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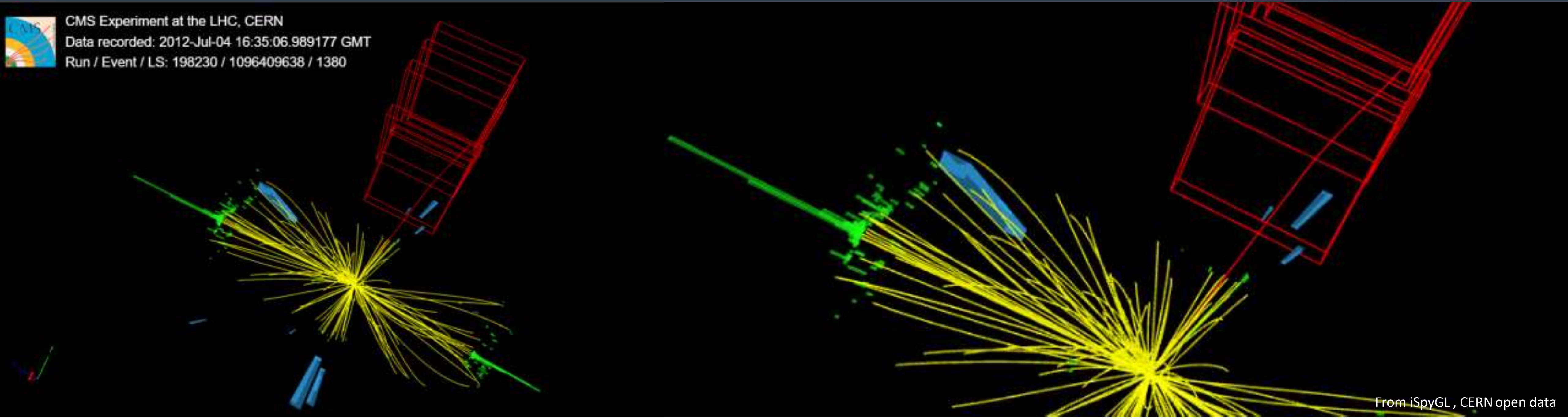


Project final

'Background estimation of MonoHiggs in $b\bar{b}$ final state using 2018 data of the CMS detector at the LHC, CERN'

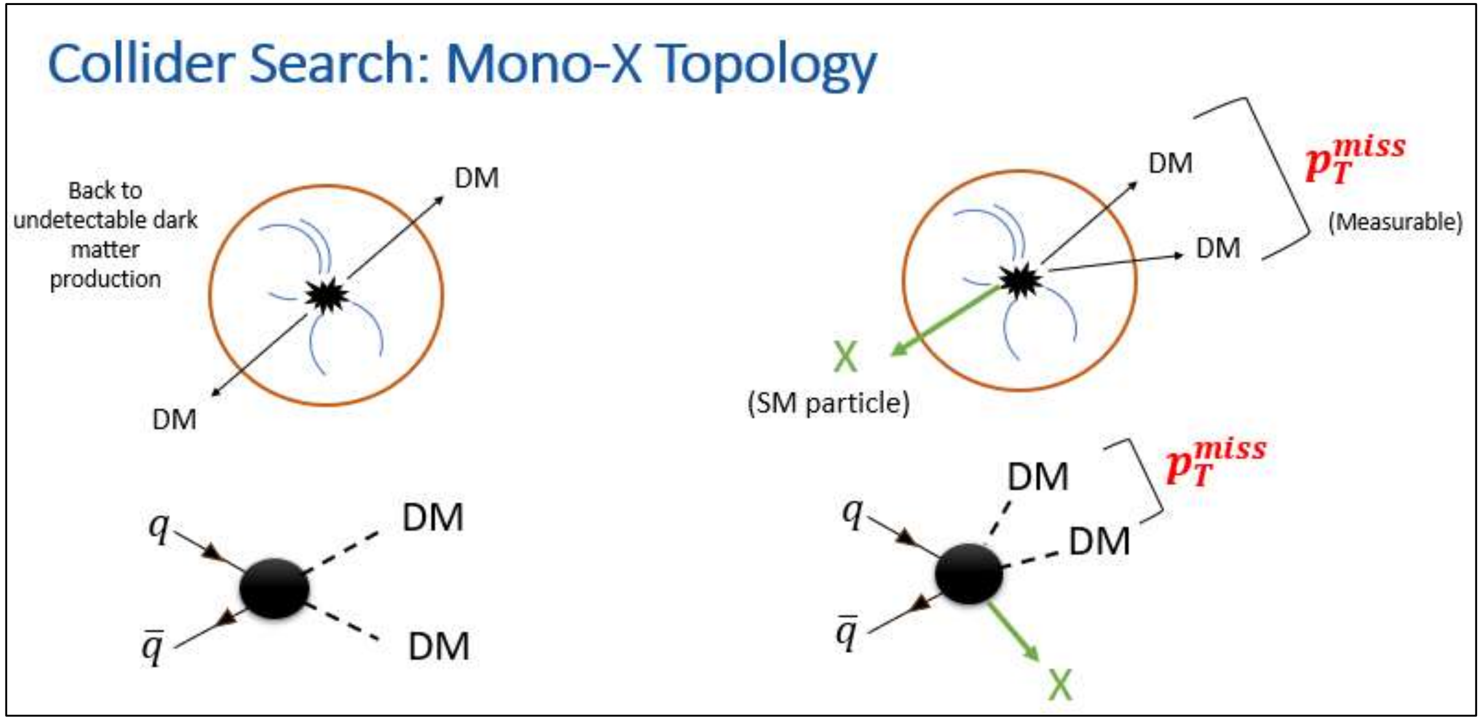
Name :	*Prayag Yadav*
Program :	*Integrated Masters of Science 10th Semester*
ID:	*19IPMP03*
Project Supervisor:	*Dr. Bhawna Gomber*

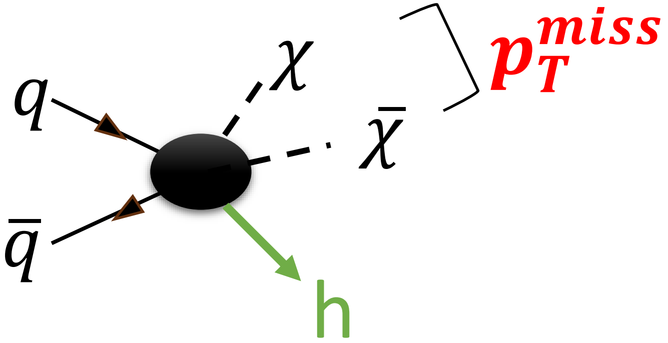
Outline

Outline

1. Recap
2. Top(e) boosted CR
3. Event Selections
4. Object Selections
5. Results
6. Kinematic plots
7. Conclusion

Recap 1





Mono Higgs Searches

1. No Initial State Radiation
2. More closely connected to DM production
3. Signal Signature has a high MET trail which helps to separate the signal from background.

H(125)->bb branching ratio is ~ 57%

My focus H(125)->bb

Final state: $\mathbf{H}(\bar{b}b) + large\ p_T^{miss}$

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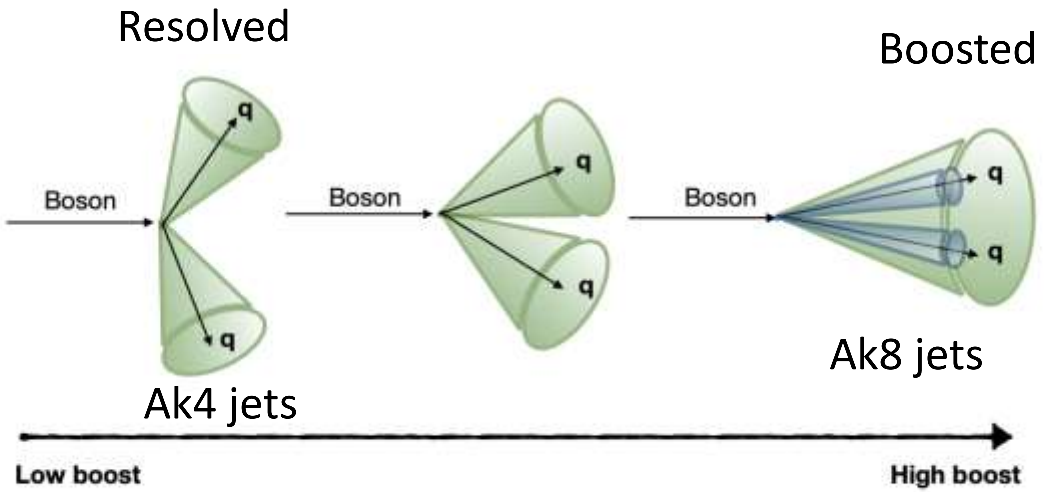
Recap 2

Backgrounds

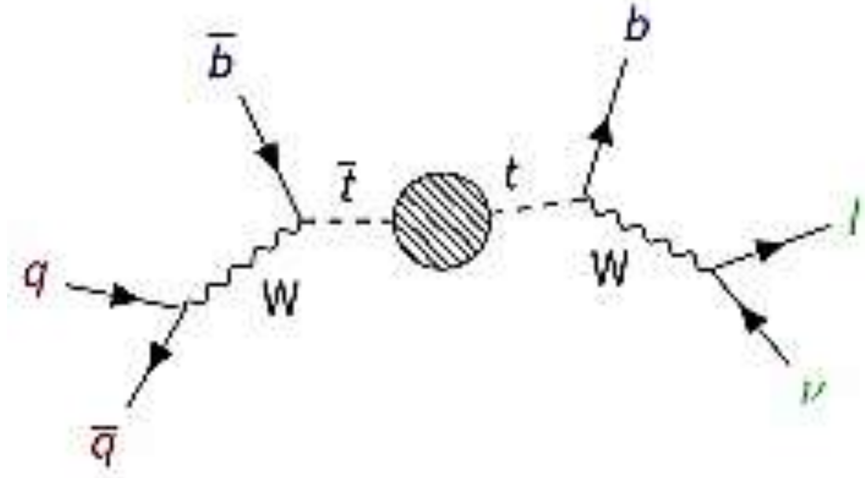
- Top quark pair production
- Single top production
- W+jets
- Z(νν)+jets
- Drell-Yan(DY)+jets
- Other minor backgrounds



Jet angular separation

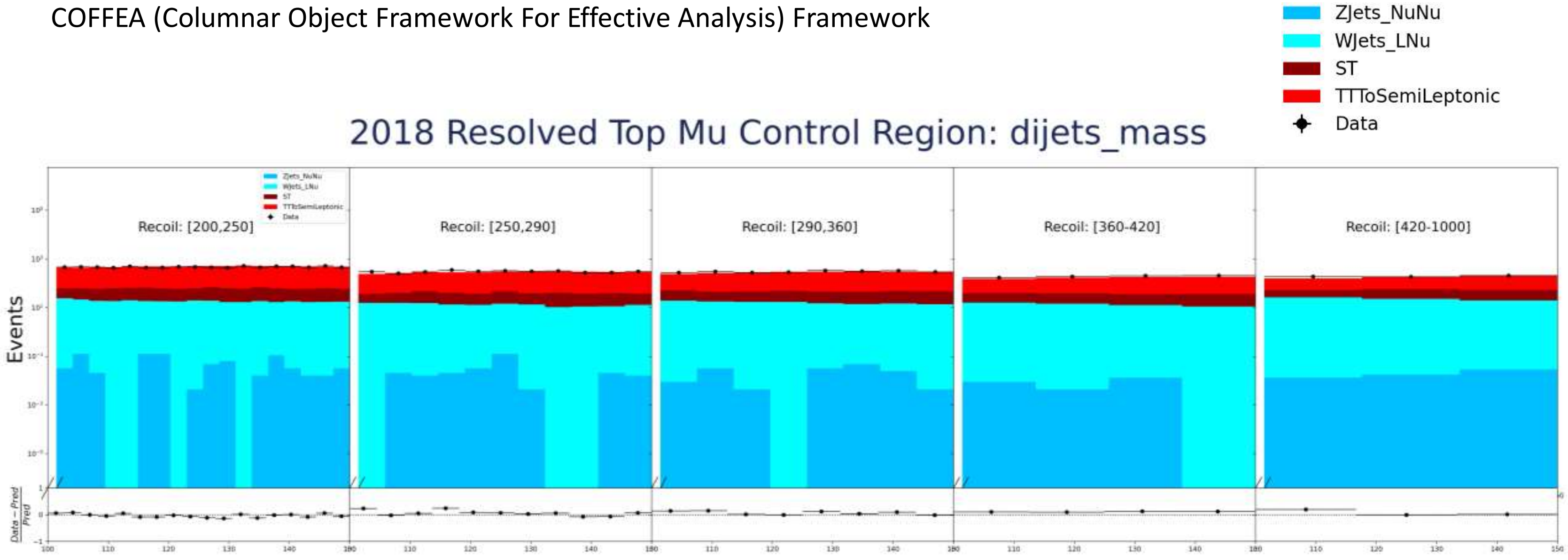
Top e Resolved jets **Top single electron**	**Top μ Resolved jets** **Top single muon**
Top e Boosted jets **Top single electron**	**Top μ Boosted jets** **Top single muon**

Lepton variety

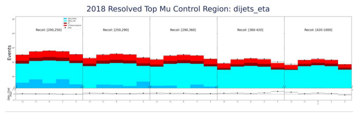


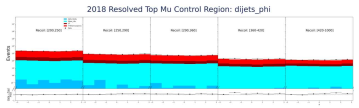
Recap 3

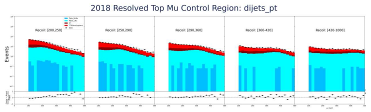
COFFEA (Columnar Object Framework For Effective Analysis) Framework

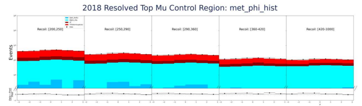


Signal Region	Top μ Control Region (single muon)
MET Trigger	MET Trigger
MET Filter	MET Filter
$p_T^{miss} > 200\ GeV$	$p_T^{miss} > 50\ GeV$ and $Recoil > 200\ GeV$
No Leptons	One Muon (No other Lepton)
Leading Jet $p_T > 50\ GeV$	Leading Jet $p_T > 50\ GeV$
Subleading Jet $p_T > 30\ GeV$	Subleading Jet $p_T > 30\ GeV$
Dijet $p_T\ > 100\ GeV$	Dijet $p_T\ > 100\ GeV$
Dijet mass between 100 GeV to 150 GeV	Dijet mass between 100 GeV to 150 GeV
Additional Jets ≤ 2	Additional Jets > 1









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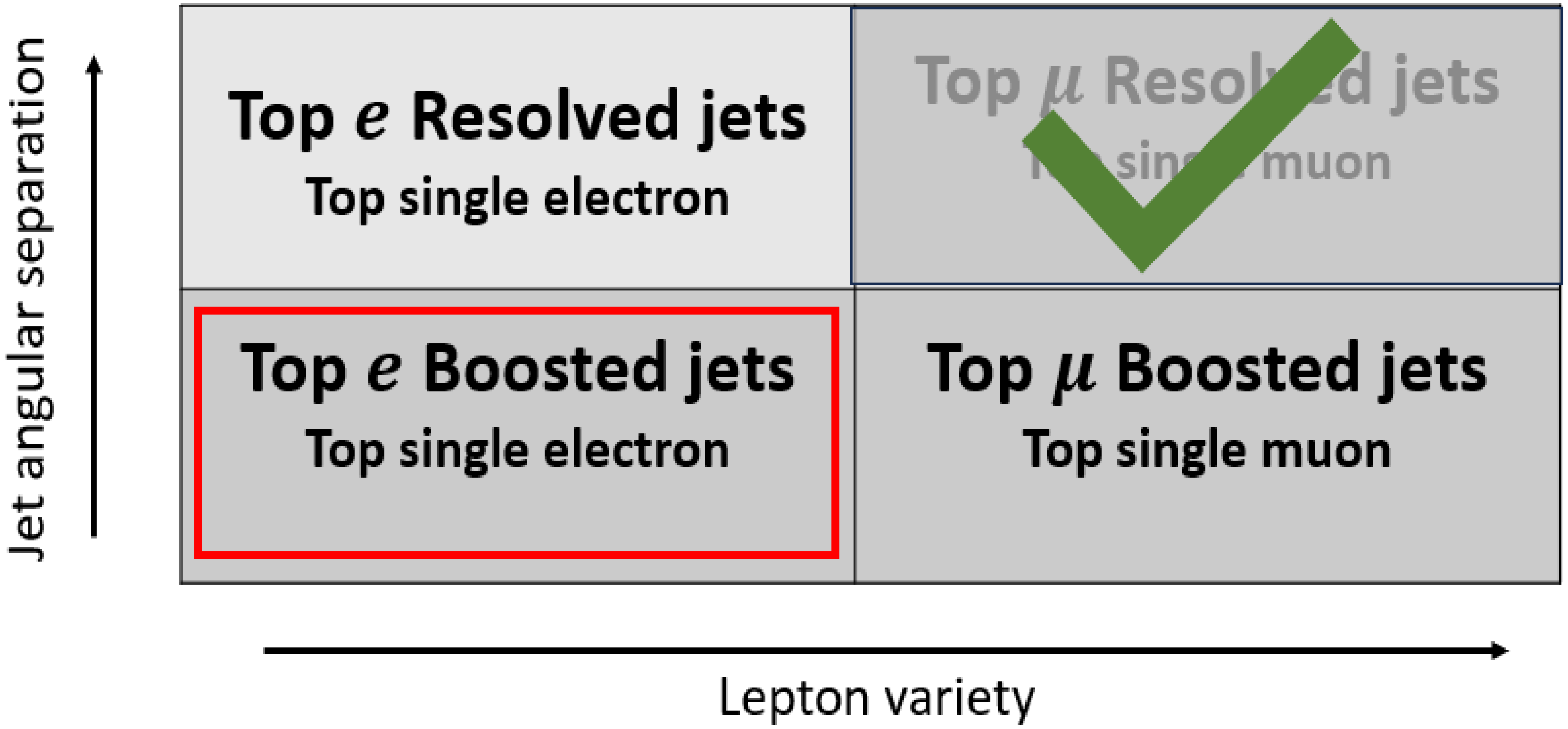
Top(e) Boosted Control Region



- Estimated the Top Muon Resolved CR (without corrections) last time.
- Estimated the Top Electron Boosted CR (with corrections) this time

Event Selections

Dataset Name	Events selected for
/EGamma/NANOAOD/Run2018[A-D]/UL2018_MiniAODv2_NanoAODv9-v1/*	Single-Electron CR 2018UL

~ 285 million events

Selection Bin	Event Selection	Description
0	No cuts	Raw
1	MET – Filters	To remove MET noise
2	Electron Trigger	Choose Single-Electron events
3	N(FatJet) = 1	One ak8 Jet only
4	N(IsoAddJet) ≤ 2	Two additional Jets
5	N(IsoLoosebTagJet) = 1	One loose b-Tagged Jet
6	N(e) = 1 & N(μ) = 0	One Electron and no Muon
7	$p_T^{miss} > 50\ GeV$	To remove QCD backgrounds
8	Recoil > 250 GeV	Final state requirement for boosted category
9	N(τ) = 0	Tau veto
10	N(γ) = 0	Photon veto
11	HEM veto	Removing HEM affected events (detector issue in 2018)

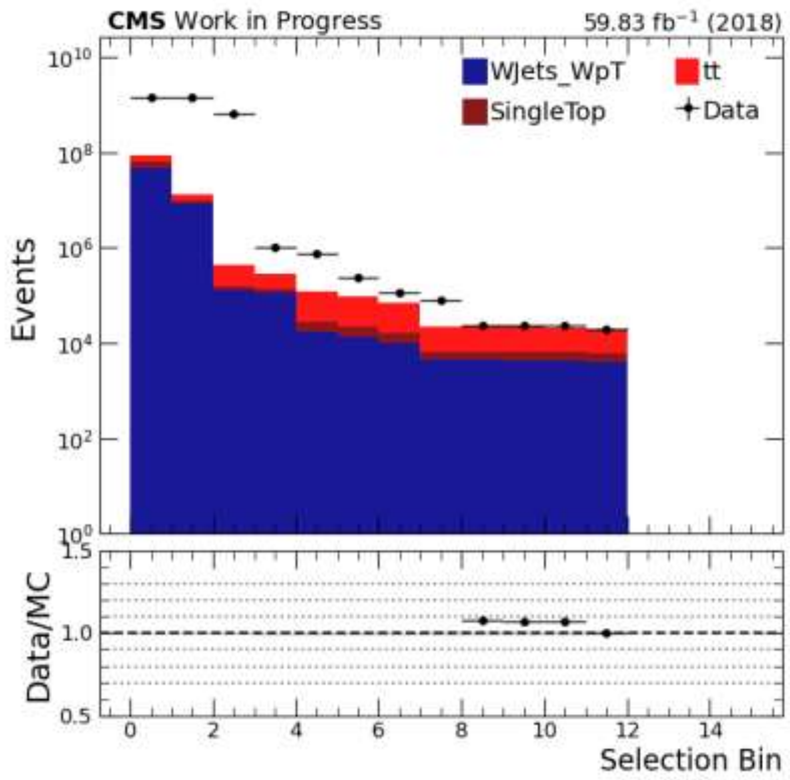


Fig: Preliminary cut-flow without corrections

Event Selections

Trigger turn-on pt

Selects events with at least one Tight electron(90% signal efficiency)

Trigger

- Electron Trigger: `HLT_Ele32_WPTight_Gsf` used for the analysis.
- This adds the advantage of reducing the analysis’s required computing time.

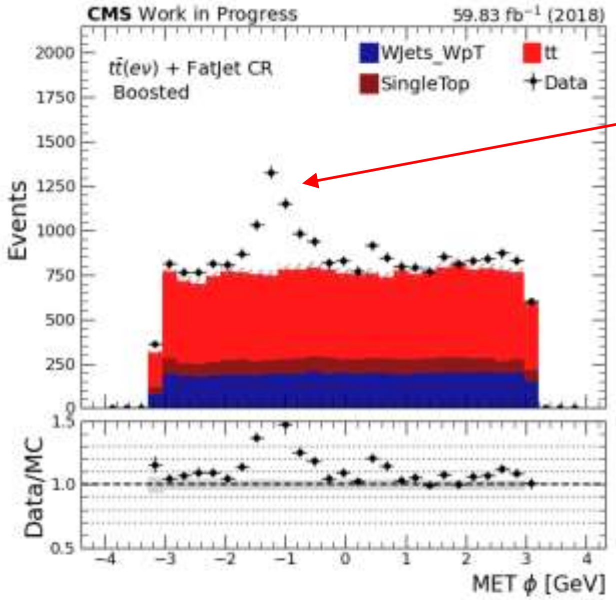
Corrections and Scale factors

- To account for different efficiencies of algorithms in Data events and Monte-Carlo simulated events, appropriate scale factors are applied on histograms produced from MC events. Some of these scale factors(SFs) and corrections are Electron-Trigger SF, b-Tagging SF, PileUp reweight SF, Jet Energy Calibration and Jet Energy Resolution, L1 prefiring and Top reweighting [36]. Each of these also carry an uncertainty with them.

Event Selections

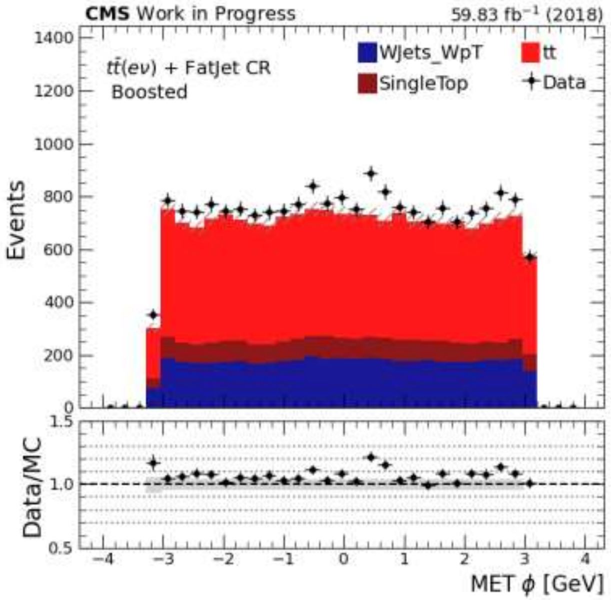
HEM Veto

In 2018, power supply of two HCAL modules in range η : -3.0 to -1.3 and φ : -1.57 to-0.87 was compromised. Therefore, in this analysis we remove any event which has at least one jet or fatjet lying in this range.



Excess in MET due to HEM issue

Fixed



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Object Selections: Fatjets (ak8 jets)

Selection	Description
$p_T > 30$ GeV	To remove low pt jet noise
$\lvert\eta\rvert < 2.5$	Extent of calorimeters
jetID ≥ 2	Tight ak8jets
70 GeV < $M_{softdrop}$ < 150 GeV	Mass around Higgs mass
ΔR(Fatjet,e) > 0.4 & ΔR(Fatjet,μ) > 0.4	Jets isolated from Electrons and Muons

- Fatjets (ak8 jets) were selected using a series of selections shown in the table.
- Since Fatjets contain two overlapping ak4 jets, their mass should be close to the Higgs mass. This is asserted by choosing the mass range of fatjets between 70 GeV to 150 GeV.

Object Selections: Additional Jets (ak4 jets)

Selection	Description
$p_T > 30$ GeV	To remove low pt jet noise
$\|\eta\| < 2.5$	Extent of calorimeters
jetID ≥ 2	Tight ak4jets
$\Delta R(jet,e) > 0.4$ & $\Delta R(jet,\mu) > 0.4$	Jets isolated from Electrons and Muons

- Unlike Fatjets, there is no selection of the mass of jets.

Object Selections: Electrons

Selection	Description
p_T > 40 GeV	To be about the trigger's turn on (32 GeV)
|η| < 2.5	Extent of calorimeters
cutBased ≥ 4	Tight Electrons
gapcuts	Remove Electrons from ECAL gap

- Electrons are selected considering the threshold of the Electron trigger.
- The trigger threshold, also known as trigger turn-on, is 32 GeV here. So the p_t cut is 40 GeV.

Object Selections: Muon , Tau and Photon

Selection	Description
p_T > 15 GeV	Remove low p_T noise
$\lvert\eta\rvert$ < 2.4	Extent of Muon chambers
isPFcand	Is a particle flow candidate
isTracker & isGlobal	Has signature in tracker and globally
looseId	Loose Muons
pfRelIso04 all < 0.25	Relative isolation from other objects

Muon selections in the analysis

Selection	Description
p_T > 20 GeV	Remove low p_T noise
$\lvert\eta\rvert$ < 2.3	Extent of calorimeters
idDecayModeOldDMs & decayMode= 5 or 6	Veto "experimental 2-prong"
idDeepTau2017v2p1VSe ≥ 8 & idDeepTau2017v2p1VSmu ≥ 2 & idDeepTau2017v2p1VSjet ≥ 8	Parameters for tau tagging algorithms

Tau selections in the analysis

Selection	Description
p_T > 20 GeV	Remove low p_T noise
$\lvert\eta\rvert$ < 2.5	Extent of calorimeters
cutBased ≥ 1	Loose Photons

Photon selections in the analysis

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Results

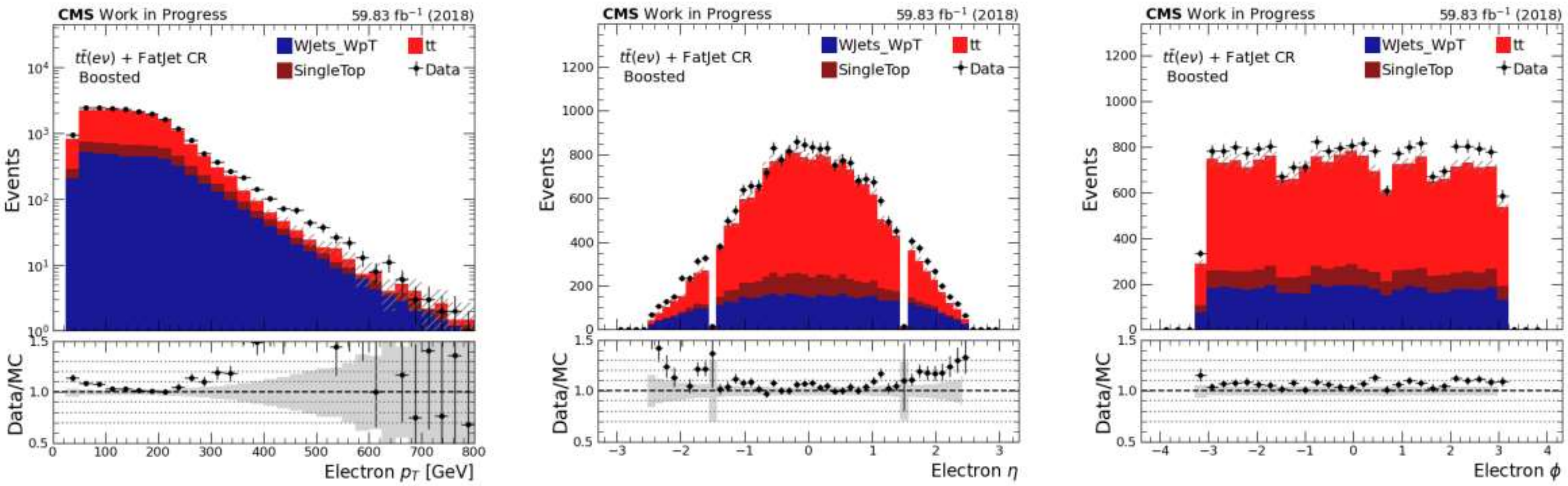
- After applying all the event selections, various analysis objects were selected following the object selections.

- Relevant kinematic variables like p_T. η, ϕ and mass were plotted for Electrons, Fatjets, additional jets, MET and Recoil.

- The various backgrounds were also scaled according to luminosity and the cross-sections of the relevant MC process.

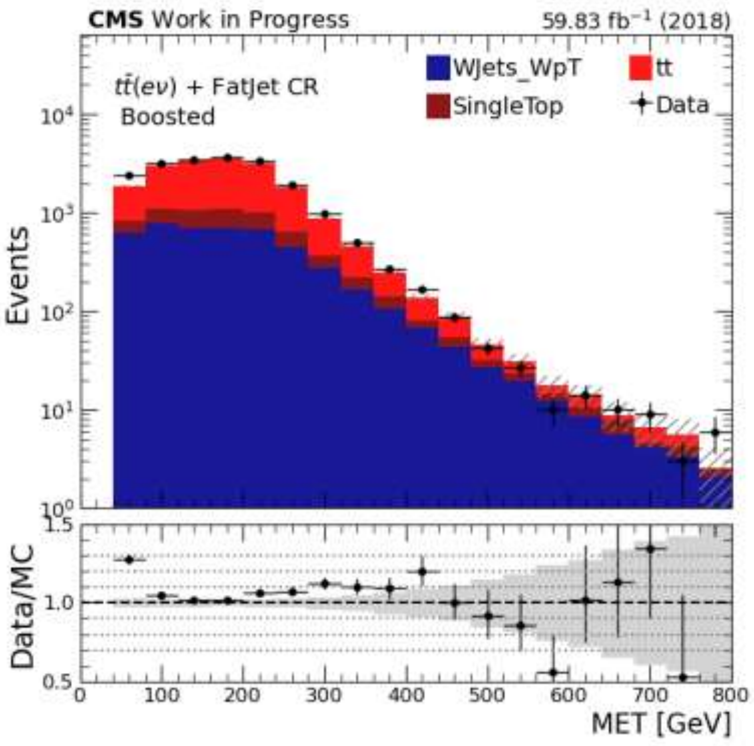
- A summary of the results is shown in the subsequent slides.

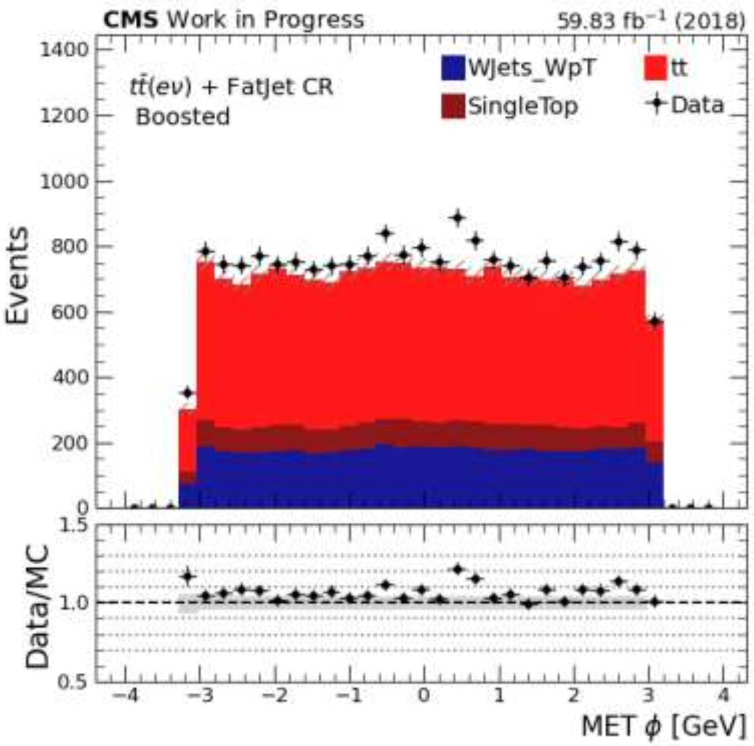
Kinematic Plots: Electron



- Electrons are an important part of the Top(e) control region because they tag the process.
- The plots show the expected shapes in the three kinematic variables.
- The Y-axis is the number of events which pass the selection in the log scale. The X-axis denotes the kinematic variables.

Kinematic Plots: Missing Transverse Energy(MET)

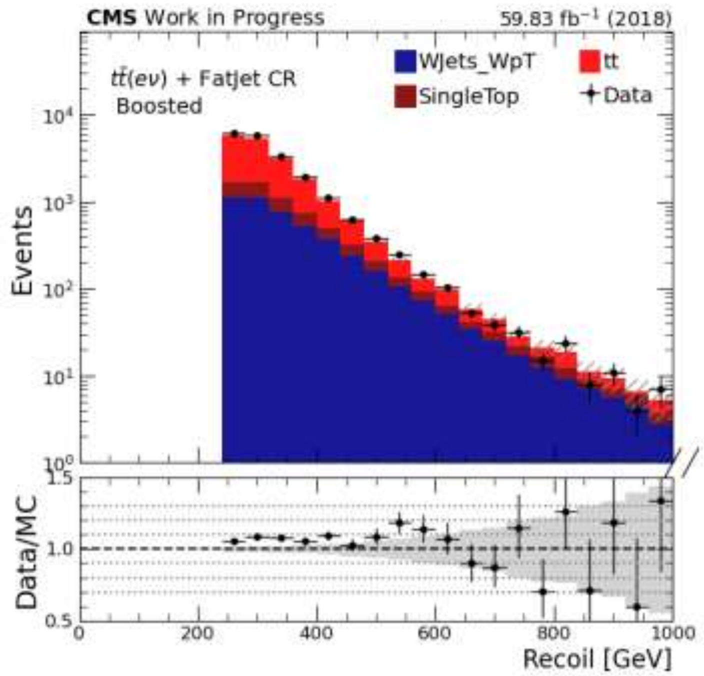


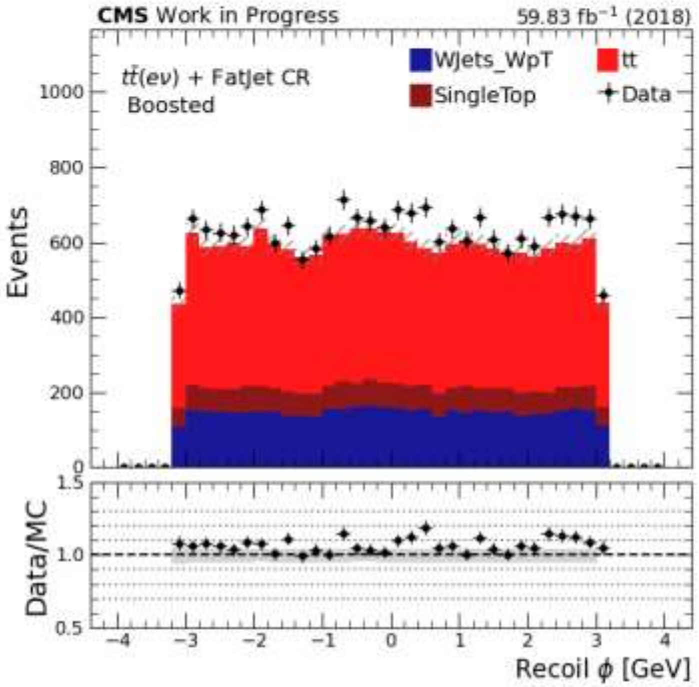


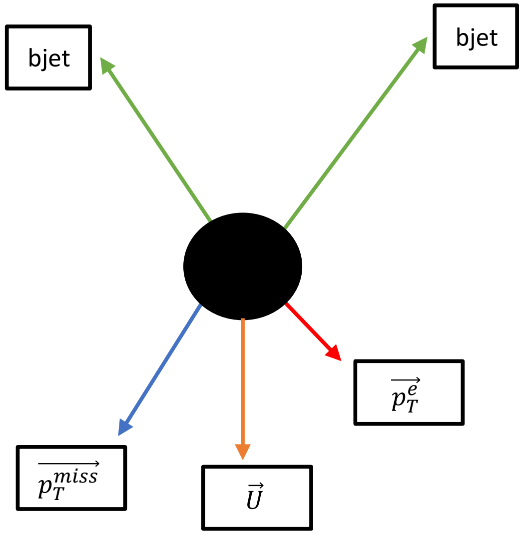
- Another important parameter in the analysis is Missing Transverse Energy.
- As expected, MET has smooth variation over the momentum ranges and is almost uniform across the ϕ direction

Kinematic Plots: Recoil

$$\vec{U} = \overrightarrow{p_T^{miss}} + \overrightarrow{p_T^{e}}$$

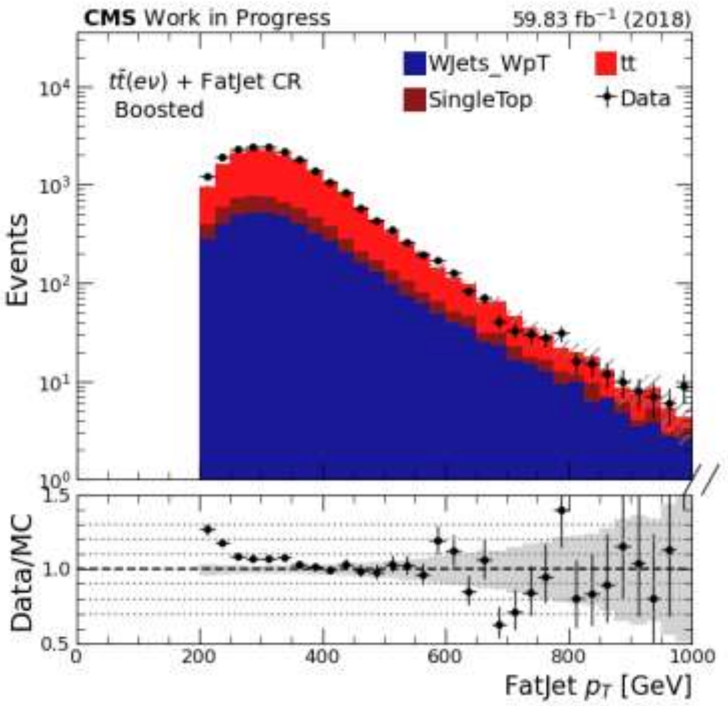


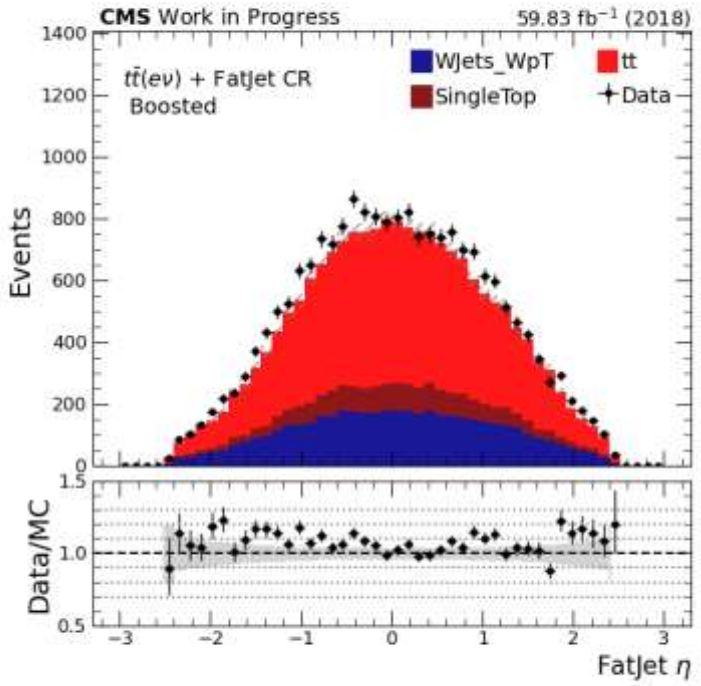




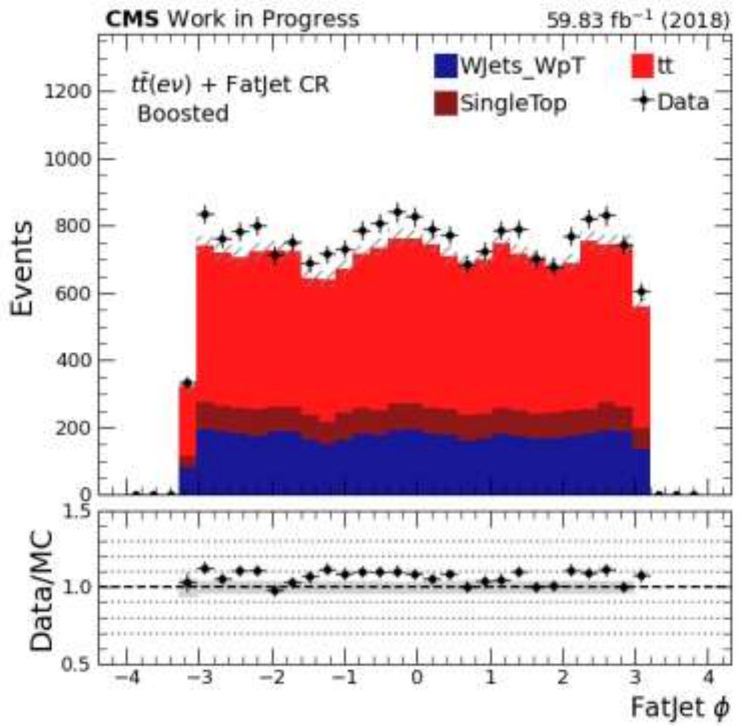
- Similar to MET, Recoil shows a smooth variation over the momentum ranges and is almost uniform across the ϕ direction.
- The Recoil > 250 GeV cut is clearly visible in the Recoil vs Events plot.

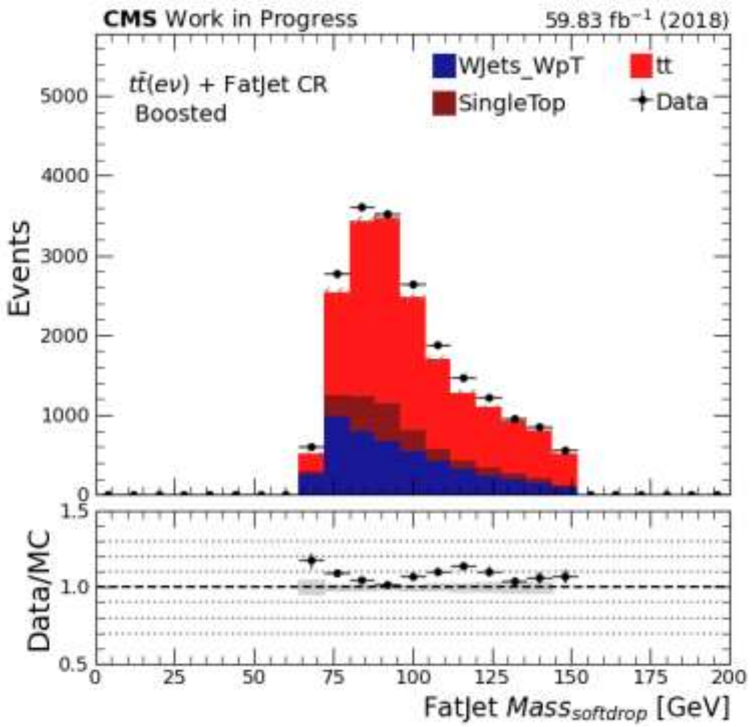
Kinematic Plots: Fatjets (ak8 jets)





Kinematic Plots: Fatjets (ak8 jets)





- Fatjet is a probe of the Higgs boson in the signal final state. The plots show a mass peak below 125 GeV (Higgs boson mass). So, it is safe to say that the majority of contributions from the top background stay below the Higgs mass.
- The mass shown in the plots is the soft-drop mass, which is the mass of the jet obtained from a soft-drop clustering algorithm.

Conclusion

- Top(e) - boosted control region was studied successfully.
- The plots in the previous slides show the contribution of various processes to the final state $\mathrm{H}(\bar{\mathrm{b}}\mathrm{b}) +$ large $\mathrm{p}_{\mathrm{T}}^{\mathrm{miss}}$.
- As expected, $t\bar{t}$, Single top and W+Jets are the major contributors to the background, in that order.
- Estimating one control region is a small step forward to a full analysis, which is beyond the scope of this thesis. Nevertheless, the study of this single CR gave a great insight into the nature of particle detection and the statistical estimation of particles in a full analysis.

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Thank you for your attention.

From iSpyGL , CERN open data

Backup Slides

Selections in Signal Region and Control Region

Resolved

Signal Region	Top μ Control Region (single muon)
MET Trigger	MET Trigger
MET Filter	MET Filter
$p_T^{miss} > 200\ GeV$	$p_T^{miss} > 50\ GeV$ and $Recoil > 200\ GeV$
No Leptons	One Muon (No other Lepton)
Leading Jet $p_T > 50\ GeV$	Leading Jet $p_T > 50\ GeV$
Subleading Jet $p_T > 30\ GeV$	Subleading Jet $p_T > 30\ GeV$
Dijet $p_T > 100\ GeV$	Dijet $p_T > 100\ GeV$
Dijet mass between 100 GeV to 150 GeV	Dijet mass between 100 GeV to 150 GeV
Additional Jets ≤ 2	Additional Jets > 1

Selections in Signal Region and Control Region

Resolved

Signal Region	Top μ Control Region (single muon)	
MET Trigger	MET Trigger	Same
MET Filter	MET Filter	Same
$p_T^{miss} > 200\ GeV$	$p_T^{miss} > 50\ GeV$ and $Recoil > 200\ GeV$	Different
No Leptons	One Muon (No other Lepton)	Different
Leading Jet $p_T > 50\ GeV$	Leading Jet $p_T > 50\ GeV$	Same
Subleading Jet $p_T > 30\ GeV$	Subleading Jet $p_T > 30\ GeV$	Same
Dijet $p_T\ > 100\ GeV$	Dijet $p_T\ > 100\ GeV$	Same
Dijet mass between 100 GeV to 150 GeV	Dijet mass between 100 GeV to 150 GeV	Same
Additional Jets ≤ 2	Additional Jets > 1	Different

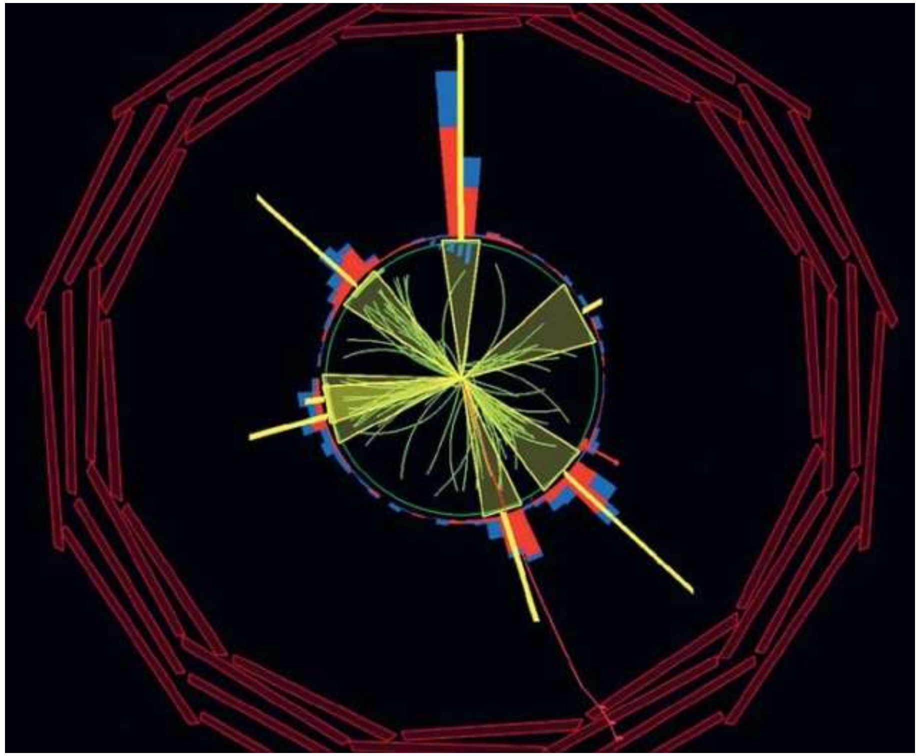
MET and Recoil criteria

- MET cuts to avoid QCD
  - Recoil

$$\mathrm{M}ET\ or\ p_T^{miss} = -\sum \overrightarrow{p_T}$$

$$\text{MET or } p_T^{miss} > 50\ GeV$$

This cut ensures that we remove the majority of QCD events



https://cerncourier.com/a/a-watershed-the-emergence-of-qcd/

QCD Multijet events have a low p_T vector sum

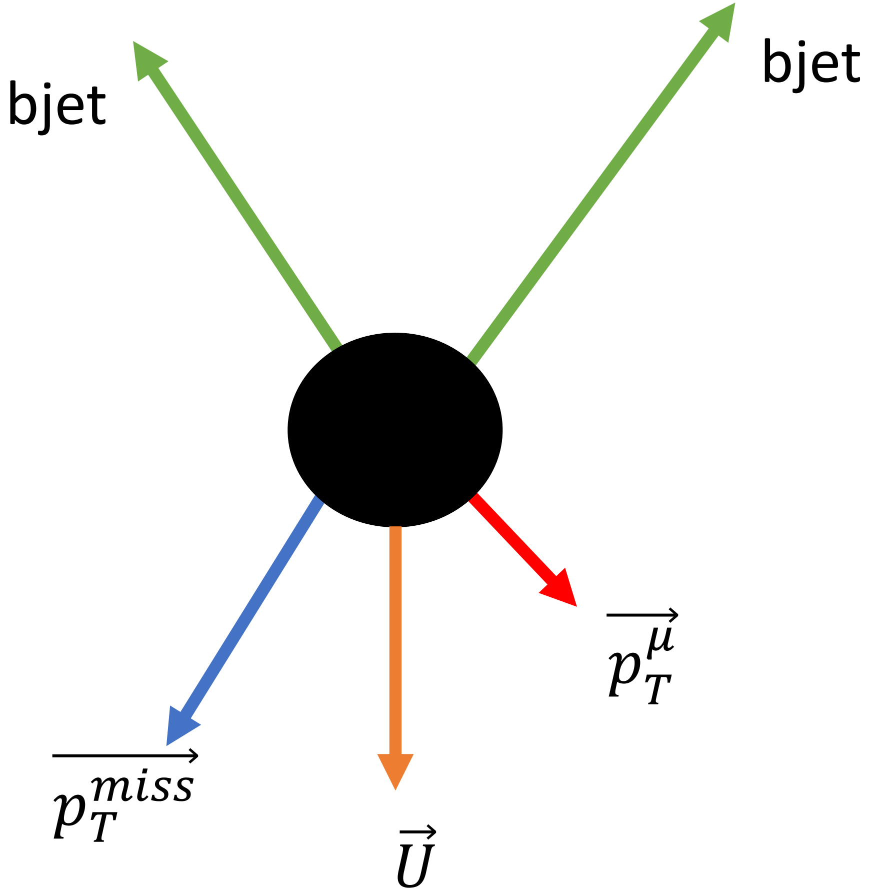
MET and Recoil criteria

- MET cuts to avoid QCD

- **Recoil**

$$\vec{U} = \overrightarrow{p_T^{miss}} + \overrightarrow{p_T^{\mu}}$$

- To mimic the effect of MET in the signal region, we define recoil which is the 2D vector sum of MET and transverse momentum of the chosen muon.



p_T criteria and mass criteria

- Leading b-Tagged Jet $p_T > 50\ GeV$
- Subleading b-Tagged Jet $p_T > 30\ GeV$

- Dijet $p_T > 100\ GeV$
- Dijet = Leading Jet + Subleading Jet

To ensure a balanced contribution from both the jets (greater angle between Higgs line of travel and b jets)

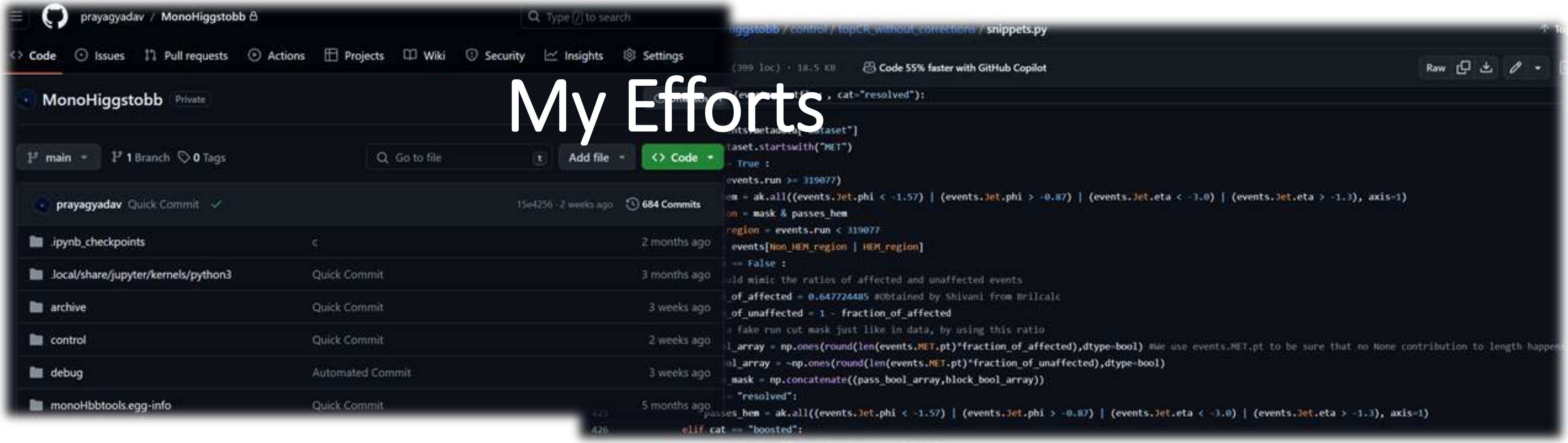
- Dijet mass between 100 GeV to 150 GeV

To get a better probability that the dijet originates from a Higgs candidate with mass ~ 125 GeV

My Efforts

- Extensively used the COFFEA (Columnar Object Framework For Effective Analysis) Framework along with various other Python data analysis packages such as Dask, NumPy, SciPy, etc.
- Preliminary development done locally in a server in lab, after which scaled to high throughput compute farms in University of Wisconsin, Madison, USA.

My Efforts



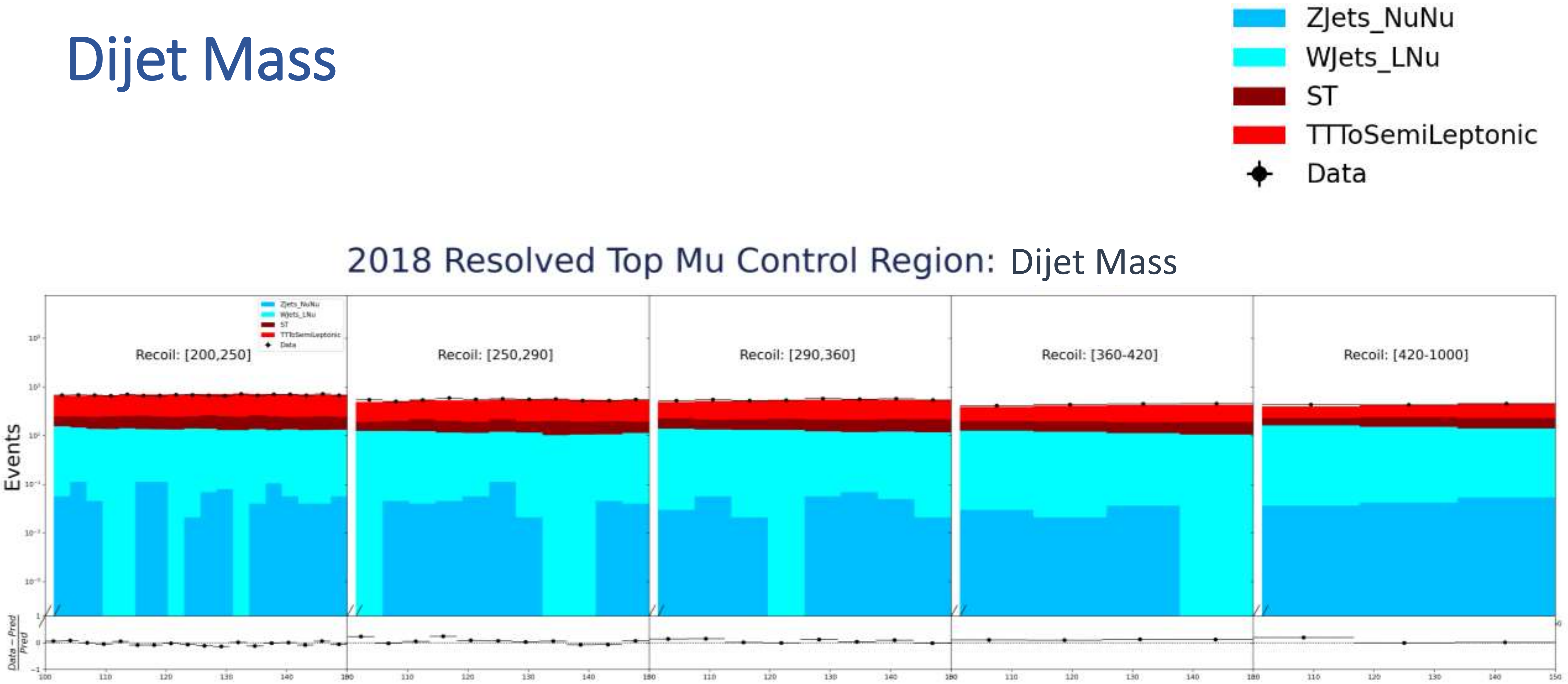
- I have performed the **Resolved Top Muon CR estimation for 2018.**
- More than **30,200 lines of code** excluding blank lines written to get to the final optimized size of less than 3000 lines.
- Almost **22 Terabytes** of samples were processed multiple times.
- Hours of development and processing in compute farms.

Plots

Top μ Resolved jets

Top single muon

Dijet Mass



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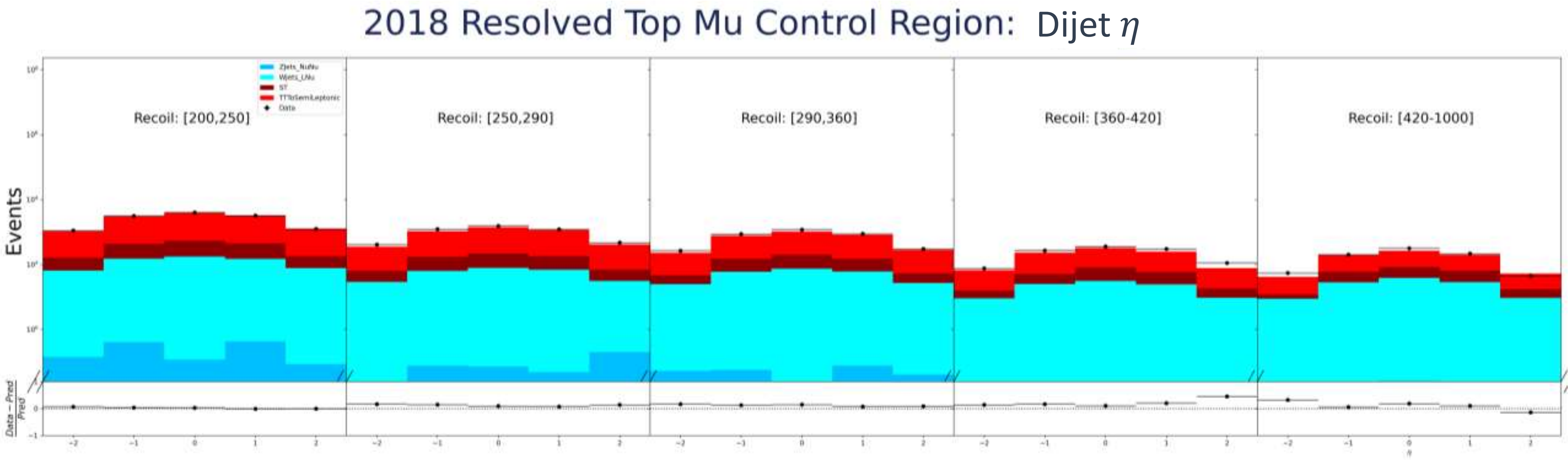
Dijet η

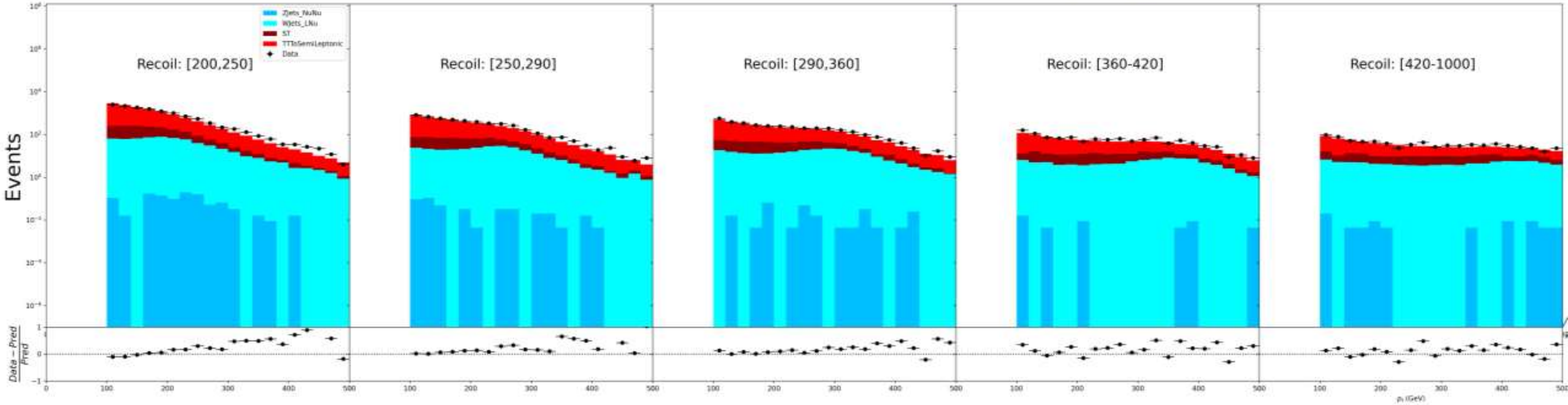

ZJets_NuNu
WJets_LNu
ST
TTToSemiLeptonic
Data


2018 Resolved Top Mu Control Region: Dijet η
Events
Recoil: [200,250]
Recoil: [250,290]
Recoil: [290,360]
Recoil: [360-420]
Recoil: [420-1000]
Data − Pred / Pred

Dijet p_T

ZJets_NuNu
WJets_LNu
ST
TTToSemiLeptonic
Data

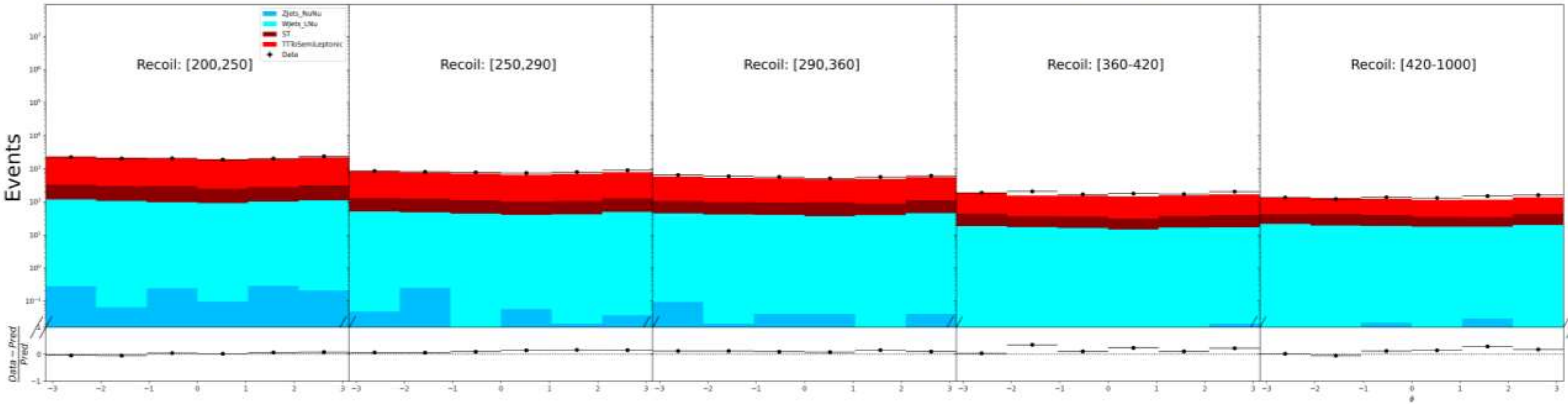
2018 Resolved Top Mu Control Region: Dijet p_T



Dijet ϕ

ZJets_NuNu
WJets_LNu
ST
TTToSemiLeptonic
Data

2018 Resolved Top Mu Control Region: Dijet ϕ



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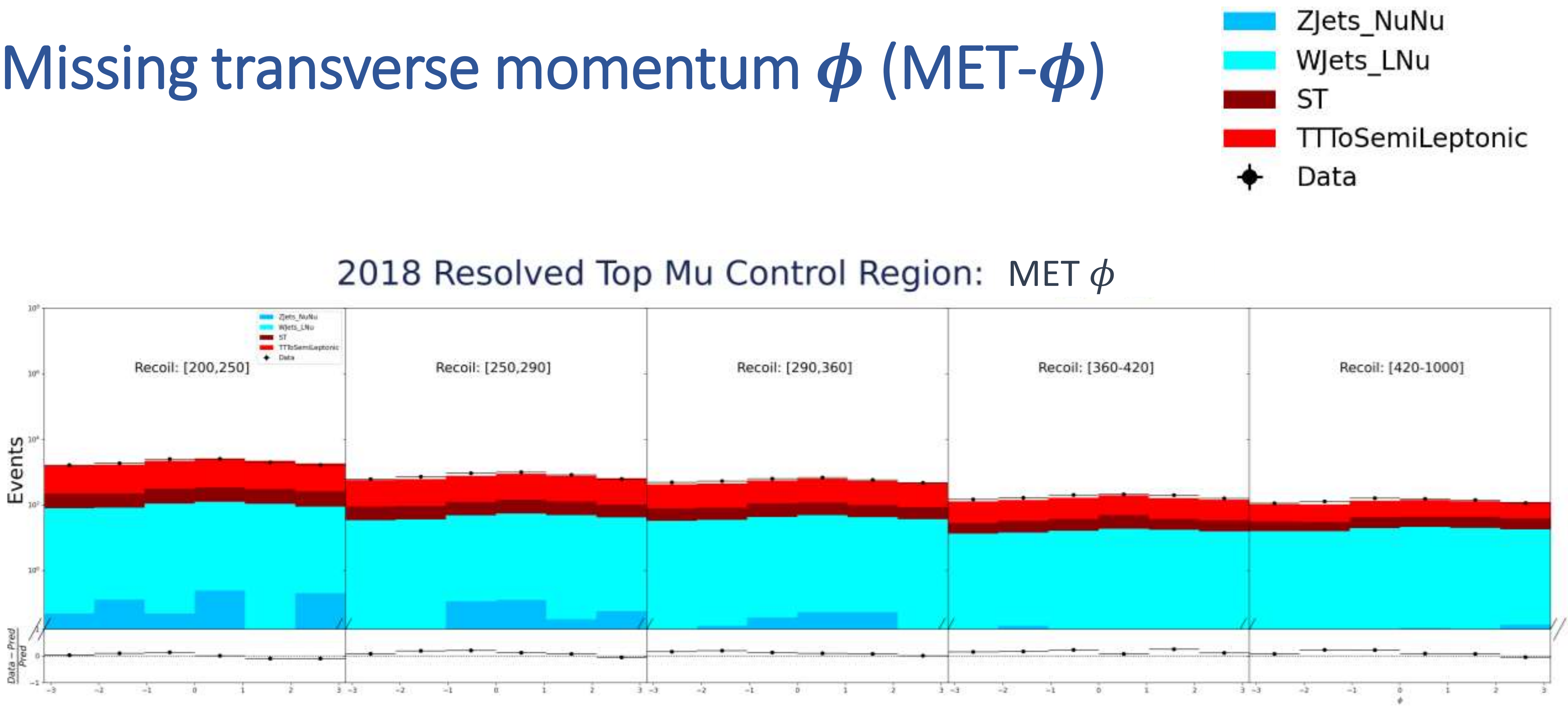
Missing transverse momentum ϕ (MET-ϕ)



Future Aspects

- Next: do single electron CR estimation so that I can estimate top background in SR using both muon and electron CR.

Quick Recap

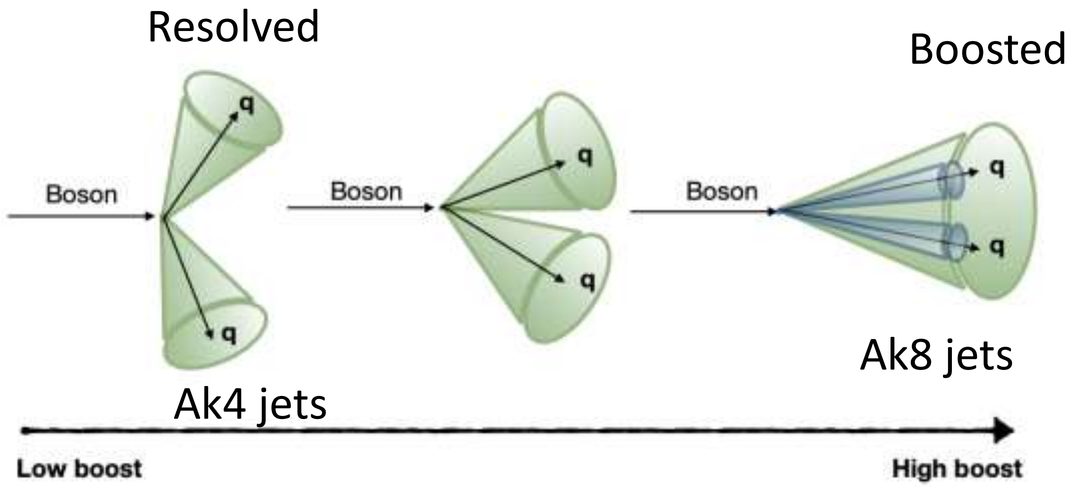
Signal and Background

- The **backgrounds** which **mimic** the dijet and missing transverse energy **signal** are :
  - Z(νν)+jets
  - W+jets
  - Drell-Yan(DY)+jets
  - Top quark pair production (tt)
  - Single top production(ST)
  - The production of the single top quark association with W boson (tW)
  - Diboson (WW, WZ, ZZ)
  - The associated production of a Higgs Boson with vector bosons (WH and ZH)

- These backgrounds are **estimated by** using samples generated by **Monte Carlo simulation** of the reactions.
- In addition to background, the 2HDMa(or closely related ZprimeBaryonic) model is also available as a simulated sample.

Signal and Background

- The signal region can be divided into two regions depending upon the Lorentz **boost** the initial Higgs:
  - Resolved (two AK4Jets)
  - Boosted (one AK8 FatJet)
- These jets are classified using various Jet reconstruction algorithms depending upon their cone radii (ΔR) values.
- These jets are then **tagged** using **a deep learning model** which assigns flavours to the jets.
- **b-jets** are chosen using a "**score**" which determines the efficiency of the selection.



Backgrounds

Z(vv)+jets
W+jets
Drell-Yan(DY)+jets
Top quark pair production (tt)
Single top production(ST)
The production of the single top quark association with W boson (tW)
Diboson (WW, WZ, ZZ)
The associated production of a Higgs Boson with vector bosons (WH and ZH)

Recap

Selections in Signal Region and Control Region

Keep in Mind

The final state
$p_T^{miss} + 2\ bjets$

Orthogonality

Allow no leptons in SR.

Force one or two leptons in CR.

The Basic Philosophy

Keep SR selections and CR selections similar but orthogonal to each other.

Selections in Signal Region and Control Region

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School of Physics

Selections in Signal Region and Control Region

The Basic Philosophy

Keep SR selections and CR selections similar but orthogonal to each other.

Keep in Mind

The final state
$p_T^{miss} + 2\ bjets$

Orthogonality

Allow no leptons in SR.

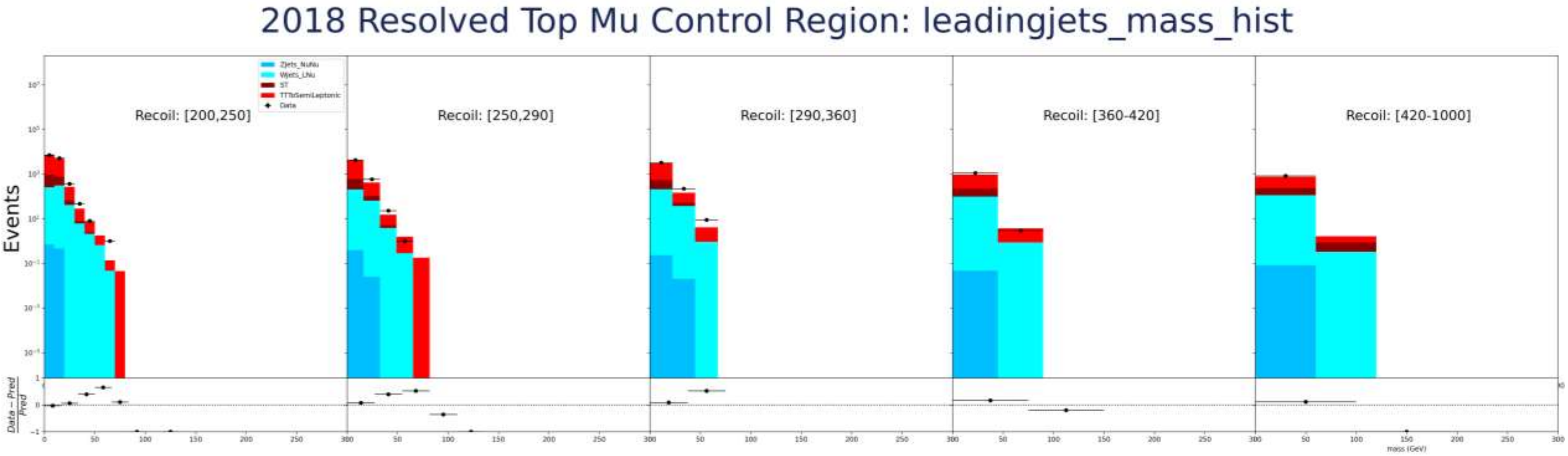
Force one or two leptons in CR.

Event Selections and Object Selections

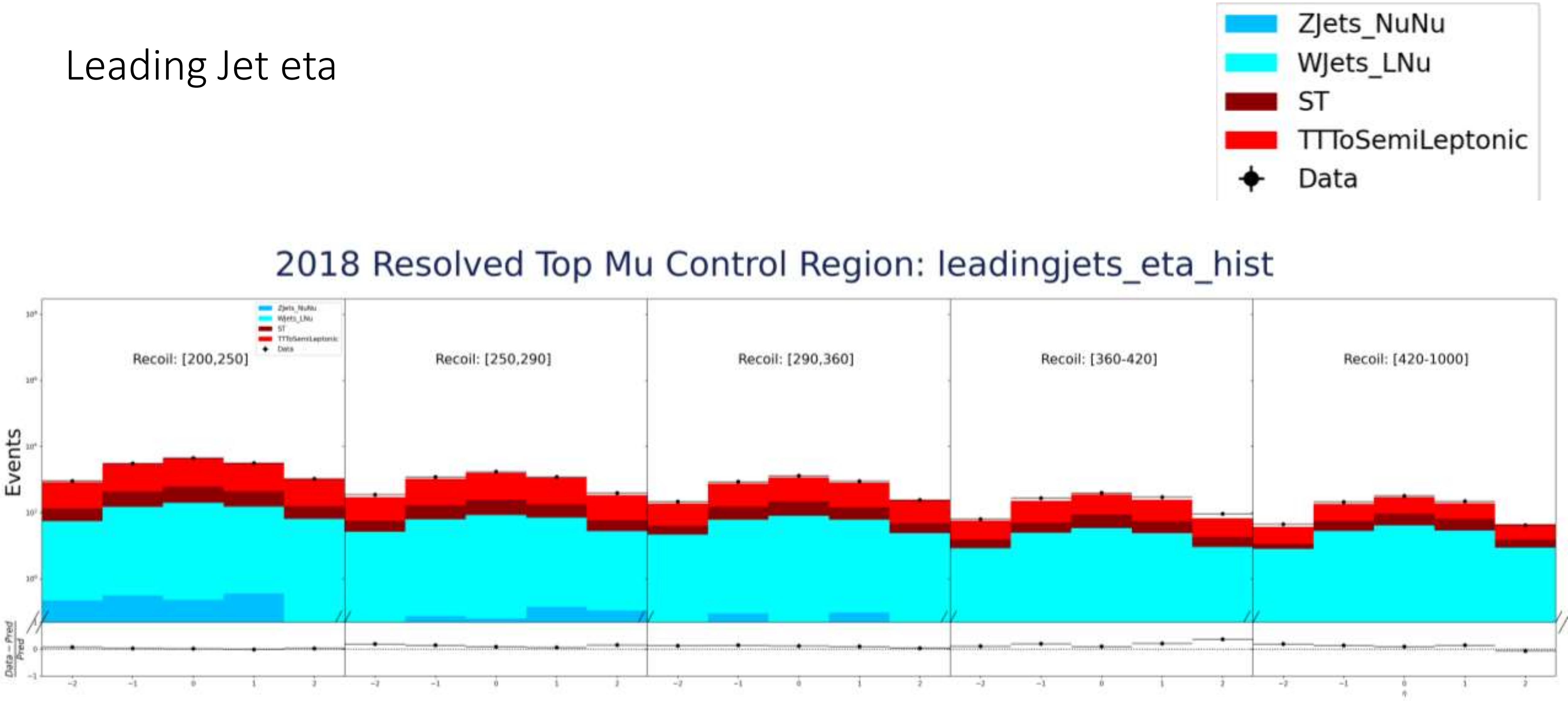
- Various selections are applied to select the most well-suited events from other events or detector noise. These selections are known as **event selections**.

- Objects are the basic analytic units such as particles or jets of particles. Various object selections are applied to choose the best object candidate with a known level of confidence and efficiency. These selections are known as **object selections**.

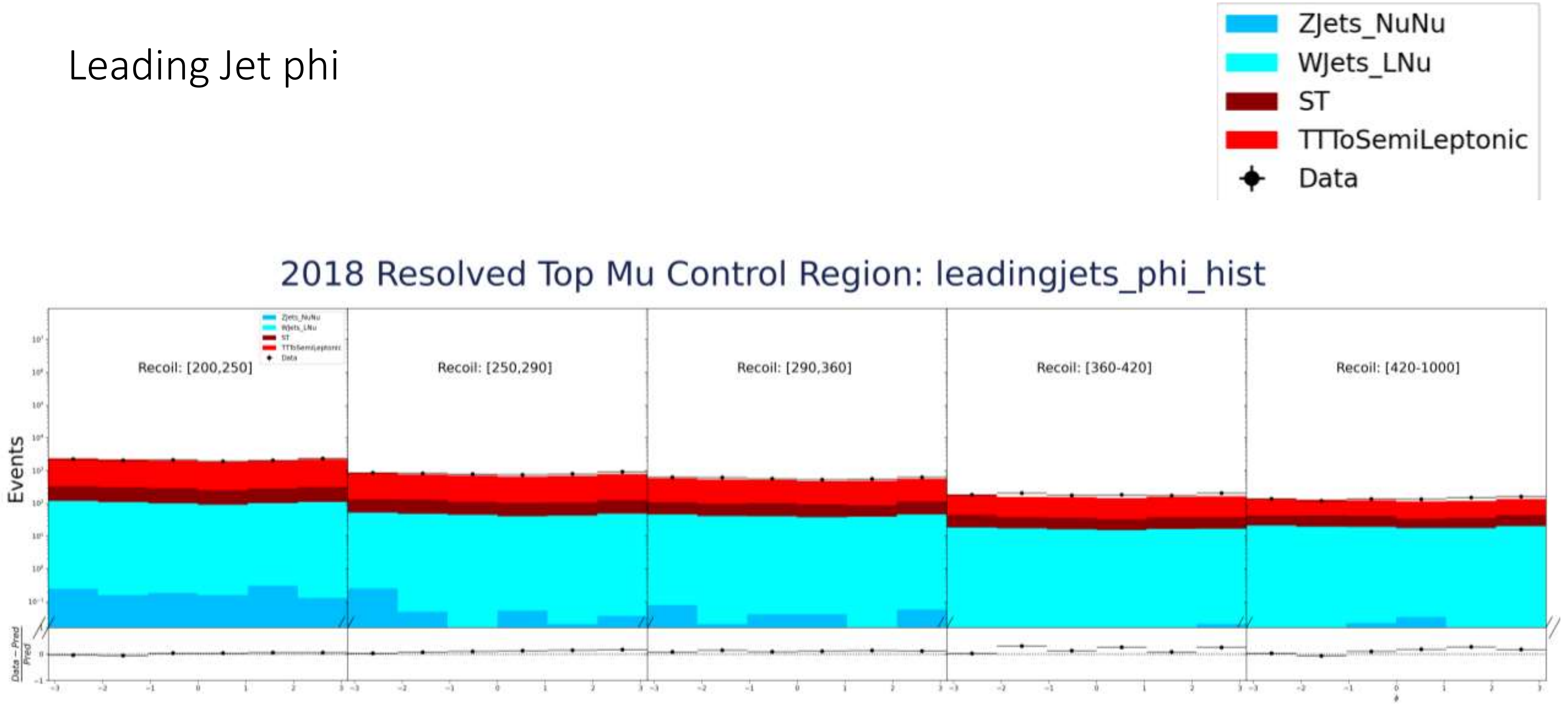
Leading Jet mass



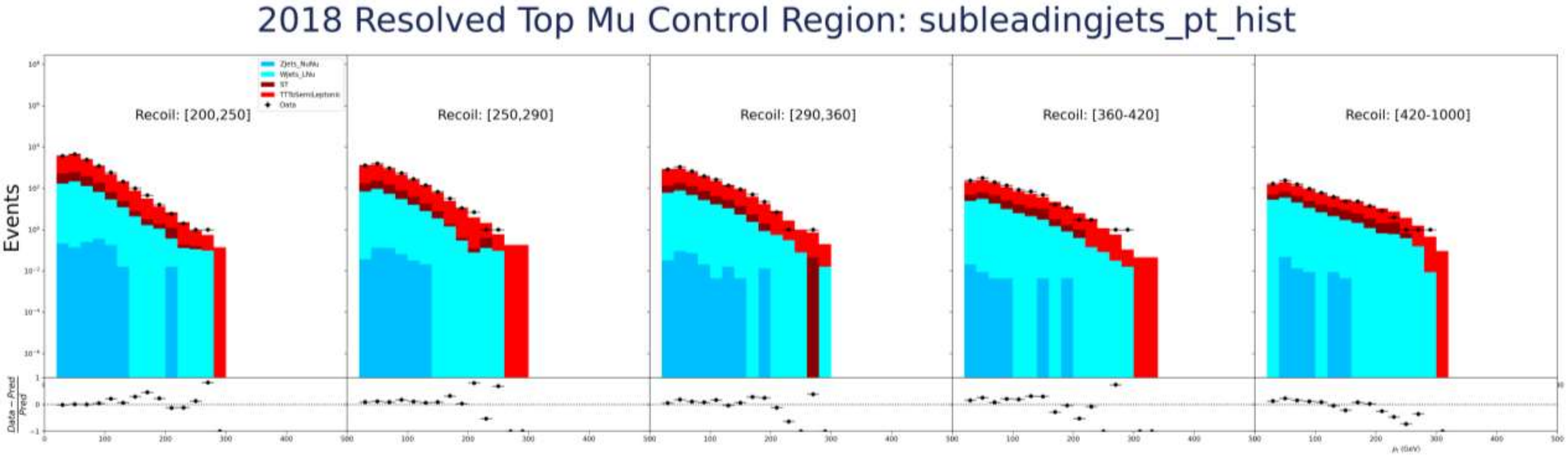
Leading Jet eta



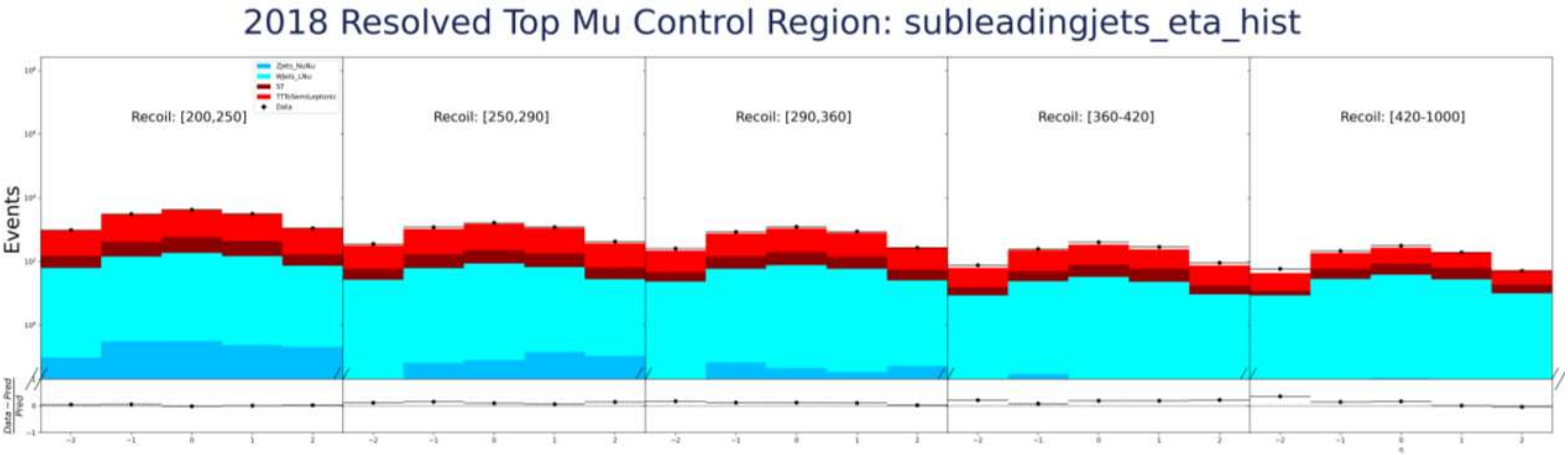
Leading Jet phi



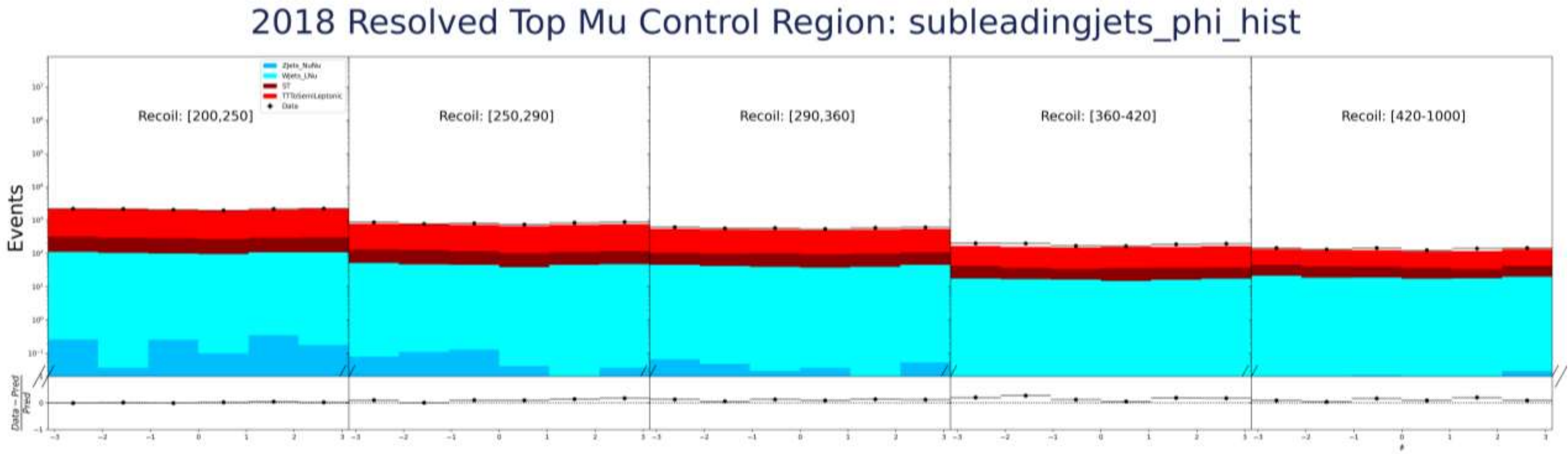
Subleading Jet pt



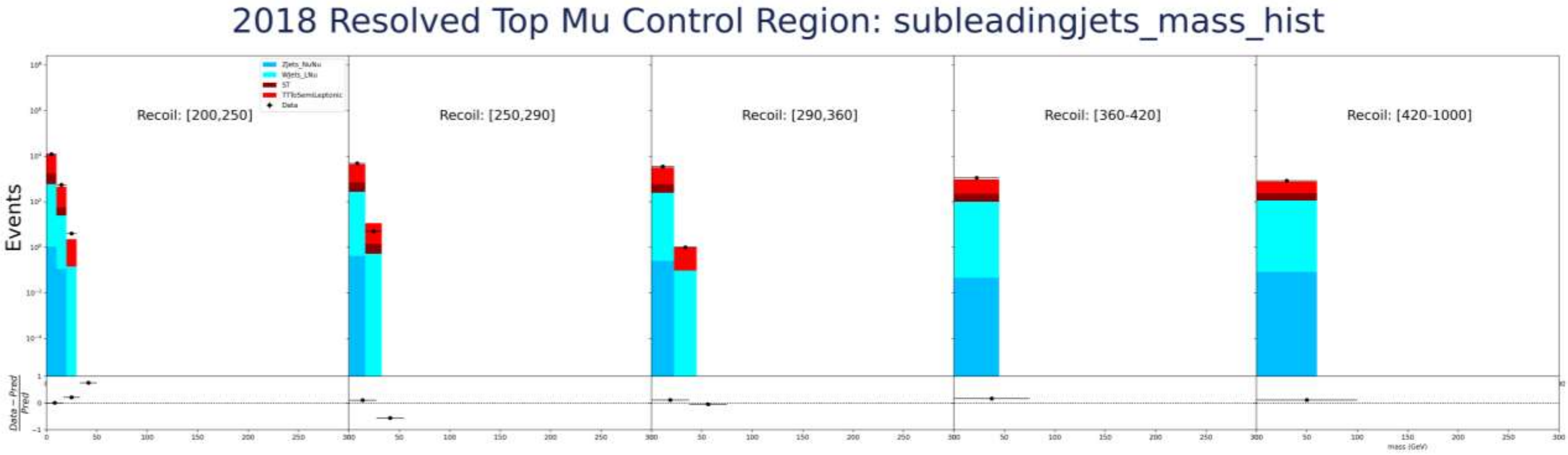
Subleading Jet eta



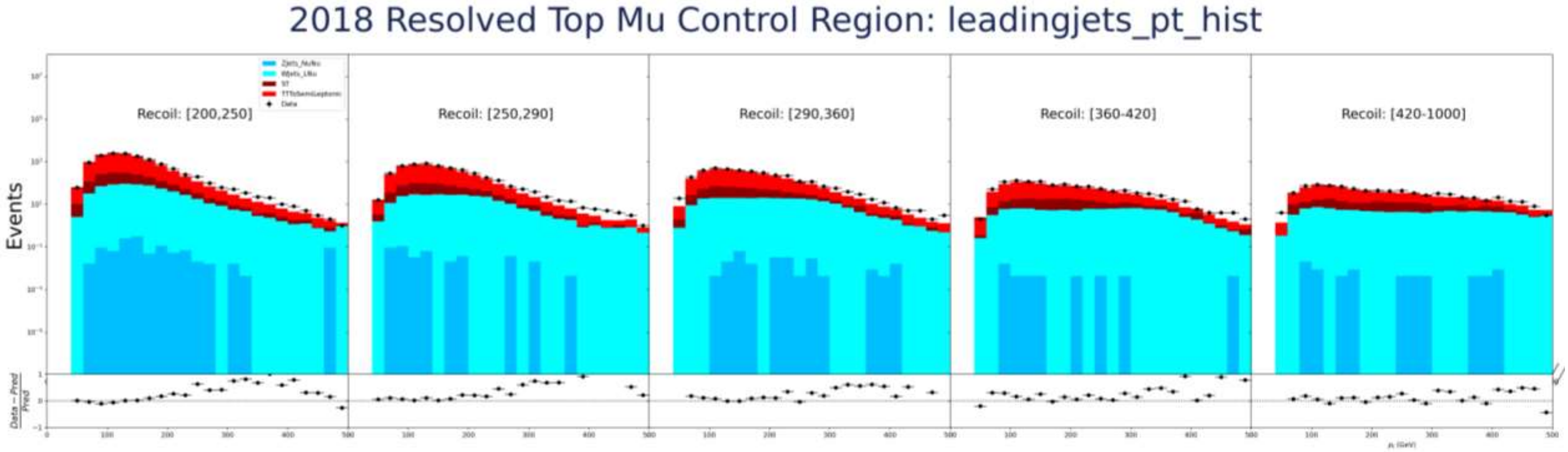
Subleading Jet phi



Subleading Jet mass

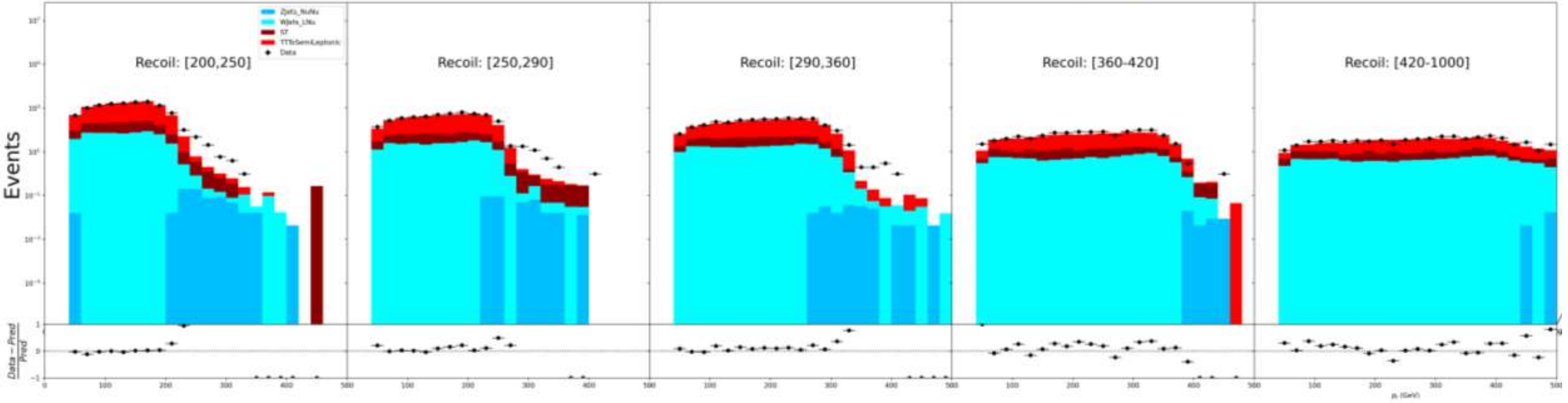


Leading Jet pt



Missing transverse momentum (p_T^{miss})

2018 Resolved Top Mu Control Region: p_T^{miss}



What is Dark matter? interact only via gravitational interactions

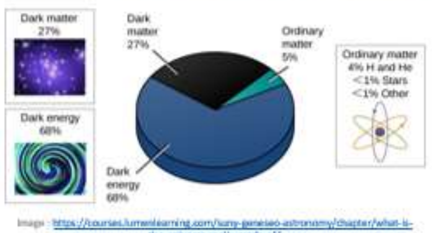
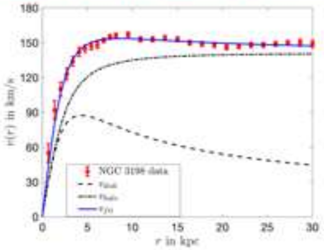
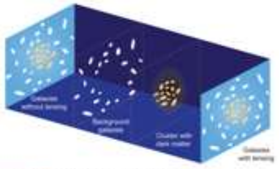


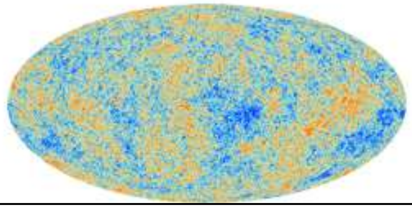
Image : https://courses.lumenlearning.com/suny-geneseo-astronomy/chapter/what-is-the-universe-really-made-of/



Venkataramani, Shankar & Newell, Alan. (2021). Pattern dark matter and galaxy scaling relations.



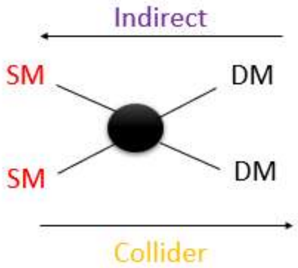
This Photo by NASA/SSU/Aurore Simonnet is licensed under CC BY-SA-NC



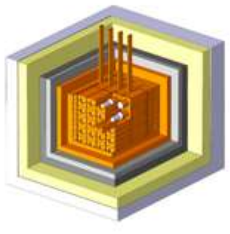
Evidences

- Astronomical Evidences
  - Rotational Curves of Spiral Galaxies
  - Gravitational Lensing
- Cosmological Evidences
  - CMB

Search for Dark Matter

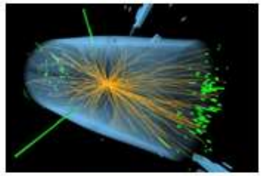


XENON Experiment

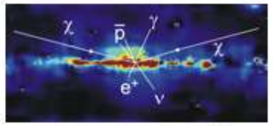


DAMA

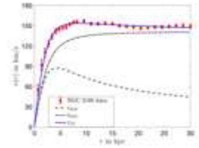
https://dama.web.roma



Collider searches at CMS



Gamma ray observations from the galaxy



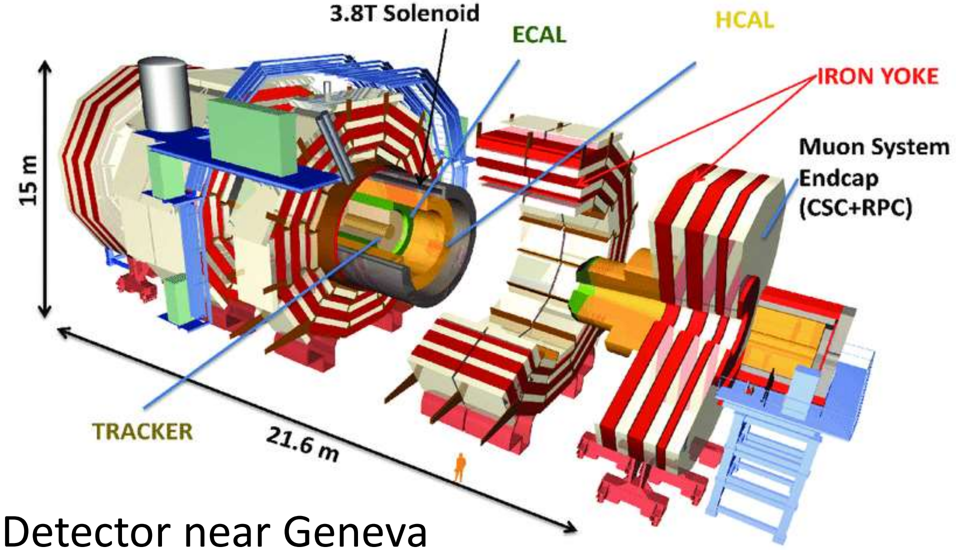
Rotation curves of galaxies

Analysis tools and Strategy

- Analysis tools like COFFEA are used. Various other tools in the python ecosystem are routinely employed.
- COFFEA is a **columnar analysis** tools which enables us to deploy **scalable** and **parallel** computing ready code for High Energy Physics.
- Run 2 data (2018,2017) of CMS is retrieved from the different CERN data tiers.
- The data is processed in various **compute clusters** available at the University of Wisconsin, Madison, USA.

Awkward Array, uproot, VECTOR, Hist, NumPy, matplotlib, SciPy, pandas, scikit learn, PyTorch, TensorFlow, jupyter

The COFFEA Framework



CMS Detector near Geneva

School of Physics

Recap

Analysis tools and Strategy

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Awkward Array uproot VECTOR Hist

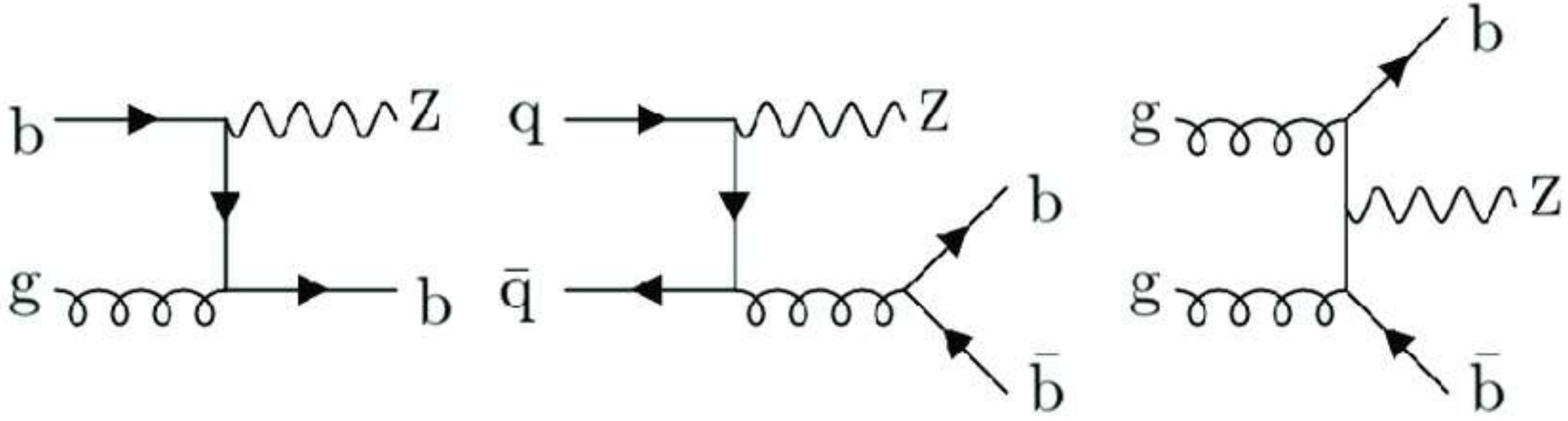
NumPy matplotlib SciPy pandas

scikit learn PyTorch TensorFlow jupyter

The COFFEA Framework

Major Backgrounds: Z+jets Control Region

- The Z+jets is the second major background to the final state.



the Z further decays
$Z \to \nu\nu$

- This background too is estimated by defining a control region which is designed to tag such a background.

https://www.researchgate.net/figure/Examples-of-Feynman-diagrams-for-Z-1-b-jet-left-and-Z-2-b-jets-middle-and-right_fig1_357171275

Major Backgrounds: Zjets Control Region

- This control is called the Zjets Control region and is further subdivided into four categories.

Jet angular separation

Z (e^+e^-) Resolved jets **Zjets di-electron**	**Z ($\mu^+\mu^-$) Resolved jets** **Zjets di-muon**
Z (e^+e^-) Boosted jets **Zjets di-electron**	**Z ($\mu^+\mu^-$) Boosted jets** **Zjets di-muon**

Lepton variety

Avoiding Detection issues

- MET Filters
  - HEM Veto

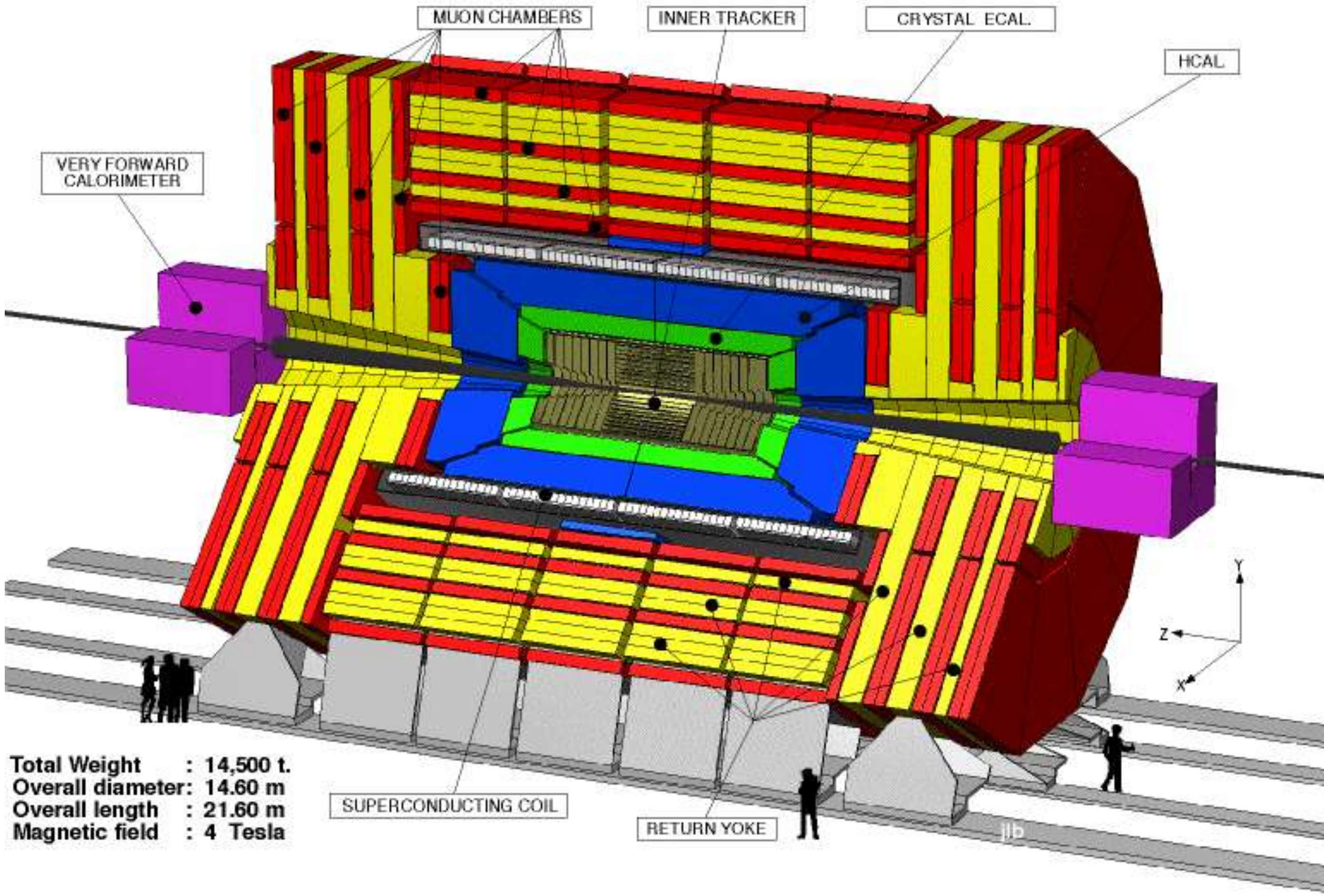
Recommended filters to remove detector noise and imperfections

```
Flag.goodVertices
Flag.globalTightHalo2016Filter
Flag.globalSuperTightHalo2016Filter
Flag.HBHENoiseFilter
Flag.HBHENoiseIsoFilter
Flag.eeBadScFilter
Flag.EcalDeadCellTriggerPrimitiveFilter
Flag.BadPFMuonFilter
Flag.BadPFMuonDzFilter
Flag.ecalBadCalibFilter
```

Avoiding Detection issues

Hadronic Calorimeter Endcaps minus (HEM) issue

- MET Filters
- **HEM Veto**

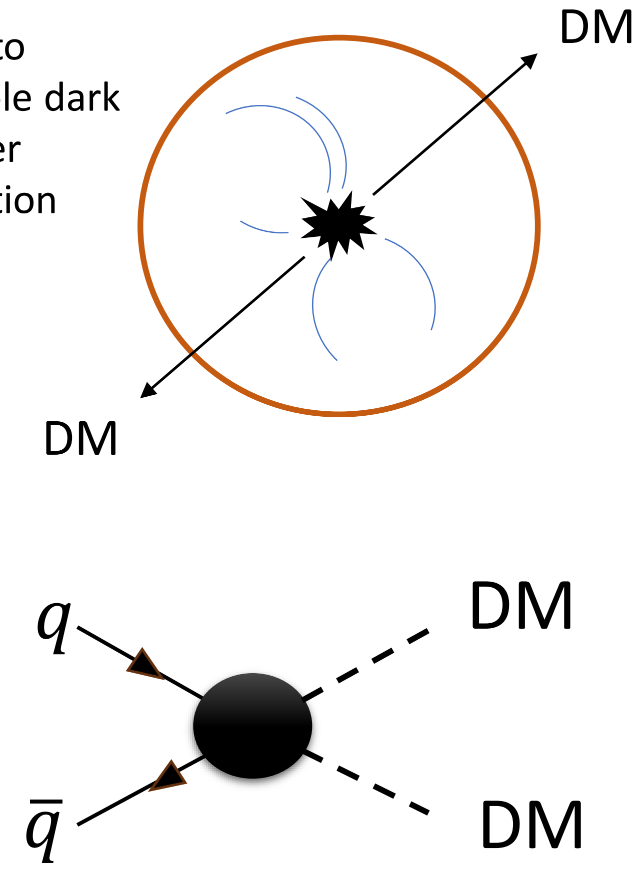


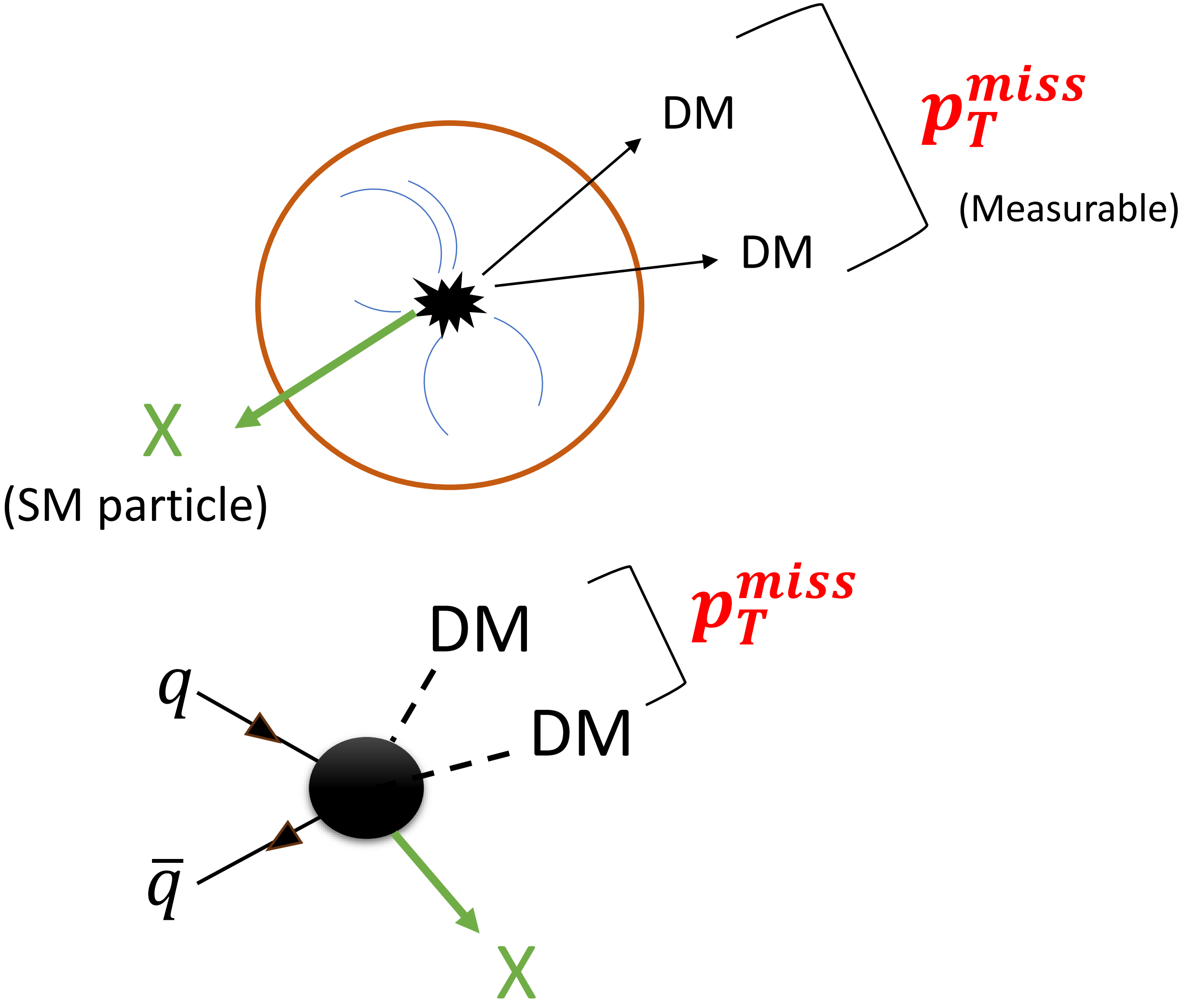
http://www.phys.ufl.edu/hee/cms/cms.html

- The endcaps of the hadron calorimeter failed to work in the region defined by $-3 < \eta < -1.3$ and $-1.57 < \phi < -0.87$ during the 2018 data taking period
- This leads to significant error in jet sensitive analyses.
- To mitigate this effect, the all the events which have at least one jet in the specified HEM region are removed from calculations.

Collider Search: Mono-X Topology

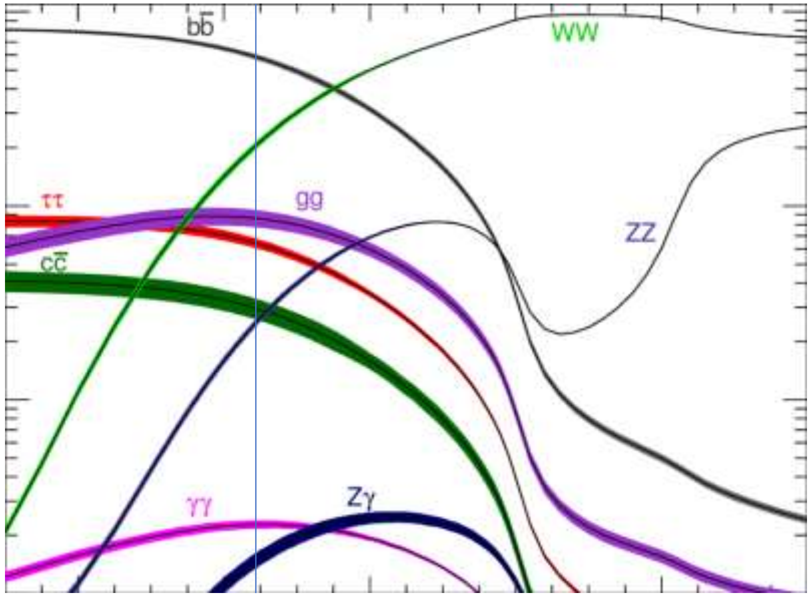
Back to undetectable dark matter production

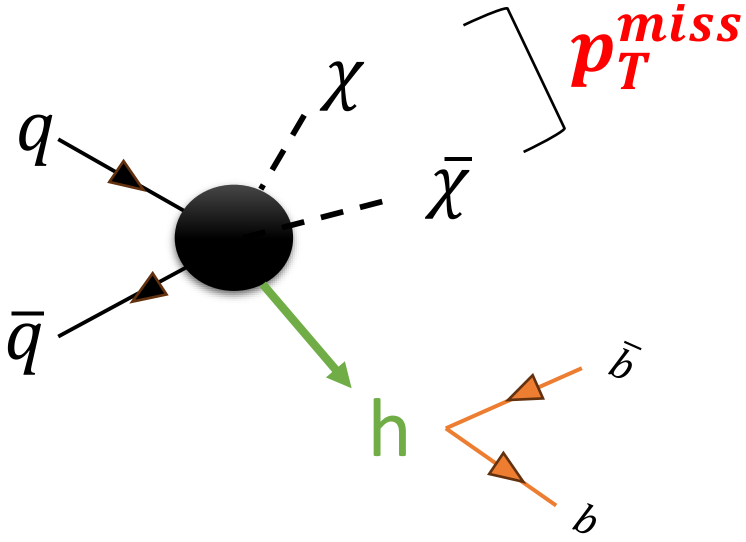




Mono Higgs Searches

1. No Initial State Radiation
2. More closely connected to DM production
3. Signal Signature has a high MET trail which helps to separate the signal from background.





H(125)->bb branching ratio is ~ 57%

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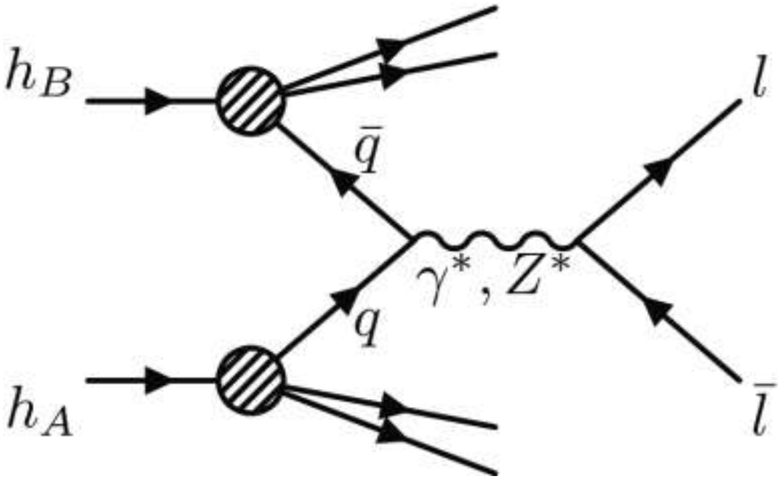
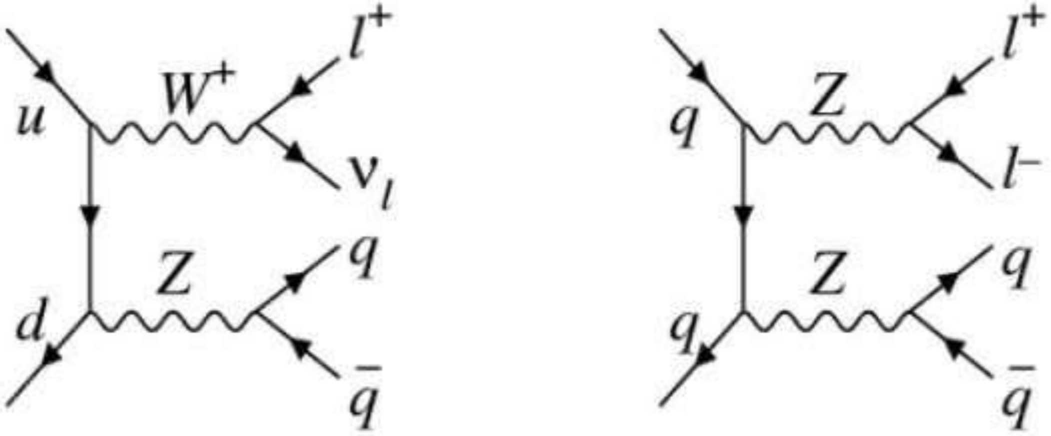
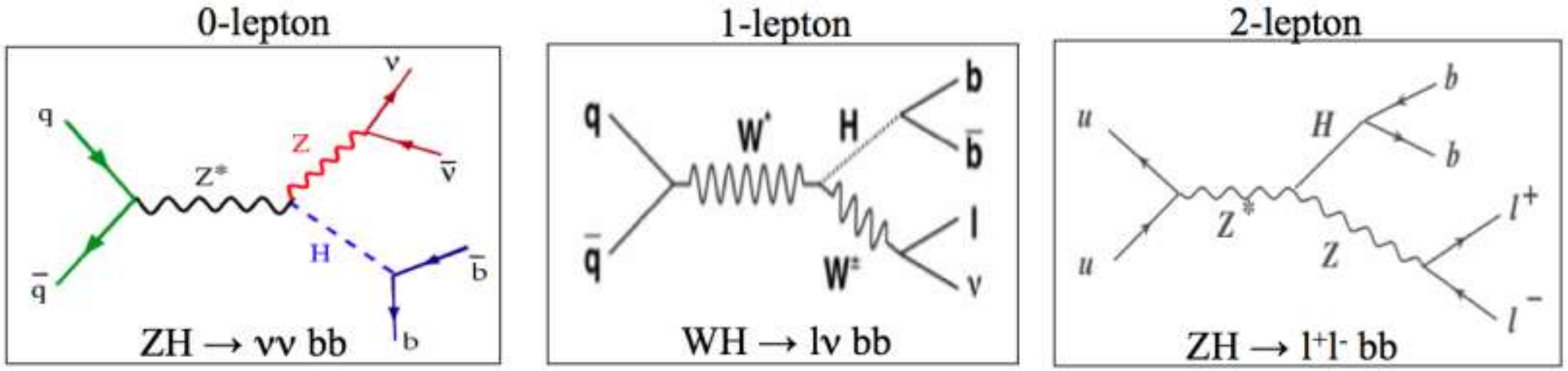
Other backgrounds (continued)



Drell-Yan+Jets

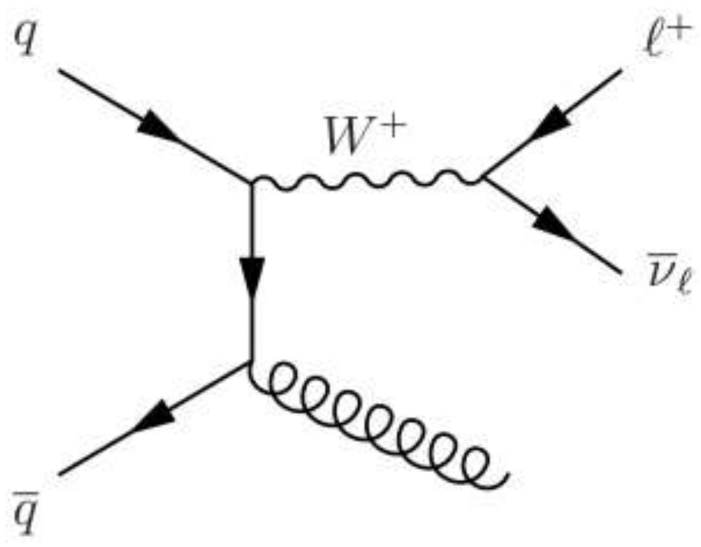


Diboson VV

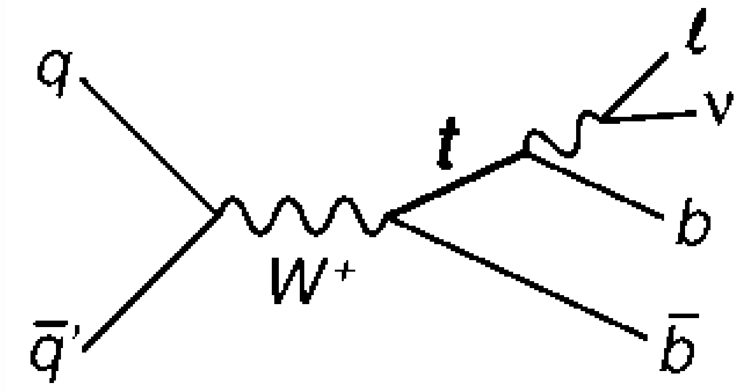


SM-Higgs

Other backgrounds



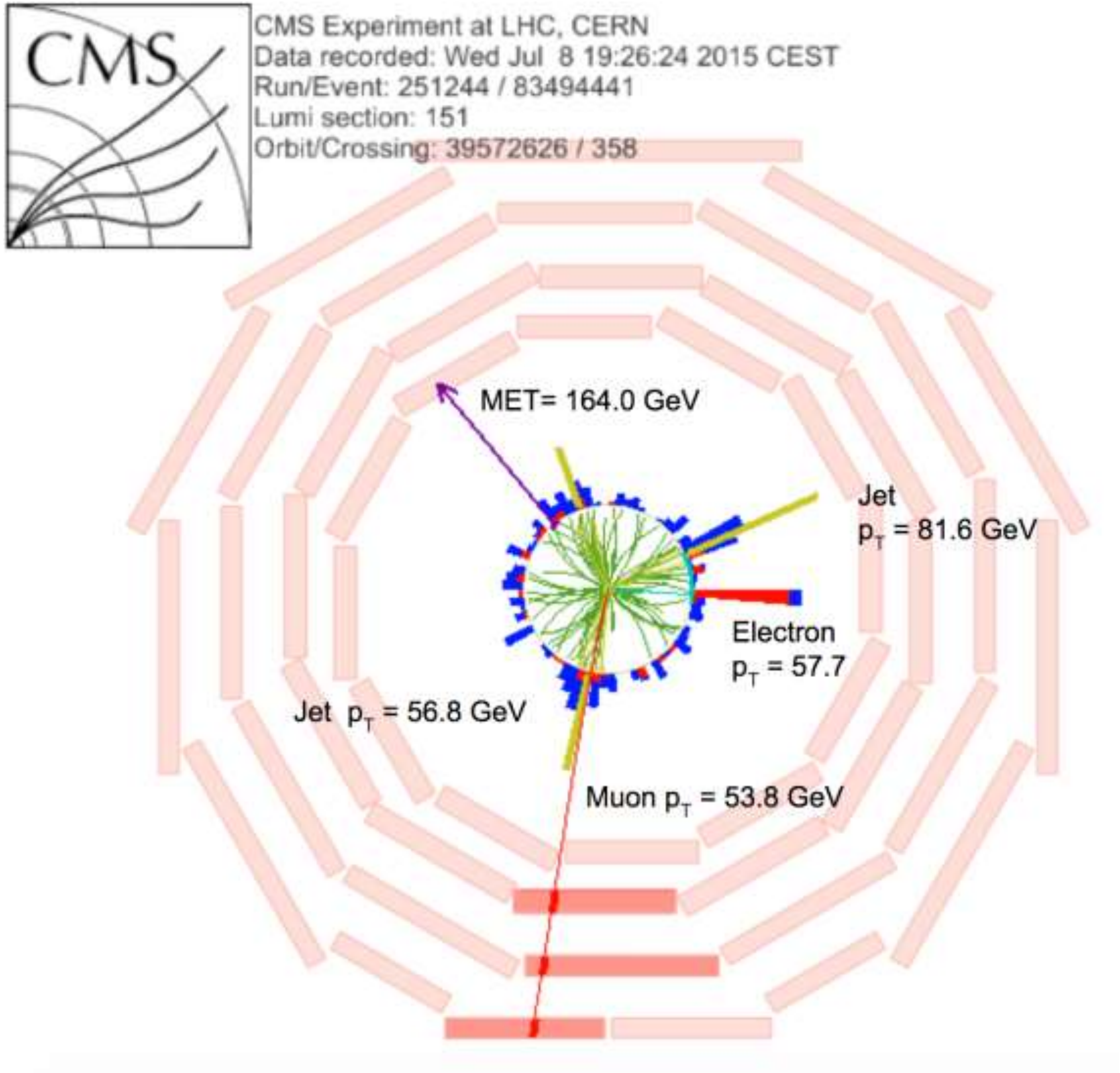
[W+Jets]



[Single Top]

Triggers

- Triggers are fast data acquisition selectors.
- A trigger 'turns on' when a group of physics components are satisfied for a proton-proton collision event.
- For this analysis, we use a High-Level Trigger which is triggered when energies of all the reconstructed MET in an event don't have a muon contribution in them.
- This is done to avoid situations in which we have a muon contribution in MET which we want to probe independently of the MET.



HLT.PFMETNoMu120_PFMHTNoMu120_IDTight

https://cds.cern.ch/record/2712881

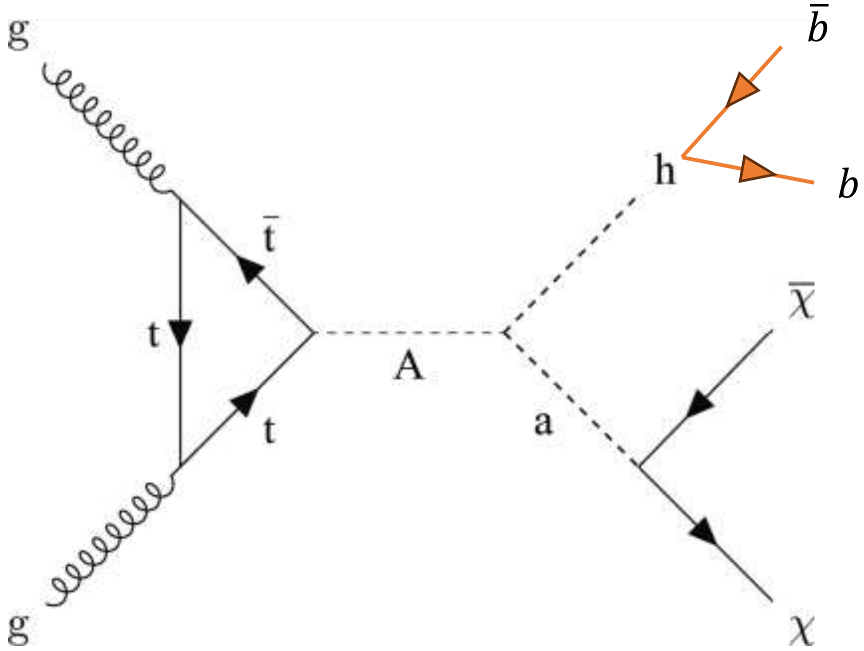
School of Physics

The 2HDMa Model

A supersymmetric model to explain dark matter

- The 2HDM Model proposes **five Higgs** :
  - Two neutral scalars (h and H)
  - Pseudoscalar A and
  - Charged Higgs(H^- and H^+ .)
- The 2HDMa model introduces a new pseudoscalar 'a' which mediates interaction between Dark particles χ and $\bar{\chi}$.

- The Higgs SM 'h' produced can decay through many channels.
- One of these channels is the **Higgs to two b-quarks**.
- These b quarks produce **jets** of particles.
- The Dark matter particles go undetected and lead to a **large missing momentum**.



Final state: $H(\bar{b}b) + p_T^{miss}$

2HDM = Two Higgs Doublet Model

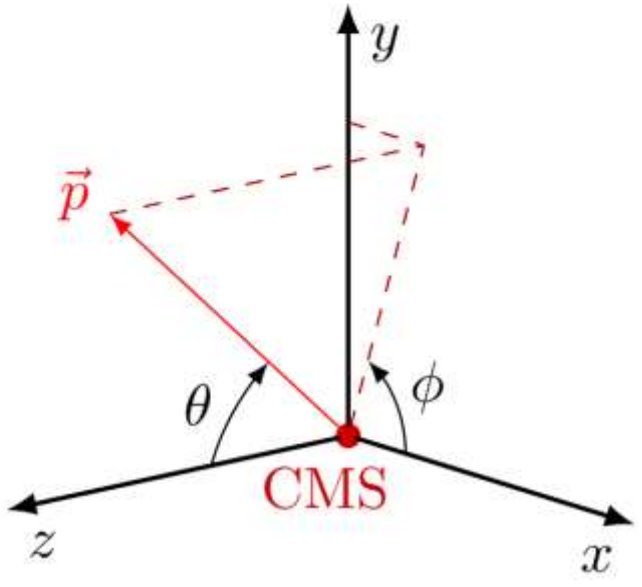
2HDMa = Two Higgs Doublet Model with a pseudoscalar mediator 'a'

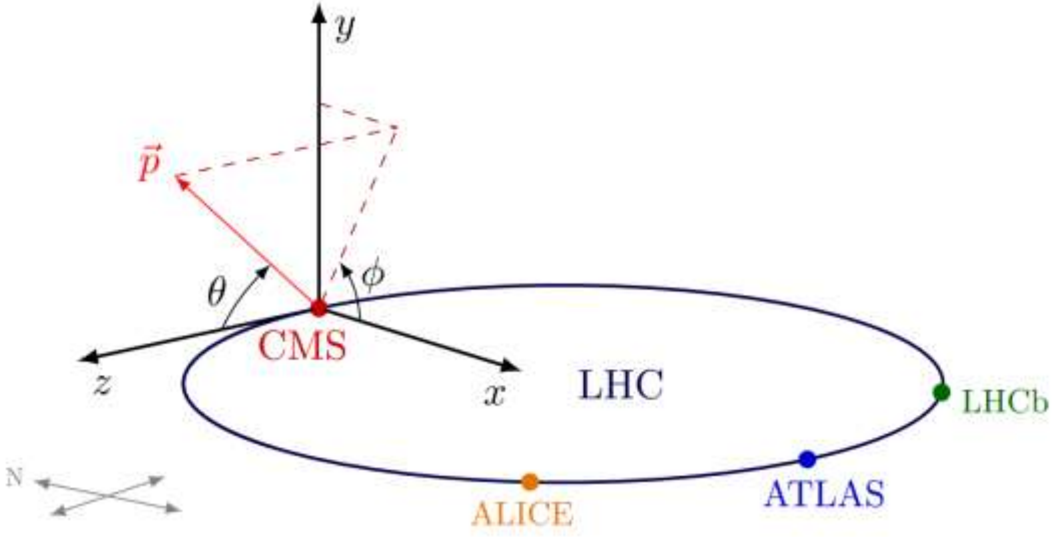
School of Physics

The Coordinate System

- The Interaction point(IP) is the origin of the coordinate system.
- X direction points to the centre of the LHC ring
- Y direction points vertically upwards.
- Z direction points towards the western side of beam axis.
- The positive angle from the x axis is the azimuthal angle ϕ .
- The positive angle from the z axis is the polar angle θ.
- Pseudorapidity is defined as:

$$\eta = -ln\left(tan\left(\frac{\theta}{2}\right)\right)$$

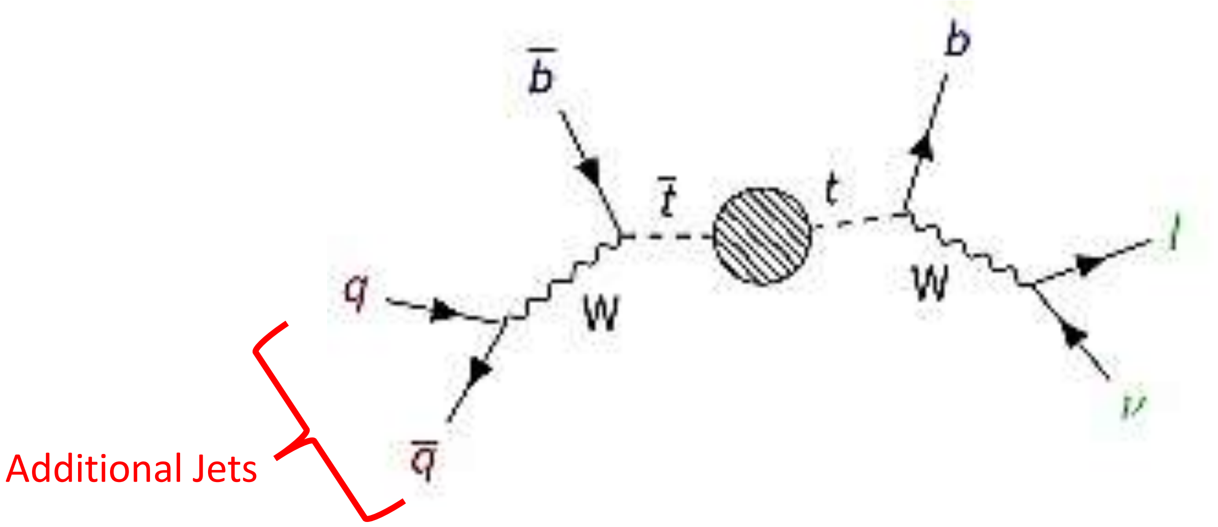




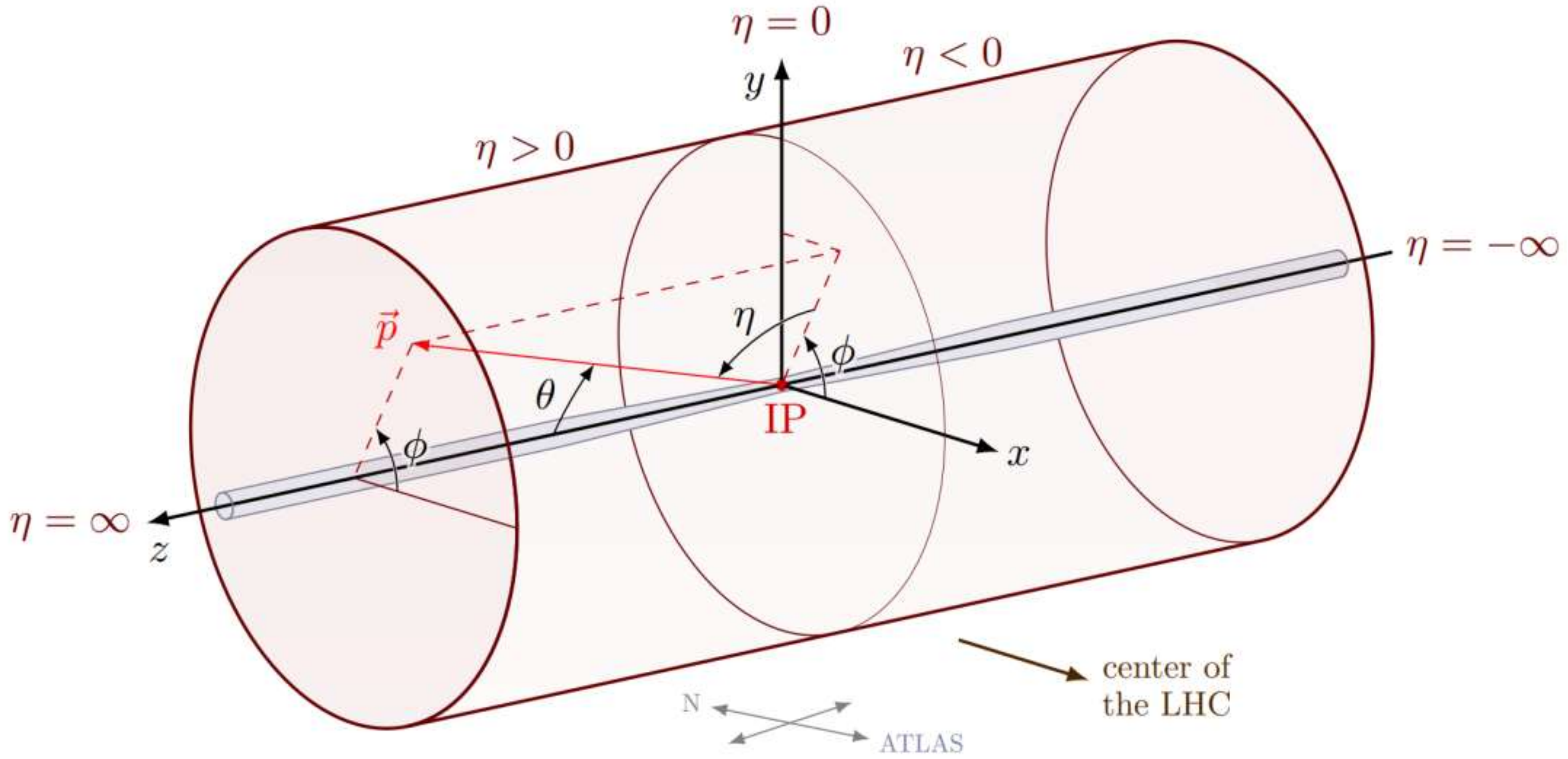
https://tikz.net/axis3d_cms/

Additional jets

- In signal region we allow less than or equal to 2 additional jets other than those required to create the dijet object.
- The topology of the backgrounds show that they tend to have at least one additional jet.
- For this reason we enforce at least one additional jet in the control Region.



The Coordinate System



https://tikz.net/axis3d_cms/

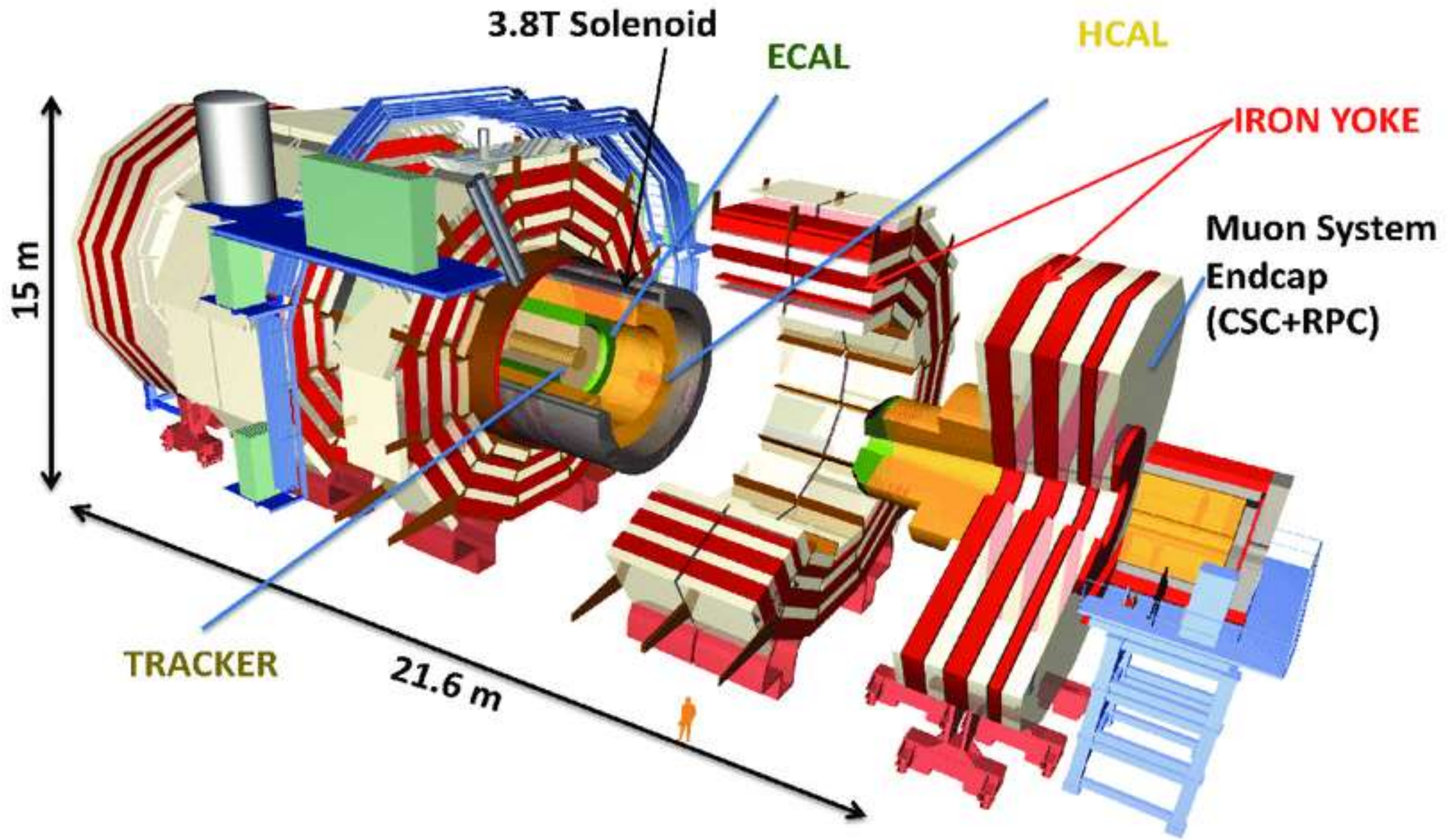
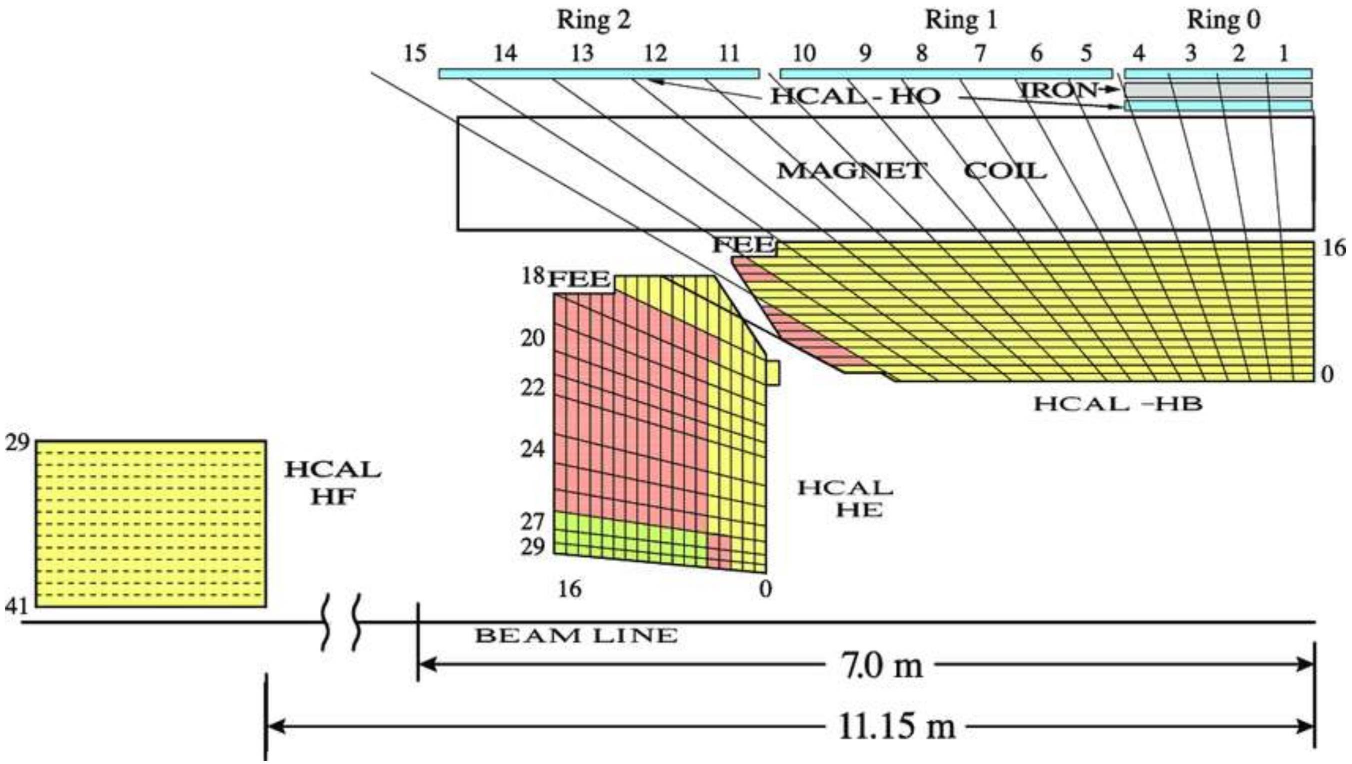


Fig : Schematic Representation of the CMS detector

Focardi, Ettore. (2012). Status of the CMS Detector. Physics Procedia. 37. 119-127.
10.1016/j.phpro.2012.02.363.

Hadronic Calorimeter

- It consist of hadron calorimeter barrel and hadron end caps which are located outside the ECAL.
- The hadron calorimeter barrel is located outside extent of ECAL (R=1.77m) and inner extent of magnetic coil(R=2.95m)
- The outer hadron calorimeter or tail catcher is placed outside the solenoid contemplating barrel calorimeter. Beyond $|\eta| = 3$, the forward calorimeter (HF)is placed at 11.2m from interaction point and a psuedorapidity up to $|\eta|=5.2$



Chatrchyan, S. & Nedelec, Patrick & Sillou, Daniel & Besancon, M. & Chipaux, Remi & Dejardin, M. & Denegri, D. & Descamps, J. & Fabbro, B. & Faure, J.L. & Ferri, Frederick & Ganjour, S. & Gentit, F & Givernaud, A. & Gras, Philippe & Monchenault, G & Jarry, P & Lemaire, M & Locci, E. & Romaniuk, Ryszard. (2010). Performance of the CMS Hadron Calorimeter with Cosmic Ray Muons and LHC Beam Data. Journal of Instrumentation. 5. T03012.

Hadronic Calorimeter

- HB consist of 36 azimuthal identical wedges covering a psuedorapidity of $|\eta|<3$ and each wedge is divided into 16 azimuthal plates, fitted in such a way that there is no projective dead material
- The first and last layer is made up of stainless steel for stability and all other layers are made in brass.
- The end cap sector covers $1.3 < |\eta| < 3.0$ and uses wavelength shifting fibers as an active medium
- These light is then analyzed by hybrid photo diodes(HPDs).

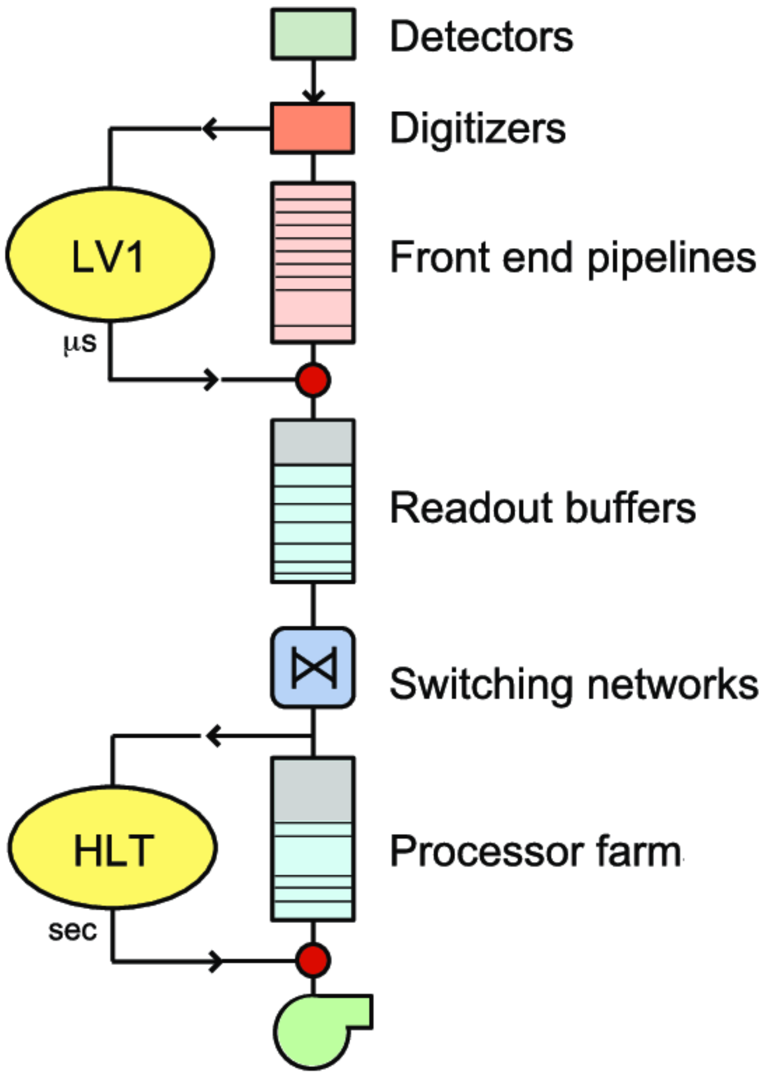
The Trigger System and Data Acquisition

- LHC produces a large interaction rates (Bunch crossing rate: 40 MHz)

- Each recorded event has a size around 1 MB; This makes it impossible to store all the data from the pp collisions at the designed bunch crossing rate.

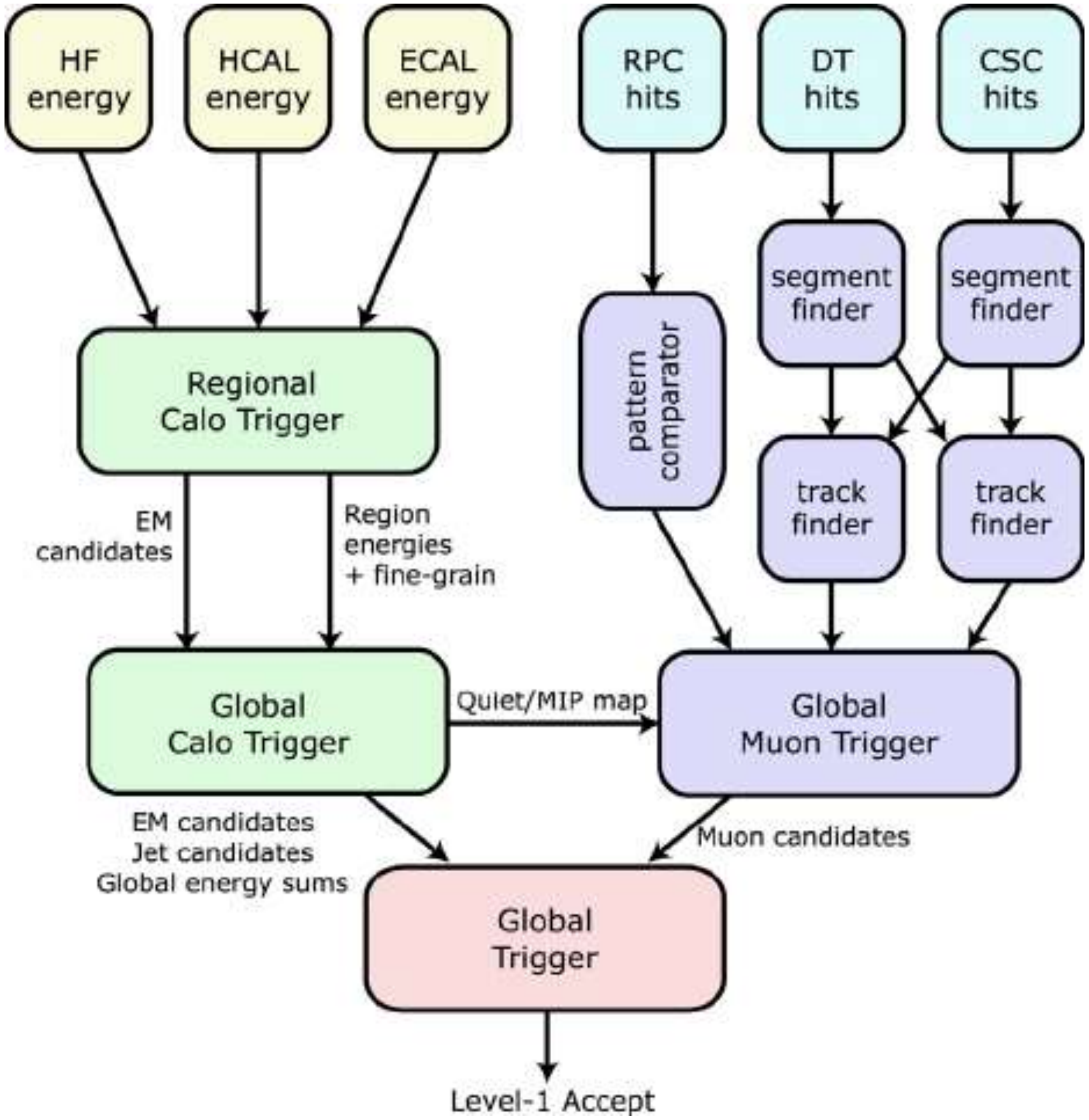
- The Trigger system, is designed to select the best events from the collisions in real time.

- The Trigger Systems consists of : Level 1 trigger (L1 Trigger) and High Level Trigger(HLT).

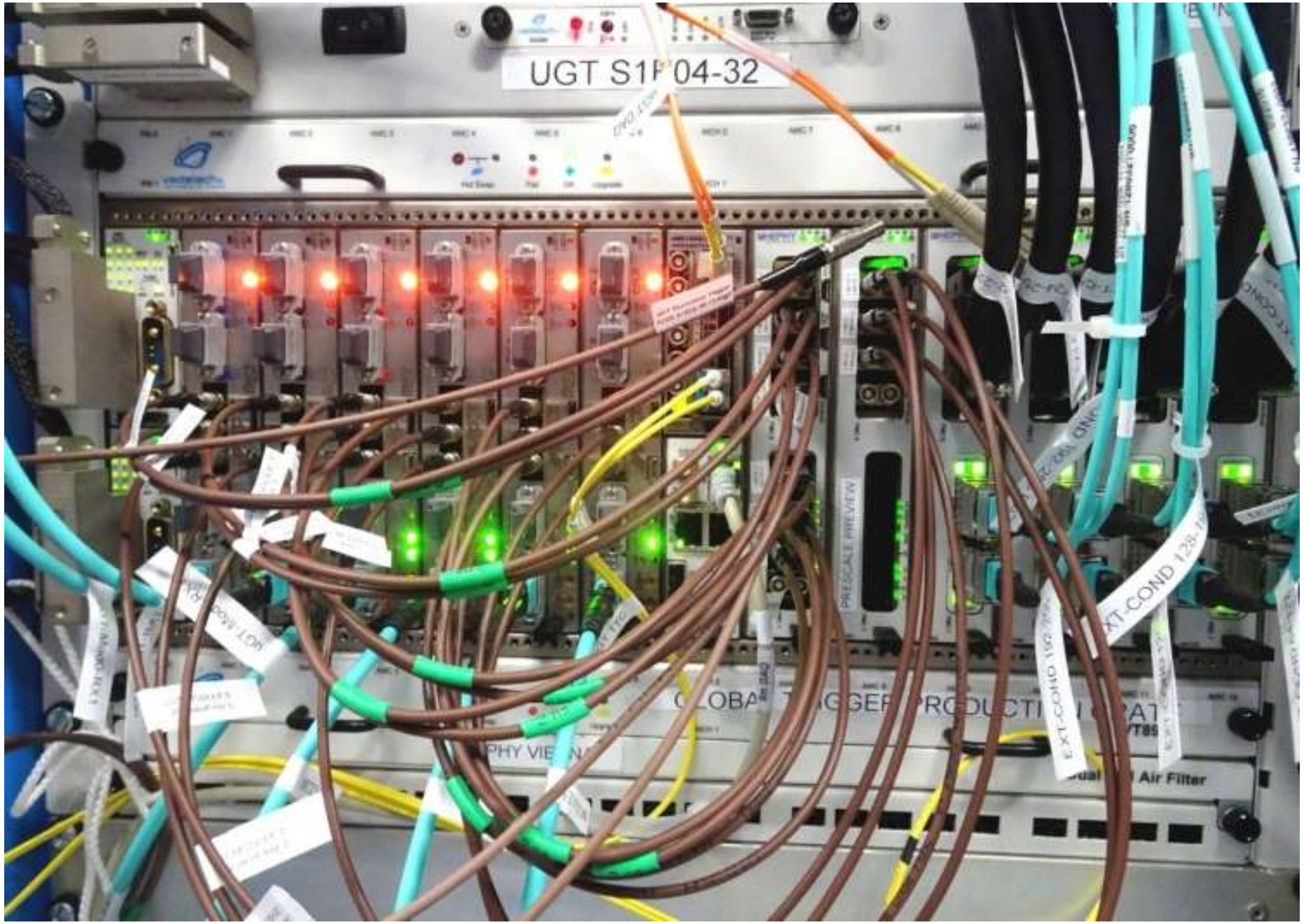


L1 Trigger

- The Level 1 trigger is a hardware based processing system which employs the use of programmable electronics like FPGAs extensively.
- The L1 trigger reduces the input crossing rate of 40MHz to an output rate of 100KHz.
- The L1 trigger follows a hierarchy as shown in the figure. The Global Trigger takes input from two , subsystems: **Calorimeter trigger** and **Muon trigger system**.
- The raw data from detector elements first reaches the “trigger primitives”. These are represented in the top of the diagram.
- The regional detectors combine the information from trigger primitives to create ranked objects. For example, an e/γ candidate has deposits energy in narrow η . The RCT identifies and sorts such objects.



L1 Trigger



- The Global Calorimeter and Global Muon Trigger, sort the trigger objects from Regional Triggers into a ranking and feed to the Global Trigger.
- The Global Trigger takes the topology of the detector and other factors into consideration. It takes into account, various physics criteria to make a decision to keep an event or not.

High Level Trigger

- HLT is a software based processing system which employs commercial microprocessor based farms for trigger. The trigger farm is composed of about 2000 PCs.
- HLT takes information from L1 at 100 kHz and makes selections to produce a final rate of about 800Hz.
- HLT is much slower than L1 and has to account for possible failures of computing nodes.
- HLT builds one full event from the event fragments it gets as input.
- HLT is also responsible for Jet Reconstruction.

An HLT rack

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