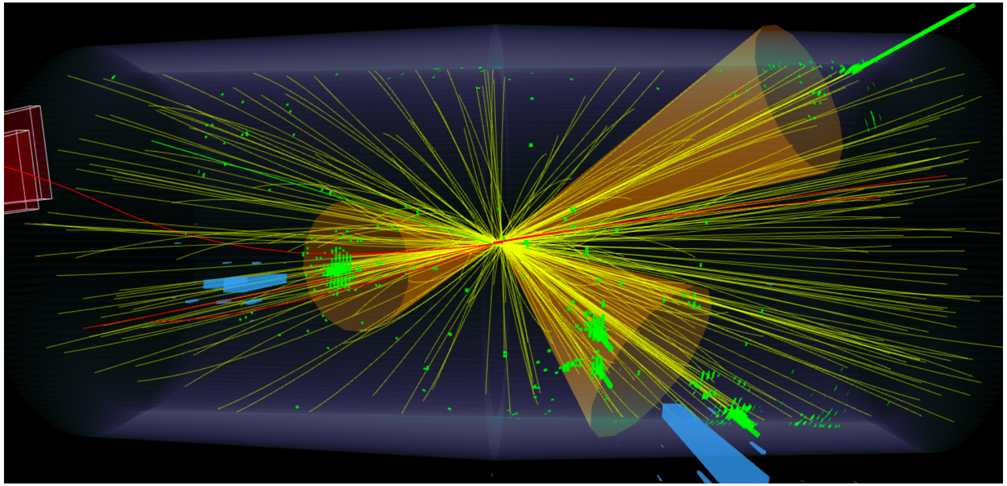
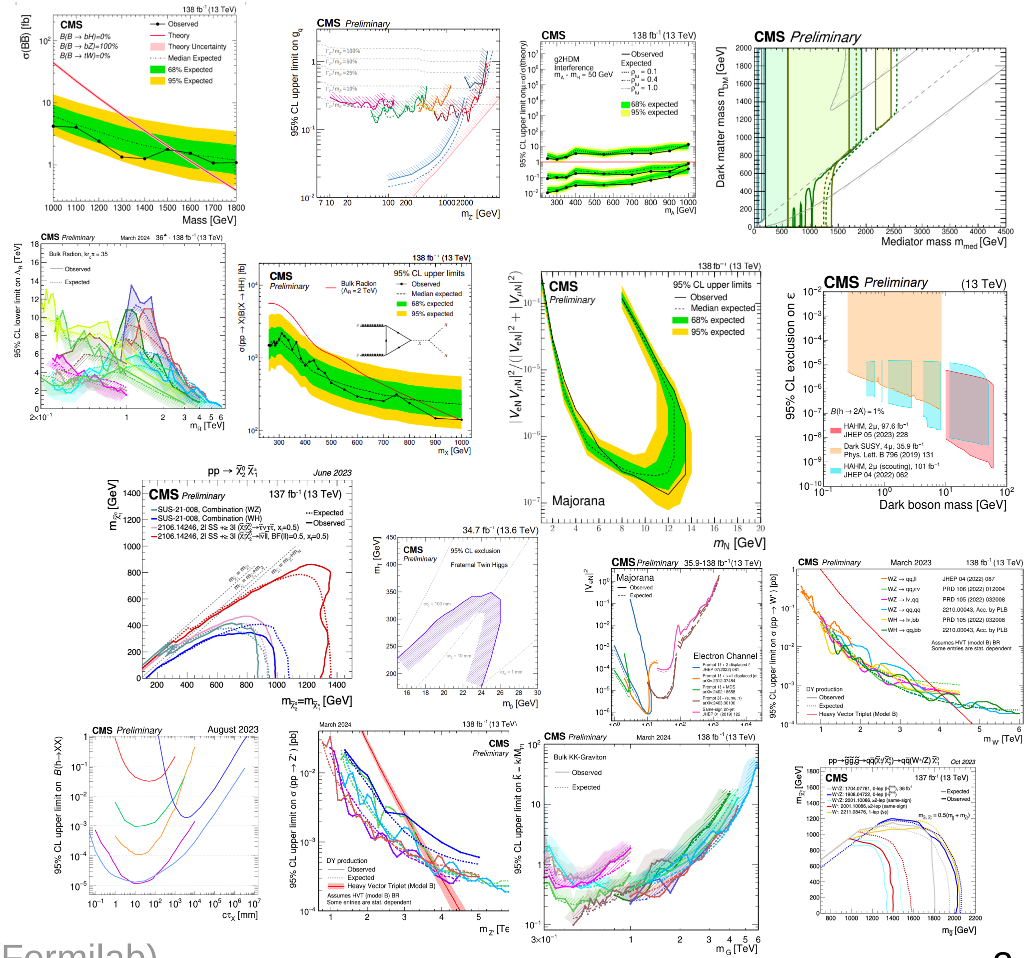
Results from CMS
Dijet Anomaly Detection Search



Oz Amram
AD4HEP Workshop
June 16th, 2025

Motivation

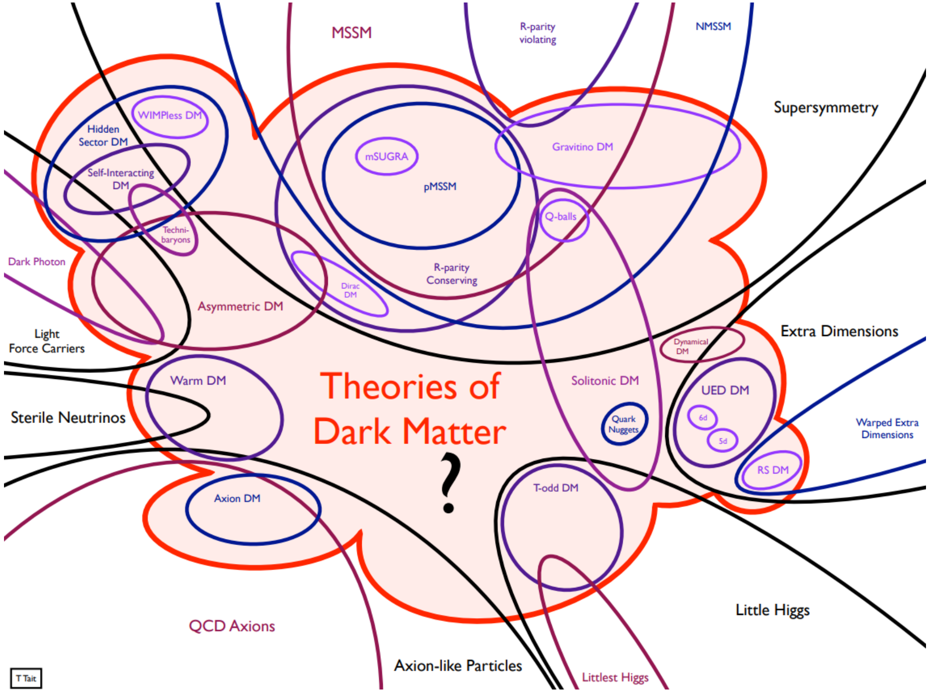
Many LHC searches but no new physics so far



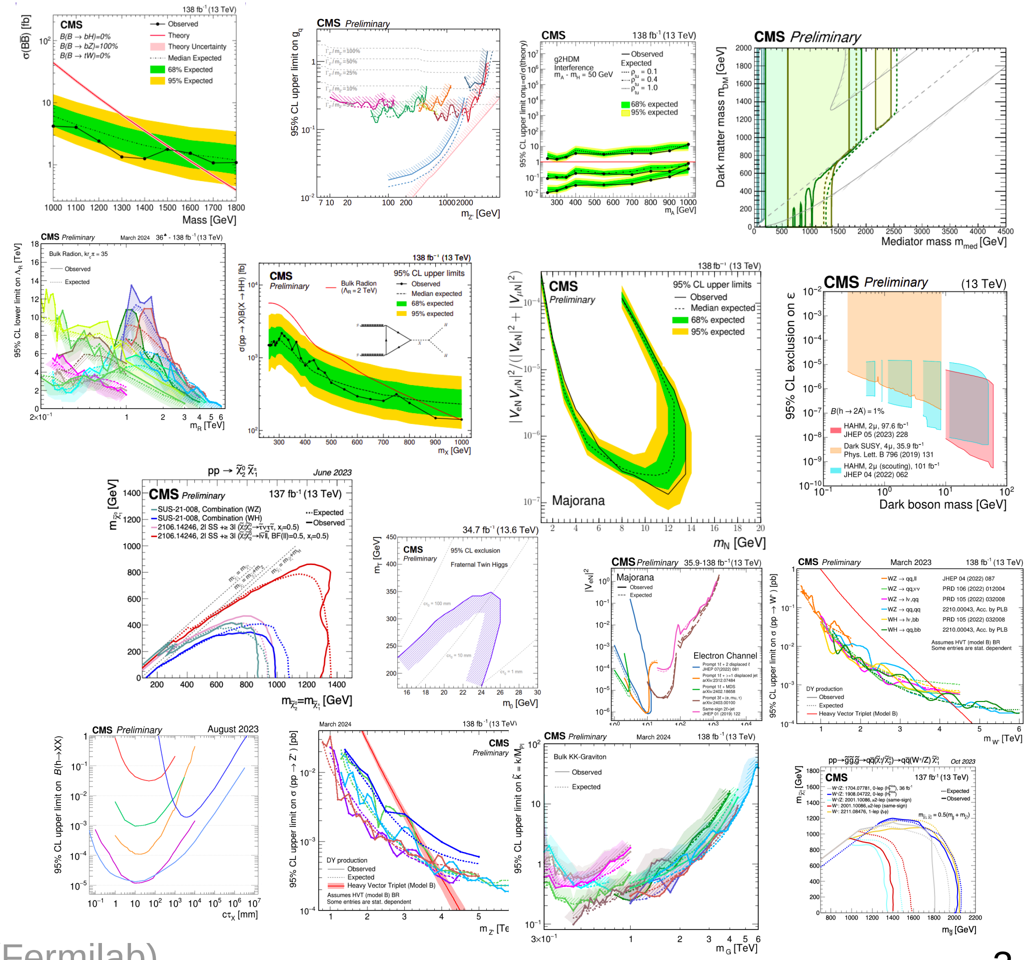
DM graphic from T. Tait

Motivation

But...



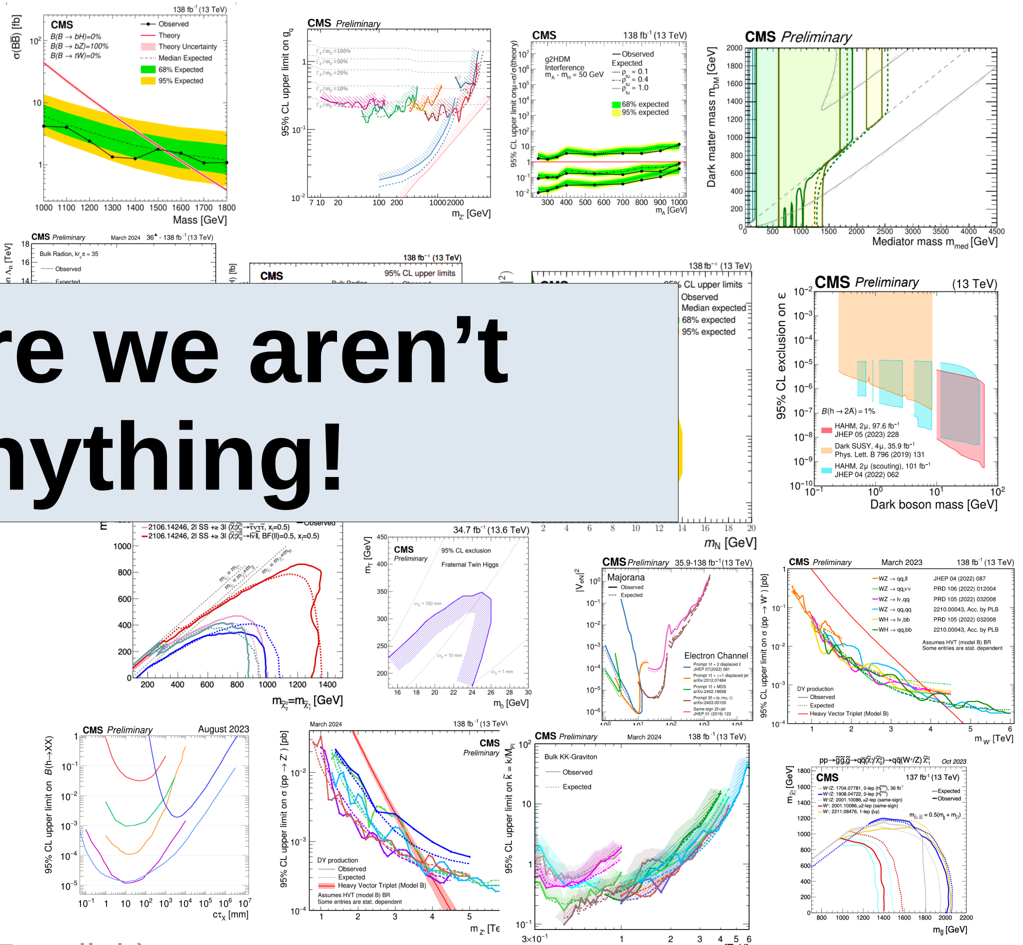
>



DM graphic from T. Tait

Motivation

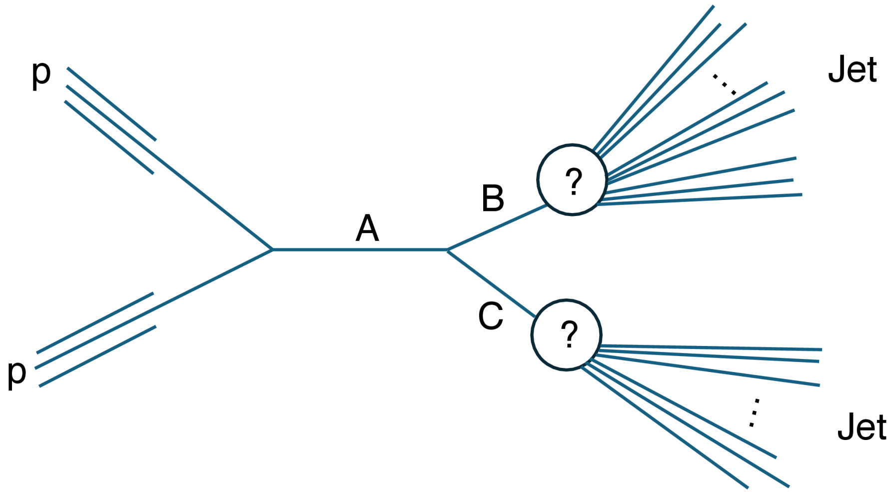
But...



Lets make sure we aren't missing anything!

DM graphic from T. Tait

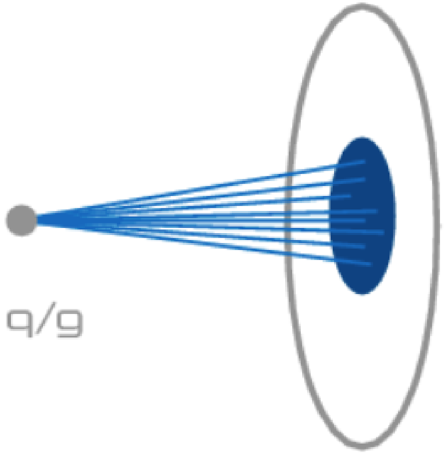
Dijet Resonance Anomaly Search

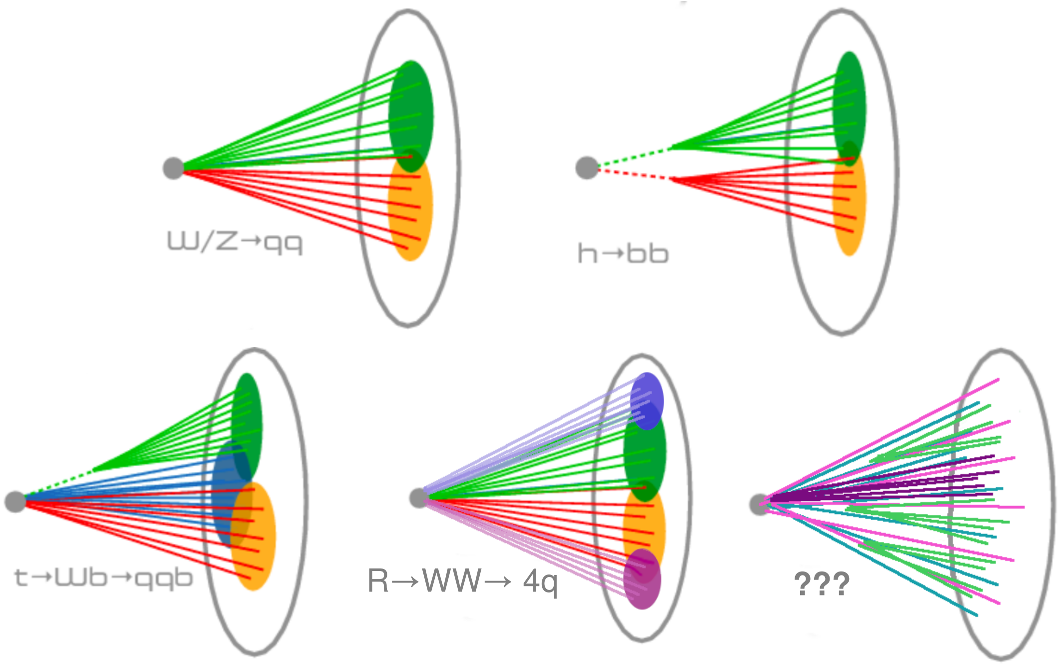


Results from
ROPP 88 067802
arXiv:2412.03747

- **A → BC** topology
  - Heavy resonance (A) → daughters B and C
  - B & C are boosted → contained in a large radius jet
- Look for B & C jets with ‘anomalous’ substructure

Jet Substructure





Typical jet

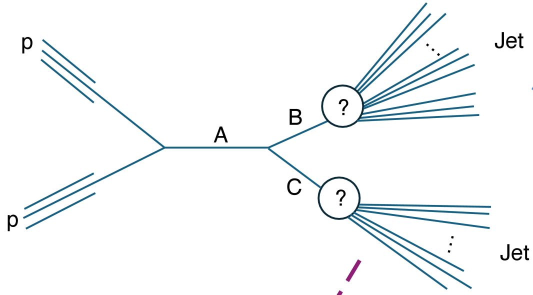
- One central axis (prong)
- From primary vertex
- ...

Anomalous jets

- Multiple prongs
- Displaced vertices
- ???

Graphics source

Signal Models



Picked a set of unexplored models to **evaluate performance**

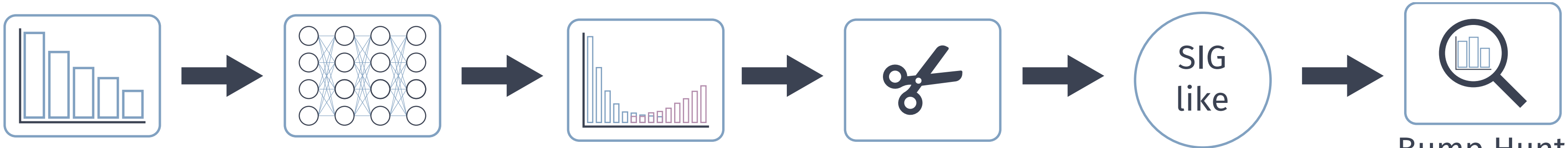
B Jet substructure

C Jet substructure

	1 prong	2 prong	3 prong	4 prong	5 prong	6 prong
1 prong		**$Q^* \to qW$** m_{Q^*} = [2,3,5] TeV m_W = [25,80,170,400] GeV				
2 prong		**$X \to YY'$** m_X = [2,3,5] TeV m_Y = [25,80,170,400] GeV $m_{Y'}$ = [25,80,170,400] GeV		**$W_{KK} \to RW \to WWW$** $m_{W_{KK}}$ = [2,3,5] TeV m_R = [170,400] GeV		
3 prong			**$W' \to tB'$** $m_{W'}$ = [2,3,5] TeV $m_{B'}$ = [25,80,170,400] GeV			
4 prong				**$X \to YH \to WWWW$** m_X = [2,3,5] TeV m_Y = [170,400] GeV m_H = [170,400] GeV		
5 prong					**$Z' \to T'T' \to tZtZ$** $m_{Z'}$ = [2,3,5] TeV $m_{T'}$ = [400] GeV	
6 prong						**$Y \to HH \to tttt$** m_Y = [2,3,5] TeV m_H = [400] GeV

Expect sensitivity to many additional kinds of signals!

Analysis Overview

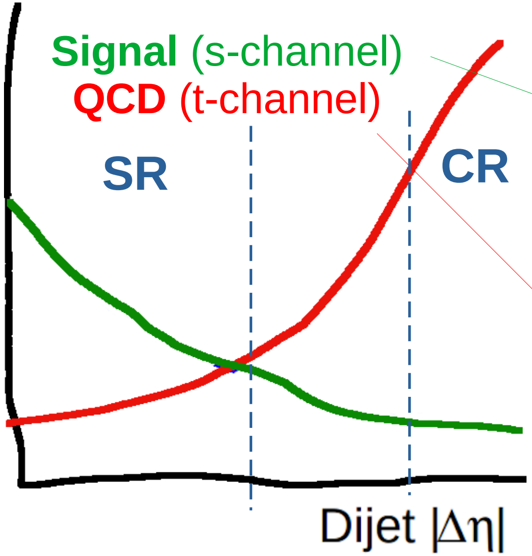


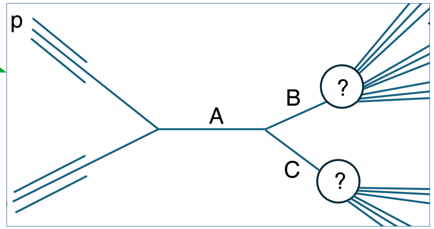
Preselected Data → Trained Model → Anomaly Metric → Cut → SIG like → Bump Hunt

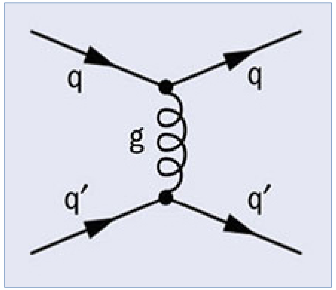
2 large radius (AK8) jets

Signal Region
|Δη| < 1.3

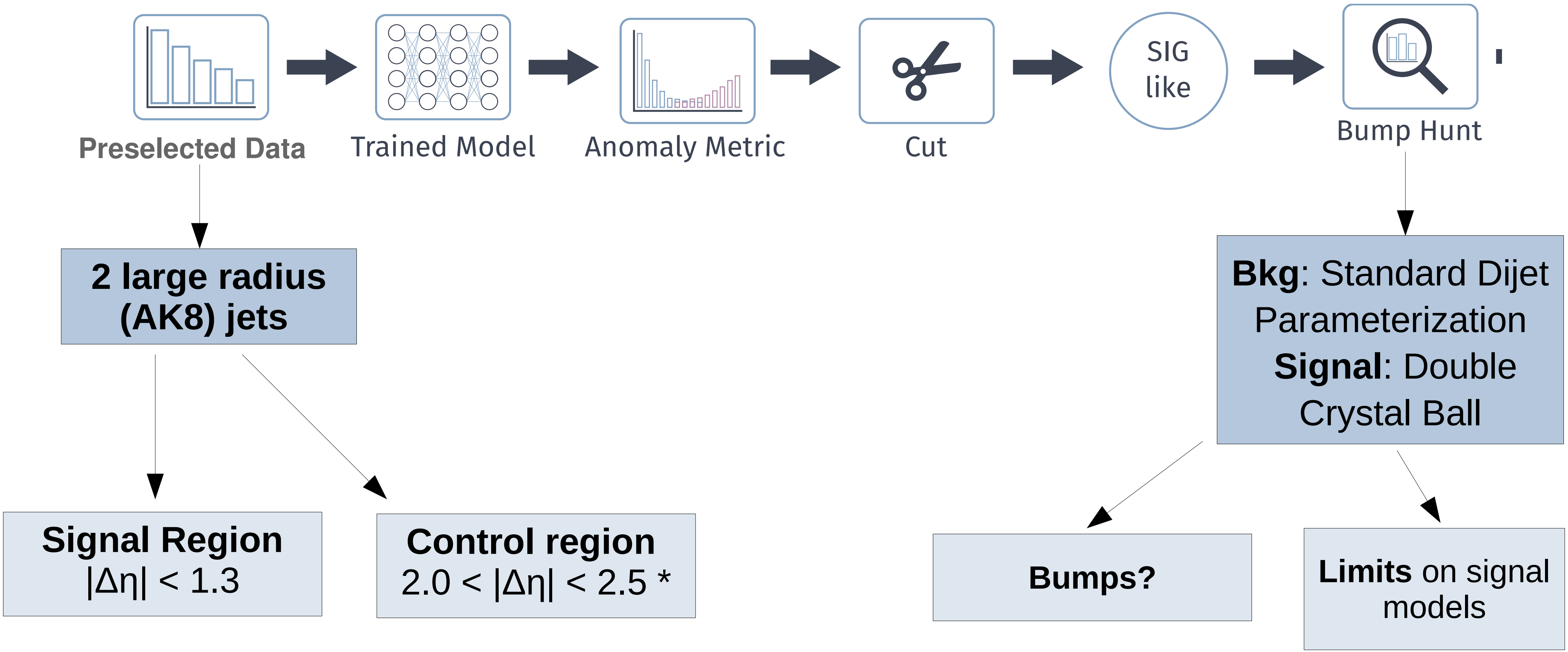
Control region
2.0 < |Δη| < 2.5 *







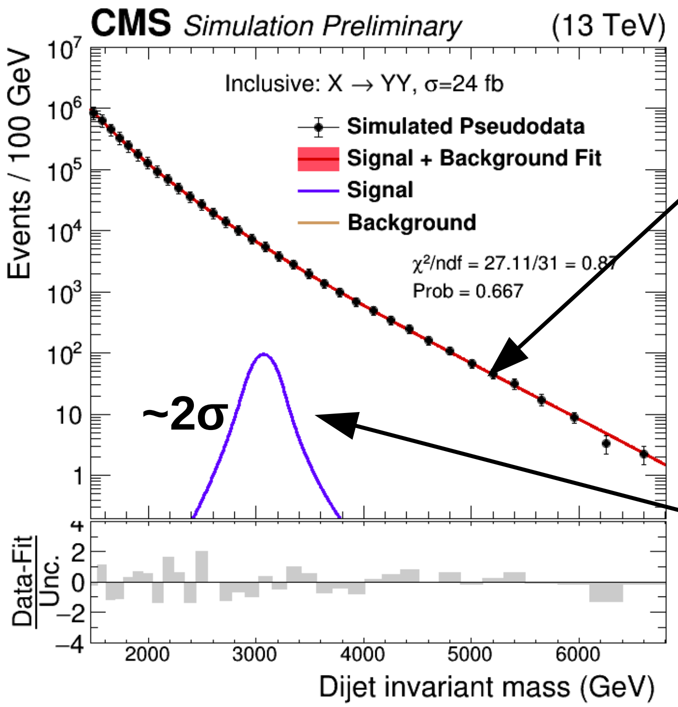
Analysis Overview



Oz Amram (Fermilab)

The Bump Hunt

CMS-NOTE -2023-013



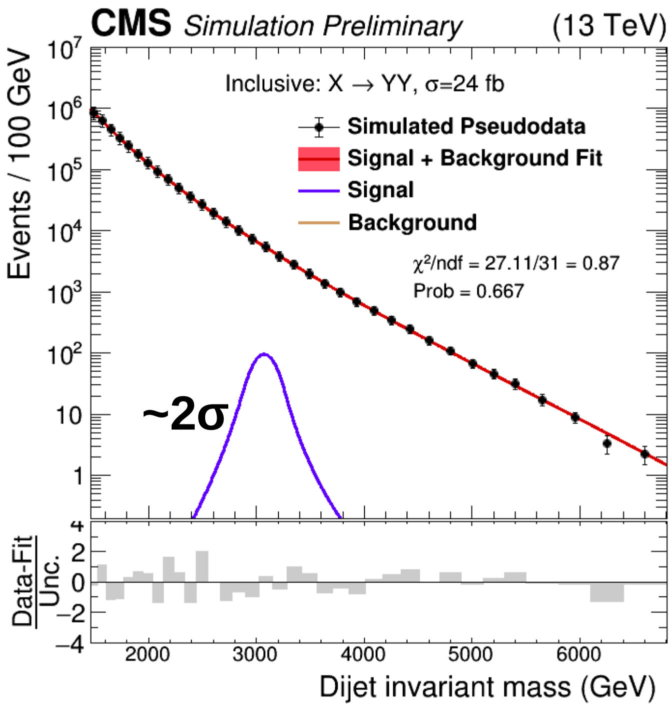
Background fit with standard analytic functions

Double Crystal Ball signal shape

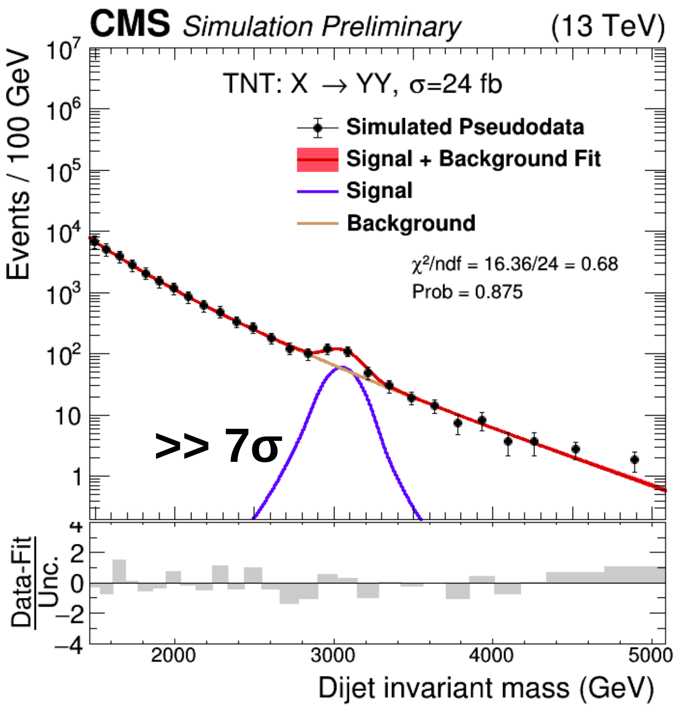
Without any substructure cuts →
Signal swamped by QCD background…

The Bump Hunt

CMS-NOTE -2023-013

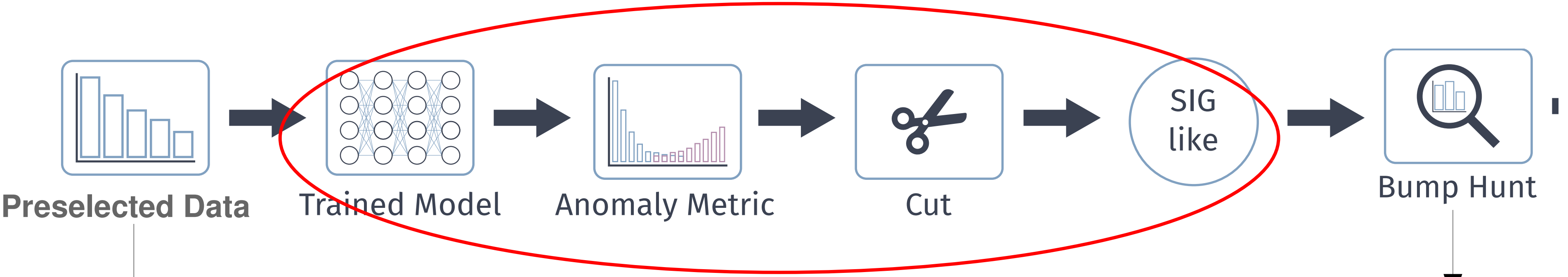


Cut on anomaly score



Anomaly detection finds hidden resonance!

Analysis Overview



The fun part!

5 different approaches

2 large radius (AK8) jets

Signal Region
$|\Delta\eta| < 1.3$

Sideband region
$2.0 < |\Delta\eta| < 2.5$ *

Bkg: Standard Dijet Parameterization
Signal: Double Crystal Ball

Bumps?

Limits on signal models (tricky)

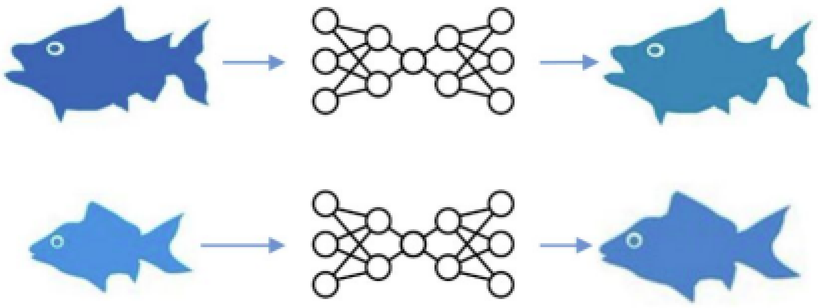
How to identify anomalous jets?

Learn QCD jets → look for outliers

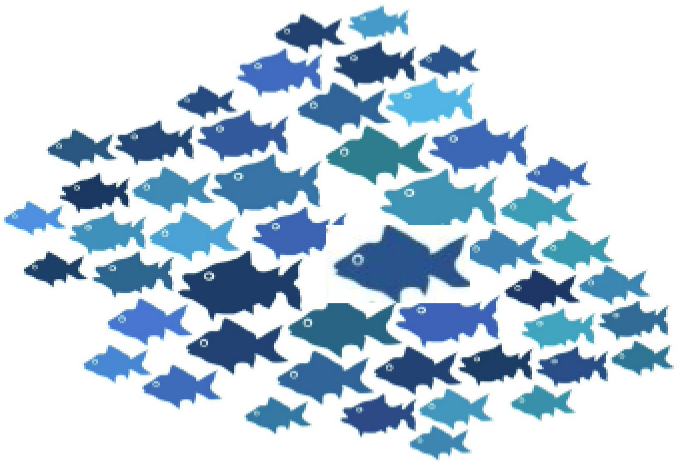
Increasing Model Dependence

Looking for Outliers

Train 'Autoencoder'



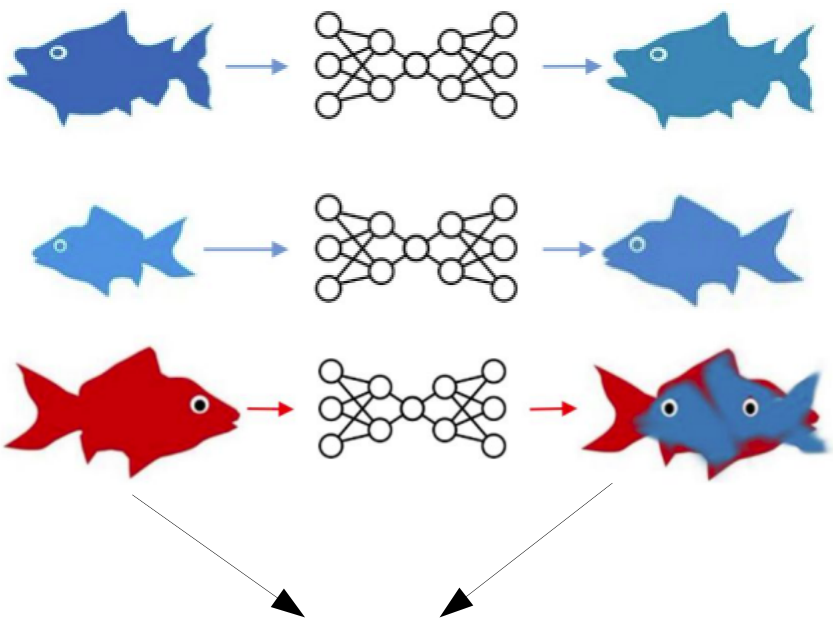
Training Sample from data sideband



Illustrations: J Gonski, A Kahn

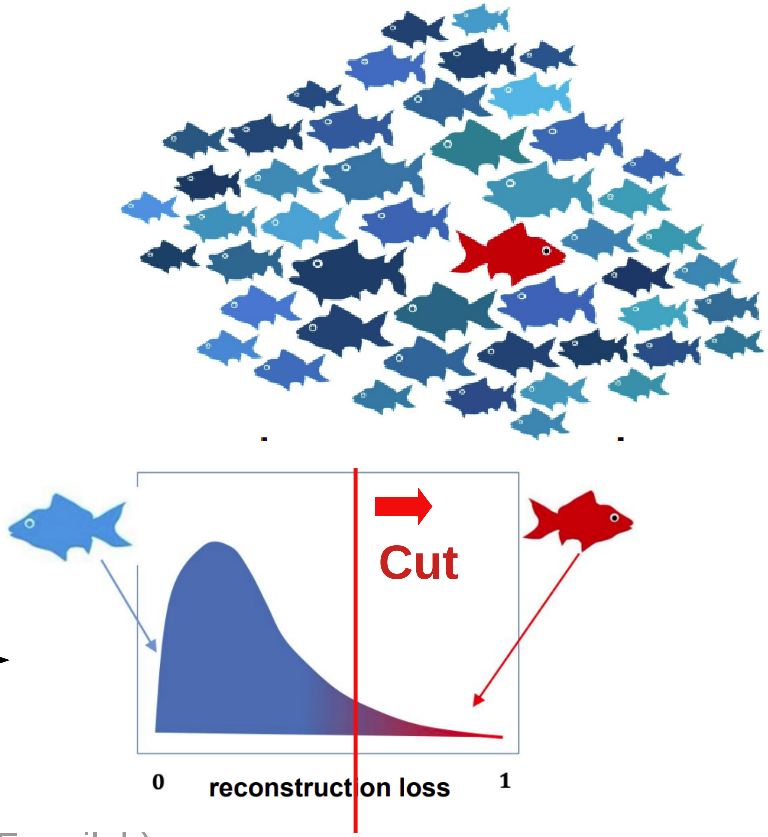
Looking for Outliers

Apply Autoencoder



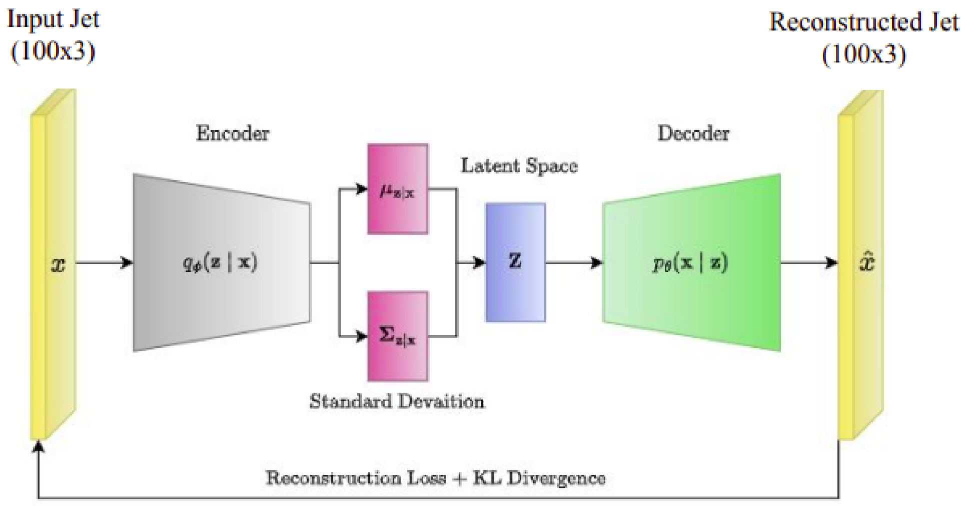
Take difference

Data from signal region



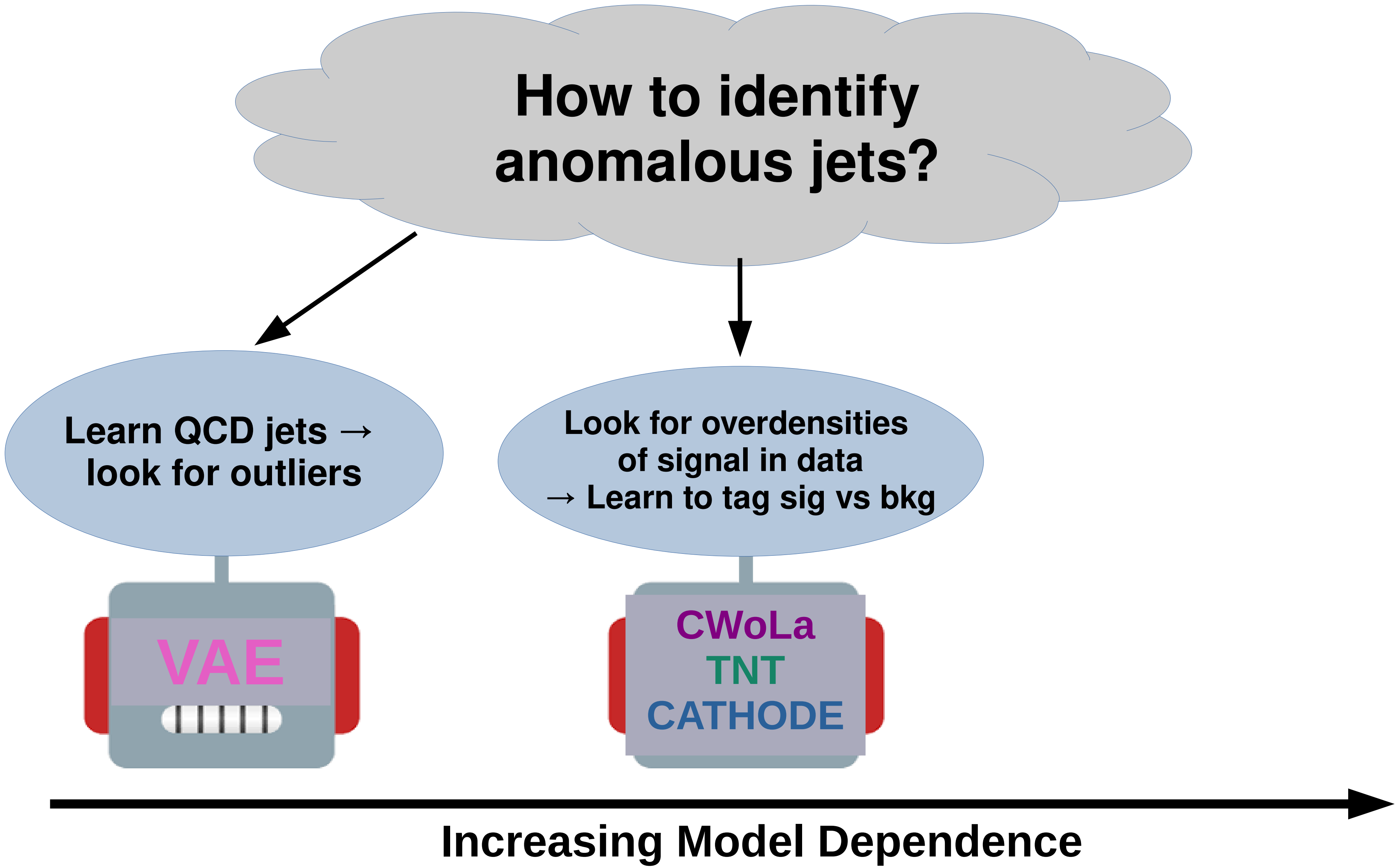
Illustrations: J Gonski, A Kahn

Variational Autoencoder (VAE)



Latent space forced to be Gaussian
thru additional term in loss

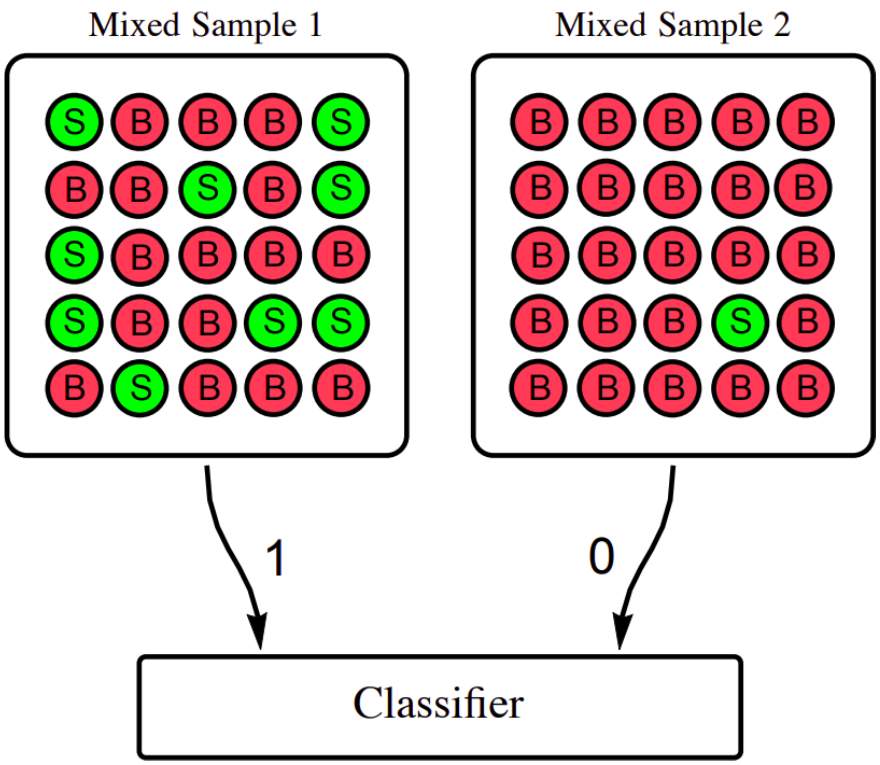
- Jet represented by up to 100 highest p_T constituents (p_x, p_y, p_z)
- 100x3 matrix compressed to latent space of size 12
- Trained on jets from $|\Delta\eta|$ sideband
  - Sampled to match SR kin.


How to identify anomalous jets?
Learn QCD jets → look for outliers
Look for overdensities of signal in data → Learn to tag sig vs bkg
VAE
CWoLa
TNT
CATHODE
Increasing Model Dependence

Weak Supervision

Aka ‘Classification Without Labels’ (CWoLa)

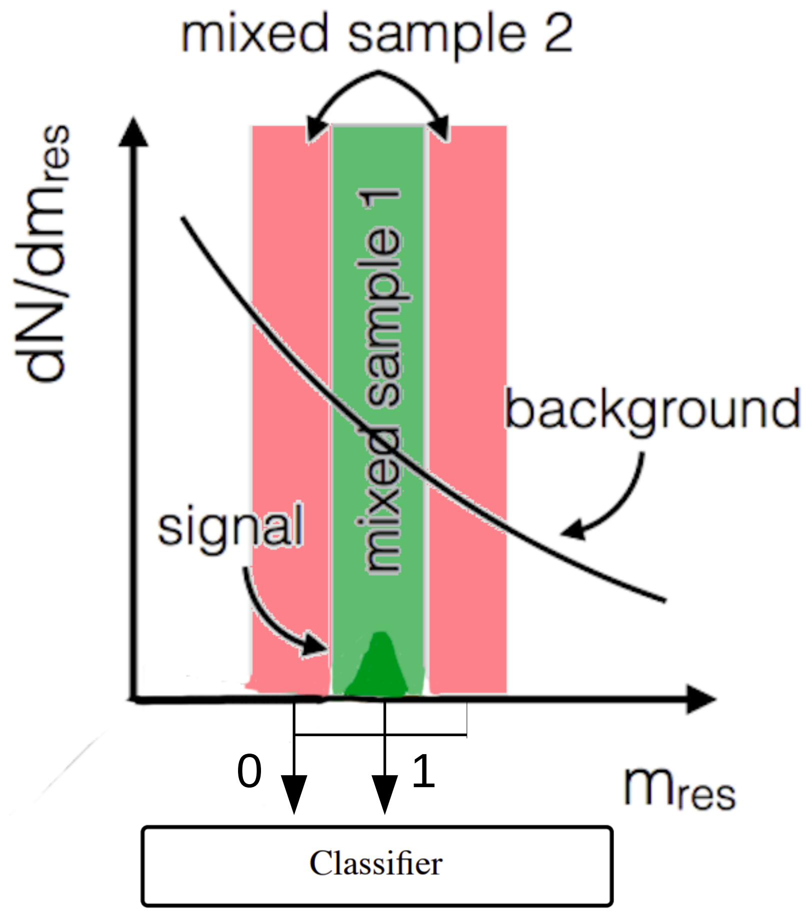
Train on two mixed samples



- Train a classifier between **signal-rich** and **background-rich** mixed samples
  - → Learns to tag signal vs. bkg
- Performance changes with amount of signal in training data
  - No signal → learn random noise
  - Lots of signal → approach ‘supervised’ (optimal) classifier

[Metodiev, Nachman, Thaler, 1708.02949]

CWoLa Hunting

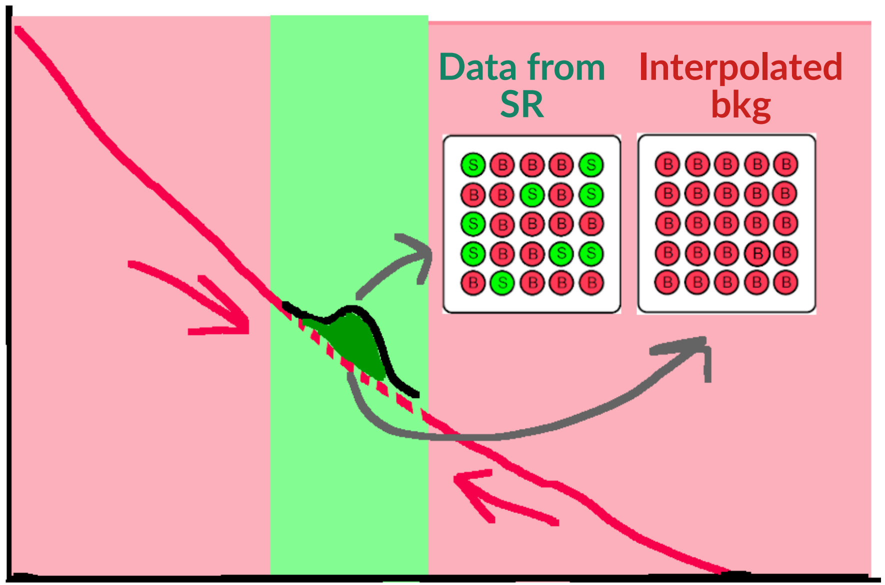


- Assume signal is a **narrow** resonance
- **Guess** a mass window where it lives
  - Train signal window vs. narrow sidebands using weak supervision
- **Repeat procedure**, scanning over different mass windows
  - (2x6 windows used)
- Need to be careful about correlations with Mjj

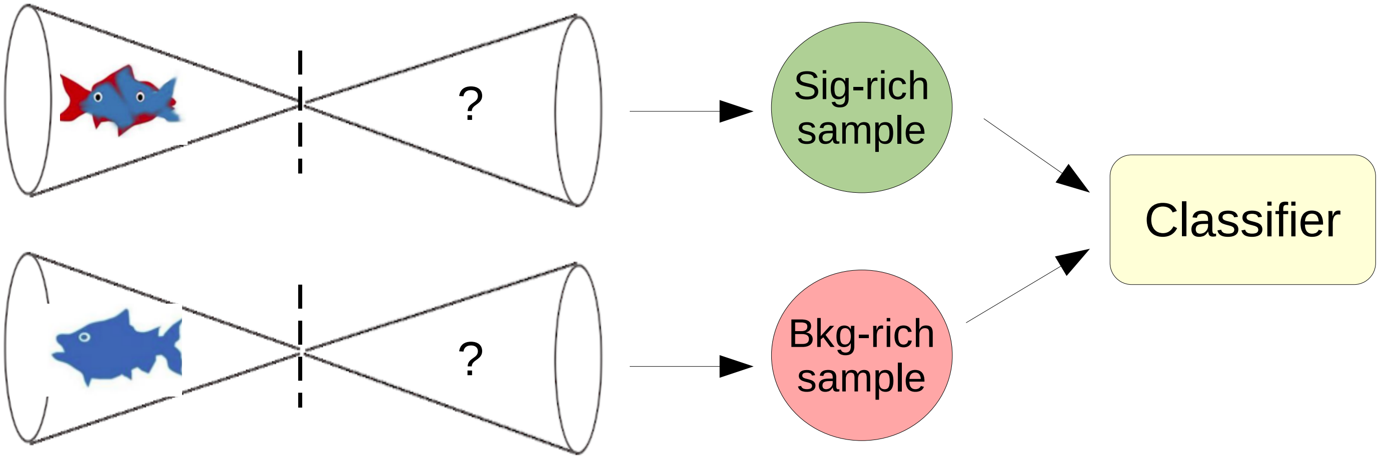
[Collins, Howe, Nachman 1902.02634]

CATHODE
Interpolates bkg events into SR to construct sample

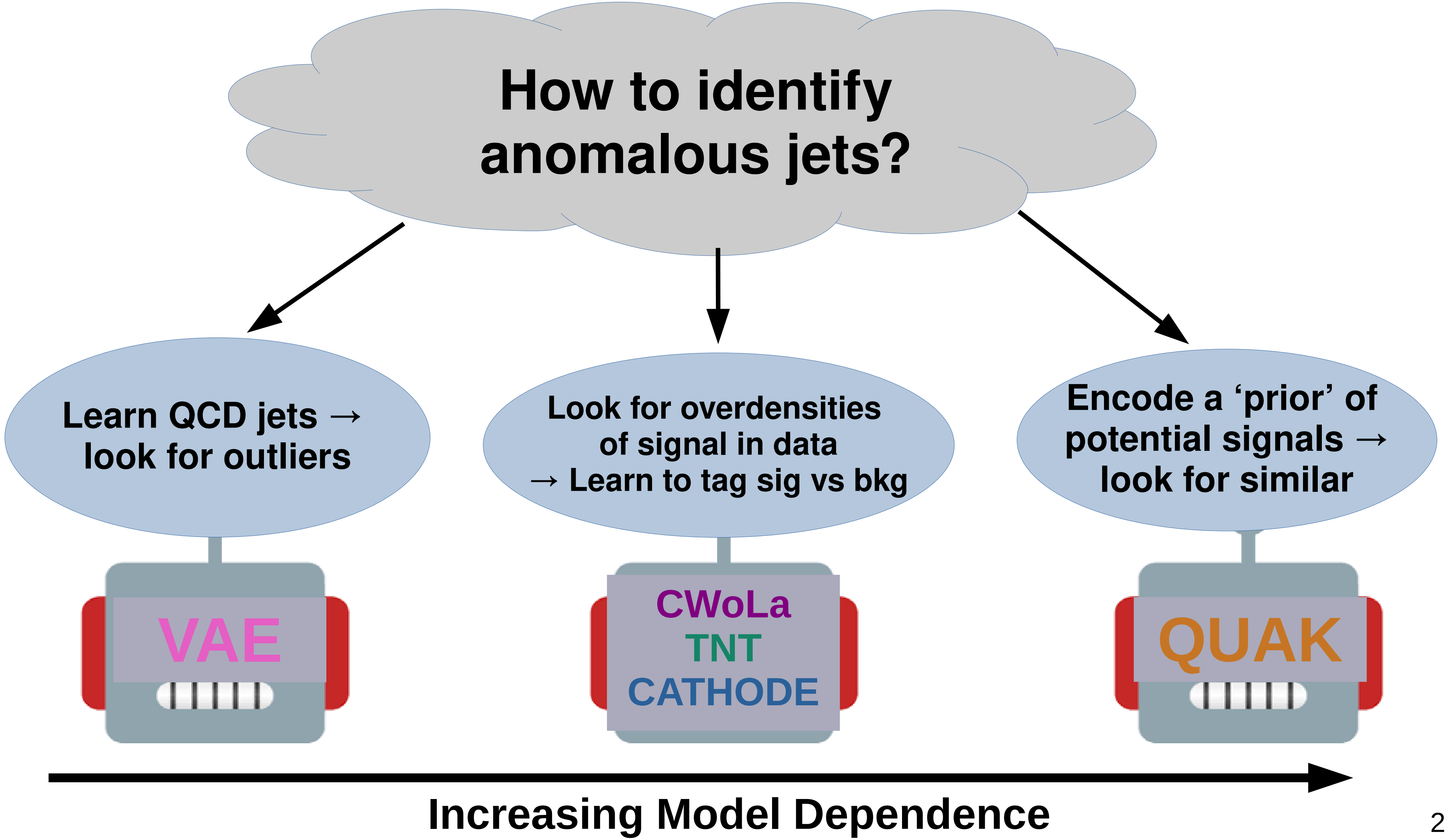
[Hallin et al 2109.00546]



Tag N' Train
purifies samples by first tagging with AE



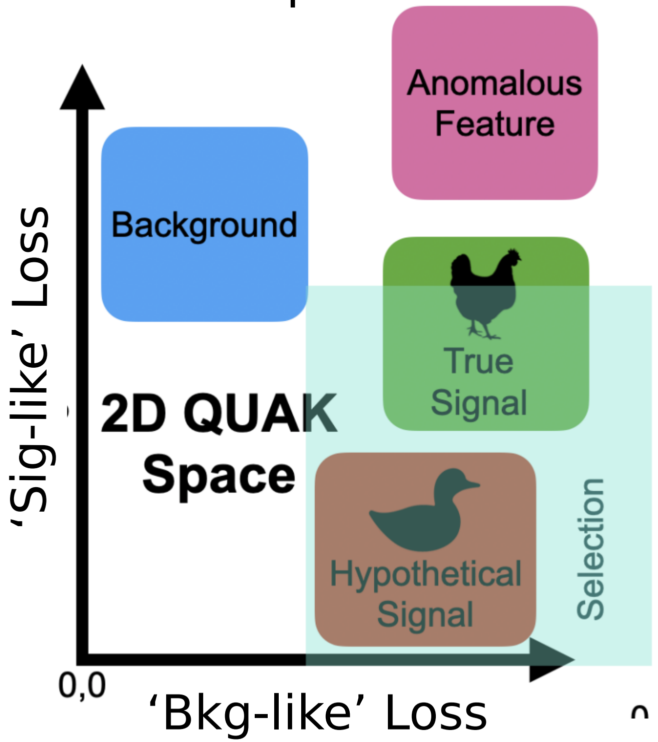
[**OA** & Suarez 2002.12376]


How to identify anomalous jets?
Learn QCD jets → look for outliers
Look for overdensities of signal in data → Learn to tag sig vs bkg
Encode a ‘prior’ of potential signals → look for similar
VAE
CWoLa
TNT
CATHODE
QUAK
Increasing Model Dependence

Quasi Anomalous Knowledge (QUAK)

- **Hybrid approach** between fully model-indep. and standard search
- **Encode a prior** on what a potential signal may look like
  - Use an AE trained on a variety of different signal MC's
- Construct 'QUAK space':
  - Loss of signal AE vs bkg AE
- Select events with low sig loss and high bkg loss

Hypothetical QUAK Space



[Park et al 2011.03550]

Input Features

Low-level features | Hand-picked high-level features

VAE

Jet Constituents
p_x, p_y, p_z

CWoLa Hunting

Jet mass
τ_{21}
τ_{32}
τ_{43}
N_{const}

Leptonic energy frac.

Sub-jets b-tag score

TNT

Same as CWoLa Hunting

CATHODE

Jet masses
τ_{41}'s

CATHODE-b

+ Subjet b-tag scores

QUAK

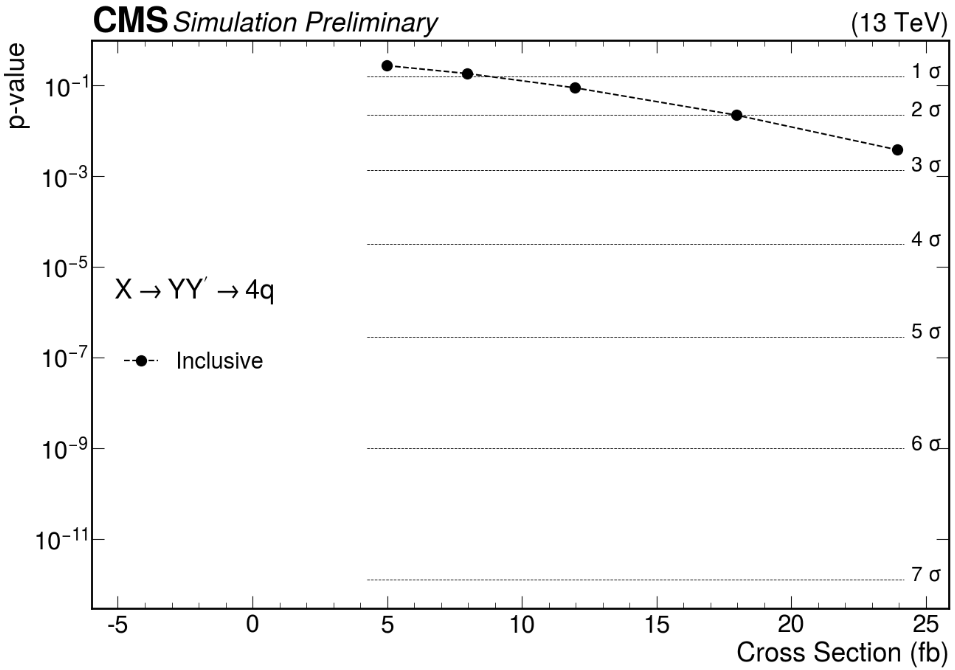
ρ = jet mass / p_T
τ_{21}'s
τ_{32}'s
τ_{43}'s
N_{const}'s

$\sqrt{\tau_{21}}/\tau_1$

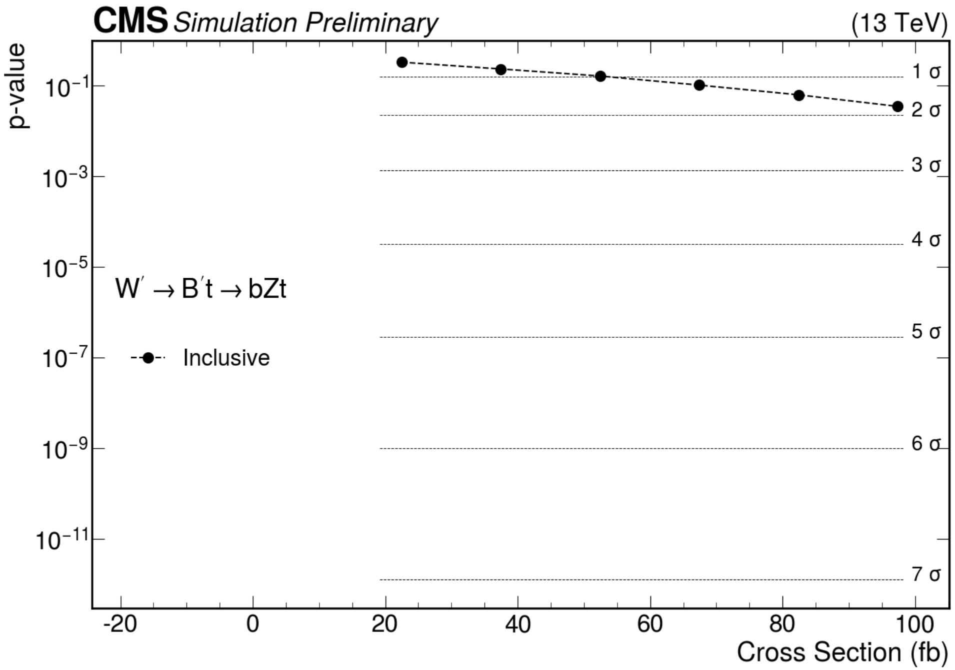
Sub-jets b-tag scores

Sensitivity

2 Pronged Signal



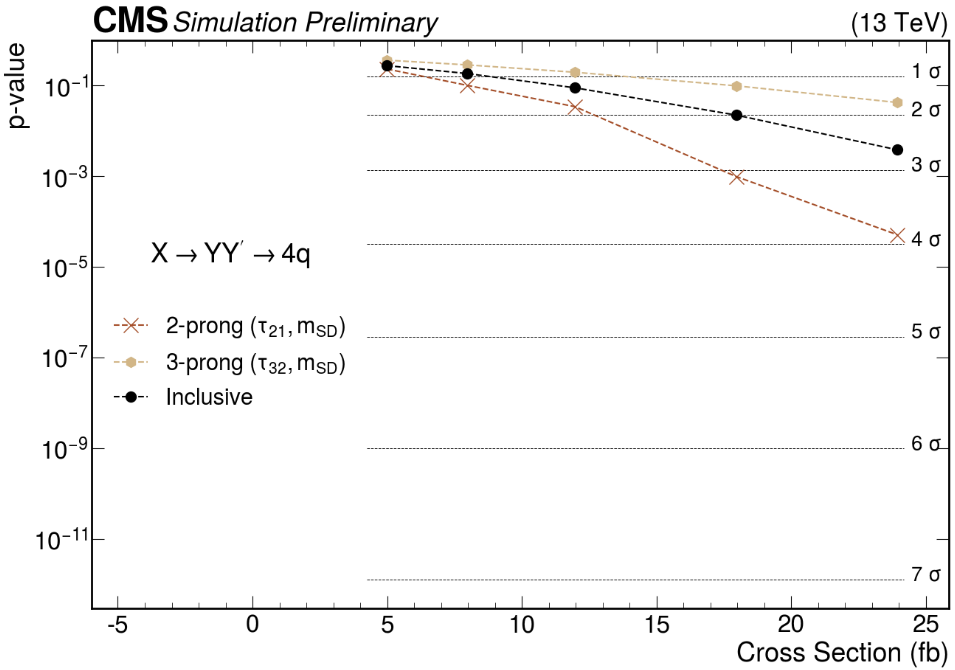
3 Pronged Signal



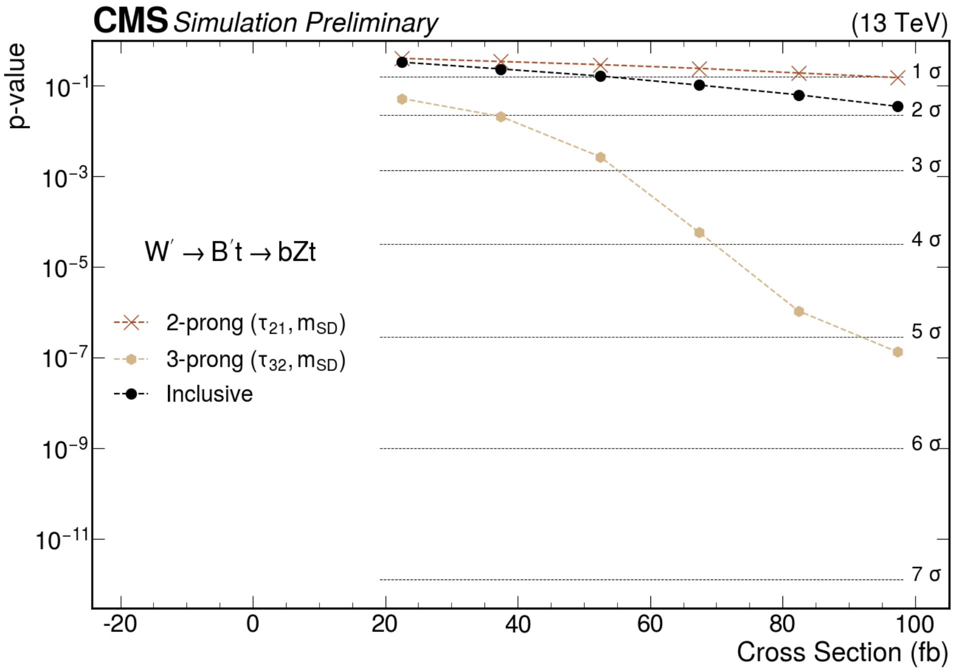
Inclusive analysis (no substructure cuts) sees only “hints”

Sensitivity

2 Pronged Signal



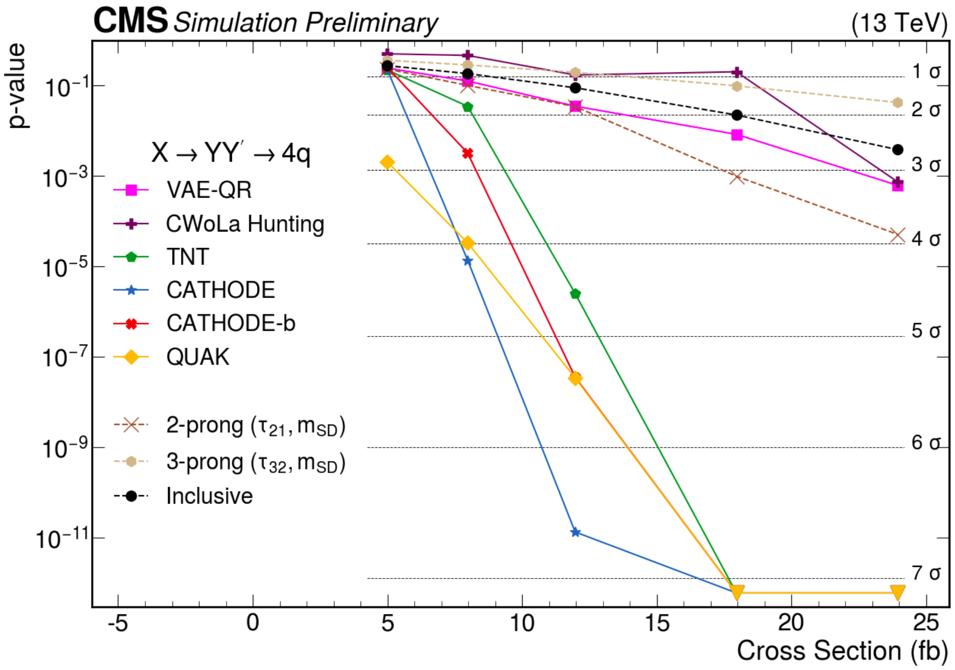
3 Pronged Signal



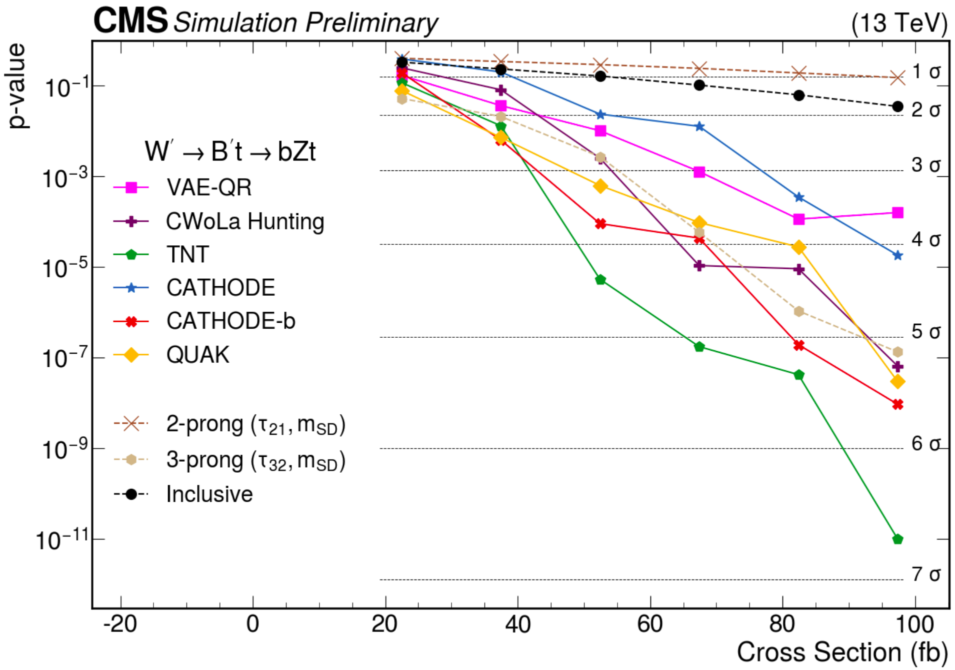
Traditional substructure cuts enhance sensitivity for a specific model, but not others

Sensitivity

2 Pronged Signal



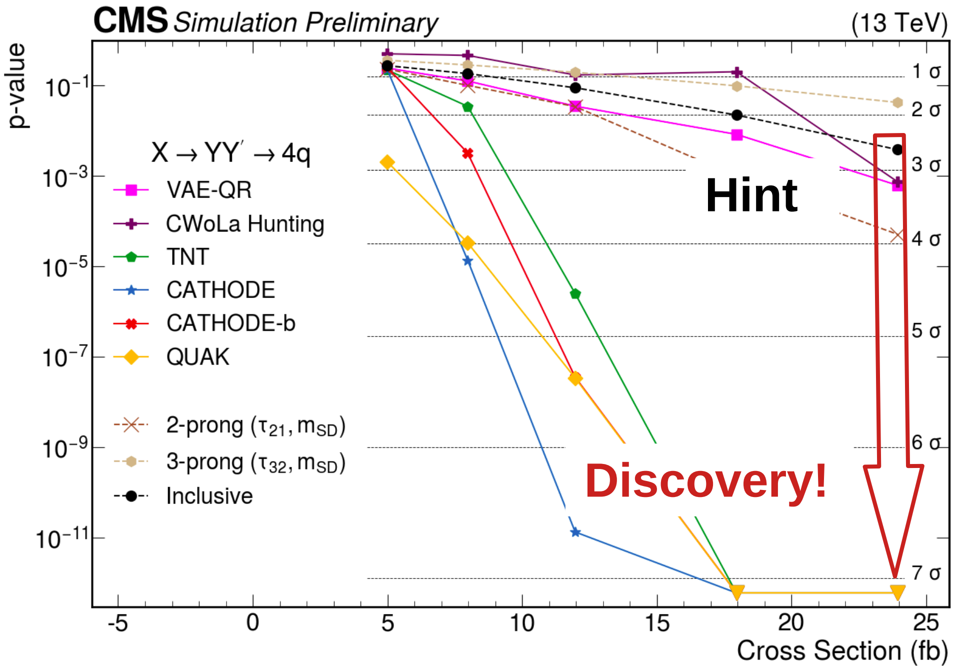
3 Pronged Signal



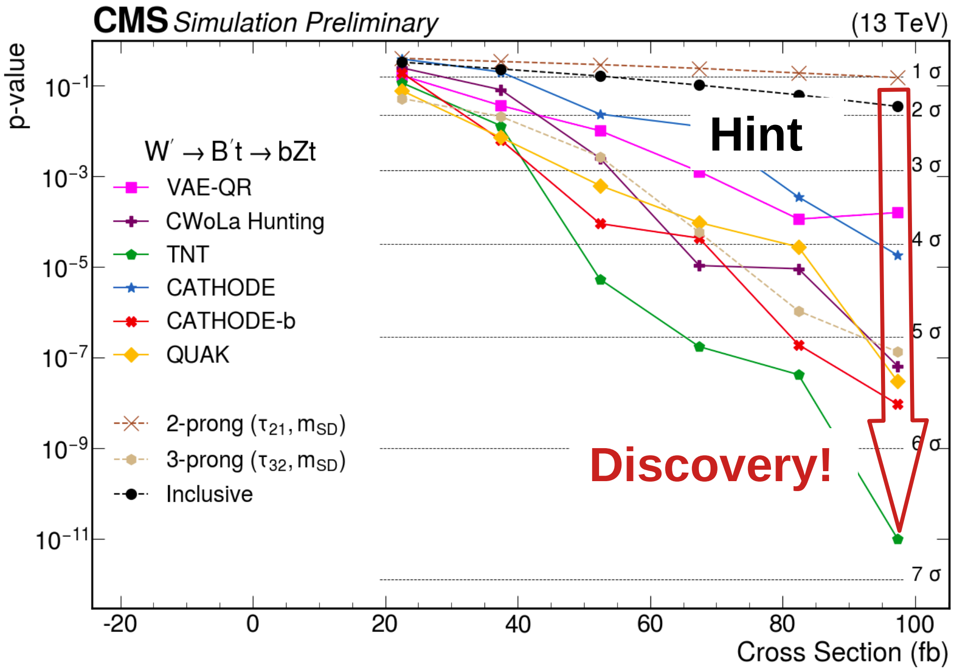
Anomaly detection enhances sensitivity for many models at once!

Sensitivity

2 Pronged Signal



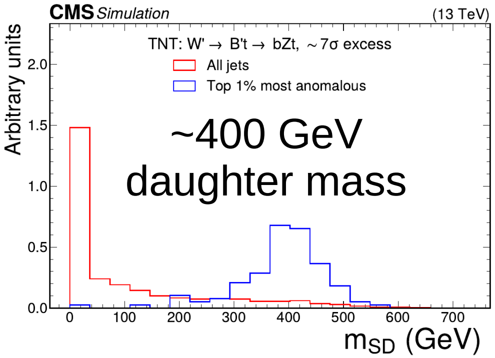
3 Pronged Signal

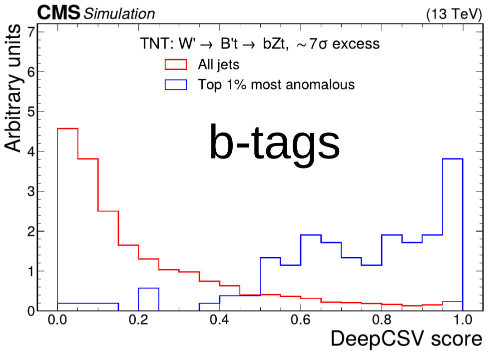


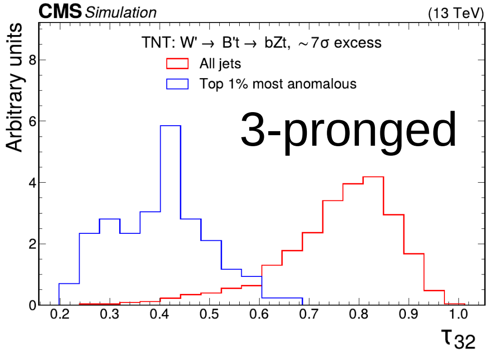
Anomaly detection enhances sensitivity for many models at once!

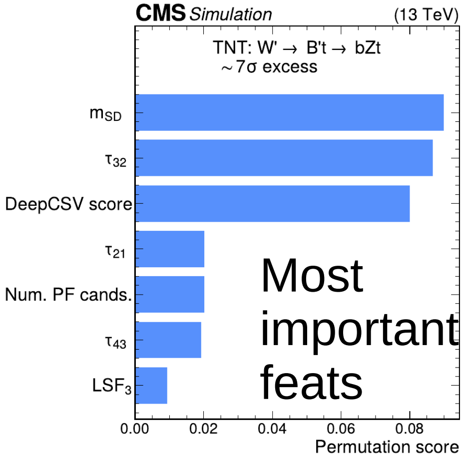
What if you see an excess?

Investigate features of most anomalous events!









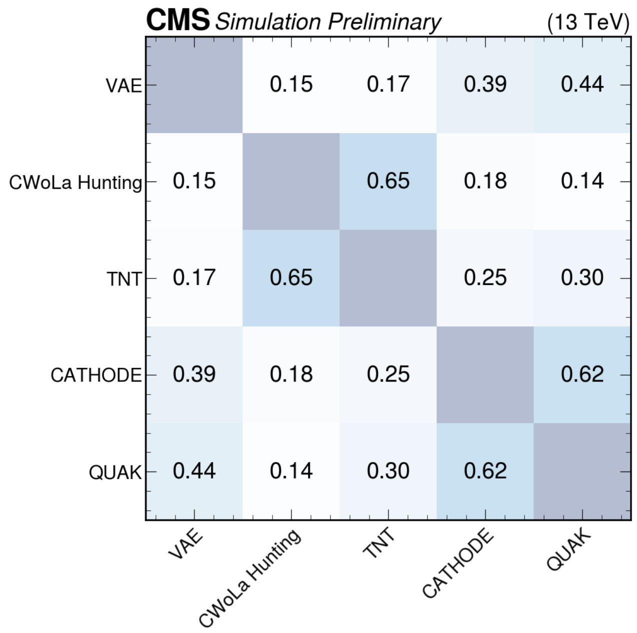
✔ Matches characteristics of injected signal

New plots from journal version

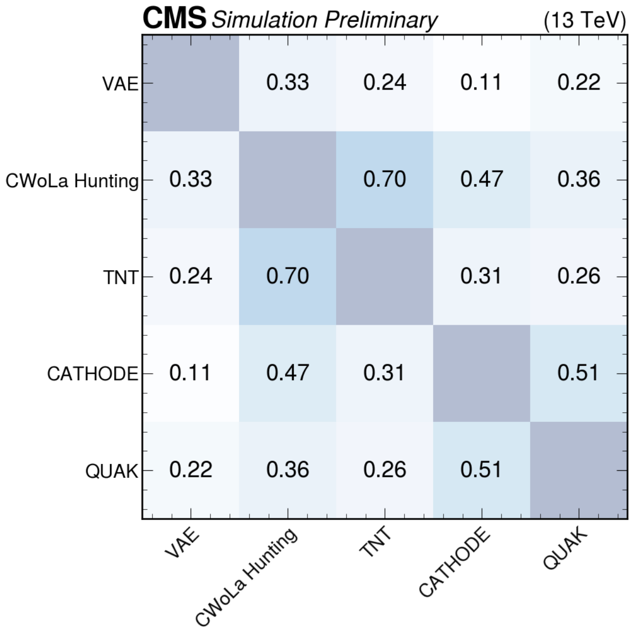
Complementary

CMS-NOTE -2023-013

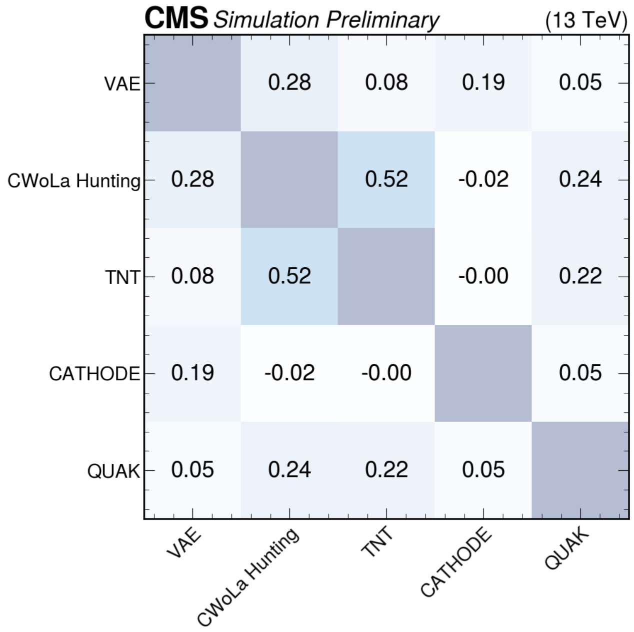
X→ YY → qq qq



W’→ B’t → bqq bqq



QCD Bkg.



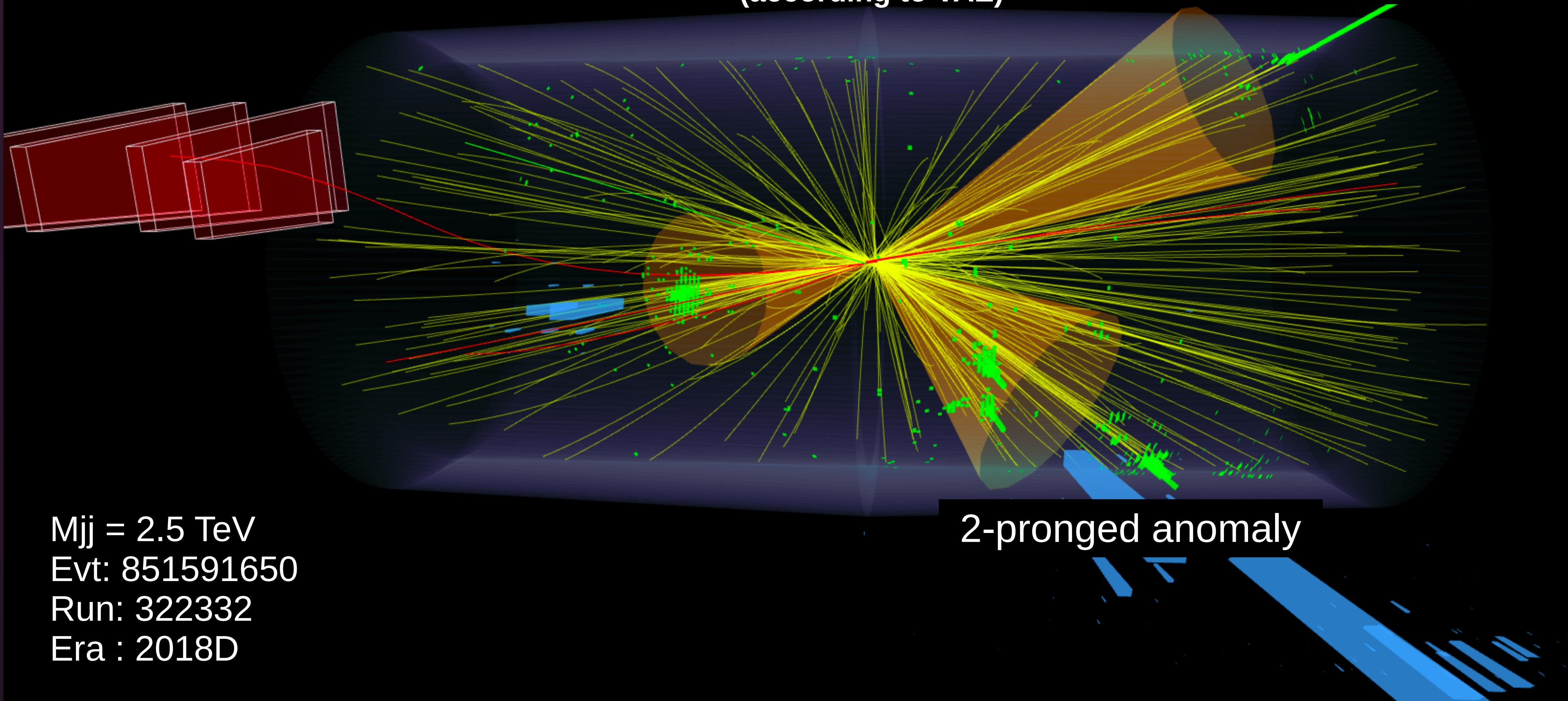
- Compute correlation coefficients between different anomaly scores
- Complementary approaches lead to relatively low correlations!

Steps to Unblinding

- ✔ No method creates artificial excesses in MC
- ✔ Can successfully find anomalies in MC
- ✔ Can characterize anomalies if found
- ✔ Apply to data $|\Delta\eta|$ sideband $\rightarrow$ no excesses

Time to apply to unblind!

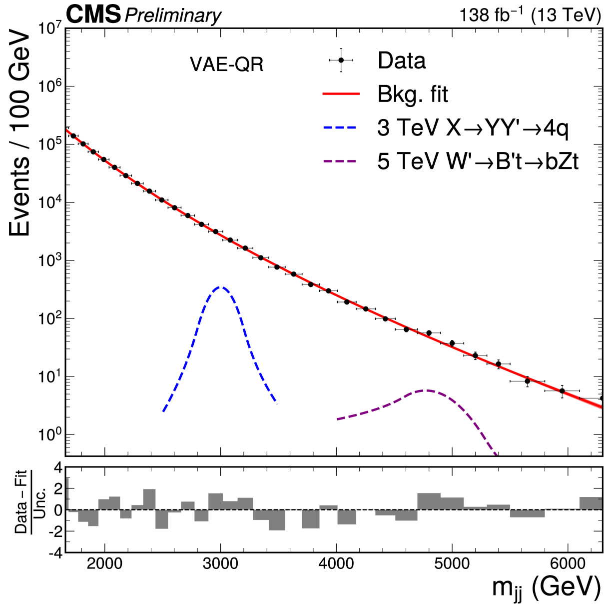
One of our most anomalous events!
(according to VAE)

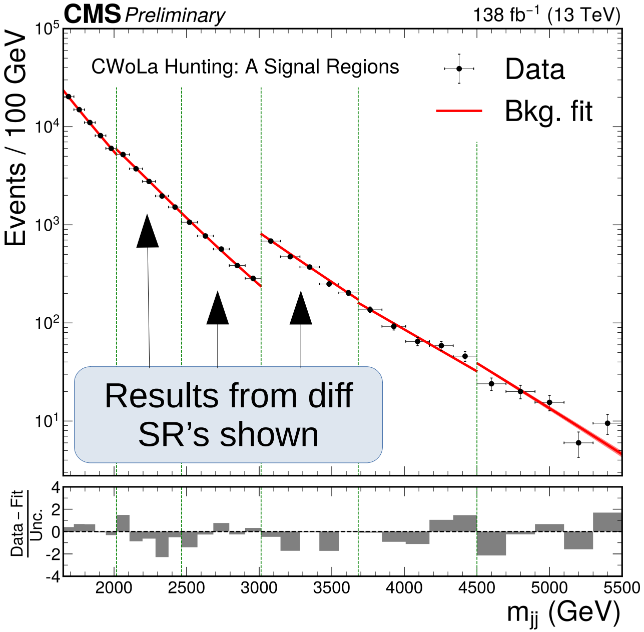


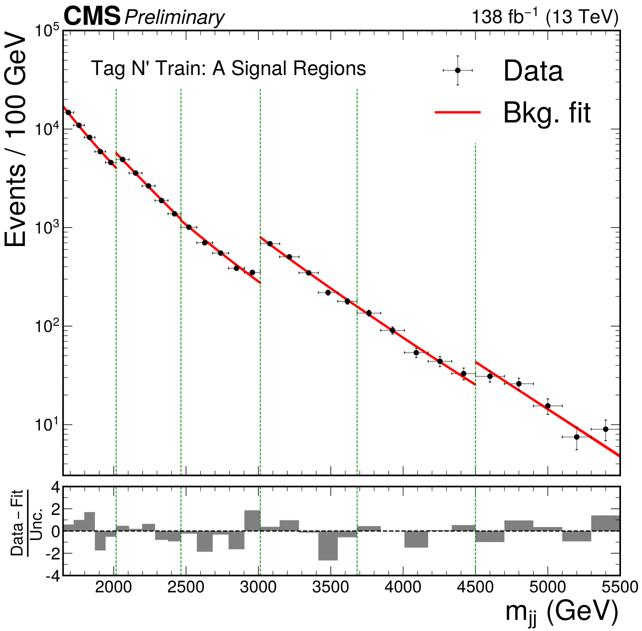
Mjj = 2.5 TeV
Evt: 851591650
Run: 322332
Era : 2018D

Search Results

No significant excesses from any method





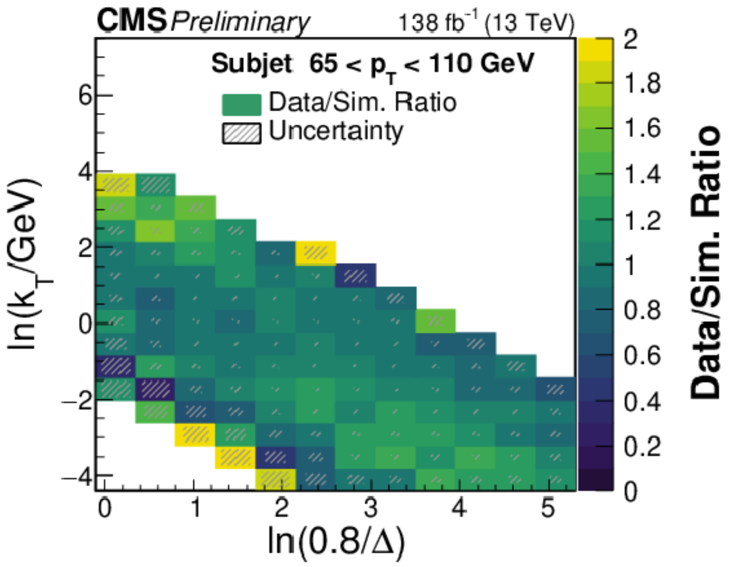


QUAK & CATHODE
results similar

What about uncertainties?

- Anomaly cut just like any other multivariate cut → no ‘special’ uncertainties
- Largest uncertainty is from MC **modeling of jet substructure**
  - Developed **new** data-driven correction + uncertainty for modeling high prong jets!

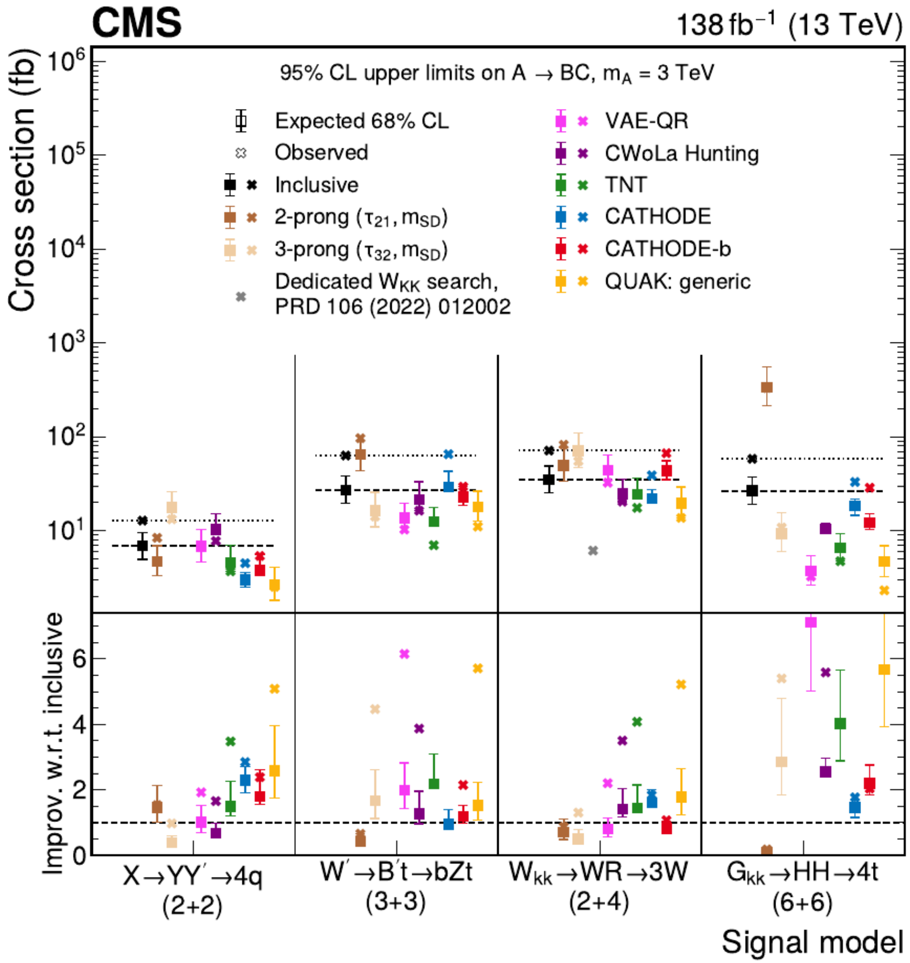
Data/MC Lund Jet Plane Correction
CMS-JME-23-001



Details in Backup

Limits

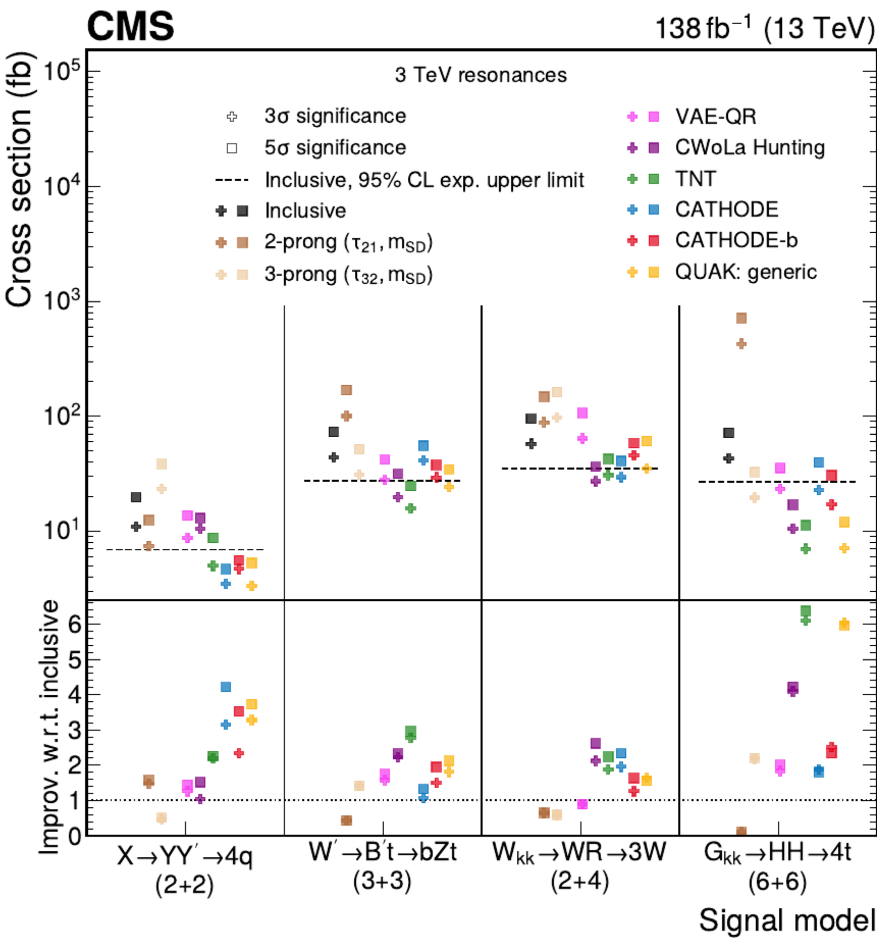
- Compute limits on benchmark from all **anomaly methods** on variety of signal models
  - Compare against **inclusive** & traditional **model-specific** approaches
  - First-ever limits on several models!
- Anomaly detection improves limits by ~**2-6x**!
  - Does not reach sensitivity of **dedicated search**



Very different sig. models!

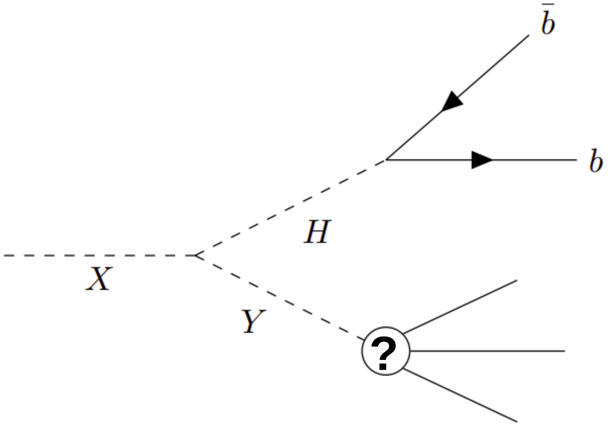
Discovery Sensitivity

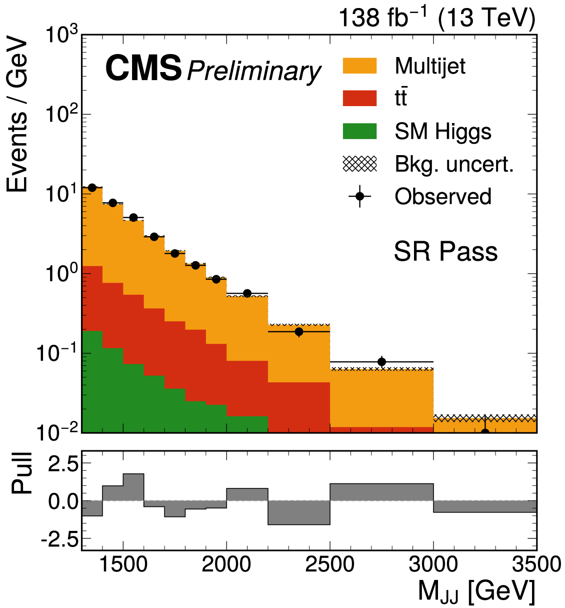
- '**Discovery focused**' performance metric
- "What cross section do I need to get an expected 3σ/5σ excess?"
- **Anomaly methods** improve sensitivity by ~**3-6x** compared to inclusive

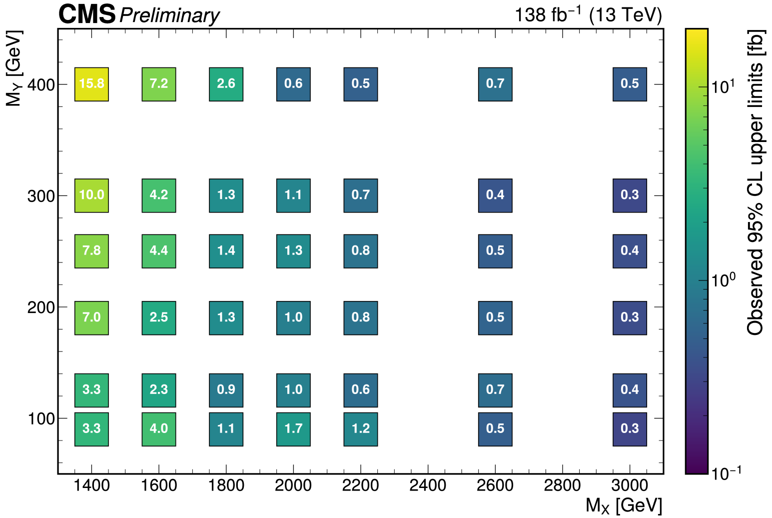


New: X→HY Search

CMS-PAS-B2G-24-015







- Re-using an AE from the dijet search
- Limits on Y→WW and Y→bqq

Conclusions

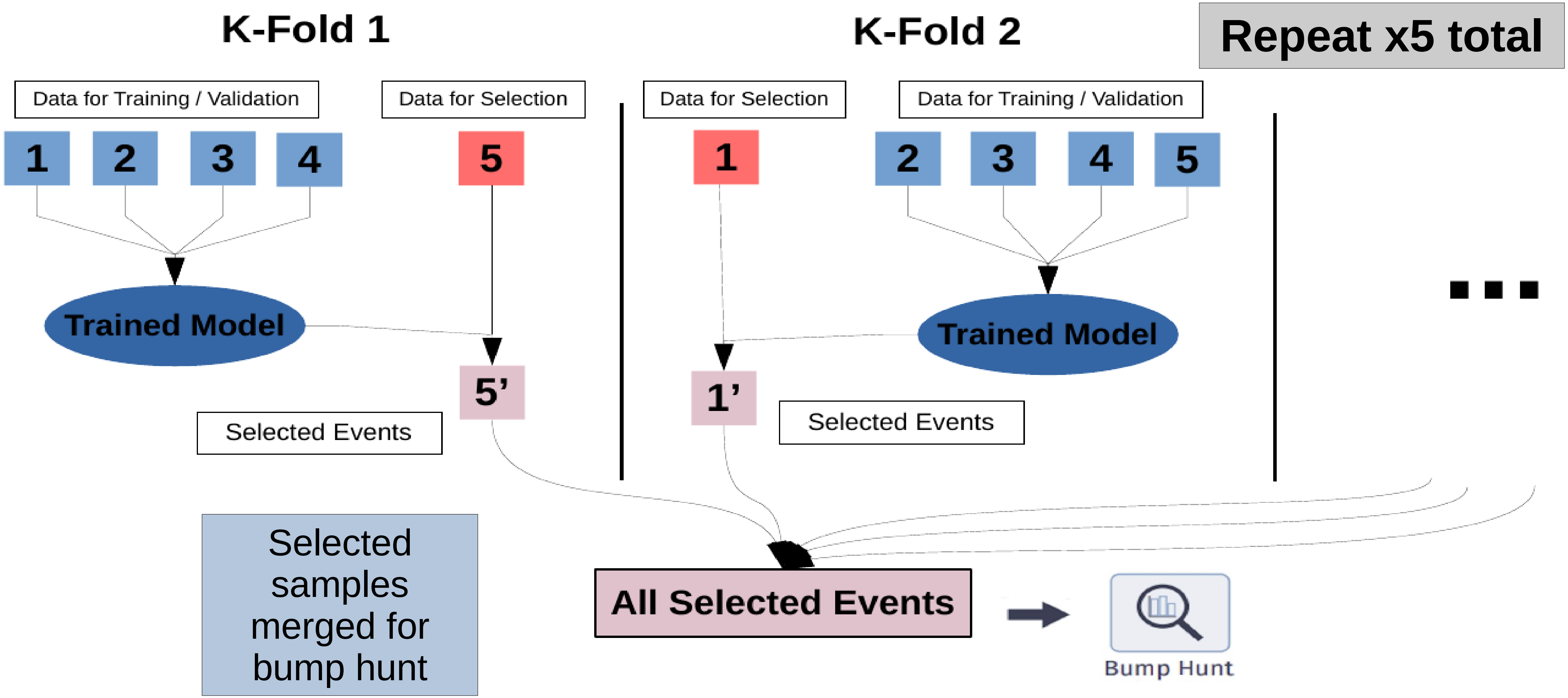
- **First** usage of **anomaly** **detection** in CMS
  - Dijet resonance search with anomalous substructure
- Demonstrated sensitivity to **broad range of signals**
- Hopefully more searches to follow!

Conclusions

- **First** usage of **anomaly detection** in CMS
  - Dijet resonance search with anomalous substructure
- Demonstrated sensitivity to **broad range of signals**
- Hopefully more searches to follow!
- **Points I am interested to discuss!**
  - What should be reported for an anomaly detection search the case of null results? (ie do we **need** limits?)
  - Is reinterpretation of weakly supervised searches impossible?
  - How can we increase adoption of AD in our collaborations?

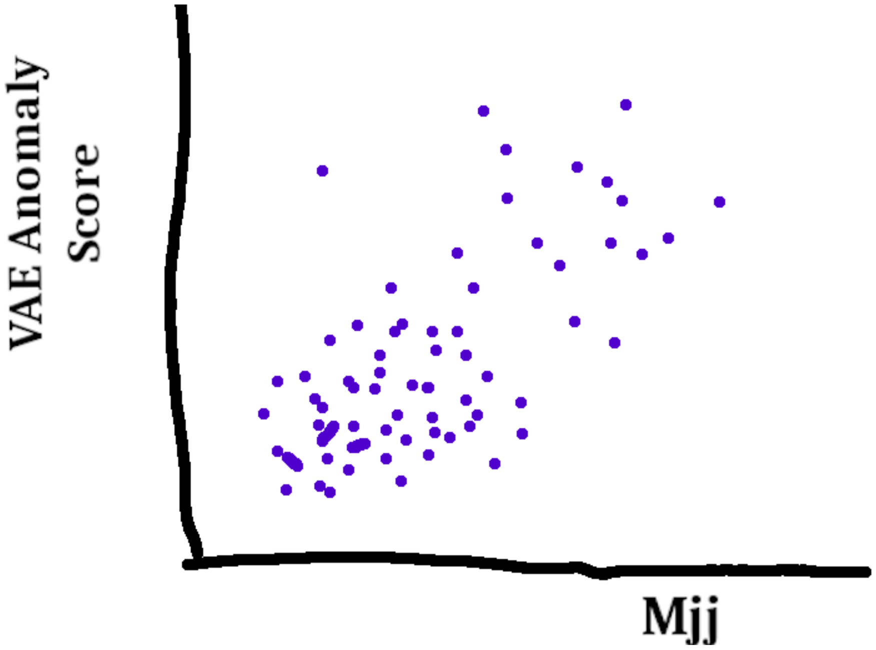
Backup

Cross Validation



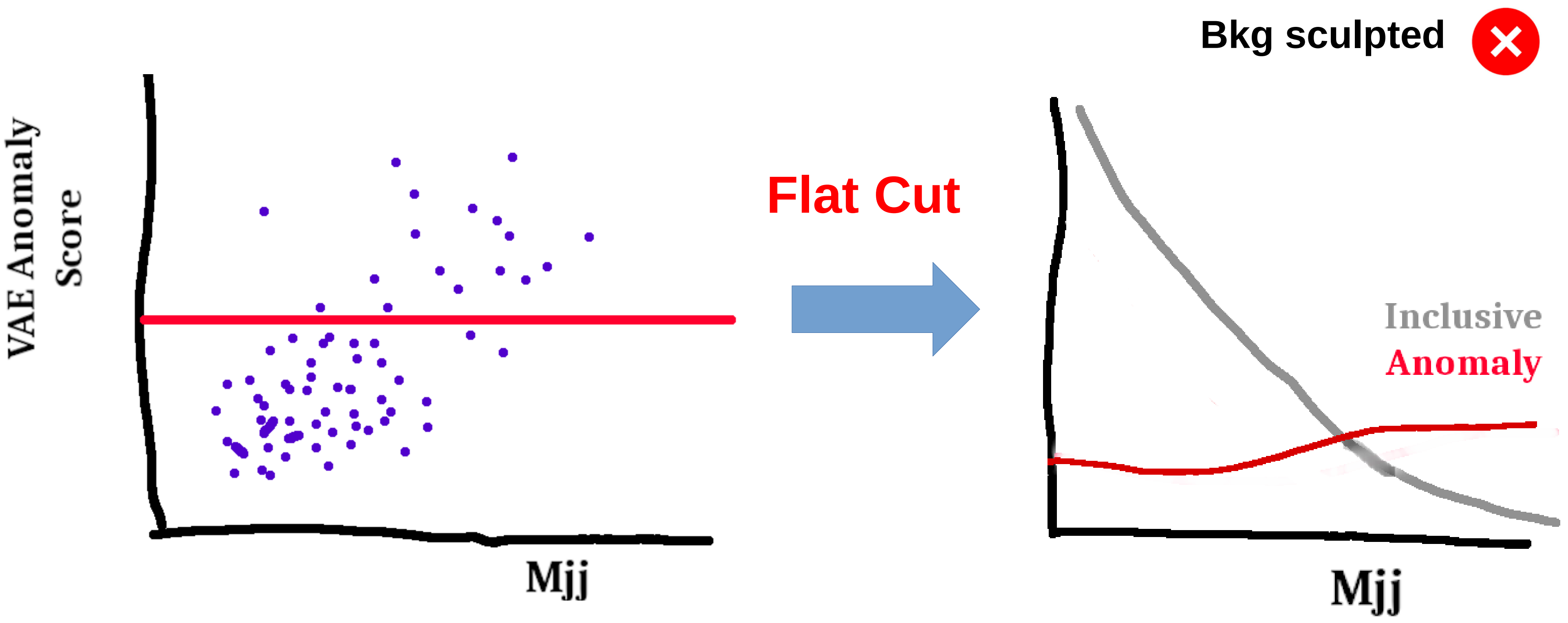
*Weakly supervised methods use additional layer of cross val for stability (see backup)

Decorrelate with Mjj



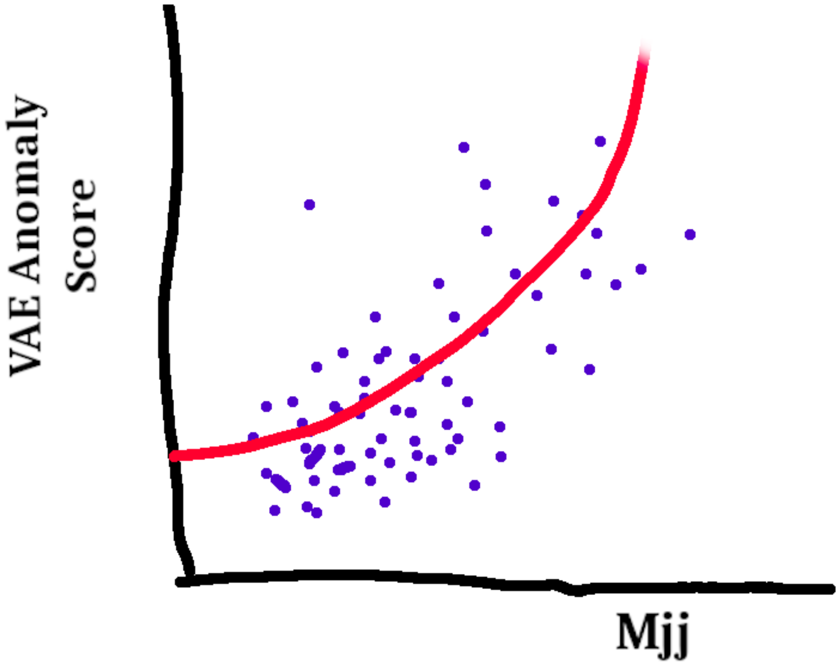
High Mjj events are rarer →
higher anomaly score

Decorrelate with Mjj



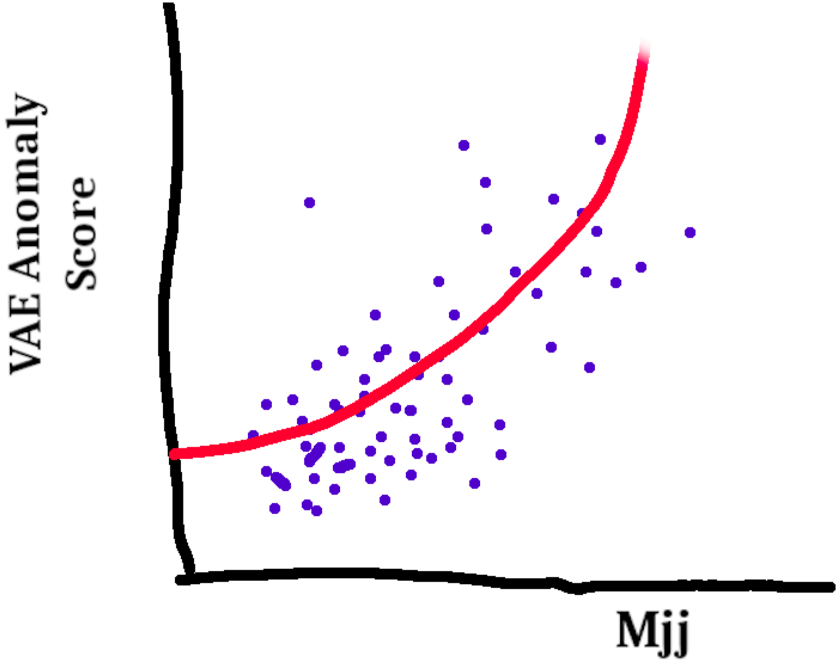
Decorrelate with Mjj

‘Quantile Regression’ (QR)



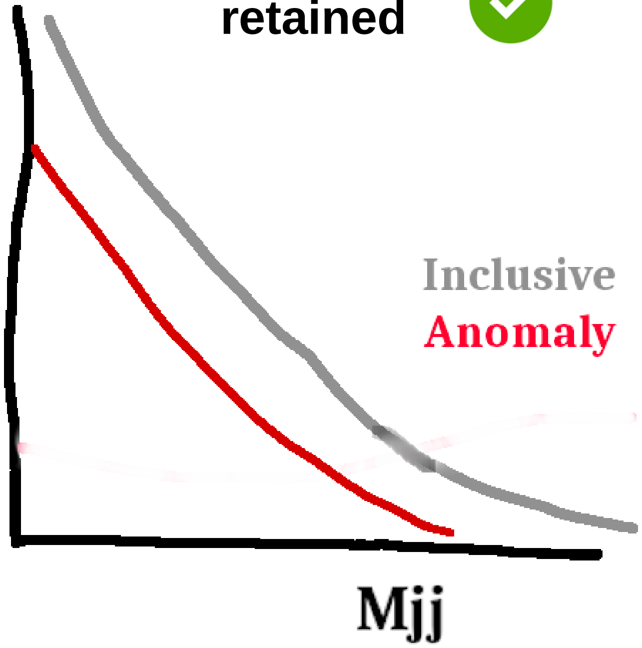
Adjust cut to have a constant efficiency vs Mjj

Decorrelate with Mjj



Cut with Flat Eff.

Bkg shape retained



Efficiency & Uncertainties

To set a limit on a **specific signal model** proceed as usual

- Signal MC + anomaly detector → efficiency
- One **complication** for weakly supervised methods : **signal eff depends on signal xsec**!
  - Dedicated methods to calibrate this (requires training lots & lots of NN’s), see backup