Higgs Hunting 2024:

New analysis methods and physics prospects for ATLAS + HL-LHC

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25/09/2024

Why do we need HL-LHC?

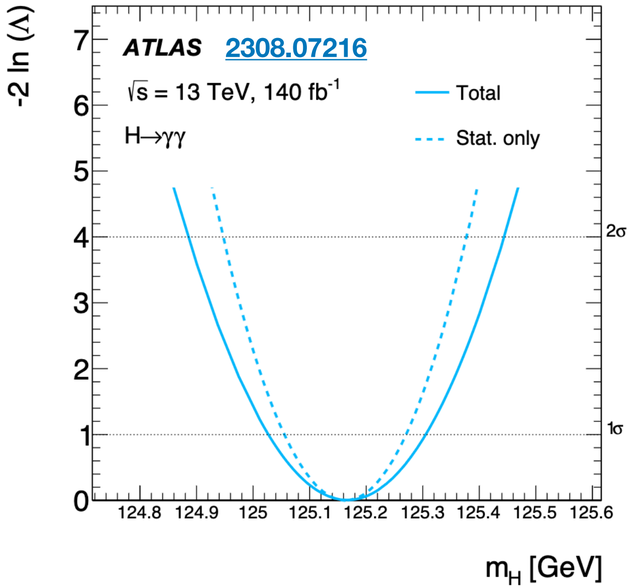
12 years on from discovery, the Higgs remains central to the SM. We've made great progress:

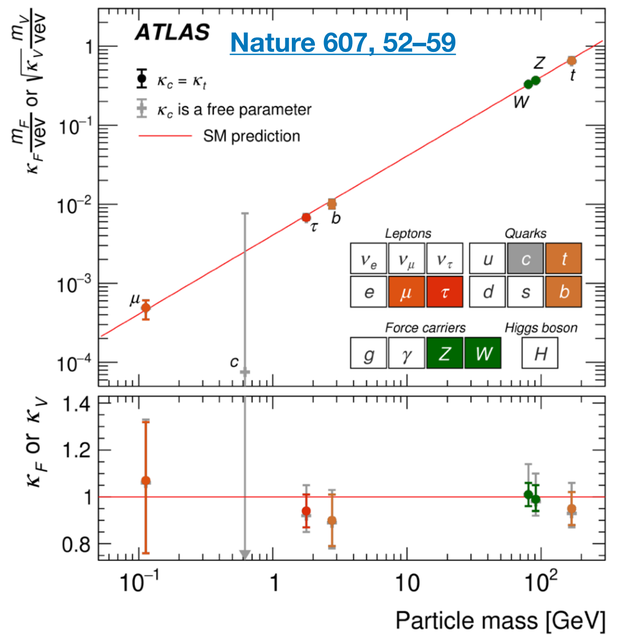
- **0.09% precision** on m_H (=125.11± 0.11 GeV) [Phys. Rev. Lett. 131, 251802] [Valerie's talk]
- Couplings measured to **5% (bosons)** and **10% (third generation fermions)** precision [George's talk]
- Huge progress in searches for coupling to **2nd generation fermions** and for **di-Higgs** production [Zhijun's talk]

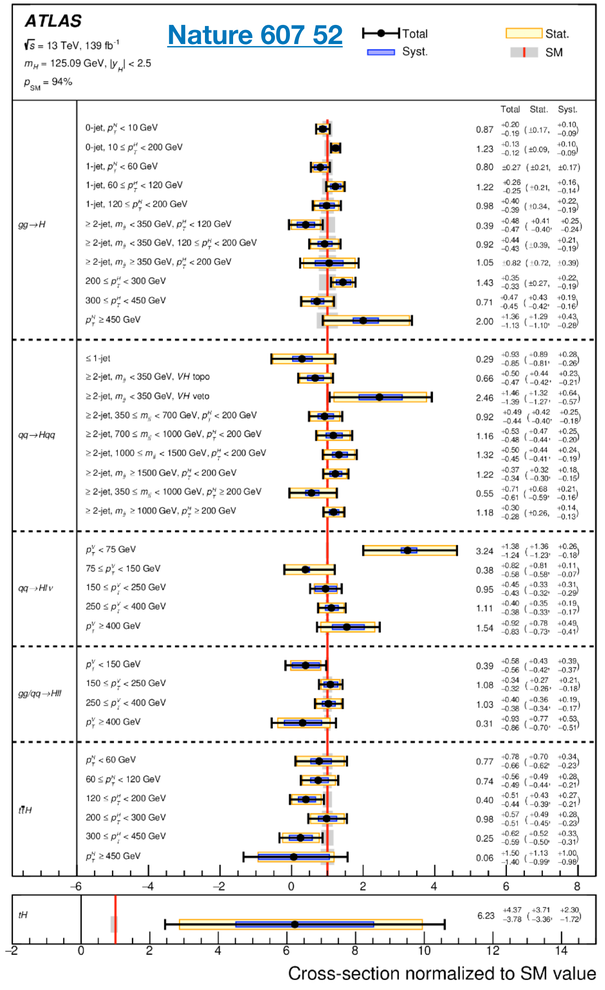
Many questions remain:

- What is the shape of the Higgs potential?
- What is dark matter?
- Origin of baryon asymmetry?

Answers require more data!







What can we expect?

Key reports:

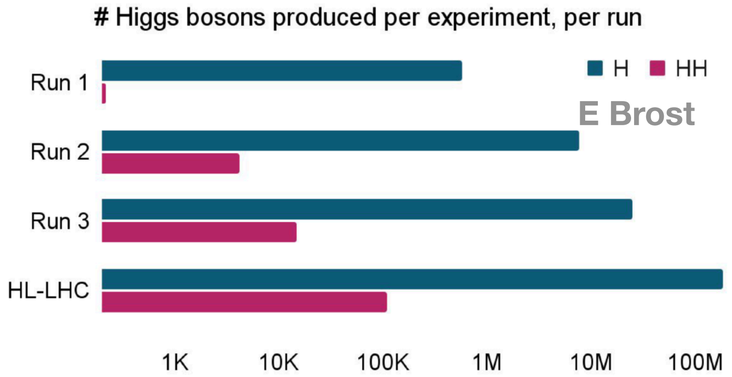
2019: CERN Yellow Report

2020: European strategy update

2022 Snowmass White Paper

How to simulate HL-LHC physics:

- Centre-of-mass energy: **13 TeV** → (13.6 TeV →) **14 TeV** ~18% increase in SM ggF HH(… more backgrounds too)
- Expected delivery of 3000 fb^{-1} (**10x** increase on Run 3)
- Uncertainties difficult to forecast — project different scenarios
- Data driven background improvements scale with $\sqrt{\mathscr{L}'/\mathscr{L}}$
- Assume negligible contribution MC stat — not guaranteed



What's missing?

- Projections are likely conservative
- New detectors — ITk & HGTD [talk from Khuram Tariq]
- Improved object reconstruction
- Improved analysis techniques

LS3: extended R&D phase

Goal: maintain or exceed current detector performance in the face of extremely challenging pileup μ=200!

Many projections made since snowmass

In several cases, analyses have already updated with **significant improvement** in physics sensitivity

Fantastic energy and development in the global Higgs community!

Single Higgs

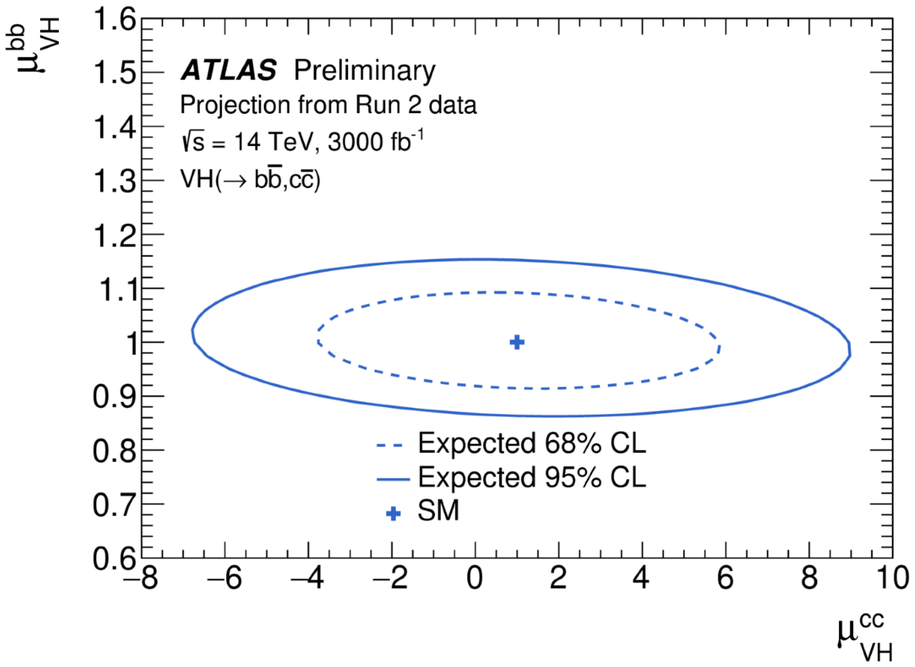
VH, H→bb/cc projections [ATL-PHYS-PUB-2021-039]

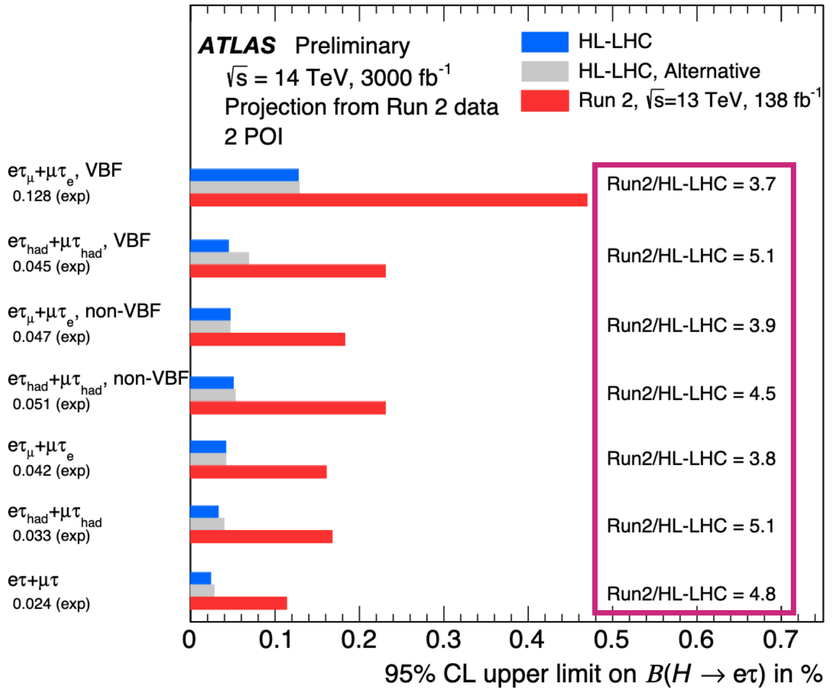
- **H→bb:** precision at HL-LHC
  - **10% precision** on μ_{VH}^{bb}
  - High precision differential measurements
- **H→cc**: the search continues at LH-LHC
  - Limit of μ_{VH}^{cc} **< 6.4** down from **< 26** vs Run 2 [2201.11428]
  - Reanalysis of Run 2 data already reduced limits to **< 11** [ATLAS-CONF-2024-010]

Motivation for new projections!

Search for lepton flavour violating H→$l\tau$ decays: [ATL-PHYS-PUB-2022-054] [Talk from Huacheng]

- **~4-5x reduction** on branching ratio limits (BR < 0.02%)
- Systematically limited at HL-LHC



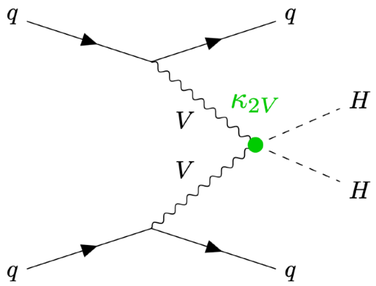


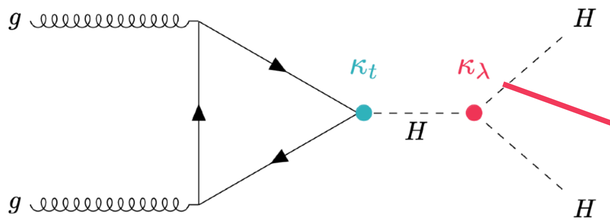
ATLAS Di-Higgs @ HL-LHC

See dedicated talks from ATLAS and CMS

HH Intro

A key motivation for the HL-LHC! Main production modes ggF and VBF probe κ_λ and κ_{2V}





Three main channels

- HH→bb$\tau\tau$, HH→bb$\gamma\gamma$, HH→bbbb (projections available)
- Several other rare / challenging decays to investigate (not covered)

Extrapolation scenarios (common with CMS)

pessimistic

- Run 2 systematics
- Theoretical unc. halved
- Baseline (syst scaled based on YR)

optimistic

- No systematics

BR	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

[Florian's talk]

HH→bbττ

Most sensitive channel for SM HH production at ATLAS

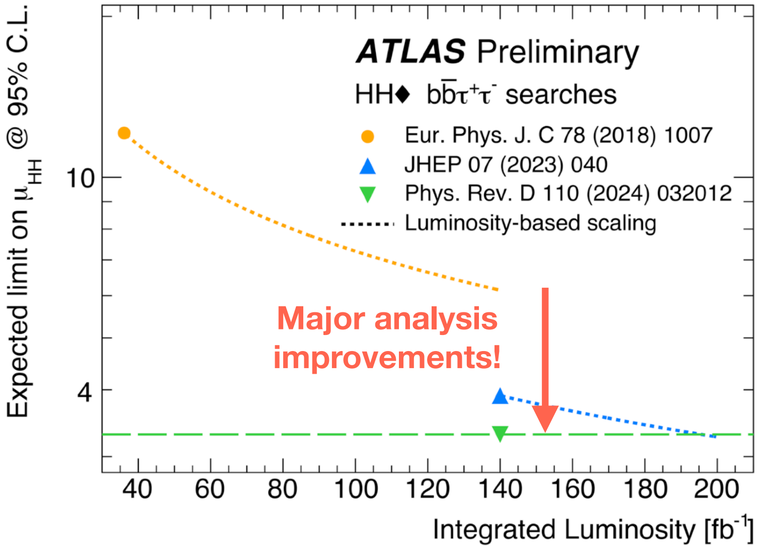
➢ Current limit $\mu_{HH} < 5.9$ → major improvements! [2404.12660]

New! HL-LHC projections with this analysis [ATL-PHYS-PUB-2024-016]

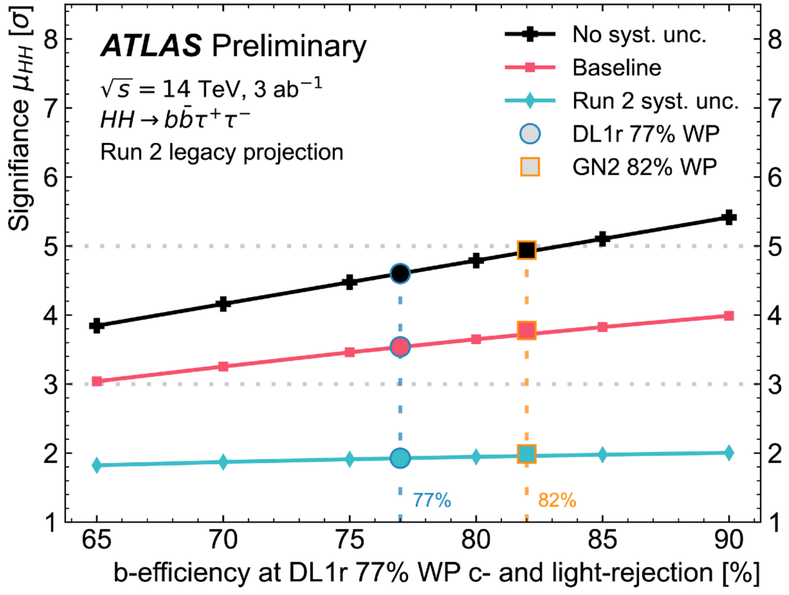
➢ Expect **3.5σ excess,** strong constraints on κ_λ and κ_{2V}

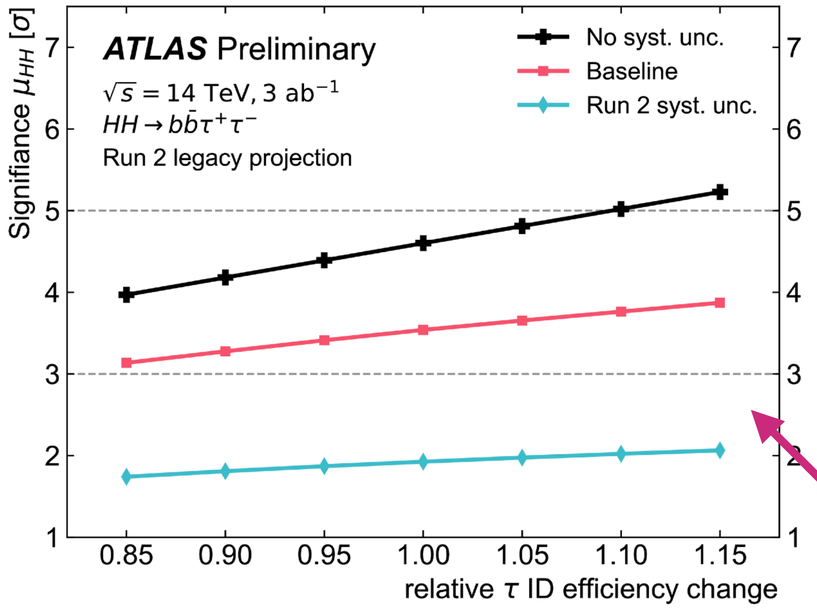
➢ Quantified impact from improved b- and τ-tagging

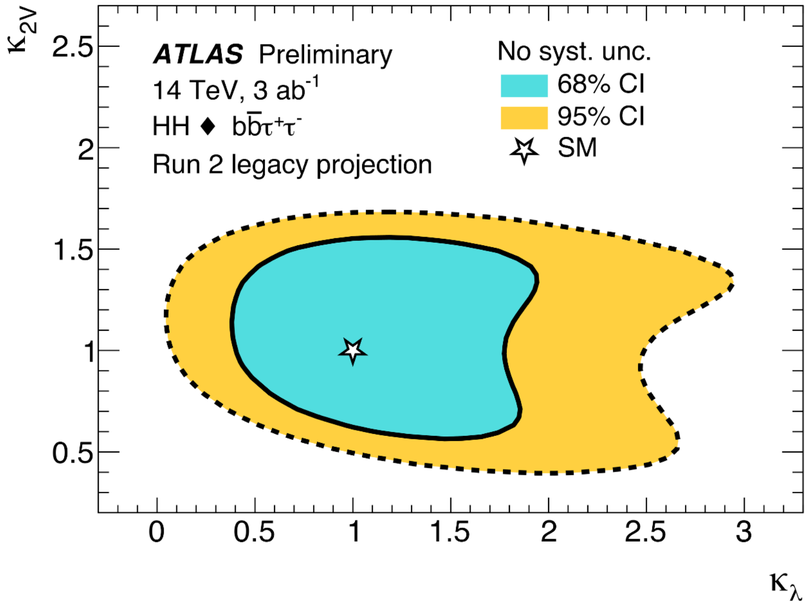
➢ **4.6σ → 4.9σ** achieved from a **5% increase in b-efficiency** (at fixed light-rejection) (for the no syst scenario)



Better sig than previous combined result







Room for tagging improvements!

HH→bb$\gamma\gamma$

Projection based on [2112.11876]

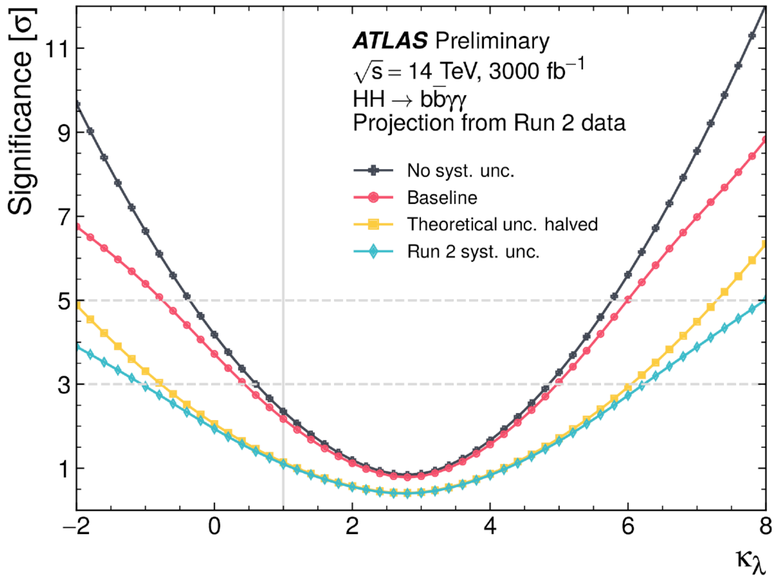
- Limits $\mu_{HH} < 4.2$, strongest constraint on κ_λ: [–1.5, 6.7]

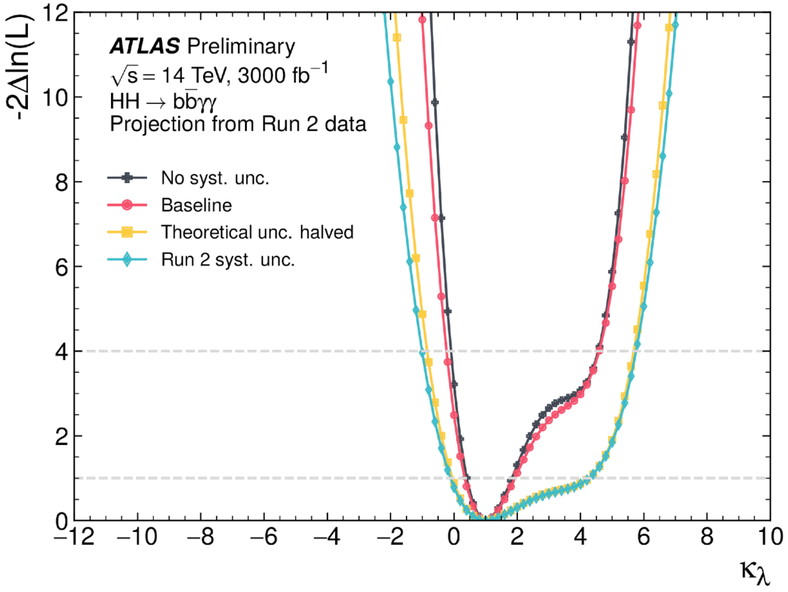
HL-LHC projections [ATL-PHYS-PUB-2022-001]

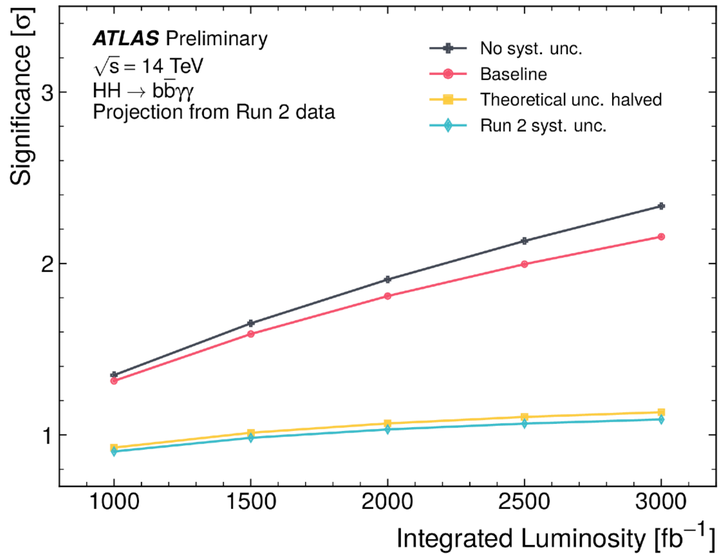
- Expect **2.2σ excess** assuming SM HH, κ_λ constrained to [0.3, 1.9]
- **Clear benefit** from luminosity (tagging) improvements!
- Main limitations:
  - Spurious signal systematic → solved with dedicated samples! [2310.12301]
  - Theoretical systematics

Needs work

Motivation for new projections!







Combined projections with previous bb$\tau\tau$ analysis [ATL-PHYS-PUB-2022-053]

HH→bbbb

Projection based on resolved ggF + VBF analysis [2301.03212]

➢ Limits $\mu_{HH} < 5.4$

HL-LHC projections [ATL-PHYS-PUB-2022-053]

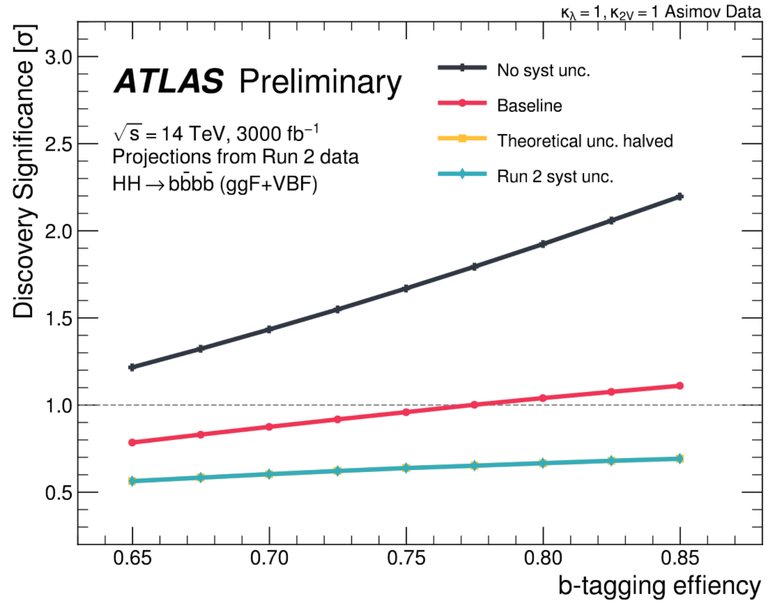
➢ Expected **1σ** excess assuming SM HH

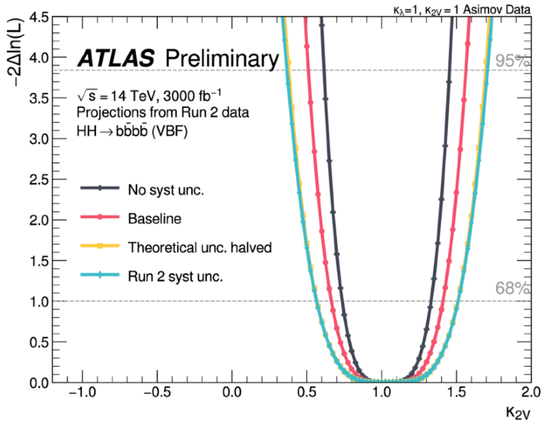
➢ Stat limited — **clear benefit** from tagging improvements!

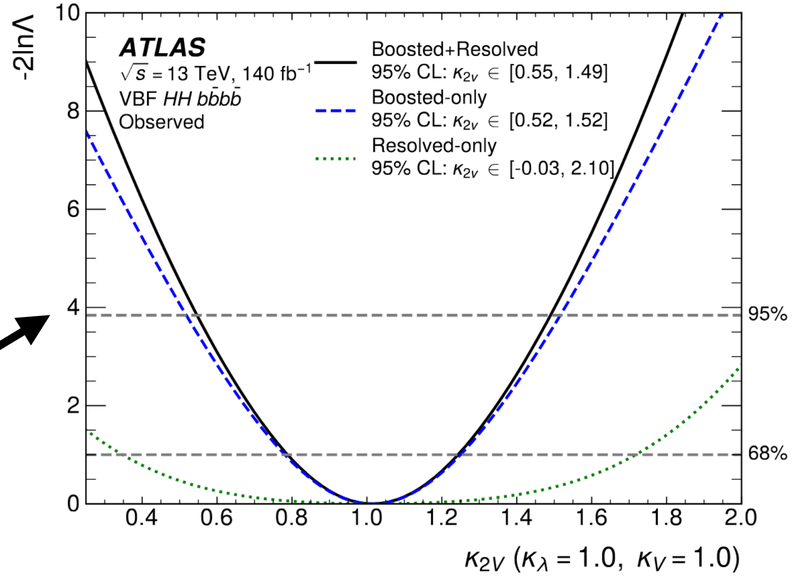
New boosted VBF analysis [2404.17193] [Zhijun's talk]

➢ Boosted topology highly sensitive to non-SM κ_{2V} → limits reduced by **2x**!

Motivation for new projections!





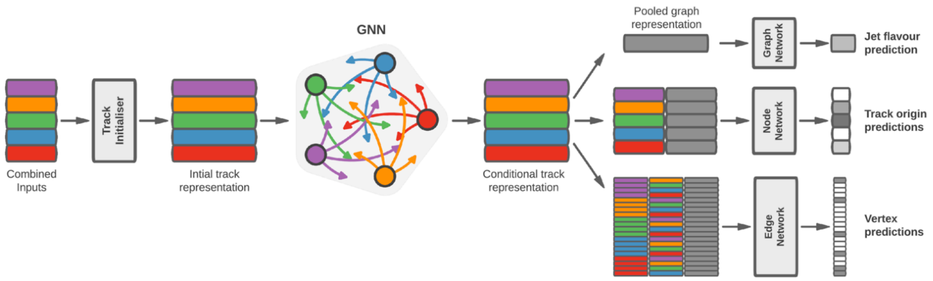


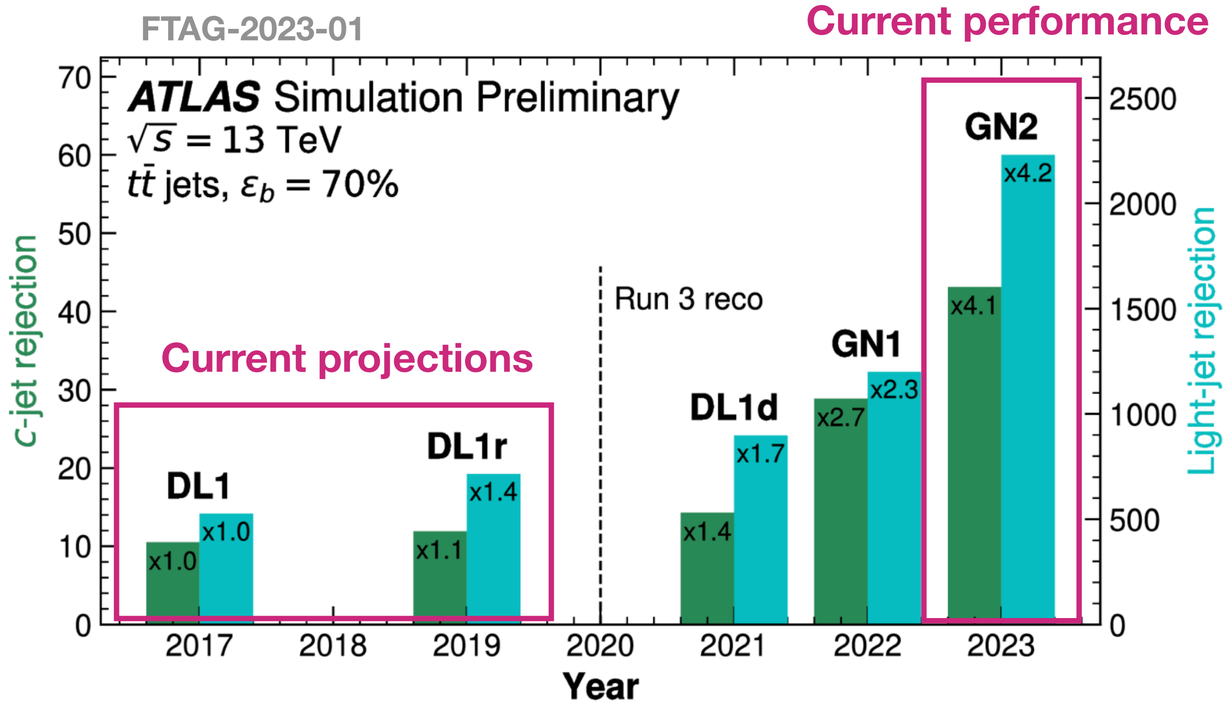
Reconstruction and analysis improvements

Improved tagging

Many signatures are still impacted by statistics at the HL-LHC.

Improved tagging can help.





Not at the ceiling yet!

- ➢ Exploit more detector information
- ➢ More architecture improvements
- ➢ New detectors for HL-LHC

Improved tagging

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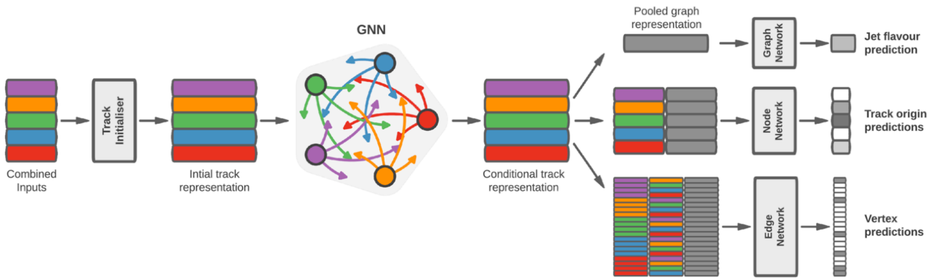
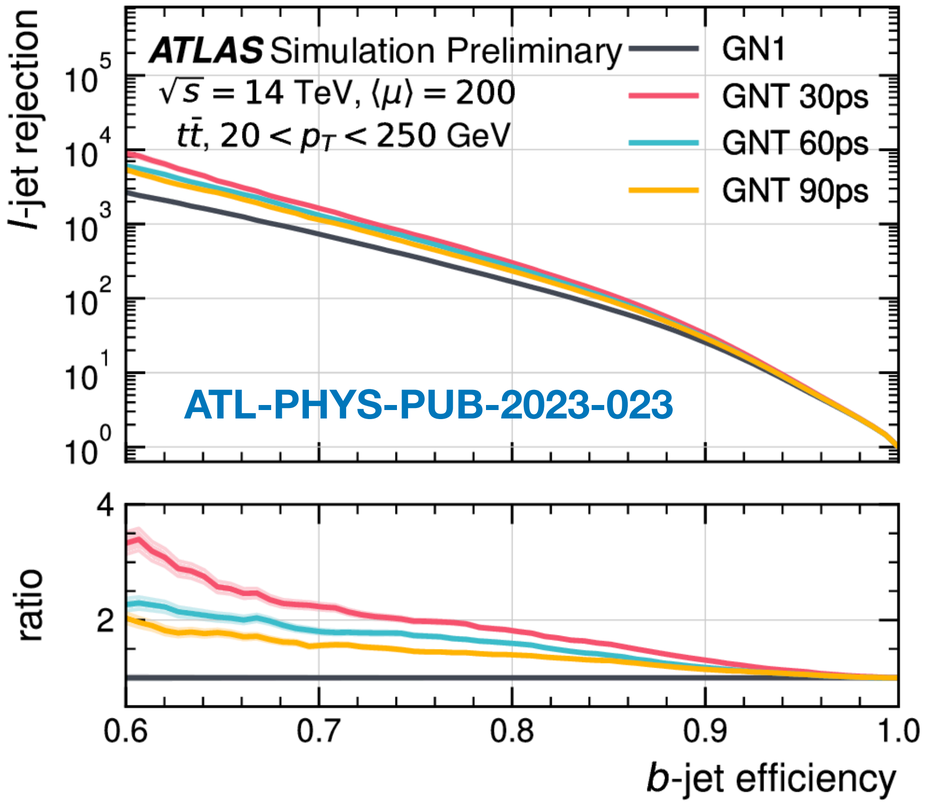
Improved tagging can help.





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More ML (1)

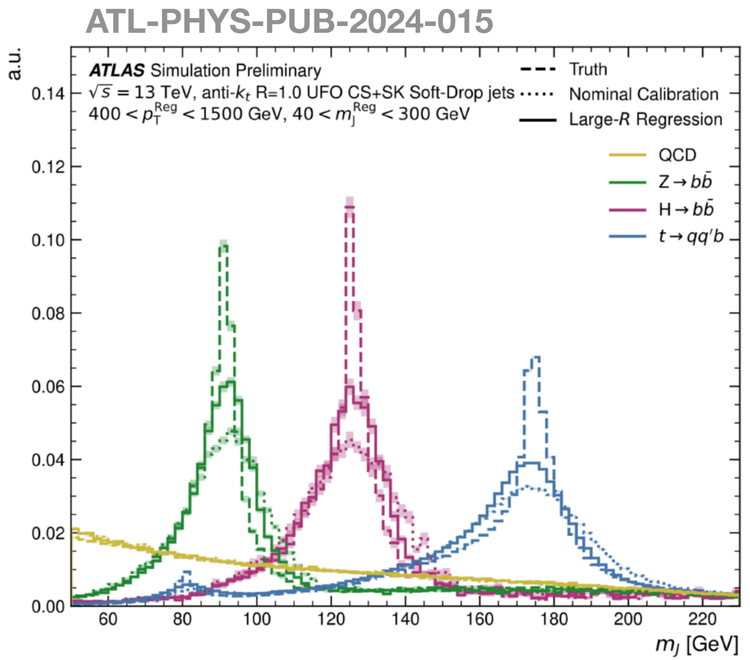
ML HAS never been more accessible! Analyses will be able train advanced models

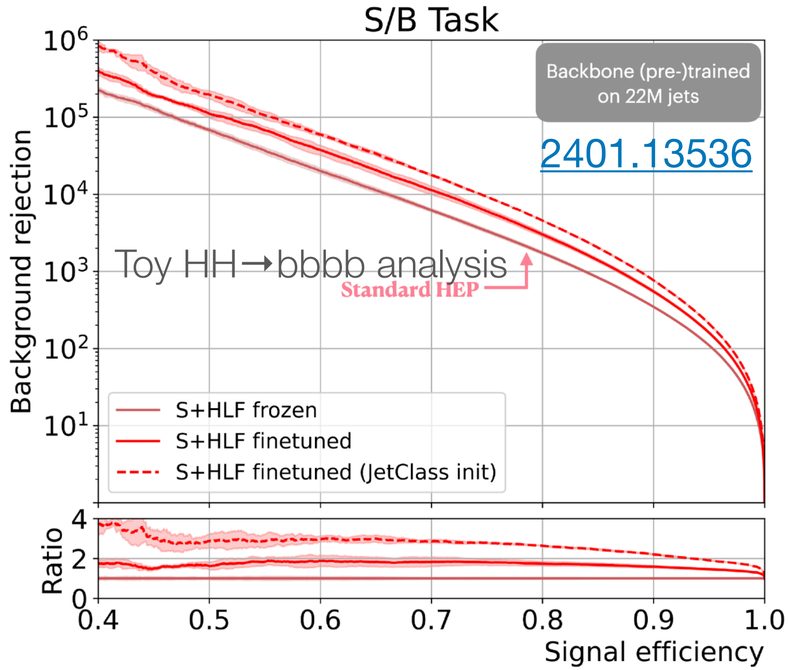
- More powerful event selection (low level inputs, GNNs, …)
- Specialised object taggers (e.g. DeXTer used in H→bb$\tau\tau$)
- Unified tagging & reconstruction (OmniLearn, Sophon, SPAnet, HyPER, etc)

Let's be cautious!

- Explainability / interpretability tradeoffs
- Harmonised tooling & models can minimise expensive trainings
  - What about fine tuning **foundation models**?

Salt: generic MVA training framework





More ML (3)

Normalising flows

- Fully calibrated model outputs with Optimal Transport [link]
  - Analyses don't need to use on suboptimal WPs
- Normalising flow for background estimation in $H \to \gamma\gamma$ [2306.11379]
  - Extract detector response from truth level quantities, including PU, correlations, and asymmetries

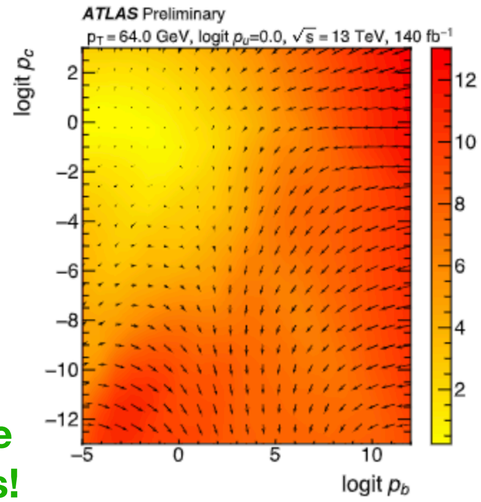
Large effective increase in background statistics!

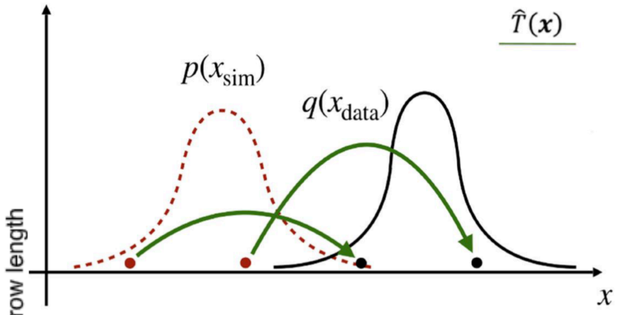
Truth tagging with GNNs

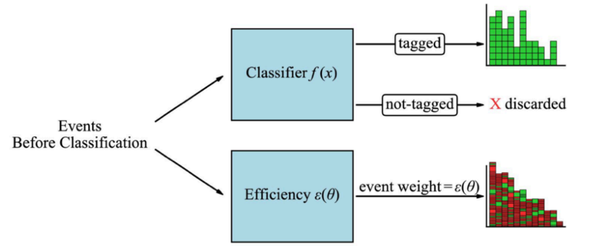
- Assign weights to background events rather than filtering
- Already in use @ ATLAS [ATLAS-CONF-2024-010] [ATL-PHYS-PUB-2022-041]

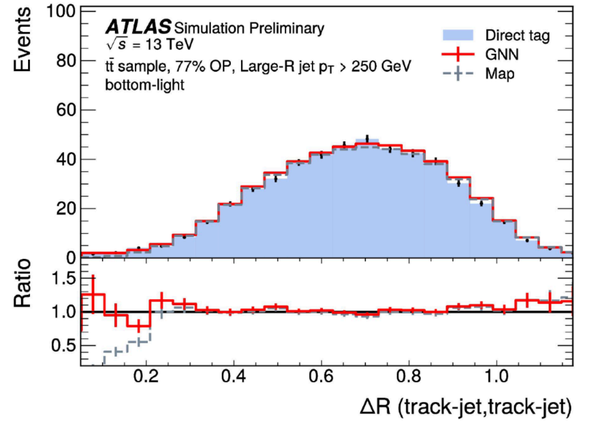
Simulation based inference [2405.15847]

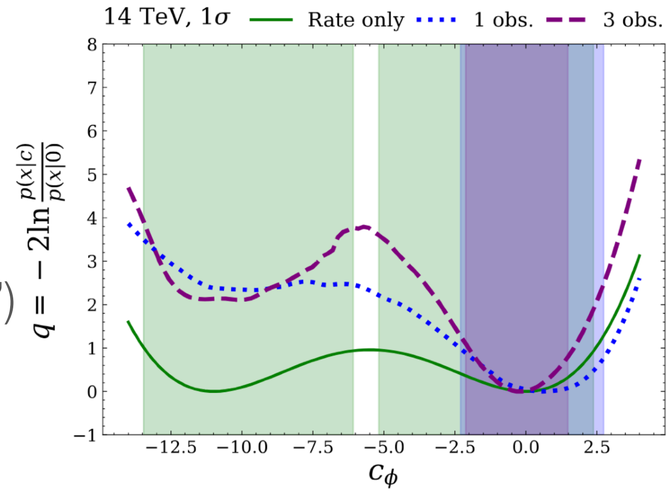
- Histograms suffer from the curse of dimensionality → limiting us to low-dimensional fits ("summary observables")
- SBI: promising set of approaches to include additional observables in statistical models











Summary

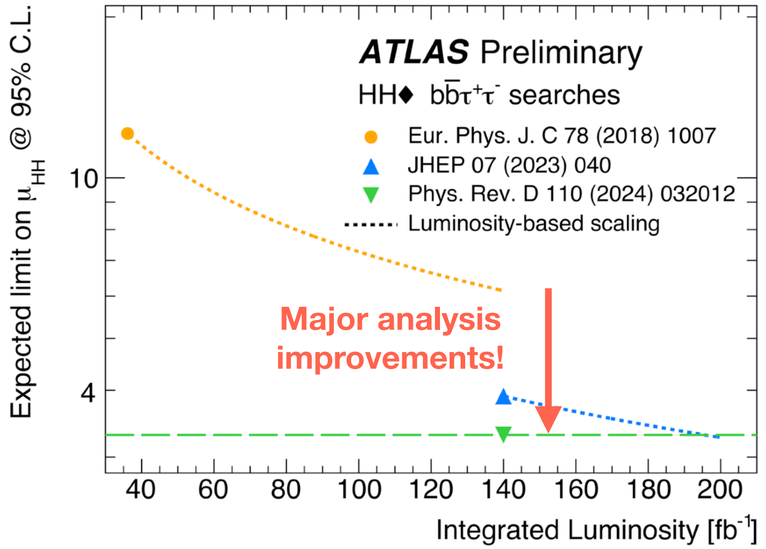
The HL-LHC will be great!

- Impressive precision achieved for many results, but many still **stat limited**
- New detectors with **larger acceptance**, **improved resolution**, and **timing info** will combat the harsh pileup conditions
  - **A lot of investment in hardware and software is still needed!!**
- Significant improvements can be expected from tagging and improved analysis methods → much of this **driven by ML**

What can we learn already?

- History has shown we are conservative when making projections
- This is good! But let's not forget to **dream big**
- Lots of improvements and great results to come

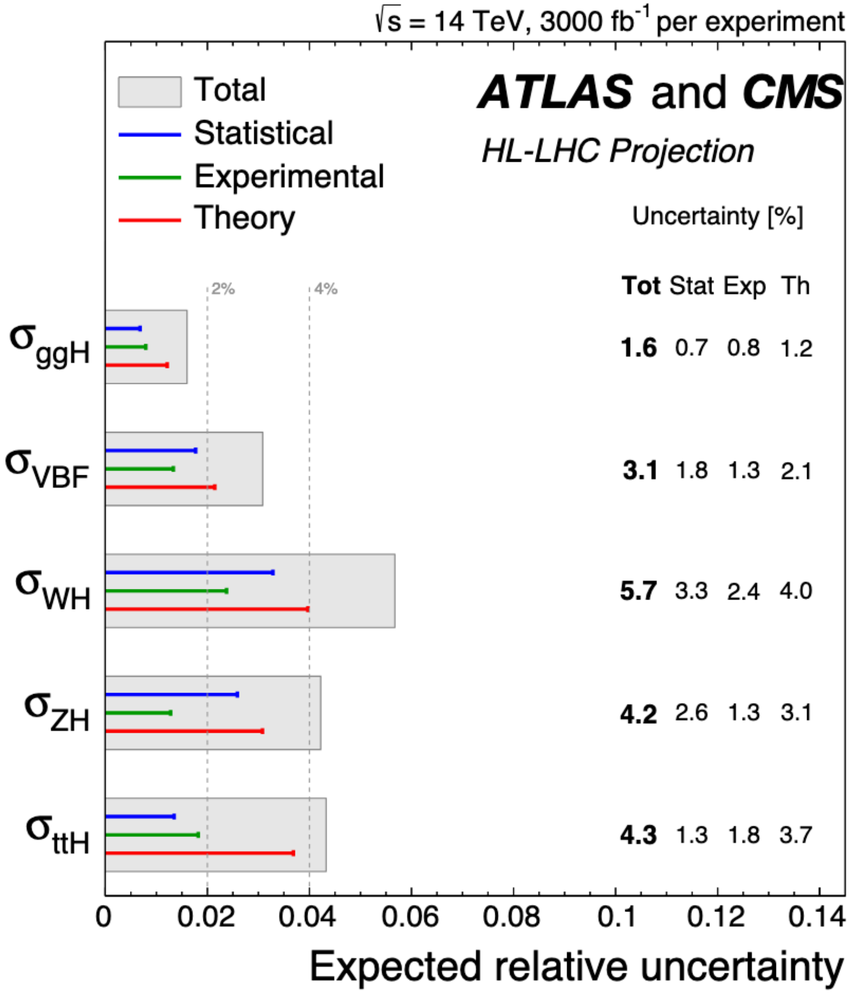
Thanks for listening!

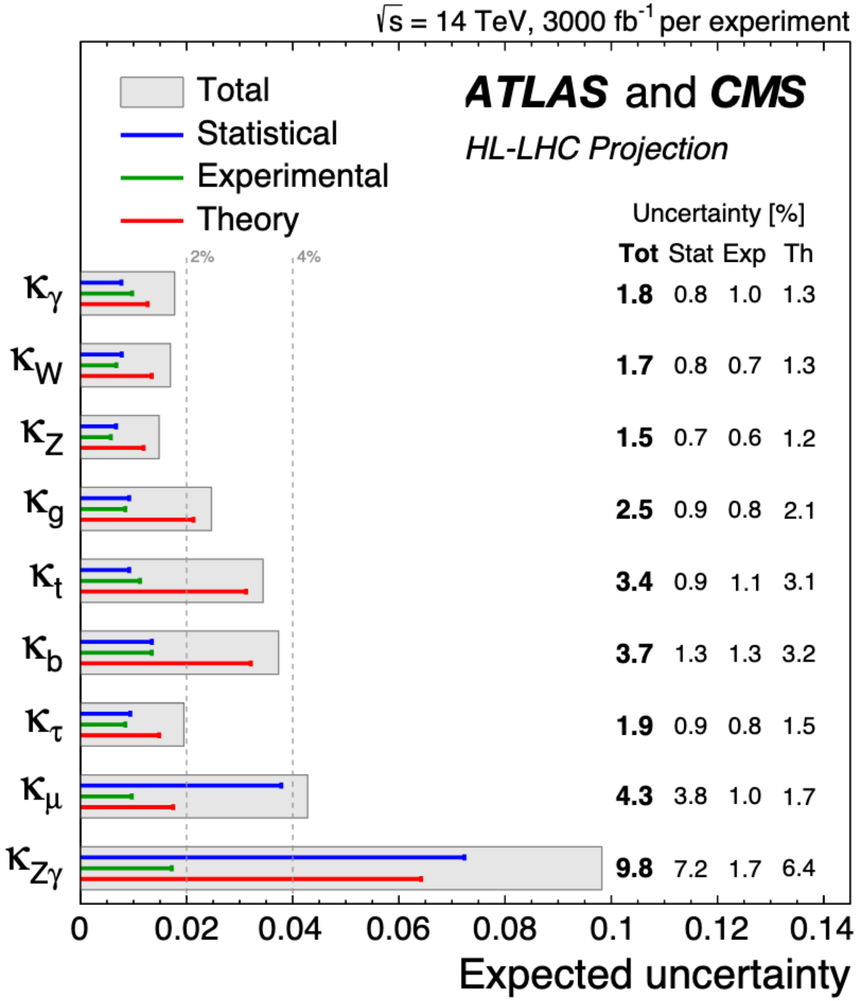


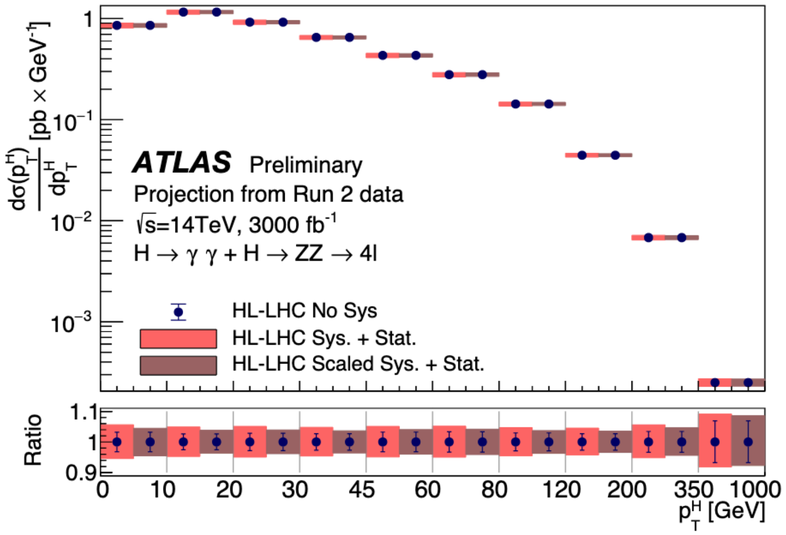
Backup

CERN Yellow Report

[link]

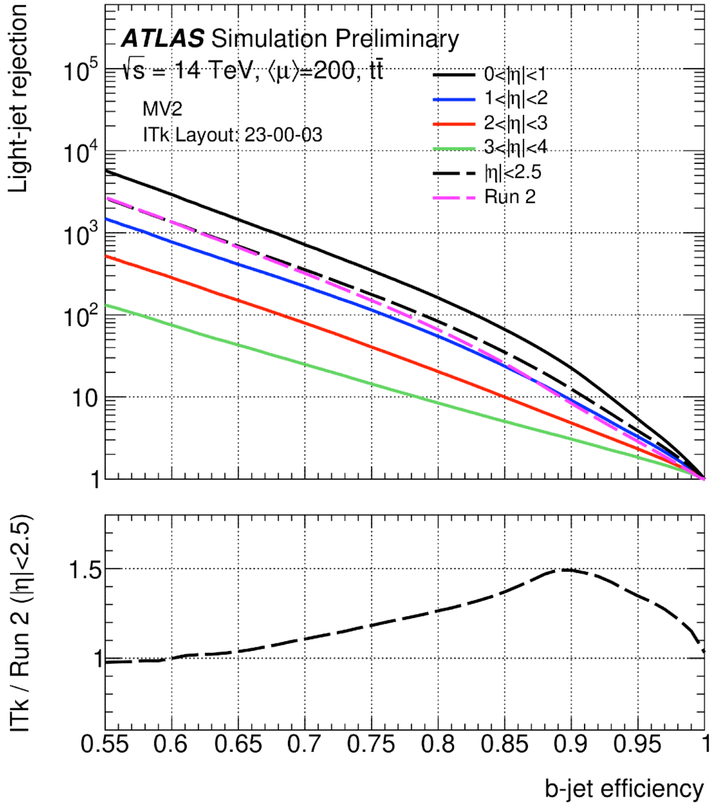






Flavour Tagging

ATL-PHYS-PUB-2021-024



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