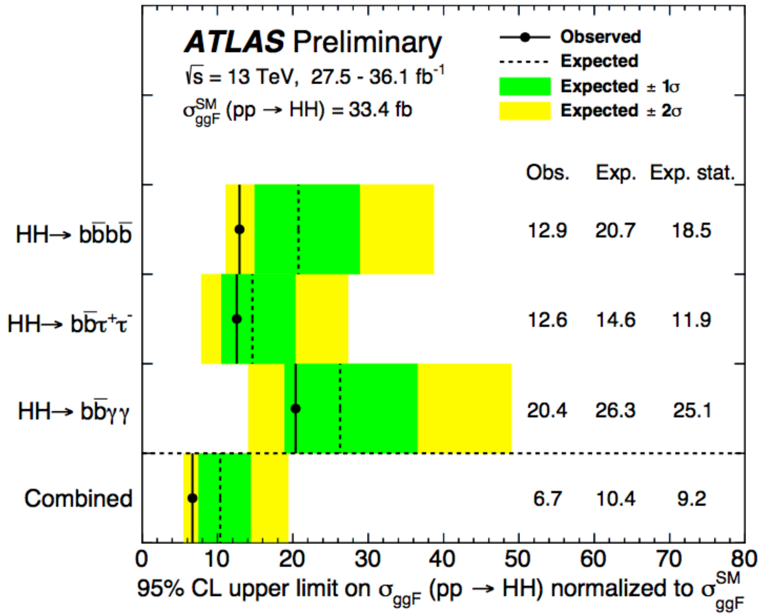
- Flagship in the ATLAS physics in the coming era.
- Resonant X→HH signature predicted in several BSM models.
  - e.g. heavy Higgs bosons (2HDM), KK graviton.
- Potential large non-resonant enhancements in HH cross section.

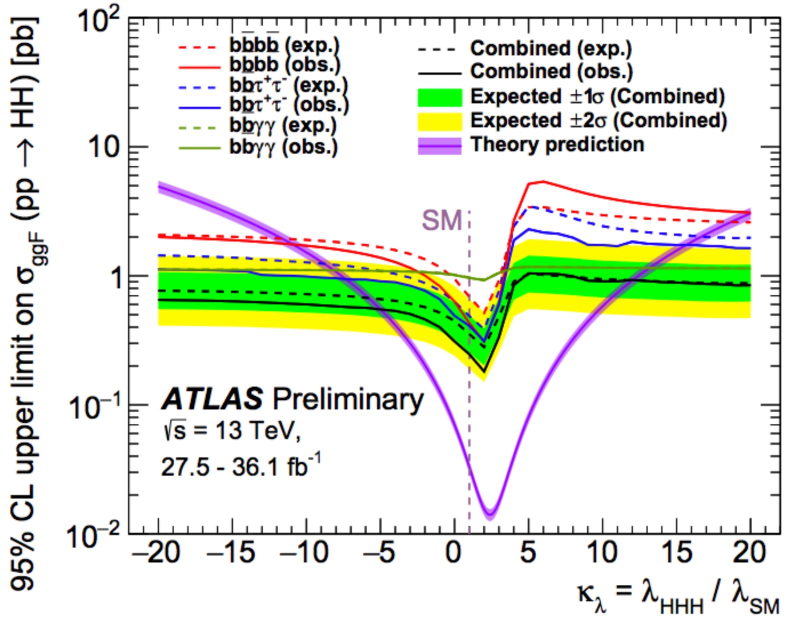


- Long-term program to measure the SM-Higgs self-coupling directly related to the Higgs potential shape.
  - Rare process due to the destructive interference: $\sigma(gg \rightarrow HH)$ = 33 fb.
  - Promising channels: $bb\gamma\gamma$, $bb\tau\tau$, 4b (current coordinator)

Search for Higgs Pair Production

- Combination results with 2015+2016 dataset

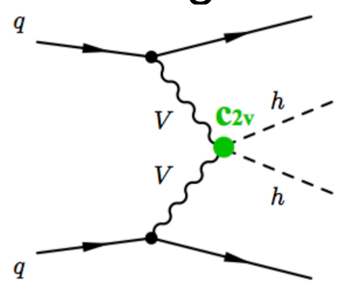




$-5.1 < \kappa_\lambda < 12.1$ (95% CL)

ATLAS-CONF-2018-043

- Full Run-2 analysis
  - Complex inclusive analysis in 2020: Full use of Machine Learning
  - New VBF analysis in 2019: KMI developed for the first time in the world. Unique sensitivity to the VVhh (c2v) coupling. Stay tuned.

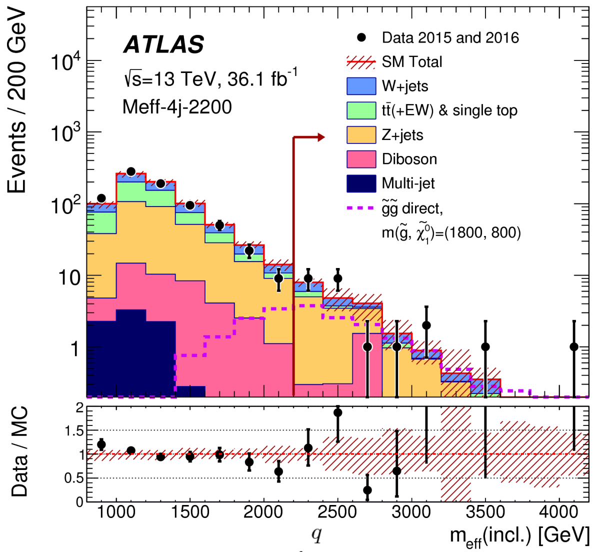


- SUSY searches

Searches for SuperSymmetry

- Search for light squarks and gluinos with jets and E_T^{miss}
  - No significant excesses over SM expectation with 36 fb^{-1}.
  - Gluino sensitivity beyond 2 TeV for the first time.

Effective mass distribution in gluino-search region



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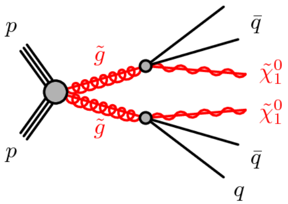
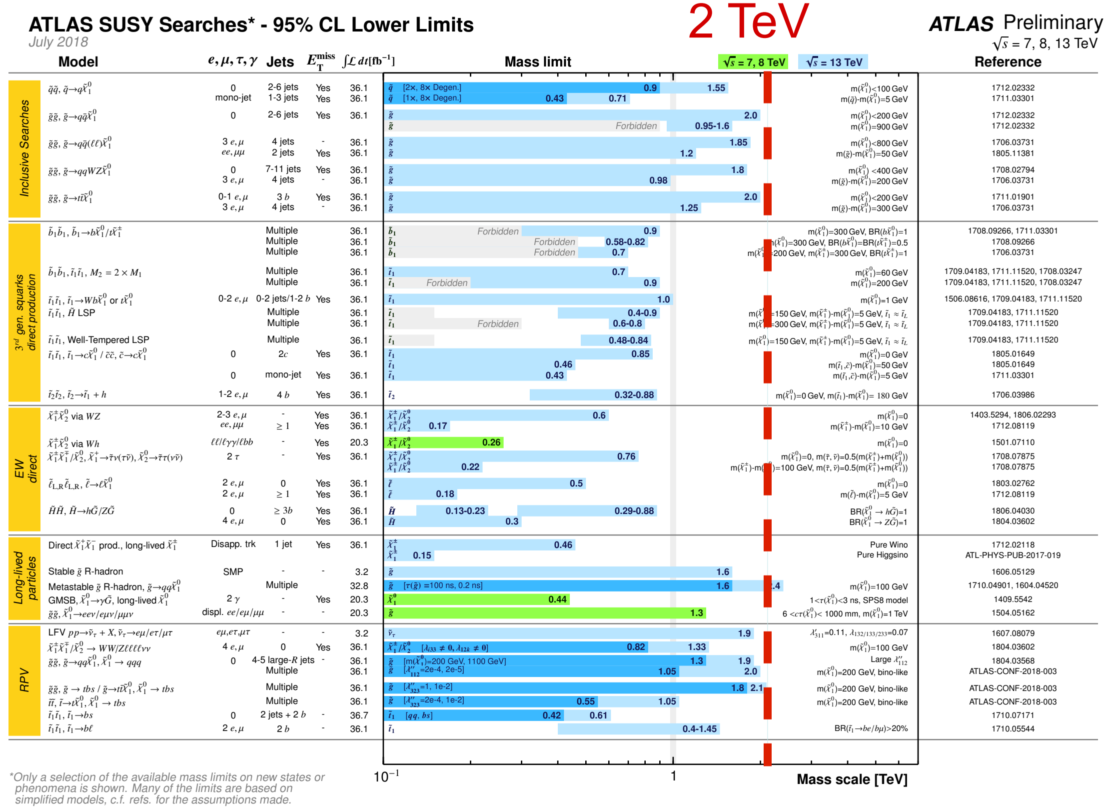


Limits on SUSY masses by various ATLAS searches

2 TeV



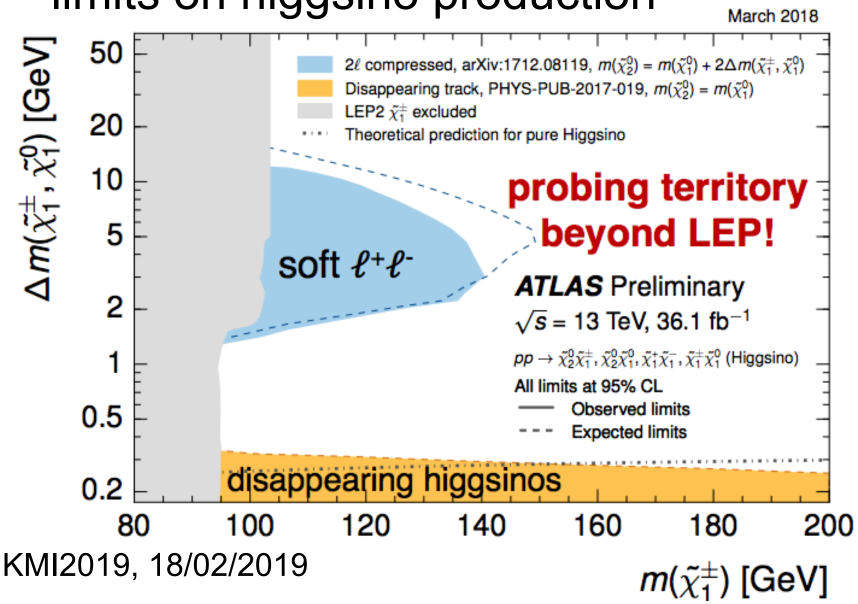
Full Run-2 analysis to conclude on this flagship search: Machine-Learning, complex fit.

Further SUSY searches: EW production

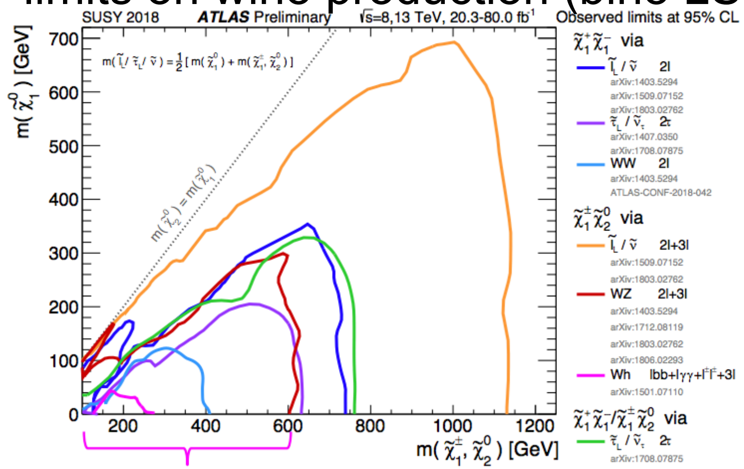
- Searches for EW SUSY with leptons
  - Weak coupling → small production rates and / or low-energy events that are difficult to distinguish from backgrounds.

  → Becoming possible with high statics. In full swing.
- Higgsinos (naturalness) and staus (DM relic density)
  - theoretically well-motivated not well-constrained at LHC.
  - ATLAS limits on compressed SUSY particles filling in the sensitivity gaps and extending to regions not probed since LEP. More to come.

limits on higgsino production



limits on wino production (bino LSP)



decays via $W^{(*)}/Z^{(*)}$

decays via sleptons

KMI's contributions:

Conclusion

- From the energy-frontier area using the ATLAS detector, we search for New Physics beyond the Standard Model.
  - No clear BSM signs in a wide range of available results with 36 or 80 fb^{-1}
  - More precise or better results with 140 fb^{-1} to come soon or gradually.
- Higgs EW Physics
  - Higgs-coupling measurements → Deviations from SM indicate BSM
    - Observation: top-H, bottom-H couplings
    - Next target: μ-H with $H \to \mu\mu$ decay
  - Search for Higgs-pair production → Flagship analysis in coming era
    - Higgs self-coupling constraints (HHH). Direct BSM Higgs search.
- SUSY Searches
  - Concluding on the searches using sophisticated analysis methods.
- >Two more decades of exciting physics yet to come
  - Run3: improvements in precision and search sensitivities with 300 fb^{-1}
  - HL-LHC: with 3000 fb^{-1} or more