Search for Dark Matter with Graph Neural Networks at CMS

ETP Meeting

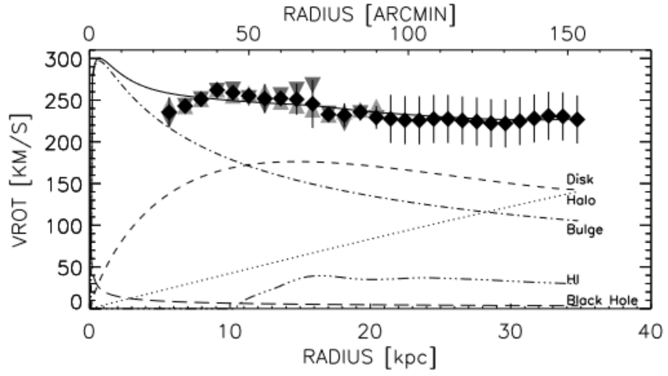
Jost von den Driesch | April 25, 2022

Outline

- Introduction to Dark Matter
- Introduction to MET reconstruction
- Part I: GraphMET
- Part II: Sensitivity analysis of different MET reconstruction methods
- Summary and Outlook

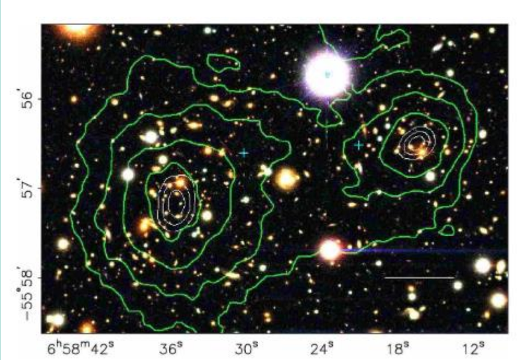
Evidence for Dark Matter

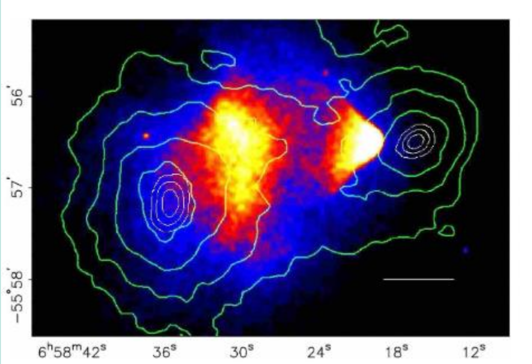
Galaxies



https://arxiv.org/pdf/astro-ph/0603143.pdf

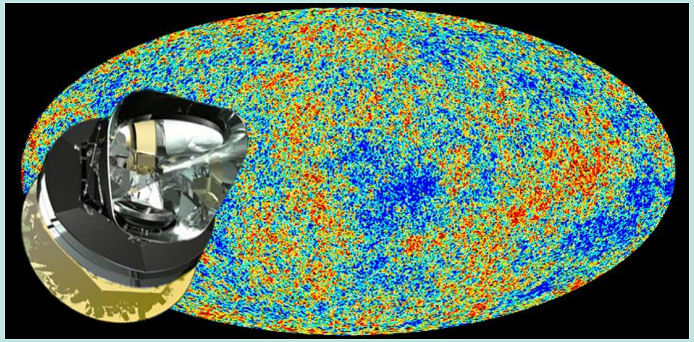
Galaxy Clusters



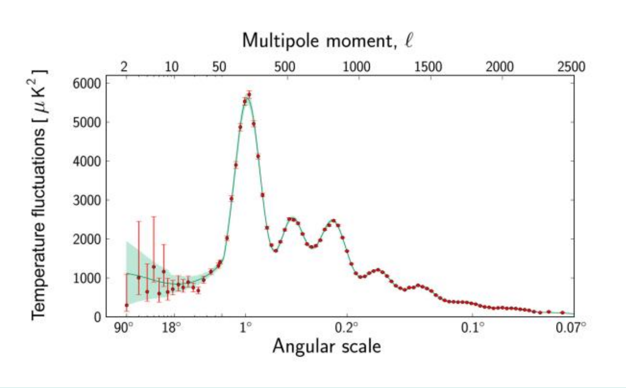


https://arxiv.org/pdf/astro-ph/0608407.pdf

Cosmic Microwave Background



http://newscenter.lbl.gov/wp-content/uploads/sites/2/Planck-and-CMB-sim-revised.jpg

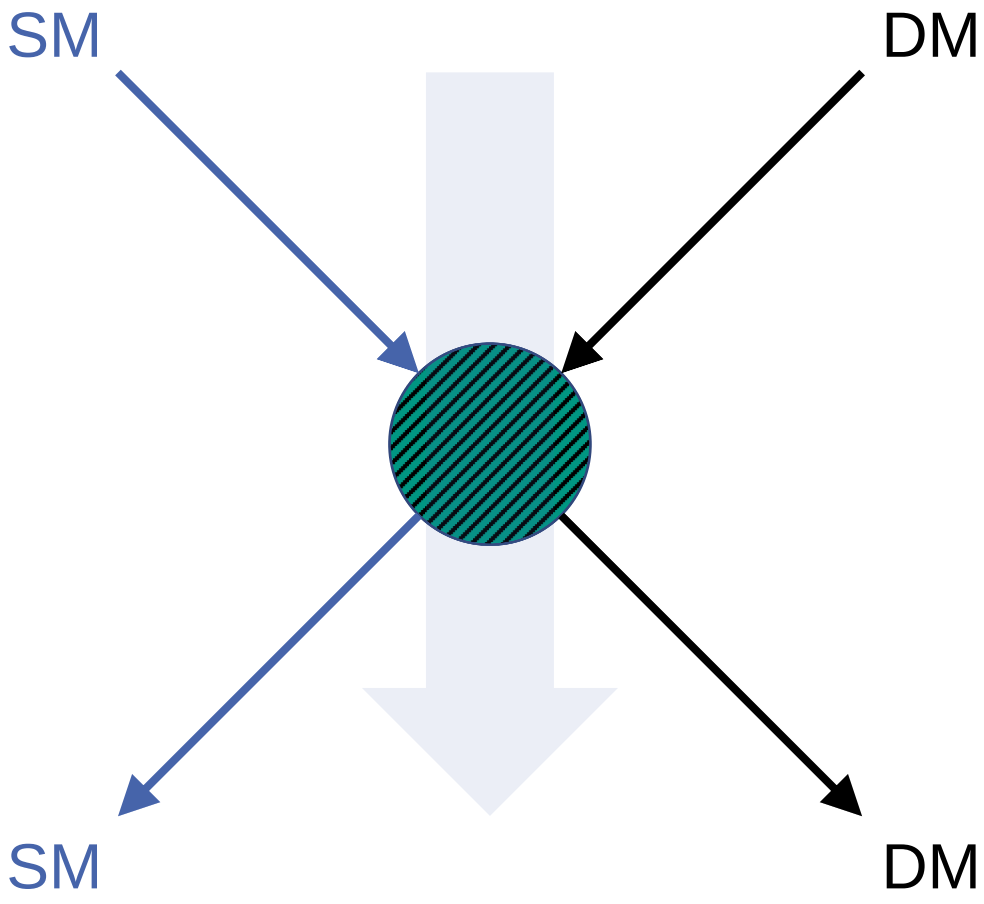


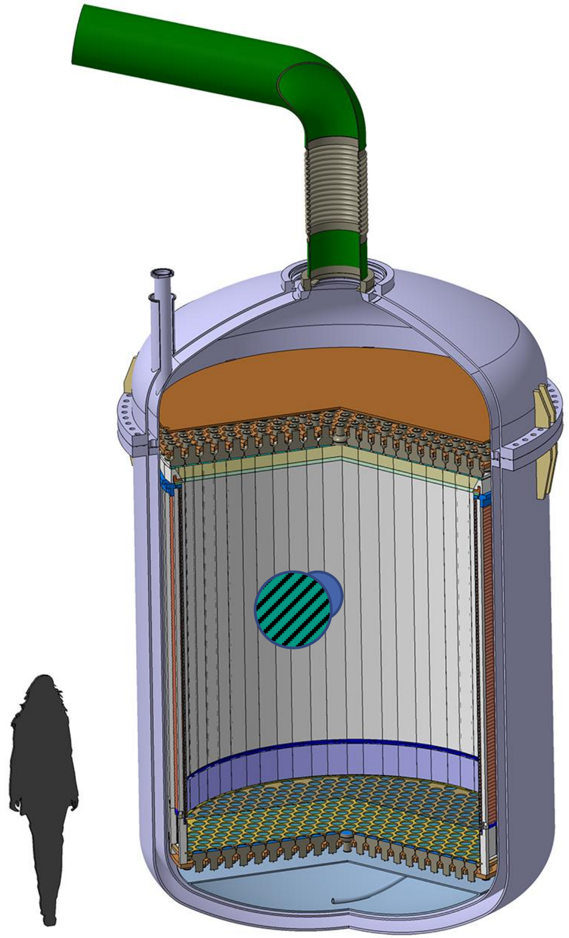
https://www.esa.int/var/esa/storage/images/esa_multimedia/images/2013/03/planck_power_spectrum/12584050-5-eng-GB/Planck_Power_Spectrum_pillars.jpg

Search for Dark Matter – Interactions

- Gravity? ✓
- Electromagnetic interaction? ✗
- Strong interaction? ✗
- Weak interaction? ?
- New interaction? ?

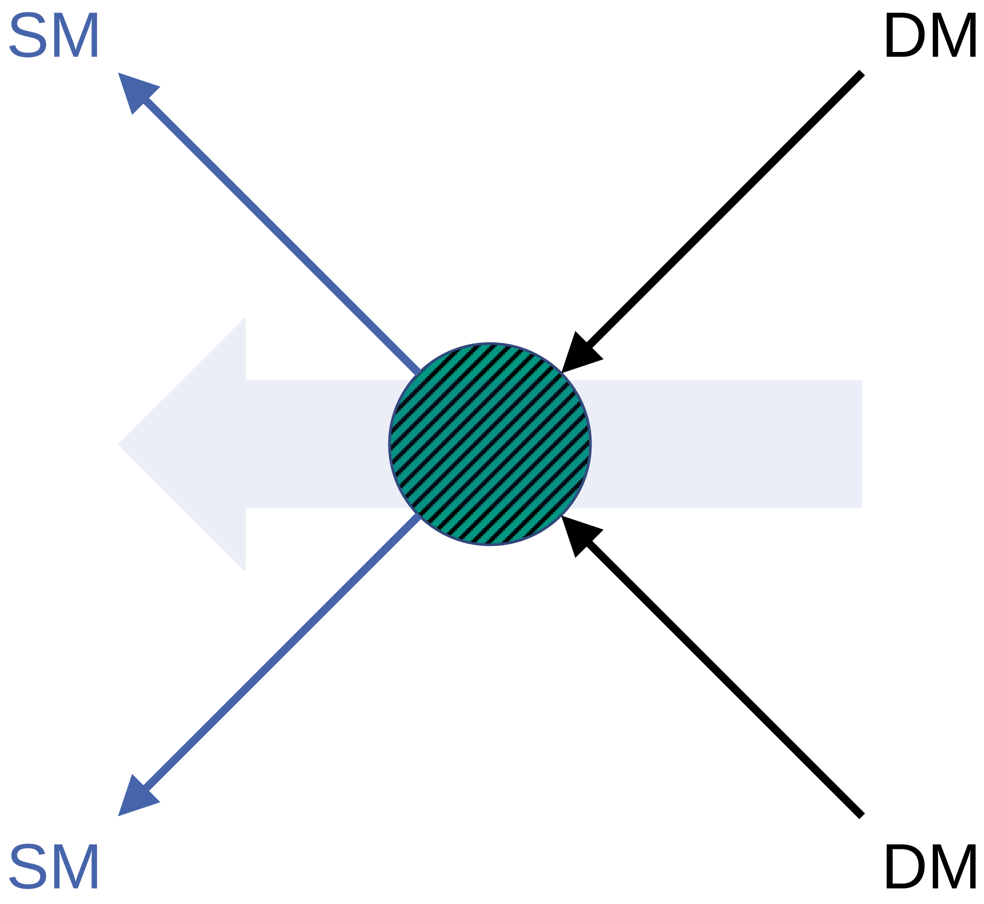
Search for Dark Matter – Direct Detection





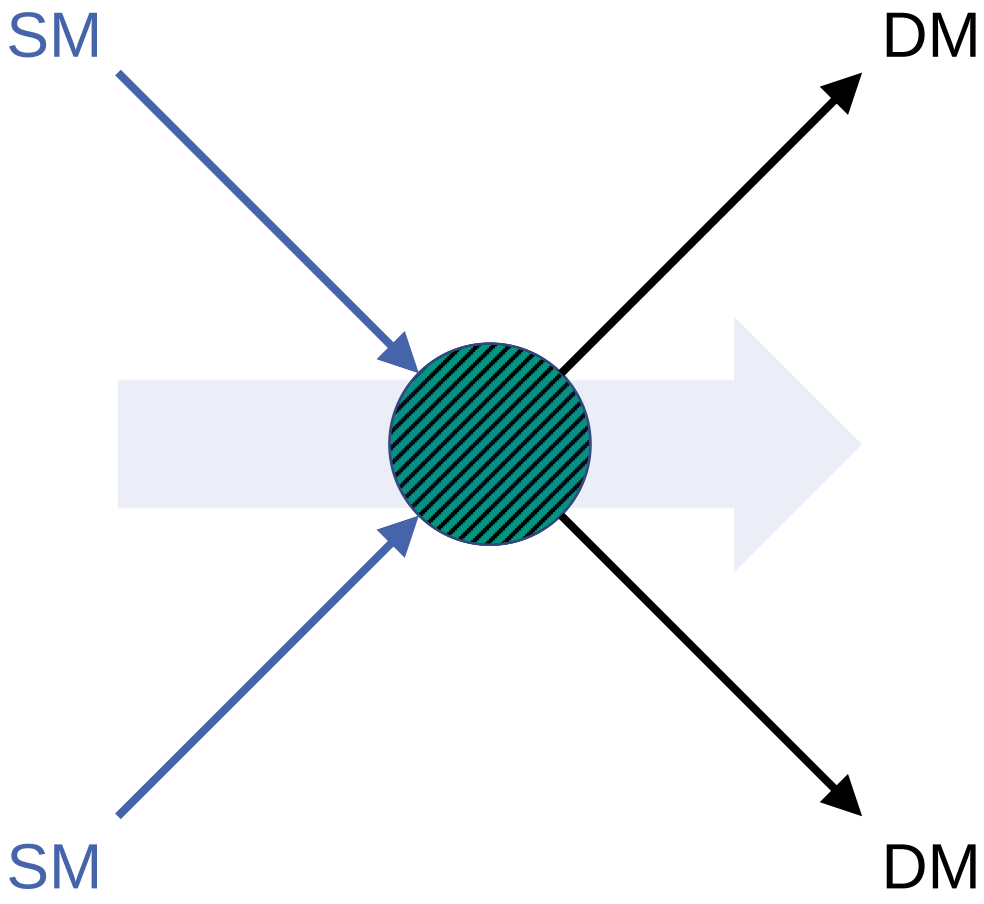
https://www.iap.kit.edu/dm/img/darwin_50t_silhouette_800px.jpg

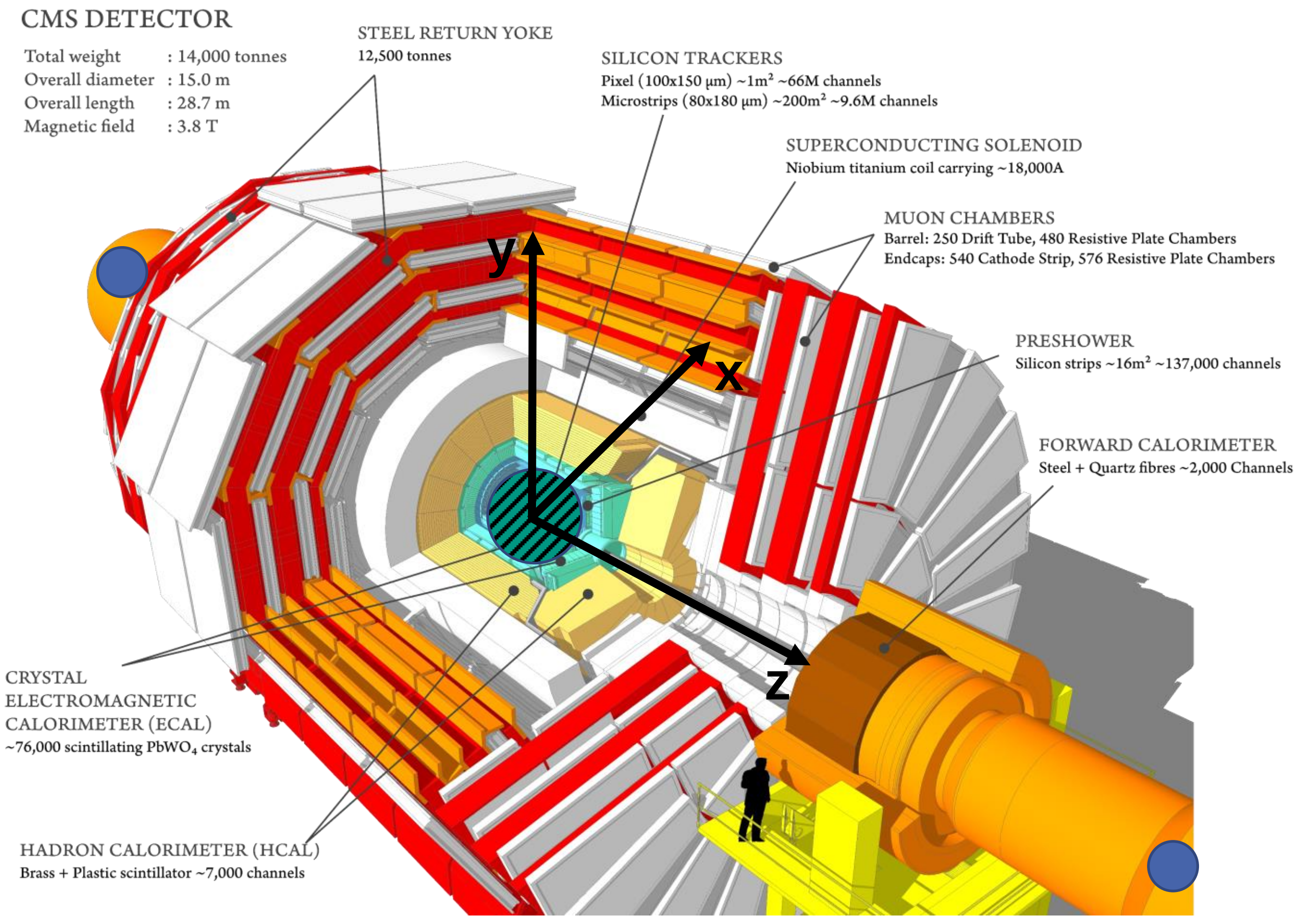
Search for Dark Matter – Indirect Detection



https://upload.wikimedia.org/wikipedia/commons/8/80/Alpha_Magnetic_Spectrometer_-_02.jpg

Search for Dark Matter – Production





https://cmsexperiment.web.cern.ch/sites/cmsexperiment.web.cern.ch/files/cms_160312_02.png

Introduction to MET Reconstruction

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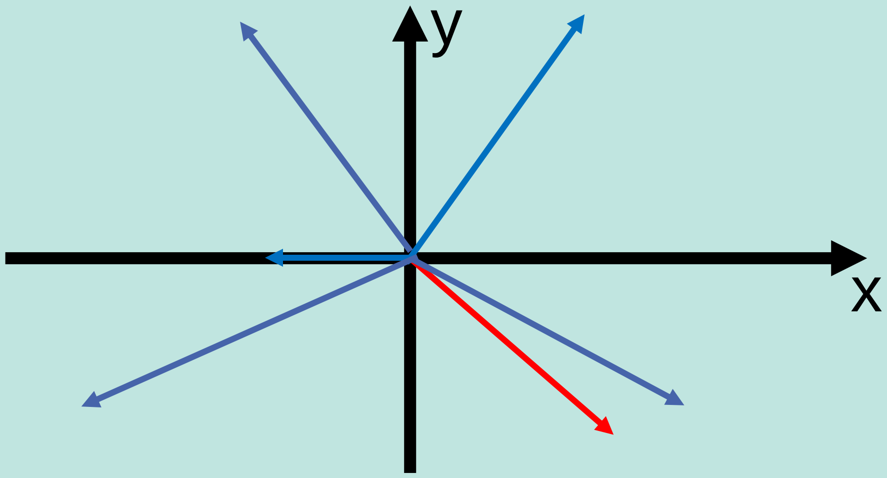
Challenge

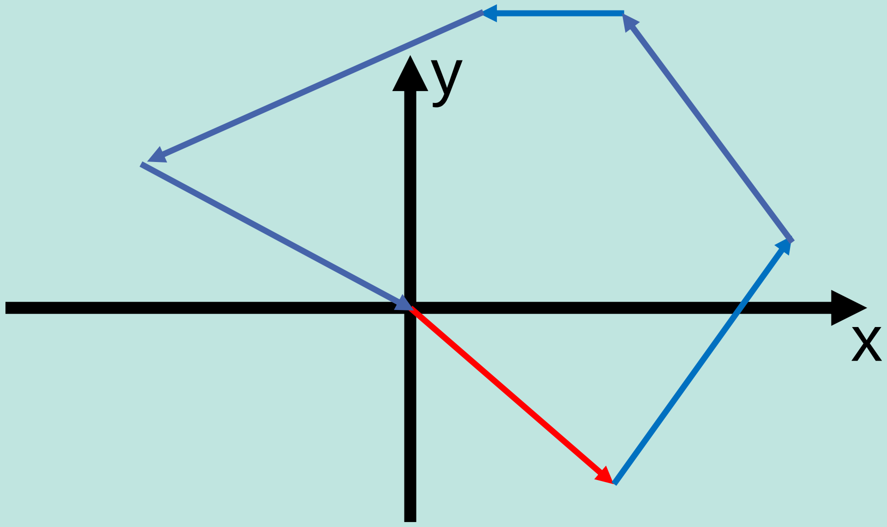
Direct measurement of DM not possible



Five detected particles and one undetectable particle in the transverse plane

Idea

Use indirect measurement



Reconstruction formula:

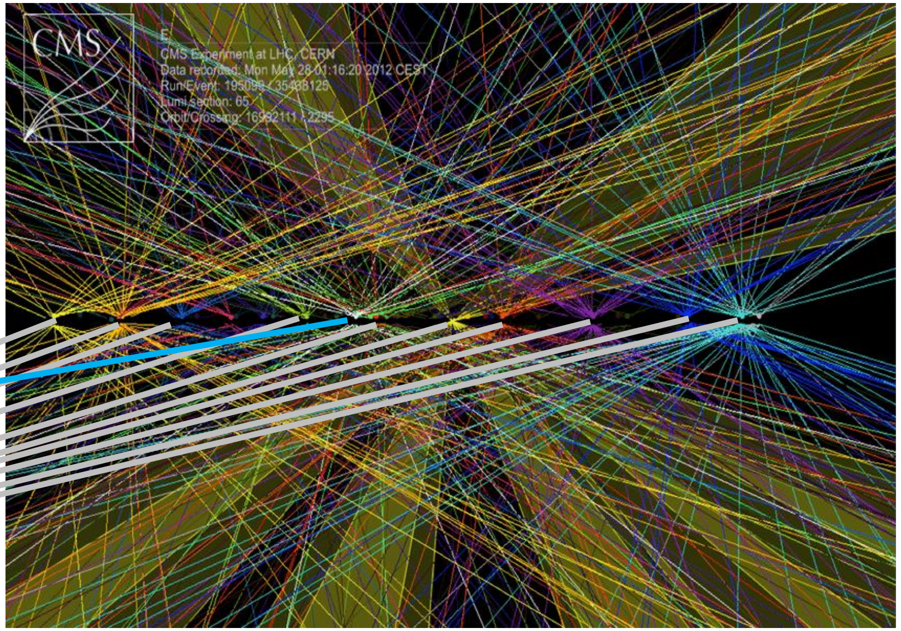
MET = - Σ $\boldsymbol{p}_T$

MET Reconstruction Methods at CMS

Particle Flow (PF) algorithm[1]

- Aim: Event reconstruction and particle identification
- Idea: Combine information of different detector components
- Typically ~ 2-3k PF candidates per event

But…



https://www.researchgate.net/publication/278086364/figure/fig1/AS:651473847320576@1532334877151/Pileup-the-number-of-individual-proton-proton-collisions-in-each-event-is-getting-of.png

$$\text{True } \mathbf{MET} = -\underbrace{\textstyle\sum \boldsymbol{p}_{T,k}}_{\text{all detected particles}} + \underbrace{\textstyle\sum \boldsymbol{p}'_{T,k}}_{\text{pileup}}$$

Main interaction (True MET) — all detected particles ($\sum p_{T,k}$) — pileup ($\sum p'_{T,k}$)

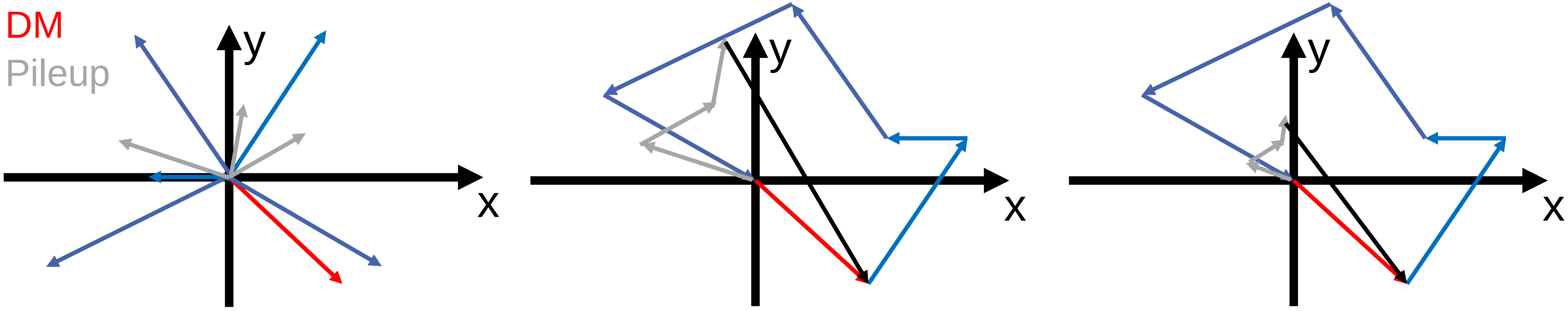
[1] https://arxiv.org/pdf/1706.04965.pdf

Main Challenge: Pileup

Ideas:

- Purist approach: no corrections → PF MET
- Apply Jet Calibrations (JEC) → MET Type I
- Introduce weights: **MET** = $- \Sigma\, w_k\, \boldsymbol{p}_{T,k}$ → PUPPI MET, DeepMET, GraphMET

Detected particles from main interaction
DM
Pileup

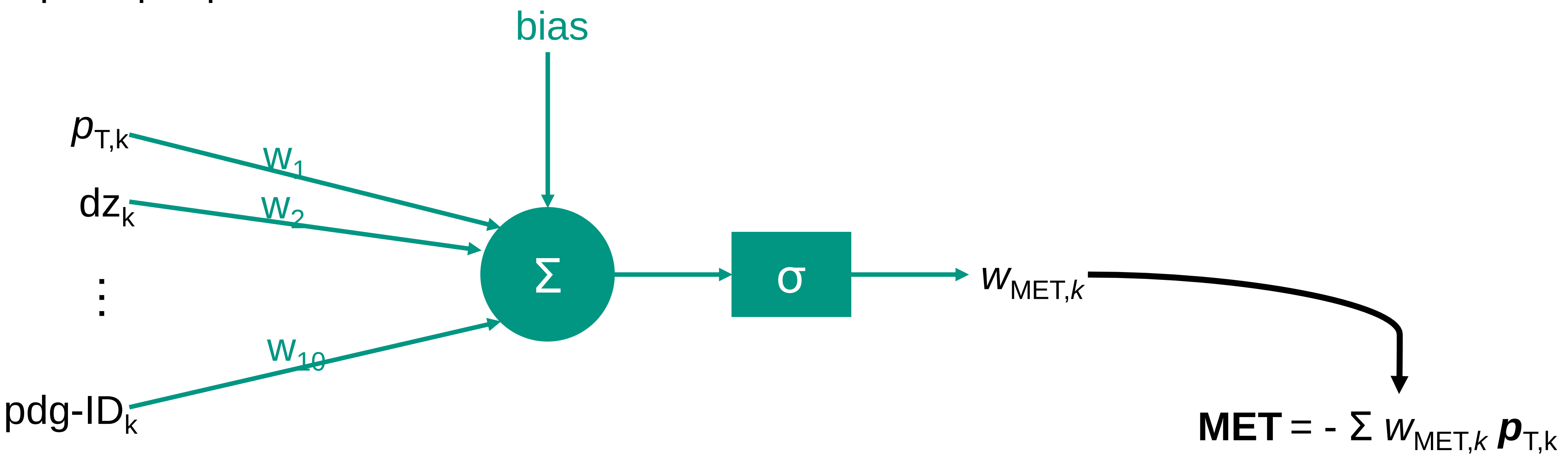


Event with pileup → **PF MET** = $- \Sigma\, \boldsymbol{p}_{T,k}$ → **MET** = $- \Sigma\, w_k\, \boldsymbol{p}_{T,k}$

From Neuron to Graph Neural Network

Neuron:

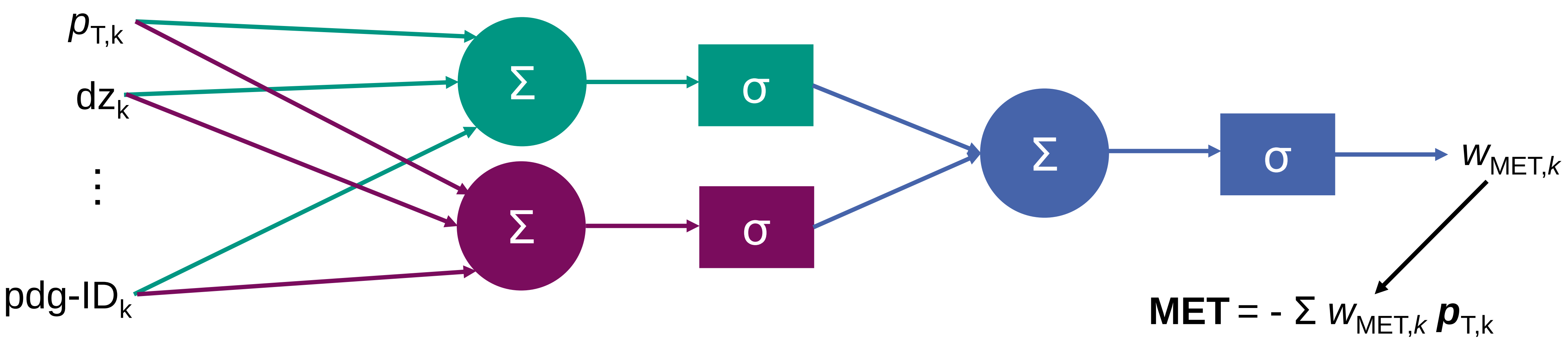
- Aggregate multi-dimensional information for each particle separately into one MET weight
- Input information: p_T, p_x, p_y, m, η, dxy, dz, electric charge, fromPV, pdg-ID
- Description per particle



From Neuron to Graph Neural Network

Neural Network:

- Several parallel and successive neurons
- Able to fit more complex models than a single neuron
- Description per particle



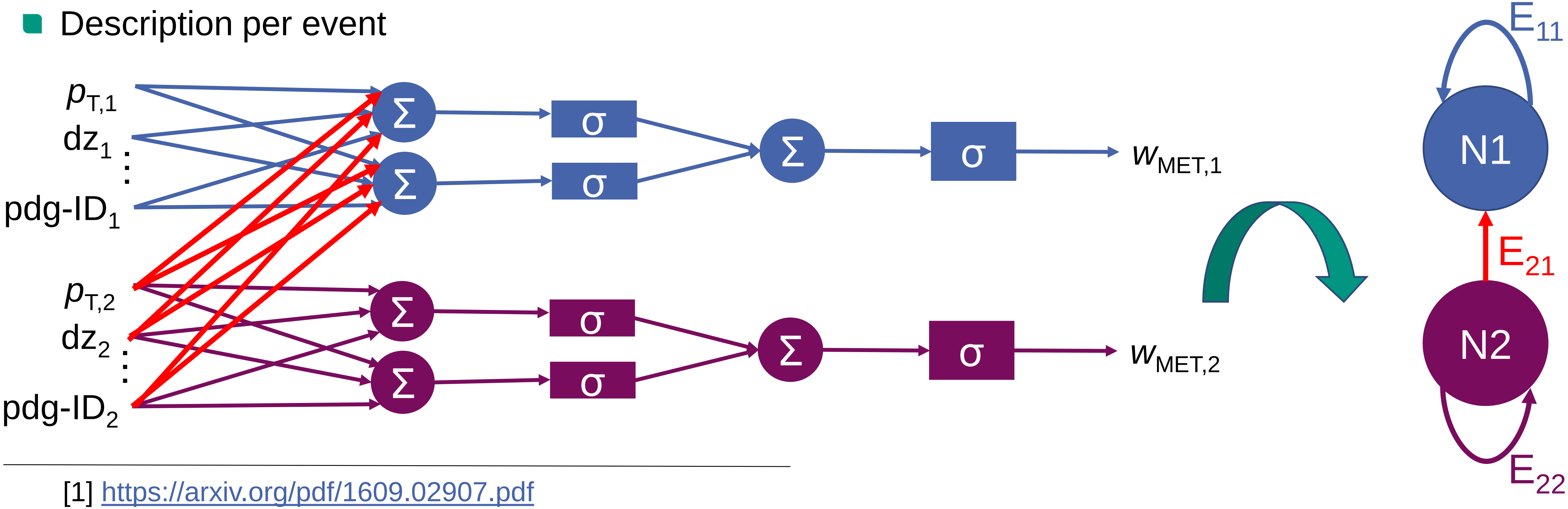
$\textbf{MET} = - \Sigma\, w_{MET,k}\, \boldsymbol{p}_{T,k}$

From Neuron to Graph Neural Network

Karlsruhe Institute of Technology

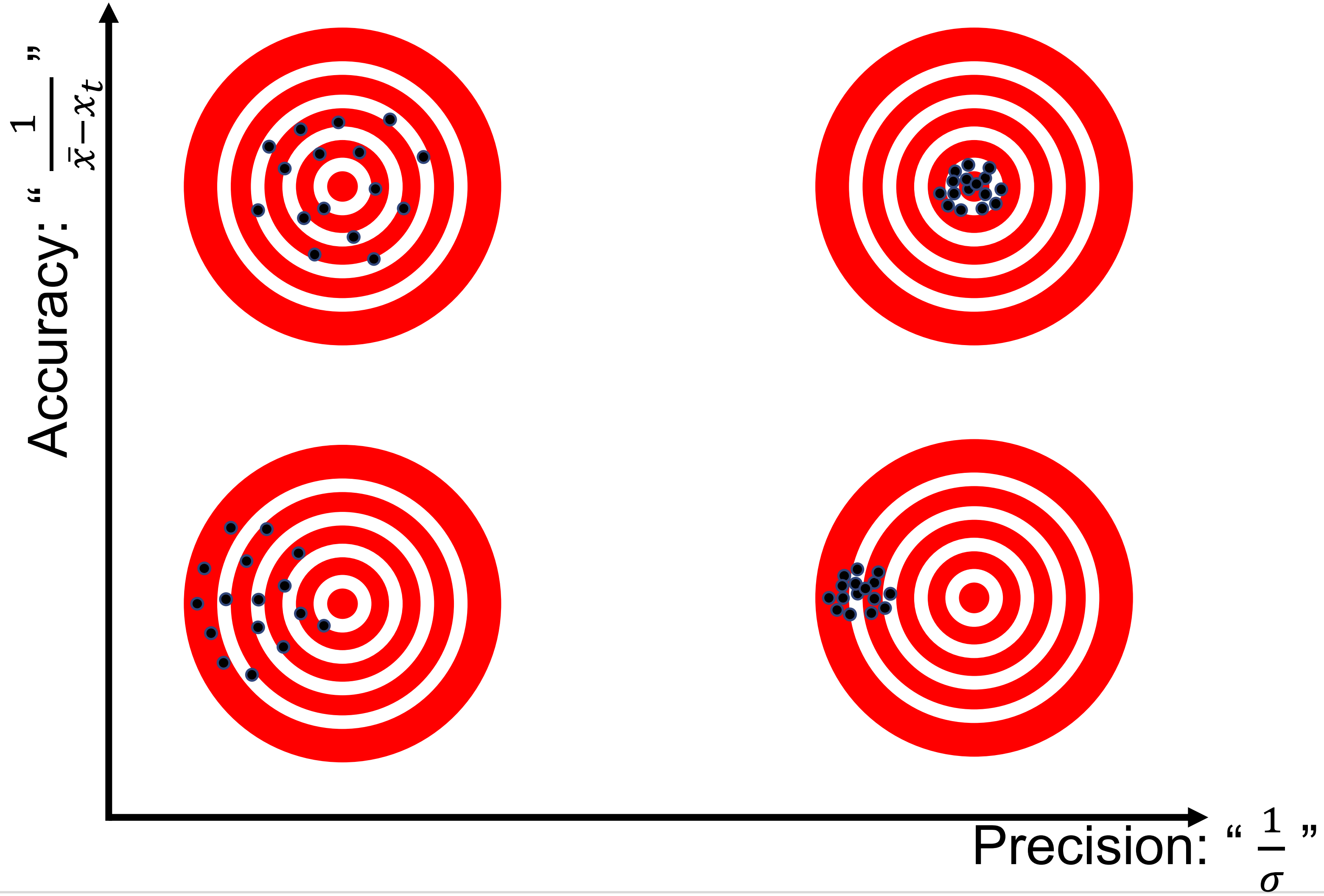
Graph Neural Network (GCNConv[1]):

- Several parallel and successive neural networks
- Able to aggregate information of several particles at once
- Description per event



[1] https://arxiv.org/pdf/1609.02907.pdf

Reminder: Accuracy vs. Precision

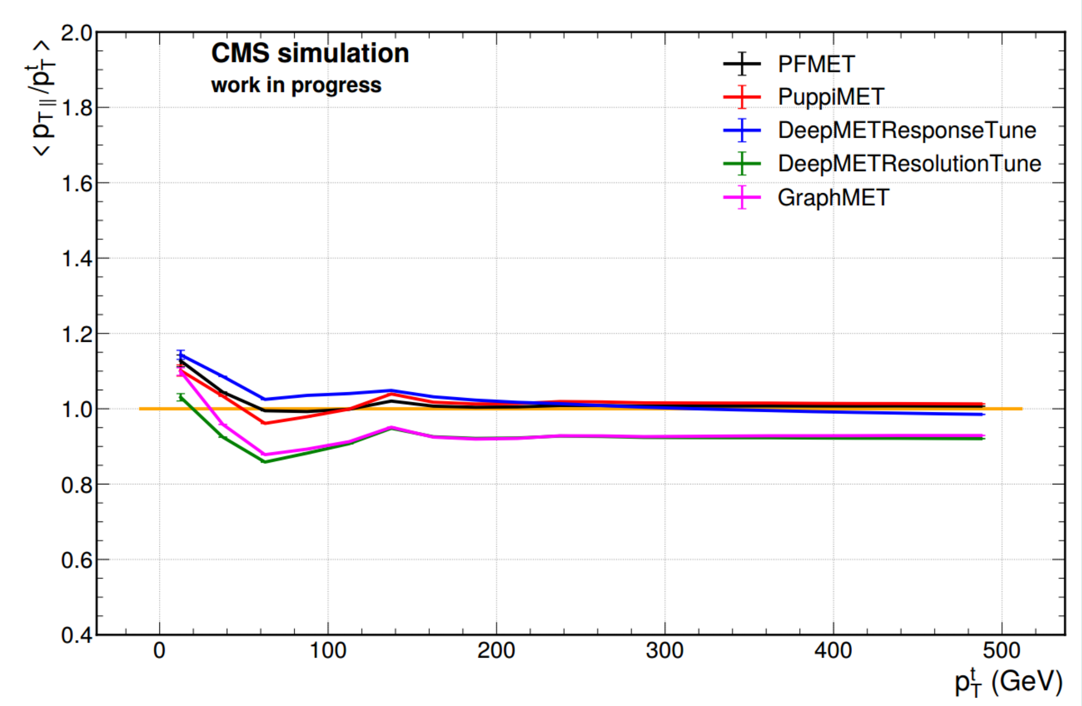


MET Reconstruction Quality

Evaluation on independent Z → $\nu\nu$ (+1Jet) sample

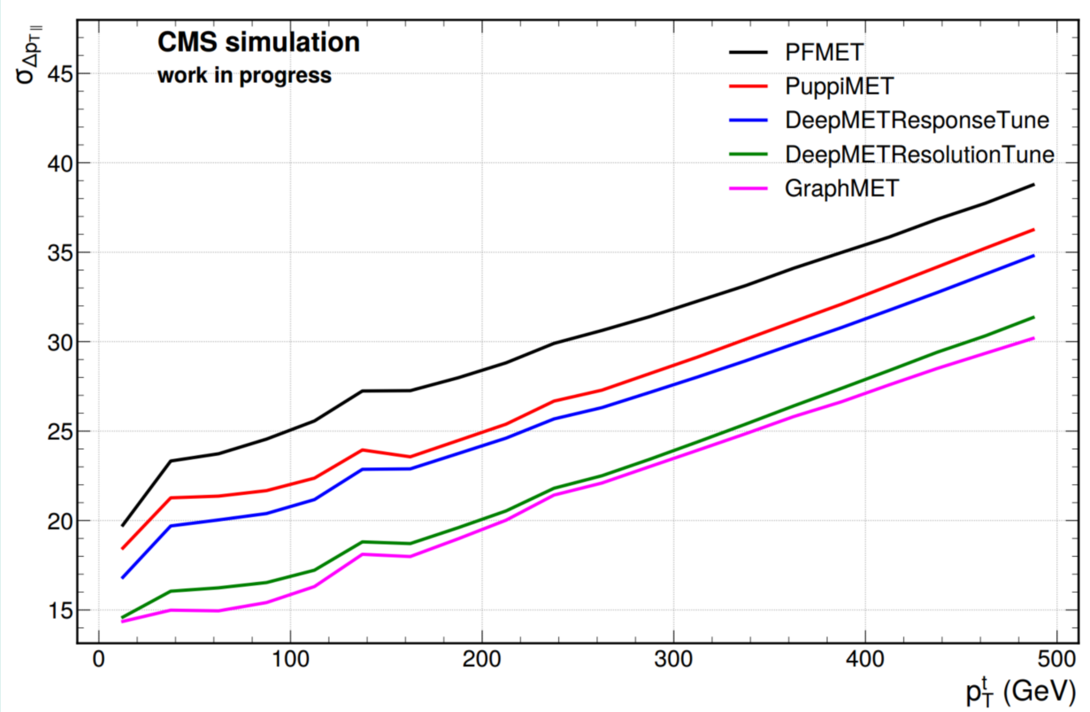
Response

- Quantifies accuracy → target value: 1



Resolution

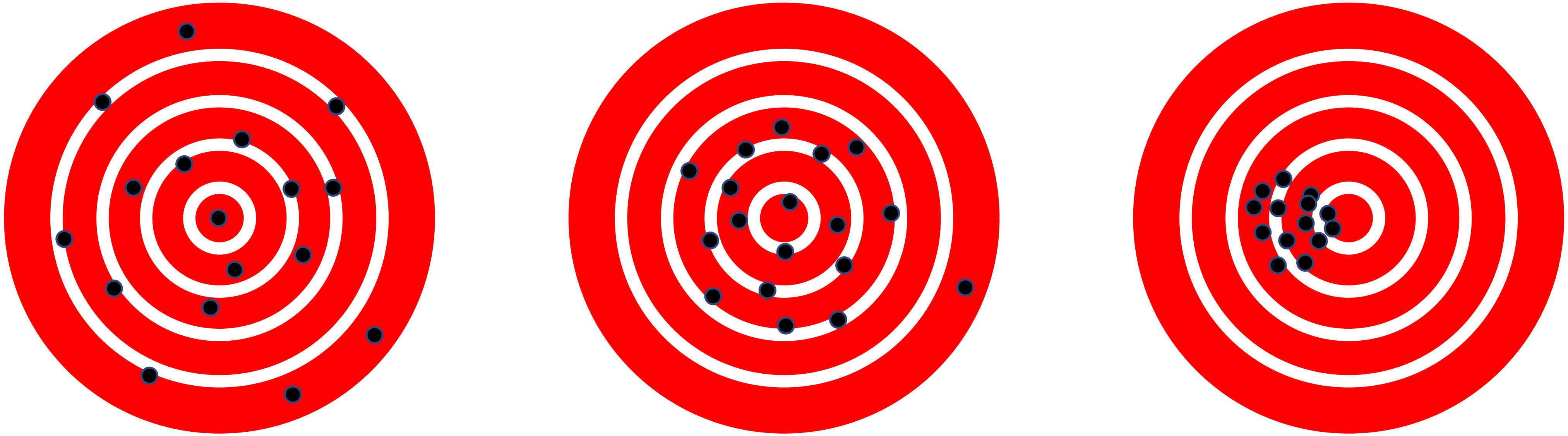
- Quantifies precision → target value: 0 GeV



Summary: MET Reconstruction Quality

Intuitive Interpretation

PFMET PUPPI MET GraphMET



Part II: Sensitivity Analysis

General Idea

- Investigate sensitivity dependency of MET estimator in an analysis sensitive to MET
- Calculate expected asymptotic upper limits with different MET methods and compare them

Setup:

- MC only analysis
  → Truth information available
- Production of data sets with PF information
  → large data sets
  → Consider only main backgrounds

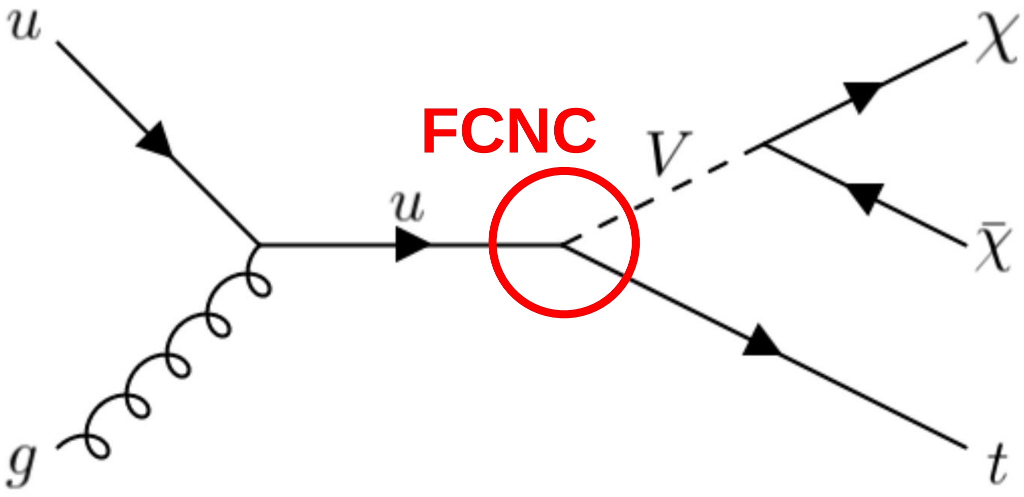
Search for Dark Matter in the Leptonic MonoTop Channel

Simplified Model

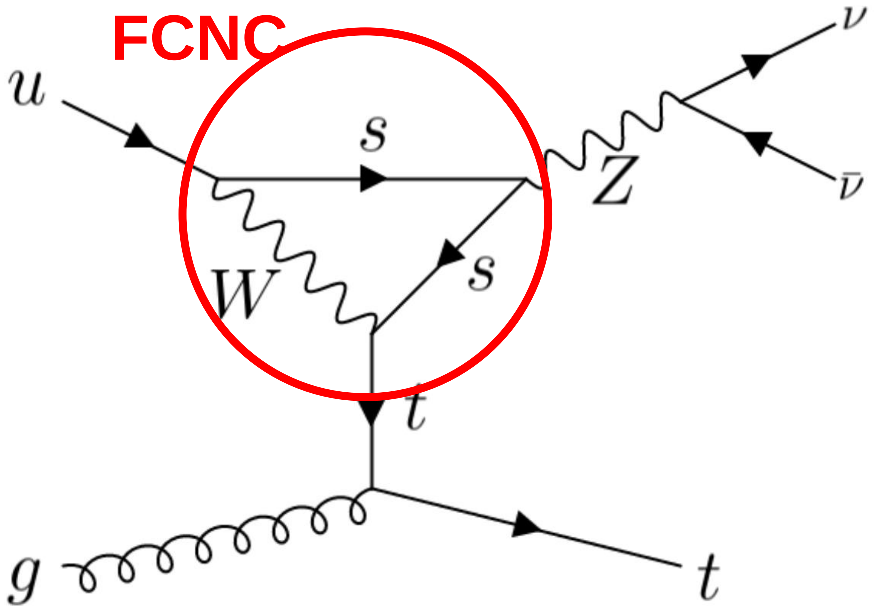
- Stable Dark Matter particle χ with mass m_χ
- Mediator V with mass m_V

Signature:

- Single top quark and large MET → suppressed in SM



signal



main theoretical background

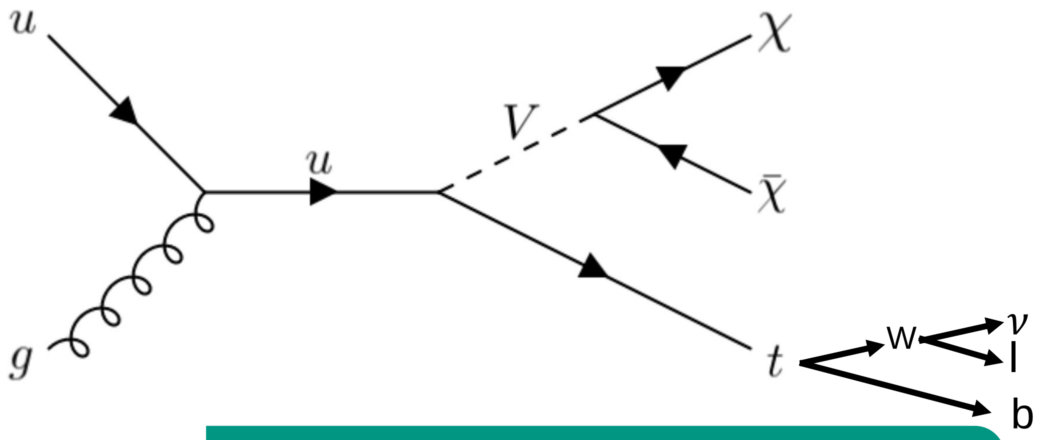
Selections Criteria for Leptonic Channel

Main Selections:
- Exactly one lepton in central region (muon or electron)
- $p_T(q1) \geq 70$ GeV in central region
- MET ≥ 100 GeV
- $\Delta\Phi(MET, q1) \geq 1.5$
- $m_T(W) \geq 40$ GeV

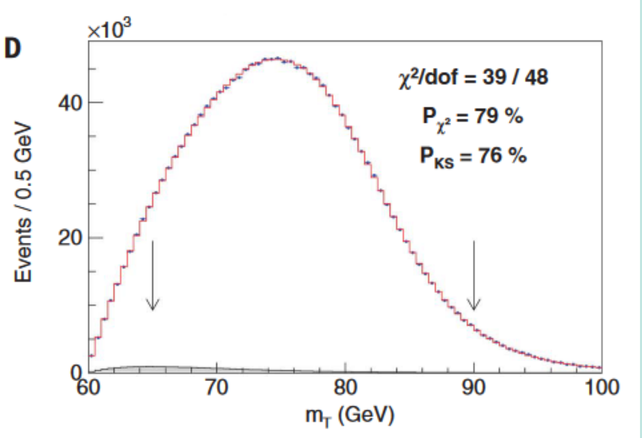
Control Regions:
- N(b-tags) = 2 → enriched in ttbar events
- N(b-tags) = 0 → enriched in W events

} Control rate in fit

Signal Region:
- N(b-tags) = 1 → enriched in monotop events



Transverse Mass
- $m_T^2(W) = 2\ MET\ p_T(l)\ (1 - \cos\Delta\Phi(MET, l))$



https://www.science.org/doi/epdf/10.1126/science.abk1781

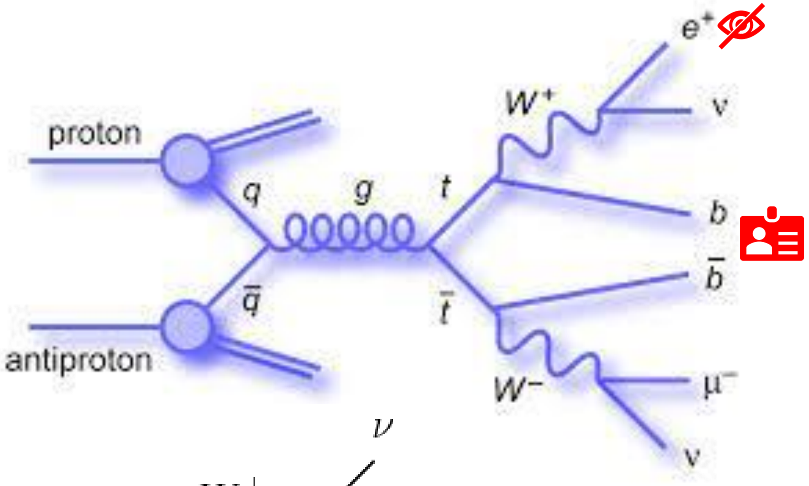
Main Backgrounds in Signal Region

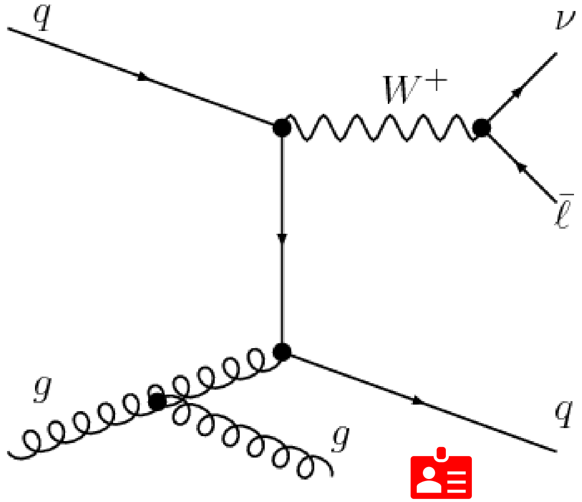
Main Selections:

- Exactly one lepton in central region (muon or electron)
- $p_T(q1) \geq 70$ GeV in central region
- MET ≥ 100 GeV
- $\Delta\Phi(\mathrm{MET}, q1) \geq 1.5$
- $m_T(W) \geq 40$ GeV

Signal Region:

- N(b-tags) = 1 → enriched in monotop events

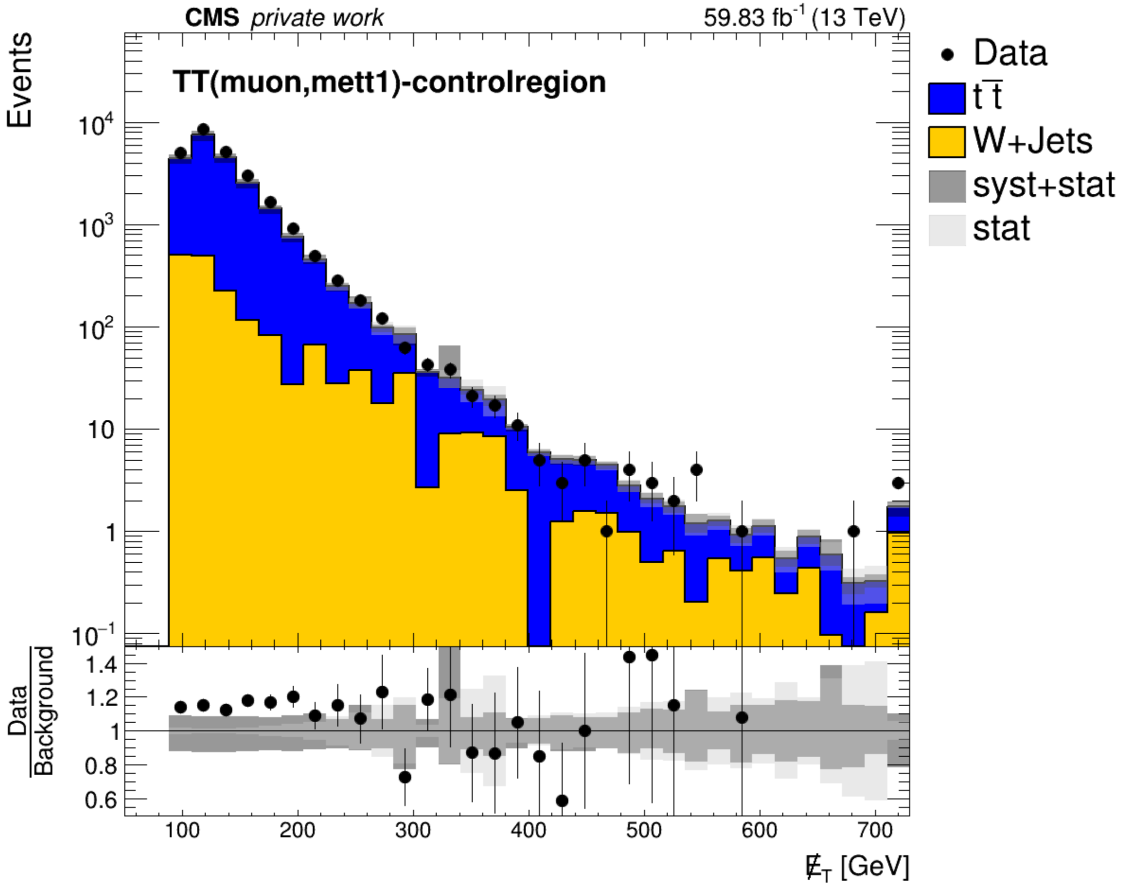




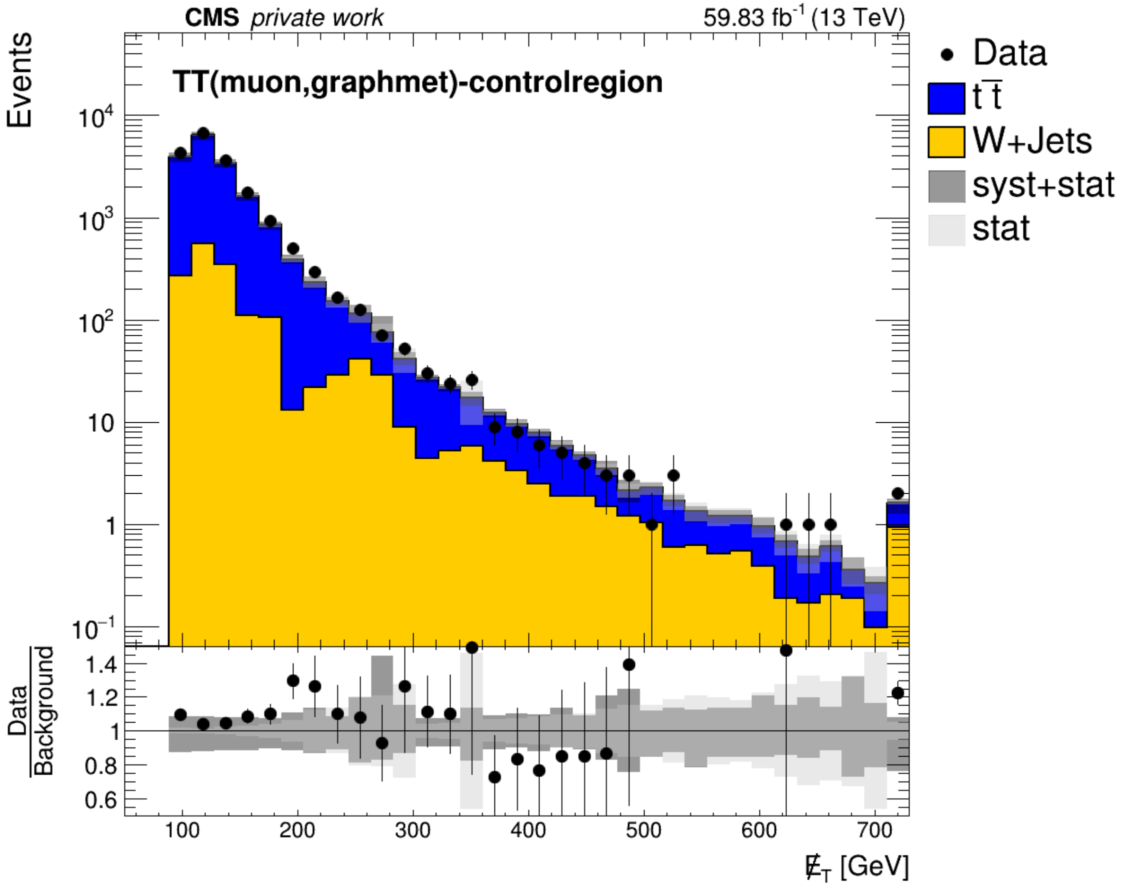
Questions to Control Regions

- Is data description by MC roughly accurate?
  - Perfect description not needed as sensitivity analysis is MC only
  - Comparison of reconstruction methods more interesting than absolute limits at this point
- Major discrepancies when using different MET reconstruction methods?
  - Shapes
  - Event-yield

Control Region MET

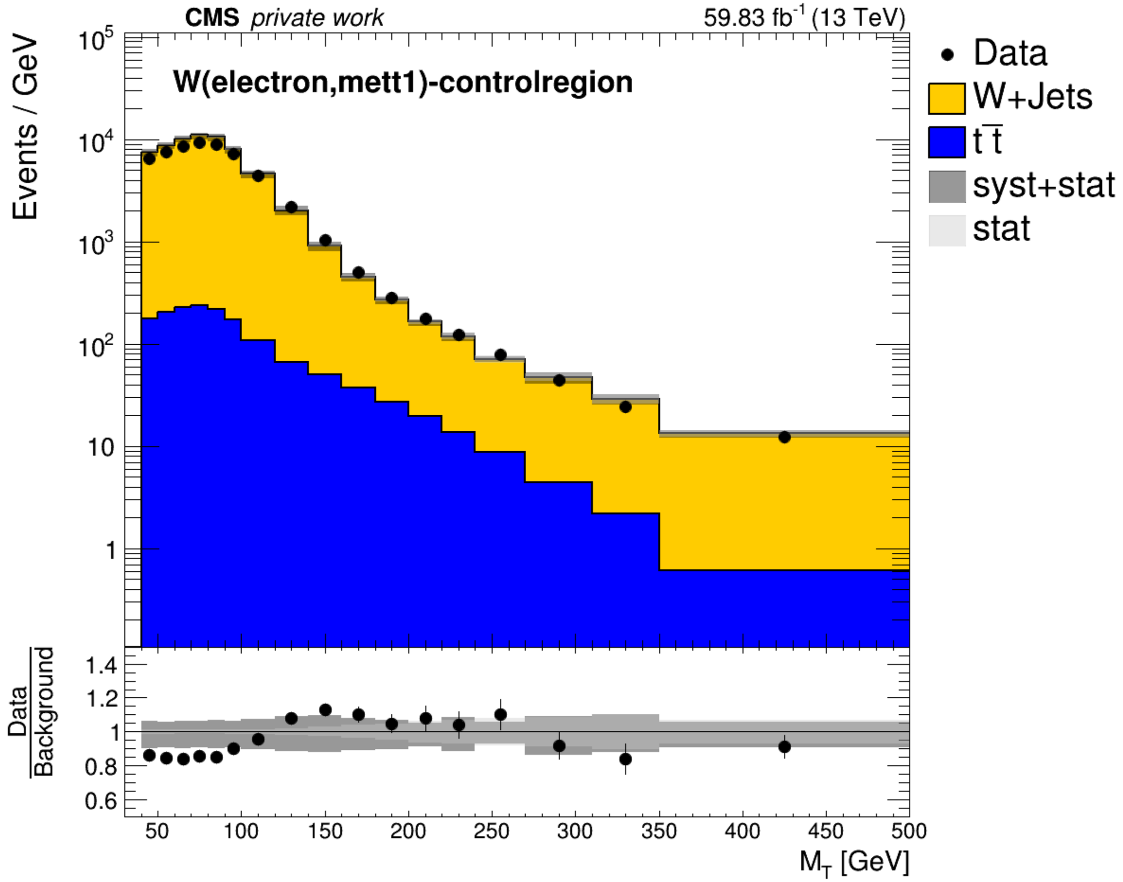


MET-Type-I
(with Jet calibrations)



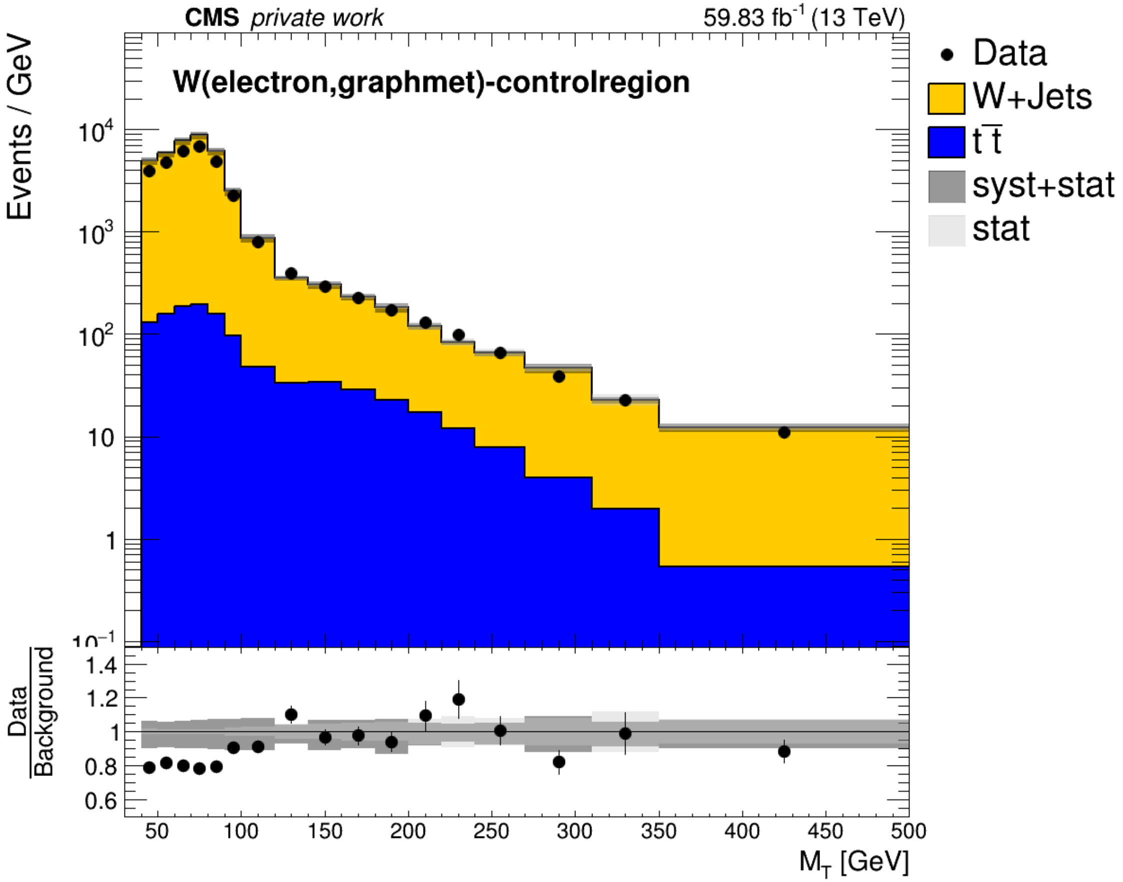
GraphMET

Control Region M_T



MET-Type-I

(with Jet calibrations)



GraphMET

Questions to Control Regions

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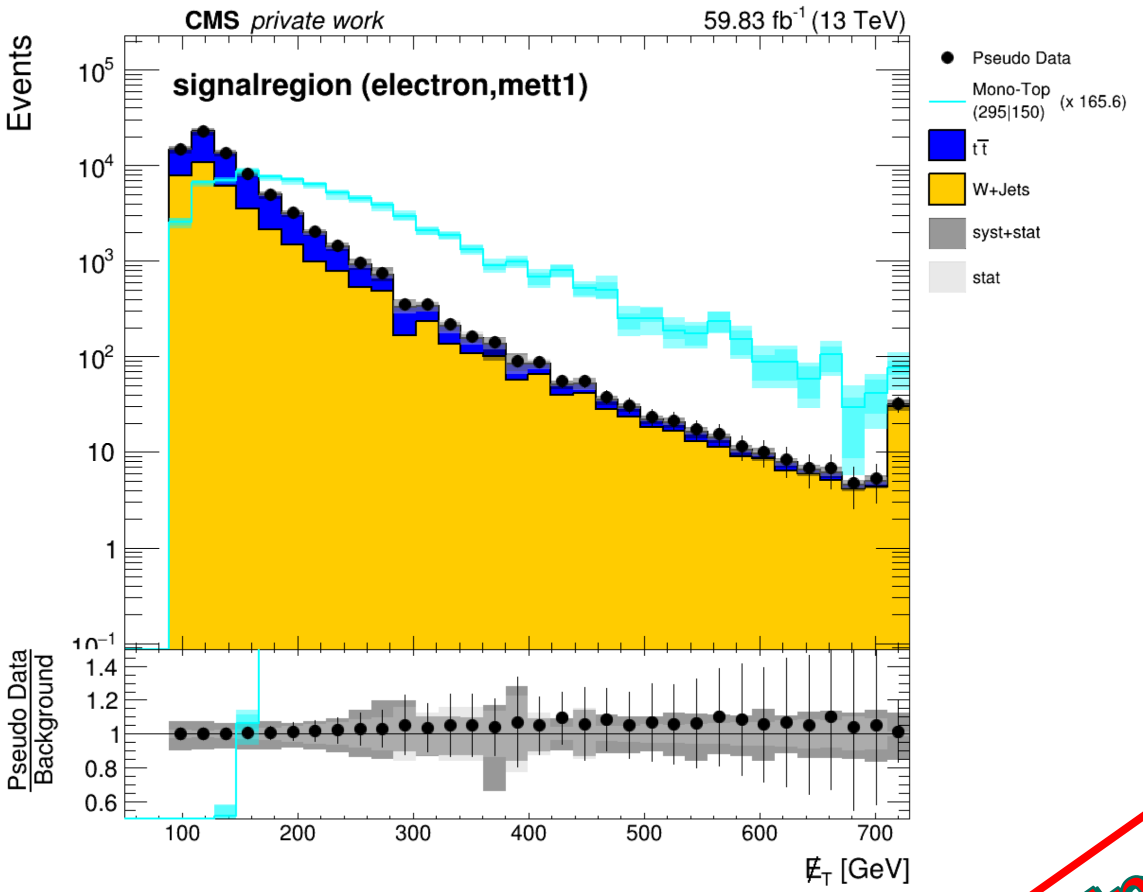
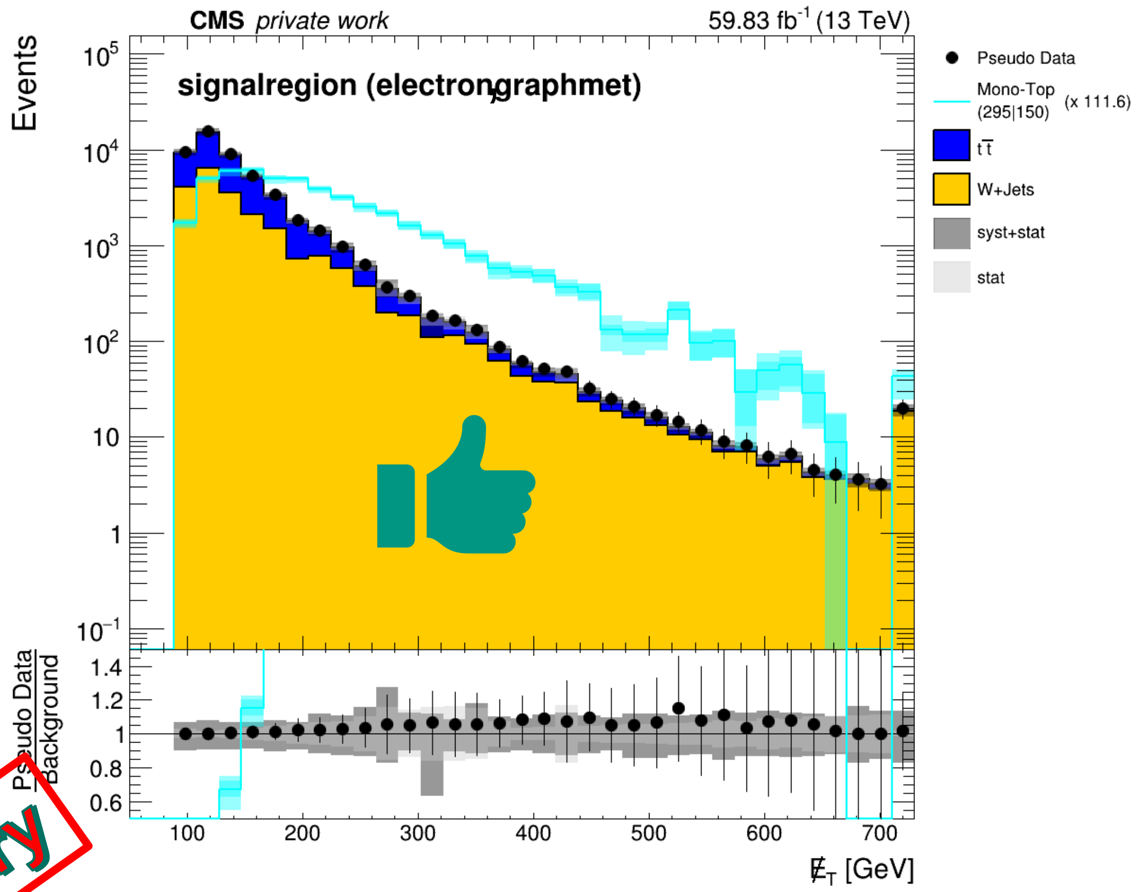
- Is data description by MC roughly accurate? ✓
  - Perfect description not needed as sensitivity analysis is MC only
  - Comparison of reconstruction methods more interesting than absolute limits at this point
- Major discrepancies when using different MET reconstruction methods?
  - Shapes ✓
    → Less smearing in M_T distribution for GraphMET due to better MET resolution
  - Event-yield ✓
    → Due to MET underestimation of GraphMET and MET cut

Signal Region MET





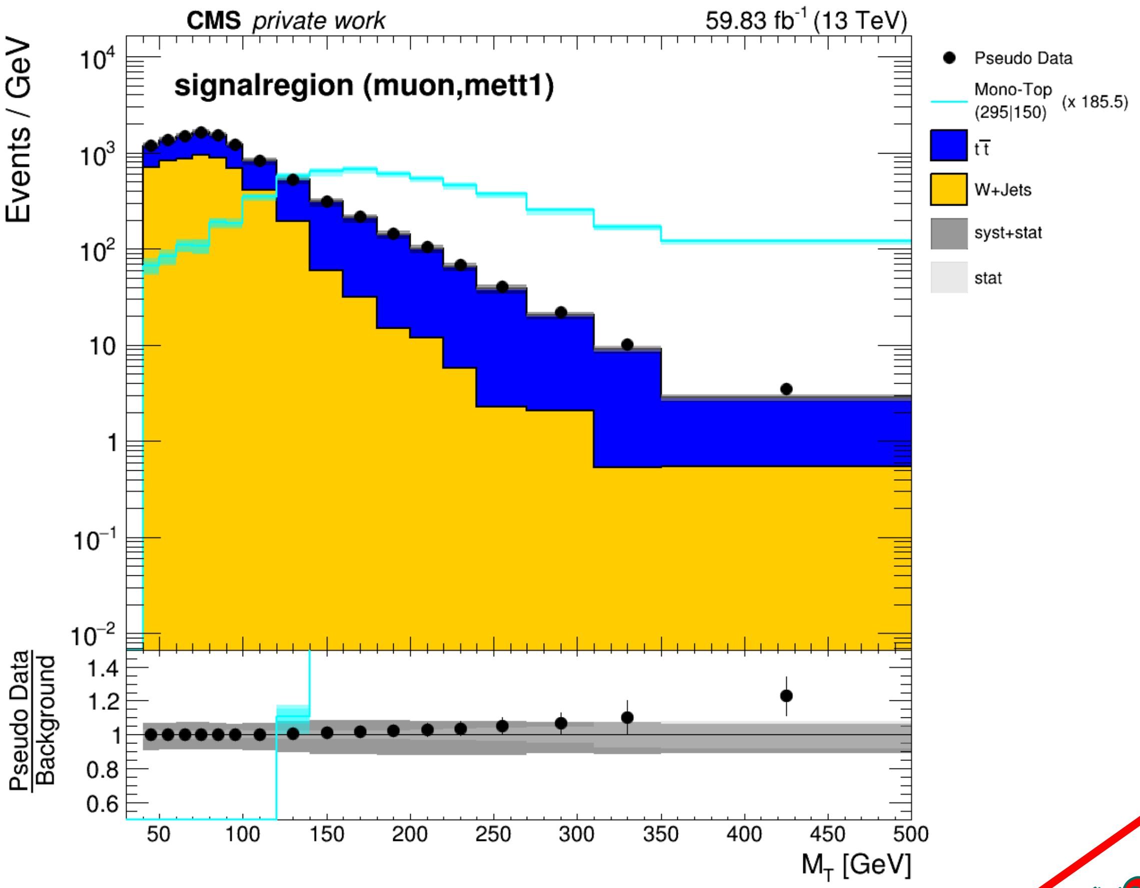
MET-Type-I
(with Jet calibrations)

$\mu^{95\%}_{\text{MET-T-I}} > \mu^{95\%}_{\text{GraphMET}}$

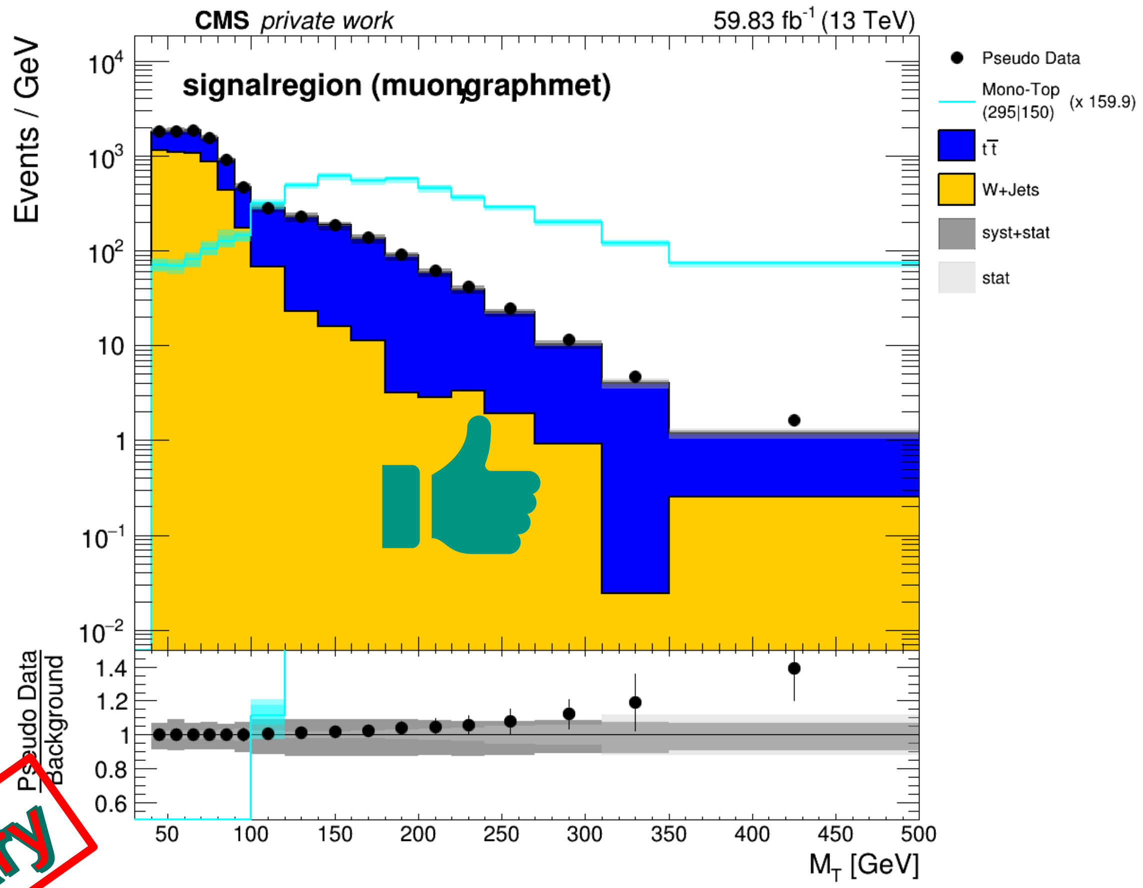
GraphMET

Preliminary

Signal Region M_T



MET-Type-I
(with Jet calibrations)



GraphMET

$\mu^{95\%}_{\text{MET-T-I}} > \mu^{95\%}_{\text{GraphMET}}$

Preliminary

Summary and Outlook

GraphMET

- Introduction of a new MET reconstruction method using GNNs
- Improved resolution
- Room for improvement in response
  - Add term in loss function
  - Apply calibration
  - Systematics should be investigated further

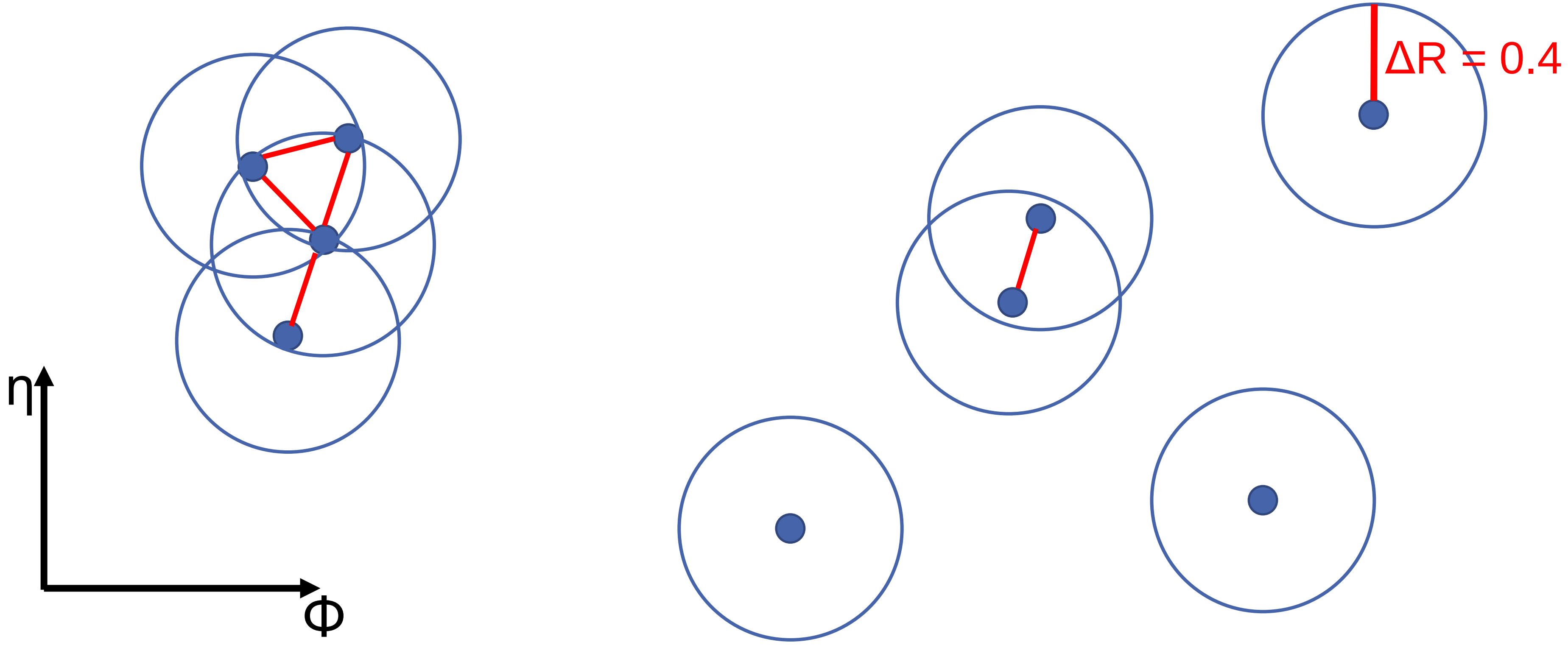
Sensitivity Analysis

- First application case for GraphMET: Search for Dark Matter in the leptonic monotop channel
- Templates don't indicate any major problems
- Expected upper limits indicate slight improvements when using GraphMET compared to MET-T1
- Further investigations
  - More background processes
  - Include GraphMET systematics

BACKUP

GraphMET – Setup

- Connection criterion for two particles: ΔR ≤ 0.4



Investigated Topologies

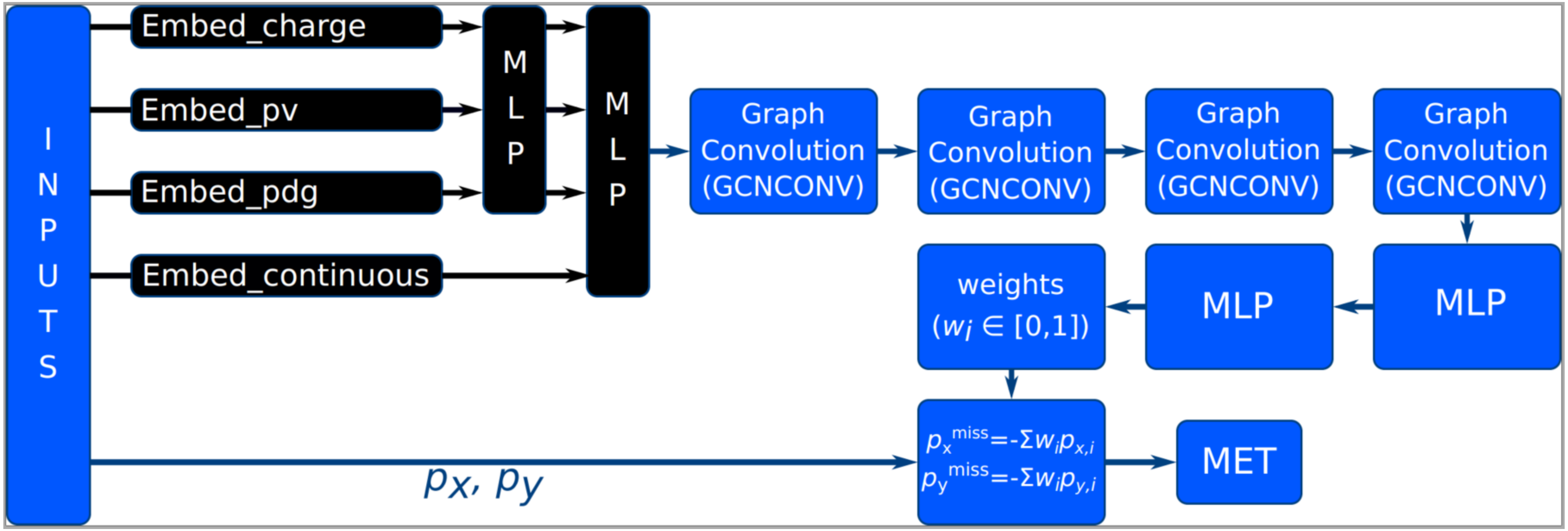
Degree of freedom	Investigated options
Graph style	**Fixed**, dynamic
Update method	**GCNConv**, Edgeconv
Embedding	**Yes**/no
Activation function	**ELU**, ReLU, sigmoid, tanh
$\Delta R \leq$	0.2, **0.4**, 0.8, 1.5
Max. number of neighbors	0, 100, 250, **500**
Number of graph layers	1, 2, 3, **4**, 5, 6
Dimension of feature vectors	8, 16, **32**, 64

(final configuration in bold letters)
Decision based on loss and computing resources

GraphMET – Setup

- Connection criterion: $\Delta R \leq 0.4$
- Loss function: $\mathcal{L}$ = Mean Squared Error (GraphMET, GenMET)
- Trainable parameters: 6256
- Activation functions: ELU
- Output-Activation: Sigmoid ➔ $w_k \in [0,1]$
- Training sample: Events with genuine MET ➔ Z → $\nu\nu$ (+ Jets)

GraphMET Architecture



Embedding for continuous and discrete variables,

four graph layers and two multi-layer perceptrons aggregating the input information into the MET weight