Ideas for Anomaly Detection in dark matter searches (?)

Dark Matter Searches

Thea Klæboe Årrestad
(ETH Zürich)

Roadmap of Dark Matter Models for Run 3
CERN Tue 14 May

14:00 **Theory and Motivation of dark Higg**
Speaker: Giorgio Arcadi

14:30 **Searches for Dark Higgs Bosons at**
Speakers: Mr Changqiao Li (Max Planck S

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Speakers: Alicia Calderon Tazon (Univer

15:10 **Review of Benchmark Models Used**
We present a review of the models use transverse energy by ATLAS, which wa were defined as bins in the E_T^{miss} signif each of these regions. No significant e benchmark models referred to as light- do not reproduce the observed dark-m constraints. We also consider the impa dark-matter summary effort by ATLAS searches. Plans are also made to provi reinterpretations of the search, but it is
Speaker: Even Simonsen Haaland (Univ

10:15 **Reinte**
In this dark se scenar betwee search
Hence,
a) dark
b) s-ch
c) Higg
Speak

10:30 **Exploration of b-philic SVJ and new discriminating observables**
After the first round of SVJ experimental results, the focus has shifted to exp

09:00 **Cosmological perspectives and constraints on t-channel models [20'+10']**
Speaker: Chiara Arina (CP3 UCLouvain)

09:30 **A theory overview on t-channel models and their LHC phenomenology [30'+10']**
Speaker: Luca Panizzi (Uppsala University)

10:10 **t-channel dark matter models and heavy flavours [25'+10']**
Speaker: Monika Blanke (Karlsruhe Institute of Technology)

10:45 Coffee break

11:15

11:35

12:05

14:00 **Dark Photon Searches on LHCb (20'+10')**
Speaker: Adrian Casais Vidal (Massachusetts Institute of Technology (MIT))

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Speaker: Yotam Soreq (Massachusetts Institute of Technology)

14:20 **LLP-DM overview: linking searches to models, and LLP experiment reach for DM model space**
Speaker: David Curtin (University of Toronto)
davidcurtin_DM-LLP...

14:55 **Multiple track signatures**
Speaker: Jackson Carl Burzynski (Simon Fraser University (CA))
Burzynski_LLPMulti...

15:20 **Signatures with MET**
Speaker: Joseph Reichert (Rutgers State Univ. of New Jersey (US))
2024-05-13 DM Wor...

15:45 **Pair-produced LLPs (to jets, leptons, photons...)**
Speaker: Audrey Katherine Kvam (University of Massachusetts (US))
PairProducedLLP_K...

16:45 **Mass-independent searches**
Speaker: Christina Wenlu Wang (California Institut

17:05 **Recasting wishlist**
Speakers: Prof. Andre Lessa (CCNH - Univ. Federal

17:30 **Update on the CODEX-b Experiment**
The High Luminosity LHC will be a tremendous feebly connected to the known SM sector. Such collision point and shielded against SM backgr cavern, around 25m from the LHCb interaction demonstrator (CODEX-β) is foreseen for installation and operation during LHC Run 3. This talk will present the latest developments and will focus on the status and plans for CODEX-β.
Speaker: Louis Henry (EPFL - Ecole Polytechnique Federale Lausanne (CH))

09:00 **Experimental introduction to extended higgs models: an ATLAS perspective (20'+10')** 30m
Speaker: Janna Katharina Behr (Deutsches Elektronen-Synchrotron (DE))

09:30 **Experimental introduction to extended higgs models: a CMS perspective (20'+10')** 30m
Speaker: Danyer Perez Adan (RWTH Aachen University (DE))

10:00 **Theory introduction to extended higgs models: a collider perspective (20'+10')** 30m
Speakers: Jose Miguel No Redondo (Conseil Europeen Recherche Nucl. (CERN)-Unknown-Unknown), Jose Miguel No Redondo

10:30 **Theory introduction to extended higgs models: a dark matter phenomenology perspective (20'+10')** 30
Speakers: Giorgio Busoni (The University of Melbourne), Giorgio Busoni (The Australian National University)

11:00 coffee break 30

11:30 **Extended Higgs Sector in Singlet-Triplet Fermionic Model for Dark Matter and Neutrino Mass (12'+3')** 15
Speaker: Dr Manimala Mitra (Institute of Physics (IOP))

11:45 **Sensitivity of 2HDMa searches to Inert Doublet Model (12'+3')** 15
Speaker: Dr Jayita Lahiri (II. Theoretical Institute for Physics, University of Hamburg)

+3') 15
he Dark Matter searches at the LHC. So far, all the 2HDMa benchmarks used by t degenerate Higgses ($m_A = m_H = m_{H^\pm}$). The latter implies, together with the of the charged Higgses, that the $A/H/H^\pm$ bosons are all constrained to be he

Ma model with a Type-I Yukawa sector, which, for moderate values of $\tan\beta$, lifts Higgs bosons to be even lighter than the SM Higgs boson. We discuss four ses and the signatures that arise in this model, some of which have not yet been the dominant channels in these benchmarks and the expected sensitivity in Run

16:00 **Searches for Extra Higgs Bosons and the 95 GeV Excess [25**
Speaker: Thomas Biekötter

16:30 **Light Higgs Bosons ATLAS+CMS [15+5]**
Speaker: Pallabi Das (Princeton University (US))

16:50 **Search for inelastic dark matter in association with a dark H**
Belle II has a unique reach for a broad class of models that postula One scenario is a model which involves inelastic dark matter, consi the presence of a dark Higgs boson. This model has a signature of

16:30 **EFT theory for Higgs to invisible** 20m
Speaker: Prof. Pyungwon Ko (KIAS (Korea Institute for Advanced Study))

17:00 **Beyond the Dark matter effective field theory and a simplified model approach at colliders** 15m
In this talk, I will review the importance of "Gauge invariance" in the search for Dark matter at the High Energy Collider including LHC.

The major topics I will include will be
1) The limit of effective field theory / simplified model approach at the High Energy collider
2) Dark matter showering at the High Energy
Speaker: Prof. Myeonghun Park (Seoultech)

17:25 **Is the light neutralino thermal dark matt**
We explore the parameter space of the phen thermal dark matter ($M_{\tilde{\chi}^0_1} \leq M_h/2$) that is c with light Higgsinos having masses betwee electroweakino searches implemented in re hints towards either a gap in the present LH and our analysis using the machine learning dedicated efforts to probe this region should detection searches for dark matter by the LU impact of light staus on the parameter spac at the LHC using XGBOOST. Finally, we also discuss the effect of non-standard cosmology on the parameter space.
Speaker: Rhitaja Sengupta (BCTP and Physikalisches Institut der Universität Bonn, Germany)

17:50 **Darkonia at Colliders** 15m
Dark matter bound states may exist within the dark sector, characterized by a substantial dark force. Depending on the spins and parity properties of the force carriers, Standard Model particles may primarily couple with either the lowest or excited bound states. We discuss the associated collider signatures at the LHC for various simplified models.
Speaker: Yang Bai

14:00 **ATLAS Higgs to invisible plans and summary** 20m
Speaker: Diallo Boye (Brookhaven National Laboratory)

14:30 **CMS Higgs to invisible plans and summary** 20m
Speaker: Andrea Malara (Universite Libre de Bruxelles (BE))

15:00 **ATLAS & CMS legacy s-channel results** 20m
Speaker: Matteo Bauce (Sapienza Universita e INFN, Roma I (IT))

15:30 **New experimental directions for s-channel** 20m

16:30 **Mono-X Signatures of a Fermionic Dark Matter at the LHC (15'+**
Speakers: Kai Ma (Shaanxi University of Technology), Prof. Shao-Feng Ge (TD

16:50 **Dark Photon Theory Landscape (25'+10')**
Speaker: Stefania Gori (UC Santa Cruz)

17:25 **Dark Photon Exploration Beyond the LHC (25'+10')**
Speaker: Bertrand Echenard (California Institute of Technology (US))

11:30 **Production of Kaluza-Klein States at LHC and Implication for Dark Matter [12+3]** 15m
t has been proposed that, in the large radius compactification (LRC) scenario, the Kaluza-Klein states might be considered as dark matter (DM) candidates. The universal extra dimension (UED) hyp states at LHC if masses lie in the accessible LHC energy sc protected by a conservation law not to decay to SM particle on production cross sections and bounds on near forward perturbation theory, i.e. cross-section bounds are obtained such as Lorentz invariance, causality and uniqueness of va properties of relevant cross sections as a function of energ
Speaker: Jnanadeva Maharana (National Institute of Science Educ
cern-dm24.pdf

11:45 **Search for Anti Quark Nuggets via their interaction wi LHC monitors [12+3]**
Anti-quark nuggets, AQNs, (ZHITNITSKY, 2003), have been s the universe, and have been proposed as an explanation of

Their size is in the µm range and their density equal to the n velocity of DM constituents (~250 km/s), the solar system streams or clusters are impinging, e.g., on the Earth, as was

Interestingly, in the LHC beam, unforeseen beam losses are be constituted of dust particles with a size in the µm range

Prezeau suggested that streaming DM constituents inciden ideas open up novel directions in the search for DM.

This talk suggests a new analysis of the UFO results at the LHC, assuming that they are eventually, at least partly, due to AQNs. Specifically, a reanalysis of the existing data from the ~4000 beam monitors since the beginning of the LHC is proposed, arguing that dust and AQNs should behave differently. The feasibility of this idea has been discussed with three CERN accelerator experts and other collaborators.
Speaker: Konstantin Zioutas (University of Patras (GR))

12:00 **The Triggerless Search for Exotic DM at Run-3 with the MoEDAL-MAPP Experiment [12+3]** 15m
The MoEDAL-MAPP experiment at Run-3 incorporates the MoEDAL and MAPP-1 (MoEDAL Apparatus for Penetrating Particles) detectors deployed at IP8 and in the UA83 tunnel on the LHC Ring, respectively. The passive, triggerless, MoEDAL detector has been taking data at Run-1 and Run-2 and is a world leader in the direct search for Highly Ionizing Particles (HIPs) at a Collider. HIP avatars of new physics include several exotic dark matter candidates including magnetic monopoles, Q-balls, nuclearites, microscopic black-hole remnants and lepton-like multi-charged constituents of composite dark matter, etc.

The MAPP-1 detector is currently being installed on the LHC ring and is primarily designed to search for Weakly Ionizing Particle (WIPs) messengers of new physics. However, it also has sensitivity to very long-lived charged and neutral particles (LLPs) exemplars of physics beyond the Standard Model, decaying to charged and photonic states. The MAPP-1 data acquisition rate is low enough that all data can be stored subject to optional "software a trigger" cuts. In this sense MAPP-1 is triggerless. The MAPP-1 detector will also be used in the search for exotic DM messengers of new physics such as: millicharged particles, light neutralinos and sterile neutrinos.
Speaker: James Pinfold (University of Alberta (CA))
DM-workshop-CER...

09:00 **A smoking gun signature of the 3HDM [20+10]**
Speaker: Dr Atri Dey (Dublin Institute for Advanced Studies)

09:30 **Fermionic Portal to Vector Dark Matter [20+10]**
We suggest a new class of models - Fermionic Portal Vector Dark Matter (FPVDM) which extends the Standard Model (dark gauge sector. While FPVDM does not require kinetic mixing and Higgs portal. It is based on the Vector-Like (VL) fer which couples the dark sector with the SM sector through the Yukawa interaction. The FPVDM framework provides a ve (DM) with Z_2 odd parity ensuring its stability. Multiple realisations are allowed depending on the VL partner and scalar explain not only DM but also could provide solutions of various BSM hints, including (g-2)_mu, flavour anomalies, W-bos measurement by CDF, etc.

Two examples will be discussed. One of them is the FPVDM realisation with only a VL top partner, which provides intere promising implications for DM direct and indirect detection experiments, relic density and collider searches. Another rea FPDM framework with a doublet of new vector-like partners of muon can simultaneously explain DM relic density togeth anomaly which has been in close focus of the HEP community over two decades. It predicts the mass of vector DM to b well as the mass of the muon partner to be below 1 TeV, and provides novel multi-lepton signatures at the LHC.

The talk is based on 2203.04681, 2204.03510 arXiv papers as well as the new one which is coming this March-April.
Speaker: Prof. Alexander Belyaev (University of Southampton & Rutherford Appleton Laboratory)

10:00 **Inelastic Dark Matter at the LHC Lifetime Frontier [20+10]**
Speaker: Max Fieg (University of California Irvine (US))

How do you search for something when

1) You don't really know what that something is
2) You know vaguely what that something is, but the parameter space is huge

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2024-05-13 DM Wor…

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10:15 Reinte…
In this … dark se… scenar… betwe… search…
Hence…
a) dark… b) s-… c) Hi…
Spea…

10:30 Expl…
After…

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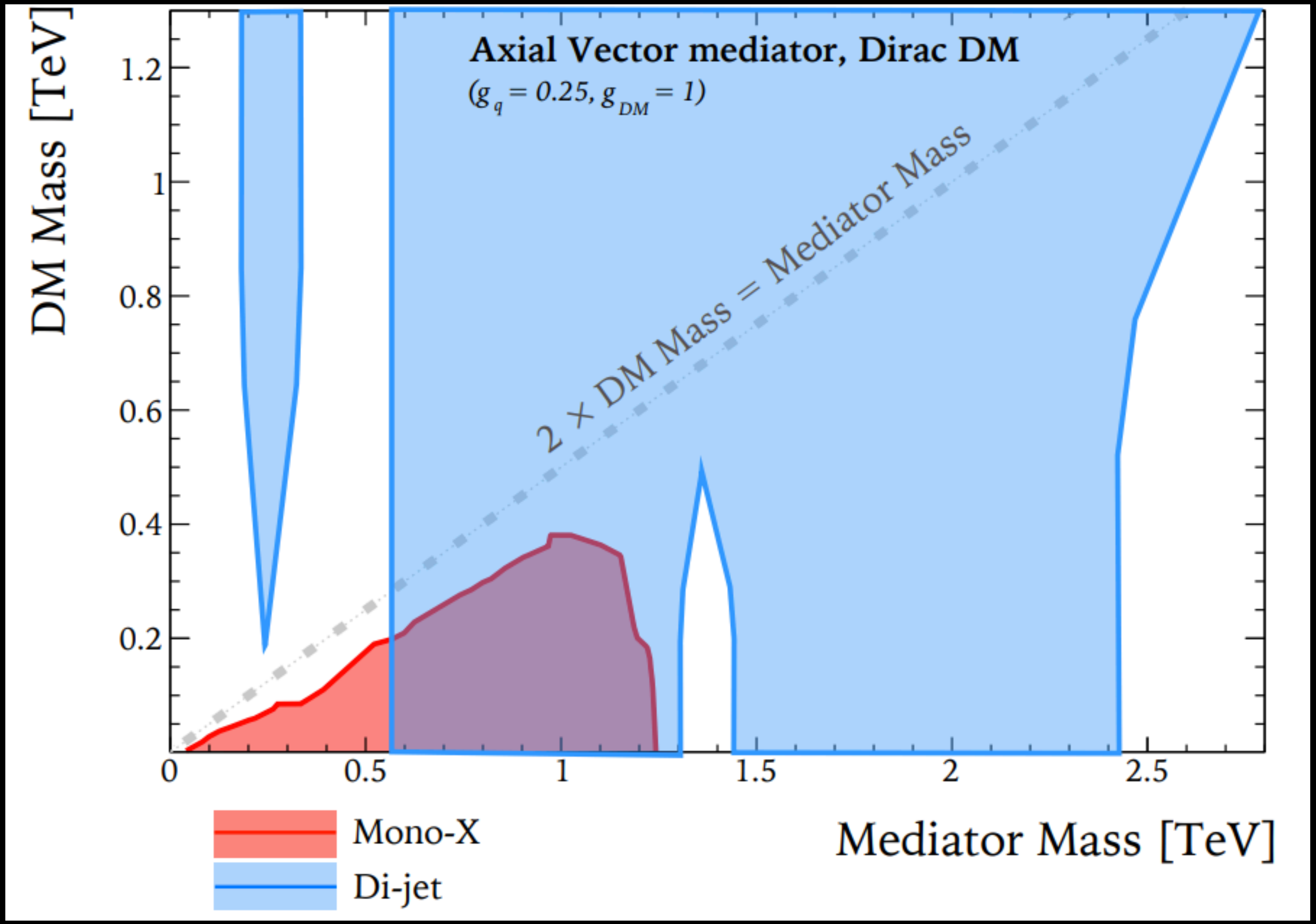
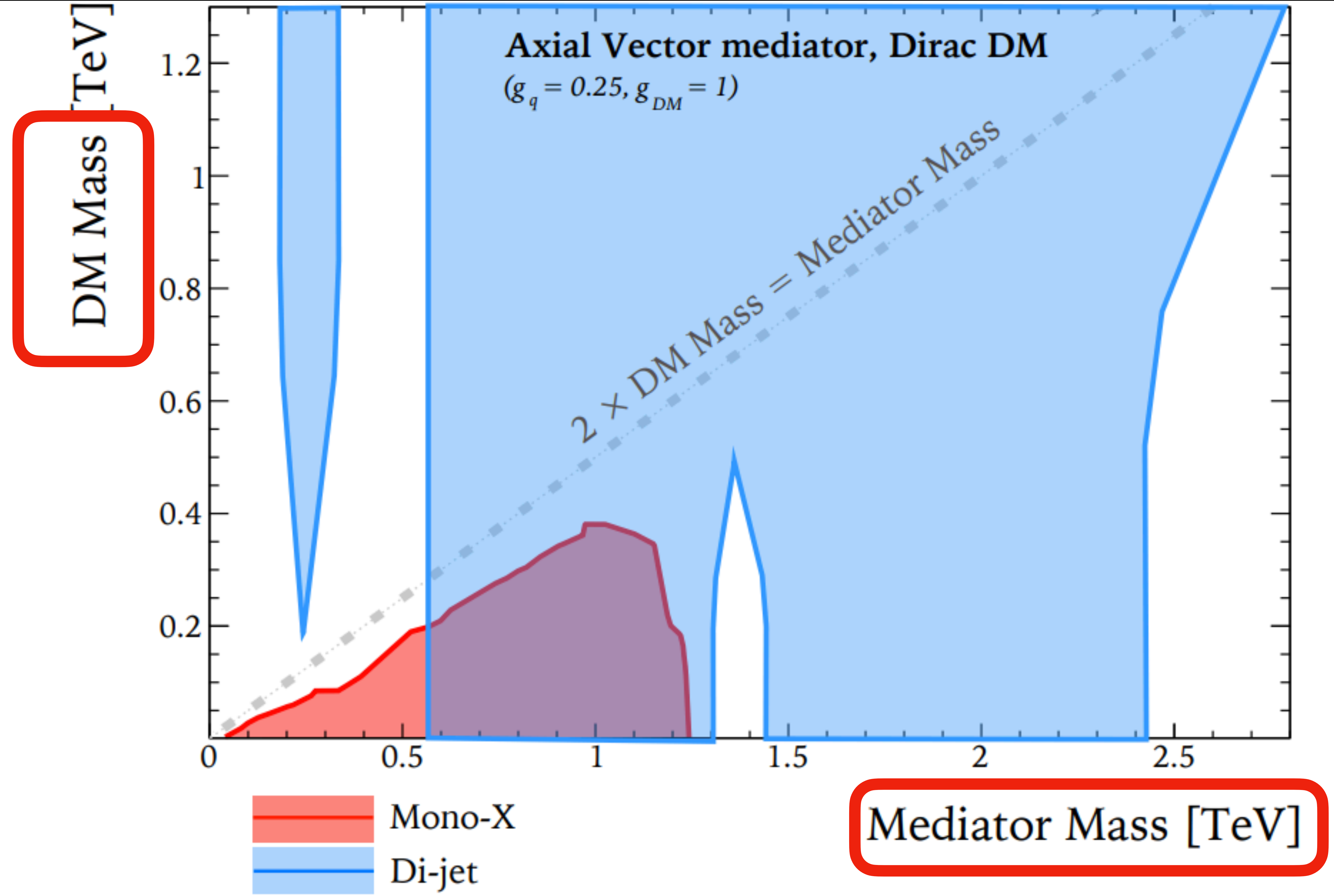
Anomaly detection for New Physics searches



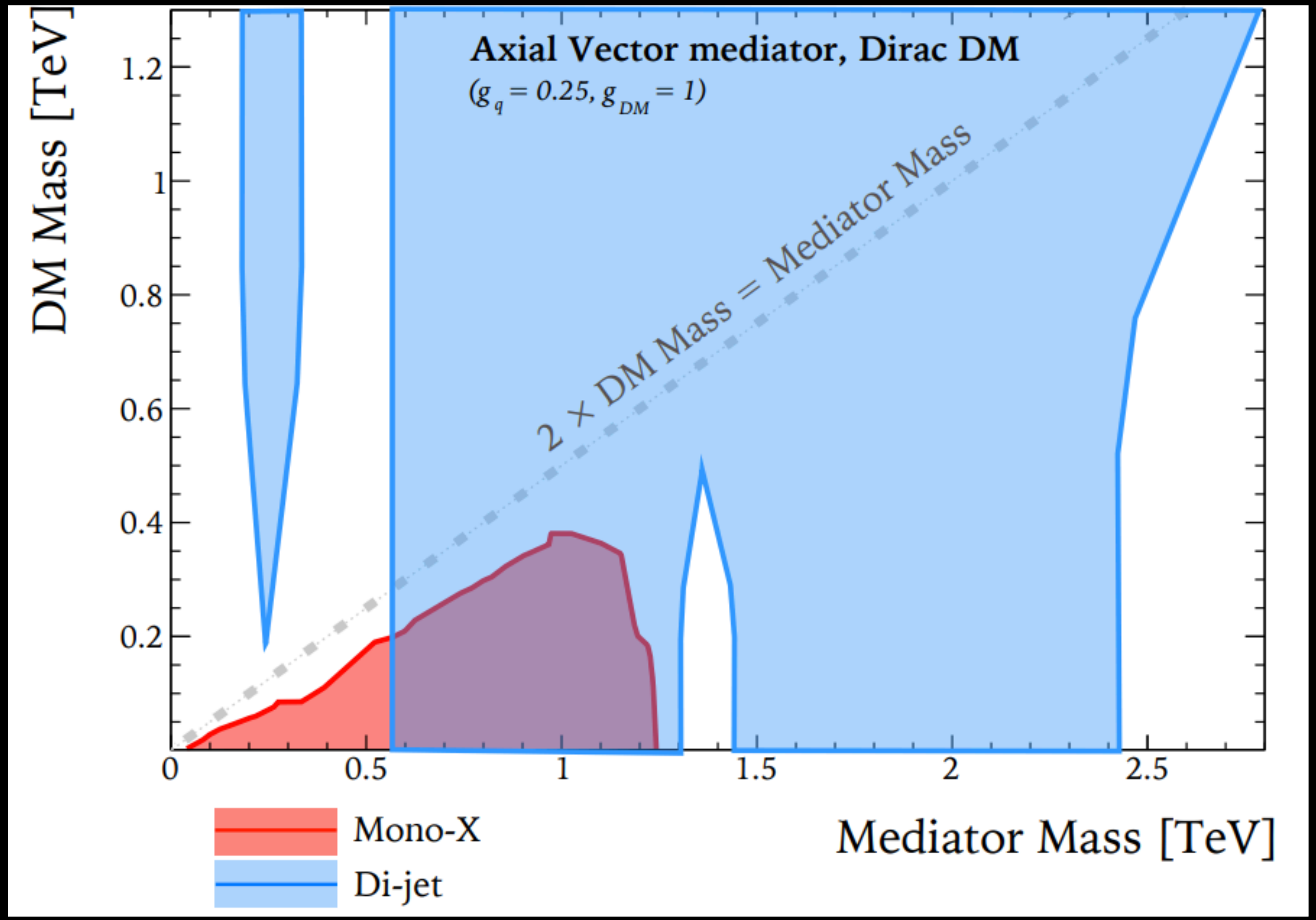
Anomaly detection for New Physics searches

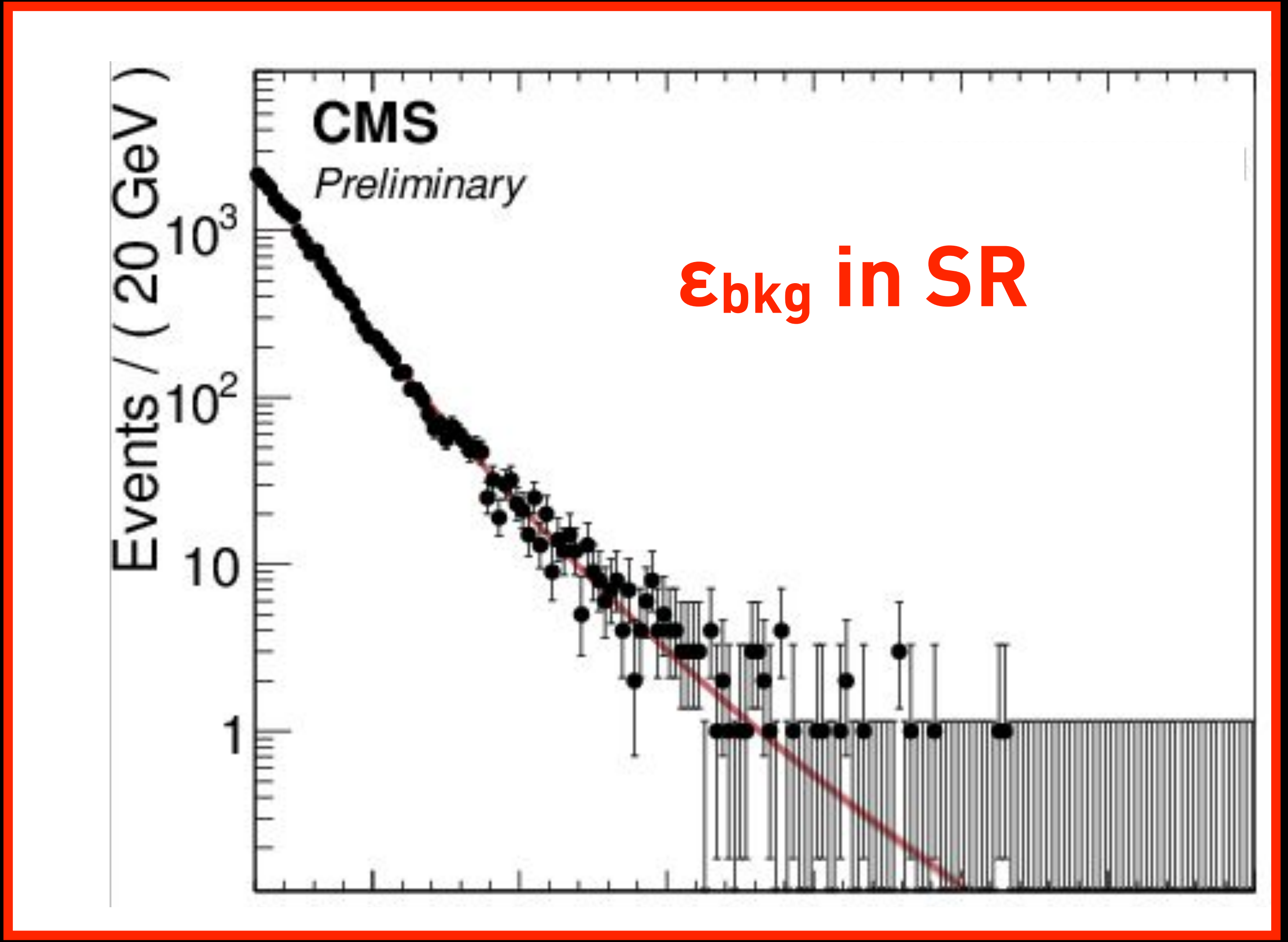


A lot of searches (= PhD students)…

Figure 5: Sketch of the constraints on a simplified model of WIMP DM where a particle with axial vector couplings of 1.0 and 0.25 to DM and SM respectively is exchanged. The constraints from mono-X (exclusion region in red) and dijet DM searches (exclusion region in blue) are shown in the plane of dark matter

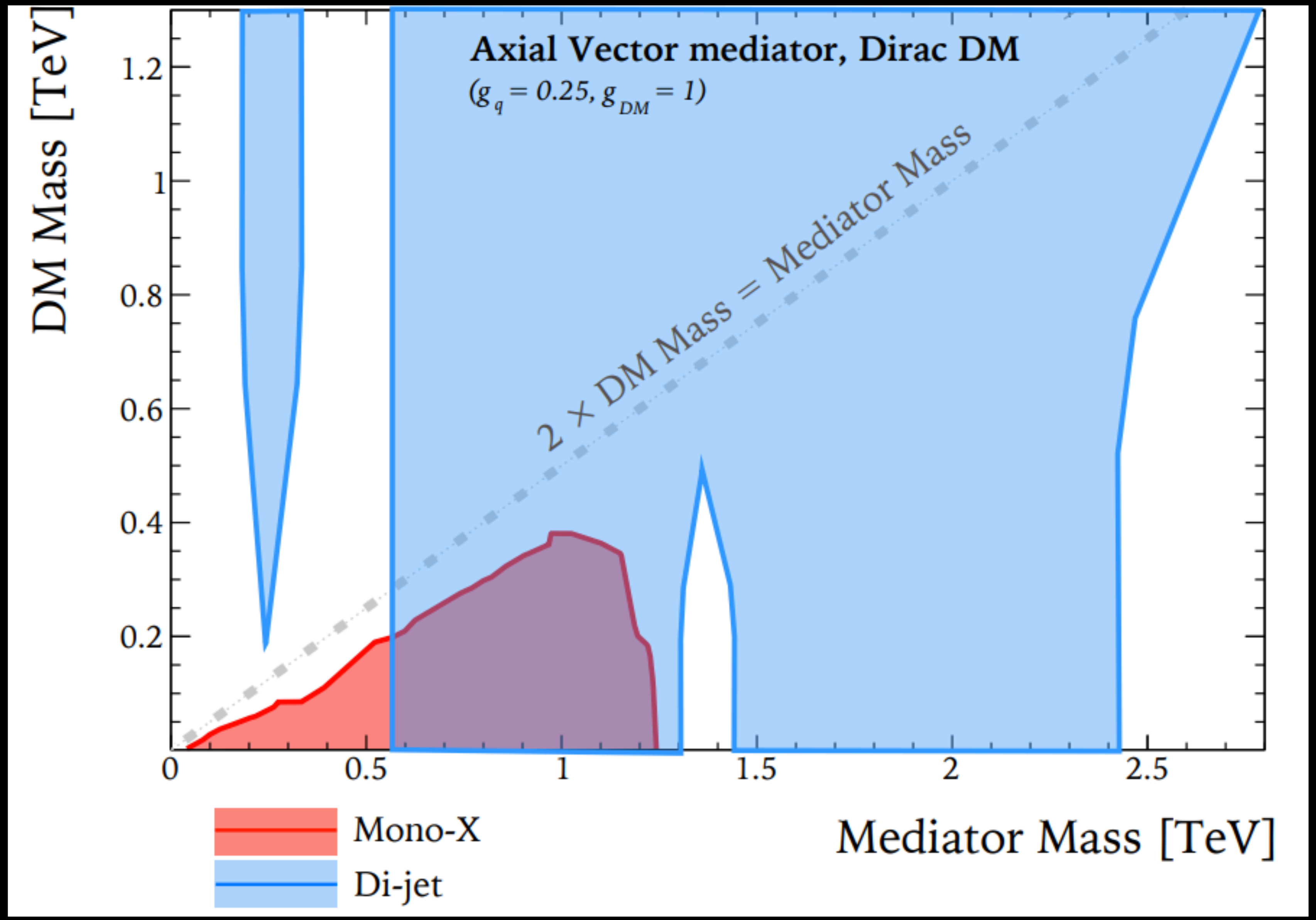
Anomaly detection for New Physics searches

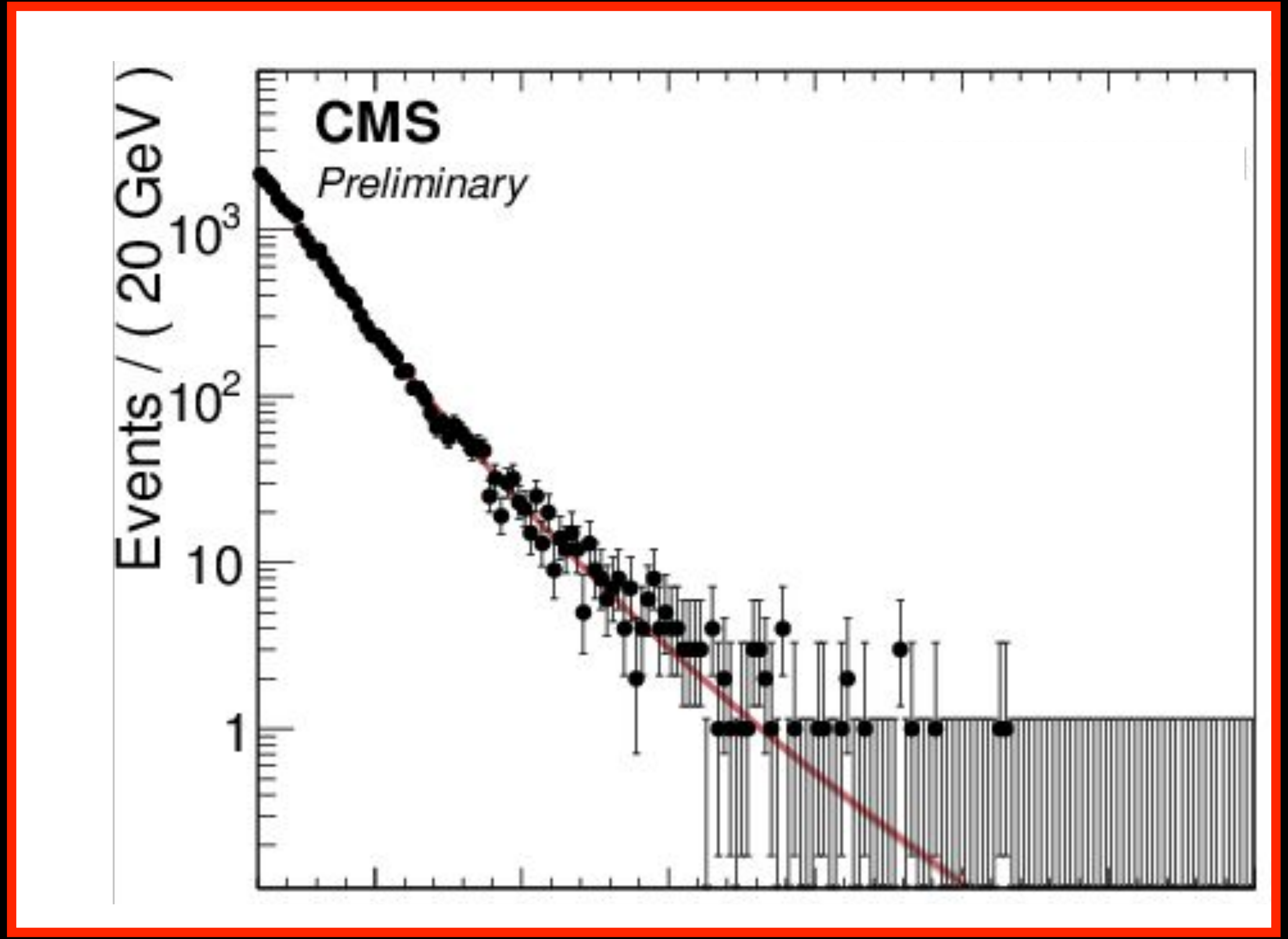




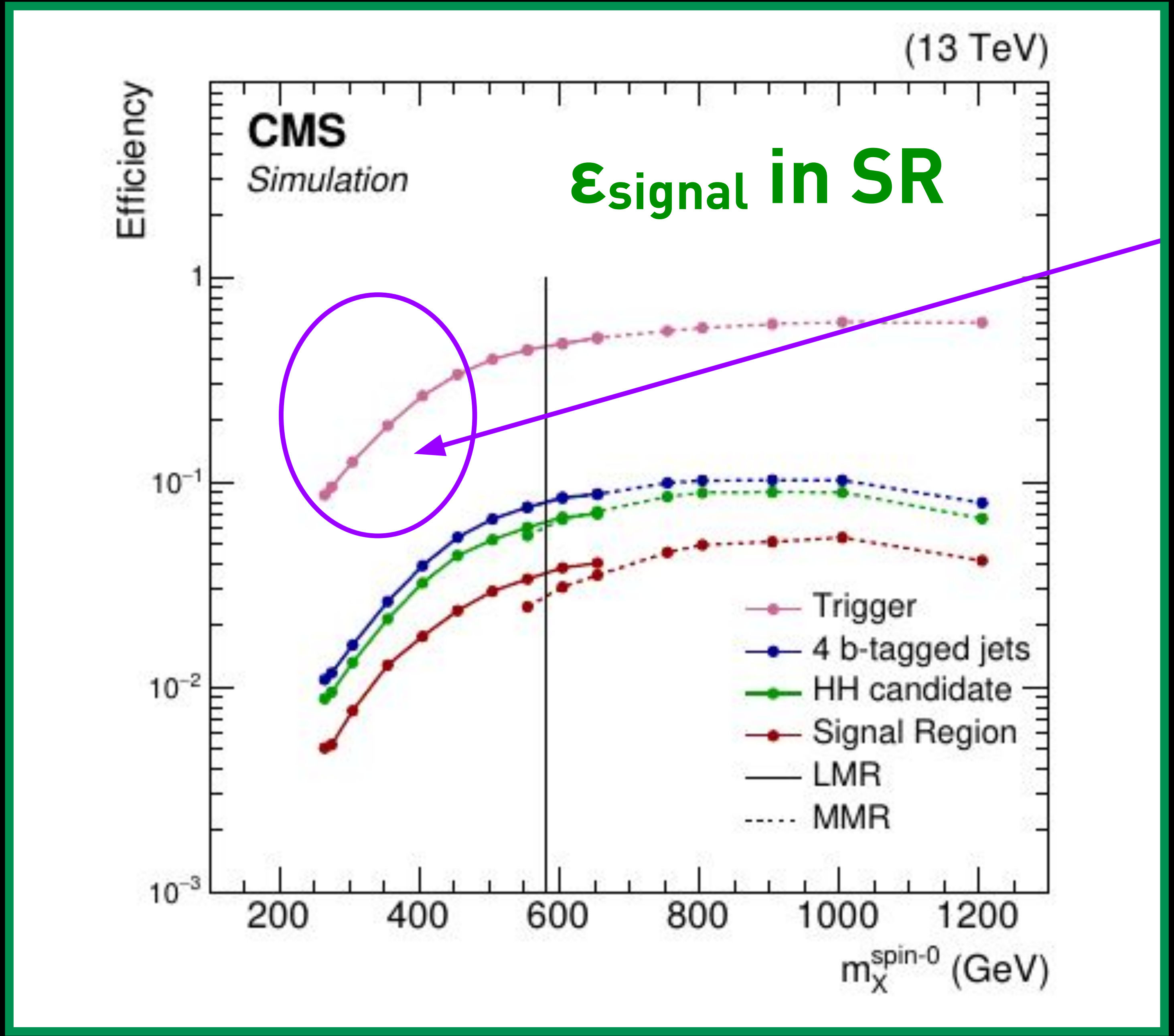
Can we reduce **this**

Anomaly detection for New Physics searches





Can we reduce
this
and maximise
this



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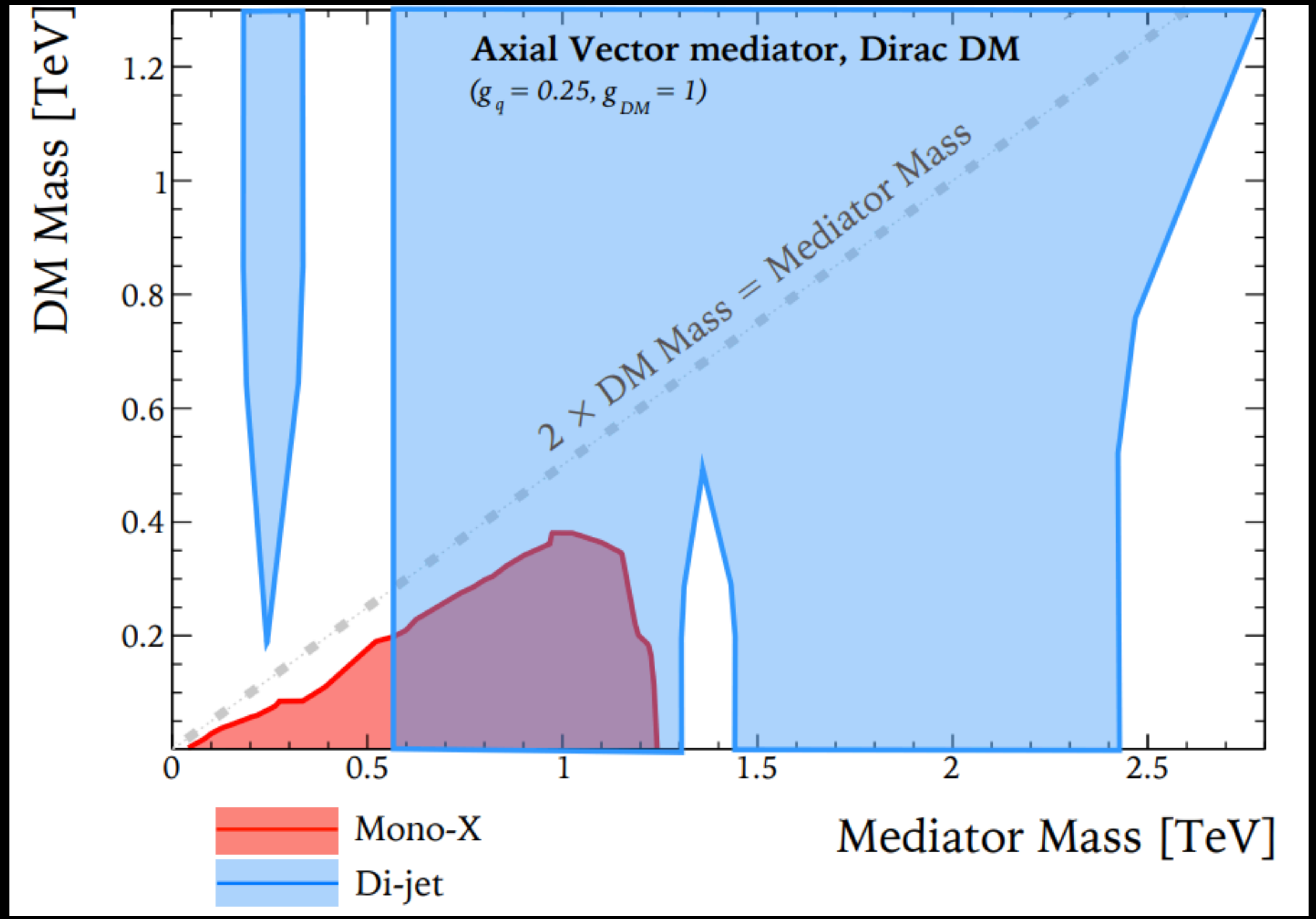
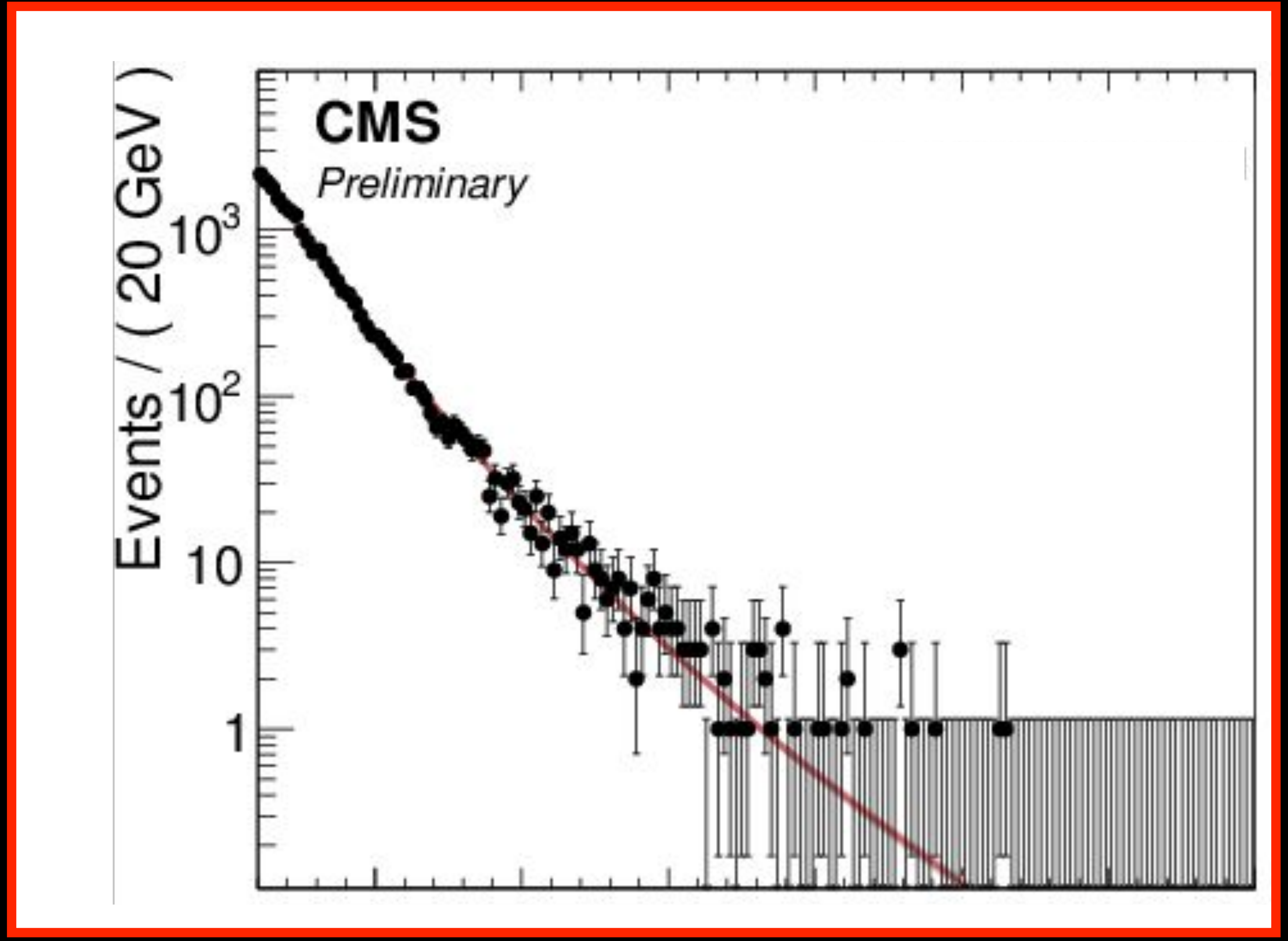
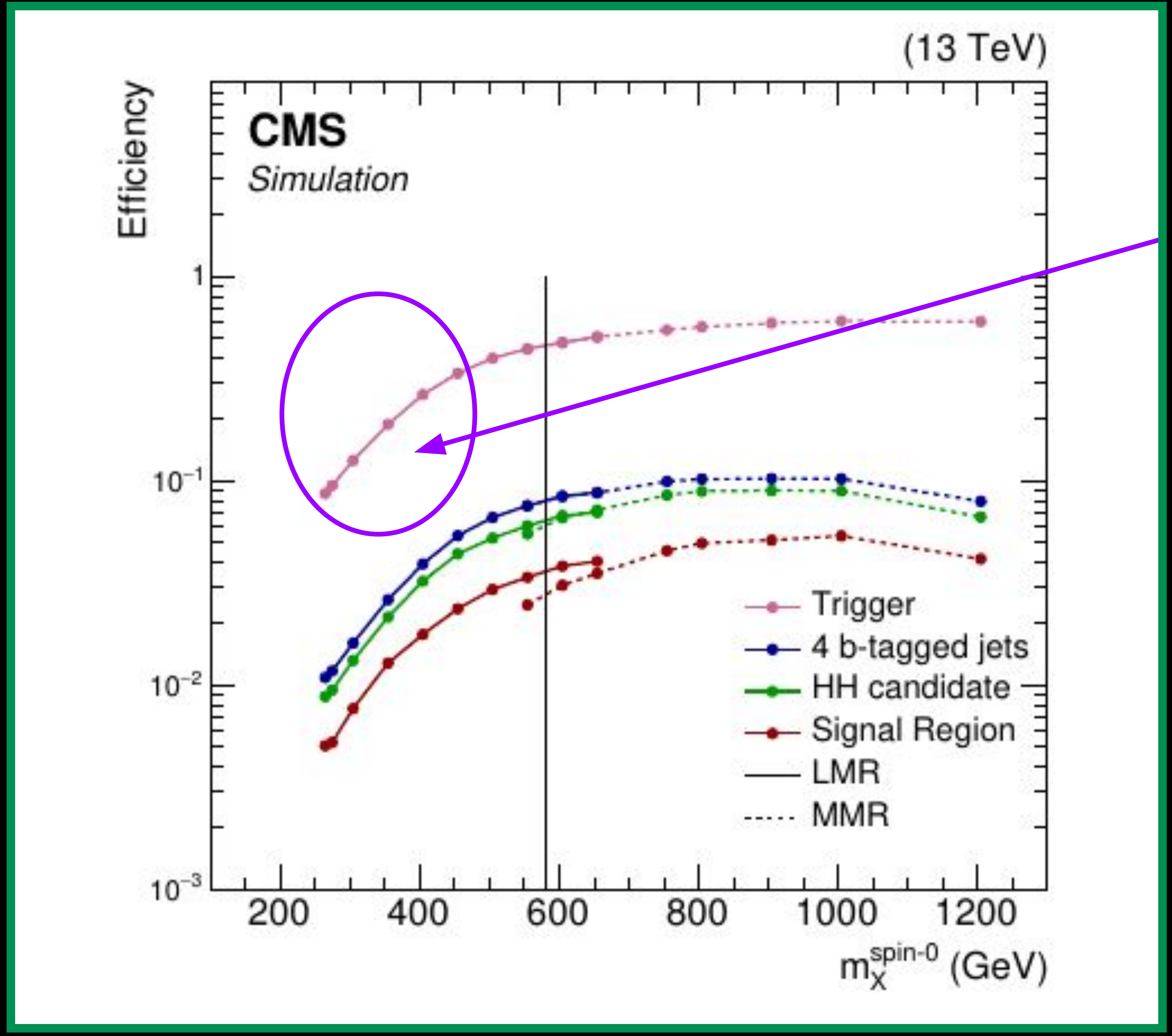




Can we reduce
this
and maximise
this
to probe hundreds of signal hypotheses all at once?



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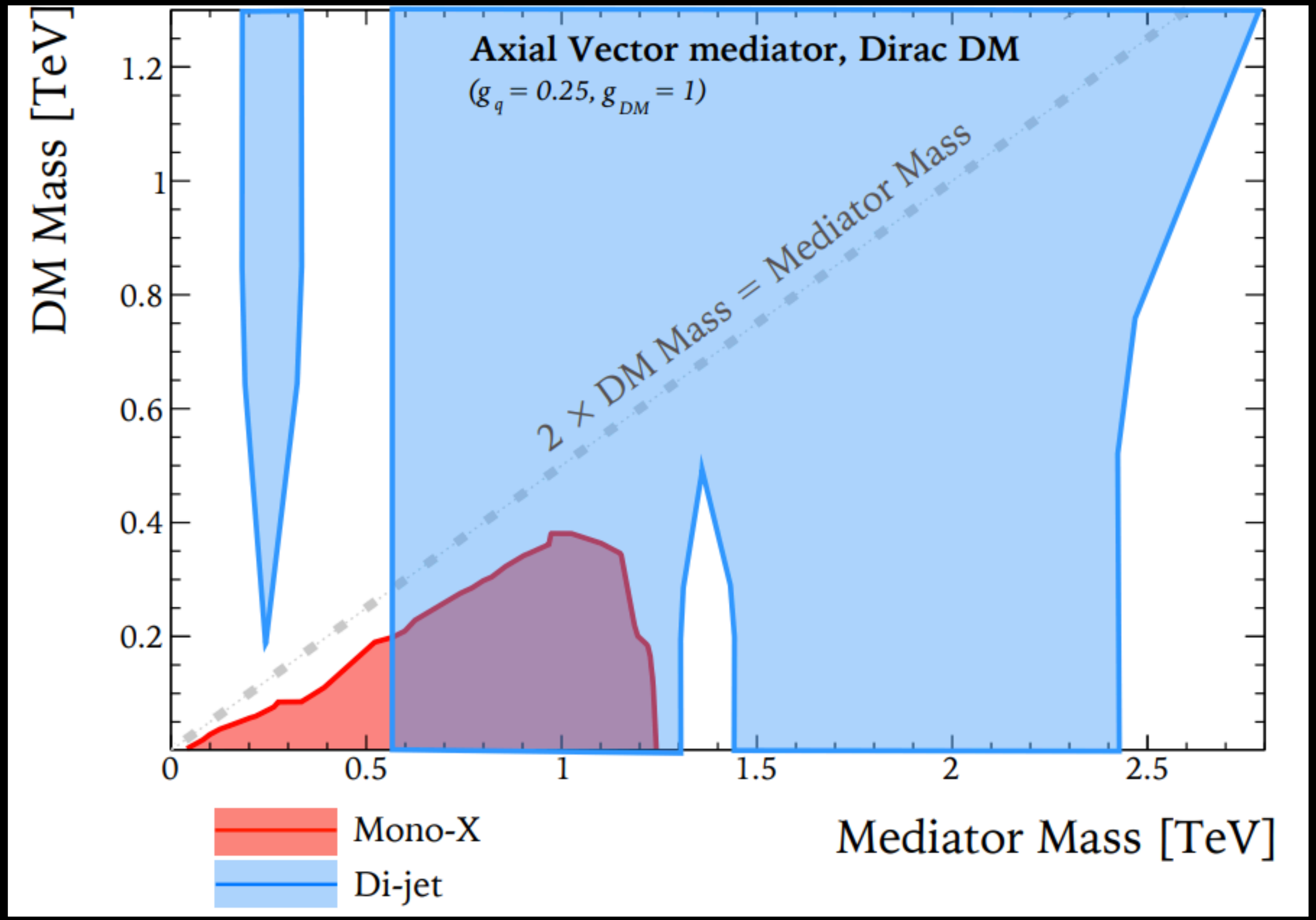
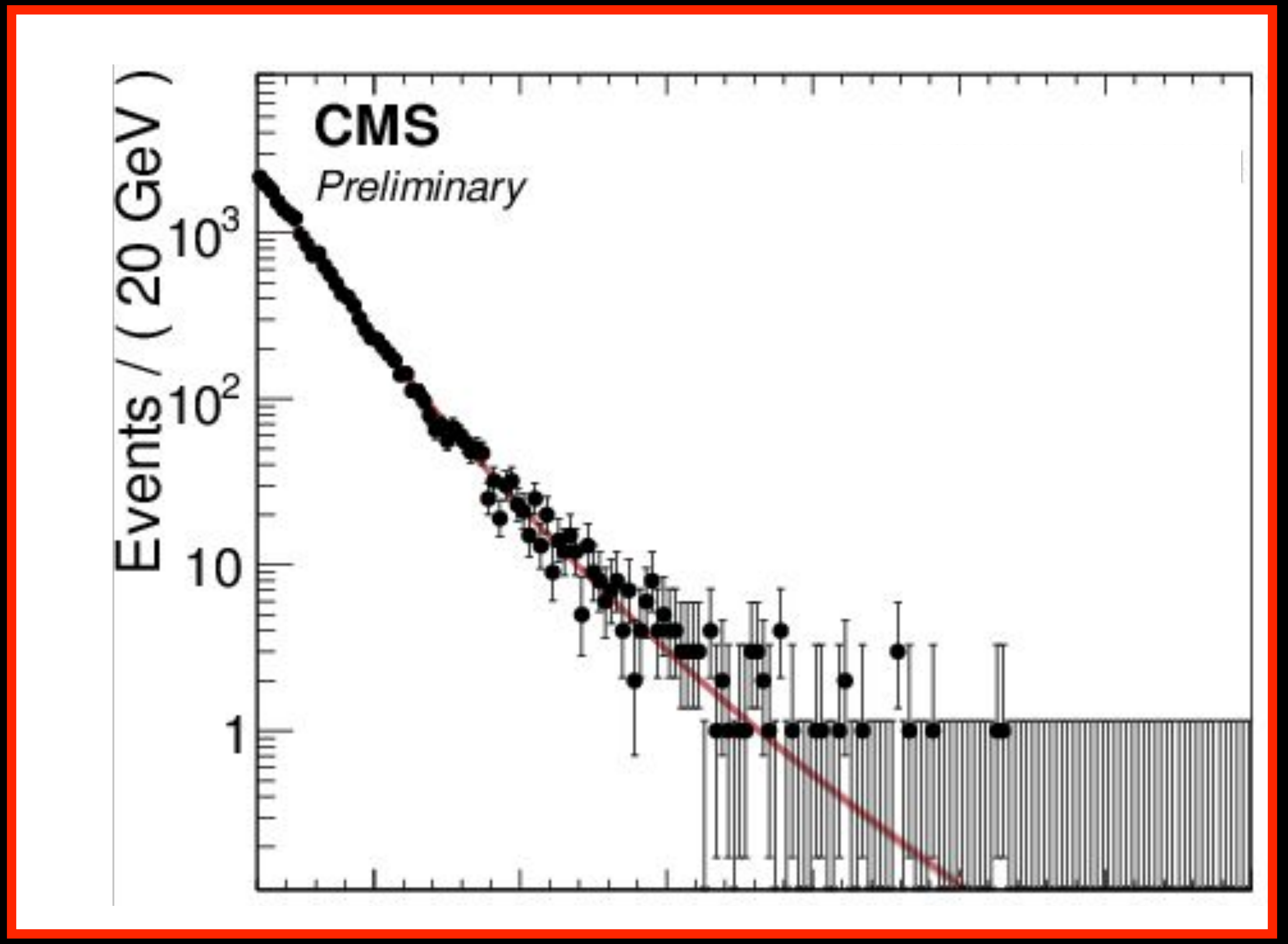
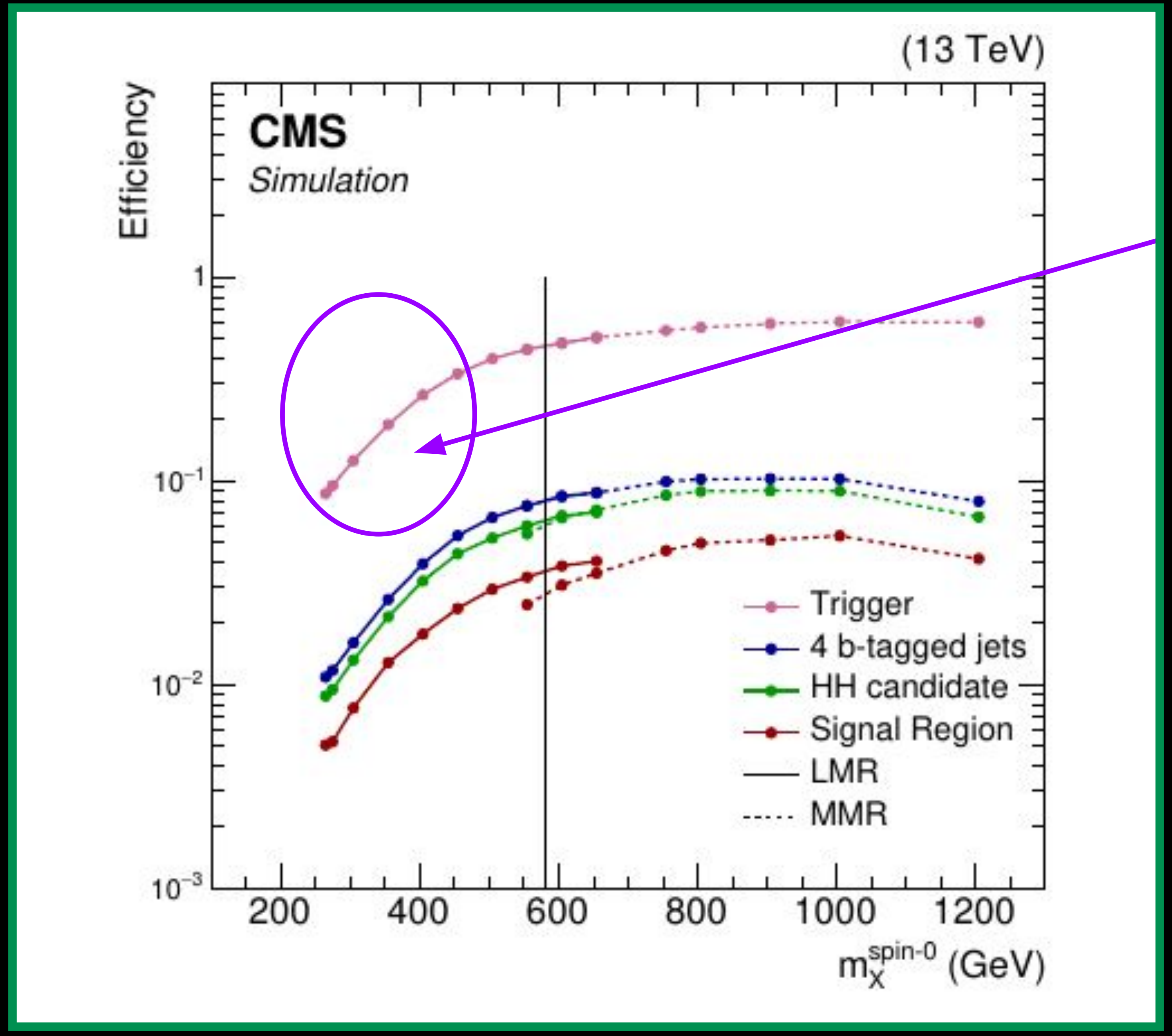




Can we reduce
this
and maximise
this
to probe hundreds of signal hypotheses all at once?
*(Maybe also some we didn't think of yet?)



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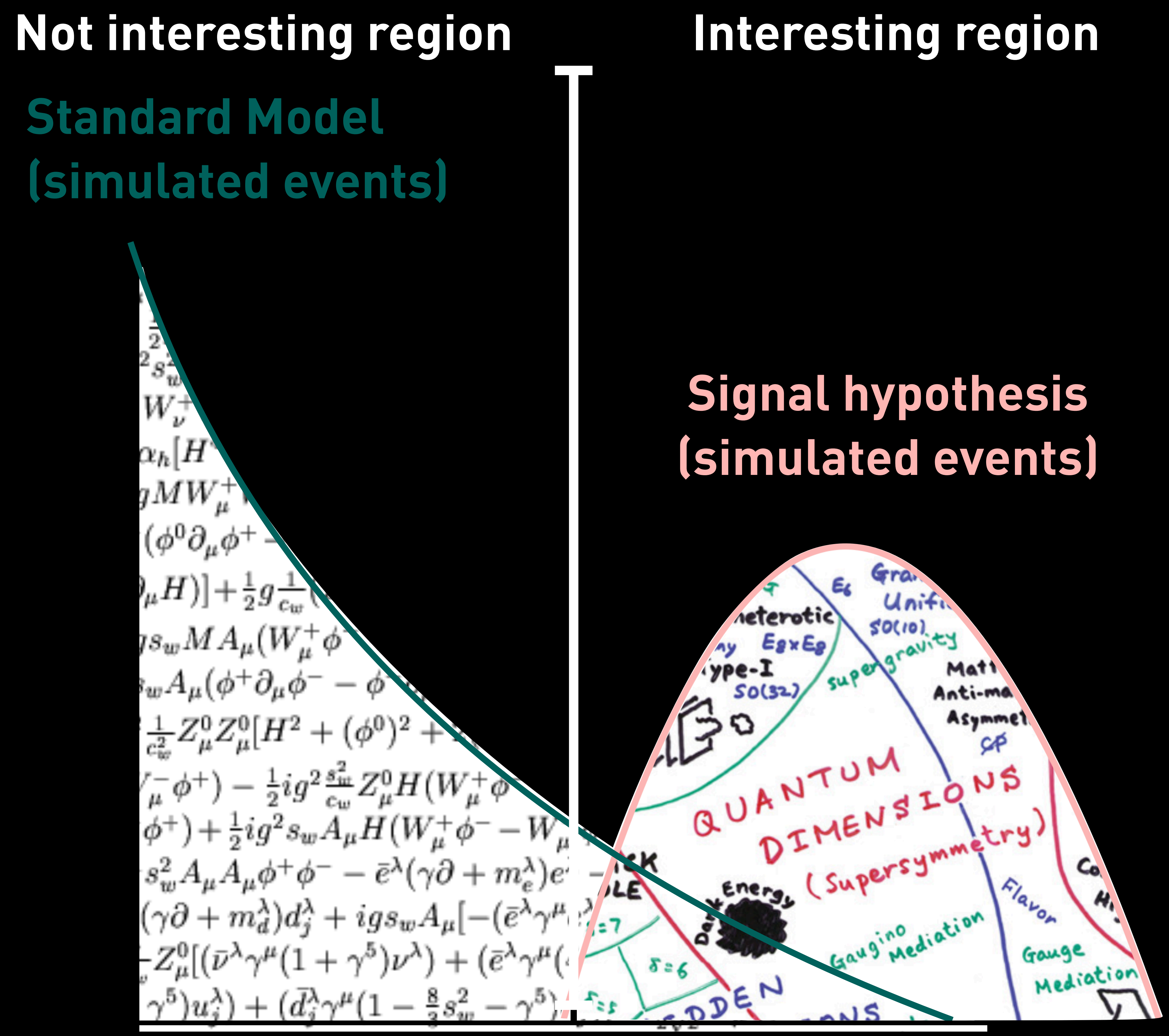

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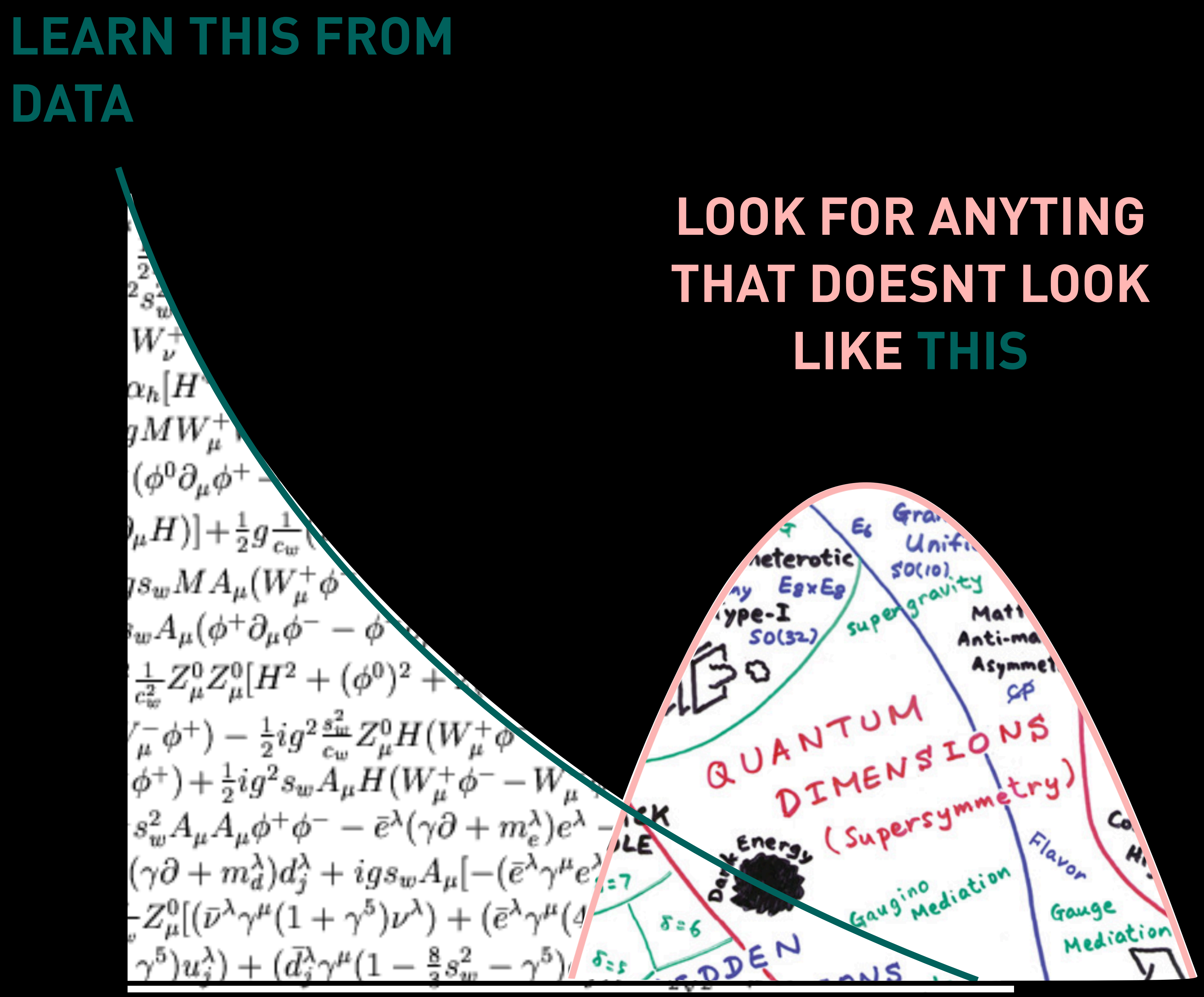
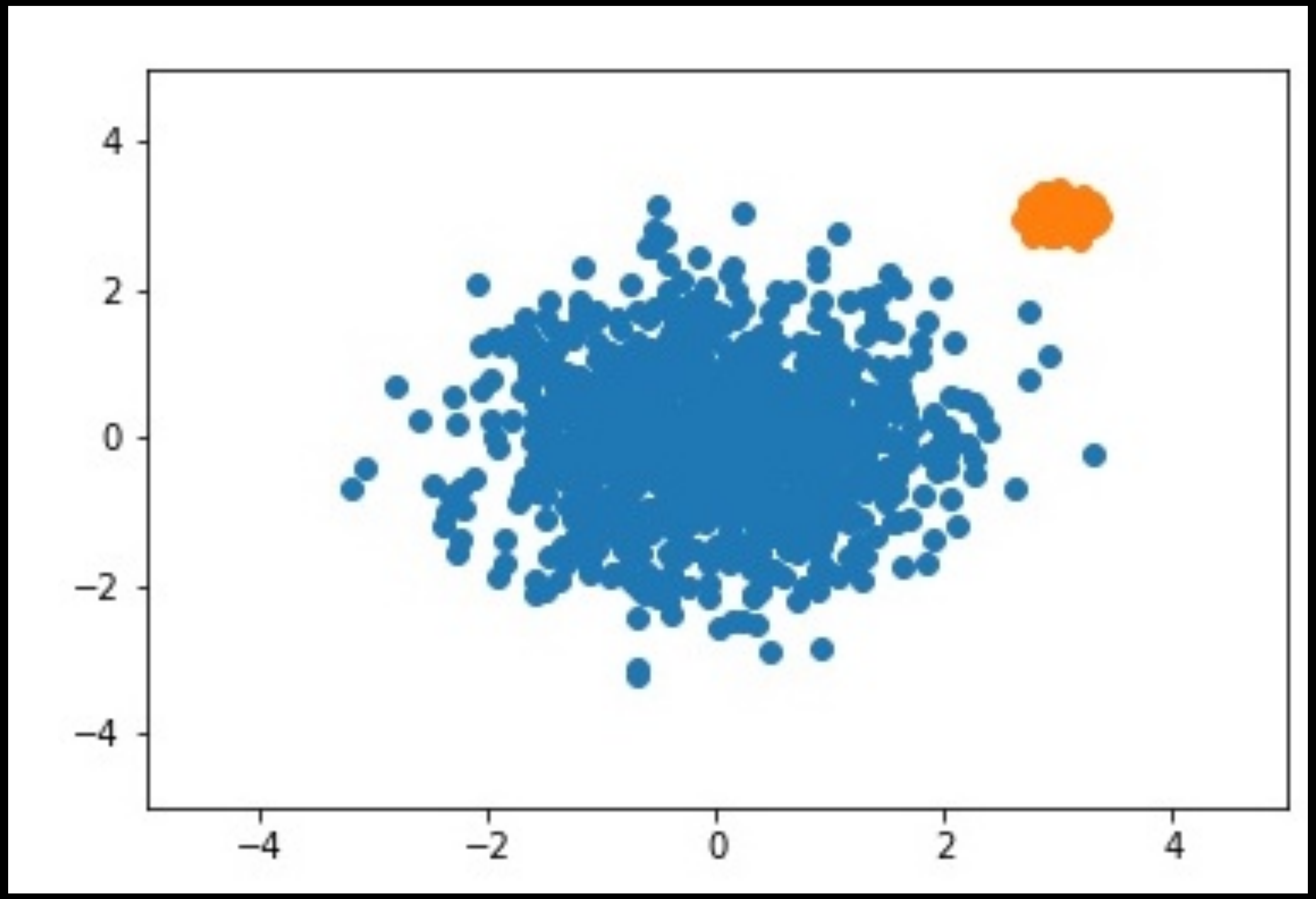


Types of anomaly detection

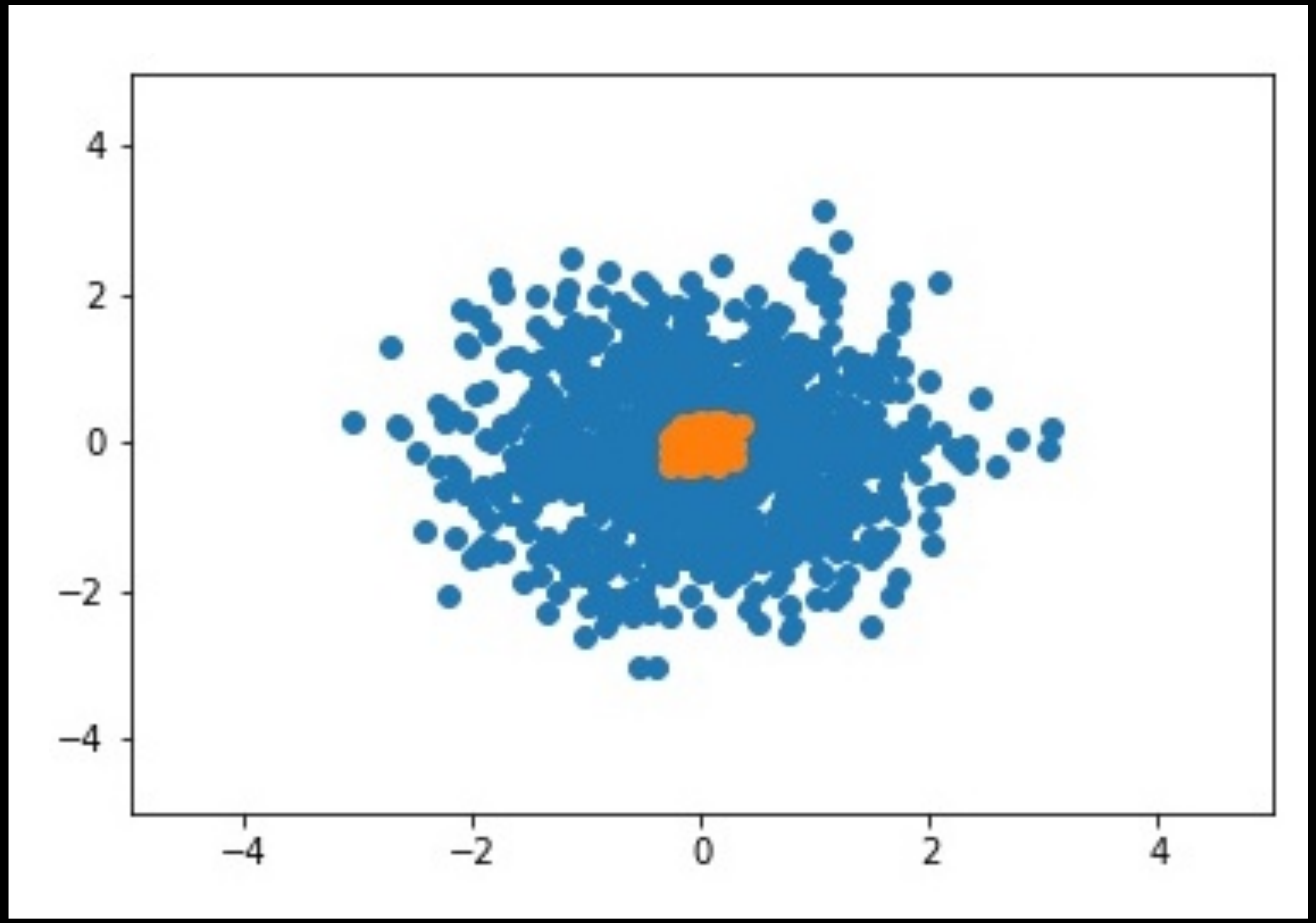
Outlier detection

Find (non-resonant) out-of-distribution datapoints



Detecting overdensities

Find (resonant) overdensities in distributions



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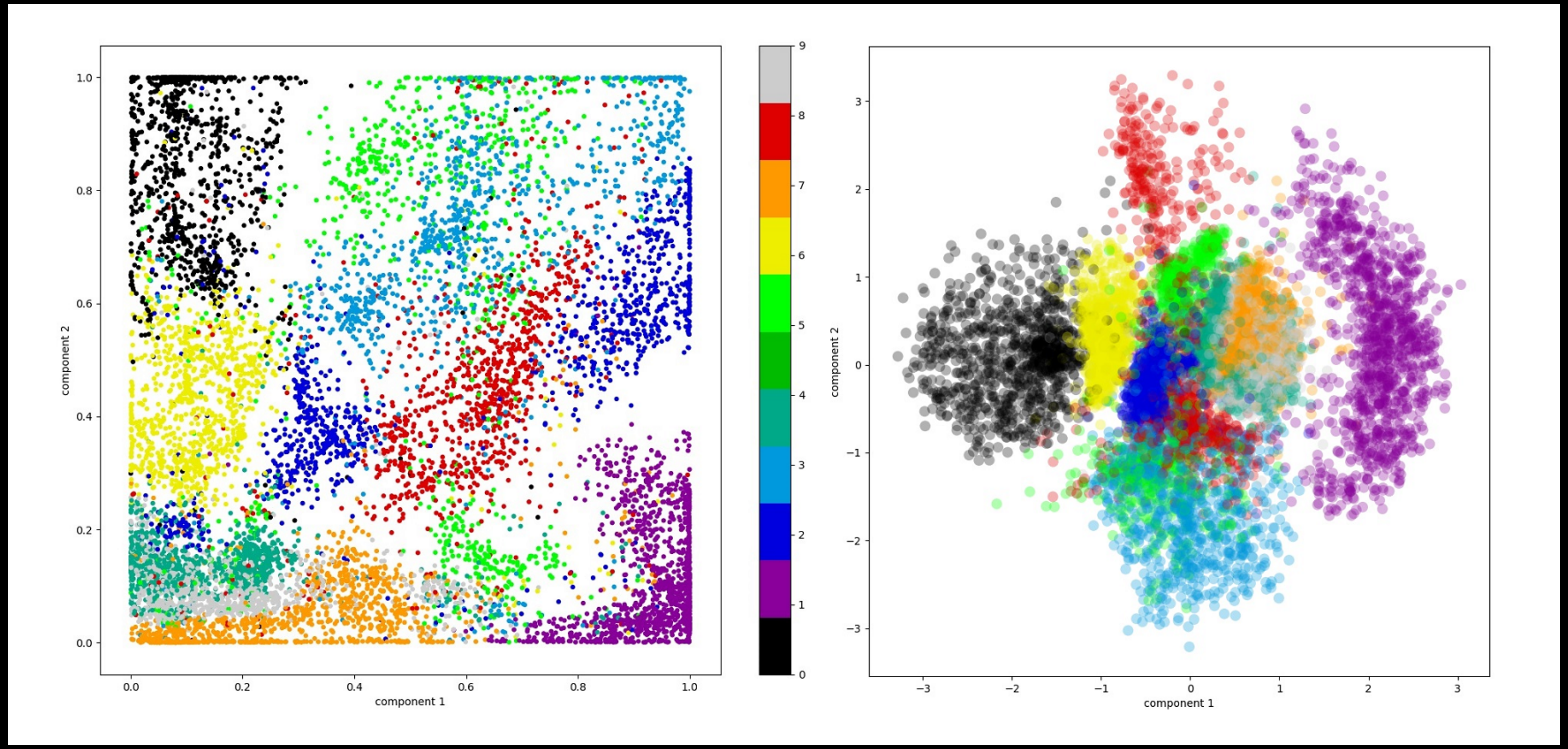


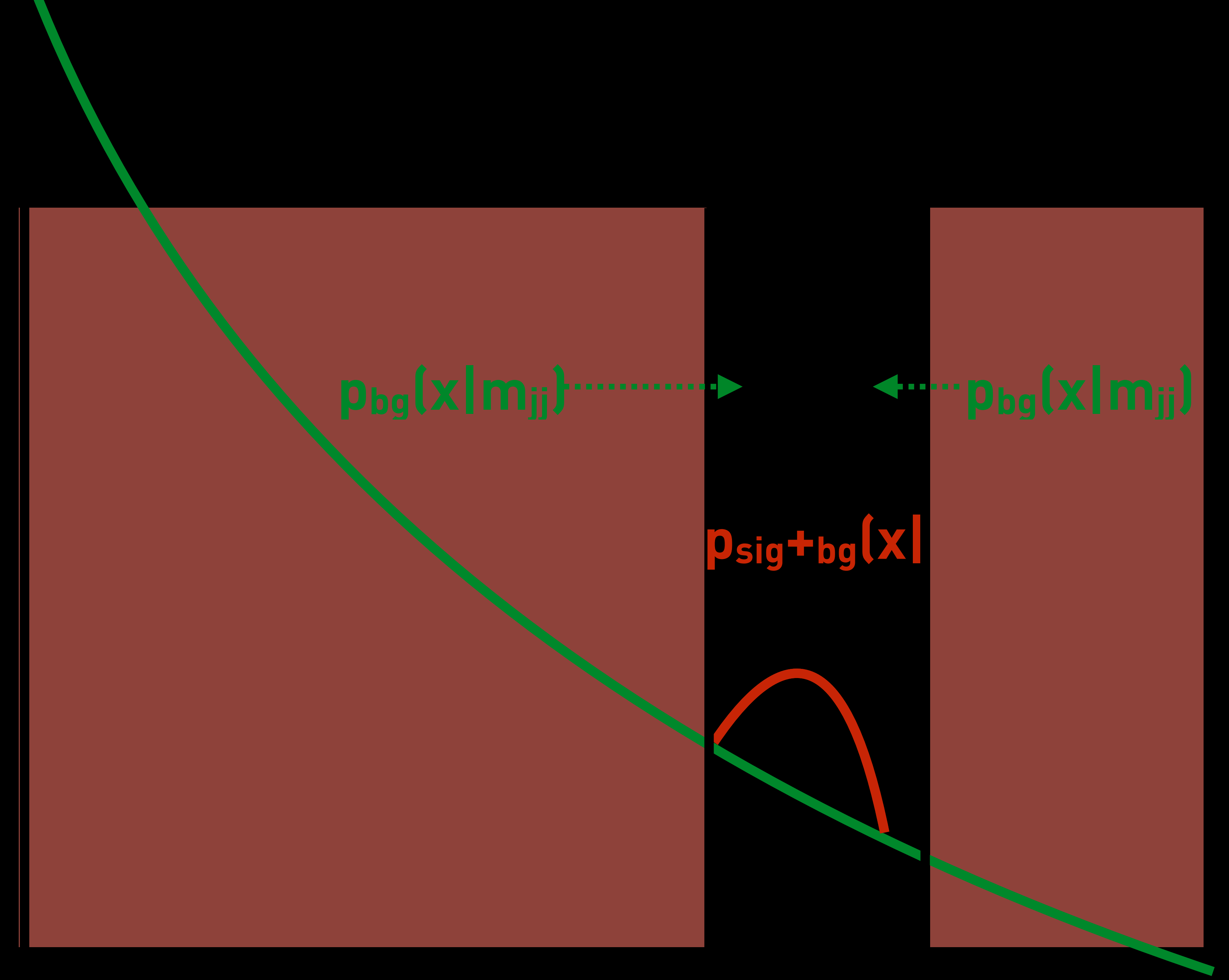
Non-resonant, tail of distributions

- Often (variational) auto-encoders
- Useful for triggering!

Caveats

- What's a good metric for optimisation?
- How to use selected events in analysis?

Detecting overdensities



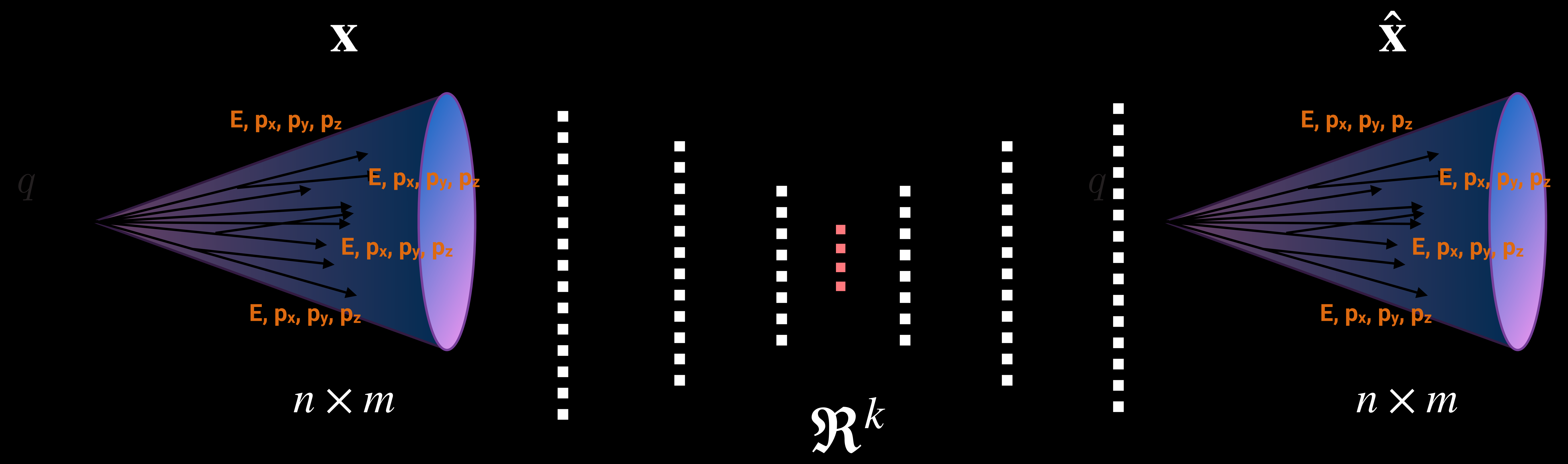
Resonant, similar to a bump hunt

- Density estimation methods
- Useful for offline analysis

Caveats

- Relies on a definition of "sideband" and a sizeable signal

Outlier detection

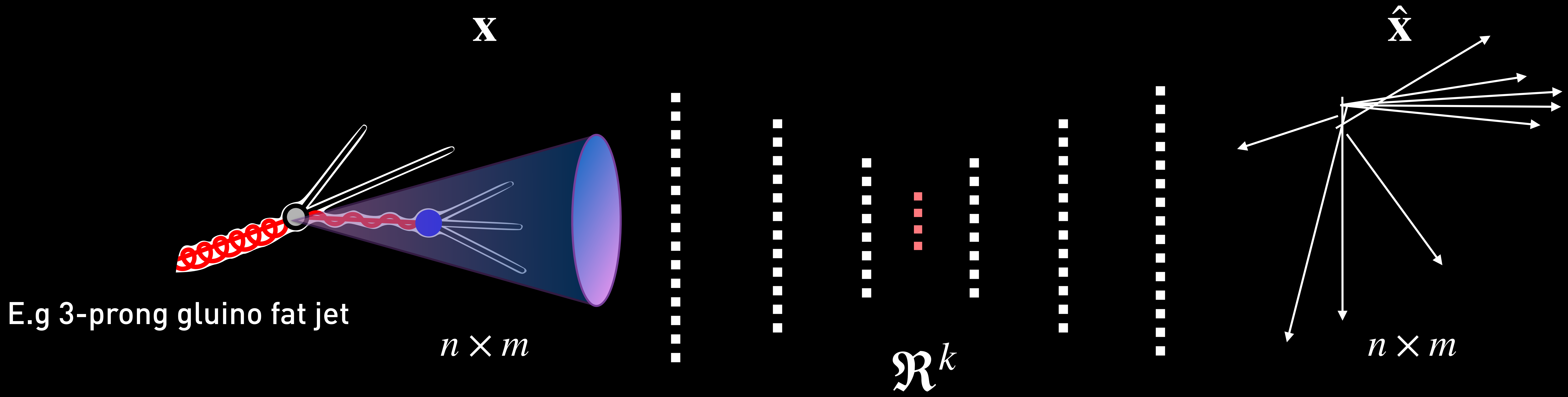


Compressed representation of x.

Latent space $\mathfrak{R}^k$, k < m×n

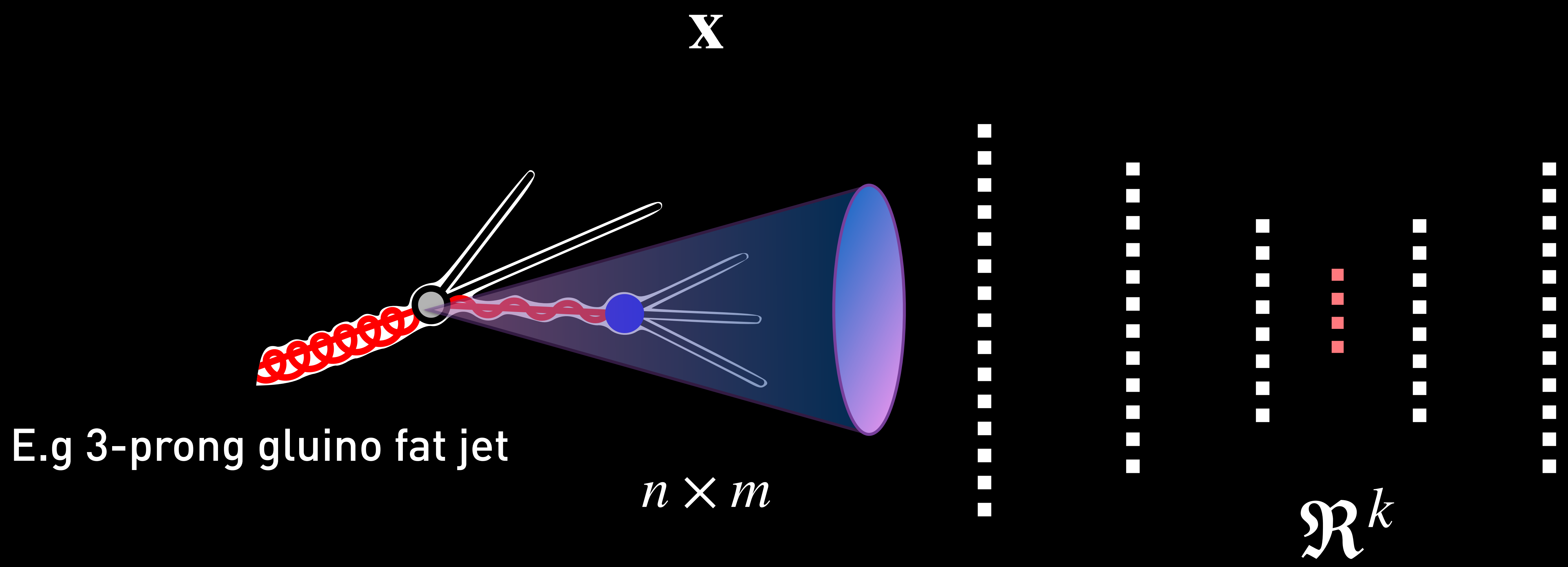
prevents memorisation of input, must learn

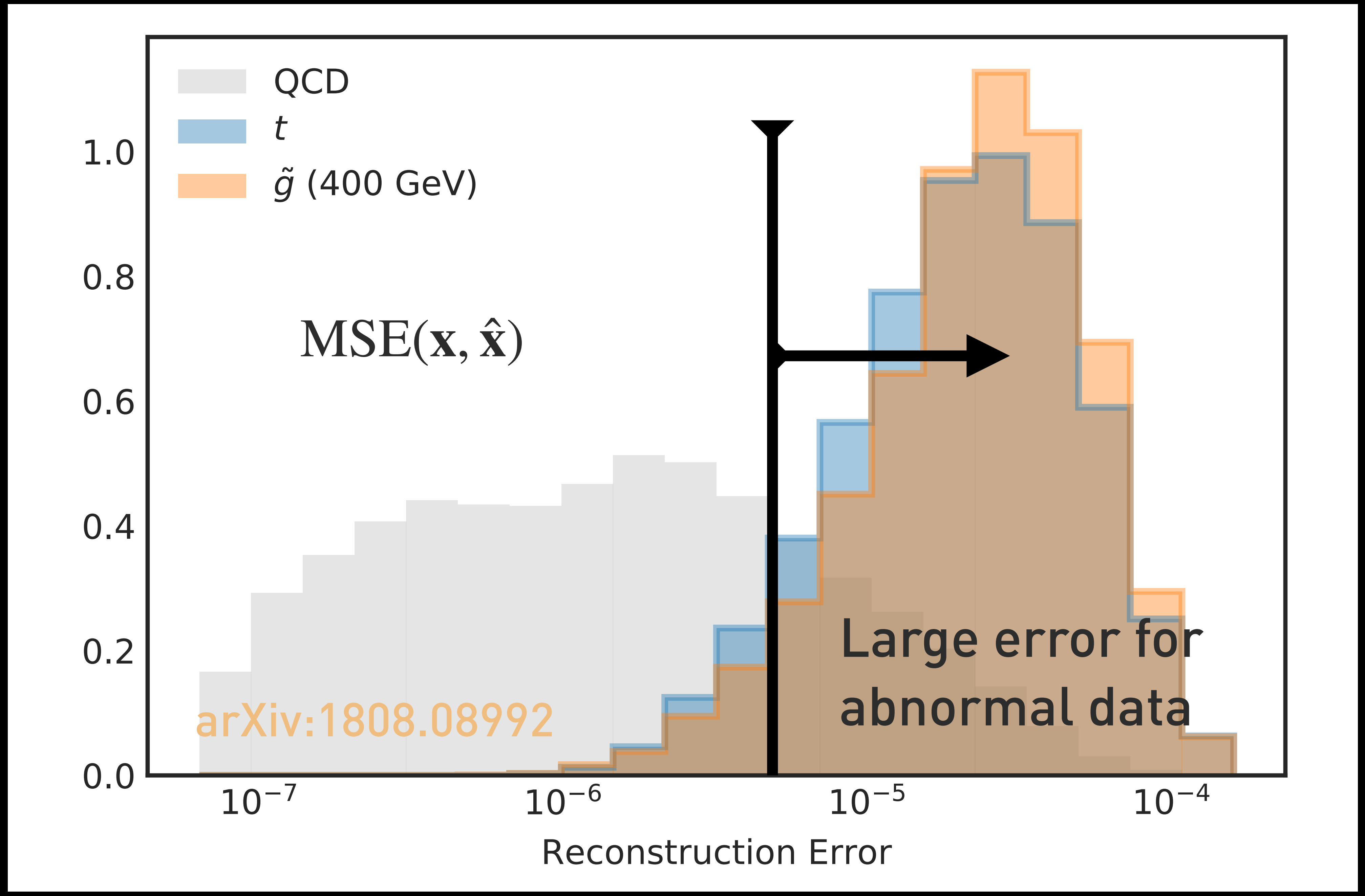
Outlier detection



$\mathscr{L}(\mathbf{x}, \hat{\mathbf{x}})$ is Mean Squared Error$(\mathbf{x}, \hat{\mathbf{x}})$, "high error events" proxy for "degree of abnormality"

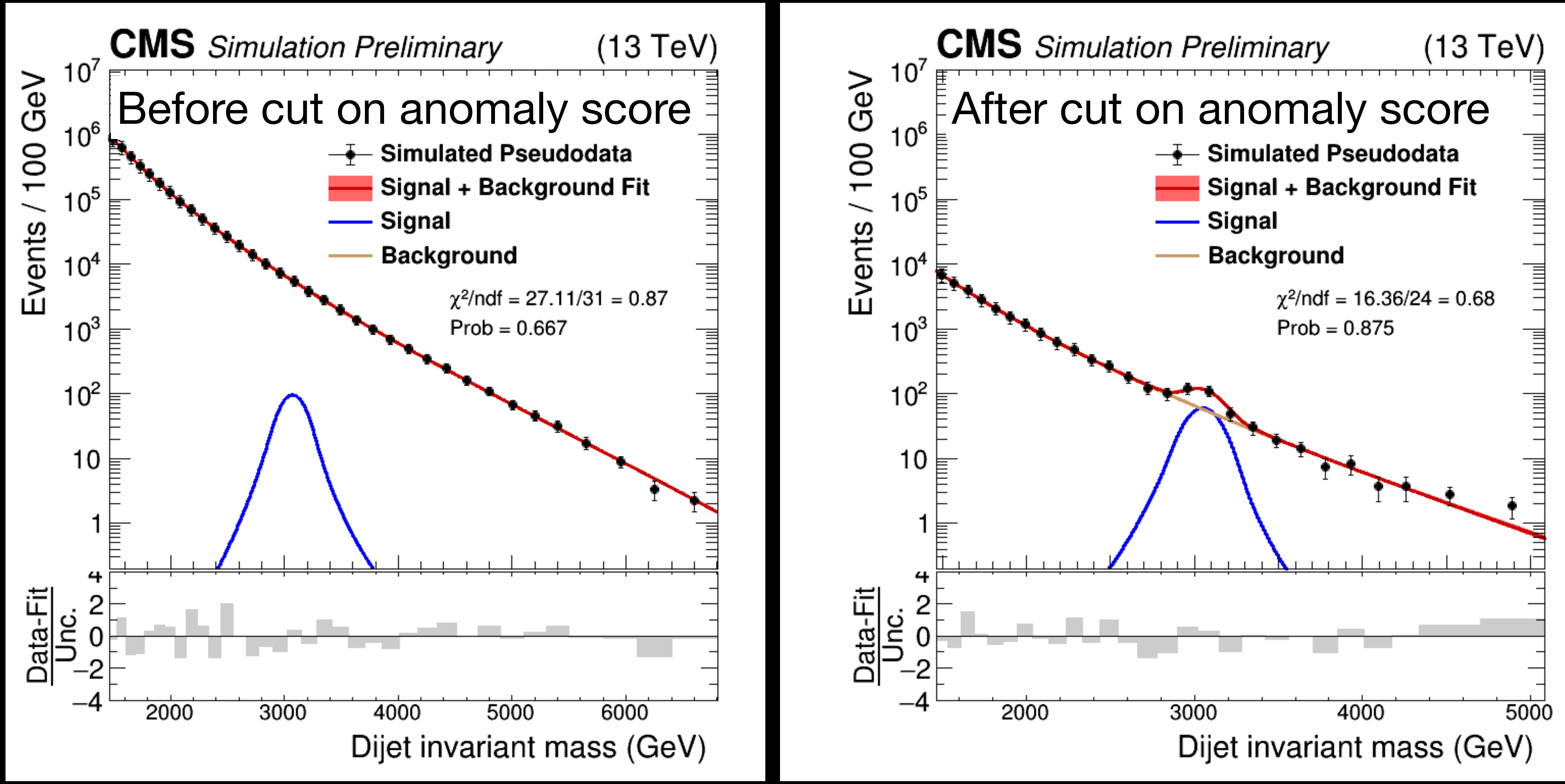
Outlier detection





Outlier detection in analysis

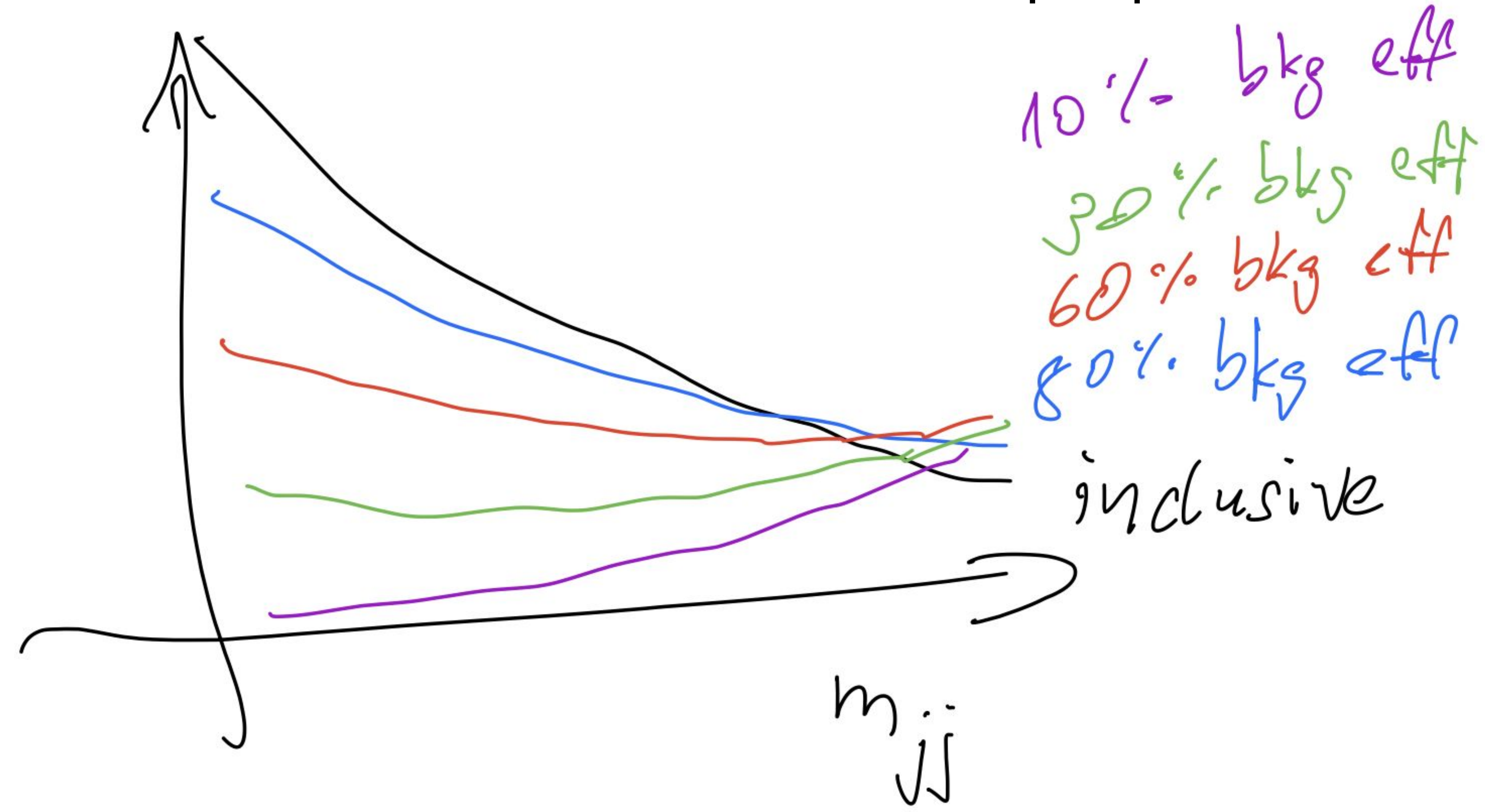
E.g CASE



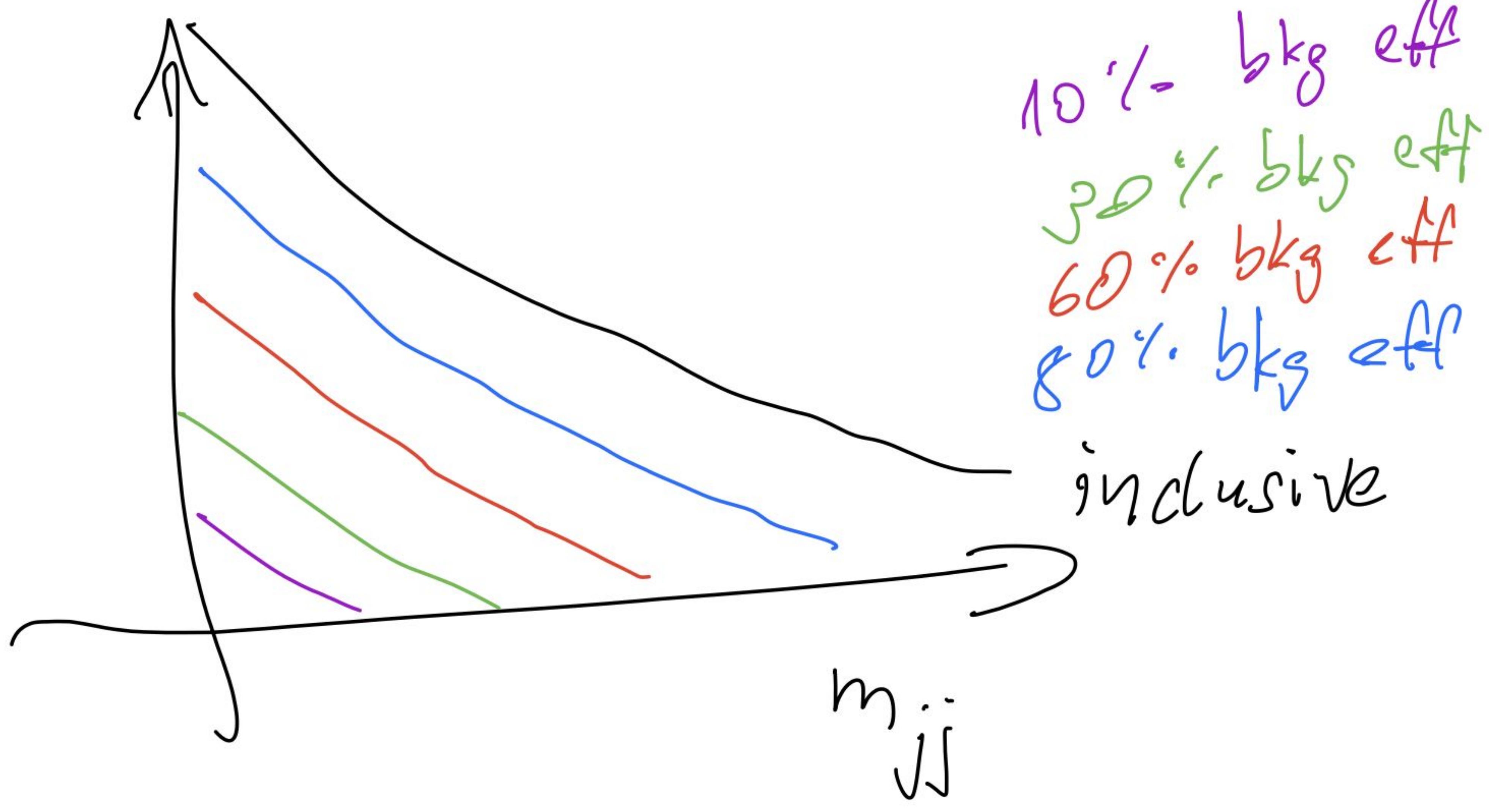
Outlier detection in analysis

E.g CASE

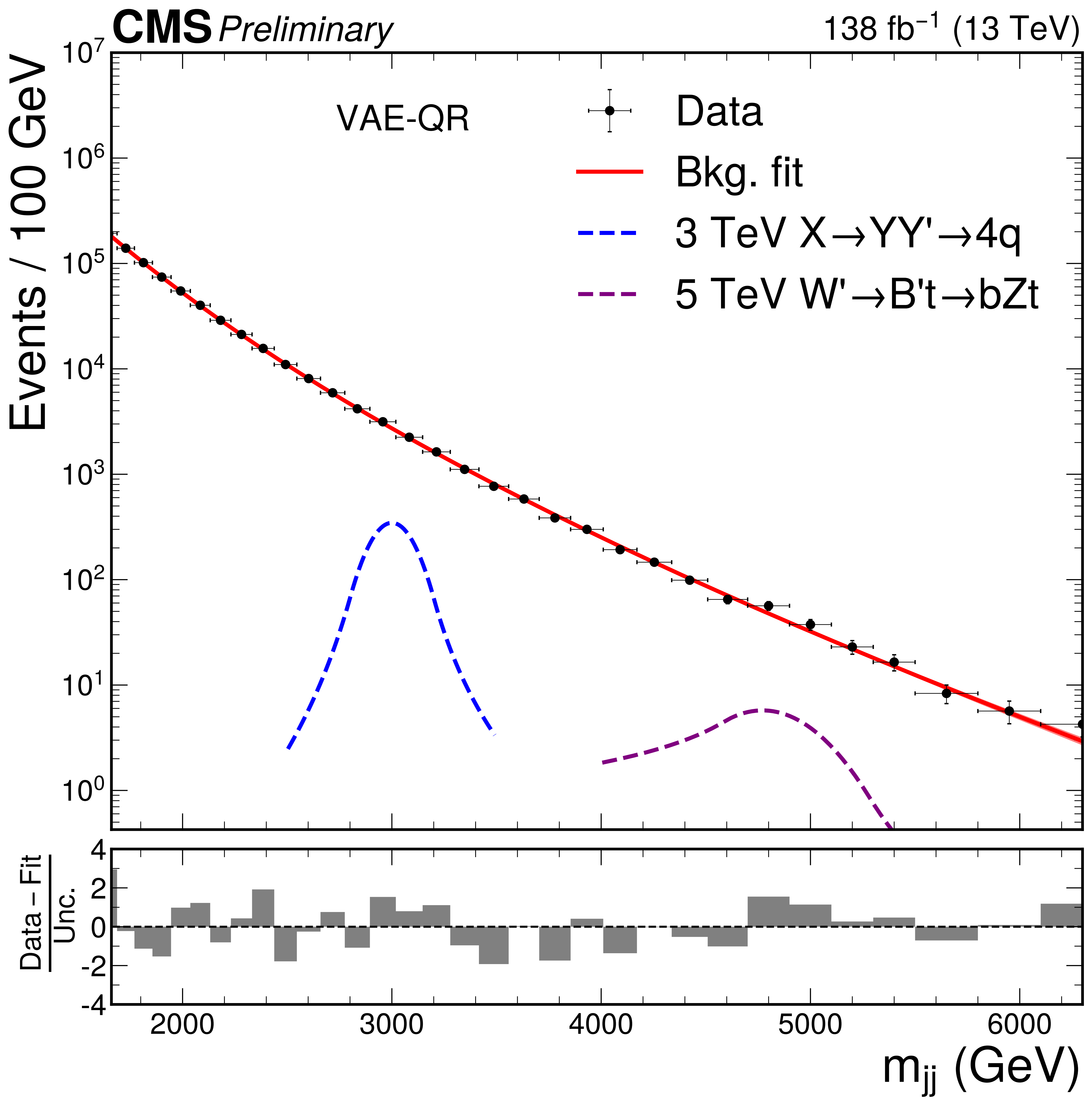
Careful! Cut on score can sculpt spectrum



Can fix using quantile regression

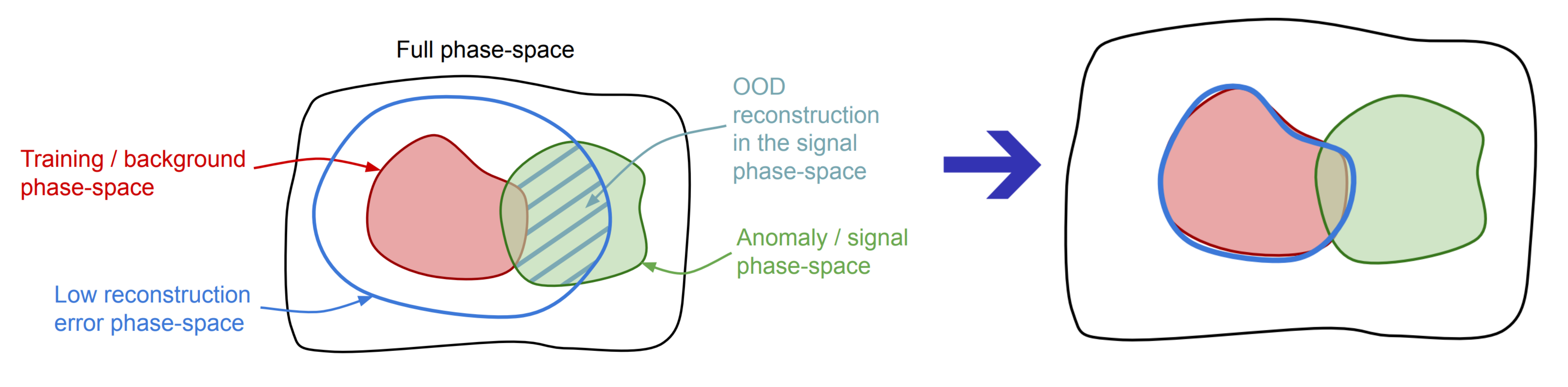


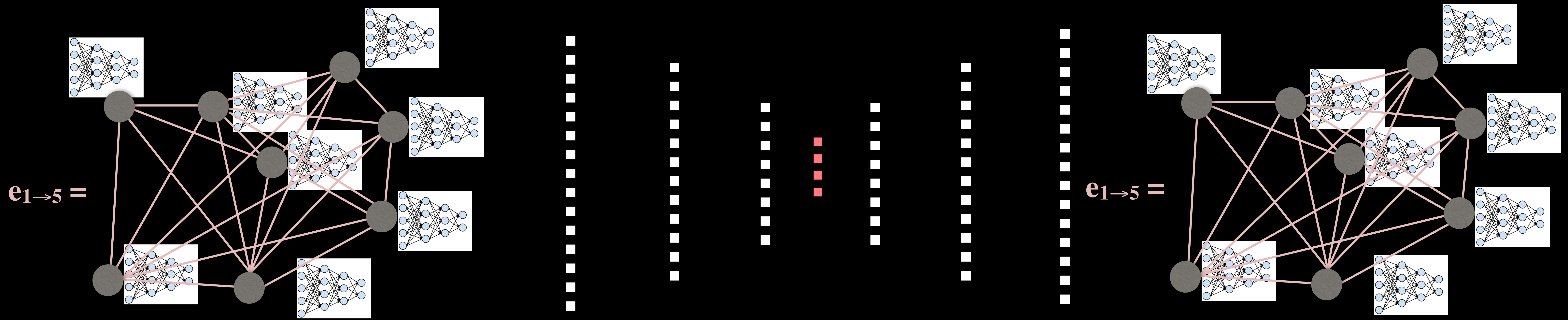
Outlier detection in analysis



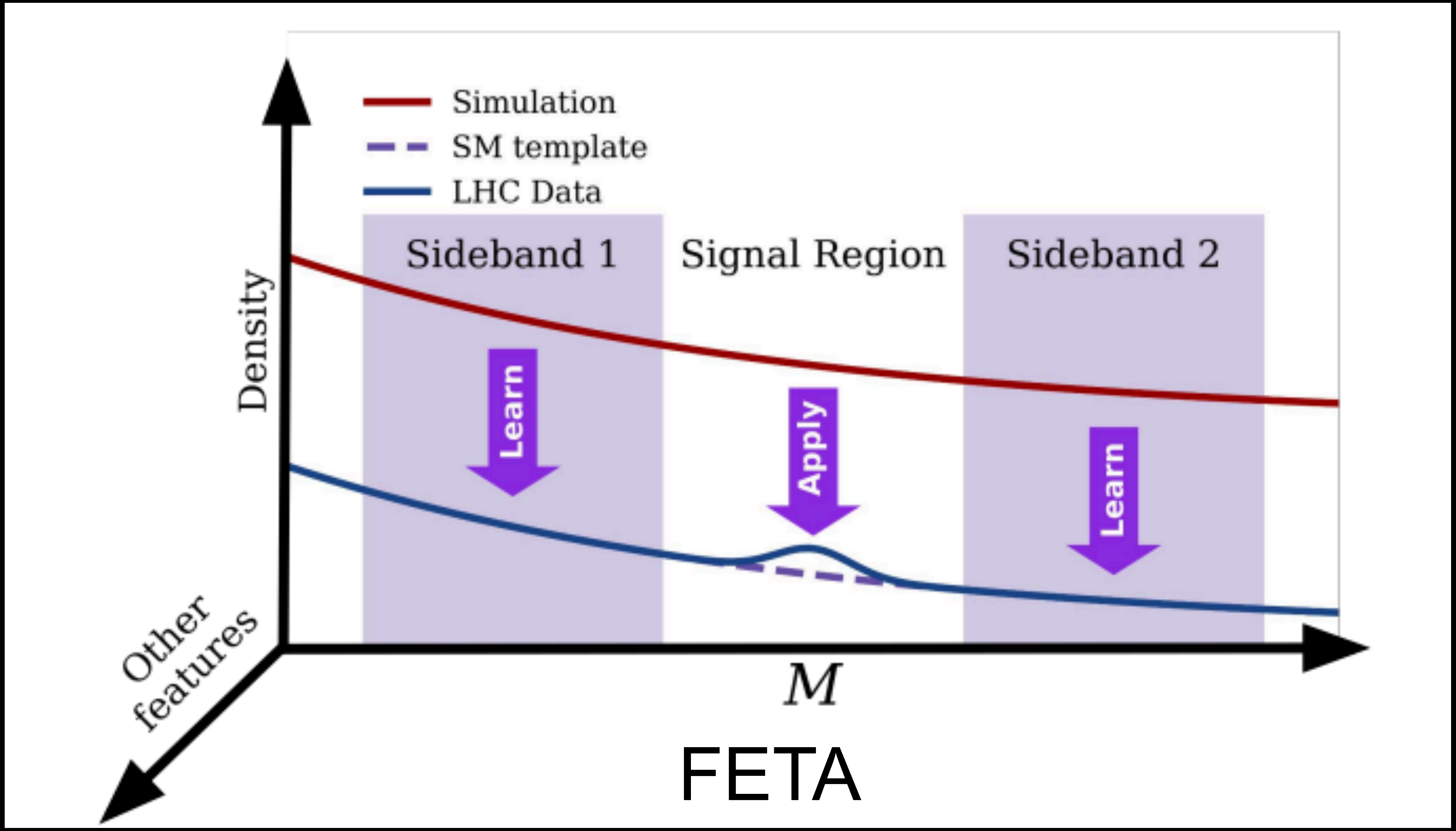
Example for semi-visible jets

F. Eble: Normalized autoencoders — R. Seidita: Lund Graph autoencoders

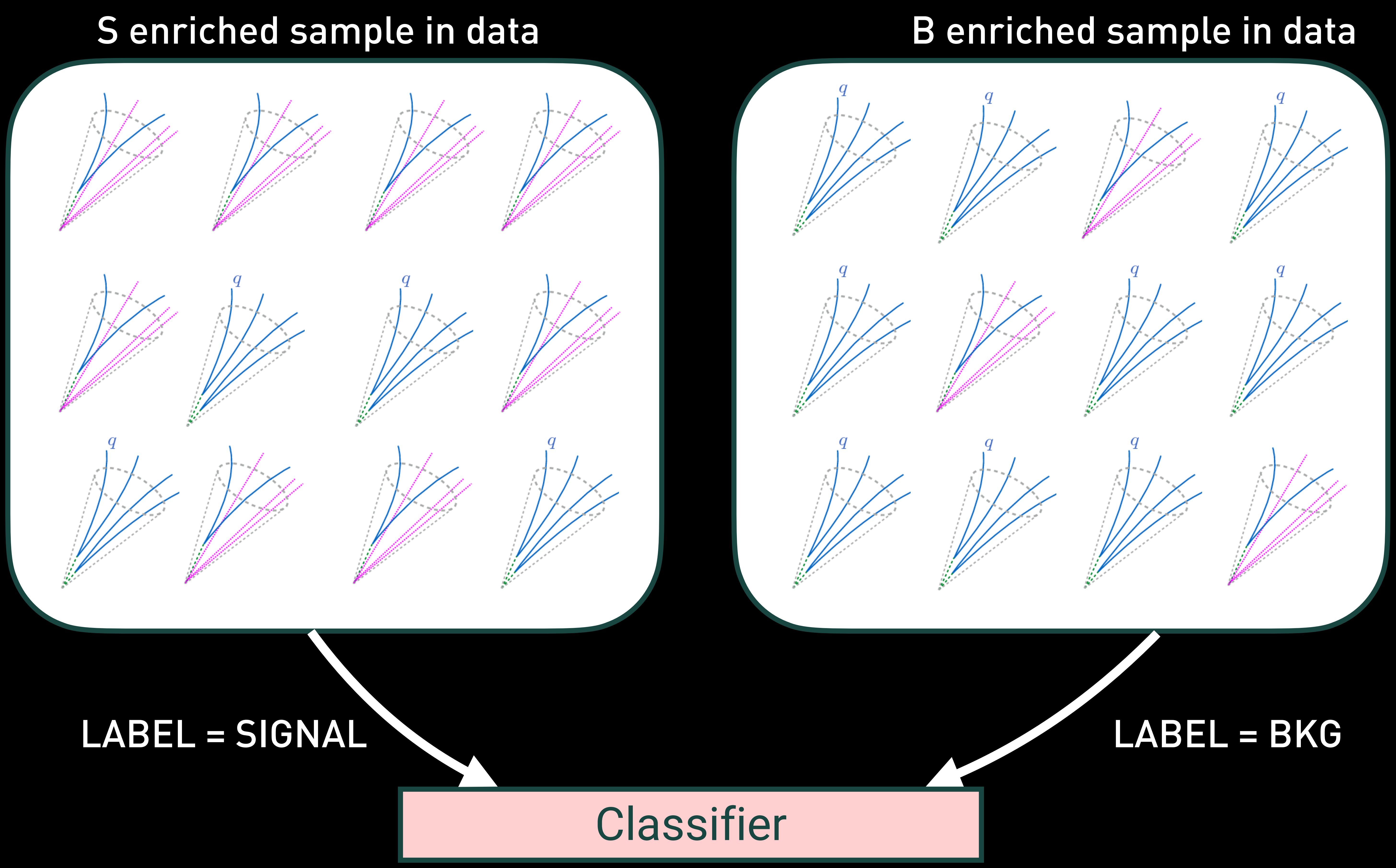




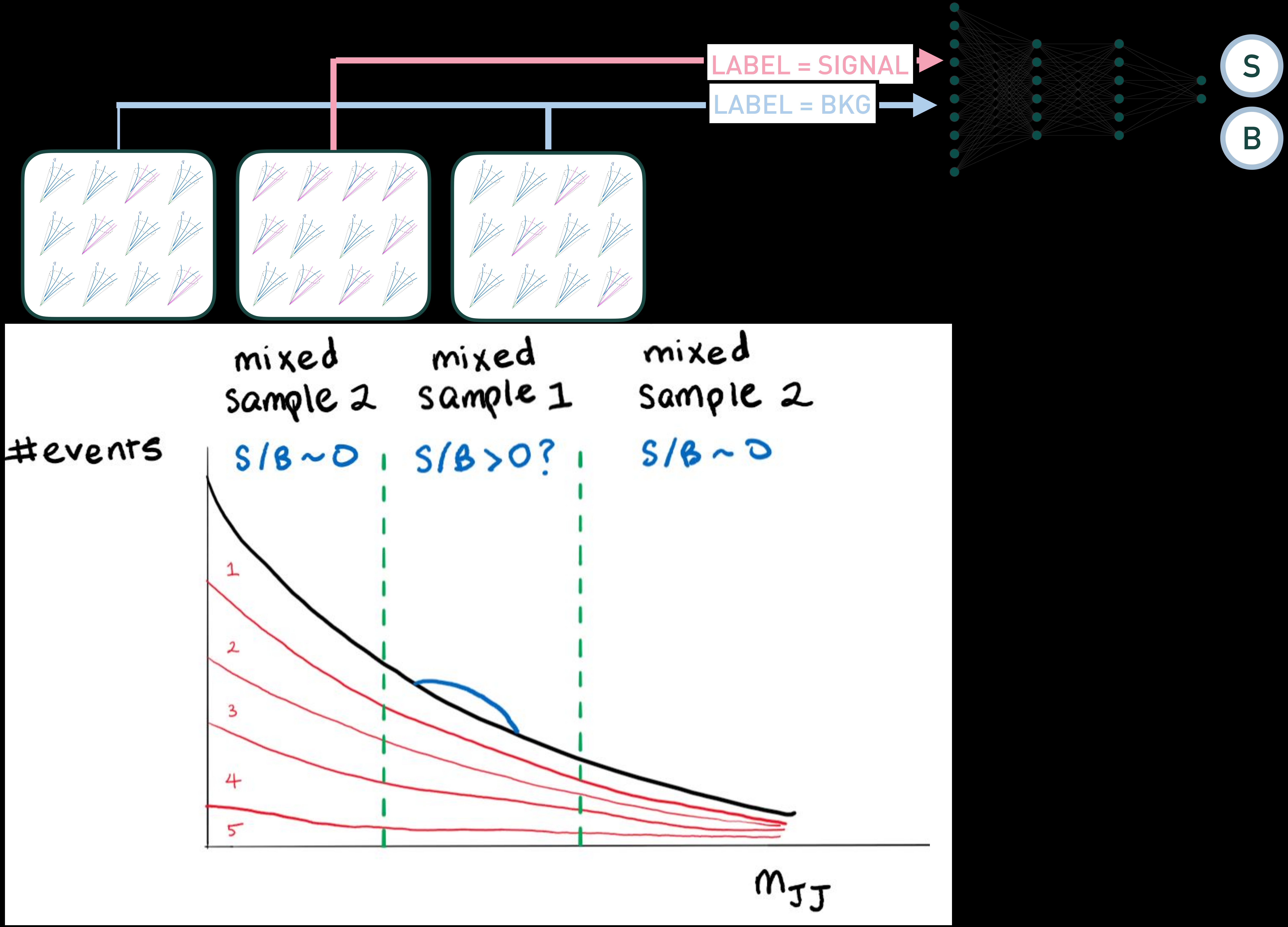
Finding overdensities

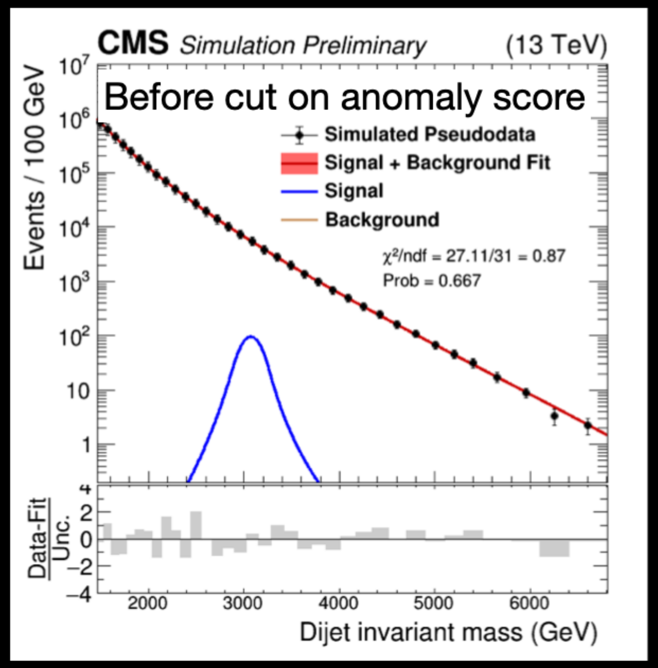


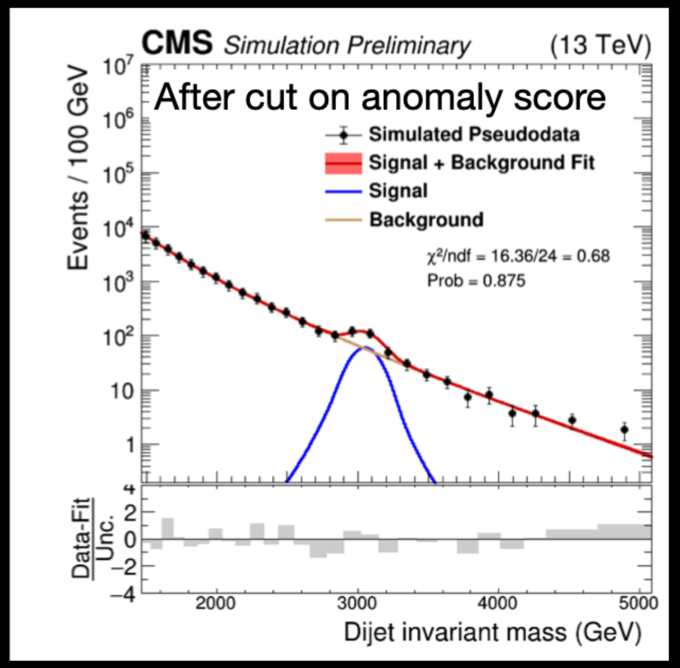
Finding overdensities - CWoLa bvumphunt

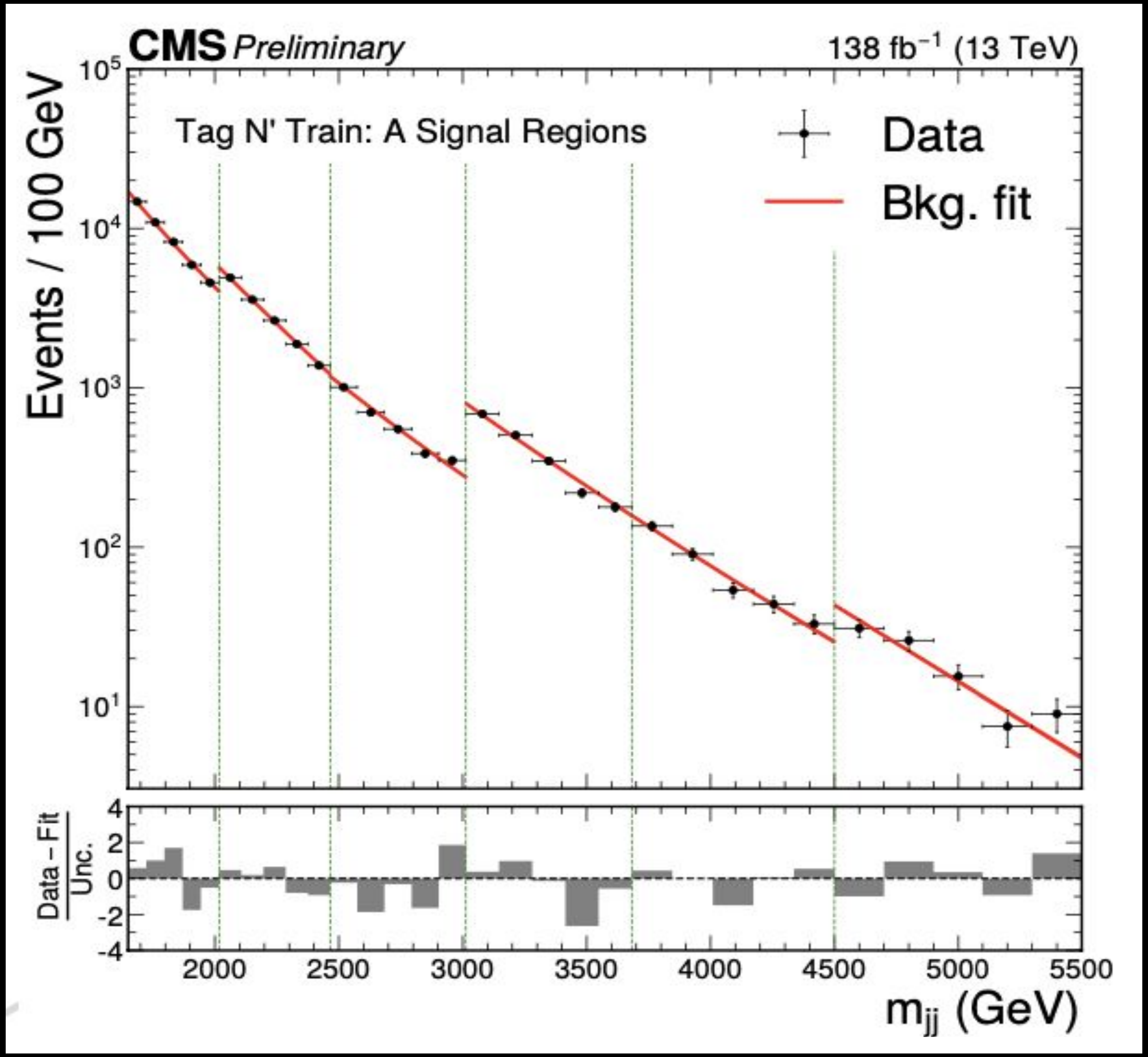


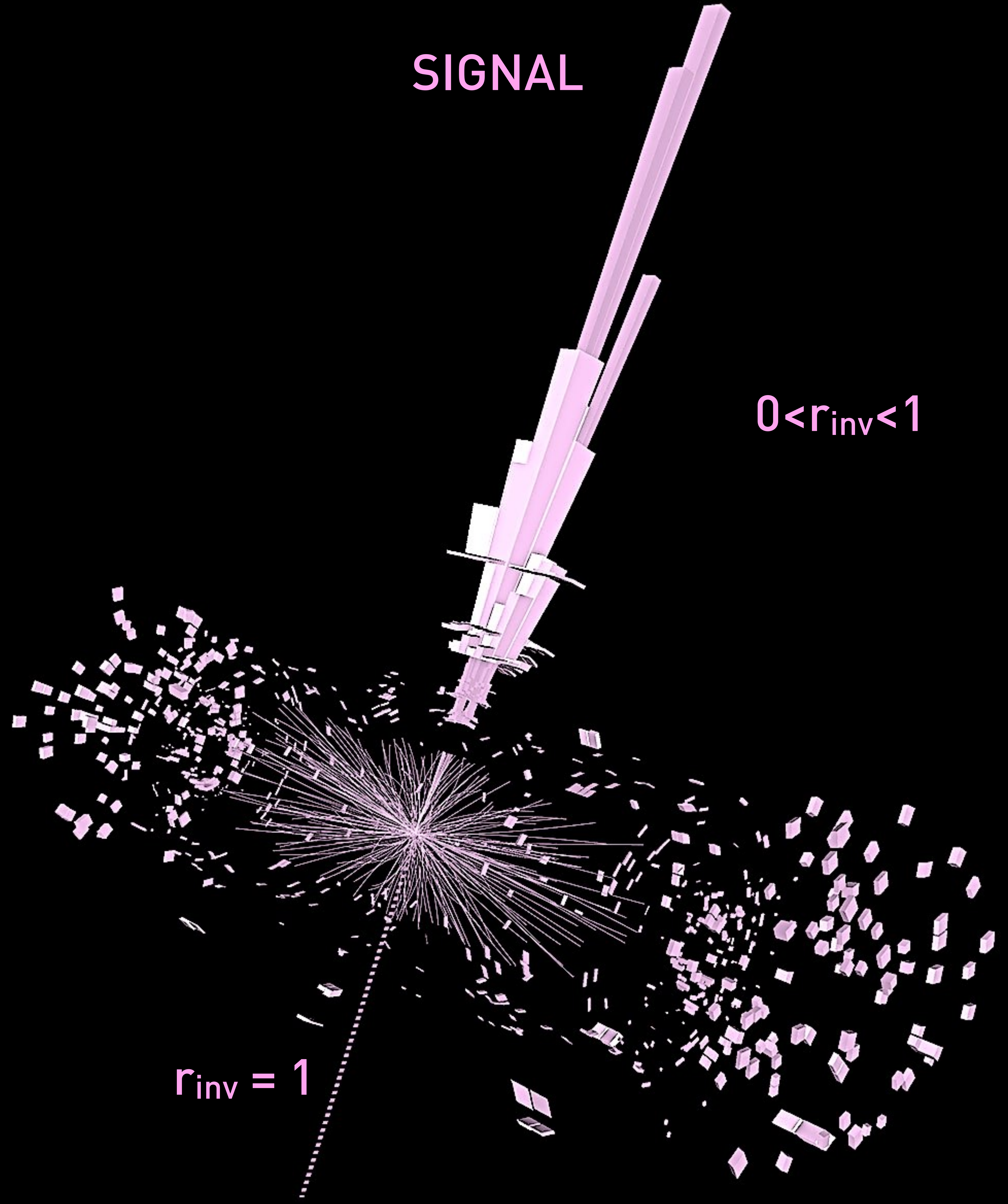
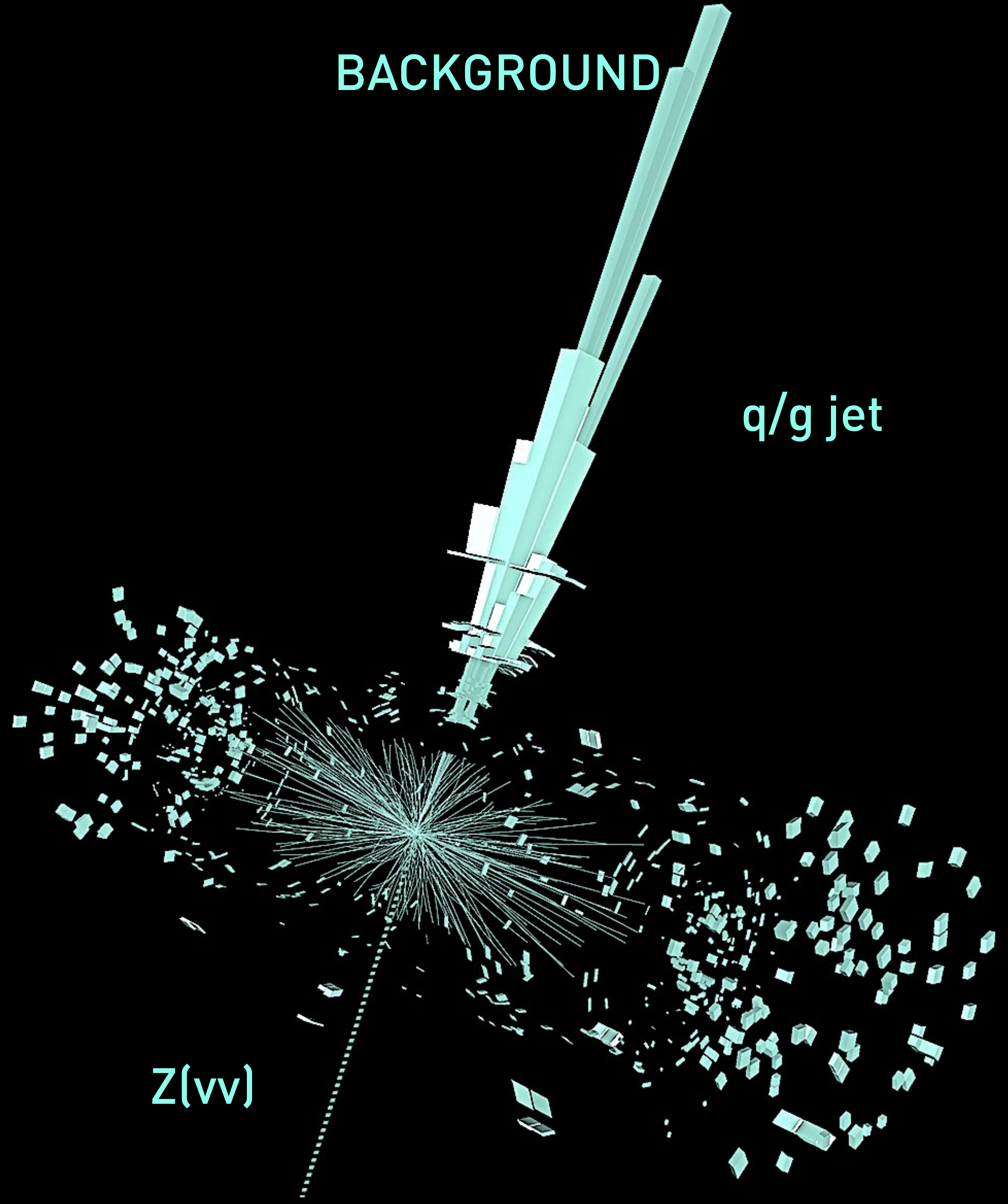
E.g <u>CASE</u>


LABEL = SIGNAL
LABEL = BKG
S
B
mixed sample 2
mixed sample 1
mixed sample 2
#events
S/B ~ 0
S/B > 0?
S/B ~ 0
1
2
3
4
5
m_{JJ}

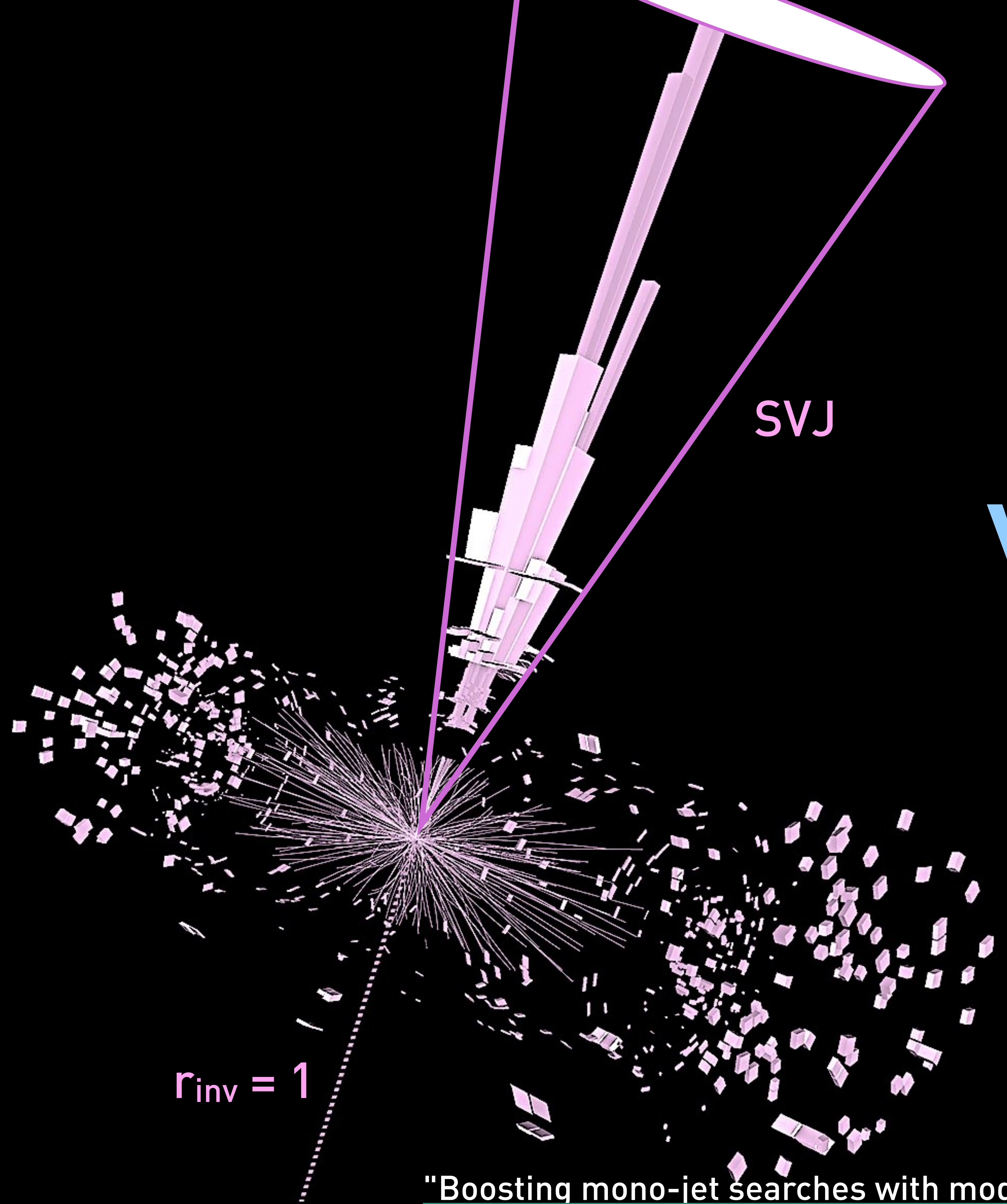

CMS Simulation Preliminary
(13 TeV)
Before cut on anomaly score
Simulated Pseudodata
Signal + Background Fit
Signal
Background
Events / 100 GeV
Data-Fit / Unc.
Dijet invariant mass (GeV)


CMS Simulation Preliminary
(13 TeV)
After cut on anomaly score
Simulated Pseudodata
Signal + Background Fit
Signal
Background
Events / 100 GeV
Data-Fit / Unc.
Dijet invariant mass (GeV)

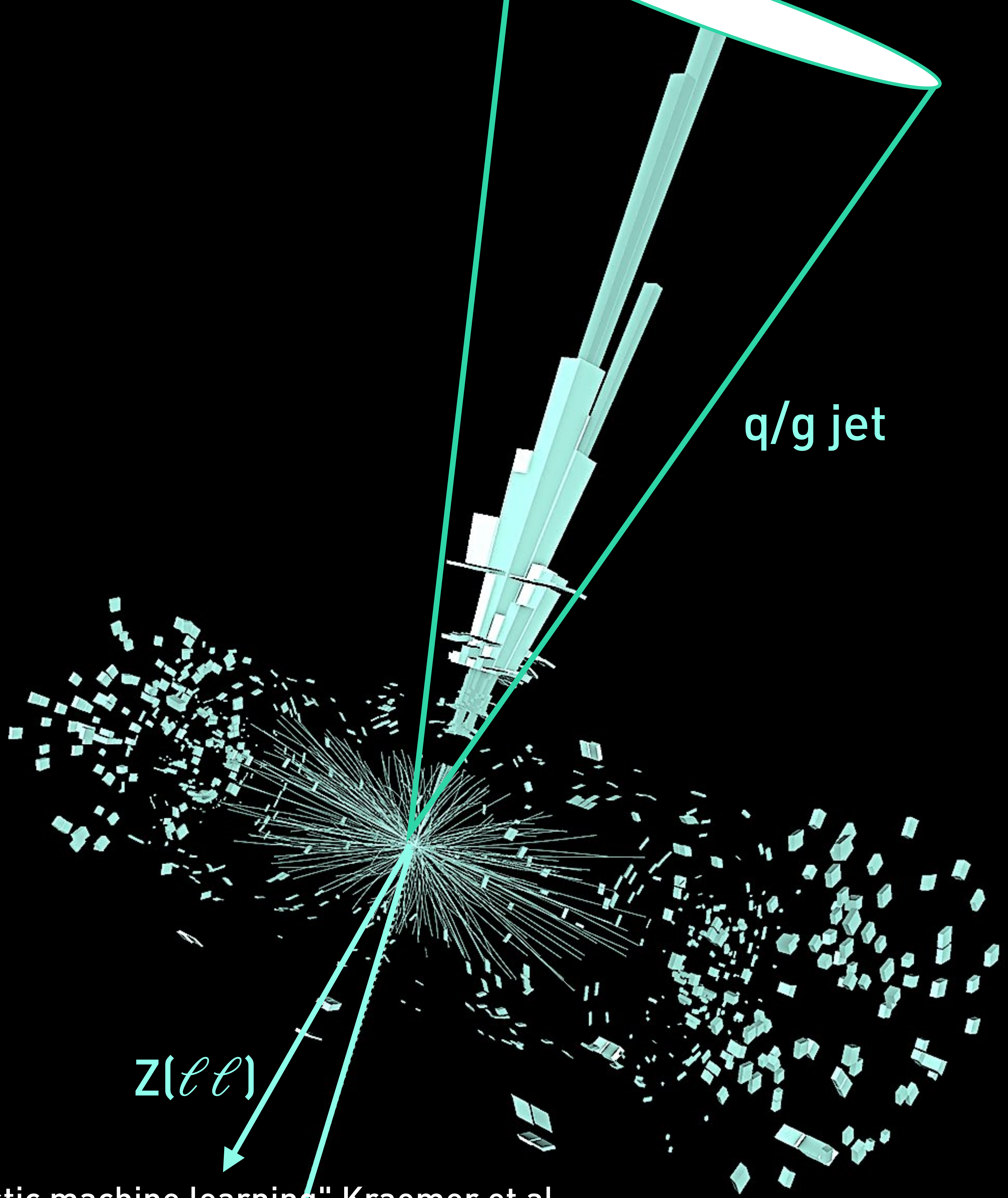

CMS Preliminary
138 fb⁻¹ (13 TeV)
Tag N' Train: A Signal Regions
Data
Bkg. fit
Events / 100 GeV
Data – Fit / Unc.
m_jj (GeV)


SIGNAL
$0<r_{inv}<1$
$r_{inv} = 1$

BACKGROUND
q/g jet
Z(νν)


0<r_inv<1
VS.
q/g jet
r_inv = 1
Z(νν)



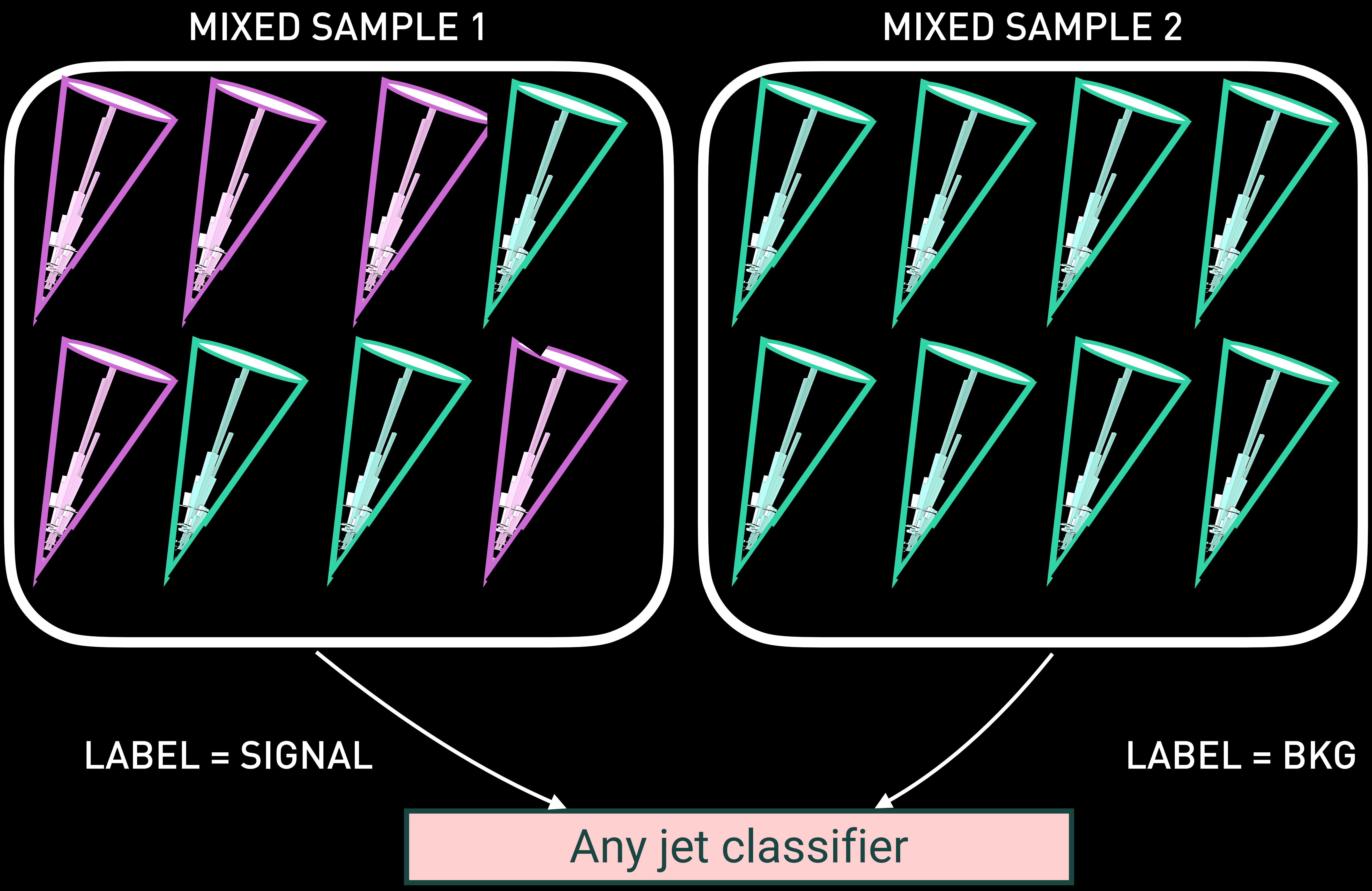
VS.



"Boosting mono-jet searches with model-agnostic machine learning" Kraemer et al.

JETS FROM
MET+JET TOPOLOGY
→ SIGNAL REGION

JETS FROM
$\ell\ell$+JET TOPOLOGY
→ SIGNAL NOT EXPECTED HERE



Density estimation
Various methods

<u>ML-based interpolation from sidebands to signal region:</u>

ANODE: interpolates densities from sidebands to the signal-region & constructs likelihood ratio

CATHODE: samples from the background model in signal region after interpolating and estimates likelihood ratio with classifier

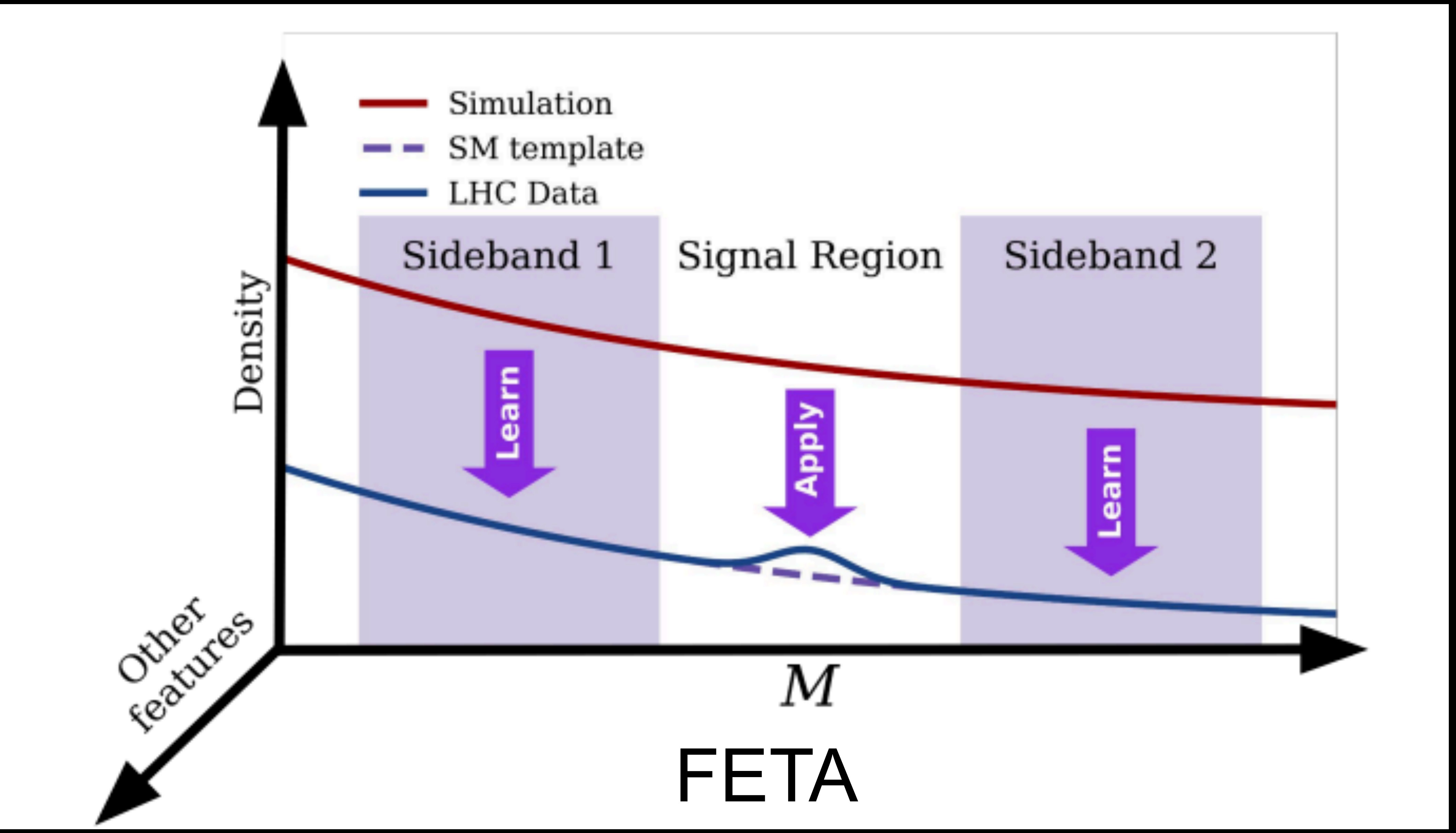
LaCATHODE: Use a in flow to perform CATHODE in latent space

CURTAINS: Train invertible NN conditioned on mass to map between sidebands

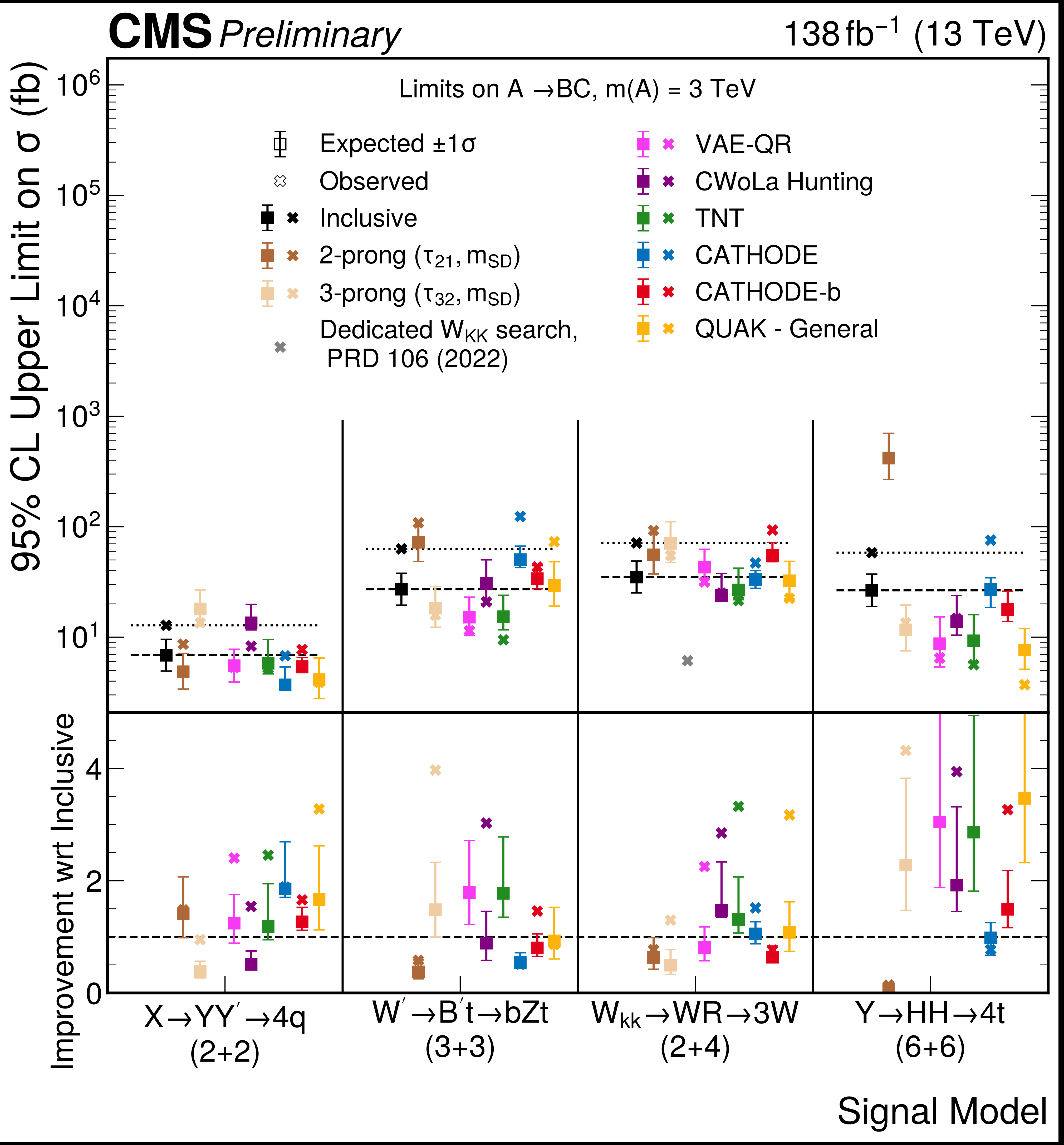
<u>ML-based MC reweighting:</u>

SALAD: Reweight simulation to match sideband, interpolate into the signal region and use a second classifier to get the likelihood

FETA: Map simulation to data in sidebands, then compare to SR data



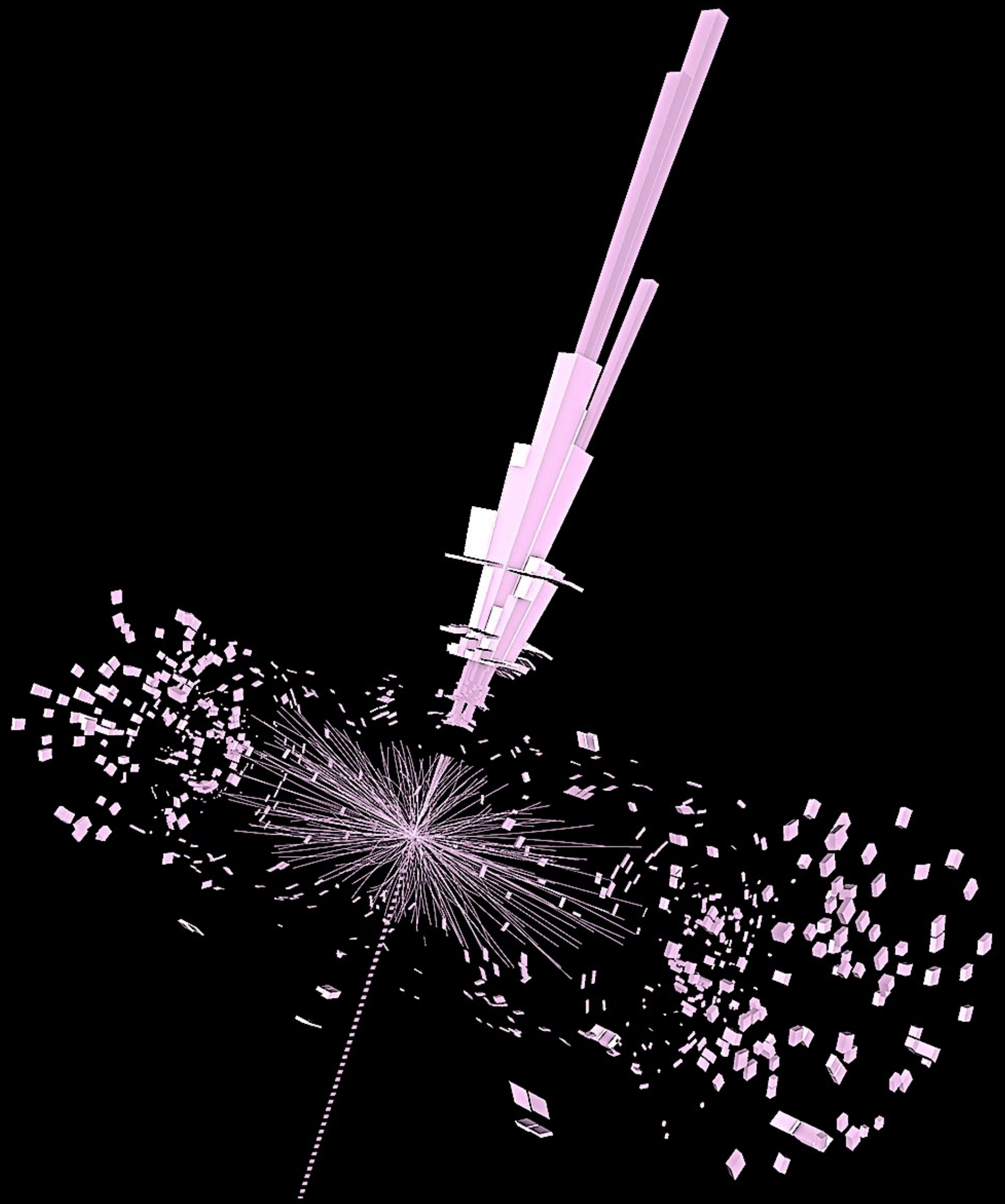
Why these methods are good for DM searches



We could cast a huge net to catch a broad range of signals in a single search!

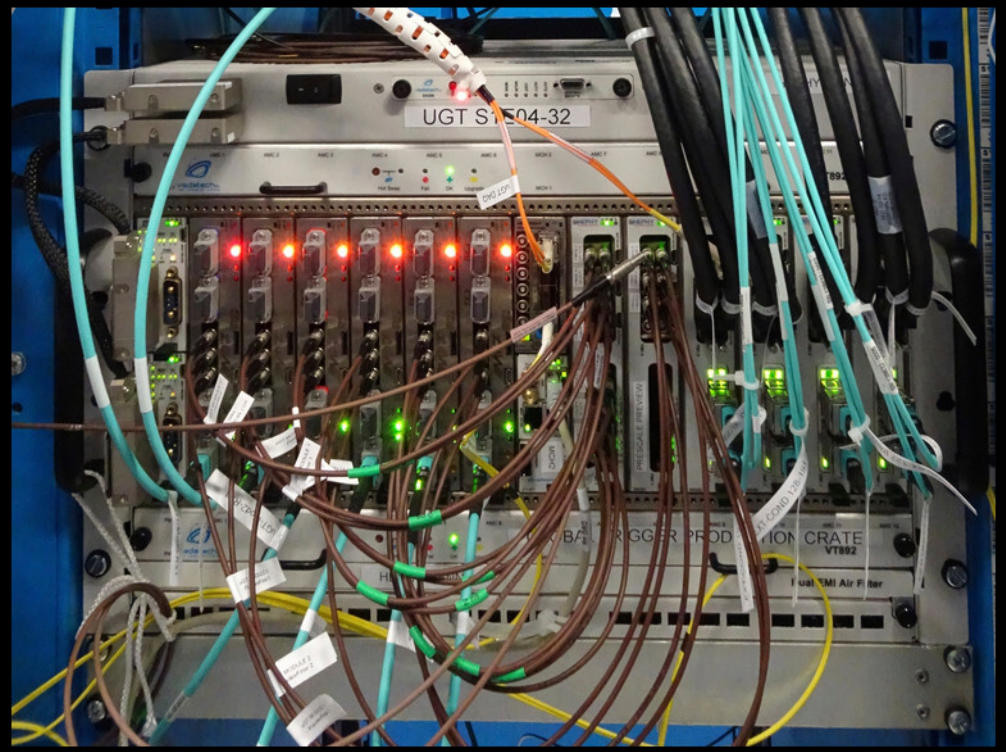
Do physics with 0.0025% of collision events, the rest is discarded!

Detector
- 100% of events left



40 MHz

Level-1 hardware trigger
- 0.3% of events left

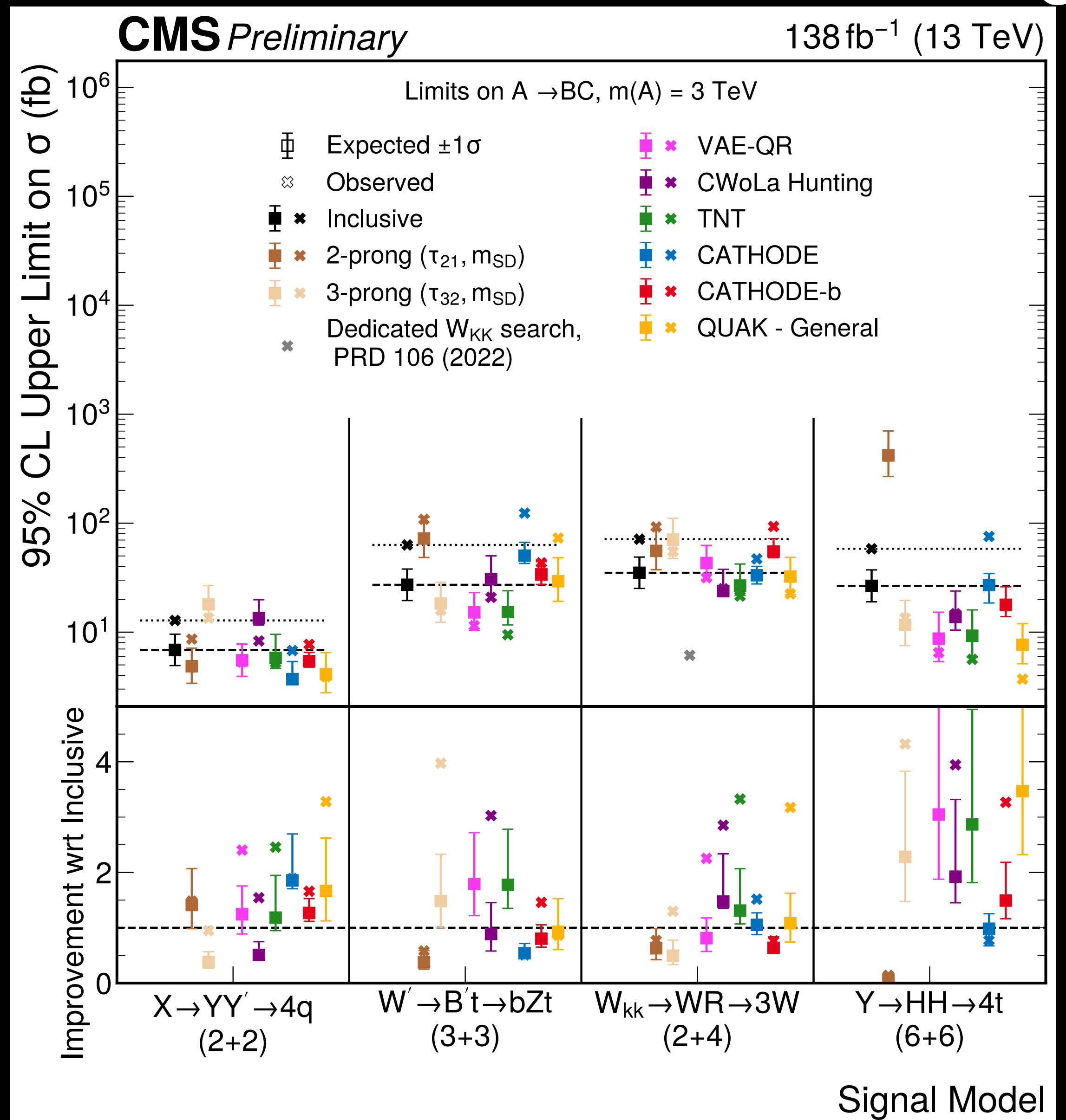


110 kHz

High Level Trigger CPU farm
- 0.0025% of events left

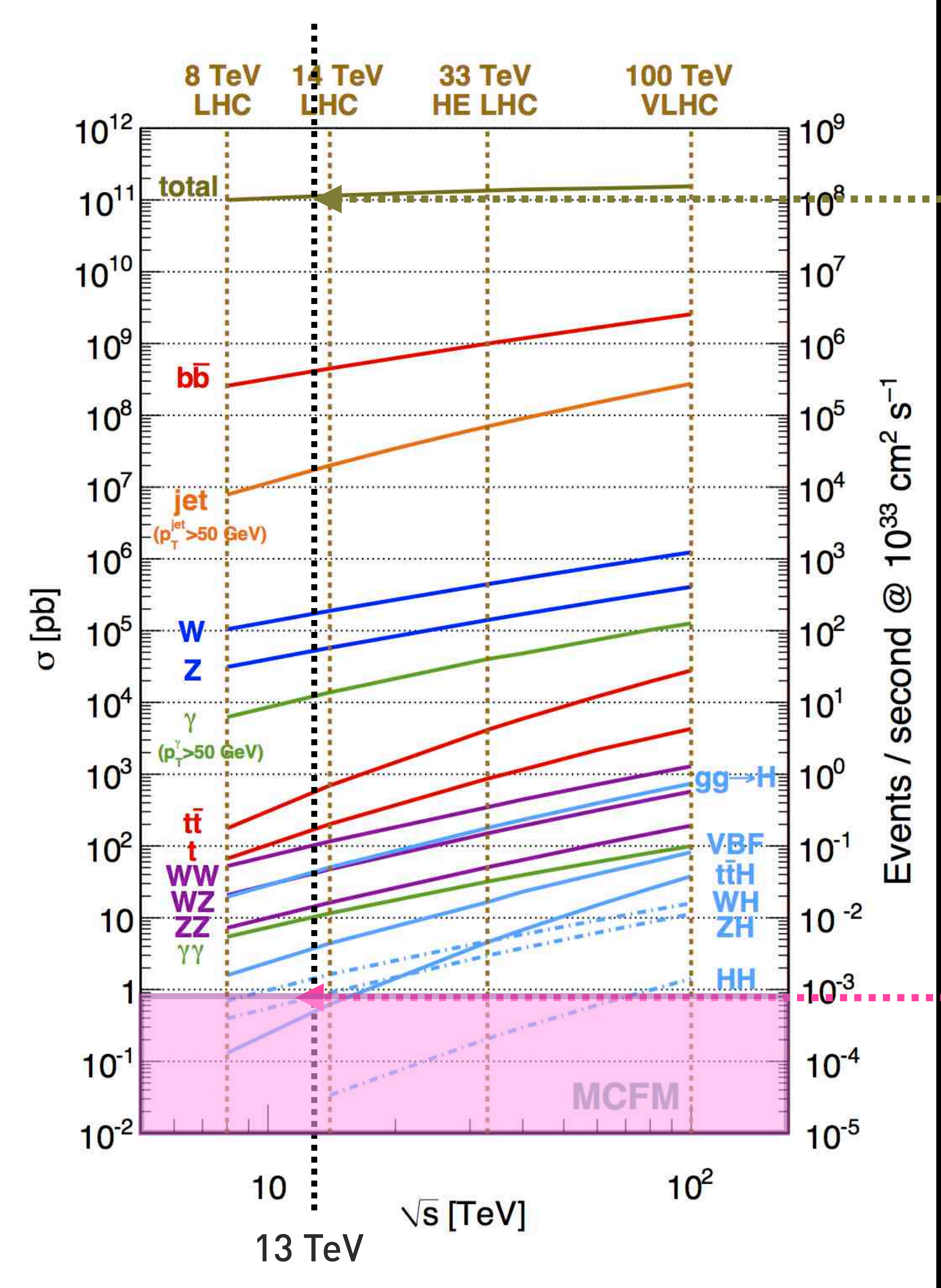
1 kHz

Offline reconstruction and storage



Probing smaller and smaller couplings, lower and lower masses

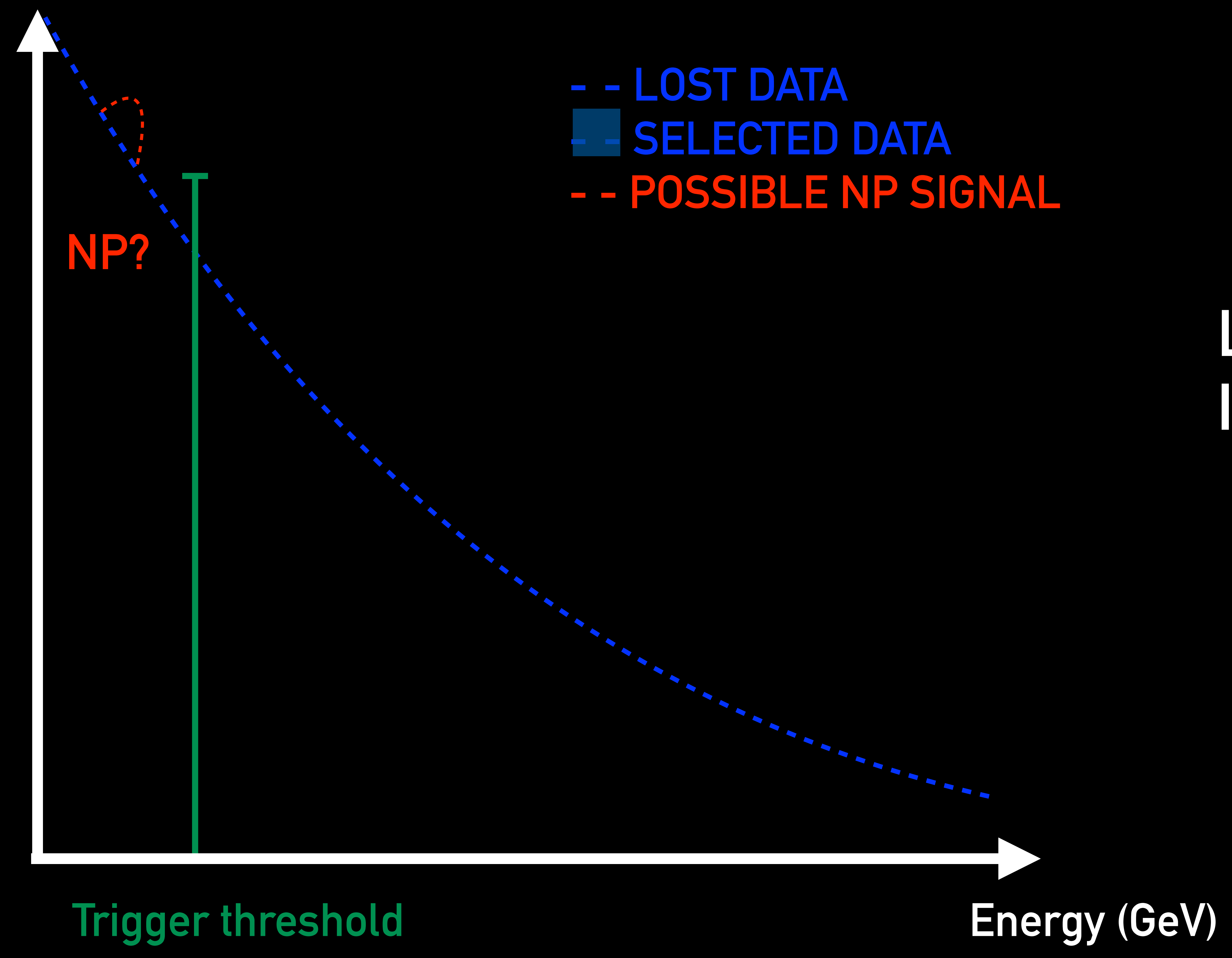
Need more statistics!



“Probability” of producing “anything”

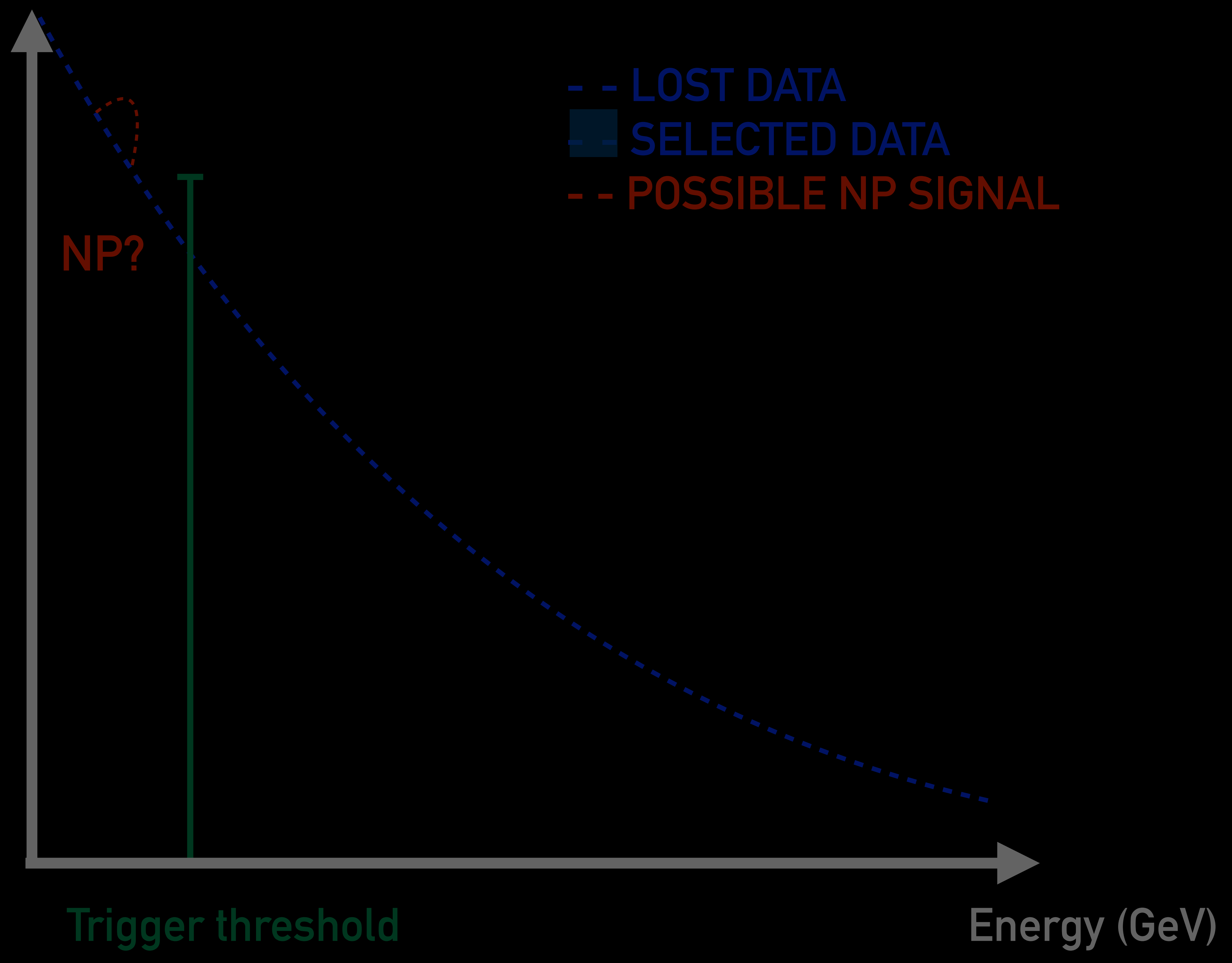
Mono-jet search limits 95% CL
0.3 - 736 fb

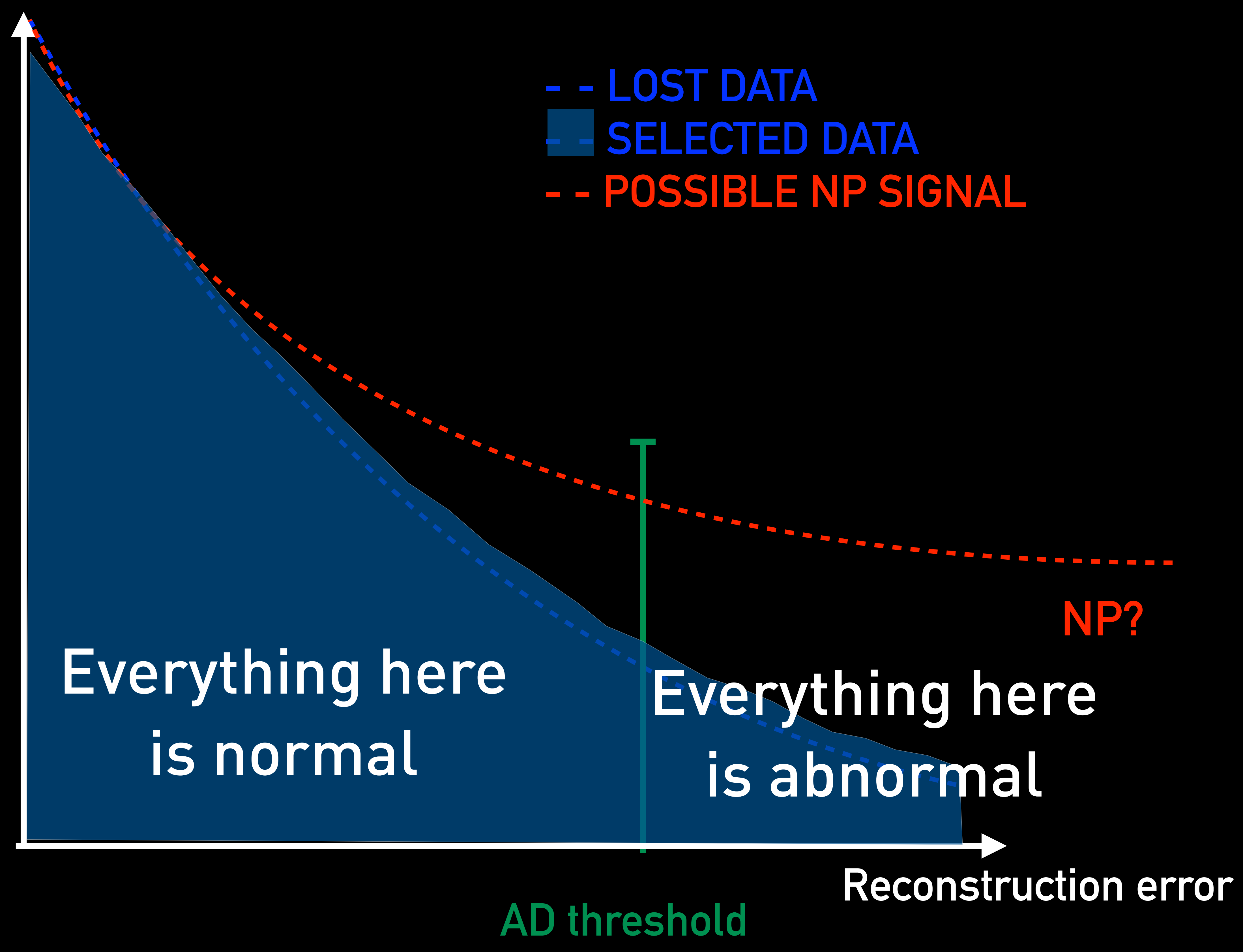
Anomaly Detection triggers



Level-1 rejects >99% of events!
Is there a smarter way to select?

Anomaly Detection triggers



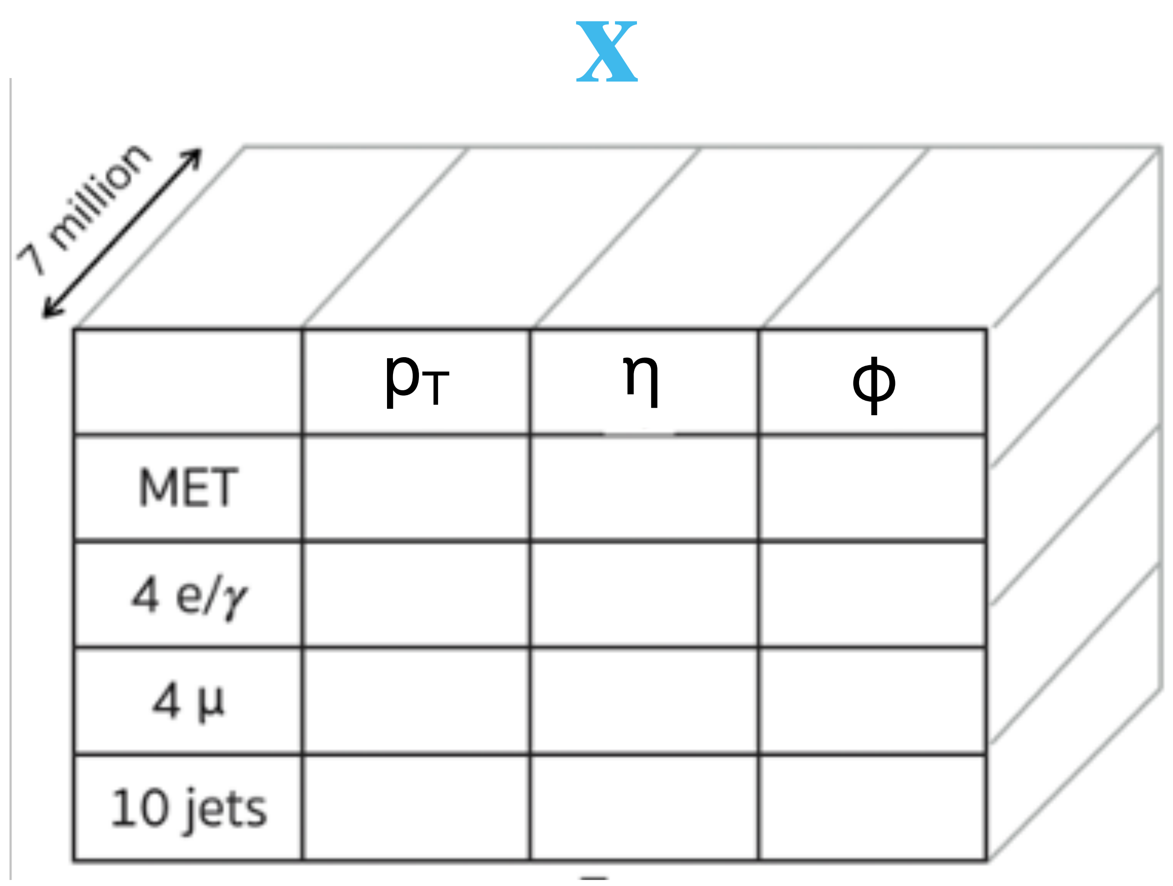


AXOL1TL

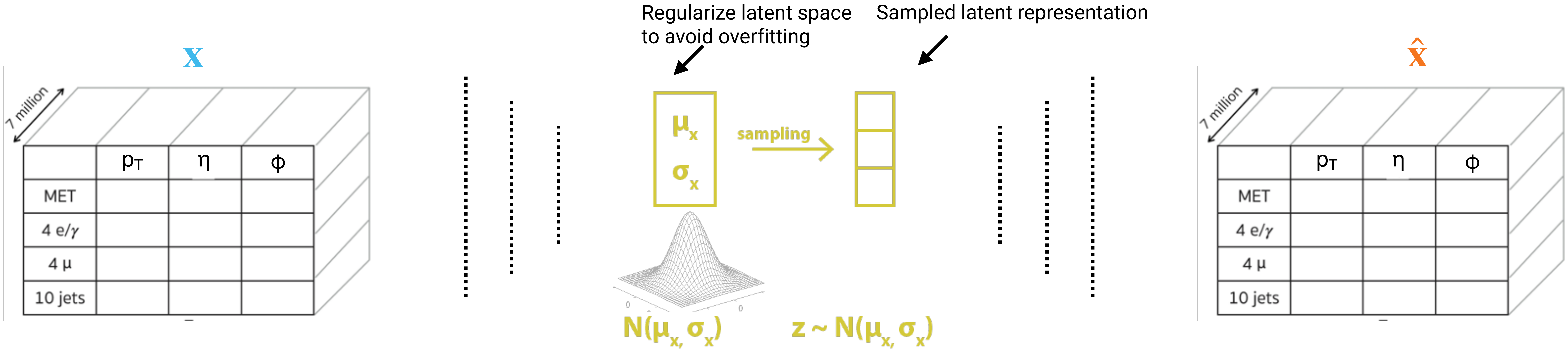
Anomaly Detection in the CMS Level 1 μGT for Run3!

Input from Run 3 μGT quantities:

- (p_T, n, ϕ) hardware integer inputs from: 1 MET, 4 e/γ, 4 μ, and 10 jet objects



AXOL1TL

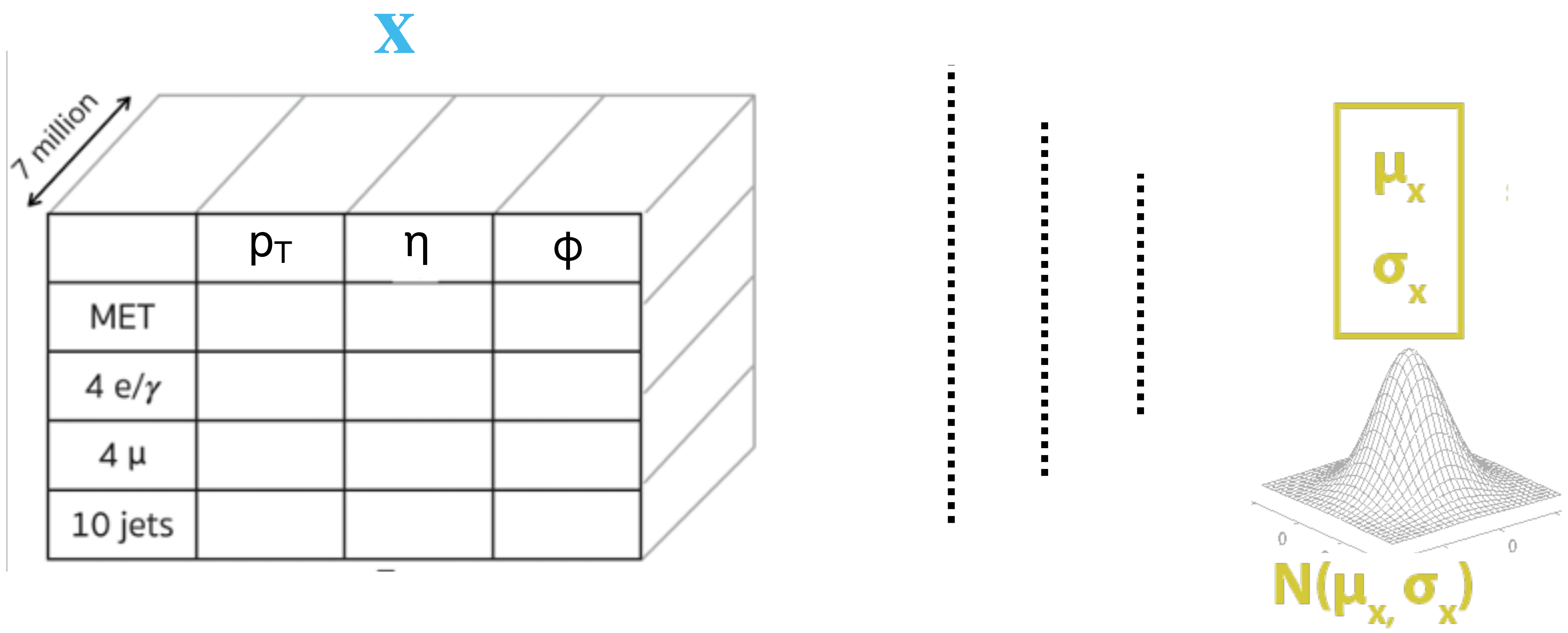


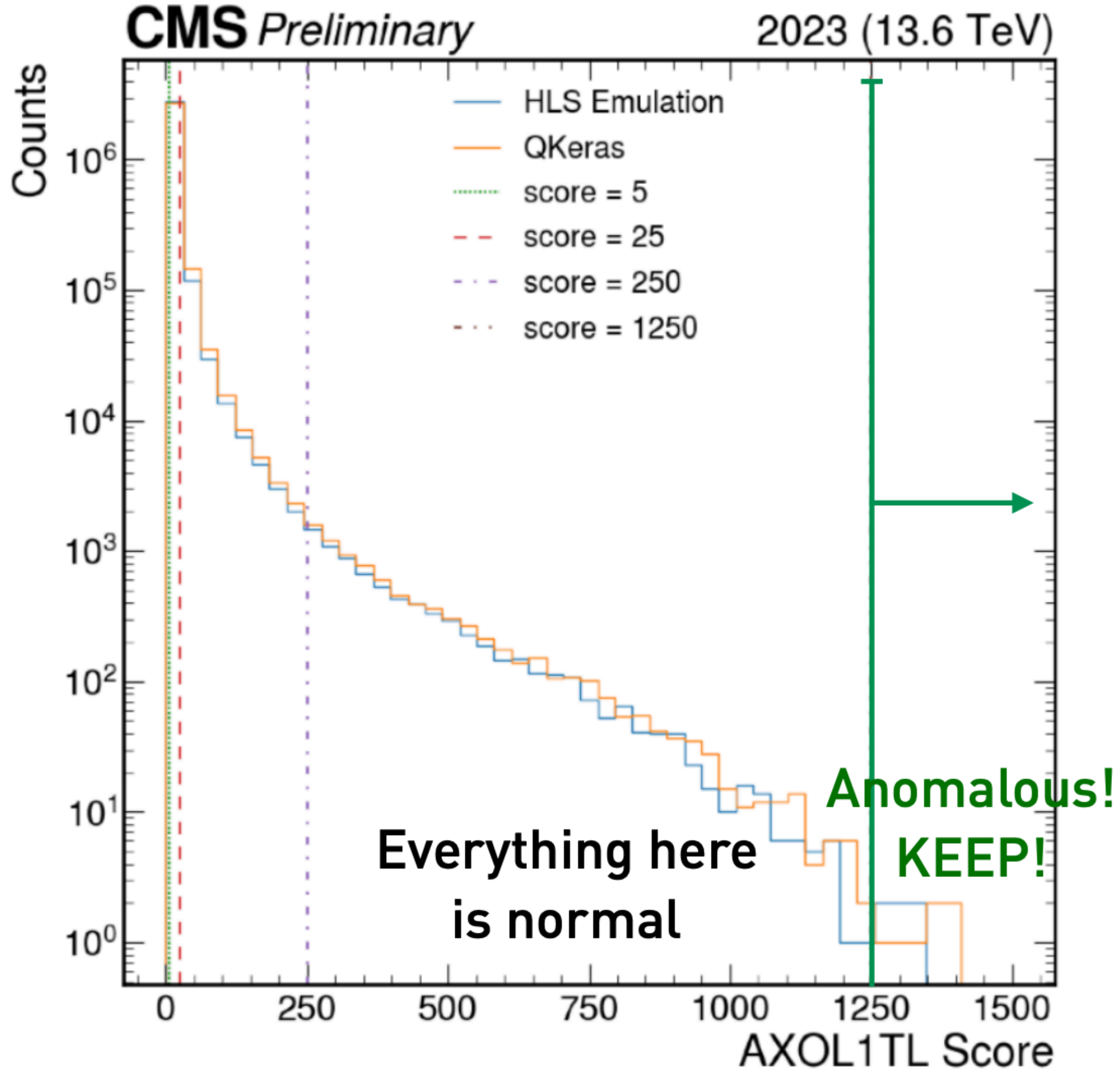
$$\text{loss} = ||x - \hat{x}||^2 + \text{KL}[\,N(\mu_x, \sigma_x), N(0, I)\,]$$

AXOL1TL

Only deploy encoder, compute degree of abnormality from patent space only

- Do not need to keep input around for MSE
- Half network size and latency!



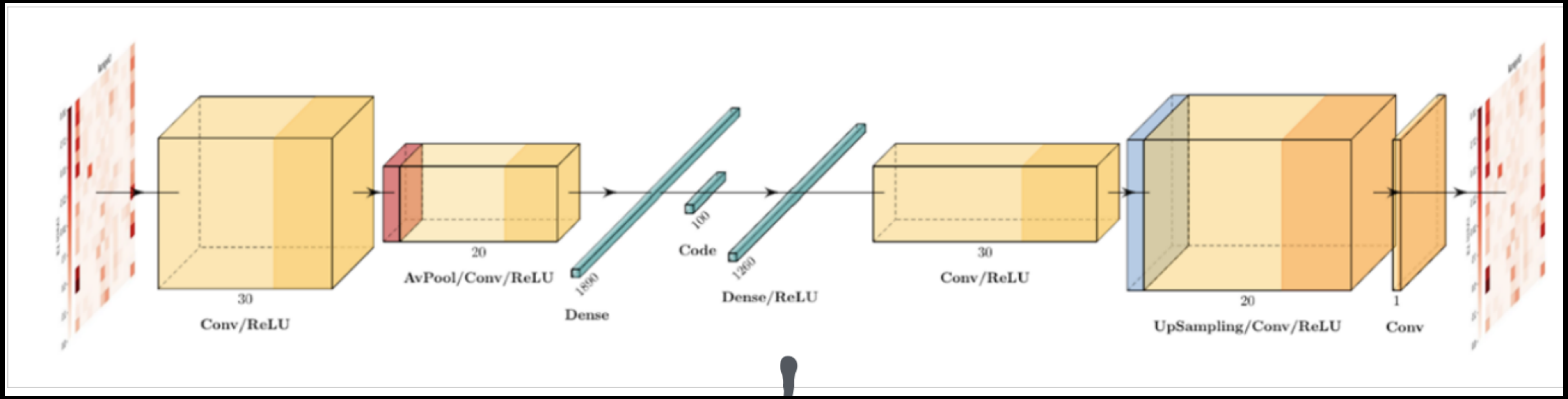


$$\text{loss} = ||x - \hat{x}||^2 + \text{KL}[\,N(\mu_x, \sigma_x), N(0, I)\,]$$

[CICADA](#)

CNN in Level-1 Calorimeter Trigger!

Represent calorimeter tower as image and use CNN auto encoder



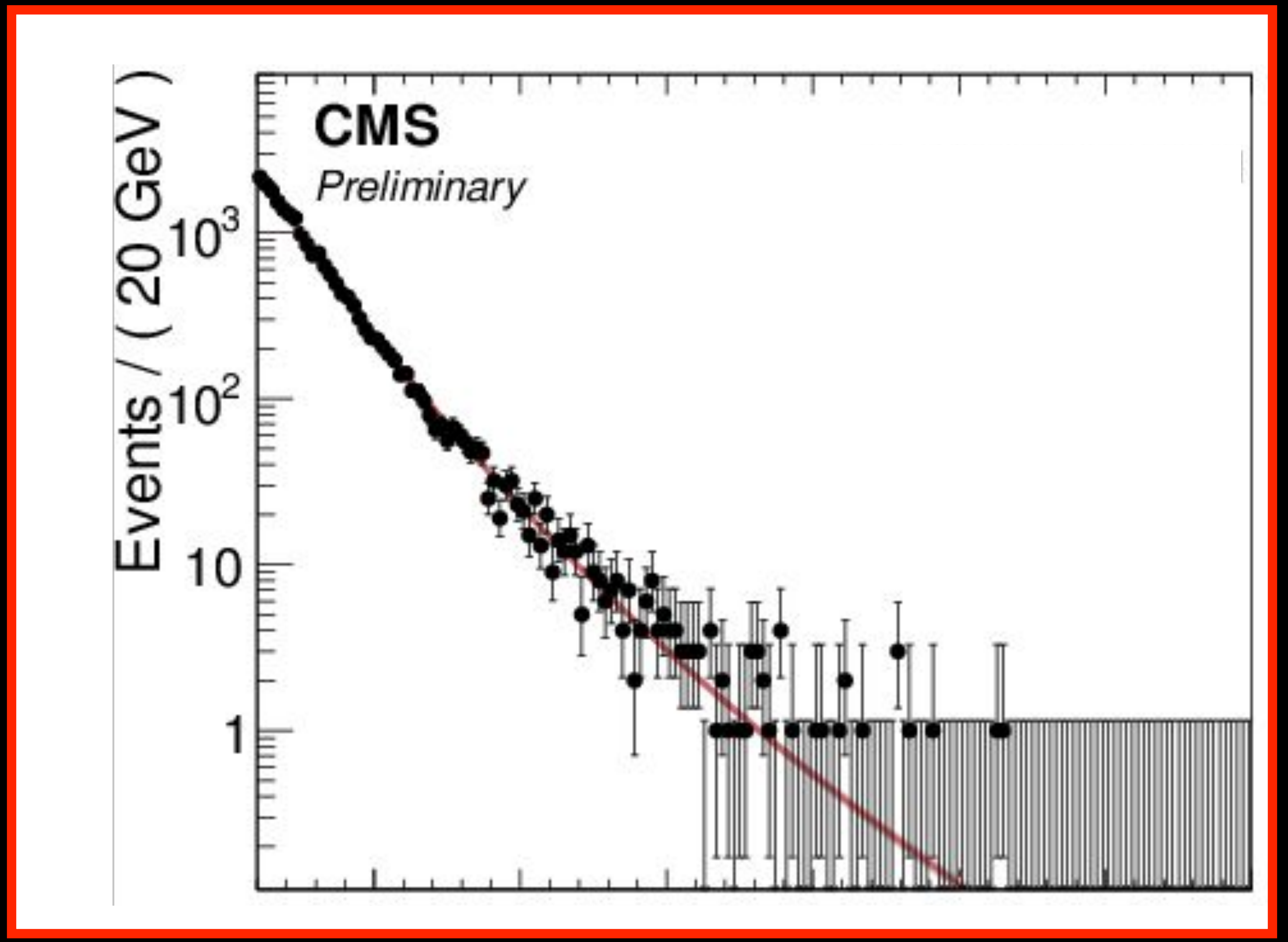
E.g Higgs $\rightarrow$ A(15 GeV) A(15 GeV) $\rightarrow$ 4b

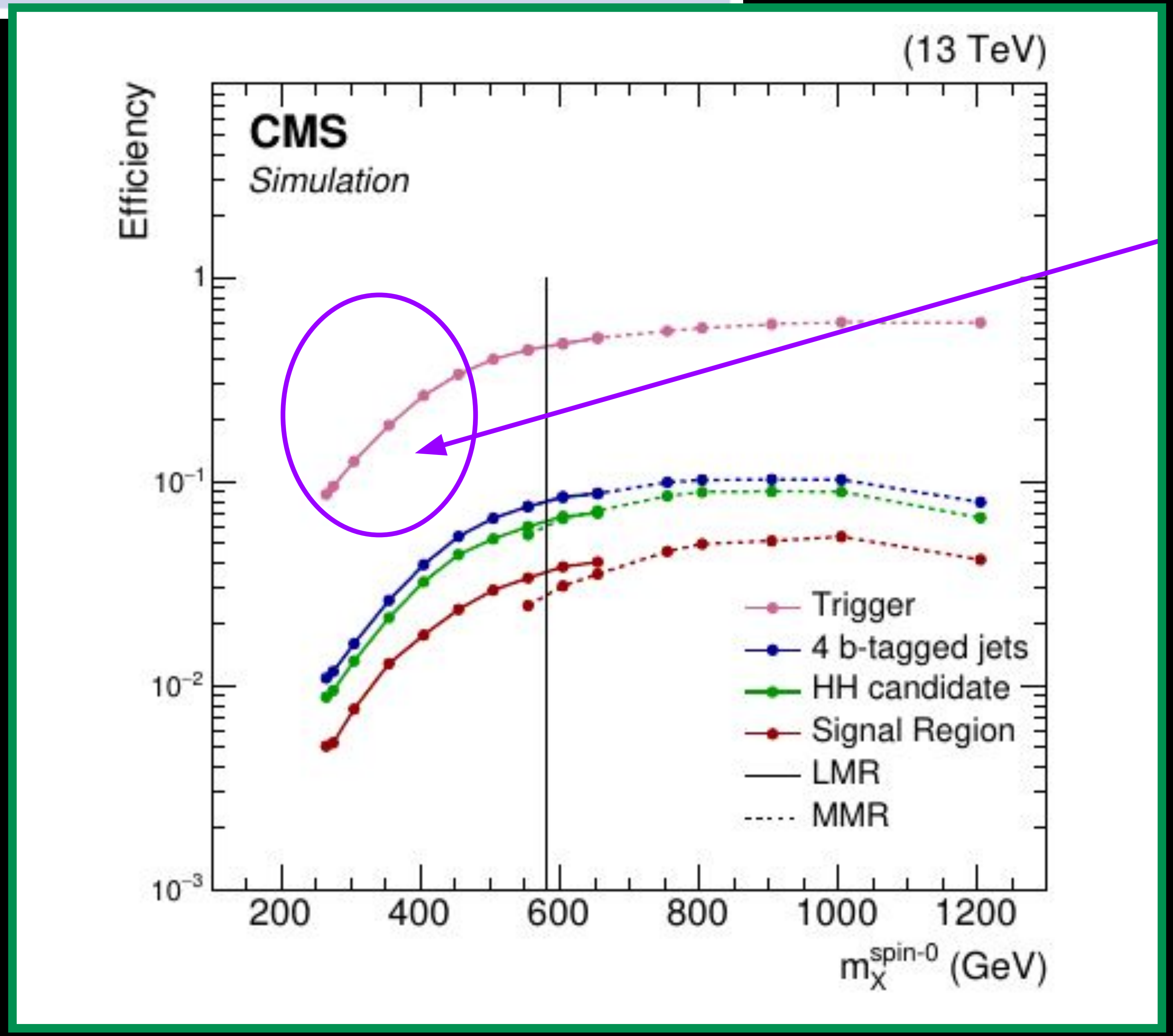
AXOL1TL Rate	1 kHz	5 kHz	10 kHz
Signal Efficiency Gain	46%	100%	133%

E.g Higgs → A(15 GeV) A(15 GeV) → 4b

We can do both of these efficiently, model-agnostic and datadriven!

Signal Efficiency Gain	46%	100%	133%





End-to-end-approach: NPLM

Alternative approach: End-to-end DNN search

- How do we get around defining a signal hypothesis?
- What is alternate hypothesis to test reference?

Idea: Assume alternate model n(x|w) can be parametrised in terms of reference model n(x|R)

$$n(x\,|\,\vec{w}) = n(x\,|\,R)e^{f(x;\vec{w})}$$ ← Set of real functions

- Let DNN parametrise alternative model

$$f(x;\vec{w}) = NN$$

End-to-end-approach: NPLM

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$$n(x\,|\,\vec{w}) = n(x\,|\,R)e^{f(x;\vec{w})}$$ ← Set of real functions

- Let DNN parametrise alternative model

$$f(x;\vec{w}) = NN$$

- Formulate loss as log likelihood.
  → Trained DNN **is** the maximum likelihood fit to data and reference log-ratio
  → best approximate of true data distribution

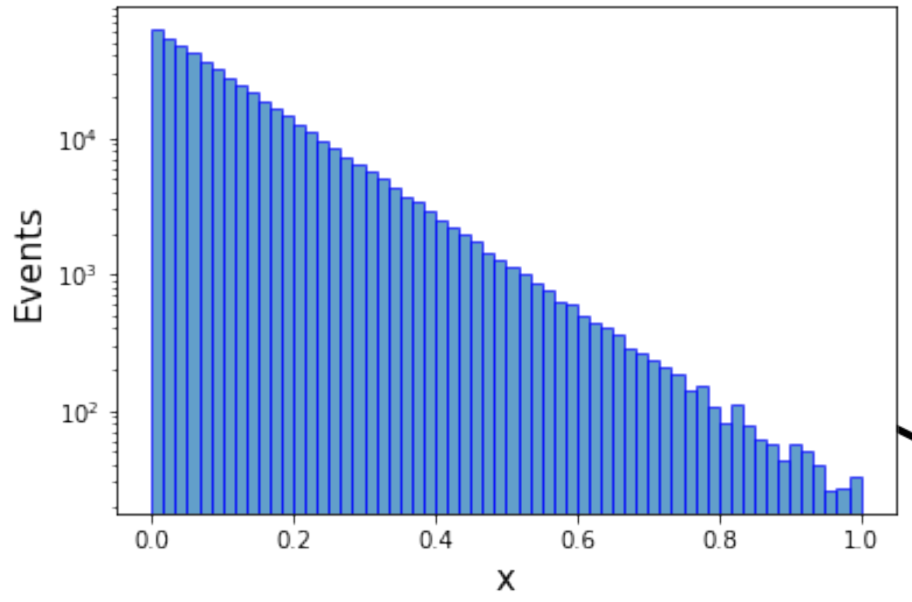
$$f(x,\widehat{\mathbf{w}}) \simeq \log\left[\frac{n(x|\mathrm{T})}{n(x|\mathrm{R})}\right]$$

← True underlying data distribution (numerator)
← MC distribution (denominator)

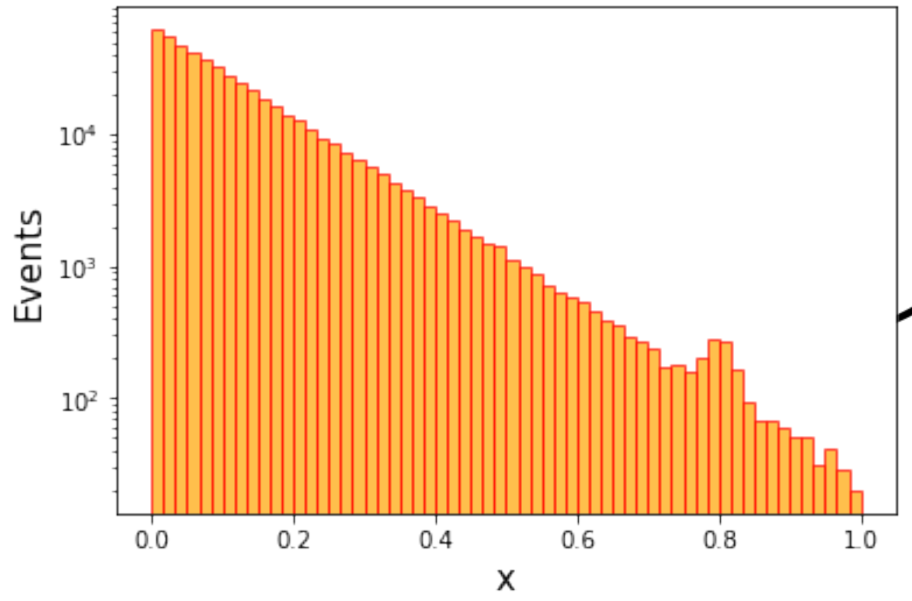
INPUTS

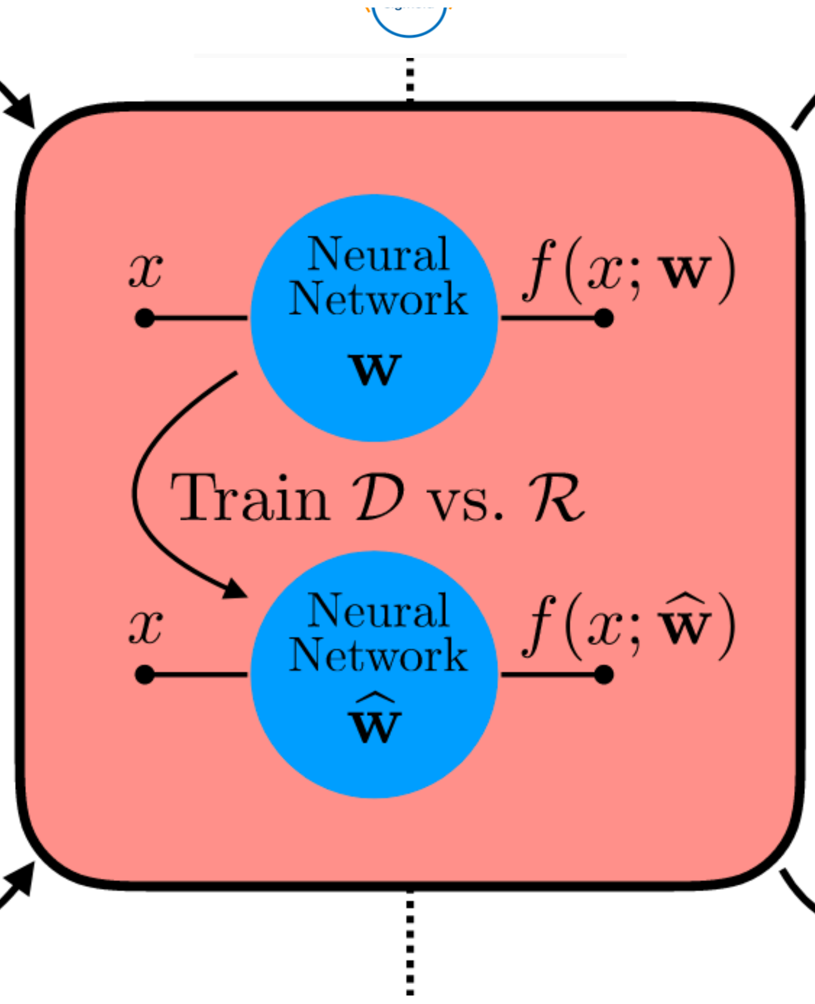
- any high level features

QCD MC R



CMS DATA D

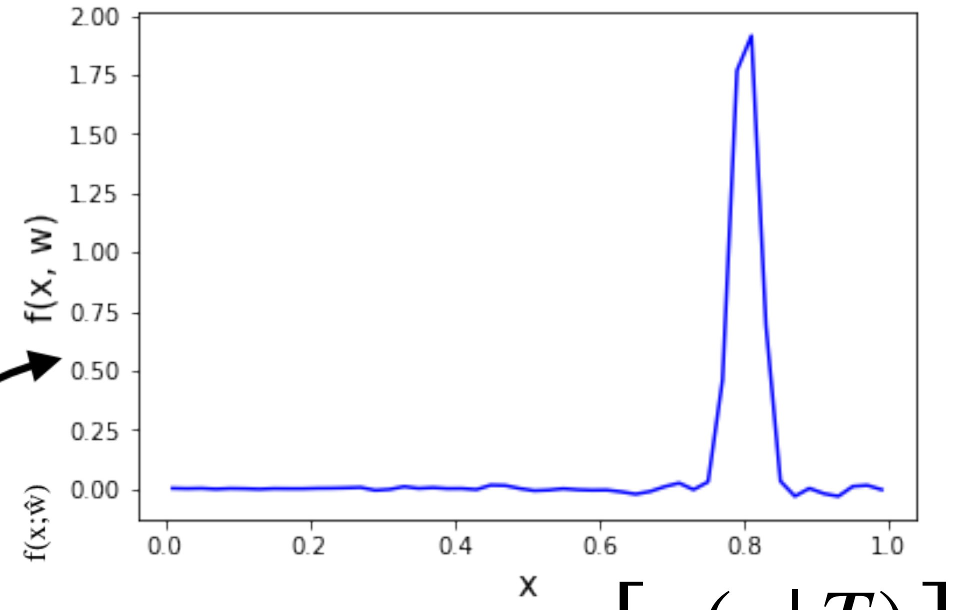




OUTPUTS

-t^{obs} and f(x; ŵ)

1) Best fit log ratio of data and MC PDFs



$$f(x,\hat{w}) \simeq \log\left[\frac{n(x\,|\,T)}{n(x\,|\,R)}\right]$$

2) test-statistic on data sample t_{obs}

$$t(\mathcal{D}) = -2\,\underset{\{\mathbf{w}\}}{\mathrm{Min}}\,L[f]$$ ← **DNN loss function!**

Can be used to build hypothesis test + p-value

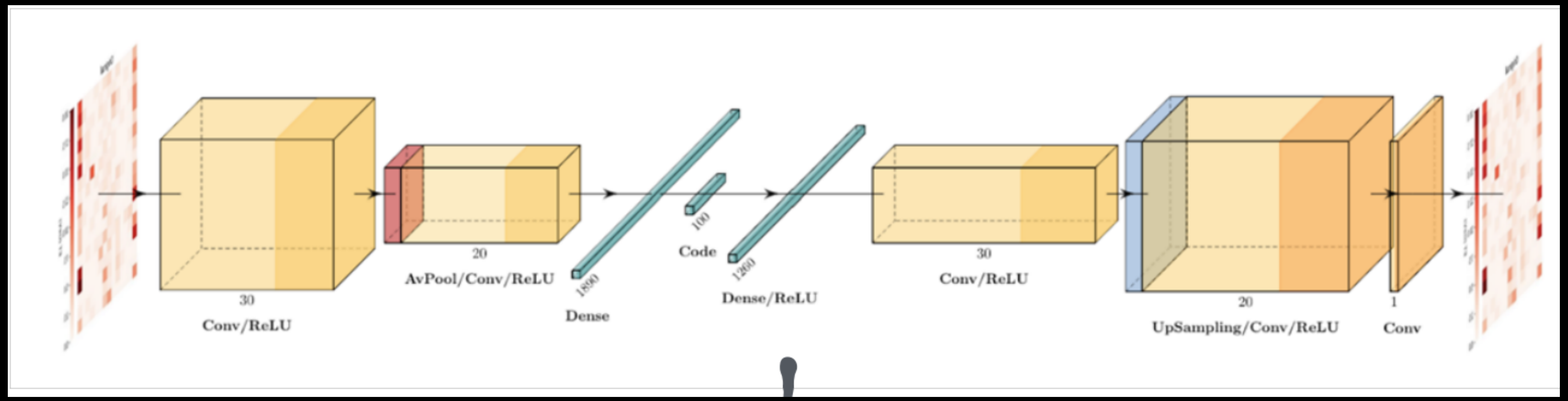
Data → toys under R, repeat

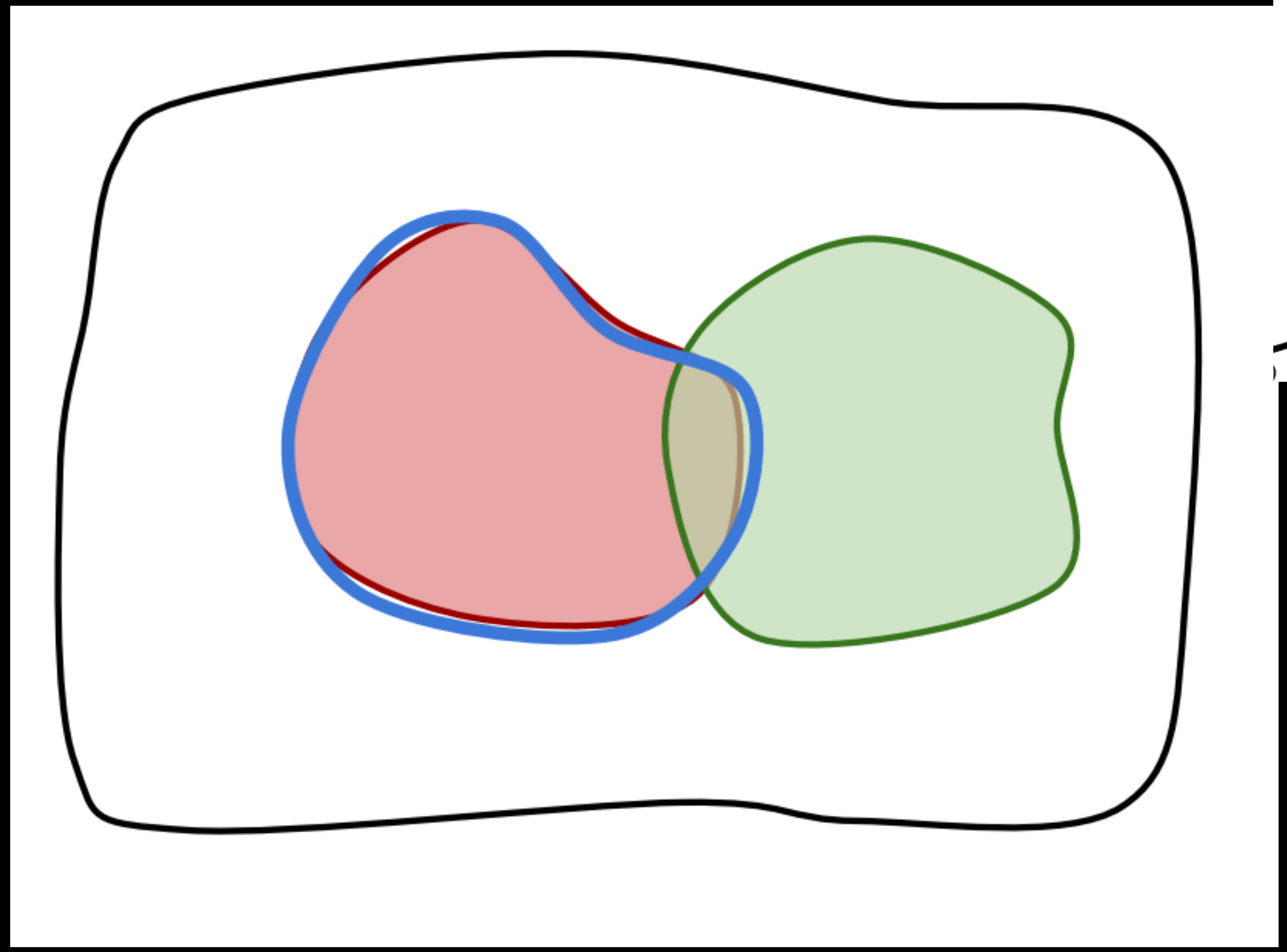
$$f(x,\widehat{\mathbf{w}}) \simeq \log\left[\frac{n(x|\mathrm{T})}{n(x|\mathrm{R})}\right]$$

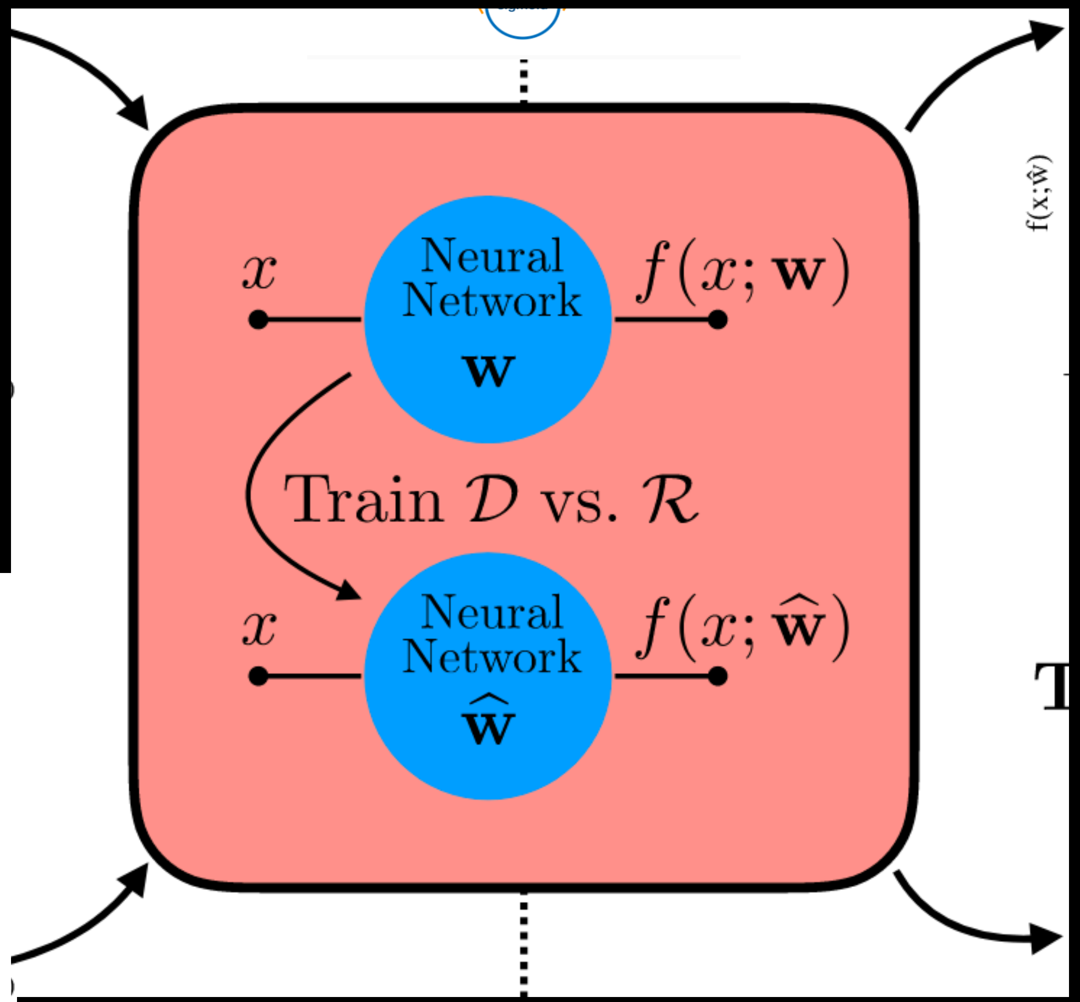
← True underlying data distribution

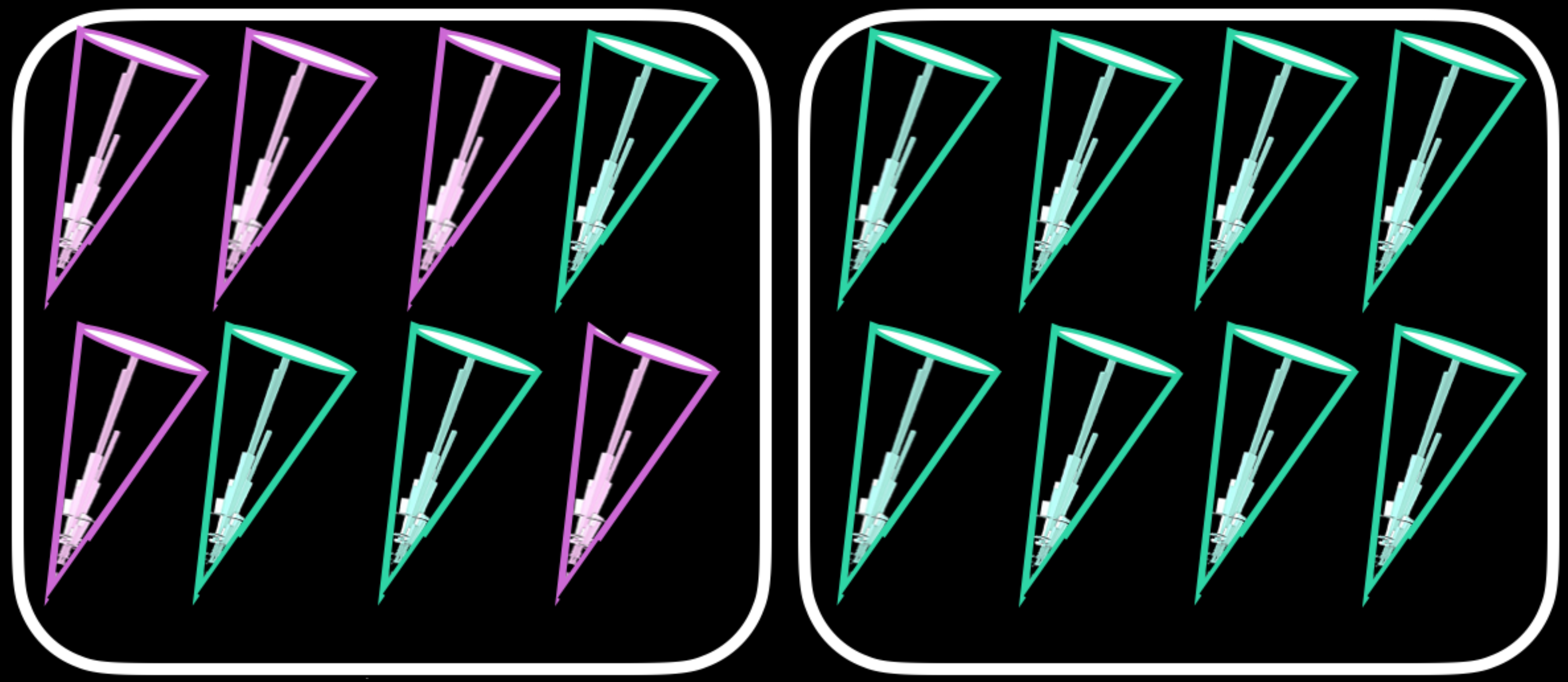
← MC distribution

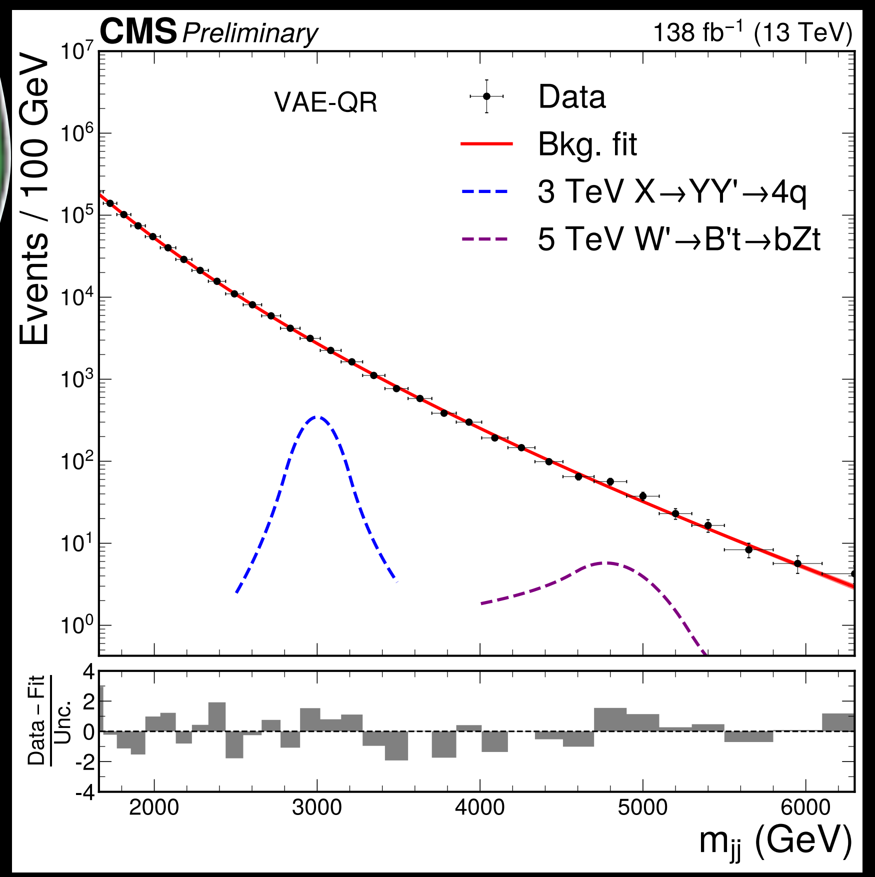
AXOL1TL

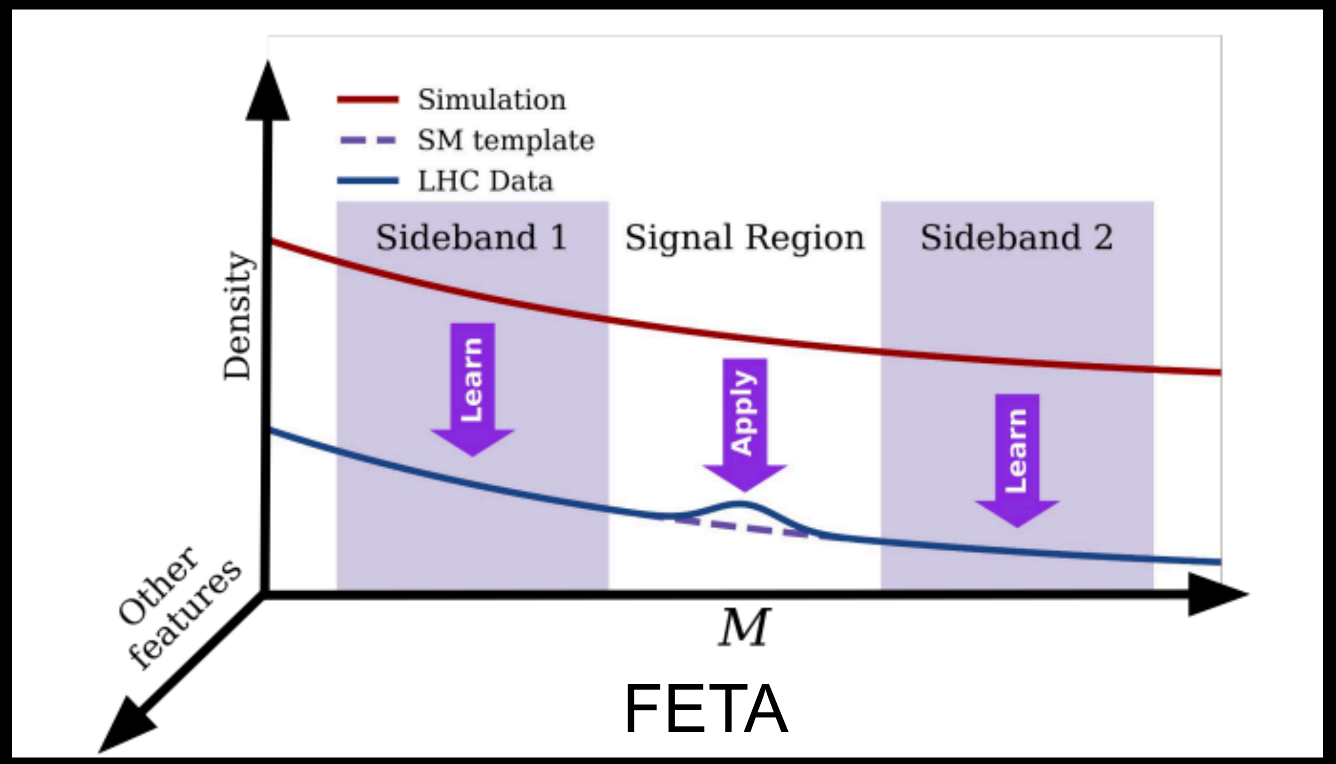

Conv/ReLU
AvPool/Conv/ReLU
Dense
Code
Dense/ReLU
Conv/ReLU
UpSampling/Conv/ReLU
Conv




x
Neural Network $\mathbf{w}$
$f(x; \mathbf{w})$
Train $\mathcal{D}$ vs. $\mathcal{R}$
x
Neural Network $\widehat{\mathbf{w}}$
$f(x; \widehat{\mathbf{w}})$


MIXED SAMPLE 1
MIXED SAMPLE 2


CMS Preliminary
138 fb^{-1} (13 TeV)
VAE-QR
Data
Bkg. fit
3 TeV X→YY'→4q
5 TeV W'→B't→bZt
Events / 100 GeV
Data – Fit / Unc.
m_{jj} (GeV)


Simulation
SM template
LHC Data
Sideband 1
Signal Region
Sideband 2
Learn
Apply
Learn
Density
Other features
M
FETA