

Hunt for the dark matter with upgraded CMS detector

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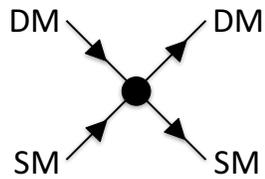
Introduction

- ❑ Dark Matter Searches at CMS
 - Mono-jet and Mono-V for Dark Higgs
 - Mono-top
 - Mono-photon
- ❑ Bottom Fermion Fusion Z' search
- ❑ CMS Phase-2 upgrade for HL-LHC
 - L1 trigger
 - MTD (MIP Timing Detector)
- ❑ Deep Learning using Supercomputer
- ❑ SITRINEO project
 - Collaborating with IPHC

Searches for Dark Matter

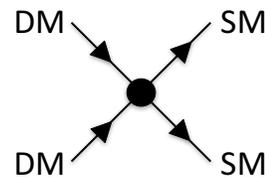
Strong evidences for the existence of Dark Matter (DM) from various astrophysical experiments.

3 complementary search strategies :



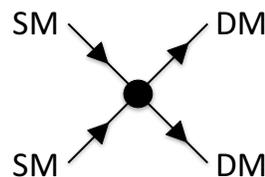
Direct detection (DD)

- DM-nucleus scattering
- Low-mass DM particles not probed yet
- Less sensitive to spin-dependent coupling



Indirect detection (ID)

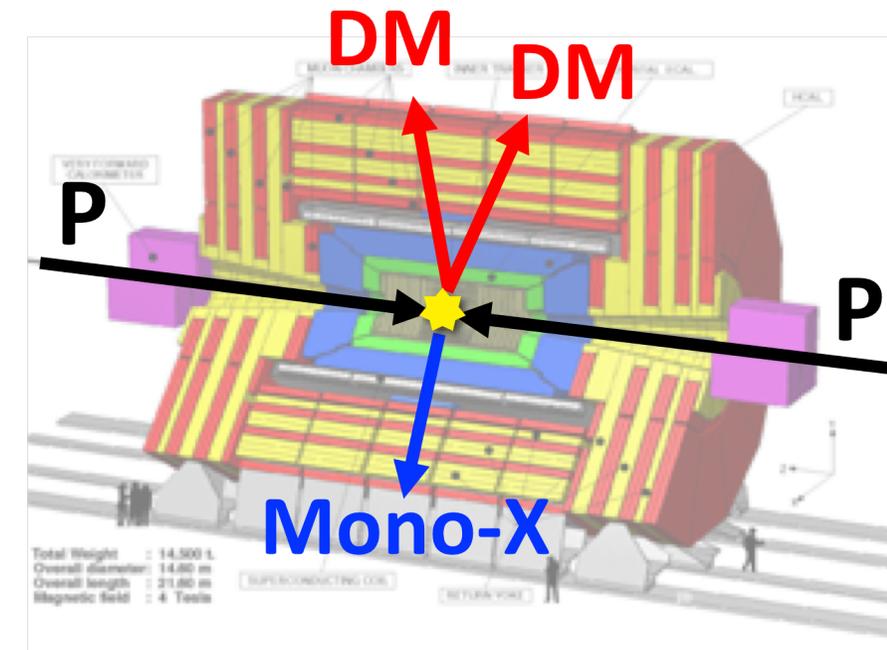
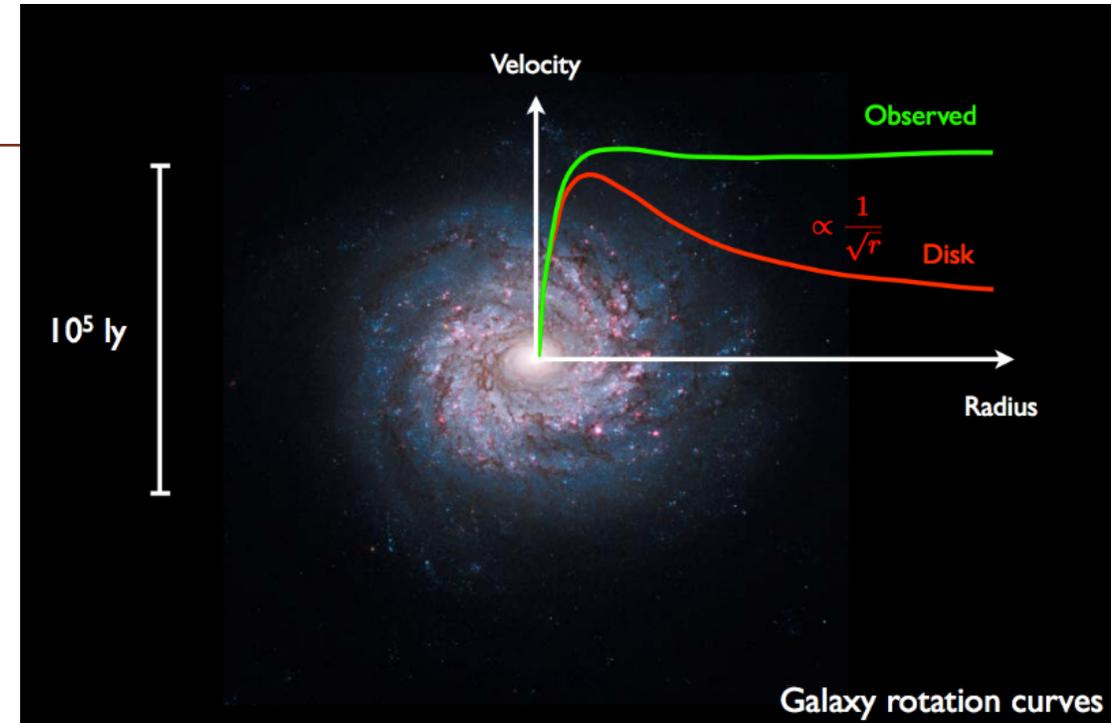
- Observe annihilation products
- Low-mass DM particles not accessible
- Depends on DM density and annihilation model



Production at colliders (PD)

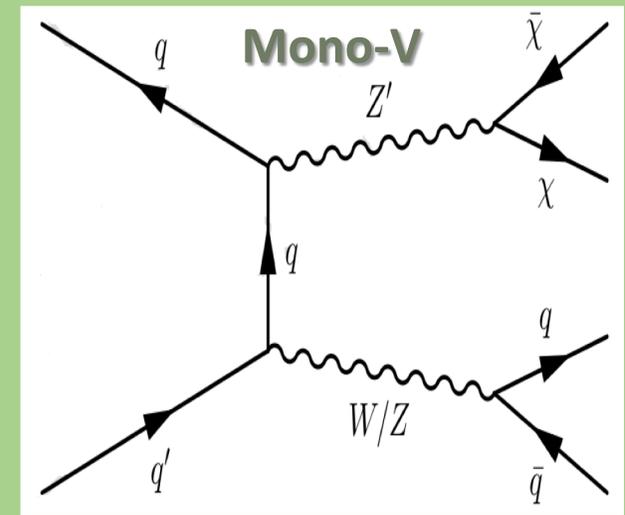
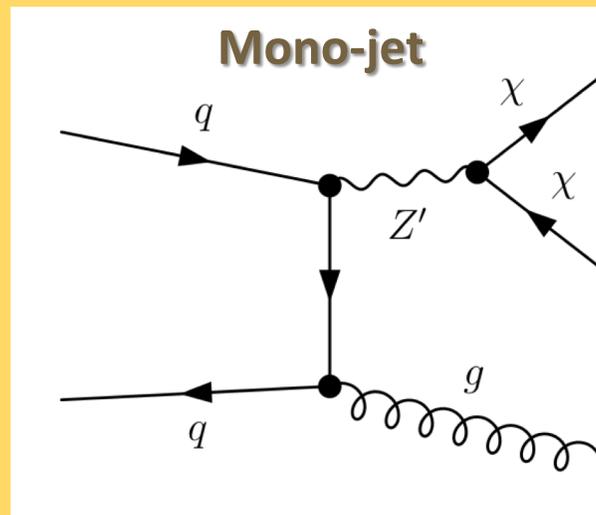
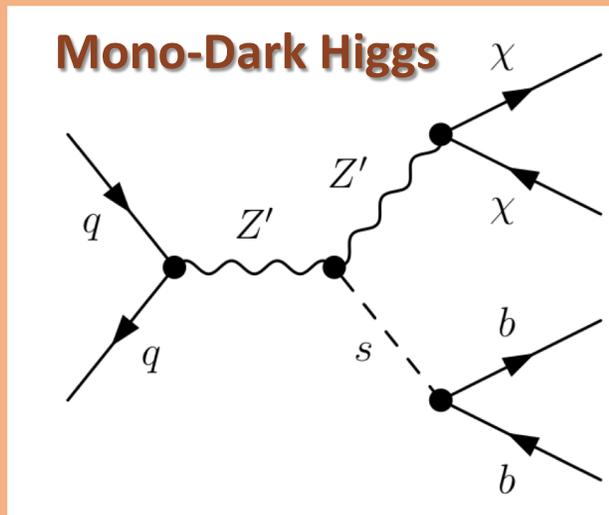
- Laboratory produced DM particles
- Sensitive to a wide mass range
- Both spin-dependent and spin-independent couplings

Need independent cross-checks!



Dark Higgs model (I)

- ❑ The presence of a Dark Higgs boson is motivated by the need to generate the masses of the particles in the dark sector
- ❑ The possibility to relax constraints from the dark matter relic abundance
 - Opening up a new annihilation channel ($\chi\chi \rightarrow ss$)
- ❑ The Dark Higgs boson decays into SM states
 - Boosted large-radius jets in association with missing transverse momentum



Dark Higgs model (II)

- Interaction Lagrangian in terms of parameters in Dark Higgs model

$$\mathcal{L}_\chi = -\frac{1}{2}g_\chi Z'^\mu \bar{\chi} \gamma^5 \gamma_\mu \chi - g_\chi \frac{m_\chi}{m_{Z'}} s \bar{\chi} \chi + 2g_\chi Z'^\mu Z'_\mu (g_\chi s^2 + m_{Z'} s)$$

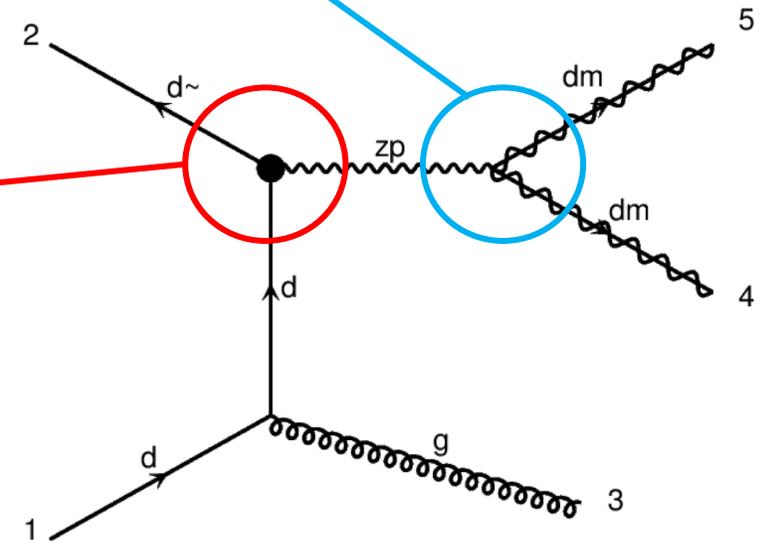
- $m_{Z'}$: mass of the Z'
- m_χ : mass of the DM
- g_χ : **axial** coupling (Z' - DM)

- Lagrangian in terms of parameters in Zprime and quarks coupling

$$\mathcal{L}_\chi = -g_q Z'^\mu \bar{q} \gamma_\mu q$$

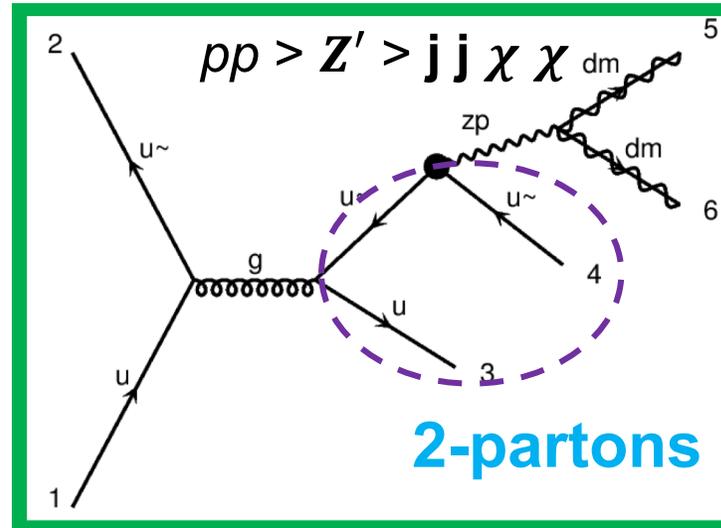
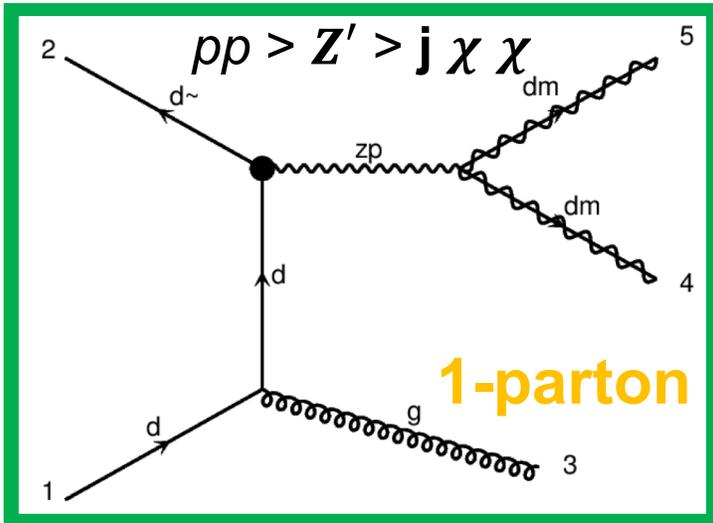
- g_q : **vector** coupling (Z' - quarks)

- m_s : mass of Dark Higgs, **independent** parameter

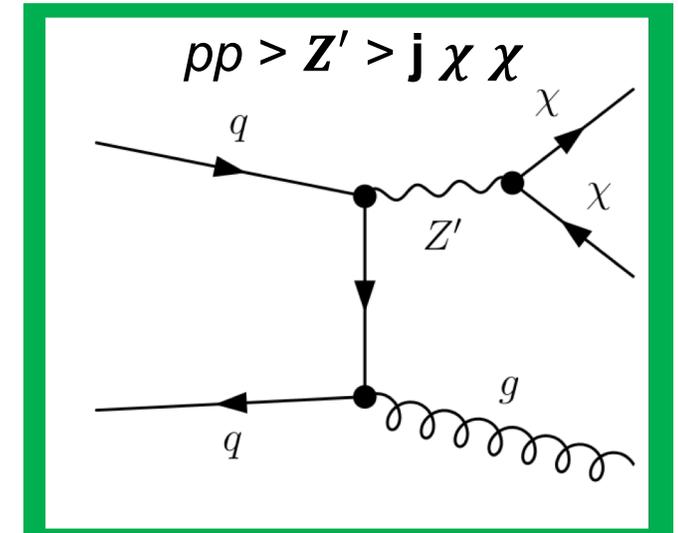


Dark Higgs model vs. Simplified model

Dark Higgs model



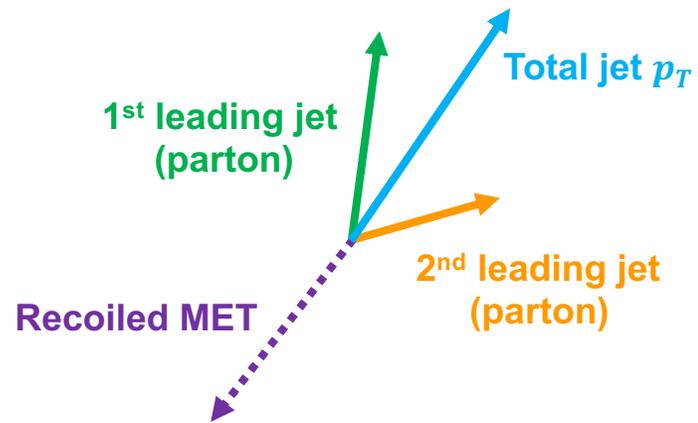
Simplified model



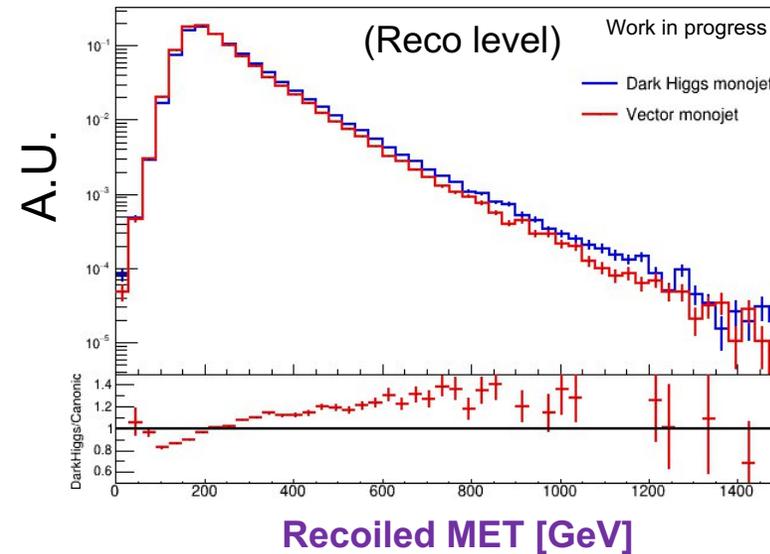
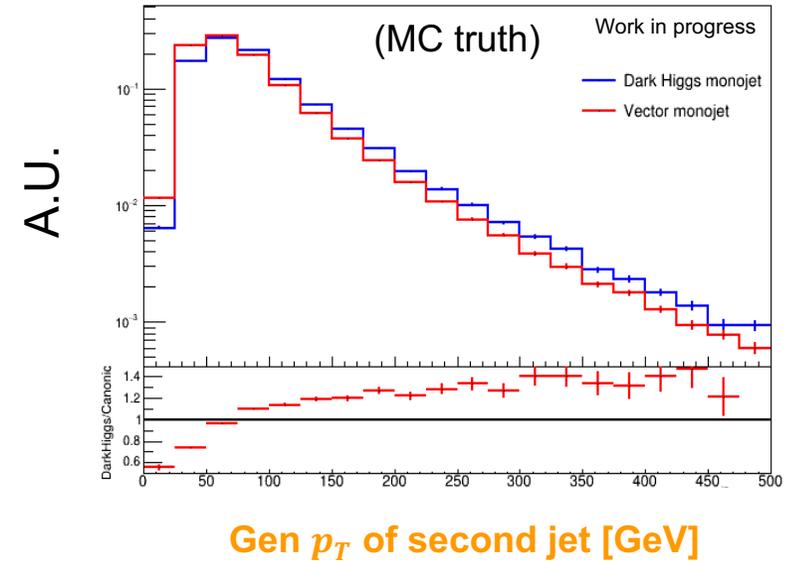
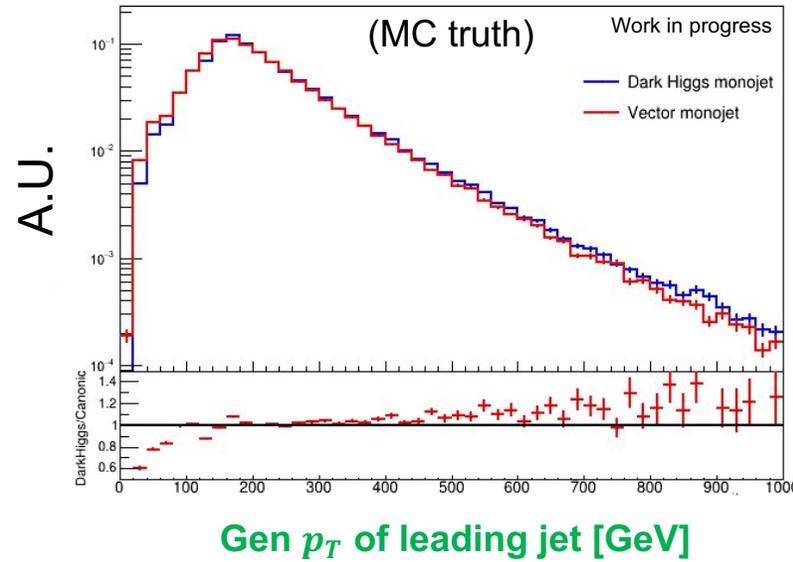
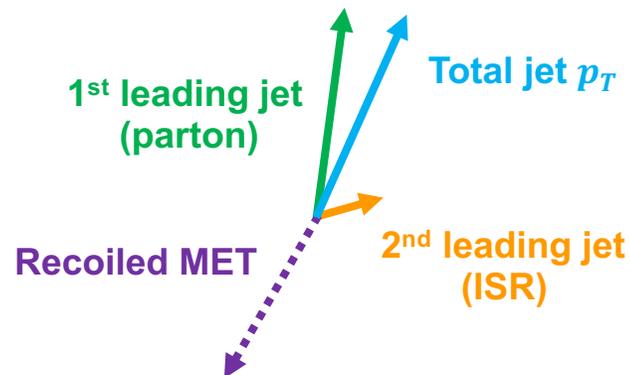
- The dark Higgs model includes both 1-parton and 2-partons production, while the Simplified model has only 1-parton production
- Therefore, second jet p_T in the dark Higgs model would be larger than that of the Simplified model
- Second jet mostly comes from
 - An additional parton in the Dark Higgs model
 - Initial state radiation in Simplified model

Comparison of kinematics between two models

Dark Higgs model (blue curve)

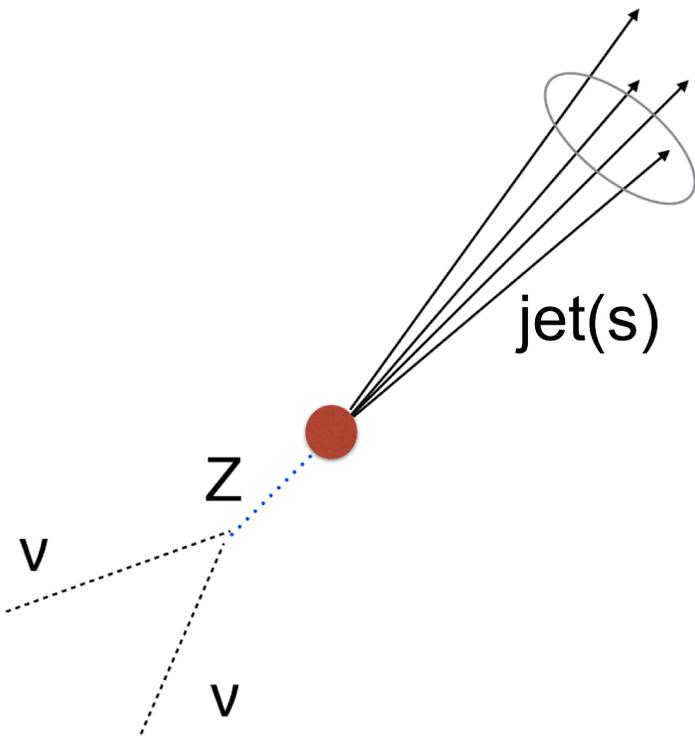


Simplified model (red curve)
(Vector monojet)

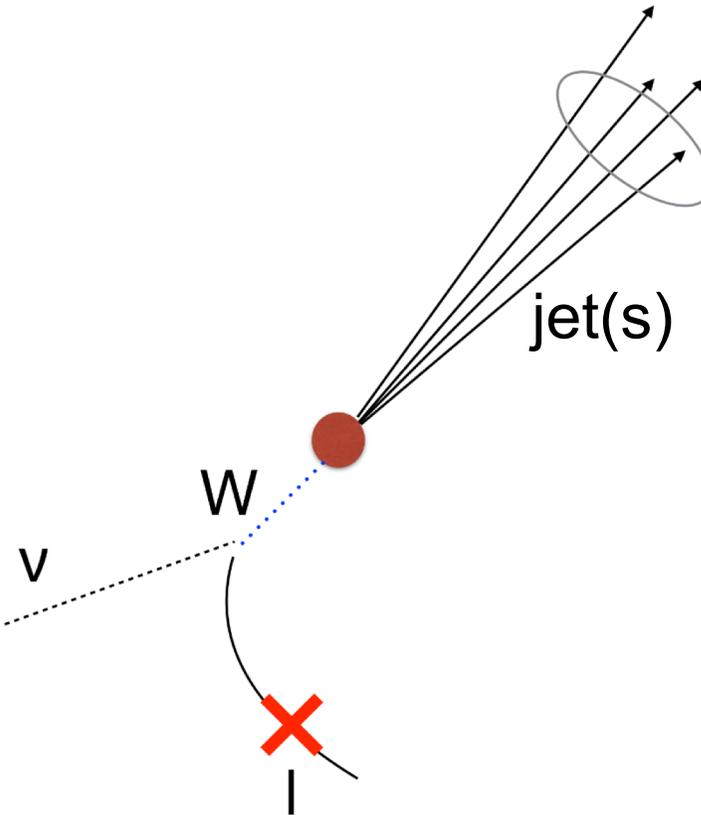


Main backgrounds

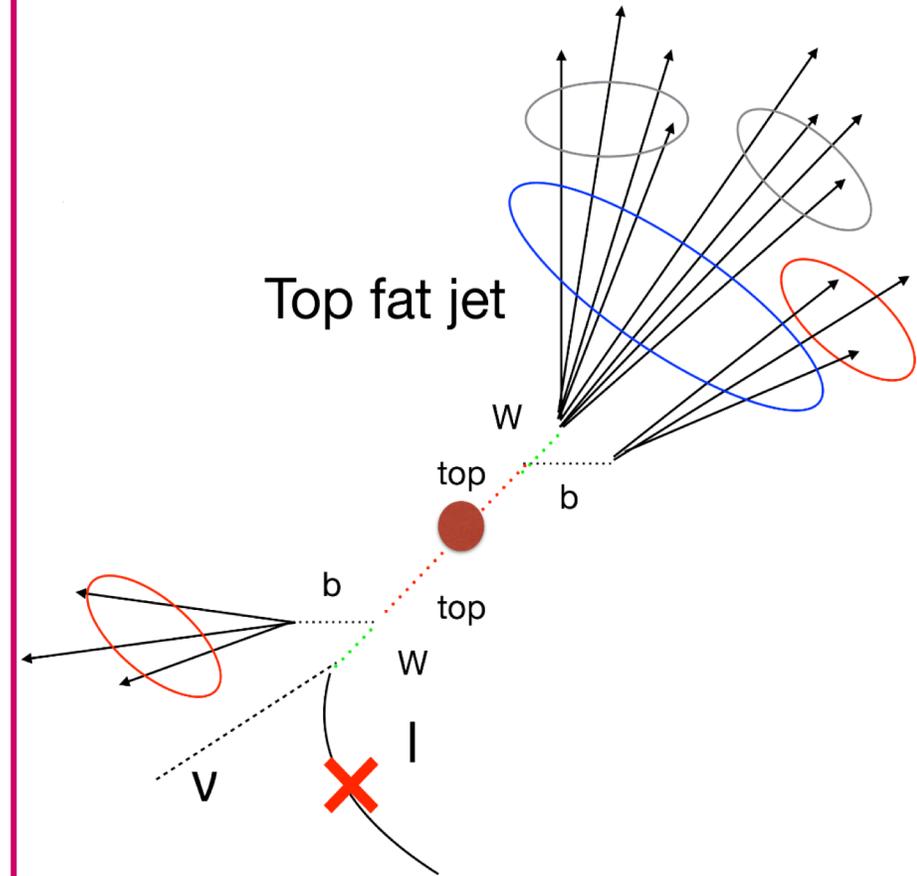
Z+jets



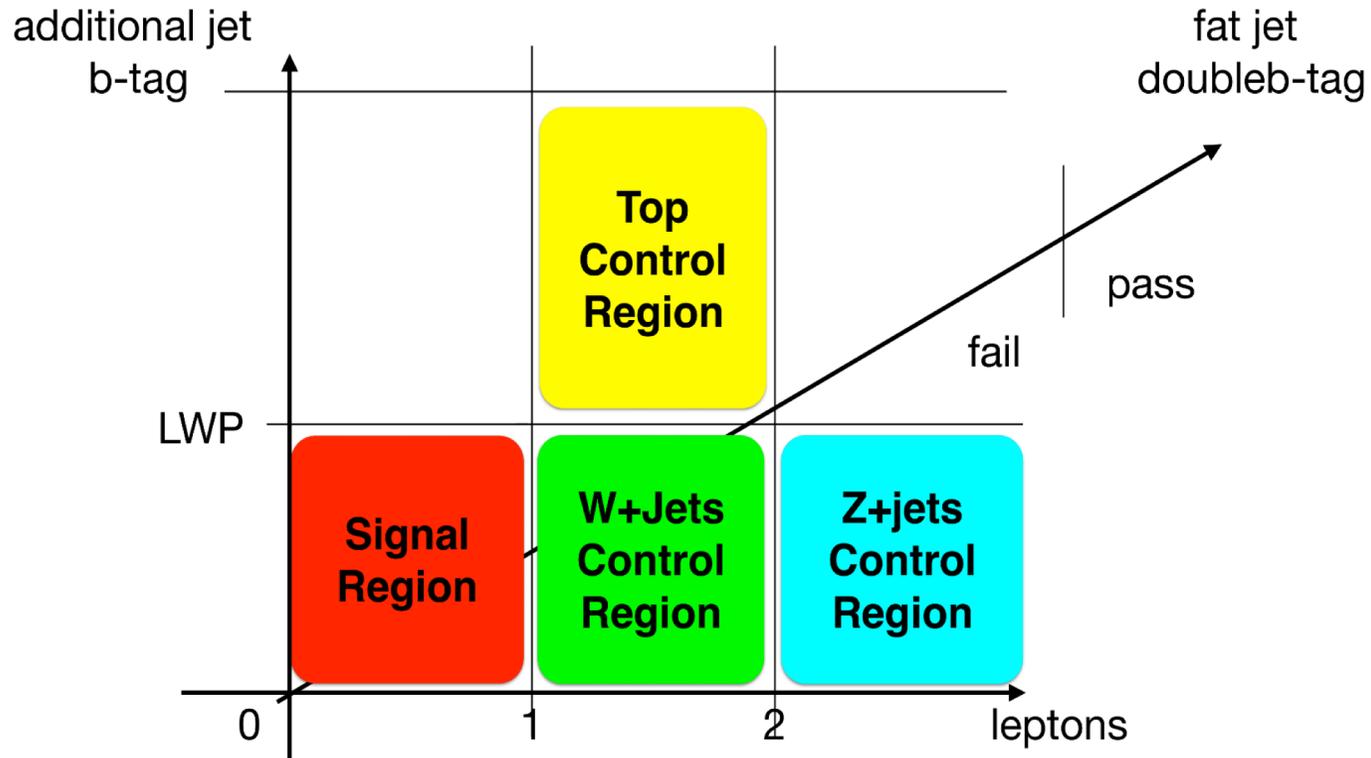
W+jets



Top-pair



Signal and Control Region



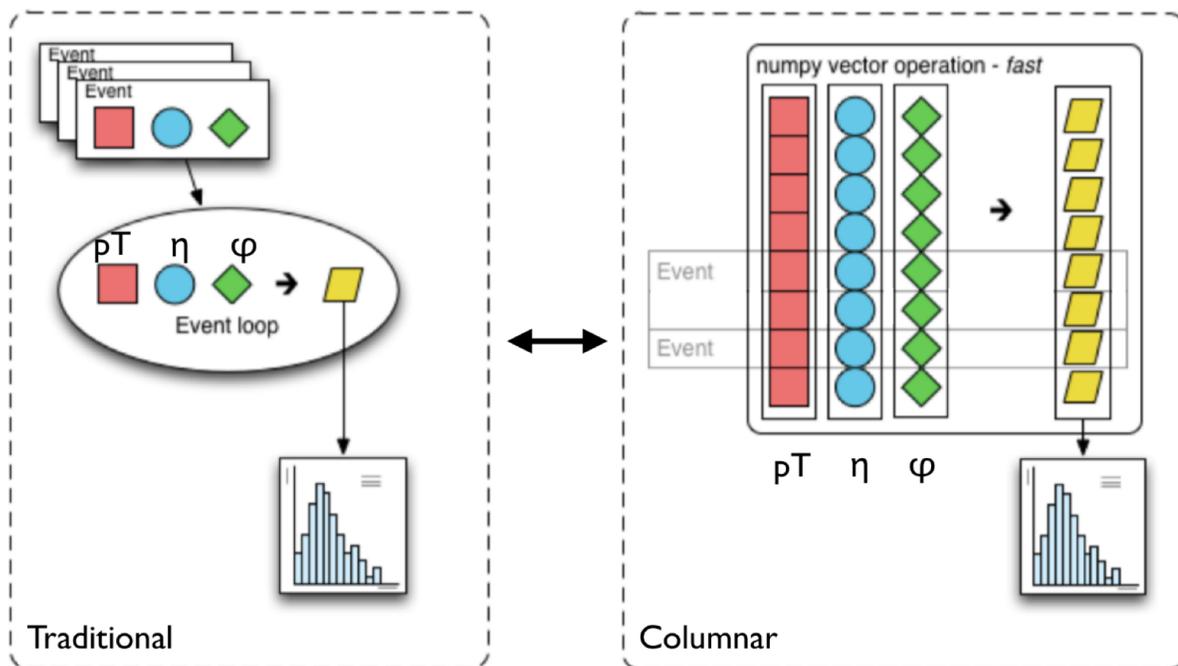
Signal Region categories

- At least one fat jet with $p_T > 200$ GeV
 - $\Delta\phi(\text{MET}, \text{jets}) > 0.8$
 - MET > 250 GeV
 - τ veto
- Mono-Dark Higgs,
Mono-V*

- At least one narrow jet with $p_T > 100$ GeV
 - $\Delta\phi(\text{MET}, \text{jets}) > 0.5$
 - MET > 250 GeV
 - τ veto
- Mono-jet*

Columnar Object Framework For Elaborate Analysis (Coffea)

Significant change of basis for an analyzer: fast and efficient processing!



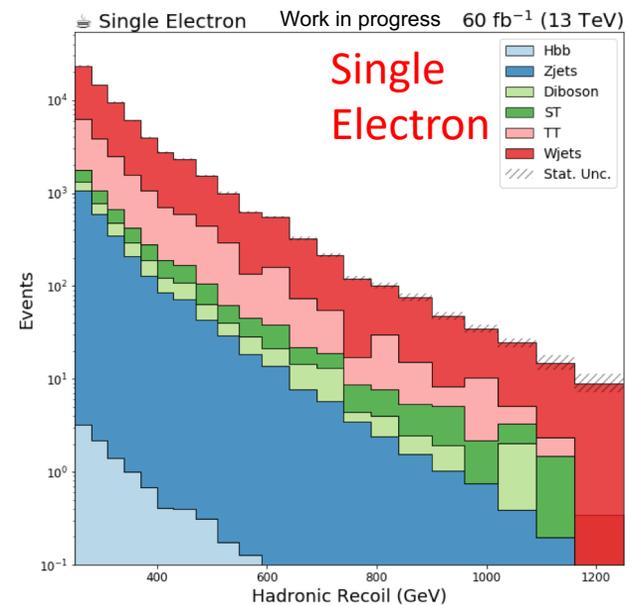
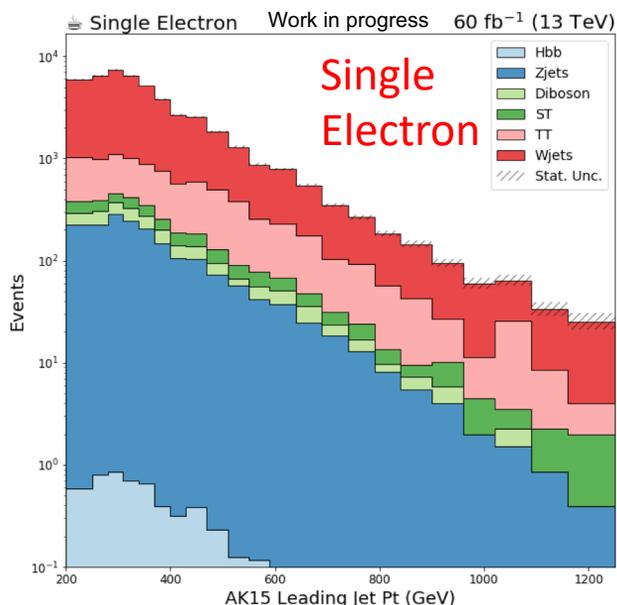
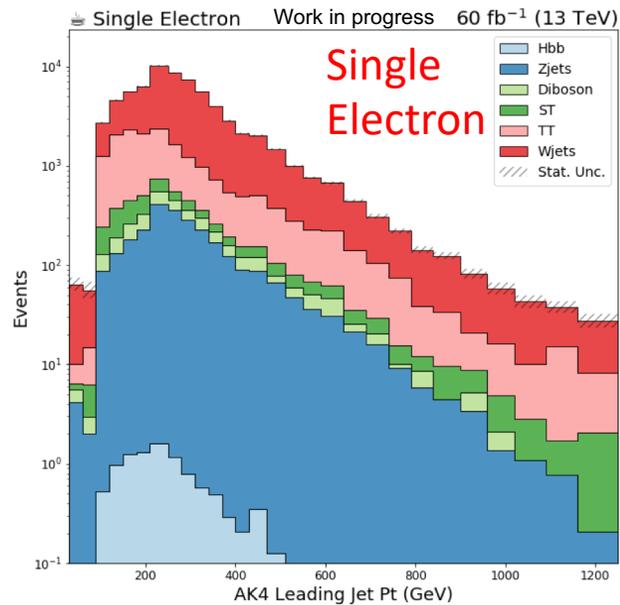
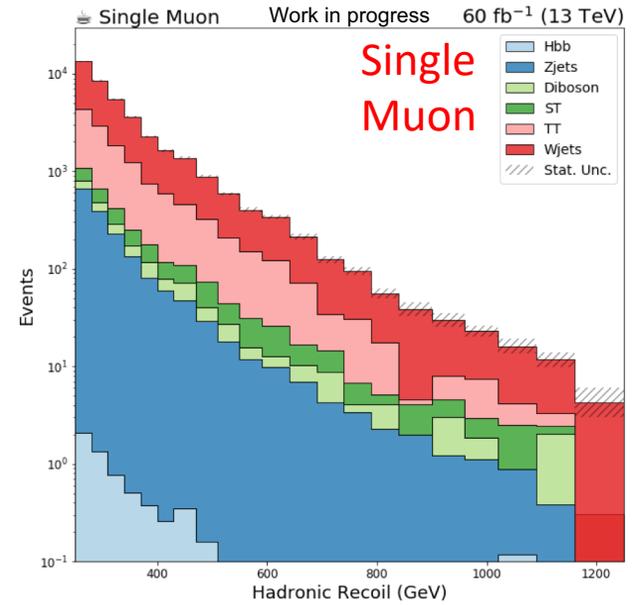
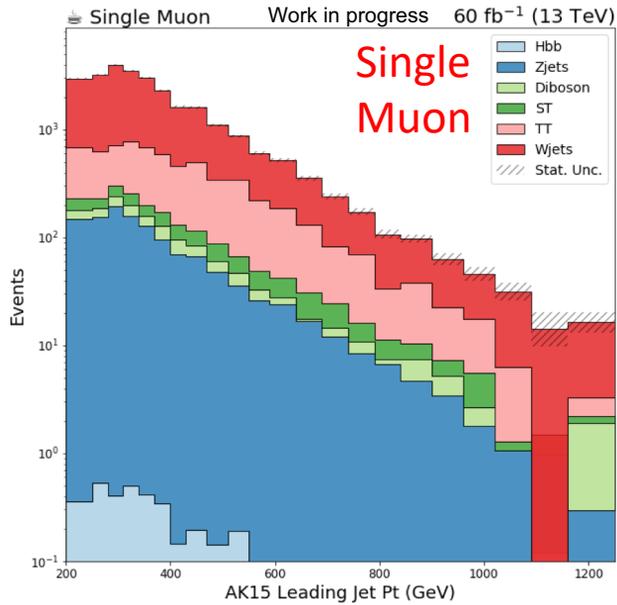
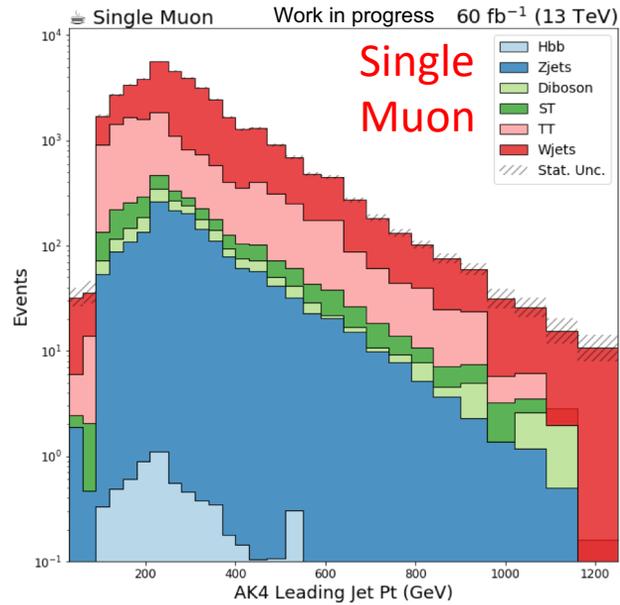
- Recast traditional data model such that attributes of physics objects are grouped into contiguous columns
- Significantly more efficient for processing than the traditional analysis workflow

❖ Steps in Coffea:

- Coffea **Harvester** – delivery of HEP event data inputs in columnar form
- Coffea **Beans** – Dataset book keeping and metadata
- Coffea **Grinder** – fast, understandable columnar analysis code
- Coffea **Pods** – plotting, template production, and intermediate fitting
- Coffea **Maker** – physics observable extraction, interface to combine HEP data, etc.



Kinematics distributions in single lepton CR using coffea

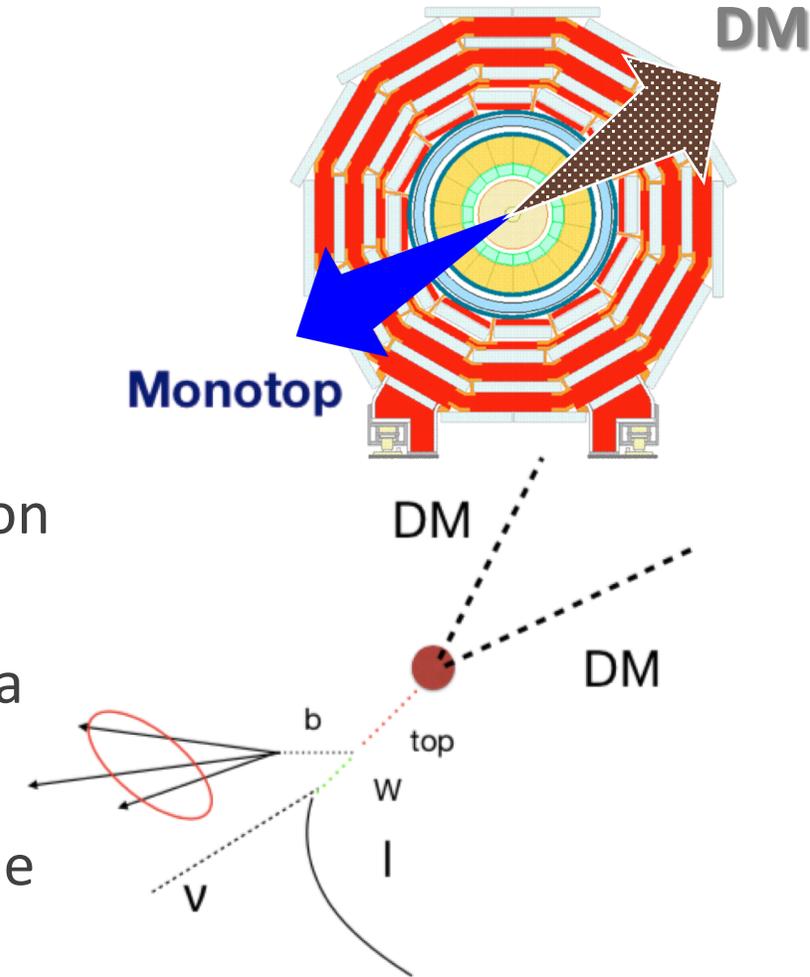


Search for Monotop

- **Goal of the Monotop:** Search for Dark Matter or new physics by exploring the process of monotop decay.

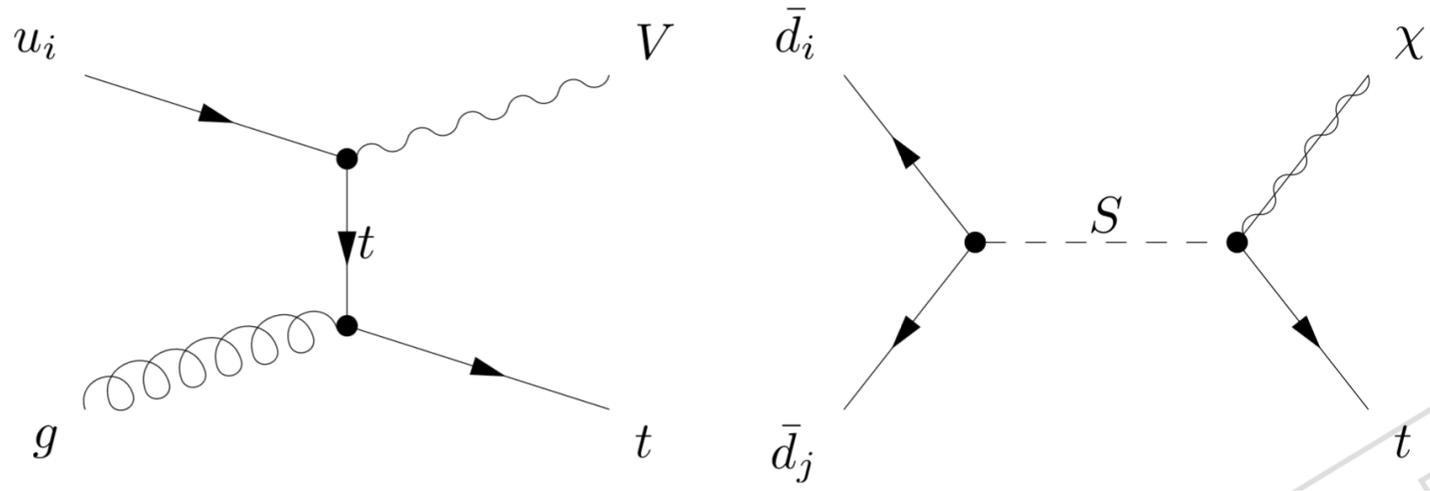
- **Strategies and Methods for the research**

- The monotop signatures consist in the production of a single top-quark observed with the presence of missing transverse energy (MET).
- A top quark decays a W boson and b quark (b jet).
- Events with a hadronically or leptonically decaying W boson resulting from top quark decay are considered.
- Hadronic monotop (EXO-16-051) published with 2016 data
 - Limited by MET trigger threshold, Top with high p_T
- Leptonic monotop would allow exploring a lower p_T regime



Theoretical Model

- Two different processes are leading to DM signatures. Both have invisible particle.
 - First, the interaction with a Neutral Flavor Changing vertex (Left)
 - Second, the production of a monotop through the exchange of a new resonant coloured field (right).



- **Importance of the results**

- Using 2016, 2017 and 2018 data in CMS, monotop search is expected to find a candidate for dark matter or new physics.

Analysis Selection and Status

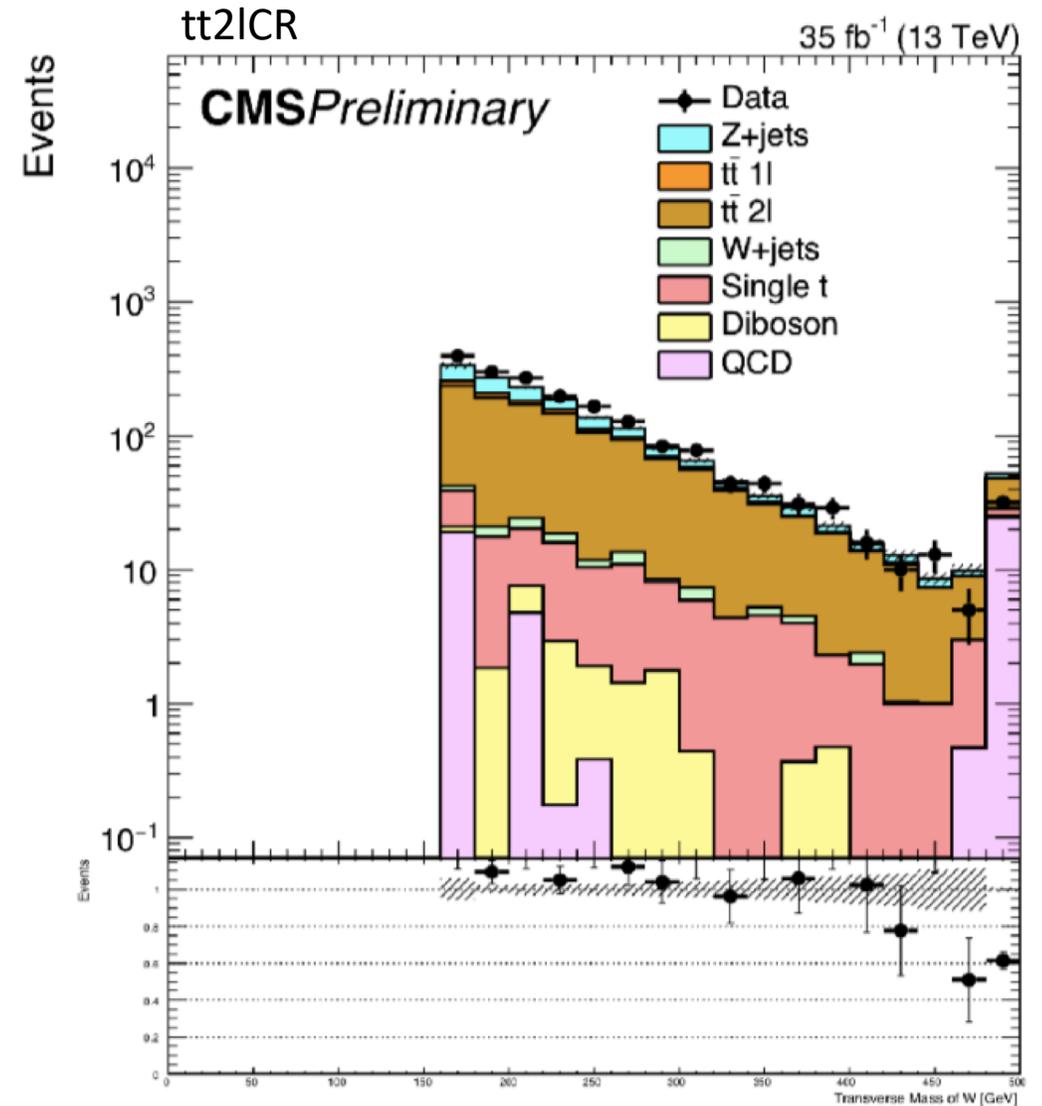
Basic Selections :

- ❑ At least one AK4jet, $p_T > 30 \text{ GeV}$
- ❑ One tight lepton, $p_T > 25 \text{ GeV}$
- ❑ Exactly one loose lepton (SR, W/tt1ICR)
- ❑ Exactly two loose leptons (tt2ICR)
- ❑ $m_T > 160 \text{ GeV}$
- ❑ τ veto
- ❑ 0/1/2 b-tagged jets, $cvs > \text{MWP}$

Status:

Basic analysis setup is in place :

- ❑ Looked 2016 dataset
- ❑ Preparing signal samples for 2017 and 2018



Dark Higgs & Monotop Analyses



[LPC-DM group webpage](https://lpc-dm.github.io/communication) : <https://lpc-dm.github.io/communication>

[Dark Higgs analysis twiki](https://twiki.cern.ch/twiki/bin/viewauth/CMS/LPCDMDarkHiggs) : <https://twiki.cern.ch/twiki/bin/viewauth/CMS/LPCDMDarkHiggs>

AN numbers:

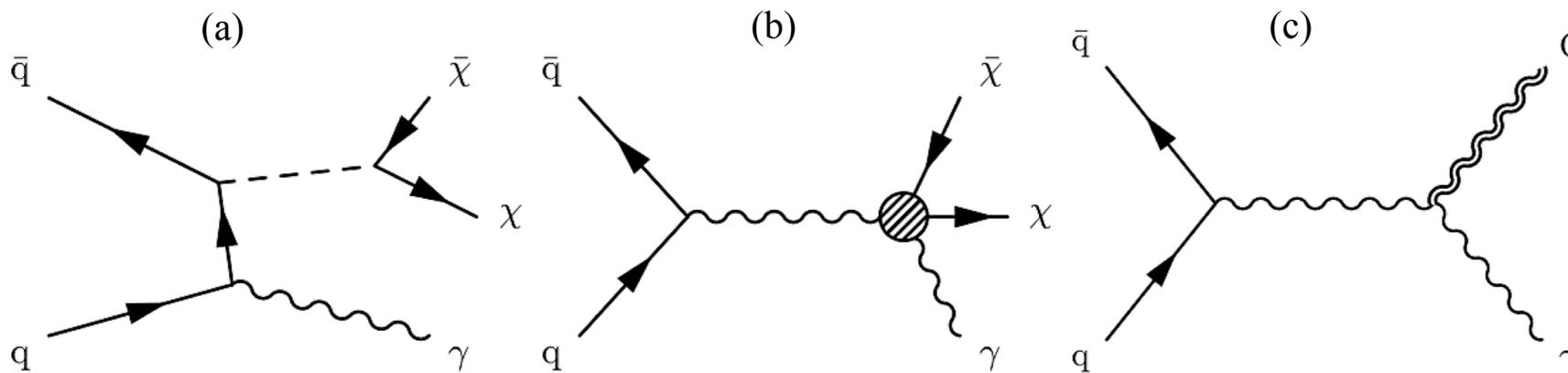
- Dark Higgs: AN-18-026
- Monotop : AN-14-279

[Analysis note gitlab](https://gitlab.cern.ch/tdr/notes/AN-18-026) : <https://gitlab.cern.ch/tdr/notes/AN-18-026>



Introduction to Monophoton analysis

- The Dark matter is one of the most compelling pieces of evidence for new physics beyond the standard model.
- If non-gravitational interactions exist between the DM and the SM particles, the DM could be produced by colliding the SM particles at high energy colliders.
- Production of the events with a photon having large transverse momentum and large missing transverse momentum (MET) is a sensitive probe to search for the DM at CERN LHC.



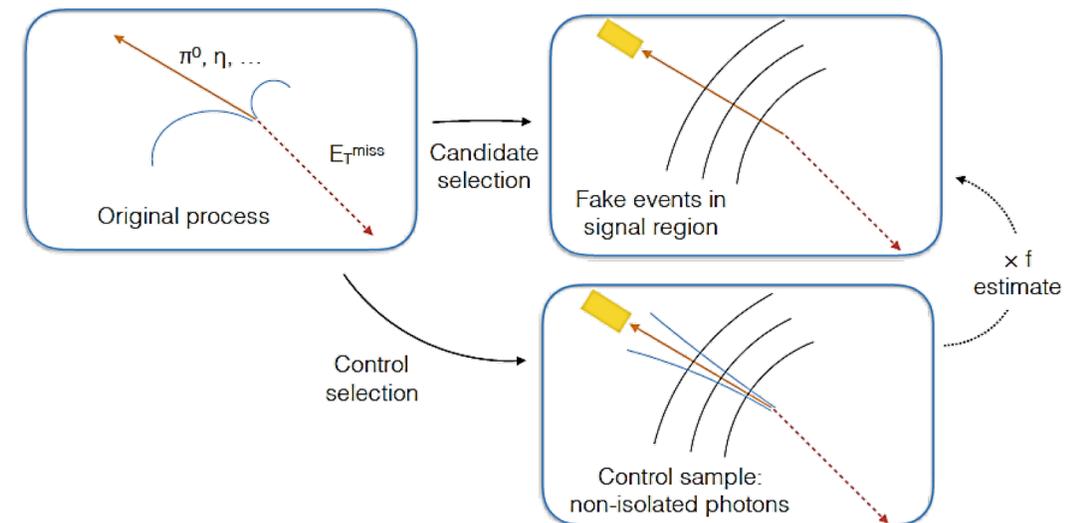
- Leading order diagram of Simplified DM model
- Dark matter production from electroweak-DM effective interaction
- Graviton production in the ADD model

The primary backgrounds

- Standard model backgrounds in monophoton signature
 - $Z(\rightarrow \nu\bar{\nu}) + \gamma$ – standard model
 - $W(\rightarrow l\nu) + \gamma$ – the charged lepton is lost or misreconstructed
 - $Z(\rightarrow l\bar{l}) + \gamma$ – lepton pair is lost or misreconstructed
 - $t\bar{t} + \gamma, t + \gamma$ – top decay leptonically and lost
- Jet energy mismeasurement
 - $\gamma + jets$ – large E_T^{miss} from mismeasured jet energy
- The candidate photon object misidentification
 - $W(\rightarrow e\nu)$ - the electrons from W boson decay are misidentified as photon
 - **Hadron misidentification** – high E_T jets fragment into π^0 or η which appear as a single electron shower, and make fake photons

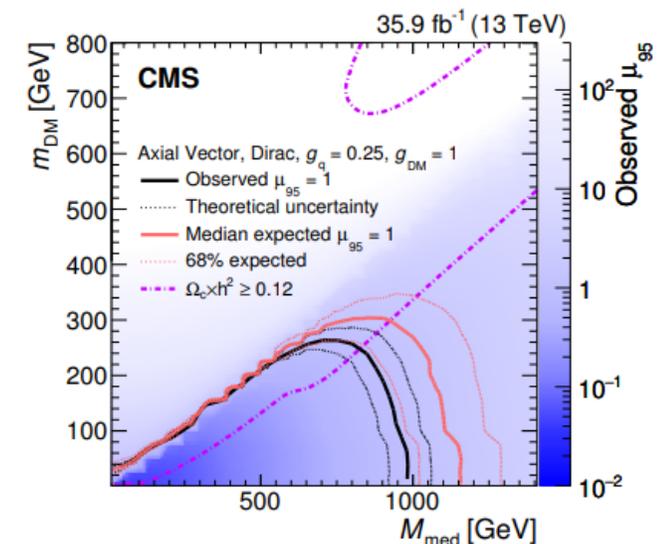
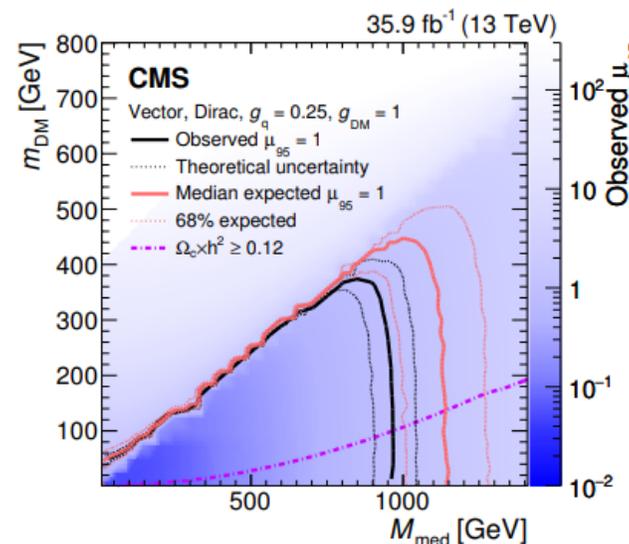
QCD fake estimation

- The low production of fake photon and large uncertainty from parton fragments make MC simulation difficult
- The MC simulation alone does not reflect the photon misidentification model, therefore the data-driven techniques used in jet fake photon estimation.
- Define the QCD jet fake ratio by using the photon template fitting in low p_T^{miss} control region.
- Apply the fake ratio to the fake photon samples in the signal region and estimate the jet faking photon contribution.



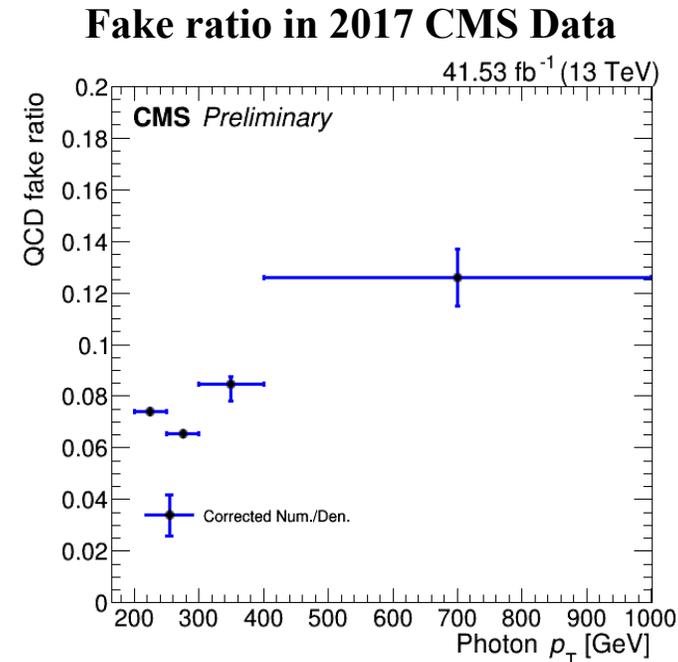
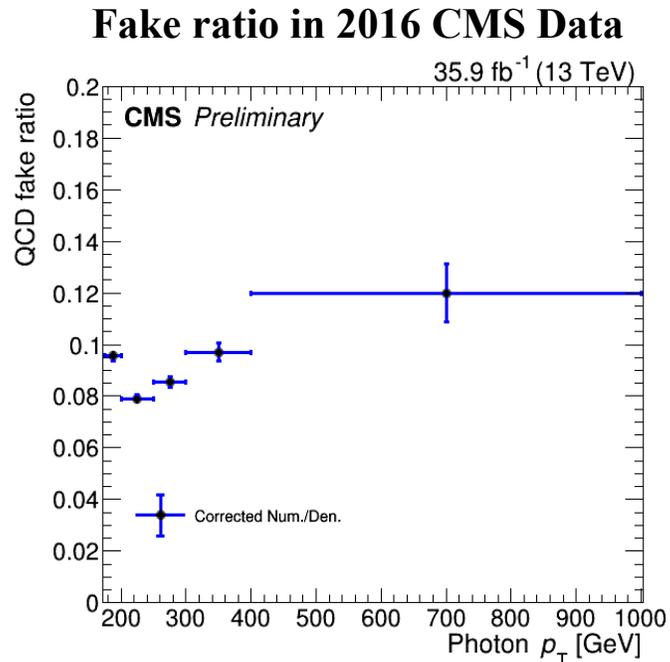
Summary of 2016 data analysis

- A search is conducted for new physics in final states containing a photon and MET in proton-proton collision at $\sqrt{s} = 13$ TeV
- Using the data collected by the CMS experimental in 2016 corresponding to an integrated luminosity of 35.9 fb^{-1}
- No deviations are observed relative to the predictions of the standard model.
- For the simplified dark matter production models considered, the observed (expected) lower limits on the mediator masses are both 950 (1150) GeV for 1 GeV dark matter mass.
- For an effective electroweak-dark matter contact interaction, the observed (expected) lower limit on the suppression parameter Λ is 850 (950) GeV



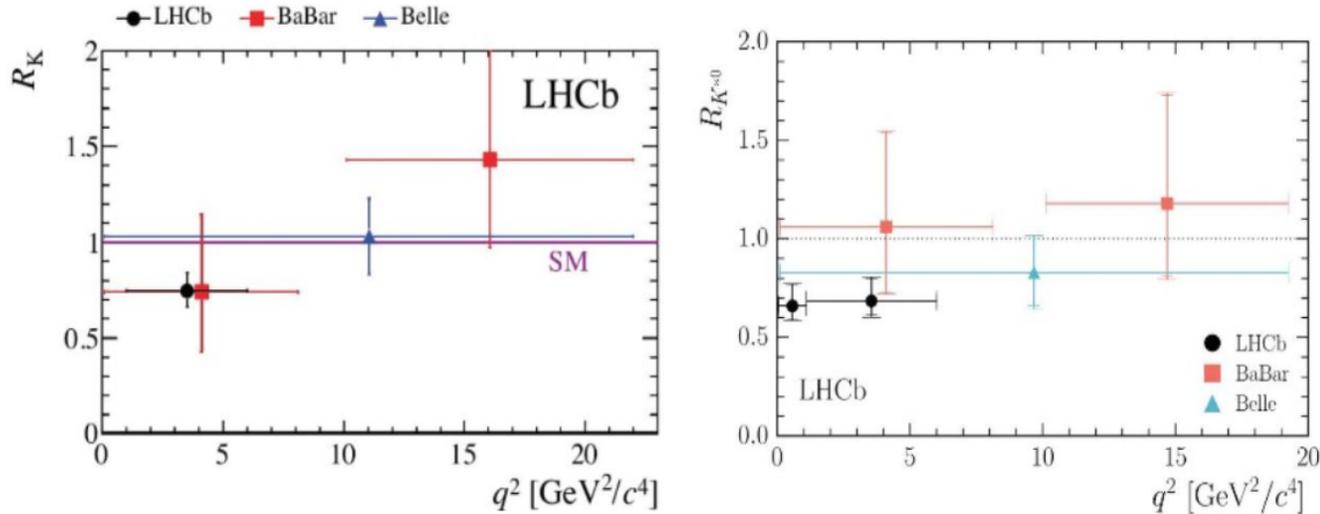
Next plan for monophoton analysis

- Analysis of 2017 data for background estimation is almost finished.
 - Fig. The QCD jet fake ratio from the fake photon passed through template fit
- Our lab is now focusing on the systematics studies for QCD background.
- The new samples for 2018 CMS data analysis are prepared.
- Event selection criteria for 2018 CMS data will be defined.



Anomalies in B meson decays

- Anomalies in B meson decays – **One of hot topics**
- Recent LHCb results shows certain deviation from SM prediction for R_K and R_{K^*}

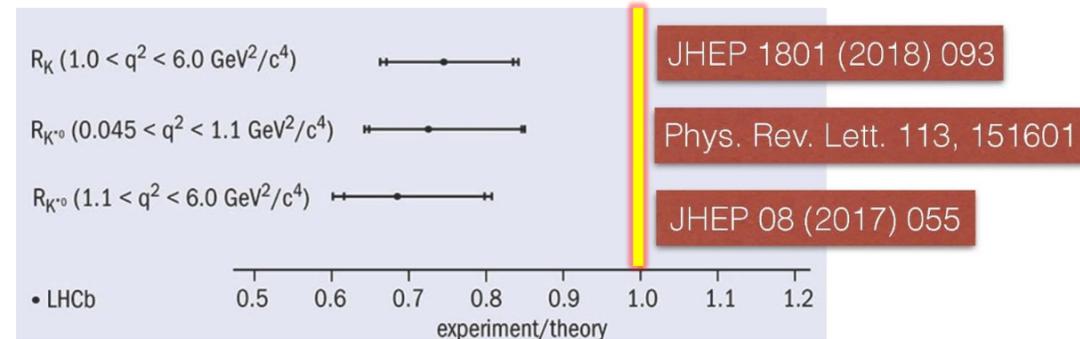


$$R_K = \frac{BR(B^+ \rightarrow K^+ \mu^+ \mu^-)}{BR(B^+ \rightarrow K^+ e^+ e^-)}$$

$$R_{K^*} = \frac{BR(B \rightarrow K^* \mu^+ \mu^-)}{BR(B \rightarrow K^* e^+ e^-)}$$

[JHEP 1801 (2018) 093]

| | $R_K^{[1,6]}$ | $R_{K^*}^{[0.045,1.1]}$ | $R_K^{[1.1,6]}$ |
|------------------|---------------------------|--------------------------|---------------------------|
| SM prediction | $0.745^{+0.097}_{-0.082}$ | $0.66^{+0.113}_{-0.074}$ | $0.685^{+0.122}_{-0.083}$ |
| LHCb measurement | 1.00 ± 0.01 | 0.92 ± 0.02 | 1.00 ± 0.01 |



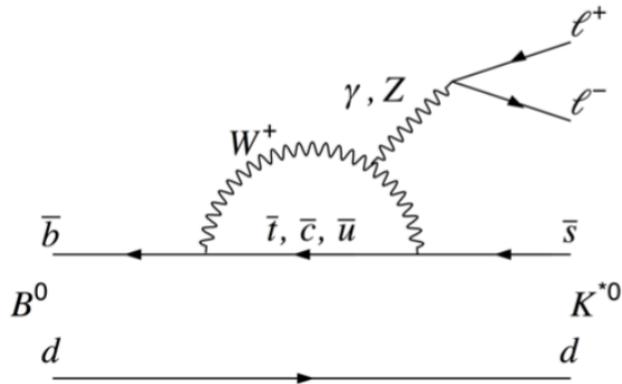
➡ Deviation at $2.4\sigma - 2.6\sigma$ from the SM prediction

Why Z' boson?

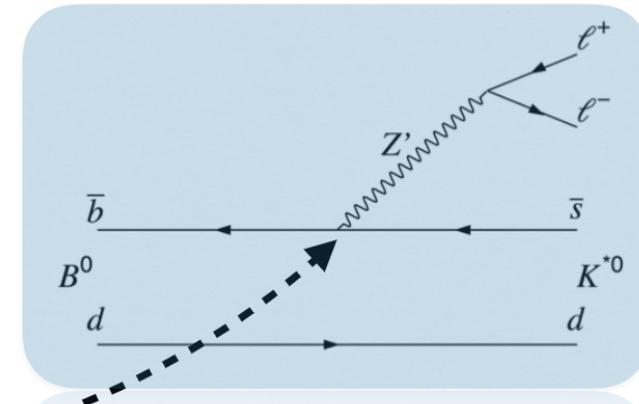
- **Z' boson** is one of the hypothetical gauge bosons that arise from extensions of the electroweak symmetry.
- Combine this results with other anomalies observed in $b \rightarrow s\mu\mu$ transition.

➡ **$\sim 4\sigma$ tension with SM prediction in B meson decay anomalies**

Standard Model (SM)



Beyond Standard Model (BSM)



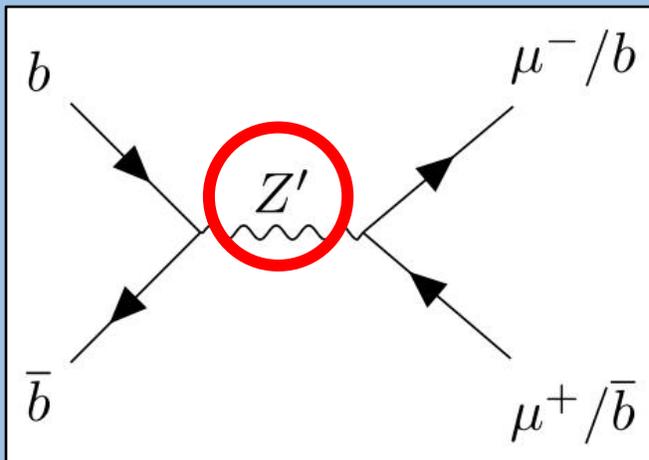
Extra $U(1)$

- New contributions to $b \rightarrow s\mu\mu$ transition can be explained in various BSM theories, in particular **involving Z' boson**

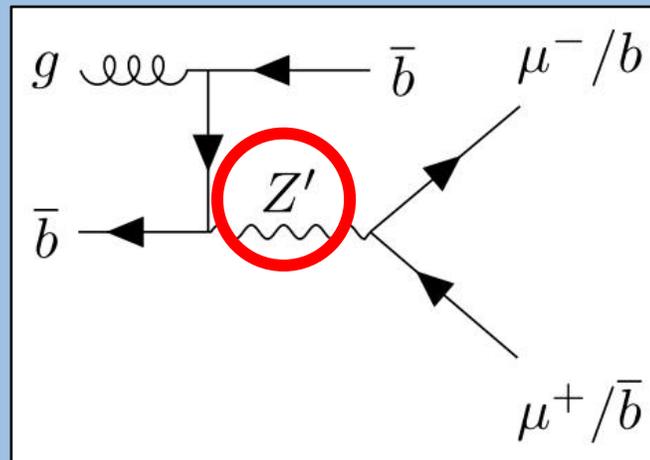
$Z' \rightarrow \mu\mu$ Production Mechanisms

- Dimuon production is the most relevant probe, and our group focused on Z' production via **Bottom Fermion Fusion (BFF)**
 - Bottom quarks from gluon splitting and sea quarks play a major role.
 - We look for a dimuon final state in association with 1 or 2 bottom-tagged jets.

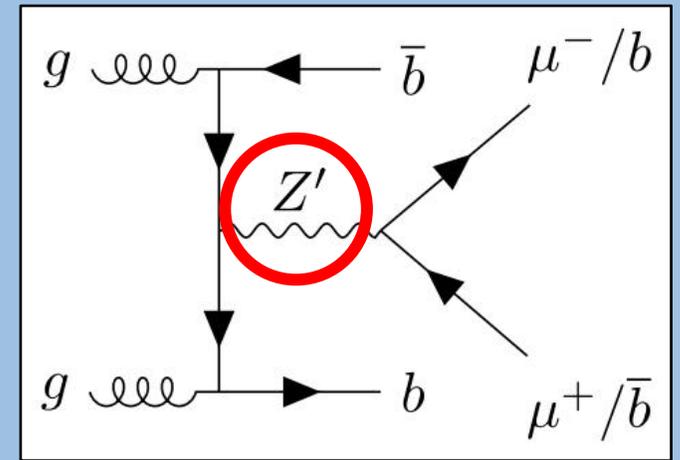
$Z' + 0$ jets



$Z' + 1$ jets

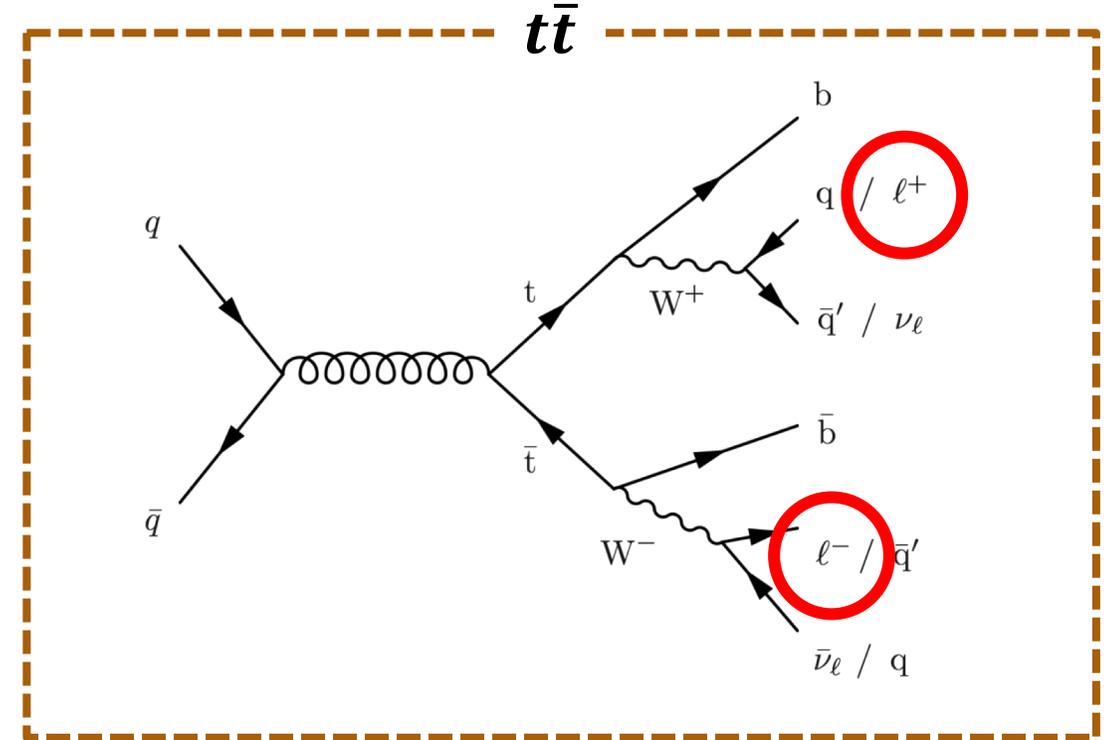
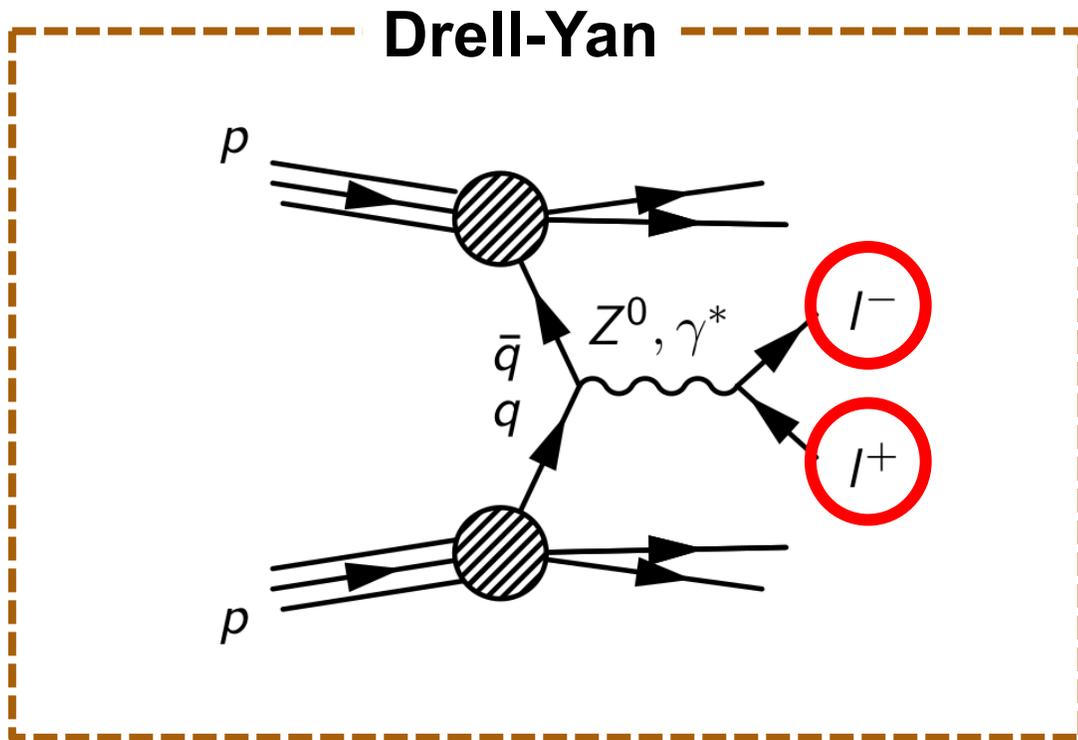


$Z' + 2$ jets



Relevant Background processes

- Some processes are possible to generate dimuon signal similar to the $Z' \rightarrow \mu\mu$ production.
- Since the processes disturb to observe target signal, they have to be removed.



| | Drell-Yan | $t\bar{t}$ |
|---------------------------|-----------|------------|
| Leading lepton-pair mass | Low | High |
| Missing transverse Energy | Low | High |



Remove them using their properties!

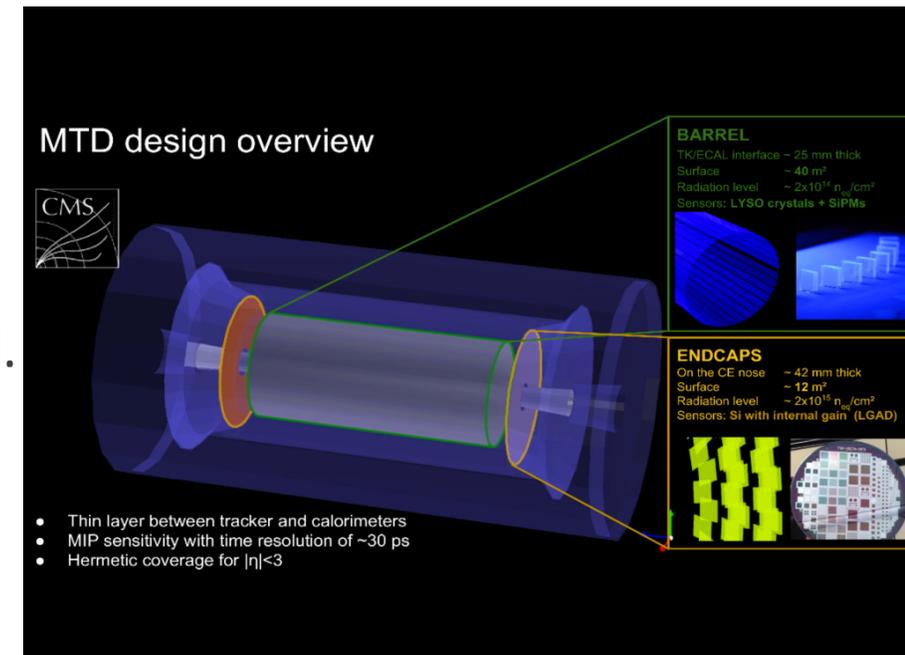
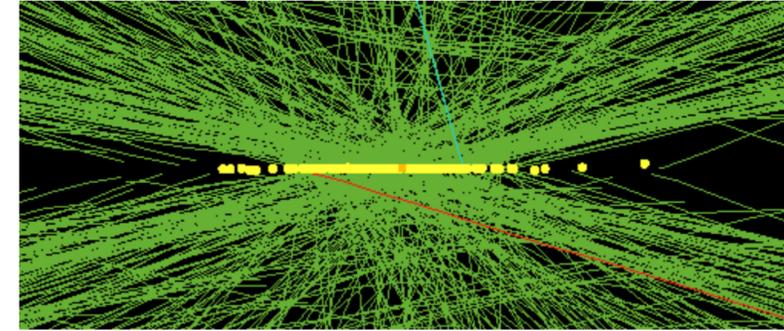
Reference

- [1] CMS-TDR-017, The Phase-2 Upgrade of the CMS Level-1 Trigger
- [2] FERMILAB-CONF-18-428-CMS, Particle Flow and PUPPI in the Level-1 Trigger at CMS for the HL-LHC, Benjamin Kreis
- [3] JHEP 1801 (2018) 093, Patterns of New Physics in $b \rightarrow sll$ transitions in the light of recent data, Bernat Capdevila

CMS Phase-2 upgrade for HL-LHC

MIP Timing Detector

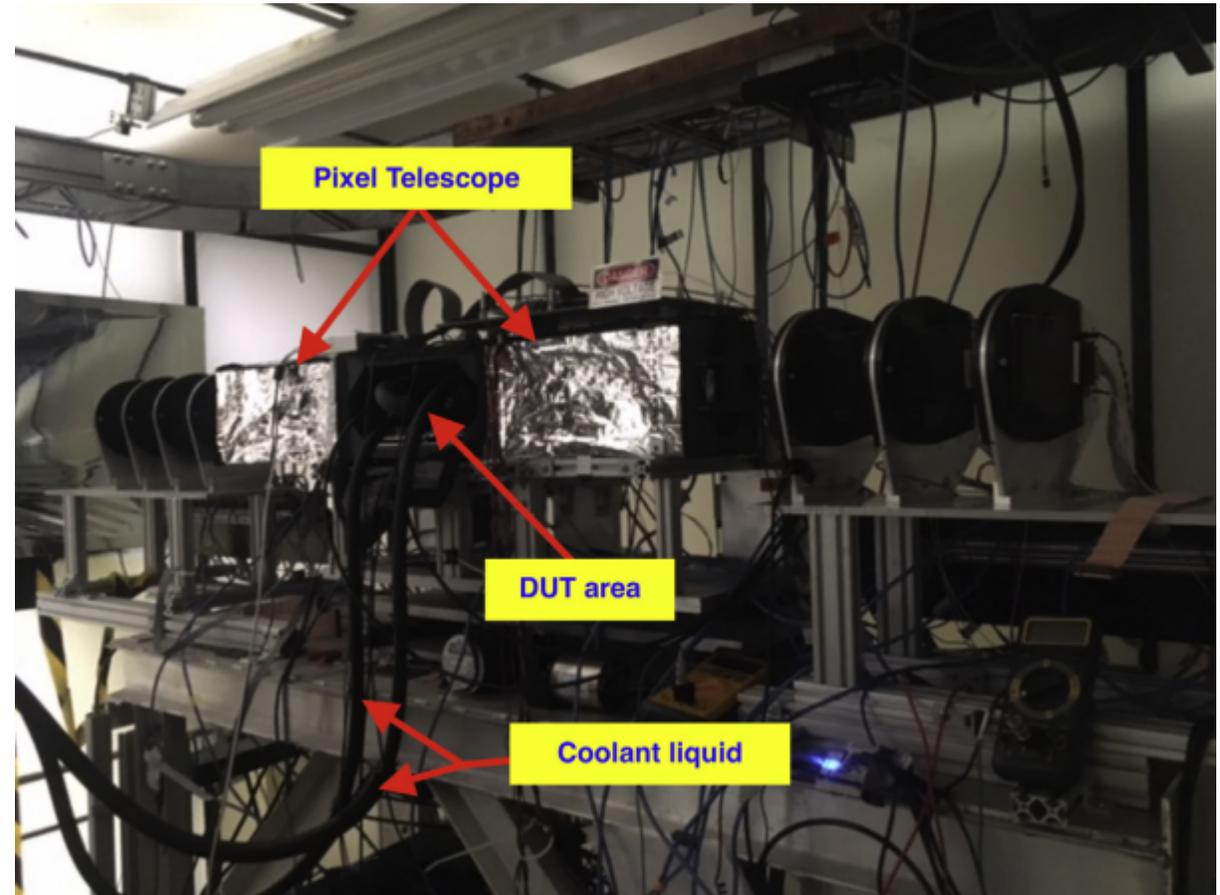
- The Pileup is a major concern in HL-LHC experiment
 - Most of the data read out will be associated with the “pile-up” collisions
 - The pileup complicates the reconstruction of the observed object.
 - Pileup is major cause of systematic uncertainty
- One way to mitigate the pileup effects is to perform a time of arrival measurement associated with each particle.
 - Such measurement will reduce the effective amount of pileup by a factor of 10
- Fermilab is conducting 120GeV proton beam test for minimum ionizing timing detector of HL-LHC upgrade.
- The goal of the MTD beam test is to select proper sensor to maintain performance while isolating the pileup from the signal.
- By analyzing the data of sensor in the beam test, we can compare the performance of detector before the HL-LHC upgrade in CMS.



2017 Fermilab Beam Test for MTD

- Fermilab performs measurements of the performance of low-gain avalanche detectors (LGAD) sensor.
- The pixel telescope detector are placed on the sides of the device under the test.
 - The pixel telescope provide tracking information
- A Photek 240 micro-channel plate (MCP-PMT) detector was placed furthest downstream
 - Provided a very precise reference timestamp
- Using the data obtained from LGAD sensor, the uniformity study were tested

Experimental setup for Fermilab test beam in 2017

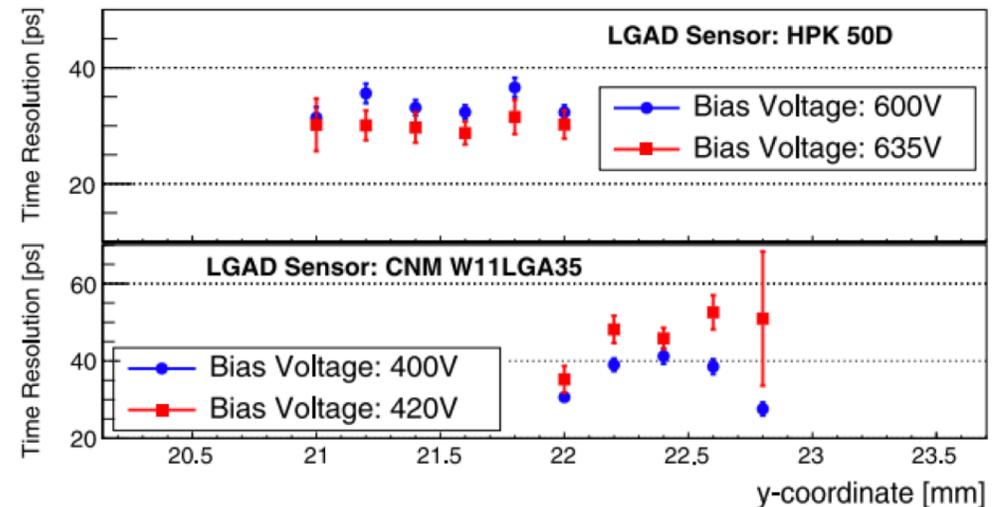
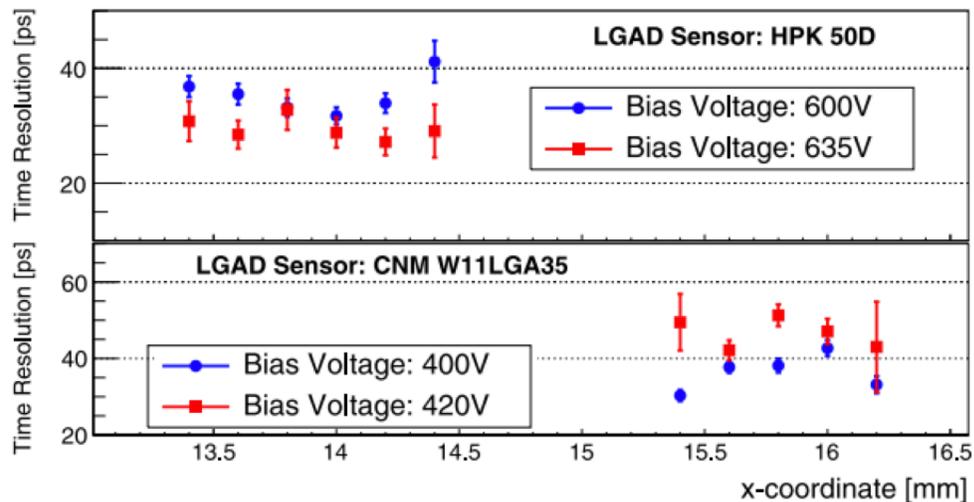


Result of Fermilab Beam Test in 2017

In order to achieve the desired timing, the sensors will need to provide high uniformity of signal response and timing resolution

The uniformity of the sensor response in pulse height -> **2%** spread

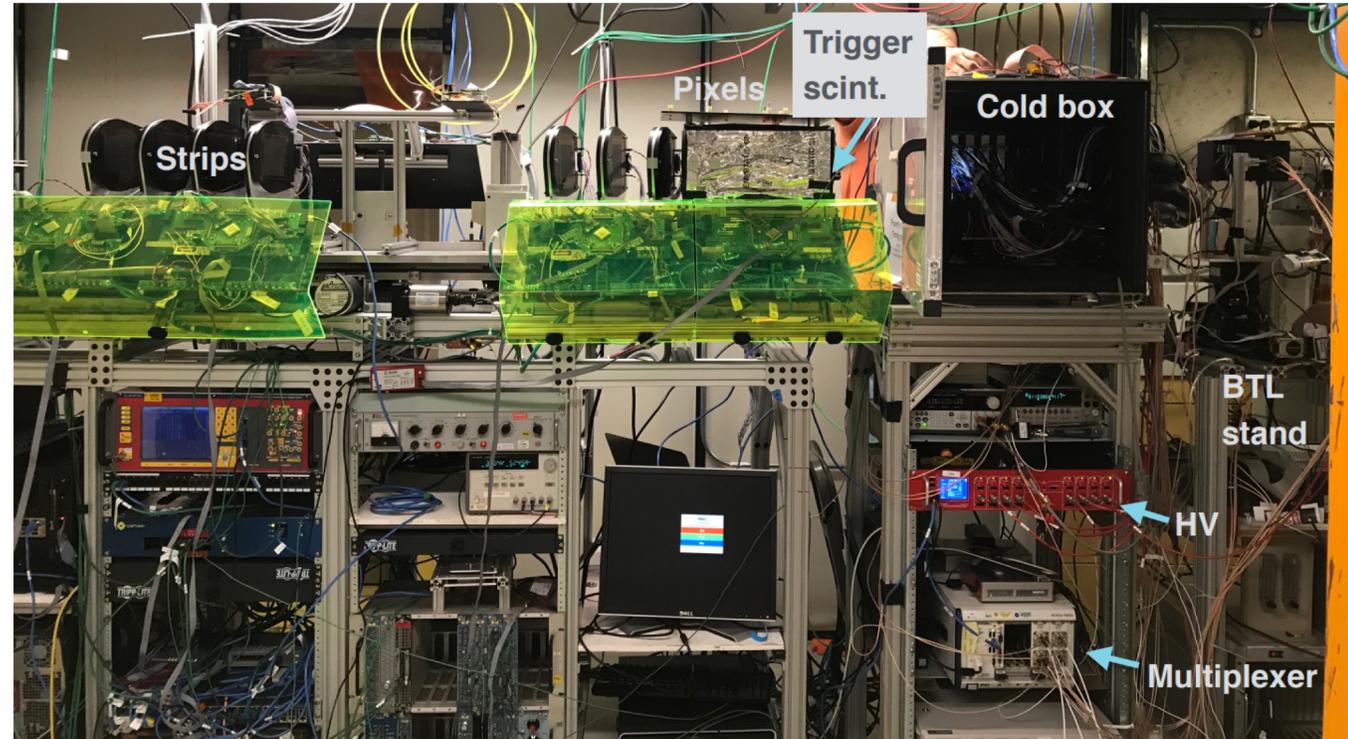
- The signal detection efficiency -> about **100%**
- Timing resolution in the sensitive areas -> **30-40 ps**
 - The spread in collision time of the pileup interactions at HL-LHC is foreseen to be approximately 200 ps.
- The “non-response” region between pixels -> about 130 μm for CNM sensors (Barcelona, Spain) and 170 μm for HPK sensors (Hamamatsu).



2019 Fermilab Beam test for MTD (new)

- The 2019 April beam test was conducted with new experimental setup
 - 40 GS/s, 100k events per acquisition
- Due to significant upgrades, tracking quality greatly improved
- With new tracker planes downstream from LGADs, reject events with scattering.
 - A strip layer replace downstream of pixel telescope
- With new oscilloscope, no loss of sync with tracker
- The uniformity study of signal of sensor is one of major task

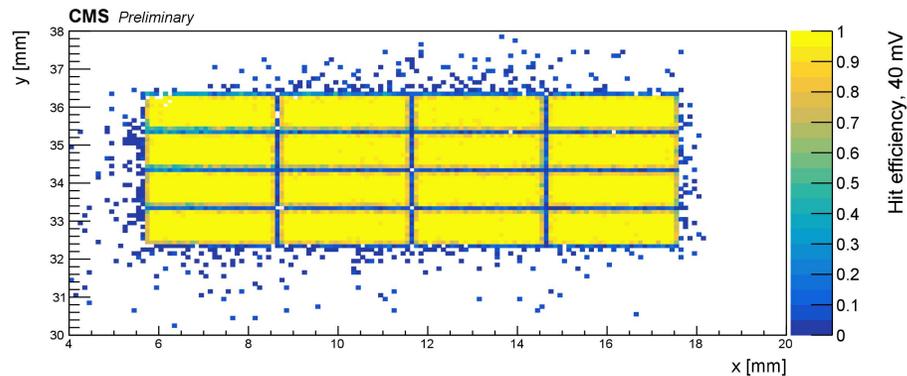
Strip+pixel telescope and ETL stand at Fermilab in 2019



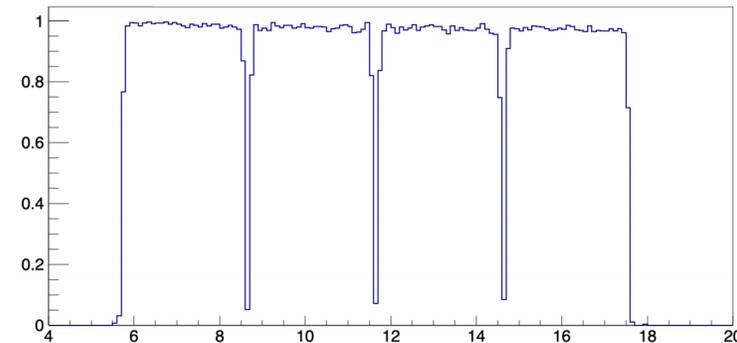
Uniformity study of the sensor response

- Verifying the sensor's performance is essential in order to achieve the correct performance
- Measurements of the uniformity of time resolution, signal amplitude and efficiency across the sensor surface of LGAD

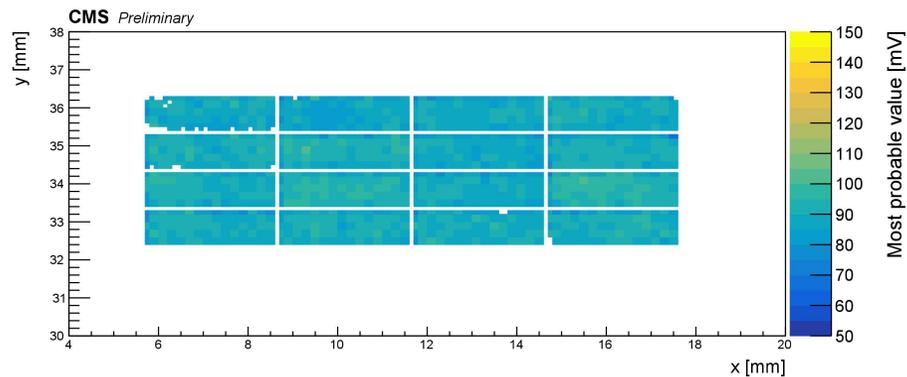
Efficiency of HPK 4x4 sensor



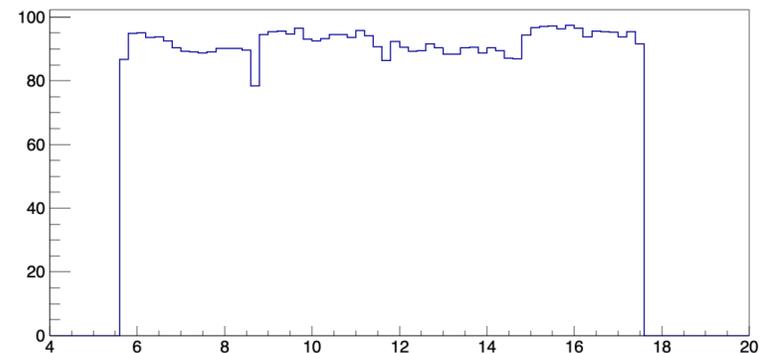
Efficiency vs X-axis



Most probable value of HPK 4x4 sensor

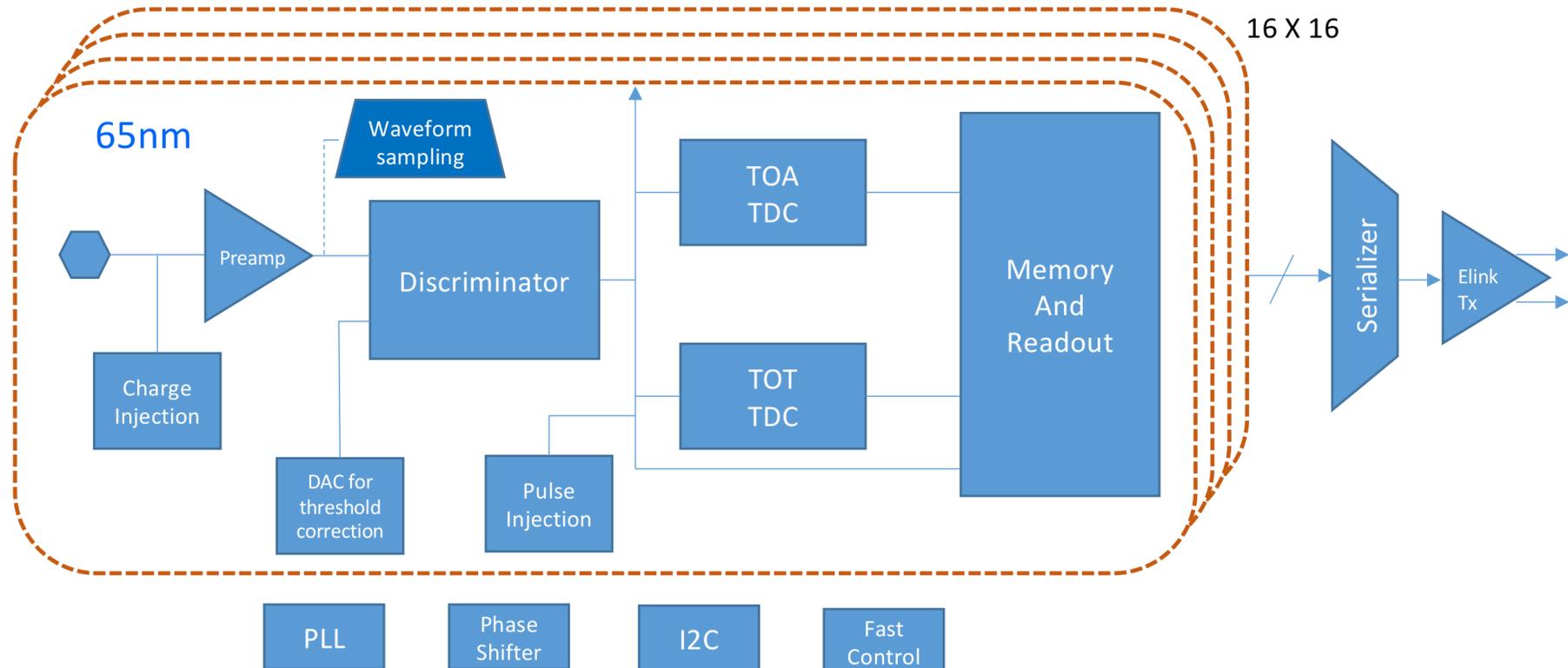


MPV vs X-axis

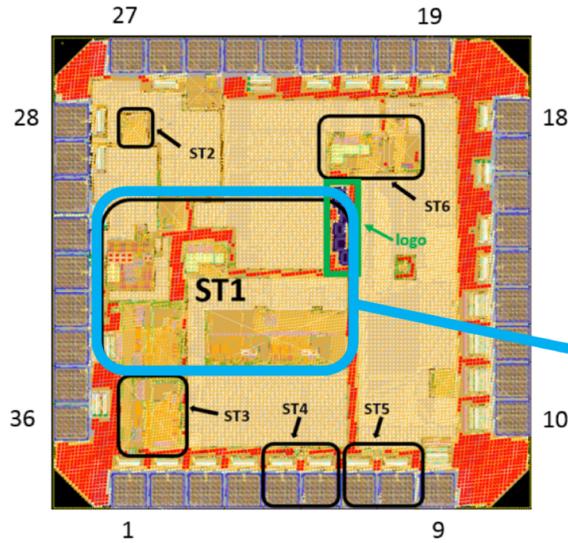


ETROC: ETL Read-Out Chip for MTD

- ETROC is bump-bonded to LGAD sensor, to handle a 16×16 pixel matrix, each $1.3 \text{ mm} \times 1.3 \text{ mm}$. chip size $\sim 21 \text{ mm} \times 21 \text{ mm}$.
- ASIC contribution to time resolution $< \sim 40 \text{ ps}$
- Targeted signal charge (1MIP): 6 fC
- TDC range: $\sim 5 \text{ ns}$ TOA and $\sim 10 \text{ ns}$ TOT
- L1 buffer latency: 12.5 us with power consumption $< 1 \text{ W/chip}$

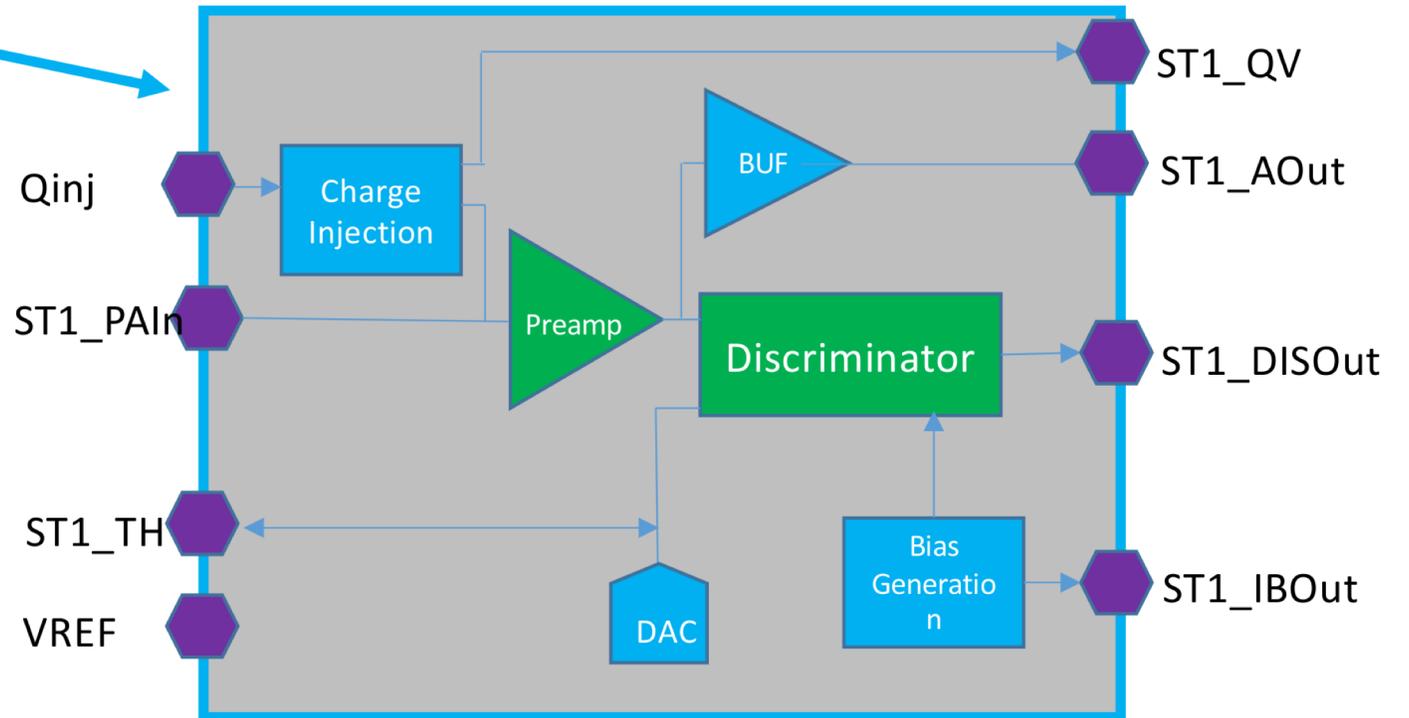


ETROC0: the First Prototype Chip



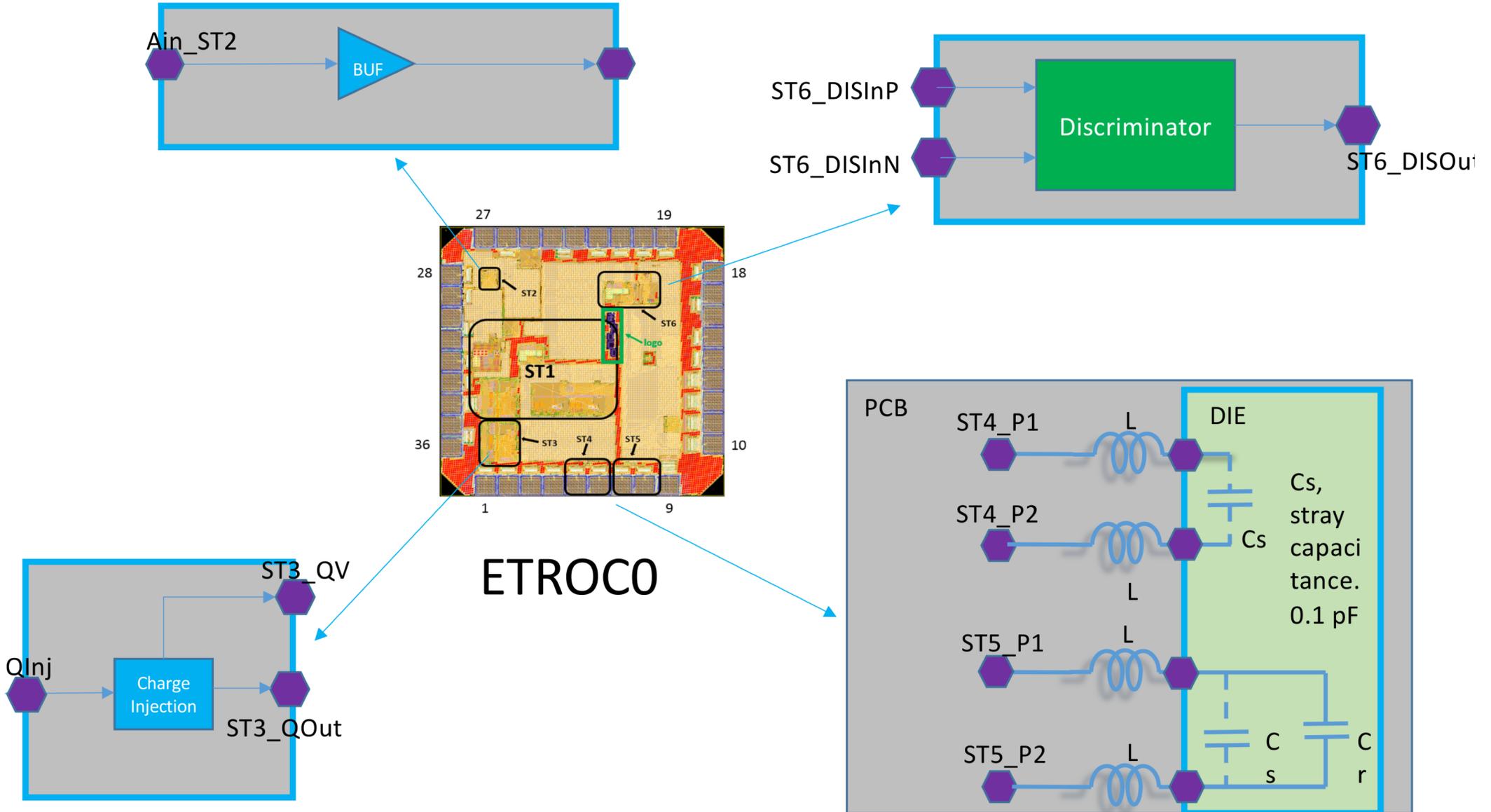
- Submitted Dec 2018
- Chip delivered end of March
- Testing started early April

Test structure ST1: the full chain

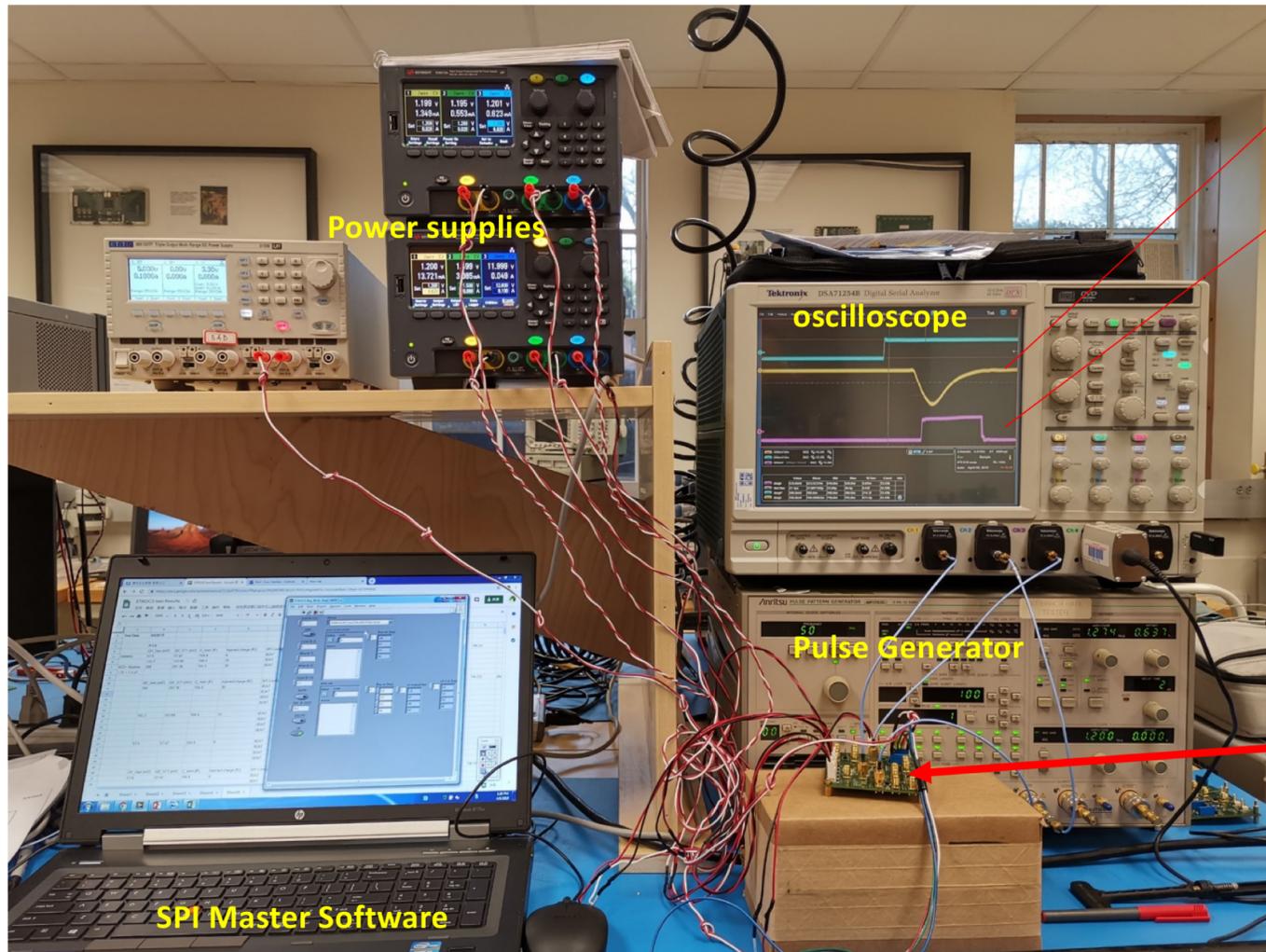


- All individual blocks can be tested separately
- Power consumption can be measured for each section separately

ETROC0: Designed for full testability



Test setup at SMU Opto-electronics Lab



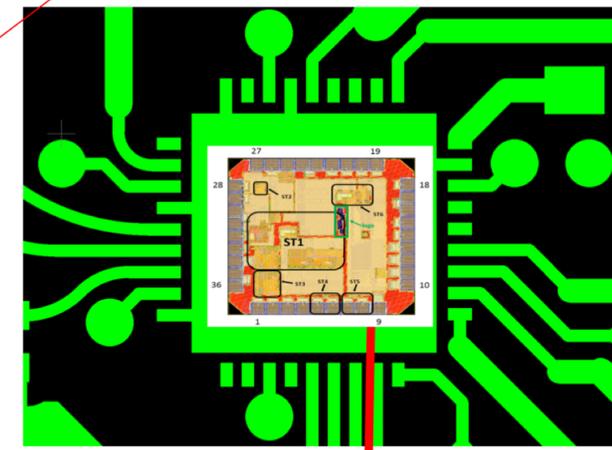
Power supplies

oscilloscope

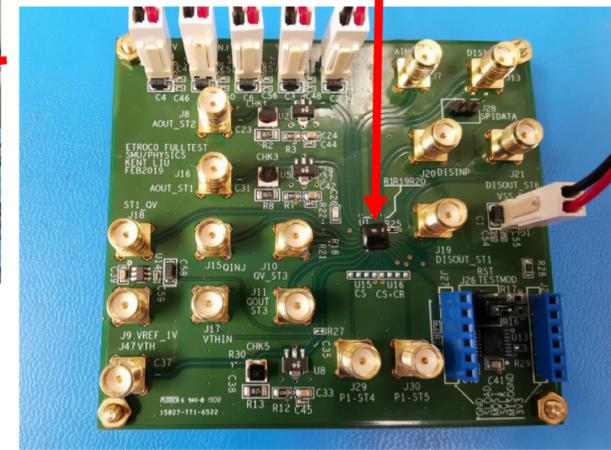
Pulse Generator

SPI Master Software

Preamp output
Discriminator output



ETROCO



Testing just started early April, 2019

L1 Correlator Trigger (L1 CT)

- The High Luminosity LHC (HL-LHC) conditions are characterized by:

- Instantaneous luminosity of $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and 140 average Pile-up (PU) events
- Large increase in the rates of the physics processes

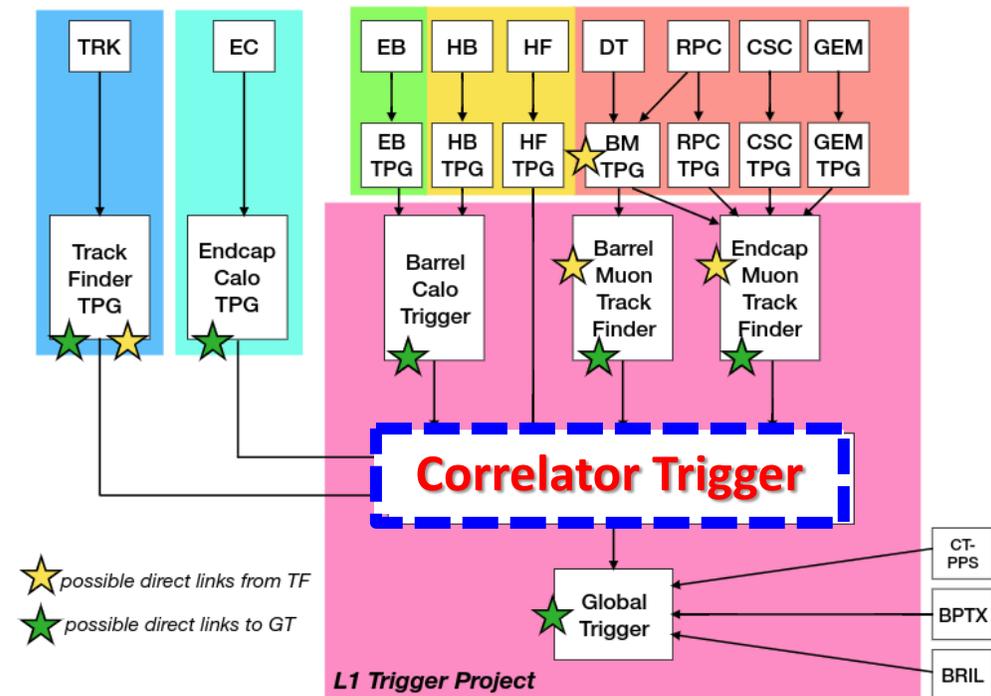
- Data flow in L1 trigger for HL-LHC

→ The L1 CT performs the role of matching and reconstructing all signals generated from the tracker, calorimeter, muon chamber, etc.

→ The events that have been reconstructed by CT are sent to the global trigger.

→ The global trigger determine to select or not.

High-level view of the Phase-2 L1 trigger



Algorithms in L1 CT (1)

● Particle-Flow (PF) algorithm

- Correlates tracks from the tracker, muon chamber and the clusters from the calorimeter to identify each final-state particle.
- Reconstruct properties of the identified particles combining the measurements of the sub-detectors

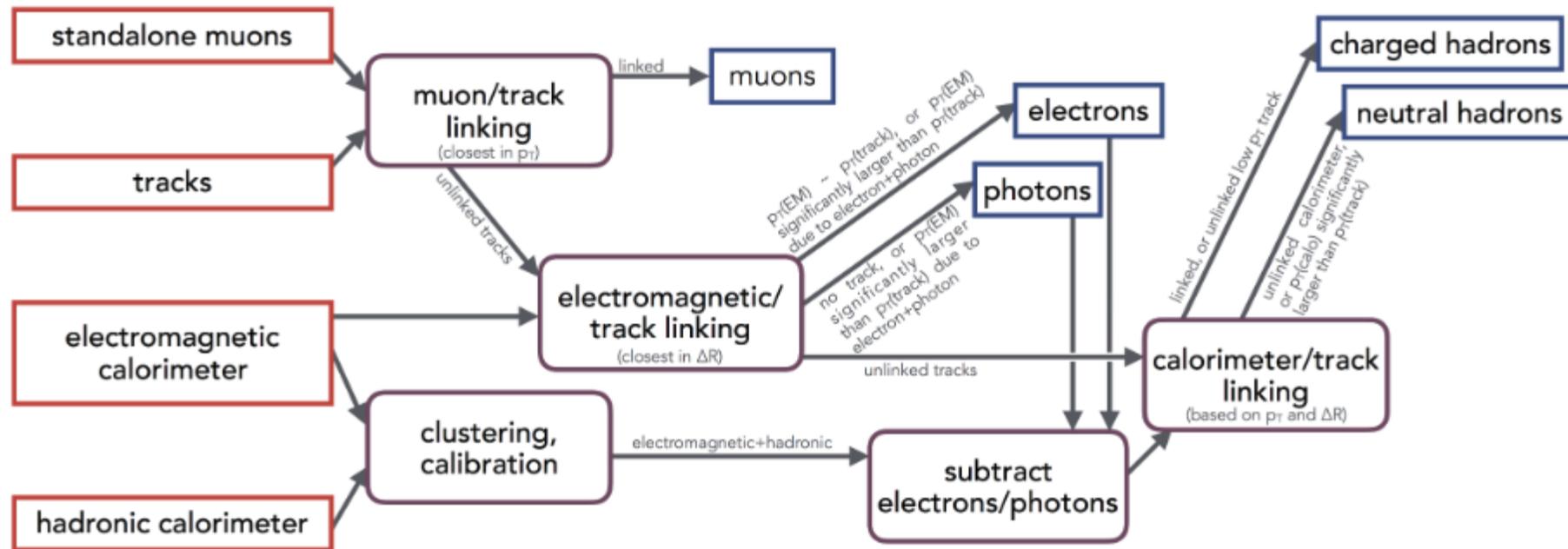


Fig. Schematic of particle flow algorithm for CMS Level-1 trigger correlator.

Algorithms in L1 CT (2)

● PileUp Per Particle Identification (PUPPI) algorithm

- The PUPPI algorithm is the best performing pileup mitigation technique used in the CMS offline reconstruction.
- Removes charged particles with tracks not originating at the primary vertex.
- Downweights neutral particles based on the probability that they originate from pileup.

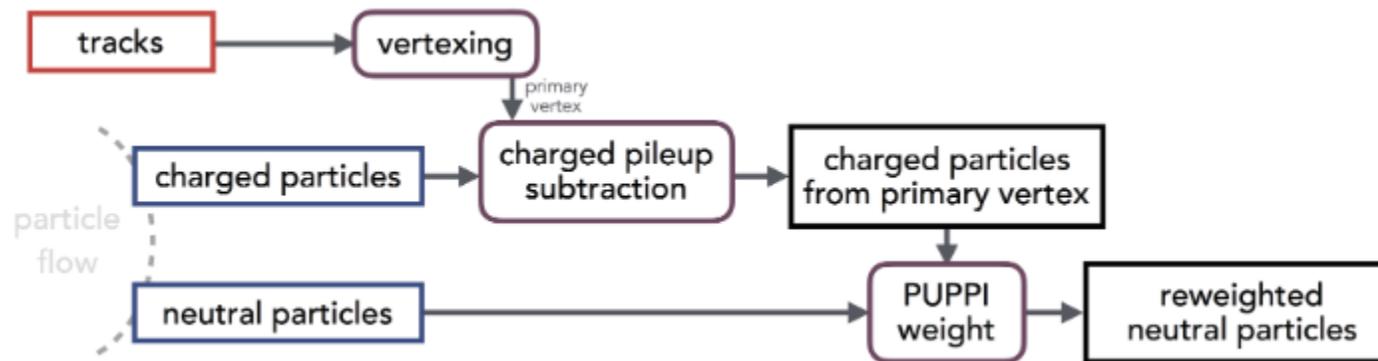


Fig. Schematic of PUPPI pileup mitigation algorithm for CMS Level-1 trigger correlator.

The **CMS Phase-2 upgrade** is expected larger pileup.

➡ **Algorithm tuning** to improve the performance.

Hardware-based Development (1)

- In environment of HL-LHC, more hardware resource will be used to control increased data.
- Therefore, this study can help the algorithm work better by reducing the amount of resources used by the hardware and reducing the computational time.

- Reducing the total data obtained in real time.
- Preserve meaningful data in events.



Fig. FPGA from Xilinx

- High Level Synthesis (HLS) enable to develop the optimized algorithm for FPGA (Field Programmable Gate Array) using C/C++ we use in this study.
- In this study, the algorithm is implemented in firmware using Vivado HLS, a software package from the Xilinx.



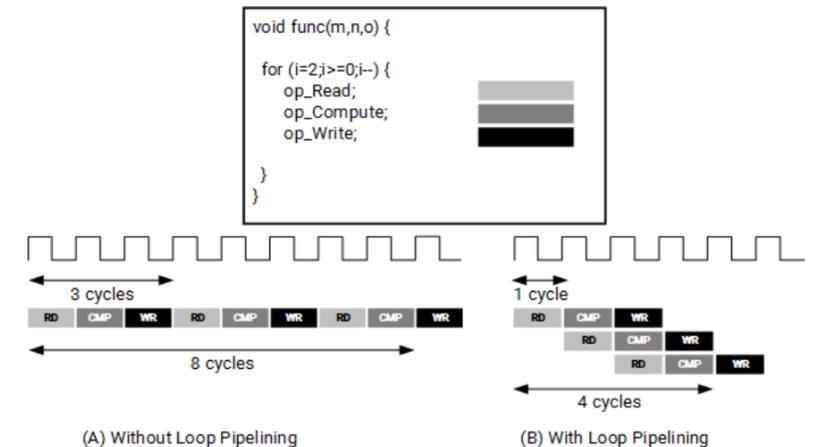
Hardware-based Development (2)

- The challenge in creating an optimal FPGA implementation is to balance FPGA resource usage with achieving the latency and throughput goals of algorithm.
 - **Latency**: the total time required for a single iteration of the algorithm to complete.
 - **Initiation interval (II)**: the number of clock cycles required before the algorithm may accept a new input.

- To optimize those things, **pragma HLS** are using.

- The **pipeline** pragma reduces the initiation interval for a function or loop. A pipelined function can process new inputs every N clock cycles. (N is initiation interval)

- For another example, **array_partition** results in Register Transfer Level with multiple small memories instead of one large memory.



X14277-110217

Machine Learning on Nurion Supercomputer at KISTI

Purpose : Perform large scale Deep Learning for new physics search

Performance test for Nurion system according to machine learning framework is in progress

- Kyungpook National University (KNU) team : Keras + TensorFlow
- Kyung Hee University (KHU) team : PyTorch (Upgraded version of Intel Caffe)

Plan

- Study top quark rare processes and improve data acquisition technique using the large scale Deep Learning for new physics search.
- Perform large scale Deep Learning with maximal performance of the Nurion system at KISTI.



Specifications of Nurion Supercomputer at KISTI

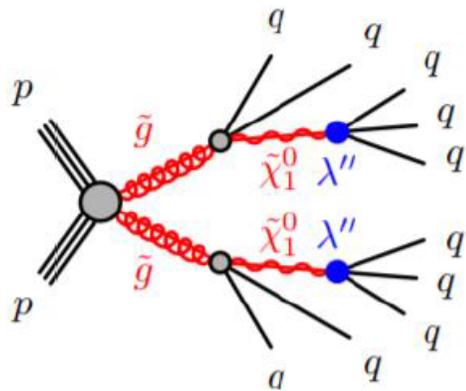
- Knights Landing (KNL) CPU node
 - Operating system : CentOS 7.4 (Linux, 64-bit)
 - CPU : Intel Xeon Phi KNL 7250, 1.4GHz, (68-core)
 - Number of node : 8305
 - Memory per node : 96GB DDR + 16GB MCDRAM
 - Theoretical performance per node : 3.0464 TFlops

Nurion Supercomputer at Korea Institute of Science and Technology Information (KISTI) in Daejeon, South Korea

Pre-performed machine learning study with Cori supercomputer

Benchmark research results by NERSC at Berkeley Lab

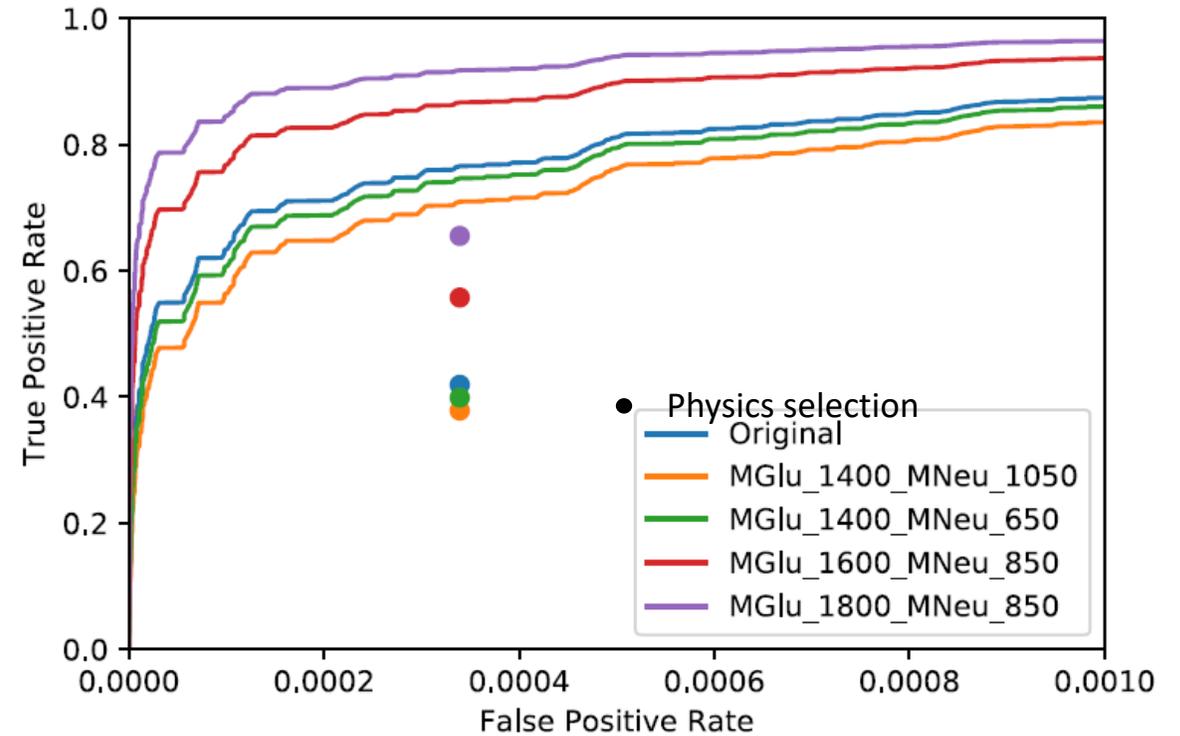
- Physics selection versus deep learning using Xeon Phi(KNL) computing resources
- Physics dataset
- Signal process: gluino cascade decay



\tilde{g} : gluino
 $\tilde{\chi}_1^0$: Neutralino
 λ'' : RPV coupling

Mass(Gluino): 1400 GeV
 Mass(Neutralino): 850 GeV

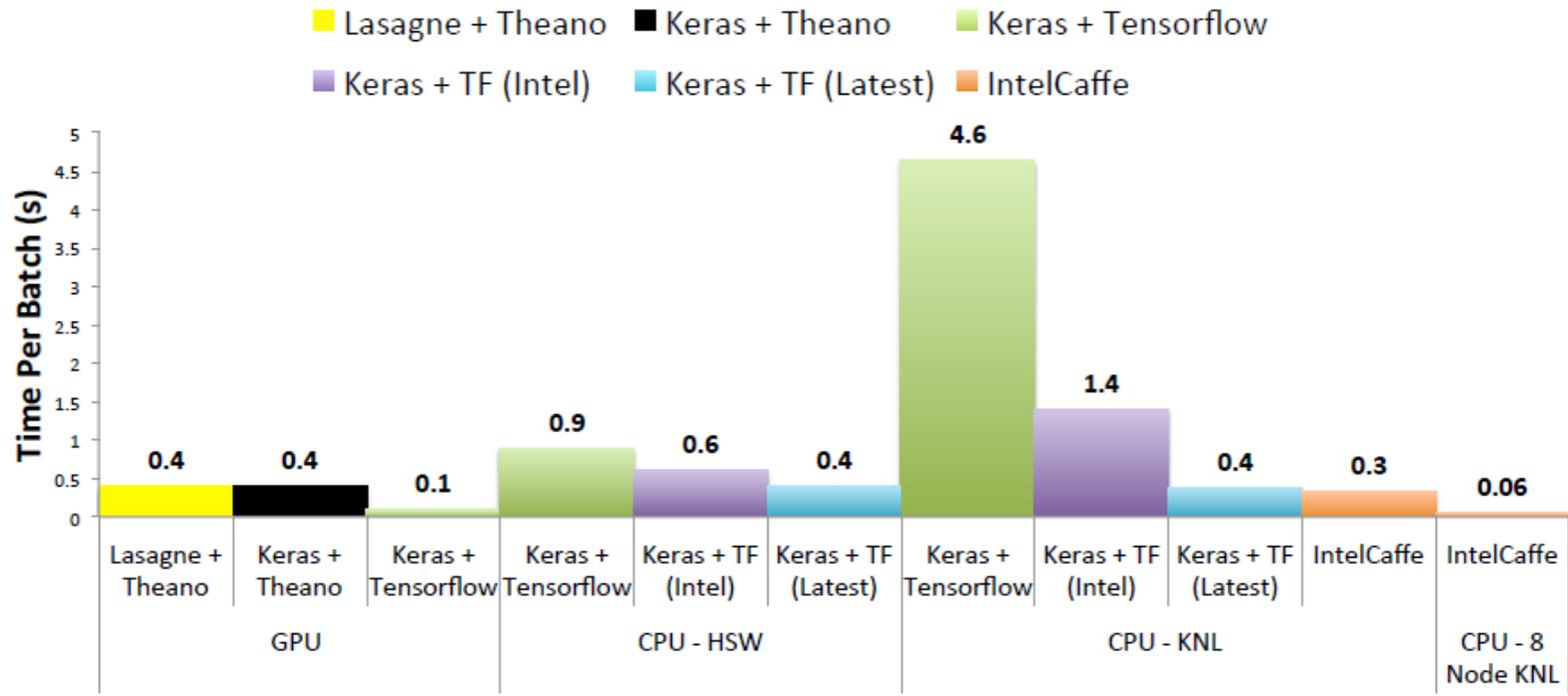
- Background process: QCD multi-jet process



[ROC curves for application of deep learning to different signal mass samples and comparison with physics selection]

- Deep learning method offers improved sensitivity than physics-variable based selections

Pre-performed machine learning study with Cori Supercomputer



- Cori's Computing resource

2388 Intel Haswell
(16 2.3 GHz cores 2.4 TeraFLOP/s)

9688 Intel Xeon Phi(KNL)
(68 1.4GHz cores with 4 Hyper Thread and 6 TeraFLOP/s)

- Comparison
Single Titan X GPU 10.2 TeraFLOPS/s

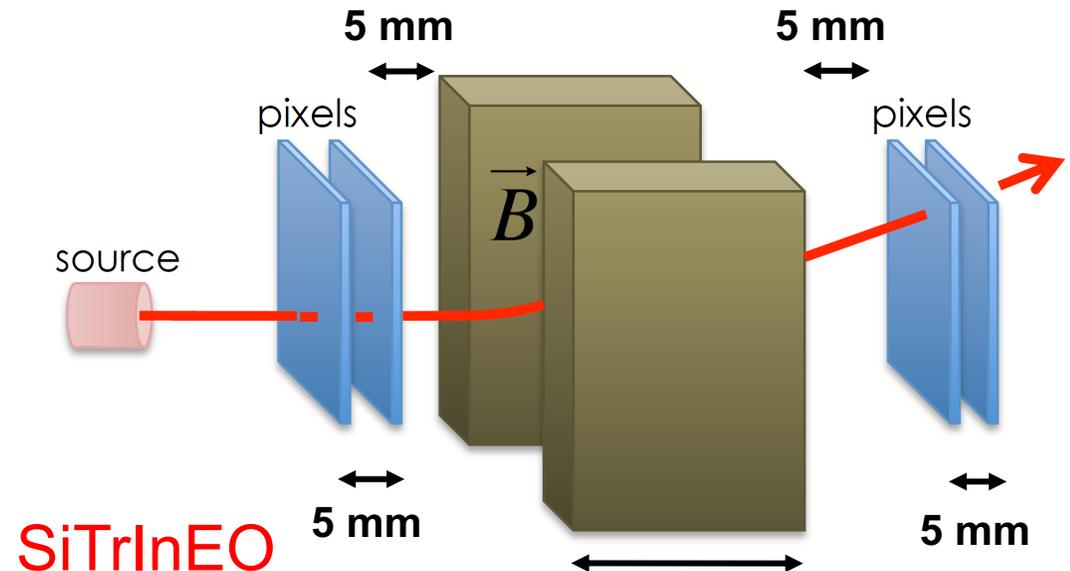
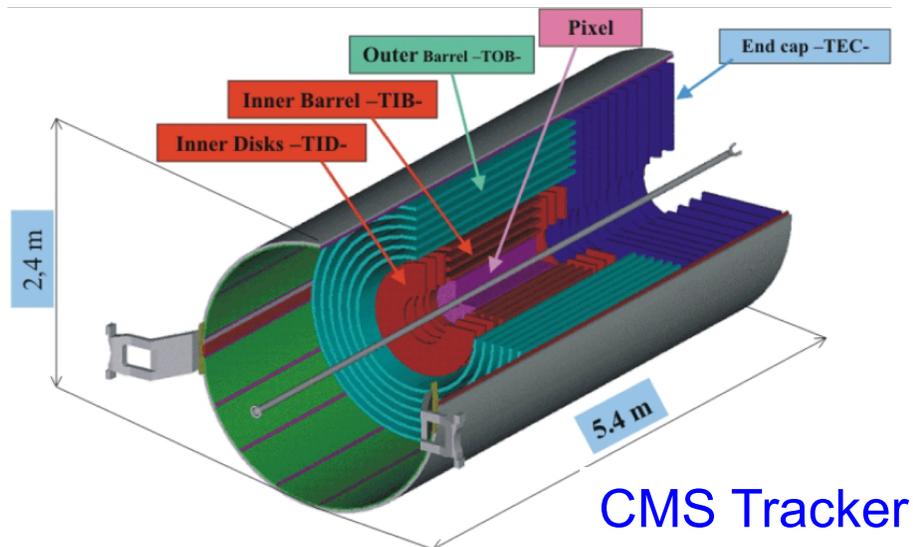
- Several optimizations by Intel for Tensorflow on CPU building on the Intel Math Kernel Library (MKL).
 - Substantial improvements in the times labeled 'TF (Intel)'.
- Further optimizations in a collaboration between NERSC and Intel
 - Using the architecture and data from this paper, as well as other use-cases, resulting in the 'TF (Latest)'.
- Performance improvements for CPU were also made in IntelCaffe
- Using 8 nodes, one can train this network approximately 6x faster than a single node
- With other collaborators, we have scaled this Caffe implementation on the same problem, but with large 224x224 images, to 9600 KNL nodes on Cori

Pre-performed machine learning study with Cori supercomputer

- The Nurion computing resource has an environment similar to the Cori.
 - Xeon Phi KNL node
- Study DM searches and top quark rare processes and improve data acquisition technique
 - Using the large scale Deep Learning for new physics search
- Perform large scale Deep Learning with maximal performance of the Nurion system
 - The Pytorch (Caffe2) to be used for the performance
 - because the multi-node of Caffe1 shows the highest performance in the benchmark research
 - The Keras+Tensorflow with multi node also used.
- Testing the performance of Nurion's computing resource using Keras+Tensorflow

Introduction to SiTrInEO

- ❑ Motivation of the **SiTrInEO** project
 - High energy physics based on the accelerator uses large-scale devices and infrastructure
 - Difficult to understand for students the principles of the tracking system
- ❑ The main purpose of the **SiTrInEO** project
 - Help students to understand the basic tracking system
- ❑ The **SiTrInEO** is conducting joint research France-Korea through two cooperative projects.
 - Supported by the **STAR program** and **FKPPL**



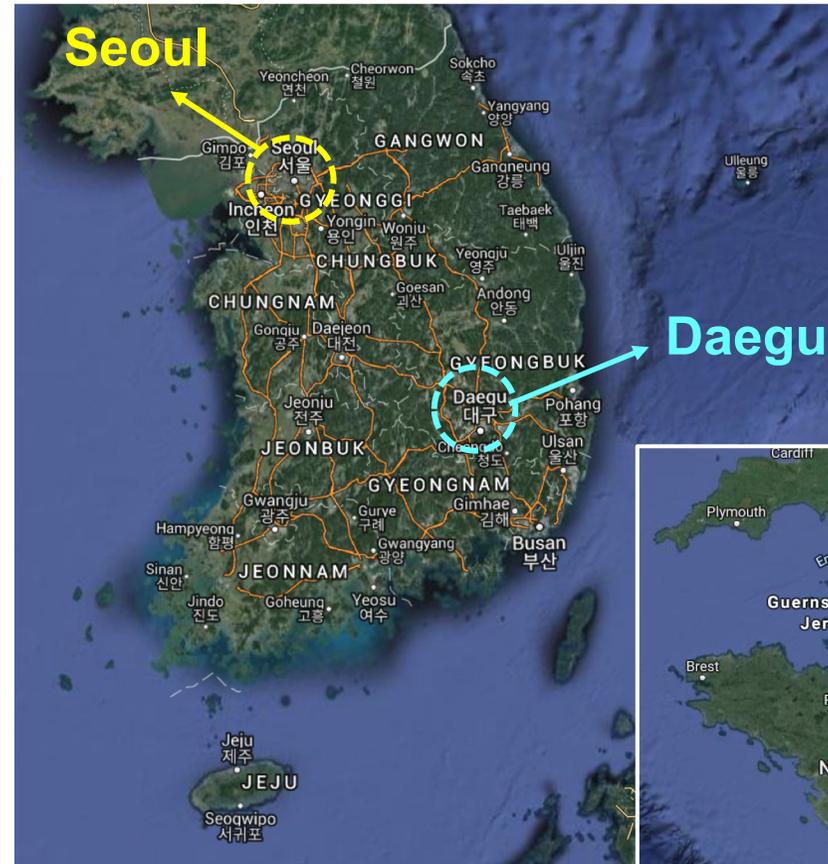
The SiTrInEO Collaboration

□ KNU (Korea)

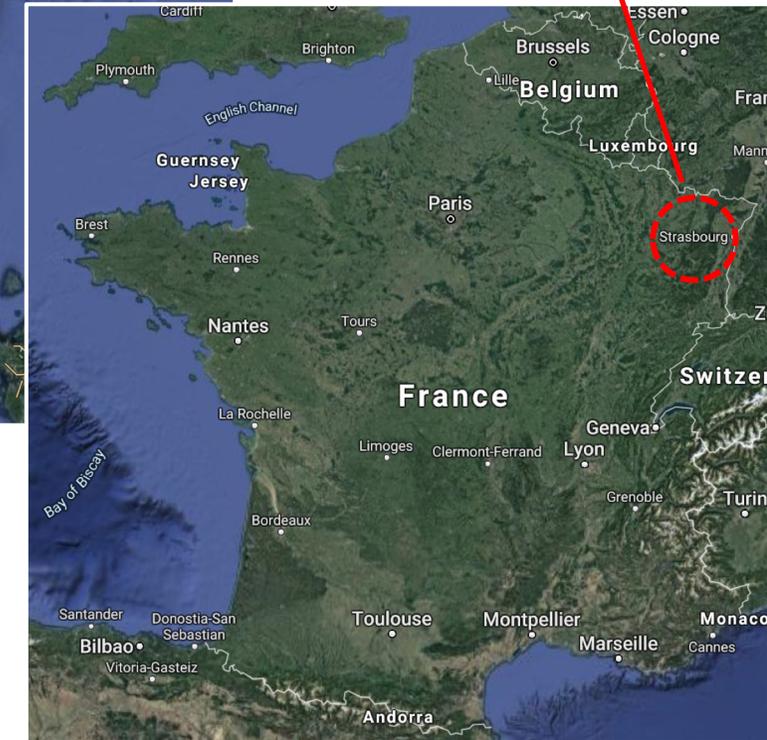
- CMS group
 - Staff: Chang-Seong Moon
 - Students: Jongho Lee, Daekwon Kim, Jeongmin Son

□ IPHC (France)

- CMS group
 - Staff: Eric Chabert, Pierre Van Hove
- PICSEL group
 - Staff: Auguste Besson
- Belle II group
 - Staff: Jerome Baudot
 - Students: Adèle Perus, Romain Schotter

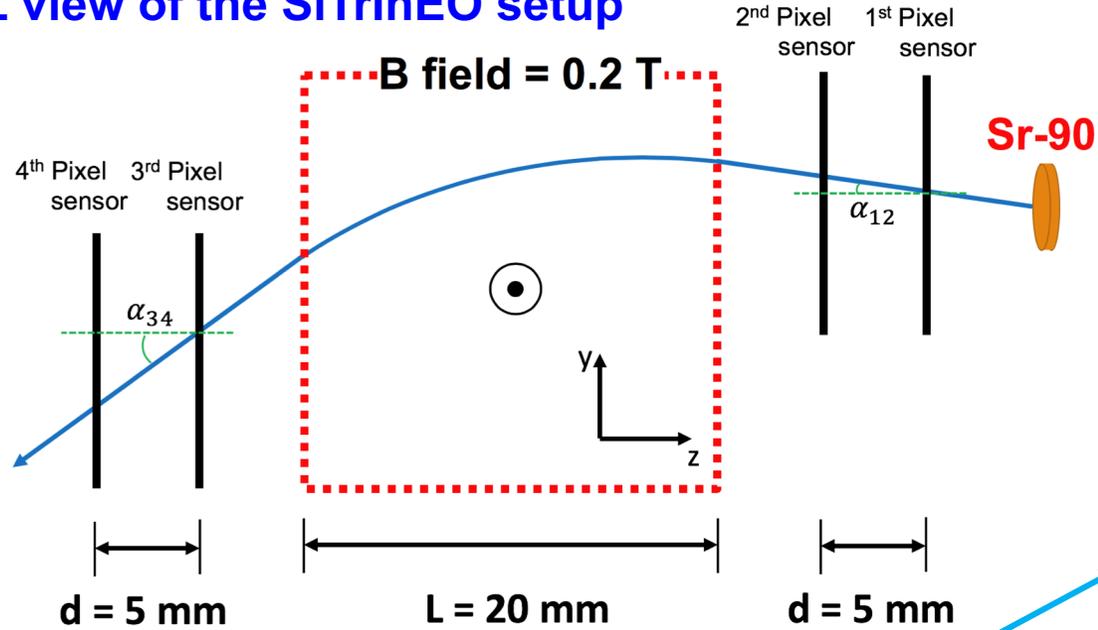


Strasbourg



Momentum Measurement Strategy

Y-Z view of the SiTrInEO setup



- Same σ_{spatial} for all pixel sensors
- Lever-arm between sensors in a pair = d
- Multiple scattering contribution only from last or first plane
- BL = bending power
- $K_1, k_2, k_3 = \text{constants}$

Lever-arm effect

Bending power

$$\frac{\sigma_p}{p} = \sqrt{k_1 \frac{\sigma_{sp}^2}{d^2} + \frac{k_2}{p^2} \left(\frac{p}{k_3 BL} \right)} \rightarrow \frac{\sigma_p}{p} \approx \frac{\sqrt{k_2}}{k_3 BL}$$

Multiple scattering

□ The formula represents:

- Lever arms (d) between sensors
- Multiple scattering between particles and materials
- Particle trajectory bending by magnetic fields (B)

□ The lever arm effect can be ignored by placing the same distance between each pair of sensors.

□ If ignoring the effects of multiple scattering:

- Ideal formula of momentum calculation

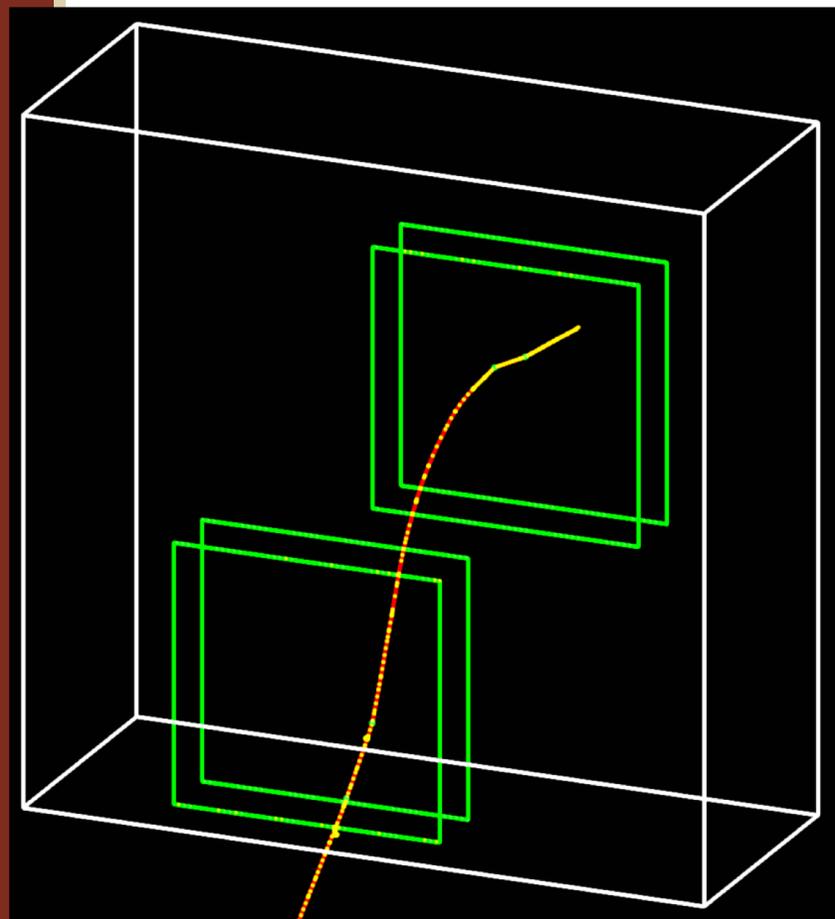
$$\rightarrow p = \frac{k_3 BL \sigma_p}{\sqrt{k_2}} \approx \frac{0.3 BL}{\Delta \alpha}$$

$$\left(\because \frac{k_3}{\sqrt{k_2}} = 0.3, \sigma_p \approx \frac{1}{\Delta \alpha} \right)$$

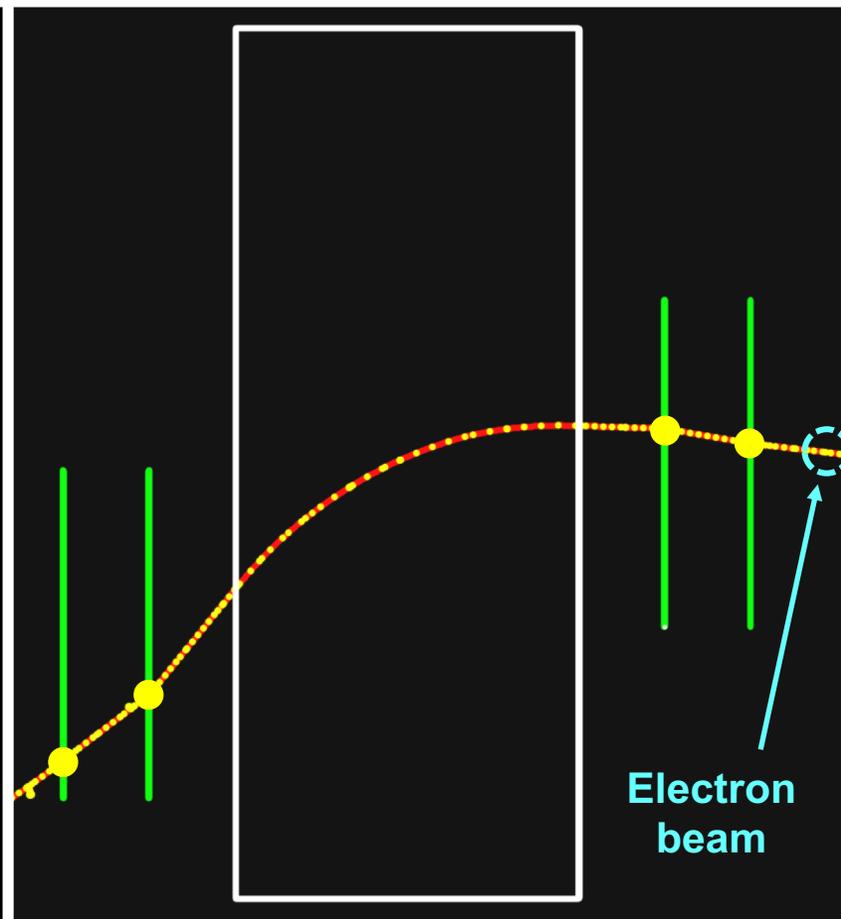
GEANT4 Simulation Studies – Event display

Based on **Electron gun sample (1.5 MeV)**, B-field magnitude : **0.2 T**

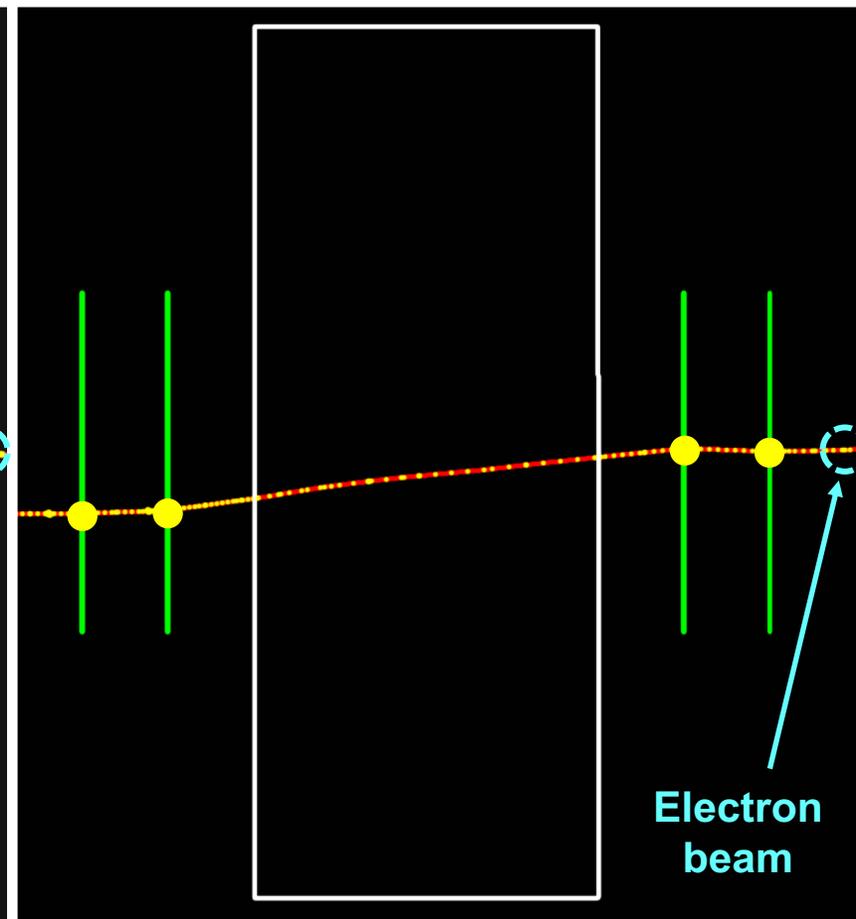
3D view



Side view (y-z plane)



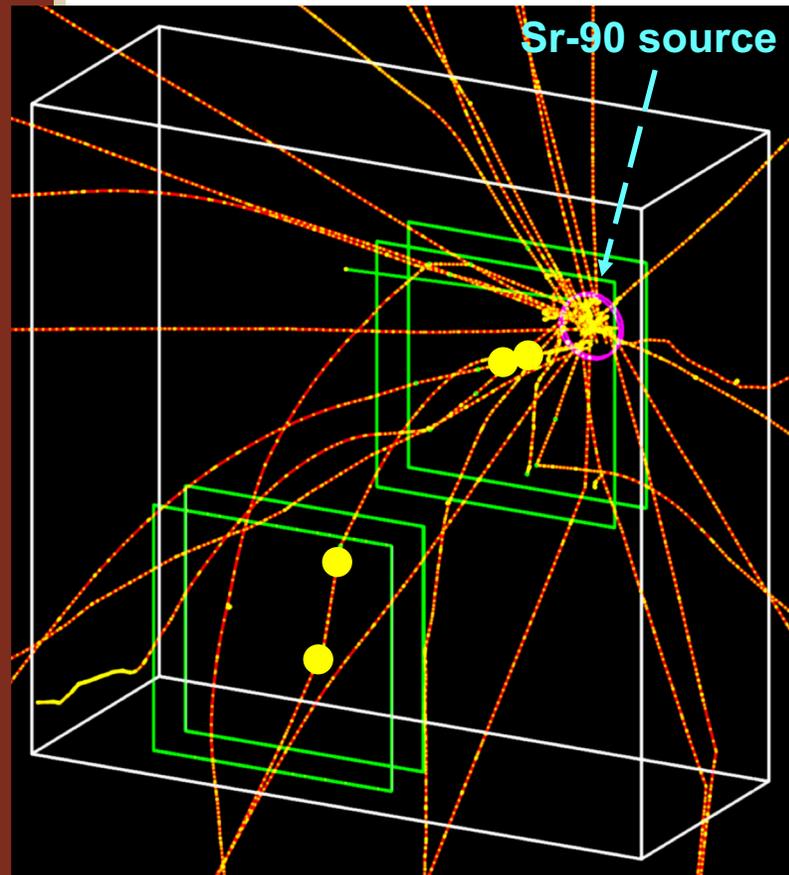
Top view (x-z plane)



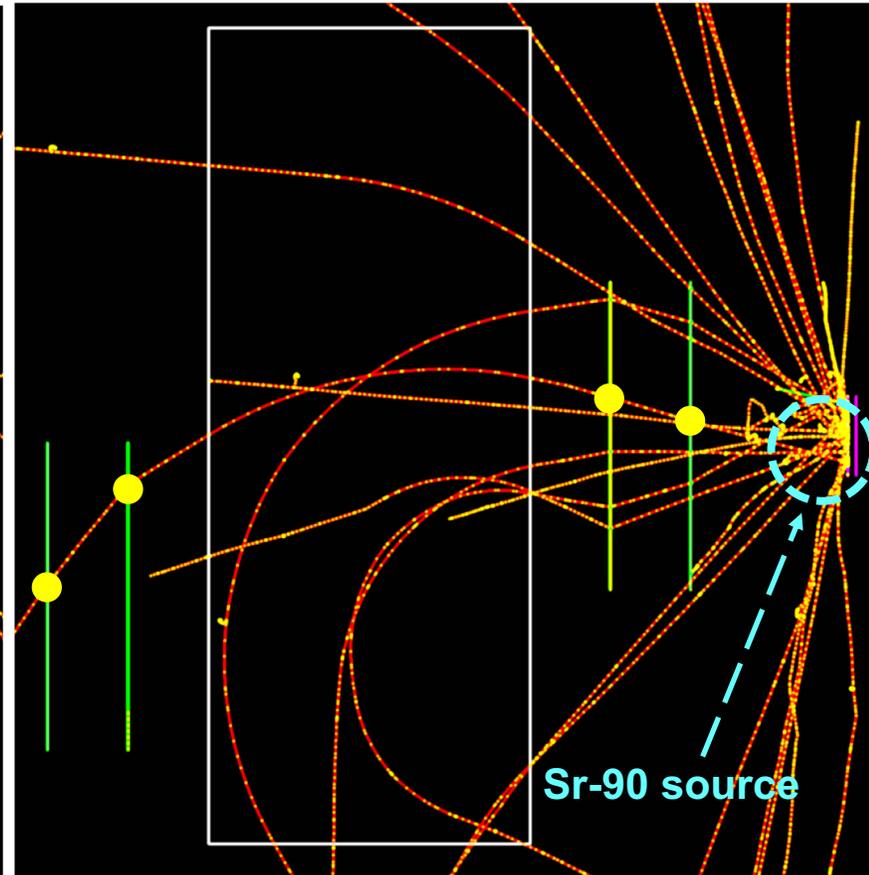
GEANT4 Simulation Studies – Event display

Based on **Sr-90 source** sample, B-field magnitude : **0.2 T**

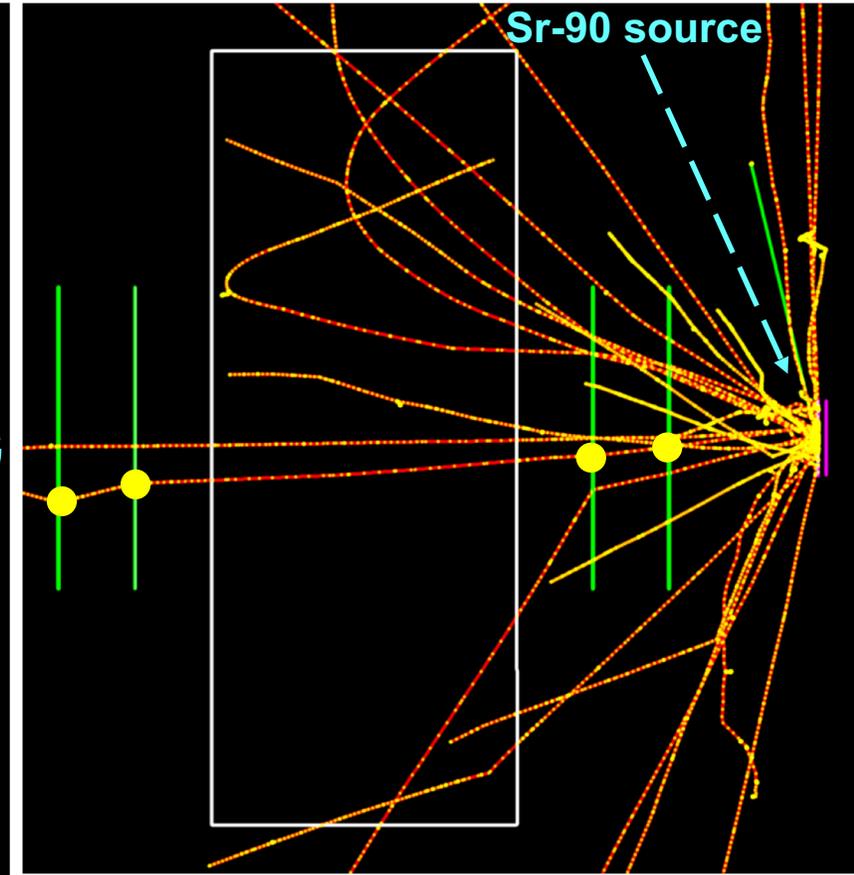
3D view



Side view (y-z plane)

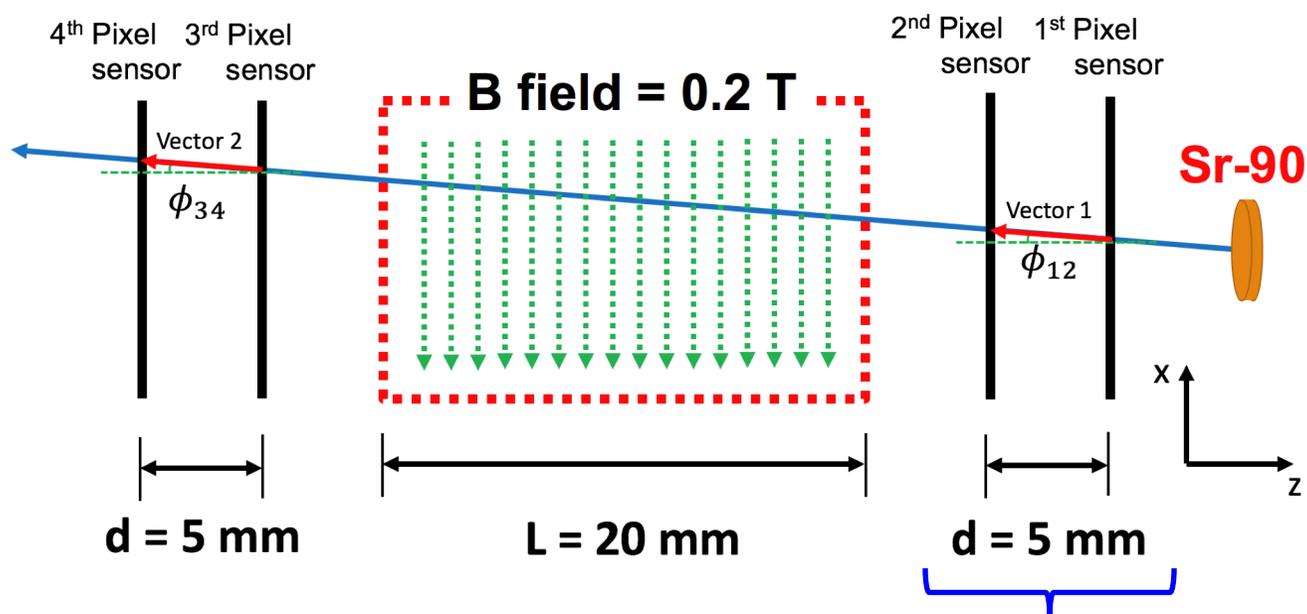


Top view (x-z plane)

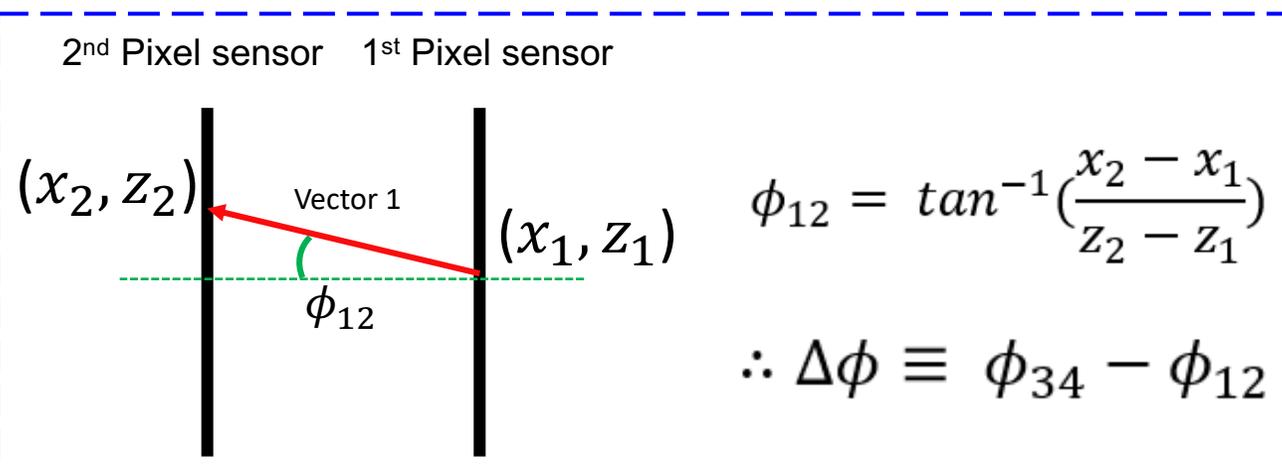


GEANT4 Simulation Studies

x-z view of the SiTrInEO setup

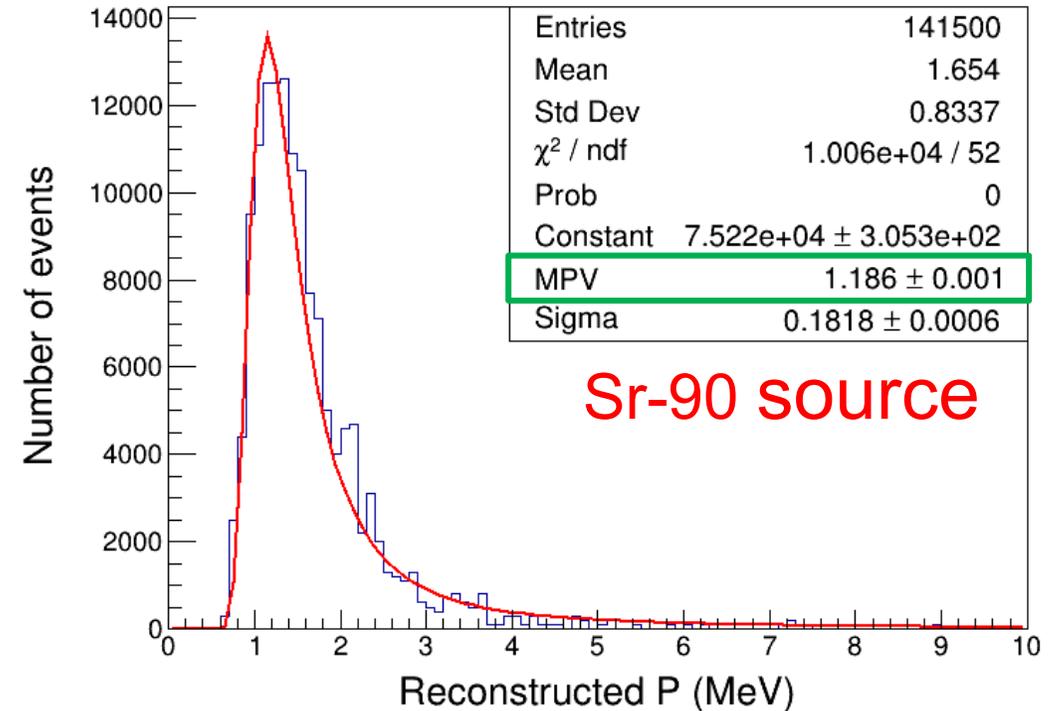
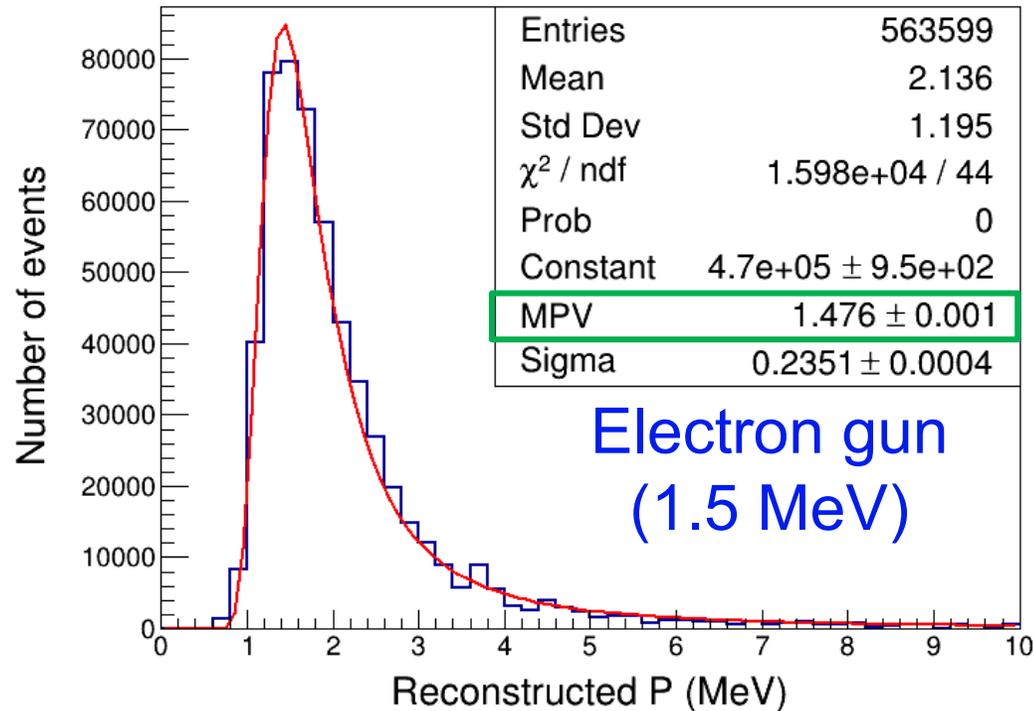


- The electron trajectory must be a straight line in x-z plane.
 - Magnetic field does not affect on electron trajectory in x-z plane.
 - The angle of Vector 1 and Vector 2 have to be the same in principle.



- ϕ_{ij} ($i = 1, 2, 3, j = 2, 3, 4$) and $\Delta\phi$ are defined as in the left figure in order to compare the angles from two vectors.

Reconstructed momentum distributions



❑ Reconstructed momentum distributions are reasonably fitted well with **Landau distribution**.

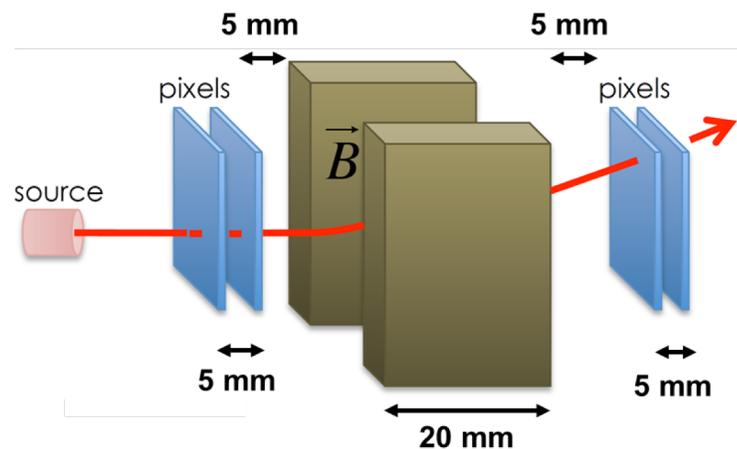
❑ **Most probable value (MPV) in both distributions:**

- Electron gun: **1.48 MeV** (Gen-level momentum: **1.5 MeV**)
- Sr-90 source: **1.19 MeV** (Average gen-level momentum: **1.43 MeV**)

❑ Investigating the reason of the low reconstructed momentum in Sr-90 source sample

“Mockup” setup at IPHC, Strasbourg

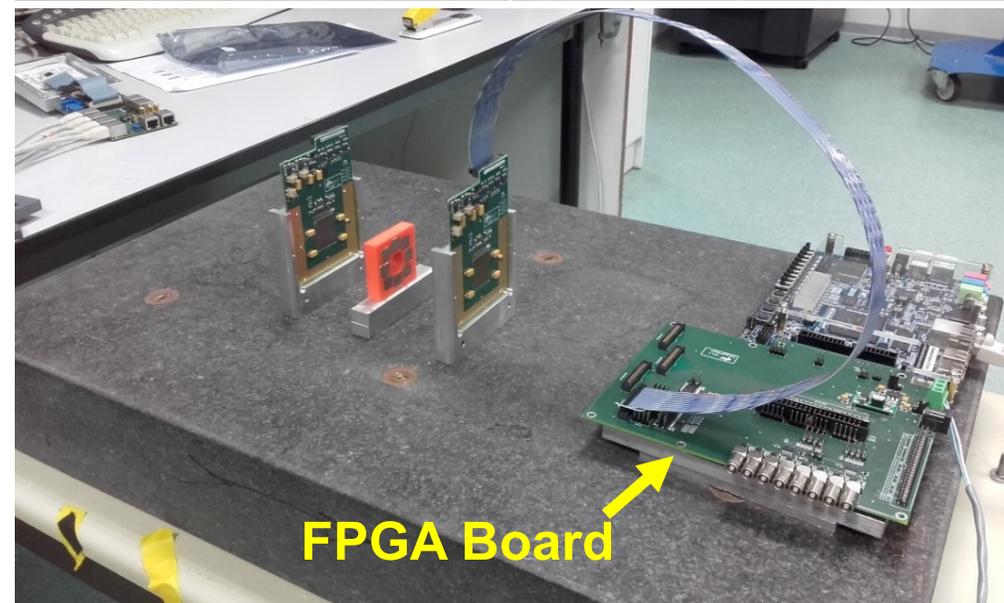
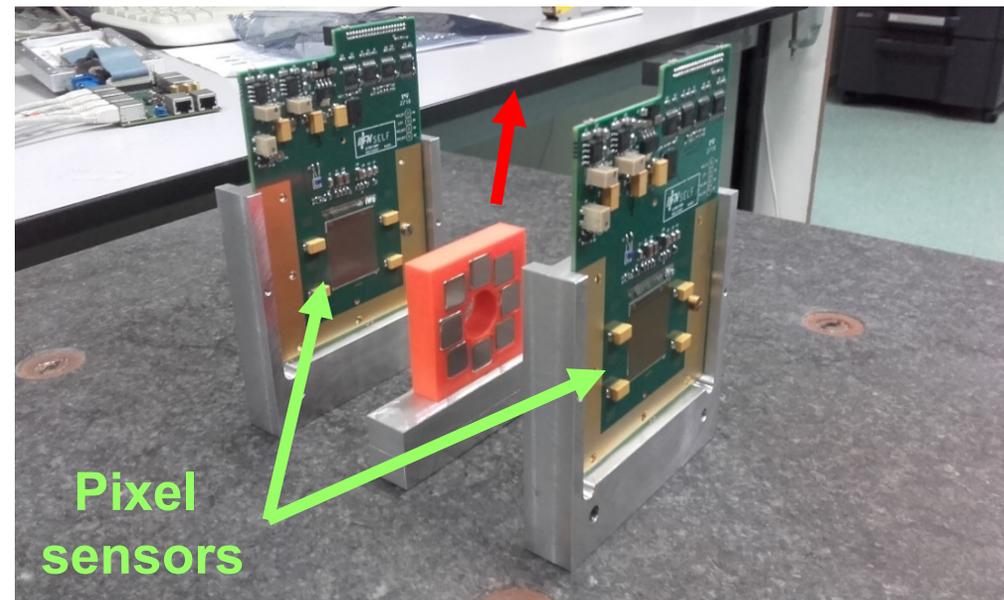
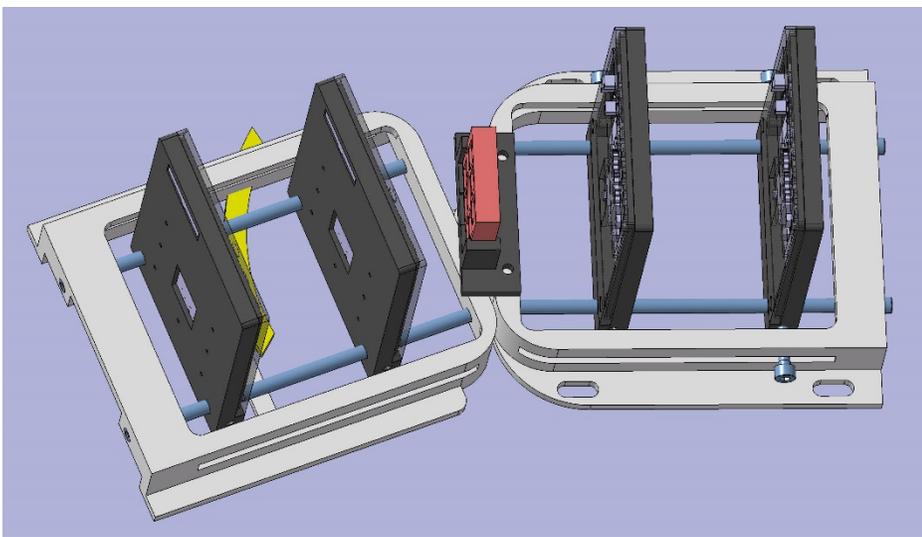
Schematic view



Realistic setup



3D sketch of the first setup for SiTrInEO



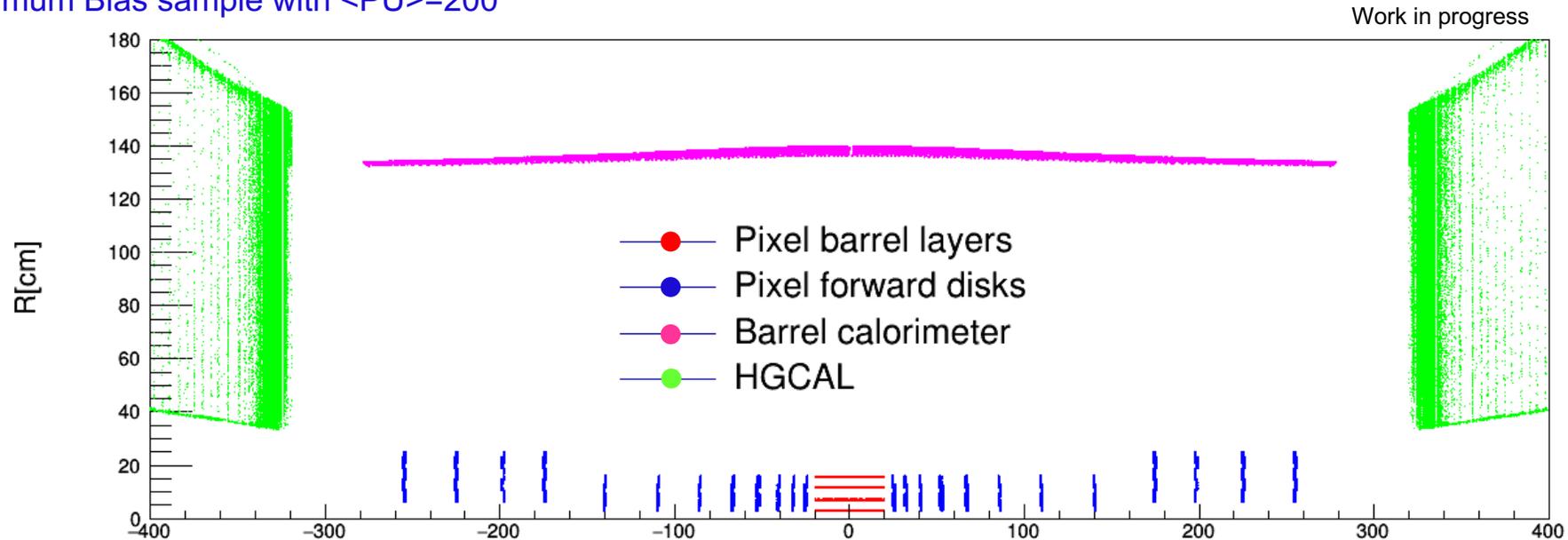
Thank you for your attention!

Introduction to pixel track isolation for electron ID

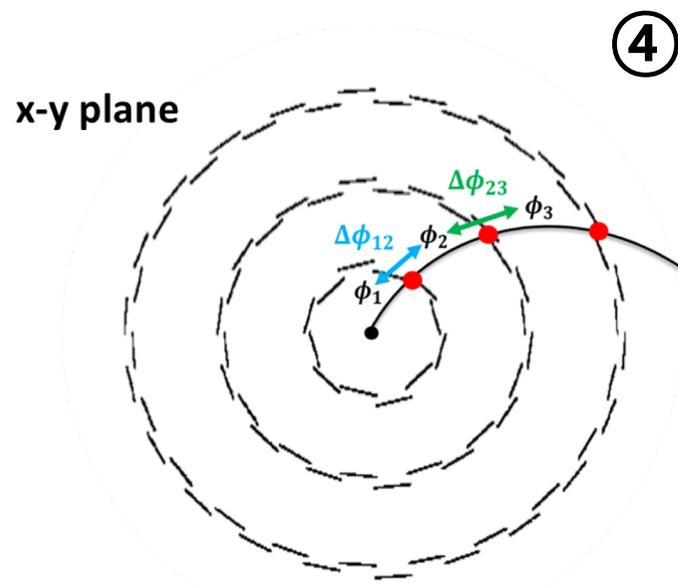
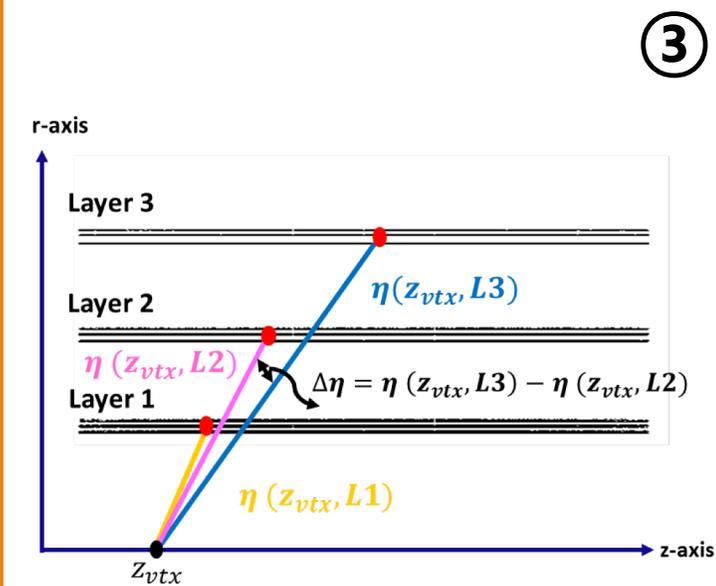
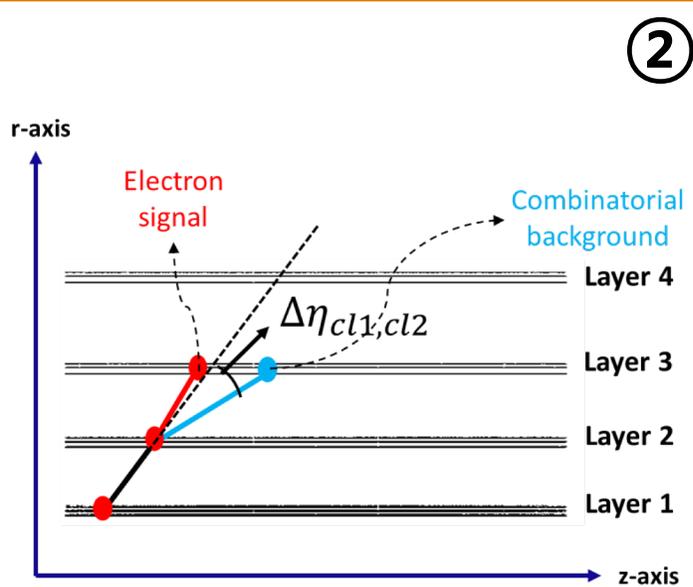
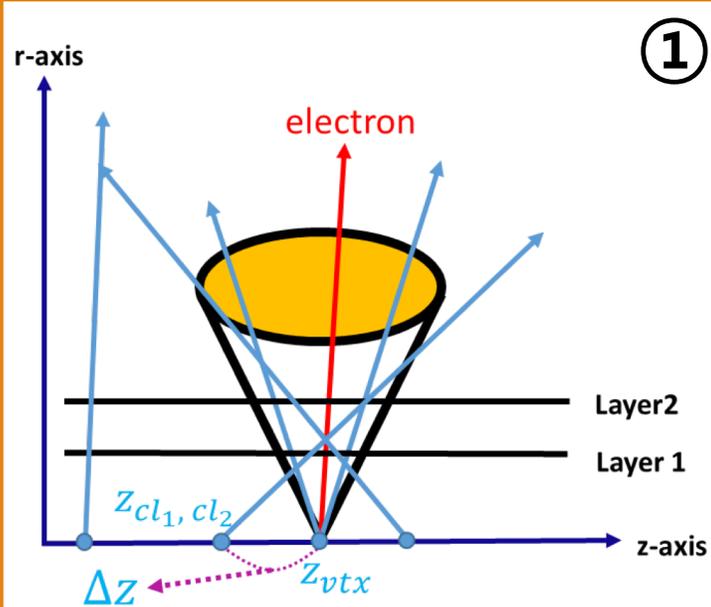
- The purpose of track isolation algorithm is an additional improvement of level-1 (L1) pixel trigger performance
- Procedure of pixel track isolation
 - Reconstructed pixel tracks using kinematic parameters
 - step 0 : Finding z vertex (z_{vtx}) of L1 electron/gamma (EG) object based on the L1 pixel trigger algorithm
 - step 1 : Select pixel cluster (cl) satisfying $\Delta R < 0.3$ cone
 - step 2 : Measure a distance (Δz) from z_{vtx} to z intercept calculated from two pixel clusters
 - step 3 : Measure $\Delta\eta_{cl1,cl2}$ of pixel track segments
 - step 4 : Measure $\Delta\eta_{vertex,cl}$ of pixel track segments
 - step 5 : Measure $\Delta\phi$ difference of pixel track segments
 - Estimation of pixel track p_T using $\Delta\phi$
 - Calculation of isolation based on the estimated p_T

Simulation framework

- Phase 2 simulation framework
 - CMS software version 10_1_7 : the same as the L1 pixel trigger algorithm.
- Sample used for track isolation studies
 - Signal windows for pixel track reconstruction in step 1 ~ step 5
 - : Single Muon without pile-up ($2 < p_T < 200$ GeV , $-3 < \eta < 3$)
 - Efficiency of pixel track isolation algorithm
 - : Single Electron with $\langle \text{PU} \rangle = 200$ ($2 < p_T < 200$ GeV , $-3 < \eta < 3$)
 - Rate reduction factor calculation for pixel track isolation algorithm
 - : Minimum Bias sample with $\langle \text{PU} \rangle = 200$



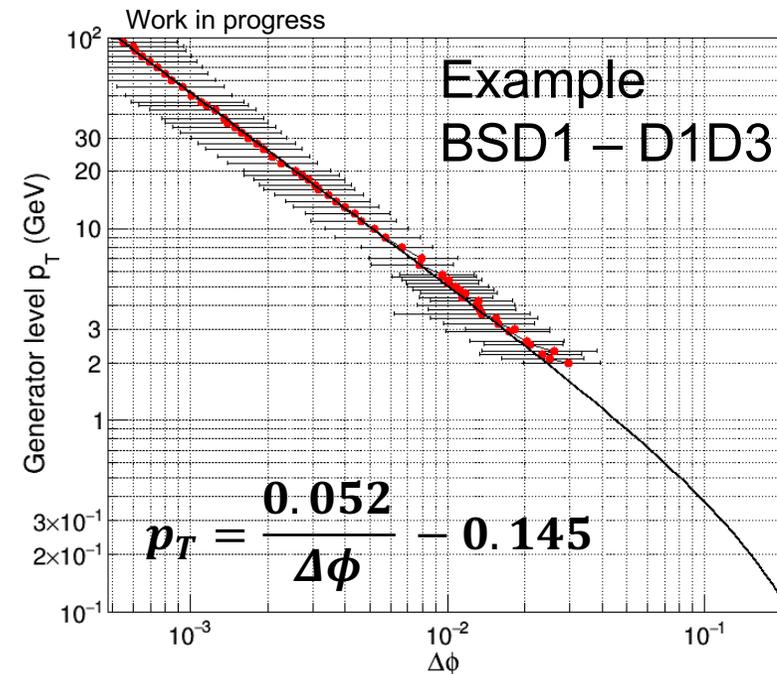
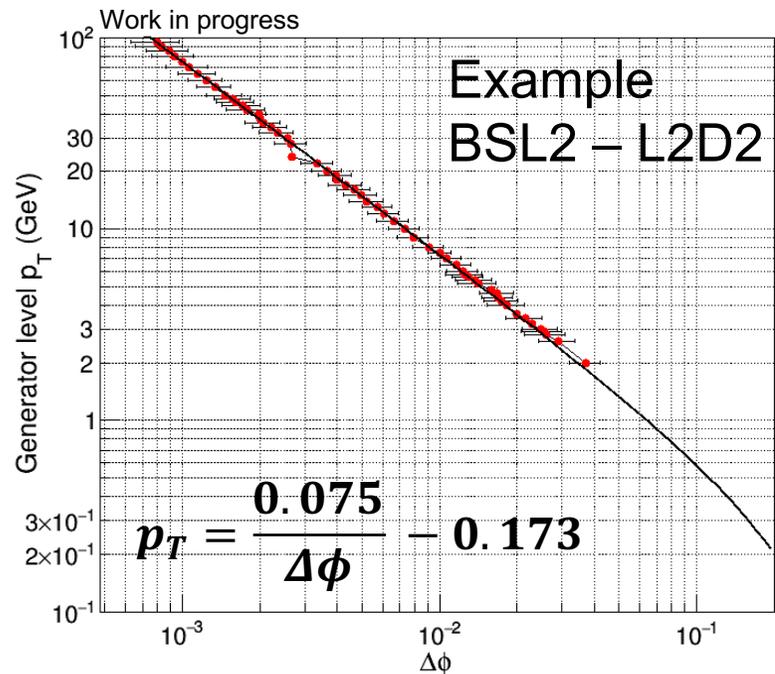
Pixel track reconstruction



- Required $\Delta R < 0.3$ to every pixel clusters in each pixel layer along L1 EG direction
- Measuring Δz which is distance between L1 EG vertex (z_{vtx}) and z-intercept of pixel track segments
- The two longitudinal angle difference $\Delta\eta_{cl_1, cl_2}$ (②) and $\Delta\eta_{z_{vtx}, cl}$ (③) requirement for signal electron track can be removed combinatorial background from pile-up interaction
- The signal track has the consistent sign of each $\Delta\phi_{12}$ and $\Delta\phi_{23}$

p_T estimation using $\Delta\phi$ of pixel track segments

- p_T of the pixel track is estimated with the correlation between the gen-level muon p_T and $\Delta\phi$ ($\phi(BS, L_i) - \phi(L_i, L_j)$)
 - $p_T = f(1/\Delta\phi)$, f : first order polynomial function for fitting
- Simulation sample
 - Gen level p_T and $\Delta\phi$ used in Single Muon events without pile-up
 - $2 < p_T < 200 \text{ GeV}$, $-3 < \eta < 3$

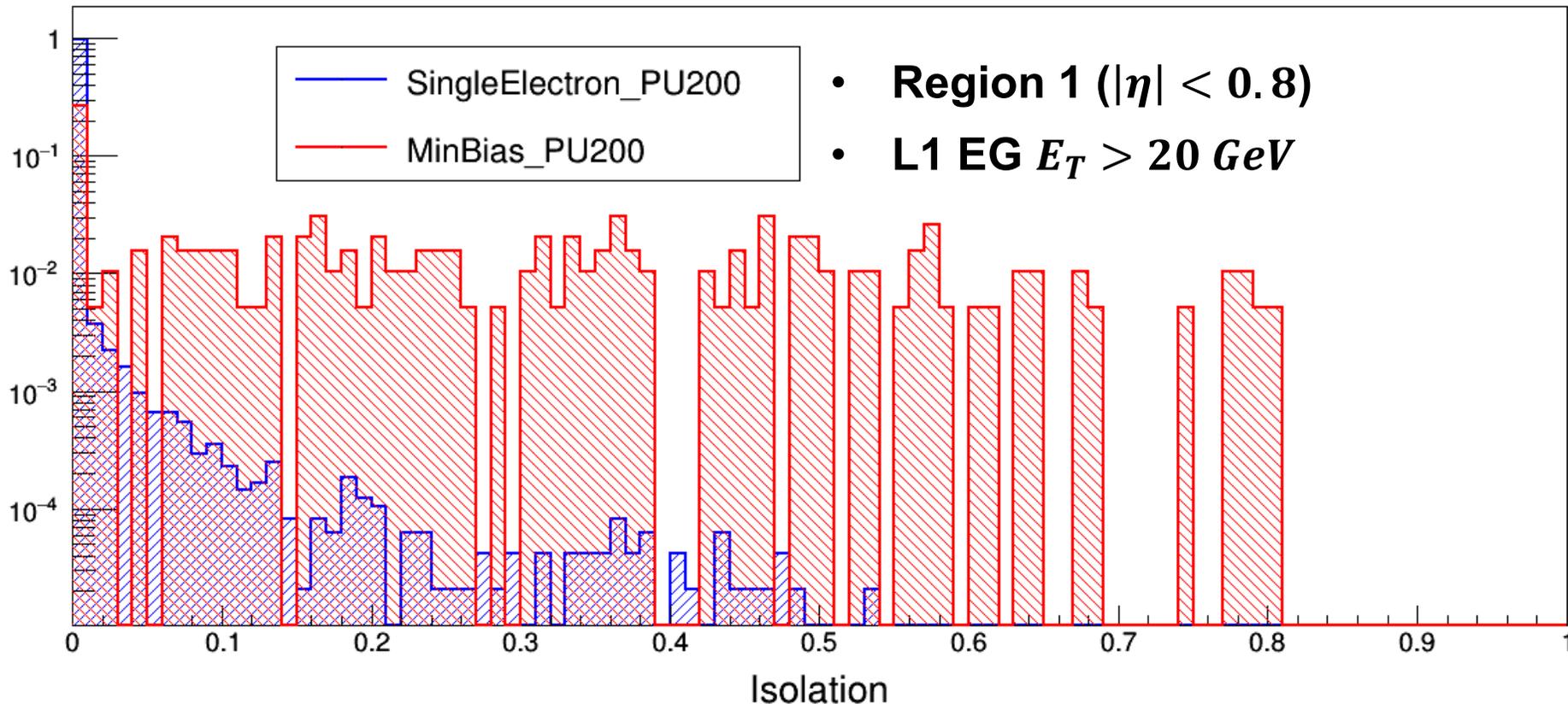


Calculation of track isolation based on the p_T

Isolation

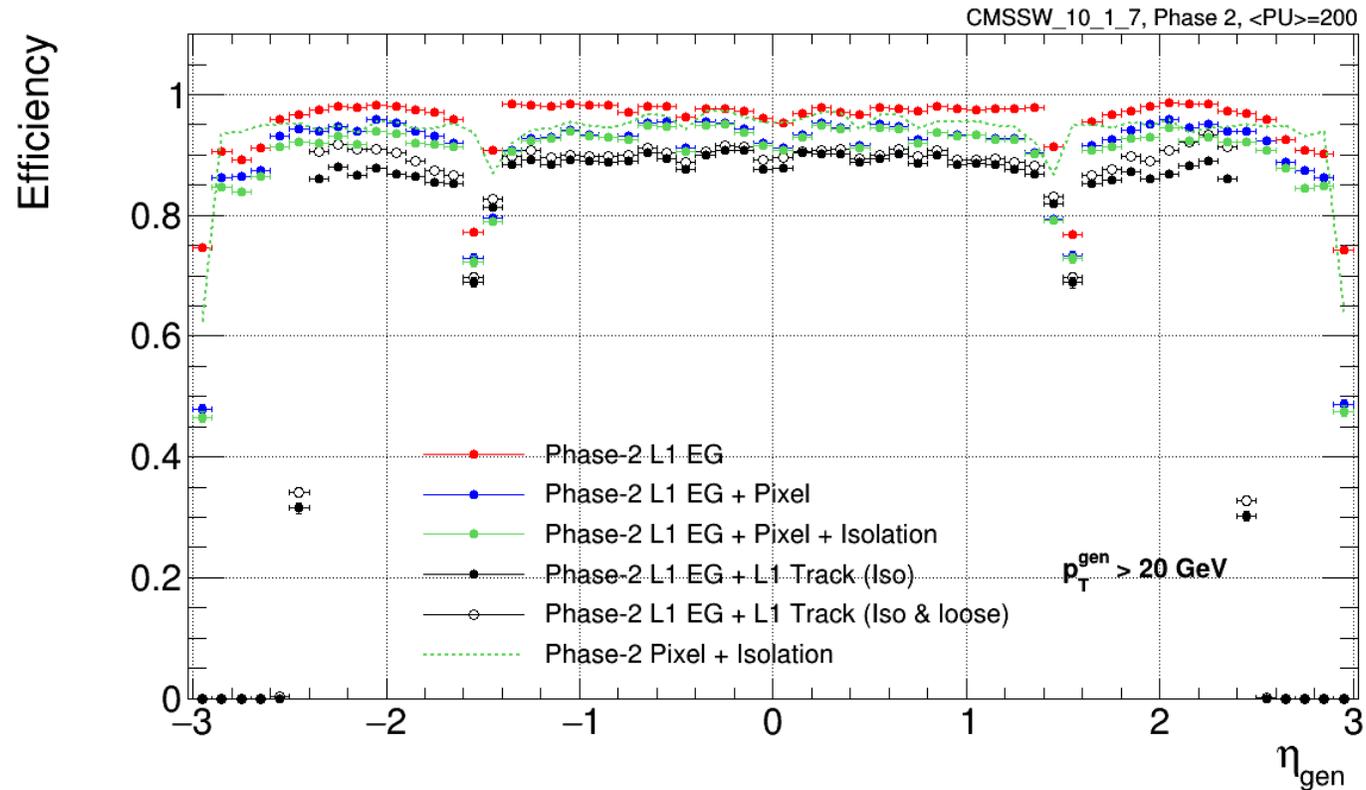
$$= \sum \frac{p_{T,i}}{p_{T,trk}}$$

- $p_{T,trk}$: linear sum of p_T of all tracks in $\Delta R < 0.3$ cone
- $p_{T,i}$: linear sum of p_T of other tracks except for the highest p_T track in $\Delta R < 0.3$ cone



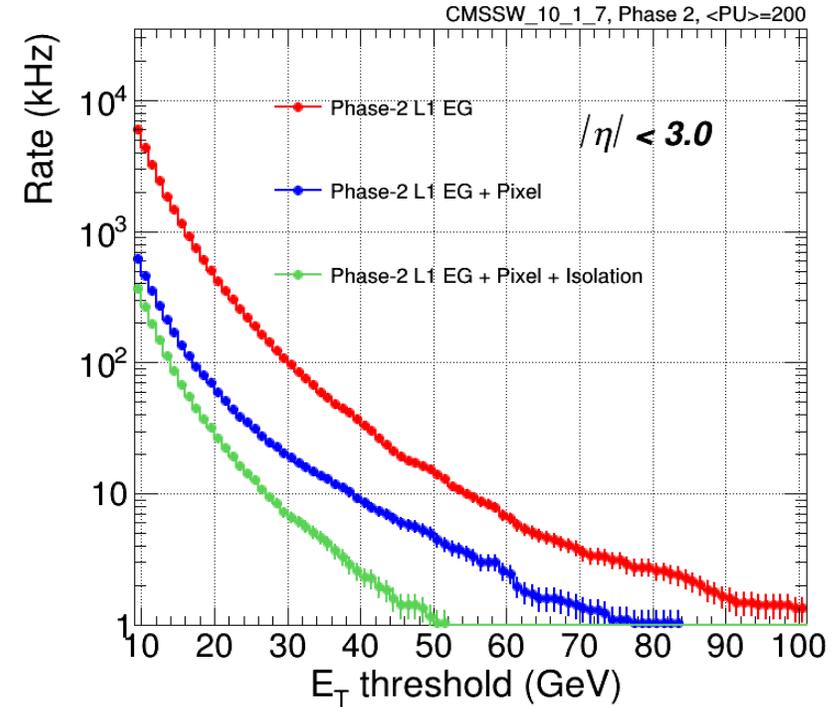
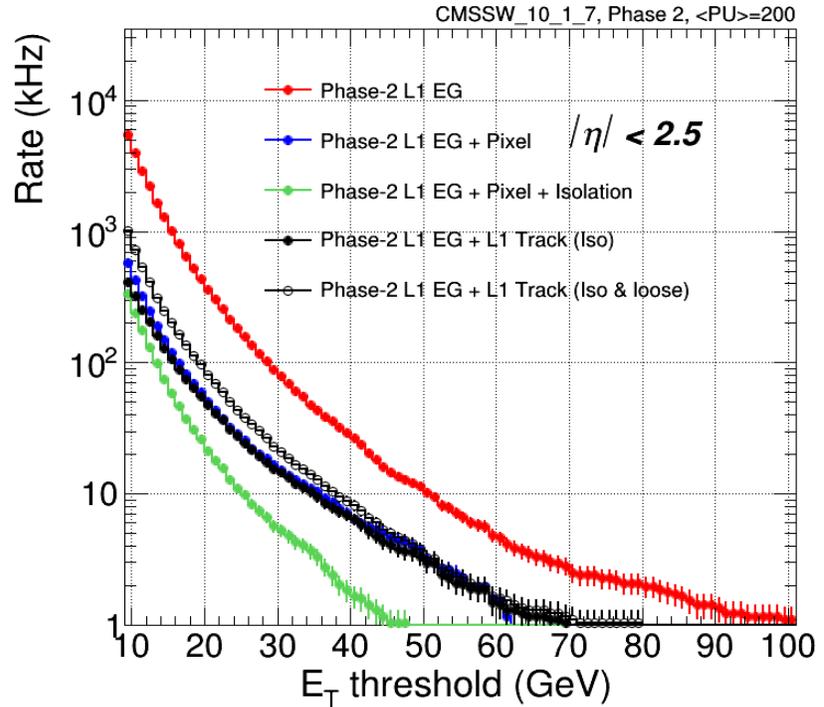
- **Signal efficiency: 99.5%**
- **Background rejection: 70.6%**

The L1 pixel trigger efficiency including isolation



| $p_T^{\text{gen}} > 20 \text{ GeV}$ | $ \eta < 1.5$ | $1.5 < \eta < 2.5$ | $2.5 < \eta < 3.0$ |
|-------------------------------------|----------------|----------------------|----------------------|
| L1 EG | 97% | 95% | 88% |
| L1 EG + Pixel | 92% | 92% | 80% |
| L1 EG + Pixel + Isolation | 92% | 90% | 79% |
| L1 EG + L1 Track (Iso) | 89% | 79% | N/A |

The L1 pixel trigger rates for whole eta range



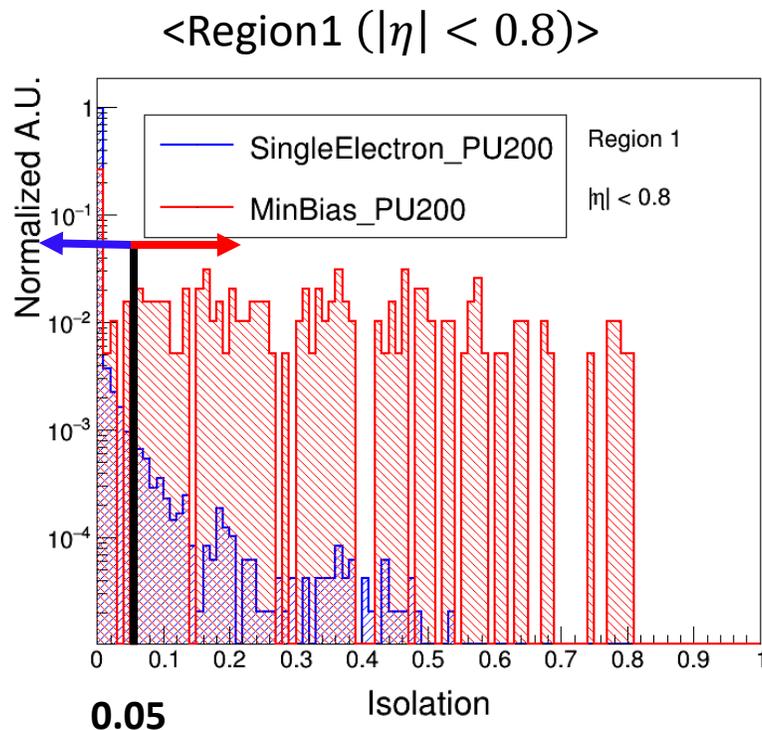
| L1 trigger at $E_T = 20$ GeV threshold | $ \eta < 2.5$ | | $ \eta < 3.0$ | |
|---|----------------|------------------|----------------|------------------|
| | Rate | Reduction factor | Rate | Reduction factor |
| L1 EG | 436 kHz | - | 505 kHz | - |
| L1 EG + Pixel | 59 kHz | 7.4 | 70 kHz | 7.2 |
| L1 EG + Pixel + Isolation | 26 kHz | 16.8 | 32 kHz | 15.8 |
| L1 EG + L1 Track (Iso) | 55 kHz | 7.9 | N/A | N/A |

Machine Learning techniques for CMS Level-1 Pixel Trigger algorithm

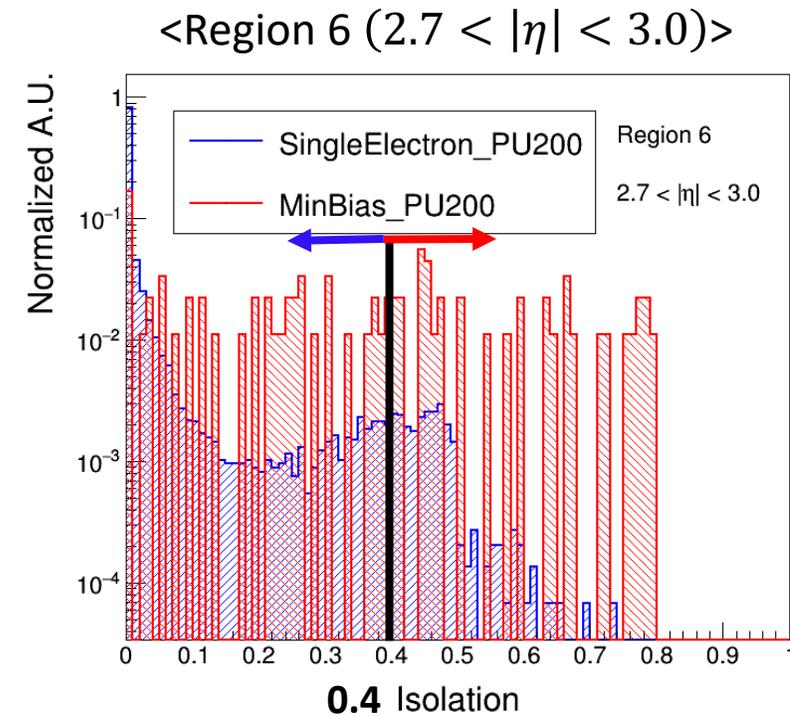
Physics Motivation

- Level-1 Pixel Electron Trigger algorithm has a good performance in region of interests 1 (R1) ($|\eta| < 0.8$)
- In region of interests 6 (R6) ($2.7 < |\eta| < 3.0$), performance is not good as R1

➤ Purpose : Improve the performance of Pixel Trigger algorithm using the Machine Learning



Sig Eff: 99.5%
Bkg Rej: 70.6%

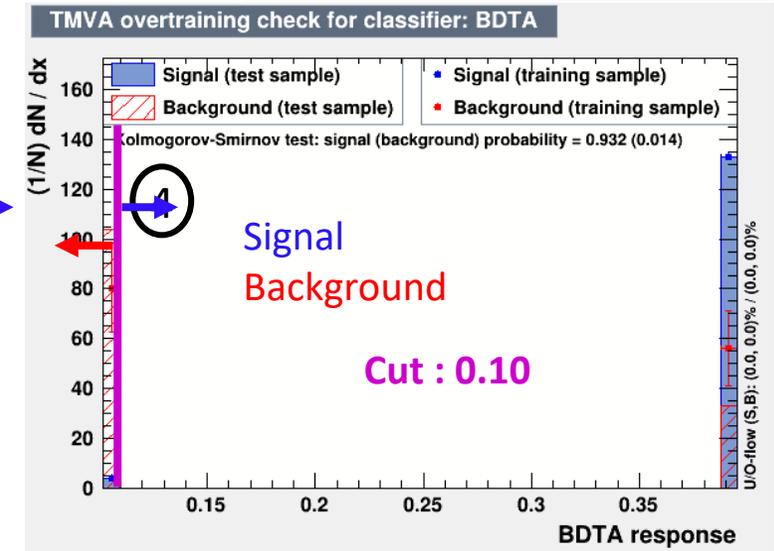
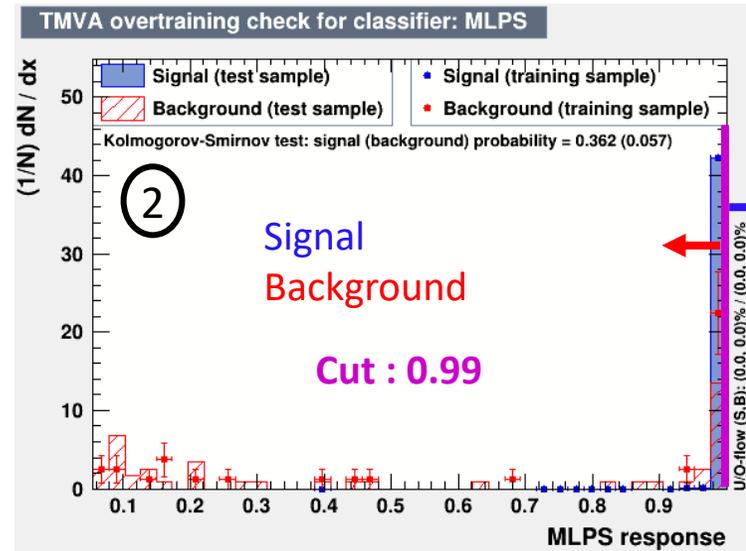
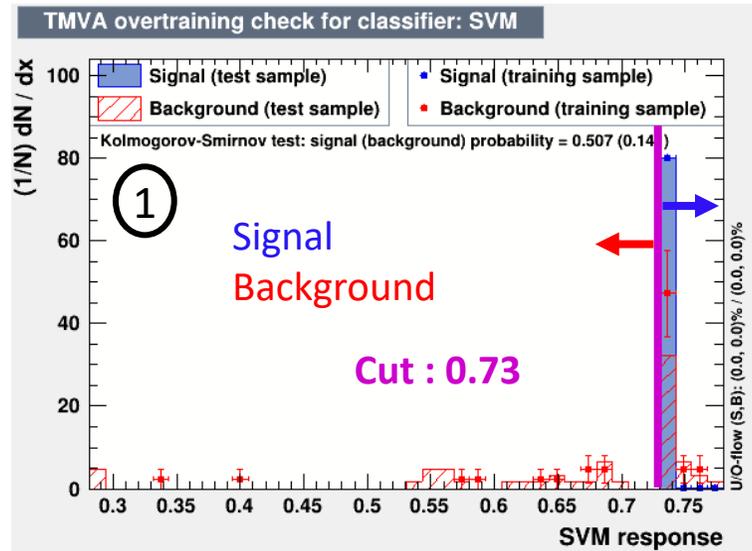


Sig Eff: 97.5%
Bkg Rej: 42.2%

Machine Learning techniques for CMS Level-1 Pixel Trigger algorithm

Classification results for R1 ($|\eta| < 0.8$)

Line is best cut value which optimize statistical significance $S/\sqrt{S+B}$



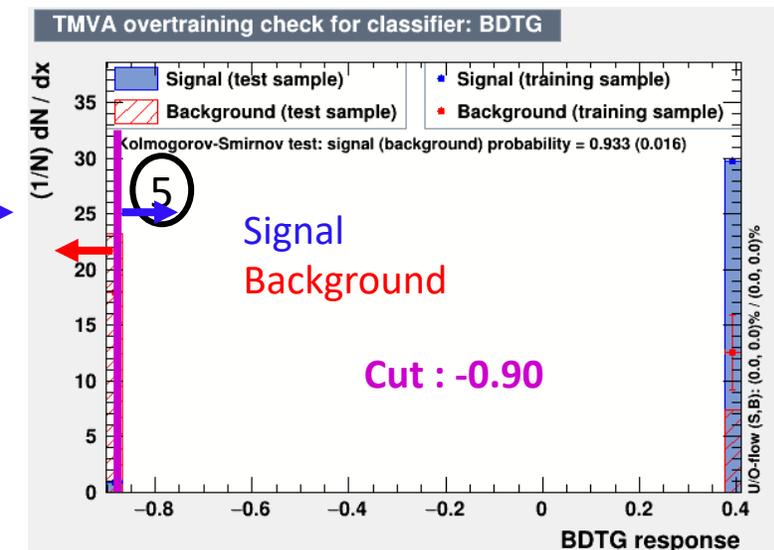
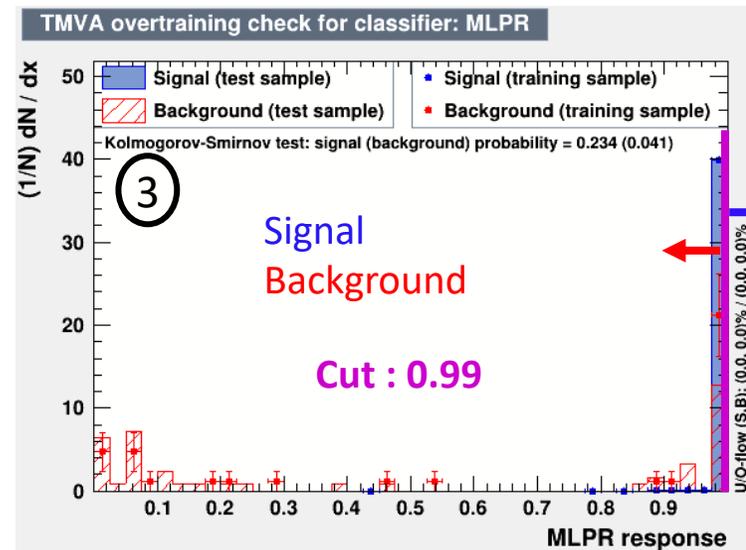
Input variable (Feature)

- Isolation value, Number of tracks

Machine Learning method

- Boosted Decision Tree (BDT)
- Multi-Layer Perceptron (MLP)
- Support Vector Machine (SVM)

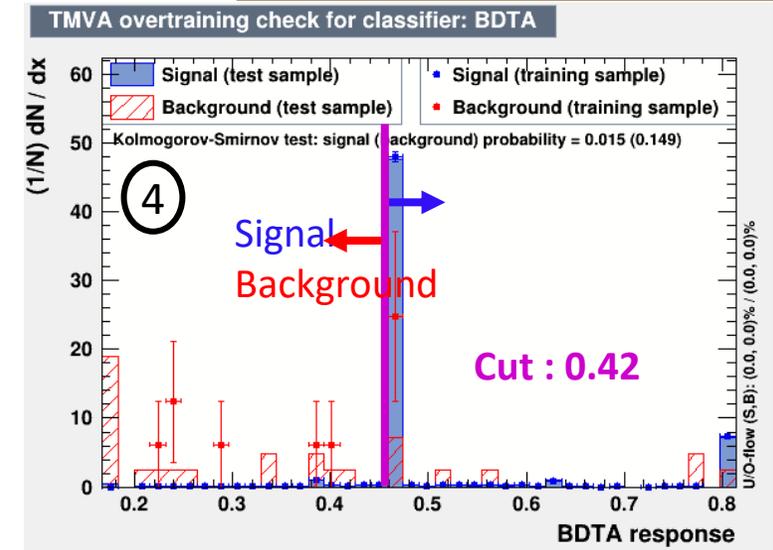
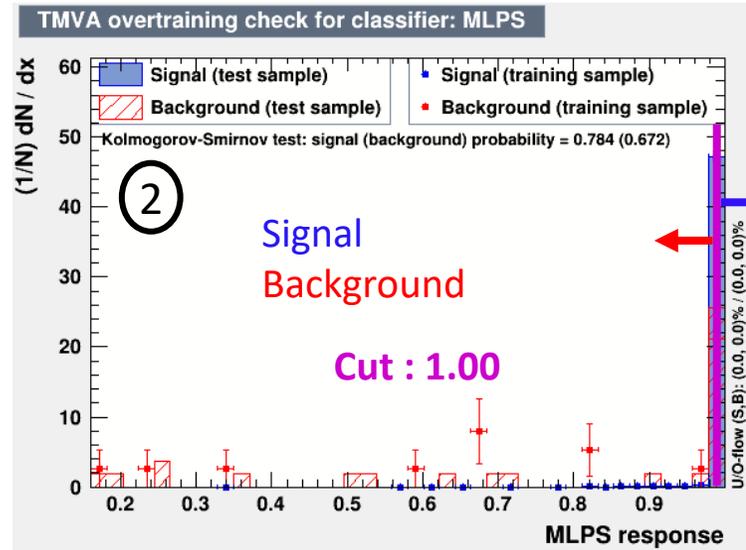
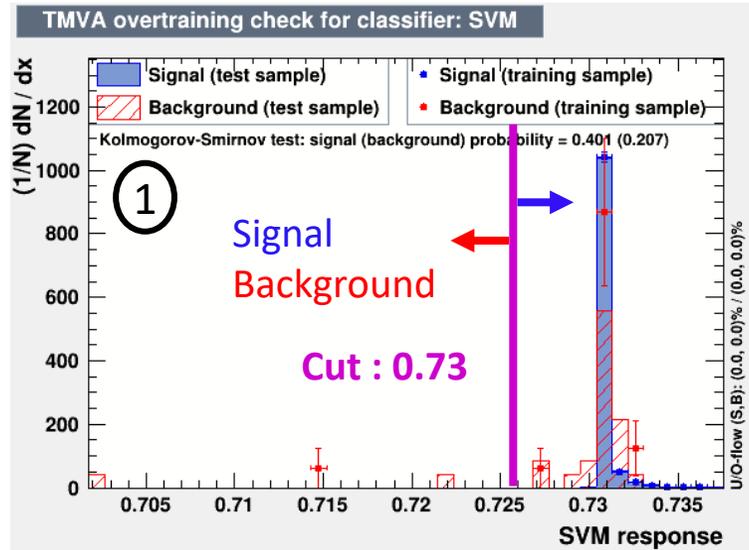
1. SVM Classifier
2. MLPS Classifier - Sigmoid activation function
3. MLPR Classifier - ReLU activation function
4. BDTA Classifier - Adaptive boosting
5. BDTG Classifier - Gradient boosting



Machine Learning techniques for CMS Level-1 Pixel Trigger algorithm

Classification results for R6 ($2.7 < |\eta| < 3.0$)

Line is best cut value which optimize statistical significance $S/\sqrt{S+B}$



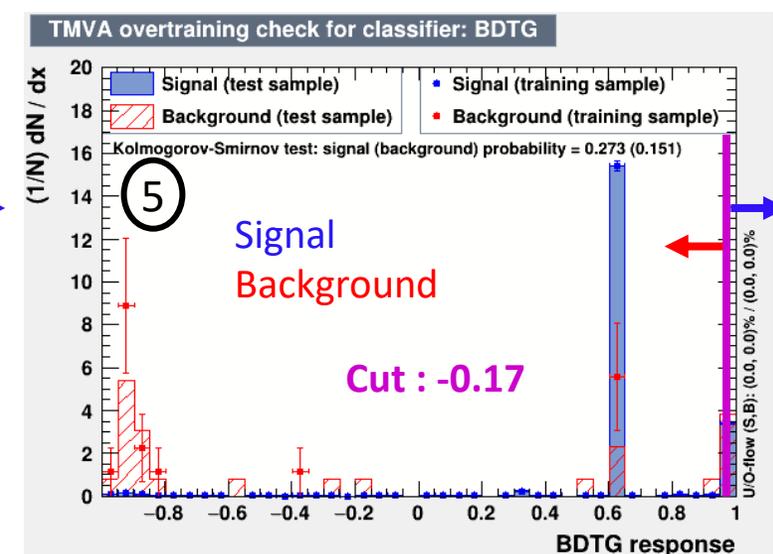
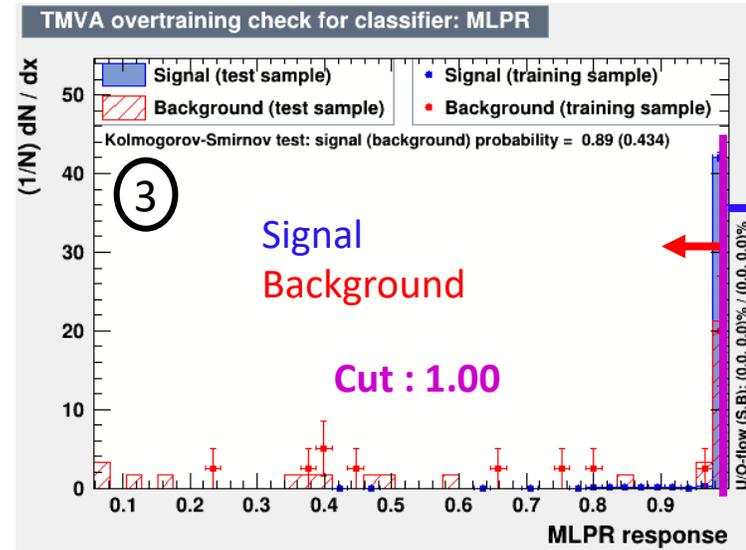
Input variable (Feature)

- Isolation value, Number of tracks

Machine Learning method

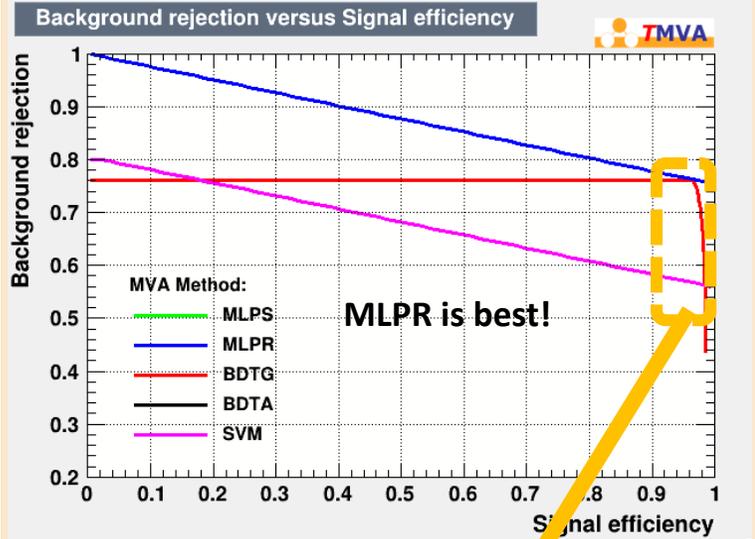
- Boosted Decision Tree (BDT)
- Multi-Layer Perceptron (MLP)
- Support Vector Machine (SVM)

1. SVM Classifier
2. MLPS Classifier - Sigmoid activation function
3. MLPR Classifier - ReLU activation function
4. BDTA Classifier - Adaptive boosting
5. BDTG Classifier - Gradient boosting

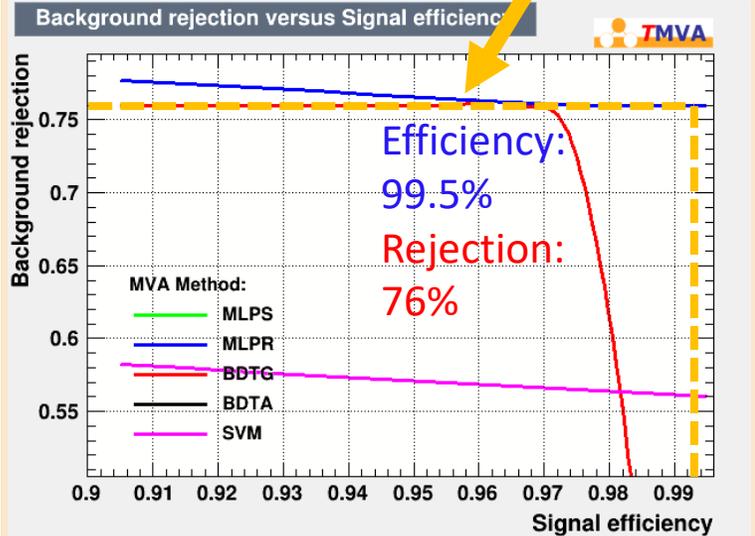


Background rejection vs Signal efficiency

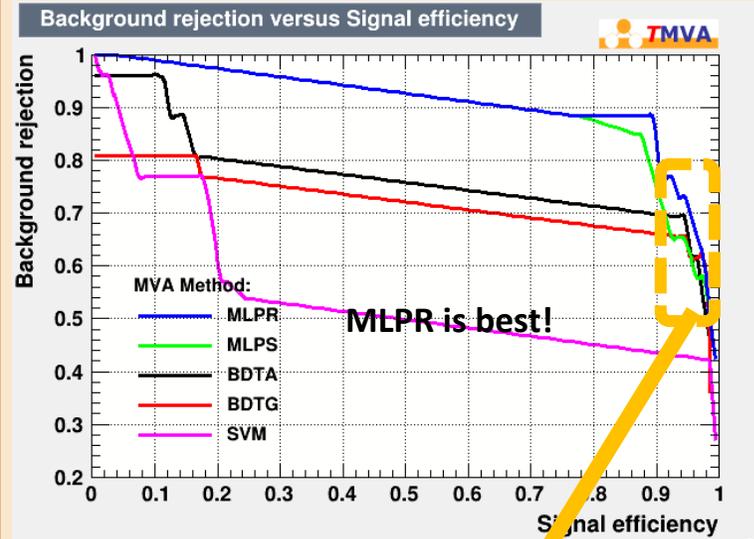
Region 1



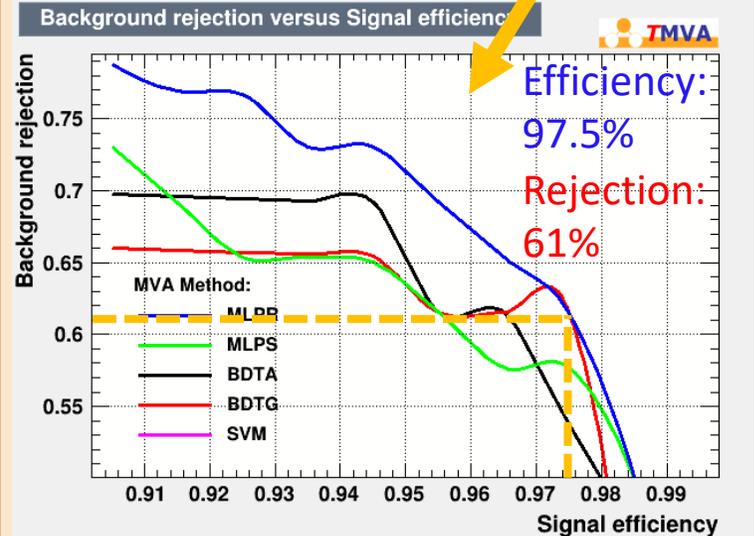
zoomed



Region 6



zoomed



Region1

- Pixel Trigger only :
 - signal efficiency 99.5%
 - background rejection: 70.6%
- Pixel Trigger & Machine Learning :
 - signal efficiency 99.5%
 - background rejection: 76%
- ✓ **Algorithm with Machine Learning removes more backgrounds ~5% point**

Region6

- Pixel Trigger only :
 - signal efficiency 97.5%
 - background rejection: 42.2%
- Pixel Trigger & Machine Learning :
 - signal efficiency 97.5%
 - background rejection: 61%
- ✓ **Algorithm with Machine Learning removes more backgrounds ~19% point**