From hadrons to hidden assumptions: My recent work in quantum chromodynamics and foundations of physics

Christine A. Aidala
University of Michigan

University of Michigan
September 11, 2019

Acknowledgments

National Science Foundation

U.S. DEPARTMENT OF ENERGY
Office of Science

FULBRIGHT

University of Michigan
Associate Professor Support Fund

M cubed

Acknowledgments: Group members 2016-present

Postdocs
- Mike Skoby
- Joe Osborn
- Sookhyun Lee

Visiting Postdoc
- Trambak Bhattacharyya

Visiting Scholars
- Dylan Manna
- Duraid Asha

Post-Bachelor's
- Tyler Ulrich
- Daniel Zile

High School Student
- Benjamin Kovacs

Ph.D. Students
- Bryan Ramson
- Joe Osborn
- Catherine Ayuso
- Nicole Lewis
- Enrique Gamez
- Kara Mattioli
- William Dean
- Jordan Roth
- Cynthia Nunez
- Desmond Shangase
- Dillon Fitzgerald
- Chami Amarasinghe
- Ceren Dag

Undergraduates
- Ezra Lesser
- Ruby Araj
- Nick Kamp
- Ashley Cavanagh
- Jessen Jia
- Hayden Hansen
- Nikhil Shankar
- Jem Guhit
- Athira K V
- Waleed El Rawi
- Erik Loyd
- Anna Cooleybeck
- Yuxi Xie
- Jessie Guo
- Micah Johnson
- Julie Rakas
- Luc Le Pottier

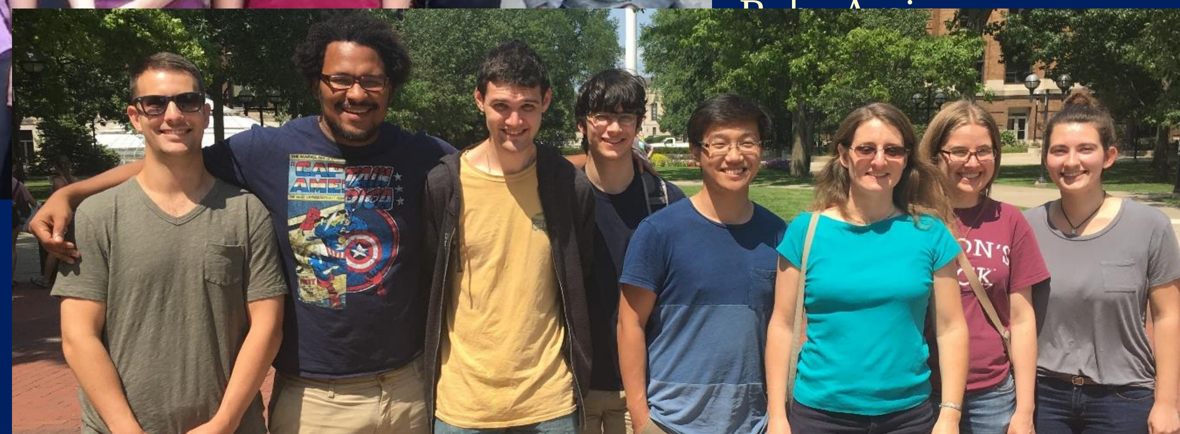
esent

ndergraduates

Ezra Lesser

Trambak Bhattacharyya

Visiting Scholars
- Dylan Manna
- Duraid Asha



- Cynthi
- Desmo Shang
- Dillon
- Chami Amara

Rawi

eybeck

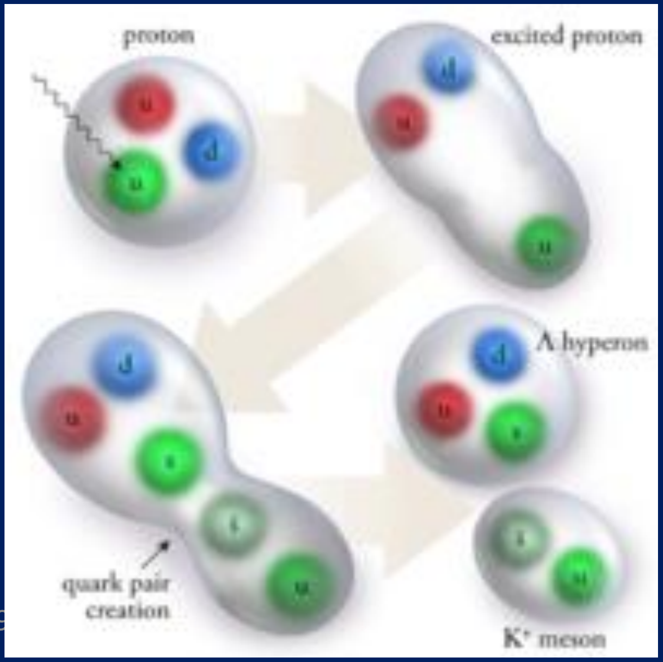
nson

tier

Quantum Chromodynamics: Theory of strong interactions

- Fundamental field theory in hand since the early 1970s—BUT . . .
- Quark and gluon degrees of freedom in the theory cannot be observed or manipulated directly in experiment!

Color *confinement*—quarks and gluons are confined to color-neutral bound states



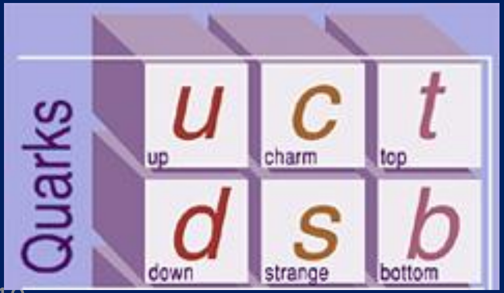
CLAS Collaboration
PRL 113, 152004 (2014)

How do we understand the visible matter in our universe in terms of the quark and gluon degrees of freedom of quantum chromodynamics?

How can studying QCD systems teach us more about fundamental aspects of QCD as a theory?

My areas of focus within QCD

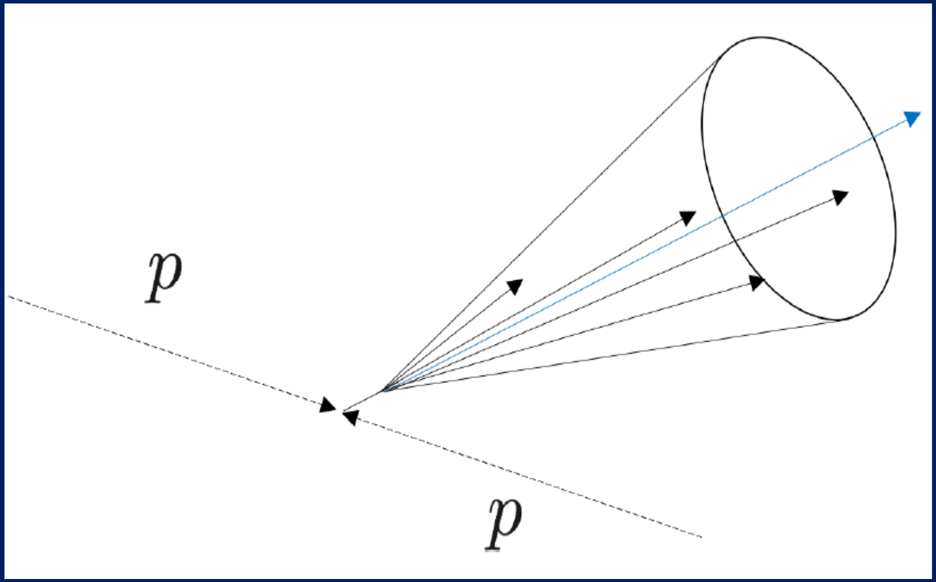
- Proton structure, specifically spin-spin and spin-momentum correlations, analogous to spin-spin and spin-orbit couplings in atoms
- Observables sensitive to non-Abelian aspects of the theory, due to the fact that gluons couple to each other
- *New focus: formation of color-neutral bound states, "hadrons," from colored quarks and gluons*
  - *"Hadronization"*



Hadron structure vs. hadron formation

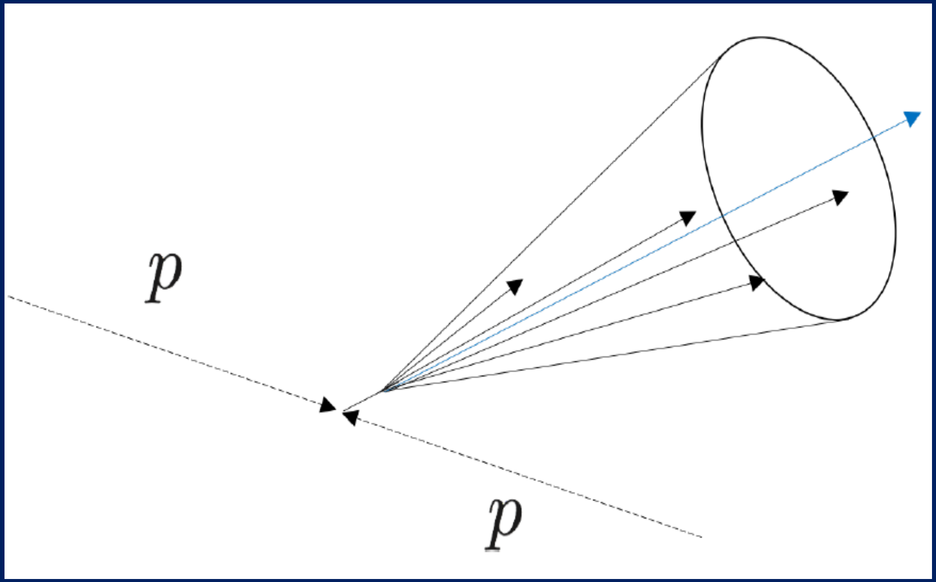
- Both relate the quark and gluon degrees of freedom of QCD to particles/states we can work with in the lab/nature
- However, hadron formation inherently dynamic—a process
  - In contrast to studying the dynamics of quarks and gluons within hadrons, e.g. via spin-momentum correlations, where really studying average dynamics
  - Thus hadronization much less developed and more open a subfield than hadron structure. . .

Jets and jet hadronization



- When a quark or gluon gets scattered out of a bound state (e.g. proton) at high energies, a series of gluon radiation and quark-antiquark pair production processes occurs
- Never see free quarks or gluons! Everything becomes part of new bound states. Get a spray of particles in your detector, a "jet"
- Developments in the last 11 years allowing robust comparison between experiment and theory have made jets powerful tools at collider facilities

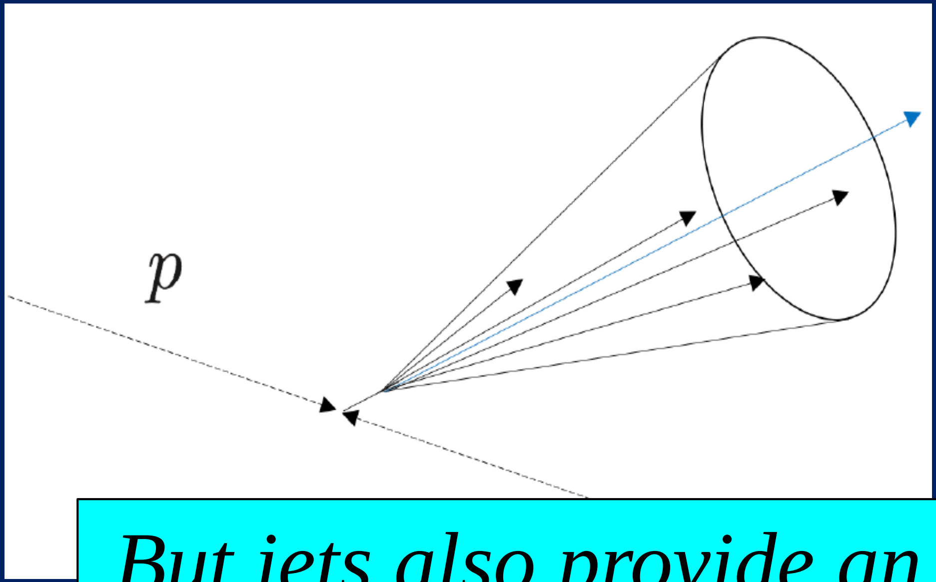
Jets and jet hadronization



- When a quark or gluon gets scattered out of a bound state (e.g. proton) at high energies, a series of gluon radiation and quark-antiquark pair production processes occurs
- Never see free quarks or gluons! Everything becomes part of new bound states. Get a spray of particles in your detector, a "jet"
- Developments in the last 11 years allowing robust comparison between experiment and theory have made jets powerful tools at collider facilities

- So a jet as a whole can provide kinematic information about the gluon or quark scattered out of a proton or produced in a decay
  - E.g. Higgs decaying to a beauty-antibeauty quark pair, observed as a jet pair

Jets and jet hadronization



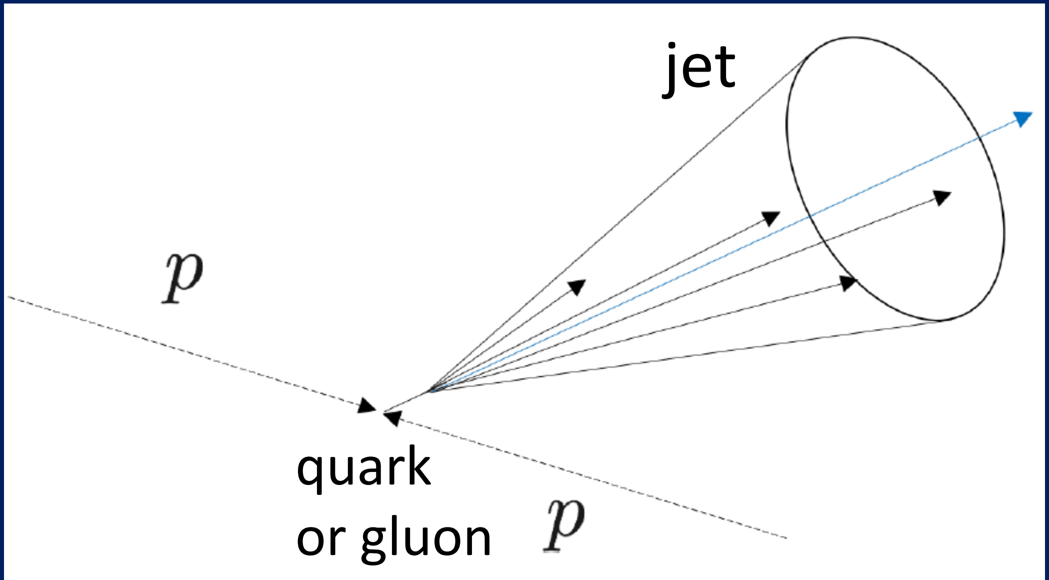
- When a quark or gluon gets scattered out of a bound state (e.g. proton) at high energies, a series of gluon radiation and quark-antiquark pair production processes occurs
- Never see free quarks or gluons! Everything becomes part of new bound states. Get a spray of particles in your detector, a "jet"
- Developments in the last 11 years allowing … nt and … at

But jets also provide an environment to study how QCD bound states form

- So a jet as a whole can provide kinematic information about the gluon or quark scattered out of a proton or produced in a decay
  – E.g. Higgs decaying to a beauty-antibeauty quark pair, observed as a jet pair

Understanding hadronization: A wish list

Courtesy Joe Osborn

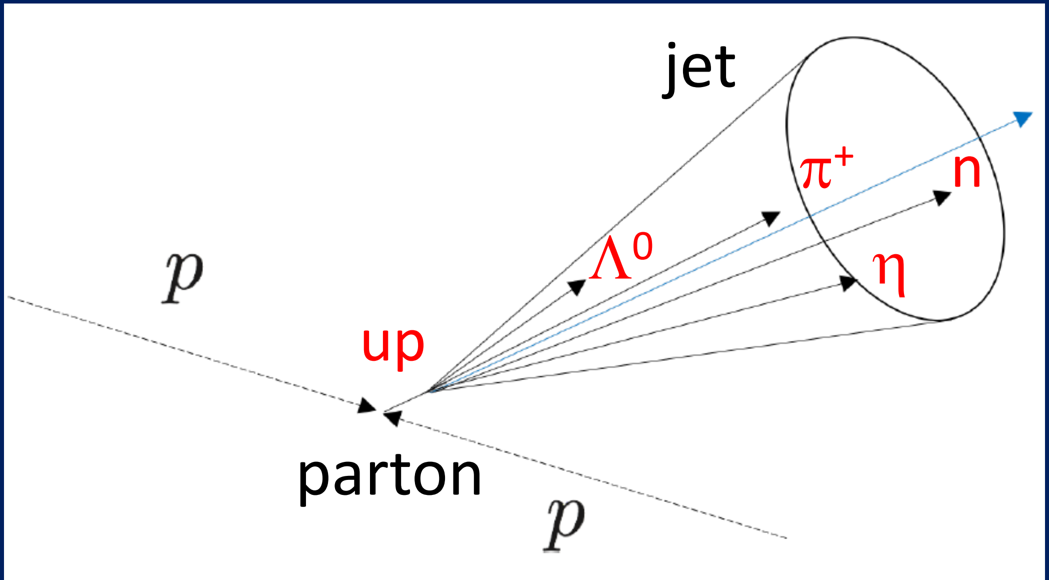


1. A way to connect the outgoing quark or gluon to the final-state hadrons

   - Jets

Understanding hadronization: A wish list

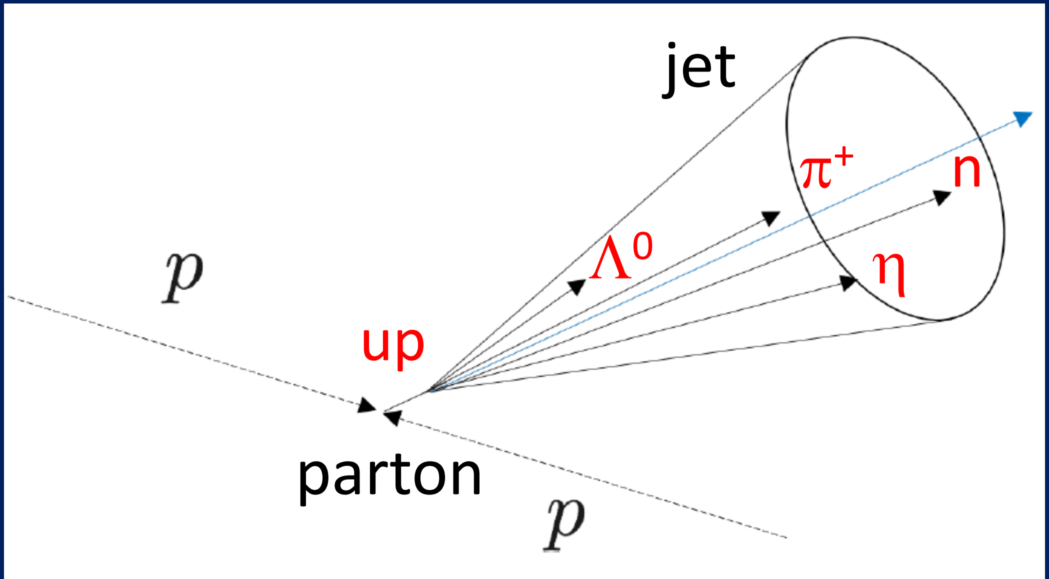
Courtesy Joe Osborn



1. A way to connect the outgoing quark or gluon to the final-state hadrons
   - Jets
2. Complete information on the flavor of the outgoing quark and the types of produced particles

Understanding hadronization: A wish list

Courtesy Joe Osborn



- Baryon vs. meson
- Correlations (e.g. strangeness, heavy flavor)
- Resonance production (ϕ, J/ψ, Y)
- …

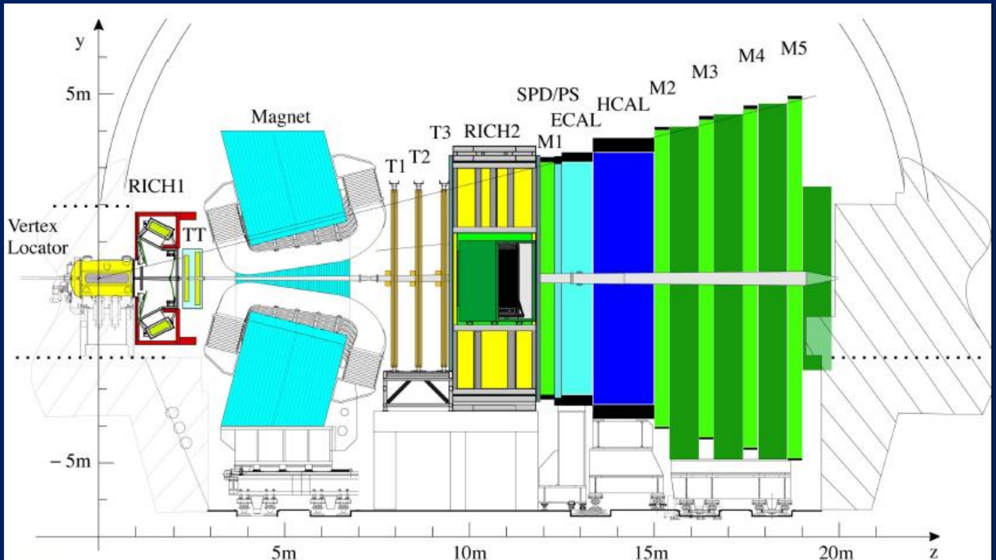
1. A way to connect the outgoing quark or gluon to the final-state hadrons
   - Jets
2. Complete information on the flavor of the outgoing quark and the types of produced particles

The Large Hadron Collider beauty experiment

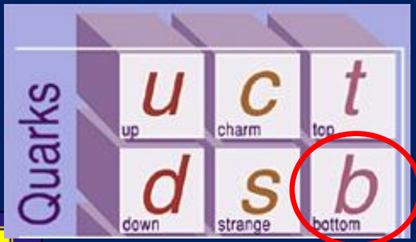
LHCb is the experiment devoted to heavy flavor at the LHC

Detector design:

- Forward geometry (close to beam pipe) to optimize acceptance for $b\bar{b}$ pairs: $2 < \eta < 5$
- Particle ID: Excellent capabilities to select exclusive decays



JINST 3, (2008) S08005
Int.J.Mod.Phys.A30 (2015) 1530022

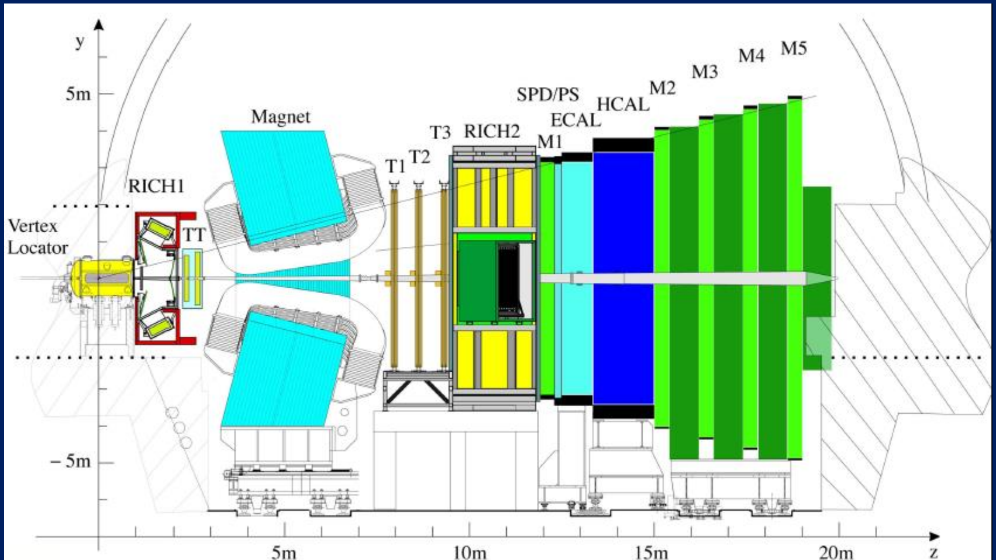


The Large Hadron Collider beauty experiment

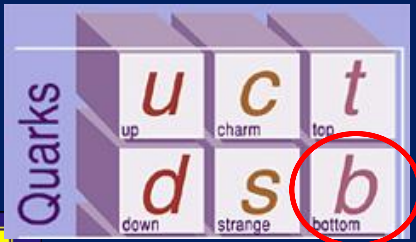
LHCb is the experiment devoted to heavy flavor at the LHC

Detector design:

- Forward geometry (close to beam pipe) to optimize acceptance for $b\bar{b}$ pairs: $2 < \eta < 5$
- Particle ID: Excellent capabilities to select exclusive decays



JINST 3, (2008) S08005
Int.J.Mod.Phys.A30 (2015) 1530022



Some features specifically attractive for hadronization:

- Full jet reconstruction with tracking, ECAL, HCAL
  - Identification of jets from charm and beauty quarks
- Charged hadron identification from $2 < p < 100$ GeV

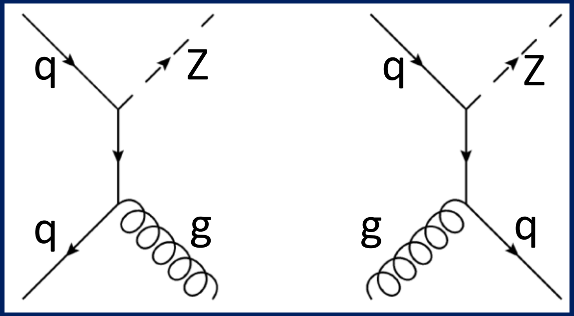
Can study identified particle distributions within jets!


Large Hadron Collider
CMS
p
p
LHCb
ATLAS
ALICE

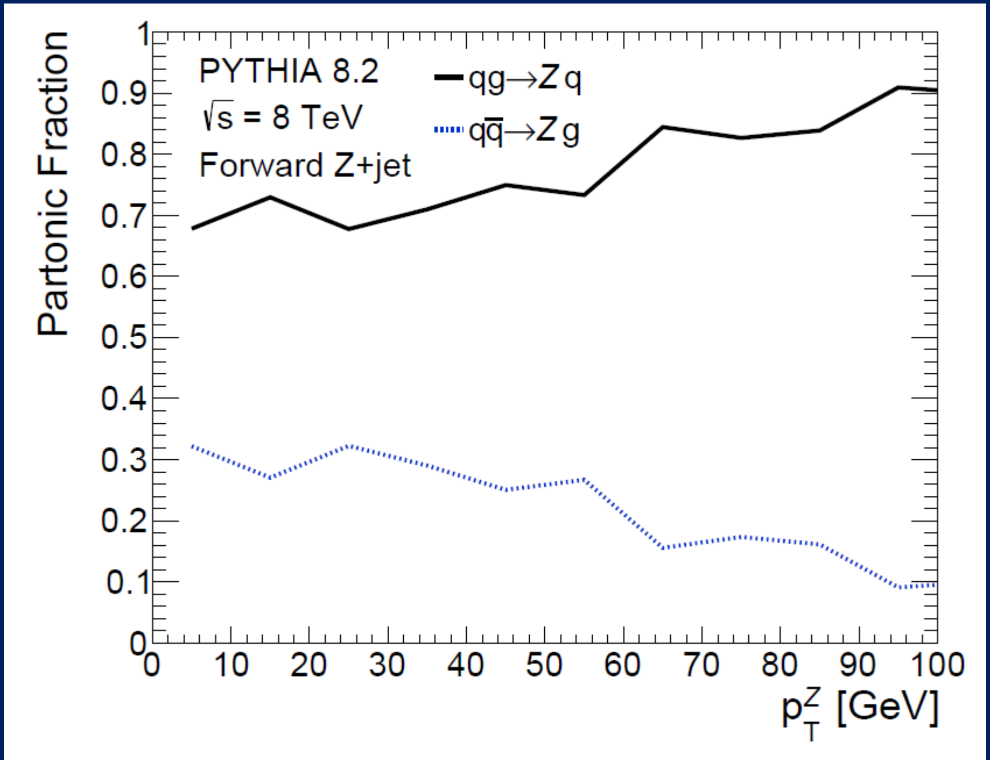
LHCb Collaboration

- ~850 scientists from 79 institutions in 18 countries
  - The “small” LHC experiment!
- U-M officially admitted as new collaborating institution Sep 2017
  - First nuclear-funded group in U.S. for LHCb (NSF)

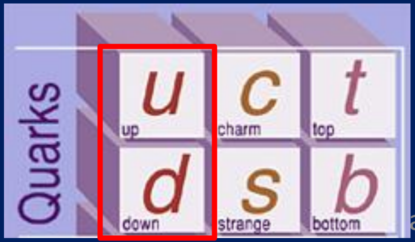
Studying hadronization in jets: Forward Z boson+jet



- Z boson+jet is predominantly sensitive to quark jets



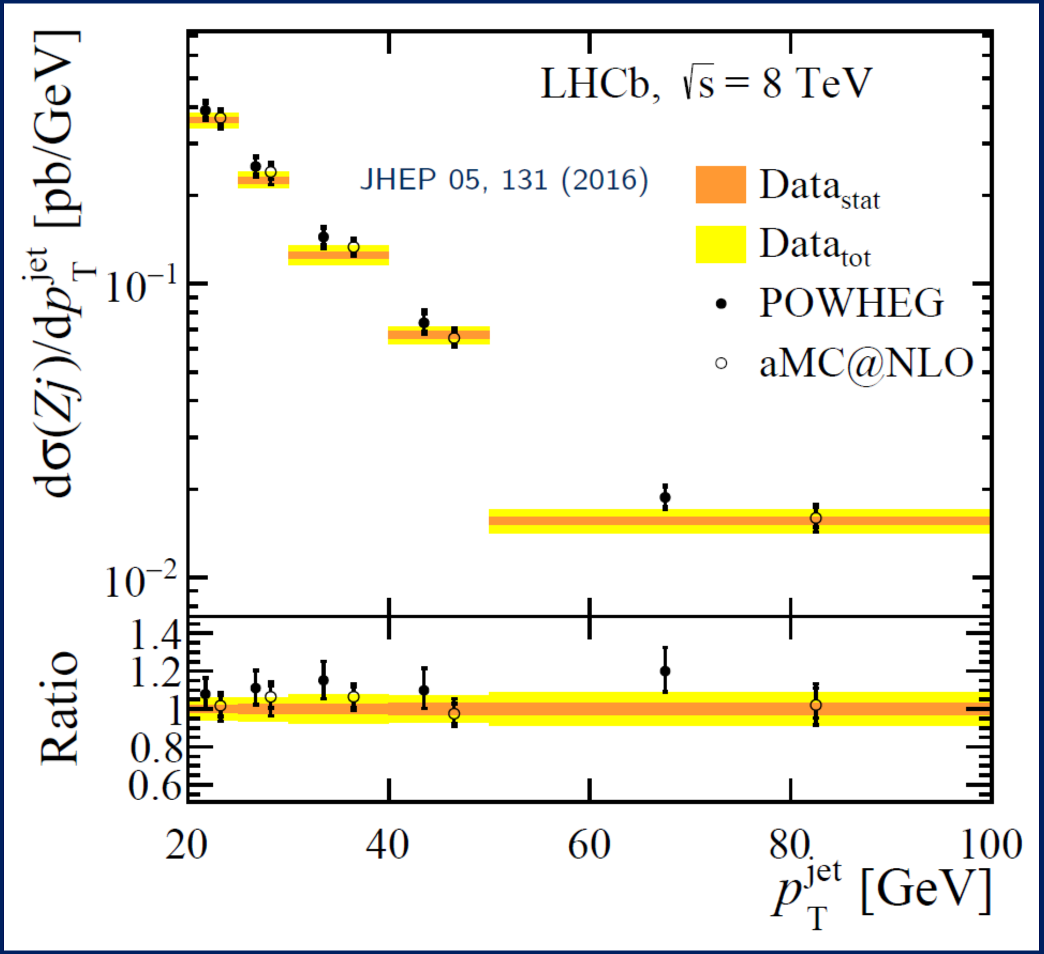
- Forward kinematics further increases fraction of *light* quark jets, in particular up and down flavored quarks



Studying hadronization in jets: Forward Z boson+jet

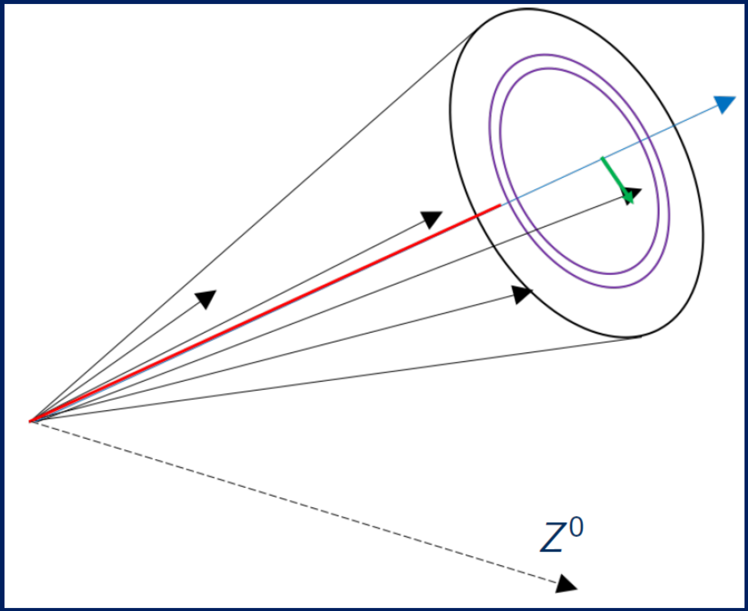
- LHCb previously measured the forward Z+jet cross section
  - JHEP 05, 131 (2016)

- Now have measured charged hadron distributions within the jet, in the same data set
  - arXiv:1904.08878
- First measurement at the LHC of charged hadrons within Z-tagged jets
- First measurement at the LHC of charged hadrons-in-jets at forward rapidity



Charged hadrons in jets: Observables

- Longitudinal momentum fraction z
  - Historically, this has typically been the only observable considered
- Transverse momentum with respect to jet axis j_T
- Radial profile r



$$z = \frac{p_{jet} \cdot p_h}{|p_{jet}|^2}$$

$$j_T = \frac{|p_h \times p_{jet}|}{|p_{jet}|}$$

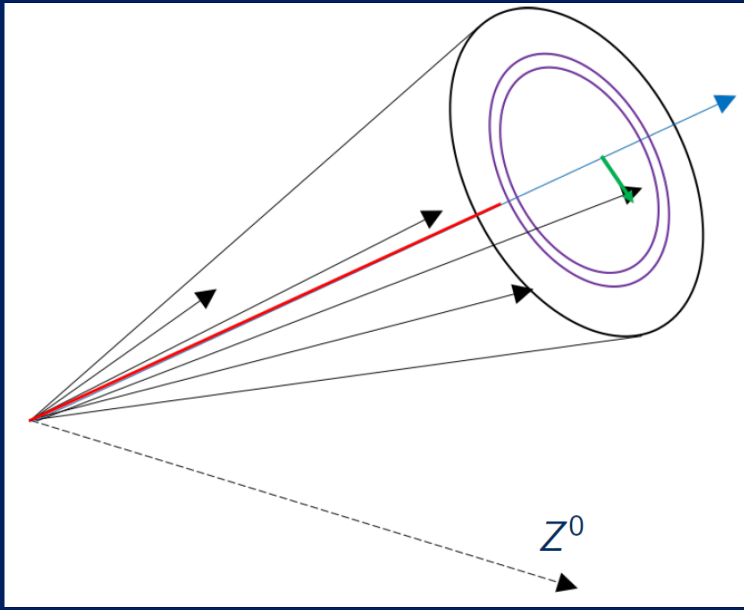
$$r = \sqrt{(\phi_h - \phi_{jet})^2 + (y_h - y_{jet})^2}$$

Charged hadrons in jets: Observables

- Longitudinal momentum fraction z
  - Historically, this has typically been the only observable considered
- Transverse momentum with respect to jet axis j_T
- Radial profile r

Lays the foundation for a broader hadronization program at LHCb utilizing

- Full particle identification!
  - Unprecedented within jets produced at a hadron collider
- Charm- and beauty-initiated jets
- Resonance production within jets
- Multiparticle correlations within a jet
- Hadron distributions in correlated jet pairs



$$z = \frac{p_{jet} \cdot p_h}{|p_{jet}|^2}$$

$$j_T = \frac{|p_h \times p_{jet}|}{|p_{jet}|}$$

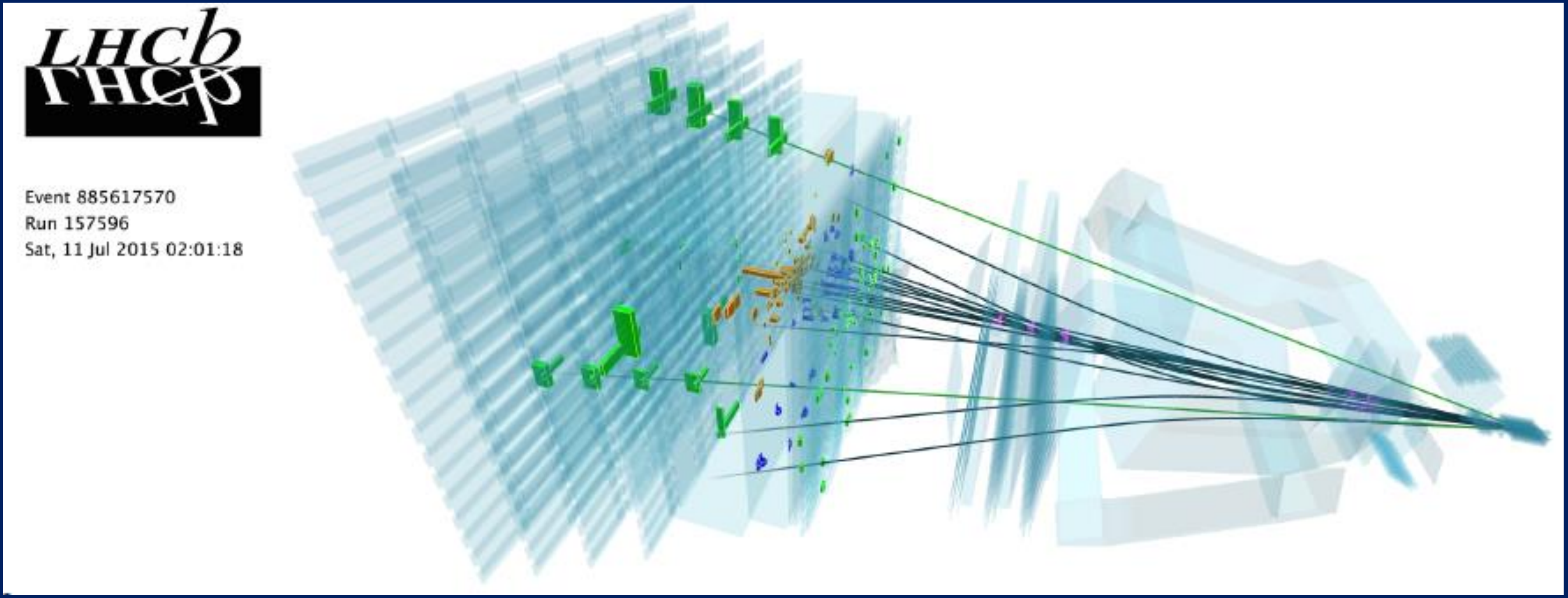
$$r = \sqrt{(\phi_h - \phi_{jet})^2 + (y_h - y_{jet})^2}$$

Work by former PD Joe Osborn

arXiv:1904.08878
LHCb-PAPER-2019-012

Analysis

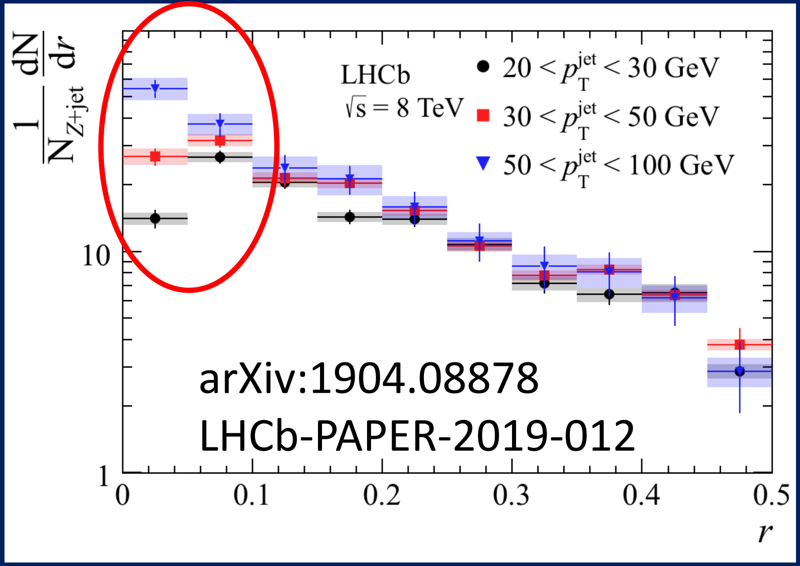
- Follow similar analysis strategy to previous ATLAS and LHCb papers
  - ATLAS: EPJC 71, 1795 (2011), NPA 978, 65 (2018)
  - LHCb: PRL 118, 192001 (2017)

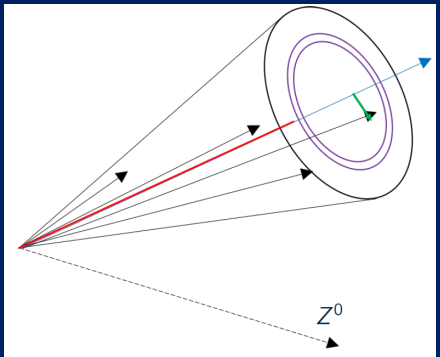


Results: Radial profiles

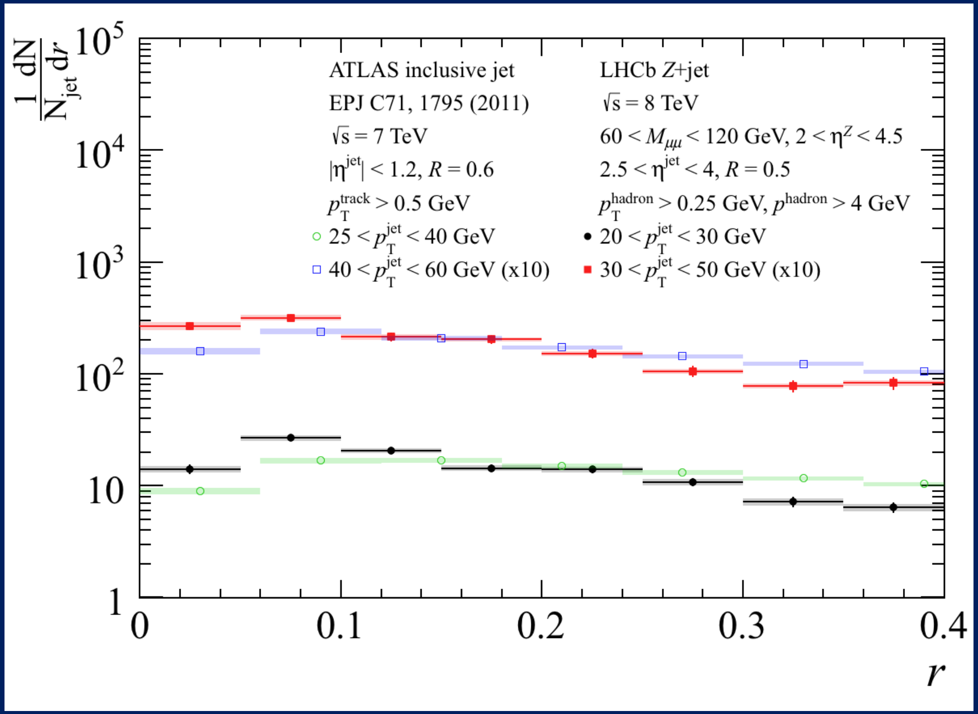
- Observe that the greater energy available in higher transverse momentum jets leads to more hadrons produced (logical)

- New: ~All of the additional particles are produced close to the jet axis, and go from a depletion close to the axis to an excess





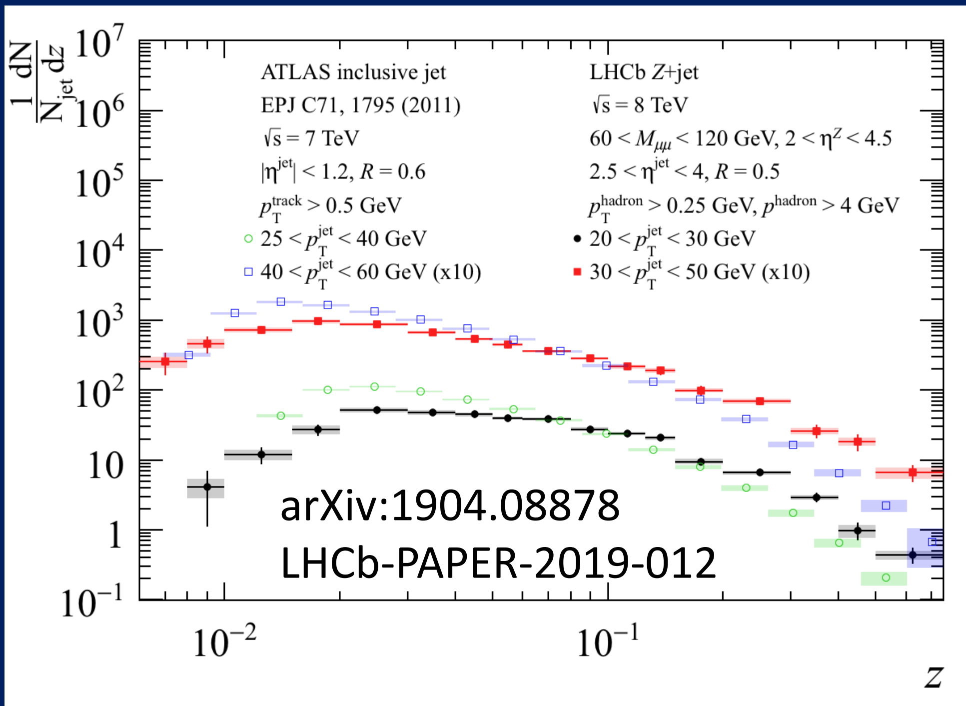
Differences between quark- and gluon-dominated jet samples: Radial profile



arXiv:1904.08878
LHCb-PAPER-2019-012

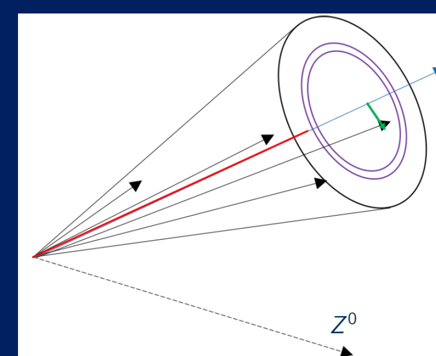
- Quark-dominated jets more collimated than gluon-dominated jets measured by ATLAS
  - I.e. more charged hadrons at small radii, fewer at large radii
  - Qualitatively agrees with conventional expectations, but this shows clear and quantitative evidence from data

Differences between quark- and gluon-dominated jet samples: Longitudinal profile

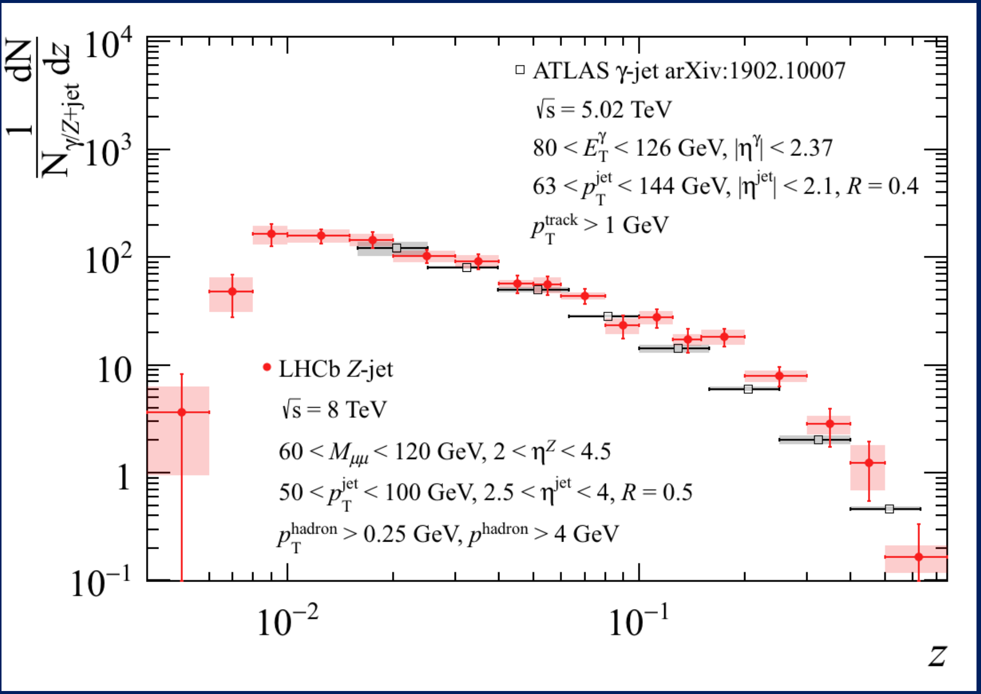


- Quark-dominated jets have relatively more hadrons produced at higher longitudinal momentum fractions than gluon-dominated jets

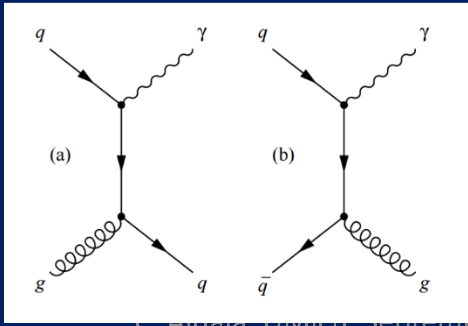
Will be interesting to follow up with an identified particle measurement. Do the hadrons produced at large momentum fractions in quark-dominated jets tend to contain a quark of the same flavor as the one that initiated the jet?



Differences between quark- and gluon-dominated jet samples: Longitudinal profile



arXiv:1904.08878
LHCb-PAPER-2019-012



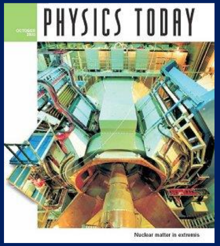
- ATLAS midrapidity γ+jet and LHCb Z+jet longitudinal momentum distributions are more similar
  - γ+jet, like Z+jet, enhances quark jet fraction
  - Further evidence that differences observed between LHCb results and ATLAS gluon-dominated results are due to differences in quark and gluon hadronization

Ongoing work on LHCb

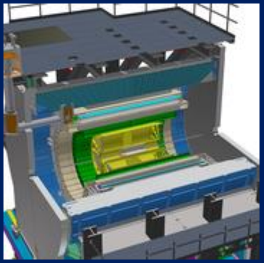
- Hadron distributions in jets initiated by a charm or beauty quark (GS Kara Mattioli)
  - Unlike lighter flavors, can explicitly identify charm and beauty jets
- Heavy and lighter quarkonia in jets
  - Υ ($b\bar{b}$ bound state) (UG Jessie Guo, PD Sookhyun Lee)
  - ϕ ($s\bar{s}$ bound state) (GS Desmond Shangase)
  - polarization of J/ψ ($c\bar{c}$ bound state) (PD Sookhyun Lee)
- Measurement of spontaneous polarization of forward Λ hyperons (uds bound state—a "heavy proton" with a strange quark) (GS Cynthia Nunez)
  - A striking unexplained effect since 1976 discovery (in which U-M was involved!) . . .
- Z boson + jet pairs to search for predicted color entanglement of quarks across colliding protons (GS Jordan Roth)

Other recent and ongoing work in QCD

PHENIX experiment at the Relativistic Heavy Ion Collider, Brookhaven National Lab (took data 2000-2016)



- First-ever experimental searches for predicted color entangled quarks *across* high-energy colliding protons—thus far inconclusive! (Former GS Joe Osborn)
  - Phys. Rev. D95, 072002 (2017)
  - Phys. Rev. D98, 072004 (2018)
  - Phys. Rev. C99, 044912 (2019)
- Measurement of spin-momentum correlations in the production of direct photons, eta mesons, and charmed mesons in transversely polarized proton-proton collisions (GS Nicole Lewis, Enrique Gamez, Dillon Fitzgerald)



sPHENIX at RHIC, BNL (start data taking 2023)

- Test beam studies for calorimeter prototypes – IEEE Trans. Nucl. Sci. 65, 2901 (2018)
- Silicon photomultiplier quality testing here on campus

E906/SeaQuest experiment at Fermilab (took data 2014-2017)

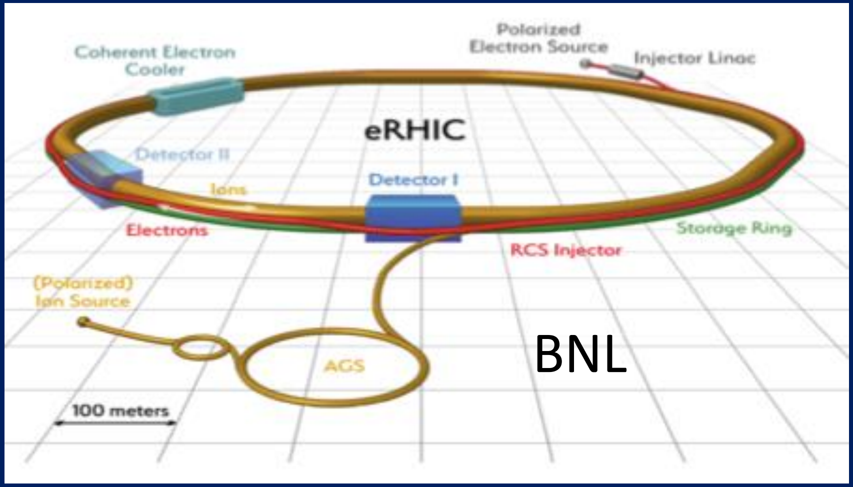
- Nucl. Inst. Meth.A930, 49 (2019)
- Measurement of enhancement of antidown quarks with respect to antiup quarks in the proton (GS Catherine Ayuso)
- Measurement of modification of J/ψ (charm-anticharm bound state) production from nuclear vs. proton targets (GS Catherine Ayuso)

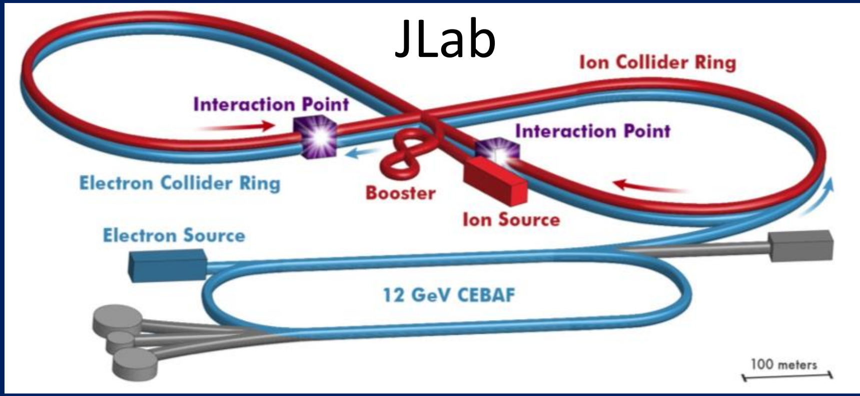
Next-generation QCD facility: The Electron-Ion Collider

Key science questions:

- *How does a nucleon acquire mass?*
- *How does the spin of the nucleon arise from its elementary quark and gluon constituents?*
- *What are the emergent properties of dense systems of gluons?*

Two candidate sites: Brookhaven National Lab and Jefferson Lab



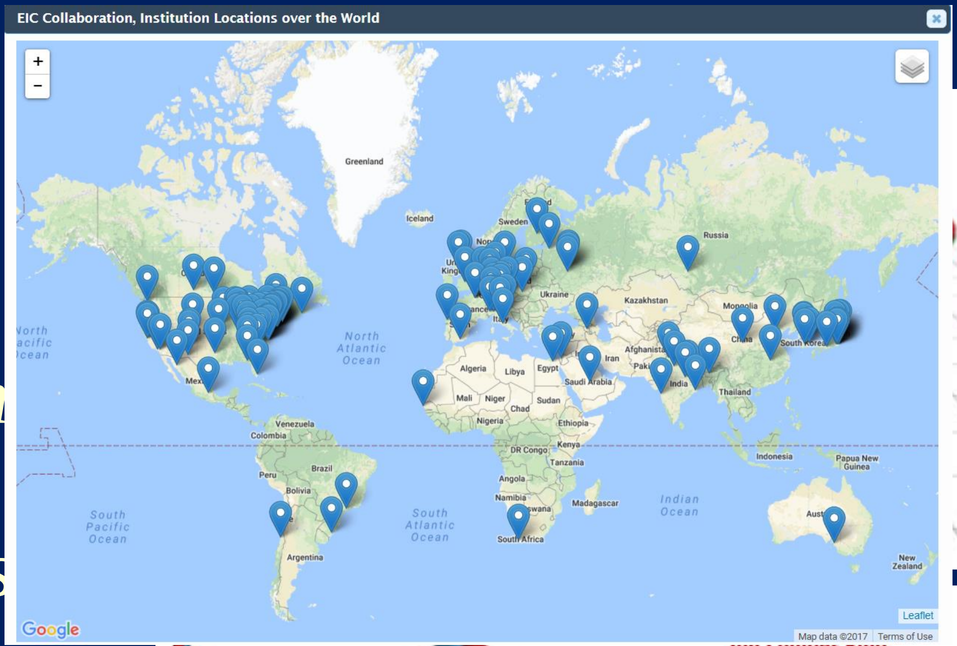


Next-generation QCD facility: The Electron-Ion Collider

Key science questions:

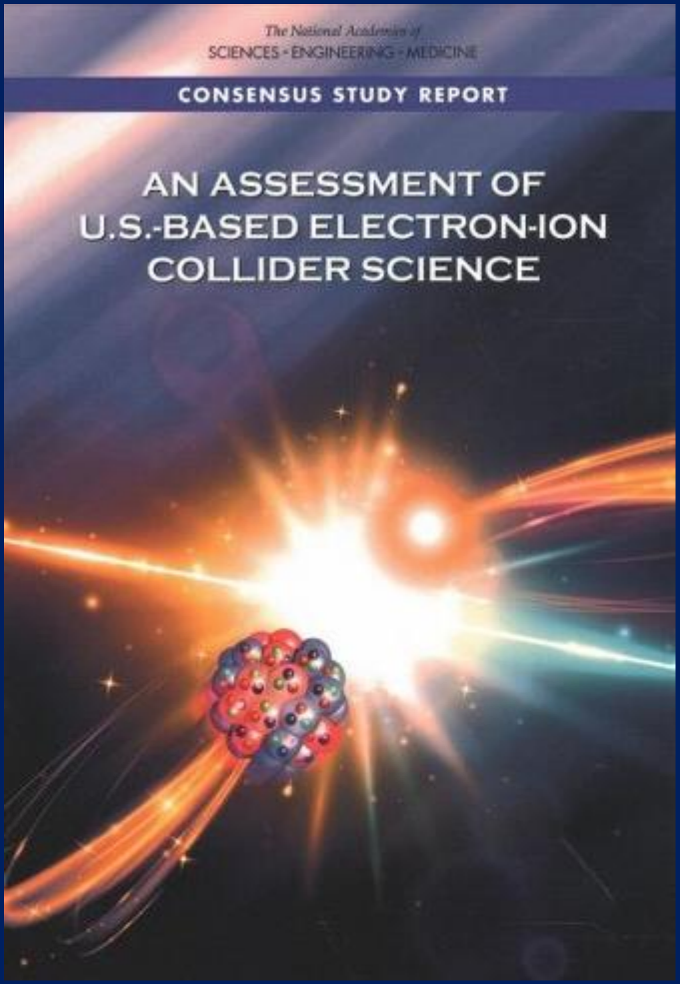
- *How does a nucleon acquire mass?*
- *How does the spin of the nucleon arise from its elementary quark and gluon constituents*
- *What are the emergent*

Two candidate sites: Brookhaven

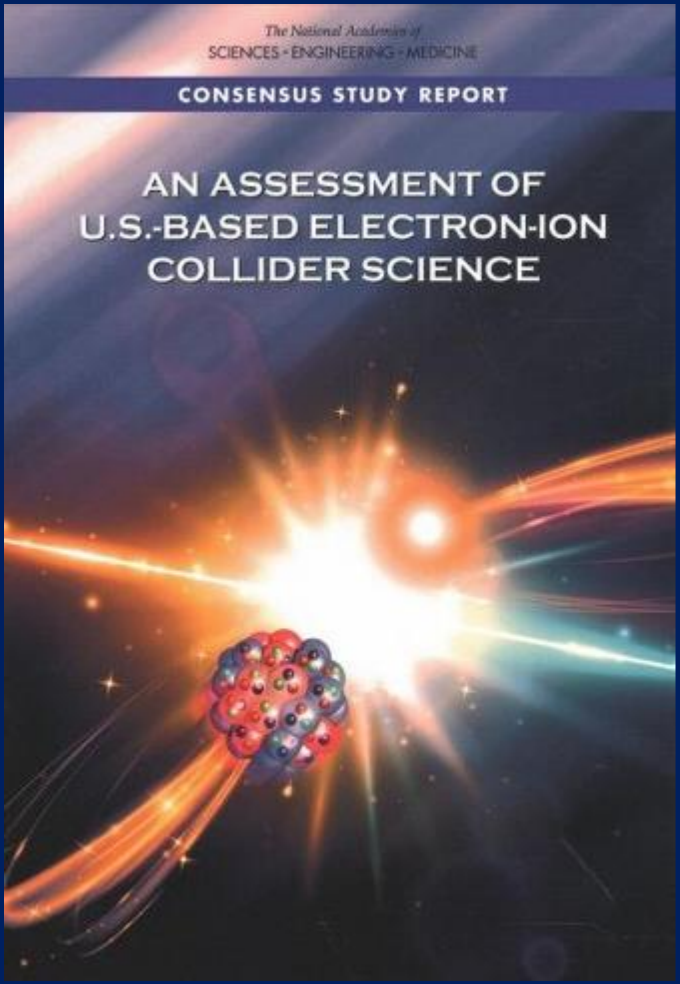


Electron-Ion Collider User Group: Currently 889 members from 190 institutions in 30 countries

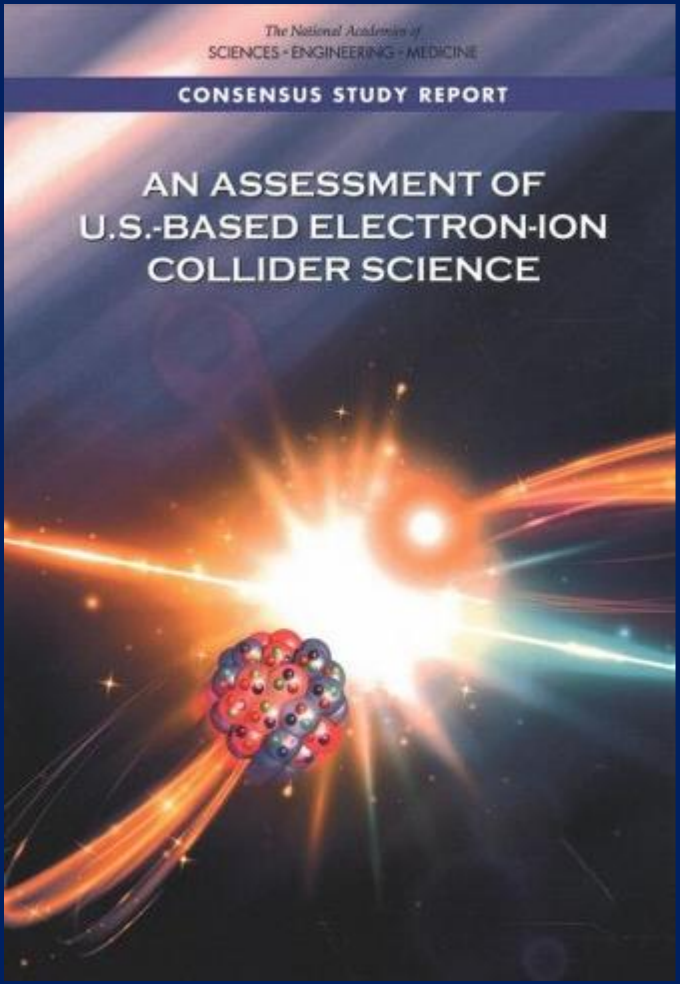
www.eicug.org

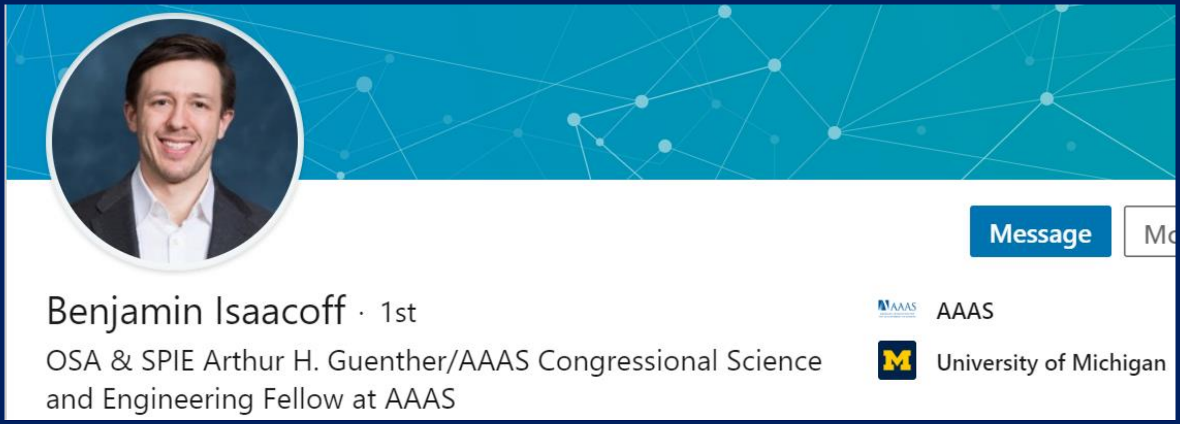


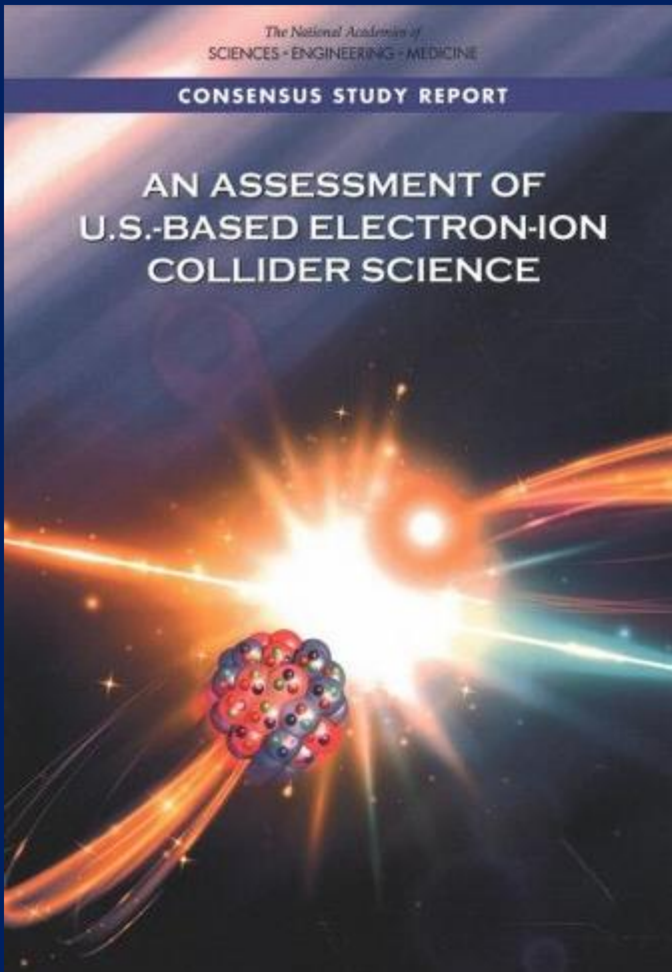
July 2018 National Academy Consensus Report found that the science that can be addressed by an EIC is “compelling, fundamental, and timely”



July 2018 National Academy Consensus Report found that the science that can be addressed by an EIC is "compelling, fundamental, and timely"


The National Academies of
SCIENCES · ENGINEERING · MEDICINE
CONSENSUS STUDY REPORT
AN ASSESSMENT OF
U.S.-BASED ELECTRON-ION
COLLIDER SCIENCE


Message
Benjamin Isaacoff · 1st
OSA & SPIE Arthur H. Guenther/AAAS Congressional Science
and Engineering Fellow at AAAS
AAAS
University of Michigan



SCIENTIFIC AMERICAN.

Cart 0 Sign In |

SCIENCES MIND HEALTH TECH SUSTAINABILITY EDUCATION VIDEO PODCASTS BLOGS PUBLICATI

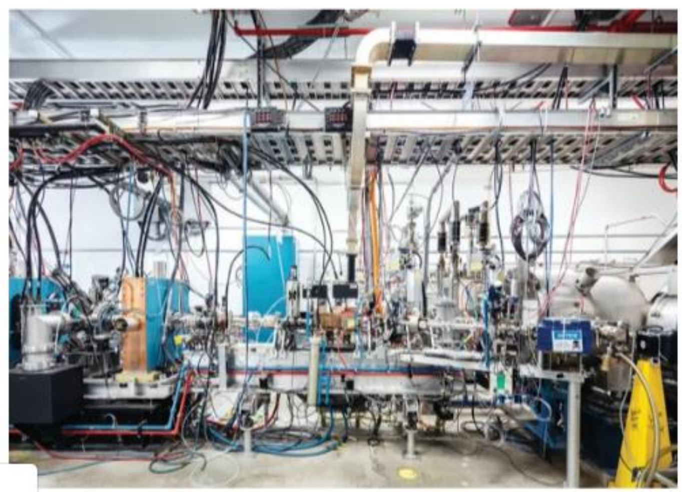
PHYSICS

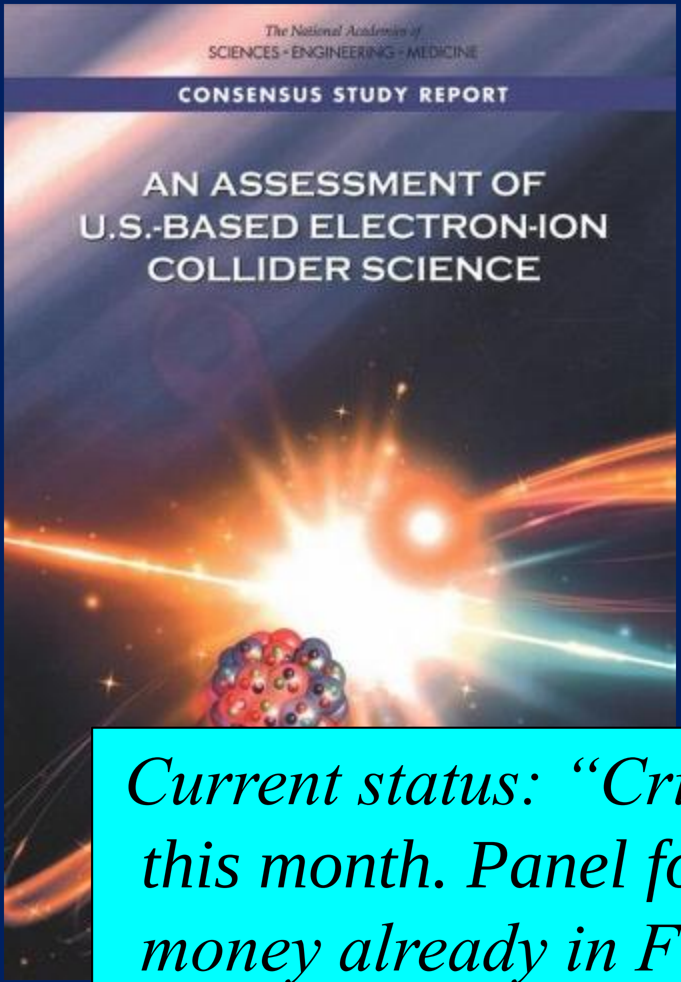
The Experiment That Will Probe the Deepest Recesses of the Atom

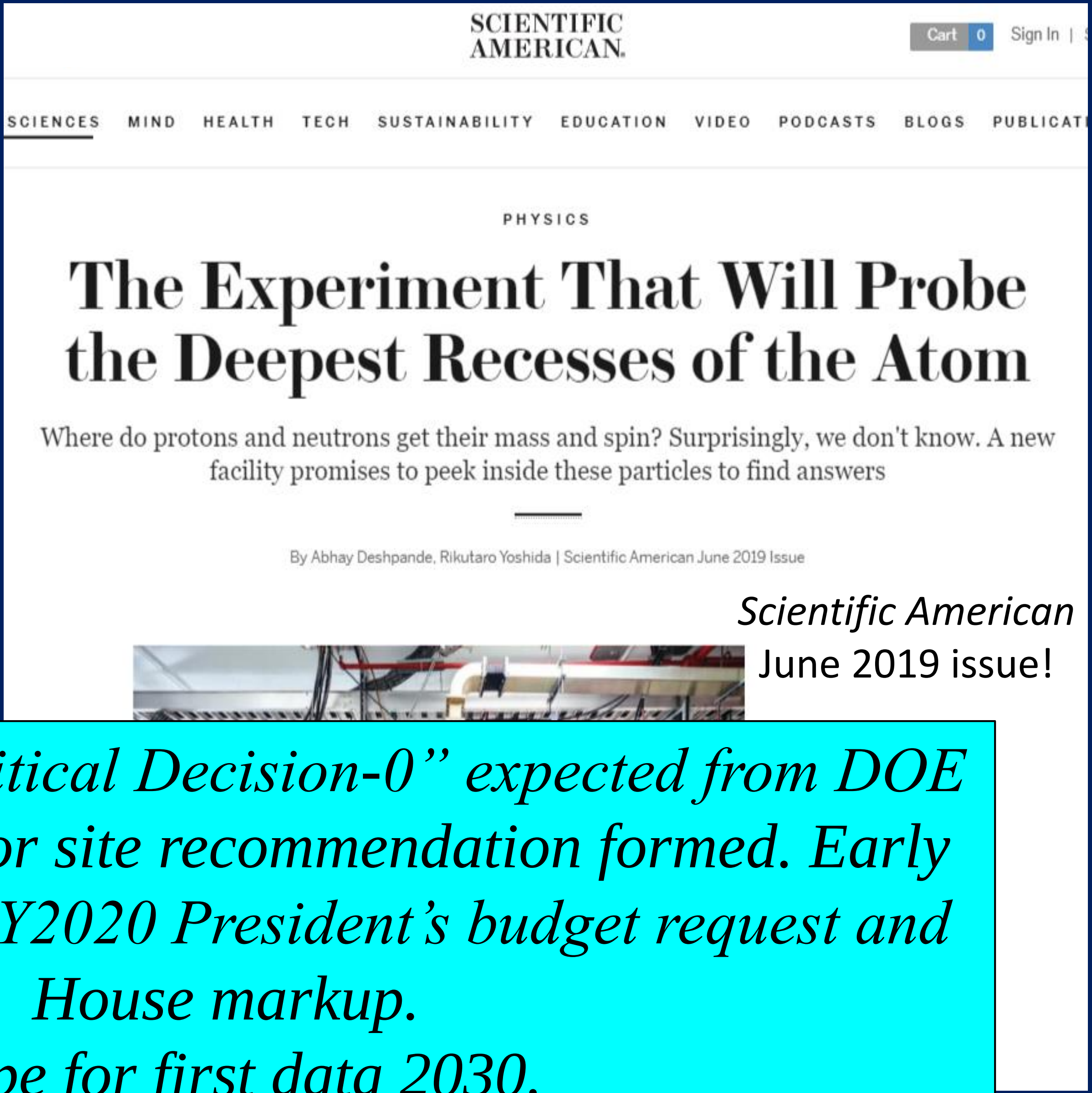
Where do protons and neutrons get their mass and spin? Surprisingly, we don't know. A new facility promises to peek inside these particles to find answers

By Abhay Deshpande, Rikutaro Yoshida | Scientific American June 2019 Issue

Scientific American June 2019 issue!






SCIENTIFIC AMERICAN.

Cart 0 Sign In |

SCIENCES MIND HEALTH TECH SUSTAINABILITY EDUCATION VIDEO PODCASTS BLOGS PUBLICATI

PHYSICS

The Experiment That Will Probe the Deepest Recesses of the Atom

Where do protons and neutrons get their mass and spin? Surprisingly, we don't know. A new facility promises to peek inside these particles to find answers

By Abhay Deshpande, Rikutaro Yoshida | Scientific American June 2019 Issue

Scientific American
June 2019 issue!

Current status: "Critical Decision-0" expected from DOE this month. Panel for site recommendation formed. Early money already in FY2020 President's budget request and House markup.
Hope for first data 2030.

Assumptions of Physics project

with Gabriele Carcassi

- The aim of the project is to find a handful of physical principles and assumptions from which the basic laws of physics can be derived
- To do that we want to develop a general mathematical theory of experimental science: the theory that studies scientific theories
  - A formal framework that forces us to clarify our assumptions
  - From those assumptions the mathematical objects are derived
  - Each mathematical object has a clear physical meaning and no object is unphysical
  - Gives us concepts and tools that span across different disciplines
  - Allows us to explore what happens when the assumptions fail, possibly leading to new physics ideas

http://assumptionsofphysics.org/

General mathematical theory of experimental science

- To do *any* kind of science, we need a set of experimentally verifiable assertions → Logic of verifiable statements
  - G. Carcassi, CAA, "Towards a general mathematical theory of experimental science." arXiv:1807.07896; also first three chapters of draft book

    http://assumptionsofphysics.org/book

- Not closed under negation, because negation of a verifiable statement not necessarily verifiable
- Only closed under *finite* conjunction (AND), because require verification in *finite time*
  - Similar to finite resources already considered in theoretical computer science
- Closed under *countable* disjunction (OR), because can't complete more than countable number of tests in *finite time*

General mathematical theory of experimental science

- Set of experimentally distinguishable objects, cases, etc. → topological space
- Implies particular topology
  - CAA, G. Carcassi, M.J. Greenfield, "Topology and experimental distinguishability." *Top. Proc.* 54, 271 (2019).

General mathematical theory of experimental science

- Set of experimentally distinguishable objects, cases, etc. → topological space
- Implies particular topology
  - CAA, G. Carcassi, M.J. Greenfield, "Topology and experimental distinguishability." *Top. Proc.* 54, 271 (2019).

Given a set X, a topology is a collection of subsets of X that
- contains X and $\emptyset$
- is not in general closed under complement
- is closed under finite intersection and arbitrary (infinite) union

General mathematical theory of experimental science

- Set of experimentally distinguishable objects, cases, etc. → topological space
- Implies particular topology
  - CAA, G. Carcassi, M.J. Greenfield, "Topology and experimental distinguishability." *Top. Proc.* 54, 271 (2019).

Given a set X, a topology is a collection of subsets of X that
- contains X and $\emptyset$
- is not in general closed under complement
- is closed under finite intersection and arbitrary (infinite) union

- If X is a **set of physically distinguishable cases**, it will have a **natural topology** that keeps track of the statements that are verifiable (e.g. corresponding to finite precision measurement)
  - Topology is the foundation for manifolds, differential geometry (i.e. geometrical vectors, integration over curves), symplectic geometry (i.e. classical Hamiltonian mechanics), Riemmanian geometry (i.e. special and general relativity)

- It will also have a **natural $\boldsymbol{\sigma}$-algebra** that keeps track of the theoretical statements we can use for predictions
  - σ-algebras are the foundation for measure theory and probability theory

General mathematical theory of experimental science

- Set of experimentally distinguishable objects, cases, etc. → topological space
- Implies particular topology
  - CAA, G. Carcassi, M.J. Greenfield, "Topology and experimental distinguishability." *Top. Proc.* 54, 271 (2019).

Given a set X, a topology is a collection of subsets of X that
- contains X and $\emptyset$
- is not in general closed under complement
- is closed under finite intersection and arbitrary (infinite) union

- If X is a **set of physically distinguishable cases**, it will have a **natural topology** that keeps track of the statements that are verifiable (e.g. corresponding to finite precision measurement)
  - Topology is the foundation for manifolds, differential geometry (i.e. geometrical vectors, integration over curves), symplectic geometry (i.e. classical Hamiltonian mechanics), Riemmanian geometry (i.e. special and general relativity)

- It will also have a **natural σ-algebra** that keeps track of the theoretical statements we can use for predictions
  - σ-algebras are the foundation for measure theory and probability theory

A σ-algebra on a set X is a collection Σ of subsets of X that
- contains X (and $\emptyset$)
- is closed under complement
- is closed under countable union (and countable intersection)

MICHIGAN

Takeaway

- Specifying a scientific theory means specifying a (countable) set of verifiable statements and their logical relationships. The role of mathematical structures in physics is to formalize the logical relationships between verifiable statements.

- The mere requirement of experimental verification (i.e. the algebra of verifiable statements) already provides a link to two fundamental mathematical structures (topologies and σ-algebras), which therefore we can *always* use in *any* physical theory

- The idea is that we can rebuild the other mathematical structures piece by piece so that we spell out the physical assumptions implicit in the most primitive objects, like quantities represented by integers and real numbers
  - E.g. measuring distance with a ruler can be broken down into verifiable statements like “the object is after the 5 cm mark”, “the object is before the 5.3 cm mark”

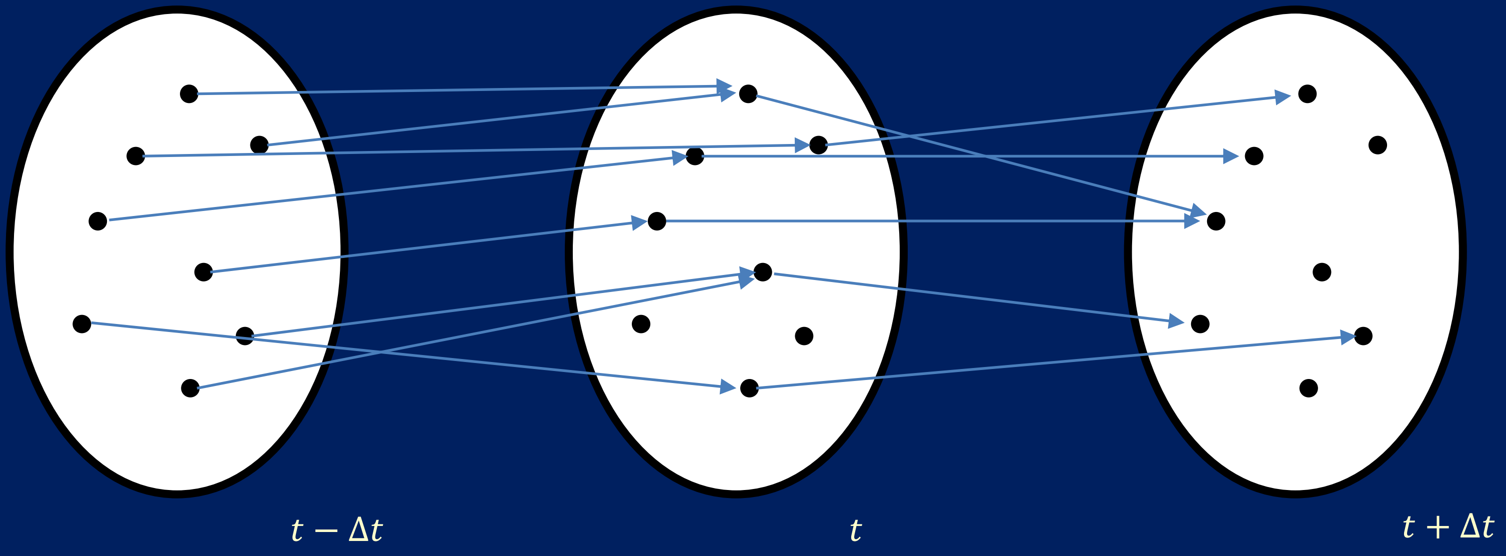
Deriving classical Hamiltonian particle mechanics under scalar and vector potential forces

- Found only two physical assumptions needed to rederive classical Hamiltonian particle mechanics
  1. Deterministic and reversible evolution

G. Carcassi, CAA, D.J. Baker, L. Bieri
J. Phys. Commun. 2, 045026 (2018)

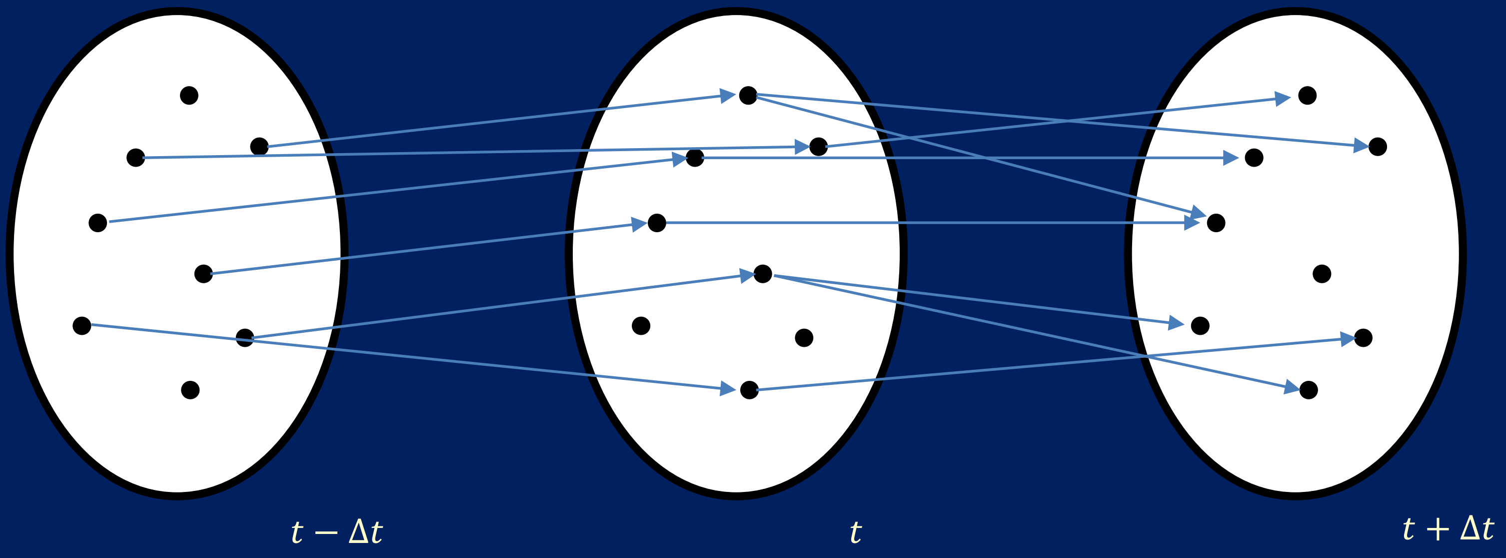
Deterministic

- A process like this is deterministic (you can predict the future)



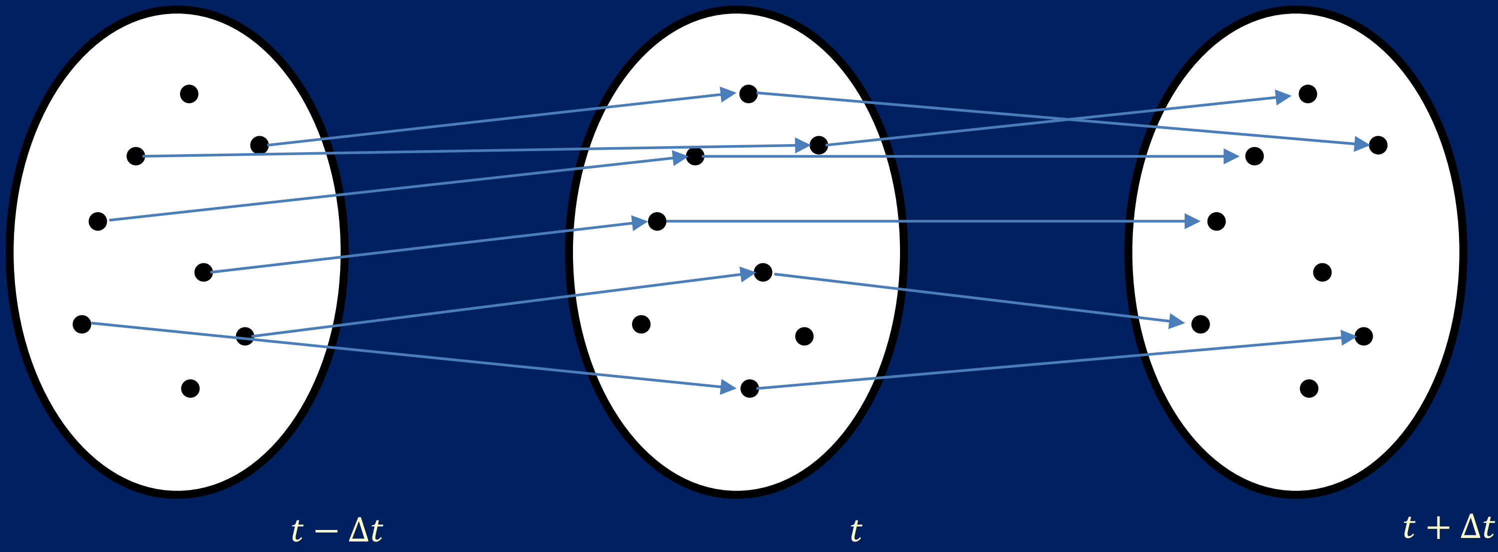
Reversible

- A process like this is reversible (you can reconstruct the past)



Deterministic and reversible

- A process like this is deterministic and reversible



Deriving classical Hamiltonian particle mechanics under scalar and vector potential forces

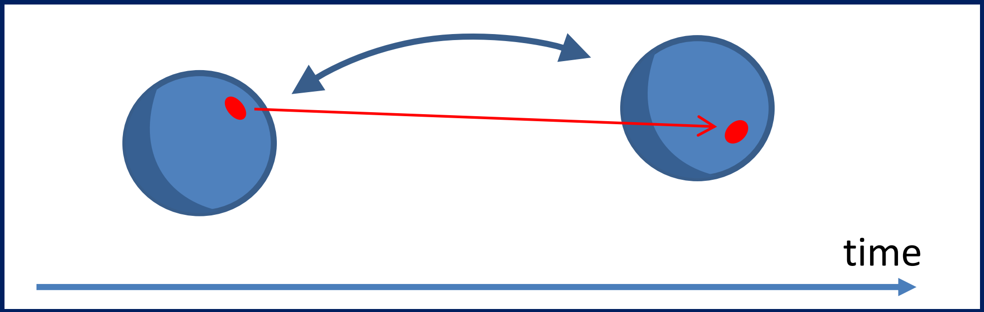
- Found only two physical assumptions needed to rederive classical Hamiltonian particle mechanics
  1. Deterministic and reversible evolution

  2a. Specifying the state of the whole is equivalent to specifying the state of the parts (infinitesimal reducibility)

G. Carcassi, CAA, D.J. Baker, L. Bieri
J. Phys. Commun. 2, 045026 (2018)

Assumption of infinitesimal reducibility

- The system is reducible to its parts: giving the state of the whole is equivalent to giving the state of the parts. The system can be subdivided indefinitely.



Deriving classical Hamiltonian particle mechanics under scalar and vector potential forces

- Found only two physical assumptions needed to rederive classical Hamiltonian particle mechanics
  1. Deterministic and reversible evolution
  2a. Specifying the state of the whole is equivalent to specifying the state of the parts (infinitesimal reducibility)

- Determinism and reversibility is more than a one-to-one map: it has to preserve the nature of the system and the type of description
  - Mathematically it will be an isomorphism in the category used to capture states, the associated verifiable statements, and their logical structure

G. Carcassi, CAA, D.J. Baker, L. Bieri
J. Phys. Commun. 2, 045026 (2018)

Deriving classical Hamiltonian particle mechanics under scalar and vector potential forces

- Found only two physical assumptions needed to rederive classical Hamiltonian particle mechanics
  1. Deterministic and reversible evolution

  2a. Specifying the state of the whole is equivalent to specifying the state of the parts (infinitesimal reducibility)

- Determinism and reversibility is more than a one-to-one map: it has to preserve the nature of the system and the type of description
  - Mathematically it will be an isomorphism in the category used to capture states, the associated verifiable statements, and their logical structure

- Symplectic manifold (phase space) a *necessary consequence of requiring coordinate-invariant distributions*
  - Conjugate variables (q, k)

G. Carcassi, CAA, D.J. Baker, L. Bieri

J. Phys. Commun. 2, 045026 (2018)

Deriving classical Hamiltonian particle mechanics under scalar and vector potential forces

- Found only two physical assumptions needed to rederive classical Hamiltonian particle mechanics
  1. Deterministic and reversible evolution
  2a. Specifying the state of the whole is equivalent to specifying the state of the parts (infinitesimal reducibility)

- Determinism and reversibility is more than a one-to-one map: it has to preserve the nature of the system and the type of description
  - Mathematically it will be an isomorphism in the category used to capture states, the associated verifiable statements, and their logical structure

- Symplectic manifold (phase space) a *necessary consequence of requiring coordinate-invariant distributions*
  - Conjugate variables (q, k)

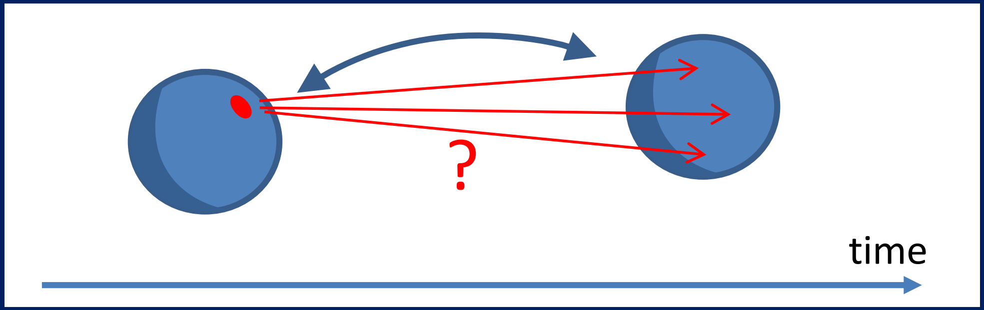
- Add a third assumption to get Euler-Lagrange equations, i.e. classical Lagrangian mechanics
  3. Equivalence between evolution of states (dynamics) and trajectories (kinematics)

G. Carcassi, CAA, D.J. Baker, L. Bieri
J. Phys. Commun. 2, 045026 (2018)

Change assumption of infinitesimal reducibility → Quantum mechanics

- To get quantum particle mechanics (Schrodinger equation), modify assumption 2
  1. Deterministic and reversible evolution (same)

  2b. *Specifying the state of the whole tells you* ***nothing*** *about the state of the parts (irreducibility)*



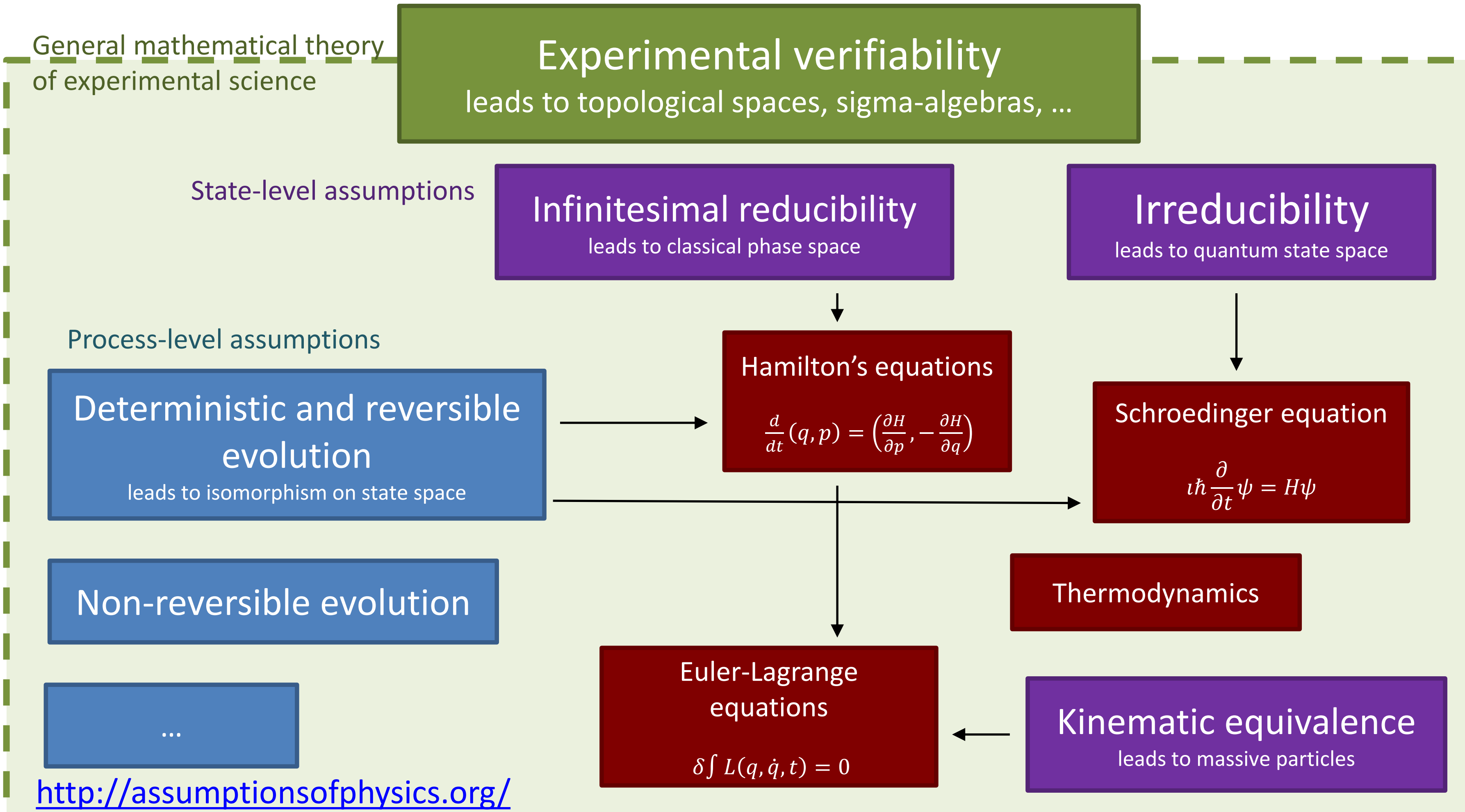
G. Carcassi, CAA, D.J. Baker, L. Bieri
J. Phys. Commun. 2, 045026 (2018)

Other neat things that come out

- Uncertainty principle and "antiparticles" come naturally from the deterministic evolution of distributions of parts
  – Classical "uncertainty principle" – information entropy conserved during Hamiltonian evolution. Minimum spread in phase space is Gaussian distribution.

  – Everything done in terms of relativistically invariant Hamiltonian—evolution in affine parameter (proper time) different from evolution in *t*. Get distinct states for which affine parameter and *t* have same direction vs. opposite.

G. Carcassi, CAA, D.J. Baker, L. Bieri
J. Phys. Commun. 2, 045026 (2018)

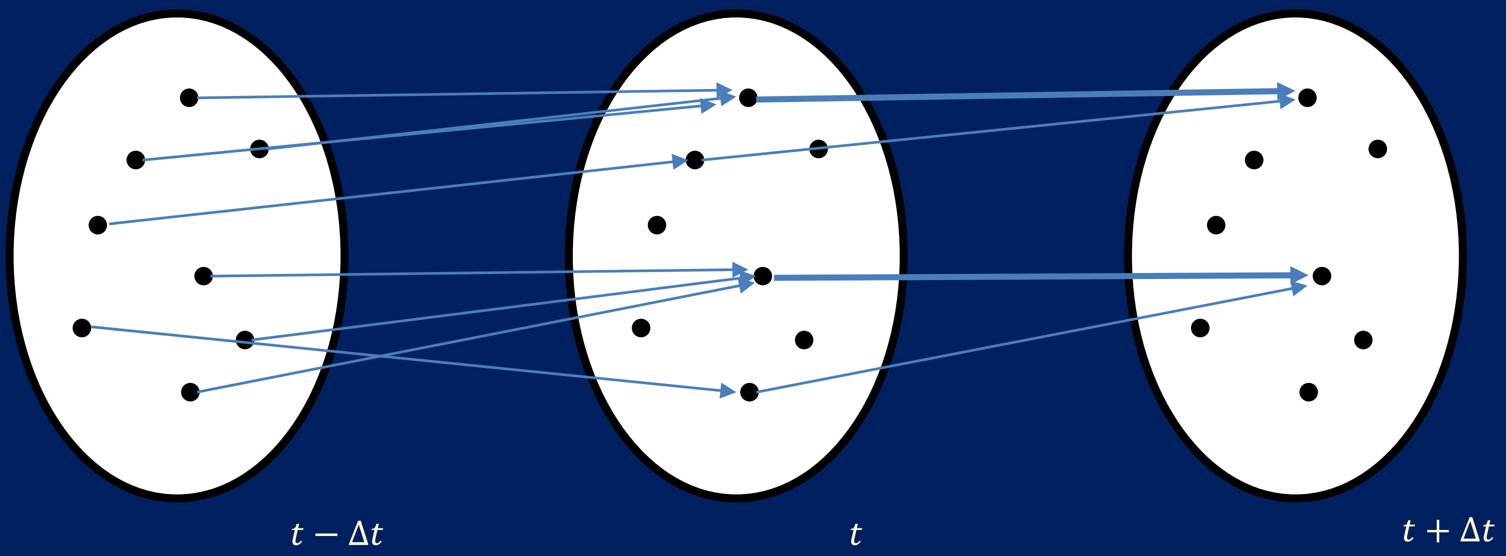

General mathematical theory of experimental science
Experimental verifiability
leads to topological spaces, sigma-algebras, …
State-level assumptions
Infinitesimal reducibility
leads to classical phase space
Irreducibility
leads to quantum state space
Process-level assumptions
Deterministic and reversible evolution
leads to isomorphism on state space
Hamilton's equations
$\frac{d}{dt}(q,p) = \left(\frac{\partial H}{\partial p}, -\frac{\partial H}{\partial q}\right)$
Schroedinger equation
$\imath\hbar\frac{\partial}{\partial t}\psi = H\psi$
Non-reversible evolution
Thermodynamics
…
Euler-Lagrange equations
$\delta\int L(q,\dot{q},t) = 0$
Kinematic equivalence
leads to massive particles
http://assumptionsofphysics.org/

Current work: Entropy, thermodynamics, and statistical mechanics

- MCubed project with Kai Sun (Physics) + Dave Baker (Philosophy)
- Generalized entropy in terms of set mappings (state evolutions)
- Require clear relation to thermodynamic, Gibbs, Boltzmann, von Neumann, and Shannon entropies

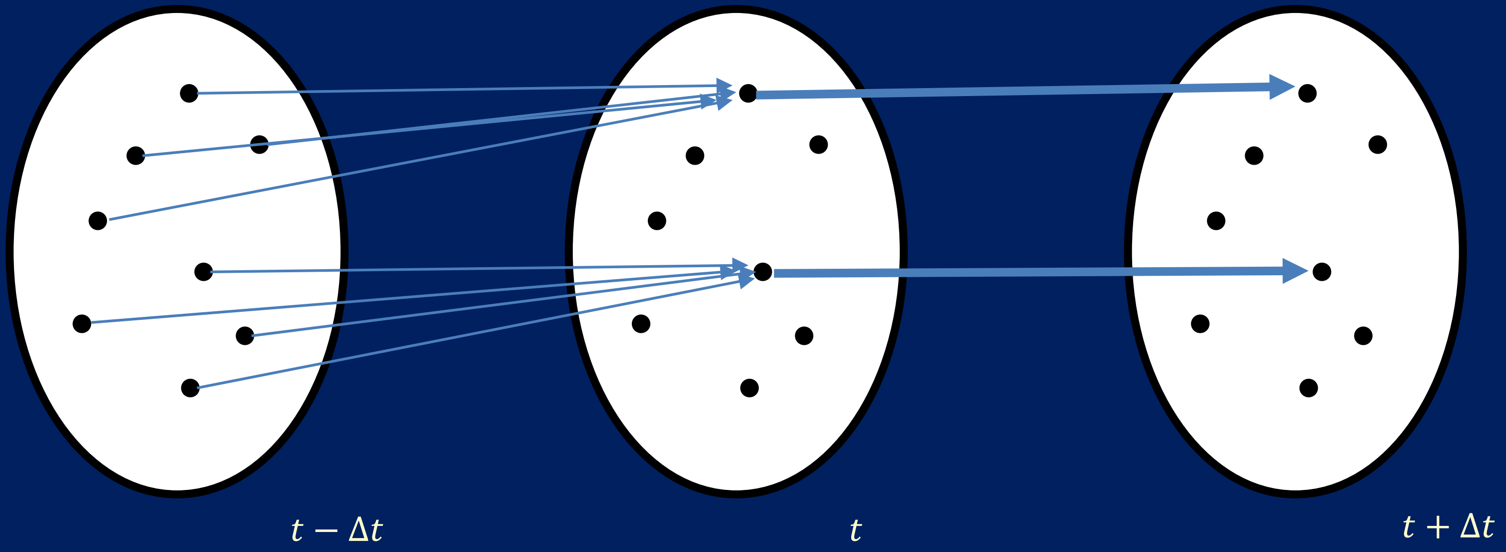
Deterministic but irreversible

- A deterministic but irreversible process concentrates evolutions (number of evolutions per state can only increase)



Equilibria

- An equilibrium does not change during the evolution (number of evolutions are maximum at equilibrium)



Long-term goals of the project

- Ultimate goal to build up and rederive all established branches of physics within a common context/framework
  - Want everything in the math to correspond to something physical

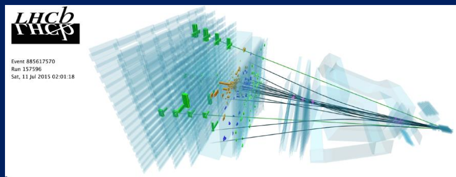
Long-term goals of the project

- Ultimate goal to build up and rederive all established branches of physics within a common context/framework
  - Want everything in the math to correspond to something physical

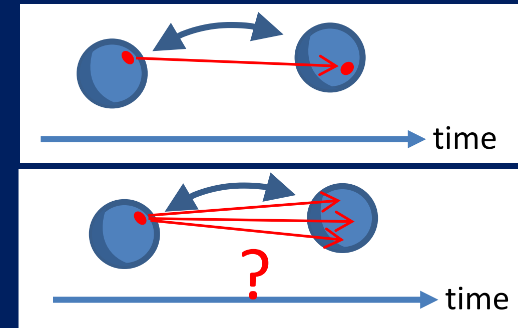
- Believe that being able to identify and articulate our physical assumptions for various systems/cases—and their necessary mathematical implications—will point us toward new directions, exploring alternative assumptions

Long-term goals of the project

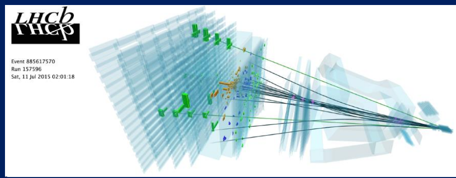
- Ultimate goal to build up and rederive all established branches of physics within a common context/framework
  - Want everything in the math to correspond to something physical
- Believe that being able to identify and articulate our physical assumptions for various systems/cases—and their necessary mathematical implications—will point us toward new directions, exploring alternative assumptions
- Potential implications for physics education as well
- Need area experts—collaborators and consultants welcome!



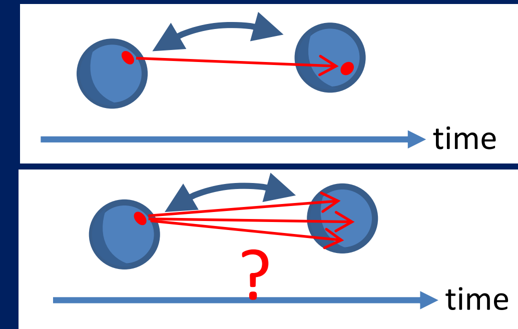
Summary



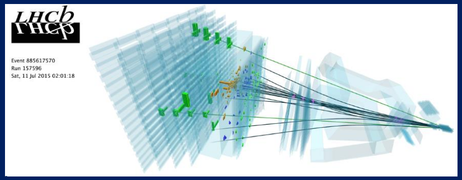
- The *formation* of QCD bound states has been vastly underexplored over prior decades compared to *structure*
- The LHCb experiment at CERN offers unprecedented opportunities to study hadronization. Our recent results measuring production of charged hadrons in light quark jets are the first in a longer-term program.



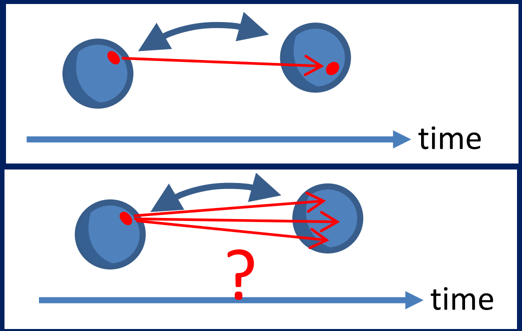
Summary



- The *formation* of QCD bound states has been vastly underexplored over prior decades compared to *structure*
- The LHCb experiment at CERN offers unprecedented opportunities to study hadronization. Our recent results measuring production of charged hadrons in light quark jets are the first in a longer-term program.
- Careful consideration of physical assumptions and their mathematical implications leads to more constrained mathematical structures than one might naively expect
- Articulation of underlying assumptions and their implications can lead to better understanding of existing theories and point toward ideas for new ones



Summary



- The *formation* of QCD bound states has been vastly underexplored over prior decades compared to *structure*
- The LHCb experiment at CERN offers unprecedented opportunities to study hadronization. Our recent results measuring production of charged hadrons in light quark jets are the first in a longer-term program.
- Careful consideration of physical assumptions and their mathematical implications leads to more constrained mathematical structures than one might naively expect
- Articulation of underlying assumptions and their implications can lead to better understanding of existing theories and point toward ideas for new ones

I've had a lot of fun embarking upon new research directions over the past few years!

Extra

Principle of Scientific Objectivity

Science is:

- *universal (same for everybody)*
- *non-contradictory (logically consistent)*
- *evidence-based (experimentally verifiable)*

Verifiable statements

- The principle of scientific objectivity tells us that science deals with assertions that are:
  – either true or false (non-contradictory)
  – for everybody (universal)
  – and experimentally verifiable (evidence-based)
- We call such assertions **verifiable statements**
  – The first two requirements are the same as in classical logic.
  – The third means we have an experimental test that we can run and, if the statement is true, it completes successfully in **finite time**

Basis $\mathcal{B}$				Verifiable statements $\mathcal{D}_X$		
e_1	e_2	e_3	…	$s_1 = e_1 \vee e_2$	$s_2 = e_1 \wedge e_3$	…
F	F	F	…	F	F	…
…	…	…	…	…	…	…
F	T	F	…	T	F	…
~~T~~	~~T~~	~~F~~	~~…~~	~~T~~	~~F~~	~~…~~
…	…	…	…	…	…	…

Possibilities X

Start with a countable set of verifiable statements (the most we can test experimentally). We call this a basis.

Construct all verifiable statements that can be verified from the basis (close under finite conjunction and countable disjunction). We call this an experimental domain

Consider all truth assignments: it is sufficient to assign the basis

Remove truth assignments that are impossible (e.g. the distance is more than 5 and less than 3)

We call the remaining lines the set of possibilities for the experimental domain (what can be found experimentally)

Each verifiable statement corresponds to a set of possibilities in which the statement is true.

The experimental domain $\mathcal{D}_X$ induces a natural topology on the set of possibilities X

The role of logic (and math) in science is to capture what is consistent (i.e. the possibilities) and what is verifiable (i.e. the verifiable statements)

States and trajectories

- The kinematic assumption means that we need to be able to relate state variables (i.e. variables that identify states) with kinematic variables (i.e. variables that identify trajectories)
- That is, we need a one-to-one map between (q^i, p_i), position and momentum, and (x^i, v^i), position and velocity. But this is not enough: we need to be able to express the density in terms of the kinematic variables. Therefore the relationships between the differentials have to be linear.
- For position we choose $q^i = x^i$ and $dq^i = dx^i$
- For momentum at constant q^i we must have something of the form
  $dp_i = mg_{ij}dv^j$ where g_{ij} is a linear transformation and m is a constant of proportionality

Massive particles under conservative forces

- If we integrate $dp_i = mg_{ij}dv^j$ we have $p_i = mg_{ij}v^j + qA_i$ where qA_i is a set of arbitrary functions of position
- We also have $d_t q^i = d_t x^i = v^i = \partial_{p_i} H = \frac{g^{ij}}{m}\left(p_j - qA_j\right)$. If we integrate $H = \frac{1}{2m}(p_i -$

Mathematical structure for space-time

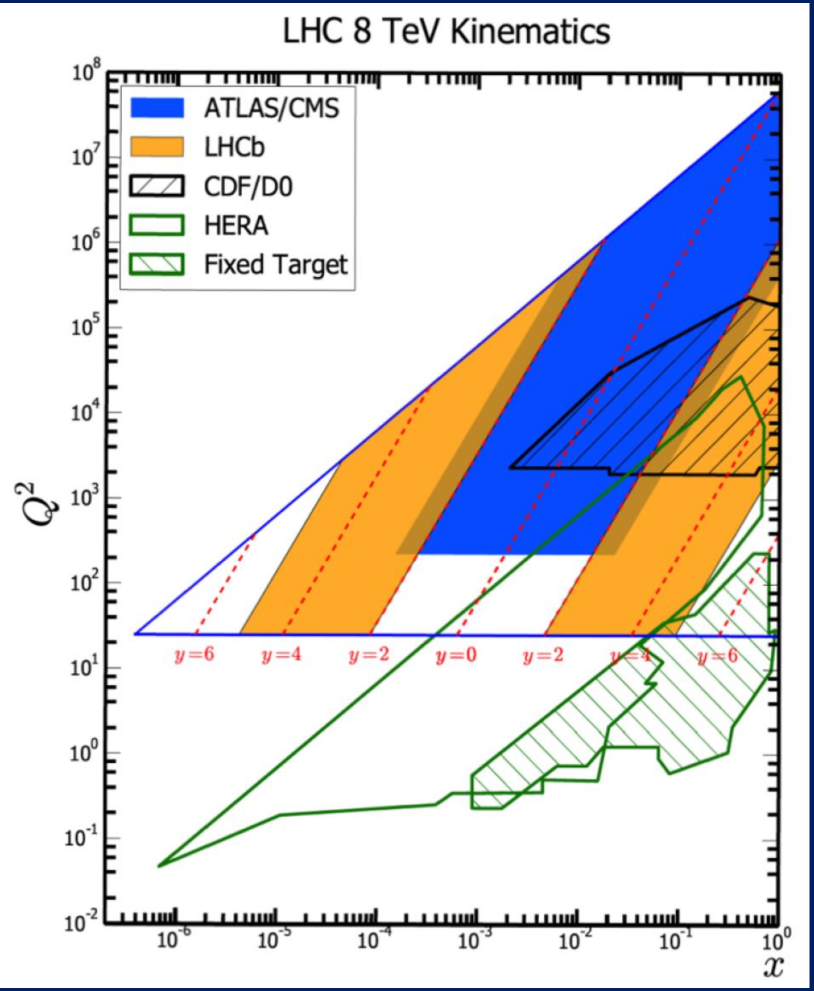
Geometry (lengths and angles) starts here: most fundamental structures are not geometrical

- Riemannian manifold
  ↳Differentiable manifold + inner product
    ↳Topological manifold + differentiable structure
      ↳Ordered topological space + locally $\mathbb{R}^n$
        ↳Topological space + order topology

- If we want to understand why (i.e. under what conditions) space-time has the structure it has, we first need to understand why (i.e. under what conditions) it is a topological space, it has an order topology, …

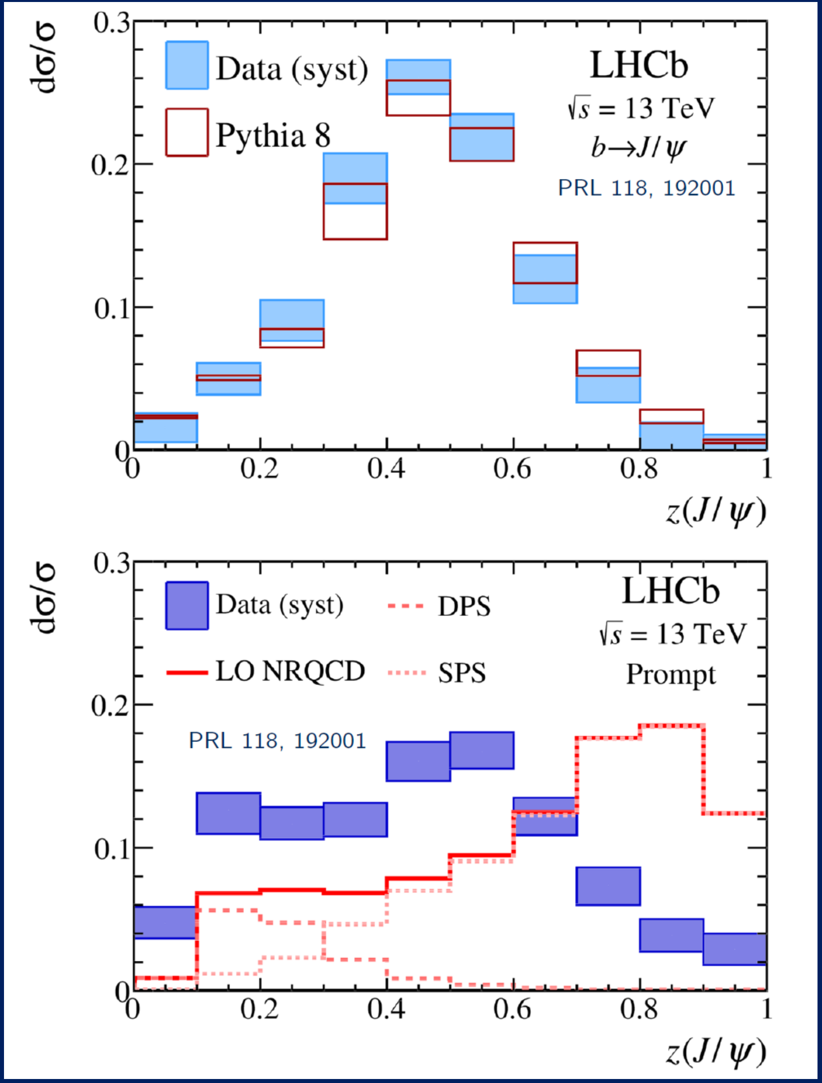
Kinematic coverage affects mix of scattering quarks and gluons

- LHCb also has unique kinematic coverage in terms of scattered quark or gluon momentum fraction x and four-momentum-transfer-squared Q^2
  - Enhanced light quark jet fraction in forward region



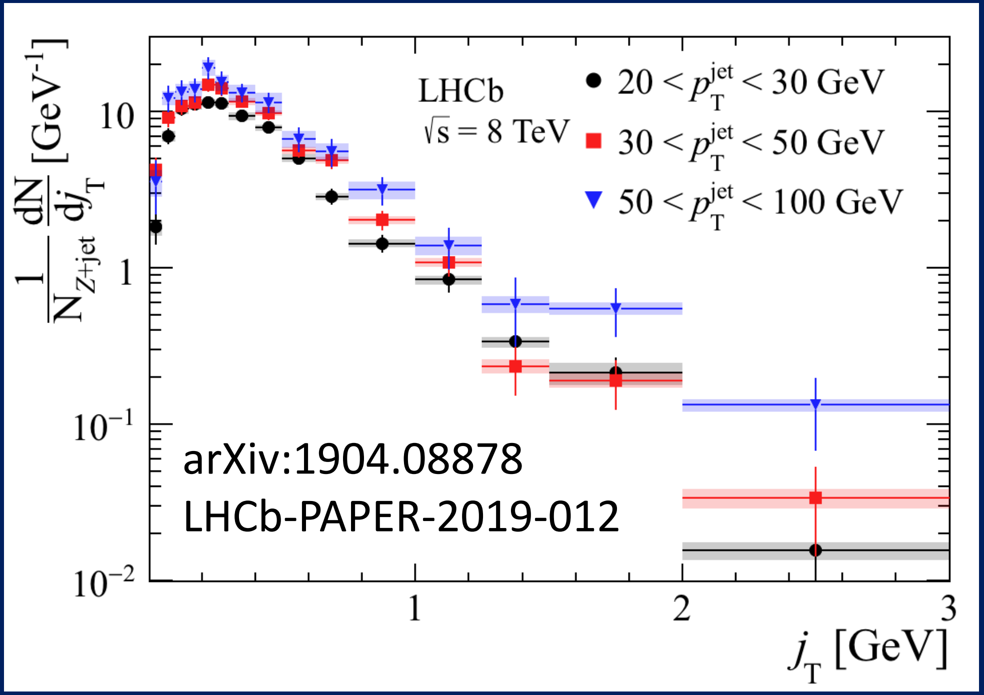
J/Ψ production in jets at LHCb

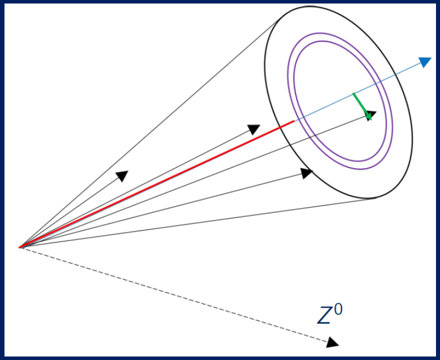
- First LHCb jet substructure measurement was J/ψ-in-jet production
  - J/ψ from b decay well described by PYTHIA
  - Prompt J/ψ-in-jet not! Can shed light on prompt J/ψ production mechanism(s). How is a prompt J/ψ produced within a jet??



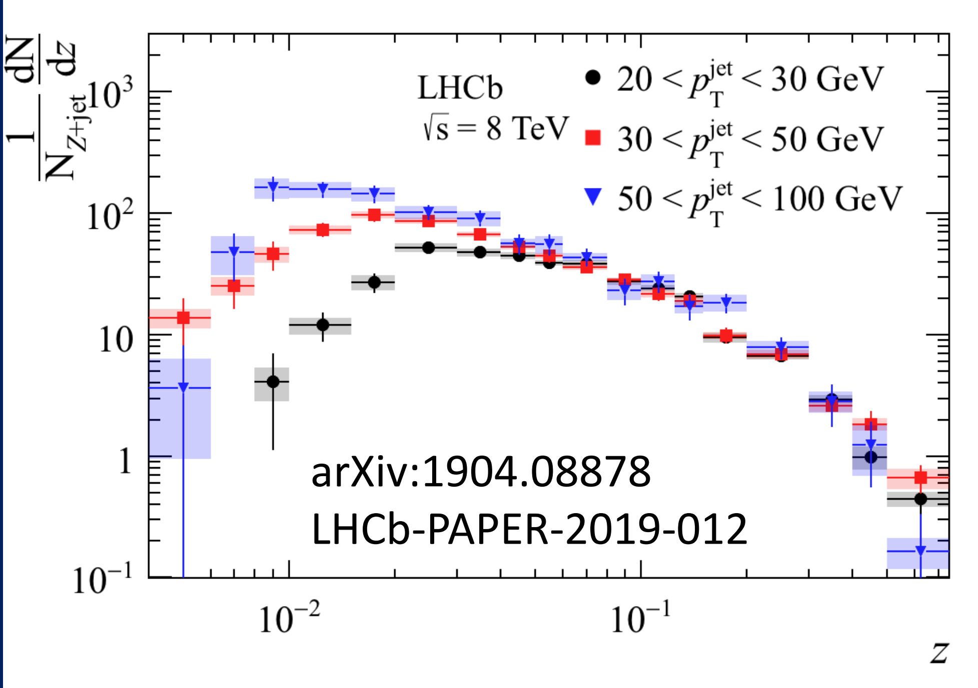
Results: Transverse momentum distributions

- Transverse momentum of hadron with respect to jet axis shows turnover from "soft" (strong coupling: not perturbatively calculable) hadron production at low jT to "hard" (weaker coupling: perturbatively calculable) hadron production due to e.g. gluon emission at larger jT
- Shapes similar as function of p_T^{jet}
- Comparison to ATLAS gluon-dominated jets shows smaller mean transverse momentum in quark-dominated Z+jet than gluon-dominated jets [animate plot?]
  - No ATLAS quark-enhanced results available, unfortunately

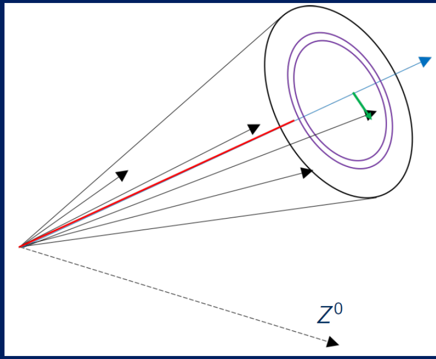




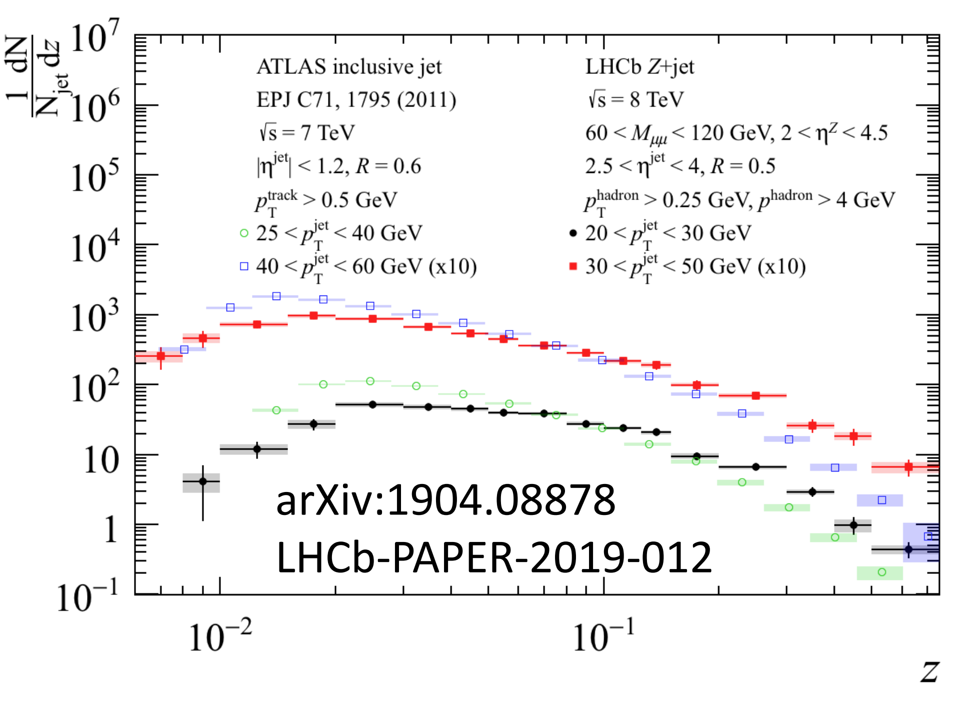
Results: Longitudinal momentum distributions

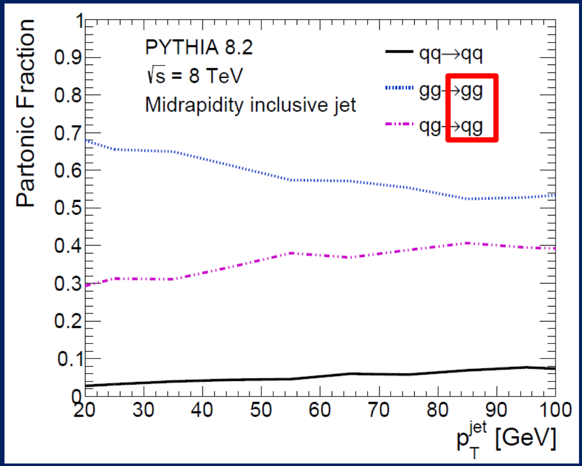


- Measurements in three jet transverse momentum (p_T^{jet}) bins, integrated over Z boson kinematics
- Longitudinal hadron-in-jet distributions independent of jet p_T at high longitudinal momentum fraction z
- Distributions diverge at low z simply due to kinematic phase space available



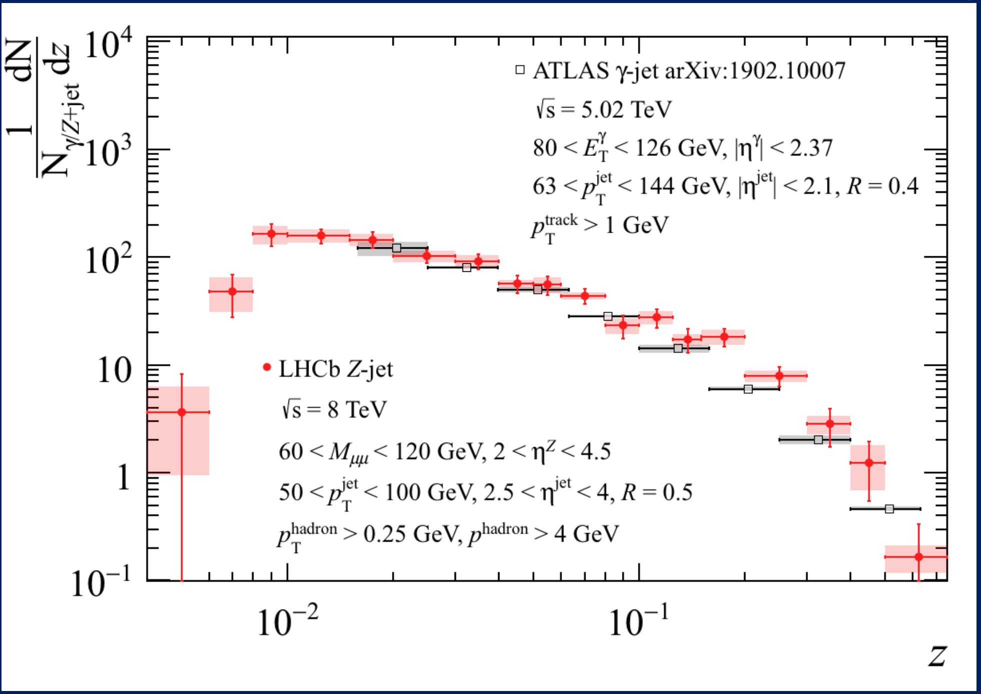
Longitudinal momentum distributions: Comparison to gluon-dominated jets from ATLAS





- Quark-dominated jets have relatively more hadrons produced at higher longitudinal momentum fractions than gluon-dominated jets
  - Will be interesting to follow up with an identified particle measurement. Do the hadrons produced at large momentum fractions in quark-dominated jets tend to contain a quark of the same flavor as the one that initiated the jet??

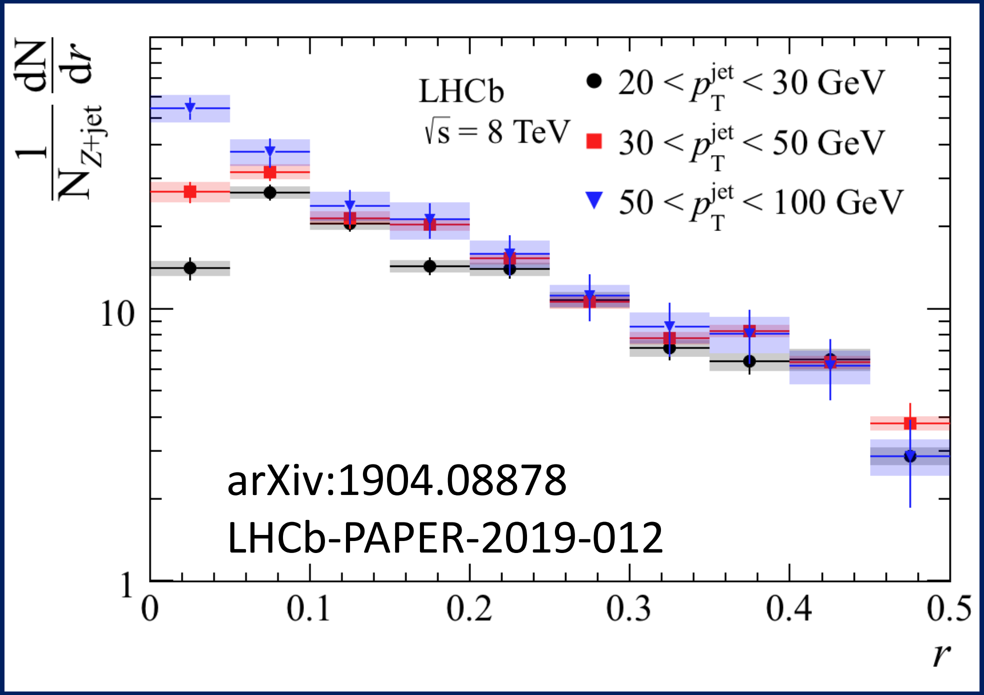
Longitudinal momentum distributions: Comparison to quark-enhanced jets from ATLAS (γ+jet)

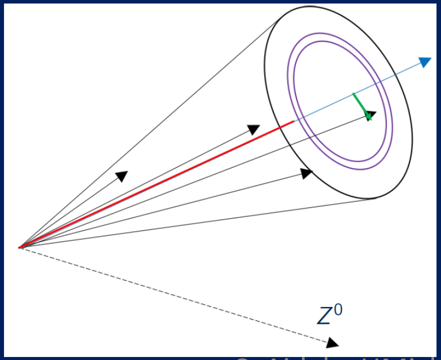


arXiv:1904.08878
LHCb-PAPER-2019-012

- ATLAS midrapidity γ+jet and LHCb Z+jet longitudinal distributions are instead very similar in the comparable jet p_T bin
  - γ+jet, like Z+jet, enhances quark jet fraction
  - Further evidence that differences observed between LHCb results and ATLAS gluon-dominated results are due to differences in quark and gluon hadronization

Results: Radial profiles

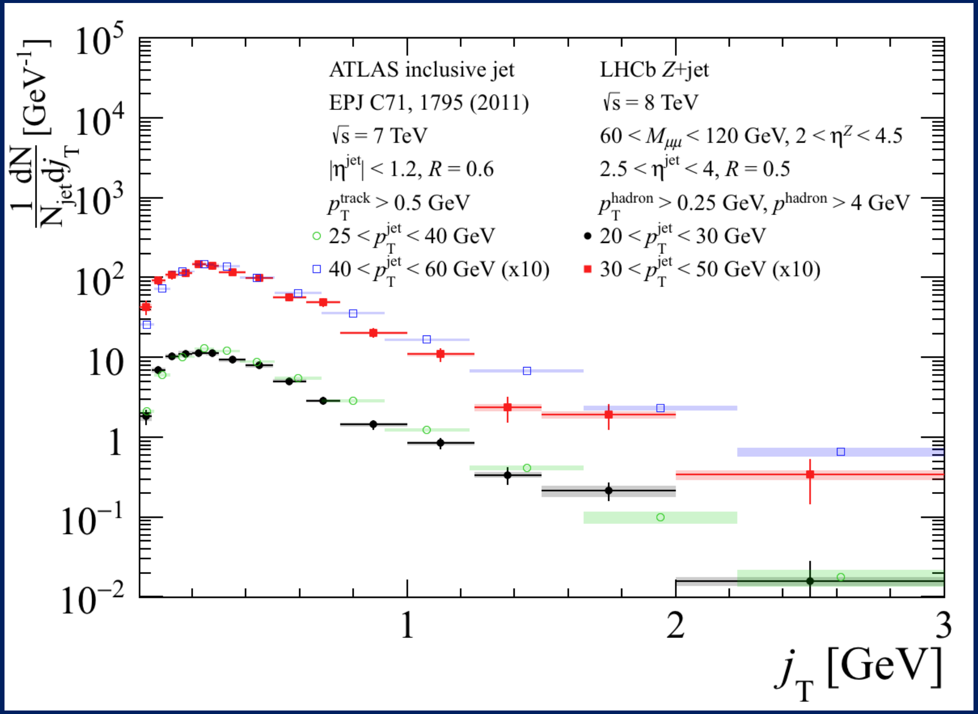




- Radial profiles largely independent of jet p_T away from the jet axis
- Multiplicity of hadrons along jet axis rises sharply with jet p_T
  - More “violent” scattering produces more particles (intuitive), most of which are close to the jet axis (not obvious)

Transverse momentum distributions: Comparison to ATLAS inclusive jets

- Transverse momentum distributions show smaller $\langle j_T \rangle$ in Z+jet vs. inclusive jet at small j_T



arXiv:1904.08878
LHCb-PAPER-2019-012

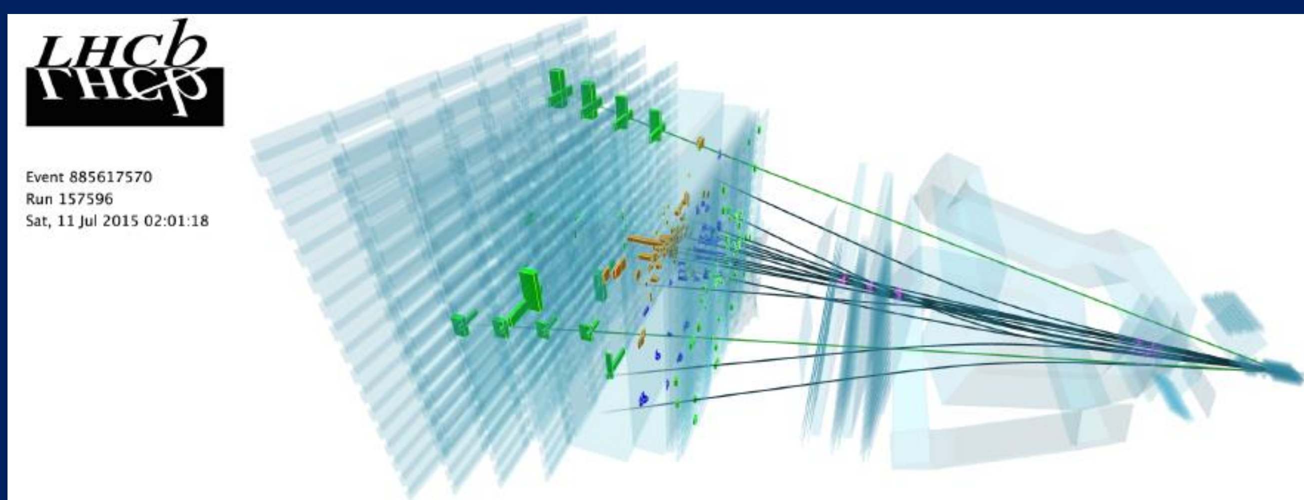
Work by former PD Joe Osborn

arXiv:1904.08878
LHCb-PAPER-2019-012

Analysis details

- Follow similar analysis strategy to previous ATLAS and LHCb papers
  - ATLAS: EPJC 71, 1795 (2011), NPA 978, 65 (2018)
  - LHCb: PRL 118, 192001 (2017)

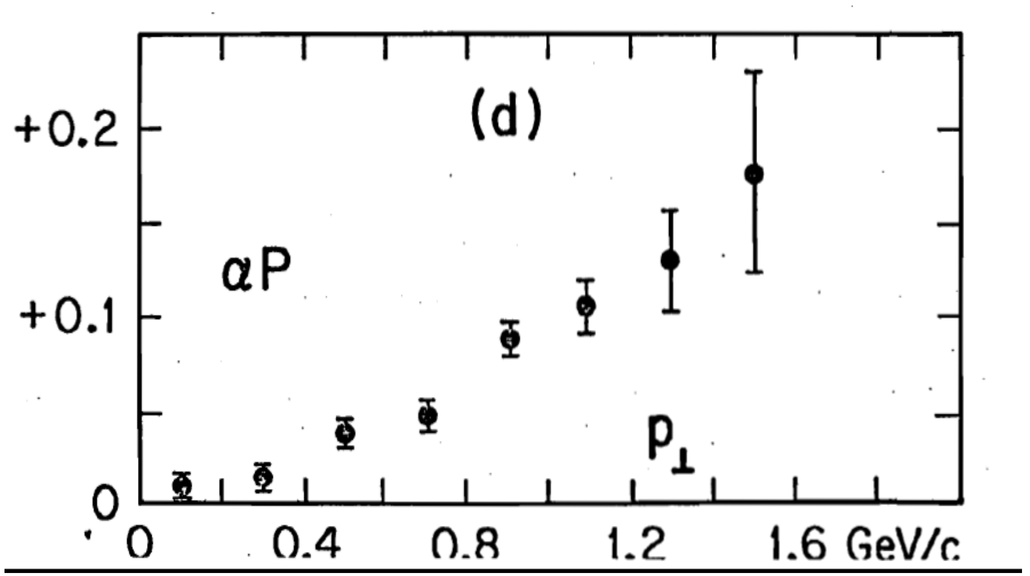
- $Z \rightarrow \mu^{+}\mu^{-}$ with $60 < M_{\mu\mu} < 120$ GeV, $2 < \eta < 4.5$
- Anti-k_T jets with $R = 0.5$, $p_T^{jet} > 20$ GeV, $2 < \eta < 4.5$
- $|\Delta\phi_{Z+jet}| > 7\pi/8$ selects 2→2 event topology
- Charged hadrons selected with $p_T > 0.25$ GeV, $p > 4$ GeV, $\Delta R < 0.5$



Hyperon polarization from unpolarized collisions

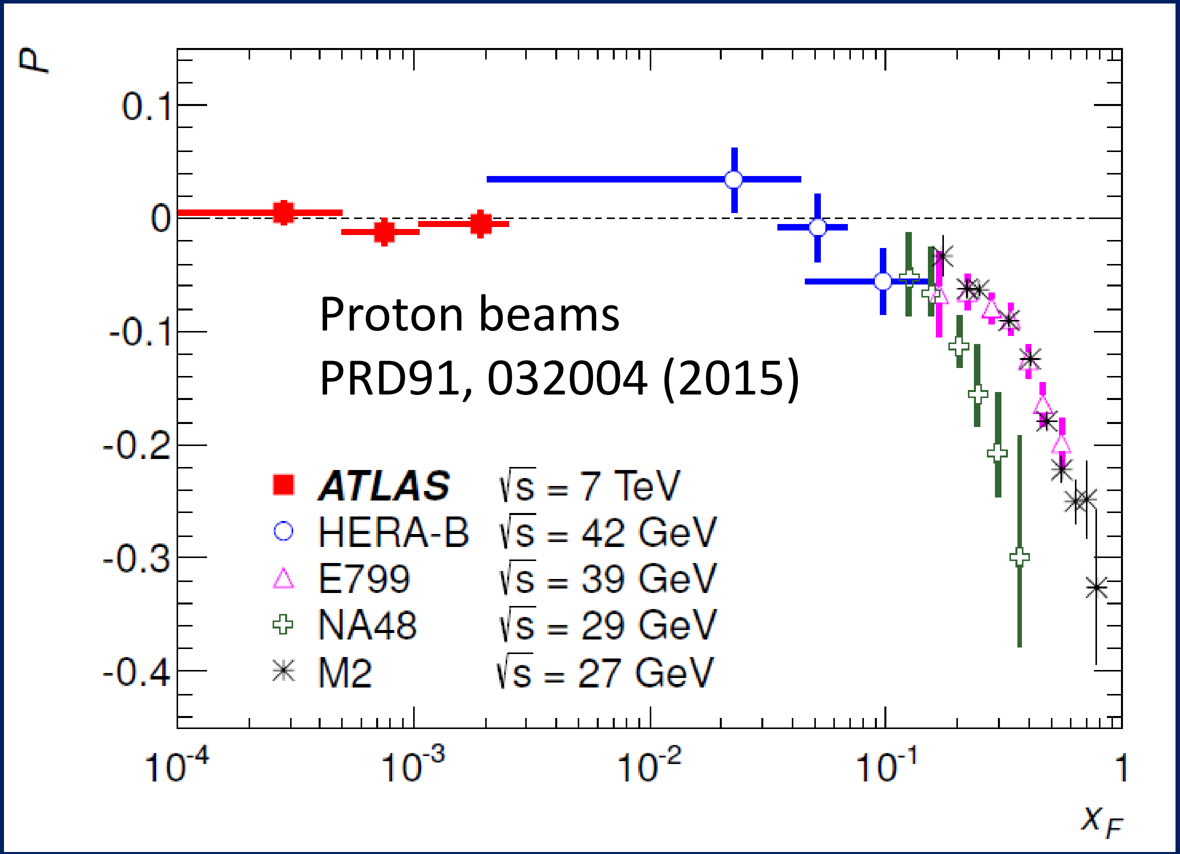
Λ^0 Hyperon Polarization in Inclusive Production by 300 GeV Protons on Beryllium

PRL36, 1113 (1976)



- 1976 lambda polarization discovery: p+Be, 300 GeV beam
- Polarization transverse to production plane up to ~20% for forward-angle lambda production; Polarizing TMD FF?
- Confirmed 1977 at CERN, p+Pt, 24 GeV beam (and by various proton-nucleus and proton-proton experiments afterwards . . .)

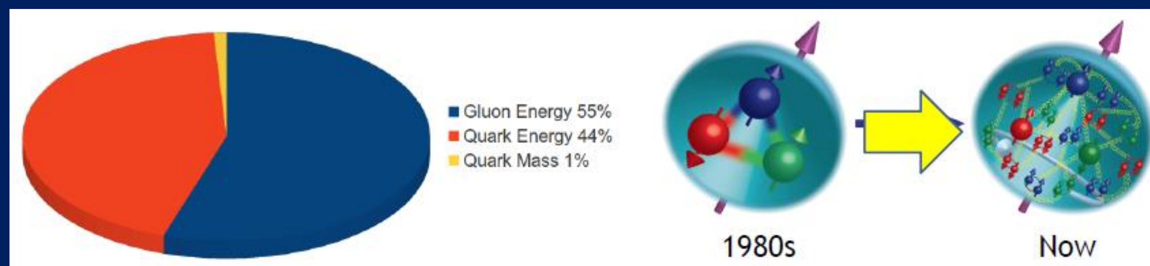
x_F dependence of lambda polarization in hadronic collisions



- Same sign and general x_F dependence for neutron beams
- But for K- and Σ- beams, positive polarization at positive x_F
- And for π- beam, positive polarization but at negative x_F!
- Consistent with zero for π+ and K+ beams

Ch. 2: Basic science to be explored

- *How does a nucleon acquire mass?* --almost 100 times greater than the sum of its valence quark masses. Cannot be understood via Higgs mechanism

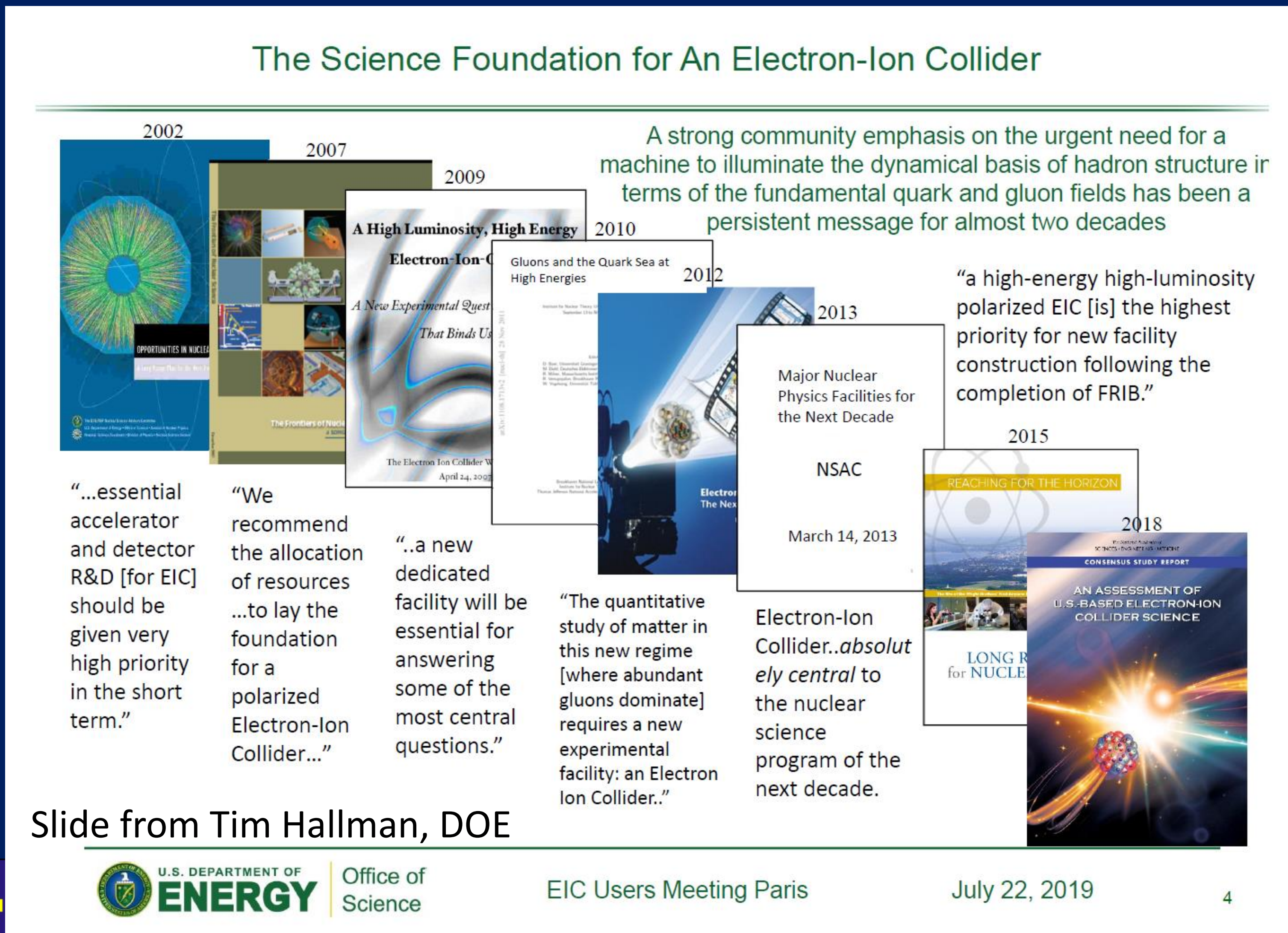


- *How does the spin (internal angular momentum) of the nucleon arise from its elementary quark and gluon constituents?* Proton spin is the basis of magnetic resonance imaging (MRI).

- *What are the emergent properties of dense systems of gluons?* How are they distributed in both position and momentum in nucleons and nuclei and how are they correlated among themselves and with the quarks and antiquarks present? *What are their quantum states?* Are there new forms of matter made of dense gluons?

The National Academies of
SCIENCES • ENGINEERING • MEDICINE

It takes a while to realize billion-dollar-scale science facilities . . .



Current Status and Path forward of EIC

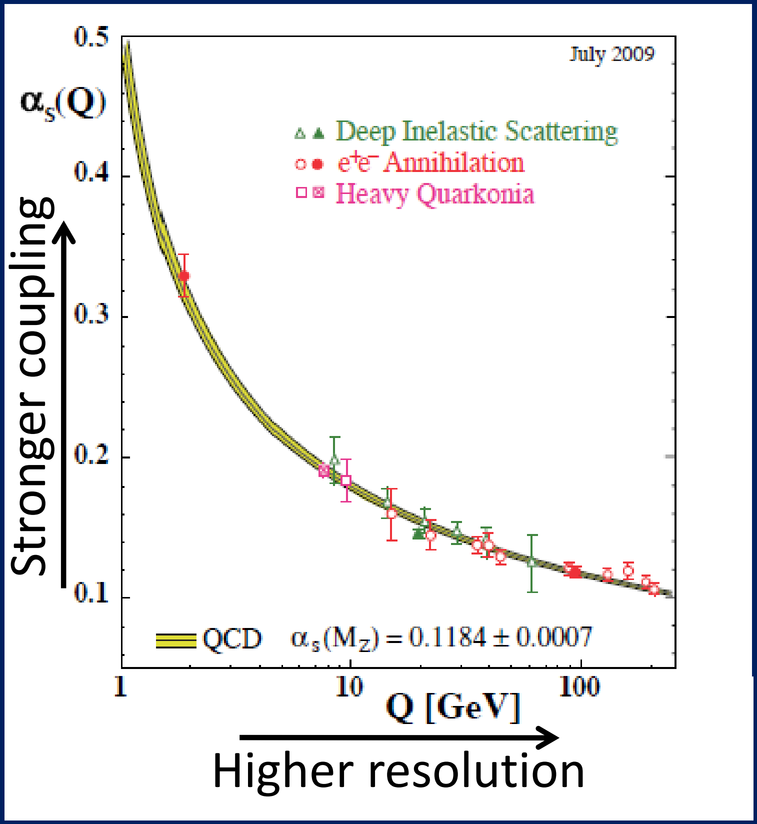
The "wickets" are substantially aligned for a major step forward on the EIC

- A Mission Need Statement for an EIC has been approved by DOE
- An Independent Cost Review (ICR) Exercise mandated by DOE rules for projects of the projected scope of the EIC is very far along
- DOE is moving forward with a request for CD-0 (approve Mission Need)
- DOE has organized a panel to assess options for siting and consideration of "best value" between the two proposed concepts
- The Deputy Secretary is the Acquisition Executive for this level of DOE Investment
- **The FY 2020 President's Request includes $ 1.5 million OPC. The FY 2020 House Mark includes $ 10 million OPC and $ 1 million TEC.**

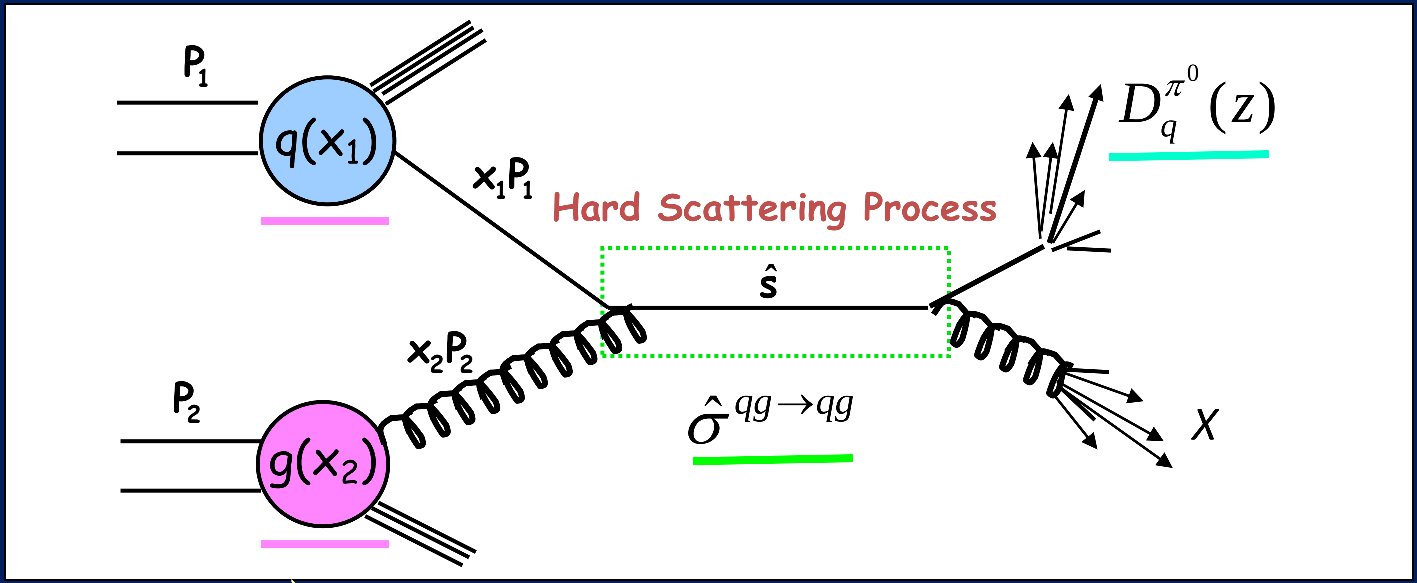
Slide from Tim Hallman, DOE Office of Science Associate Director for Nuclear Physics, at July meeting in Paris

Perturbative QCD

- Running of strong coupling constant with energy (*asymptotic freedom*)—weak coupling at high energies (short distances)
- Perturbative expansions as in QED (but many more diagrams due to gluon self-coupling!!)



Predictive power of perturbative QCD



$$\sigma\left(pp \to \pi^0 X\right) \propto \underline{q(x_1) \otimes g(x_2)} \otimes \underline{\hat{\sigma}^{qg\to qg}\left(\hat{s}\right)} \otimes \underline{D_q^{\pi^0}(z)}$$

High-energy processes have predictable rates given:

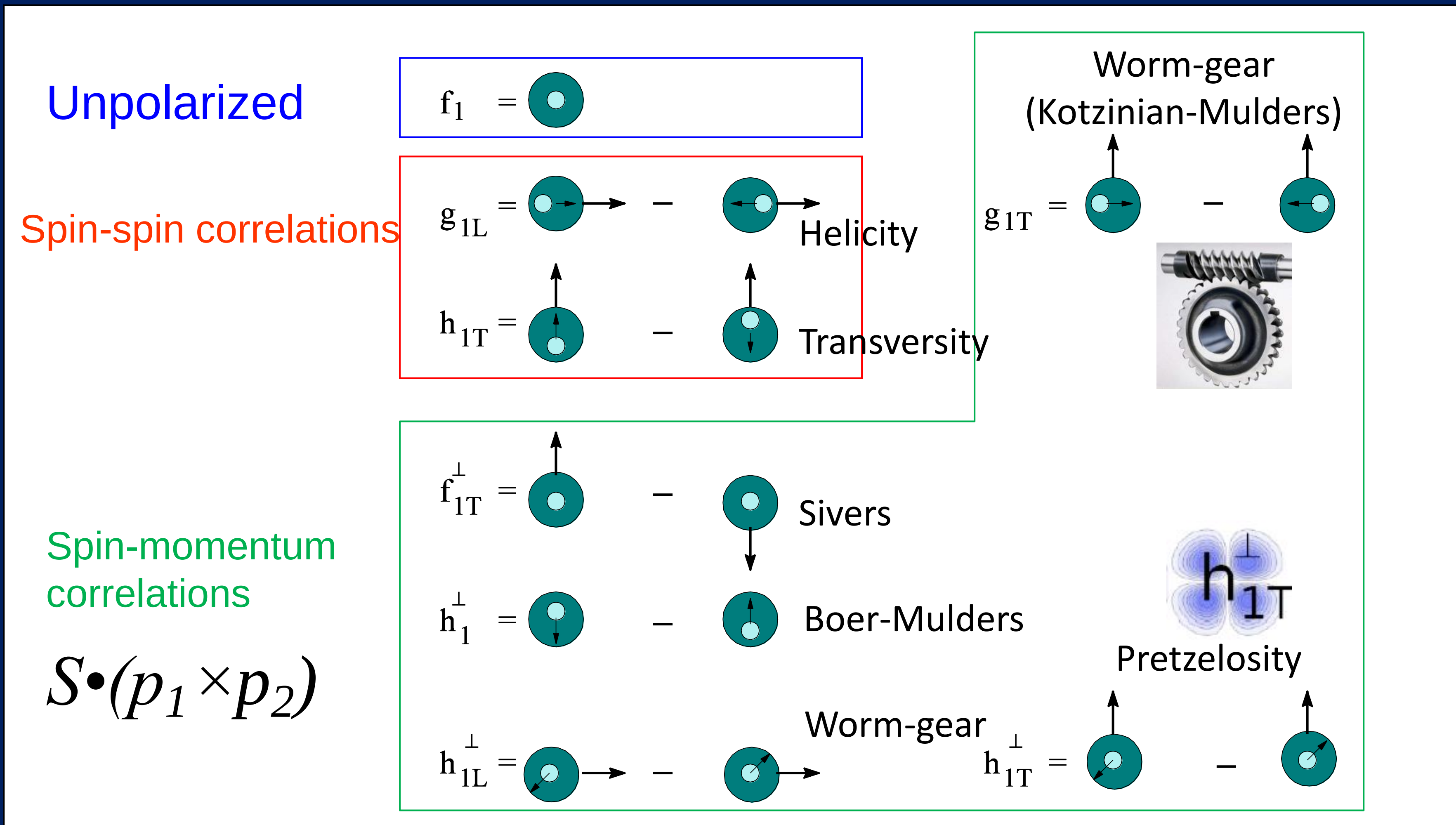
- Partonic hard scattering rates (calculable in pQCD)
- Parton distribution functions (need experimental input)
- Fragmentation functions (need experimental input)

$\left.\right\}$ **Universal non-perturbative factors**

Relativistic Heavy Ion Collider (RHIC)

- Ion collisions from 6 GeV-200 GeV
  - Energy scan to map out QCD phase diagram
  - Au+Au, d+Au, ^{3}He+Au, Cu+Au, Cu+Cu, p$^{\uparrow}$+Au, p$^{\uparrow}$+Al, U+U—control system size and geometry (e.g. Au, Cu spherical, ^{3}He “triangular”, U ellipsoidal)
- *Polarized* proton-proton collisions ranging in center-of-mass energy 62-510 GeV, >50% polarization

Spin-spin and spin-momentum correlations in QCD bound states



Review of spin-spin and spin-momentum correlations in the proton:
Aidala, Bass, Hasch, Mallot – Rev. Mod. Phys. 85, 655-691 (2013)