New developments in anomaly detection and model independent searches for new physics with machine learning

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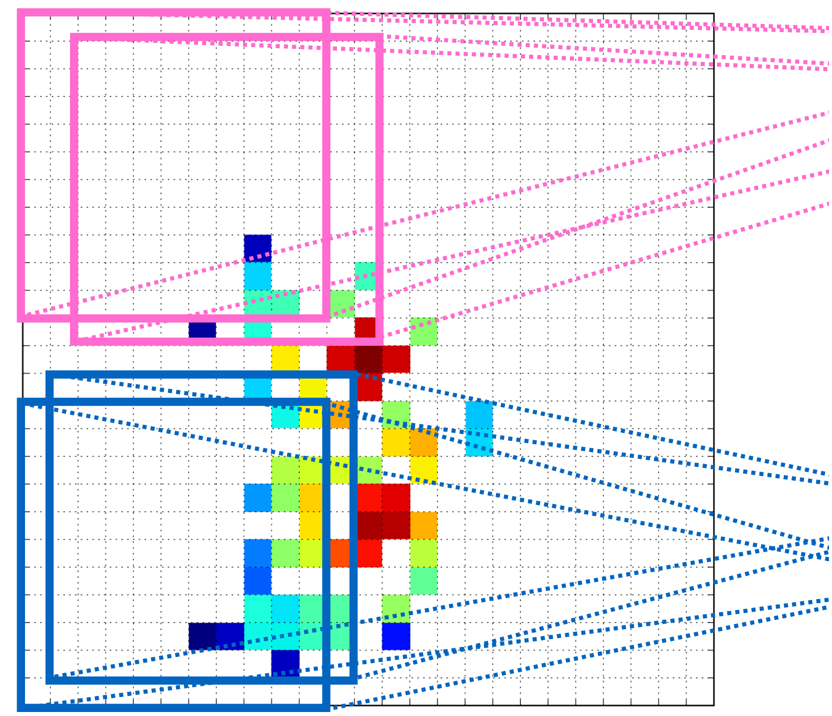

LHCP
May 2022

Questions in particle physics

Theoretical and **experimental** questions motivate a deep exploration **of the fundamental structure of nature**

Dark matter

Hierarchy problem

Strong CP

Dark energy

Flavor puzzles

Baryogengesis

We have performed thousands of hypothesis tests & have no significant evidence for physics beyond the Standard Model

Three possibilities

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(2) Patience! (new physics is rare)

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This is what keeps me up at night!

(3) We are not looking in the right place

The Path Forward

There are two complementary paths forward:

(1) Identify new, specific, well-motivated places to look

This is still an incredibly important direction and has resulted in new directions like long-lived particle searches

(2) Look in many places all at once

Focus of today's talk!

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The Path Forward

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Focus of today's talk!

There is no free lunch: for any particular model, (2) will be less sensitive than (1). We need both search paradigms!

Why not just look everywhere?

Why not just look everywhere?

(a) There are a lot of places to look

	$A \to BC$	$B=\mathrm{SM}$									$B=\mathrm{BSM}$
		e	μ	τ	q/g	b	t	γ	Z/W	H	
$C=\mathrm{SM}$	e	Z'	$\not{R}$	$\not{R}$	LQ	LQ	LQ	L^*	L^*	L^*	
	μ		Z'	$\not{R}$	LQ	LQ	LQ	L^*	L^*	L^*	
	τ			Z'	LQ	LQ	LQ	L^*	L^*	L^*	
	q/g				Z'	W'	T'	Q^*	Q^*	Q'	
	b					Z'	W'	Q^*	Q^*	B'	Many
	t						Z'	Q^*	T'	T'	
	γ							H	H	Z_{KK}	
	Z/W								H	$H^\pm/A$	
	H									H	
$C=\mathrm{BSM}$		Consider just the di-object search for resonant A → B C									Many

J. Kim, K. Kong, BN, D. Whiteson, *JHEP 04 (2020) 30*, 1907.06659

Why not just look everywhere?

(a) There are a lot of places to look

		e	μ	τ	q/g	b	t	γ	Z/W	H	BSM $\to$ SM$_1$ $\times$ SM$_1$				BSM $\to$ SM$_1$ $\times$ SM$_2$				BSM $\to$ complex			
											q/g	γ/π^0's	b	$\cdots$	tZ/H	bH		$\cdots$	$\tau qq'$	eqq'	$\mu qq'$	$\cdots$
	e	[37, 38]	[39, 40]	[39]	∅	∅	∅	[41]	[42]	∅	∅	∅	∅		∅	∅	∅		∅	[43, 44]	∅	
	μ		[37, 38]	[39]	∅	∅	∅	[41]	[42]	∅	∅	∅	∅		∅	∅	∅		∅	∅	[43, 44]	
	τ			[45, 46]	∅	[47]	∅	∅	∅	∅	∅	∅	∅		∅	∅	∅		[48, 49]	∅	∅	
	q/g				[29, 30, 50, 51]	[52]	∅	[53, 54]	[55]	∅	∅	∅	∅		∅	∅	∅		∅	∅	∅	
	b					[29, 52, 56]	[57]	[54]	[58]	[59]	∅	∅	∅		[60]	∅	∅		∅	∅	∅	
	t						[61]	∅	[62]	[63]	∅	∅	∅		[64]	[60]	∅		∅	∅	∅	
	γ							[65, 66]	[67–69]	[68, 70]	∅	∅	∅		∅	∅	∅		∅	∅	∅	
	Z/W								[71]	[71]	∅	∅	∅		∅	∅	∅		∅	∅	∅	
	H									[72, 73]	[74]	∅	∅		∅	∅	∅		∅	∅	∅	
BSM $\to$ SM$_1$ $\times$ SM$_1$	q/g										∅	∅	∅		∅	∅	∅		∅	∅	∅	
	γ/π^0's											[75]	∅		∅	∅	∅		∅	∅	∅	
	b												[76, 77]		∅	∅	∅		∅	∅	∅	
	⋮																					
	⋮																					
BSM $\to$ SM$_1$ $\times$ SM$_2$	tZ/H																					
	bH																					
	⋮																					
	⋮																					
BSM $\to$ complex	$\tau qq'$																					
	eqq'																					
	$\mu qq'$																					
	⋮																					
	⋮																					

Consider just the di-object search for resonant A → B C

…most cases are uncovered!

J. Kim, K. Kong, BN, D. Whiteson, *JHEP 04 (2020) 30*, 1907.06659

Why not just look everywhere?

(a) There are a lot of places to look

(b) You would find a lot of excesses

Best to cast a wide net in a smart way !

Outline: Casting a Wide **Net(work)**

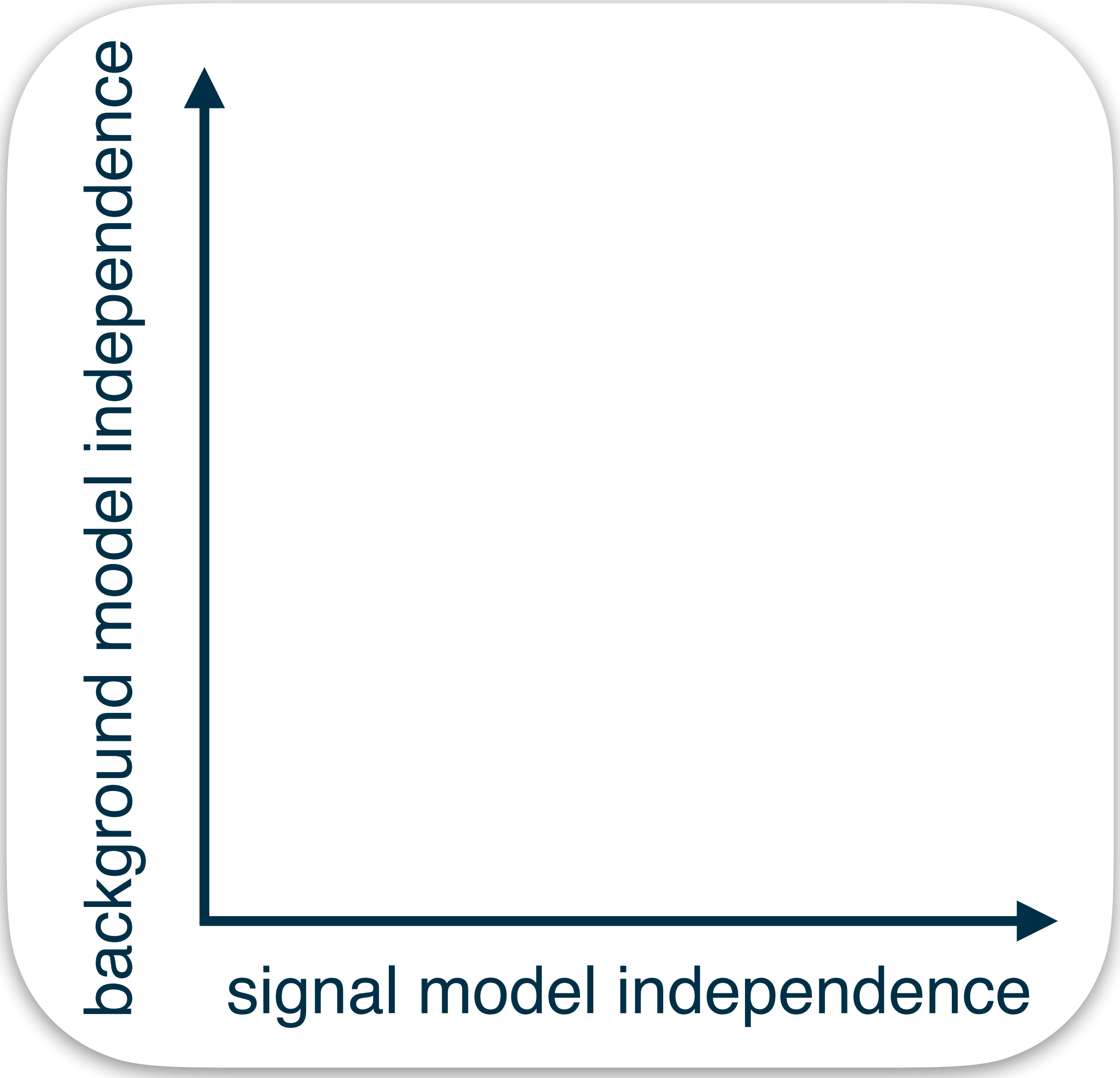
1. The landscape of model dependence
2. Overview of new ideas
3. Resonant anomaly detection
4. The future (and why you should be part of it!)

Anomaly **in this talk means unanticipated new physics (!)**

Landscape of Model Dependence

Suppose you want to search for a new signal process

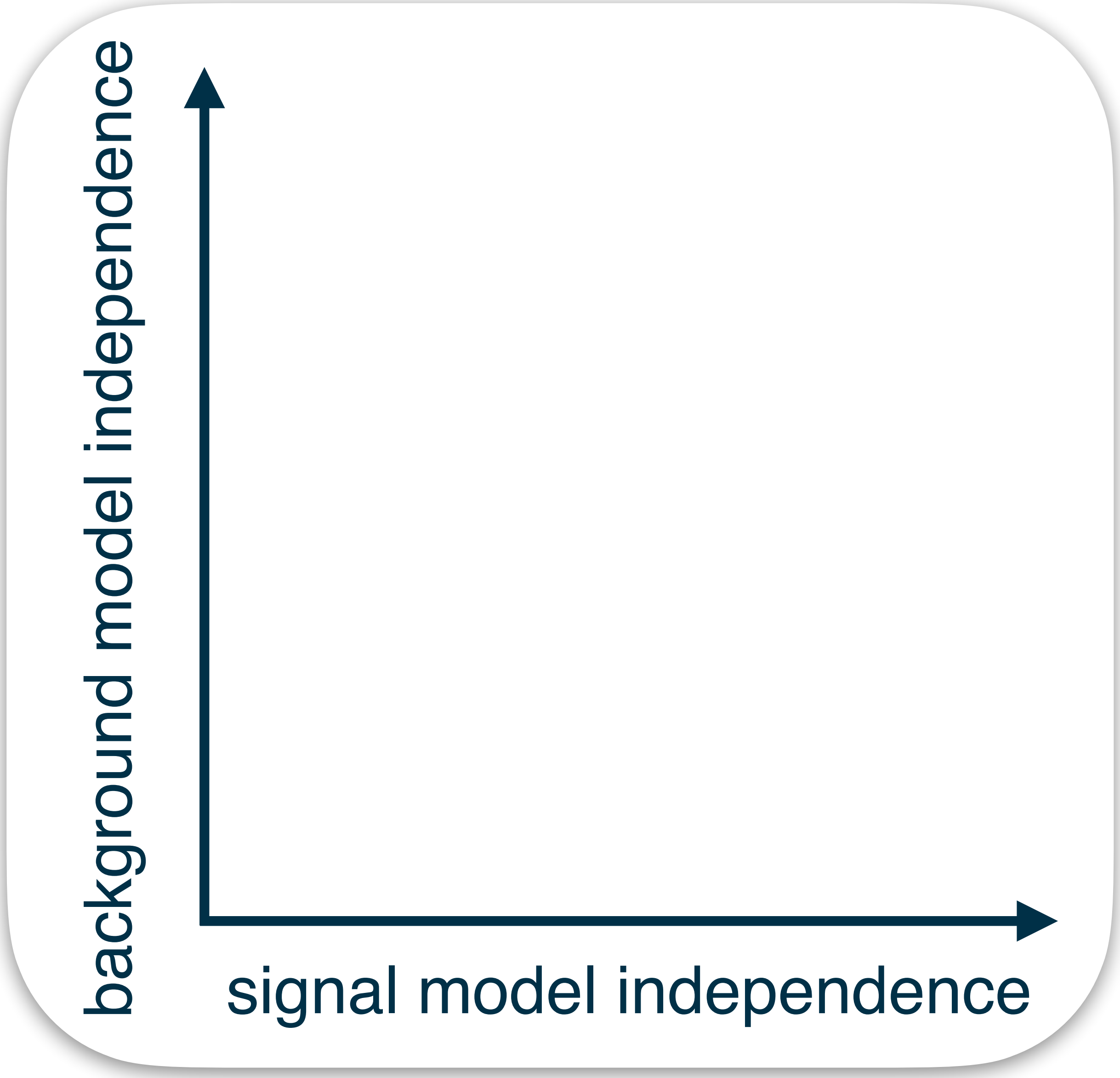
Landscape of Model Dependence



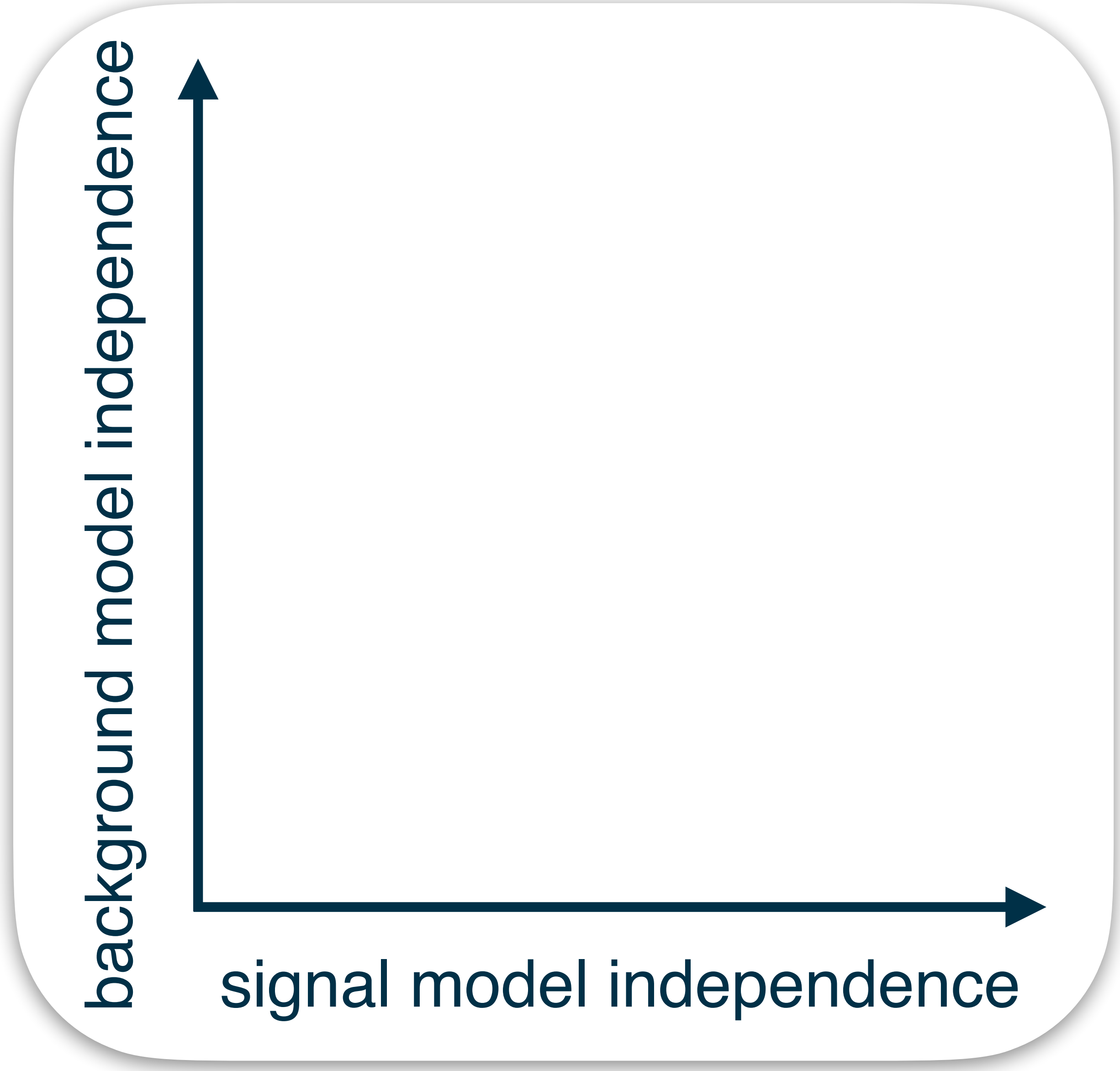
Signal sensitivity

Suppose you want to search for a new signal process

Landscape of Model Dependence



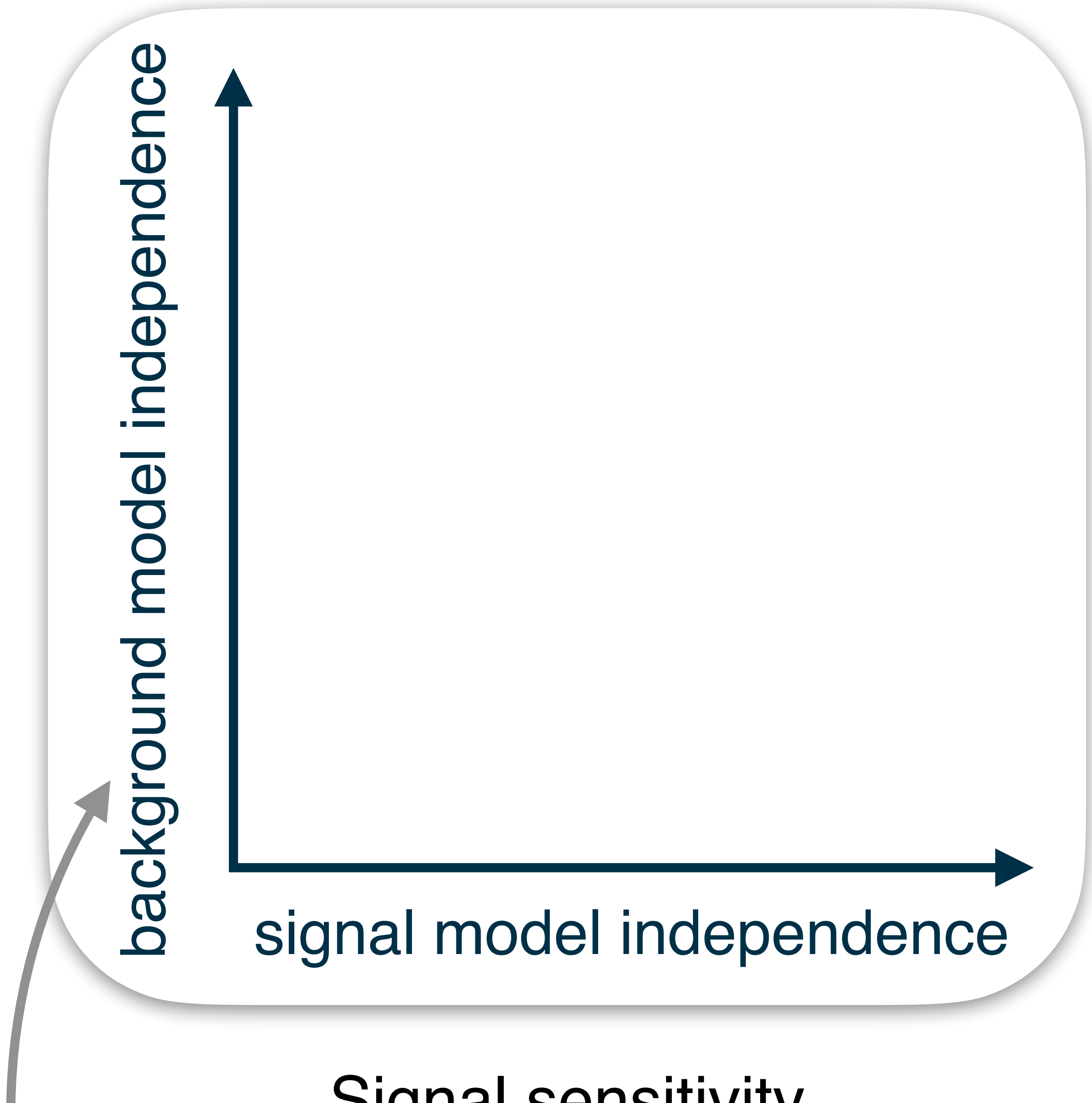
Signal sensitivity



Background specificity

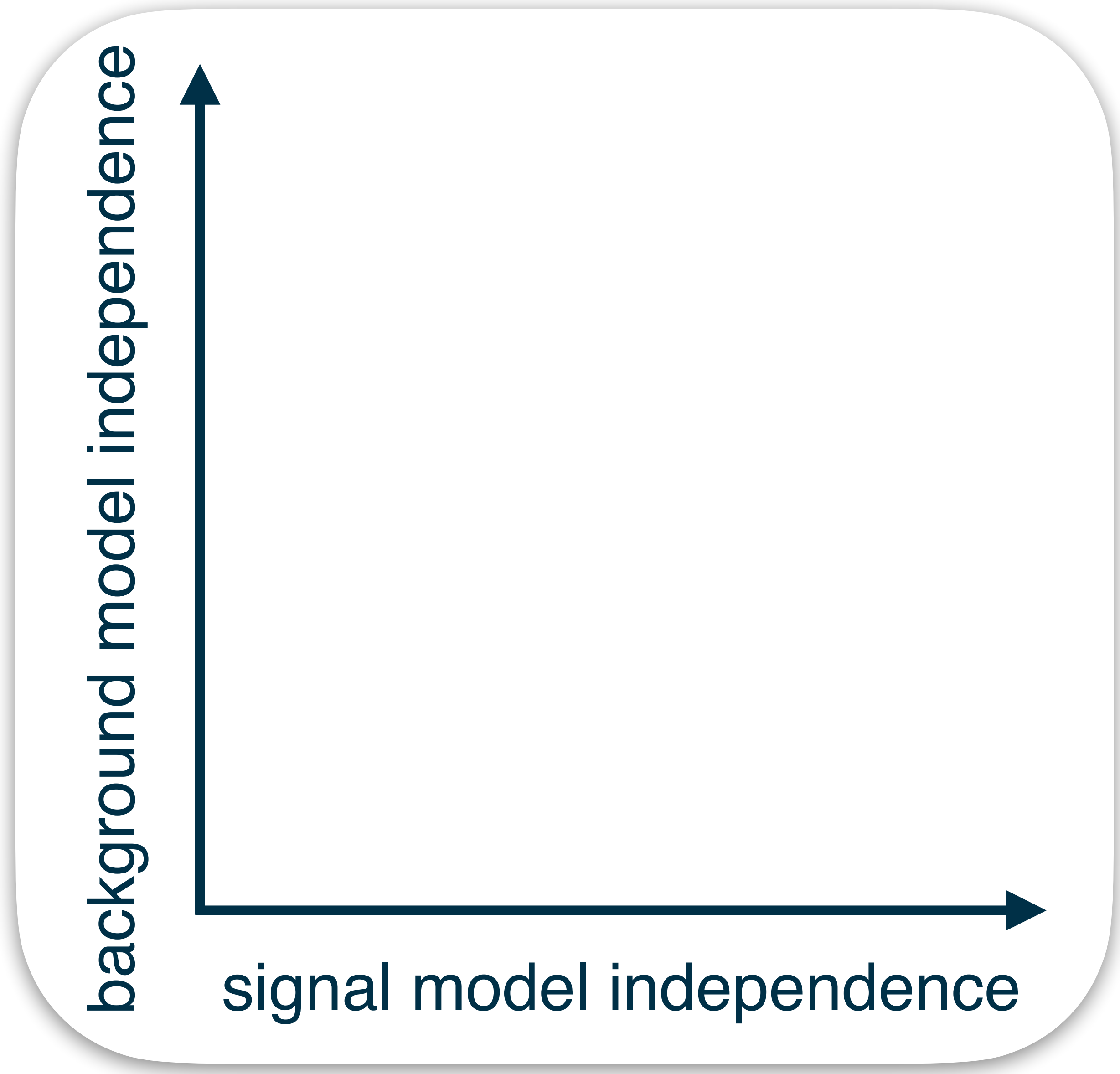
Suppose you want to search for a new signal process

Landscape of Model Dependence



Standard Model

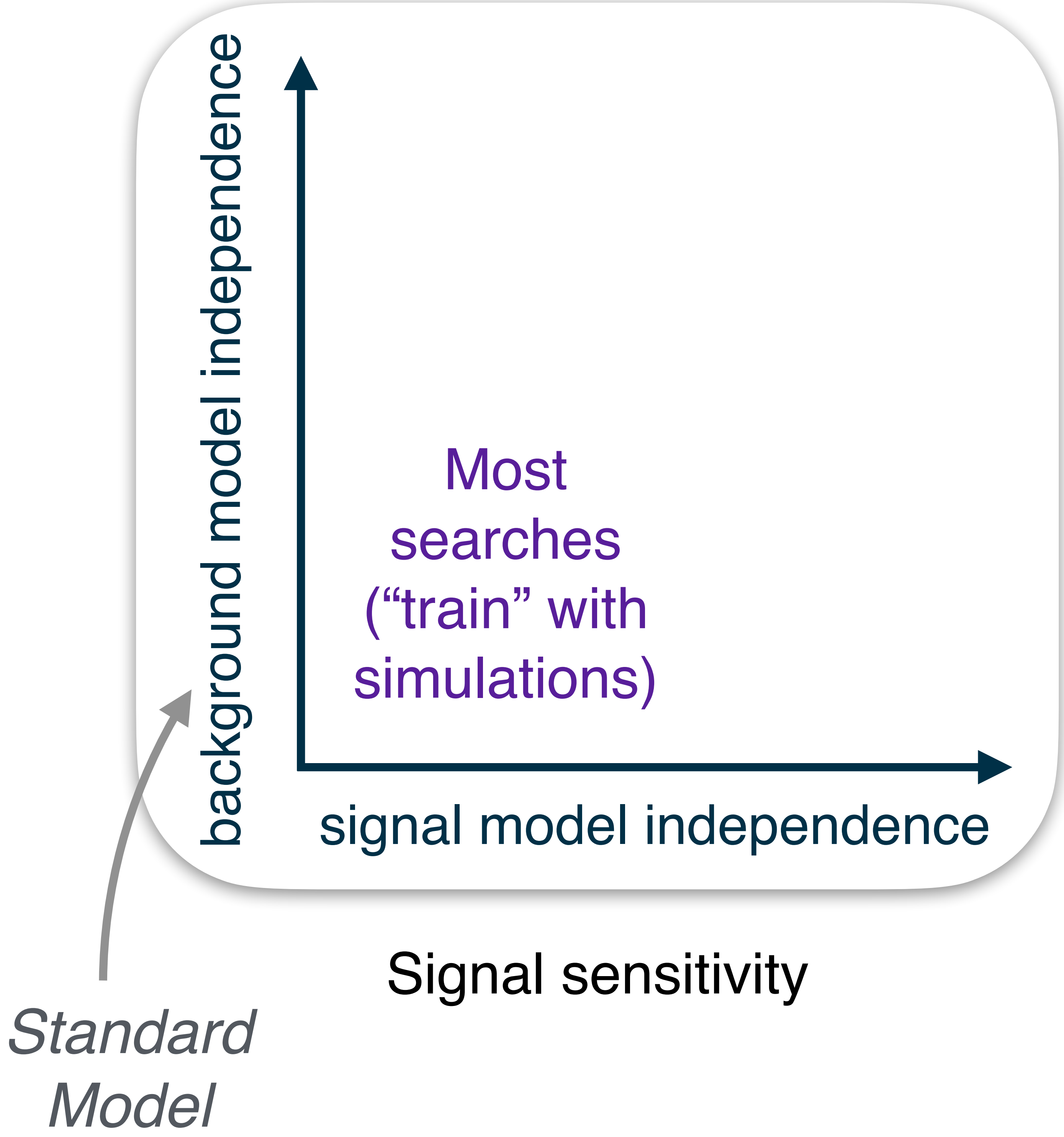
Signal sensitivity



Background specificity

G. Karagiorgi, G. Kasieczka, S. Kravitz, BN, D. Shih,
Nature Reviews Physics (2022), 2112.03769

Landscape of Model Dependence

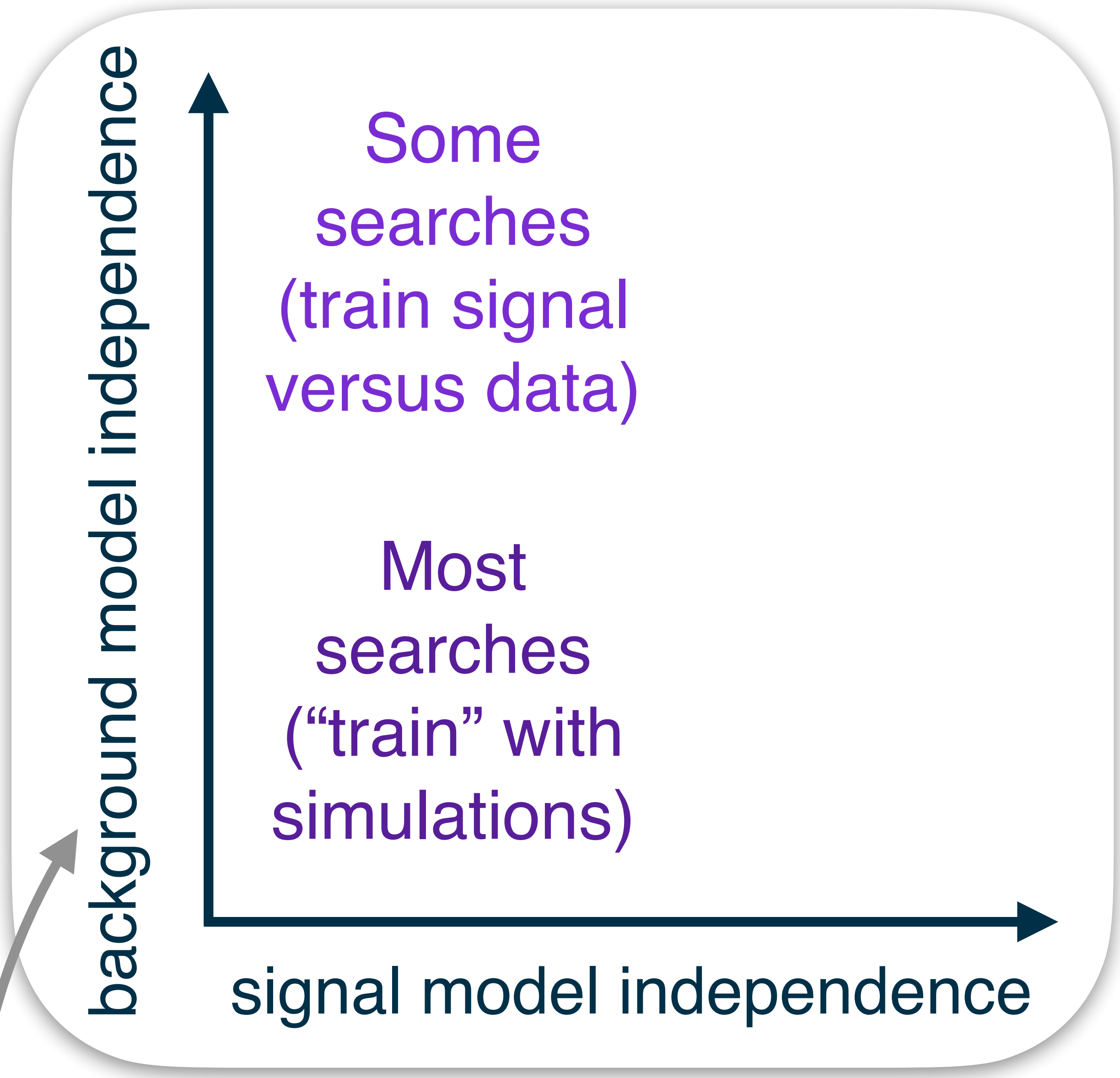


Signal sensitivity

> 99% of searches at the LHC and elsewhere are of this type

"train" is in quotes because such searches may or may not use machine learning

Landscape of Model Dependence



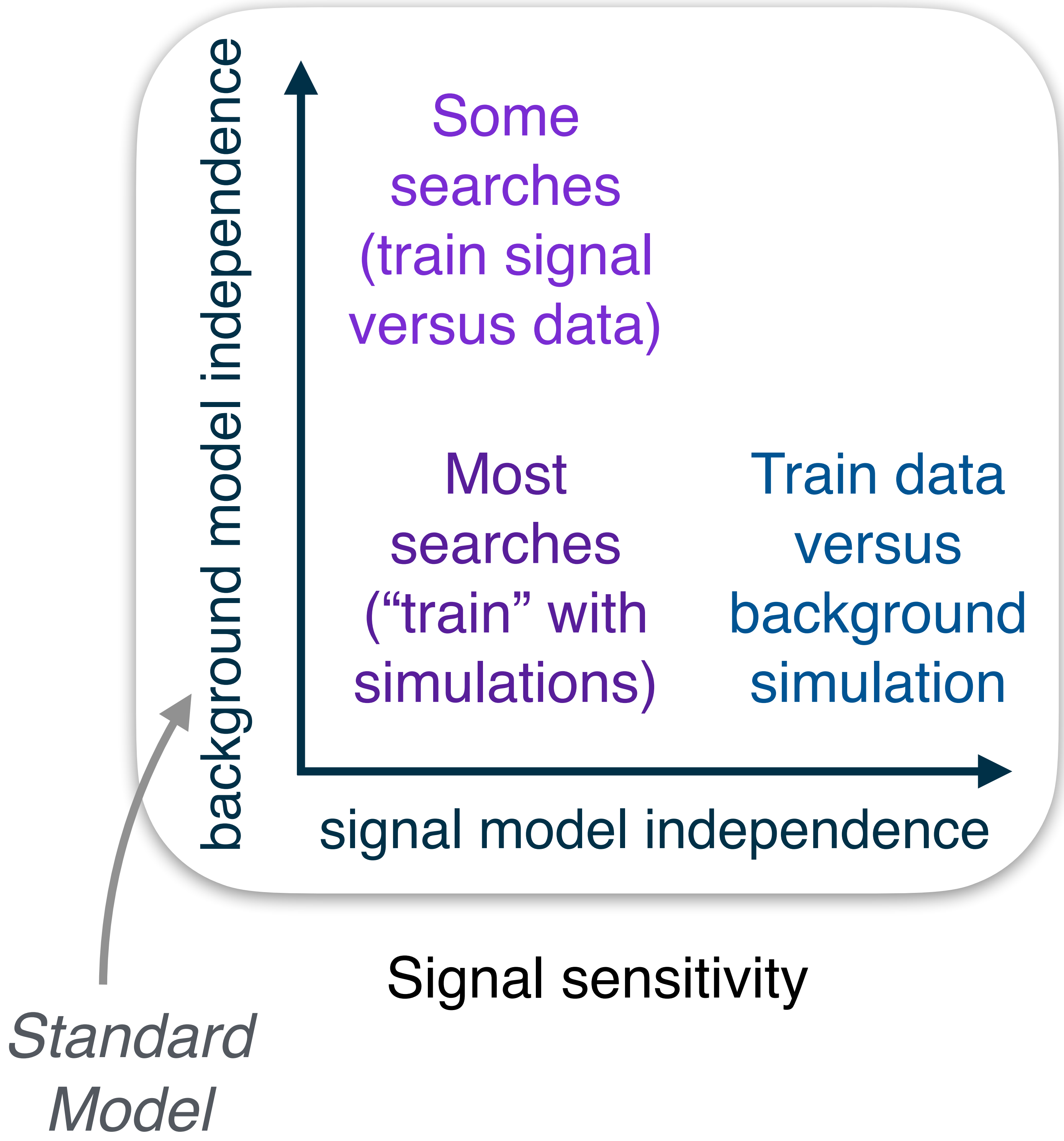
Signal sensitivity

Standard Model

e.g. signal simulation versus calibration data

standard approach when signal is clean and well-understood, but background is not, e.g. $h \to \gamma\gamma$

Landscape of Model Dependence

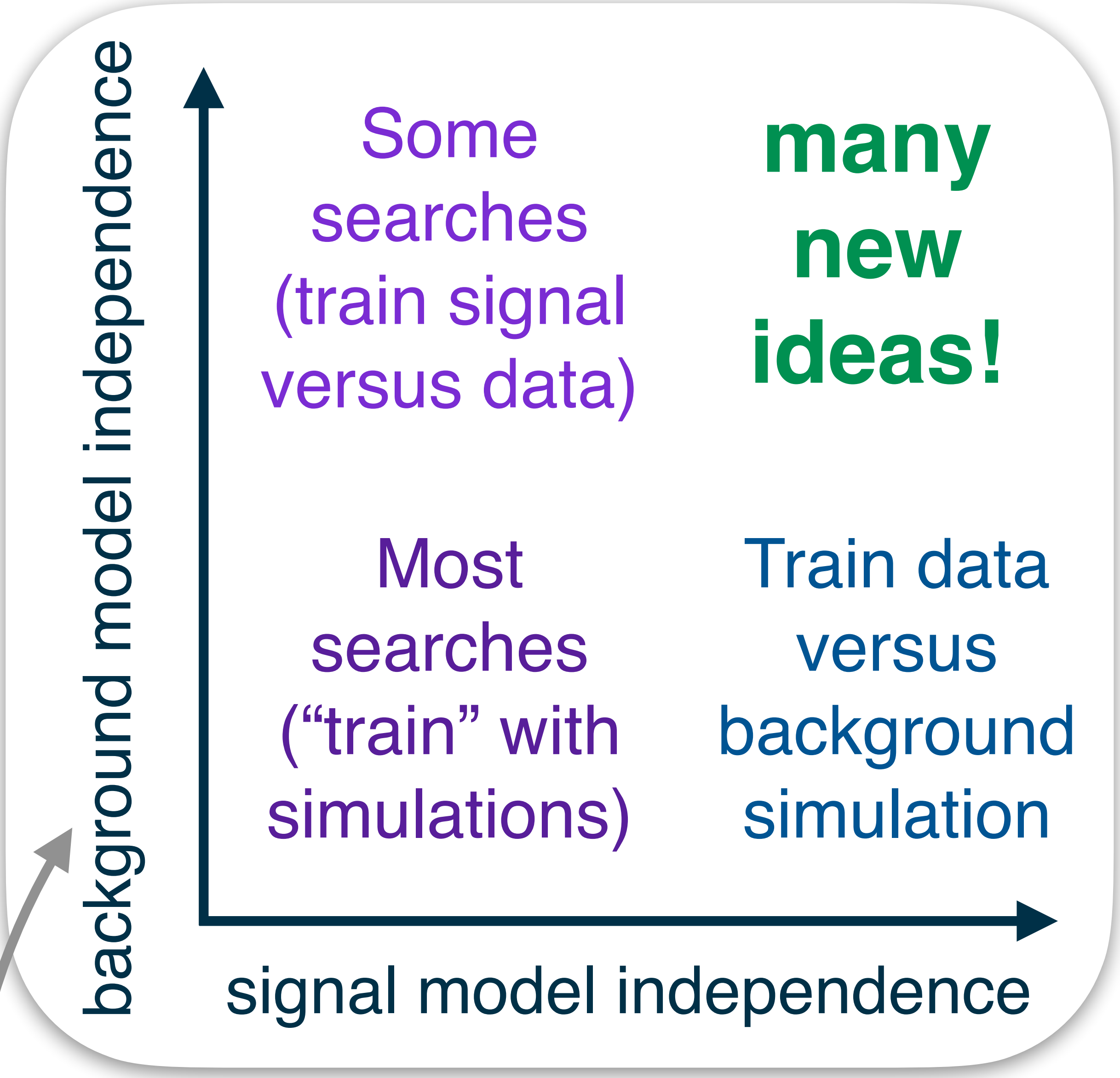


Signal sensitivity

signal model *independent*
background model *dependent*

There is a history of these searches at the LHC, Tevatron, HERA, LEP

Landscape of Model Dependence



Signal sensitivity

Standard Model

There are many new ideas that make use of modern machine learning

The goal is to learn **directly from data**, injecting as little bias as possible

For a recent review, see G. Karagiorgi, G. Kasieczka, S. Kravitz, BN, D. Shih, Nature Reviews Physics (2022), 2112.03769

Overview of New Ideas

I like to categorize new ideas based on the core assumption about the BSM, which is intimately related to the technique ***supervision***

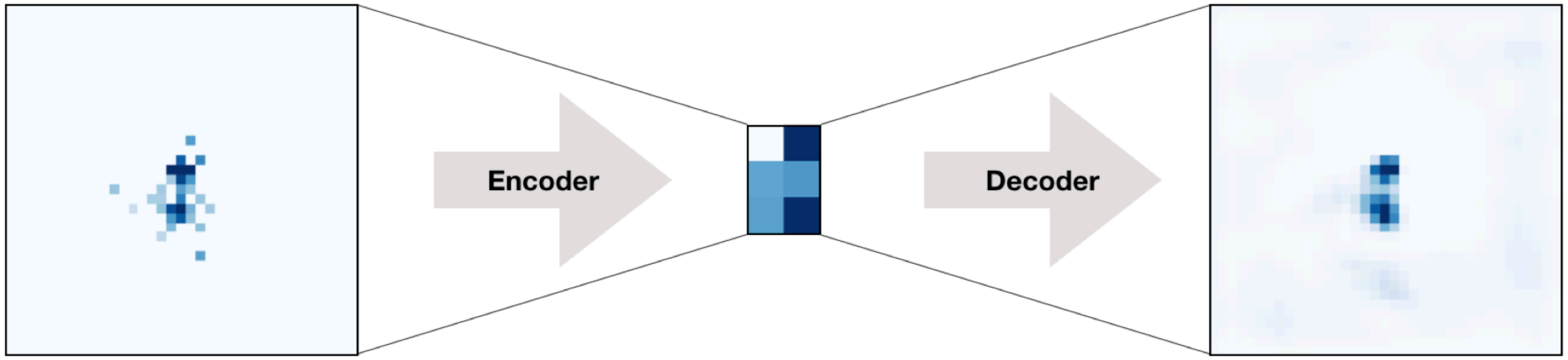
Unsupervised = no labels
Weakly-supervised = noisy labels
Semi-supervised = partial labels
Supervised = full label information

This is most searches. You simulate the signal (label = 1), simulate the background (label = 0) and "train" a classifier to distinguish the 1's from the 0's.

Unsupervised

Unsupervised = no labels

Typically, the goal of these methods is to look for events with **low *p(background)***



One strategy (autoencoders) is to try to compress events and then uncompress them. When x = uncompres(compress(x)), then x probably has low p(x).

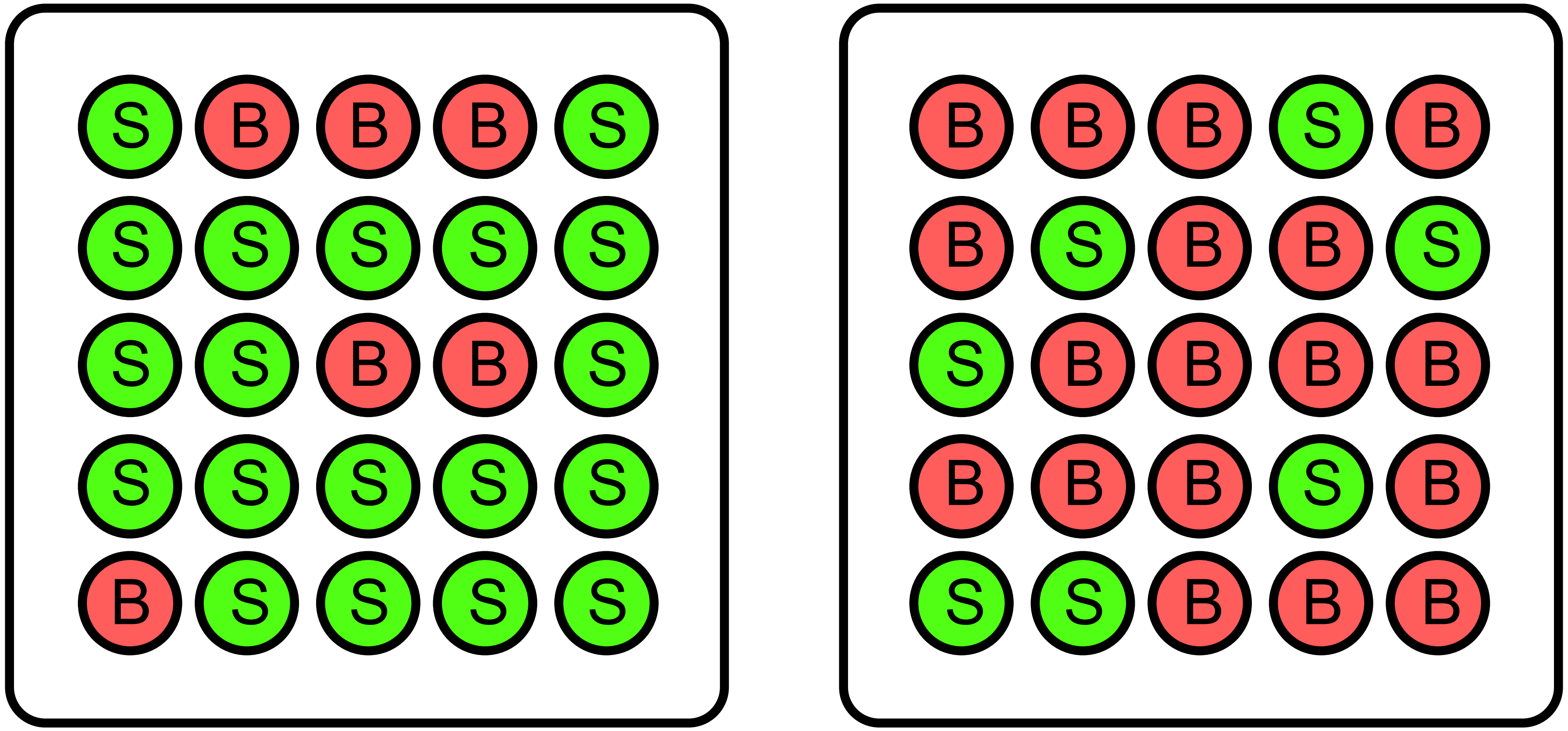
M. Farina, Y. Nakai, D. Shih, 1808.08992; T. Heimel, G. Kasieczka, T. Plehn, J. Thompson, 1808.08979; + many more

Weakly-supervised

Weakly-supervised = noisy labels

Typically, the goal of these methods is to look for events with high *p(possibly signal-enriched)/p(possibly signal-depleted)*

Signal enriched　　　Signal depleted



E. Metodiev, BN, J. Thaler, 1708.02949; J. Collins, K. Howe, BN, 1805.02664; + many more

Semi-supervised

Semi-supervised = partial labels

Typically, these methods use some signal simulations to build signal sensitivity

Image credit: https://www.particlezoo.net

vs

e.g. SM background versus many signals

Overview of New Ideas

Approach:	**Unsupervised**	**Weakly supervised**
BSM assumption	Signal is rare (low p)	Signal is an over density (high p ratio)
Main drawback	rare is not invariant* under coordinate transformations!	need two samples

*for a detailed discussion about this, see K. Desai, BN, J. Thaler, 2112.05722

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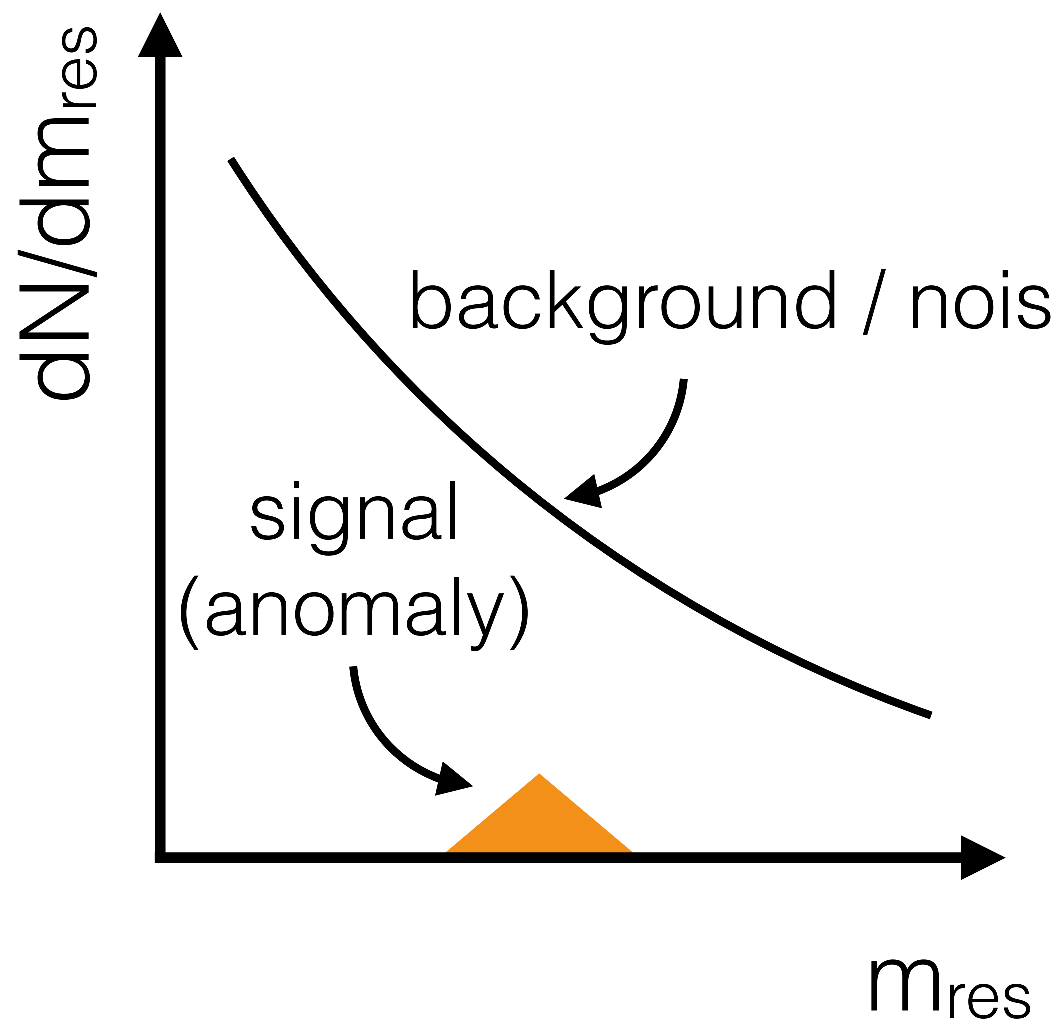
Cannonical example: resonances!

*for a detailed discussion about this, see K. Desai, BN, J. Thaler, 2112.05722

Resonant Anomalies

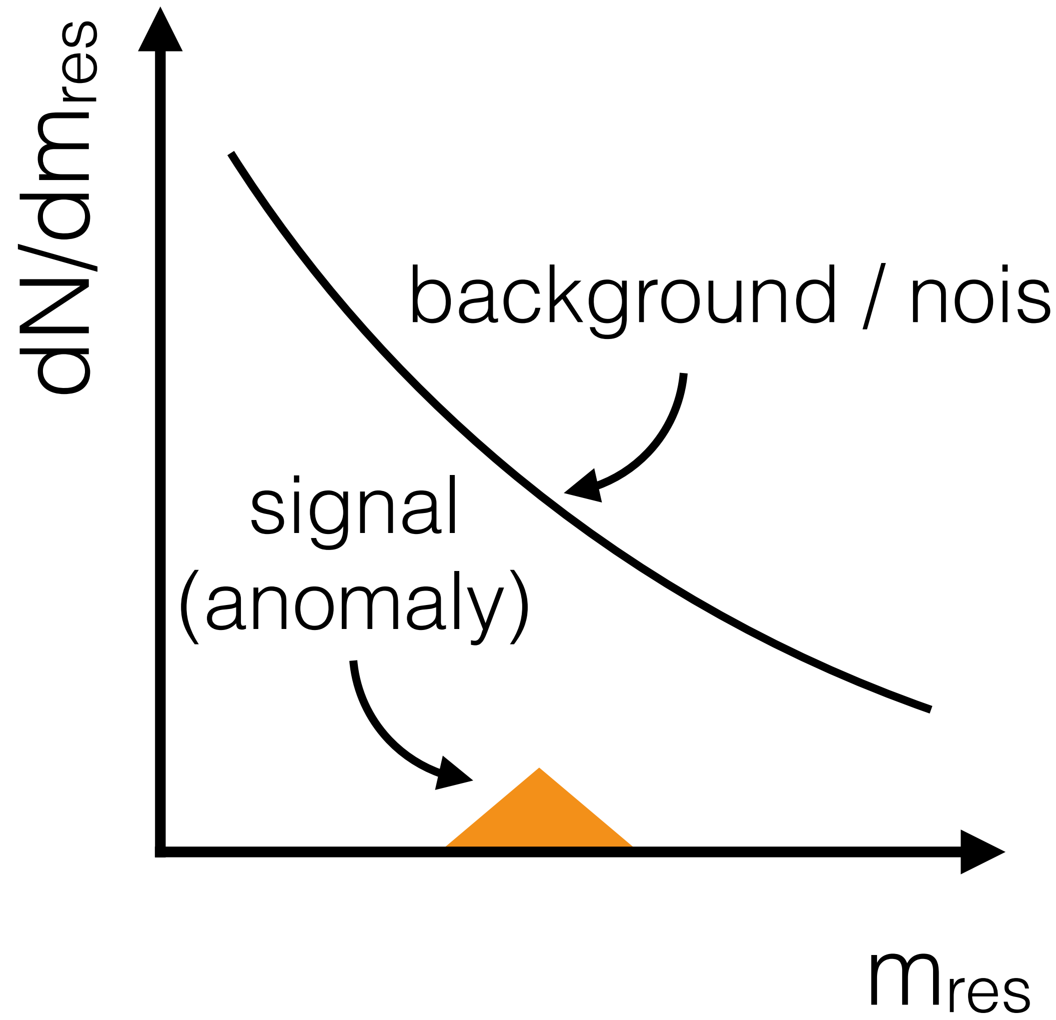
A relatively general, but powerful assumption is that the anomaly is localized somewhere in phase space.



Generically true when there are on-shall new particles.

A Worked Example: dijets @ LHC

I'll walk you through a weakly-supervised approach.



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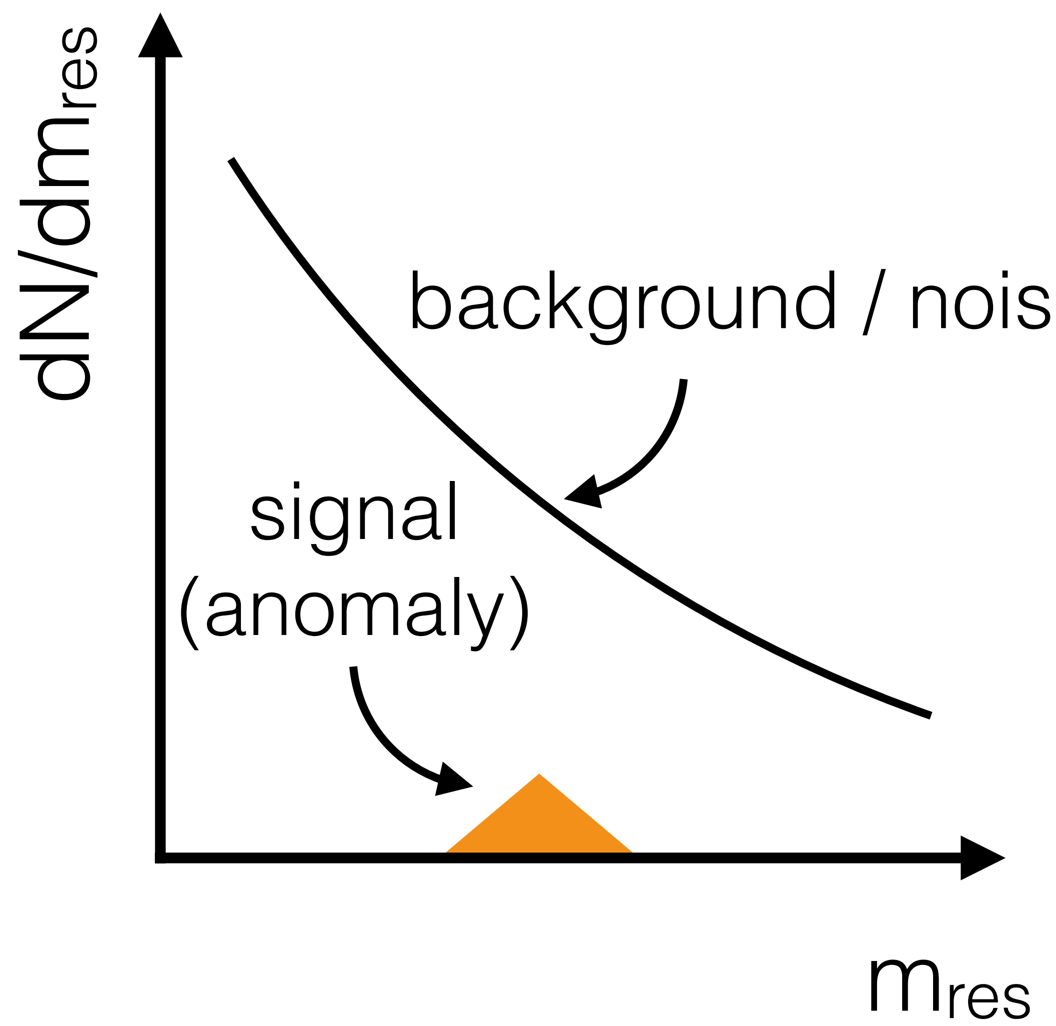
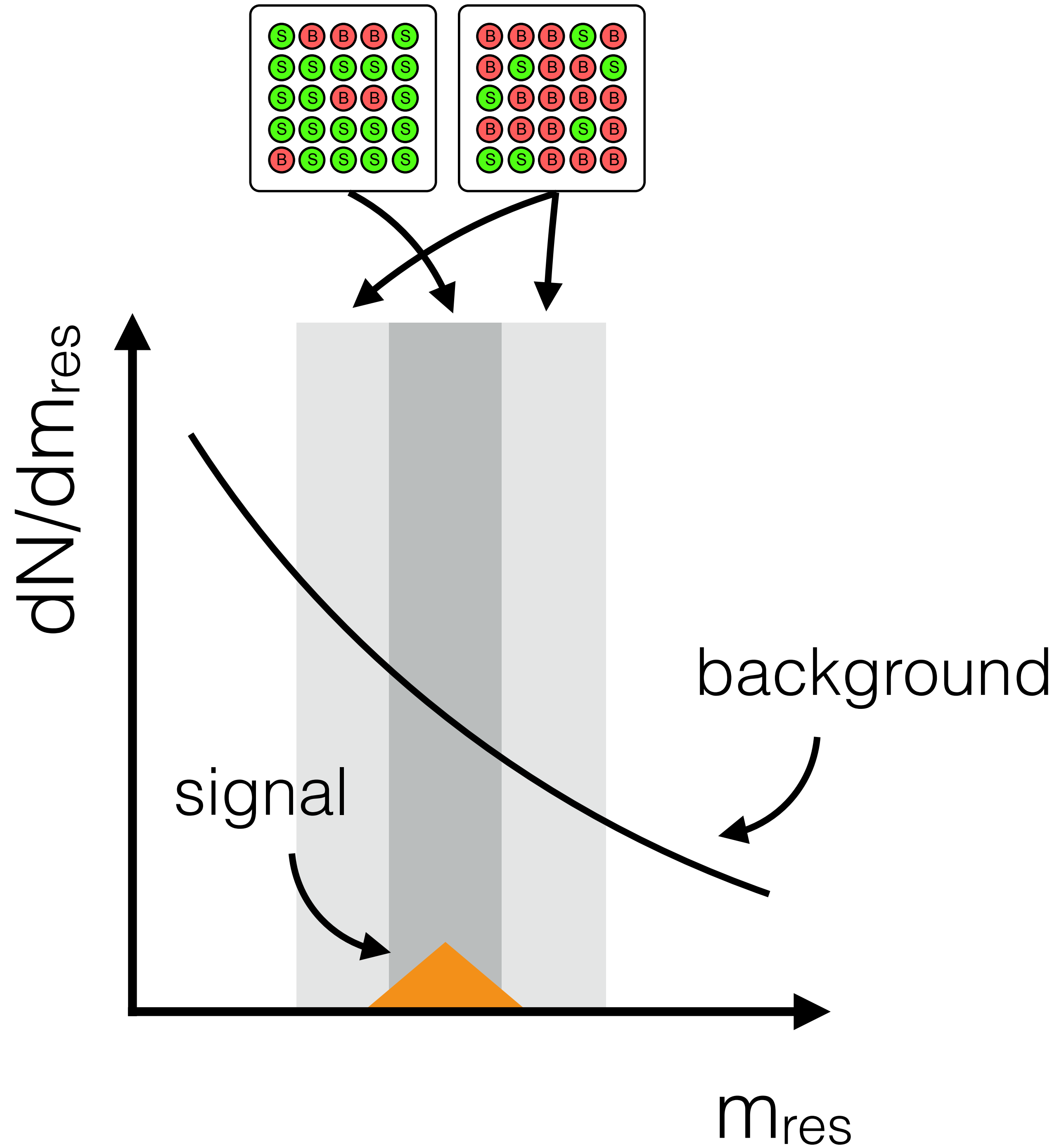


First: we will need to generate noisy labels.

A Worked Example: dijets @ LHC



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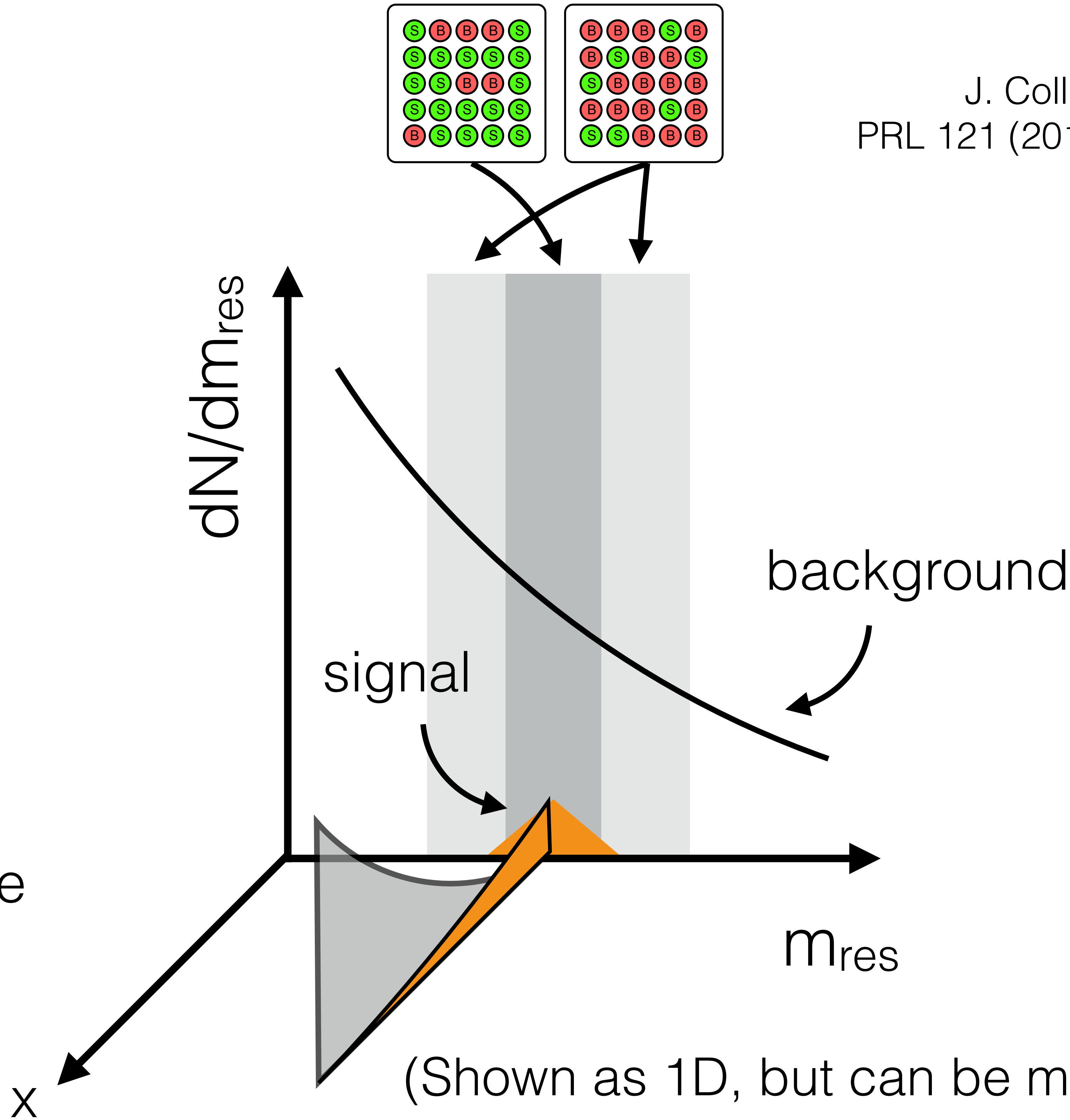
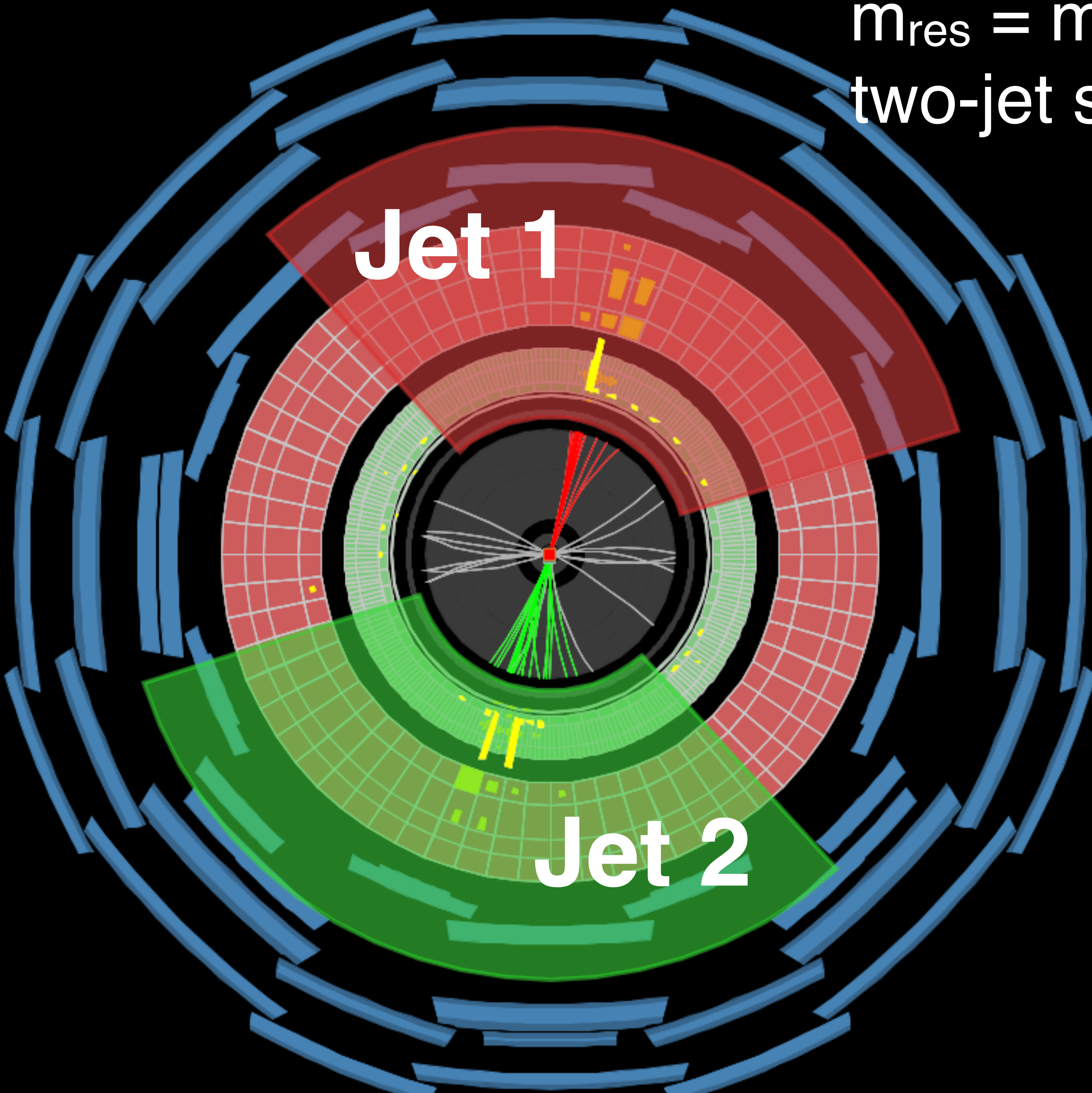
J. Collins, K. Howe, BN,
PRL 121 (2018) 241803, 1805.02664



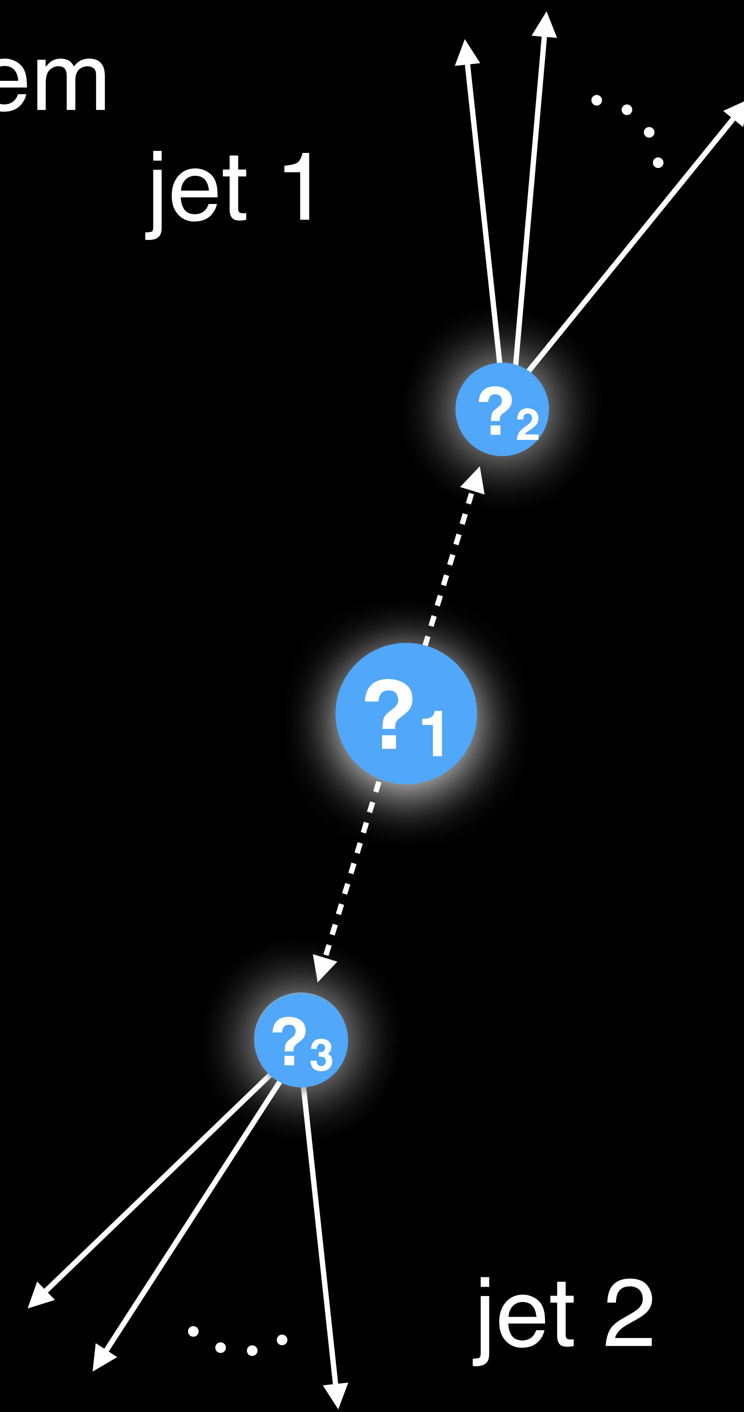
Extended feature space for machine learning

(Shown as 1D, but can be many-dimensional)

Example: two-jet search



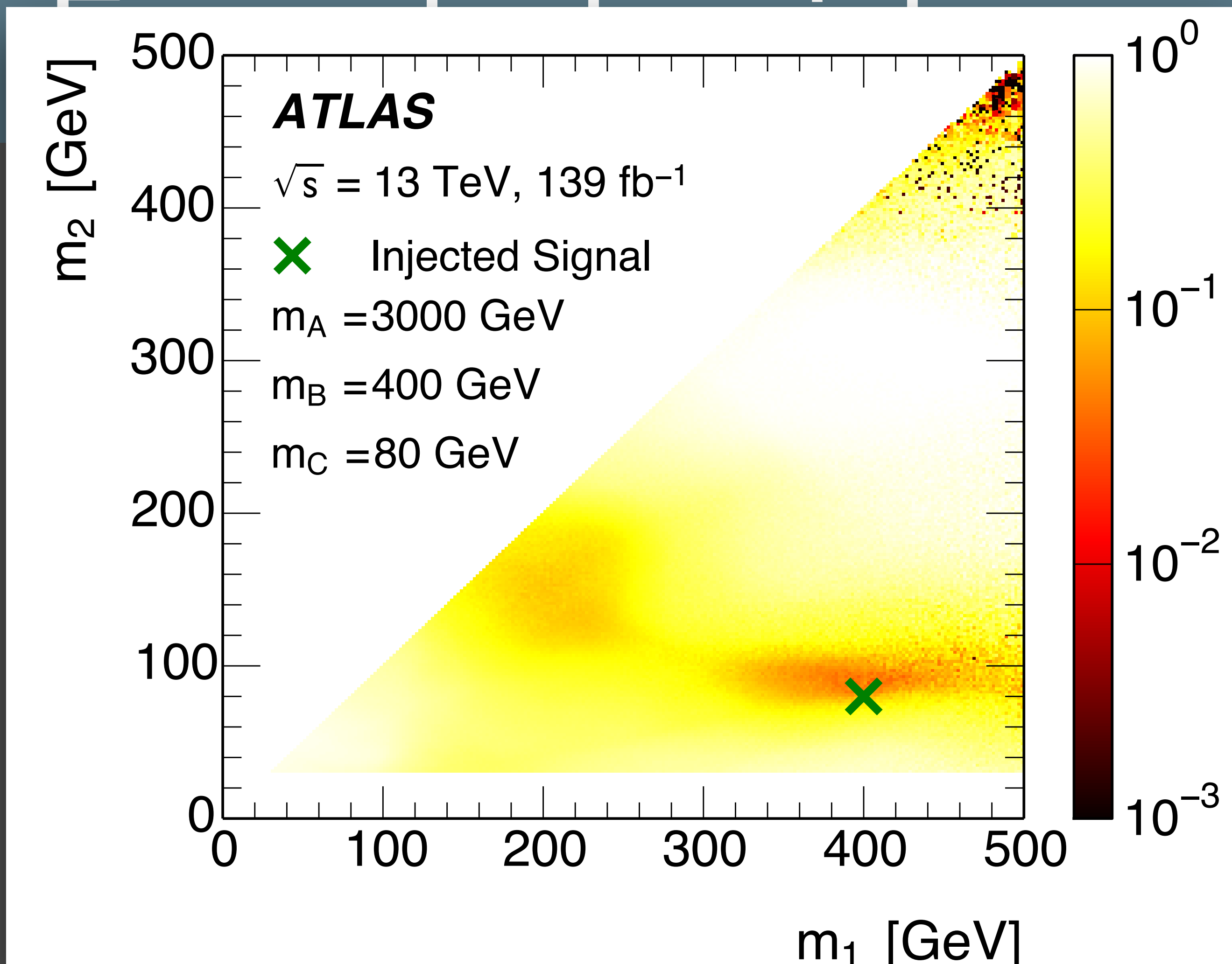
m_{res} = mass of two-jet system



collisions in/out of page

x = many features of the two jets

res = mass of



A first version of this search has been performed by ***ATLAS***!

Phys. Rev. Lett. 125 (2020) 131801, 2005.02983

ATLAS EXPERIMENT

Collaboration Site | Physics Results

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updates > briefing > Machine learning qualitatively changes the search for new particles

Physics Briefing

Tags: machine learning, analysis

Machine learning qualitatively changes the search for new particles

13 May 2020 | By ATLAS Collaboration

Extensions

While powerful, the approach I’ve just described has multiple challenges when scaling up.

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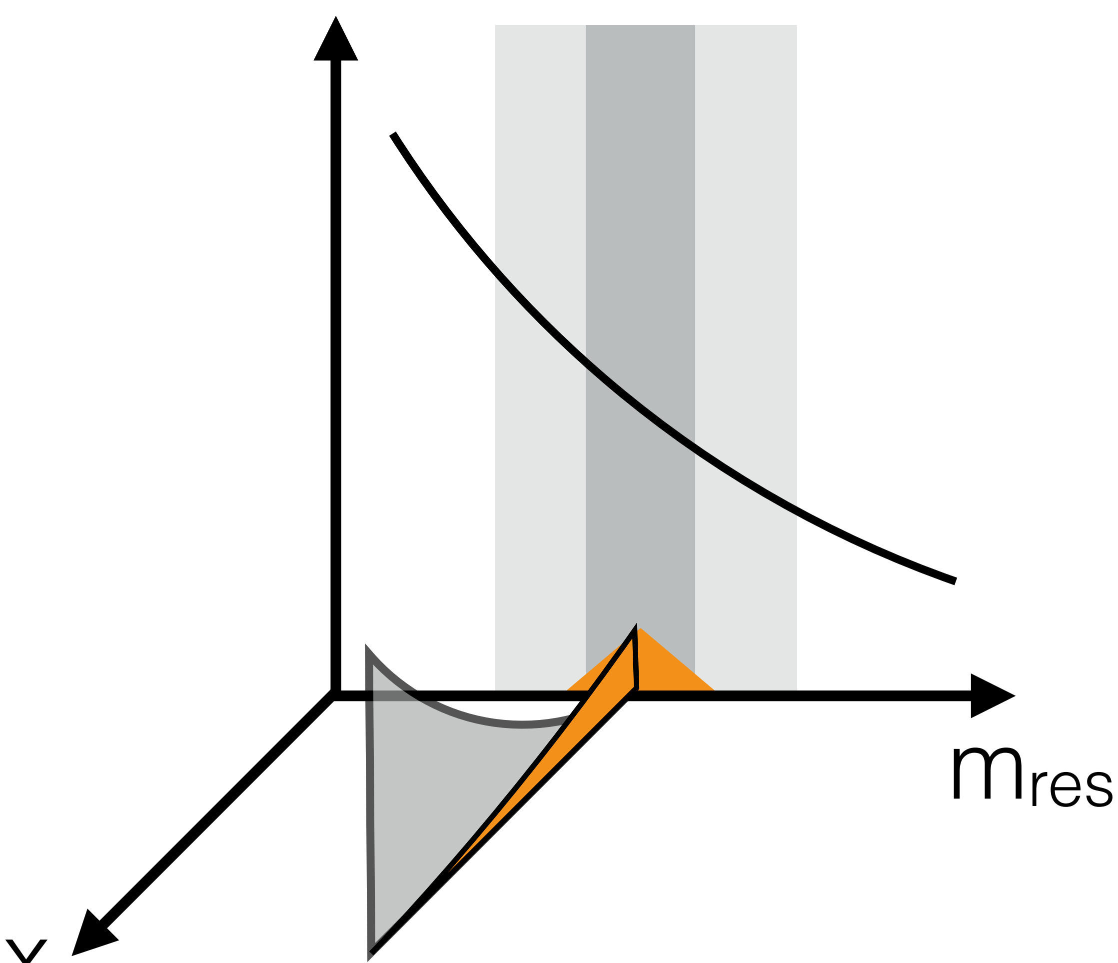
Example Challenge: Decorrelation



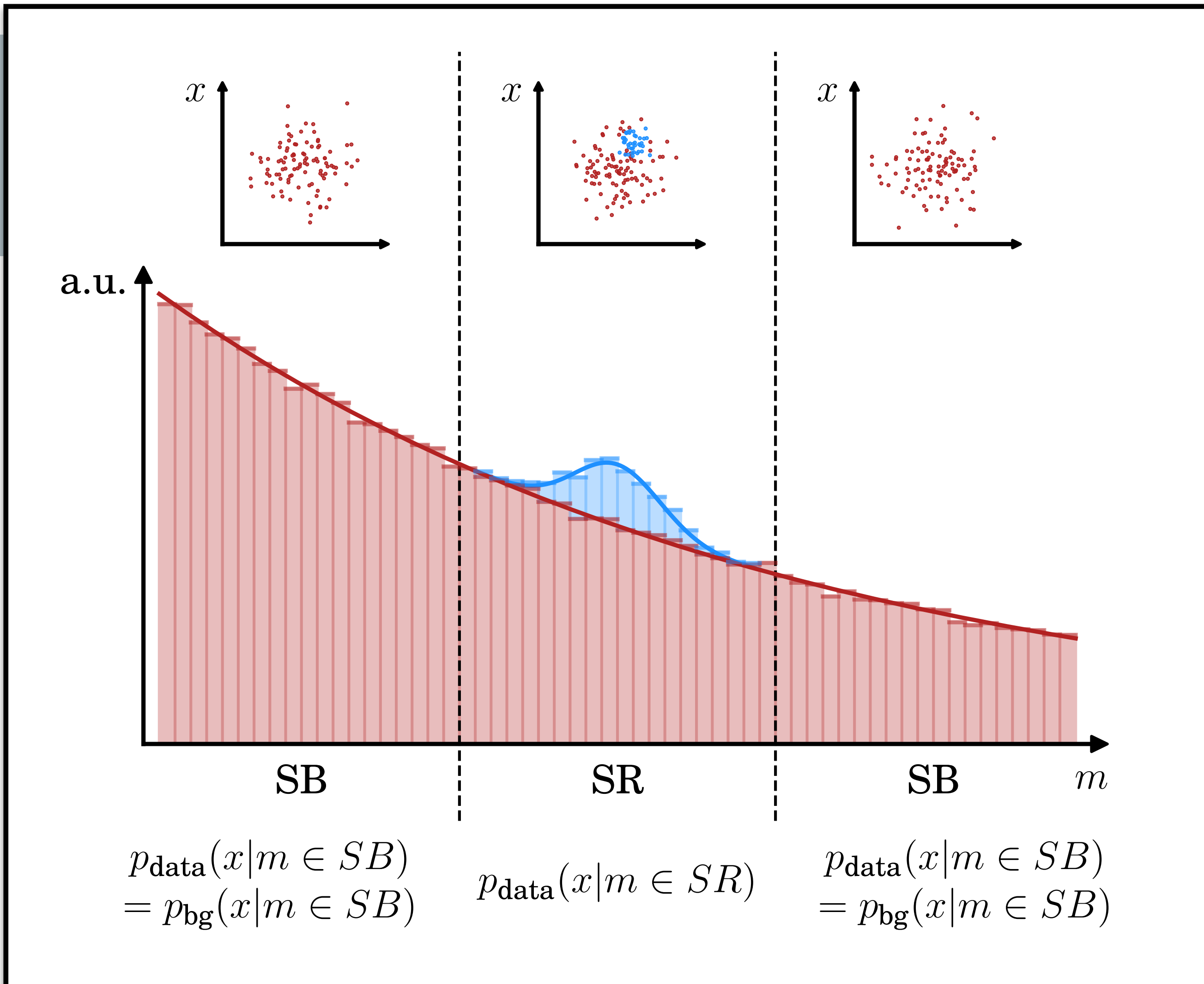
The approach doesn't work if m_{res} and x are strongly related.

For instance, consider the extreme case where m_{res} is part of x.

See also e.g. J. Raine et al., 2203.09470

K. Benkendorfer, L. Le Pottier, BN, 2009.02205
A. Hallin et al., 2109.00546
A. Andreassen, BN, D. Shih, PRD 101 (2020) 095004, 2001.05001
BN and D. Shih, PRD 101 (2020) 075042, 2001.04990

…proach I've just described
…ges when scaling up.



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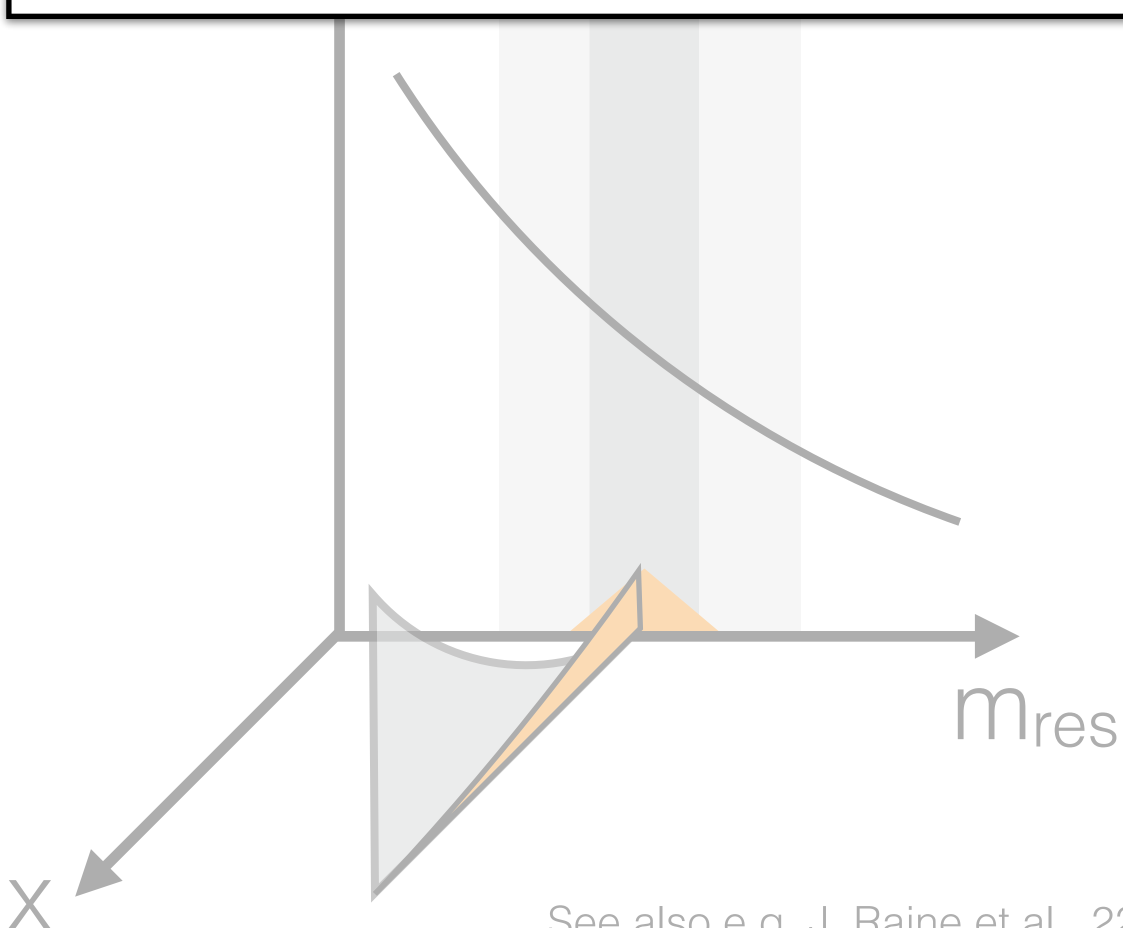

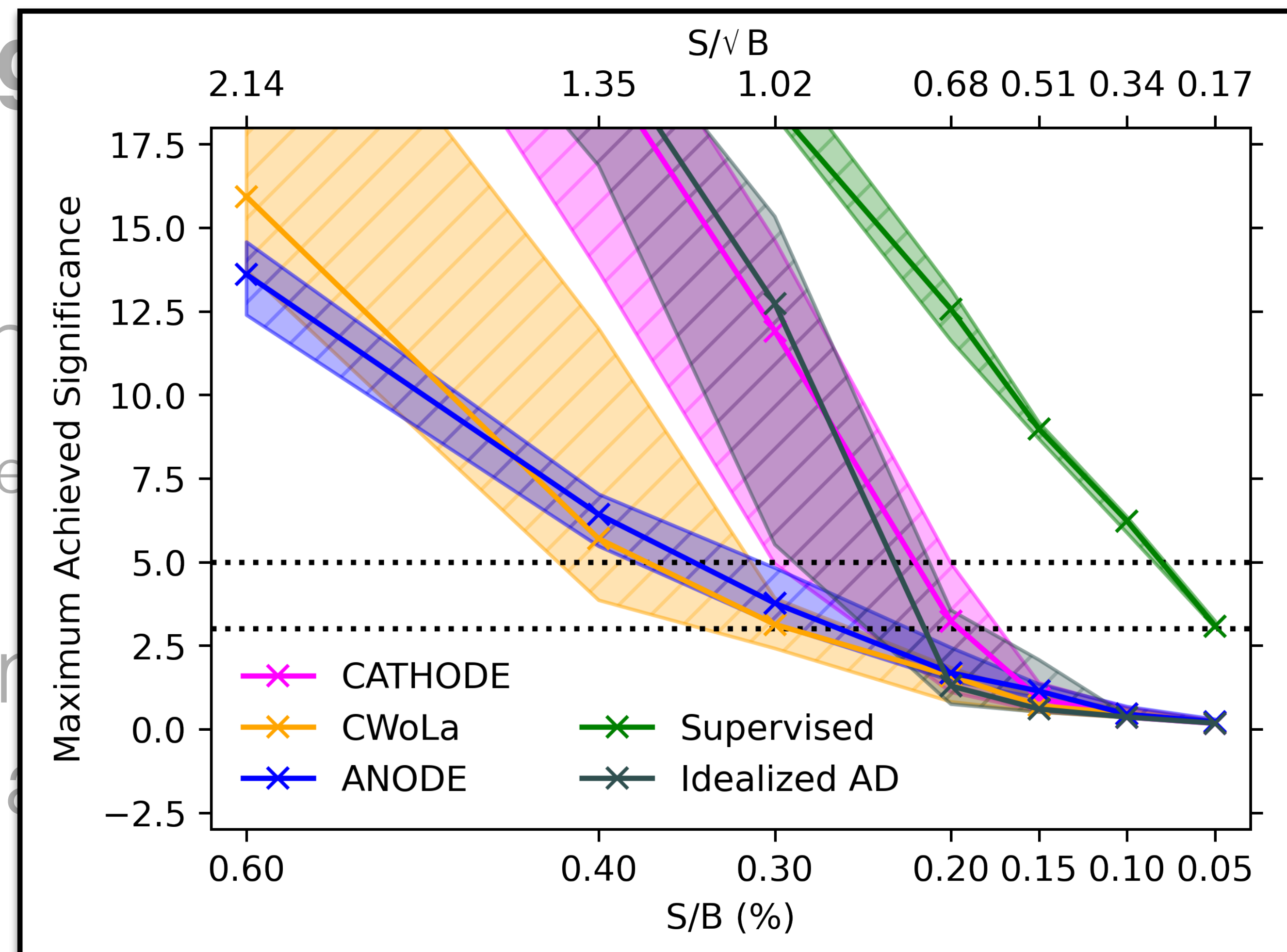

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See also e.g. J. Raine et al., 2203.09470

Extensions

While powerful, the approach I've just described has multiple challenges when scaling up.

We also need to benchmark new approaches.

Comparing model independent approaches is difficult, which is why we put together the LHC Olympics datasets + challenge

(see also Dark Machines and ADC2021)

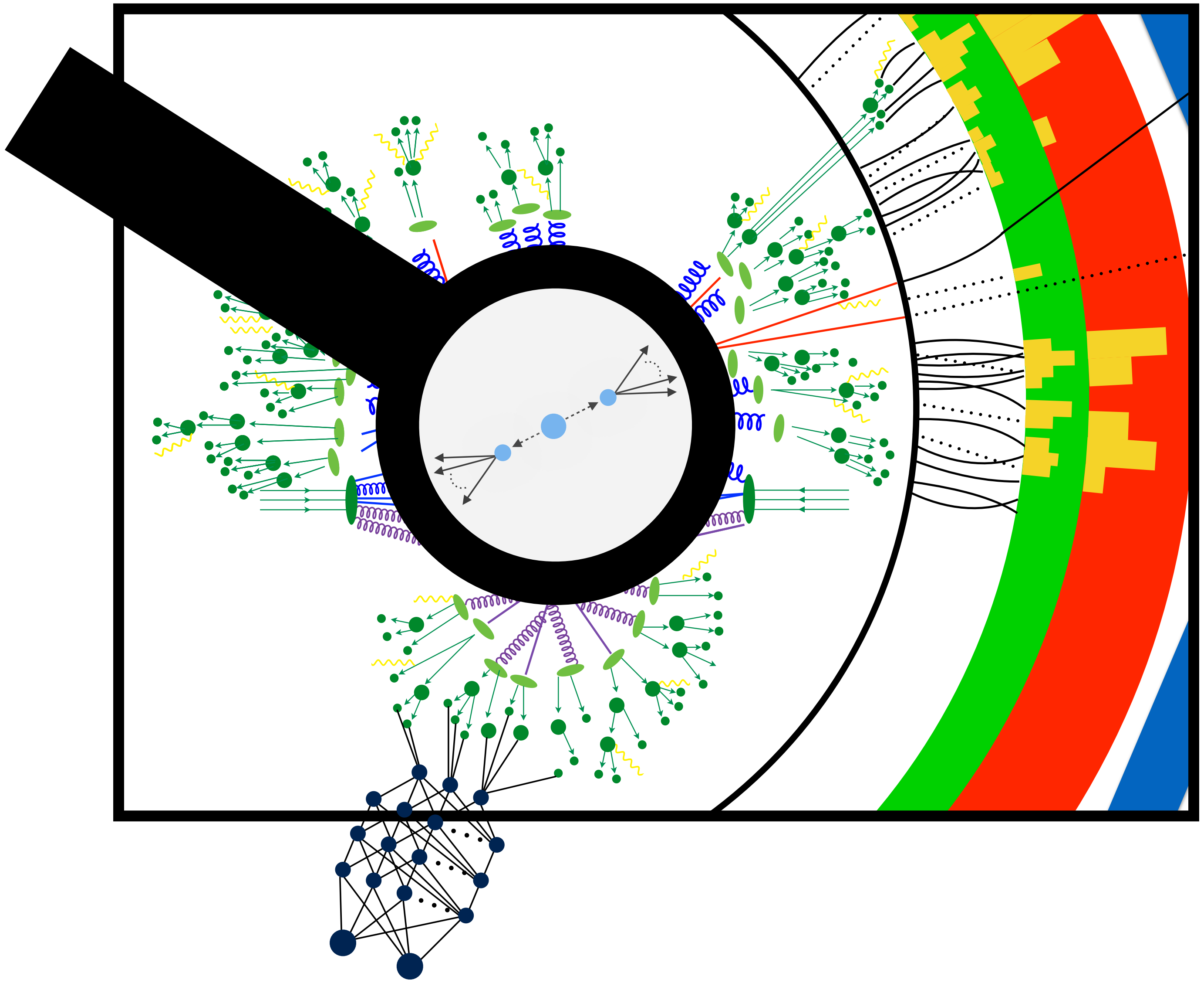
G. Kasieczka, BN, D. Shih et al., 2101.08320

The Future

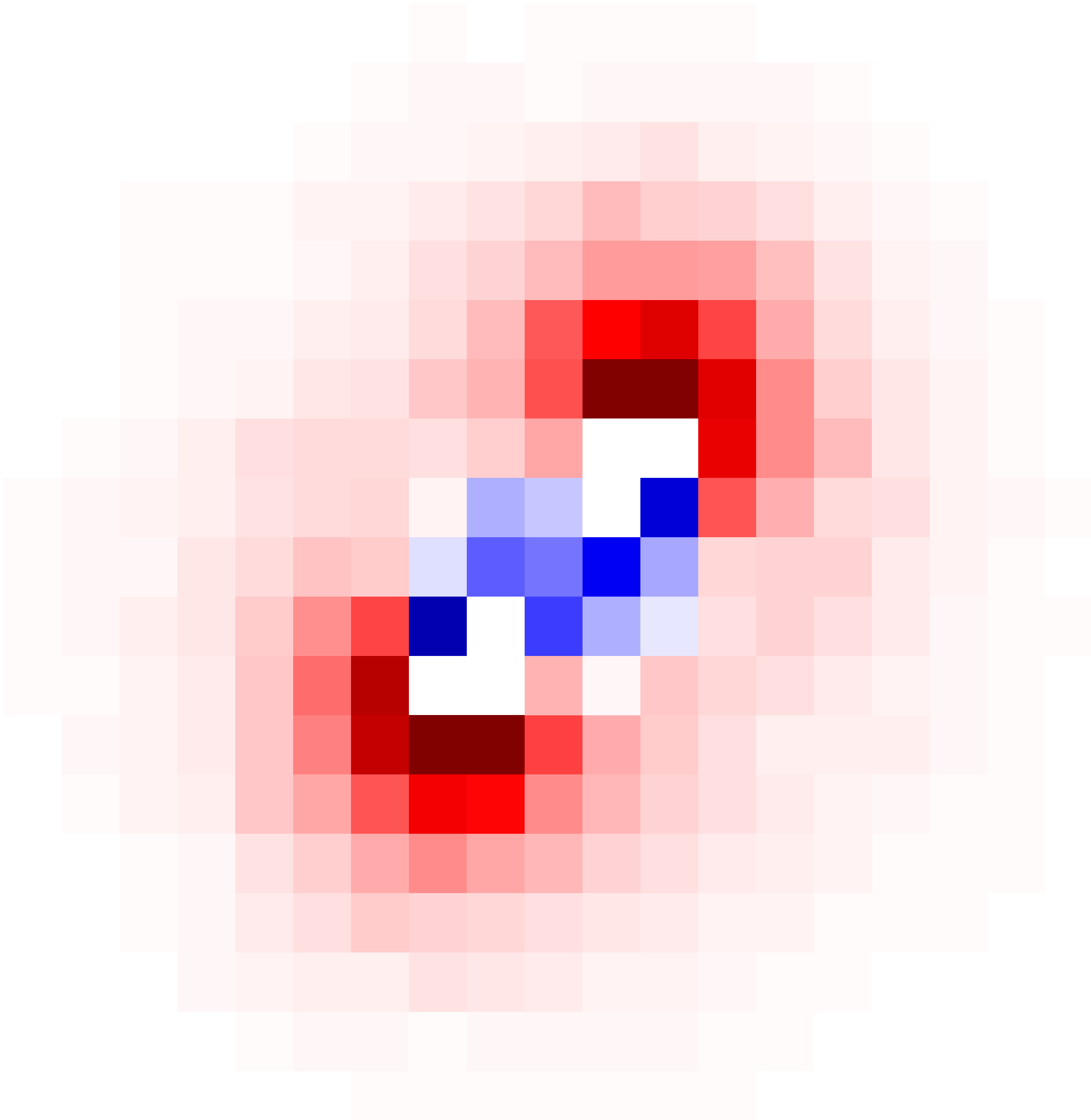
It is an exciting time to work on anomaly detection for the LHC and beyond!

This is a rapidly growing area with lots of room for innovation (and from physicists!)

We will need many approaches to achieve broad coverage



See the Living Review for more refs!



Fin.

Backup

Results with data

Phys. Rev. Lett. 125 (2020) 131801, 2005.02983