ATLAS Physics Prospects for HL-LHC

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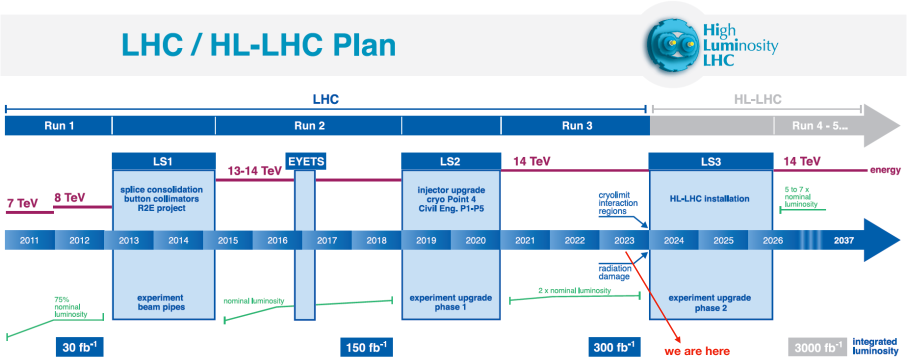
on behalf of the ATLAS collaboration

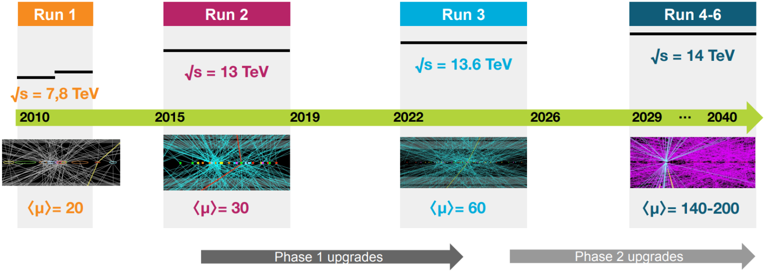
ICNFP 2023 (July 10-23, 2023)

HL-LHC Timeline



- **Run 3 just starting:** ~2x ATLAS and CMS datasets by 2025
- **Major boost in statistics expected with HL-LHC data-taking from 2029:**
  - 5 – 7.5x nominal instantaneous luminosity
  - Up to 3000 fb^{-1} integrated luminosity, Run 1 – 3 ~10% of total HL-LHC dataset

Challenges from pile-up



Elizabeth Brost Higgs @10 Symposium

- **High luminosity + pile-up conditions are particularly challenging for data-taking:**
  - Detector irradiation
  - Higher occupancy
  - Higher trigger rates
- **Require improvements for experiments in all areas:**
  - Detectors themselves
  - Trigger menu and hardware
  - Object reconstruction
  - Software and computing
  - Physics analysis techniques

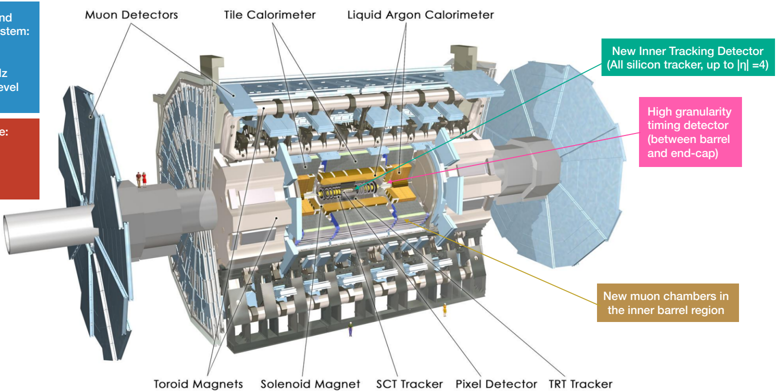
ATLAS Detector Upgrade

Upgraded Trigger and Data Acquisition System:

- L0: 1MHz
- Event Filter: 10kHz
- Improved High-Level Trigger

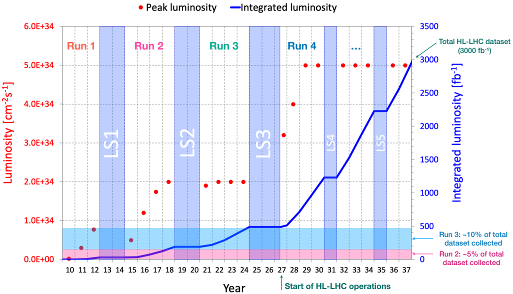
Electronics Upgrade:

- LAr Calorimeter
- Tile Calorimeter
- Muon system



How do we extrapolate results to HL-LHC?

- **Start from:**
  - Published LHC Run 2 results, or
  - Simulations (usually using a simplified detector simulation such as DELPHES)
- **Adapt to HL-LHC conditions:**
  - Center-of-mass energy: 13 TeV $\rightarrow$ 14 TeV (affect cross-section of various processes)
  - Pile-up: 30 $\rightarrow$ 200
  - Larger dataset: 140 fb^{-1} $\rightarrow$ 3000 fb^{-1}
  - Simulated detector and reconstruction performance
  - Theory and experimental uncertainties: usually present a few scenarios



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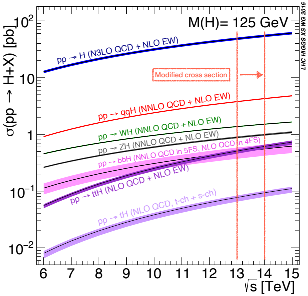
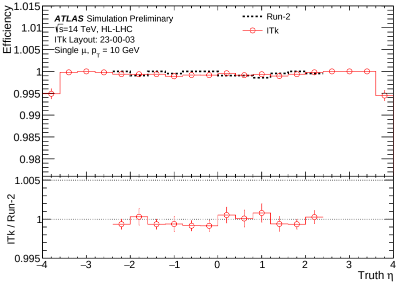


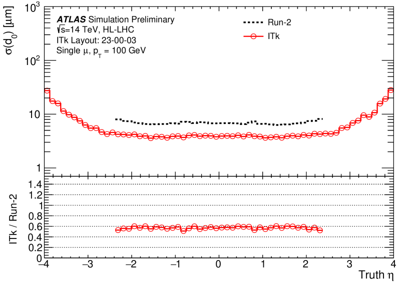
Systematic Uncertainties

- Projections of systematic uncertainties rely on **significant assumptions**
- Common treatments: ATL-PHYS-PUB-2021-023
  - **Detector and trigger performance** comparable to Run 2
    - New detectors and reconstruction algorithms expected to counteract pile-up effects
  - **Most experimental uncertainties** expected to decrease
    - Clever use of larger datasets and new detectors
    - 1% goal for luminosity uncertainty
  - **Theory uncertainties** reduced by factor of 2
    - Improvements expected in perturbative corrections, PDFs, α_S
  - **Statistical uncertainties** scaled by $1/\sqrt{L}$
  - **Uncertainties on methods** such as non-statistical uncertainties on data-driven techniques kept the same
  - Uncertainties due to **statistics of available MC simulation** set to 0
  - Systematics driven by **intrinsic detector limitations** left unchanged

ITk upgrade performance - tracking

- **Tracking efficiency** for 10 GeV muons without pile-up compatible with Run 2
- **Transverse impact parameter** d_0 resolution for 100 GeV muons improved by a factor 2
- **Longitudinal impact parameter** z_0 resolution for 100 GeV muons improved by a factor 4 respectively
- **Transverse momentum resolution** expected to outperform the Run 2 resolution





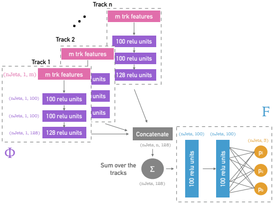
Flavor Tagging

- Access **flavor tagging performance** using the most up-to-date simulation of the upgraded **Inner Tracker (ITk)**
- Algorithms trained and evaluated with $t\bar{t}$ and Z' MC samples at $\sqrt{s} = 14$ TeV

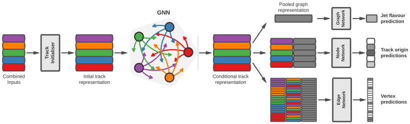
DIPS: Based on deep sets
ATL-PHYS-PUB-2020-014

DL1d: Based on deep neural network
Eur. Phys. J. C 79 (2019) 970

GN1: Based on graph neural network
ATL-PHYS-PUB-2022-027
The auxiliary track classification and vertex finding objectives contribute significantly to the performance of the jet classification

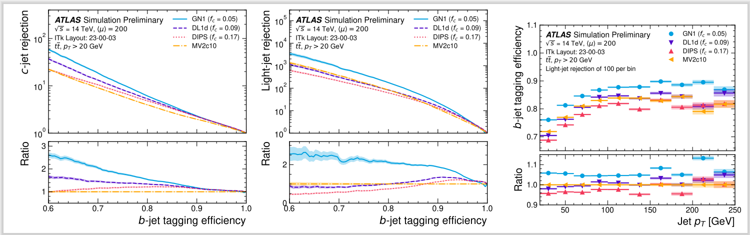


DIPS



GN1

- **Significant improvement in b-jet tagging efficiency for the new taggers** w.r.t. MV2c10 (used for previous upgrade studies)
- At 70% btag WP, the GN1 tagger shows more than factor of 2 improvement in the $t\bar{t}$ sample



$t\bar{t}$ sample

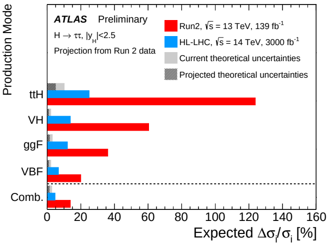
ATL-PHYS-PUB-2022-047

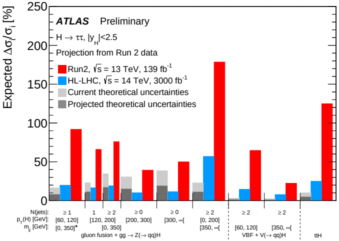
- Results for the Z' sample can be found in the Appendix

Measurement of $H \to \tau\tau$ cross-section

ATL-PHYS-PUB-2022-003

- **Total $H \to \tau\tau$ cross-section**
  - $H \to \tau\tau$ cross-section measured with 5% precision at HL-LHC
  - Dominated by theoretical uncertainties on the signal prediction
- **Production cross-section**
  - ggF and VBF: dominated by theory uncertainties on the signal prediction
  - VH: similar contributions from exp. uncertainties and stat. uncertainties
  - ttH: dominated by exp. uncertainties
- **STXS measurements studied with Run 2 categories**
  - Cross-section precision from 7% to 50%



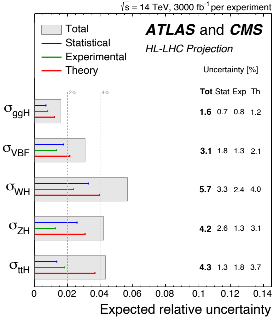


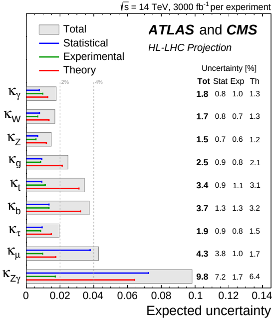
Higgs couplings to SM particles ATL-PHYS-PUB-2022-018

- Higgs couplings move into precision regime
- $H \to \mu\mu$ and $H \to Z\gamma$ measurements still limited by **size of the collected dataset**
- Other couplings dominated by **theoretical uncertainties** (despite assumed /2 improvement)

Higgs couplings to charm, bottom ATL-PHYS-PUB-2021-039

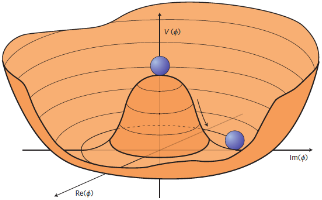
- VH, $H \to c\bar{c}$ channel combined with VH, $H \to b\bar{b}$
- Direct measurement within reach at HL-LHC: constraint on charm quark modifier of $|\kappa_c| < 3$ and ratio with the bottom quark modifier of $|\kappa_c/\kappa_b| < 2.7$



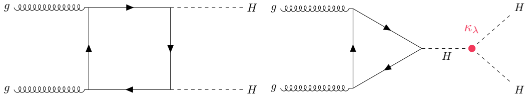


Higgs pair production and self-coupling

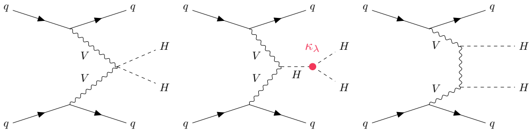
- The **Higgs self-coupling** (coupling modifier κ_λ) is one of the Higgs boson properties that is still largely unconstrained. Its value determines the **shape of the Higgs potential**.
- The Higgs self-coupling can be directly accessed through **Higgs pair (HH) production**
  - SM HH production is an **extremely rare process** with cross-section 1000x smaller than single Higgs production. Only $\sim$4000 events expected in Run 2.
  - Finding evidence for HH production is **feasible at the HL-LHC**, $\sim$100,000 events expected



Higgs Potential



Gluon-gluon fusion

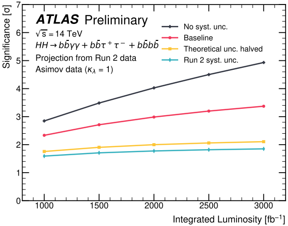


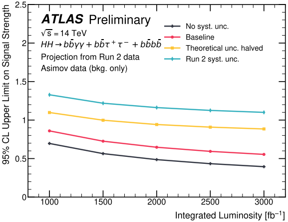
Vector boson fusion

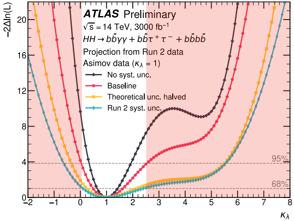
Higgs pair production and self-coupling

Combination of HH searches $b\bar{b}b\bar{b}$ + $b\bar{b}\tau\tau$ + $b\bar{b}\gamma\gamma$ ATL-PHYS-PUB-2022-053

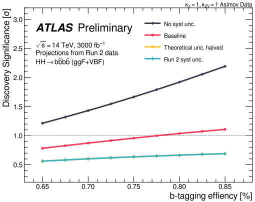
- Discovery significance of 3.4 σ
- 95% CL upper limit on SM HH signal strength at 0.55
- κ_λ constrained within [0.0, 2.5] at 95% CL (possibility of excluding κ_λ = 0)

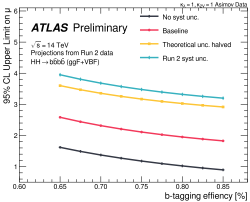






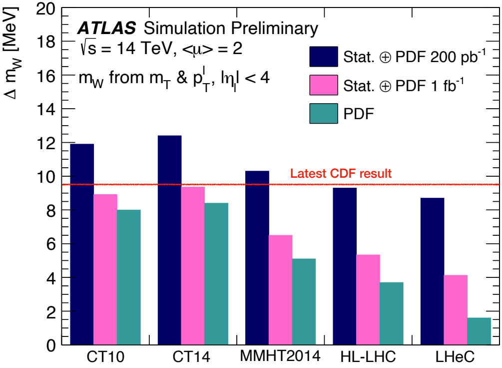
Sensitivity of $b\bar{b}b\bar{b}$ channel driven by **btag performance** (potential improvement from ITk)





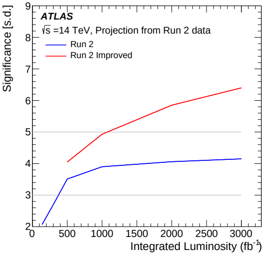
Measurement of the W mass ATL-PHYS-PUB-2018-026

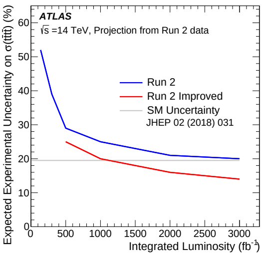
- W mass measurement at low μ will benefit from
  - Extended tracking coverage: uncertainty reduced by 25%
  - Improved PDF precision: PDF systematics halved
  - Larger dataset: 200 pb^{-1} per week at $\langle \mu \rangle = 2$
- With 200 pb^{-1}, precision of 8.6 (stat) + 3.7 (PDF syst) = 9.3 MeV
- As comparison, precision from latest CDF result is 9.4 MeV



Measurement of $t\bar{t}t\bar{t}$ cross section ATL-PHYS-PUB-2022-004

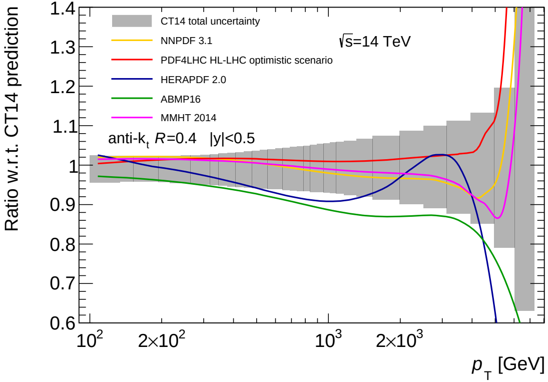
- **Two systematic scenarios:**
  - Run 2 (pessimistic): same as Run 2 values
  - Run 2 improved (optimistic): scaled according to HL-LHC expectations
- **In the Run 2 improved scenario:**
  - Expected SM signal significance of **6.4** σ (up from 2 σ in Run 2)
  - Cross-section measurement uncertainty of **14%** (down from 50% in Run 2)
  - Improvement mainly driven by
    - Smaller uncertainty on the $t\bar{t}$ cross-section
    - Smaller uncertainties related to ttV + jets with heavy-flavor jets and jet flavor tagging





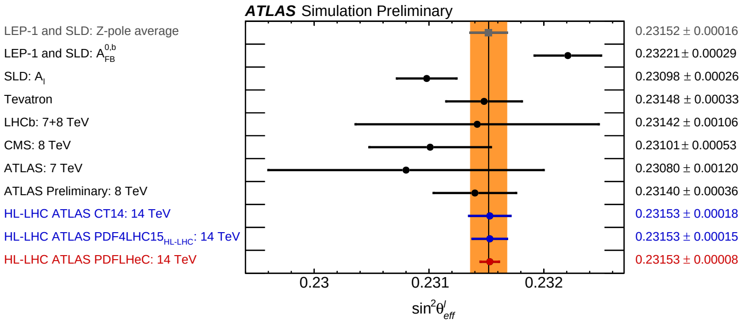
Measurements of differential jet and photon ATL-PHYS-PUB-2018-051

- Significant increase in reach of differential QCD measurements at the HL-LHC:
  - Single-jet p_T 3.5 $\rightarrow$ 5 TeV
  - Dijet m_{jj} 9 $\rightarrow$ 11.5 TeV
  - γ+jet $E_T(\gamma)$, p_T(jet) 1.5 $\rightarrow$ 3.5 TeV, $m(\gamma$+jet) 3.3 $\rightarrow$ 7 TeV
- Large differences between various PDF predictions at high pT
  - Strong impact of HL-LHC measurements improve determination of proton PDFs



Measurement of the electroweak mixing angle ATL-PHYS-PUB-2018-037

- Precision measurement of $\sin^2\theta_{\text{eff}}$ using forward-backward asymmetry in Drell-Yan dilepton event
- Benefits from improved forward lepton reconstruction + statistics
- Better precision than individual LEP-1 and SLD measurements (3σ discrepancy)

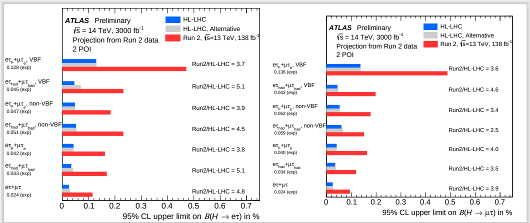


BSM physics

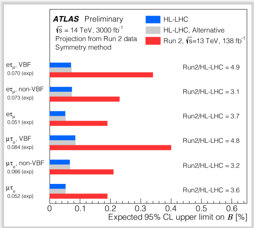
Search for lepton-flavor violating decays $H \to e\tau$ and $H \to \mu\tau$

ATL-PHYS-PUB-2022-054

- **Two background estimation methods**
  - MC template method: dominated by systematics (jet E_T^{miss}, fake bkg estimate)
  - Symmetry method: $\tau_\ell \ell$ channels only, dominated by stat. unc. on data-driven bkg prediction
- **Results from MC template method:**
  - Expected 95% CL upper limits on $\mathcal{B}$ for $H \to e\tau(\mu\tau)$ are 0.024 % (0.024 %)
  - Improvement w.r.t. Run2 results of a factor 4.8 (3.9) for $H \to e\tau(\mu\tau)$ searches.



MC template method

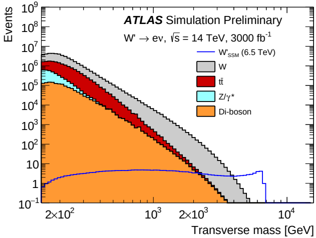


Symmetry method

BSM resonance searches

Heavy Z'/W' search

ATL-PHYS-PUB-2018-044

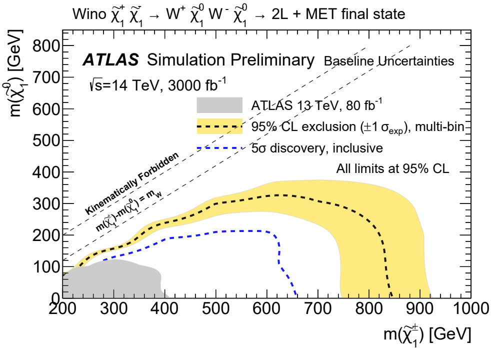


- **Many BSM models predict heavy resonances manifesting as bump in tail of mass spectrum**: heavy gauge bosons, excited leptons, Majorana neutrinos...
- **Leptonic channels typically exhibit best sensitivity**: often rely on dedicated lepton reco. / identification
- **HL-LHC will increase reach of searches to weaker couplings and higher masses**

Model	Run 2 exclusion [TeV]	HL-LHC exclusion [TeV]
Right-handed W'	3.15	4.9
Sequential Standard Model W'	5.6	7.9
Right-handed Z'	5.4	5.8
Sequential Standard Model Z'	6.1	6.5

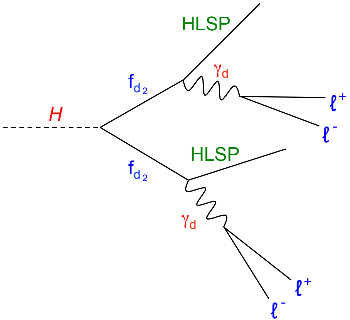
Electroweak SUSY searches (staus, charginos and neutralinos) ATL-PHYS-PUB-2018-048

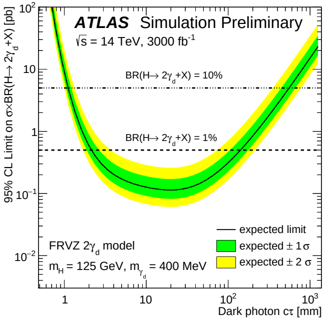
- The 95% CL expected exclusion potentials at the HL-LHC reach **200 GeV higher** in mass than the discovery potentials
- Larger benefit from HL dataset due to smaller cross-sections



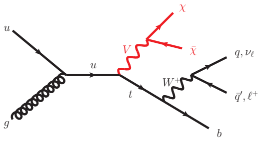
Searches for dark photons decaying to displaced muons ATL-PHYS-PUB-2019-002

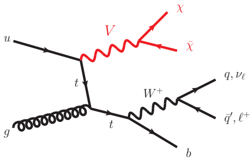
- Search for neutral long-lived particles decaying to pairs of muons
- Standard algorithms tailored for reconstruction of prompt particles but new algorithms developed during Run 2-3 can be successfully adapted for HL-LHC detectors
- Phase-2 upgrades (muon timing detector, muon triggers) also opportunities to **exploit new capabilities for trigger and reconstruction**

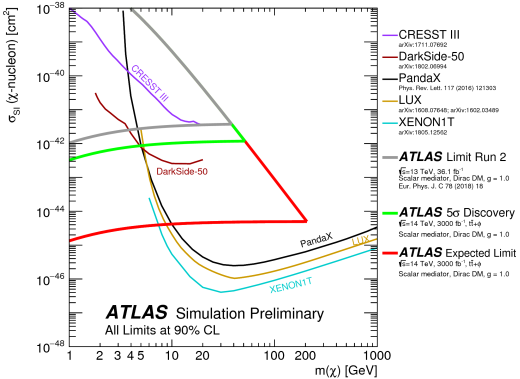




- **Search for associated production of DM with SM detectable particles** (e.g. mono-X, X=Z/H/top): look for excess in tail of MET or m_T distributions
  - DM search in mono-top final states ATL-PHYS-PUB-2018-024
- Sizeable improvements w.r.t. Run 2 possible thanks to increased dataset + improved systematics: complementary to direct detection experiments





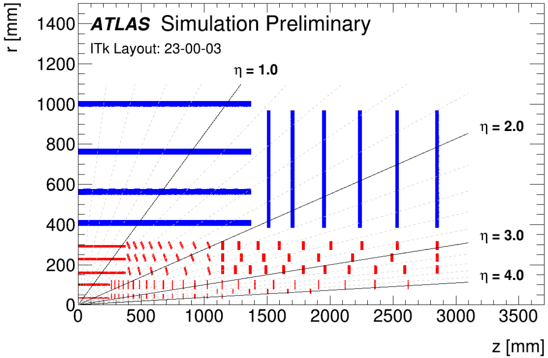


Conclusion and Outlook

- HL-LHC data-taking represents an **unprecedented challenge** and requires improvements to:
  - Trigger menu and hardware
  - Event reconstruction
  - Software and computing
  - Physics analysis techniques
  - ✦ Hard work and creativity in reconstruction and analysis techniques already evident since last round of projections
- Extremely **rich and exciting physics programs** ahead:
  - **Higgs physics:** precise determination of Higgs properties, probing of small Higgs couplings
  - **Standard Model:** ultimate precision measurement of fundamental SM parameters
  - **Beyond Standard Model:** direct improvement in mass reach for many models, new analysis techniques can help close gaps in unexplored regions of phase space
  - **Flavor physics + Heavy-ion physics**

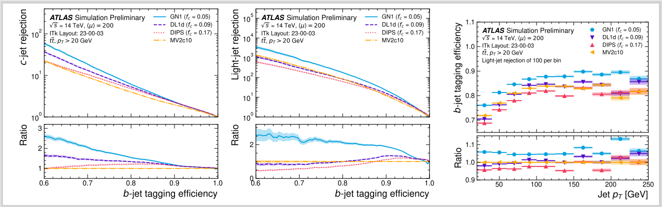
Backup - The ATLAS Inner Tracker

- The current **Inner Detector (ID)** will be replaced with a new all-silicon **Inner Tracker (ITk)**
  - Made of a **Pixel Detector** surrounded by a **Strip Detector**
  - Recently updated layout includes reducing the radius of the **innermost pixel layer** motivated by the expected improvement in **tracking performance**
  - Also improved **high-level object reconstruction and identification**, including primary vertices, jet flavor-tagging, electrons, and converted photons

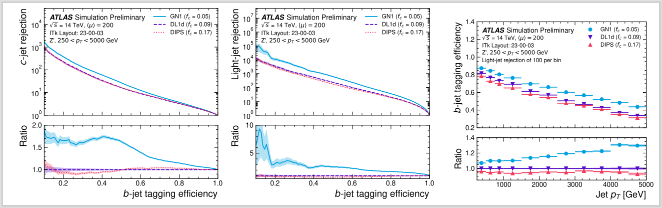


ATL-PHYS-PUB-2021-024

- B-jet tagging efficiency for new taggers w.r.t. MV2c10 (used for previous upgrade studies)



$t\bar{t}$ sample



Z' sample

ATL-PHYS-PUB-2022-047