$t\bar{t}+\geq 1b$ modeling studies for the $t\bar{t}H(b\bar{b})$ analysis and b-tagging upgrade studies for the ATLAS tracker

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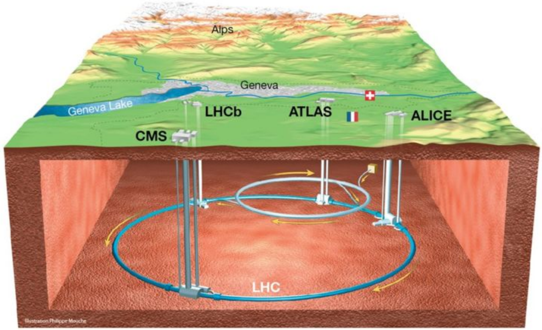
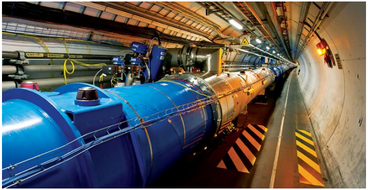
Outline

- Introduction: LHC, ATLAS and Higgs discovery
- $\mathrm{t\bar{t}H(b\bar{b})}$ analysis and $\mathrm{t\bar{t}}$ modeling studies.
- B-tagging upgrade studies for the ATLAS tracker @HL-LHC.
- Summary

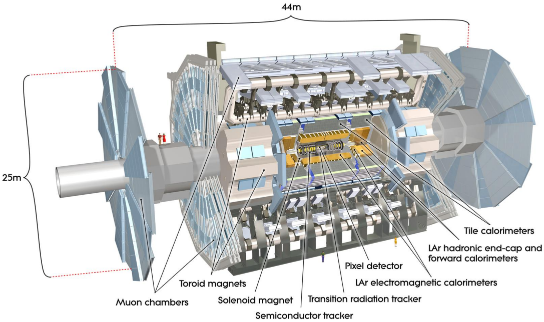
The Large Hadron Collider (LHC)

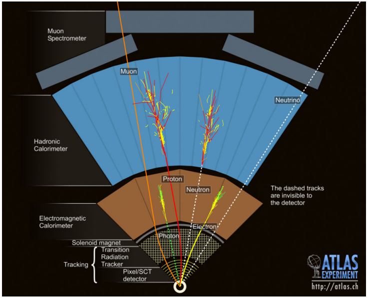
- 27 km ring, collides two beams of protons at high center of mass energies.
- LHC Run phases: Run 1 (2010-2013) @7-8 TeV, Long Shut down (LS1) 2013-2015, Run 2 (2013-2018) @13 TeV.
- 4 main experiments: ATLAS and CMS (general purpose), ALICE (Quark Gluon Plasma), LHCb (B physics)





The ATLAS experiment

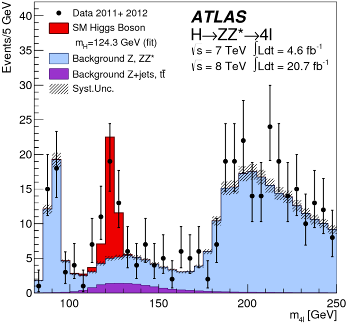


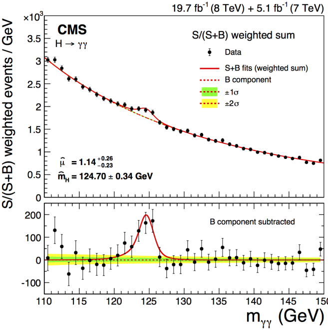


- **ATLAS** reconstructs physics objects (electrons, photons, jets, MET) based on a combination of subdetectors: tracker, electromagnetic and hadronic calorimeters, muon spectrometer.
- ATLAS probes phenomena within the SM and beyond (SUSY, Dark matter,..)
- Within the **SM sector**, the main focus of ATLAS is the **search for the Higgs boson and measurements of its properties**.

Higgs boson discovery

- In July 2012, **ATLAS** and **CMS** announced the Higgs boson discovery. This led to the 2013 physics Nobel prize.



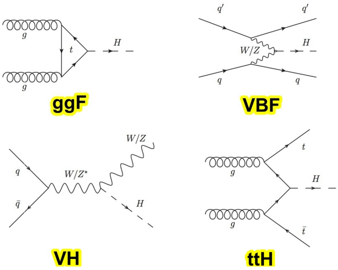


Higgs boson discovered... Yay!!!!

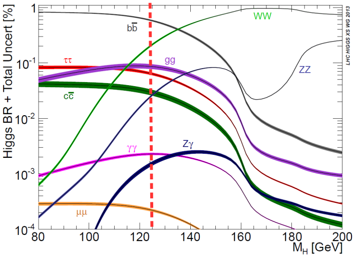
$\Rightarrow$ Well ... not quite!!!

Higgs boson measurements

Production modes



Decay channels



- Higgs mass ≈ 125 GeV, spin (0), parity (+).
- H→ $\gamma\gamma$, WW*, ZZ*, $\tau\tau$ (discovered).
- Evidence for Higgs coupling to bottom quarks and “VH” production (arXiv:1708.03299).
- Only indirect constraints on the top Yukawa coupling (ggF, $H \to \gamma\gamma$) assuming no BSM contributions to loops. A direct observation is yet evading measurement :-(!!!
- So far, all measurements are consistent with the SM.

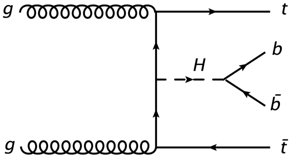
Part I

$t\bar{t}H(b\bar{b})$ analysis and $t\bar{t}$ modeling studies

Top Yukawa coupling and the $t\bar{t}H$ channel

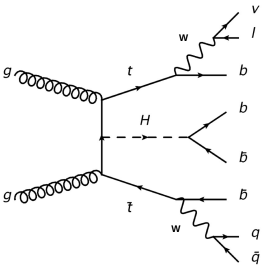
- In the SM, the top Yukawa coupling (y_t) is the strongest (heaviest particle... as heavy as a Gold atom!!!).
- A sensitive probe with great potential to shed light on new physics beyond the SM.
- Targeting processes where the Higgs boson is produced in association with top quarks is the only way to observe directly this coupling $\Rightarrow$ $\mathbf{t\bar{t}H}$

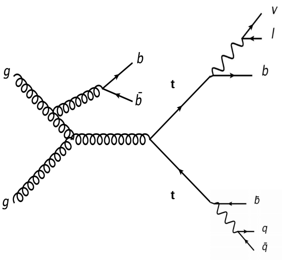
$\boxed{t\bar{t}H(b\bar{b})}$



In the search for $t\bar{t}H(b\bar{b})$: Strategy

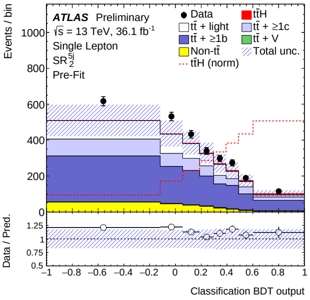
- $t\bar{t}H(b\bar{b})$ channel exploits the large branching ratio of $H \to bb$ (58%) and the leptonic decays of top quarks $\Rightarrow$ distinctive signature.
- Two channels based on the number of leptons in the final state: single lepton, dilepton.
- To increase sensitivity, events are further categorized based on the number of jets and how likely these are to contain a B hadron "b-tagged" $\Rightarrow$ Signal -rich (-depleted) regions.
- $t\bar{t}H(b\bar{b})$ channel is overwhelmed with the $t\bar{t}$ + jets background ($t\bar{t}+ \geq 1b$: irreducible background)





In the search for $t\bar{t}H(b\bar{b})$: Main challenge

Uncertainty source	$\Delta\mu$	
$t\bar{t}+\geq 1b$ modelling	$+0.46$	-0.46
Background model statistics	$+0.29$	-0.31
b-tagging efficiency and mis-tag rates	$+0.16$	-0.16
Jet energy scale and resolution	$+0.14$	-0.14
$t\bar{t}H$ modelling	$+0.22$	-0.05
$t\bar{t}+\geq 1c$ modelling	$+0.09$	-0.11
JVT, pileup modelling	$+0.03$	-0.05
Other background modelling	$+0.08$	-0.08
$t\bar{t}+$light modelling	$+0.06$	-0.03
Luminosity	$+0.03$	-0.02
Light lepton (e,μ) id., isolation, trigger	$+0.03$	-0.04
Total systematic uncertainty	$+0.57$	-0.54
$t\bar{t}+\geq 1b$ normalisation	$+0.09$	-0.10
$t\bar{t}+\geq 1c$ normalisation	$+0.02$	-0.03
Intrinsic statistical uncertainty	$+0.21$	-0.20
Total statistical uncertainty	$+0.29$	-0.29
Total uncertainty	$+0.64$	-0.61



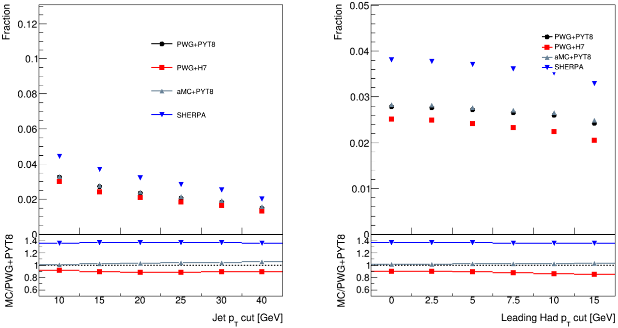
ATLAS-CONF-2017-076

Limiting factor of the analysis$\Rightarrow$ the **poor modeling of the $t\bar{t}+$jets ($t\bar{t}+\geq 1b$)** by the available "state of the art" MC generators.

$t\bar{t}$ modeling studies for $t\bar{t}H(b\bar{b})$ -I

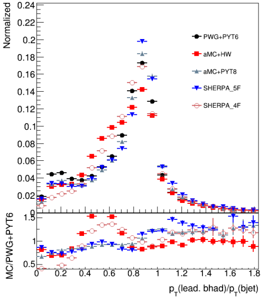
- $t\bar{t}+\text{jets}$ events are categorized based on the flavor of additional jets into : $t\bar{t}+\geq 1b$, $t\bar{t}+\geq 1c$ and $t\bar{t}+\text{light}$.
- Large differences between $t\bar{t}$ generators were observed before due to the definition of these fractions.
- Detailed studies have been performed to investigate the definition impact (on the analysis) and have shown that the differences among $t\bar{t}$ generators are fairly stable against various definitions $\Rightarrow$ crucial point for the analysis .

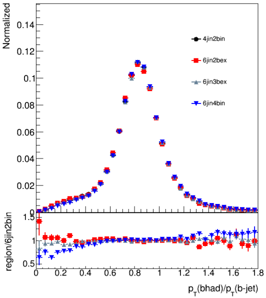
$t\bar{t}+\geq 1b$ fraction

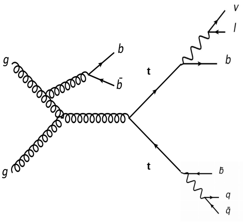


$t\bar{t}$ modeling studies for $t\bar{t}H(b\bar{b})$ -II

- In-depth studies of the modeling of $t\bar{t}+\geq 1b$ related kinematics have been undergone to understand better the differences between the available predictions.
- Kinematic differences between B hadrons and b-jets from parton shower and matrix element have been closely examined.



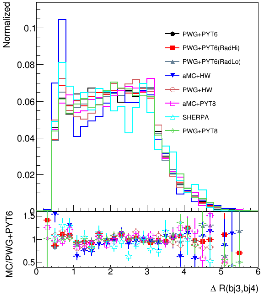




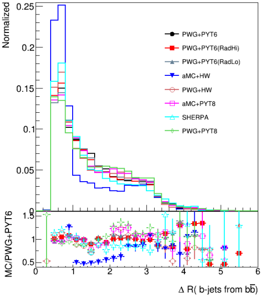
$t\bar{t} + \geq 1b$ studies for differential measurements analysis

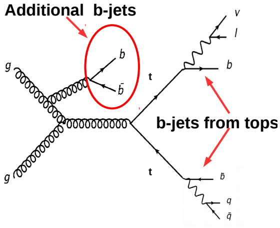
- A method to reconstruct the top quarks based on the final state objects needs to be developed.
- This method is essential as separating b-jets from $t\bar{t}$ and $b\bar{b}$ is crucial to measure pure kinematic distributions and be more sensitive to differences among generators.

p_T ordering separation



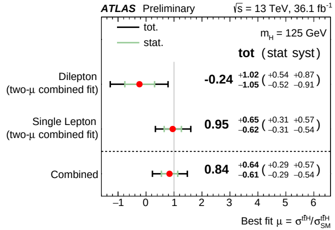
Matching separation

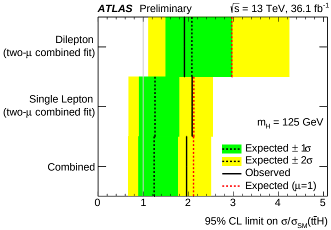




Results: Evidence for $t\bar{t}H$!!!

Signal Strength: $\mu = \frac{\sigma_{obs}}{\sigma_{SM}}$





- Results compatible with the SM.
- Significance w.r.t background only hypothesis: 1.4σ (exp: 1.6σ)
- Evidence for $t\bar{t}H(b\bar{b})$ when combining with other decay modes ($H \to ZZ \to 4l$, $H \to \gamma\gamma$): $4.2\ \sigma$ (exp: $3.8\ \sigma$)

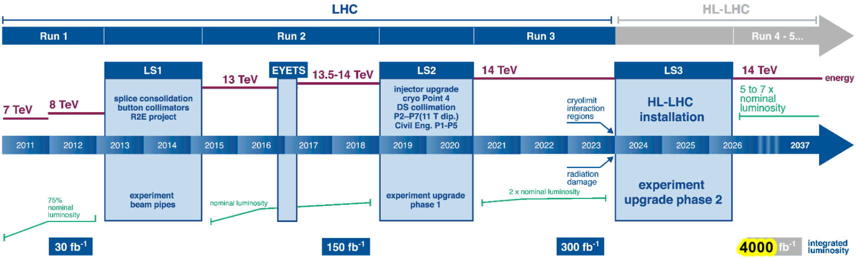
Part II

B-tagging upgrade studies for the **ATLAS tracker (ITk) @HL-LHC**

HL-LHC upgrade (I)

- High Luminosity LHC upgrade planned during LS3 (2024-2026).

⇒ **Luminosity** reflects how many collisions (p-p) will take place in the accelerator.

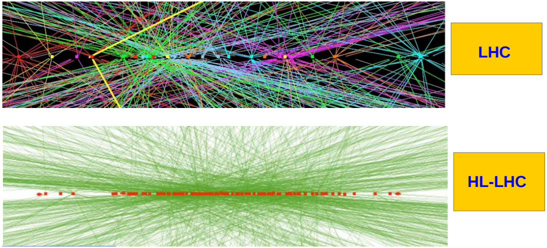


HL-LHC upgrade (II)

Challenges:

⇒ x10 increase in integrated luminosity ($4ab^{-1}$) → radiation damage.

⇒ Pileup increase: 25 @LHC → 200 @HL-LHC → better tracking needed.

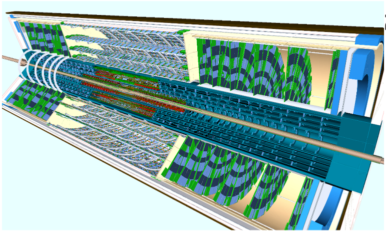


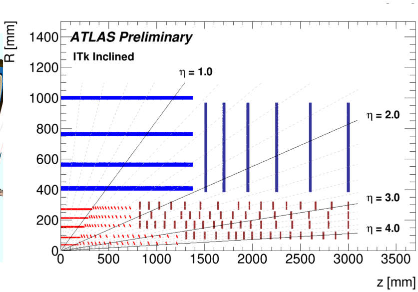
⇒ ATLAS will replace the ID with the Inner Tracker (ITk) to cope with HL-LHC extreme conditions.

ATLAS Phase II upgrade: Inner Tracker

- ⇒ All Silicon detector with coverage up to $|\eta| < 4$:
- ⇒ Strip detector: outer part, consists of 4 barrel layers and 6 End-Cap disks ($|\eta| < 2.7$).
- ⇒ Pixel detector: inner part, consists of 5 barrel layers.

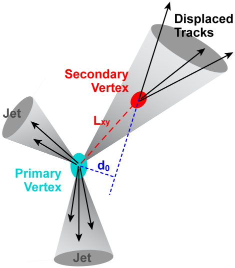
ATL-TDR-025

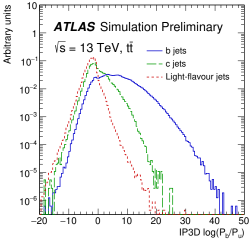




B-tagging in a nutshell

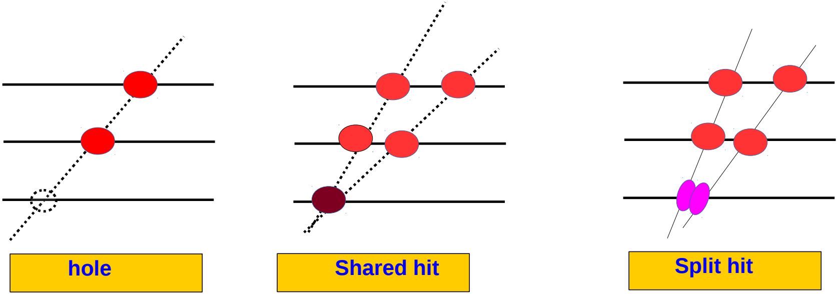
- Crucial tool for all analyses having b-jets in the final state e.g $t\bar{t}H(b\bar{b})$.
- To identify b-jets, b-tagging exploits the long lifetime of B hadrons $\sim$ 1.5 ps:
  - B hadron decay vertex displaced w.r.t the primary vertex(PV): secondary vertex (SV)
  - Massive SV (up to 5 GeV)
  - Tracks from B decays have large impact parameters (incompatible with PV) (d_0, z_0).
- These information are fed to the b-tagging algorithms (e.g IP3D) to distinguish b-jets from those originating from c quarks (c-jets) and light jets (g,u,d,s)



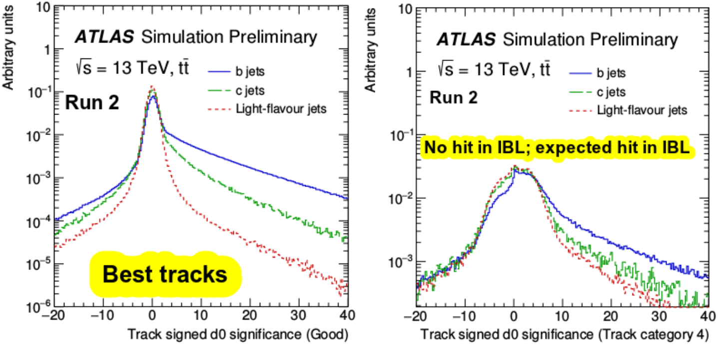


IPTag track categorization I

- The IP3D weight is computed based on the Log Likelihood Ratio (LLR) formalism which utilizes tracks categorization.
- Run 2 tracks categories (14) were designed such that each track is assigned a quality criterion based on its hit pattern $\Rightarrow$ dependent on the ID geometry (IBL).



IPTag track categorization II



$\Rightarrow$ For ITk, these categories need to be redefined in a way that is consistent with the ITk geometry

IPTag optimization for ITk I

- 3 track categorizations, consistent with ITk geometry, were defined combining tracks kinematic and hit pattern criteria.

ITk configurations

Configuration 1

- **$|\eta|<1$: tracks subdivided based on the hit pattern similarly to Run 2 but a reduced list of 8 categories is used rather than 14.**
- **$1<|\eta|<2$**
- **$2<|\eta|<3$**
- **$|\eta|>3$**

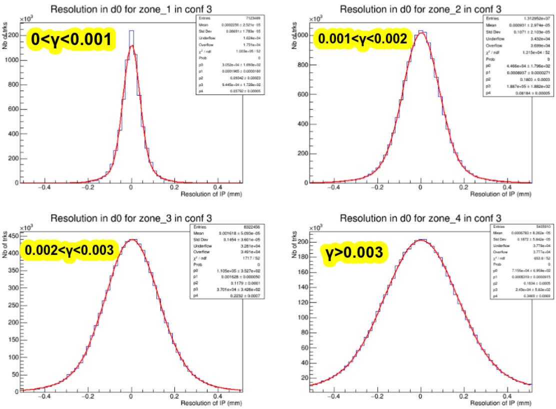
Configuration 2

- **$|\eta|<1$: tracks subdivided based on the hit pattern similarly to Run 2 but a reduced list of 8 categories is used rather than 14.**
- **Tracks within $1<|\eta|<2$, $2<|\eta|<3$, $|\eta|>3$ are subdivided based on the hit pattern.**

Configuration 3

- **$|\eta|<1$: tracks subdivided based on the hit pattern similarly to Run 2 but a reduced list of 8 categories is used rather than 14.**
- **Tracks with $|\eta|>1$ are subdivided into 4 gamma zones.**

Example: γ separation in configuration 3

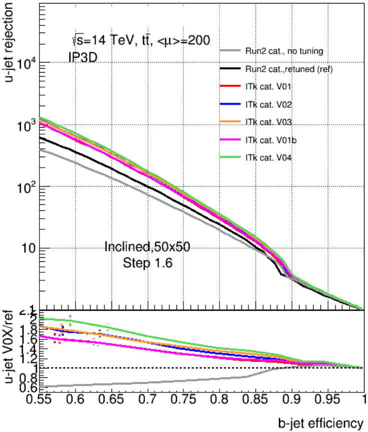


$$\gamma = \frac{1}{p_T\sqrt{Sin\theta}}$$

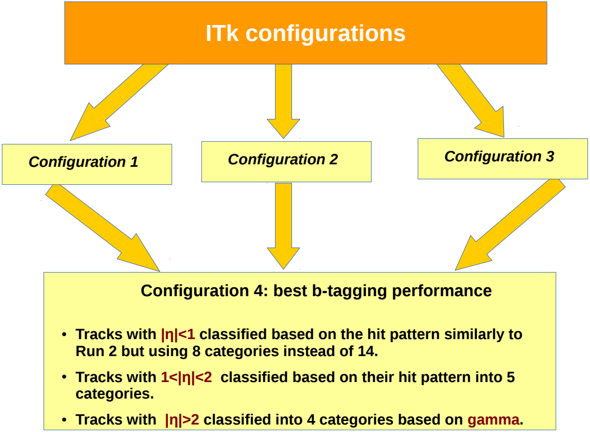
- γ reflects how much multiple scattering a track undergoes.

b-tagging performance with each configuration

- For each configuration, the b-tagging performance was checked to choose a baseline categorization.

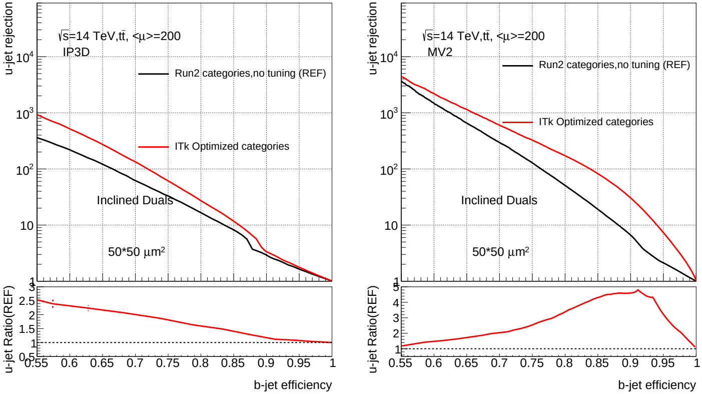


IPTag optimization for ITk II



- Configuration 4 is adopted as the basline for the ITk pixel studies (Technical Design report TDR).

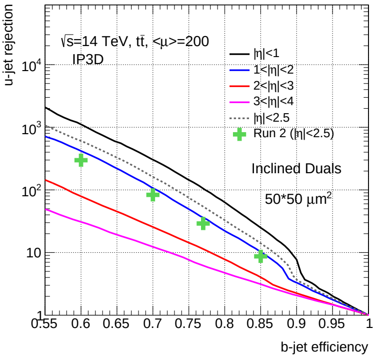
Gain in b-tagging performance



⇒ MV2 is a b-tagging discriminant based on training Boosted Decision Trees (BDT) and incorporates IP3D as input.

⇒ Making use of the ITk categories enhances greatly the performance: up to 100% @70% b-tagging efficiency.

Gain in b-tagging performance w.r.t Run 2



- Adopting the new track categorization for ITk not only recovers the Run 2 b-tagging performance but also **exceeds** it.
- These plots are included in the ITk pixel TDR (currently in the review process).

Summary and outlooks

$t\bar{t}+\geq 1b$ modeling for the $t\bar{t}H(b\bar{b})$ analysis

- ⇒ The top Yukawa coupling is a great probe to shed light on new physics.
- ⇒ $t\bar{t}H(b\bar{b})$ grants direct access to observe the top Yukawa coupling.
- ⇒ The bottleneck of this analysis is the poor modeling of the overwhelming $t\bar{t}+\mathrm{jets}$ ($t\bar{t}+\geq 1b$) background.
- ⇒ In depth studies of the $t\bar{t}+\geq 1b$ process have been carried out to understand better the differences among the available MC predictions.
- ⇒ Providing differential measurements of $t\bar{t}+\geq 1b$ is becoming critical to provide inputs for theorists to improve the modeling of this process.

B-tagging upgrade studies for ITk

- ⇒ ATLAS will replace the ID with ITk to cope with HL-LHC extreme conditions.
- ⇒ B-tagging is a crucial tool for analyses involving b-jets and it has to be optimized taking into account the new tracker geometry.
- ⇒ New track categorization has been designed and optimized in terms of b-tagging performance for IP3D. It results in even better performance w.r.t to Run 2 with ID.


THANK YOU FOR YOUR ATTENTION
ANY QUESTION?
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Backups

Poor modeling of $t\bar{t}$