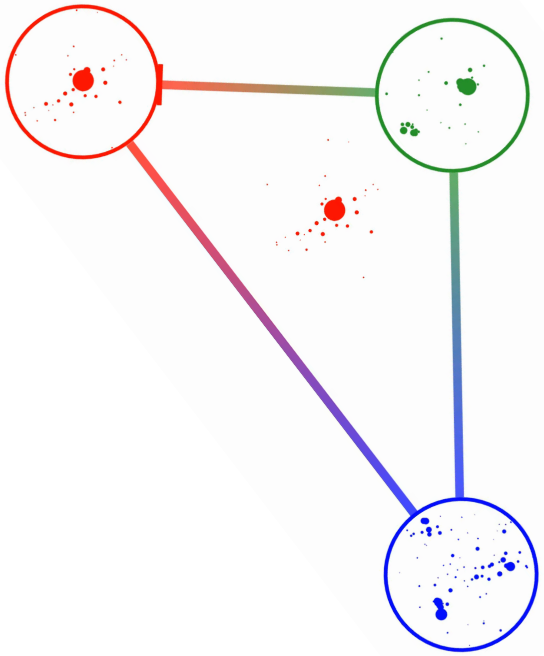
Data ex Machina
Machine Learning with Public Collider Data

AI & Physics, Applied Machine Learning Days 2020

Eric M. Metodiev

Center for Theoretical Physics

Massachusetts Institute of Technology



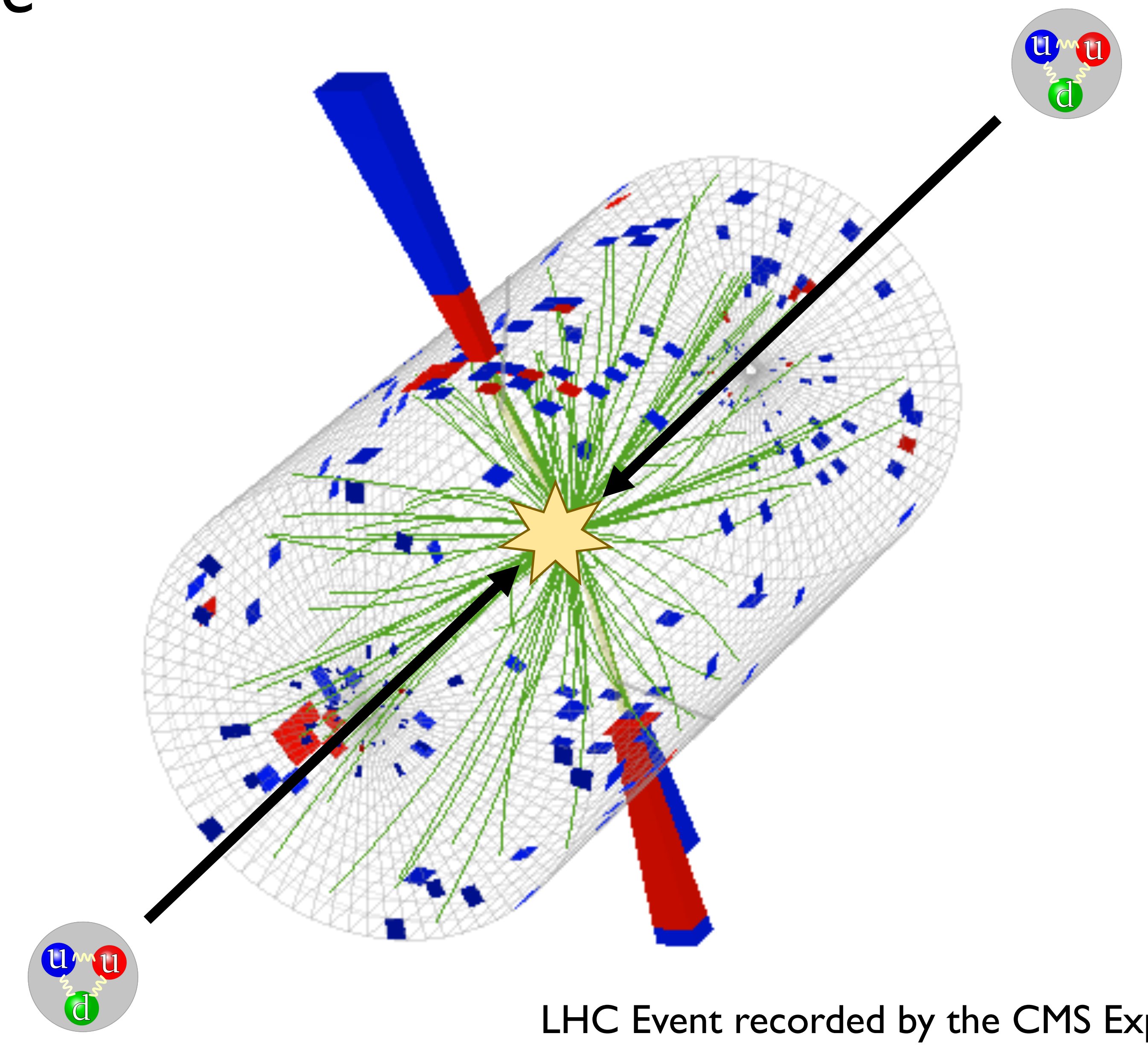
Patrick Komiske

Radha Mastandrea

Preksha Naik

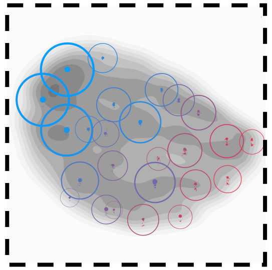
Jesse Thaler

Collision Course

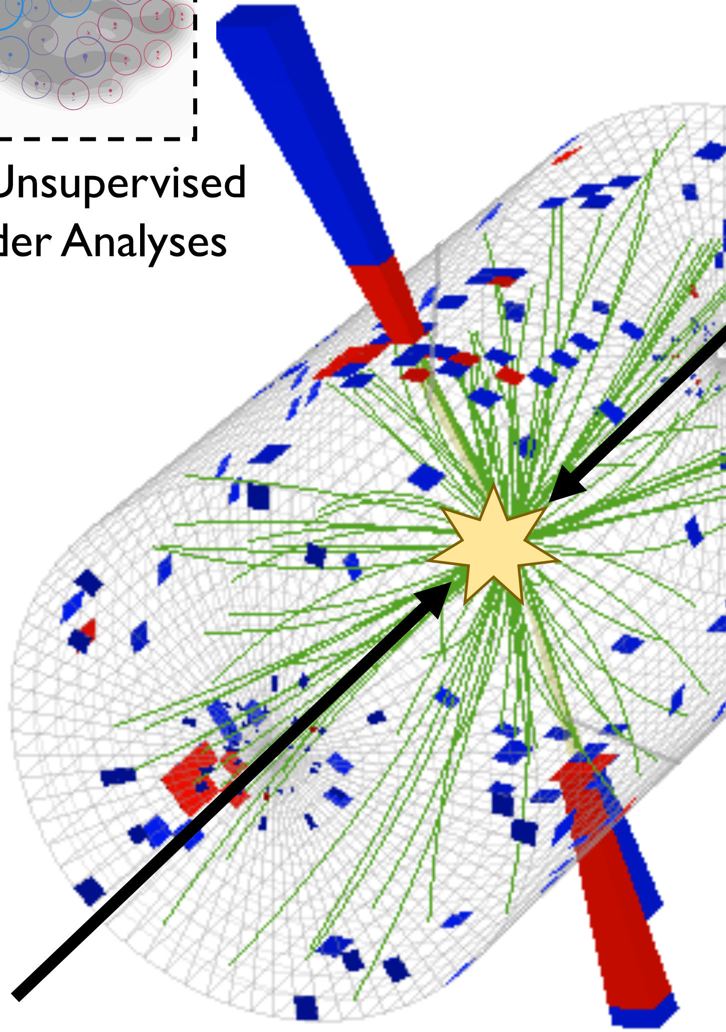


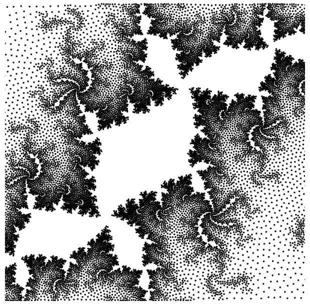
LHC Event recorded by the CMS Experiment at CERN

Collision Course



New Unsupervised
Collider Analyses

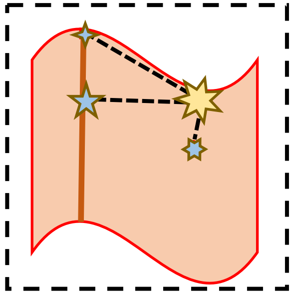




Optimal Transport
[OTML Workshop, NeurIPS 2019]

CMS opendata

Public Collider Data
[opendata.cern.ch]



New Insights into
Quantum Field Theory

[h/t Jesse Thaler]

opendata CERN

About

opendata.cern.ch

Explore more than **two petabytes** of open data from particle physics!

jet primary dataset

Search

search examples: collision datasets, keywords:education, energy:7TeV

Explore

datasets
software
environments
documentation

Focus on

ATLAS
ALICE
CMS
LHCb
OPERA
Data Science

Get started

CMS Open Data

Download a CMS "AOD" file: [2011A Jet Primary Dataset]

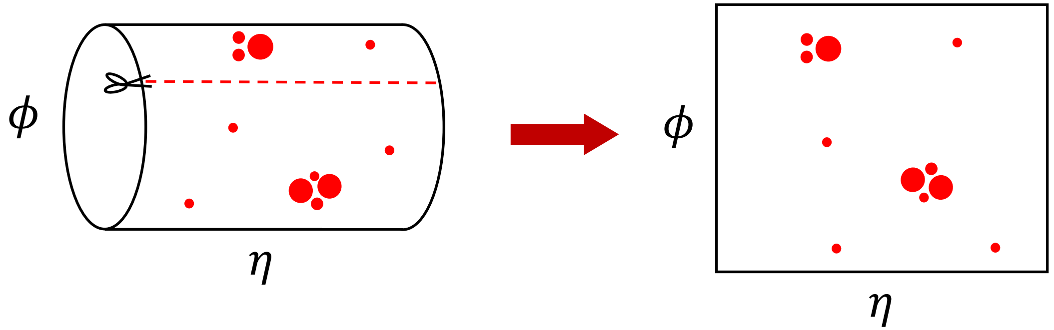
04913DA0-8B3F-E311-924F-0025901AD38A.root 966.3 MB

Fifteen lines of code later…

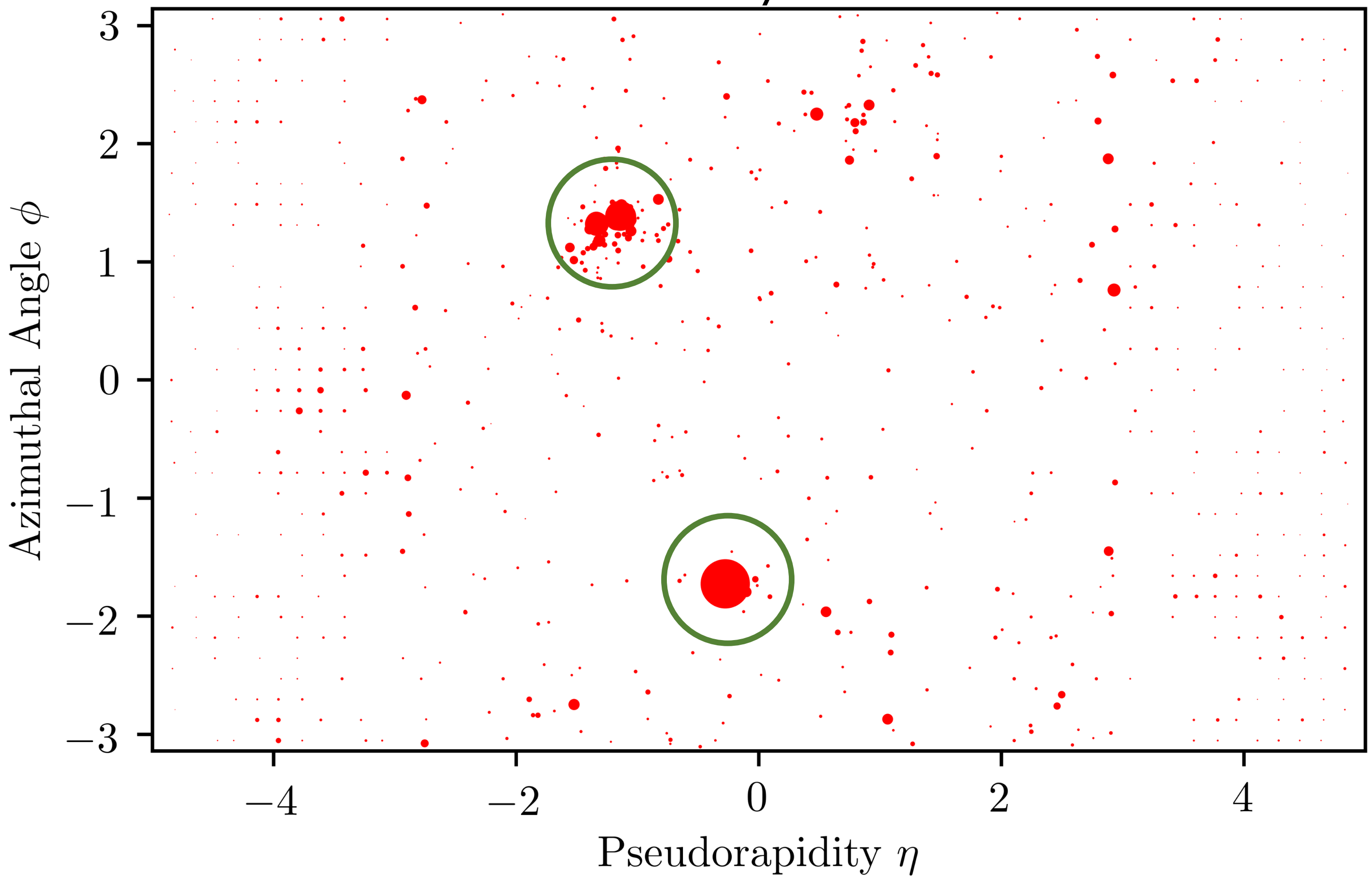
```
import uproot

# load in the specified file with uproot
file = uproot.open('~/Downloads/04913DA0-8B3F-E311-924F-0025901AD38A.root')
events = file[b'Events;1']

# read particle transverse momenta (pts), pseudorapidity (eta), and azimuth (phi)
PFCkey = b'recoPFCandidates_particleFlow__RECO.obj'
pts  = events[PFCkey + b'.pt_'].array()
etas = events[PFCkey + b'.eta_'].array()
phis = events[PFCkey + b'.phi_'].array()
```

```
import numpy as np
import matplotlib.pyplot as plt

# choose an event
ind = 6457

# plot the collision event of interest
plt.scatter(etas[ind], phis[ind], s=pts[ind], lw=0, color='red')

# plot settings
plt.xlim(-5, 5)
plt.ylim(-np.pi, np.pi)
plt.xlabel('Pseudorapidity $\eta$')
plt.ylabel('Azimuthal Angle $\phi$')

plt.show()
```

Thanks to the [uproot] package! uproot



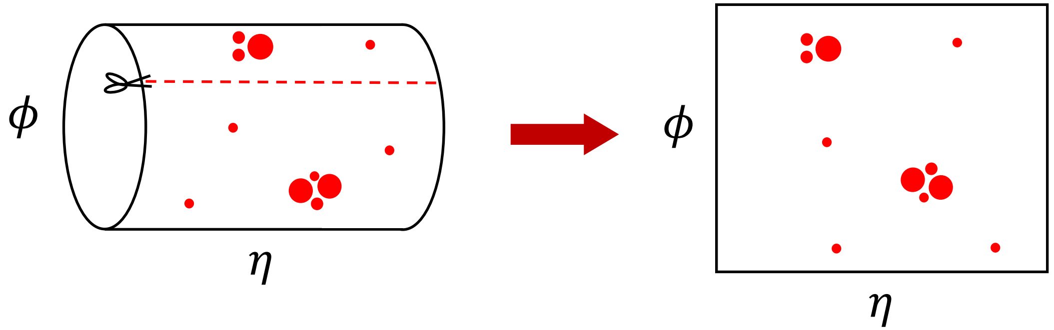
A real collision event recorded by CMS!

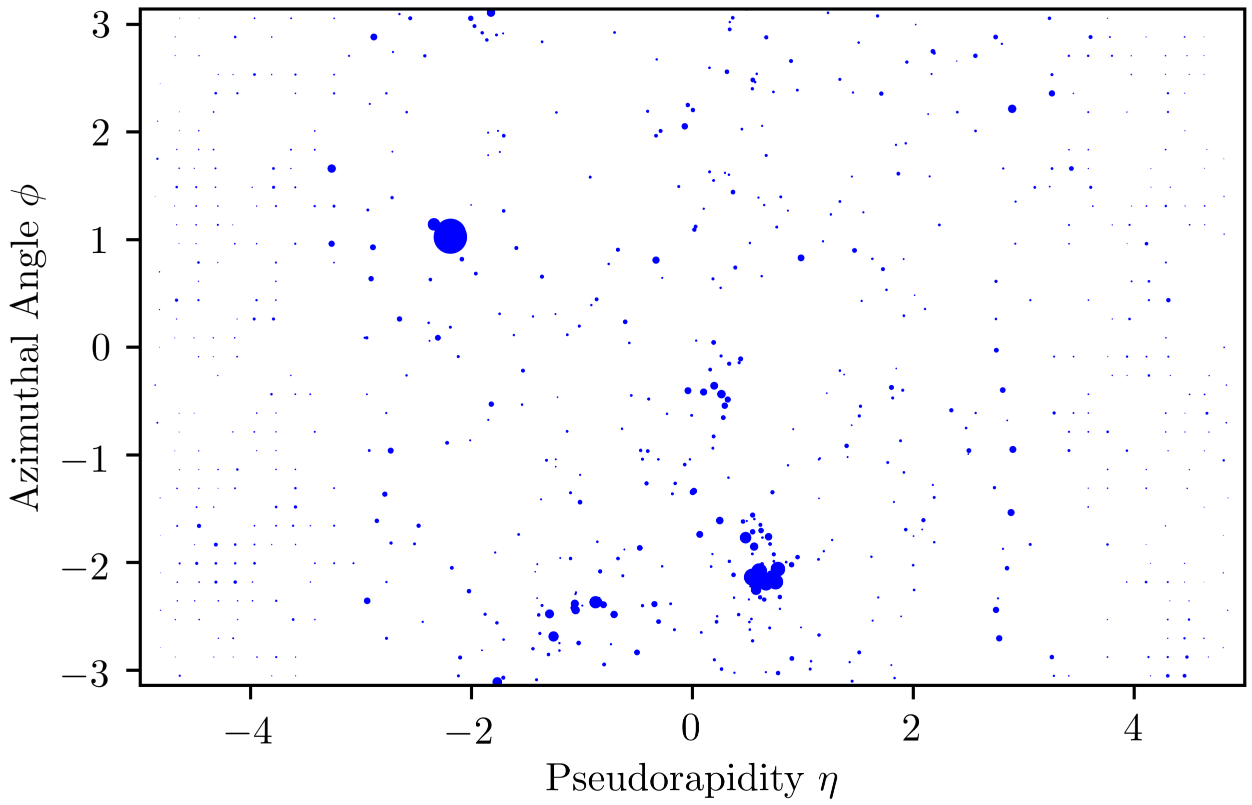


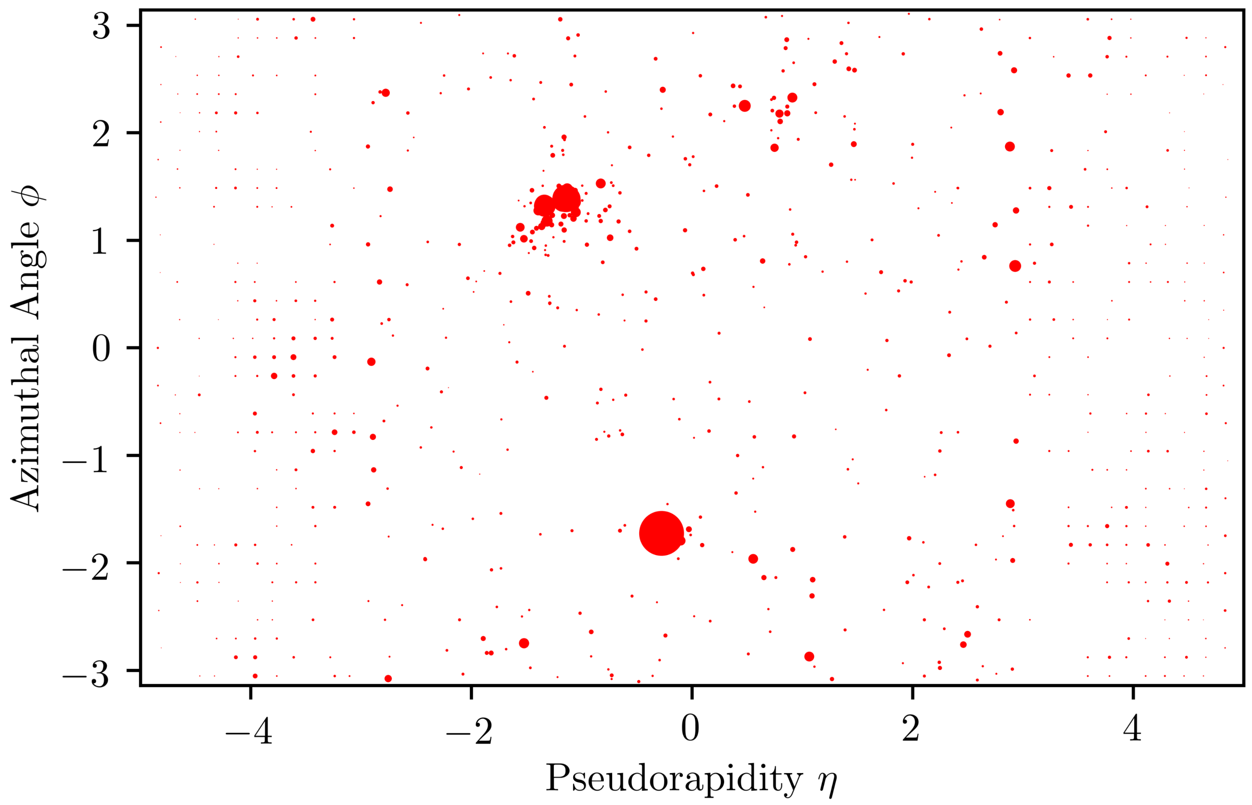
When are two collisions similar?

Many unsupervised methods rely on a **distance matrix.**

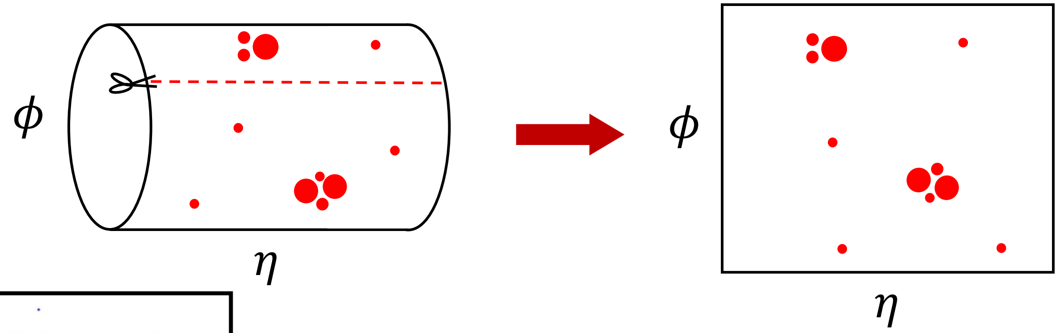
Need a physically-sensible **metric** between events!



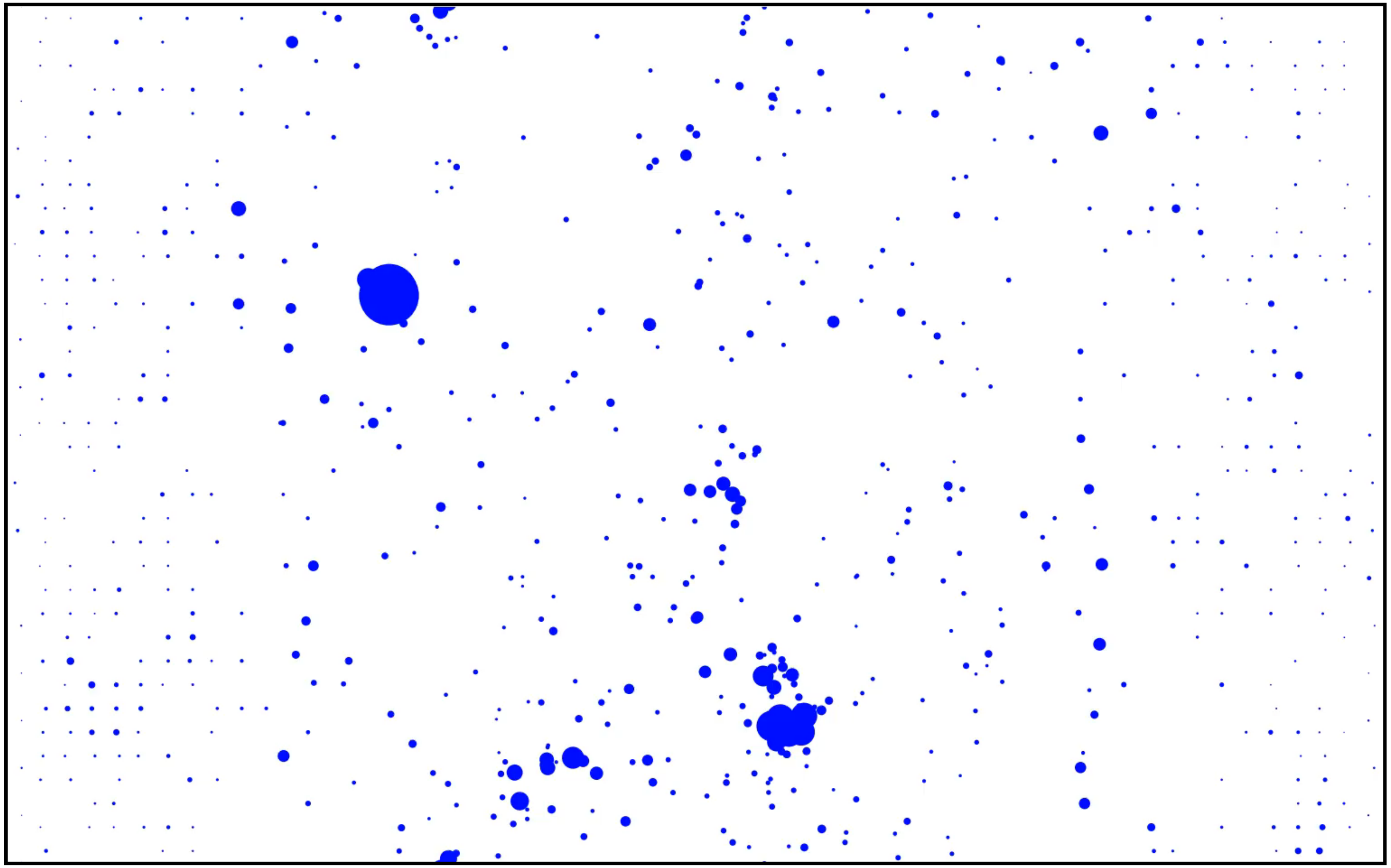




When are two collisions similar?



The Earth Mover's (or Wasserstein) Distance



The "work" required to rearrange one collision event into another!

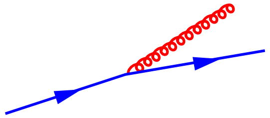
Plus a cost to create or destroy energy.

Optimal Transport Problem

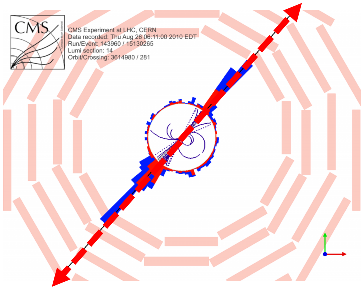
Here using python optimal transport

[Komiske, **EMM**, Thaler, PRL 2019]

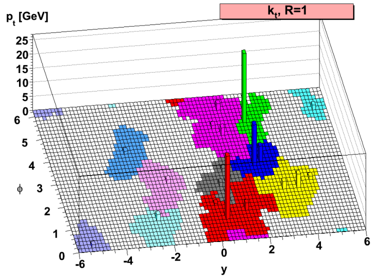
Six Decades of Collider Techniques



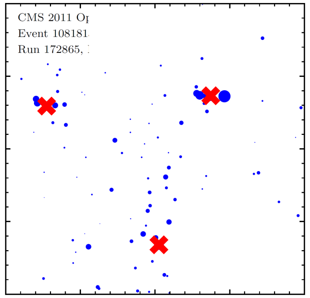
Taming infinities



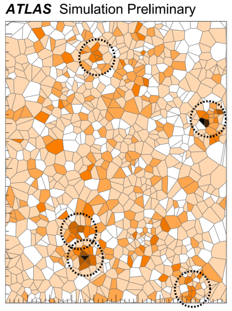
Event Shapes



Jet Algorithms



Jet Substructure



Pileup

1960

2020

1962-1964
Infrared Safety
[Kinoshita, JMP 1962]
[Lee, Nauenberg, PR 1964]

1977
Thrust, Sphericity
[Farhi, PRL 1977]
[Georgi, Machacek, PRL 1977]

1993
k_T jet clustering
[Ellis, Soper, PRD 1993]
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[Doskhitzer, Leder, Moretti, Webber, JHEP 1997]

2010-2015
N-(sub)jettiness, XCone
[Stewart, Tackmann, Waalewijn, PRL 2010]
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[Stewart, Tackmann, Thaler, Vermilion, Wilkason, JHEP 2015]

2014-2019
Constituent Subtraction
[Berta, Spousta, Miller, Leitner, JHEP 2014]
[Berta, Masetti, Miller, Spousta, JHEP 2019]

And many more!

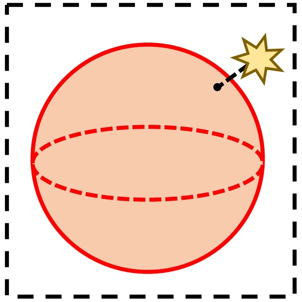
Six Decades of Collider Techniques as Optimal Transport!

[Komiske, **EMM**, Thaler, *to appear*]

Smooth function of energy distribution are finite in QFT

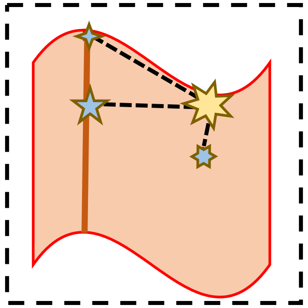
$$\mathrm{EMD}(\mathcal{E}, \mathcal{E}') < \delta \;\to\; |\mathcal{O}(\mathcal{E}) - \mathcal{O}(\mathcal{E}')| < \epsilon$$

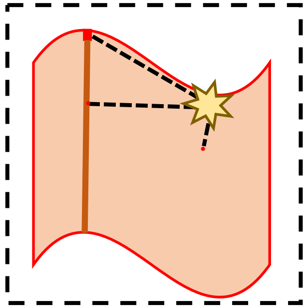
Event shapes as distances to the 2-particle manifold



$$t(\mathcal{E}) = \min_{|\mathcal{E}'|=2} \mathrm{EMD}(\mathcal{E}, \mathcal{E}')$$

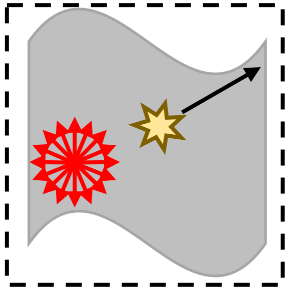
Jets are N-particle event approximations





$$\mathcal{J}(\mathcal{E}) = \underset{|\mathcal{E}'|=N}{\mathrm{argmin}}\, \mathrm{EMD}(\mathcal{E}, \mathcal{E}')$$

Subtract a pileup as a uniform distribution



$$\mathcal{E} - \mathcal{U}$$

Taming infinities | Event Shapes | Jet Algorithms | Jet Substructure | Pileup

1960 – 2020

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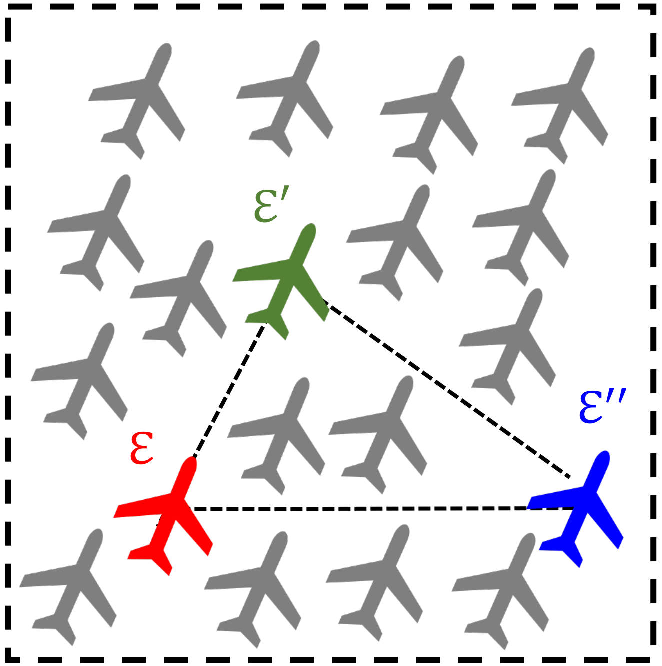
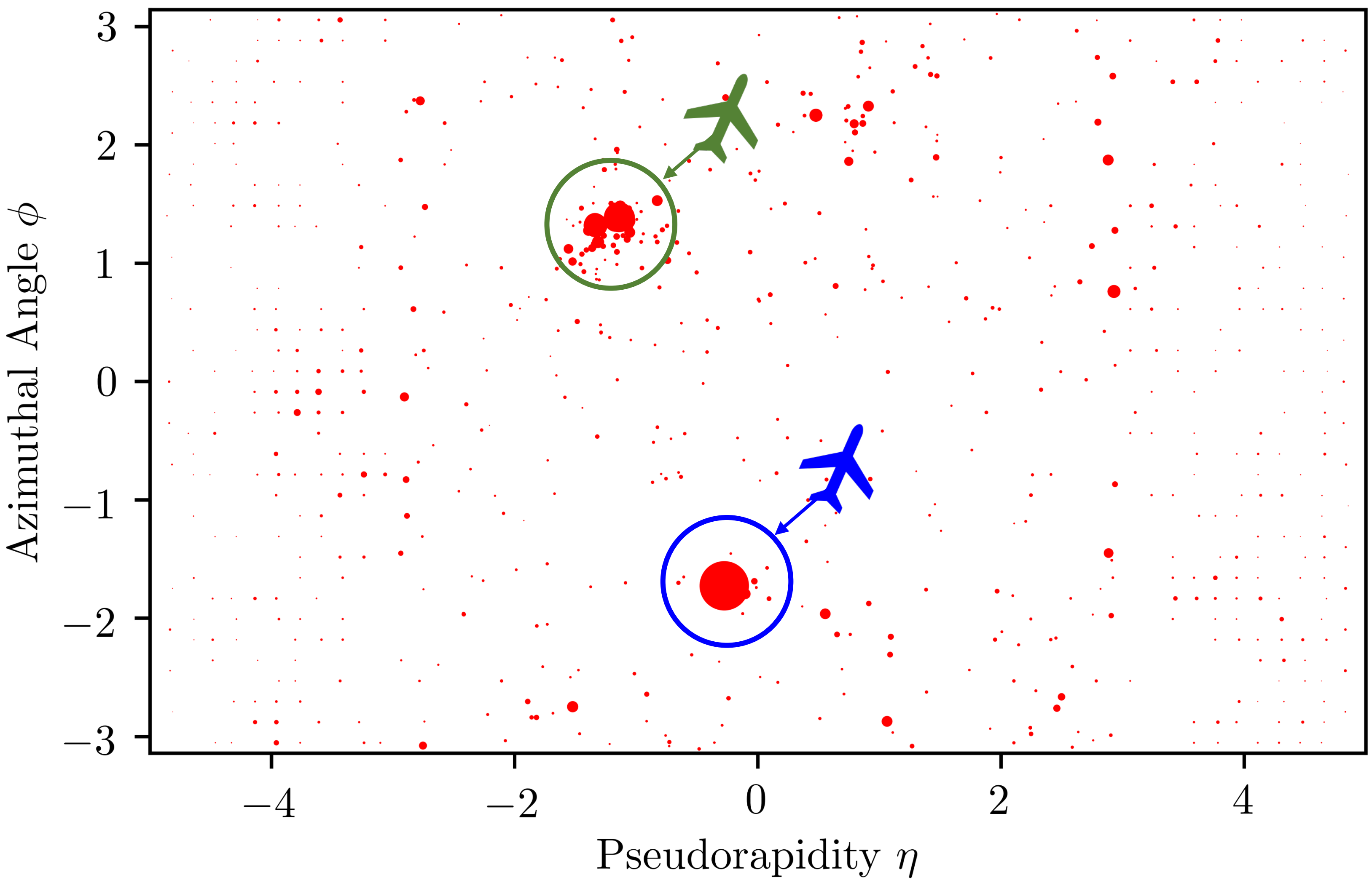
And many more!

Exploring the Space of Jets



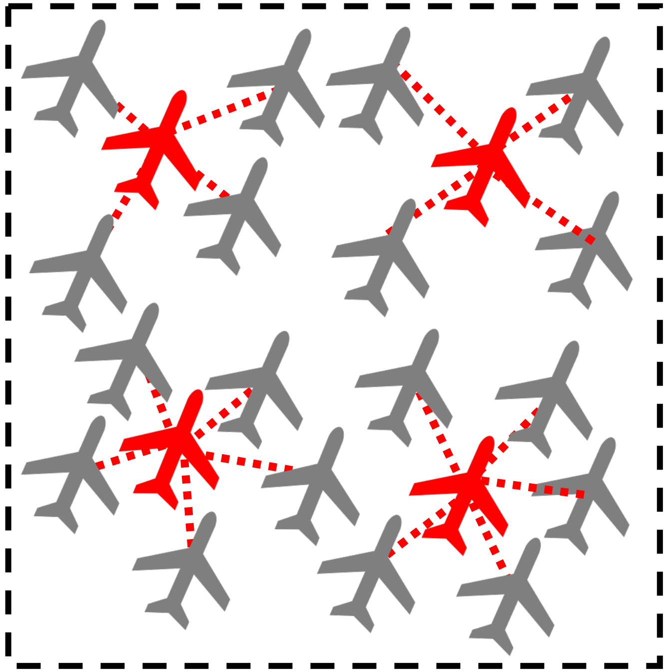
$\text{EMD}(\mathcal{E}, \mathcal{E}') + \text{EMD}(\mathcal{E}', \mathcal{E}'') \geq \text{EMD}(\mathcal{E}, \mathcal{E}'')$



Most Representative Jets

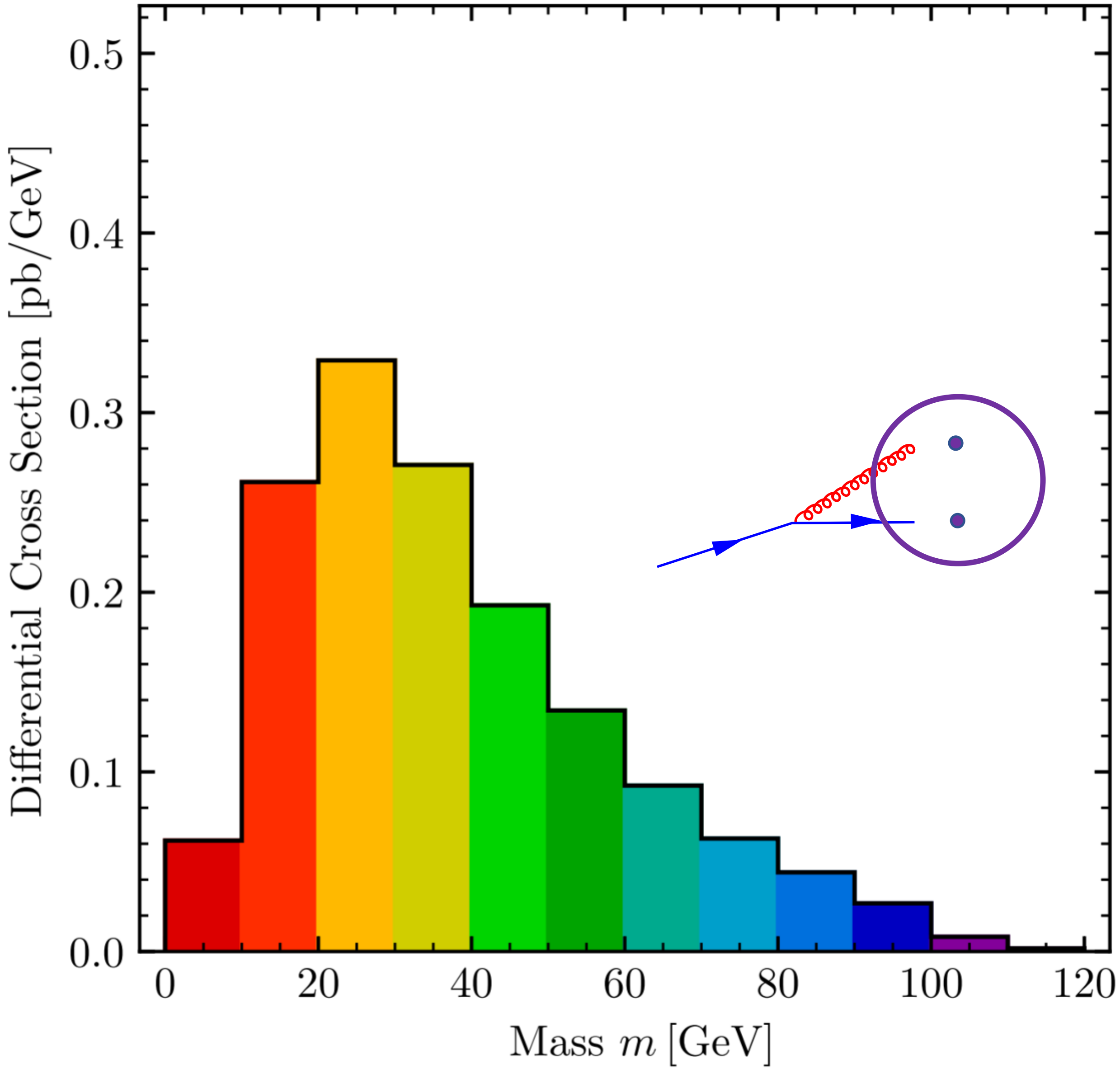
Jet Mass: $m = \left(\sum_{i=1}^{M} p_i^\mu\right)^2$

Measures how "wide" the jet is.



[Komiske, Mastandrea, **EMM**, Naik, Thaler, 1908.08542]

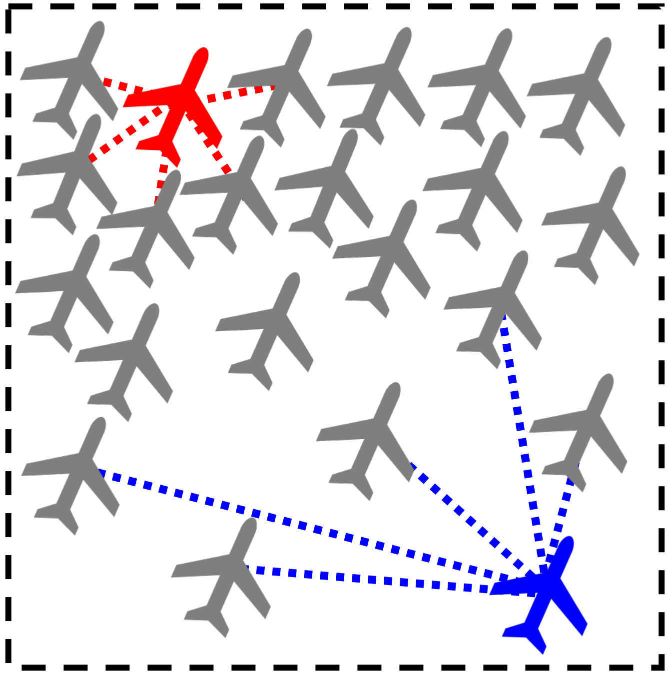
Jet Mass Histogram

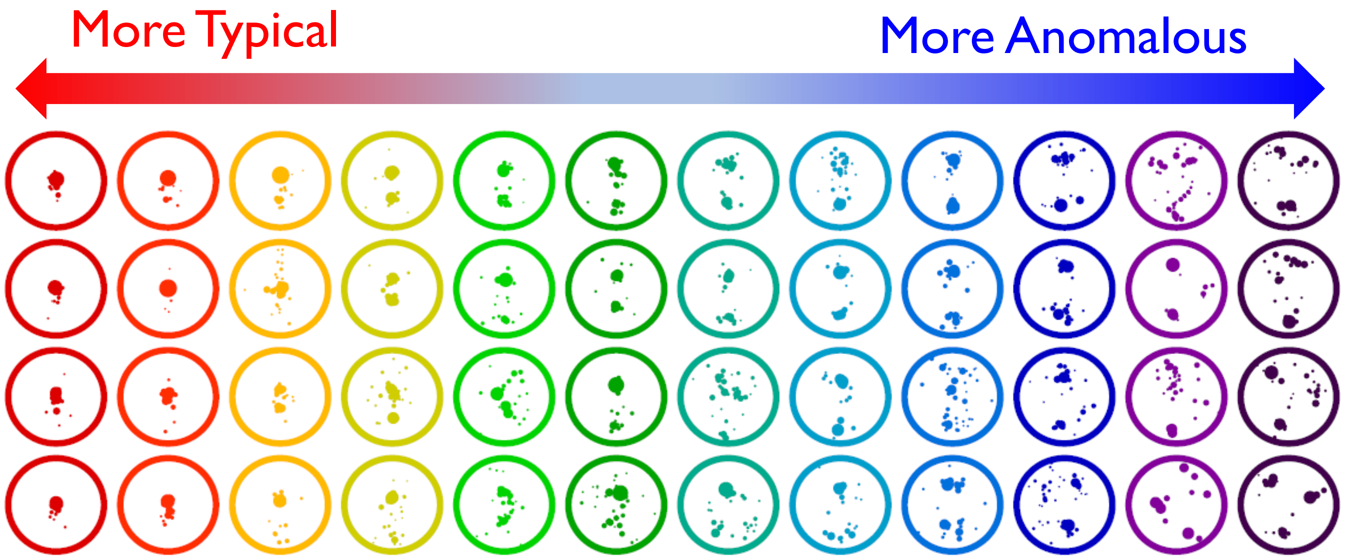


Towards Anomaly Detection

Mean EMD to Dataset:

$$\bar{Q}(\mathcal{E}) = \sum_{i=1}^{N} \mathrm{EMD}\,(\mathcal{E}, \mathcal{E}_i)$$



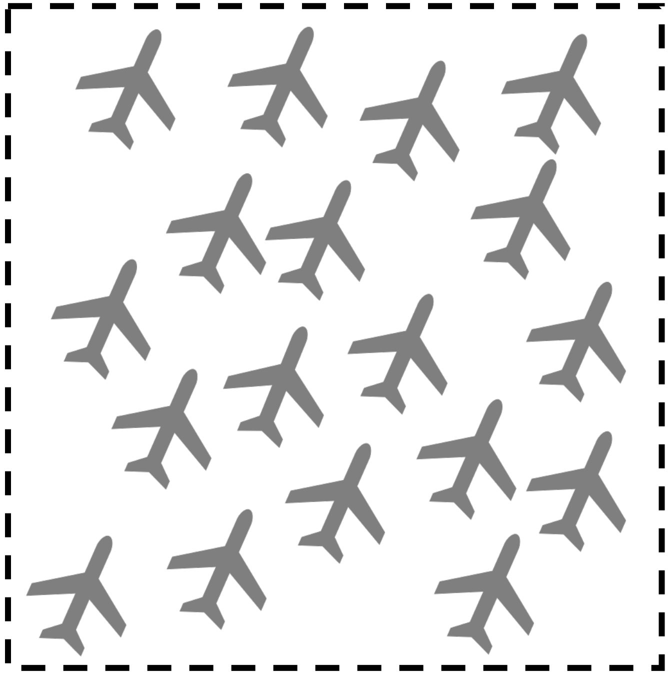


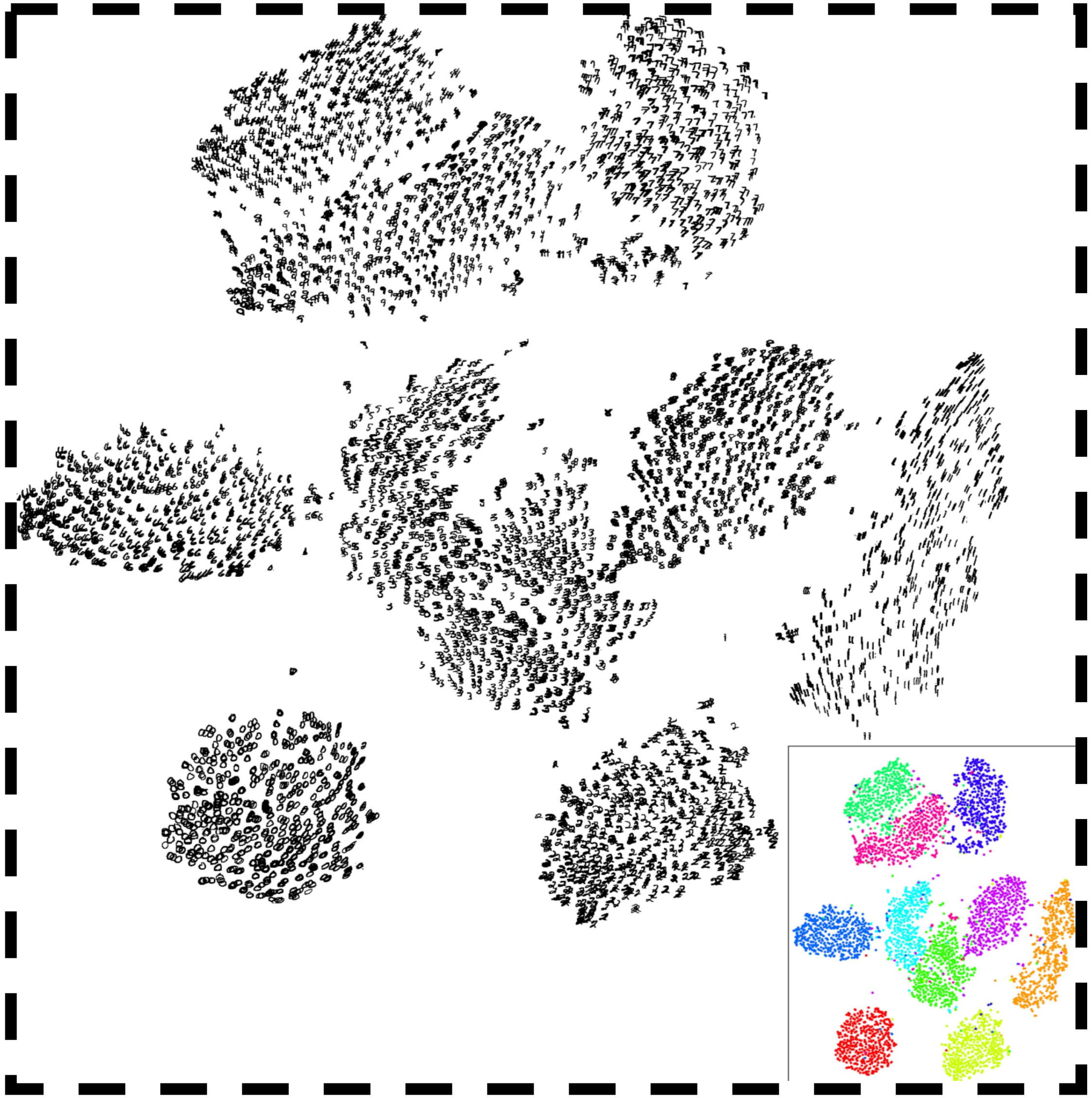
Complements recent developments in anomaly detection for collider physics.

[Collins, Howe, Nachman, 1805.02664]
[Heimel, Kasieczka, Plehn, Thompson, 1808.08979]
[Farina, Nakai, Shih, 1808.08992]
[Cerri, Nguyen, Pierini, Spiropulu, Vlimant, 1811.10276]

Visualizing the Manifold

What does the space of jets look like?





t-SNE embedding

[van der Maaten, Hinton, JMLR 2008]

Visualizing the Manifold

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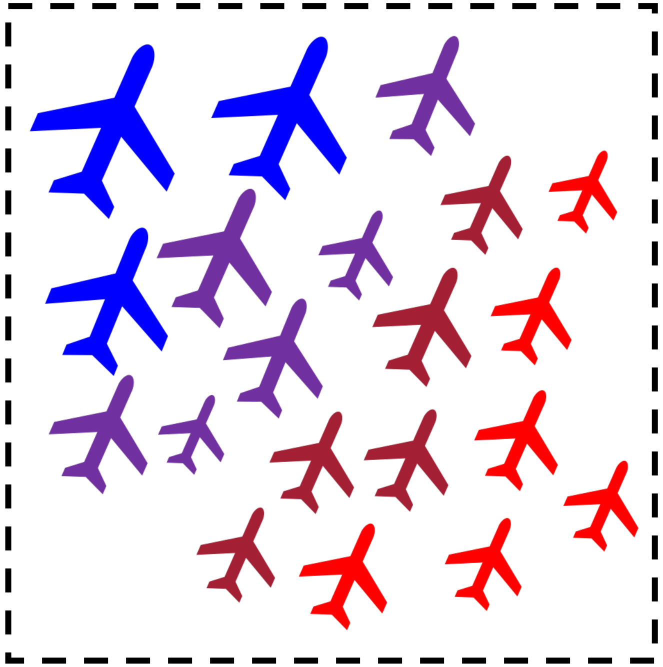

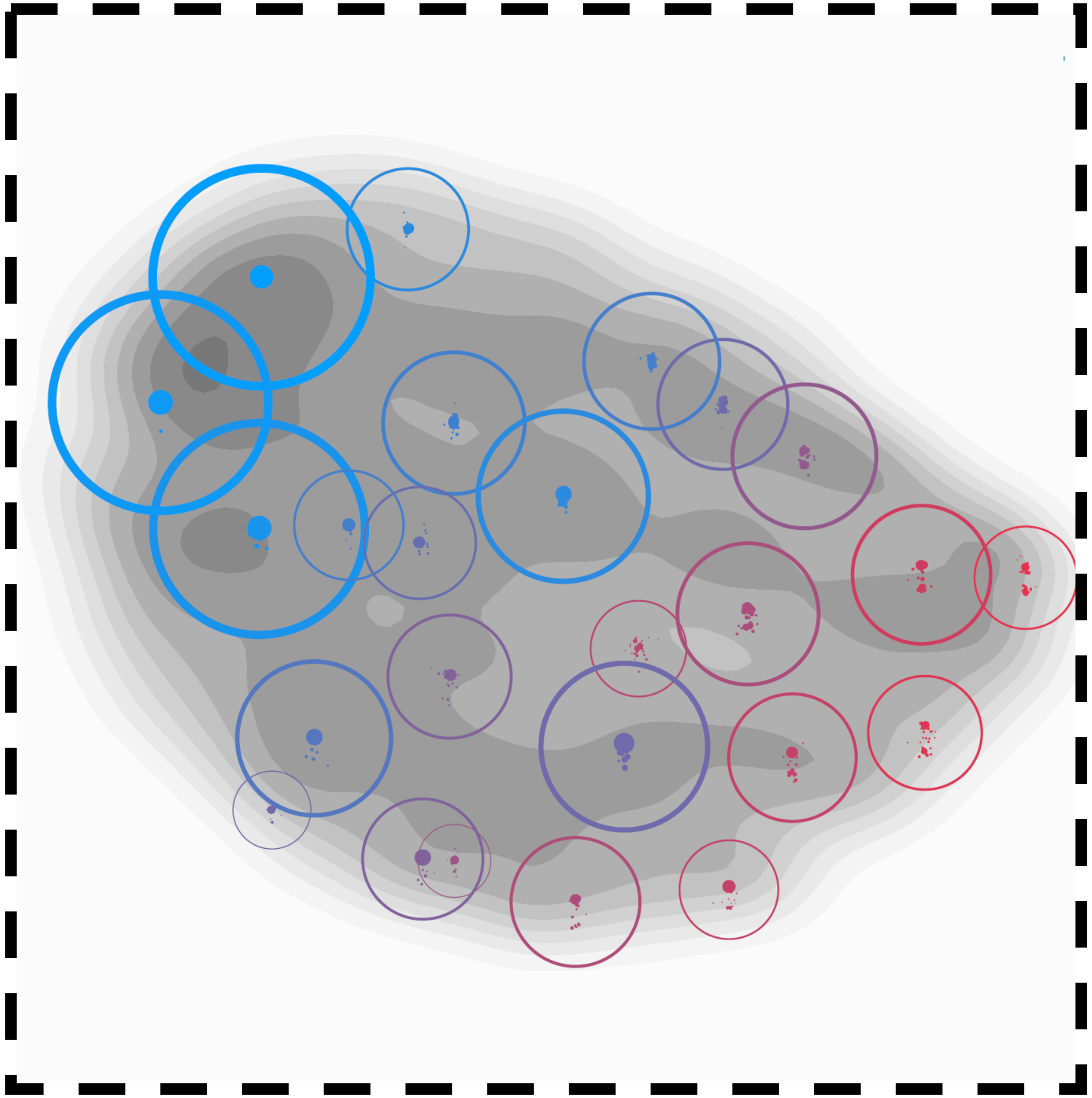

t-SNE embedding: 25-medoid jets shown

[van der Maaten, Hinton, JMLR 2008]

[Komiske, Mastandrea, **EMM**, Naik, Thaler, 1908.08542]

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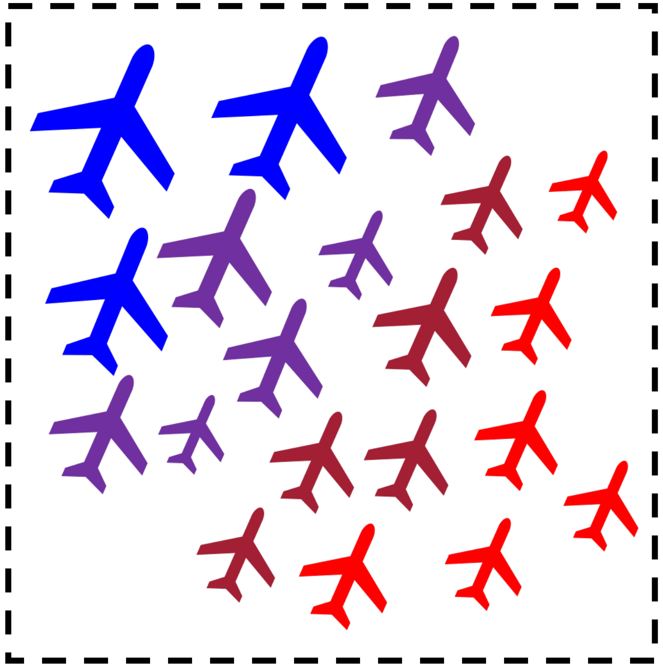
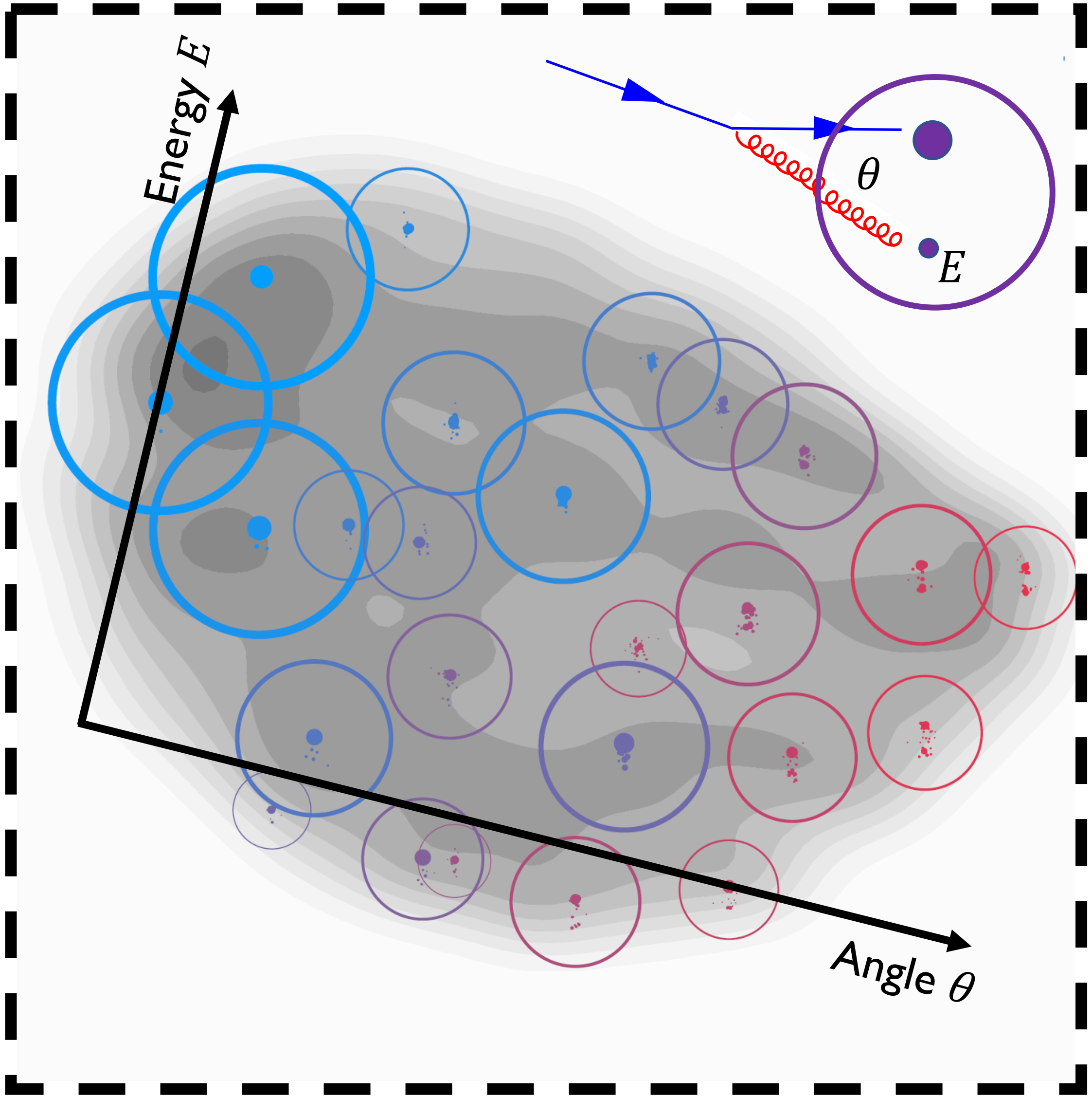




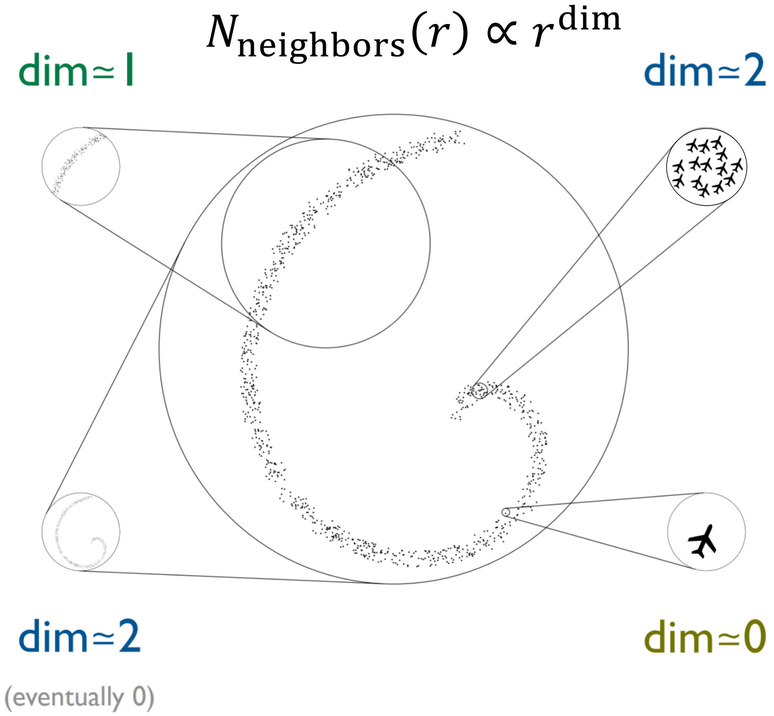
t-SNE embedding: 25-medoid jets shown

[van der Maaten, Hinton, JMLR 2008]

[Komiske, Mastandrea, **EMM**, Naik, Thaler, 1908.08542]

Correlation Dimension

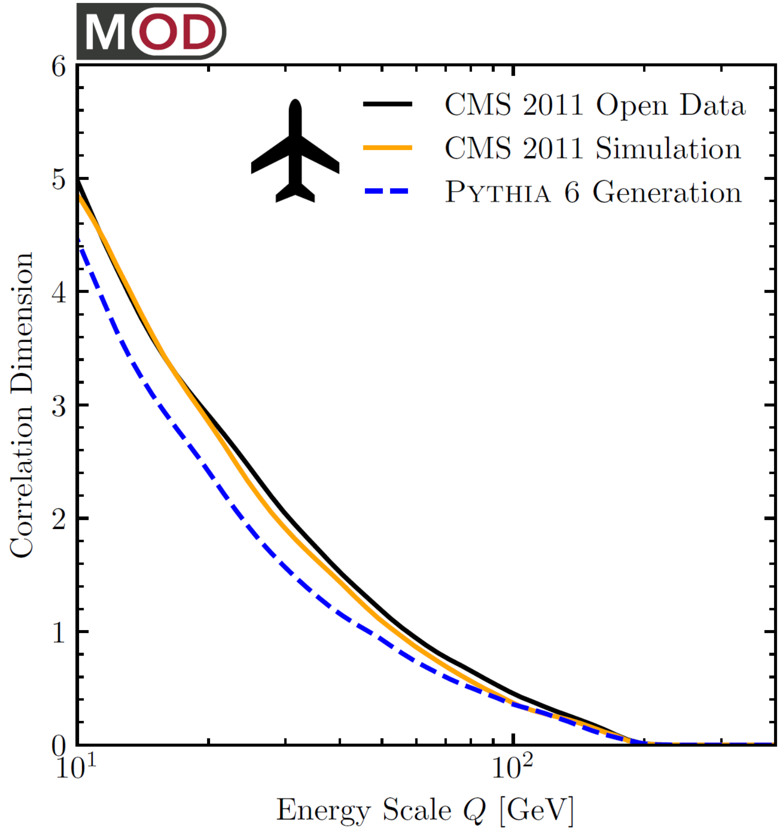
Conceptual Idea



$$\dim(Q) = Q \frac{\partial}{\partial Q} \ln \sum_{i=1}^{N} \sum_{j=1}^{N} \Theta[\mathrm{EMD}(\mathcal{E}_i, \mathcal{E}_j) < Q]$$

[Grassberger, Procaccia, PRL 1983] [Kegl, NeurIPS 2002]

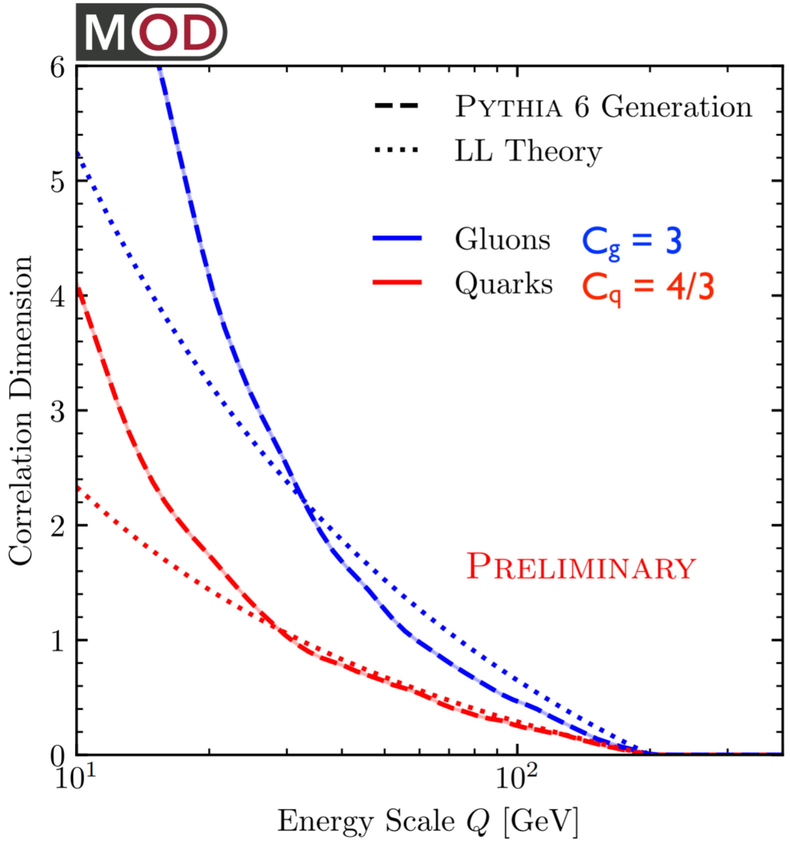
Experimental Data



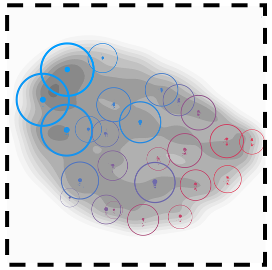
Dimension blows up at low energies.

[Komiske, Mastandrea, **EMM**, Naik, Thaler, 1908.08542]

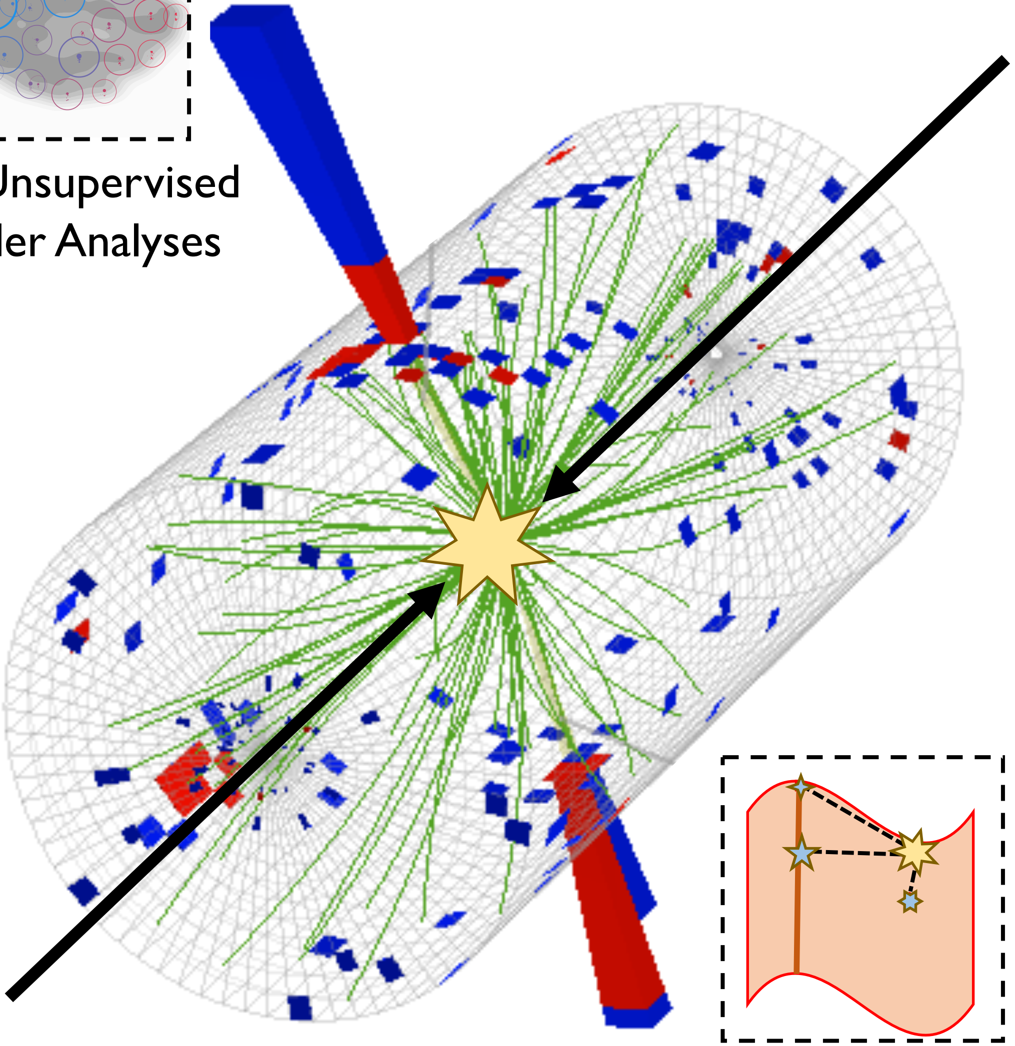
Theoretical Calculation

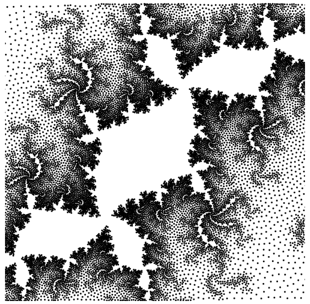


Thank You!



New Unsupervised Collider Analyses





Optimal Transport
[OTML Workshop, NeurIPS 2019]

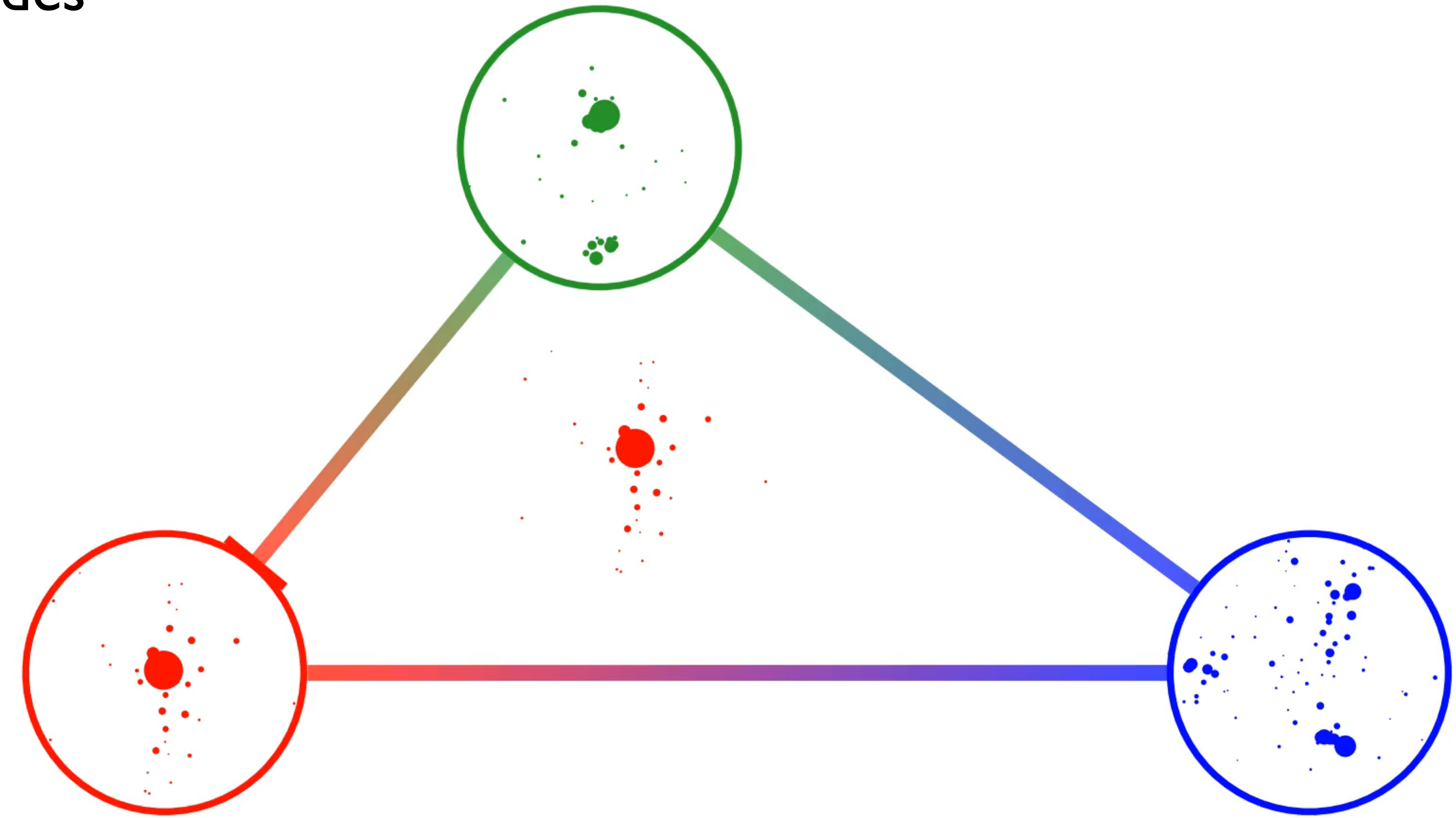
opendata

Public Collider Data
[opendata.cern.ch]

New Insights into Quantum Field Theory

Publicly released jet dataset

Extra Slides



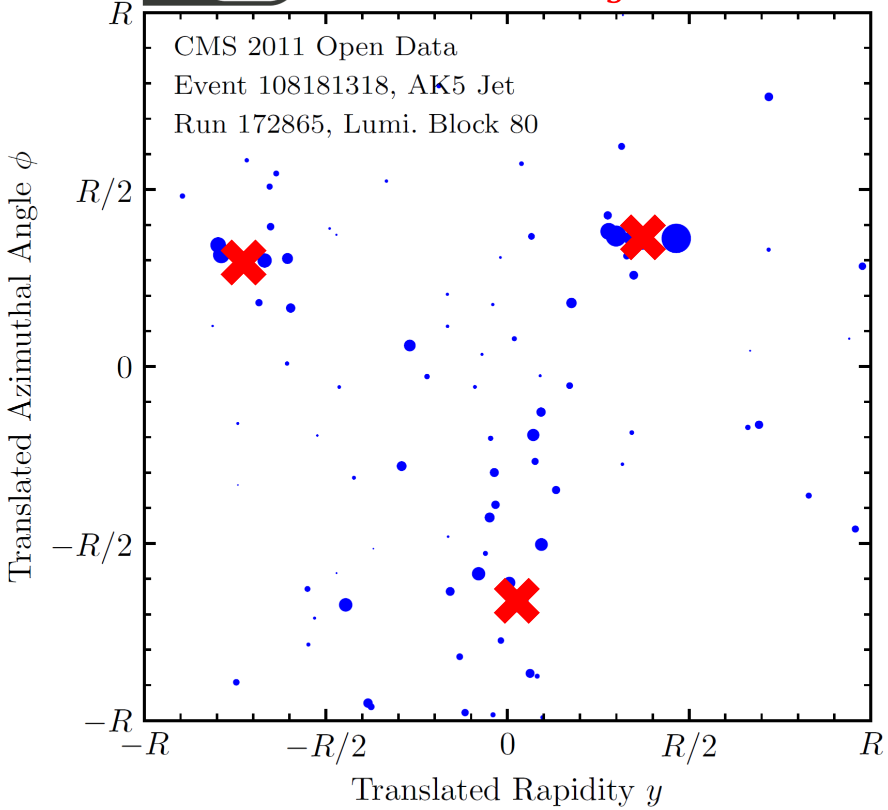
A Geometric Language for Observables

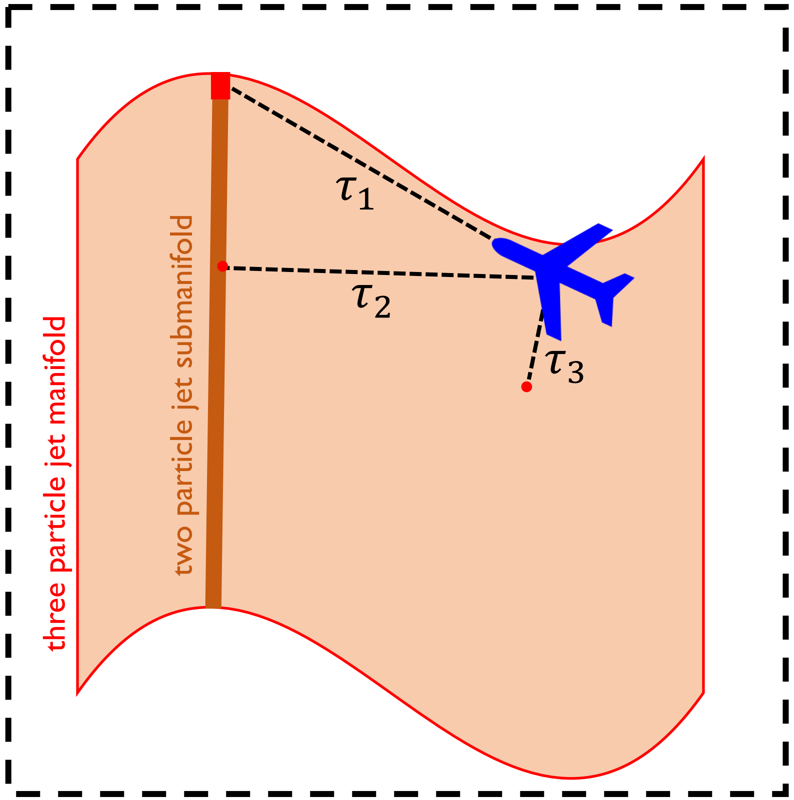
***N*-(sub)jettiness** is the EMD between the event and the closest N-particle event.

$$\tau_N(\mathcal{E}) = \min_{N\text{ axes}} \sum_{i=1}^{M} E_i \min\{\theta_{1,i}^{\beta}, \theta_{2,i}^{\beta}, \dots, \theta_{N,i}^{\beta}\} \longrightarrow \tau_N(\mathcal{E}) = \min_{|\mathcal{E}'|=N} \mathrm{EMD}(\mathcal{E}, \mathcal{E}').$$

β-Wasserstein distance

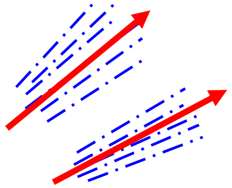
$N = 3, \quad \tau_3 \ll 1$





Geometry in the space of events

A Geometric Language for Observables

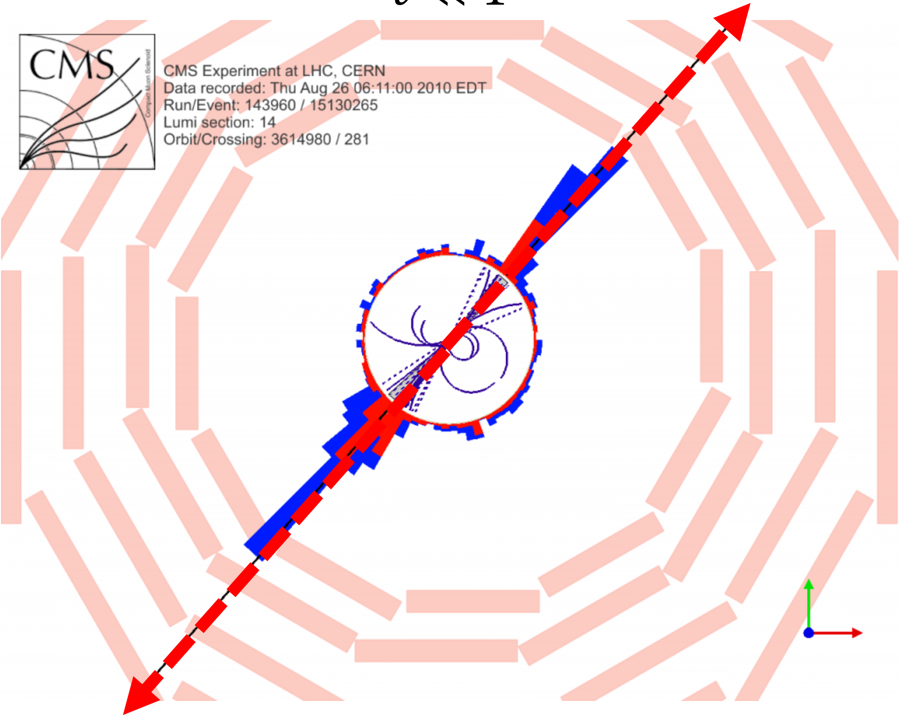


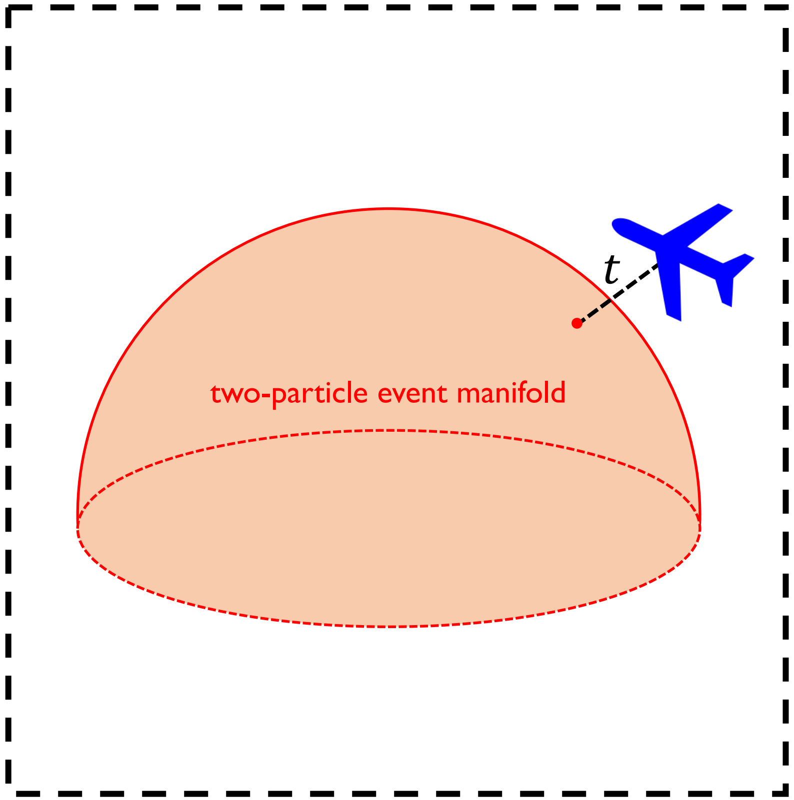
Thrust is the EMD between the event and the closest two-particle event.

$$t(\mathcal{E}) = E - \max_{\hat{n}} \sum_i |\vec{p}_i \cdot \hat{n}| \longrightarrow t(\mathcal{E}) = \min_{|\mathcal{E}'|=2} \text{EMD}(\mathcal{E}, \mathcal{E}')$$

with $\theta_{ij} = \hat{n}_i \cdot \hat{n}_j$, $\hat{n} = \vec{p}/E$

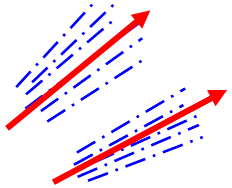
$t \ll 1$





Geometry in the space of events

A Geometric Language for Observables

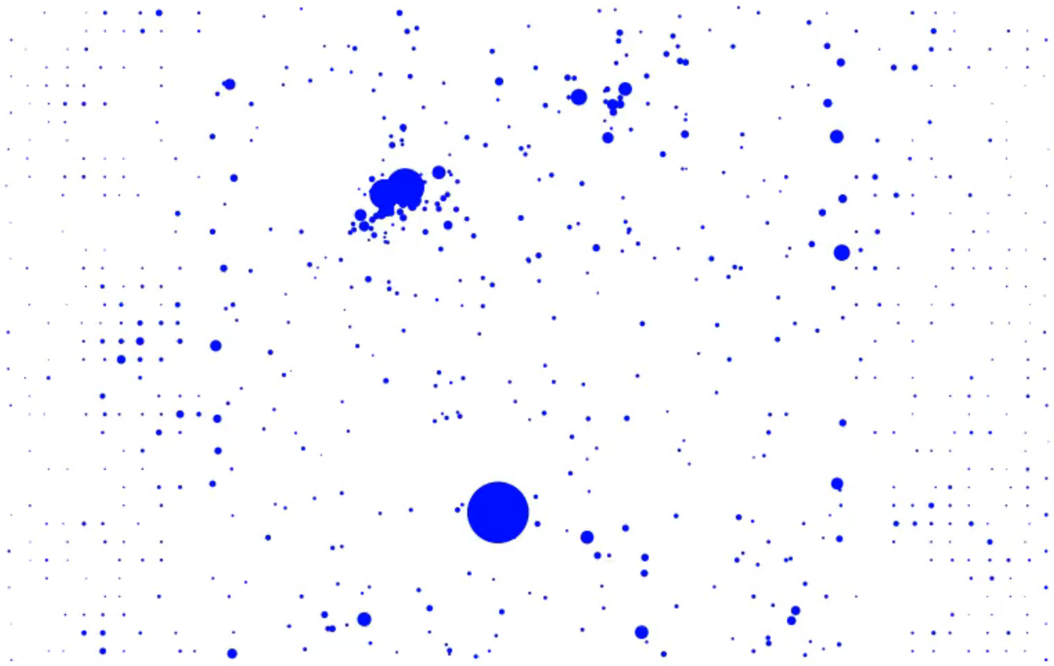


Isotropy is a new observable to probe how "uniform" an event is.

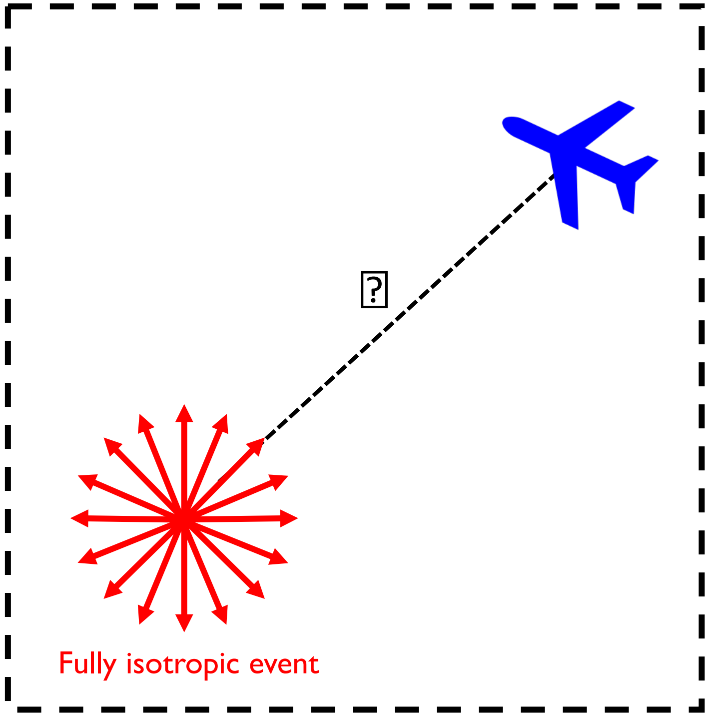
It is sensitive to very different new physics signals than existing event shapes.

e.g. uniform radiation from micro black holes [Cari Cesarotti and Jesse Thaler, coming soon!]

$?(\mathcal{E}) = \mathrm{EMD}(\mathcal{E}, \mathcal{E}_{\mathrm{iso}})$ where $\mathcal{E}_{\mathrm{iso}}$ is a fully isotropic event

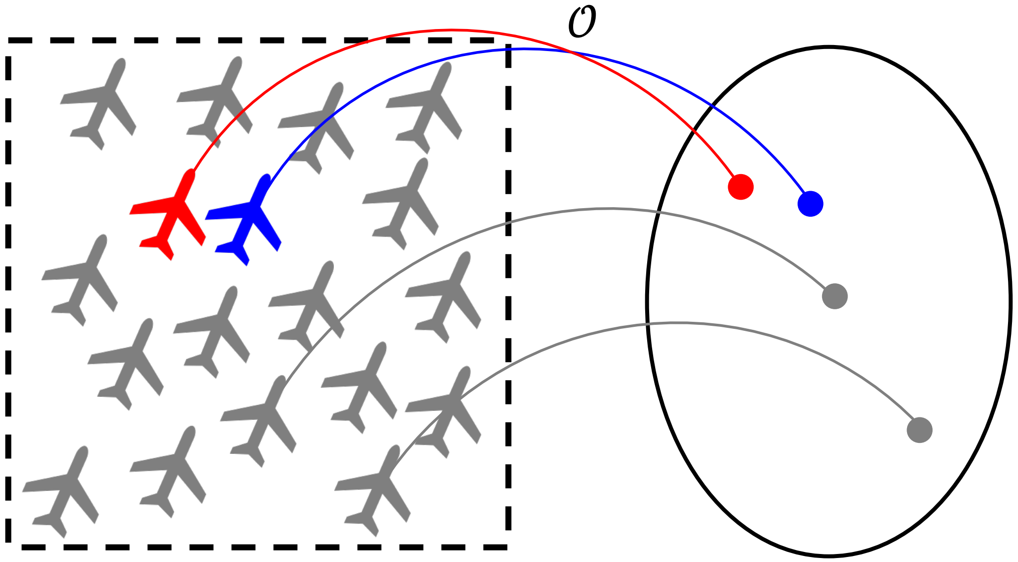


dijet event from CMS Open Data



A Geometric Language for Observables

Events close in EMD are close in any infrared and collinear safe observable!



Additive IRC-safe observables: $\mathcal{O}(\mathcal{E}) = \sum_{i=1}^{M} E_i \, \Phi(\hat{n}_i)$

Energy Mover's Distance

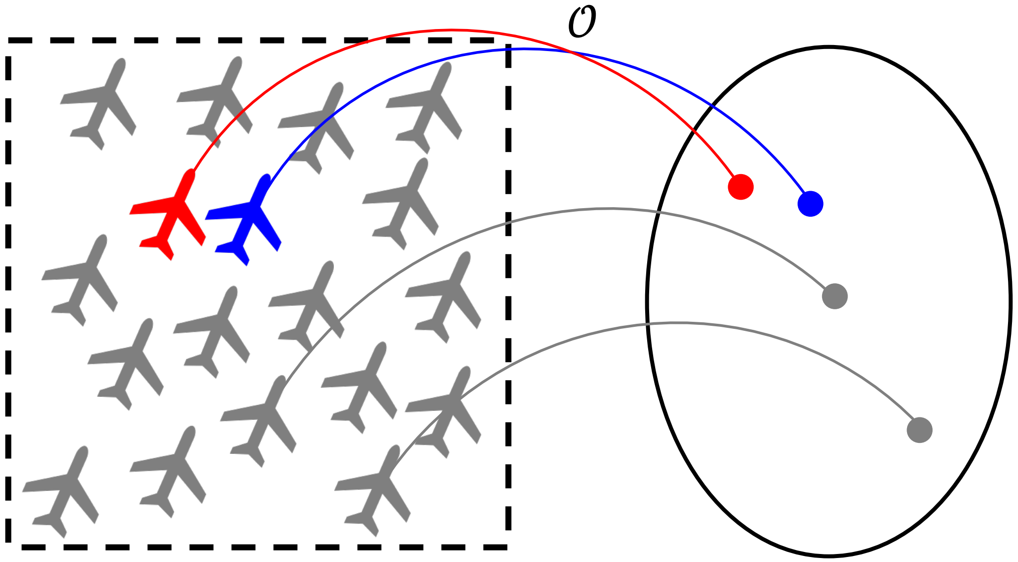
$$\boxed{\mathrm{EMD}(\mathcal{E}, \mathcal{E}') \geq \frac{1}{RL} \left|\mathcal{O}(\mathcal{E}) - \mathcal{O}(\mathcal{E}')\right|}$$

Difference in observable values

"Lipschitz constant" of Φ
i.e. bound on its derivative

A Geometric Language for Observables

Events close in EMD are close in any infrared and collinear safe observable!



Jet angularities with $\beta \geq 1$:

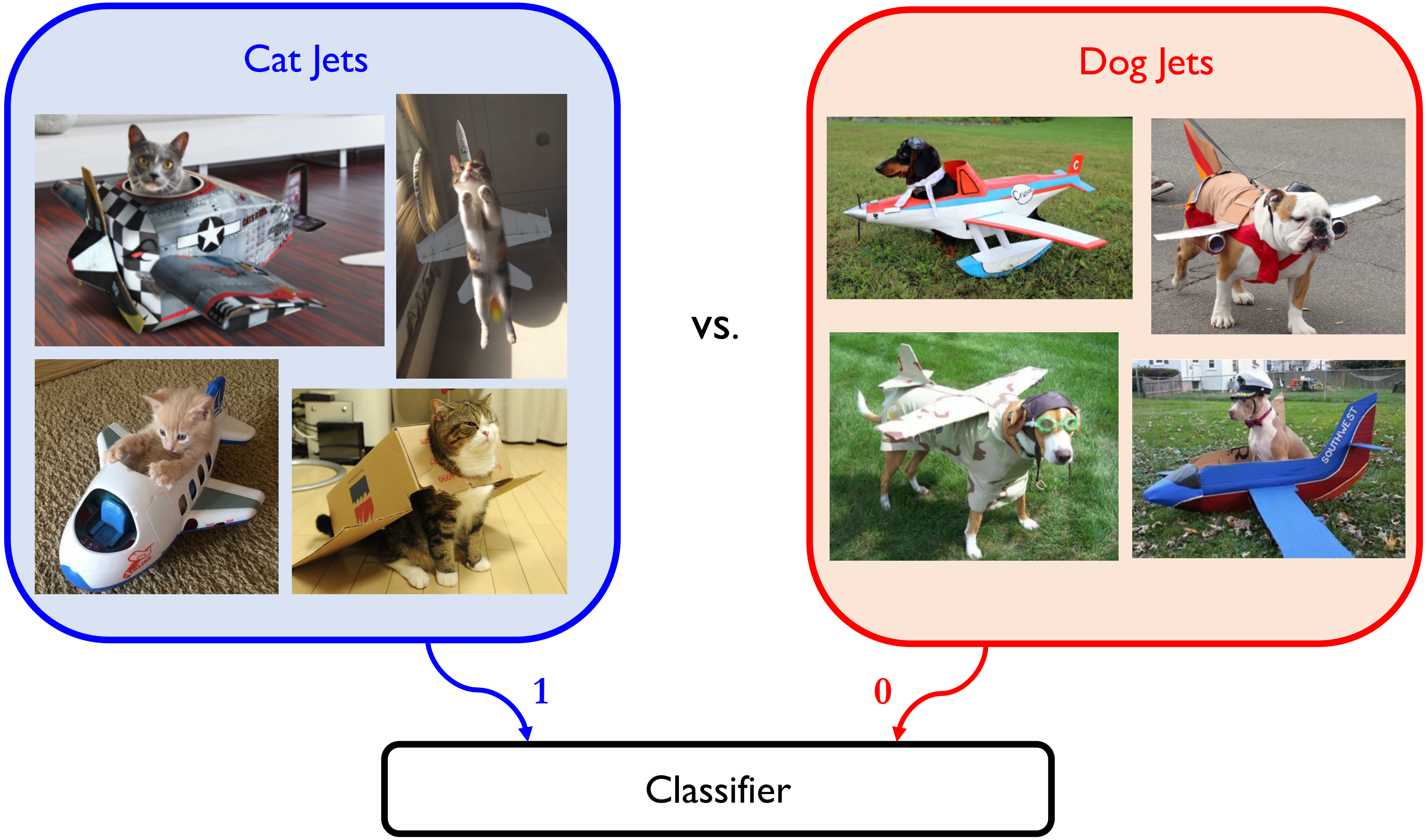
[C. Berger, T. Kucs, and G. Sterman, 0303051]

[A. Larkoski, J. Thaler, and W. Waalewijn, 1408.3122]

$$\lambda^{(\beta)} = \sum_{i=1}^{M} E_i \, \theta_i^{\beta}$$

$$\boxed{\left|\lambda^{(\beta)}(\mathcal{E}) - \lambda^{(\beta)}(\mathcal{E}')\right| \leq \beta \, \mathrm{EMD}(\mathcal{E}, \mathcal{E}')}$$

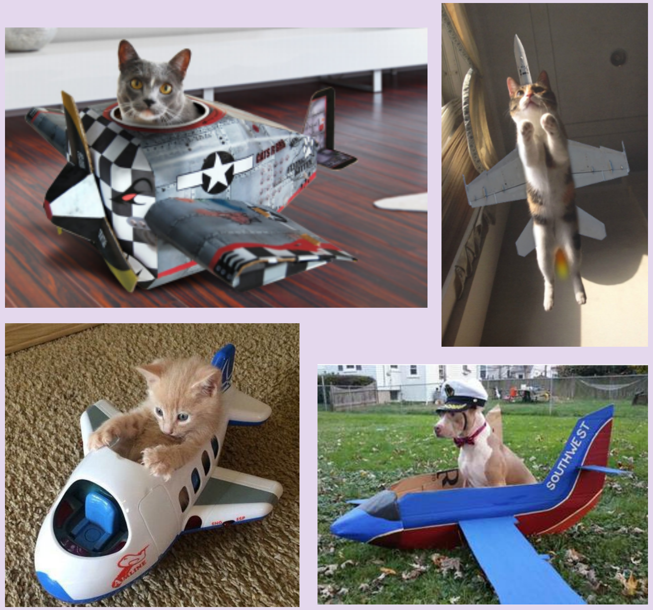
Training on pure samples: Cat jets vs. Dog jets



Training on mixed samples: Cat jets vs. Dog jets

Classification Without Labels (CWoLa)

Cat-enriched Jets



vs.

Dog-enriched Jets

1

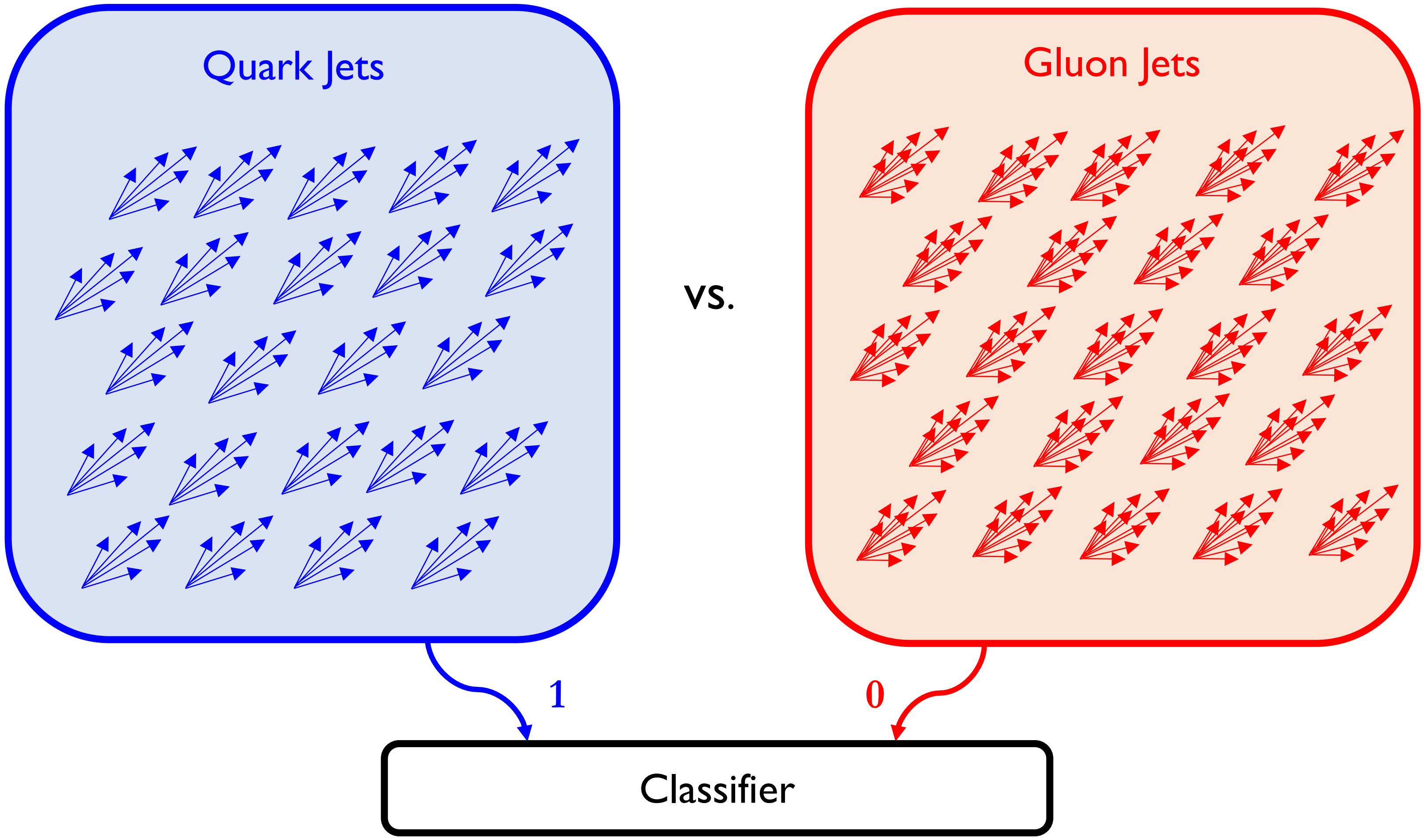
0

Classifier

Used by CMS for ttbb! [CMS 1909.05306]

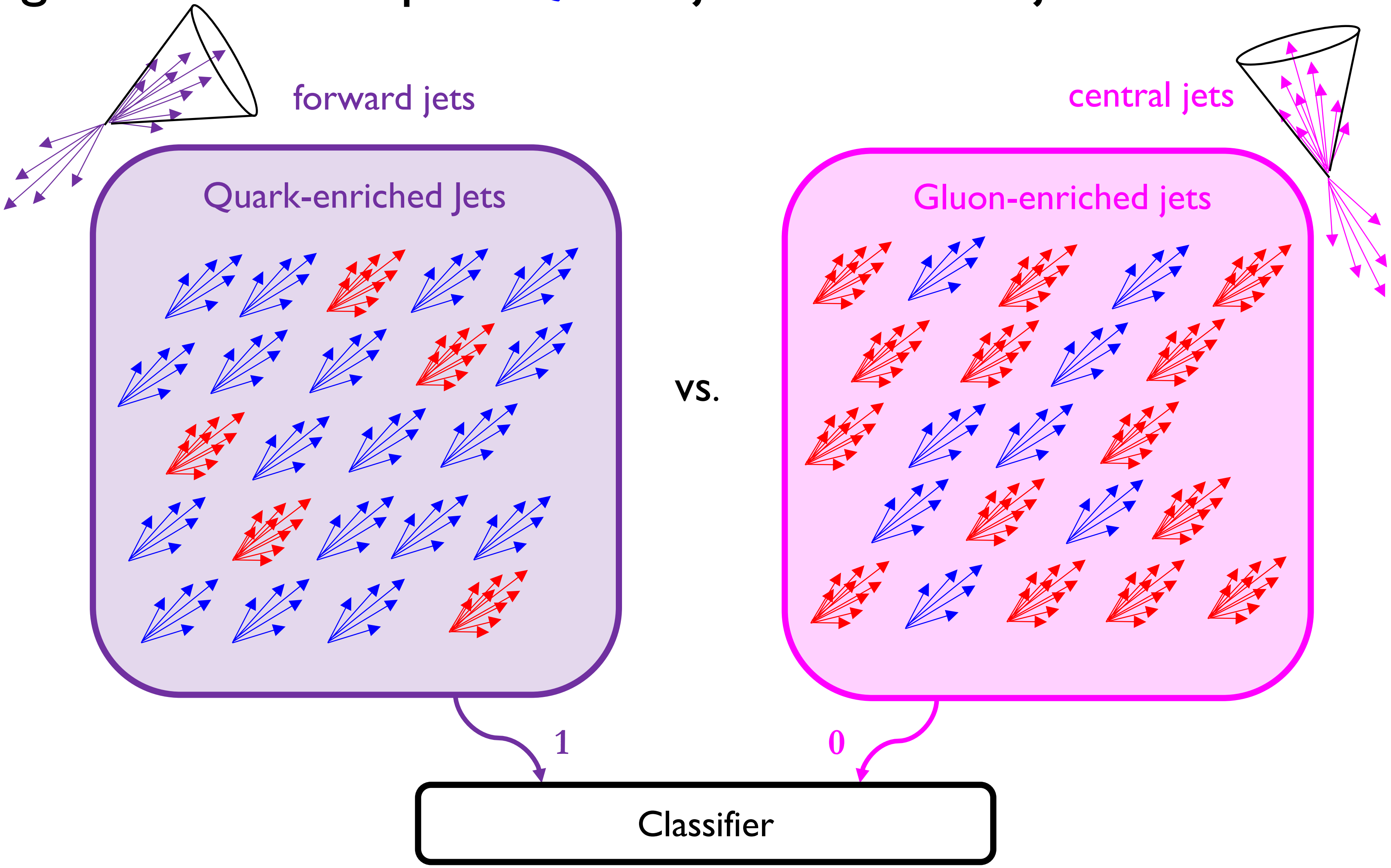
This defines an equivalent classifier to the pure case!

Training on pure samples: Quark jets vs. Gluon jets



Training on mixed samples: Quark jets vs. Gluon jets

Classification Without Labels (CWoLa)

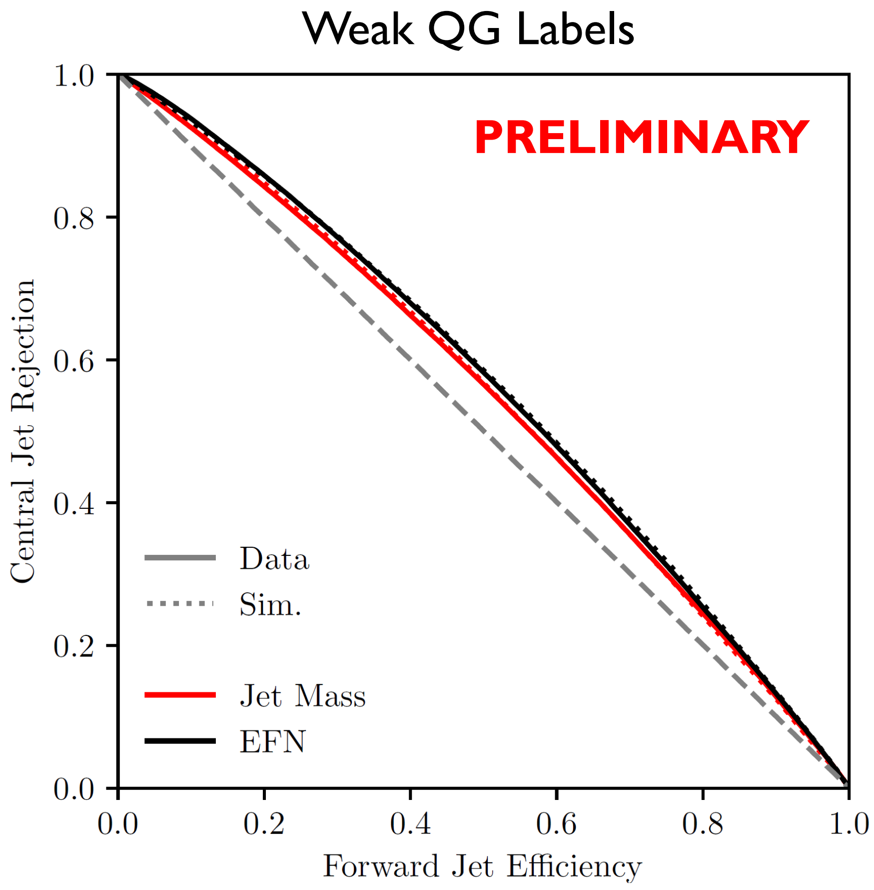


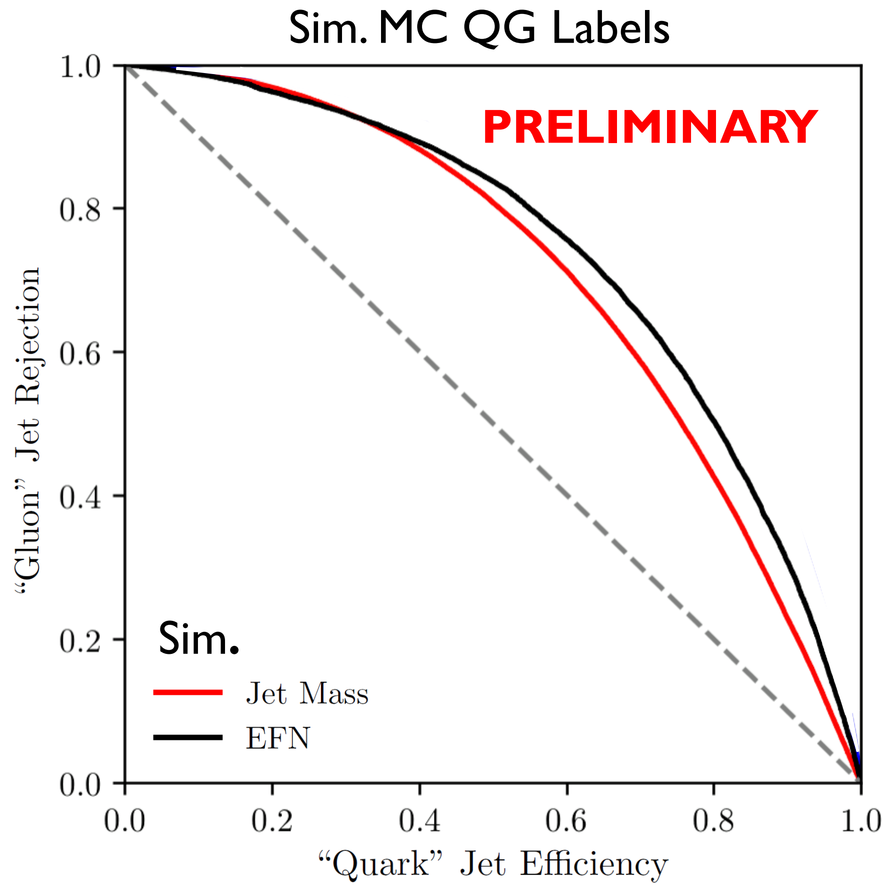
[**EMM**, B. Nachman, J. Thaler, 1708.02949]
[P.T. Komiske, **EMM**, B. Nachman, M.D. Schwartz, 1801.10158]
[L. Dery, B. Nachman, F. Rubbo, A. Schwartzman, 1702.00414] [T. Cohen, M. Freytsis, B. Ostdiek, 1706.09451]

Training on Data!

Central Jets $(|\eta^{\mathrm{jet}}| < 0.7)$: ~45% quark jets

Forward Jets $(|\eta^{\mathrm{jet}}| > 0.7)$: ~65% quark jets





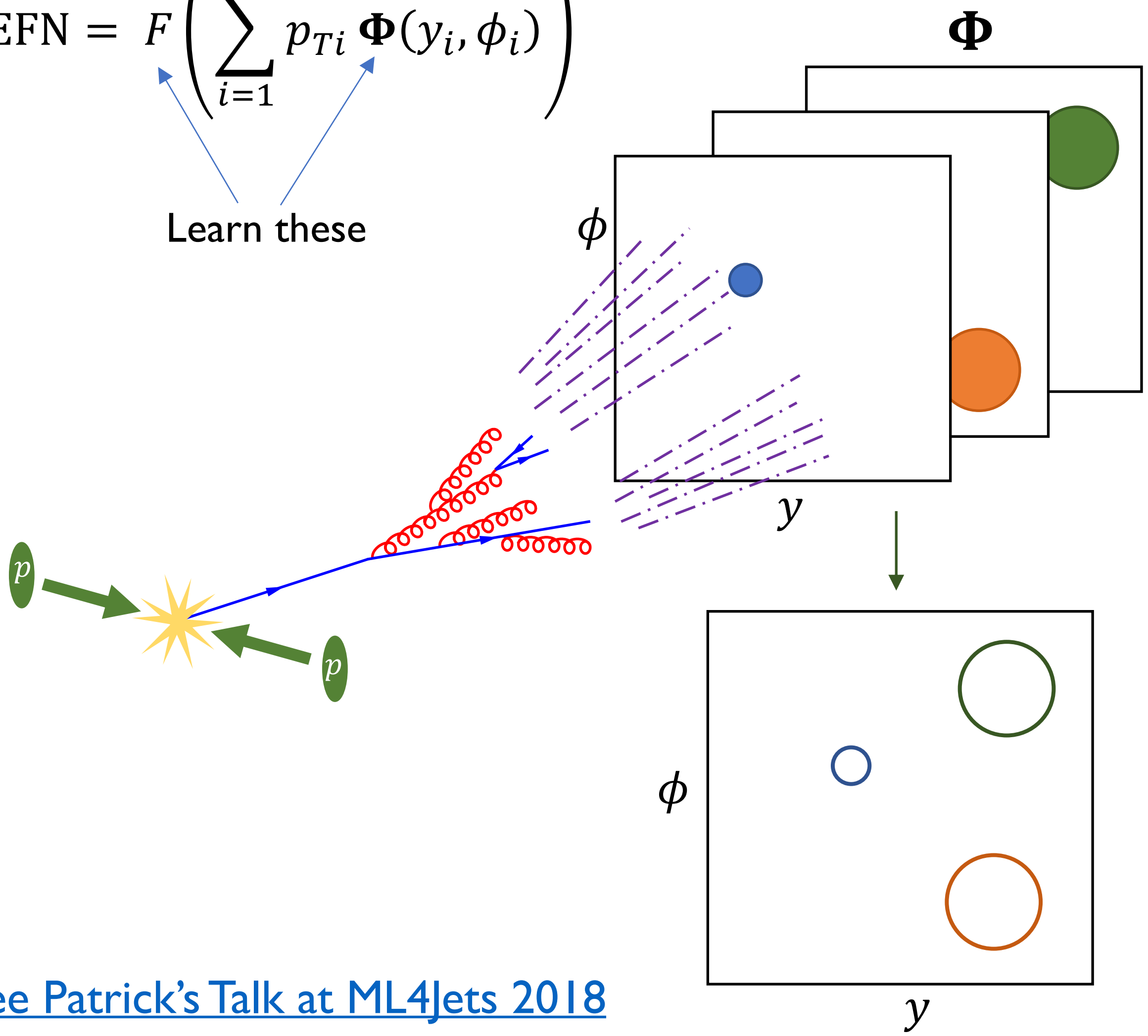
To reduce sample dependence, we train an EFN on tracks with $p_T^{\mathrm{PFC}} > 1$ GeV and remove pileup.

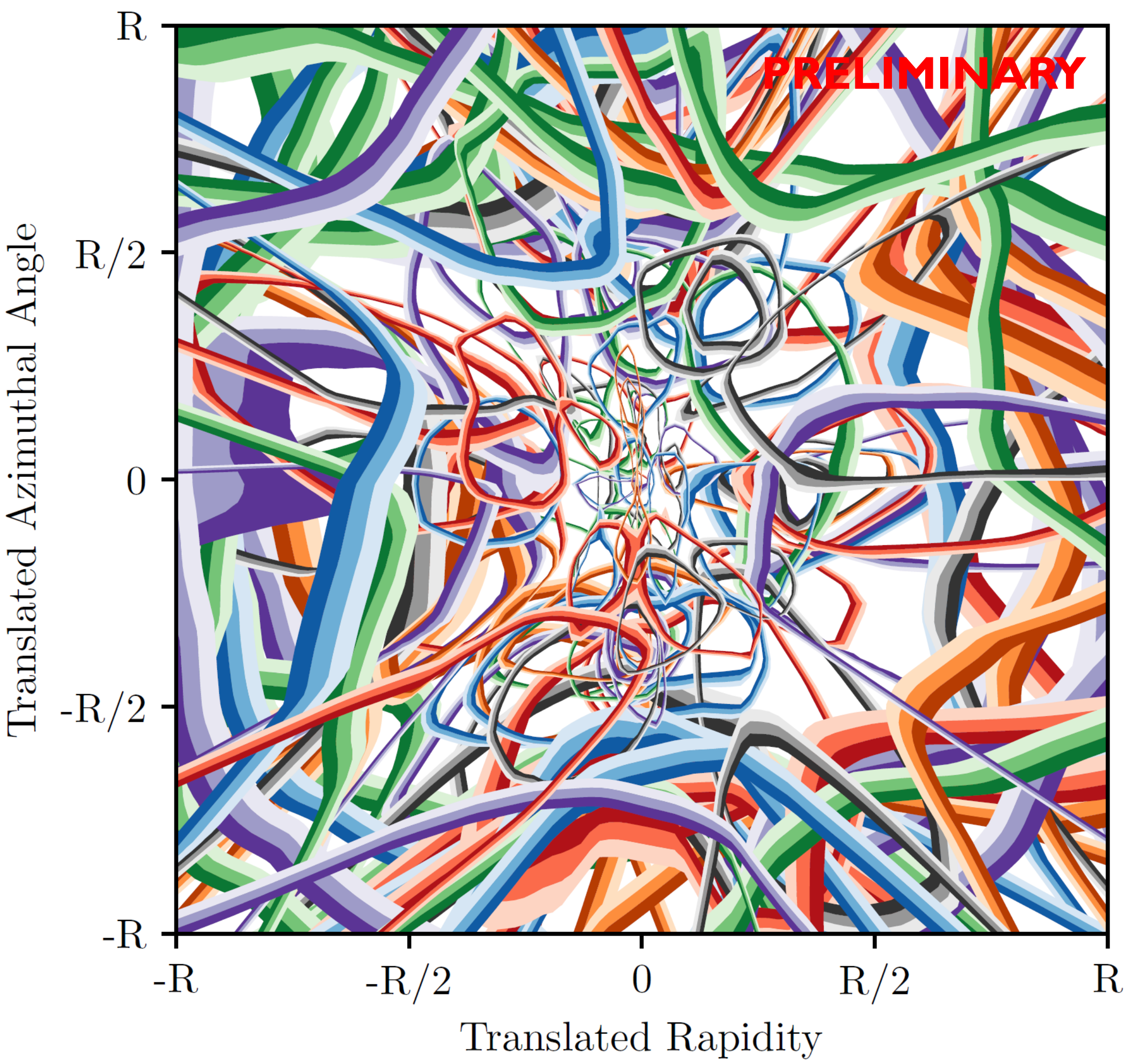
Or high-dimensional unfolding? See Patrick's Talk

What is the model learning?

$$\text{EFN} = F\left(\sum_{i=1}^{M} p_{Ti}\,\mathbf{\Phi}(y_i,\phi_i)\right)$$

Learn these





Visualizing 256 filters for EFN (weakly) trained on data

[See Patrick's Talk at ML4Jets 2018]

Exploring the Space of Jets: Correlation Dimension

Sketch of leading log (one emission) calculation:

$$\dim_{q/g}(Q) = Q\frac{\partial}{\partial Q}\ln \sum_{i=1}^{N}\sum_{j=1}^{N}\Theta[\mathrm{EMD}(\mathcal{E}_i,\mathcal{E}_j) < Q]$$

$$= Q\frac{\partial}{\partial Q}\ln \Pr\,[\mathrm{EMD} < Q]$$

$$= Q\frac{\partial}{\partial Q}\ln \Pr\,[\lambda^{(\beta=1)} < Q; C_{q/g} \to 2\,C_{q/g}]$$

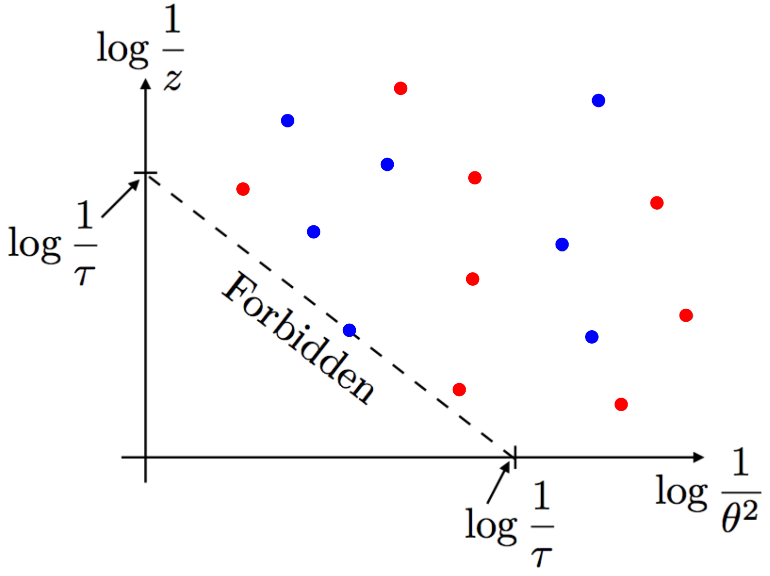
$$= Q\frac{\partial}{\partial Q}\ln \exp\left(-\frac{4\alpha_s C_{q/g}}{\pi}\ln^2\frac{Q}{p_T/2}\right)$$

$$= -\frac{8\alpha_s C_{q/g}}{\pi}\ln\frac{Q}{p_T/2}$$

+ 1-loop running of α_s

$$C_q = C_F = \frac{4}{3}$$

$$C_g = C_A = 3$$



[A. Larkoski, 1709.06195]