Prospects for Single- and Di-Higgs Measurements at the HL-LHC with the ATLAS Experiment

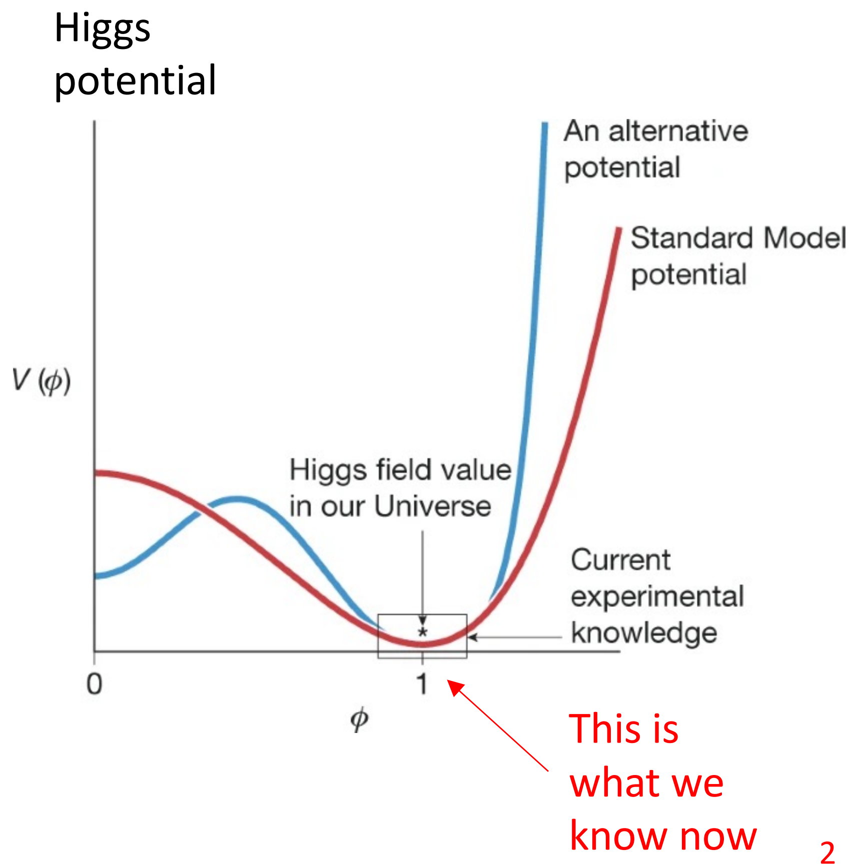
Song-Ming Wang
Academia Sinica

On behalf of the ATLAS Collaboration

Higgs Physics

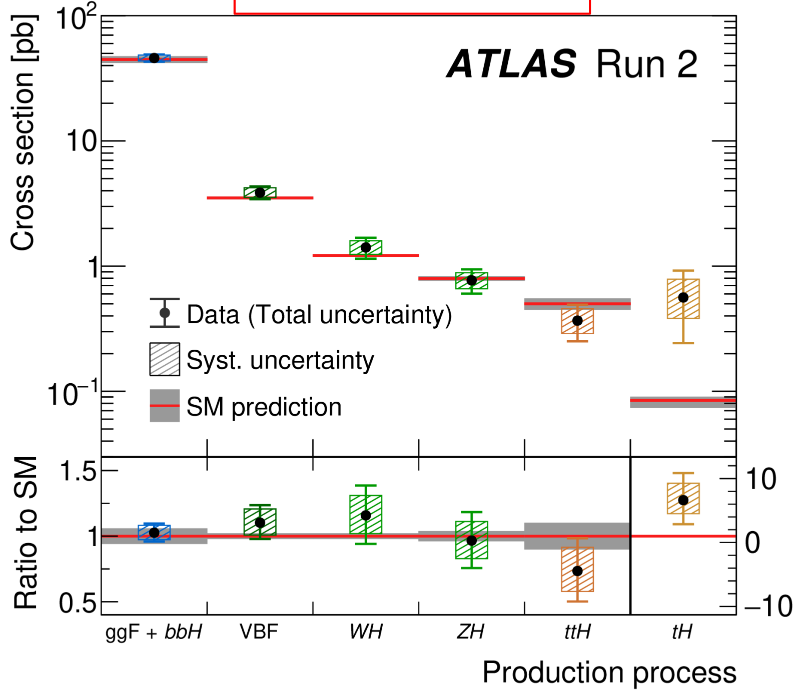
- In Standard Model (SM) all Higgs properties are defined once its mass is known
- Still many open questions in SM
- Alternate theories predict different properties of the Higgs boson, and/or existence of more Higgs bosons
- Higgs self-coupling (λ_{HHH}) determines the shape of the Higgs potential , and links to the naturalness/hierarchy problem

- After Higgs boson was discovered 12 years ago, vast program was launched to measure its properties with ATLAS Run 1 + Run 2 data
- However larger data sample is needed for
  - Precision measurements to check compatibility with SM predictions
    - To observe any deviation from the SM expectation that hints new physics
  - Precise measurement of the Higgs potential which determines the dynamics of the Higgs field



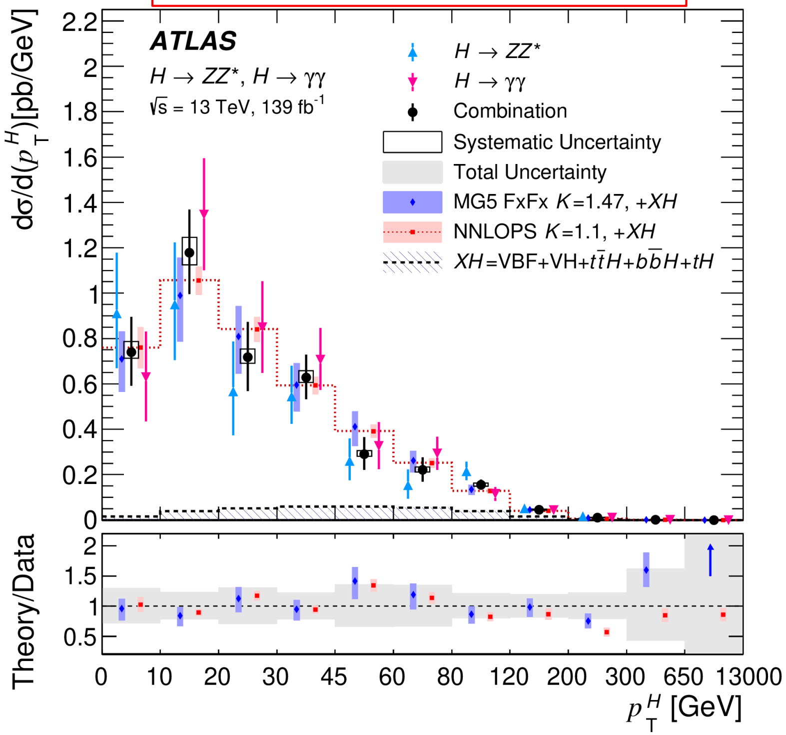
Where Do We Stand Now : Single-Higgs

productions



- Observed main production channels (ggF, VBF, VH, ttH), and couplings to gauge bosons ($\gamma\gamma$,WW,ZZ) and 3rd gen. fermions (τ, b, t)
- Productions, decays and couplings are measured at O(10%) precision in best channels
- Probing couplings to 2nd gen. ferimons and rare decay
  - H→ $\mu\mu$ (@ 2σ) , H→ $Z\gamma$ (@ 2.2σ)
  - $\sigma(VH(\rightarrow cc))$: < 11.3 × SM observed (95%CL) **NEW!**
    - see Francesco Armando Di Bello's talk

differential cross section



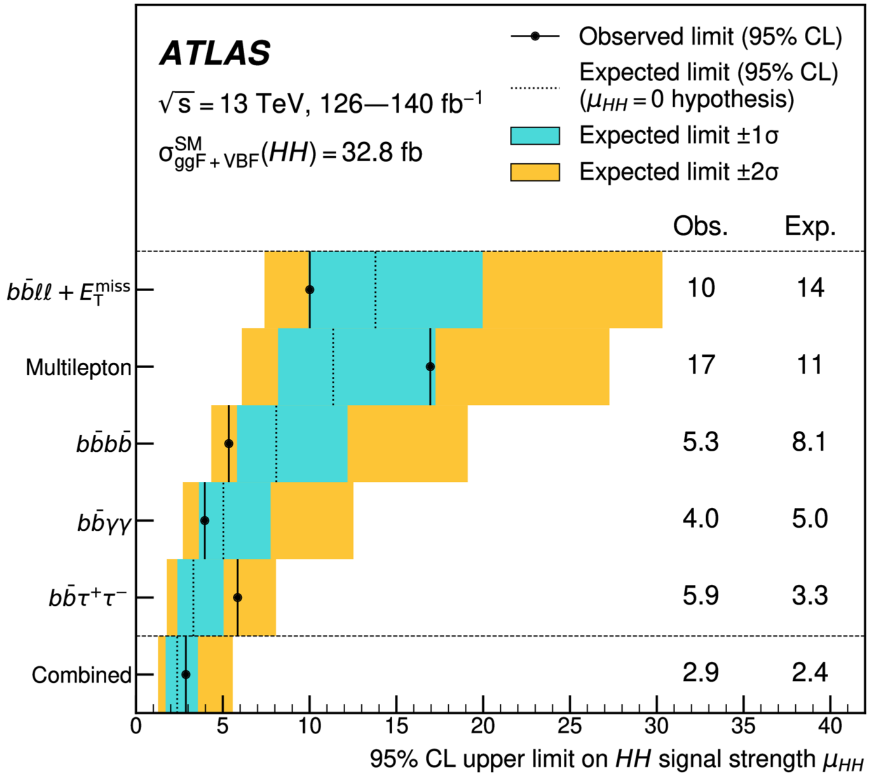
- Probe kinematic features of Higgs boson
  - E.g. pT(H), $|y_H|$, Njet, pT(lead jet)
  - pT(H) precision:
    - ~20-30% @<300 GeV
    - ~60% @ 300-650 GeV

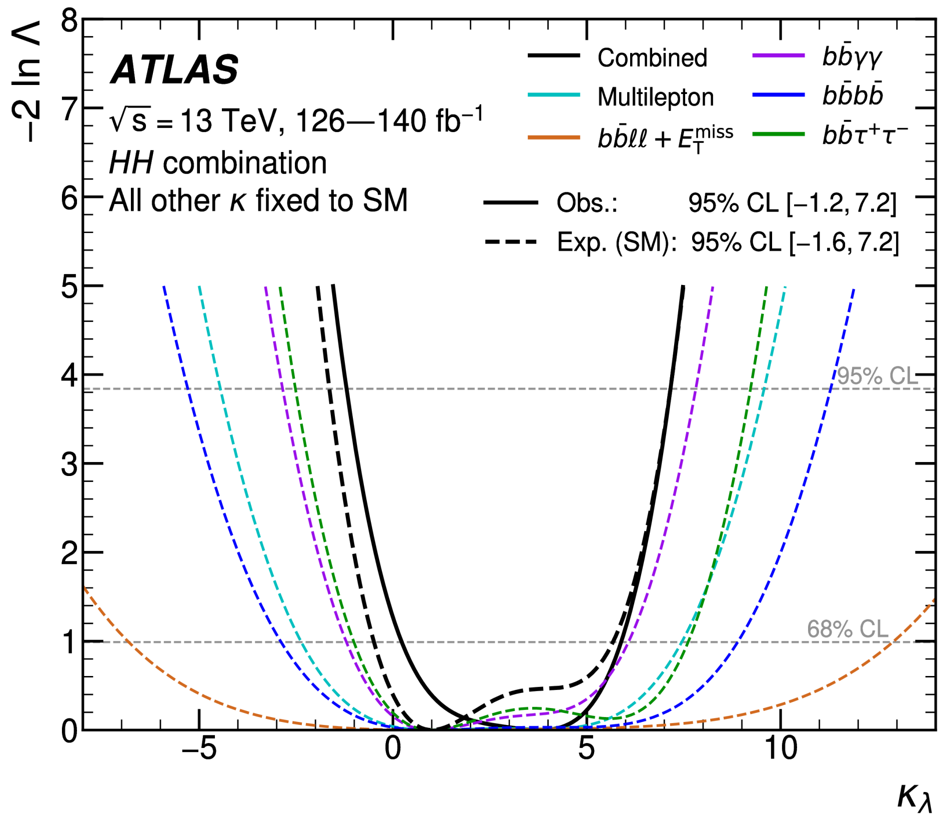
Nature 607, 52-59 (2022) | JHEP 05 (2023) 028

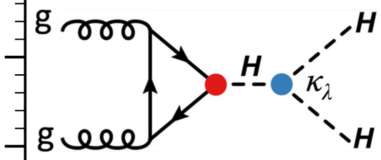
Where Do We Stand Now : Di-Higgs

arXiv:2406.09971

- Recent combined results from several searches with full Run 2 data







$$\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda^{SM}_{HHH}}$$

- Limits on HH production rate at 95% CL
  - Obs (exp) = 2.9 (2.4) × SM
- Significance : Obs (exp) = 0.4 (1.0) σ

- Likelihood scan on κ_λ (self-coupling modifier)
- κ_λ constrained at 95% CL interval:
  - Obs (exp) = [-1.2, 7.2] ([-1.6, 7.2])

HL-LHC

ave. pileup $<\mu>$~20

$<\mu>$~35

$<\mu>$~60

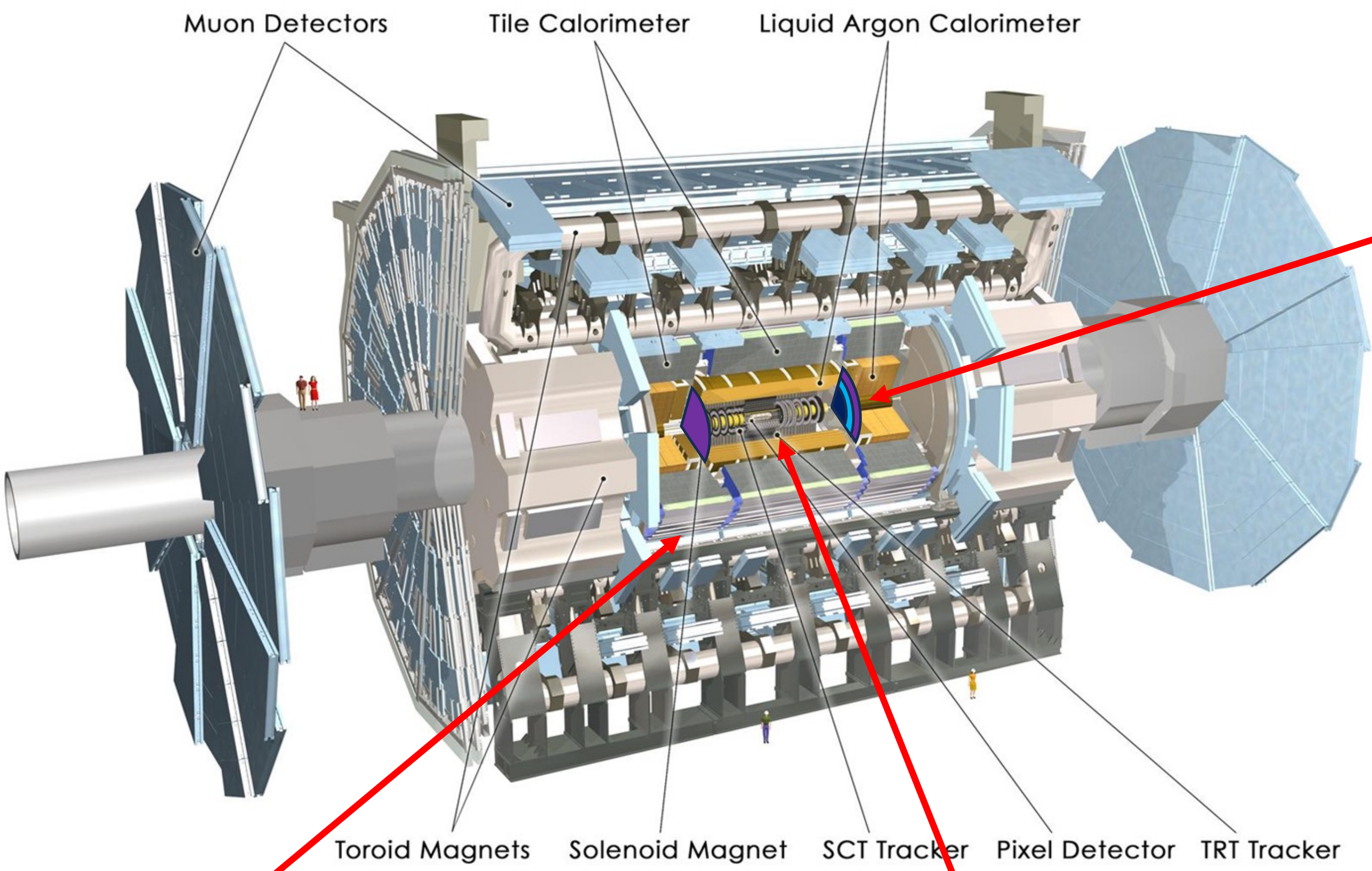
$<\mu>$~140-200

- Run 2: $\int L$~140 fb^{-1} , $\sqrt{s}$=13 TeV
- Run 3: expected $\int L$~250 fb^{-1}, $\sqrt{s}$=13.6 TeV

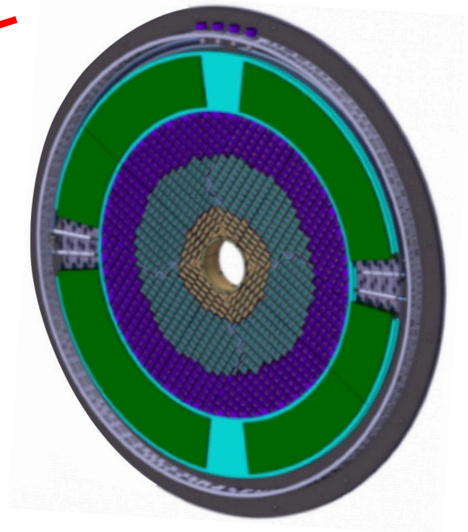
- HL-LHC:
  - $\sqrt{s}$=13.6-14 TeV
  - $L \sim 5\text{-}7\times10^{34} cm^{-2}s^{-1}$
  - $\int L$~3000 fb^{-1}
  - Ave. #of interactions per crossing ~140-200

- High lumi and pileup pose challenging conditions to the experiment
  - Larger beam background and detector irradiation, higher trigger rates, higher particle density in detector
- Require improvements in many areas of the experiment:
  - Detector, trigger and readout electronics, software and computing, analysis techniques

ATLAS Upgrade for HL-LHC



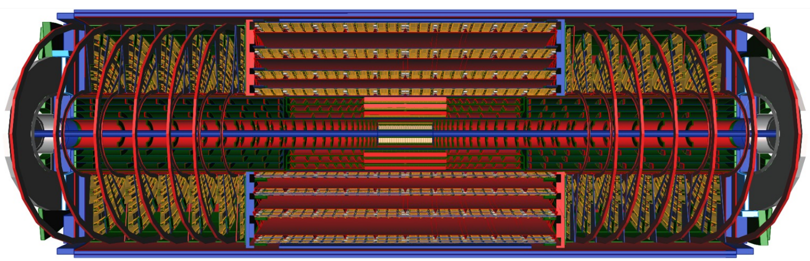
High Granularity Timing Detector (HGTD)
Forward region (2.4<|η|<4.0)
Low-Gain Avalanche Detectors (LGAD) with 30 ps track resolution



Upgraded Trigger and Data Acquisition system
Level-0 Trigger at 1 MHz
Improved High-Level Trigger (150 kHz full scan tracking)

New Muon Chambers
Inner barrel region with new RPC and sMDT detectors

New Inner Tracking Detector (ITK)
All silicon, up to |η|=4

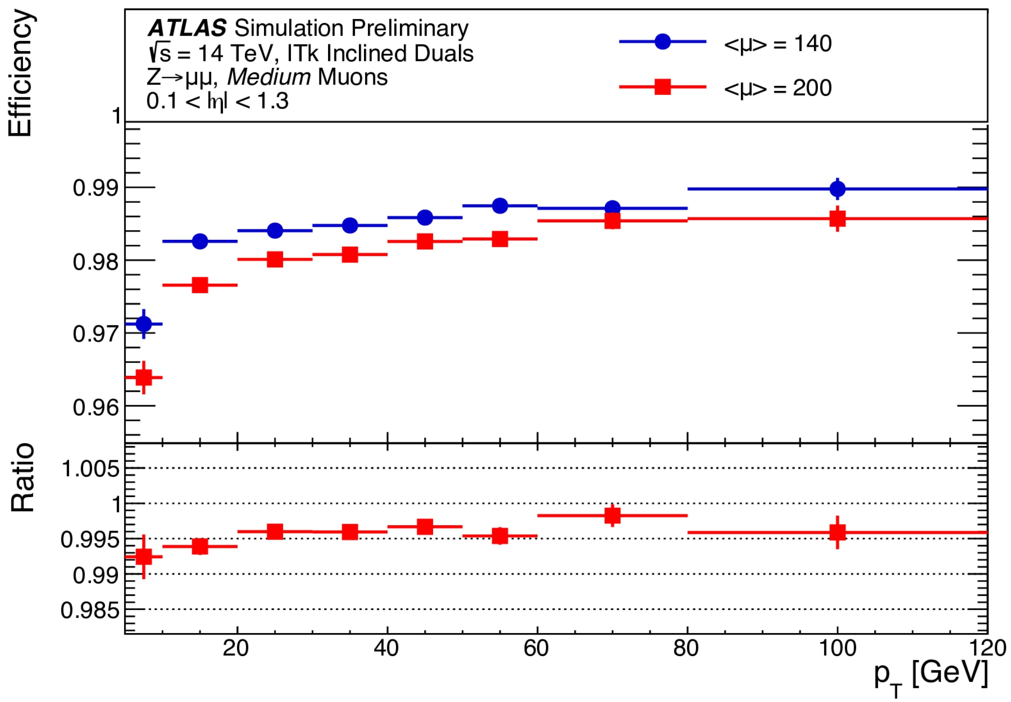


Electronics Upgrades
LAr Calorimeter,
Tile Calorimeter, Muon System

Additional small upgrades
Luminosity detectors (1% precision goal)
HL-ZDC

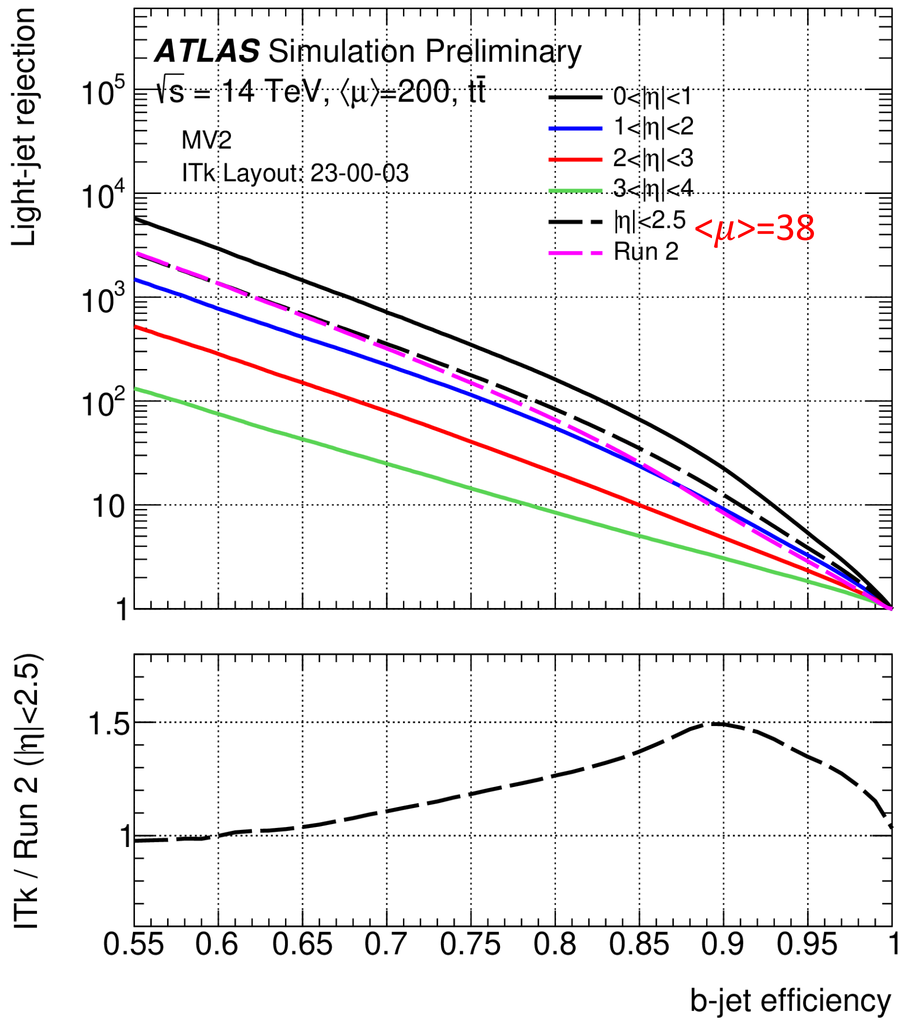
Detector Expected Performance

ATL-PHYS-PUB-2021-023



- Good muon reconstruction and identification efficiency efficiency at high pileup
- Important for measuring Higgs boson kinematic features and properties

ATL-PHYS-PUB-2021-024



- b-jet identification performance at $<\mu>=200$ is similar (or better) compare to Run2 at $<\mu>=38$
- Plays crucial role in HH search, where most sensitive channels have at least a bb pair

Physics Projection to HL-LHC

- Assume center of mass energy at 14 TeV and total integrated luminosity is 3000 fb^{-1}
- **Methods for projection:**
  - **Detailed simulations** are used to access performance of upgraded detector and HL-LHC condition
  - **Extrapolate** existing results or **parametric simulations** to allow full re-optimization of the analyses
- **Systematic uncertainties scenarios :**

- **Run 2 ("S1") :**
  - Use Run2 uncertainties, assuming the higher pile-up effects will be compensated by detector upgrades
- **Theoretical uncertainties halved :**
  - Use Run 2 uncertainties, but reduce theoretical uncertainties by half
- **No systematic uncertainties :**
  - Only consider statistical uncertainty

- **Baseline ("S2") :**
  - Theory uncertainties ½ of Run 2
  - No simulation statistical uncertainty
  - luminosity uncertainty ~1%
  - Statistical uncertainty reduced by $1/\sqrt{L}$
  - Uncertainties due to detector limitations remain unchanged or revised according to simulation studies of upgraded detector.

*** Baseline scenario is used in presented projected results, unless specified otherwise

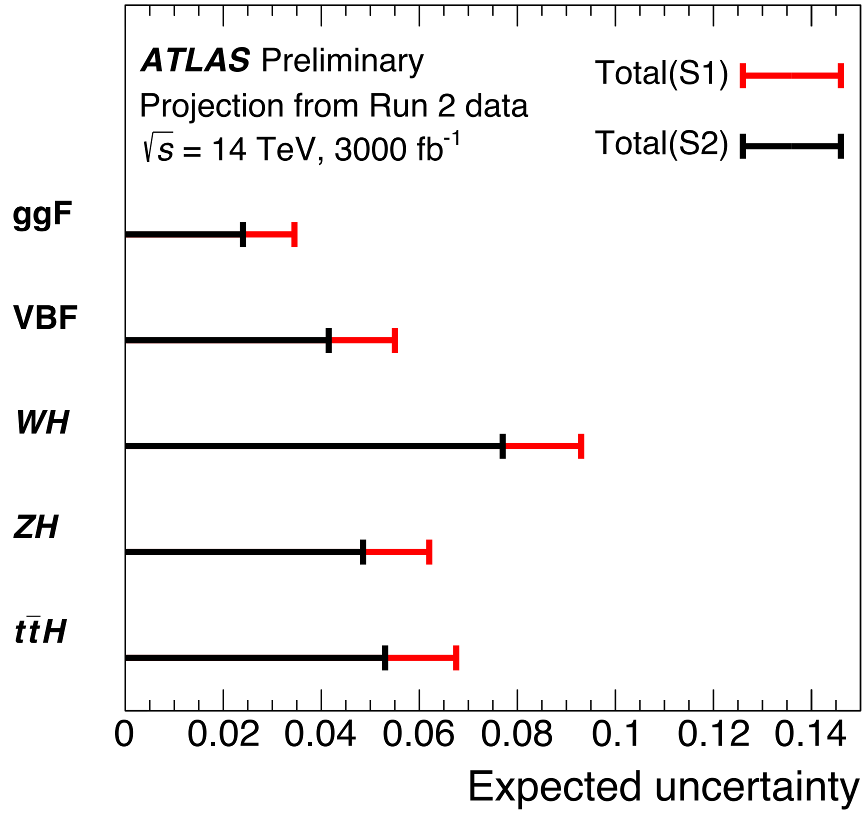
ATL-PHYS-PUB-2022-053

HL-LHC Projection : Single-Higgs

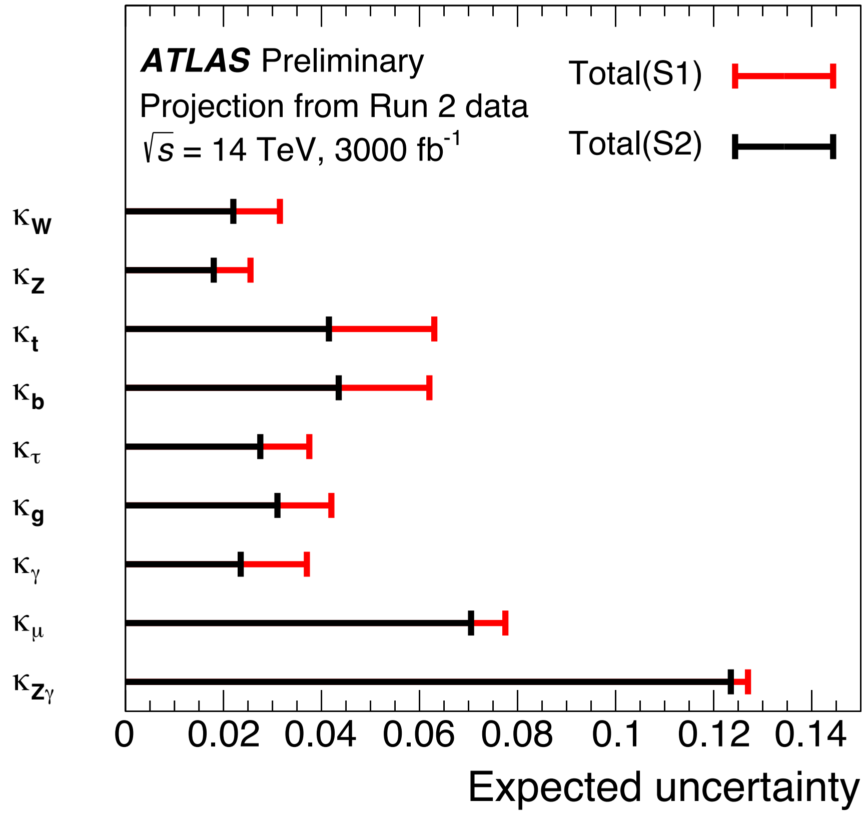
Projections for Production and Couplings Measurements

- Combined all major production/decay mode measurements

productions



couplings



- ggF can be measured at ~2%
- WH can be measured at ~8%

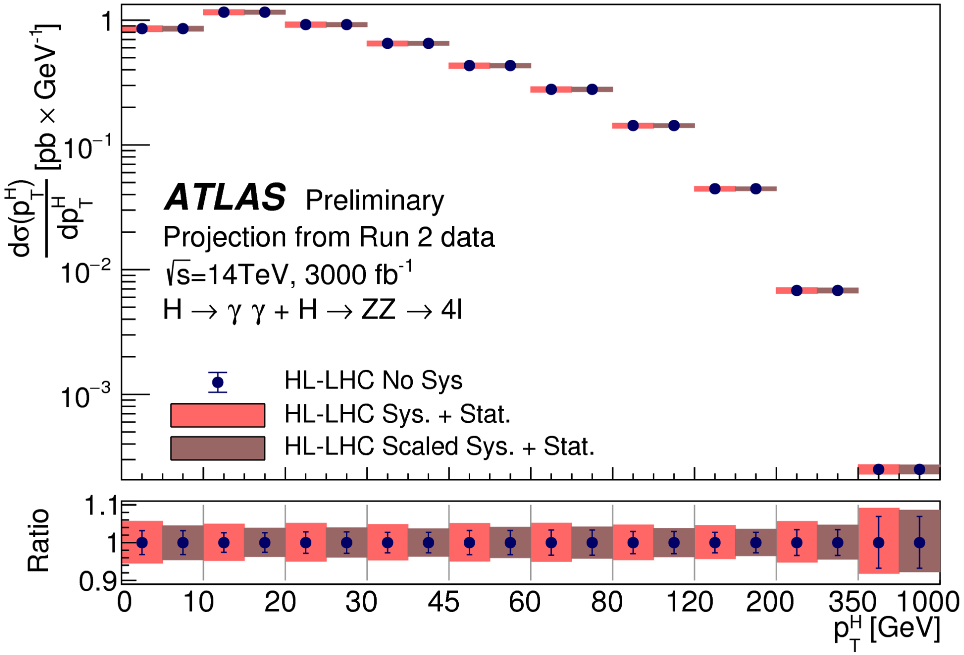
- Reaching few % precision
- μ and $Z\gamma$ reaching ~10% precision, dominated by statistical uncertainties

ATL-PHYS-PUB-2018-054

- Most measurements' uncertainties are dominated by systematics

Projections for Differential and Mass Measurements

differential cross section



- pT(H):
  - Expect to probe with precision of
    - ~5% at pT(H) < 350 GeV
    - ~10% at pT(H) ~350-1000 GeV
  - Low pT: sensitive to couplings to c, b quarks
  - High pT: sensitive to new heavy particles in ggF loop

ATL-PHYS-PUB-2018-040 | CERN-2019-007

ATL-PHYS-PUB-2018-054

Higgs Mass

- At LHC, most precise H mass measurement is via
  - $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow 4l$ decays
- Current PDG average (ATLAS+CMS):
  - $m_H = 125.20 \pm 0.11$ GeV
- ATLAS most recent measurement (Run 1+2):
  - $m_H = 125.11 \pm 0.09 \pm (stat) \pm 0.06\ (syst)$
    $= 125.11 \pm 0.11$ GeV
- Extrapolated ATLAS Run 2 (36 fb^{-1}) 4μ results to 3000 fb^{-1}
  - Total uncertainty vary from 52 to 33 MeV

Expected Higgs mass precision with 3 ab^{-1} (ATLAS)

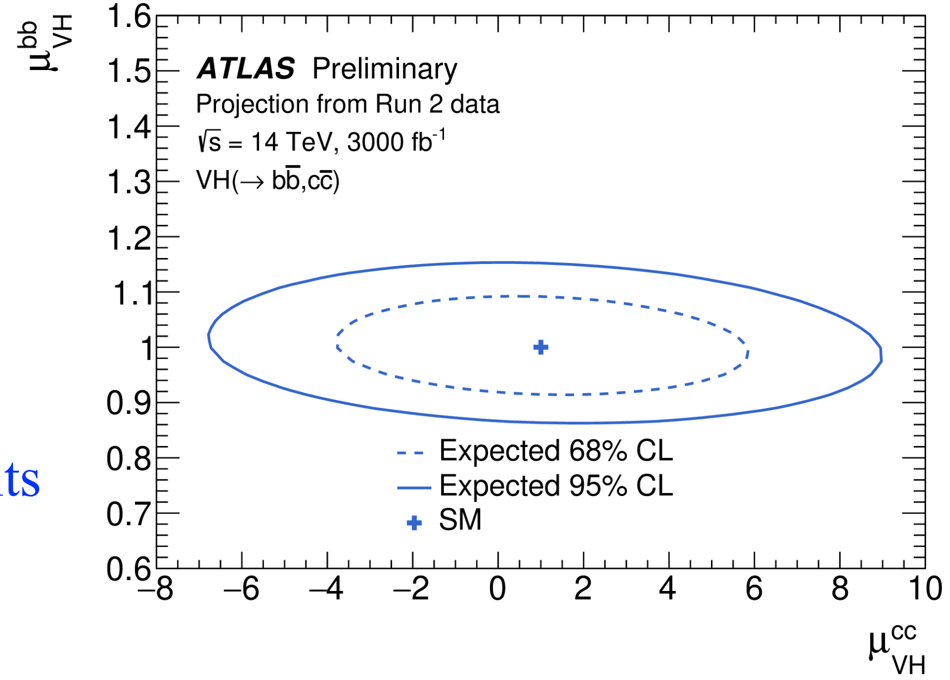
	Δ_{tot} (MeV)	Δ_{stat} (MeV)	Δ_{syst} (MeV)
Current Detector (Run 2, S1 scenario)	52	39	35
μ momentum resolution improvement by 30% or similar	47	30	37
μ momentum resolution/scale improvement of 30% / 50%	38	30	24
μ momentum resolution/scale improvement 30% / 80%	33	30	14

- Expect better resolution from CMS (stronger mag. field)
  - ➔ expect uncertainty < 20 MeV when CMS+ATLAS

Projections for Higgs coupling to Charm, Bottom

ATL-PHYS-PUB-2021-039

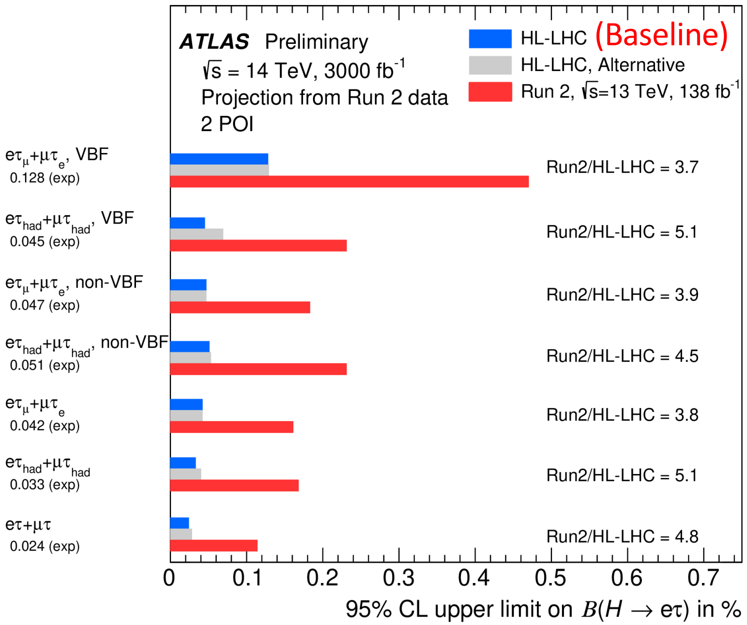
- H(→cc) , H(→bb) couplings are probed via VH production
- Projection with an earlier full Run-2 results
- Expected best fit signal strengths:
  - $\mu_{VH}^{bb} = 1.00 \pm 0.06$
  - $\mu_{VH}^{cc} = 1.00 \pm 3.20$
- Expected constraint of $|\kappa_c/\kappa_b|$
  - $|\kappa_c/\kappa_b| < 2.7$ at 95% CL
- Projection for VH(→cc) will be significantly improved when extrapolated from latest Run 2 results
  - e.g. improved flavor tagging, use MVA

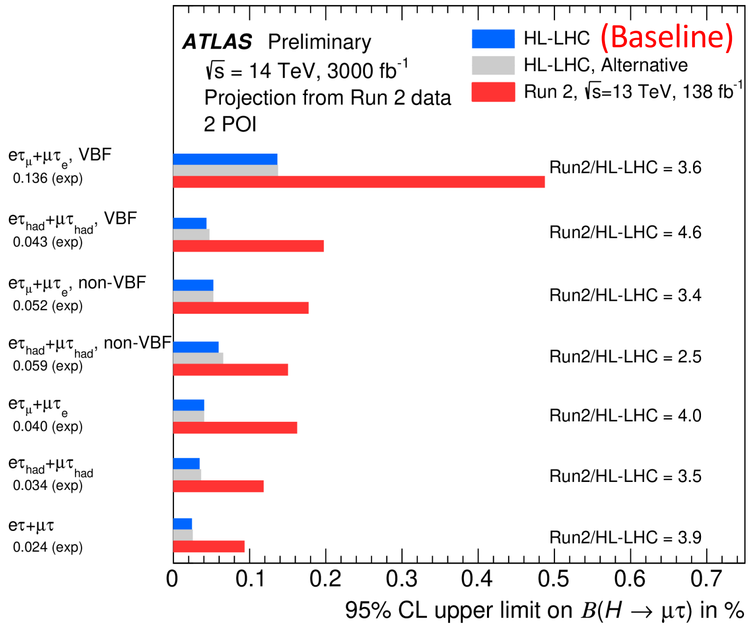


- Higgs to charm coupling will still be difficult at HL-LHC
  - Will require improvement in the analysis method, better c-jet tagging, advance multivariate techniques

Projection for LFV of Higgs Decay

- Lepton Flavor Violation (LFV) Higgs decay is predicted in several BSM models (e.g. extended Higgs sector, composite Higgs, warped extra dimensions)
- Recent ATLAS direct search (Run2, 139 fb^{-1}) set 95% CL limits:
  - $BR(H \to e\tau) = 0.2\%$ (expt. 0.12%), $BR(H \to \mu\tau) = 0.18\%$ (expt. 0.09%)
- Extrapolated this Run2 result to project search sensitivity at HL-LHC





Alternative: simulation statistical uncertainty scaled by $1/\sqrt{L}$

- Projected expected limit on BR at 95% CL:
  - $BR(H \to e\tau) = 0.024^{+0.010}_{-0.007}\ \%$
  - $BR(H \to \mu\tau) = 0.024^{+0.010}_{-0.007}\ \%$
- A factor of ~3-5 improvement over Run2 results

JHEP 07 (2023) 166	ATL-PHYS-PUB-2022-054

HL-LHC Projection : Di-Higgs

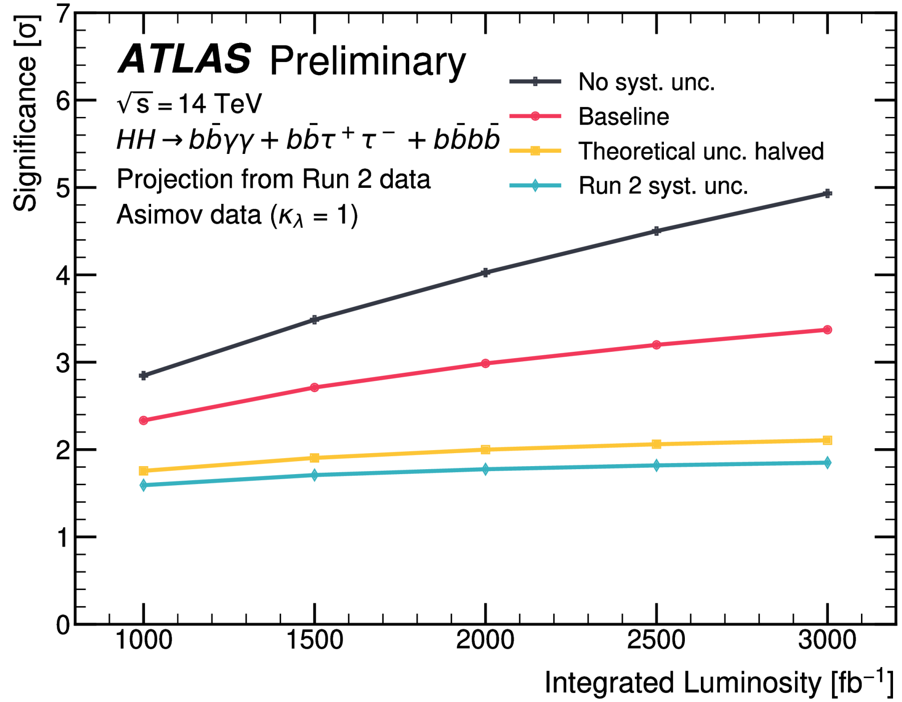
Projection for $HH \rightarrow bb\gamma\gamma, bb\tau\tau, bbbb$

Most sensitive decay modes :

- HH→bbbb : highest BR, large BG from multi-jets
- HH→bbγγ : clean, but small BR
- HH→bbττ : moderate BG and BR

- Extrapolated the full Run 2 results of the three most sensitive channels to project reach at HL-LHC

- **HH discovery significance:**
  - New individual and combined projection significantly improved over previous projection
  - New ATLAS combined projection (stat. only) : 4.9 σ
  - Previous ATLAS+CMS combined projection (stat. only) : 4.5 σ
  - Large improvement achieved over last few years
    - update to object recon. and identification, analysis methods



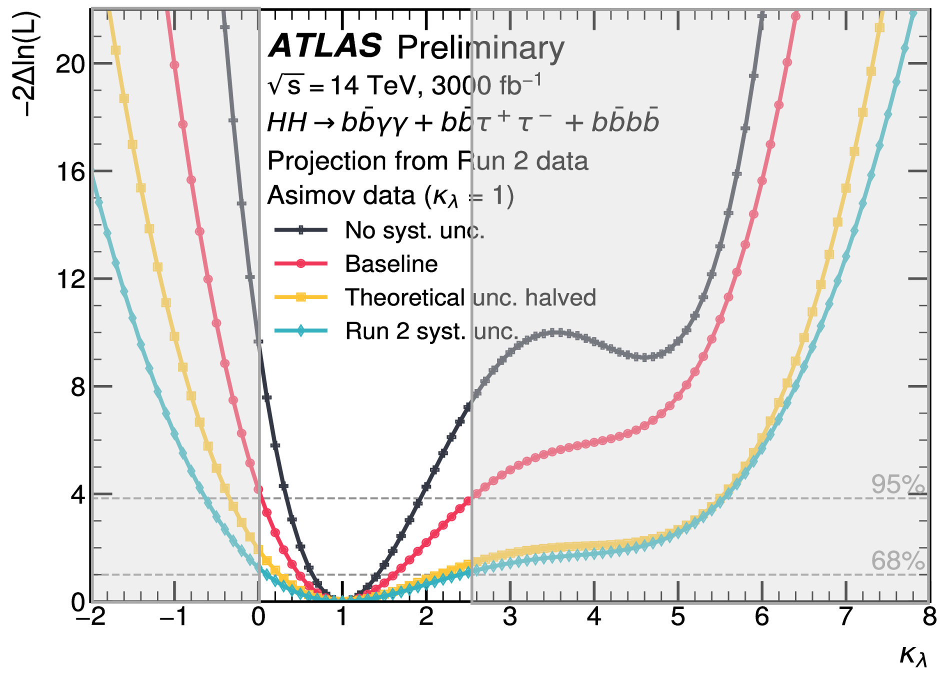
Uncertainty scenario	Significance [σ] $b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	$b\bar{b}b\bar{b}$	Combination	Combined signal strength precision [%]
No syst. unc.	2.3 (2.1)	4.0 (2.5)	1.8 (1.4)	4.9 (3.5)	−21/+22
Baseline	2.2 (2.0)	2.8 (2.1)	0.99 (0.61)	3.4 (3.0)	−30/+33
Theoretical unc. halved	1.1	1.7	0.65	2.1	−47/+48
Run 2 syst. unc.	1.1	1.5	0.65	1.9	−53/+65

- Numbers in red are from previous projection

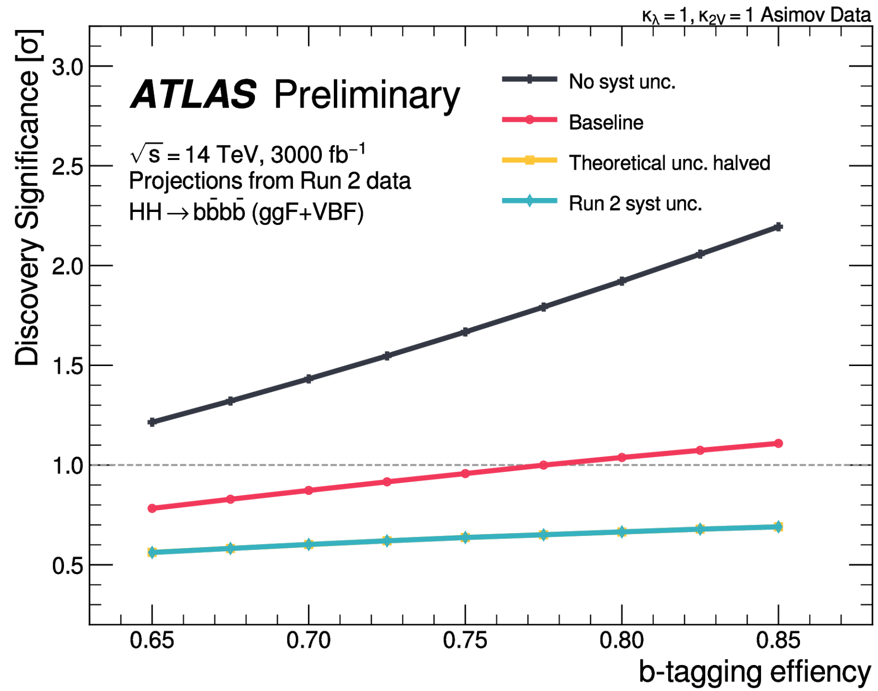
CERN-2019-007 | ATL-PHYS-PUB-2022-053

Projection for $HH \rightarrow bb\gamma\gamma$, $bb\tau\tau$, $bbbb$

- Higgs self-coupling modifier (κ_λ) :
  - Constraint within (Baseline scenario) :
    - [0.5, 1.6] at 68% CL
    - [0.0, 2.5] at 95% CL



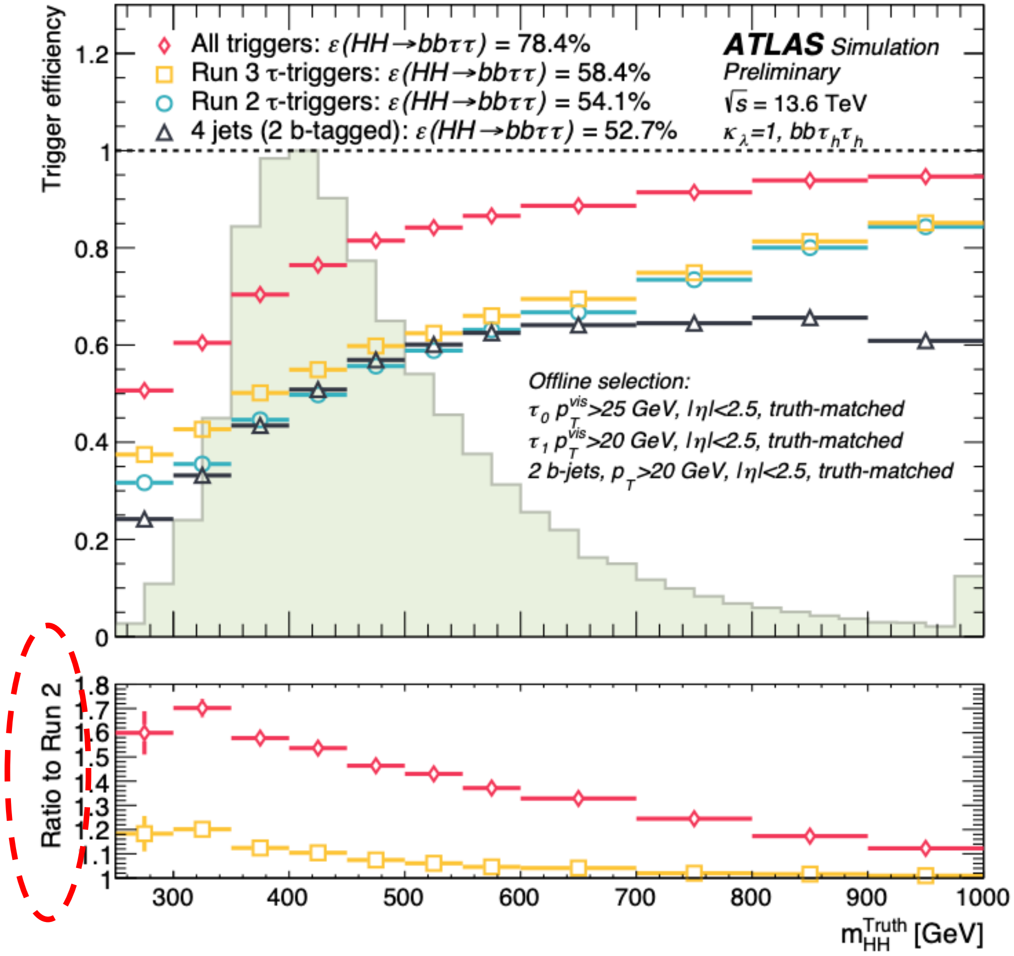
- At HL-LHC, systematic uncertainty become limiting factor
- Sensitivity driven by:
  - Theoretical uncertainties:
    - HH production
    - Single H production w/ b-jets
  - Background modeling
  - Object reconstruction and identification performance (e.g. b-tagging, tau ID)



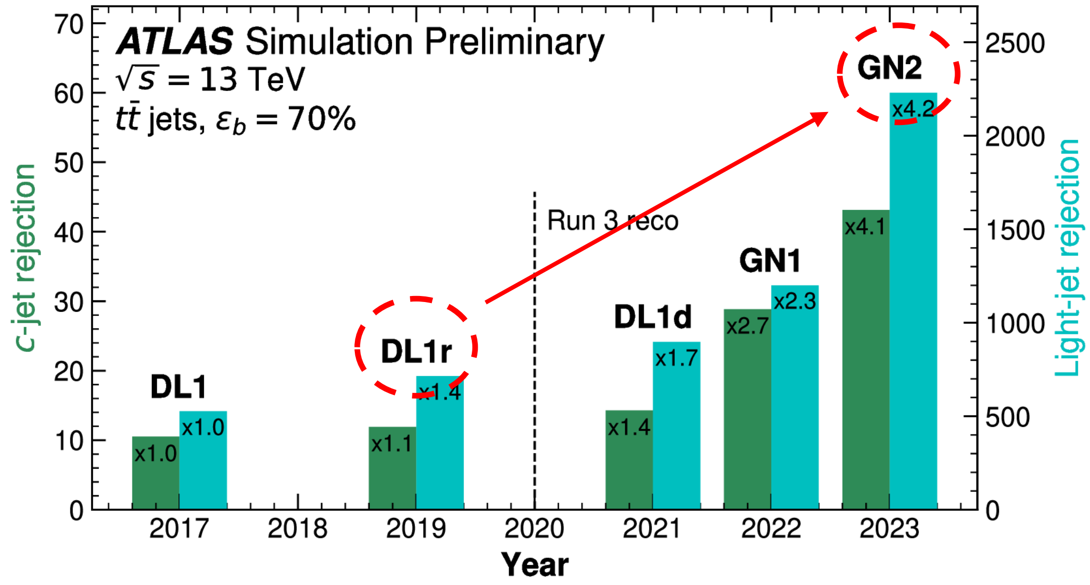
ATL-PHYS-PUB-2022-053

What's Coming for Run 3

(triggers for $bb\tau\tau$) (ATLASTauTriggerPublicResults)



(FTAG-2023-01) (b-tagging algorithm)



- Benefit from increase signal acceptance with new triggers, improved object ID, and more refined analyses,…

Summary

- HL-LHC will bring many times more data than we have now
- Provide great opportunity for Higgs precision measurements
  - Higgs productions and decays can be measured to a few percent precision
  - May reach 3 σ evidence for HH search by ATLAS
    - 5 σ discovery is within reach if we continue to improve the analysis and detector performance, and combine both CMS and ATLAS results.
- However HL-LHC will present many challenges that require many improvements and novel ideas for a successful program

ATLAS Talks on Higgs and HL-LHC Upgrades at ICHEP-2024

- Measurement of the ttH->bb process with the ATLAS experiment : Zefran Rozario
- Measurements of Higgs boson production with top quarks with the ATLAS detector : Filip Nechansky
- Measurements of the Higgs boson mass and width with the ATLAS detector : Rafael Coelho Lopes De Sa
- Measurements of Higgs boson coupling properties to tau leptons with the ATLAS detector : Christopher Young
- Measurements of the CP structure of Higgs-boson couplings with the ATLAS detector : Matthew Joseph Basso
- Measurements of Higgs boson cross-sections and their interpretation with the ATLAS experiment : Xiao Yang
- Measurements of Higgs boson coupling properties to bottom quarks and charm quarks with the ATLAS detector : Francesco Armando Di Bello
- Probing the nature of electroweak symmetry breaking with Higgs boson pairs in ATLAS : Dilia Maria Portillo Quintero
- Search for rare processes and lepton-flavor-violating decays of Higgs boson at the ATLAS experiment : Bing Zhou
- Search for HH or X->SH production in final states with one or two light leptons and a pair of tau-leptons with the ATLAS detector : Babar Ali
- Searches for singly- and doubly-charged Higgs bosons in ATLAS : Yasuyuki Horii
- Searches for resonances decaying to pairs of Higgs bosons in ATLAS : Andrea Coccaro
- Searches for axion-like-particles (ALPs) in Higgs boson decays in ATLAS : Paula Martinez Suarez

- ATLAS upgrades for High Luminosity LHC : Joleen Renee Pater
- LUCID-3: the upgrade of the ATLAS Luminosity detector for High Luminosity LHC : Jack Lindon
- Towards an ATLAS luminosity measurement at HL-LHC : Christian Ohm
- Integration test of a new inner-station TGC system for the ATLAS experiment at HL-LHC : Arisa Wada
- Expected performance of the ATLAS ITk detector for HL-LHC : Helen Hayward
- The High-Granularity Timing Detector for ATLAS at HL-LHC : Alexander Leopold