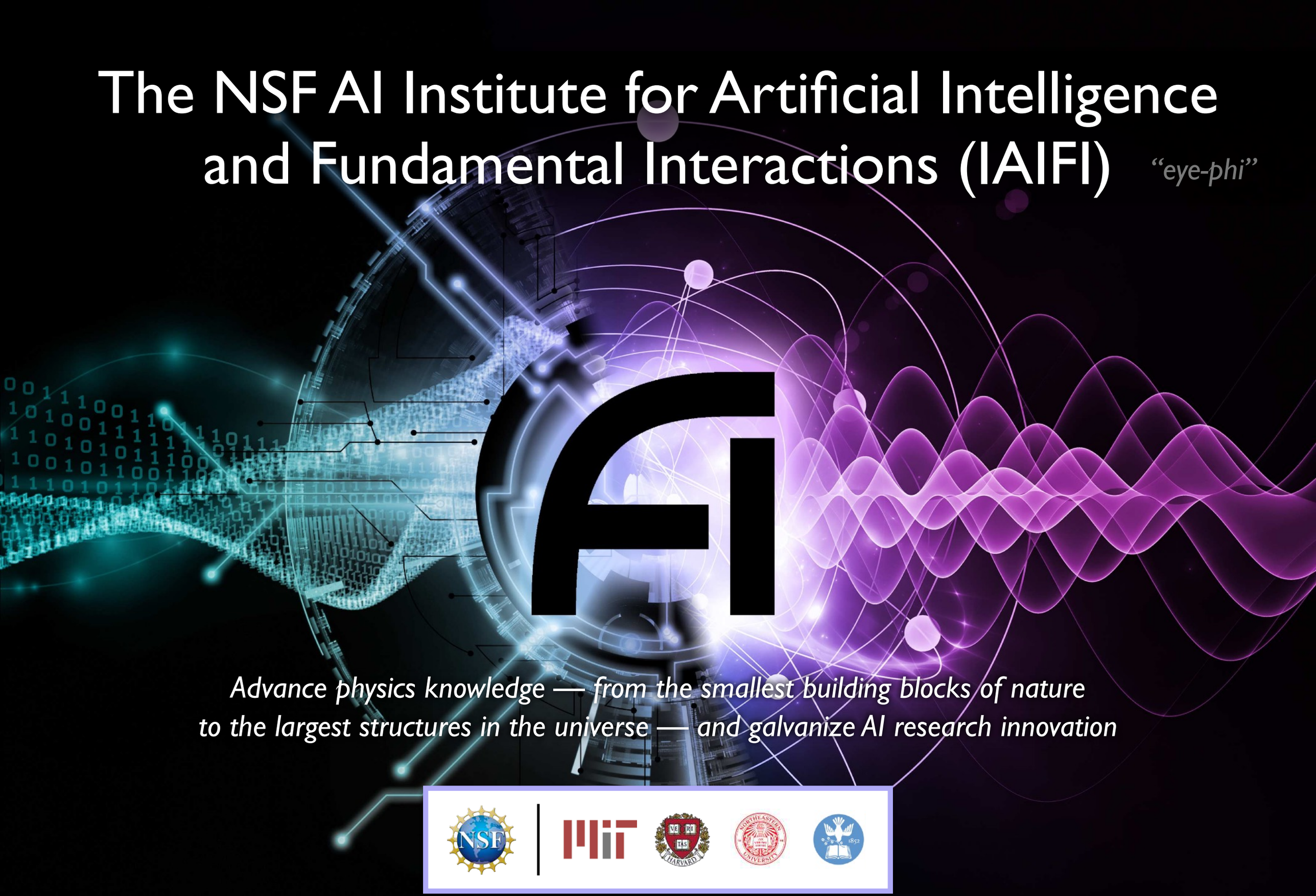
The Geometry of Particle Collisions: Hidden in Plain Sight

Jesse Thaler

(since January 2020)

Stochastics and Statistics Seminar, MIT Statistics and Data Science Center — December 3, 2021

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, MIT News Announcement]

New! PhD in Physics, Statistics & Data Science

≈ Physics PhD + 4 courses (probability, statistics, computation, data analysis)

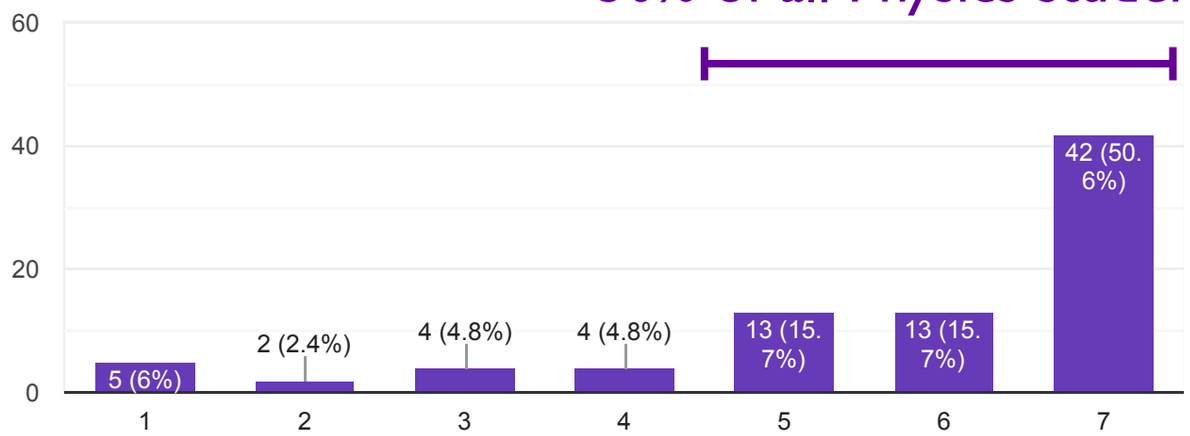
MIT Physics

MIT STATISTICS + DATA SCIENCE CENTER

How interested would you be in submitting and defending a PhD thesis that uses statistical methods in a substantial way?

83 responses

≈30% of all Physics students (!)

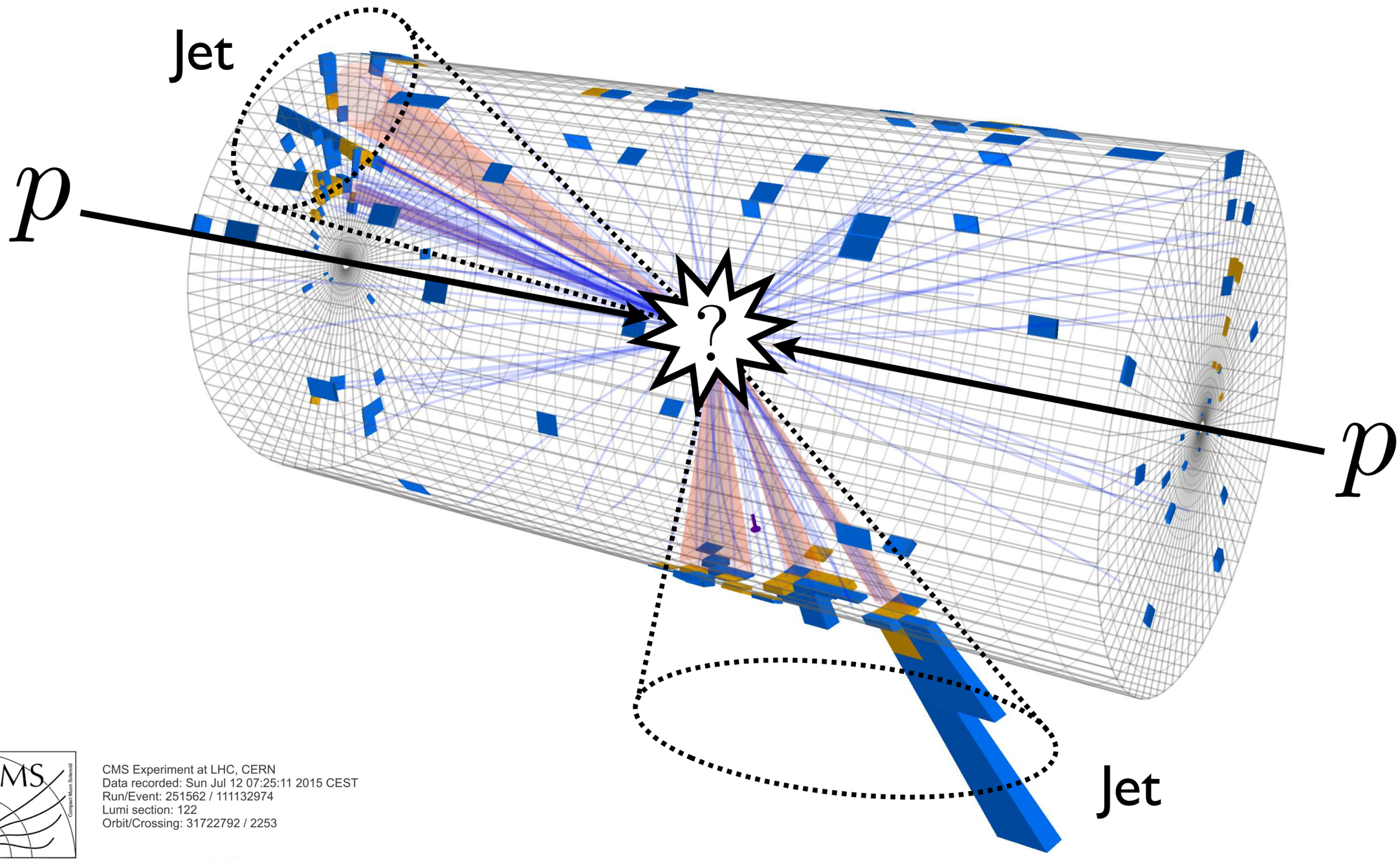


Respondent #11: "I think ML is the most important thing happening in the world right now and should be incorporated into any STEM degree."

Congratulations, Dr. Constantin Weisser! (March 30, 2021)

[https://physics.mit.edu/academic-programs/graduate-students/psds-phd/]

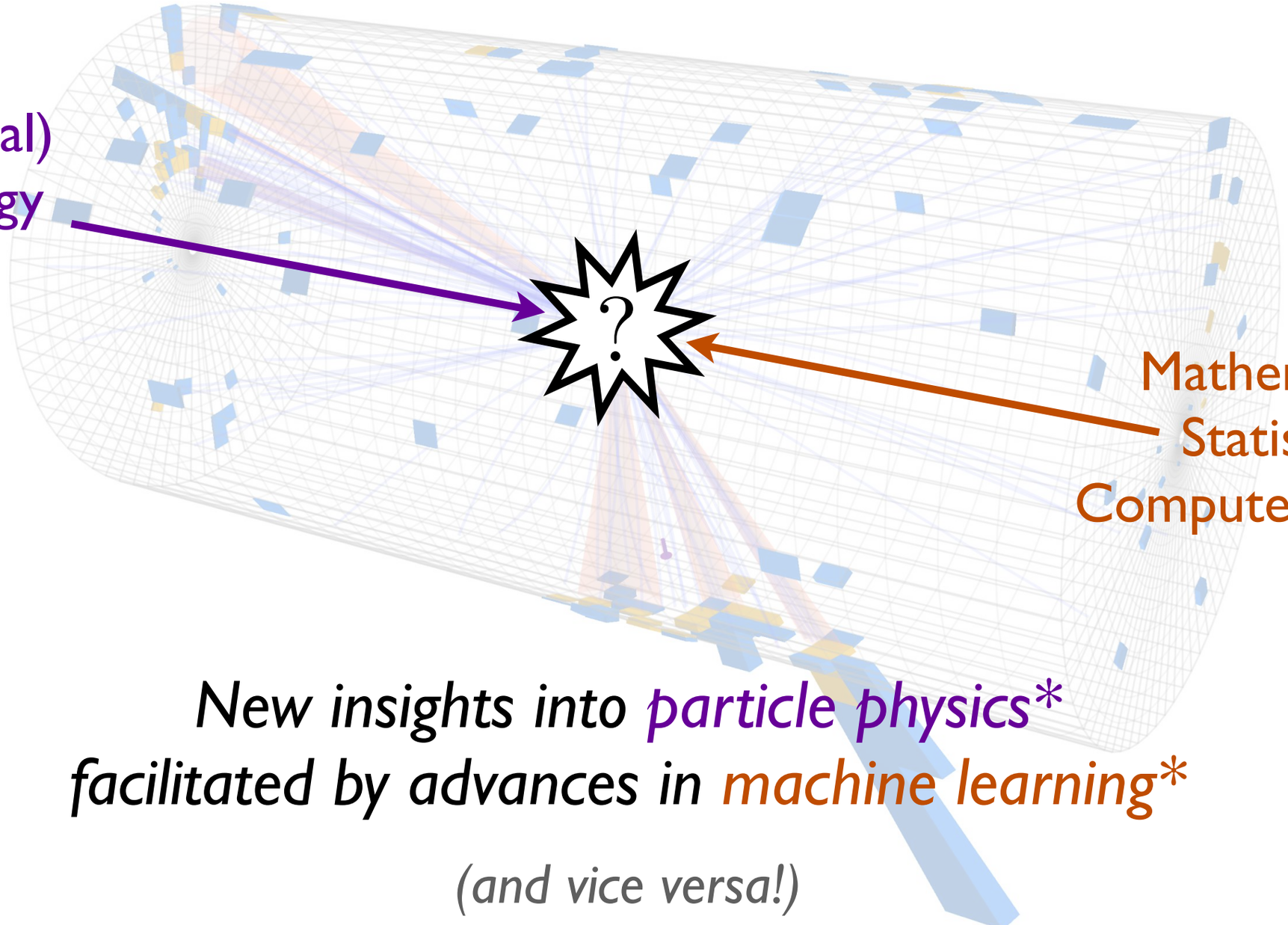
“Collision Course”



CMS Experiment at LHC, CERN
Data recorded: Sun Jul 12 07:25:11 2015 CEST
Run/Event: 251562 / 111132974
Lumi section: 122
Orbit/Crossing: 31722792 / 2253

“Collision Course”

“Theoretical Physics for Machine Learning”
Aspen Center for Physics, January 2019



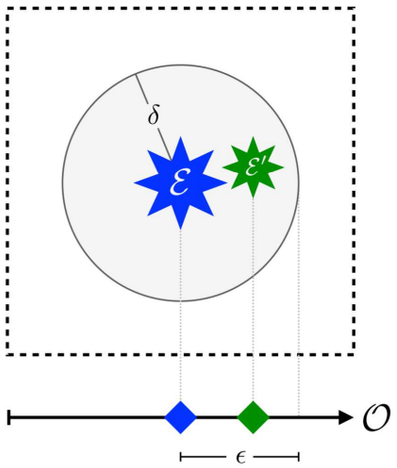
*New insights into particle physics**
*facilitated by advances in machine learning**

(and vice versa!)

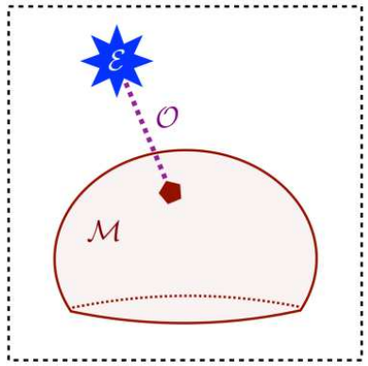
Today: Hidden in "Plane" Sight

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

IRC Safety is smoothness in the space of events

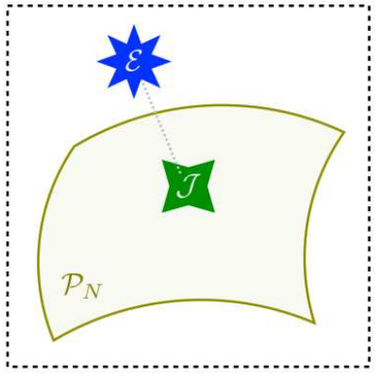


Event shapes are distances from events to manifolds.



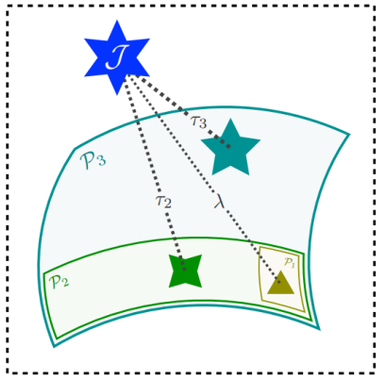
$$\mathcal{O}(\mathcal{E}) = \min_{\mathcal{E}' \in \mathcal{M}} \mathrm{EMD}_{\beta,R}(\mathcal{E}, \mathcal{E}')$$

Jets are projections to few-particle manifolds.



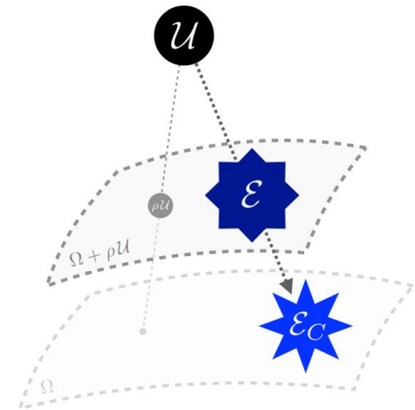
$$\mathcal{J} = \underset{\mathcal{E}' \in \mathcal{P}_N}{\mathrm{argmin}} \, \mathrm{EMD}_{\beta,R}(\mathcal{E}, \mathcal{E}')$$

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]

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

Jet Algorithms

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

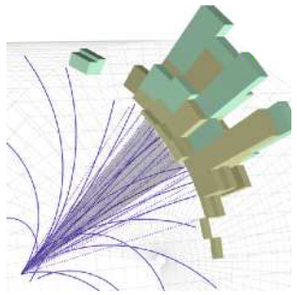
2014-2019
Constituent Subtraction
[Berta, Spousta, Miller, Leitner, JHEP 2014]
[Berta, Masetti, Miller, Spousta, JHEP 2019]

1960 — 2020

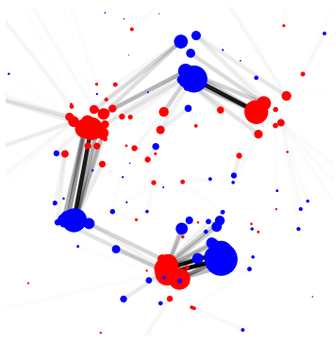
And many more!

[Komiske, Metodiev, JDT, JHEP 2020; timeline from Metodiev]

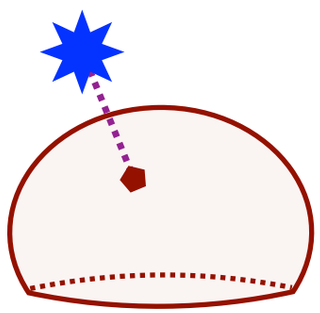
Outline



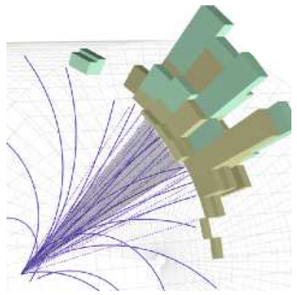
Going with the (Energy) Flow



The Energy Mover's Distance



Revealing a Hidden Geometry

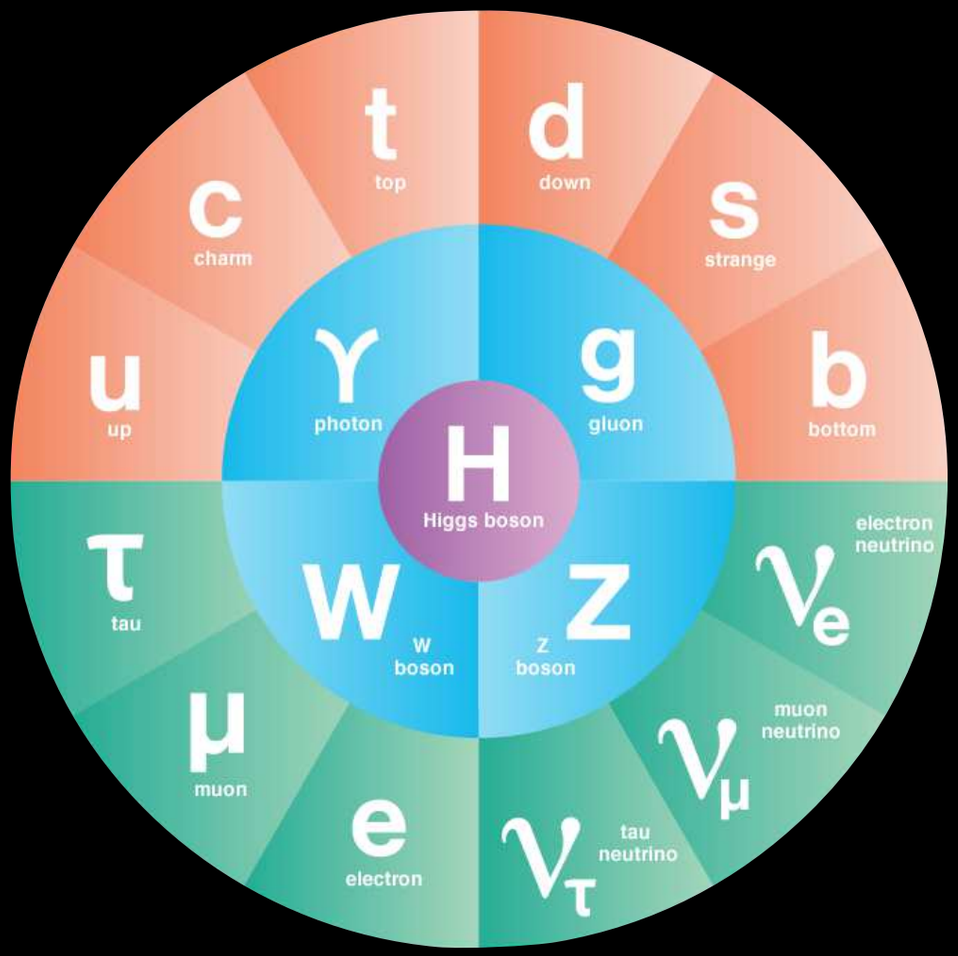


Going with the (Energy) Flow

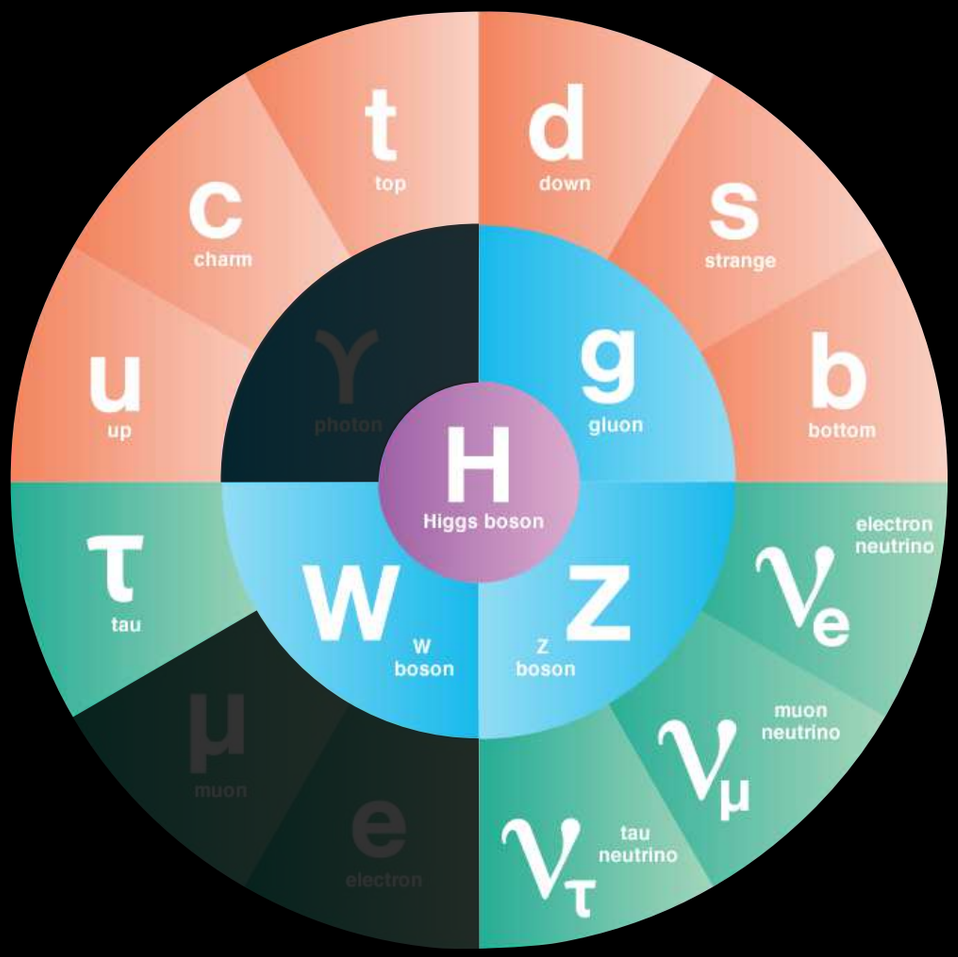
The Energy Mover's Distance

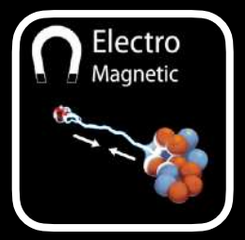
Revealing a Hidden Geometry

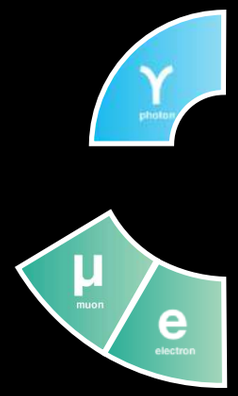
Particle Physics 101



Particle Physics 101







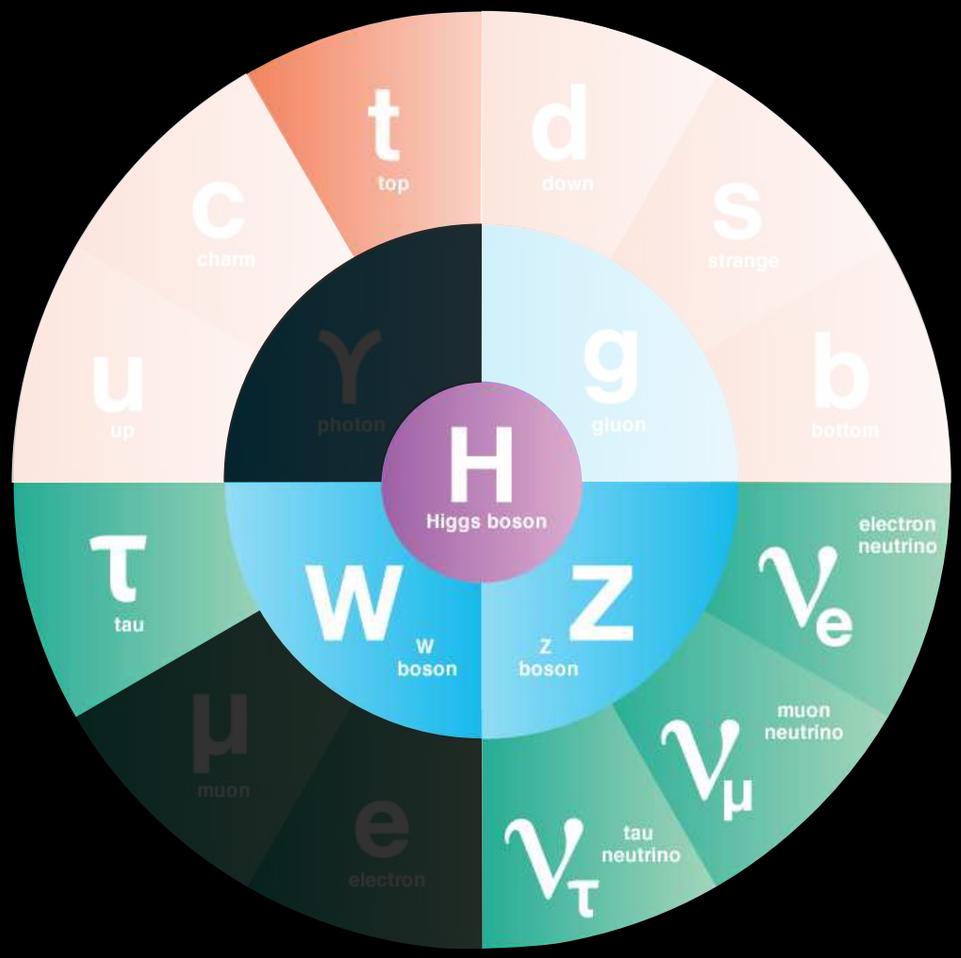
γ photon

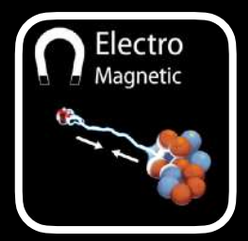
$e^{\pm}$ electron

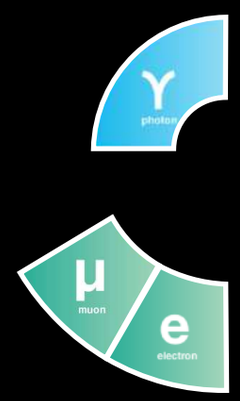
$\mu^{\pm}$ muon

elementary

Particle Physics 101

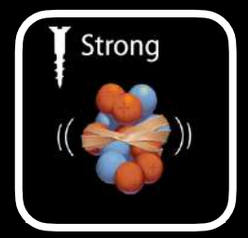


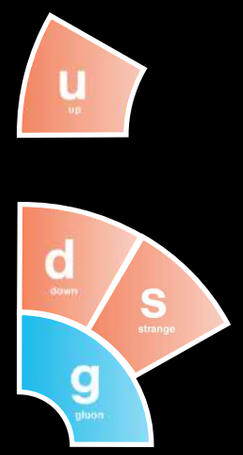




QCD Confinement

Quarks & Gluons



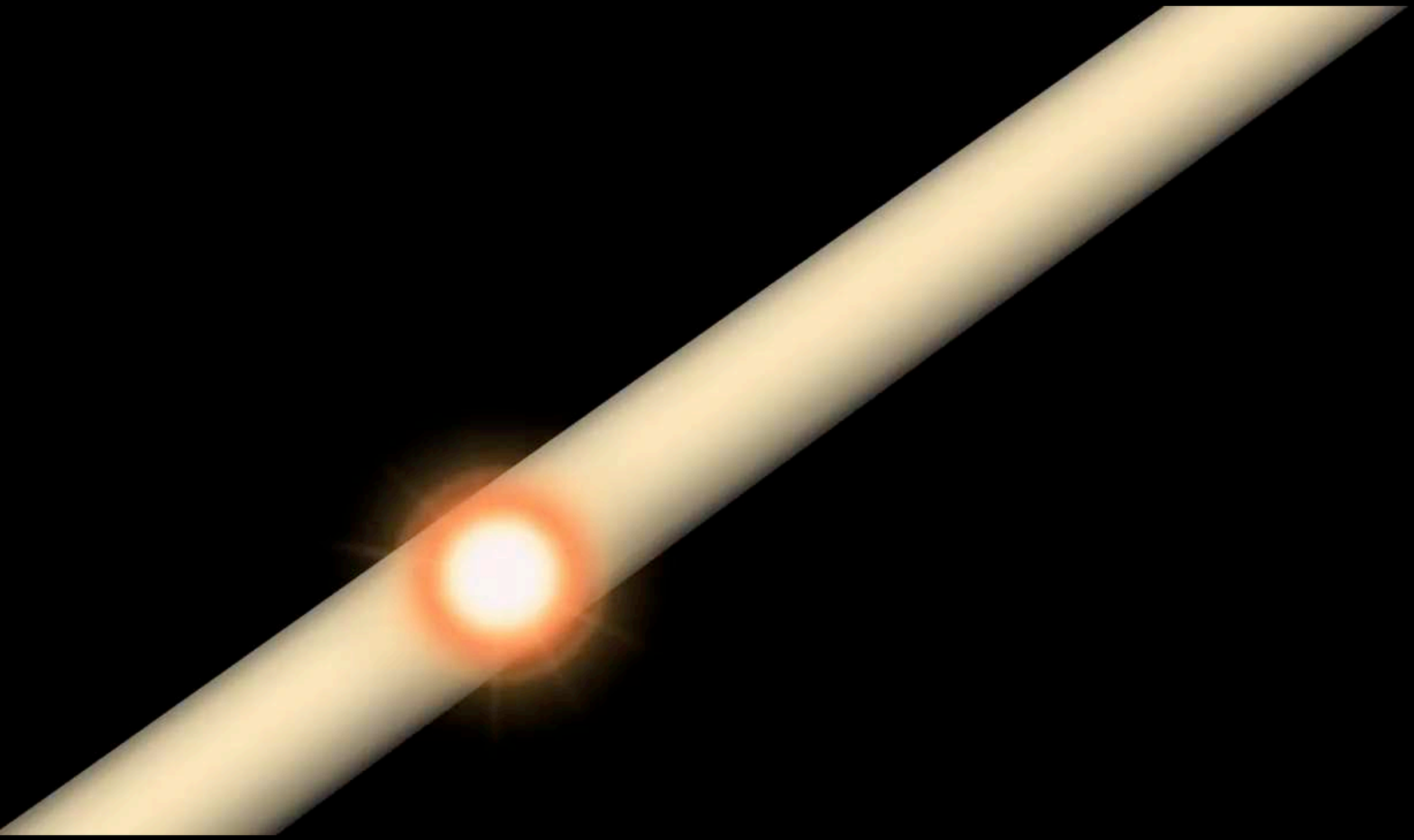


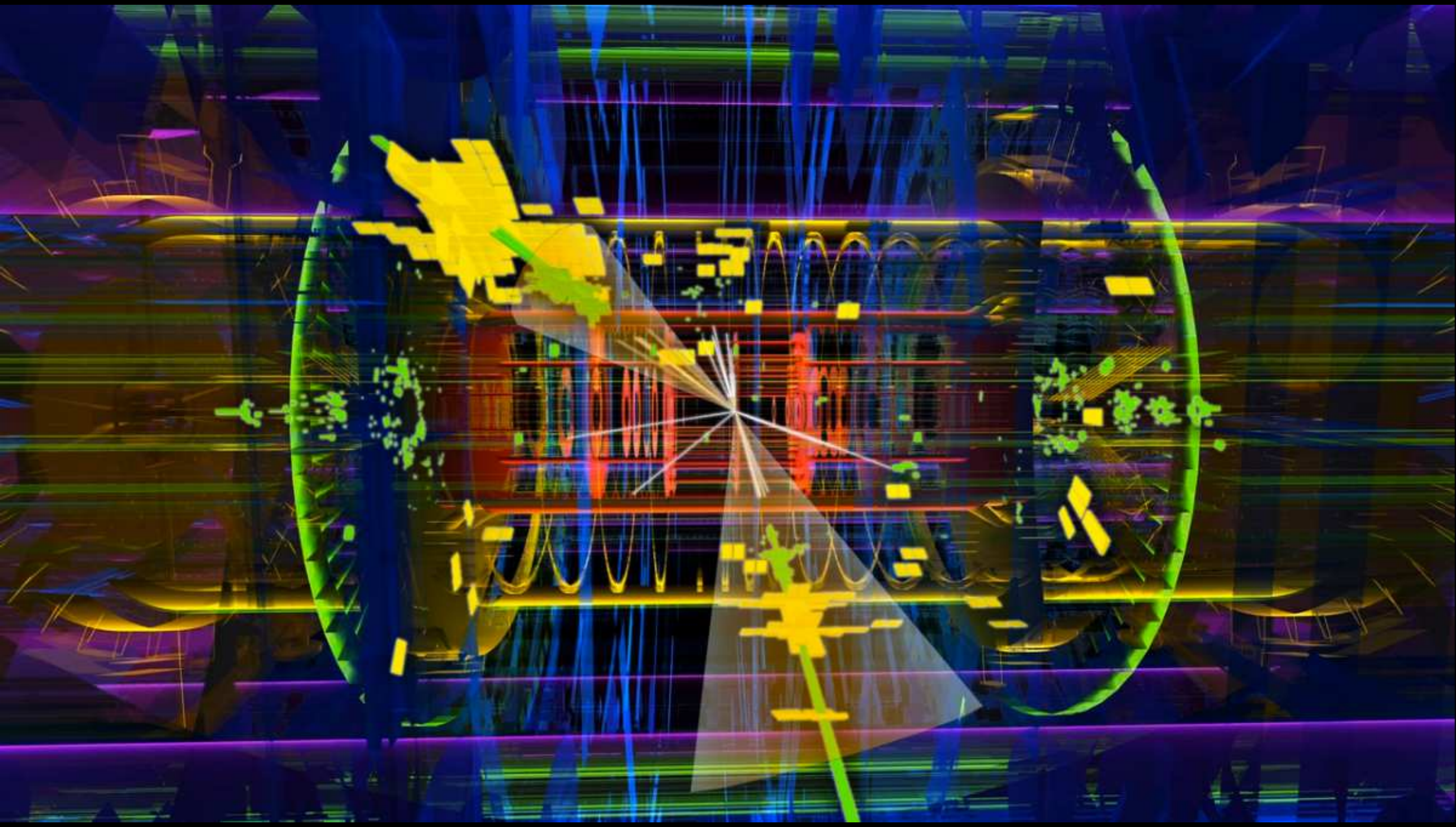
elementary

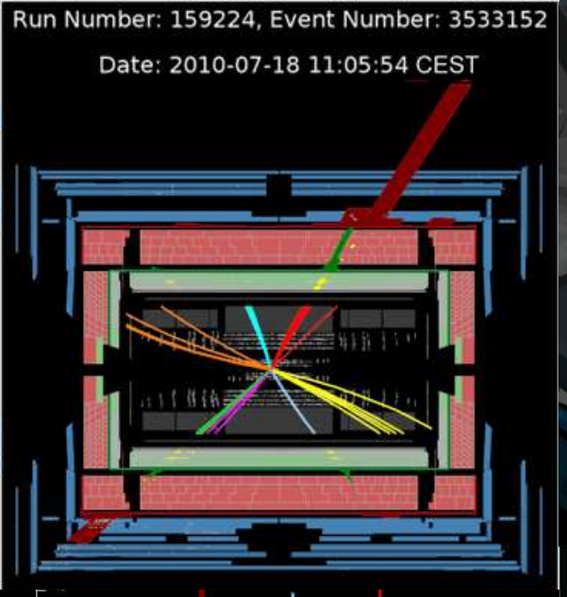
γ	photon
$e^{\pm}$	electron
$\mu^{\pm}$	muon

composite

$\pi^{\pm}$	pion
$K^{\pm}$	kaon
K_L^0	K-long
$p/\overline{p}$	proton
$n/\overline{n}$	neutron



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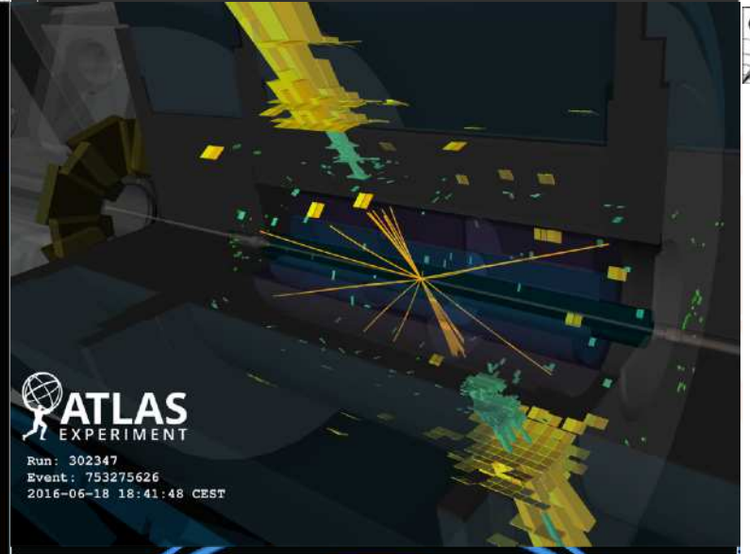
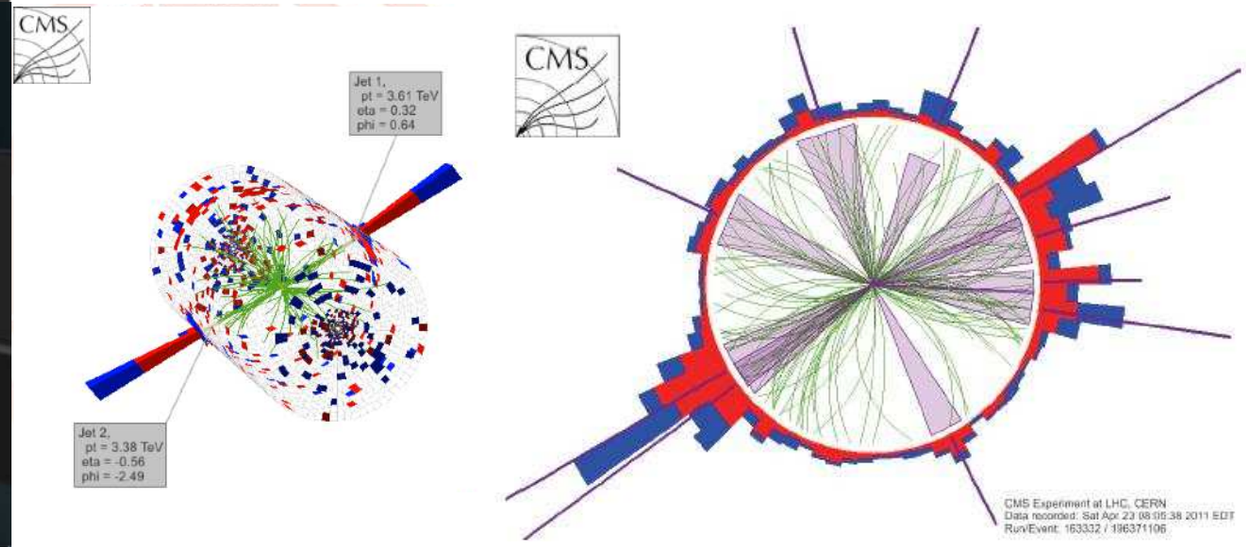
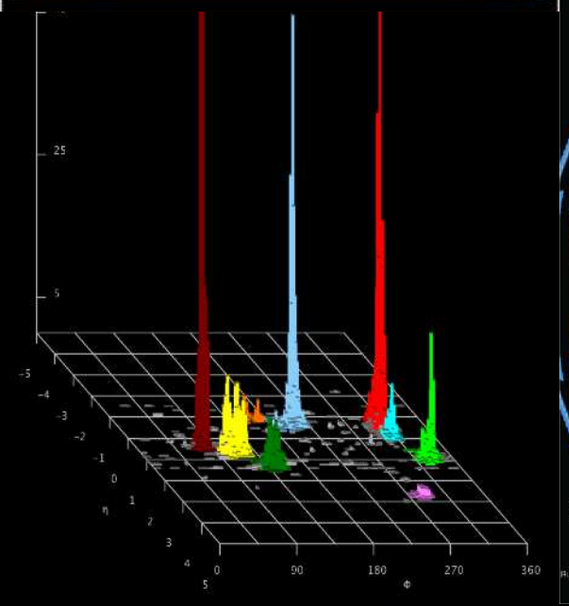
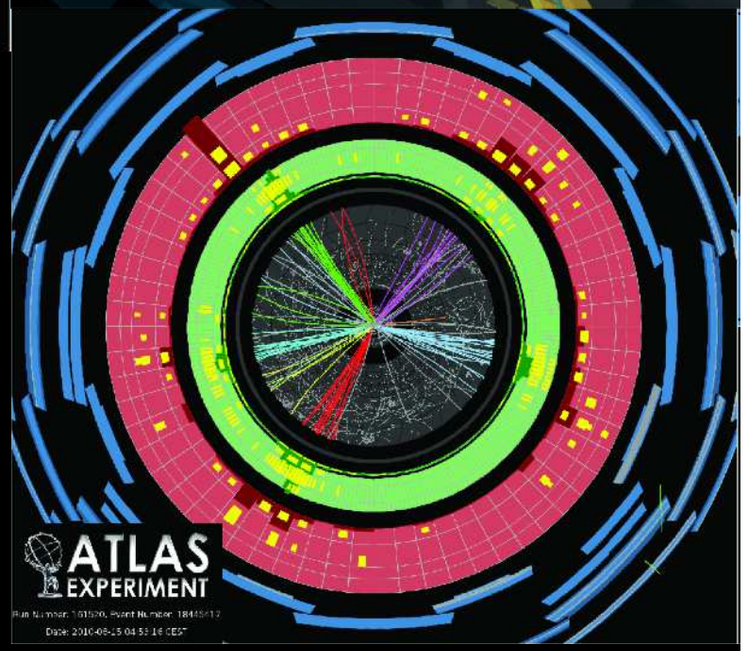
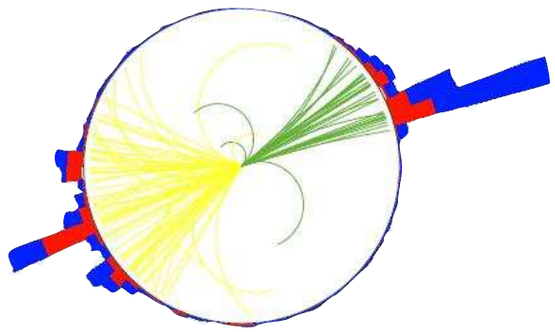
Date: 2010-07-18 11:05:54 CEST

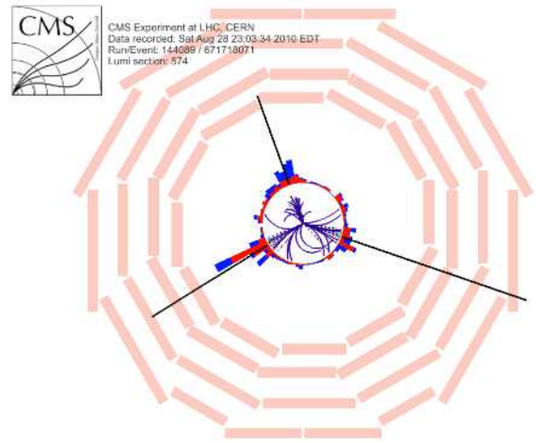

ATLAS
EXPERIMENT
Run: 302347
Event: 753275626
2016-06-18 18:41:48 CEST

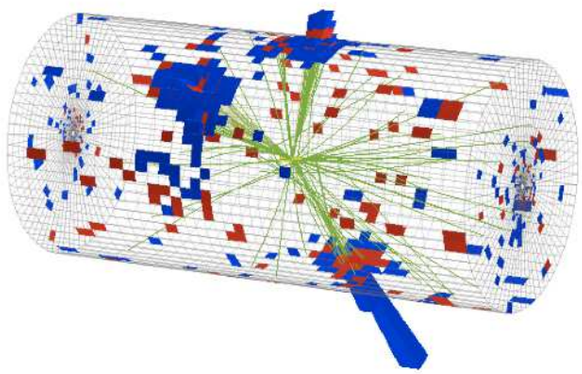

CMS
Jet 1,
pt = 3.61 TeV
eta = 0.32
phi = 0.64
Jet 2,
pt = 3.38 TeV
eta = -0.56
phi = -2.49
CMS
CMS Experiment at LHC, CERN
Data recorded: Sat Apr 23 08:05:38 2011 EDT
Run/Event: 163332 / 196371106

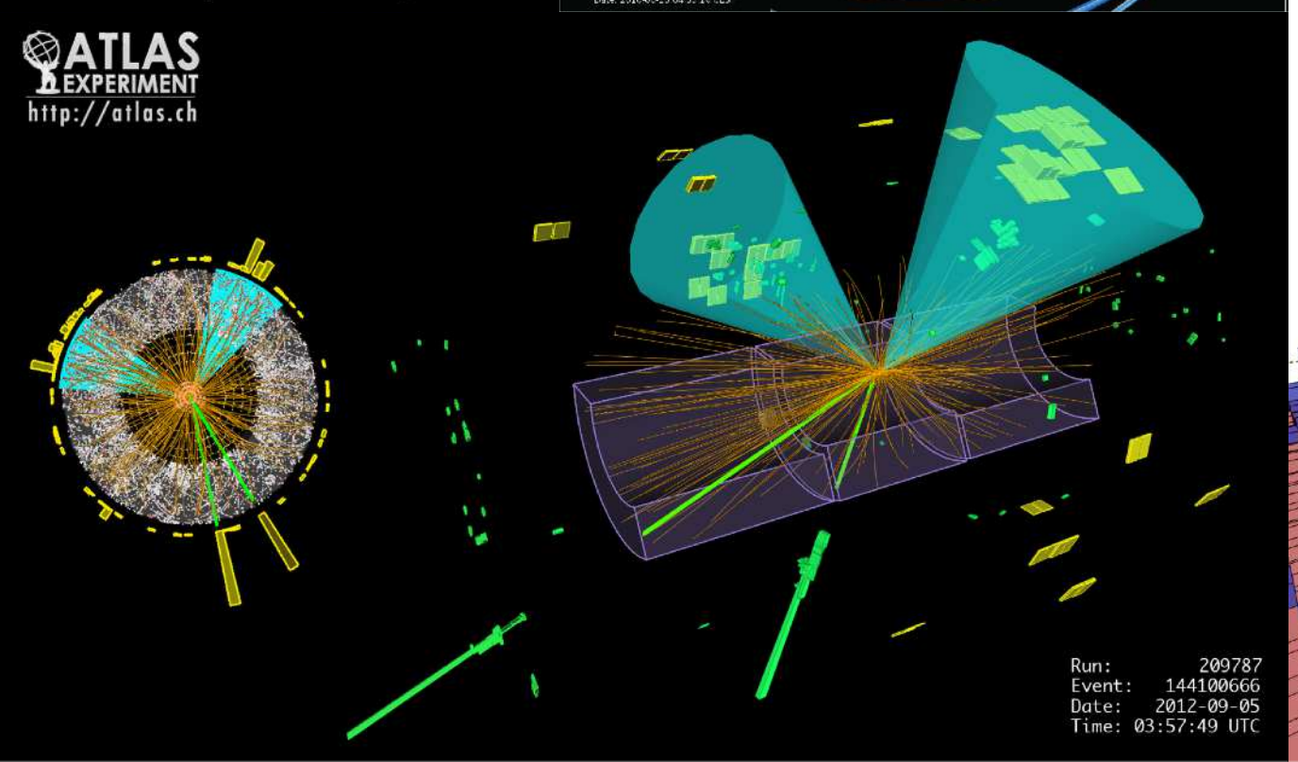

25
5
-5
-4
-3
-2
-1
0
1
2
3
4
5
0
90
180
270
360
η
φ

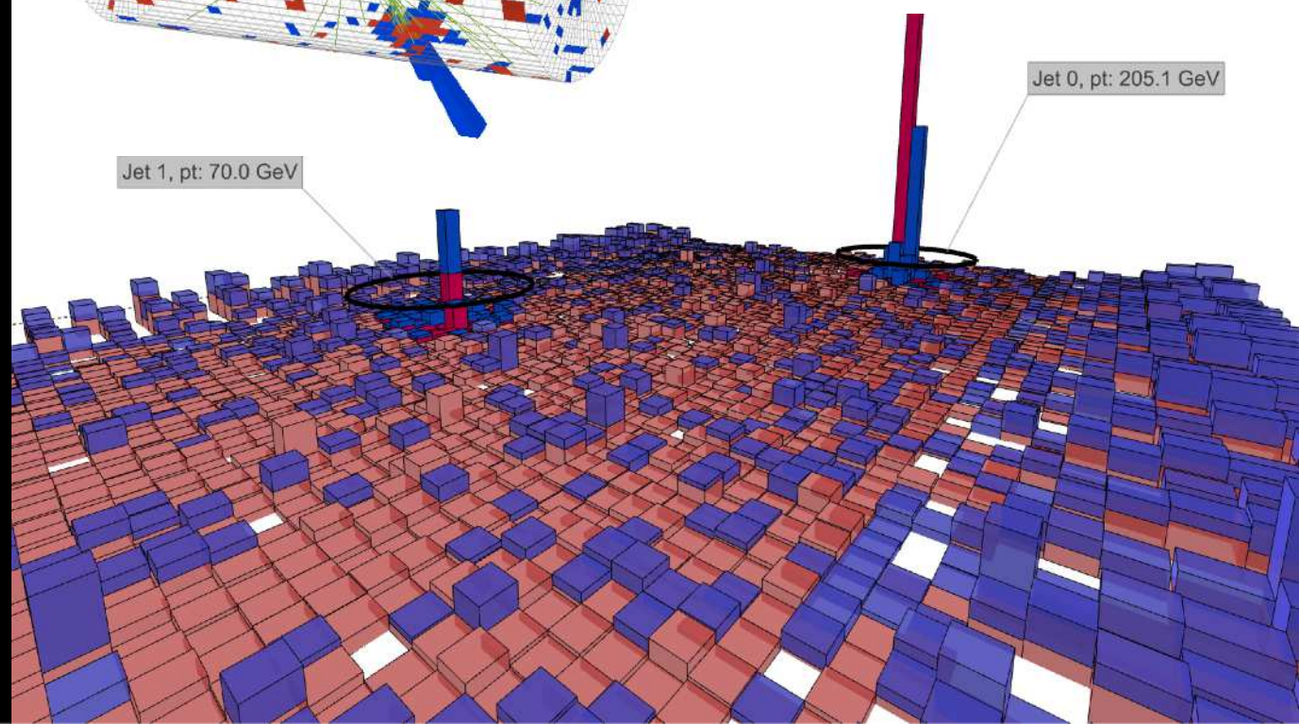

ATLAS
EXPERIMENT




CMS
CMS Experiment at LHC, CERN
Data recorded: Sat Aug 28 23:03:34 2010 EDT
Run/Event: 144089 / 671718071
Lumi section: 574

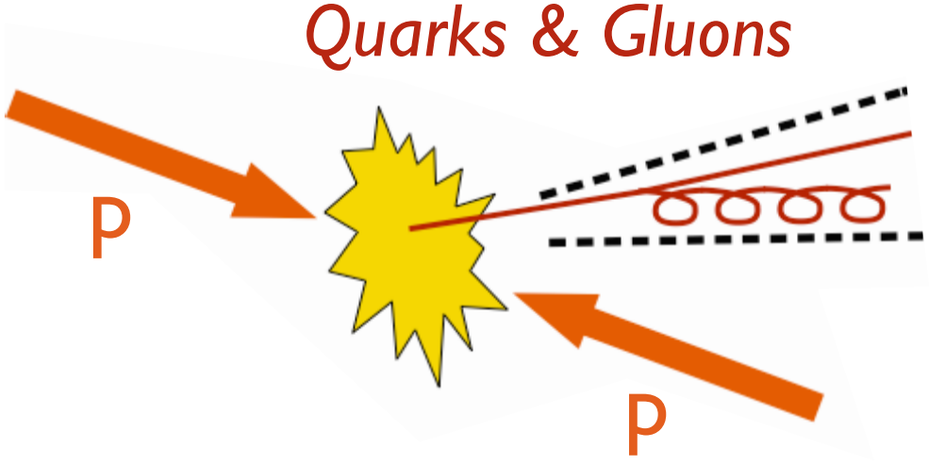



ATLAS
EXPERIMENT
http://atlas.ch
Run: 209787
Event: 144100666
Date: 2012-09-05
Time: 03:57:49 UTC


Jet 0, pt: 205.1 GeV
Jet 1, pt: 70.0 GeV

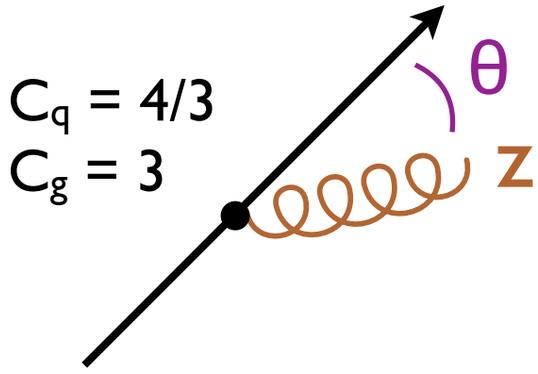
Energy Flow Representation

Emphasizes infrared and collinear safety



Altarelli-Parisi Splitting

Core prediction of QCD

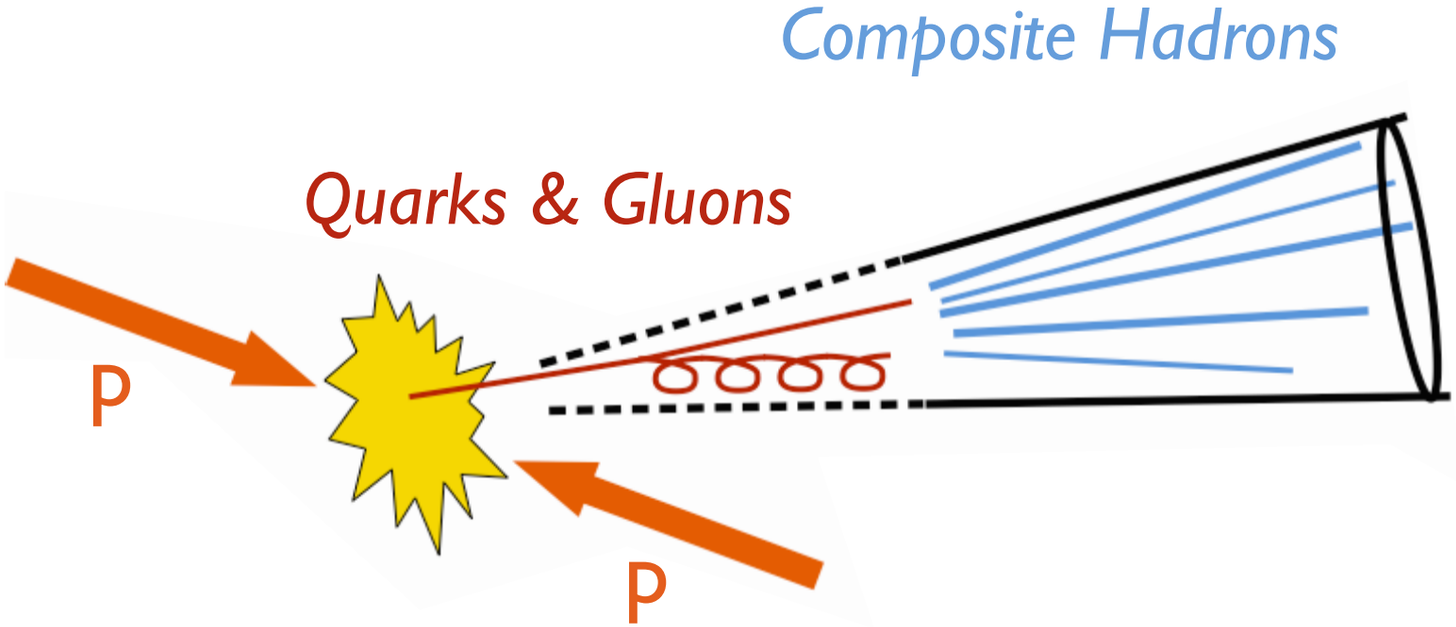


$$\mathrm{d}P_{i\to ig} \simeq \frac{2\alpha_s}{\pi} C_i \frac{\mathrm{d}\theta}{\theta} \frac{\mathrm{d}z}{z}$$

Collinear Soft

Energy Flow Representation

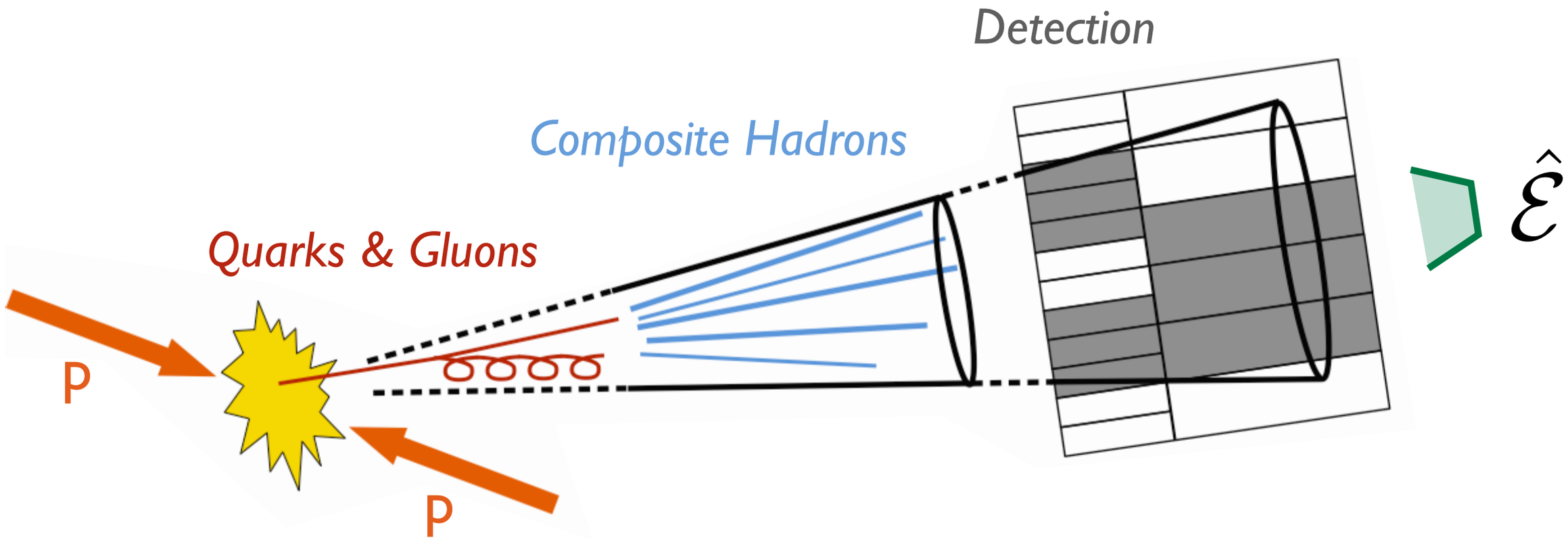
Emphasizes infrared and collinear safety



Energy Flow Representation

Emphasizes infrared and collinear safety

Theory



Energy Flow:

Robust to hadronization and detector effects

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

[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]

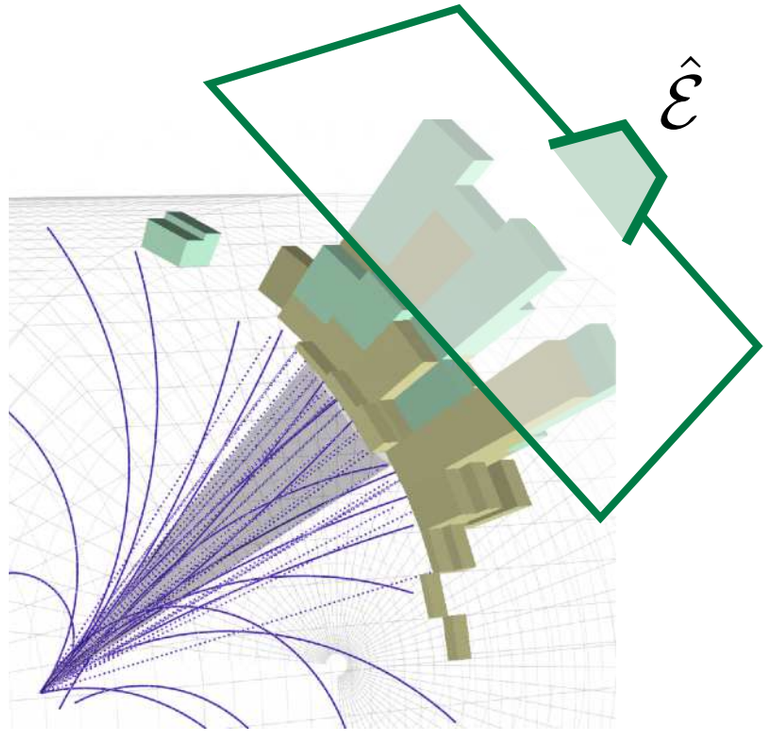
Jets as Weighted Point Clouds

- Energy-Weighted Directions

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

Energy — Direction

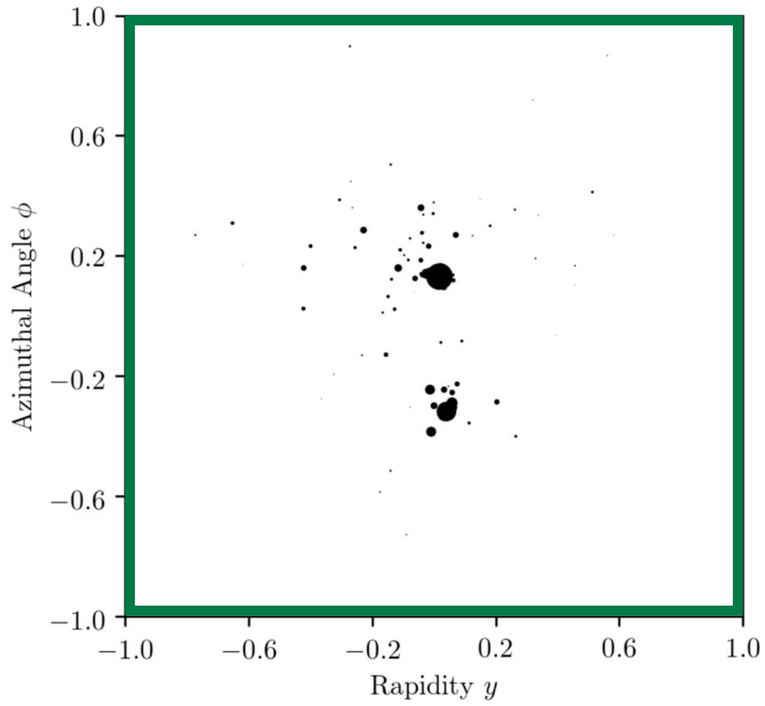
(suppressing "unsafe" charge/flavor information)

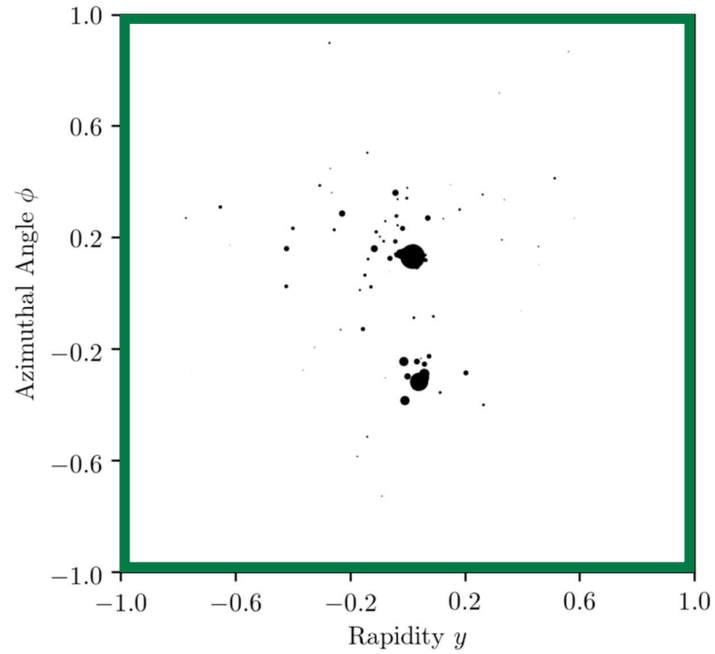


- Equivalently: Energy Density

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

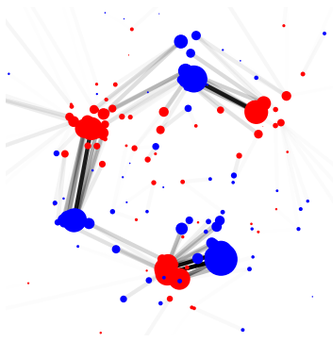
Energy — Direction





When restricted to IRC safe information, jets/events are naturally represented as energy densities

Going with the (Energy) Flow



The Energy Mover's Distance

Revealing a Hidden Geometry

If you ask your local computational geometry expert how to process densities…

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; Kantorovich, 1939; Vaserštein, 1969; Wikipedia]

The Earth Mover's Distance

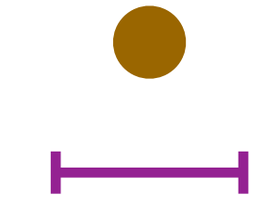
Optimal Transport:

[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

Déblai

Remblai

[h/t Niles-Weed, ML4Jets 2020; Monge, 1781; Kantorovich, 1939; Vaserštein, 1969; Wikipedia]

The Earth Mover's Distance

Optimal Transport:

[Peleg, Werman, Rom, IEEE 1989;
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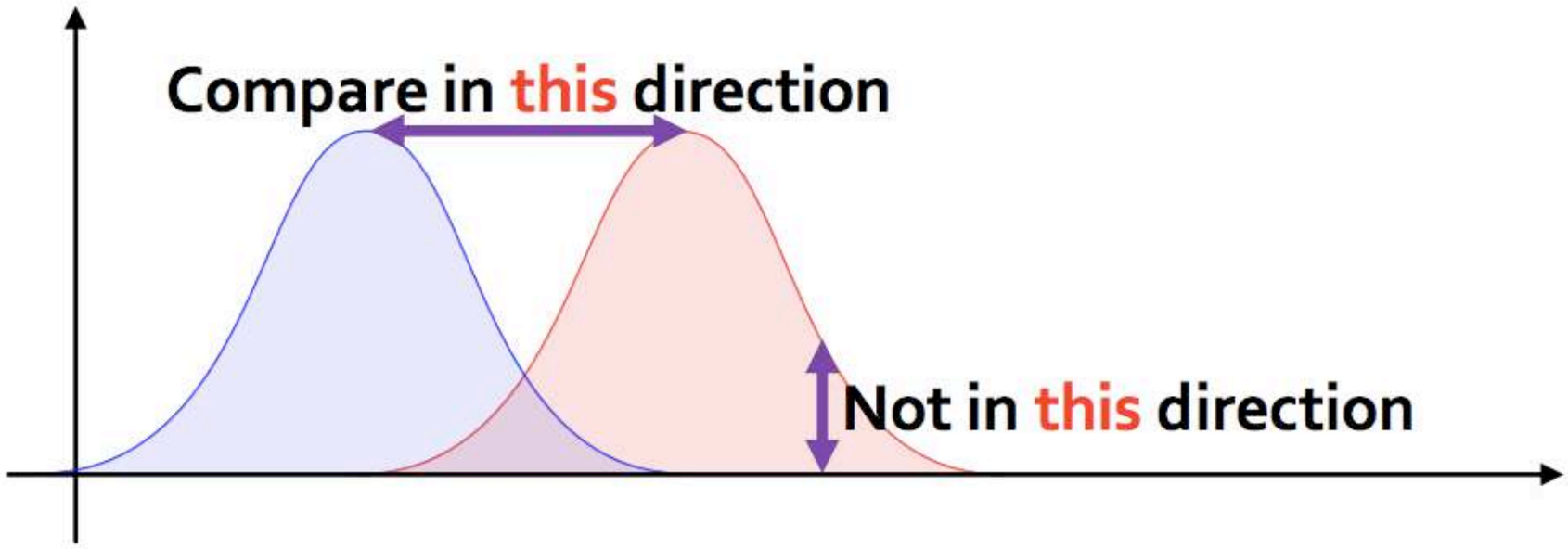
Minimum "work" (stuff x distance) to make one distribution look like another distribution

"Horizontal" comparison (EMD) yields better dynamic range than "vertical" comparison (e.g. KL)

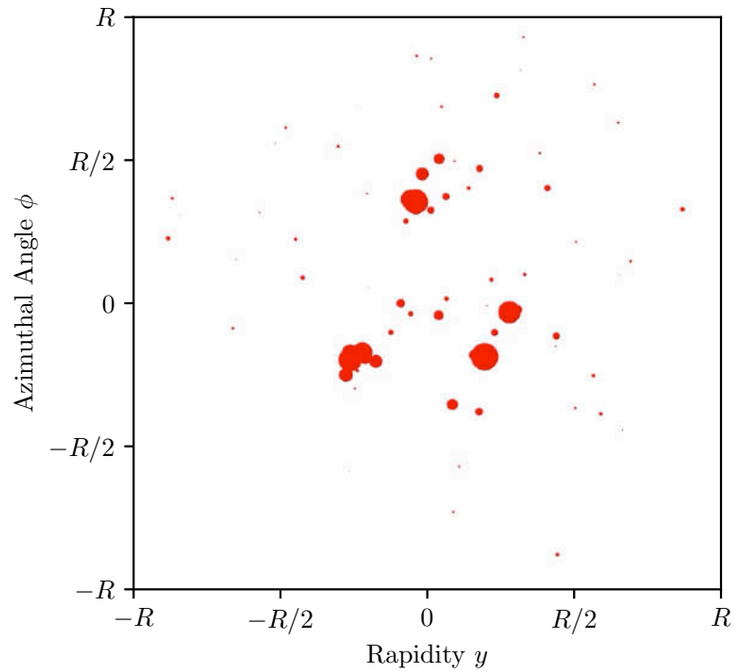


[figure from Kun, Math ∩ Programming]

[h/t Niles-Weed, ML4Jets 2020; Monge, 1781; Kantorovich, 1939; Vaserštein, 1969; Wikipedia]

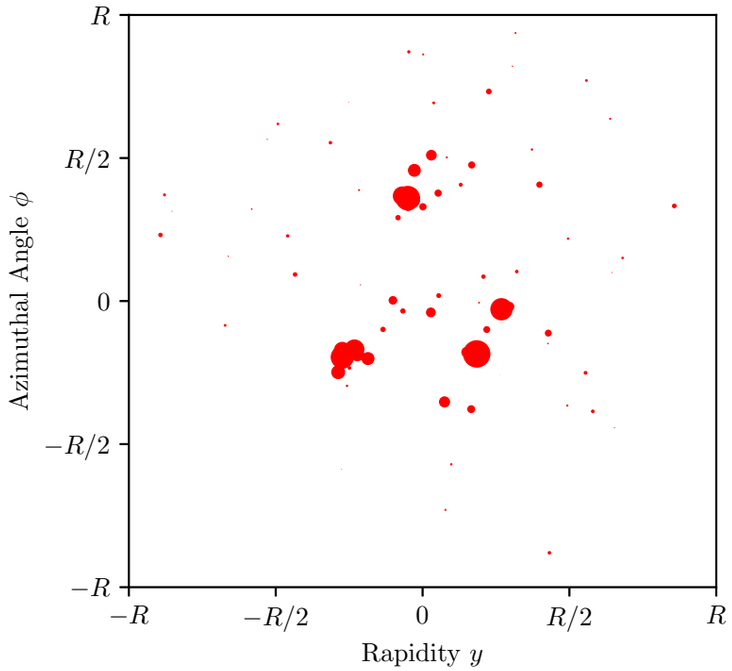
Similarity of Two Energy Flows

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

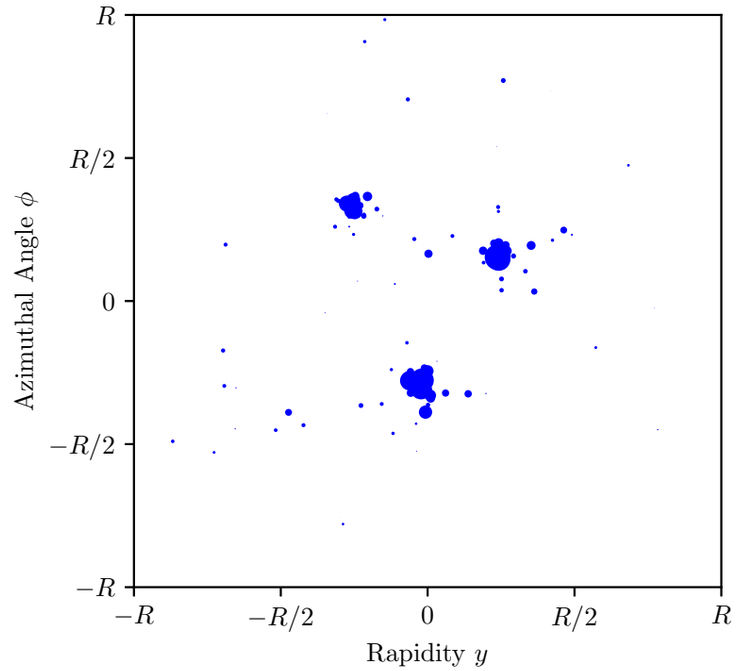


Optimal Transport:

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

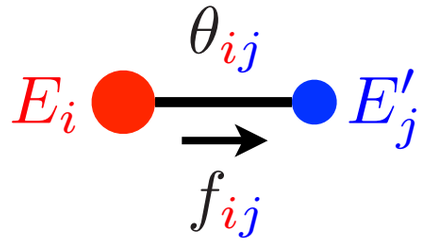


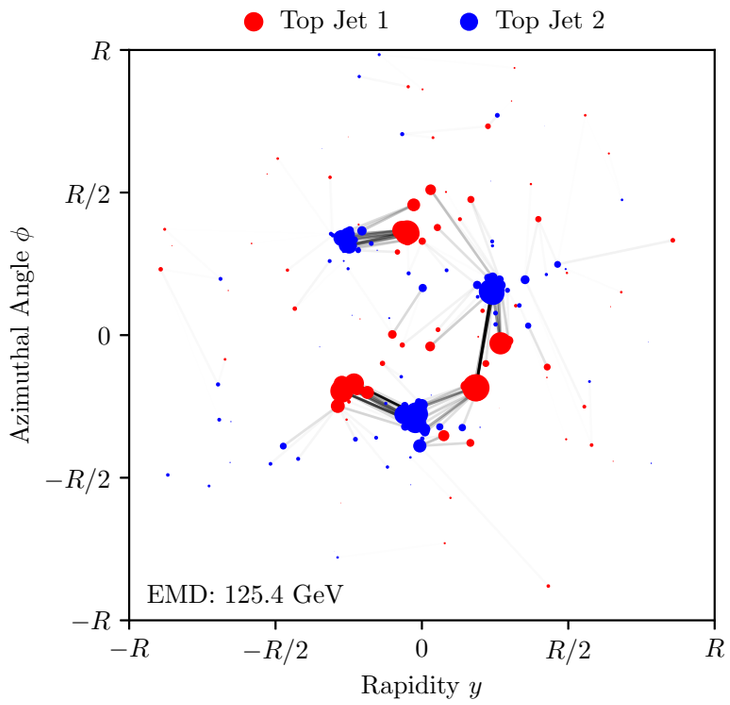
125.4 GeV

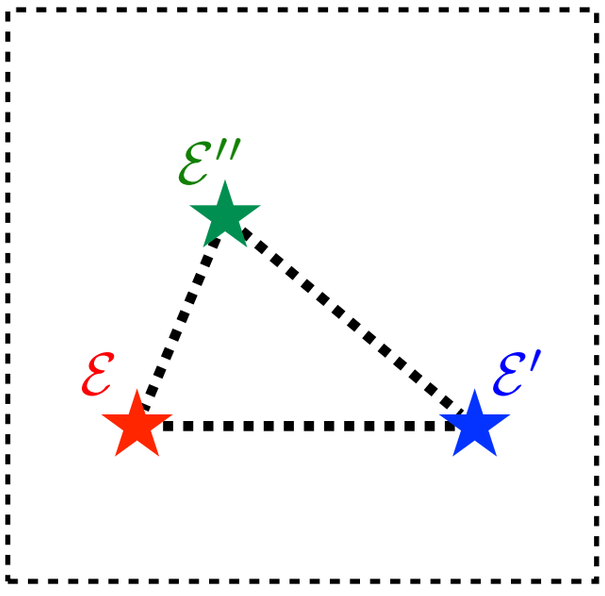


[Komiske, Metodiev, JDT, PRL 2019; code at Komiske, Metodiev, JDT, energyflow.network]

The 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

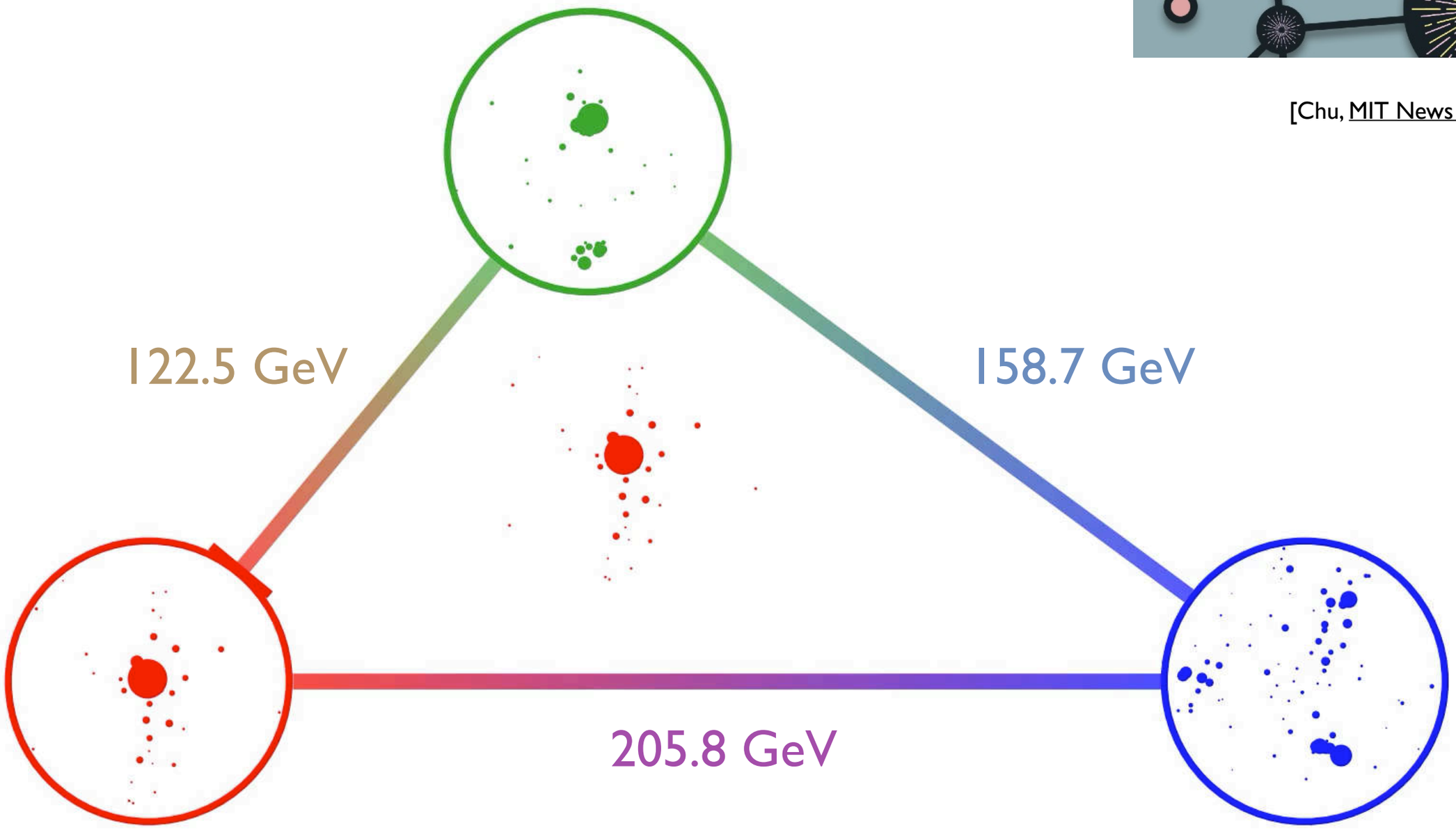
$$0 \leq \mathrm{EMD}(\mathcal{E}, \mathcal{E}') \leq \mathrm{EMD}(\mathcal{E}, \mathcal{E}'') + \mathrm{EMD}(\mathcal{E}', \mathcal{E}'')$$

(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, EPJC 2021]
[see computational speed up in Cai, Cheng, Craig, Craig, PRD 2020]

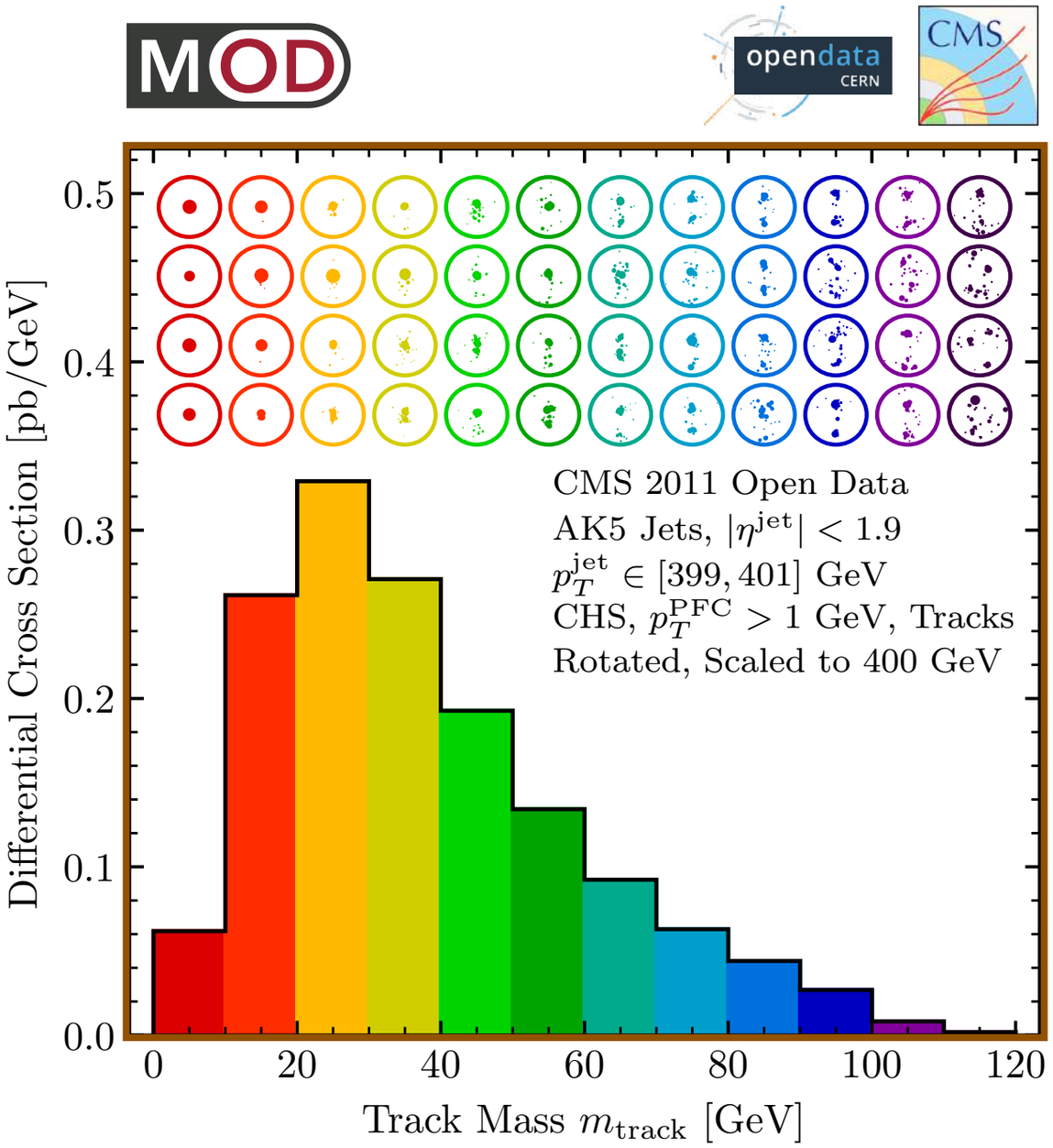
Similarity of Three Energy Flows

[Chu, MIT News July 2019]

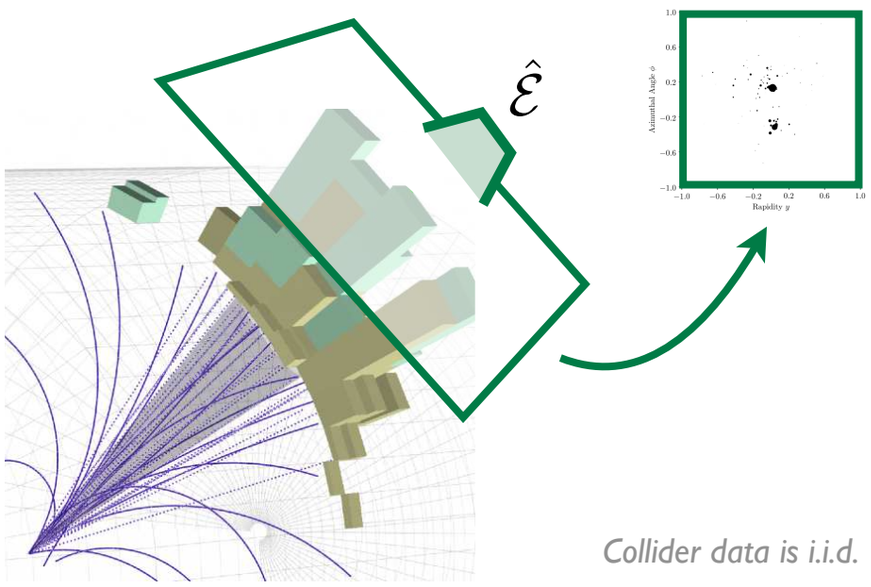


[Komiske, Metodiev, JDT, PRL 2019; code at Komiske, Metodiev, JDT, energyflow.network; see alternative graph network approach in Mullin, Pacey, Parker, White, Williams, JHEP 2021]

The Forest and the Trees



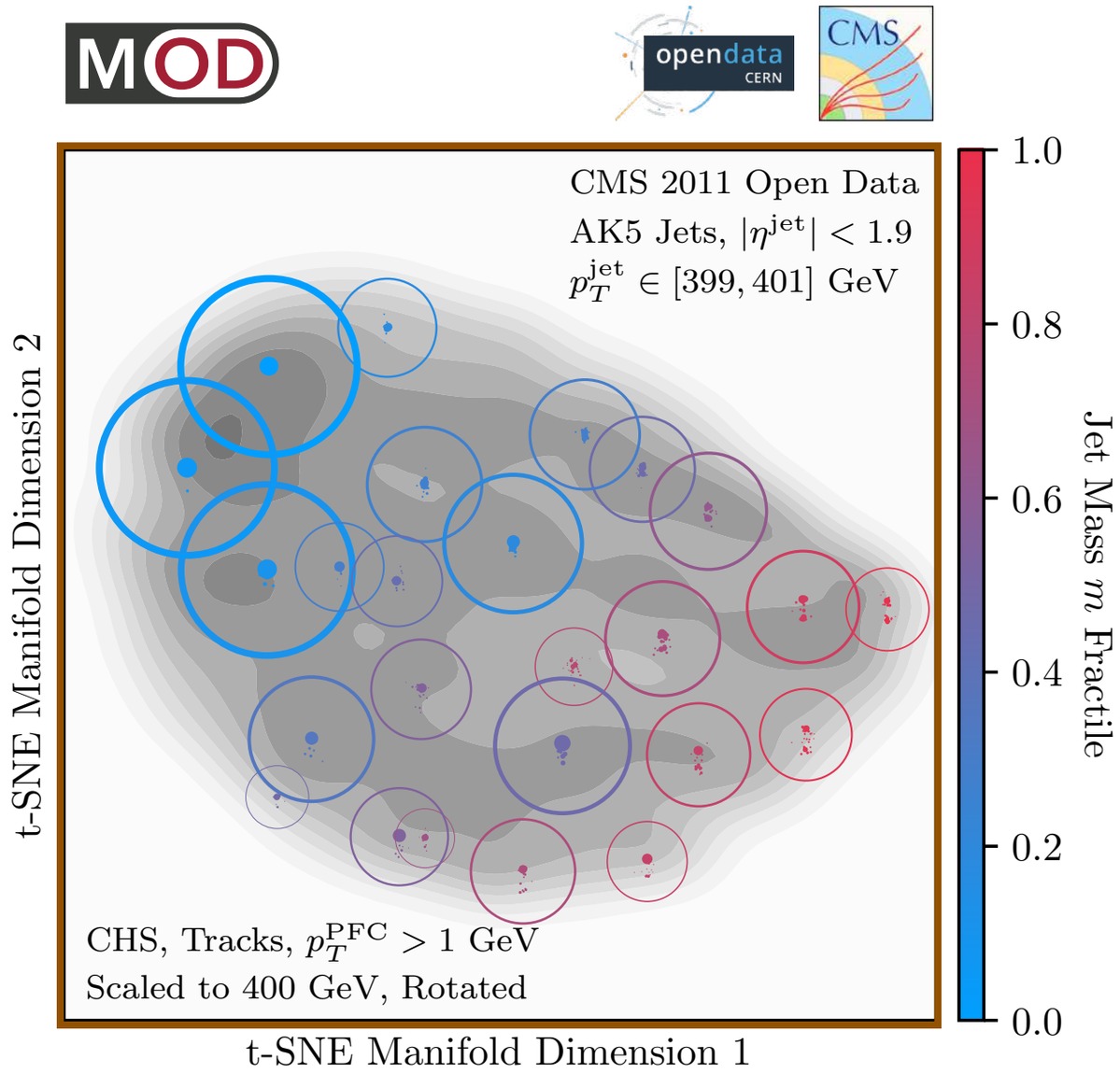
A *Histogram* of *Observables*



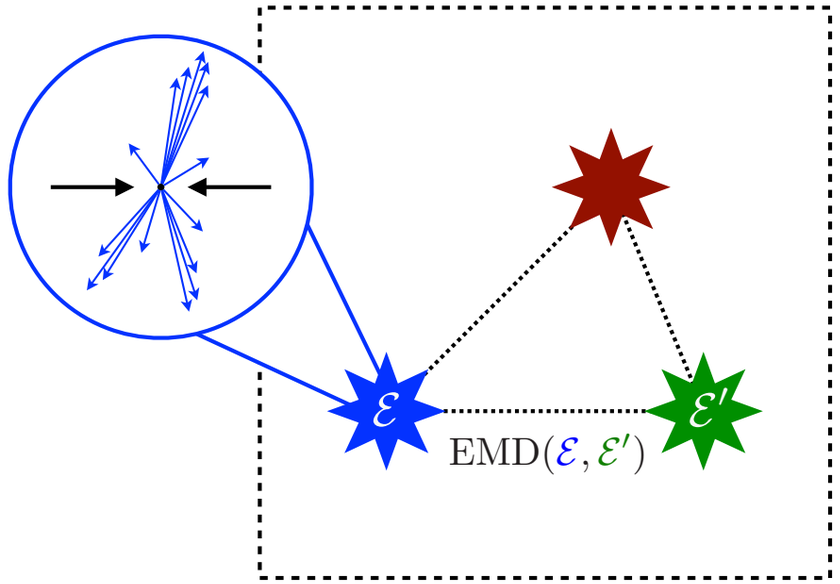
Collider data is i.i.d.

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

Building the Forest from the Trees



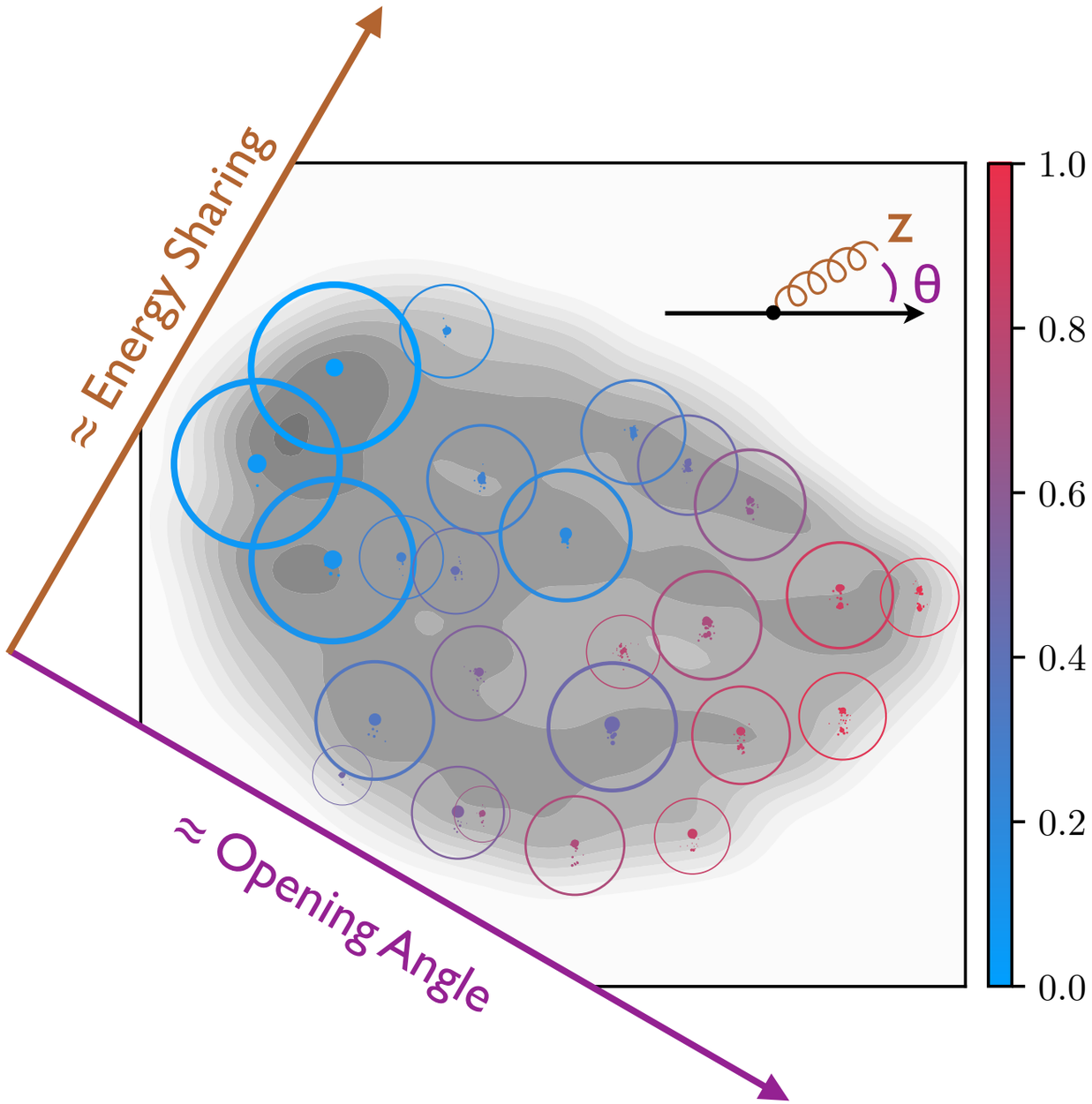
The Space of Energy Flows



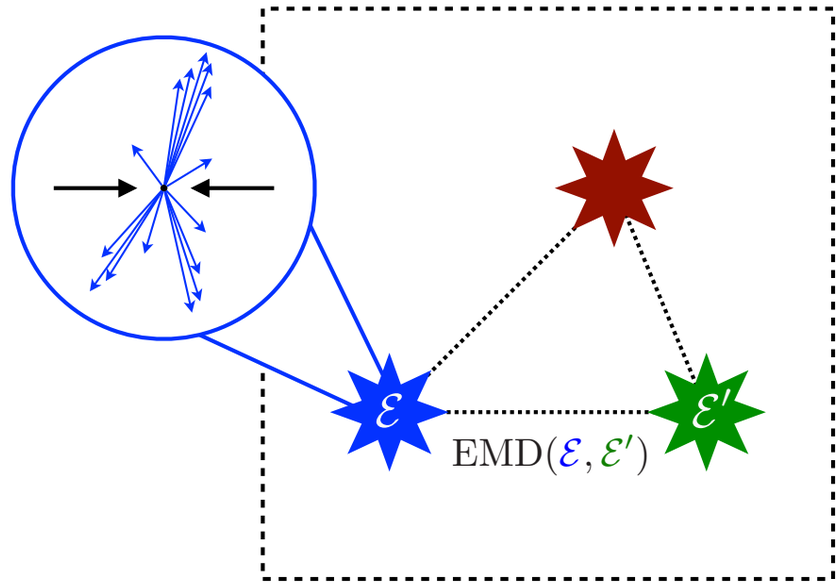
[Komiske, Mastandrea, Metodiev, Naik, JDT, PRD 2020; using van der Maaten, Hinton, JMLR 2008; using CMS Open Data]




Building the Forest from the Trees



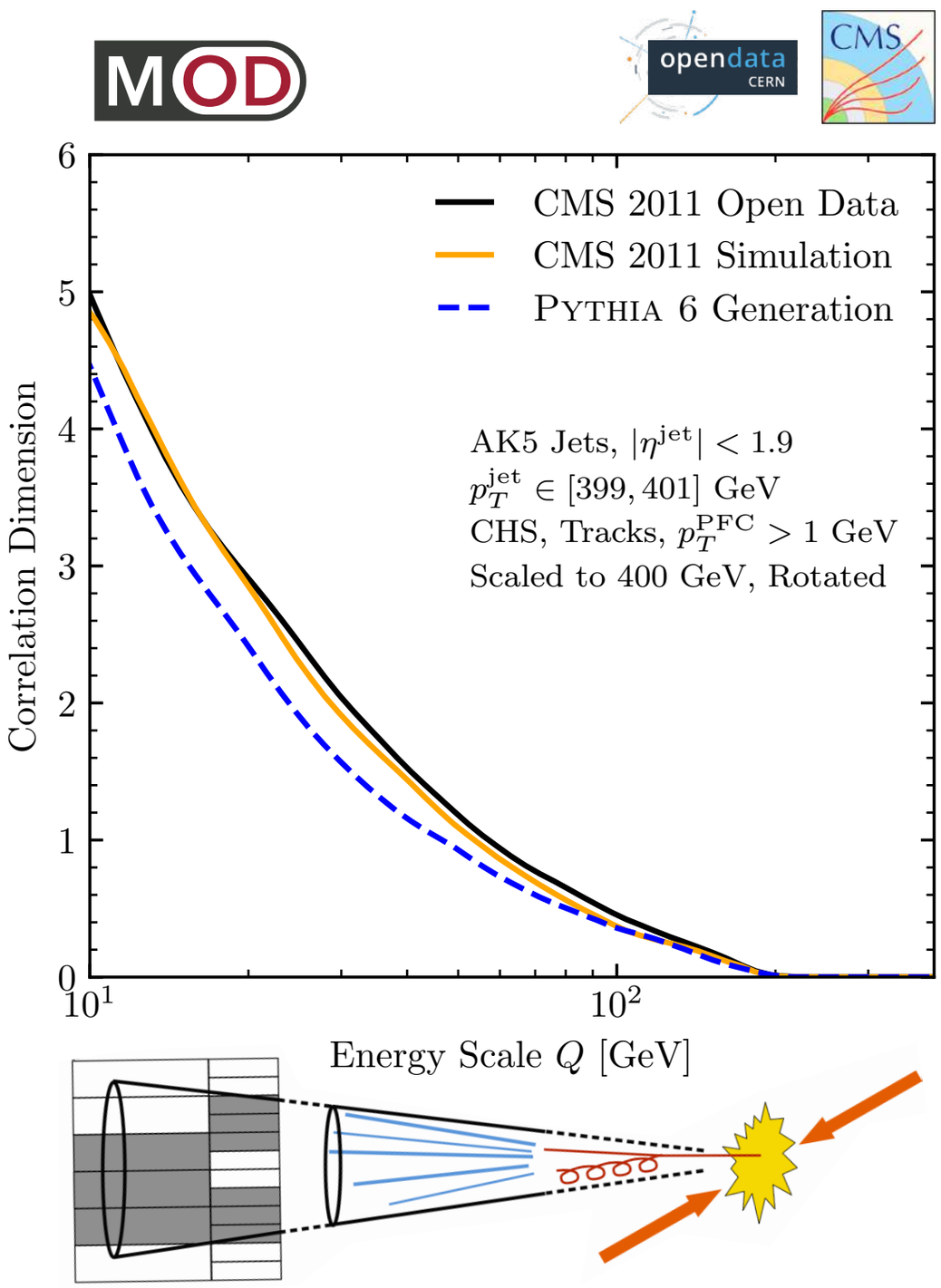
The Space of Energy Flows



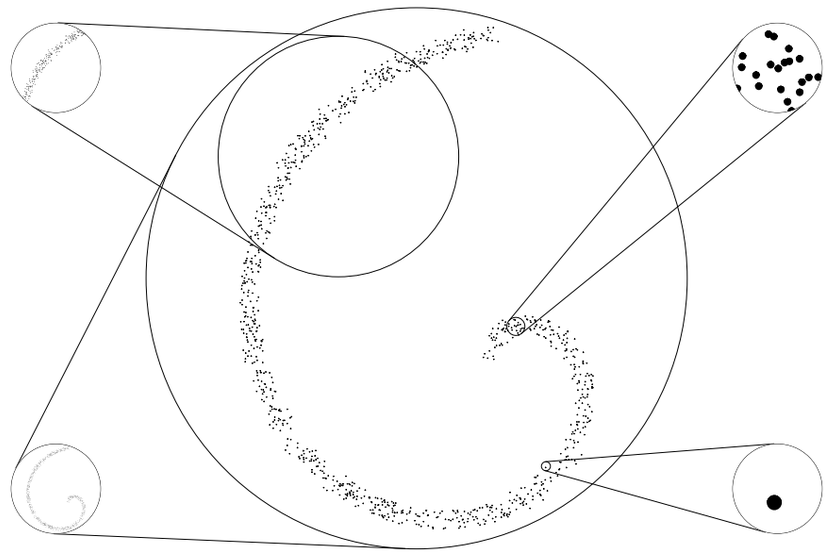
[Komiske, Mastandrea, Metodiev, Naik, JDT, PRD 2020; using van der Maaten, Hinton, JMLR 2008; using CMS Open Data]



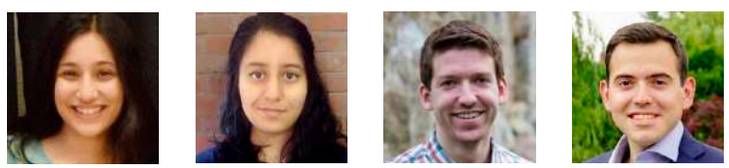

A Super-Fractal Forest made from Trees

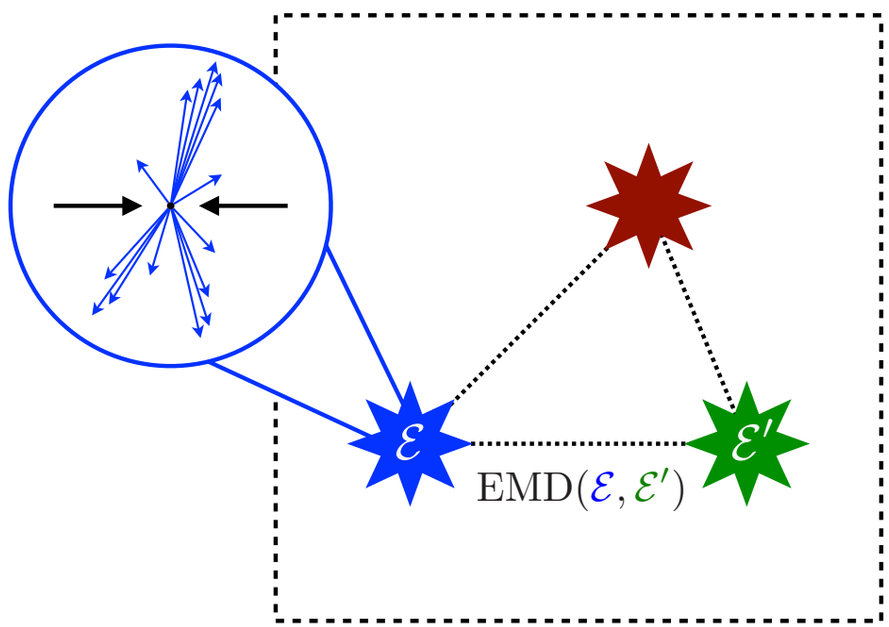


Dimension of Space of Energy Flows



[Komiske, Mastandrea, Metodiev, Naik, JDT, PRD 2020; using Grassberger, Procaccia, PRL 1983; Kégl, NIPS 2002; using CMS Open Data]

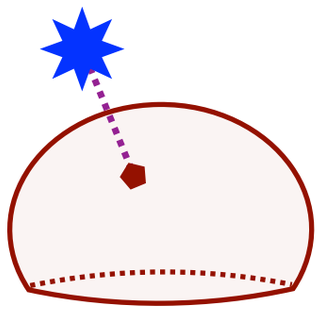




Viewed through the data science lens,
the EMD unlocks a suite of
geometric analysis strategies

Going with the (Energy) Flow

The Energy Mover's Distance

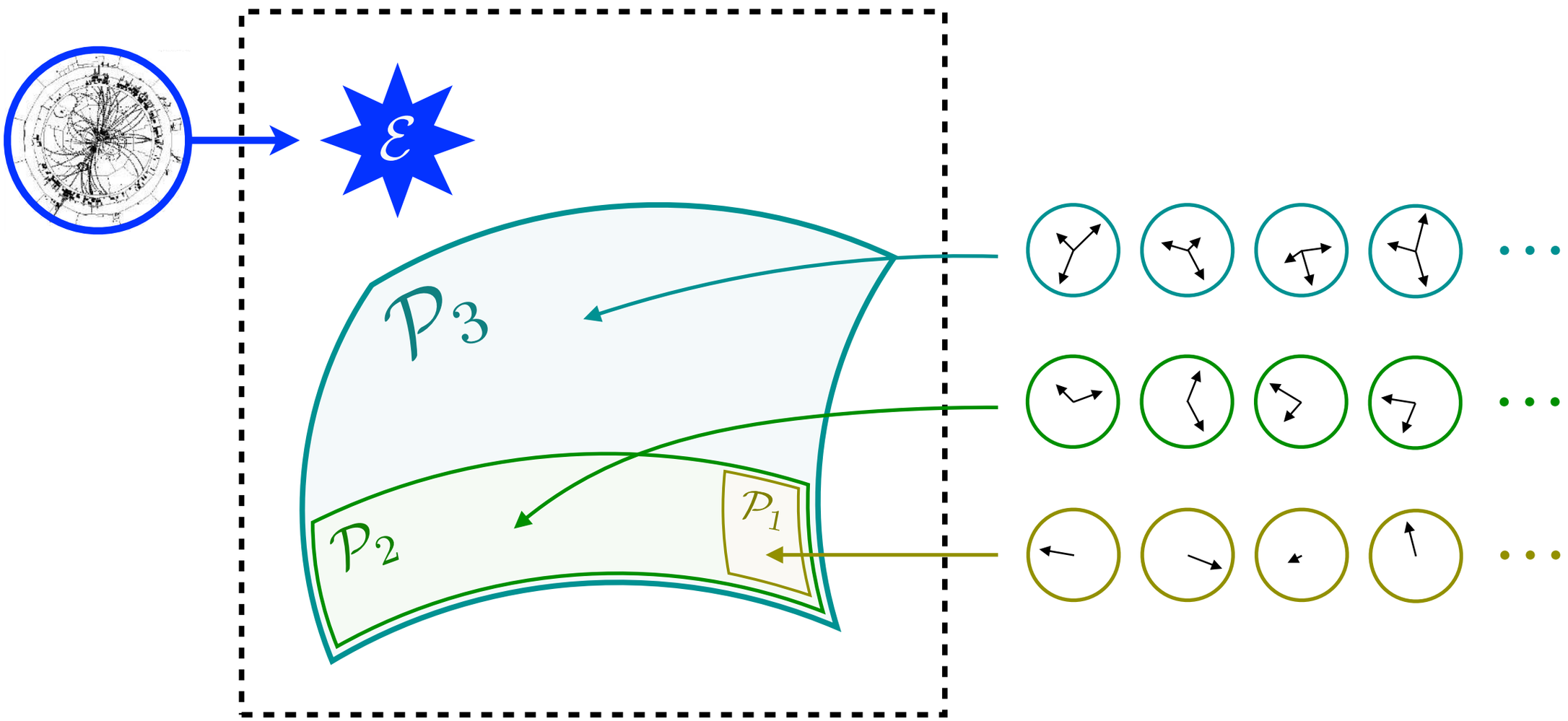


Revealing a Hidden Geometry

Given a metric space, the first geometric object you might think to construct is…

Introducing N-particle Manifolds

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

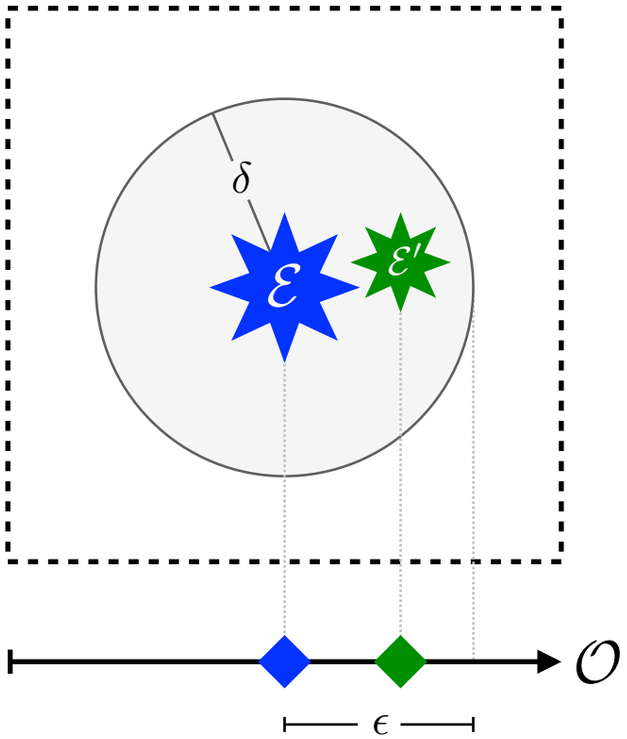


$\mathcal{P}_N \supset \mathcal{P}_{N-1} \supset \ldots \supset \mathcal{P}_2 \supset \mathcal{P}_1$ by soft/collinear limits

[see related discussion in Larkoski, Melia, PRD 2020]

Introducing N-particle Manifolds

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



Infrared & Collinear Safety

≈ calculable in perturbative quantum field theory

*is**

Continuity in EMD Space

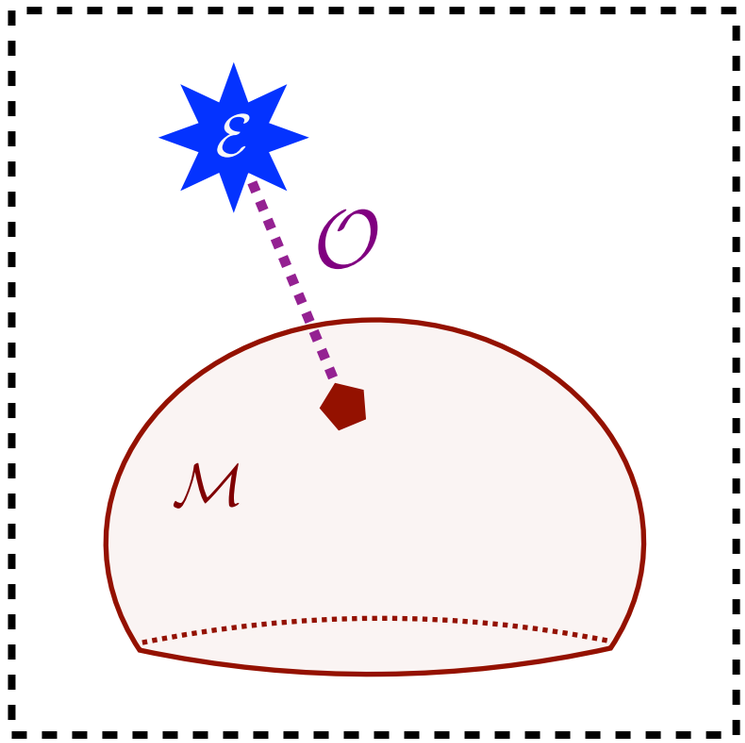
[Komiske, Metodiev, JDT, JHEP 2020]
[Sterman, Weinberg, PRL 1977; Sterman, PRD 1979]
[see also Banfi, Salam, Zanderighi, JHEP 2005; Larkoski, Marzani, JDT, PRD 2015]

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

[see related discussion in Larkoski, Melia, PRD 2020]

Manifolds for Observables

One Event



Set of Events

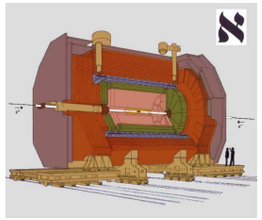
Distance of Closest Approach ⇒ Observable

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

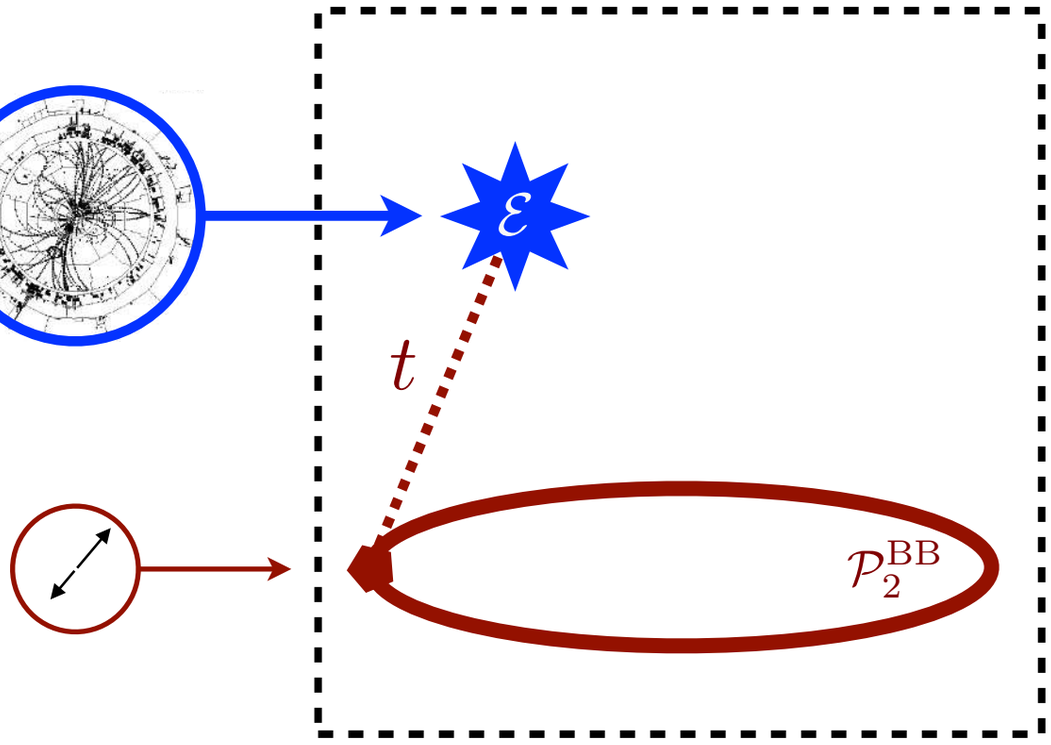
[Komiske, Metodiev, JDT, JHEP 2020]

E.g. Thrust

How dijet-like is an event?



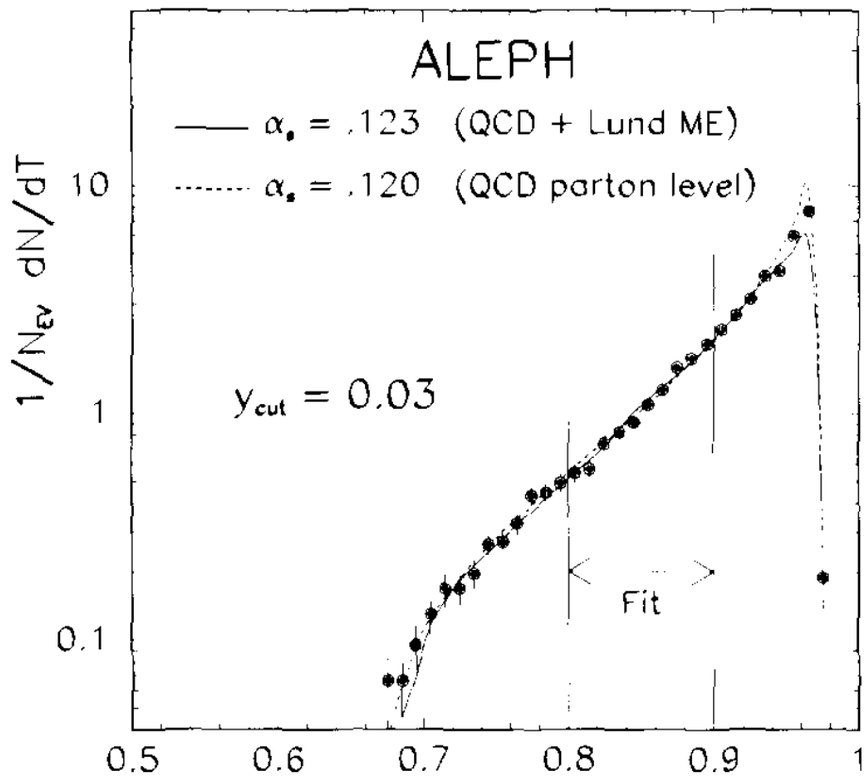
$$t(\mathcal{E}) = \min_{\mathcal{E}' \in \mathcal{P}_2^{\text{BB}}} \text{EMD}_2(\mathcal{E}, \mathcal{E}')$$



All Back-to-Back Two Particle Configurations

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

(using β=2 EMD variant)



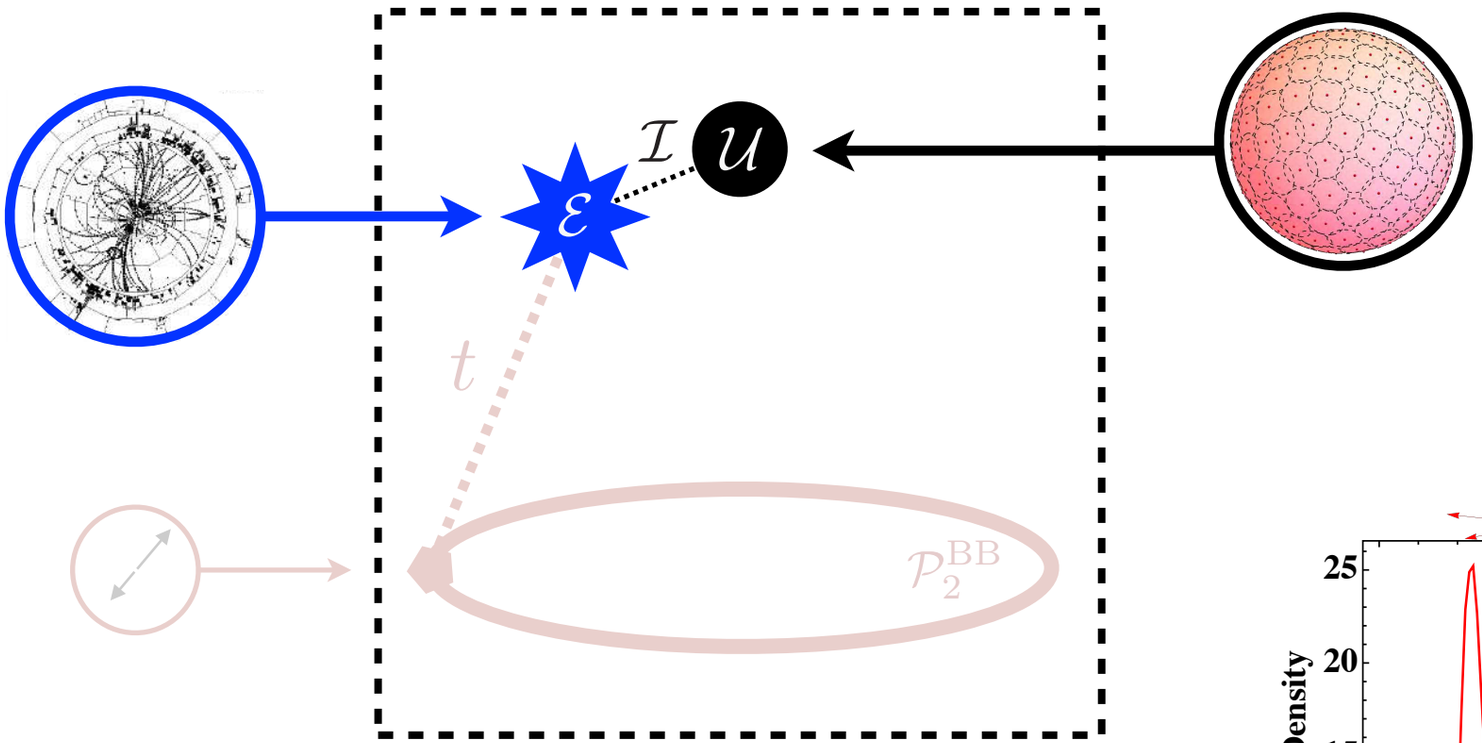
$$1 - \frac{t}{2E_{\text{CM}}}$$

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

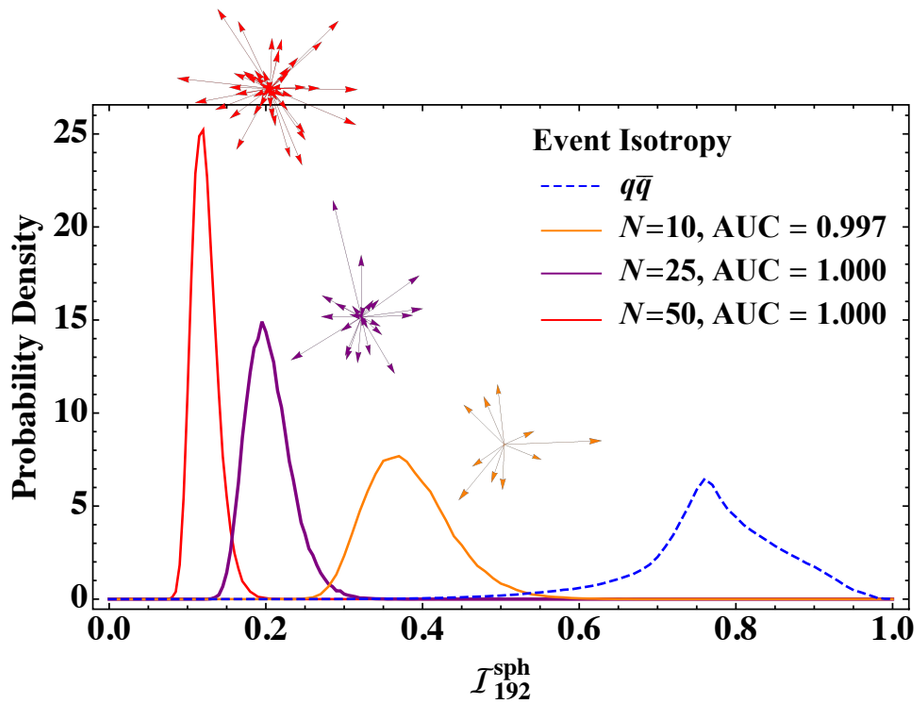
[Komiske, Metodiev, JDT, JHEP 2020]
[Brandt, Peyrou, Sosnowski, Wroblewski, PL 1964; Farhi, PRL 1977; ALEPH, PLB 1991]

New! Event Isotropy

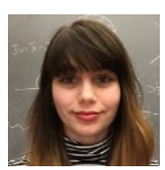
How isotropic is an event?



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

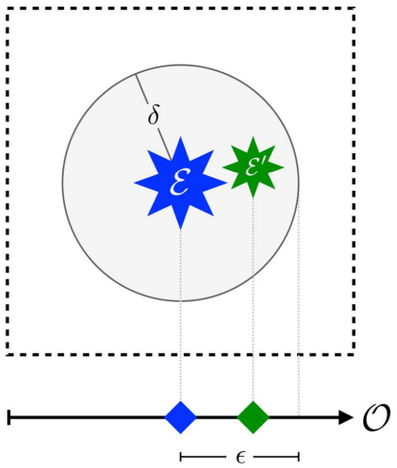


[Cesarotti, JDT, JHEP 2020;
see also Cesarotti, Reece, Strassler, JHEP 2021]

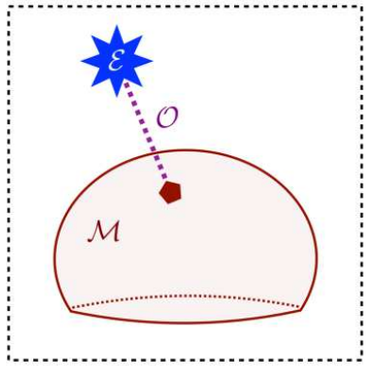


Six Decades of Collider Physics Translated into a New Geometric Language!

IRC Safety is smoothness in the space of events

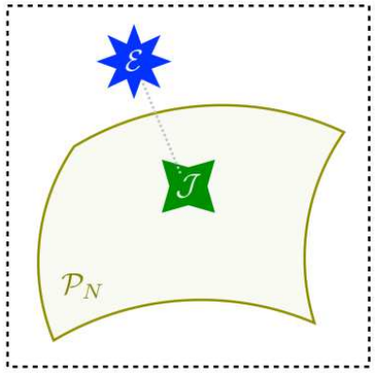


Event shapes are distances from events to manifolds.



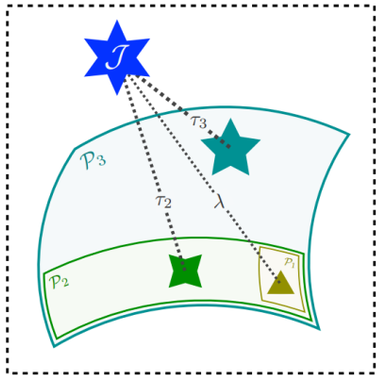
$$\mathcal{O}(\mathcal{E}) = \min_{\mathcal{E}' \in \mathcal{M}} \mathrm{EMD}_{\beta,R}(\mathcal{E}, \mathcal{E}')$$

Jets are projections to few-particle manifolds.



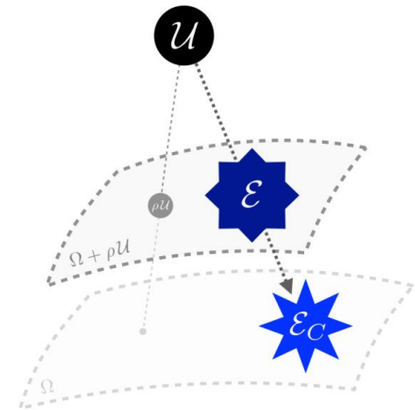
$$\mathcal{J} = \underset{\mathcal{E}' \in \mathcal{P}_N}{\mathrm{argmin}} \, \mathrm{EMD}_{\beta,R}(\mathcal{E}, \mathcal{E}')$$

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

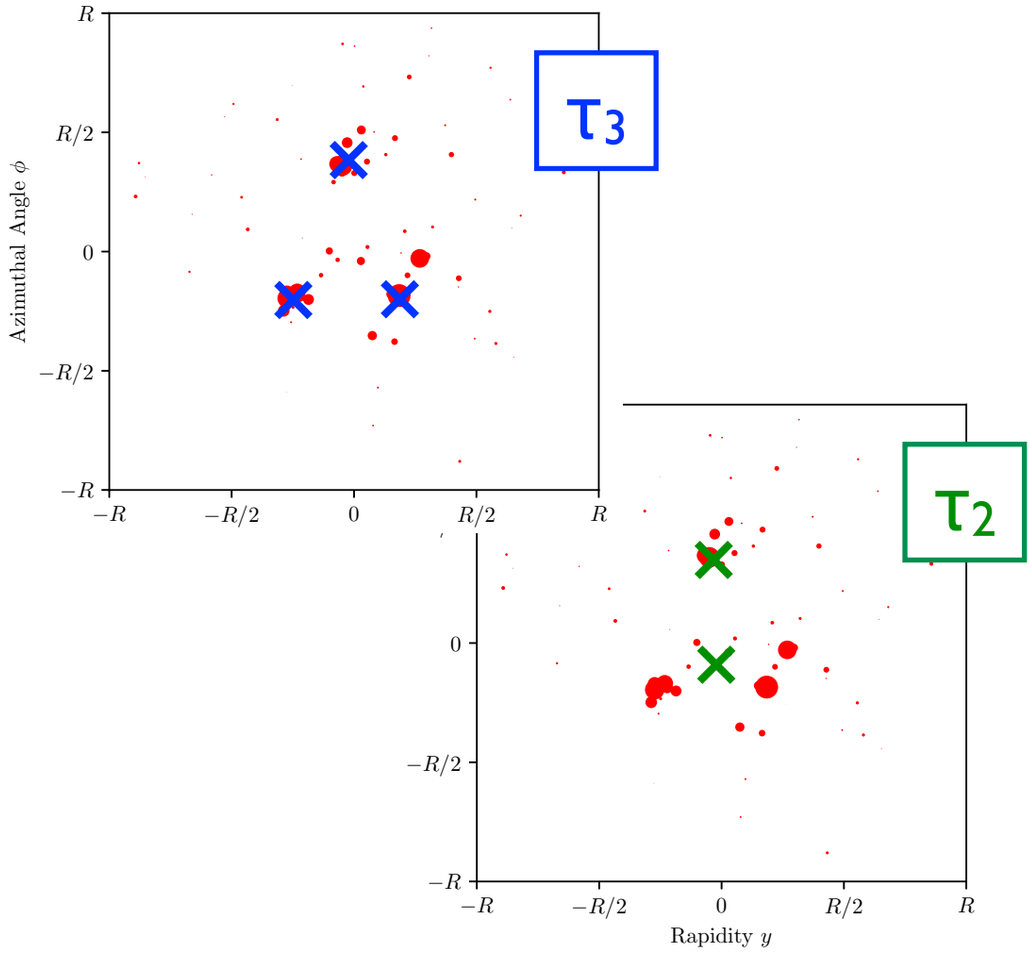
And many more!

[Komiske, Metodiev, JDT, JHEP 2020; timeline from Metodiev]

N-subjettiness

Ubiquitous jet substructure observable used for almost a decade…

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

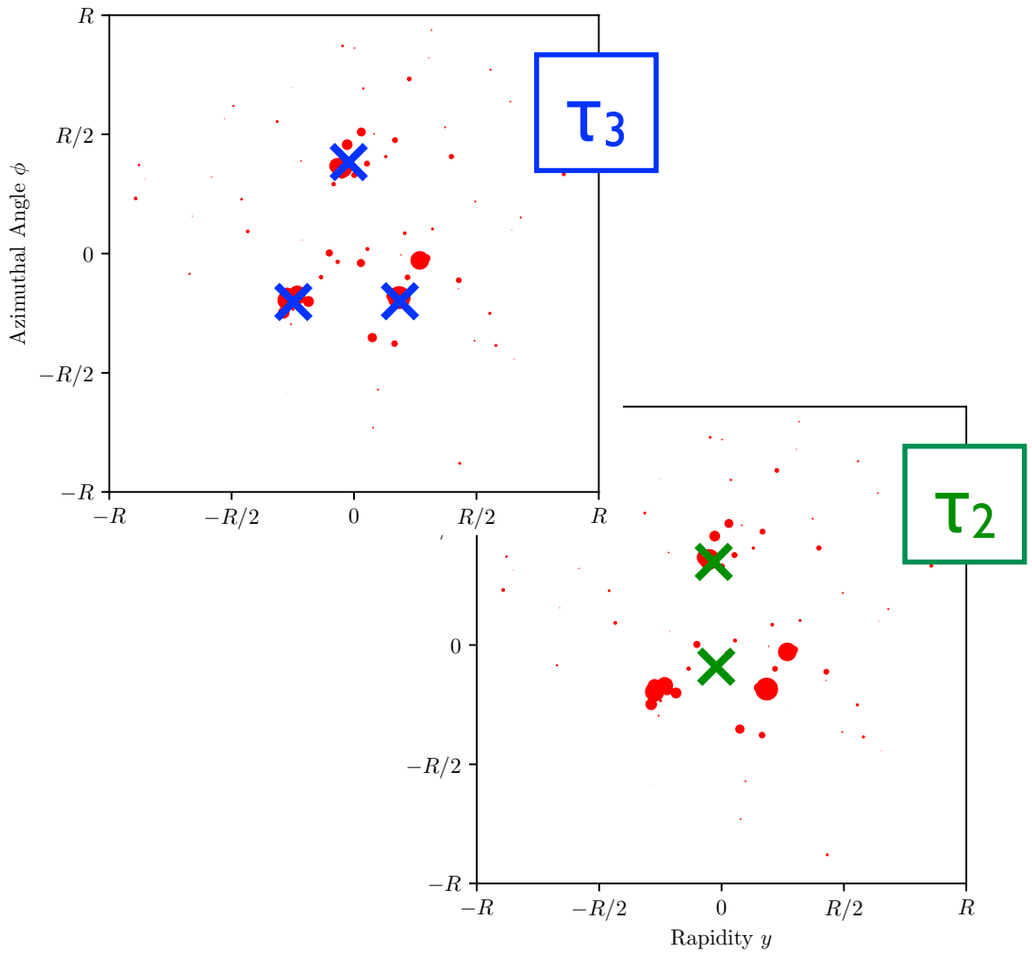


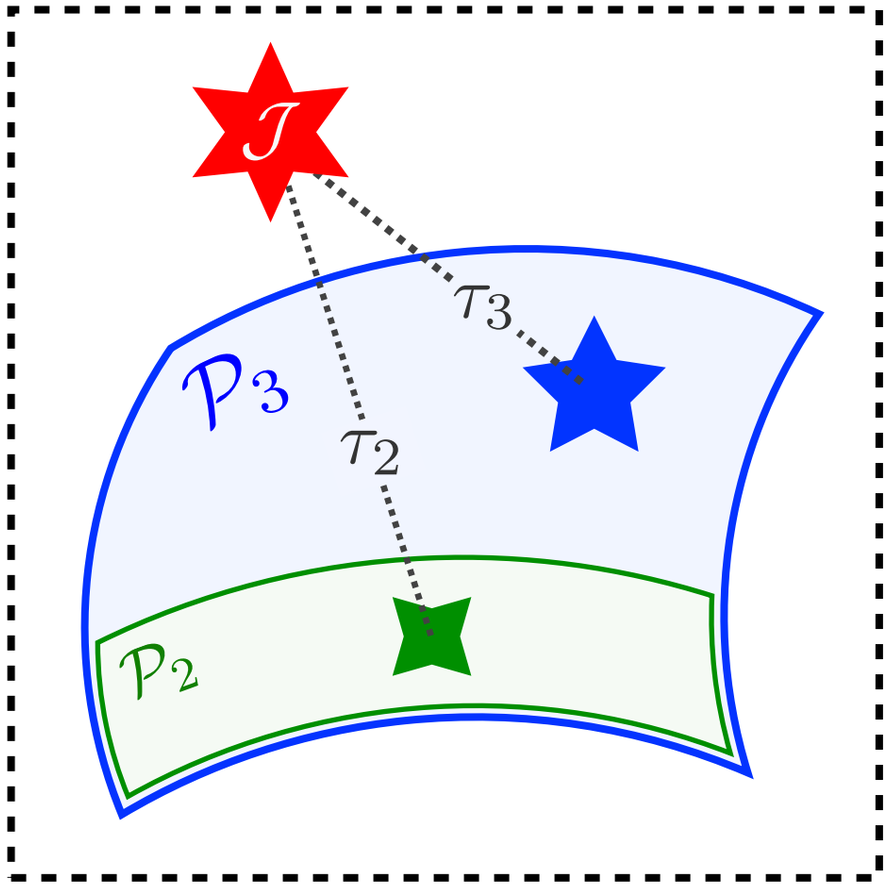
[JDT, Van Tilburg, JHEP 2011, JHEP 2012;
based on Brandt, Dahmen, ZPC 1979; Stewart, Tackmann, Waalewijn, PRL 2010]

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]

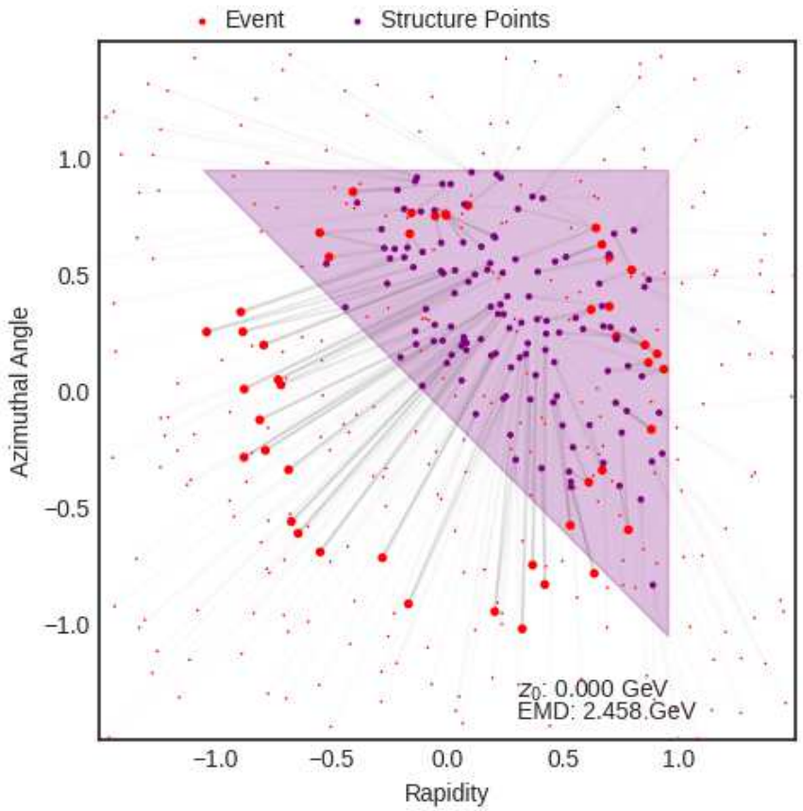


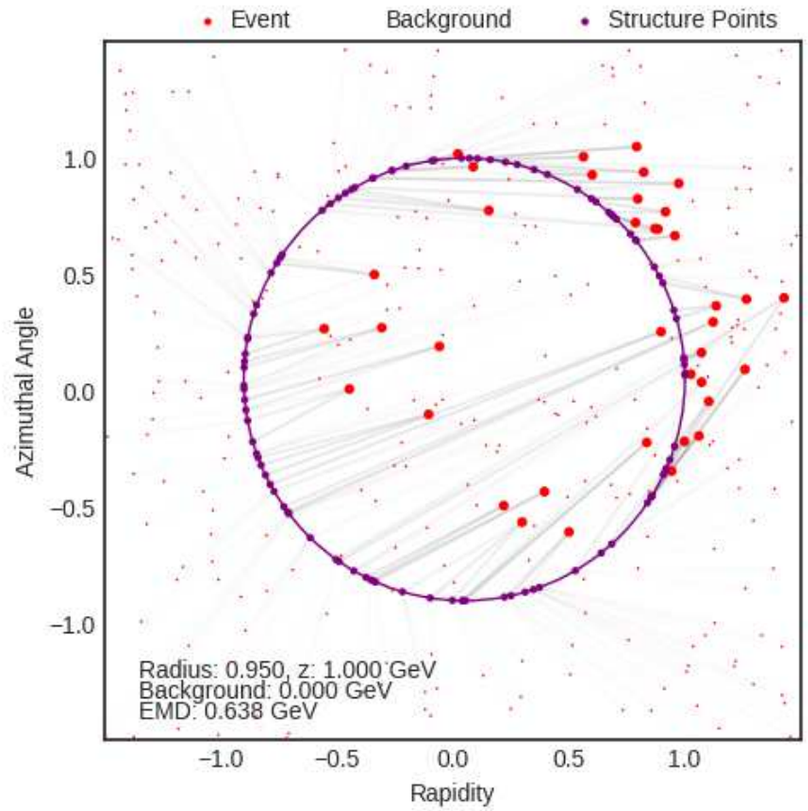
Deep Manifold Learning

Optimal transport meets gradient descent

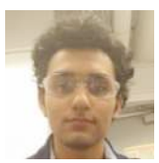
$$\mathcal{O}(\mathcal{E}) = \min_{\mathcal{E}' \in \mathcal{M}} \mathrm{EMD}(\mathcal{E}, \mathcal{E}')$$

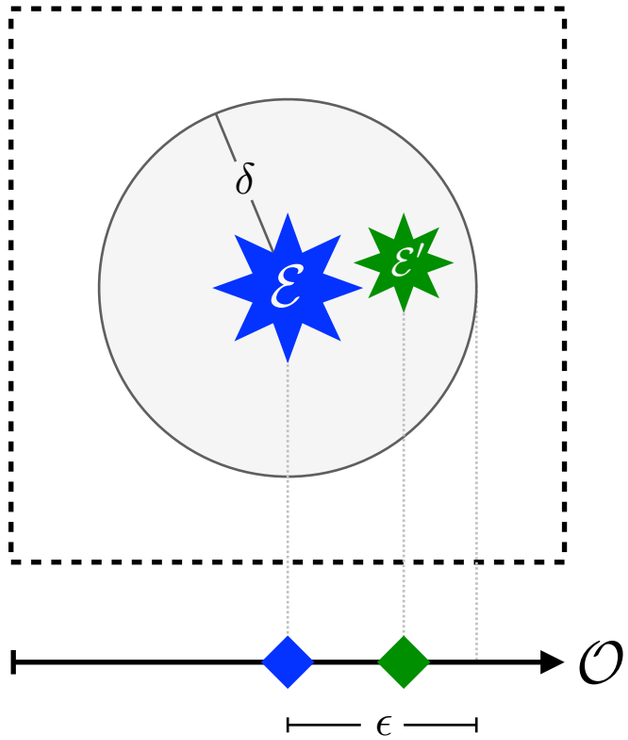
How triangle-like / ring-like is this jet?





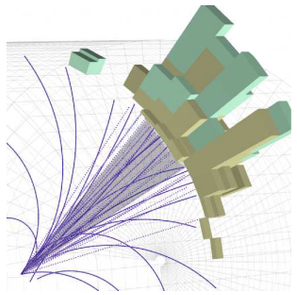
[Ba, Dogra, Gambhir, JDT, in progress;
inspired by Tankala, Tasissa, Murphy, Ba, arXiv 2020]

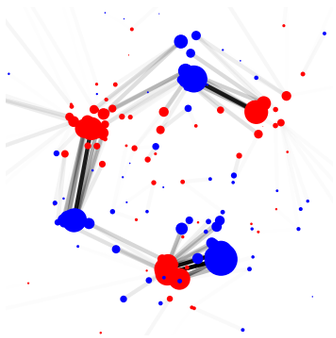
We are just beginning to leverage the conceptual richness of optimal transport for high-energy physics application

Summary



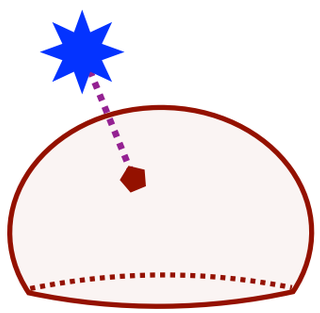
Going with the (Energy) Flow

Restricting our attention to IRC safe information is a theoretically motivated data analysis strategy



The Energy Mover's Distance

Optimal transport allows us to triangulate the space of collider events and define an emergent geometry



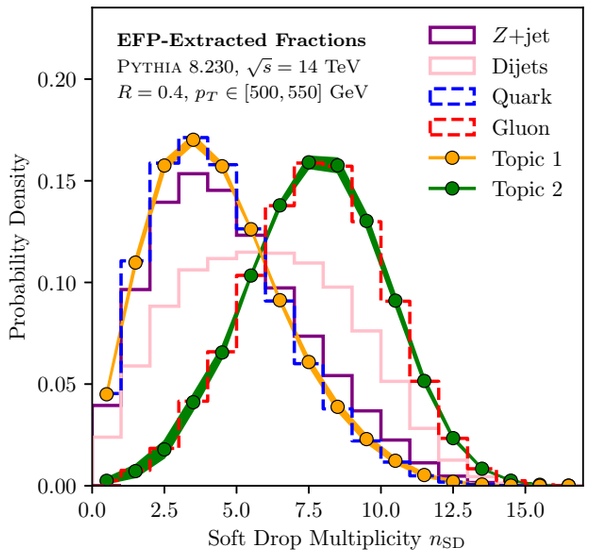
Revealing a Hidden Geometry

We can gain new perspectives on concepts/techniques in QFT and collider physics from the last half century

Backup Slides

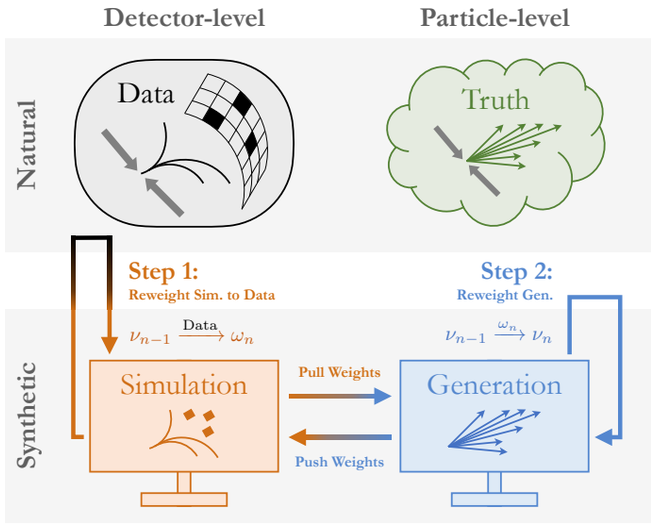
Recent Collisions

Quark/Gluon Definitions via Blind Source Separation



[Komiske, Metodiev, JDT, JHEP 2018; Brewer, JDT, Turner; PRD 2021]

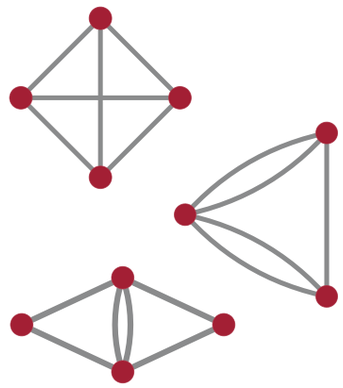
Detector Deconvolution via Binary Classification



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

Kinematic Decomposition via Graph Theory

Edges d	Leafless Multigraphs Connected A307317	Leafless Multigraphs All A307316
1	0	0
2	1	1
3	2	2
4	4	5
5	9	11
6	26	34
7	68	87
8	217	279
9	**718**	**897**
10	**2 553**	**3 129**
11	**9 574**	**11 458**
12	**38 005**	**44 576**
13	**157 306**	**181 071**
14	**679 682**	**770 237**
15	**3 047 699**	**3 407 332**
16	**14 150 278**	**15 641 159**

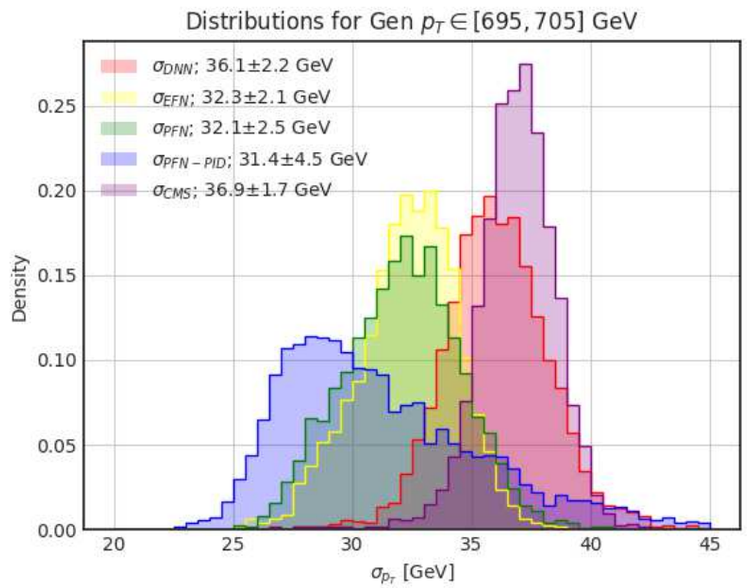


[Komiske, Metodiev, JDT, JHEP 2018, PRD 2020]

High Energy Physics ⇔ *Mathematics, Statistics & Computer Science*

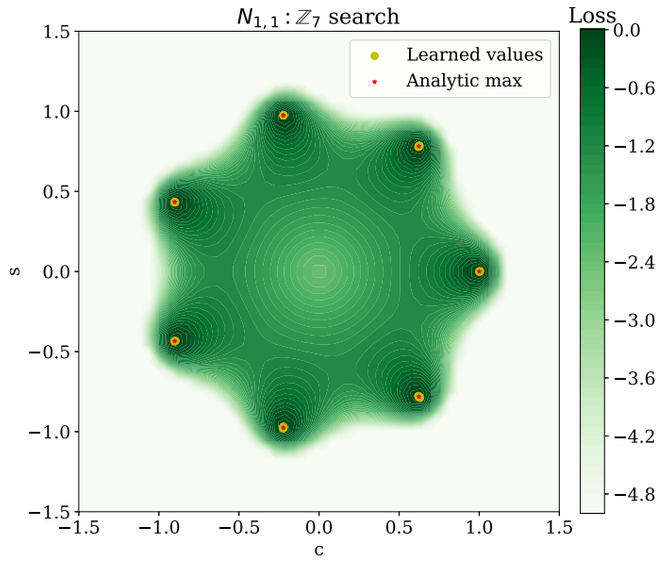
Ongoing Collisions

Frequentist Jet Calibration via Gaussian Ansatz



[Nachman, Gambhir, JDT, in progress]

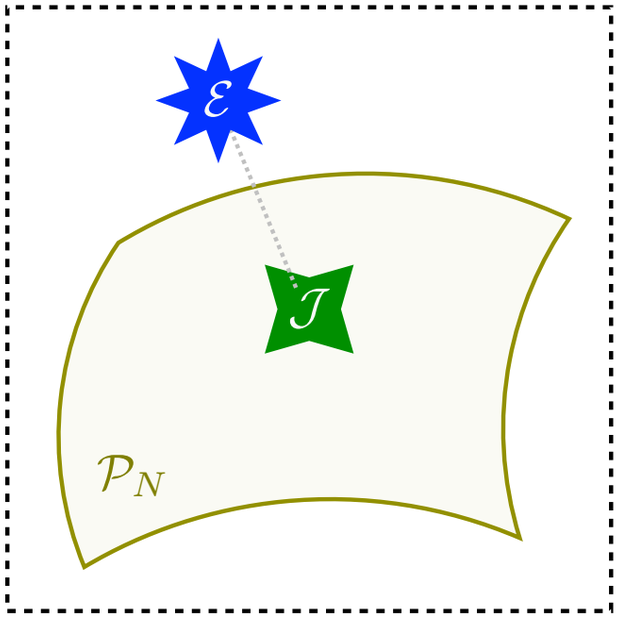
Symmetry Discovery via Adversarial Learning



[Desai, Nachman, JDT, NeurIPS 2021 ML4PS]

High Energy Physics ⇔ *Mathematics, Statistics & Computer Science*

More Fun with N-particle Manifolds



N-jettiness

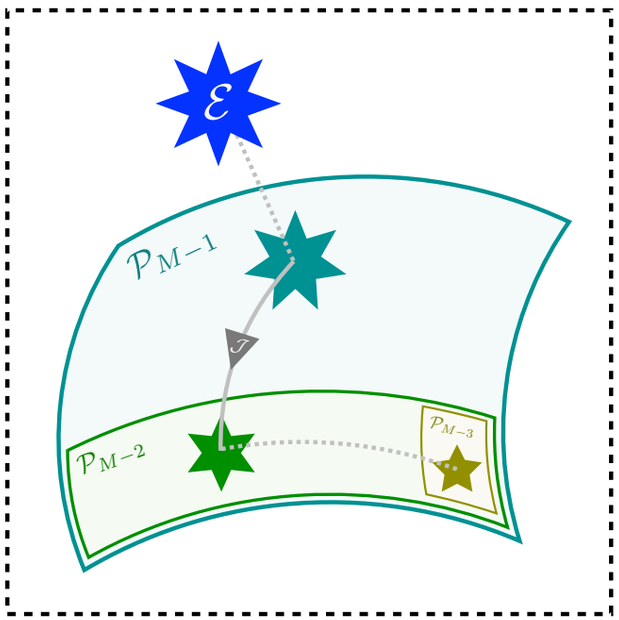
Distance of closest approach to N-particle manifold

[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]



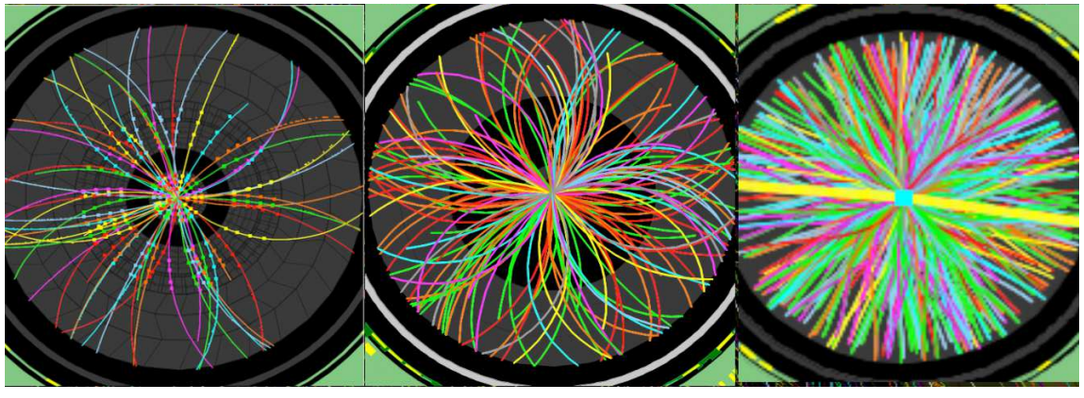
Sequential Jet Recombination

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]

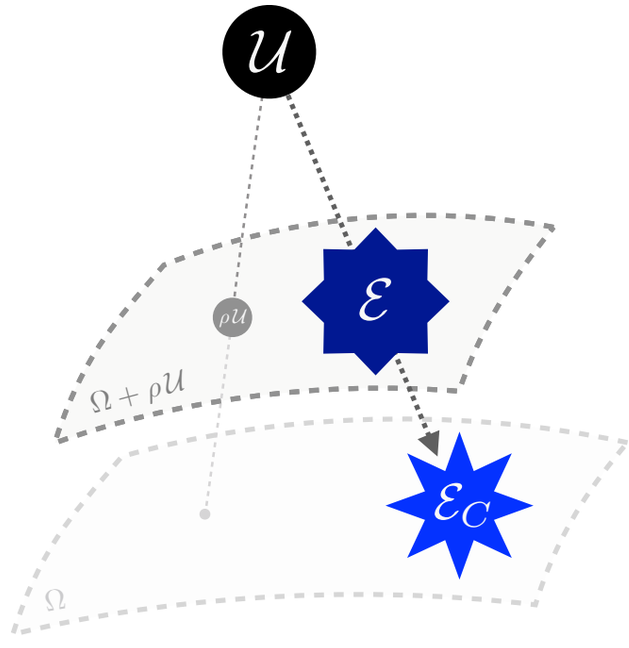
[Komiske, Metodiev, JDT, JHEP 2020]

Pileup Mitigation



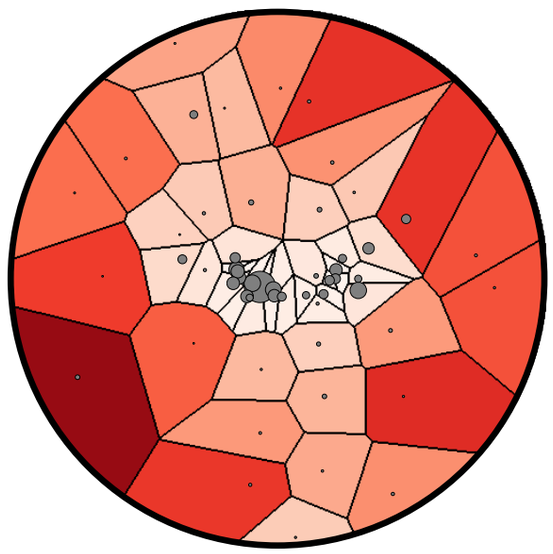
[see review in Soyez, PR 2019]

Uniform event contamination from overlapping proton-proton collisions



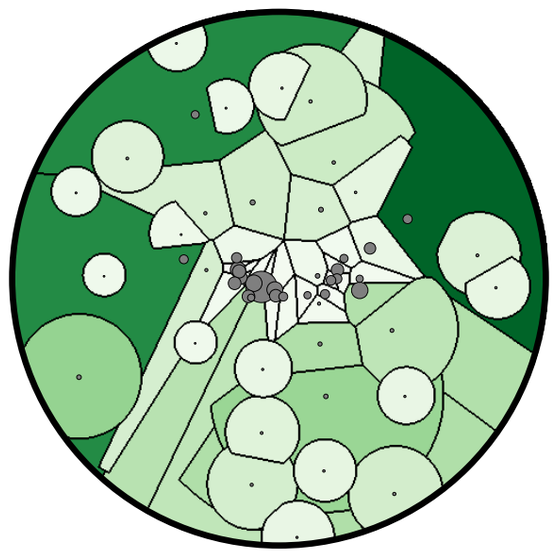
Pileup Mitigation:
"Move away" from uniform event

Voronoi



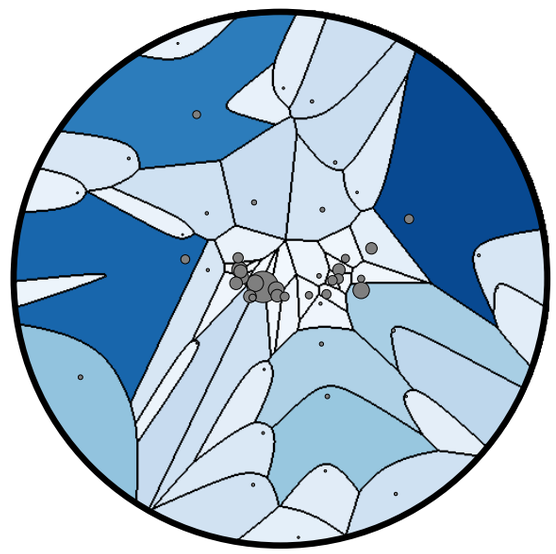
[Cacciari, Salam, Soyez, JHEP 2008]

Constituent Subtraction



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

Apollonius



[Komiske, Metodiev, JDT, JHEP 2020]

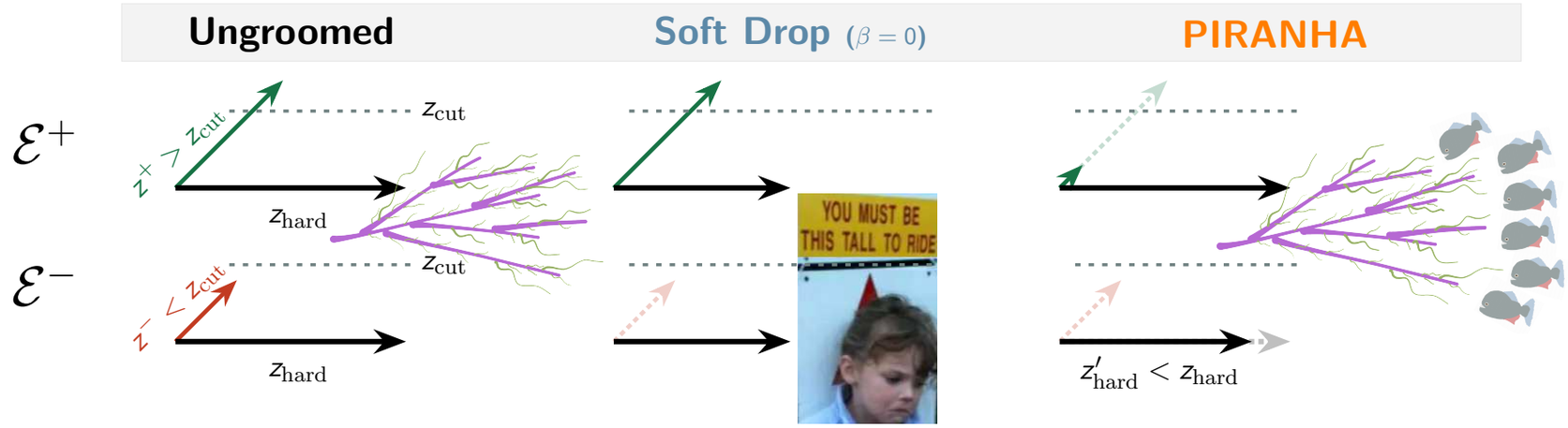
Pileup and Infrared Radiation AnNiHilAtion

Recursive Safe Subtraction: tree-based approx. to optimal transport grooming

Jet grooming
removes soft junk from jets to get high energy information

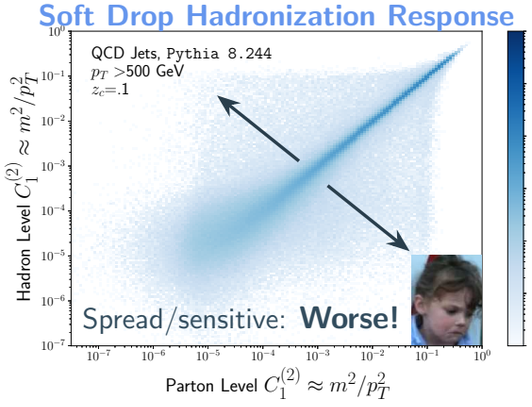
Popular groomers at LHC
use **discontinuous hard cutoffs** ($z_{\rm cut}$), **sensitive** to hadronization and detector effects

PIRANHA grooming
grooms **continuously** without hard cutoffs, using **geometry and optimal transport**

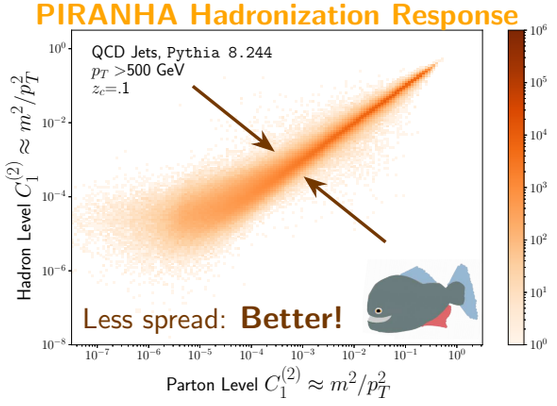


Eating up the competition:
PIRANHA groomed jets are **less sensitive** to hadronization and detector effects, offering **greater precision** in the study of our subatomic universe

Soft Drop Hadronization Response



PIRANHA Hadronization Response



[Slides from Sam Alipour-fard]
[Alipour-fard, Komiske, Metodiev, JDT, in progress]

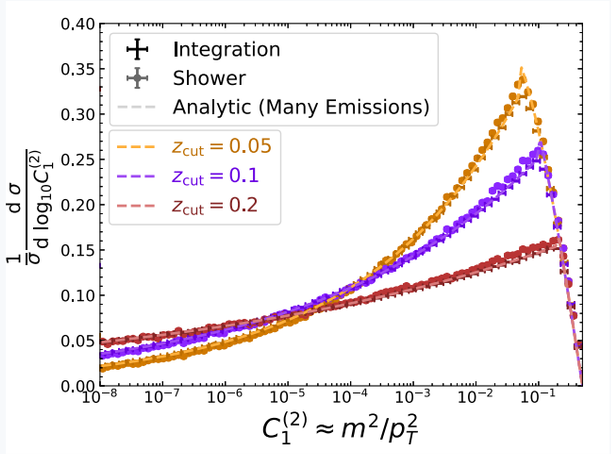


Pileup and Infrared Radiation AnNiHilAtion

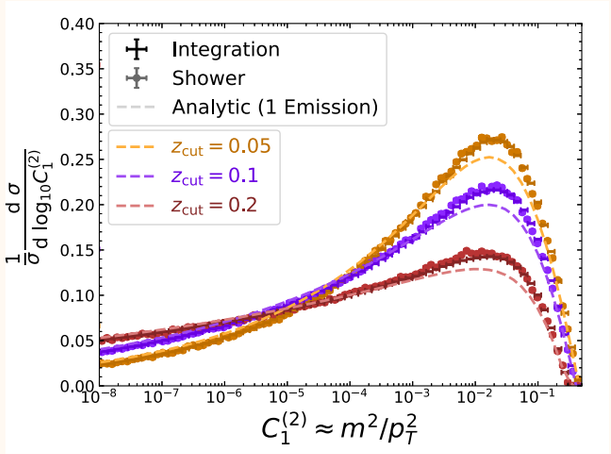
Recursive Safe Subtraction: tree-based approx. to optimal transport grooming

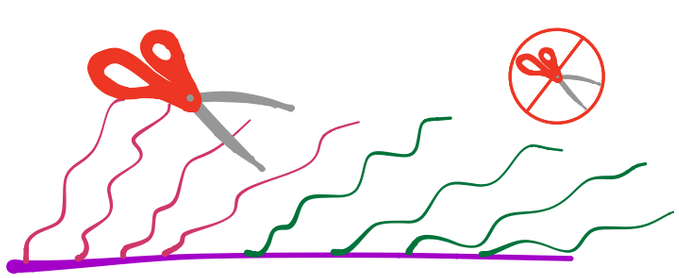
Fixed coupling, **multiple emission** calculations:

Soft Drop/mMDT

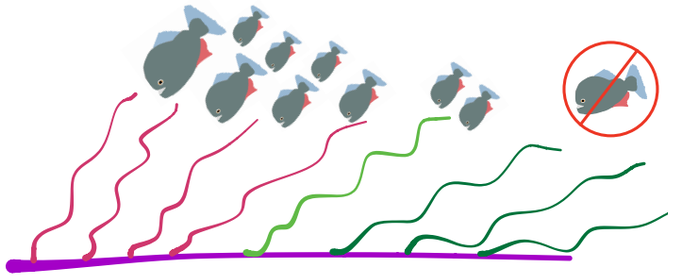


PIRANHA-RSS ($f = 1$)





Sharp cutoff → kink



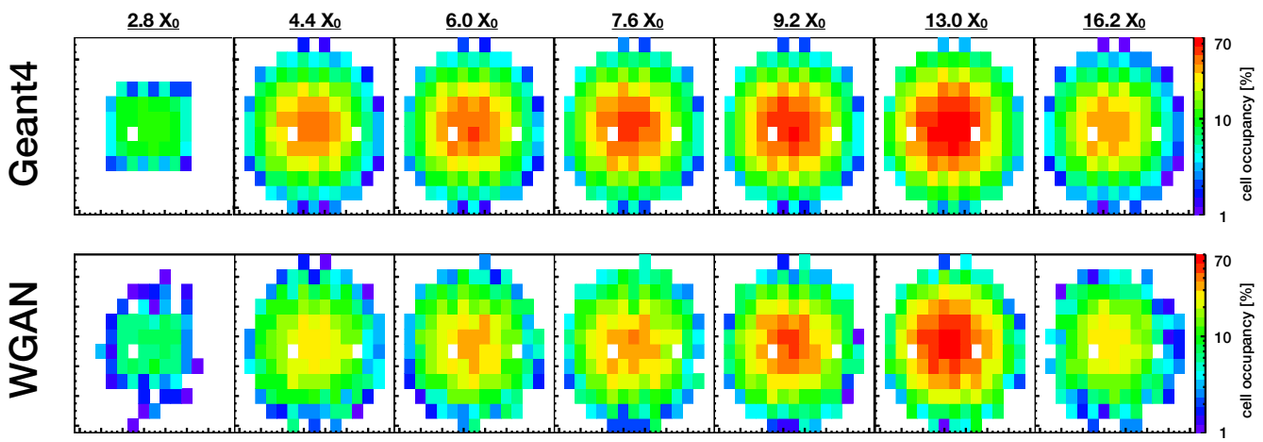
No sharp cutoff → smooth

[Slides from Sam Alipour-fard]
[Alipour-fard, Komiske, Metodiev, JDT, in progress]



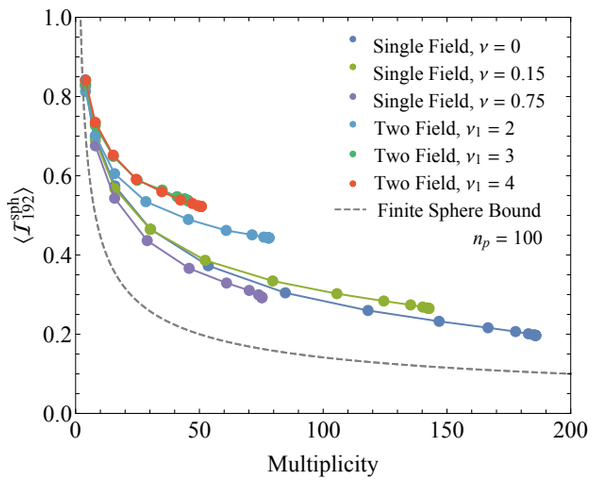
Wasserstein in HEP

Generative Modeling



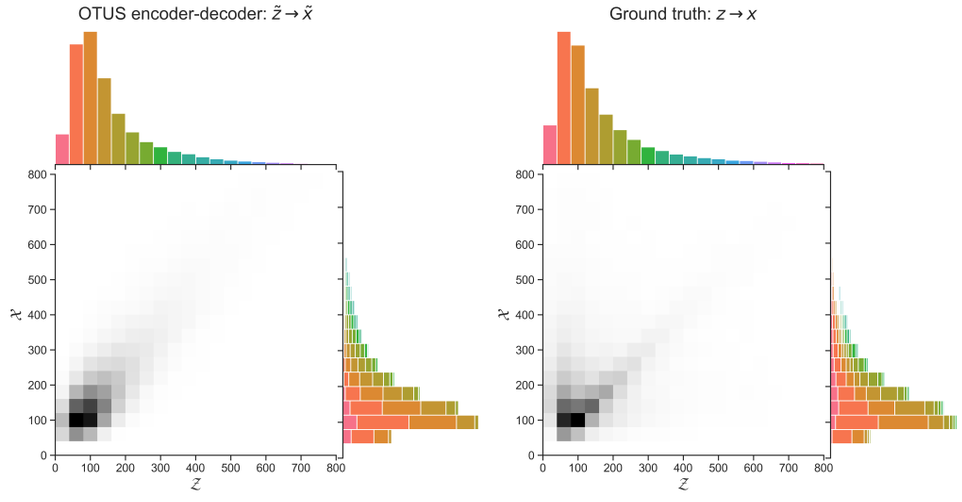
[Erdmann, Geiger, Glombitza, Schmidt, CSBS 2018; Erdmann, Glombitza, Quast, CSBS 2019; Chekalina, Orlova, Ratnikov, Ulyanov, Ustyuzhanin, Zakharov, CHEP 2018]

BSM Characterization



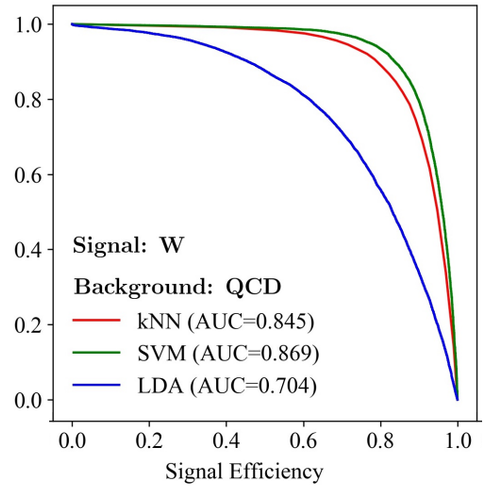
[Cesarotti, Reece, Strassler, JHEP 2021, arXiv 2020]

Estimated Simulation/Unfolding



[Howard, Mandt, Whiteson, Yang, arXiv 2021]

Jet Classification



[Cai, Cheng, Craig, Craig, PRD 2020]

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