

# Testing QCD universality

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# What am I doing here?

## THE STANDARD MODEL OF FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model is a quantum theory that summarizes our current knowledge of the physics of fundamental particles and fundamental interactions (interactions are manifested by forces and by decay rates of unstable particles).

### FERMIONS

**Leptons** spin = 1/2

Flavor	Mass GeV/c <sup>2</sup>	Electric charge
$\nu_e$ lightest neutrino	$(0-2) \times 10^{-9}$	0
$e^-$ electron	0.000511	-1
$\nu_\mu$ middle neutrino	$(0.009-2) \times 10^{-9}$	0
$\mu^-$ muon	0.106	-1
$\nu_\tau$ heaviest neutrino	$(0.05-2) \times 10^{-9}$	0
$\tau^-$ tau	1.777	-1

**Quarks** spin = 1/2

Flavor	Approx. Mass GeV/c <sup>2</sup>	Electric charge
$u$ up	0.002	2/3
$d$ down	0.005	-1/3
$c$ charm	1.3	2/3
$s$ strange	0.1	-1/3
$t$ top	173	2/3
$b$ bottom	4.2	-1/3

### BOSONS

**Unified Electroweak** spin = 1

Name	Mass GeV/c <sup>2</sup>	Electric charge
$\gamma$ photon	0	0
$W^-$	80.39	-1
$W^+$	80.39	+1
$Z^0$ Z boson	91.188	0

**Strong (color)** spin = 1

Name	Mass GeV/c <sup>2</sup>	Electric charge
$g$ gluon	0	0

**Higgs Boson** spin = 0

Name	Mass GeV/c <sup>2</sup>	Electric charge
$H$ Higgs	126	0

### Structure within the Atom

### Properties of the Interactions

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass - Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	$W^+$ $W^-$ $Z^0$	$\gamma$	Gluons
Strength at:	$10^{-41}$ m $3 \times 10^{-17}$ m	0.8 $10^{-4}$	1 1	25 60

### Neutrinos

Neutrinos are produced in the sun, supernovae, reactors, accelerator collisions, and many other processes. Any produced neutrino can be described as one of three neutrino flavor states  $\nu_e$ ,  $\nu_\mu$ , or  $\nu_\tau$ , labelled by the type of charged lepton associated with its production. Each is a defined quantum mixture of the three definite-mass neutrinos  $\nu_1$ ,  $\nu_2$ , and  $\nu_3$  for which currently allowed mass ranges are shown in the table. Further exploration of the properties of neutrinos may yield powerful clues to puzzles about matter and antimatter and the evolution of stars and galaxy structures.

### Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or - charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g.  $Z^0$ ,  $\gamma$ , and  $\eta$ , and not  $K^0$ ,  $D^0$ , or  $B^0$ ) are their own antiparticles.

### Unsolved Mysteries

Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, microscopic black holes, and/or evidence of string theory.

#### Why is the Universe Accelerating?

The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmological Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?

#### Why No Antimatter?

Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?

#### What is Dark Matter?

Invisible forms of matter make up much of the mass observed in galaxies and clusters of galaxies. Does the dark matter consist of new types of particles that interact very weakly with ordinary matter?

#### Are there Extra Dimensions?

An indication for extra dimensions may be the extreme weakness of gravity compared with the other three fundamental forces. Gravity is so weak that a small magnet can pick up a paper clip overwhelming Earth's gravity.

### Particle Processes

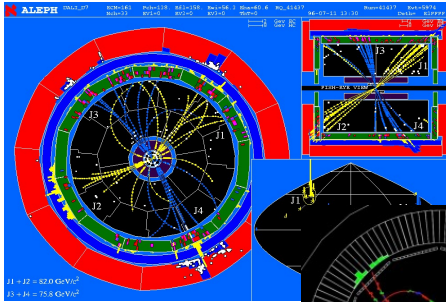
These diagrams are an artist's conception. Orange shaded areas represent the cloud of gluons.

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Jim Siegrist, talk to NSD prior to turn-on of RHIC (late 1990s):  
 “Once supersymmetry is discovered, all this is Nuclear Physics.”

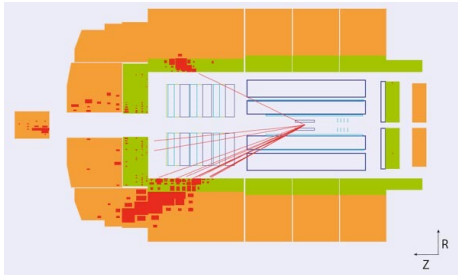
# QCD at Colliders

Past



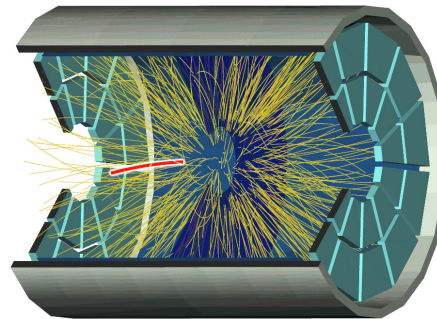
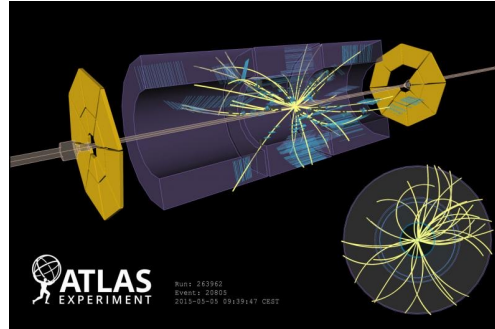
$e^+e^-$ : LEP, SLC

$e^+p$ : HERA



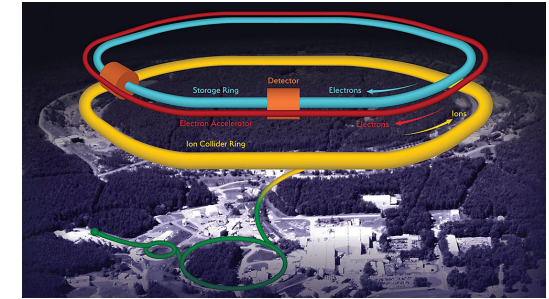
Present

$p+p$ ,  $A+A$ : LHC, RHIC



Future

$e^+p$ ,  $e^+A$ : EIC



$e^+e^-$ : LBNL?

Final states strongly dominated by QCD  
 Past colliders: archived data now being analyzed by modern tools  
 Last decade: major advances in QCD theory+exp (SCET, grooming,...)

Opportunity: comprehensive QCD analysis using data from multiple colliders

→ can we learn something new and interesting about QCD universality?

# Example: testing the universality of hadronization across collision systems

*work in progress*

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112 consider in our study. The goal is to study universality of nonperturbative corrections  
113 to perturbative QCD predictions that can then be measured in experiments. There  
114 are two types of “universality” that we mean here: (i) universality of nonperturbative  
115 effects in different observables in the same collider environment, and (ii) universality  
116 of nonperturbative effects in different (but related) observables in different collider  
117 environments. We will consider both types, though the type (ii) is certainly stronger.

# Event shape in DIS: N-Jettiness

Kang et. al.,  
Phys.Rev.D88:054004 (2013)

Global event shape measuring collimation of event along jet and beam directions

- Do jet reco; select N hardest jets in event
- N+1 axes  $q$ : beam + N jets
- For each hadron  $i$ : 4-vec projection onto each axis; select minimum  $q \cdot p$

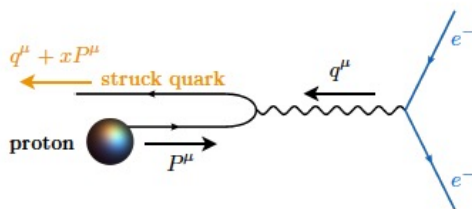
$$\tau_N = \frac{2}{Q^2} \sum_{i \in X} \min\{q_B \cdot p_i, q_1 \cdot p_i, \dots, q_N \cdot p_i\},$$

$\tau_N \rightarrow 0 =$  perfectly collimated jets  
 $\tau_N \rightarrow 1 =$  spherically distributed event

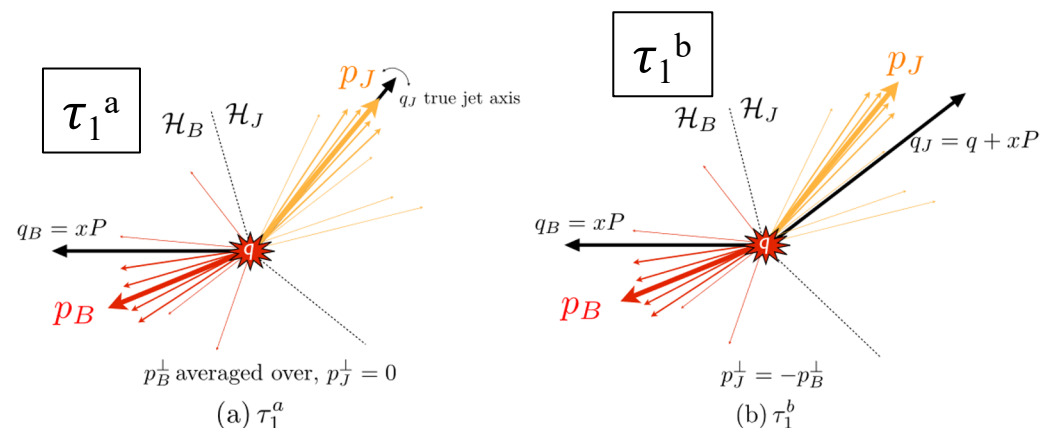
1-jettiness

$$\tau_1 = \frac{2}{Q^2} \sum_{i \in X} \min\{q_B \cdot p_i, q_J \cdot p_i\}$$

Breit frame



Choices of jet direction



$q$ : jet reco

$q$ : kinematic balance

# Non-perturbative corrections to $\tau$

SCET factorization:

$$\frac{1}{\sigma} \frac{d\sigma}{d\tau} = \frac{1}{\sigma} \int dk \left( \frac{d\sigma_{\text{PT}}}{d\tau} \left( \tau - \frac{k}{Q} \right) F \left( k - c_\tau \Omega_1 \right) \right), \quad \text{or} \quad \langle \tau \rangle = \langle \tau \rangle_{\text{PT}} + \frac{c_\tau \Omega_1}{Q}$$

Hard component  
Perturbatively calculable

Soft component  
NP

$c_\tau$ : pure number  
 $\Omega \sim \Lambda_{\text{QCD}}$

$\Omega$  is process-dependent but SCET predicts simple and deep scaling rules between:

- e+p DIS (HERA, EIC): event shapes ( $\tau_1$ )
- p+p (LHC, RHIC): recoil jet mass for  $\gamma/Z + 1$  jet (isolated)

Probes the same QCD matrix element  $\rightarrow$  new (and, we hope, incisive) test of QCD universality

Experimental issues being worked out

- data: HERA (H1 archived); LHC (ATLAS, ALICE, CMS, LHCb)

Similar connection to event shapes in  $e^+e^-$ ?

- Color flow is different than with hadron in initial state
- Work in progress
- Candidate for LBNL  $e^+e^-$  Collider science program