Exploring The (Metric) Space of Collider Events

ATLAS-Theory Lunch Seminar

Eric M. Metodiev

Center for Theoretical Physics

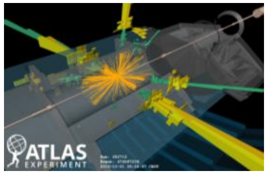
Massachusetts Institute of Technology

Joint work with Patrick Komiske and Jesse Thaler

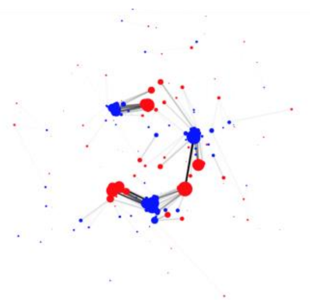
[1902.02346]

April 17, 2019

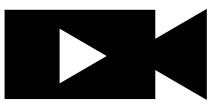
Outline



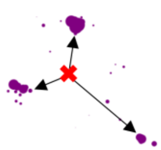
When are two events similar?



The Energy Mover's Distance

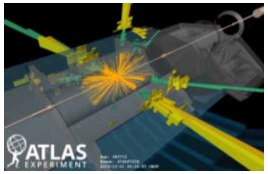


Movie Time



Applications

Outline



When are two events similar?

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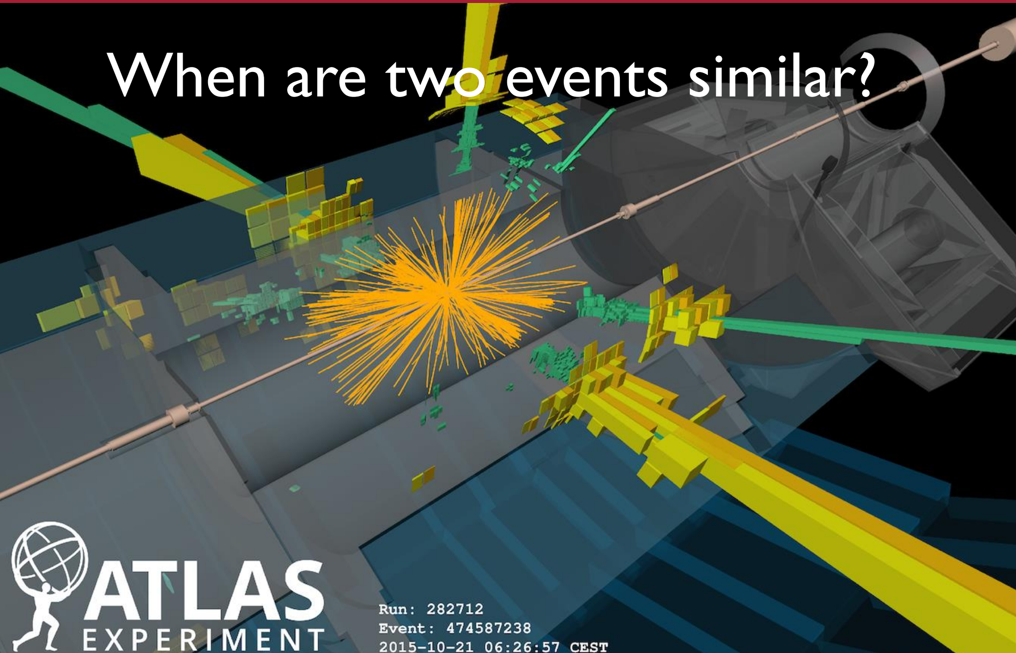
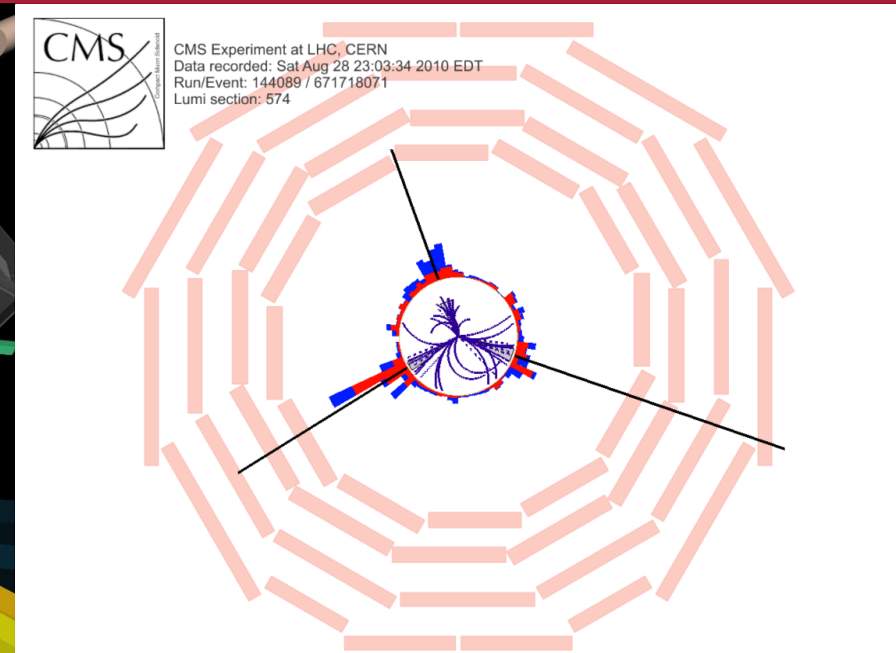
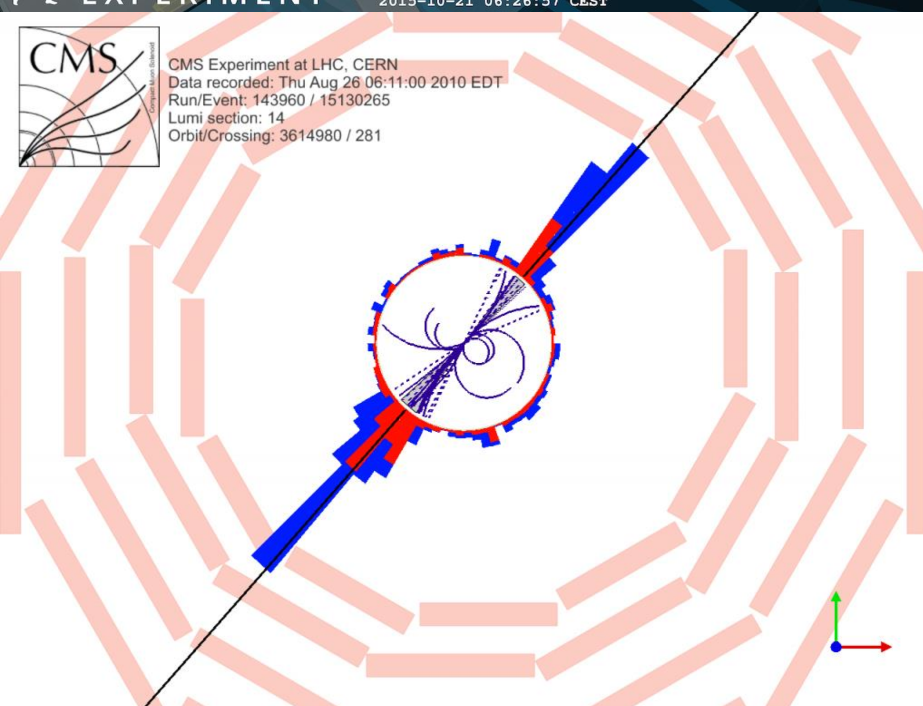
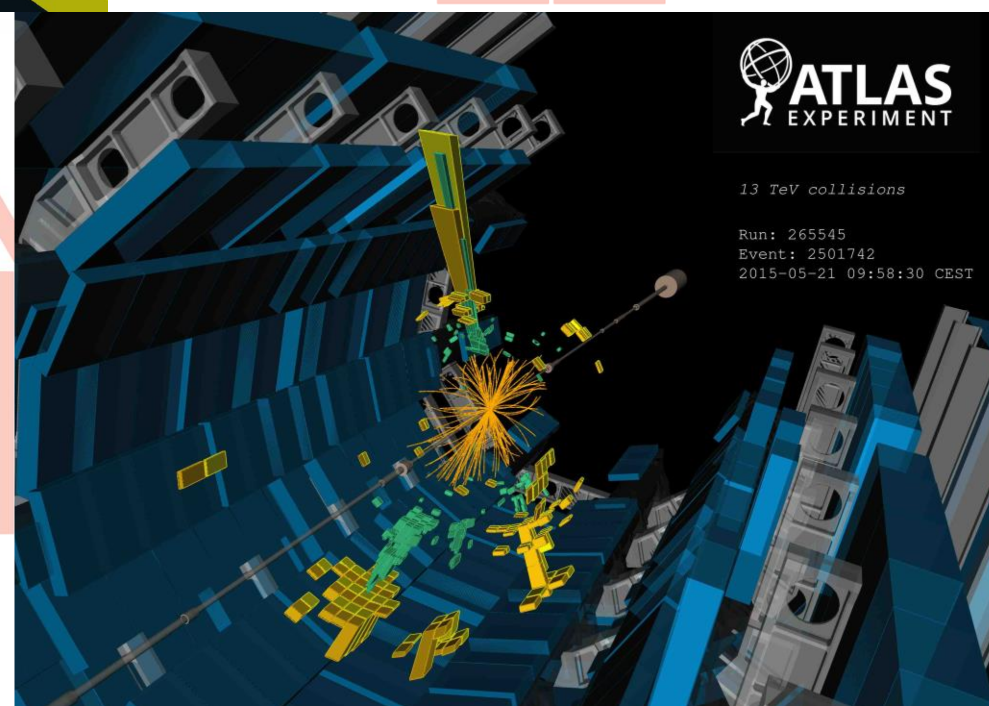
Applications

When are two events similar?



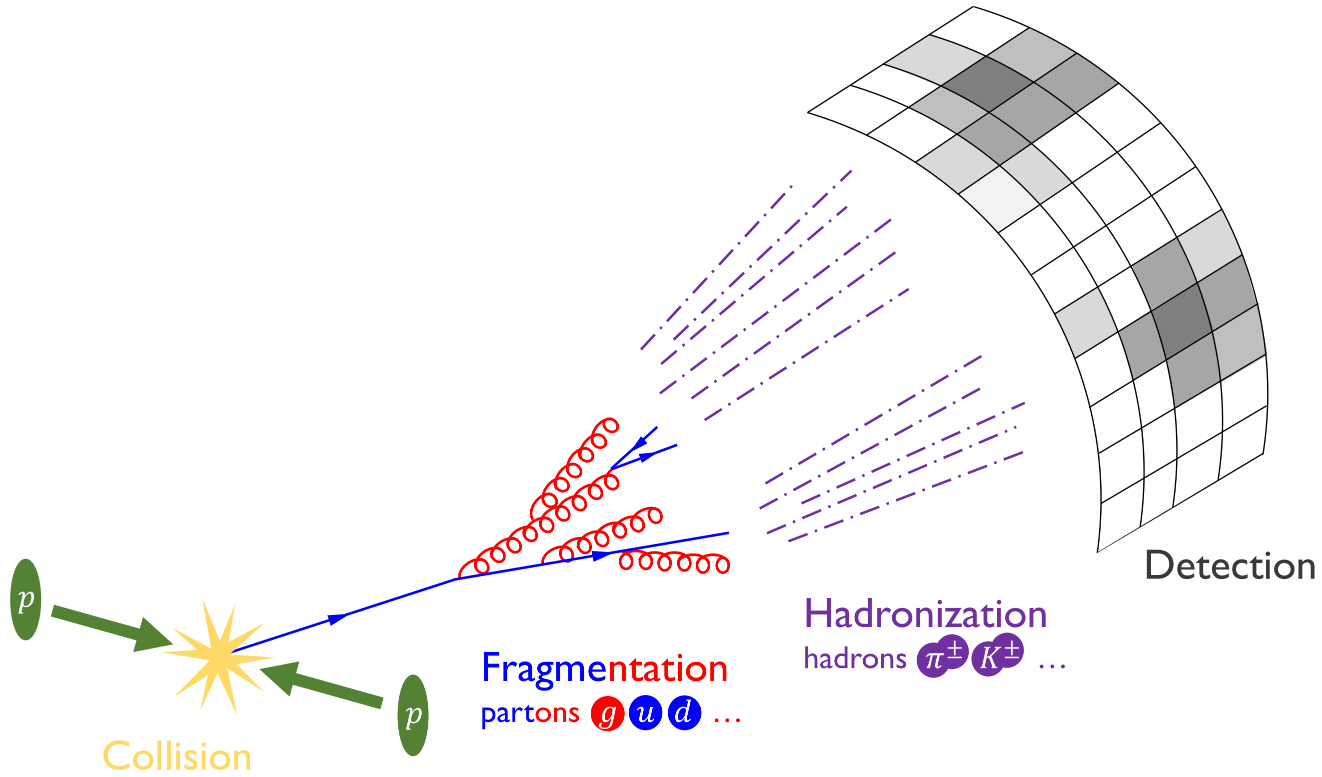






When are two collider events similar?

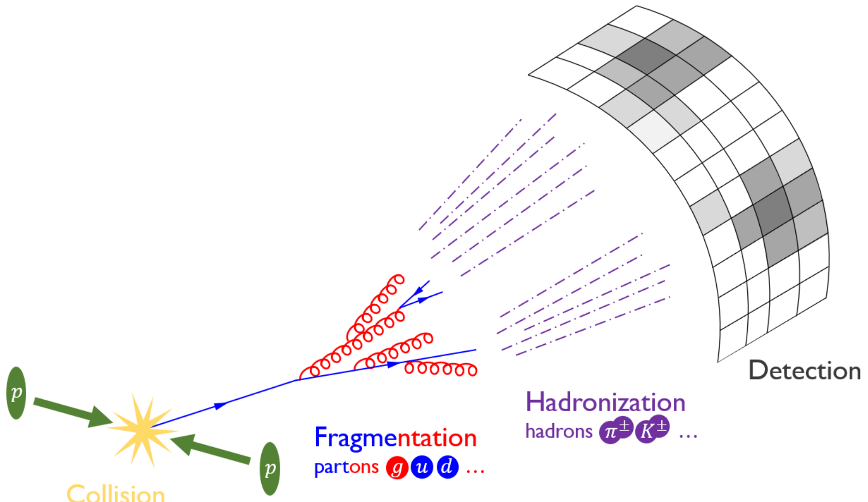
How an event gets its shape



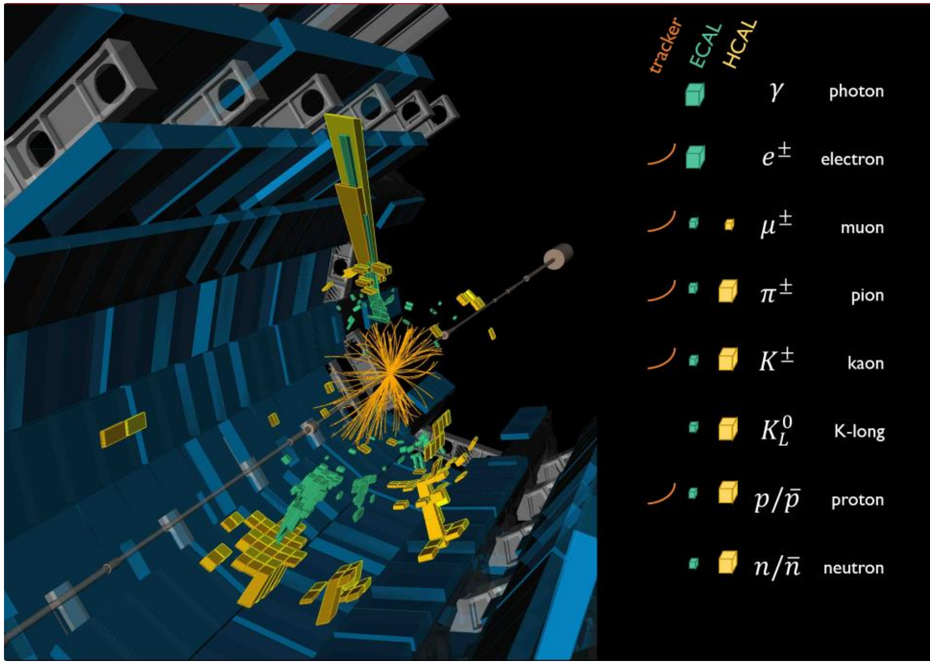
When are two collider events similar?

A collider event is…

Theoretically: very complicated



Experimentally: very complicated



However:

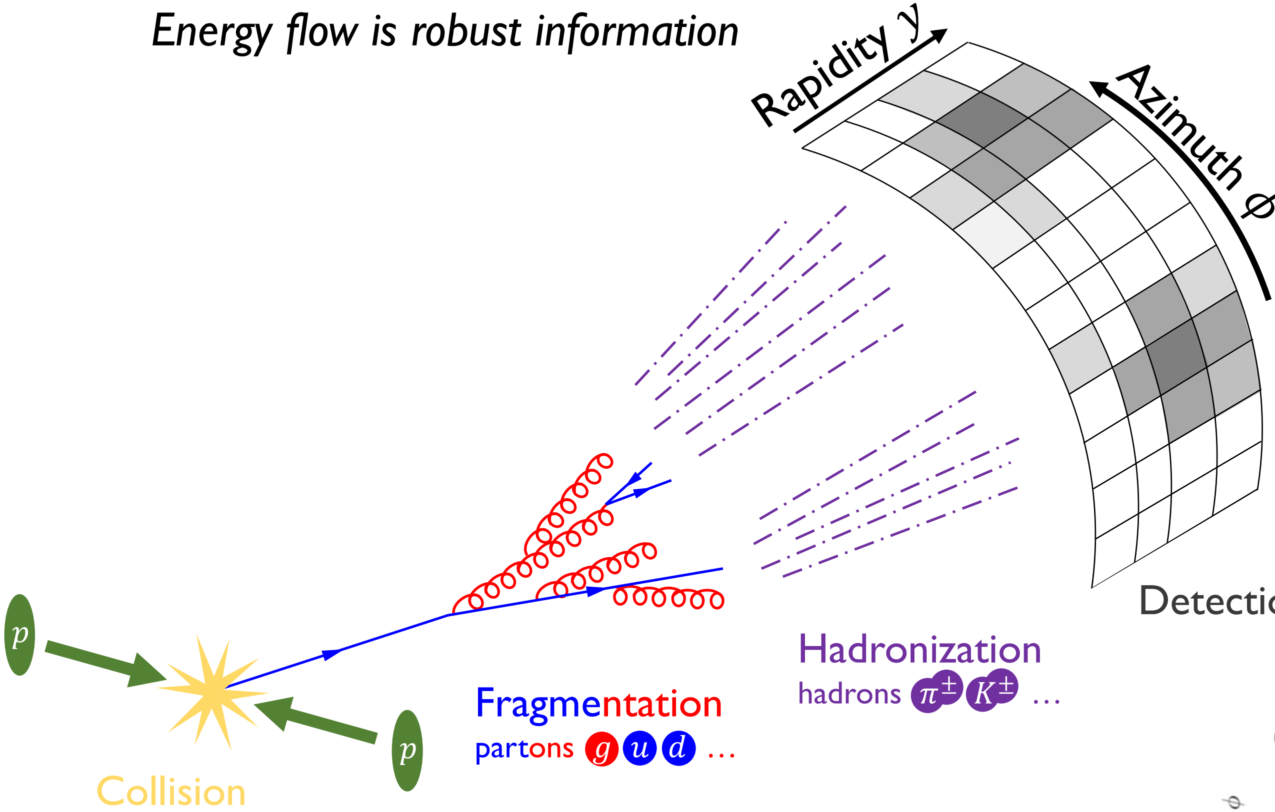
The *energy flow* (distribution of energy) is the information that is robust to:
fragmentation, hadronization, detector effects, …

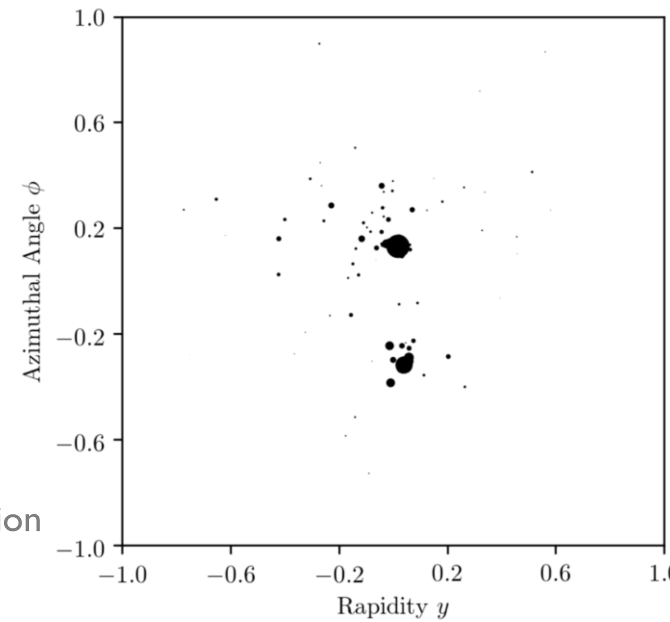
[N.A. Sveshnikov, F.V. Tkachov, 9512370]
[F.V. Tkachov, 9601308]
[P.S. Cherzor, N.A. Sveshnikov, 9710349]

Energy flow ⇔ Infrared and Collinear (IRC) Safe information

When are two collider events similar?

Energy flow is robust information





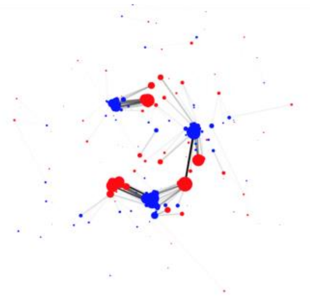
Treat events as distributions of energy: $$\sum_{i=1}^{M} E_i \, \delta(\hat{n} - \hat{p}_i)$$

energy direction

Ignoring particle flavor, charge…

Outline

When are two events similar?



The Energy Mover's Distance

Movie Time

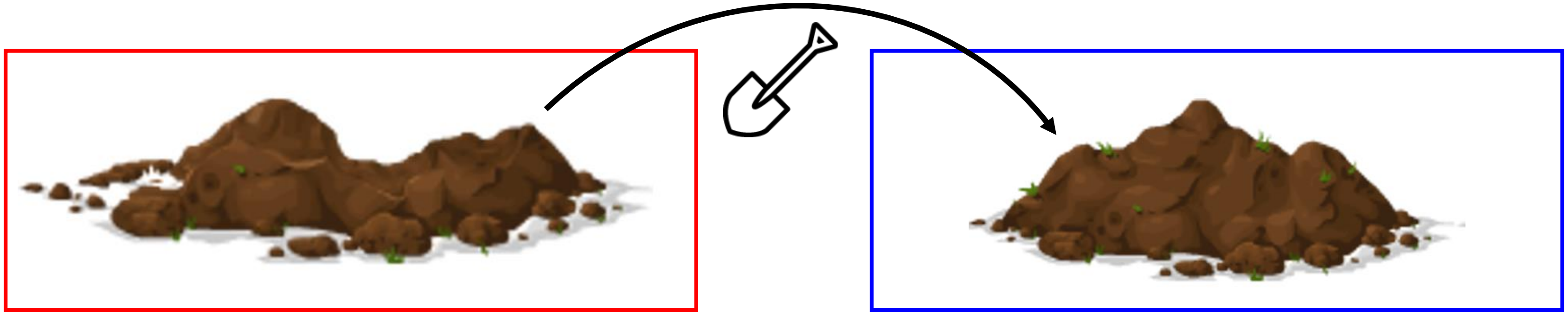
Applications

The Energy Mover's Distance

Review: The Earth Mover's Distance

Earth Mover's Distance: the minimum "work" (stuff x distance) to rearrange one pile of dirt into another

[S. Peleg, M. Werman, H. Rom]
[Y. Rubner, C. Tomasi, and L.J. Guibas]



Metric on the space of (normalized) distributions: *symmetric, non-negative, triangle inequality*

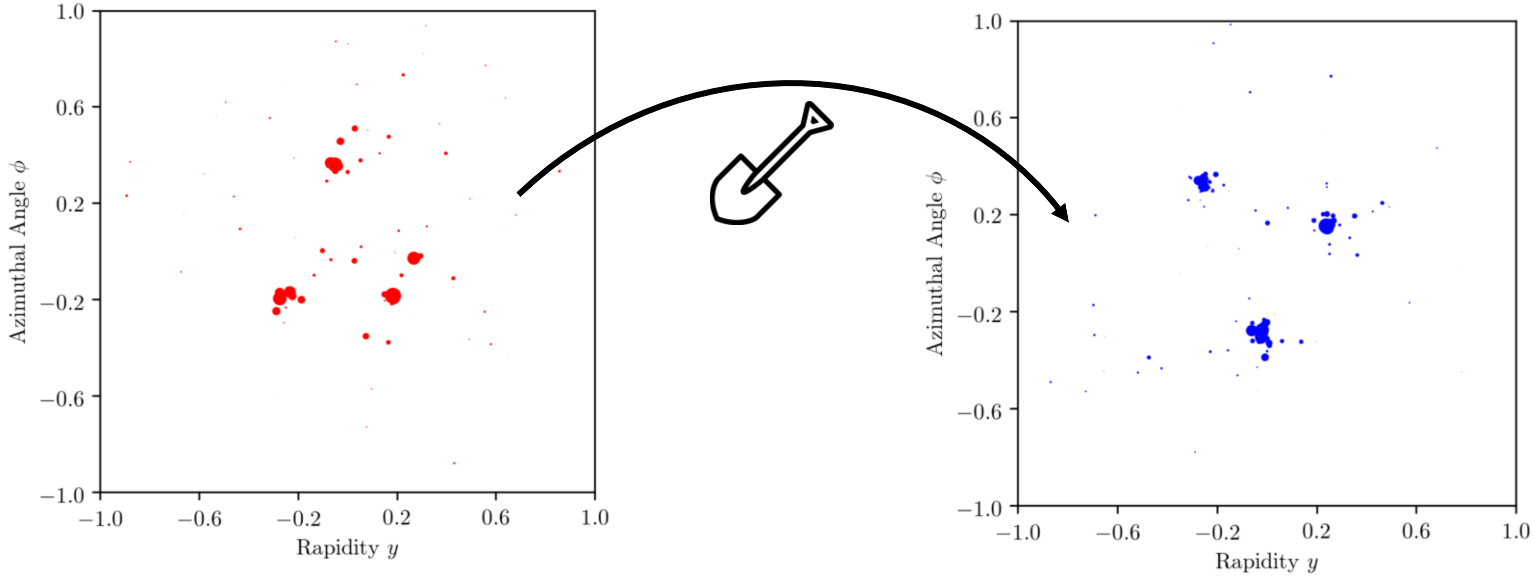
Distributions are close in EMD ⇔ their expectation values are close.

Also known as the 1-Wasserstein metric.

The Energy Mover's Distance

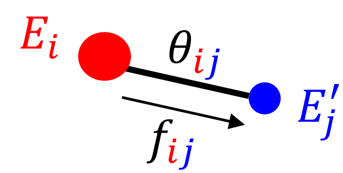
From Earth to Energy

Energy Mover's Distance: the minimum "work" (energy x angle) to rearrange one *event* (pile of energy) into another [P.T. Komiske, EMM, J. Thaler, 1902.02346]



$$\mathrm{EMD}(\mathcal{E}, \mathcal{E}') = \min_{\{f\}} \sum_{i=1}^{M} \sum_{j=1}^{M'} f_{ij} \frac{\theta_{ij}}{R}$$

Difference in radiation pattern



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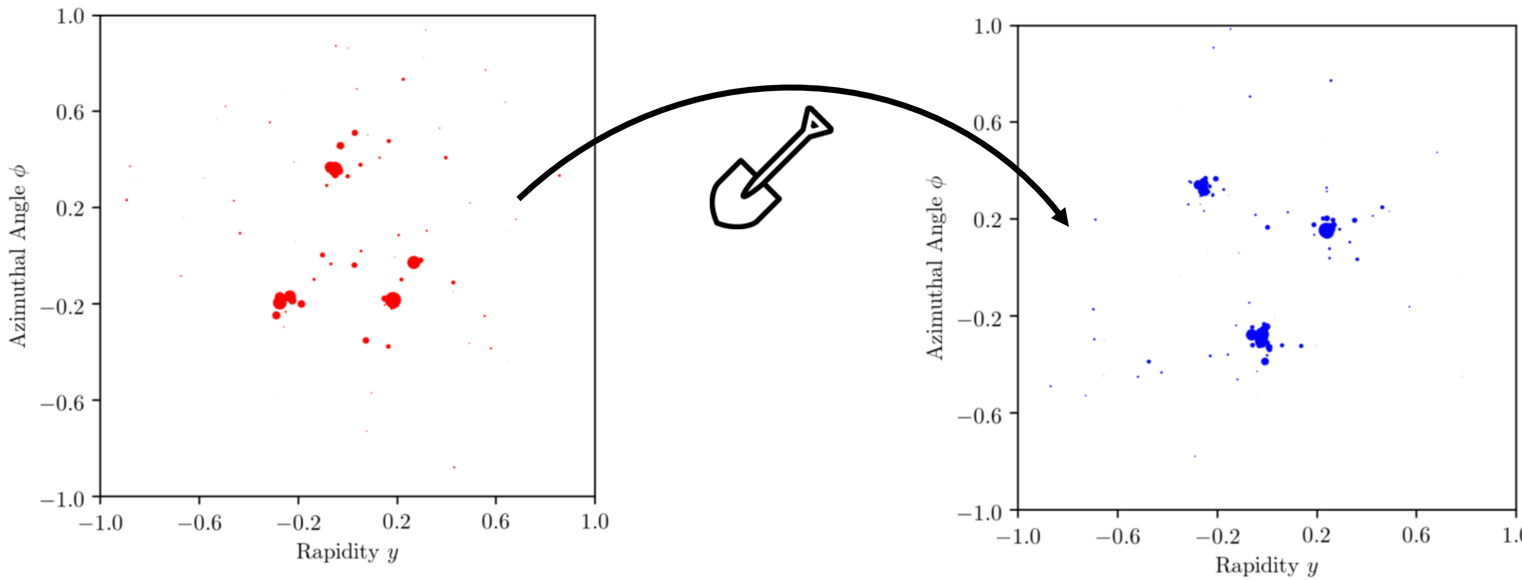
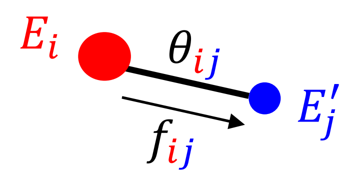


$$\mathrm{EMD}(\mathcal{E},\mathcal{E}') = \min_{\{f\}} \sum_{i=1}^{M}\sum_{j=1}^{M'} f_{ij}\frac{\theta_{ij}}{R} + \left|\sum_{i=1}^{M} E_i - \sum_{j=1}^{M'} E'_j\right|$$

Difference in radiation pattern

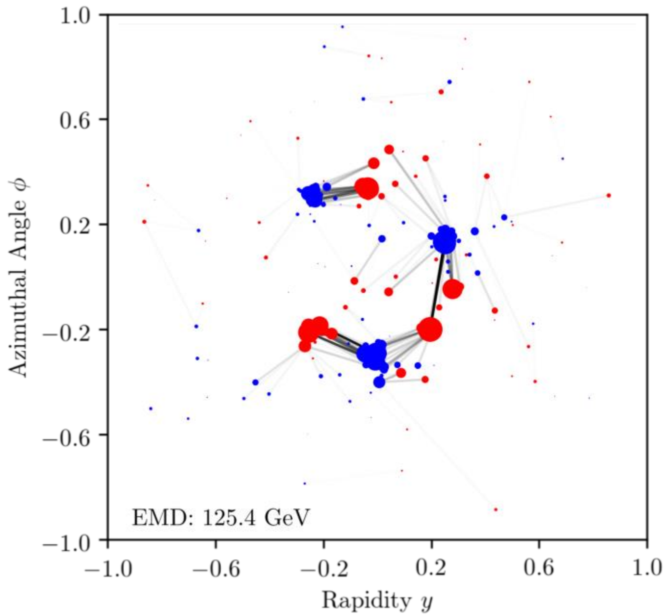
Difference in total energy



The Energy Mover's Distance

From Earth to Energy

Energy Mover's Distance: the minimum "work" (energy x angle) to rearrange one *event* (pile of energy) into another [P.T. Komiske, EMM, J. Thaler, 1902.02346]



EMD has dimensions of energy

True metric as long as $R \geq \frac{1}{2}\theta_{\max}$

$R \geq$ the jet radius, for conical jets

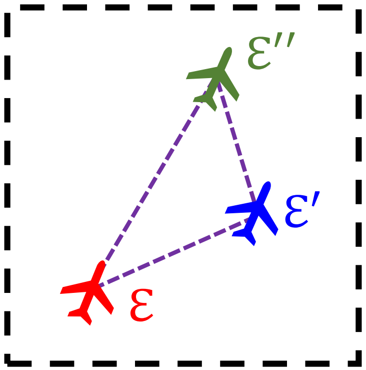
Solvable via Optimal Transport problem.

~1ms to compute EMD for two jets with 100 particles.

$$\text{EMD}(\mathcal{E},\mathcal{E}') = \min_{\{f\}} \sum_{i=1}^{M}\sum_{j=1}^{M'} f_{ij}\frac{\theta_{ij}}{R} + \left|\sum_{i=1}^{M} E_i - \sum_{j=1}^{M'} E'_j\right|$$

Difference in radiation pattern

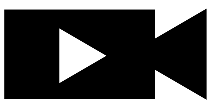
Difference in total energy



Outline

When are two events similar?

The Energy Mover's Distance

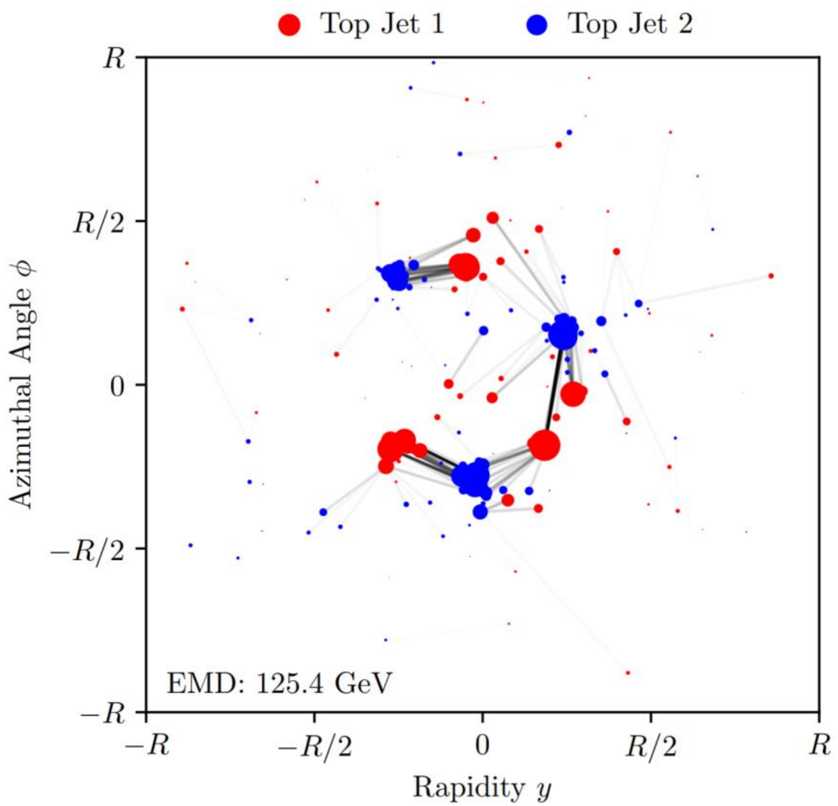


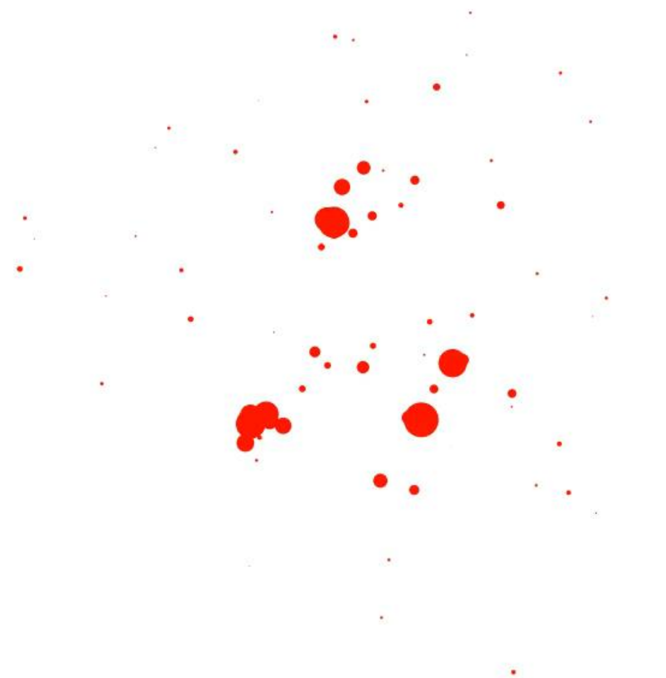
Movie Time

Applications

Movie Time: Visualizing the EMD

Taking a walk in the space of events

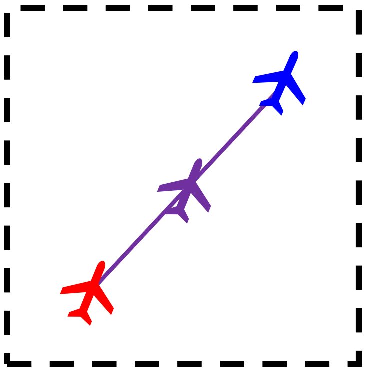




EMD is the cost of an optimal transport problem.

We also get the *shortest path* between the events.

Interpolate along path to visualize!

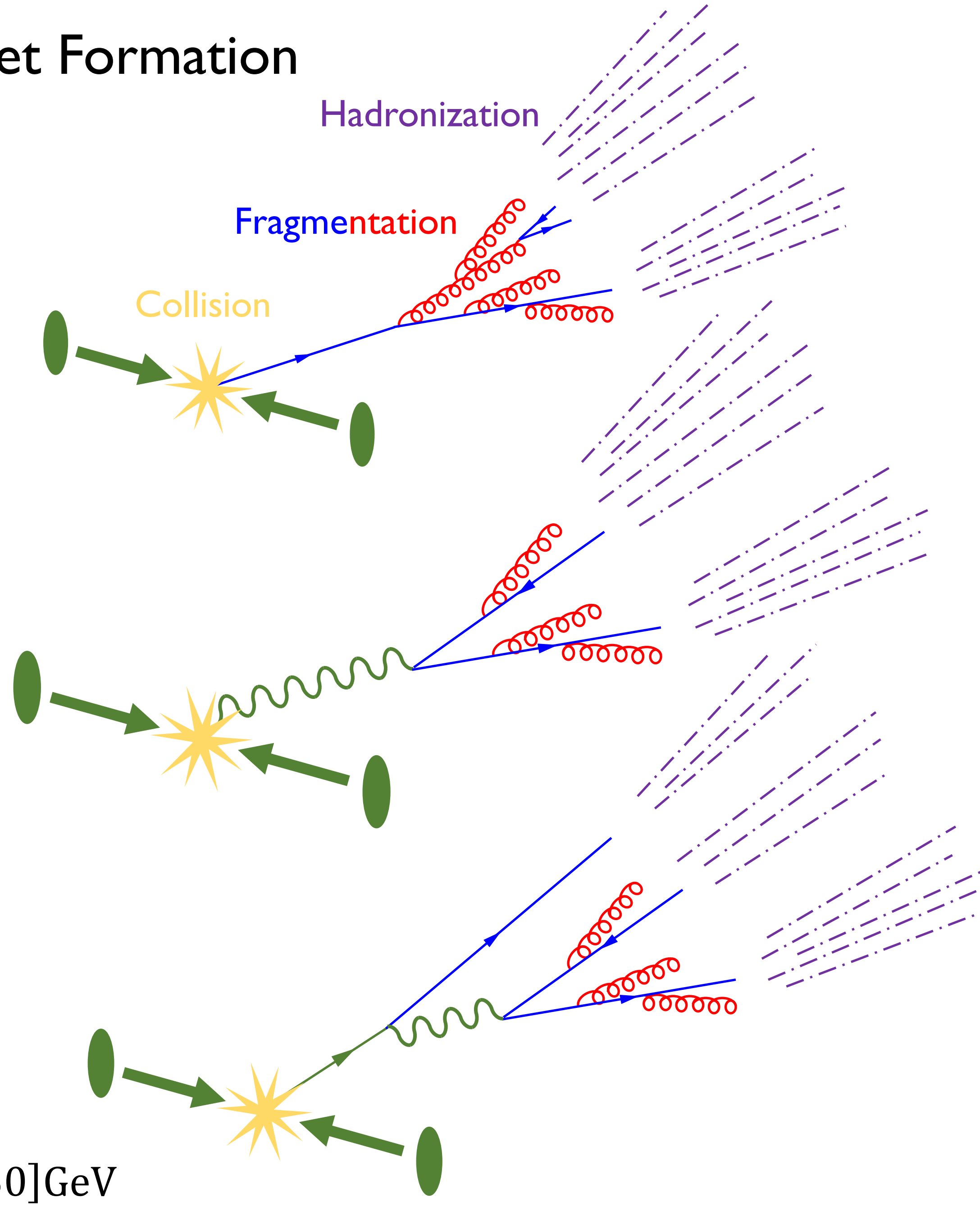


Movie Time: Visualizing Jet Formation

QCD Jets

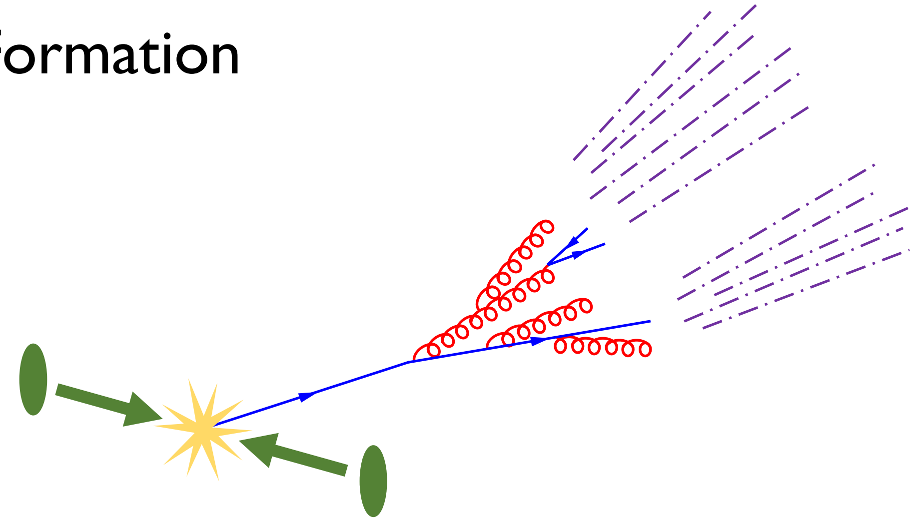
***W* Jets**

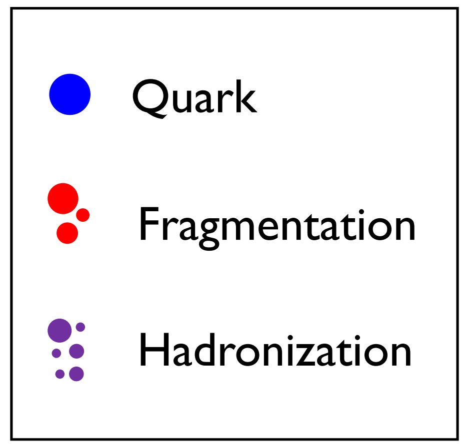
Top Jets

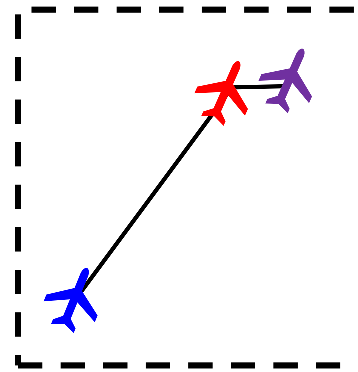


Pythia 8, $R = 1.0$ jets, $p_T \in [500,550]\mathrm{GeV}$

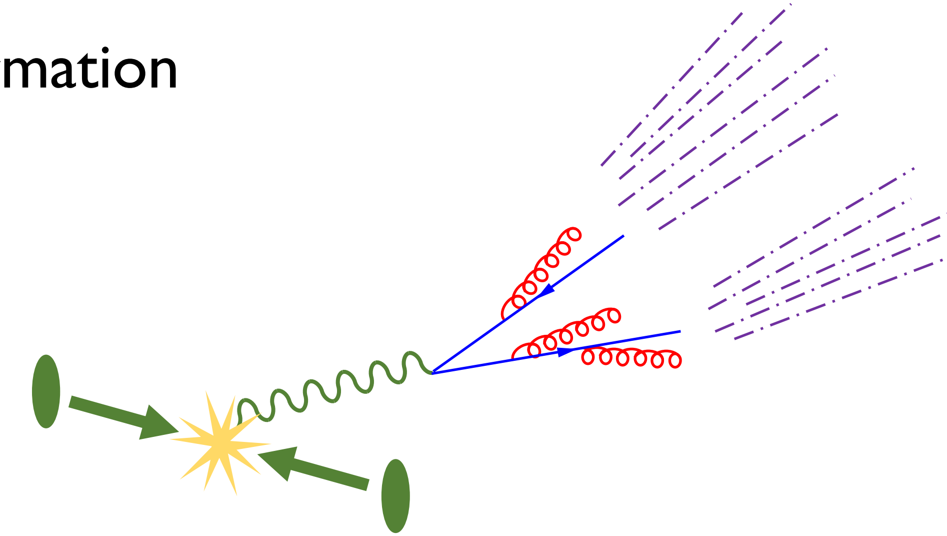
Movie Time: Visualizing QCD Jet Formation

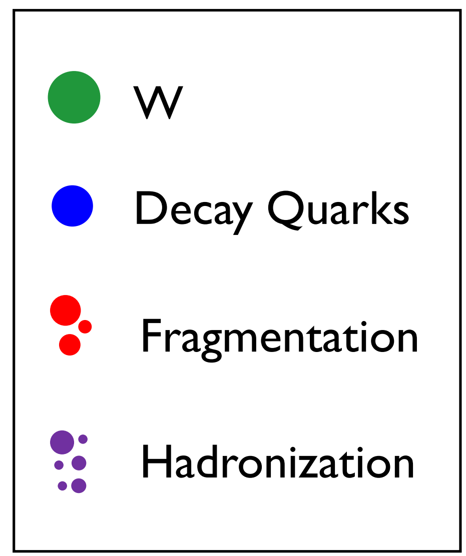


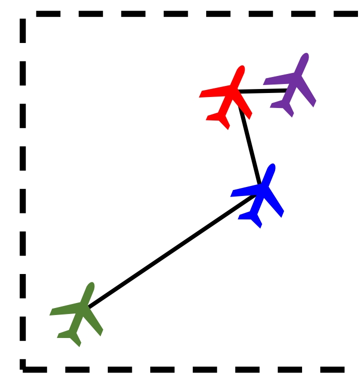




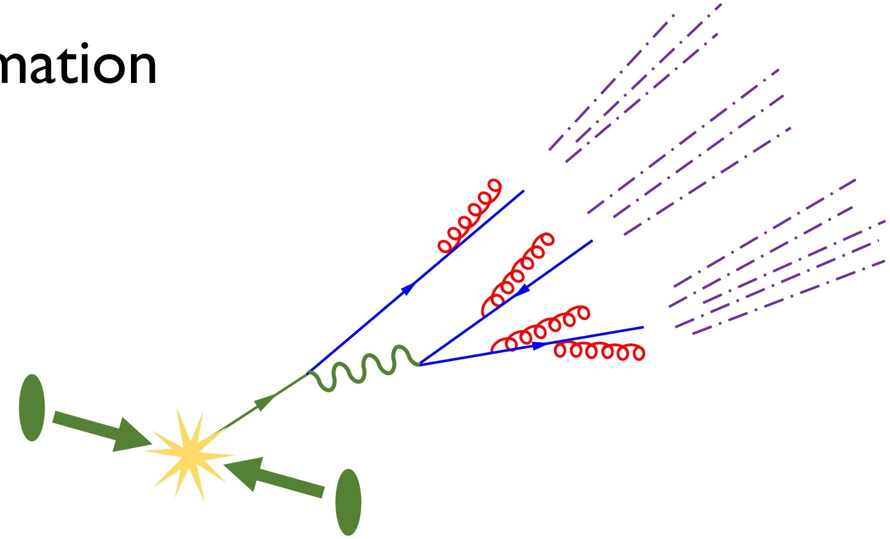
Movie Time: Visualizing W Jet Formation

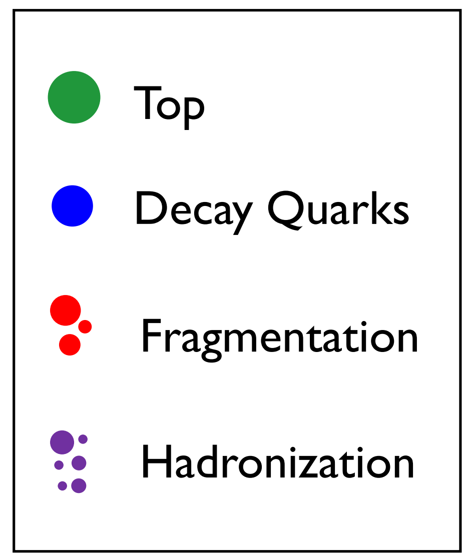


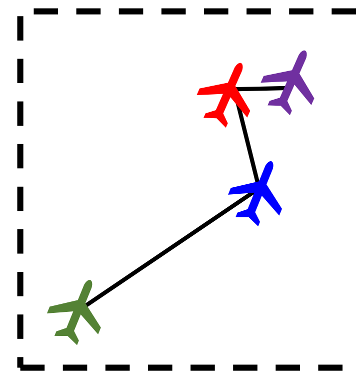




Movie Time: Visualizing Top Jet Formation







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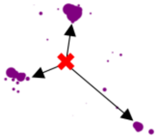
The Energy Mover's Distance

Movie Time



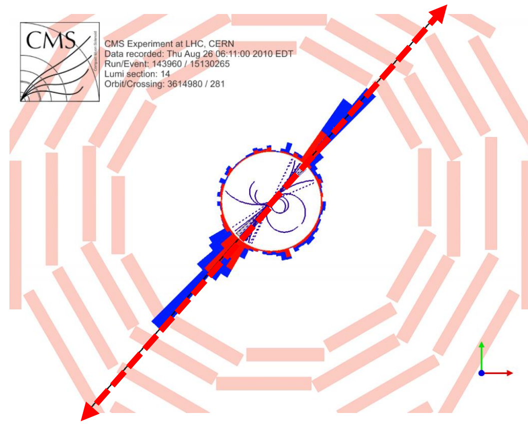
Applications

Old Observables in a New Language

Thrust is the EMD between the event and two back-to-back particles.

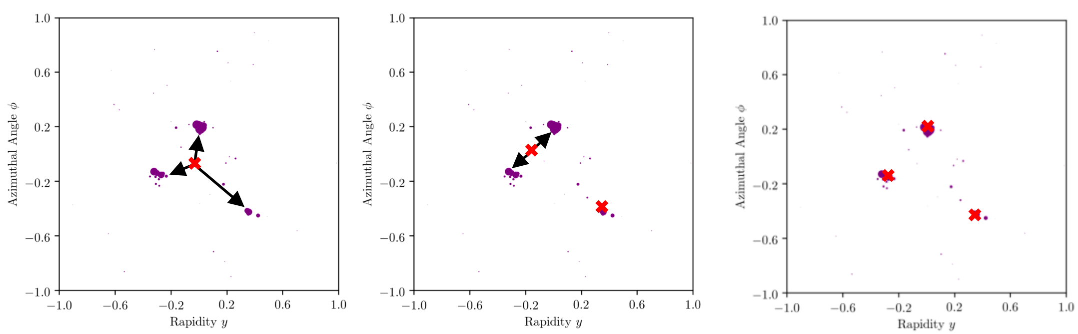
$$t = E - \max_{\hat{n}} \sum_i |\vec{p}_i \cdot \hat{n}| \longrightarrow t(\mathcal{E}) = \min_{|\mathcal{E}'|=2} \mathrm{EMD}(\mathcal{E}, \mathcal{E}')$$

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

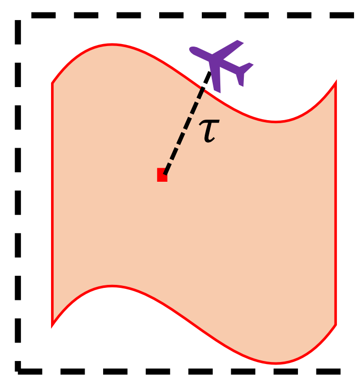


***N*-(sub)jettiness** is the EMD between the event and the closest N-particle event.

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



$\beta \neq 1$ is p-Wasserstein distance with $\mathrm{p} = \beta$.



EMD and IRC-Safe Observables

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

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

Earth Mover's Distance

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

Difference in observable values

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

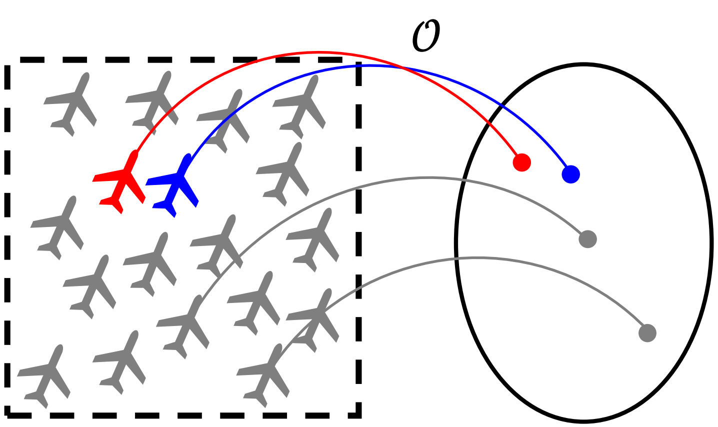
e.g. jet angularities:

[C. Berger, T. Kucs, and G. Sterman, 0303051]
[A. Larkoski, J. Thaler, and W. Waalewijn, 1408.3122]

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

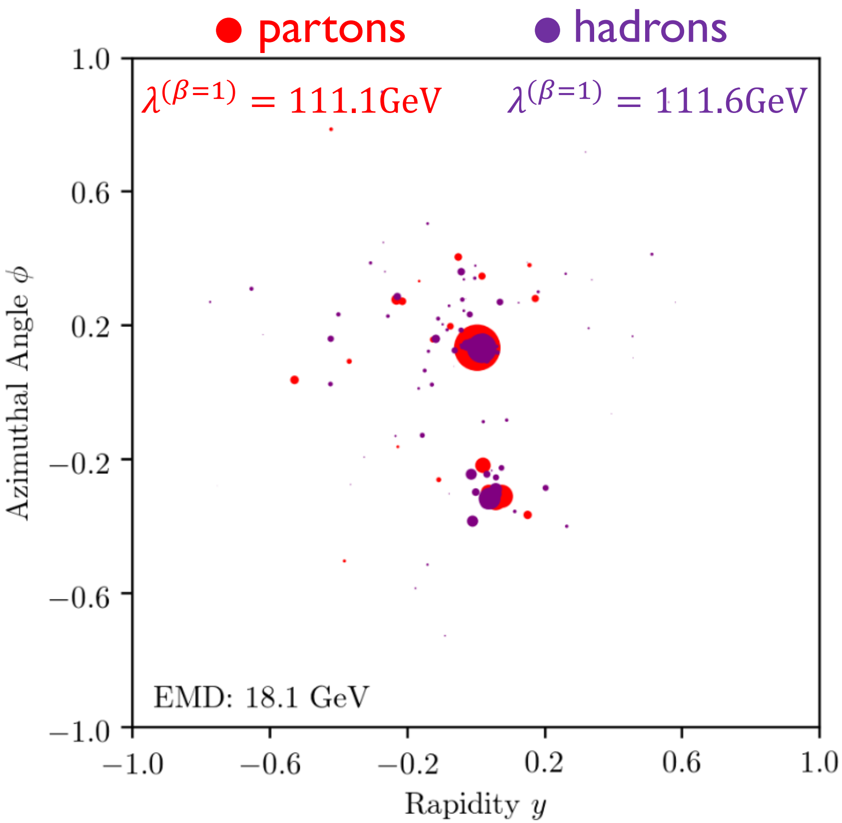
For $\beta \geq 1$ jet angularities:

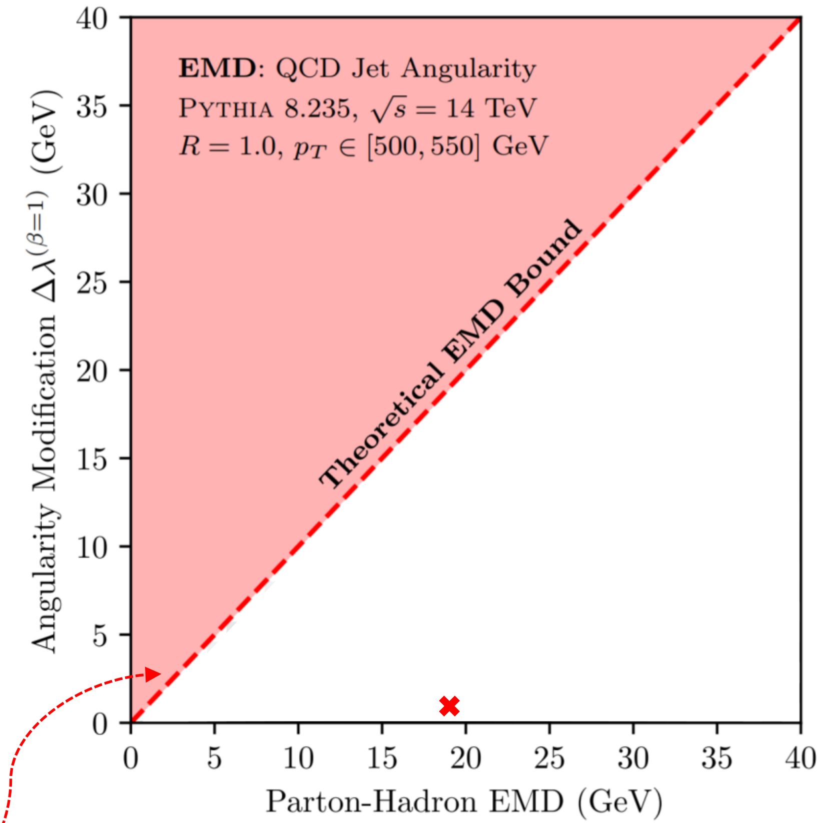
$$|\lambda^{(\beta)}(\mathcal{E}) - \lambda^{(\beta)}(\mathcal{E}')| \leq \beta \, \text{EMD}(\mathcal{E}, \mathcal{E}')$$



Quantifying event modifications: Hadronization

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





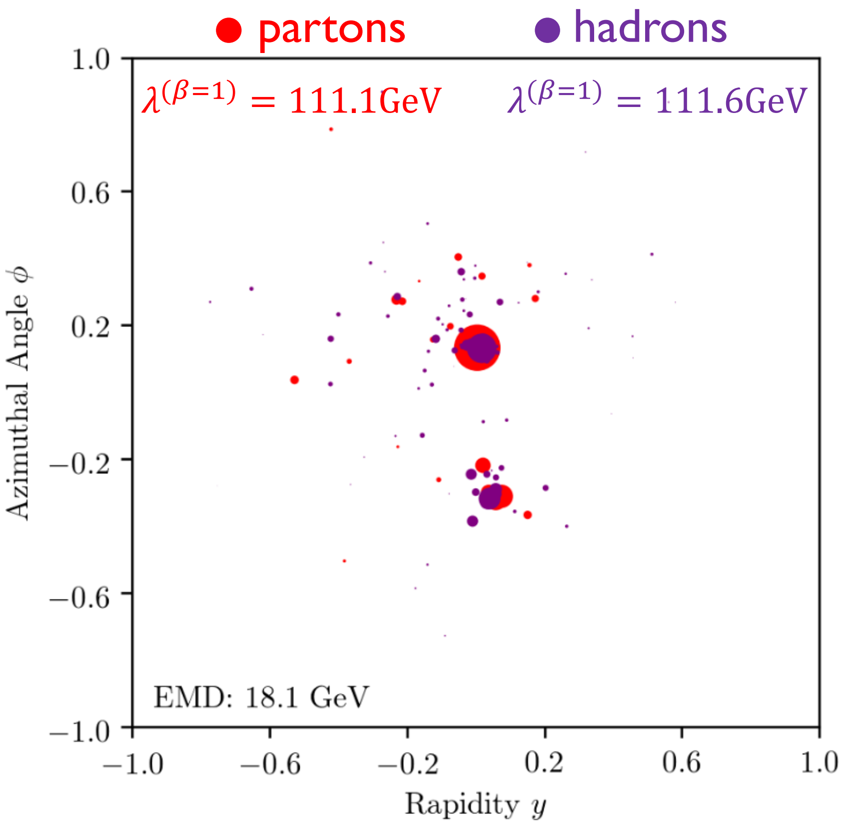
$\mathcal{E} = \mathcal{E}_{\text{partons}}$

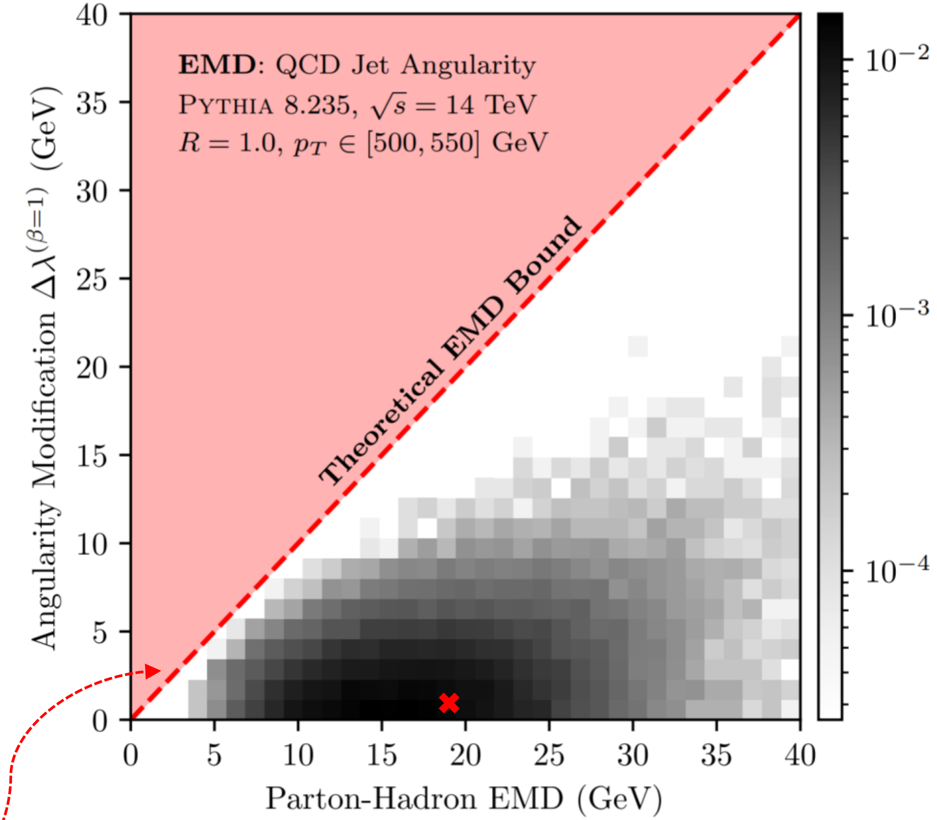
$\mathcal{E}' = \mathcal{E}_{\text{hadrons}}$

$$\boxed{\left|\lambda^{(\beta=1)}(\mathcal{E}) - \lambda^{(\beta=1)}(\mathcal{E}')\right| \leq \text{EMD}(\mathcal{E}, \mathcal{E}')}$$

Quantifying event modifications: Hadronization

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





$\mathcal{E} = \mathcal{E}_{\text{partons}}$

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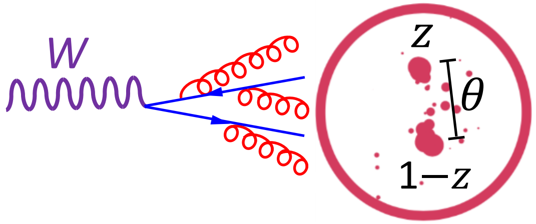
$$\boxed{\left|\lambda^{(\beta=1)}(\mathcal{E}) - \lambda^{(\beta=1)}(\mathcal{E}')\right| \leq \text{EMD}(\mathcal{E}, \mathcal{E}')}$$

Exploring the Space of Events: *W* jets



W jets are 2-pronged and constrained by *W* mass:

$$z(1-z)\theta^2 = \frac{p_{\mu J}^2}{p_T^2} = \frac{m_W^2}{p_T^2}$$

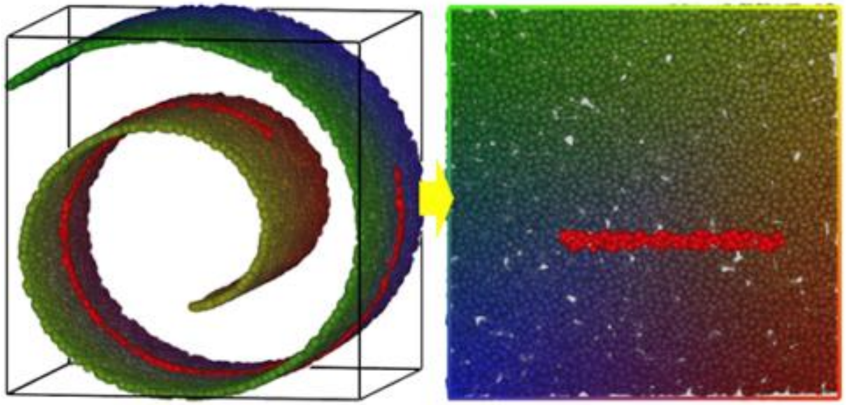
Hence we expect a **two**-dimensional space of *W* jets: z, φ

After φ rotation, **one**-dimensional: z

Visualize the space of events with t-Distributed Stochastic Neighbor Embedding (t-SNE).

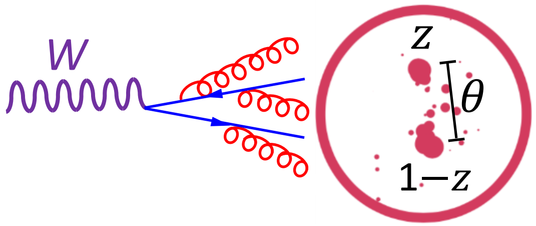
[L. van der Maaten, G. Hinton]

Finds an embedding into a low-dimensional manifold that respects distances.



Src: http://web-ext.u-aizu.ac.jp/~shigeo/home.html

Exploring the Space of Events: W jets



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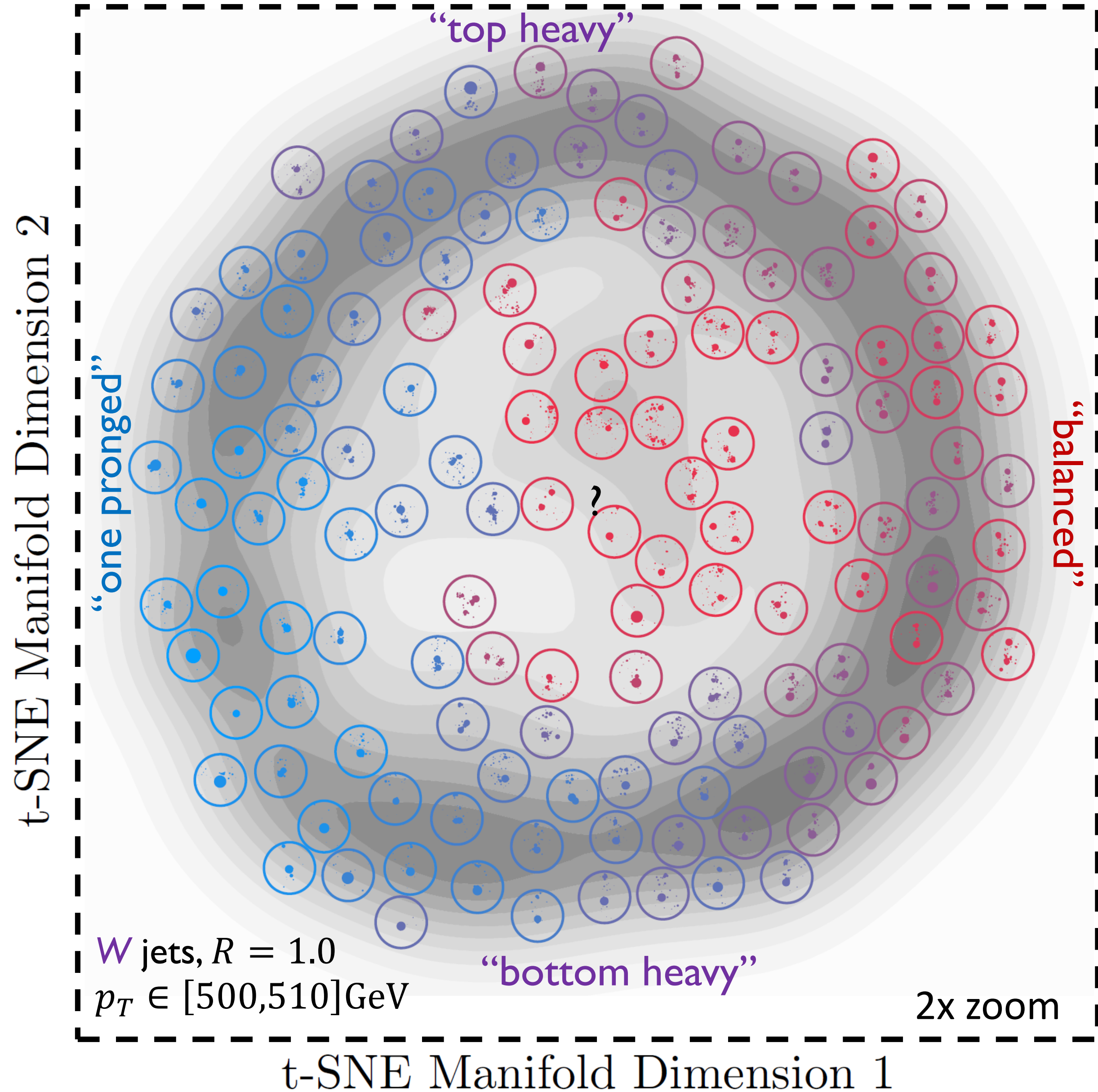


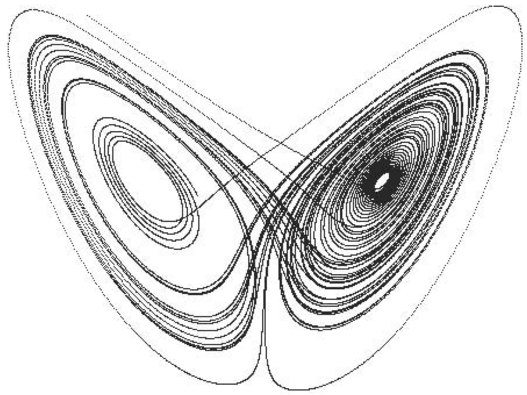
Exploring the Space of Jets: Correlation Dimension

VOLUME 50, NUMBER 5 PHYSICAL REVIEW LETTERS 31 JANUARY 1983

Characterization of Strange Attractors

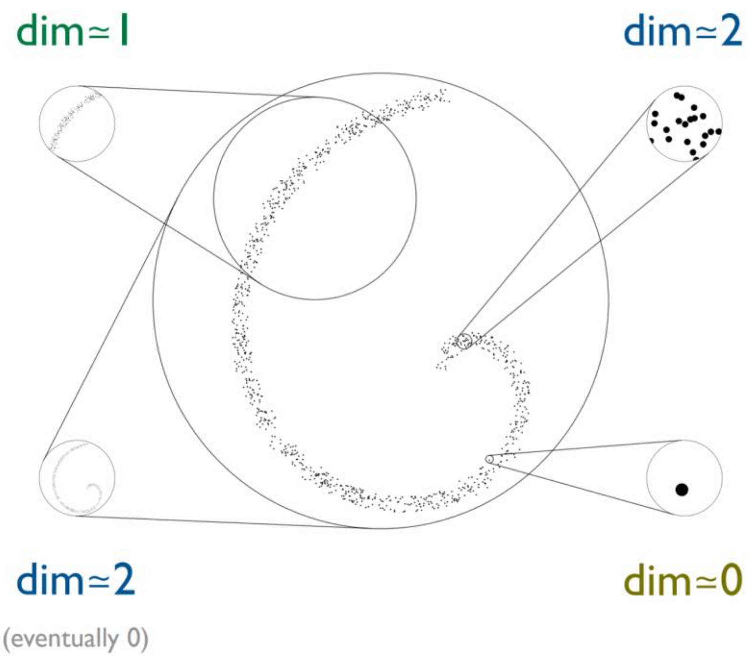
Peter Grassberger[a] and Itamar Procaccia
Chemical Physics Department, Weizmann Institute of Science, Rehovot 76100, Israel
(Received 7 September 1982)

A new measure of strange attractors is introduced which offers a practical algorithm to determine their character from the time series of a single observable. The relation of this new measure to fractal dimension and information-theoretic entropy is discussed.



Intuition:

$$N_{\underset{\text{points}}{\text{neighboring}}}(r) \propto r^{\text{dim}} \quad \Longrightarrow \quad \text{dim}(r) = r\frac{\partial}{\partial r}\ln N_{\text{neighbors}}(r)$$



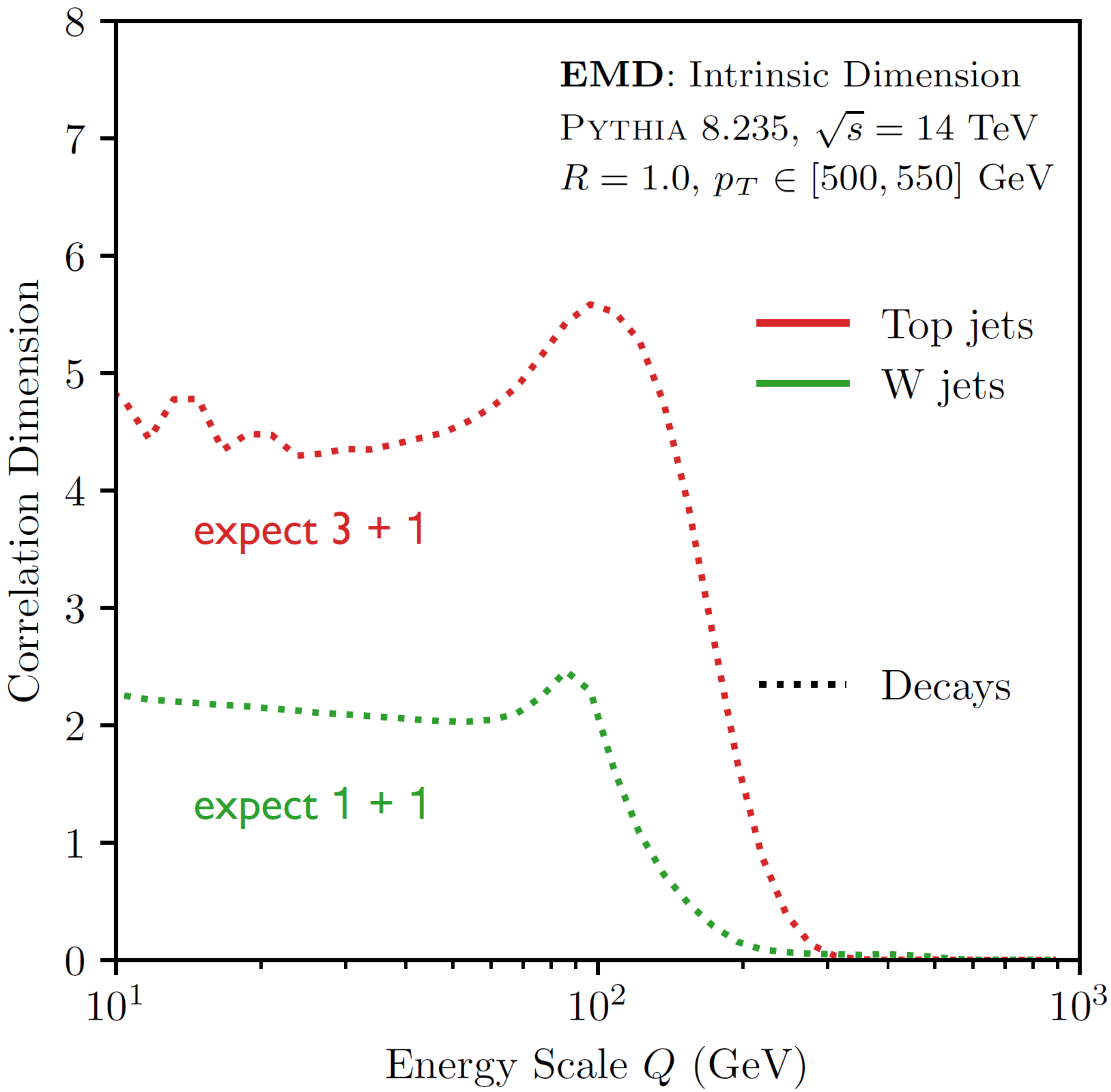
Correlation dimension:

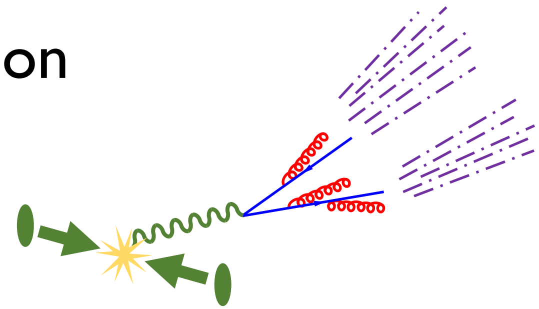
$$\boxed{\text{dim}(Q) = Q\frac{\partial}{\partial Q}\ln \sum_{i=1}^{N}\sum_{j=1}^{N}\Theta[\text{EMD}(\mathcal{E}_i,\mathcal{E}_j) < Q]}$$

Energy scale Q dependence

Count neighbors in ball of radius Q

Exploring the Space of Jets: Correlation Dimension





QCD jets are simplest.

W jets are more complicated.

Top jets are most complex.

"Decays" have ~constant dimension.

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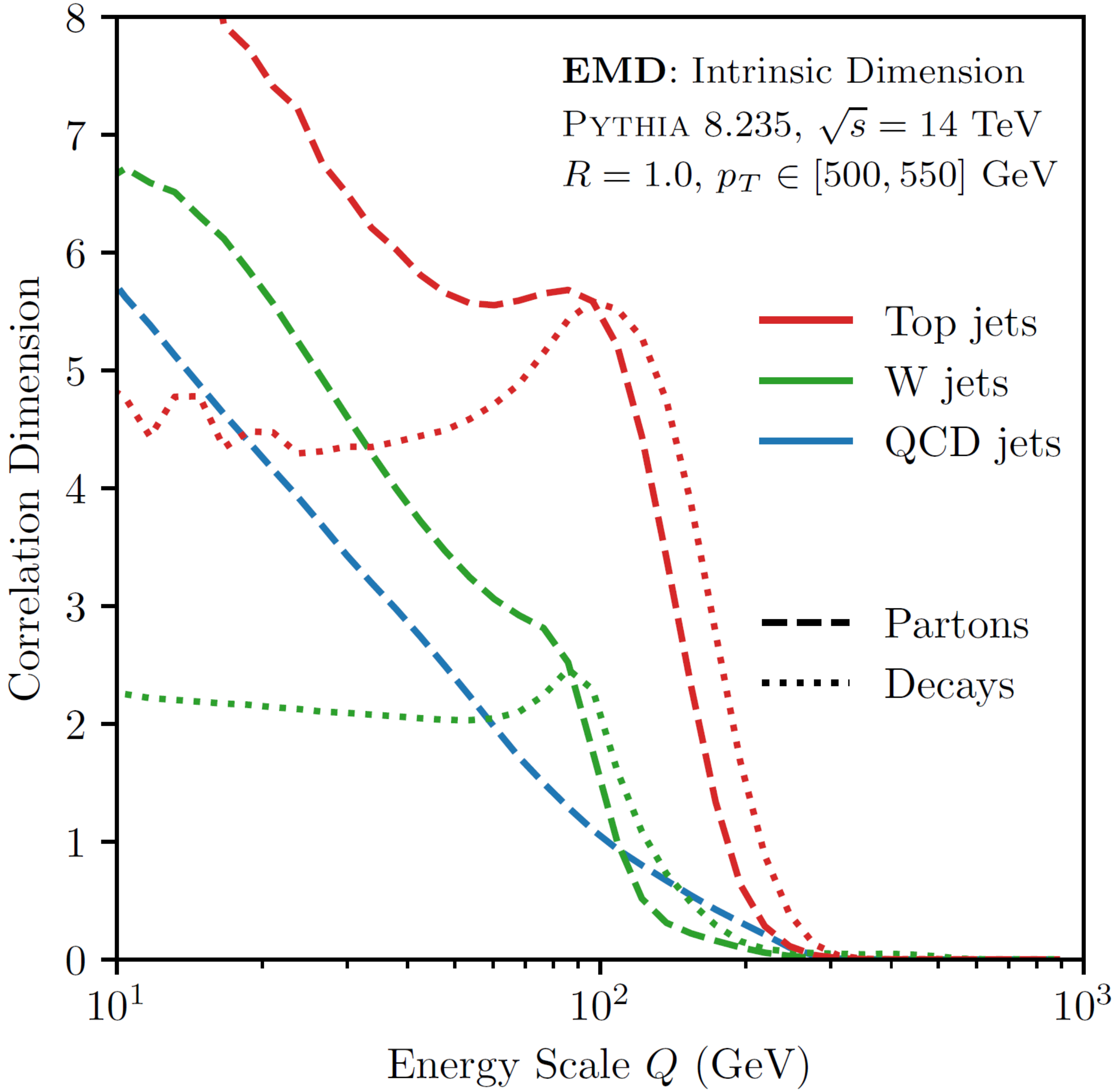

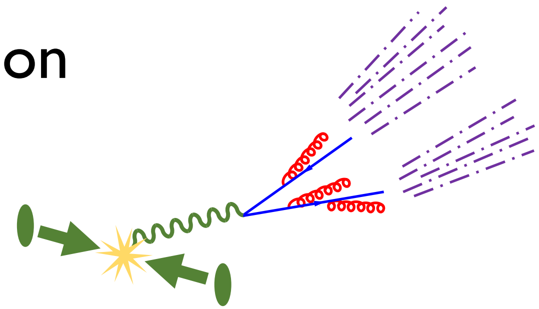

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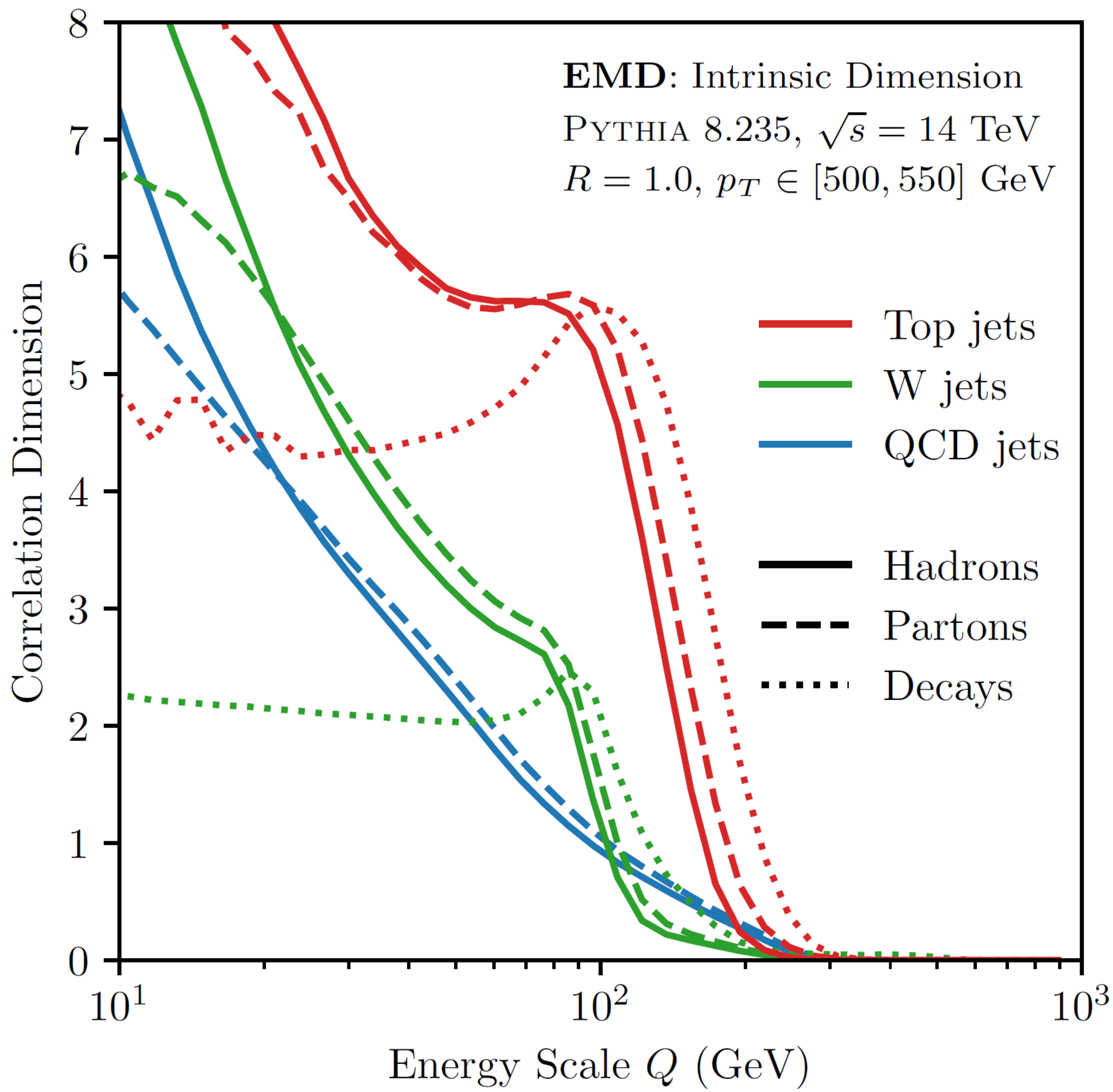

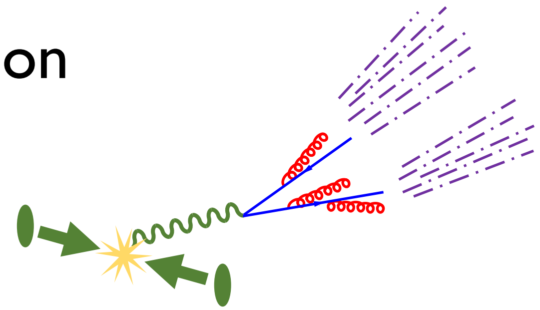

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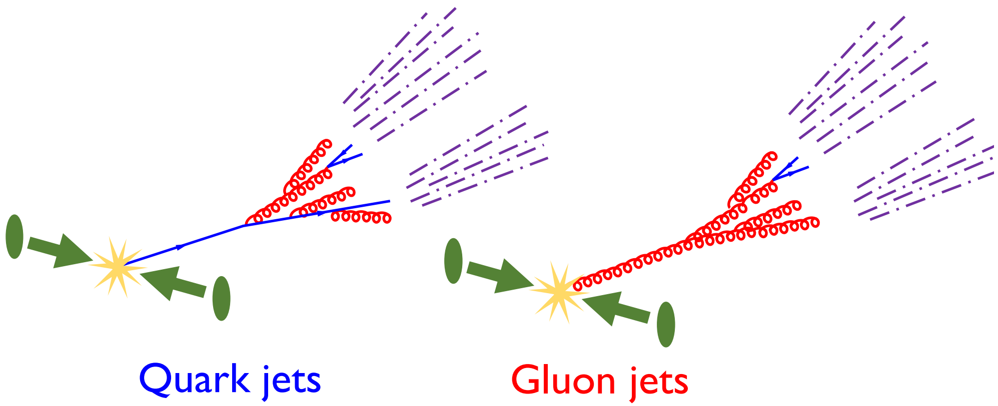

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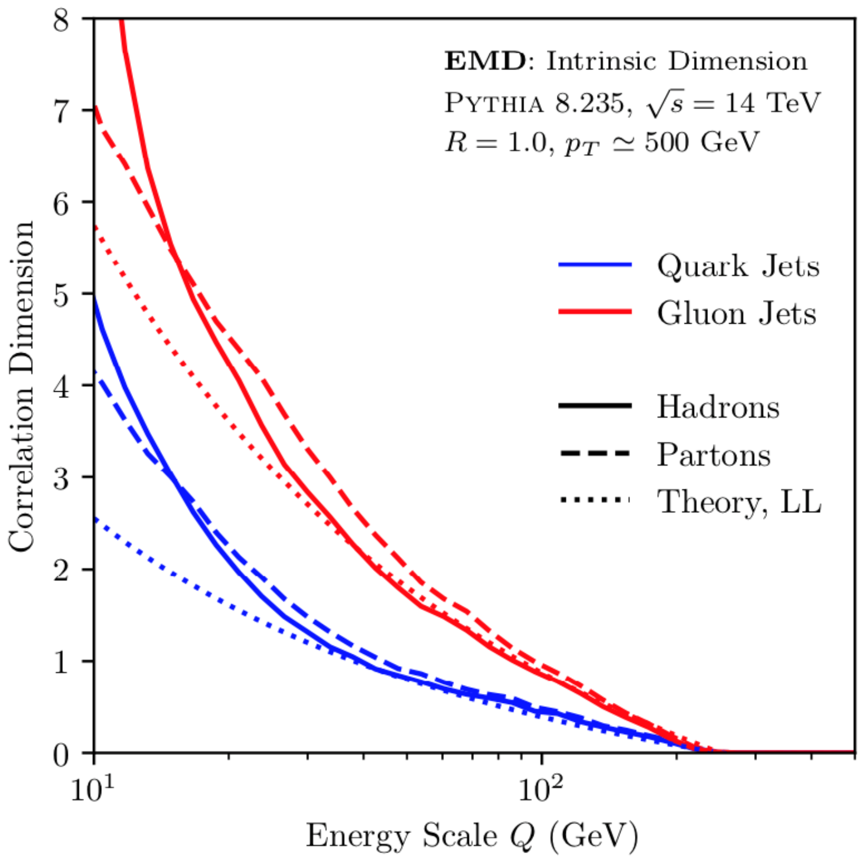
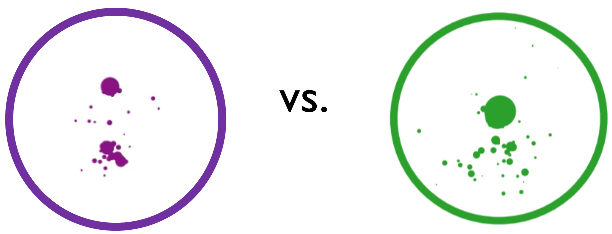


Dimension blows up at low energies.

Jets are "more than fractal"?

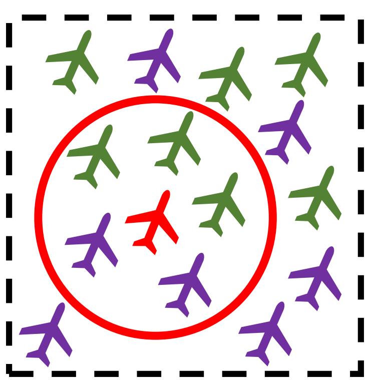
Exploring the Space of Events: Jet Classification

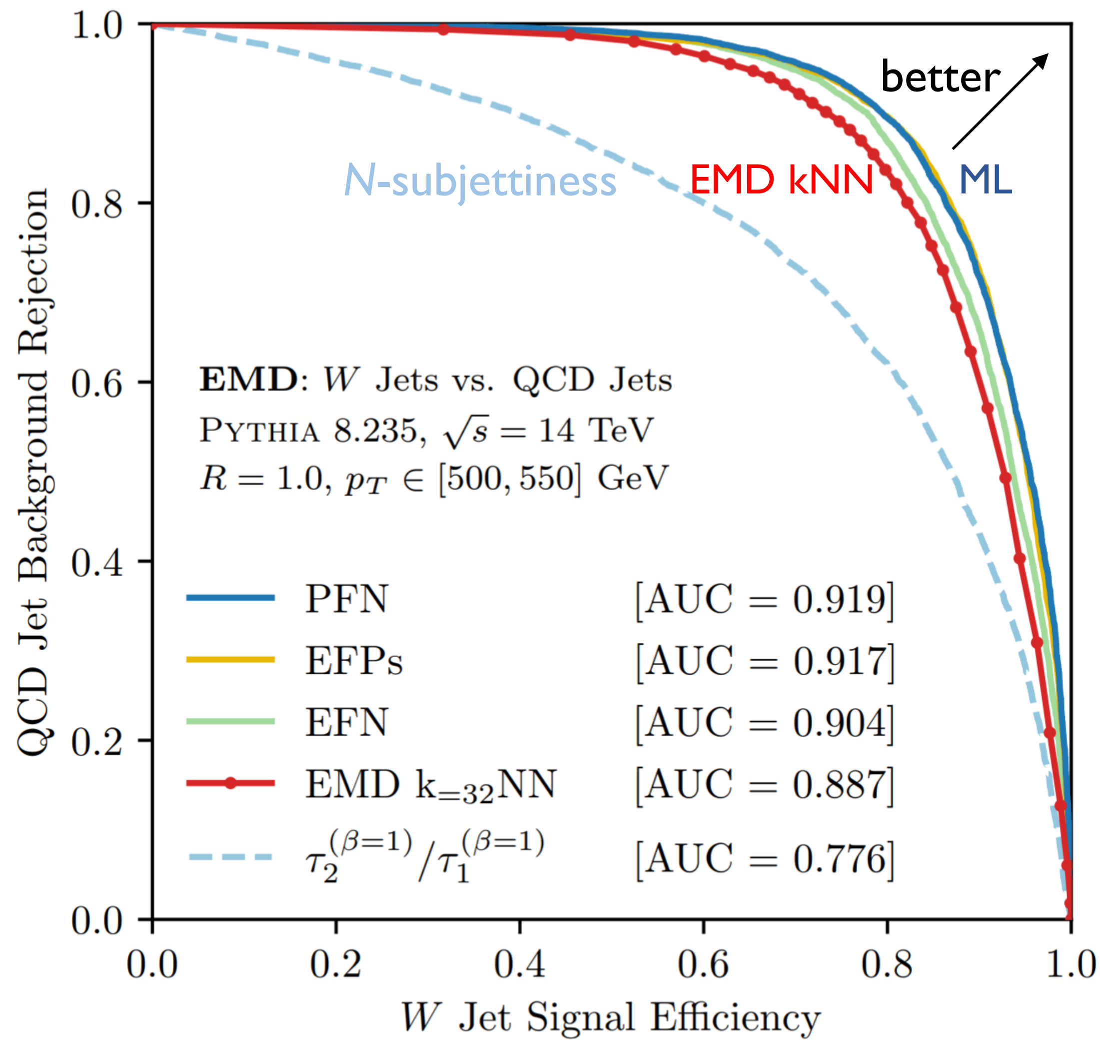
Classify *W* jets vs. QCD jets



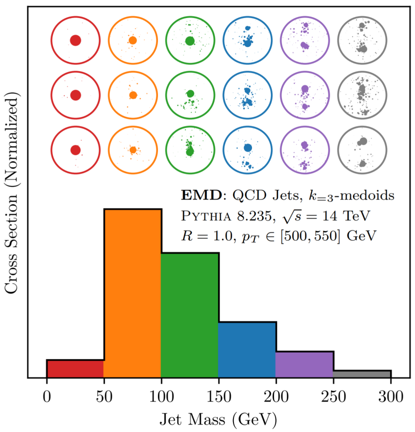
Look at a jet's nearest neighbors (kNN) to predict its class.

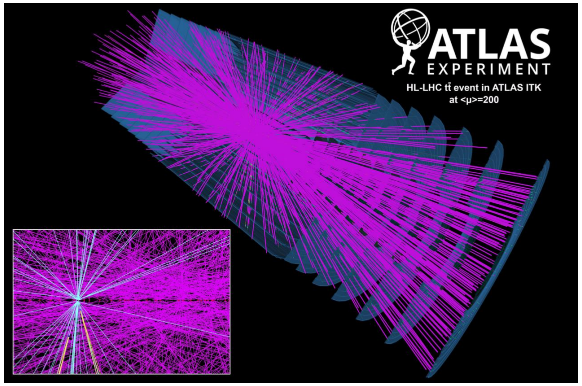
Nearing performance of ML.





Going Beyond





Quantifying pileup mitigation

New histogram and data visualizations

Clustering sets of events

New observables through EMD geometry

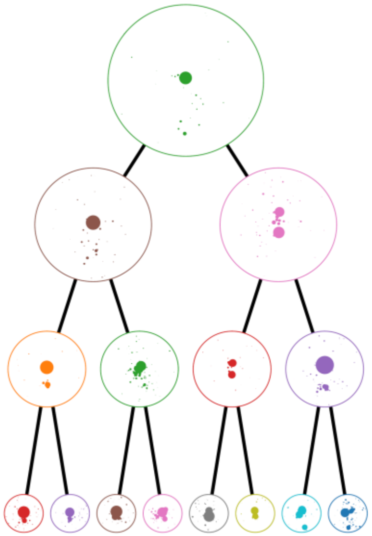
EMD for density estimation (& unfolding?)

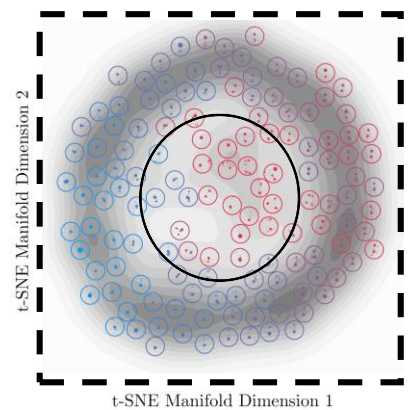
"Event" mover's distance between ensembles?

Model (in)dependent anomaly detection?

Train ML models to optimize EMD directly?

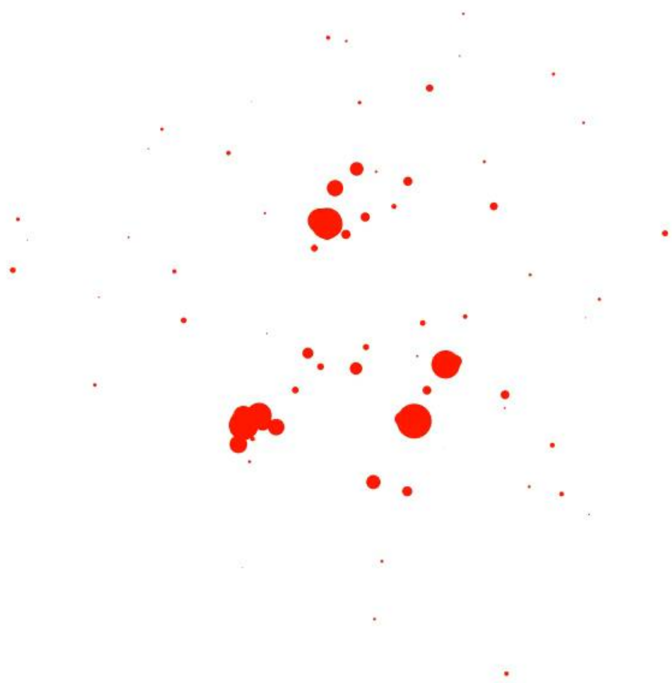
Include flavor information?



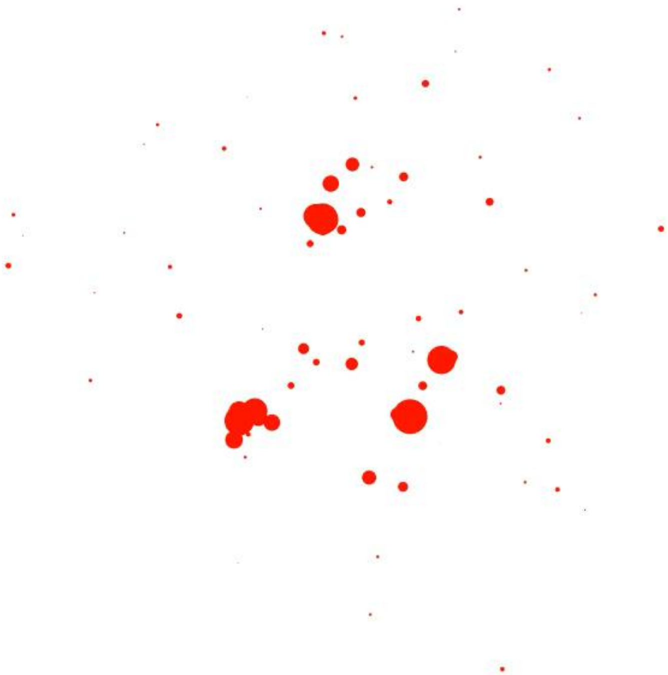


The End

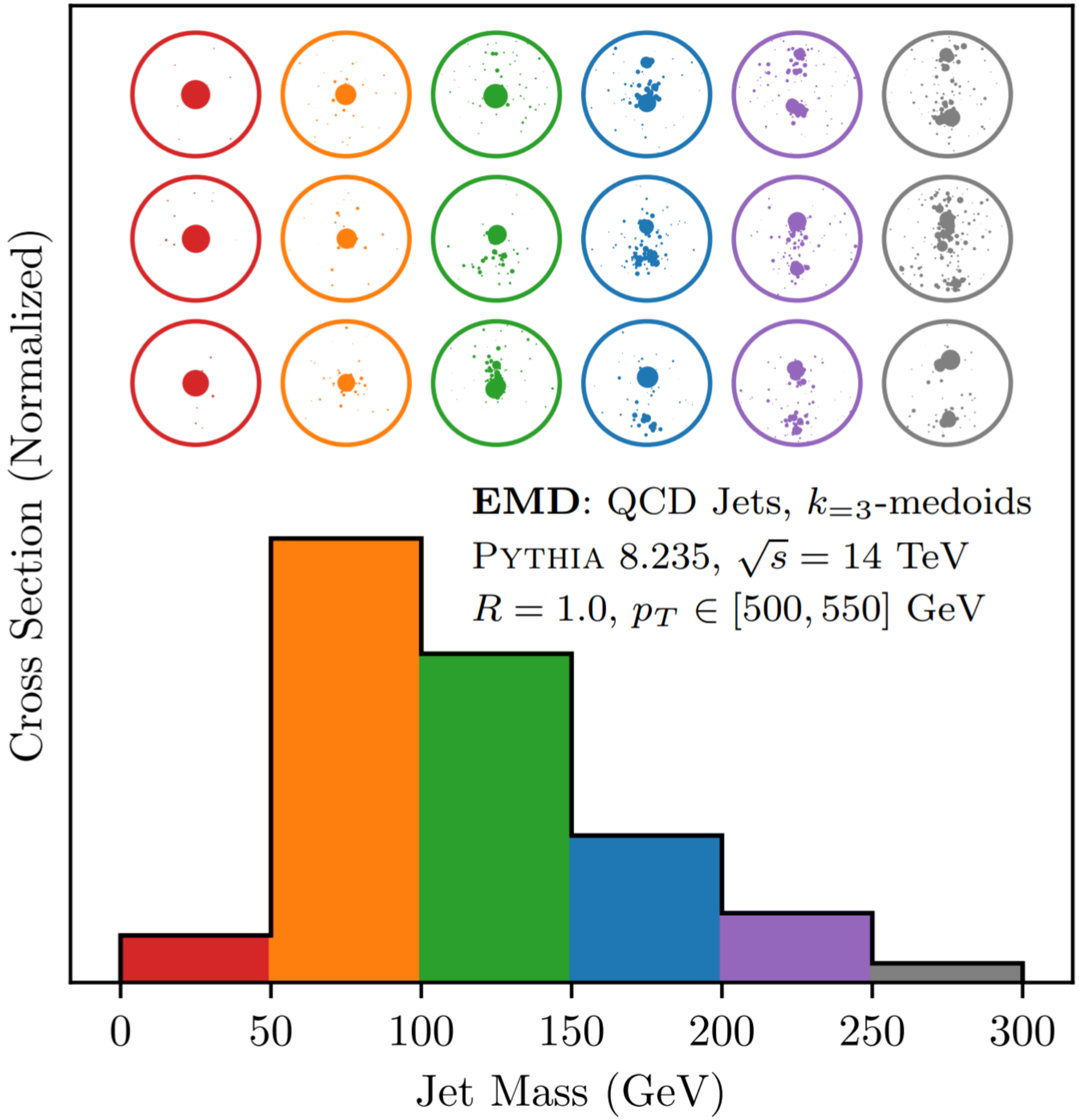
Thank you!



Extra Slides



Exploring the Space of Events: *k*-medoids



Observables

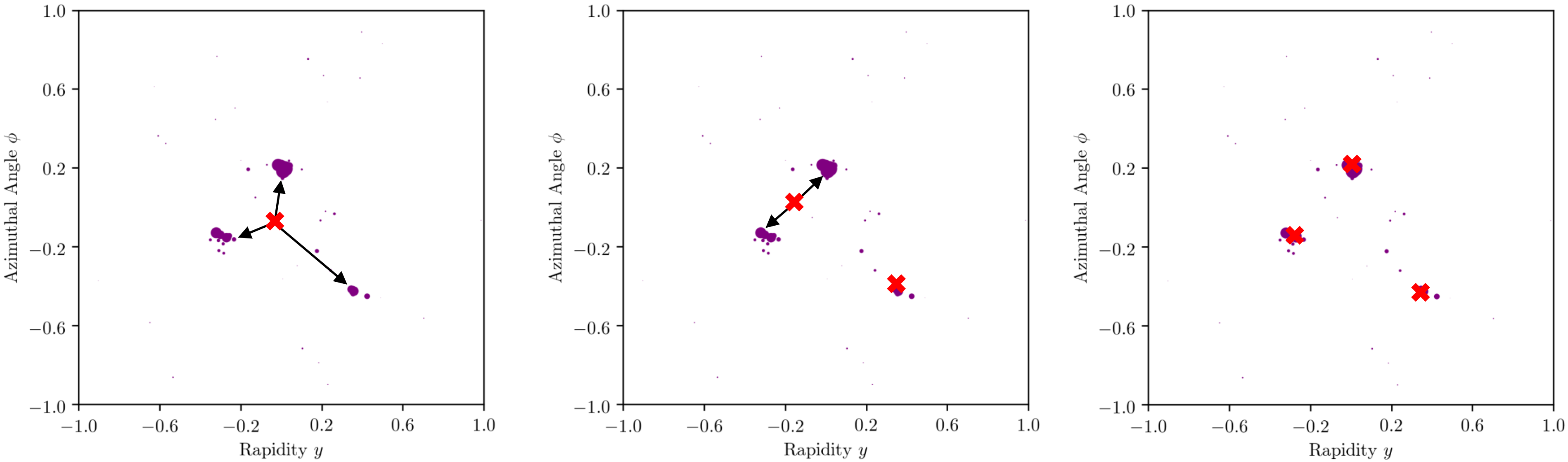
[I. Stewart, F. Tackmann, W. Waalewijn, 1004.2489]
[J. Thaler, K. Van Tilburg, 1011.2268]
[J. Thaler, K. Van Tilburg, 1108.2701]

N-(sub)jettiness:

$$\tau_N^{(\beta)} = \sum_{i=1}^{M} E_i \min_{N \text{ axes}} \{\theta_{1,k}^{\beta}, \theta_{2,k}^{\beta}, \dots, \theta_{N,k}^{\beta}\}$$

measures how well jet energy is aligned into N (sub)jets

$\tau_1/E \gg 0$ $\quad$ $\tau_1/E > \tau_2/E \gg 0$ $\quad$ $\tau_3/E \simeq 0$



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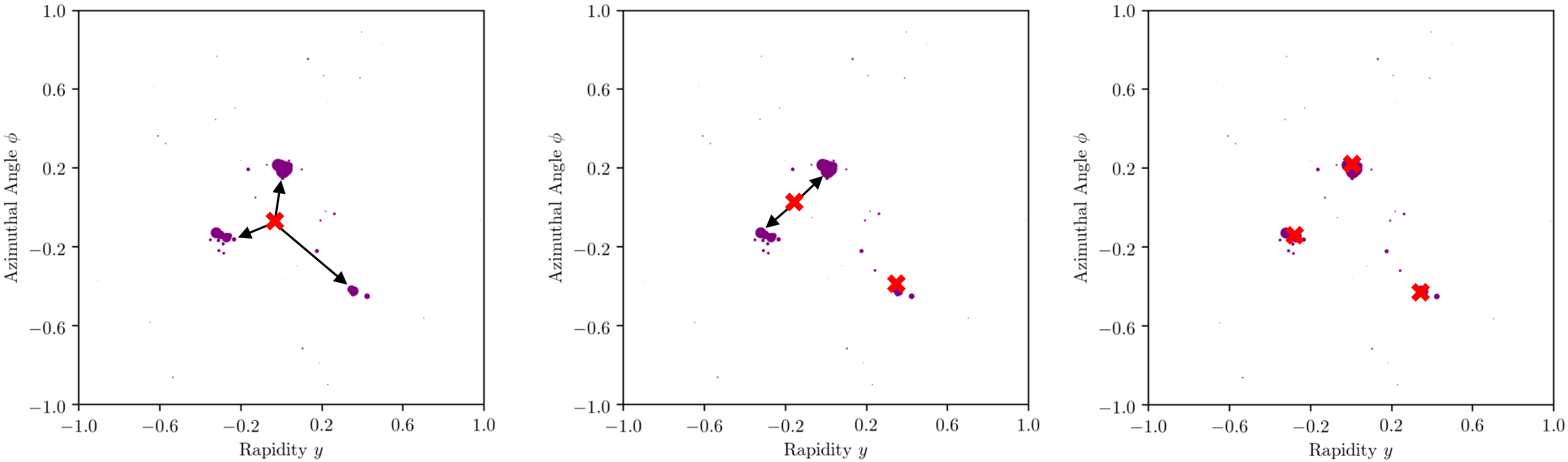


N-subjettiness is the EMD between the event and the closest N-particle event.

$$\tau_N(\mathcal{E}) = \min_{|\mathcal{E}'|=N} \mathrm{EMD}(\mathcal{E}, \mathcal{E}').$$

$\beta \neq 1$ corresponds to other p-Wasserstein distances with $\mathrm{p} = \beta$.

Observables

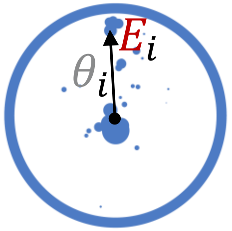
Getting quantitative

Take any additive IRC-safe observable: $\mathcal{O}(\mathcal{E}) = \sum_{i=1}^{M} E_i \, \Phi(\hat{p}_i)$

e.g. jet angularities: $\lambda^{(\beta)} = \sum_{i=1}^{M} E_i \, \theta_i^{\beta}$

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

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



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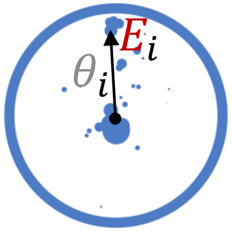

Via the Kantorovich-Rubinstein dual formulation of EMD:

Earth Mover's Distance

Difference in observable values

$$\mathrm{EMD}(\mathcal{E}, \mathcal{E}') \geq \frac{1}{RL} \left| \sum_{i=1}^{M} E_i \Phi(\hat{p}_i) - \sum_{j=1}^{M'} E'_j \, \Phi(\hat{p}_j{}') \right| = \frac{1}{RL} \left| \mathcal{O}(\mathcal{E}) - \mathcal{O}(\mathcal{E}') \right|$$

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

Observables

Getting quantitative

Take any additive IRC-safe observable: $\mathcal{O}(\mathcal{E}) = \sum_{i=1}^{M} E_i \, \Phi(\hat{p}_i)$

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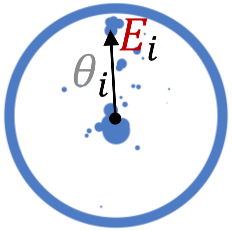

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"Lipschitz constant" of Φ
i.e. bound on its derivative

For $\beta \geq 1$ jet angularities, $L = \beta / R$ over the jet cone, so:

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

The EMD provides a robust upper bound to any modifications of these observables.

Observables

Key idea: Energy-weighted angular structures contain all the IRC-safe information.

$$\frac{1}{RL}\left|\sum_{i=1}^{M} E_i \Phi(\hat{p}_i) - \sum_{j=1}^{M'} E_j' \, \Phi(\hat{p}_j{}') \right| \leq \mathrm{EMD}(\mathcal{E}, \mathcal{E}')$$

Theorem: Any infrared and collinear safe observable $\mathcal{O}$ can be approximated arbitrarily well as:

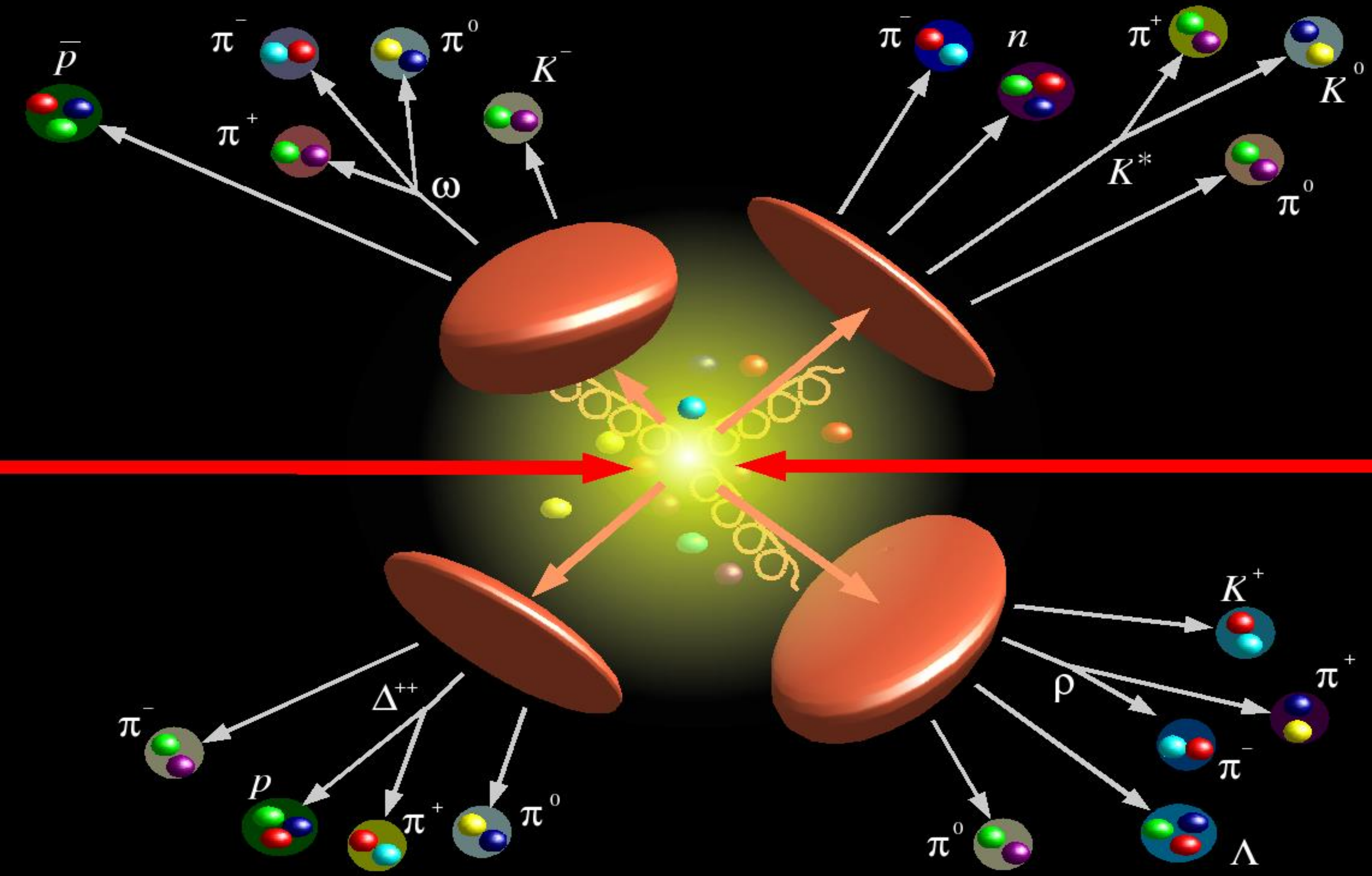
$$\mathcal{O}(p_1, \ldots, p_M) = F\left(\sum_{i=1}^{M} E_i \, \vec{\Phi}(\hat{p}_i)\right)$$

for some $\Phi\colon \mathbb{R}^2 \to \mathbb{R}^\ell$ and F: $\mathbb{R}^\ell \to \mathbb{R}$ and sufficiently large ℓ.

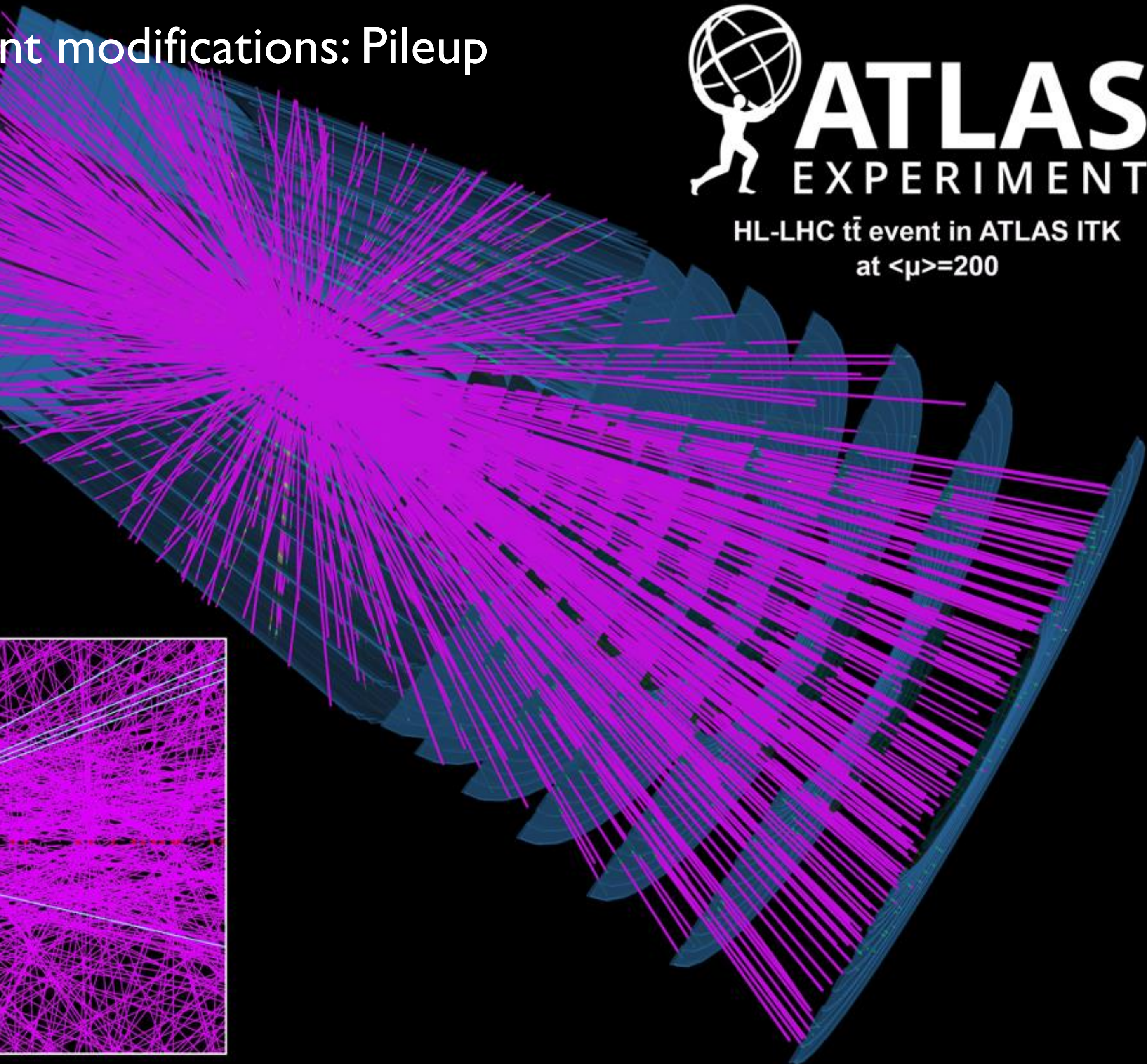
[M. Zaheer, *et al.*, 1703.06114]
[P.T. Komiske, EMM, J. Thaler, 1810.05165]

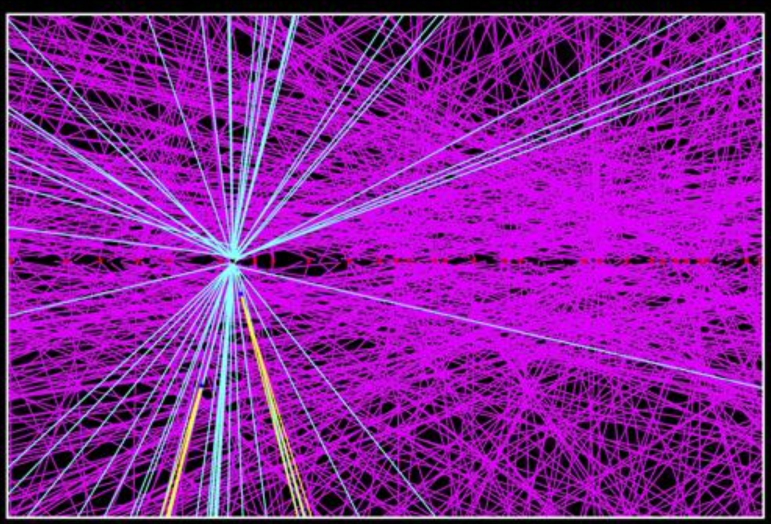
Events close in EMD are close in all infrared and collinear safe information!

Quantifying event modifications: Hadronization



Quantifying event modifications: Pileup





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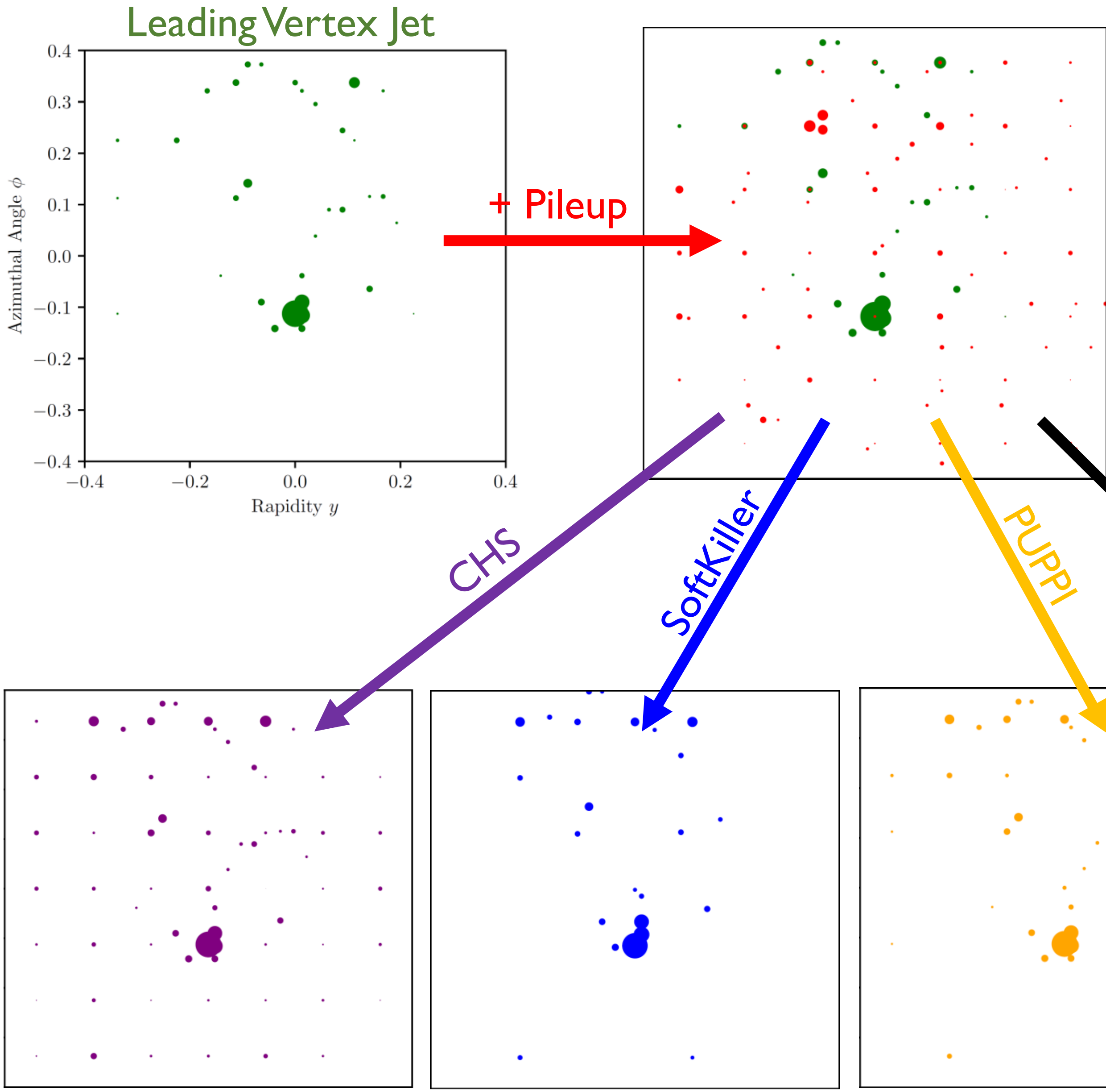


How can we quantify pileup mitigation?

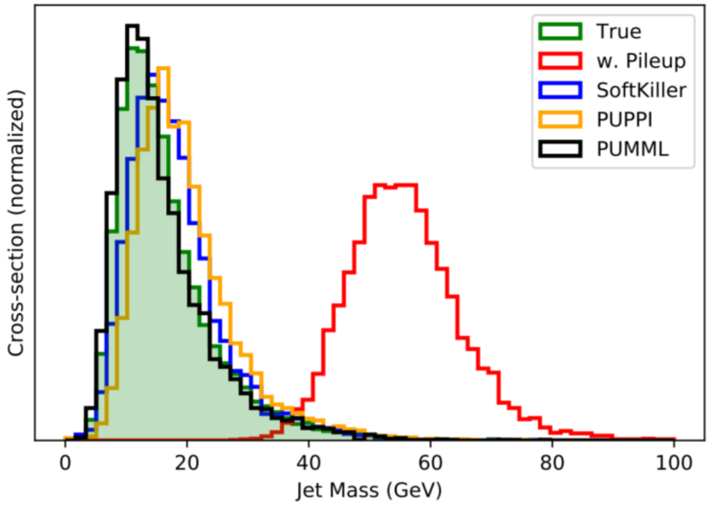
[M. Cacciari, G.P. Salam, G. Soyez, 1407.0408]

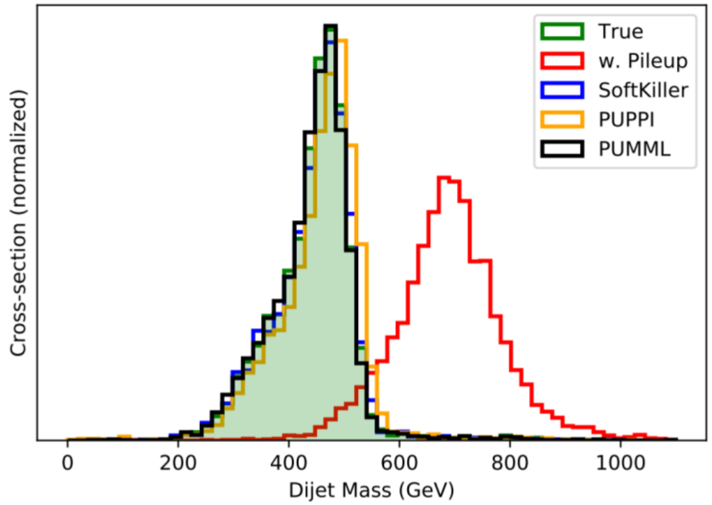
[D. Bertolini, P. Harris, M. Low, N. Tran, 1407.6013]

[P.T. Komiske, EMM, B. Nachman, M.D. Schwartz, 1707.08600]

Quantifying event modifications: Pileup

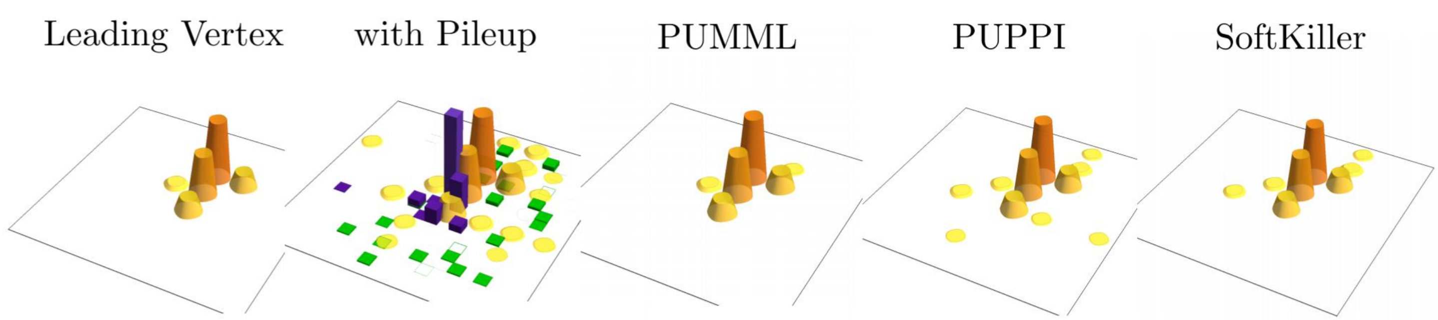
Compare on a collection of observables?





Requires ad hoc choices of observables.

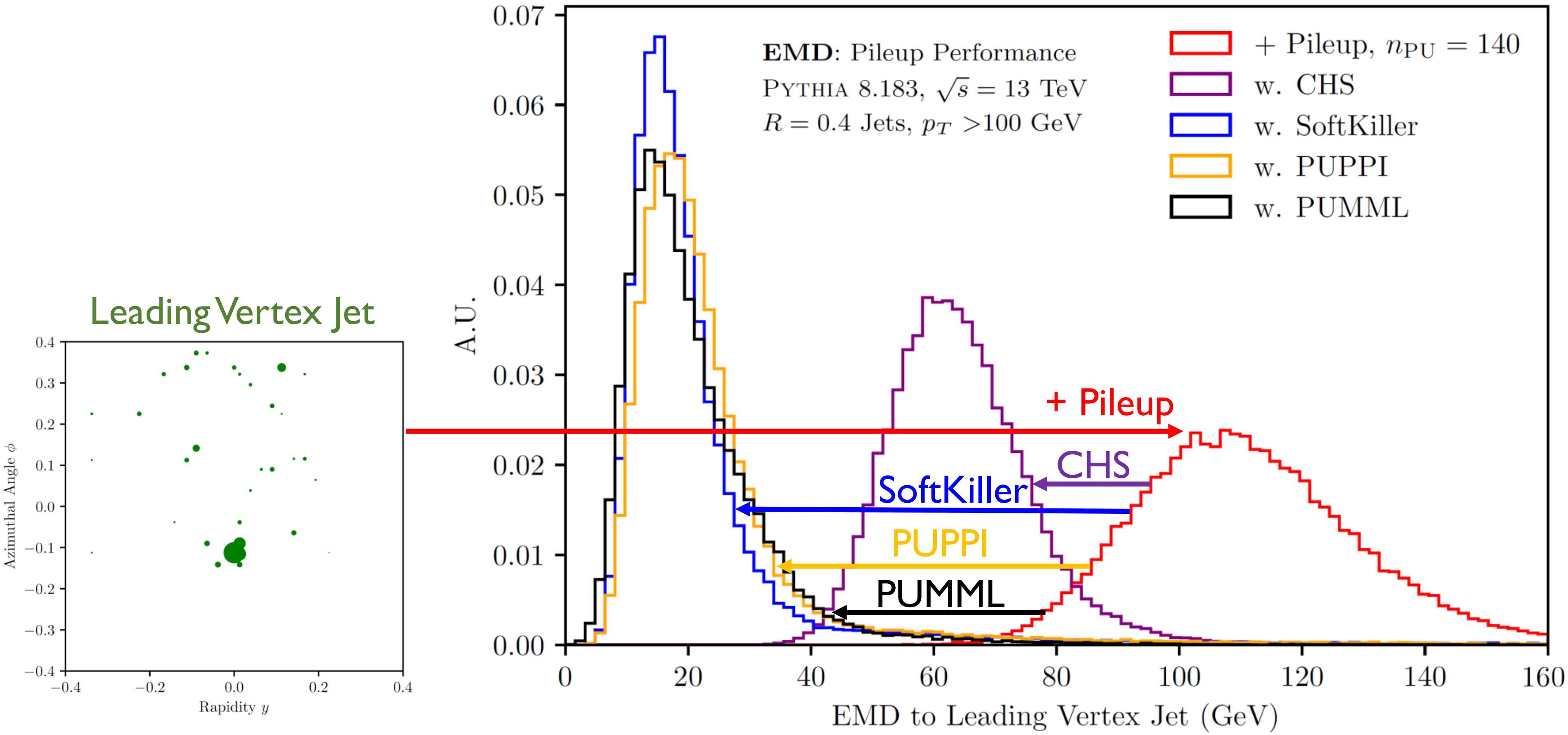
Compare calorimeter images pixel by pixel?



Discontinuous under physically-sensible single-pixel perturbations.
Undesirable behavior with increasing resolution.

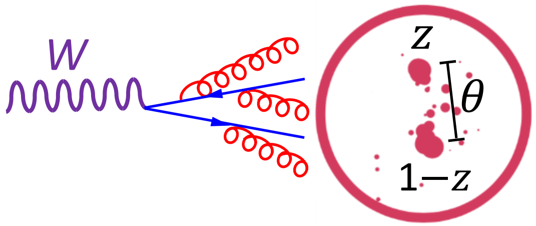
Quantifying event modifications: Pileup

Measure pileup mitigation performance with EMD!



Guarantees performance on IRC safe observables.
Stable under physically-sensible perturbations.
Train to optimize EMD with machine learning?

Exploring the Space of Events: *W* jets



W jets are 2-pronged:

z: Energy Sharing of Prongs
θ: Angle between Prongs
φ: Azimuthal orientation

Constrained by *W* mass:

$$z(1-z)\theta^2 = \frac{p_{\mu J}^2}{p_T^2} = \frac{m_W^2}{p_T^2}$$

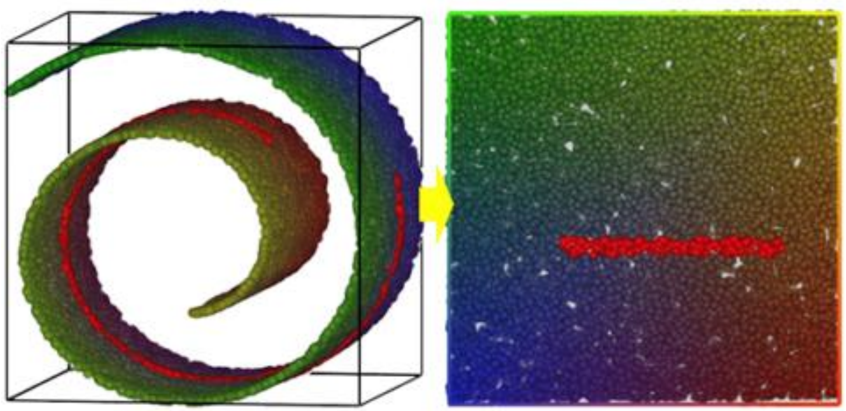
Hence we expect a **two**-dimensional space of *W* jets.

After φ rotation: **one**-dimensional

Visualize the space of events with t-Distributed Stochastic Neighbor Embedding (t-SNE).

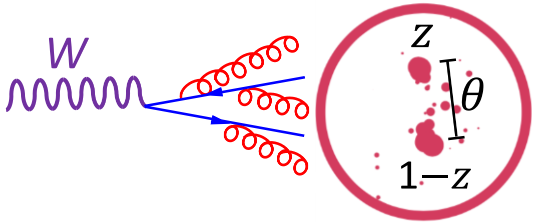
[L. van der Maaten, G. Hinton]

Finds an embedding into a low-dimensional manifold that respects distances.



Src: http://web-ext.u-aizu.ac.jp/~shigeo/home.html

Exploring the Space of Events: W jets



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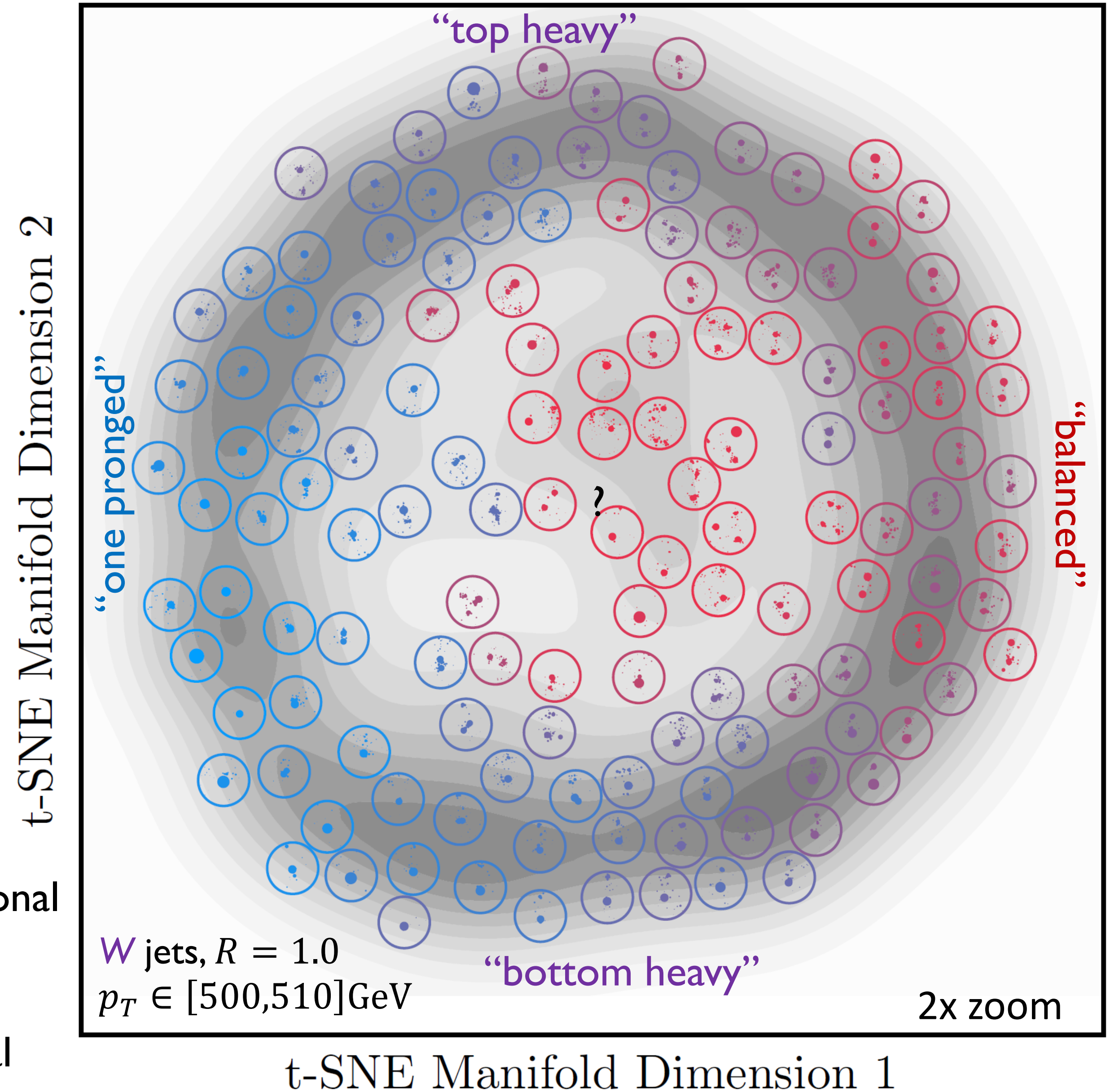
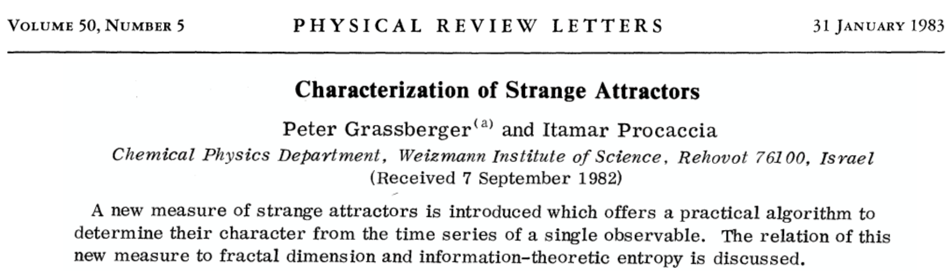
After φ rotation: **one**-dimensional



Exploring the Space of Jets: Correlation Dimension



VOLUME 50, NUMBER 5 PHYSICAL REVIEW LETTERS 31 JANUARY 1983

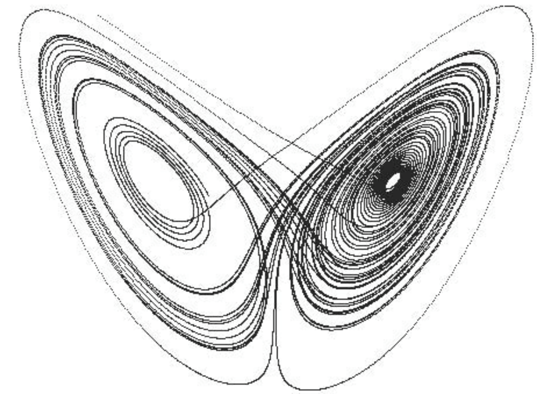
Characterization of Strange Attractors

Peter Grassberger[a] and Itamar Procaccia

Chemical Physics Department, Weizmann Institute of Science, Rehovot 76100, Israel

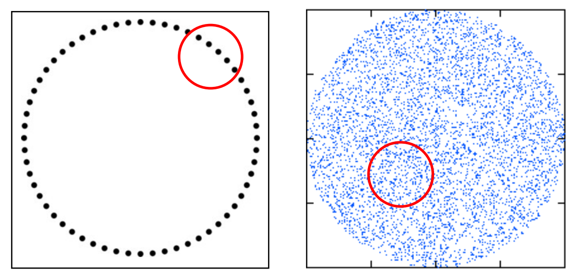
(Received 7 September 1982)

A new measure of strange attractors is introduced which offers a practical algorithm to determine their character from the time series of a single observable. The relation of this new measure to fractal dimension and information-theoretic entropy is discussed.



Intuition:

$$\underset{\text{points}}{N_{\text{neighboring}}}(r) \propto r^{\text{dim}} \quad \Longrightarrow \quad \dim(r) = \mathrm{r}\frac{\partial}{\partial r}\ln N_{\text{neighbors}}(r)$$



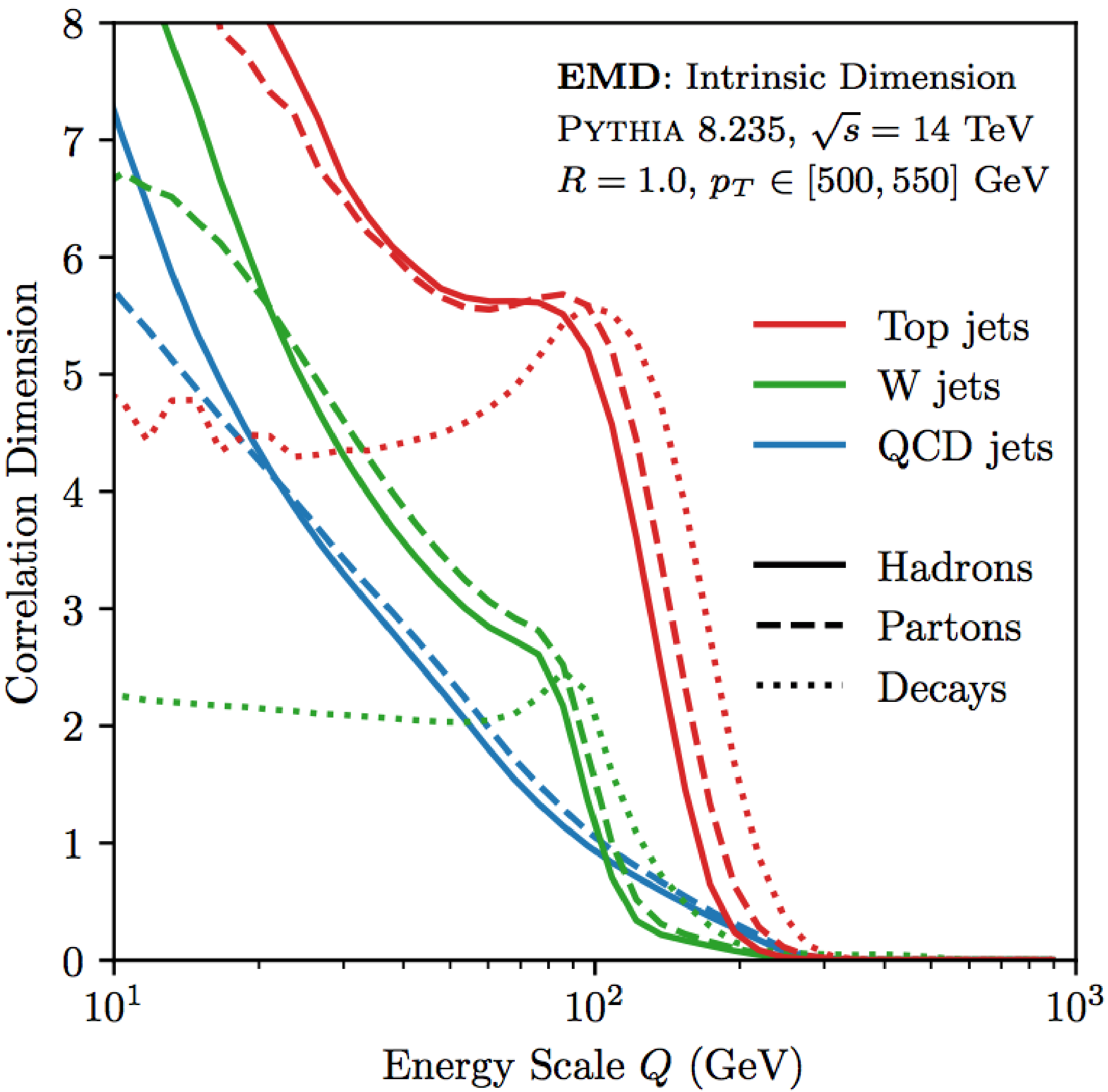
Correlation dimension:

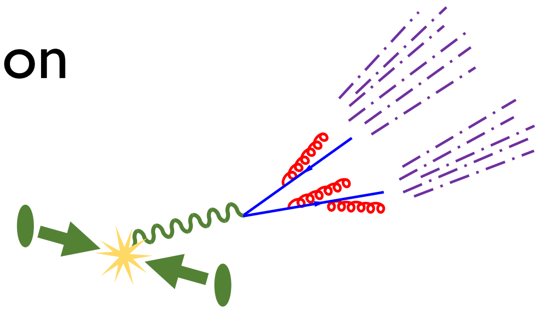
$$\boxed{\dim(Q) = Q\frac{\partial}{\partial Q}\ln \sum_{i=1}^{N}\sum_{j=1}^{N}\Theta[\mathrm{EMD}(\mathcal{E}_i,\mathcal{E}_j) < Q]}$$

Energy scale Q dependence

Count neighbors in ball of radius Q

Exploring the Space of Jets: Correlation Dimension





QCD jets are simplest.

W jets are more complicated.

Top jets are most complex.

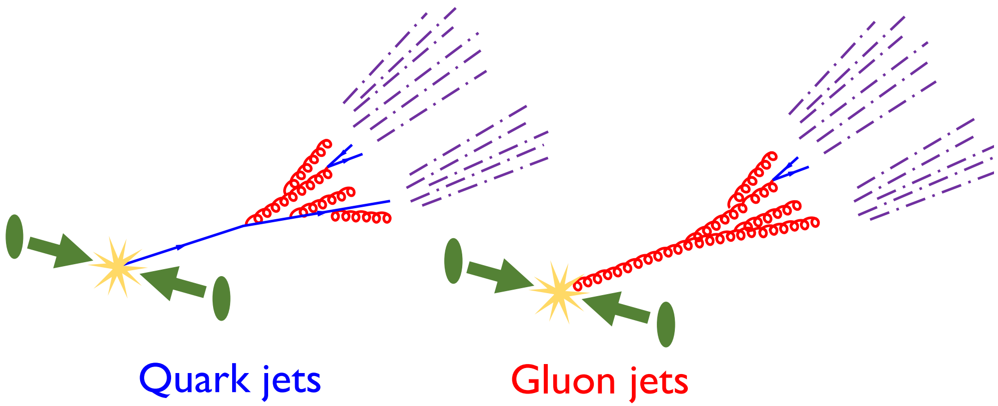
"Decays" have ~constant dimension.

Fragmentation becomes more complex at lower energy scales.

Hadronization becomes relevant at scales around 20 GeV.

Can we understand this analytically?

Exploring the Space of Jets: Correlation Dimension

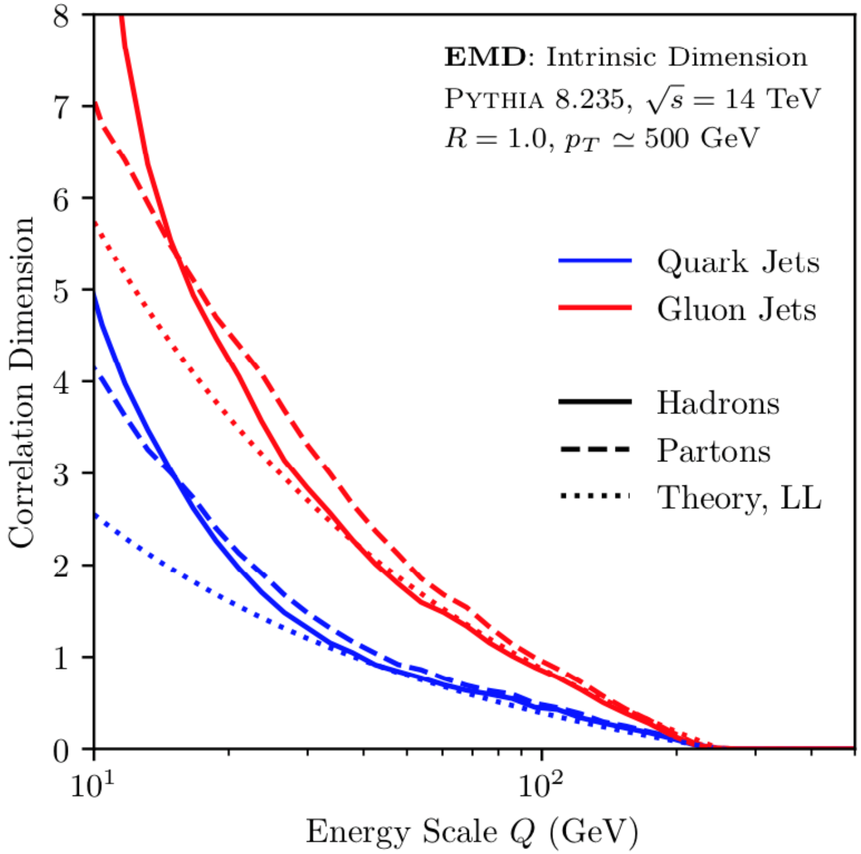


$$\text{At LL:} \quad \dim_{q/g}(Q) = -\frac{8\alpha_s C_{q/g}}{\pi} \ln \frac{Q}{p_T/2}$$

+ 1-loop running of α_s

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

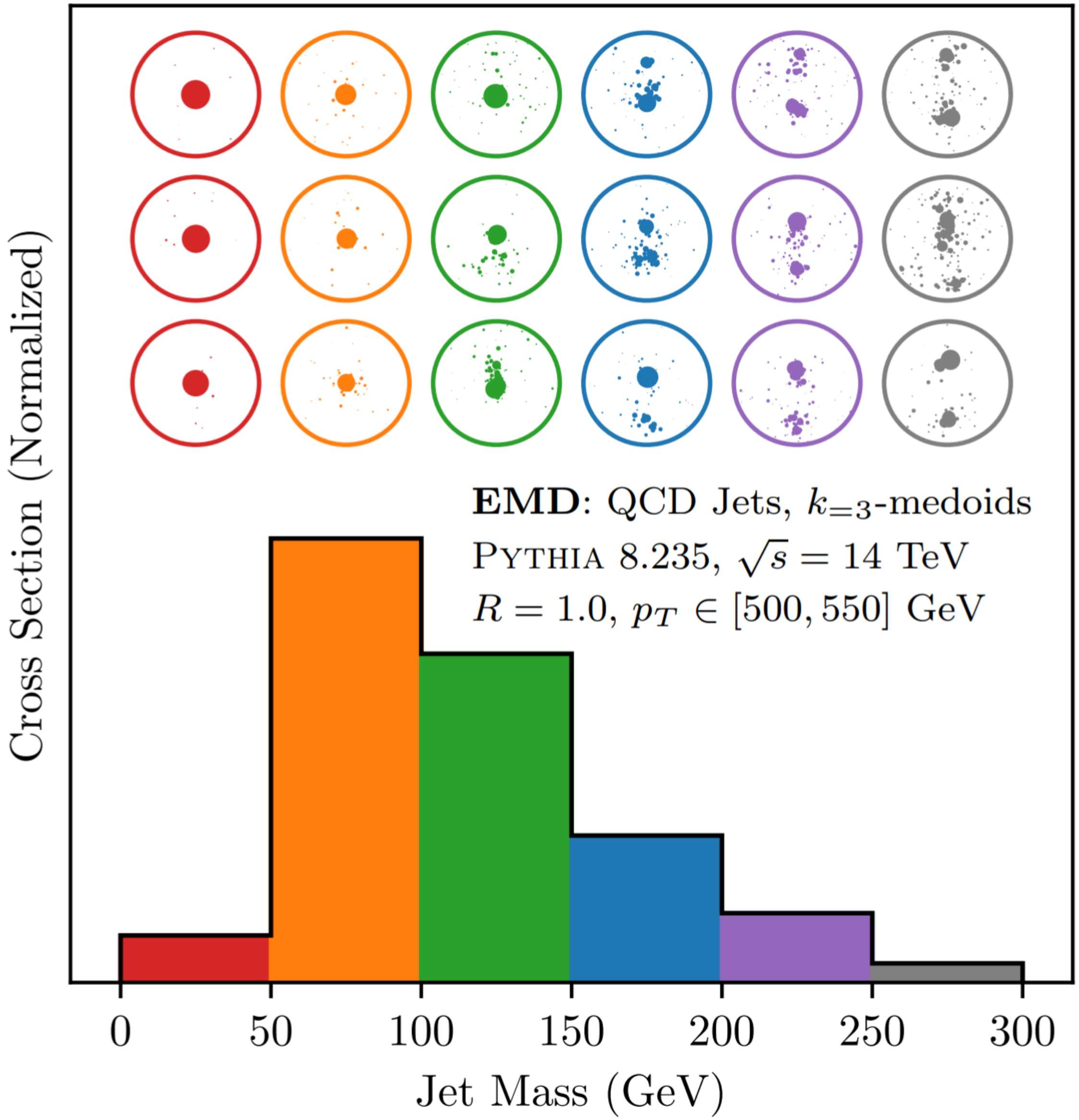
$$C_g = C_A = 3$$



Dimension blows up at low energies.

Jets are "more than fractal"?

Exploring the Space of Events: *k*-medoids



Exploring the Space of Events: Jet Classification

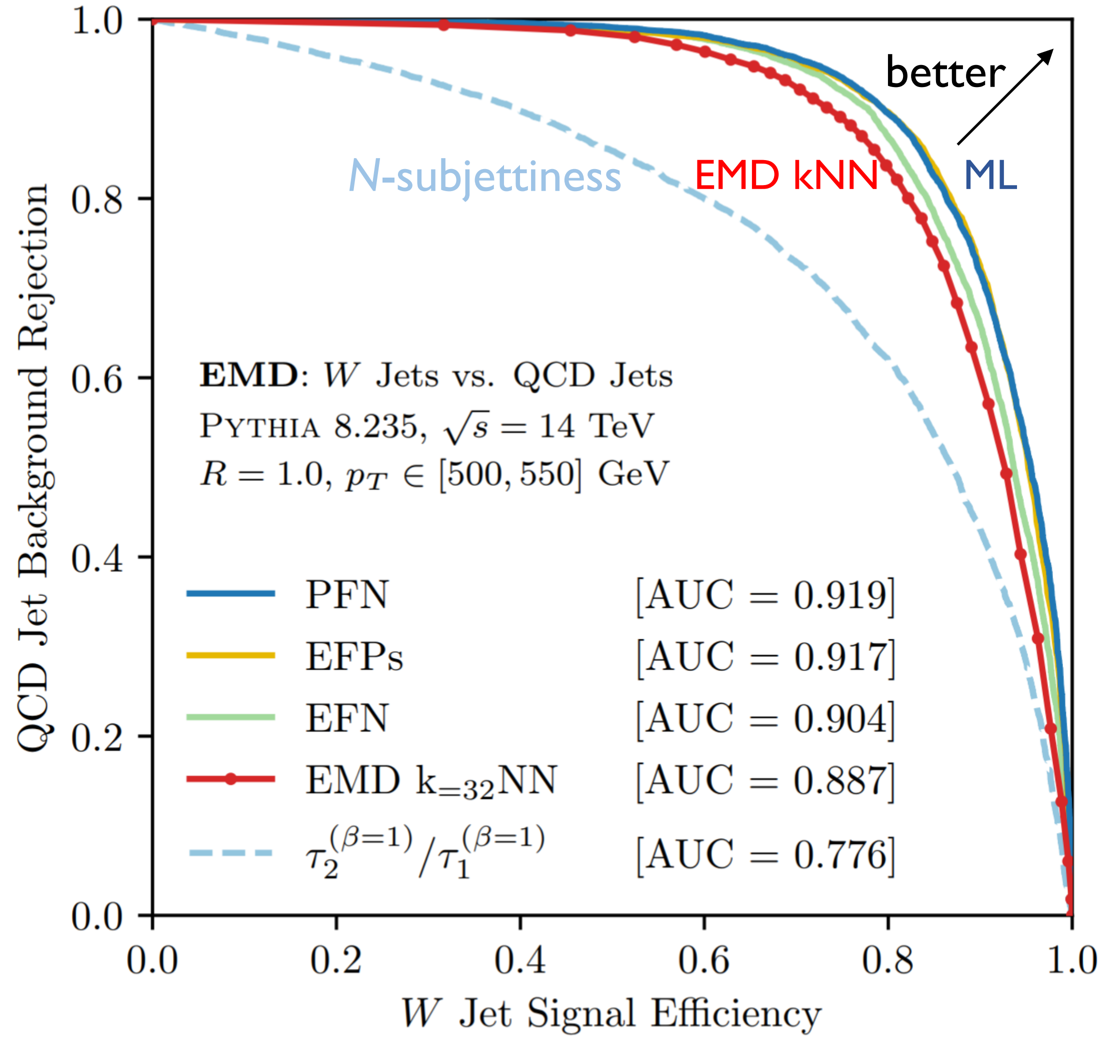
Classify *W* jets vs. QCD jets

vs.

Look at a jet's nearest neighbors (kNN) to predict its class.

Optimal IRC-safe classifier with enough data.

Nearing performance of ML.



Exploring the Space of Events

Use EMD as a measure of event similarity

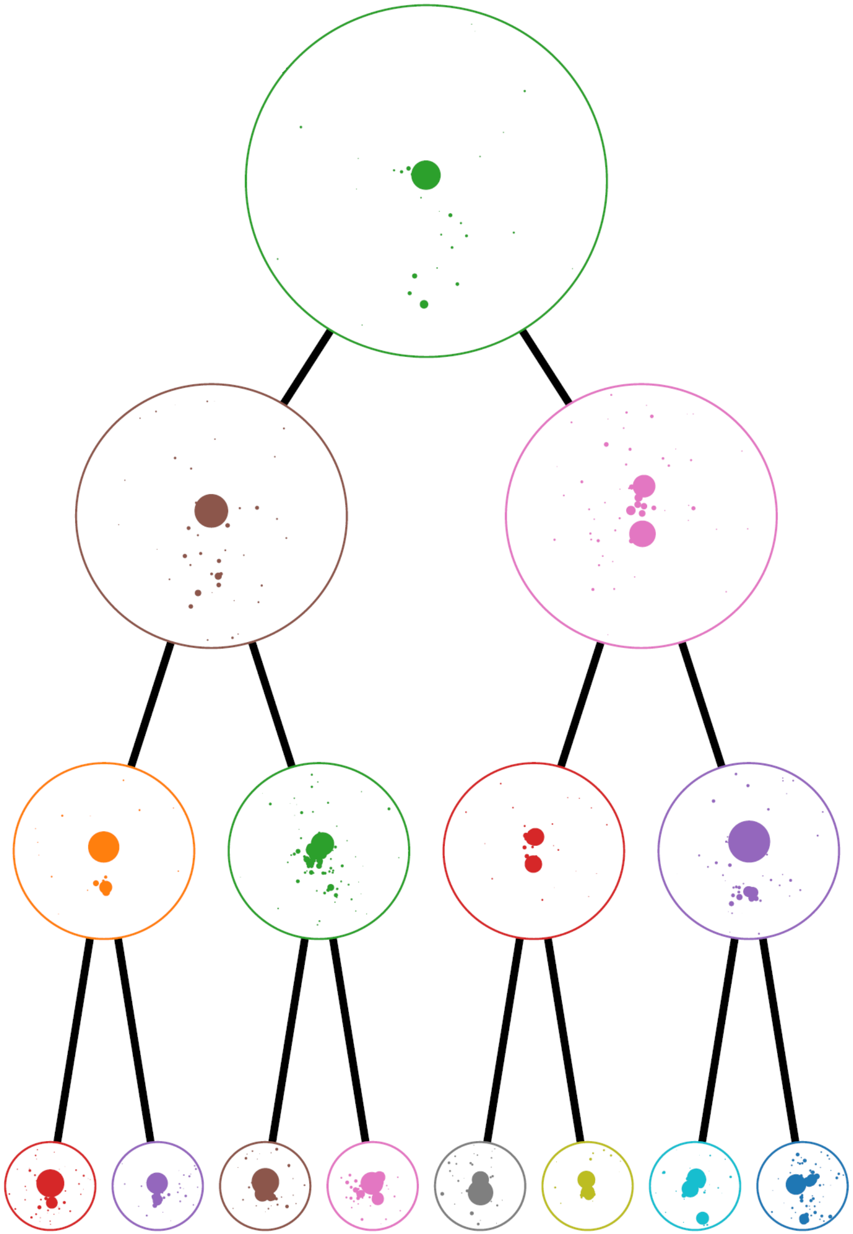
Unsupervised clustering algorithms can be used to cluster events

Jets are clusters of particles
???? are clusters of jets

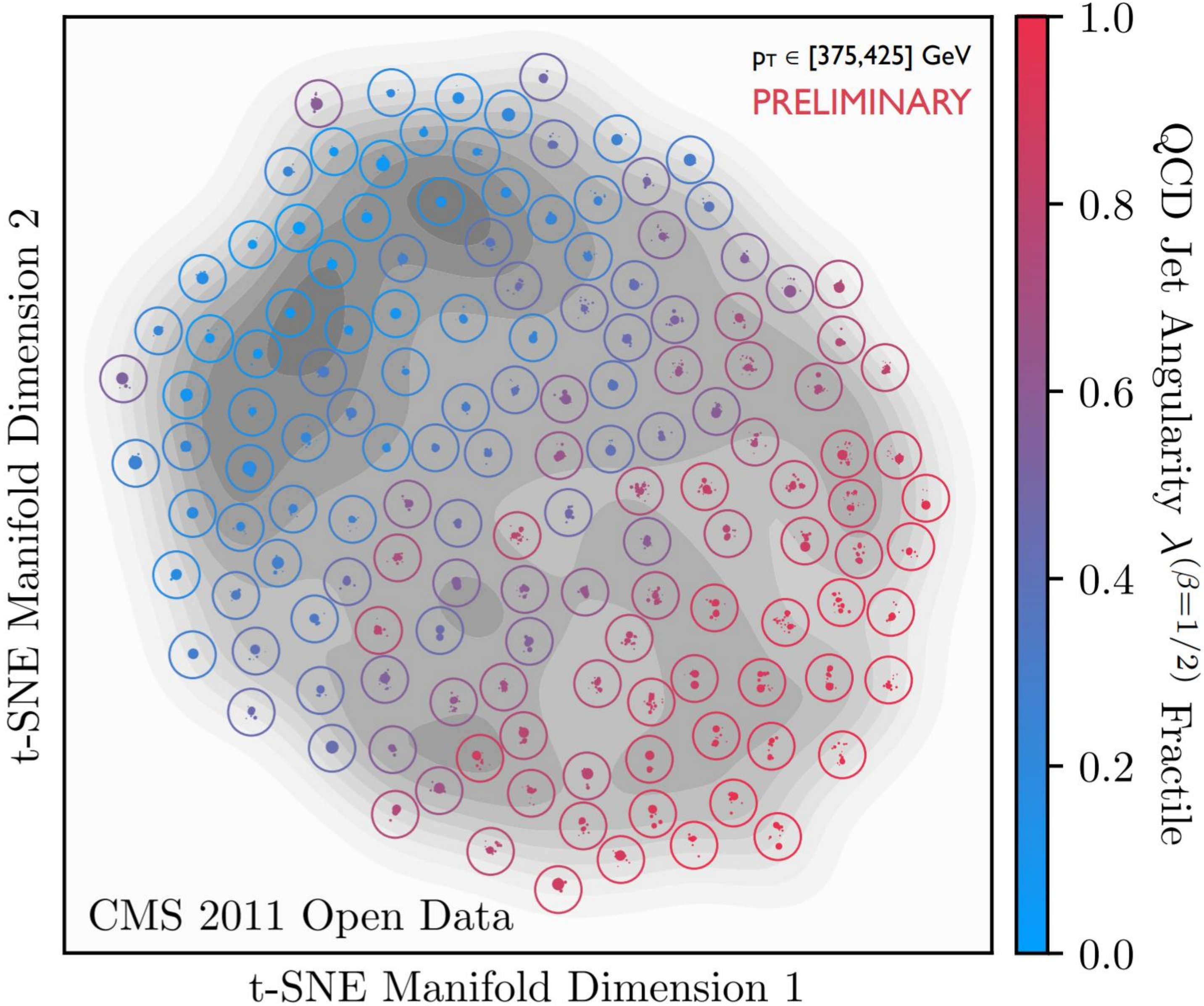
VP Tree: O(log(N)) neighbor query time

Much more to explore.

Vantage Point (VP) Tree



Exploring the Space of Events: QCD Jets



Exploring the Space of Jets: Correlation Dimension

Sketch of leading log (one emission) calculation:

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

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

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

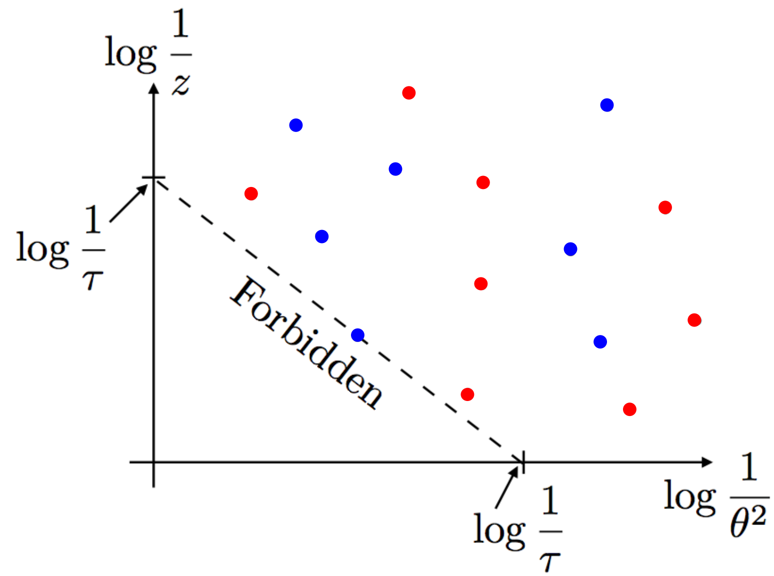
$$= Q\frac{\partial}{\partial Q}\ln \exp\left(-\frac{4\alpha_s C_{q/g}}{\pi}\ln^2\frac{Q}{p_T/2}\right)$$

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

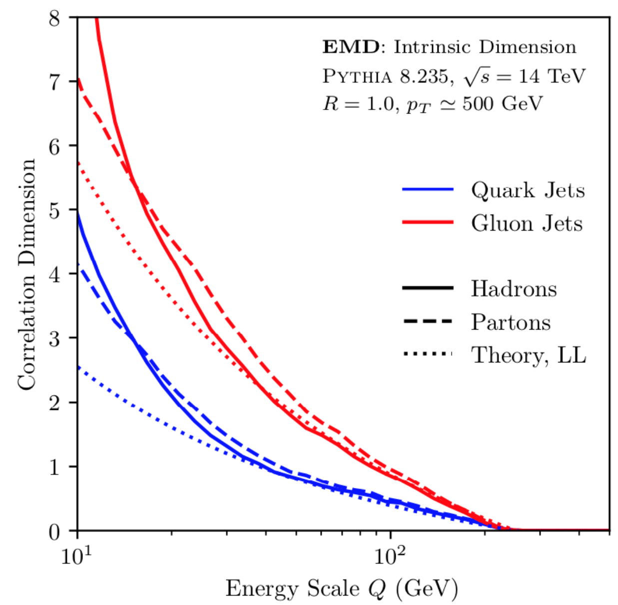
+ 1-loop running of α_s

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

$$C_g = C_A = 3$$

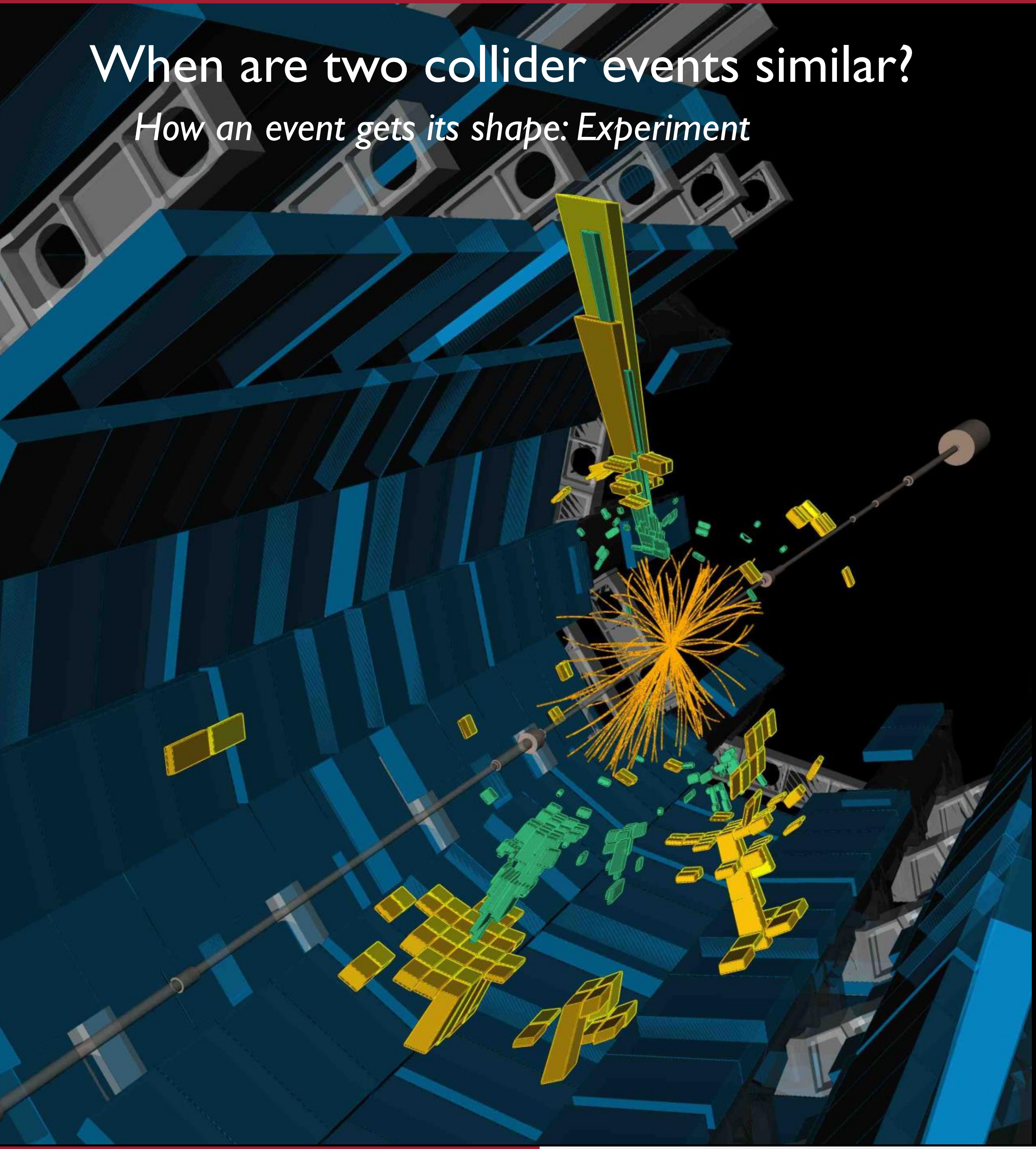


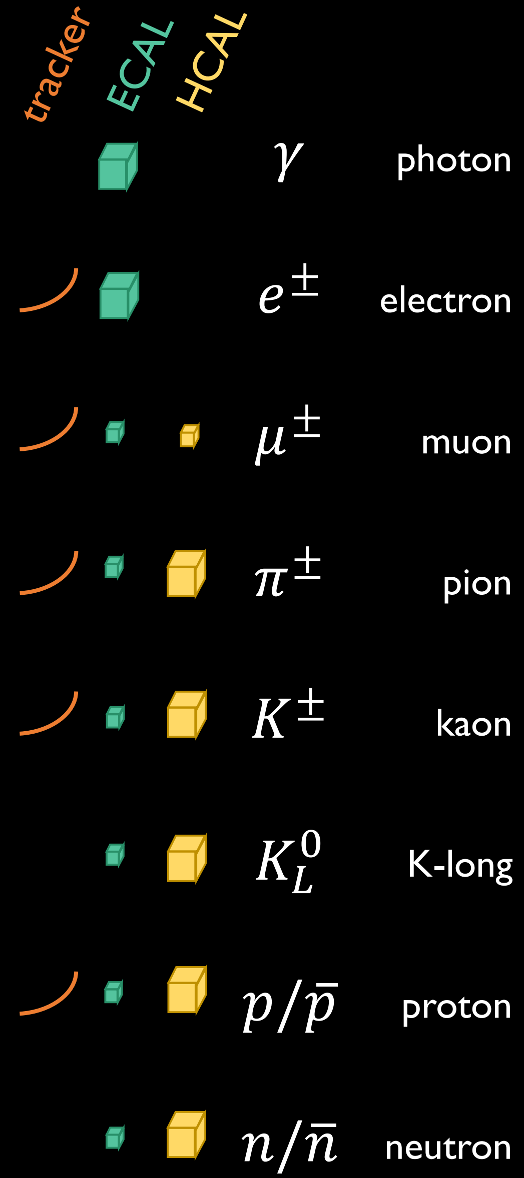
[A. Larkoski, 1709.06195]



When are two collider events similar?

How an event gets its shape: Experiment





Pileup Mitigation with PUMML