

# Collision Course

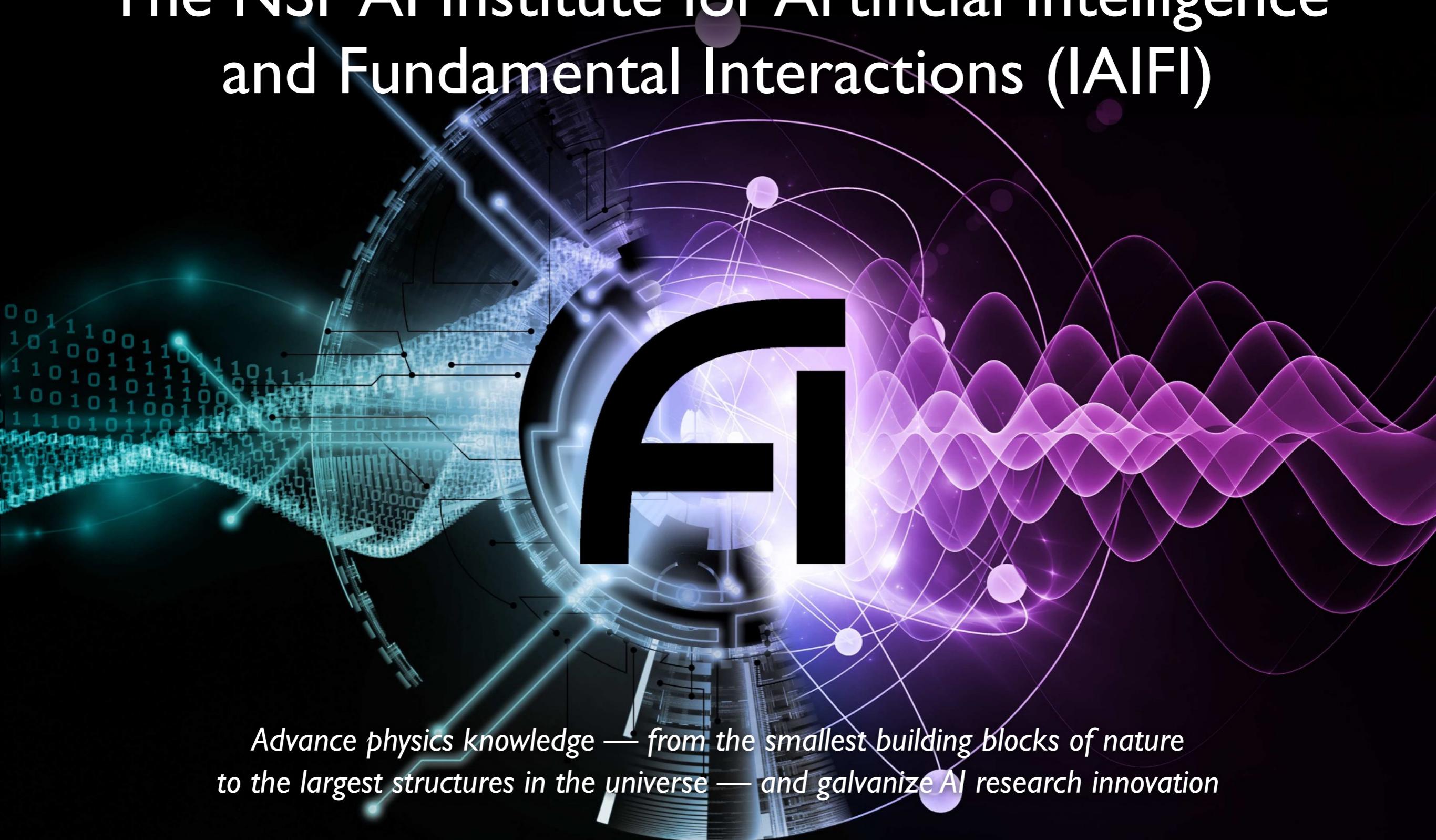
## Particle Physics meets Machine Learning

Jesse Thaler



Israel Physics Colloquium — November 9, 2020

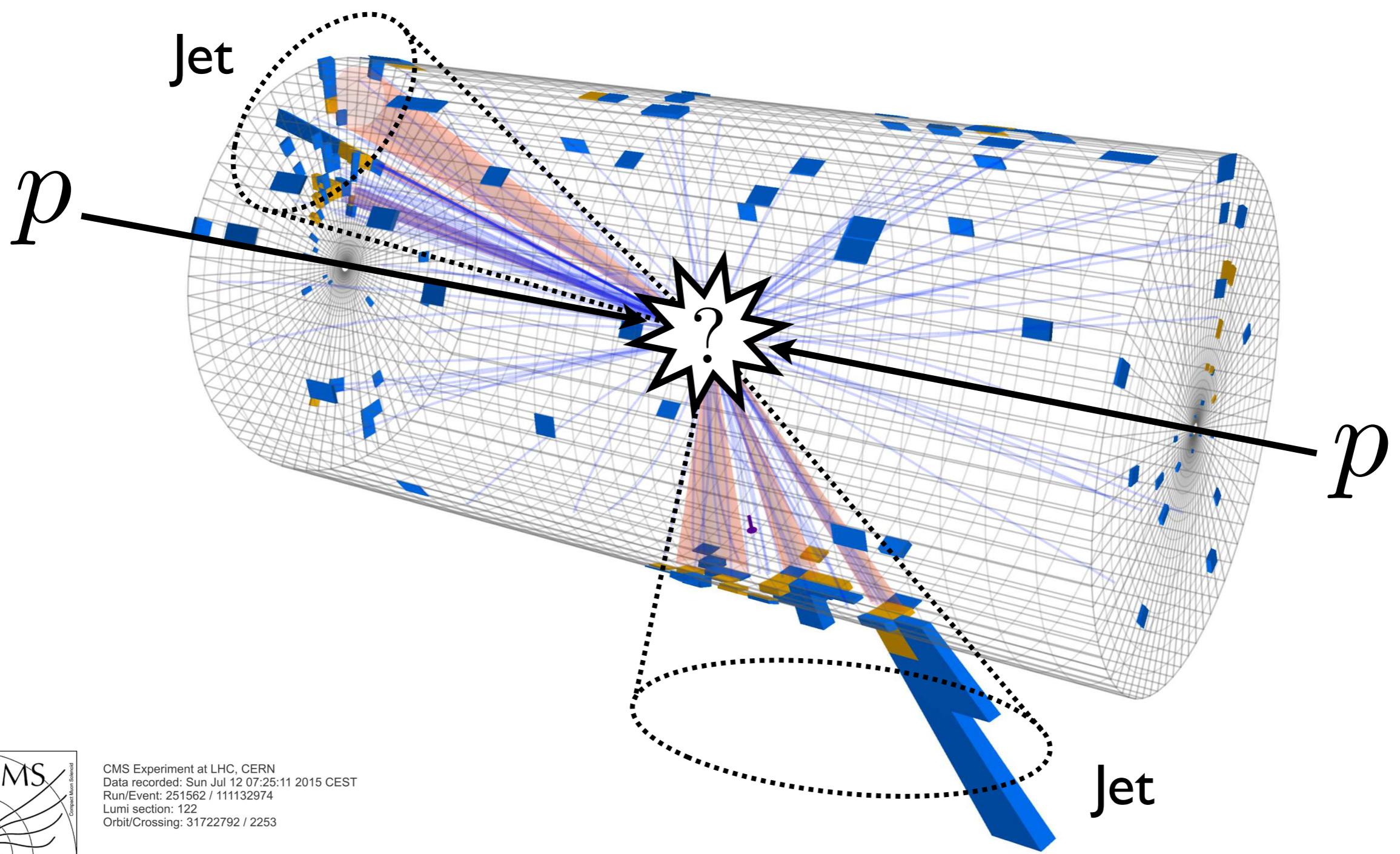
# The NSF AI Institute for Artificial Intelligence and Fundamental Interactions (IAIFI)



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

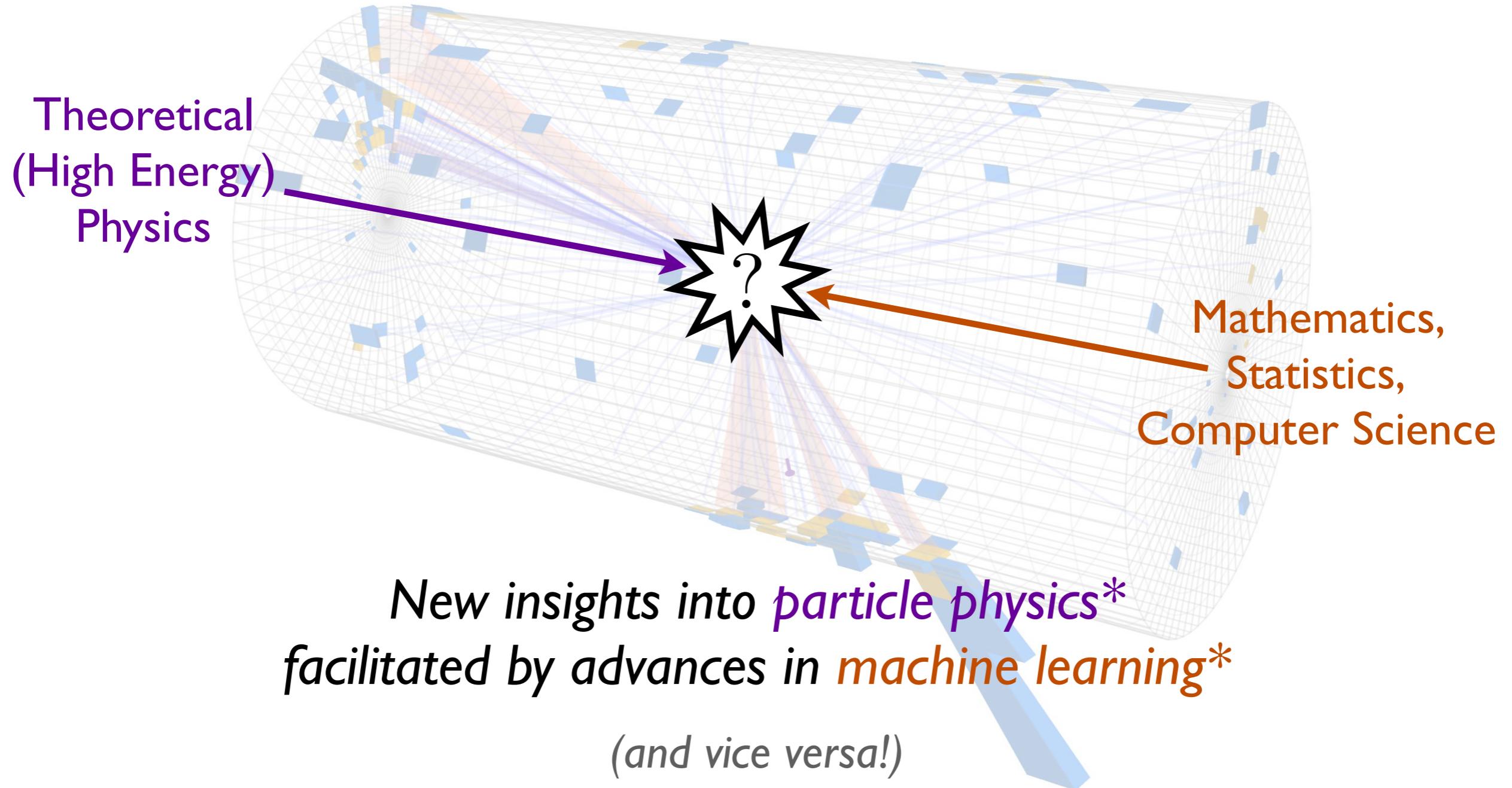
[<http://iaifi.org>, MIT News Announcement]

# “Collision Course”



# “Collision Course”

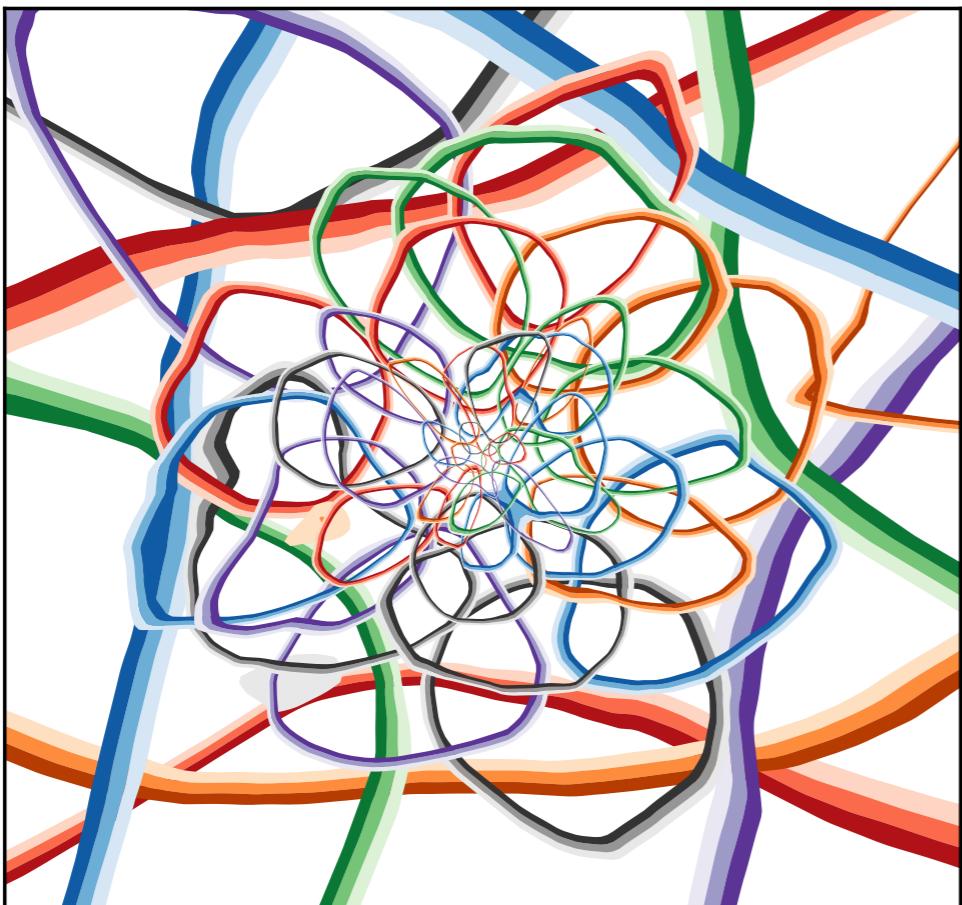
“Theoretical Physics for Machine Learning”  
Aspen Center for Physics, January 2019



# Two Anecdotes

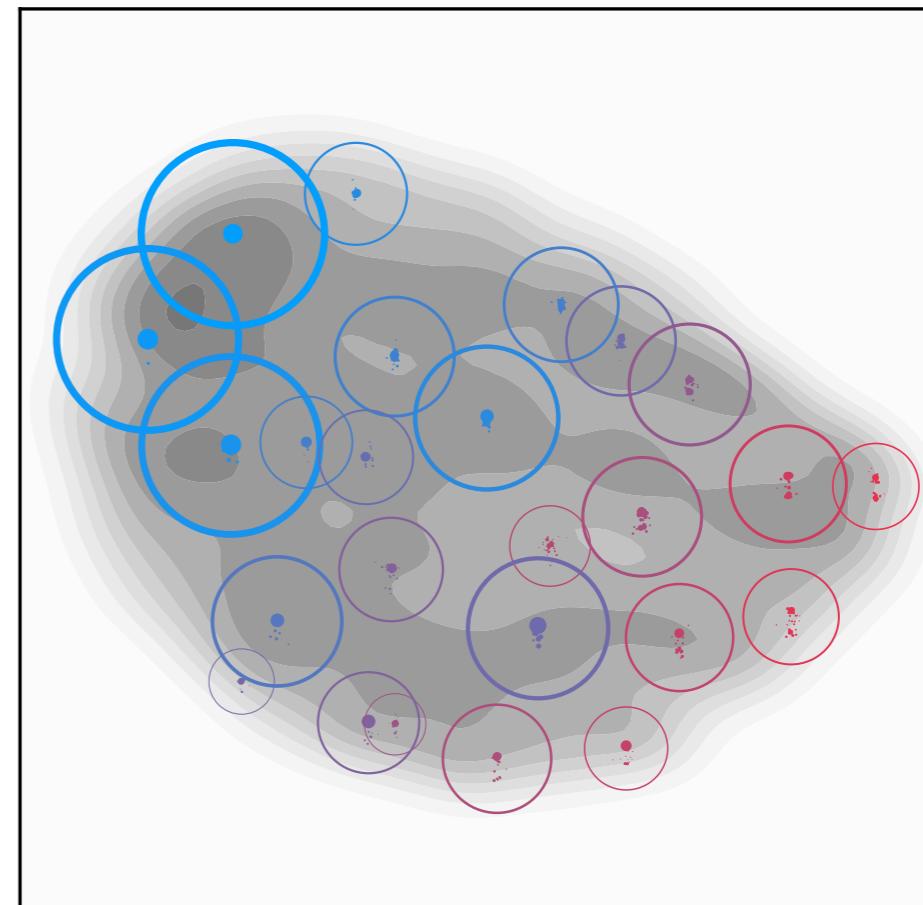


## Teaching a Machine to “Think Like a Physicist”



[Komiske, Metodiev, JDT, [JHEP 2019](#)]

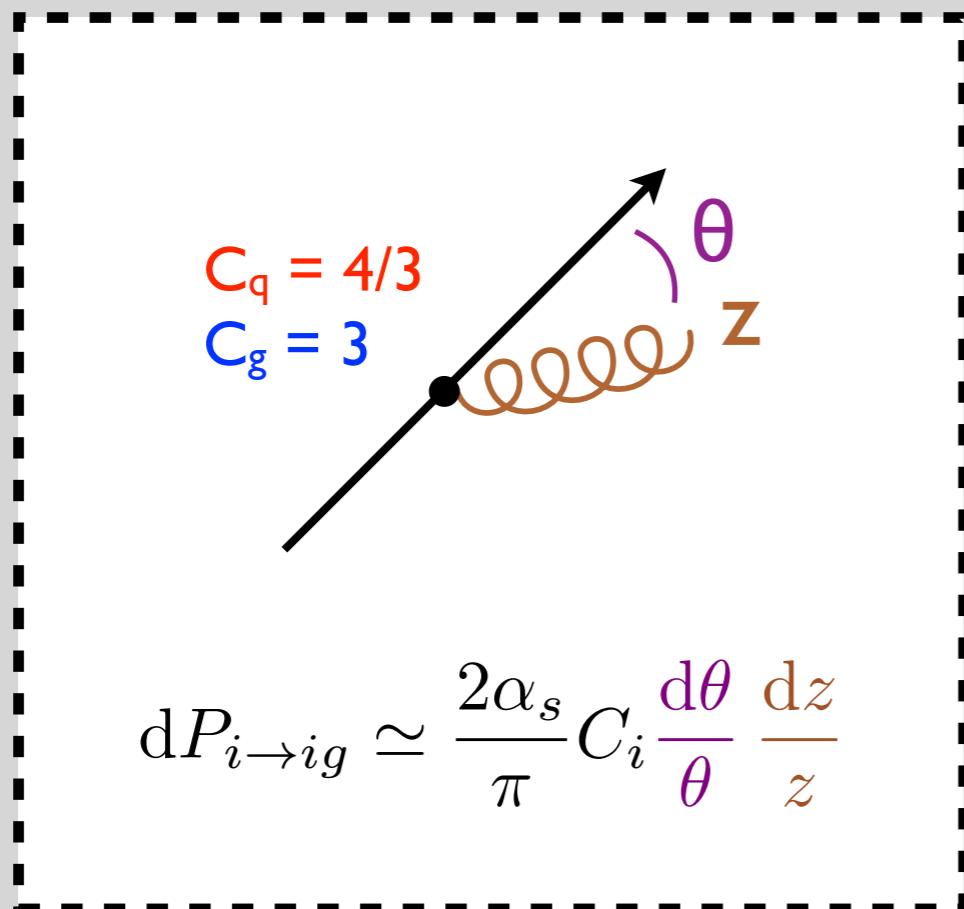
## Letting Collider Data Speak for Itself



[Komiske, Mastandrea, Metodiev, Naik, JDT, [PRD 2020](#);  
based on Komiske, Metodiev, JDT, [PRL 2019](#)]

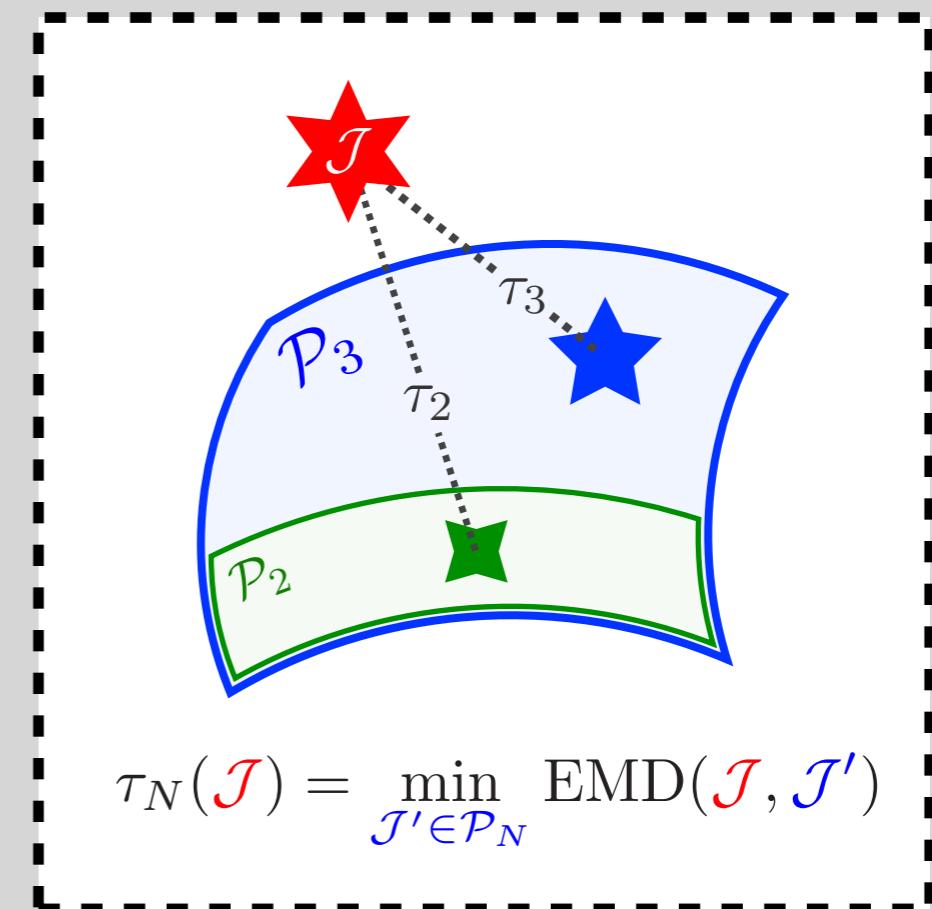
*Data analysis strategies motivated by the  
symmetries and structures of particle physics*

## Exploiting a Core Prediction of QCD



[Altarelli, Parisi, [NPB 1977](#)]

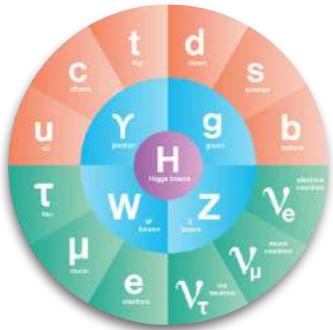
## Nested Singularities of Gauge Theories



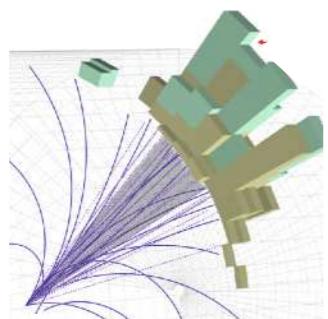
[Stewart, Tackmann, Waalewijn, [PRL 2010](#); JDT, Van Tilburg, [JHEP 2011](#), [JHEP 2012](#); rephrased via Komiske, Metodiev, JDT, [JHEP 2020](#)]

New perspectives on key theoretical concepts

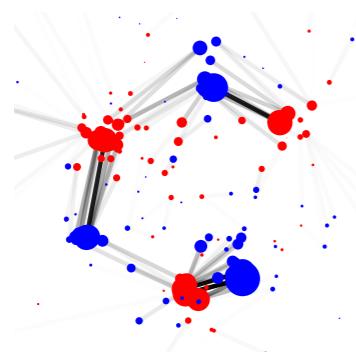
# Outline



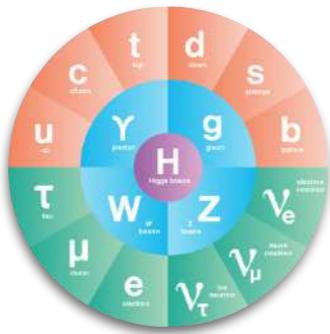
## Particle Physics 101



What is a Collider Event?



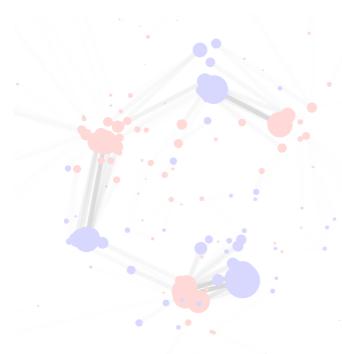
When are Collider Events Similar?



# Particle Physics 101

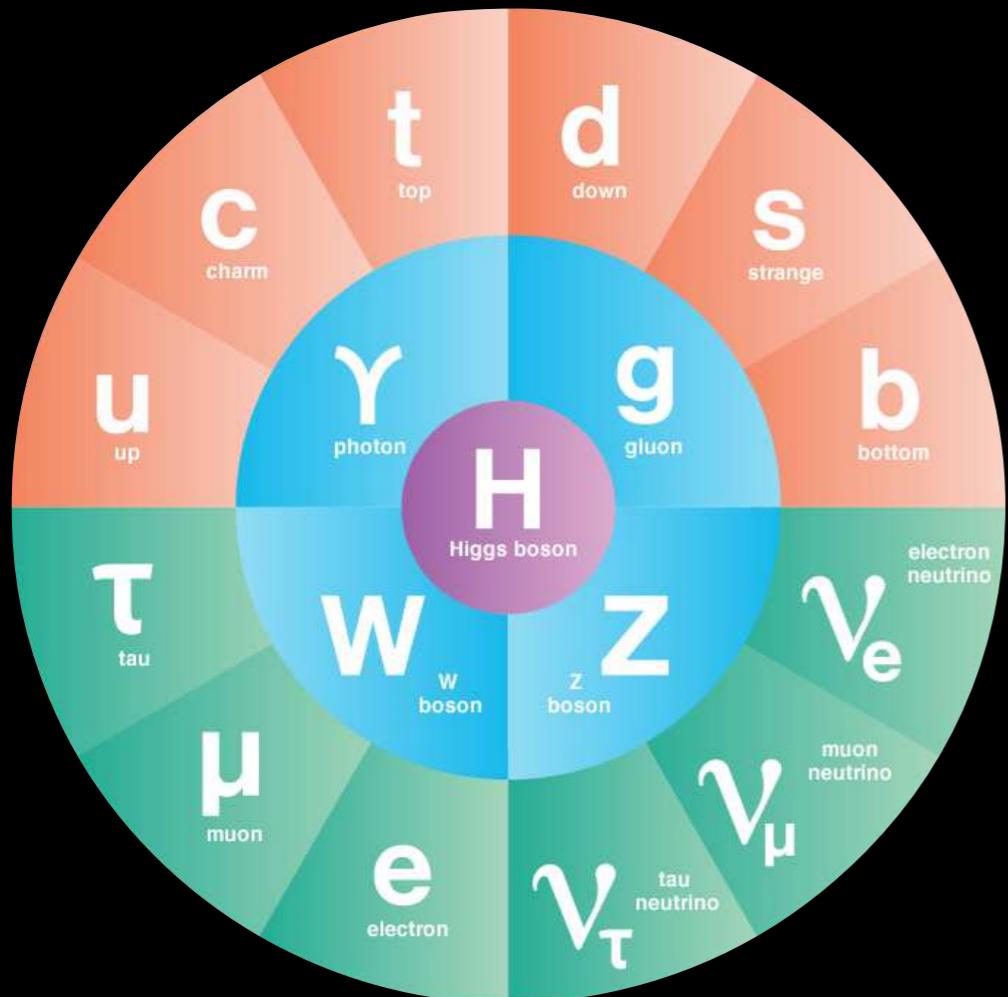


What is a Collider Event?

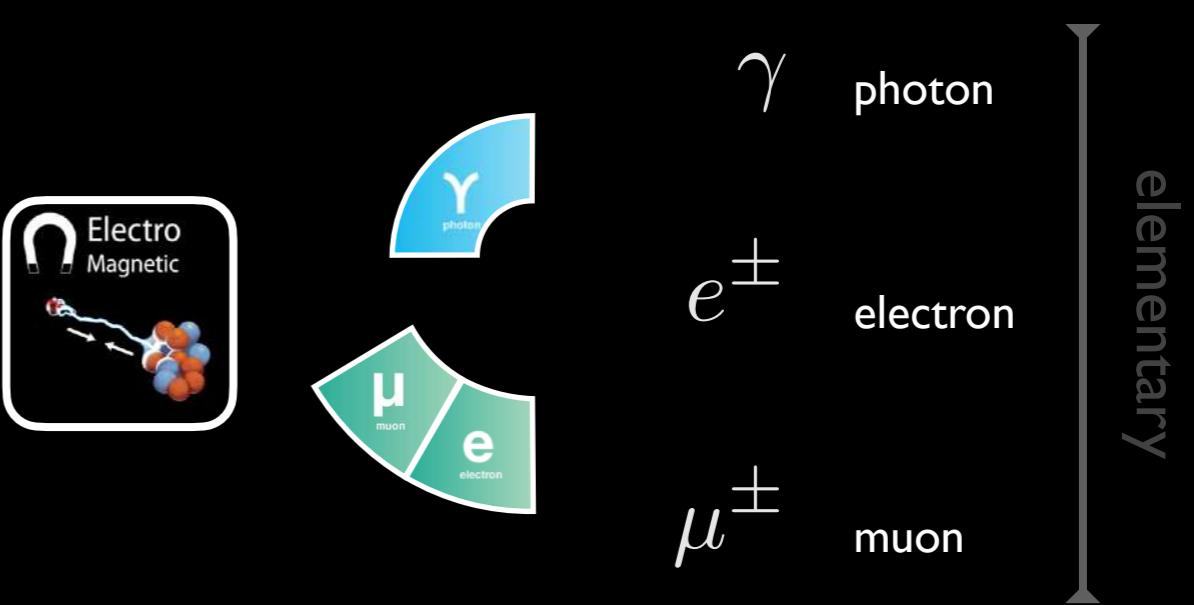
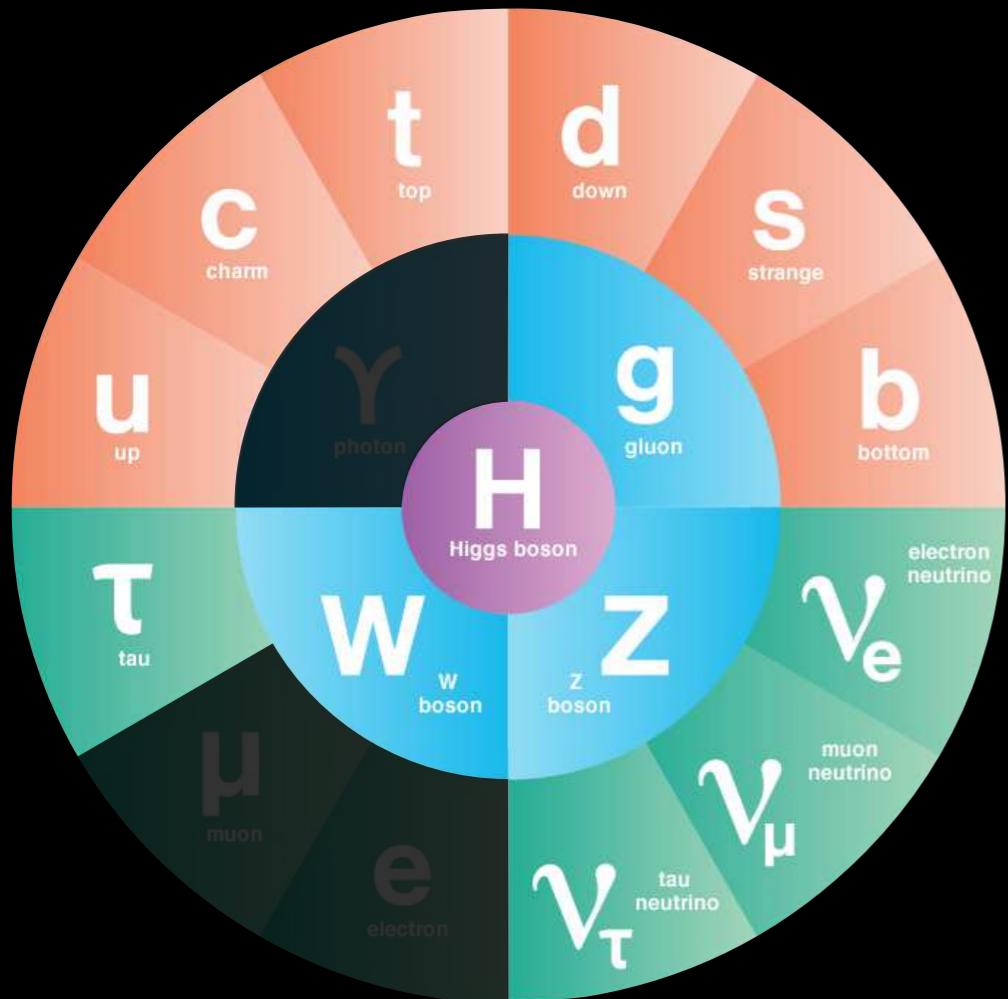


When are Collider Events Similar?

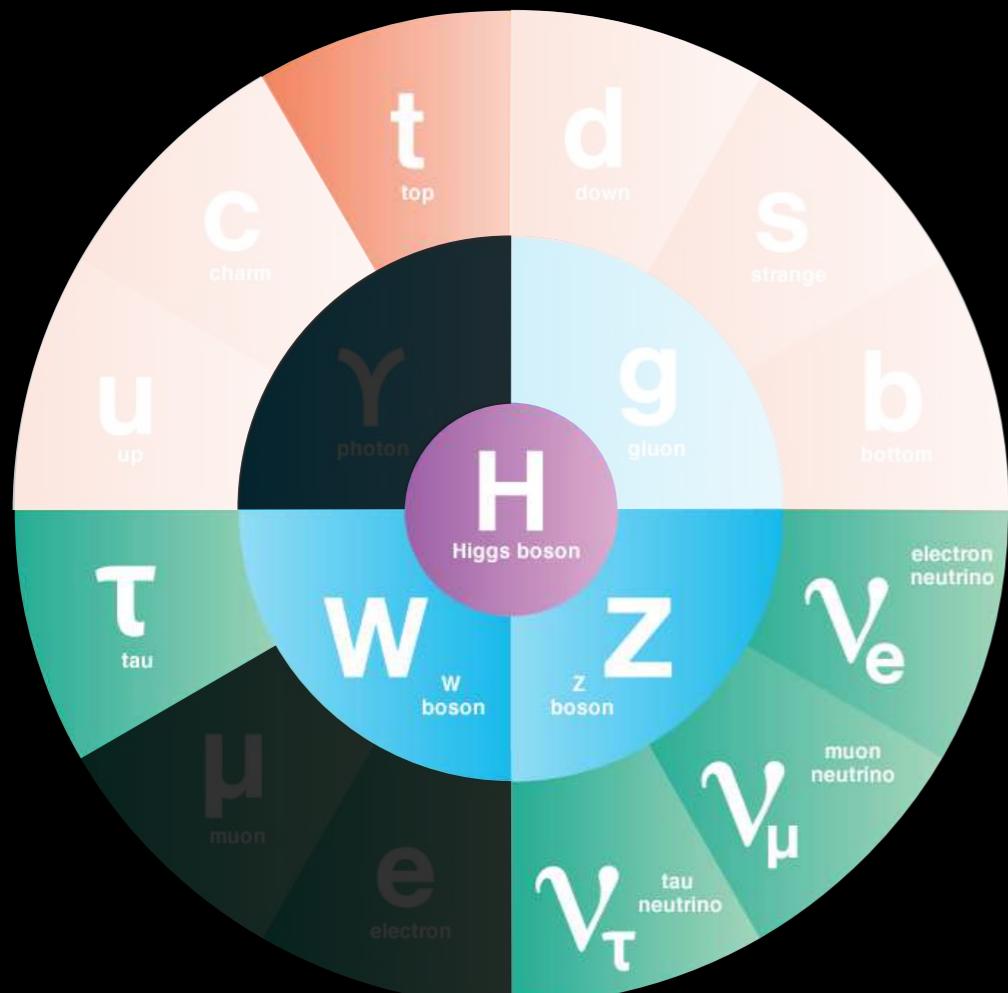
# Particle Physics 101



# Particle Physics 101

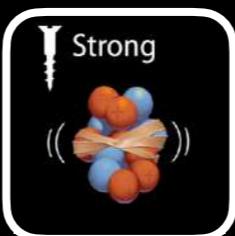


# Particle Physics 101

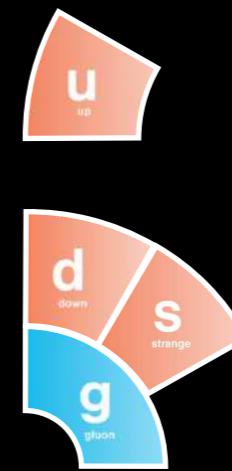


*QCD Confinement*

Quarks  
&  
Gluons



$\gamma$	photon	elementary
$e^+$	electron	
$\mu^+$	muon	composite
$\pi^+$	pion	
$K^+$	kaon	composite
$K_L^0$	K-long	
$p/\bar{p}$	proton	composite
$n/\bar{n}$	neutron	



$n/\bar{n}$  neutron

T E H M



$\gamma$

photon



$e^+$

electron



$\mu^+$

muon



$\pi^+$

pion



$K^+$

kaon



$K_L^0$

K-long



$p/\bar{p}$

proton



$n/\bar{n}$

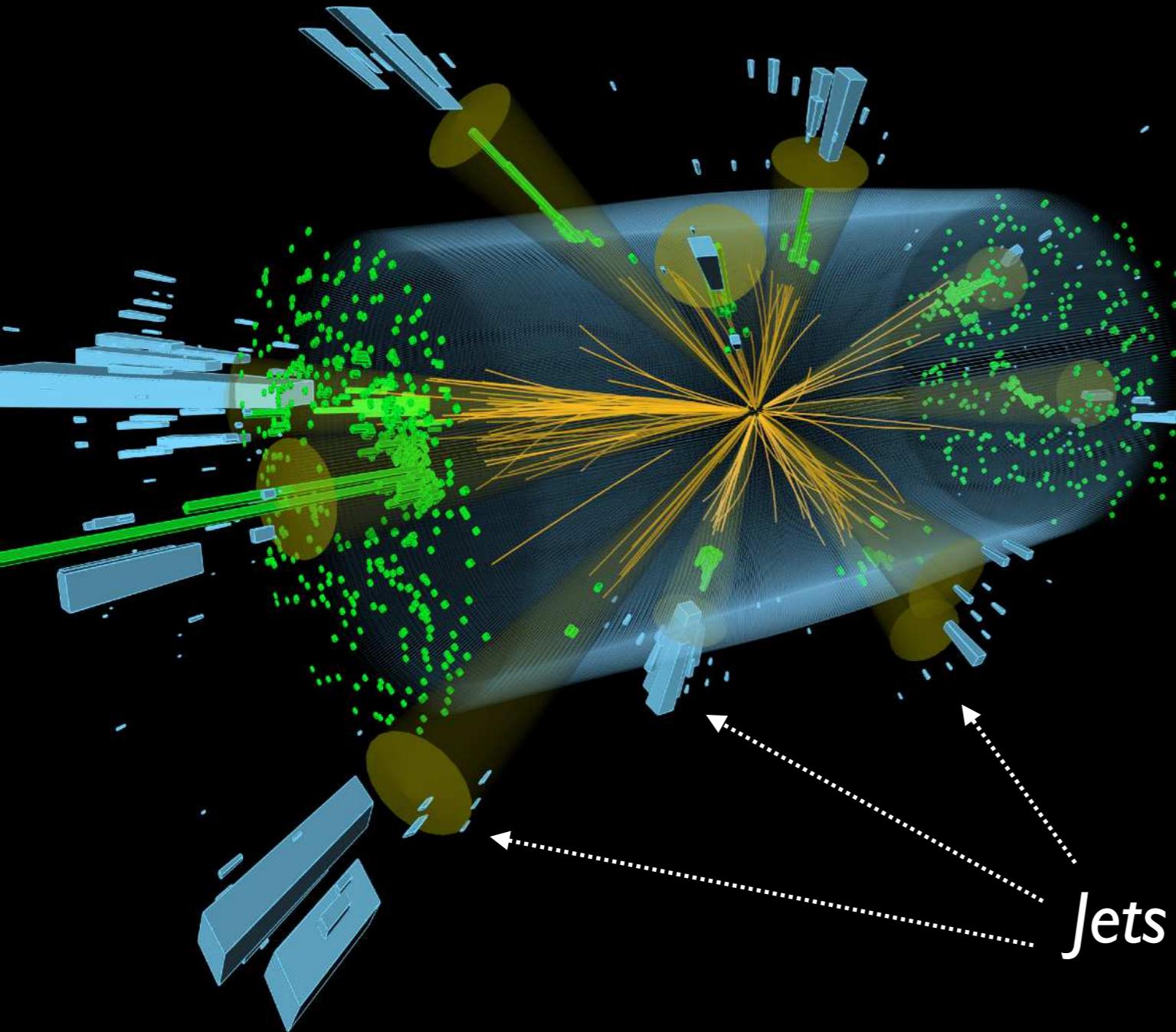
neutron

elementary

composite

# Collider Event

Every 25 nanoseconds at the LHC



T E H M



$\gamma$

photon



$e^+$

electron



$\mu^+$

muon



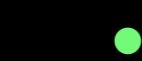
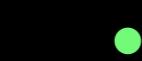
$\pi^+$

pion



$K^+$

kaon



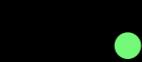
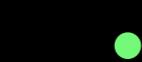
$K_L^0$

K-long



$p/\bar{p}$

proton

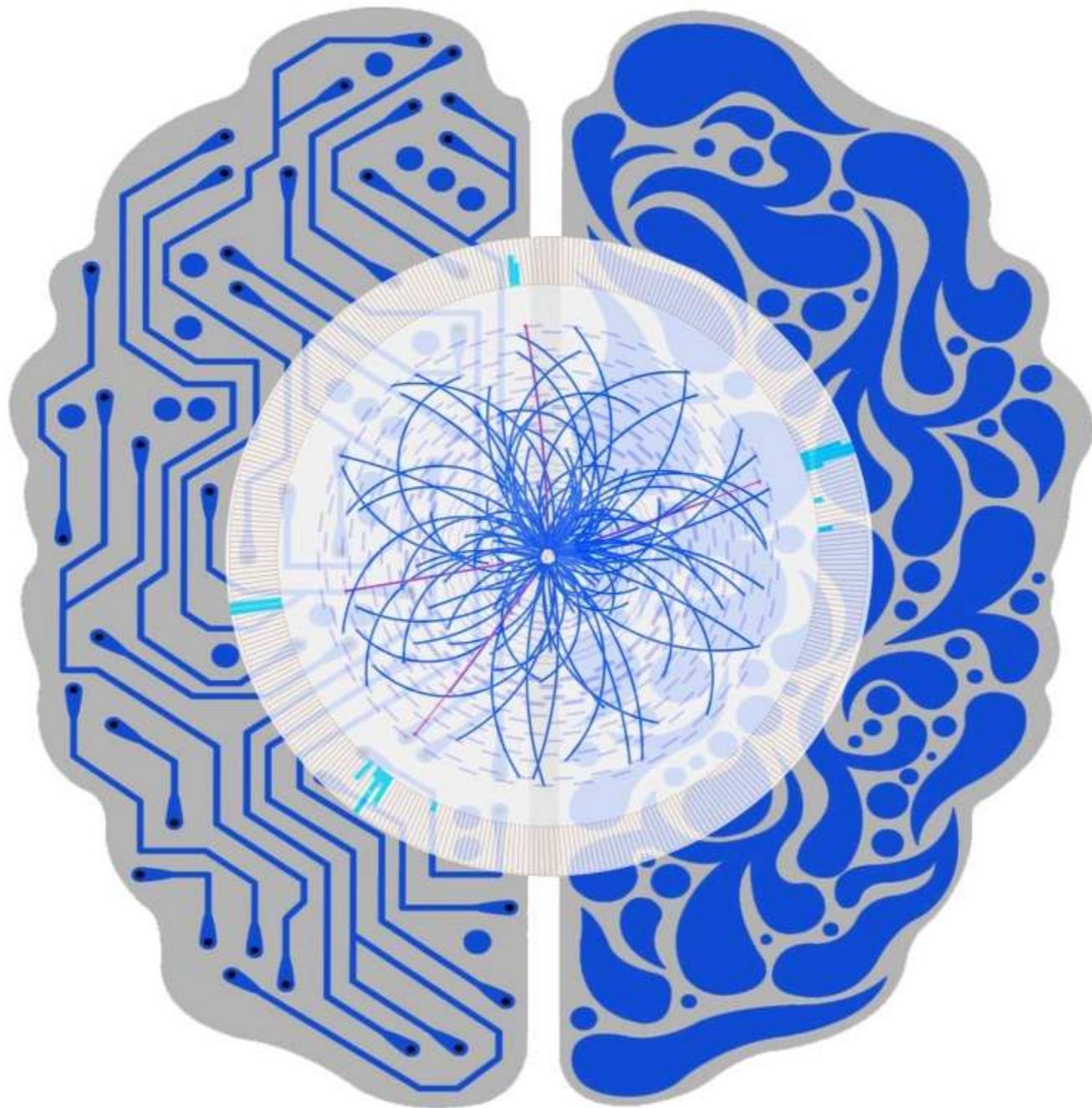


$n/\bar{n}$

neutron

elementary

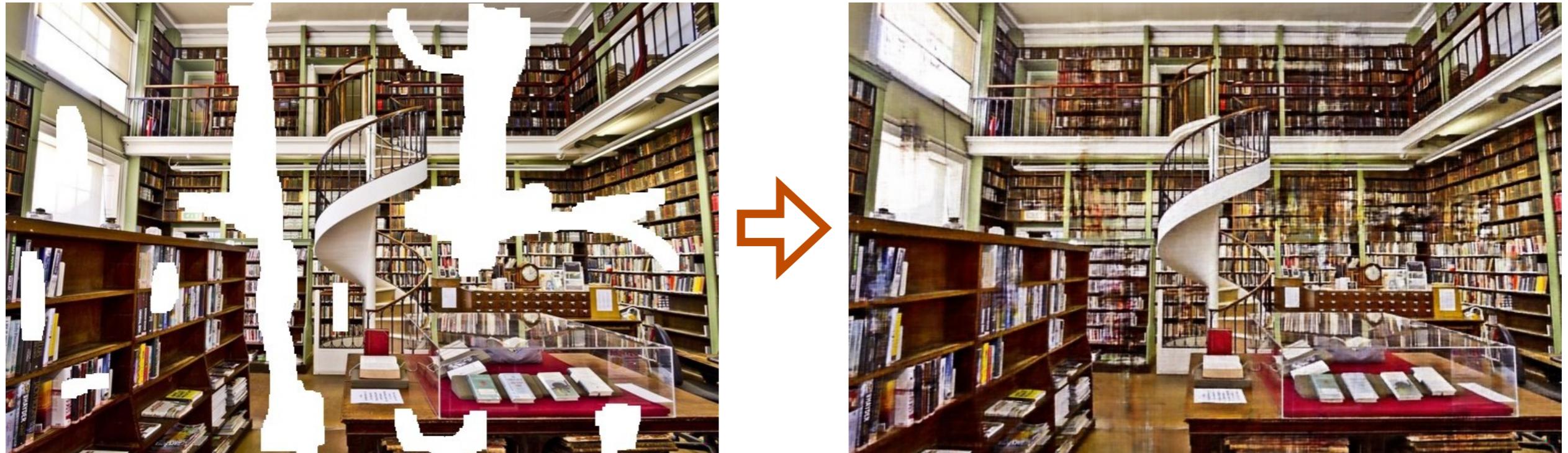
composite



## *The Rise of Machine Learning*

# Deep Learning

*E.g. Inpainting*

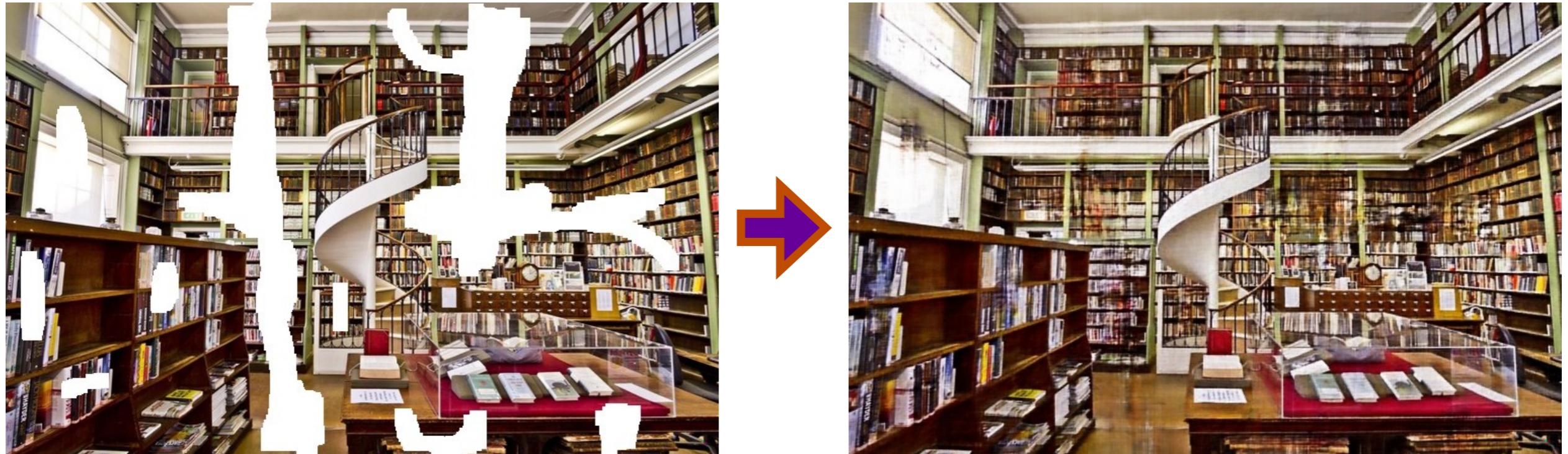


increased computational power and large data sets

[Ulyanov, Vedaldi, Lempitsky, CVPR 2018]

# Deep Learning meets Deep Thinking

E.g. *Inpainting*



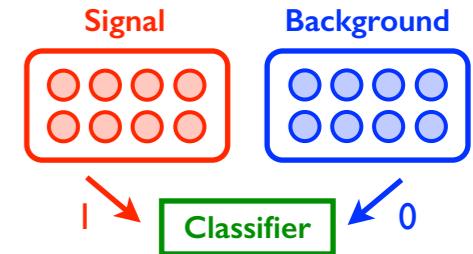
Using randomly initialized neural network (!)

Progress made by understanding the structure of problems  
(not just increased computational power and large data sets)

[Ulyanov, Vedaldi, Lempitsky, CVPR 2018]

# E.g. Quark/Gluon Classification

“Hello, World!” of Jet Physics



Find  $h\left(\begin{array}{c} \nearrow \\ \nearrow \\ \nearrow \\ \nearrow \end{array}\right)$  such that

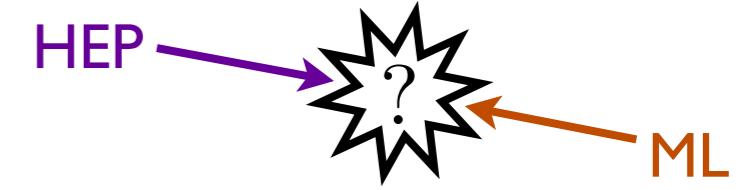
$$h(\text{Quark}) = 1$$
$$h(\text{Gluon}) = 0$$

Best you can do:  $h(\mathcal{J}) = \frac{p(\mathcal{J}|Q)}{p(\mathcal{J}|Q) + p(\mathcal{J}|G)}$

(Neyman-Pearson lemma)

[see e.g. Gras, Höche, Kar, Larkoski, Lönnblad, Plätzer, Siódmok, Skands, Soyez, JDT, [JHEP 2017](#); Komiske, Metodiev, Schwartz, [JHEP 2017](#); Komiske, Metodiev, JDT, [JHEP 2018](#)]

# E.g. Search for Supersymmetry

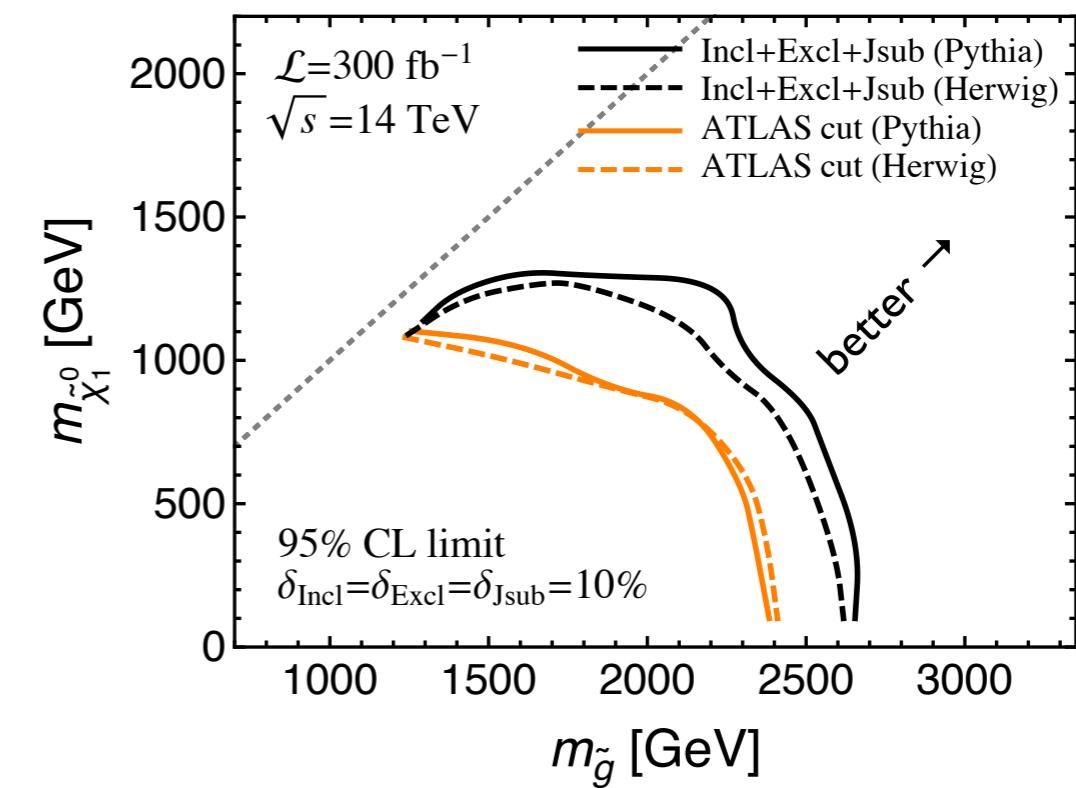
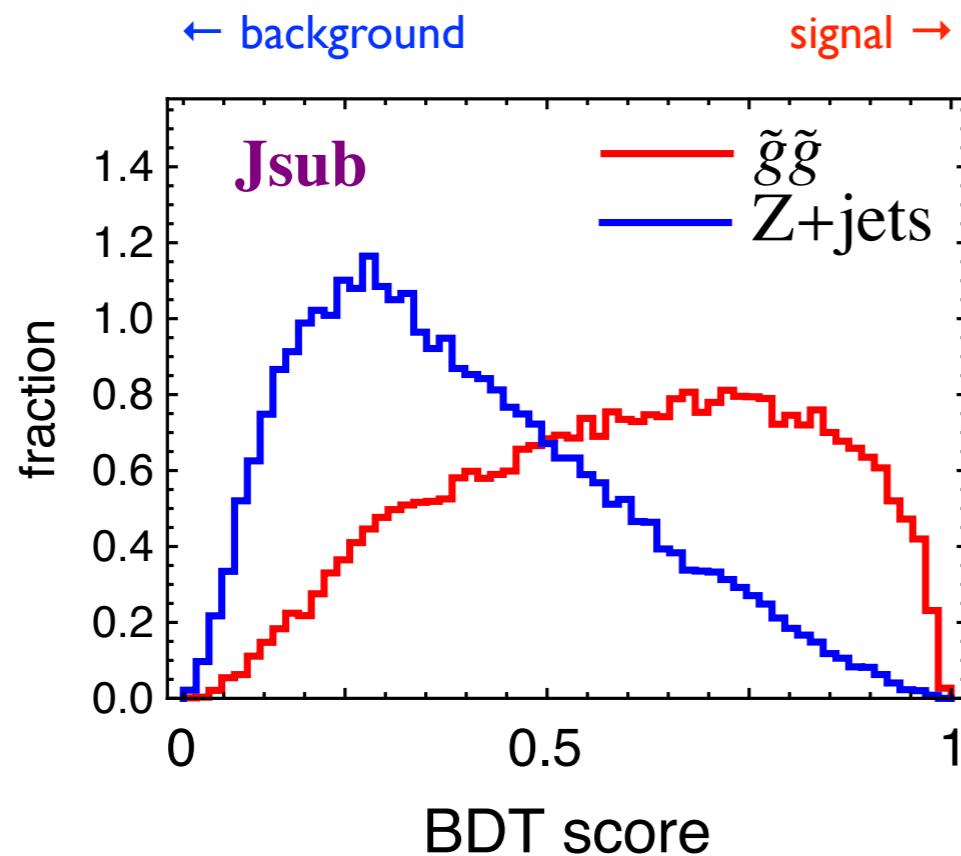
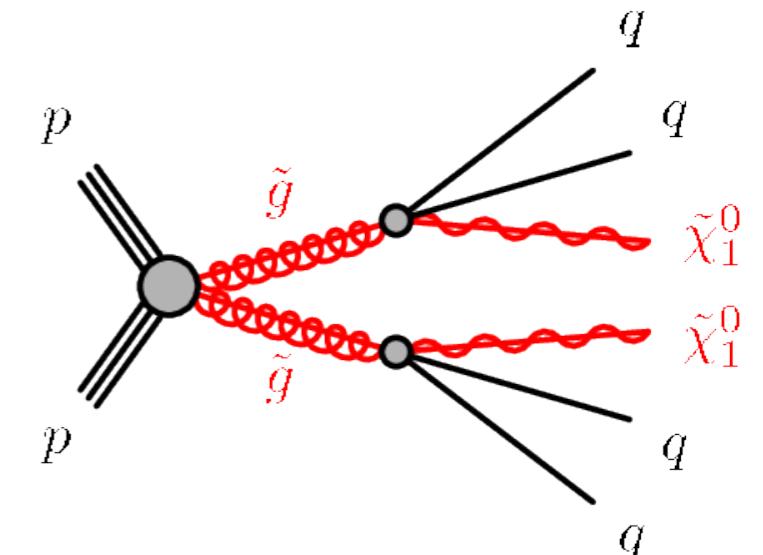


**Classifier:** Boosted decision tree (for each of 4 jets)

**Inputs:** Jet mass, width, track multiplicity

**Signal:** Quark enriched

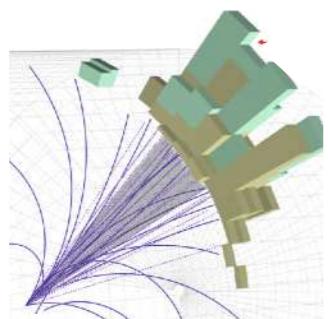
**Background:** Gluon enriched



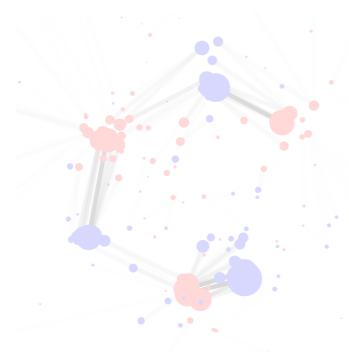
[Bhattacherjee, Mukhopadhyay, Nojiri, Sakakie, Webber, [JHEP 2017](#)]



# Particle Physics 101



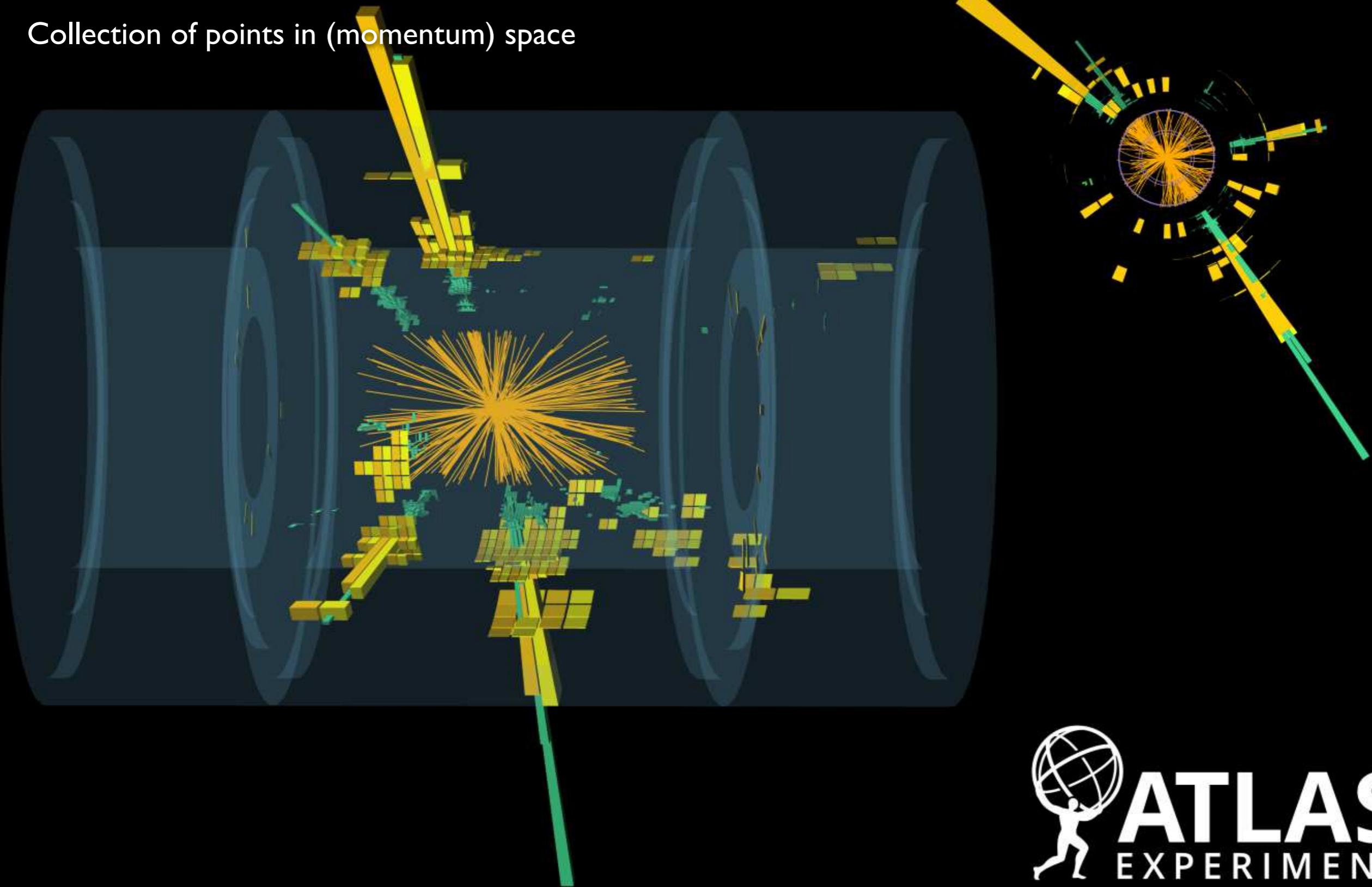
## What is a Collider Event?



## When are Collider Events Similar?

# Collider Event

Collection of points in (momentum) space



# Point Cloud

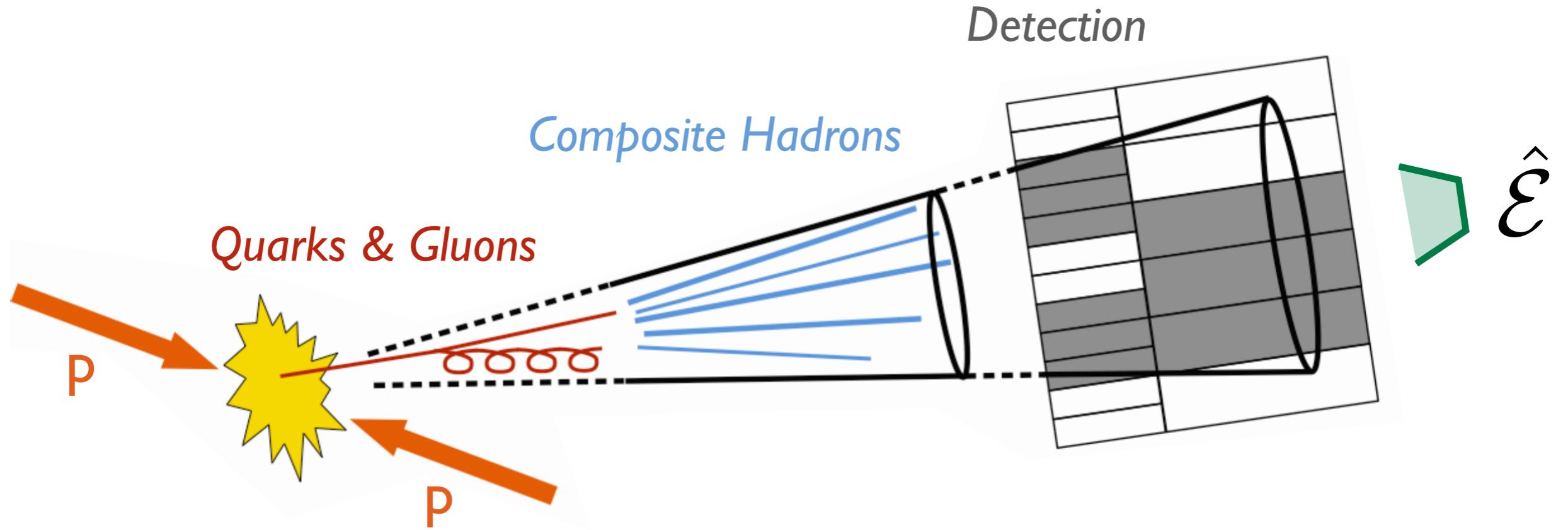
Collection of points in (position) space



[Popular Science, 2013]

# Jet Formation from QCD

Theory

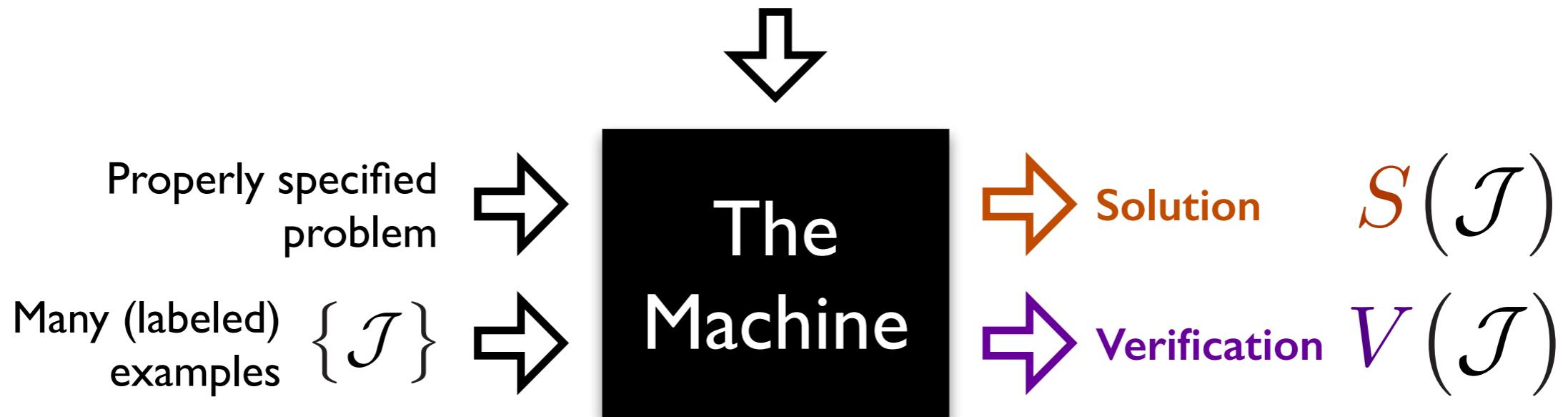
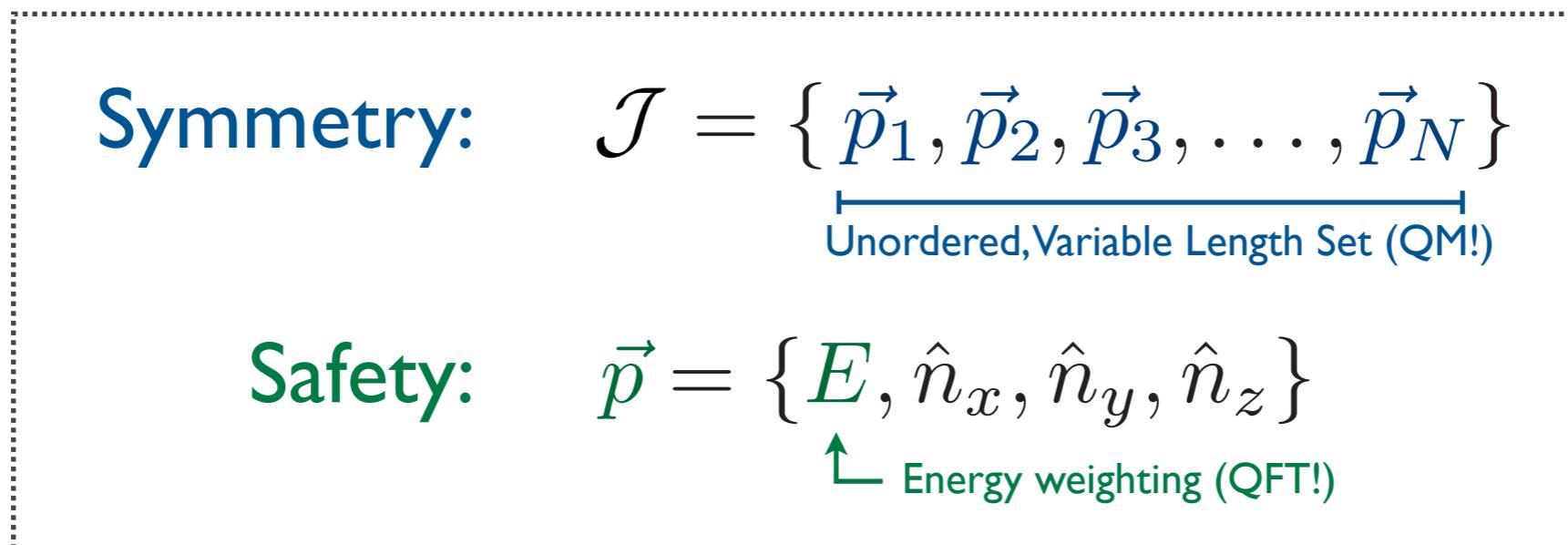


**Energy Flow:**  
Robust to hadronization and detector effects

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

[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](#)]

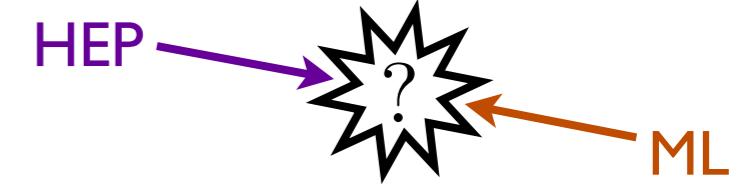
# “Thinking” Like a Physicist



*Check that answer  
is physically sensible*

# Energy Flow Networks

Architecture designed around **symmetries** and **interpretability**



$$S(\mathcal{J}) = F(V_1, V_2, \dots, V_\ell)$$
$$V_a(\mathcal{J}) = \sum_{i \in \mathcal{J}} E_i \Phi_a(\hat{n}_i)$$

Permutation invariant  $\downarrow$  Linear weights (i.e. safe)  $\downarrow$

Parametrized with Neural Networks

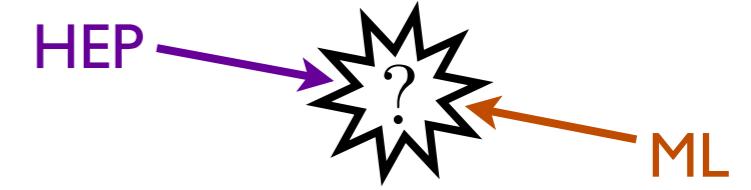
*Provably describes any\* **safe** observable (!)*  
*Excellent jet classification performance*

[Komiske, Metodiev, JDT, [JHEP 2019](#); see also Komiske, Metodiev, JDT, [JHEP 2018](#); code at [energyflow.network](#); special case of Zaheer, Kottur, Ravanbakhsh, Poczos, Salakhutdinov, Smola, [NIPS 2017](#)]



# Energy Flow Networks

Architecture designed around symmetries and *interpretability*



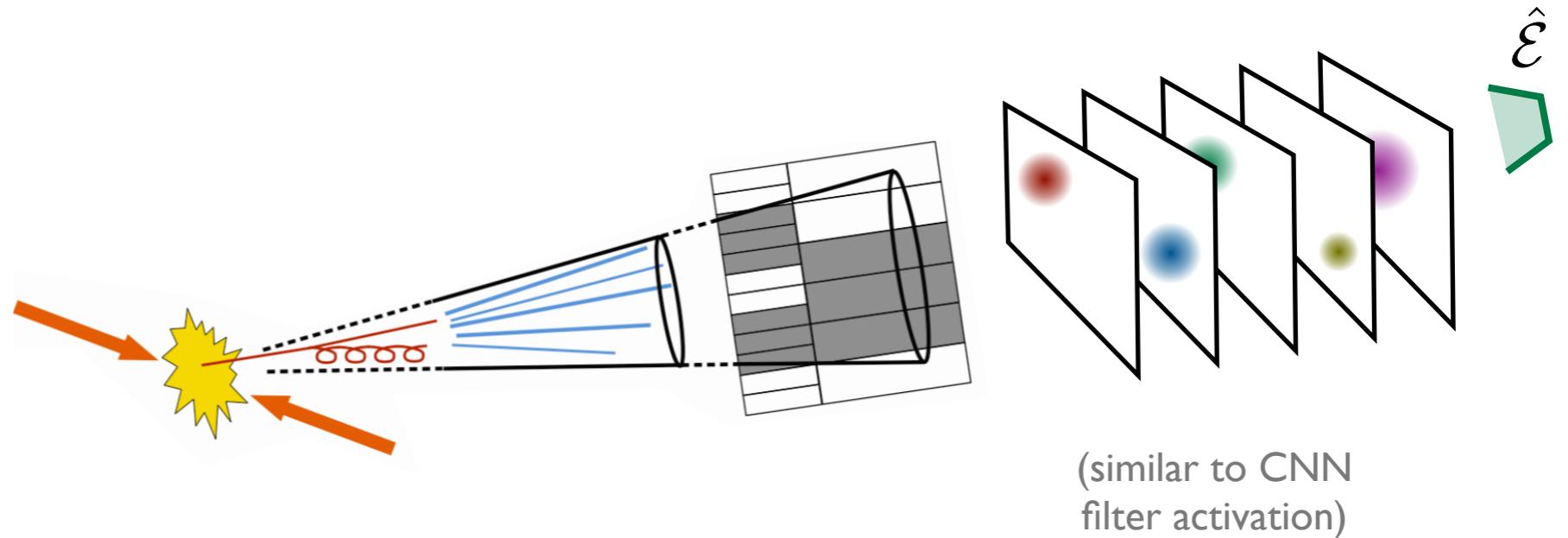
$$S(\mathcal{J}) = F(V_1, V_2, \dots, V_\ell)$$

Latent space of dim  $\ell$

$V_a(\mathcal{J}) = \sum_{i \in \mathcal{J}} E_i \Phi_a(\hat{n}_i)$

Can visualize if  $\ell$  is small

Easy to plot!

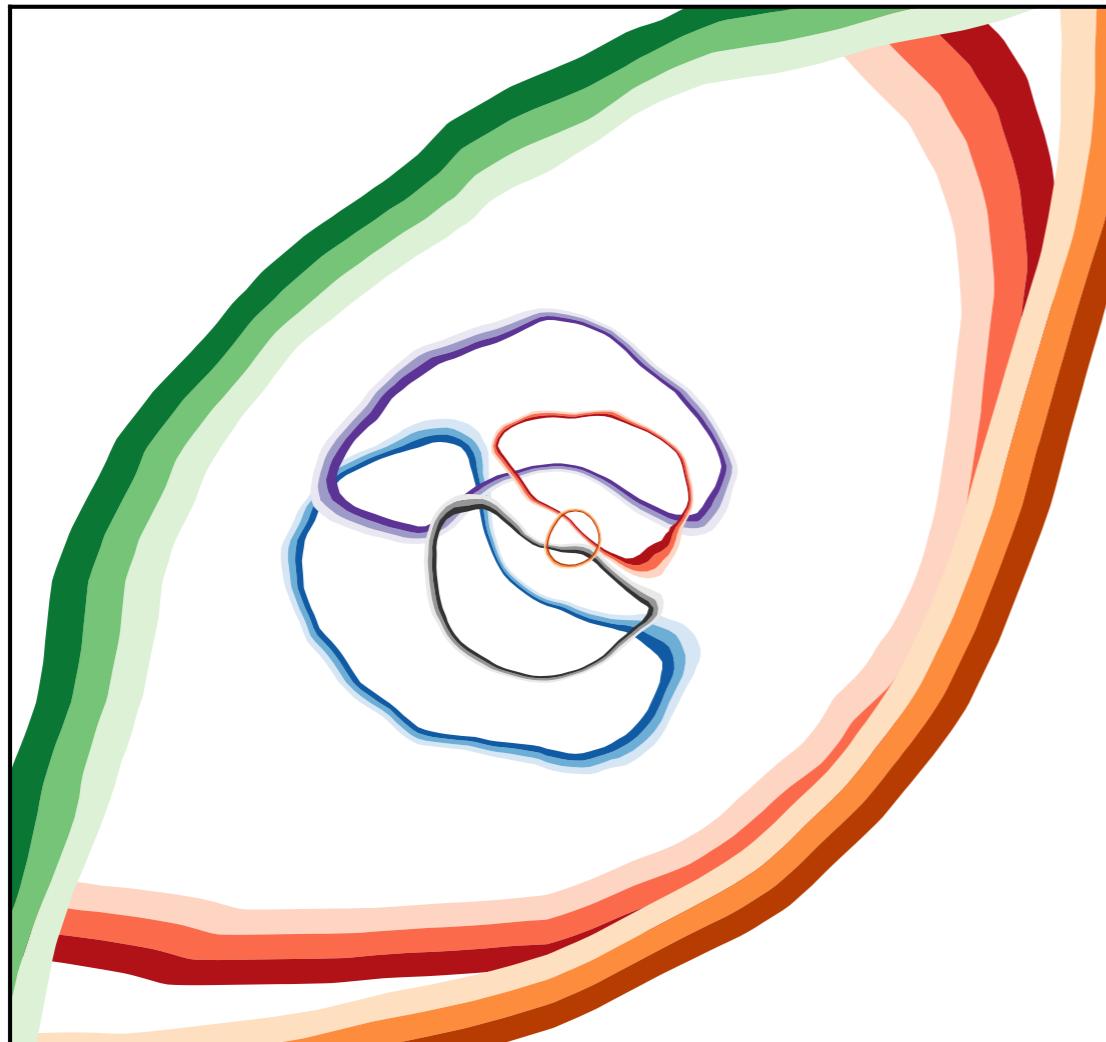


[Komiske, Metodiev, JDT, [JHEP 2019](#); see also Komiske, Metodiev, JDT, [JHEP 2018](#); code at [energyflow.network](#); special case of Zaheer, Kottur, Ravanbakhsh, Poczos, Salakhutdinov, Smola, [NIPS 2017](#)]

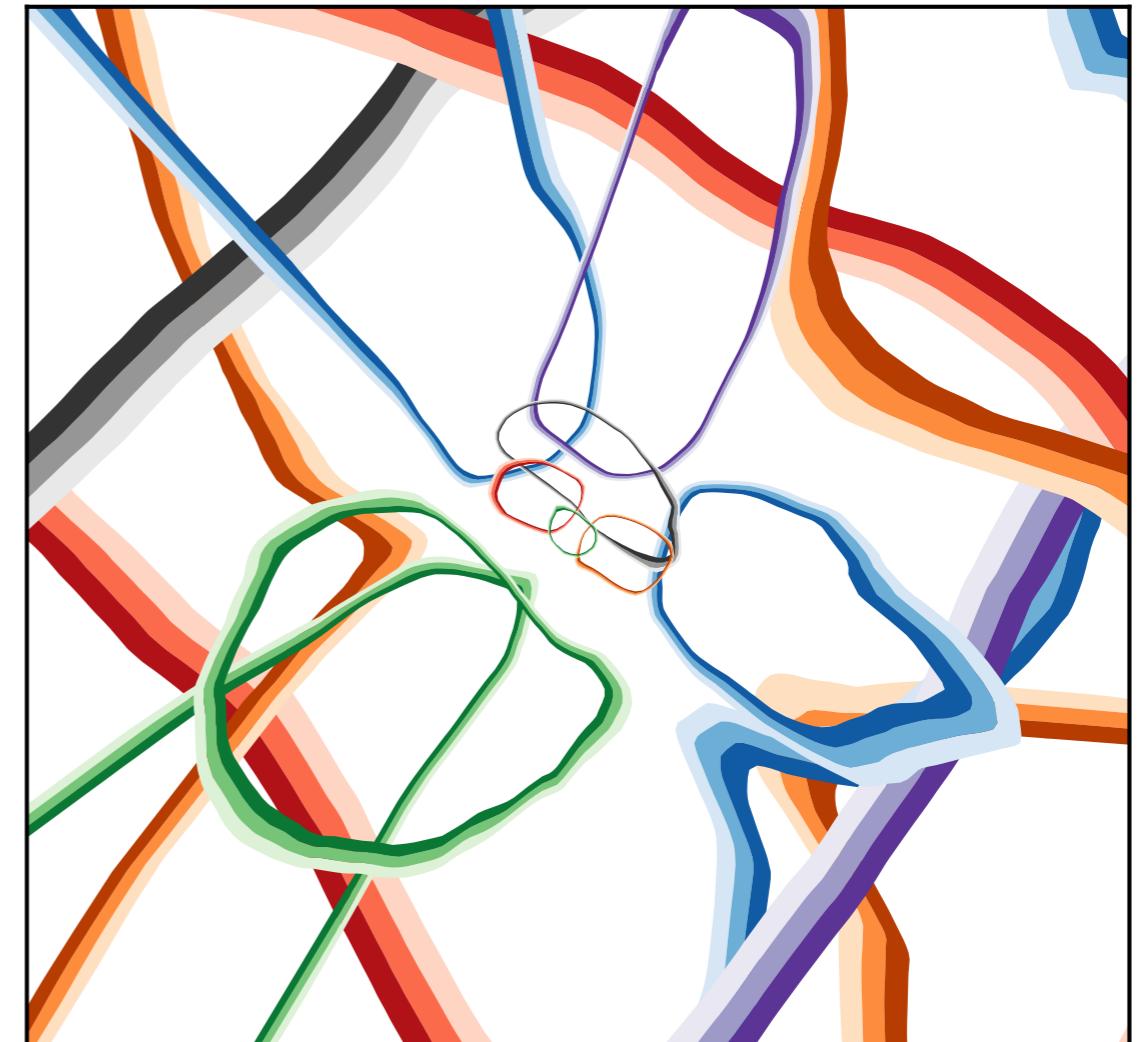


# Psychedelic Network Visualization

Latent Dimension 8



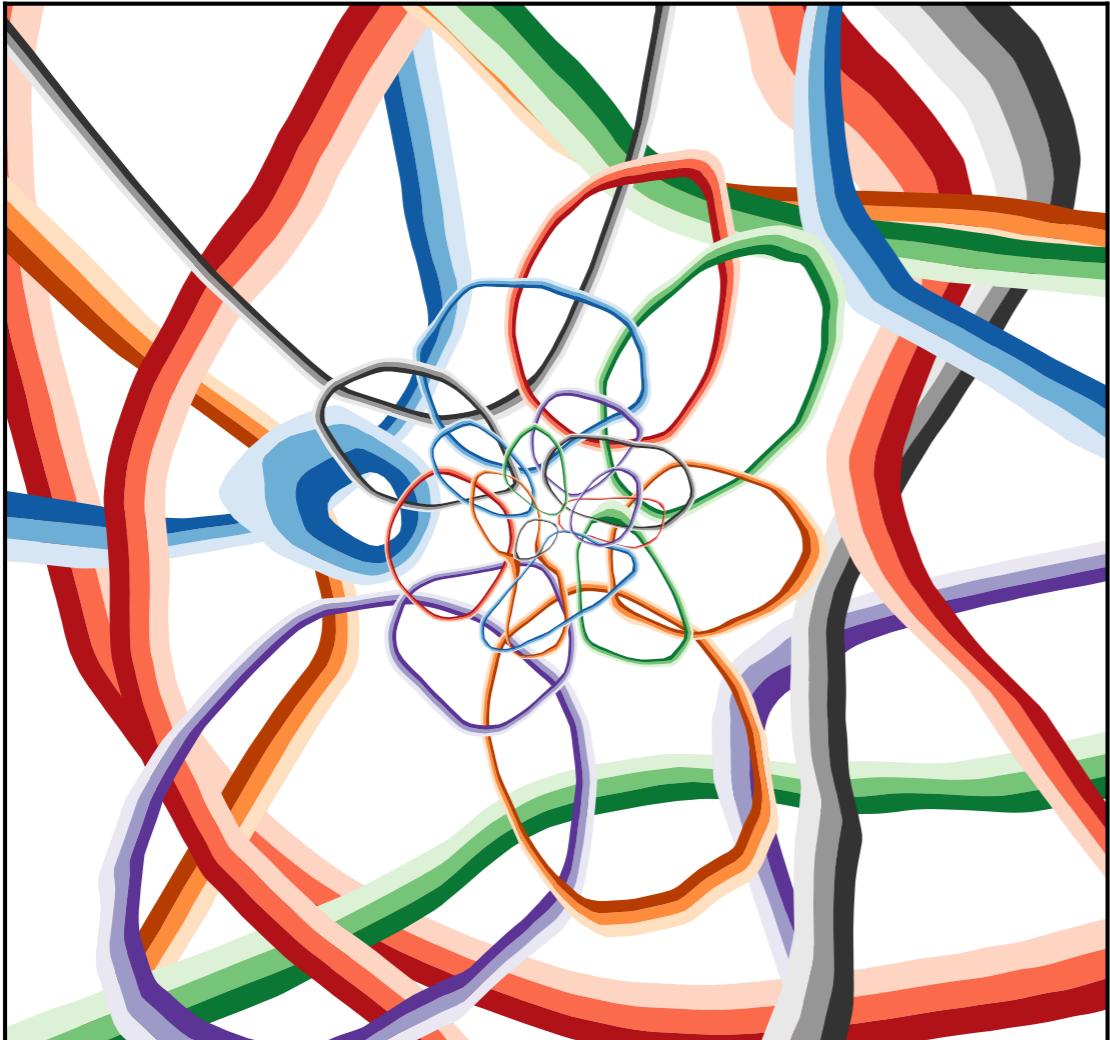
Latent Dimension 16



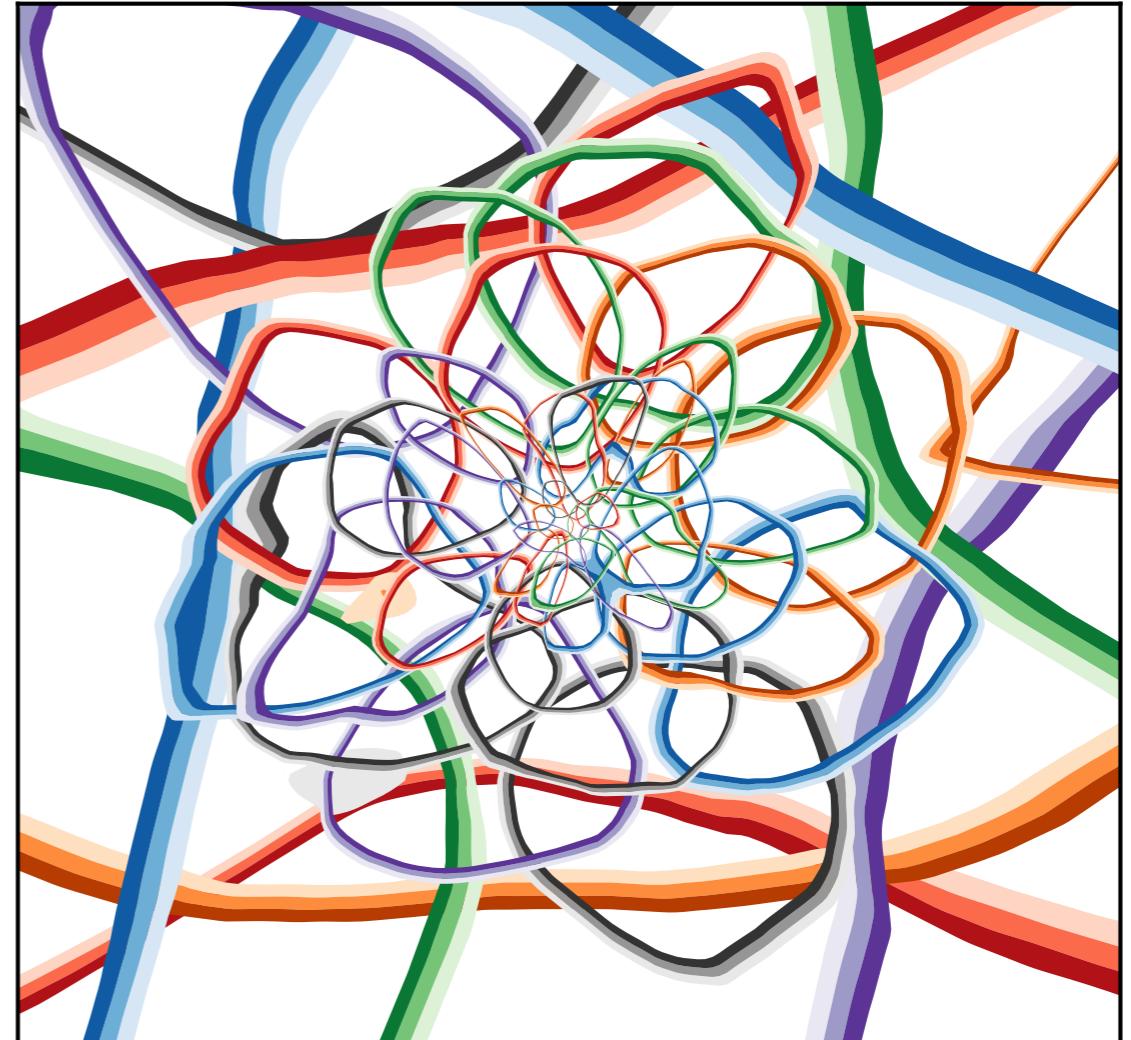
For the case of **quark** vs. **gluon** classification

# Psychedelic Network Visualization

Latent Dimension 32

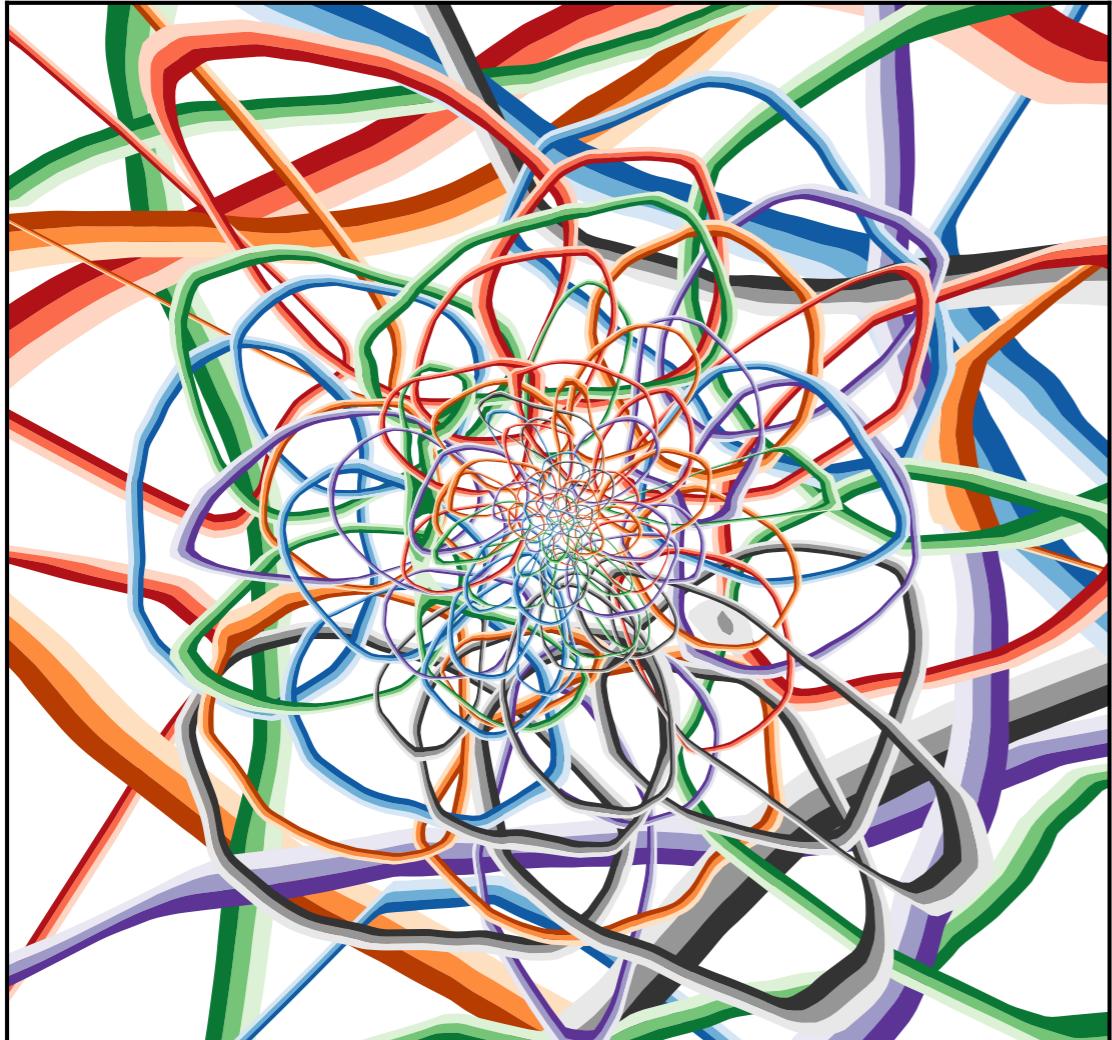


Latent Dimension 64

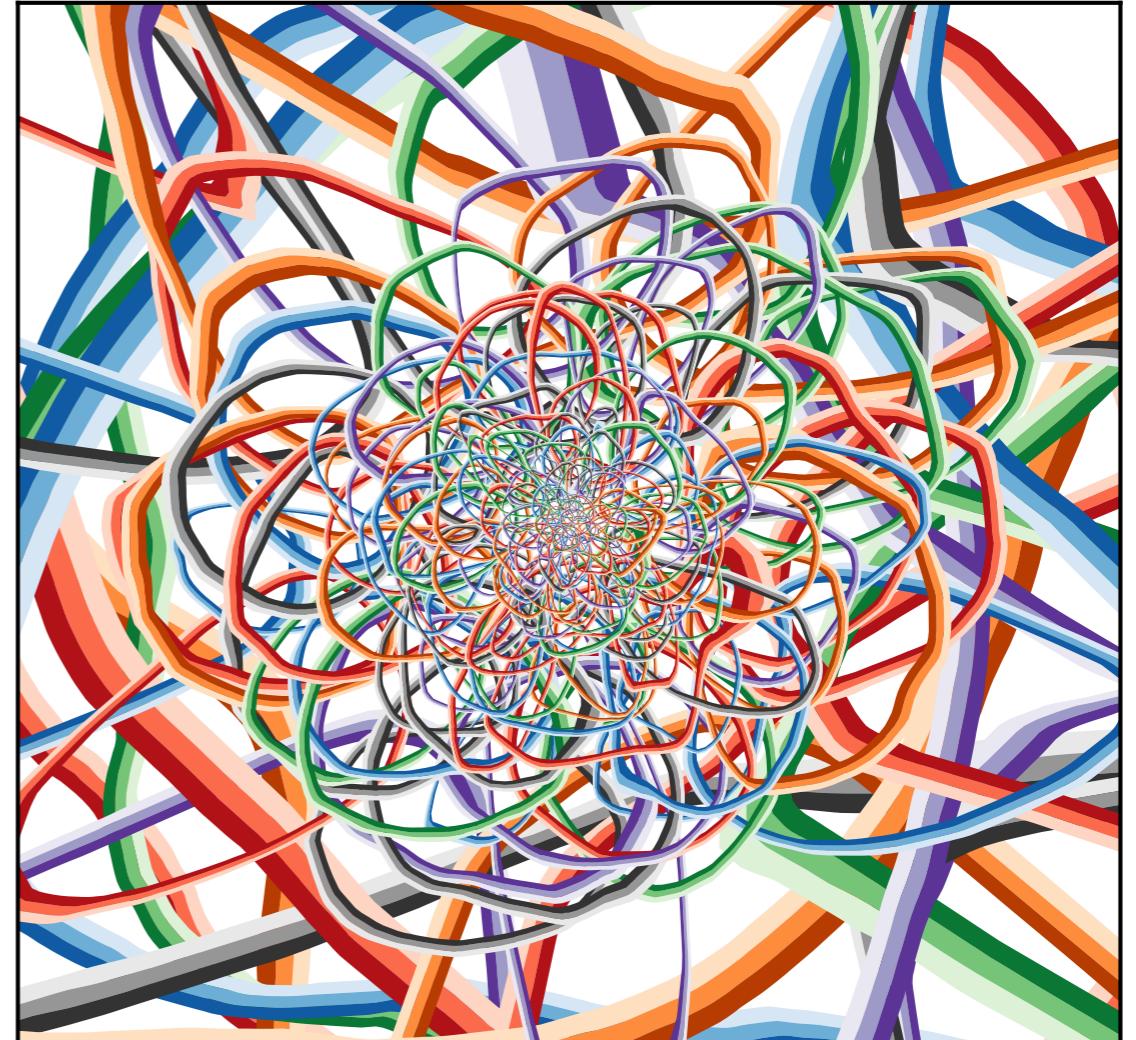


# Psychedelic Network Visualization

Latent Dimension 128

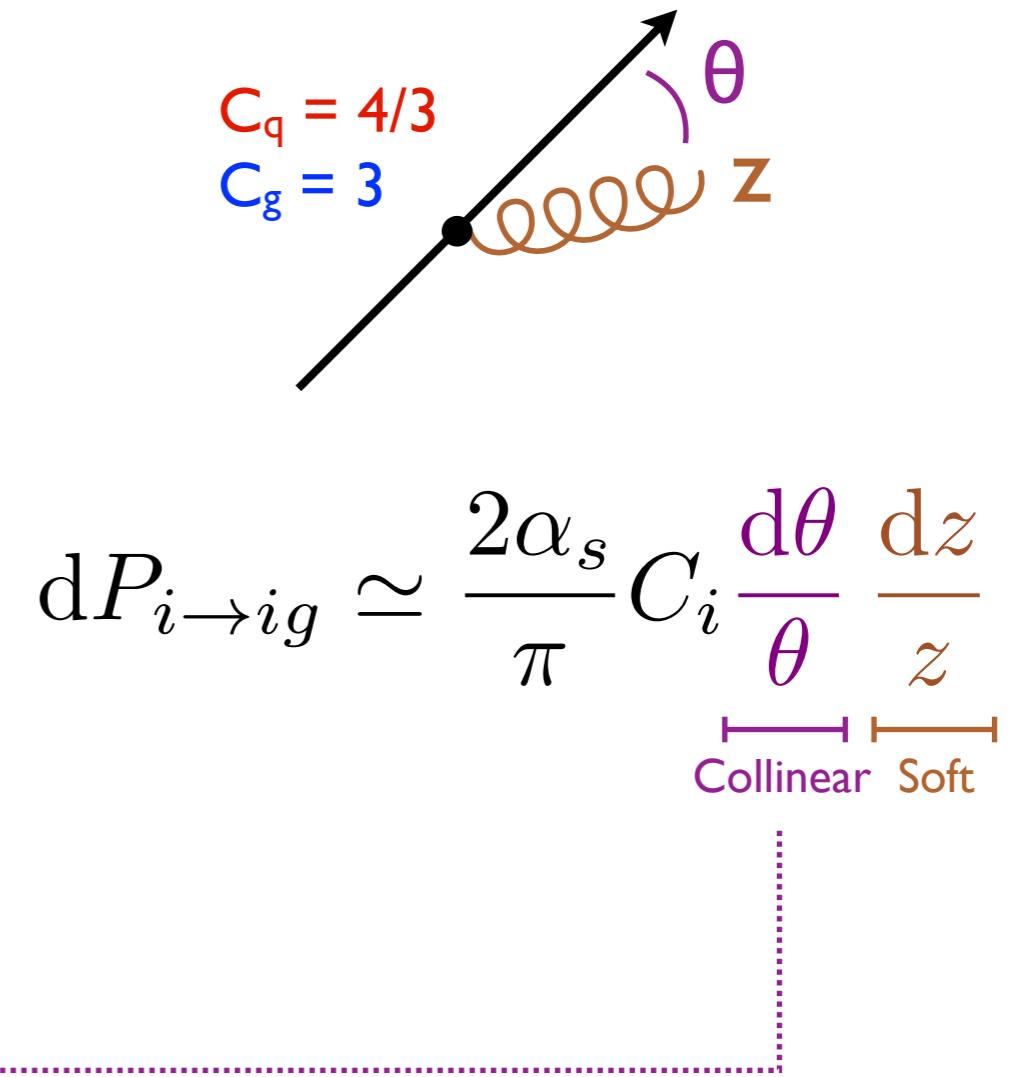
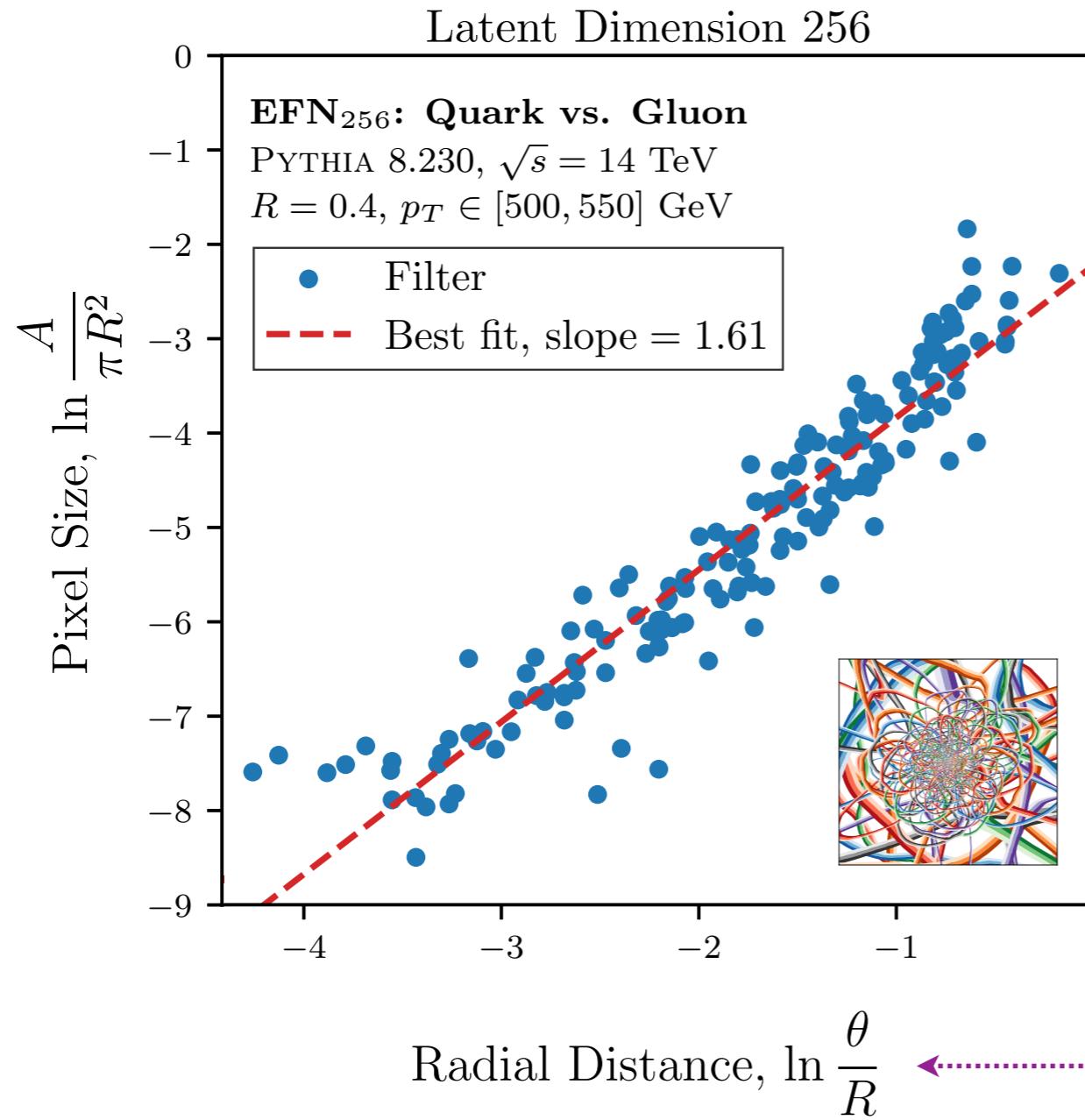


Latent Dimension 256



*Singularity structure of QCD!*

# Machine Learning Collinear QCD



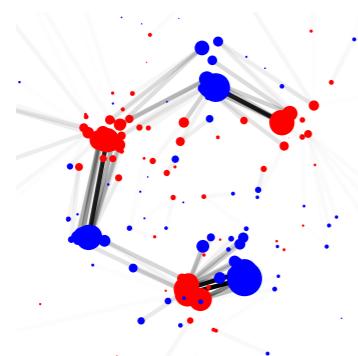
[Komiske, Metodiev, JDT, JHEP 2019]



# Particle Physics 101



What is a Collider Event?

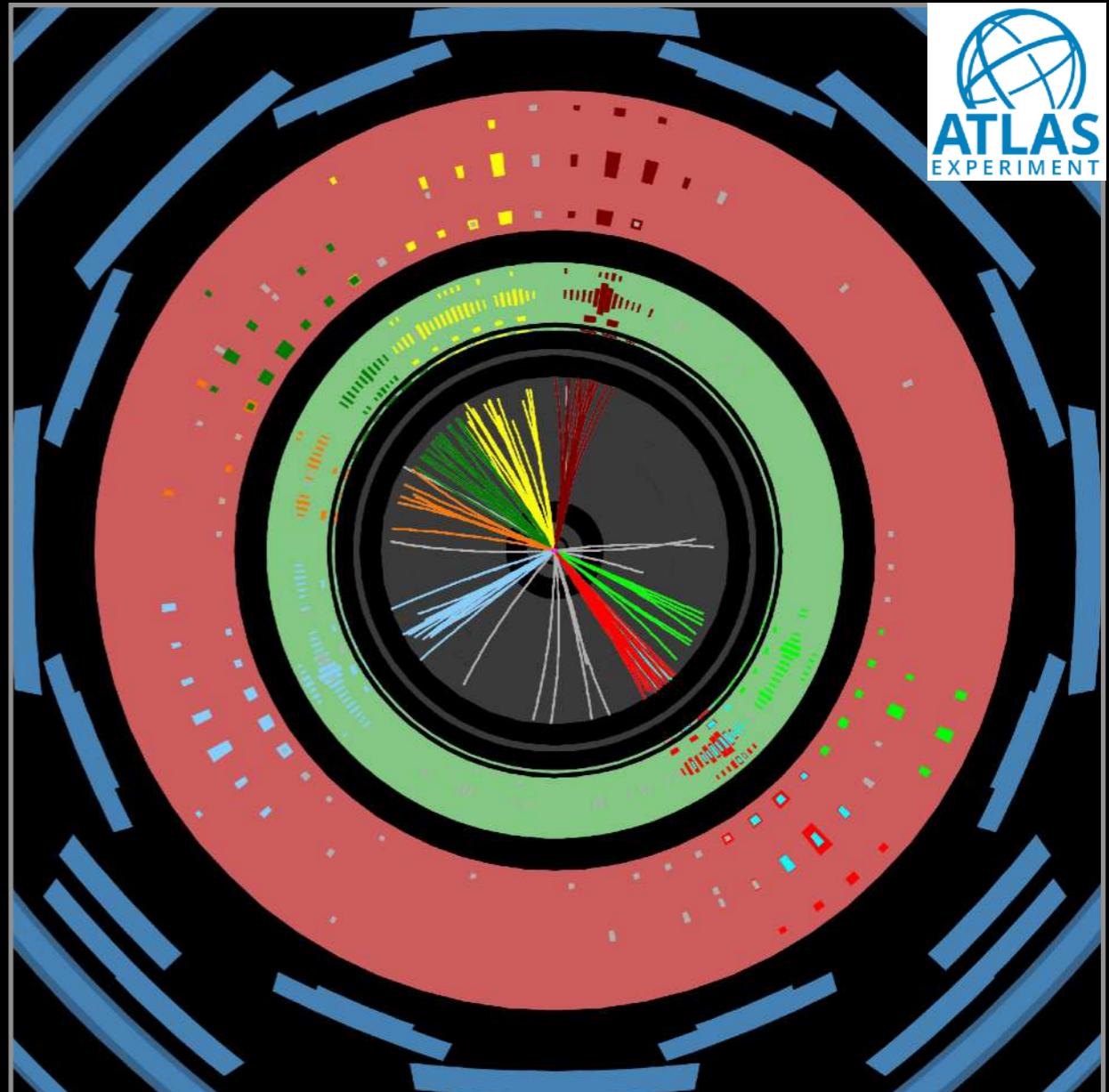
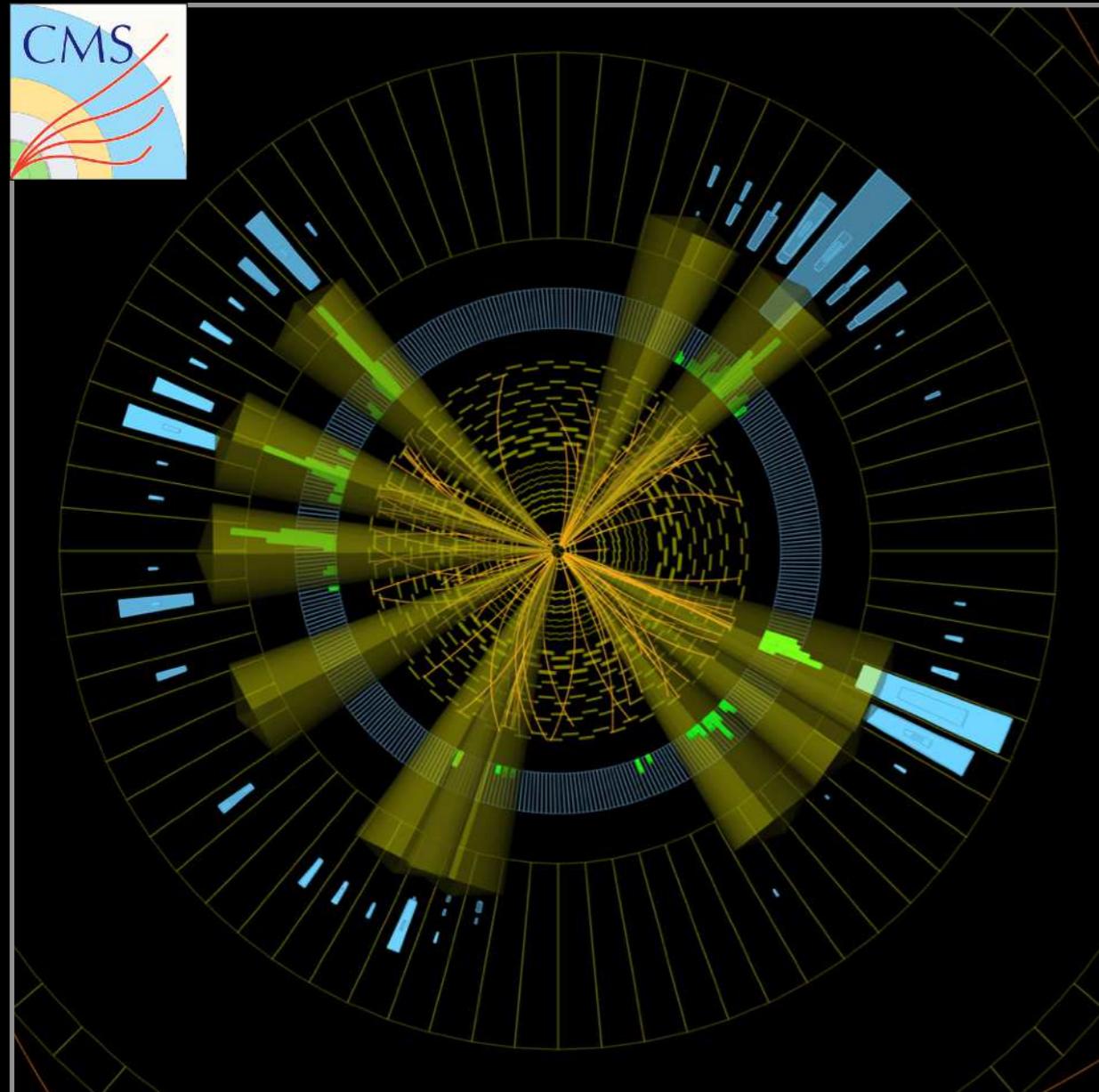


When are Collider Events Similar?

# Two Collider Events

Two collections of points in (momentum) space

How “close” are these?

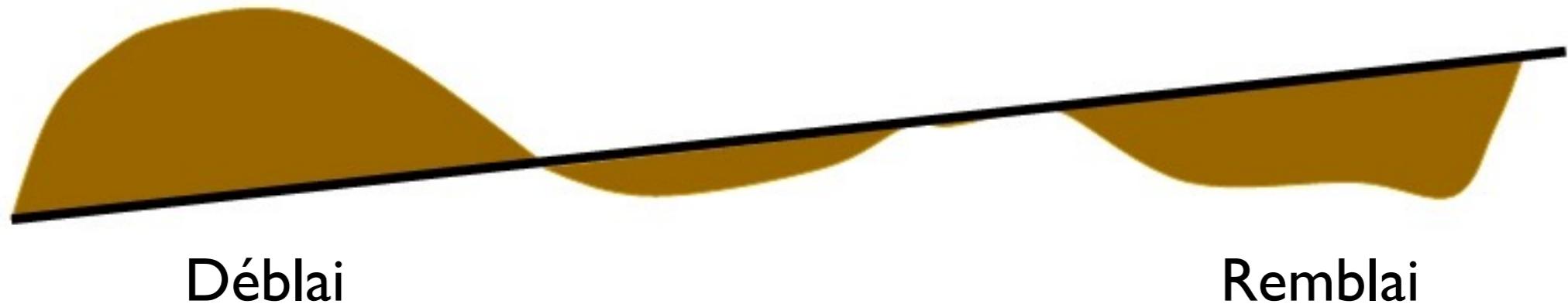


# The Earth Mover's Distance

## 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



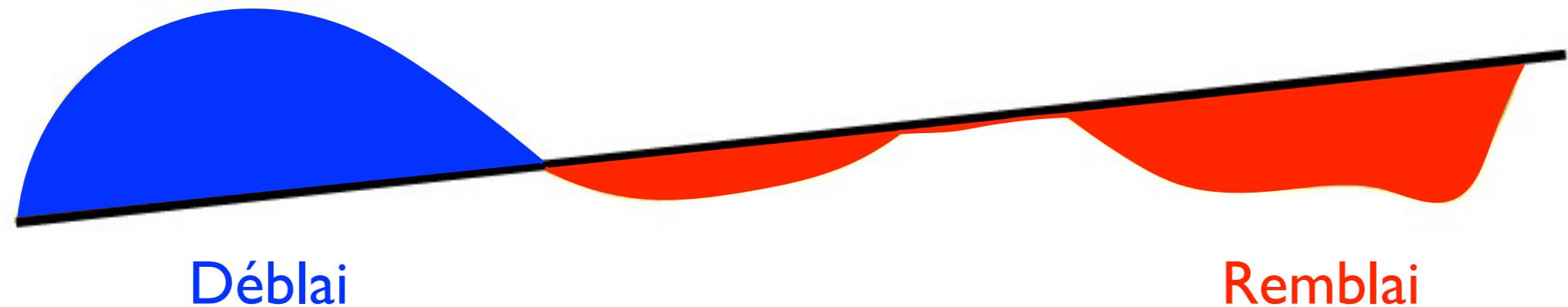
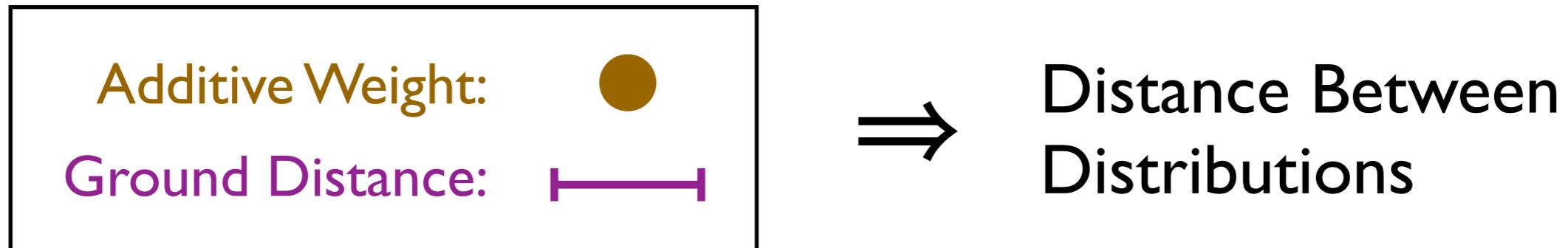
[h/t Niles-Weed, [ML4Jets 2020](#); Monge, 1781; Vaserštejn, 1969; [Wikipedia](#)]

# The Earth Mover's Distance

Optimal Transport:

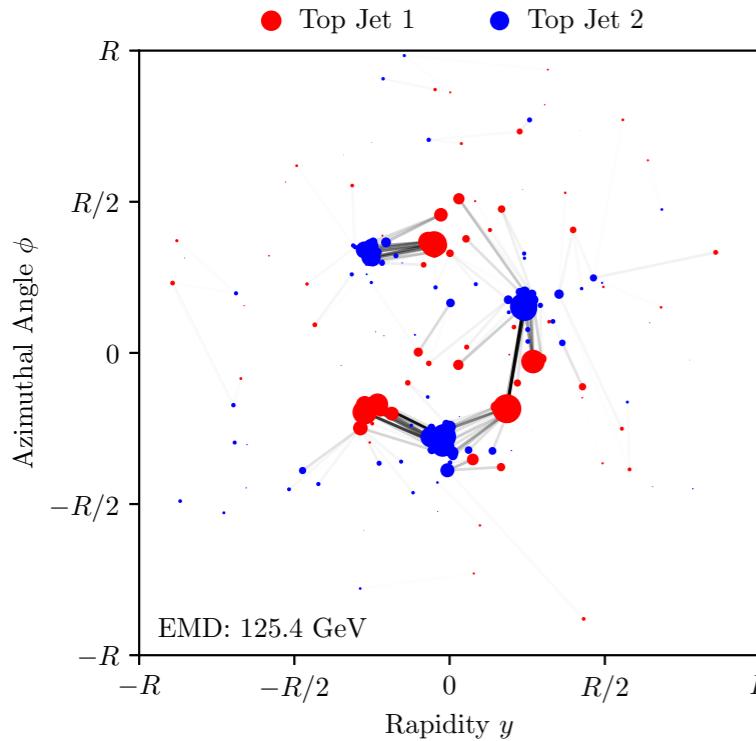
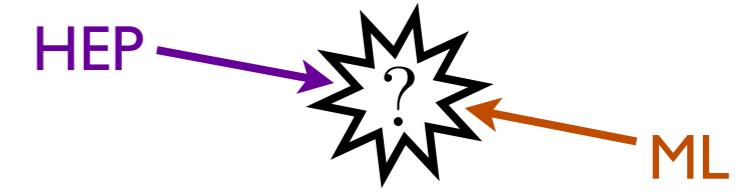
[Peleg, Werman, Rom, [IEEE 1989](#);  
Rubner, Tomasi, Guibas, [ICCV 1998](#), [ICCV 2000](#);  
Pele, Werman, [ECCV 2008](#); Pele Taskar, [GSI 2013](#)]

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

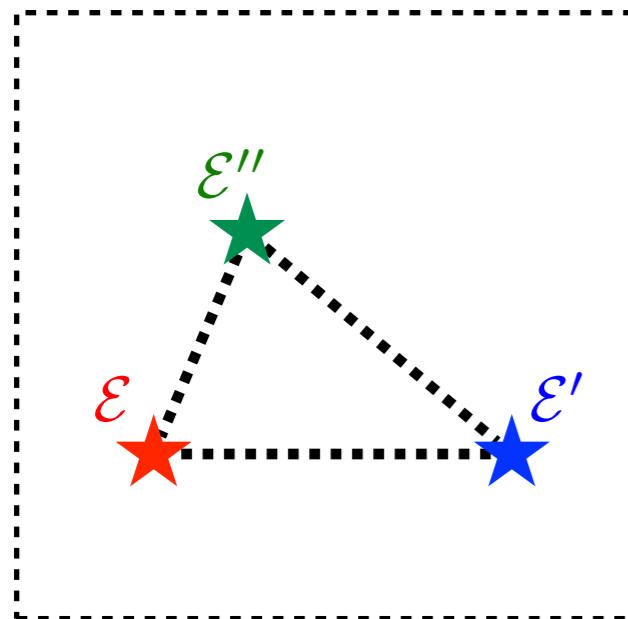
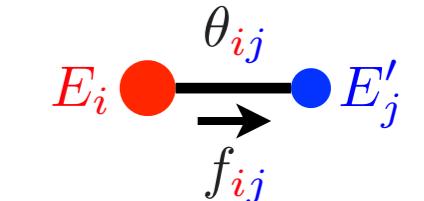


Optimal transport of energy flows...

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

↑  
in GeV

Cost to move energy      Cost to create energy



...defines a metric on the space of events

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

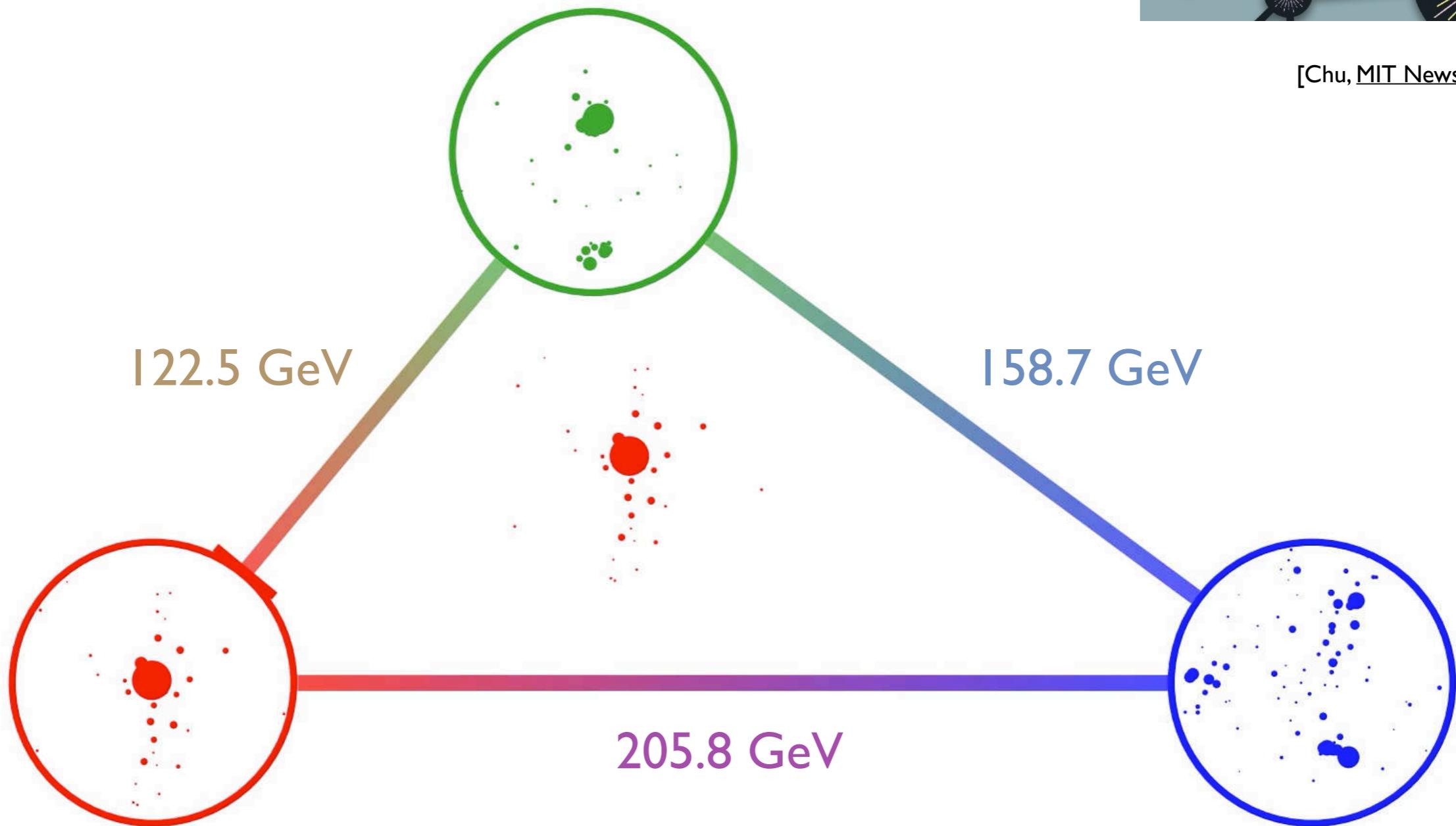
(assuming  $R \geq \theta_{\max}/2$ , i.e.  $R \geq$  jet radius for conical jets)

[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](#)]

# Triangulating the Space of Jets



[Chu, MIT News July 2019]



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

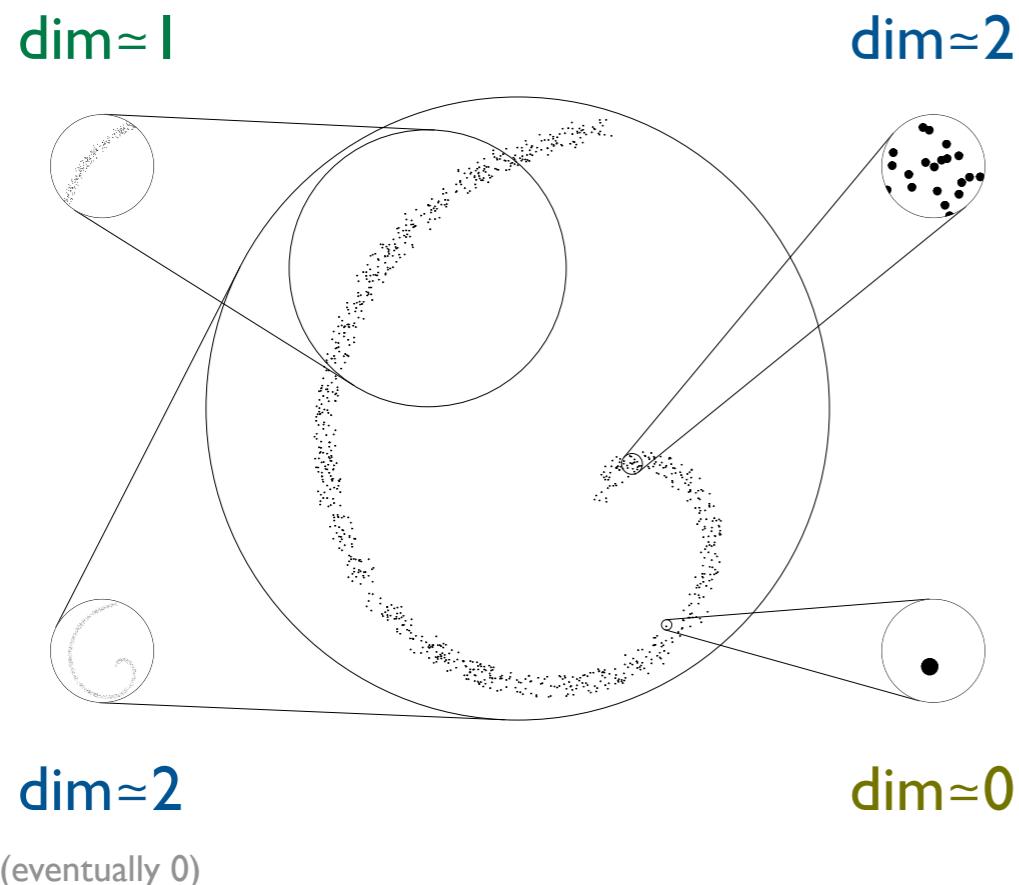
*What can you do with a metric?*

# 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](#)]



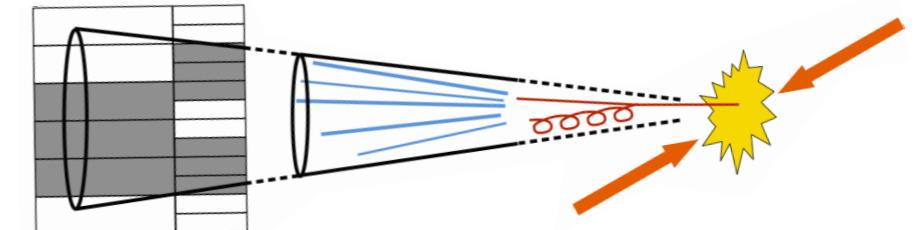
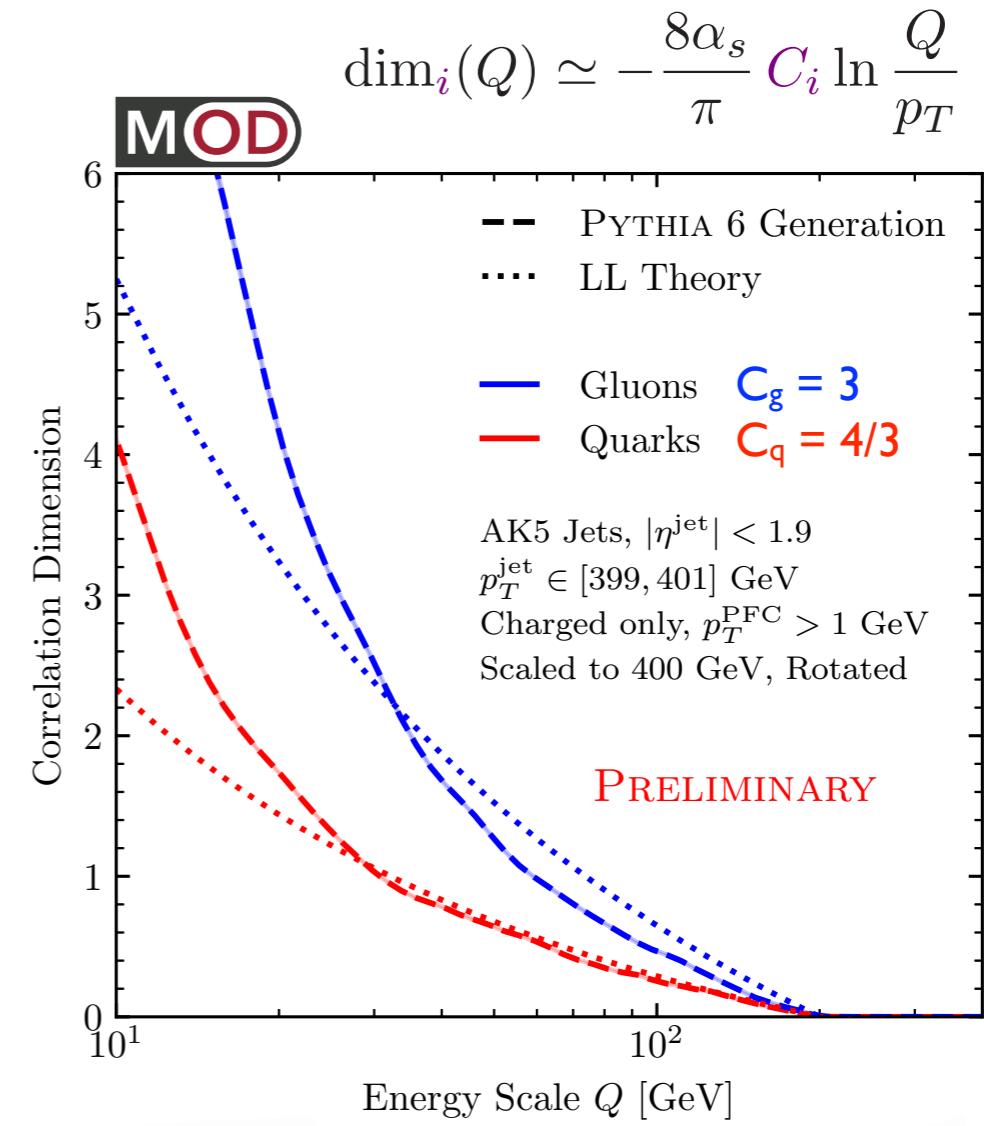
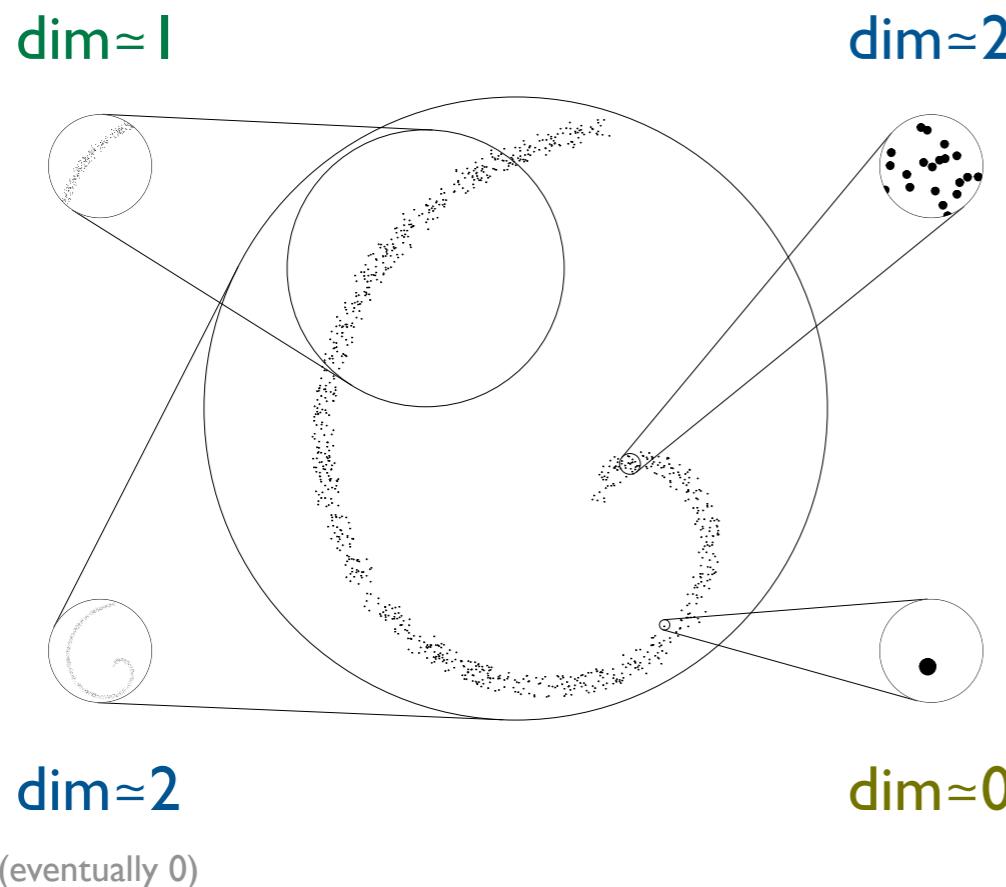
# Dimensionality of Space of Jets



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

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

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



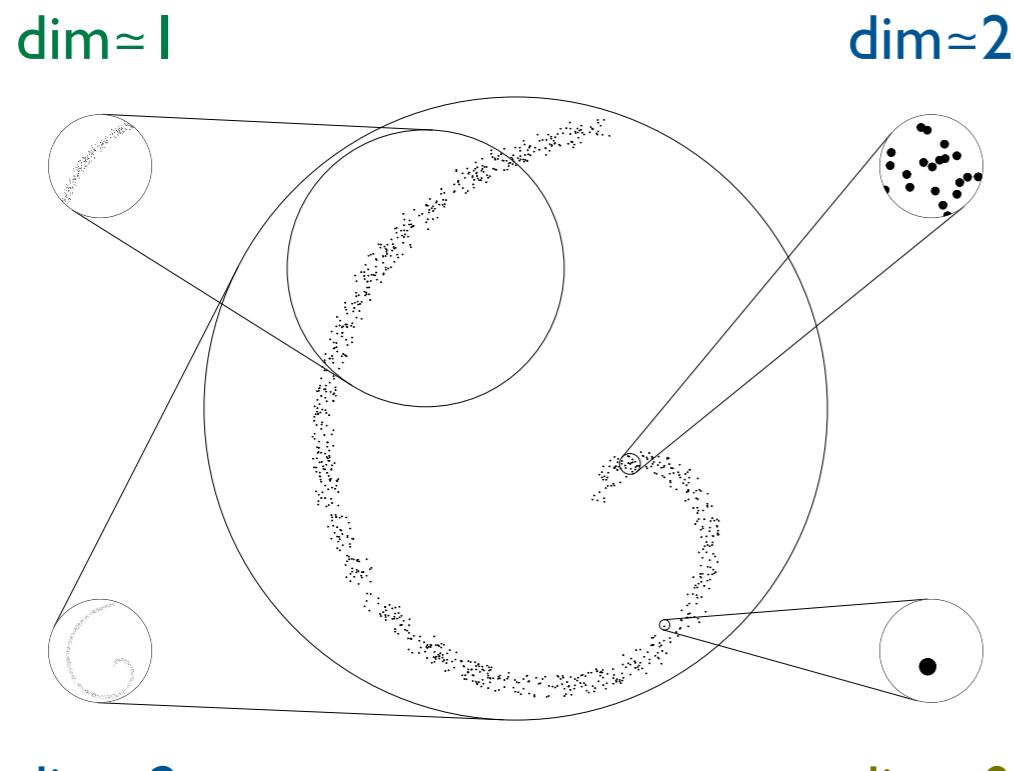
# Dimensionality of Space of Jets



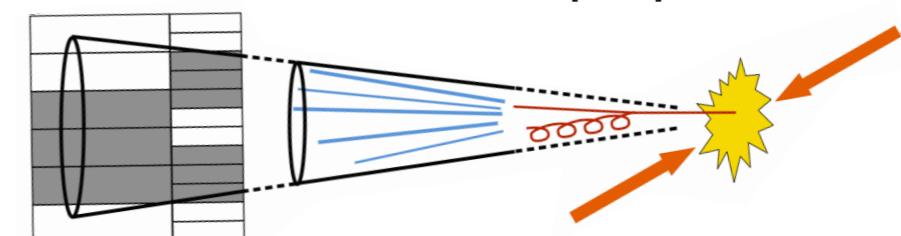
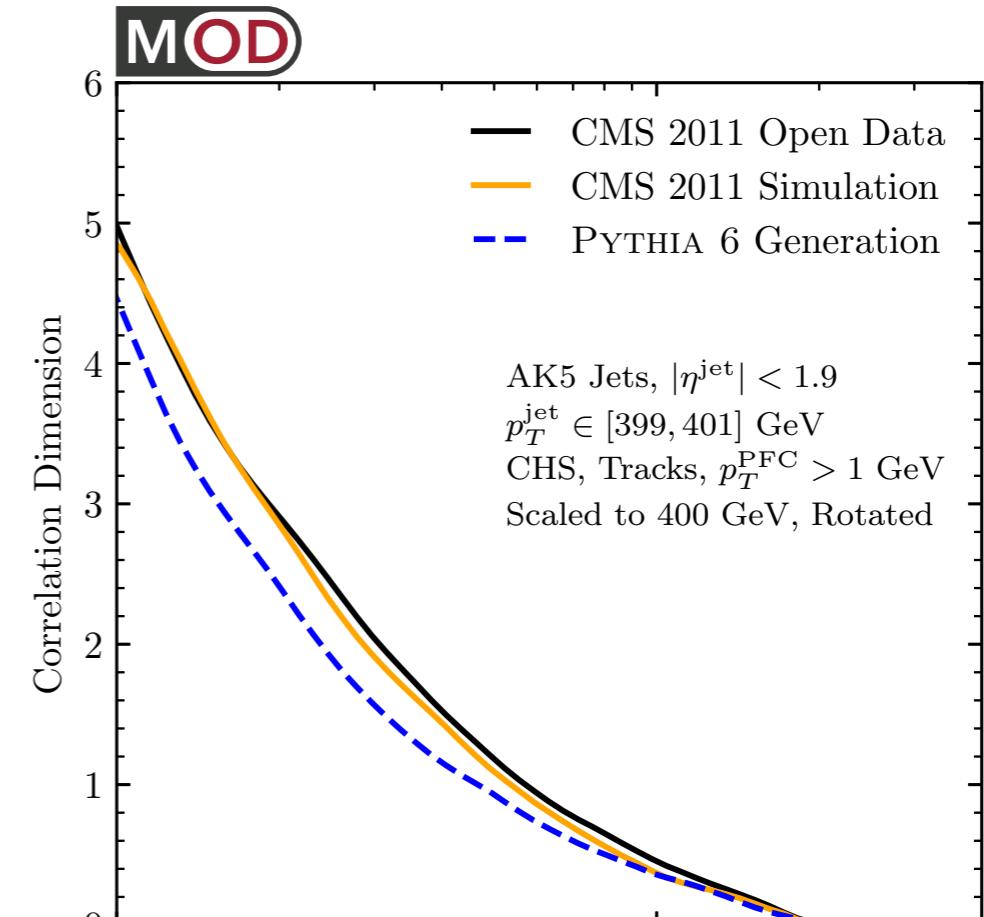
$$N_{\text{neighbors}}(r) \sim r^{\dim}$$

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



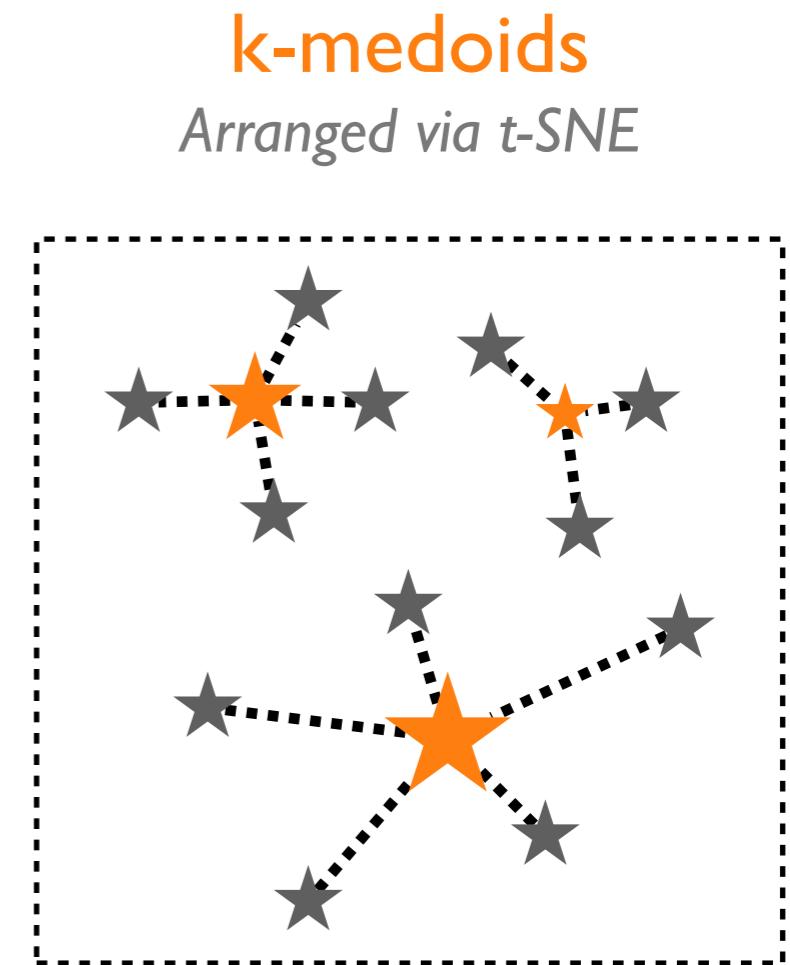
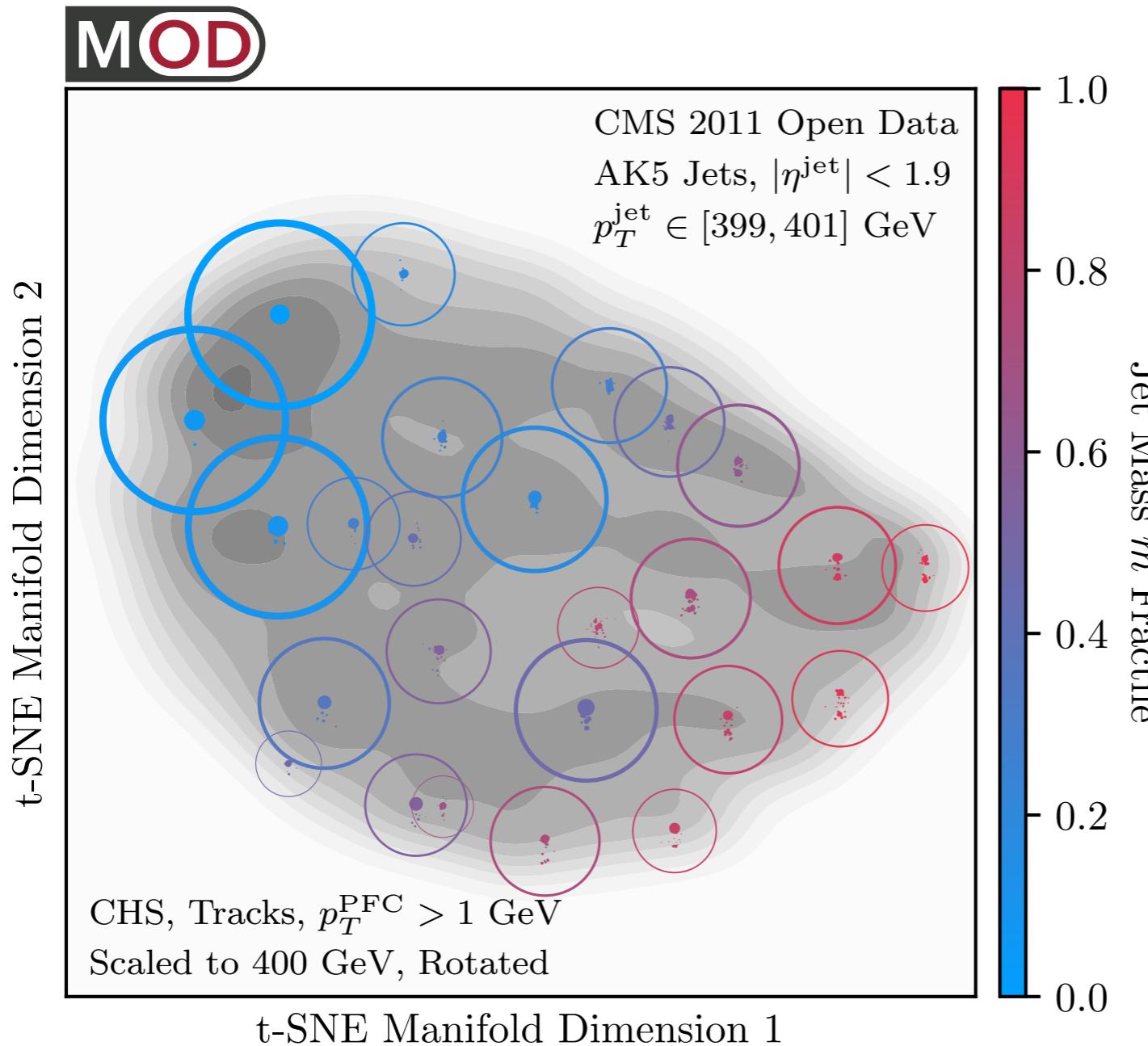
(eventually 0)



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



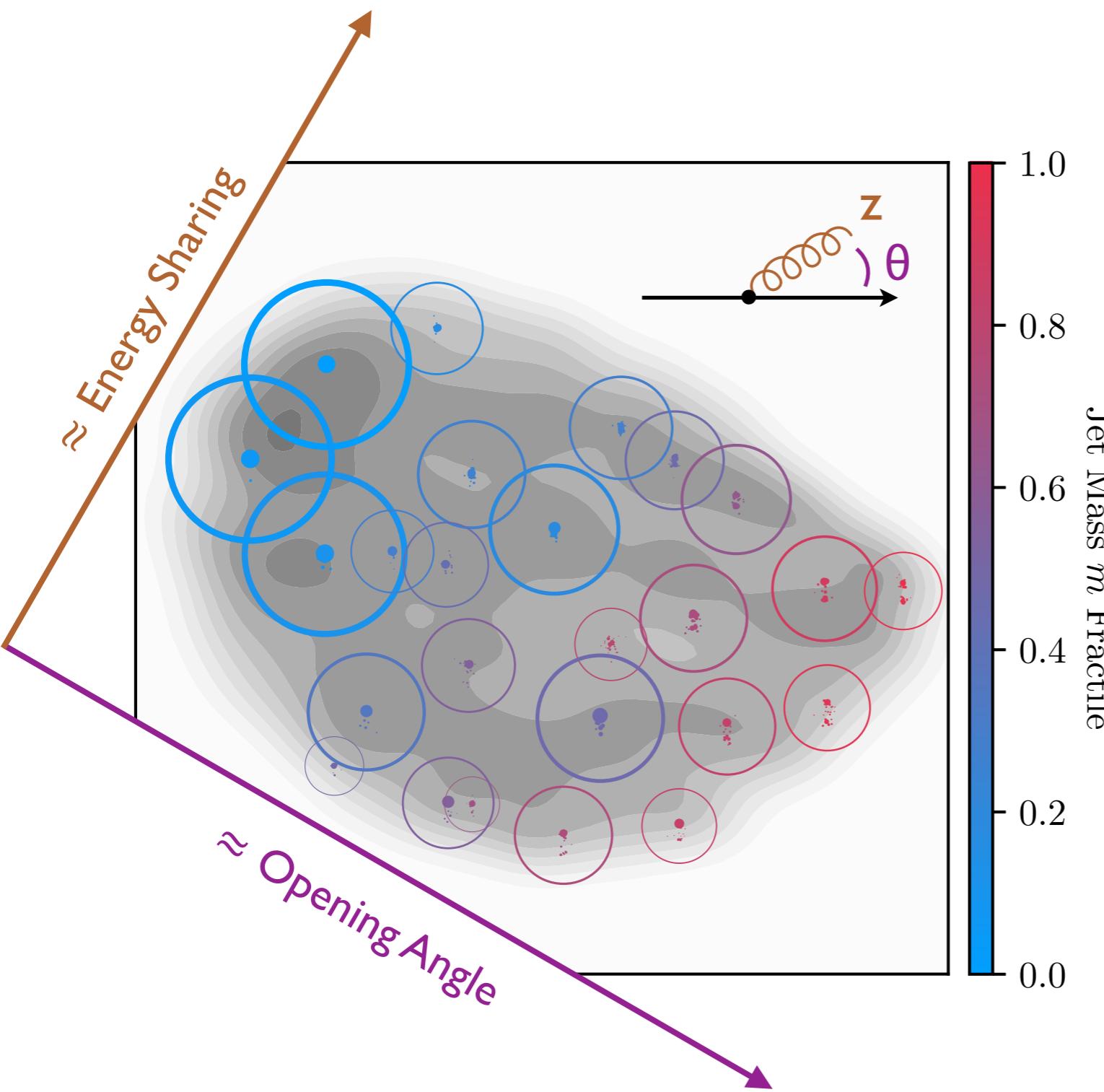
# Most Representative Jets



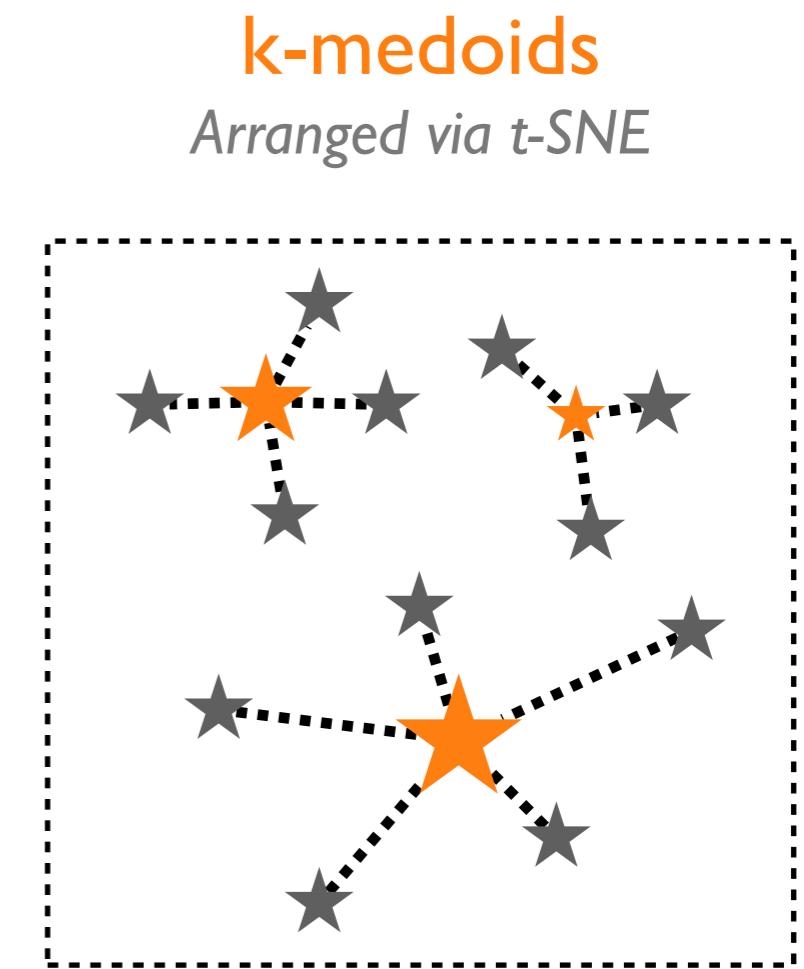
[Komiske, Mastandrea, Metodiev, Naik, JDT, [PRD 2020](#);  
using van der Maaten, Hinton, [JMLR 2008](#)]



# Most Representative Jets



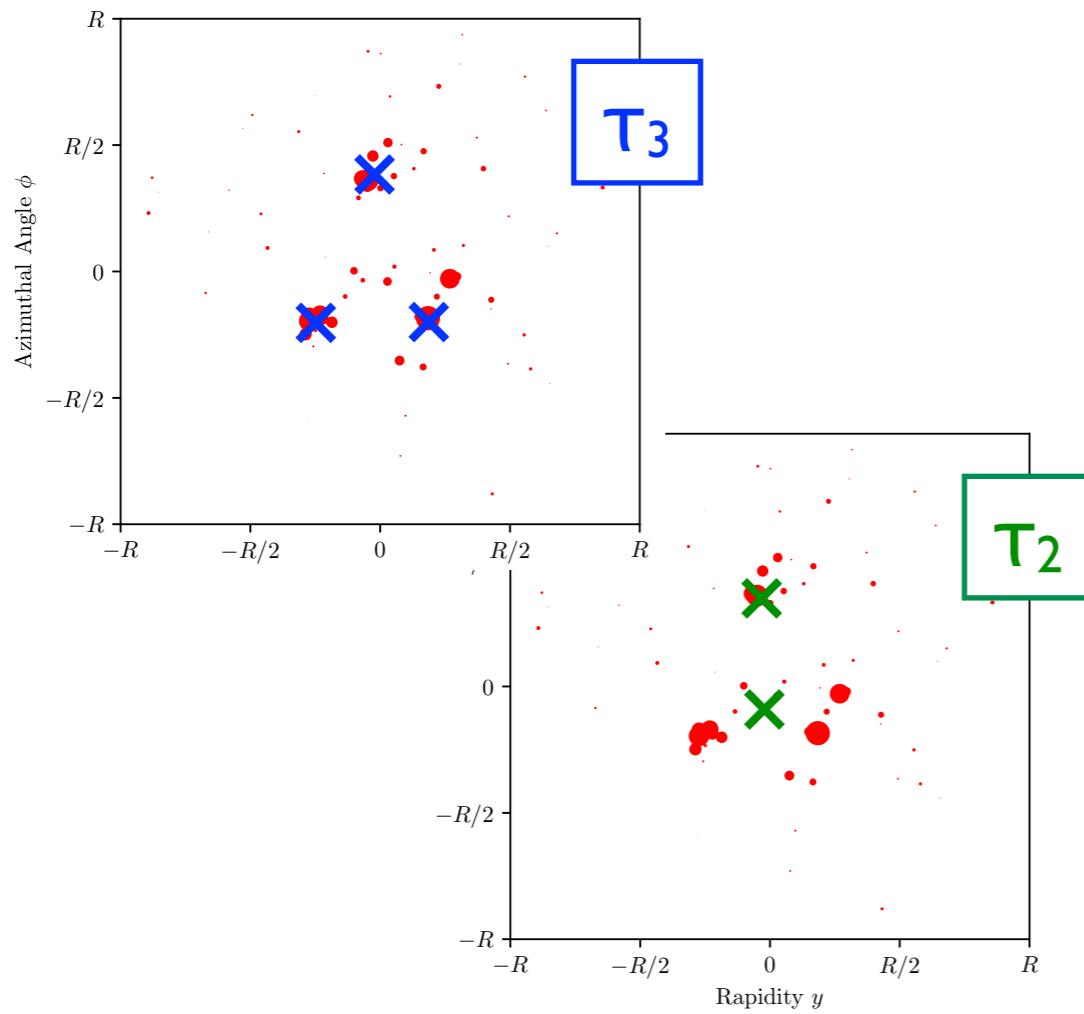
[Komiske, Mastandrea, Metodiev, Naik, JDT, [PRD 2020](#);  
using van der Maaten, Hinton, [JMLR 2008](#)]



# N-subjettiness

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

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

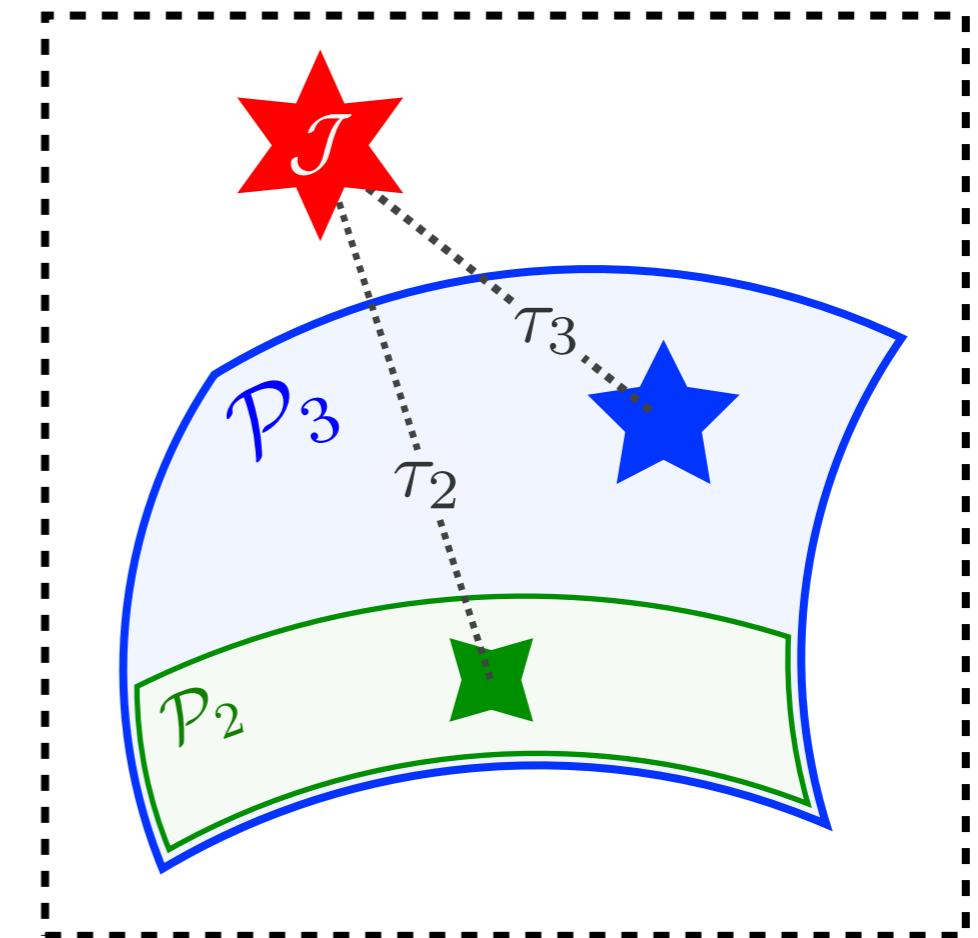
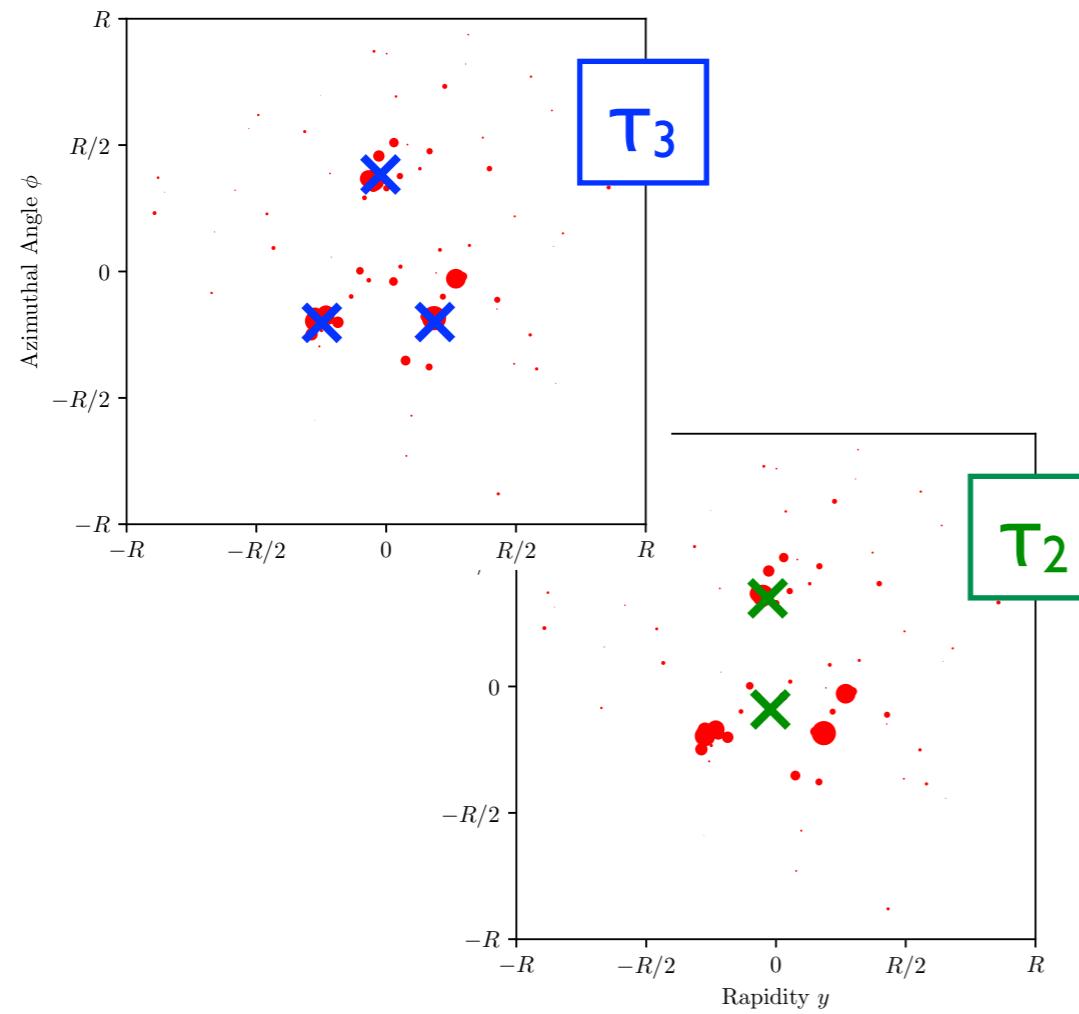


[JDT, Van Tilburg, [JHEP 2011](#), [JHEP 2012](#);  
based on Brandt, Dahmen, [ZPC 1979](#); Stewart, Tackmann, Waalewijn, [PRL 2010](#)]

# N-subjettiness = Point to Manifold EMD

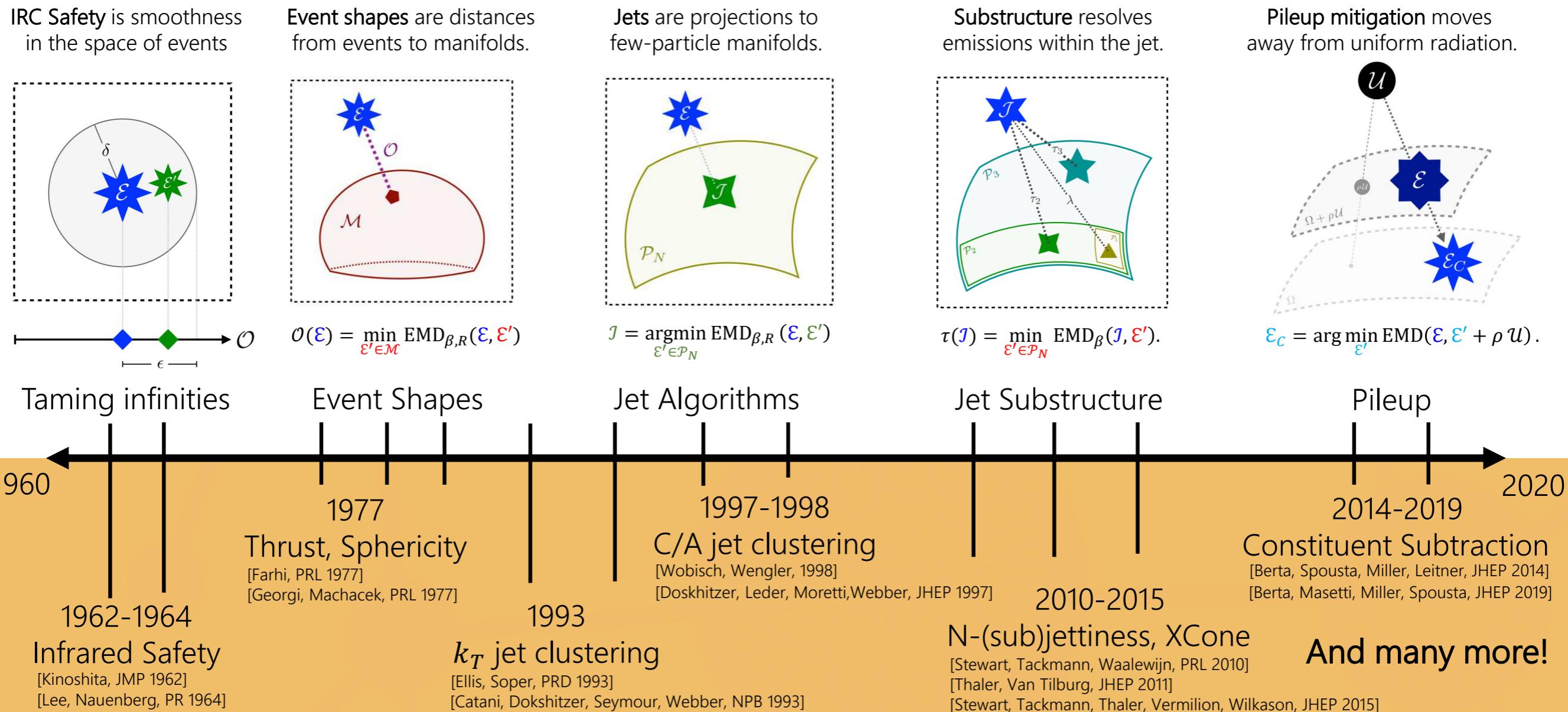
*...is secretly an optimal transport problem*

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

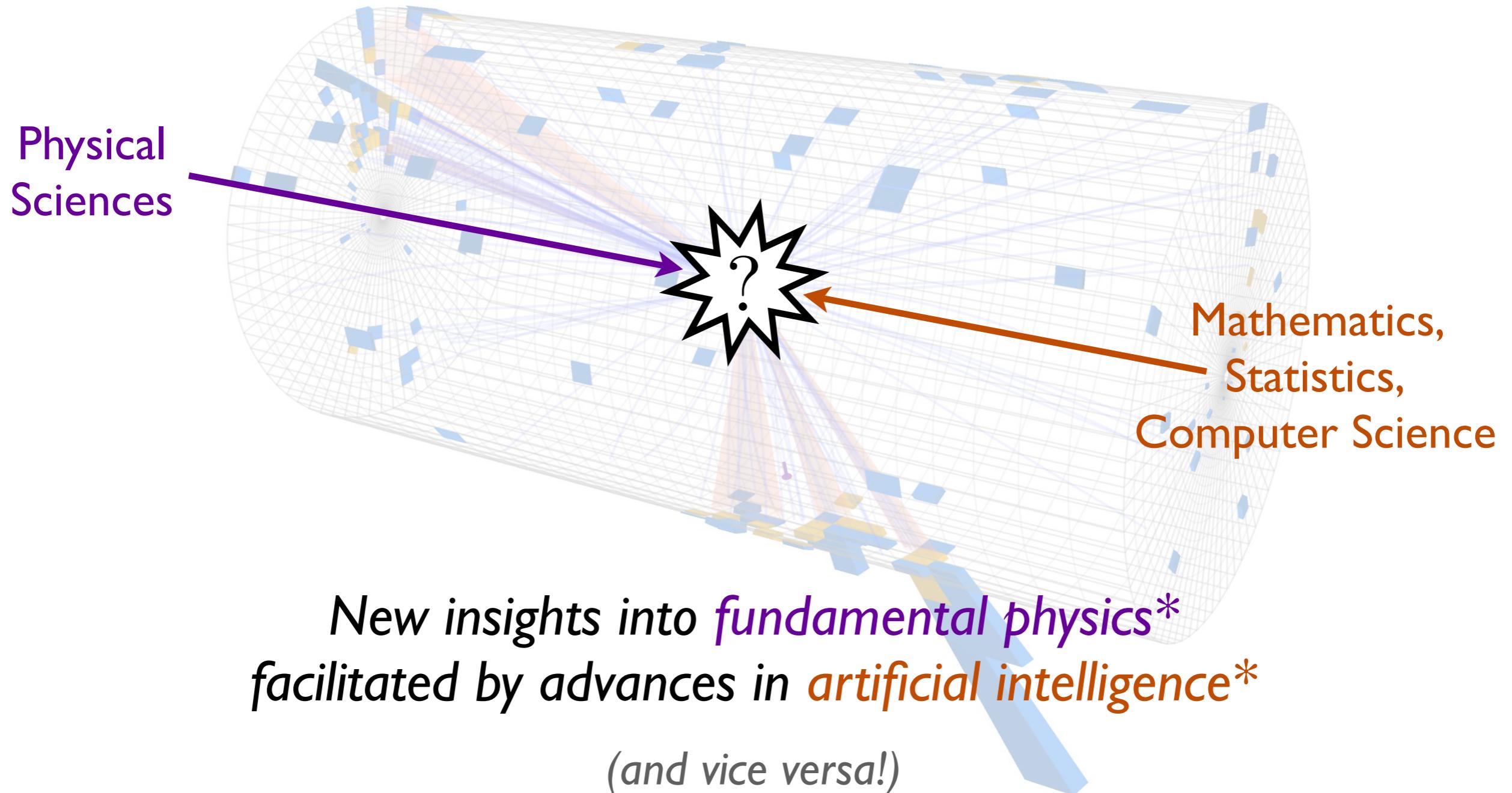


[JDT, Van Tilburg, [JHEP 2011](#), [JHEP 2012](#);  
rephrased via Komiske, Metodiev, JDT, [JHEP 2020](#); see opposite limit in Cesarotti, JDT, [JHEP 2020](#)]

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



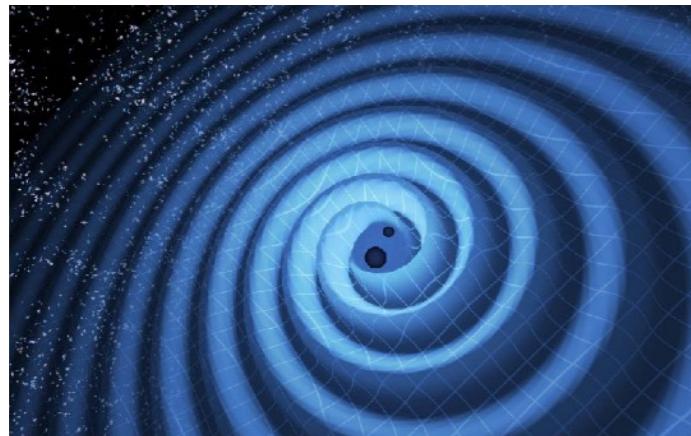
# “Collision Course”



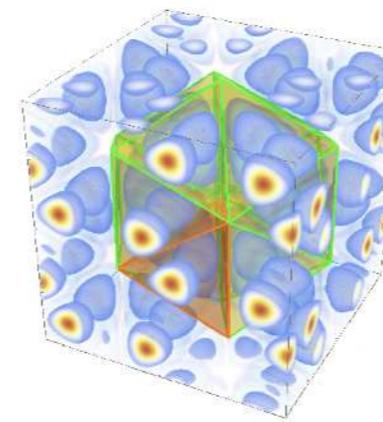
# *Artificial Intelligence $\Leftrightarrow$ Fundamental Interactions*



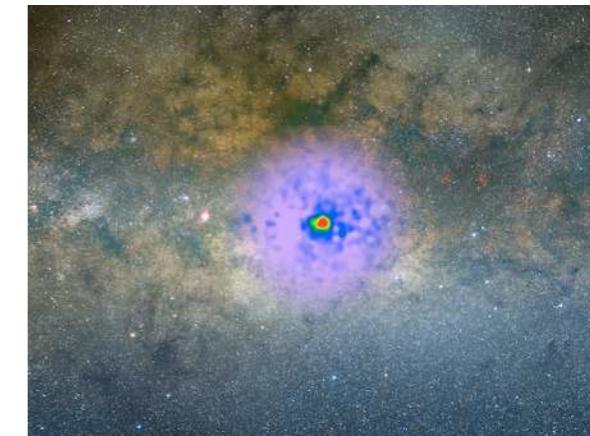
*Gravitational Waves*



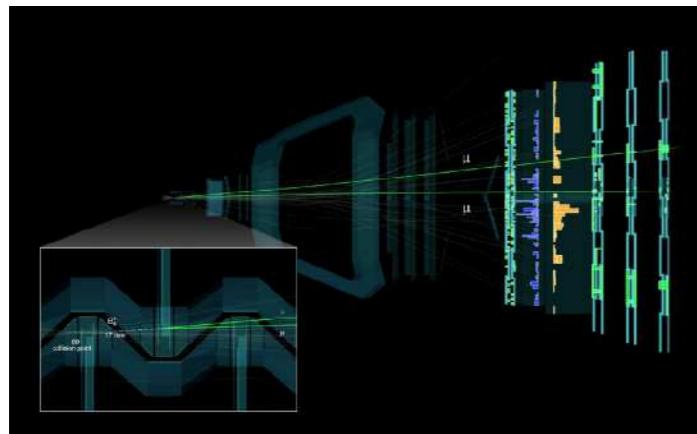
*Nuclear Physics*



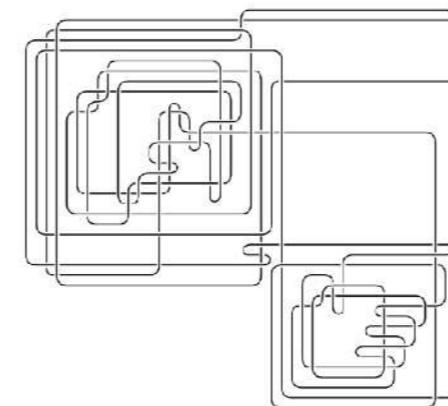
*Astrophysics*



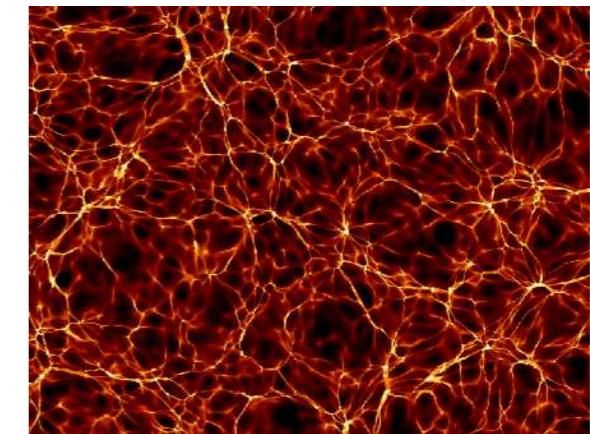
*Particle Colliders*



*Mathematical Physics*



*Dark Matter*

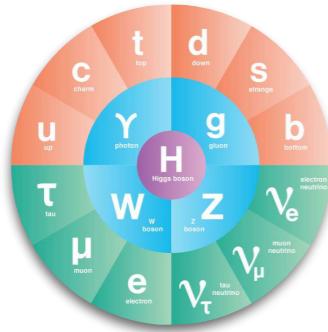
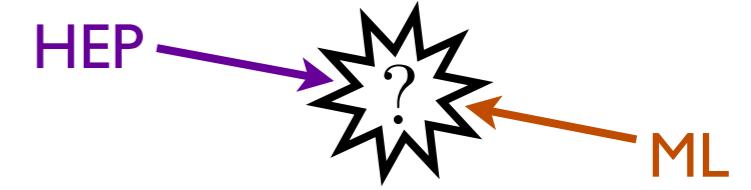


...

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

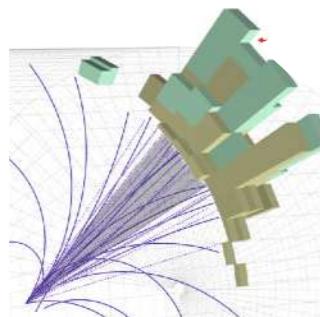
[<http://iaifi.org>]

# Summary



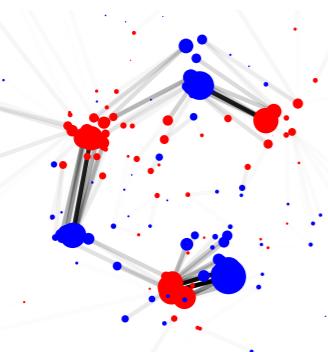
## Particle Physics 101

*High-energy collisions can yield insights into fundamental physics  
Machine learning offers powerful tools to analyze collision debris*



## What is a Collider Event?

*Unordered set of particles describing energy flow of jets  
Inspires network architectures designed for symmetry and safety*

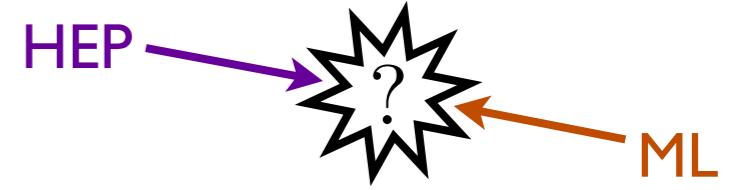


## When are Collider Events Similar?

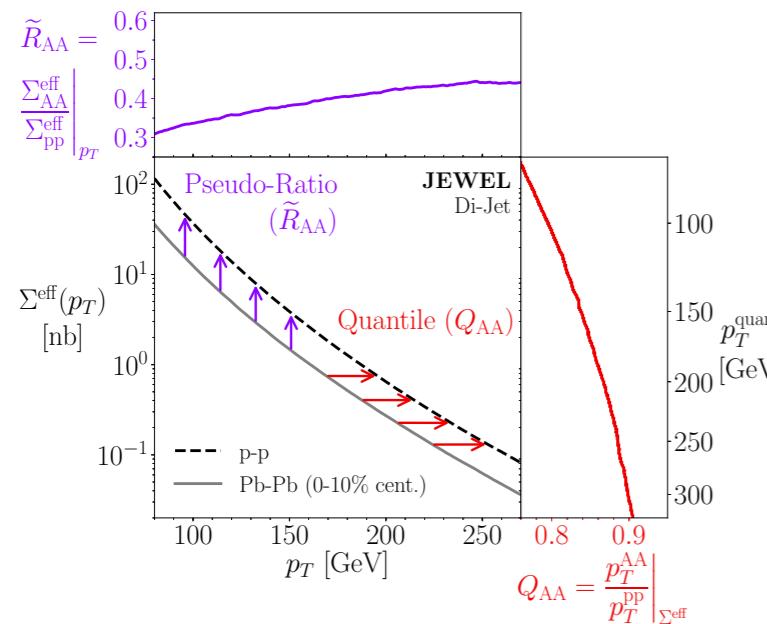
*When their energy flows are similar  
Inspires unsupervised learning strategies based on event geometry*

# *Backup Slides*

# More Collisions

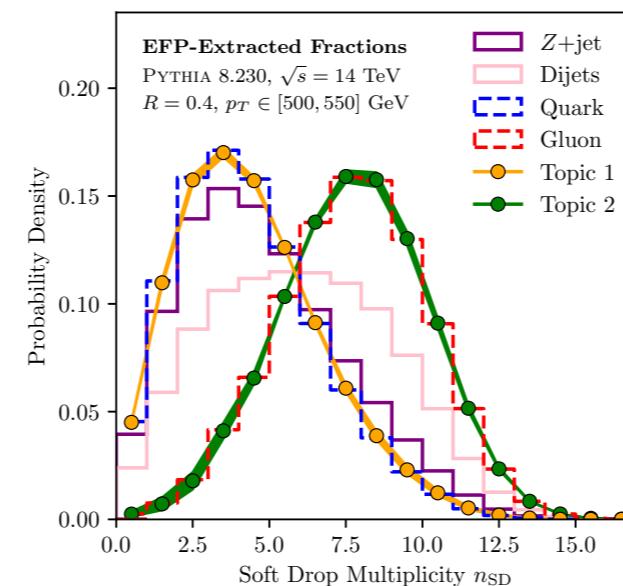


## Jet Quenching via Optimal Transport



[Brewer, Milhano, JDT, PRL 2019]

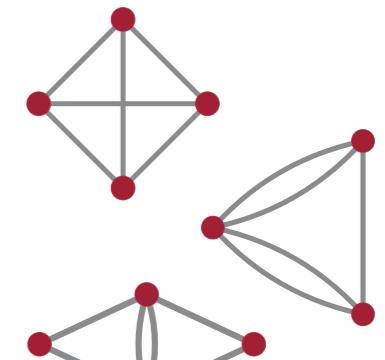
## Quark/Gluon Definitions via Blind Source Separation



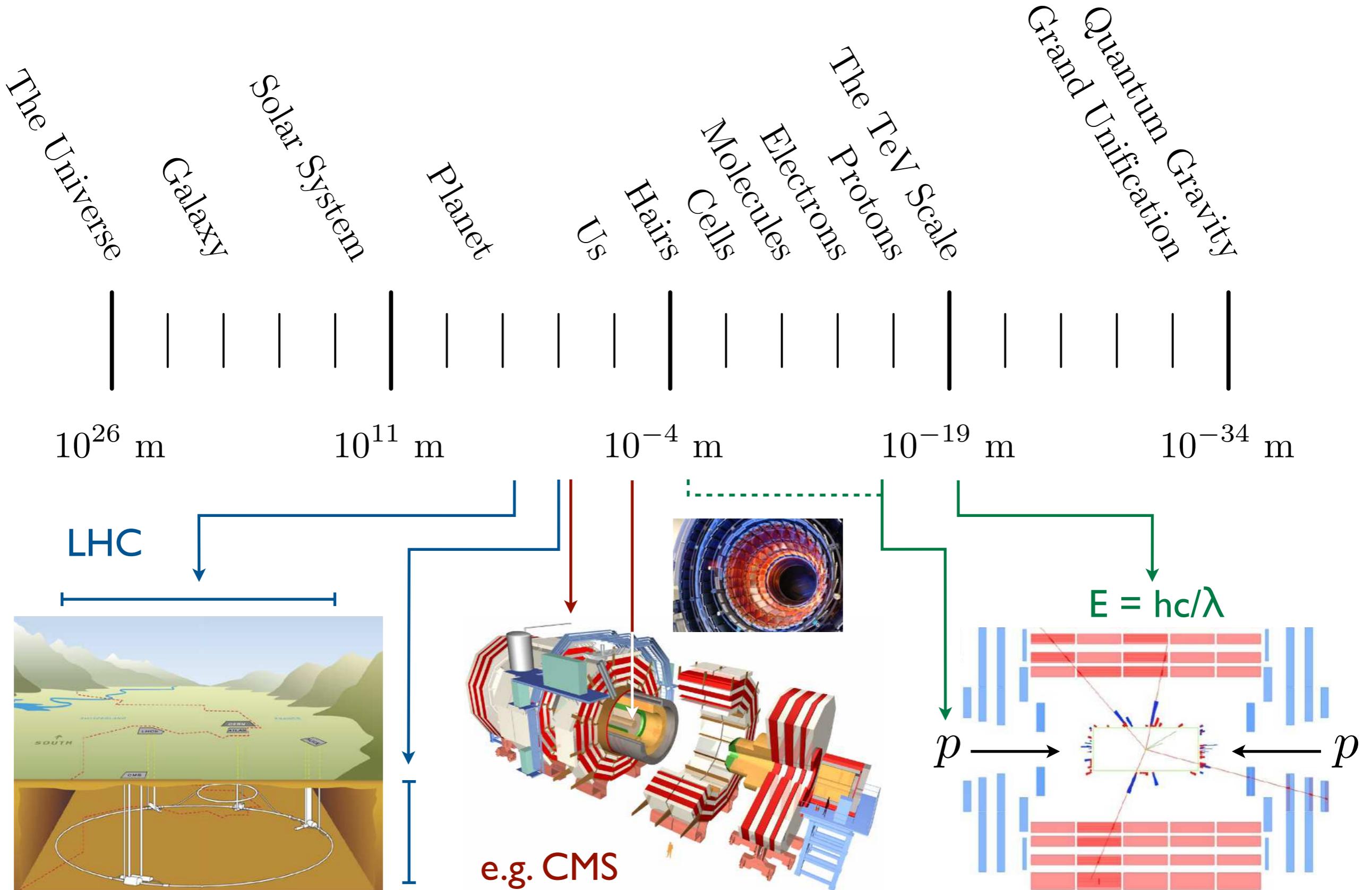
[Komiske, Metodiev, JDT, JHEP 2018;  
Brewer, JDT, Turner; arXiv 2020]

## Kinematic Decomposition via Graph Theory

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



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



## Mesons

$\pi^\pm \pi^0 \eta K^\pm K^0 \eta' D^\pm D^0 D_s^\pm \eta_c B^\pm B^0 B_s^0 \eta_b \dots$   
 $\rho^\pm \rho^0 \omega K^{*\pm} K^{*0} \phi D^{*\pm} D^{*0} D_s^{*\pm} J/\psi B^{*\pm} B^{*0} B_s^{*0} \Upsilon \dots$

## Baryons

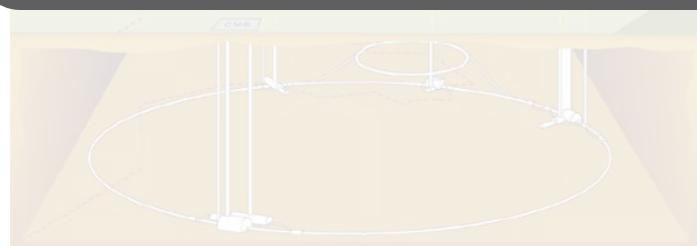
$p n \Lambda^0 \Sigma^+ \Sigma^0 \Sigma^- \Xi^0 \Xi^- \dots$   
 $\Delta^{++} \Delta^+ \Delta^0 \Delta^- \Sigma^{*+} \Sigma^{*0} \Sigma^{*-} \Xi^{*0} \Xi^{*-} \Omega^- \dots$

## Tetraquarks

$X(3872) Y(4260) Z(4430) \dots$

## Pentaquarks

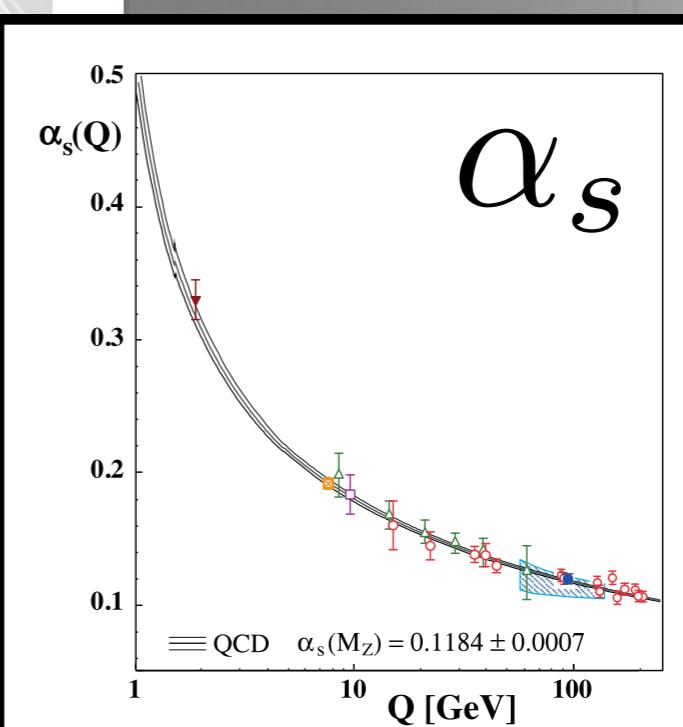
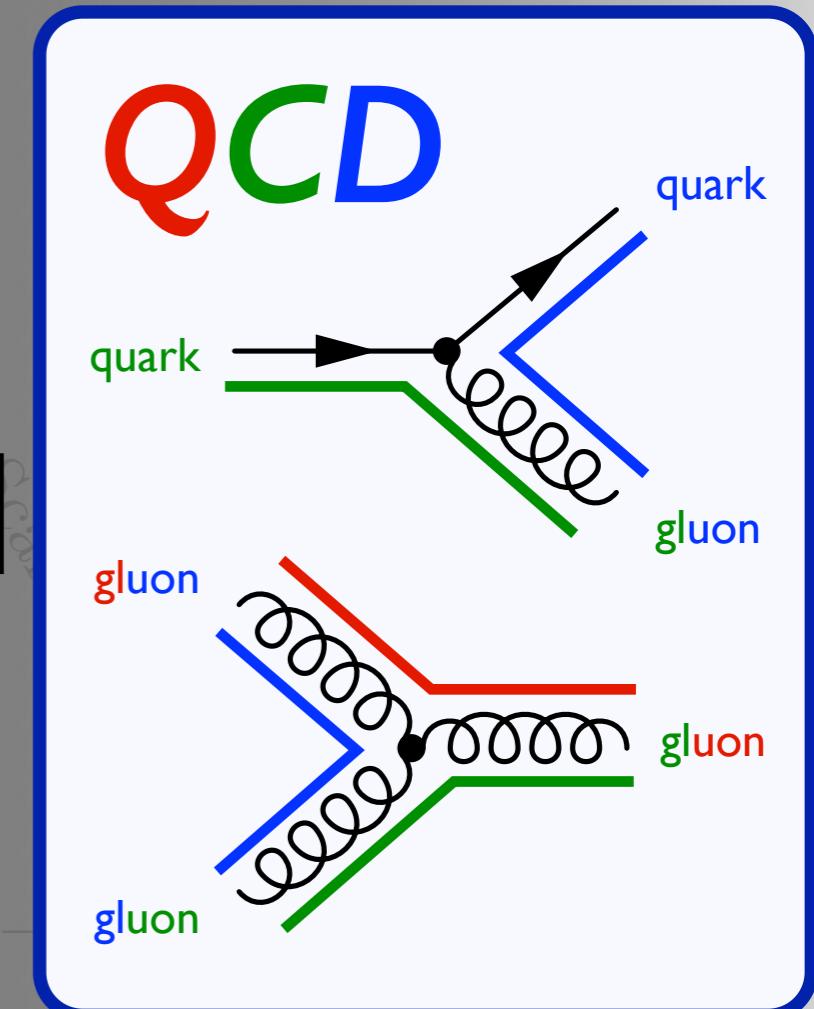
$P_c^+(4450) \dots$



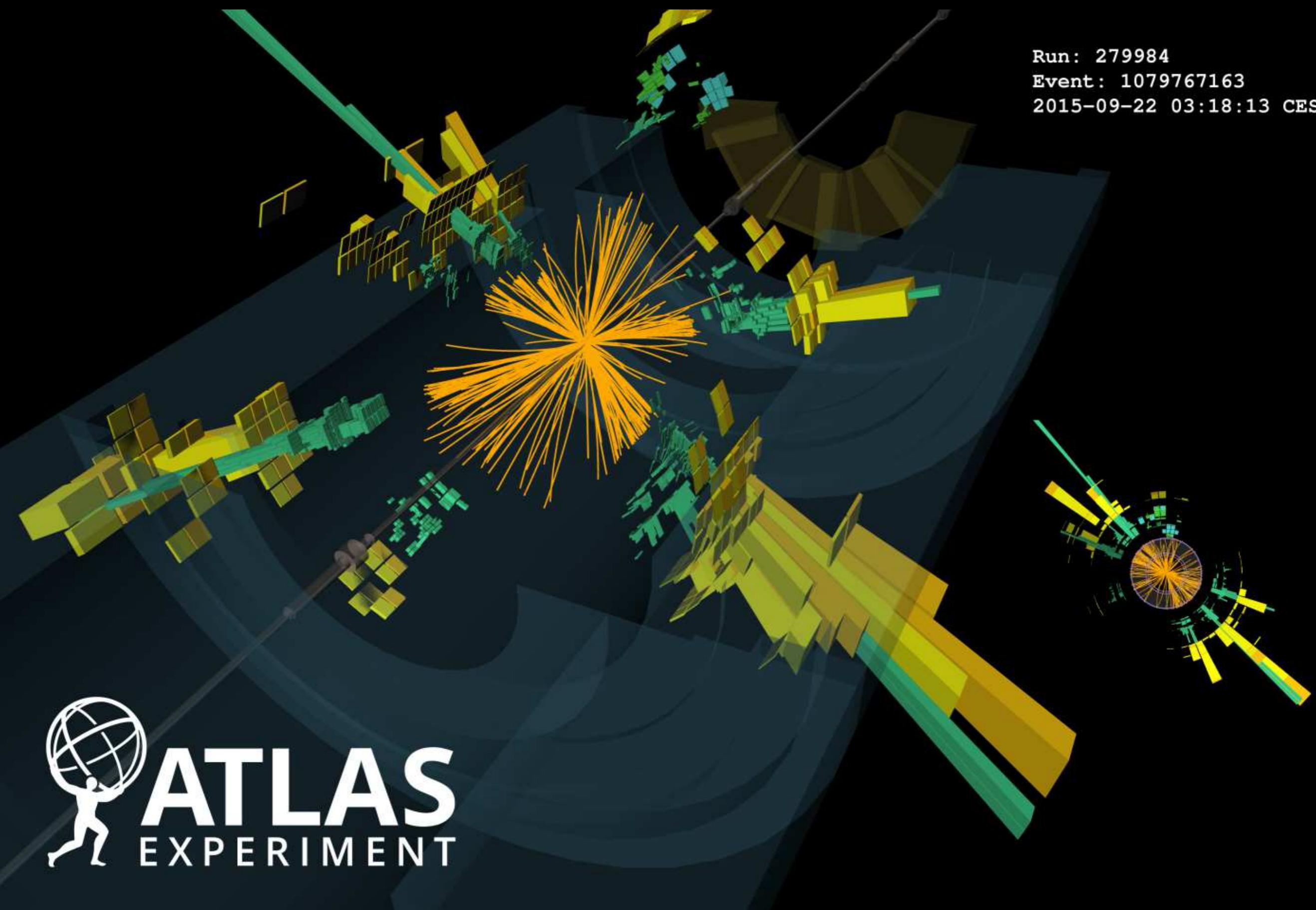
|

e.g. CMS

Jets

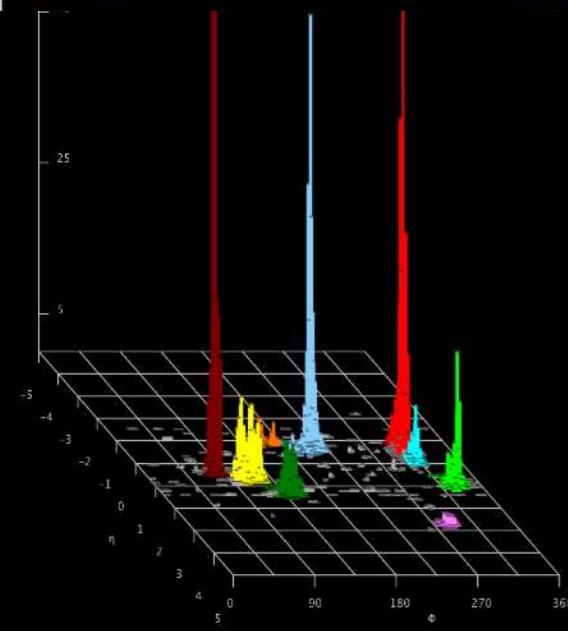
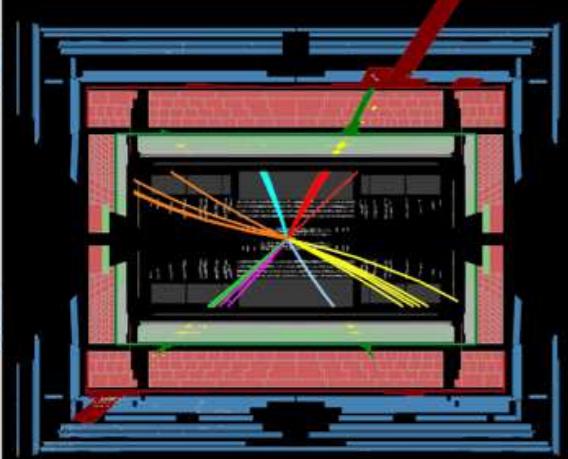


Run: 279984  
Event: 1079767163  
2015-09-22 03:18:13 CEST

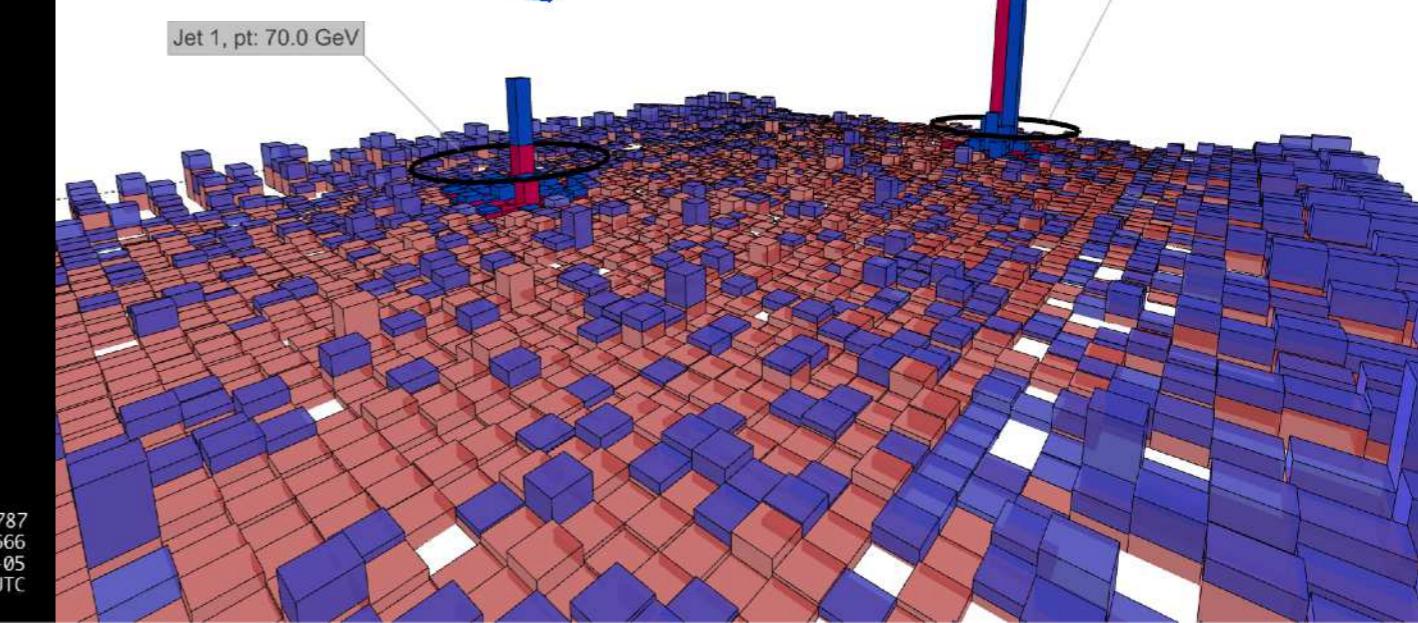
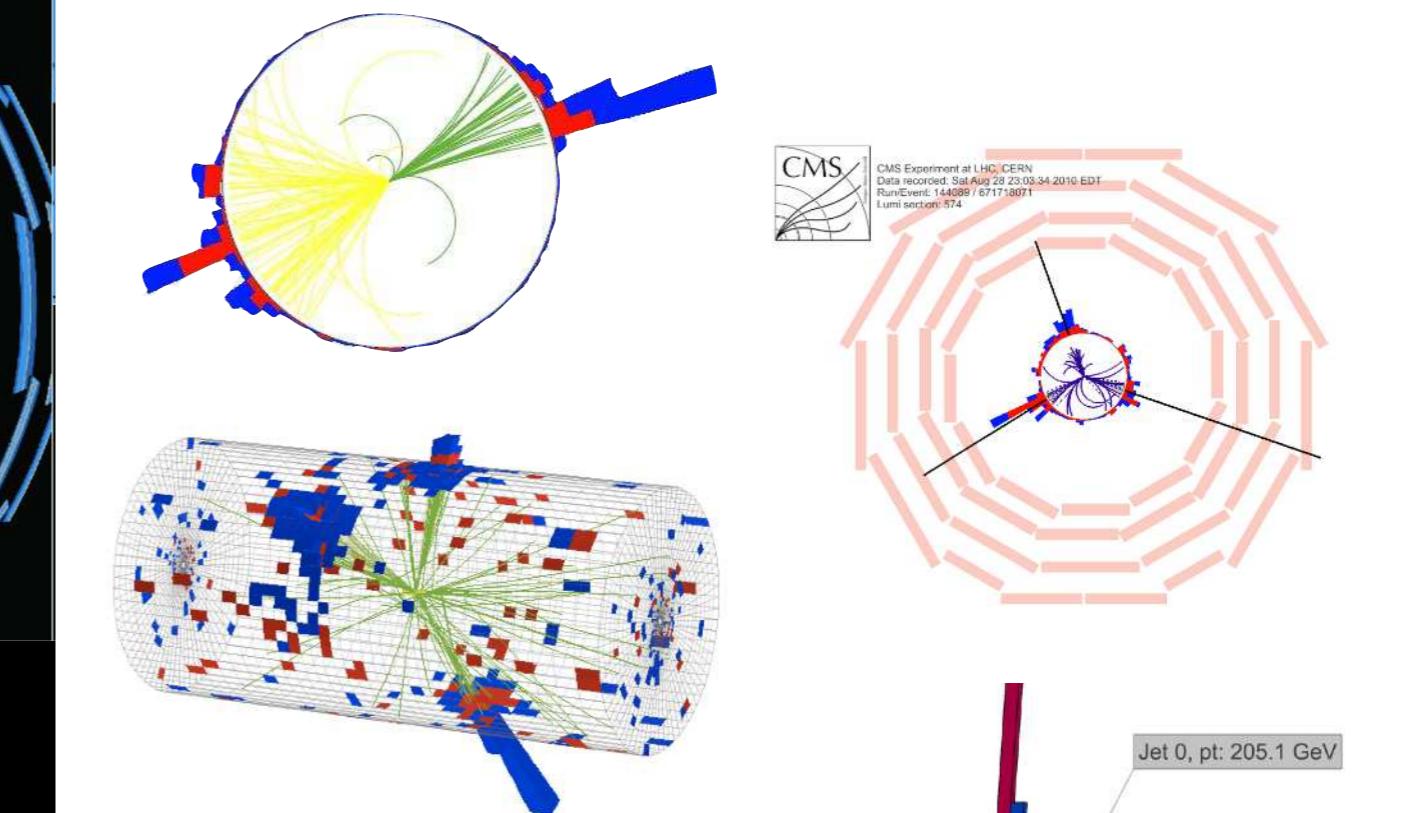
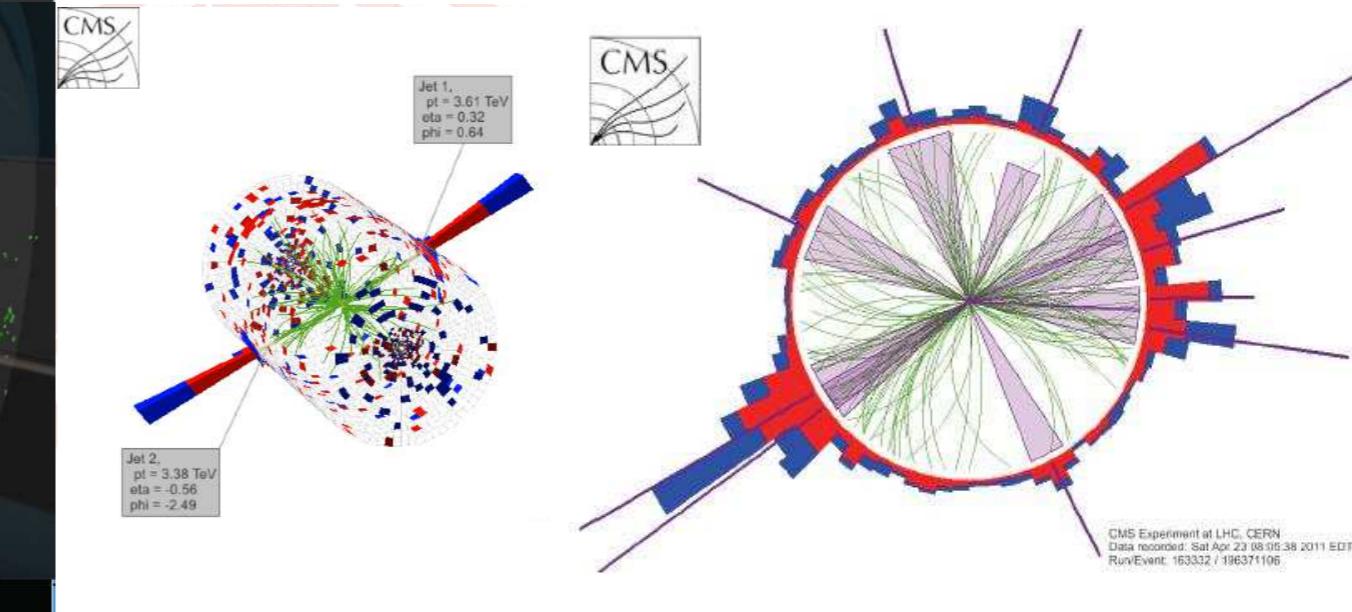
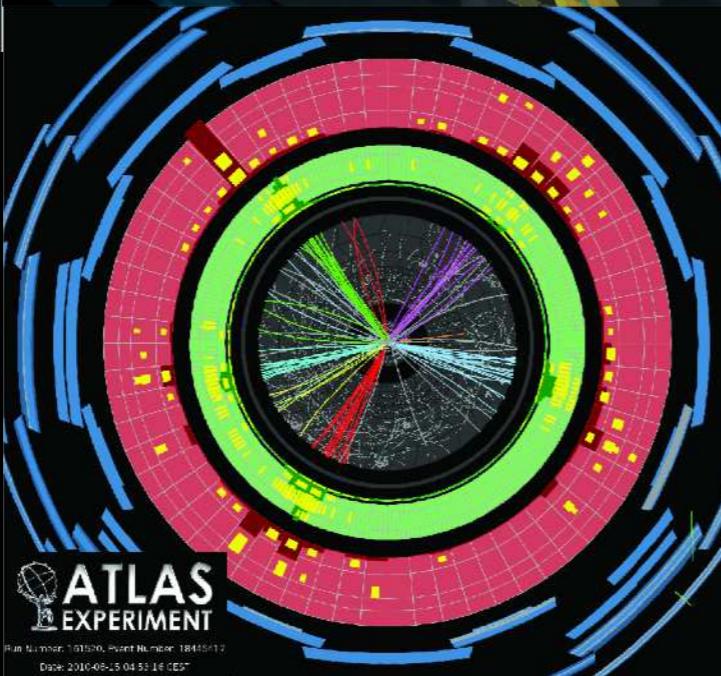
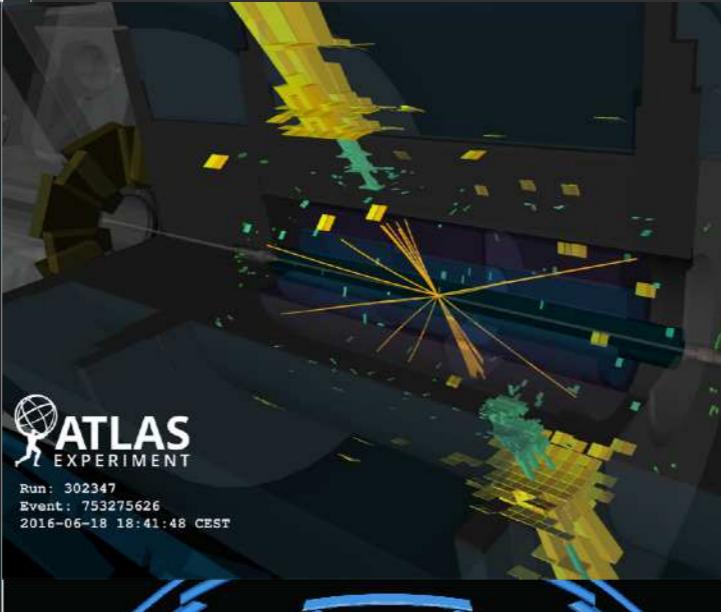
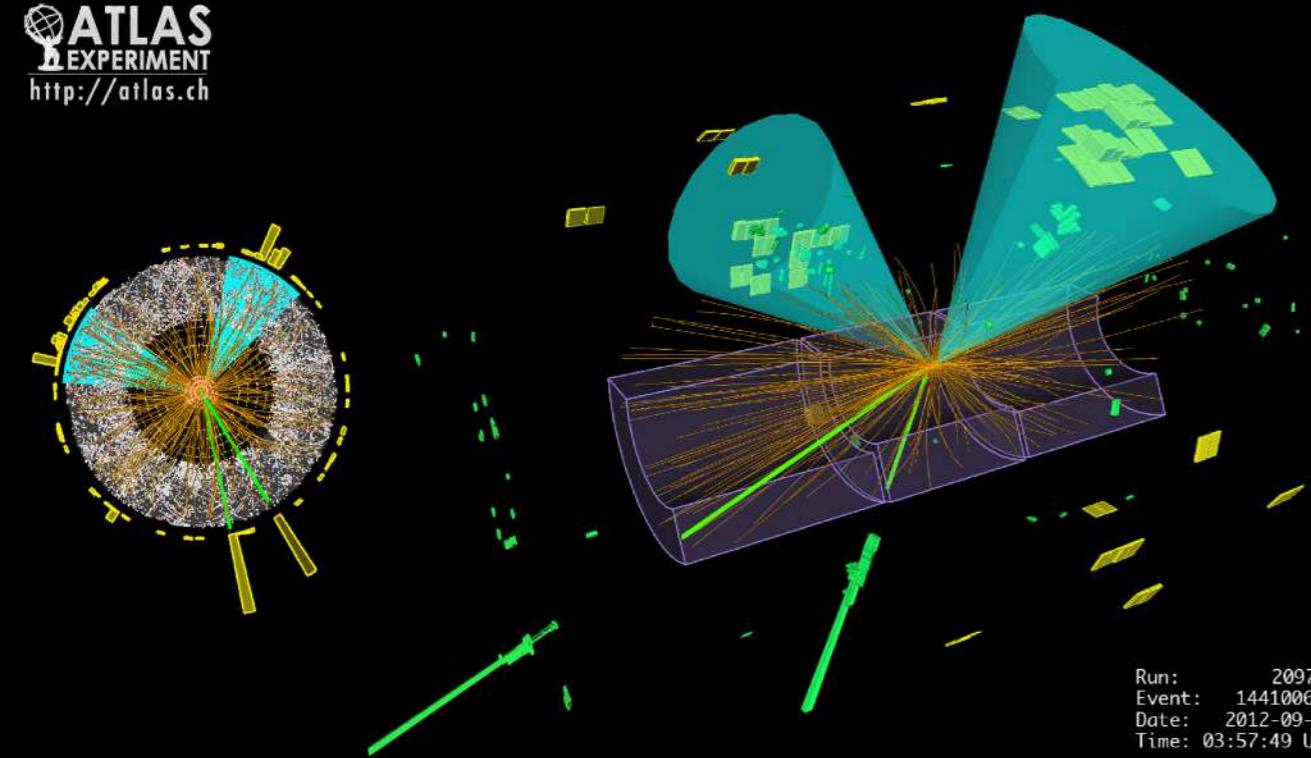


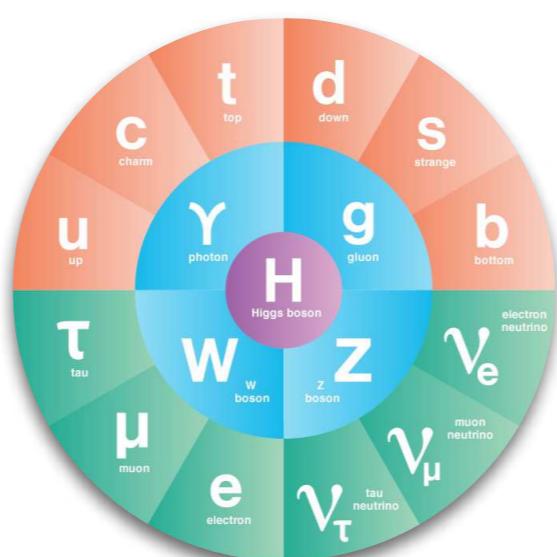
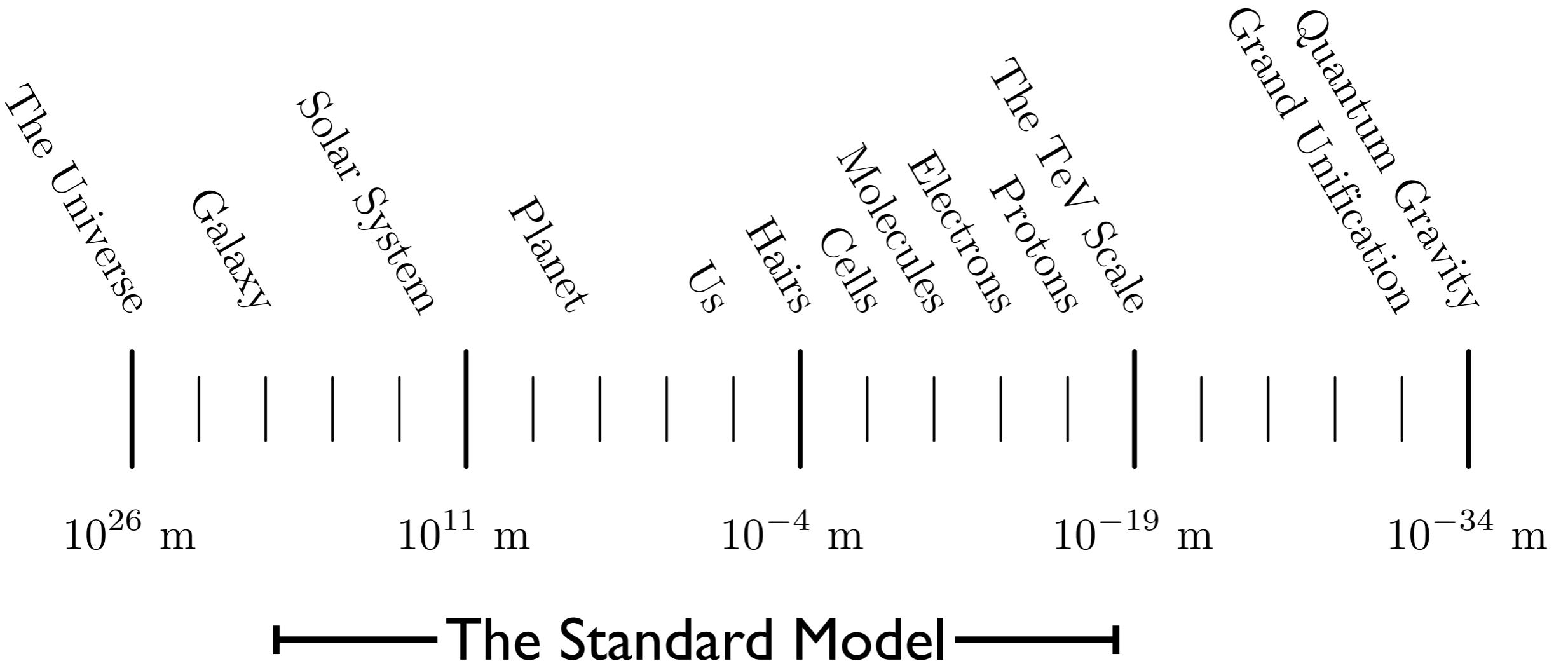
Run Number: 159224, Event Number: 3533152

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



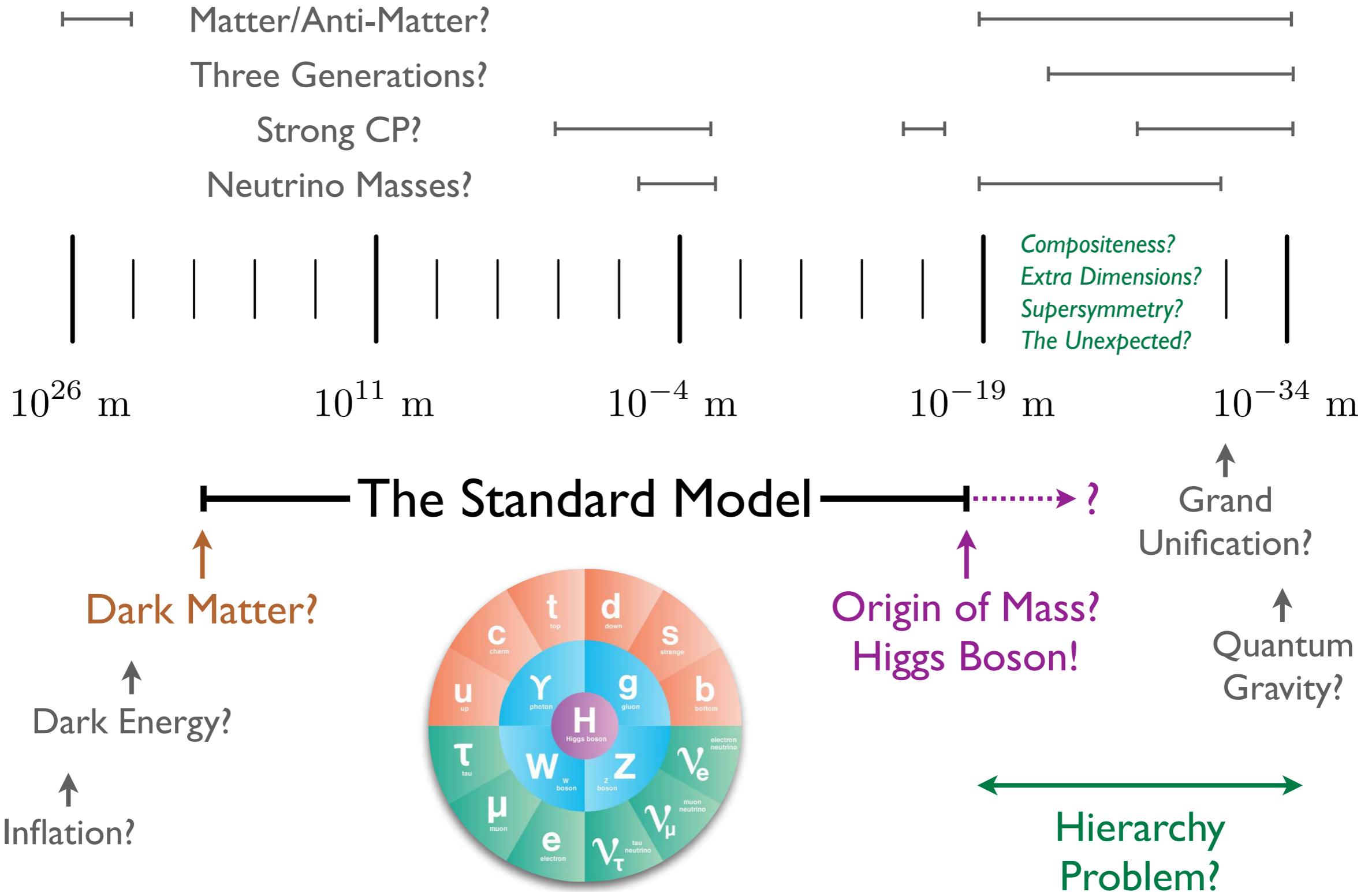
**ATLAS**  
EXPERIMENT  
<http://atlas.ch>

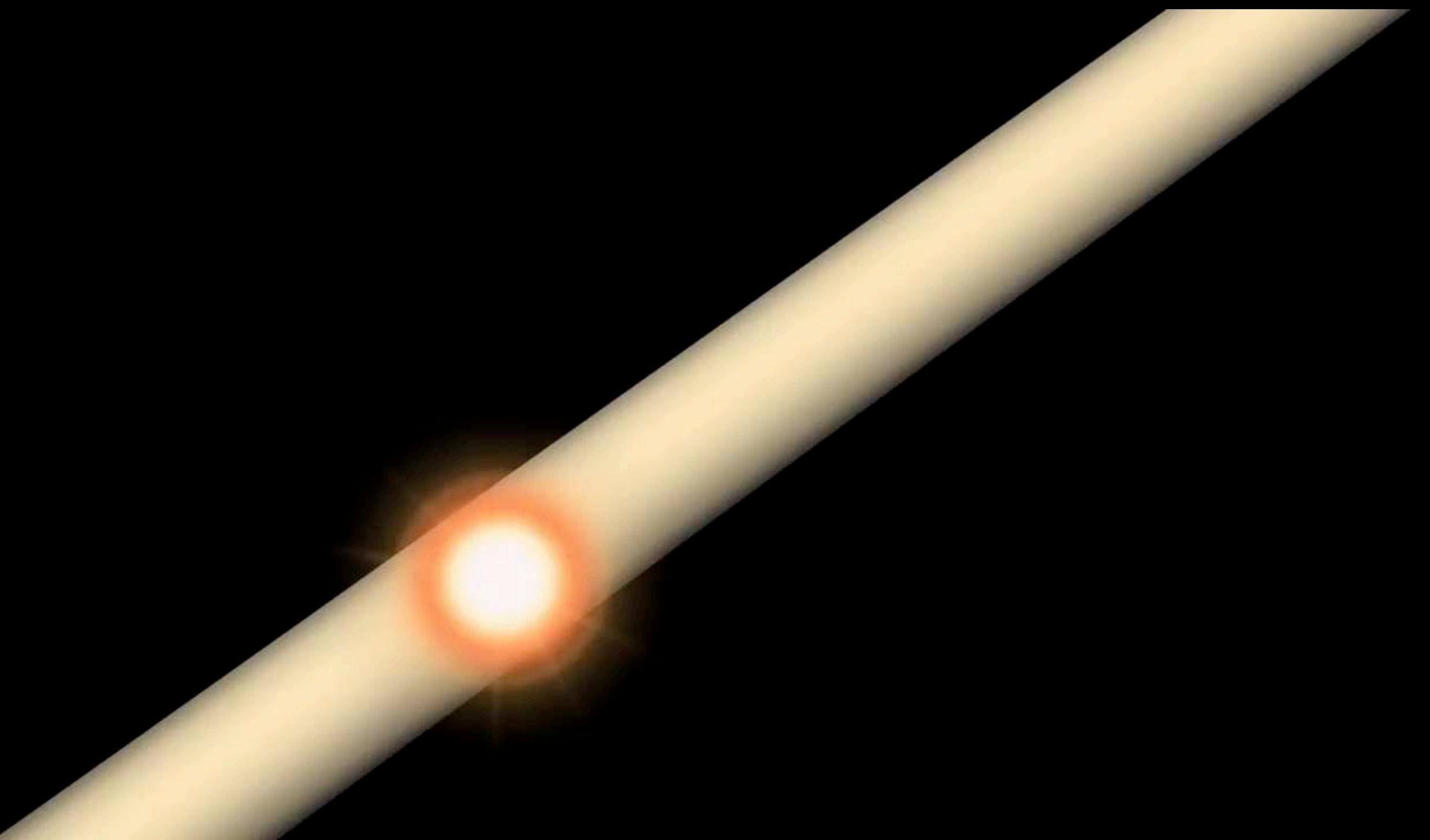




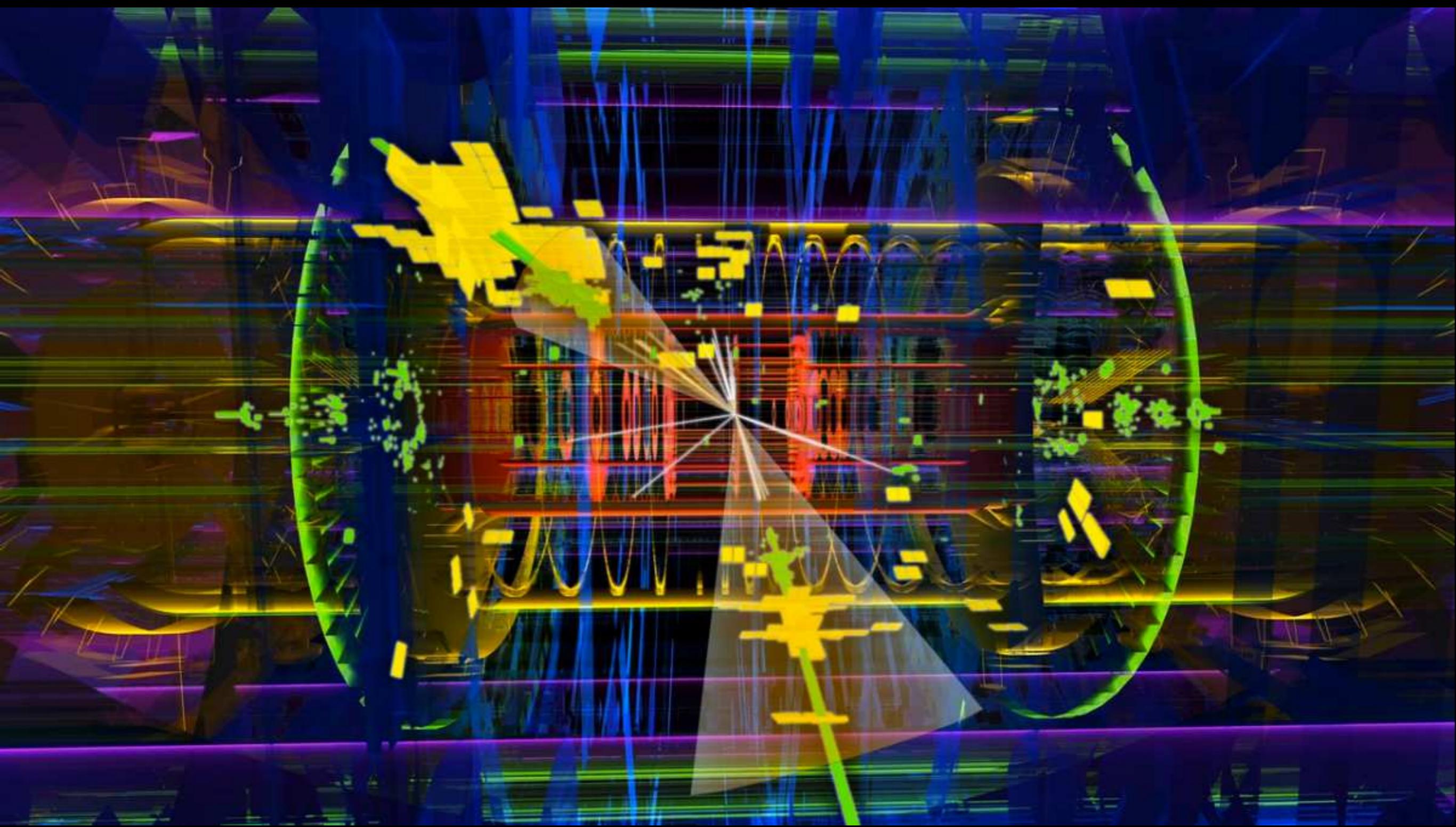
# Puzzles in Particle Physics

SnowMass2021





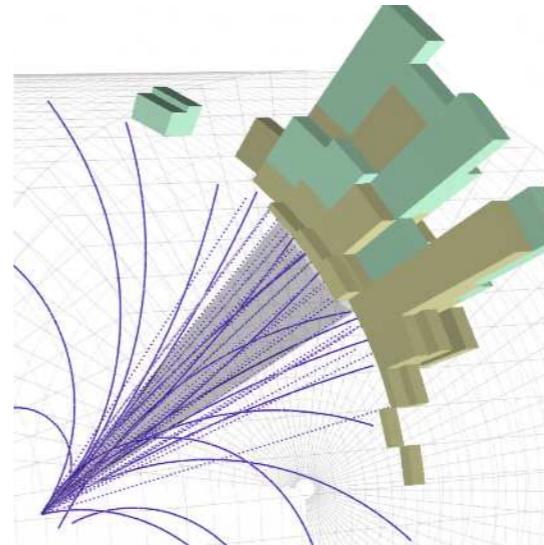




# Cartoon of Machine Learning

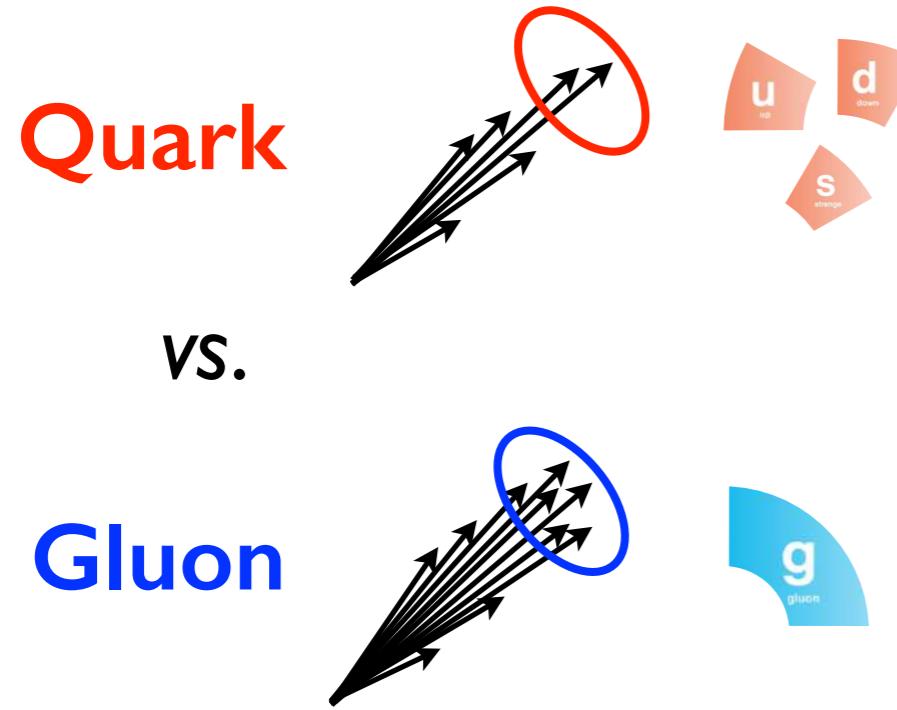
“ML4Jets”  
NYU, January 2020

For this talk:  $\mathcal{J}$  = jet

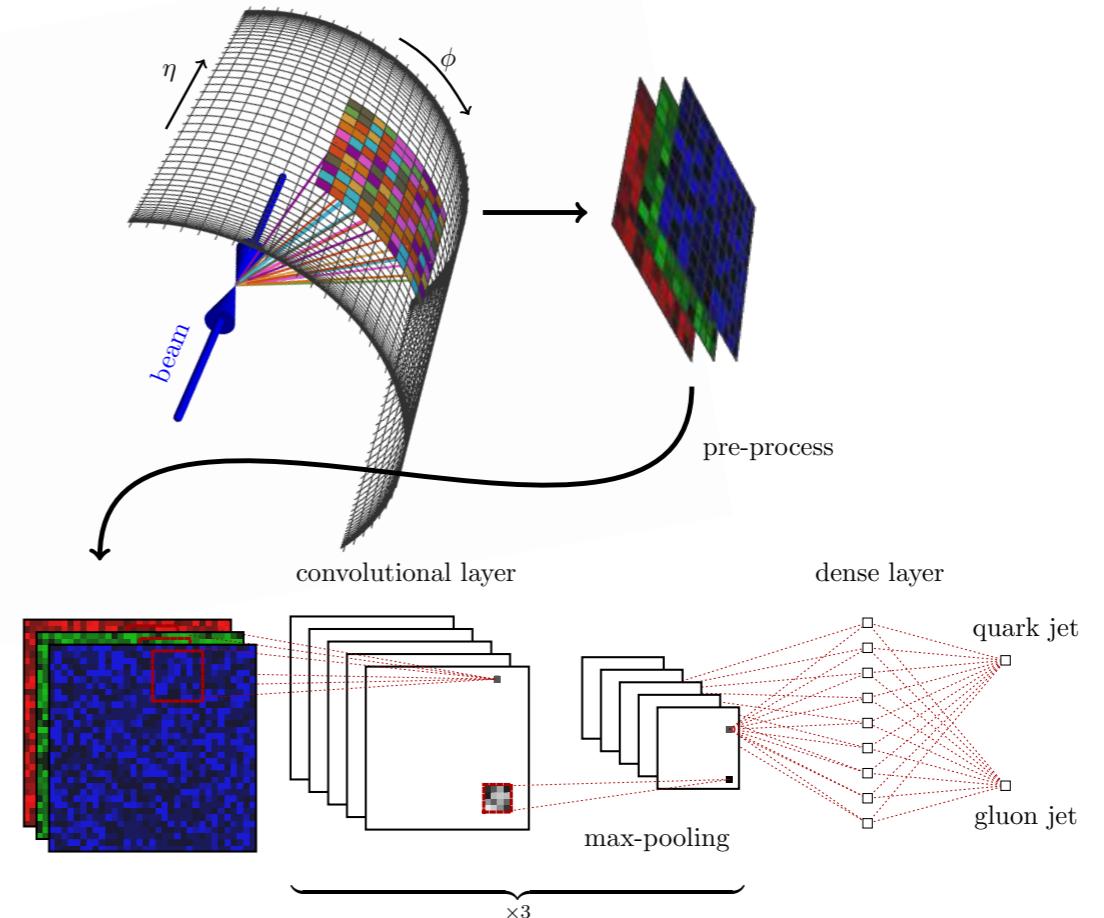


# From Curmudgeon...

*Jet classification via image recognition*



Multi-channel convolutional neural networks



[e.g. Komiske, Metodiev, Schwartz, [JHEP 2017](#);  
cf. Gras, Höche, Kar, Larkoski, Lönnblad, Plätzer, Siódak, Skands, Soyez, [JHEP 2017](#)]



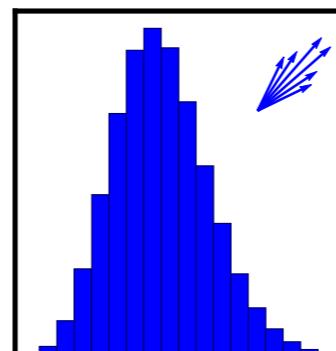
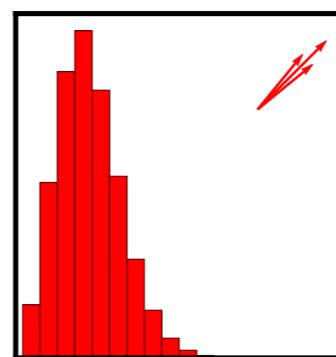
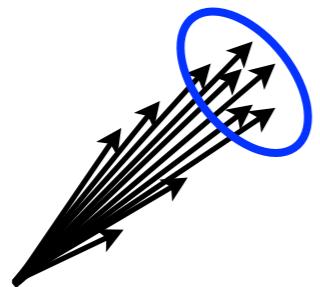
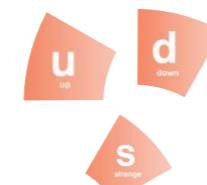
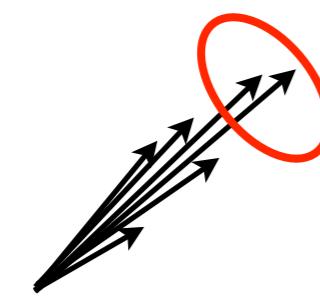
# ...to Evangelist

*Jet flavor definitions via natural language processing*

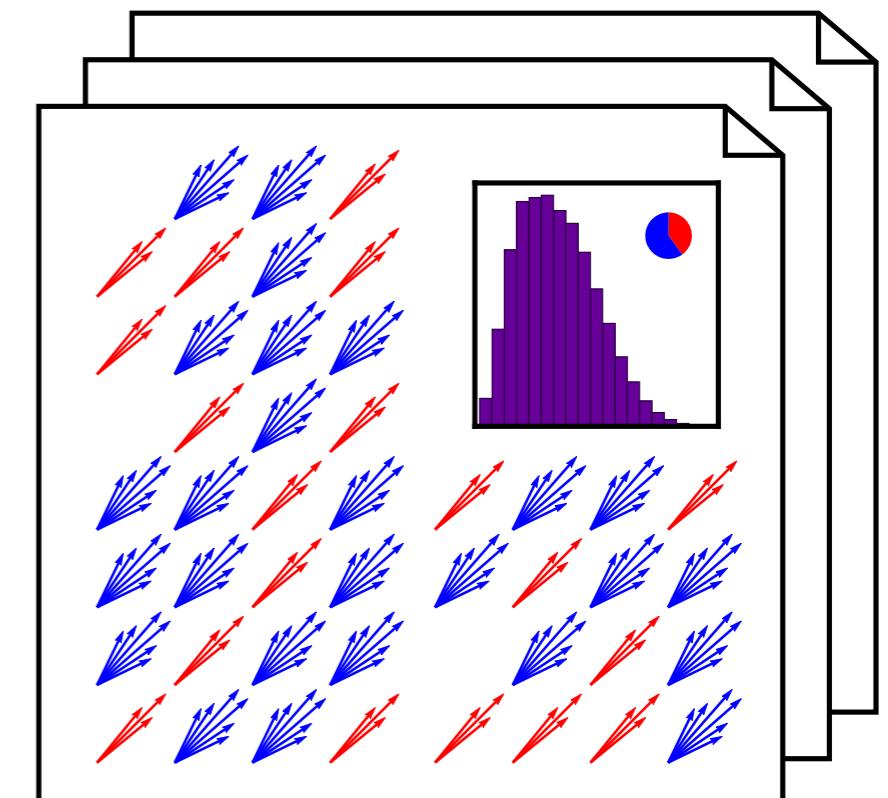
Quark

vs.

Gluon



Topic Modeling / Blind Source Separation



[Komiske, Metodiev, JDT, [JHEP 2018](#);  
using Metodiev, Nachman, JDT, [JHEP 2017](#); Metodiev, JDT, [PRL 2018](#); Komiske, Metodiev, JDT, [JHEP 2019](#)]



# Principles of Fundamental Physics

*Robustness of Energy Flow*

[Komiske, Metodiev, JDT, JHEP 2018]



Patrick Komiske



Eric Metodiev



SF



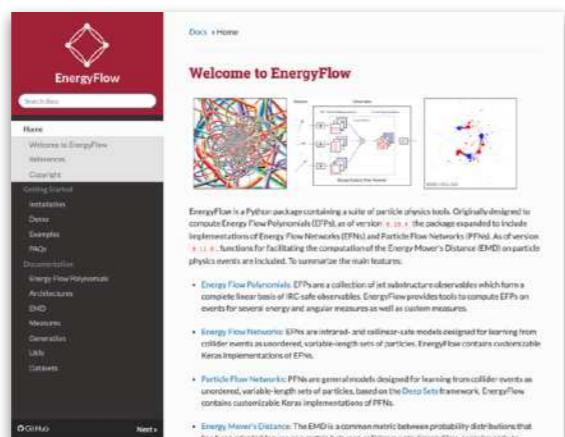
**Power of Artificial Intelligence**

*Point Cloud Learning*

[Zaheer, Kottur, Ravanbakhsh, Poczos, Salakhutdinov, Smola, NIPS 2017]

# Energy Flow Networks

<https://energyflow.network/>  
[Komiske, Metodiev, JDT, JHEP 2019]



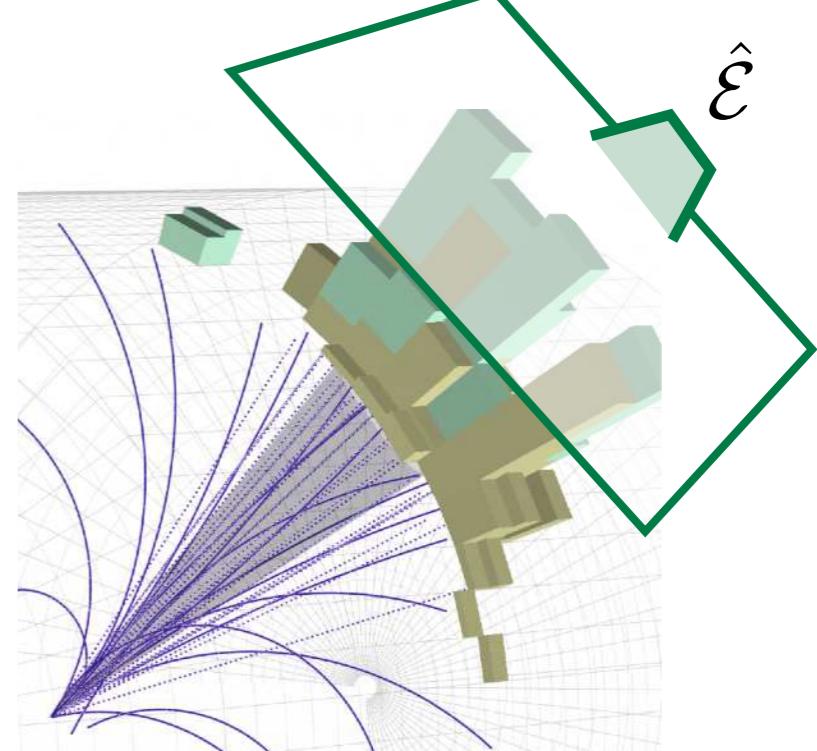
# Jets as Weighted Point Clouds

- Energy-Weighted Directions

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

↑      |  
Energy      Direction

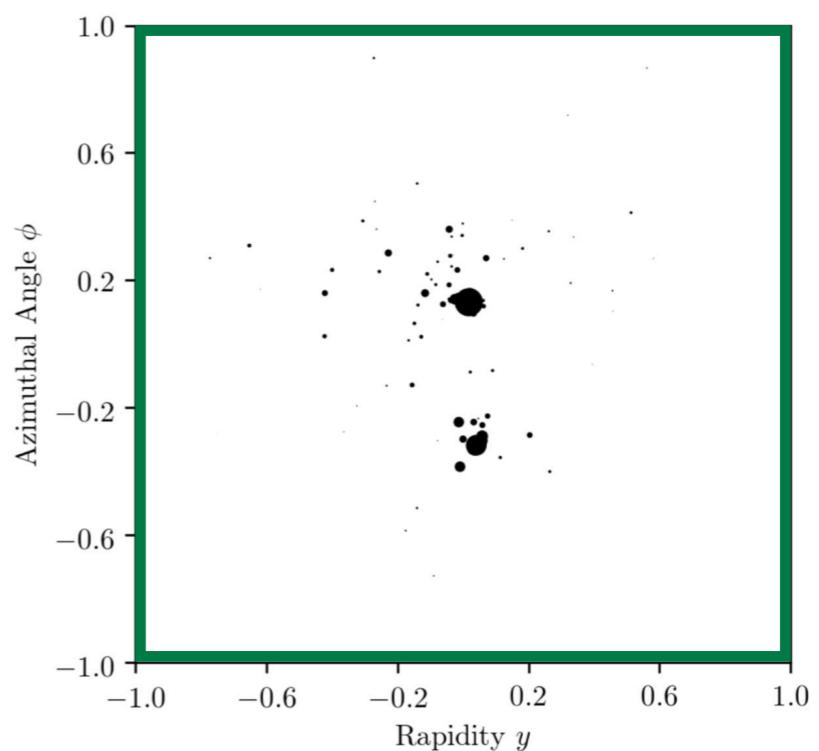
(suppressing “unsafe” charge/flavor information)



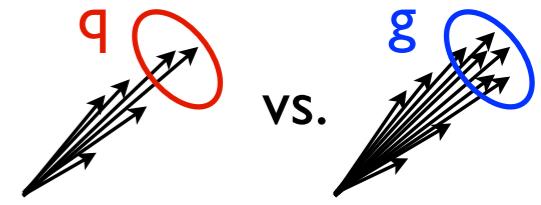
- Equivalently: Energy Density

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

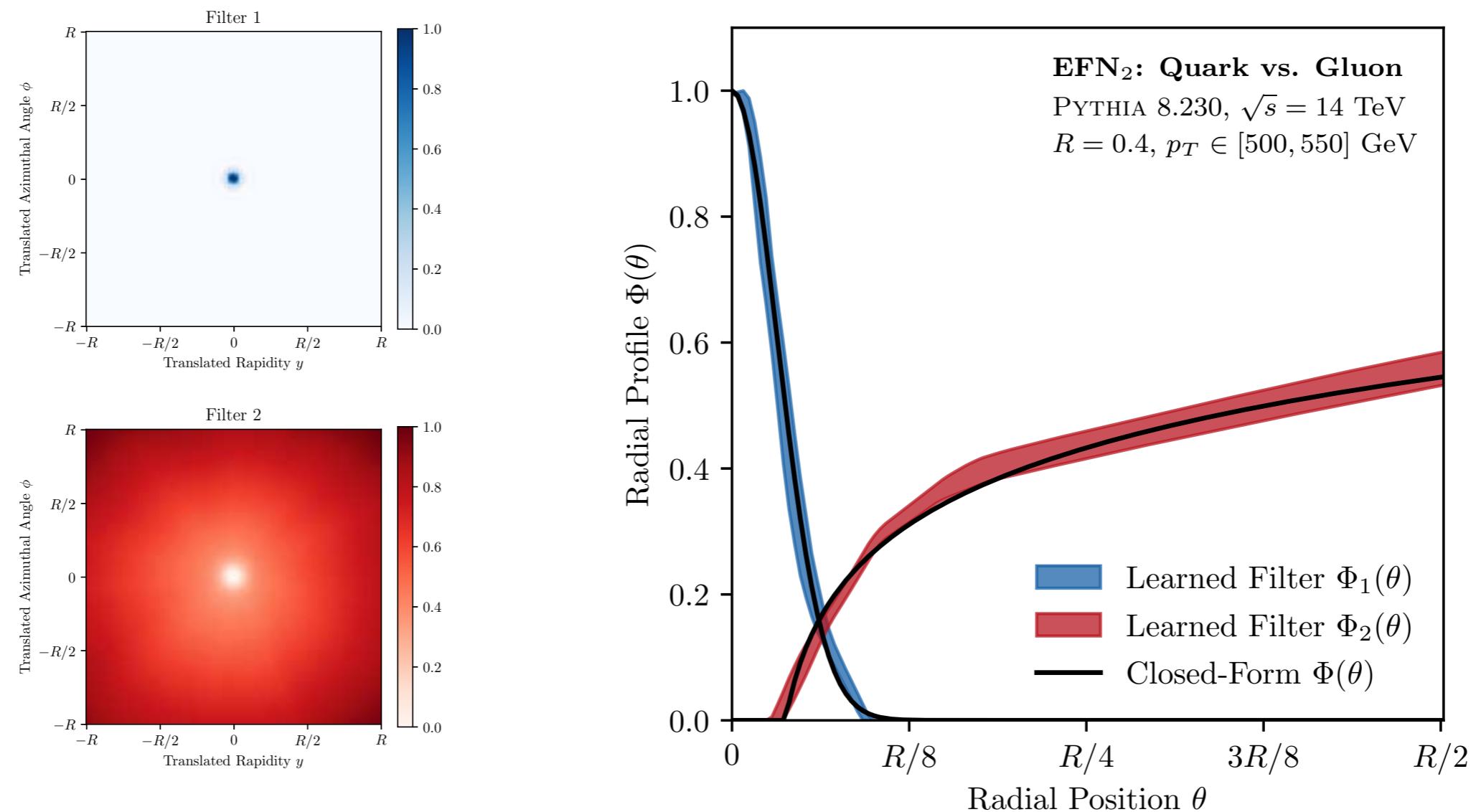
↑      ↑  
Energy      Direction



# Learning from the Machine



For  $\ell = 2$  EFN, radial moments:  $\sum_{i \in \text{jet}} z_i f(\theta_i)$  cf. Angularities:  
 $f(\theta) = \theta^\beta$



[Komiske, Metodiev, JDT, JHEP 2019;  
cf. Larkoski, JDT, Waalewijn, JHEP 2014; using Berger, Kucs, Sterman, PRD 2003; Ellis, Vermilion, Walsh, Hornig, Lee, JHEP 2010]

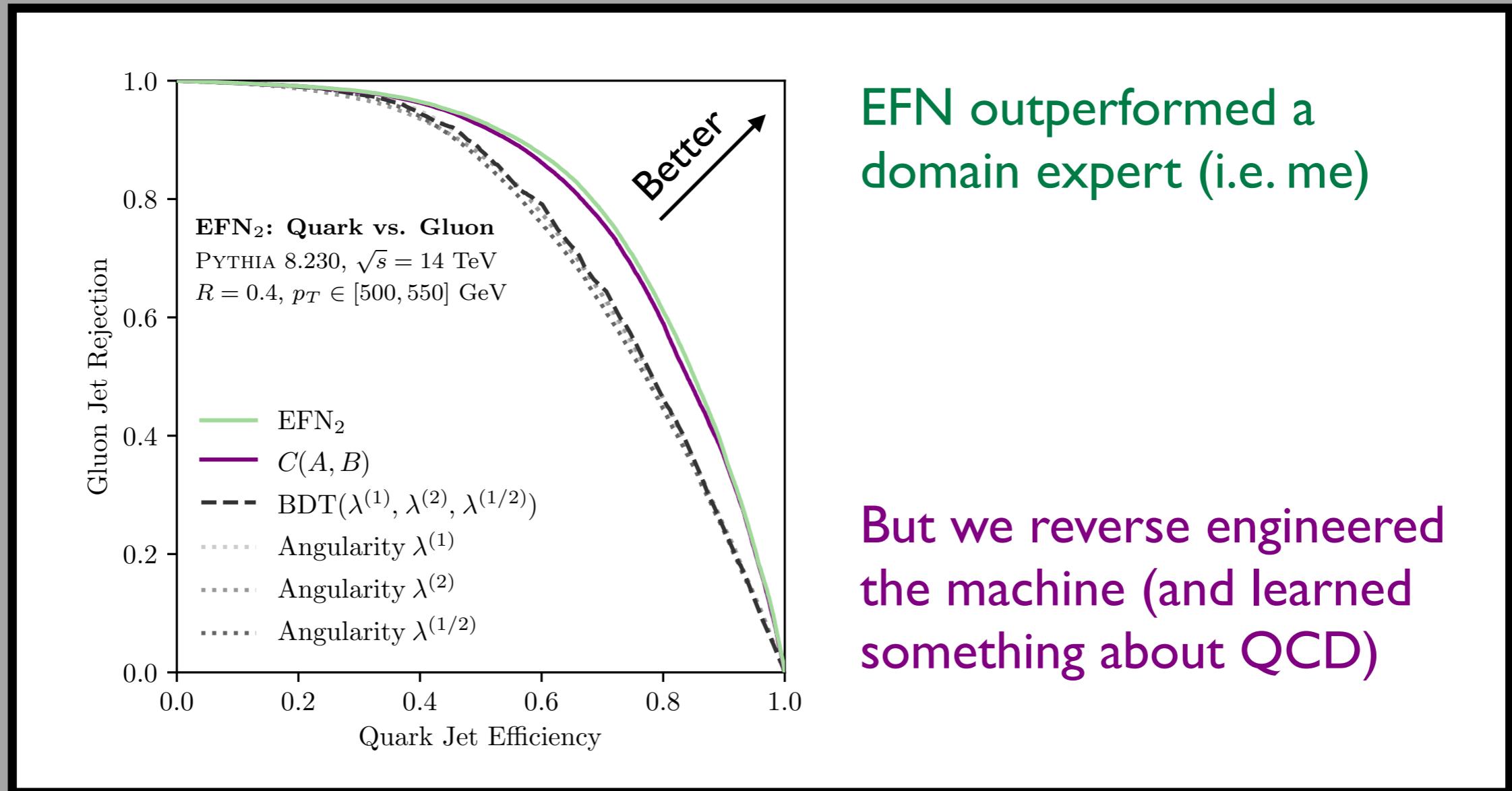
# Learning from the Machine



For  $\ell = 2$  EFN, radial moments:

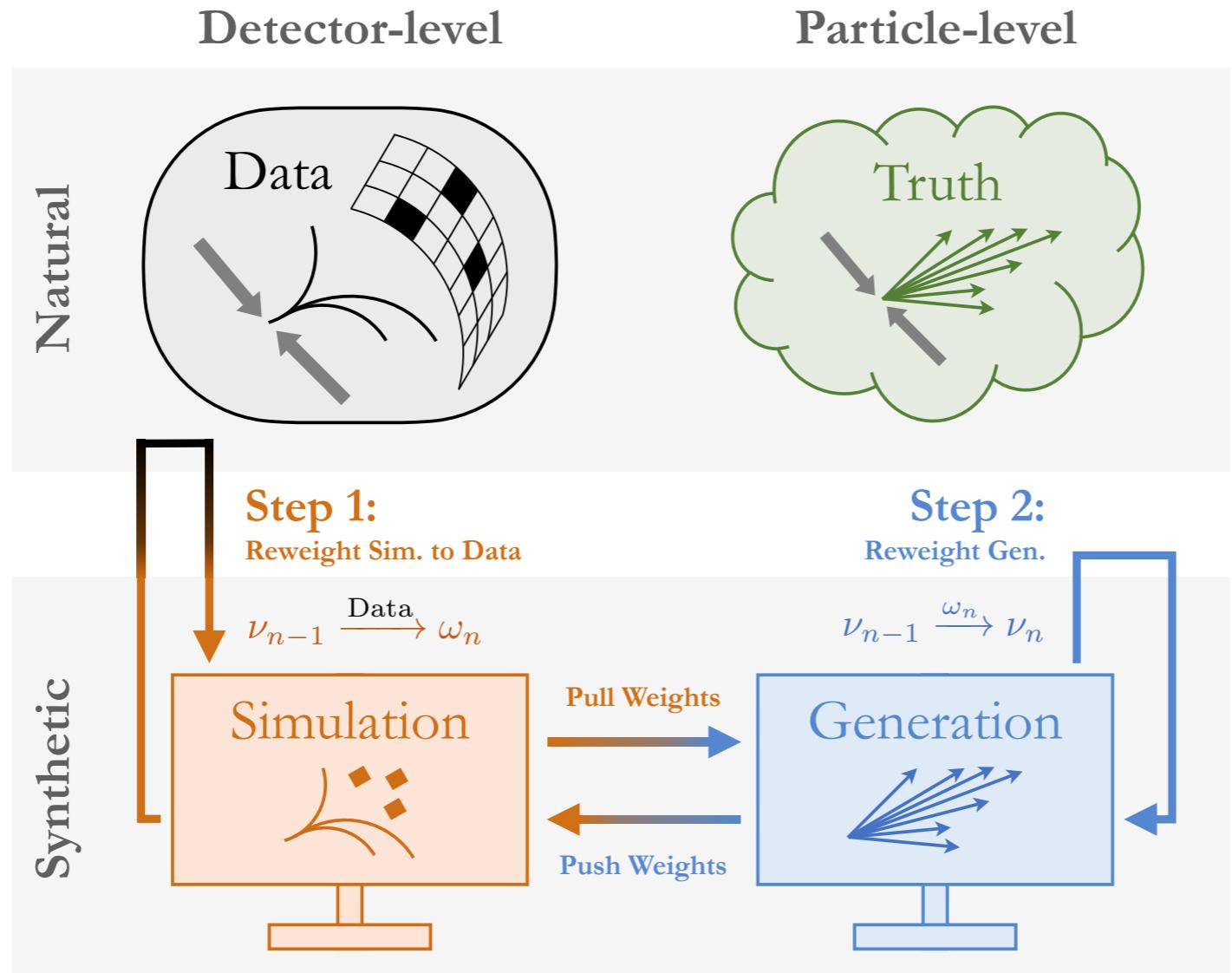
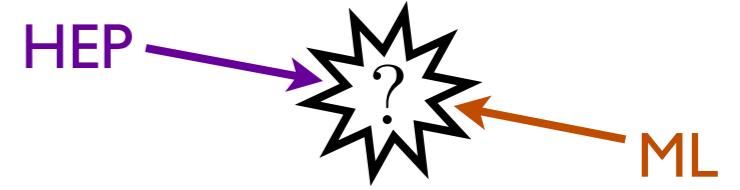
$$\sum_{i \in \text{jet}} z_i f(\theta_i)$$

cf. Angularities:  
 $f(\theta) = \theta^\beta$



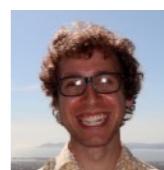
[Komiske, Metodiev, JDT, [JHEP 2019](#);  
cf. Larkoski, JDT, Waalewijn, [JHEP 2014](#); using Berger, Kucs, Sterman, [PRD 2003](#); Ellis, Vermilion, Walsh, Hornig, Lee, [JHEP 2010](#)]

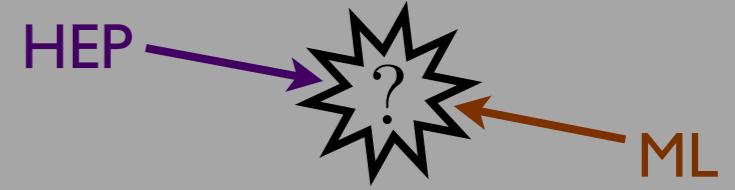
# OmniFold



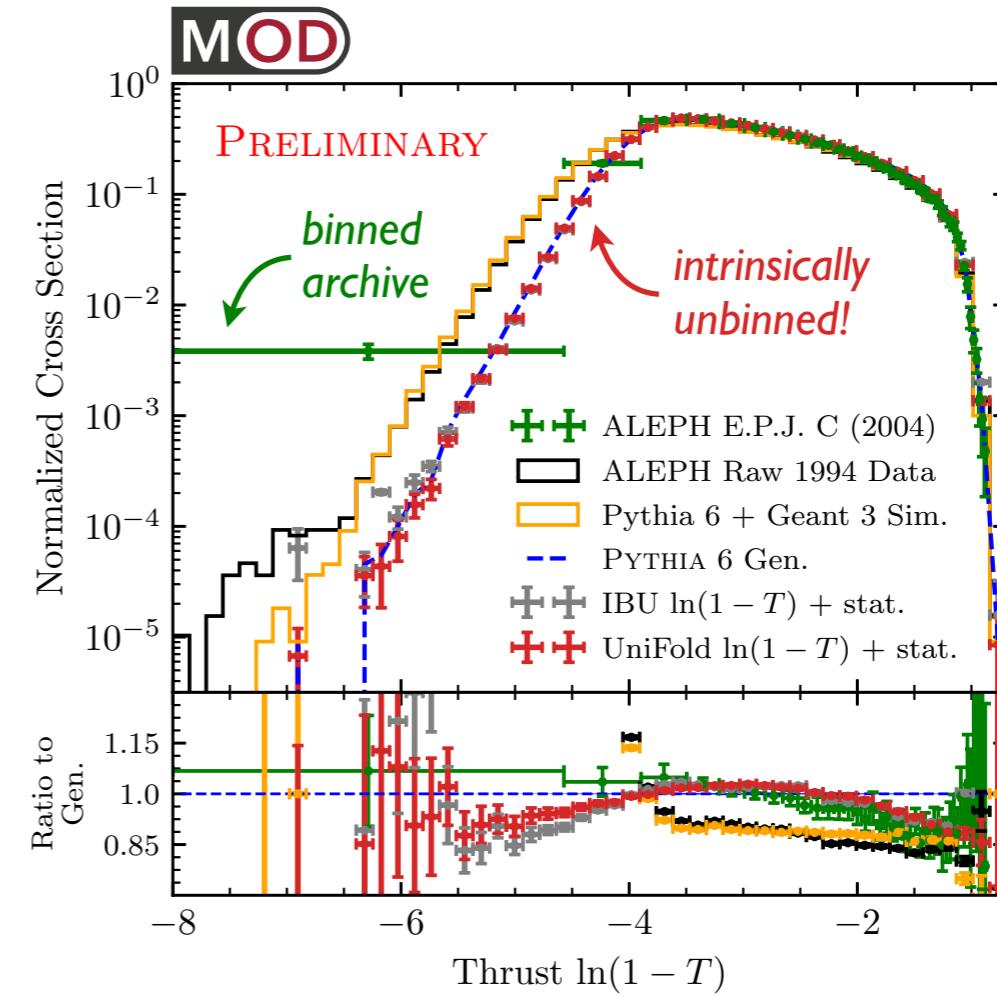
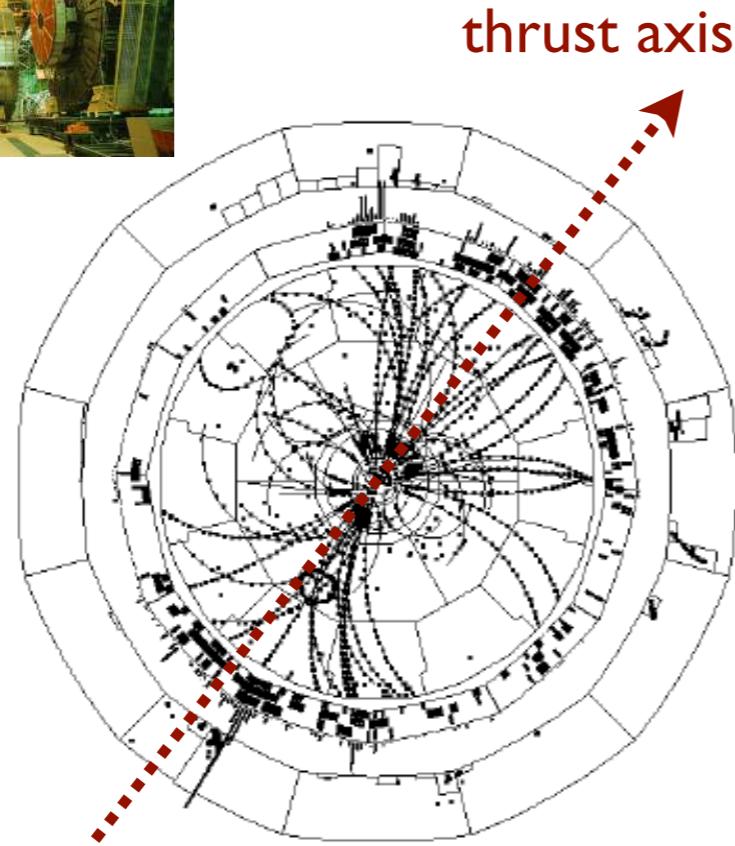
*Multi-dimensional unbinned detector corrections via iterated binary classification*

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

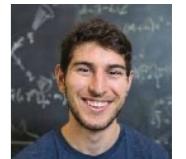




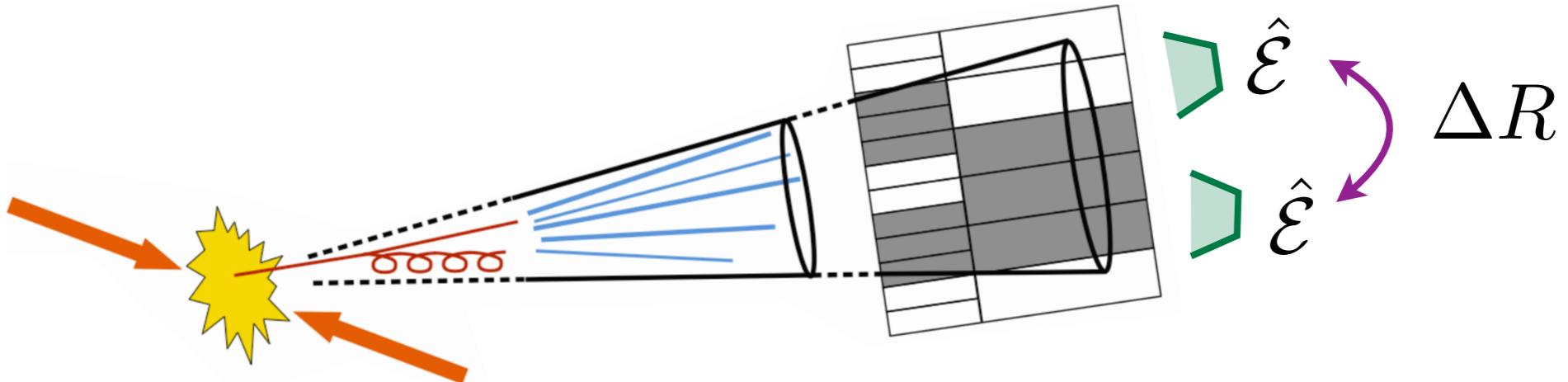
## Back to the Future with ALEPH Archival Data



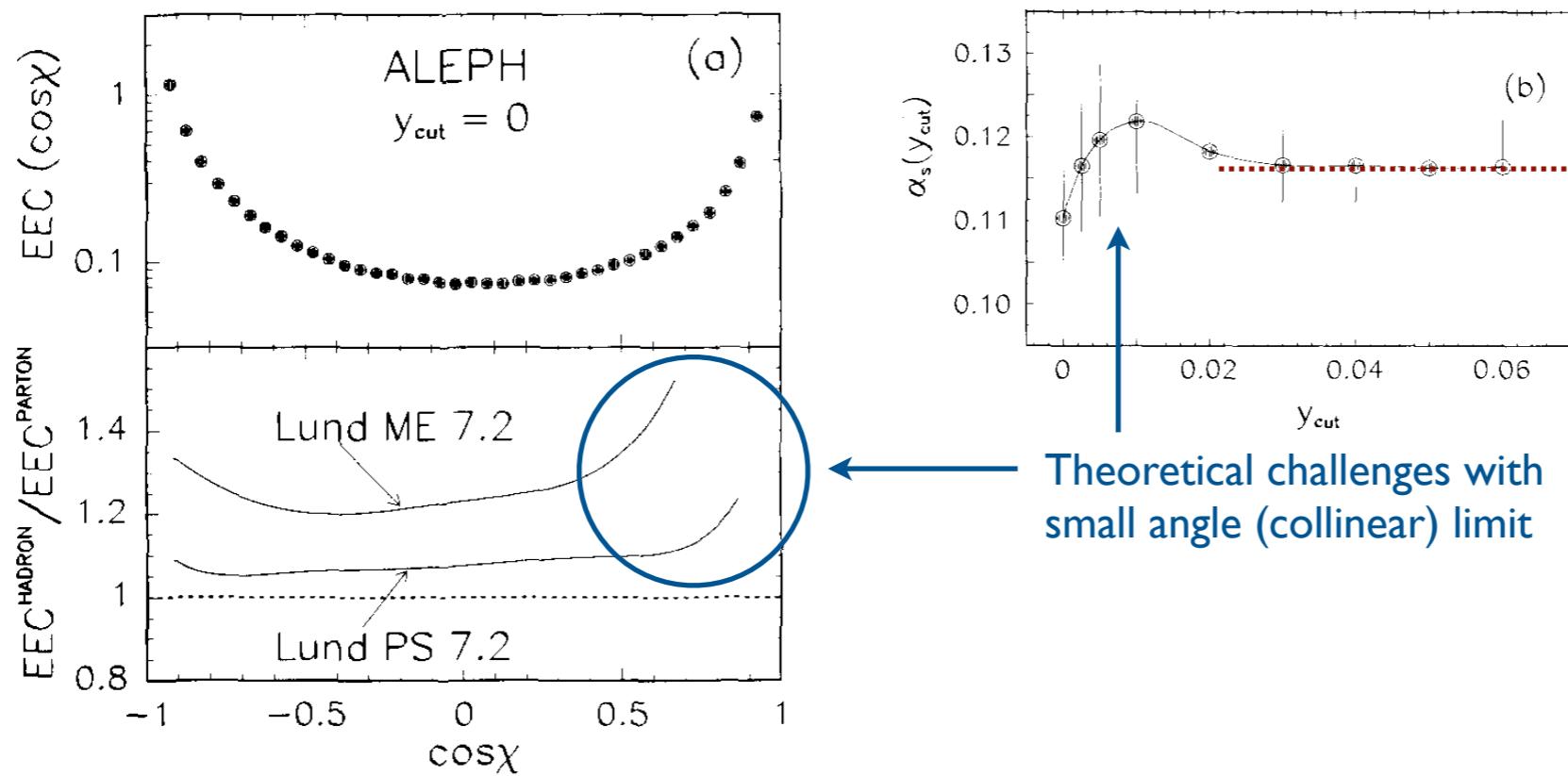
[talk by Badea, [ICHEP 2020](#); cf. ALEPH, [EPJC 2004](#)  
 [see also Badea, Baty, Chang, Innocenti, Maggi, McGinn, Peters, Sheng, JDT, Lee, [PRL 2019](#)]



# Energy-Energy Correlators

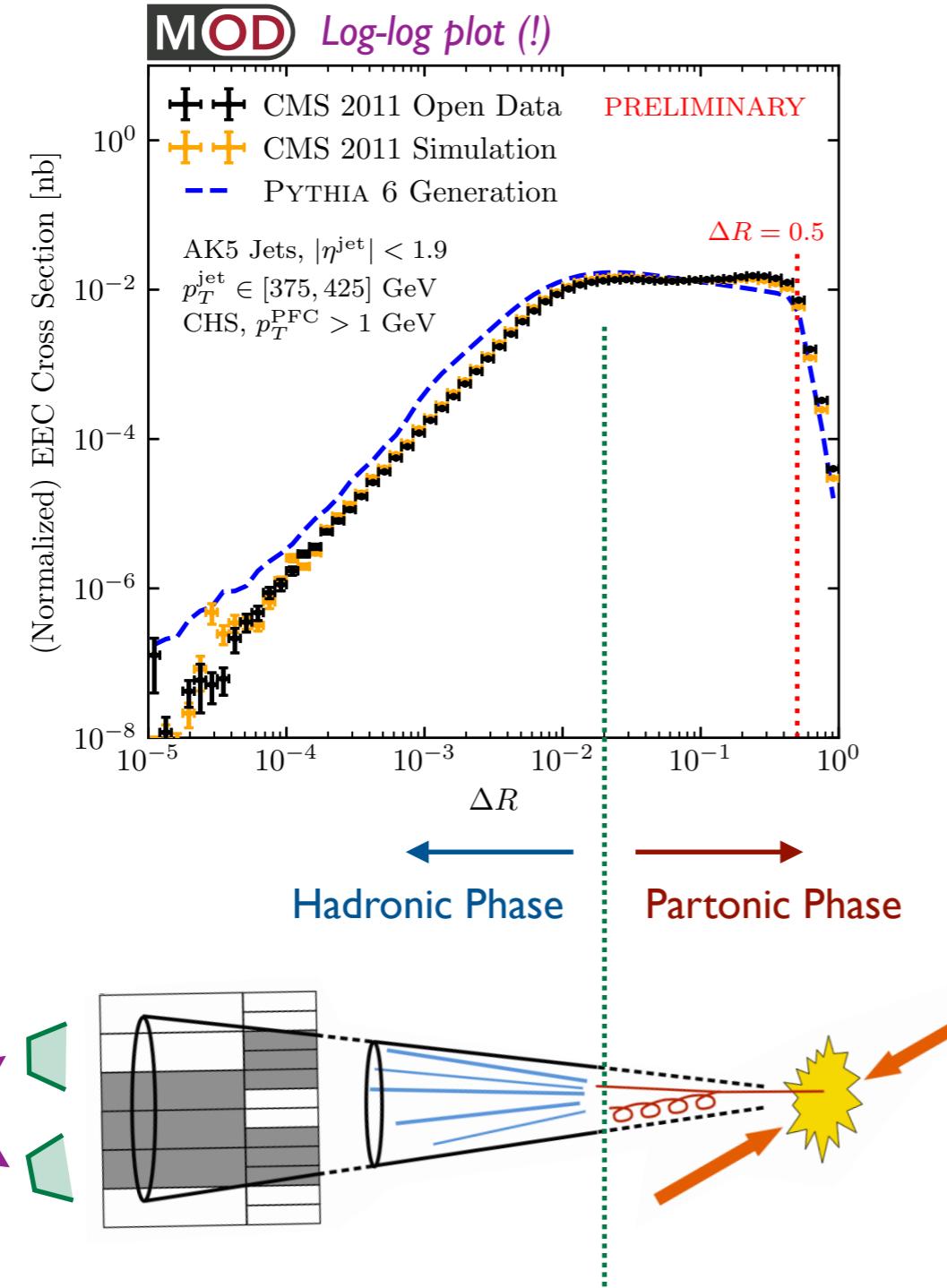


A long history in probing collinear dynamics of QCD



[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...)

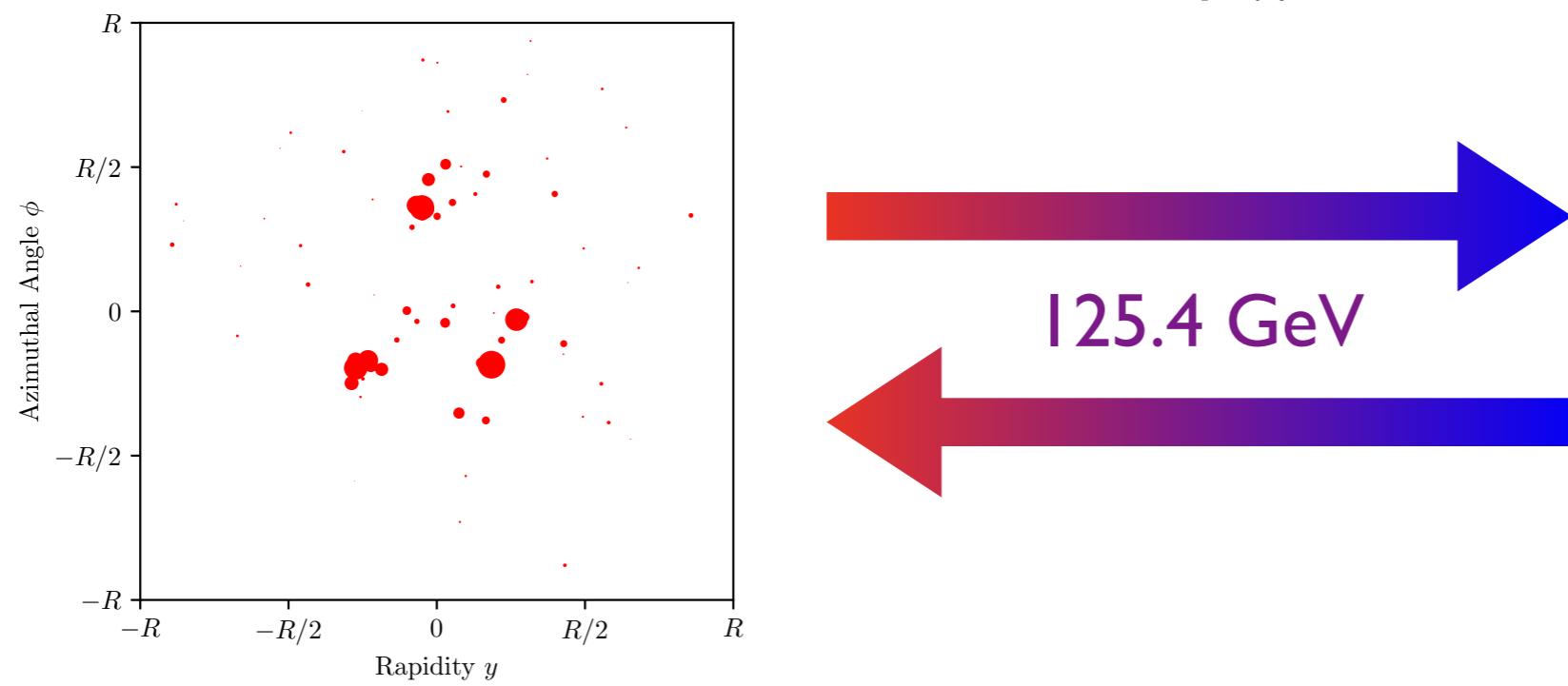
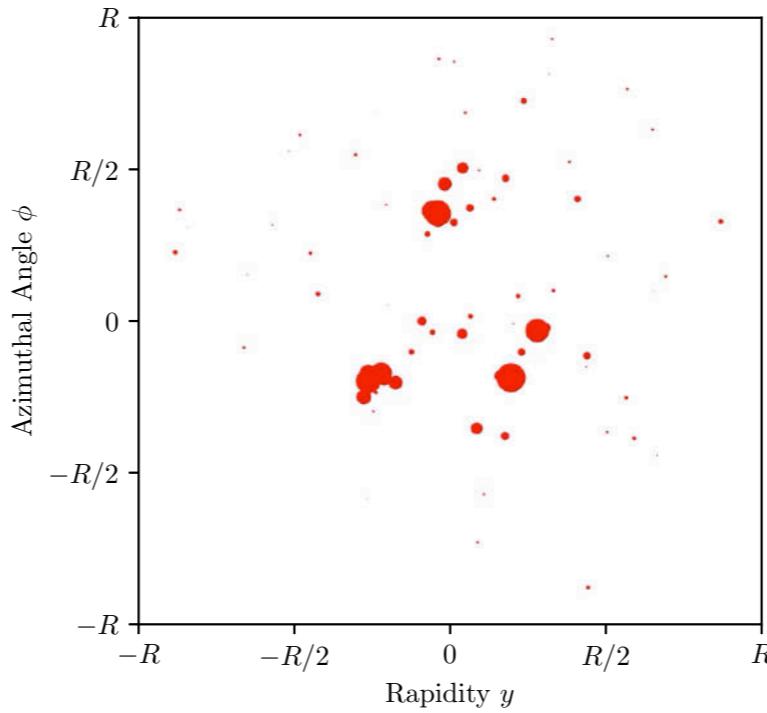
We do this within single jets in the pT range specified in the plot, and the dashed vertical red line is the jet radius (beyond which things don't really make sense).

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

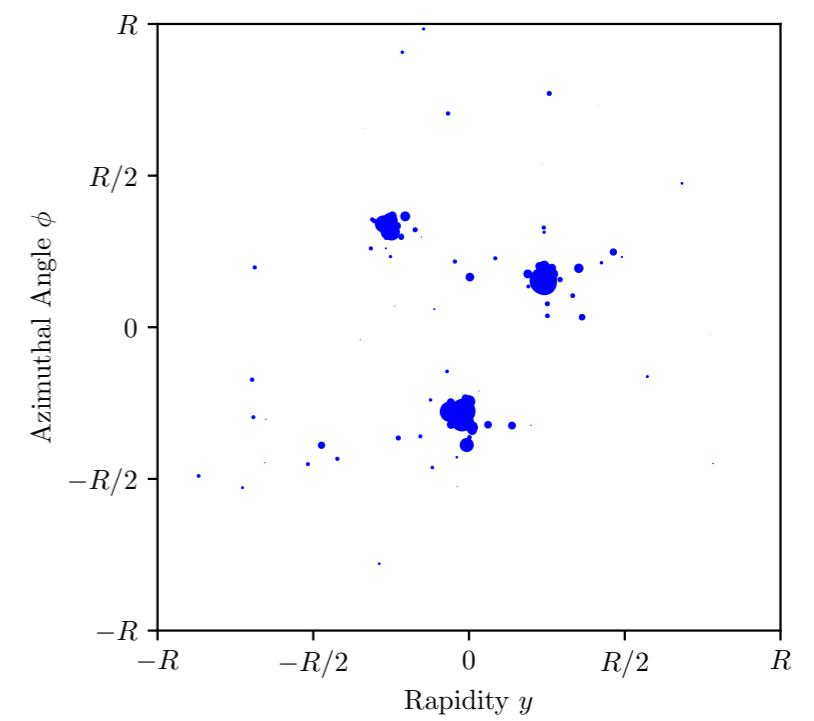


# Similarity of Two Energy Flows?

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

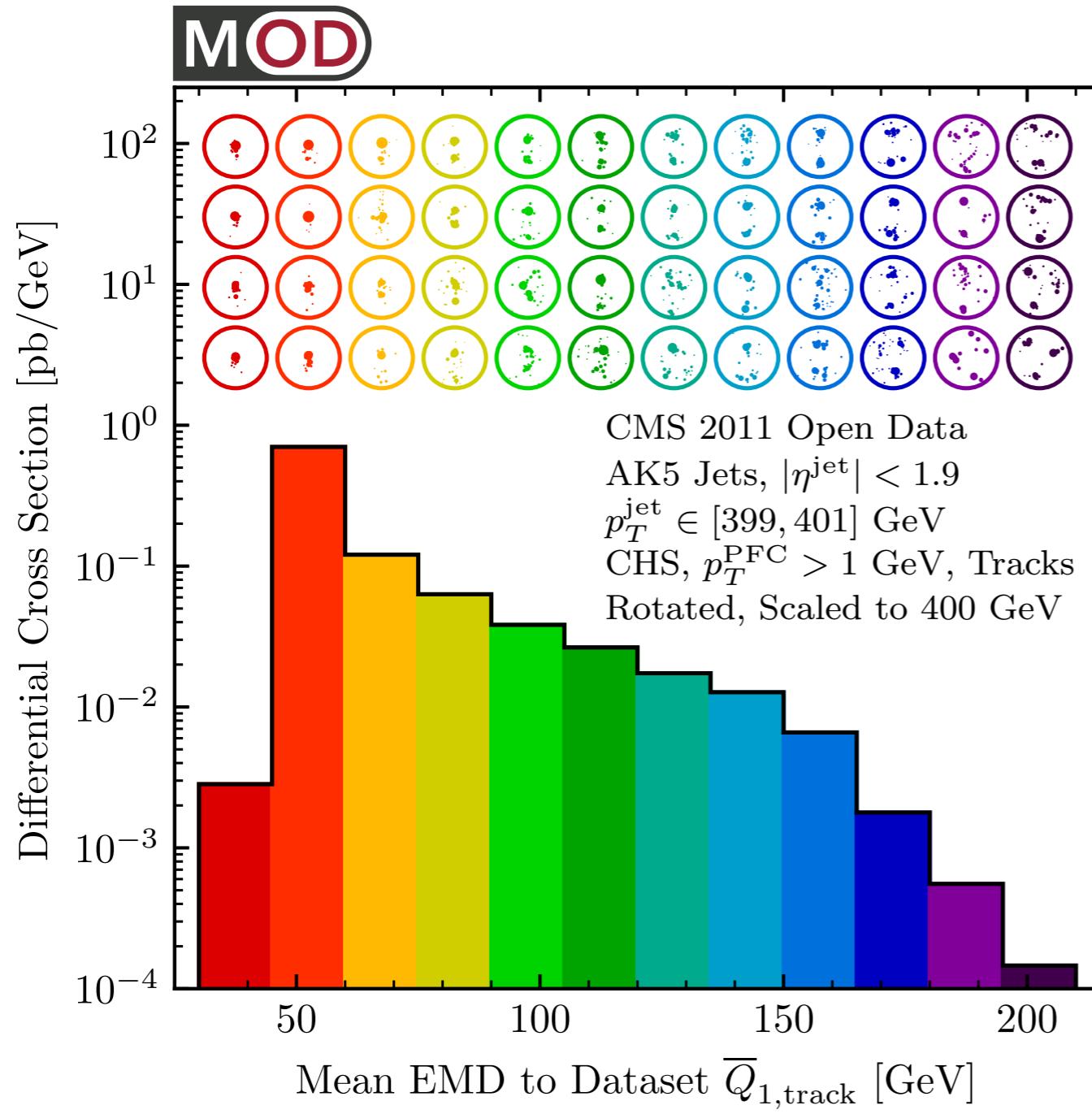


Optimal Transport:  
*Earth Mover's Distance*  
a.k.a. *1-Wasserstein metric*

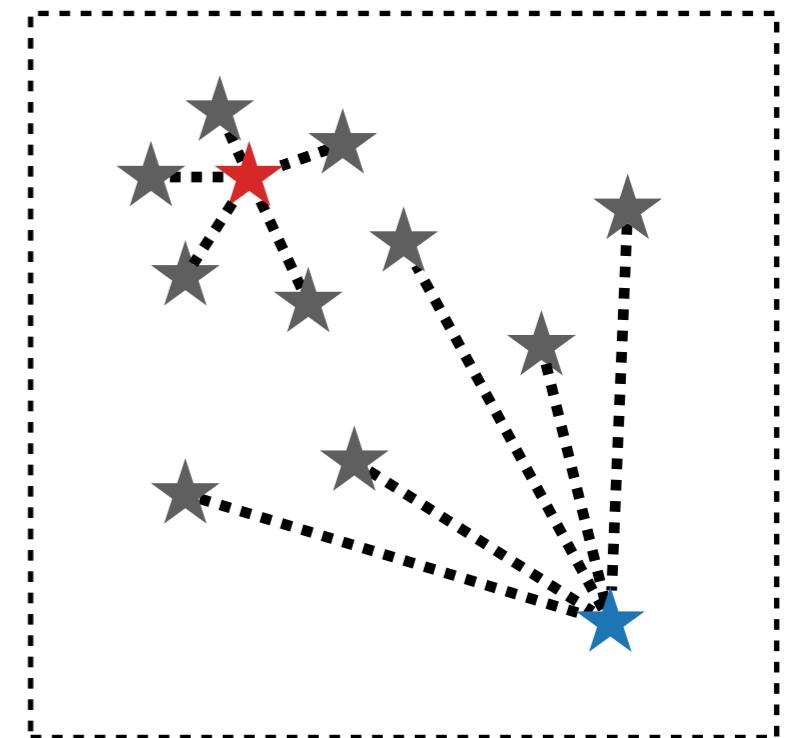


[Komiske, Metodiev, JDT, PRL 2019; code at Komiske, Metodiev, JDT, [energyflow.network](#)]

# Least Representative Jets



New Physics?  
Or tails of QCD?



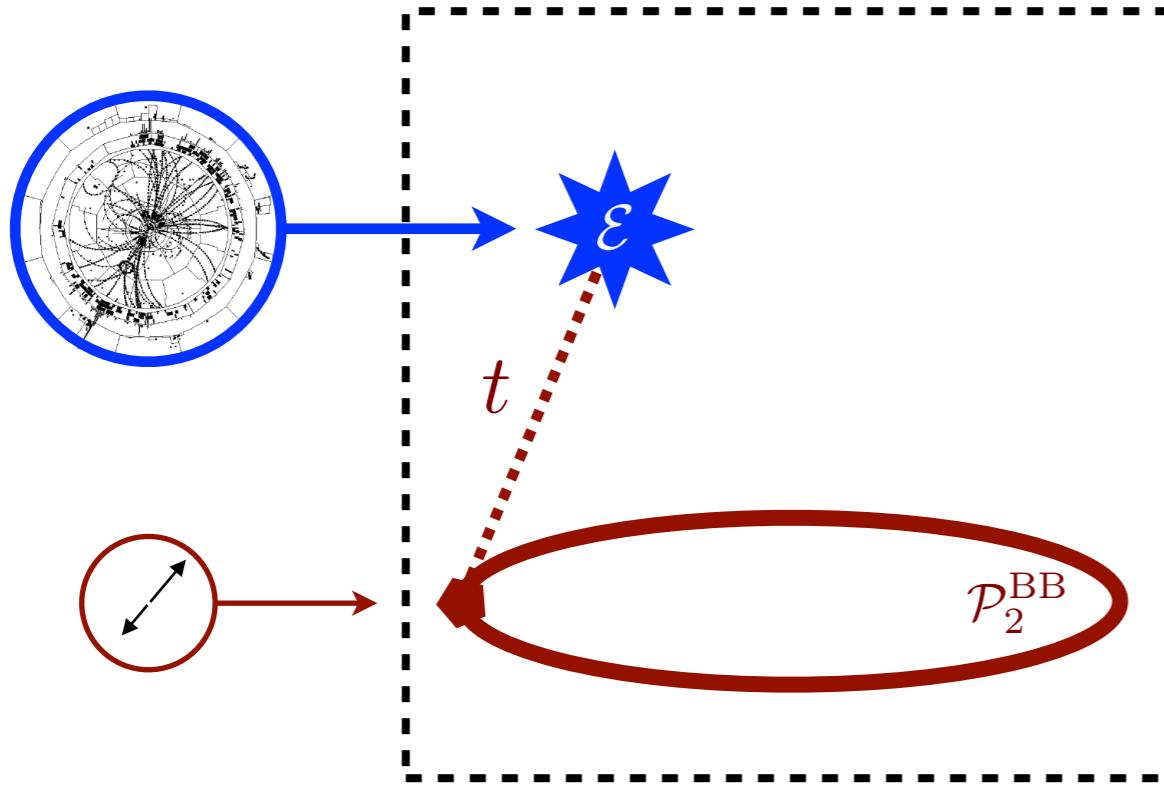
[Komiske, Mastandrea, Metodiev, Naik, JDT, PRD 2020]



# Back to the Future with Thrust

How dijet-like is an event?

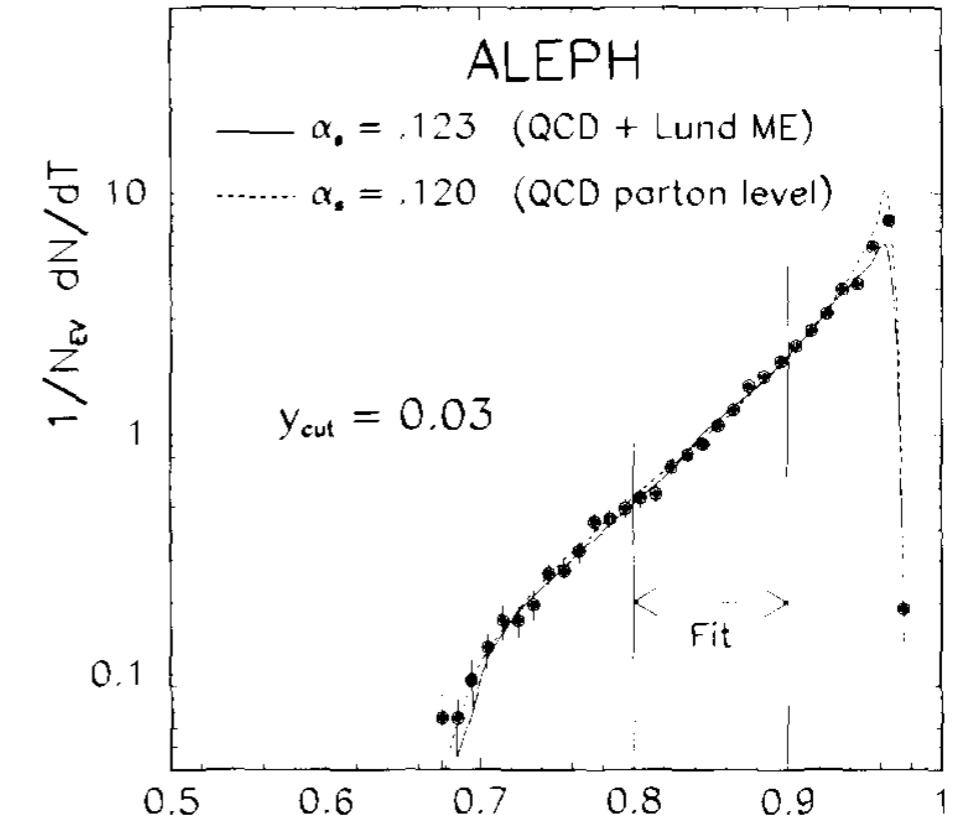
$$t(\mathcal{E}) = \min_{\mathcal{E}' \in \mathcal{P}_2^{\text{BB}}} \text{EMD}_2(\mathcal{E}, \mathcal{E}')$$



All Back-to-Back Two Particle Configurations

$$\mathcal{P}_2^{\text{BB}} = \left\{ \begin{array}{c} \text{red circles with arrows} \\ \dots \end{array} \right\}$$

(using  $\beta=2$  EMD variant)



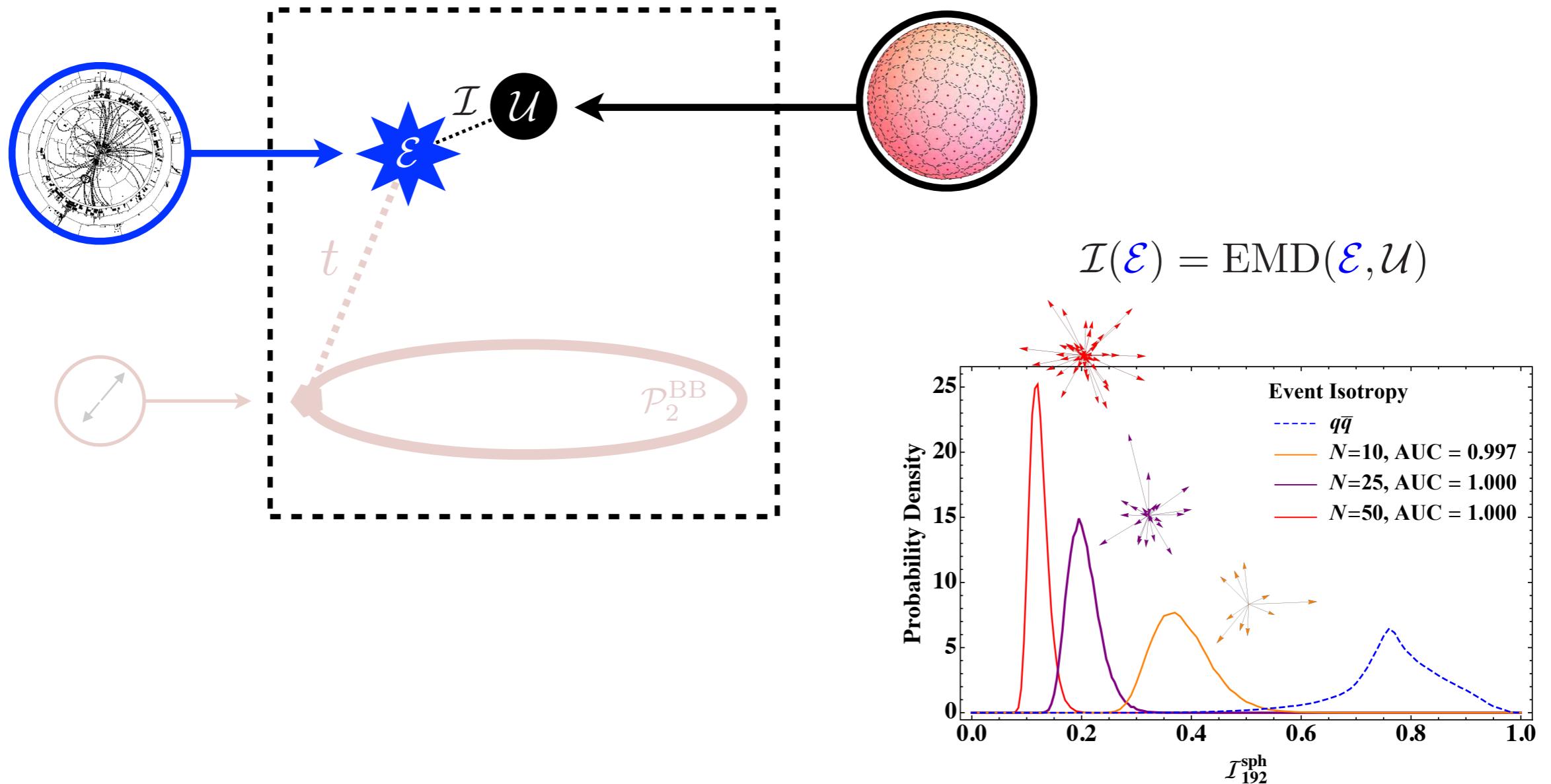
$$1 - \frac{t}{2E_{\text{CM}}}$$

(flipped, linear version of  
ALEPH thrust plot from before)

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

# Event Isotropy from Collider Geometry

How isotropic is an event?



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

