

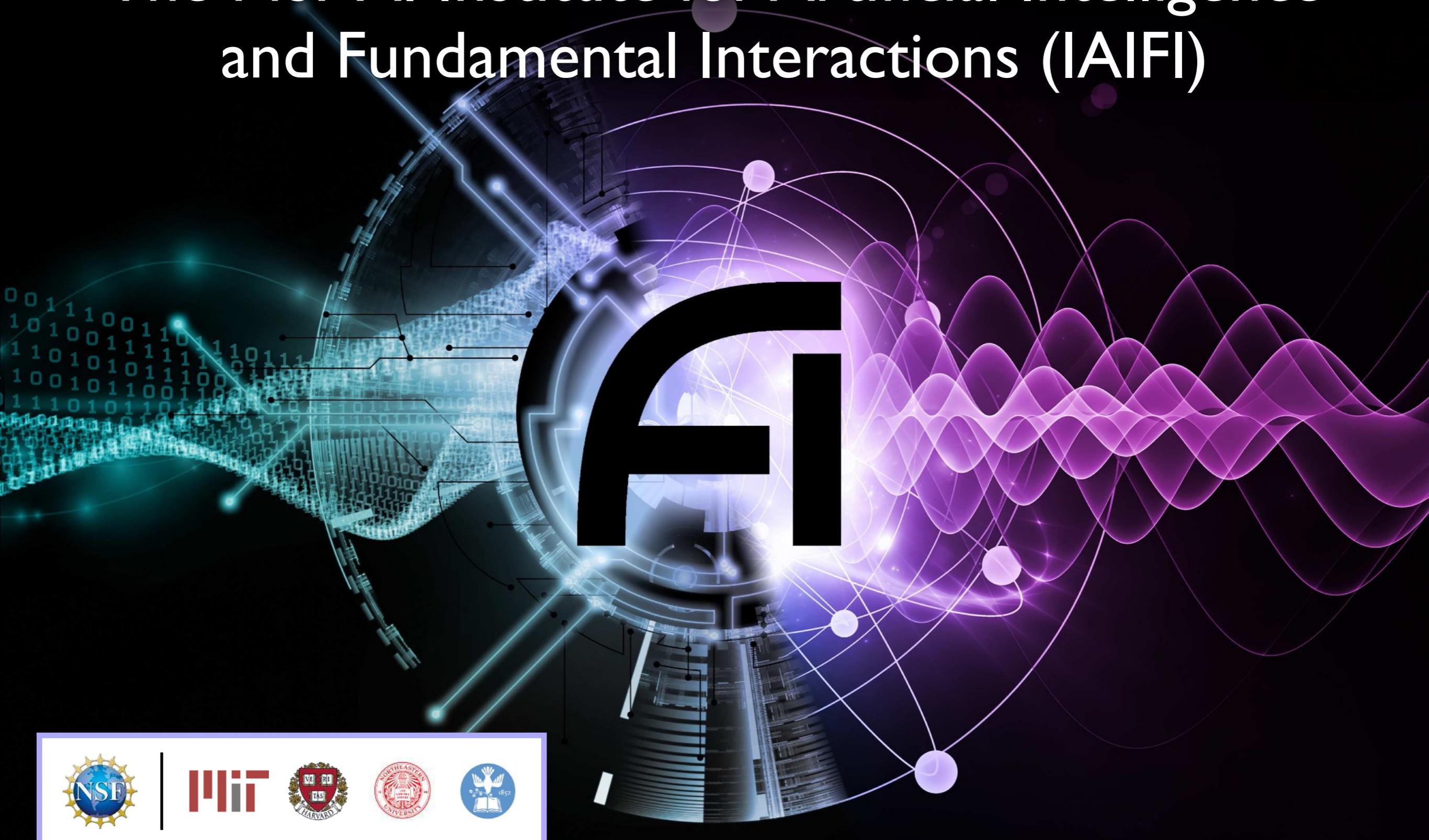
The Hidden Geometry of Particle Collisions

Jesse Thaler



8.398 — November 13, 2020

The NSF AI Institute for Artificial Intelligence and Fundamental Interactions (IAIFI)



[<http://iaifi.org/>, MIT News Announcement]

The NSF AI Institute for Artificial Intelligence and Fundamental Interactions (IAIFI)

“eye-phi”



*Advance physics knowledge — from the smallest building blocks of nature
to the largest structures in the universe — and galvanize AI research innovation*



Pulkit Agrawal
Lisa Barsotti
Isaac Chuang
William Detmold
Bill Freeman
Philip Harris
Kerstin Perez
Alexander Rakhlin

Phiala Shanahan
Tracy Slatyer
Marin Soljacic
Justin Solomon
Washington Taylor
Max Tegmark
Jesse Thaler
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Demba Ba
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Cora Dvorkin
Daniel Eisenstein
Doug Finkbeiner
Matthew Schwartz
Yaron Singer
Todd Zickler



James Halverson
Brent Nelson

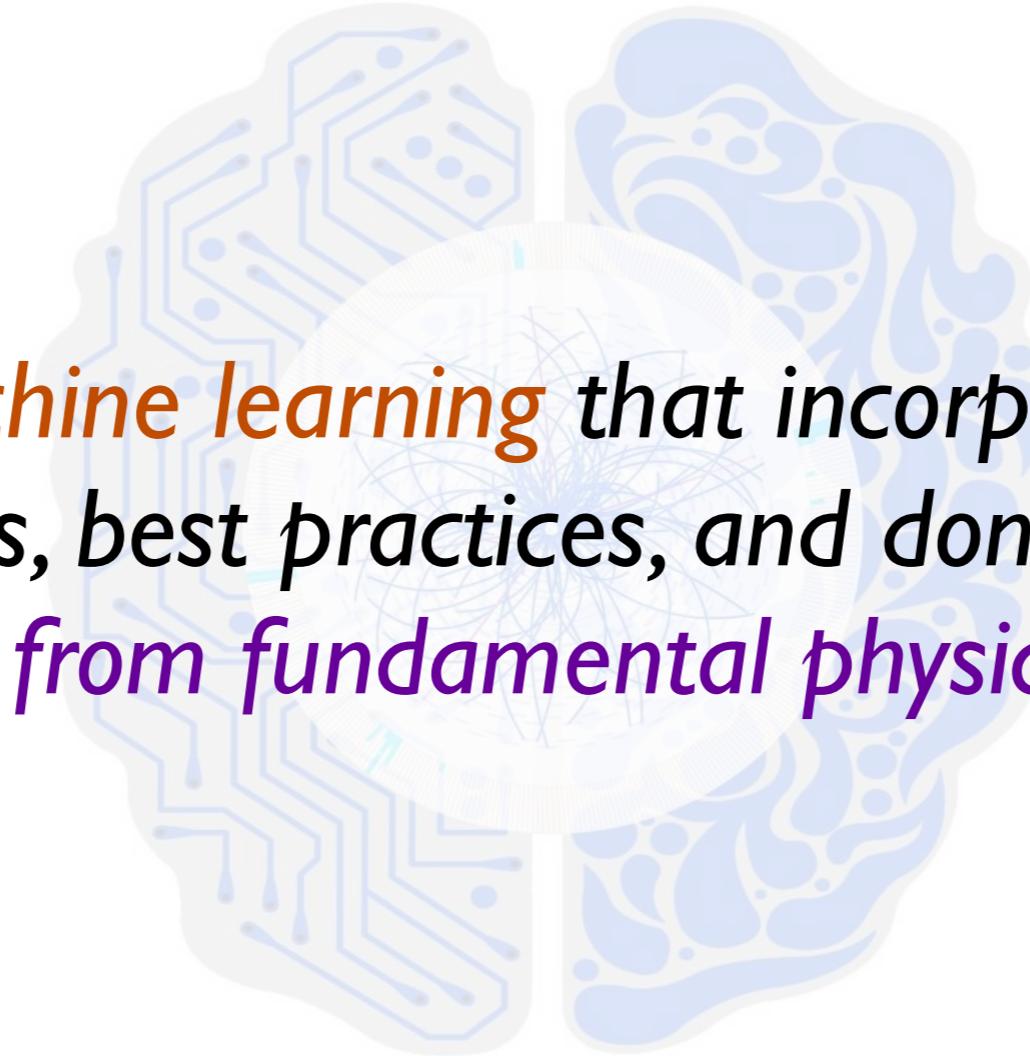
The Northeastern University seal logo.

MIT c Boston Area: Critical Mass for Transformative Ab Initio AI Research

AI²: Ab Initio Artificial Intelligence



*Machine learning that incorporates
first principles, best practices, and domain knowledge
from fundamental physics*



*Symmetries, conservation laws, scaling relations, limiting behaviors, locality, causality,
unitarity, gauge invariance, entropy, least action, factorization, unit tests,
exactness, systematic uncertainties, reproducibility, verifiability, ...*

AI²: Ab Initio Artificial Intelligence

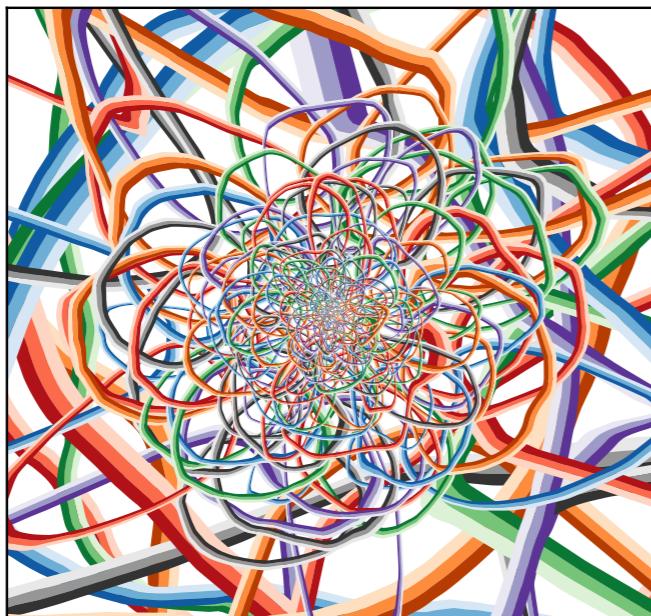


Convolutional Neural Networks \Leftrightarrow Translational Equivariance

\Rightarrow Momentum Conservation

Energy Flow Networks \Leftrightarrow

Identical Particles (QM)
Infrared/Collinear Safety (QFT)



[Komiske, Metodiev, JDT, JHEP 2019]

$$\begin{matrix} \text{AI} \\ \times \text{AI} \\ = \text{AI}^2 \end{matrix}$$

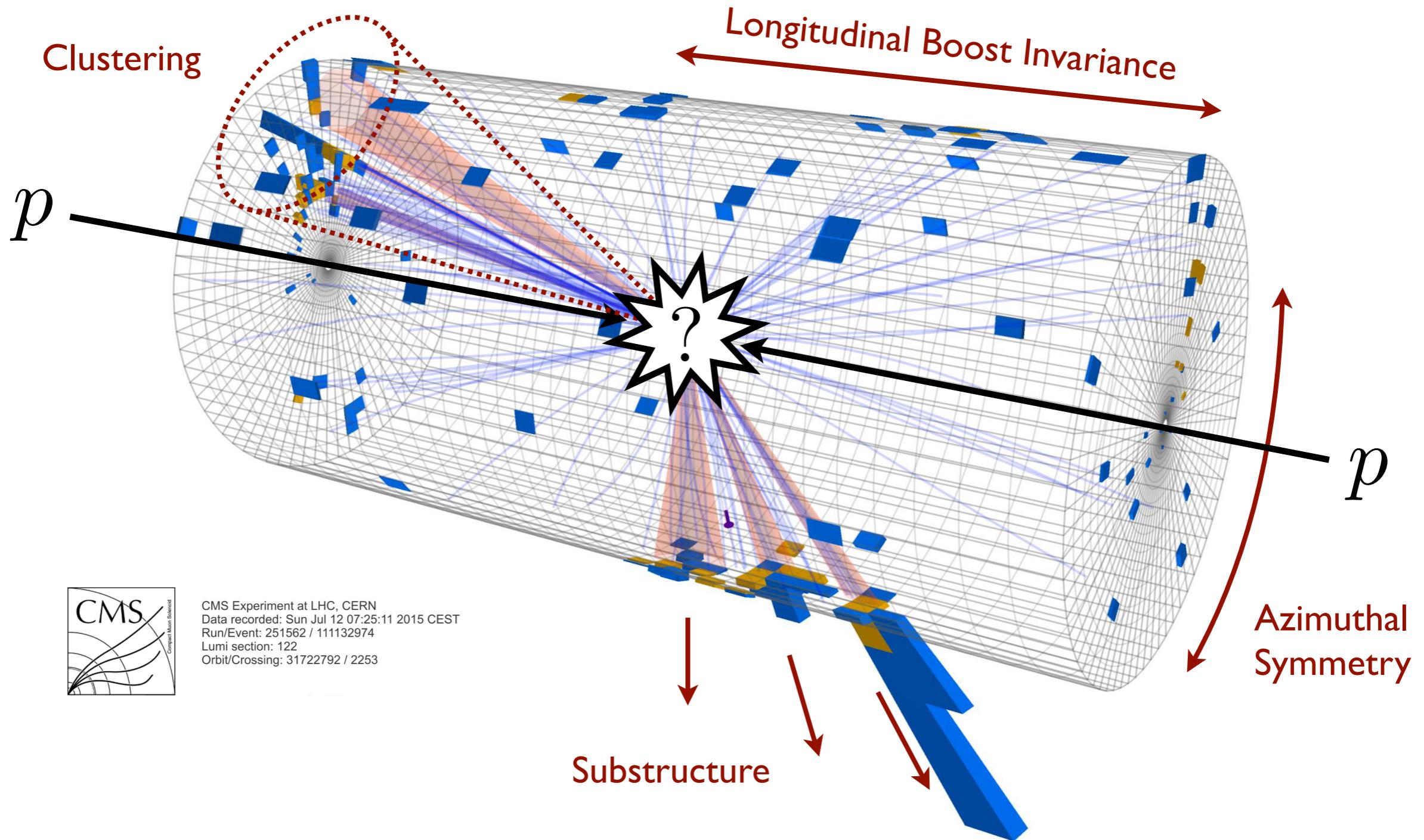
Powerful strategy to
analyze LHC collisions

Efficient neural network
for point clouds

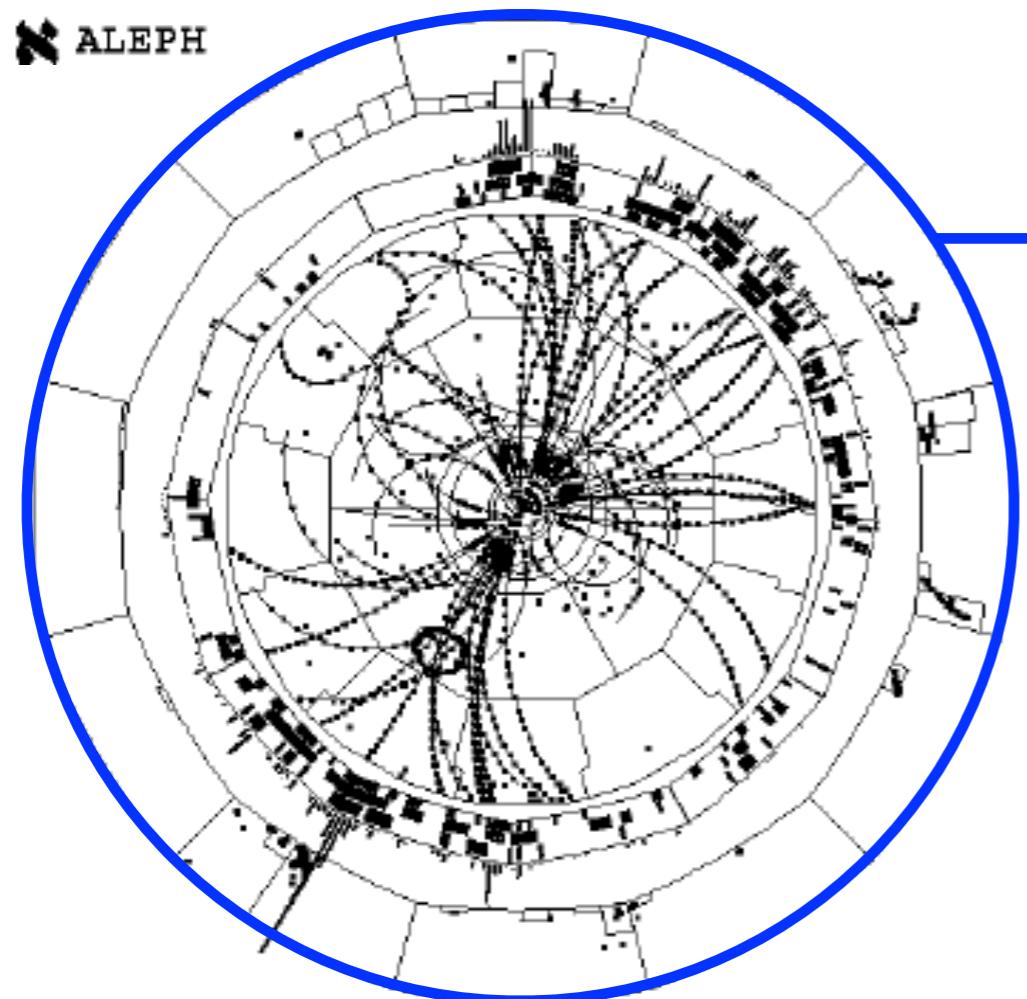
Cross-cutting research
across disciplines

Today:
Collider Physics \Leftrightarrow *Optimal Transport*

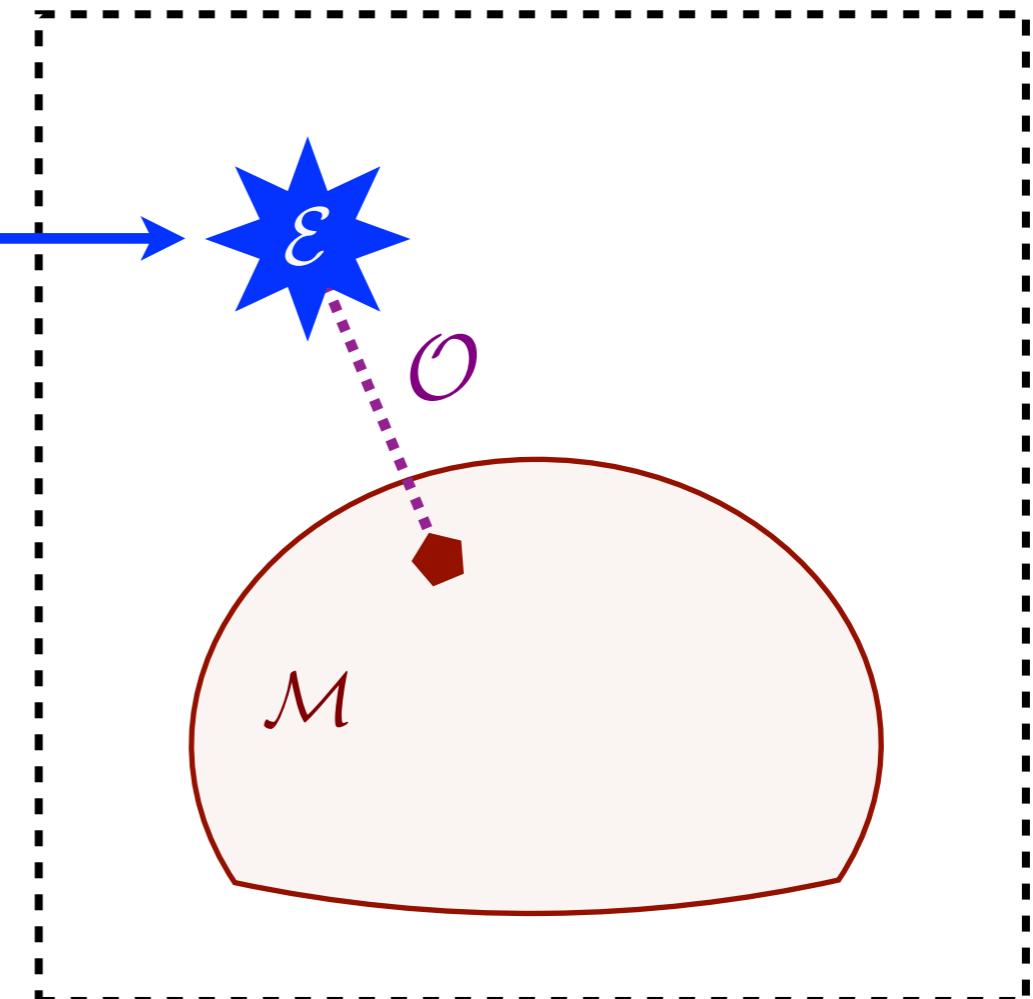
The Manifest Geometry of One Collision



The Hidden Geometry of Particle Collisions



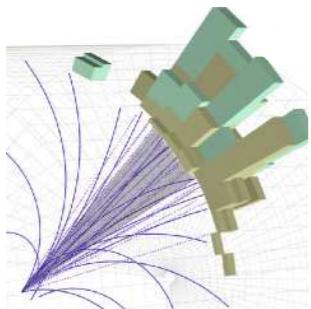
One Collider Event



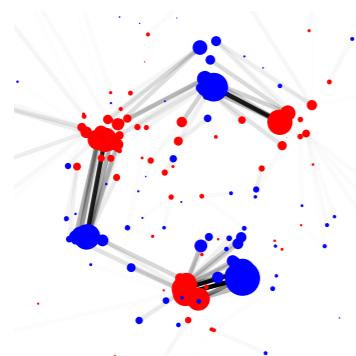
Distance to a Manifold in Event Space

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

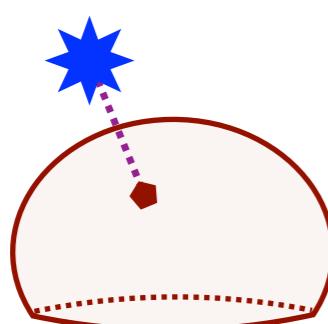
Outline



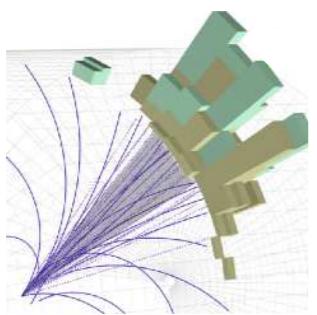
What is a Collider Event?



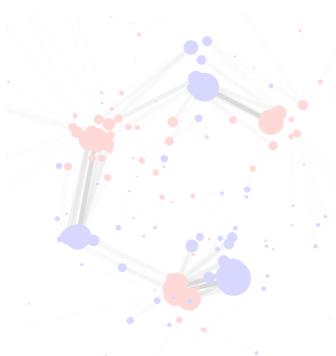
When are Events Similar?



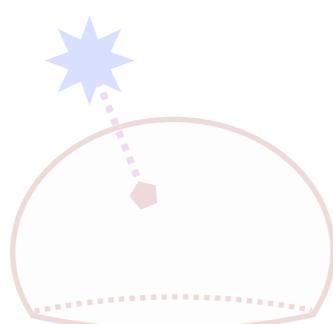
What can be Geometrized?



What is a Collider Event?



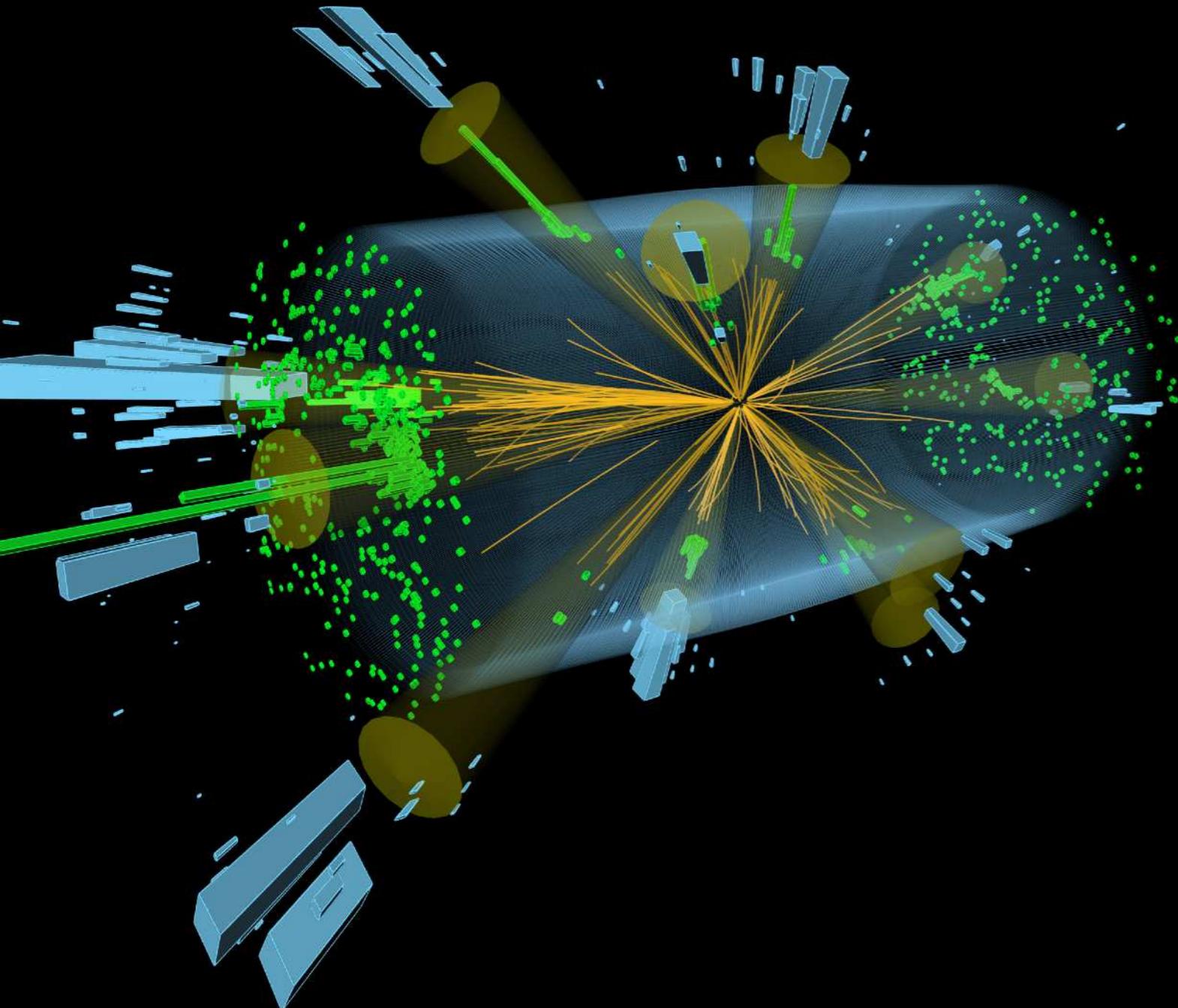
When are Events Similar?



What can be Geometrized?

Collider Event

Collection of points in (momentum) space



T E H M

 γ

photon

 e^+

electron

 μ^+

muon

 π^+

pion

 K^+

kaon

 K_L^0

K-long

 p/\bar{p}

proton

 n/\bar{n}

neutron

elementary

composite

Point Cloud

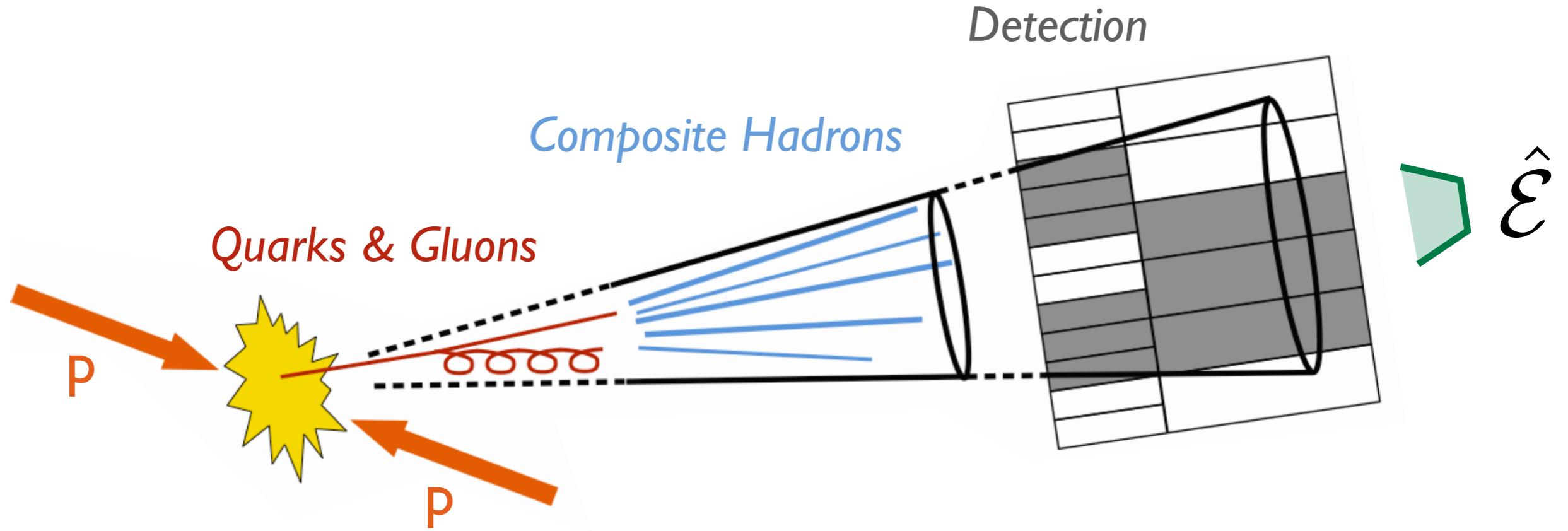
Collection of points in (position) space



[Popular Science, 2013]

Jet Formation from QCD

Theory



Energy Flow:
Robust to hadronization and detector effects

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

[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](#)]

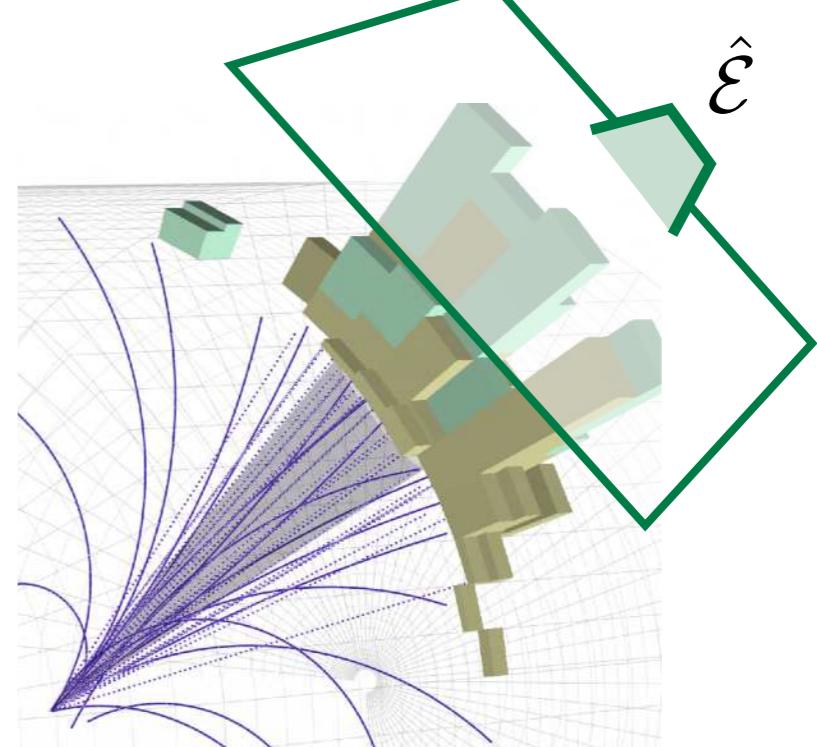
Jets as Weighted Point Clouds

- Energy-Weighted Directions

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

↑ |
Energy Direction

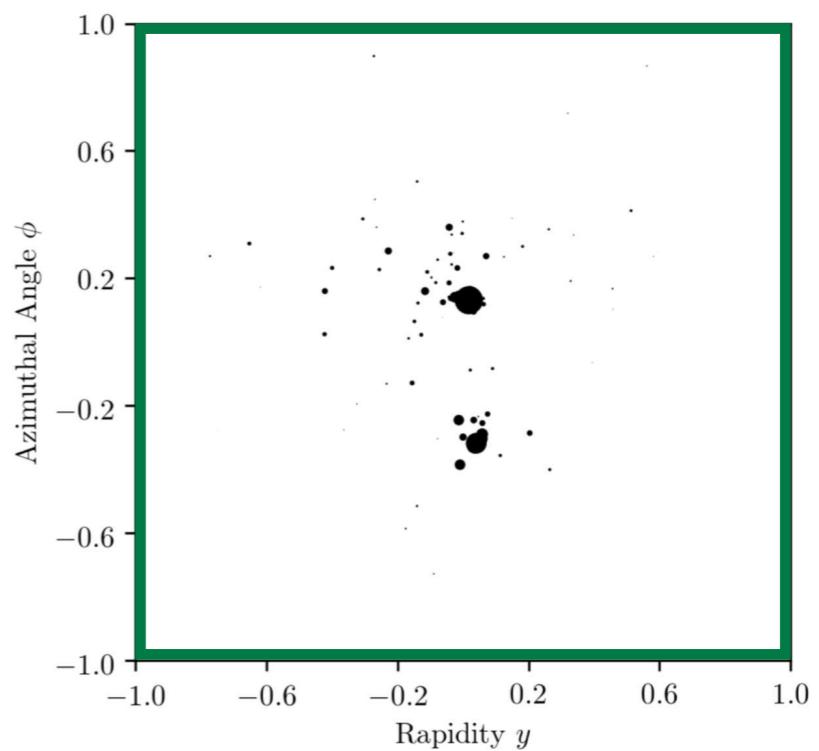
(suppressing “unsafe” charge/flavor information)



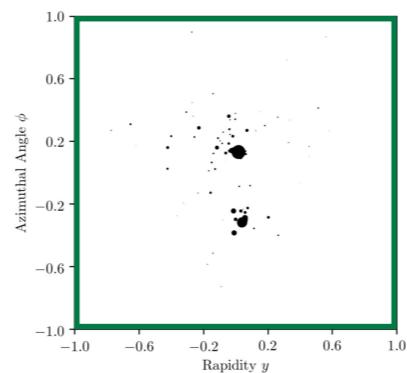
- Equivalently: Energy Density

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

↑ ↑
Energy Direction



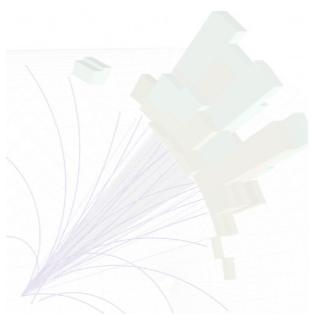
What is a Collider Event?



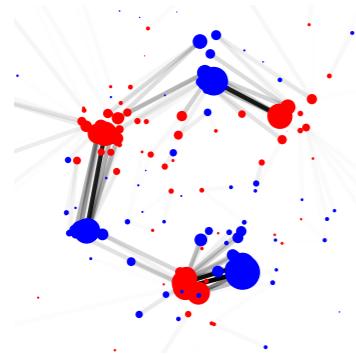
“Calo” Energy Density

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

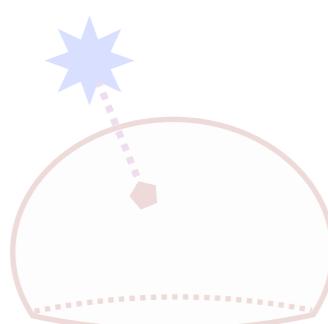
(see backup for relevance to ML and QCD)



What is a Collider Event?



When are Events Similar?

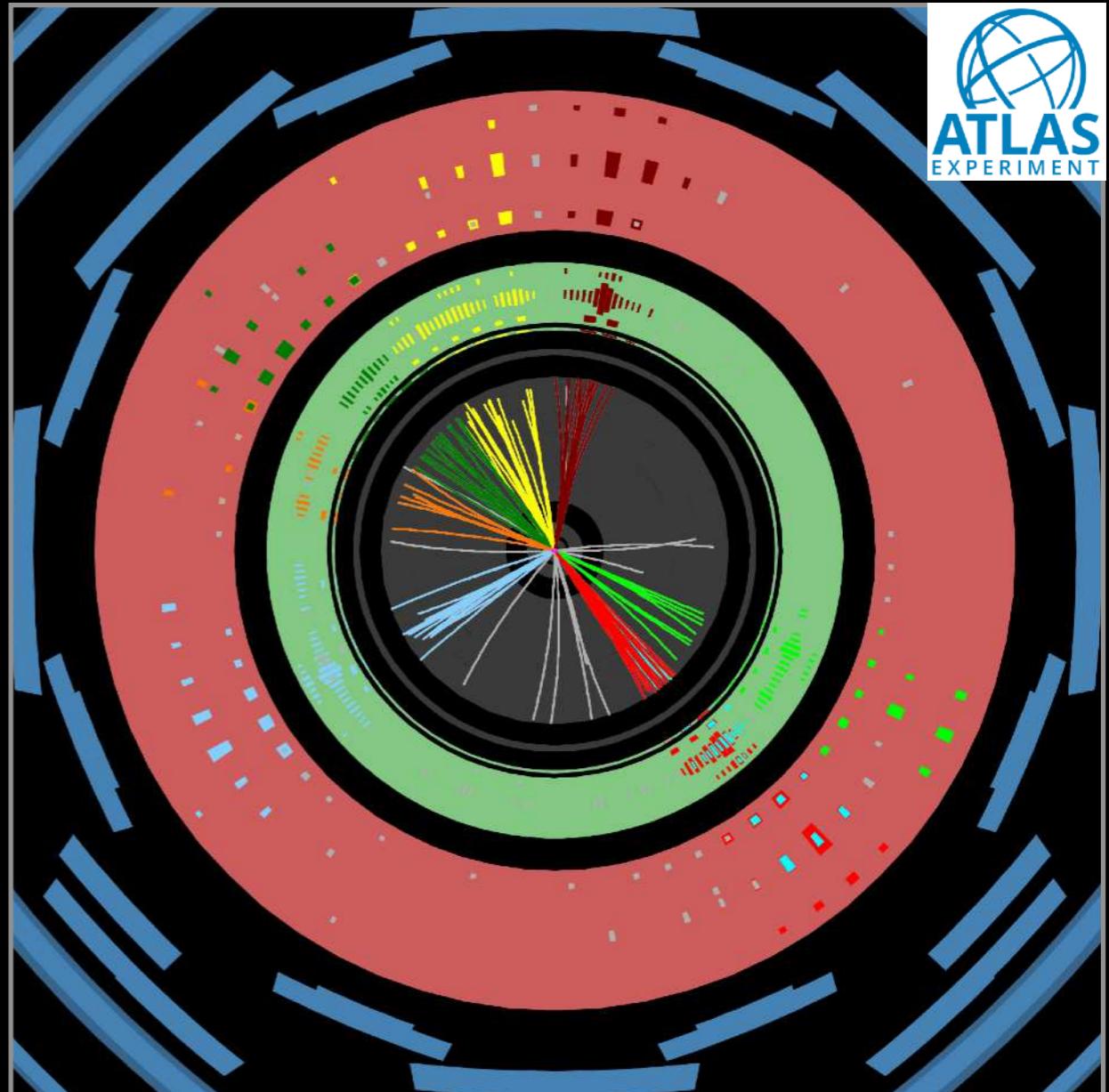
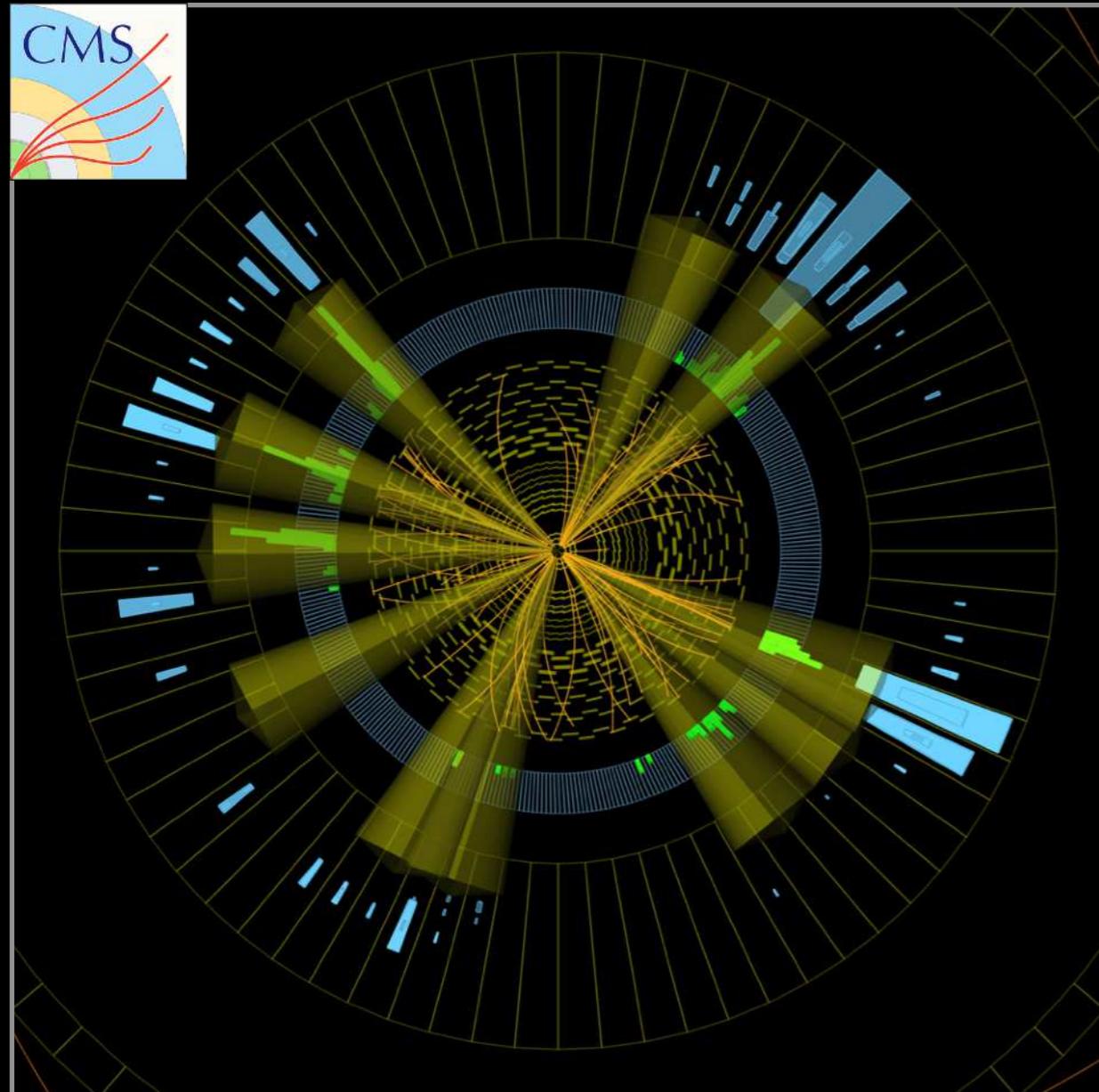


What can be Geometrized?

Two Collider Events

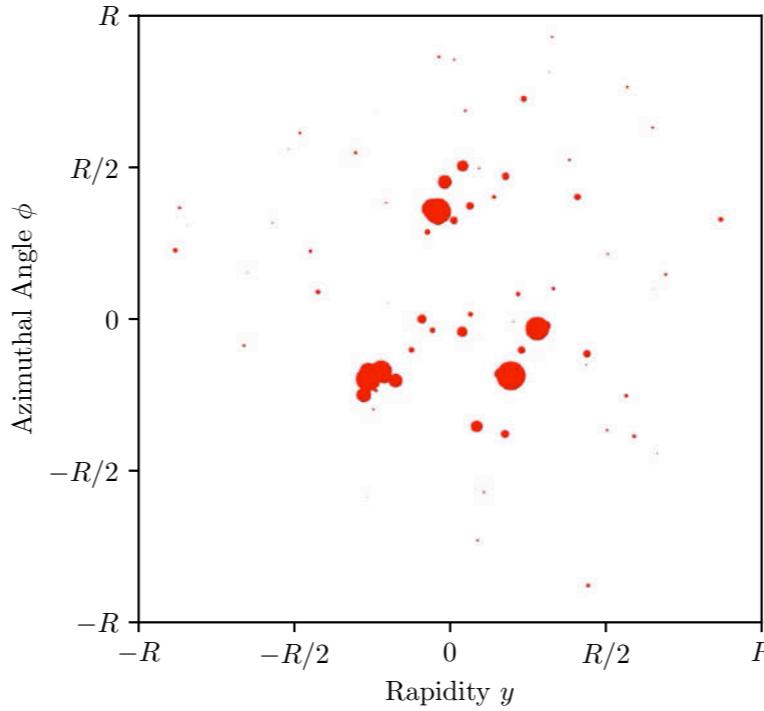
Two collections of points in (momentum) space

How “close” are these?

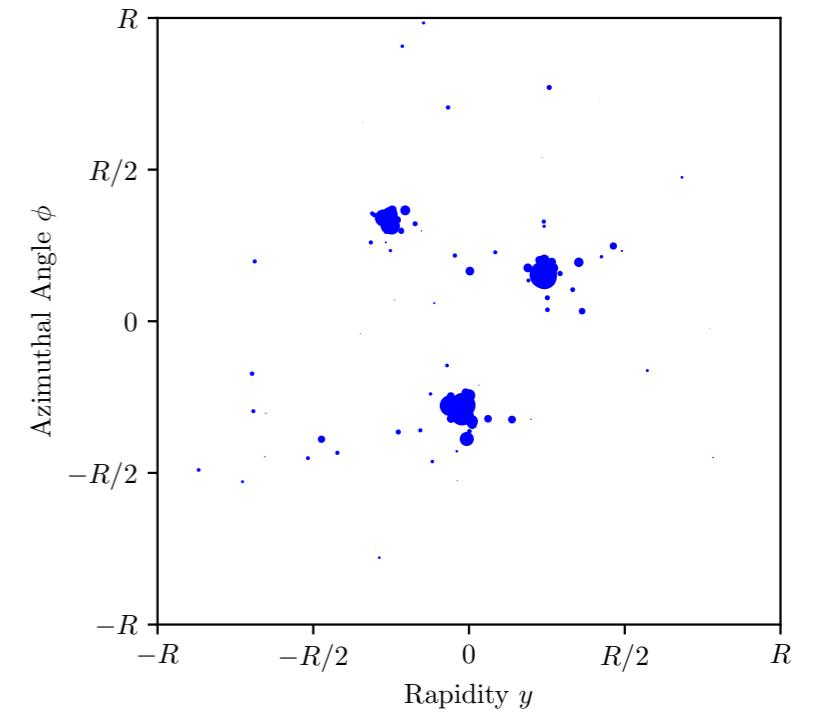
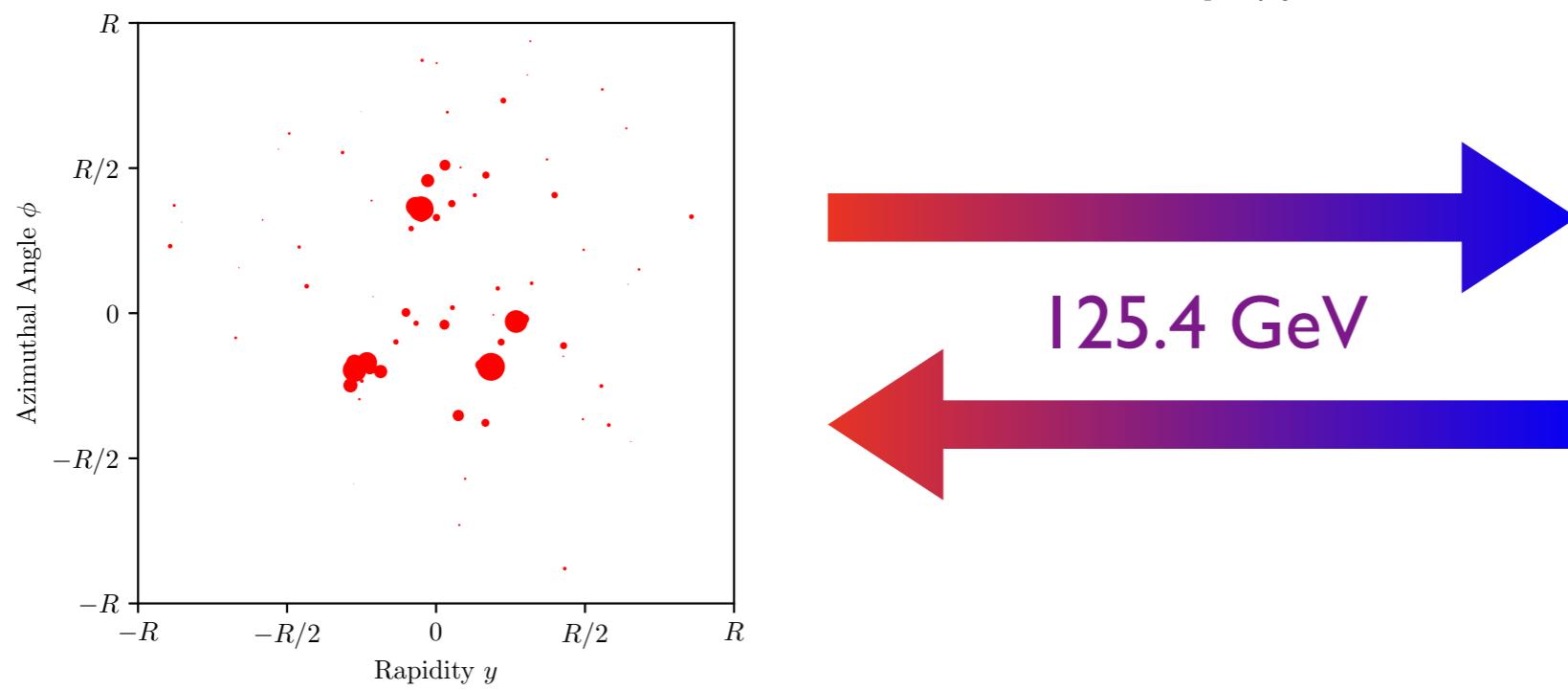


Similarity of Two Energy Flows?

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



Optimal Transport:
Earth Mover's Distance
a.k.a. l -Wasserstein metric



[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](#), [ICCV 2000](#);
Pele, Werman, [ECCV 2008](#); Pele Taskar, [GSI 2013](#)]

Minimum “work” (stuff \times distance) to make one distribution look like another distribution



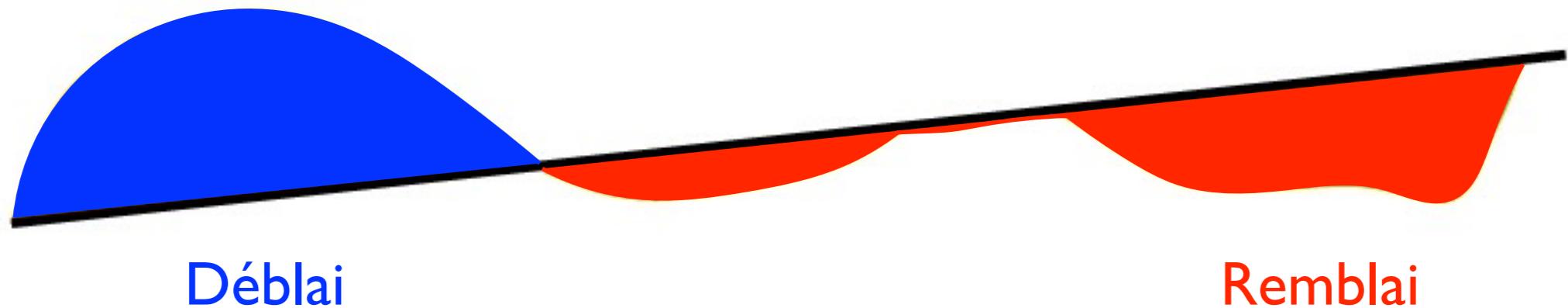
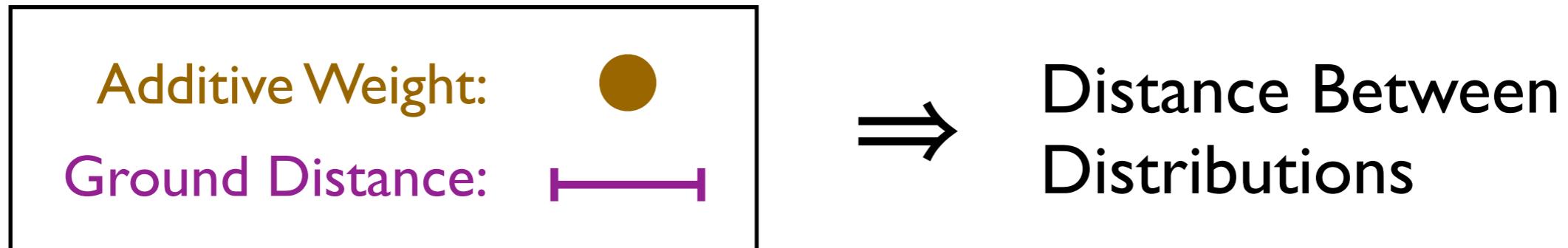
[h/t Niles-Weed, [ML4Jets 2020](#); Monge, 1781; Vaserštejn, 1969; [Wikipedia](#)]

The Earth Mover's Distance

Optimal Transport:

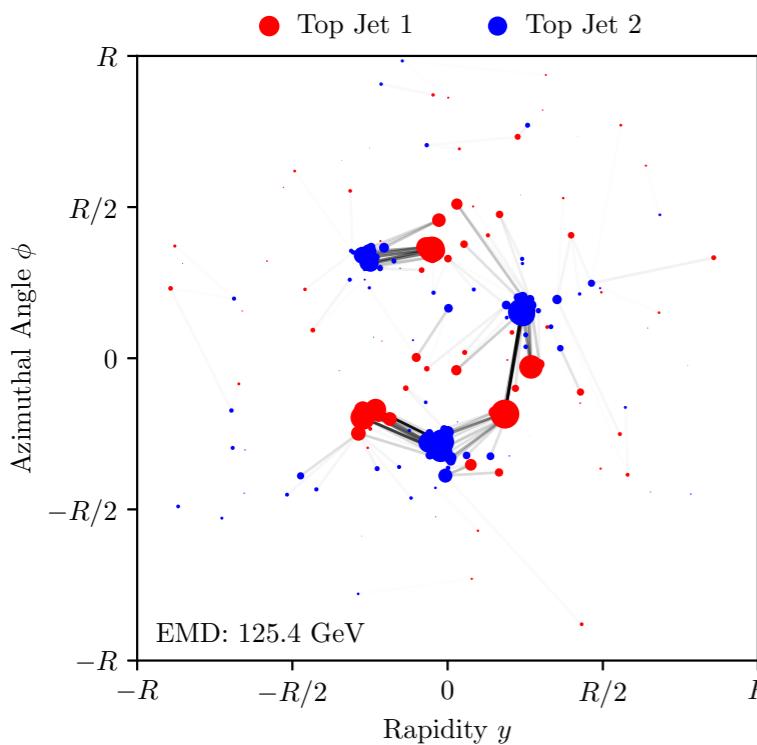
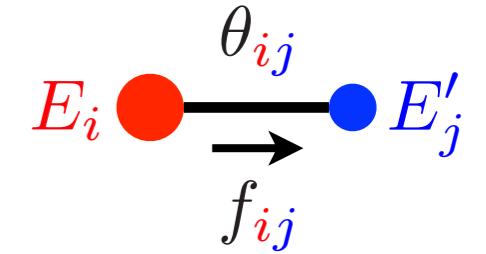
[Peleg, Werman, Rom, [IEEE 1989](#);
Rubner, Tomasi, Guibas, [ICCV 1998](#), [ICCV 2000](#);
Pele, Werman, [ECCV 2008](#); Pele Taskar, [GSI 2013](#)]

Minimum “work” (**stuff** × **distance**) to make
one distribution look like **another distribution**



[h/t Niles-Weed, [ML4Jets 2020](#); Monge, 1781; Vaserštejn, 1969; [Wikipedia](#)]

The Energy Mover's Distance



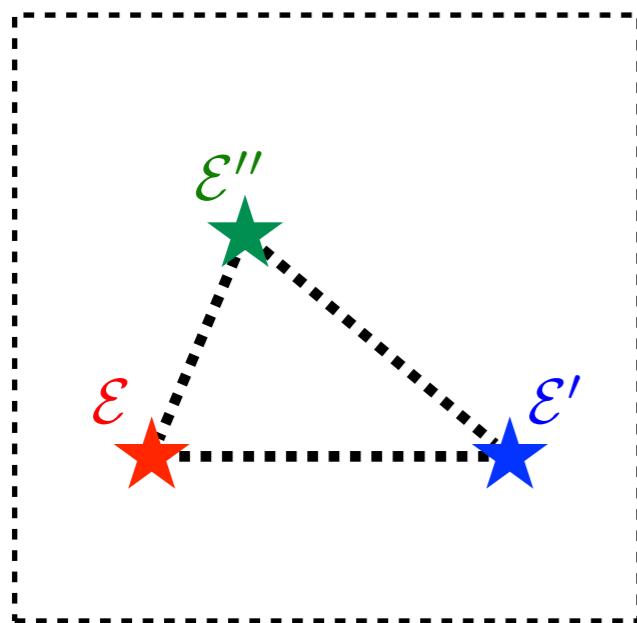
Optimal transport between energy flows...

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

↑
in GeV

Cost to move energy

Cost to create energy



...defines a metric on the space of events

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

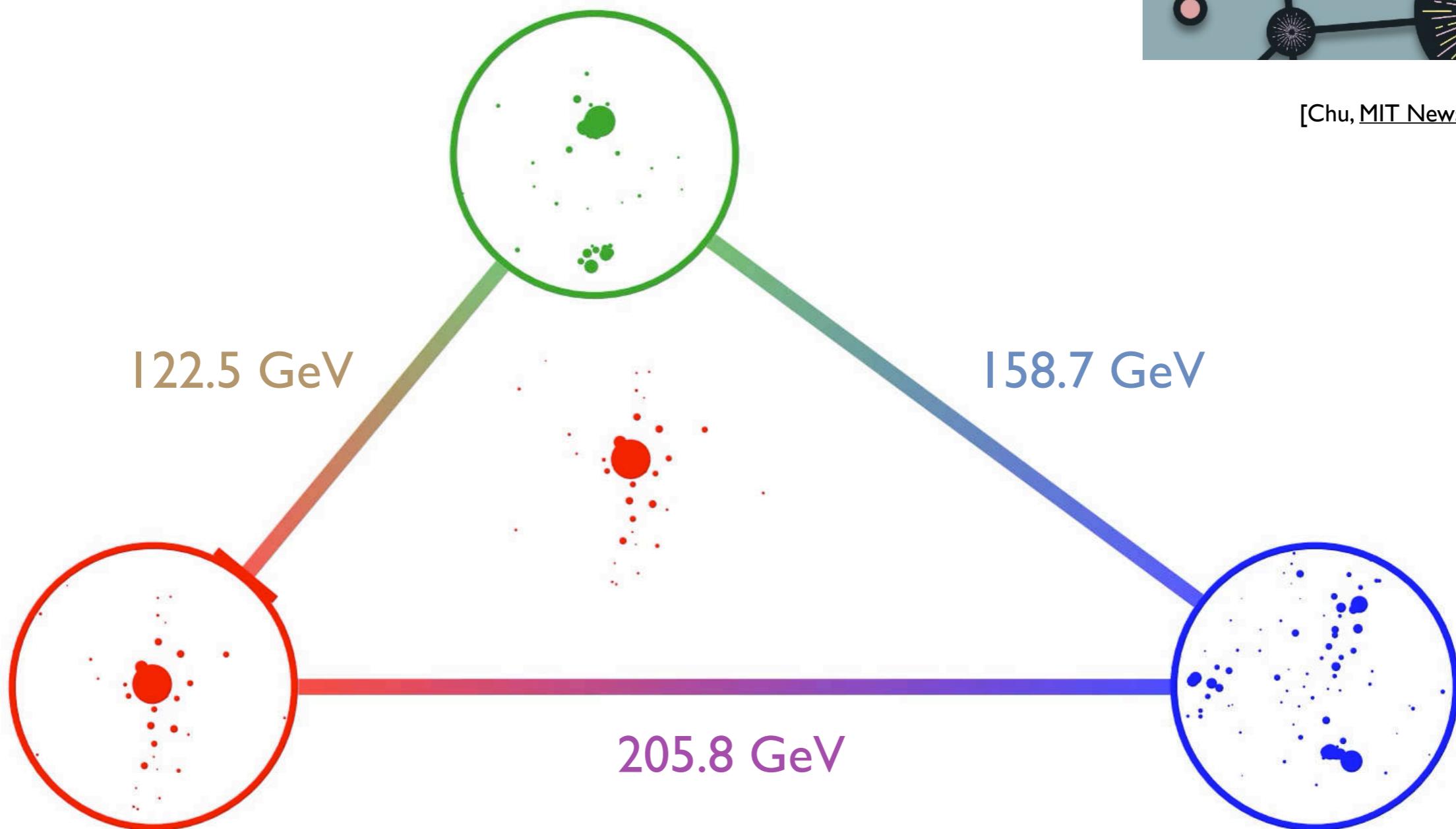
(assuming $R \geq \theta_{\max}/2$, i.e. $R \geq$ jet radius for conical jets)

[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]



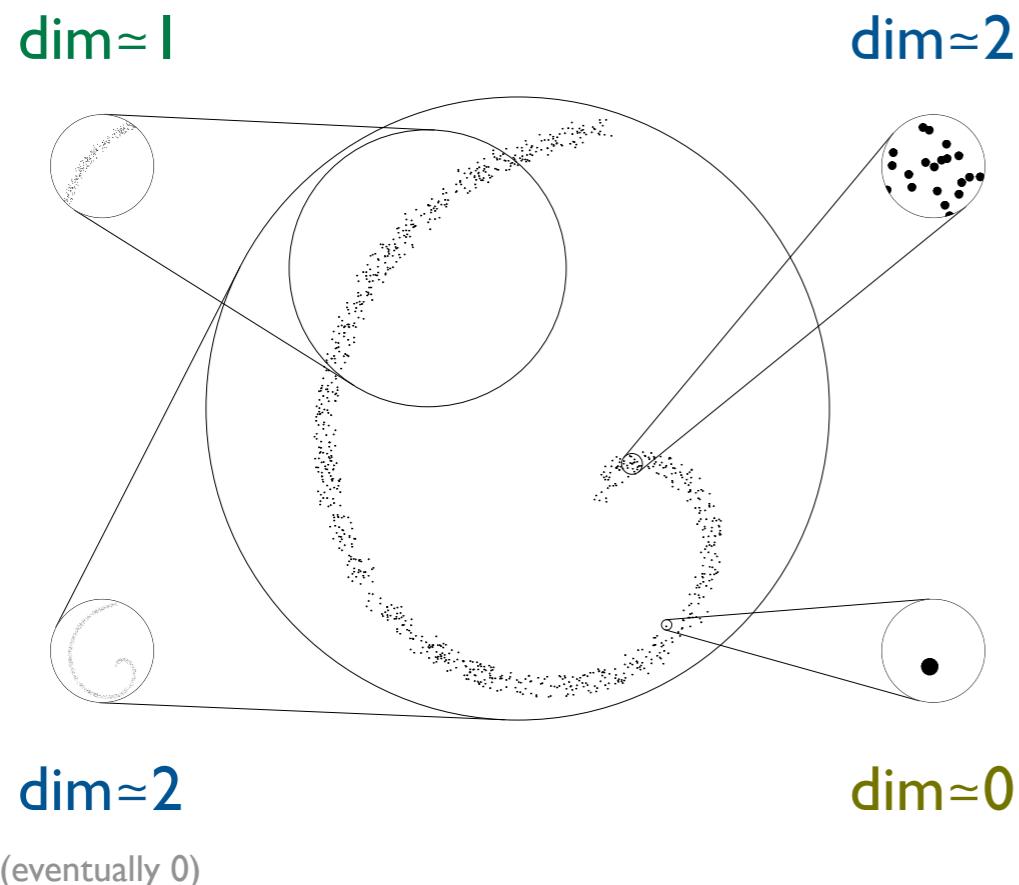
[Komiske, Metodiev, JDT, PRL 2019; code at Komiske, Metodiev, JDT, [energyflow.network](#); see alternative graph network approach in Mullin, Pacey, Parker, White, Williams, arXiv 2019]

Dimensionality of Space of Jets

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

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

[Grassberger, Procaccia, [PRL 1983](#); Kégl, [NIPS 2002](#)]



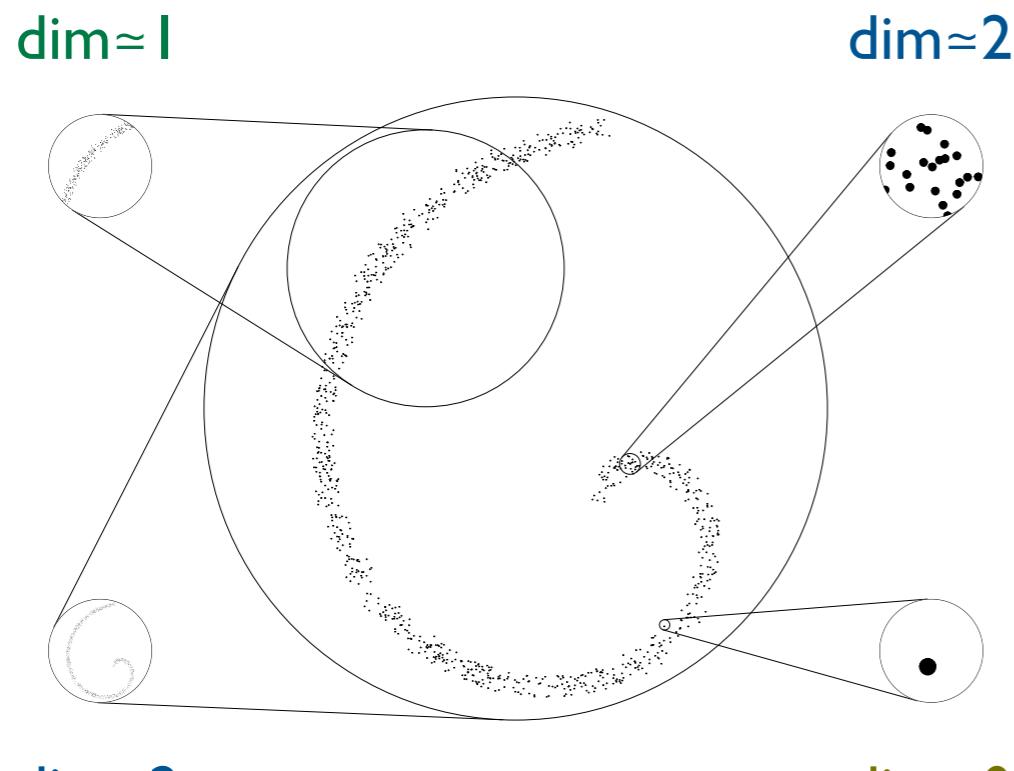
Dimensionality of Space of Jets



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

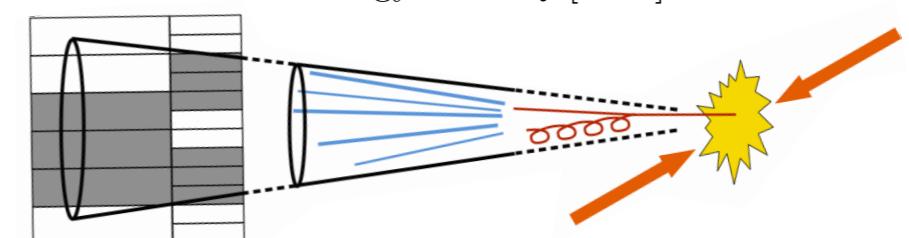
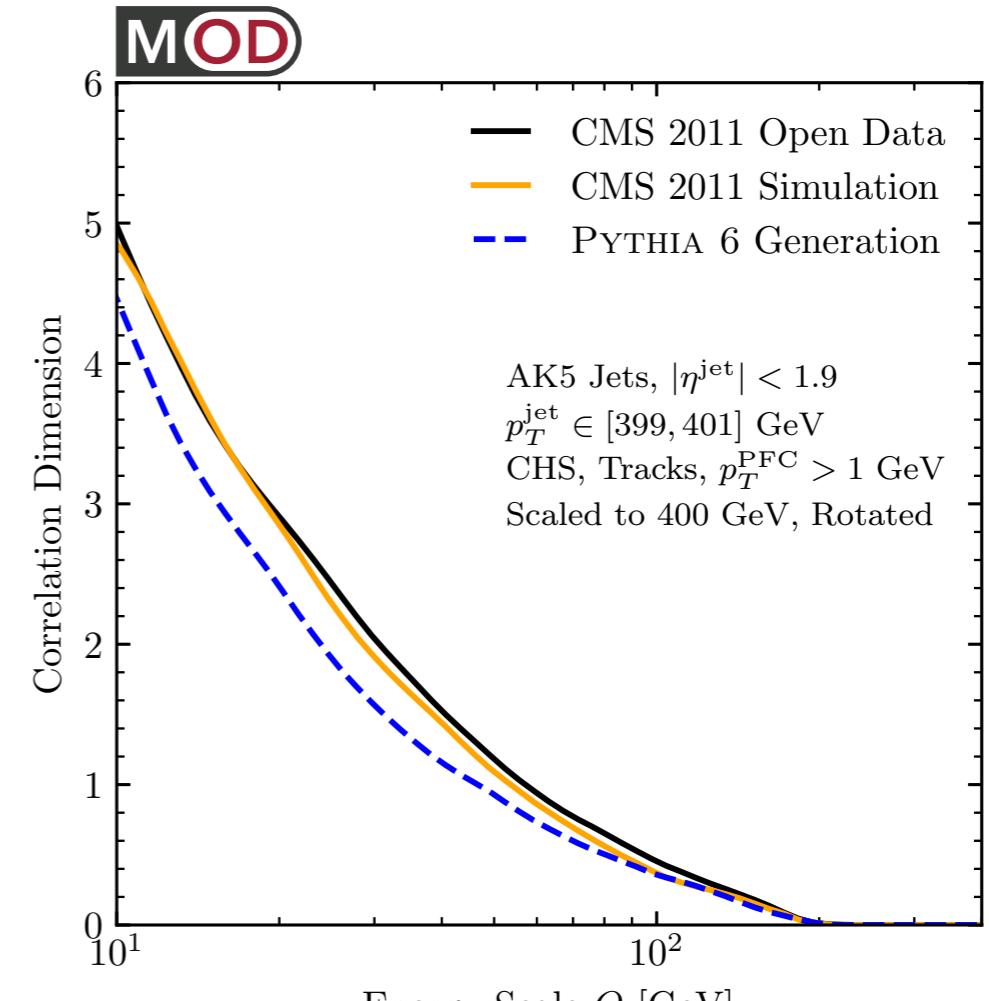
$$\Rightarrow \dim(r) \sim r \frac{\partial}{\partial r} \ln N_{\text{neighbors}}(r)$$

[Grassberger, Procaccia, [PRL 1983](#); Kégl, [NIPS 2002](#)]

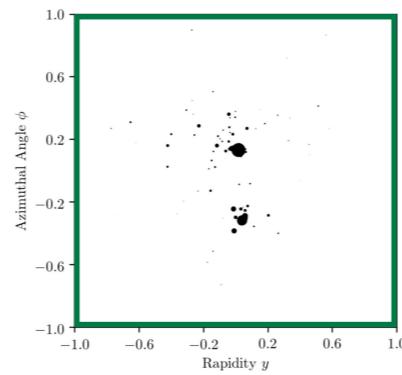


(eventually 0)

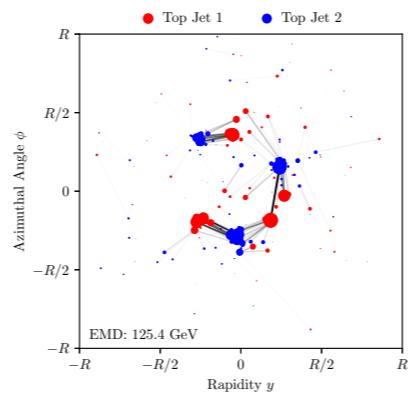
[Komiske, Mastandrea, Metodiev, Naik, [JDT, PRD 2020](#);
using [CMS Open Data](#)]



What is a Collider Event?



When are Events Similar?



“Calo” Energy Density

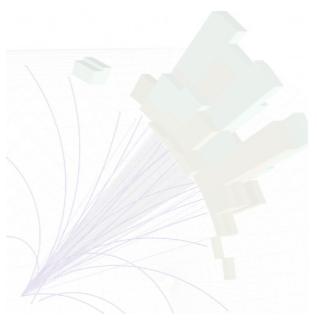
$$\mathcal{E}(\hat{n}) = \sum_i E_i \delta(\hat{n} - \hat{n}_i)$$

(see backup for relevance to ML and QCD)

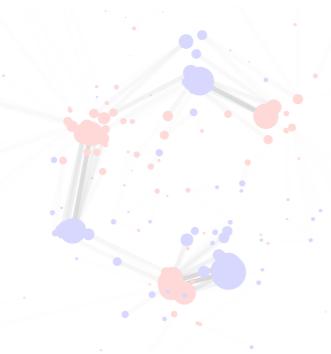
Small Energy Mover's Distance

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

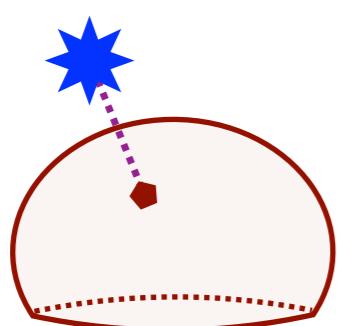
(see backup for more applications)



What is a Collider Event?



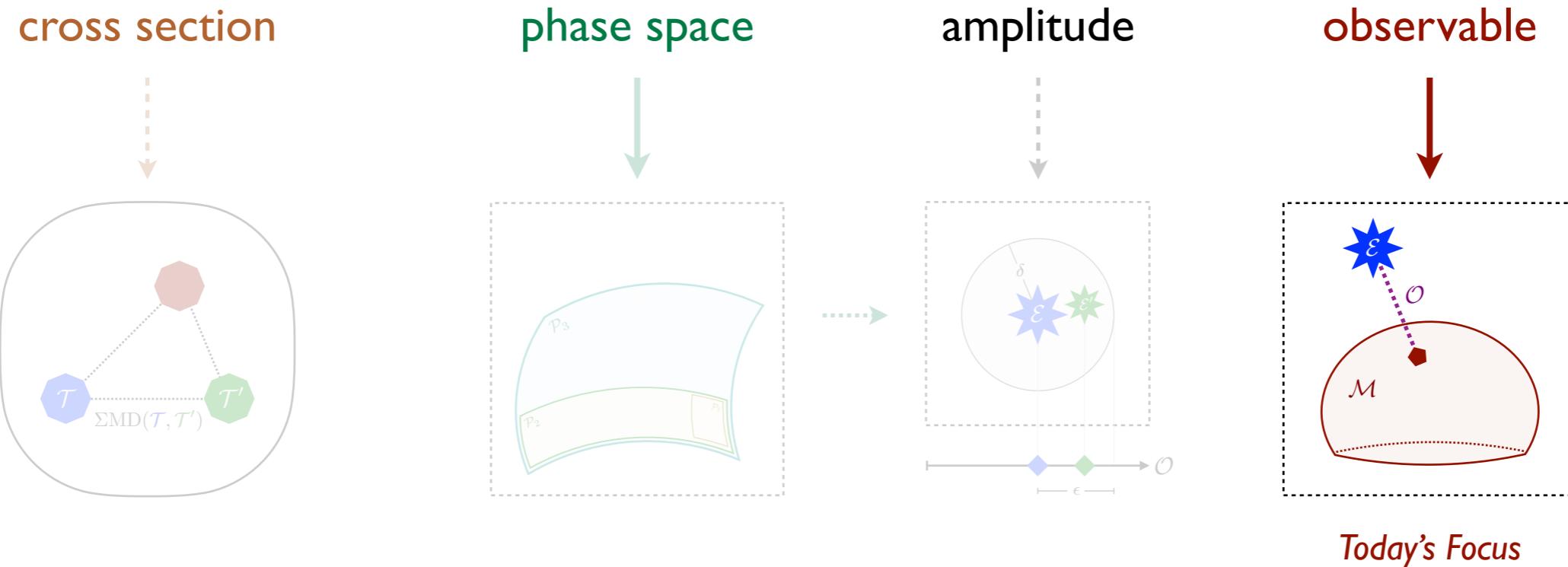
When are Events Similar?



What can be Geometrized?

Master Formula for Collider Physics

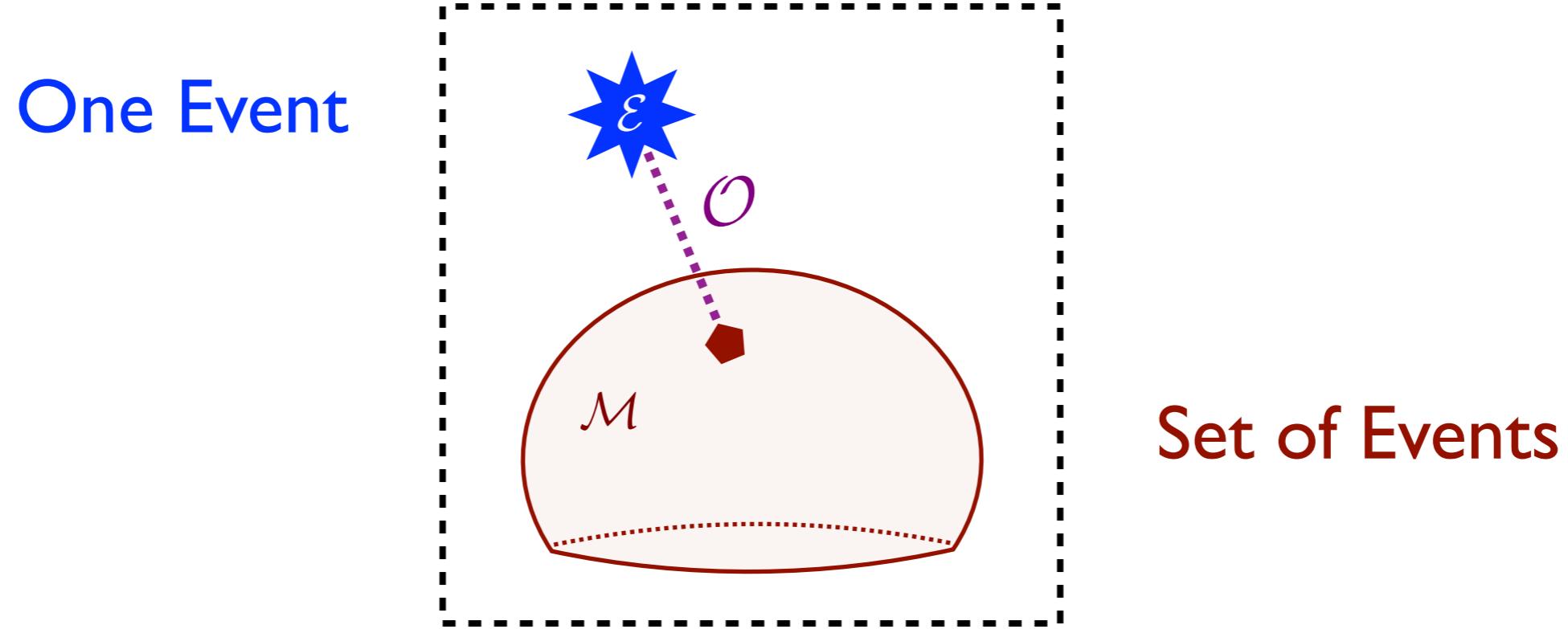
$$\sigma_{\text{obs}} \simeq \frac{1}{2E_{\text{CM}}^2} \sum_{n=2}^{\infty} \int d\Phi_n |\mathcal{M}_{AB \rightarrow 12\dots n}|^2 f_{\text{obs}}(\Phi_n)$$



[Komiske, Metodiev, JDT, [JHEP 2020](#)]

Manifolds for Observables

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



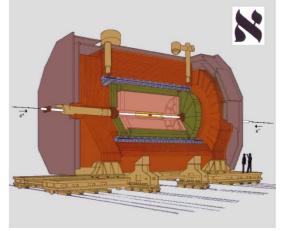
Distance of Closest Approach \Rightarrow Observable

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

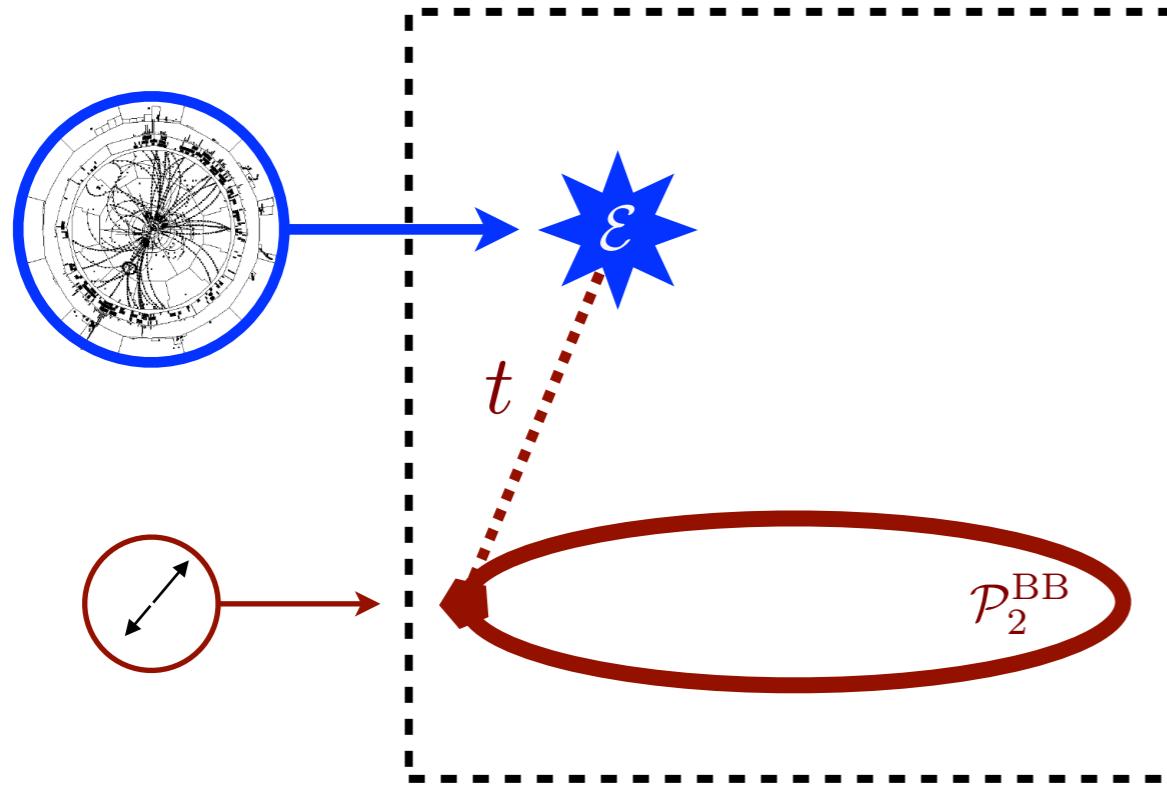
[Komiske, Metodiev, JDT, [JHEP 2020](#)]

E.g. Thrust

How dijet-like is an event?



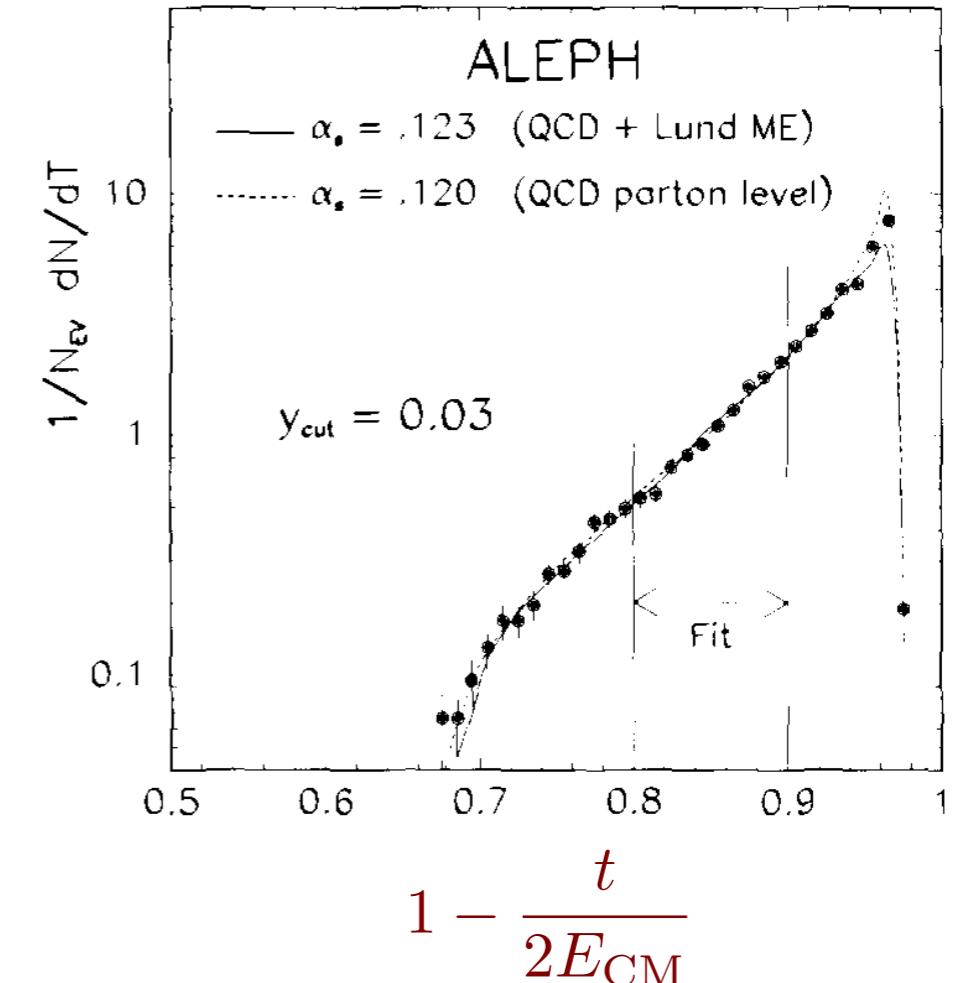
$$t(\mathcal{E}) = \min_{\mathcal{E}' \in \mathcal{P}_2^{\text{BB}}} \text{EMD}_2(\mathcal{E}, \mathcal{E}')$$



All Back-to-Back Two Particle Configurations

$$\mathcal{P}_2^{\text{BB}} = \left\{ \begin{array}{c} \text{circle with } \nearrow \searrow \\ \text{circle with } \nearrow \nwarrow \\ \text{circle with } \swarrow \nearrow \\ \text{circle with } \swarrow \nwarrow \end{array} \dots \right\}$$

(using $\beta=2$ EMD variant)



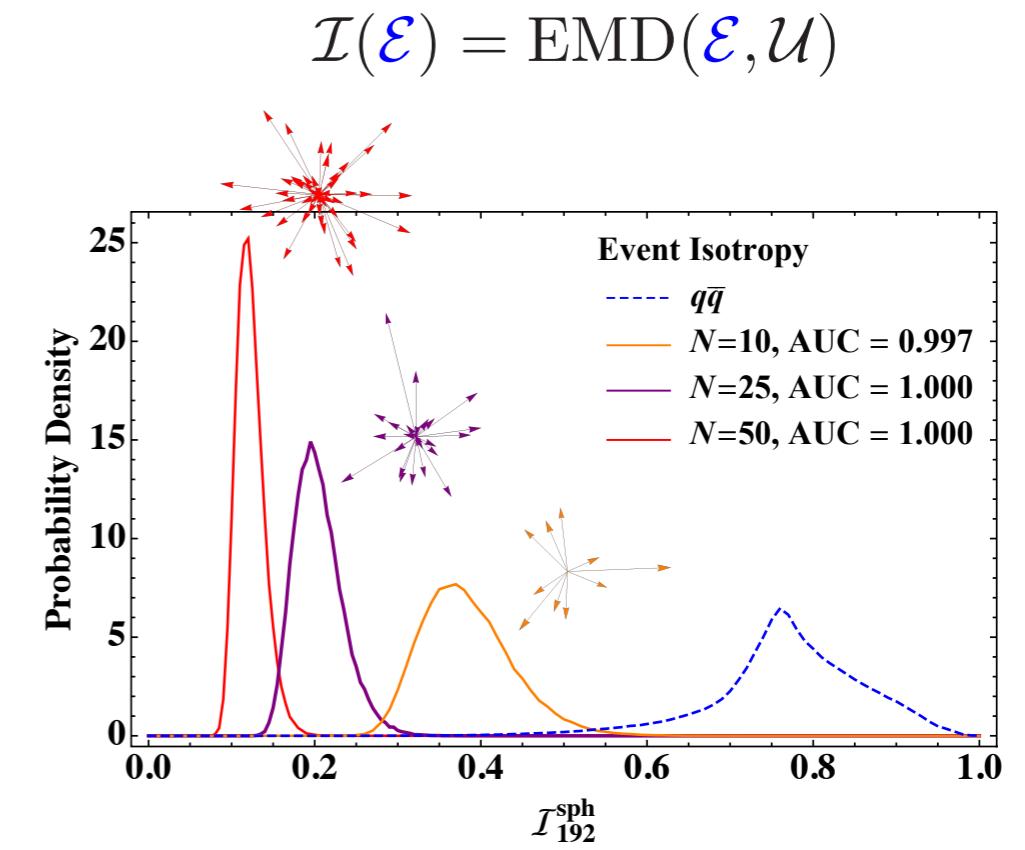
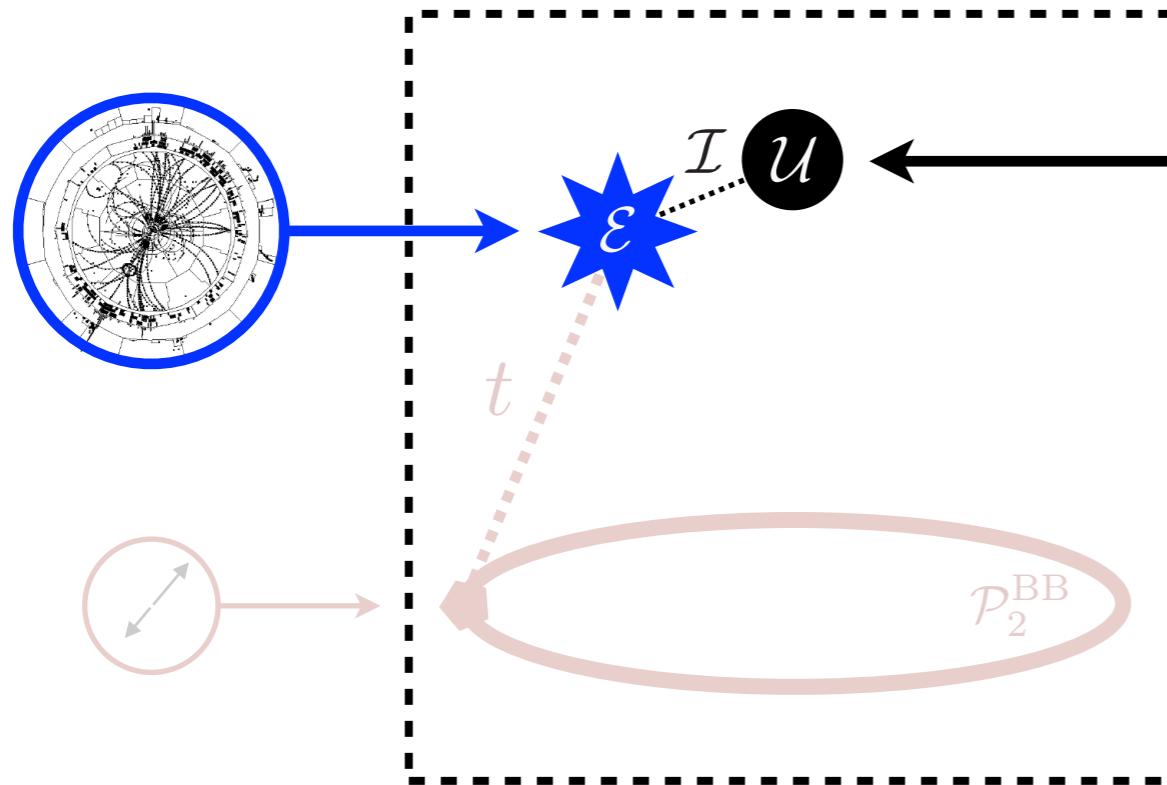
$$1 - \frac{t}{2E_{\text{CM}}}$$

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

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

New! Event Isotropy

How isotropic is an event?

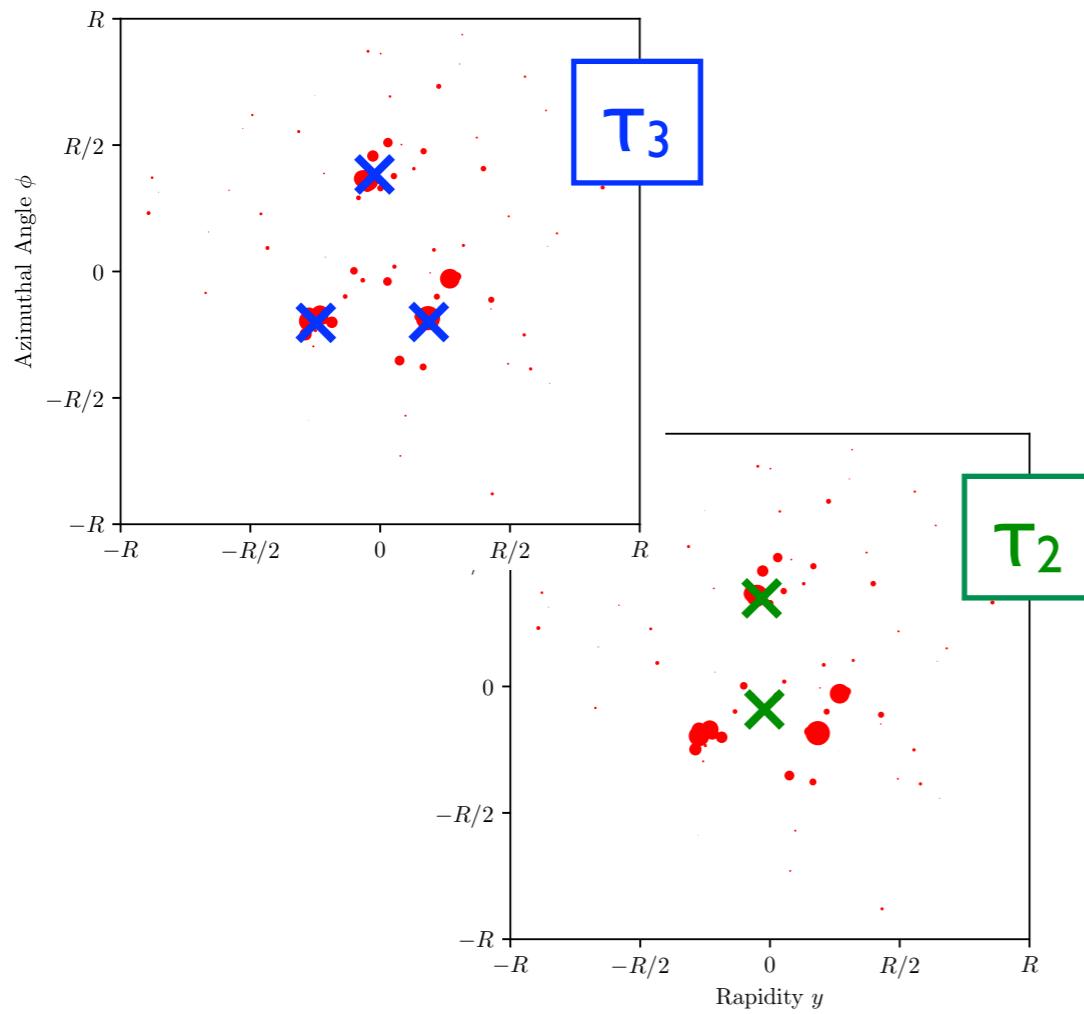


[Cesarotti, JDT, [JHEP 2020](#);
see also Cesarotti, Reece, Strassler, [arXiv 2020](#)]

N-subjettiness

Ubiquitous jet substructure observable used for almost a decade...

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

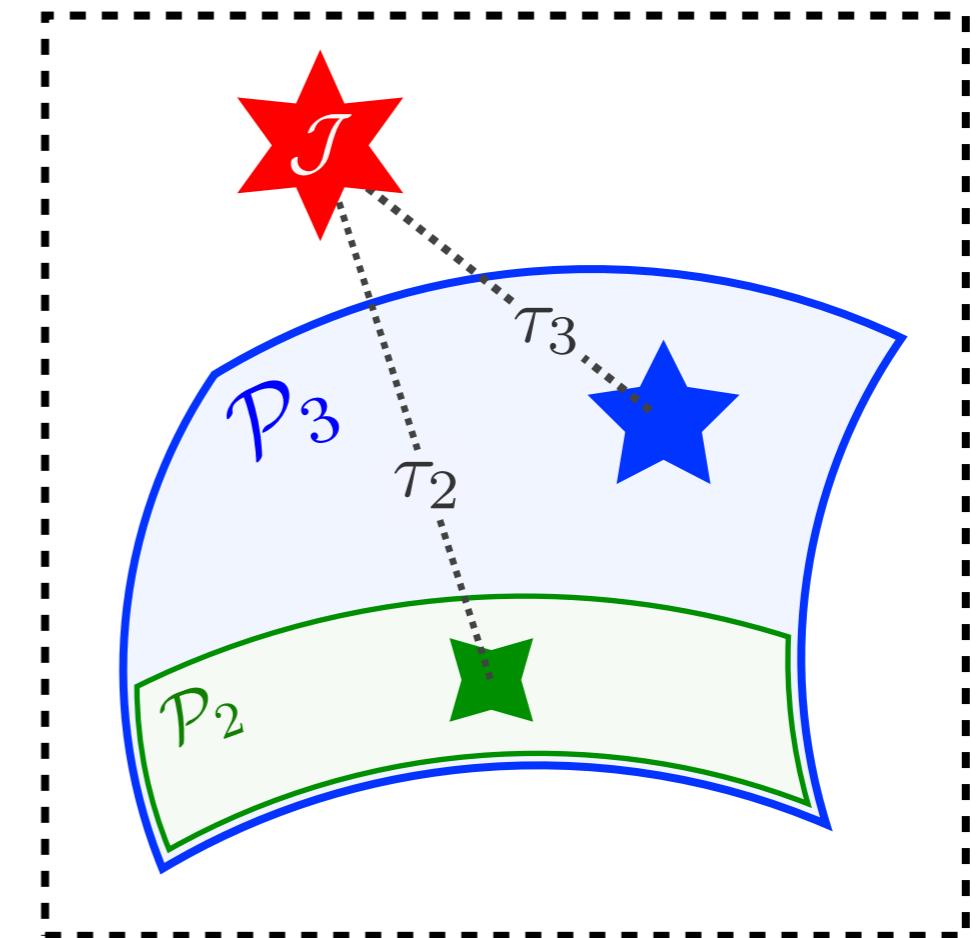
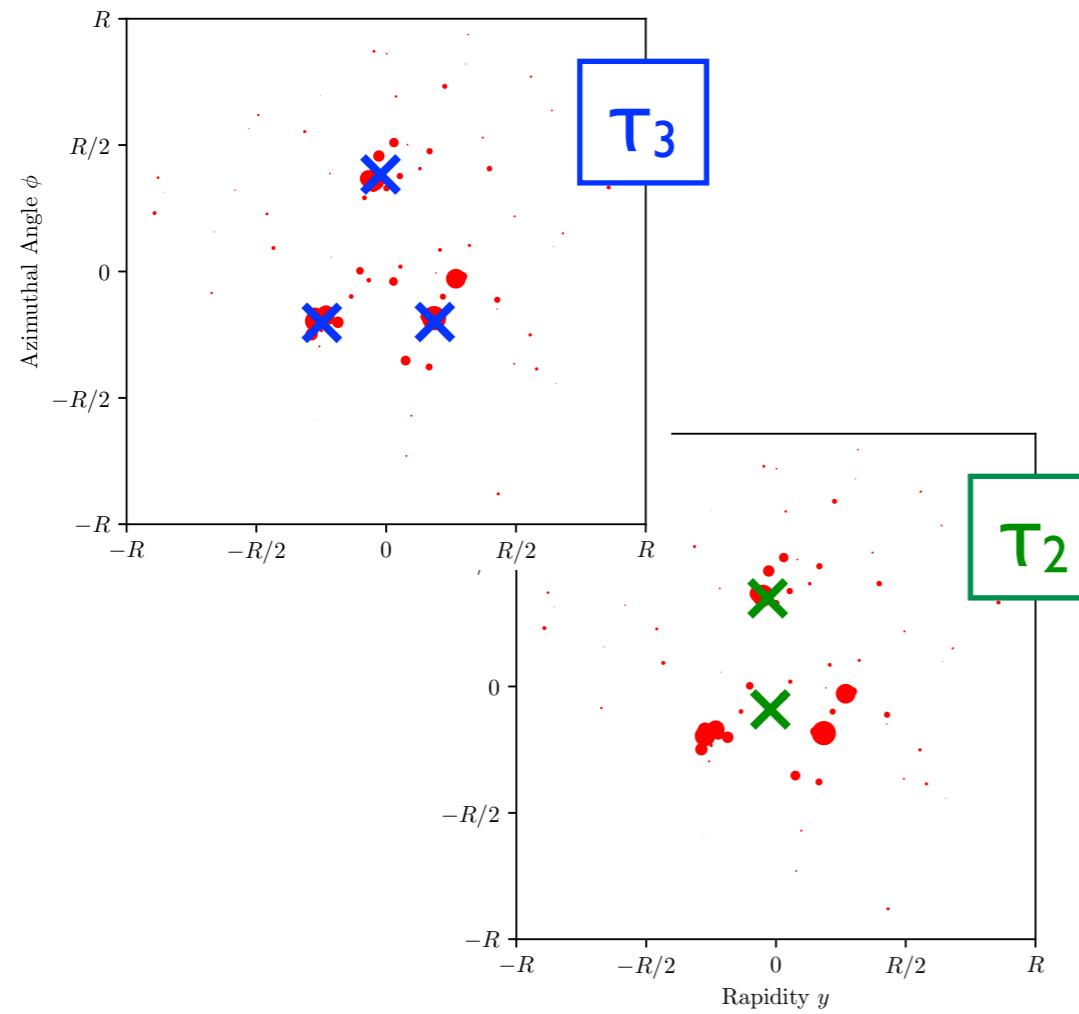


[JDT, Van Tilburg, [JHEP 2011](#), [JHEP 2012](#);
based on Brandt, Dahmen, [ZPC 1979](#); Stewart, Tackmann, Waalewijn, [PRL 2010](#)]

N-subjettiness = Point to Manifold EMD

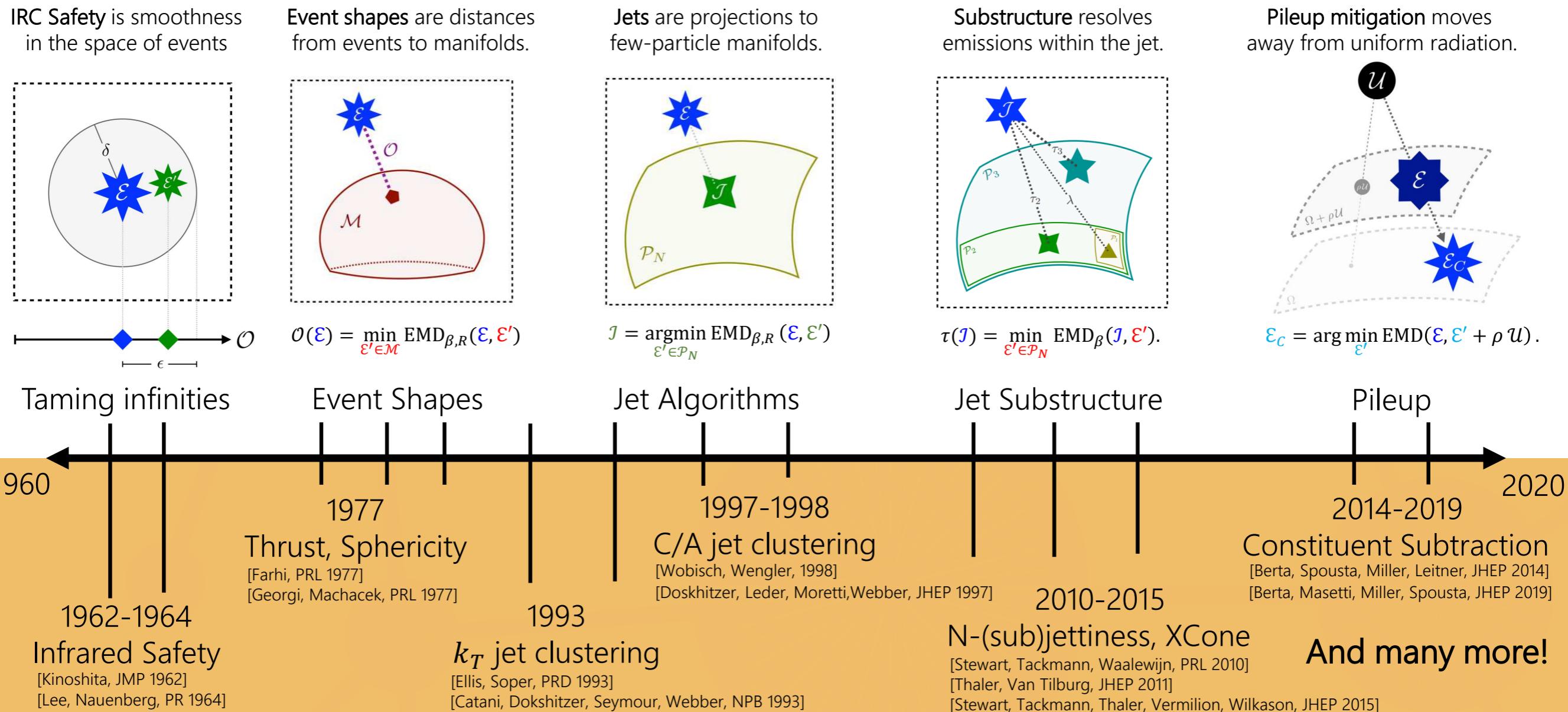
...is secretly an optimal transport problem

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



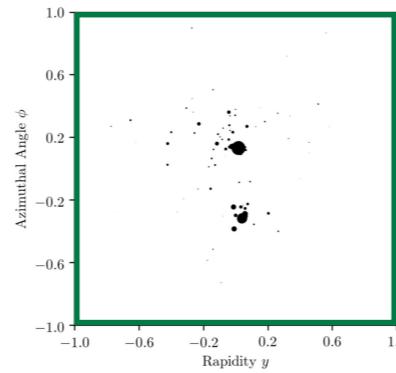
[JDT, Van Tilburg, [JHEP 2011](#), [JHEP 2012](#);
rephrased in the language of Komiske, Metodiev, JDT, [PRL 2019](#)]

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

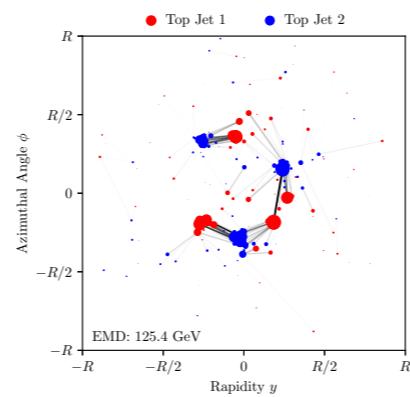


[timeline from Eric Metodiev]

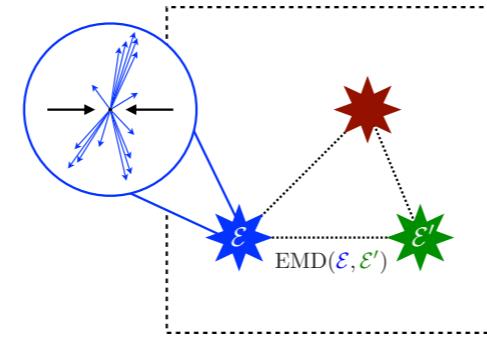
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“Calo” Energy Density

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(see backup for relevance to ML and QCD)

Small Energy Mover’s Distance

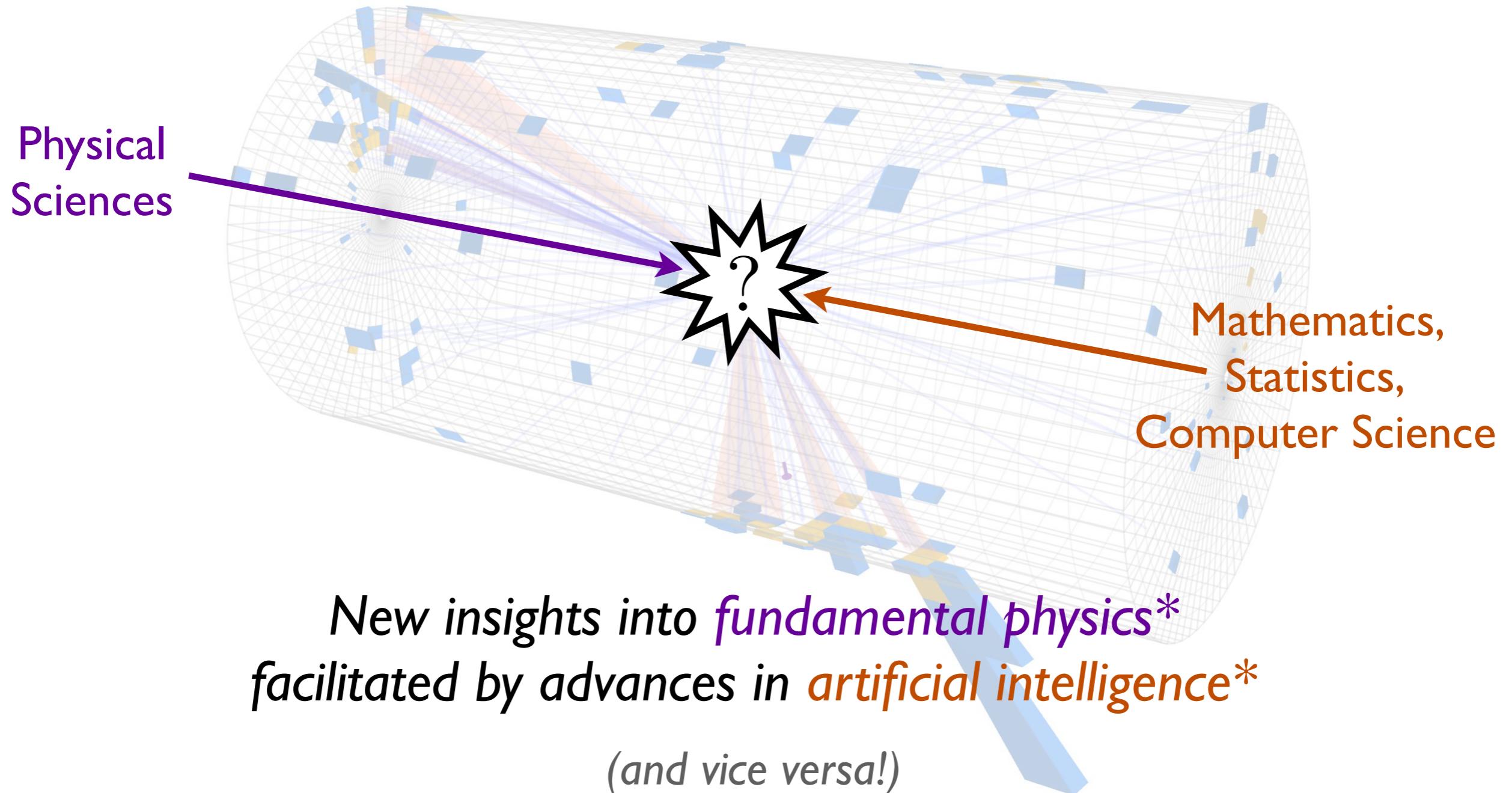
$$\text{EMD}(\mathcal{E}, \mathcal{E}') = \min_{\{f\}} \sum_i \sum_j f_{ij} \frac{\theta_{ij}}{R} + \left| \sum_i E_i - \sum_j E'_j \right|$$

(see backup for more applications)

Half Century of Collider Physics and Quantum Field Theory

(see backup for more cartoons)

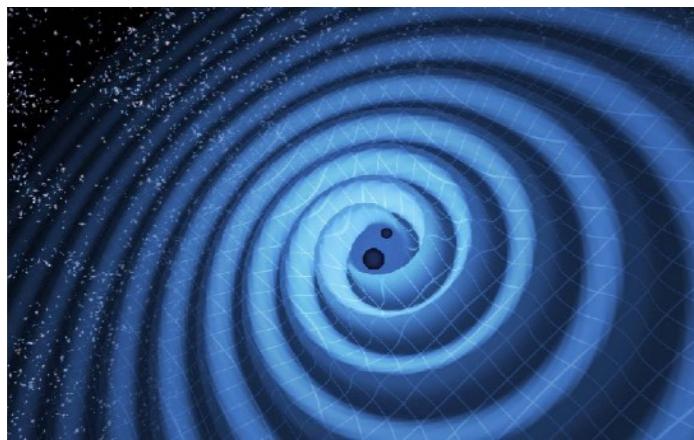
“Collision Course”



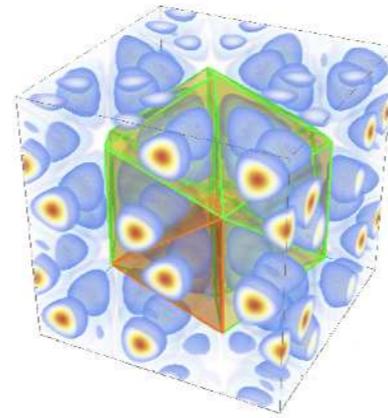
Artificial Intelligence \Leftrightarrow Fundamental Interactions



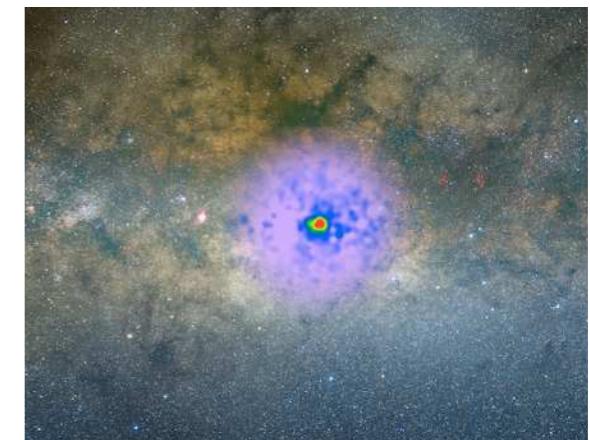
Gravitational Waves



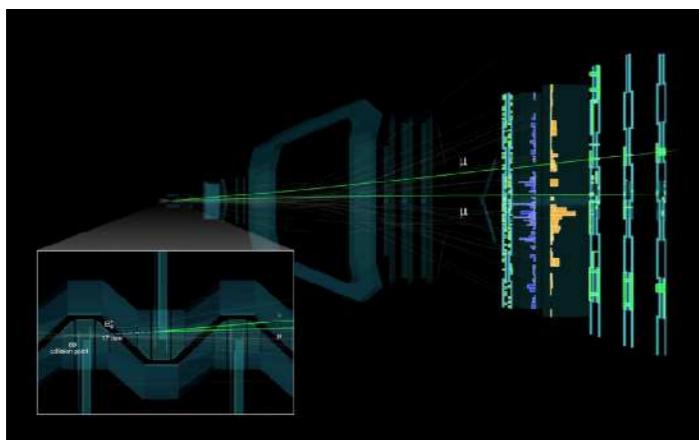
Nuclear Physics



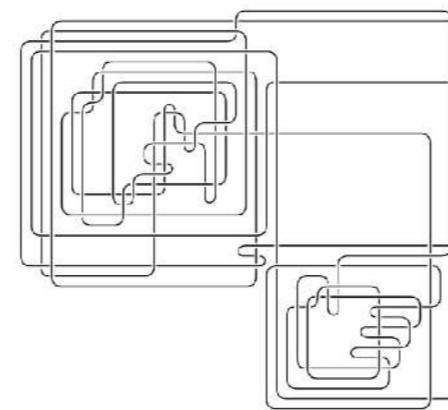
Astrophysics



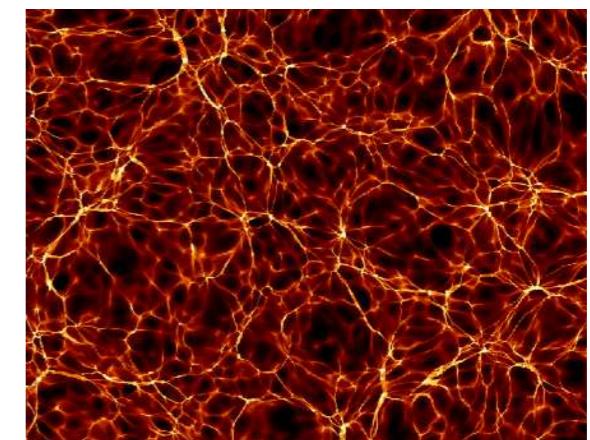
Particle Colliders



Mathematical Physics



Dark Matter



...

The NSF AI Institute for Artificial Intelligence and Fundamental Interactions (IAIFI) “eye-phi”

*Advance physics knowledge — from the smallest building blocks of nature
to the largest structures in the universe — and galvanize AI research innovation*



<http://iaifi.org/>

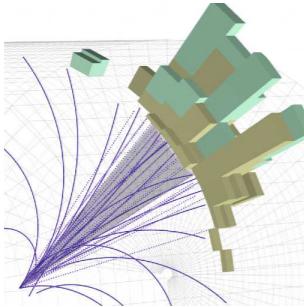
Physics
Theory



Physics
Experiment

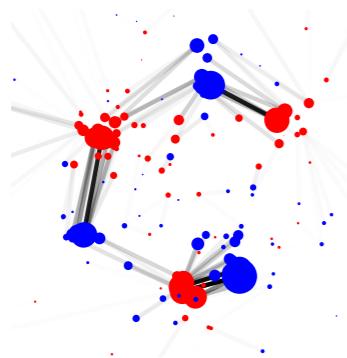


Summary



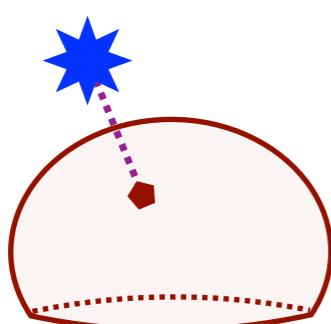
What is a Collider Event?

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



When are Events Similar?

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

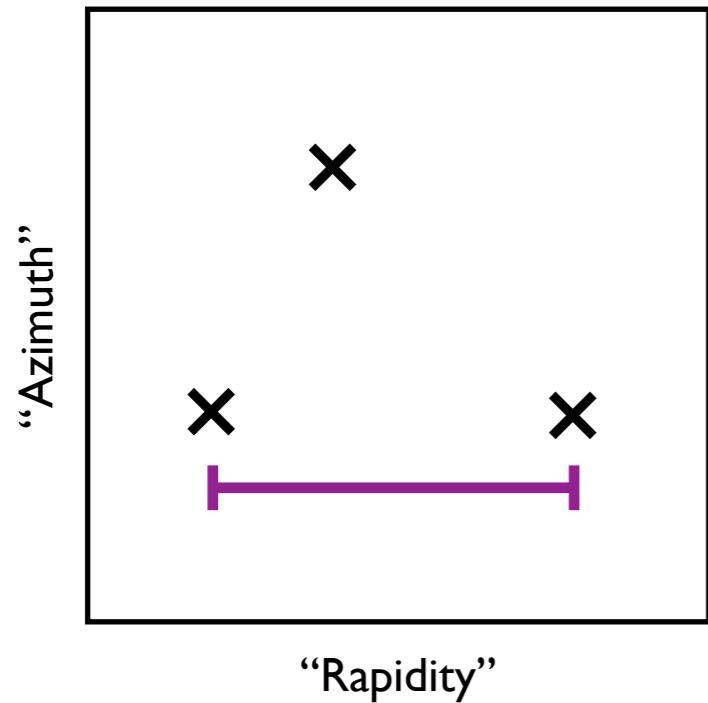


What can be Geometrized?

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

How far down does this rabbit hole go?

Direction Space



x = Direction

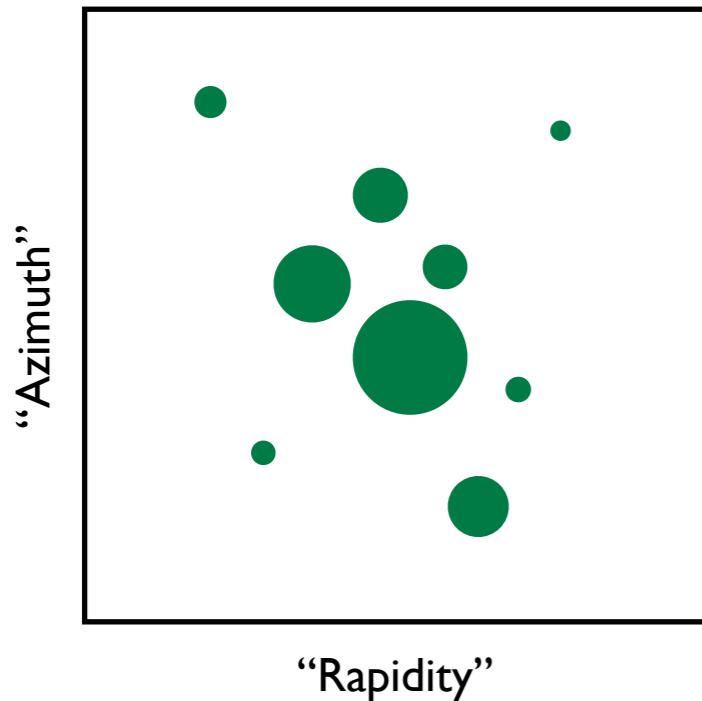
= Angular Distance

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

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

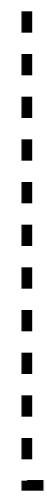
(for massless particles)

Direction Space Distribution



● = Weighted Direction

— = Angular Distance



★ = Event

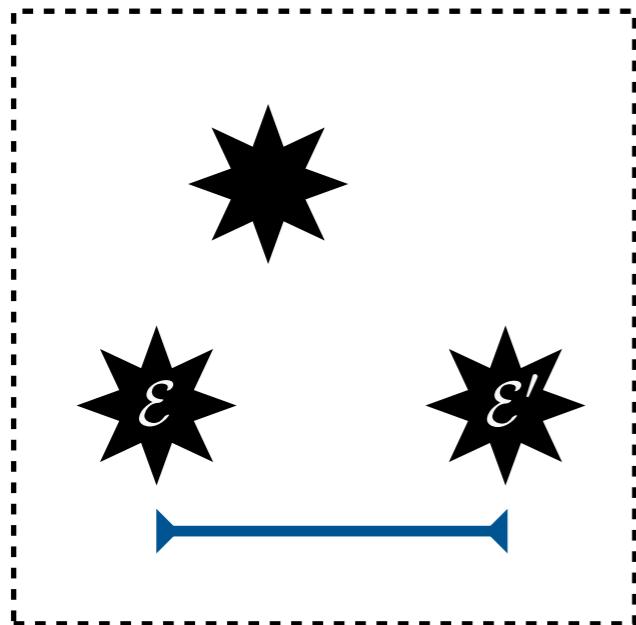
$$n_i^\mu = \frac{p_i^\mu}{E_i} = (1, \hat{n})^\mu$$

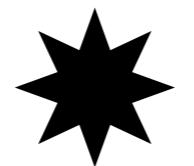
$$w_i = E_i$$

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

(for massless particles)

Event Space



 = Event
 = EMD
Energy
Mover's Distance

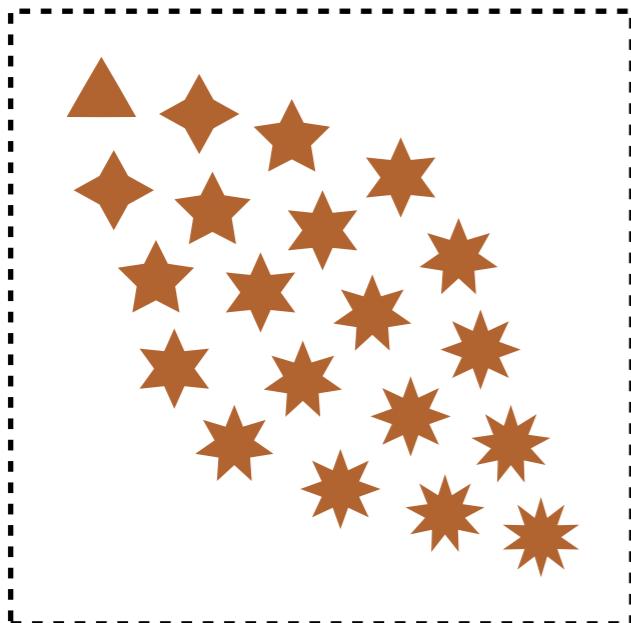
$$\mathcal{E}(\hat{n}) = \sum_i E_i \delta(\hat{n} - \hat{n}_i)$$

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

(for equal total energy)

[Komiske, Metodiev, JDT, PRL 2019]

Event Space Distribution



= Weighted Event

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

$$w_a = \sigma_a$$

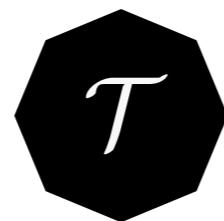
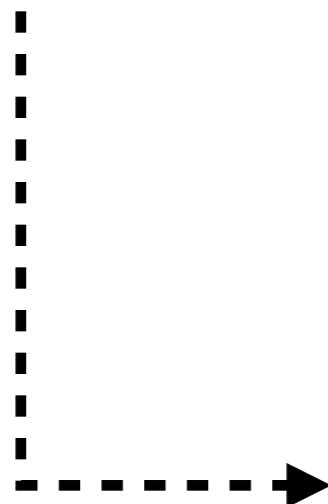


= EMD

Energy
Mover's Distance

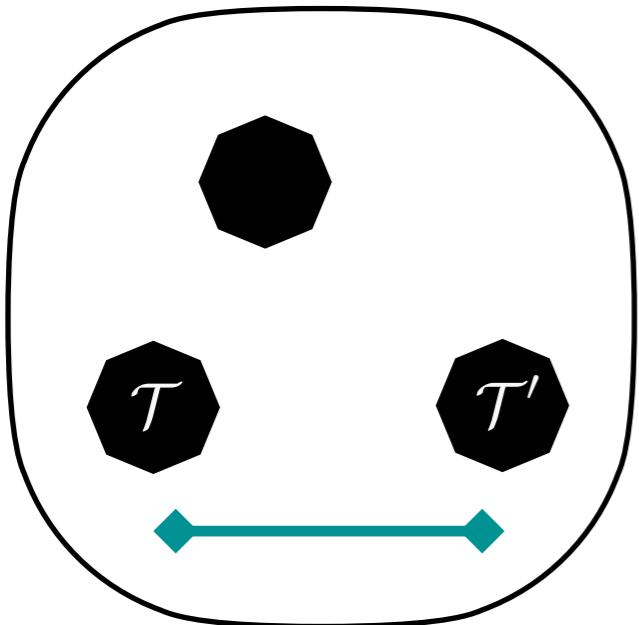
$$\text{EMD}(\mathcal{E}, \mathcal{E}') = \min_{\{f\}} \sum_i \sum_j f_{ij} \theta_{ij}$$

(for equal total energy)



= Theory

Theory Space



● = Theory

↔ = ΣMD
Cross-Section
Mover's Distance

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

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

(for equal total xsec)

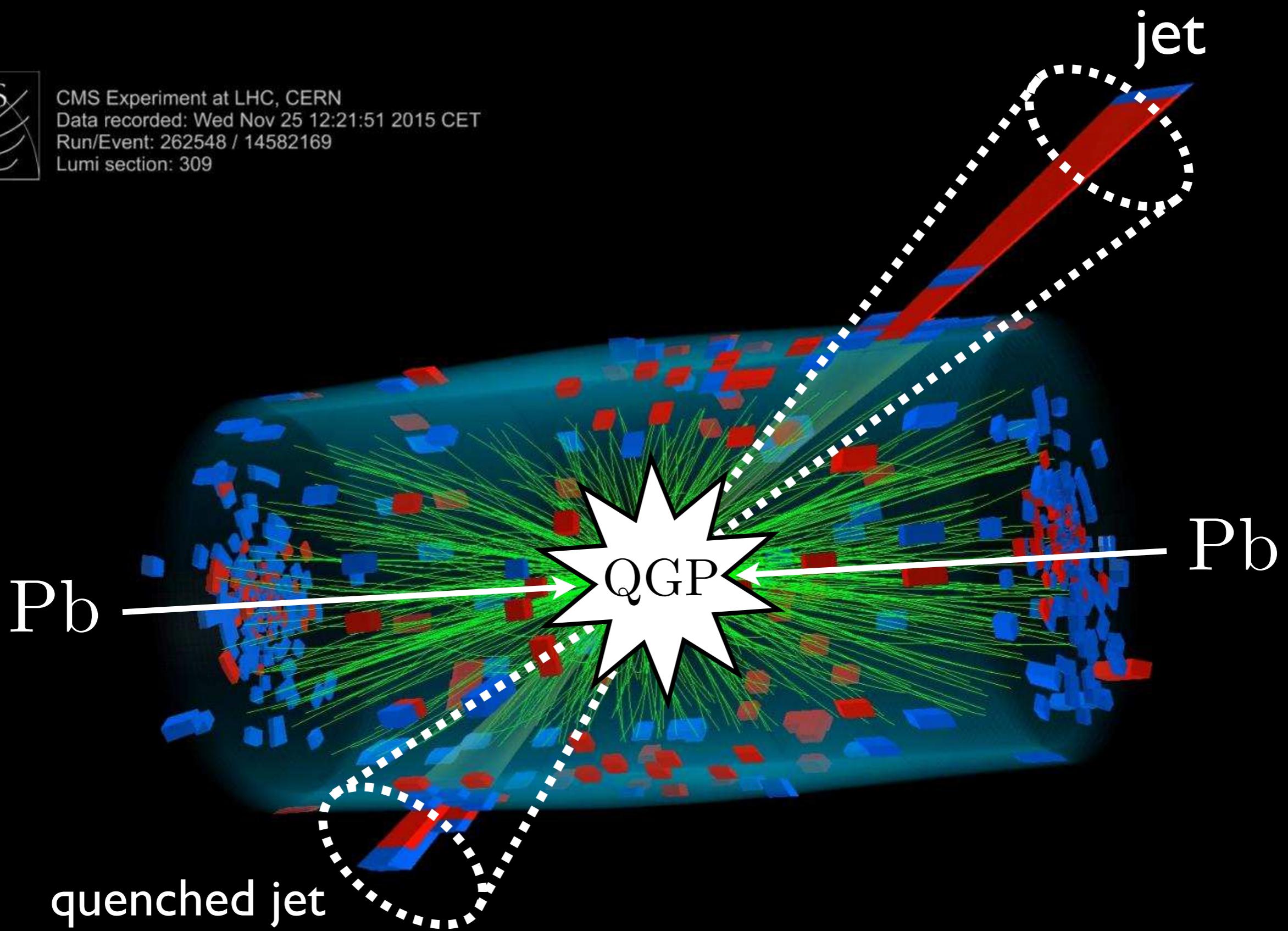
A distance between theories!

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

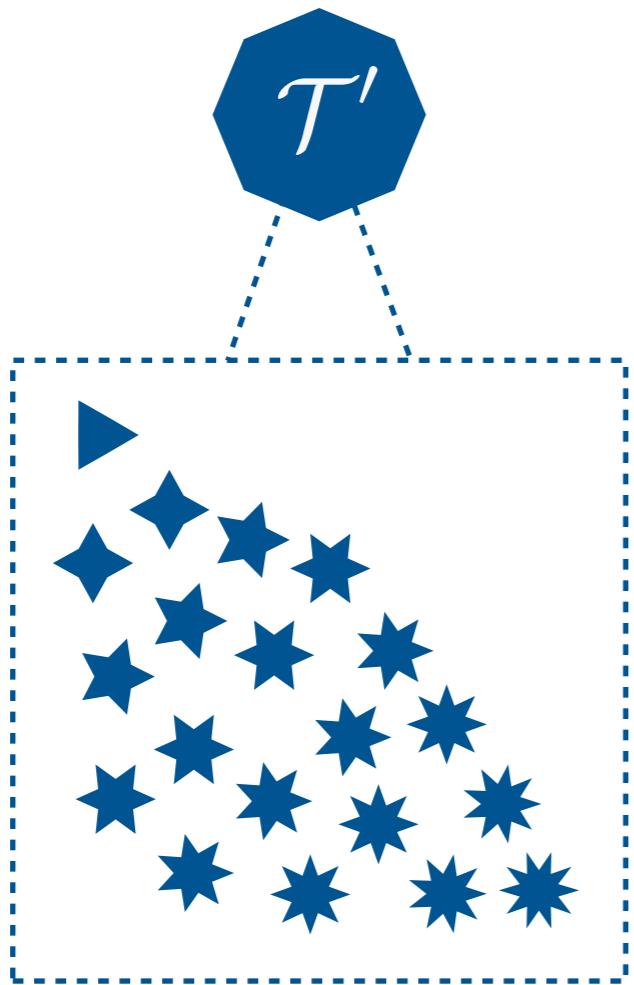
[Komiske, Metodiev, JDT, [JHEP 2020](#)]



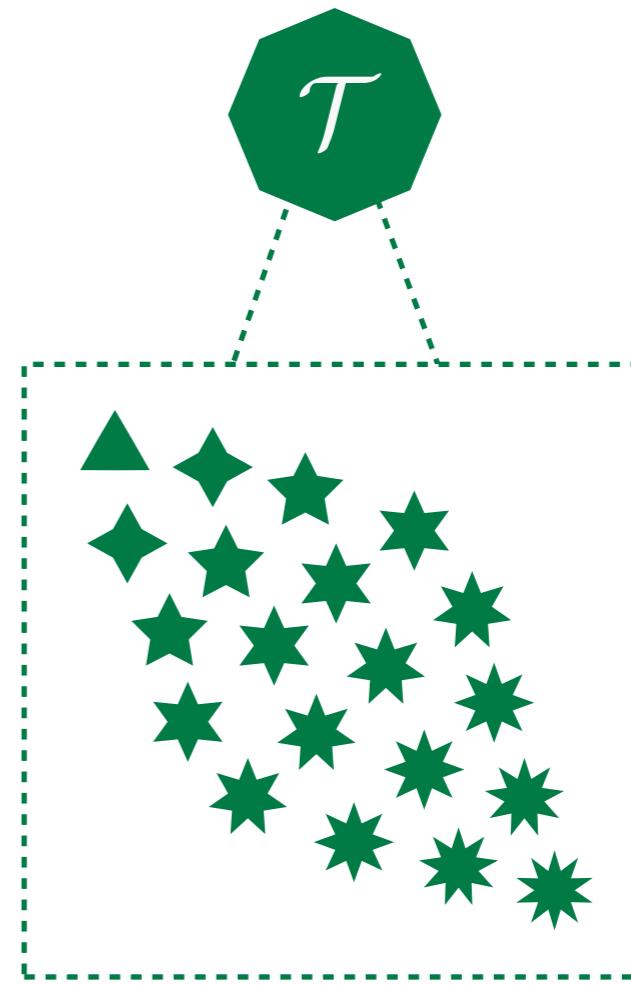
CMS Experiment at LHC, CERN
Data recorded: Wed Nov 25 12:21:51 2015 CET
Run/Event: 262548 / 14582169
Lumi section: 309



Theory Prime: In-Medium QCD



Theory: Vacuum QCD

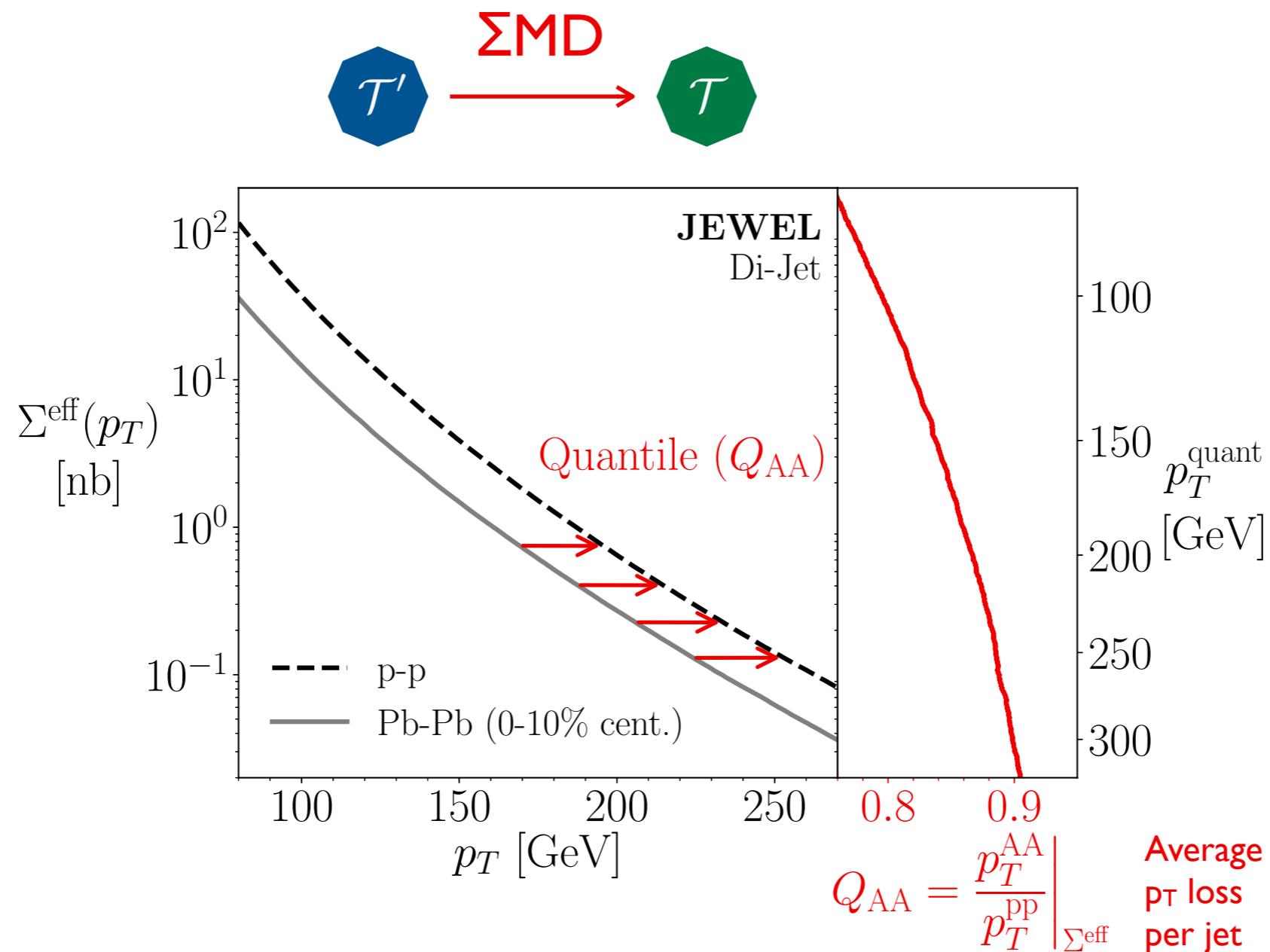


ΣMD
 \iff

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

Jet Quenching via Quantile Matching

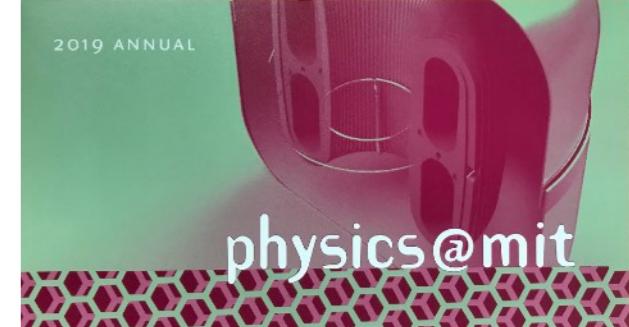
Equivalent to following a geodesic in theory space (!)



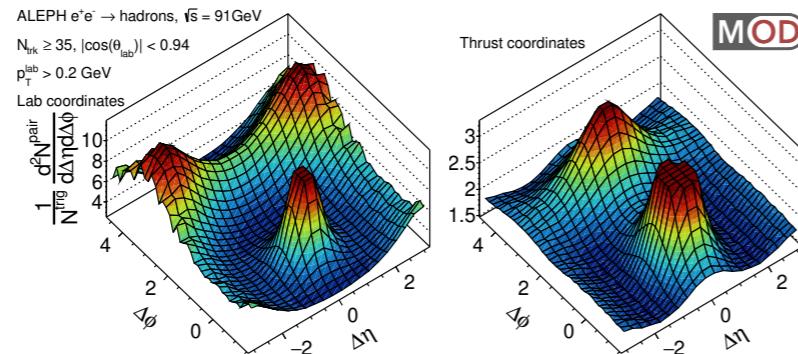
[Brewer, Milhano, JDT, PRL 2019]

More Backup Slides

Collaborations Across MIT Physics

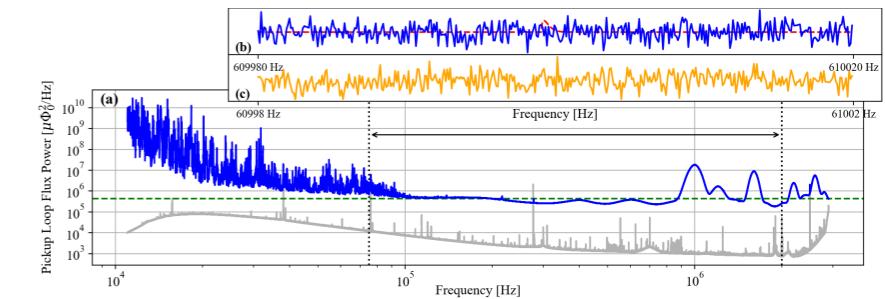


Back (to Back) to the Future



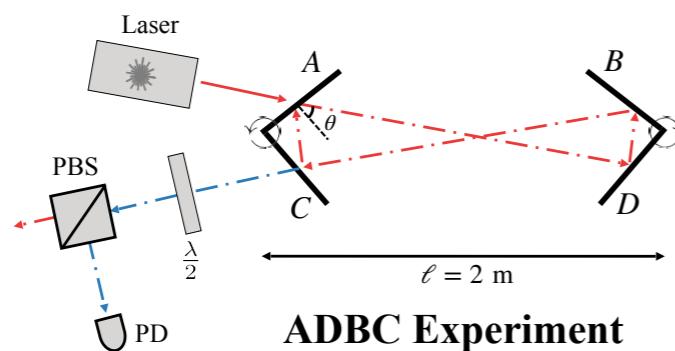
[Badea, Baty, Chang, Innocenti, Maggi, McGinn, Peters, Sheng, JDT, Lee, [PRL 2019](#)]

. Abracadabra .



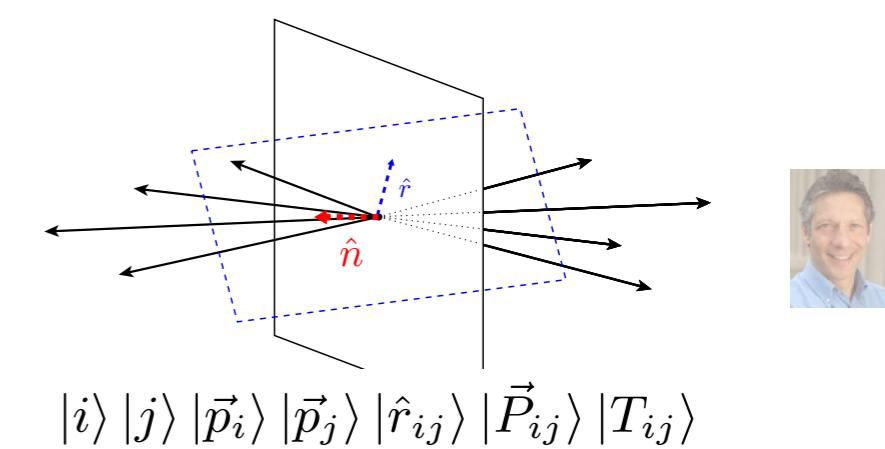
[Ouellet, Salemi, Foster, Henning, Bogorad, Conrad, Formaggio, Kahn, Minervini, Radovinsky, Rodd, Safdi, JDT, Winklehner, Winslow, [PRL 2019](#)]

Shining Light on Dark Matter



[Liu, Elwood, Evans, JDT, [PRD 2019](#)]

Quantum Collider Physics



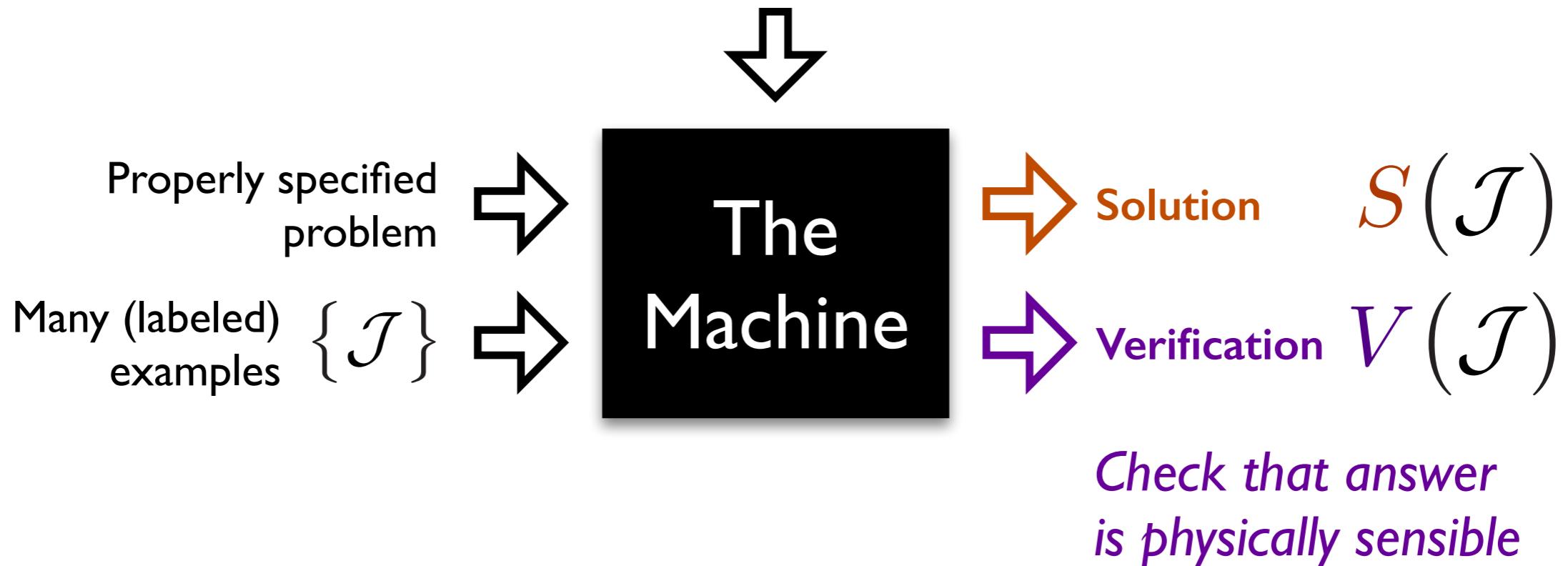
[Wei, Naik, Harrow, JDT, [PRD 2020](#); inspired by Farhi, [PRL 1977](#)]

Aside: Machine Learning for Jets

“ML4Jets”
NYU, January 2020

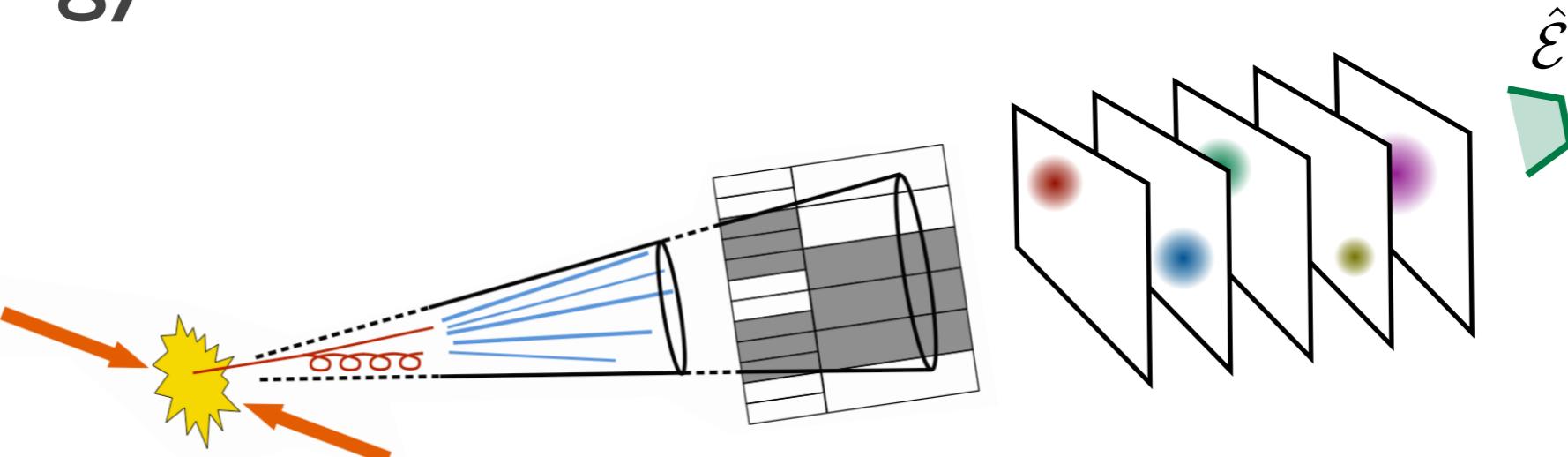
Symmetry: $\mathcal{J} = \{ \vec{p}_1, \vec{p}_2, \vec{p}_3, \dots, \vec{p}_N \}$
Unordered, Variable Length Set (QM!)

Safety: $\vec{p} = \{ E, \hat{n}_x, \hat{n}_y, \hat{n}_z \}$
Energy weighting (QFT!)

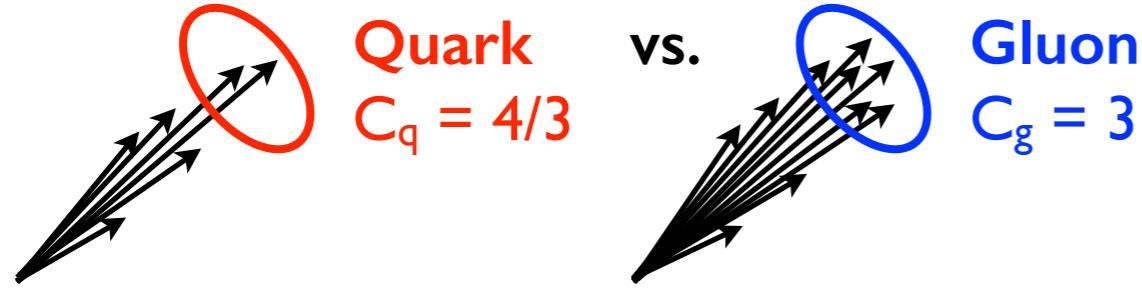


*Check that answer
is physically sensible*

E.g. Energy Flow Networks

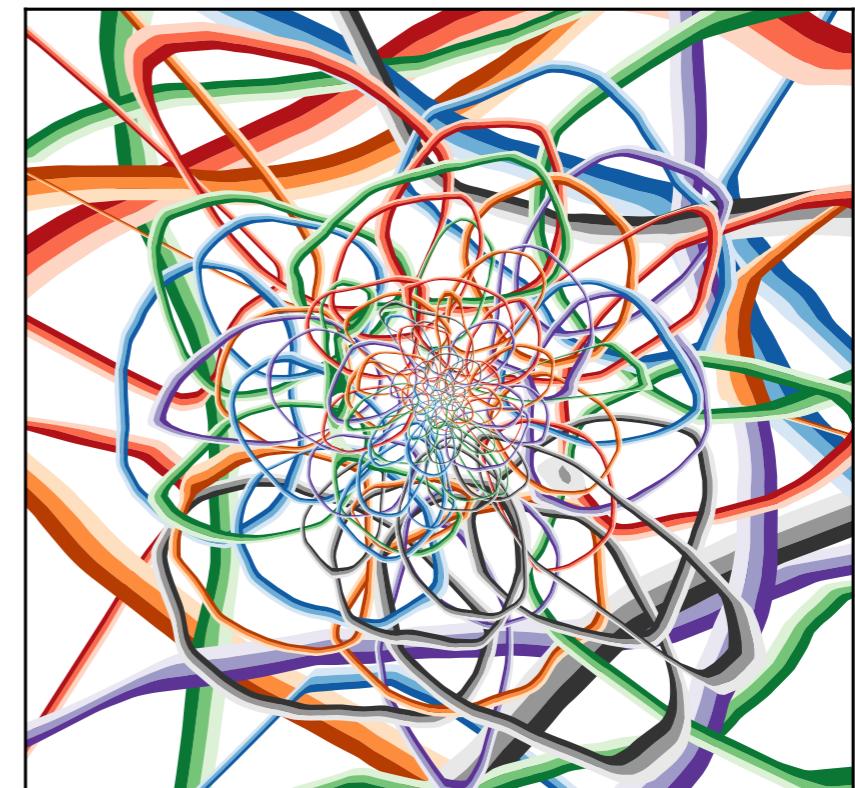
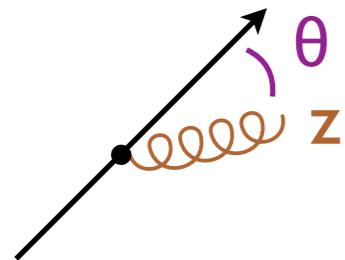


Learning QCD singularities!



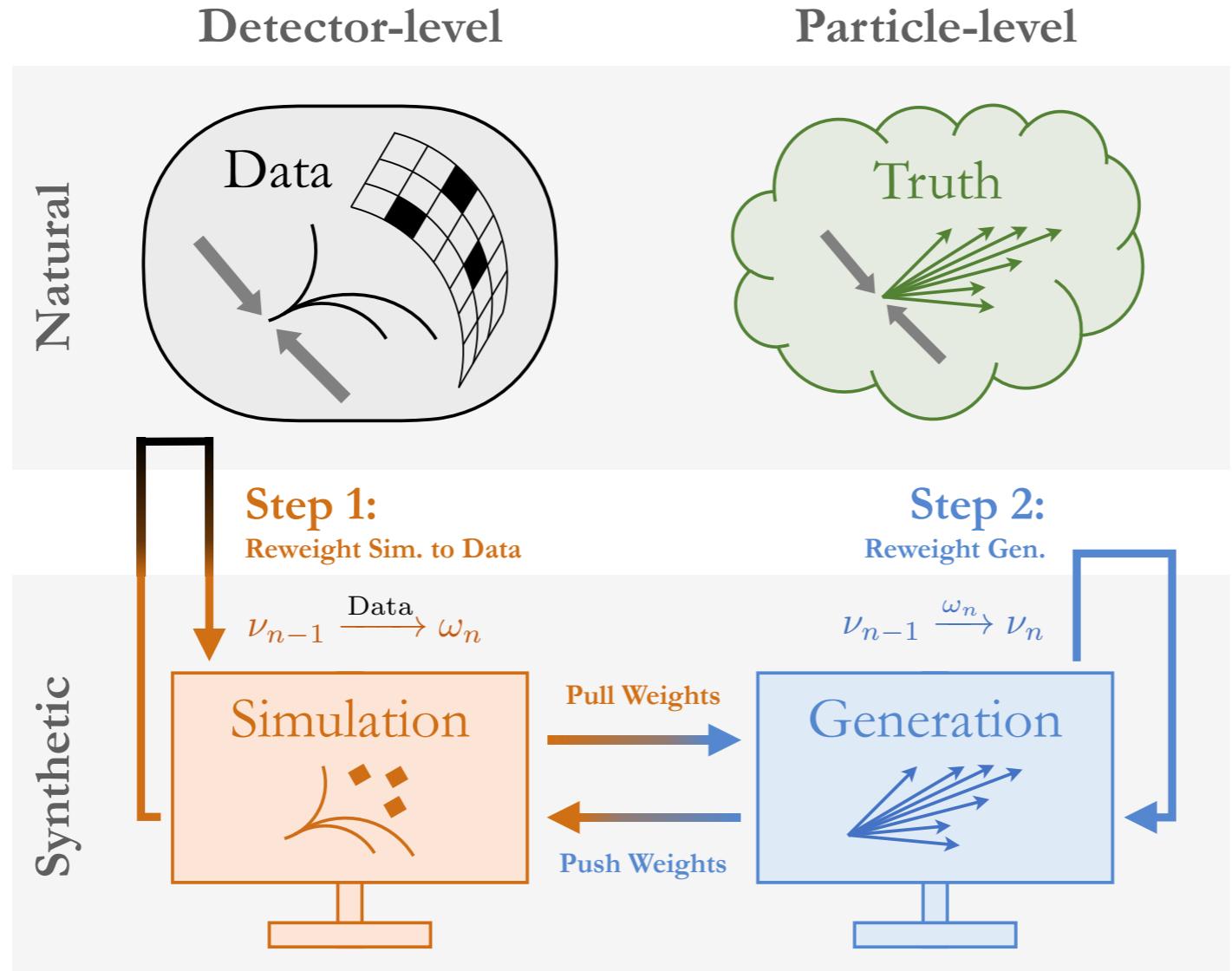
AP splitting probability:

$$dP_{i \rightarrow ig} \simeq \frac{2\alpha_s}{\pi} C_i \frac{d\theta}{\theta} \frac{dz}{z}$$



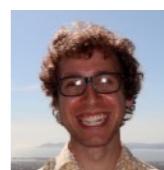
[Komiske, Metodiev, JDT, [JHEP 2019](#); see also Komiske, Metodiev, JDT, [JHEP 2018](#), [PRD 2020](#); special case of Zaheer, Kottur, Ravanbakhsh, Poczos, Salakhutdinov, Smola, [NIPS 2017](#)]

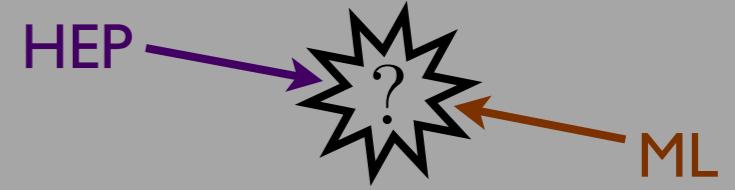
OmniFold



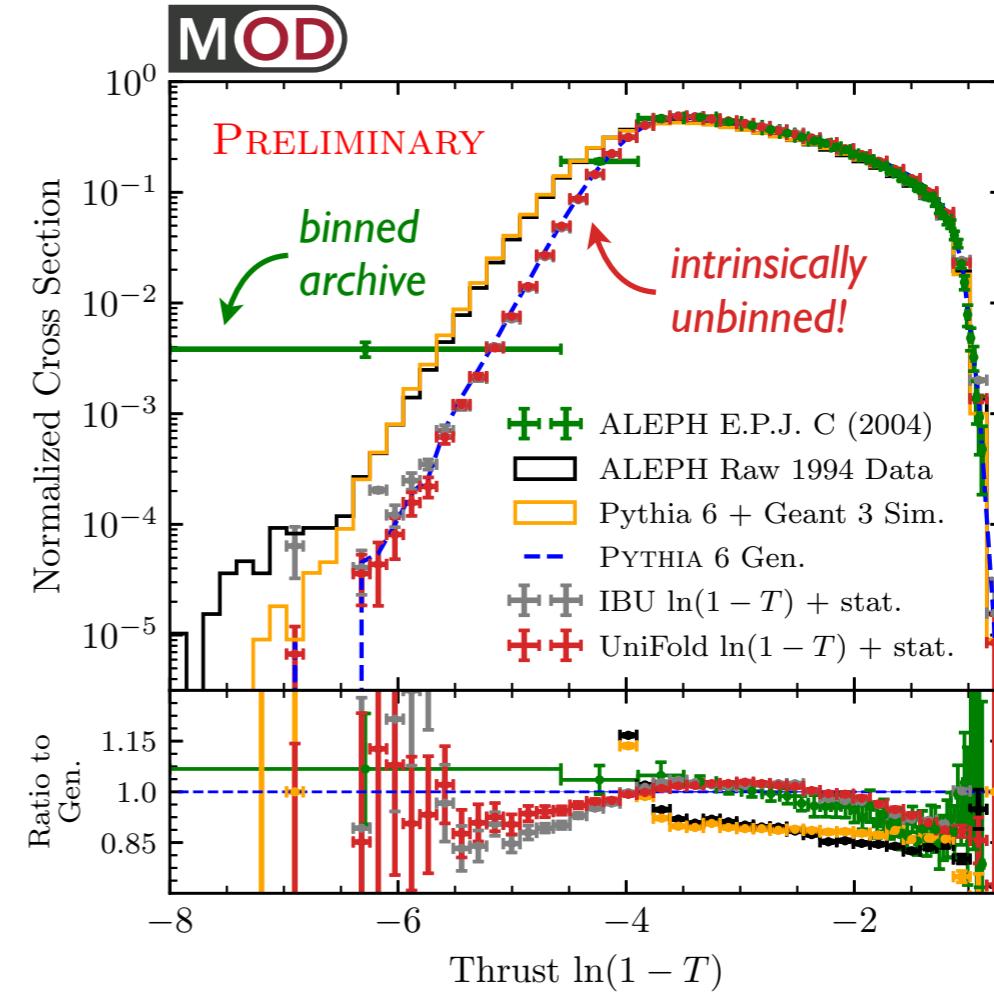
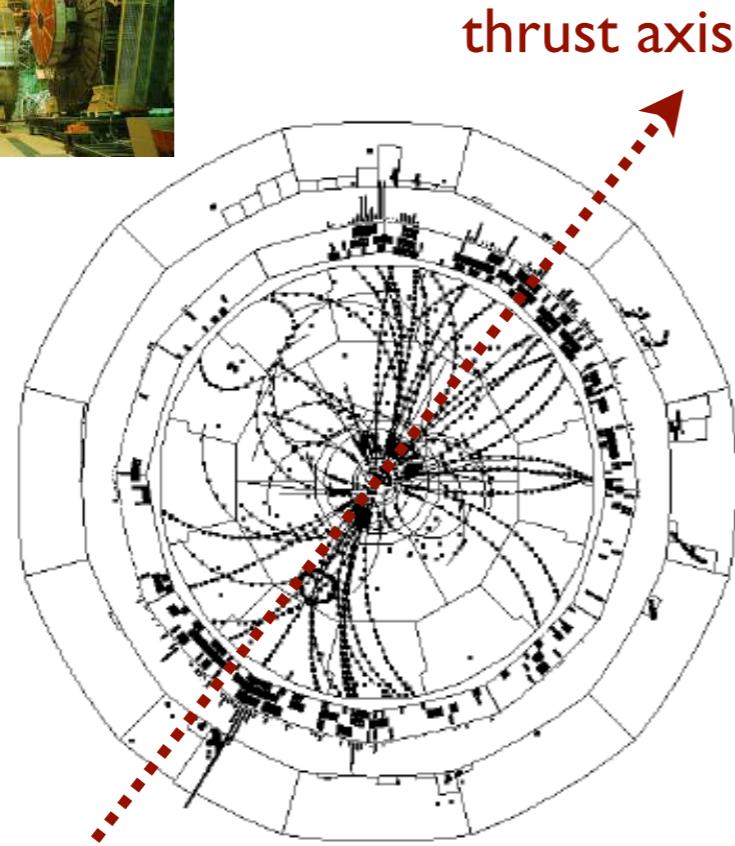
Multi-dimensional unbinned detector corrections via iterated binary classification

[Andreassen, Komiske, Metodiev, Nachman, JDT, [PRL 2020](#)]

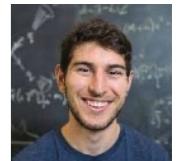




Back to the Future with ALEPH Archival Data



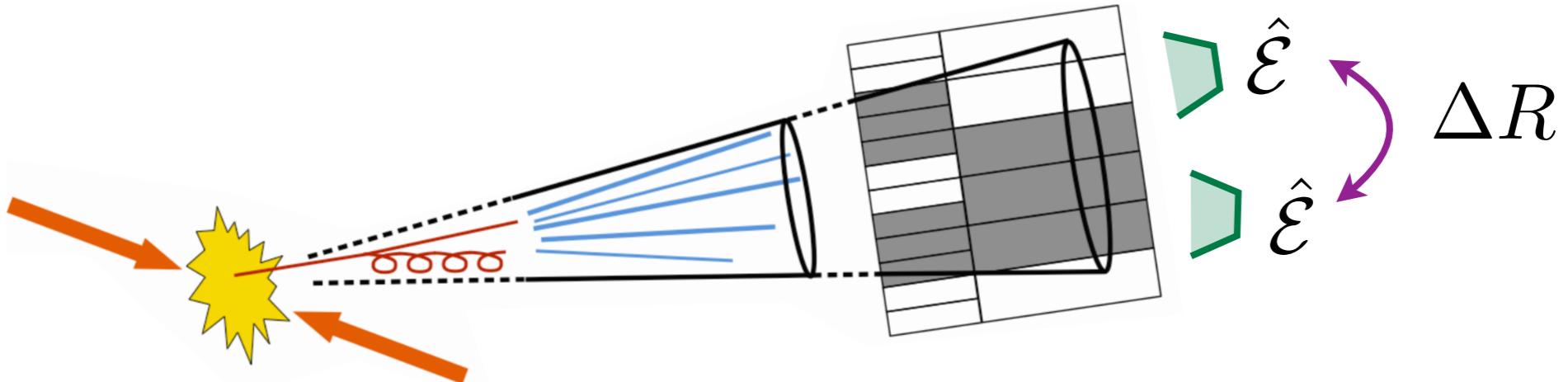
[talk by Badea, [ICHEP 2020](#); cf. ALEPH, [EPJC 2004](#)
 [see also Badea, Baty, Chang, Innocenti, Maggi, McGinn, Peters, Sheng, JDT, Lee, [PRL 2019](#)]



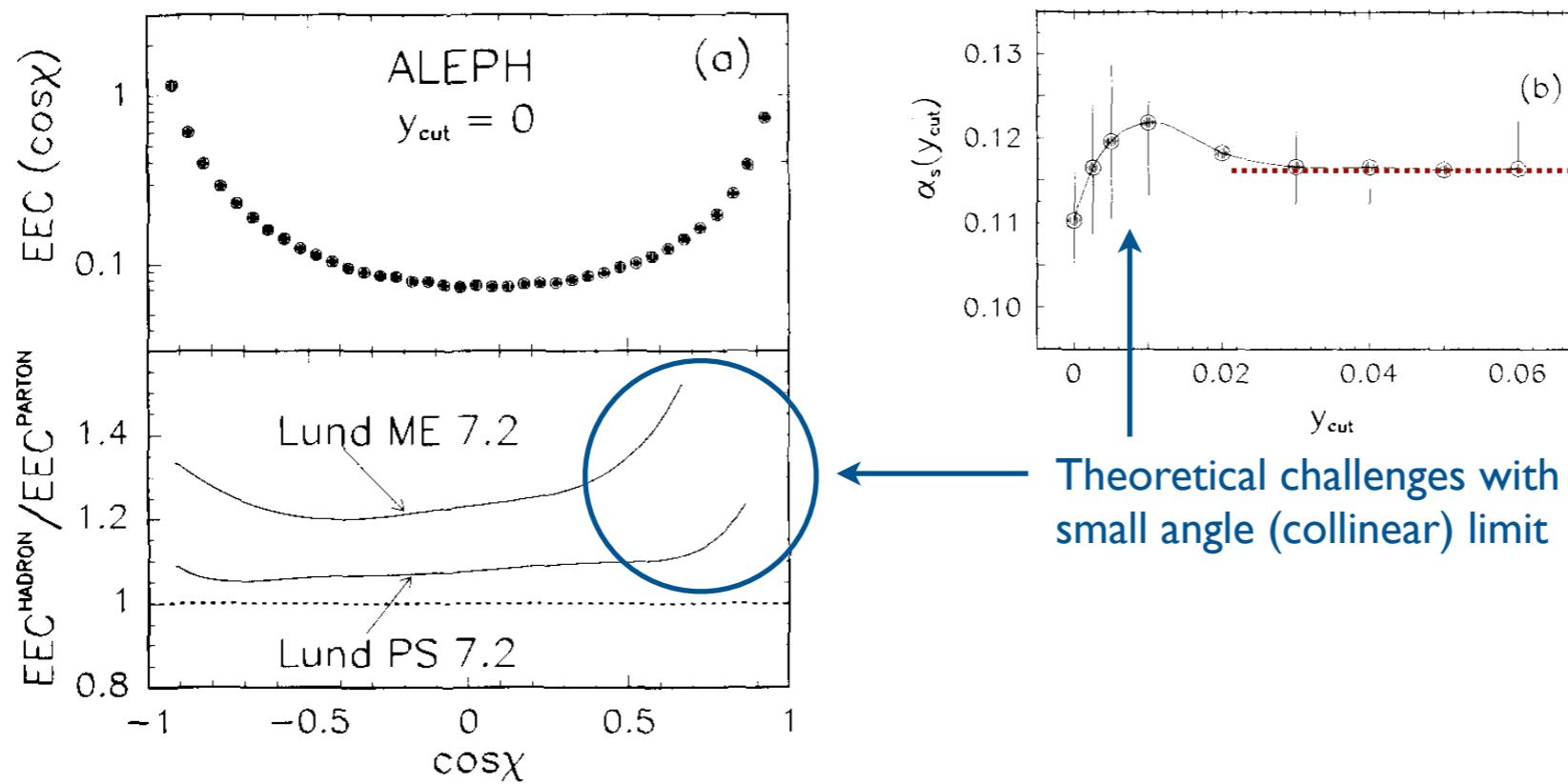
[Andreassen, Komiske, Metodiev, Nachman, JDT, [PRL 2020](#)]



Energy-Energy Correlators

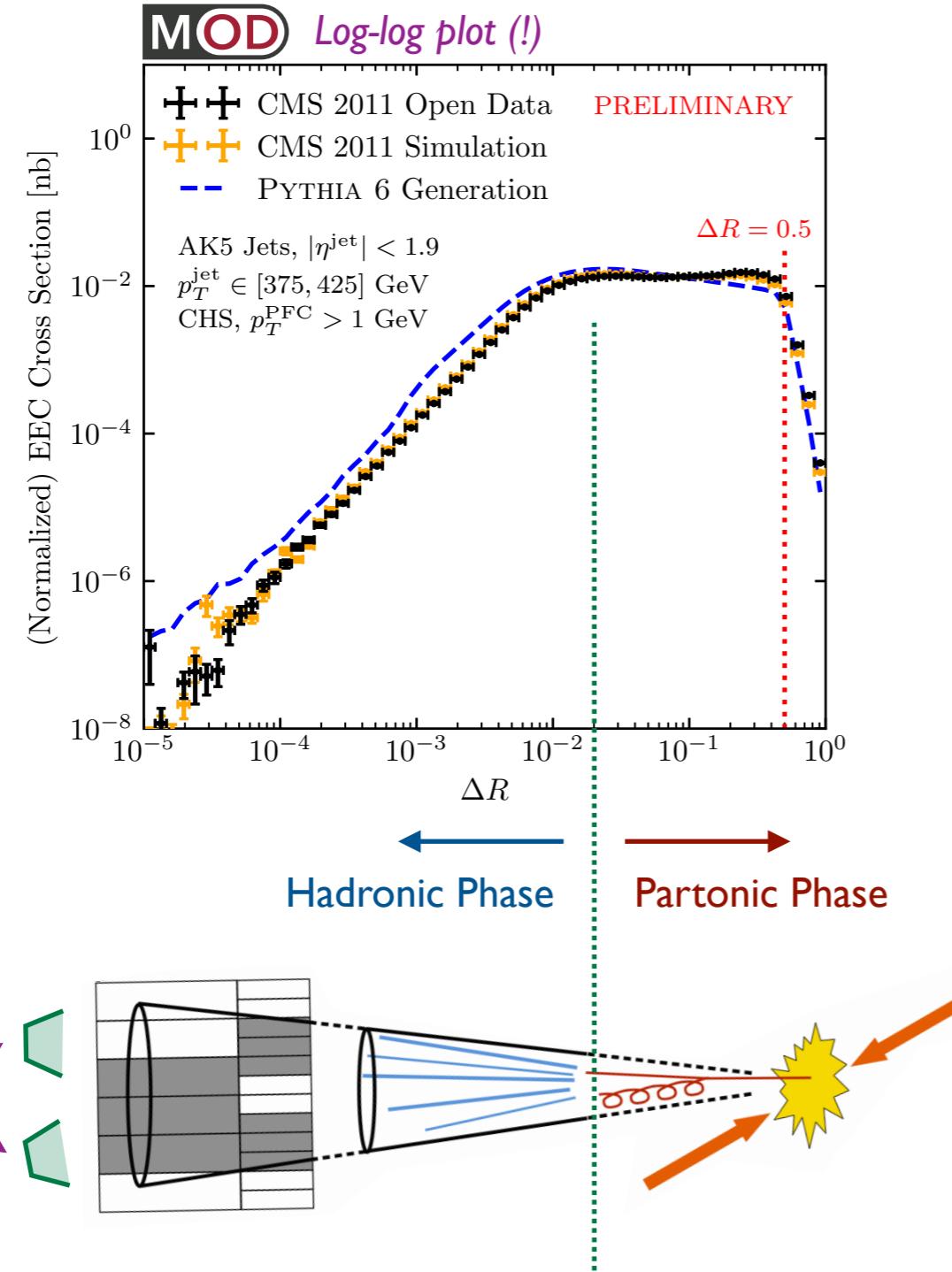


A long history in probing collinear dynamics of QCD



[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 **BOSTON 2019**

Jesse Thaler

EE(E)C?

To: Ian Moult

July 24, 2019 at 2:01 PM

JT

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

Preliminary EEC plot

To: Ian Moult, Cc: Patrick Komiske

July 24, 2019 at 10:16 PM

JT

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](#)]

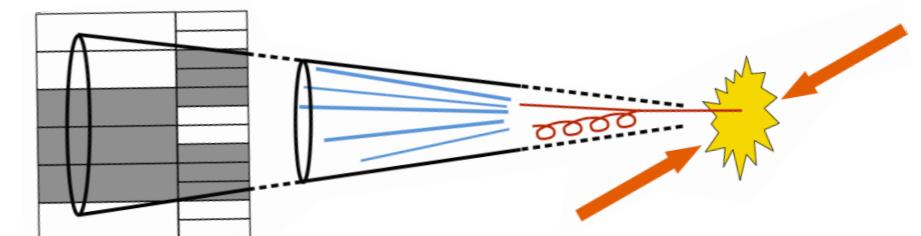
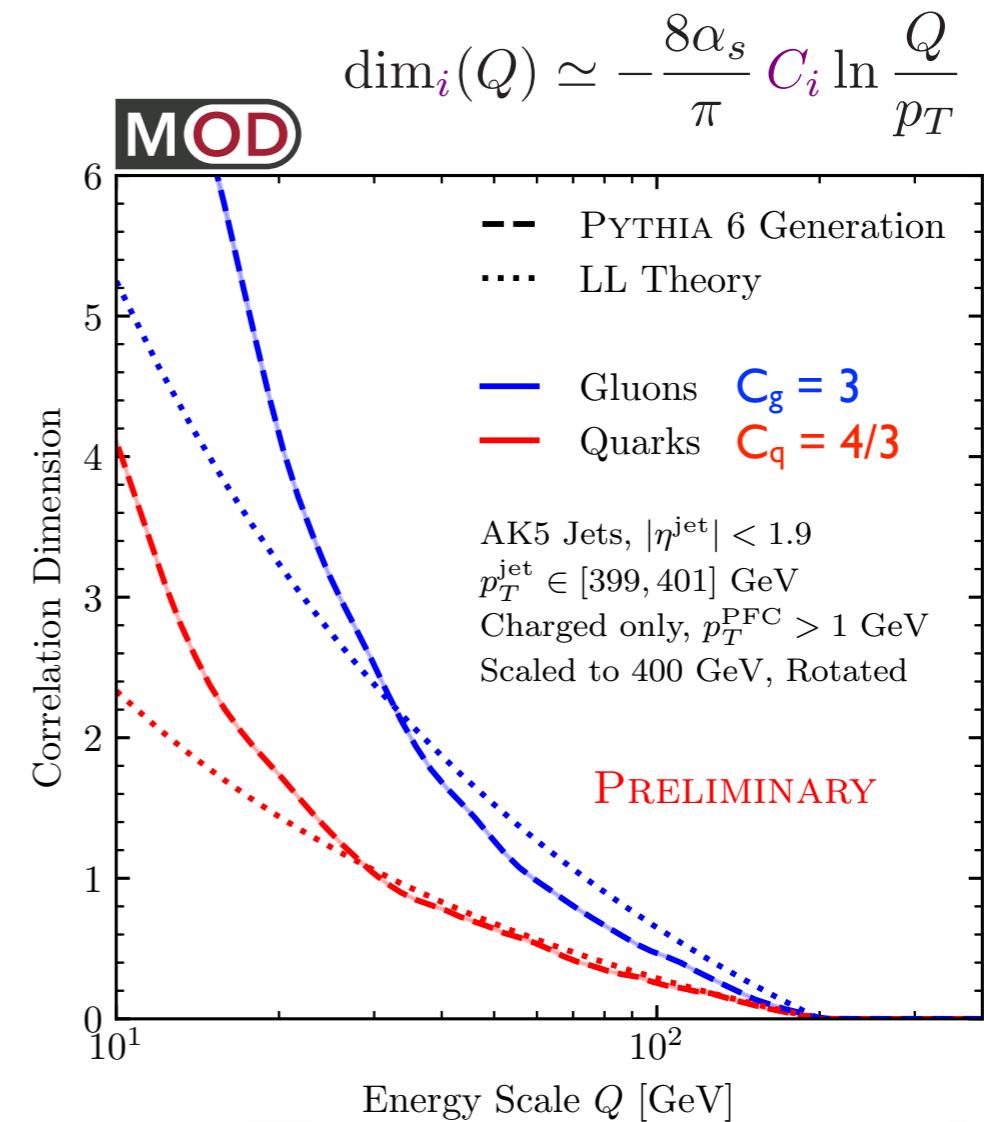
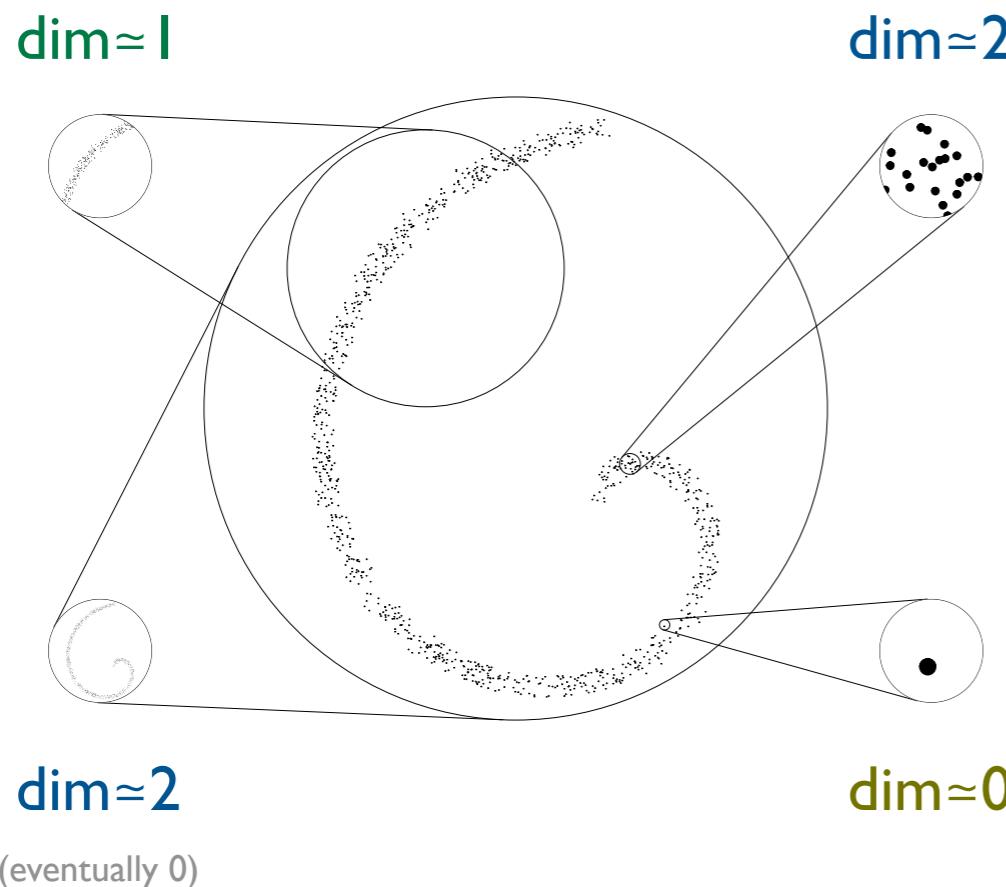
Dimensionality of Space of Jets



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

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

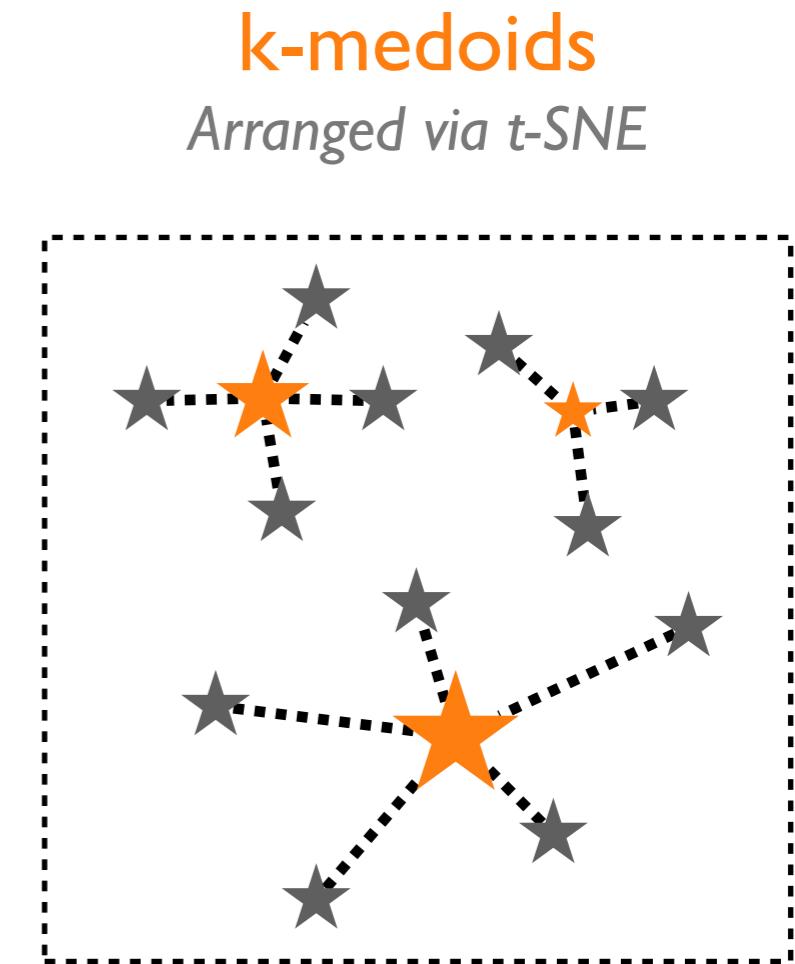
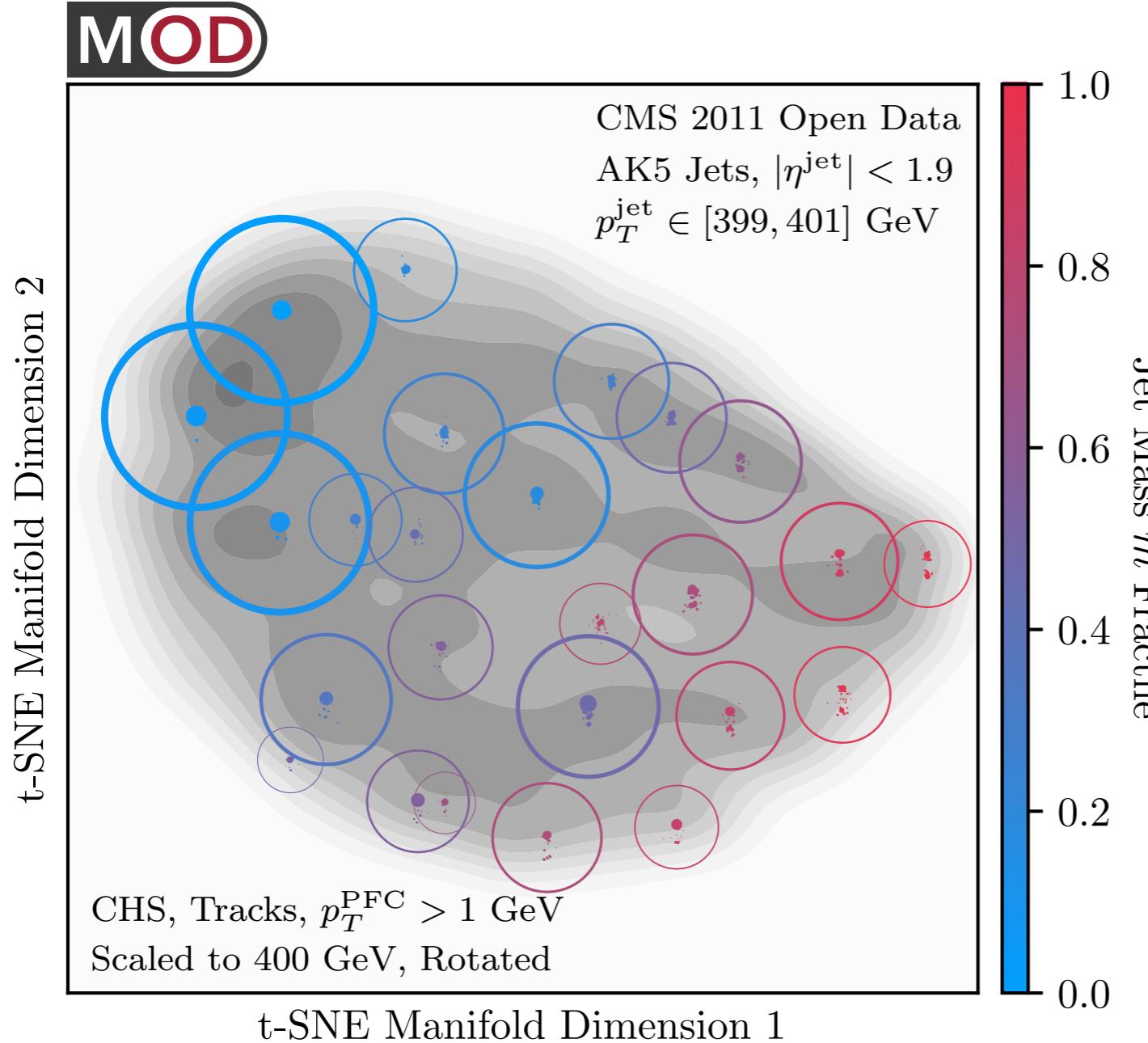
[Grassberger, Procaccia, [PRL 1983](#); Kégl, [NIPS 2002](#)]



Most Representative Jets



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

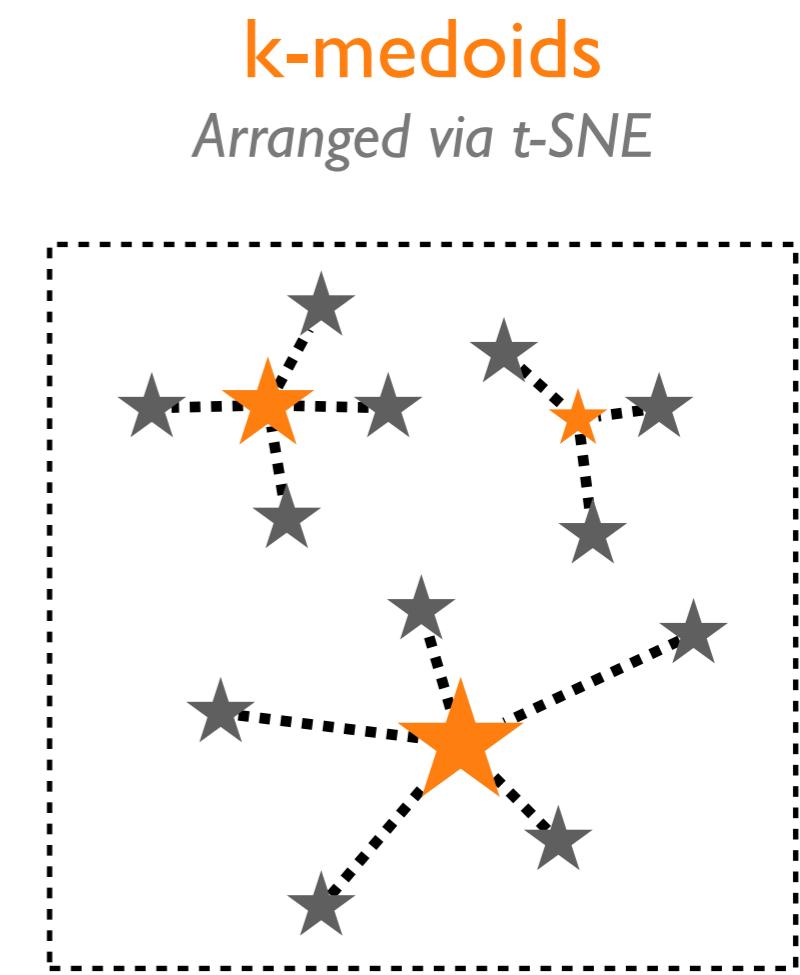
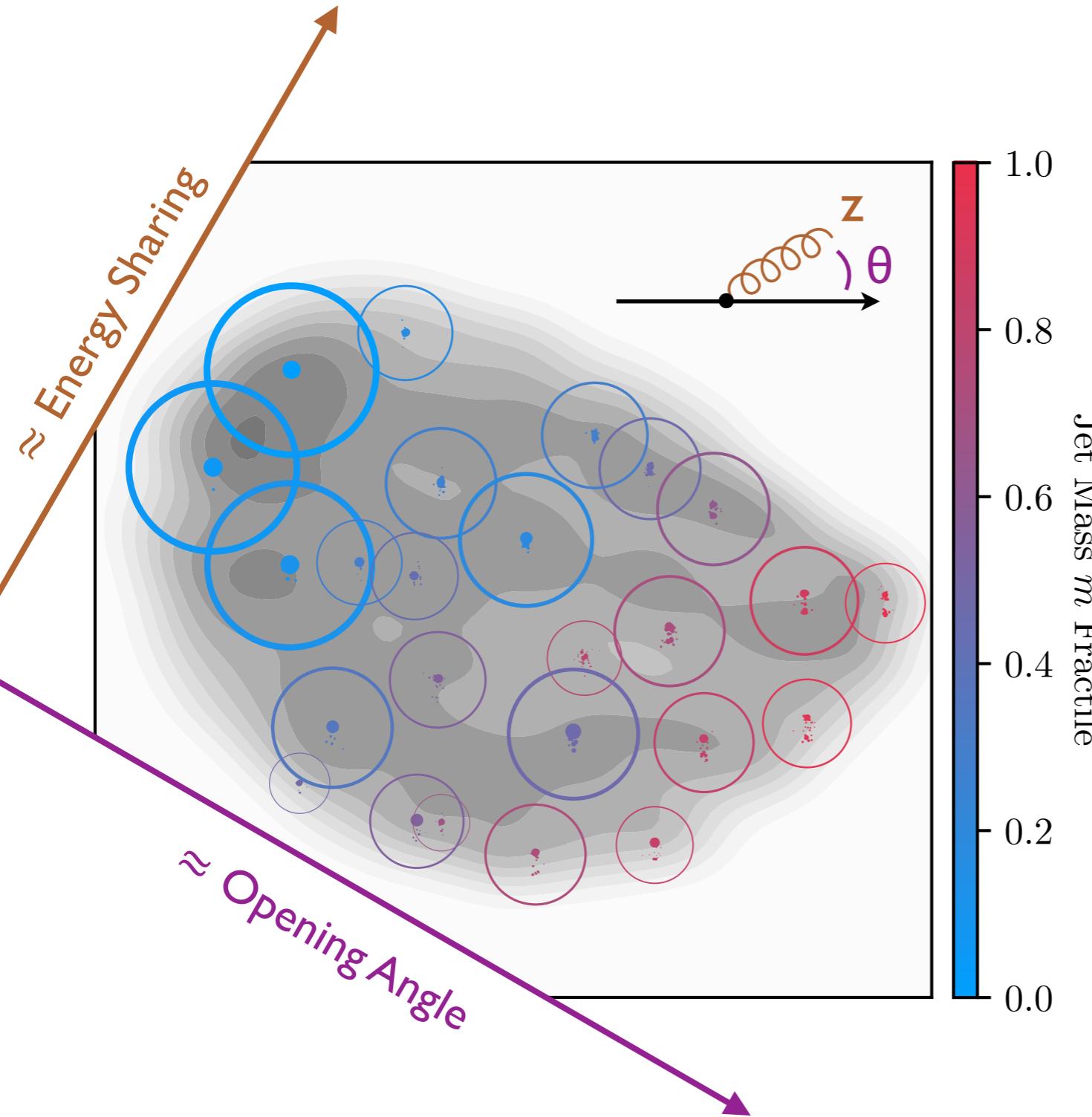


[Komiske, Mastandrea, Metodiev, Naik, JDT, *PRD* 2020; using van der Maaten, Hinton, *JMLR* 2008]

Most Representative Jets

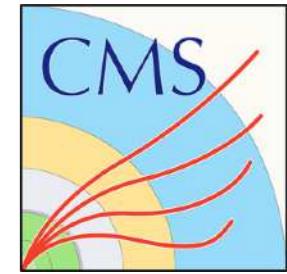


[<http://opendata.cern.ch/>]

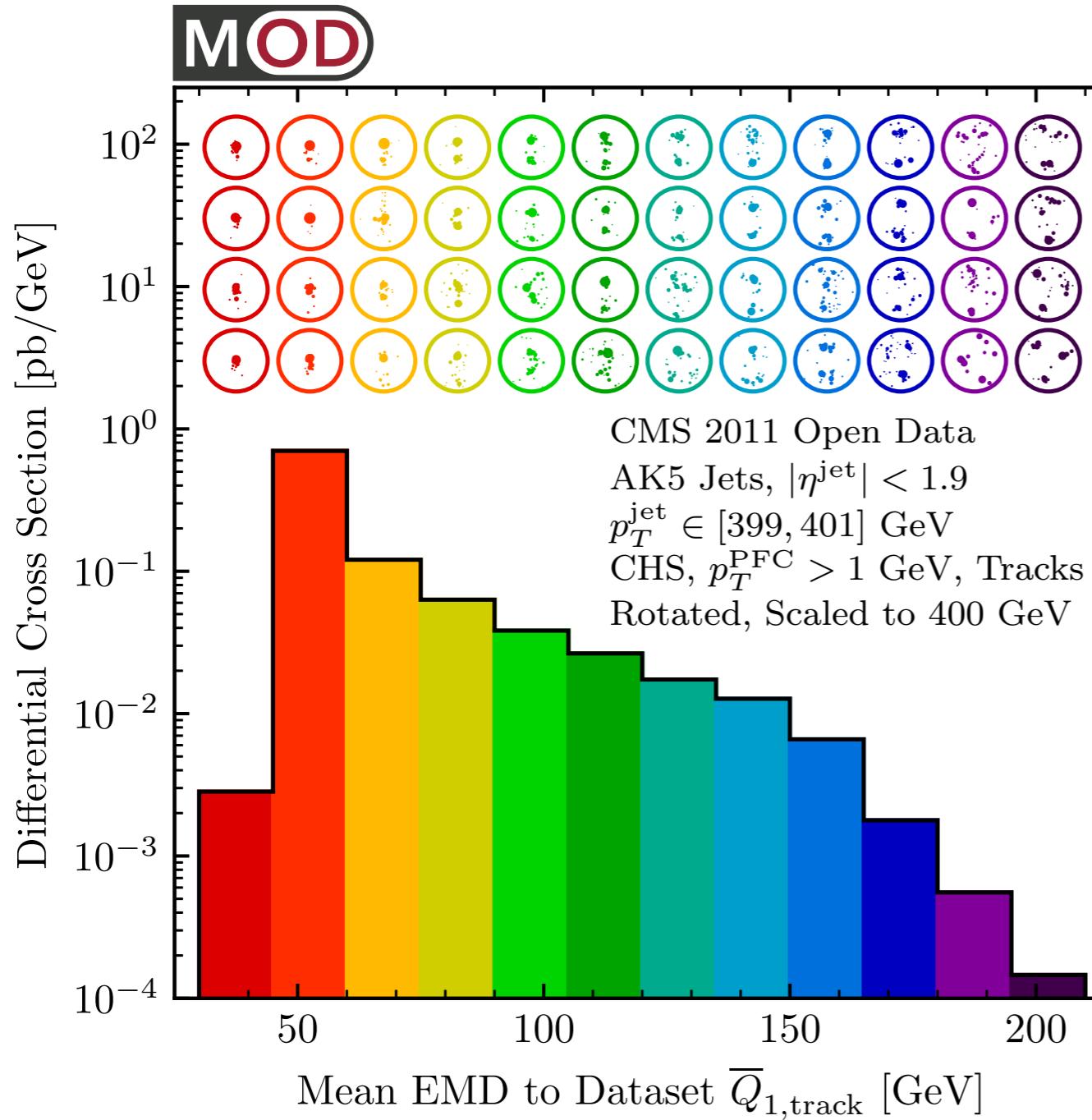


[Komiske, Mastandrea, Metodiev, Naik, JDT, PRD 2020; using van der Maaten, Hinton, JMLR 2008]

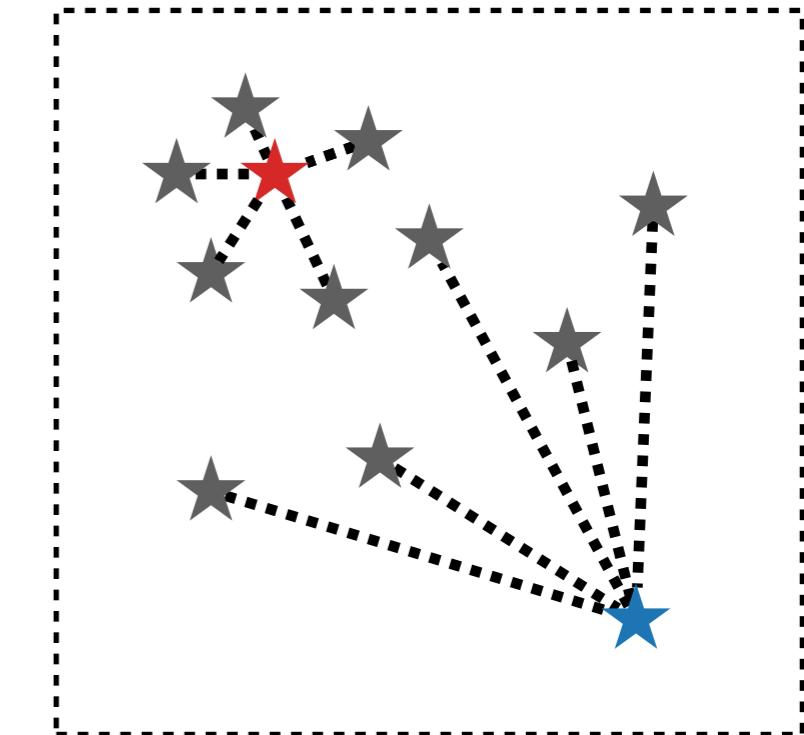
Least Representative Jets



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



New Physics?
Or tails of QCD?

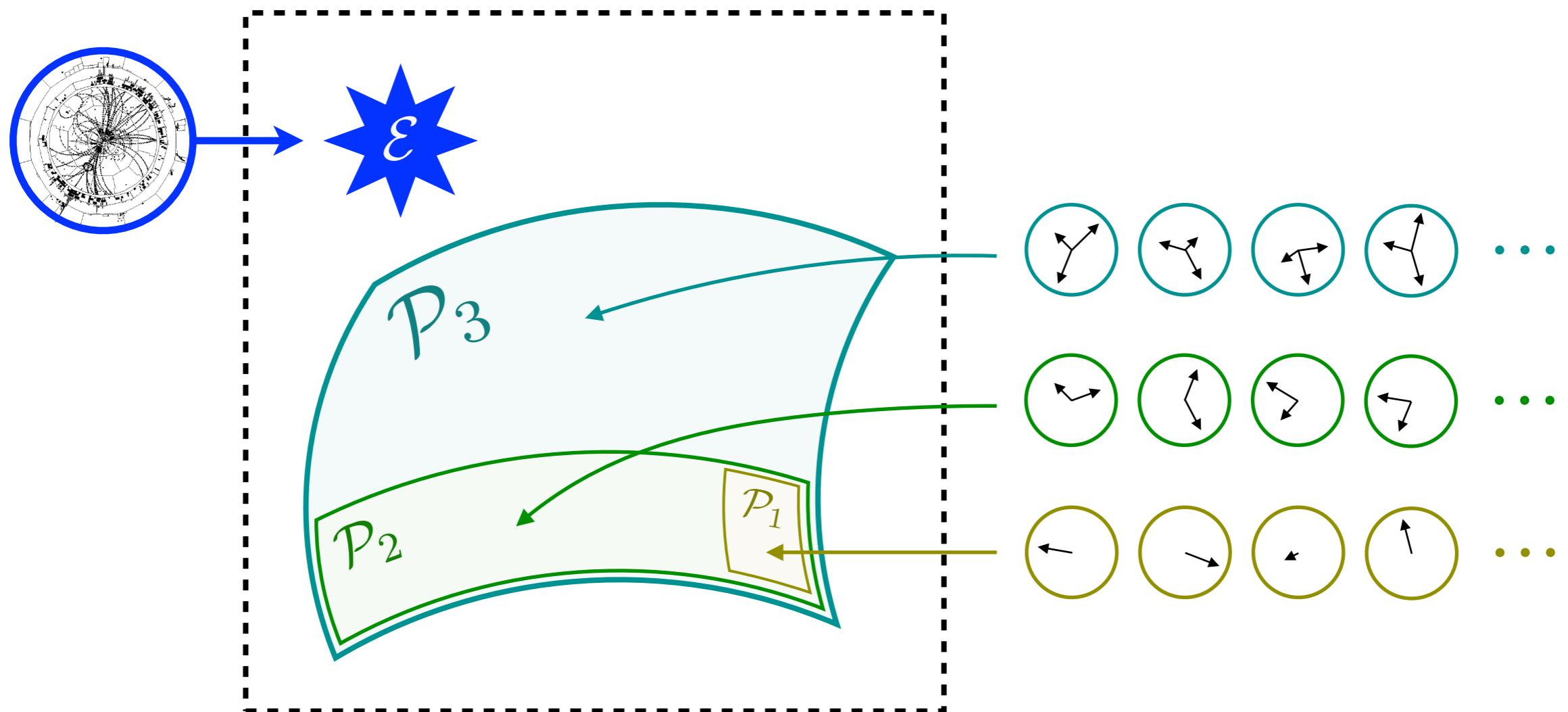


[Komiske, Mastandrea, Metodiev, Naik, JDT, [PRD 2020](#)]

Introducing N-particle Manifolds

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

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

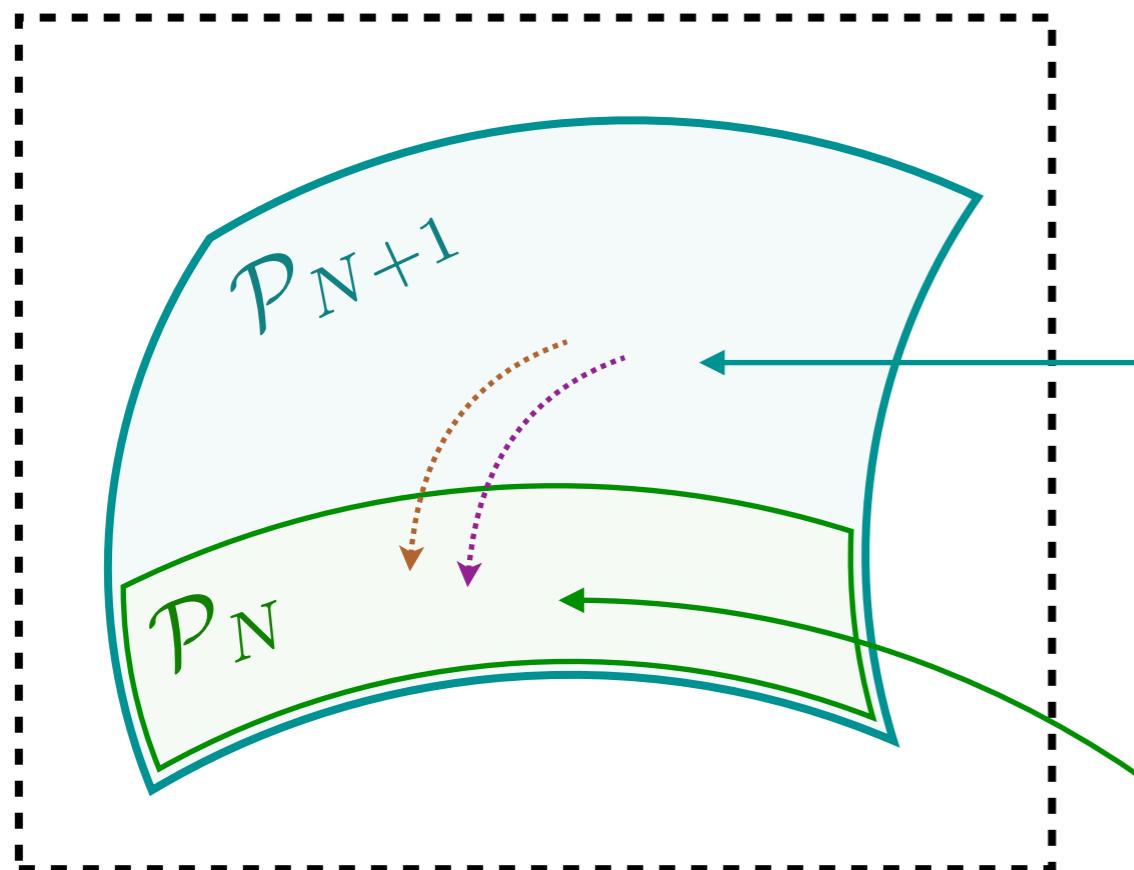
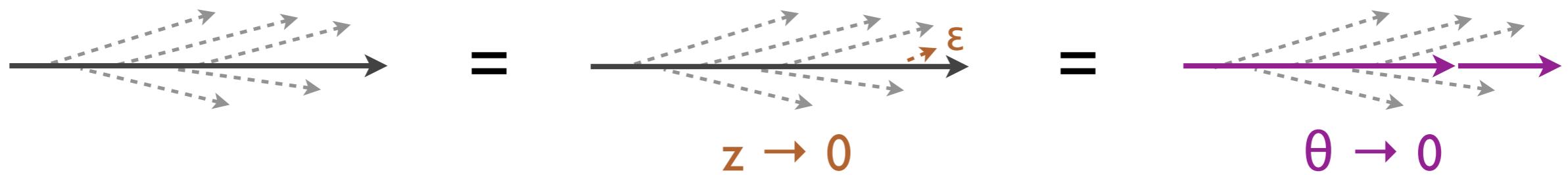


$\mathcal{P}_N \supset \mathcal{P}_{N-1} \supset \dots \supset \mathcal{P}_2 \supset \mathcal{P}_1$ by **soft/collinear** limits

When are Two Events the Same?

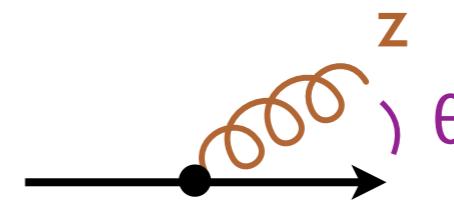
$$\mathcal{E}(\hat{n}) = \sum_i E_i \delta(\hat{n} - \hat{n}_i)$$

Energy Flow unchanged by infinitesimal soft/collinear emissions



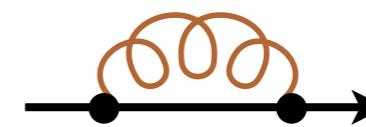
Infrared divergences “live” together!

Real:



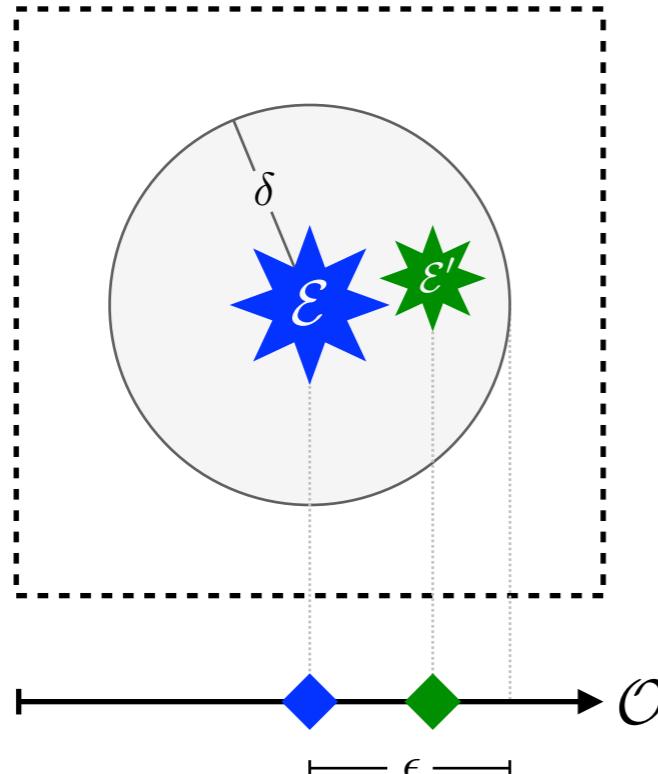
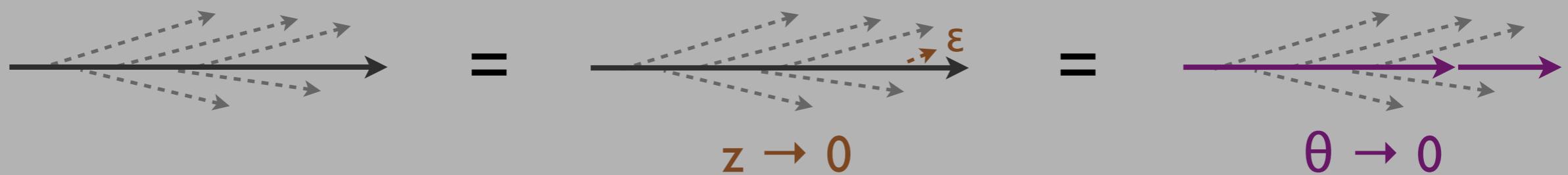
$$dP_{i \rightarrow ig} \simeq \frac{2\alpha_s}{\pi} C_i \frac{dz}{z} \frac{d\theta}{\theta}$$

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*

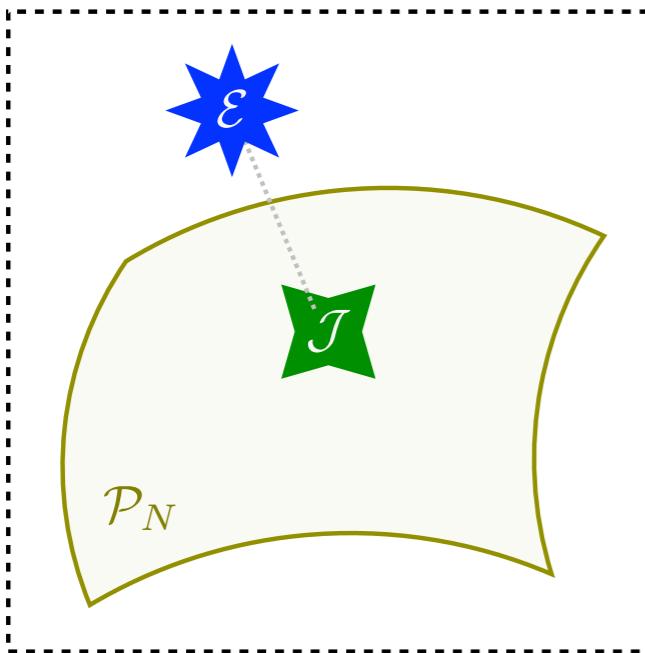
Continuity in EMD Space

[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 $|\mathcal{M}_{AB \rightarrow 12\dots n}|^2$ directly in this space?

More Fun with N-particle Manifolds



N-jettiness

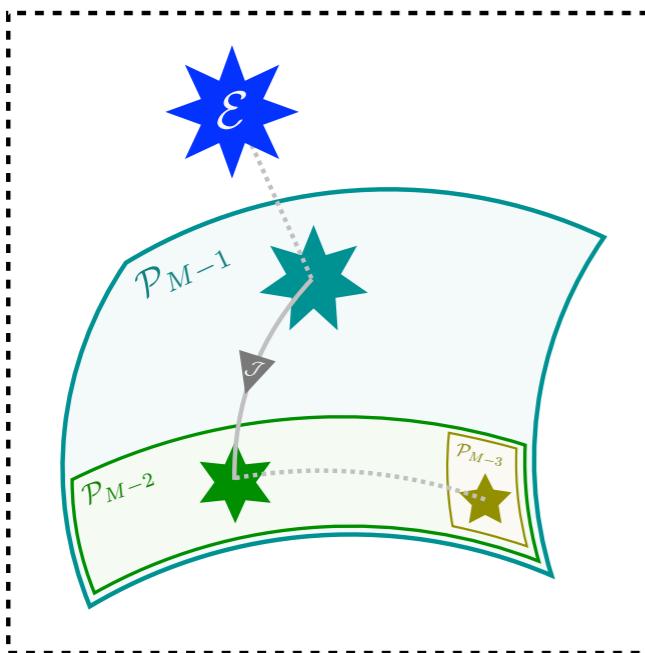
Distance of closest approach to N-particle manifold

[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

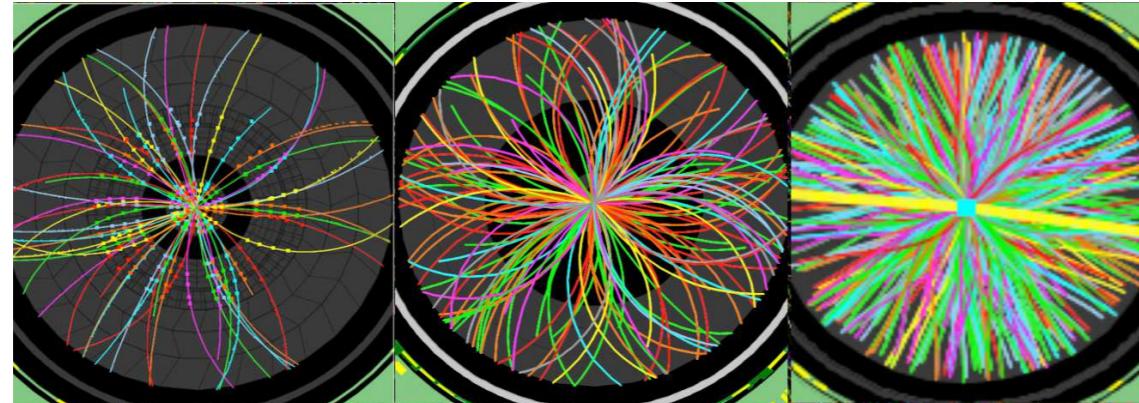
[Catani, Dokshitzer, Seymour, Webber, [NPB 1993](#); Ellis, Soper, [PRD 1993](#)]

[Dokshitzer, Leder, Moretti, Webber, [JHEP 1997](#); Wobisch, Wengler, [arXiv 1999](#)]

[Butterworth, Couchman, Cox, Waugh, [CPC 2003](#); Larkoski, Neill, JDT, [JHEP 2014](#)]

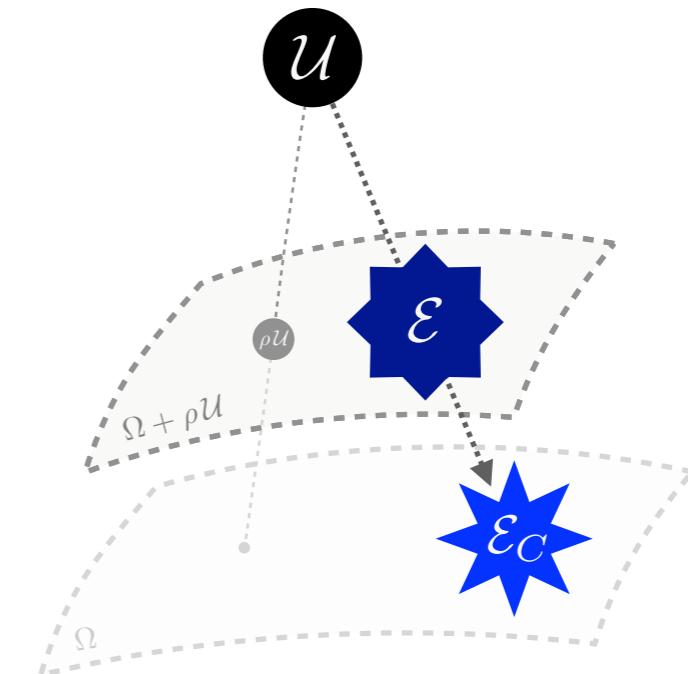
[Komiske, Metodiev, JDT, [JHEP 2020](#)]

Pileup Mitigation



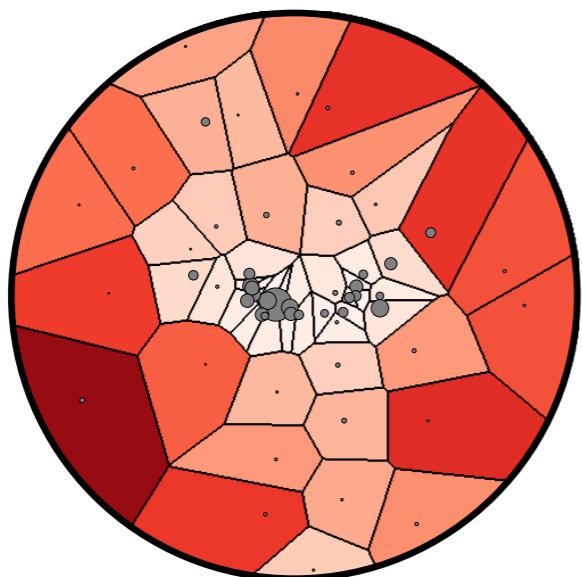
[see review in Soyez, PR 2019]

Uniform event contamination from overlapping proton-proton collisions



Pileup Mitigation:
“Move away” from uniform event

Voronoi



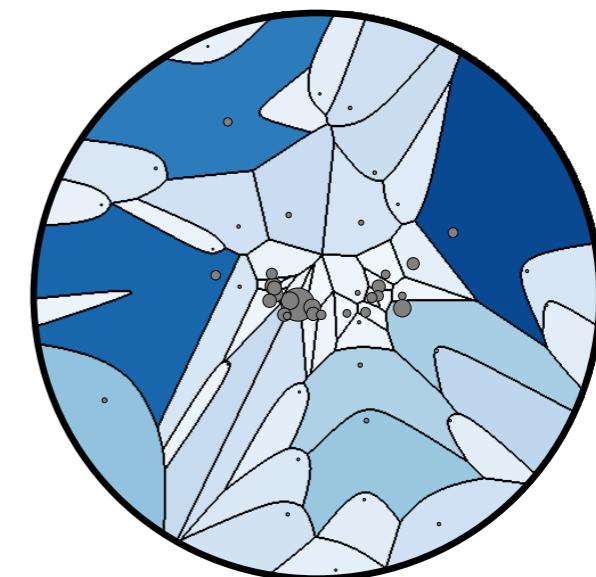
[Cacciari, Salam, Soyez, JHEP 2008]

Constituent Subtraction



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

Apollonius



[Komiske, Metodiev, JDT, JHEP 2020]