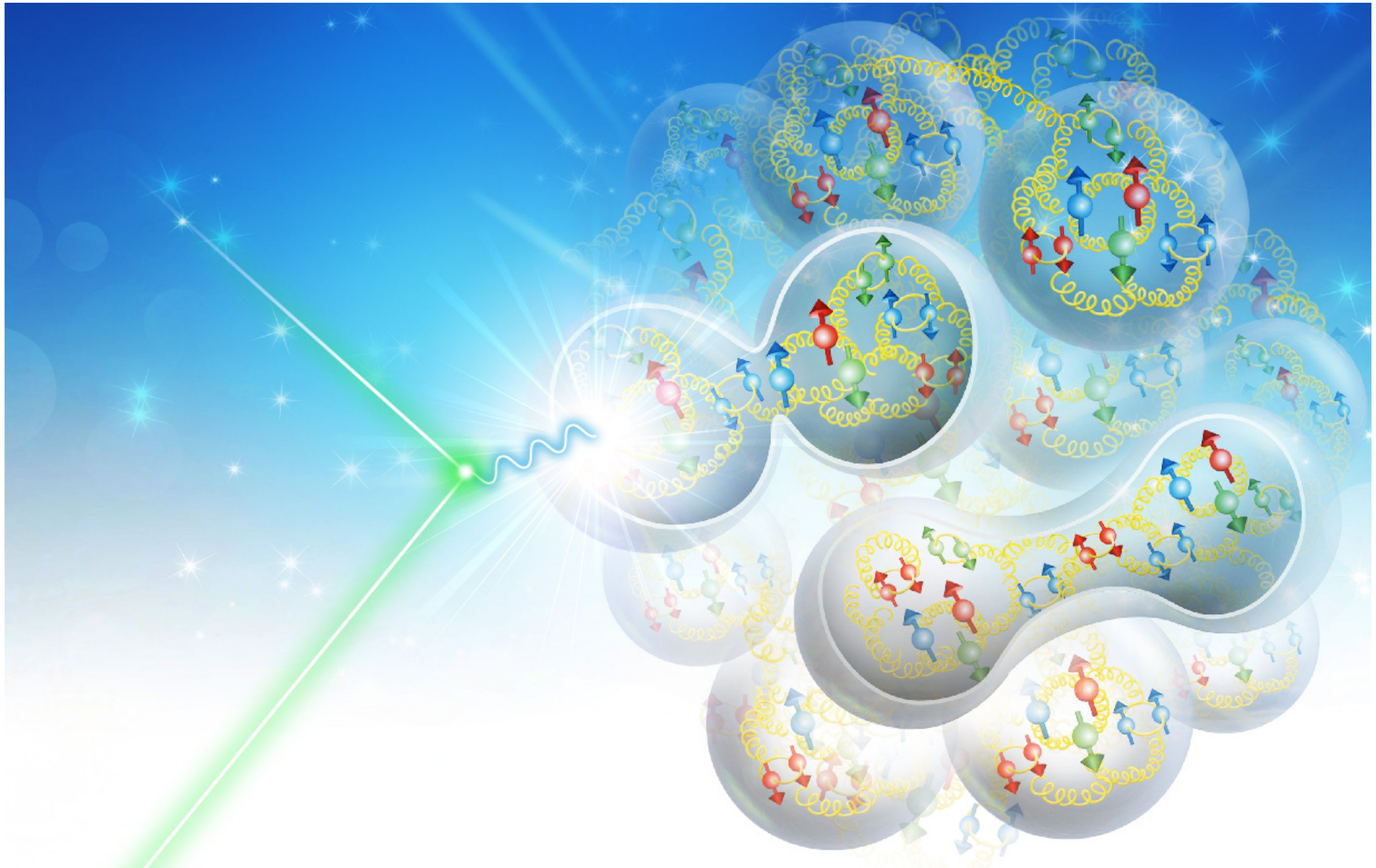
TMD measurements and requirements at the EIC

Towards a New Frontier in Nuclear Physics



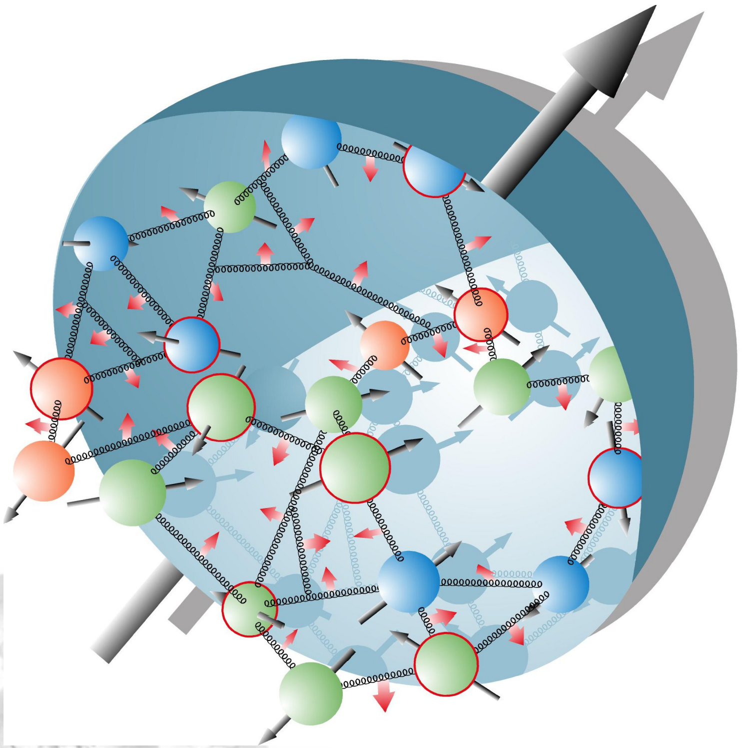
EIC²

EIC Center at Jefferson Lab

Markus Diefenthaler

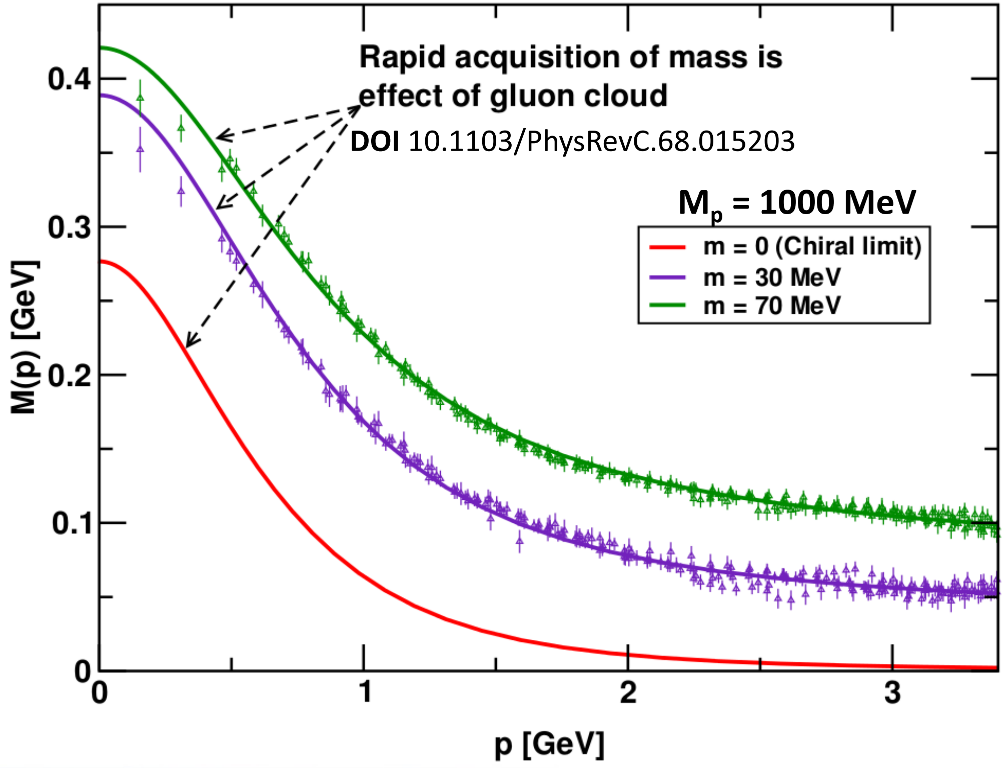
The dynamical nature of nuclear matter

Nuclear Matter Structures and interactions are inextricably mixed up



Ultimate goal Understand how matter at its most fundamental level is made

Observed properties of bound states such as mass and spin emerge out of the complex system

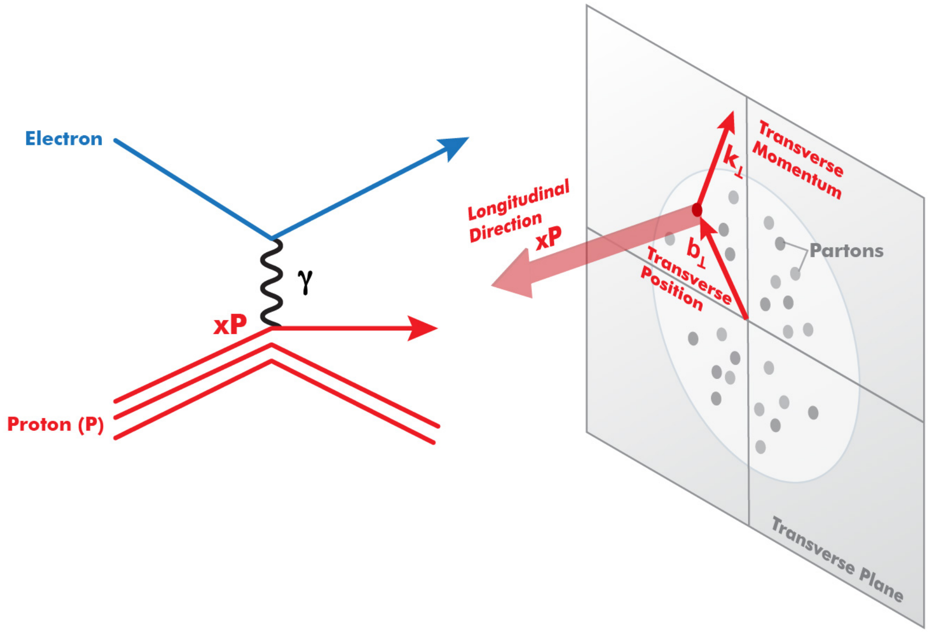


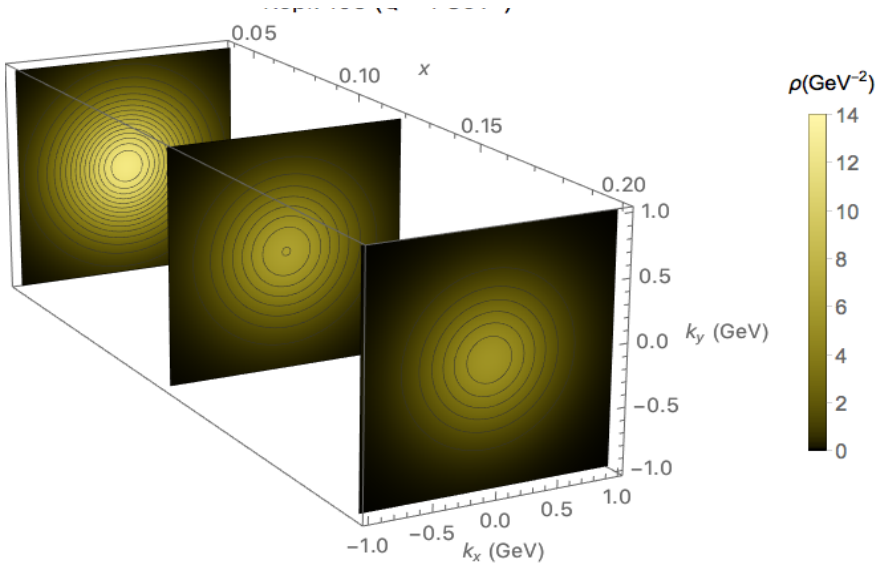
To reach goal precisely image quarks and gluons and their interactions

Jefferson Lab

Transverse-momentum dependent PDFs

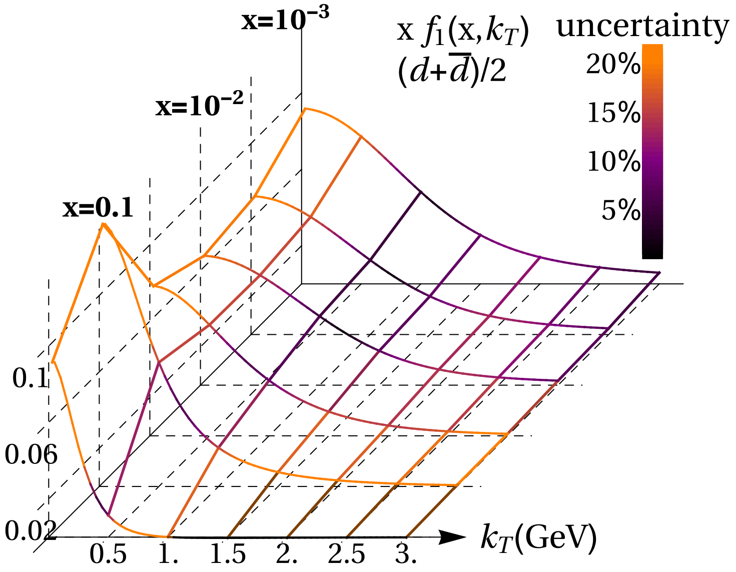
Novel QCD phenomena





JHEP 1706 (2017) 081

arXiv:1902.08474



3D imaging in space and momentum

longitudinal structure (PDF)
+ transverse position Information (GPDs)
+ transverse momentum information (TMDs)

order of a few hundred MeV

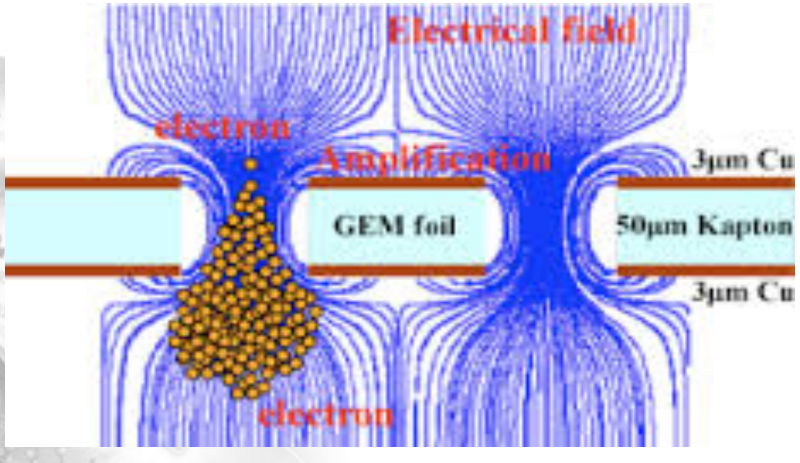
Advances in Nuclear Physics

Quantum Chromodynamics

$$
\begin{aligned}
\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2\,\mathrm{d}y\,\mathrm{d}q_\mathrm{T}^2} = {} & \frac{4\pi^2\alpha^2}{9Q^2 s}\sum_{j,j_A,j_B} e_j^2 \int \frac{\mathrm{d}^2\boldsymbol{b}_\mathrm{T}}{(2\pi)^2} e^{i\boldsymbol{q}_\mathrm{T}\cdot\boldsymbol{b}_\mathrm{T}} \\
& \times \int_{x_A}^{1} \frac{\mathrm{d}\xi_A}{\xi_A} f_{j_A/A}(\xi_A;\mu_{b_*})\, \tilde{C}^{\mathrm{CSS1,\,DY}}_{j/j_A}\left(\frac{x_A}{\xi_A}, b_*; \mu_{b_*}^2, \mu_{b_*}, C_2, a_s(\mu_{b_*})\right) \\
& \times \int_{x_B}^{1} \frac{\mathrm{d}\xi_B}{\xi_B} f_{j_B/B}(\xi_B;\mu_{b_*})\, \tilde{C}^{\mathrm{CSS1,\,DY}}_{\bar{j}/j_B}\left(\frac{x_B}{\xi_B}, b_*; \mu_{b_*}^2, \mu_{b_*}, C_2, a_s(\mu_{b_*})\right) \\
& \times \exp\left\{-\int_{\mu_{b_*}^2}^{\mu_Q^2} \frac{\mathrm{d}\mu'^2}{\mu'^2}\left[A_{\mathrm{CSS1}}(a_s(\mu');C_1)\ln\left(\frac{\mu_Q^2}{\mu'^2}\right) + B_{\mathrm{CSS1,\,DY}}(a_s(\mu');C_1,C_2)\right]\right\} \\
& \times \exp\left[-g^{\mathrm{CSS1}}_{j/A}(x_A,b_\mathrm{T};b_\mathrm{max}) - g^{\mathrm{CSS1}}_{\bar{j}/B}(x_B,b_\mathrm{T};b_\mathrm{max}) - g_K^{\mathrm{CSS1}}(b_\mathrm{T};b_\mathrm{max})\ln(Q^2/Q_0^2)\right] \\
& + \text{suppressed corrections.}
\end{aligned}
$$

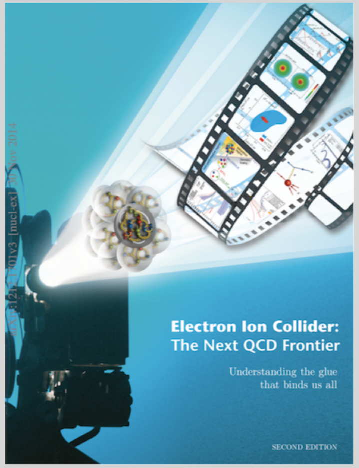
Accelerator technologies

Detector technologies

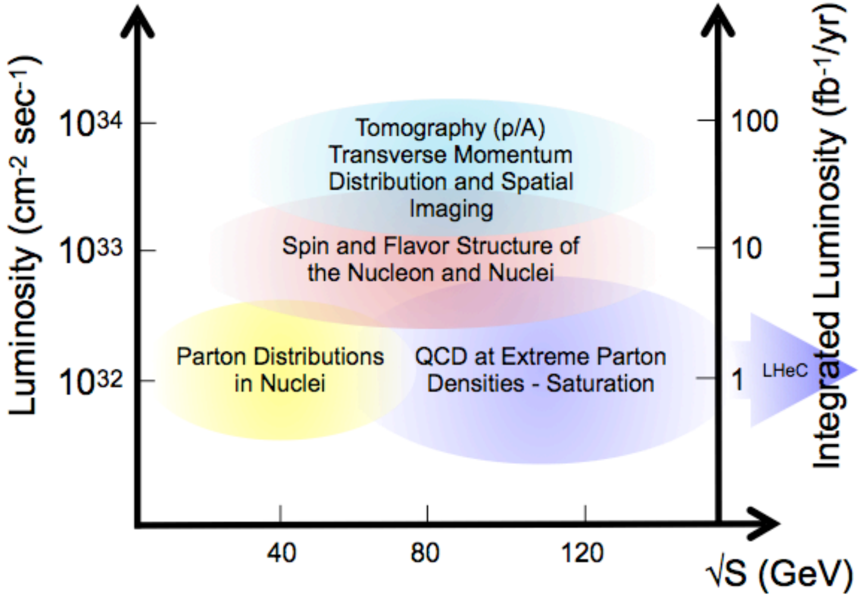


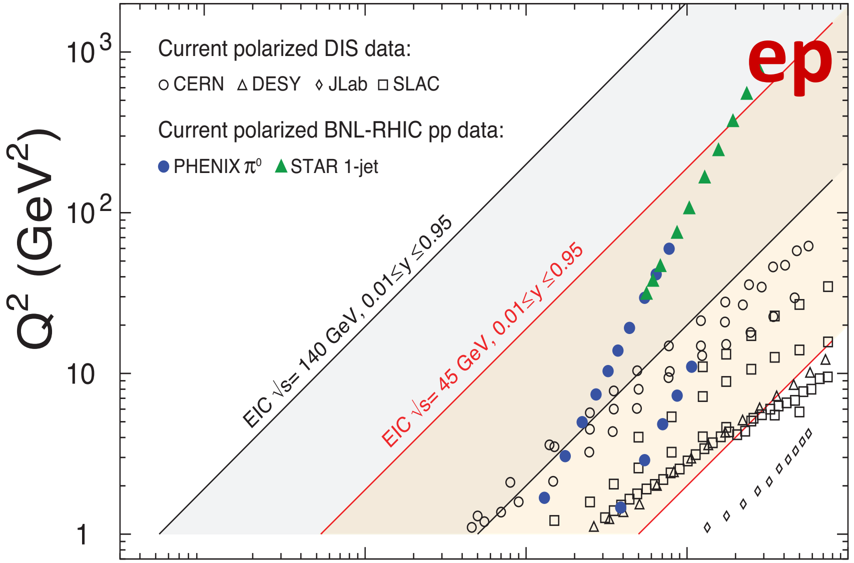
Computer technologies

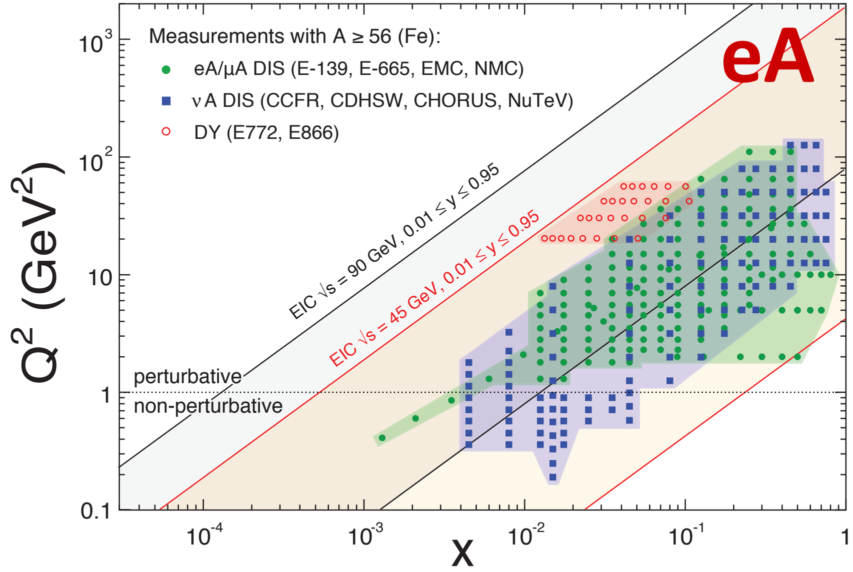
Electron-Ion Collider: Frontier accelerator facility in the U.S.



Study **structure** and **dynamics** of **nuclear matter** in **ep** and **eA collisions** with high luminosity and versatile range of beam energies, beam polarizations, and beam species.







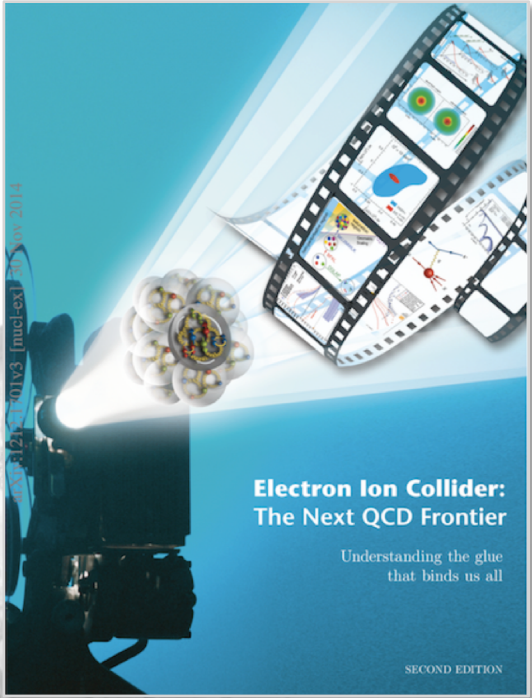
Jefferson Lab

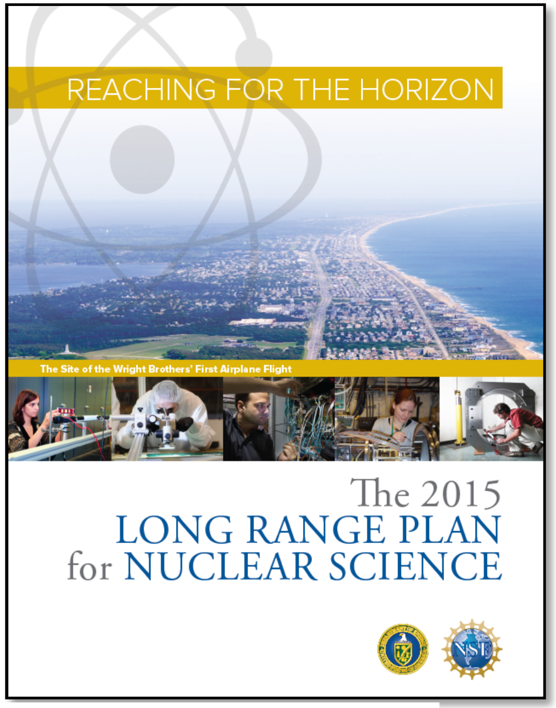
Why an Electron-Ion Collider?

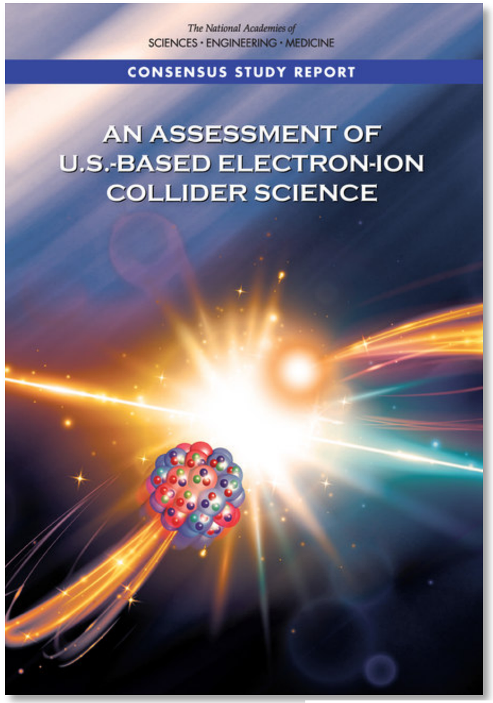
Right tool:

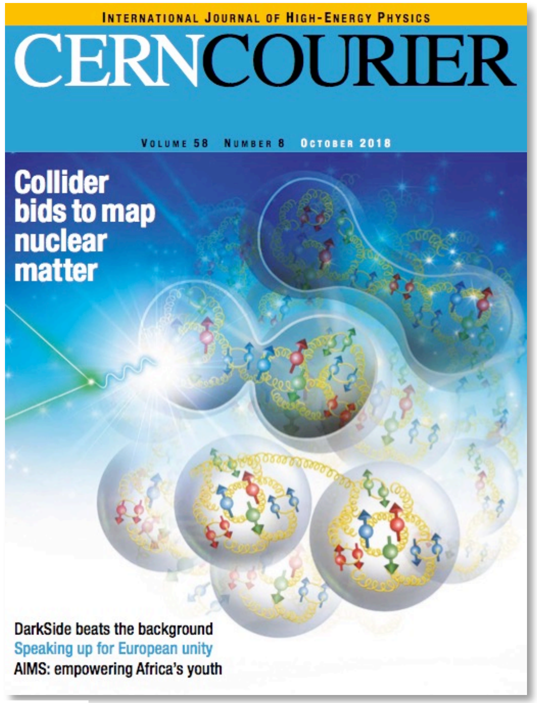
- to precisely **image quarks and gluons** and their interactions
- to explore the new **QCD frontier of strong color fields in nuclei**
- to understand **how matter at its most fundamental level is made**.

Understanding of nuclear matter is **transformational**, perhaps in an even more dramatic way than how the understanding of the atomic and molecular structure of matter led to new frontiers, new sciences and new technologies.

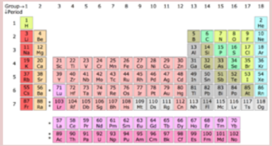
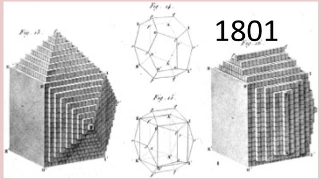
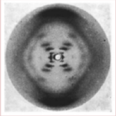
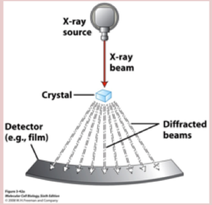
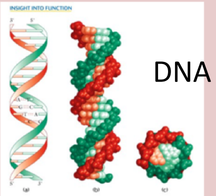
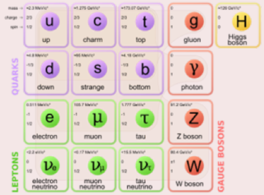
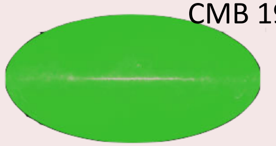
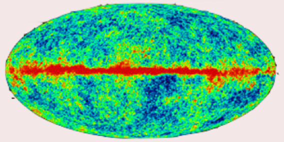
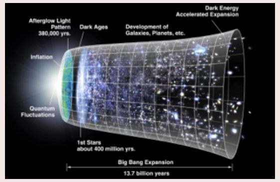
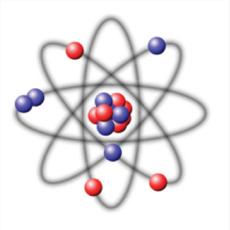
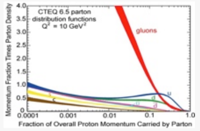
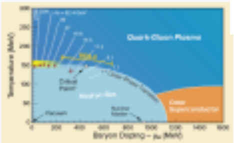
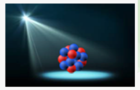
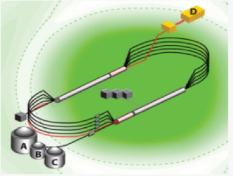
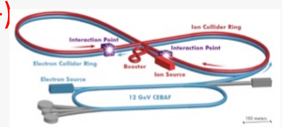




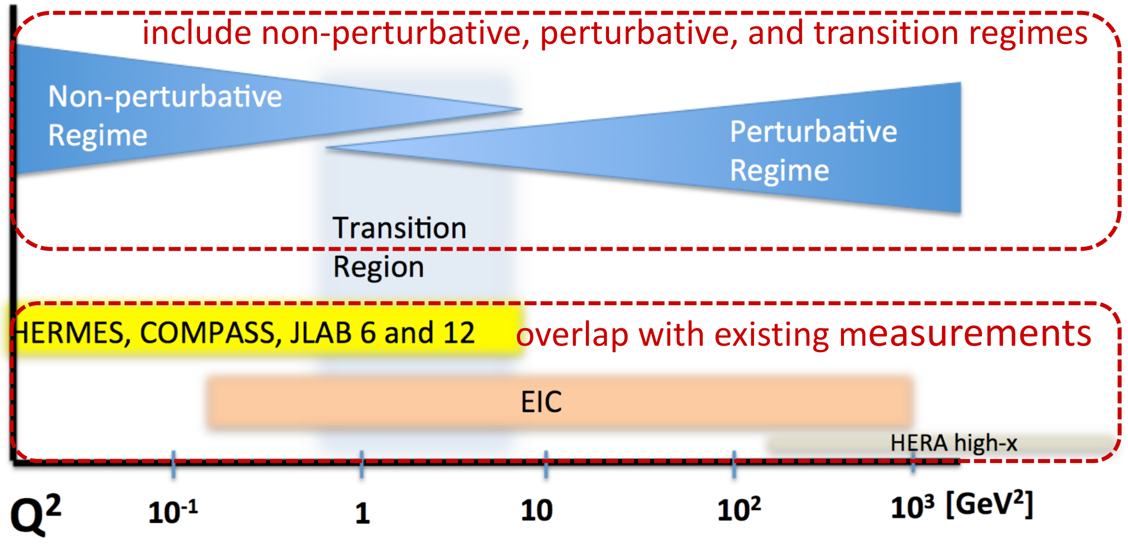


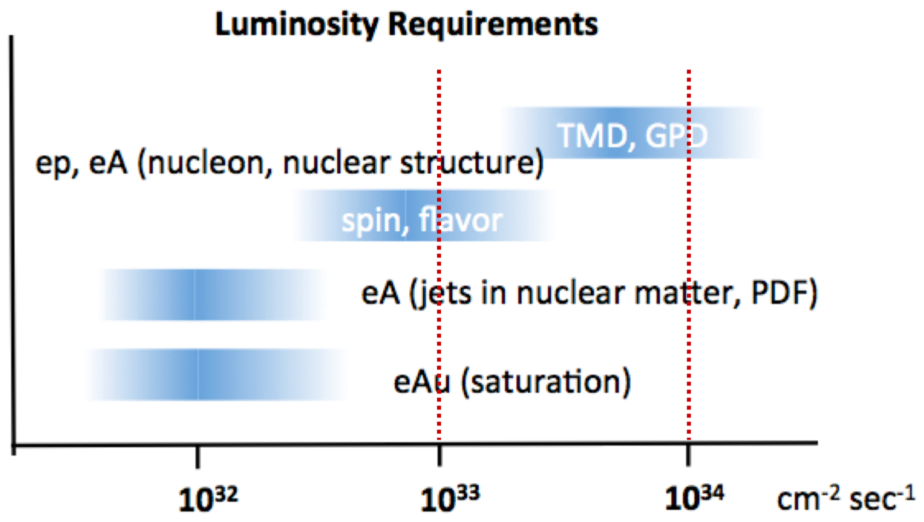


EIC: A new frontier in science

Dynamical System	Fundamental Knowns	Unknowns	Breakthrough Structure Probes (Date)	New Sciences, New Frontiers
Solids 	Electromagnetism Atoms 	Structure 1801 	X-ray Diffraction (~1920)  	Solid state physics Molecular biology DNA 
Universe 	General Relativity Standard Model 	Quantum Gravity, Dark matter, Dark energy. Structure CMB 1965 	Large Scale Surveys CMB Probes (~2000)  	Precision Observational Cosmology 
Nuclei and Nucleons 	Perturbative QCD Quarks and Gluons $\mathcal{L}_{QCD} = \bar{\psi}(i\partial\!\!\!/ - gA\!\!\!/)\psi - \frac{1}{2}\mathrm{tr}\, F_{\mu\nu}F^{\mu\nu}$	Non-perturbative QCD Structure 2017   	CEBAF12 (2018)   Electron-Ion Collider (2025+) 	Structure & Dynamics in QCD 

EIC: Ideal facility for studying TMDs





Various beam energy

broad Q^2 range for

- studying TMD evolution
- disentangling non-perturbative and perturbative regimes
- overlap with existing experiments

High luminosity

Multi-dimensional analysis on event level high statistics in five or more dimensions and multiple particles

EIC: Ideal facility for studying TMDs

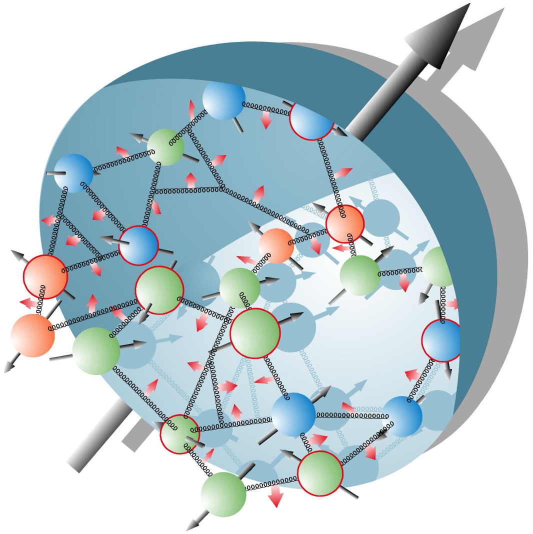
Polarization

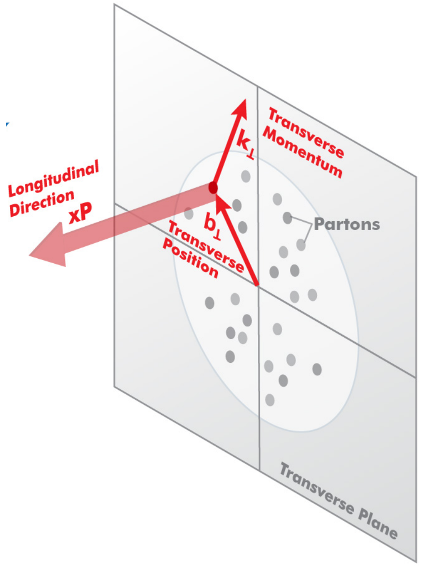
Understanding hadron structure cannot be done without understanding spin:

- polarized **electrons** and
- polarized **protons/light ions (d, ^{3}He)** including tensor polarization for d

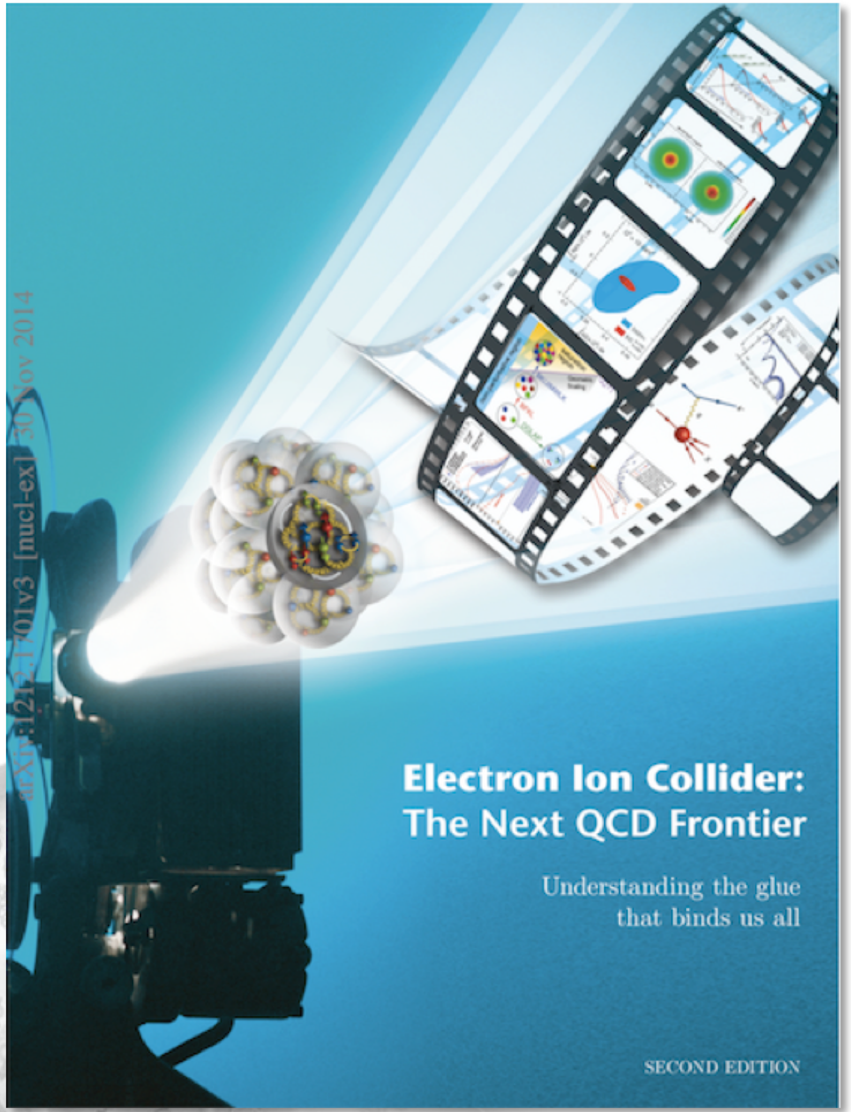
Longitudinal and transverse and polarization of light ions (d, ^{3}He)

- 3D imaging in space and momentum
- spin-orbit correlations encoded in TMDs





TMD program in EIC White Paper



Ultimate measurement of TMDs for quarks

- **high luminosity**
    - high-precision measurement
    - multi-dimensional analysis (x, Q^2, ϕ_{S}, z, P_t, ϕ_h)
- **broad x coverage** $0.01 < x < 0.9$
- **broad Q^2 range** disentangling non-perturbative / perturbative regimes

First (?) measurement of TMDs for sea quarks

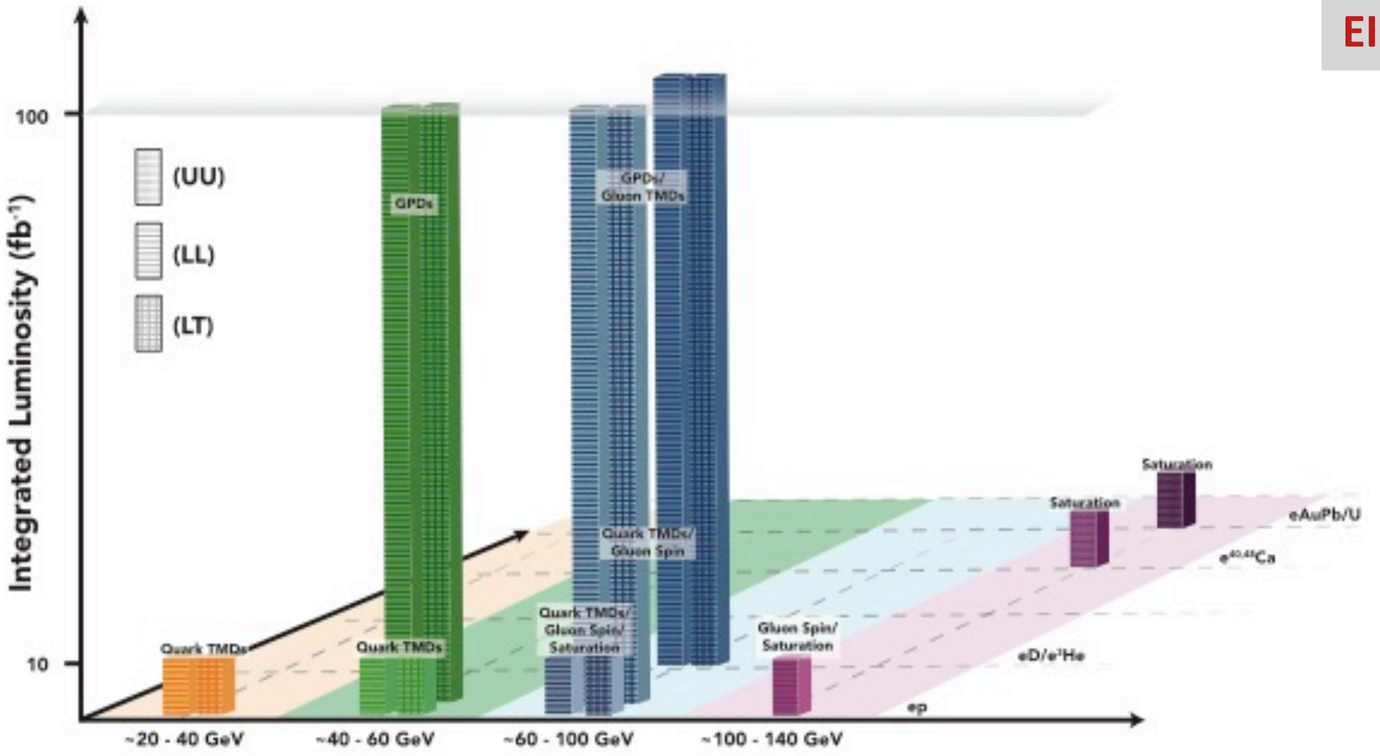
First (?) measurement of TMDs for gluons

Nuclear dependence of TMDs

Systematic factorization studies

Projected luminosity needs (EIC Whitepaper)

EIC luminosity ~650 fb^{-1}



EIC luminosity 100 – 1000 times HERA luminosity:

- **0.6 fb^{-1} to 6 fb^{-1}/week** of running or
- **average luminosity** (while running) **of 10^{33} to 10^{34} cm^{-2} s^{-1}**

6 fb^{-1}/week ➔ 100 fb^{-1}/year assuming 10^7 s in year (running ~1/3 of the year or a *snowmass* year)

We cannot start the TMD program without high luminosity.
We need high-luminosity at the start of physics running at the EIC.

Requirements for TMD measurements

Discussion

- What are our goals for the TMD program at the EIC?
- How do we accomplish our goals?
- What can we do now and what do we need to do now?
- **E.g.**: We need to know R_{SIDIS} and we plan to measure it at Jefferson Lab.

- **Theory**
  - If we have precise measurements of TMDs what do we learn about big questions, e.g., chiral symmetry breaking, confinement, spin of the nucleon etc.? What will be our next steps?
  - Extraction of TMDs from SIDIS measurements requires comprehensive understanding of TMD hadronization
  - **Interplay Theory and Experiment** "*It will be **joint progress of theory and experiment** that moves us forward, not in one side alone*" Donald Geesaman (ANL, former NSAC Chair)

- **Accelerator** Building the right probe: High luminosity, sensitivity to intrinsic transverse momenta

- **Detector** Total acceptance detector and particle identification over a broad momentum range, optimize detector design

- **Analysis** Multi-dimensional analysis on event level, **high-precision MCEG (this talk)**

Jefferson Lab

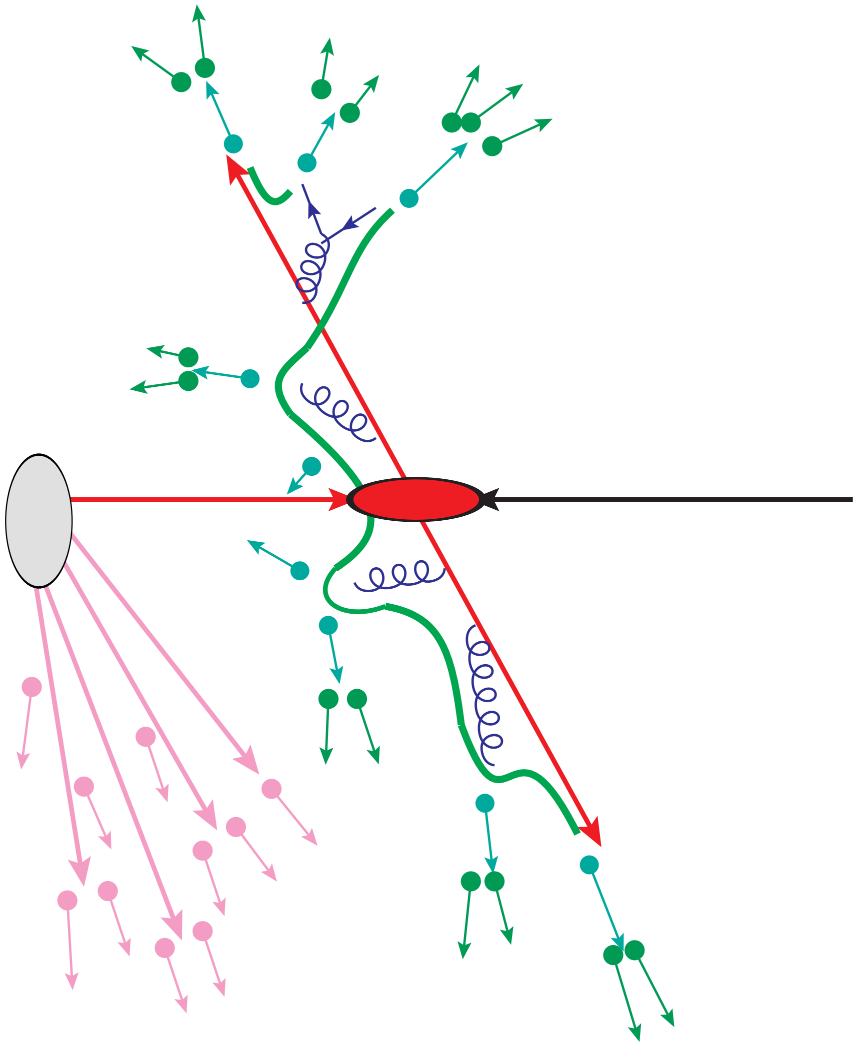
Monte Carlo Event Generator

MCEG

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

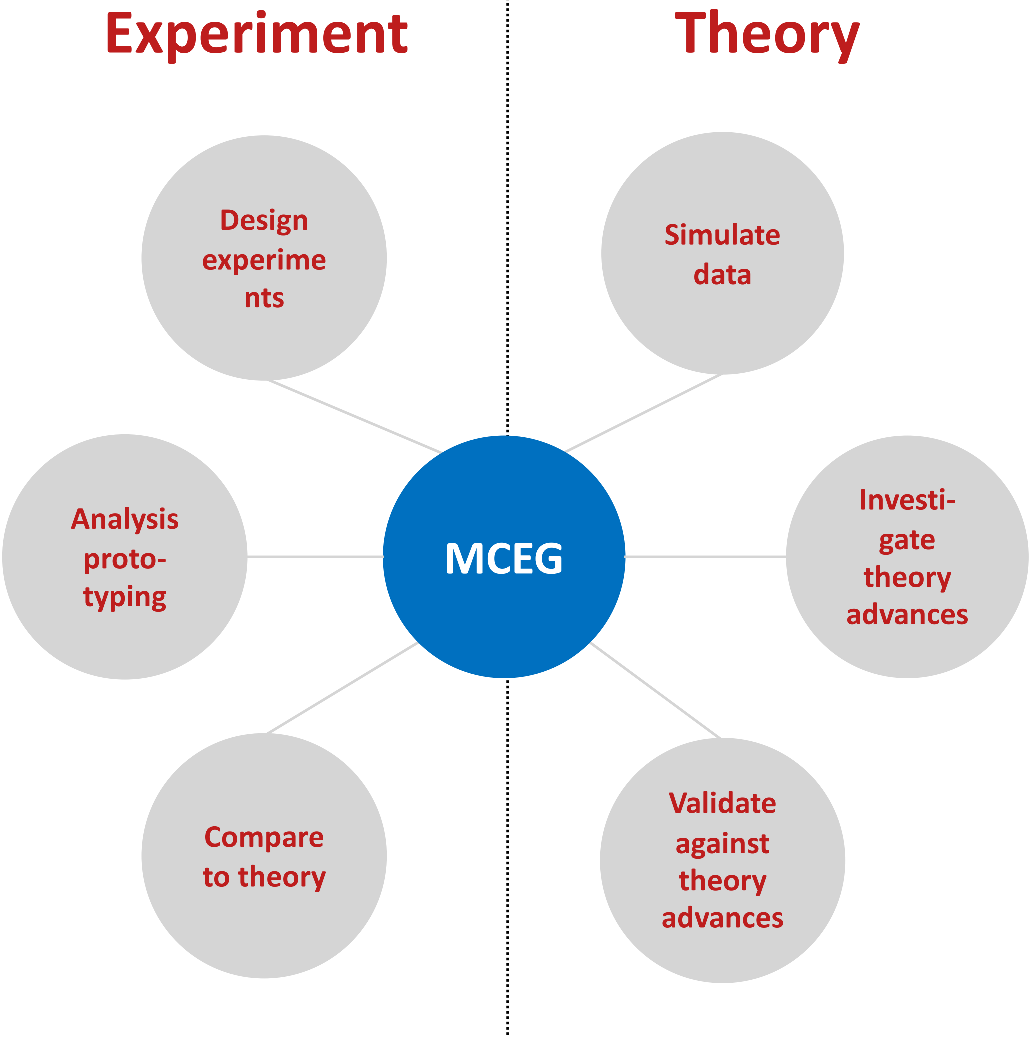
MCEG algorithm

1. Generate kinematics according to fixed-order matrix elements and a PDF.
2. QCD Evolution via parton shower model (resummation of soft gluons and parton-parton scatterings).
3. Hadronize all outgoing partons including the remnants according to a model.
4. Decay unstable hadrons.



Jefferson Lab

MCEG in Experiment and Theory

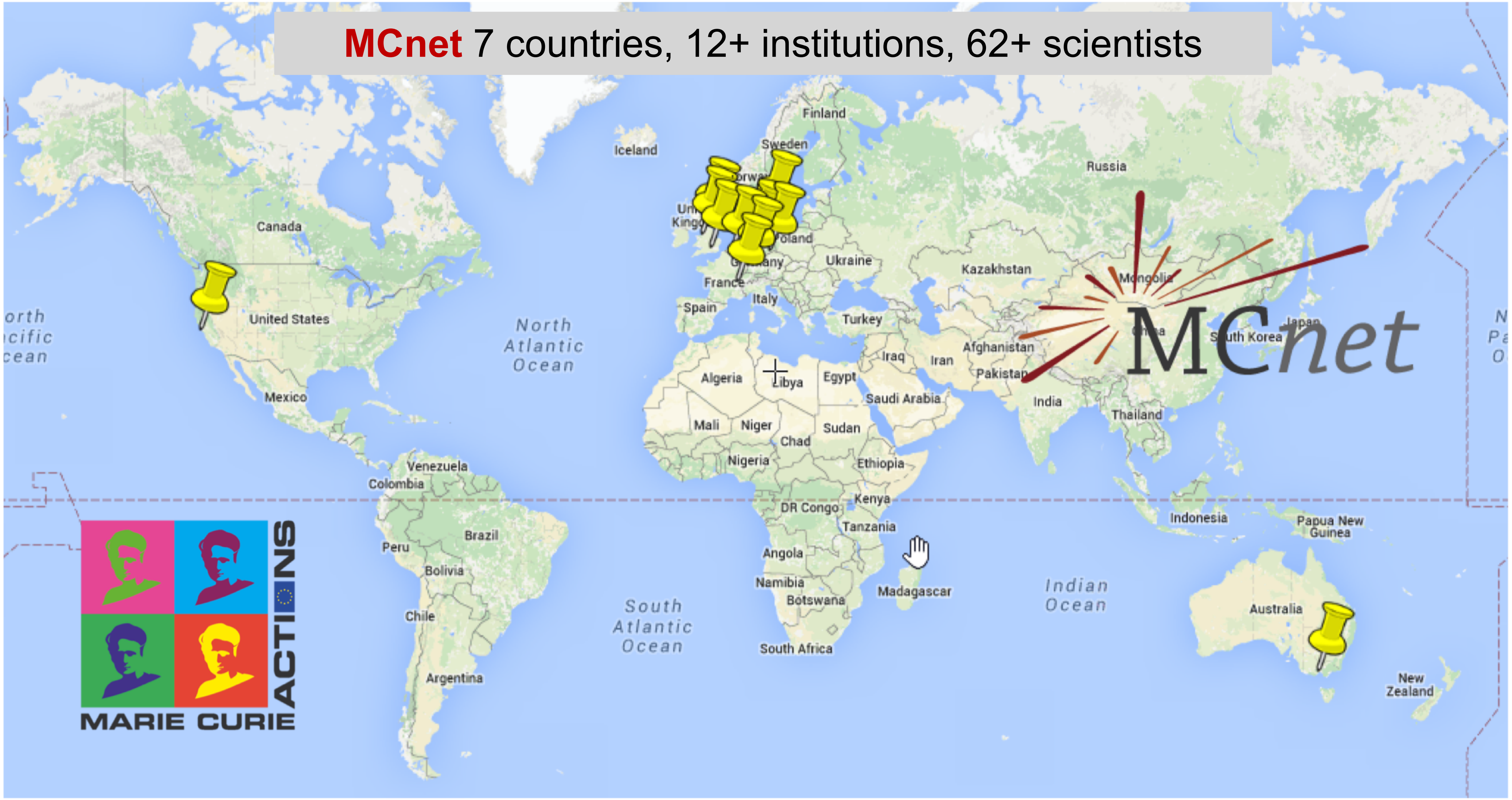


Lesson from HEP high-precision QCD measurements require high-precision MCEGs

Jefferson Lab

MCEG Developers

MCnet 7 countries, 12+ institutions, 62+ scientists



Workshops: MCEGs for future ep and eA facilities

MCEG2018 19–23 March 2018

- Started as satellite workshop during POETIC-8

P O E T I C 8
8th International Conference on Physics Opportunities at an ElecTron-Ion-Collider
19-23 March 2018, University of Regensburg

- Collaboration EIC User Group (EICUG) – MCnet

Goal of workshop series

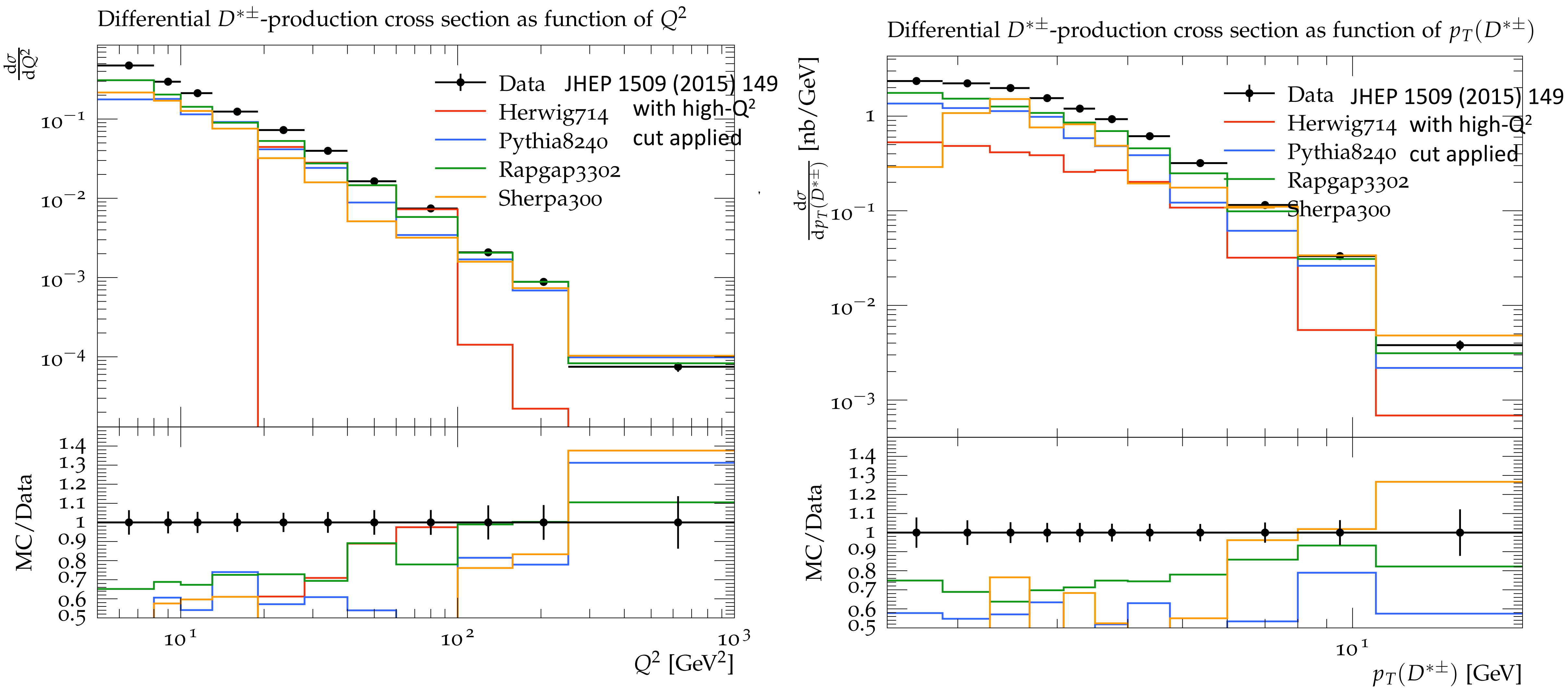
- Requirements for MCEGs for ep and eA
- R&D for MCEGs for ep and eA

MCEG2019 20–22 February 2019

- Status of ep and eA in general-purpose MCEG
- Status of NLO simulations for ep
- TMDs and GPDs and MCEGs
- Merging QED and QCD effects

Comparisons to combined H1 and ZEUS analysis

A. Verbytskyi (MPI Munich)



Pythia (1978 – now)

General-purpose MCEG

- extensively used for e^+e^-, ep and pp physics, e.g. at LEP, HERA, Tevatron, and LHC
- as a building block used in heavy-ion and cosmic-ray physics
- recent pA effort in Pythia8 with Angantyr model

Pythia 6 product of over thirty years of progress

Pythia 8 successor to Pythia 6, standalone generator, but several optional hooks for links to other programs are provided

MCEG2018 and **MCEG2019**

- possible to generate DIS events with the new dipole shower implementation
- higher-order corrections via Dire plugin, soon part of Pythia core
- photoproduction for hard and soft QCD processes, also hard diffraction

Hadron Emission Reactions With Interfering Gluon (1986 – now)

General-purpose MCEG

- developed throughout the era of LEP
- introduced cluster hadronization model

Distinctive features

- automatic generation of hard processes and decays with full spin correlations for many BSM models
- completely generic matching and merging
- hard and soft multiple partonic interactions to model the underlying event and soft inclusive interactions
- sophisticated hadronic decay models, e.g., for bottom hadrons and τ leptons.

- two shower options with spin correlations and NLO matching
- good description for single-particle properties in DIS
- also QED radiation for angular-ordered shower

Simulation of High Energy Reactions of PArticles (2004 – now)

General-purpose MCEG

- e^+e^-, ep and pp physics , e.g. at LEP, HERA, Tevatron, and LHC
- also eγ and $\gamma\gamma$ physics

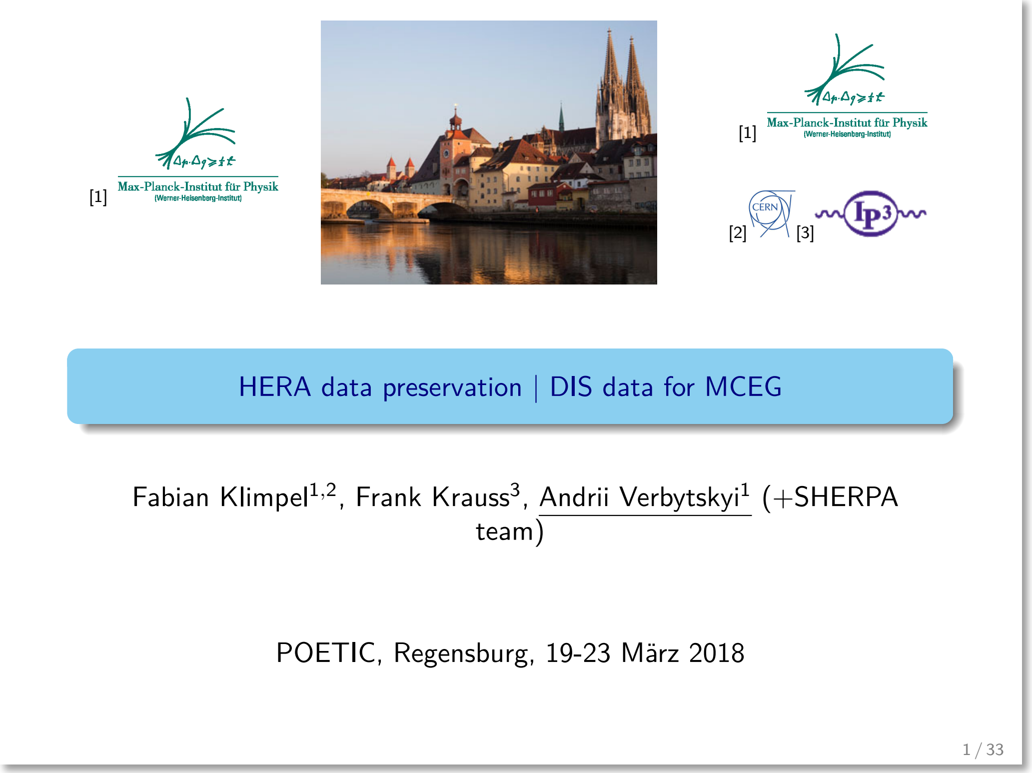
Modular MCEG (C++ from the beginning)

- full simulation is split into well defined event phases, based on QCD factorization theorems
- each module encapsulates a different aspect of event generation for high-energy particle reactions

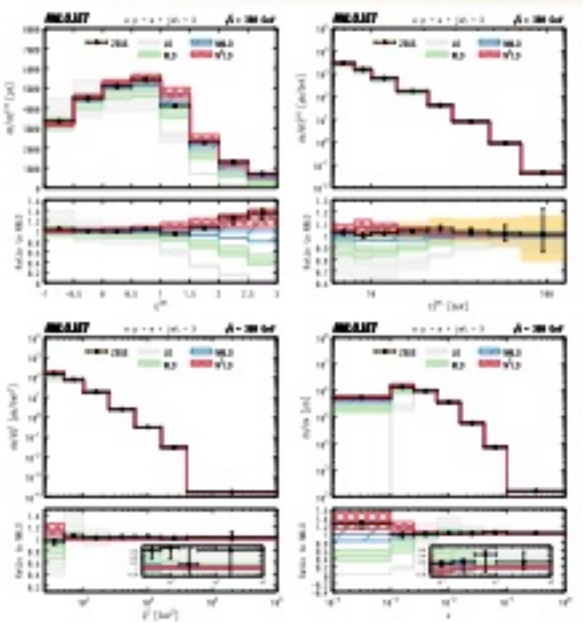
Versatile MCEG

- automated generation of tree-level matrix elements
- two fully-fledged matrix element generators with highly advanced phase-space integration methods

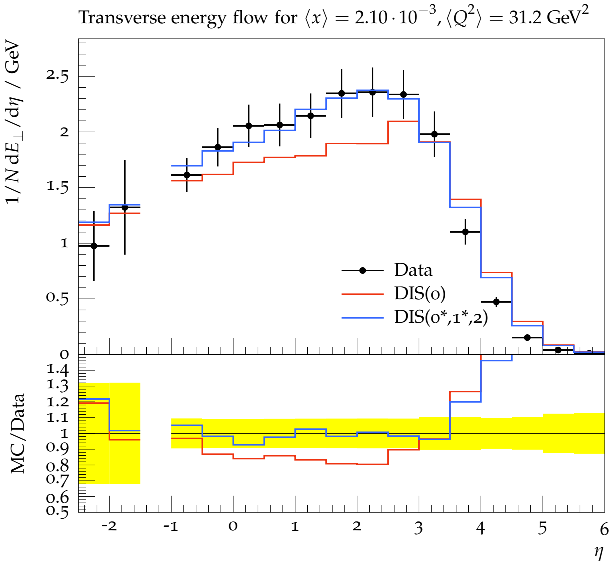
MCEG2018 and **MCEG2019**



- DIS with ME corrections and PS merging
- good description of jet data at low Q^2 with $\gtrsim$ 3 partons in the final state
- automated NLO matching with Powheg method, applicable for jets at high-Q^2



arXiv:1803.09973



Fixed-order QCD

- QCD calculations available up to N^{3}LO for inclusive DIS
- Peculiarities of DIS require careful selection of scales
- Excellent description of experimental data from HERA

MC event simulation

- DIS simulations available in all three event generation frameworks
- NLO matching & merging standard, NNLO matching available
- Peculiarities of DIS require careful selection of clustering history
- Very good description of wide range of experimental data

TMDs and MCEGs

Vibrant community

MCEG Workshop
DESY, February 2019

F Hautmann
TMDs from Parton Branching

First all flavor. all Q^2, all x and all k_t TMD at NLO determined.

- Introduction
- The Parton Branching (PB) method
- New results and applications

F Hautmann: MCEG Workshop, DESY - February 2019 1

TMD and parton shower: CASCADE-3

Hannes Jung (DESY)

with contributions from
A. van Hameren, K. Kutak, A. Kusina,
A. Bermudez Martinez, P. Connor F. Hautmann, O. Lelek, R. Zlebcik

- From inclusive to exclusive distributions
  - Parton Branching method for TMDs

First TMD parton shower using higher order splitting function.

H. Jung, TMD and Parton Shower CASCADE3 , MCEG for future ep facilities, Hamburg, Feb 2019 1

NCN

nTMD using PB method

Krzysztof Kutak

Instytut Fizyki Jądrowej
im. Henryka Niewodniczańskiego
Polskiej Akademii Nauk

First all Q^2, all x, all k_t TMD at NLO for nuclei. Comparison with DY data (pp, pPb, CMS)

Updates for KaTie

Andreas van Hameren
Institute of Nuclear Physics
Polish Academy of Sciences
Kraków

presented at the
MCEGs for future ep and eA facilities
21-02-2019, DESY, Hamburg

First ever off-shell hard process calculation for ep including all flavors.

Lively discussion: Factorization Theorem and MCEG approaches

To what extent are TMDs a result of a coherent branching evolution as, e.g., implemented in Herwig

Next: Comparison to TMD theory

Extract TMD from the different MCs and compare to analytic results.

UNIVERSITÀ
DEGLI STUDI DI TRIESTE

21st February 2019,
DESY,
Hamburg

INFN
Istituto Nazionale di Fisica Nucleare

Revisited version of a recursive model for the fragmentation of polarized quarks

Albi Kerbizi
University of Trieste, Trieste INFN Section

Lund string + 3P0; good description of Collins and di-hadron asymmetries; Boer-Mulders, jet handedness can be simulated.

CASCADE

CASCADE

Eur. Phys. J. C (2010) 70: 1237–1249
DOI 10.1140/epjc/s10052-010-1507-z

THE EUROPEAN PHYSICAL JOURNAL C

Special Article - Tools for Experiment and Theory

The CCFM Monte Carlo generator CASCADE Version 2.2.03

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Abstract CASCADE is a full hadron level Monte Carlo event generator for ep, γp and $p\bar{p}$ and pp processes, which uses the CCFM evolution equation for the initial state cascade in a backward evolution approach supplemented with off-shell matrix elements for the hard scattering. A detailed program description is given, with emphasis on parameters the user wants to change and common block variables which completely specify the generated events.

TMDs from parton branching and parton showers in MC event generators

MCEG2018

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in collaboration with
A. Bermudez-Martinez, F. Hautmann, A. Lelek, V. Radescu, R. Zlebcik
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- Why TMDs are needed
  - TMDs for hadron-hadron collisions
- New developments
  - parton branching algorithm to solve evolution equations
    - benchmark tests
    - advantages for integrated PDFs
  - determination of TMD densities at NLO with xFitter
- Application to DY production
- Application to TMD parton showers

H. Jung, MDs from parton branching and parton showers in MC event generators, POETIC2018 MC satellite WS, Regensburg, March 22, 2018 1

CCFM evolution

- BFKL variant including large x
- √s >> M

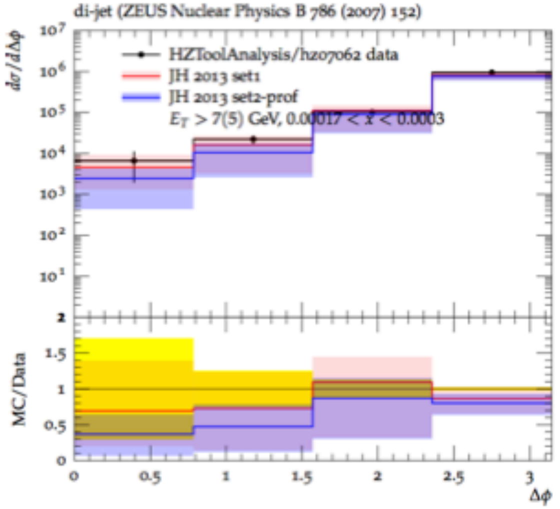
Parton Branching

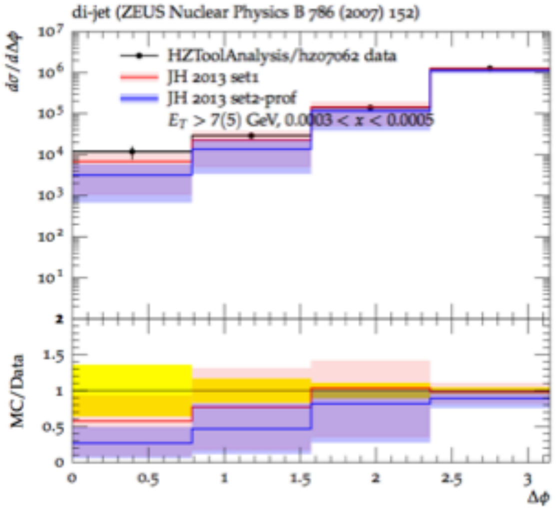
- evolution equation, connected in a controllable way with DGLAP evolution of collinear PDF
- applicable over broad kinematic range from low to high k_T,

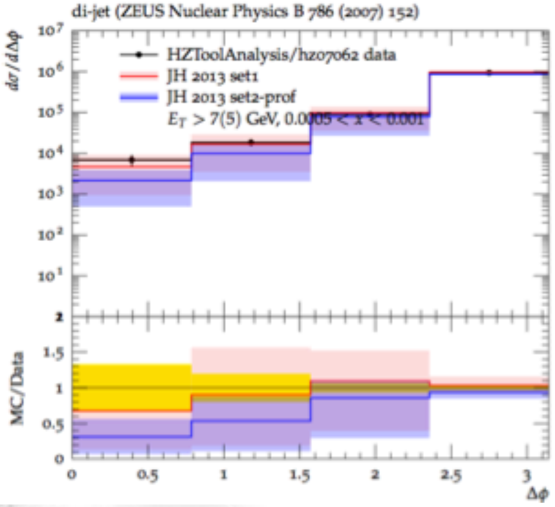
DIS dijet azimuthal distribution from CASCADE

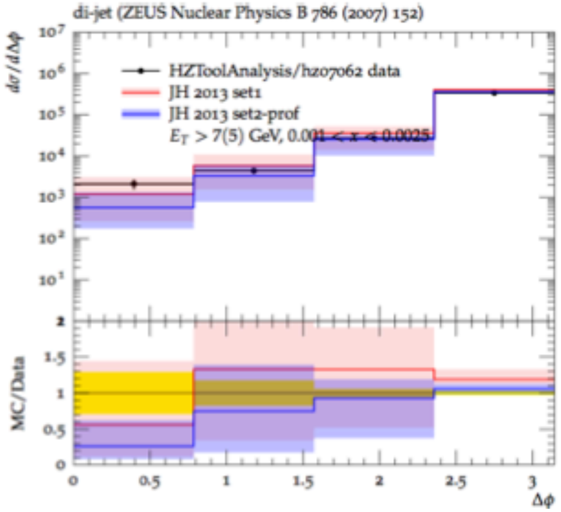
Slide prepared by F. Hautmann (University of Oxford)

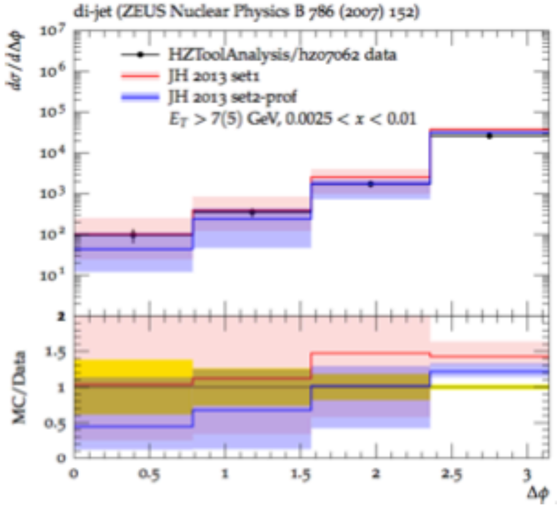
- CASCADE with TMD pdfs from precision F2 and F2-charm data
- ZEUS 2007 jet measurements





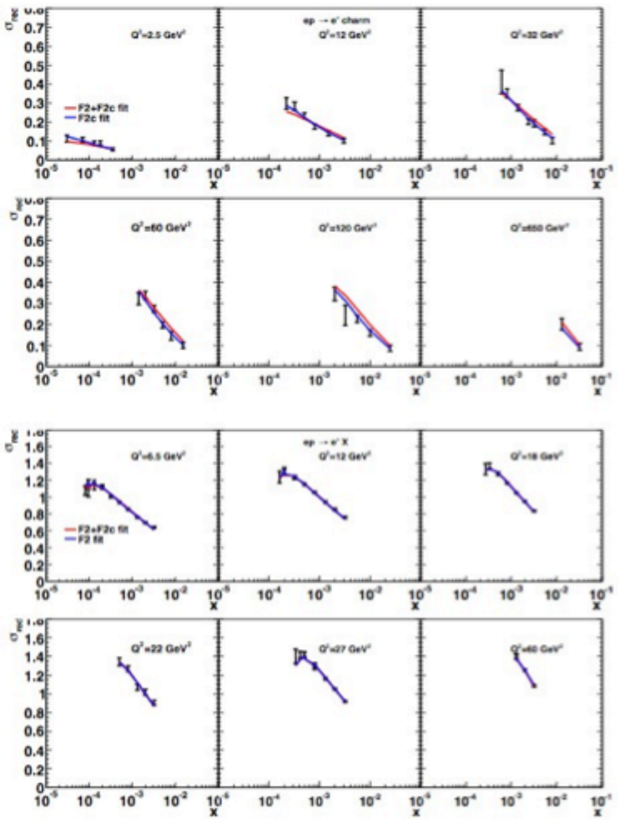






Gluon TMDs from precision DIS data using CCFM evolution

Slide prepared by F. Hautmann (University of Oxford)



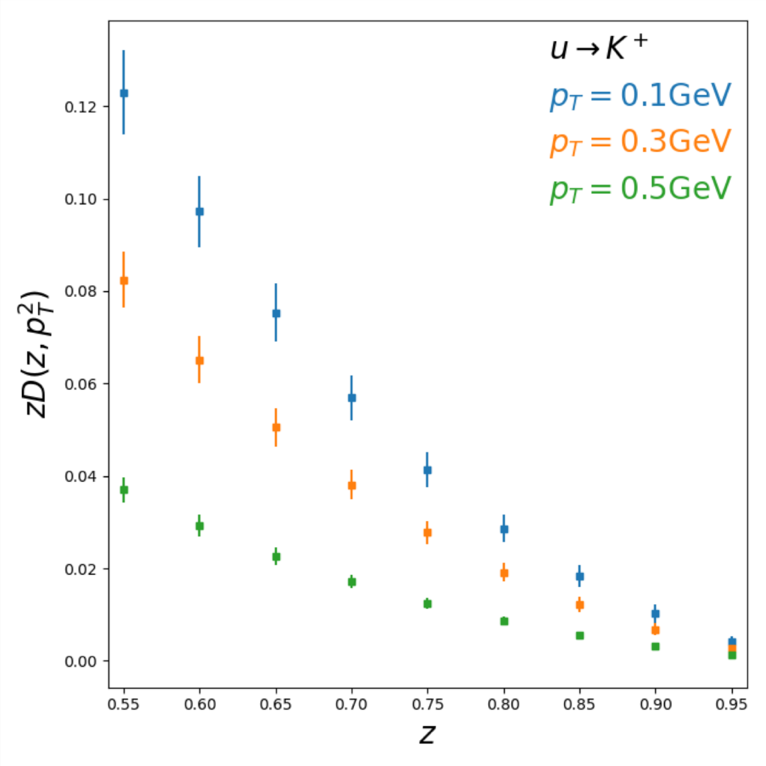
[Hautmann and Jung, Nucl. Phys. B 883 (2014) 1]

- Good description of inclusive DIS data with TMD gluon
- Sea quark yet to be included at TMD level
- Uses uPDFevolv evolution code arXiv:1407.5935 [hep-ph]
- Fit performed with xFitter arXiv:1410.4412 [hep-ph]

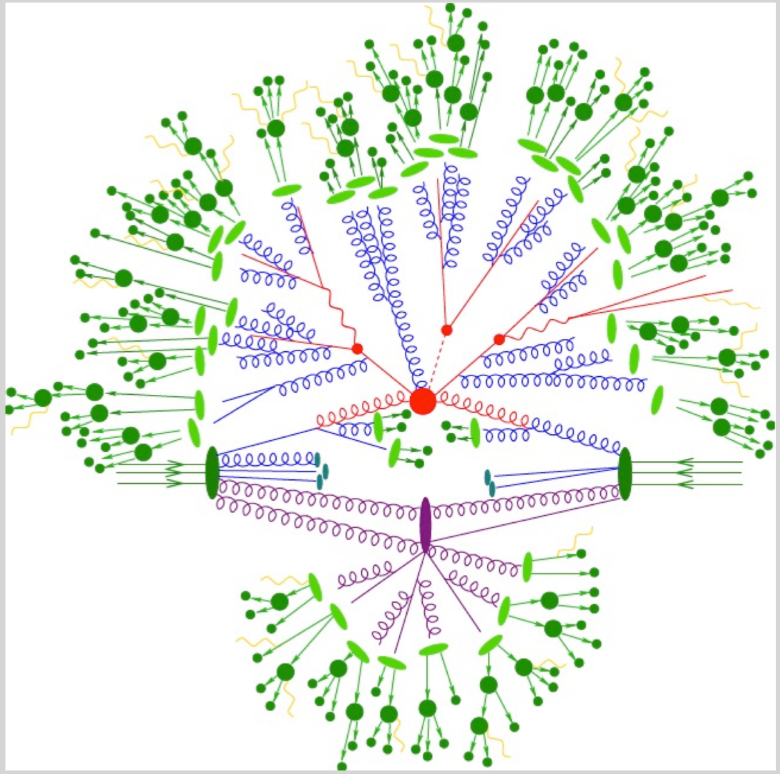
	$\chi^2/ndf(F_2^{(\mathrm{charm})})$	$\chi^2/ndf(F_2)$	$\chi^2/ndf\left(F_2 \text{ and } F_2^{(\mathrm{charm})}\right)$
3-parameter	0.63	1.18	1.43
5-parameter	0.65	1.16	1.41

Studying hadronization in two complementary approaches

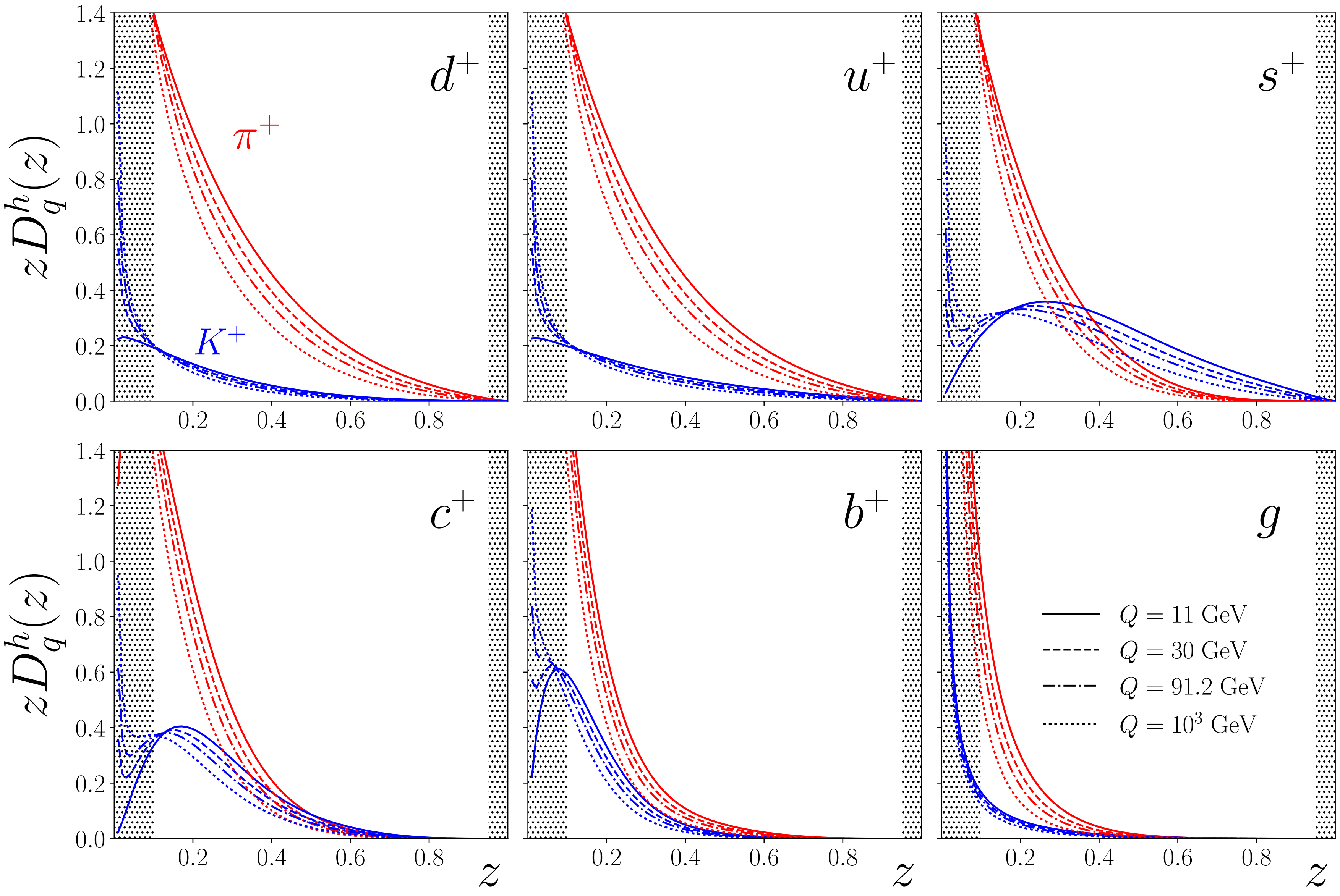
Purely phenomenological description with empirical fragmentation functions using factorization theorems in pQCD



Hadronization models folded with many parameters to describe experimental observations as applied in Monte Carlo Event Generators.



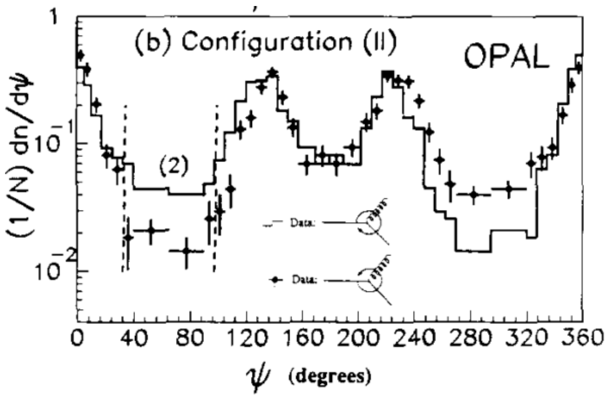
Fit π and K FFs from Pythia8 pseudodata using pQCD @ NLO



Understanding the hadronization process

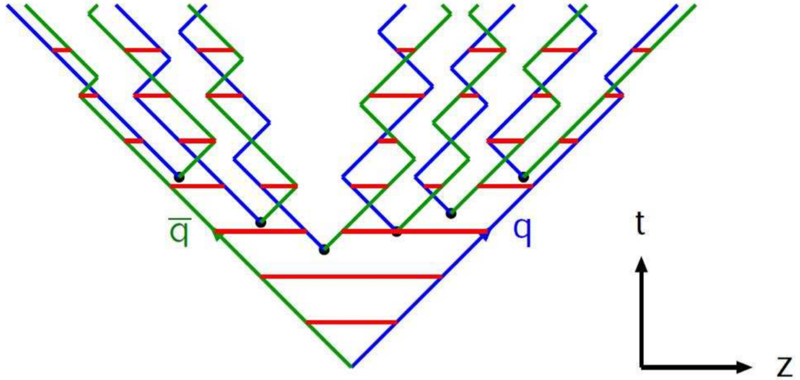
LUND String Model for hadronization (1977 – *now*)

- simple but powerful phenomenological model
- no (promising) new hadronization models in last 40 years
- **LDRD project at Jefferson Lab**
  - review
  - connect with modern QCD, including TMD and spin effects

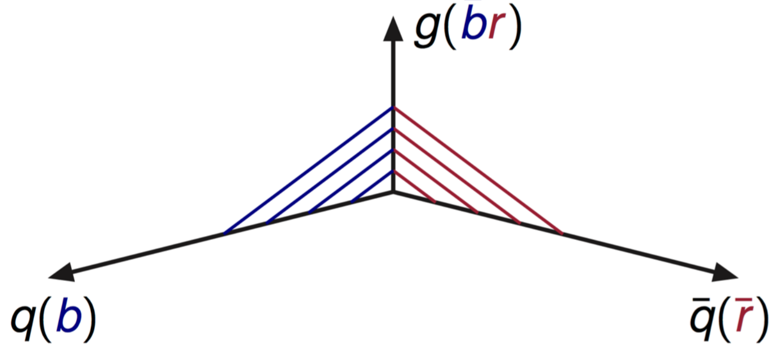


evidence of string effects
particle flow asymmetry at OPAL

String breakup



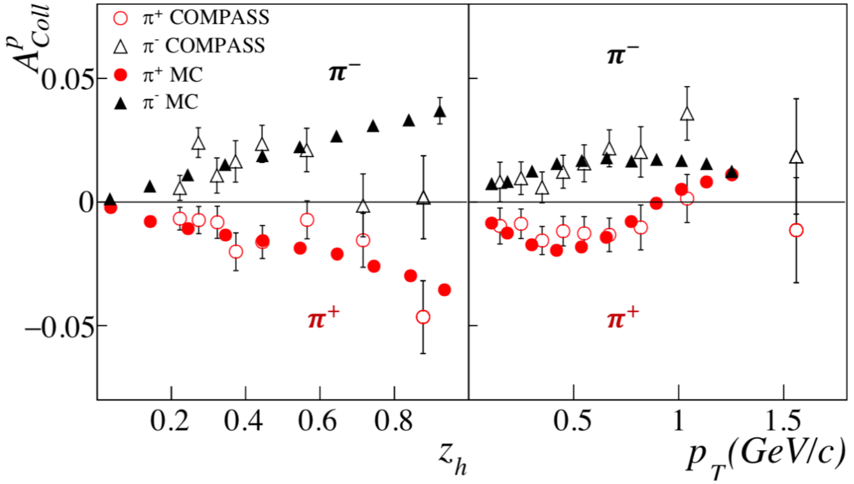
String drawing



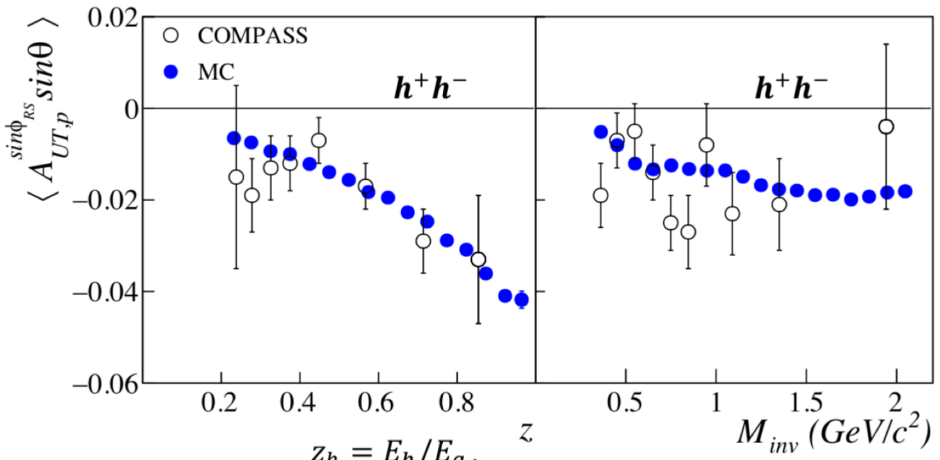
Recursive model for the fragmentation of polarized quarks

Albi Kerbizi (Trieste)

COMPASS Collins SSA



COMPASS di-hadron asymmetry



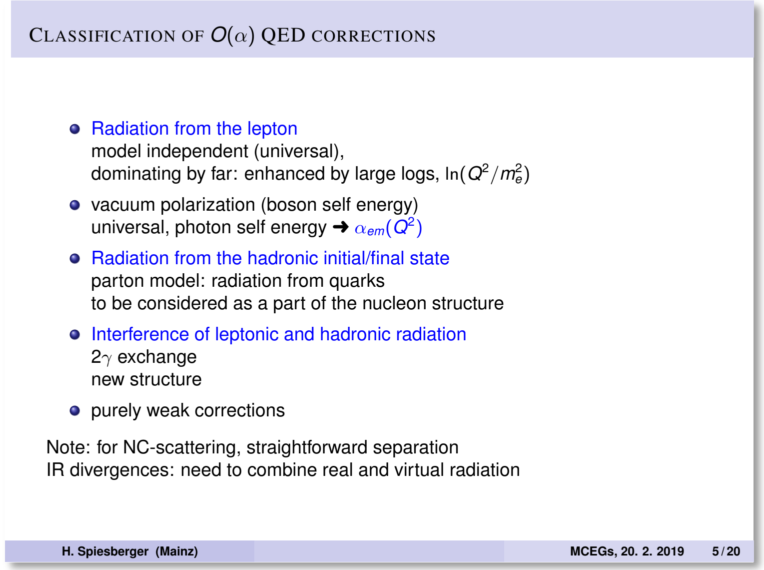
$z_h = E_h / E_{q_A}$

$z = z_{h^+} + z_{h^-}$

- The string + $^3P_0$ model for pseudo-scalar meson emission has been implemented in a stand alone MC code
- The comparison with experimental data on Collins and di-hadron asymmetries is very promising
- Other effects like Boer-Mulders or jet-handedness can be simulated

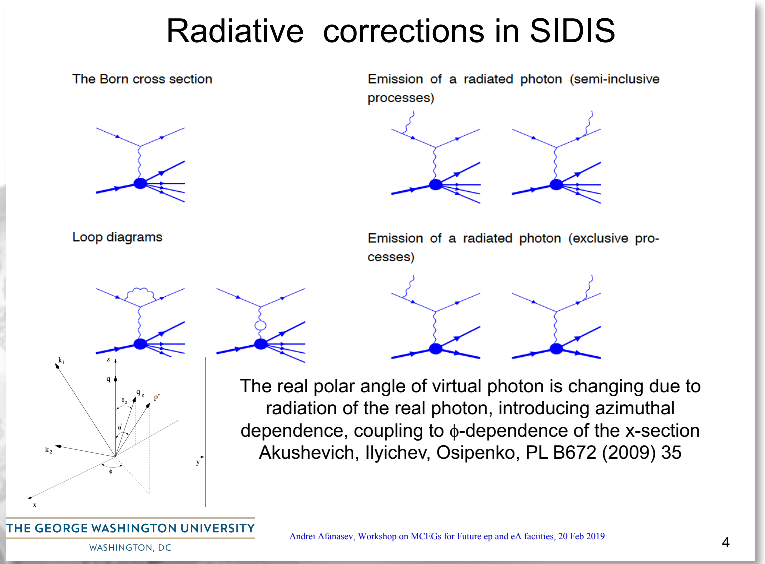
- The same results can be obtained with different choices for the $\check{g}$ function acting on the spin-independent correlations between quark transverse momenta
- The choice $\check{g} = 1/\sqrt{N_a(\varepsilon_h^2)}$ guarantees again LR symmetry and allows to simplify
  - the formalism and the analytical calculations
  - **the improvement of the simulations (i.e. adding vector mesons) → ongoing**
  - **the interface with external event generators and in particular with PYTHIA → ongoing**

Merging QED and QCD effects



Hubert Spiesberger (Mainz): QED corrections for electron scattering

- High-precision measurements need careful treatment of radiative corrections.
- Closely related to experimental conditions need full Monte Carlo treatment (Unfolding) including simulation of hadronic final states.
- The basics are known and available …
- … but improvements are needed.



Andrei Afanasev (GWU): Semi-analytic vs. Monte-Carlo Approaches for QED Corrections to SIDIS

- Consistent approach to address RC for SSA in polarized SIDIS
- SSA due to two-photon exchange need to be included in analysis of SSA from strong interaction, of same size at JLAB experiments
- More detailed calculation of the two-photon exchange at quark level required: elastic scattering, inclusive, semi-inclusive, and exclusive DIS

MCEG–HERA comparisons and MCEG validation for ep

Rivet example

SIDIS analysis at HERMES

```
// Extract the particles other than the lepton
const FinalState& fs = apply<FinalState>(event, "FS");
Particles particles;
particles.reserve(fs.particles().size());
const GenParticle* dislepGP = dl.out().genParticle();
foreach (const Particle& p, fs.particles()) {
  const GenParticle* loopGP = p.genParticle();
  if (loopGP == dislepGP)
    continue;
  particles.push_back(p);
}

// Apply HERMES cuts.
bool validx = (x > 0.023 && x < 0.6);
if (q2 < 1. || w2 < 10. || y < 0.1 || y > 0.85 || !validx)
  vetoEvent;

// good inclusive event, let's do bookkeeping before we look at the hadrons
dis_tot += weight;
dis_x->fill(x, weight);
dis_Q2->fill(q2, weight);

for (size_t ip1 = 0; ip1 < particles.size(); ++ip1) {
  const Particle& p = particles[ip1];

  // get the particle index, check if it is a particle of interest
  const int part_idx = get_index(p.genParticle()->pdg_id());
  if (part_idx < 0) {
    continue;
  }

  // we have a particle of interest, let's calculate the kinematics
  // z
  const double z = (p.momentum() * pProton) / (pProton * q);
  // pt
  const double pth = sqrt(p.momentum().pT2());

  // get our z index, if negative, we have a particle outside of [.2, .8]
  const int z_idx = calc_zslice(z);
  if (z_idx < 0) {
    continue;
  }

  // store the events and make cuts where necessary
  //
  // pt cut for variables not binned in pt
  if (pth > 0 && pth < 1.2) {
    mult_z[part_idx]->fill(z, weight);
    mult_zx[part_idx][z_idx]->fill(x, weight);
    mult_zQ2[part_idx][z_idx]->fill(q2, weight);
  }
  mult_zpt[part_idx][z_idx]->fill(pth, weight);
}
```

- **MCEG R&D** requires *easy* access to *data*
- data := analysis description + data points

- **HEP** existing workflow for MCEG R&D using tools such as Rivet and Professor

- **Detailed comparisons between modern MCEG and HERA data**
  - workshop on **Rivet for ep** (Feb 18—20 2019)
  - mailing list **rivet-ep-l@lists.bnl.gov**
  - HERA data not (yet) included in MCEG tunes

MCEG-data comparisons in Rivet will be critical to **tune the MCEGs to DIS data and theory predictions**.

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Summary

- EIC will enable us to embark on a **precision study of the nucleon and the nucleus at the scale of sea quarks and gluons**, over all of the kinematic range that are relevant.
- This requires a **high luminosity**, **highly versatile EIC**.
- **TMD studies** for sea quarks and gluons will allows us to image quarks and gluons and their interactions and to gain a more comprehensive understanding of QCD.
- What we learn at JLAB 12 and later EIC, together with advances enabled by FRIB and LQCD studies, will open the door to **a transformation of Nuclear Physics**.