Search for FCPs at the LHC

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Fractionally Charged Particles (FCP)

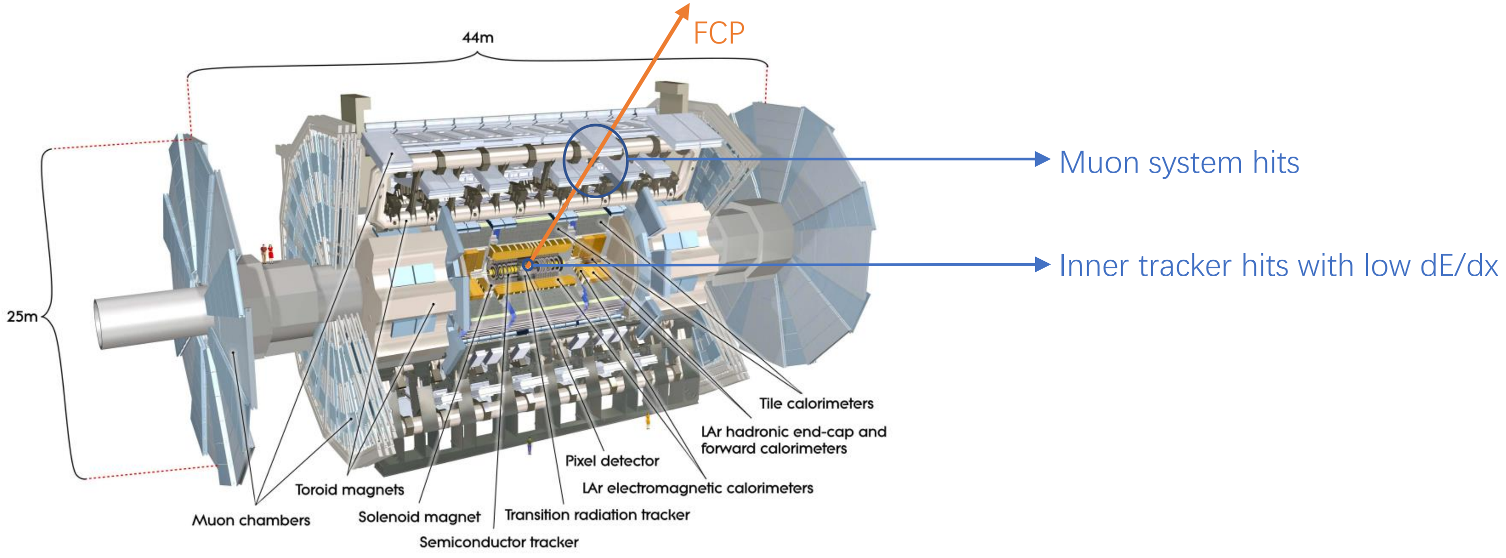
- All unconfined particles have electric charge as integer multiples of e, which can not been explained by most theories.
- Search for FCPs relates to many BSM theories like some GUTs.
- Search for FCPs
  - in bulk matters
  - from outside the earth
  - from collider experiments or particle accelerator and fixed targets
  - ...

FCP Search at Colliders

- FCP have been searched in many other collider experiments, mostly in electron-positron colliders
  - For example, OPAL have searched for FCPs at LEP and the upper limits on the production cross-section of FCPs with ±2/3, ±4/3 and ±5/3e and mass range $45 < m_X < 95$ GeV varies between 0.005 and 0.020 pb
- LHC provides much higher total energy (13TeV) and can be used to search for FCPs with higher mass

FCP Detector Signature

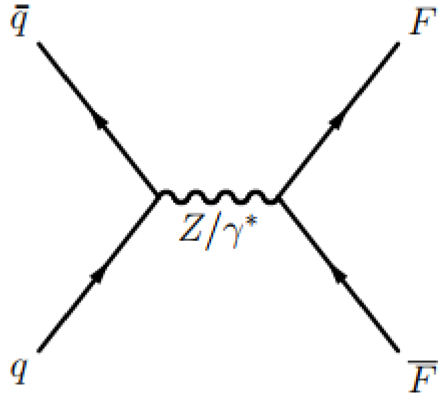
- FCPs are assumed to be heavy, long-lived particles and participate only in EM-weak interaction.
  - FCPs can hit silicon detectors and hits from FCPs should have lower dE/dx (if searching for FCPs with charge lower than e)
  - Long-lived FCPs can pass through the whole detector, so they can hit muon system
  - There should be nearly no energy deposition from FCPs in calorimeters since they are assumed to have large mass



Signal & Main Backgrounds

FCP signal:

- Usual assumptions
  - Non-integer charge
  - Participate only in EM-weak interaction
- Pair production via s-channel exchange of $Z^{(*)}/\gamma^*$
  - Assumed to be the leading production channel
- Have long lifetime and pass through whole detector, reconstructed as "muons" , with smaller dE/dx



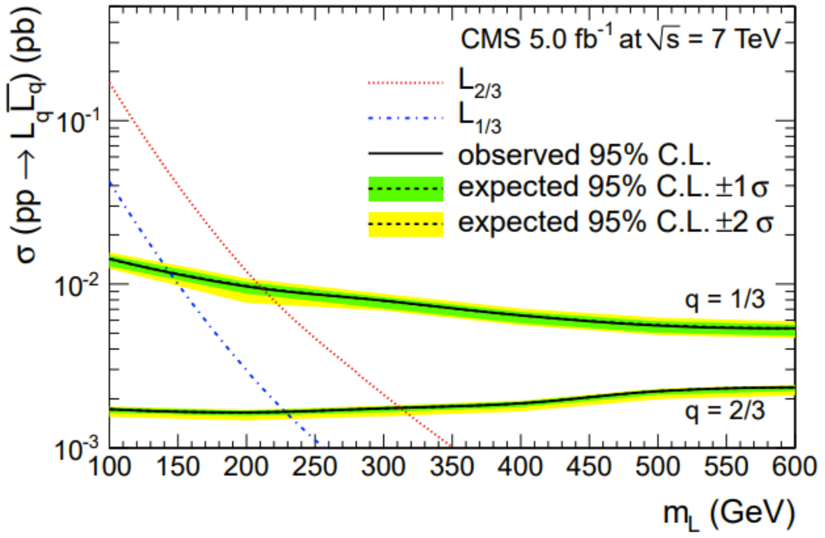
Background:

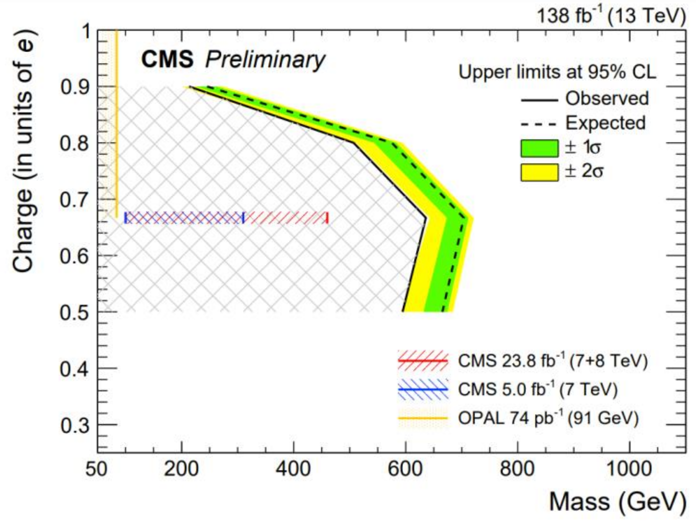
- Zmumu events should contribute most of background
  - Dimuon production would be main background since FCPs perform like muons and are produced in pairs in main channel
  - High mass FCP pairs tend to large invariant mass
  - Most of high mass muon pairs come from Zmumu in standard model

Long-lived FCP Search by CMS

- Results of searches for FCPs from CMS
  - Based on 5.0 fb^{-1} 7 TeV data, exclude FCPs with 2e/3 charge and mass below 310 GeV
  - Based on 5.0 fb^{-1} 7 TeV data and 18.8 fb^{-1} 8 TeV , exclude FCPs with 2e/3 charge and mass below 480 GeV
  - Based on 138 fb^{-1} 13 TeV data, exclude FCPs with 2e/3 charge and mass below 636 GeV

- All these searches have used silicon pixel and strip detector dE/dx and the time-of-flight measurement from the muon system.





Next slides focus on the latest search based on 138 fb^{-1} 13 TeV data.

Trigger & Events Selection in CMS Search

- Trigger: single muon trigger with a p_T threshold of 50 GeV

- Candidate track selection:
  - geometrically matched to a muon
  - $p_T > 55$ GeV, $|\eta| < 1.5$ and match the primary vertex of the event
  - at least 5 hits are required overall in the tracker, among which one should be in the pixel detector
  - time of track arriving at muon system should be larger than the time from primary vertex to muon system at speed of light
  - the maximum angle between the candidate track and any other high-p_T (>35GeV) track or muon is required to be smaller than 2.8 radians

- Event selection: contain exactly 1 or 2 candidate tracks

- Search & control region:
  - Search region: events with only one track and events with two tracks with invariant mass smaller than 80 or larger than 100 GeV
  - Control region: events with two tracks that have an invariant mass between 80 and 100 GeV

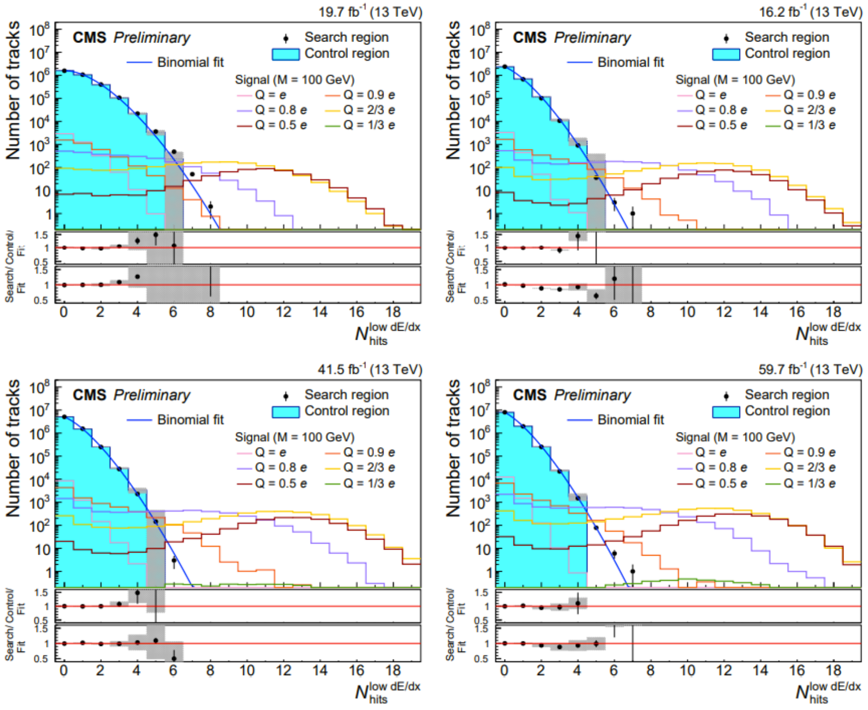
Discriminate FCPs in CMS Search

Because of their lower ionization, or stopping power, FCP tracks have a larger number of tracker hits with low dE/dx with respect to particles with charge e.

To discriminate signal from background muons, they count the number of track hits with a low value of dE/dx ($N_{\text{hits}}^{\text{low dE/dx}}$).

Thresholds of “low dE/dx” are chosen layer-dependent to enforce an equal average binomial probability for each tracker layer due to different instrumental effects and in particular radiation damage.

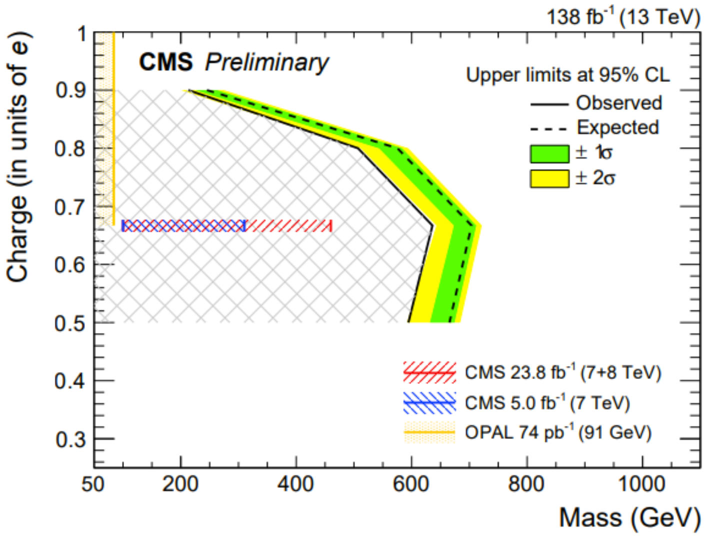
In bins correspond to $N_{\text{hits}}^{\text{low dE/dx}}$ = 5, 6, 7, 8, and ⩾ 9 for the early 2016 data set, and $N_{\text{hits}}^{\text{low dE/dx}}$ hits = 4, 5, 6, and ⩾ 7, for the late 2016, 2017, and 2018 data sets, the number of observed and expected tracks are counted.



Distribution of $N_{\text{hits}}^{\text{low dE/dx}}$ in the search and control regions

Result from CMS Search

The existence of fractionally charged particles is excluded up to a mass of 636 GeV for a signal of charge Q = 2/3 e



Exclusion region (hatched) at 95% CL in the FCP charge-mass plane for the considered signal model.

	Early 2016	Late 2016	2017	2018
N^{observed}	0	1	0	1
$N^{\text{expected}}_{\text{Background}}$	0.04	0.09	0.22	0.09
Fit function	±3771%	±159%	±231%	±19%
Fit range	±30%	±0.3%	±14%	±28%
$N^{\text{expected}}_{\text{signal}}$	602	988	2720	3622
L1 trigger inefficiency	5.0%	5.0%	5.0%	5.0%
Energy loss sim. in muon system	+3.8%-2.7%	+3.8%-2.7%	+3.8%-2.7%	+3.8%-2.7%
Muon detector inefficiency	3.0%	3.0%	3.0%	3.0%
Luminosity	2.5%	2.5%	2.3%	2.5%
Selection	2.0%	2.0%	2.0%	2.0%
dE/dx corrections	3.8%	1.1%	2.3%	1.7%
Limited signal sample	<1%	<1%	<1%	<1%

Number of tracks observed, expected for background events, and expected for signal events, in the highest $N^{\text{low dE/dx}}_{\text{hits}}$ bin, as well as corresponding systematic uncertainties. $N^{\text{expected}}_{\text{signal}}$ comes from FCP with 100GeV mass and 2/3e.

Strategy of ATLAS

- There have not been an search for long-lived FCPs in ATLAS experiment, and we are working on the first search of this kind in ATLAS (currently at the R&D phase).

- Difference between ATLAS and CMS in FCP search
  - Performance of ATLAS inner tracker is not as good as CMS, which means we may have lower trigger efficiency and dE/dx sensitivity than CMS
  - ATLAS have generally better and larger muon system than CMS, they can play a more important role than CMS muon system. ATLAS muon system can provide TOF/speed with better resolution, which is important especially in high mass FCP search.
  - With the help of multiple sensitive variables, the sensitivity can be competitive.

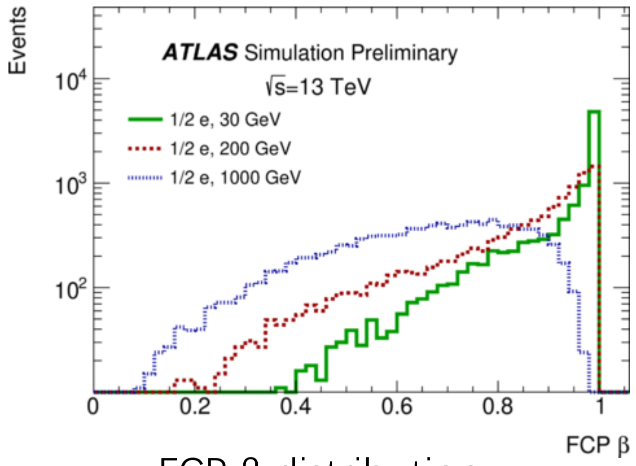
Simulation Studies

- ➢ As first step, we have finished some simulation studies of FCP performance in ATLAS, and results are now shown in an ATLAS pub note.

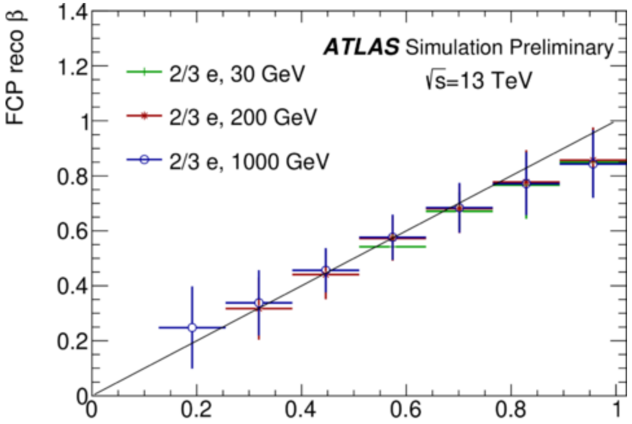
- ➢ Events of FCP production through Drell-Yan process are generated with different FCP charge and mass
  - Events are generated by MadGraph5_aMC@NLO v2.3.3 with A14 tune and LHAPDF for parton distribution functions and PYTHIA for hadronization
  - FCP mass points are set to 30, 100, 200, 500 and 1000GeV, and charge points are set to 1/3, 1/2, 2/3 and 4/5e

- ➢ FCP truth & reconstructed kinematic attributes, reconstructed dE/dx and some trigger efficiencies are simulated
  - dE/dx comes from pixel detectors, TRT and MDT

Simulation Performance



FCP β distribution

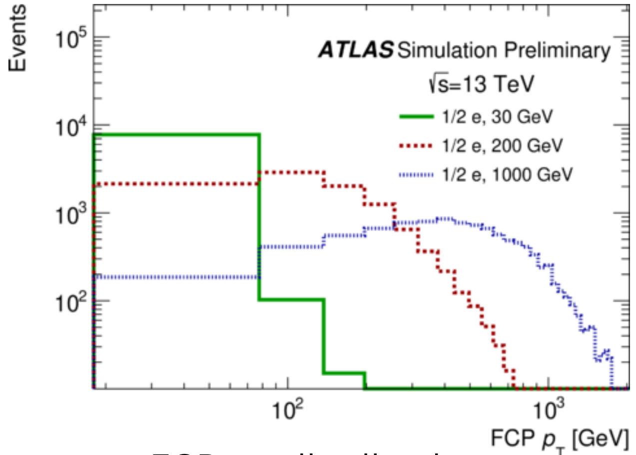


FCP reconstructed β vs. truth β

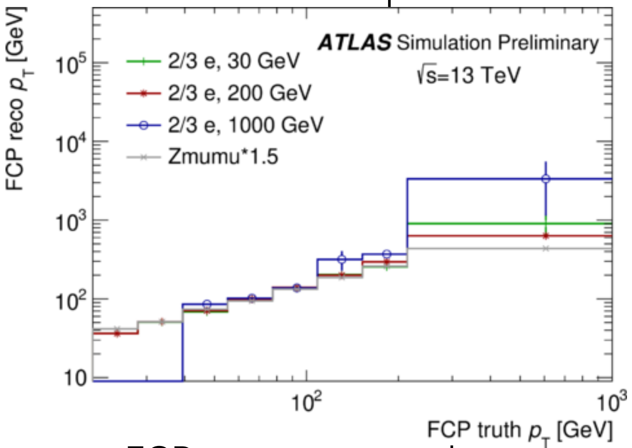
β is reconstructed via time constants and TOF from MDT and RPC detectors

FCPs with larger mass tend to have smaller β

β reconstruction generally have good performance



FCP p_T distribution



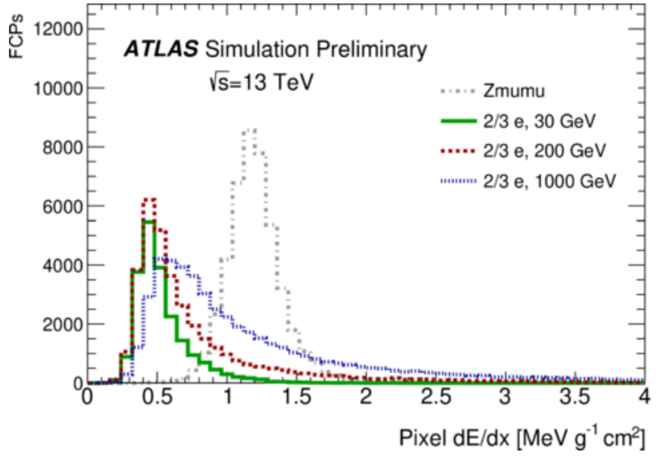
FCP reconstructed p_T vs. truth p_T

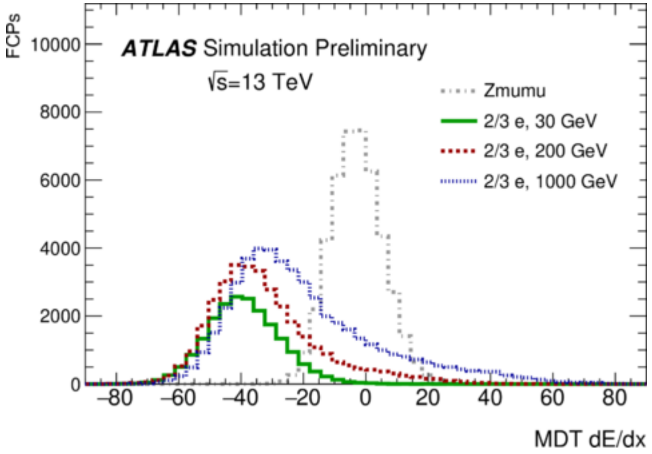
$p_T \sim 1/Q * \text{muon } P_T$

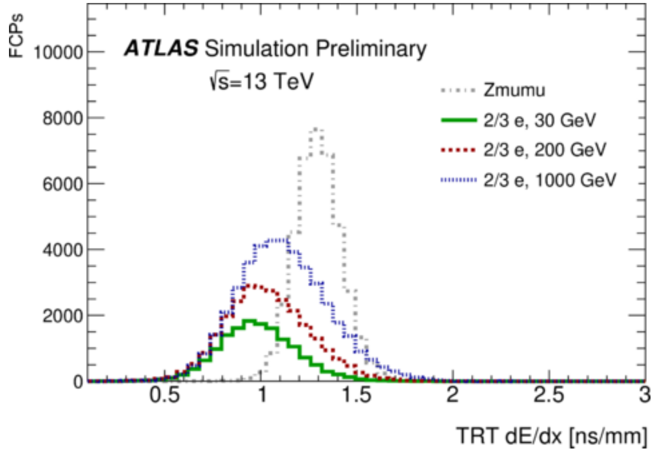
FCPs with larger mass tend to have larger p_T

P_T reconstruction have good performance except in very high region.

Simulation Performance of dE/dx







	$1/3\ e$	$1/2\ e$	$2/3\ e$
1000 GeV	$(97.44 \pm 0.29)\%$	$(96.90 \pm 0.15)\%$	$(97.95 \pm 0.09)\%$
200 GeV	$(98.1 \pm 0.4)\%$	$(95.87 \pm 0.27)\%$	$(96.40 \pm 0.13)\%$
30 GeV	$(98.47 \pm 0.35)\%$	$(97.54 \pm 0.32)\%$	$(96.80 \pm 0.13)\%$

Efficiencies of valid MDT dE/dx for FCP tracks

	$1/3\ e$	$1/2\ e$	$2/3\ e$
1000 GeV	$(48.6 \pm 0.9)\%$	$(75.8 \pm 0.4)\%$	$(86.98 \pm 0.21)\%$
200 GeV	$(48.8 \pm 1.6)\%$	$(73.9 \pm 0.6)\%$	$(76.51 \pm 0.29)\%$
30 GeV	$(51.63 \pm 1.41)\%$	$(68.52 \pm 1.00)\%$	$(71.35 \pm 0.34)\%$

Efficiencies of valid TRT dE/dx for FCP tracks

TRT dE/dx is based on mean ToT of hits and MDT dE/dx use the mean ADC counts of ionization charge.

Pixel dE/dx have best resolution and tracks always have valid pixel dE/dx.

MDT dE/dx also have good resolution and high efficiency for FCP tracks.

TRT dE/dx perform worst in discriminate FCP from muons, and it have low efficiency especially for low mass and charge.

Simulation Performance

	$1/3\ e$	$1/2\ e$	$2/3\ e$
1000 GeV	$(1.36 \pm 0.07)\%$	$(8.65 \pm 0.17)\%$	$(13.64 \pm 0.21)\%$
200 GeV	$(2.43 \pm 0.12)\%$	$(17.73 \pm 0.29)\%$	$(31.7 \pm 0.4)\%$
100 GeV	$(2.70 \pm 0.14)\%$	$(19.55 \pm 0.34)\%$	$(34.6 \pm 0.4)\%$
30 GeV	$(3.754 \pm 0.097)\%$	$(25.3 \pm 0.5)\%$	$(42.9 \pm 0.5)\%$

RPC L1 trigger efficiencies (with lowest p_T threshold)

	$1/3\ e$	$1/2\ e$	$2/3\ e$
1000 GeV	$(3.66 \pm 0.13)\%$	$(7.86 \pm 0.19)\%$	$(17.75 \pm 0.27)\%$
200 GeV	$(0.88 \pm 0.08)\%$	$(2.57 \pm 0.26)\%$	$(17.86 \pm 0.34)\%$
100 GeV	$(0.22 \pm 0.05)\%$	$(0.93 \pm 0.09)\%$	$(18.1 \pm 0.4)\%$
30 GeV	$(0.018 \pm 0.006)\%$	$(0.48 \pm 0.09)\%$	$(22.2 \pm 0.5)\%$

Combined HLT efficiencies

	$1/3\ e$	$1/2\ e$	$2/3\ e$
1000 GeV	$(0.160 \pm 0.016)\%$	$(4.47 \pm 0.08)\%$	$(14.22 \pm 0.14)\%$
200 GeV	$(0.0050 \pm 0.0029)\%$	$(0.635 \pm 0.032)\%$	$(7.00 \pm 0.10)\%$
100 GeV	$(0.0033 \pm 0.0024)\%$	$(0.094 \pm 0.011)\%$	$(8.72 \pm 0.12)\%$
30 GeV	$(0.00 + 3.07e - 3)\%$	$(0.075 \pm 0.011)\%$	$(3.86 \pm 0.07)\%$

Final efficiencies
(ratio of final reconstructed particles and truth FCPs number)

	Requirements
HLT_mu50	at least one muon with $p_T > 50$ GeV
HLT_mu26_ivarmedium	at least one muon with $p_T > 26$ GeV and isolation "medium"
HLT_mu10_mgonly_L1LATE-MU10_J50	at least one MuGirl muon with $p_T > 10$ GeV in the next bunch crossing of L1_J50 (L1 trigger with requirement p_T of one jet > 50 GeV)
HLT_mu10_mgonly_L1LATE-MU10_XE40	at least one MuGirl muon with $p_T > 10$ GeV in the next bunch crossing of L1_XE40 (L1 trigger with requirement p_T of E_T^{miss} > 40 GeV)
HLT_j420	at least one jet with $p_T > 420$ GeV

List of HLTs

ATLAS have low reconstruction efficiencies for FCPs, especially for low charge ones. Even for FCPs with 2/3e, trigger efficiencies are very low. This means only if we achieve high signal efficiency as well as high Zmumu rejection, we can have sensitivity comparable to CMS.

Preparation of ATLAS Data Analysis

- Pixel dE/dx, MDT dE/dx and β are selected as sensitivity variables to discriminate FCP in preliminary fitting research
- Distribution of these variables from simulation have discrepancy with data and should be calibrated
  - Much of the discrepancy of pixel dE/dx may come from radiation damage out of assumption
- Invariant mass region of muon pairs near Z mass can be used for calibration since almost all events in this region are Zmumu. Off-Z-peak region can be used for validation, with large pixel dE/dx cut for MDT validation and large MDT dE/dx cut for pixel validation, this can also avoid signal region.

Calibration region:

Muon selection:
- p_T > 30GeV
- $|\eta|$ < 2.5
- $z_0 \sin\theta$ < 0.5, significance of d_0 < 3
- quality: loose
- type: combined muon

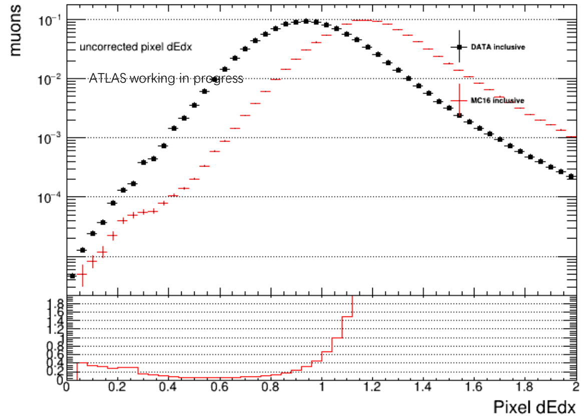
Event selection (Zmumu control region):
- leading muon p_T > 35GeV
- number of muon = 2
- 80GeV < mass(mu, mu) < 100GeV

Validation region:

Muon selection:
- p_T > 30GeV
- $|\eta|$ < 2.5
- $z_0 \sin\theta$ < 0.5, significance of d_0 < 3
- quality: loose
- type: combined muon
- Pixel dE/dx > 1 (only for MDT dEdx & Beta(T))
- MDT dE/dx > -10 (only for Pixel dEdx)

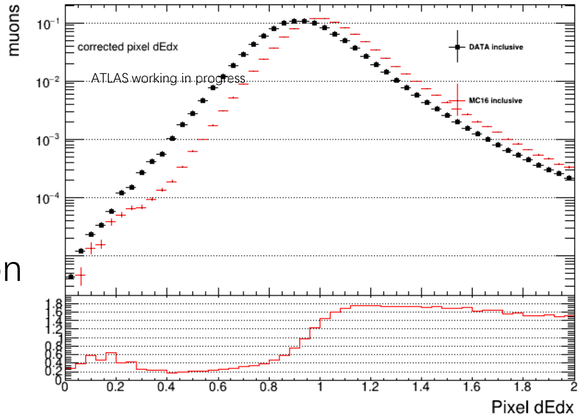
Event selection (Zmumu control region):
- leading muon p_T > 35GeV
- number of muon = 2
- mass(mu, mu) > 100GeV

Pixel dE/dx Calibration

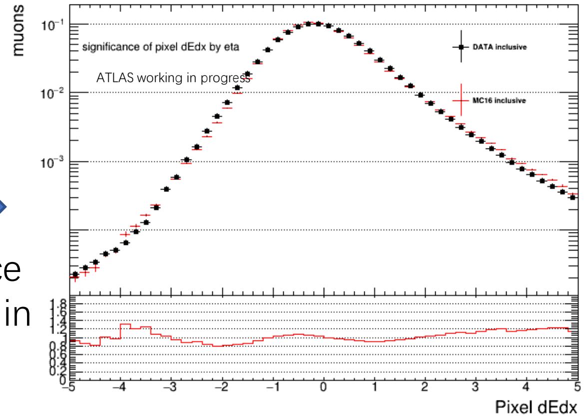


Raw pixel dE/dx

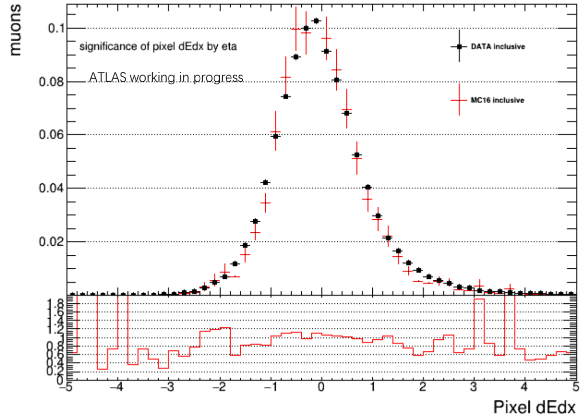
A modification tool for radiation damage



Significance calculation in eta bins



Pixel dE/dx Significance by eta bins

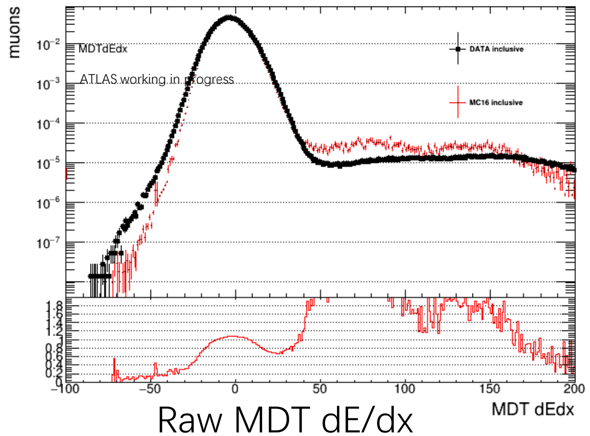


Pixel dE/dx Significance by eta bins in validation region

Significance of modified pixel dE/dx by eta bins from MC and data fits well in calibration region.

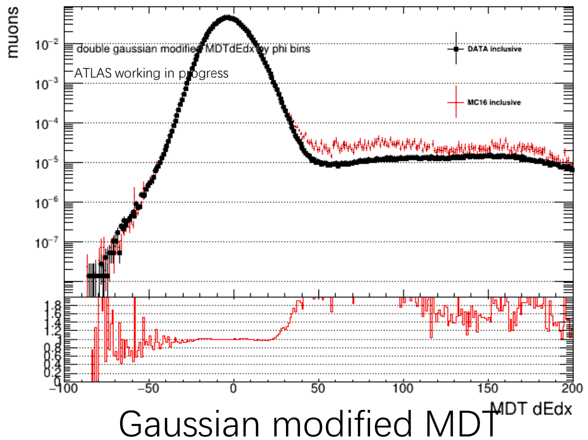
Performance in validation region is generally good near central region. For low dE/dx region, the performance should be checked in another region with more samples.

MDT dE/dx Calibration

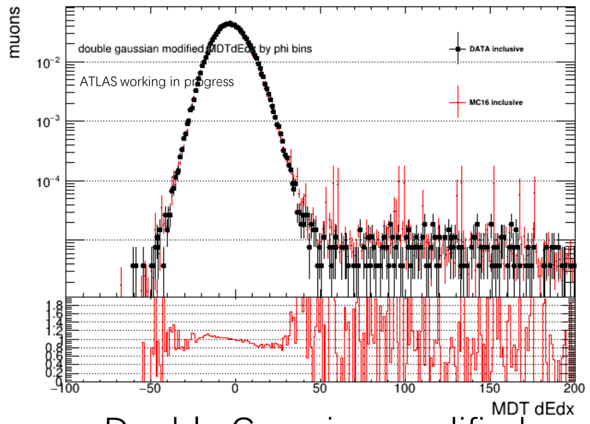


Raw MDT dE/dx

Fit distribution from both data and MC with double gaussian function in phi bins, then modify dE/dx from MC samples



Gaussian modified MDT dE/dx by phi bins

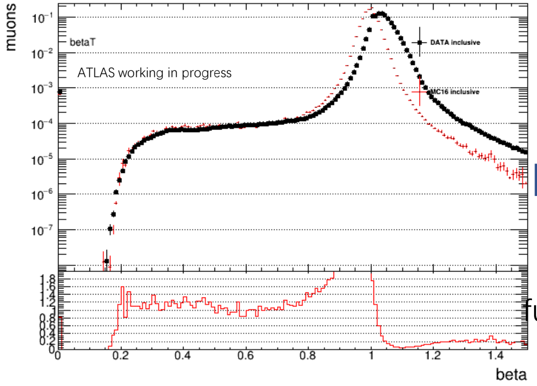


Double Gaussian modified MDT dE/dx by phi bins

Double gaussian modification by phi bins significantly reduced the discrepancy between data and MC.

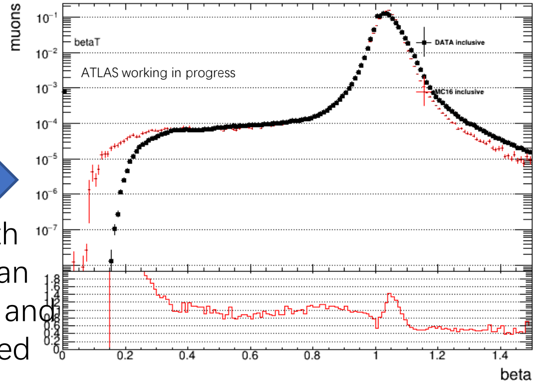
Just like pixel dE/dx, this modification performs well near peak in validation region, but more samples are needed for checking performance in low dE/dx region.

β Calibration



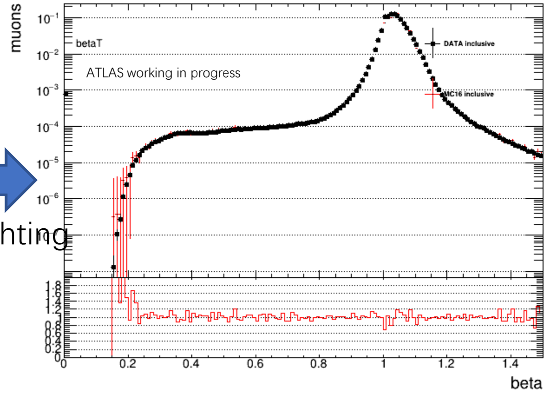
Fit with gaussian function and modified

Raw β



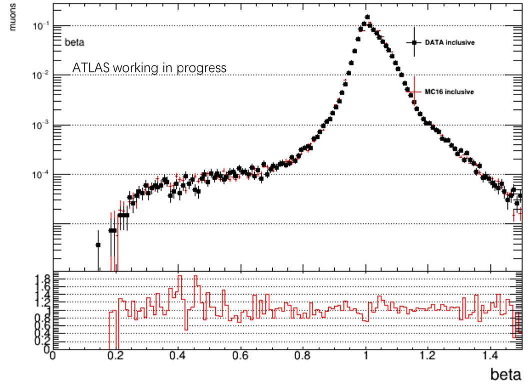
Reweighting

Gaussian modified β



Gaussian modified & reweighted β

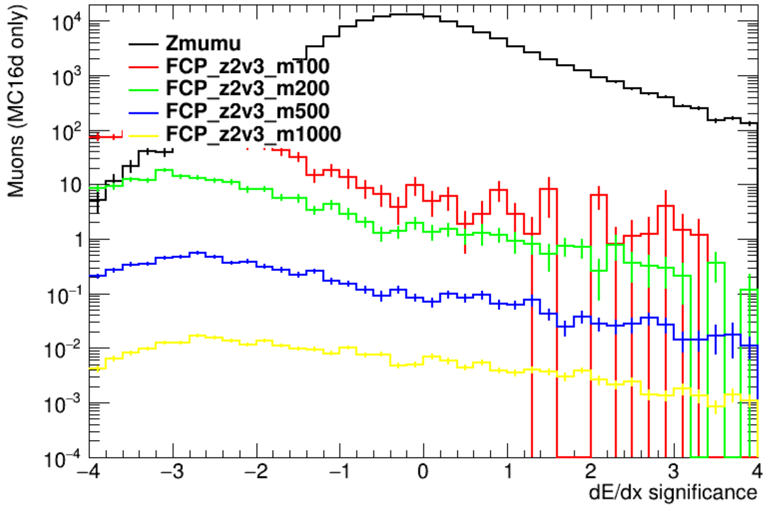
Here β is average of β from RPC and MDT TOF, with additional drift time in MDT considered.



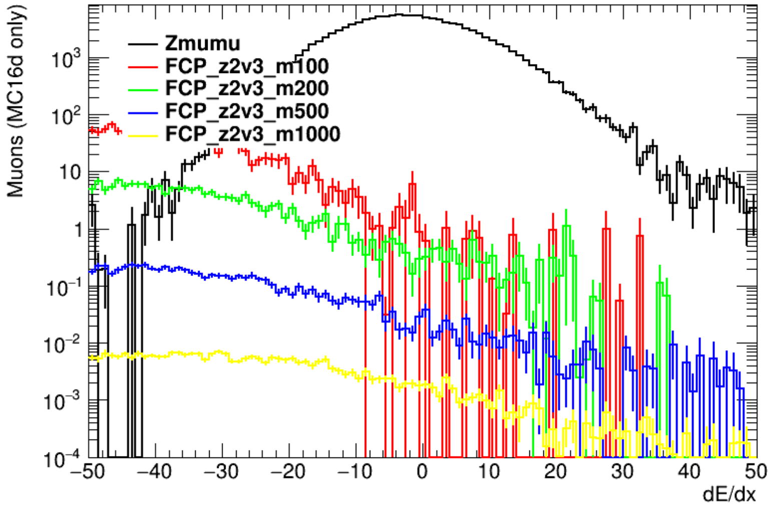
Gaussian modified & reweighted β in validation region

Gaussian modification (mostly for peak region) and reweighting works well in validation region.

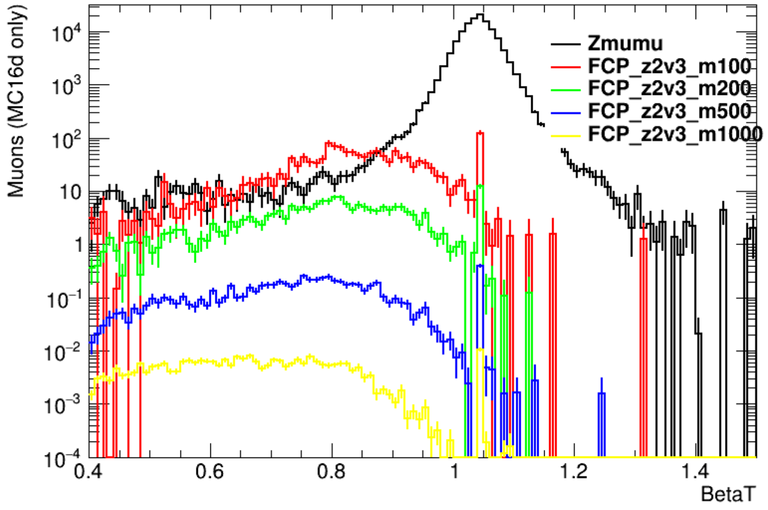
Performance of Sensitive Variables



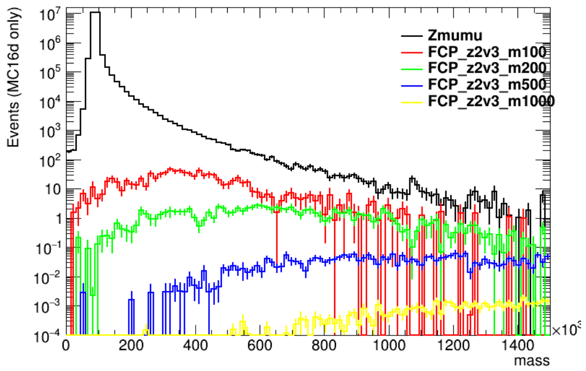
significance of pixel dE/dx



MDT dE/dx



β

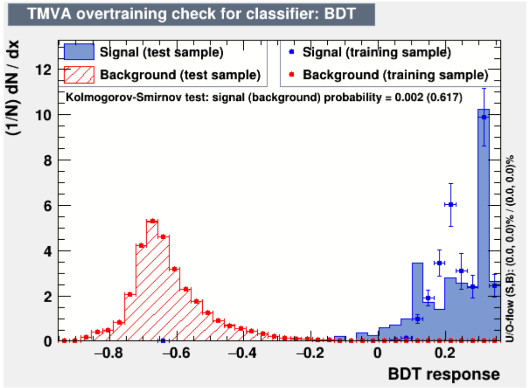


muon pair mass

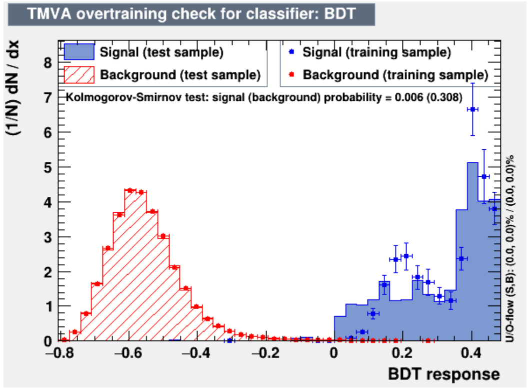
Though not considered as a sensitive variable, large muon pair mass also reject many Zmumu backgrounds.

Much better resolution than CMS. CMS 13TeV results claims about half background rejection from TOF & distance cut. For $\beta < 0.95$ cut, we have 98.5% Zmumu rejection, and FCP efficiencies are 83.1% for 100GeV, 89.8% for 200GeV, 95.6% for 500GeV and 95.1% for 1000GeV.

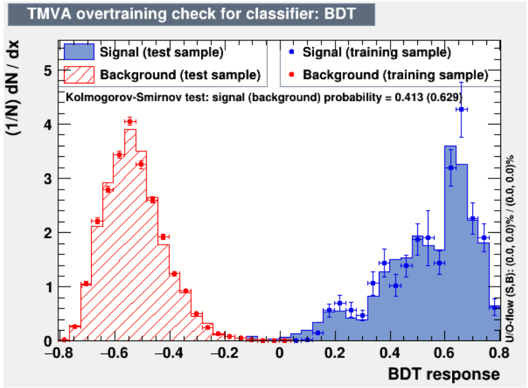
Expected Sensitivity



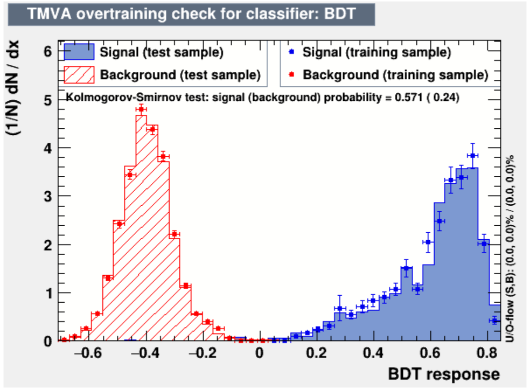
BDT discriminant of [100,200)



BDT discriminant of [200,300)



BDT discriminant of [300,400)



BDT discriminant of [400,∞)

A preliminary statistic-only fitting research with simple BDTs have been implemented.

BDTs are trained in 4 different muon pair invariant mass region, with inclusive FCP samples with different mass as signal and Zmumu as background.

There have been some overtraining shown in the BDT results, which indicates further tunning is needed and final performance could be a bit worse.

Upper limits from statistic-only fitting with bins of muon pair invariant mass and this early BDT discriminant.

Upper limits of FCP production cross-section can be level of 0.1fb (comparable to CMS)

Conclusion

- Search for FCPs is important for many new physics theories.
- LHC is very suitable for search for long-lived, heavy FCPs.
- CMS has searched for FCPs based on data with different mass and luminosity, and the latest result has exclude FCPs with 2e/3 charge and mass below 636 GeV.
- There has not been this kind of search in ATLAS. ATLAS should have some unique advantages in searching for FCPs with better Muon System.
- We are currently working on FCP search with ATLAS 13TeV data. Taking advantage of multiple sensitive variables, we expect to get results generally comparable to CMS.