Search for Fractionally Charged Particles at 13 TeV with the ATLAS Detector

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Motivation of FCPs Search

- Standard SU(2) × U(1) gauge group does not forbid FCPs

$$\mathcal{L}_{\mathrm{EW}} = \sum_{\psi} \bar{\psi}\gamma^{\mu}\left(i\partial_{\mu} - g'\frac{1}{2}Y_{\mathrm{W}}B_{\mu} - g\frac{1}{2}\boldsymbol{\tau}\mathbf{W}_{\mu}\right)\psi$$

Charge can be arbitary since Y_W can be arbitary for new particles.

- FCPs are also possible in many BSMs

Electric and magnetic charges in superstring models
Xiao-Gang Wen and Edward Witten, Nuclear Physics B261 (1985) 651-677

In superstring models unit charge can be multiple of e/n where vacuum state is $M^4 \times K$ and $\pi_1(K) = \mathbf{Z}_n$

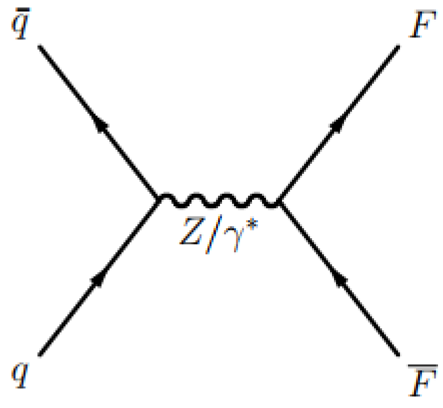
- FCPs (usually with very low charge) exist in some dark matter theories with additional gauge fields than standard model.

Search for FCPs is an important part of general search for new physics.

Signal & Main Backgrounds

FCP signal:

- Usual assumptions
  - Non-integer charge (and smaller than e)
  - 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

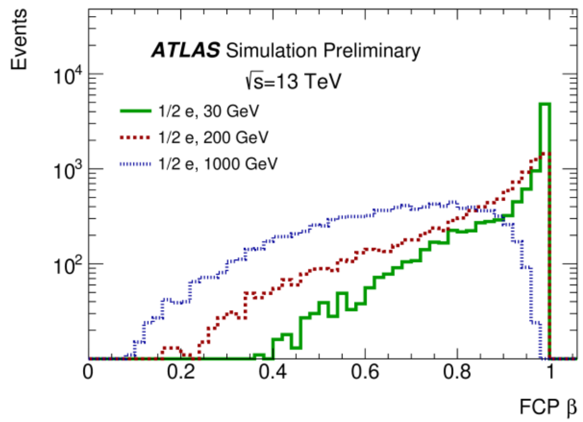


Background:

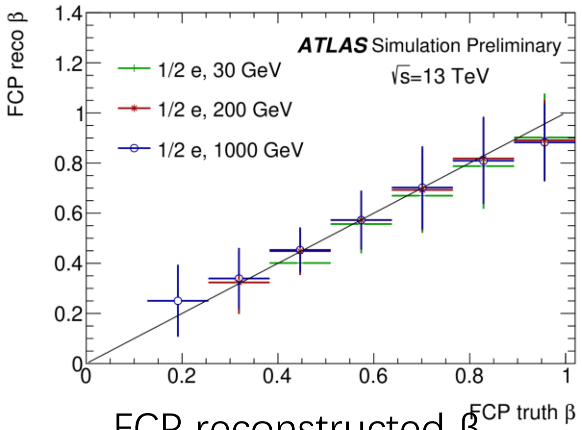
- Zmumu events should contribute to most of background
  - Most muon pairs with high invariant mass from pp collision are produced in Zmumu events

Simulation of FCPs Production

- As first step, we have finished some simulation studies of FCP production and detector performance in ATLAS [Simulation and expected detector performance of fractionally charged particles in ATLAS]
  - 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 β distribution

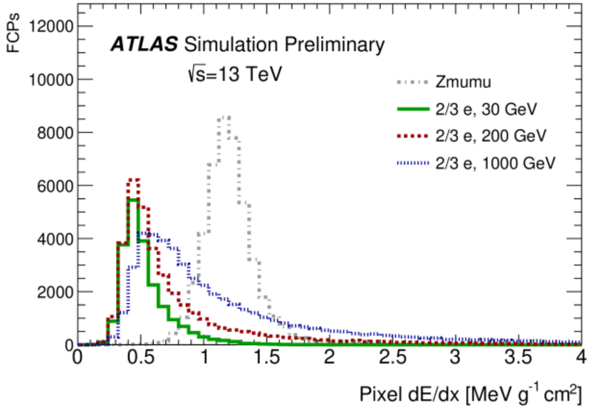


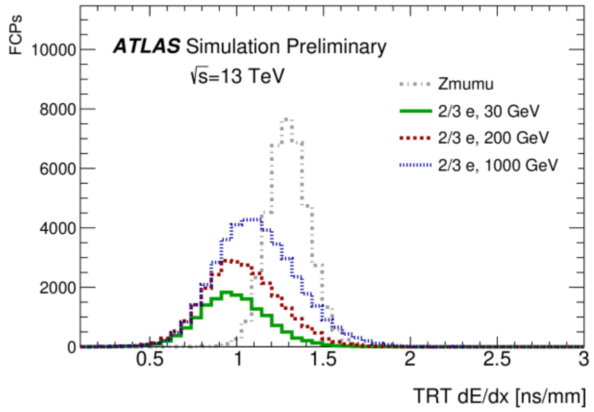
FCP reconstructed β vs. truth β

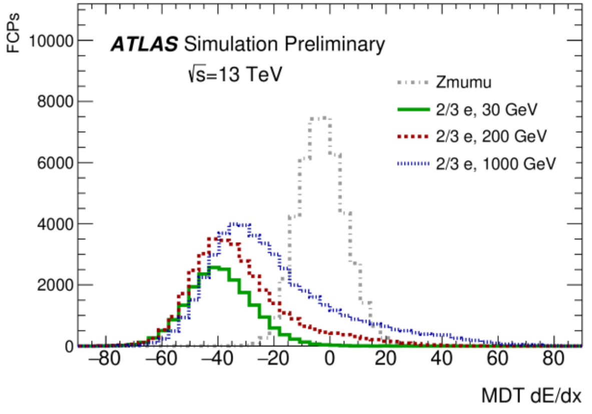
β is reconstructed via time constants and TOF from MDT and RPC detectors

β reconstruction has good performance

Simulation Performance of dE/dx







Tracks always valid pixel dE/dx (efficiency = 1)

	$1/3\ e$	$1/2\ e$	$2/3\ e$
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 & MDT dE/dx here are not defined as standard dE/dx. 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 are valid for all tracks.

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

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

Trigger & Reconstruction Efficiencies

	$1/3\ e$	$1/2\ e$	$2/3\ e$
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 total yields)

	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 sensitive HLTs for FCP

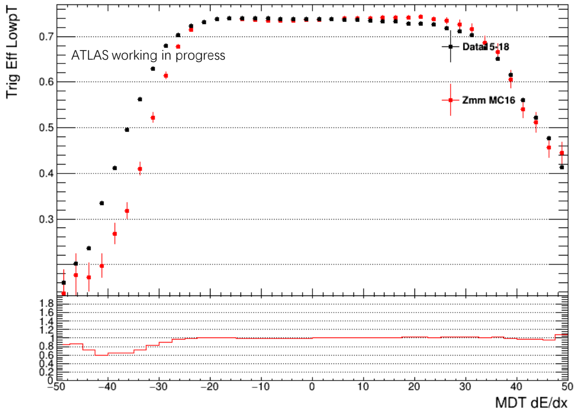
We can hardly search for 1/3 e FCPs with ATLAS due to nearly 0 trigger & reconstruction efficiencies.

Though efficiencies for 2/3 e FCPs are also low, search for them is possible with highly efficient discriminator.

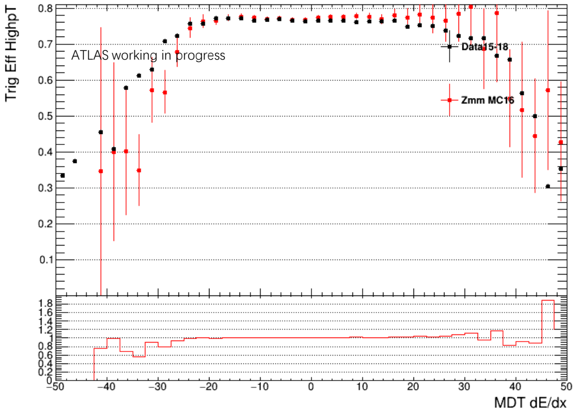
Calibration of Single Muon Trigger

- Most Zmumu events fire single muon triggers: HLT_mu26_ivarmedium for data 16-18 & HLT_mu20_iloose_L1MU15 data 15 (low pT muon trigger) and HLT_mu50 (high pT muon trigger)

- Trigger efficiencies are calculated with second muons in events in which the first muon fire a single muon trigger



Low pT muon trigger efficiency vs. MDT dE/dx



High pT muon trigger efficiency vs. MDT dE/dx

Single muon trigger efficiencies of data and Monte Carlo have discrepancy in low MDT region. No significant discrepancy is found in other regions of sensitive variables.

Monte Carlo events with low MDT dE/dx muons are reweighted to have total events trigger efficiencies with data events in same muons 4-momentum and MDT dE/dx regions.

Calibration of Sensitive Variables

- Pixel dE/dx, MDT dE/dx and β are selected as sensitivity variables to discriminate FCP in preliminary fitting research
- Invariant mass region of muon pairs near Z mass can be used for calibration since almost all events in this region are Zmumu events.
- 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, they can also avoid signal region.

Calibration region:

Muon selection:

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

Event selection (Zmumu control region):

- leading muon $p_T > 35$GeV
- number of muon = 2
- 80GeV < mass(mu, mu) < 100GeV

Validation region:

Muon selection:

- $p_T > 30$GeV
- $|\eta| < 2.5$
- $z_0 \sin\theta < 0.5$, 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)

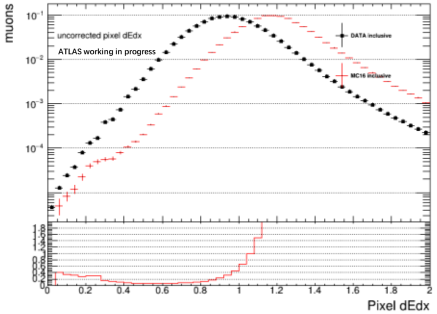
Event selection (Zmumu control region):

- leading muon $p_T > 35$GeV
- number of muon = 2
- mass(mu, mu) > 100GeV

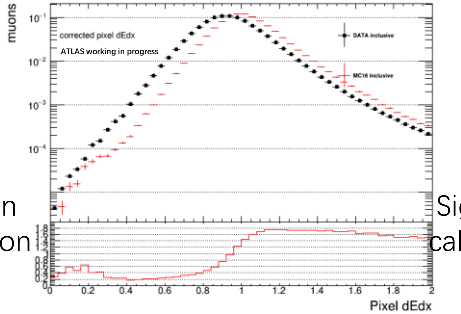
Calibration of Sensitive Variables

Calibration

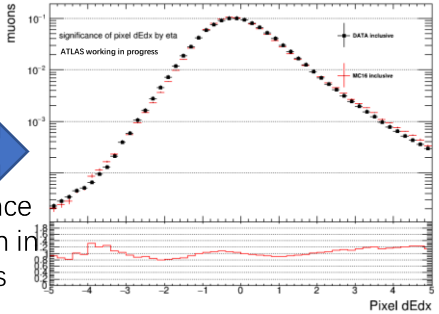
Pixel dE/dx



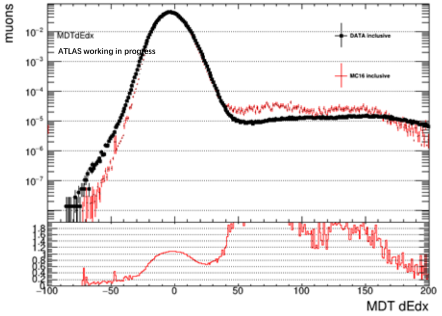
A modification tool for radiation damage



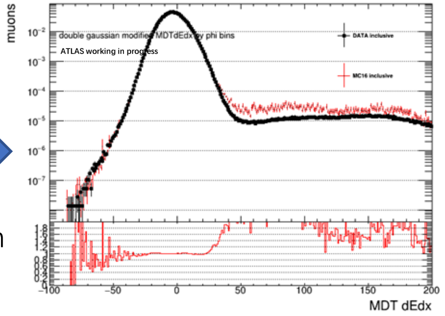
Significance calculation in eta bins



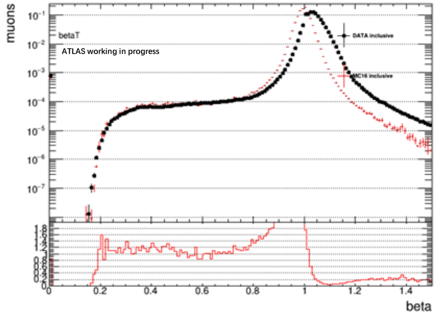
MDT dE/dx



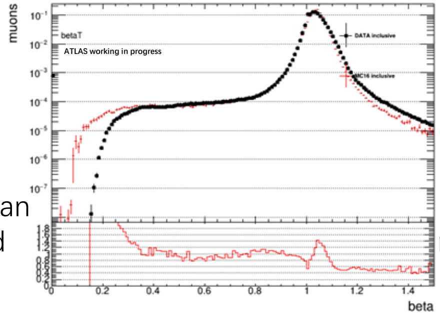
Fit distribution from both data and MC with double gaussian function in phi bins, then modify dE/dx from MC samples



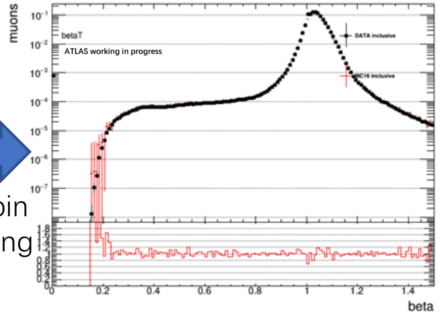
β



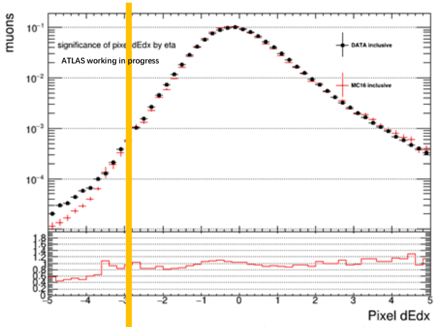
Fit with gaussian function and modified



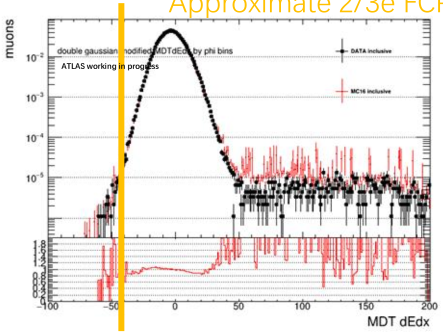
Bin-by-bin reweighting

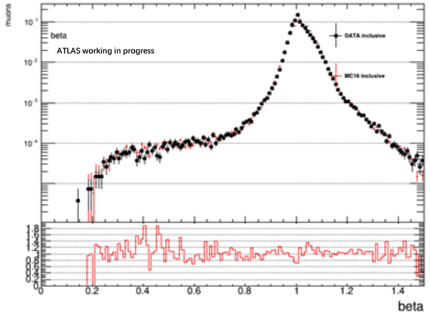


Validation Region

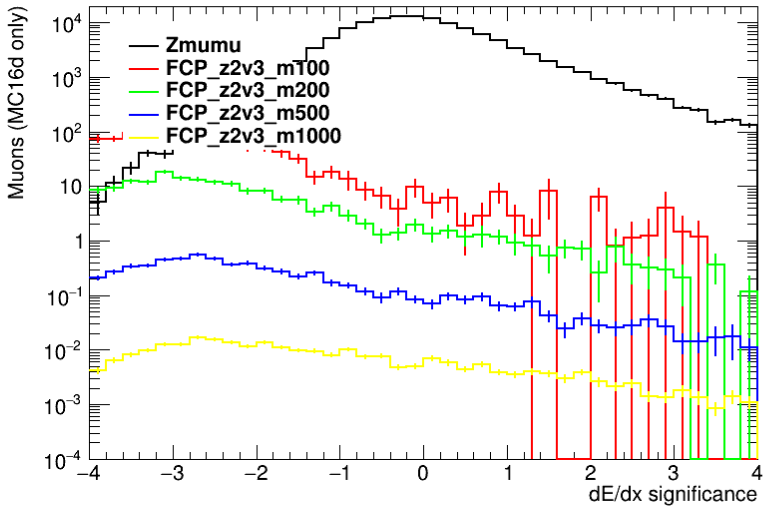


Approximate 2/3e FCPs peak

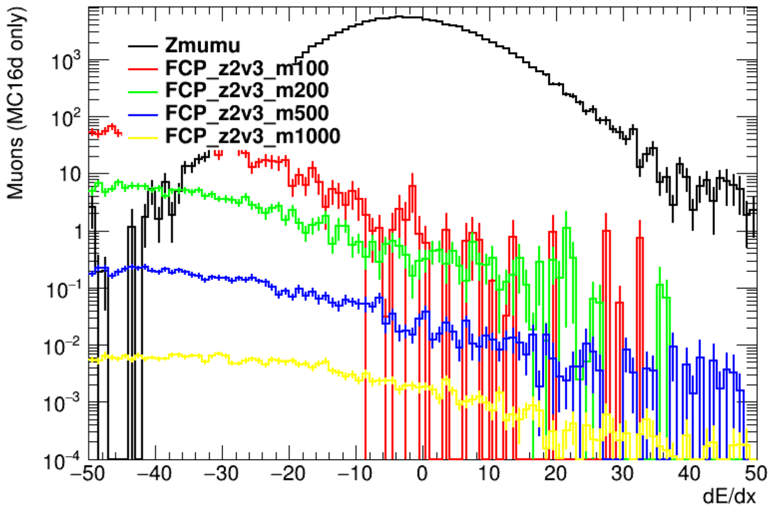




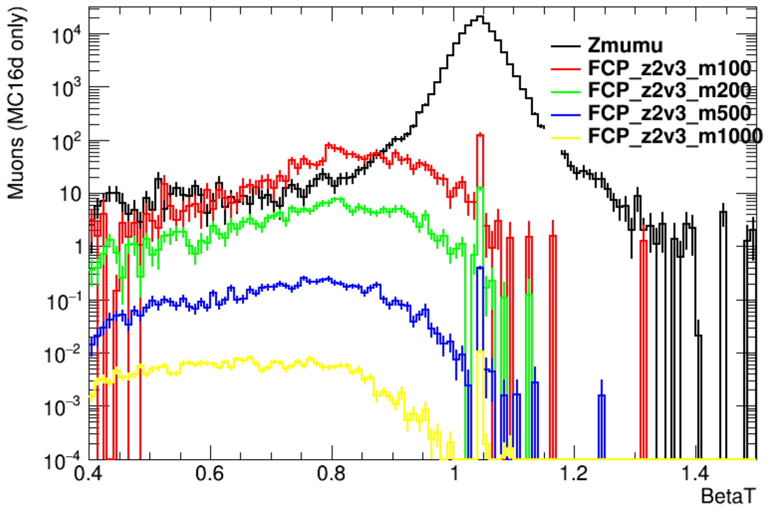
Calibrated Sensitive Variables



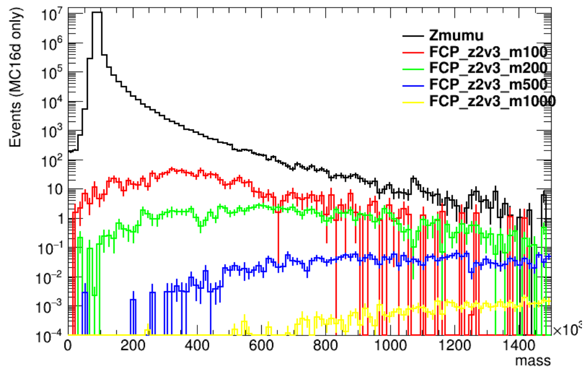
significance of pixel dE/dx



MDT dE/dx



β



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

Found to have good resolution and can perform an important role in MVA.

muon pair mass

*We do not actually know mass of particle objects, here all of them are set to muon mass (106MeV)

Preliminary BDT Discriminator

Training sample:

Background:

Zmumu

Signal:

Inclusive 2/3e FCP sample of 100, 200 and 500GeV mass.
FCPs with different mass are reweighted to same total weight.

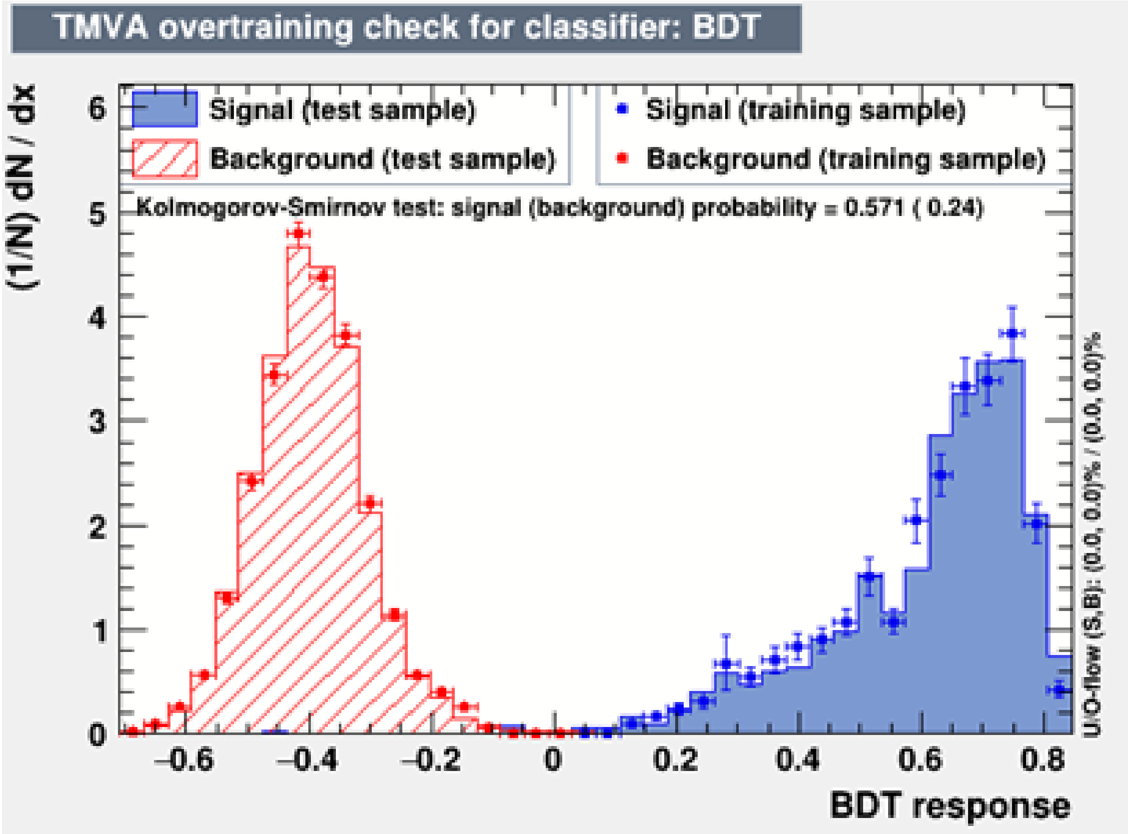
Pre-selection:

Muon selection:

Muons and staus(heavy muon like particles)
$p_T > 30GeV$
$|\eta| < 2.5$
$z_0 \sin\theta < 0.5$, significance of $d_0 < 3$
quality: loose
type: combined muon

Event selection :

leading muon $p_T > 35GeV$
number of muon = 2
mass(mu, mu) > 100GeV



Data-driven Background Estimation: Scale

- We use ABCD methods to estimate the scale of background muons in signal region currently
  - Muons in events which pass preselection are divided to ABCD regions by significance of pixel dE/dx and MDT dE/dx
  - Background muons in signal region should have β≈1 and are similar to MIPs, their dE/dx should follow Landau distribution and pixel & MDT dE/dx should be independent
  - Number of background muons in A (signal) region can be estimate by $N_{A\_background} = \frac{N_B N_D}{N_C}$
  - BCD region also contains small portion of signal (< 2% for all)

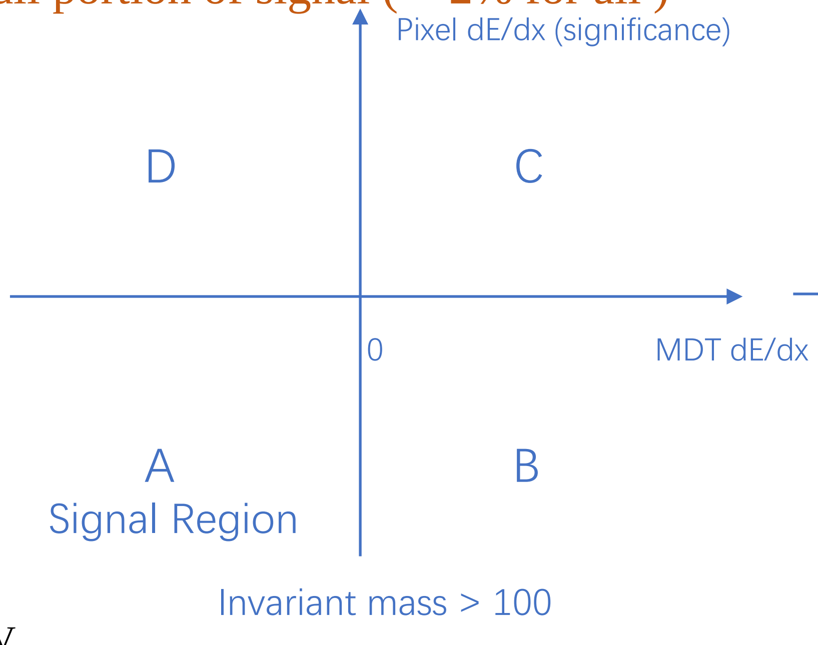
Pre-selection:

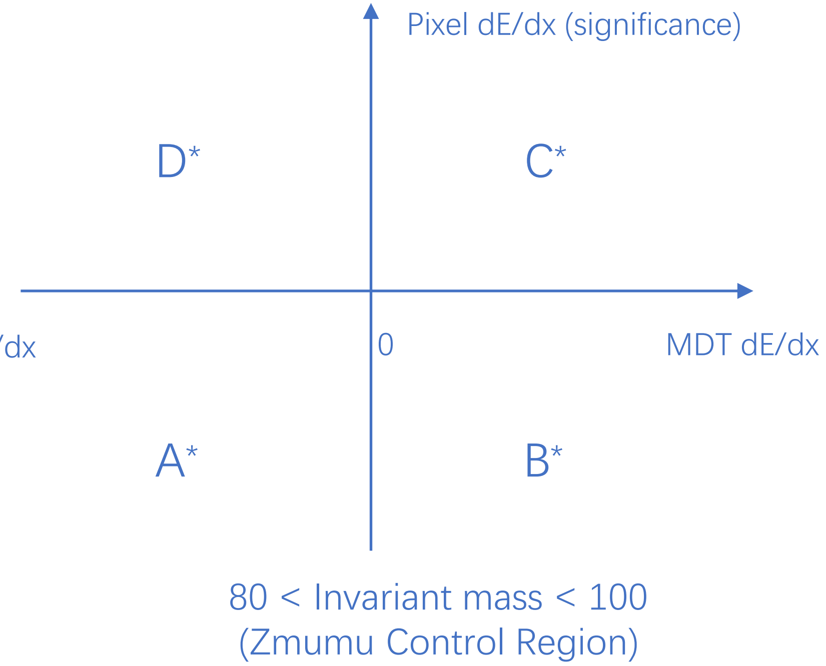
Muon selection:

Muons and staus(heavy muon like particles)
$p_T > 30$GeV
$|\eta| < 2.5$
$z_0 \sin\theta < 0.5$, significance of $d_0 < 3$
quality: loose
type: combined muon

Event selection :

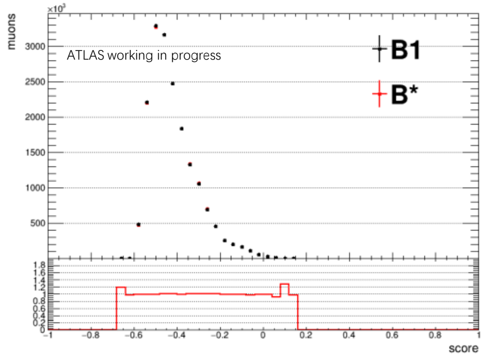
leading muon $p_T > 35$GeV
number of muons ≥ 2
invariant mass of leading muons pair > 80GeV

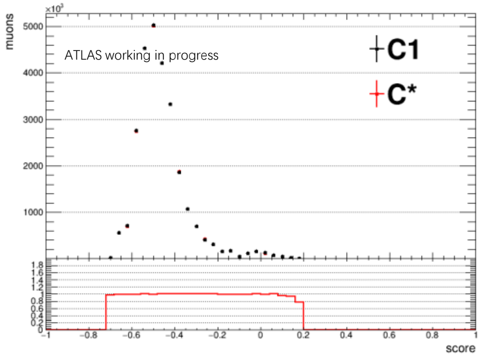


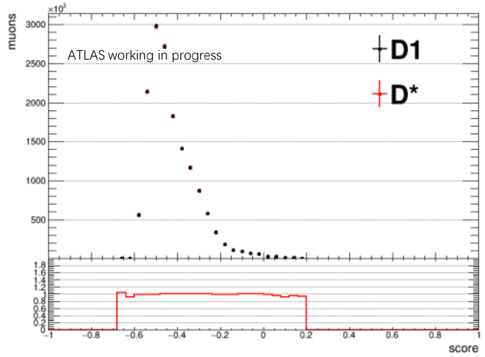


Data-driven Background Estimation: Shape

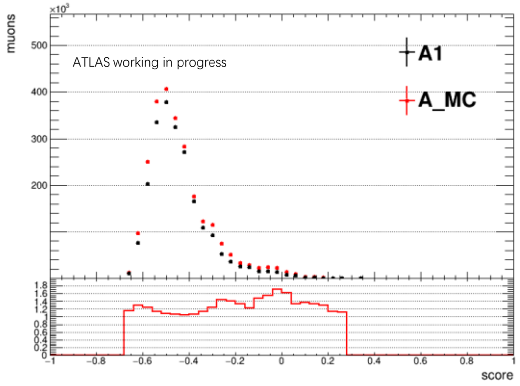
- Our statistic analysis will be based on BDT score bins, currently we use shape of BDT score distribution in A* (Zmumu) region to estimate the shape in A(signal) region
  - Invariant mass of muon pairs are not used in BDT training
  - Shape of BCD regions and B*C*D* regions are very similar







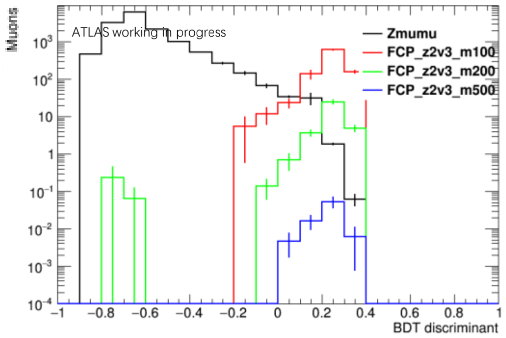
B1, C1 and D1 means distributions in B, C, D regions rescaled to those in B*, C*, D* region



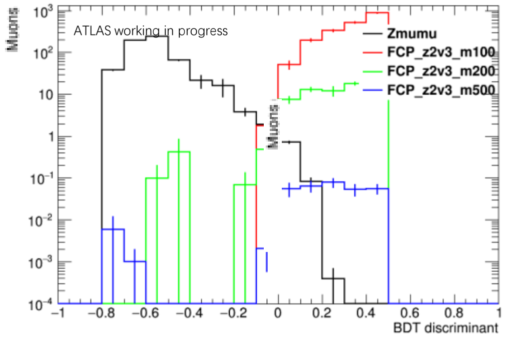
A1 is final estimated backgrounds with scale from ABCD methods and shape from A* region, A_MC are backgrounds from Zmumu Monte Carlo samples in same region.

Background-only Fitting

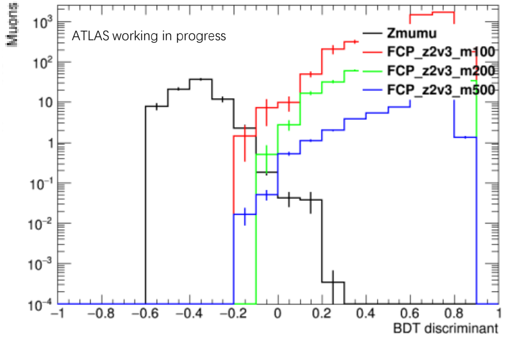
- This fitting use ‘data’ consists of Data-driven estimated background and no signal, providing a statistic-only fitting results
- Since statistic uncertainty should contribute very most of uncertainty of this search, this fitting gave us expectation of our final results



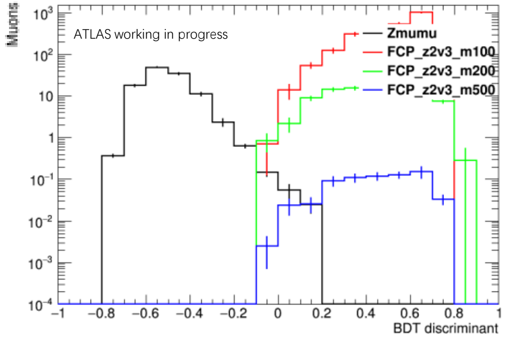
100 < invariant mass / GeV < 200



200 < invariant mass / GeV ≤ 300



300 < invariant mass / GeV ≤ 400



400 < invariant mass / GeV

Upper limits of FCP production cross-section at the 95% C.L.

100 GeV 2/3 e FCP	0.31fb
200 GeV 2/3 e FCP	0.20fb
500 GeV 2/3 e FCP	0.11fb

This background-only fitting has shown better results for high mass FCPs than any of previous search of this kind, we expect a good final results of this search.

Latest CMS search at 13TeV has excluded cross sections above 0.28 fb (0.39 pb) for FCPs production with 2e/3 charge and 640(60) GeV mass.

Summary

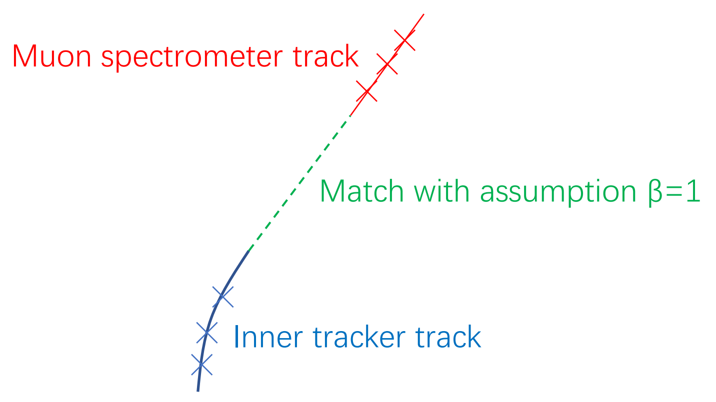
- Search for FCPs is an important part of search for new physics.
- This search aims at ‘muon like’ FCPs with long lifetime and participate in EM-weak interaction.
- We use mainly pixel & MDT dE/dx and β for discriminating FCP from muons.
- After calibration of trigger efficiencies and sensitive variables, our background-only fitting has shown a good result especially for high mass FCP.

Backup

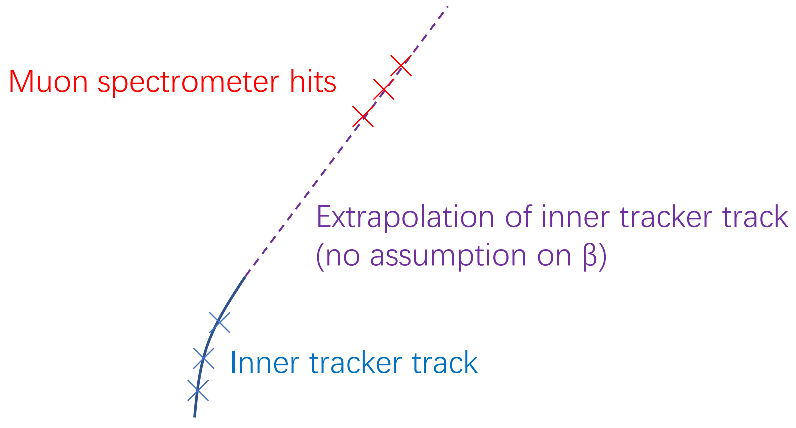
Reconstruction of FCPs

As kind of muon-like particles, FCPs are reconstructed through standard muon reconstruction and MuGirl reconstruction in ATLAS.

- Standard muon reconstruction: tracks are reconstructed in both inner tracker and muon spectrometer firstly, then trying to match them with assumption that particle travel with speed of light.
- For MuGirl reconstruction, tracks from inner tracker are extrapolated to muon spectrometer, then looking for hits in the corresponding detectors.

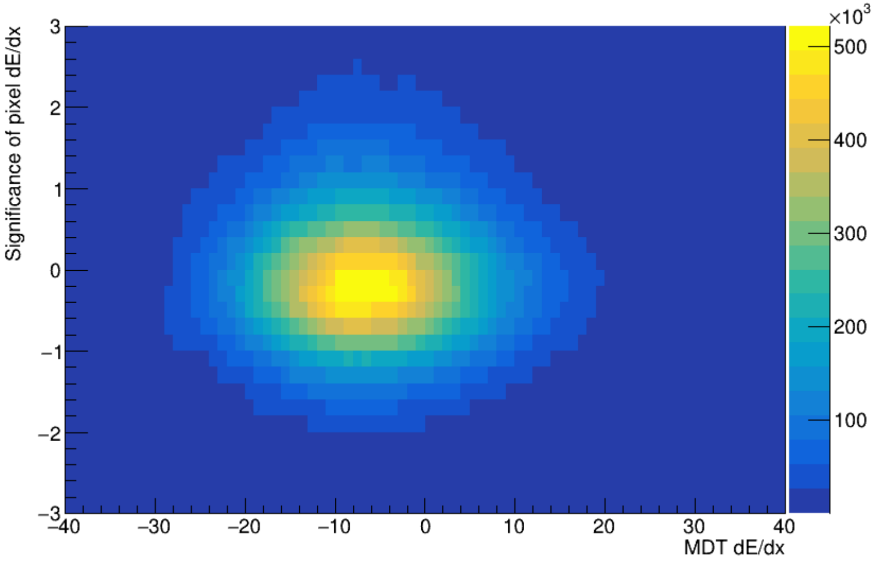


Standard muon reconstruction

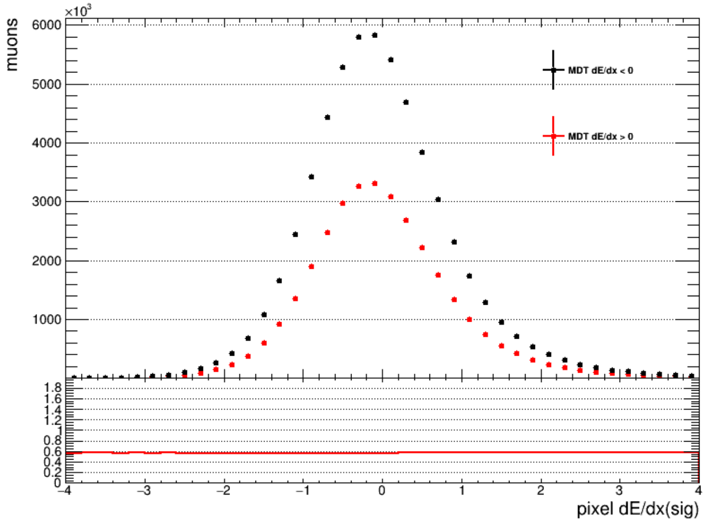


MuGirl reconstruction

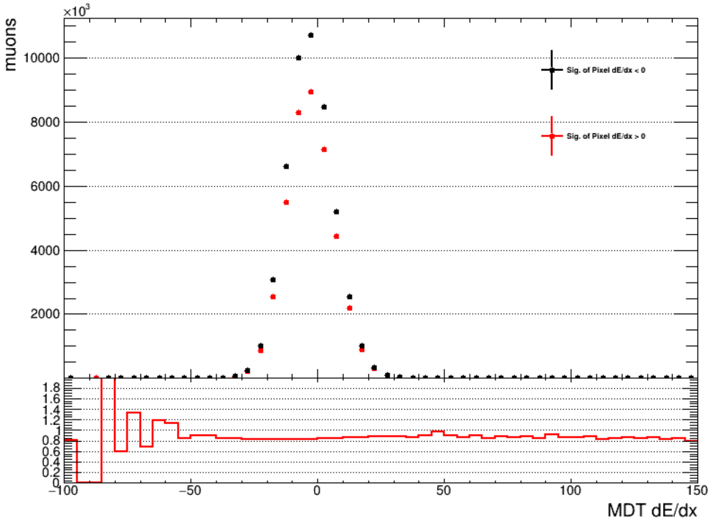
Pixel & MDT dE/dx Correlation



pixel vs. MDT dE/dx in Zmumu region
Covariance: -0.0091
Correlation Factor: -0.0010



pixel dE/dx in different MDT dE/dx region
(Data in Z control region)



MDT dE/dx in different pixel dE/dx region
(Data in Z control region)

For A*B*C*D* regions in Zmumu control region, $\frac{N_{A*}N_{C*}}{N_{B*}N_{D*}} = 1.020$