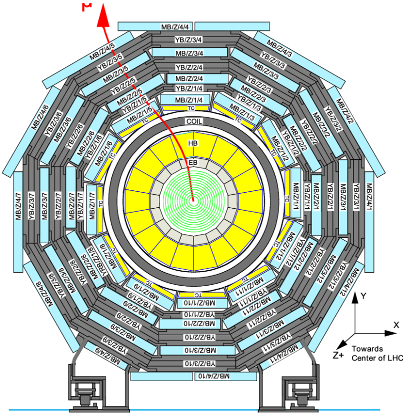
A muon tracking algorithm for Level 1 trigger in the CMS barrel muon chambers during HL-LHC

Jaime León Holgado

On behalf of the CMS Collaboration

International Conference on High Energy Physics 2020, July 29th

More information about this talk can be found *here*.



In the CMS barrel, muon trigger and reconstruction are performed by the Drift Tube chambers (DT), complemented by a system of RPC.

High Luminosity-LHC

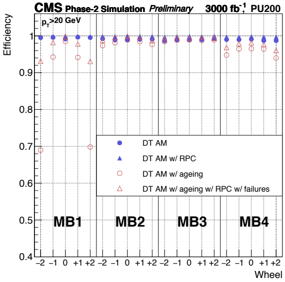
- **Increasing** LHC instantaneous luminosity up to 7.5×10^{34} from the present 2×10^{34} $\text{cm}^{-2}\text{s}^{-1}$.
- Present DT on-detector electronics going to be substituted for a system that digitalizes signals and pushes every hit to a new back-end in charge of **trigger primitive** generation.

The Analytical Method (AM)

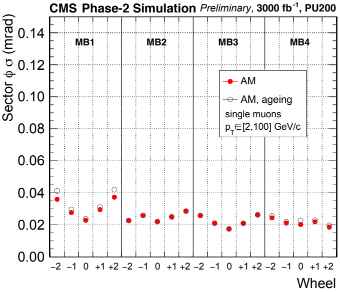
1. Grouping.
2. Fitting.
3. Correlation.
4. DT+RPC Super-primitive combination

Performance evaluation in simulation

- The algorithm's performance has been evaluated in a sample of simulated single-muons with an average pile-up of 200 collisions/BX.
- **Efficiencies** are calculated with respect to offline segments with quality cuts and geometrically matched to the generated muons. Only trigger primitives in the right BX are considered efficient.
- **Resolutions** are computed with respect to the simulated hits in the muon chambers.



Good efficiency in the whole detector, small decrease from ageing expected (at HL-LHC end).



Sector ϕ resolution (< 0.05 mrad) improving $\sim$ 6 times w.r.t Phase 1.

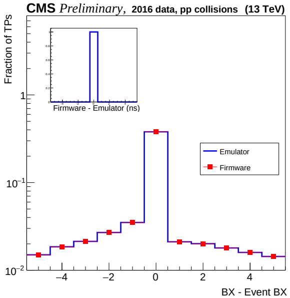
Performance evaluation in data

Firmware-emulator comparison

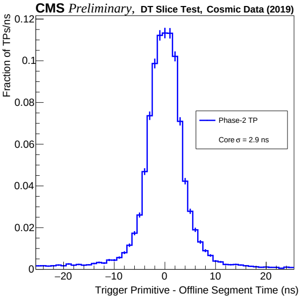
- Injecting hits from selected $Z \to \mu\mu$ events from 2016 real collision data.
- Comparing the primitives obtained with the same hits and lateralities in firmware and emulator.

DT Slice Test

- One CMS sector instrumented with the new front-end and back-end prototypes.
- One of these back-end boards runs the AM firmware, so it can be validated using real cosmic muons.



Agreement to the Least Significant Bit.



Inherent online time resolution of few ns.

The CMS Level-1 Endcap Muon Trigger at the High-Luminosity LHC

Virtual

40th International Conference of High Energy Physics

July 29th, 2020

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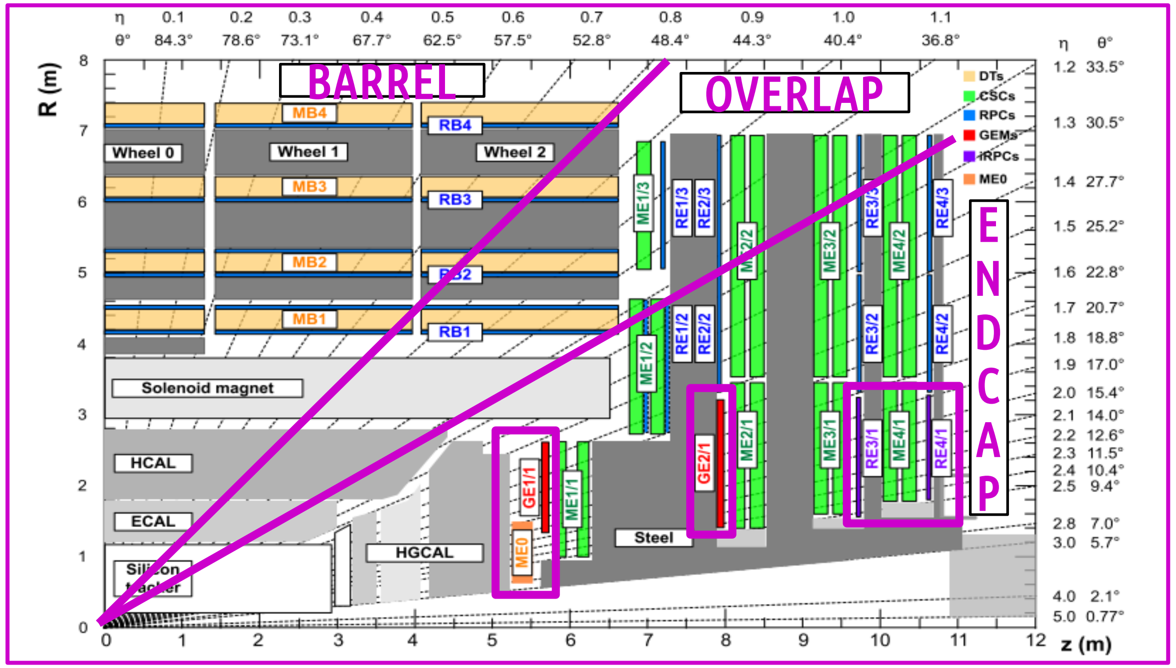
CMS Phase-2 Muon Detectors & Level-1 Trigger Upgrade

New territory to be explored at the High Luminosity-LHC

- $\sqrt{s}$ = 14 TeV pp collisions, 7.5 x $10^{34}cm^{-2}\,s^{-1}$ instantaneous luminosity, 200 pile-up (PU)
- Challenging data-taking conditions: High particle multiplicity & intense radiation environment
- Upgrades to overcome challenges & fully exploit 4000 fb^{-1} of integrated luminosity

Muon Subdetectors Upgrade

- Consolidated electronics in current Phase-1 chambers
- More accurate information for the Level-1 trigger
  - Position, time, quality & bend of local hits (stubs)
- Extended coverage in forward region (up to |η|=2.8)

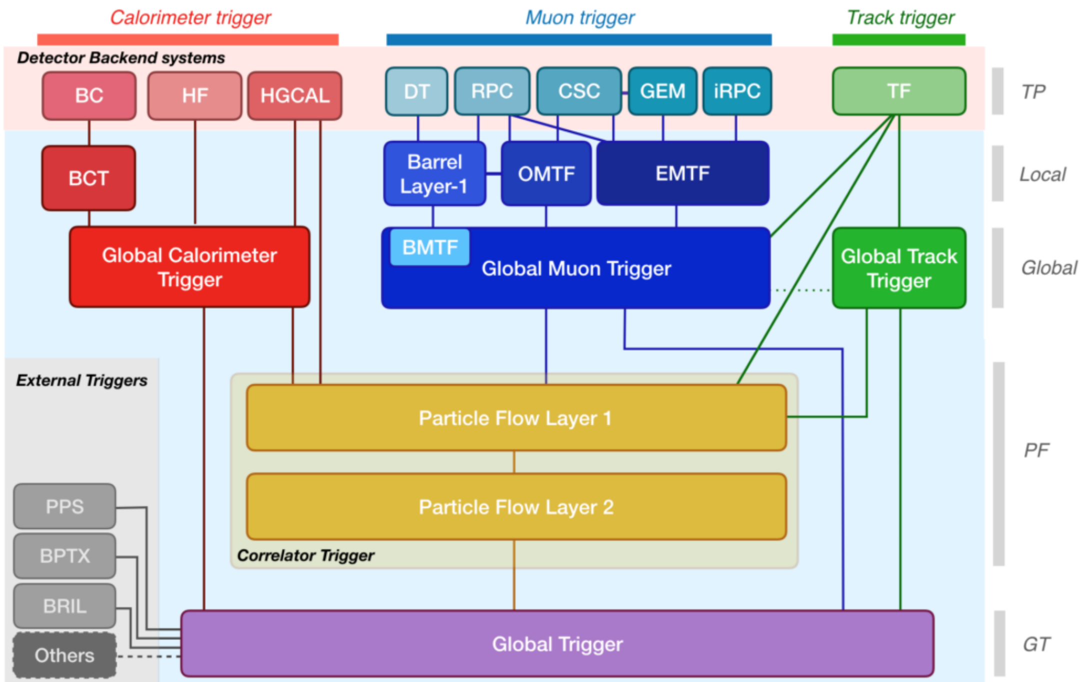


Level-1 Trigger Upgrade

12.5 μs latency

750 kHz output bandwidth

State-of-art hardware technologies



- Architecture with four independent trigger paths:
  - Calorimeter, muon, tracker & particle-flow
- New correlator layer:
  - Multiple objects correlation & high-level triggers generation

Triggering on endcap muons at the HL-LHC

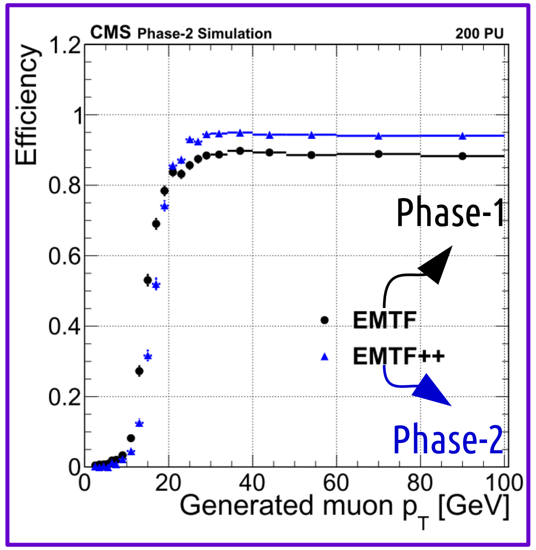
Momentum resolution improvement is key → Rate mitigation & access to lower trigger thresholds

LOCAL

Endcap standalone prompt muon reconstruction (EMTF++)

Region with complex detector geometry, nonuniform magnetic field & punch-through

- Set of stubs compatible with a muon track are found via pattern recognition
- Stub information is then used to get P_T-assignment using a neural network(NN)
- ~20 kHz rate at 20 GeV P_T threshold → ~2.5 x lower rate w.r.t. Phase-1 algorithm (EMTF)
- Similar technique allows for displaced muon reconstruction



GMT

Track-correlated muons in Global Muon Trigger (GMT) / Correlator

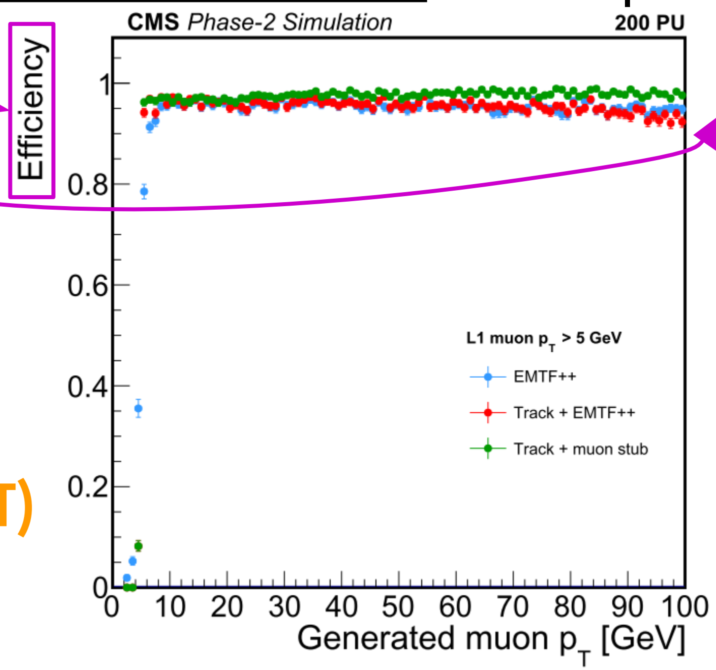
Tracker tracks (Tk) are matched to EMTF++ tracks or individual muon stubs via P_T-dependent $\Delta\phi/\Delta\eta$ windows to push further the performance:

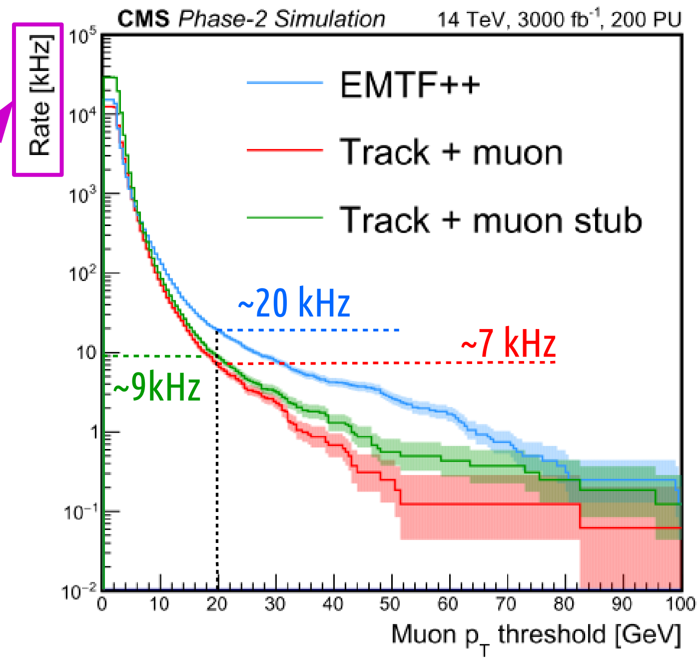
- Tk + EMTF++: 15-30%→3% P_T resolution
- Tk + muon stub: ~99% efficient for P_T >5 GeV

Topological muons, e.g. 'Muon-jet' with 3 objects

- Better acceptance at low P_T & forward region

  $\tau \to 3\mu$ decays: ~5-10 x better than Phase-1 trigger





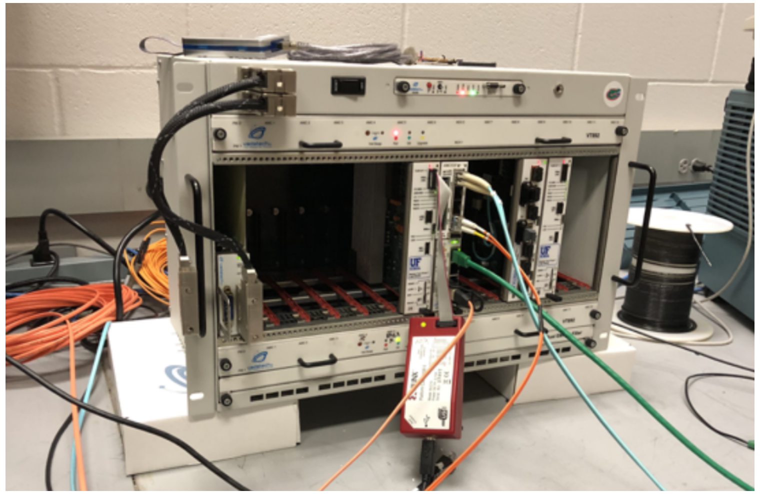
GT

All GMT objects are sent to the global trigger (GT)

to issue the L1 decision based on the menu of (muon) algorithms

HL-LHC Endcap Muon Trigger Prospects

Preliminary hardware demonstration



Endcap muon trigger demonstrator setup

We have tests already performed with Virtex 9 Ultrascale+ (VU9P) FPGA

- EMTF++ algorithm
  - Phase-1 track-building firmware
  - NN firmware is written in Vivado HLS via HLS4ML software
  - Resources will be able to accommodate prompt & displaced muons
- Tk + EMTF++ correlator
  - Firmware implementation is validated with simulated muons
  - Resource usage is modest & dominated by look-up tables

Summary and Outlook

- Broad physics phase space will be explored given the Phase-2 upgrades & the unprecedented large dataset
- The new and improved endcap muon trigger objects will enable a large part of the HL-LHC program
- First hardware demonstrators shows the feasibility of the new endcap muon algorithms
- A rich software, firmware and hardware program is on-going

References:

[1] CMS Collaboration, The Phase-2 Upgrade of the CMS Muon Detectors, CERN-LHCC-2017-012 (2017)

[2] CMS Collaboration, The Phase-2 Upgrade of the CMS Level-1 Trigger, CERN-LHCC-2020-004 (2020)

University of Colorado
Boulder

Performing precision measurements and new physics searches at the HL-LHC with the upgraded CMS Level-1 Trigger

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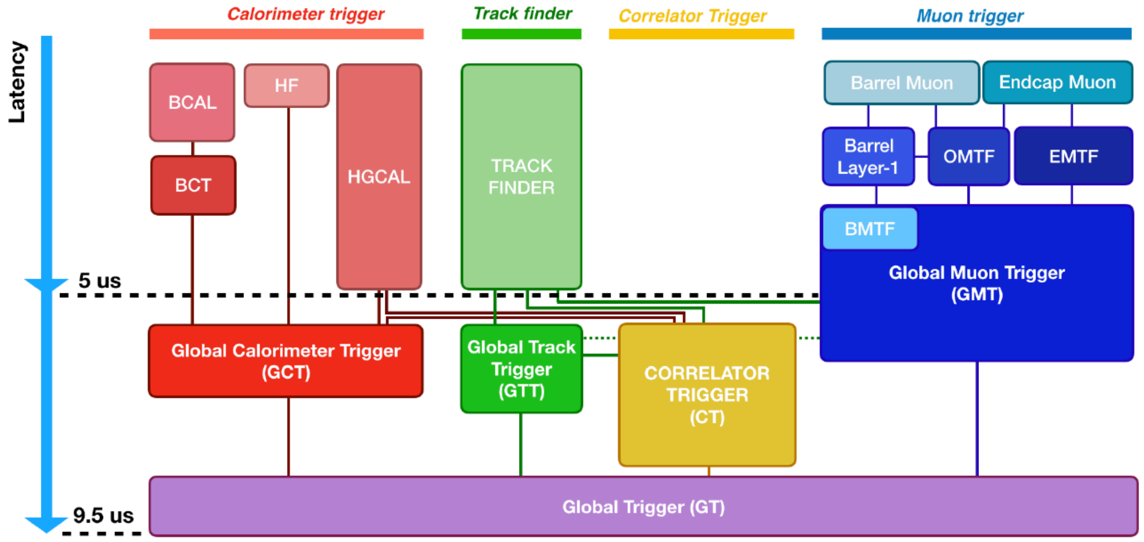
CMS Phase-2 Trigger

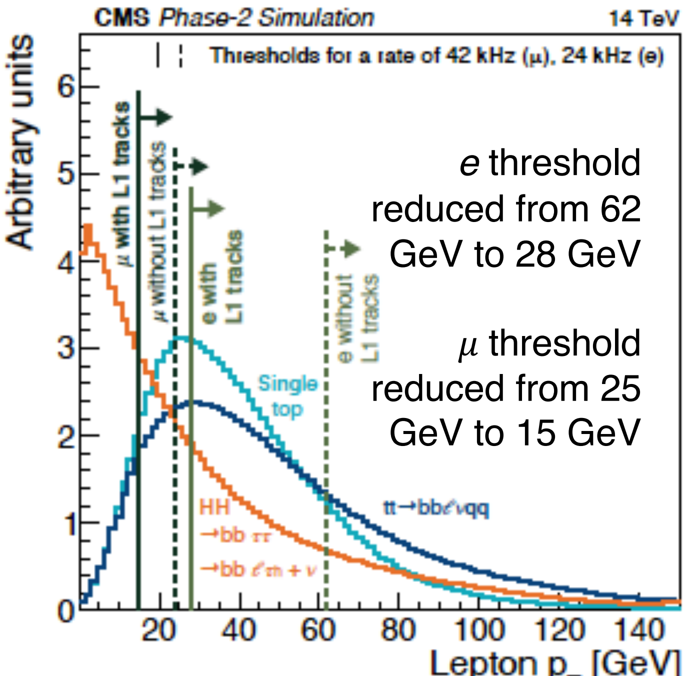
- Upgrades to the Level-1 (L1) trigger
  - Improved electronics to handle the increased pileup (PU)
  - Add tracking to L1 trigger
  - Increase total latency 12.5 μs
    - Allows use of information from the tracker and high-granularity calorimeter information
    - Allows more time for algorithms, including higher-level object reconstruction and identification
  - Improved algorithms
    - More information (increase from 2 TB/s to 63 TB/s)
    - Potential for particle-flow (global event) reconstruction
    - Potential for machine learning based approaches
- **Maintain physics performance from Run 2**
  - Improved algorithms achieve lower rates, even in a more challenging PU environment
- **Increase physics reach**
  - Tracking at Level-1, particle-flow algorithms, and machine learning based approaches can reach a broader spectrum of physics analyses



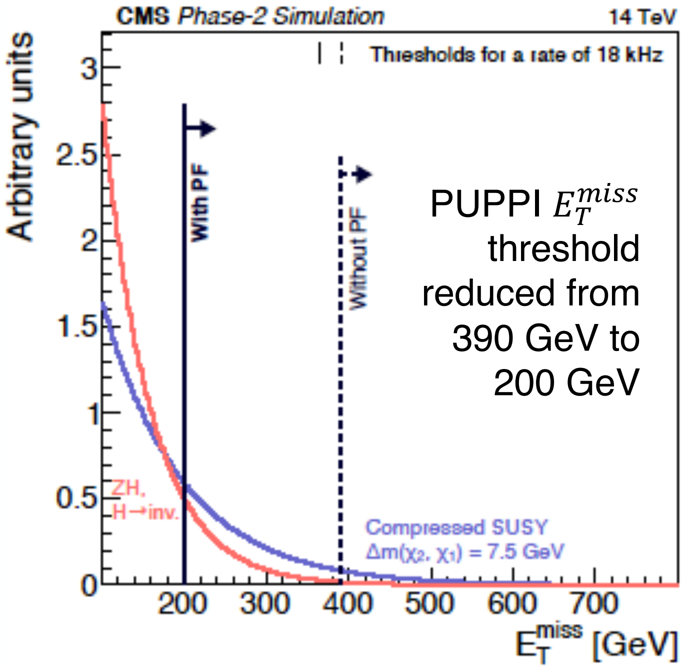
The CMS L1 Phase-2 upgraded trigger design

Reduced trigger thresholds

- L1 trigger menu can maintain the physics performance from the current running (Run 2), even at 200 PU
- Many of the upgraded trigger algorithms achieve lower rates
  - Releases bandwidth to allow for some lower thresholds
  - Choose thresholds to increase the acceptance for key physics signals (i.e. energy sums, lepton p_T, jets)



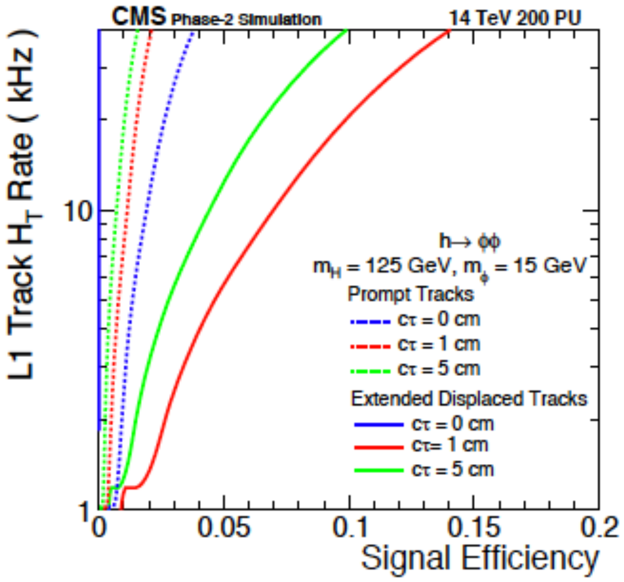
Use of tracking at L1 drastically reduces the p_T thresholds for electrons and muons

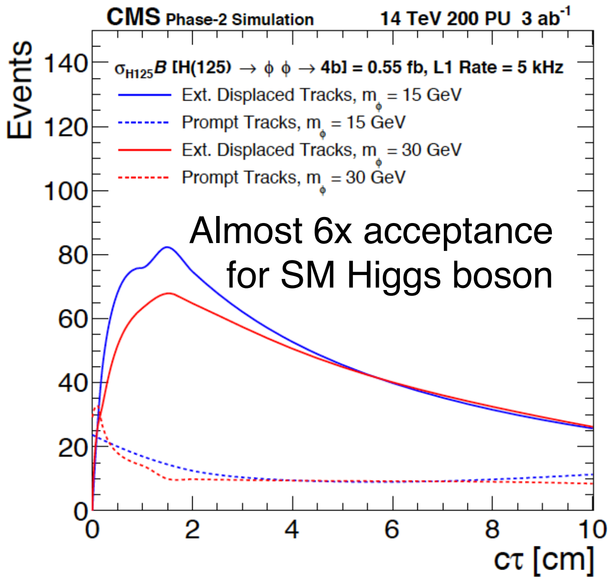


Use of particle-flow algorithms reduces the threshold for missing transverse energy by almost 200 GeV

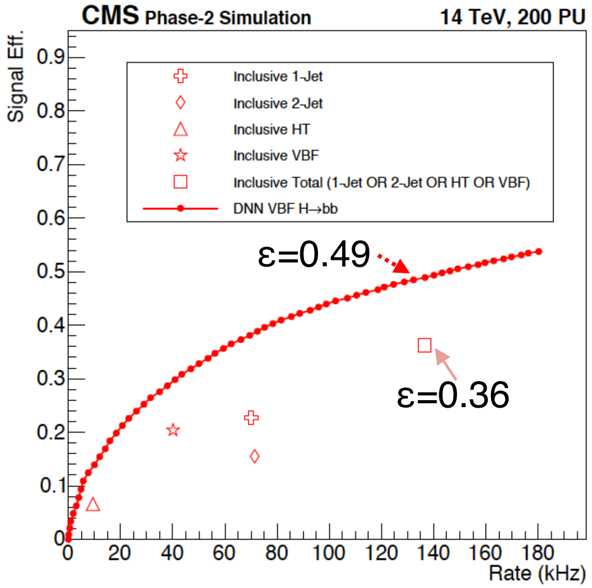
New physics searches

- Displaced jets:
  - An extension of the L1 track-finding, clustered tracks without a beamspot constraint
  - Provides a new handle to trigger on Beyond the Standard Model (BSM) physics, such as exotic decays of the SM Higgs





- Particle-flow and machine learning:
  - The τ trigger algorithm is based on a particle-flow approach combined with a dedicated neural network discriminator
  - Improved energy resolution of hadronic objects provided by particle-flow reconstruction is beneficial to the development of triggers targeting specific signatures such as VBF



A deep neural net outperforms all cut-based algorithms for an inclusive VBF $H \to b\bar{b}$ trigger

L1 Trigger Algorithms at CMS for the HL-LHC[1]

e/γ, Jets, E_T^{miss} and τ_h

Jack Li (Northeastern University)

On behalf of the CMS collaboration

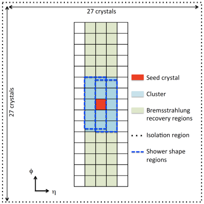
ICHEP, 28 Jul-6 Aug, 2020

[1]Based on CMS-TDR-021

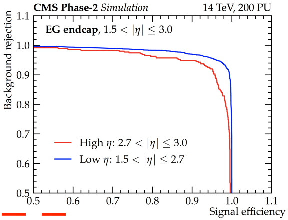
Electrons and Photons

- Calorimeter upgrades
  - Crystal granularity in barrel
  - New high-granularity calorimeter (HGCAL) in endcap

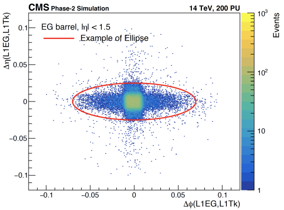
- e/γ reconstruction in barrel
  - Seeding+clustering+ ID&isolation



- e/γ reconstruction in endcap
  - 3D shower information provided by HGCAL
  - BDT is implemented
    - High background rejection & signal efficiency



- L1 tracks
  - Matched with calorimeter objects
  - Track isolation



Efficiency	calorimeter only	track-matched
30GeV	97.5%	84.5%
40GeV	98.7%	88.0%

Table 1: Single electron efficiency in the barrel

Rate	calorimeter only	track-matched
30GeV	78.2 kHz	19.0 kHz
40GeV	25.5 kHz	8.3 kHz

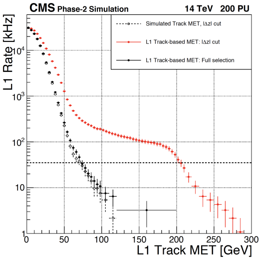
Table 2: Trigger rate of the barrel L1 objects

Summary

- Improved efficiency and resolution due to higher granularity
- Reduced trigger rate due to L1 tracks

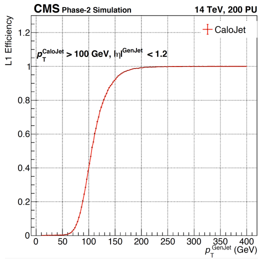
Jets and Energy Sums

- Track-only jet and MET
  - Relies on track purity
  - Reduces the threshold significantly (below)



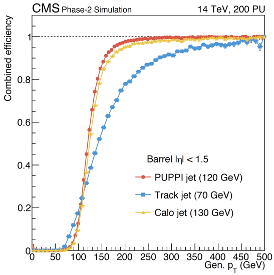
- Particle-flow (PF) based
  - Jets
    - The performance is close to that of the offline AK4 algorihtm when using PUPPI inputs
  - MET
    - Takes PUPPI inputs

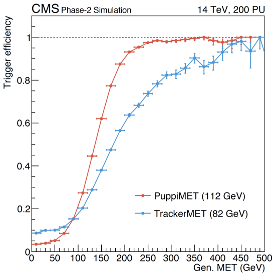
- Calorimeter-only jets (right)



Summary

- Improved resolution and efficiency for PF-based algorithm
- Standalone algorithms add robustness





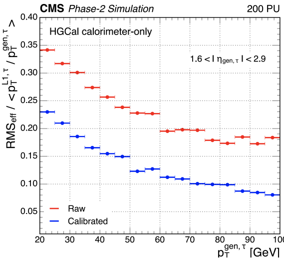
Hadronic τ

- Calorimeter-only τ_h
  - Similar to calorimeter based jet finding
  - Possible improvements in the HGCAL with BDT

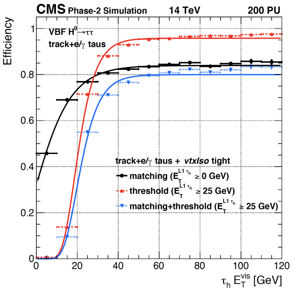
- Track+e/γ τ_h
  - Associates e/γ clusters with tracks
  - Simple yet efficient

- PF-based τ_h
  - Neural network + PUPPI inputs
  - More complicated firmware
  - Capable of identifying a τ_h every 25 ns

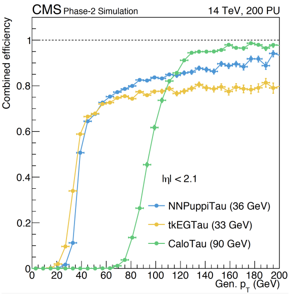
- Energy calibration with BDT regression (Calo-only)



- Track+e/γ



- Comparison of different algorithms (right)



Summary

- Different algorithms are complementary to each other

The Particle Flow Algorithm in the Phase II Upgrade of the CMS Level-1 Trigger

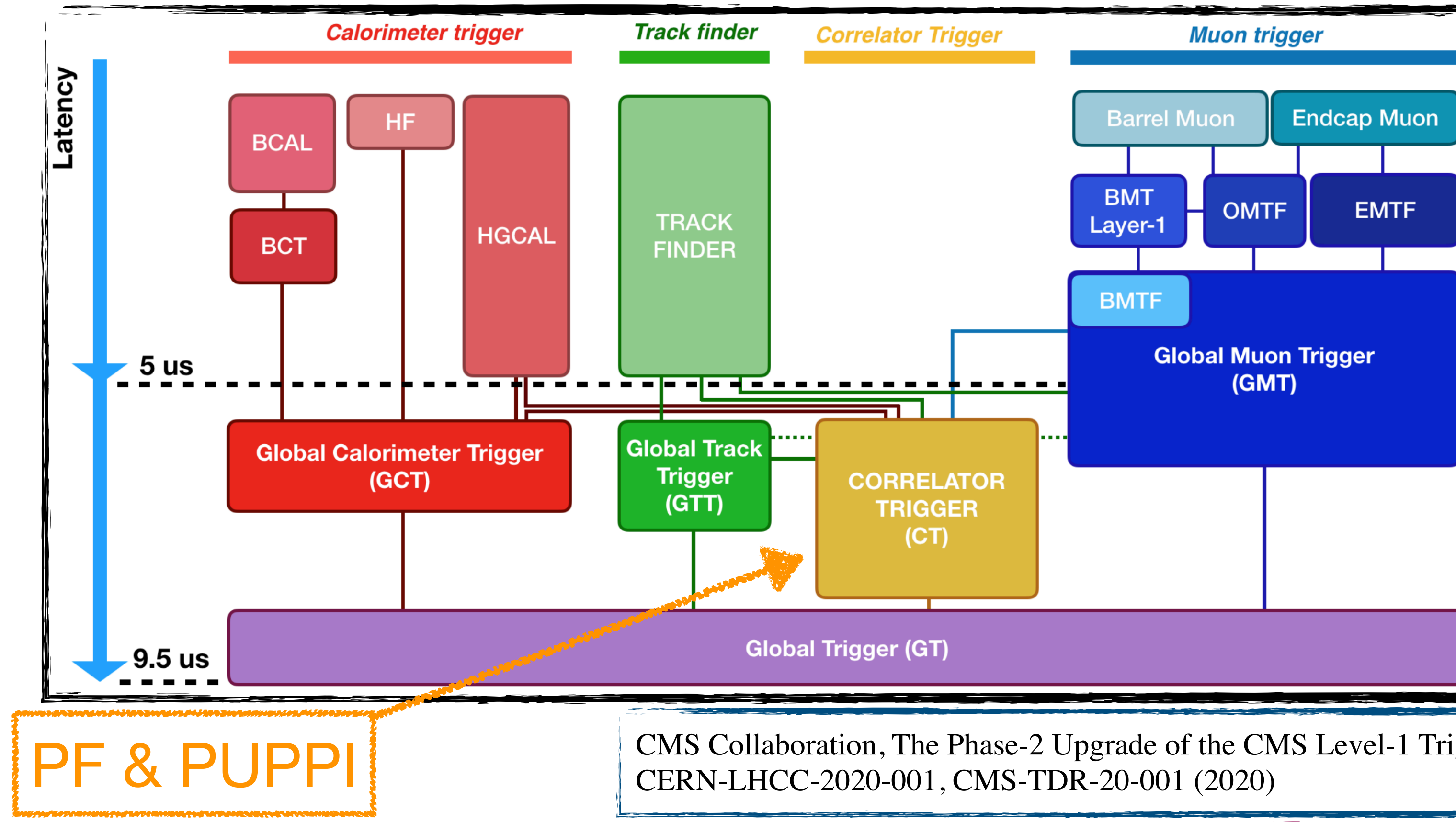
Dylan Rankin (MIT)
On behalf of the CMS Collaboration

ICHEP 2020

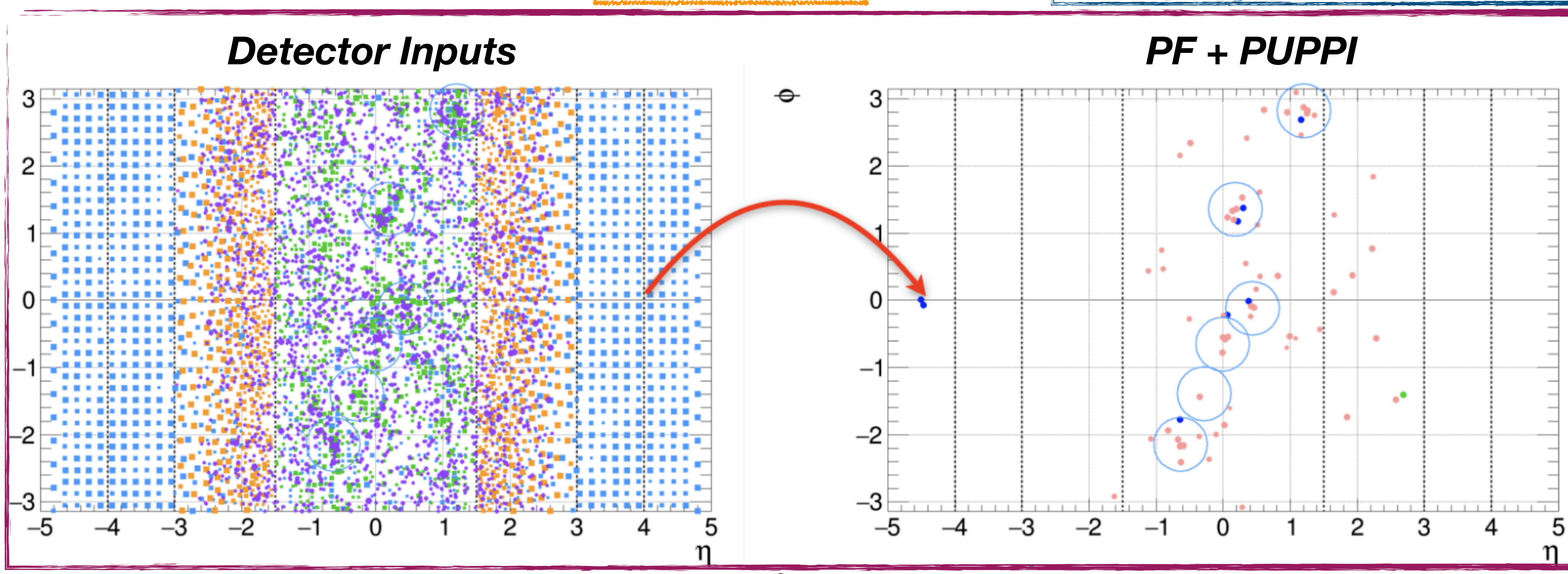
July 29th, 2020

Introduction

- Phase II CMS upgrade adds information from tracking detector to Level-1 trigger
- Enables (among others):
  - Particle flow (**PF**)
  - Pile-Up Per Particle Identification (**PUPPI**)
- Critical to maintaining performance in harsh HL-HLC environment, high pileup
- PF + PUPPI requirements:
  - Run in ~ 2 μs
  - Process events at 40 MHz

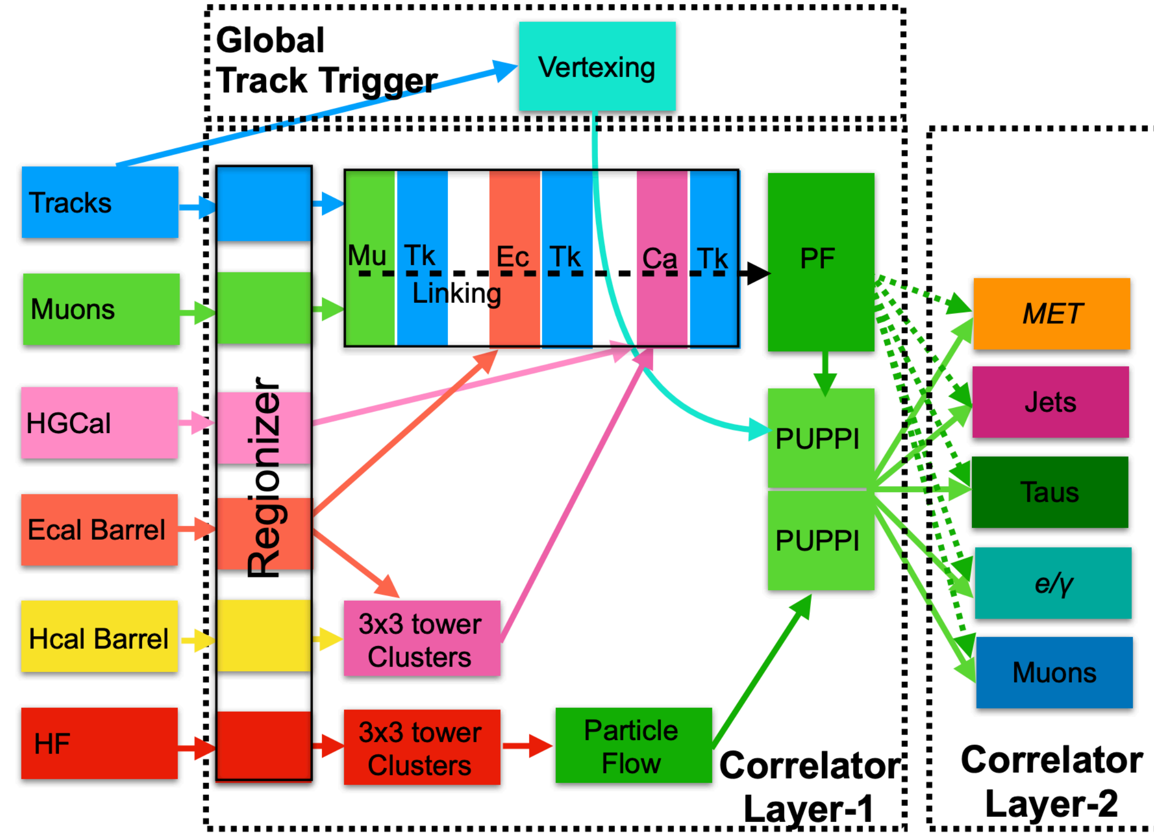


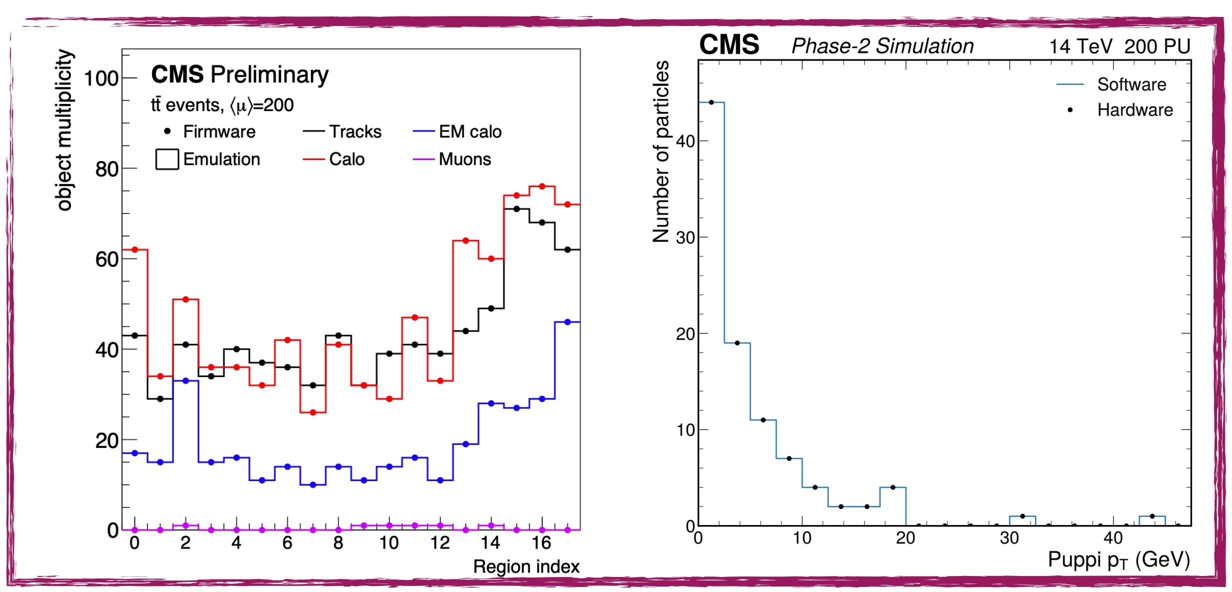
CMS Collaboration, The Phase-2 Upgrade of the CMS Level-1 Trigger, CERN-LHCC-2020-001, CMS-TDR-20-001 (2020)

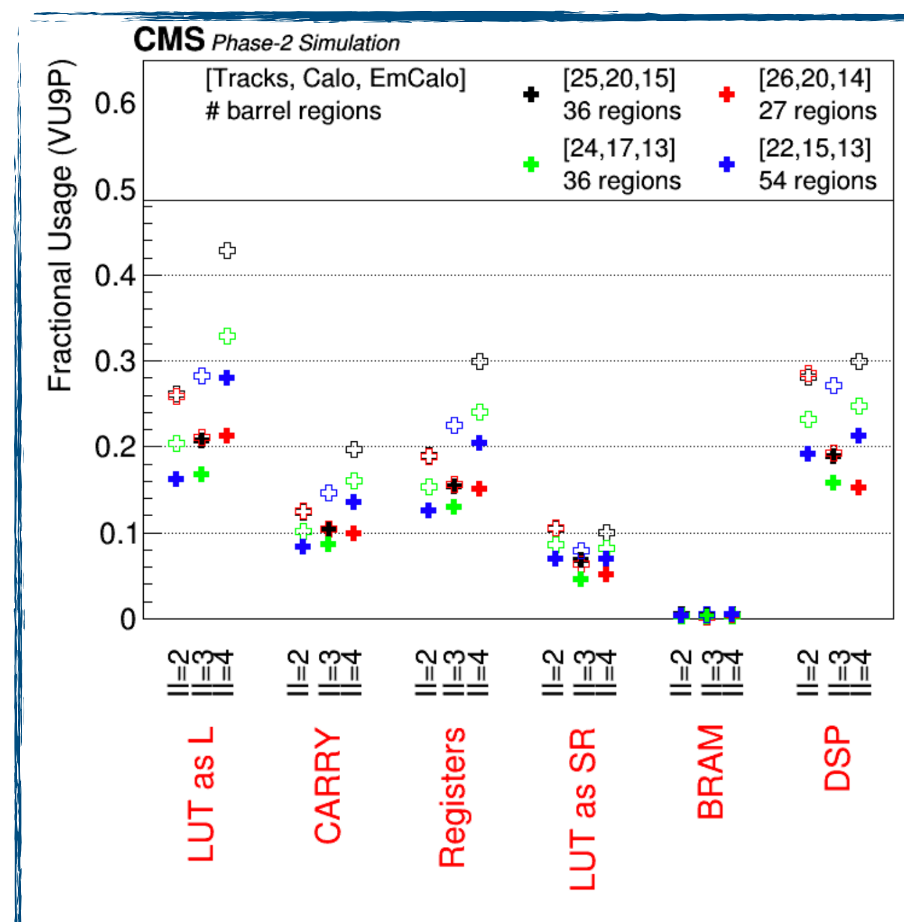


Implementation and Testing

- Design separated into multiple blocks to handle inputs from detectors with different rates and schemes
  - Layer-1
    - Partition inputs into regions (regionizer)
    - Particle flow
    - PUPPI
  - Layer-2
    - Object reconstruction
- Significant work in balancing performance and FPGA resources/latency
- Implemented using High Level Synthesis
- Tested on prototype boards with targeted Virtex Ultrascale 9+ (VU9P) FPGA, 25 Gbps GTY links
  - Perfect agreement between HW and emulation



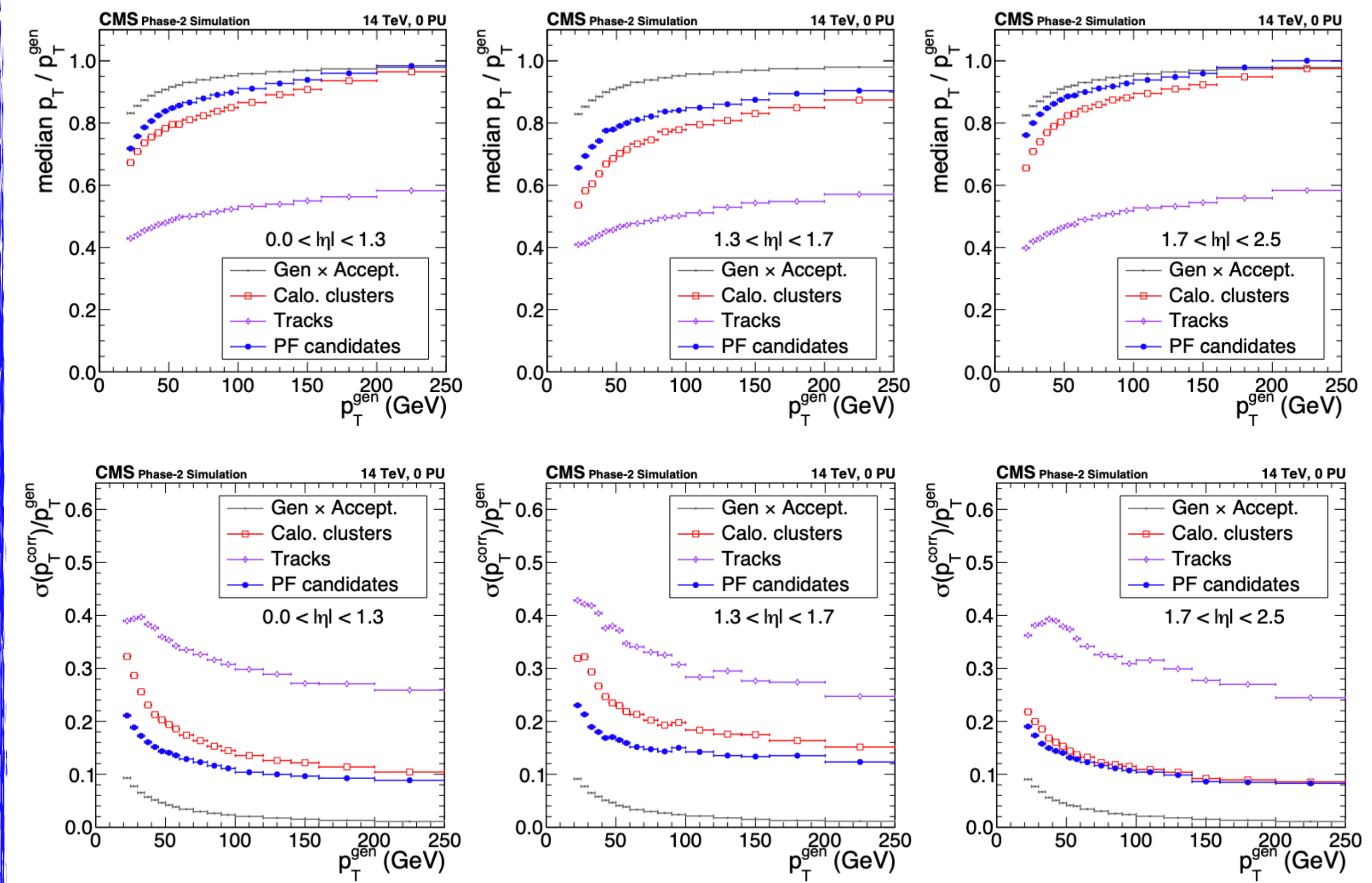




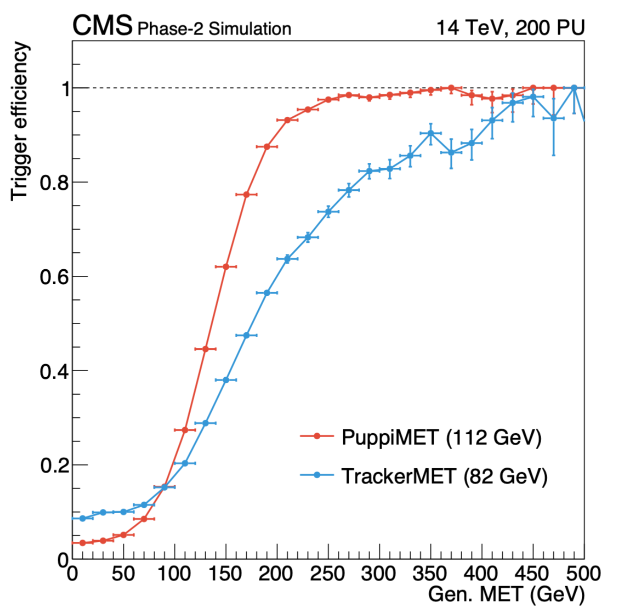
Performance

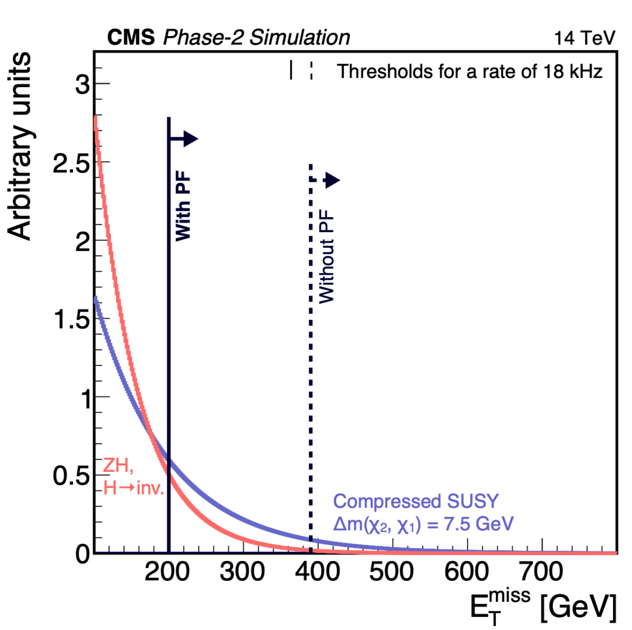
- Compared to calo- or track-only:
  - Improved jet response and resolution with PF
  - **Sharper** and **earlier** turn-ons possible with PUPPI across trigger landscape (MET, τ_h, H_T)
- Major gains in signal acceptance

Jets

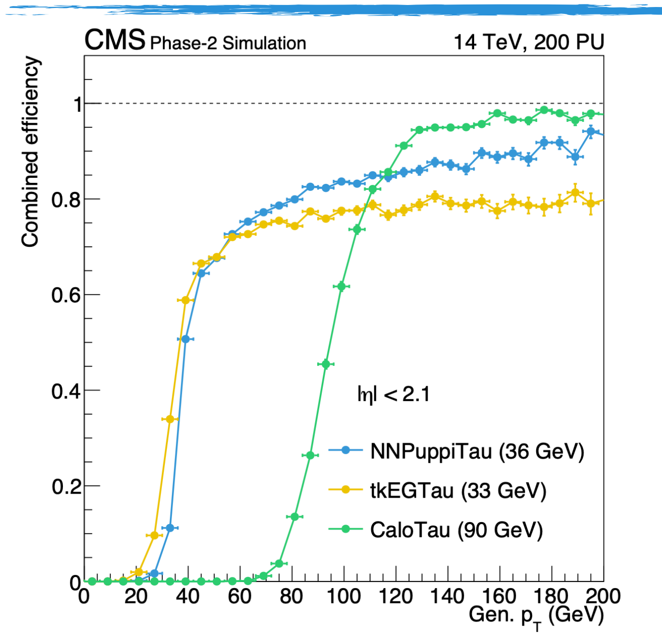


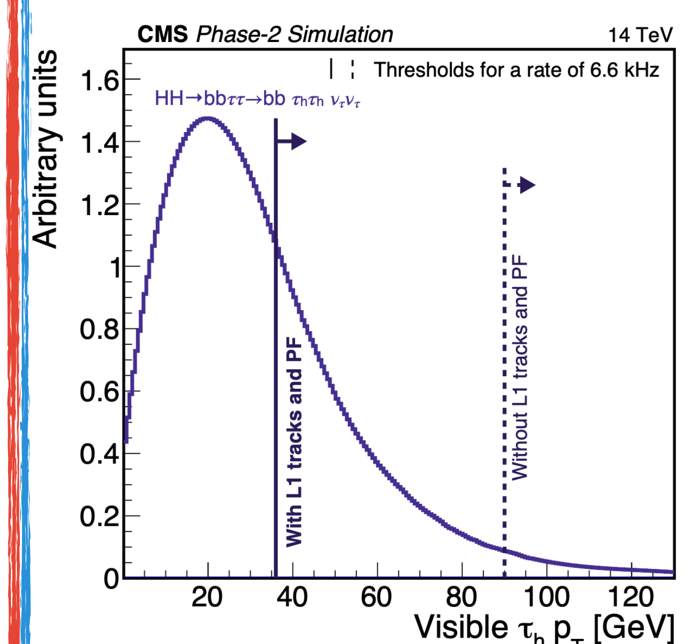
MET



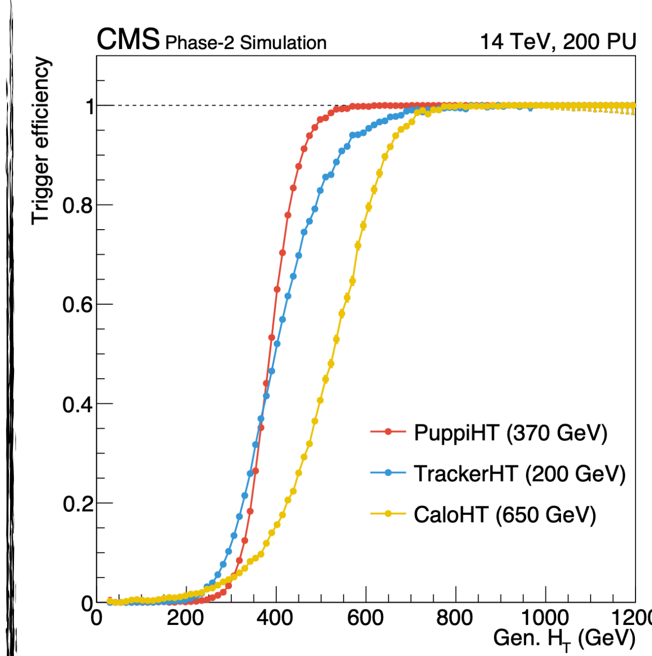


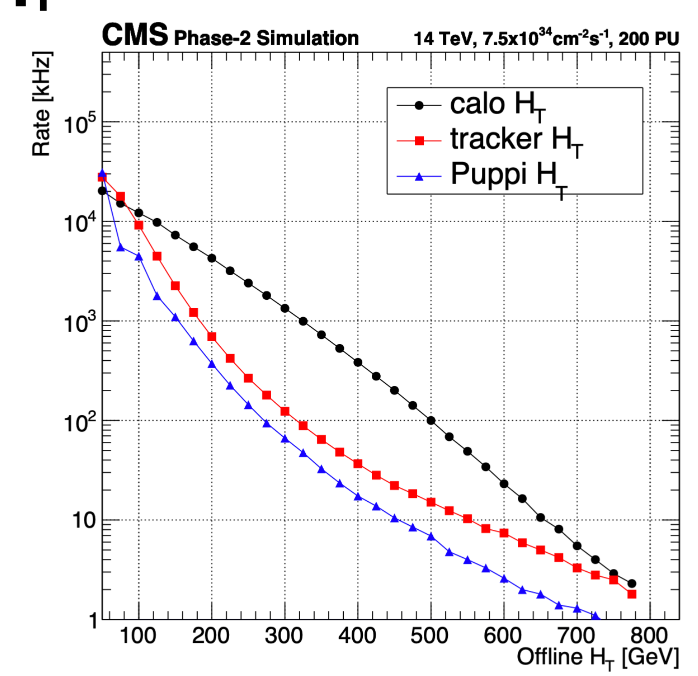
τ_h





H_T





Measurement of Liquid Scintillator Nonlinearity

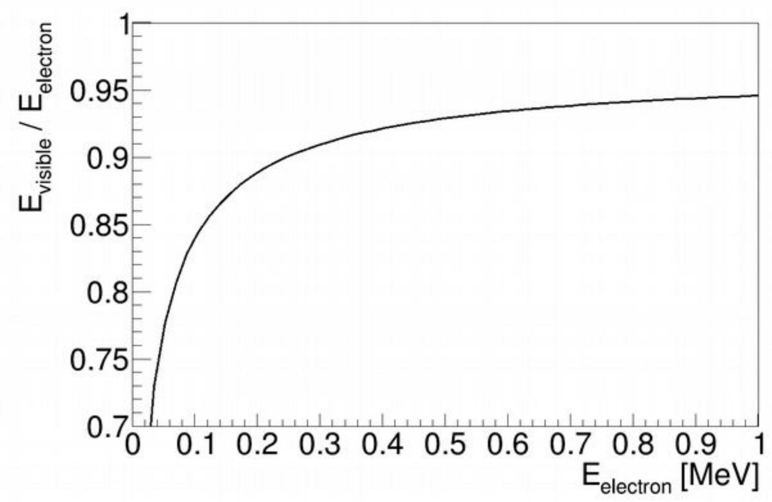
Tadeáš Dohnal[1], Vít Vorobel[1], Tomáš Tměj[1], Viktor Pěč[2]

[1]Charles University, Czech Republic
[2]University of Sheffield, United Kingdom

Liquid Scintillator Nonlinearity

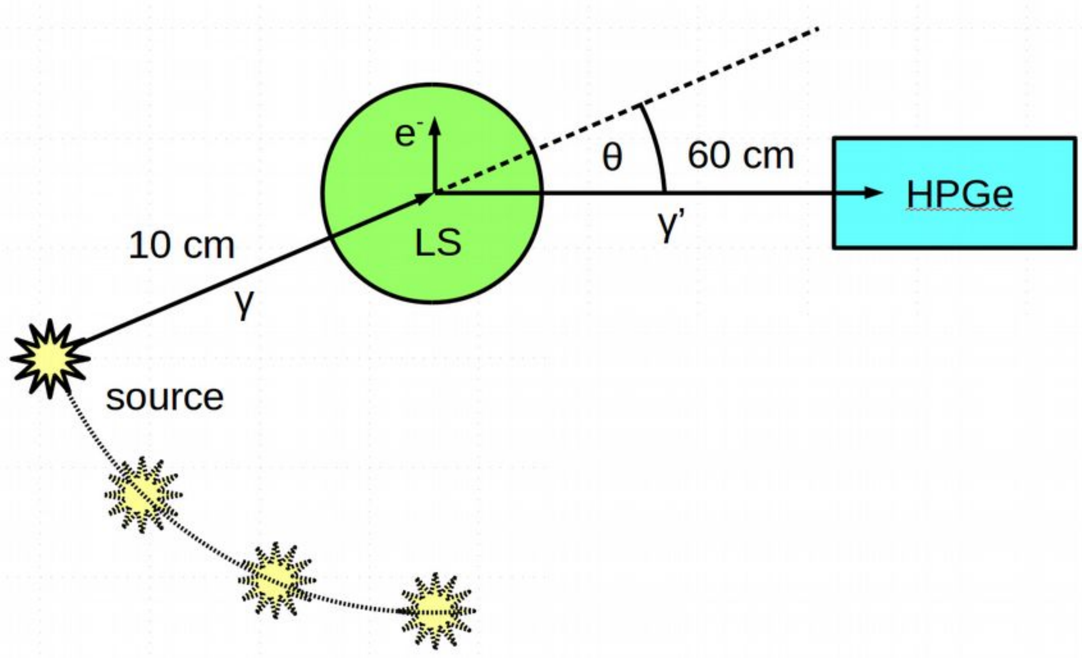
- In liquid scintillators, the dependence of the amount of scintillation light on the energy deposited by the incident particle is not exactly linear

Example for electron:



- Knowledge of nonlinearity is important for reactor neutrino experiments that commonly use liquid scintillators

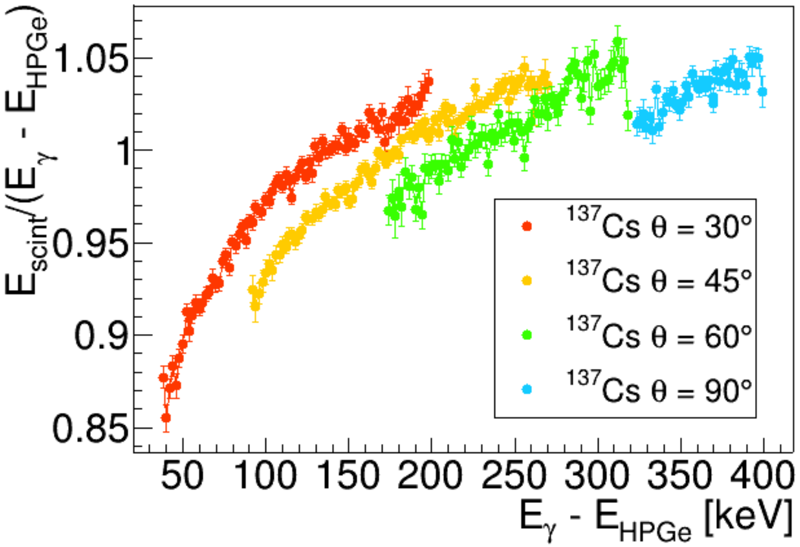
Experimental Setup



- Gamma of known energy scatters in the liquid scintillator
- Recoiled electron energy measured in the liquid scintillator
- Scattered gamma energy measured by HPGe detector
- Results are compared

Data Analysis & Preliminary Results

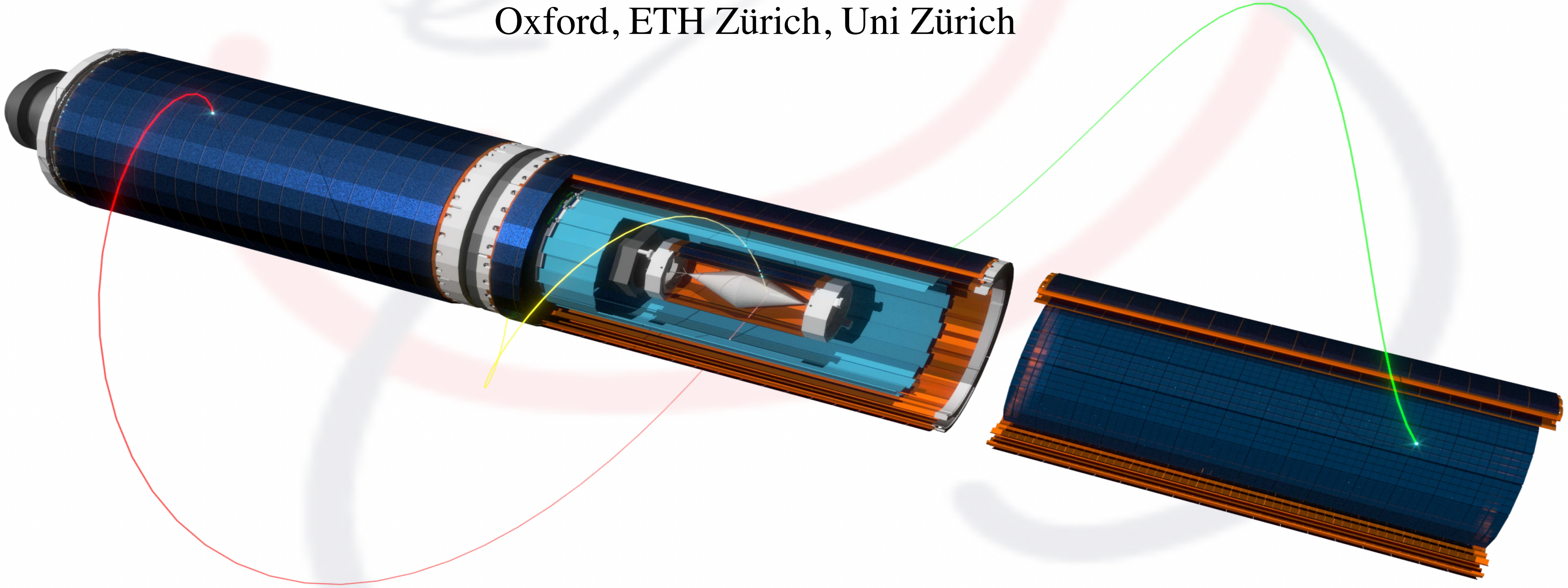
- Several samples measured, liquid scintillator nonlinearity observed in all of them
- There are many detector-induced effects which need to be addressed (detectors' own nonlinear responses, temporal instability, light collection & PMT efficiency nonuniformity etc.)
- Example of results:



The Mu3e Experiment Searching for the Lepton Flavour Violating Decay $\mu^+ \rightarrow e^+ e^+ e^-$

Afaf Wasili* on behalf of the Mu3e Collaboration**

*) University of Liverpool, Afaf.Wasili@Liverpool.ac.uk
**) Paul Scherrer Institute (PSI), Uni Bristol, Uni Geneva, Uni Heidelberg, KIT Karlsruhe, Uni Liverpool, UCL London, JGU Mainz, Uni Oxford, ETH Zürich, Uni Zürich



The Mu3e Experiment @ PSI

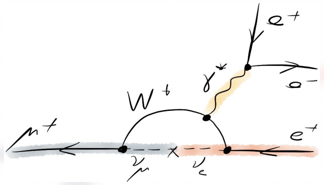
Motivation & Challenges

Search for Lepton Flavour Violation:

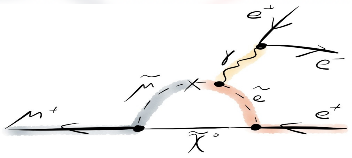
Decay : $\mu^+ \rightarrow e^+ e^+ e^-$

- Negligible in Standard Model (**Br < 10^{-54}**)
- Can be enhanced in New Physics : (SUSY, leptoquarks, etc.), any observed decay will point to NP

- Current status: **Br < 10^{-12} (SINDRUM)** at 90% CL
- **Mu3e Phase I**: Aiming for **O(10^{-15})** sensitivity at existing πE5 beamline**: 10^8 μ/s**
- **Mu3e Phase II**: Aiming for **O(10^{-16})** sensitivity at a new high-intensity muon beamline (HiMB)**: >10^9 μ/s**



Muon decay in the SM



Muon decay BSM (SUSY)

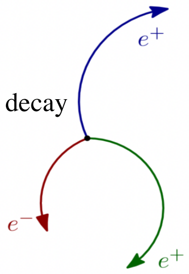
Signal:

- Three tracks: $\mu^+ \rightarrow e^+ e^+ e^-$
- Decay at rest
- $P_e < 53$ MeV/c
- Common vertex
- Coincide in time
- $\Sigma P = 0$, $\Sigma E = m_\mu$

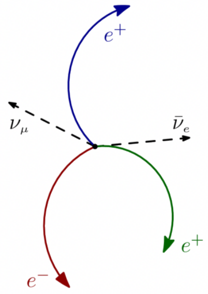
Background:

- Internal conversion background (IC BG): $\mu^+ \rightarrow e^+ e^+ e^- \nu^+ \nu^-$ (suppressed by good momentum resolution)
- Accidental background (Acc. BG): Michel $\mu^+ \rightarrow e^+ \nu^+ \nu^-$ with $e^+ e^-$, etc (suppressed by good time and vertex resolution)

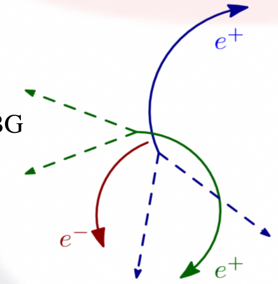
Signal decay



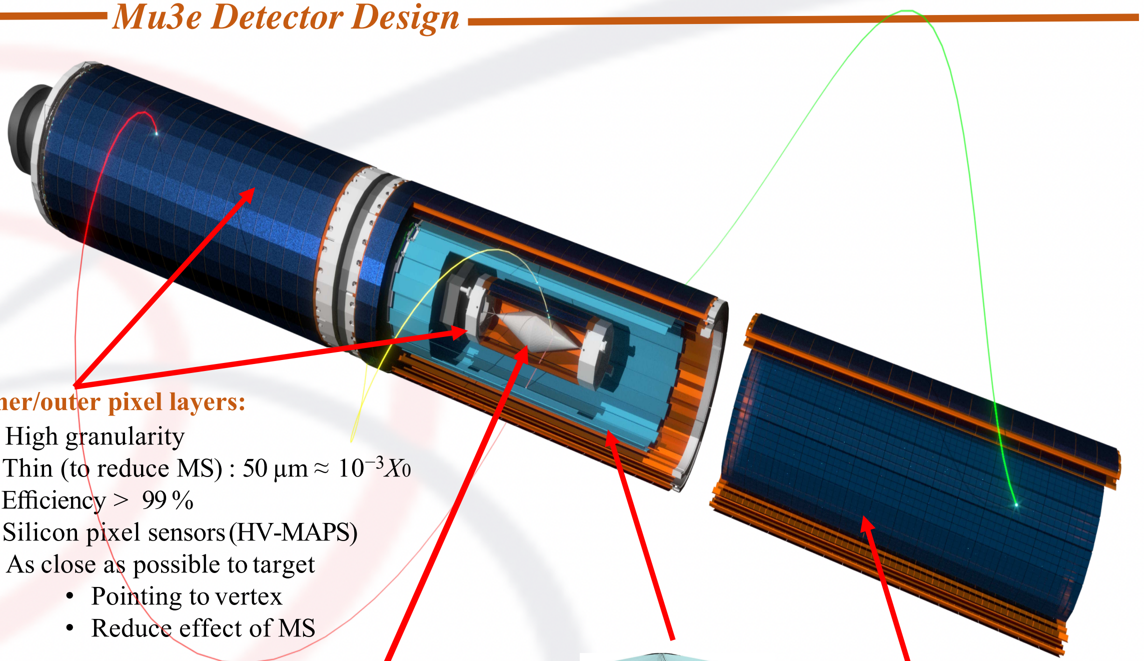
IC BG



Acc. BG

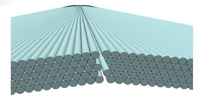


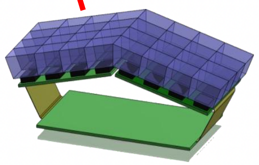
Mu3e Detector Design



Inner/outer pixel layers:

- High granularity
- Thin (to reduce MS) : 50 μm ≈ $10^{-3} X_0$
- Efficiency > 99 %
- Silicon pixel sensors (HV-MAPS)
- As close as possible to target
  - Pointing to vertex
  - Reduce effect of MS





Target:

- Hollow double cone Mylar stopping target
- vertex separation

Fibre/tile timing detector:

- Precise timing
- Suppress Acc. BG
- Charge ID

Simulation and Track/Vertex Reconstruction of the Mu3e Detector

Reconstruction

- Full detector Simulation (Geant4) in 50 ns framelength with 4.3v.v

Track Reconstruction

Triplet:

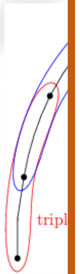
- Track is a sequence of triplets
- Basic block for track reconstruction
- 3 hits (combination 2 helices)
- Optimization the nonlinear problem multiple scattering

Short tracks:

- 4 hits in the silicon layers
- Seeds for long tracks

Long (recurl tracks):

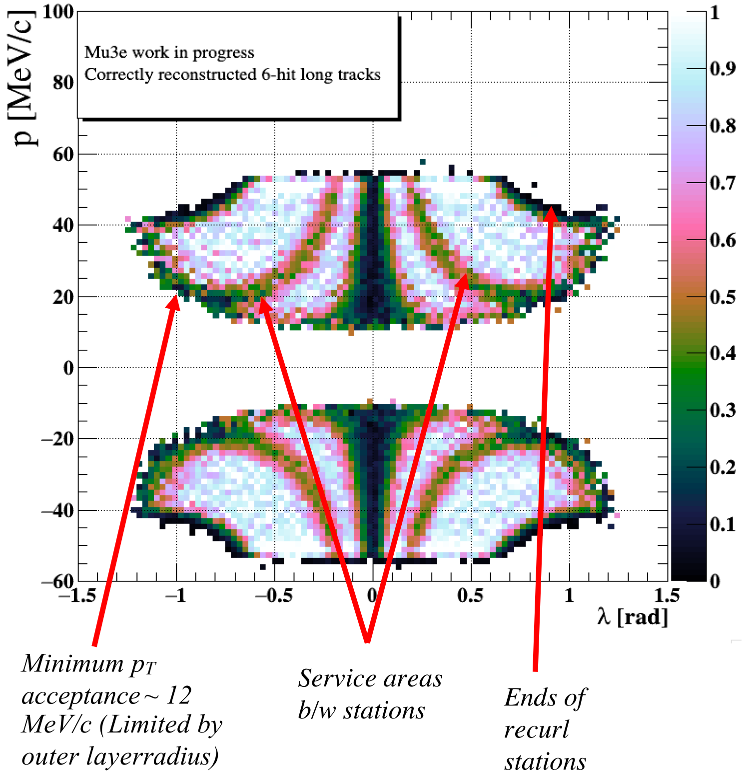
- Combine 1 short track with 2 hits in recurl detector (6 hits)
- Combine 2 short tracks (8hits)



Acceptance and Efficiency

- **Track reconstruction:** Building tracks from 4, 6- or 8-pixel hits.
- **Detector performance and efficiency:** (radius of outer layer is represented by the lower edge in the efficiency plot, length of the detector is represented by missing corners and gaps between stations), the mu3e detector has a tracking efficiency of ~ 90%

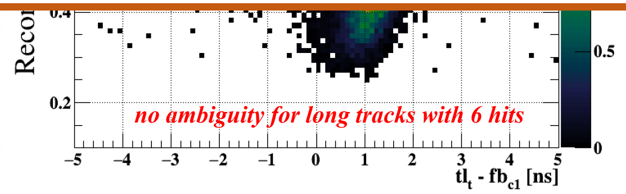
See detailed slides in indico for details.



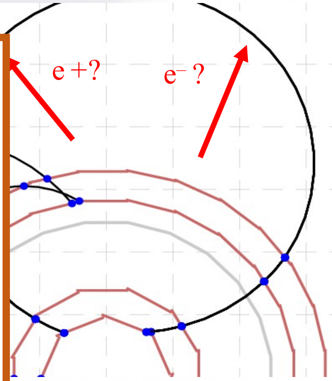
Track/Vertex Efficiency After Track ... Space Distribut...

(Mu3e ...

Phase space		
events in acceptance		
relative to events in acceptance		
events after track reconstruction		
relative to events in acceptance		
events with reconstructed vertex	[illegible]	[illegible]
relative to events in acceptance	0.907(5)	0.708(5)
relative to events after track reconstruction	0.998(8)	0.998(8)
events with reconstructed vertex after cuts	0.290(1)	0.163(1)
relative to events with reconstructed vertex before cuts	0.776(4)	0.866(7)
relative to events in acceptance	0.704(4)	0.614(4)
relative to events after reconstruction	0.789(4)	0.879(7)

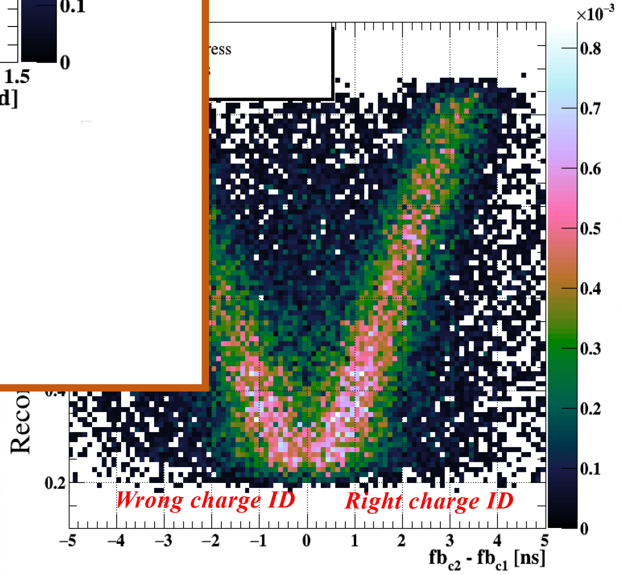


Timing and Charge ID



...r central 8-hit tracks:

...long 8-hit track:
...direction
...me information and path
...ween fibre hits

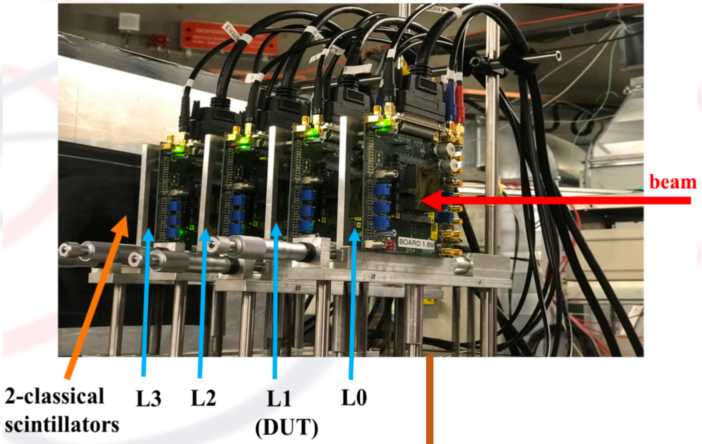


Test-beam Data Acquisition System and Characterisation of HV-MAPS

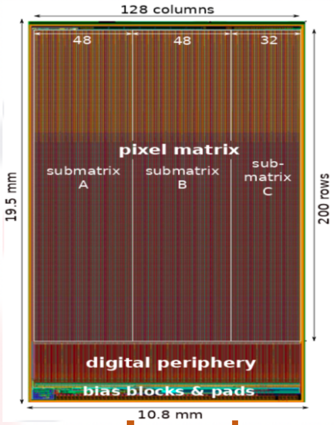
Test-beam @ PSI

The beam with momentum 270 MeV (pion, electrons, and muons), and electrical current is 1860.10μA at πM1 beam area in PSI

Setup of MuPix Telescope



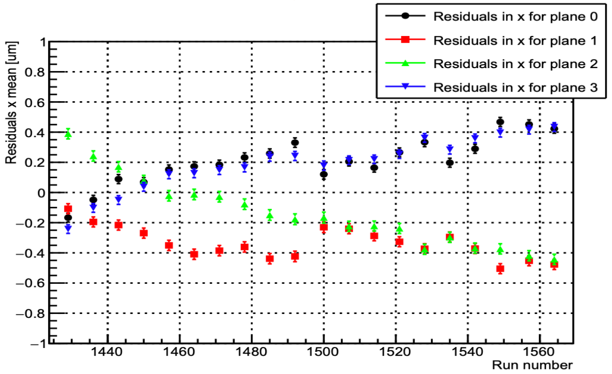
- 3-layers of MuPix8 sensors with DUT layer
- Layer 1 is DUT layer
- 2-classical trigger scintillators
- All PCBs were connected to a HV power supply, and set to - 60 V for all MuPix8 measurements

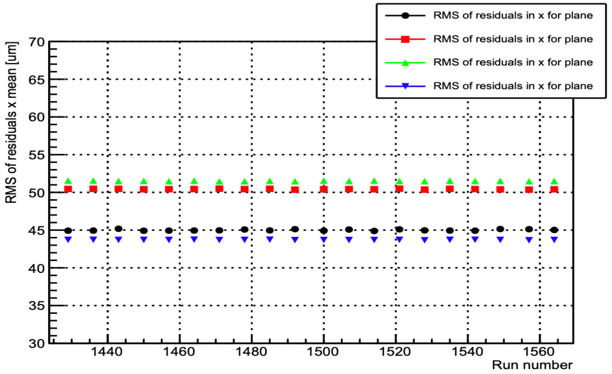


MuPix8 sensor?

- First large prototype in MuPix group
- Pixels have a size of $81\times80\mu m^2$
- Pixels are arrayed in 128×200pixel matrix
- Fast charge collection (O(1ns))
- Integrated readout electronics
- Thickness: 100 μm

Alignment Stability



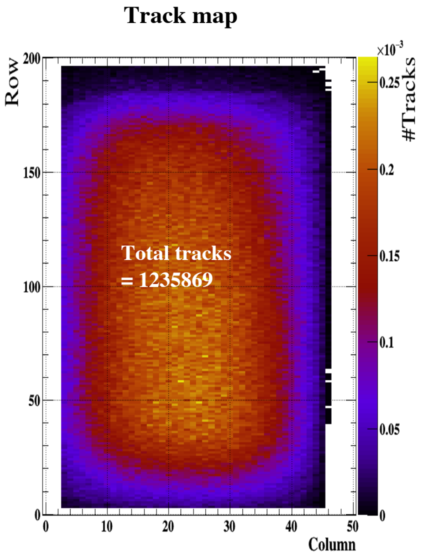


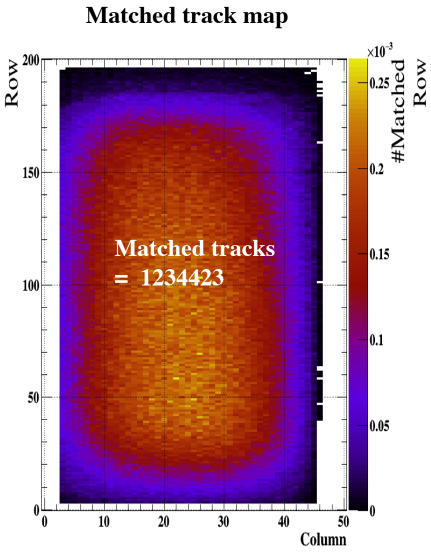
Efficiency Analysis

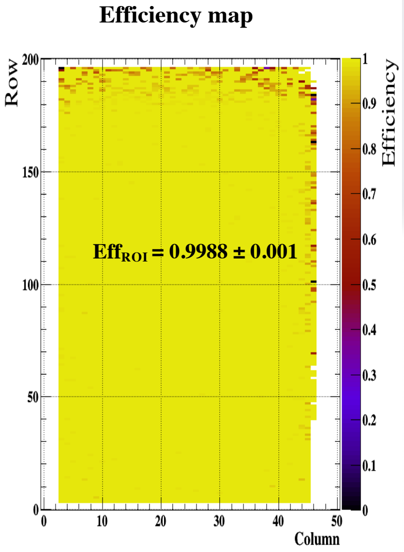
- Efficiency of run 1429 with threshold 545 mV

$$\mathrm{Eff_{ROI}} = \frac{\#\text{matched tracks}}{\#\text{total tracks}}$$

$$\text{Noise rate per pixel} = \frac{\#\text{hits} - \#\text{matched tracks}}{\text{runtime}\ .\ \#\text{pixels}}$$







Efficiency and Noise Rate per Pixel for Different DAQ Runs