

Large Hadron Collider Physics (Biased) Overview

Haichen Wang

University of California, Berkeley
Lawrence Berkeley National Laboratory

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Outline

- Status and plan of the Large Hadron Collider
- Higgs Physics
- Top Physics
- Prospect for the High Luminosity LHC

Disclaimer:

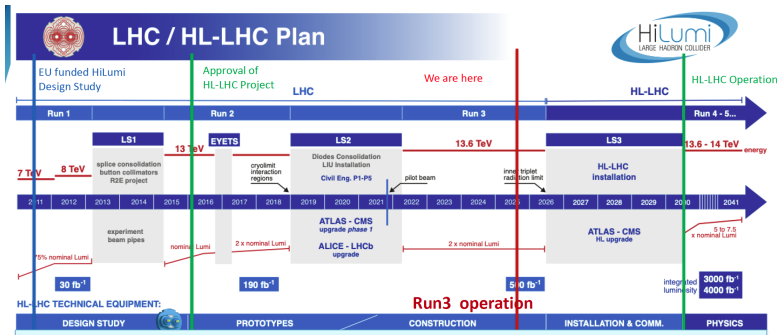
most direct BSM searches, electroweak, QCD measurements, flavor physics, heavy ion physics are not covered

The Large Hadron Collider



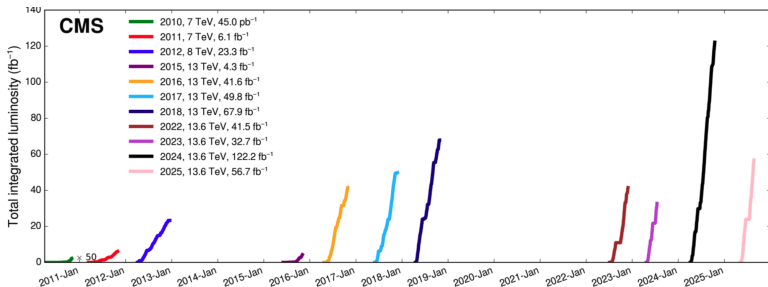
LHC Timeline and Evolution

- **1983–1994:** Concept, magnet feasibility, and CERN Council approval
- **1998–2008:** Civil engineering, magnet installation, hardware commissioning
- **2010–2025:** Physics exploitation (Run 1–3)
- **2026–2029:** Long Shutdown 3 (LS3) – HL-LHC installation
- **2030–2040 + :** HL-LHC operation, delivering up to 3000 fb^{-1}



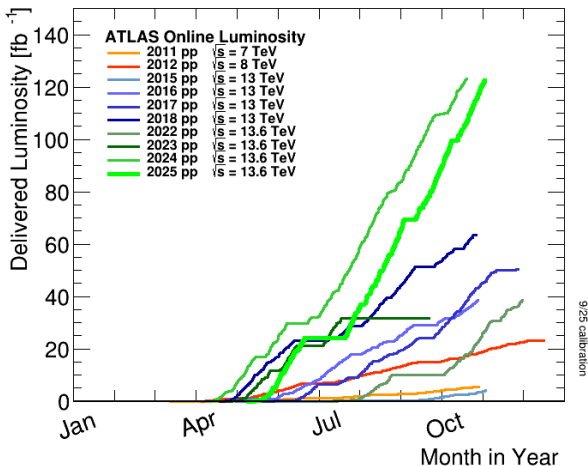
Run 3 Performance and Achievements

- Routine operation at $\sim 2\times$ design luminosity
- Average production rate: **$0.83 \text{ fb}^{-1}/\text{day}$** , peak: **$1.5 \text{ fb}^{-1}/\text{day}$**
- Accumulated luminosity: **415 fb^{-1} @ 13 TeV + 30 fb^{-1} @ 7 TeV**



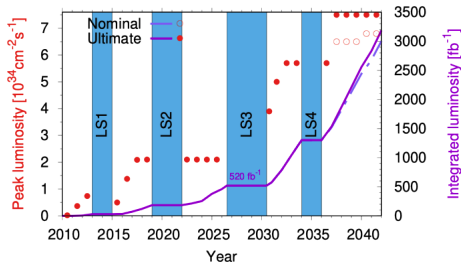
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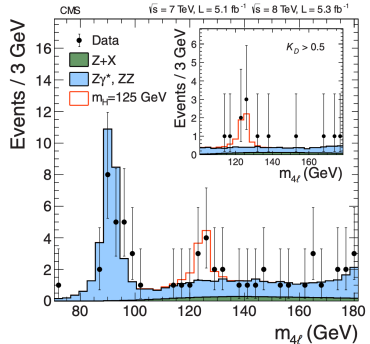
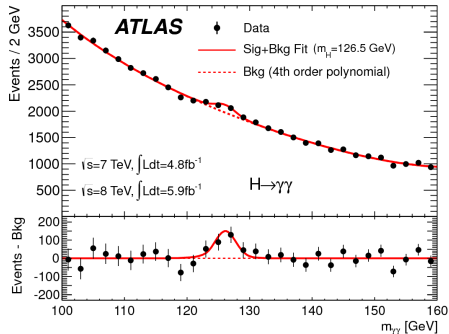


High Luminosity LHC

- from mid-2026 to mid-2030
Long Shutdown 3
- installation of new magnets and other components for HL-LHC
- Run 4 will continue to run at $\sqrt{s} = 13.6$ TeV
- Run 5 will reach the designed energy $\sqrt{s} = 14.0$ TeV
- 3 ab^{-1} expected by the end of the HL-LHC



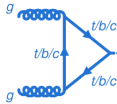
Higgs boson discovery



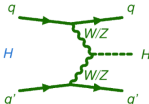
- The “Higgs mechanism” was proposed in 1964 by Peter Higgs, and Francois Englert and Robert Brout, independently
- In 2012, it was observed by both ATLAS and CMS experiment
- Since then, LHC experiments continue to characterize the Higgs boson

Higgs boson productions and decays at the LHC

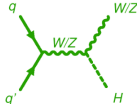
Terms in the SM lagrangian tell us how the Higgs boson might be produced at the LHC and how they might decay



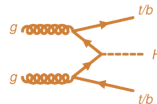
13 TeV 48.5 pb
13.6 TeV 52.2 pb



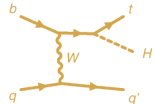
3.78 pb
4.08 pb



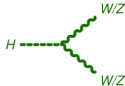
2.25 pb
2.40 pb



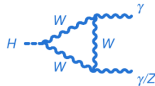
0.51 pb
0.57 pb



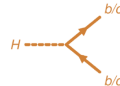
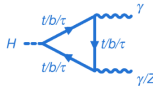
0.074 pb
0.087 pb



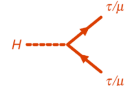
WW 21.4 %
ZZ 2.62 %



$\gamma\gamma$ 0.227 %
 $Z\gamma$ 0.153 %



bb 58.2 %
cc 2.89 %



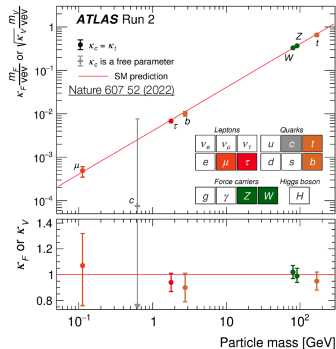
$\tau\tau$ 6.27 %
 $\mu\mu$ 0.0218 %

Higgs Couplings and the κ Framework

- Coupling-modifier framework: test for deviations from SM

$$\sigma_i \times \mathcal{B}_f = (\sigma_i^{\text{SM}} \times \mathcal{B}_f^{\text{SM}}) \kappa_i^2 \kappa_f^2 / \kappa_H^2$$

- κ_V scales all vector-boson couplings, κ_f all fermionic ones
- Run 1–3 measurements: consistent with SM within 5–10 %
- Couplings follow particle mass

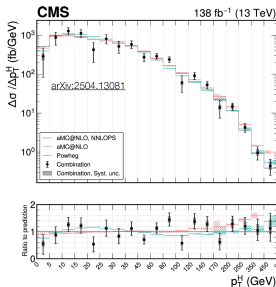


Precision Measurement of Higgs boson properties

LHC experiments performed a suite of precision measurements and searches for rare decays

Differential distribution measurement

Example: Higgs p_T

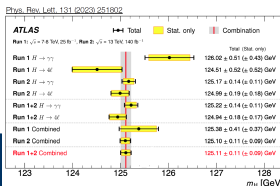


Higgs mass measurement

ATLAS Run1 + Run 2

$m_H = 125.11 \pm 0.11$ GeV CMS Run1 + Run 2

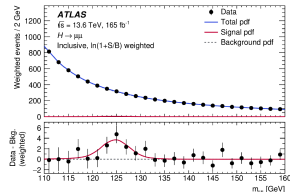
$m_H = 125.09 \pm 0.12$ GeV Uncertainty $< 0.12\%$



Second generation coupling

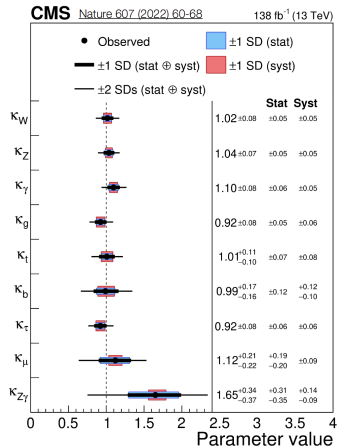
$\text{BR}(H \rightarrow \mu\mu)$

$\sim 10^{-4}$ ATLAS Run 2 and Run 3: 3.4σ (obs) (2.5σ exp)



Detailed Higgs Coupling Measurements by Channel

- Production modes: ggF , VBF , VH , $t\bar{t}H$, tH
- Decay channels:
 - Bosonic — $H \rightarrow \gamma\gamma$, $ZZ^* \rightarrow 4\ell$, $WW^* \rightarrow \ell\nu\ell\nu$, $Z\gamma$
 - Fermionic — $H \rightarrow b\bar{b}$, $\tau\tau$, $\mu\mu$, $c\bar{c}$



Higgs Total Width Measurements

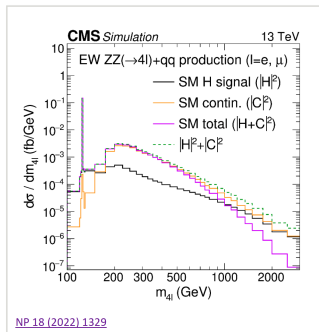
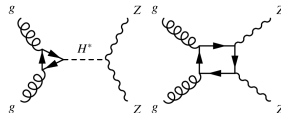
- Standard Model expectation: $\Gamma_H^{\text{SM}} \approx 4.1$ MeV
- Indirect methods:** on-shell / off-shell ratio in $H \rightarrow ZZ, WW$

$$\sigma_{\text{on}} \propto \frac{\kappa_i \kappa_f}{\Gamma}$$

$$\sigma_{\text{off}} \propto \kappa_i \kappa_f$$

$$\frac{\mu_{\text{off}}}{\mu_{\text{on}}} = \frac{\Gamma_H}{\Gamma_H^{\text{SM}}}$$

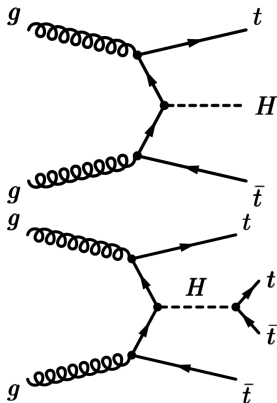
- The most precise measurements made in ZZ^* final states: ATLAS: $\Gamma_H = 4.3^{+2.7}_{-1.9}$ MeV; CMS: $3.0^{+2.0}_{-1.5}$ MeV



Higgs total width constraint from top Yukawa processes

ATLAS also made a novel measurement using top-Yukawa induced processes to constrain Higgs total width

- Proposed by Qing-Hong Cao, et al (Phys.Rev.D 95 (2017) 5, 053004)
- Avoid assumptions made about running of ggH coupling, which is unknown when BSM is present
- $\Gamma_{H,\text{exp}} < 75 \text{ MeV}$ ($\Gamma_{H,\text{obs}} < 450 \text{ MeV}$)
- always important to check the same parameter using complementary approaches



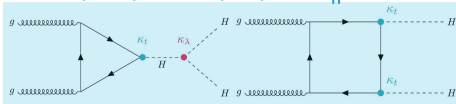
Phys. Lett. B 861 (2025) 139277

Higgs Self-Coupling and Di-Higgs Production Overview

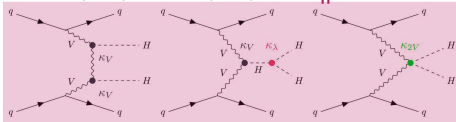
Measurements of Higgs boson pair production directly probe of the Higgs potential:

$$V(h) = \frac{1}{2}m_H^2 h^2 + \lambda v h^3 + \frac{\lambda}{4} h^4 + \dots$$

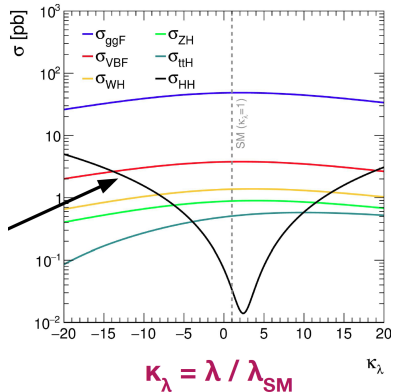
30.77 (34.13) fb at 13 (13.6) TeV, $m_H = 125$ GeV



1.69 (1.87) fb at 13 (13.6) TeV, $m_H = 125$ GeV

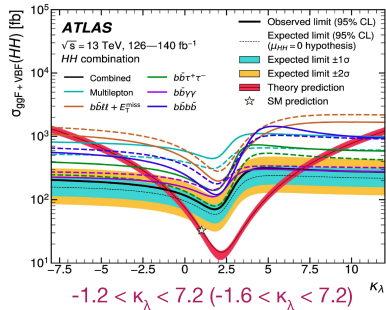
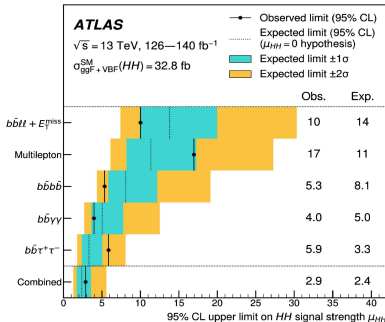


- destructive interference between self-coupling and top-Yukawa induced



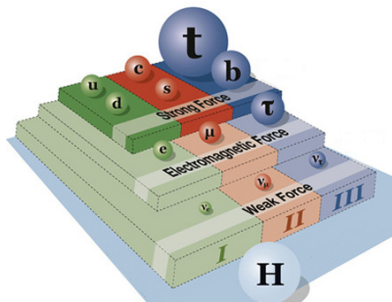
Combined Di-Higgs Results and Self-Coupling Constraints

- Channels combined: $b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$, $b\bar{b}b\bar{b}$, $b\bar{b}WW$, $b\bar{b}ZZ$, $b\bar{b}VV$
- ATLAS Run 2 combination: $1.2 < \kappa_\lambda < 7.2$ (95 % CL)
- CMS Run 2 combination: $3.4 < \kappa_\lambda < 9.8$
- ATLAS + CMS combined (280 fb⁻¹): 1.1 σ (obs), 1.3 σ (exp)
- Extended fits including single-Higgs parameters tighten the constraint to $1.3 < \kappa_\lambda < 6.1$



Top Quark Sector

- The top quark is the most massive elementary particle in the Standard Model (SM)
- Its large Yukawa coupling suggests that the top quark plays a unique role in the electroweak symmetry breaking
- Measurements and searches involving top quarks could help us to uncover Beyond the SM physics

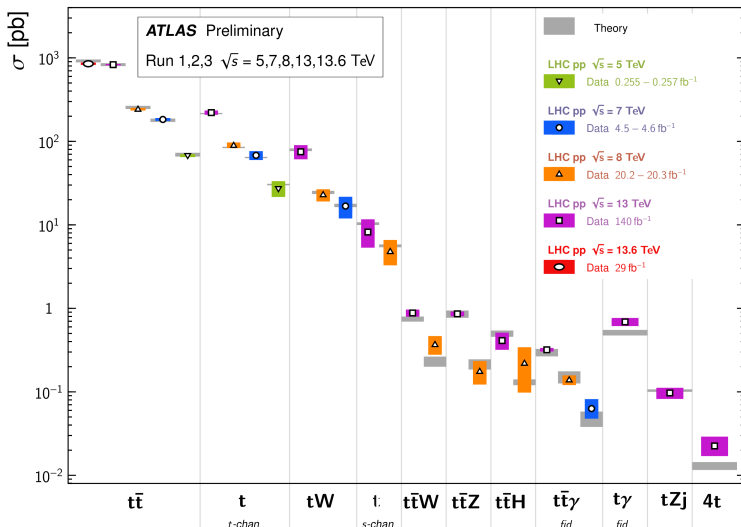


The LHC is a top quark factory

Cross sections of Top quark processes span over several orders of magnitudes!

Top Quark Production Cross Section Measurements

Status: May 2025

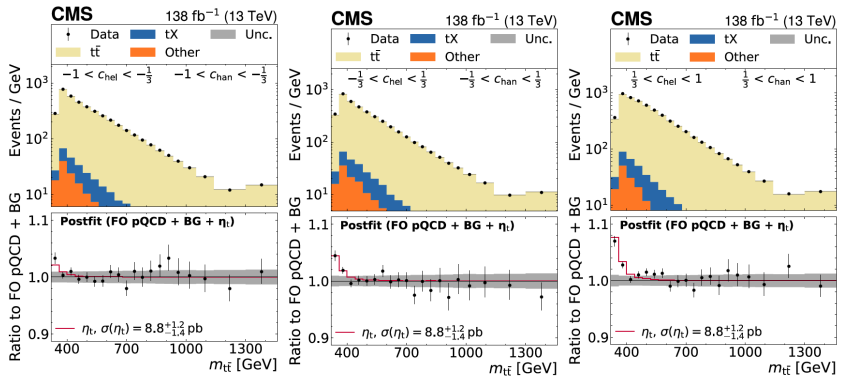


$t\bar{t}$ Production Near Threshold — Background and Common Approach

- Near threshold ($m_{t\bar{t}} \approx 2m_t \simeq 345$ GeV) the system becomes non-relativistic:
 - gluon exchange induces QCD binding effects → **quasi-bound toponium** enhancement
 - potential interplay with virtual Higgs exchange and electroweak (EW) loops
- Both **CMS** and **ATLAS** study this region using full Run-2 datasets
 - high-precision reconstruction of dilepton $t\bar{t}$ events
 - profile-likelihood fits in ($m_{t\bar{t}}$, spin-correlation observables)
 - compare pQCD predictions vs NRQCD-reweighted models

CMS Results: Observation of Threshold Enhancement

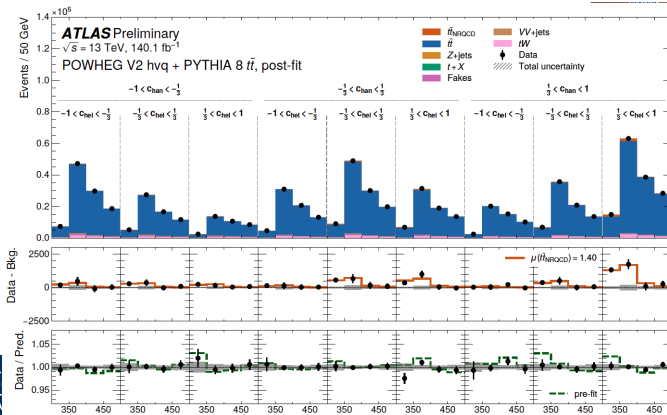
- Full Run-2 dataset (138 fb^{-1} , **dilepton** channel)
- Clear excess in $m_{t\bar{t}}$ 340–380 GeV and spin-correlation observables
- Fit with pseudoscalar (η_t) model gives $\sigma(\eta_t) = 8.8^{+1.2}_{-1.4} \text{ pb}$ vs 6.4 pb (NRQCD prediction)
- Background-only hypothesis excluded at $> 5\sigma$



ATLAS Results: Confirmation and Top-Yukawa Constraint

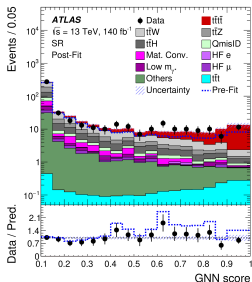
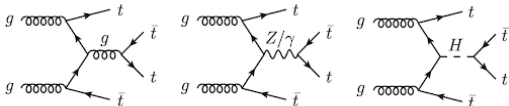
- Dedicated Run-2 analysis (140 fb⁻¹, dilepton and lepton+jets channels)
- Observed (Exp.) significance = **7.7 σ** (**5.7 σ**)
- Measured $\sigma(t\bar{t}_{\text{NRQCD}}) = 9.0 \pm 1.3$ pb vs theory 6.4 pb
- Consistent with CMS result and NRQCD predictions
- Extracted top-Yukawa coupling from EW effects:

$$Y_t^2 < 2.1 \quad (|\kappa_t| < 1.45, \text{ 95\% CL})$$



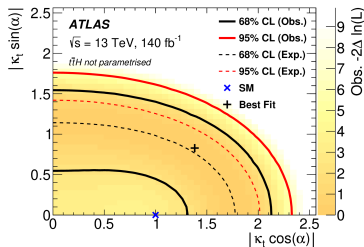
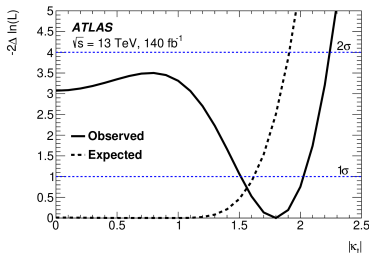
Observation of the Four-top production

The simultaneous production of four top quarks has a cross section of ≈ 12 fb at the LHC13 TeV



- Excess in four-top signal like GNN region
- The signal is $> 6\sigma$ from the background-only hypothesis
- The size of the four-top signal is almost twice as large the SM prediction, but it is still within 2σ

Constraint on the Higgs-Top Yukawa from Four-Top



- The overall strength of the H-t interaction is about 1.8 ± 0.3 , but within 2σ from SM
- The uncertainty is small thanks to the rate's quartic dependence on κ_t
- ATLAS CP interpretation inspired by Phys. Rev. D 99, 113003 (2019) (Qing-Hong Cao et. al).

Search for Rare Top Quark decays

The LHC has produced a few hundred millions of $t\bar{t}$ events, a large sample to search for BSM top quark decays

Example: Flavor Changing Neutral Current

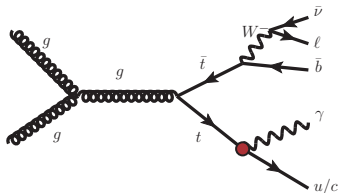
At LHC, top FCNC searches focus on vertices such as

- t - q - g t - q - γ
- t - q - Z t - q - H

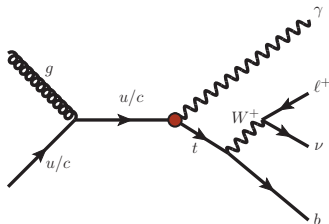
where q is an up-type quark (u, c)

- Searches are designed to capture both FCNC decays in $t\bar{t}$ and single top production via FCNC vertex
- Constraints are set on FCNC decay BR
 - separate charm- and up- channels
- Constraints FCNC EFT operators

FCNC decays

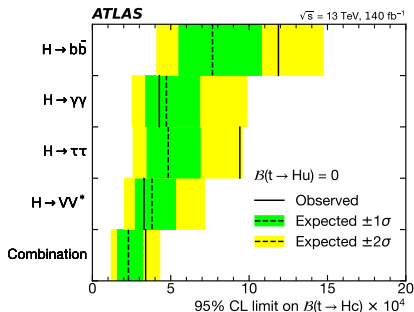
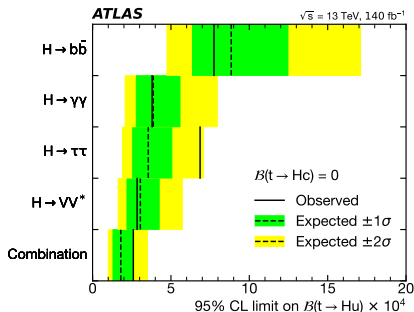


FCNC production



ATLAS FCNC tqH search combination

- **Combination of four searches in different Higgs decay channels**
- Multi-lep analysis contributes to both $H \rightarrow VV^*$ and $H \rightarrow \tau\tau$, with $H \rightarrow VV^*$ being the most sensitive channel

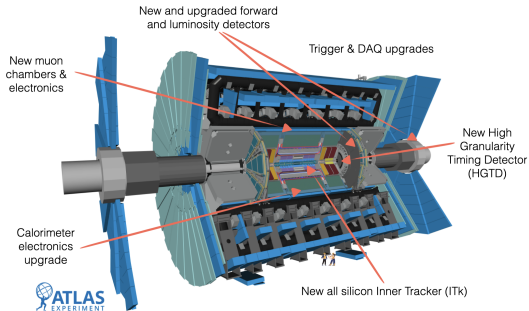


The combined ATLAS observed (expected) upper limits on the branching ratio are

- $B(t \rightarrow Hu) < 2.8 \text{ (3.0)} \times 10^{-4}$ $B(t \rightarrow Hc) < 3.3 \text{ (3.8)} \times 10^{-4}$.

Prospect for HL-LHC

- CMS and ATLAS will be significantly upgraded
- Both will have all new silicon trackers with extended η coverage (up to 4.0)
- Timing detectors to mitigate pile-up
- Upgraded electronics for calorimeter, muon, data acquisition, trigger
- LHC + HL-LHC $\Rightarrow$ 3000 fb $^{-1}$ expected



Trigger/HLT/DAQ

- Track information in L1-Trigger
- L1-Trigger: 12.5 μ s latency – output 750 kHz
- HLT output 7.5 kHz

Barrel ECAL/HCAL

- Replace FE/BE electronics
- Lower ECAL operating temp. (8 °C)

Muon Systems

- Replace DT & CSC FE/BE Electronics
- Complete Muon coverage in region $1.5 < \eta < 2.4$

New Endcap Calorimeters

- High granularity
- 3D capable

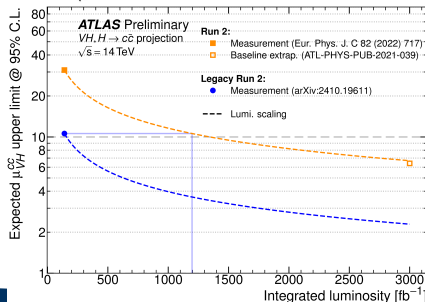
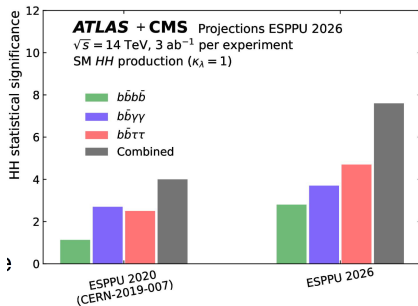
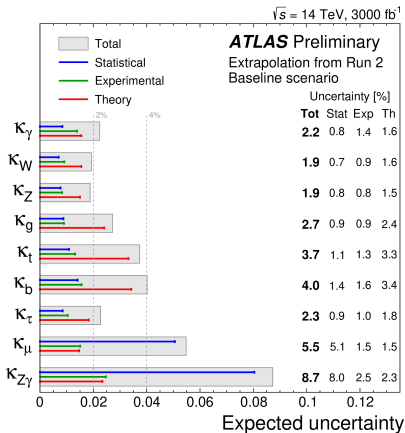
New Tracker

- Rad. tolerant – high granularity – significant less material
- 40 MHz selective readout ($p_T > 2$ GeV) in Outer Tracker for L1-Trigger
- Extended coverage to $\eta=4$

New Precision Timing Detector

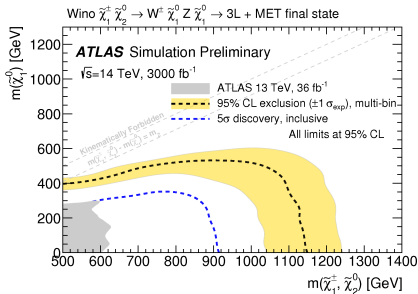
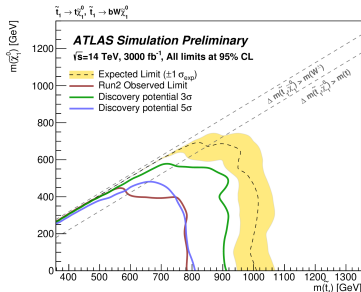
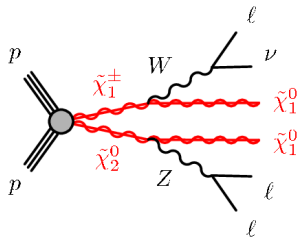
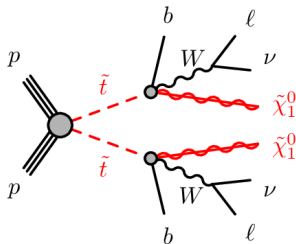
- Barrel: Crystal + SiPM
- Endcap: Low Gain Avalanche Diodes

Prospect for HL-LHC



Prospect for HL-LHC

Phase space for “natural” SUSY will be severely limited



Closing remarks

- The LHC has a lifetime of 30+ years, and it is finishing its Run 3 in summer 2026
 - only about $O(1/10)$ of its ultimate dataset
 - Physics topics evolve over this life cycle (SUSY and other direct searches earlier in the program; precision measurement and rare processes more feasible later in the cycle)
 - detectors also improve over time, opening up new capabilities, especially at the start of the HL-LHC. New searches will be performed, thanks to extended η coverage and improved readout and trigger
- Analysis methods and new ideas matter
 - Good examples: measurement of four top production, Higgs total width measurement
 - Artificial intelligence and machine learning enables significant improvement, e.g., it was never expected that the LHC would have over 5σ sensitivity for Higgs pair production.
- LHC will play a critical role elucidating the nature of any discovery that might be made by other upcoming high energy physics experiments in dark matter direct detection, flavor physics, neutrino physics, etc.
 - most likely a discovery in a non-collider experiment would suggest signals observable at the LHC and/or future collider