

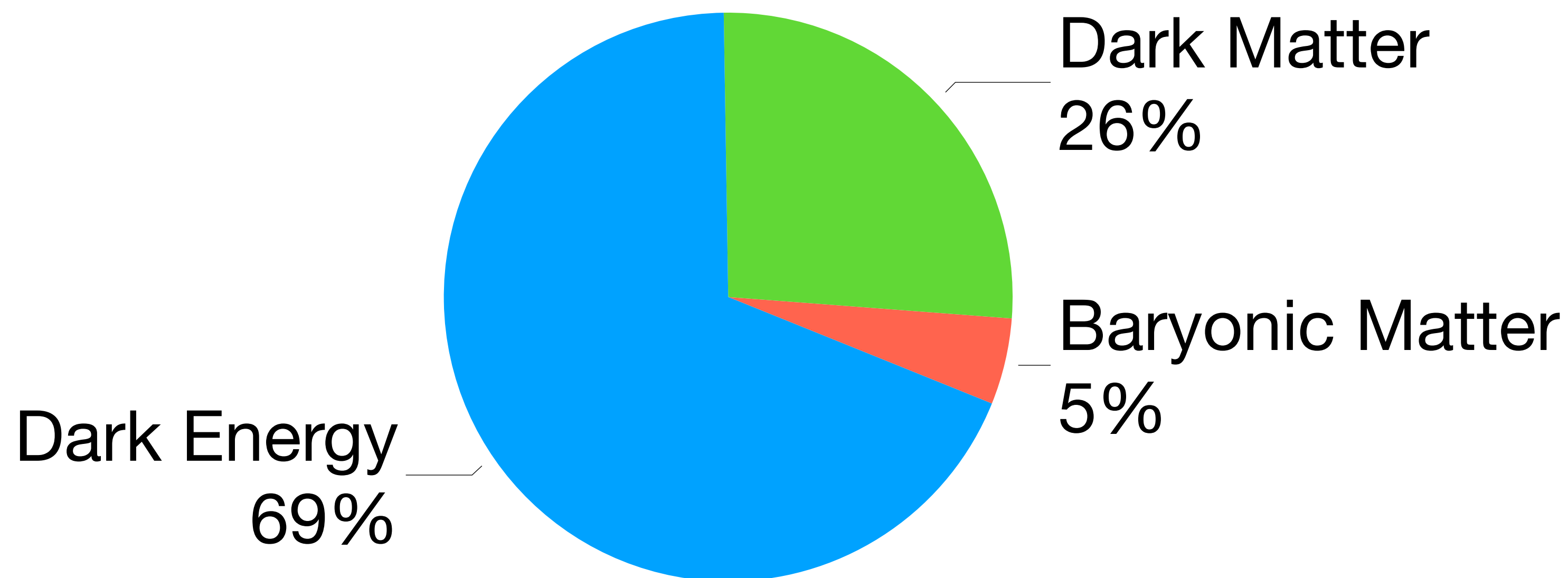
# Searching for Dark Matter at the LHC with GNN

Rafał Masełek

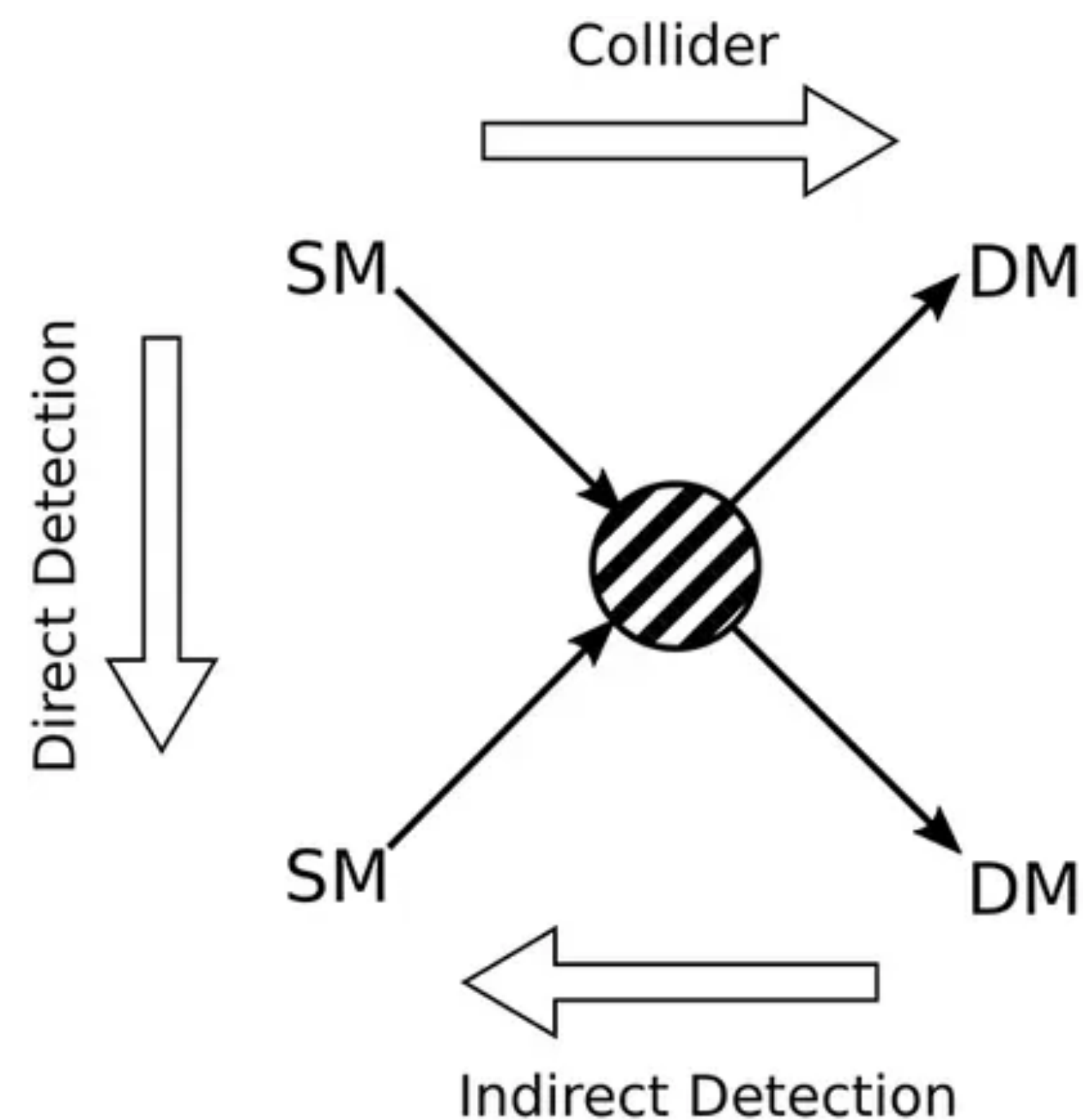
in collaboration with K. Sakurai and M. Nojiri

AISSAI Toulouse workshop 02-10-2024

# Dark Matter

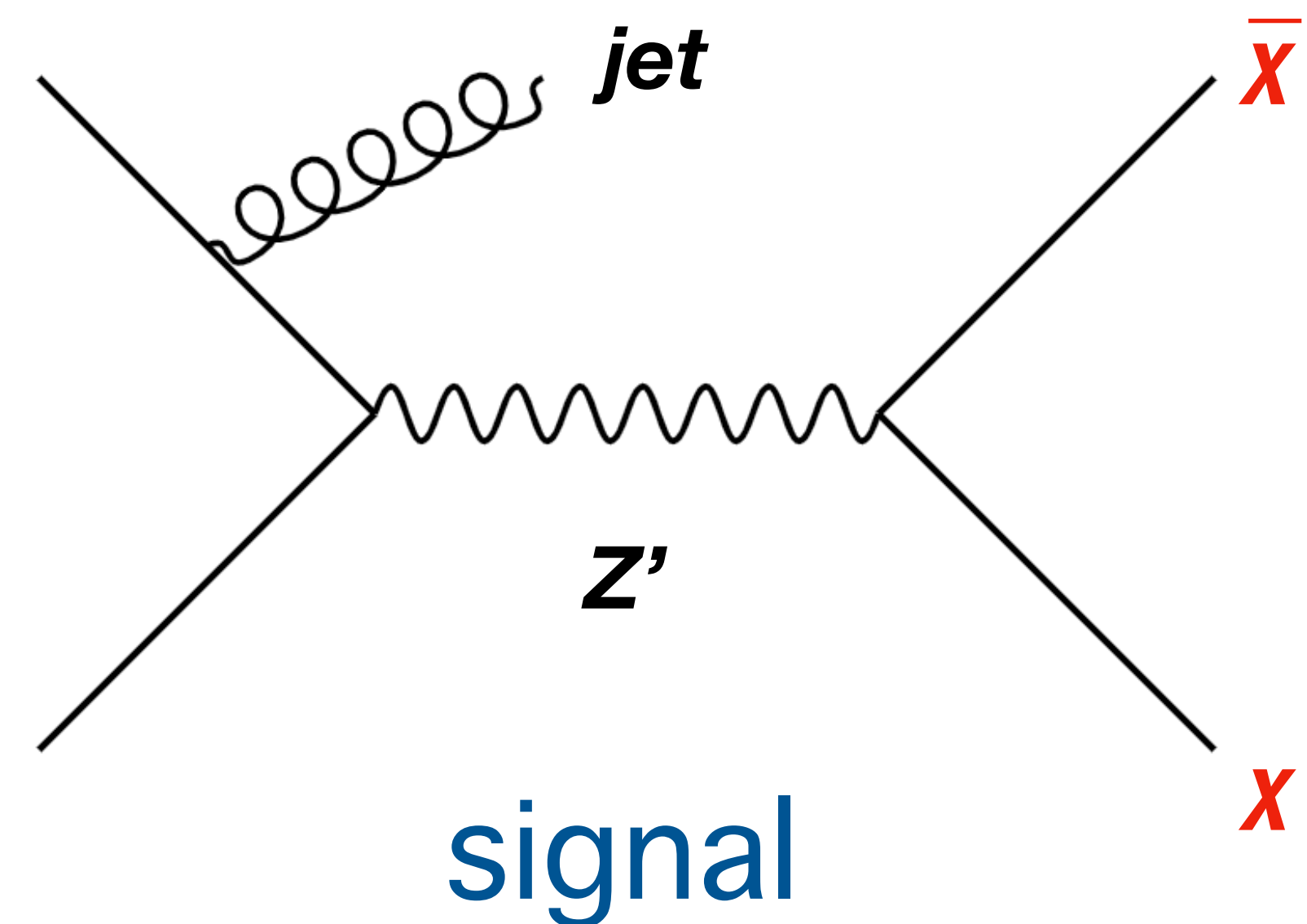
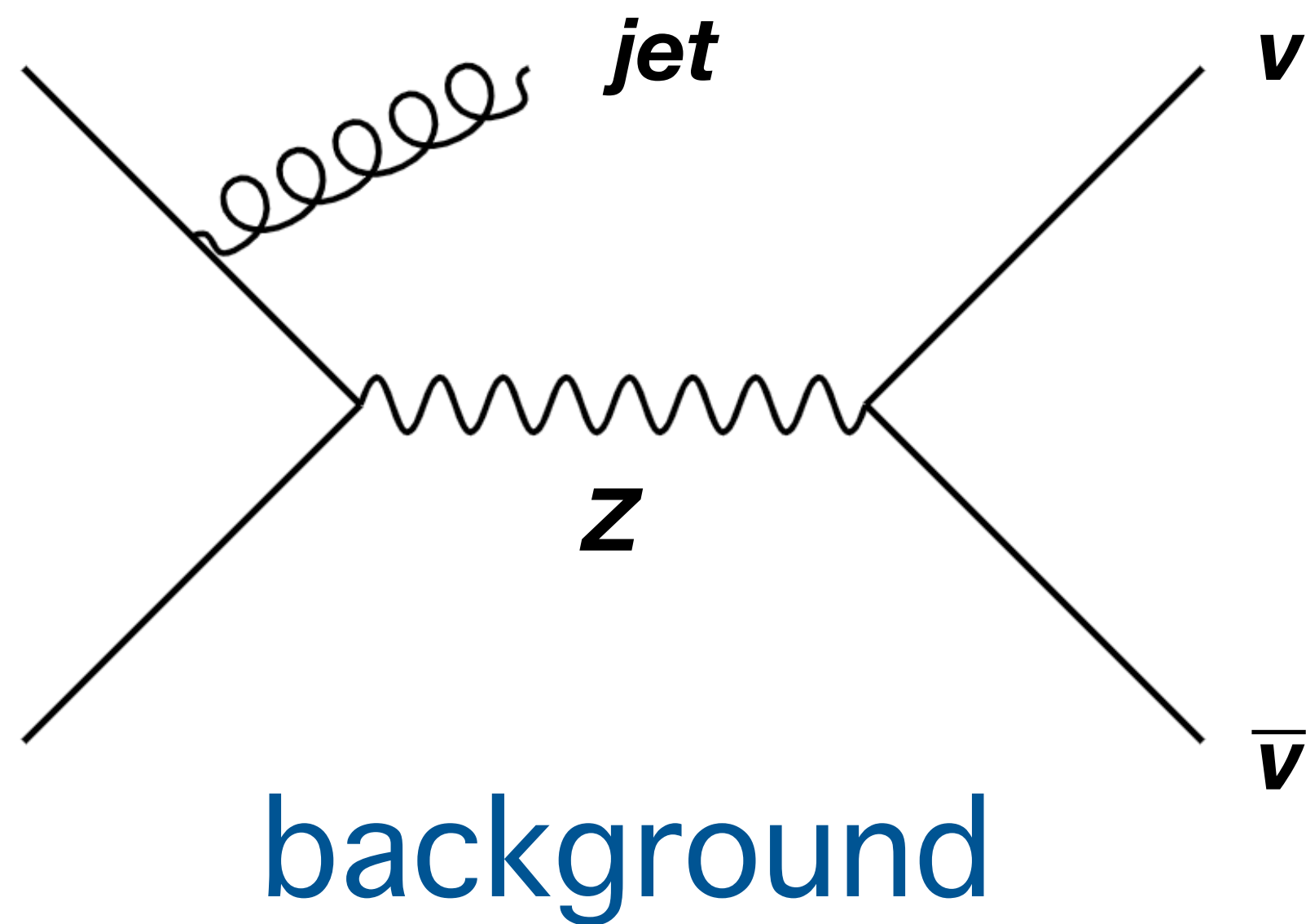


- ⊛ long-lived over the age of the Universe
- ⊛ feebly-interacting with photons and baryons
- ⊛ not too hot



# DM searches @ LHC — Monojet

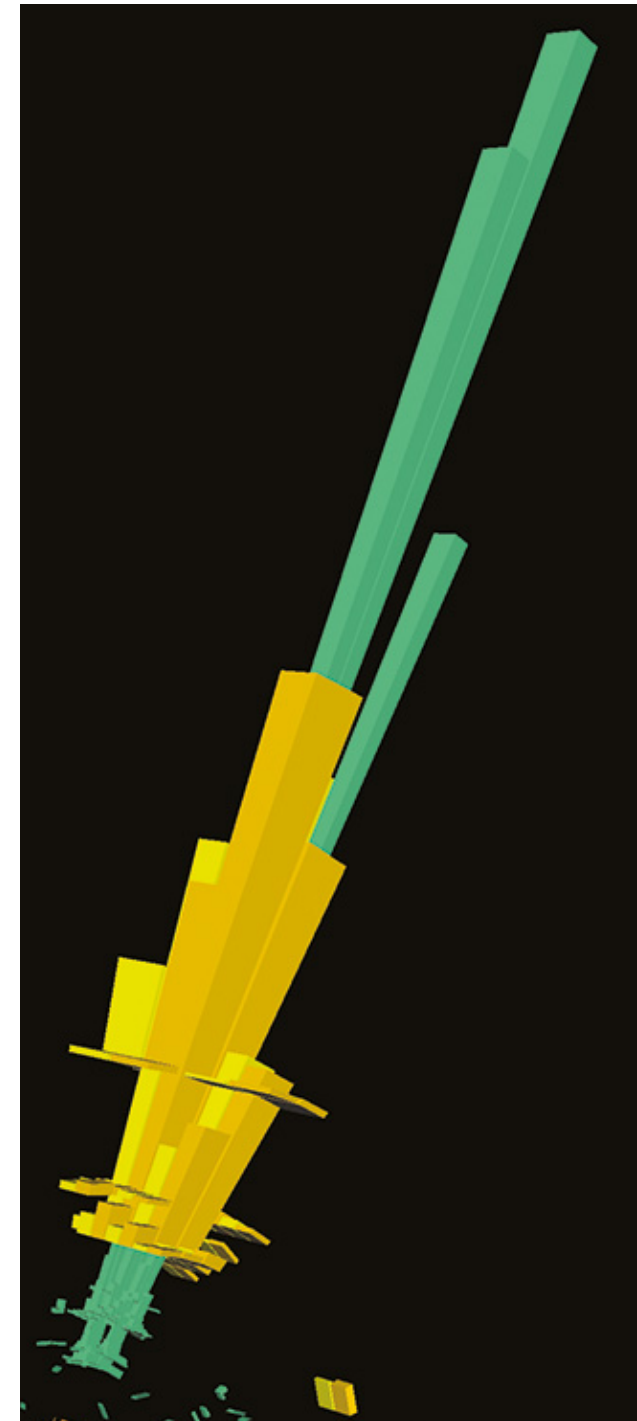
**Monojet channel** = one (or more but few) high-momentum jet recoiling against a missing transverse momentum and no isolated leptons



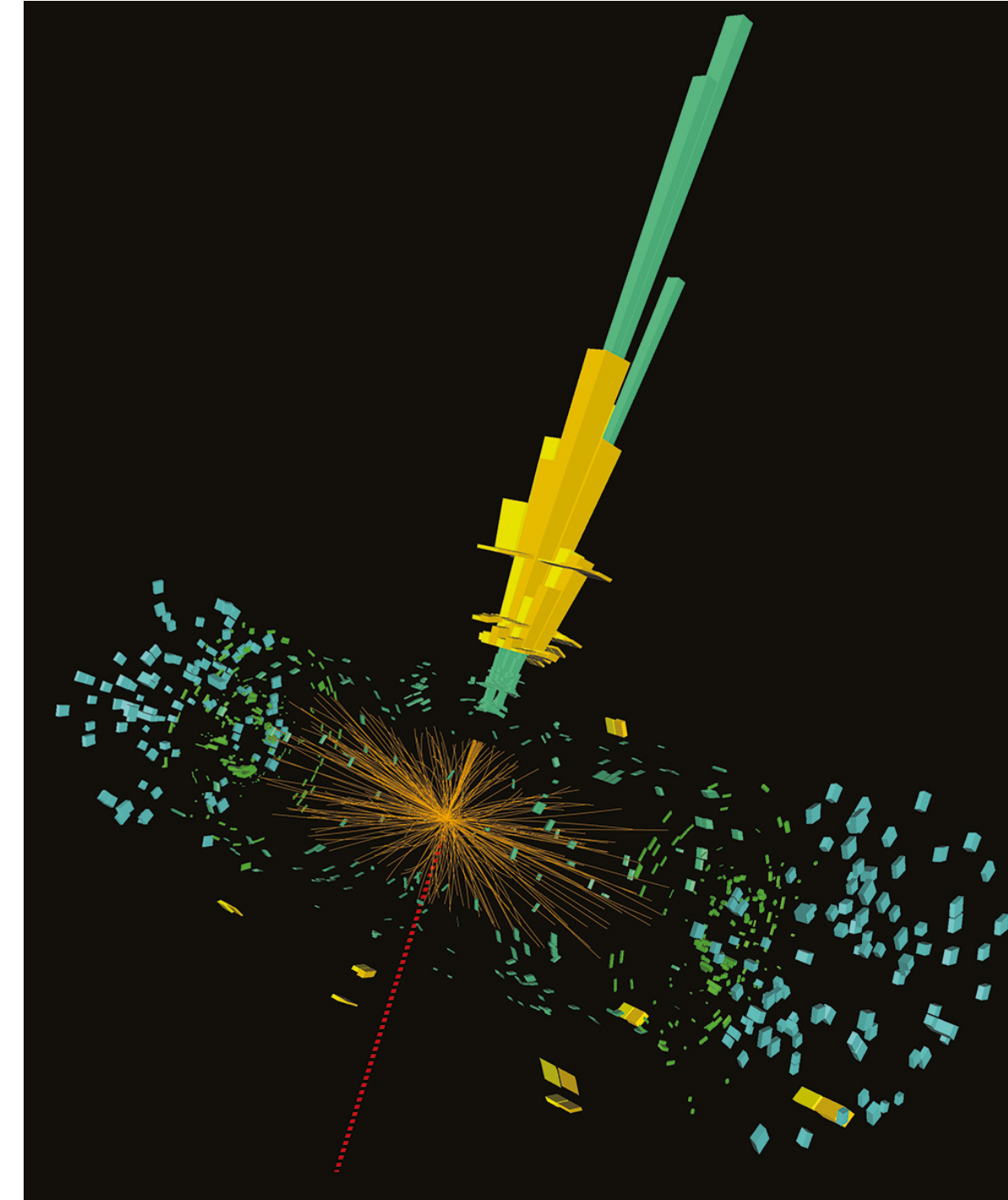
# Heterogenous data



particle



jet



events

low  
level



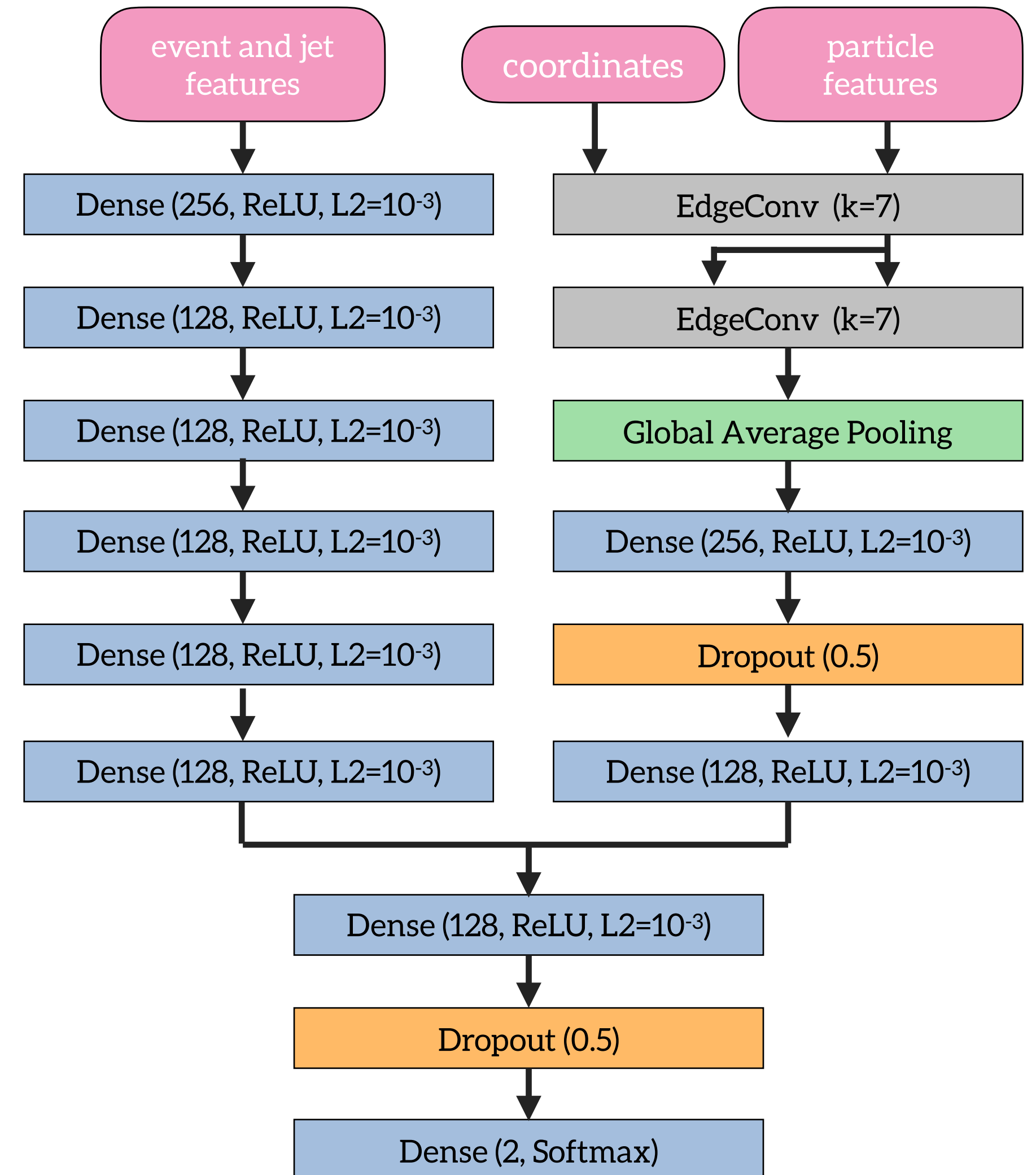
high  
level

# Analysis

## Preanalysis

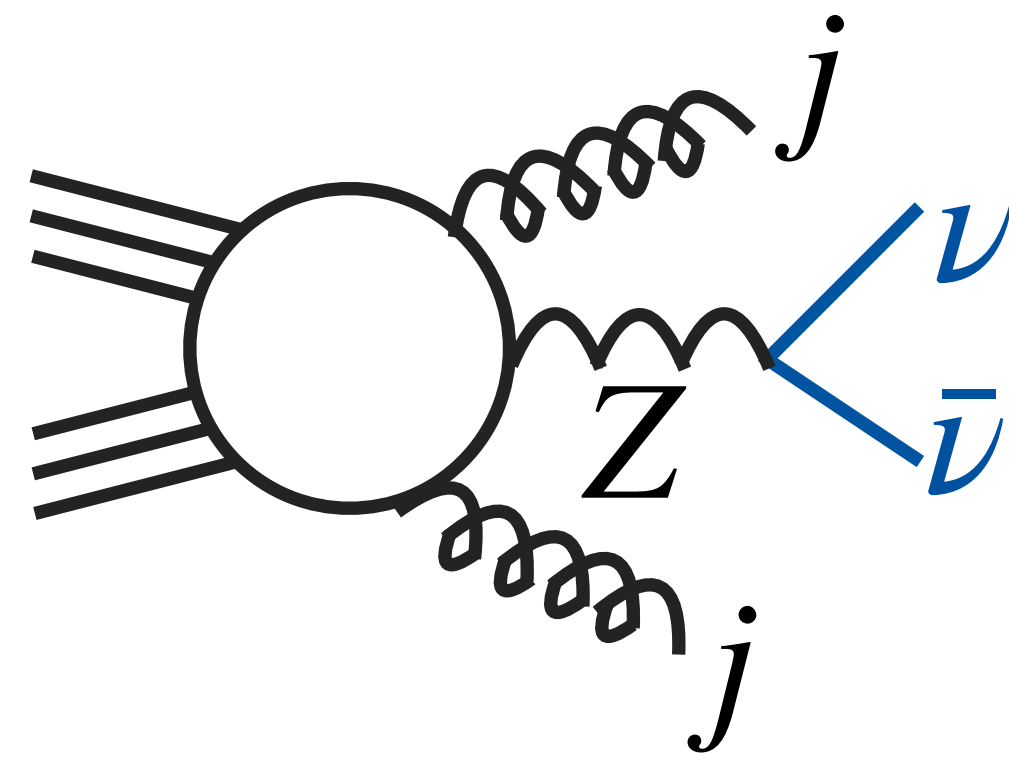
- $4 \geq \#\text{jets} \geq 2$
- $p_T^{1j} > 520 \text{ GeV}$
- $\eta^{1j} < 2.0$
- $p_T^{2j} > 320 \text{ GeV}$
- $\eta^{2j} < 2.0$
- $\text{MET} > 820 \text{ GeV}$
- lepton veto
- $\Delta\phi(j^{1,2,3}, p_T^{\text{miss}}) > 0.8$
- $\Delta\phi(j^4, p_T^{\text{miss}}) > 0.4$
- $\text{MET}/\sqrt{H_T} > 16 \sqrt{\text{GeV}}$
- $M_{\text{eff}} > 1600 \text{ GeV}$
- **particle  $p_T > 1/5/10 \text{ GeV}$**

## GNN model



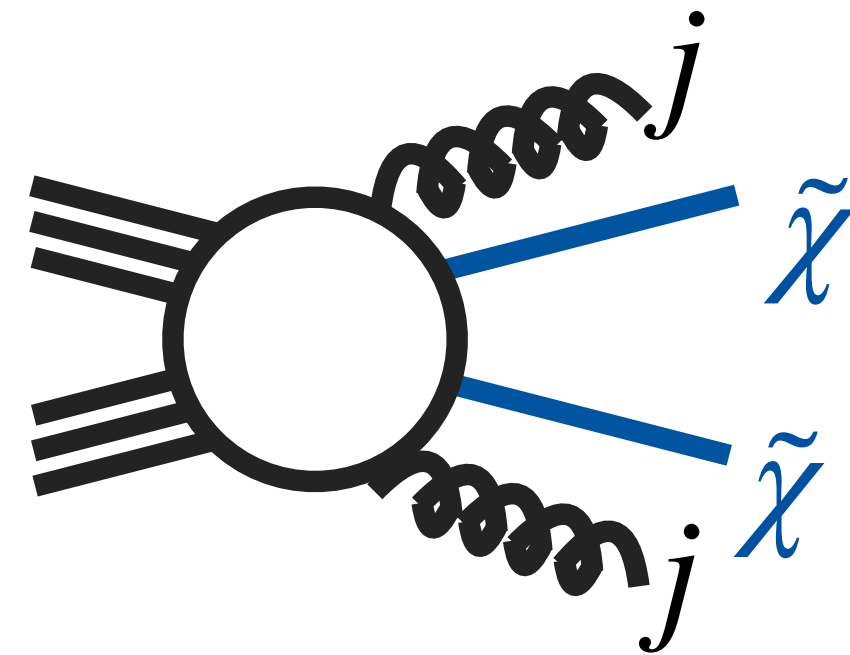
# supersymmetric benchmark model

SM background

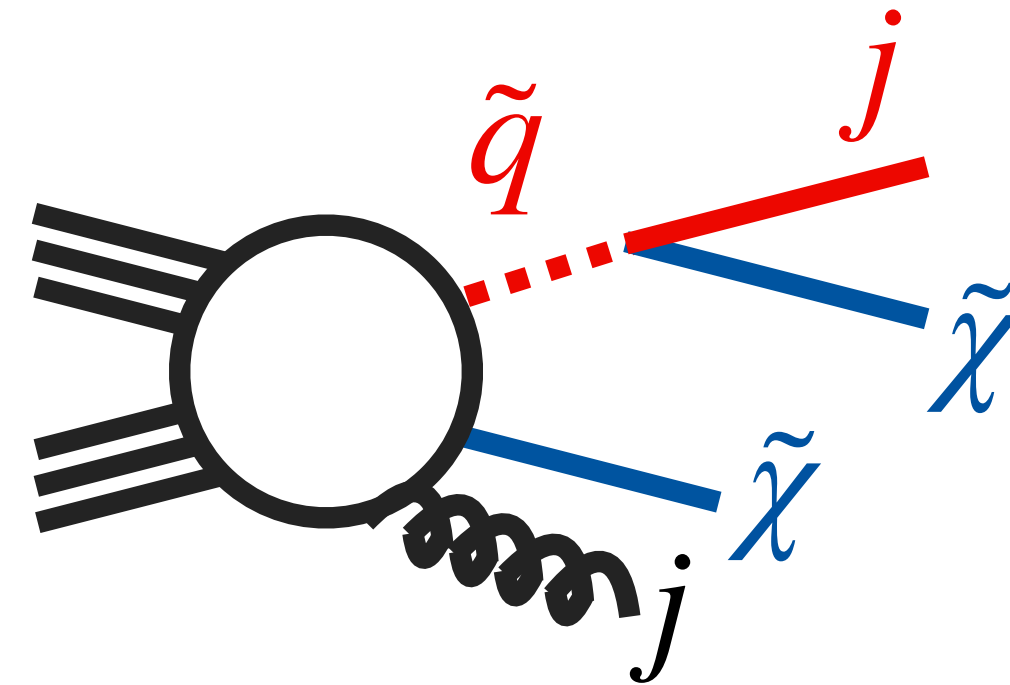


$(Z \rightarrow \nu\bar{\nu}) + \text{jets}$

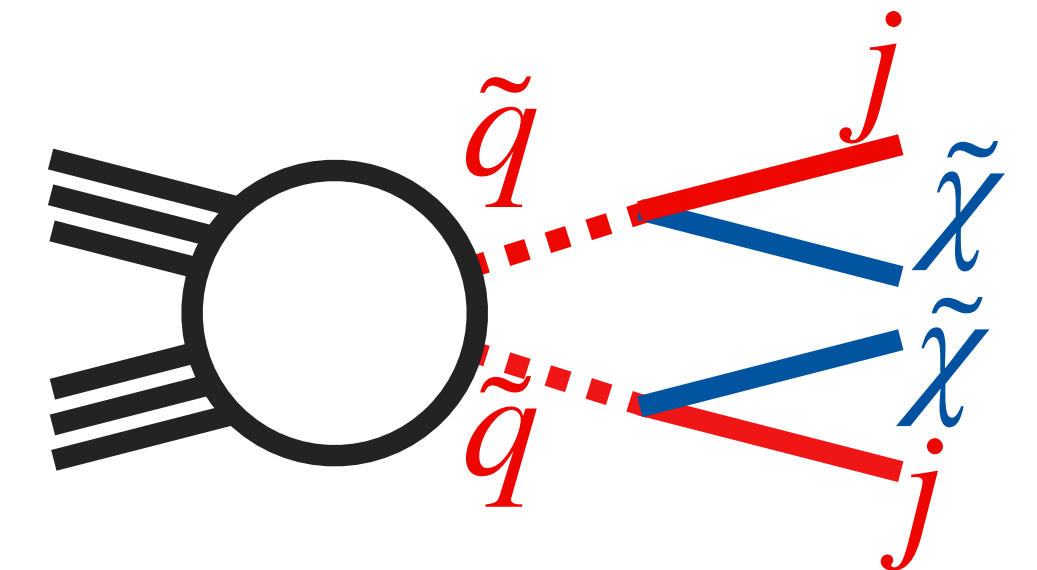
Contributing signal processes



neutralino-neutralino



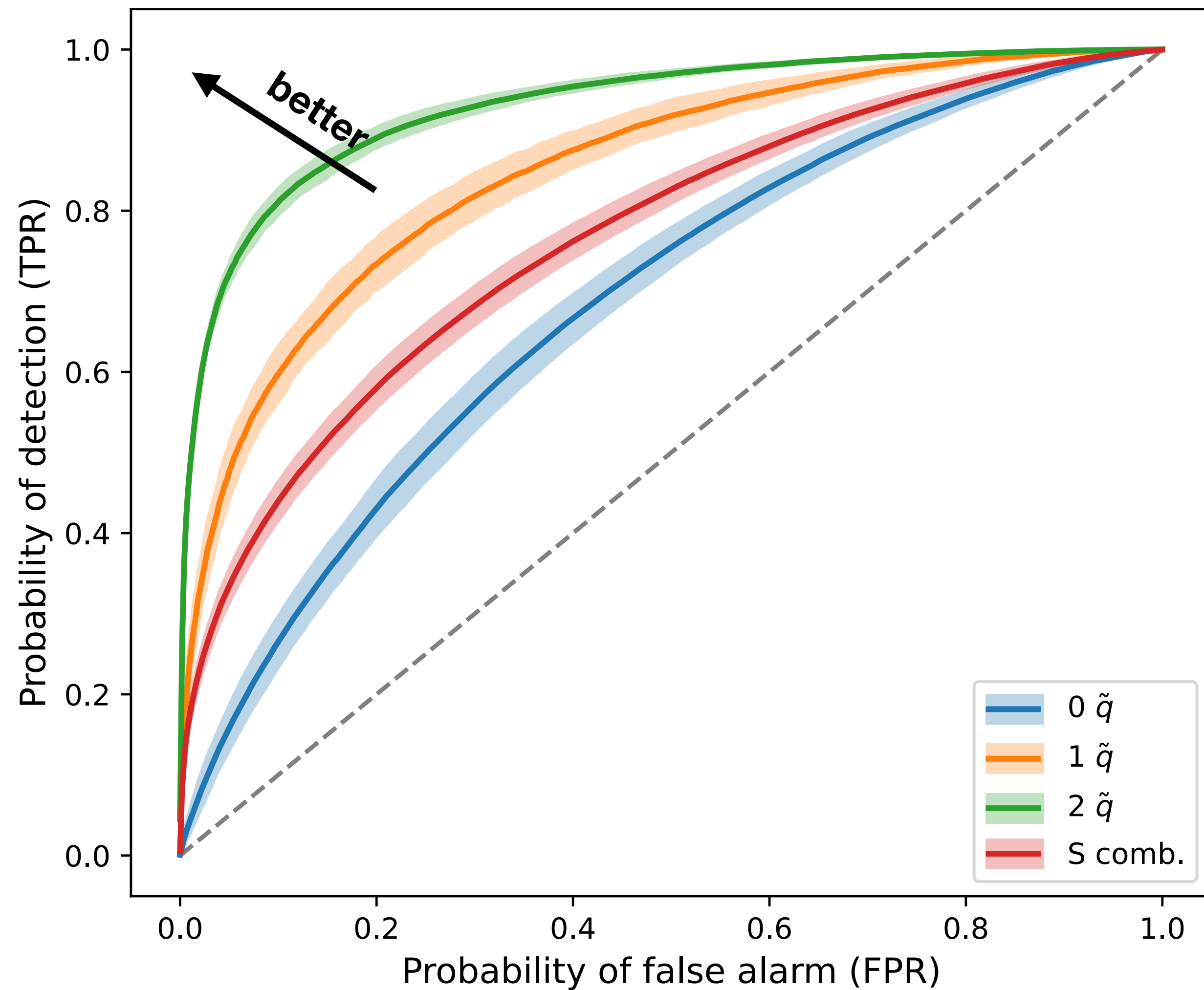
neutralino-squark



squark-squark

neutralino =  wino  
 higgsino  
 bino

# Evaluation (winos)

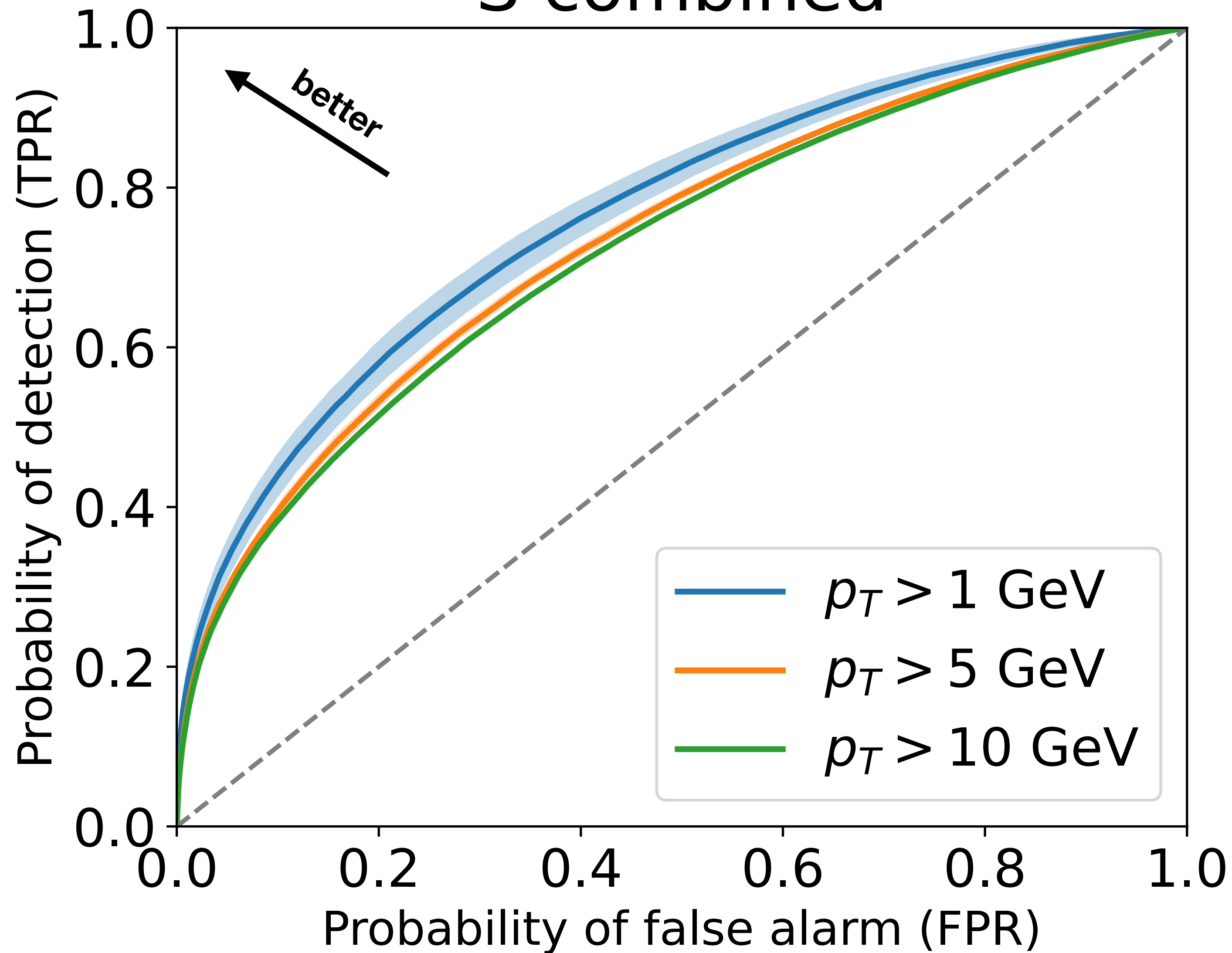


$m_{\tilde{W}} = 300 \text{ GeV}, m_{\tilde{q}} = 2200 \text{ GeV}$

More decaying squarks  
=>  
easier classification

# particles' $p_T$ cut

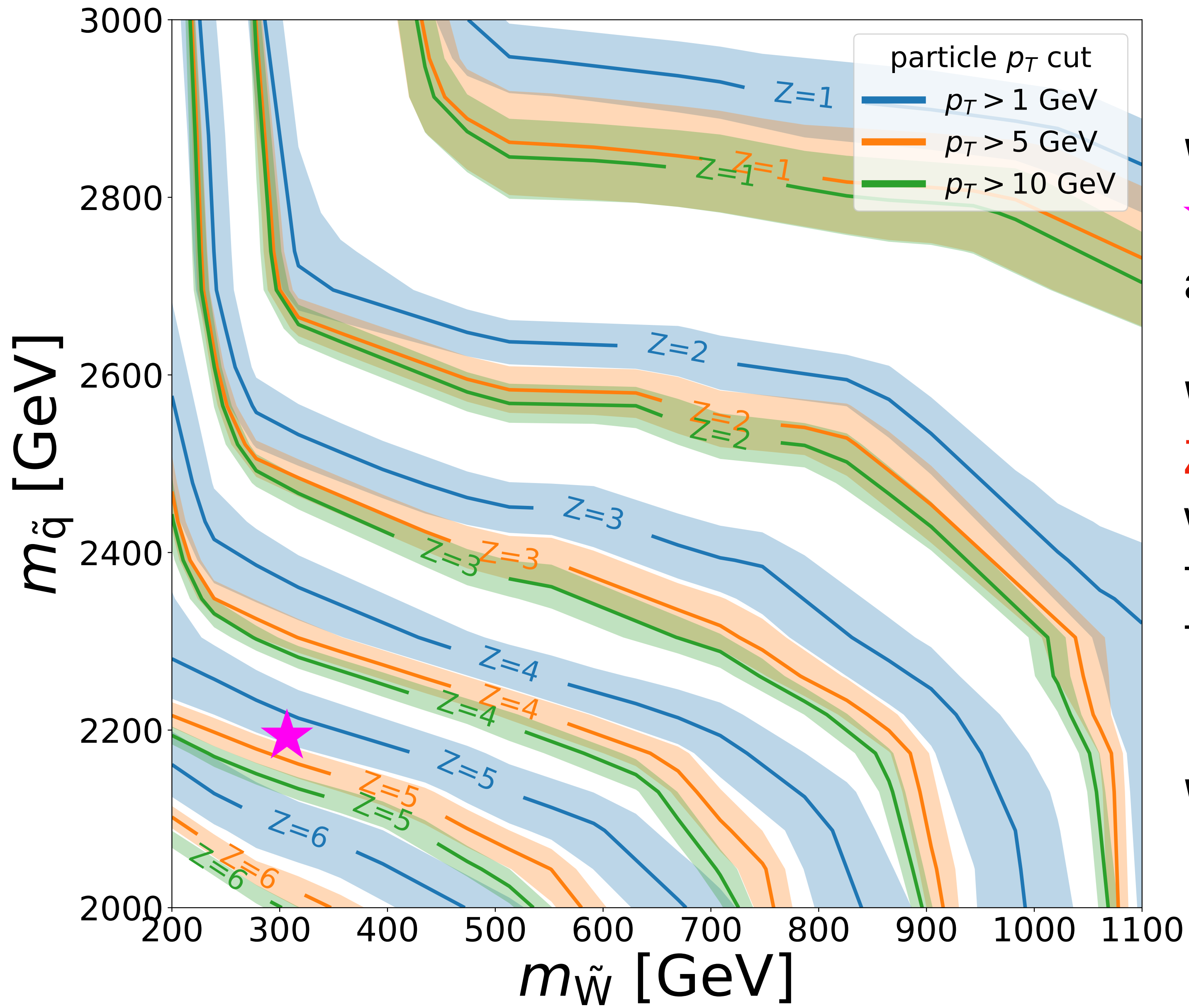
S combined



Lower  $p_T$  cut  
=>  
better result but  
larger uncertainty



# HL-LHC limit for winos



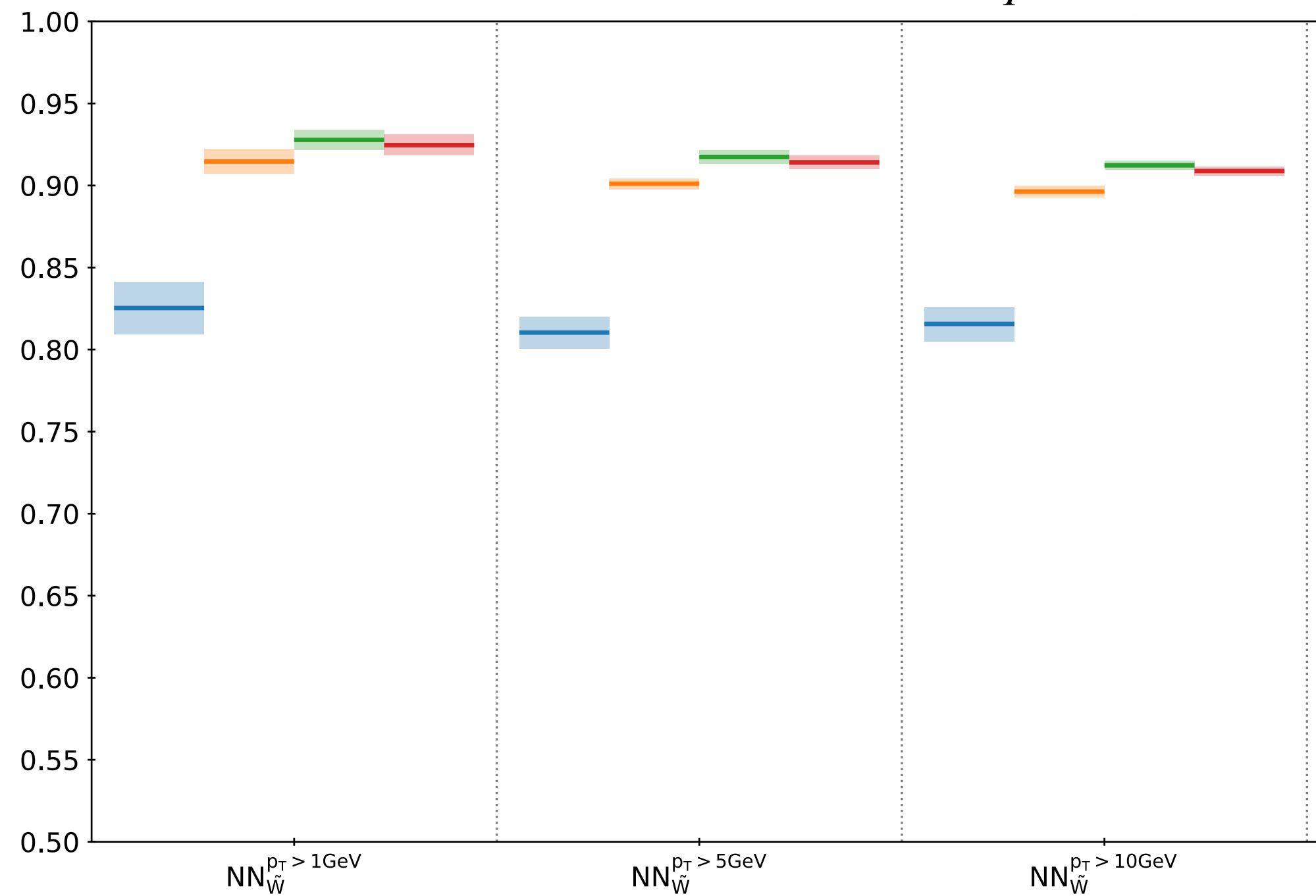
We train model on wino-like neutralino with  $\star m_{\tilde{W}} = 300$  GeV,  $m_{\tilde{q}} = 2200$  GeV and evaluate it on multiple mass points.

We calculate naive significance  $Z = S / \sqrt{(S+B)}$ , which estimates statistical significance that we could get if GNN model was used to experimental data.

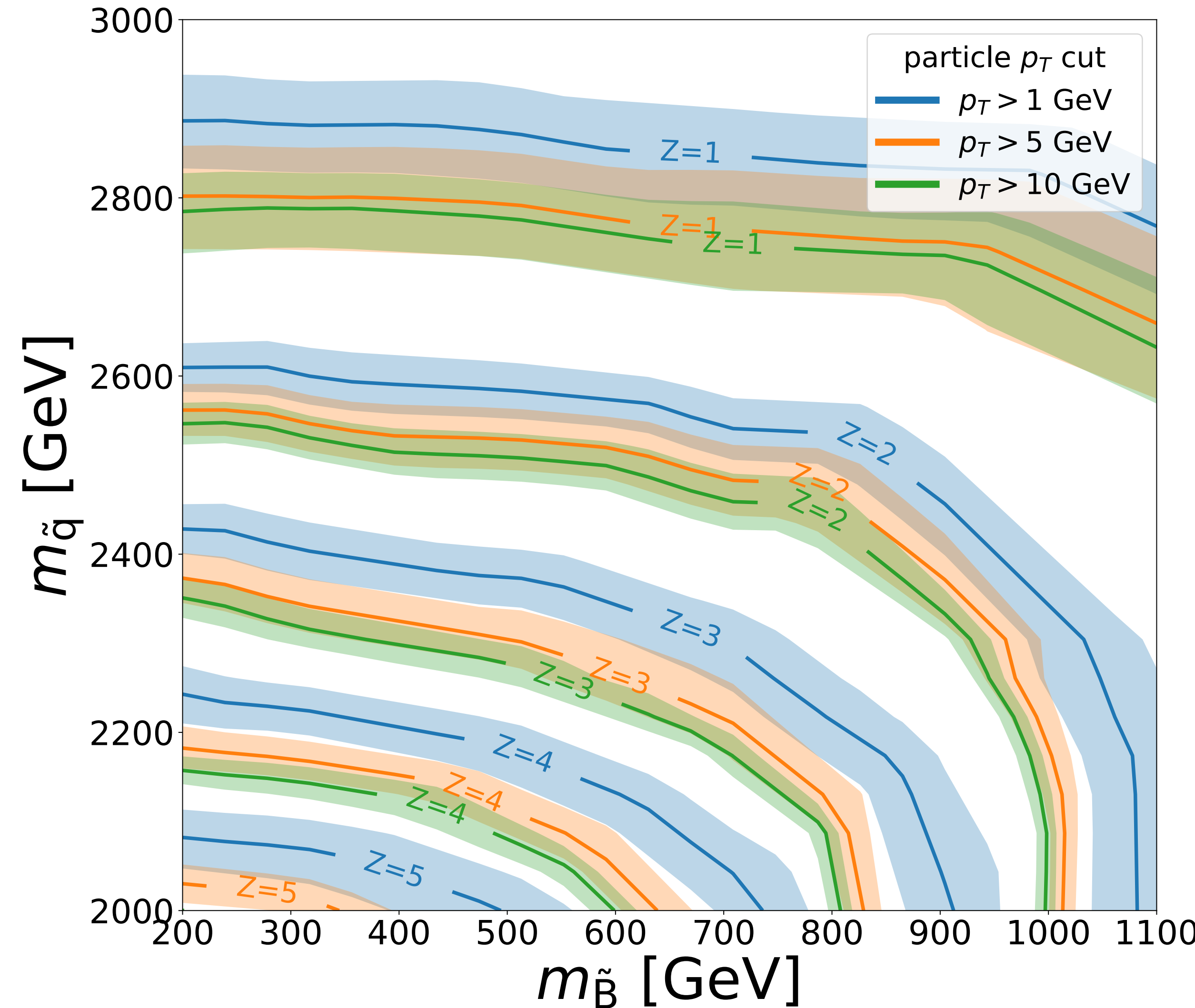
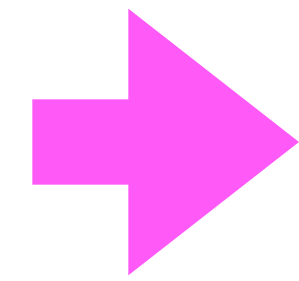
We do the same for higgsinos.

# What about binos?

evaluated on  $m_{\tilde{B}} = 300$  GeV,  $m_{\tilde{q}} = 2200$  GeV



GNN model



# Summary

⊗ Dark Matter can be searched @ LHC

⊗ We introduce new analysis based on GNN

⊗ SUSY as a benchmark model:

⊗ neutralino pair production

⊗ neutralino-squark associated production

⊗ squark-pair production

⊗ We evaluate our model:

⊗ sample composition is crucial: the more squarks the easier classification

⊗ high robustness against a change of the neutralino type

⊗ high robustness against change of the masses of sparticles

⊗ We derive limits on masses of new particles:

⊗ we train models for winos and higgsino

⊗ we derive limits on binos using model trained on winos

⊗ we derive  $Z=S/\sqrt{(S+B)}$  for Run-3 and HL-LHC

## Searching for Dark Matter at the LHC with GNN

Rafał Masełek<sup>1,2</sup> in collaboration with M. Nojiri<sup>3</sup> and K. Sakurai<sup>2</sup>

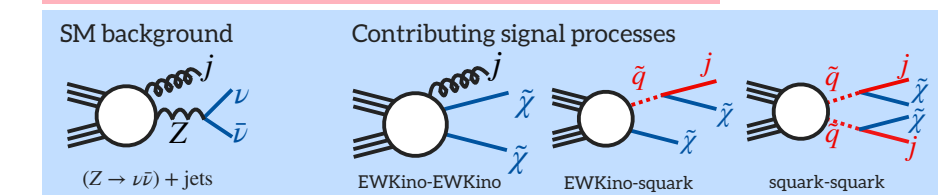
1. Laboratoire de Physique Subatomique et de Cosmologie (LPCS), Université Grenoble-Alpes, CNRS/IN2P3, 53 Avenue des Martyrs, F-38026 Grenoble, France  
2. Institute of Theoretical Physics, Faculty of Physics, University of Warsaw, ul. Pasteura 5, PL-02-093 Warsaw, Poland  
3. Theory Center, IPNS, KEK, Oho 1-1, Tsukuba, Ibaraki 305-0801, Japan

### 1 Introduction

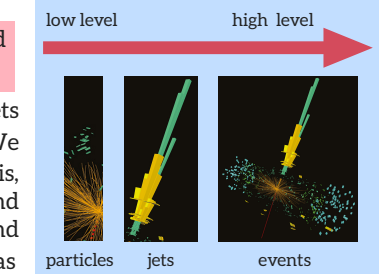
Dark Matter particles can be discovered at the LHC using the monojet channel:  
**Monojet** = at least 1 (but not more than a few) hard jet recoiling against  $p_T^{\text{miss}}$  and no leptons.

Since DM is neutral, the detectors register only jets and  $p_T^{\text{miss}}$ , which makes the search challenging. We tackle the problem with a novel GNN-based analysis, using data at different levels: particles, jets and events. We consider the dominant SM background ( $Z \rightarrow \nu\bar{\nu}$ ) + jets, and take SUSY simplified model as our benchmark DM scenario. DM candidate is wino- or higgsino-like neutralino that can be produced directly or via decaying squark. We assess the algorithm and derive the detection prospects for Run 3 and HL-LHC.

**We study MSSM with neutralino as DM benchmark.**



**We use heterogeneous data**

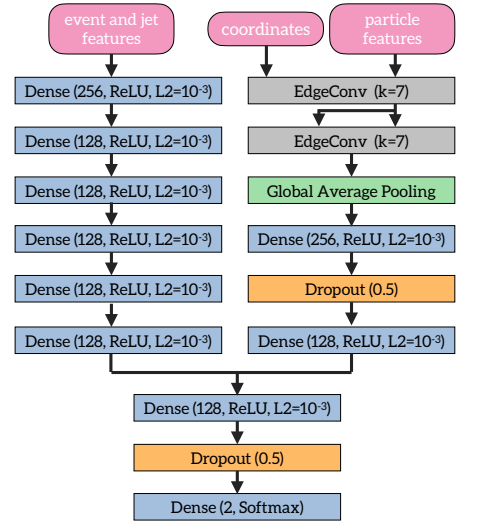


### 2 Analysis

#### Preselection

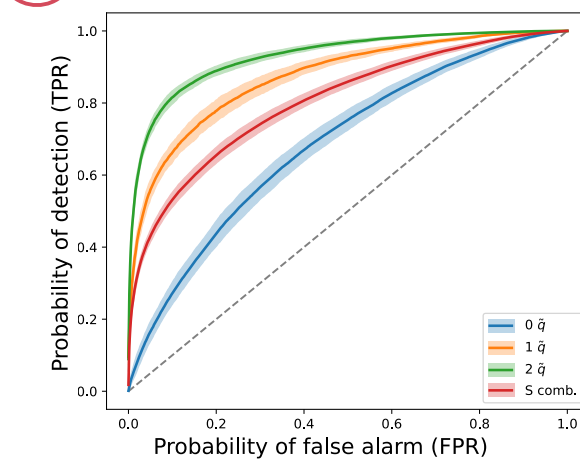
- $5 > \# \text{jets} > 1$
- $p_T^{\text{miss}} > 520 \text{ GeV}$
- $\eta^{\text{miss}} < 2.0$
- $p_T^{\text{miss}} > 320 \text{ GeV}$
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- $\Delta\phi(j^{1,2,3}, p_T^{\text{miss}}) > 0.8$
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- $\text{MET}/\sqrt{H_T} > 16 \sqrt{\text{GeV}}$
- $M_{\text{eff}} > 1600 \text{ GeV}$
- $p_T^{\text{particle}} > 1/5/10 \text{ GeV}$

#### GNN architecture



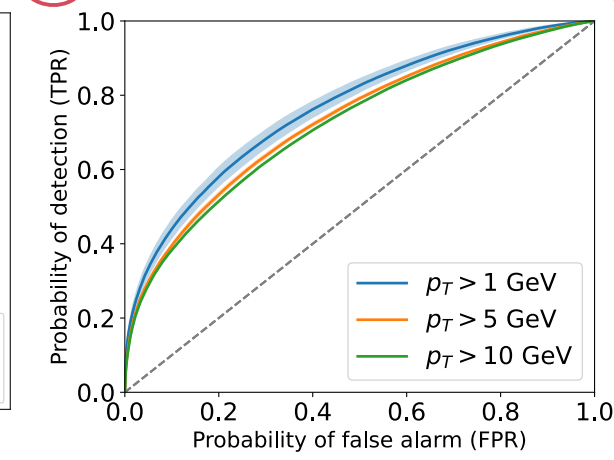
**We propose analysis based on Convolutional Graph NN.**

### 3 Evaluation



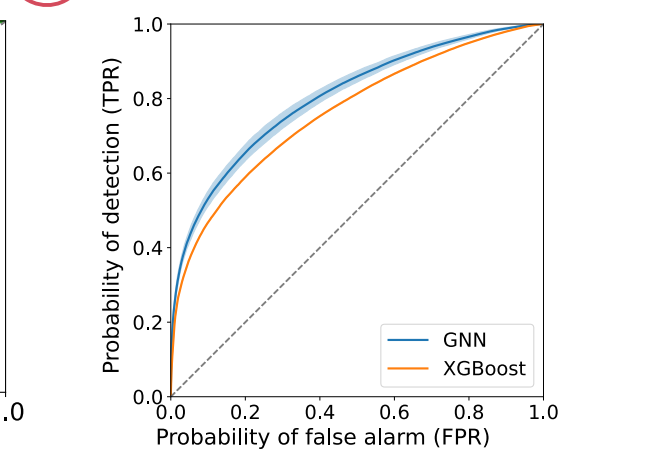
Events with decaying squarks (green and orange) are easier to classify because the resulting jets are boosted. Events without squarks (blue) closely resemble SM background, making them more challenging. Total performance (red) highly depends on the composition of the considered sample.

### 4 Impact of the $p_T^{\text{particle}}$ cut



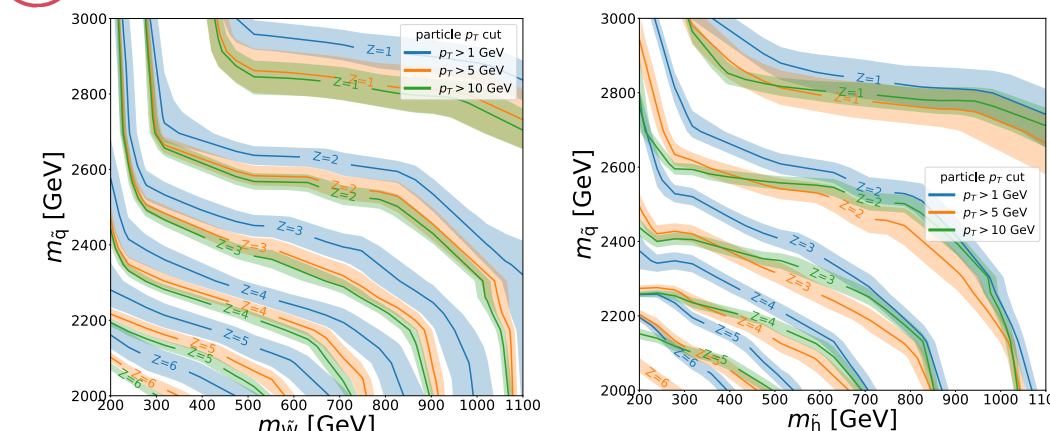
A higher cut on particles'  $p_T$  leads to more stable results and decreased classification performance. The effect is strongest for events without decaying squarks. Information in soft particles is difficult to learn but helpful in discrimination, particularly for the most challenging signal events.

### 5 GNN vs. BDT



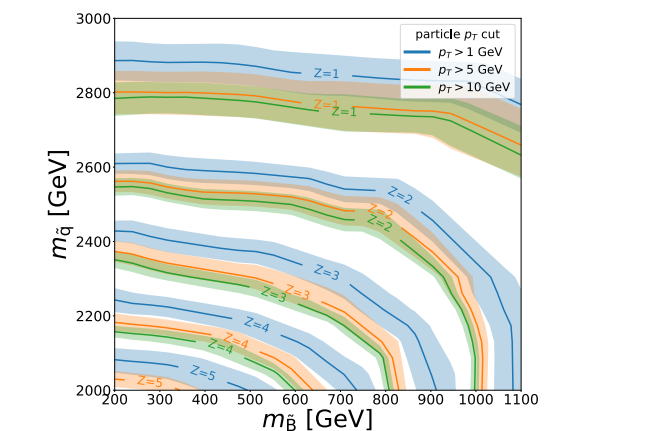
We compare our algorithm with Boosted Decision Trees and we find that **BDTs** are more stable but offer **worse classification performance** for all classes of signal events.

### 6 Limits on sparticle masses



We use our GNN algorithm trained on a single ( $m_{\tilde{g}} = 300 \text{ GeV}$ ,  $m_{\tilde{h}} = 2.2 \text{ TeV}$ ) mass point to calculate naive statistical significance,  $Z = S/\sqrt{S+B}$ , for a grid of mass points. Contours corresponding to different values of  $Z$  approximate exclusion/discovery limits with statistical significance  $Z\sigma$ . We present results for winos (left) and higgsinos (right), for HL-LHC with  $L = 3 \text{ ab}^{-1}$ .

### 7 Application to Binors

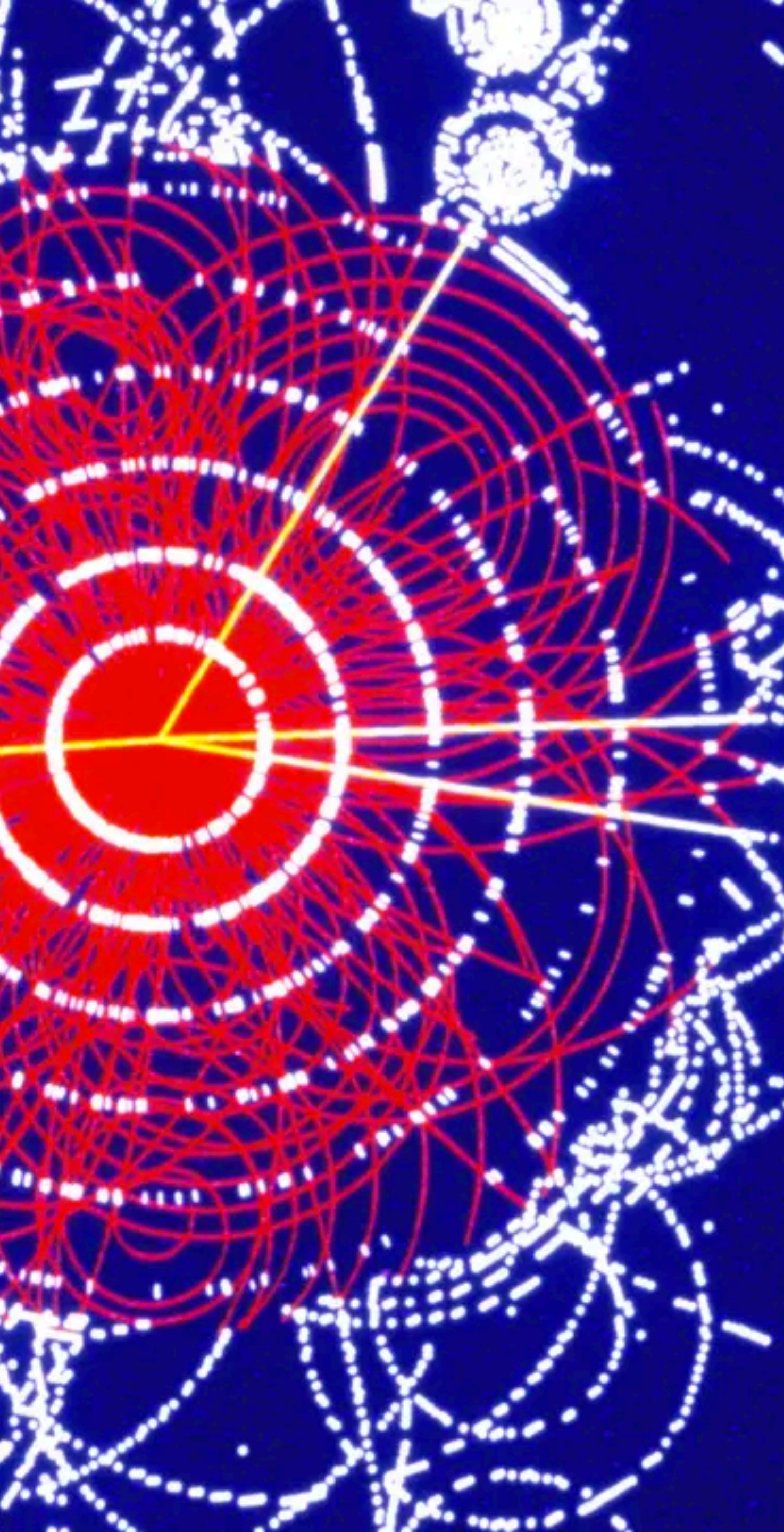


We demonstrate the robustness of our approach by reusing a GNN model trained on a single mass point for wino-like neutralino to derive limits on bino-like neutralinos. This is possible because bino samples consist solely of events with decaying squarks, which are easy to discriminate from SM.



Thank you for attention!

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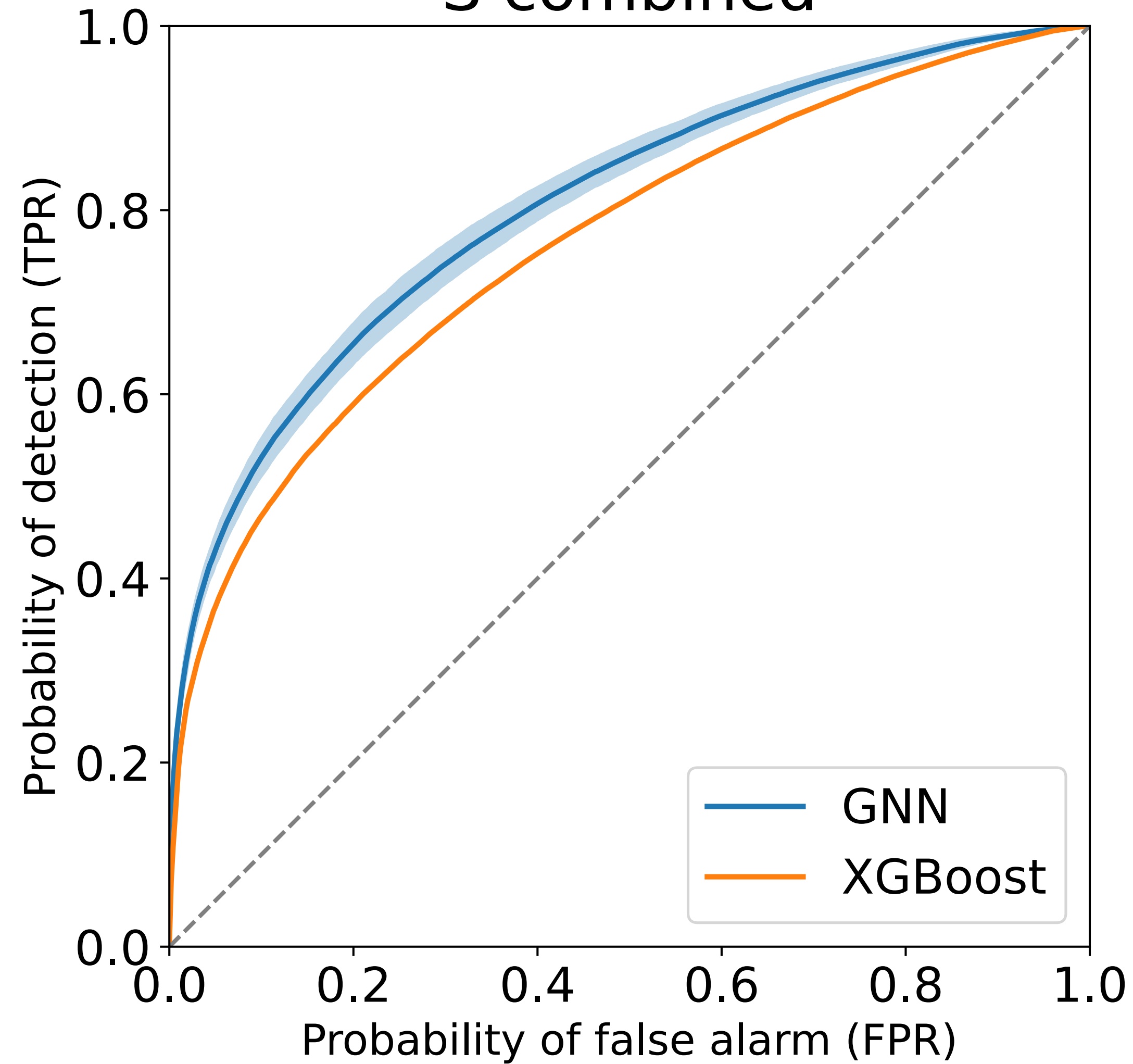
# Backup slides

Rafał Masełek

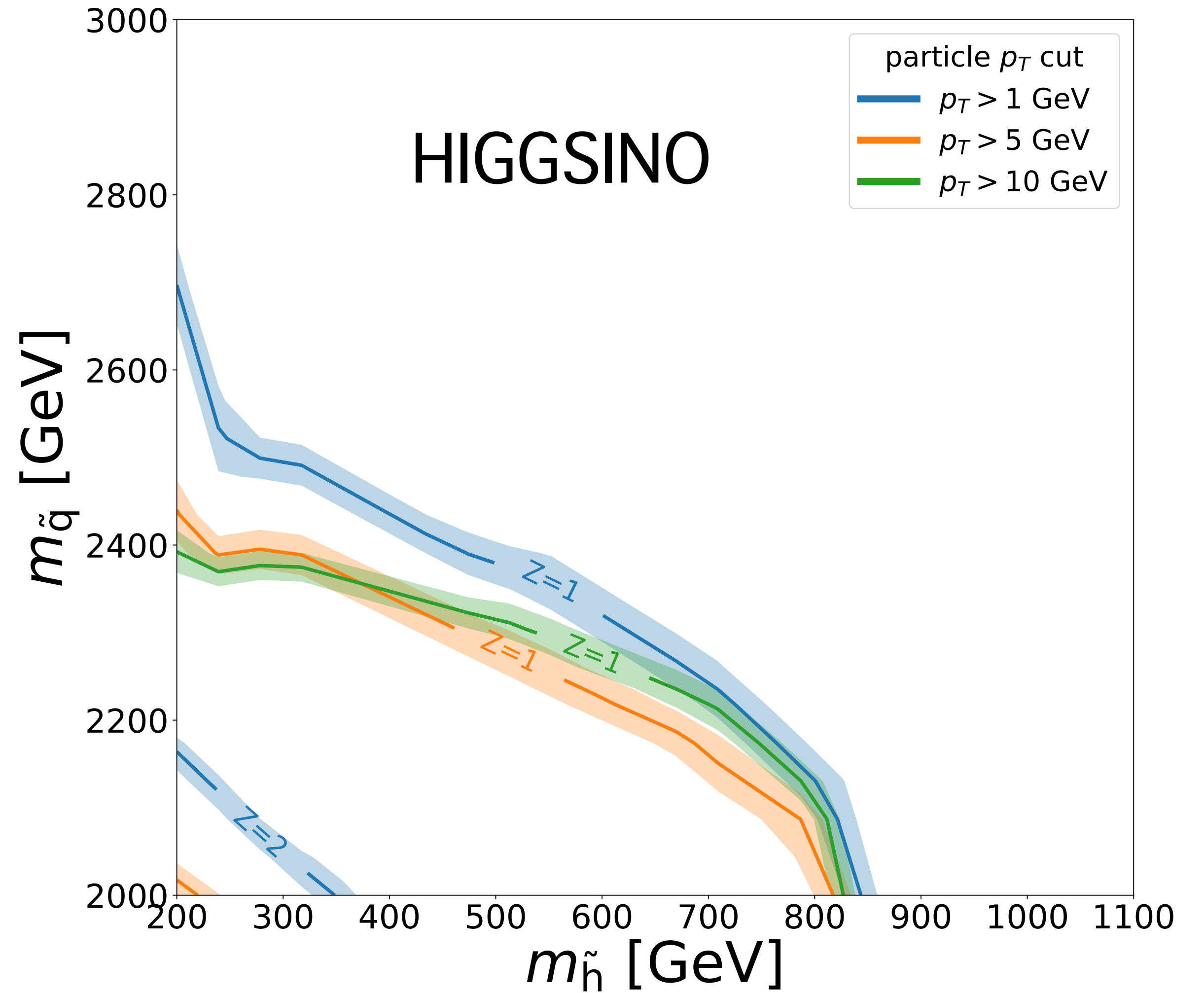
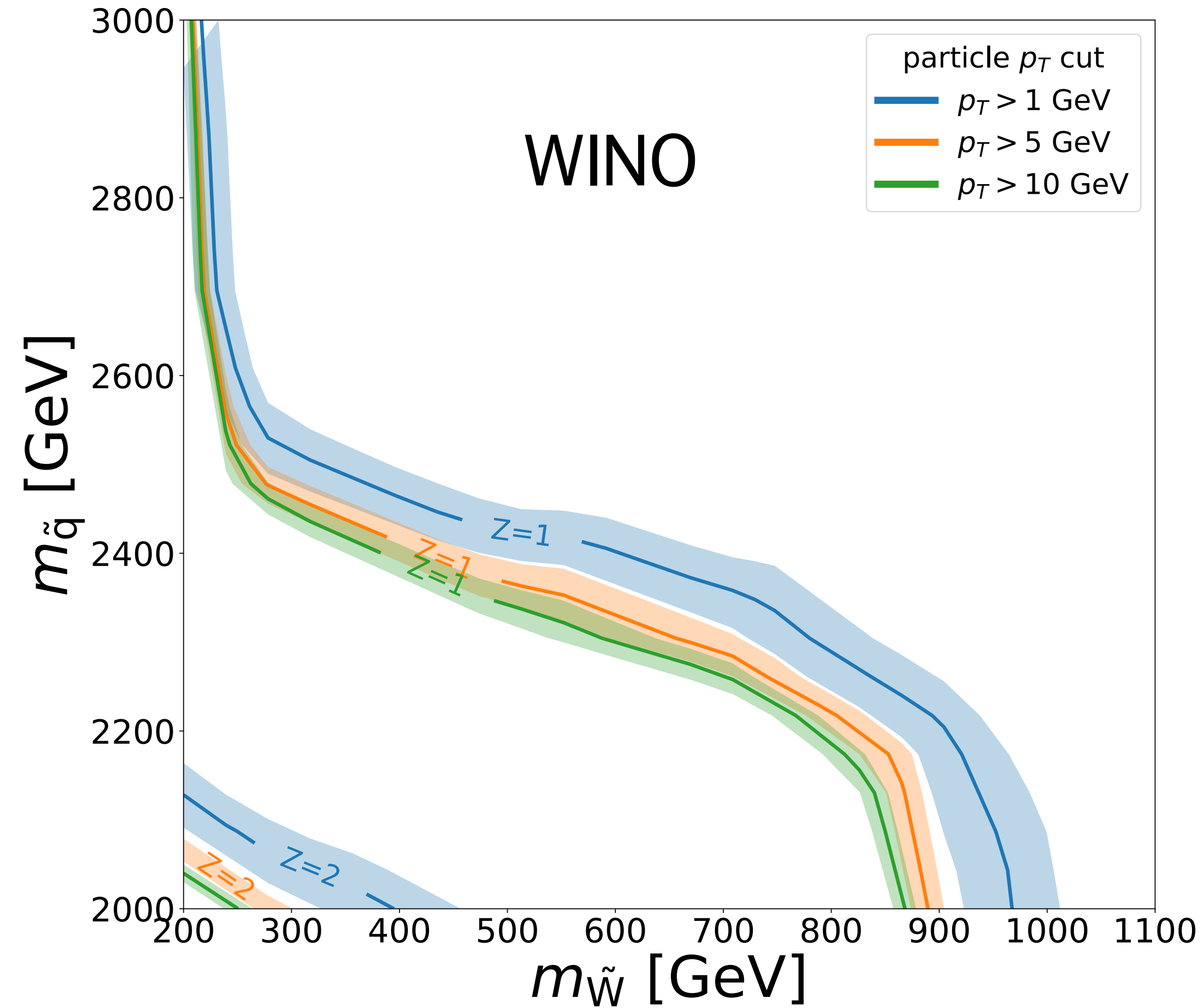
R. Masełek AISSAI Toulouse 02-10-2024

# GNN vs. BDT

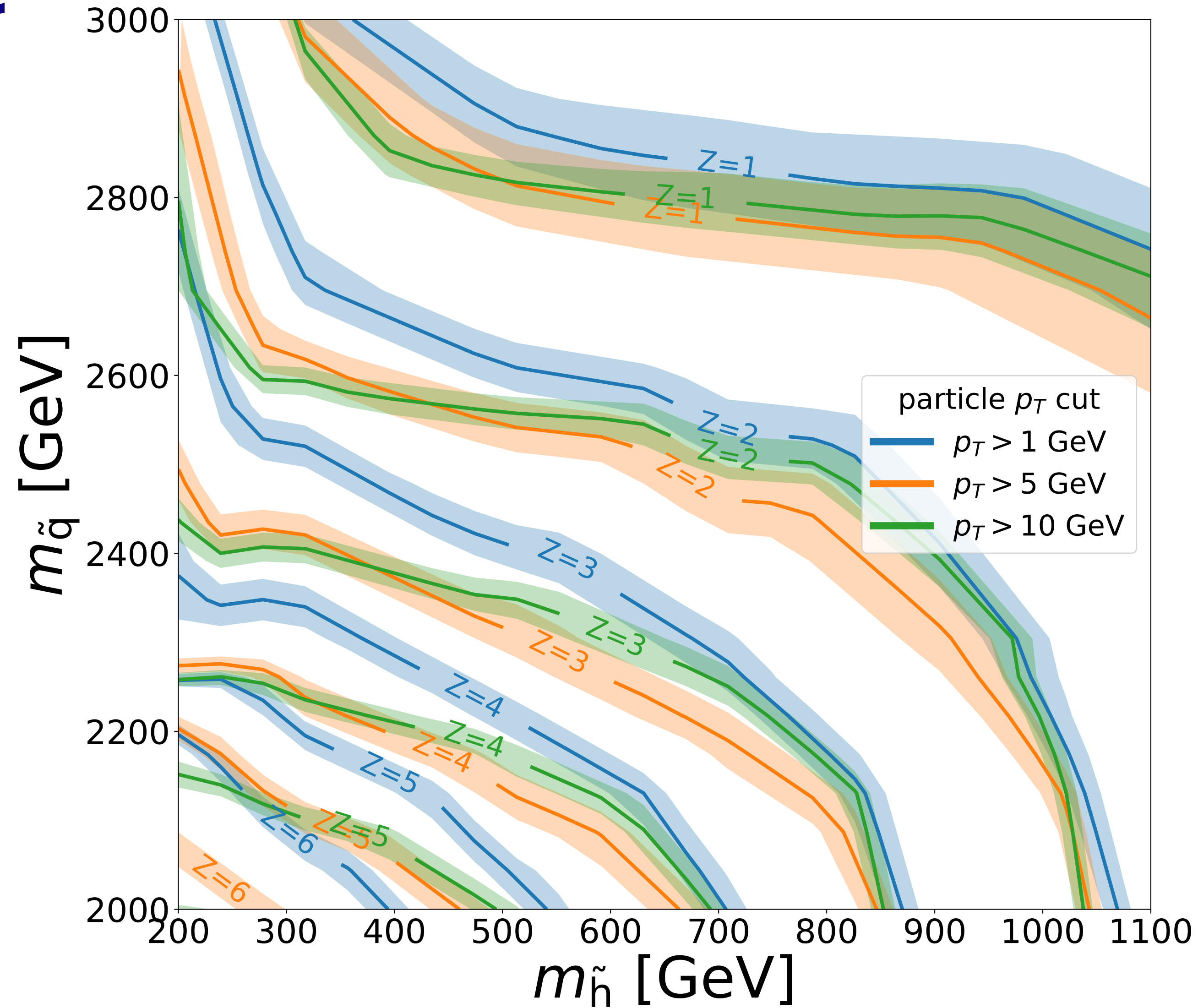
S combined



# Limits for Run-3 LHC



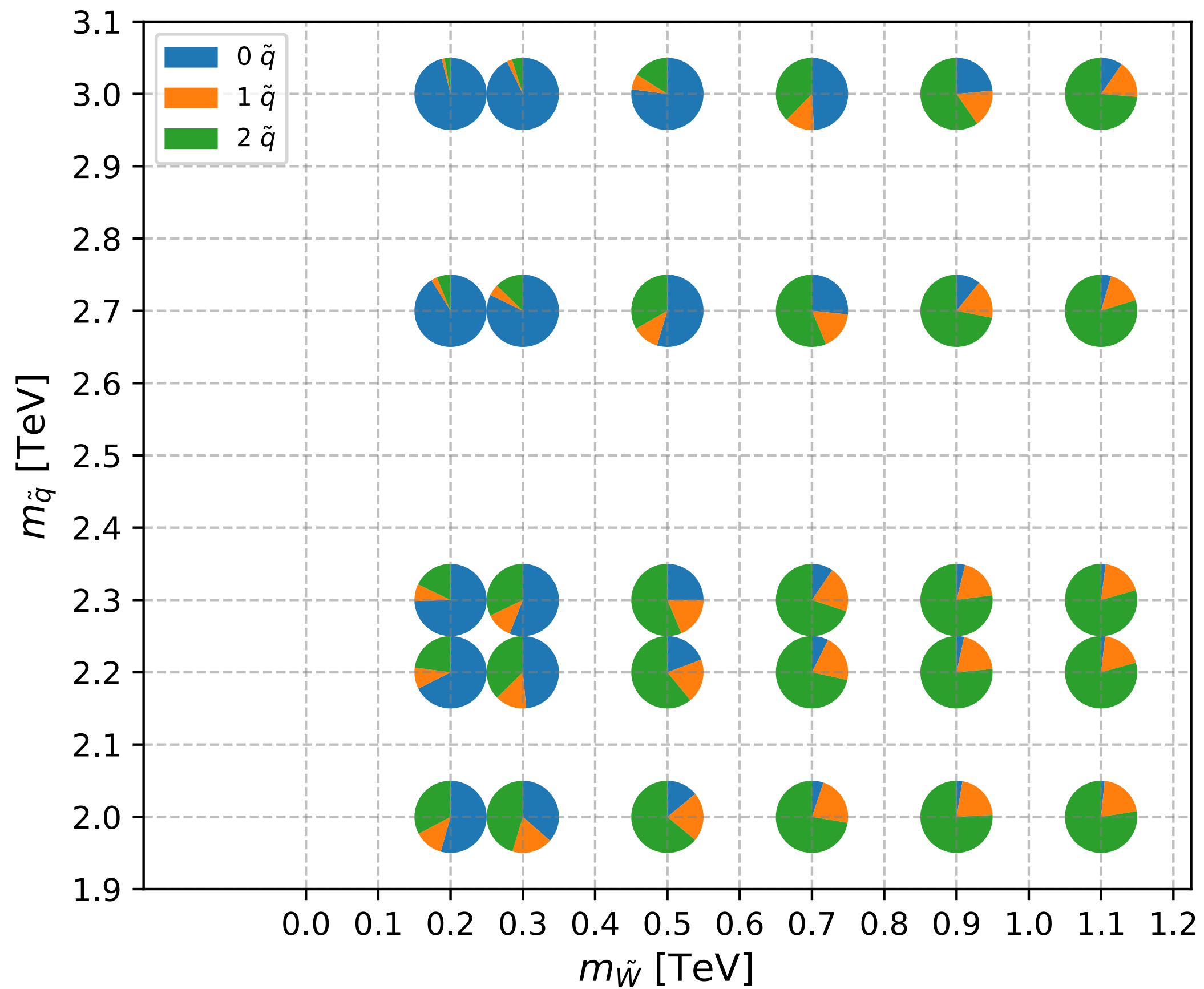
# Higgsino limits for HL-LHC





# Sample composition

WINO



HIGGSINO

