

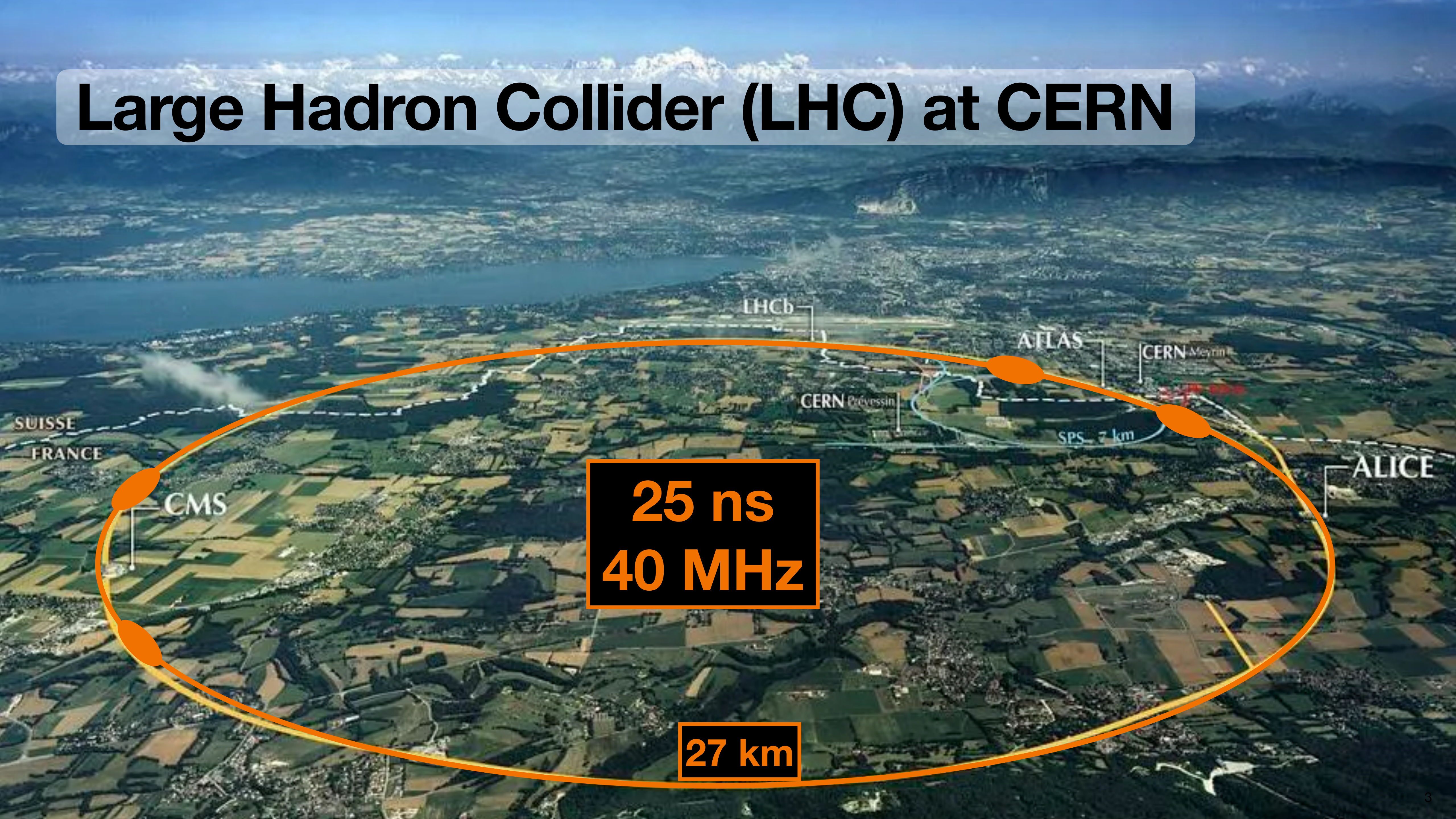
Introduction to Anomaly Detection at the LHC

Dylan Rankin
November 23rd, 2024

Large Hadron Collider (LHC) at CERN



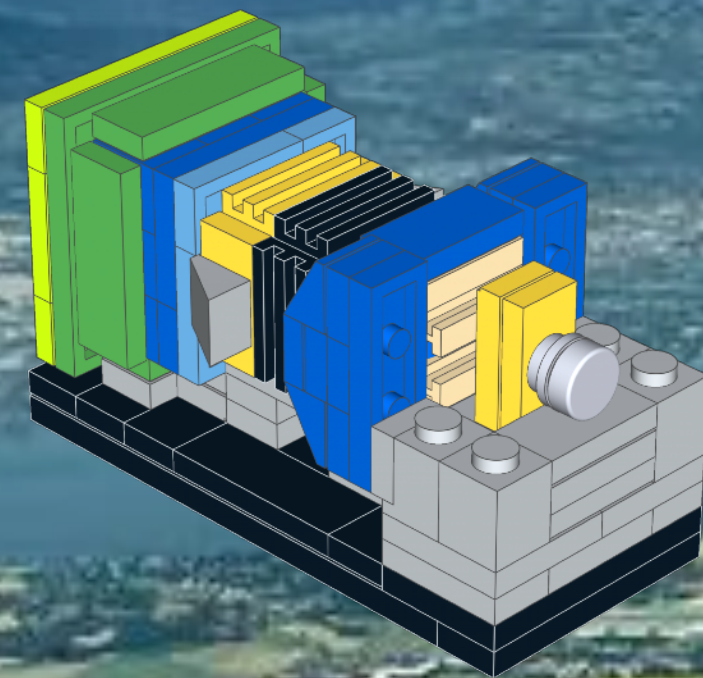
Large Hadron Collider (LHC) at CERN



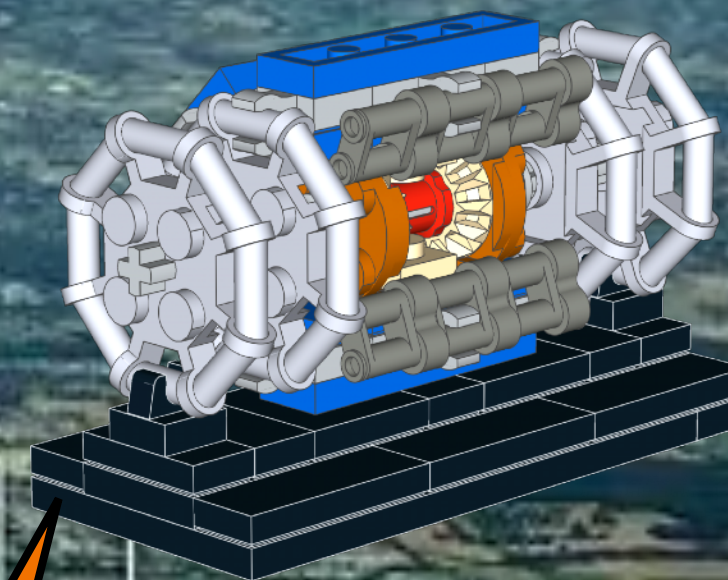
25 ns
40 MHz

27 km

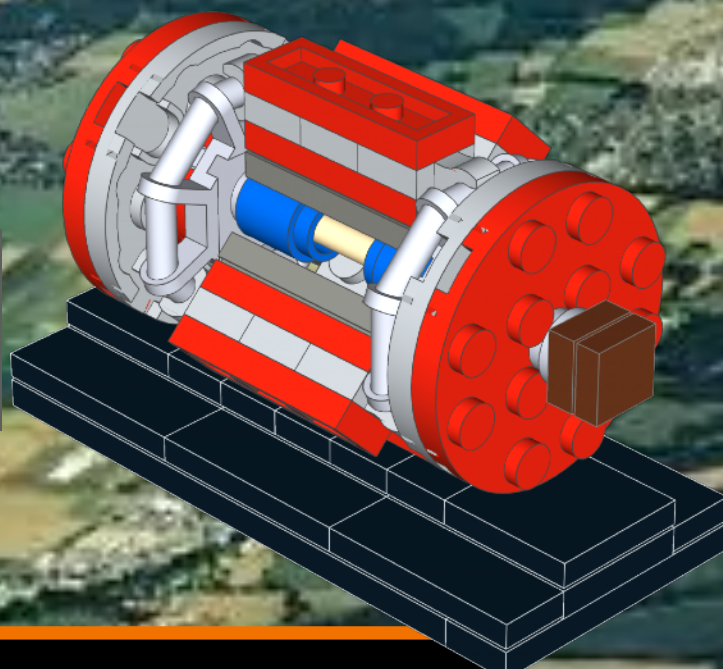
Large Hadron Collider (LHC) at CERN



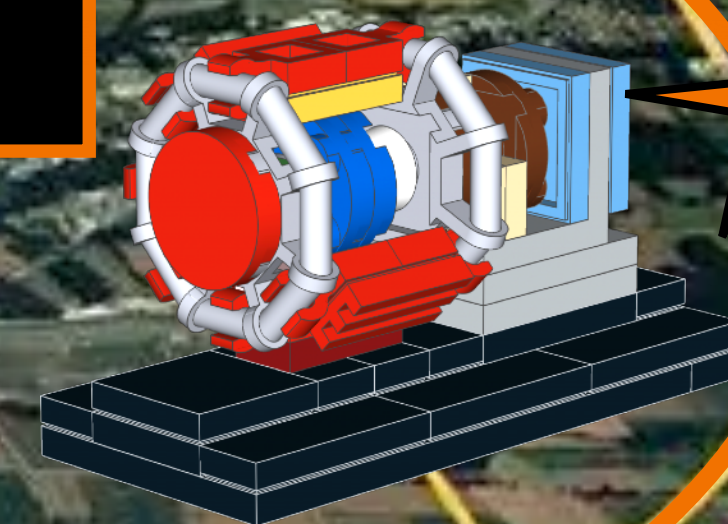
LHCb



ATLAS



CMS



ALICE

25 ns
40 MHz

10^{11} proton
bunch

10^{11} proton
bunch

27 km

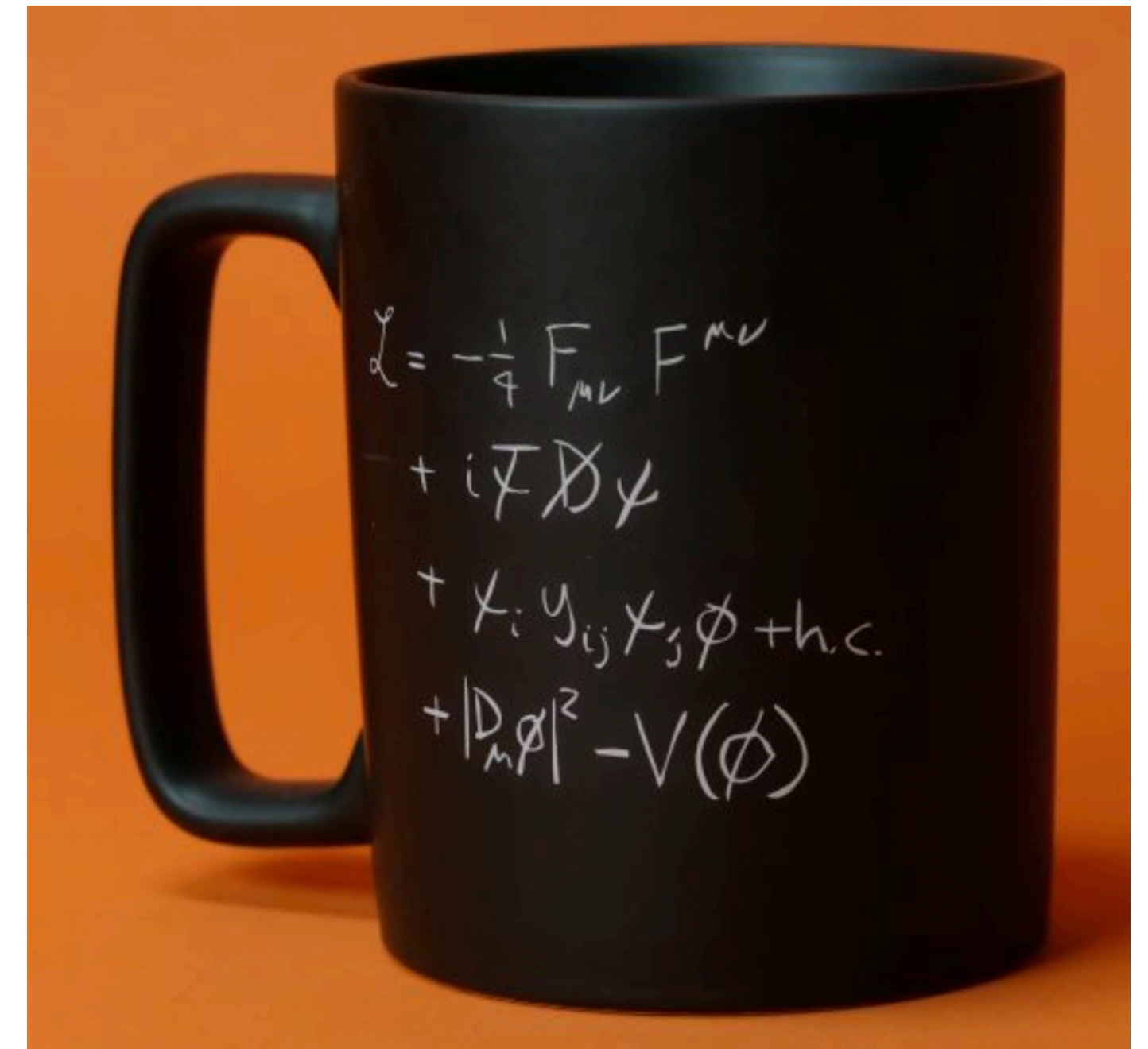
SUISSE
FRANCE

CERN Provenance

SPS 7 km

The Standard Model

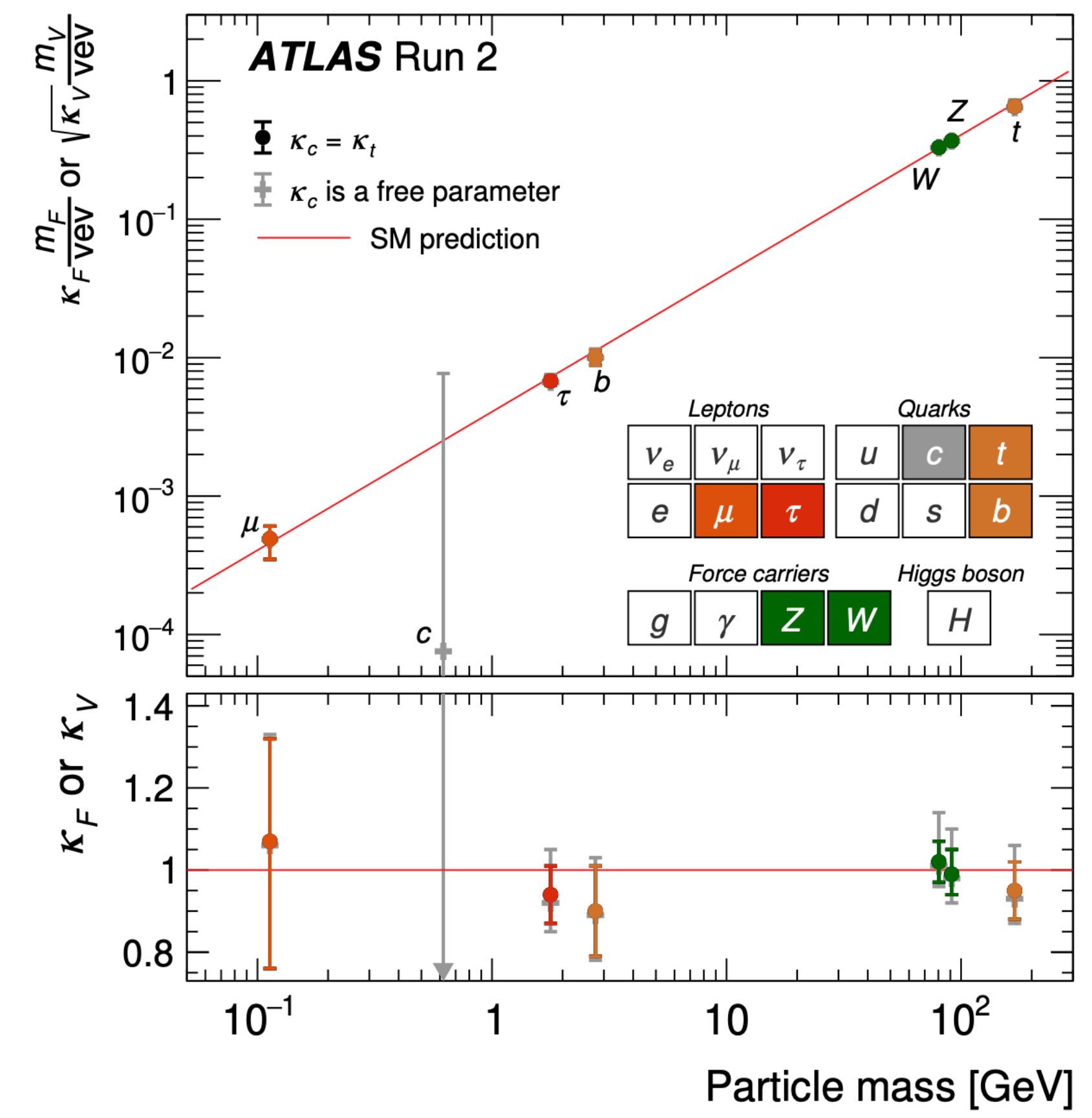
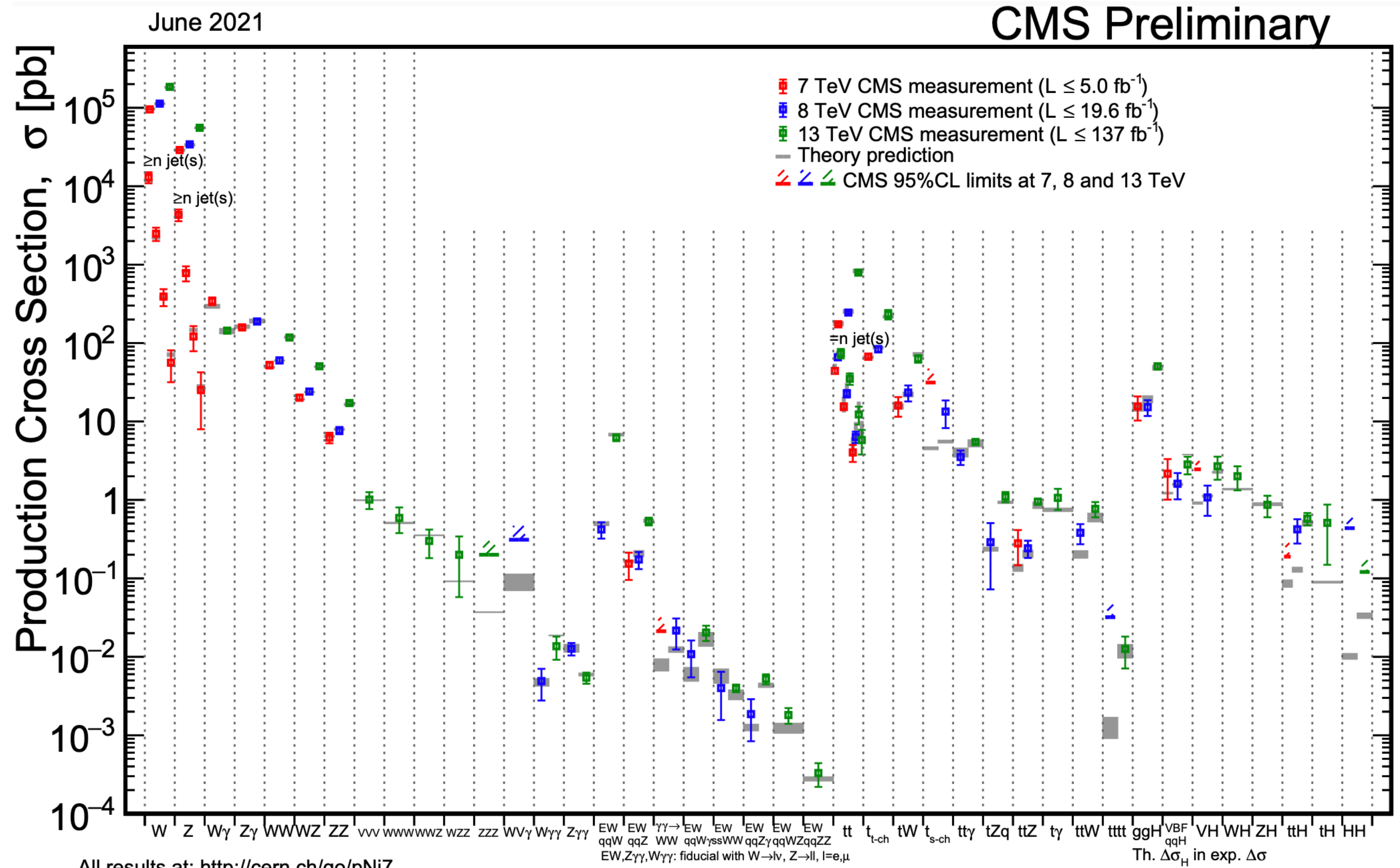
	<p>mass → $\approx 2.3 \text{ MeV}/c^2$</p> <p>charge → $2/3$</p> <p>spin → $1/2$</p> <p>u</p> <p>up</p>	<p>mass → $\approx 1.275 \text{ GeV}/c^2$</p> <p>charge → $2/3$</p> <p>spin → $1/2$</p> <p>c</p> <p>charm</p>	<p>mass → $\approx 173.07 \text{ GeV}/c^2$</p> <p>charge → $2/3$</p> <p>spin → $1/2$</p> <p>t</p> <p>top</p>	<p>mass → 0</p> <p>charge → 0</p> <p>spin → 1</p> <p>g</p> <p>gluon</p>	<p>mass → $\approx 126 \text{ GeV}/c^2$</p> <p>charge → 0</p> <p>spin → 0</p> <p>H</p> <p>Higgs boson</p>	
QUARKS	<p>mass → $\approx 4.8 \text{ MeV}/c^2$</p> <p>charge → $-1/3$</p> <p>spin → $1/2$</p> <p>d</p> <p>down</p>	<p>mass → $\approx 95 \text{ MeV}/c^2$</p> <p>charge → $-1/3$</p> <p>spin → $1/2$</p> <p>s</p> <p>strange</p>	<p>mass → $\approx 4.18 \text{ GeV}/c^2$</p> <p>charge → $-1/3$</p> <p>spin → $1/2$</p> <p>b</p> <p>bottom</p>	<p>mass → 0</p> <p>charge → 0</p> <p>spin → 1</p> <p>γ</p> <p>photon</p>		
	<p>mass → $0.511 \text{ MeV}/c^2$</p> <p>charge → -1</p> <p>spin → $1/2$</p> <p>e</p> <p>electron</p>	<p>mass → $105.7 \text{ MeV}/c^2$</p> <p>charge → -1</p> <p>spin → $1/2$</p> <p>μ</p> <p>muon</p>	<p>mass → $1.777 \text{ GeV}/c^2$</p> <p>charge → -1</p> <p>spin → $1/2$</p> <p>τ</p> <p>tau</p>	<p>mass → $91.2 \text{ GeV}/c^2$</p> <p>charge → 0</p> <p>spin → 1</p> <p>Z</p> <p>Z boson</p>	GAUGE BOSONS	
	LEPTONS	<p>mass → $< 2.2 \text{ eV}/c^2$</p> <p>charge → 0</p> <p>spin → $1/2$</p> <p>ν_e</p> <p>electron neutrino</p>	<p>mass → $< 0.17 \text{ MeV}/c^2$</p> <p>charge → 0</p> <p>spin → $1/2$</p> <p>ν_μ</p> <p>muon neutrino</p>	<p>mass → $< 15.5 \text{ MeV}/c^2$</p> <p>charge → 0</p> <p>spin → $1/2$</p> <p>ν_τ</p> <p>tau neutrino</p>		<p>mass → $80.4 \text{ GeV}/c^2$</p> <p>charge → ± 1</p> <p>spin → 1</p> <p>W</p> <p>W boson</p>



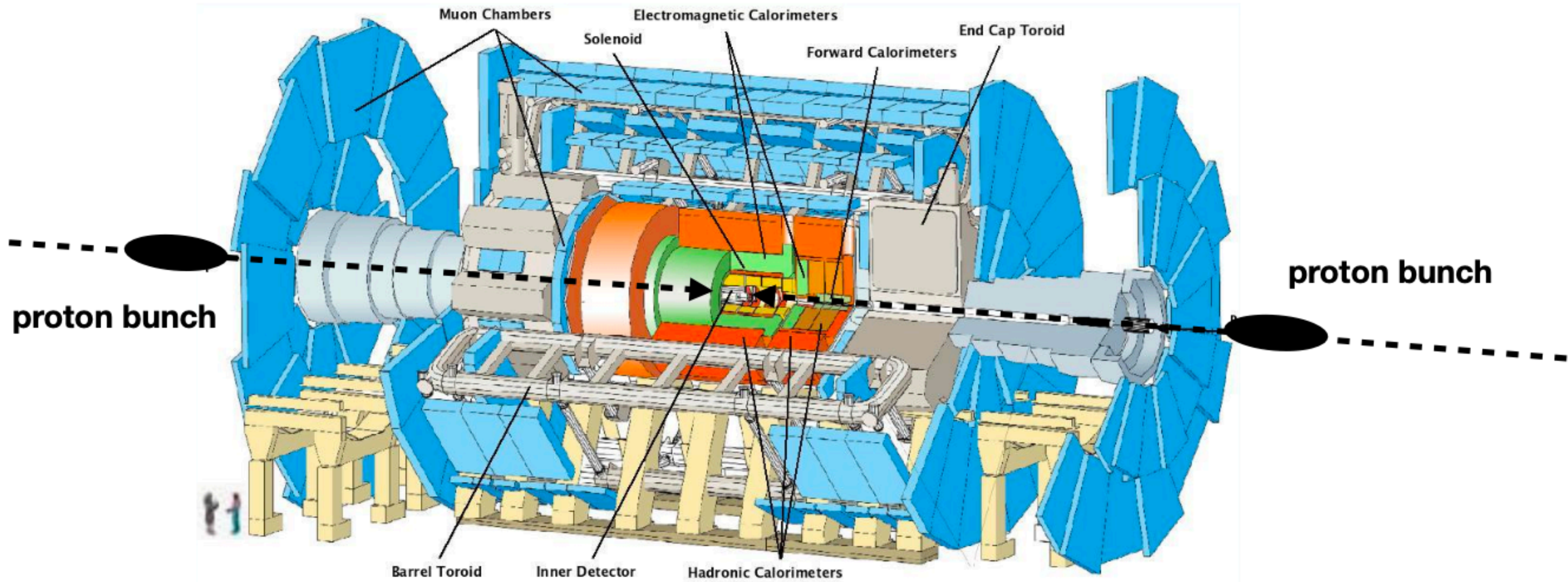
Standard Model Measurements

Standard Model cross sections

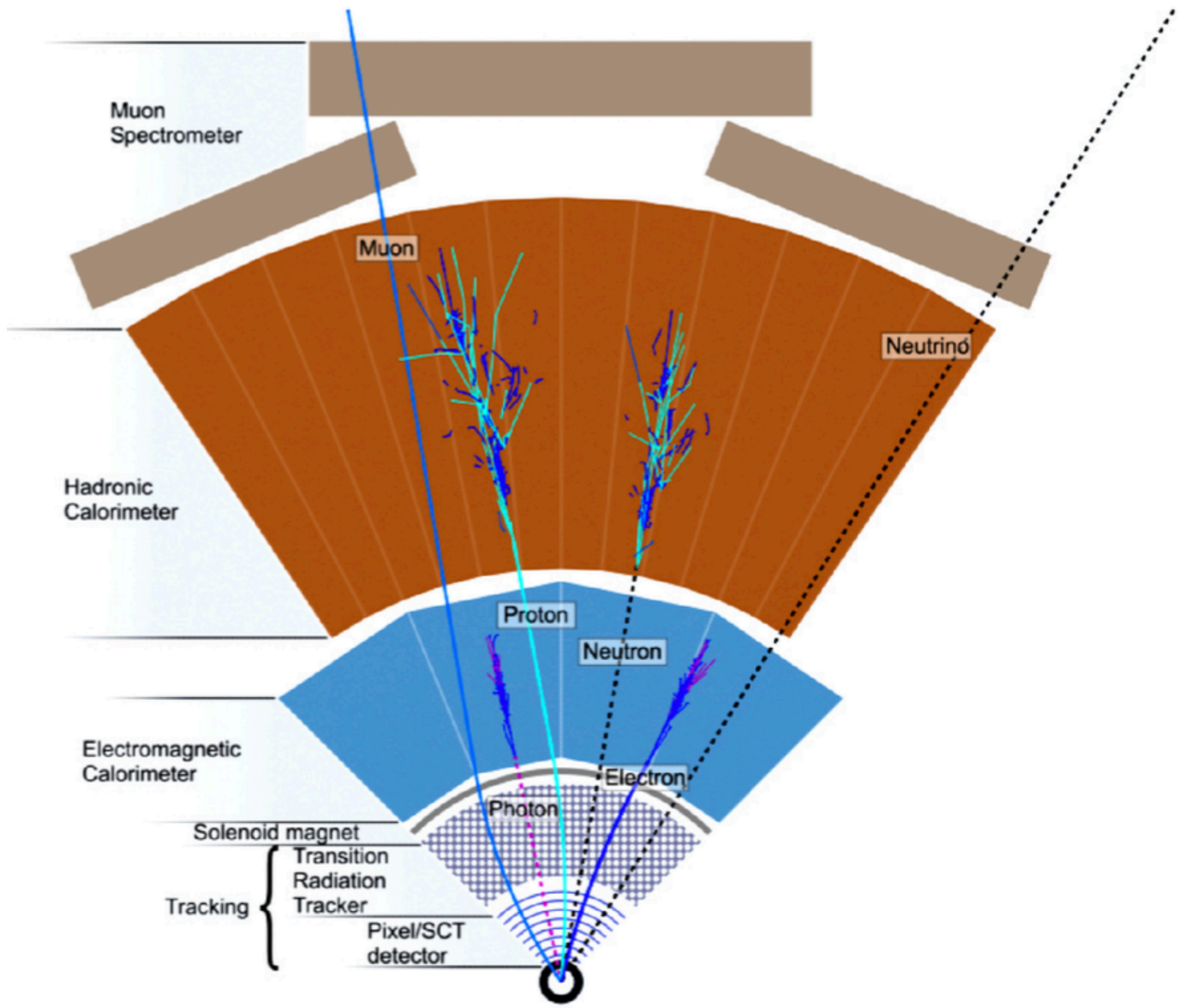
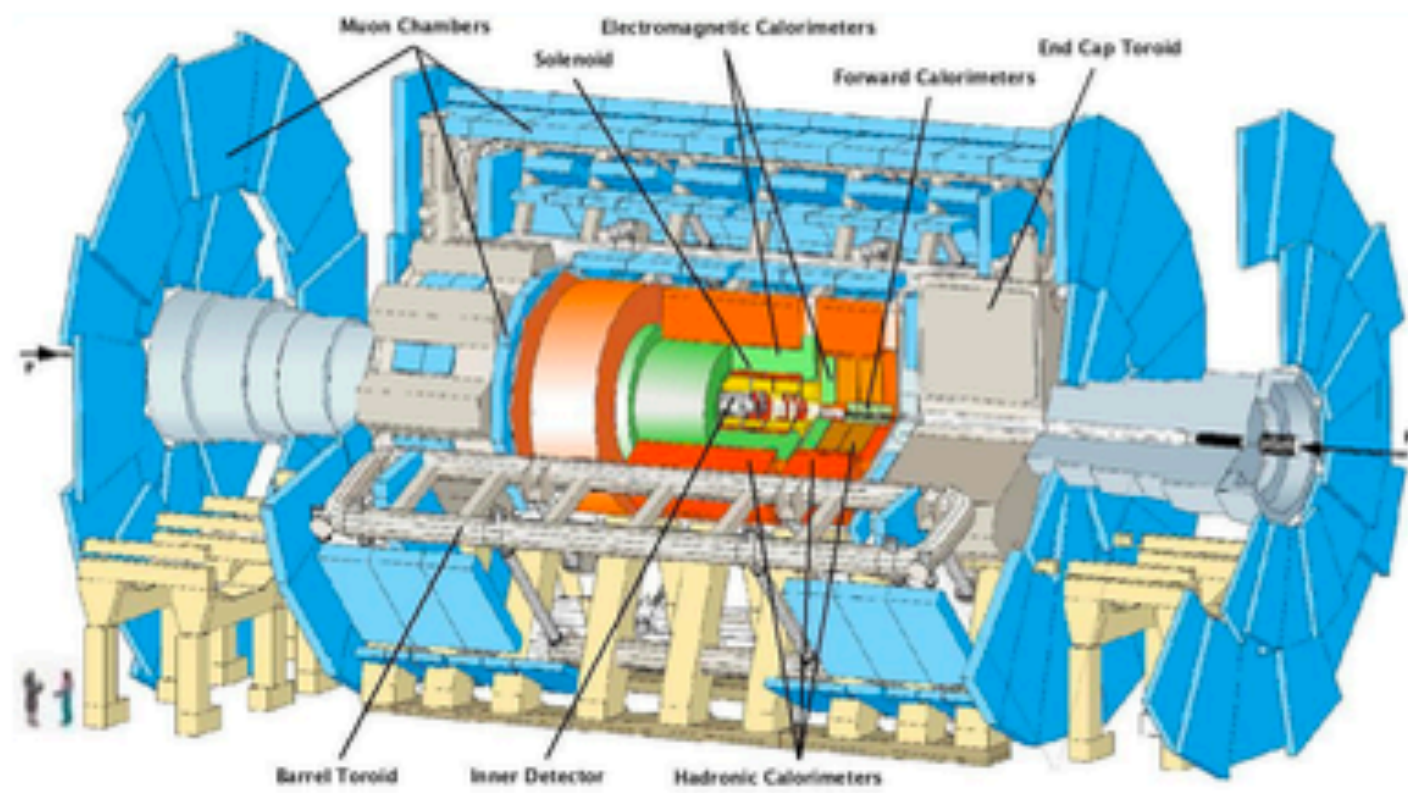
Higgs boson couplings



A Toroidal LHC Apparatus (ATLAS)

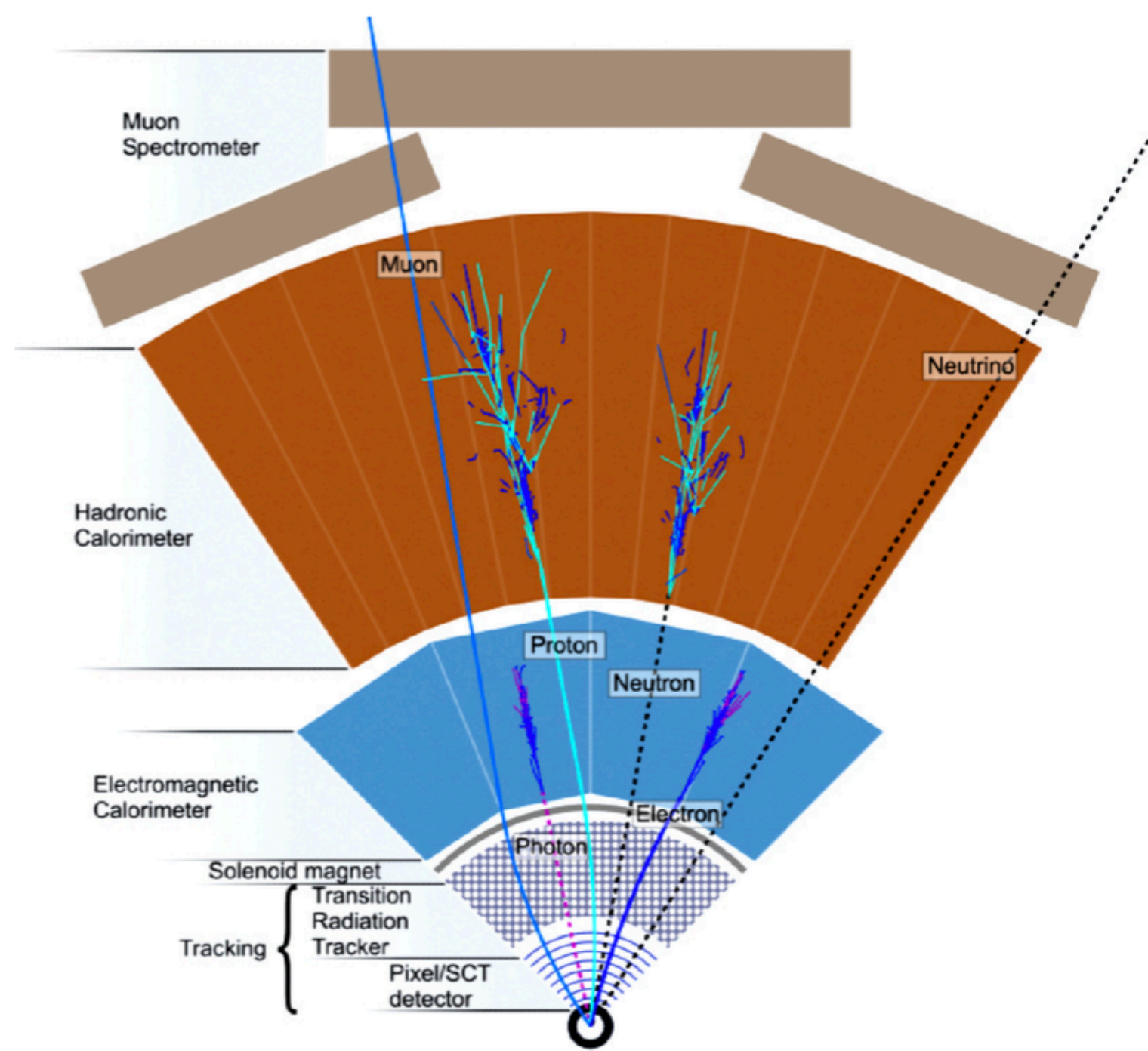


ATLAS Slice

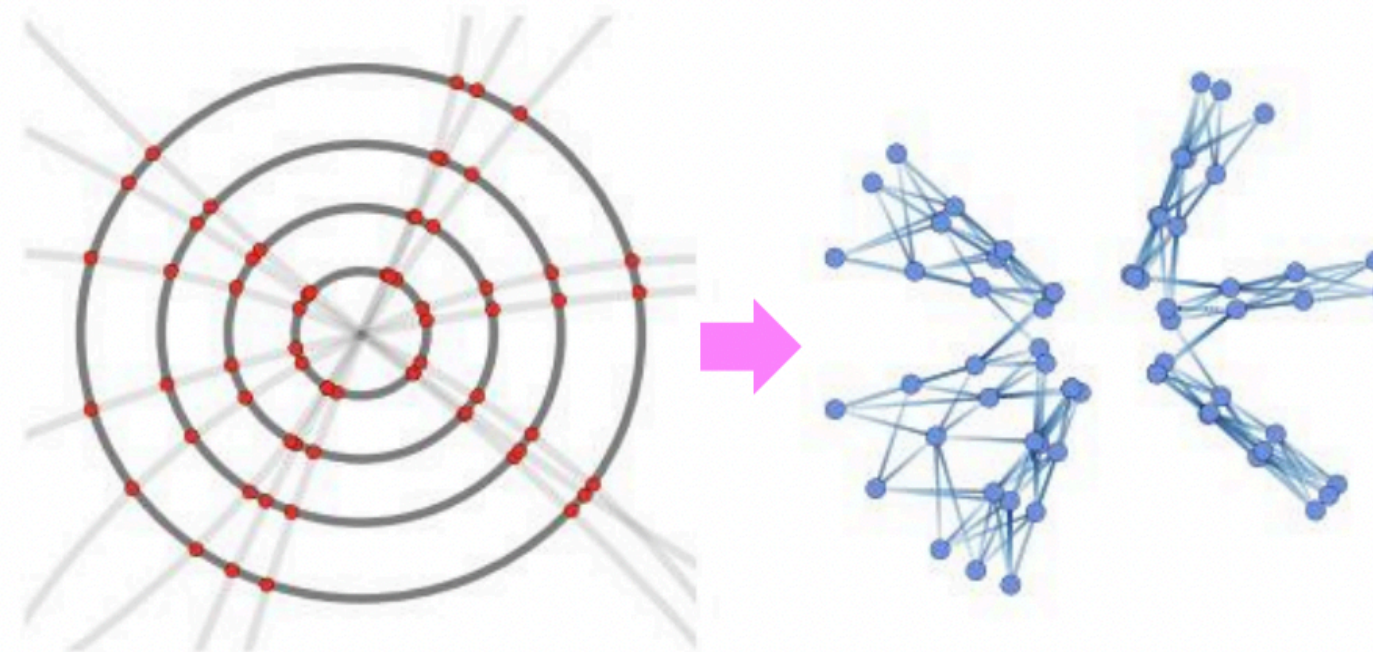


ML in High Energy Physics (HEP)

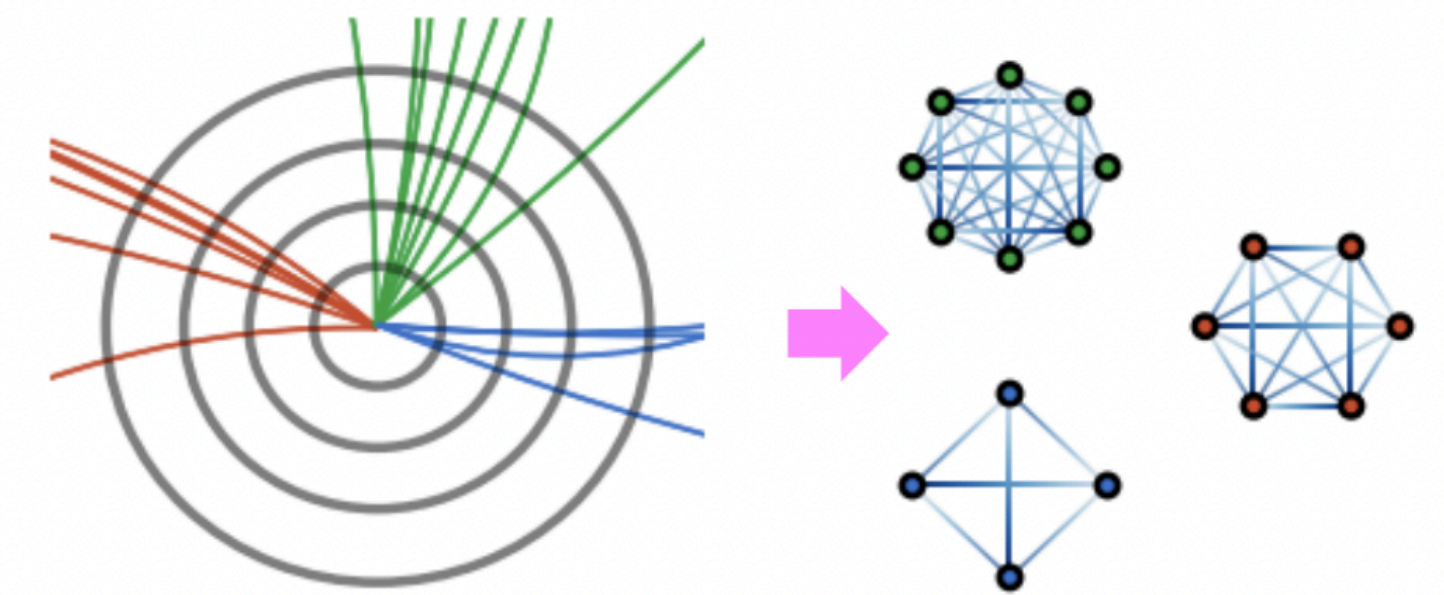
- ML is becoming more and more popular, HEP/LHC no exception
- Better algorithms → improved performance



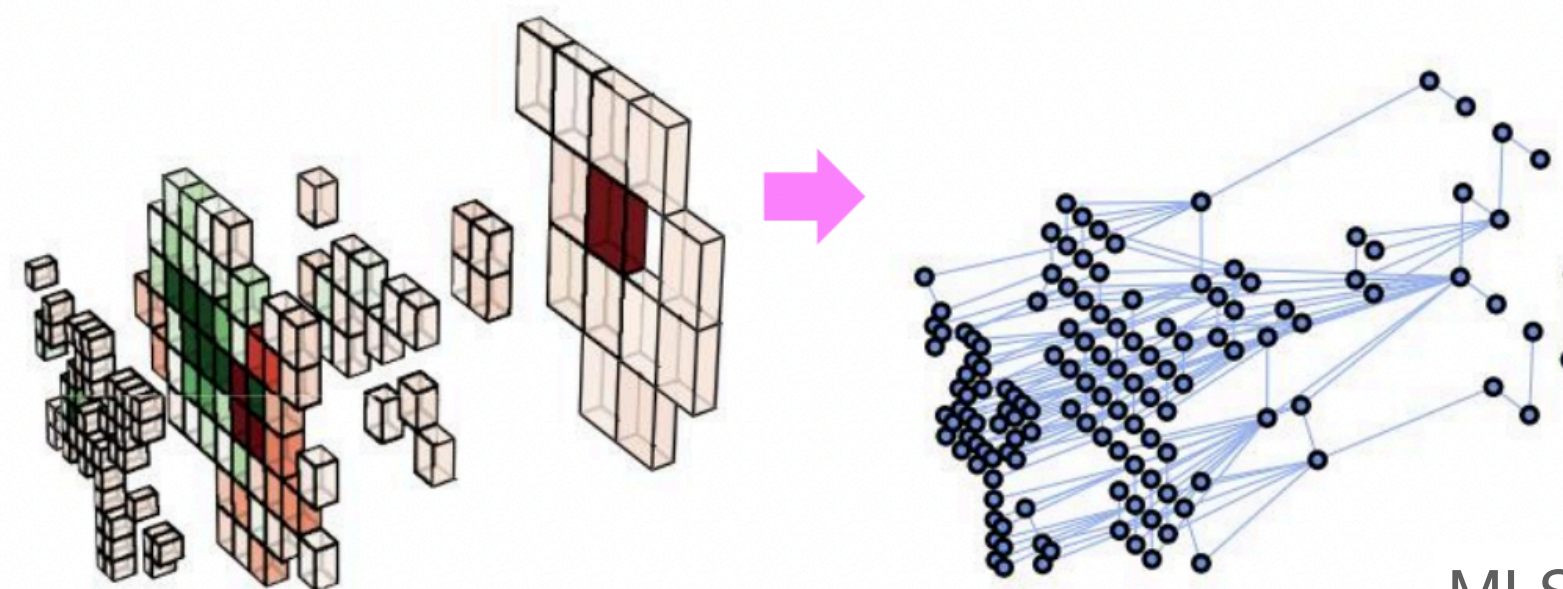
Tracking: Finding Trajectories from space-points



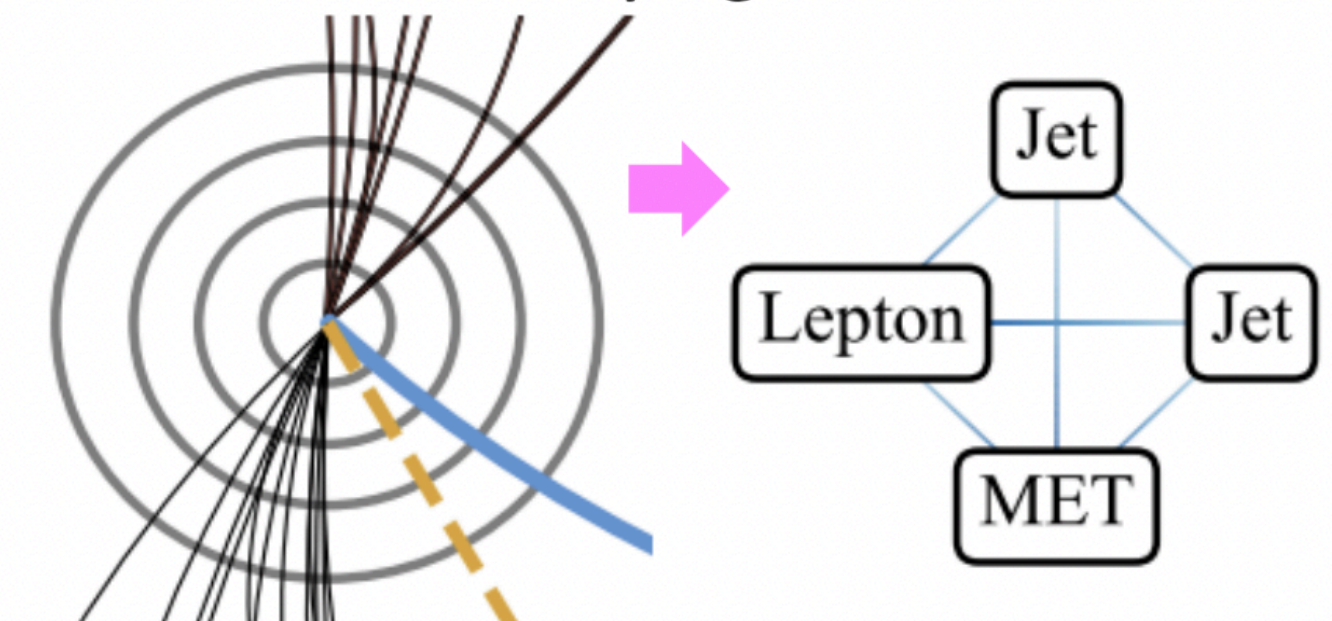
Classifying Jets (streams of particles)



Calorimeter cluster analysis



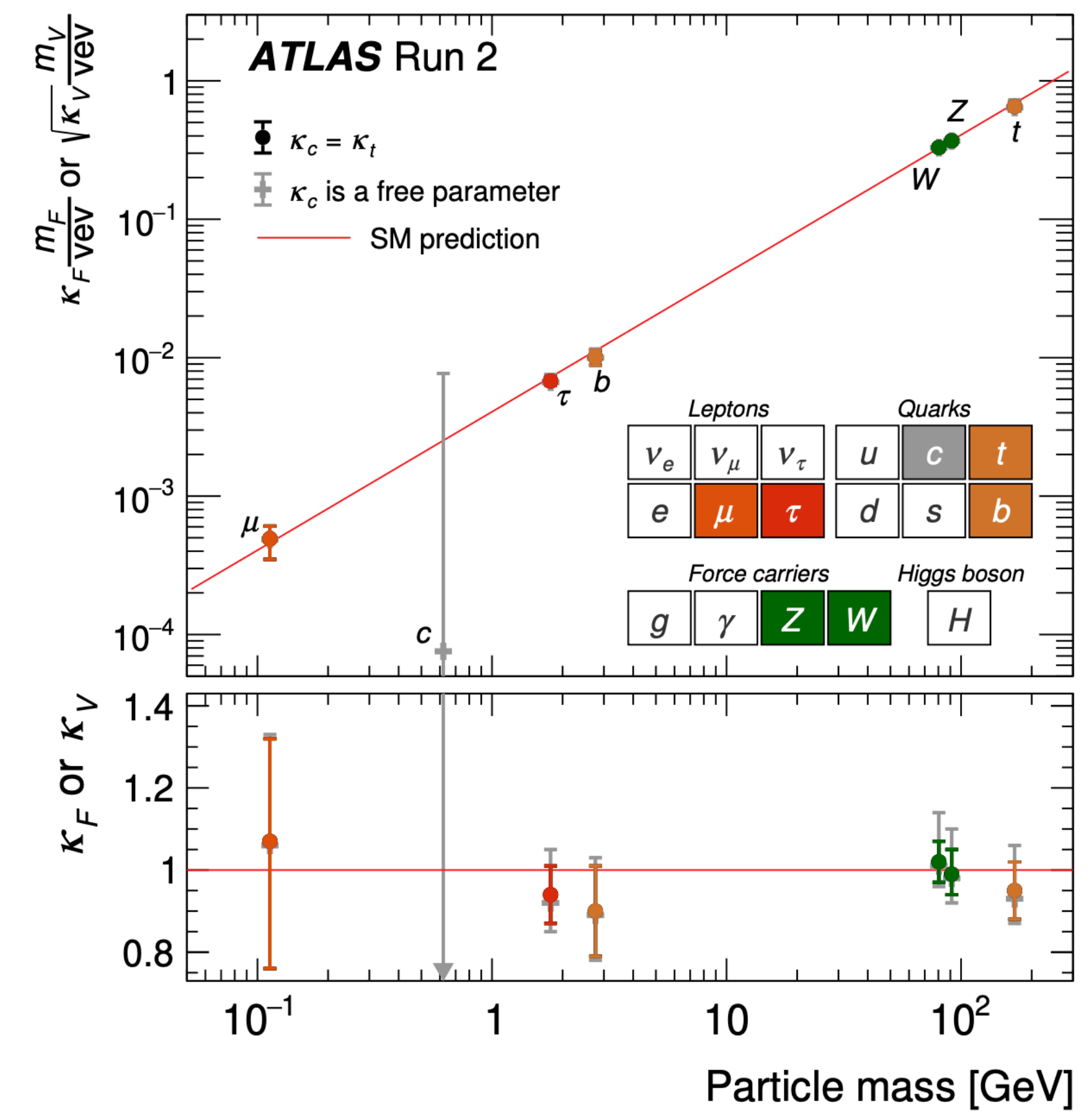
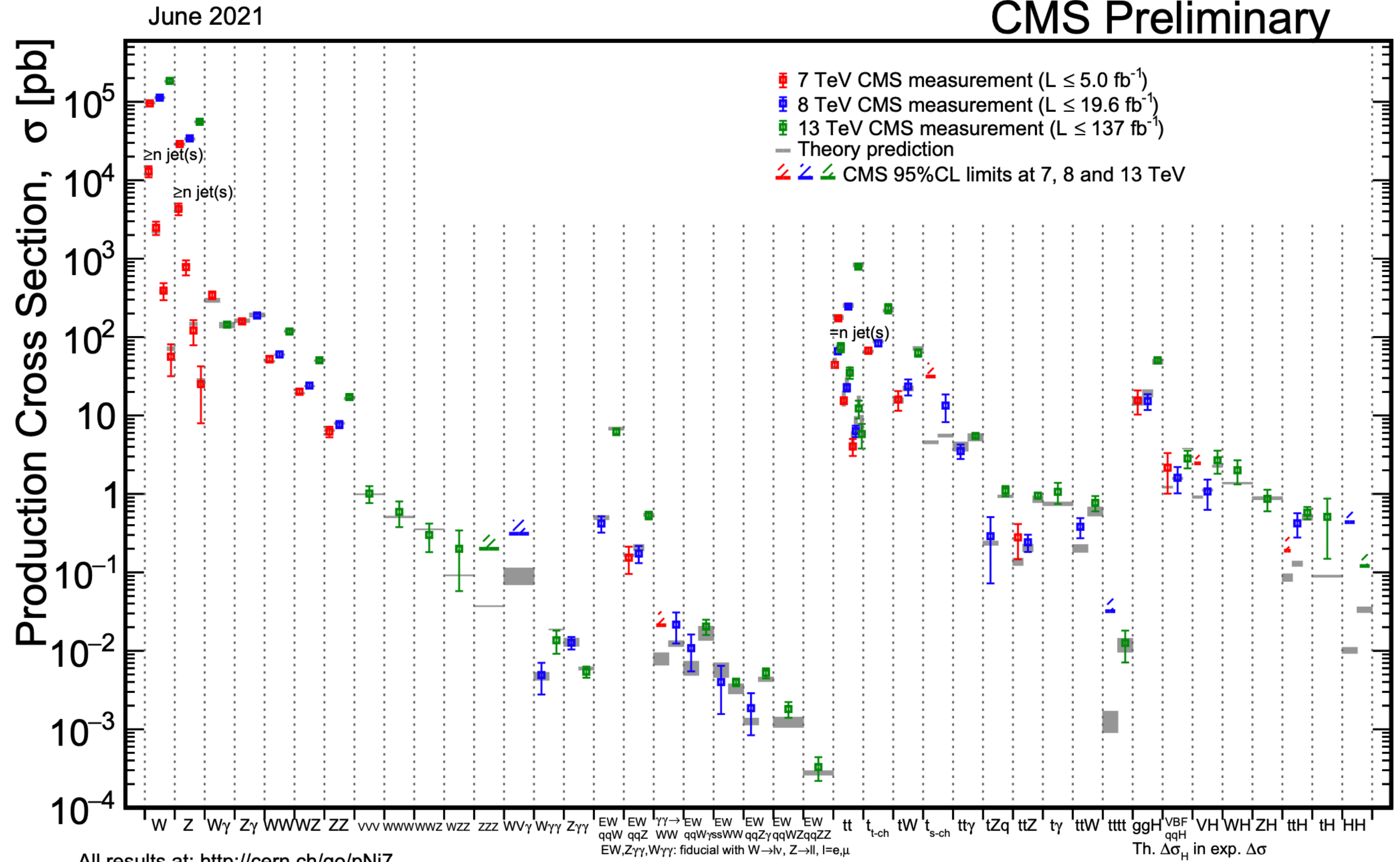
Classifying Events



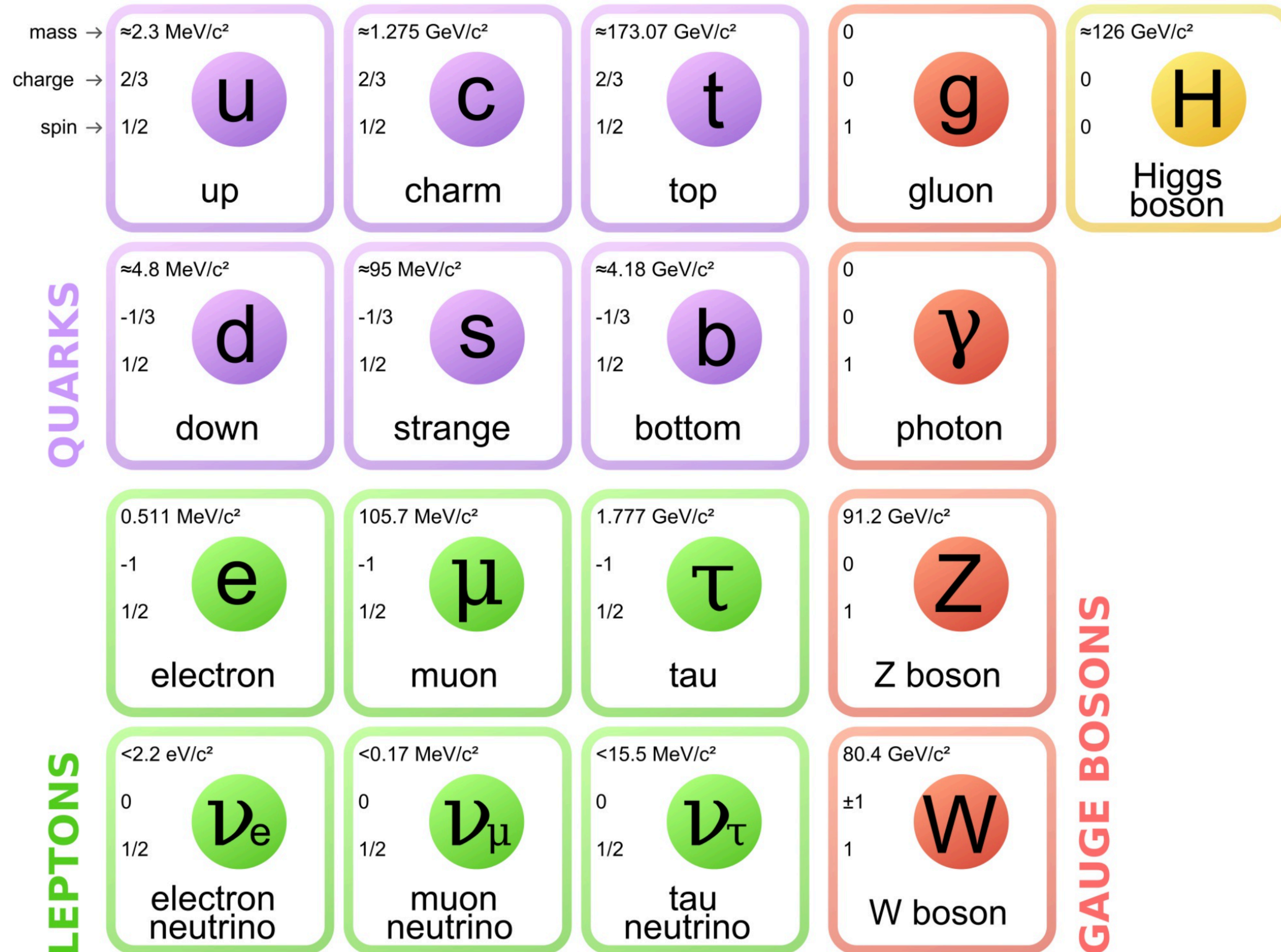
Standard Model Measurements

Standard Model cross sections

Higgs boson couplings



The Standard Model



Beyond the Standard Model?

	mass →	$\approx 2.3 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 173.07 \text{ GeV}/c^2$	0	$\approx 126 \text{ GeV}/c^2$
c charge →		2/3	2/3	2/3	0	0
spin →		1/2	1/2	1/2	1	0
		u up	c charm	t top	g gluon	H Higgs boson
QUARKS		$\approx 4.8 \text{ MeV}/c^2$	$\approx 95 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	?
		-1/3	-1/3	-1/3	0	?
		1/2	1/2	1/2	1	?
		d down	s strange	b bottom	γ photon	X Dark matter?
		$0.511 \text{ MeV}/c^2$	$105.7 \text{ MeV}/c^2$	$1.777 \text{ GeV}/c^2$	$91.2 \text{ GeV}/c^2$	
		-1	-1	-1	0	
		1/2	1/2	1/2	1	
		e electron	μ muon	τ tau	Z Z boson	
LEPTONS		$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 15.5 \text{ MeV}/c^2$	$80.4 \text{ GeV}/c^2$	
		0	0	0	± 1	
		1/2	1/2	1/2	1	
		ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
						GAUGE BOSONS

Beyond the Standard Model?

	mass →	$\approx 2.3 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 173.07 \text{ GeV}/c^2$	0	$\approx 126 \text{ GeV}/c^2$
	c charge →	$2/3$	$2/3$	$2/3$	0	0
	spin →	$1/2$	$1/2$	$1/2$	1	0
		u up	c charm	t top	g gluon	H Higgs boson
QUARKS		$\approx 4.8 \text{ MeV}/c^2$	$\approx 95 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	?
		$-1/3$	$-1/3$	$-1/3$	0	?
		$1/2$	$1/2$	$1/2$	1	?
		d down	s strange	b bottom	γ photon	X Dark matter?
		$0.511 \text{ MeV}/c^2$	$105.7 \text{ MeV}/c^2$	$1.777 \text{ GeV}/c^2$	$91.2 \text{ GeV}/c^2$	
		-1	-1	-1	0	
		$1/2$	$1/2$	$1/2$	1	
		e electron	μ muon	τ tau	Z Z boson	
LEPTONS		$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 15.5 \text{ MeV}/c^2$	$80.4 \text{ GeV}/c^2$	
		0	0	0	± 1	
		$1/2$	$1/2$	$1/2$	1	
		ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
					GAUGE BOSONS	

Beyond the Standard Model?

	mass →	$\approx 2.3 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 173.07 \text{ GeV}/c^2$	0	$\approx 126 \text{ GeV}/c^2$?
QUARKS	^c charge →	2/3	2/3	2/3	0	0	?
	spin →	1/2	1/2	1/2	1	0	?
		u up	c charm	t top	g gluon	H Higgs boson	? ???
		$\approx 4.8 \text{ MeV}/c^2$	$\approx 95 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	?	?
		-1/3	-1/3	-1/3	0	?	?
		1/2	1/2	1/2	1	?	?
		d down	s strange	b bottom	γ photon	X Dark matter?	Z' New force carrier?
		0.511 MeV/c^2	105.7 MeV/c^2	1.777 GeV/c^2	91.2 GeV/c^2		
		-1	-1	-1	0		
		1/2	1/2	1/2	1		
		e electron	μ muon	τ tau	Z Z boson		
LEPTONS		$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 15.5 \text{ MeV}/c^2$	80.4 GeV/c^2		
		0	0	0	± 1		
		1/2	1/2	1/2	1		
		ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson		

Beyond the Standard Model?

ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: March 2023

ATLAS Preliminary

$\int \mathcal{L} dt = (3.6 - 139) \text{ fb}^{-1}$ $\sqrt{s} = 13 \text{ TeV}$

Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
Extra dimen.	ADD $G_{KK} + g/q$	$0, e, \mu, \tau, \gamma$	$1-4j$	Yes	139	M_D 11.2 TeV $n=2$
	ADD non-resonant $\gamma\gamma$	2γ	-	-	36.7	M_S 8.6 TeV $n=3$ HLZ NLO
	ADD QBH	-	$2j$	-	139	M_{th} 9.4 TeV $n=6$
	ADD BH multijet	-	$\geq 3j$	-	3.6	M_{th} 9.55 TeV $n=6, M_D=3 \text{ TeV, rot BH}$
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2γ	-	-	139	$G_{KK} \text{ mass}$ 4.5 TeV $k/\overline{M}_{Pl} = 0.1$
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	$G_{KK} \text{ mass}$ 2.3 TeV $k/\overline{M}_{Pl} = 1.0$
	Bulk RS $g_{KK} \rightarrow tt$	$1, e, \mu$	$\geq 1b, \geq 1J/2j$	Yes	36.1	$g_{KK} \text{ mass}$ 3.8 TeV $\Gamma/m = 15\%$
	2UED / RPP	$1, e, \mu$	$\geq 2b, \geq 3j$	Yes	36.1	KK mass 1.8 TeV Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow tt) = 1$
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2, e, \mu$	-	-	139	$Z' \text{ mass}$ 5.1 TeV
	SSM $Z' \rightarrow \tau\tau$	2τ	-	-	36.1	$Z' \text{ mass}$ 2.42 TeV
	Leptophobic $Z' \rightarrow bb$	-	$2b$	-	36.1	$Z' \text{ mass}$ 2.1 TeV
	Leptophobic $Z' \rightarrow tt$	$0, e, \mu$	$\geq 1b, \geq 2j$	Yes	139	$Z' \text{ mass}$ 4.1 TeV $\Gamma/m = 1.2\%$
	SSM $W' \rightarrow \ell\nu$	$1, e, \mu$	-	-	139	$W' \text{ mass}$ 6.0 TeV
	SSM $W' \rightarrow \tau\nu$	1τ	-	-	139	$W' \text{ mass}$ 5.0 TeV
	SSM $W' \rightarrow tb$	-	$\geq 1b, \geq 1j$	-	139	$W' \text{ mass}$ 4.4 TeV
	HVT $W' \rightarrow WZ$ model B	$0-2, e, \mu$	$2j/1j$	Yes	139	$W' \text{ mass}$ 4.3 TeV
	HVT $W' \rightarrow WZ \rightarrow \ell\nu \ell' \ell'$ model C	$3, e, \mu$	$2j$ (VBF)	Yes	139	$W' \text{ mass}$ 340 GeV
	LRT $Z' \rightarrow WW$ model B	$1, e, \mu$	$2j/1j$	Yes	139	$Z' \text{ mass}$ 3.9 TeV
	HVSM $W_R \rightarrow \mu N_R$	2μ	$1j$	-	80	$W_R \text{ mass}$ 5.0 TeV $g_V = 3, g_V c_H = 1, g_R = 0, g_V = 3, m(N_R) = 0.5 \text{ TeV, } g_L = g_R$
CI	CI $qqqq$	-	$2j$	-	37.0	Λ 21.8 TeV η_{LL}
	CI $\ell\ell qq$	$2, e, \mu$	-	-	139	Λ 35.8 TeV η_{LL}
	CI $eebs$	$2, e$	$1b$	-	139	Λ 1.8 TeV $g_s = 1$
	CI $\mu\mu bs$	$2, \mu$	$1b$	-	139	Λ 2.0 TeV $g_s = 1$
	CI $tttt$	$\geq 1, e, \mu$	$\geq 1b, \geq 1j$	Yes	36.1	Λ 2.57 TeV $ C_{4\ell} = 4\pi$
DM	Axial-vector med. (Dirac DM)	-	$2j$	-	139	m_{med} 3.8 TeV $g_a = 0.25, g_s = 1, m(\chi) = 10 \text{ TeV}$
	Pseudo-scalar med. (Dirac DM)	$0, e, \mu, \tau, \gamma$	$1-4j$	Yes	139	m_{med} 376 GeV $g_a = 1, g_s = 1, m(\chi) = 1 \text{ GeV}$
	Vector med. Z' -2HDM (Dirac DM)	$0, e, \mu$	$2b$	Yes	139	$m_{Z'}$ 3.0 TeV $\tan\beta = 1, g_Z = 0.8, m(\chi) = 100 \text{ GeV}$
	Pseudo-scalar med. 2HDM+a	multi-channel	-	-	139	m_a 800 GeV $\tan\beta = 1, g_s = 1, m(\chi) = 10 \text{ GeV}$
LQ	Scalar LQ 1 st gen	$2, e$	$\geq 2j$	Yes	139	LQ mass 1.8 TeV $\beta = 1$
	Scalar LQ 2 nd gen	$2, \mu$	$\geq 2j$	Yes	139	LQ mass 1.7 TeV $\beta = 1$
	Scalar LQ 3 rd gen	$1, \tau$	$2b$	Yes	139	LQ ₃ mass 1.49 TeV $\mathcal{B}(LQ_3^u \rightarrow br) = 1$
	Scalar LQ 3 rd gen	$0, e, \mu$	$\geq 2j, \geq 2b$	Yes	139	LQ ₃ mass 1.24 TeV $\mathcal{B}(LQ_3^u \rightarrow \nu\nu) = 1$
	Scalar LQ 3 rd gen	$\geq 2, e, \mu, \geq 1\tau, \geq 1j, \geq 1b$	-	-	139	LQ ₃ mass 1.43 TeV $\mathcal{B}(LQ_3^u \rightarrow t\tau) = 1$
	Scalar LQ 3 rd gen	$0, e, \mu, \geq 1\tau, 0-2j, 2b$	-	-	139	LQ ₃ mass 1.26 TeV $\mathcal{B}(LQ_3^u \rightarrow b\nu) = 1$
	Vector LQ mix gen	multi-channel	$\geq 1j, \geq 1b$	Yes	139	LQ ₃ mass 2.0 TeV $\mathcal{B}(U_1 \rightarrow t\mu) = 1, \text{Y-M coupl.}$
	Vector LQ 3 rd gen	$2, e, \mu, \tau$	$\geq 1b$	Yes	139	LQ ₃ mass 1.96 TeV $\mathcal{B}(LQ_3^u \rightarrow br) = 1, \text{Y-M coupl.}$
Vector-like fermions	VLQ $TT \rightarrow Zt + X$	$2e/2\mu \geq 3e, \mu \geq 1b, \geq 1j$	-	-	139	T mass 1.46 TeV SU(2) doublet
	VLQ $BB \rightarrow Wt/Zb + X$	multi-channel	-	-	36.1	B mass 1.34 TeV SU(2) doublet
	VLQ $T_{5/3} T_{5/3} T_{5/3} \rightarrow Wt + X$	$2(SS) \geq 3, e, \mu \geq 1b, \geq 1j$	Yes	36.1	$T_{5/3}$ mass 1.64 TeV $\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3} Wt) = 1$	
	VLQ $T \rightarrow Ht/Zt$	$1, e, \mu, \geq 1b, \geq 3j$	Yes	139	T mass 1.8 TeV SU(2) singlet, $\kappa_T = 0.5$	
	VLQ $Y \rightarrow Wb$	$1, e, \mu, \geq 1b, \geq 1j$	Yes	36.1	Y mass 1.85 TeV $\mathcal{B}(Y \rightarrow Wb) = 1, c_Y(Wb) = 1$	
	VLQ $B \rightarrow Hb$	$0, e, \mu, \geq 2b, \geq 1j, \geq 1j$	-	-	139	B mass 2.0 TeV SU(2) doublet, $\kappa_B = 0.3$
	VLL $\tau' \rightarrow Z\tau/H\tau$	multi-channel	$\geq 1j$	Yes	139	τ' mass 898 GeV SU(2) doublet
Excited ferm.	Excited quark $q^* \rightarrow qg$	-	$2j$	-	139	$q^* \text{ mass}$ 6.7 TeV only u' and d' , $\Lambda = m(q^*)$
	Excited quark $q^* \rightarrow q\gamma$	1γ	$1j$	-	36.7	$q^* \text{ mass}$ 5.3 TeV only u' and d' , $\Lambda = m(q^*)$
	Excited quark $b^* \rightarrow bg$	-	$1b, 1j$	-	139	$b^* \text{ mass}$ 3.2 TeV $\Lambda = 4.6 \text{ TeV}$
	Excited lepton τ^*	2τ	$\geq 2j$	-	139	$\tau^* \text{ mass}$ 4.6 TeV
Other	Type III Seesaw	$2, 3, 4, e, \mu$	$\geq 2j$	Yes	139	$N_R \text{ mass}$ 910 GeV $m(W_R) = 4.1 \text{ TeV, } g_L = g_R$
	LRSM Majorana ν	$2, \mu$	$2j$	-	36.1	$N_R \text{ mass}$ 3.2 TeV DY production
	Higgs triplet $H^{\pm\pm} \rightarrow W^\pm W^\pm$	$2, 3, 4, e, \mu$ (SS)	various	Yes	139	$H^{\pm\pm} \text{ mass}$ 350 GeV DY production
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2, 3, 4, e, \mu$ (SS)	-	-	139	$H^{\pm\pm} \text{ mass}$ 1.08 TeV DY production, $ q = 5e$
	Multi-charged particles	-	-	-	139	multi-charged particle mass 1.59 TeV DY production, $ q = 5e$
	Magnetic monopoles	-	-	-	34.4	monopole mass 2.37 TeV DY production, $ g = 1g_D, \text{ spin } 1/2$

$\sqrt{s} = 13 \text{ TeV}$ partial data $\sqrt{s} = 13 \text{ TeV}$ full data

LEPTON

1/2 ν_e electron neutrino

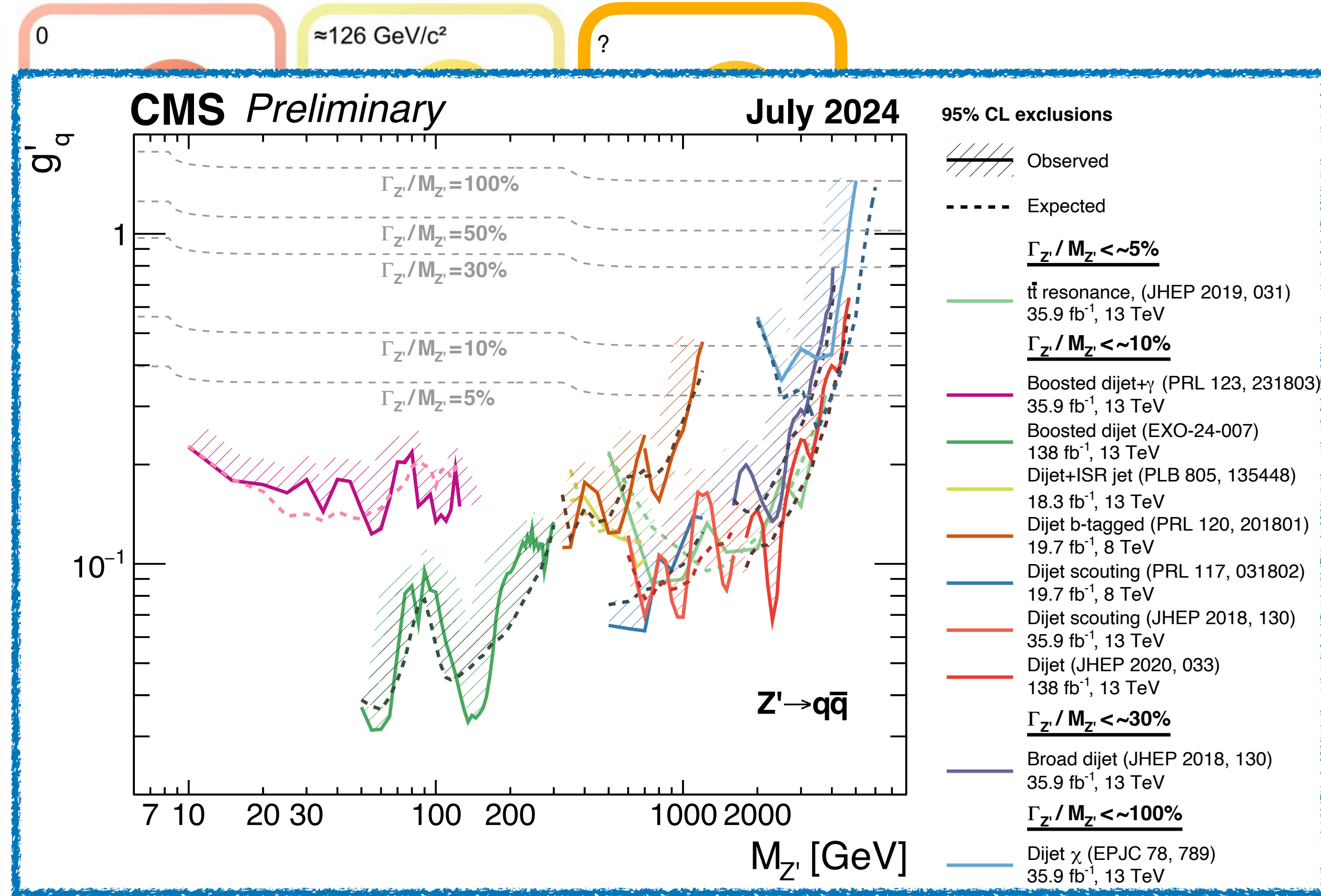
1/2 ν_μ muon neutrino

1/2 ν_τ tau neutrino

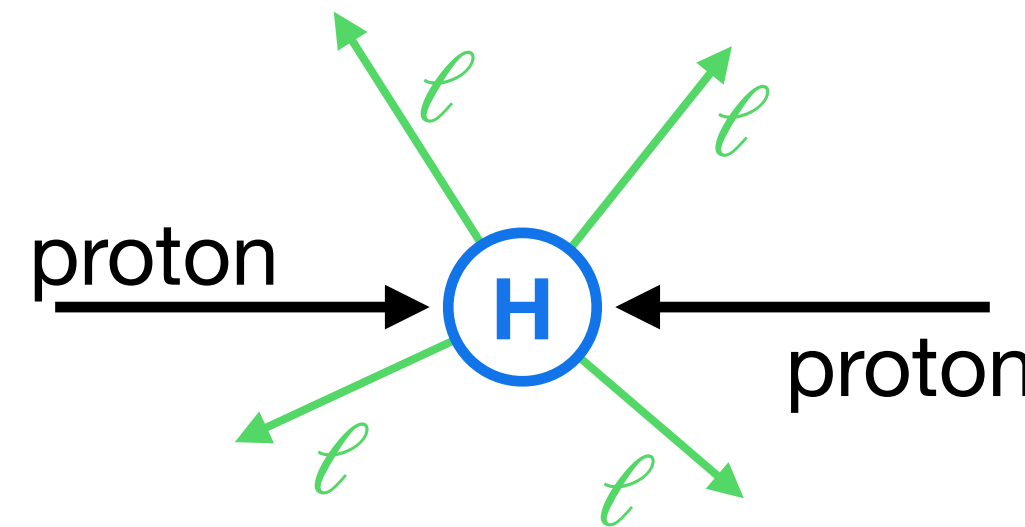
1 W W boson

GAUGE B

Searches have yet to find new particles...

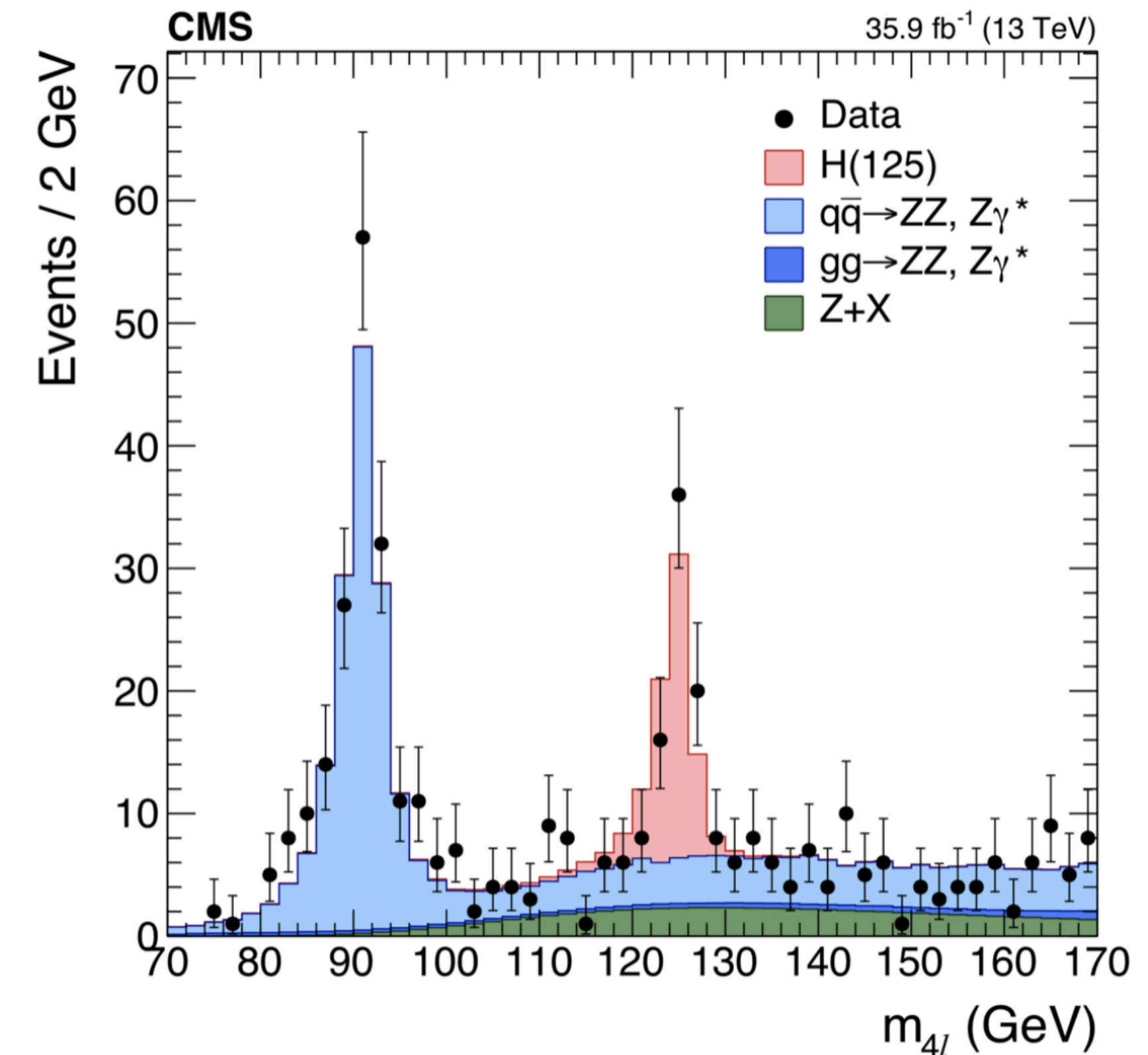


Standard LHC Searches



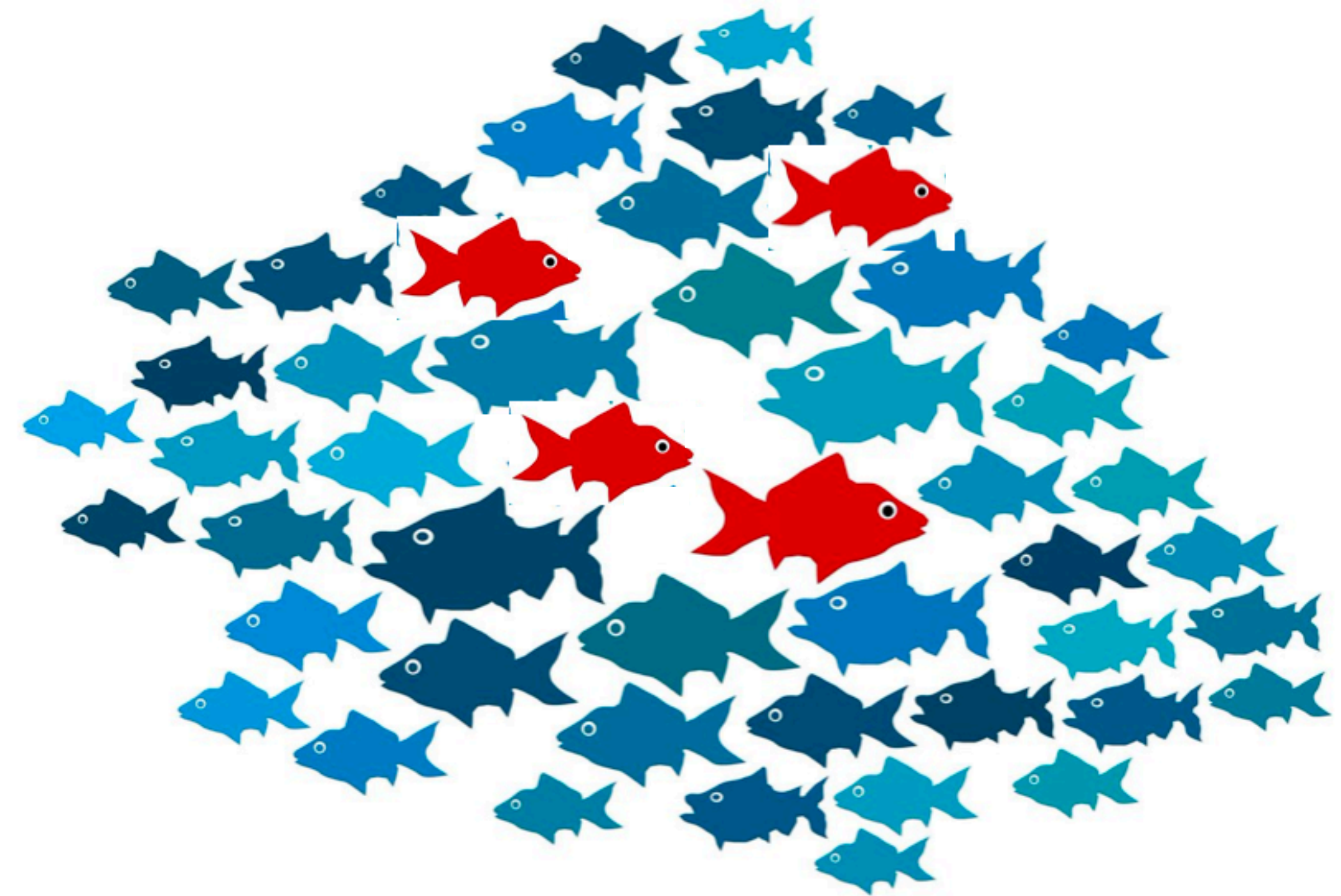
- Most searches have similar basic strategy
- Search for new particle decaying to specific particles ($H \rightarrow 4\ell$)
- Select set of events that match this (eg. have 4ℓ)
- Define some variable based on this

$$(f(\ell_1, \ell_2, \ell_3, \ell_4) \sim E_{\ell_1} + E_{\ell_2} + E_{\ell_3} + E_{\ell_4})$$
- Compare the # of events we expect to find based on Standard Model (simulation) to the # of events we actually measure (data) (■ + ■ + ■ vs. ●)



Anomaly Detection

- What if we don't know exactly what we are looking for?
 - *Select set of events that match what?*
 - *Define what variable?*
- ML offers unique solution to this challenge (no traditional alternative)
 - Broad field of ***anomaly detection (AD)***



Unsupervised Learning

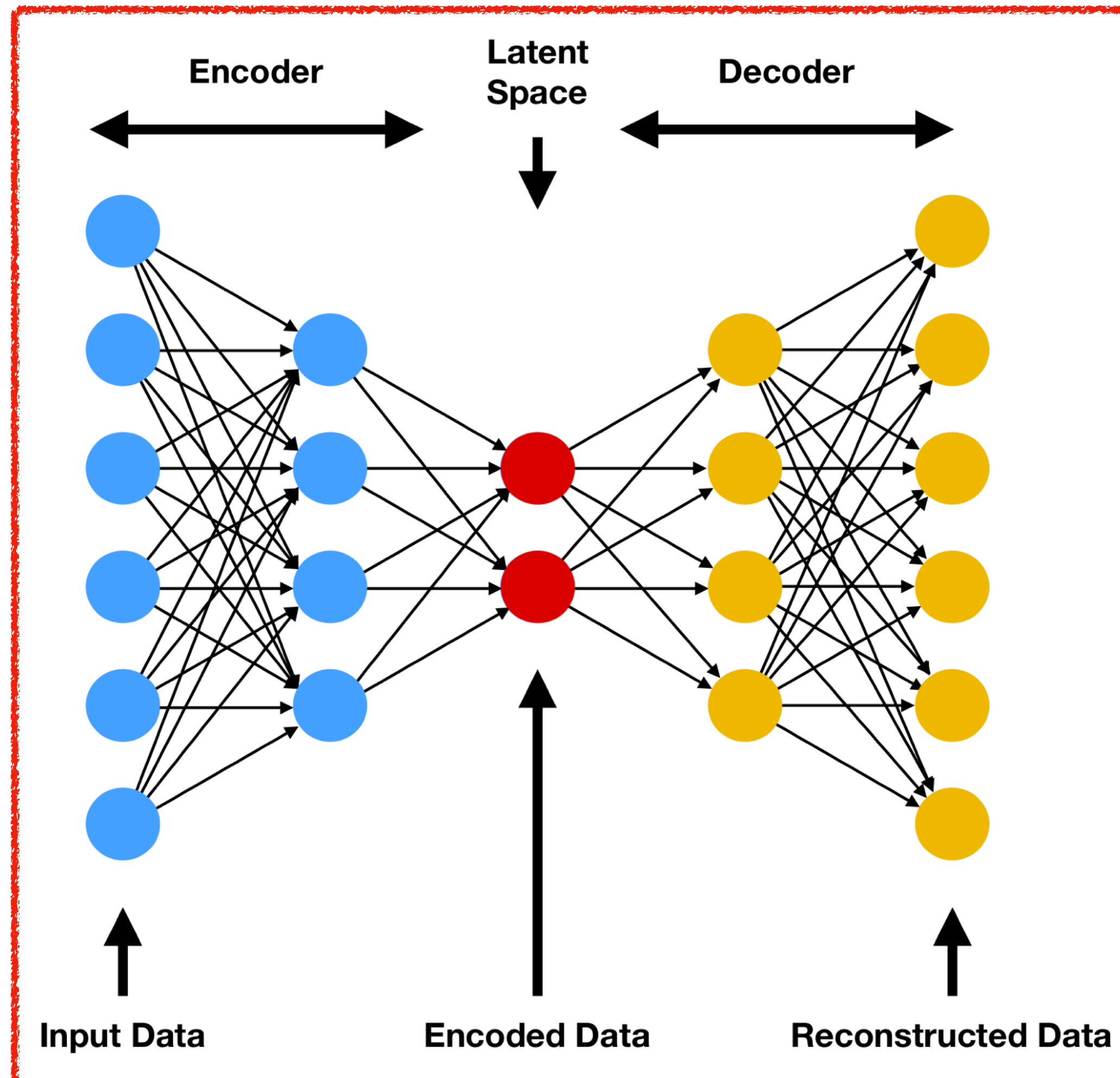
- What if we don't have/can't use labels? → “Unsupervised learning” or “self-supervised learning”

- **Autoencoder (AE):**

$$\text{Loss} = \frac{1}{N} \sum_{i=1}^N (x_i - \hat{x}_i)^2$$

mean squared error (MSE)

- AE is just simplest form of unsupervised learning

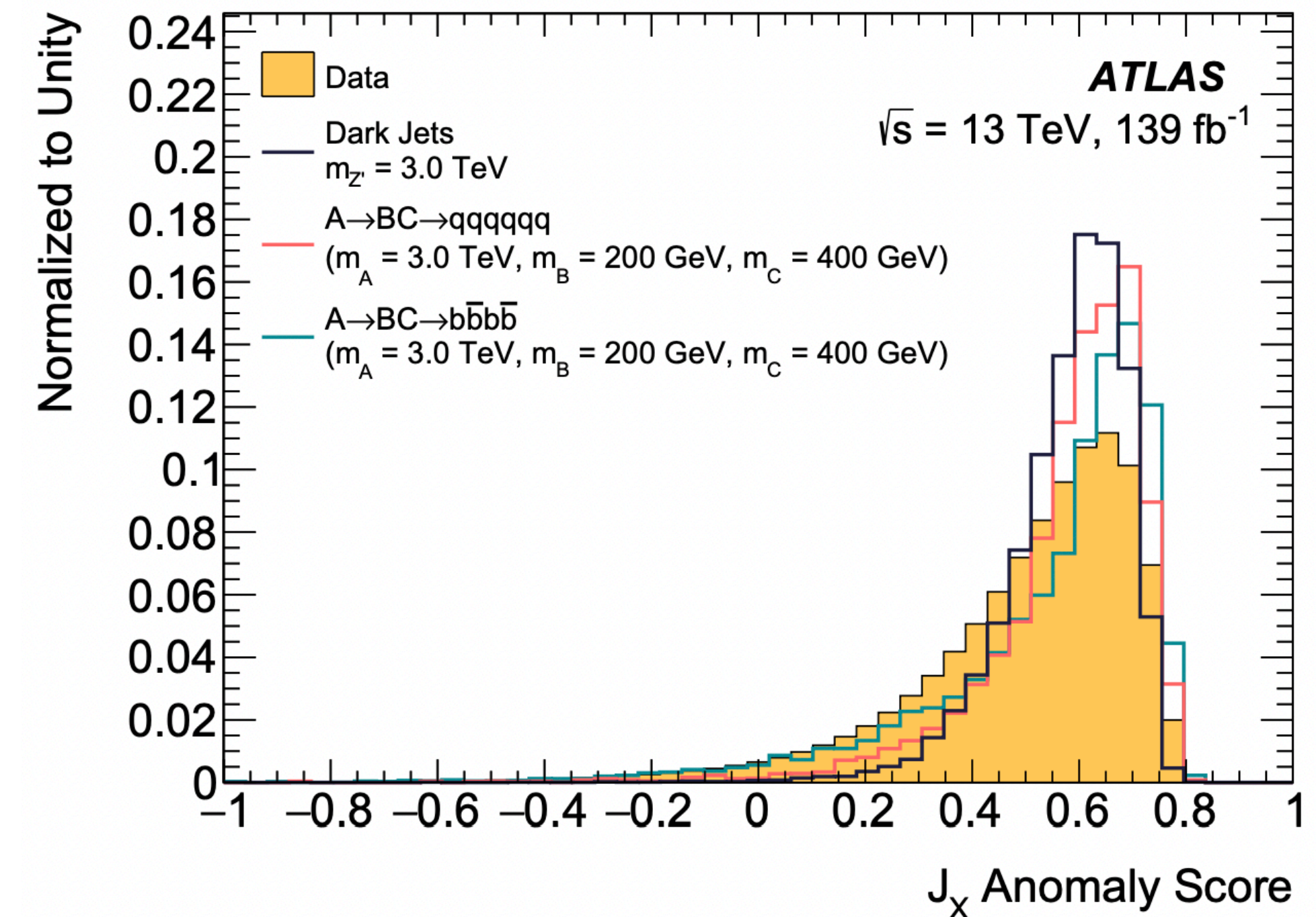
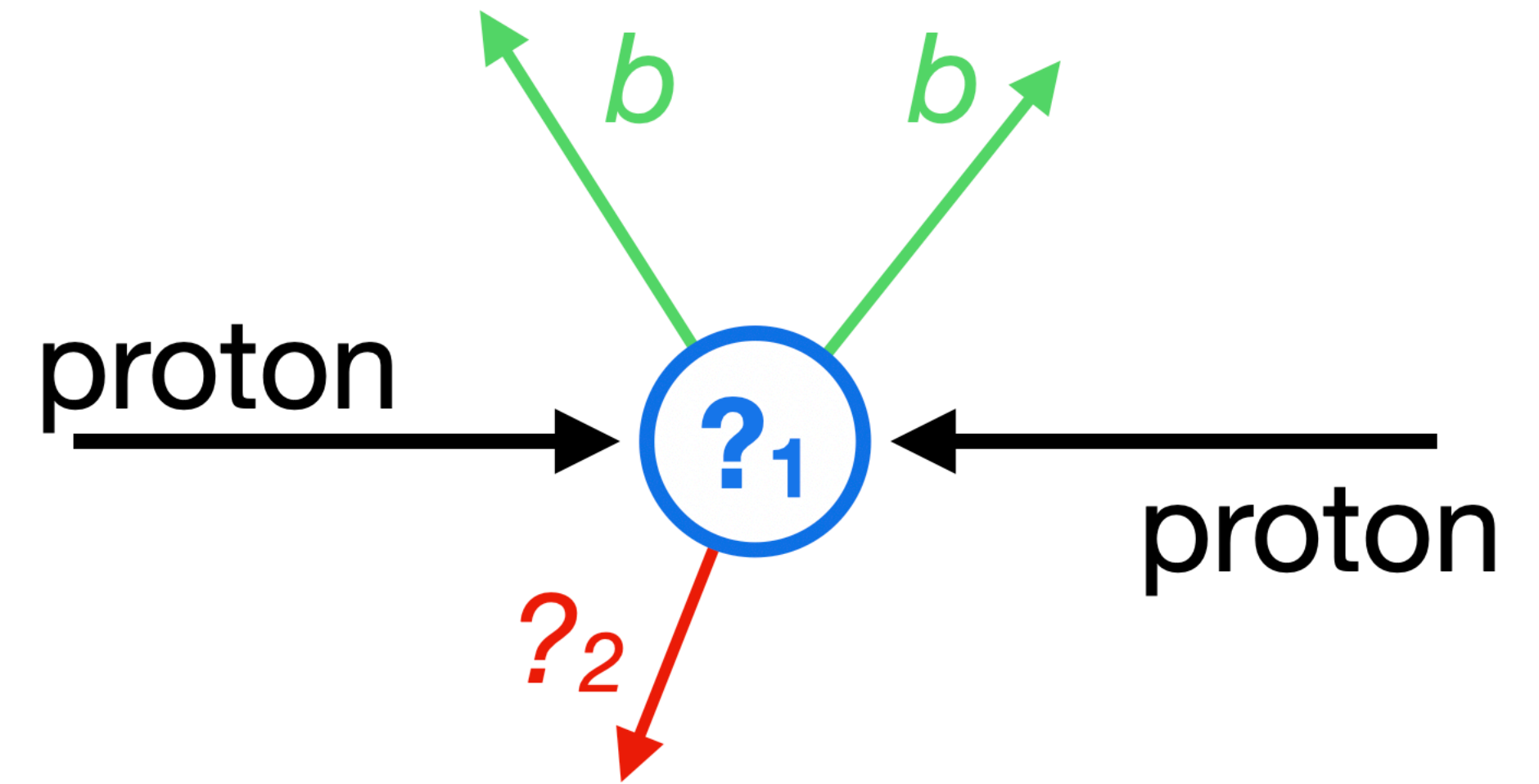


Anomaly Detection

- Train AE using known Standard Model processes
- Events with new particles may not reconstruct well

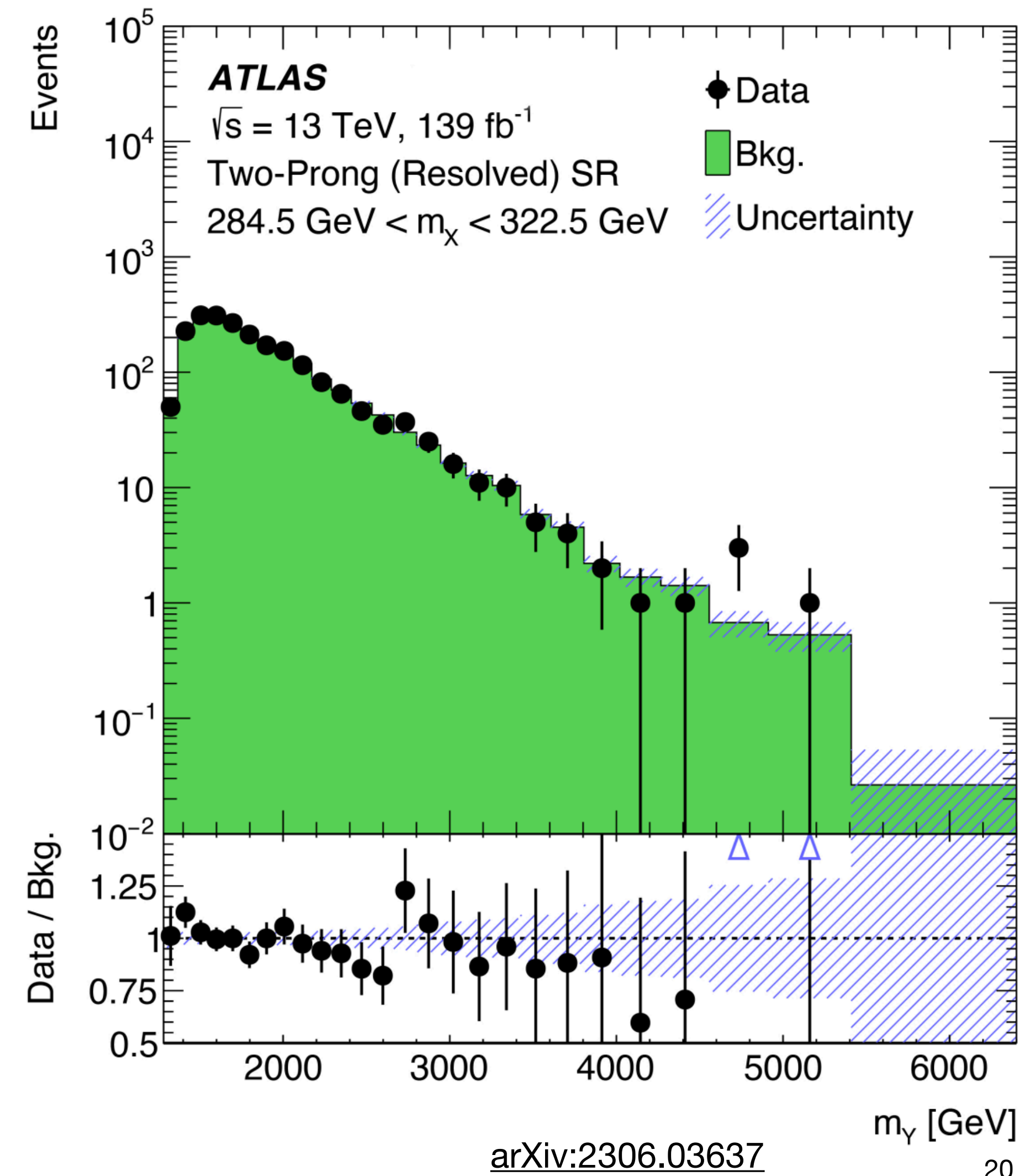
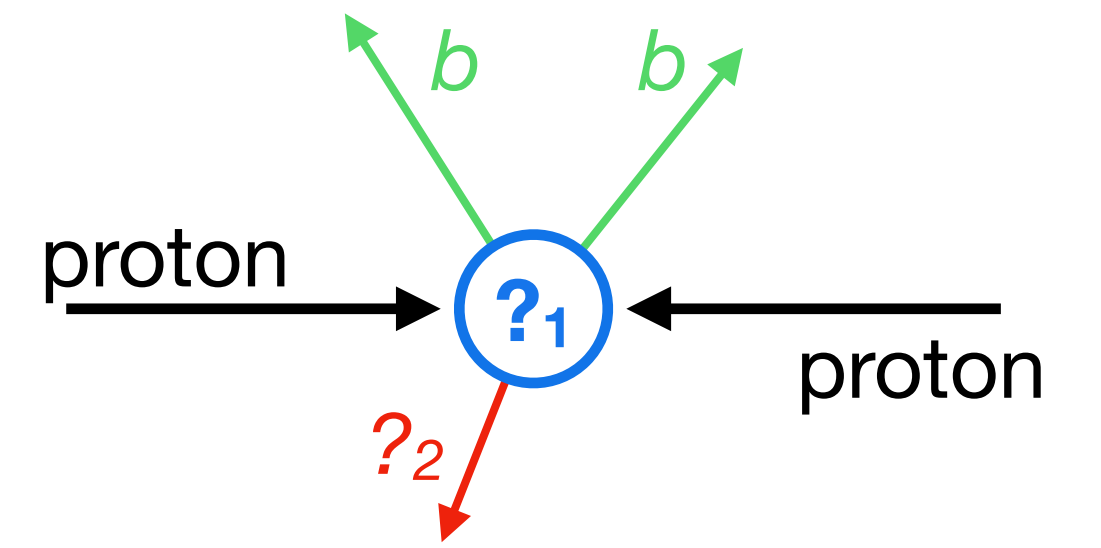
- *Select set of events that don't reconstruct well*

- $f(b_1, b_2, ?) \sim E_{b_1} + E_{b_2} + E_{?_1}$



Anomaly Detection

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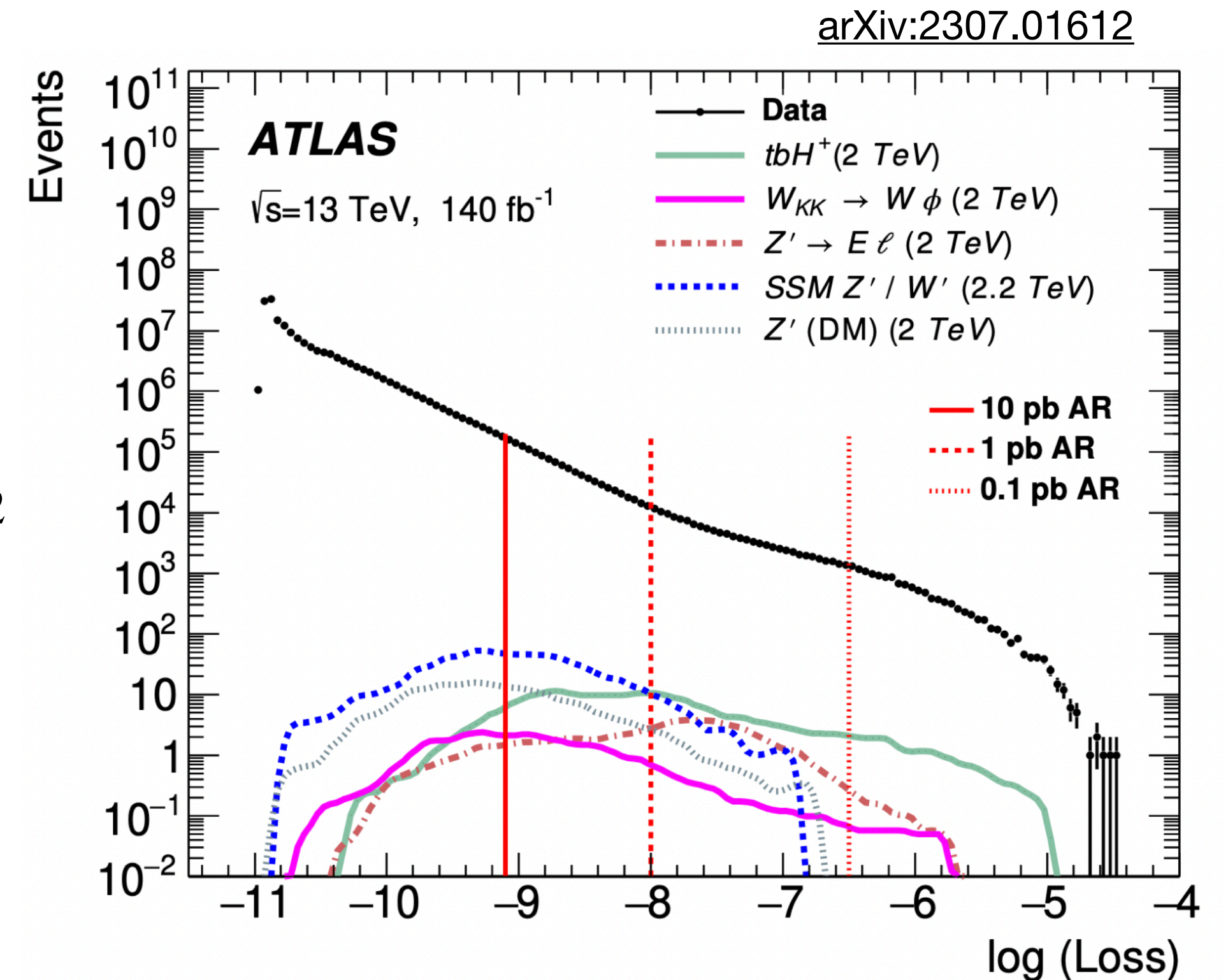
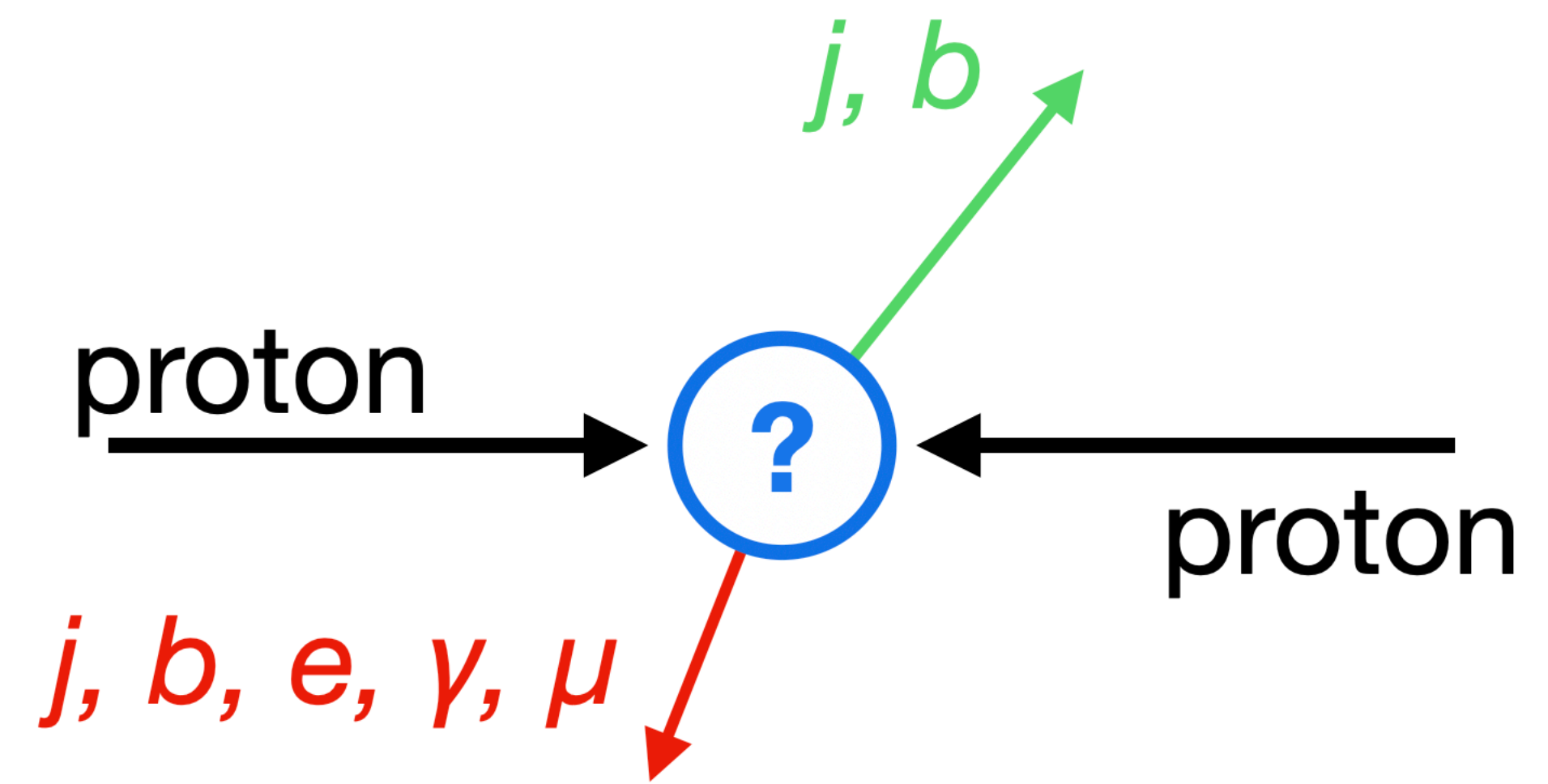


Anomaly Detection

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- *Select set of events that don't reconstruct well*

- $f(\{j, b\}_1, \{j, b, e, \gamma, \mu\}_2) \sim E_{\{j, b\}_1} + E_{\{j, b, e, \gamma, \mu\}_2}$

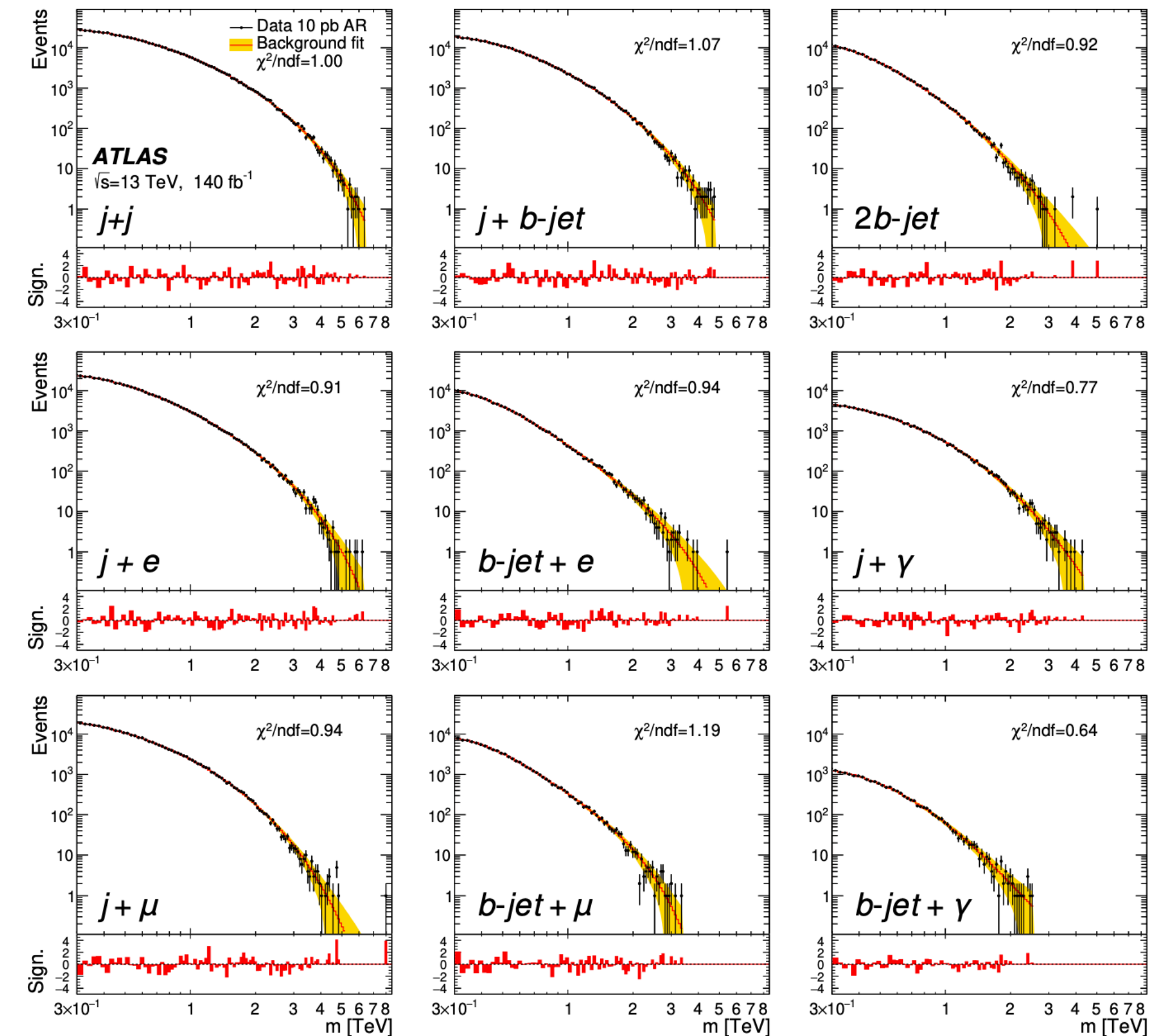
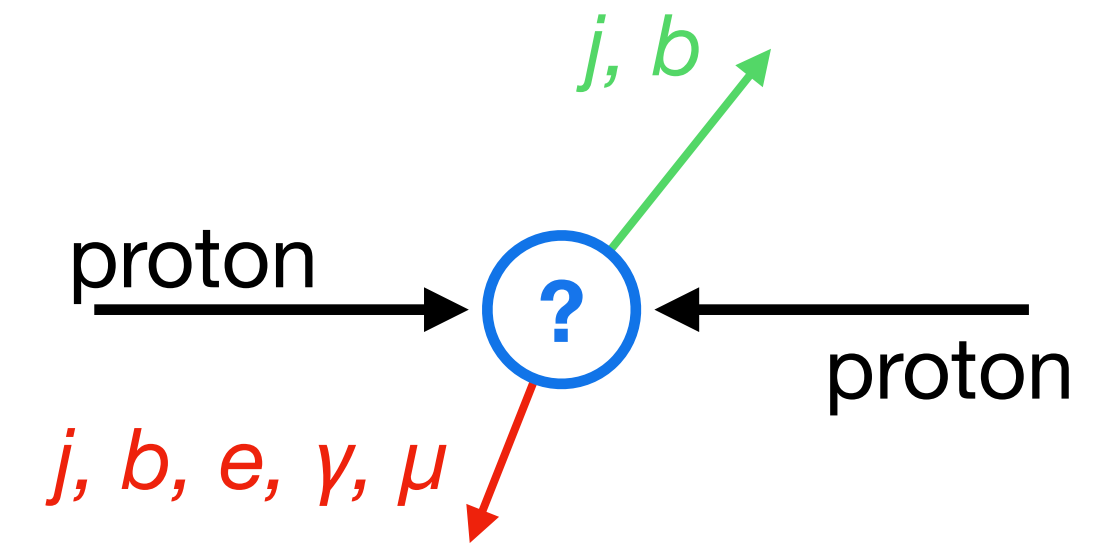


Anomaly Detection

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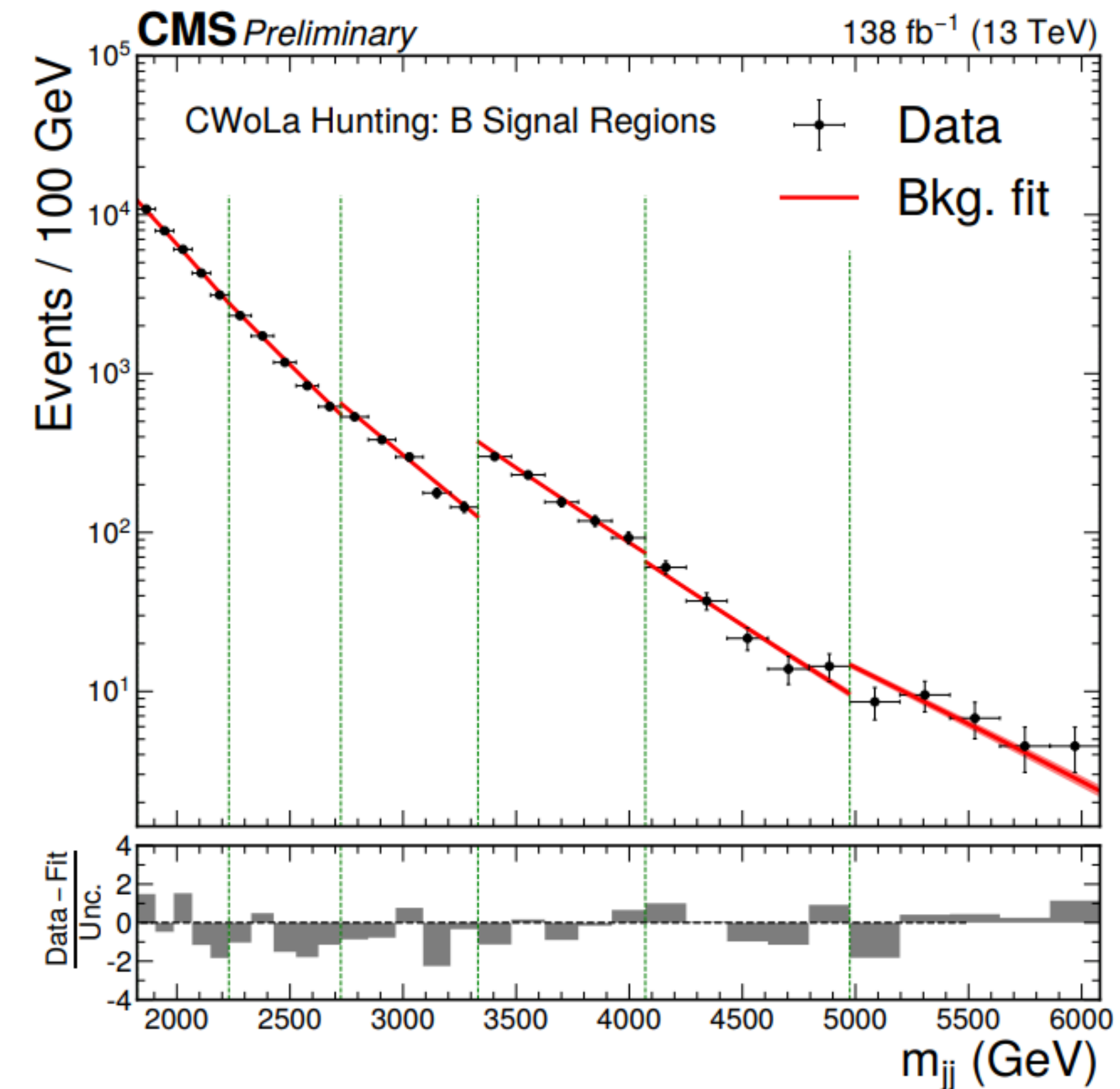
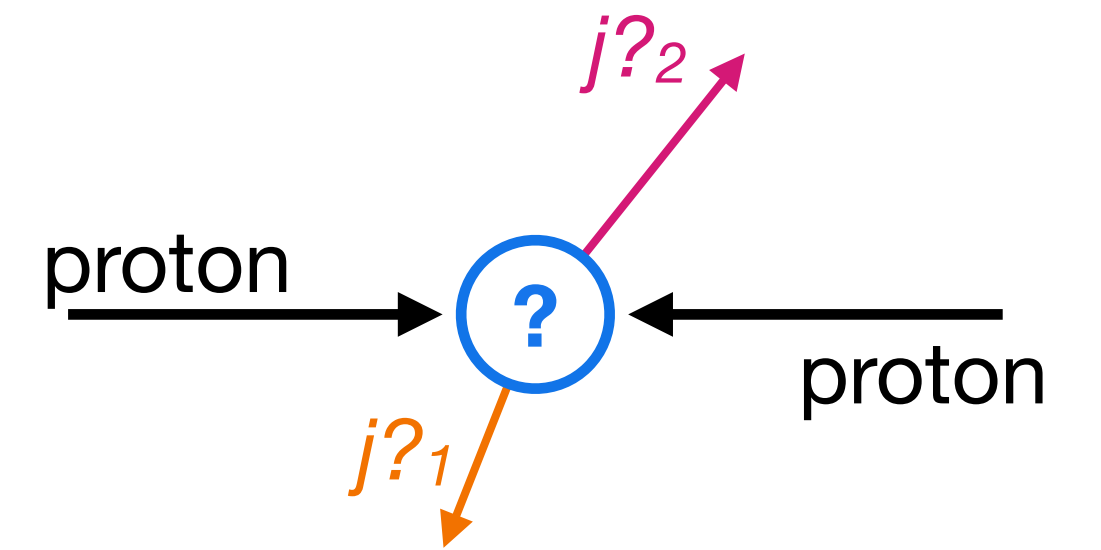
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Anomaly Detection

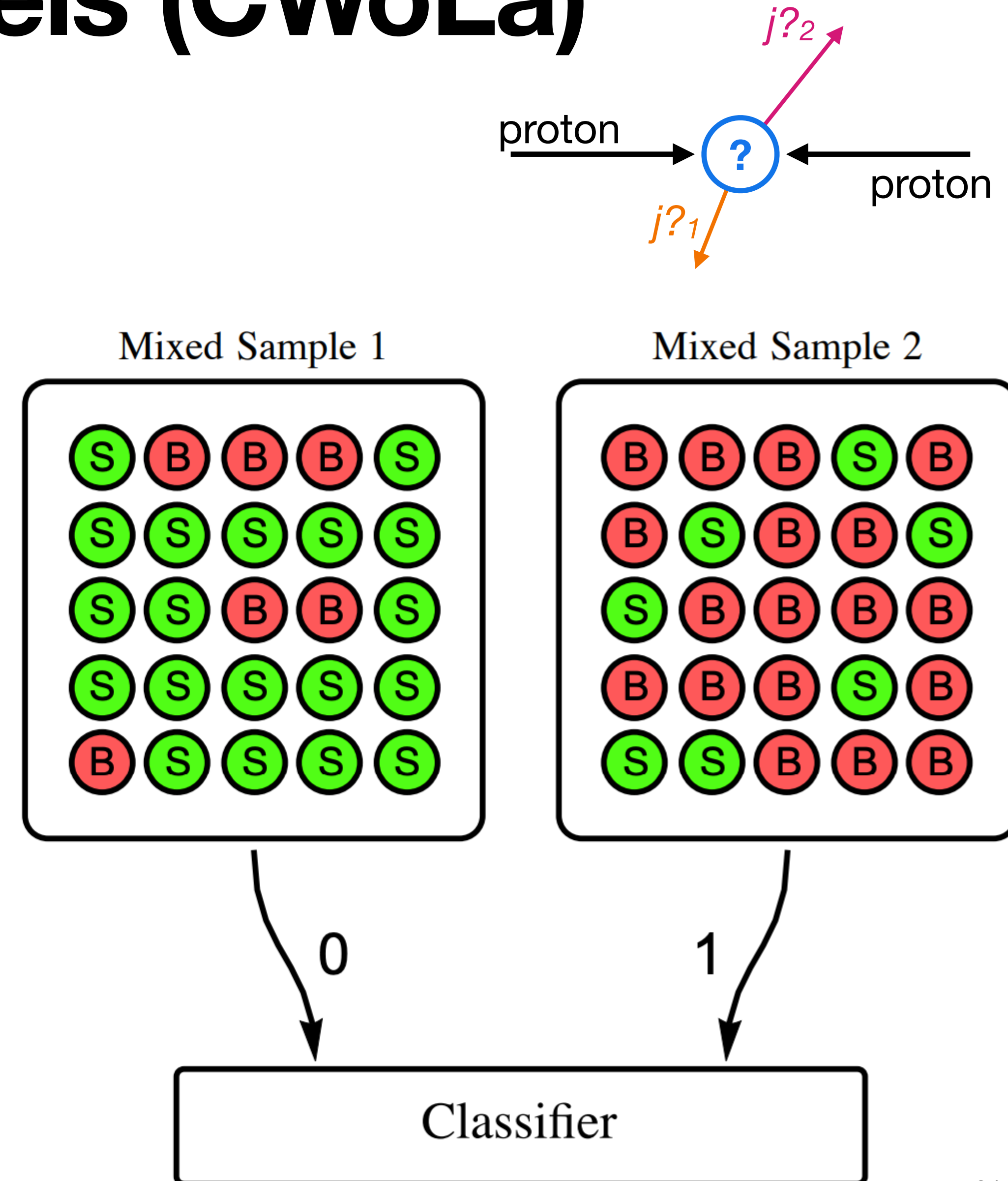
- General AD can be much worse than a dedicated search
- Some methods try to use some concept of signal, still remain insensitive to details
- “Semi-supervised” techniques

- $f(j^?_1, j^?_2) \sim E_{j^?_1} + E_{j^?_2}$



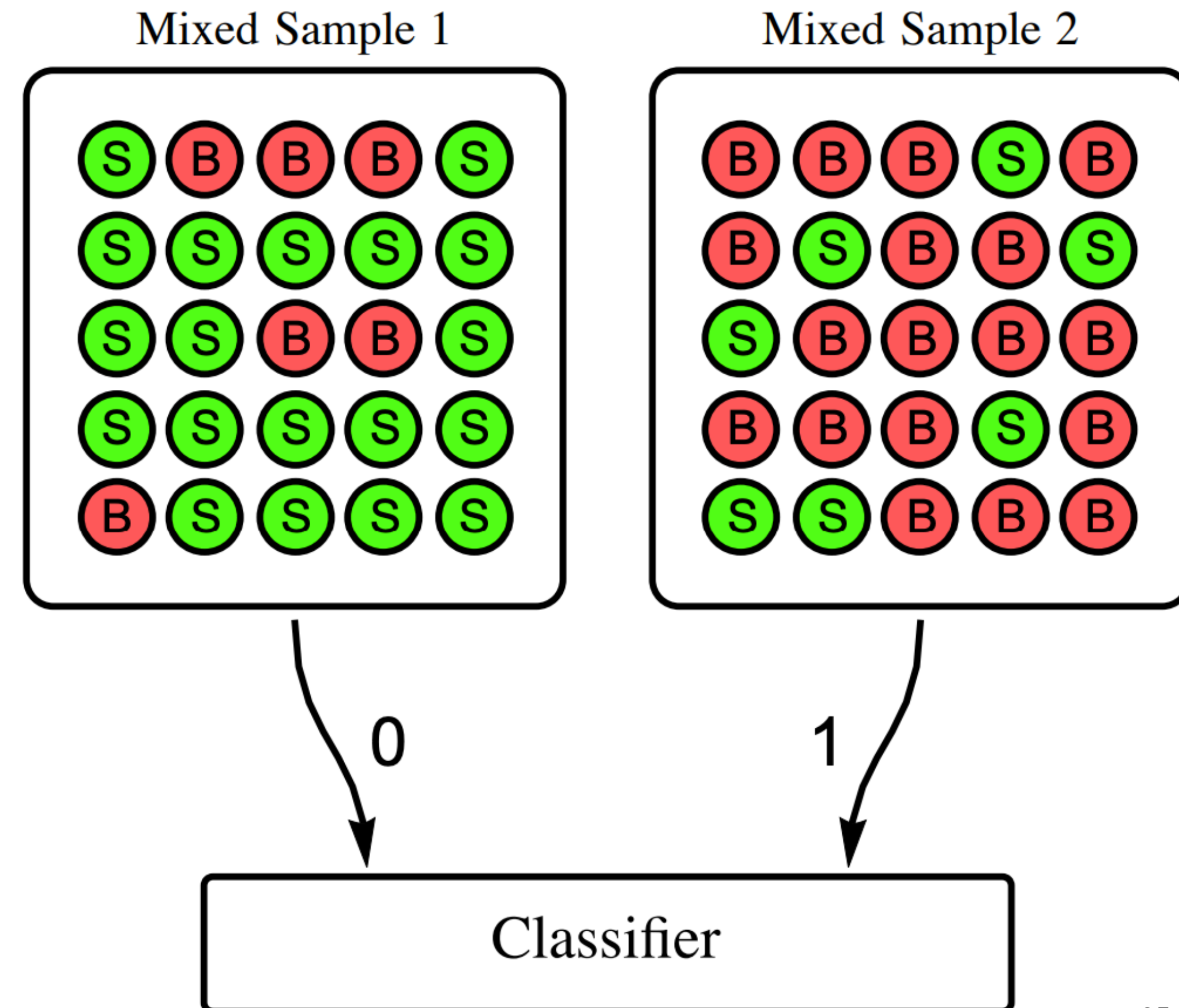
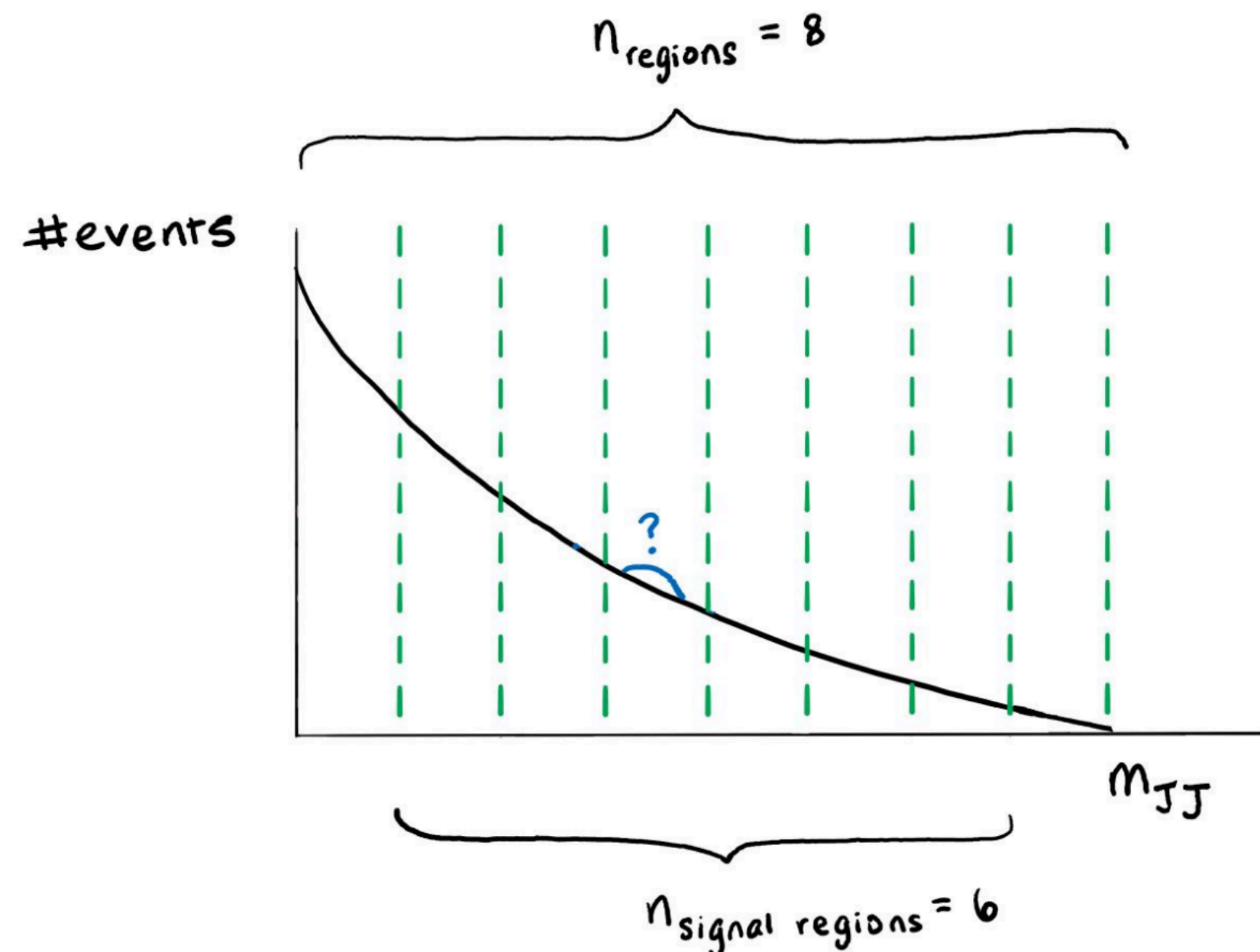
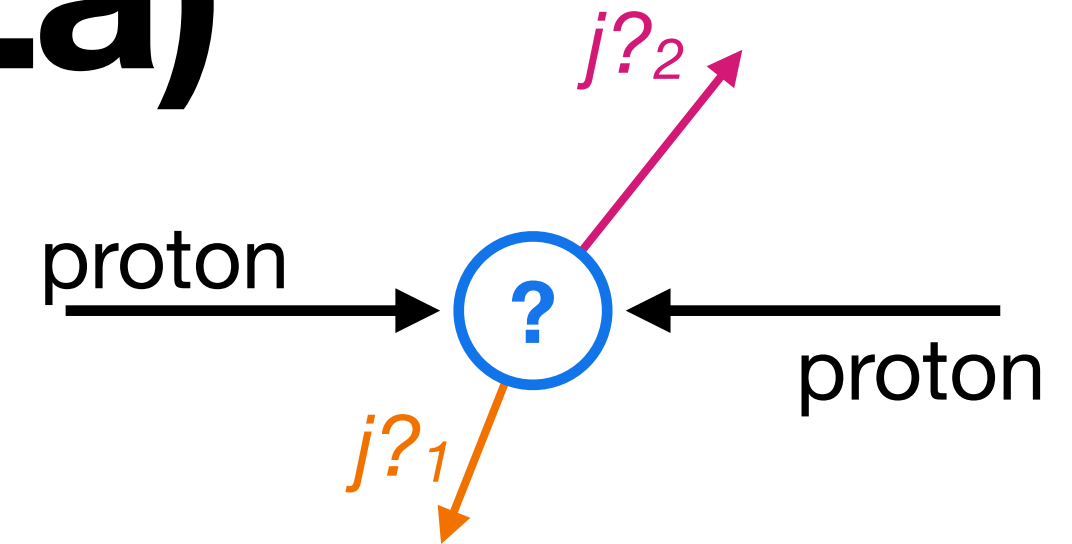
Classification Without Labels (CWoLa)

- Semi-supervised method [[arXiv:1708.02949](https://arxiv.org/abs/1708.02949)]
- Requires only $f(j^?_1, j^?_2) \sim E_{j^?_1} + E_{j^?_2}$
- If **?** is localized in $f(\cdot)$, can train supervised classifier based on mixed samples
 - In the limit this will approach normal supervised performance: classifier learns find whats different about sample 1 and 2 (S vs. B)



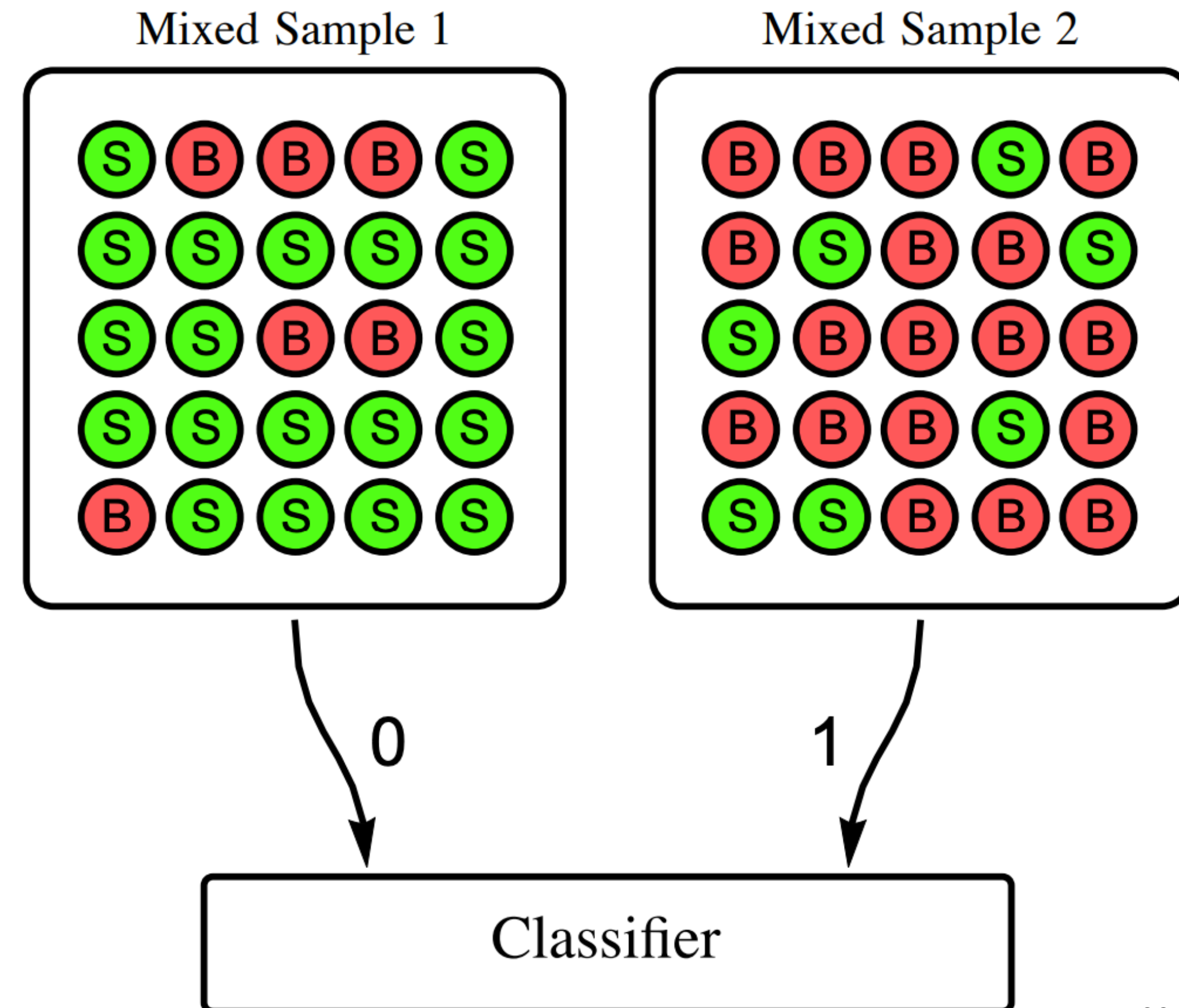
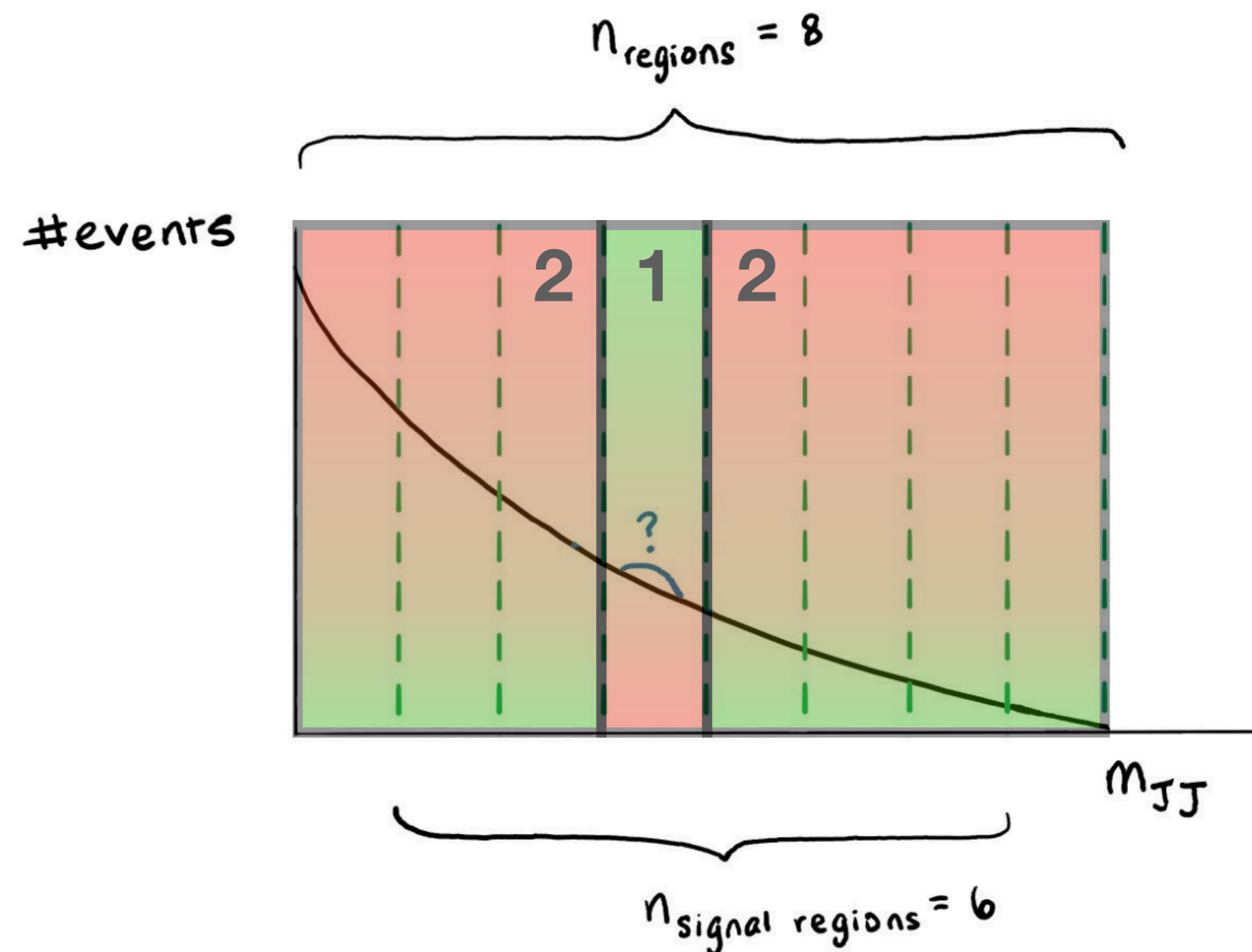
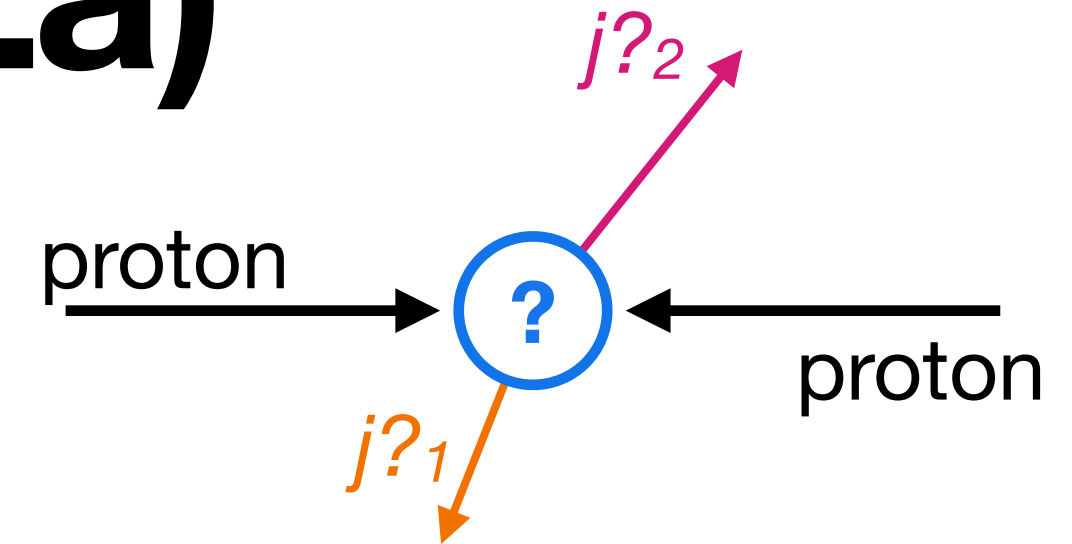
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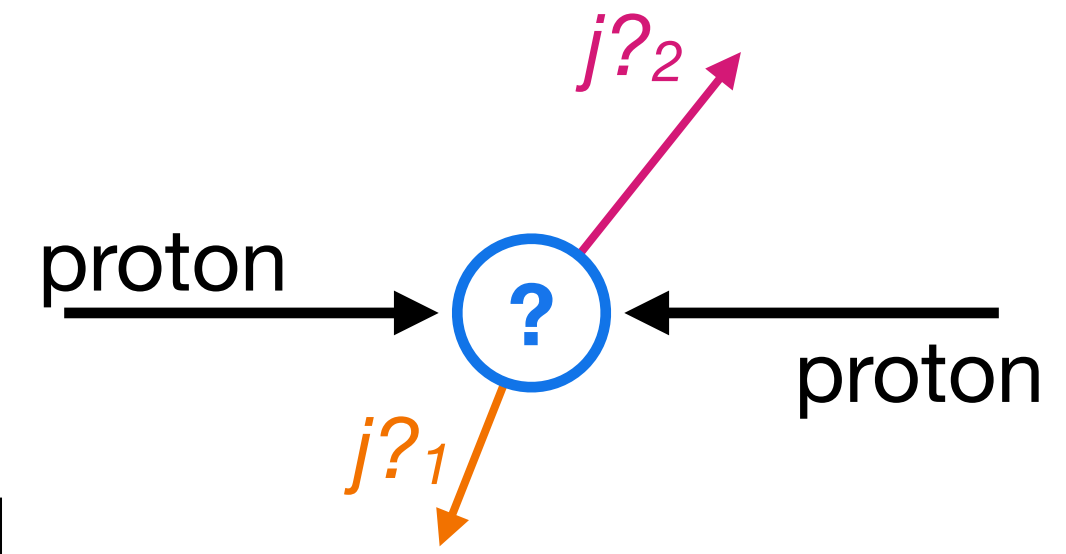
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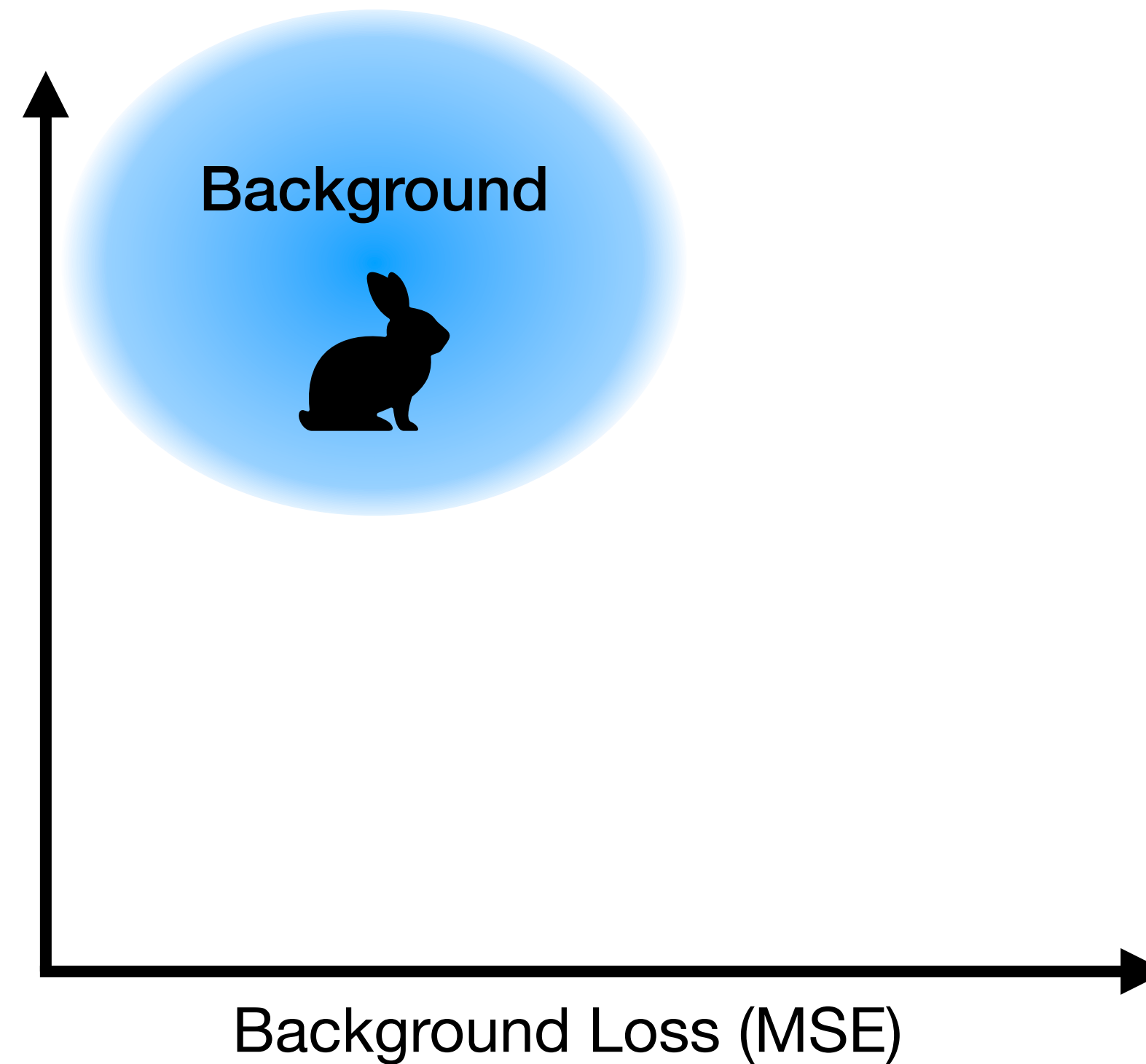
Quasi-Anomalous Knowledge: [2011.03550]

- What if you has some general idea of what signals might look like, but you aren't sure?
- Also possible to set some criteria on roughly what signal should look like, what features it might have
 - Want to point AD in the right direction
- Ideally want method that doesn't break down if the hypothesis turns out to be wrong (like supervised classifiers typically do)



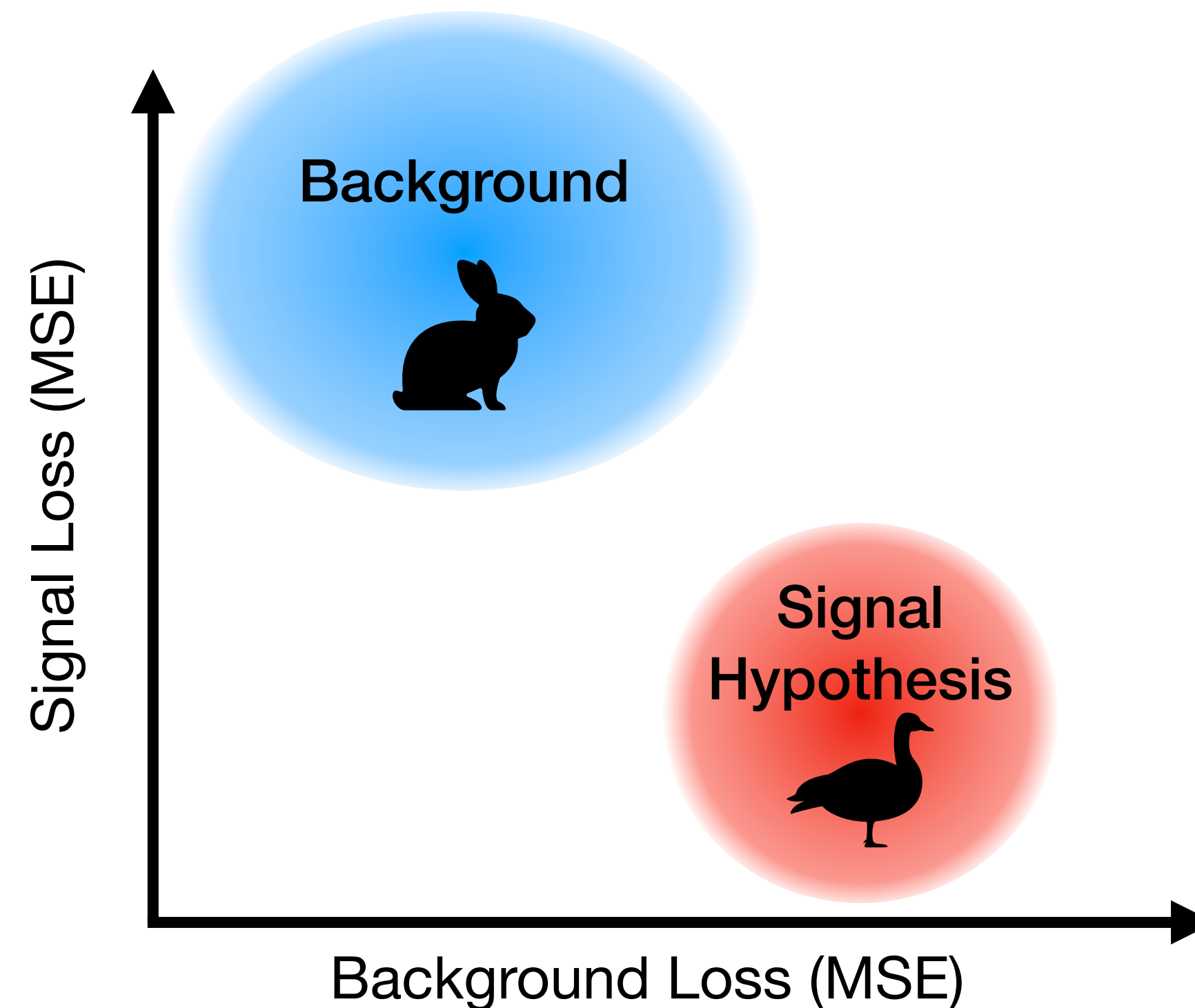
QUAK

- Train an AE for background
- Train an AE for hypothetical signal(s)
- Construct N-dimension QUAK space from losses



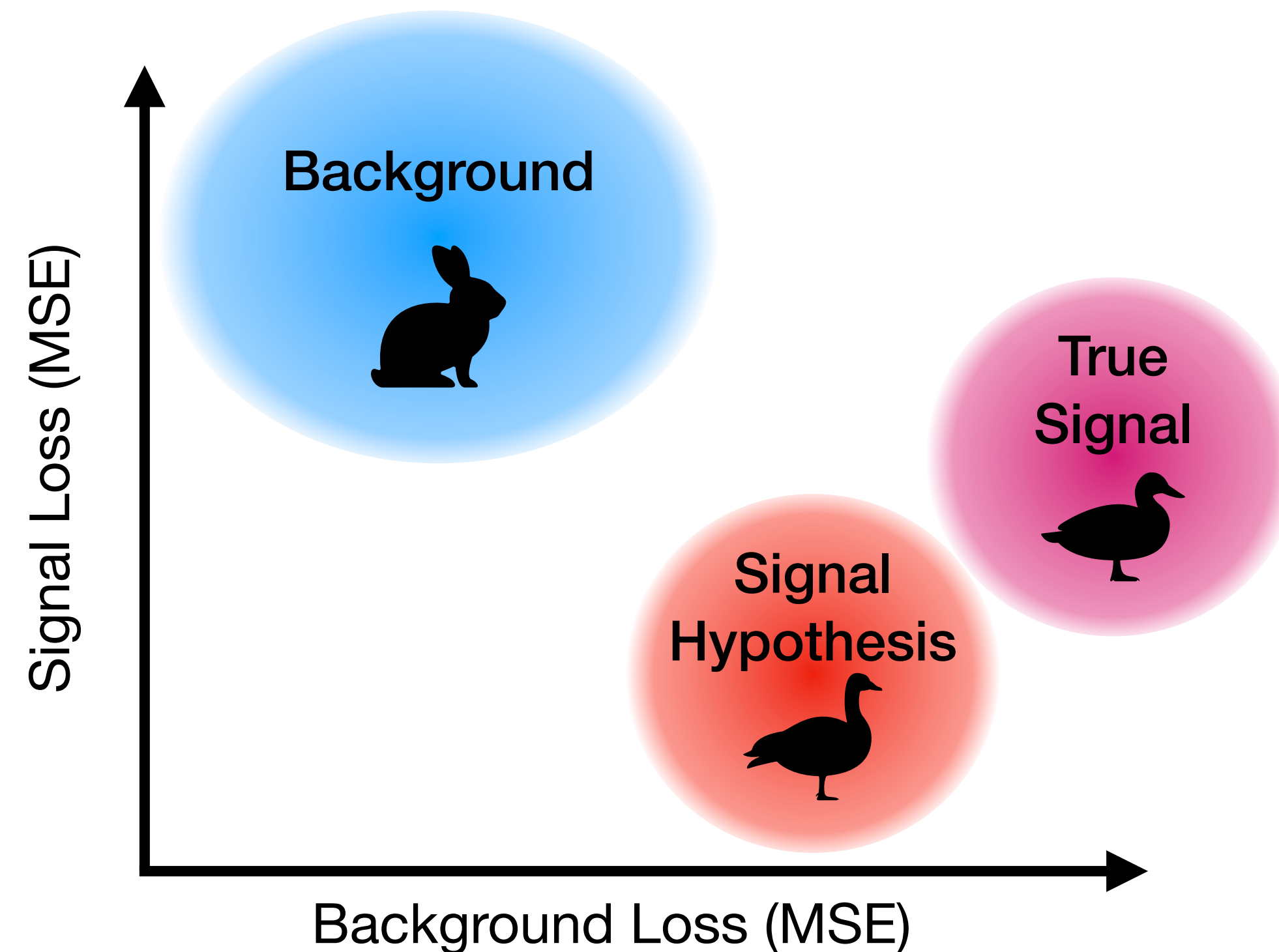
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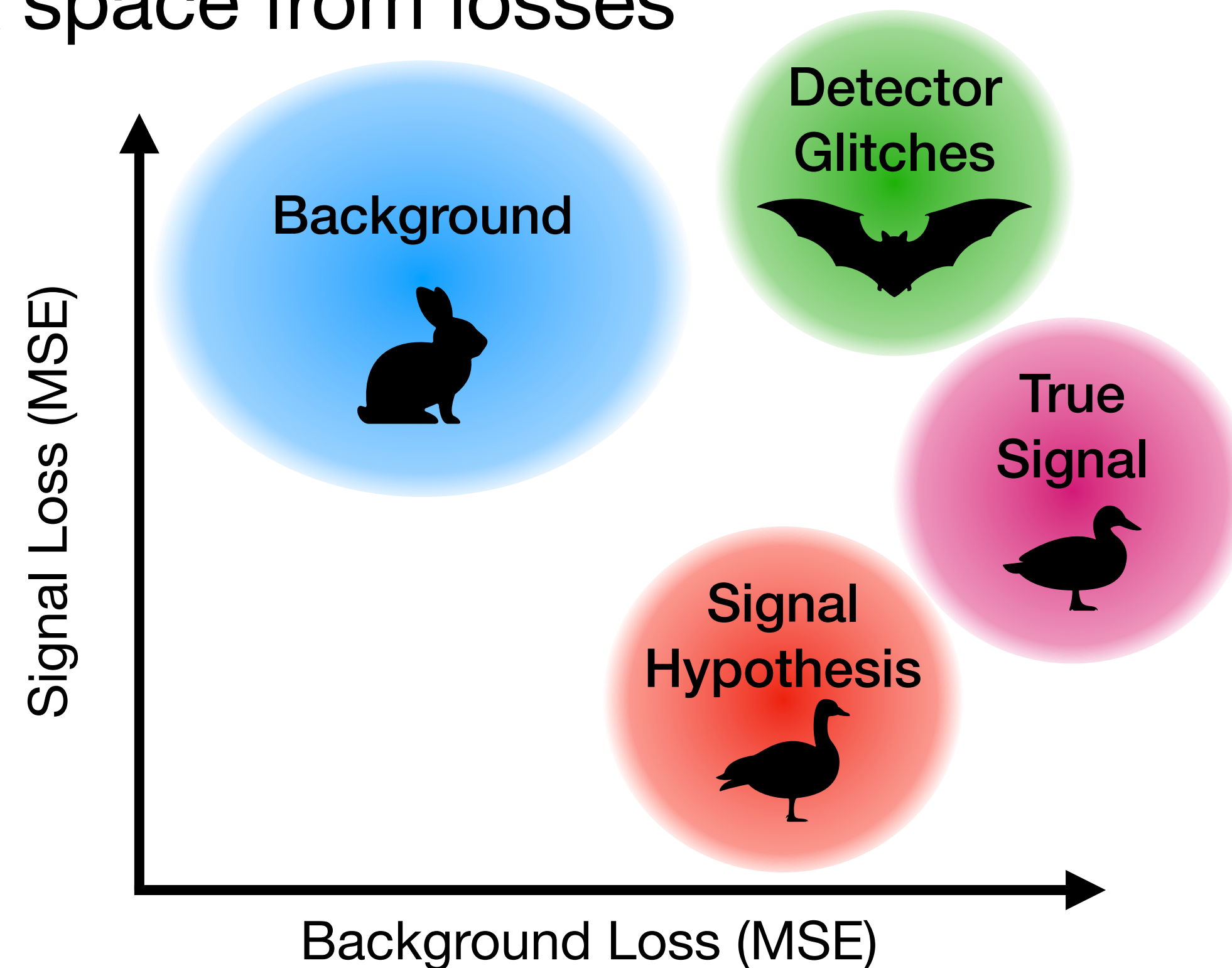
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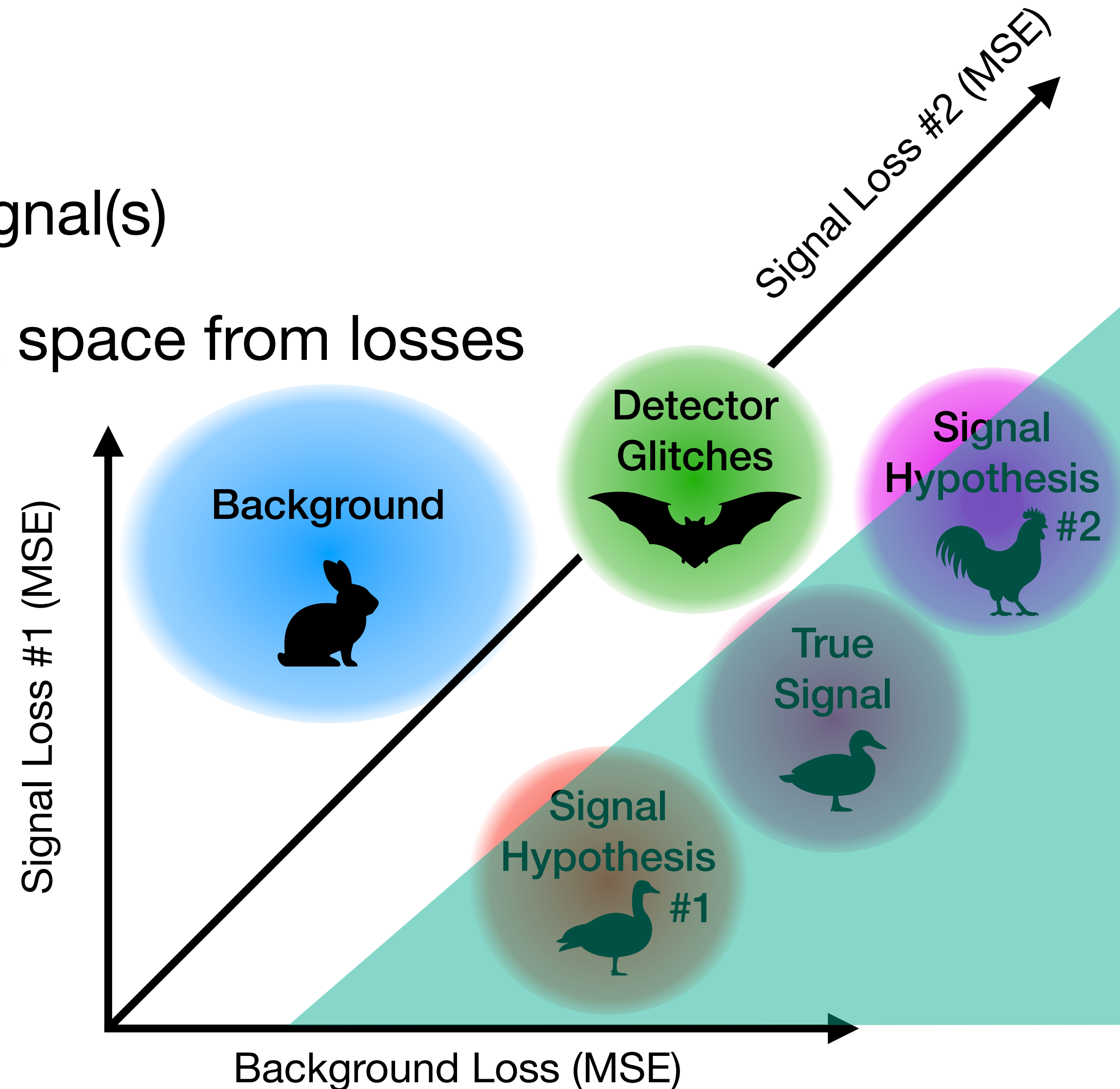
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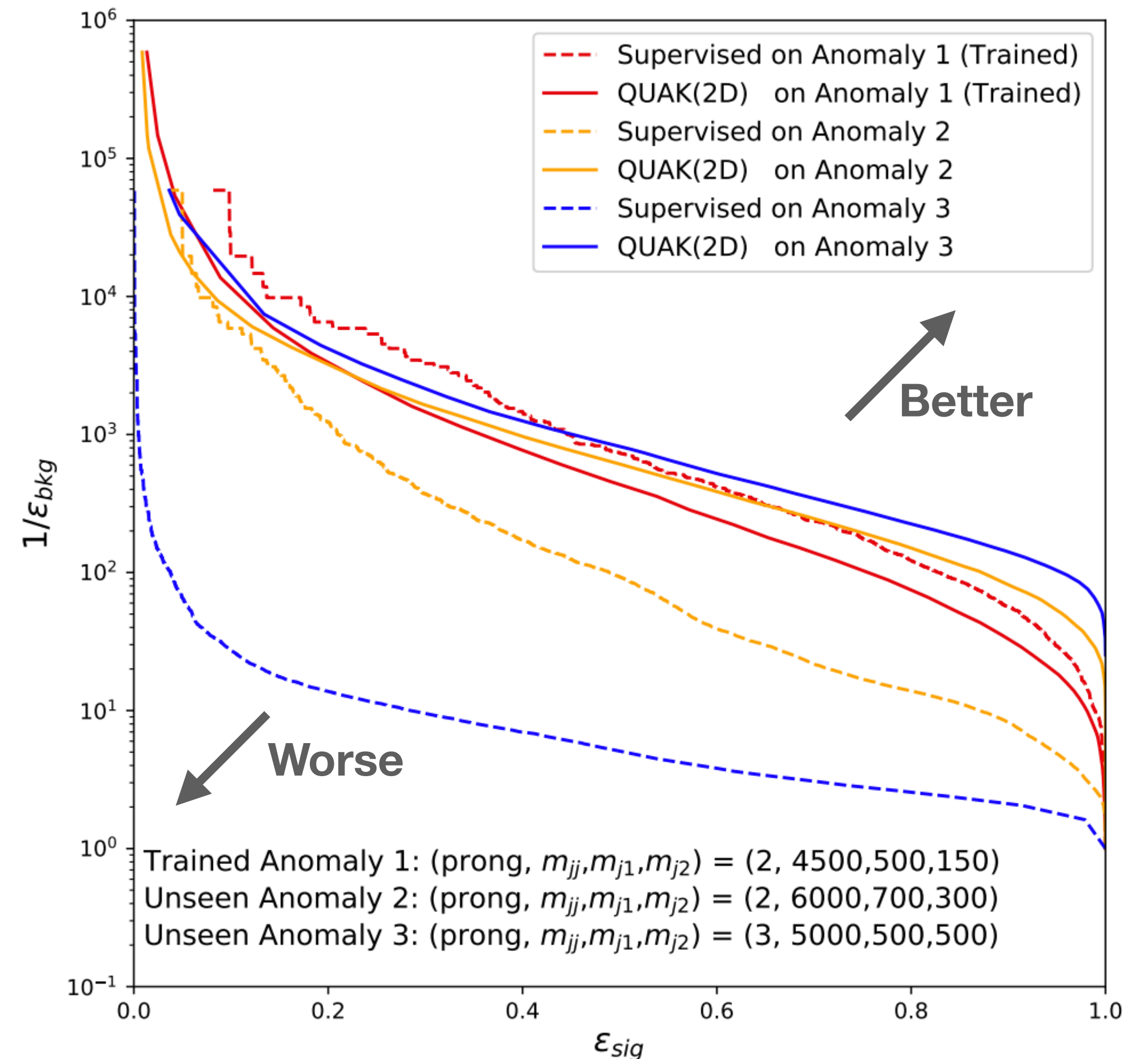
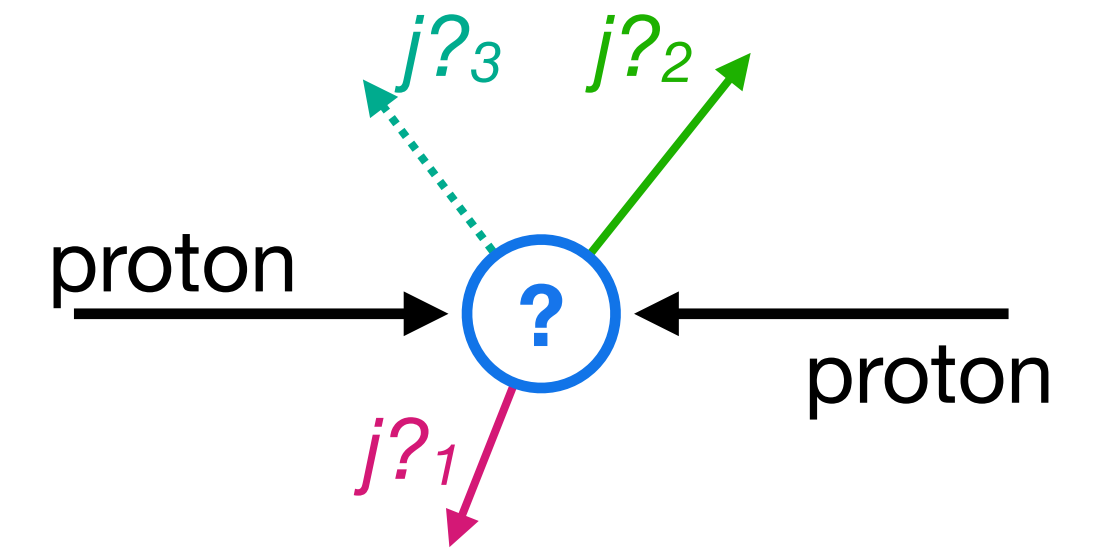
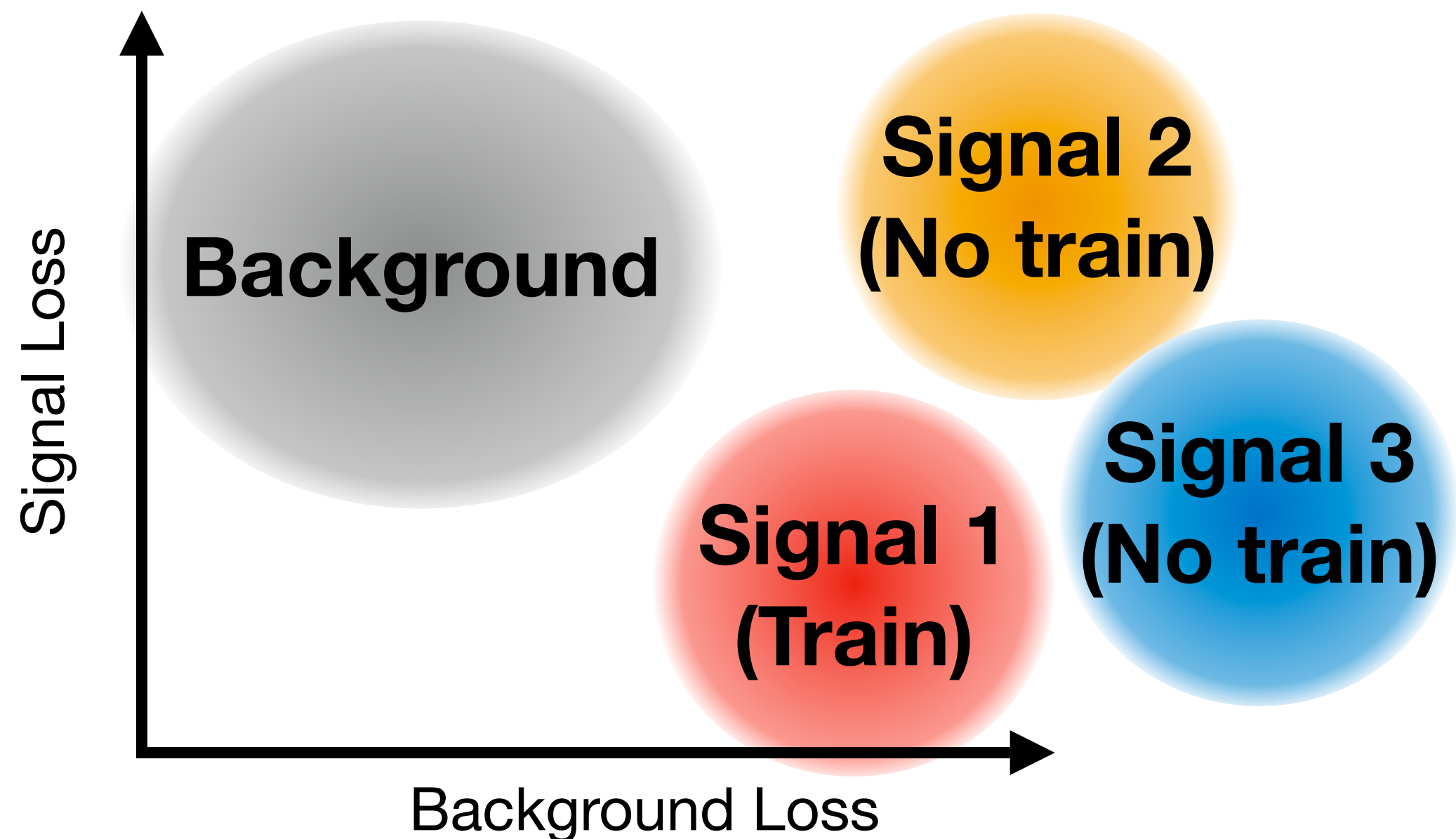
QUAK

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QUAK

- QUAK can perform similarly to supervised methods when given correct signal
- QUAK **greatly outperforms** supervised methods when signal hypothesis is wrong



Conclusions

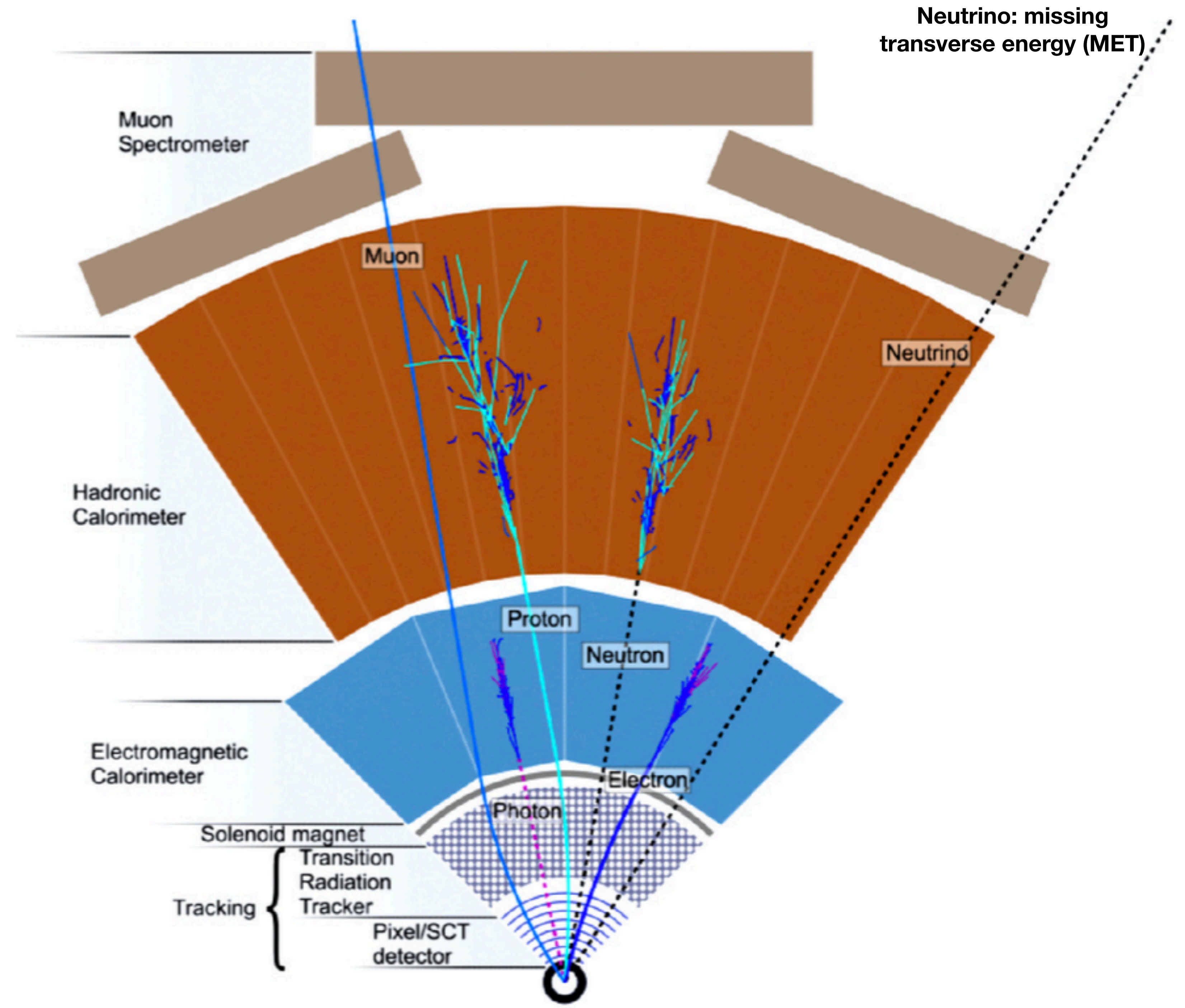
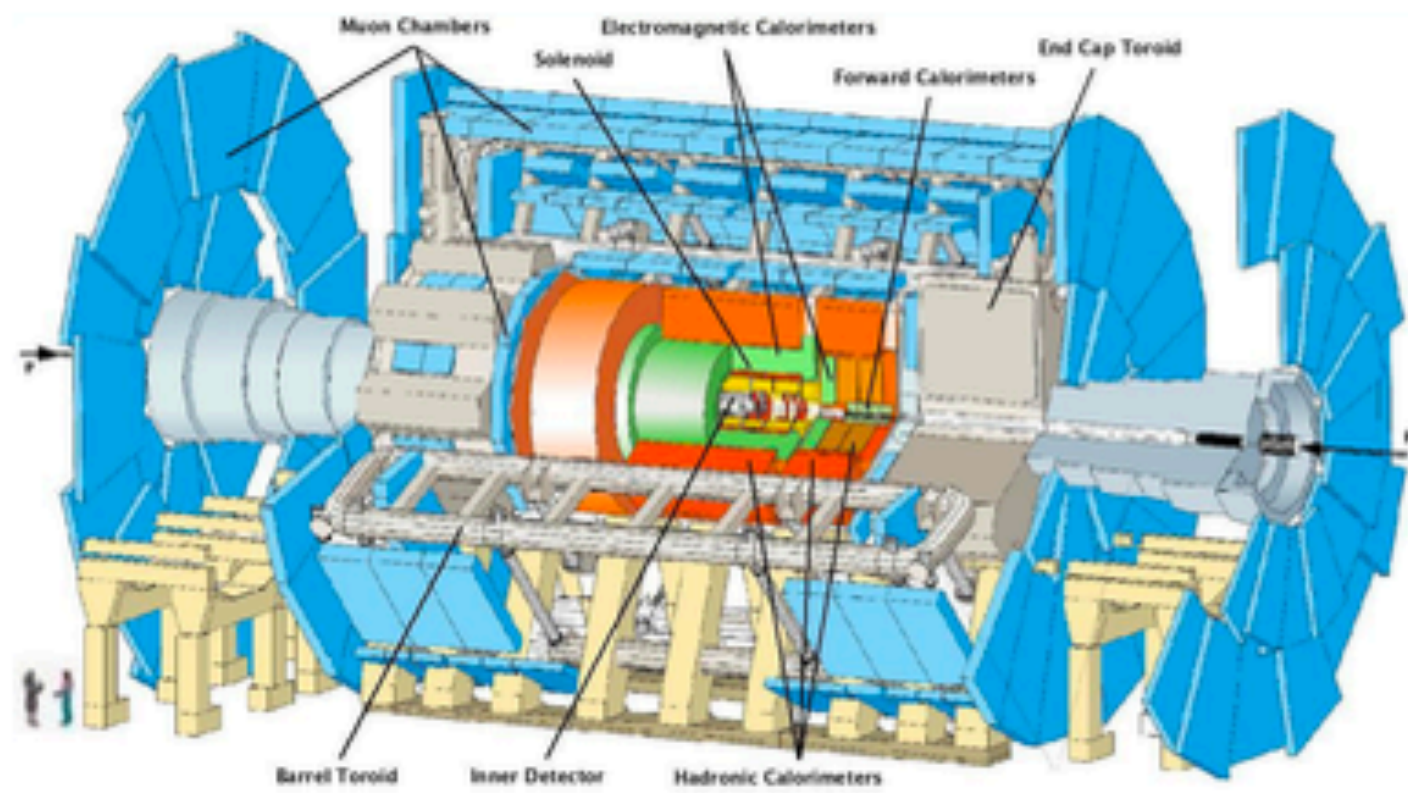
- I hope you learned a little bit about LHC research and anomaly detection
- Many more AD methods I didn't have time to mention
 - TNT, CATHODE, SALAD, CURTAINS, ...
- Very active area of research at the LHC!
- Recent AD sessions at ML4Jets2024 conference give a nice flavor of cutting edge ideas [1][2]

[1] <https://indico.cern.ch/event/1386125/timetable/?view=standard#b-587345-anomaly-detection>

[2] <https://indico.cern.ch/event/1386125/timetable/?view=standard#b-587346-anomaly-detection>

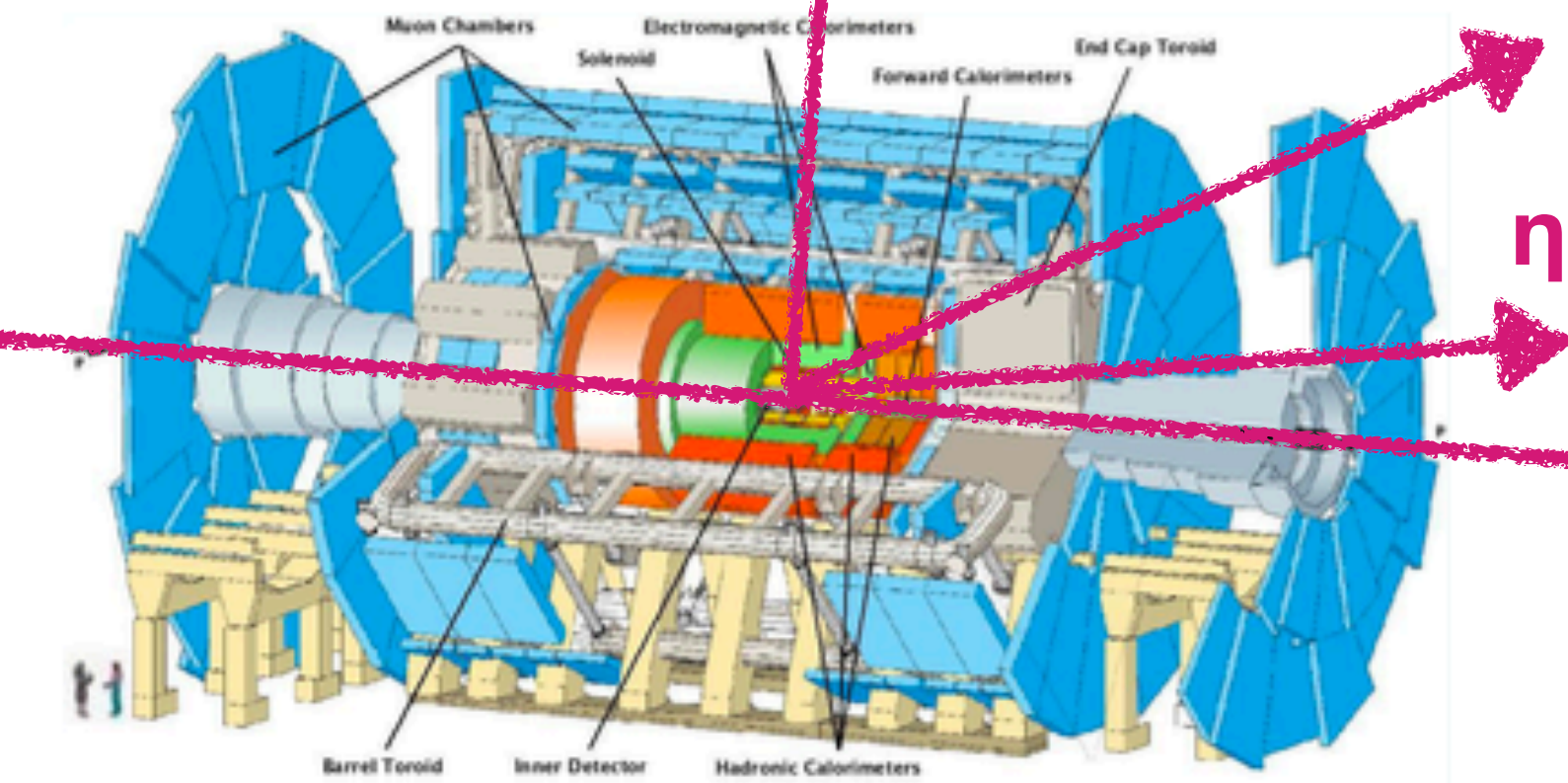
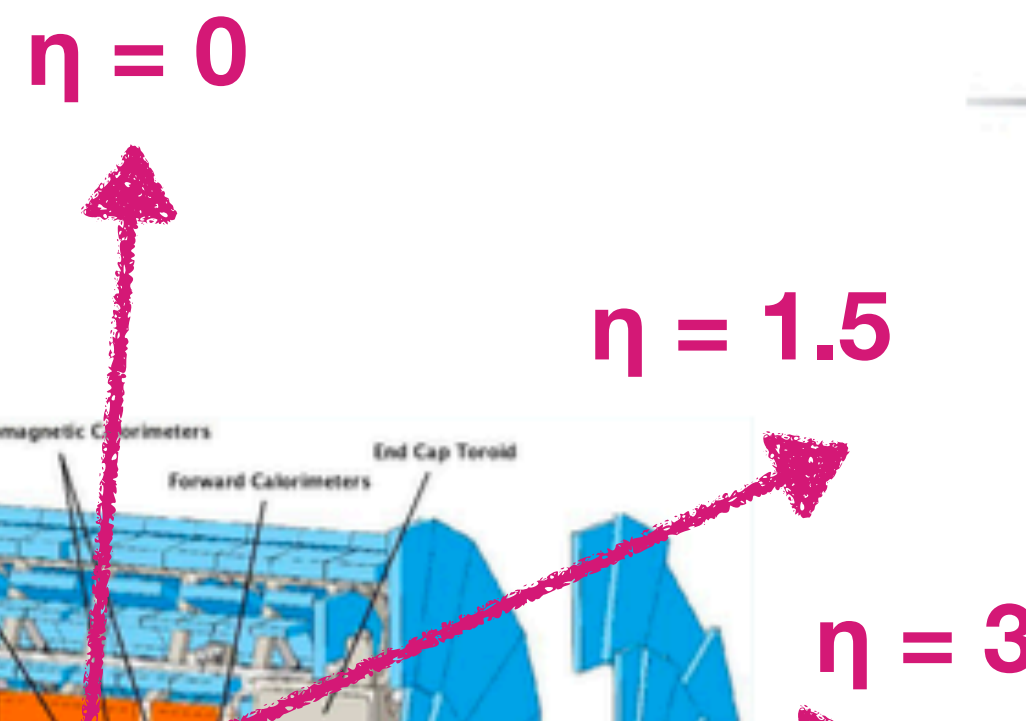
BACKUP

ATLAS Slice

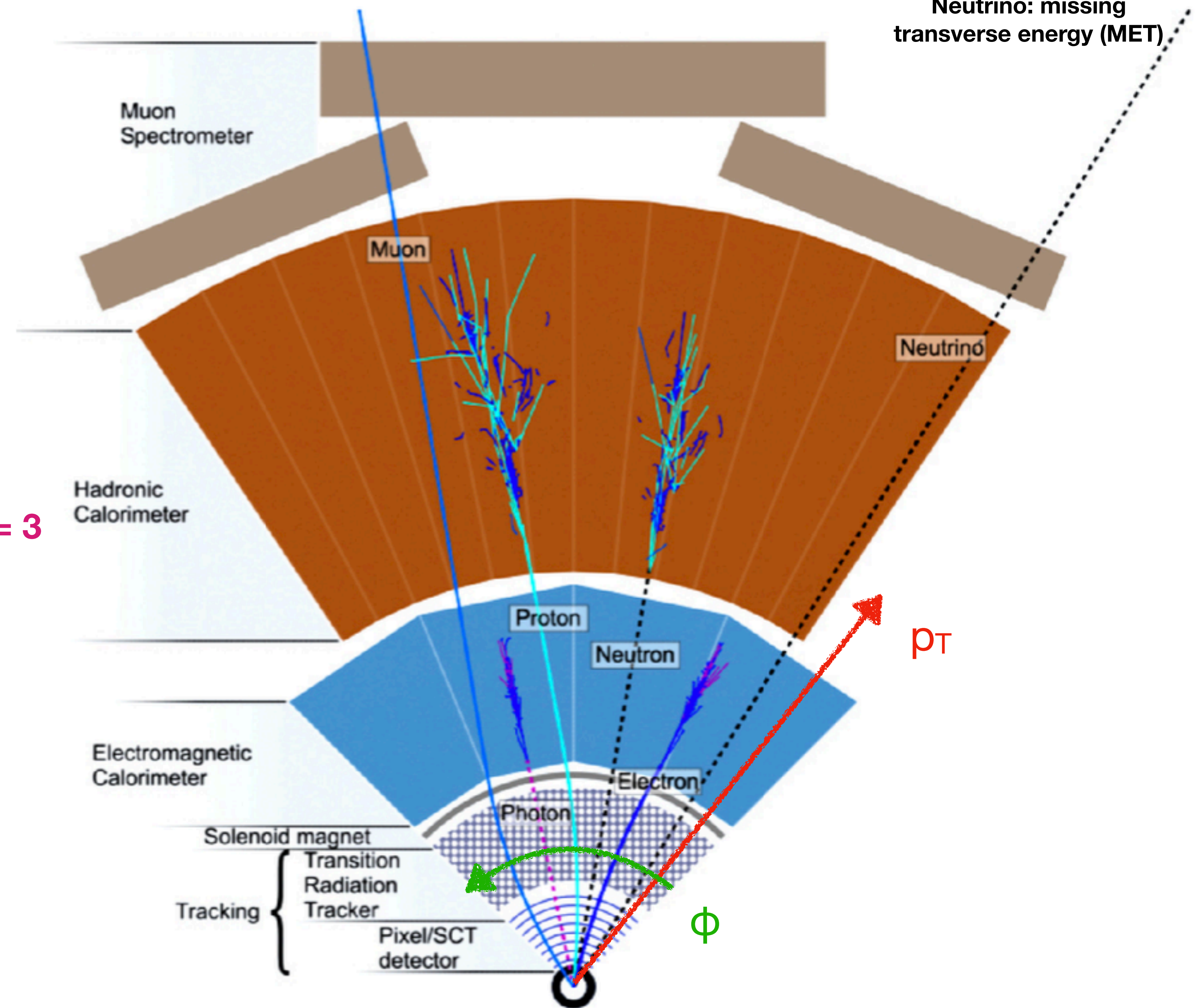


ATLAS Slice

Neutrino: missing transverse energy (MET)

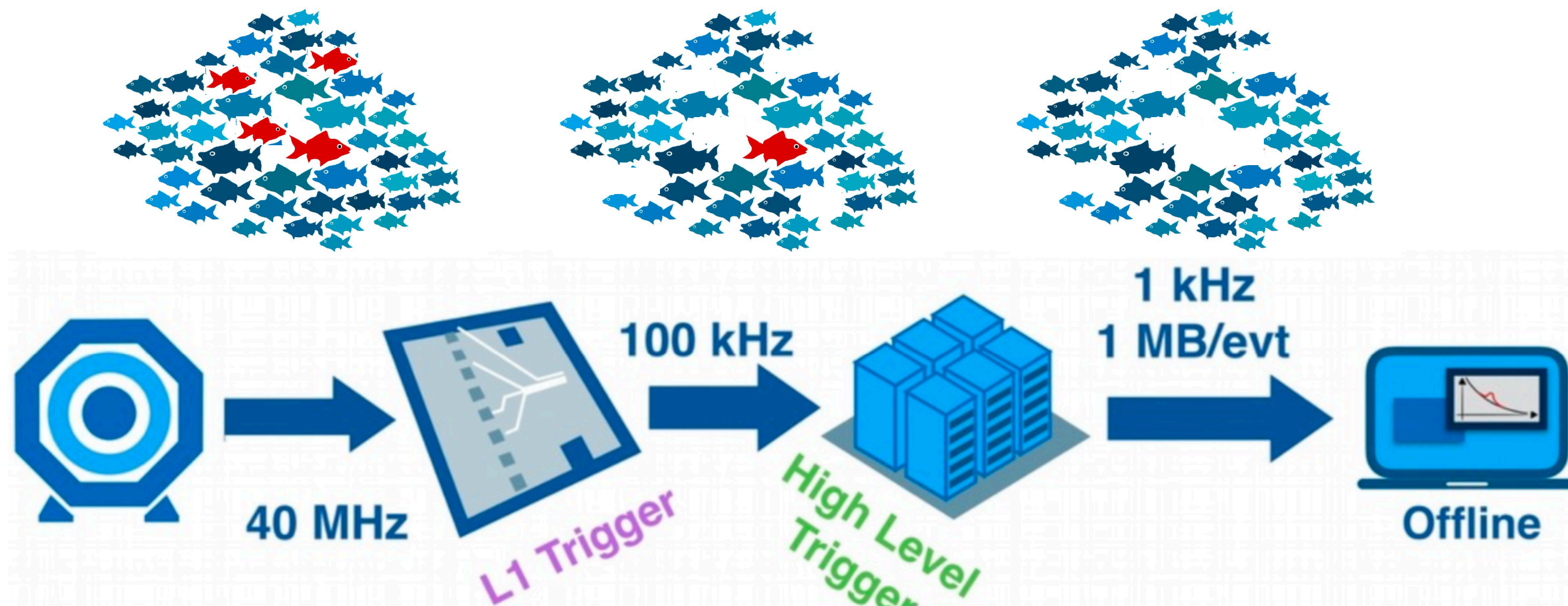


$$\mathbf{p}_4 = (\rho_T, \eta, \phi, E)$$



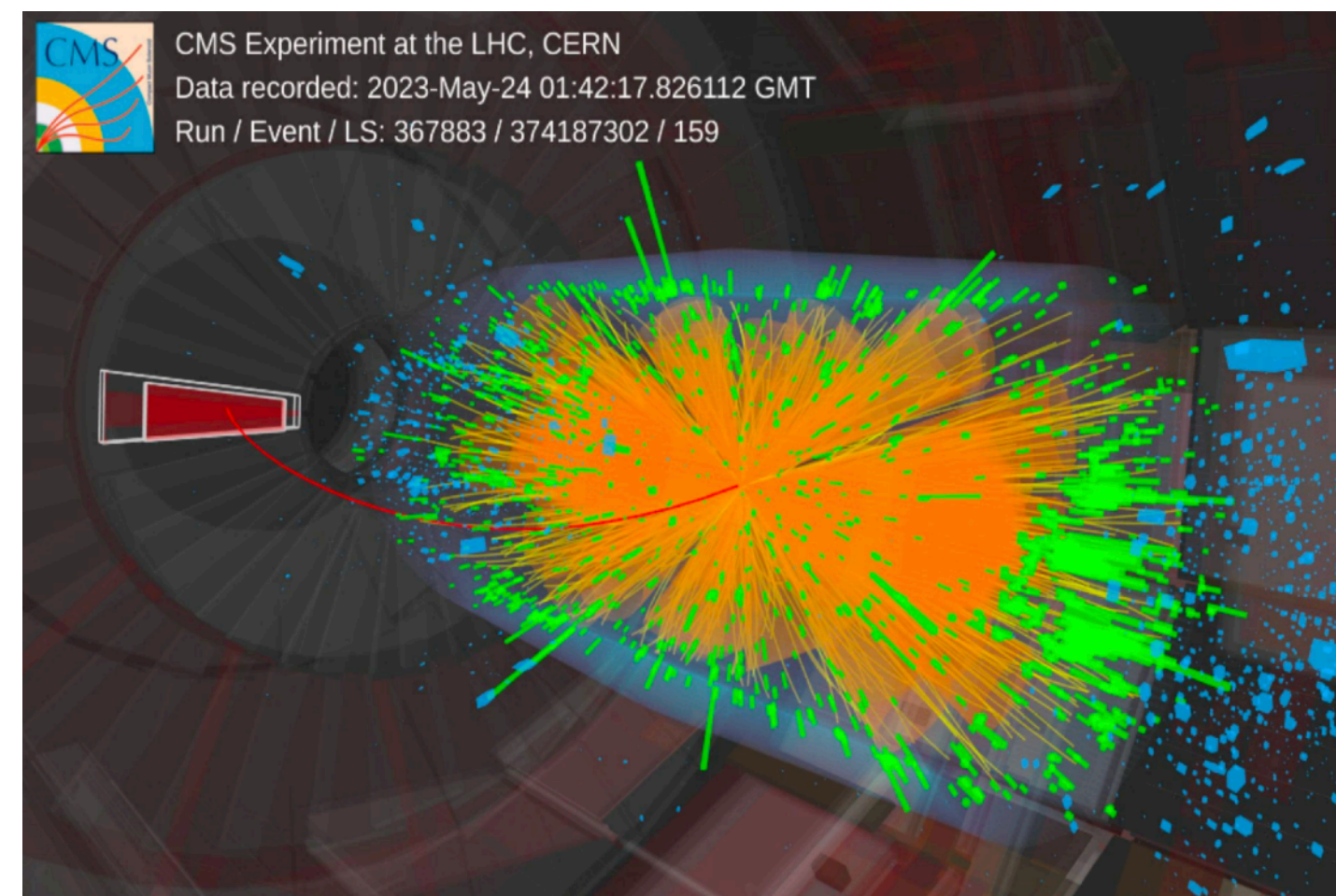
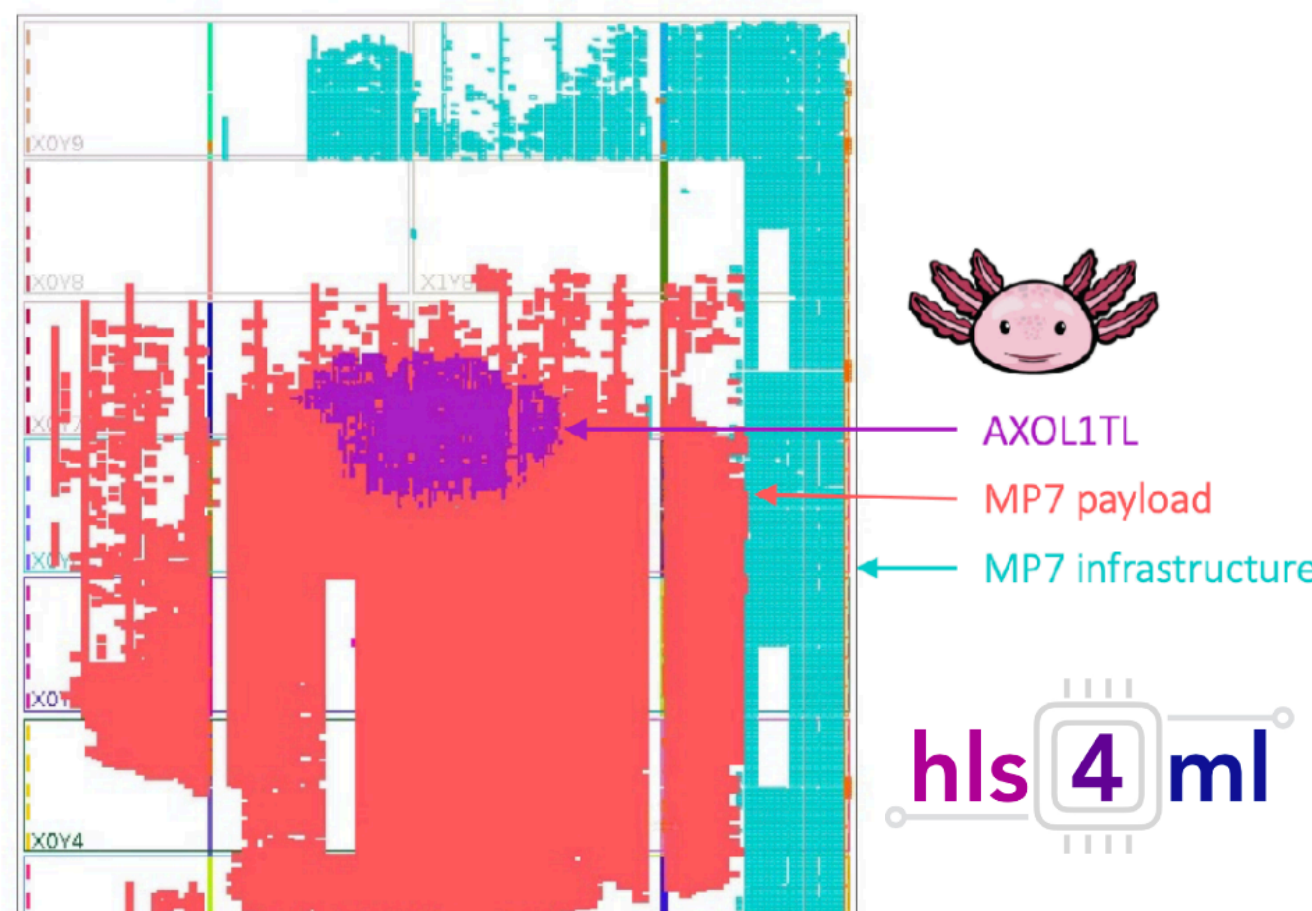
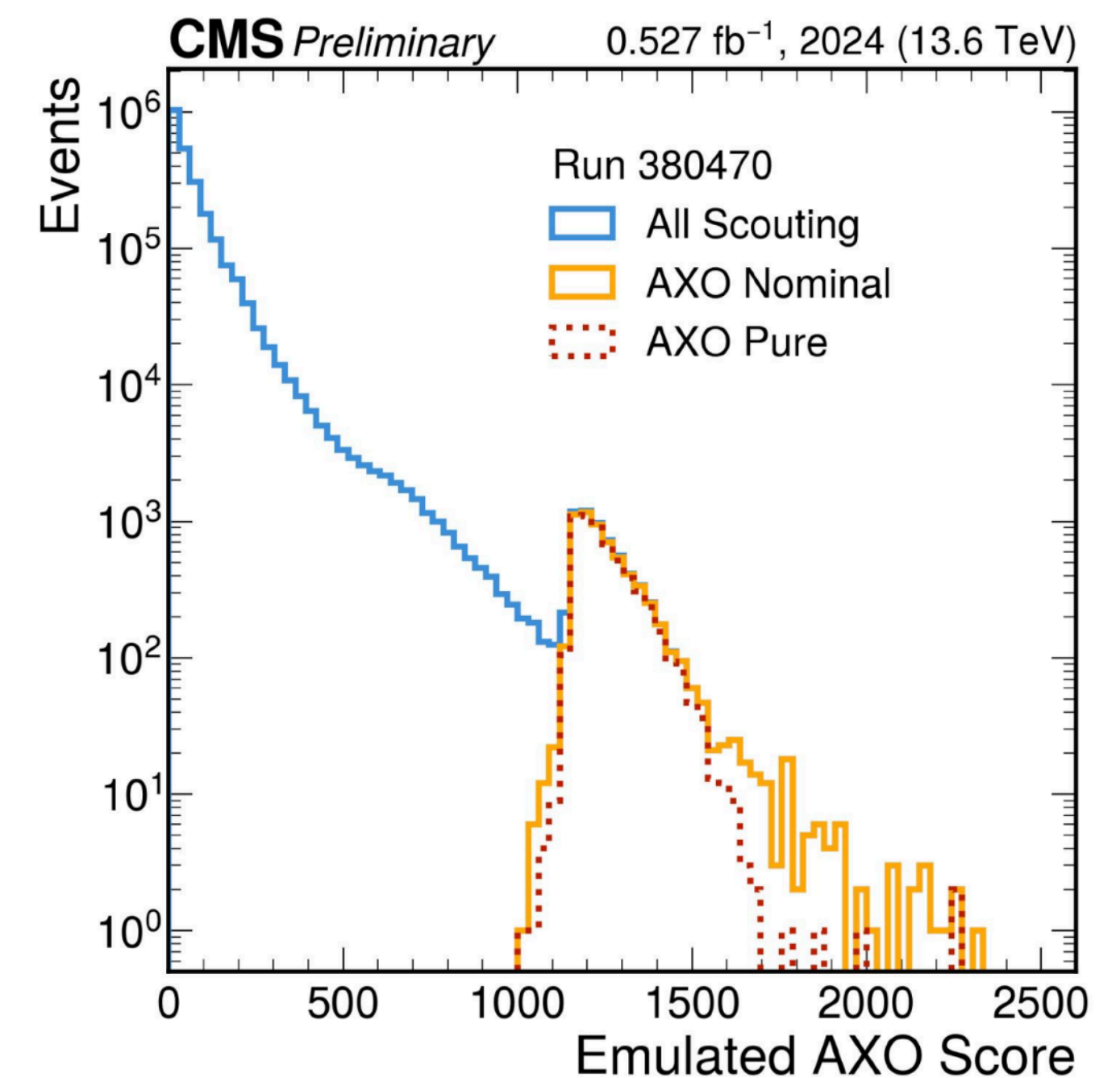
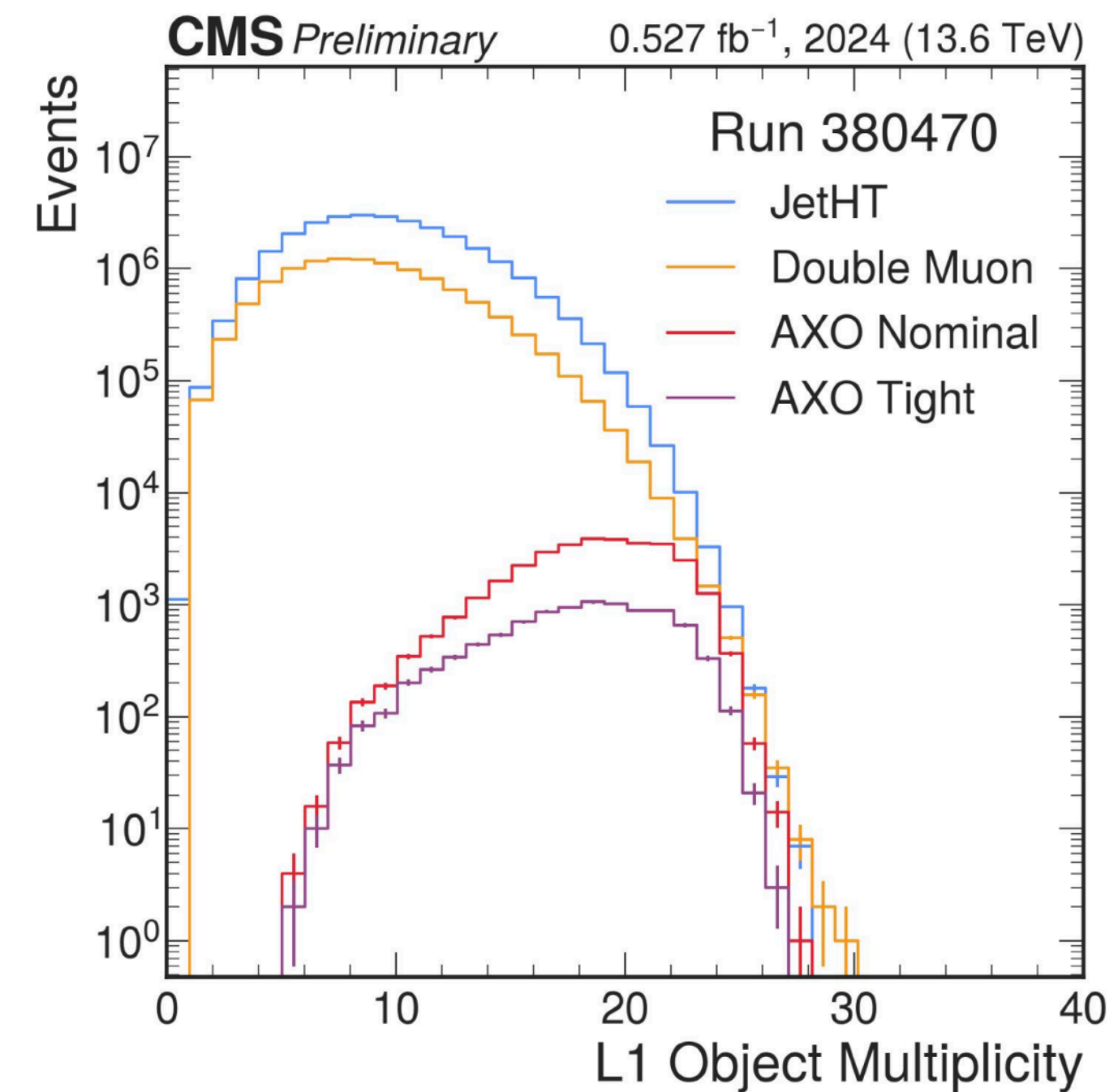
L1 Trigger AD

- Depending on anomaly, we could have none left in recorded data
- Low-latency ML is the only option! (eg. autoencoders)



L1 Trigger AD

- CMS has already deployed multiple AD algorithms in trigger
 - AXOL1TL [CMS DP-2023/079, CMS DP-2024/059] & CICADA [CMS DP-2023/086] (see Noah's talk later [1])
- Currently collecting interesting events that would have been missed
 - Network preferentially identifies large multiplicity events, potentially large gains in new physics acceptance
- Development ongoing in ATLAS as well



[1] <https://indico.cern.ch/event/1387540/timetable/?view=standard#66-realtime-anomaly-detection>