1-Jettiness + HERA Comparison

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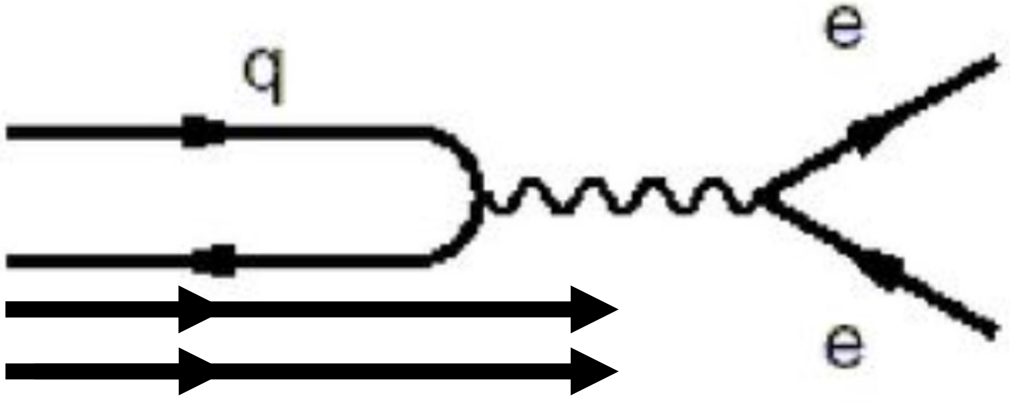
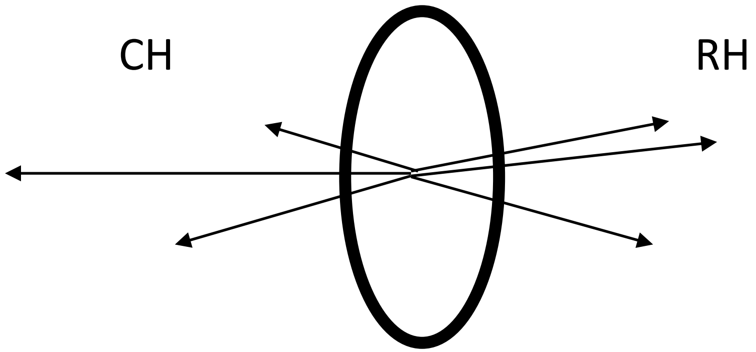
Group Meeting 6/22

The Breit Frame + Thrust

- Breit frame, “infinite-momentum” frame or “brick wall” frame
- Frame in which struck quark has momentum reversed

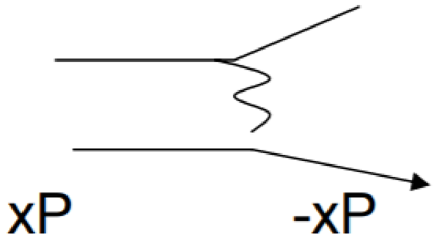




- In Breit frame DIS, you have the quark getting its momentum reversed and the proton remnants continuing forward.
- This lends itself to a measurement of “hemispheres” in Breit frame, corresponding to participant quark vs. remnant, so called “current hemisphere” (CH) and “remnant hemisphere” (RH)

Aside: Breit Frame Transformation

- If the scattered lepton is measured accurately, the lorentz transformation to the Breit frame can be made from the lab frame



$$x\vec{P} + \vec{q} = -x\vec{P}$$

$$2x\vec{P} + \vec{q} = 0$$

$$BF : boost : 2x\vec{P} + \vec{q}$$

$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

$$Q^2 = 2E_e E'_e (1 - \cos\Theta_{e'})$$

Measure of resolution power

$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta'_e}{2}\right)$$

Measure of inelasticity

$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

Measure of momentum fraction of struck quark

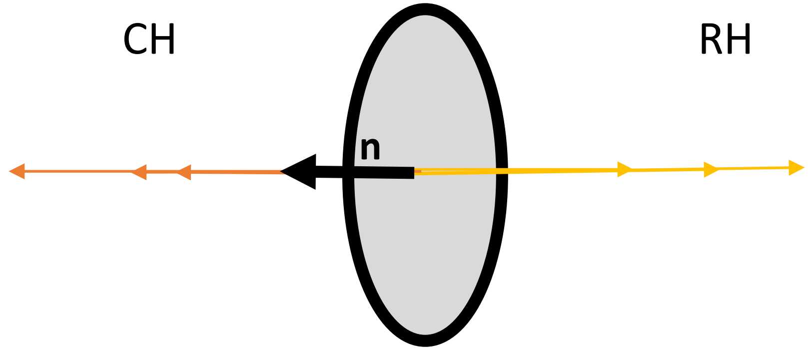
- Need to learn x, q from lepton
  - For EIC, may need to learn P and E_e from t_0 due to crab crossing?
- By finding Q^2 and y from lepton, x and q are defined.
- Lepton energy scale is a very important systematic in BF studies

The Breit Frame + Thrust

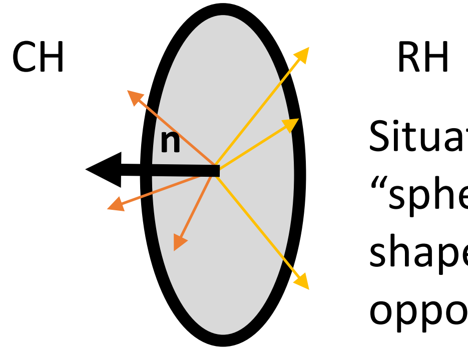
- This version of thrust (below; as used by HERA experiments) measures the longitudinal momentum components of particles in current hemisphere projected onto the current hemisphere axis
  - Note: Variable can also be studied in e^+e^-!
- This crucially omits the remnant hemisphere, making it non-global

n = boson direction
$\mathbf{P}_h$ = hadron momenta in CH

$$\tau = 1 - \frac{\sum_{h \in CH} |\mathbf{p}_h \cdot \mathbf{n}|}{\sum_{h \in CH} |\mathbf{p}_h|} = 1 - \frac{\sum_{h \in CH} |p_{h\,z}|}{\sum_{h \in CH} |\mathbf{p}_h|}.$$



Situation where τ = 1, longitudinal projection of CH particle momenta onto hemisphere axis is 0, high "thrust" in current direction

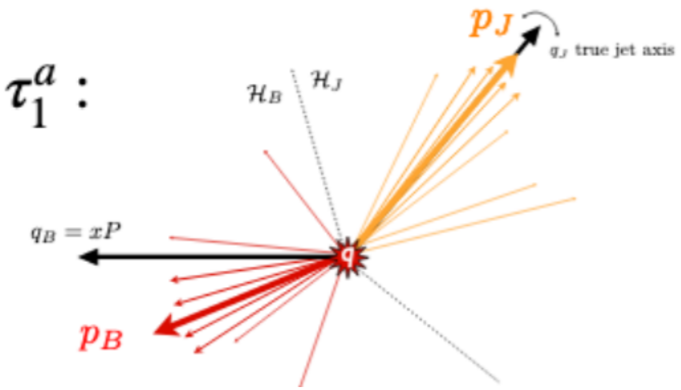


Situation with low thrust, high "spherocity" – another event shape variable effectively opposite of thrust

1-Jettiness

- Event shape observable with theoretical calculation uncertainty of the order of 1%, sensitivity to α_s and PDFs (non-perturbative parameter α_0?)
  - To be compared to inclusive/dijet extractions in DIS with uncertainties of ~10%
- “1-jettiness” in DIS measures final states with beam radiation + one additional jet, NOT the same as thrust from above, remnant is included in measurement
- Measure 1-Jettiness cross section with high precision, theory does the rest.
- Caveat: Larger systematic error due to non-cancellation of hadronic energy scale (unlike in thrust)

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



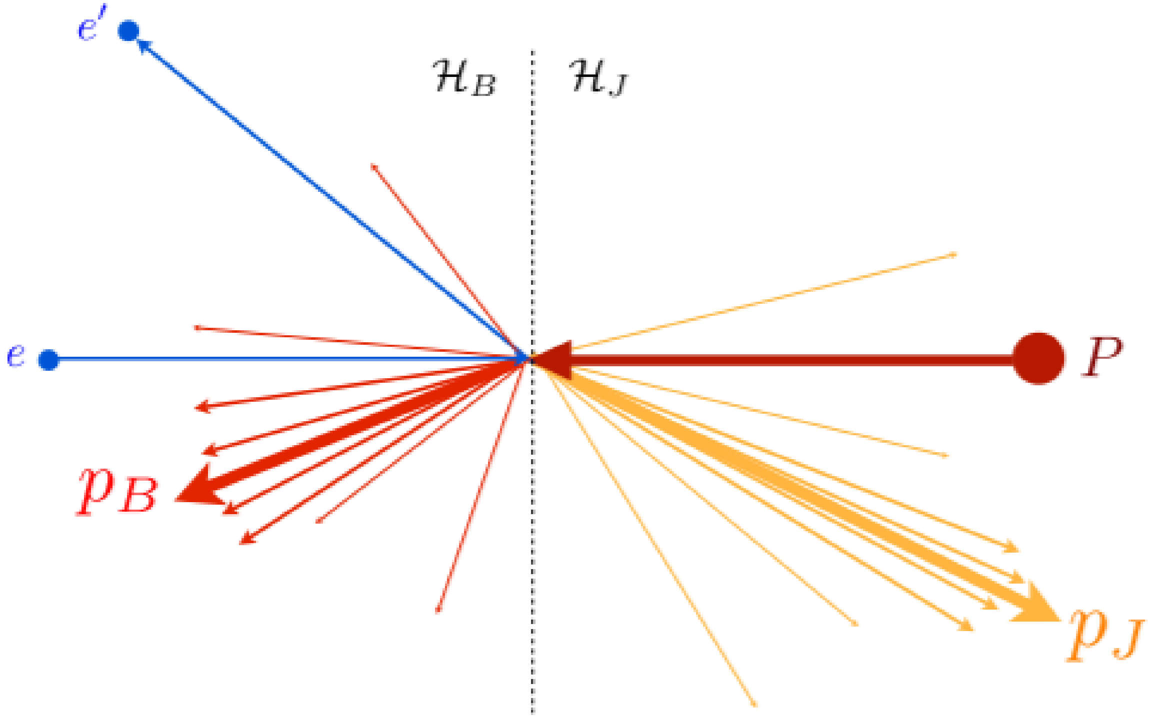
qB and qJ are 4-vectors along the nuclear beam and the jet directions respectively

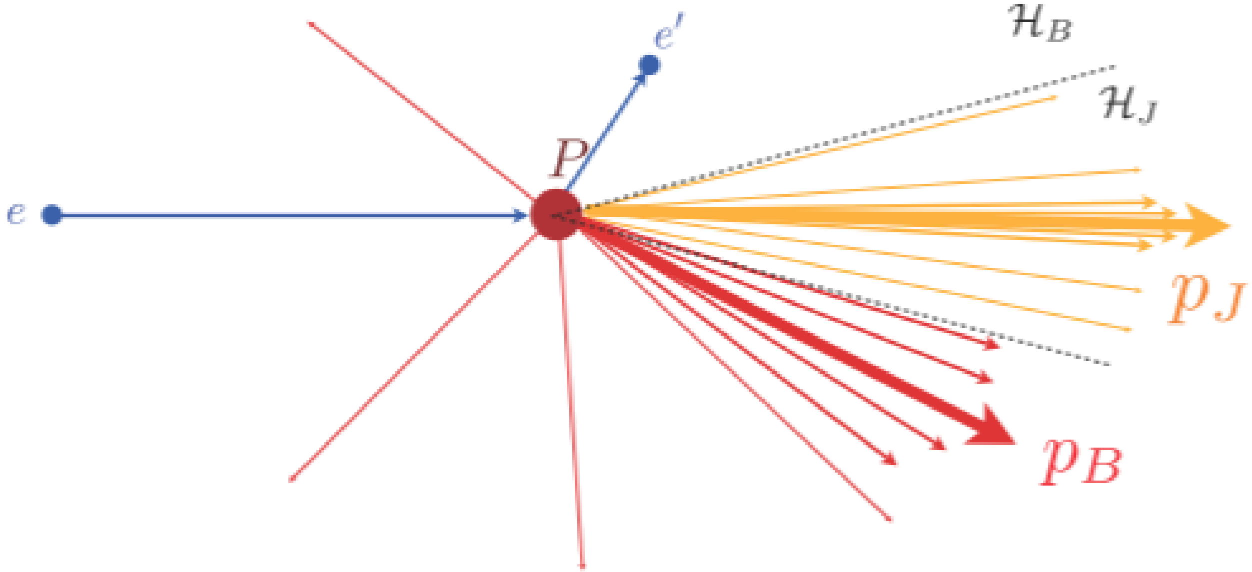
The observable is a scalar product of 4-vectors, frame invariant.

τ_1->0 : 2 jets, one along the beam direction from ISR from the proton
τ_1->1: >2 jets in the final state

Put simply: minimizing dot products W.R.T beam or jet = group into hemispheres based on which 4-vector is closest, beam or jet

Working with 4-Vectors, so mass plays a role -> **PID!**





1-Jettiness in the center-of-momentum frame

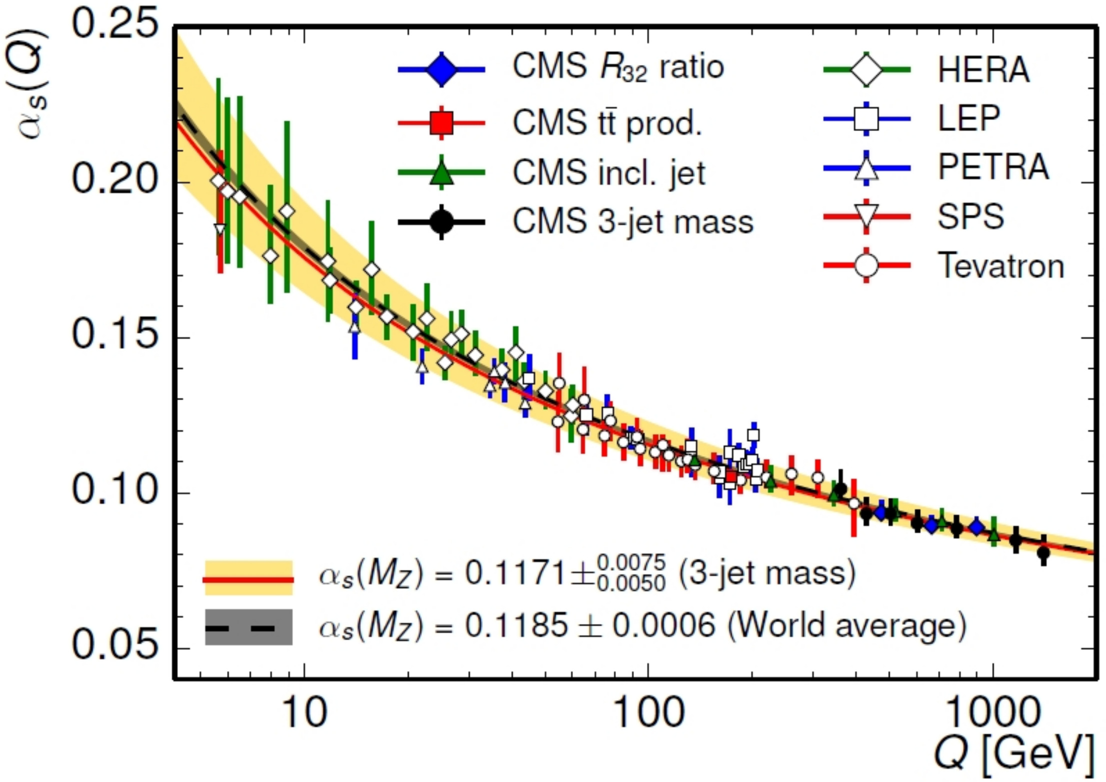
1-Jettiness in the fixed target frame

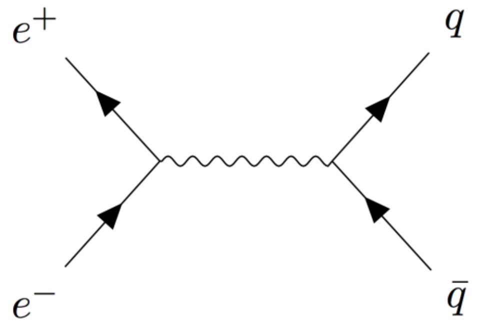
EIC Lab frame will be somewhere in-between

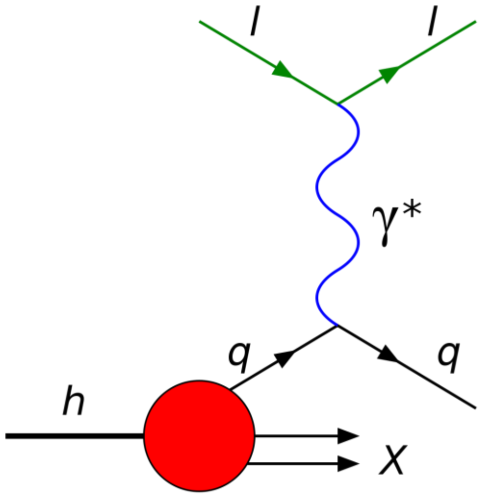
(HERA had lab-to-CM boost of $\gamma = 2.86$)

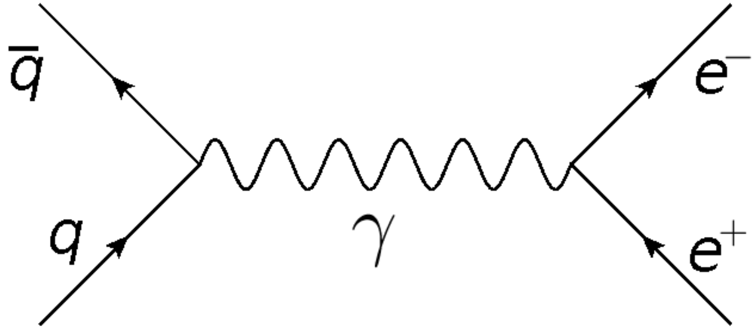
1-Jettiness and α_s

- α_s is the only coupling parameter in QCD, needs to be experimentally measured and checked in as many channels as possible
- Unique running of α_s is a byproduct of the complexity and richness of QCD
- Measurement of α_s through standard "knockout" DIS, calculable to N^3LL
- Crossing symmetry with e^+e^-, h+h collisions







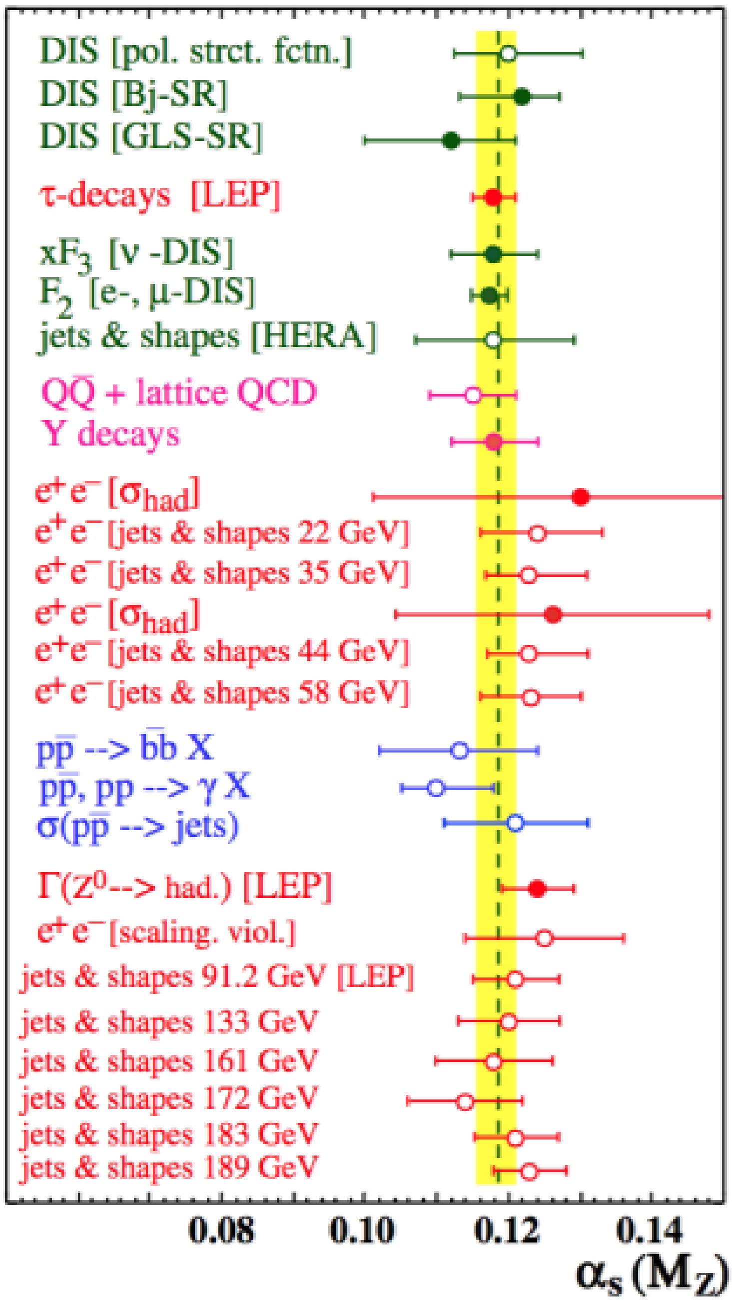


1-Jettiness

- Many lessons to be learned from HERA, where similar event shape observables were readily measured in DIS
- EIC has an advantage due to luminosity, lower higher-order cross sections (dipole DIS etc.), ability to vary collision energy, hopefully better detectors
- e+h fixed target experiments generally haven't had enough $\sqrt{s}$ to produce jets regularly and separate them in the lab frame (also detectors often non-hermetic)
- EIC in conjunction with theoretical improvements can likely provide significant improvement on uncertainty over HERA, (HERA and LEP* measurements dominated by theoretical uncertainty, revisit/combine with EIC measurements?)

$$\alpha_s(m_Z) = 0.1215 \pm 0.0012 \pm 0.0061$$

LEP value ± Exp. Uncert. ± Theo. Uncert



*Might be fun to look at data from an experiment that shut down when I was 5

1-Jettiness

For the Yellow Report, it's necessary to quantify the feasibility of this measurement at the EIC to see whether or not it's worth including in the physics program.

Key points

-Globalness? impact of experimental η,θ cutoffs
-Impact of non-perfect PID (pion mass assumption)
-Tracking limitations
-Impact of low momentum cutoffs for tracks imposed by the magnetic field
-Limitations induced by the response of the hadronic and electromagnetic calorimetry
-Explore different modes of measurment (track-only, track+EMCAL, track+EMCAL+HCAL)

Our goal

Estimate a final τ_1 cross section uncertainty considering all possible sources of experimental systematics: positron energy calibration, uncertainty of the hadronic energy scale, tracking efficiency uncertainty, model dependency of correction factors, unfolding uncertainties, lumi determination etc

My small contribution is to dig into HERA experiments and quantify the ways in which the EIC can make the measurement more or less precisely than they did.

Big question: why did they only analyze HERA I data?

Total of 82.2 pb^{-1} integrated luminosity from HERA I analyzed by ZEUS (in 2006) and 106 pb^{-1} from HERA I from H1 (in 2006)… < 2 days of EIC run time at initial luminosity if my math is correct. 10 fb^{-1}/183 days (6 months), **55 pb^{-1}/day**

Possible that at the time, theoretical uncertainty still dominated experimental so nobody wanted to spend their time improving on the measurement.

Extraction of α_s in any channel is a delicate balance of complicated theory (scheme dependences etc. that I don't understand) with experimental measurements

In principle, if Chris Lee and collaborators are correct about the precision of their calculations, simply re-analyzing HERA in terms of 1-Jettiness could yield a significant improvement in the uncertainties

Process	Collab.	Value	Exp.	Th.	Total	(%)
(1) Inc. jets at low Q^2	H1	0.1180	0.0018	$^{+0.0124}_{-0.0093}$	$^{+0.0125}_{-0.0095}$	$^{+10.6}_{-8.1}$
(2) Dijets at low Q^2	H1	0.1155	0.0018	$^{+0.0124}_{-0.0093}$	$^{+0.0125}_{-0.0095}$	$^{+10.8}_{-8.2}$
(3) Trijets at low Q^2	H1	0.1170	0.0017	$^{+0.0091}_{-0.0073}$	$^{+0.0093}_{-0.0075}$	$^{+7.9}_{-6.4}$
(4) Combined low Q^2	H1	0.1160	0.0014	$^{+0.0094}_{-0.0079}$	$^{+0.0095}_{-0.0080}$	$^{+8.2}_{-6.9}$
(5) Trijet/dijet at low Q^2	H1	0.1215	0.0032	$^{+0.0067}_{-0.0059}$	$^{+0.0074}_{-0.0067}$	$^{+6.1}_{-5.5}$
(6) Inc. jets at medium Q^2	H1	0.1195	0.0010	$^{+0.0052}_{-0.0040}$	$^{+0.0053}_{-0.0041}$	$^{+4.4}_{-3.4}$
(7) Dijets at medium Q^2	H1	0.1155	0.0009	$^{+0.0045}_{-0.0035}$	$^{+0.0046}_{-0.0036}$	$^{+4.0}_{-3.1}$
(8) Trijets at medium Q^2	H1	0.1172	0.0013	$^{+0.0053}_{-0.0032}$	$^{+0.0055}_{-0.0035}$	$^{+4.7}_{-3.0}$
(9) Combined medium Q^2	H1	0.1168	0.0007	$^{+0.0049}_{-0.0034}$	$^{+0.0049}_{-0.0035}$	$^{+4.2}_{-3.0}$
(10) Inc. jets at high Q^2 (anti-k_T)	ZEUS	0.1188	$^{+0.0036}_{-0.0035}$	$^{+0.0022}_{-0.0022}$	$^{+0.0042}_{-0.0041}$	$^{+3.5}_{-3.5}$
(11) Inc. jets at high Q^2 (SIScone)	ZEUS	0.1186	$^{+0.0036}_{-0.0035}$	$^{+0.0025}_{-0.0025}$	$^{+0.0044}_{-0.0043}$	$^{+3.7}_{-3.6}$
(12) Inc. jets at high Q^2 (k_T; HERA I)	ZEUS	0.1207	$^{+0.0038}_{-0.0036}$	$^{+0.0022}_{-0.0023}$	$^{+0.0044}_{-0.0043}$	$^{+3.6}_{-3.6}$
(13) Inc. jets at high Q^2 (k_T; HERA II)	ZEUS	0.1208	$^{+0.0037}_{-0.0032}$	$^{+0.0022}_{-0.0022}$	$^{+0.0043}_{-0.0039}$	$^{+3.6}_{-3.2}$
(14) Inc. jets in γp (anti-k_T)	ZEUS	0.1200	$^{+0.0024}_{-0.0023}$	$^{+0.0043}_{-0.0032}$	$^{+0.0049}_{-0.0039}$	$^{+4.1}_{-3.3}$
(15) Inc. jets in γp (SIScone)	ZEUS	0.1199	$^{+0.0022}_{-0.0022}$	$^{+0.0047}_{-0.0042}$	$^{+0.0052}_{-0.0047}$	$^{+4.3}_{-3.9}$
(16) Inc. jets in γp (k_T)	ZEUS	0.1208	$^{+0.0024}_{-0.0023}$	$^{+0.0044}_{-0.0033}$	$^{+0.0050}_{-0.0040}$	$^{+4.1}_{-3.3}$
(17) Jet shape	ZEUS	0.1176	$^{+0.0013}_{-0.0028}$	$^{+0.0091}_{-0.0072}$	$^{+0.0092}_{-0.0077}$	$^{+7.8}_{-6.5}$
(18) Subjet multiplicity	ZEUS	0.1187	$^{+0.0029}_{-0.0019}$	$^{+0.0093}_{-0.0076}$	$^{+0.0097}_{-0.0078}$	$^{+8.2}_{-6.6}$
HERA average 2004		0.1186	±0.0011	±0.0050	±0.0051	±4.3
HERA average 2007		0.1198	±0.0019	±0.0026	±0.0032	±2.7

PS: Axions?

- https://arxiv.org/abs/2006.09721
- Paper published a few days ago by XENON 1T “Observation of Excess Electronic Recoil Events in XENON1T”
- “The solar axion model has a 3.5 σ significance”
- Axions provide a neat explanation for the strong CP problem, namely why should the θ parameter contributing to CP-violation in QCD be so darn small? (Current limit is $< 10^{-10}$ radians)
- Highlights the huge variation in experimental techniques used to test QCD!

3.3 tons of ultra pure liquid Xenon!

as usual, grains of salt abound.