Flavour tagging at HL-LHC

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Game of Flavours, CMS Heavy flavour tagging Workshop,
Dubrovnik, 30 April - 3 May 2019
why the HL-LHC?

• strong case to go on exploring the TeV scale:
  – Standard Model works very well but does not explain everything
    • low mass of Higgs boson and naturalness hypothesis advocate for the existence of new particles at the TeV scale
    • SM does not provide Dark Matter particle candidate
  – currently no evidence for new physics

• HL-LHC will deliver 3000 - 4000 fb\(^{-1}\), allowing
  – detailed studies of the Higgs boson: standard model or BSM?
  – precise measurements of standard model, rare processes: indirect evidence for new physics?
  – search for new particles and processes at the TeV scale (dark matter candidate)
  – investigate any anomaly / signal found at Run 3
Phase-2 luminosity
- instantaneous: $5.0 \text{ to } 7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- integrated: 3000 to 4000 fb$^{-1}$

Challenges
- high pileup from 140 to 200
- high irradiation
Phase-2 detectors requirements

- maintain and improve the current physics performance during the entire HL-LHC
- detectors must resist to the high radiation levels: many have to be replaced in LS3!
- improve the detector granularity (trackers, forward calorimeters)
- install timing layers
- fast trigger and fast read-out
- higher band-width
  - up to 10 / 7.5 kHz in ATLAS/CMS with 5 times more tracks and >5 times more channels)
- computing challenge!
ATLAS and CMS upgrades

- tracker granularity increased by a factor ~5 (pixel and strips), reduced material by a factor 2, pixel extension up to $|\eta| < 4$
- precision timing detectors
- track reconstruction in hardware trigger:
  - ATLAS: 1 MHz (up to 4 MHz) with regional tracker readout (Fast TracKer)
  - CMS: 40 MHz with outer tracker (track $p_T > 2$-3 GeV) (track-$p_T$ at L1)
- new read-out electronics for calorimeters
- new high granularity calorimeter in endcap for CMS ($1.5 < |\eta| < 3.0$)
- extended muon detector coverage (up to $|\eta| < 2.8$)
Phase-2 tracker: ATLAS

All silicon tracker

Strip detector:
- 4 barrel layers + 2x6 endcap disks
- acceptance up to $|\eta| < 2.6$
- modules with stereo angles (52 mrad barrel / 40 mrad endcap)
  - $\geq 2$ measurements / layer or disk

Pixel detector:
- 5 barrel layers (4 layers Phase 1) of inclined dual sensors for $|\eta| > 1$  
  - reduces material (and cost) and improves tracking performance
- endcap rings allowing improved coverage (with reduced material) up to $|\eta| < 4.0$ ($|\eta| < 2.5$ Phase 1)
- pixel pitch 50 x 50 $\mu$m$^2$ (50 x 250 (400) $\mu$m$^2$ Phase 1)
Phase-2 tracker: CMS

- **Outer Tracker**: design driven to provide tracks ($p_T > 2$-$3$ GeV) at 40 MHz to the **L1 trigger** => each module consists of 2 closely spaced sensors (~mm)
  - **Pixel-strip (PS) modules**: macro-pixel (1.5 mm x 100 µm), strip (2.4 cm x 100 µm) tilted in Barrel (hermetic coverage with less modules)
  - **Strip-strip (2S) modules**: strips (5 cm x 90 µm)

- **Inner Tracker (Pixel)**:
  - extended coverage up to $|\eta| < 4.0$
  - 6x better granularity than current Phase 1 pixel: 50x50 µm² or 25x100 µm² considered
  - improved material budget and radiation tolerance

> 1 billion pixels and strips
ATLAS: endcap disks $2.4 < |\eta| < 4.0$

CMS: barrel layer + endcap disks $|\eta| < 3.0$

- pileup vertices spread along beam direction ($\sigma_z \sim 5 \text{ cm}$) and time ($\sigma_t \sim 190 \text{ ps}$): precision timing ($\sigma_t \sim 35 \text{ ps}$) for charged (and neutral) particles allows to reduce pileup contamination
  - $\rightarrow$ 4D (space+time) vertex reconstruction
  - $\rightarrow$ factor 4-5 reduction of vertex merging rate and number of pileup tracks associated to the signal primary vertex (PV)

see talk from Paolo Meridiani
Muon reco+id efficiency

Muon detectors in Phase-2:

- will benefit from the improved tracking resolution and coverage
- muon id extended from $|\eta| < 2.5$ to $2.7$ (ATLAS) and from $|\eta| < 2.4$ to $2.8$ (CMS)
- important to be able to measure the b-tagging efficiency at HL-LHC with real data using muon-jets in multijet events or isolated muons (and electrons) in ttbar events

Note: without new small wheel
track resolution

• improved resolution and extended $\eta$ range with Phase-2 pixels (here for muons)
  • transverse impact parameter resolution $\sigma(d_0)$ crucial for b-tagging

for CMS, see talk from Mia Tosi:

here and in the following simulated performances:
ATLAS: 50x50 $\mu$m$^2$ pixels
  no timing used
CMS: 100x25 $\mu$m$^2$ pixels
  timing in some b-tag plots

20 $\mu$m

10 $\mu$m

1%
track efficiency and fake rate

- using tracks from PV, reconstruction efficiency > 85% for $p_T > 1$ GeV
  keeping low fake rates even at high pileup and high $|\eta|$.
- benefit from the large number of sensitive layers and of the reduced material.
track efficiency in jet core

• improved tracking in jet core thanks to better tracker granularity
• important for high $p_T$ jets and boosted objects measurements!
• good primary vertex reconstruction efficiency, even at high pileup
• timing will help to reduce merged PVs along z
PV selection efficiency

- based on vertex with highest $\Sigma p_T^2$ for tracks (ATLAS) or for track jets + MET (CMS)
- high efficiency but reduced for physics signals with fewer jets or charged particles
**b-tagging performance**

**ATLAS:** b-tagging capability up to $|\eta| < 4$

improved performance wrt Run 2, even at high pileup

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**about MV2, see talk from Chris Pollard:**
https://indico.cern.ch/event/795581/contributions/3335184/attachments/1837023/3010236/CMSFTag20190502.pdf
**b-tagging performance (cont.)**

**CMS:**
- b jet tagging efficiency and c and light jets mistagging parametrized as a function of jet $p_T / \eta$ for Delphes studies
- performance preserved for high $p_T$ jets in the full acceptance

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**here for DeepCSV, see talk from Petra Van Mulders:**
**CMS:** with timing information, b-tagging performance improves and is moderately sensitive to the high pileup conditions.

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**CMS Phase-2 Simulation**

$t\bar{t}$, $PU = 200$, jet $p_T > 30$ GeV

- udsg jet misid. = 0.01
- without MTD
- with MTD

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LHC  

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HL-LHC
ATLAS and CMS: expect that most of the systematics will be reduced by a factor up to 2 at HL-LHC (as compared to now)

- light jet mistag: 5% / 10% / 15 % uncertainty for 10^{-1} / 10^{-2} / 10^{-3} udsg efficiency)
- b jet tagging uncertainty (1% min.): c jet mistag rate uncertainty:

- applied to HL-LHC physics prospects (CERN Yellow reports 2019)
Conclusion

- the new detectors going to be built for the Phase 2 upgrades deserve to be exploited with the best precision and efficiency

- significant efforts have been deployed to evaluate their (promising) performance in realistic conditions

- but much has still to be done to improve the simulation, reconstruction and objects identification, especially to cope with the high pileup environment

- new developments have already started in order to define the future triggers and to innovate in using computing resources.
references

- **ATL-PHYS-PUB-2019-005:** [https://cds.cern.ch/record/2655304](https://cds.cern.ch/record/2655304)
  - Expected performance of the ATLAS detector at the High-Luminosity LHC

- **ATLAS-TDR-030, CERN-LHCC-2017-021:** [https://cds.cern.ch/record/2285585](https://cds.cern.ch/record/2285585)
  - Technical Design Report for the ATLAS Inner Tracker Pixel Detector

- **ATLAS-TDR-026, CERN-LHCC-2017-017:** [https://cds.cern.ch/record/2285580](https://cds.cern.ch/record/2285580)
  - Technical Design Report for the Phase-II Upgrade of the ATLAS Muon Spectrometer

- **CMS-NOTE-2018-006:** [http://cds.cern.ch/record/2650976](http://cds.cern.ch/record/2650976)
  - Expected performance of the physics objects with the upgraded CMS detector at the HL-LHC

- **CERN-LHCC-2017-027:** [http://cds.cern.ch/record/2296612](http://cds.cern.ch/record/2296612)
  - Technical Proposal for a MIP Timing Detector in the CMS experiment Phase 2 upgrade

- **CMS-TDR-019, CERN-LHCC-2017-023:** [http://cds.cern.ch/record/2293646](http://cds.cern.ch/record/2293646)
  - The Phase-2 Upgrade of the CMS Endcap Calorimeter

- **CMS-TDR-014, CERN-LHCC-2017-009:** [https://cds.cern.ch/record/2272264](https://cds.cern.ch/record/2272264)
  - The Phase-2 Upgrade of the CMS Tracker
additional material
Trigger/DAQ upgrades

ATLAS

- L0 muons calorimeters (40 MHz)
- L1 Tracks (1 MHz)
- Switching network (400 kHz)
- HLT (Up to 10 kHz)
- Processor farms (30 GB/s)
- Readout buffers (6 µs)

CMS

- CMS Outer Tracker tracks Pt ≥ 2 GeV
- CMS full Tracker RO
- 750 kHz (5 MB evt size)
- 30 Tbps (7.5 kHz)
- HLT (40 GB/s)
- Readout buffers (12.5 µs)

ATLAS option for 4 MHz L0 regional Tracker RO

High Level trigger output

from D. Contardo, Split 2018