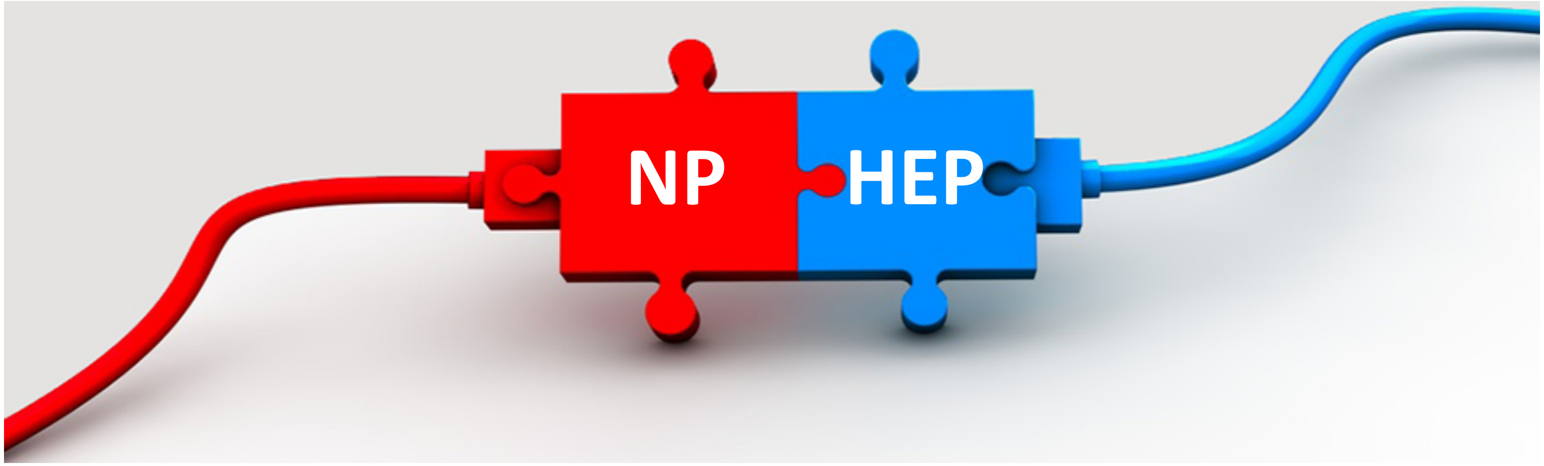
Mapping the hadronization description in the Pythia MCEG to the correlation functions of TMD factorization



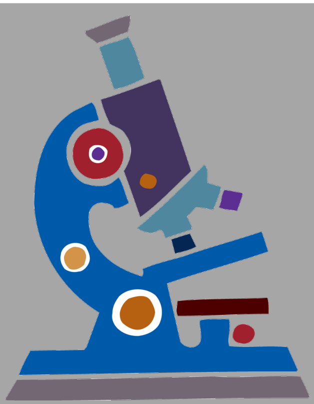
3D Nucleon Tomography Workshop,
March 15th – 17th 2017

LDRD project at Jefferson Lab

LDRD:
LABORATORY DIRECTED
RESEARCH & DEVELOPMENT

Study of hadronization

Correlation functions of TMD factorization ⟷ Pythia Monte Carlo Event Generator



Urgent requirement: MCEG for TMDs.

Unique approach: Connection between hadronization phenomena in **NP** and **HEP**.

By doing so: Improve theoretical framework for TMDs.

LDRD personnel

JLab

Pythia

Other

Experimentalists

+ Jake Ethier
+ Eric Moffat
+ Andrea Signori

Theorists

Section

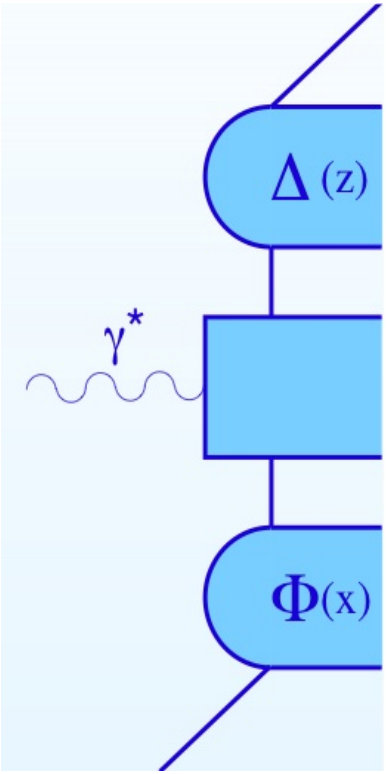
QCD factorization and TMDs

TMDs and QCD factorization

QCD
- non-abelian gauge theory
- self-consistent theory of a fundamental interaction

QCD factorization theorem
- defines quarks and gluons and their dynamics
- allows to study QCD in experiments

Broadening our understanding of QCD
- studying the QCD factorization theorem for TMDs
- studying the related transition regions
- studying TMD evolution



FF

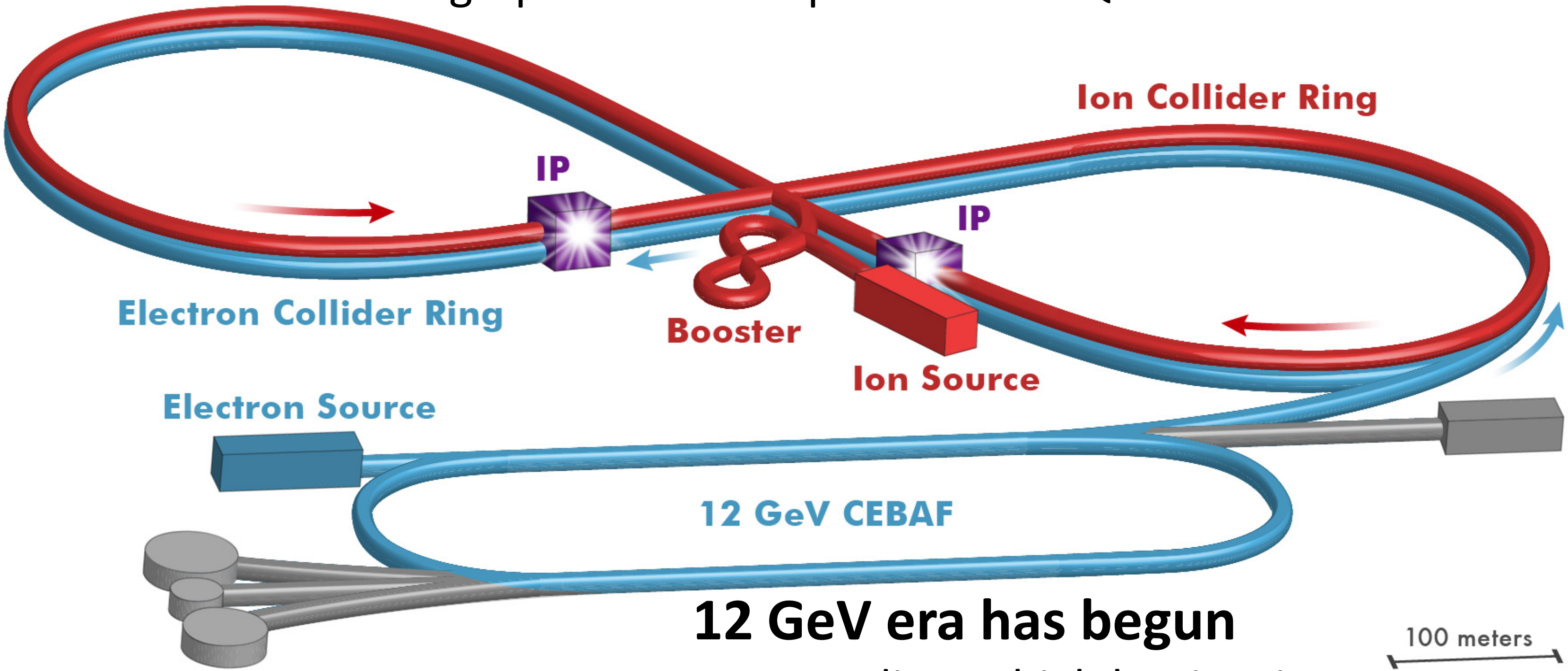
hard scattering

PDF

Upcoming TMD measurements

Electron-Ion Collider on horizon

High-precision non-perturbative QCD era



12 GeV era has begun

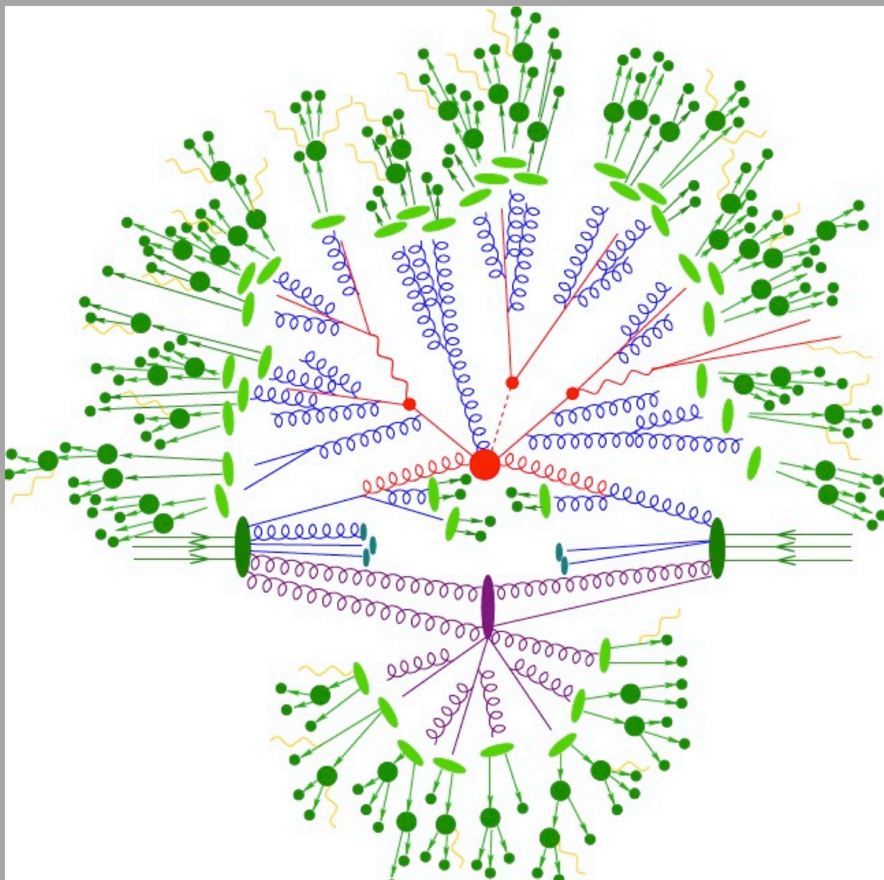
TMD studies at high luminosity

Urgent requirement: high-precision Monte Carlo Event Generator for TMDs

Section

Monte Carlo Event Generators and Pythia

Monte Carlo Event Generator (MCEG)



Map: hard scattering, evolution through radiation, secondary scatterings, dynamical fragmentation with string model, initial-state p_T-dependence

MCEG:

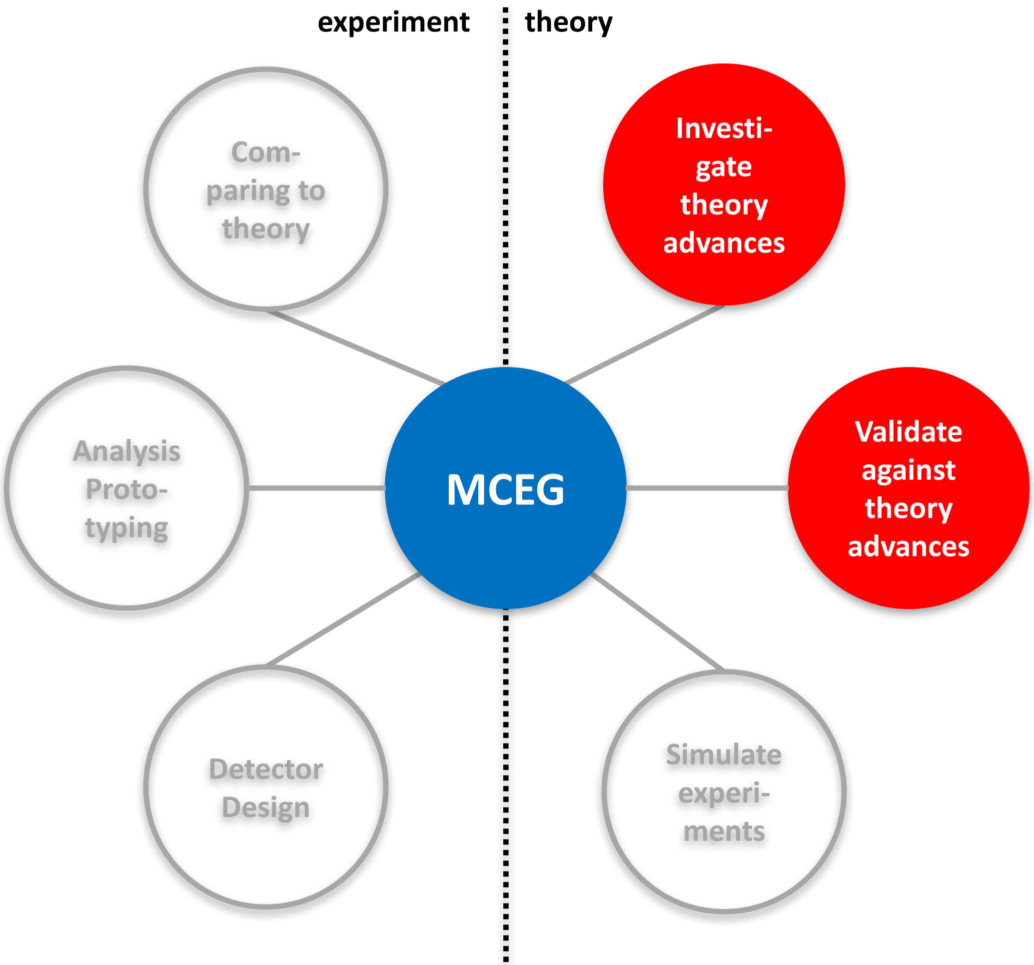
- faithful representation of QCD dynamics
- based on QCD factorization and evolution equations

Algorithm of general-purpose MCEG:

- generate kinematics according to fixed-order matrix elements and a PDF
- parton shower model for resummation of soft gluons and parton-parton scatterings
- hadronize all outgoing partons including the remnants according to a model
- decay unstable hadrons

MCEG in HEP and NP

Lesson from HEP:
high-precision QCD measurements require high-precision MCEGs

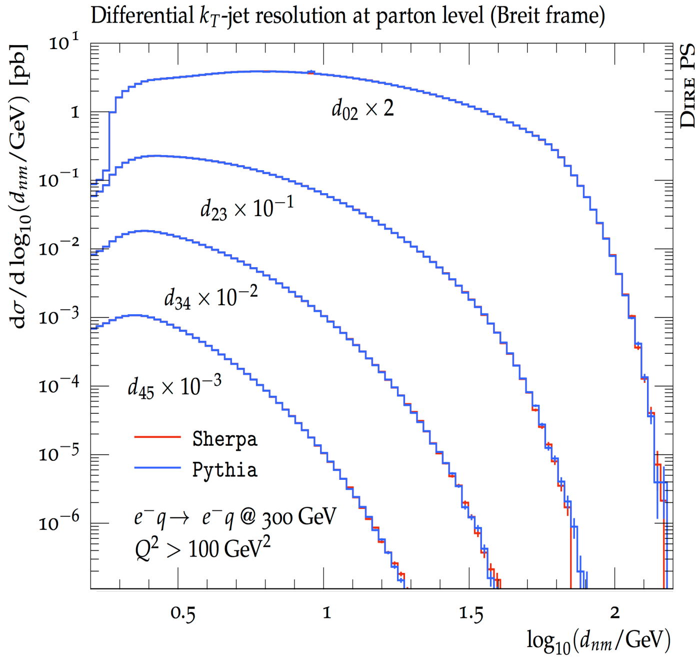


General-purpose MCEG: HERWIG, Pythia, SHERPA

DIRE parton shower

Parton shower:
numerical, fully differential solution of evolution equation by iterating parton decay

DIRE:
- **Fundamental goal**: compare directly to analytical approaches, e.g., the one by Collins-Soper-Sterman
- **Unique verification**: implemented in both Pythia and Sherpa



Section

High-energy and nuclear physics

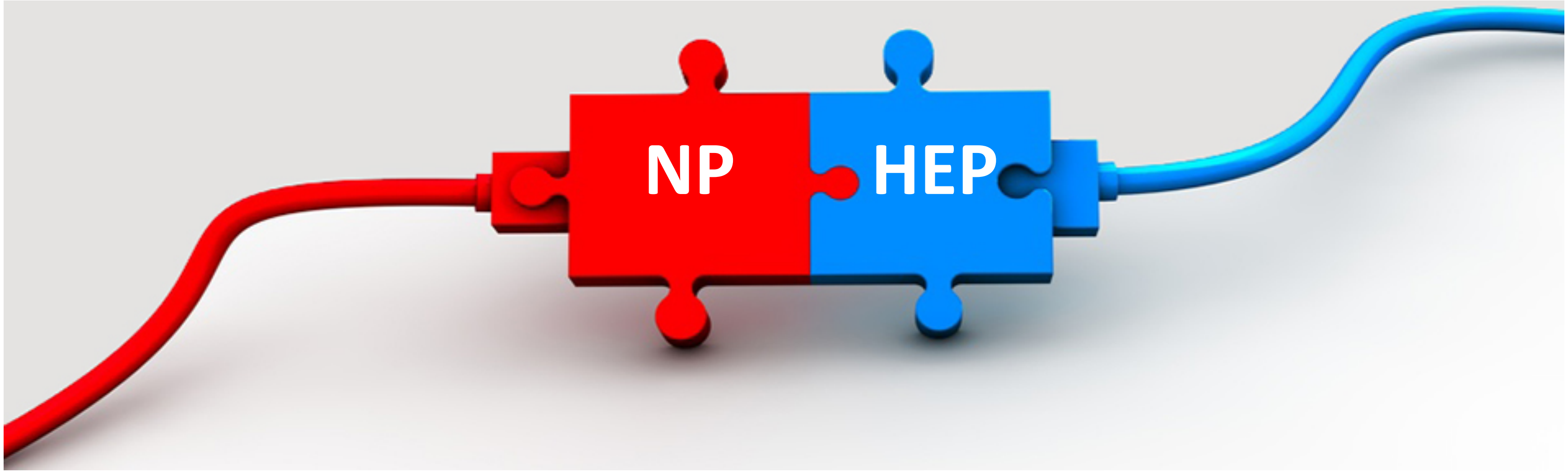
Measurements in NP and HEP

Nuclear physics (NP)

- investigation of nucleon and nuclear structure and associated dynamics
- observables of non-perturbative QCD
- non-perturbative quark-gluon dynamics parameterized in PDFs and FFs

High energy physics (HEP)

- investigation of the elemental constituents of matter and energy and their interactions
- observables of perturbative QCD
- perturbative QCD calculations up to $N^{N}LO$
- assuming the knowledge of the hadron structure / PDFs at low energies



Connection between NP and HEP

NP in HEP: **non-perturbative QCD**, in particular **hadronization**

- **background suppression**, relevant for any analysis and also for the *new physics* searches
- **reducing systematic uncertainties**, e.g., of non-perturbative QCD models
- **high-precision measurements,** e.g., improving the knowledge on the coupling constants by studying the p_T spectra

HEP in NP:

- combine MCEG approaches with first principle QCD calculations to proceed with QCD studies of non-perturbative structure

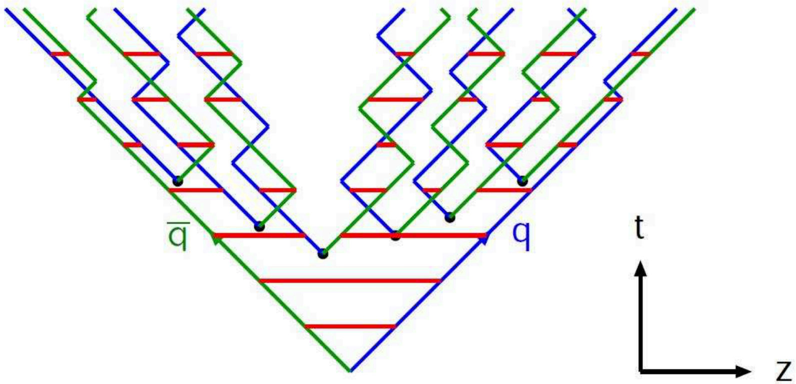
Section

Early state of the LDRD project

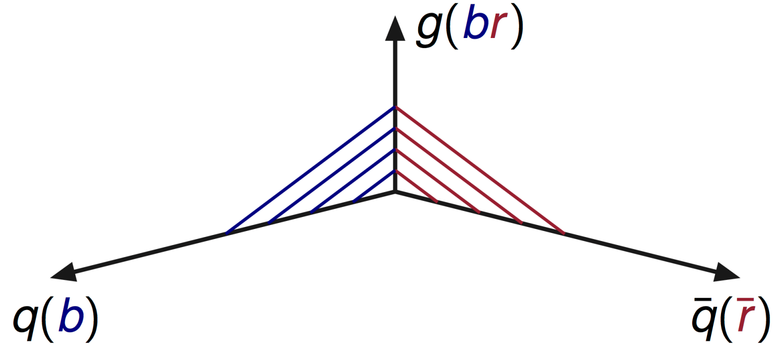
LDTMDP Meeting • Jefferson Lab • Newport News, Virginia
February 20-22, 2017

LUND string hadronization

String breakup



String drawing



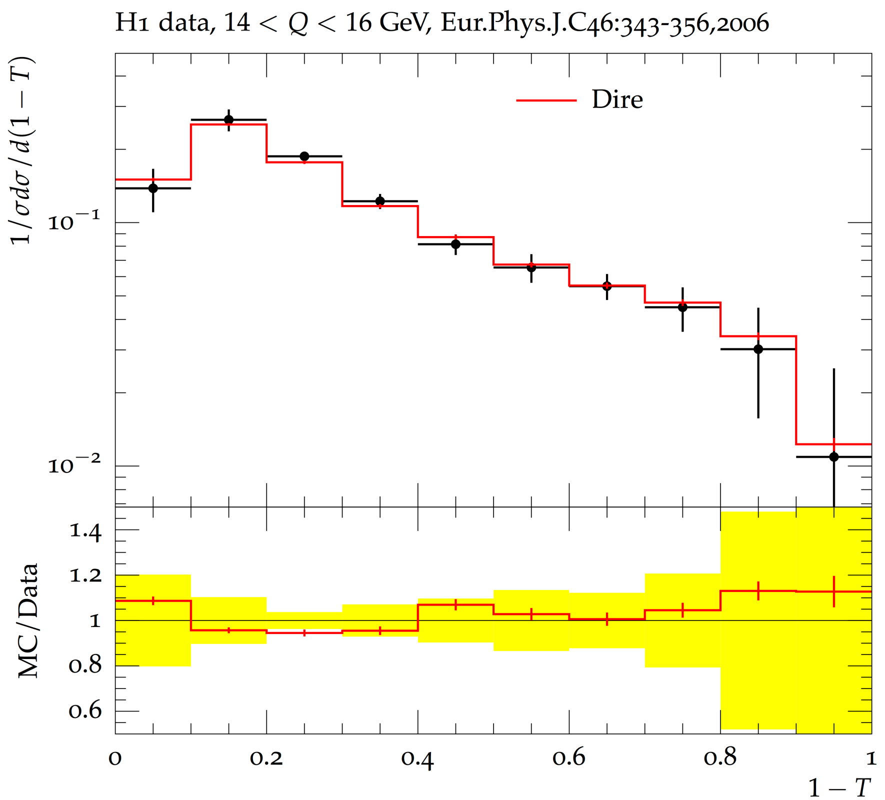
PYTHIA8/DIRE at low energies

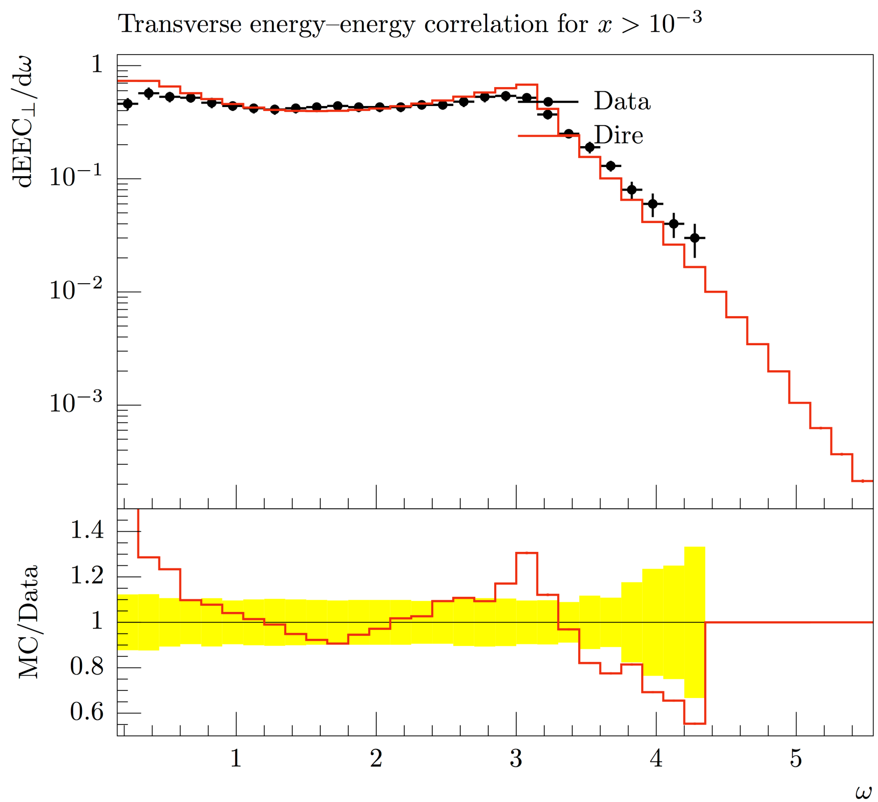
, e.g., at W = 10 GeV:

- average number of primary hadrons is < 6
- two hadrons will be produced by the final, somewhat ad-hoc, decay of the string into two hadrons
- for sea-quarks one hadron comes from a somewhat ad-hoc remnant treatment

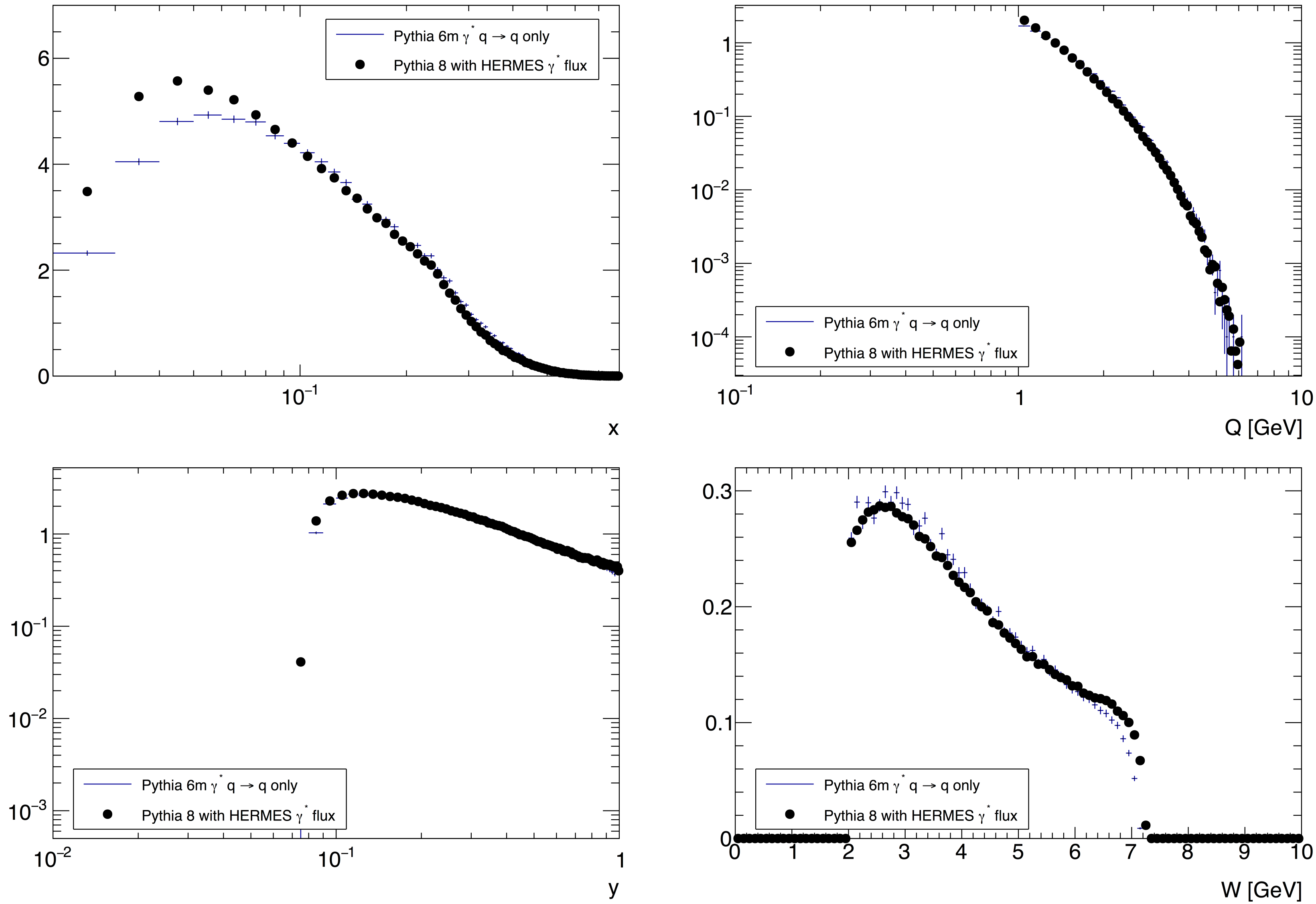
Tuning and **possible modifications** required.

Pythia8+DIRE and DIS





Pythia8+DIRE at low energies



Summary

LDRD:
LABORATORY DIRECTED
RESEARCH & DEVELOPMENT

Study of hadronization, started in FY17

Correlation functions of TMD factorization ⟷ Pythia Monte Carlo Event Generator

Current Status:

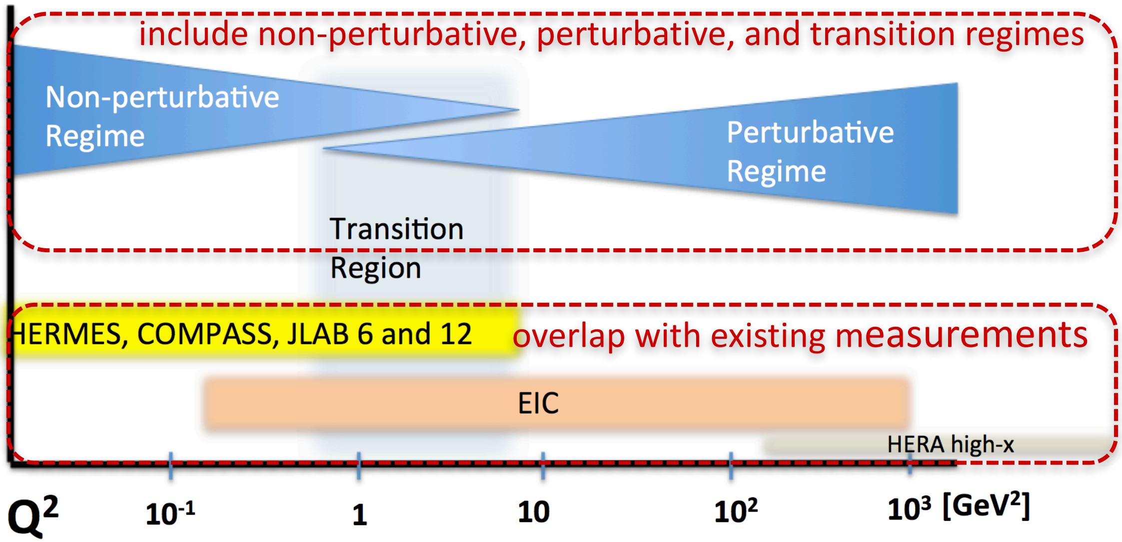
- identify mismatches between factorization theorem and Pythia

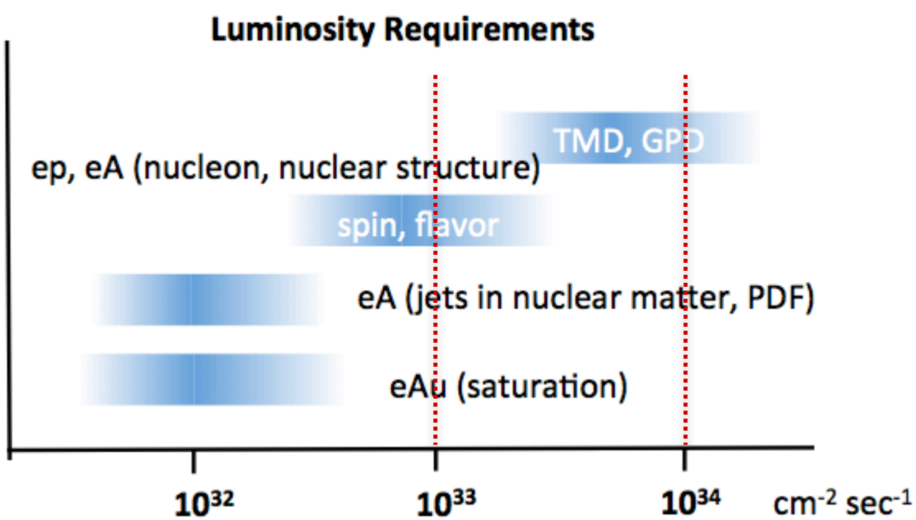
- establish Pythia8+DIRE as SIDIS generator
- FF analysis from Pythia

Addendum

TMD analysis at the EIC and requirements

EIC: Ideal facility for studying QCD





Various beam energy:

broad Q^2 range for

- studying evolution to Q^2 of ~1000 GeV^2
- disentangling non-perturbative and perturbative regimes
- overlap with existing experiments

High luminosity:

high precision

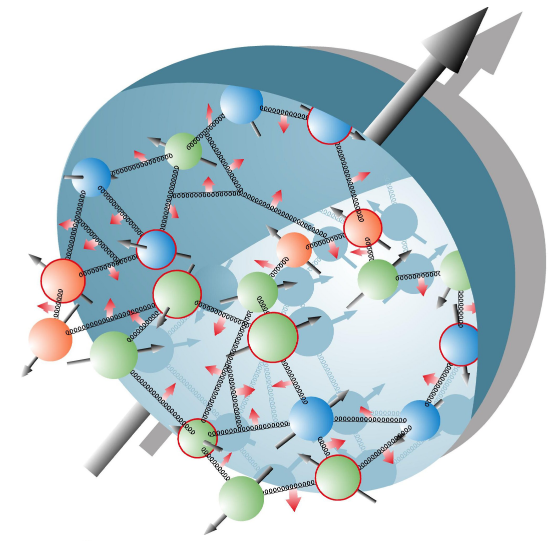
- for various measurements
- in various configurations

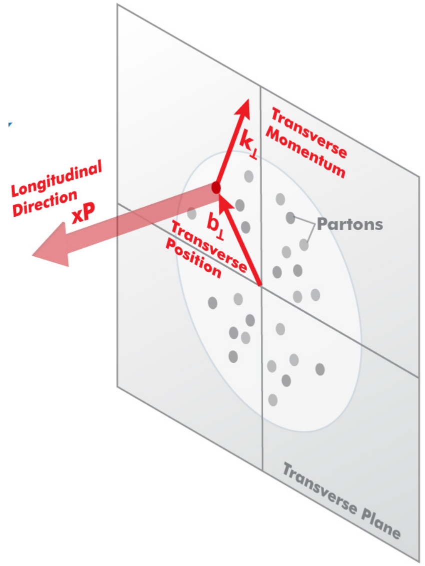
EIC: Ideal facility for studying QCD

Polarization
Understanding hadron structure cannot be done without understanding spin:
- polarized **electrons** and
- polarized **protons/light ions**

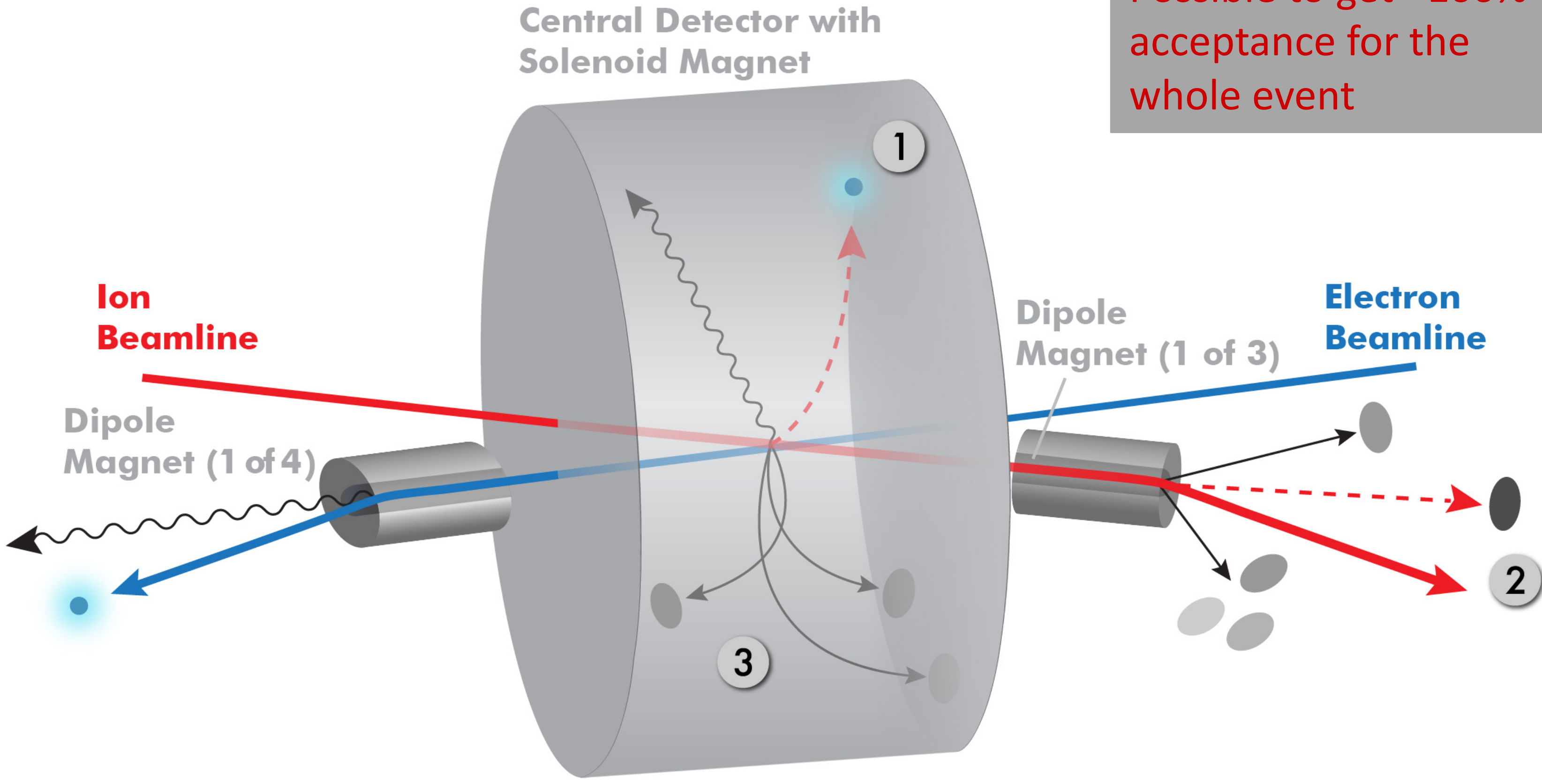
Transverse and longitudinal polarization of light ions (p, d, ^{3}He):
- 3D imaging in space and momentum
- spin-orbit correlations

Broad range in A from hydrogen to uranium isotopes:
- 3D imaging in space and momentum
- hadronization in the nuclear medium
- EMC effect for gluons
- gluon saturation





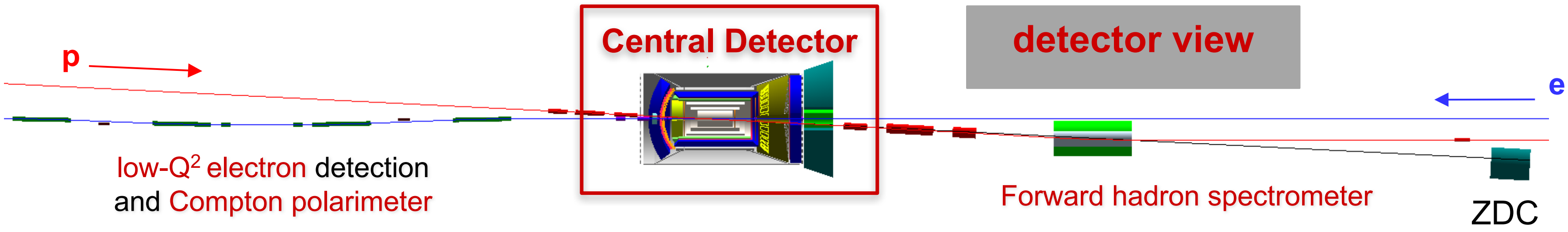
Interaction region concept



Possible to get ~100% acceptance for the whole event

Total acceptance detector (and IR)

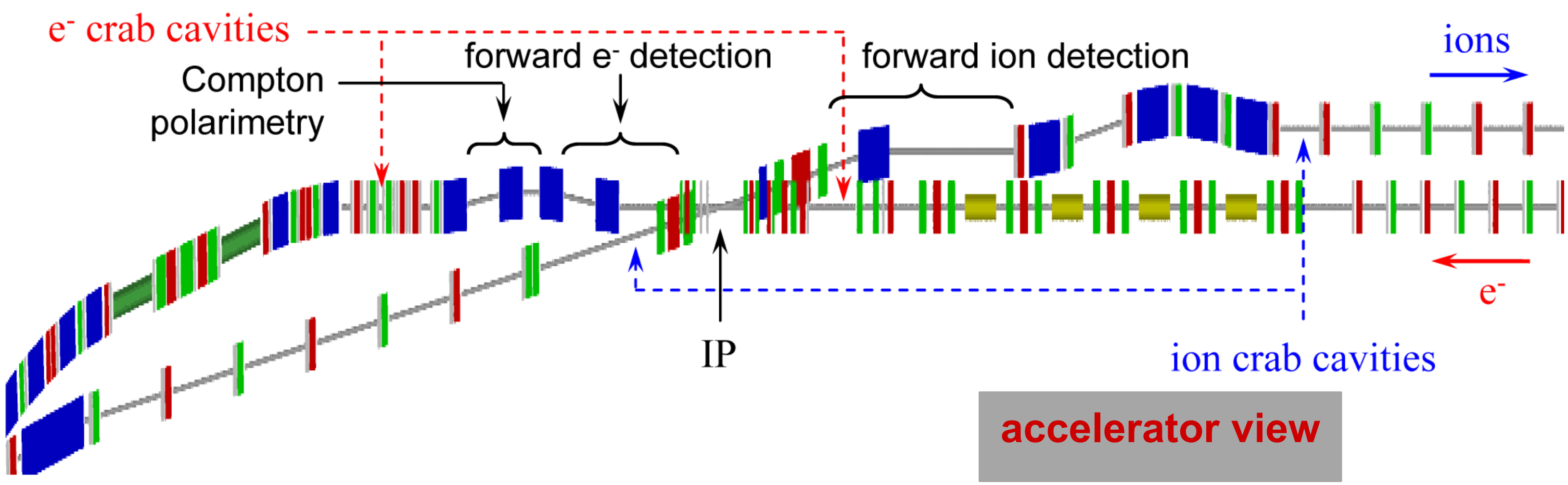
Detector and interaction region



Extended detector: 80m

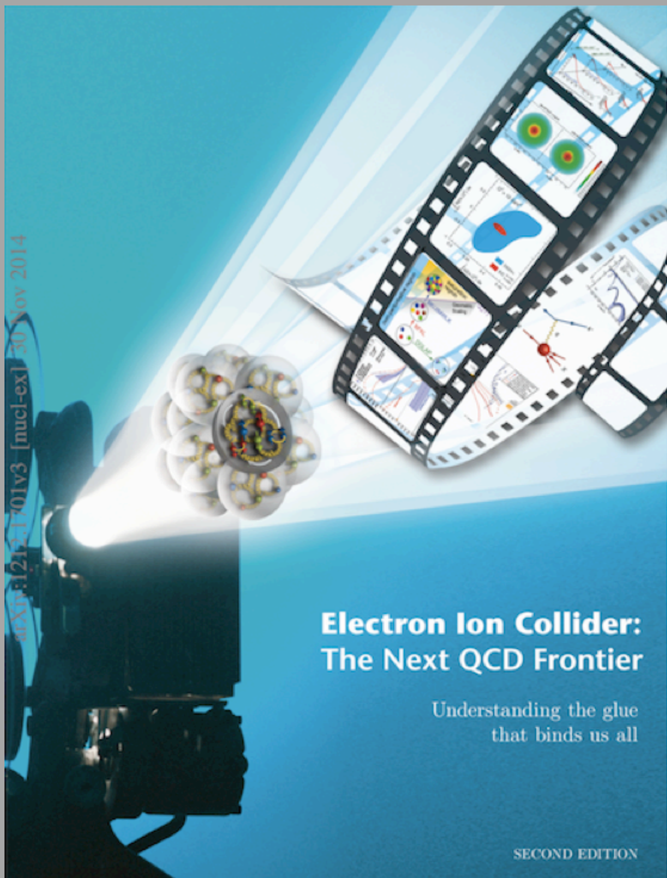
30m for multi-purpose chicane, 10m for central detector, 40m for the forward hadron spectrometer

fully integrated with accelerator lattice



TMD program in EIC White Paper

EIC: The Next QCD Frontier



Eur.Phys.J. A52 (2016) no.9, 268

Ultimate measurement of TMDs for quarks

- high-precision, total acceptance measurements
- multi-dimensional analysis
  $(x,\ Q^2,\ \phi_{S},\ z,\ P_t,\ \phi_h)$
- broad *x*-coverage: $0.01 < x < 0.9$ (high-*x*)
- broad Q^2 range for disentangling non-perturbative and perturbative regimes and fpr overlap with existing experiments

First measurement of TMDs for sea quarks

First measurement of TMDs for gluons

Systematic study of QCD factorization

Selected analysis requirements

Ultimate measurement of TMDs for quarks

- high-precision measurements require **high-precision analysis tools**:
    - high-precision MCEG
    - radiative corrections, integrated into MCEG as physics and detector smearing does not factorize
    - high-precision, multi-dimensional statistical analysis, e.g., using unfolding algorithm (HERMES, LHC)
- R_{SIDIS} from JLab 12GeV
- **long-lived data repositories** of TMD experiment (HERMES, COMPASS, RHIC, JLAB)
    - document analysis publicly for analysis and theory development (RIVET)
    - combined *global* analysis (e.g., HERA fit), perhaps even on event level

Requirements not only for EIC program but also for JLab 12 GeV program.
Adiabatic transition from JLab 12GeV to EIC.

EIC Software Consortium (ESC)

Interfaces and integration

- connect existing frameworks / toolkits
- identify the key pieces for a future EIC toolkit
- collaborate with other R&D consortia

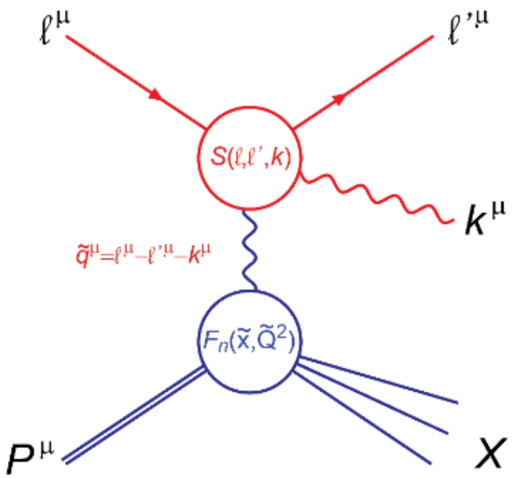
Planning for the future with future compatibility

- workshop to discuss new scientific computing developments and trends
- incorporating new standards
- validating our tools on new computing infrastructure

Organizational efforts with an emphasis on communication

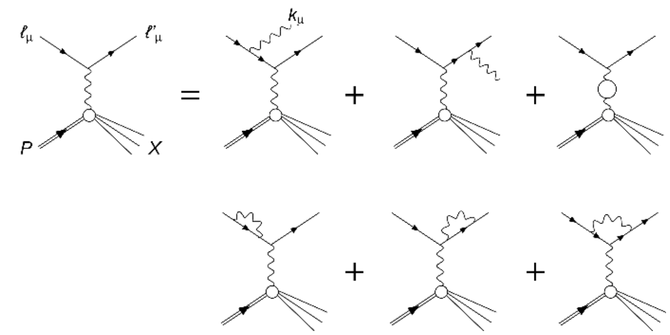
- build an active working group and foster collaboration
- documentation about available software
- maintaining a software repository
- workshop organization

ESC project on radiative corrections



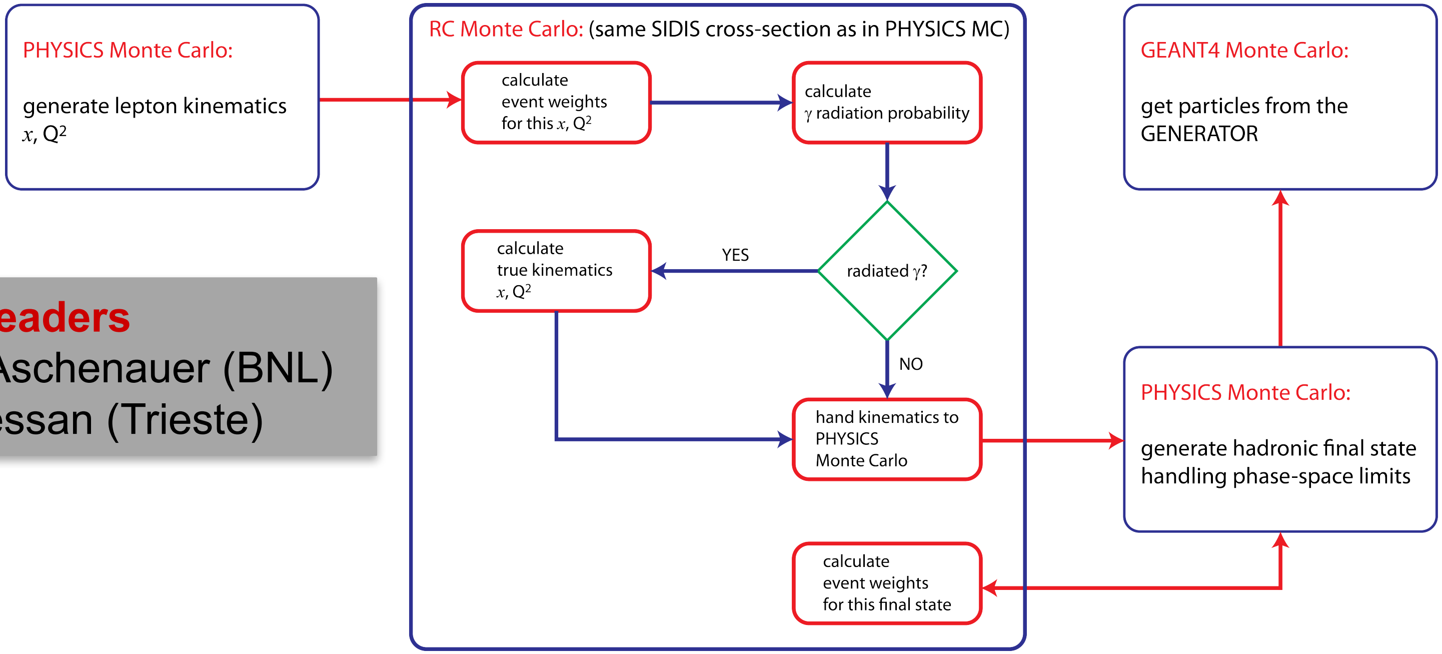
$$\bar{Q}^2 = -(\ell - \ell' - k)^2$$

$$\bar{x} = \frac{\bar{Q}^2}{2P \cdot (\ell - \ell' - k)}$$



- Photon radiation from the leptons modify the one boson cross-section and change the DIS kinematics on the event by event basis
- The direction of the virtual photon is different from the one reconstructed from the leptons, giving rise to:
  - False asymmetries in the azimuthal distribution of hadrons calculated with respect to the virtual photon direction
  - Smearing of the kinematic distributions (e.g. z and P_{hT})
- To take into account correctly this effect in the SIDIS cross-section we need both the correct weights for every event and an unfolding procedure for the smearing. THIS can ONLY be done by using a Monte Carlo code for RC

Status of ESC project on radiative corrections



Project leaders
- E.-C.Aschenauer (BNL)
- A. Bressan (Trieste)

Deliverables achieved at the end of FY17:

- Calculate radiative corrections for transverse polarized observables to measure TMDs and polarized exclusive observables.
- Provide proof that the MC phase space constrains on the hadronic final state is equal to calculating radiative corrections for each polarized and unpolarized semi-inclusive hadronic final state independently.
- Define a software framework and develop a library based on this framework, which integrates the radiative corrections depending on polarization and other determining factors in a wrapper-software.

ESC related workshop