The Hidden Geometry of Particle Collisions

Jesse Thaler

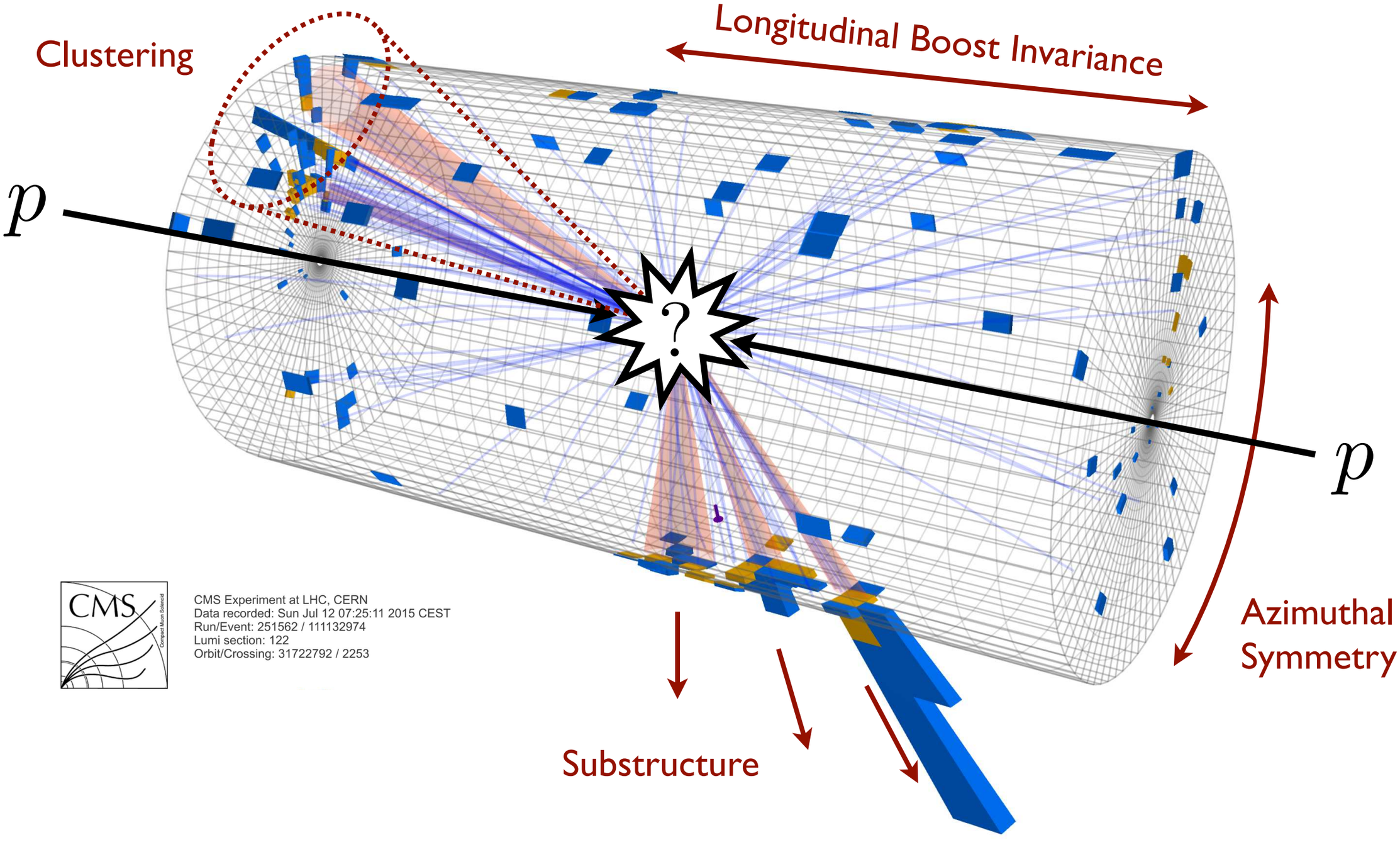
Research Progress Meeting, Lawrence Berkeley National Laboratory — November 5, 2020

Wearing my New Hat…

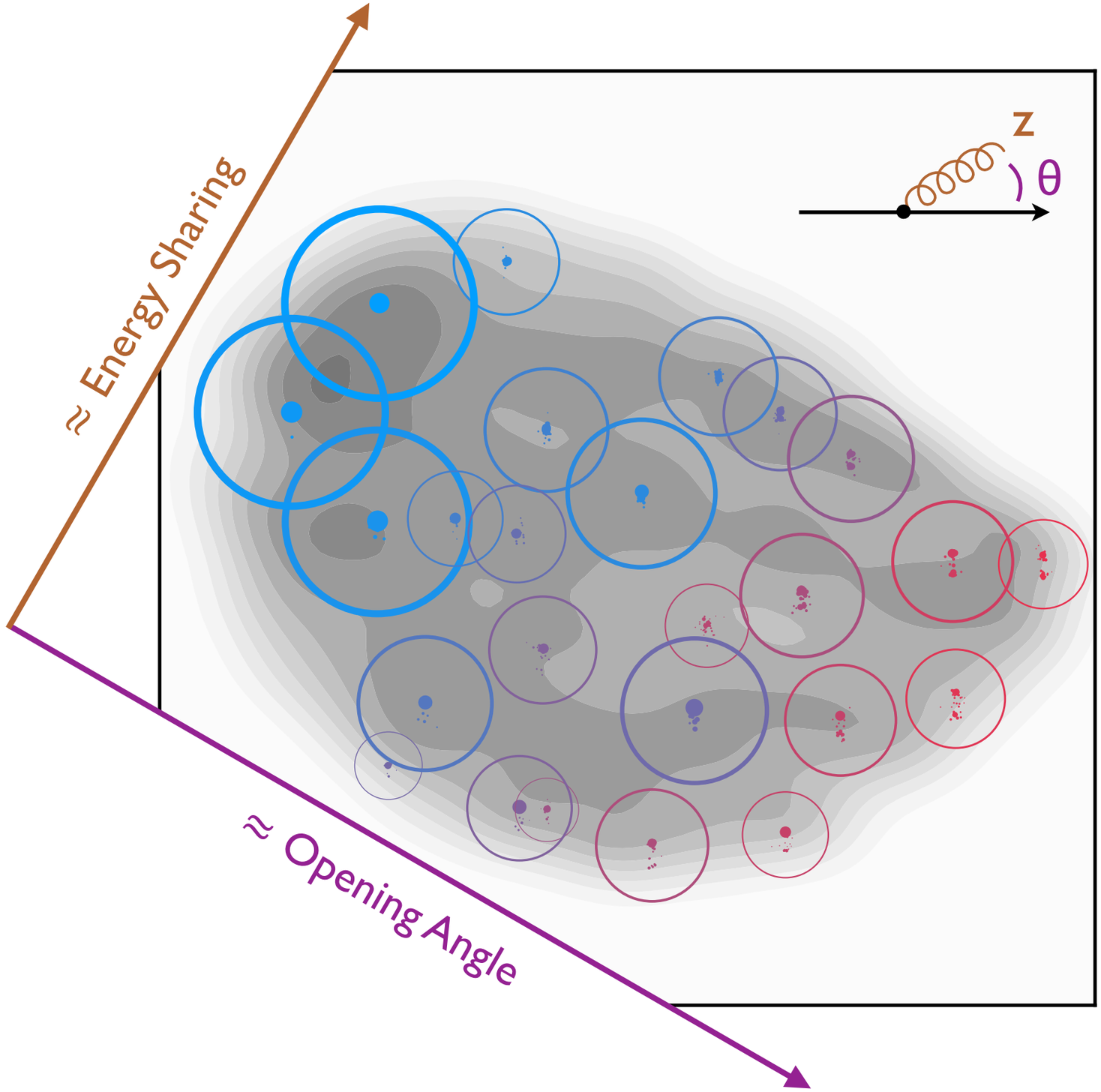
The NSF AI Institute for
Artificial Intelligence and Fundamental Interactions

http://iaifi.org/

The Manifest Geometry of One Collision



The Emergent Geometry of Many Collisions



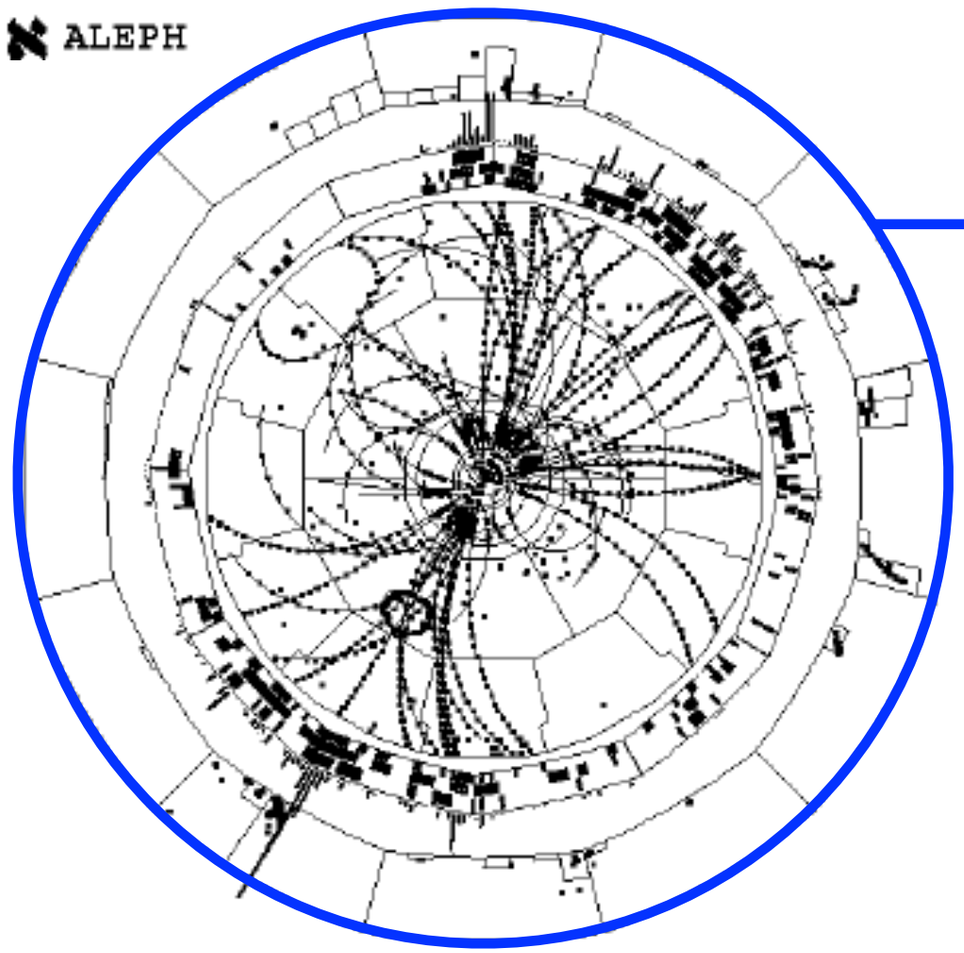
[See LBNL ATLAS-Theory Lunch talk by Metodiev, April 17, 2019]



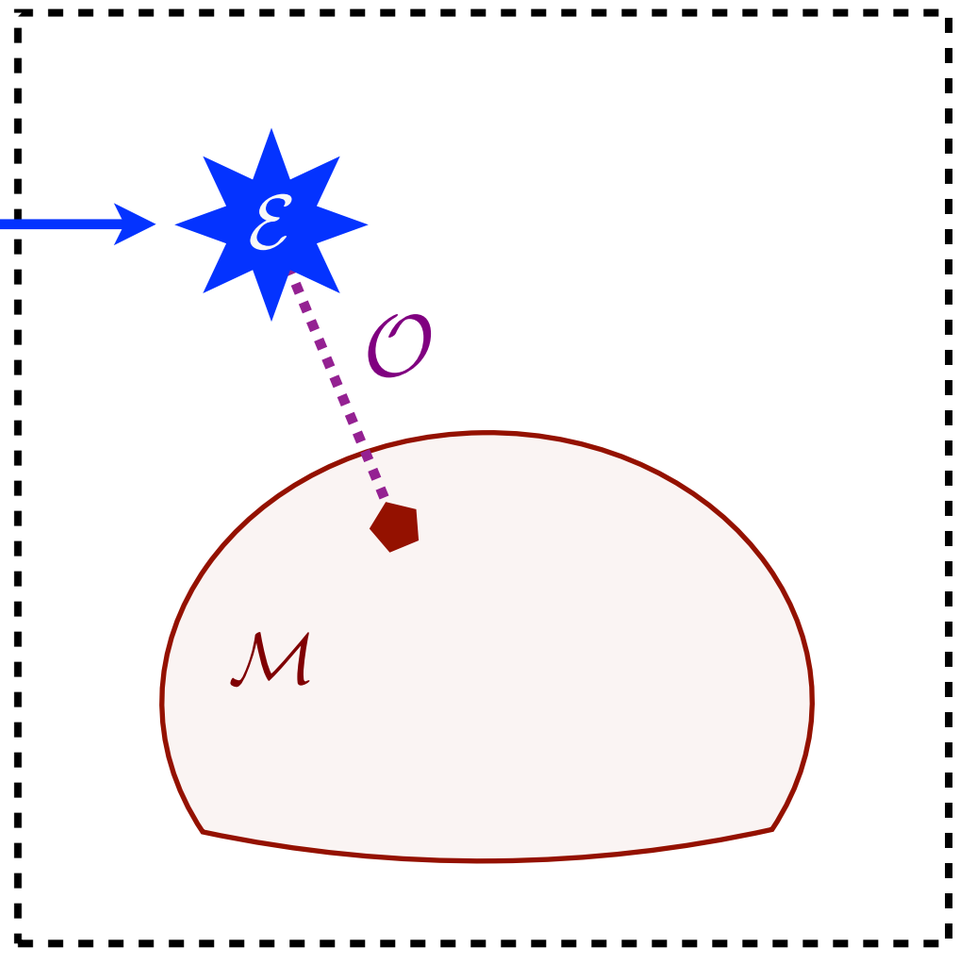

[Komiske, Mastandrea, Metodiev, Naik, JDT, PRD 2020; based on Komiske, Metodiev, JDT, PRL 2019; using EnergyFlow and CMS Open Data]

The Hidden Geometry of Particle Collisions

E.g. Classic QCD Event Shapes



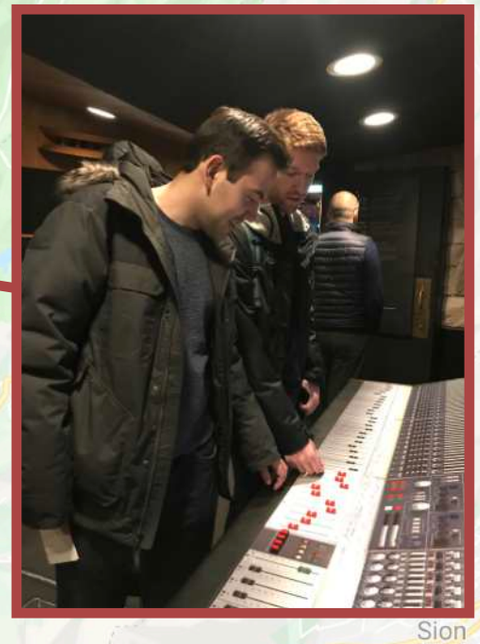
One Electron-Positron Event



Distance to a Manifold in Event Space

[Komiske, Metodiev, JDT, JHEP 2020]
[Brandt, Peyrou, Sosnowski, Wroblewski, PL 1964; Farhi, PRL 1977]

Scenes from My Sabbatical

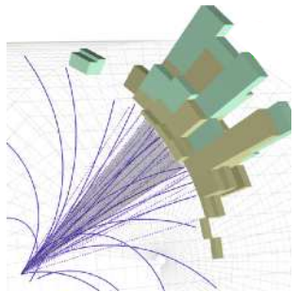


Eric Metodiev

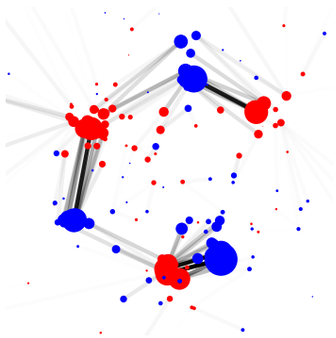
Patrick Komiske

[February 2019;
Simons Sabbatical Fellowship]

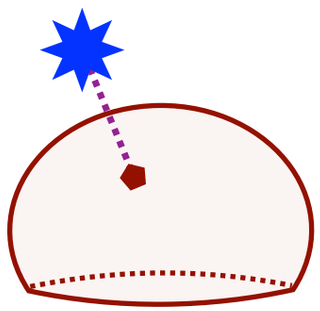
Outline



What is a Collider Event?



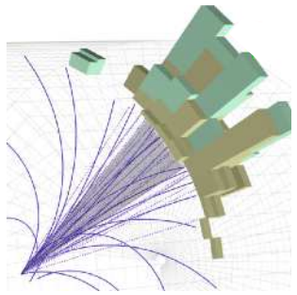
When are Events Similar?



What can be Geometrized?

Pause

Interrupt me or drop questions in the chat, and I'll try to answer them as I go



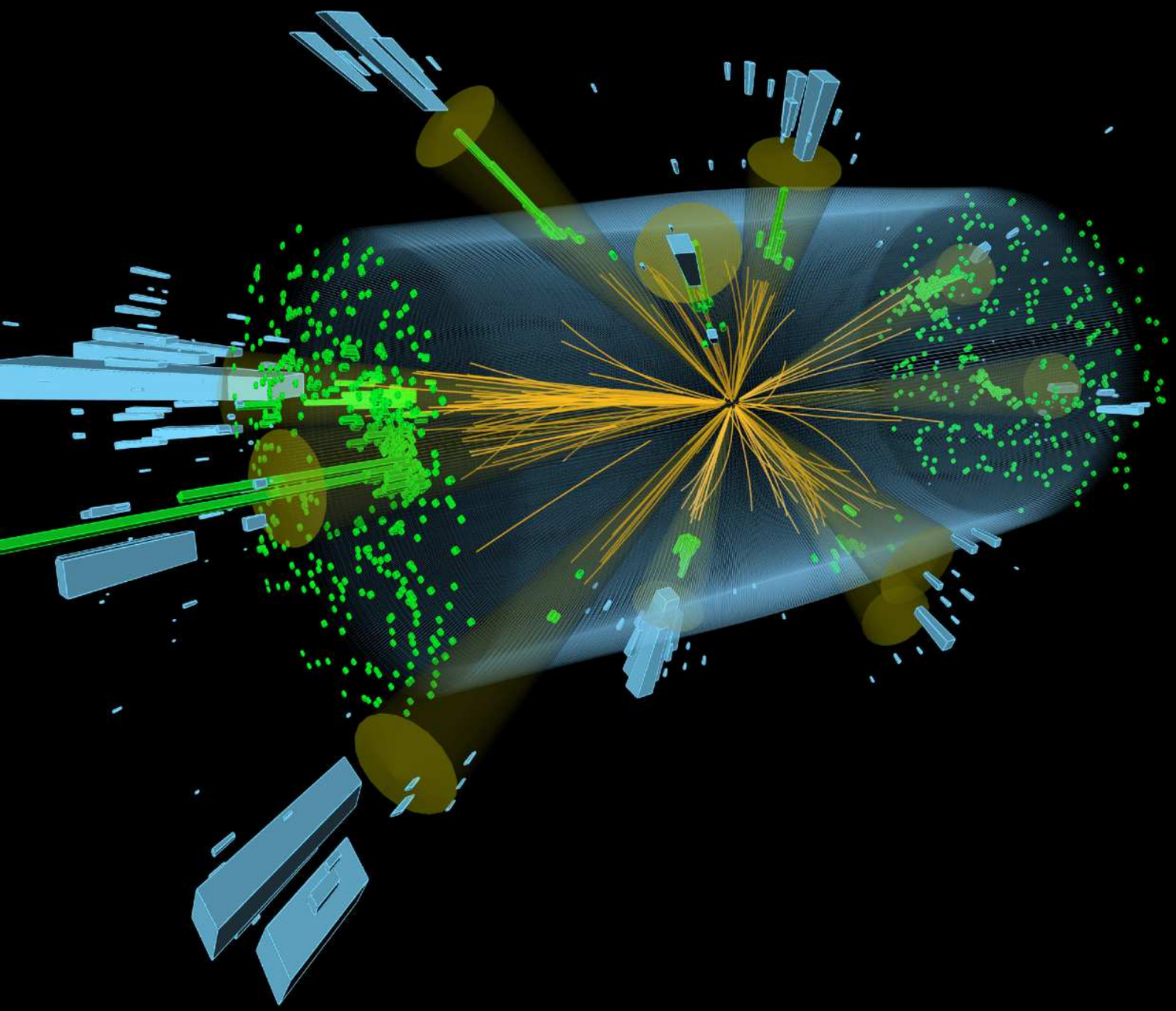
What is a Collider Event?

When are Events Similar?

What can be Geometrized?

Collider Event

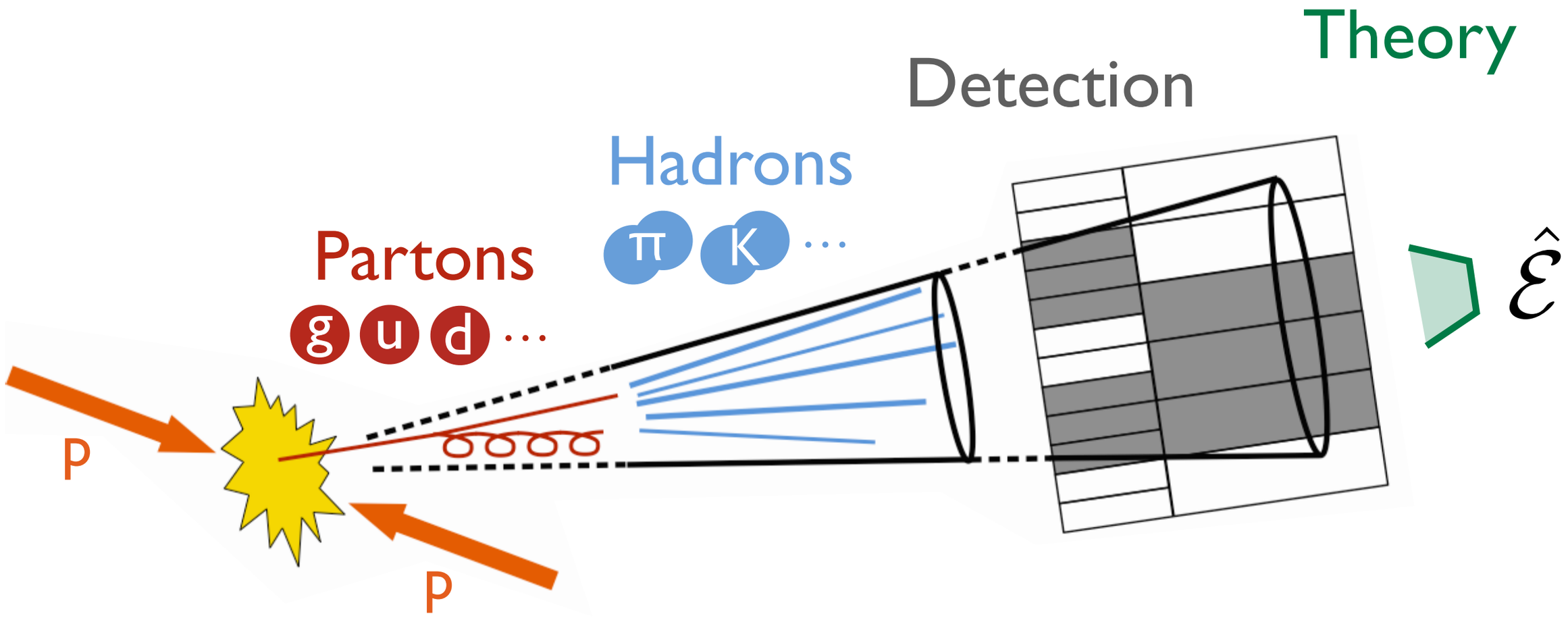
Collection of points in momentum space



T E H M

γ	photon	elementary
$e^{\pm}$	electron	elementary
$\mu^{\pm}$	muon	elementary
$\pi^{\pm}$	pion	composite
$K^{\pm}$	kaon	composite
K^0_L	K-long	composite
$p/\overline{p}$	proton	composite
$n/\overline{n}$	neutron	composite

Jet Formation Process



Stress-energy flow:

Robust to non-perturbative and detector effects
Well-defined for massless gauge theories

$$\hat{\mathcal{E}} \simeq \lim_{t\to\infty} \hat{n}_i T^{0i}(t, vt\hat{n})$$

[see e.g. Sveshnikov, Tkachov, PLB 1996; Hofman, Maldacena, JHEP 2008; Mateu, Stewart, JDT, PRD 2013; Belitsky, Hohenegger, Korchemsky, Sokatchev, Zhiboedov, PRL 2014; Chen, Moult, Zhang, Zhu, PRD 2020]

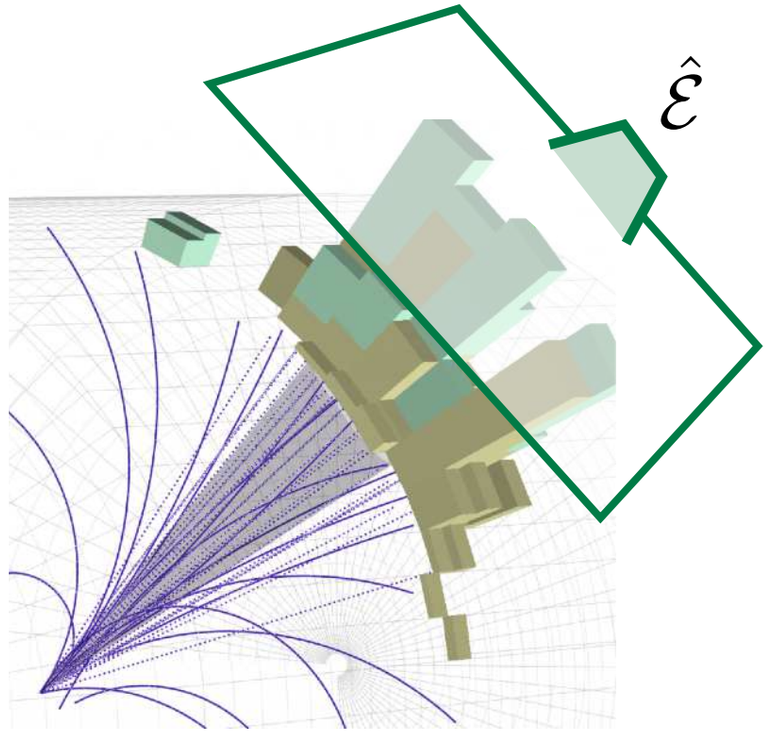
Jets as Weighted Point Clouds

- Energy-Weighted Directions

$$\vec{p} = \{E, \hat{n}_x, \hat{n}_y, \hat{n}_z\}$$

Energy — Direction

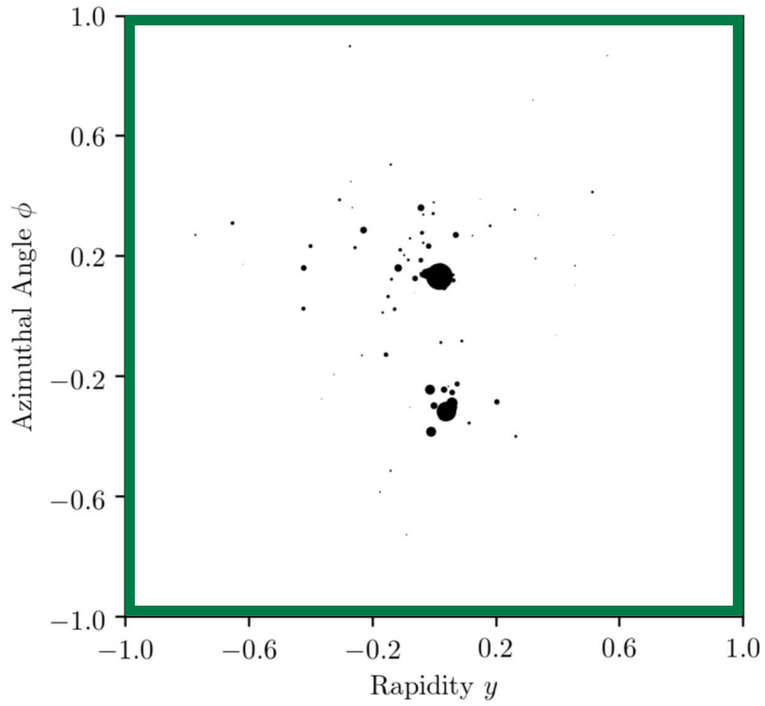
(suppressing "unsafe" charge/flavor information)



- Equivalently: Energy Density

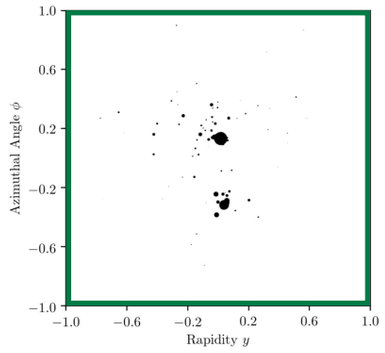
$$\rho(\hat{n}) = \sum_{i \in \mathcal{J}} E_i \, \delta^{(2)}(\hat{n} - \hat{n}_i)$$

Energy — Direction



Pause

What is a Collider Event?

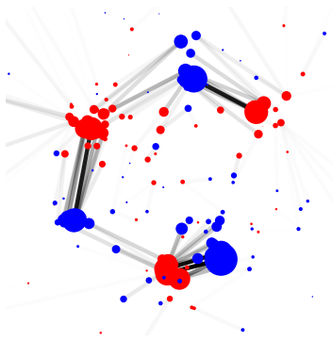


"Calo" Energy Density

$$\mathcal{E}(\hat{n}) = \sum_i E_i \, \delta(\hat{n} - \hat{n}_i)$$

(see backup for relevance to ML and QCD)

What is a Collider Event?

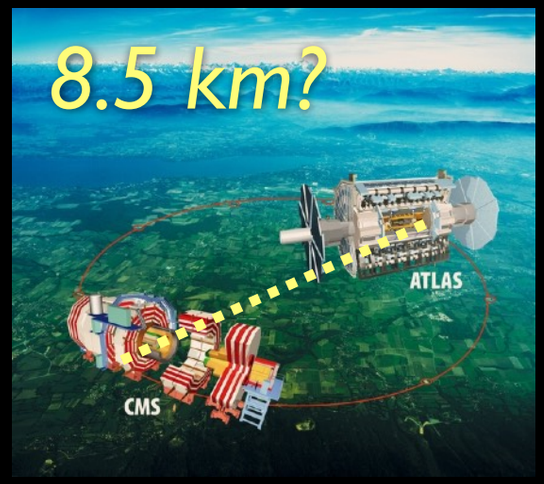


When are Events Similar?

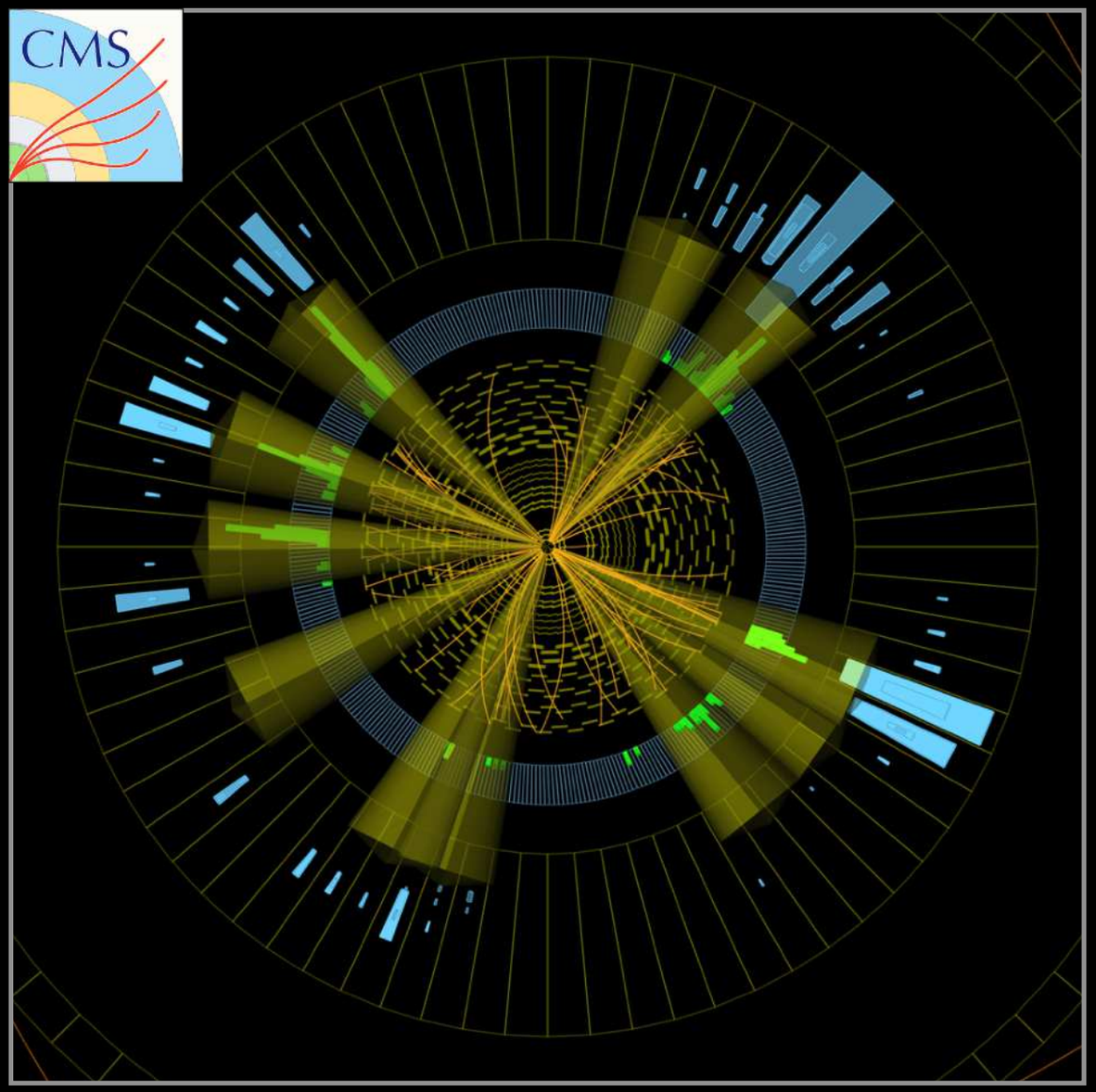
What can be Geometrized?

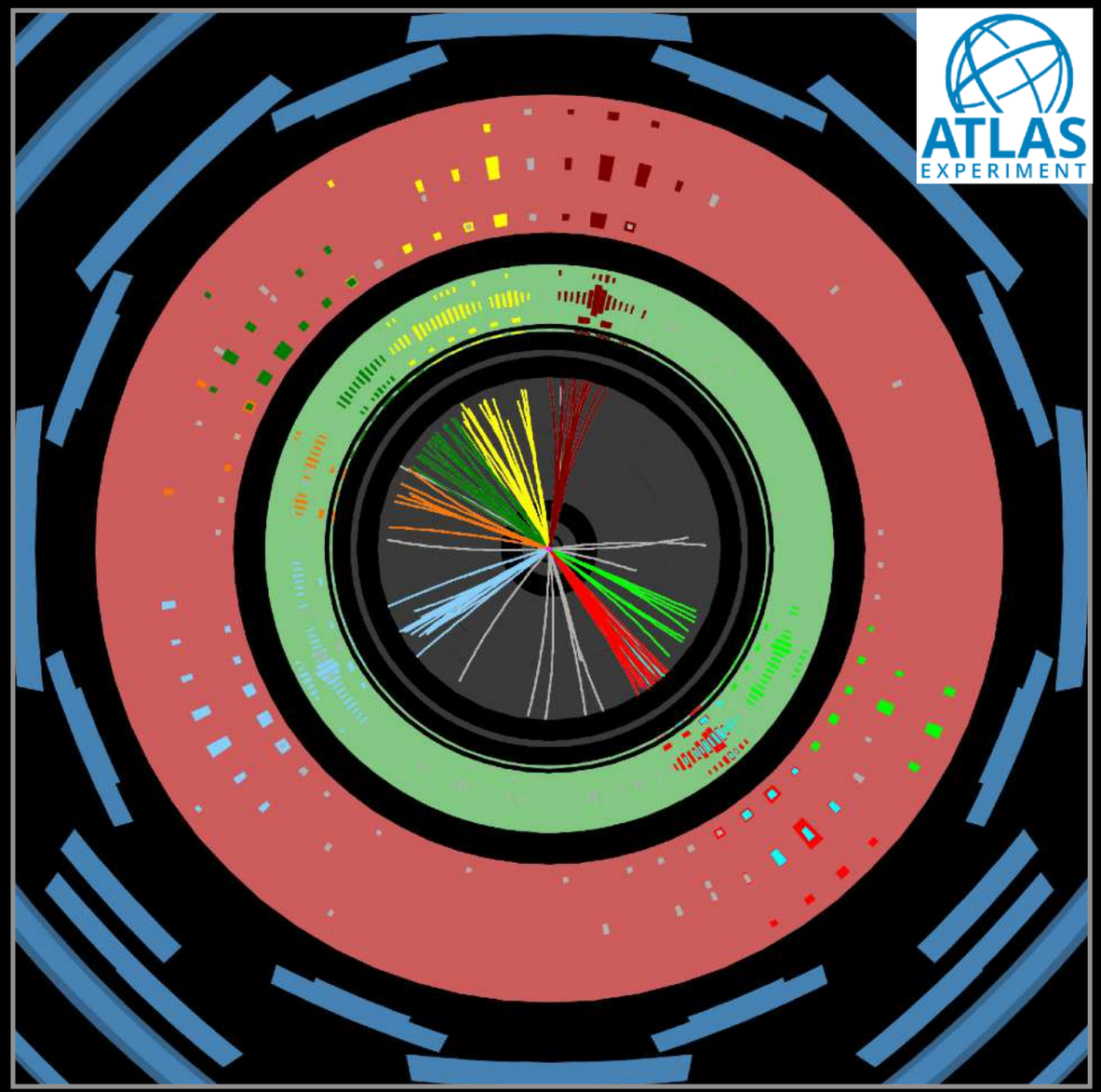
Two Collider Events

Two collections of points in (momentum) space



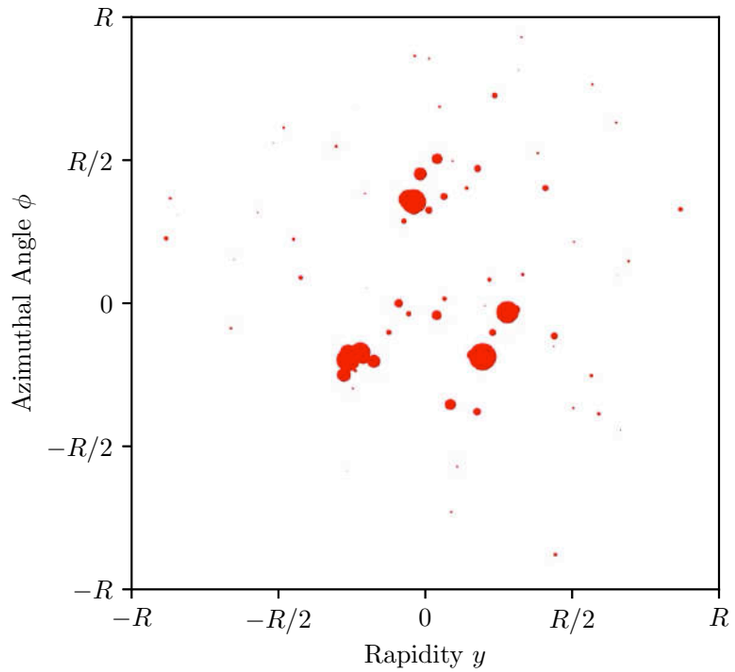
How "close" are these?





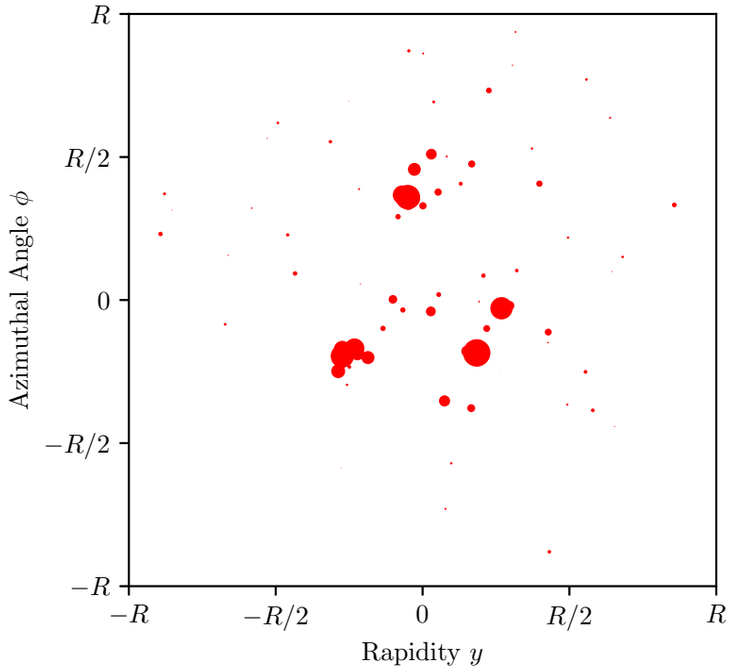
Similarity of Two Energy Flows?

$$\mathcal{E}(\hat{n}) = \sum_i E_i \, \delta(\hat{n} - \hat{n}_i)$$

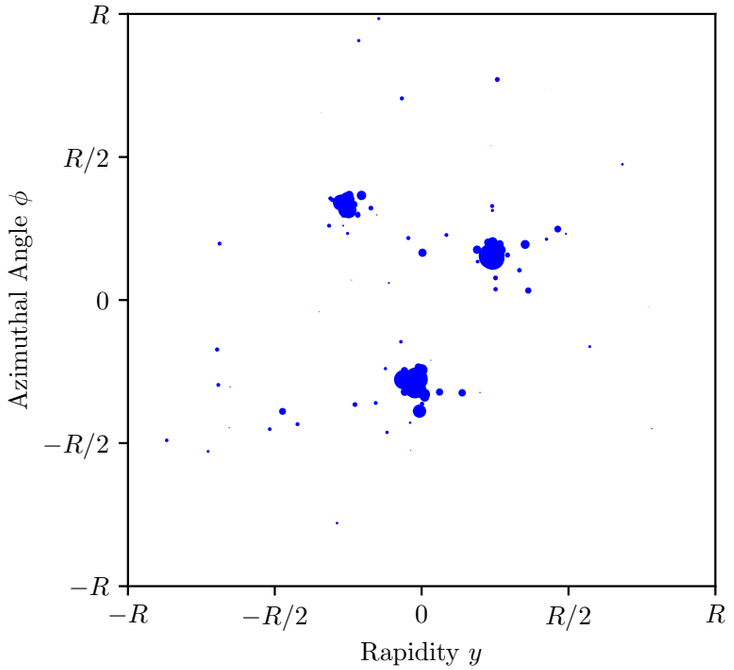


Optimal Transport:

Earth Mover's Distance
a.k.a. 1-Wasserstein metric



125.4 GeV



[Komiske, Metodiev, JDT, PRL 2019; code at Komiske, Metodiev, JDT, energyflow.network]

The Earth Mover's Distance

Optimal Transport:

[Peleg, Werman, Rom, IEEE 1989;
Rubner, Tomasi, Guibas, ICCV 1998, ICJV 2000;
Pele, Werman, ECCV 2008; Pele Taskar, GSI 2013]

Minimum "work" (stuff x distance) to make one distribution look like another distribution

Déblai

Remblai

[h/t Niles-Weed, ML4Jets 2020; Monge, 1781; Vaserštein, 1969; Wikipedia]

The Earth Mover's Distance

Optimal Transport:

[Peleg, Werman, Rom, IEEE 1989;
Rubner, Tomasi, Guibas, ICCV 1998, IJCV 2000;
Pele, Werman, ECCV 2008; Pele Taskar, GSI 2013]

Minimum "work" (stuff x distance) to make one distribution look like another distribution

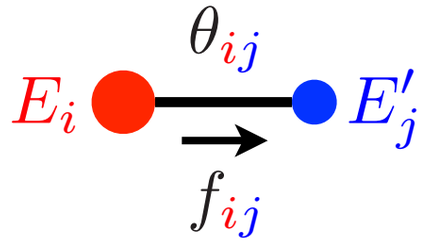
Additive Weight:

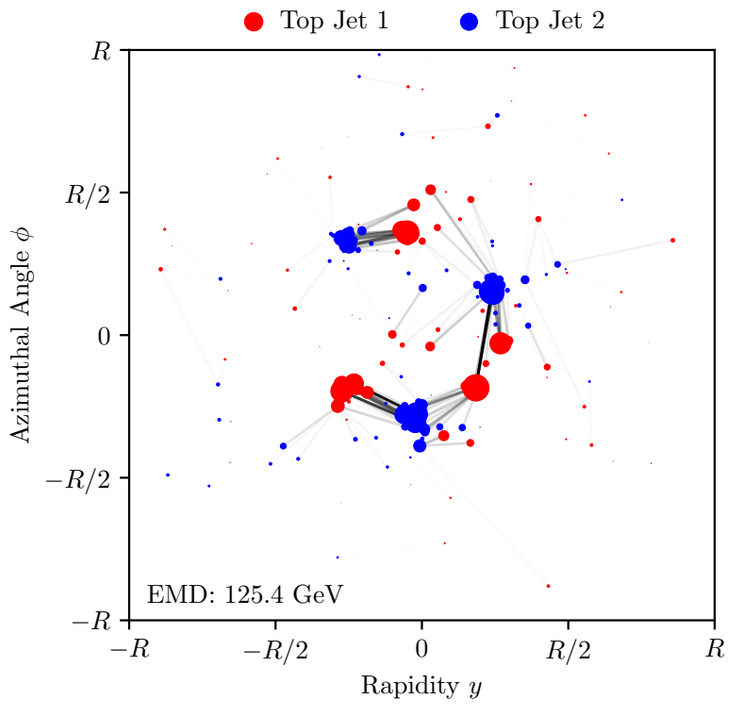
Ground Distance:

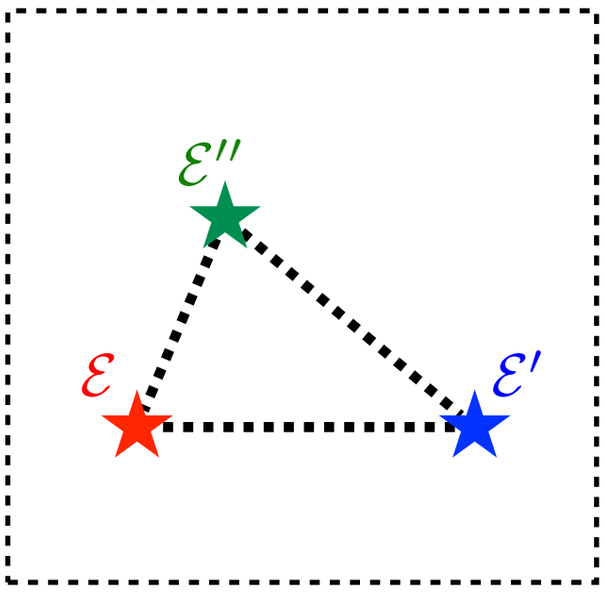
$\Rightarrow$ Distance Between Distributions

[h/t Niles-Weed, ML4Jets 2020; Monge, 1781; Vaseršteĭn, 1969; Wikipedia]

The Energy Mover's Distance







Optimal transport between energy flows…

$$\mathrm{EMD}(\mathcal{E}, \mathcal{E}') = \min_{\{f\}} \sum_i \sum_j f_{ij} \frac{\theta_{ij}}{R} + \left| \sum_i E_i - \sum_j E'_j \right|$$

in GeV

Cost to move energy

Cost to create energy

…defines a metric on the space of events

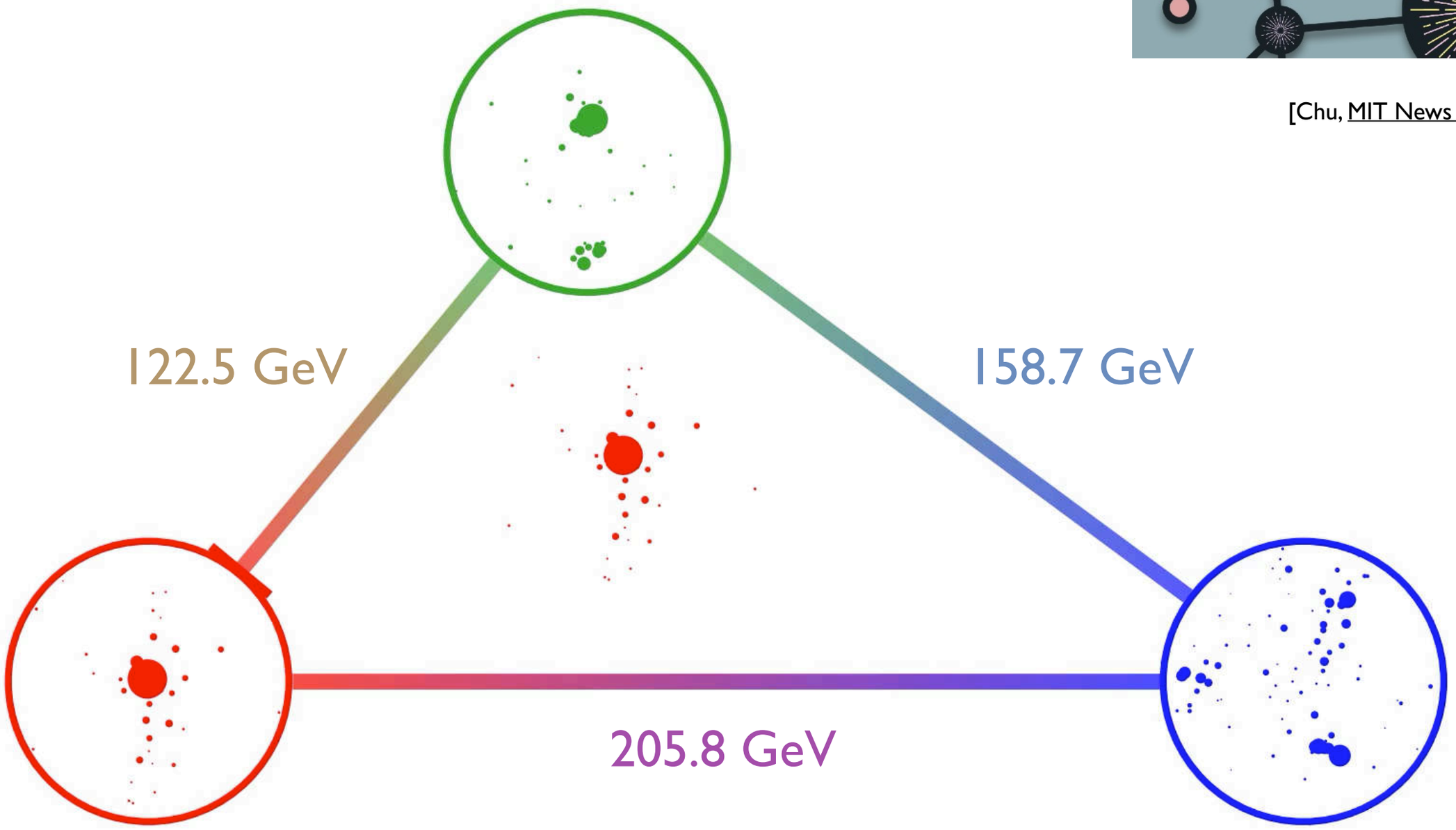
$$0 \leq \mathrm{EMD}(\mathcal{E}, \mathcal{E}') \leq \mathrm{EMD}(\mathcal{E}, \mathcal{E}'') + \mathrm{EMD}(\mathcal{E}', \mathcal{E}'')$$

(assuming $R \geq \theta_{max}/2$, i.e. $R \geq$ jet radius for conical jets)

[Komiske, Metodiev, JDT, PRL 2019;
see also Pele, Werman, ECCV 2008; Pele, Taskar, GSI 2013;
[see flavored variant in Crispim Romão, Castro, Milhano, Pedro, Vale, arXiv 2020]
[see computational speed up in Cai, Cheng, Craig, Craig, arXiv 2020]

Similarity of Three Energy Flows?

[Chu, MIT News July 2019]

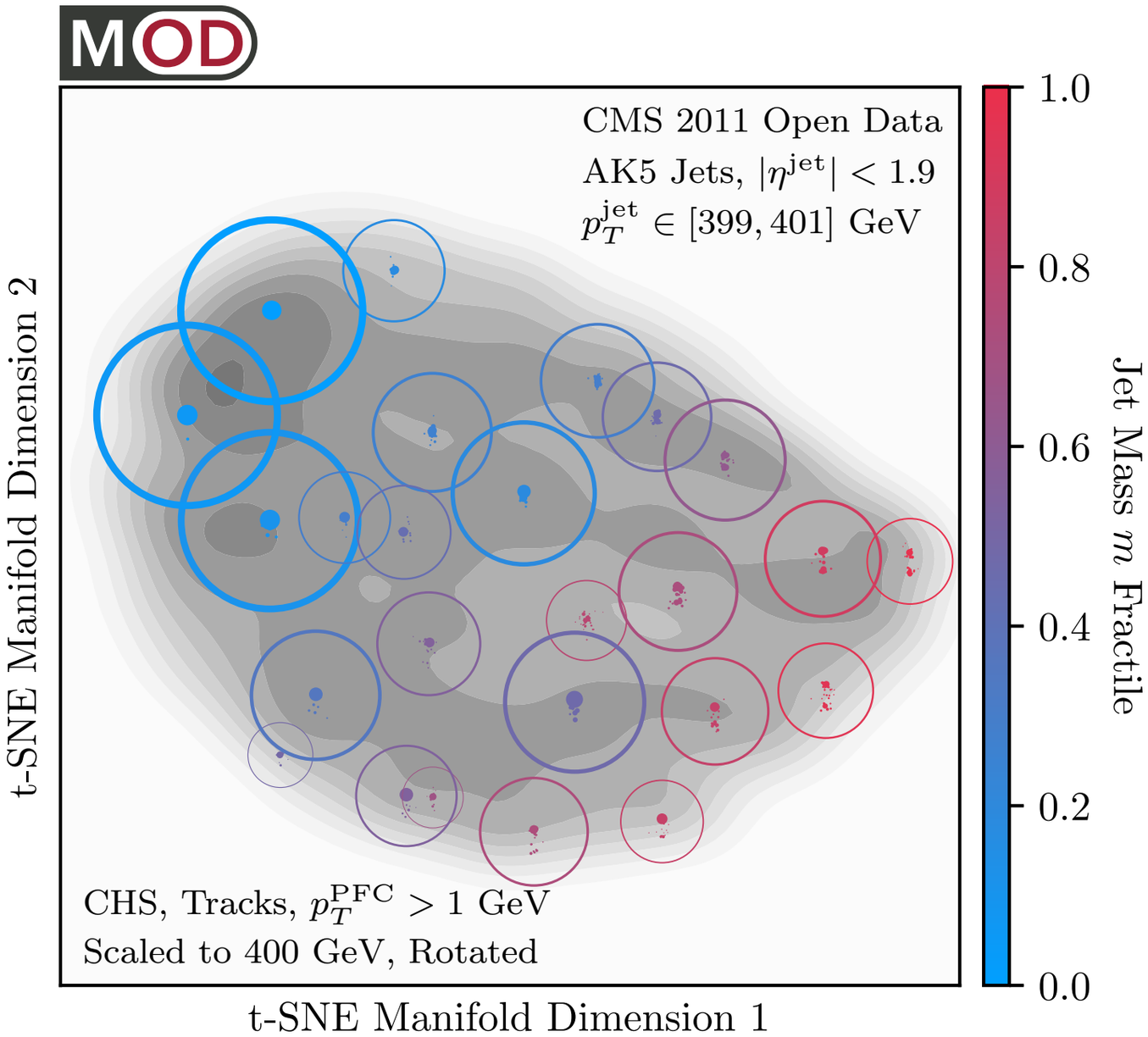


[Komiske, Metodiev, JDT, PRL 2019; code at Komiske, Metodiev, JDT, energyflow.network; see alternative graph network approach in Mullin, Pacey, Parker, White, Williams, arXiv 2019]

What can you do with a metric?

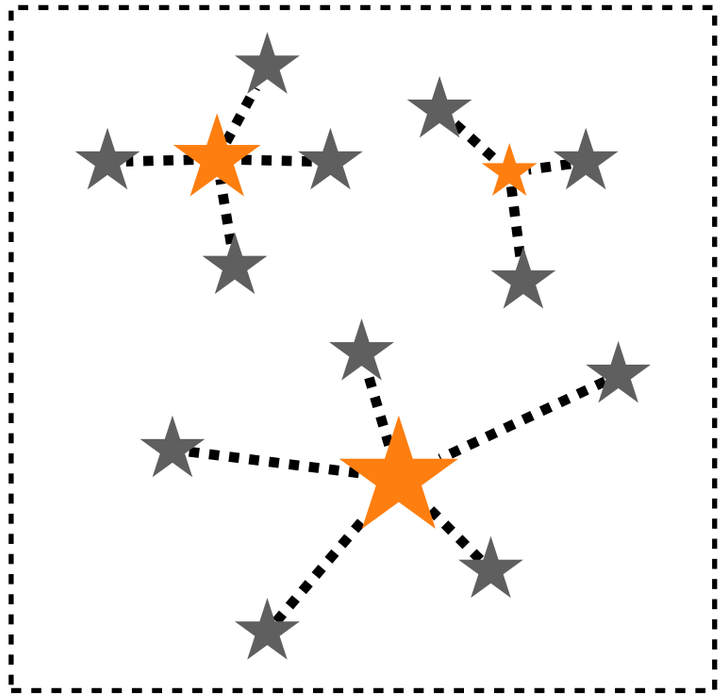
Most Representative Jets

[http://opendata.cern.ch/]



k-medoids

Arranged via t-SNE



[Komiske, Mastandrea, Metodiev, Naik, JDT, PRD 2020; using van der Maaten, Hinton, JMLR 2008]

Most Representative Jets

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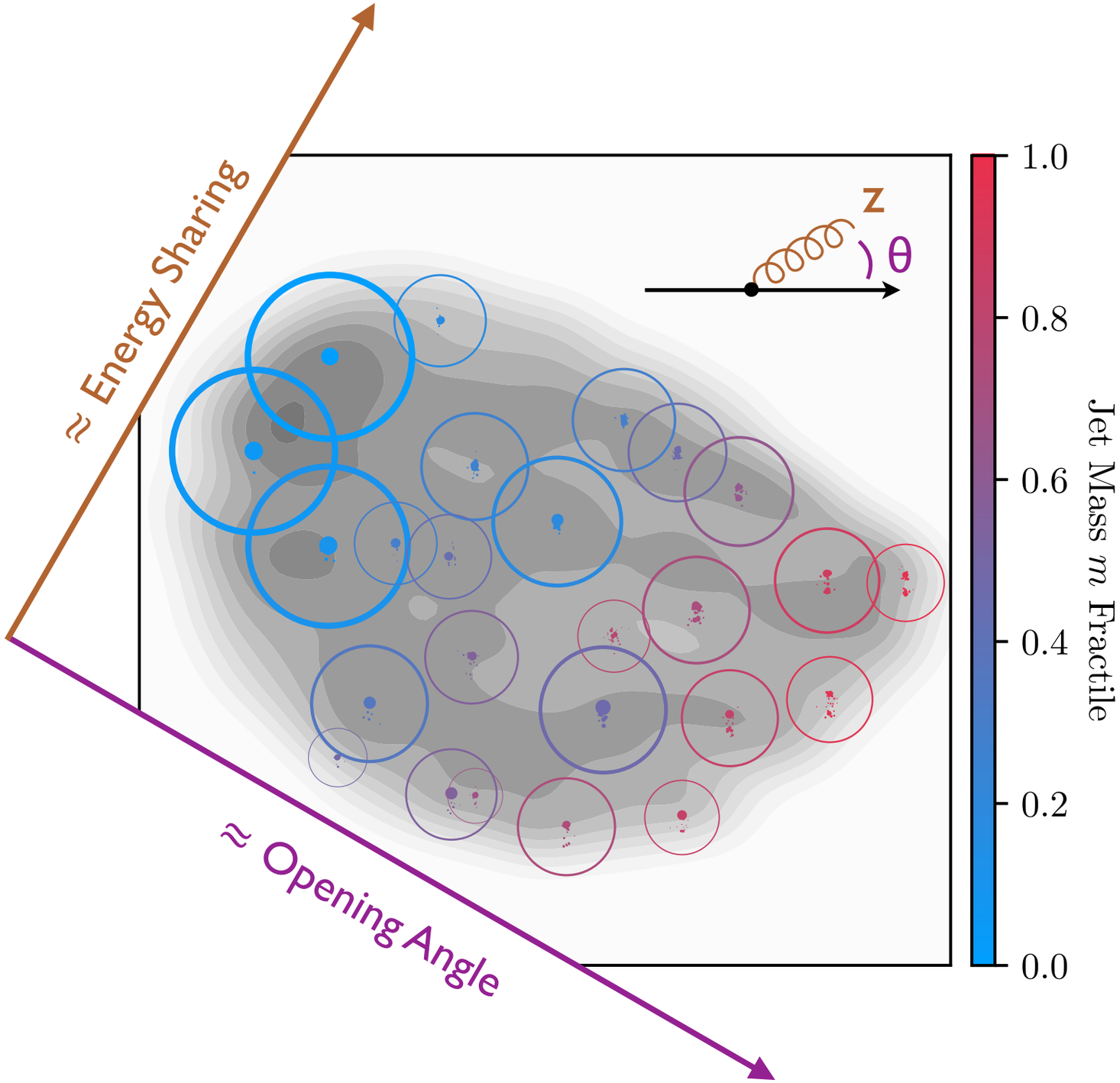

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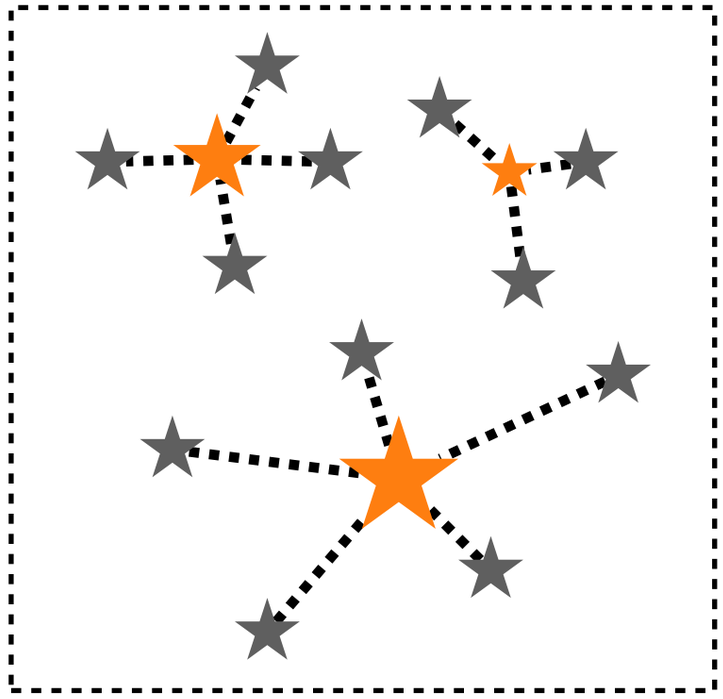
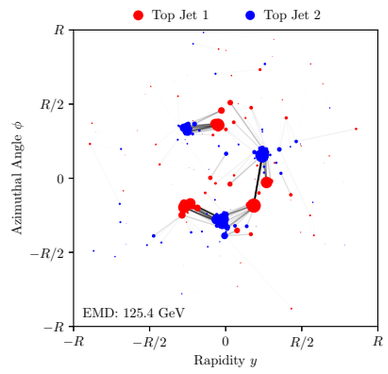


[Komiske, Mastandrea, Metodiev, Naik, JDT, PRD 2020; using van der Maaten, Hinton, JMLR 2008]

Pause

When are Events Similar?



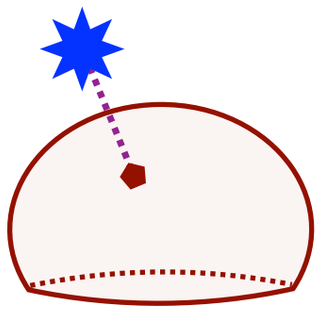
Small Energy Mover's Distance

$$\mathrm{EMD}(\mathcal{E}, \mathcal{E}') = \min_{\{f\}} \sum_i \sum_j f_{ij} \frac{\theta_{ij}}{R} + \left| \sum_i E_i - \sum_j E'_j \right|$$

(see backup for more applications)

What is a Collider Event?

When are Events Similar?

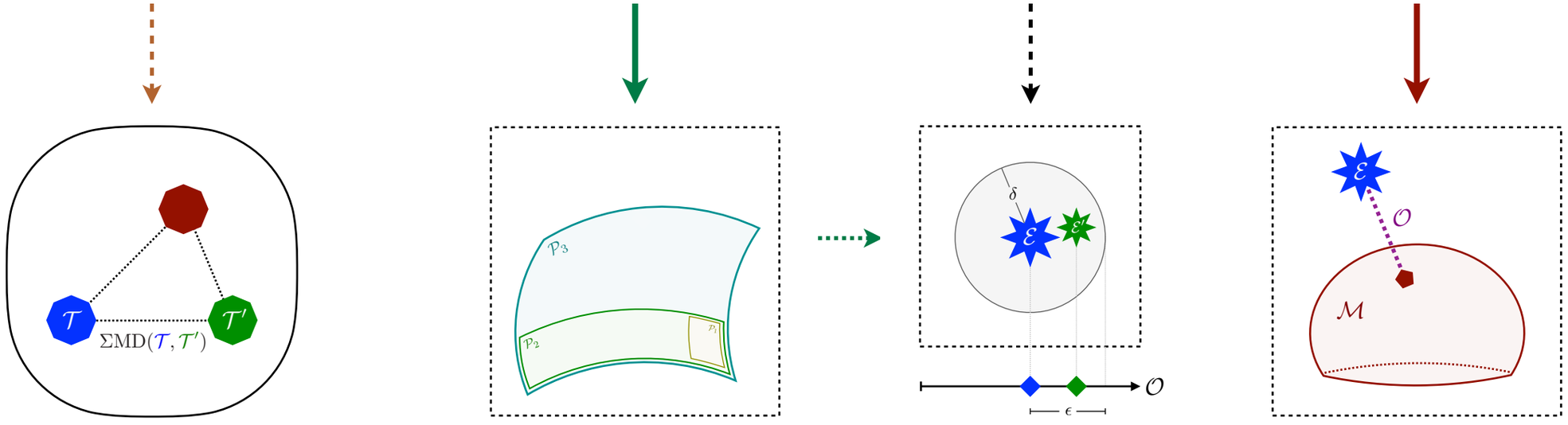


What can be Geometrized?

Master Formula for Collider Physics

$$\sigma_{\text{obs}} \simeq \frac{1}{2E_{\text{CM}}^2} \sum_{n=2}^{\infty} \int \mathrm{d}\Phi_n \, |\mathcal{M}_{AB\to 12\ldots n}|^2 \, f_{\text{obs}}(\Phi_n)$$

cross section | phase space | amplitude | observable

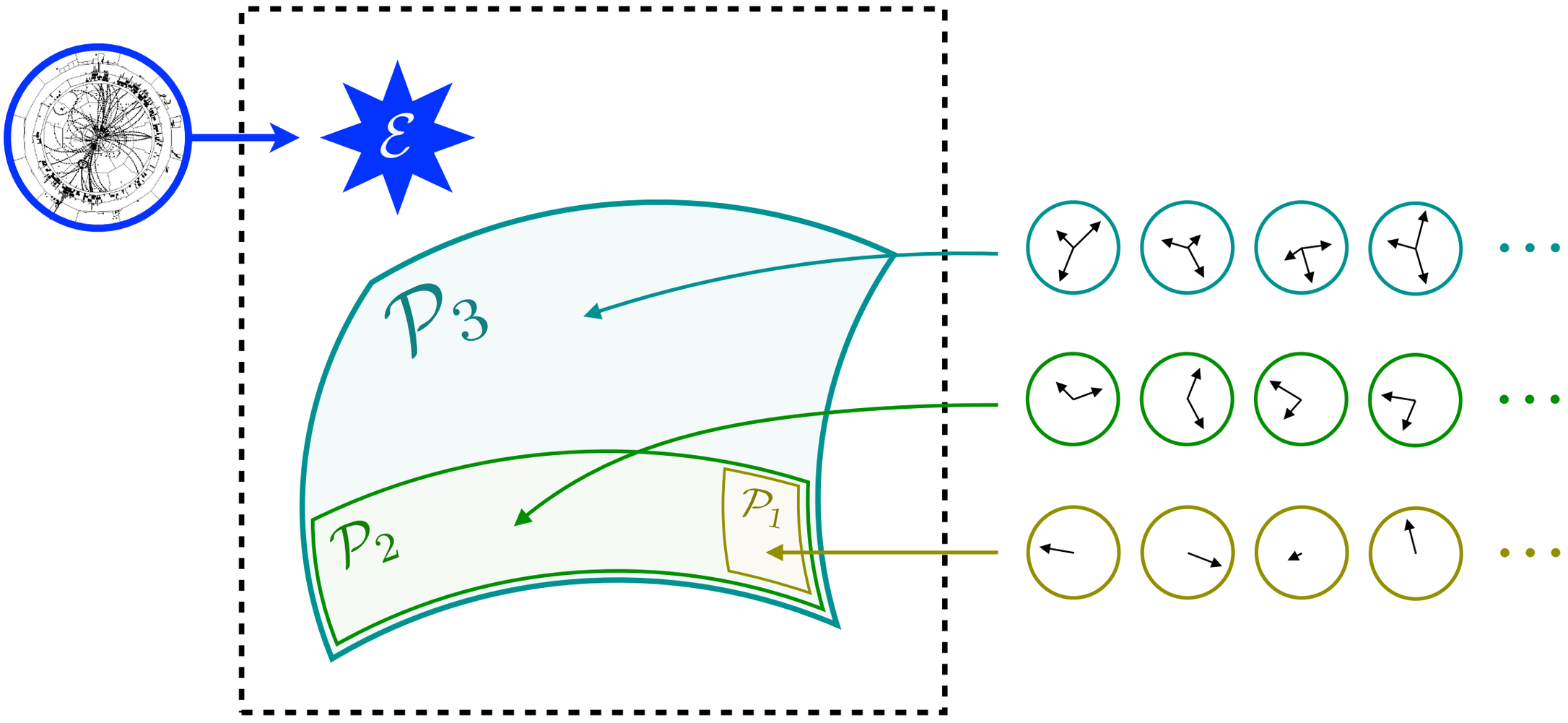


[Komiske, Metodiev, JDT, JHEP 2020]

Introducing N-particle Manifolds

$$\sum_{n=2}^{\infty} \int \mathrm{d}\Phi_n$$

$\mathcal{P}_N$ = set of all N-particle configurations

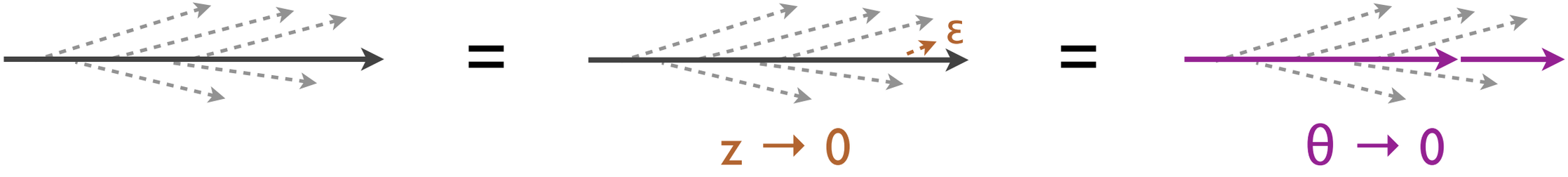


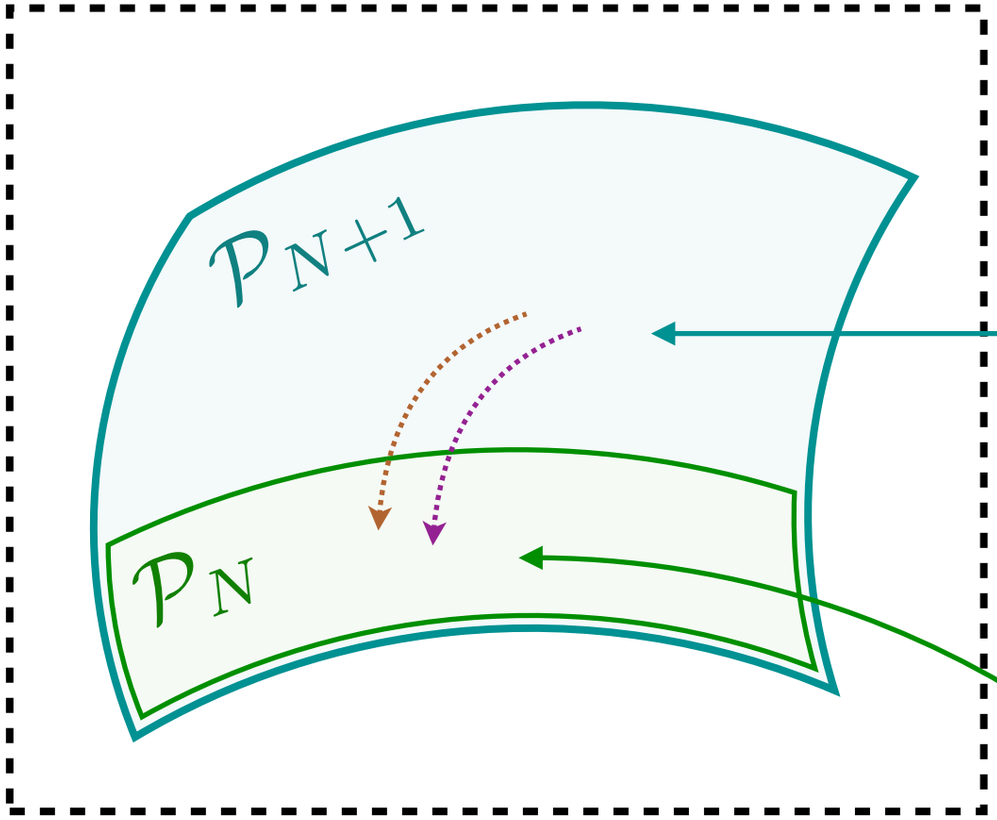
$\mathcal{P}_N \supset \mathcal{P}_{N-1} \supset \ldots \supset \mathcal{P}_2 \supset \mathcal{P}_1$ by soft/collinear limits

When are Two Events the Same?

$$\mathcal{E}(\hat{n}) = \sum_i E_i \, \delta(\hat{n} - \hat{n}_i)$$

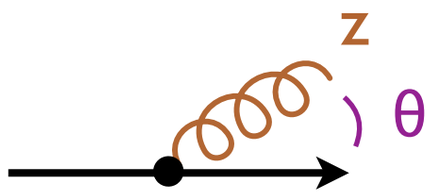
Energy Flow unchanged by infinitesimal soft/collinear emissions





Infrared divergences "live" together!

Real:

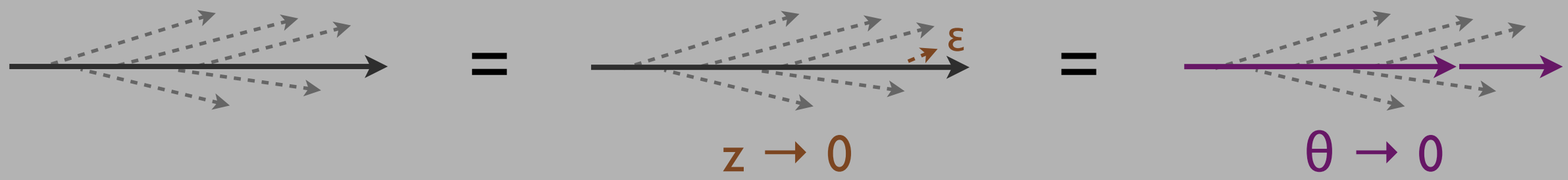


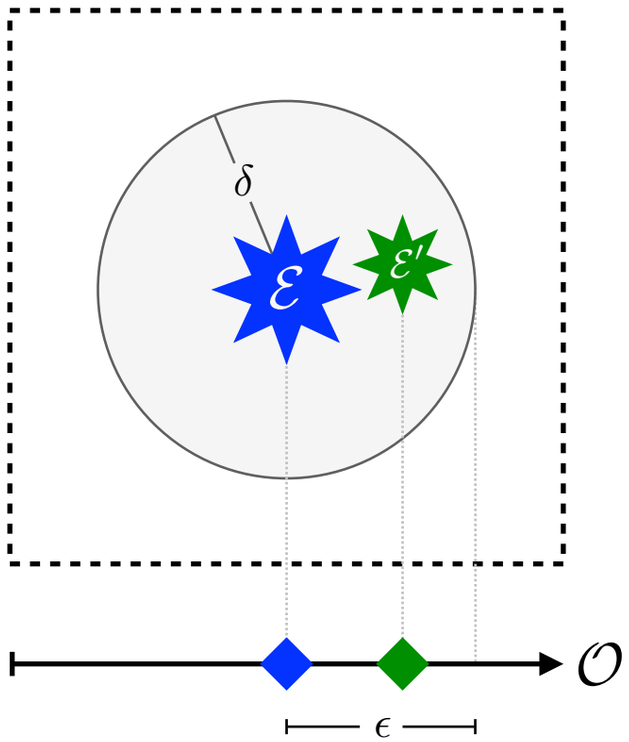
$$\mathrm{d}P_{i\to ig} \simeq \frac{2\alpha_s}{\pi} C_i \, \frac{\mathrm{d}z}{z} \, \frac{\mathrm{d}\theta}{\theta}$$

Virtual:

When are Two Events the Same?

Energy Flow unchanged by infinitesimal soft/collinear emissions





Infrared & Collinear Safety

≈ calculable in perturbative quantum field theory

*is**

Continuity in EMD Space

[Komiske, Metodiev, JDT, JHEP 2020]
[Sterman, Weinberg, PRL 1977; Sterman, PRD 1979]
[see also Banfi, Salam, Zanderighi, JHEP 2005]

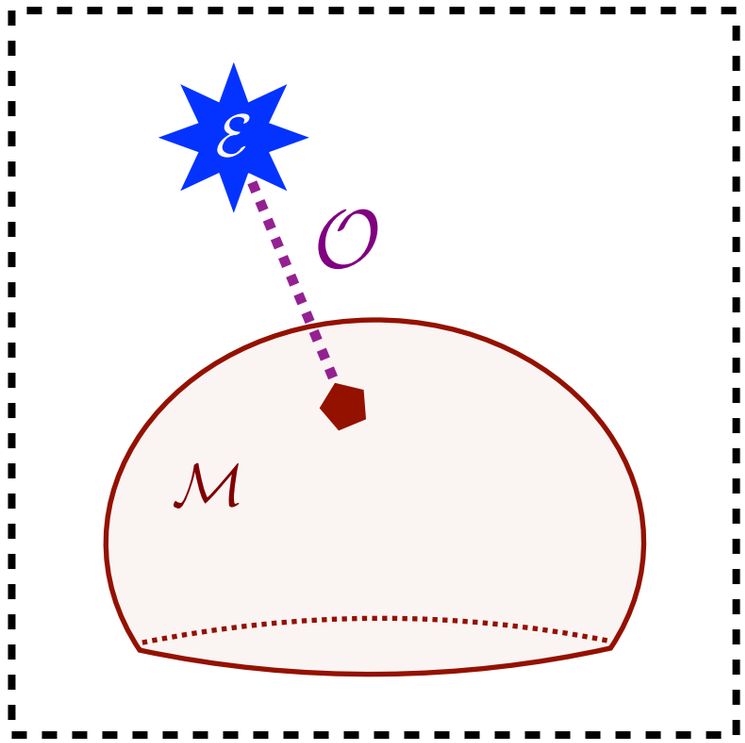
EMD seems to define the "natural" geometry for massless gauge theories

Open question: Can you define $\left|\mathcal{M}_{AB\to 12\ldots n}\right|^2$ directly in this space?

Manifolds for Observables

$f_{\text{obs}}(\Phi_n)$

One Event



Set of Events

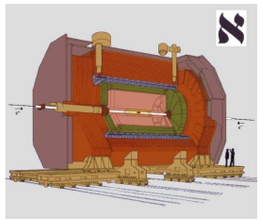
Distance of Closest Approach ⇒ Observable

$$\mathcal{O}(\mathcal{E}) = \min_{\mathcal{E}' \in \mathcal{M}} \text{EMD}(\mathcal{E}, \mathcal{E}')$$

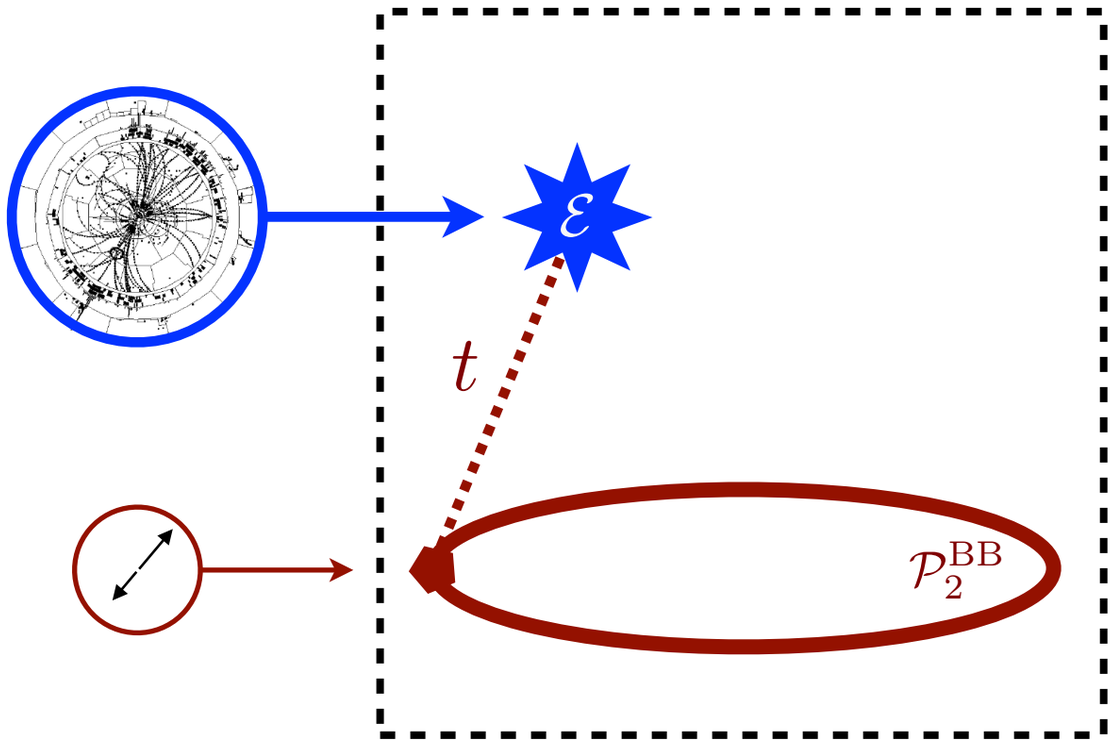
[Komiske, Metodiev, JDT, JHEP 2020]

E.g. Thrust

How dijet-like is an event?



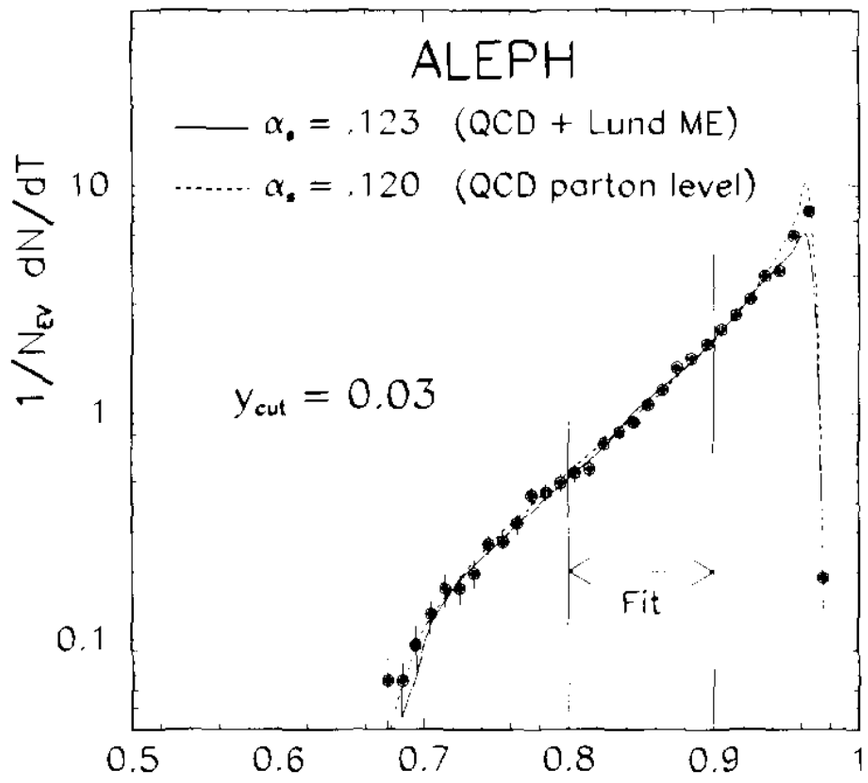
$$t(\mathcal{E}) = \min_{\mathcal{E}' \in \mathcal{P}_2^{\text{BB}}} \text{EMD}_2(\mathcal{E}, \mathcal{E}')$$



All Back-to-Back Two Particle Configurations

$$\mathcal{P}_2^{\text{BB}} = \left\{ \quad \cdots \right\}$$

(using β=2 EMD variant)



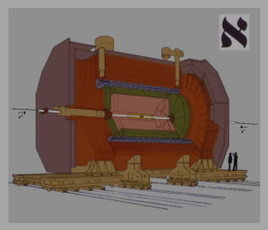
$$1 - \frac{t}{2E_{\text{CM}}}$$

cf. $T(\mathcal{E}) = \max_{\hat{n}} \frac{\sum_i |\vec{p}_i \cdot \hat{n}|}{\sum_j |\vec{p}_j|}$

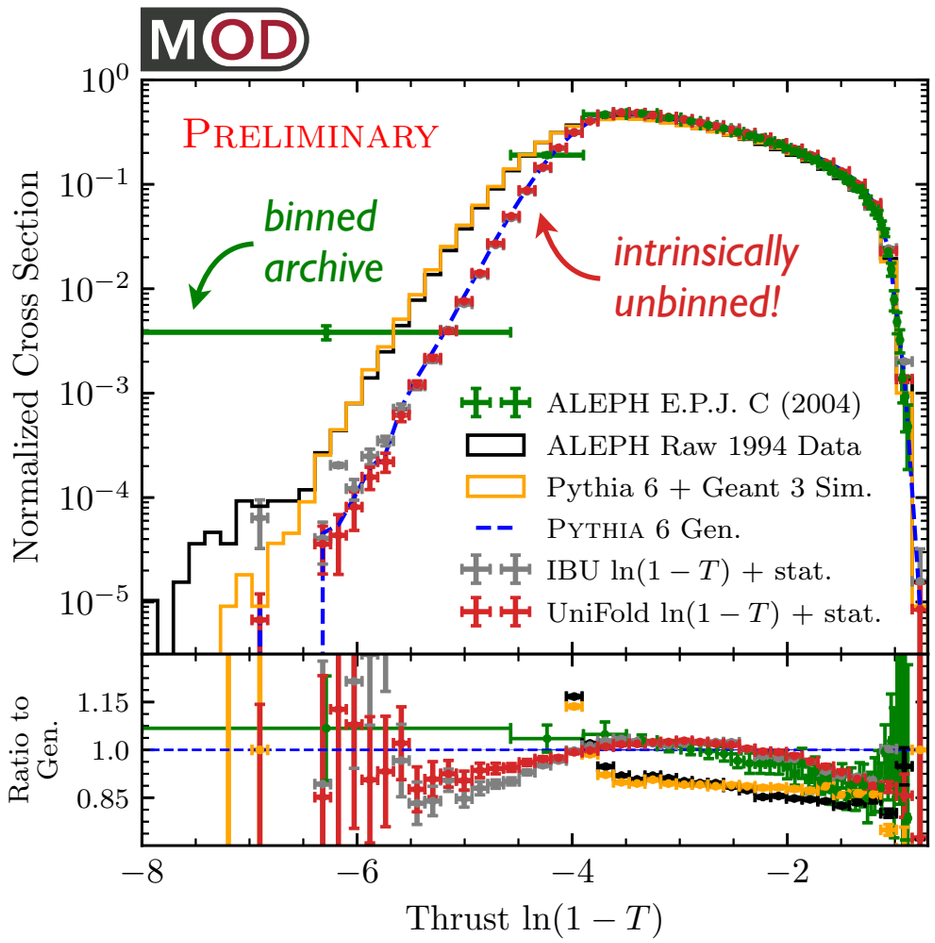
[Komiske, Metodiev, JDT, JHEP 2020]
[Brandt, Peyrou, Sosnowski, Wroblewski, PL 1964; Farhi, PRL 1977; ALEPH, PLB 1991]

E.g. Thrust

How dijet-like is an event?



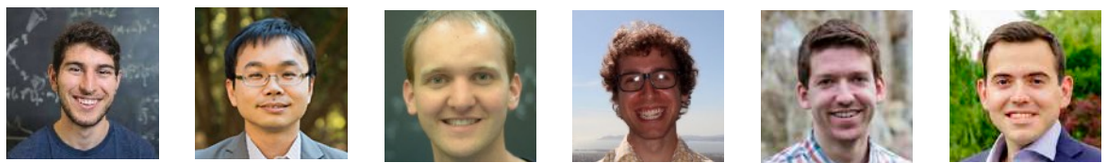
Back to the Future with ALEPH Archival Data



OmniFold

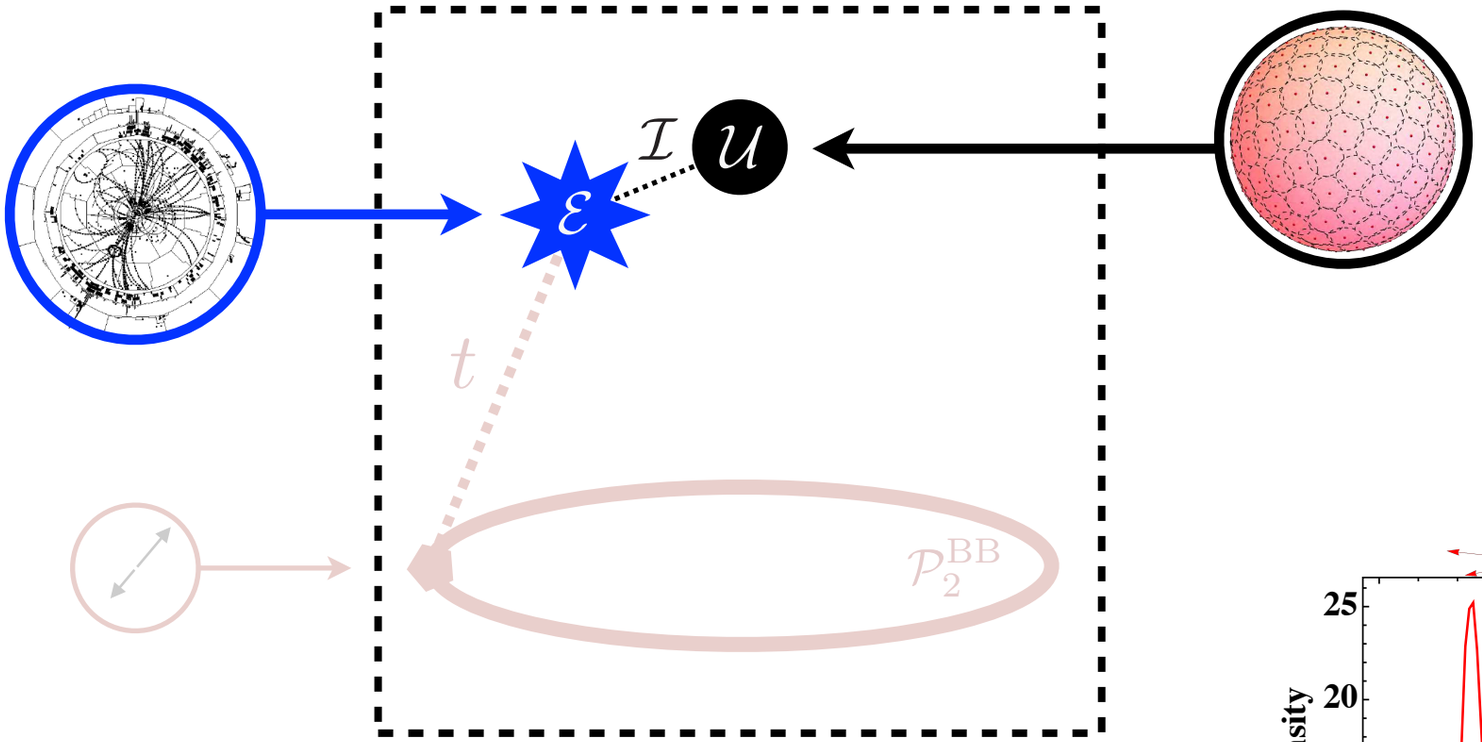
Multi-dimensional unbinned
detector corrections
via machine learning

[talk by Badea, ICHEP 2020; cf. ALEPH, EPJC 2004]
[using Andreassen, Komiske, Metodiev, Nachman, JDT, PRL 2020]
[see Badea, Baty, Chang, Innocenti, Maggi, McGinn, Peters, Sheng, JDT, Lee, PRL 2019]

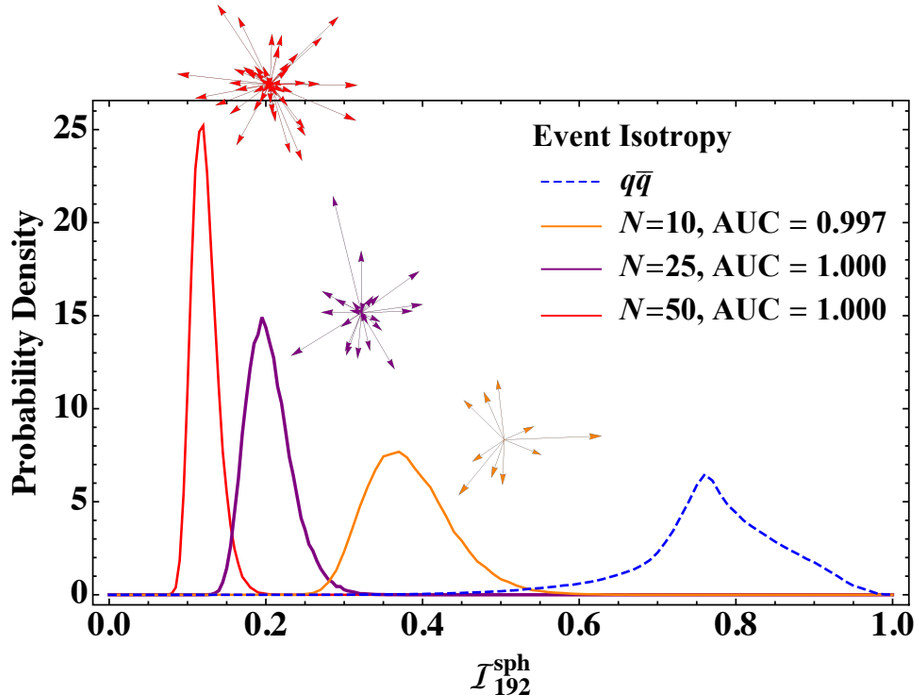


New! Event Isotropy

How isotropic is an event?



$$\mathcal{I}(\mathcal{E}) = \mathrm{EMD}(\mathcal{E},\mathcal{U})$$

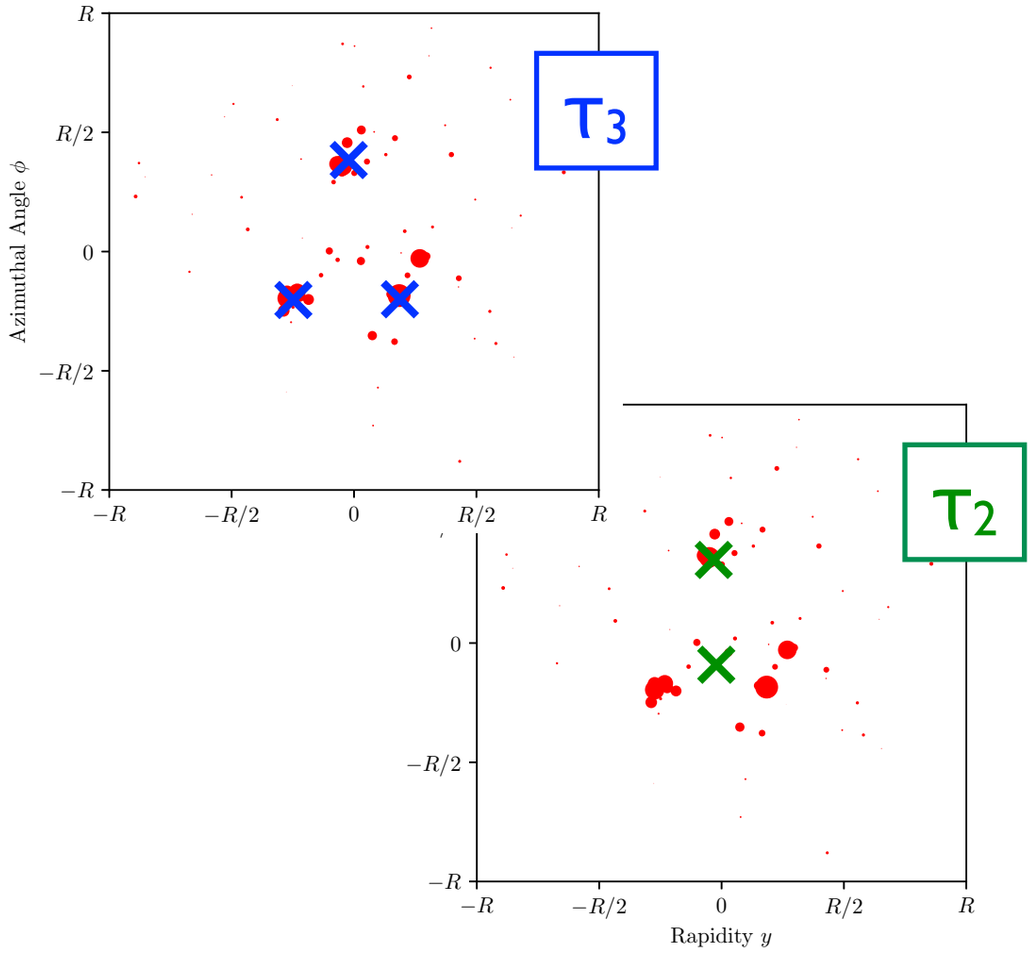


[Cesarotti, JDT, JHEP 2020;
see also Cesarotti, Reece, Strassler, arXiv 2020]

N-subjettiness

Ubiquitous jet substructure observable used for almost a decade…

$$\tau_N(\mathcal{J}) = \min_{N \text{ axes}} \sum_i E_i \min\{\theta_{1,i}, \theta_{2,i}, \ldots, \theta_{N,i}\}$$

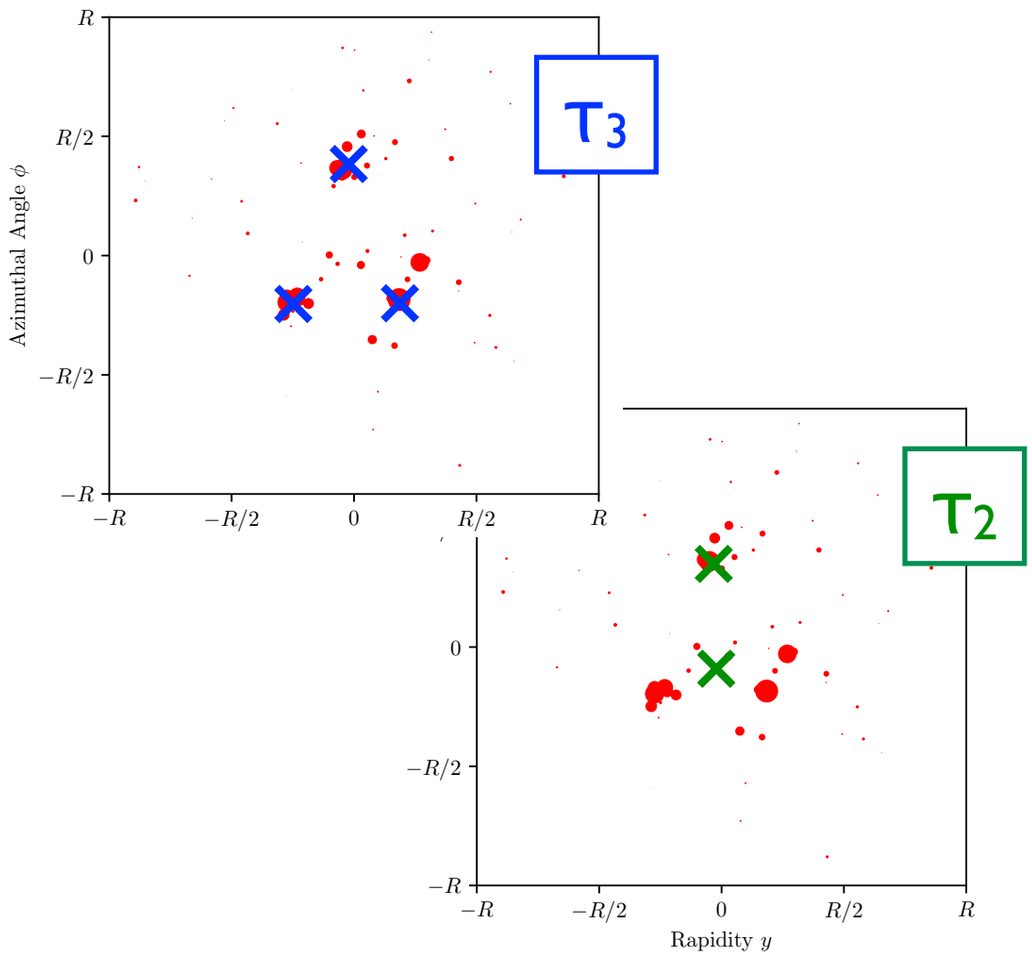


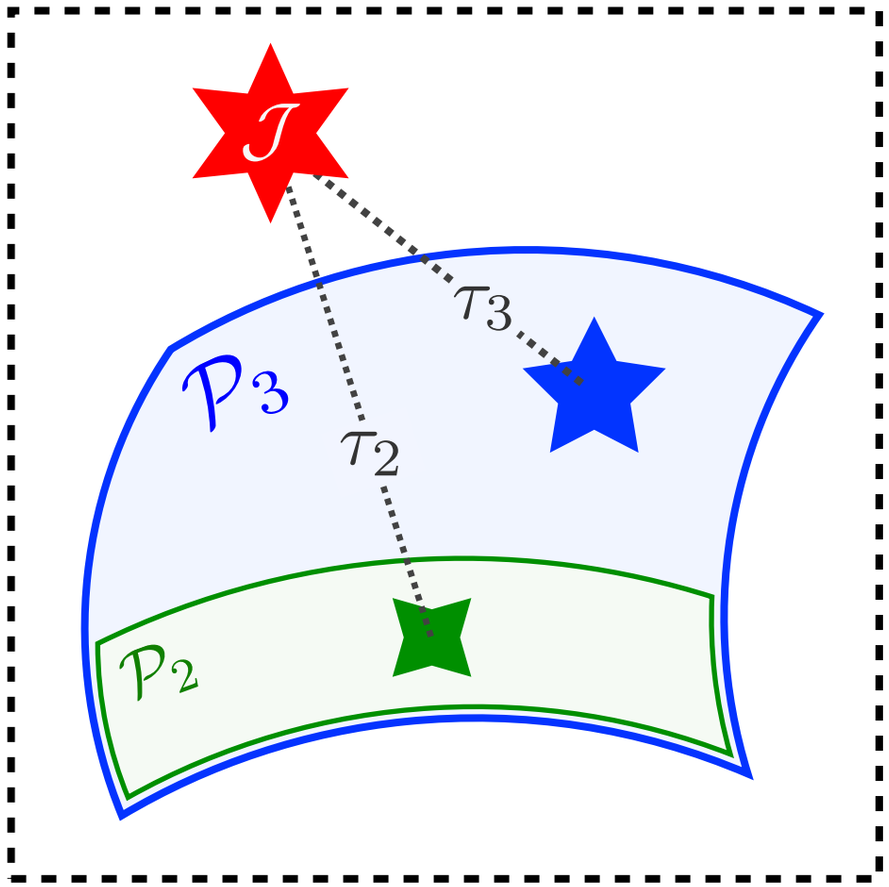
[JDT, Van Tilburg, JHEP 2011, JHEP 2012;
based on Brandt, Dahmen, ZPC 1979; Stewart, Tackmann, Waalewijn, PRL 2010]

N-subjettiness = Point to Manifold EMD

…is secretly an optimal transport problem

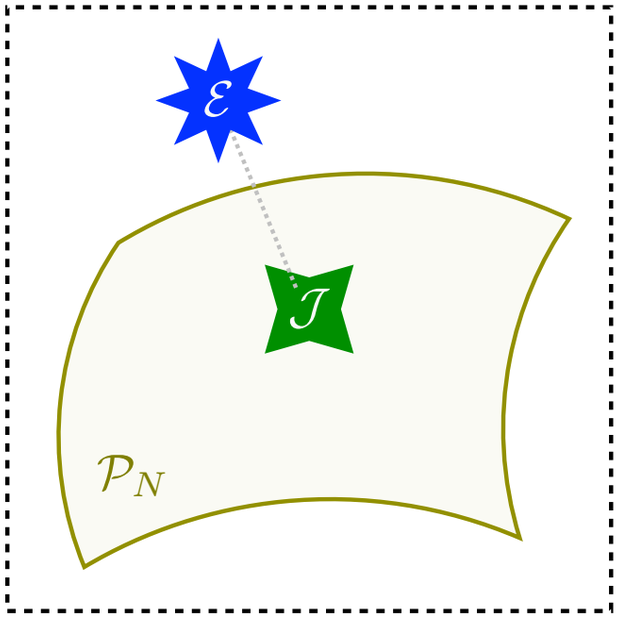
$$\tau_N(\mathcal{J}) = \min_{\mathcal{J}' \in \mathcal{P}_N} \mathrm{EMD}(\mathcal{J}, \mathcal{J}')$$





[JDT, Van Tilburg, JHEP 2011, JHEP 2012;
rephrased in the language of Komiske, Metodiev, JDT, PRL 2019]

More Fun with N-particle Manifolds



N-jettiness

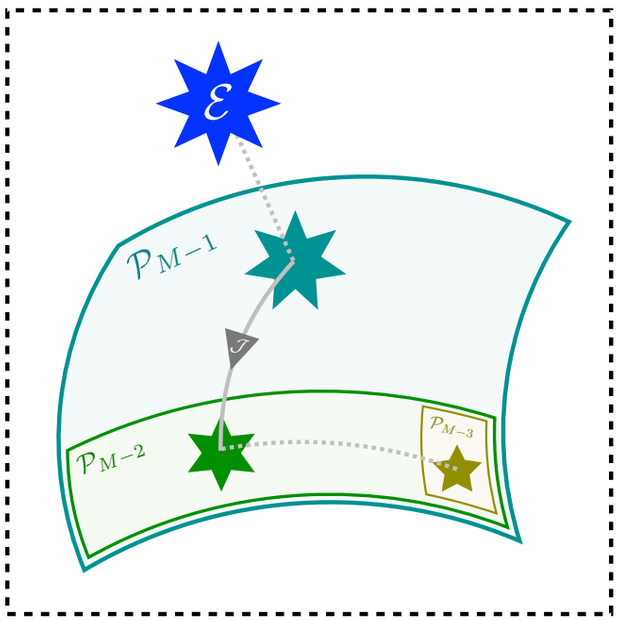
Distance of closest approach to N-particle manifold

[Brandt, Dahmen, ZPC 1979; Stewart, Tackmann, Waalewijn, PRL 2010]

Exclusive Cone Jet Finding

Point of closest approach on N-particle manifold

[Stewart, Tackmann, JDT, Vermilion, Wilkason, JHEP 2015]



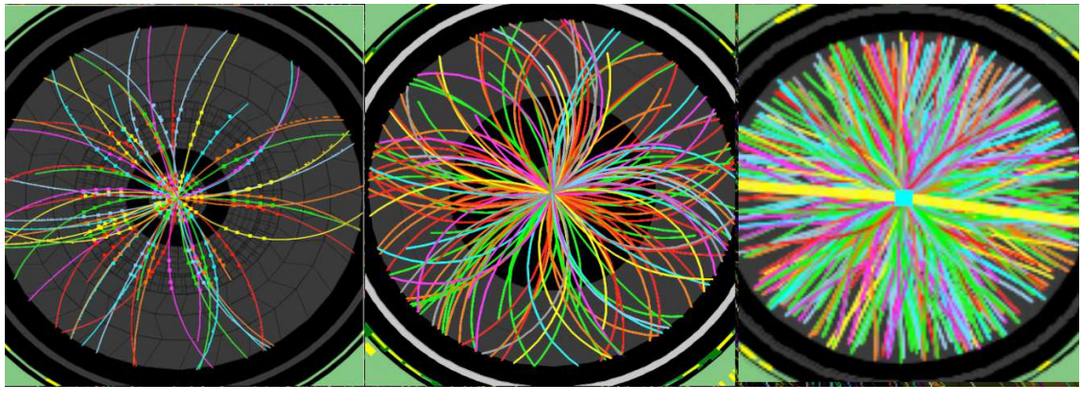
Sequential Jet Recombination

Iteratively stepping between various N-particle manifolds

[Catani, Dokshitzer, Seymour, Webber, NPB 1993; Ellis, Soper, PRD 1993]
[Dokshitzer, Leder, Moretti, Webber, JHEP 1997; Wobisch, Wengler, arXiv 1999]
[Butterworth, Couchman, Cox, Waugh, CPC 2003; Larkoski, Neill, JDT, JHEP 2014]

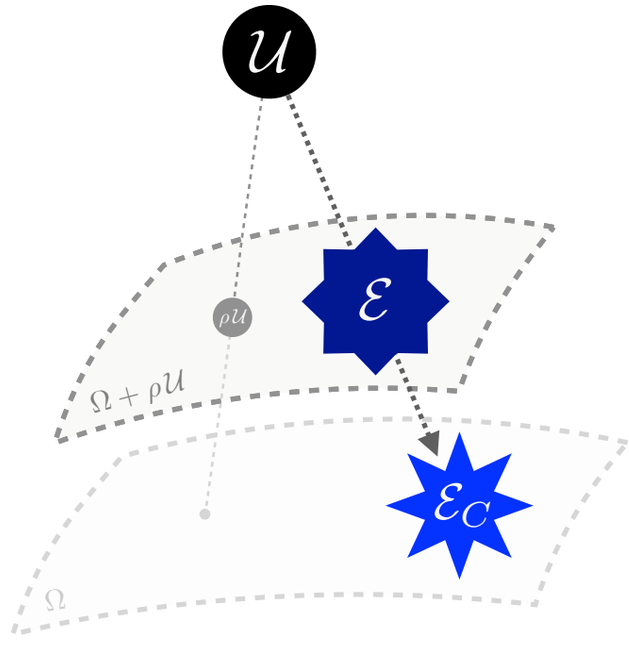
[Komiske, Metodiev, JDT, JHEP 2020]

Pileup Mitigation



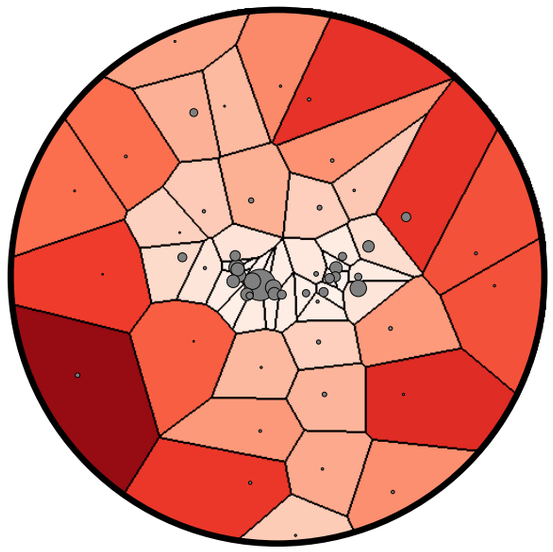
[see review in Soyez, PR 2019]

Uniform event contamination from overlapping proton-proton collisions



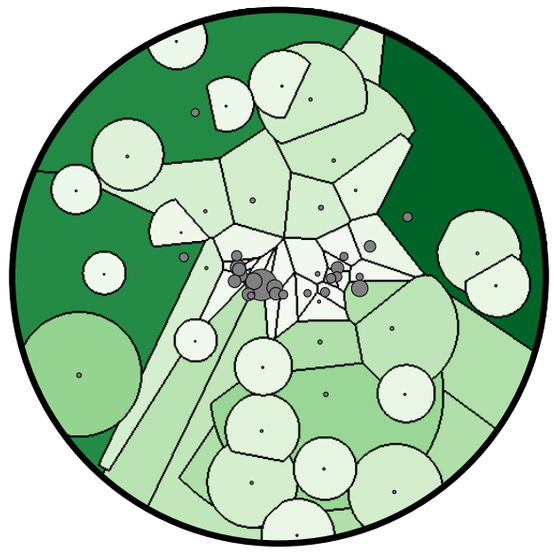
Pileup Mitigation:
"Move away" from uniform event

Voronoi



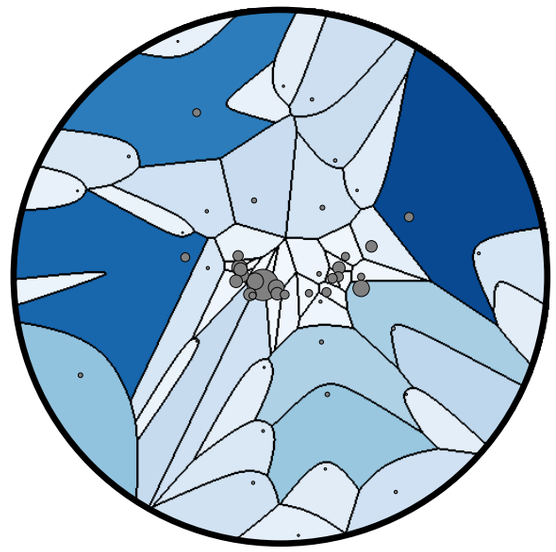
[Cacciari, Salam, Soyez, JHEP 2008]

Constituent Subtraction



[Berta, Spousta, Miller, Leitner, JHEP 2014]

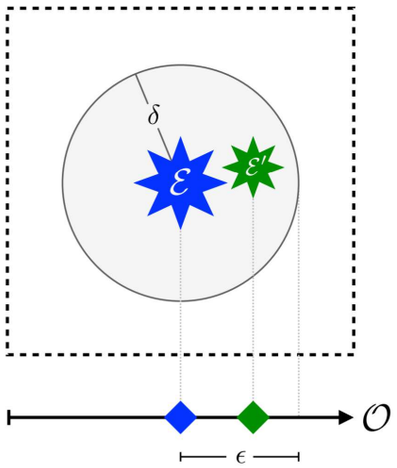
Apollonius



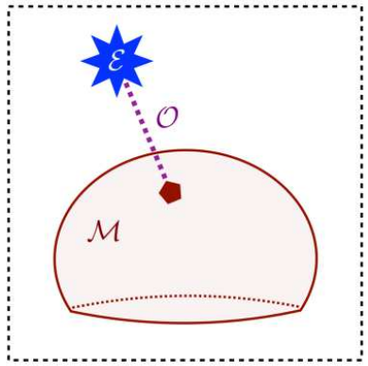
[Komiske, Metodiev, JDT, JHEP 2020]

Six Decades of Collider Physics Translated into a New Geometric Language!

IRC Safety is smoothness in the space of events

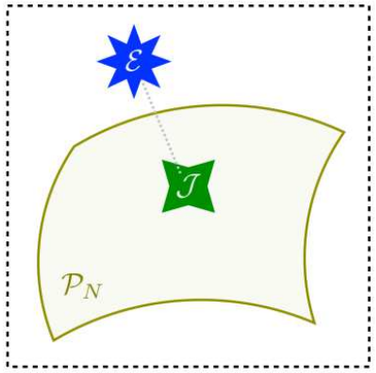


Event shapes are distances from events to manifolds.



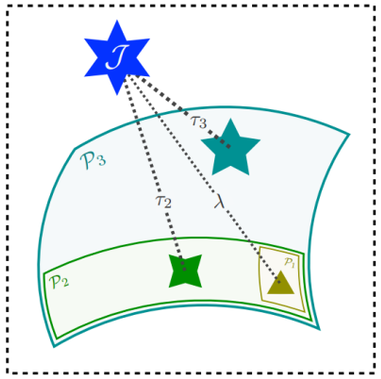
$$\mathcal{O}(\mathcal{E}) = \min_{\mathcal{E}' \in \mathcal{M}} \mathrm{EMD}_{\beta,R}(\mathcal{E}, \mathcal{E}')$$

Jets are projections to few-particle manifolds.



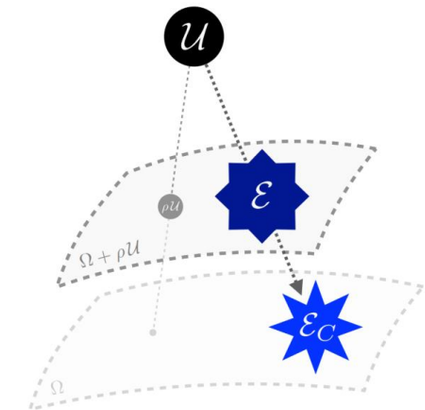
$$\mathcal{J} = \operatorname*{argmin}_{\mathcal{E}' \in \mathcal{P}_N} \mathrm{EMD}_{\beta,R}(\mathcal{E}, \mathcal{E}')$$

Substructure resolves emissions within the jet.



$$\tau(\mathcal{J}) = \min_{\mathcal{E}' \in \mathcal{P}_N} \mathrm{EMD}_{\beta}(\mathcal{J}, \mathcal{E}').$$

Pileup mitigation moves away from uniform radiation.



$$\mathcal{E}_C = \arg\min_{\mathcal{E}'} \mathrm{EMD}(\mathcal{E}, \mathcal{E}' + \rho\,\mathcal{U})\,.$$

Taming infinities

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

Event Shapes

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

Jet Algorithms

1993
k_T jet clustering
[Ellis, Soper, PRD 1993]
[Catani, Dokshitzer, Seymour, Webber, NPB 1993]

1997-1998
C/A jet clustering
[Wobisch, Wengler, 1998]
[Doskhitzer, Leder, Moretti,Webber, JHEP 1997]

Jet Substructure

2010-2015
N-(sub)jettiness, XCone
[Stewart, Tackmann, Waalewijn, PRL 2010]
[Thaler, Van Tilburg, JHEP 2011]
[Stewart, Tackmann, Thaler, Vermilion, Wilkason, JHEP 2015]

Pileup

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

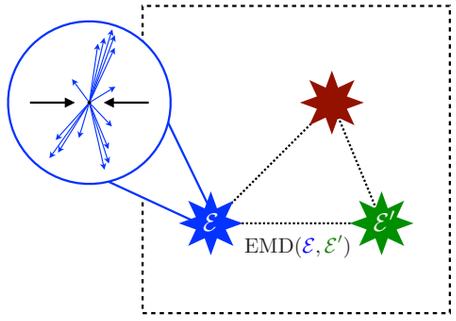
1960 — 2020

And many more!

[timeline from Eric Metodiev]

Pause

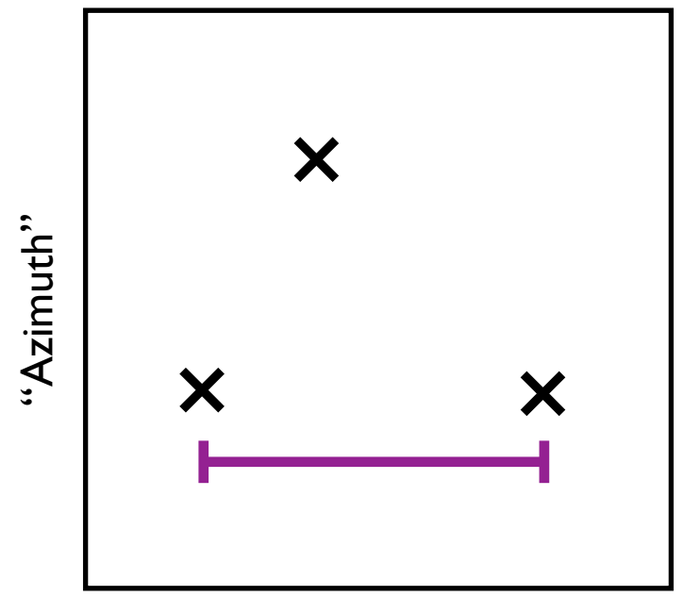
What can be Geometrized?



IRC Safety, Observables,
Jet Algorithms, Pileup Mitigation

How far down does this rabbit hole go?

Direction Space



× = Direction

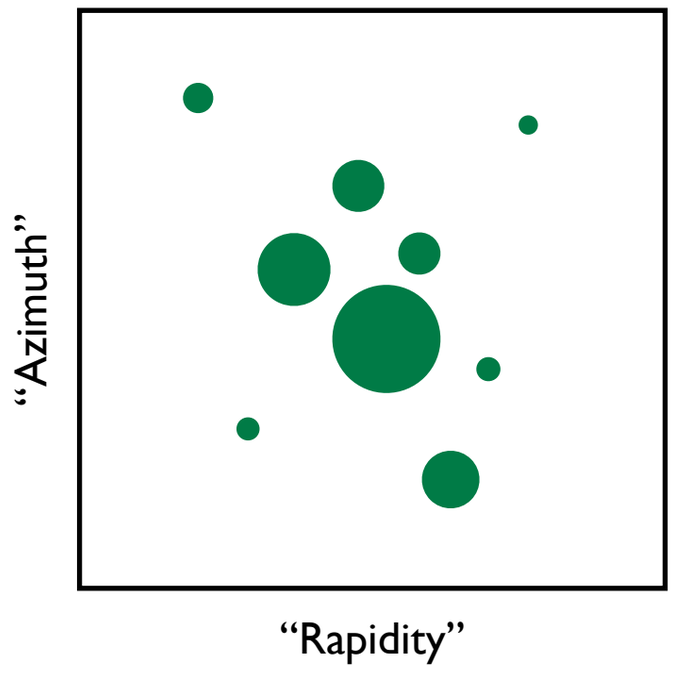
$$n_i^\mu = \frac{p_i^\mu}{E_i} = (1, \hat{n})^\mu$$

⟷ = Angular Distance

$$\theta_{ij} = \sqrt{2 n_i^\mu n_{j\mu}}$$

(for massless particles)

Direction Space Distribution



= Weighted Direction

$$n_i^\mu = \frac{p_i^\mu}{E_i} = (1, \hat{n})^\mu$$

$$w_i = E_i$$

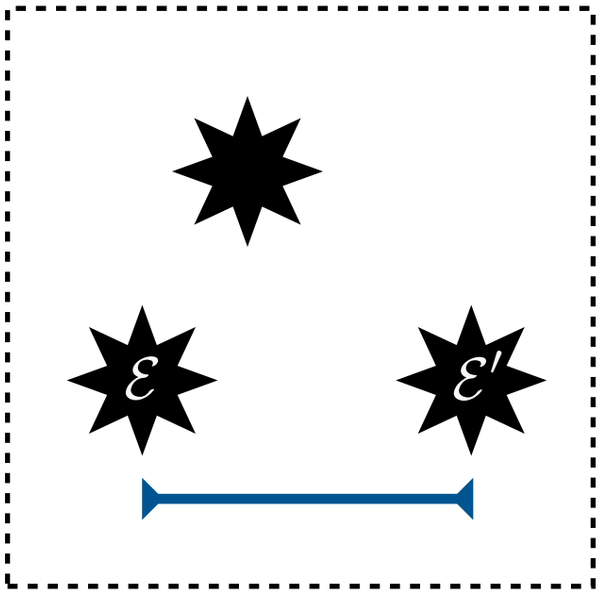
= Angular Distance

$$\theta_{ij} = \sqrt{2 n_i^\mu n_{j\mu}}$$

(for massless particles)

= Event

Event Space



= Event

$$\mathcal{E}(\hat{n}) = \sum_i E_i \, \delta(\hat{n} - \hat{n}_i)$$

= EMD

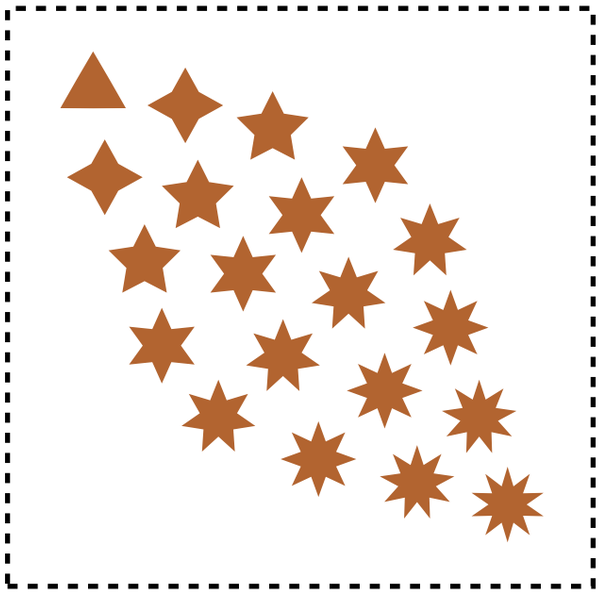
Energy
Mover's Distance

$$\mathrm{EMD}(\mathcal{E}, \mathcal{E}') = \min_{\{f\}} \sum_i \sum_j f_{ij} \theta_{ij}$$

(for equal total energy)

[Komiske, Metodiev, JDT, PRL 2019]

Event Space Distribution



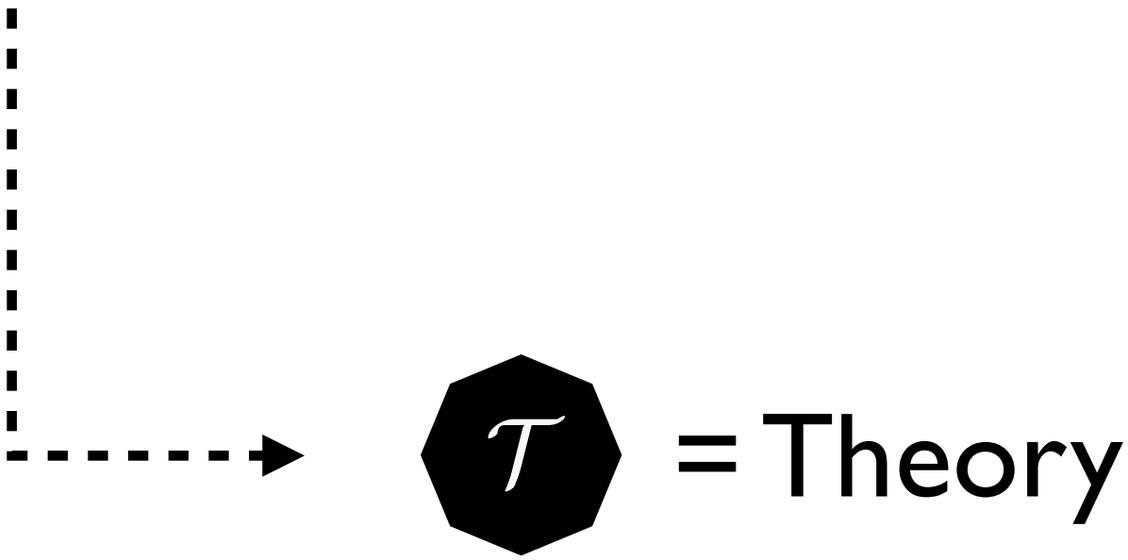
= Weighted Event $\quad \mathcal{E}(\hat{n}) = \sum_i E_i \, \delta(\hat{n} - \hat{n}_i)$

$w_a = \sigma_a$

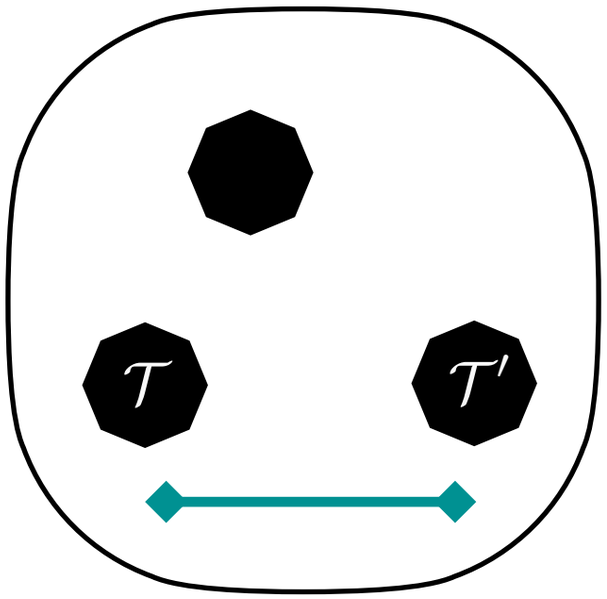
= EMD $\quad \mathrm{EMD}(\mathcal{E}, \mathcal{E}') = \min_{\{f\}} \sum_i \sum_j f_{ij} \theta_{ij}$

Energy
Mover's Distance

(for equal total energy)



Theory Space



= Theory $\quad \mathcal{T}(\mathcal{E}) = \sum_a \sigma_a \, \delta(\mathcal{E} - \mathcal{E}_a)$

= ΣMD $\quad \Sigma\mathrm{MD}(\mathcal{T}, \mathcal{T}') = \min_{\{\mathcal{F}\}} \sum_a \sum_b \mathcal{F}_{ab} \mathrm{EMD}(\mathcal{E}_a, \mathcal{E}'_b)$

Cross-Section Mover's Distance

(for equal total xsec)

A distance between theories!

(e.g. EMD : N-jettiness :: ΣMD : k-eventiness)

[Komiske, Metodiev, JDT, JHEP 2020]

CMS Experiment at LHC, CERN
Data recorded: Wed Nov 25 12:21:51 2015 CET
Run/Event: 262548 / 14582169
Lumi section: 309

jet

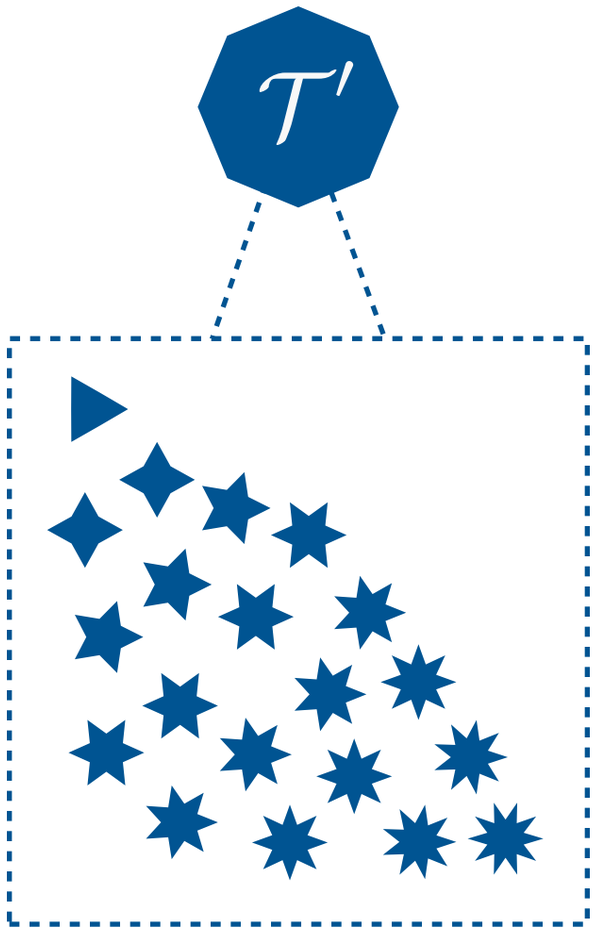
Pb

QGP

Pb

quenched jet

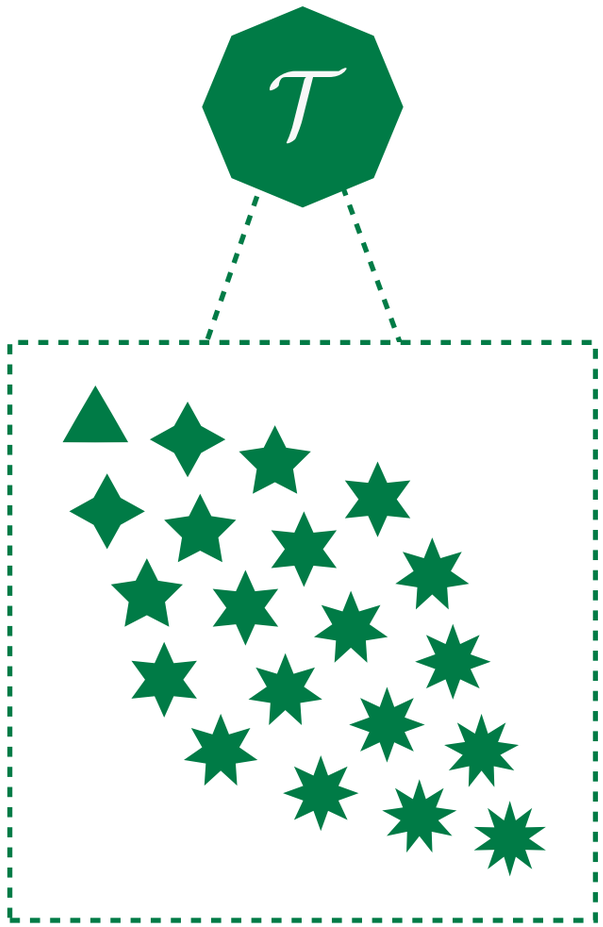
Theory Prime:
In-Medium QCD



ΣMD

⇔

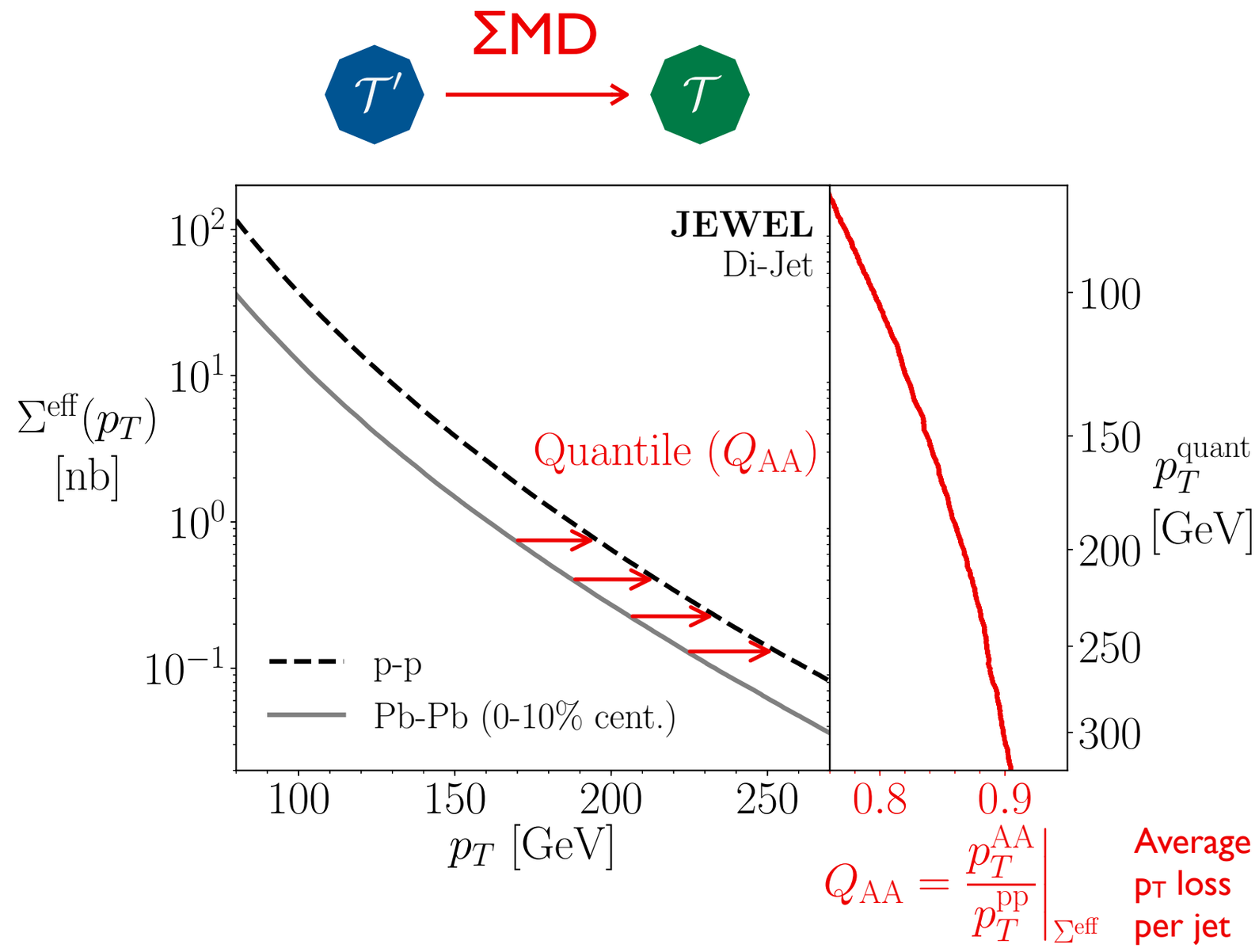
Theory:
Vacuum QCD



Optimal transportation plan defines mapping between in-medium jets and vacuum jets!

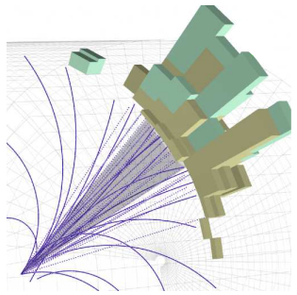
Jet Quenching via Quantile Matching

Equivalent to following a geodesic in theory space (!)



[Brewer, Milhano, JDT, PRL 2019]

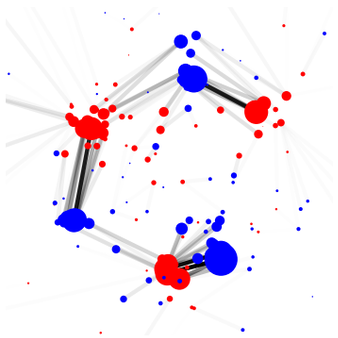
Summary



What is a Collider Event?

An unordered set of particles that describes the energy flow away from the collision point

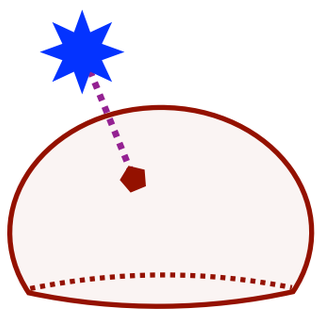
(ask me about ML & QCD)



When are Events Similar?

When they are close in the geometric space triangulated by the energy mover's distance

(ask me more about EMD)



What can be Geometrized?

Many concepts/techniques in quantum field theory and collider physics from the last half century

Fin

Backup Slides

Point Cloud

Collection of points in position space

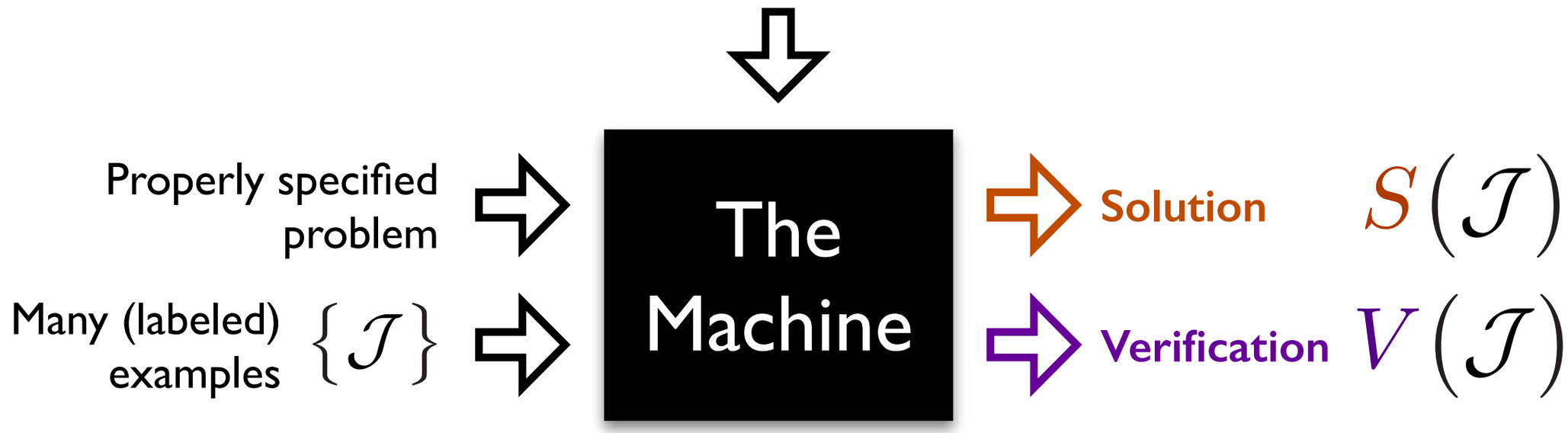
[Popular Science, 2013]

Aside: Machine Learning for Jets

Symmetry: $\mathcal{J} = \{\underbrace{\vec{p}_1, \vec{p}_2, \vec{p}_3, \ldots, \vec{p}_N}_{\text{Unordered, Variable Length Set (QM!)}}\}$

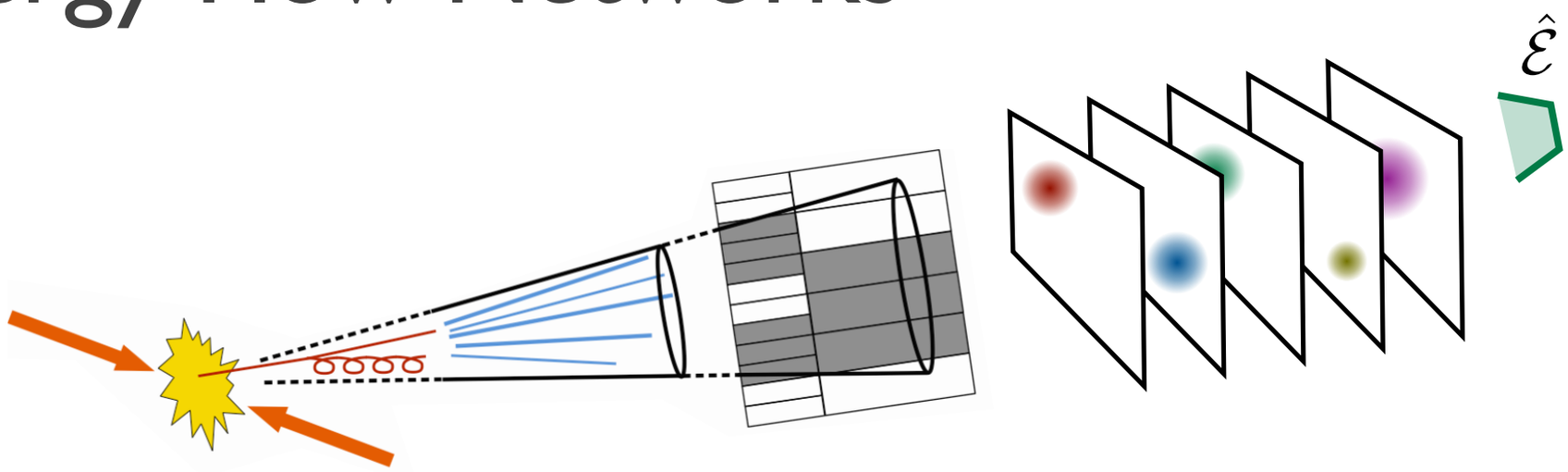
Safety: $\vec{p} = \{E, \hat{n}_x, \hat{n}_y, \hat{n}_z\}$

Energy weighting (QFT!)

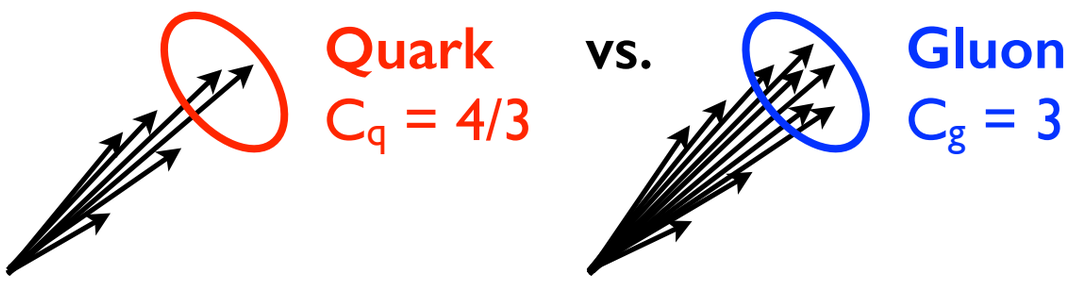


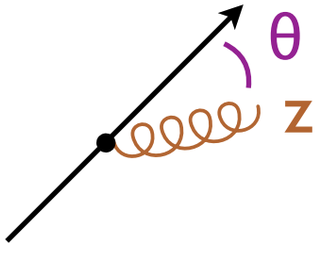
Check that answer is physically sensible

E.g. Energy Flow Networks



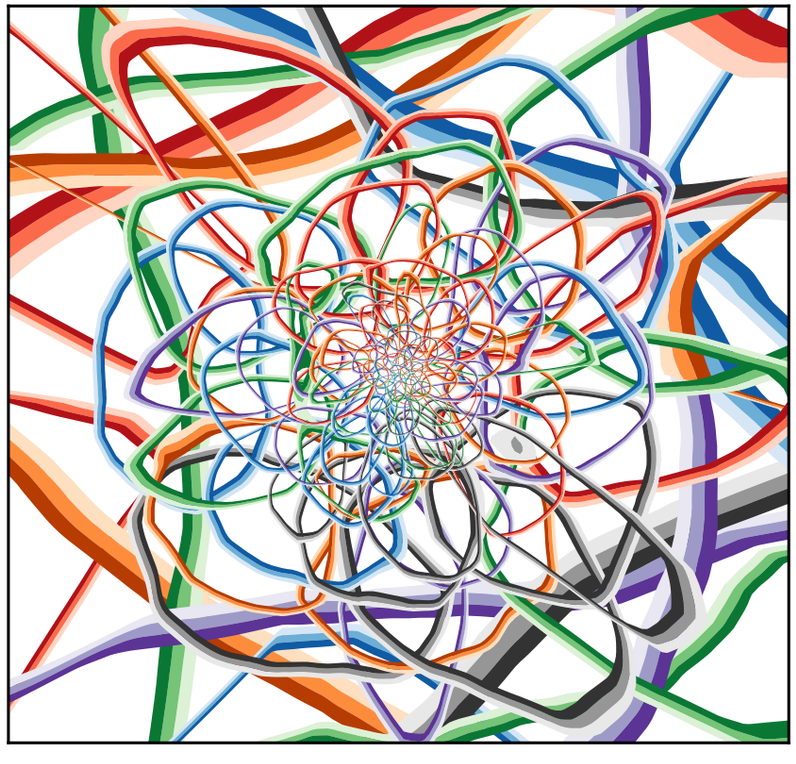
Learning QCD singularities!





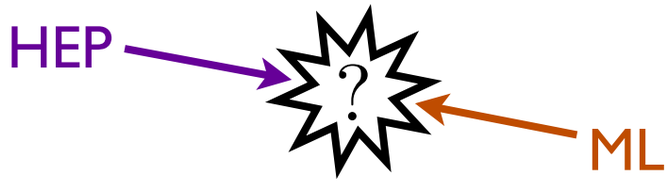
AP splitting probability:

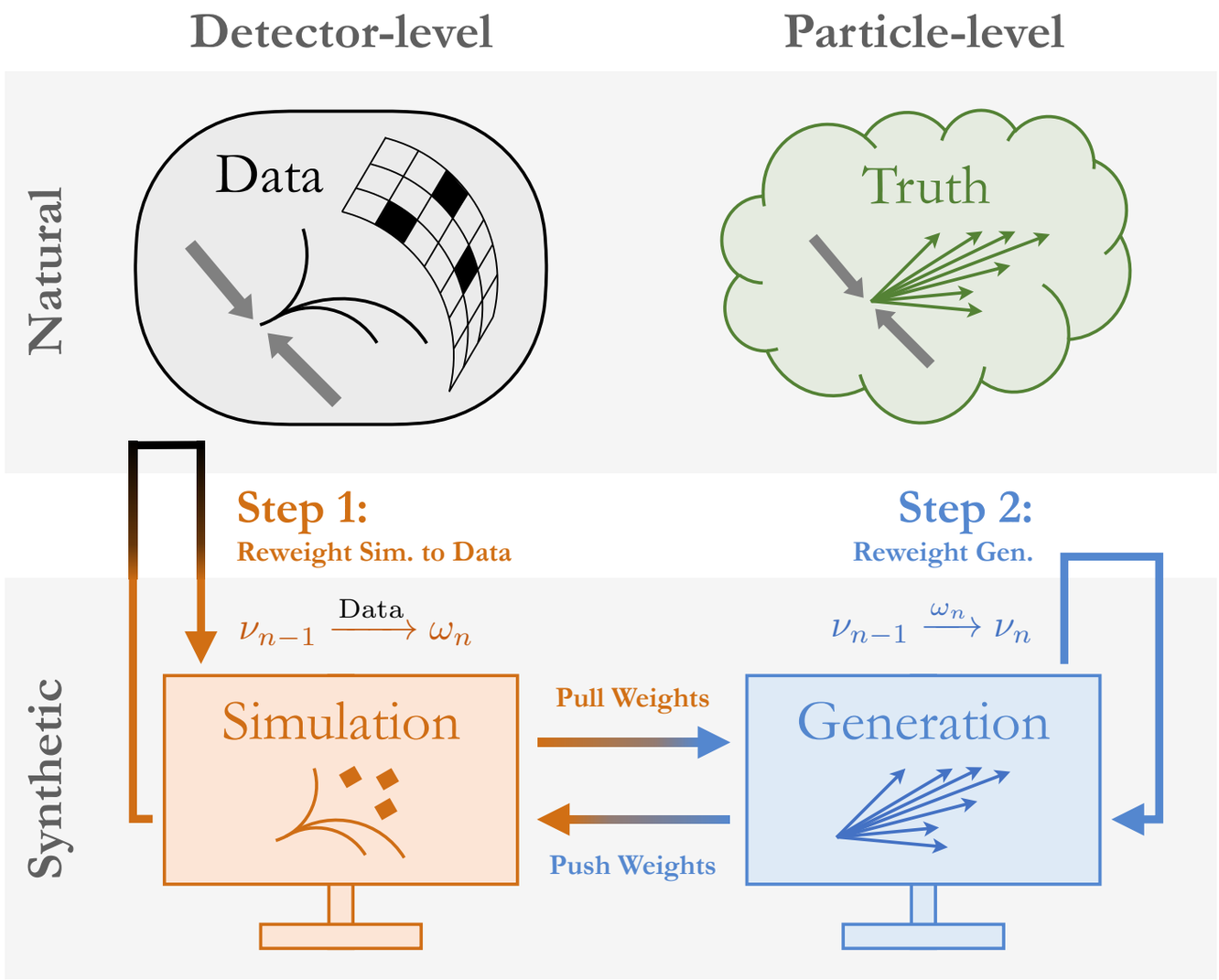
$$\mathrm{d}P_{i\to ig} \simeq \frac{2\alpha_s}{\pi} C_i \frac{\mathrm{d}\theta}{\theta} \frac{\mathrm{d}z}{z}$$



[Komiske, Metodiev, JDT, JHEP 2019; see also Komiske, Metodiev, JDT, JHEP 2018, PRD 2020; special case of Zaheer, Kottur, Ravanbakhsh, Poczos, Salakhutdinov, Smola, NIPS 2017]

OmniFold



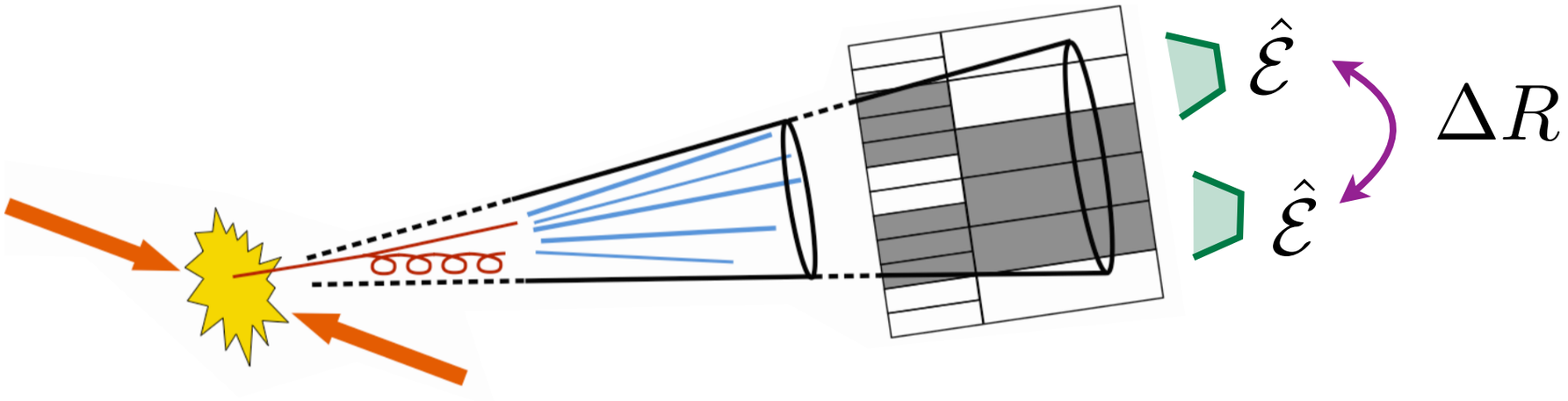


Using, e.g., Energy Flow Networks

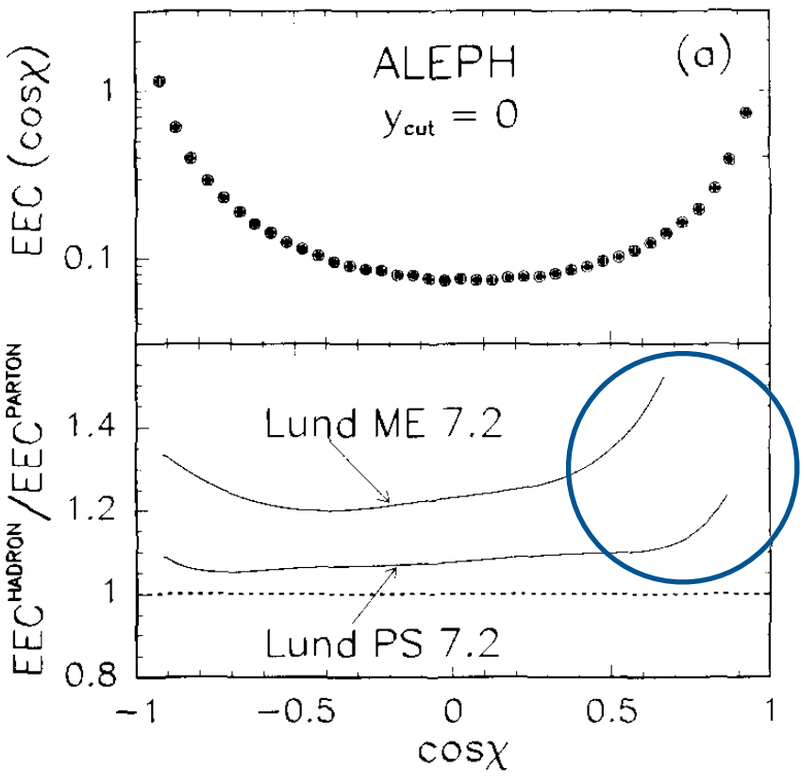
Multi-dimensional unbinned detector corrections via iterated binary classification

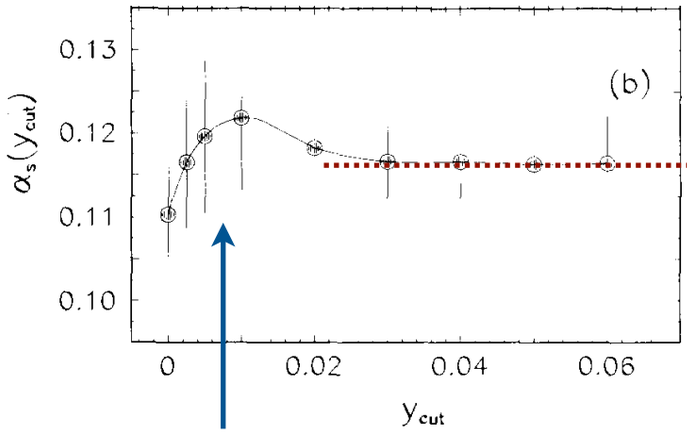
[Andreassen, Komiske, Metodiev, Nachman, JDT, PRL 2020]

Energy-Energy Correlators



A long history in probing collinear dynamics of QCD



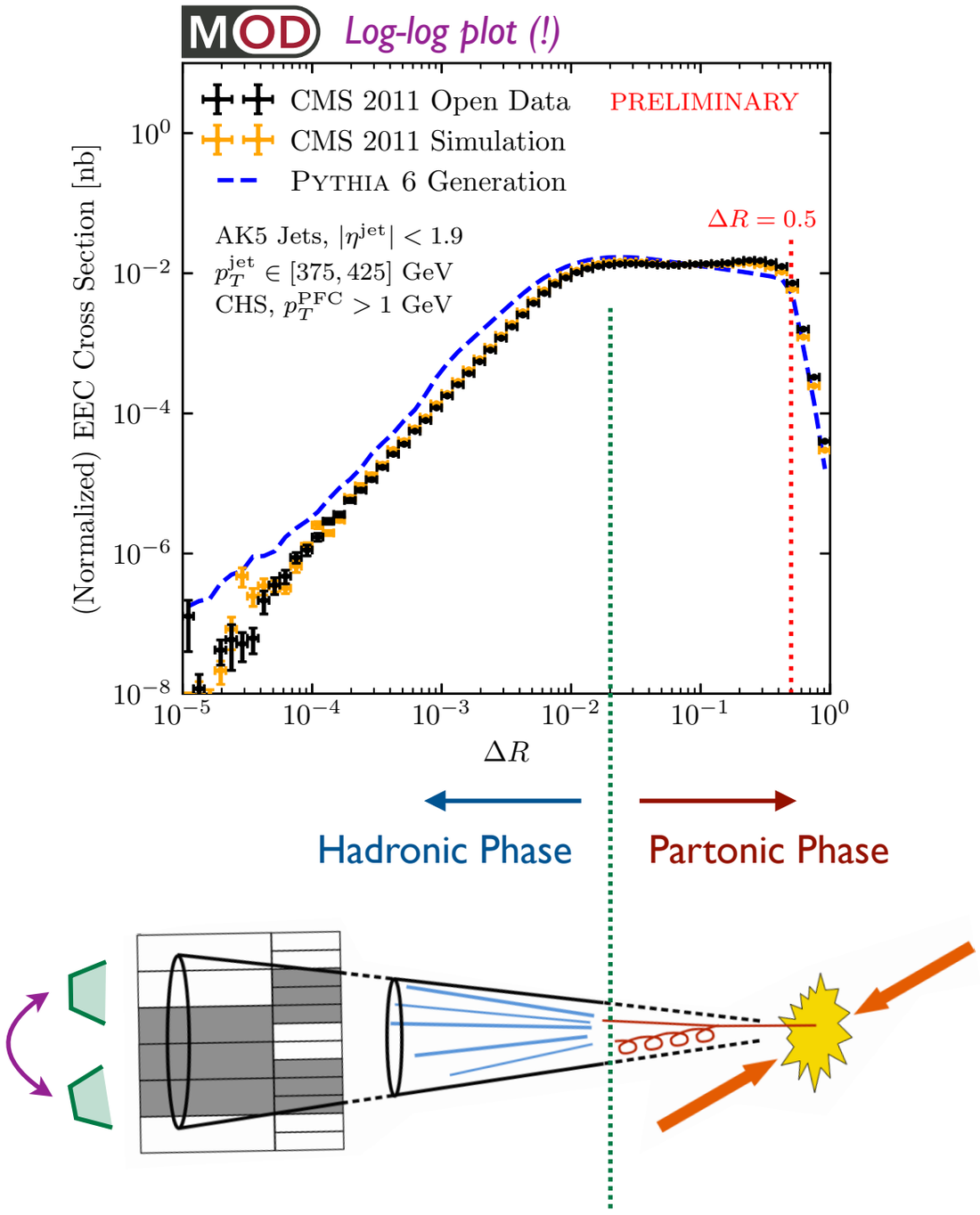


Extracting the strong coupling constant

Theoretical challenges with small angle (collinear) limit

[Basham, Brown, Ellis, Love, PRL 1978; ALEPH, PLB 1991; see Chen, Moult, Zhang, Zhu, PRD 2020]

QCD Phase Transition in Jets?



Behind the scenes at BOOST 2019

Jesse Thaler July 24, 2019 at 2:01 PM JT
EE(E)C?
To: Ian Moult

Hi Ian,

I appreciate the provocative lunch! At some point, we should talk about what you might want to see measured on the CMS Open Data with respect to EE(E)C.

Cheers,
Jesse

Jesse Thaler July 24, 2019 at 10:16 PM JT
Preliminary EEC plot
To: Ian Moult, Cc: Patrick Komiske

Hi Ian,

Below is a preliminary EEC plot on the CMS Open Data, made by Patrick. (Strictly speaking, this is the pT-pT-Correlator...)

We do this within single jets in the pT range specified in the plot, and the dashed vertical red line is the jet radius (beyond which things don't really make sense).

[Komiske, Moult, JDT, et al., in progress; see talks by Moult, BOOST 2019, BOOST 2020]


Dimensionality of Space of Jets

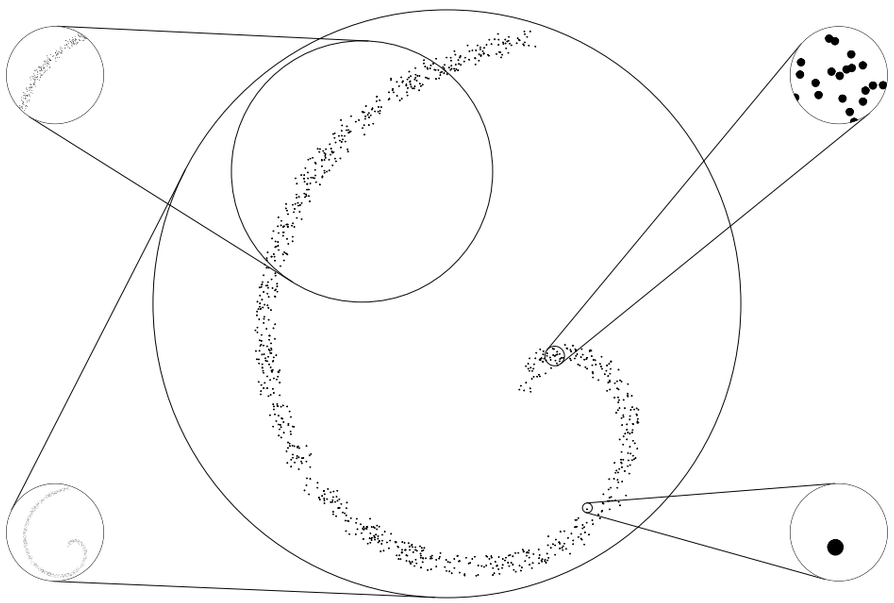
$$N_{\text{neighbors}}(r) \sim r^{\dim}$$

$$\Rightarrow \quad \dim(r) \sim r \frac{\partial}{\partial r} \ln N_{\text{neighbors}}(r)$$

[Grassberger, Procaccia, PRL 1983; Kégl, NIPS 2002]

dim≃1

dim≃2



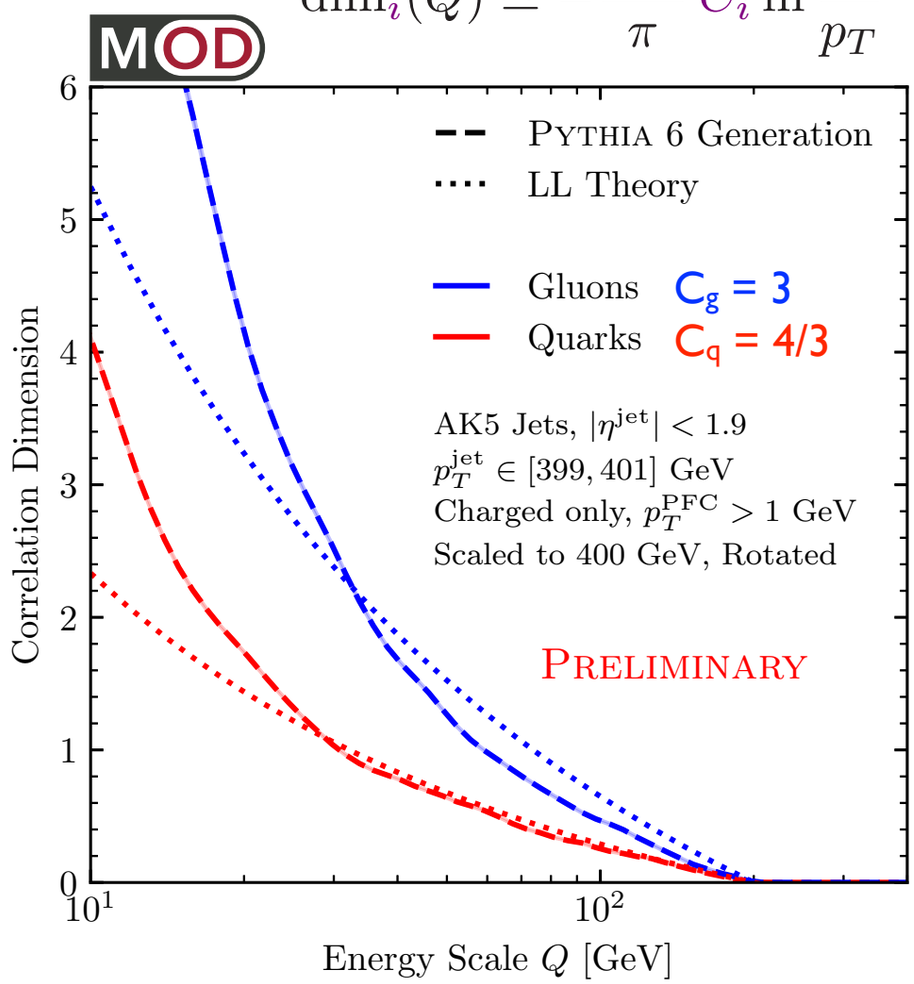
dim≃2

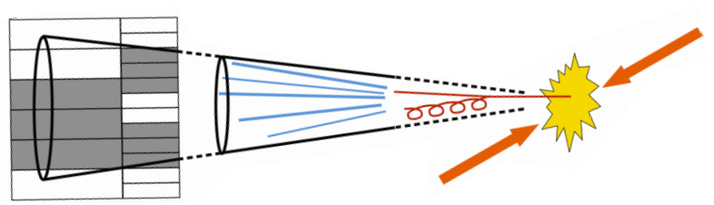
(eventually 0)

dim≃0

QCD Calculation

$$\dim_i(Q) \simeq -\frac{8\alpha_s}{\pi} C_i \ln \frac{Q}{p_T}$$





Dimensionality of Space of Jets

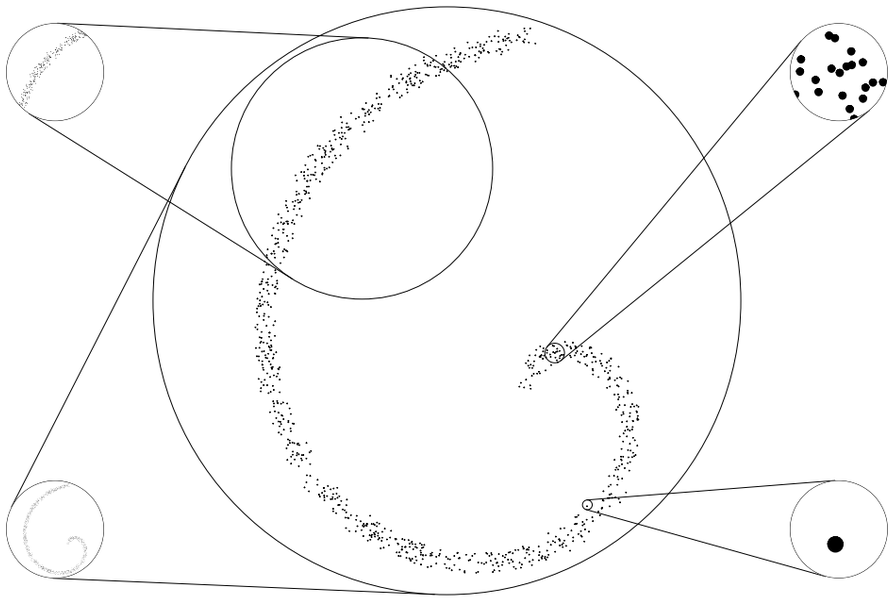
[http://opendata.cern.ch/]

$$N_{\text{neighbors}}(r) \sim r^{\dim}$$

$$\Rightarrow \quad \dim(r) \sim r \frac{\partial}{\partial r} \ln N_{\text{neighbors}}(r)$$

[Grassberger, Procaccia, PRL 1983; Kégl, NIPS 2002]

dim≃1 dim≃2

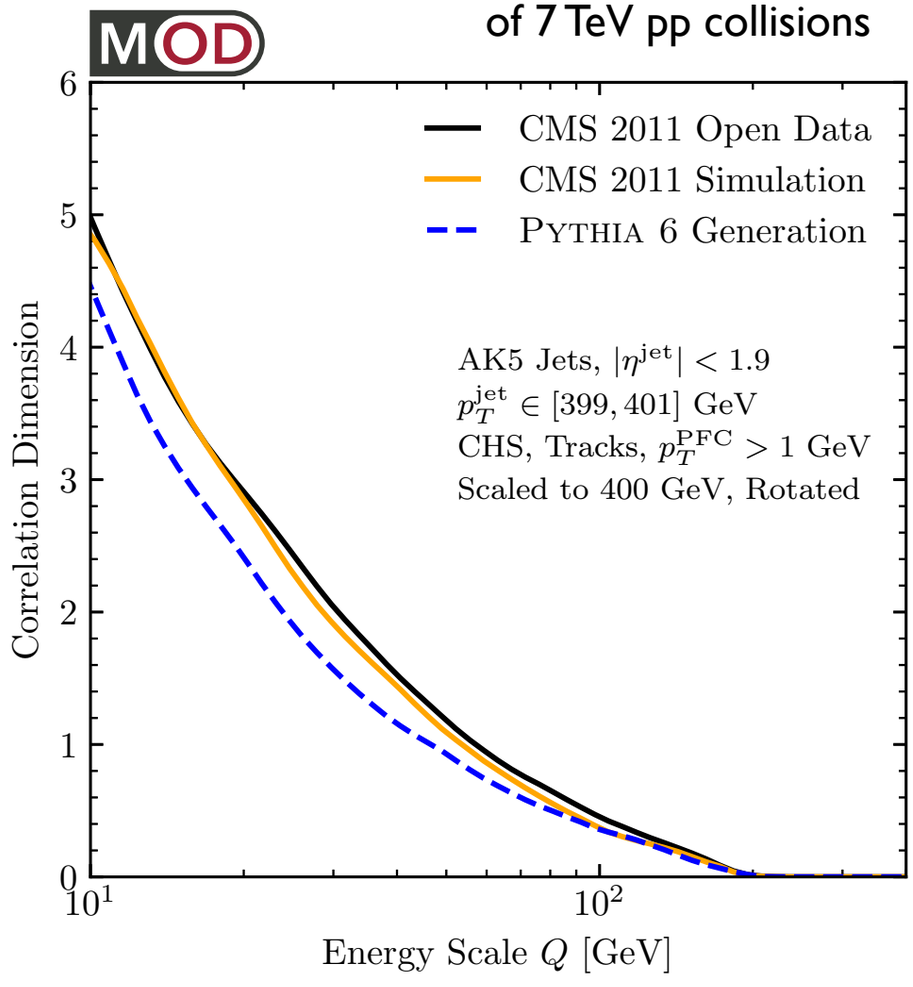


dim≃2 dim≃0

(eventually 0)

CMS Open Data

400 GeV jets in 2.3 fb^{-1} of 7 TeV pp collisions

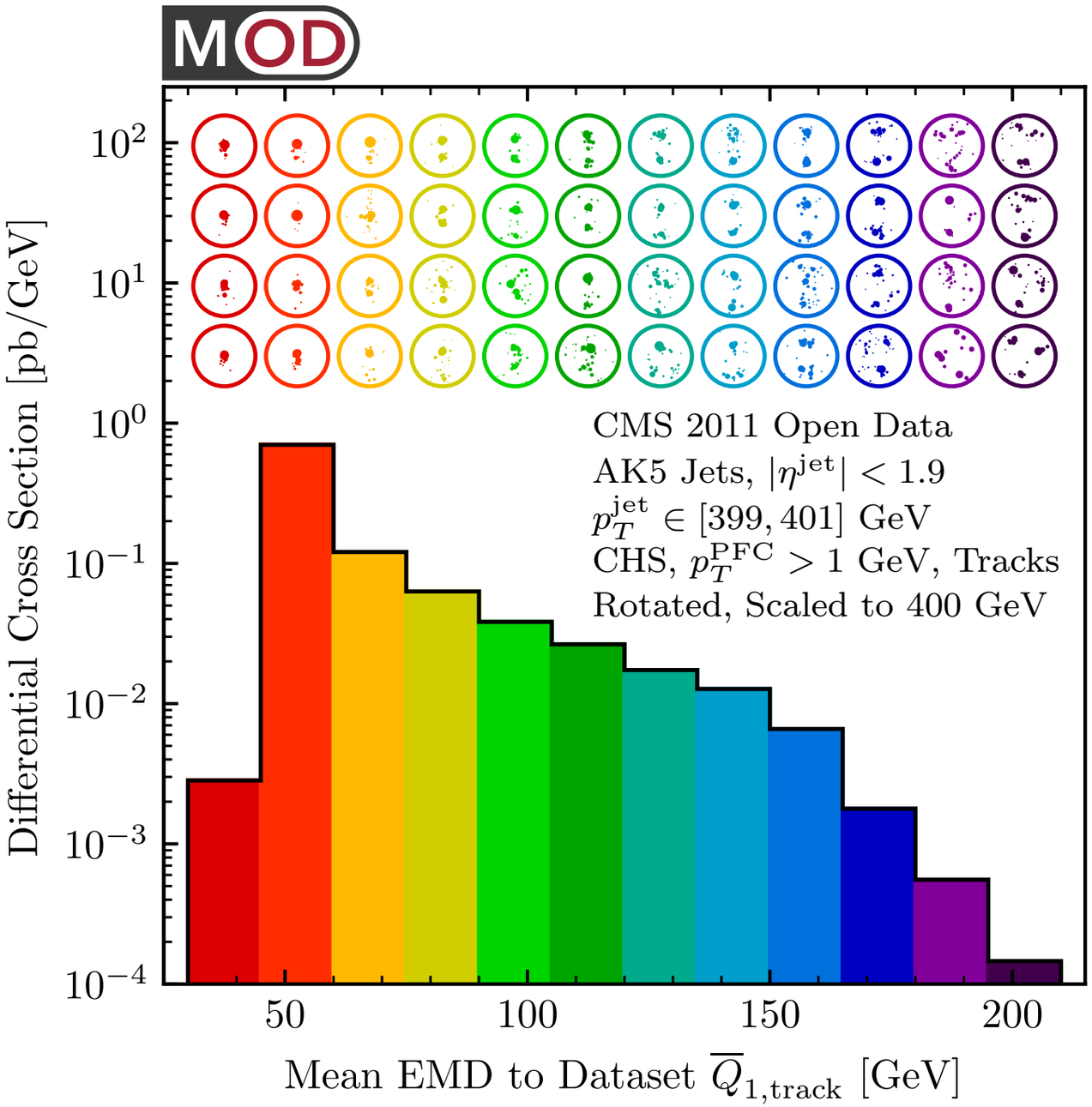


[Komiske, Mastandrea, Metodiev, Naik, JDT, PRD 2020]



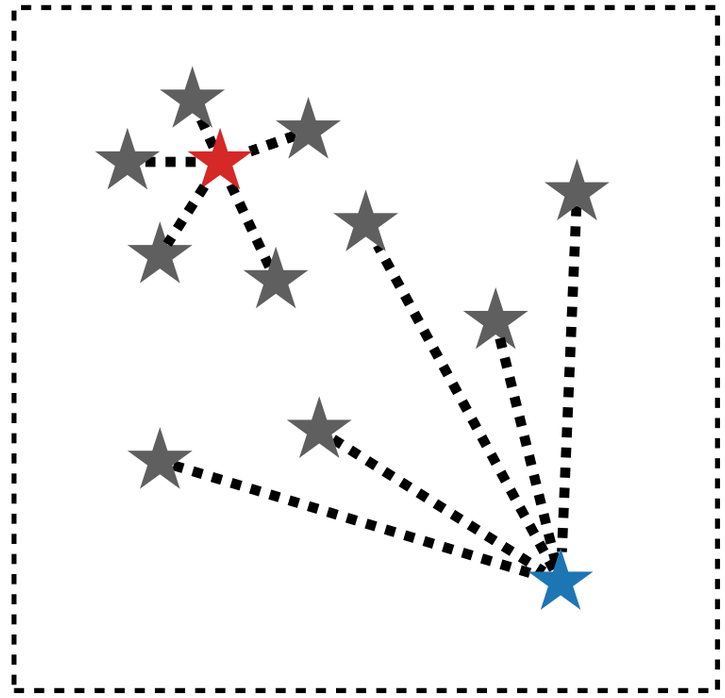

Least Representative Jets

[http://opendata.cern.ch/]



New Physics?

Or tails of QCD?



[Komiske, Mastandrea, Metodiev, Naik, JDT, PRD 2020]

Additional Travel Documentation