Collision Course

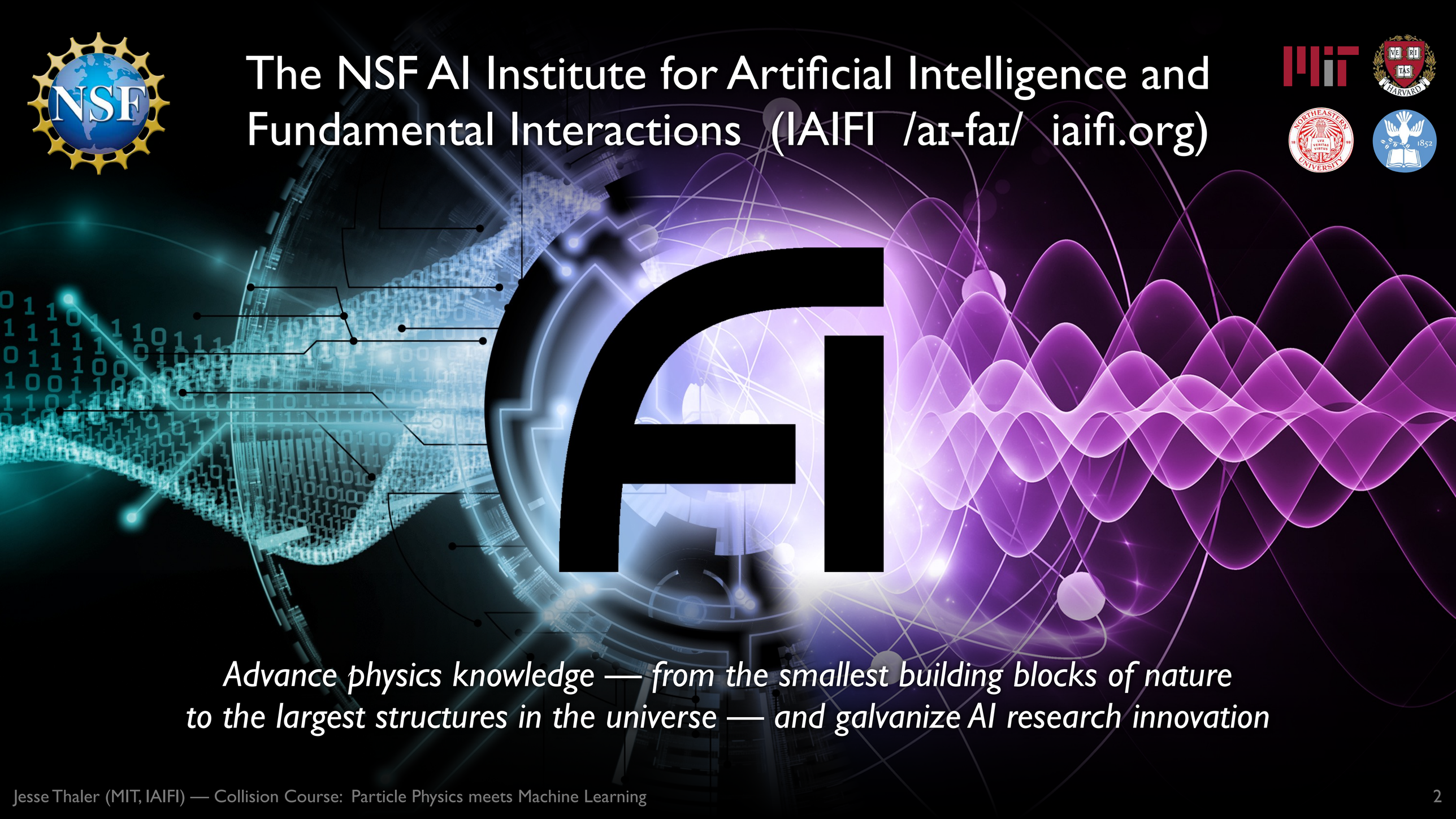
Particle Physics meets Machine Learning

Jesse Thaler

Director, NSF Institute for Artificial Intelligence and Fundamental Interactions

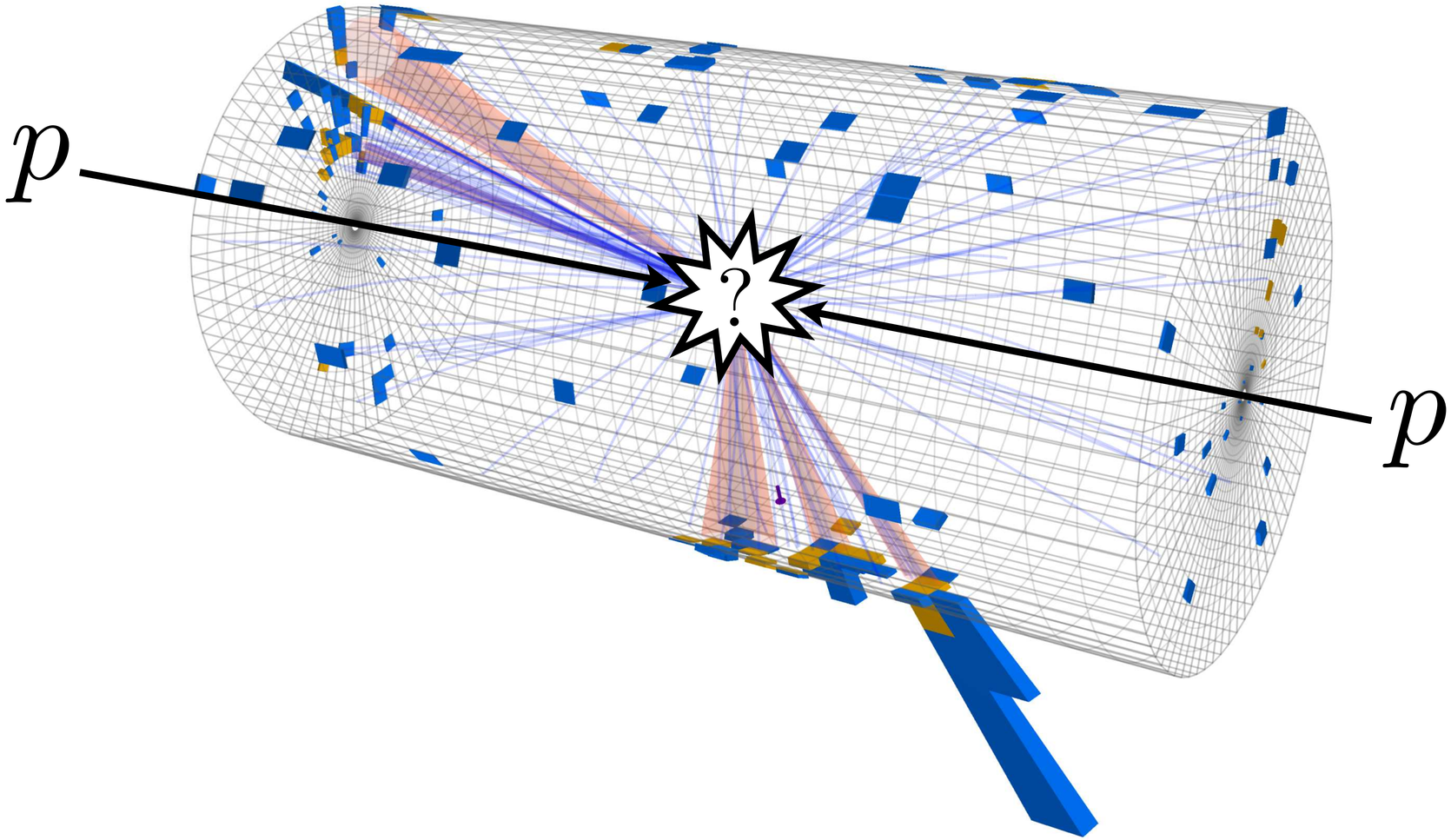
PhD Open Days, IST Lisbon — November 22, 2021

The NSF AI Institute for Artificial Intelligence and Fundamental Interactions (IAIFI /aɪ-faɪ/ iaifi.org)



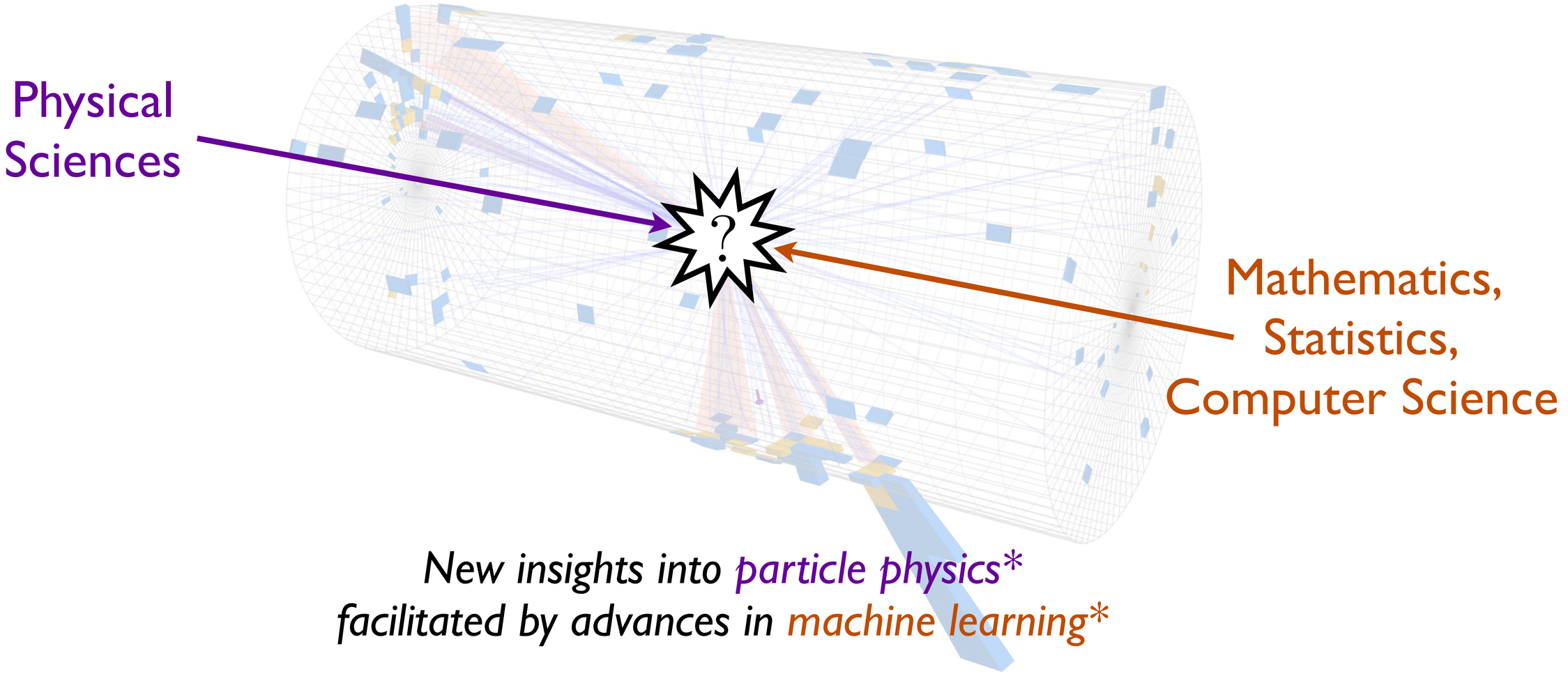
Advance physics knowledge — from the smallest building blocks of nature to the largest structures in the universe — and galvanize AI research innovation

“Collision Course”



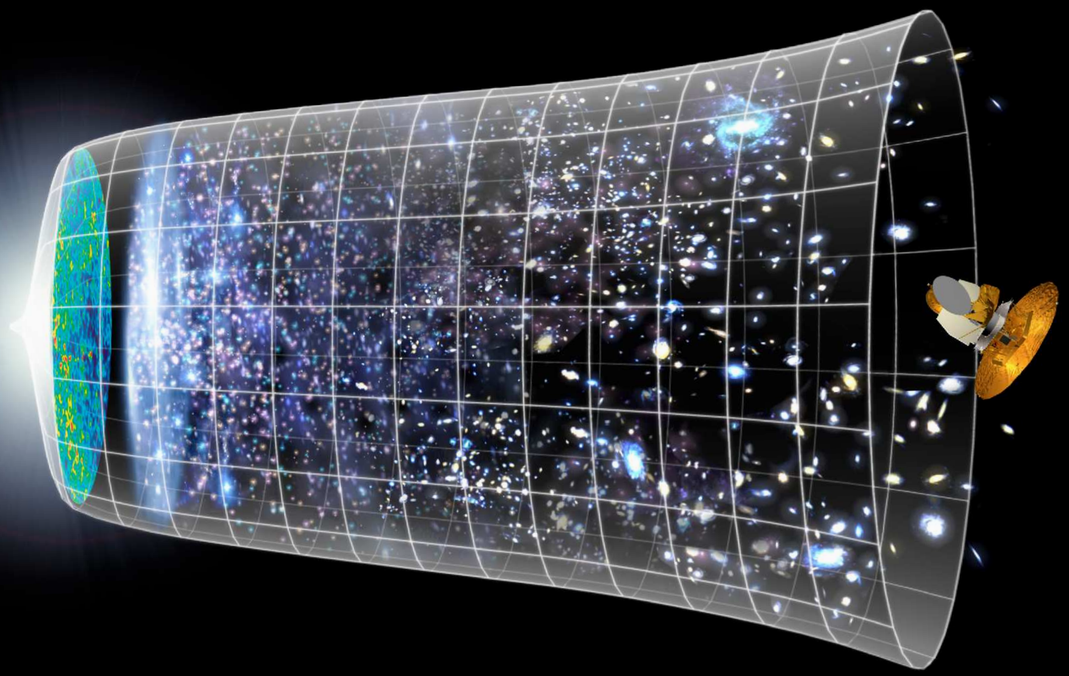
[CMS Detector at the Large Hadron Collider]

“Collision Course”

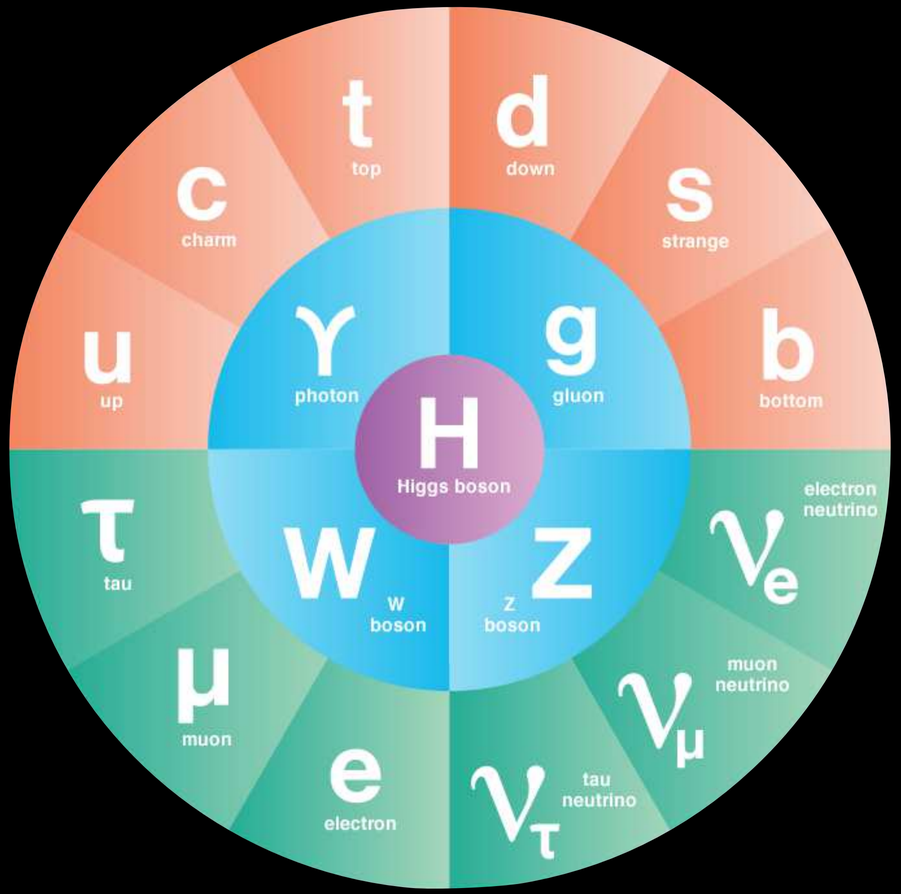


*New insights into particle physics**
*facilitated by advances in machine learning**

Big Bang Cosmology



Standard Model

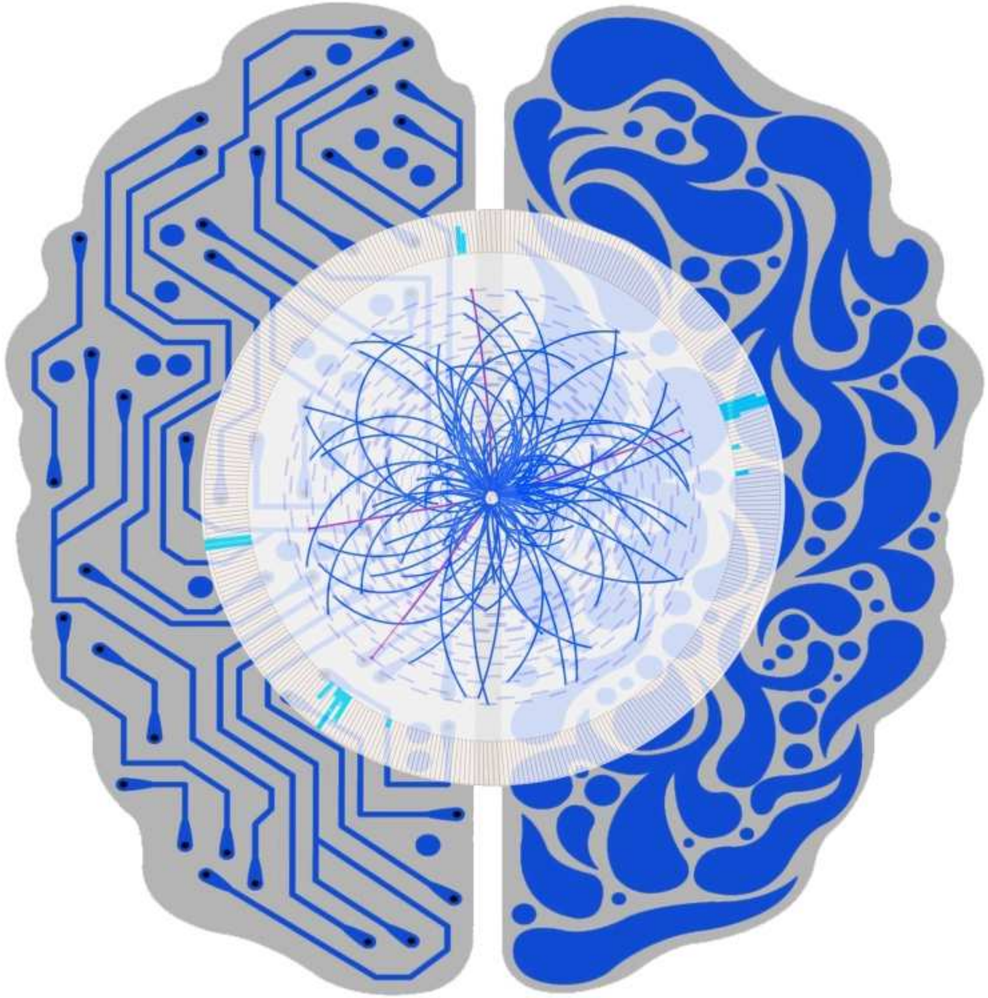


Big Bang Cosmology

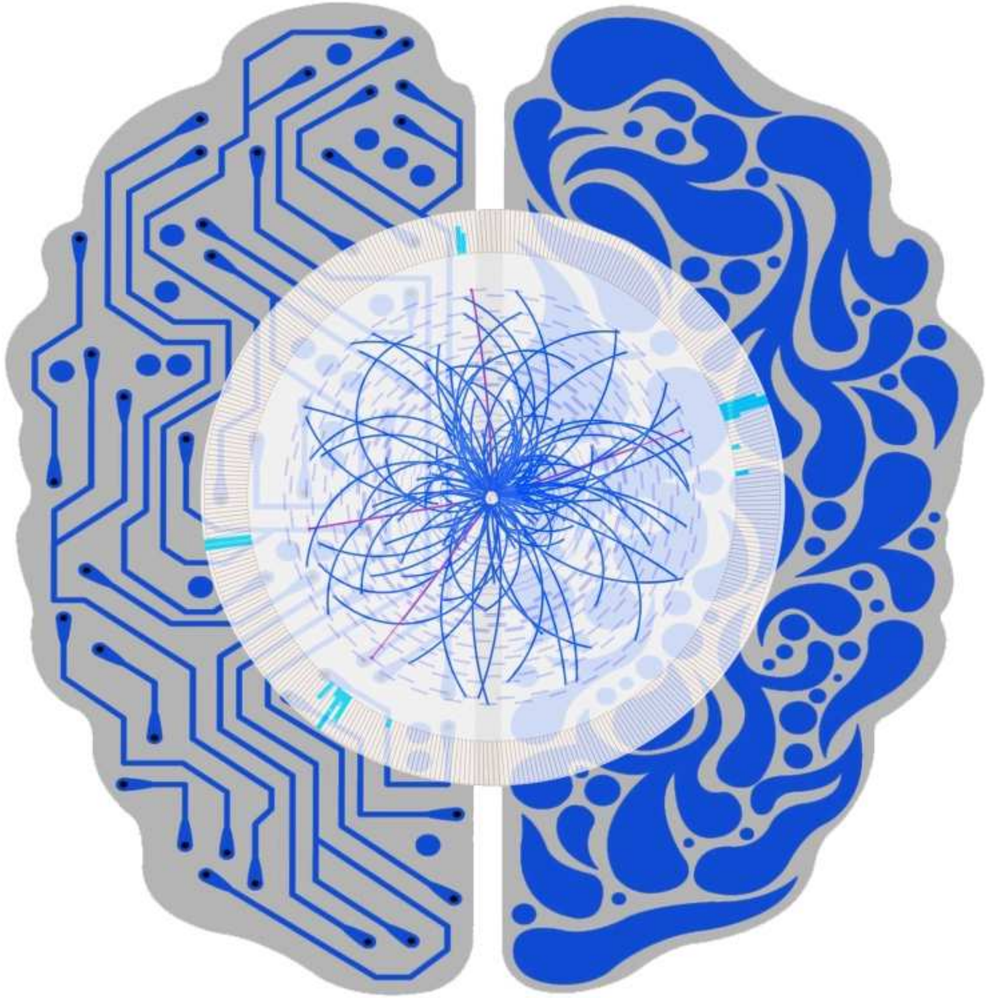
Standard Model

Pillars of Fundamental Physics

Triumphs of Human Intelligence



Can we teach a machine to "think" like a physicist?



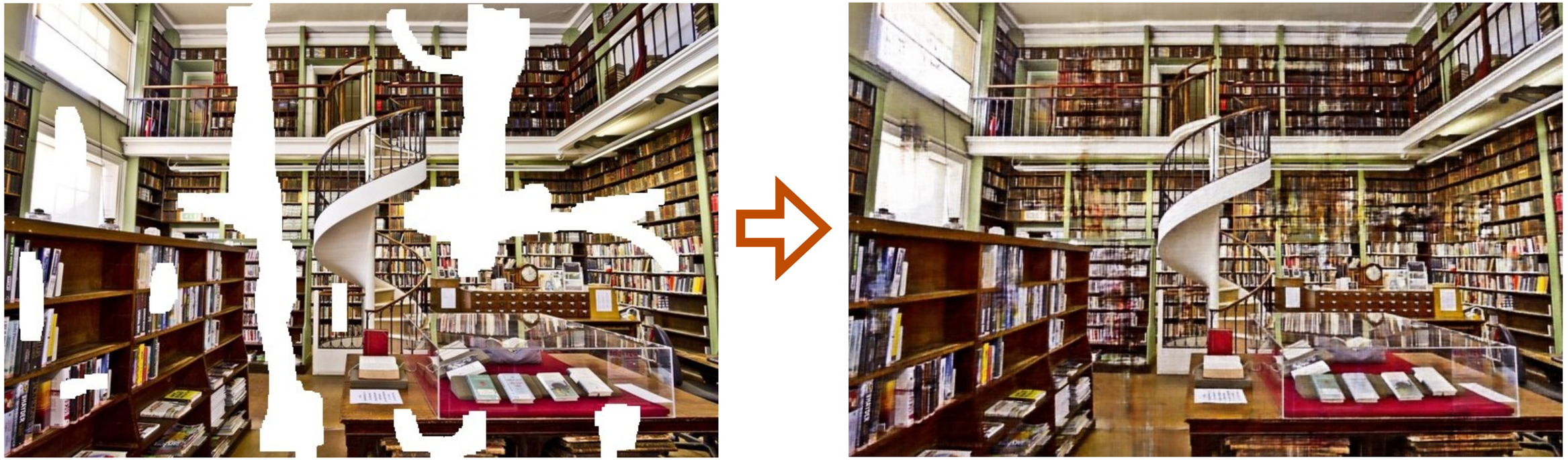
Can we teach a machine to "think" like a physicist?

The New York Times

By Dennis Overbye Nov. 23, 2020

Can a Computer Devise a Theory of Everything?

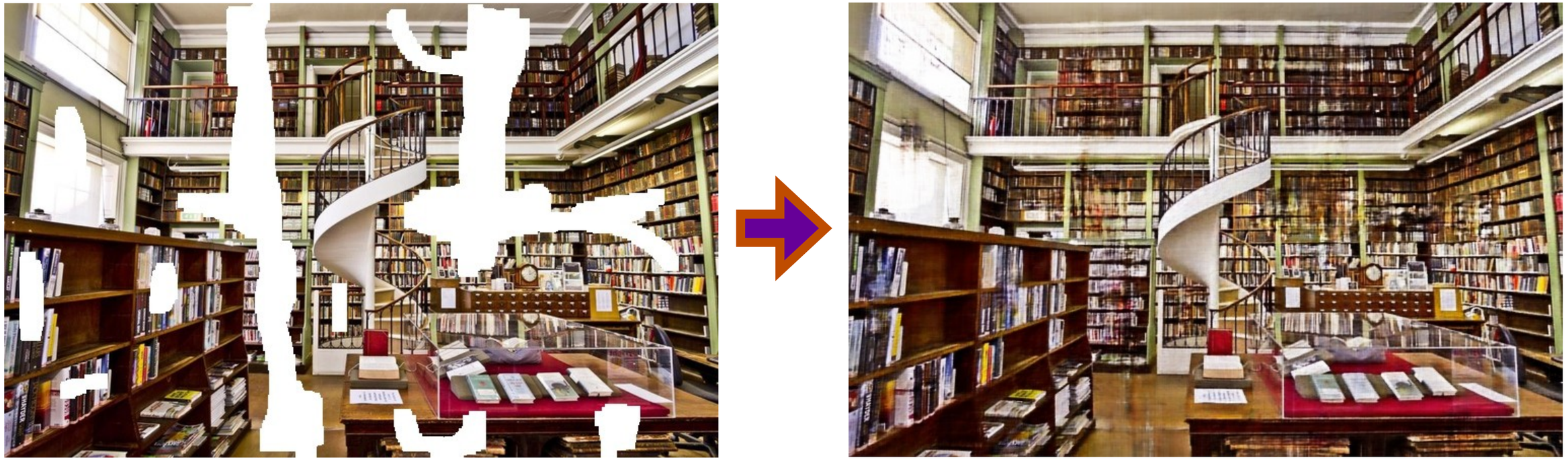
Deep Learning



Large data sets, increased computational power

[Ulyanov, Vedaldi, Lempitsky, CVPR 2018]

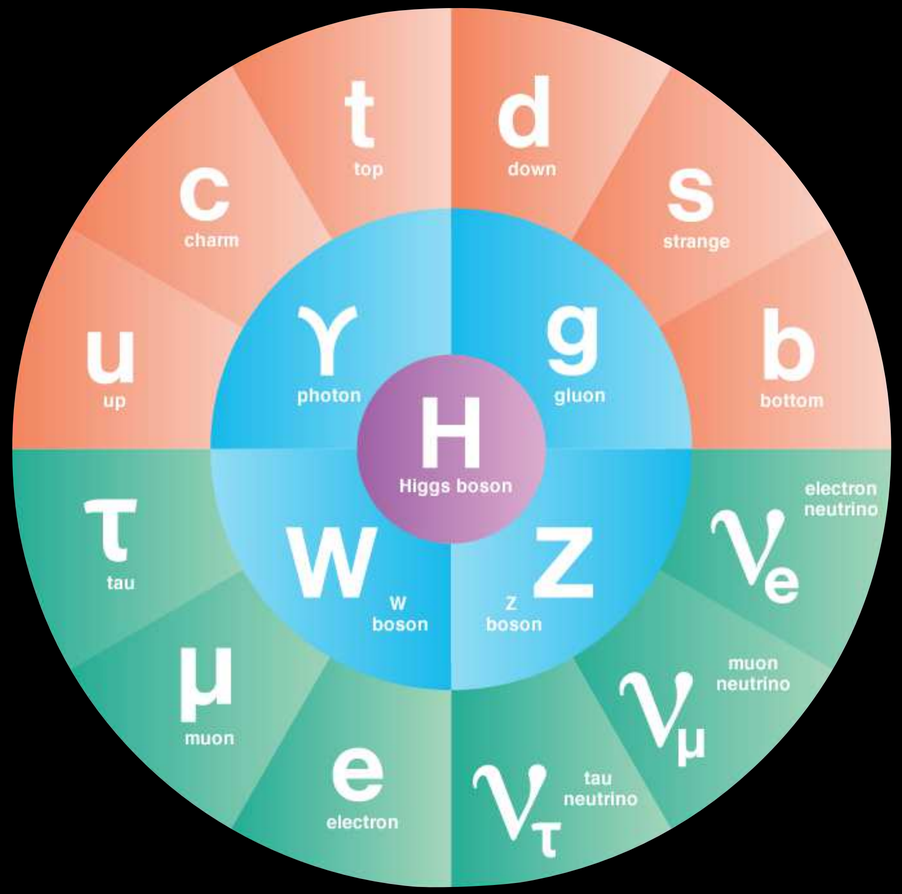
Deep Learning meets Deep Thinking



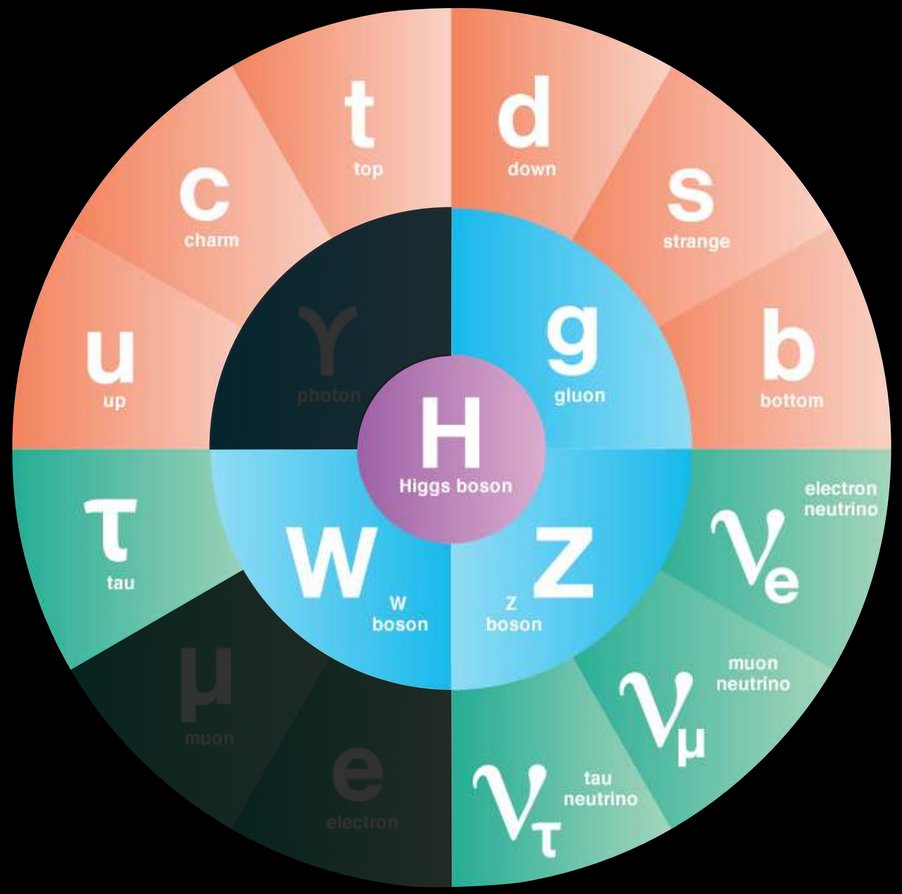
Large data sets, increased computational power, and understanding structure of problems

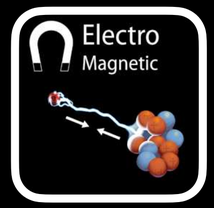
[Ulyanov, Vedaldi, Lempitsky, CVPR 2018]

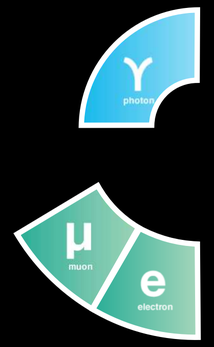
Standard Model of Particle Physics



Standard Model of Particle Physics







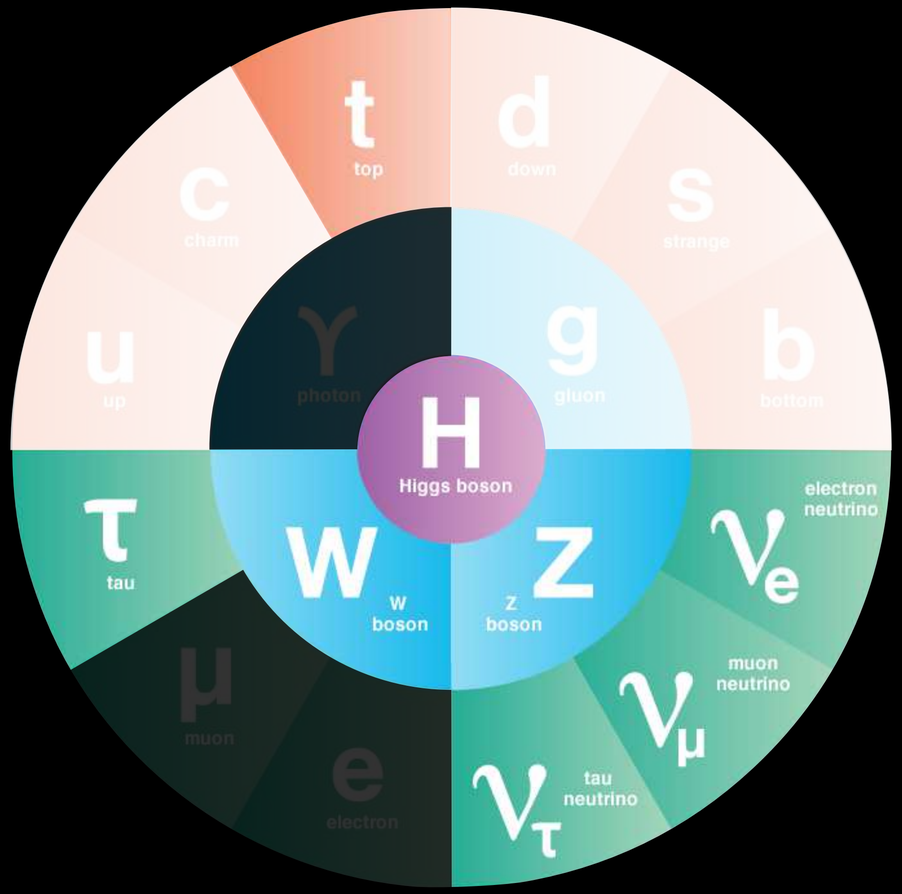
Elementary

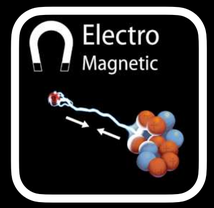
γ photon

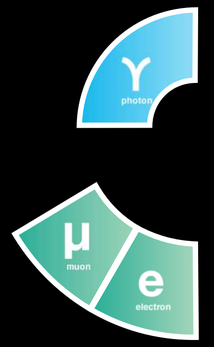
$e^{\pm}$ electron

$\mu^{\pm}$ muon

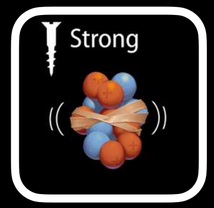
Standard Model of Particle Physics

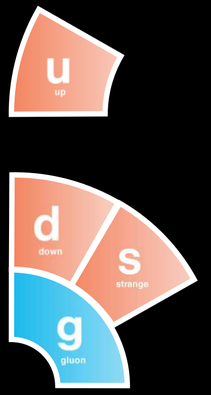






Quarks
&
Gluons





Elementary

γ photon

$e^{\pm}$ electron

$\mu^{\pm}$ muon

Composite

$\pi^{\pm}$ pion

$K^{\pm}$ kaon

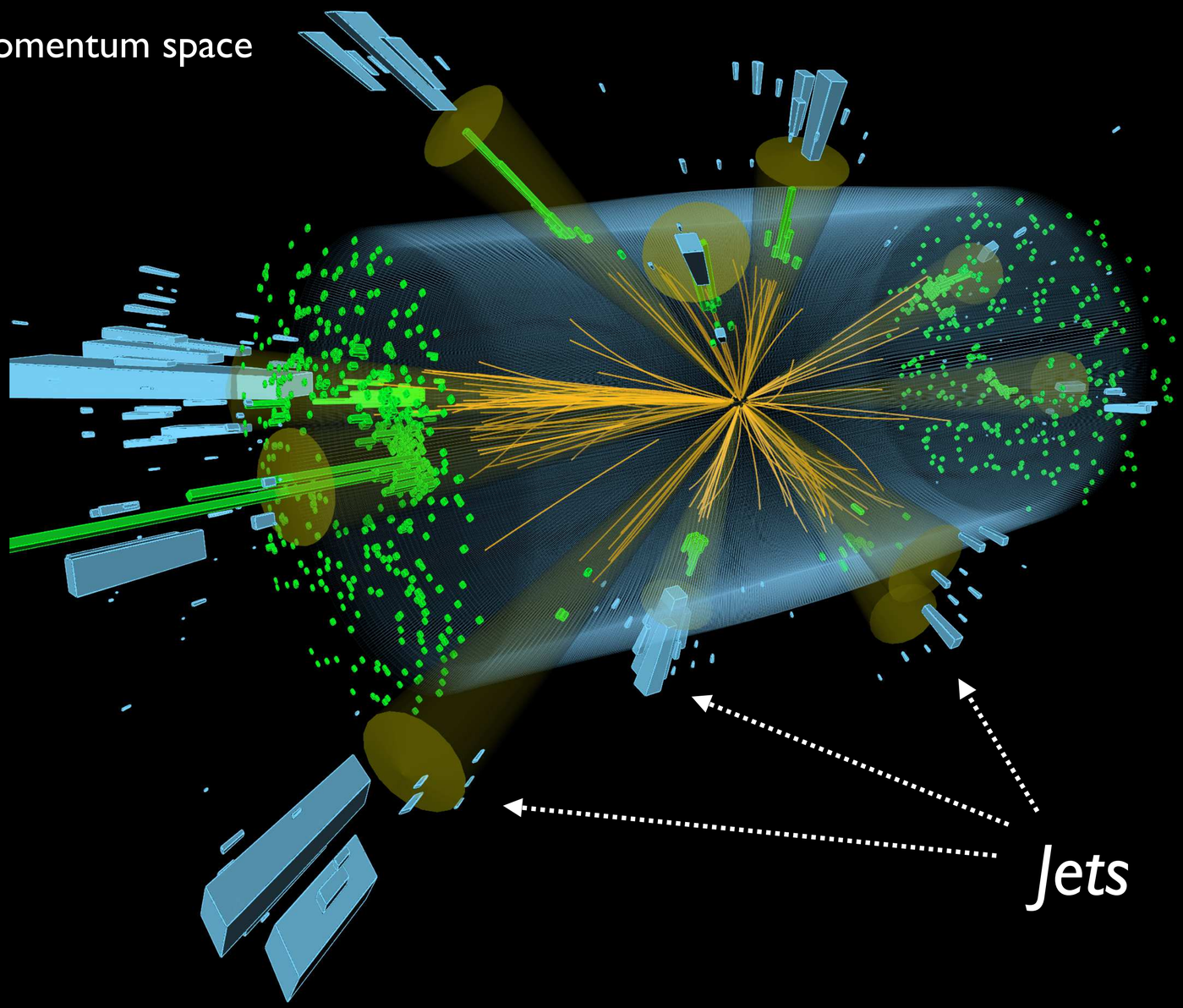
K_L^0 K-long

$p/\overline{p}$ proton

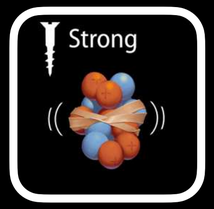
$n/\overline{n}$ neutron

Collider Event

Collection of points in momentum space



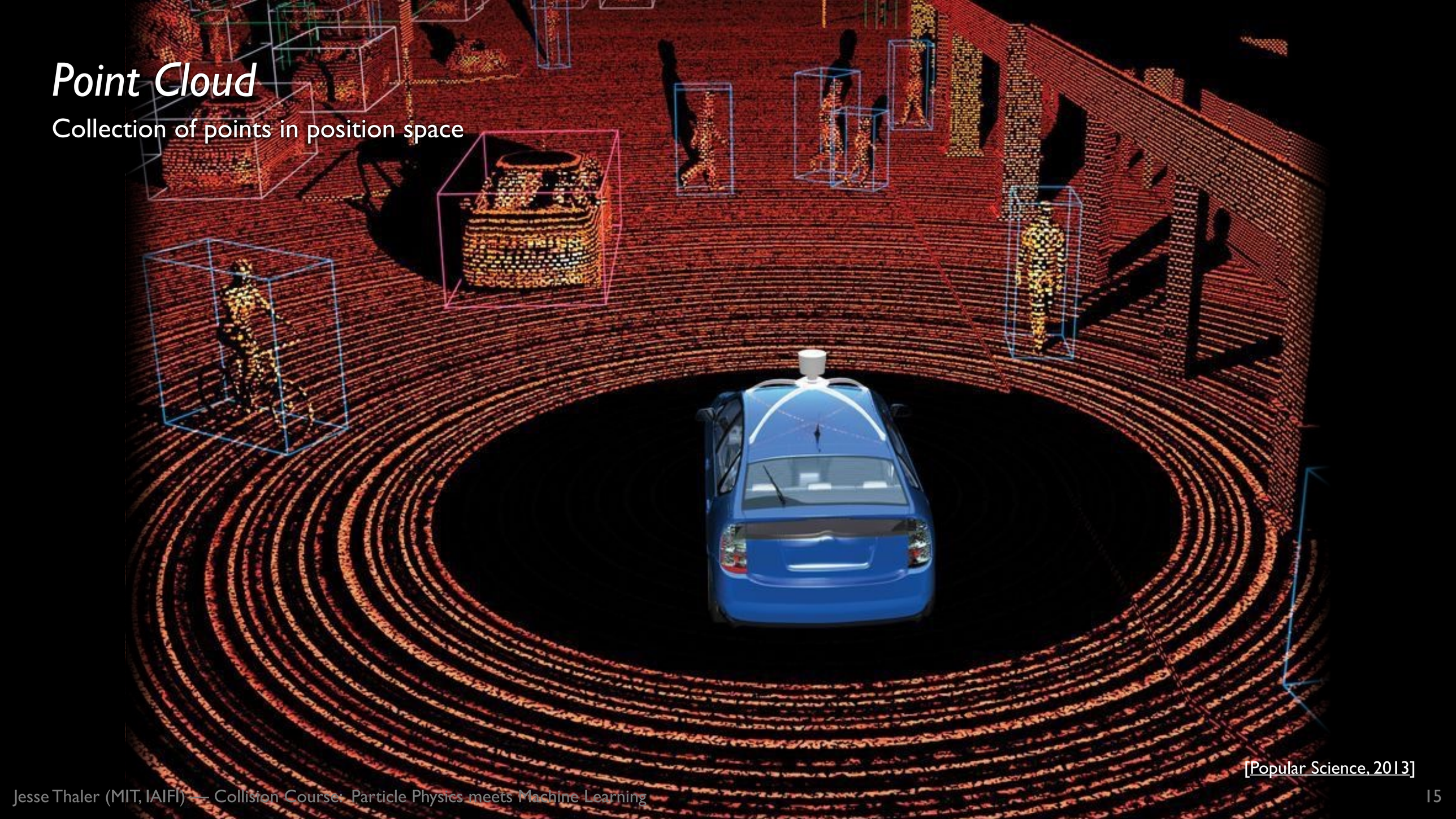
Jets



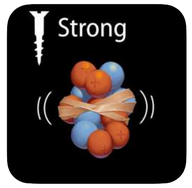
Manifestation of
Quarks & Gluons

Point Cloud

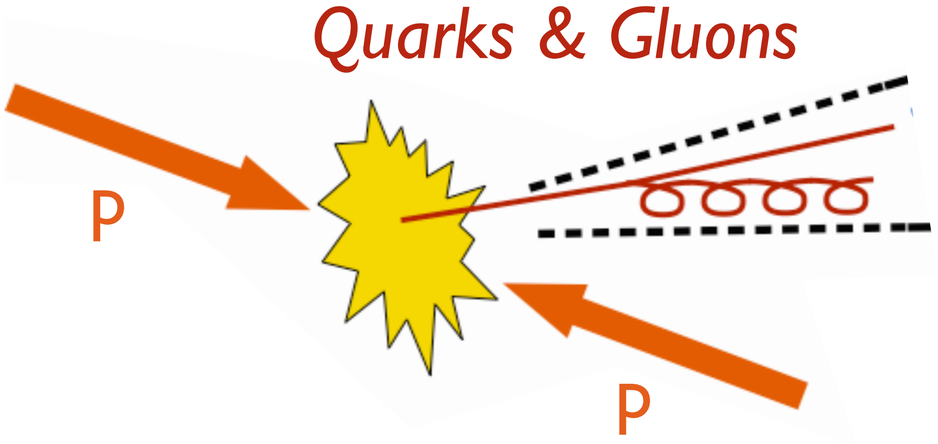
Collection of points in position space

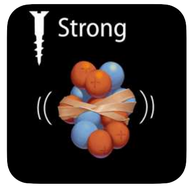


[Popular Science, 2013]



Dynamics of Jet Formation





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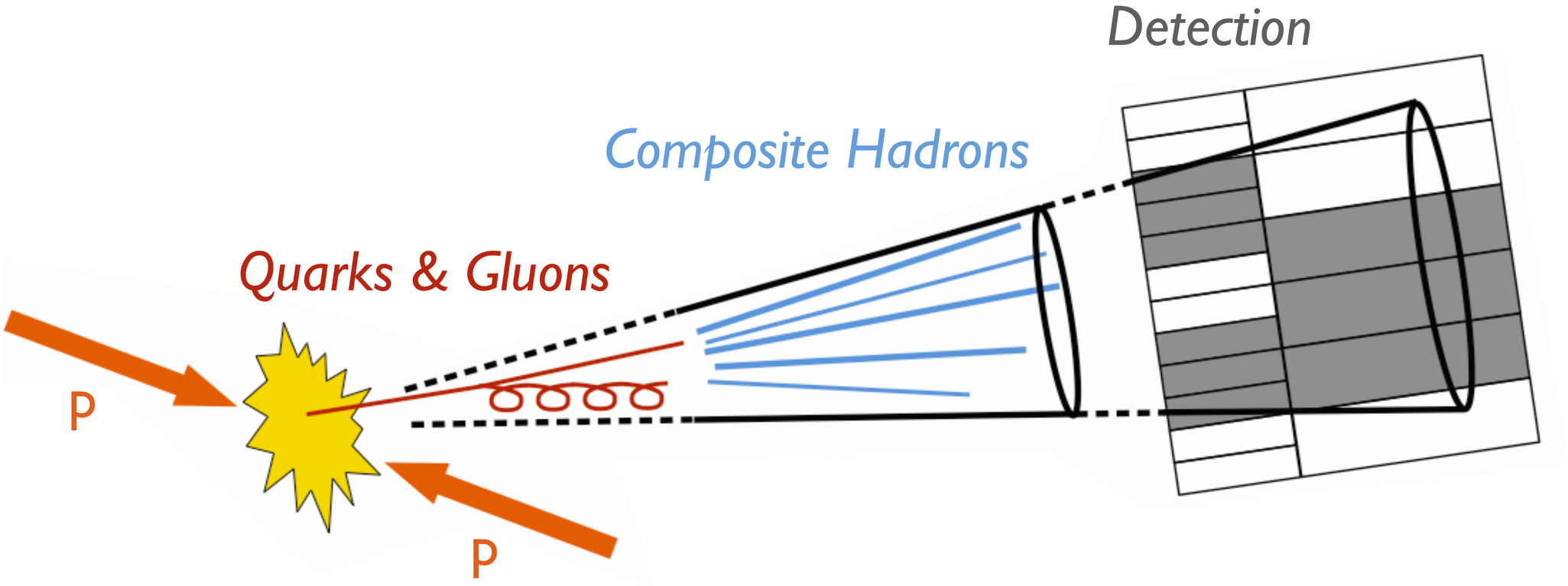


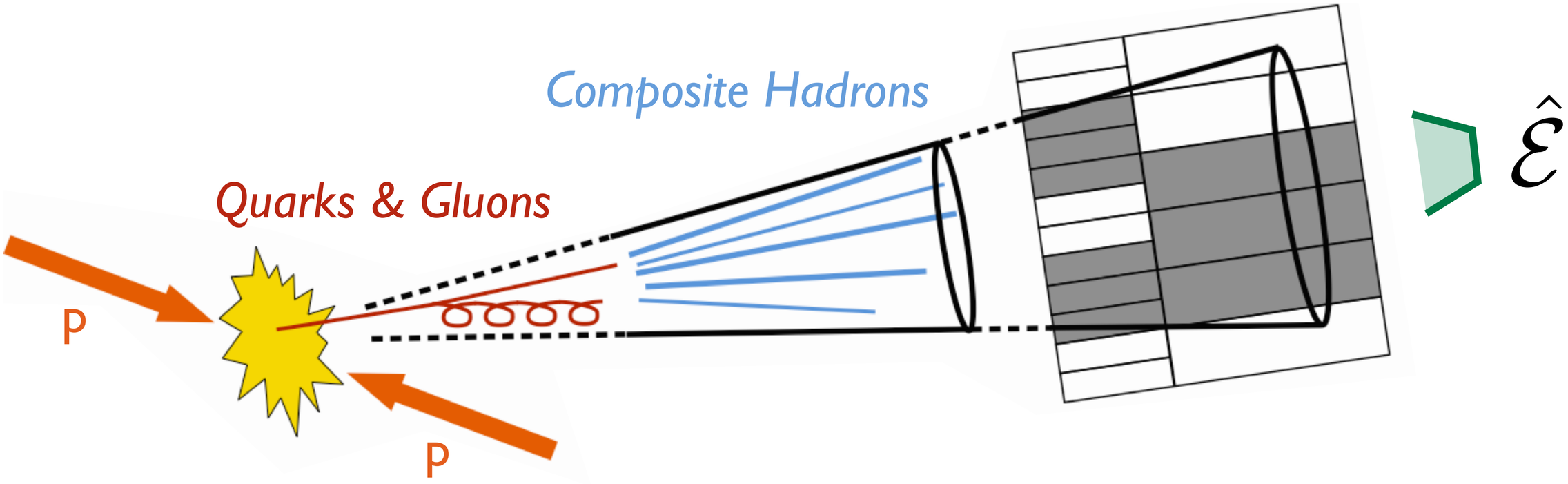
Dynamics of Jet Formation

Theory

Detection

Composite Hadrons

Quarks & Gluons



"Energy Flow"

Robust to hadronization and detection

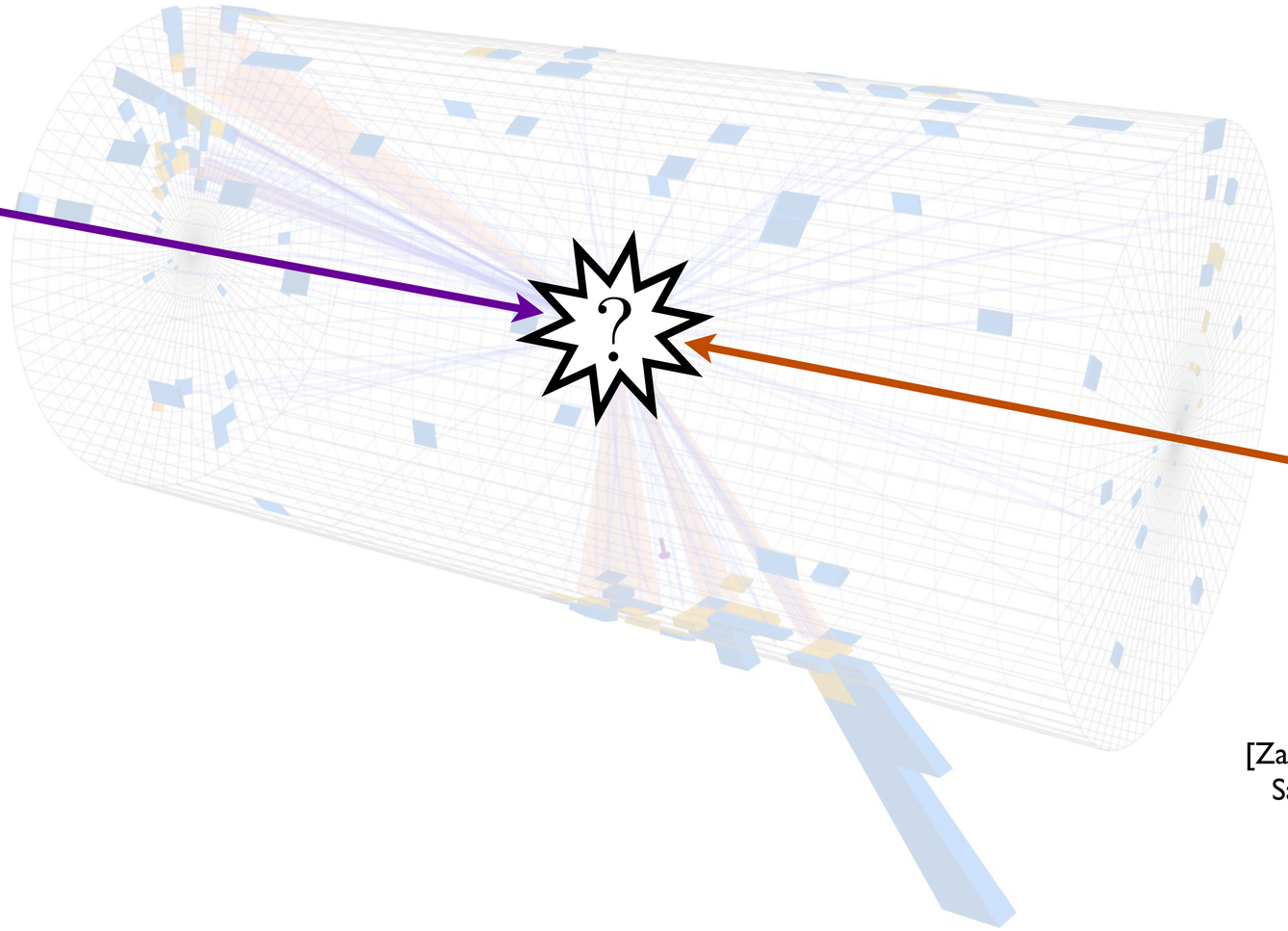
$$\hat{\mathcal{E}} \simeq \lim_{t\to\infty} \hat{n}_i T^{0i}(t, vt\hat{n})$$

[Sveshnikov, Tkachov, PLB 1996]

Principles of Fundamental Physics

Robustness of Energy Flow

[Komiske, Metodiev, JDT, JHEP 2018]



Power of Artificial Intelligence

Point Cloud Learning

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

Patrick Komiske

Eric Metodiev

Principles of Fundamental Physics

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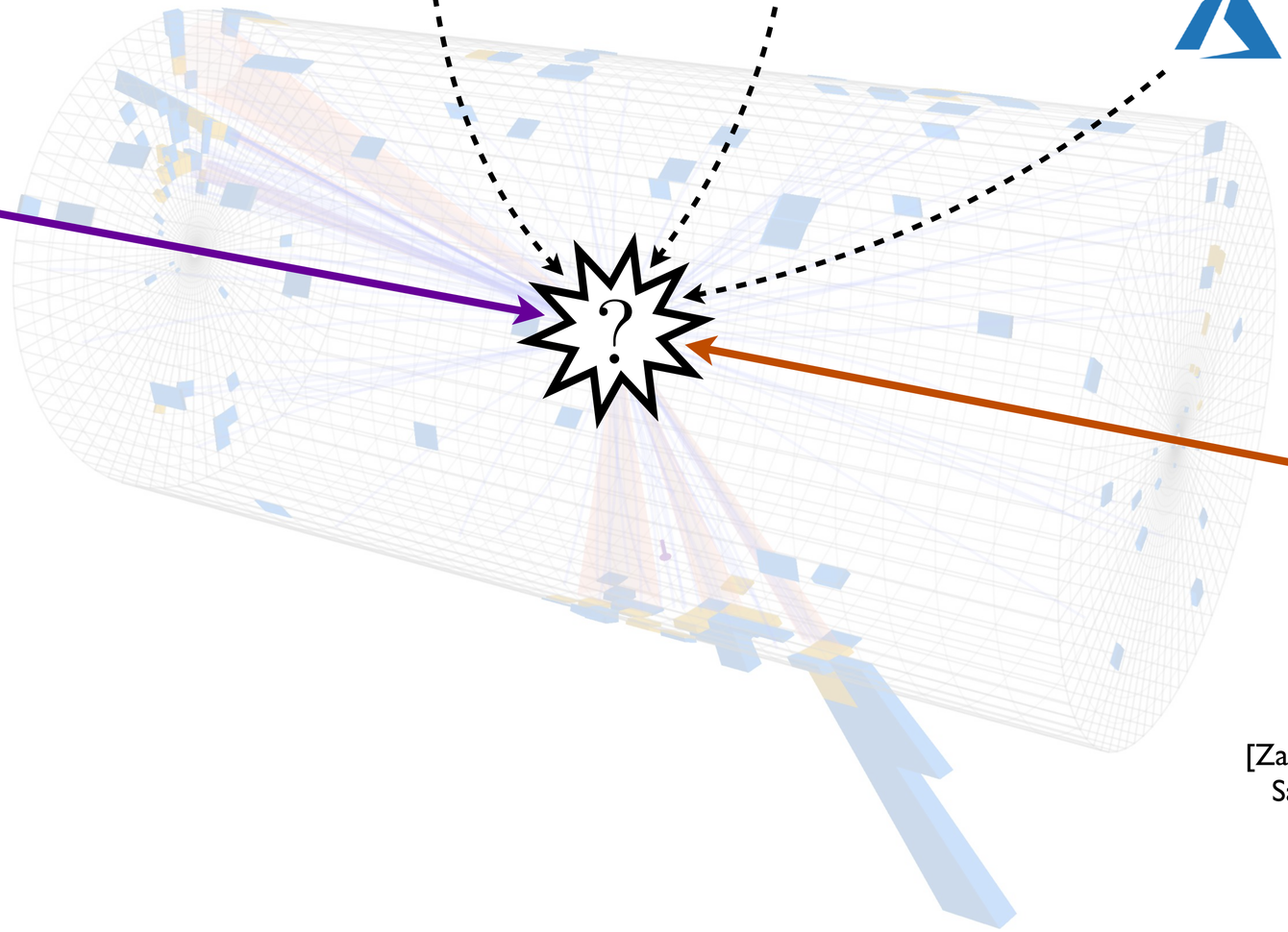

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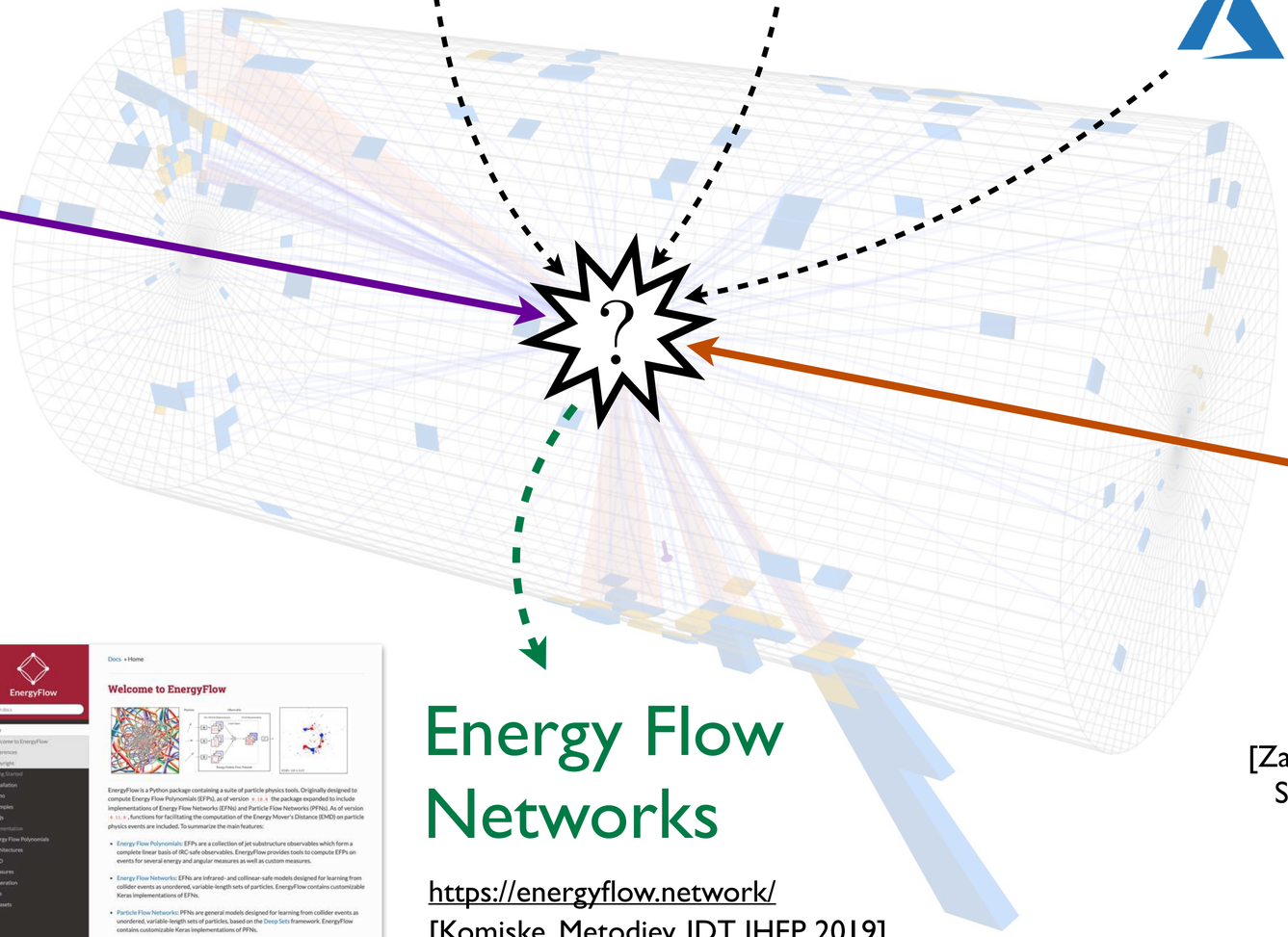

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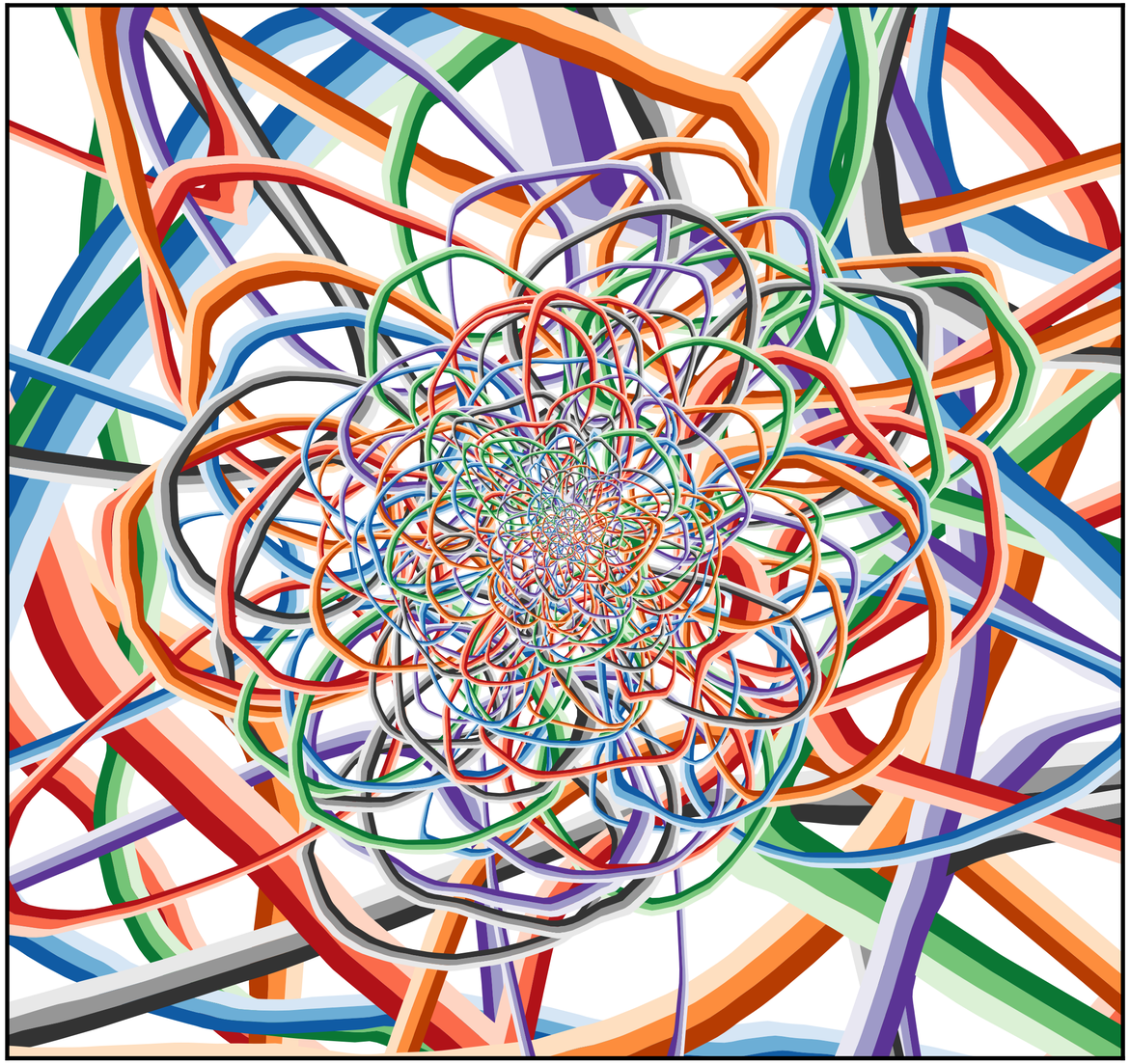
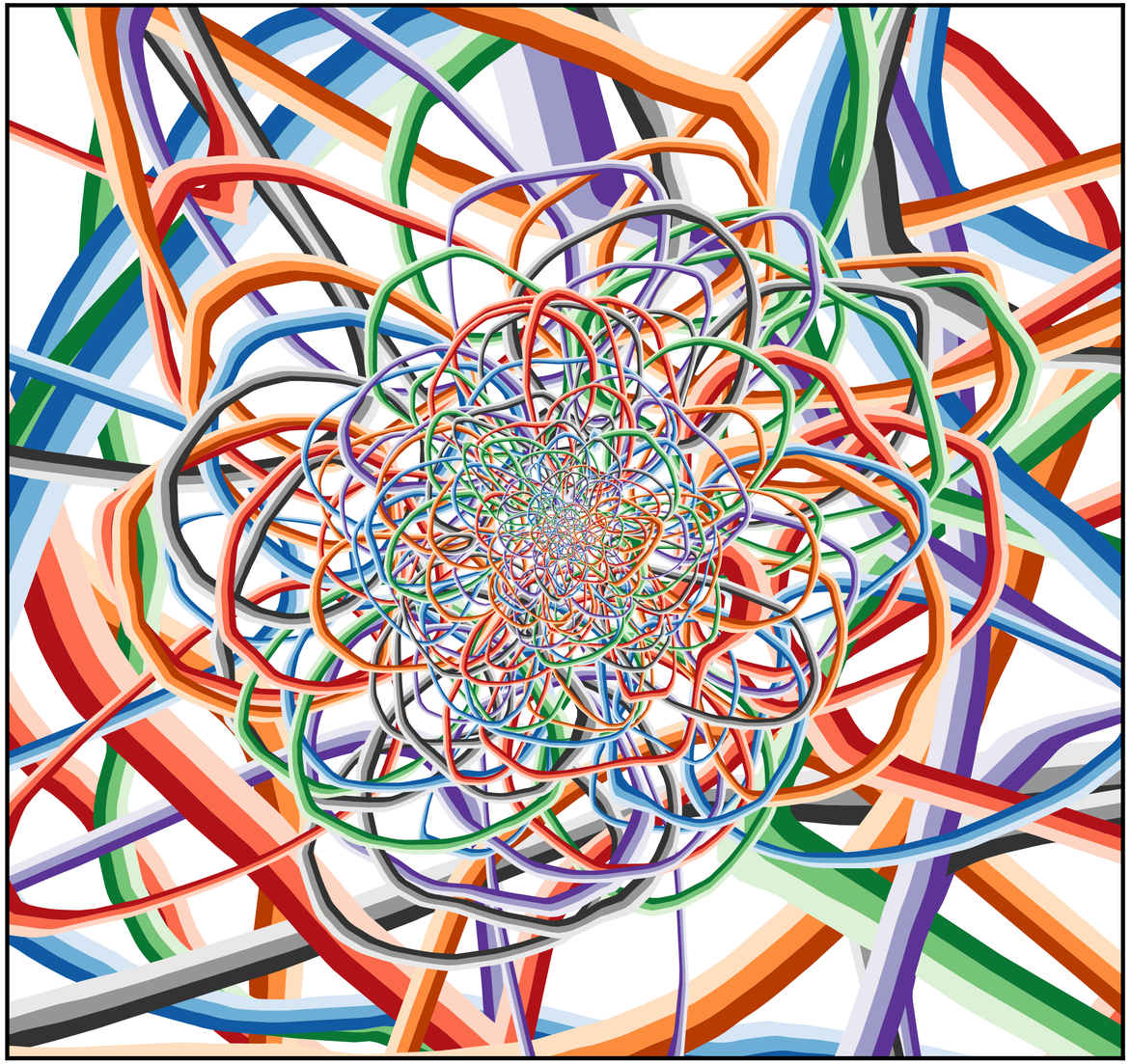
Energy Flow Networks

https://energyflow.network/

[Komiske, Metodiev, JDT, JHEP 2019]



[Komiske, Metodiev, JDT, JHEP 2019]



"Hello, World!" of Jets:

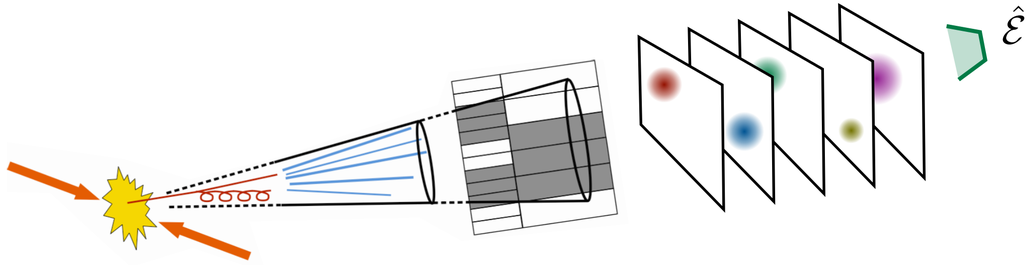
Quark 

vs. Gluon 

Energy Flow Network:

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

Strategy for Verification:



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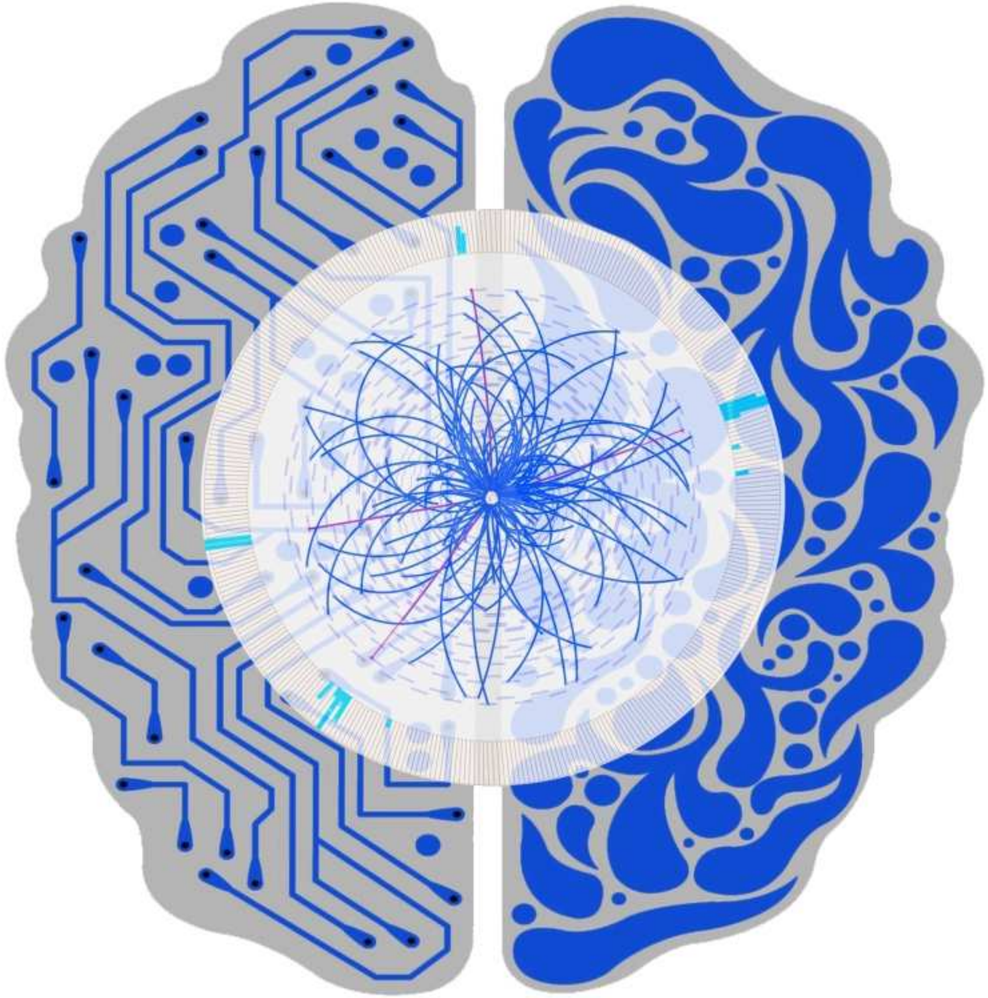
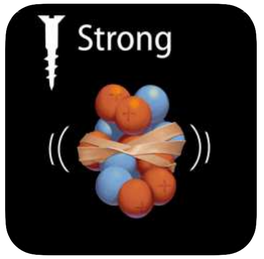
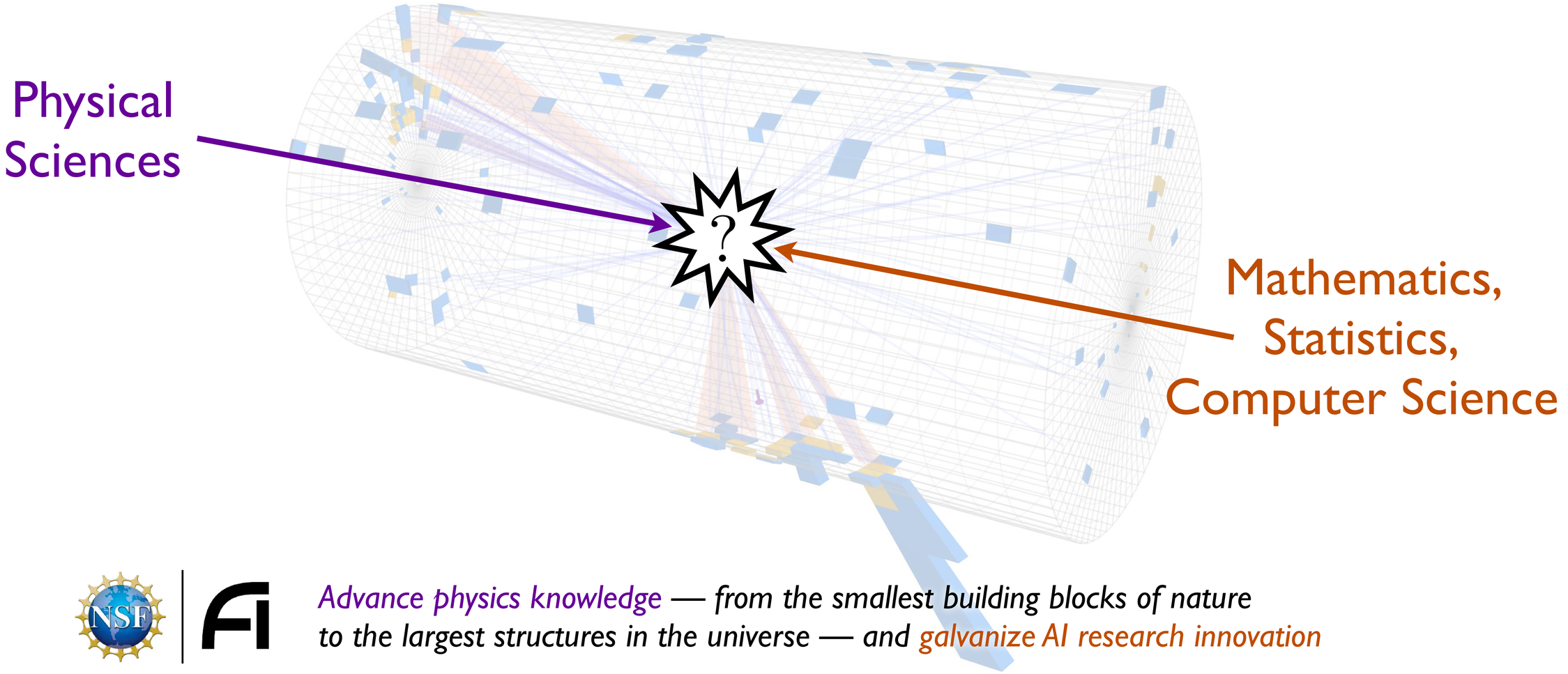


We taught a machine to "think" like a physicist…



…and it learned fractal structure of strong force!

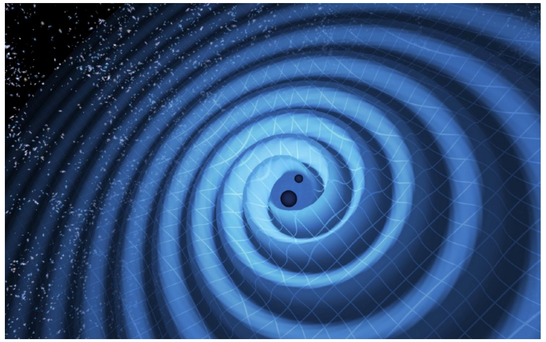
“Collision Course”



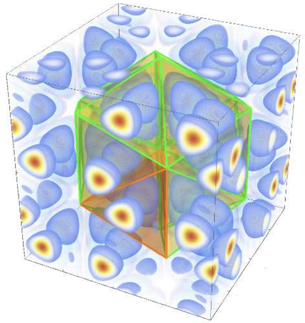
Advance physics knowledge — from the smallest building blocks of nature to the largest structures in the universe — and galvanize AI research innovation

Artificial Intelligence ⇔ Fundamental Physics

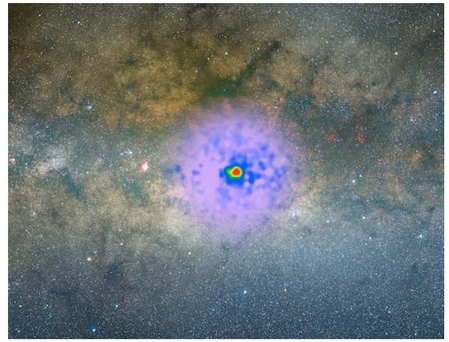
Gravitational Waves



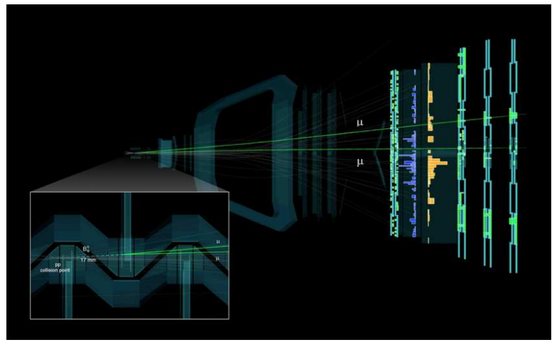
Nuclear Physics



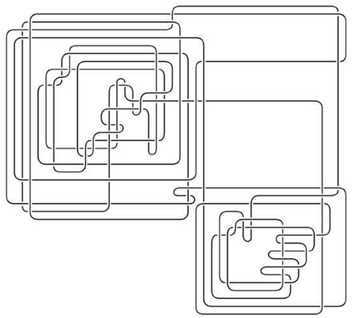
Astrophysics



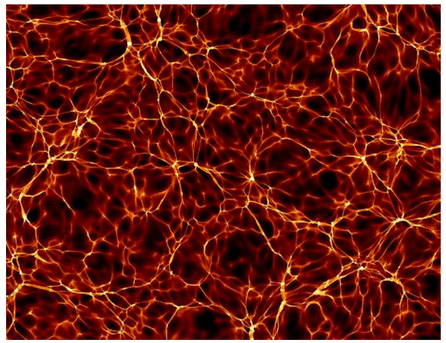
Particle Colliders



Mathematical Physics



Dark Matter



...

[iaifi.org]

IAIFI Postdoctoral Fellows

The "Gluons" of IAIFI

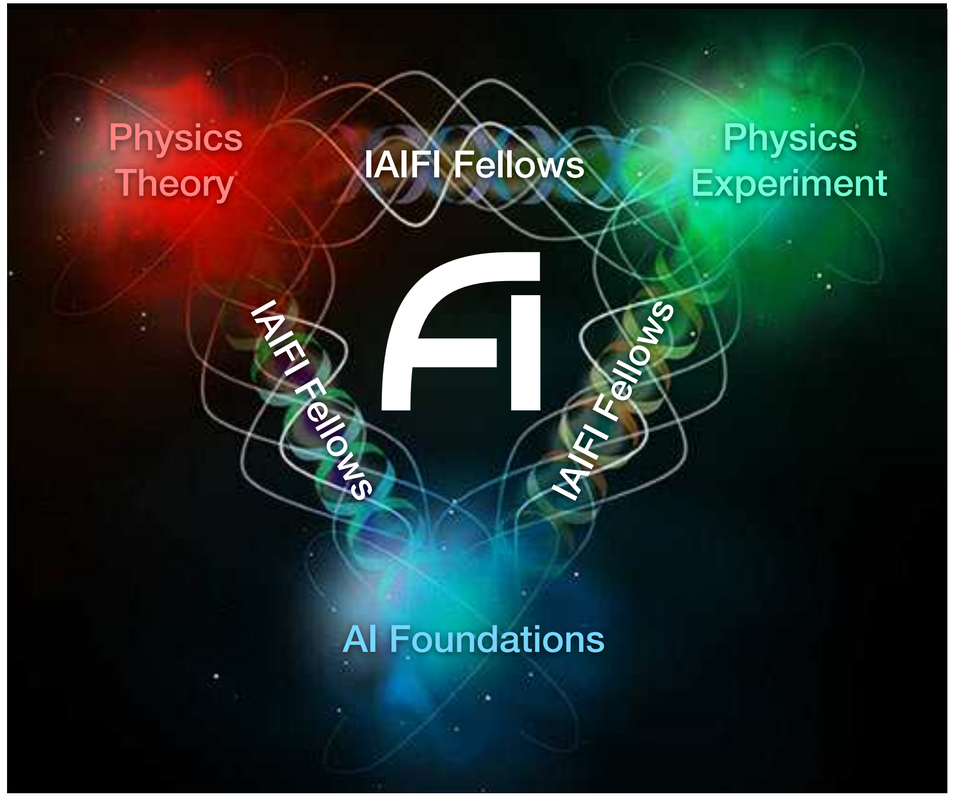
Anna Golubeva

Di Luo

Siddharth Mishra-Sharma

Ge Yang

and you?



Progress driven by early-career talent with cross-disciplinary expertise

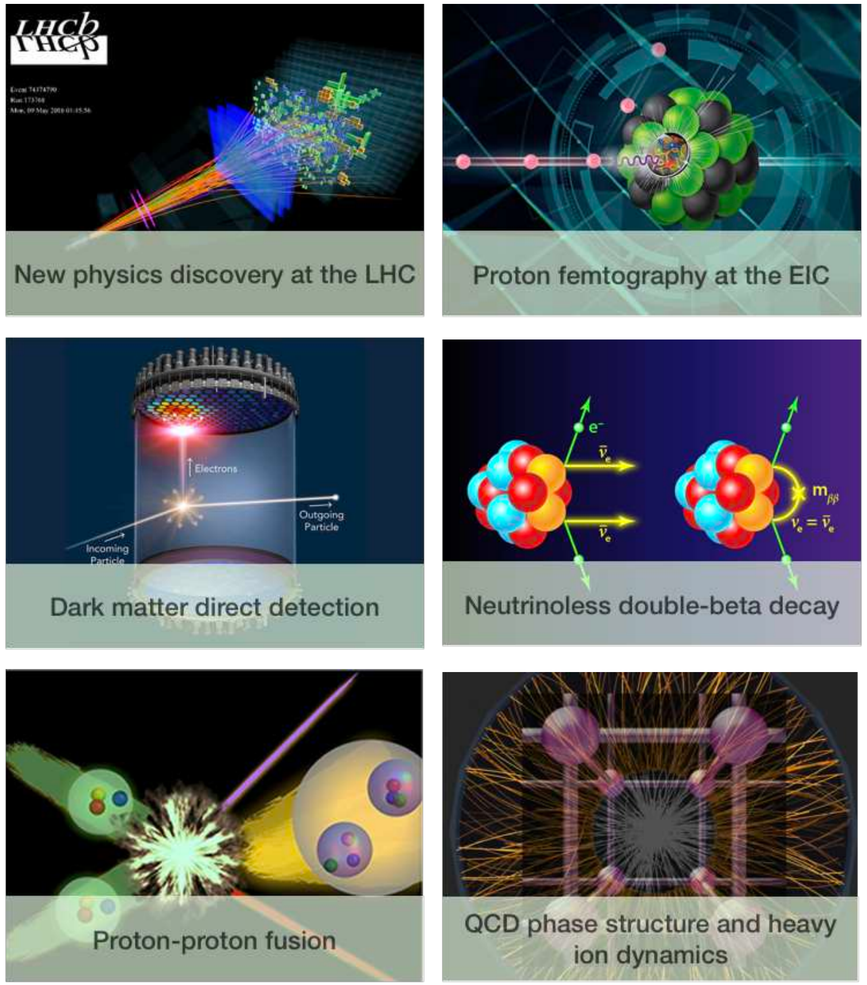
[Applications open again in Summer 2022, https://iaifi.org/fellows.html]

AI²: Ab Initio Artificial Intelligence

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

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

AI² for Theoretical Physics



E.g. Lattice Field Theory for Nuclear/Particle Physics

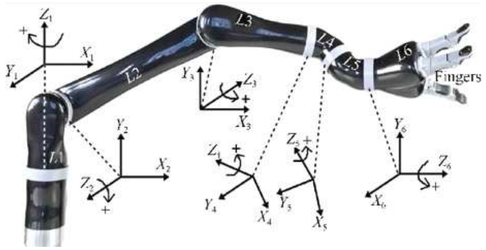
Industry collaboration to develop custom AI tools

Google DeepMind Massachusetts Institute of Technology

Achieves 1000-fold acceleration while
preserving symmetries & guaranteeing exactness

Tools designed for physics find
interdisciplinary applications

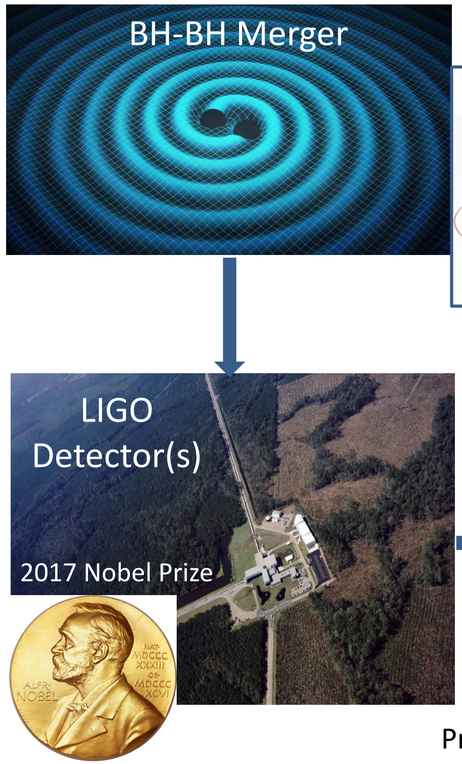
Robotics

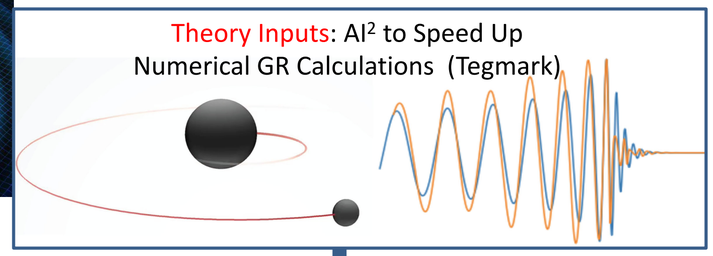


[Kanwar, Albergo, Boyda, Cranmer, Hackett, Racanière, Rezende, Shanahan, PRL 2020]

AI² for Experimental Physics

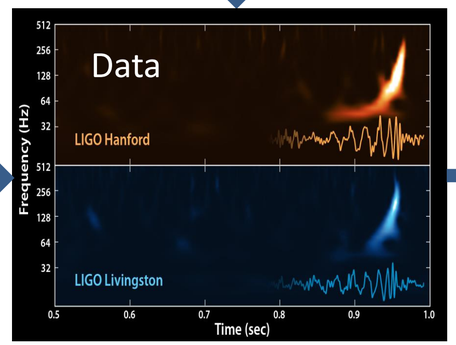
E.g. Gravitational Wave Interferometry at LIGO

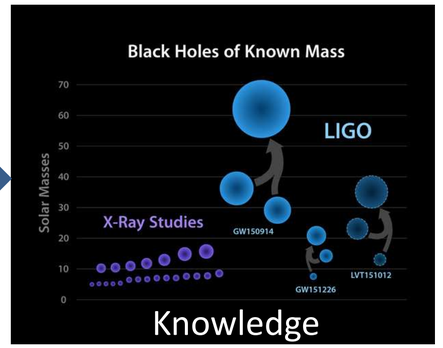




LHC Fast-ML to speed up multi-messenger astrophysics (Harris)

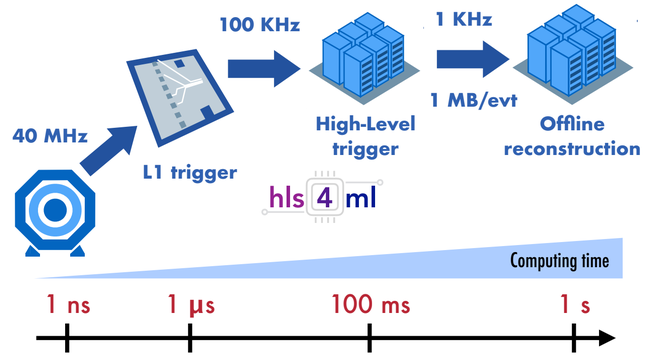
Autoencoders improve LIGO's sensitivity by 20% [2005.06534]

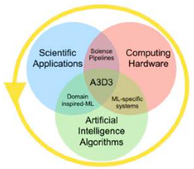




Propose using RL for Noise Reduction (Barsotti, Rakhlin)

Outgrowth of Sub-Microsecond Inference for LHC Triggering



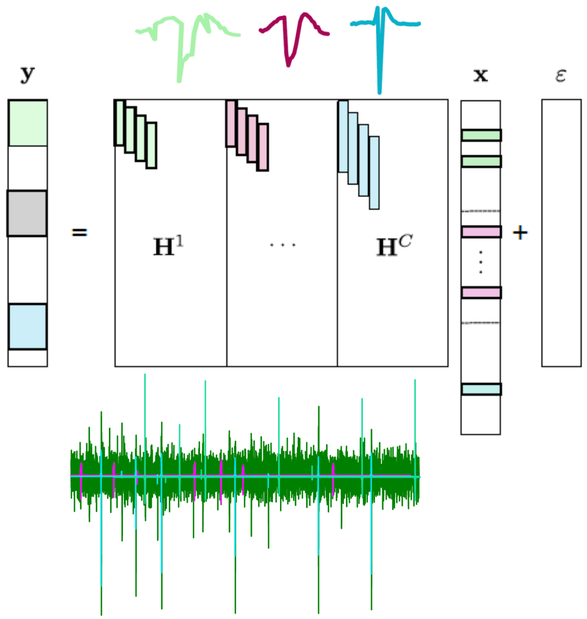


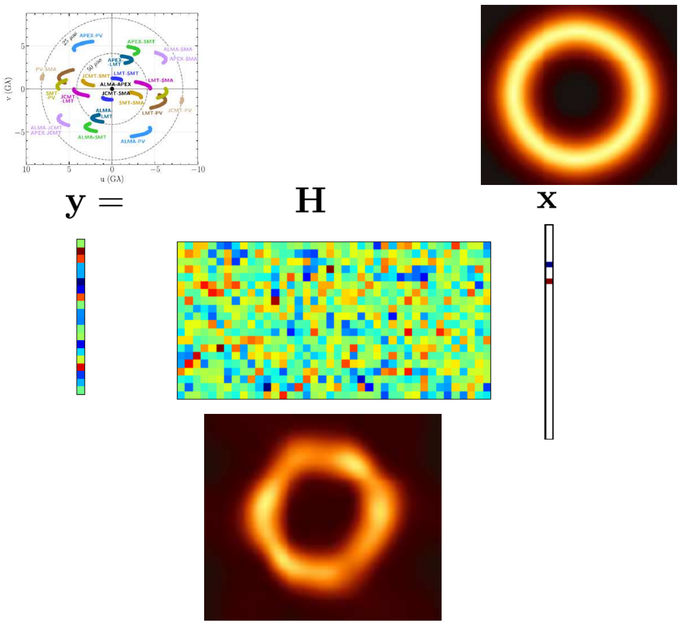
New NSF Institute! Accelerated AI Algorithms for Data-Driven Discovery

[Duarte, Han, Harris, Jindariani, Kreinar, Kreis, Ngadiuba, Pierini, Rivera, Tran, Wu, JINST 2018]

AI² for Foundational AI

E.g. Deconvolution Across Disciplines

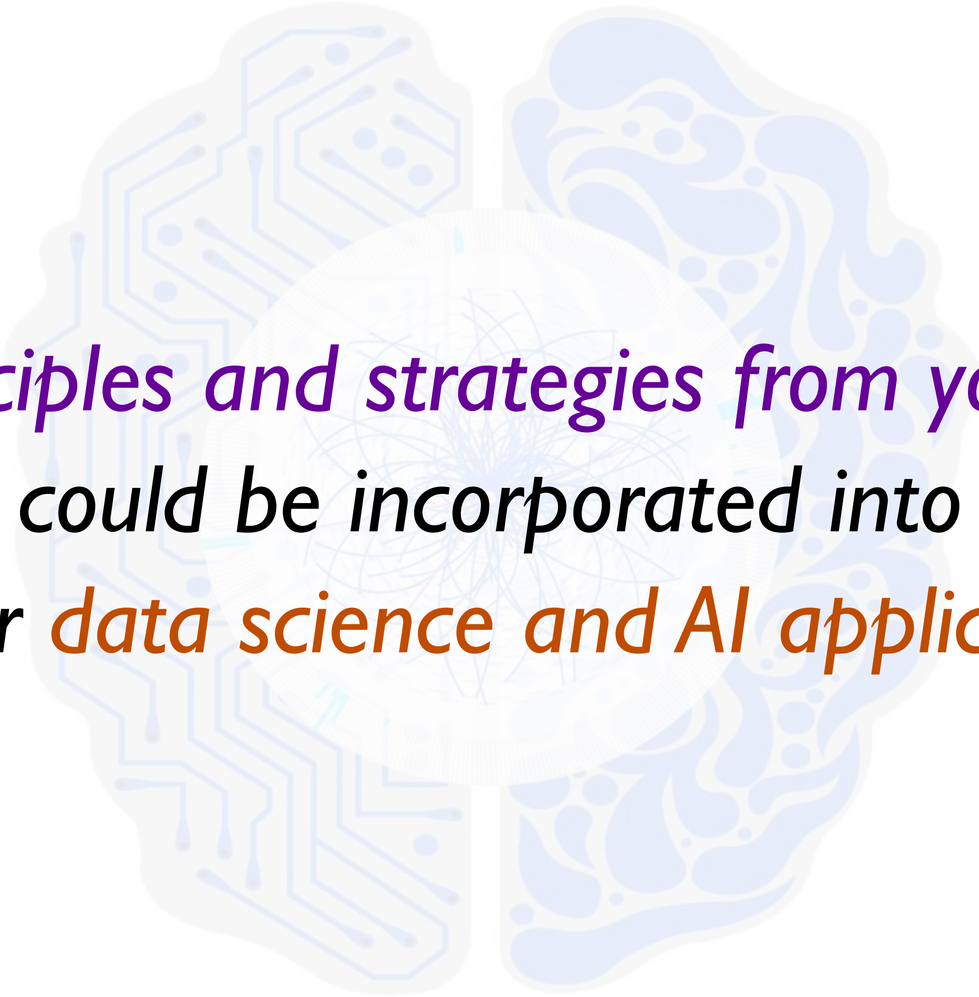




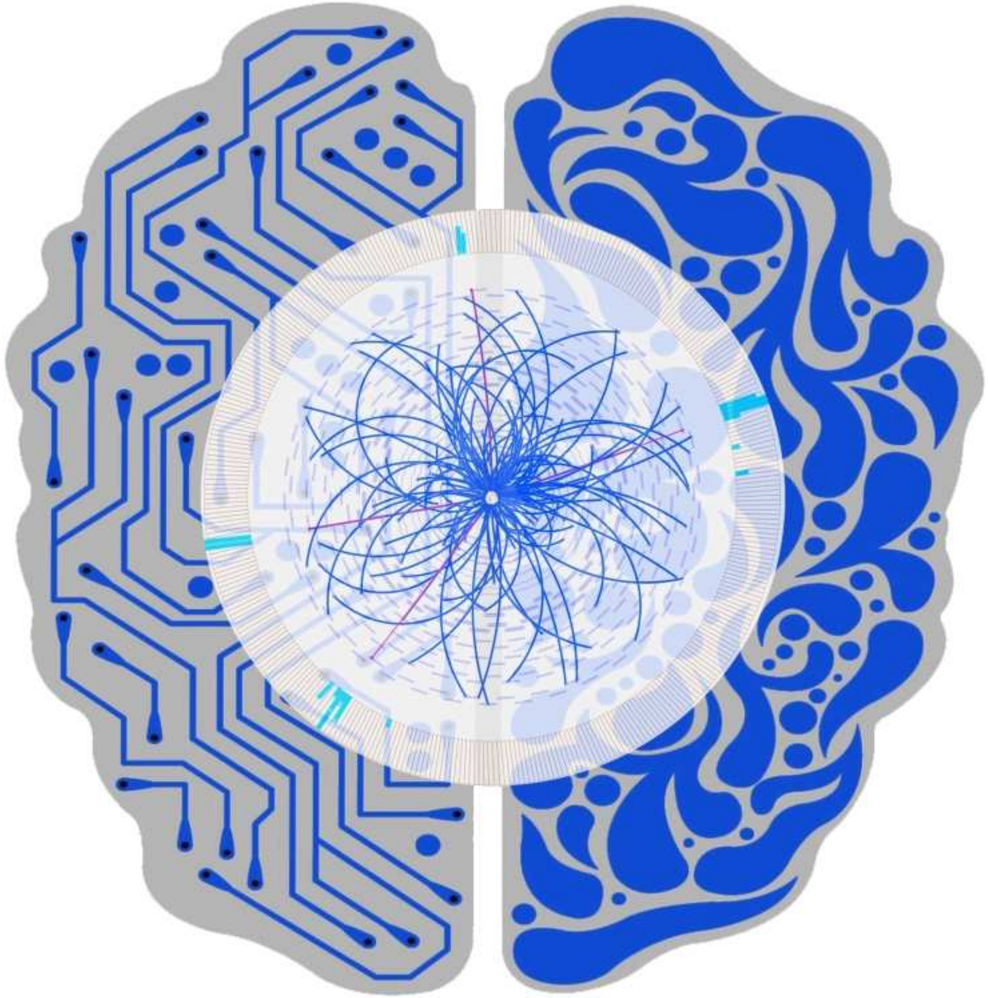
Sparse Coding Networks and Neuronal Source Separation

Event Horizon Telescope and Black Hole Imaging

[Ba; Freeman]



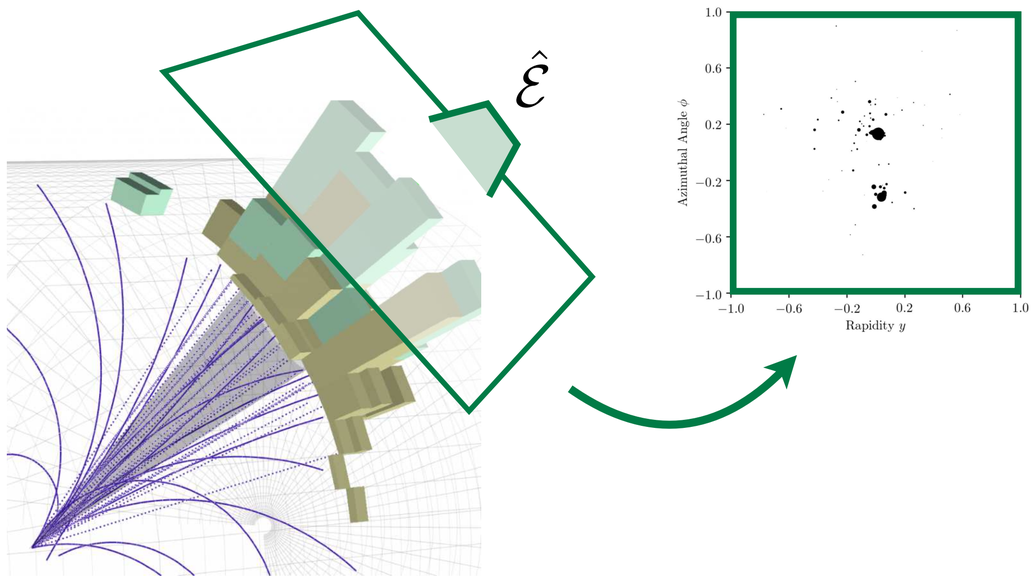
What principles and strategies from your domain could be incorporated into broader data science and AI applications?

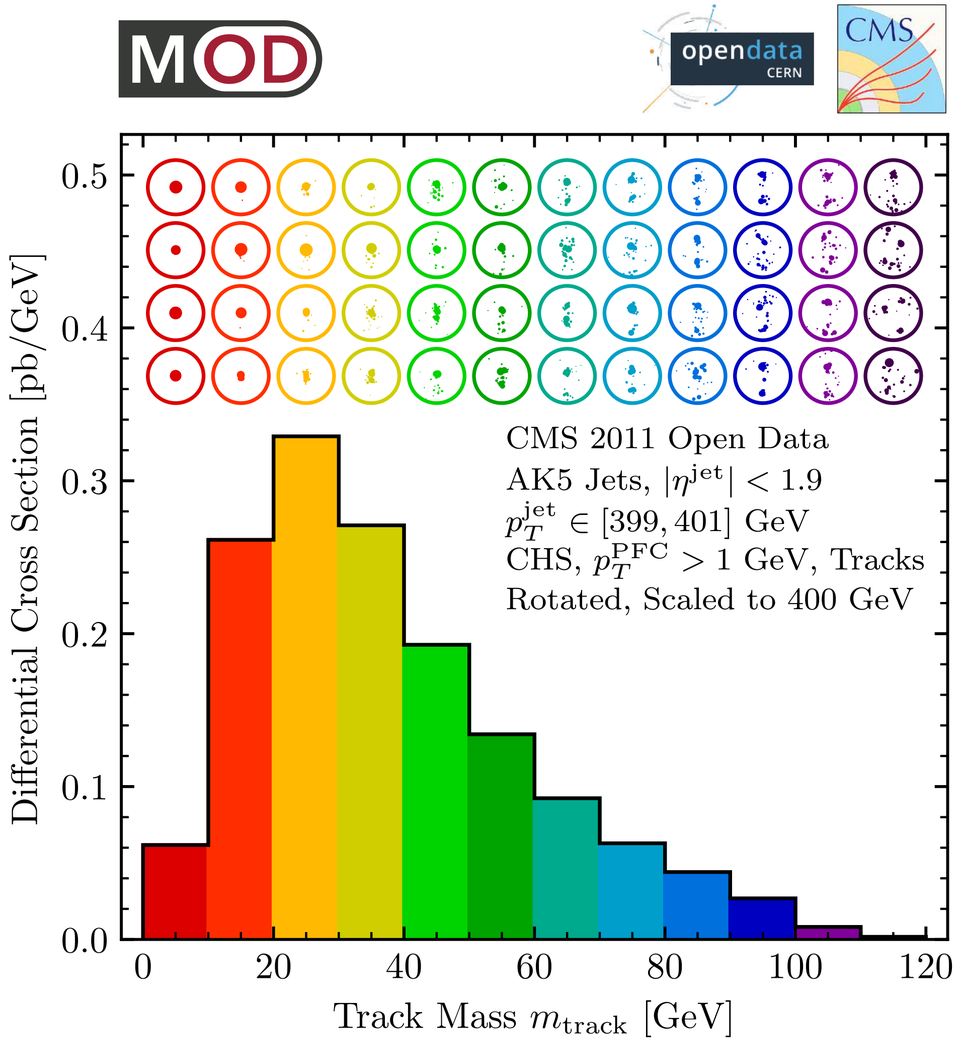


Can we teach a physicist to "think" like a machine?

The Forest and the Trees

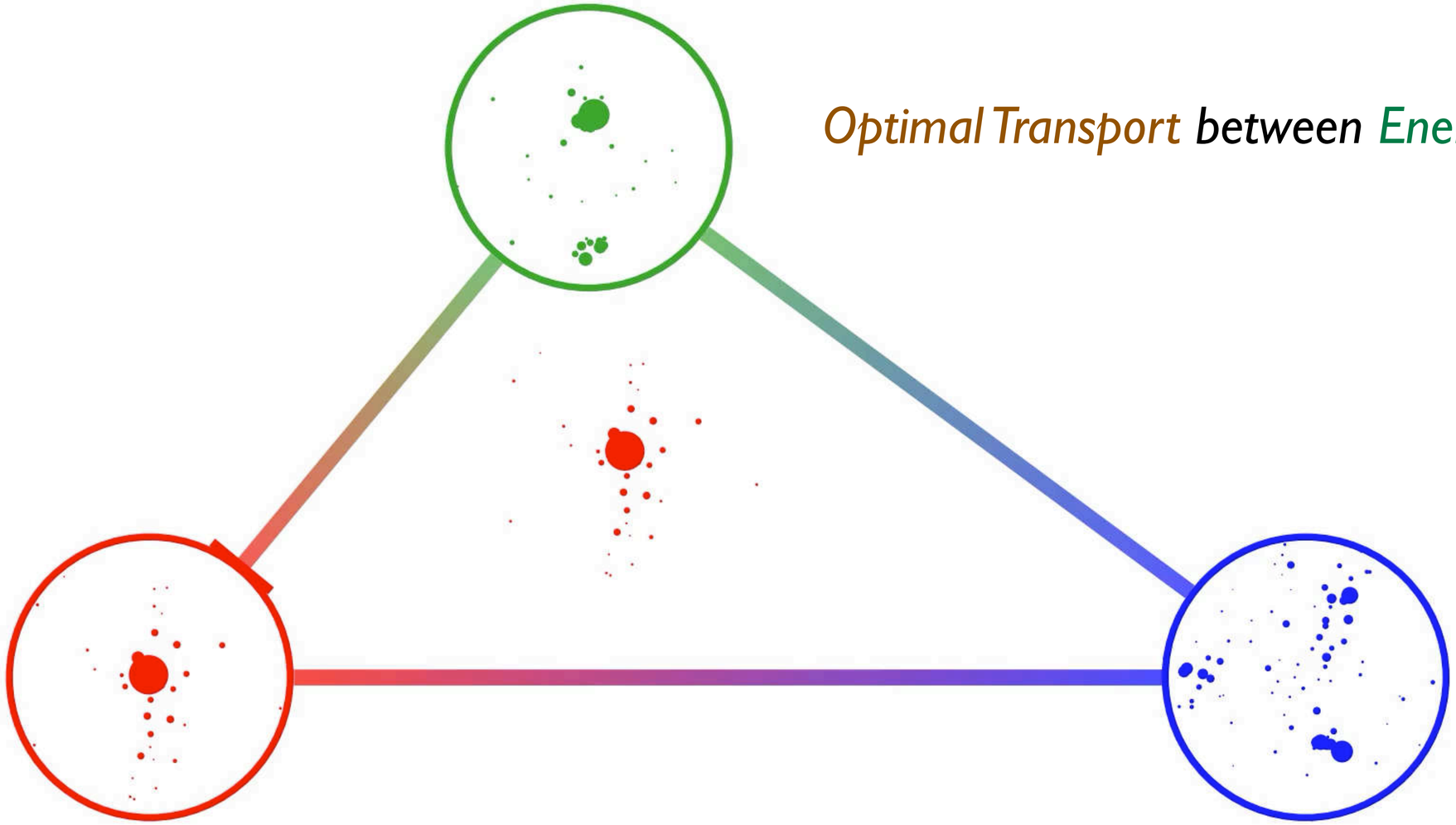
Building a Histogram of Observables





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

Triangulating a Social Network of Trees

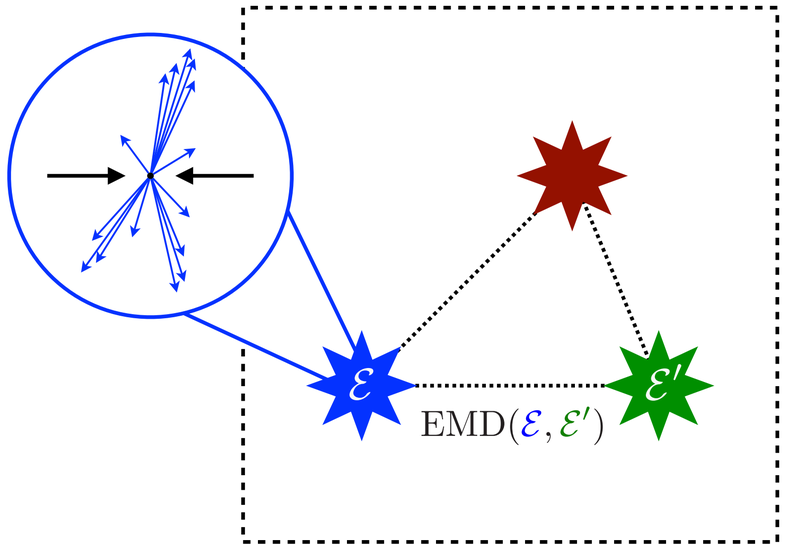


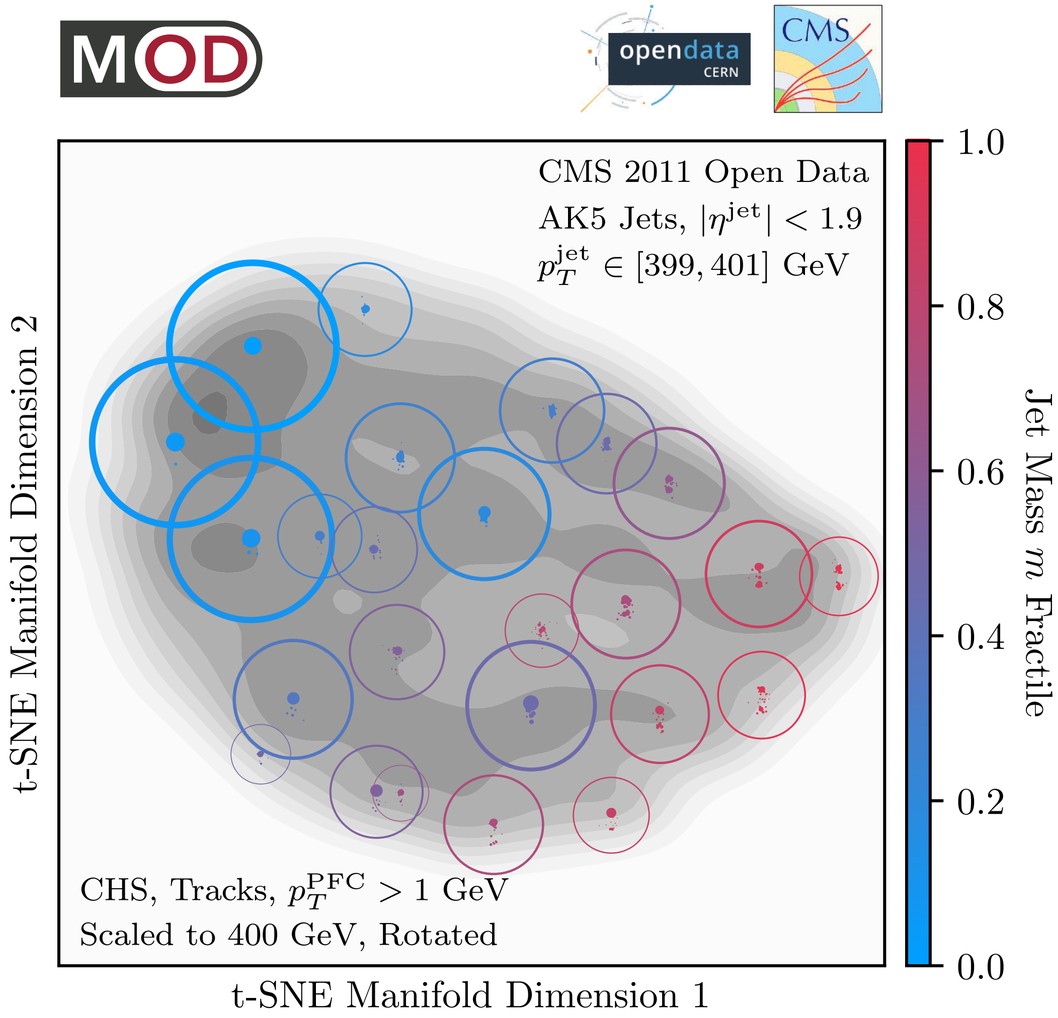
Optimal Transport between *Energy Flows*

[Komiske, Metodiev, JDT, PRL 2019; see variant in Crispim Romão, Castro, Milhano, Pedro, Vale, EPJC 2021]

A Forest made from Trees

Building the Space of Energy Flows

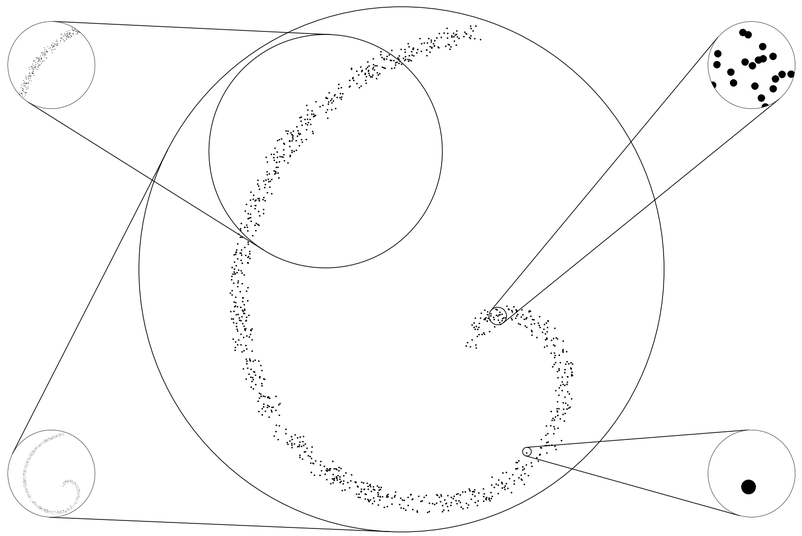


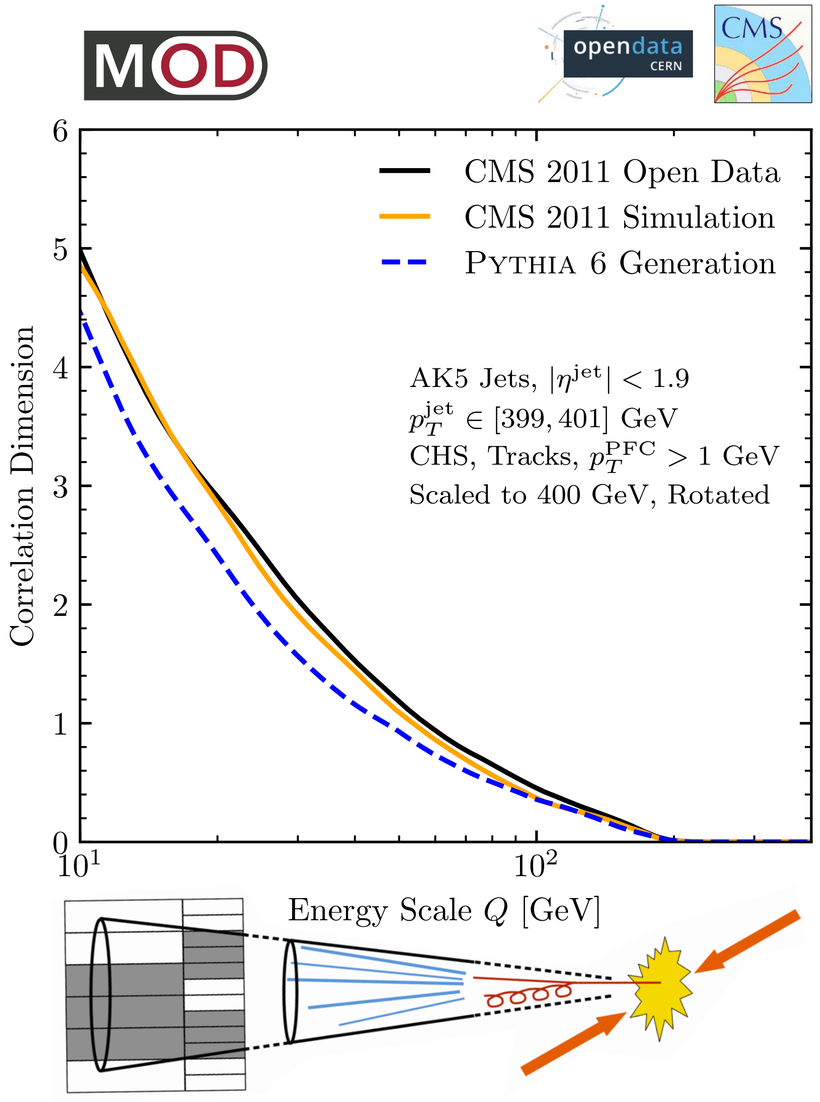


[Komiske, Mastandrea, Metodiev, Naik, JDT, PRD 2020]

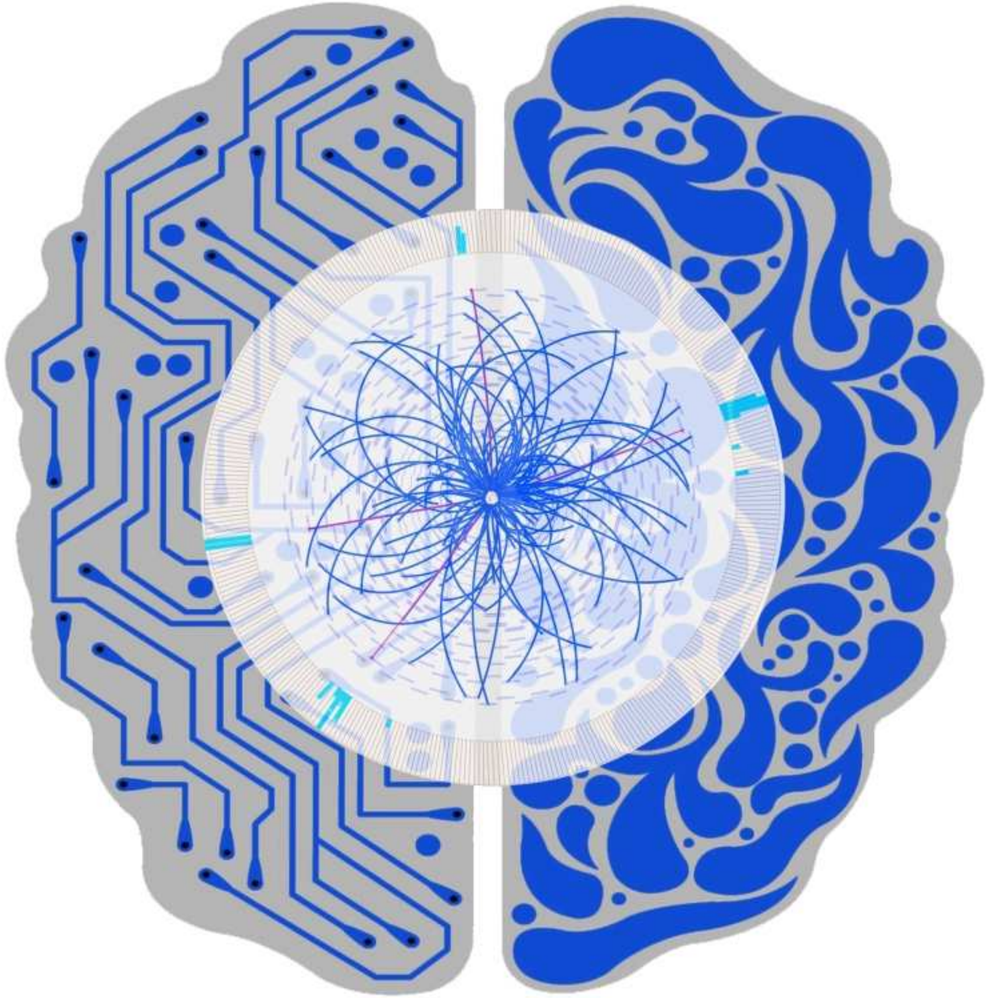
A Super-Fractal Forest made from Trees

Dimensionality of the Space of Energy Flows

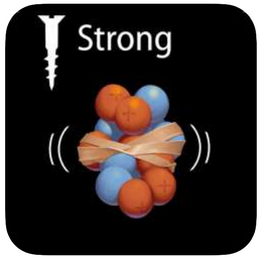




[Komiske, Mastandrea, Metodiev, Naik, JDT, PRD 2020]



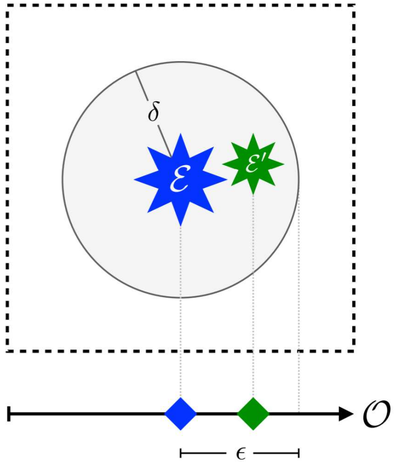
We taught ourselves to "think" like a machine…

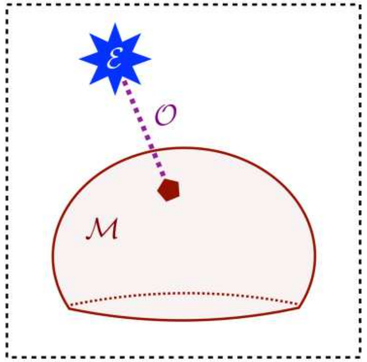


…and we gained new insights into strong force!

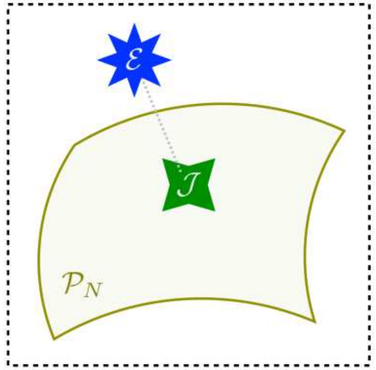
Six Decades of Collider Physics Translated into New Geometric Language!

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

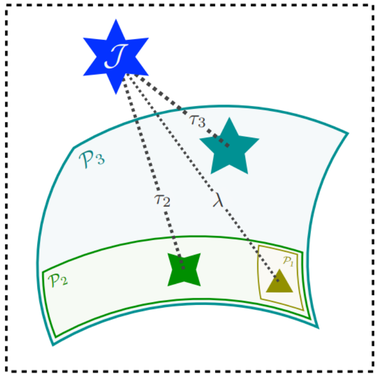




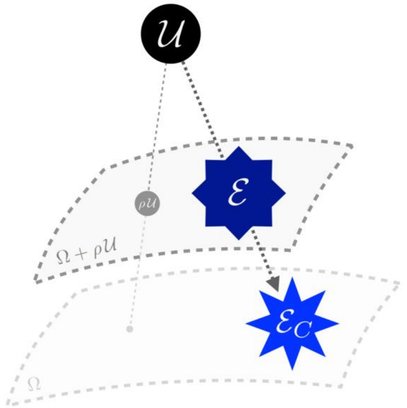
$$\mathcal{O}(\mathcal{E}) = \min_{\mathcal{E}' \in \mathcal{M}} \mathrm{EMD}_{\beta,R}(\mathcal{E}, \mathcal{E}')$$



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



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



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

Taming infinities

Event Shapes

Jet Algorithms

Jet Substructure

Pileup

1960

2020

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

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]

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

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

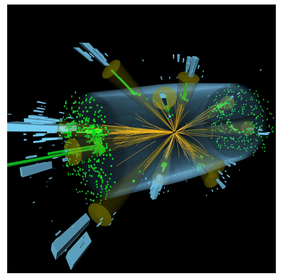
2014-2019
Constituent Subtraction
[Berta, Spousta, Miller, Leitner, JHEP 2014]
[Berta, Masetti, Miller, Spousta, JHEP 2019]

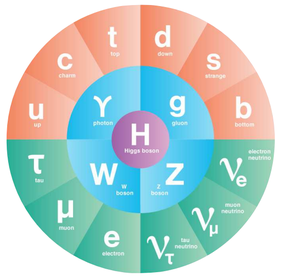
And many more!

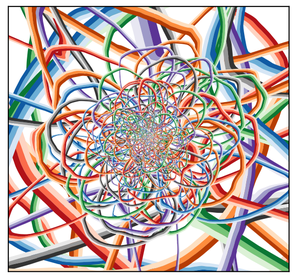
“Collision Course”

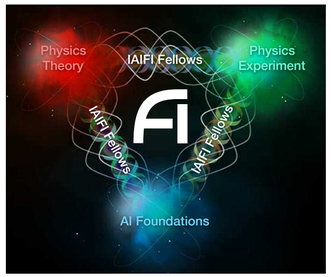
Physical Sciences

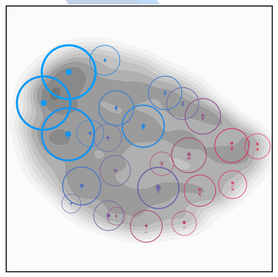
Mathematics, Statistics, Computer Science

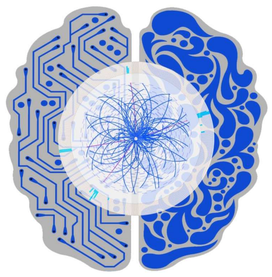


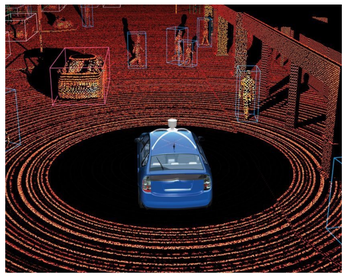


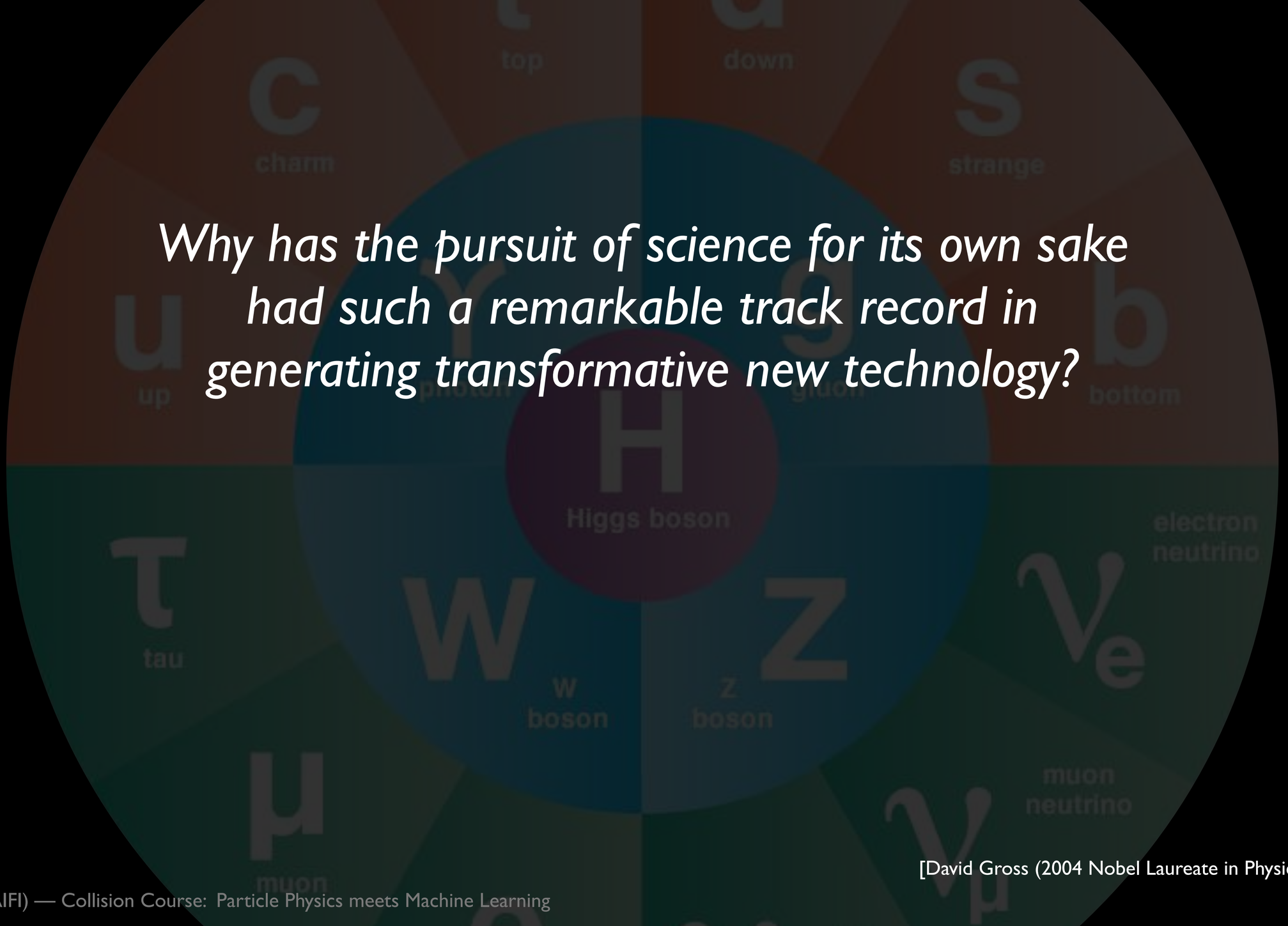












Why has the pursuit of science for its own sake had such a remarkable track record in generating transformative new technology?

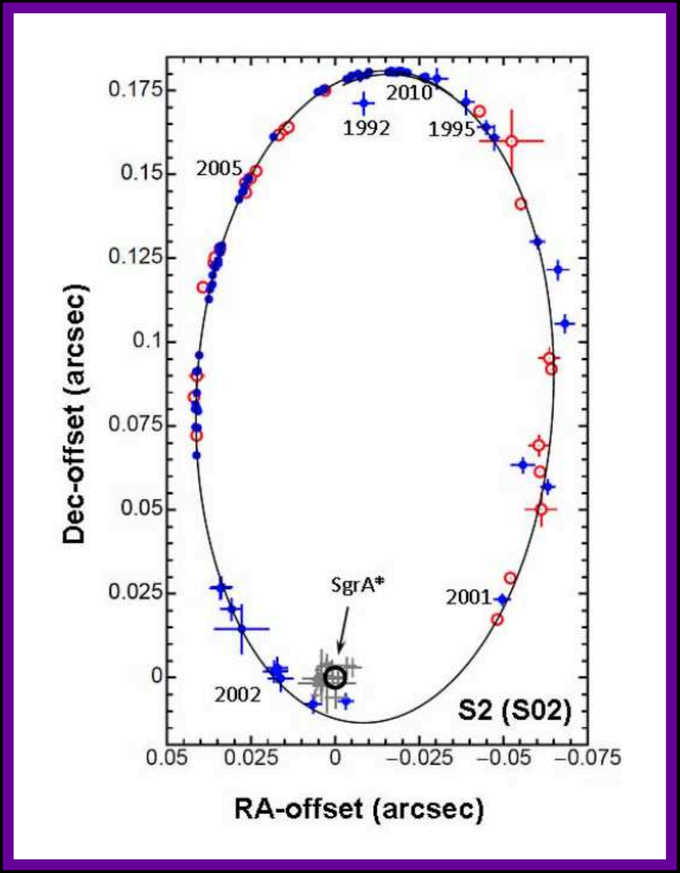
[David Gross (2004 Nobel Laureate in Physics), IJMPA 2016]

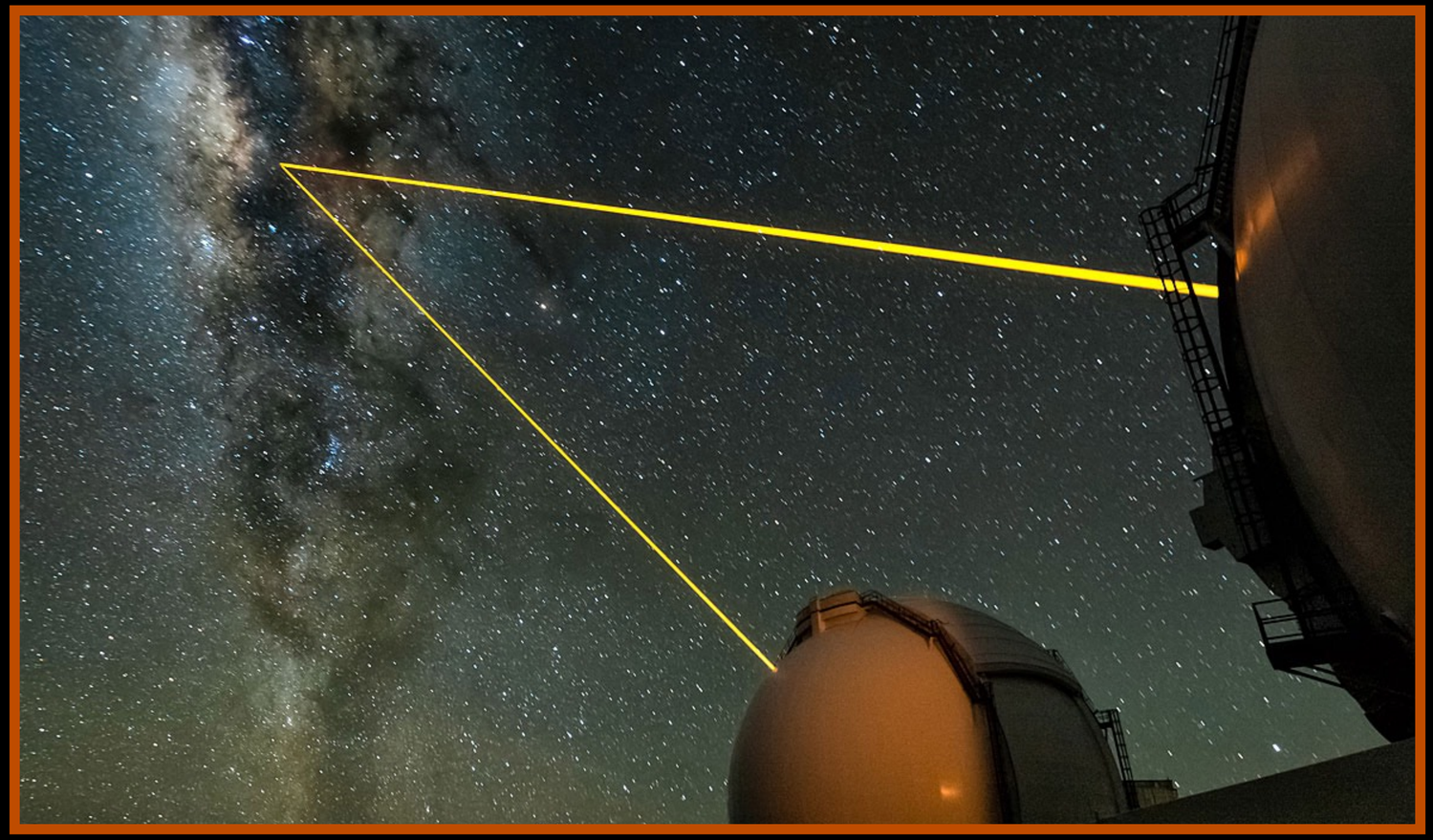
Why has the pursuit of science for its own sake had such a remarkable track record in generating transformative new technology?

The reason must be that Nature poses deeper and more challenging questions than humans can do, and the struggle to understand Nature forces us to invent better and deeper ideas than we would if left to our devices.

[David Gross (2004 Nobel Laureate in Physics), IJMPA 2016]

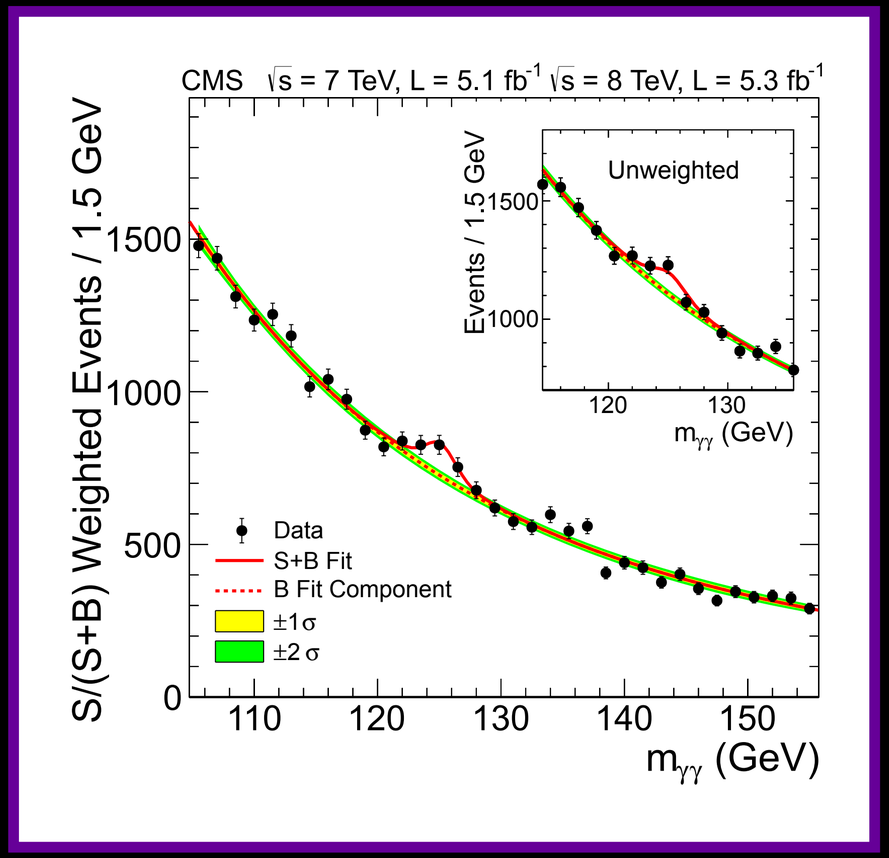
Sagittarius A*: Supermassive Black Hole in Heart of our Galaxy

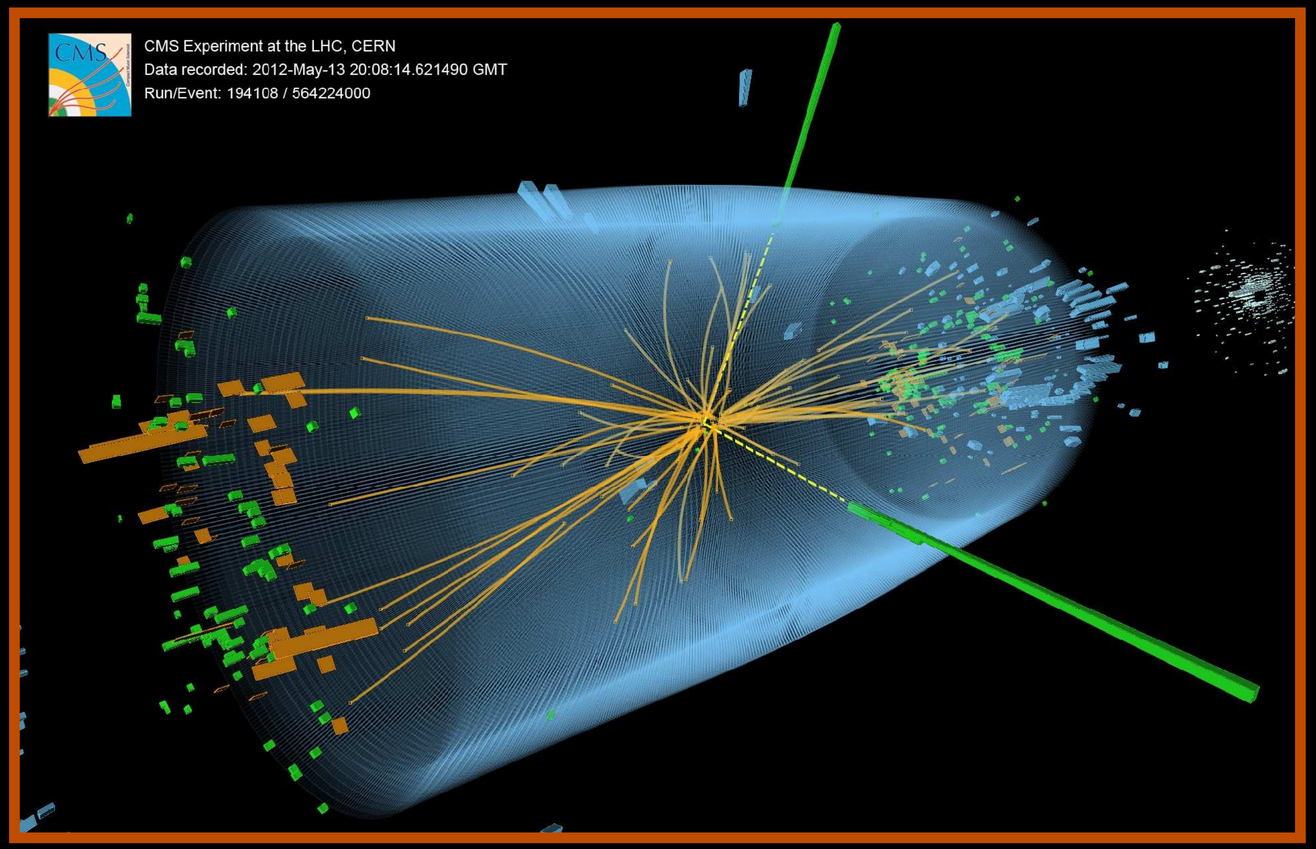




[2020 Nobel Prize in Physics: Penrose, Genzel, Ghez]

Higgs Boson: Fundamental Particle at Heart of Standard Model





[2013 Nobel Prize in Physics: Englert, Higgs]