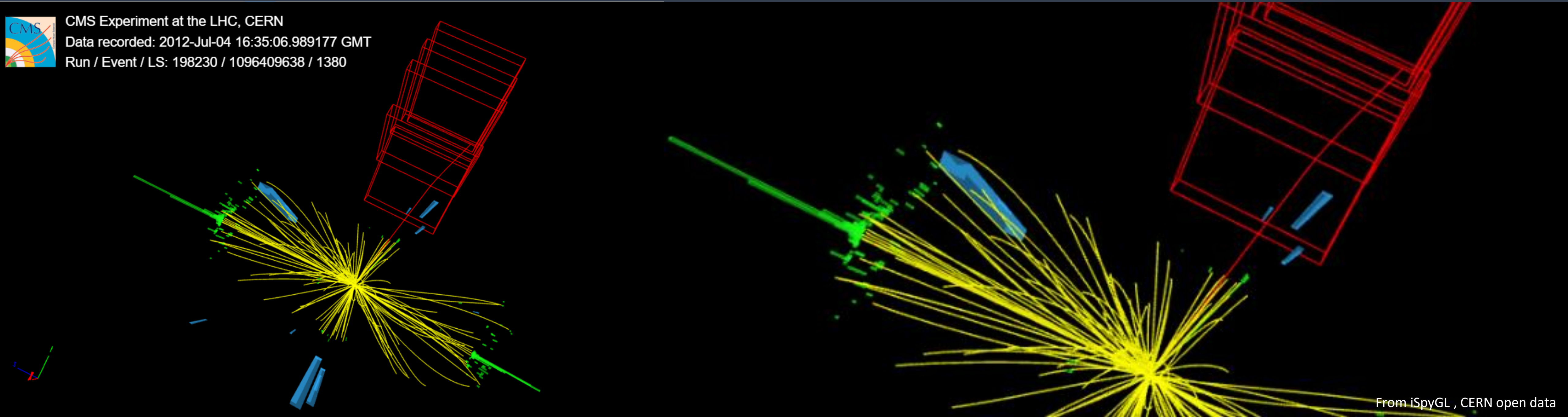
School of Physics

हैदराबाद विश्वविद्यालय
University of Hyderabad



Project update

‘Search for dark matter in the MonoHiggs to $b\bar{b} + p_T^{miss}$ final state’

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Program : *Integrated Masters of Science 10th Semester*
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Project Supervisor: *Dr. Bhawna Gomber*

Outline

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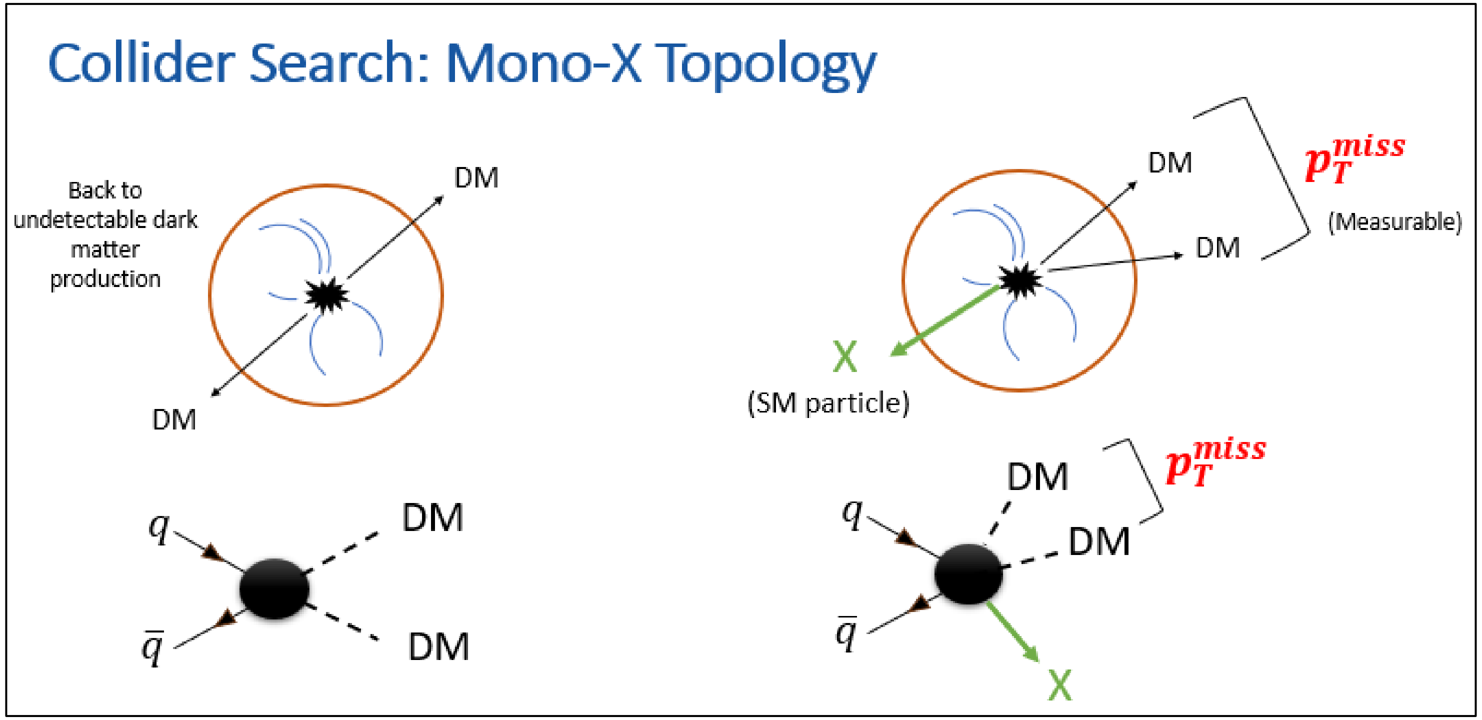
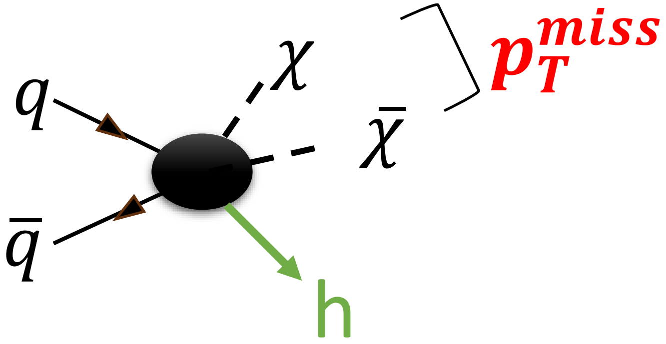
Outline

1. Signal and background
2. Major backgrounds
3. Event Selections and Object Selections
    1. Signal Region
    2. Control Region
4. The Top μ resolved CR
5. Future plan
6. References

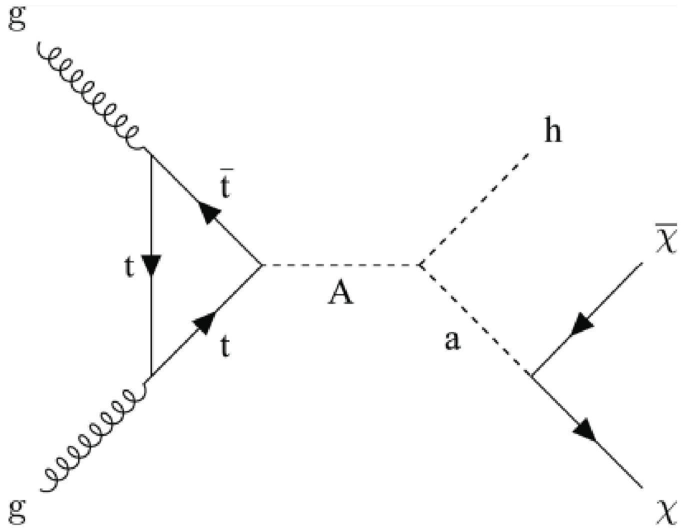




Mono Higgs Searches

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.

The 2HDMa Model



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

My focus H(125)->bb

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

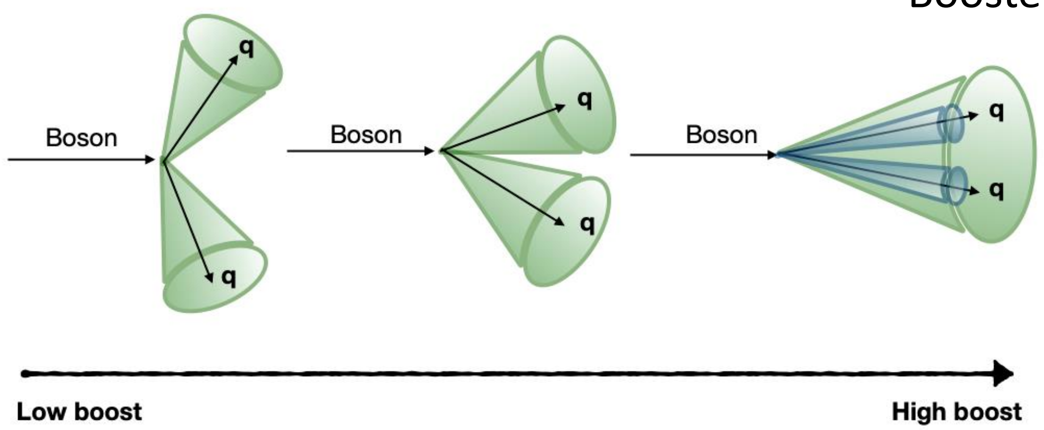
Recap

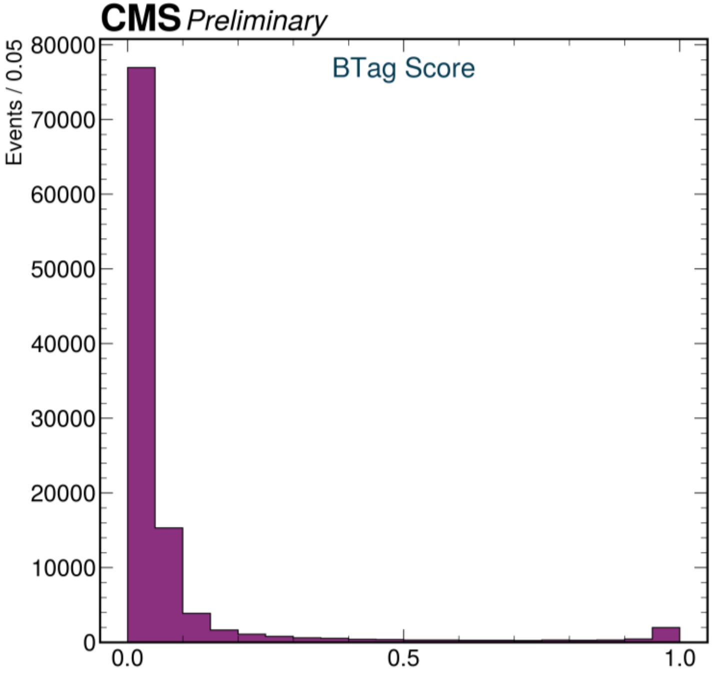
Signal and Background

- 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.

Resolved

Boosted





2018 DATA

1 Million events processed

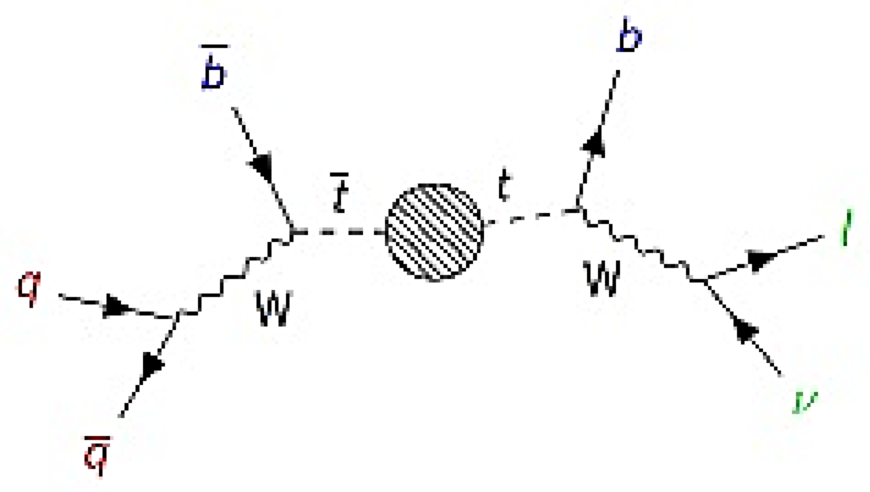
Signal and Background

- 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.

Major Backgrounds: top Control Region

- The top-top is the major background to the final state.



- This background is estimated by defining a ‘Control Region’ which is designed to tag such a background.

Diagram: https://www.phys.ksu.edu/reu/archive/2022/mclennan.html

Major Backgrounds: top Control Region

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

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

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**.

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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Force one or two leptons in CR.

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Keep in Mind

The final state

$$p_T^{miss} + 2\ bjets$$

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.

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

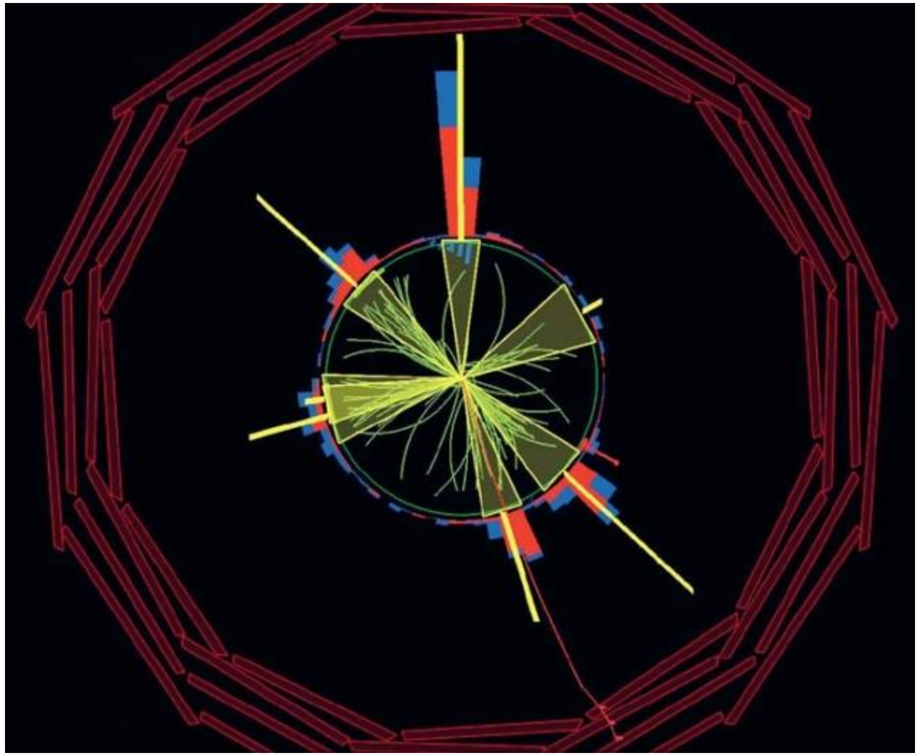
MET and Recoil criteria

- MET cuts to avoid QCD
  - Recoil

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

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

This cut ensures that we remove the majority of QCD events



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

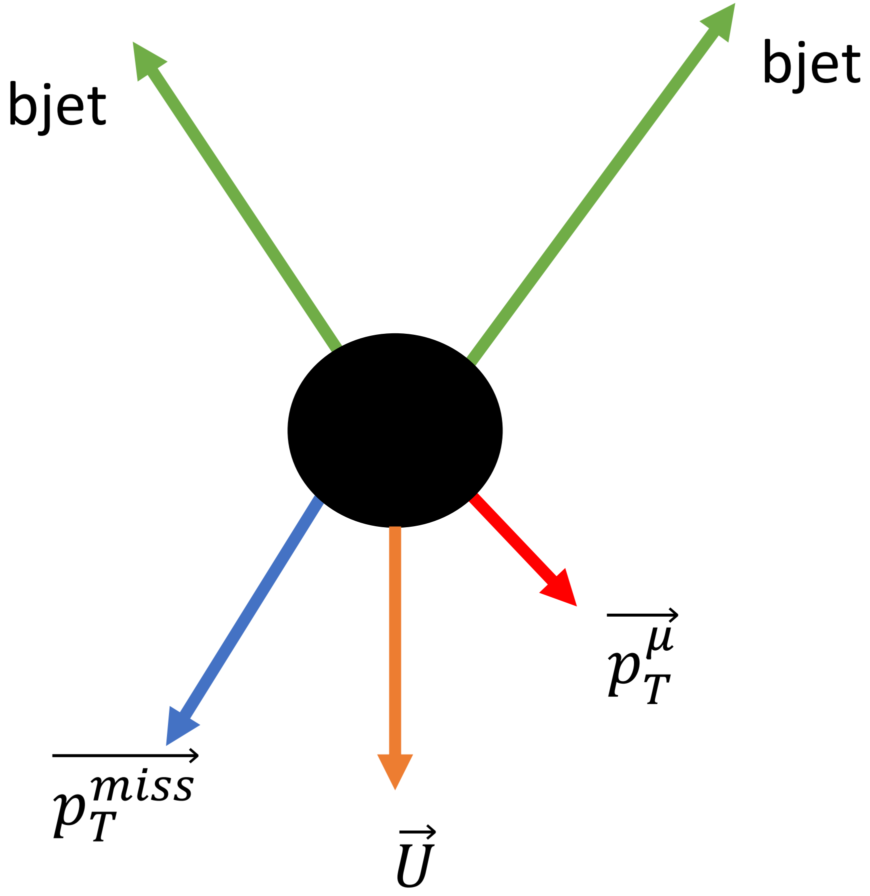
QCD Multijet events have a low p_T vector sum

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)

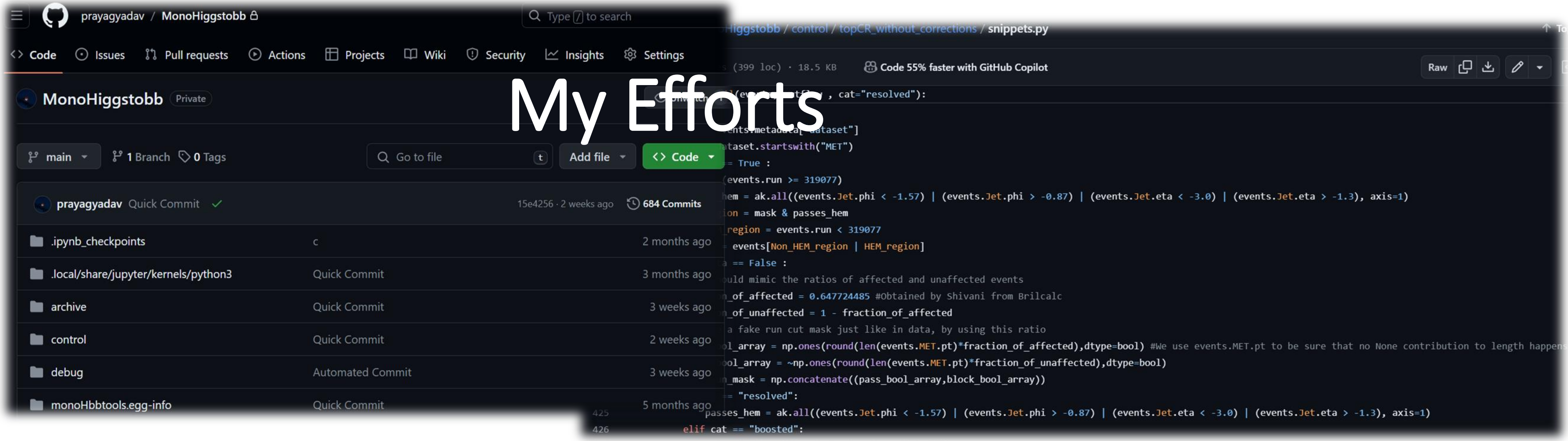
- Dijet mass between 100 GeV to 150 GeV

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



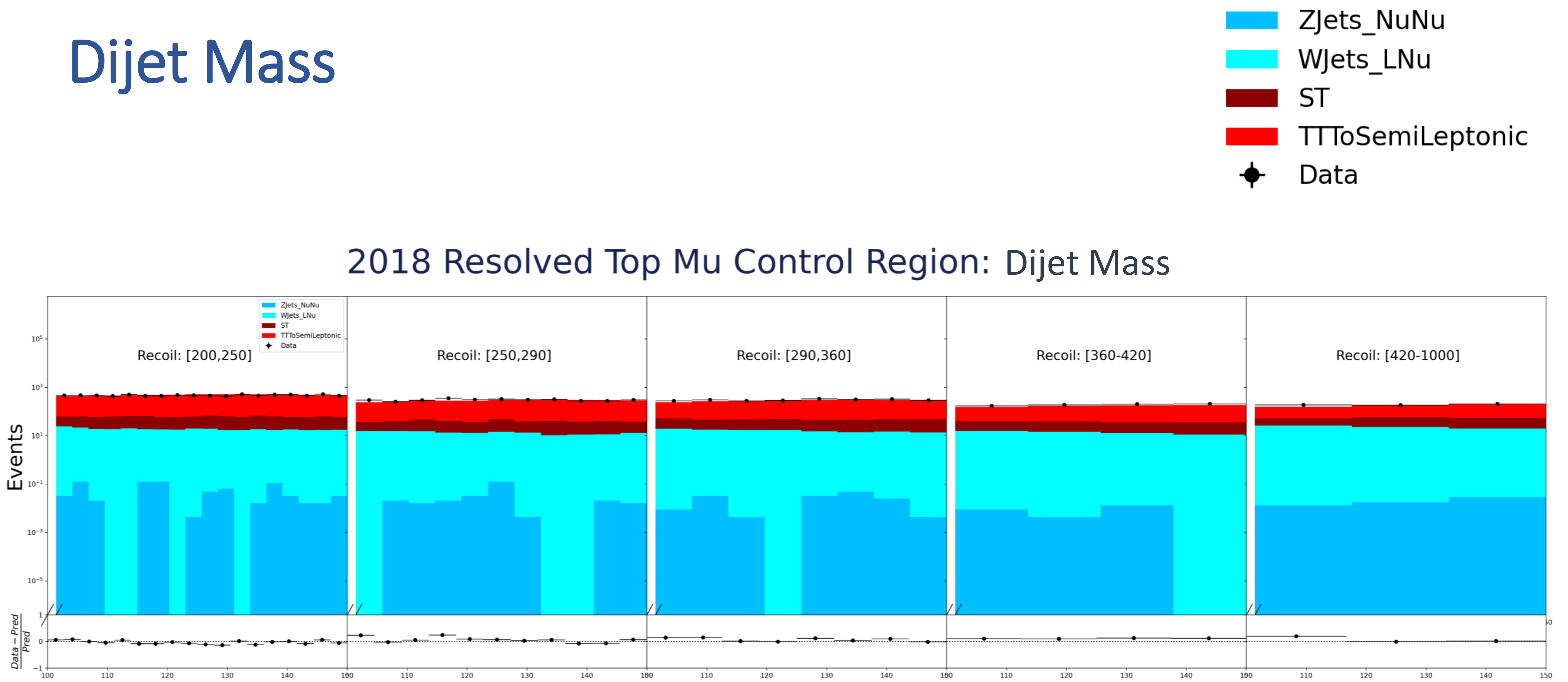
- I have performed the **Resolved Top Muon CR estimation for 2018.**
- More than **30,200 lines of code** excluding blank lines written to get to the final optimized size of less than 3000 lines.
- Almost **22 Terabytes** of samples were processed multiple times.
- Hours of development and processing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

Plots

Top μ Resolved jets

Top single muon

Dijet Mass



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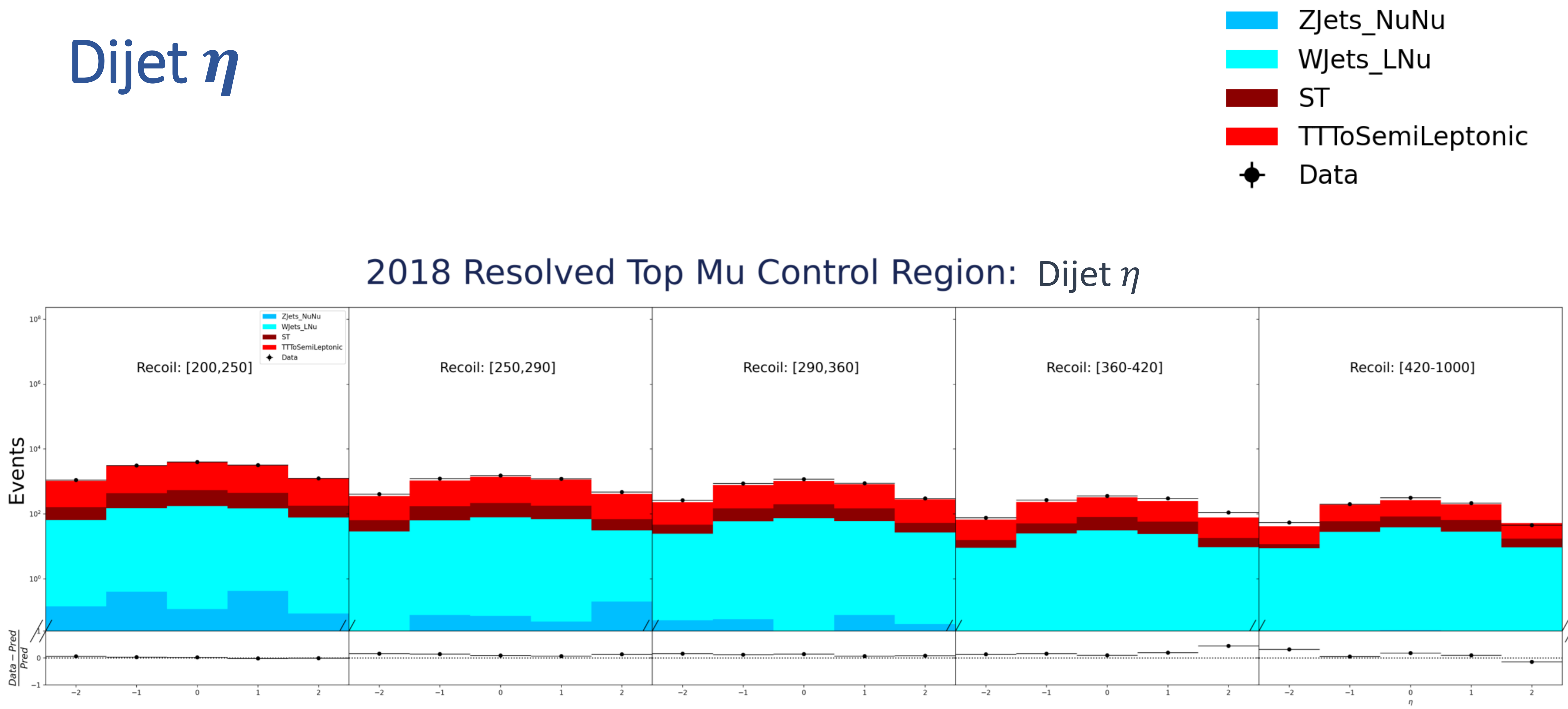
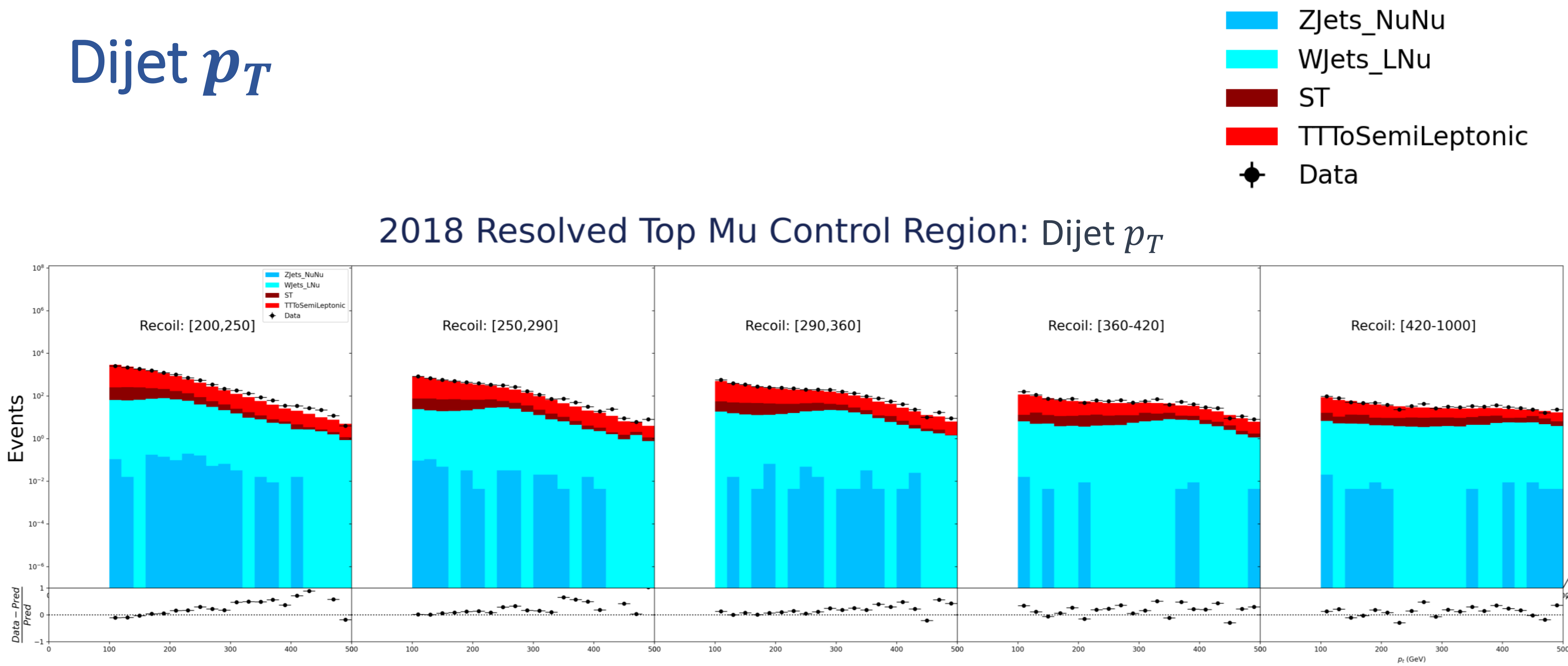
Dijet η

2018 Resolved Top Mu Control Region: Dijet η



Dijet p_T



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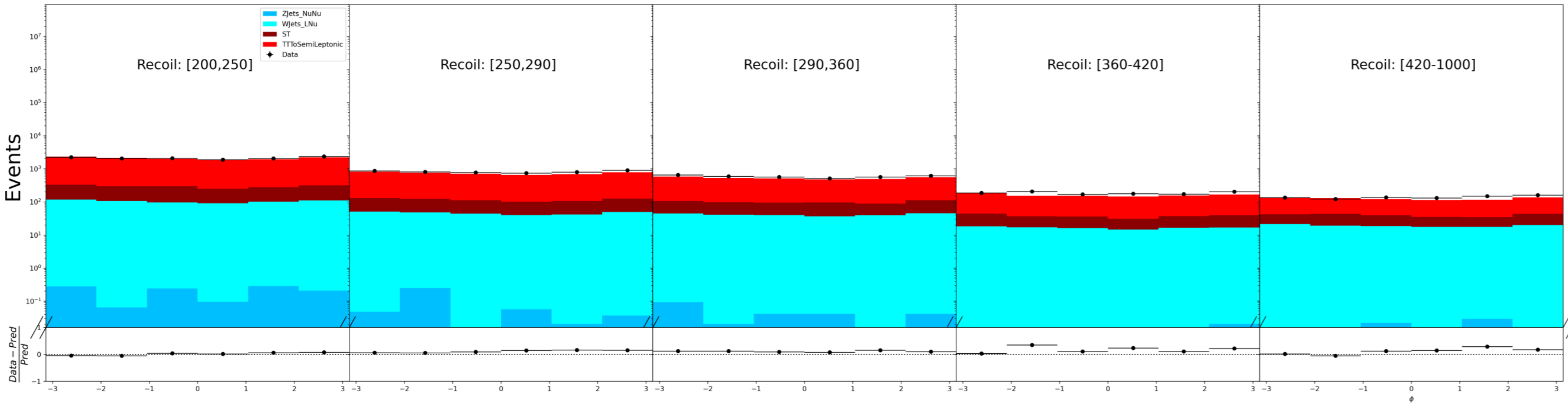
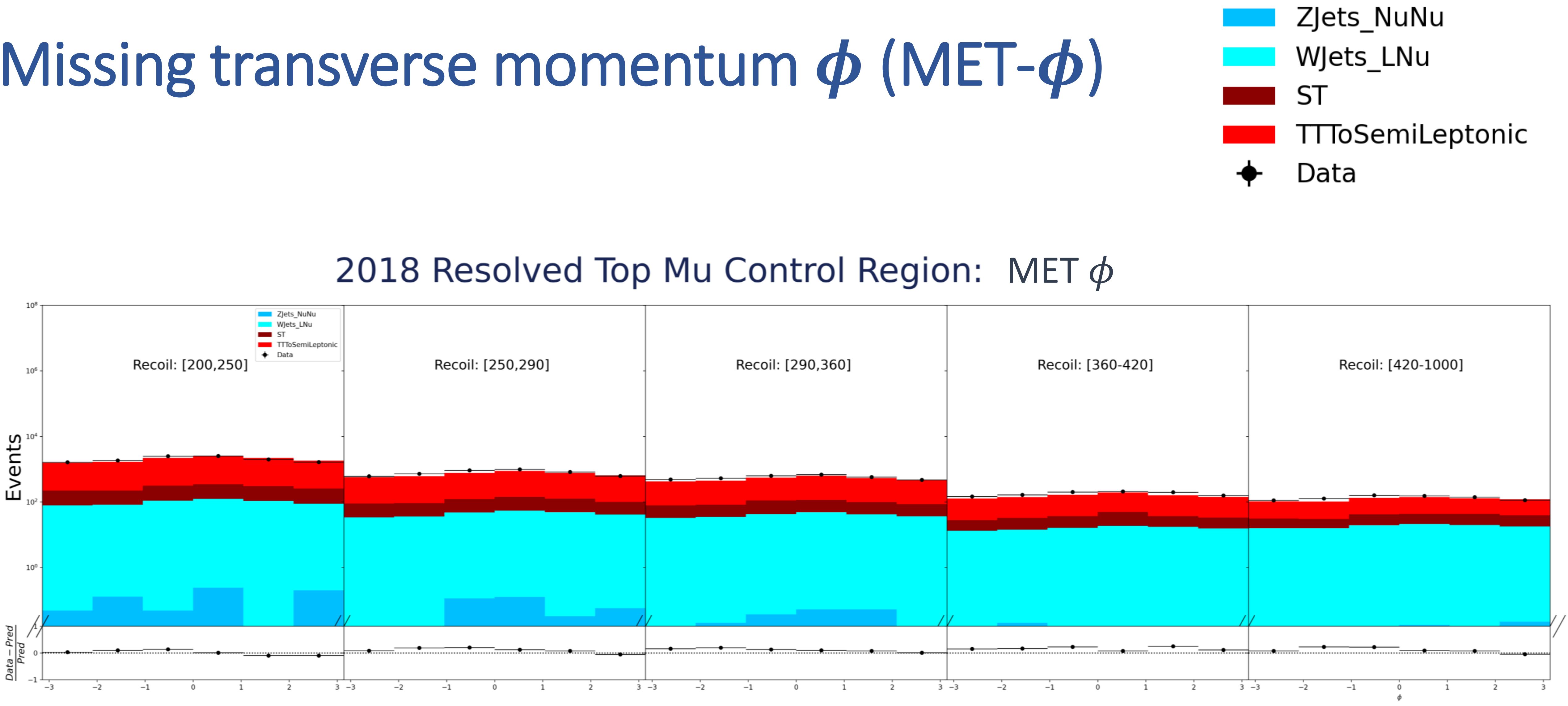
Dijet ϕ

- ZJets_NuNu
- WJets_LNu
- ST
- TTToSemiLeptonic
- Data

2018 Resolved Top Mu Control Region: Dijet ϕ



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.

References

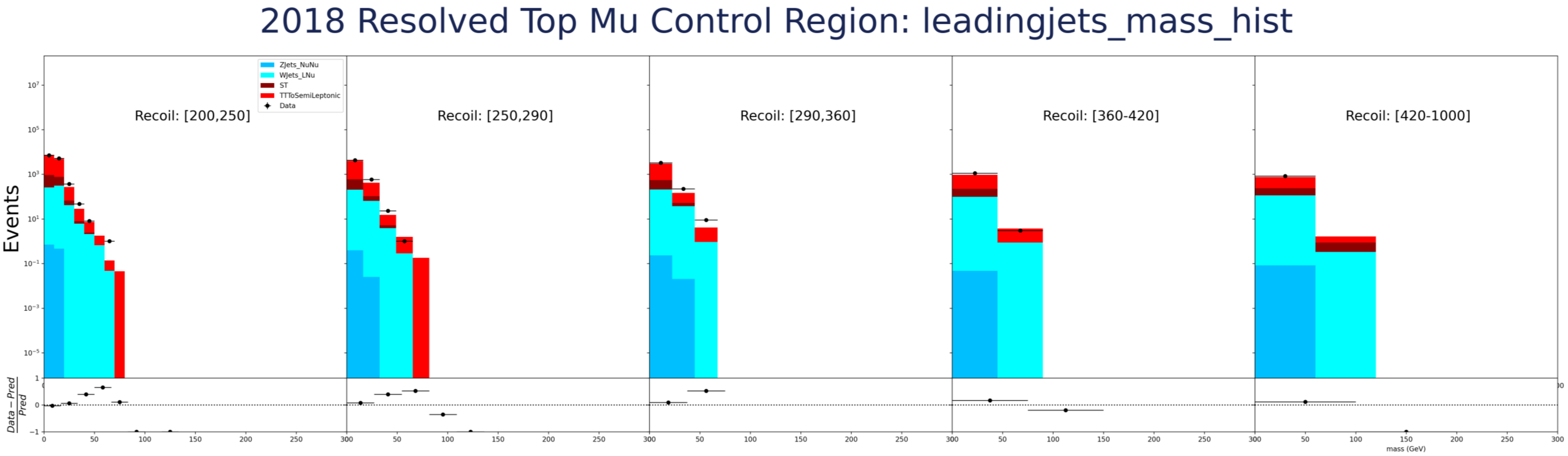
- Search for dark matter produced in association with a Higgs boson decaying to a pair of bottom quarks- Askew et. al.
- Sirunyan, A.M., Tumasyan, A., Adam, W. *et al.* Search for dark matter produced in association with a Higgs boson decaying to a pair of bottom quarks in proton–proton collisions at $\sqrt{s}$=13TeV. *Eur. Phys. J. C* **79**, 280 (2019). https://doi.org/10.1140/epjc/s10052-019-6730-7
- Indirect detection of Dark Matter candidates in gamma-rays by Lars Bergström in 2007
- Teresa Marrodán Undagoitia, & Ludwig Rauch (2015). Dark matter direct-detection experiments. Journal of Physics G: Nuclear and Particle Physics, 43(1), 013001.
- LHC Higgs Cross Section Working Group., Denner, A., Heinemeyer, S. et al. Standard model Higgs-boson branching ratios with uncertainties. Eur. Phys. J. C **71**, 1753 (2011). https://doi.org/10.1140/epjc/s10052-011-1753-8
- The CMS collaboration., Sirunyan, A.M., Tumasyan, A. et al. Search for associated production of dark matter with a Higgs boson decaying to $\bar{b}b$ or $\gamma\gamma$ at $\sqrt{s}$ = 13 TeV. J. High Energ. Phys. 2017, 180 (2017). https://doi.org/10.1007/JHEP10(2017)180

Thank you for your attention.

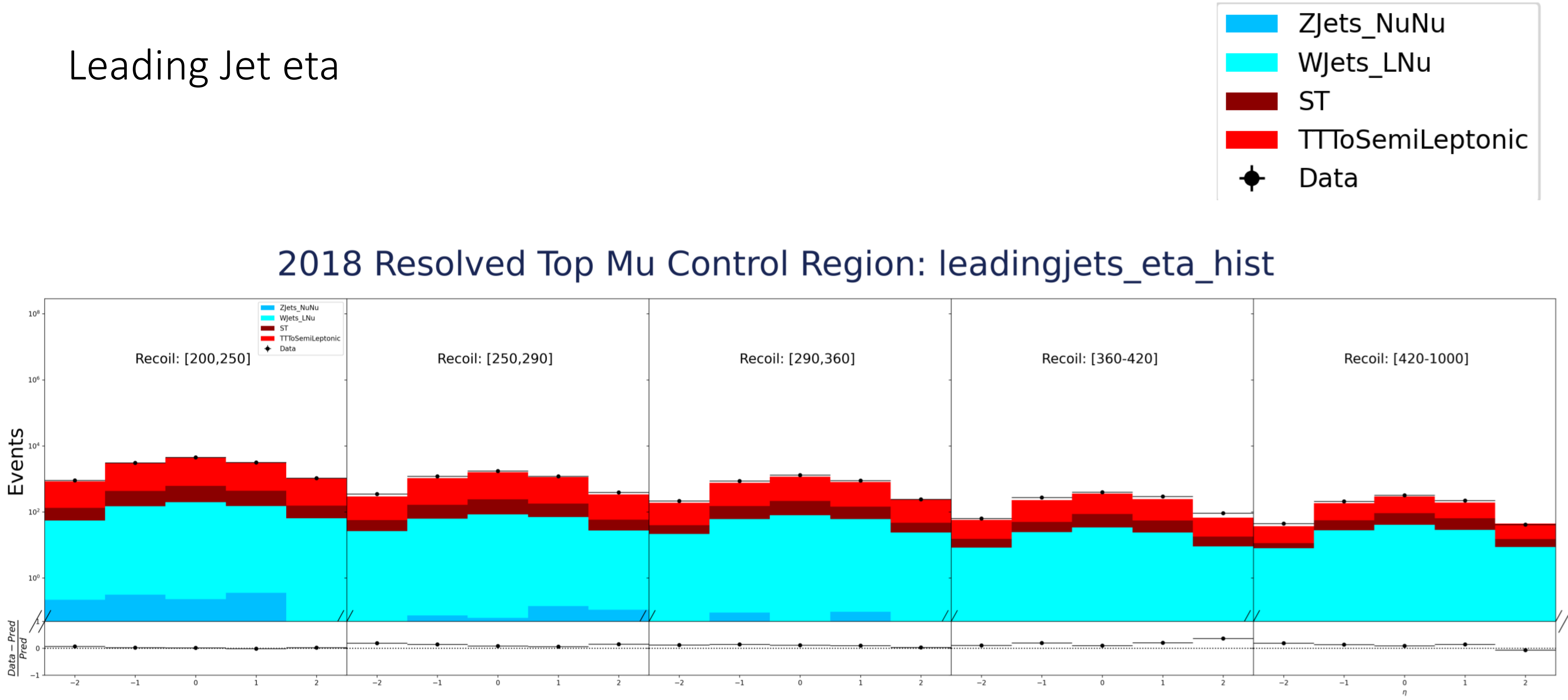
Backup Slides

Quick Recap

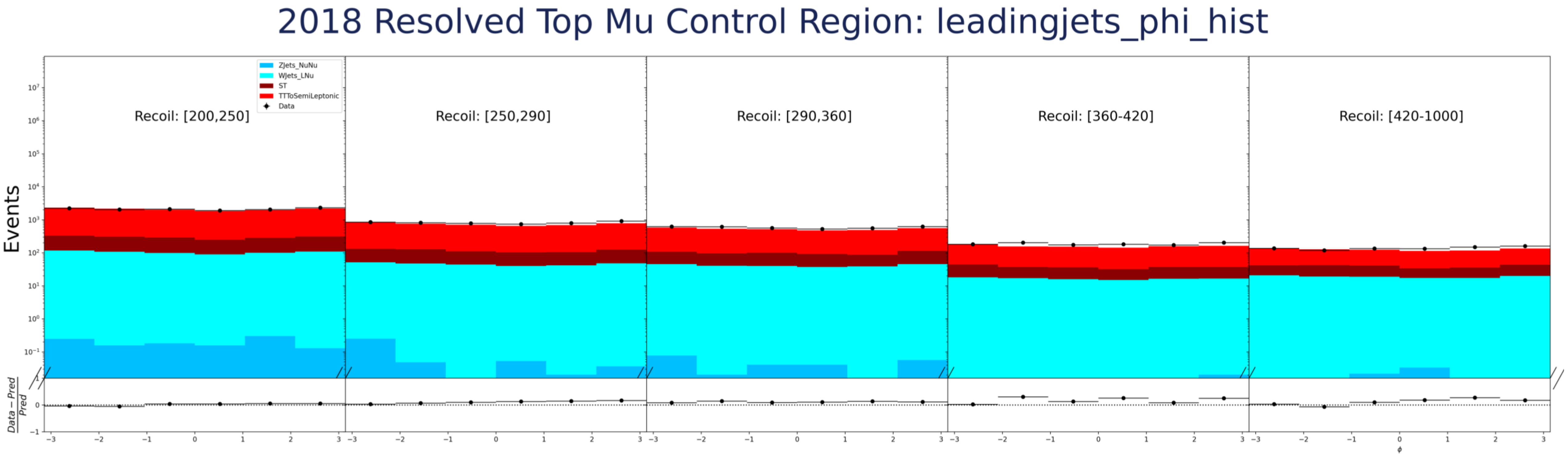
Leading Jet mass



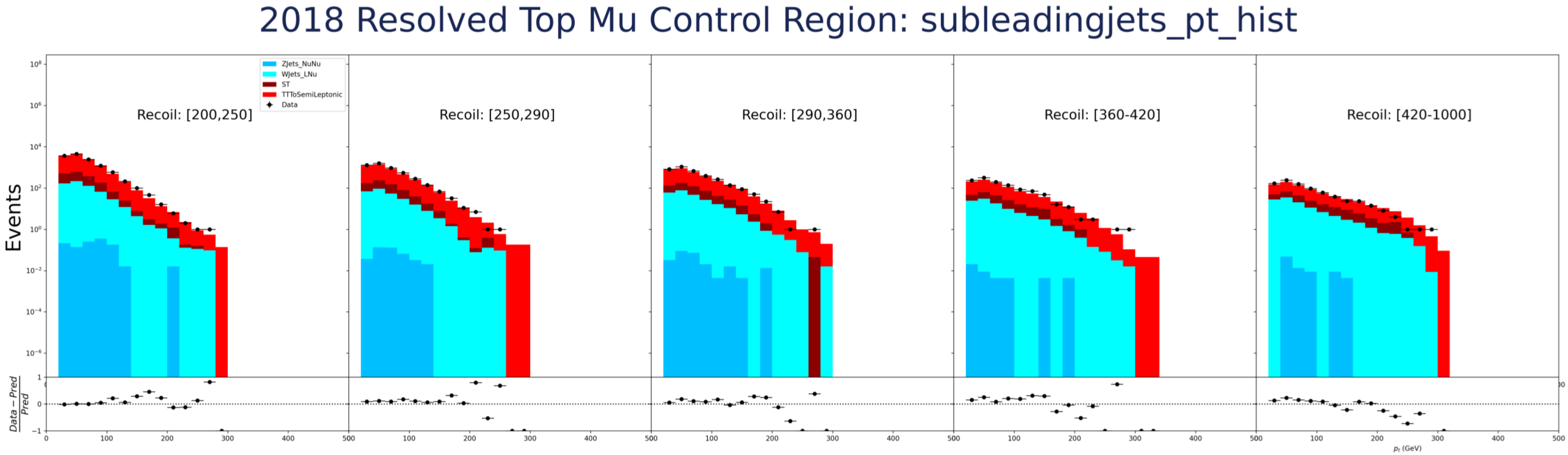
Leading Jet eta



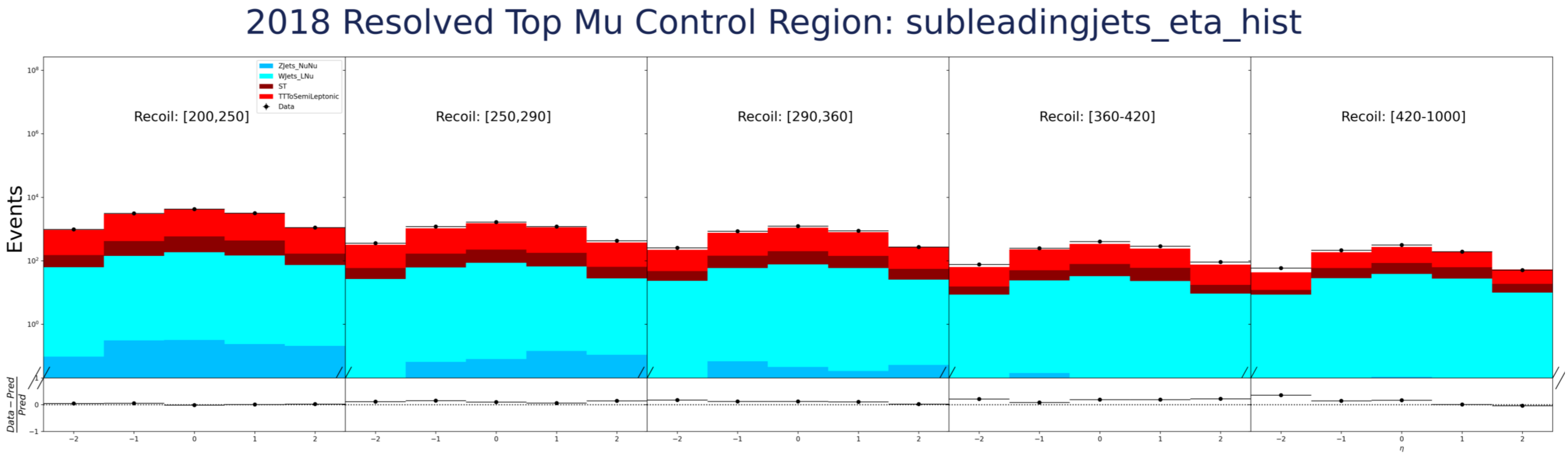
Leading Jet phi



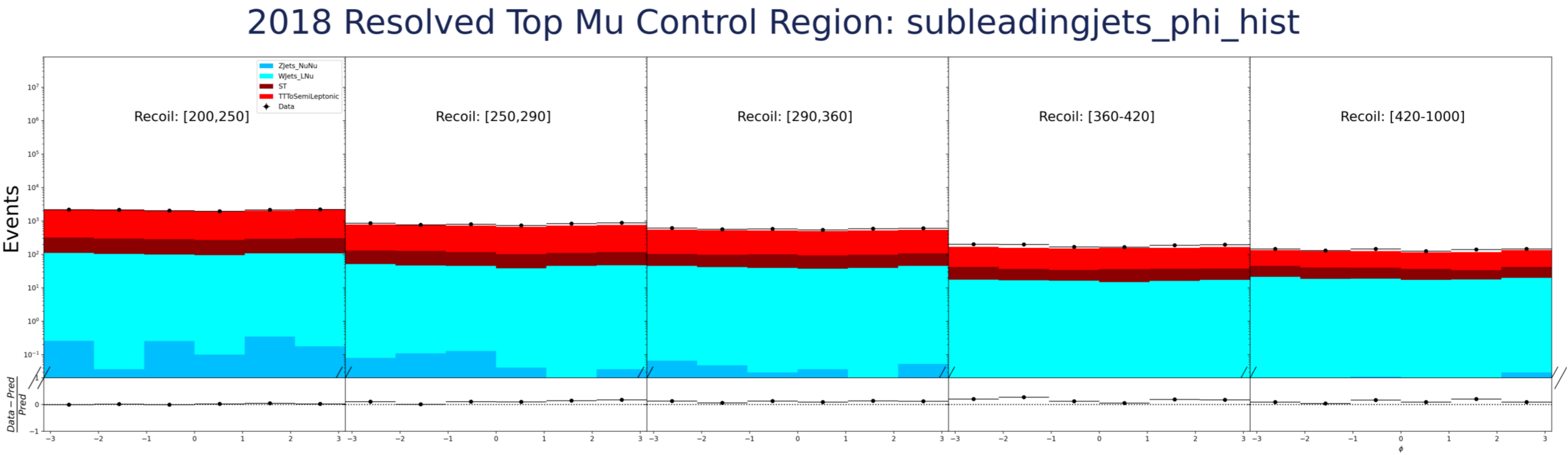
Subleading Jet pt



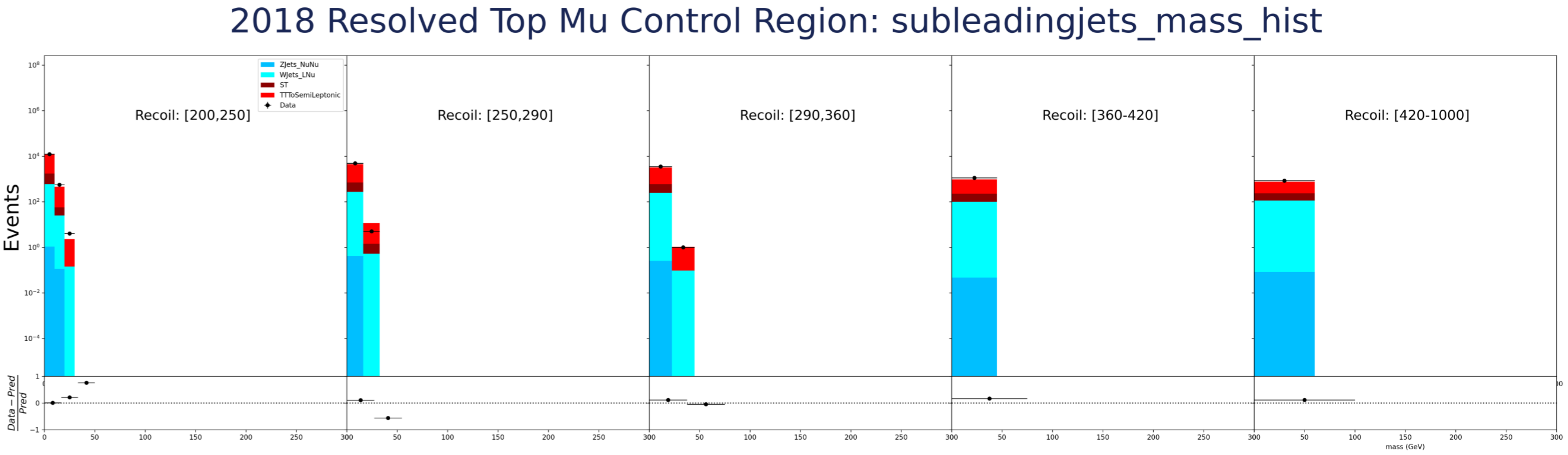
Subleading Jet eta



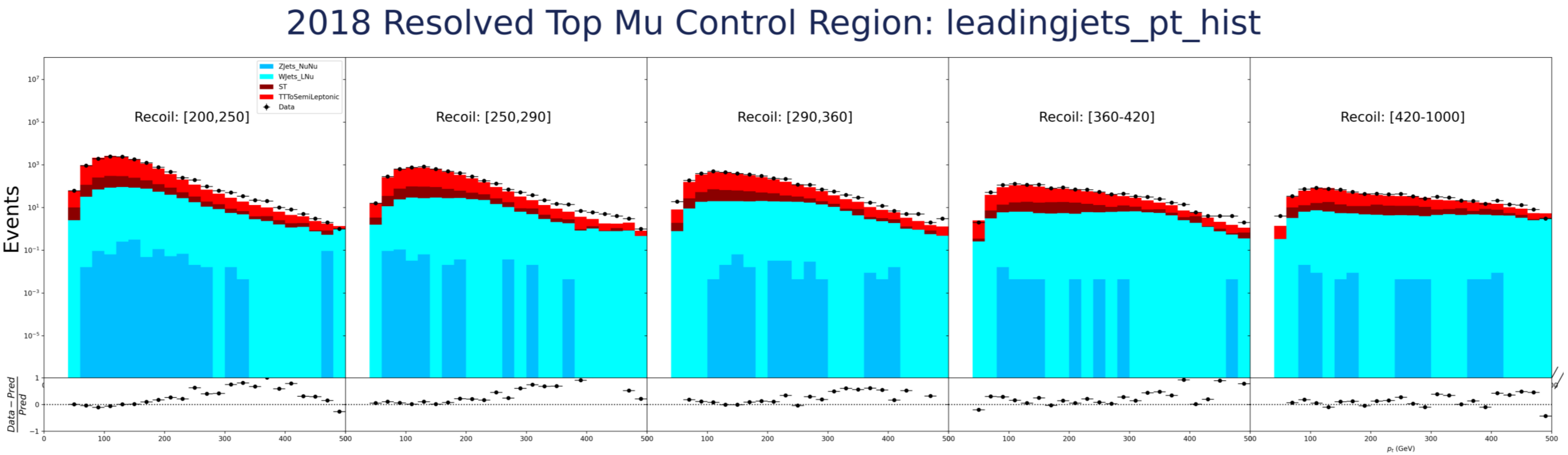
Subleading Jet phi



Subleading Jet mass

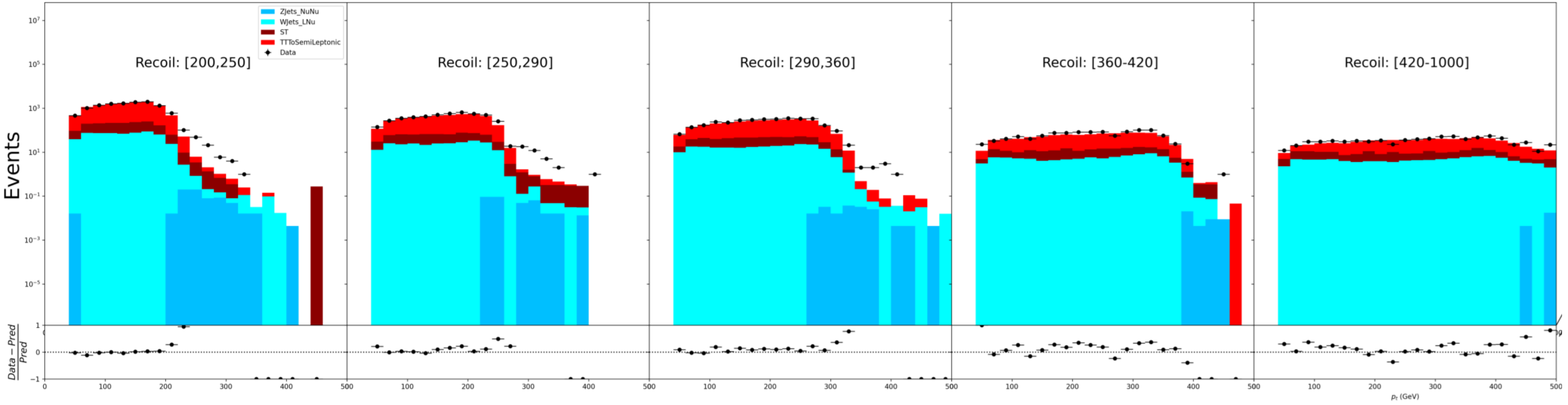


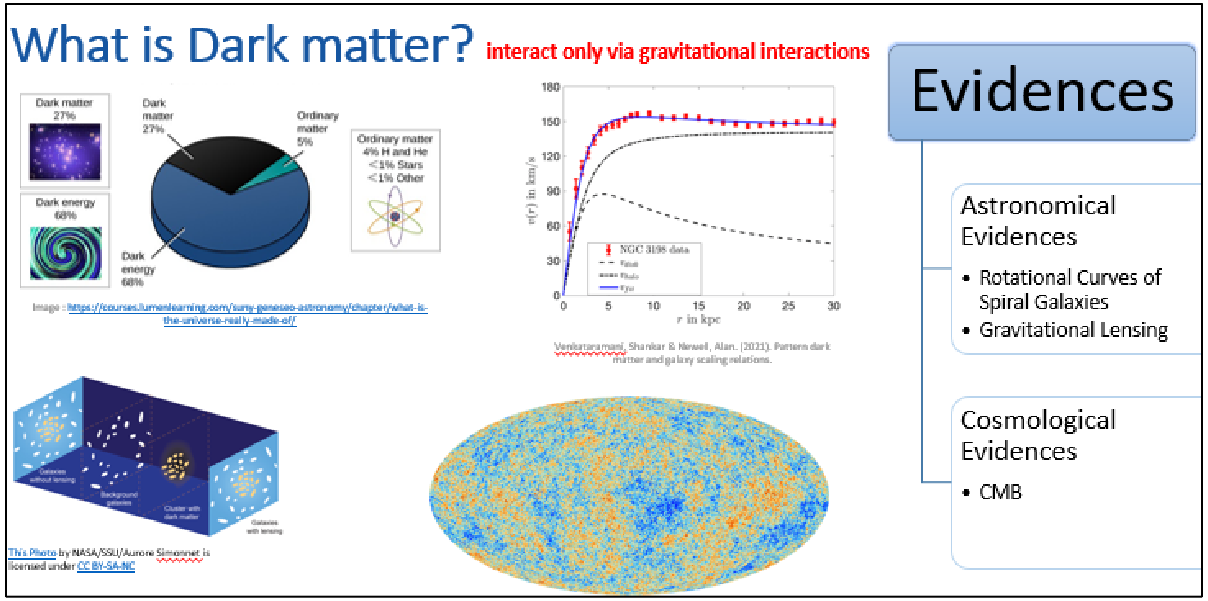
Leading Jet pt

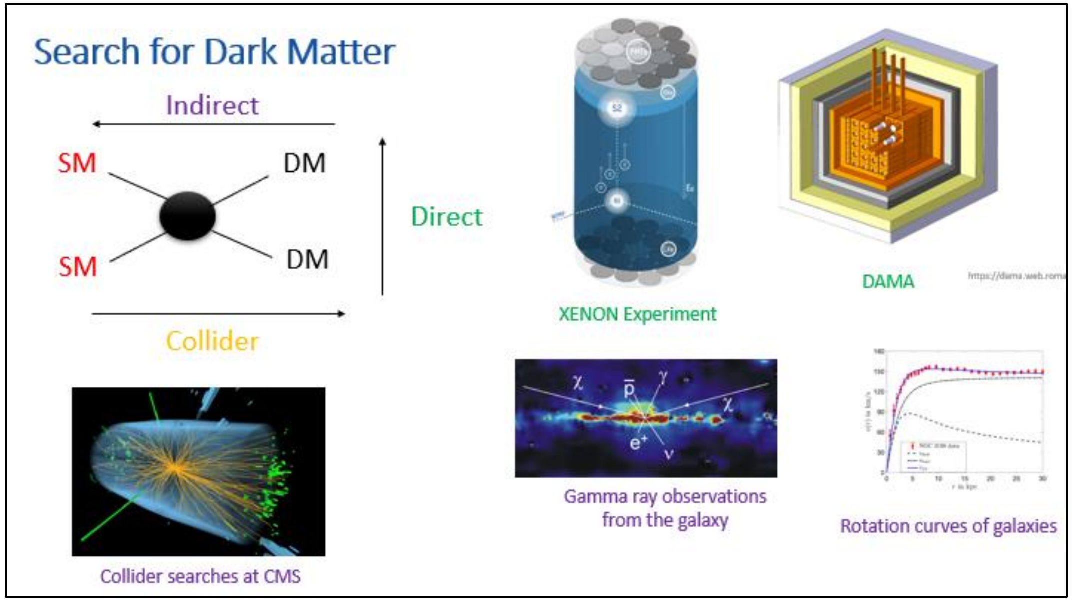


Missing transverse momentum (p_T^{miss})

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



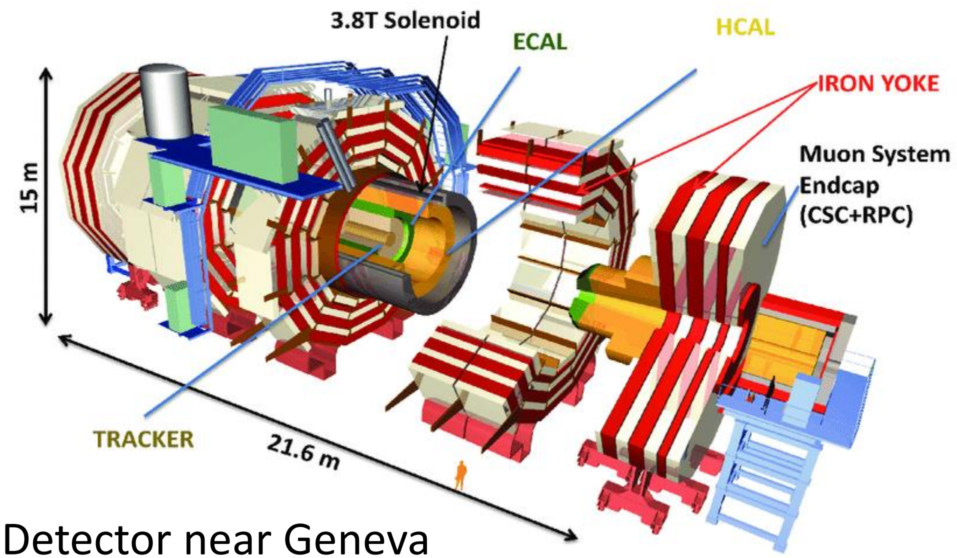




Analysis tools and Strategy

- 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.

The COFFEA Framework



CMS Detector near Geneva

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Recap

Analysis tools and Strategy

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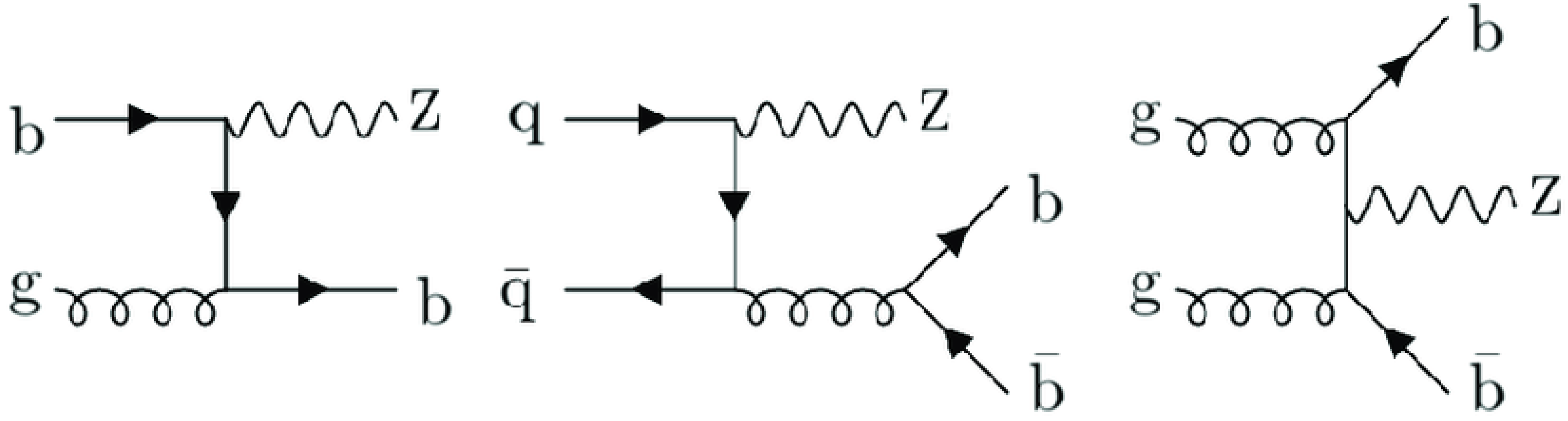
The COFFEA Framework

Major Backgrounds: Z+jets Control Region

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



the Z further decays
$Z \rightarrow \nu\nu$

- 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

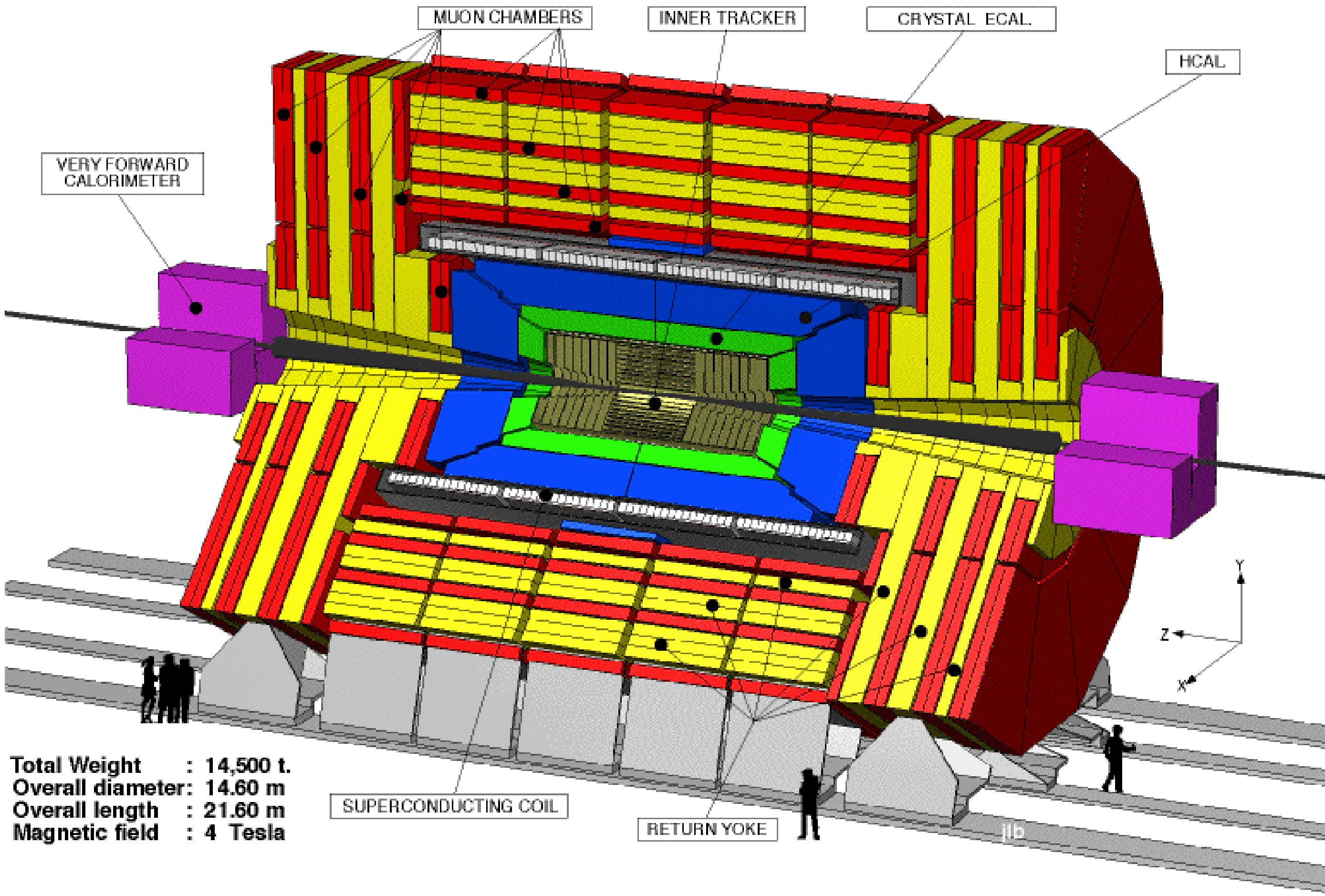
```
Flag.goodVertices
Flag.globalTightHalo2016Filter
Flag.globalSuperTightHalo2016Filter
Flag.HBHENoiseFilter
Flag.HBHENoiseIsoFilter
Flag.eeBadScFilter
Flag.EcalDeadCellTriggerPrimitiveFilter
Flag.BadPFMuonFilter
Flag.BadPFMuonDzFilter
Flag.ecalBadCalibFilter
```

Avoiding Detection issues

Hadronic Calorimeter Endcaps minus (HEM) issue

- MET Filters
- **HEM Veto**

- 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.



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

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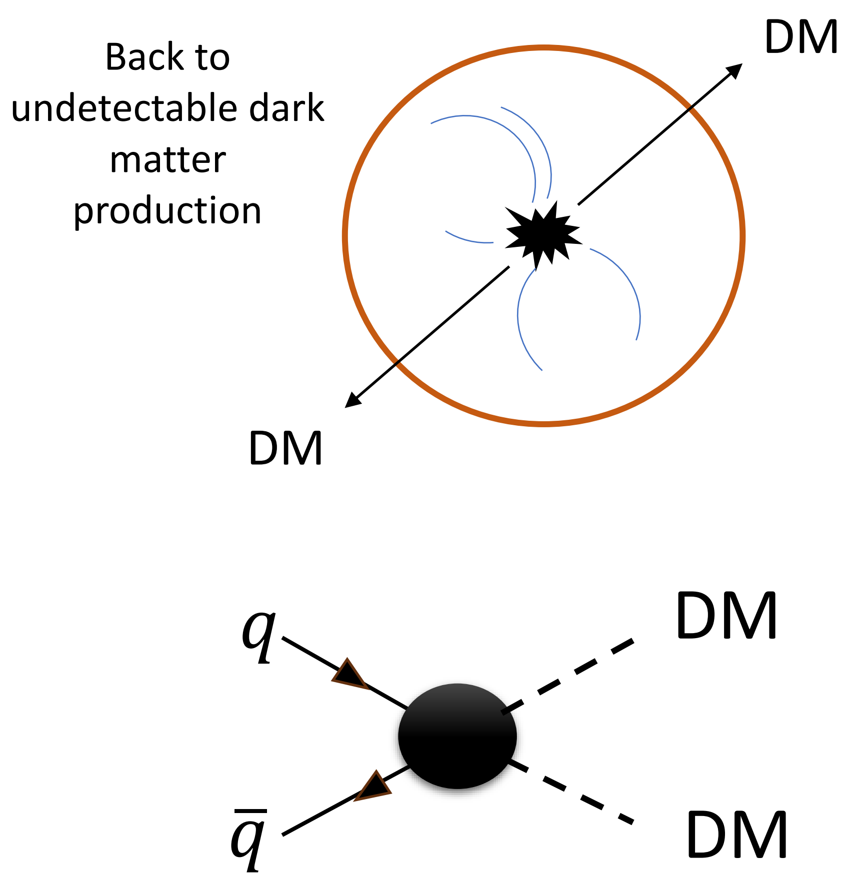
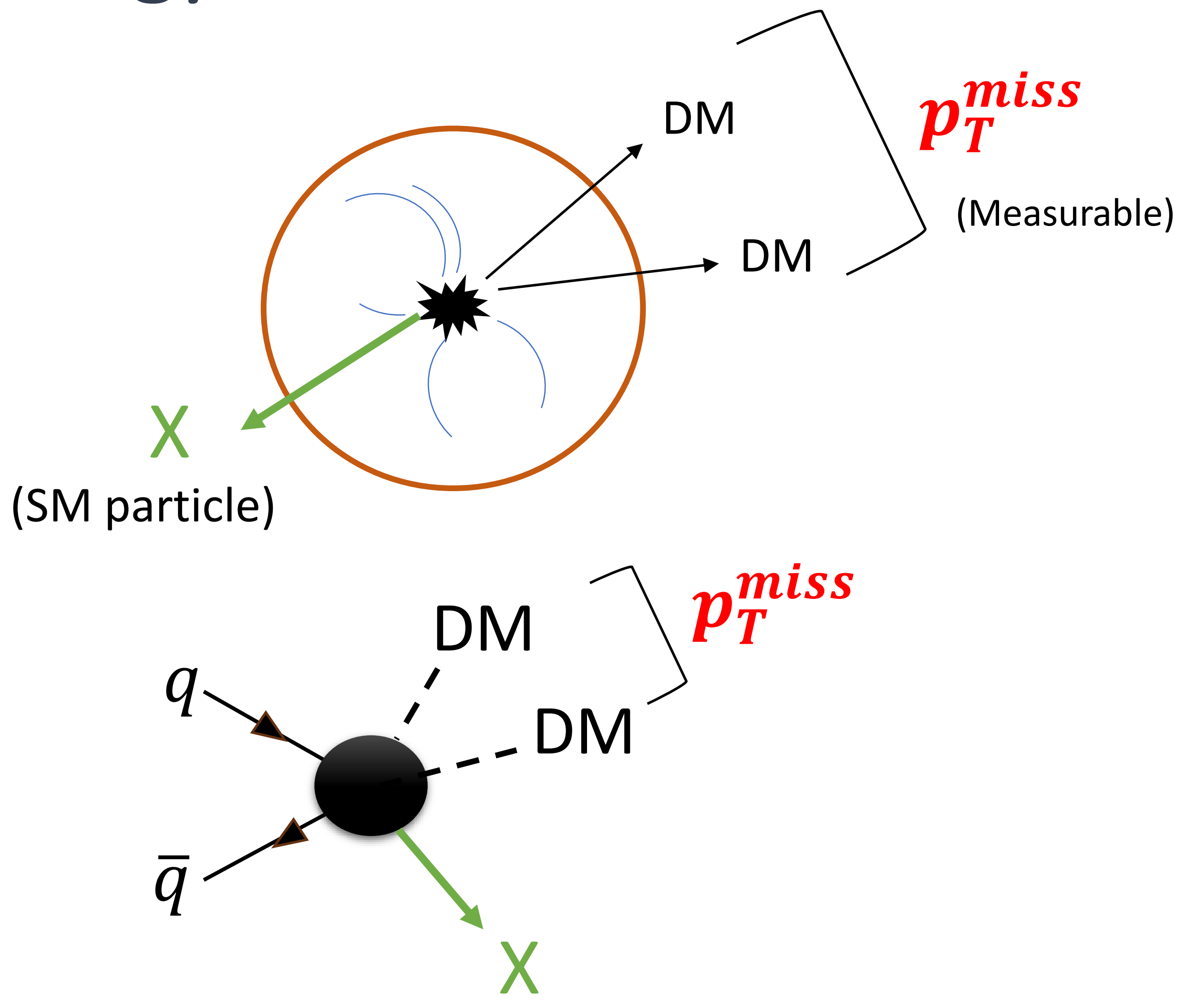
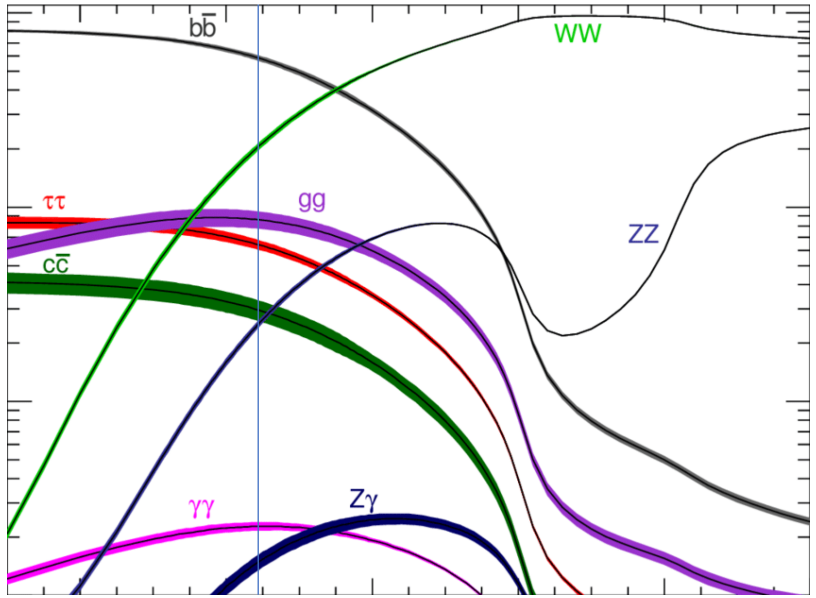
Collider Search: Mono-X Topology

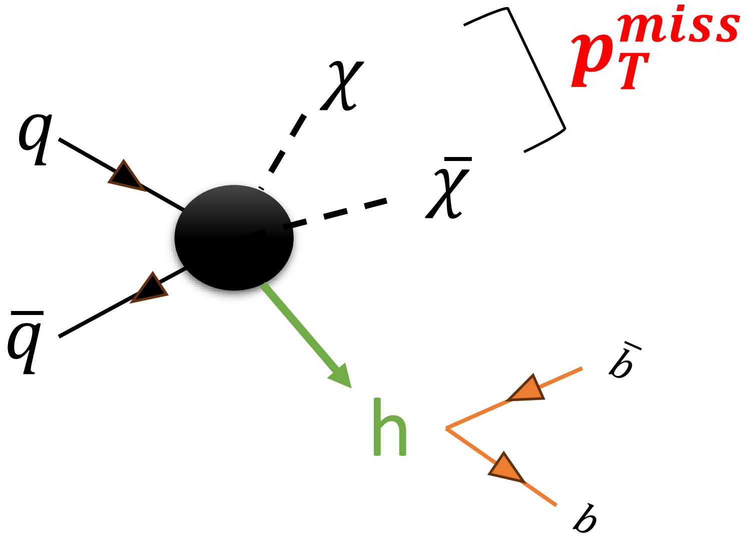




Mono Higgs Searches

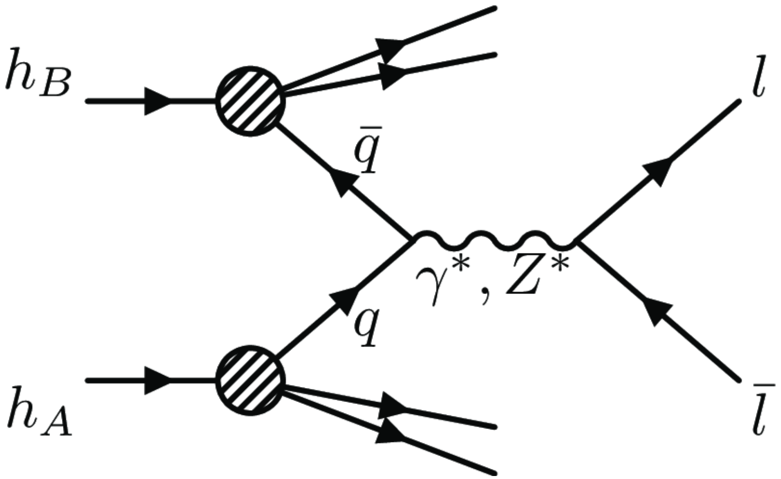
1. No Initial State Radiation
2. More closely connected to DM production
3. Signal Signature has a high MET trail which helps to separate the signal from background.



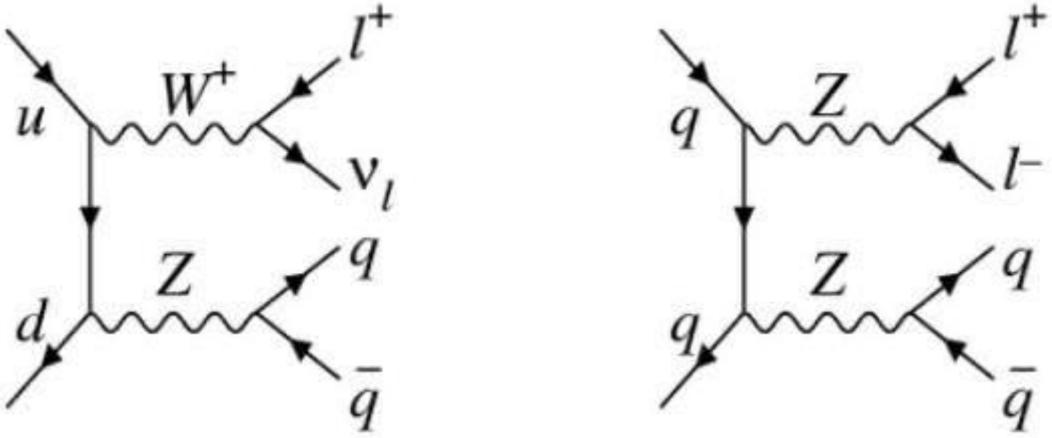


H(125)->bb branching ratio is ~ 57%

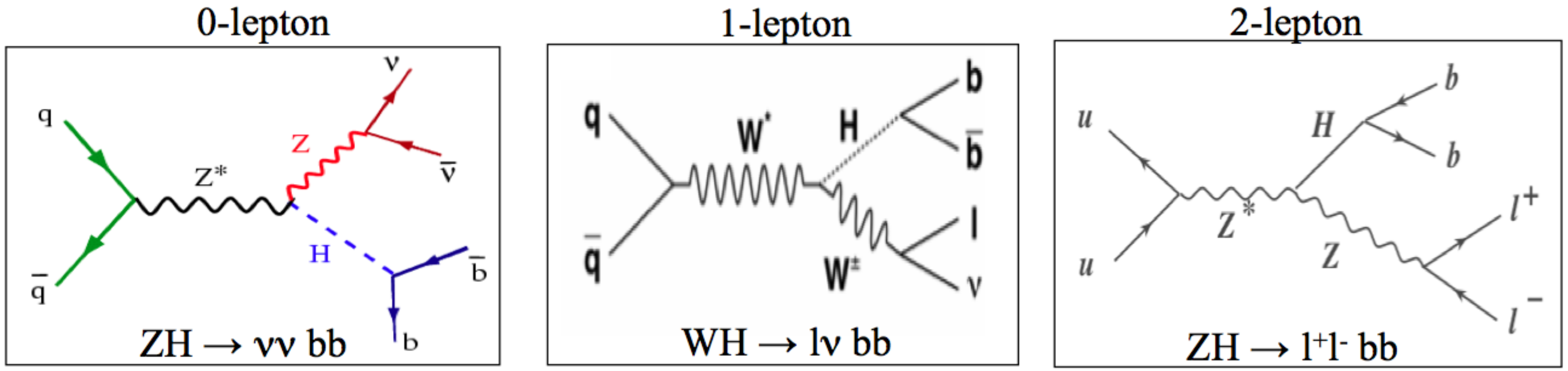
Other backgrounds (continued)



Drell-Yan+Jets



Diboson VV



SM-Higgs

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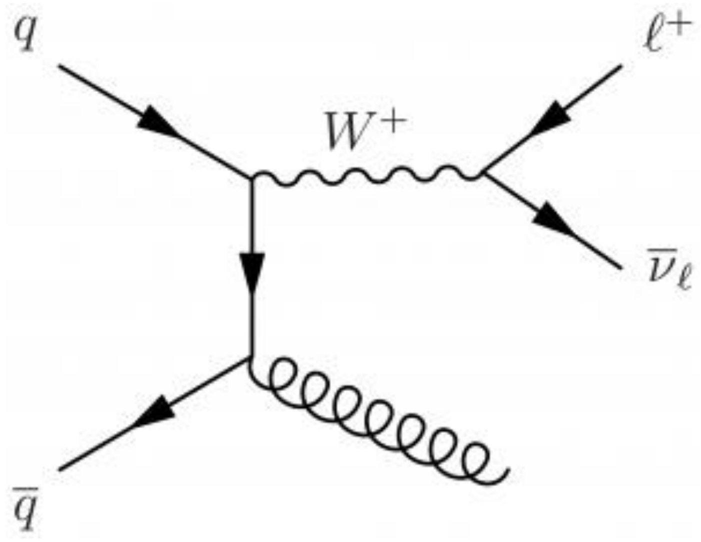
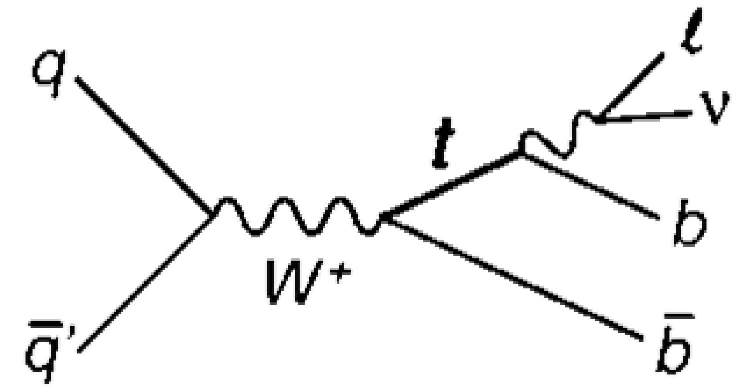
Other backgrounds



W+Jets



Single Top

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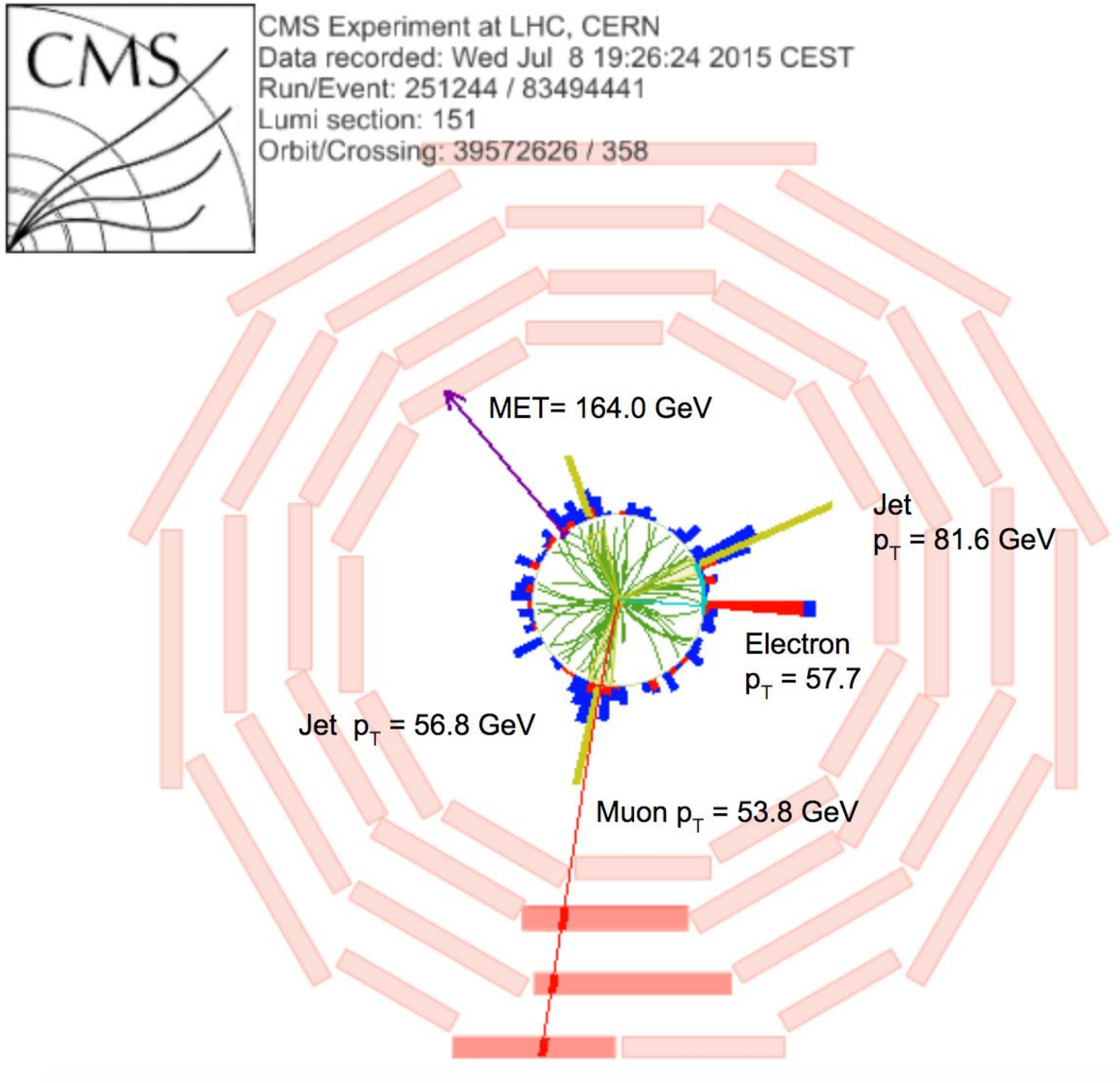
Triggers

- 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.



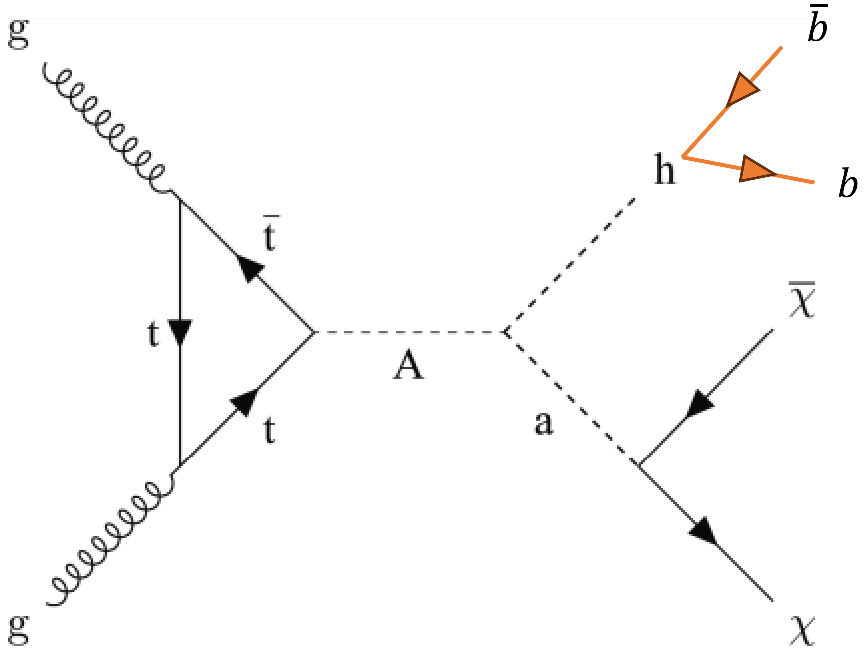
HLT.PFMETNoMu120_PFMHTNoMu120_IDTight

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

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**.

2HDM = Two Higgs Doublet Model

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

2HDMa = Two Higgs Doublet Model with a pseudoscalar mediator ‘a’

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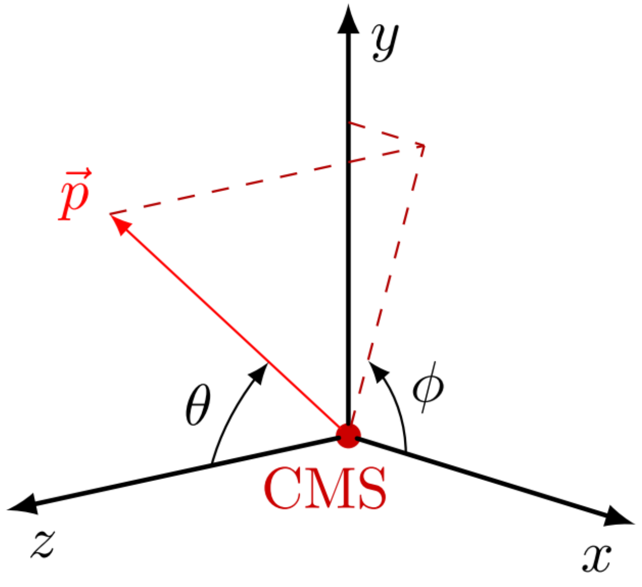
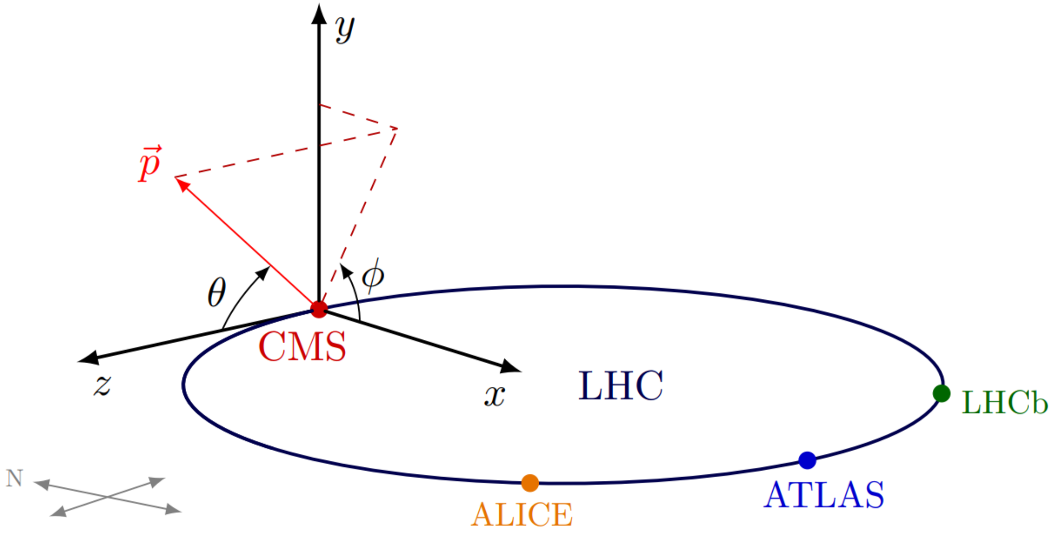
The Coordinate System

- 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:

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

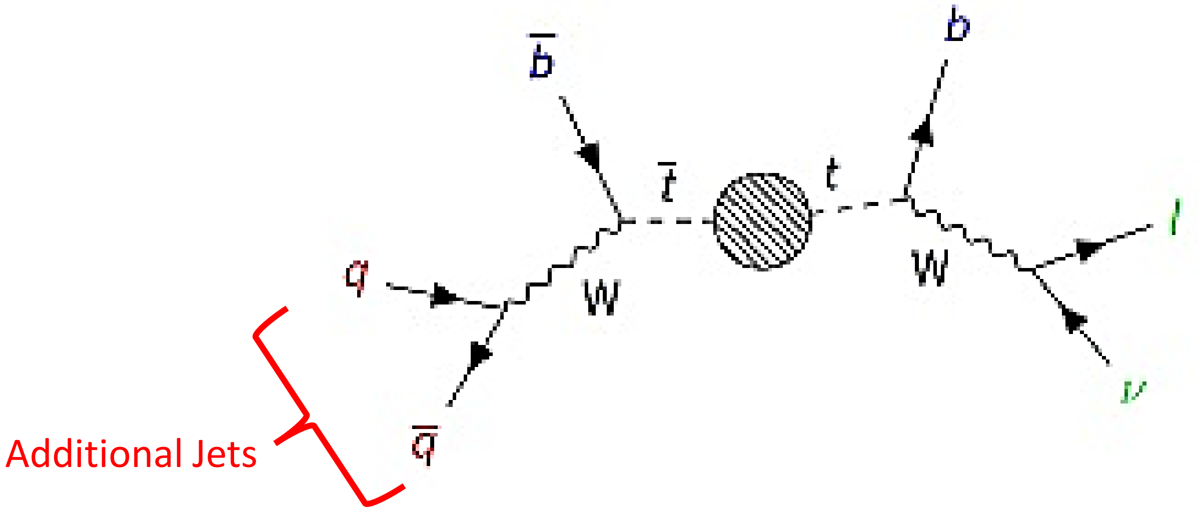




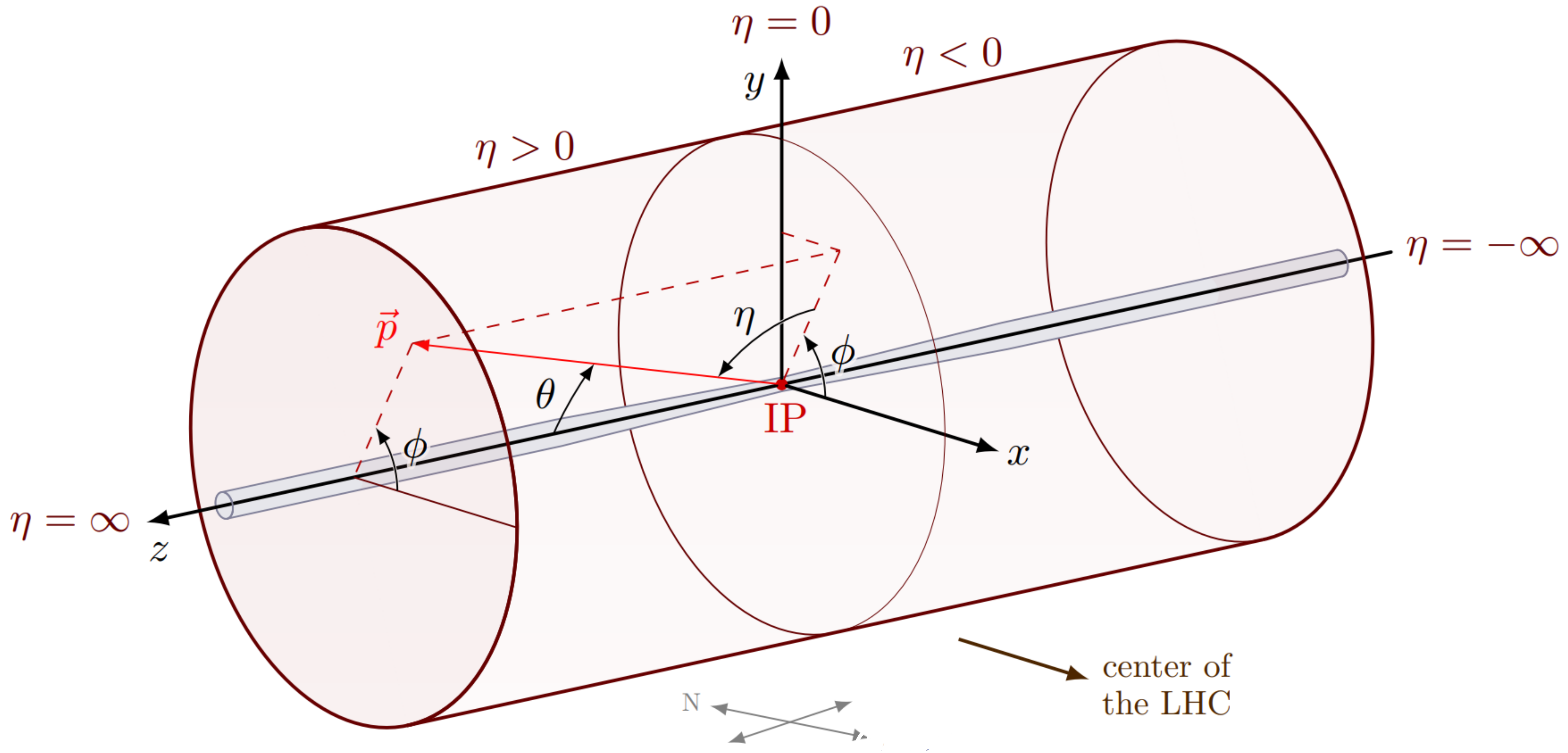
https://tikz.net/axis3d_cms/

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



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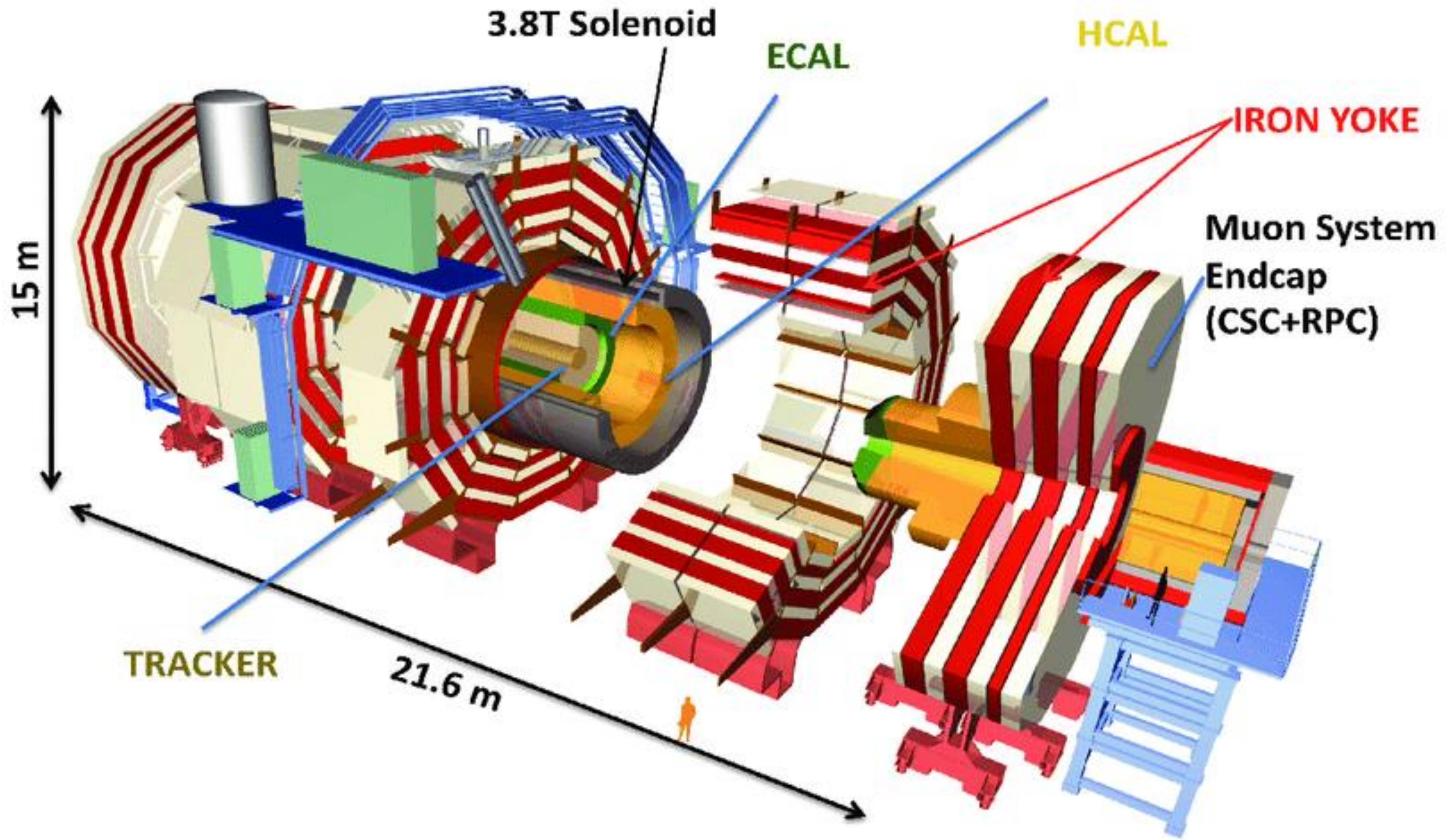
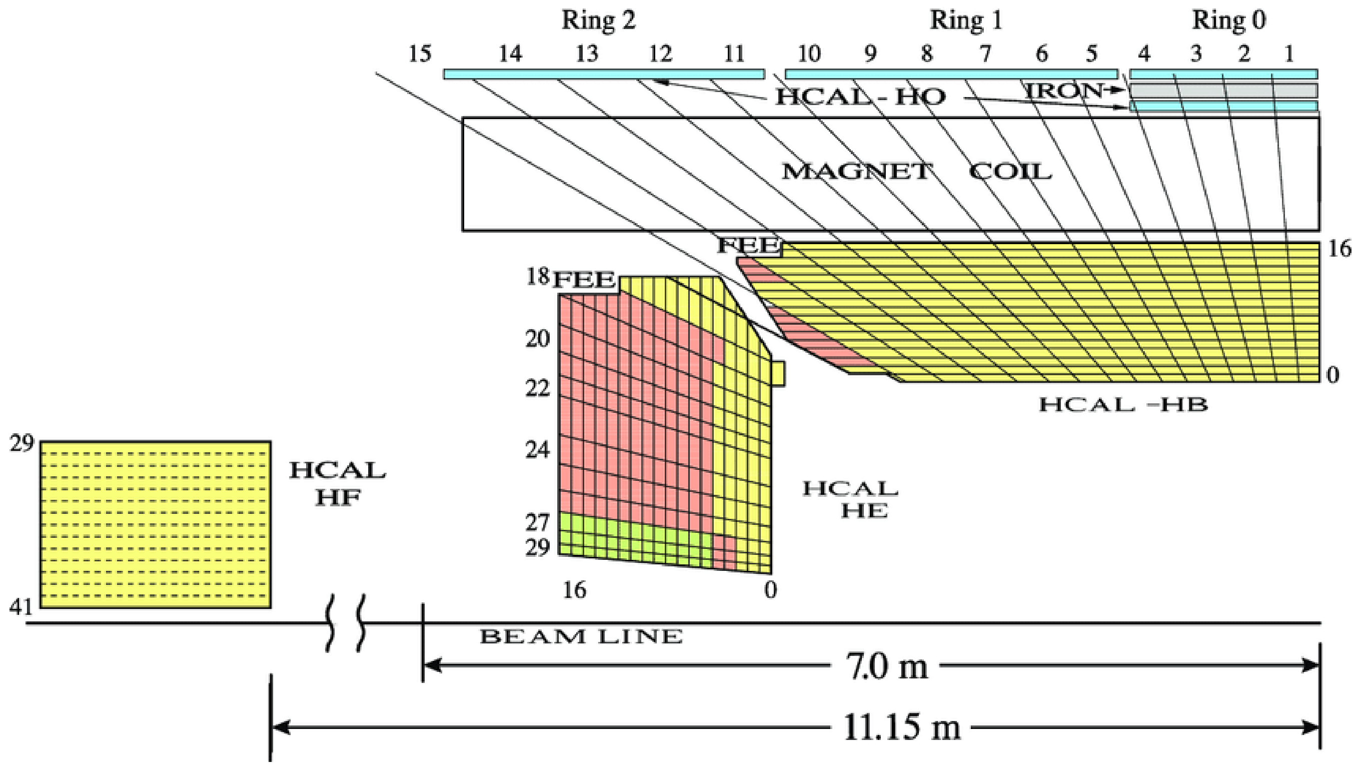


Fig : Schematic Representation of the CMS detector

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 |η| = 3, the forward calorimeter (HF)is placed at 11.2m from interaction point and a psuedorapidity up to |η|=5.2



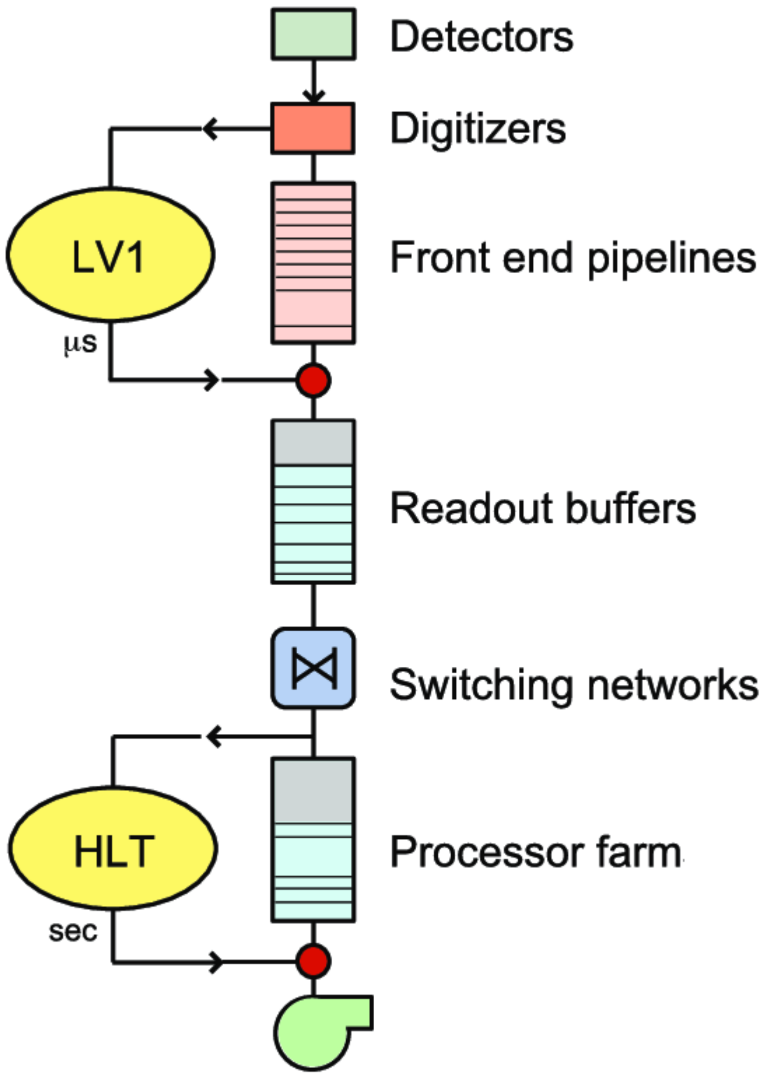
Chatrchyan, S. & Nedelec, Patrick & Sillou, Daniel & Besancon, M. & Chipaux, Remi & Dejardin, M. & Denegri, D. & Descamps, J. & Fabbro, B. & Faure, J.L. & Ferri, Frederick & Ganjour, S. & Gentit, F & Givernaud, A. & Gras, Philippe & Monchenault, G & Jarry, P & Lemaire, M & Locci, E. & Romaniuk, Ryszard. (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).

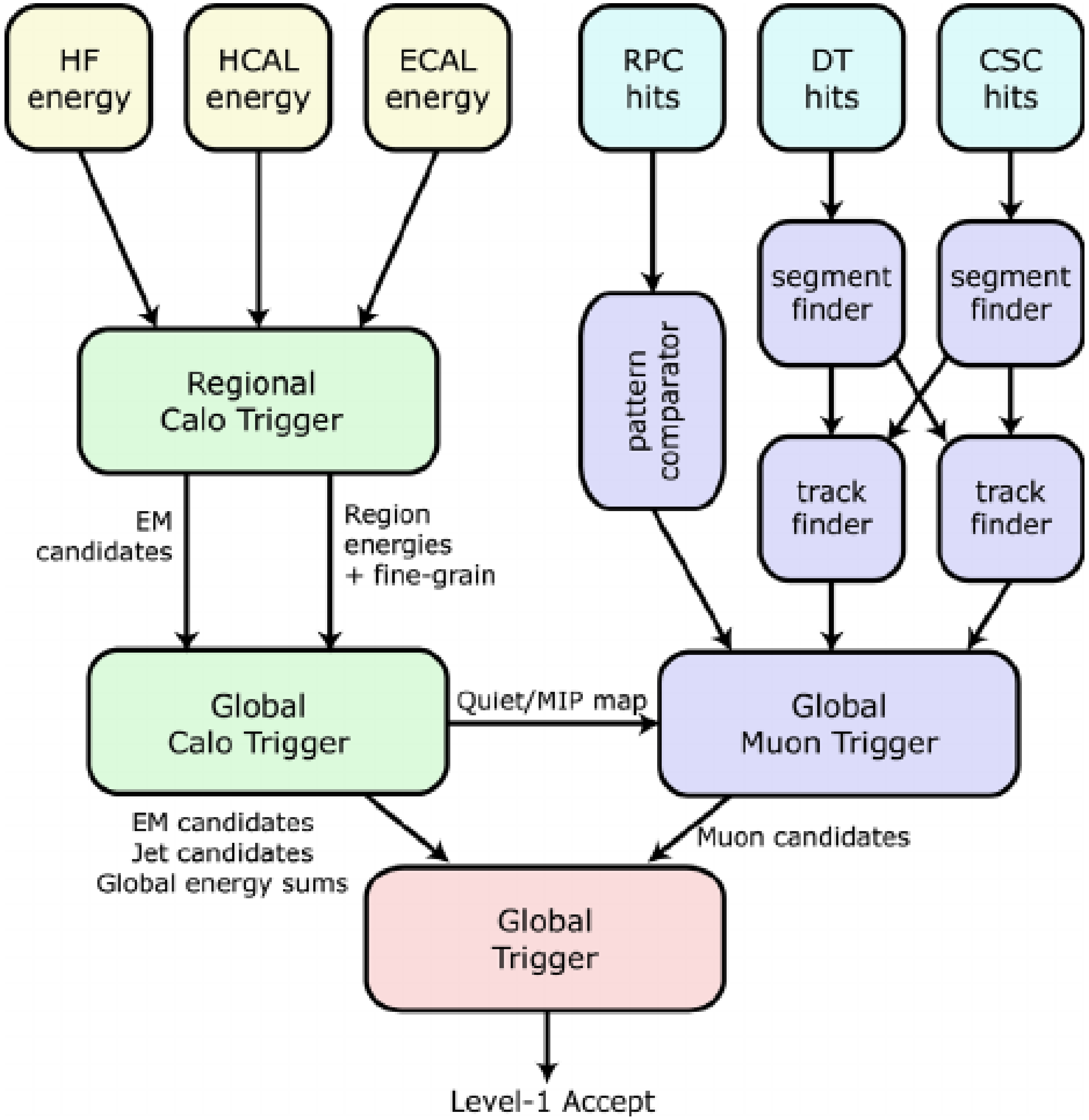
The Trigger System and Data Acquisition

- 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).

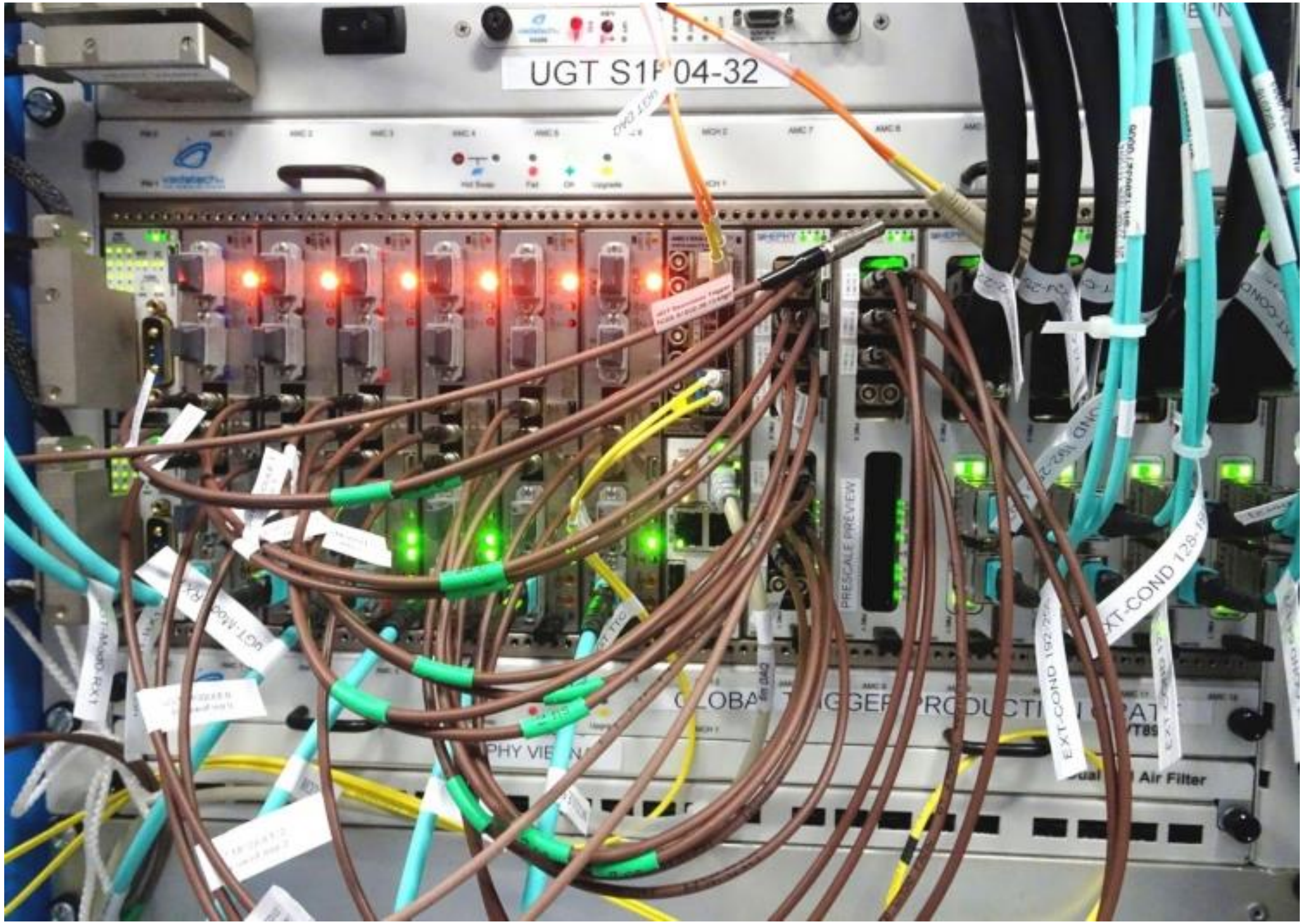


L1 Trigger

- 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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