Phase-2 Tracking for ITk based on ACTS and Higgs self-coupling

Luis Falda Coelho, Noemi Calace, Ricardo Gonçalo

7th IDPASC/LIP PhD Students Workshop

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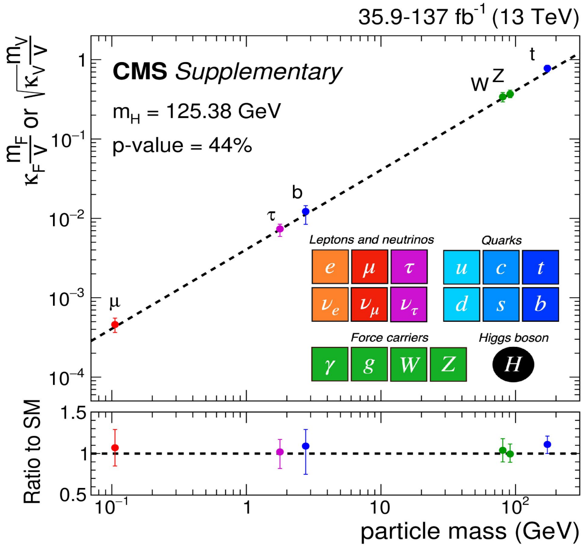
Supported by CERN doctoral grant

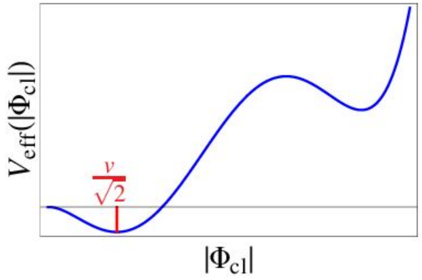
The Higgs Boson and Search for New Physics

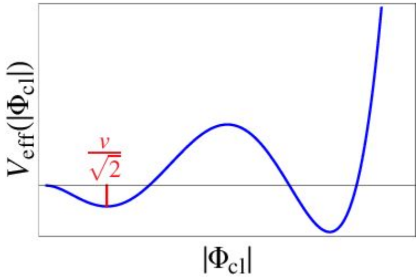
- On July 2012, ATLAS and CMS announced the discovery of a scalar particle consistent with the Higgs boson
- 10 years later - significant improvements in our knowledge of the Higgs properties, but still **very little understanding of the shape of the Higgs potential**



Determination of the Higgs potential has implications for a several fundamental phenomena:

- Nature of the EW phase transition in the early universe (which defines the viability of models of EW **baryogenesis**)
- Meta-stability of the EW vacuum
- **Constraints on BSM** (such as some inflation models that require H-gravity coupling)

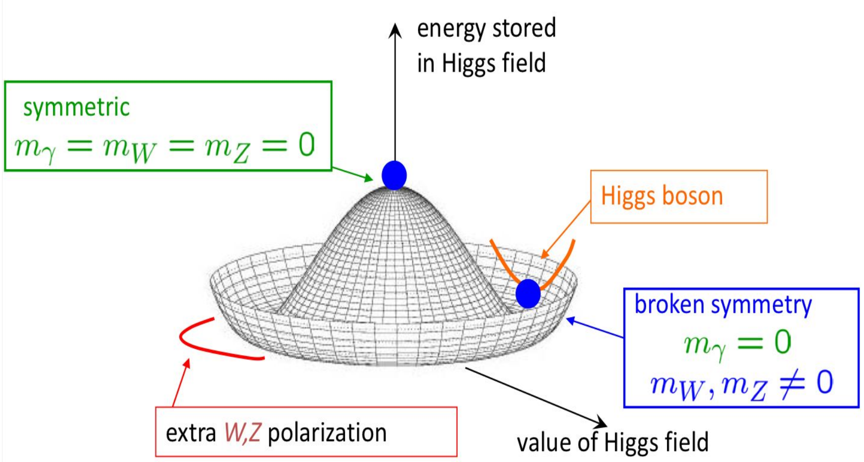


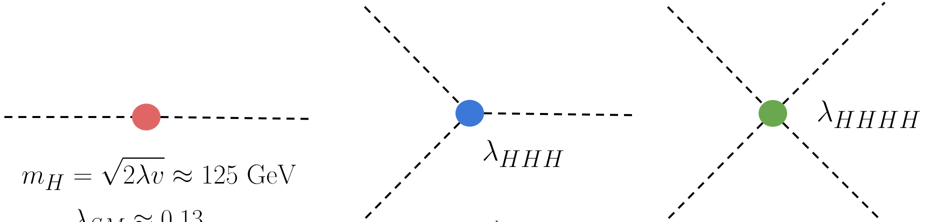


Electroweak Symmetry Breaking and Trilinear Coupling

SM Higgs mechanism demands a Higgs self-coupling

$$V(h) \approx \boxed{\frac{1}{2}m_H^2 h^2} + \boxed{\lambda v h^3} + \boxed{\frac{1}{4}\lambda h^4} + \ldots$$





$m_H = \sqrt{2\lambda v} \approx 125\ \mathrm{GeV}$

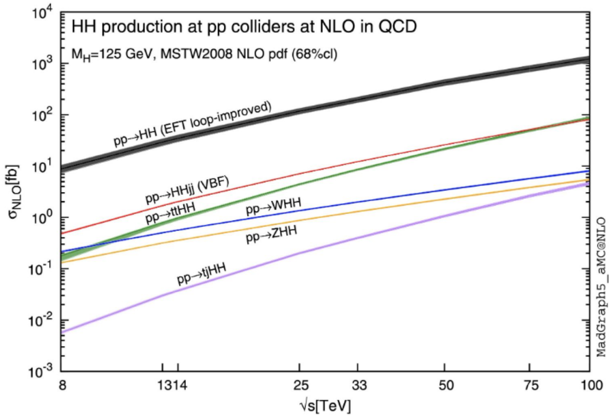
$\lambda_{SM} \approx 0.13$

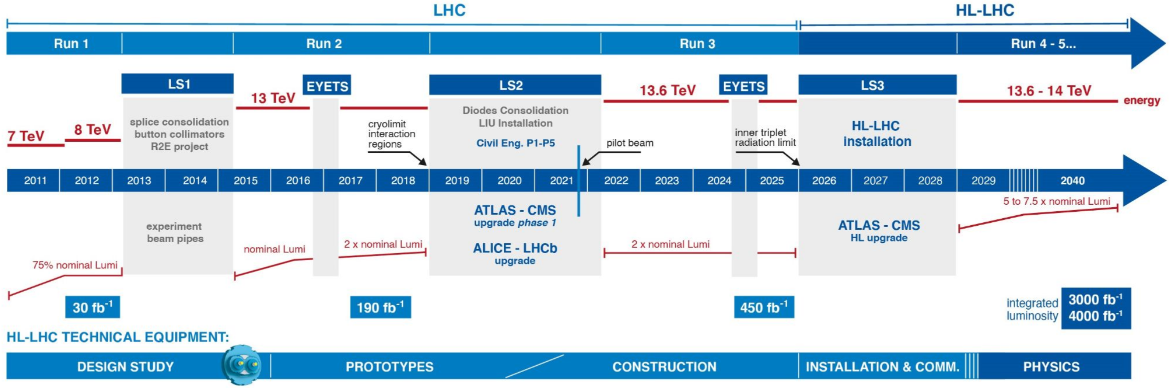
λ_{HHHH} probably out of reach of HL-LHC

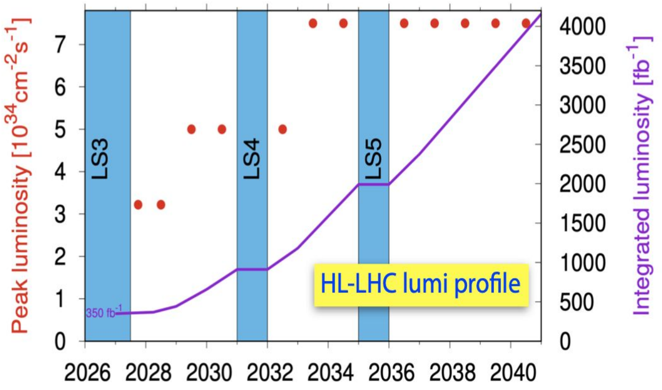
λ_{HHH} can be directly measured via HH production

The High-Luminosity LHC

- SM HH cross-section is ~**1000x smaller** than single Higgs production
- HL-LHC plans to collect **4000 fb^{-1}**
- Require excellent tracking performance despite **harsh pile-up environment**
- The ATLAS detector will need **significant improvements** and upgrades to cope with the HL-LHC integrated luminosity

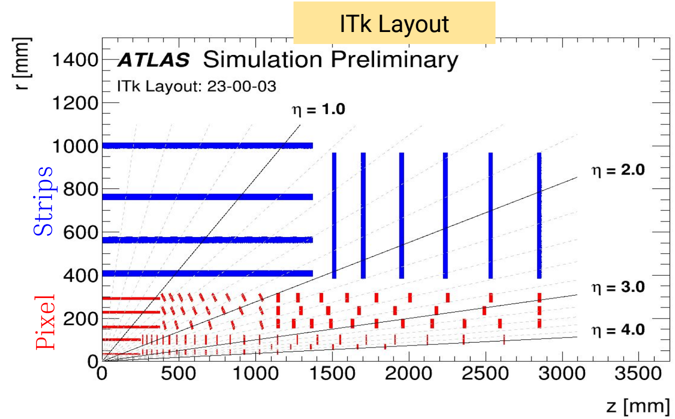


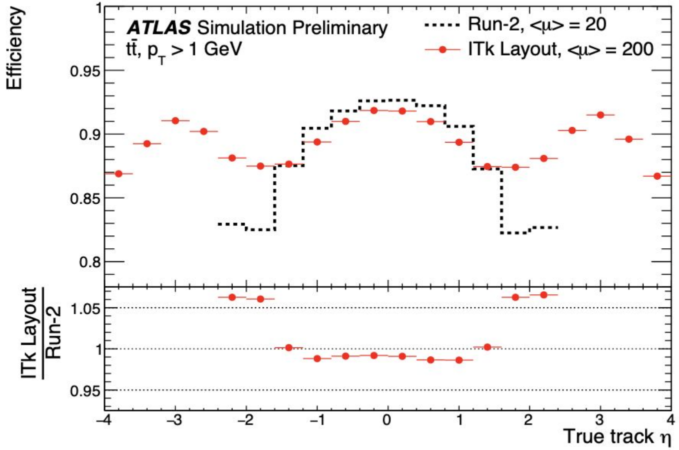




The Inner Tracker Detector

- The current **Inner Detector (ID) will be completely replaced by an all-silicon Inner Tracker (ITk)** with improved granularity and an extended track-reconstruction coverage up to $|\eta| < 4$.
- Tracking of charged particles is one of the the **most complex and CPU consuming** phases of event reconstruction
- Will become even greater computational challenge during HL-LHC:
  - Require more **efficient algorithms** that can provide excellent tracking performance
- Tracking is essential for high sensitivity on HH production:
  - Crucial for b-tagging efficiency - important final states containing b quarks: $HH \rightarrow bbbb$, $HH \rightarrow bb\tau\tau$, $HH \rightarrow bb\gamma\gamma$
  - Tau identification: $HH \rightarrow bb\tau\tau$
  - Good vertex definition and pile-up mitigation extending the track-to-vertex matching to the very-forward region in η





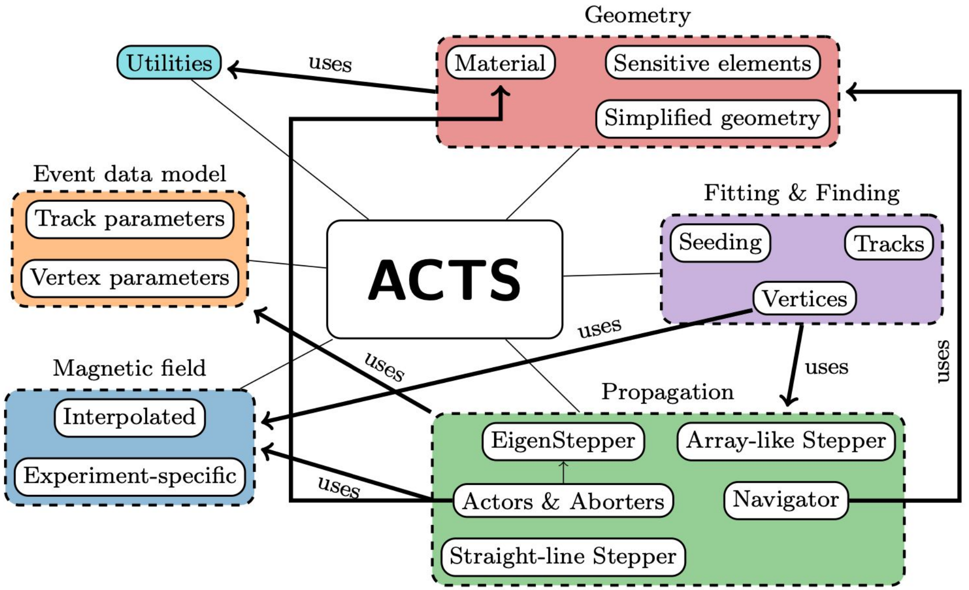
Experiment-independent toolkit for (charged) particle track reconstruction in HEP experiments [arXiv:2106.13593]

- Implemented in modern C++17
- Thread-safe for parallelization/vectorization
- Fully agnostic to detection technologies, detector design, and the event processing framework
- Highly customizable and extendable

ATLAS decided to extensively use ACTS software and profit of thread-safety and high-performing software during HL-LHC

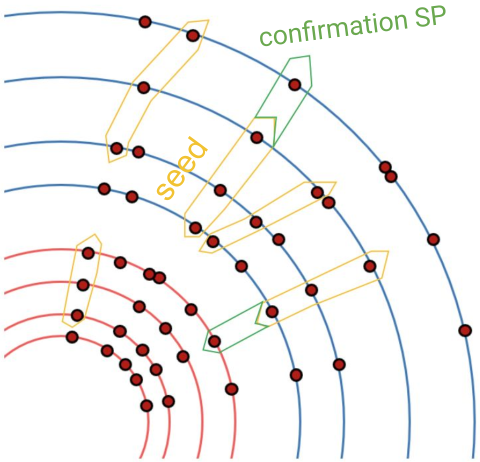
Requires **optimization of ACTS for the ITk** track reconstruction in ATLAS!

Github: https://github.com/acts-project/acts



Implementation of ITk Seeding in ACTS

- Implement ITk seeding algorithm developed in Athena (current ATLAS algorithm) in ACTS
- Port all **ITk optimizations** required to run in a high pile-up environment from Athena to ACTS
- Integrate into Athena and validate the performance
- Guarantee **equivalent physics performance while significantly increasing CPU performance**



The Seeding Algorithm:

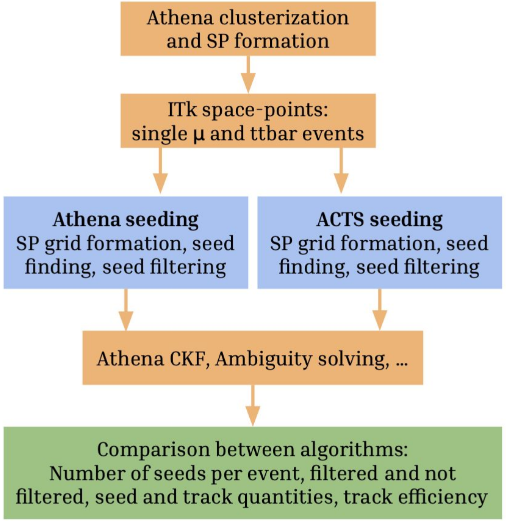
- Starts by forming track seeds consisting of **triplets of space-points (SP)** in either Pixel or Strip detectors based on geometrical assumptions relative to the interaction point
- Apply geometric and compatibility cuts to **reduce the number of potential seeds that may not lead to high quality tracks**
- Apply a seed confirmation procedure to rank seeds based on a weight and reject the ones that do not satisfy the quality criteria

Implementation of ITk Seeding in ACTS

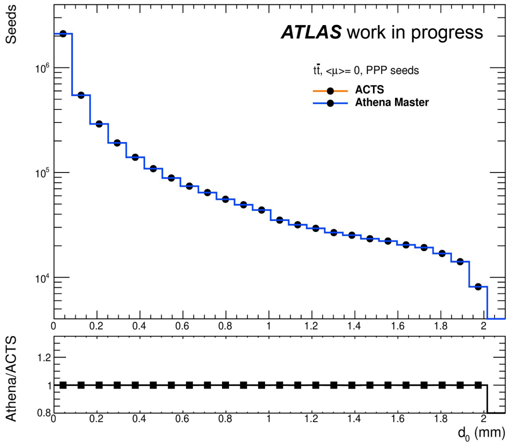
ITk seeding algorithm was implemented in ACTS and validated against the ATLAS algorithm:

- Comparing seed variables in every seeding stage, as well as reconstructed track parameters and tracking efficiency
- **Excellent agreement** for both Pixel and Strip seeds!
- CPU validation is still ongoing

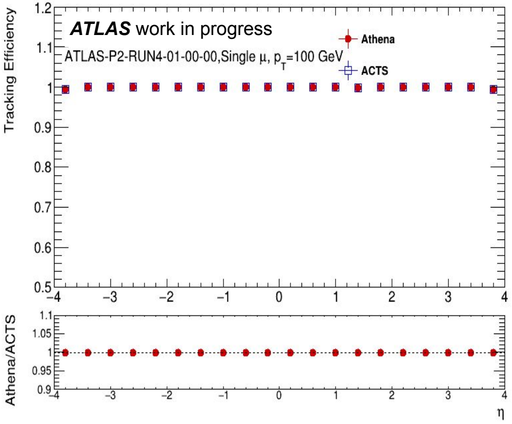
Check out my poster for more information!



Athena vs ACTS seed variables



Athena vs ACTS tracking efficiency



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Backup

HH Decay Channels

Trade-off between large branching ratio vs clean final state

HH → bbbb:

- Largest branching fraction for SM Higgs
- Suffers from a large multi-jet background

HH → bbγγ:

- Excellent trigger and reconstruction efficiency of photons, and excellent invariant mass resolution
- Low branching fraction

HH → bbττ:

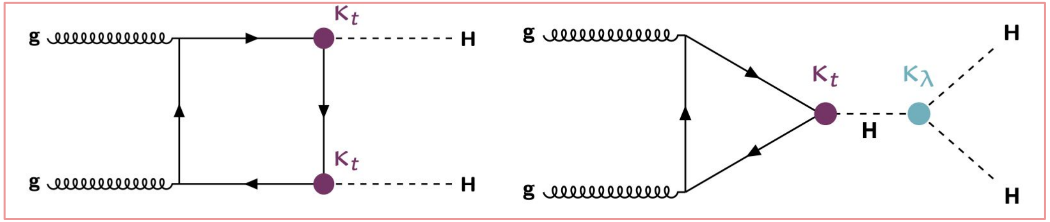
- Compromise between rate and background contamination
- Yields stringent limits on HH production from an individual channel

	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%

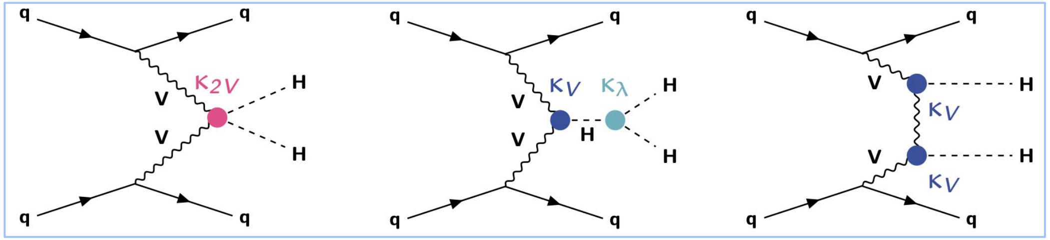
HH Production at the LHC

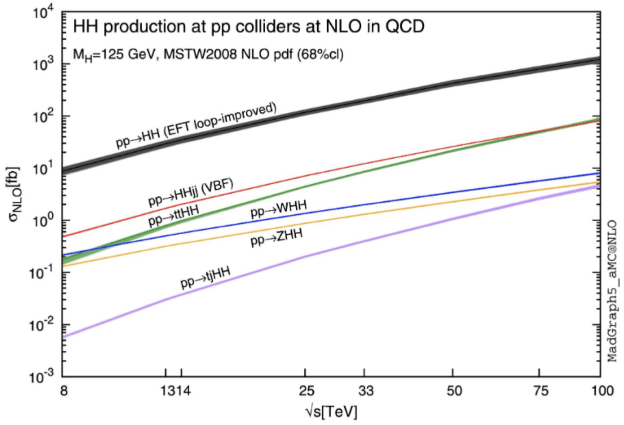
HH cross-section is ~1000x smaller than single Higgs production

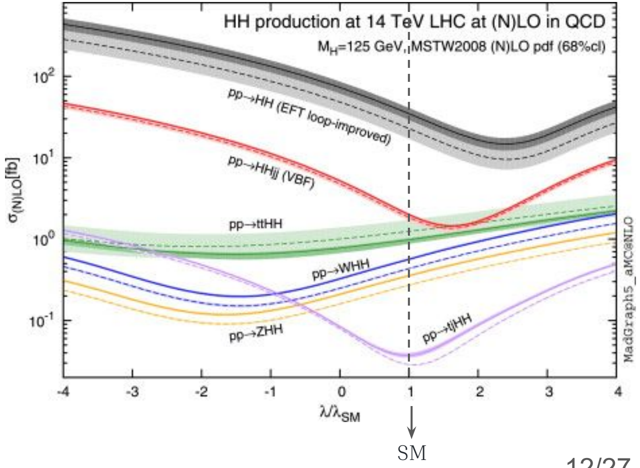
Gluon Fusion (ggF) $\rightarrow \sigma_{ggF}(pp \rightarrow HH) = 31.05$ fb



Vector Boson Fusion (VBF) $\rightarrow \sigma_{VBF}(pp \rightarrow HH) = 1.73$ fb







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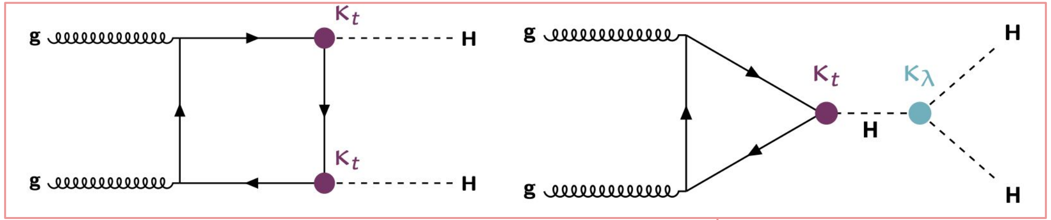
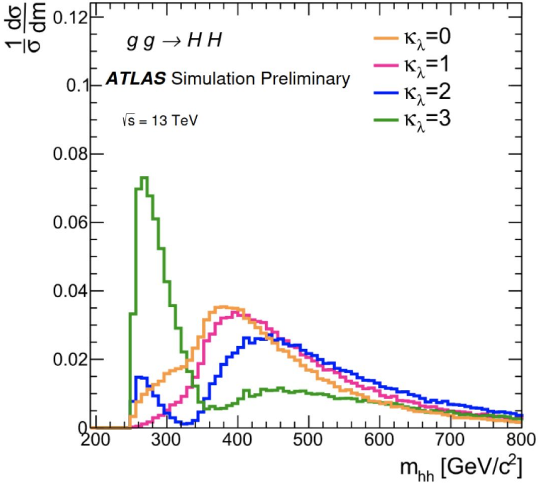
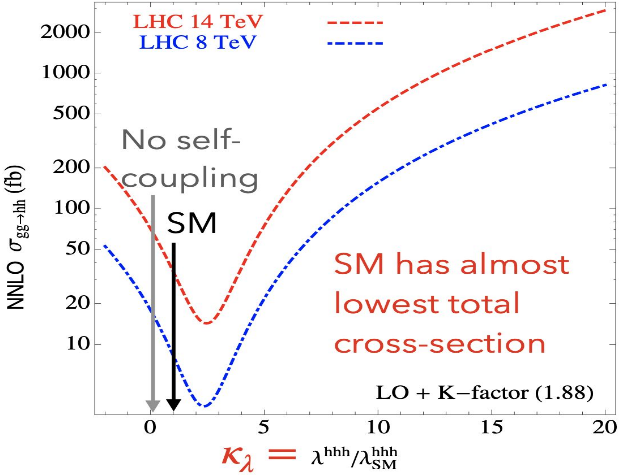
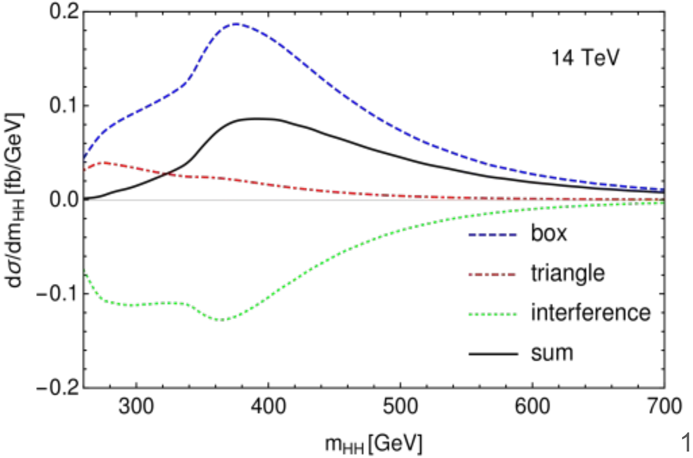






Destructive interference between diagrams

Large changes in m_{HH} with coupling strength



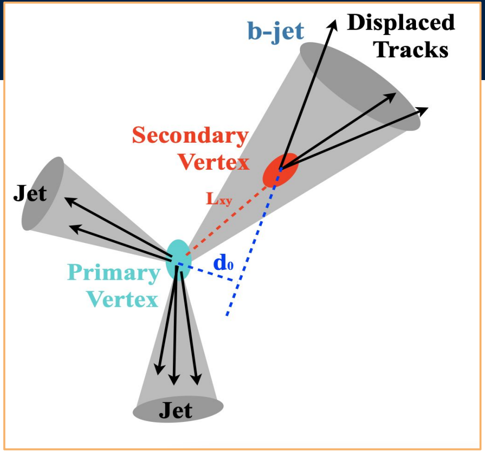
Run 2 Improvements - Flavour Tagging

- Good b-jet Identification is critical for most HH analysis
- Exploit relatively long lifetimes of b-hadrons and b-decay displaced from interaction point
- Identify displacement using tracks → tracking is crucial!
- Several correlated variables are combined in multivariate discriminant
- Multi-dimensional outputs **P(light)**, **P(c-jet)**, **P(b-jet)** corresponding to the probability of a jet to be classified as a **b-jet**, **c-jet** or a **light-flavor jet**

MV2 (BDT) from 2015+2016 replaced by a new Deep feed-forward neural network (DL1R) using same inputs

All HH analyses moved to a higher efficiency working point

b-jet tagging efficiency increased 70% → 77%



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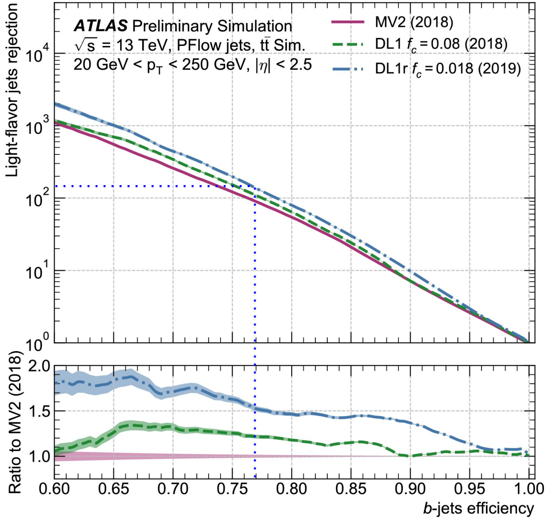
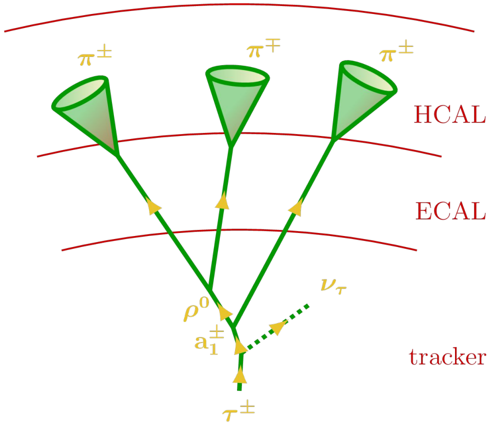


Run 2 Improvements - Tau Identification

- Important for HH → bbττ analysis
- Short decay length, typically decay before they reach the Inner Detector
- Only the decay products of the tau leptons can be observed
- Mostly decays hadronicaly (65%)
- Almost all hadronic tau lepton decays include one (72%) or three (22%) charged pions and the majority (68%) include one or more neutral pions
- Novel algorithm to identify decay products of hadronic tau decays
- RNN - exploit the physical order of the reconstruction chain
- Employing information from reconstructed **charged-particle tracks** and **clusters** of energy in the calorimeter associated to tau candidates as well as **high-level discriminating variables**



ATL-PHYS-PUB-2019-033

New recurrent neural network (RNN) with factor 2 performance improvement compared to BDT (from 2015 + 2016)