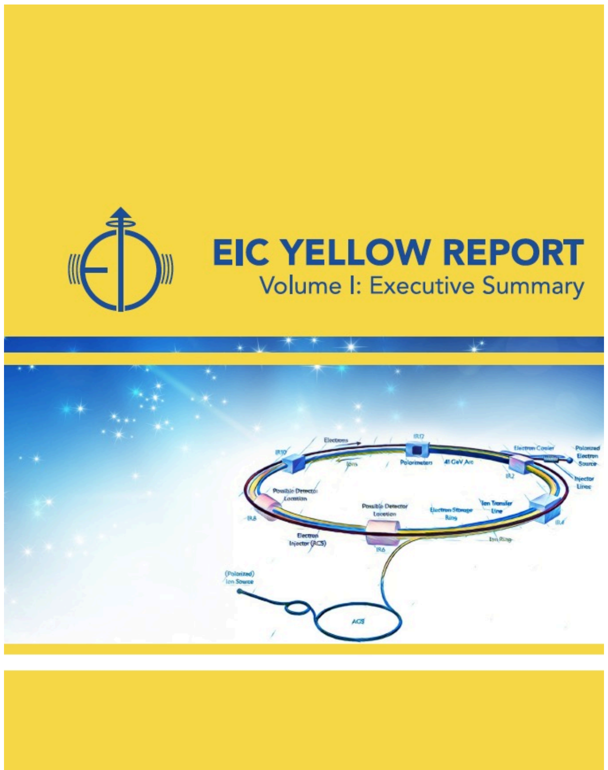
Measurements of α_s and QCD universality at EIC + HERA (+ LHC + RHIC?)

Peter J.

EIC Group Meeting, March 30 2021

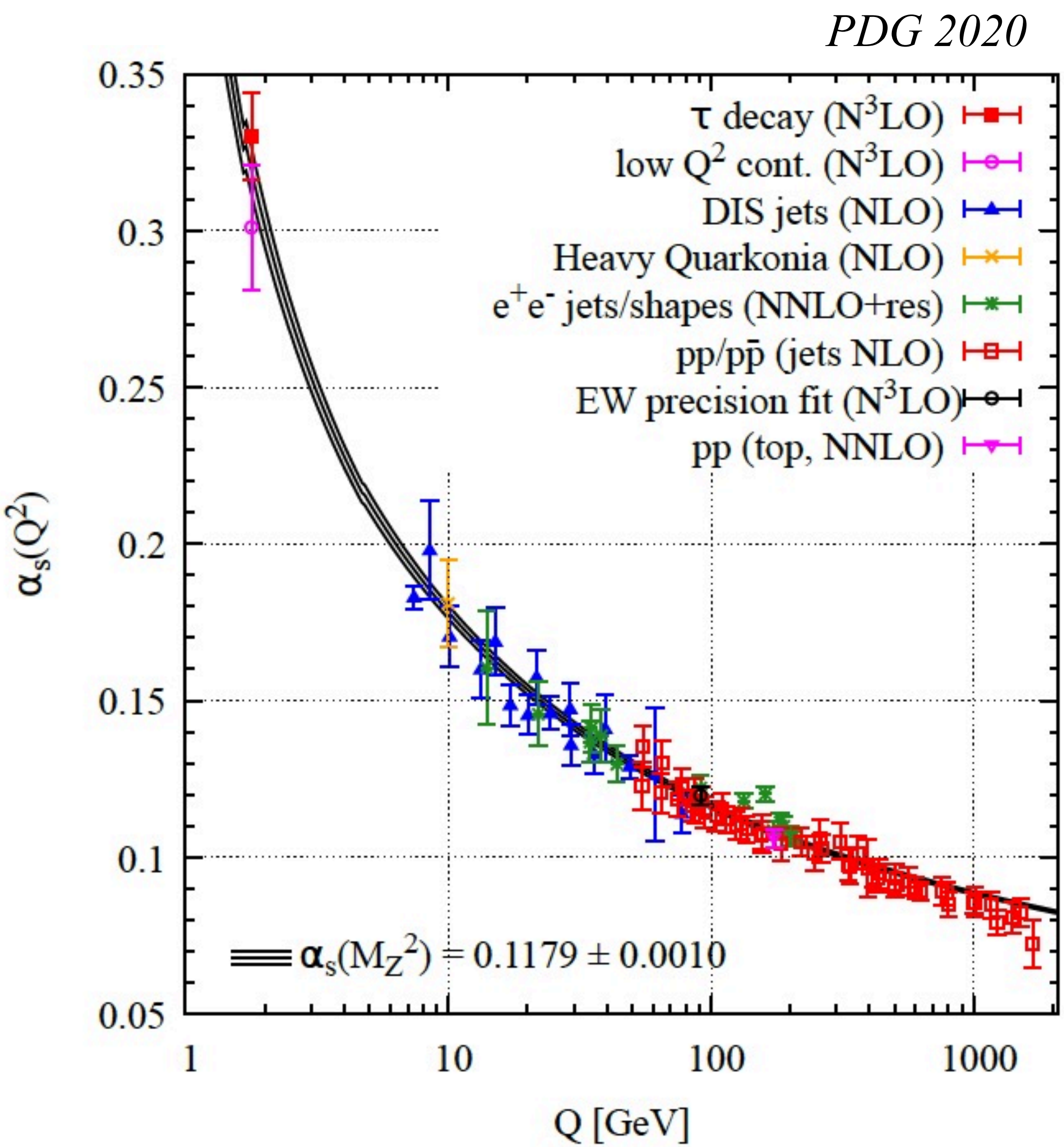


Contents

EIC YR: strong emphasis on “applied QCD” (or perhaps “emergent QCD”)

Less emphasis on “basic QCD” (or “fundamental QCD”?) – see next slides for definition

“Basic QCD” I: running of α_s



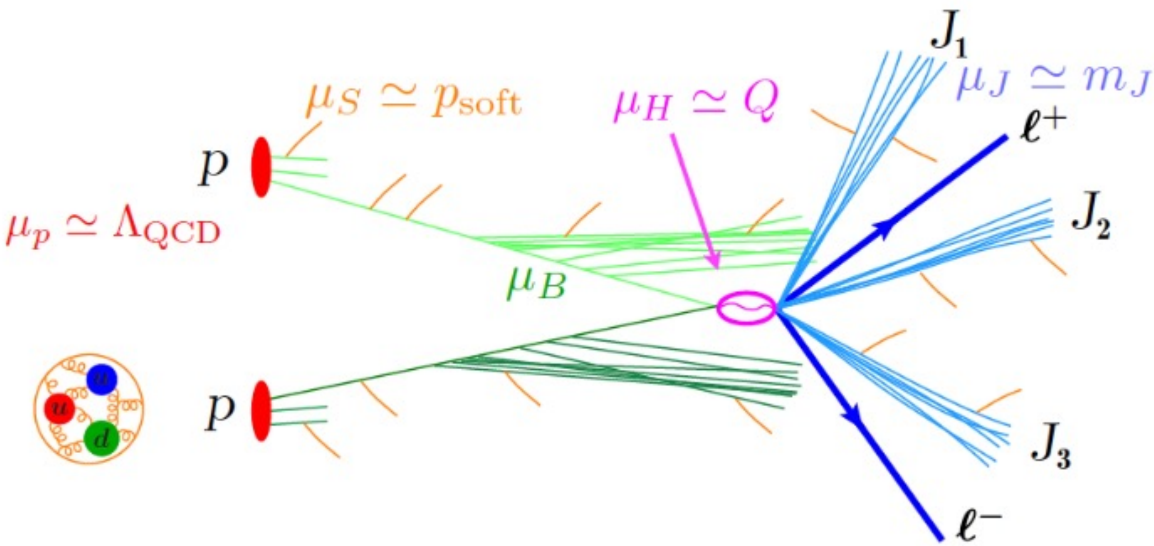
Can next-generation event shape measurements of in DIS at HERA and EIC provide new constraints at moderate Q^2?

"Basic QCD" II: SCET factorization

beam hard jet pert. soft

$$\hat{\sigma}_{\text{fact}} = \mathcal{I}_a \mathcal{I}_b \otimes H \otimes \prod_i J_i \otimes S$$

μ_B μ_H μ_J μ_S



SCET: Hard, Jet (and sometimes Soft) functions are "universal"

- Same functions apply to different processes in DIS (evt shapes; jet mass)
- Same (or calculably related) functions apply in pp (γ/Z+jet → jet mass)

Can we test the claim of universality experimentally at EIC/HERA + LHC/RHIC?

Reminder: N-Jettiness in DIS

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.p

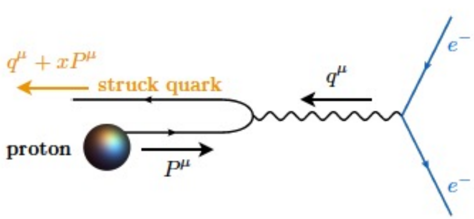
$$\tau_N = \frac{2}{Q^2} \sum_{i \in X} \min\{q_B \cdot p_i, q_1 \cdot p_i, \ldots, q_N \cdot p_i\},$$

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

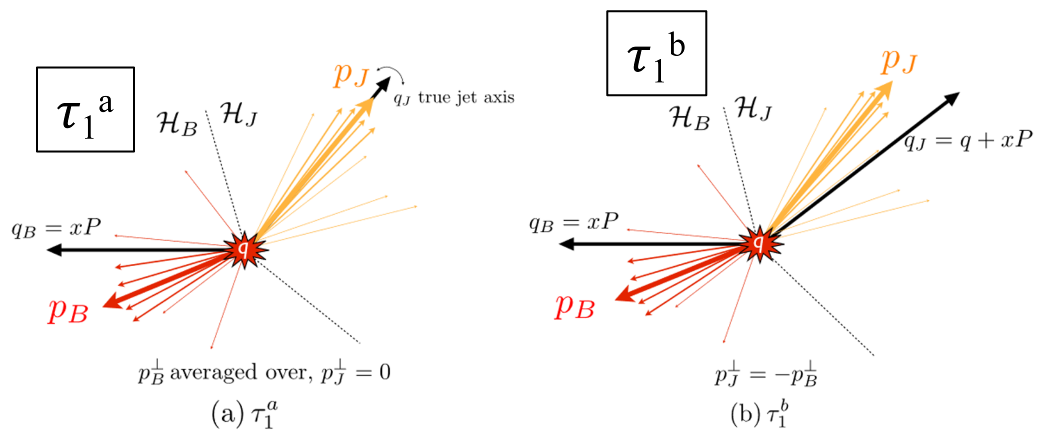
1-jettiness

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

Breit frame



Choices of jet direction



q: jet reco ***q***: kinematic balance

1-jettiness: theory

C. Lee et al., EIC YR

SCET factorization:

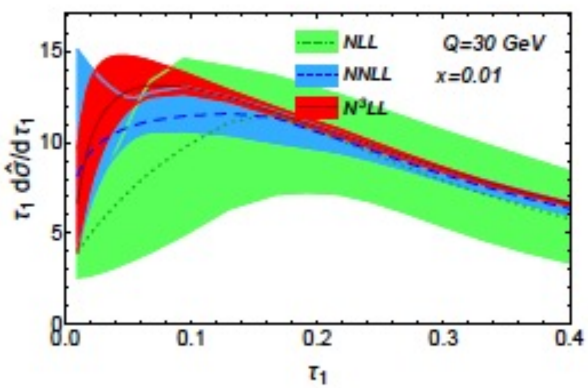
$$\frac{d\sigma}{dx\,dQ^2\,d\tau_1^a} = \frac{d\sigma_0}{dx\,dQ^2}\int dt_J\,dt_B\,dk_S\,\delta\Big(\tau_1^a - \frac{t_J+t_B}{Q^2} - \frac{k_S}{Q}\Big) J_q(t_J,\mu)\,S(k_S,\mu)$$
$$\times \sum_q H_q(y,Q^2,\mu)\,B_q(t_B,x,\mu) + \sigma_{\rm ns}(x,Q^2,\tau_1^a)\,,$$

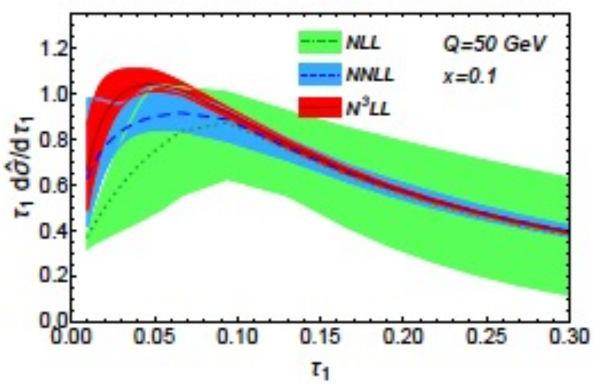
$$\frac{d\sigma_0}{dx\,dQ^2} = \frac{2\pi\alpha_{\rm em}^2}{Q^4}\big[(1-y)^2+1\big]$$

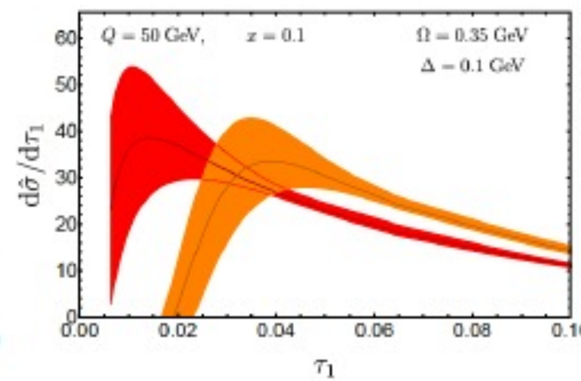
Universal fns:
- H: hard
- J: jet
- B: beam
- S: soft

τ_1^b

Universal NP factor ***Ω***



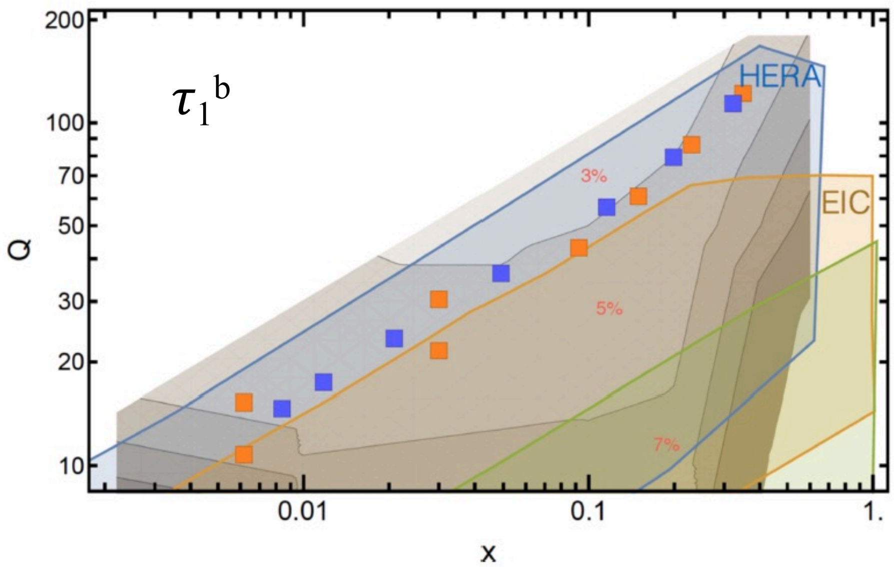




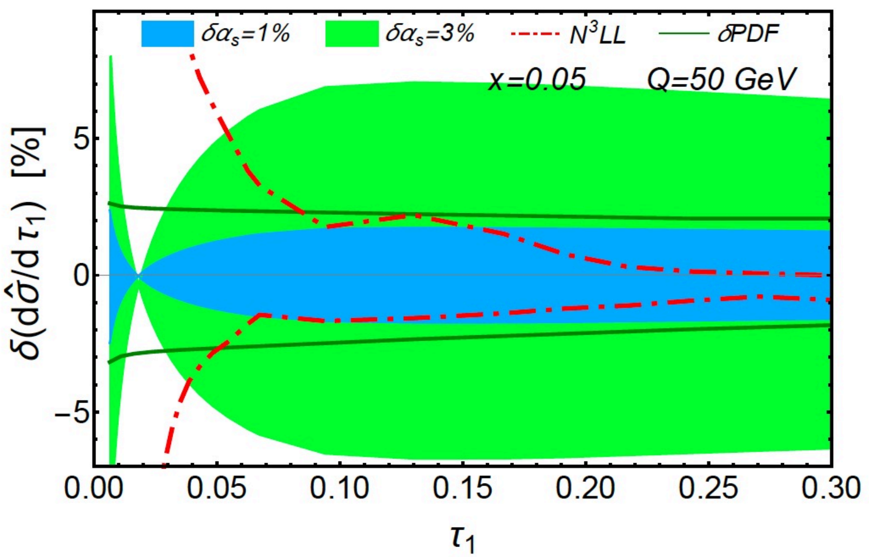
1-jettiness theory projections: N^{3}LL resummed

C. *Lee et al., EIC Yellow Report*

Theory uncertainty in (x,Q)



Theory uncertainty components (x=0.05,Q=50)



N^{3}LL scale variations and PDF uncert; similar in magnitiude to 1% uncertainty in α_s

Sets goal for experimental precision:

~2-3% exp sys uncert provides ~1% constraint on α_s

So now let's look at EIC experimental capabilities…

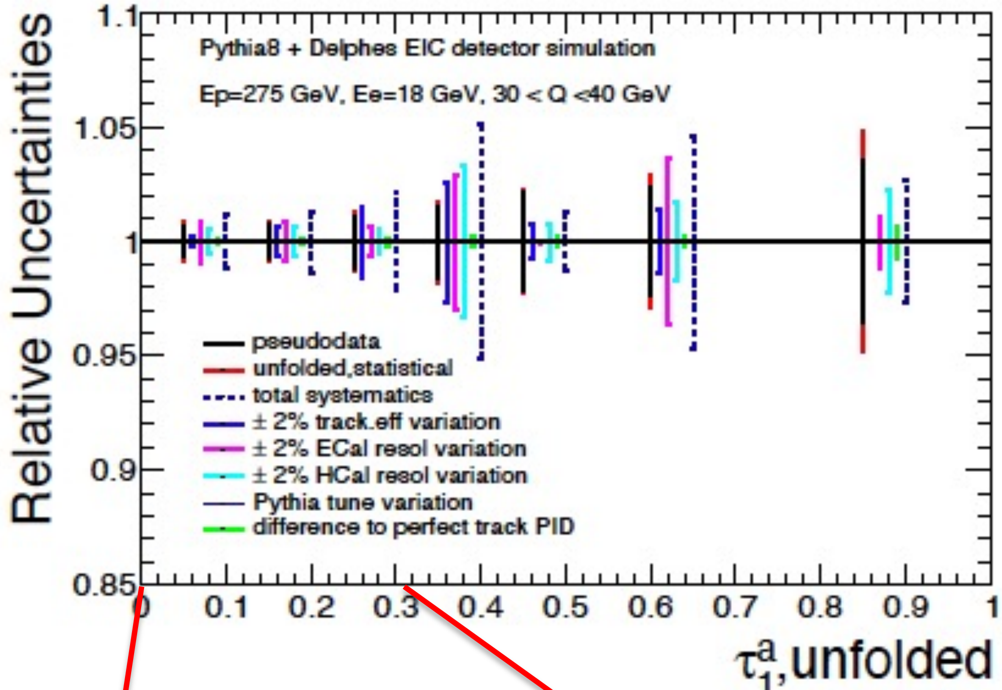
EIC YR study: α_s measurement projections

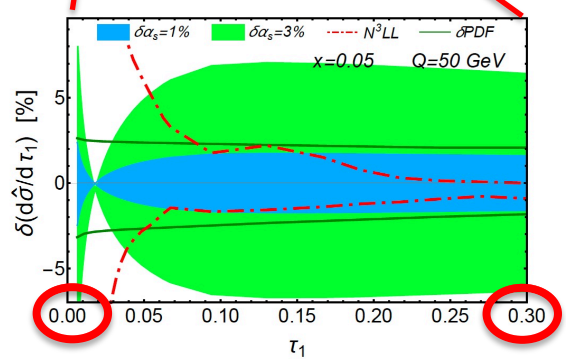
Iterative Bayesian unfolding

- variation in unfolded distr for each systematic source

Largest variations due to ECal and HCal

- Track-based measurement may be competitive



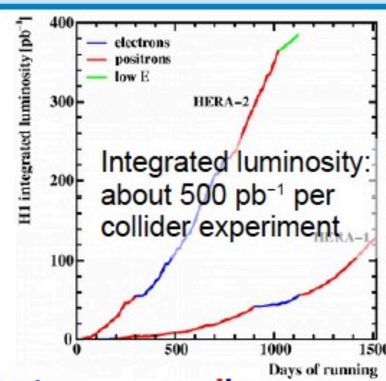


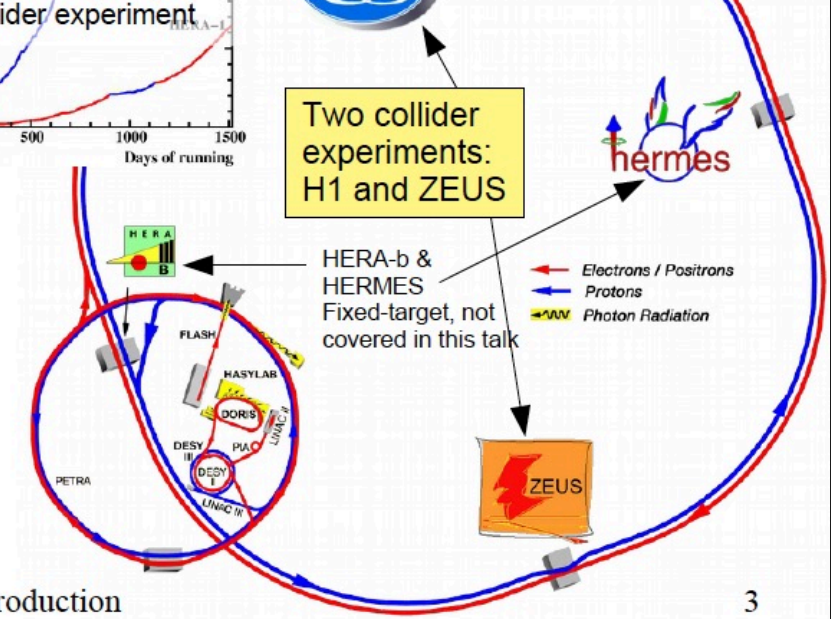
EIC Yellow Report message:

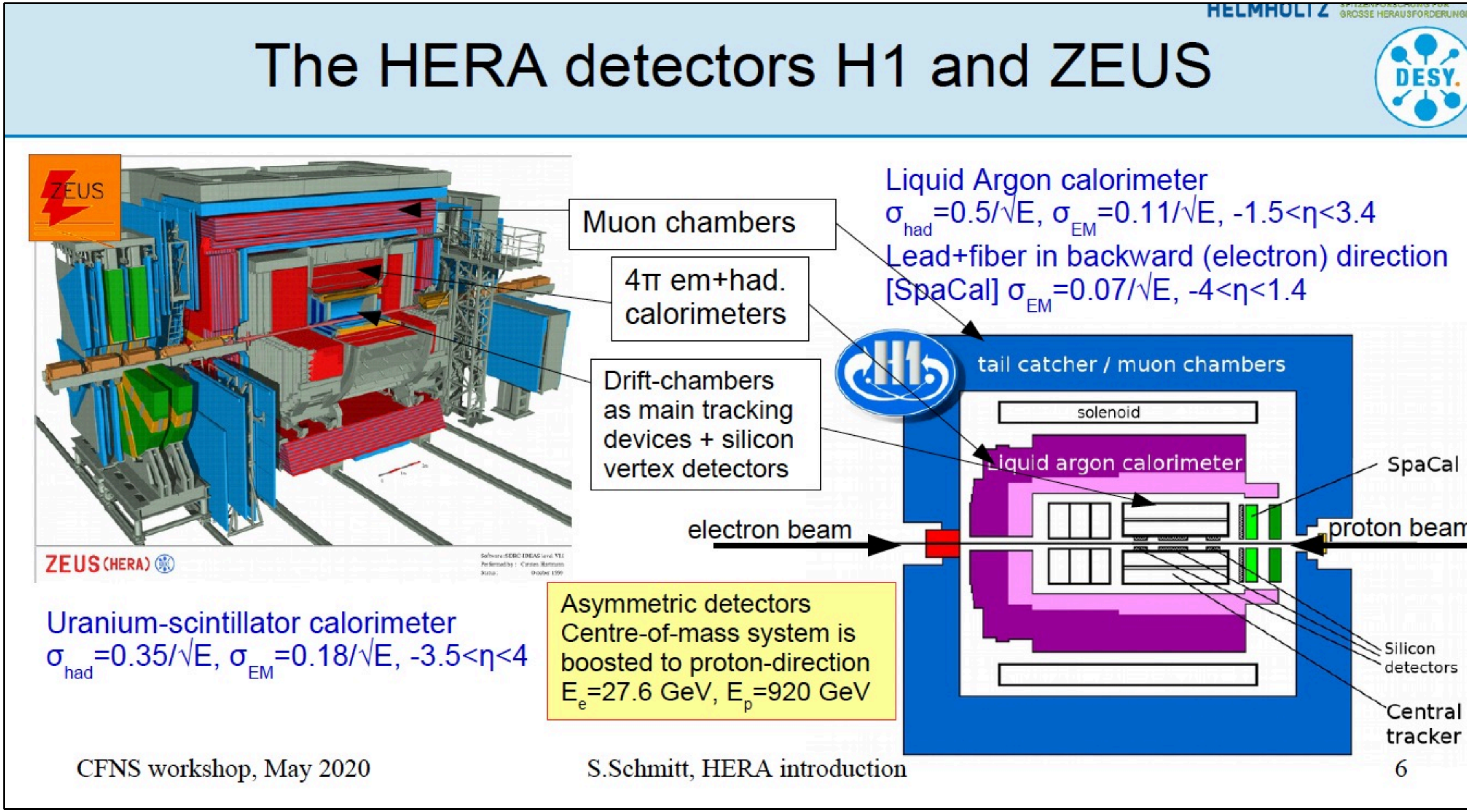
- exp uncert ~ few %
- in the ballpark of what is needed for competitive constraint of α_s 👍

The HERA collider

- Operated from 1992 to 2007
- Circumference 6.3 km
- Electrons or positrons colliding with protons
- Proton: 460-920 GeV, Leptons 27.6 GeV
- Peak luminosity ~7×10^{31} $cm^{-2}s^{-1}$
- Lepton beam polarisation up to 40-60% (Sokolov-Ternov effect, rise-time ~30 minutes)






The HERA detectors H1 and ZEUS
DESY.
ZEUS
Muon chambers
4π em+had. calorimeters
Drift-chambers as main tracking devices + silicon vertex detectors
ZEUS (HERA)
Uranium-scintillator calorimeter
σ_had=0.35/√E, σ_EM=0.18/√E, -3.5<η<4
Asymmetric detectors
Centre-of-mass system is boosted to proton-direction
E_e=27.6 GeV, E_p=920 GeV
Liquid Argon calorimeter
σ_had=0.5/√E, σ_EM=0.11/√E, -1.5<η<3.4
Lead+fiber in backward (electron) direction
[SpaCal] σ_EM=0.07/√E, -4<η<1.4
tail catcher / muon chambers
solenoid
Liquid argon calorimeter
SpaCal
electron beam
proton beam
Silicon detectors
Central tracker
CFNS workshop, May 2020
S.Schmitt, HERA introduction
6

Groomed event shapes in DIS

Y. Makris arXiv:2101.02708

Centauro clustering metric:

$$d_{ij} = (\Delta\bar{\eta}_{ij})^2 + 2\bar{\eta}_i\bar{\eta}_j(1-\cos\Delta\phi_{ij})$$

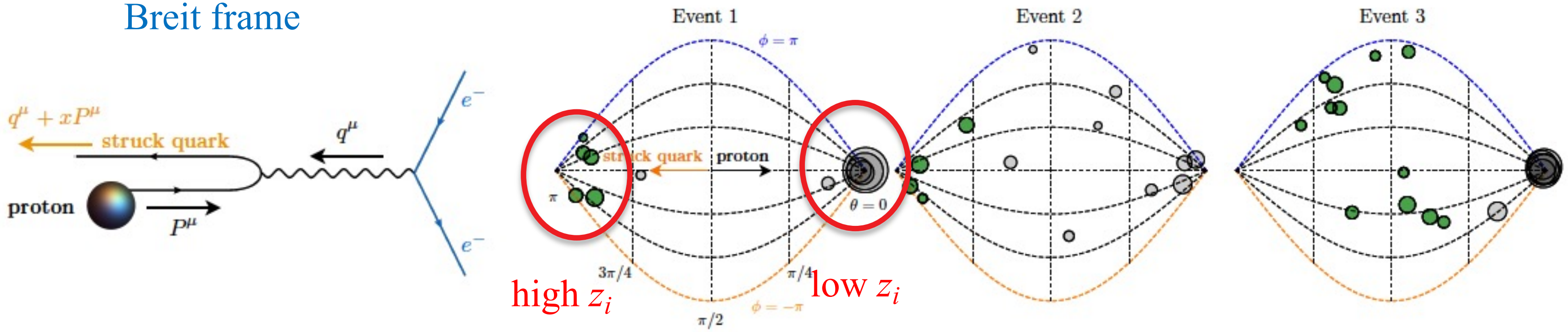
$$\bar{\eta}_i \equiv 2\sqrt{1+\frac{q\cdot p_i}{x_B P\cdot p_i}} \xrightarrow[\text{frame}]{\text{Breit}} \frac{2p_i^\perp}{p_i^+}$$

Groom entire DIS event: decluster the event in the order that it was clustered, stop once condition is met

$$z_i = \frac{P\cdot p_i}{P\cdot q} \xrightarrow[\text{frame}]{\text{Breit}} z_i = n\cdot p_i/Q = p_i^+/Q\,. \qquad \frac{\min(z_i,z_j)}{z_i+z_j} > z_{\rm cut}\,,$$

PYTHIA 8 events
√s=63 GeV, Q~10 GeV

Breit frame



disk area ~ particle energy
green: survives grooming

Groomed event shapes (cont'd)

Calculate event shape only with particles that survive grooming

Groomed Invariant Mass (GIM)

$$m^2_{\mathrm{gr.}} \equiv \Big(\sum_i p_i^\mu\Big)^2$$

Groomed 1-Jettiness

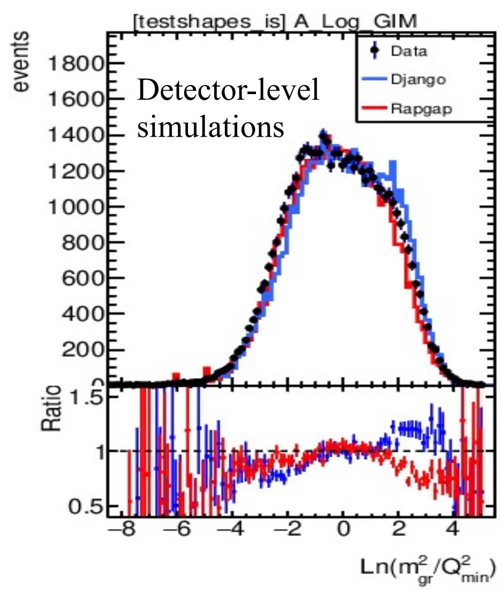
$$\tau_1 = \frac{2}{Q^2} \sum_{i \in \mathrm{gr.\ ent.}} \min(q_B \cdot p_i,\, q_J \cdot p_i)$$

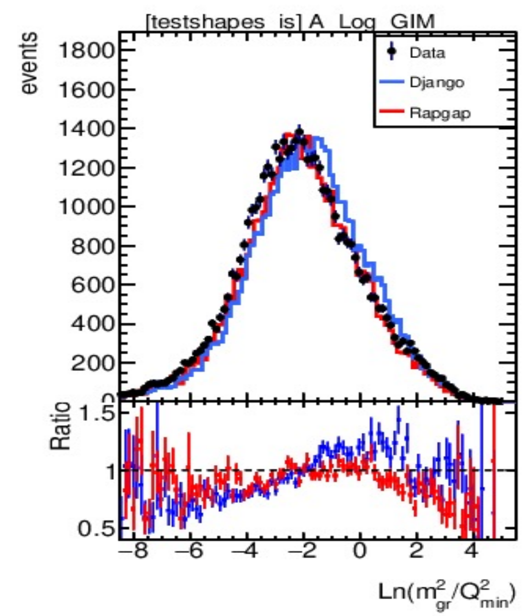
H1 analysis status (H. Klest/SBU et al.):

- $150 < Q^2 < 20000$
- $.2 < y < .7$
- $-1.5 < \eta < 2.75$
- 03-04 Data set, ~50k events passing cuts
- Grooming collimates event, less susceptible to acceptance losses

Groomed mass and groomed 1-jettiness in DIS:

- analysis in progress
- good agreement of models (det-level) with data
- next step: unfolding (omnifold)





Django: diffractive https://inspirehep.net/literature/372027
Rapgap: dipole https://inspirehep.net/literature/363265

Universality in Event Shapes I

arxiv:1209.3782

Power Corrections to Event Shapes with Mass-Dependent Operators

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[2] *IFIC, UVEG - CSIC, Apartado de Correos 22085, E-46071, Valencia, Spain*

We introduce an operator depending on the "transverse velocity" r that describes the effect of hadron masses on the leading $1/Q$ power correction to event-shape observables. Here, Q is the scale of the hard collision. This work builds on earlier studies of mass effects by Salam and Wicke [1] and of operators by Lee and Sterman [2]. Despite the fact that different event shapes have different hadron mass dependence, we provide a simple method to identify universality classes of event shapes whose power corrections depend on a common nonperturbative parameter. We also develop an operator basis to show that at a fixed value of Q, the power corrections for many classic observables can be determined by two independent nonperturbative matrix elements at the 10% level. We compute the anomalous dimension of the transverse velocity operator, which is multiplicative in r and causes the power correction to exhibit non-trivial dependence on Q. The existence of universality classes and the relevance of anomalous dimensions are reproduced by the hadronization models in Pythia 8 and Herwig++, though the two programs differ in the values of their low-energy matrix elements.

Universality in Event Shapes II

arxiv:1303.6952

Using 1-Jettiness to Measure 2 Jets in DIS 3 Ways

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[2] *Theoretical Division, MS B283, Los Alamos National Laboratory, Los Alamos, NM 87545, USA*

We predict cross sections in deep inelastic scattering (DIS) for the production of two jets—one along the proton beam direction created by initial state radiation (ISR) and another created by final state radiation after the hard collision. Our results include fixed order corrections and a summation of large logarithms up to next-to-next-to-leading logarithmic (NNLL) accuracy in resummed perturbation theory. We make predictions for three versions of a DIS event shape 1-jettiness, each of which constrains hadronic final states to be well collimated into two jets along the beam and final-state jet directions, but which differ in their sensitivity to the transverse momentum of the ISR from the proton beam. We use the tools of soft collinear effective theory (SCET) to derive factorization theorems for these three versions of 1-jettiness. The sensitivity to the ISR gives rise to significantly different structures in the corresponding factorization theorems—for example, dependence on either the ordinary or the generalized $k_\perp$-dependent beam function. Despite the differences among 1-jettiness definitions, we show that the leading nonperturbative correction that shifts the tail region of their distributions is given by a single universal nonperturbative parameter Ω_1, even accounting for hadron mass effects. Finally, we give numerical results for Q^2 and x values explored at the HERA collider, emphasizing that the target of our factorization-based analyses is to open the door for higher-precision jet phenomenology in DIS.

Testing universality in DIS

Y. Makris and C. Lee

- Work in Breit frame
- Run a jet finder (Centauro)
- Select events with only one jet in the current hemisphere
- Calculate two objects:
  - τ_1 from particles in jet
  - z-distribution from all other particles

$$\text{Inside jet:} \quad \tau$$

$$\text{Outside jet:} \quad z < z_{\text{cut}} \tag{20}$$

where

$$\tau = \frac{2}{Q^2}\sum_{i\in J} q_J\cdot p_i = \frac{2}{Q^2}\, q_J\cdot\Big(\sum_{i\in J} p_i\Big) = \frac{2q_J\cdot p_J}{Q^2}\Big|_{q_J=(Q/2)n_J} = \frac{n_J\cdot p_J}{Q} \tag{21}$$

$$z = \sum_{i\notin J} z_i = \frac{2x}{Q^2}P\cdot\Big(\sum_{i\notin J} p_i\Big) = \frac{2xP\cdot p_B}{Q^2}\Big|_{q_B=xP} = \frac{2q_B\cdot p_B}{Q^2} \tag{22}$$

Using conservation of momentum we can obtain z for the jet constituents only

$$1 = \sum_i z_i = \sum_{i\in J} z_i + \sum_{i\notin J} z_i = z_J + z \quad \Rightarrow \quad z = 1 - z_J \tag{23}$$

Intuitive interpretation of the variable z_J can be given in two frames

$$\text{Breit frame:} \quad z_J = p_J^+/Q + \mathcal{O}\Big(\frac{m_P^2}{Q^2}\Big)$$

$$P\ \text{rest-frame:} \quad z_J = \frac{E_{\text{jet}}}{E_{\gamma*}} \tag{24}$$

$1 - z_J \ll 1$ ensures radiation outside the jet is collimated. Critical point for the factorization theorem in the "2-jet" limit shown in the next slide

Factorization in Breit frame

Y. Makris and C. Lee

leptonic hadronic

$$\frac{d\sigma}{dx\,dQ^2\,d\tau_1} = \sum_{I,I'=V,A} L^{II'}_{\mu\nu}(x,Q^2)\,W^{II'\mu\nu}(x,Q^2,\tau_1)$$

V=vector
A=axial

$\tau \sim z, z_{\rm cut} \ll Q$ we can follow the steps of the 1-jettiness paper to show the form of the factorization theorem.

This theorem holds for every reasonable jet algorithm implemented in any frame.

soft jet

$$W^{II'}_{\mu\nu}(x,Q^2,\tau,z)\Big|_{\rm Bf} = 2(2\pi)\,Q^4 \int dk_J dk_B S_{\rm Bf}(k_J,k_B,n\cdot\bar{n},\mu) J_q(Q^2\tau - Qk^J,\mu)$$
$$\Big[H^{II'}_{\mu\nu}(q^2,\bar{n},n)\mathcal{B}_q(Q^2 z - Qk_B,x,\mu) + H^{II'}_{\mu\nu}(q^2,n,\bar{n})\mathcal{B}_{\bar{q}}(Q^2 z - Qk_B,x,\mu)\Big] \quad (30)$$

hard beam

and the corresponding soft function,

$$S_{\rm Bf}(k_J,k_B,n_J\cdot n_B,\mu) = \frac{1}{N_C}\,{\rm tr}\sum_{X_s}|\langle X_s|[Y^\dagger_{\bar{n}}Y_n](x)\rangle|^2\,\delta\Big(k_J - \sum_{i\in X_s}\Theta_{\rm alg.}(k_i,X_s)\bar{n}\cdot k_i\Big)$$
$$\delta\Big(k_B - \sum_{i\in X_s}[1-\Theta_{\rm alg.}(k_i,X_s)]n\cdot k_i\Big) \quad (31)$$

To proceed need "anti-kT like" algorithms to get read of clustering effects close to the jet boundary.

Soft function universality

$$S_{\rm Bf}(k_J, k_B, n_J{\cdot}n_B, \mu) = \frac{1}{N_C}\,{\rm tr}\Big\langle [Y_n^\dagger Y_{\bar n}]\,\delta\Big(k_J - \int dr dy d\phi\, f^J_{\rm alg.}(r,y,\phi)\hat{\mathcal{E}}_T(r,y,\phi)\Big) \times \delta\Big(k_B - \int dr dy d\phi\, f^B_{\rm alg.}(r,y,\phi)\hat{\mathcal{E}}_T(r,y,\phi)\Big)[Y_{\bar n}^\dagger Y_n]\Big\rangle \quad (32)$$

where

$$\hat{\mathcal{E}}_T(r,y,\phi)|X_s\rangle = \sum_{i\in X_s} m_{iT}\;\delta(r-r_i)\delta(y-y_i)\delta(\phi-\phi_i)|X_s\rangle \quad (33)$$

Note that no approximations in the massless limit are done for the Centauro algorithm.
Also there is no expansion in the jet radius (R) here.

Universal NP shift

$$\tau_{\rm hadr.} = \tau_{\rm part.} + \frac{\Omega^J_{\rm alg.}}{Q} \qquad z_{\rm hadr.} = z_{\rm part.} + \frac{\Omega^B_{\rm alg.}}{Q}$$

$$\Omega^\kappa_{\rm alg.} = C^\kappa_{\rm alg.}\frac{1}{N_C}\,{\rm tr}\Big\langle [Y_n^\dagger Y_{\bar n}]\hat{\mathcal{E}}_T(y=0)[Y_{\bar n}^\dagger Y_n]\Big\rangle \quad (38)$$

Prefactor

QCD matrix element

including mass effects:	$C^J_{\rm Ce.} = R/2\,,$	$C^B_{\rm Ce.} = 2/R$	
up to mass correction:	$C^J_{\rm SI} = \tan\frac{R}{2}\,,$	$C^B_{\rm SI} = \cot\frac{R}{2}$	(40a)

Remarkably simple and general prediction
Can test via Q-dependence, jet R-dependence

Soft matrix element: discussion

$$\frac{1}{N_C}\,\mathrm{tr}\left\langle [Y_n^\dagger Y_{\bar{n}}]\hat{\mathcal{E}}_T(y=0)[Y_{\bar{n}}^\dagger Y_n]\right\rangle$$

Expectation value of product of light-like Wilson lines: fundamental object in QCD

Calculable on the lattice?

- Technical barrier: lattice calculates only space-like paths
- Similar issue as lattice calculation of pdfs: forefront of lattice QCD
- TBD: discuss with lattice theorists

arxiv:2102.05044

Alternative?

Simulating collider physics on quantum computers using effective field theories

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Simulating the full dynamics of a quantum field theory over a wide range of energies requires exceptionally large quantum computing resources. Yet for many observables in particle physics, perturbative techniques are sufficient to accurately model all but a constrained range of energies within the validity of the theory. We demonstrate that effective field theories (EFTs) provide an efficient mechanism to separate the high energy dynamics that is easily calculated by traditional perturbation theory from the dynamics at low energy and show how quantum algorithms can be used to simulate the dynamics of the low energy EFT from first principles. As an explicit example we calculate the expectation values of vacuum-to-vacuum and vacuum-to-one-particle transitions in the presence of a time-ordered product of two Wilson lines in scalar field theory, an object closely related to those arising in EFTs of the Standard Model of particle physics. Calculations are performed using simulations of a quantum computer as well as measurements using the IBMQ Manhattan machine.

Universality tests: next steps for experiment

Continue H1 analysis, bring to publication

Evaluate for EIC:

- Detector requirements?
- Analysis/computational requirements? E.g. omnifold

Connection to LHC:

- p+p $\rightarrow \gamma/Z$ + 1 jet (exclusive); measure jet mass
- ATLAS/CMS may be possible
- ALICE needs some thought

Connection to RHIC

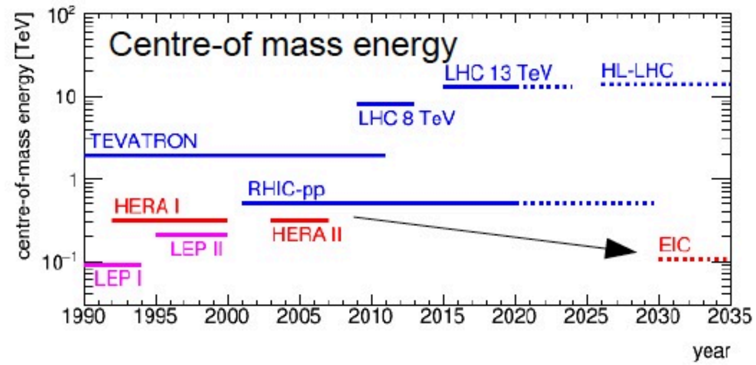
- p+p $\rightarrow \gamma$ + 1 jet (exclusive); measure jet mass
- STAR? sPHENIX?

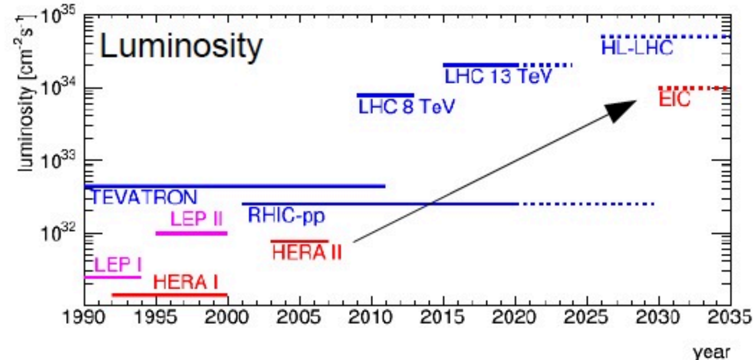
Extra slides

Compare EIC and HERA

- HERA at construction time: energy frontier (E_p~Tevatron, E_e~ ½ LEP)

  Detectors were designed for discoveries, not so much for precision
- EIC compared to HERA:
  - Reduced center-of-mass energy ×0.3
  - Much higher luminosity ×100
  - Better lepton polarisation
  - Target polarisation
  - Heavy targets
  - Much improved detectors: tracking, acceptance, particle identification, forward detectors, ...





CFNS workshop, May 2020

S.Schmitt, HERA introduction