TMD measurements and requirements at the EIC

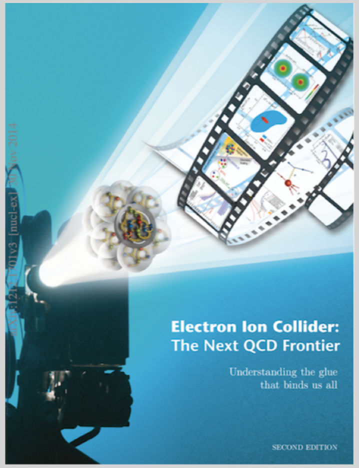
EIC science and TMDs

Thoughts on:

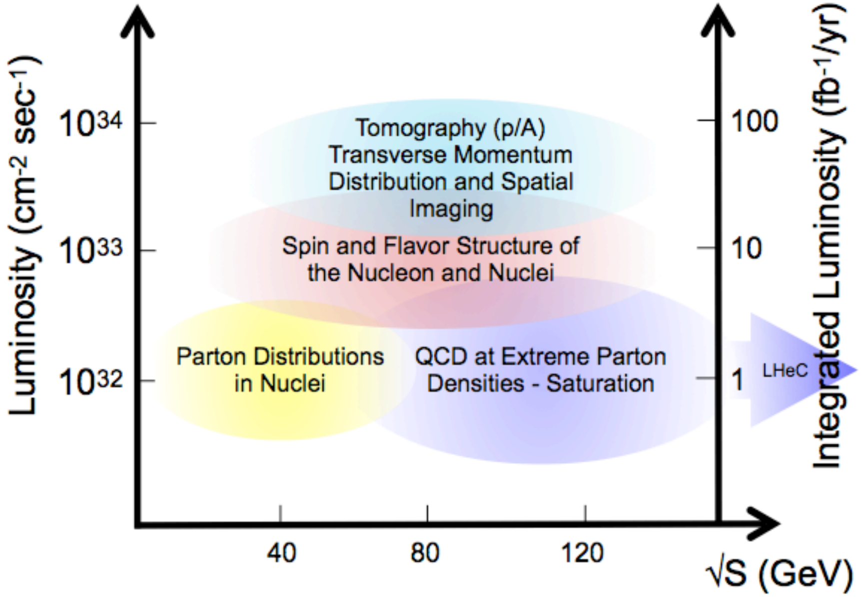
- theory requirements
- accelerator requirements
- detector requirements
- computing requirements

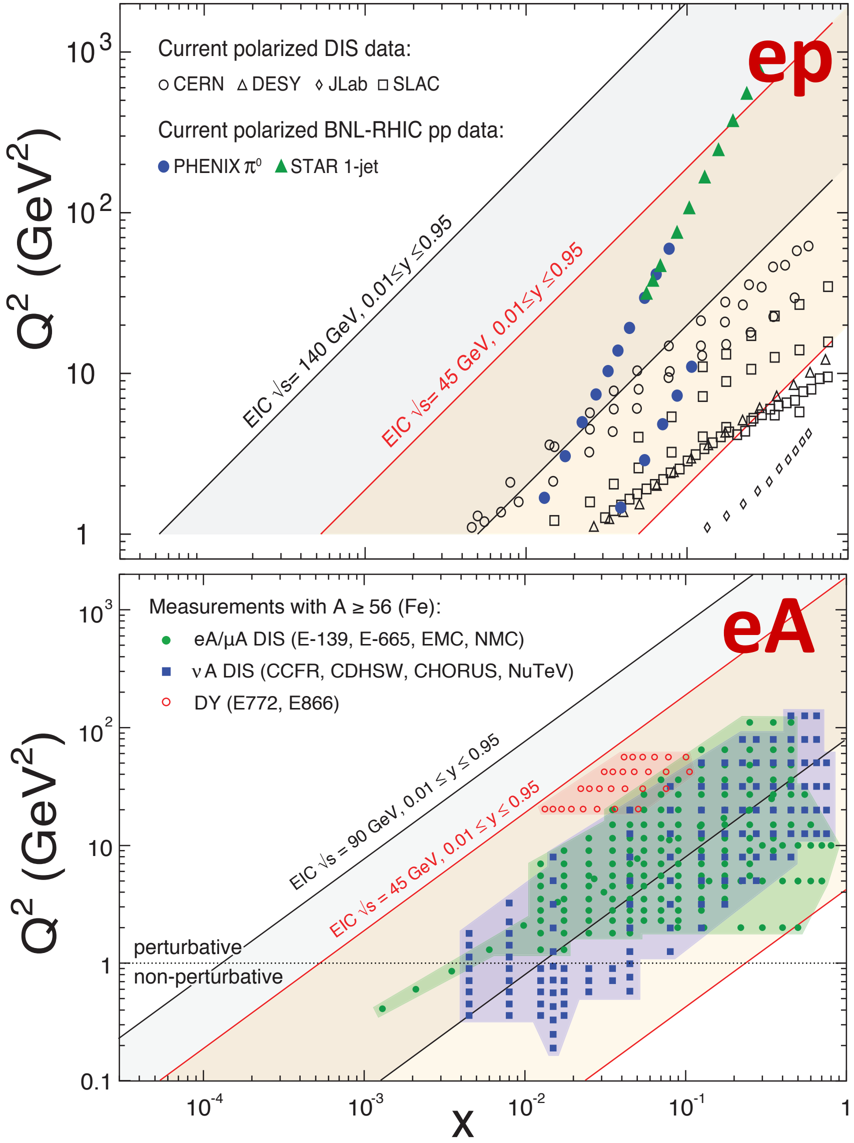
Markus Diefenthaler

EIC science program

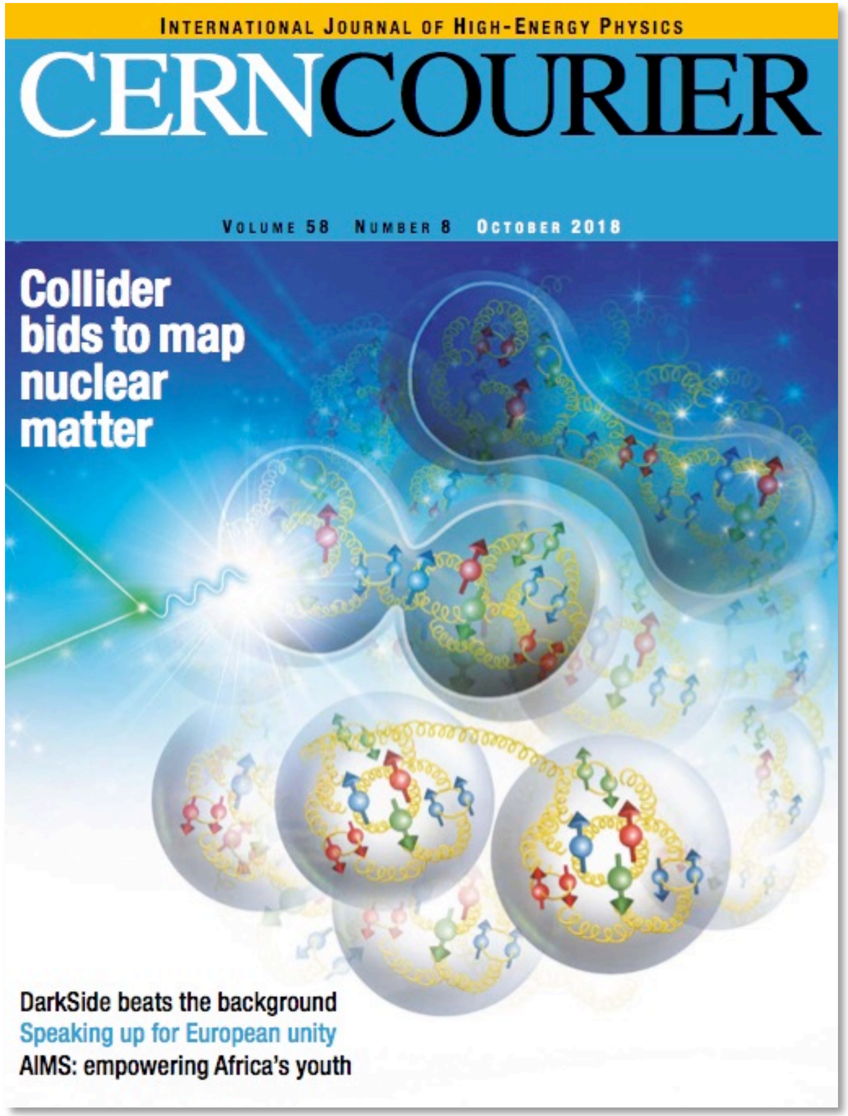


Study **structure** and **dynamics** of **nuclear matter** in **ep** and **eA collisions** with high luminosity and versatile range of beam energies, beam polarizations, and beam species.





EIC science and TMDs



EIC's scientific goals: in brief

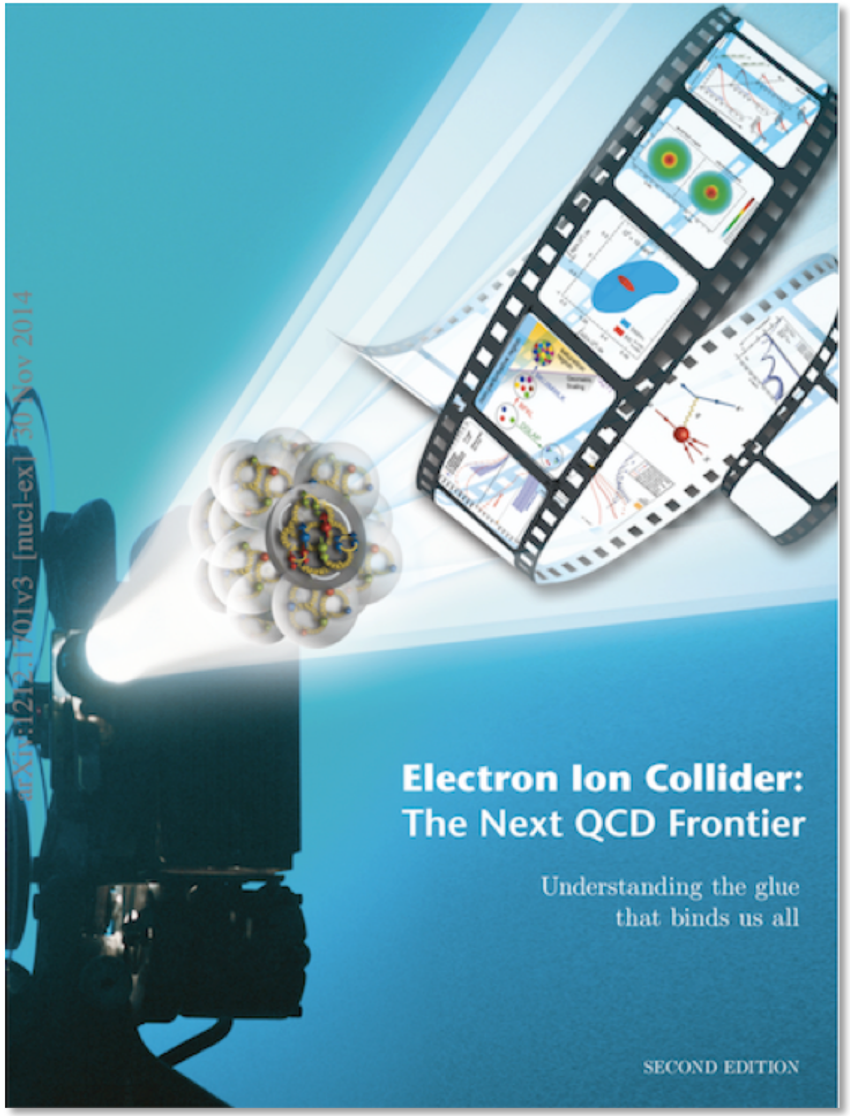
An electron–ion collider would answer core questions about strongly interacting matter:

- How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon? How do the nucleon properties emerge from quark and gluon interactions?
- How do colour-charged quarks and gluons, and colourless jets, interact with a nuclear medium? How do confined hadronic states emerge from quarks and gluons? How do quark–gluon interactions create nuclear binding?
- How does a dense nuclear environment affect quarks and gluons, their correlations, and their interactions? What happens to the gluon density in nuclei: does it saturate at high energy, giving rise to gluonic matter with universal properties in all nuclei, even the proton?

TMDs of free nucleons

TMDs of bound nucleons

TMD program in EIC White Paper



Ultimate measurement of TMDs for quarks

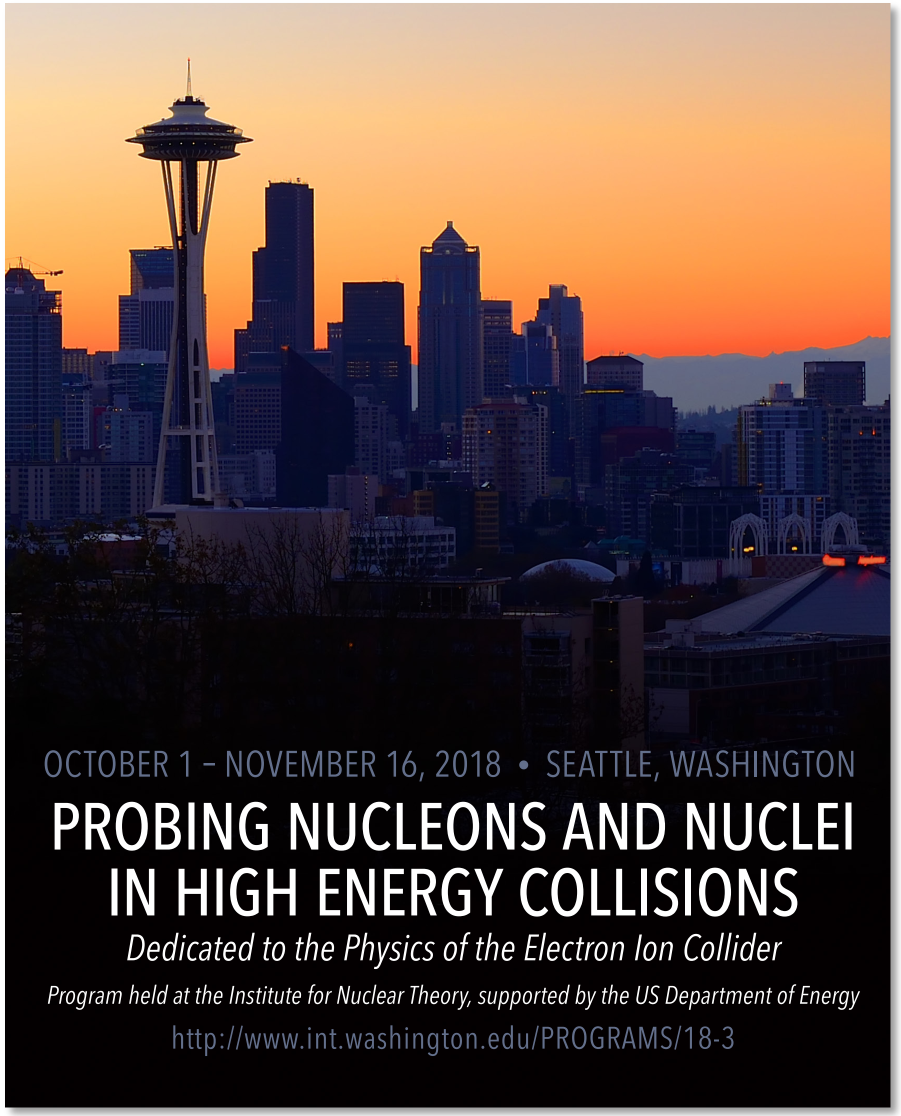
- **high luminosity**
  - high-precision measurement
  - multi-dimensional analysis (x, Q^2, ϕ_S, z, P_t, ϕ_h)
- **broad *x* coverage** $0.01 < x < 0.9$
- **broad Q^2 range** disentangling non-perturbative / perturbative regimes

First (?) measurement of TMDs for sea quarks

First (?) measurement of TMDs for gluons

Systematic factorization studies

INT-18-3: Further developing the TMD program at the EIC



Week 2: Workshop on Transverse spin and TMDs
Conveners Harut Avakian, Alessandro Bacchetta, Daniel Boer, Zhongbo Kang

The focus will be shifted to the physics of TMDs such as TMD factorization and evolution, phenomenological implementations, relation to jet physics, and lattice results.

Weeks 5 & 6: *eA* collisions
Conveners Giovanni Chirilli, Charles Hyde, Anna Stasto, Thomas Ullrich, Bowen Xiao

These two weeks will focus on the physics of electron-ion collisions. Topics such as nuclear PDF/TMD/GPD, (…)

Requirements for TMD measurements

- **Theory** General considerations
- **Accelerator** Building the right probe
- **Detector** Total acceptance detector and particle identification
- **Computing** Towards the next generation research model in nuclear physics, simulations

Goal

- 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.

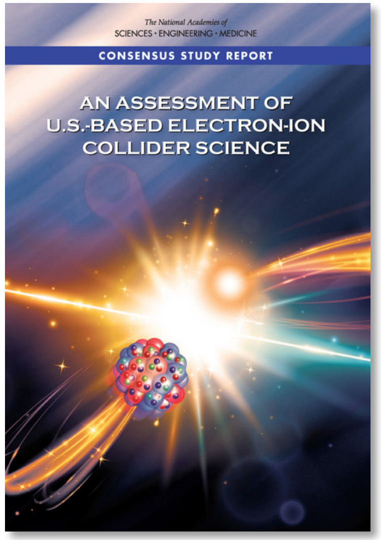
Theory

Developing our science further

Theory requirements

- TMD collaboration covering all topics:
    - TMD factorization
    - TMD evolution
    - TMD global analysis
    - Lattice QCD and TMDs
    - etc.

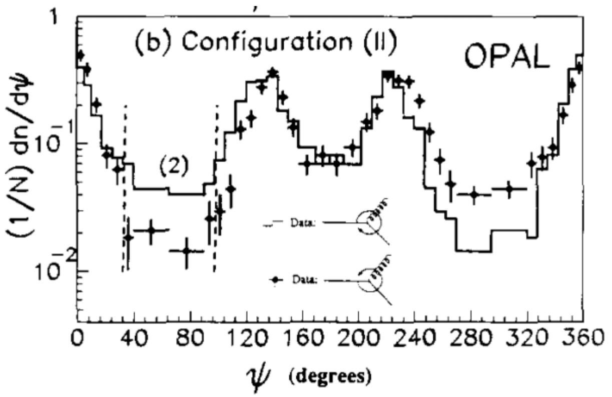
- **Food for thought**: Two related questions:
    - Can we explain to the Scientific American reader why TMDs are a key part of the EIC science program?
    - If we have precise measurements of TMD PDFs what do we learn about big questions, e.g., chiral symmetry breaking, confinement, spin of the nucleon etc.?



Understanding the hadronization process

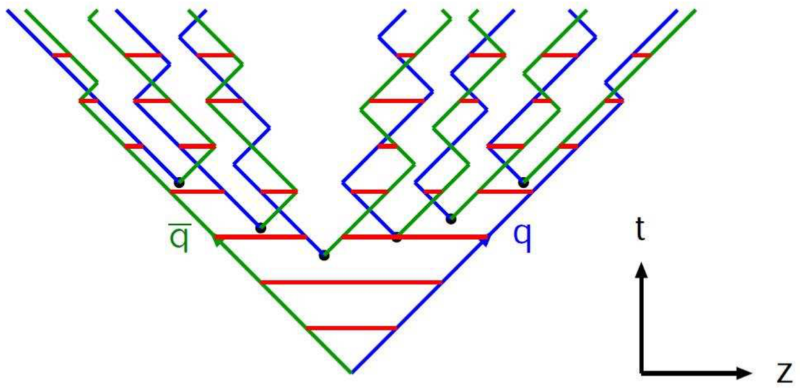
LUND String Model for hadronization (1977 – *now*)

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

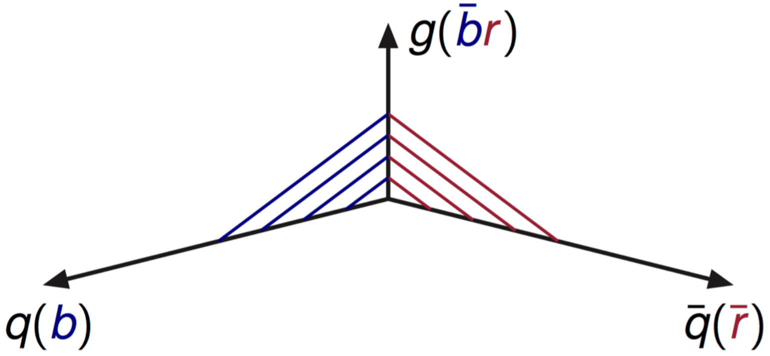


evidence of string effects
particle flow asymmetry at OPAL

String breakup



String drawing



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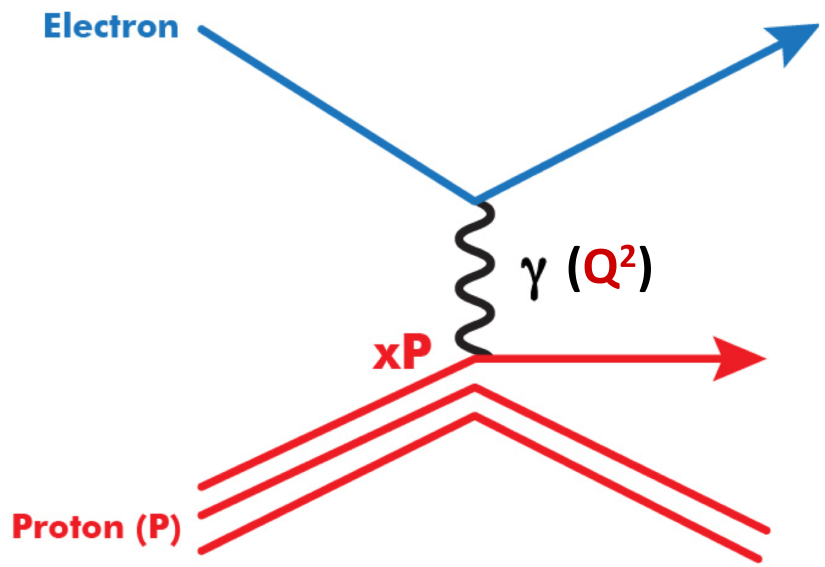
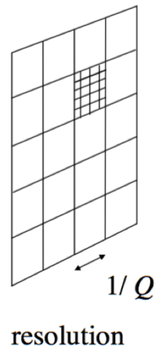
Accelerator design

Designing the right probe

Electron-Proton Scattering

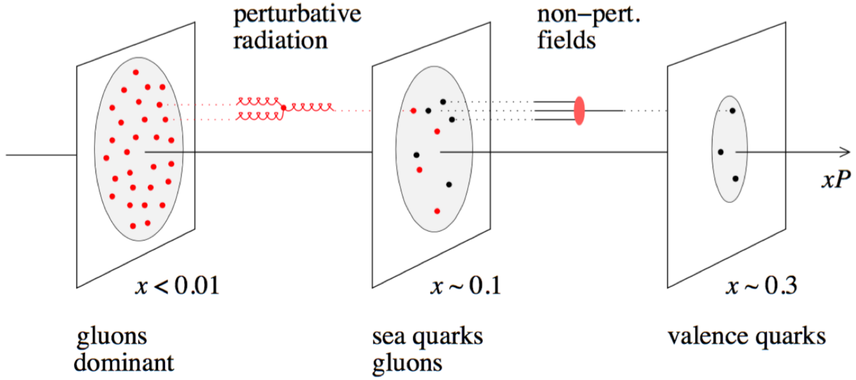


Ability to change Q^2 changes the resolution scale



Q^2 = 400 GeV^2
=> 1/Q = 0.01 fm

Ability to change x projects out different configurations where different dynamics dominate



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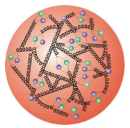
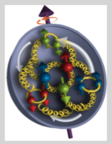
Where EIC Needs to be in x (nucleon)

← Saturation Regime: Needs to be Accessed via Ions

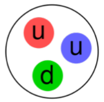
Collective Regime



Many-body Regime



Few-body Regime



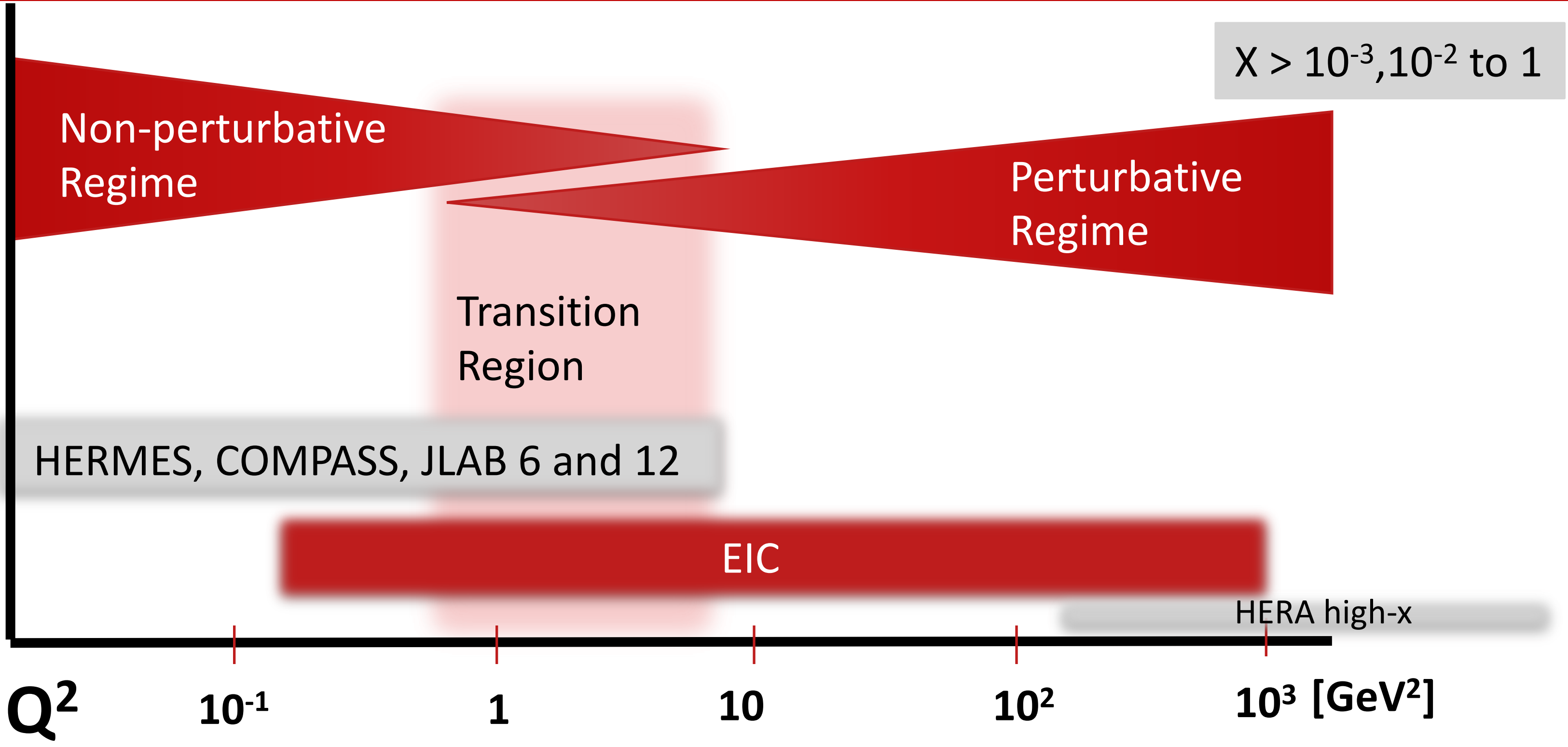
10^{-4} — 10^{-3} — 10^{-2} — 10^{-1} — 1 X (for proton)

QCD Radiation Dominated (Studied at HERA)

Hadron Structure Dominated

Main interest for EIC Nucleon/Nuclear Program

Where EIC needs to be in Q^2



- Include non-perturbative, perturbative and transition regimes
- Provide long evolution length and up to Q^2 of ~1000 GeV^2 (~.005 fm)
- Overlap with existing measurements

Disentangle Pert./Non-pert., Leading Twist/Higher Twist

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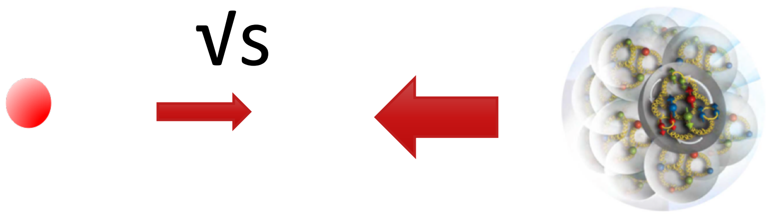
Designing The Right Probe: √s

What are the right parameters for the collider for the EIC science program?

We know the x range: down to ~ 10^{-3-4}
We know the Q^2 range: up to ~1000 GeV^2

$Q^2=sxy$, $s=4E_eE_{hadron}$
→ energies we need.

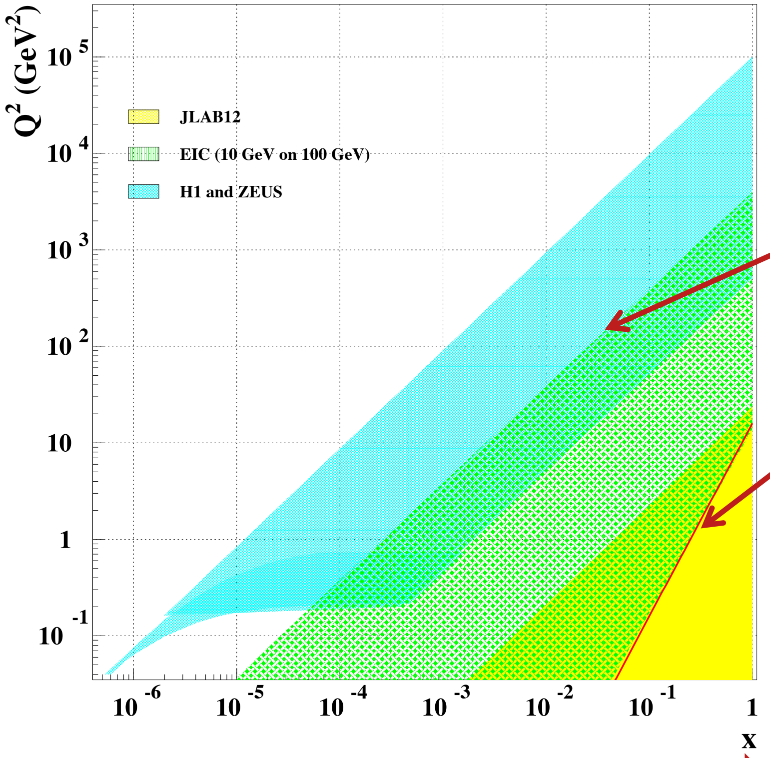
√s



order 10 GeV electron

order 100 GeV/u ion

JLEIC parameters (nucleon)



Cross section decreases rapidly with higher X

This edge determined by √s:
√s = 65 GeV

This edge determined by proton beam energy:
E_{proton} < 100 GeV -> $E_{electron}$ = 10 GeV^2

Measure at x of 10^{-3} to 1, exclusive processes
Luminosity: x 10 to 100 that of HERA

Sets some of the basic parameters of the JLEIC design

JLEIC design strategy: High luminosity and polarization

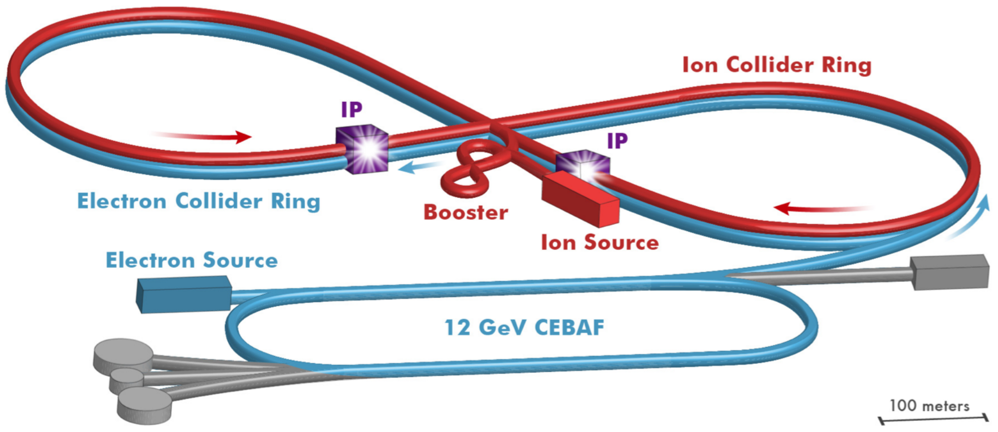
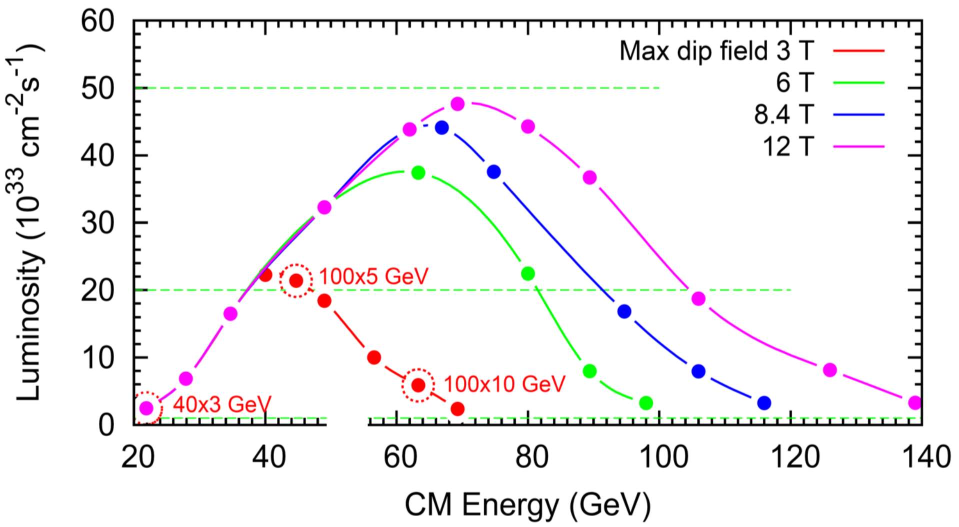


Figure-8 shaped ring-ring collider

- zero **spin tune** (net spin precession)
- energy-independent **spin tune**

- **polarization** easily preserved and manipulated:
  - by small solenoids
  - by other compact spin rotators

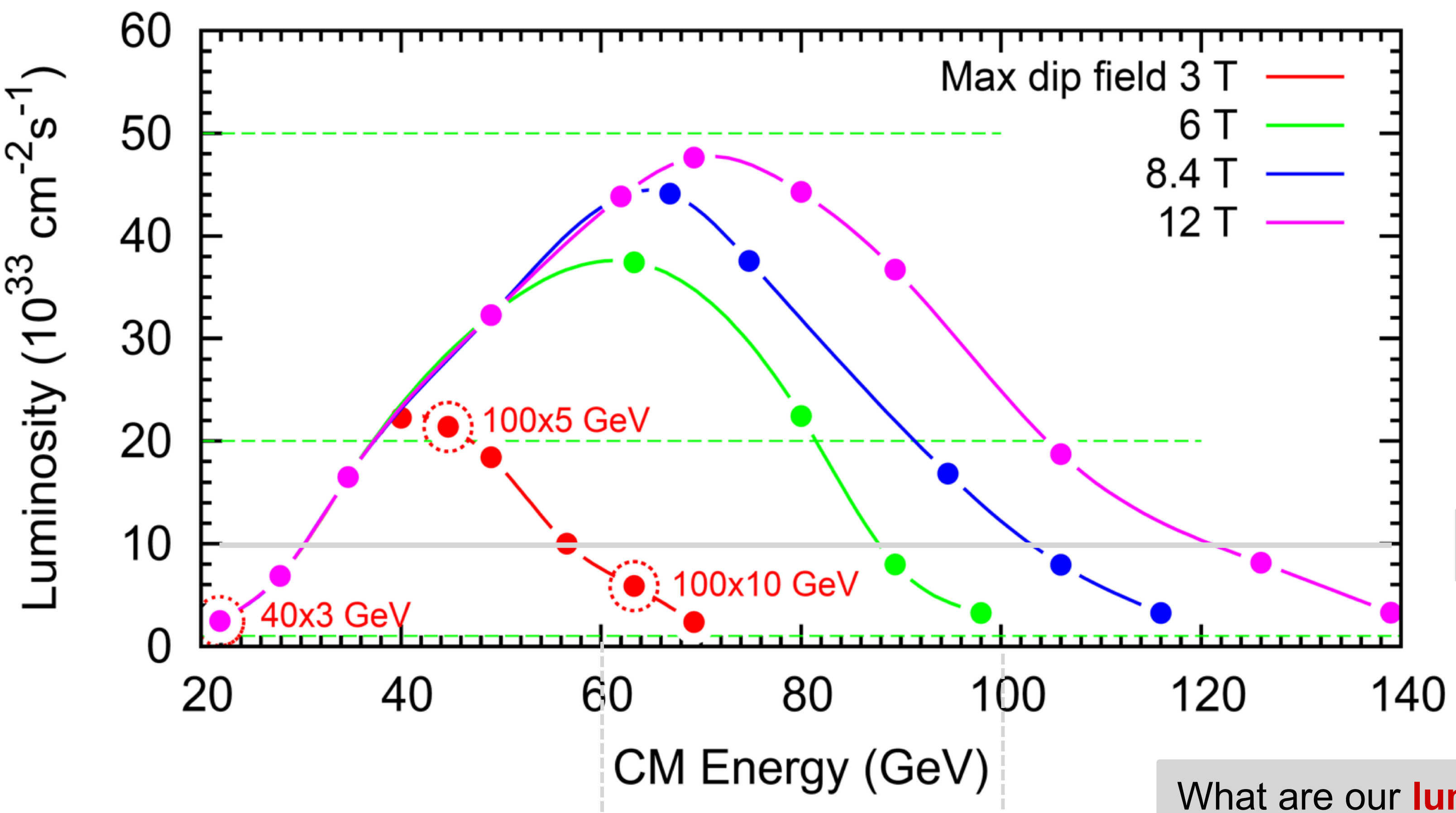


High luminosity

- high-rate collision of short bunches
  - with small emittance
  - with low charge
- **ion beam:** high-energy electron cooling (R&D)
- **electron beam:** synchrotron radiation damping

Technology choice determines initial and upgraded energy reach.

Luminosity Needs (White Paper)



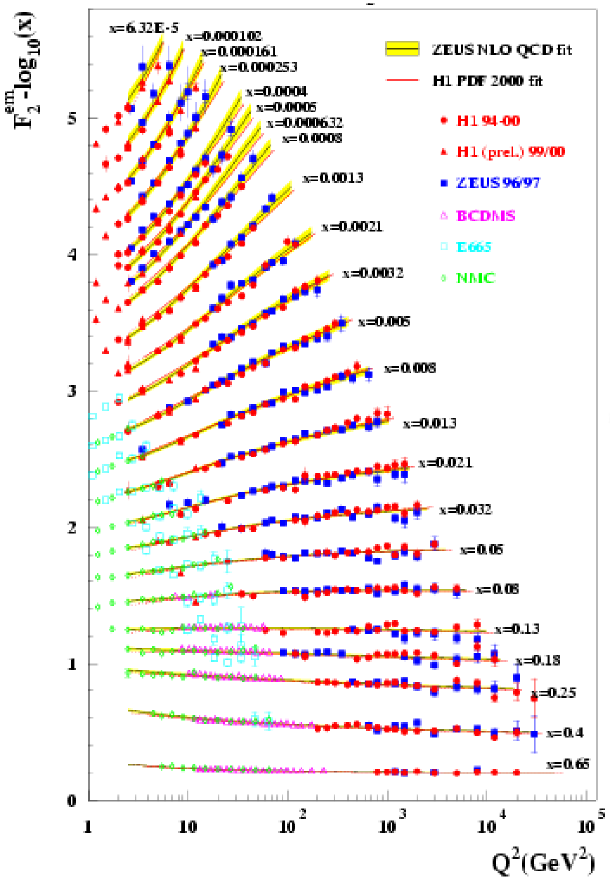
10^{34}

Quark TMD (LL+LT)	10+10	10+10	10+10	fb^{-1}
Gluon TMD (LL+LT)			100+100	fb^{-1}

What are our **luminosity requirements for the updated TMD program**? What results would we like to obtain from the first few years of EIC running?

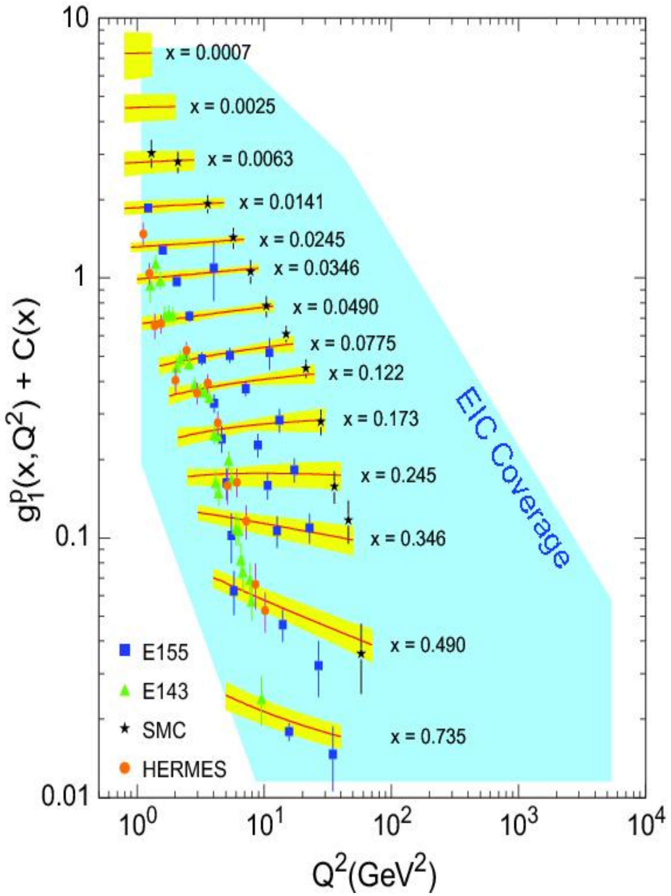
Luminosity requirements

World Data on F_2^p



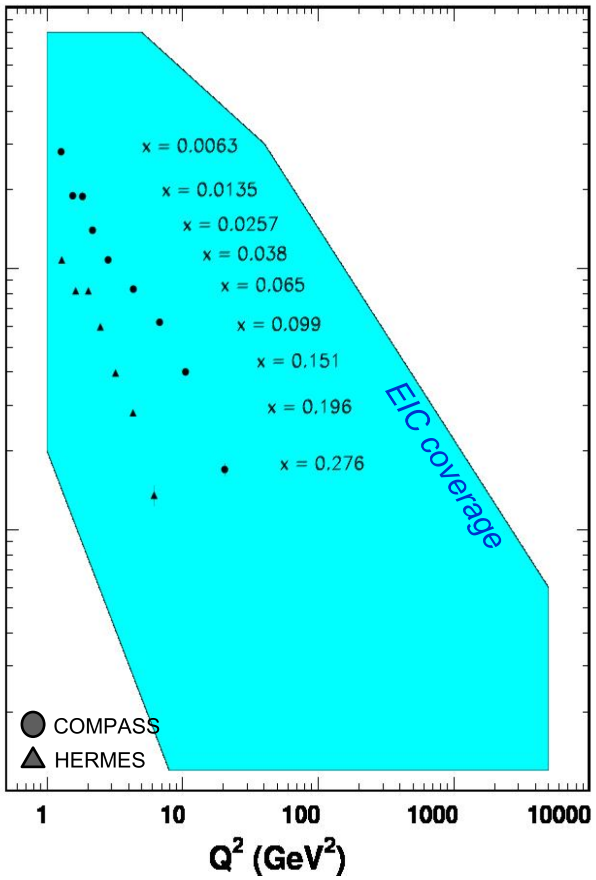
momentum

World Data on g_1^p



spin

World Data on h_1^p



transverse spin

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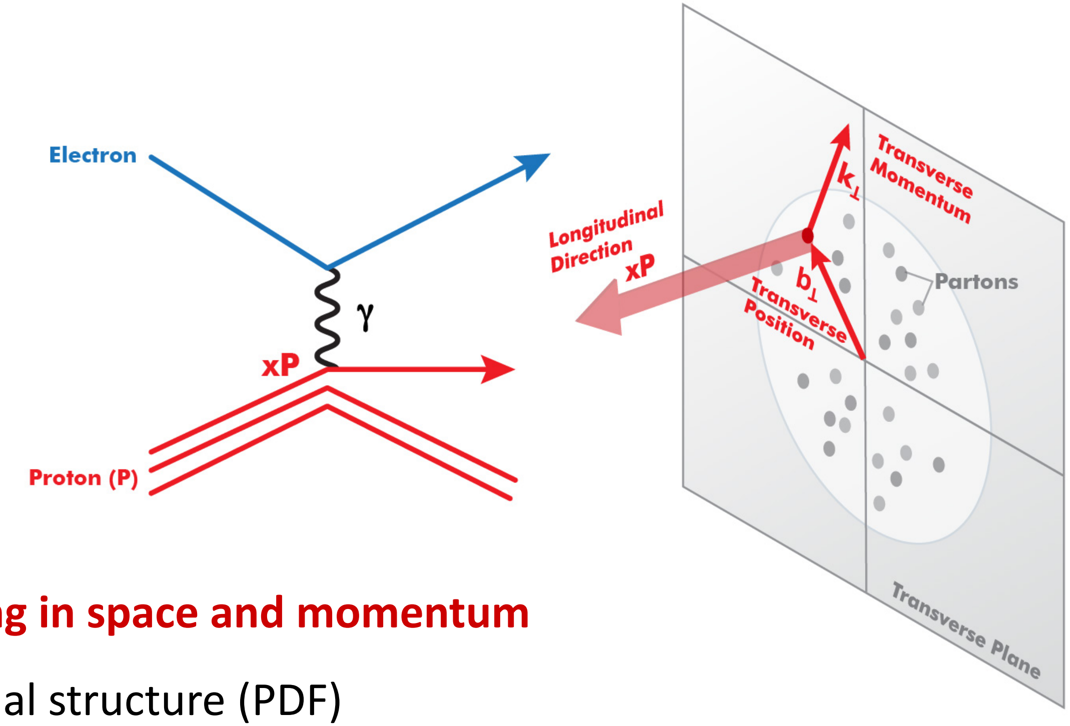
Detector design

General design considerations

Mapping position and motion of quarks and gluons

Study nuclear matter **beyond longitudinal description** makes the **requirements for IR and detector design different** from all previous colliders including HERA.



3D imaging in space and momentum

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

order of a few hundred MeV **measurement**

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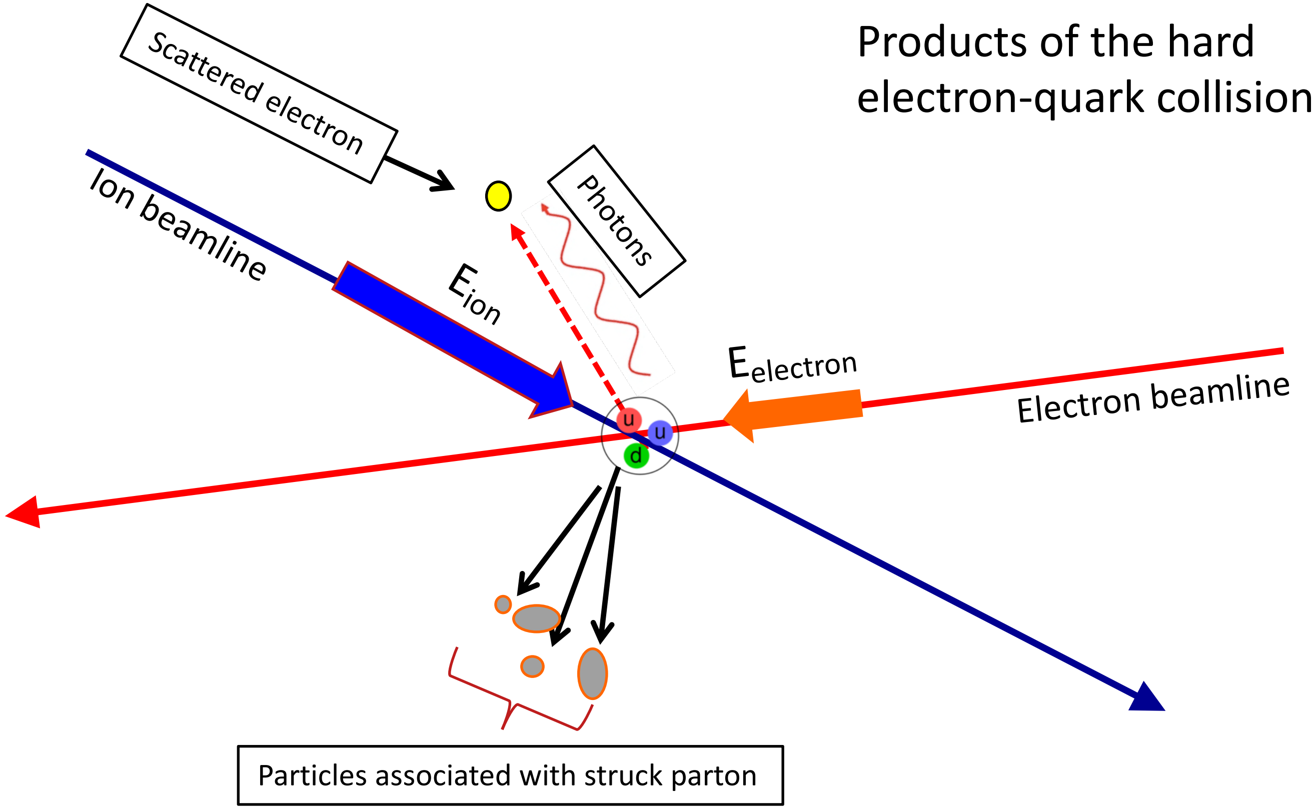
Particle Identification

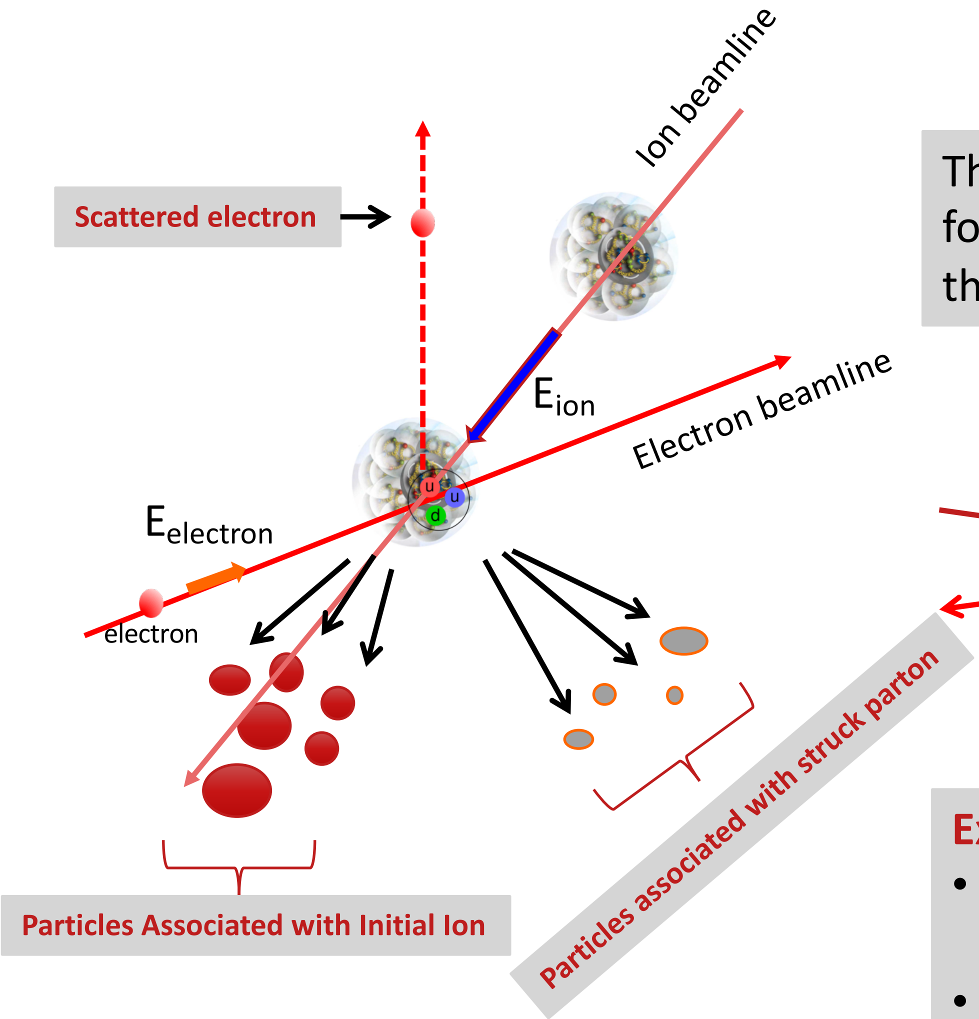


Products of the hard electron-quark collision

Transverse and flavor structure measurement of the nucleon and nuclei: The particles associated with struck parton must have its species identified and measured. **Particle ID much more important than at HERA** colliders.

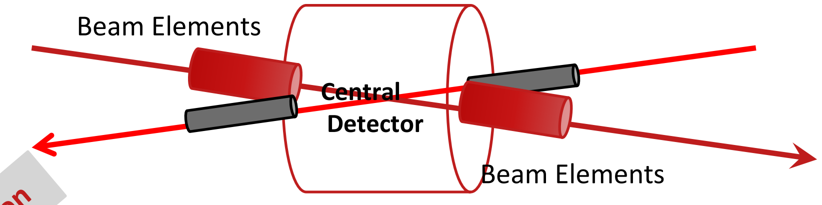
Gluon TMDs Vertex reconstruction much more important than HERA fixed target.

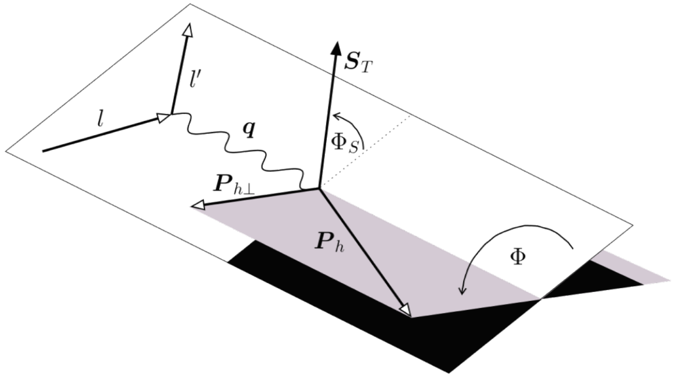
Final-state particles



The aim is to get **~100% acceptance** for all final state particles, and measure them with good resolution.

For TMD measurements ~4π coverage w.r.t. virtual-photon direction





Experimental challenges:

- beam elements limit forward acceptance
- central Solenoid not effective for forward

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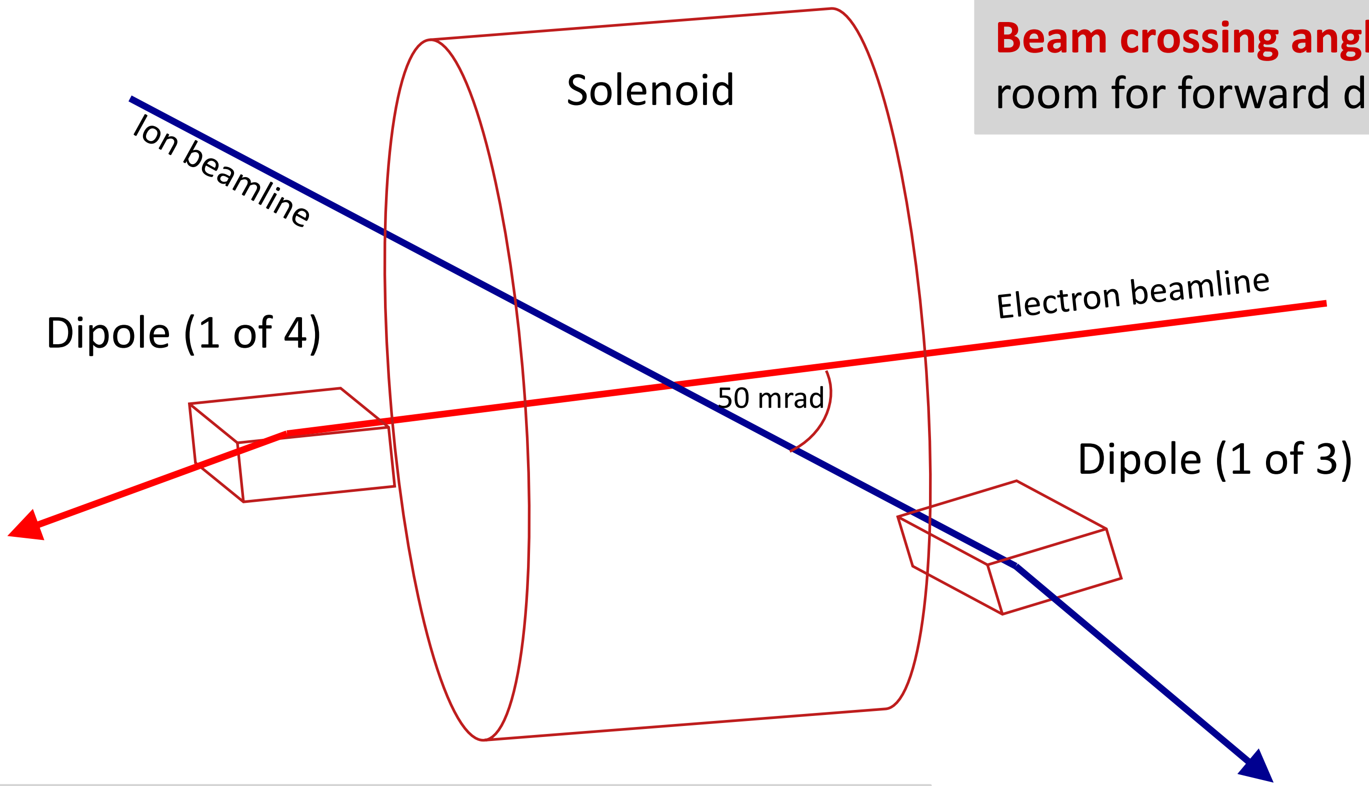
Interaction region concept

NOT TO SCALE!

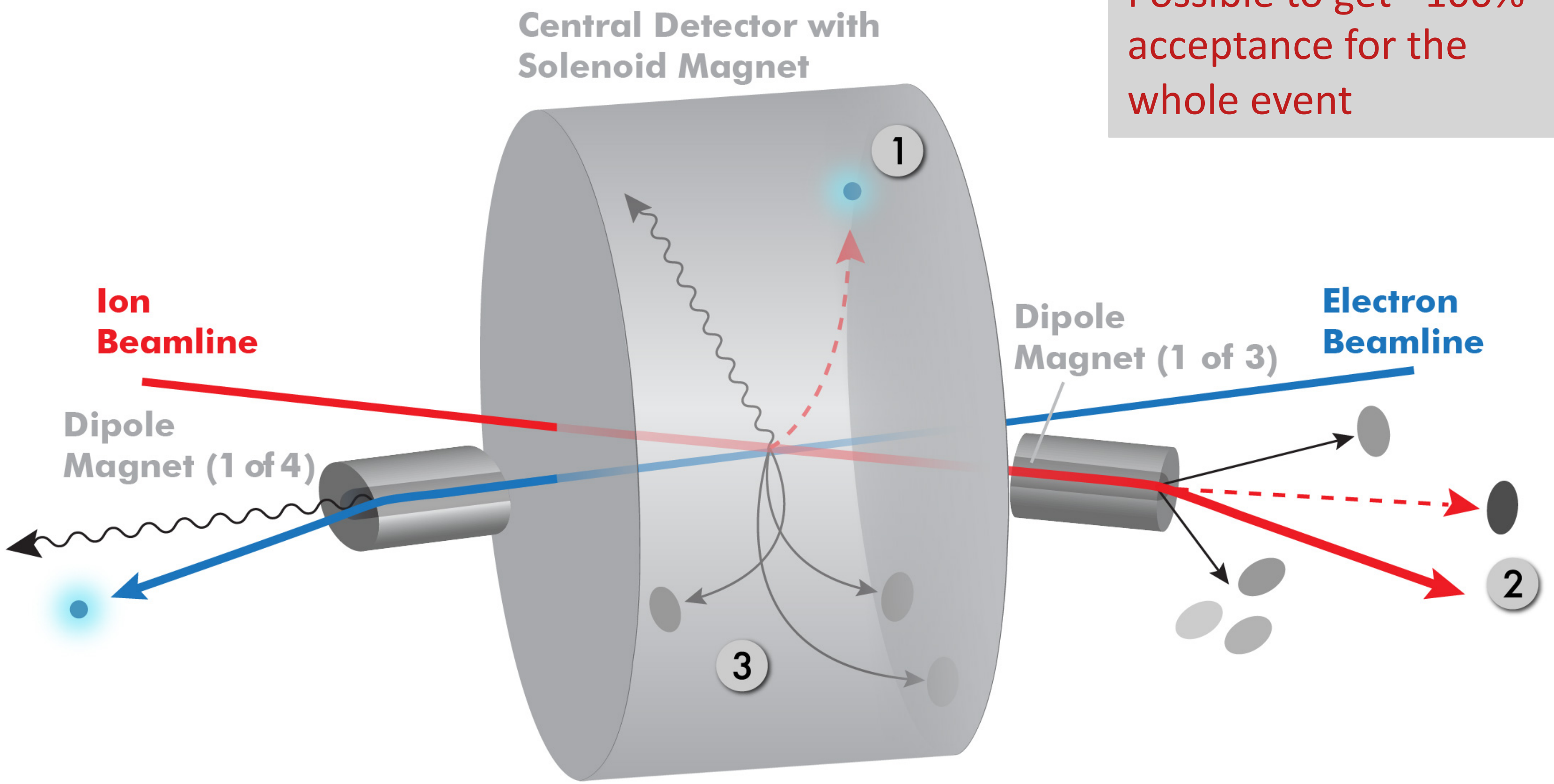
Beam crossing angle creates room for forward dipoles



Dipoles analyze the forward particles
and create space for detectors in the forward direction

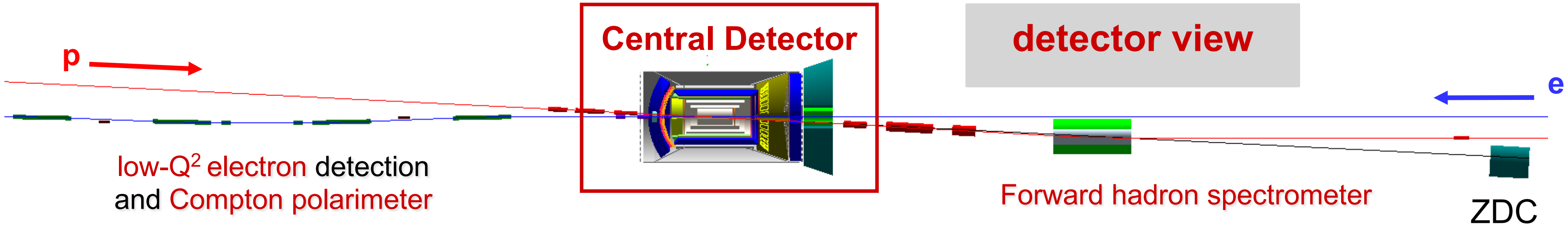
Interaction region concept

Possible to get ~100% acceptance for the whole event



Total acceptance detector (and IR)

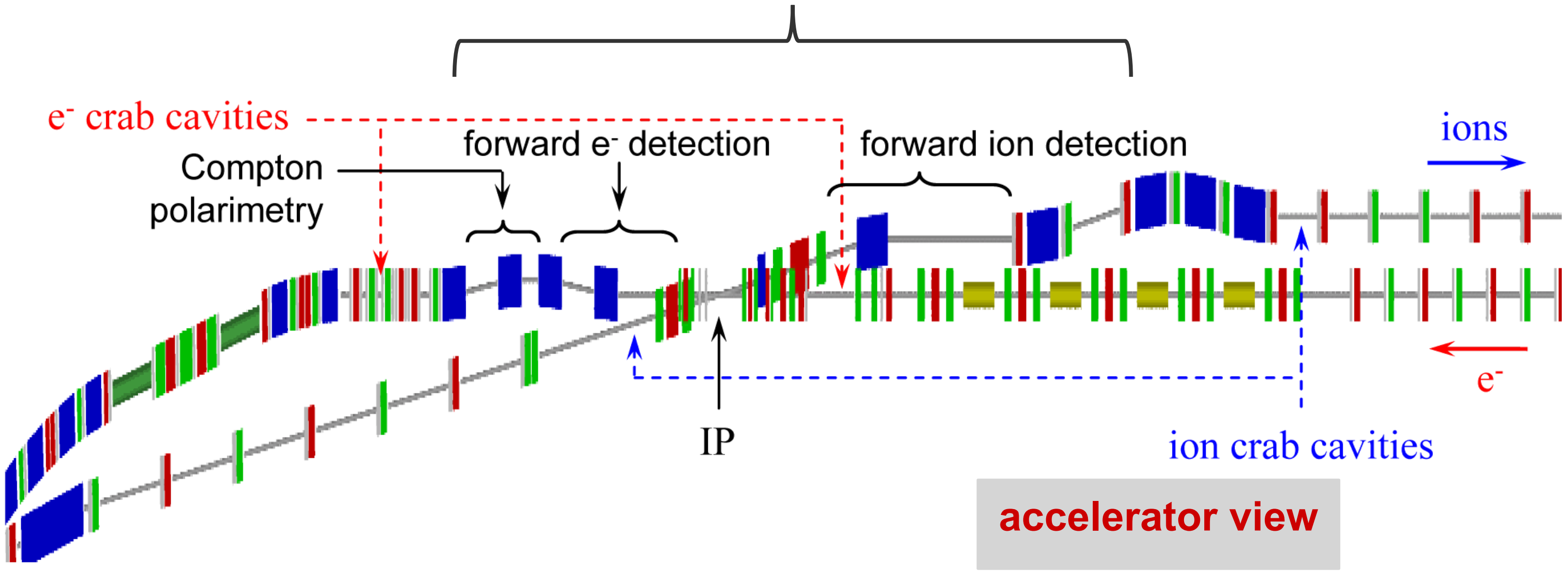
Detector and interaction region



Extended detector: 80m

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

fully integrated with accelerator lattice



Computing

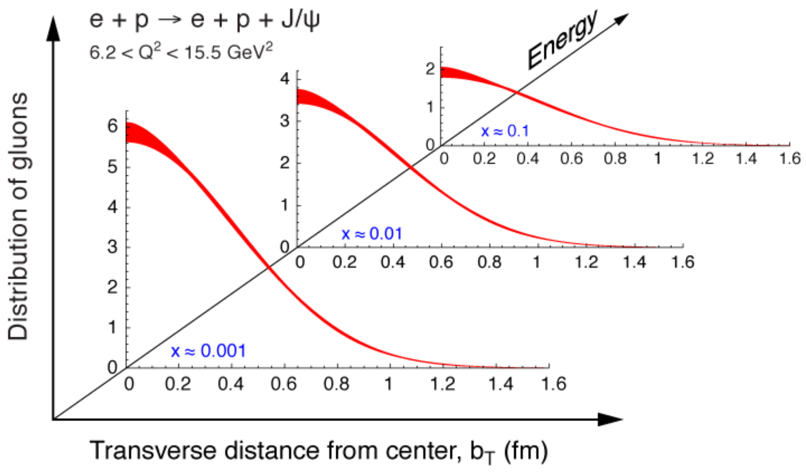
Towards the next generation research model in NP Simulations

Computing Challenges in Nuclear Physics (NP)

NP experiments driven by beam intensity, polarization, exquisite control of background and systematics

multi-dimensional challenges

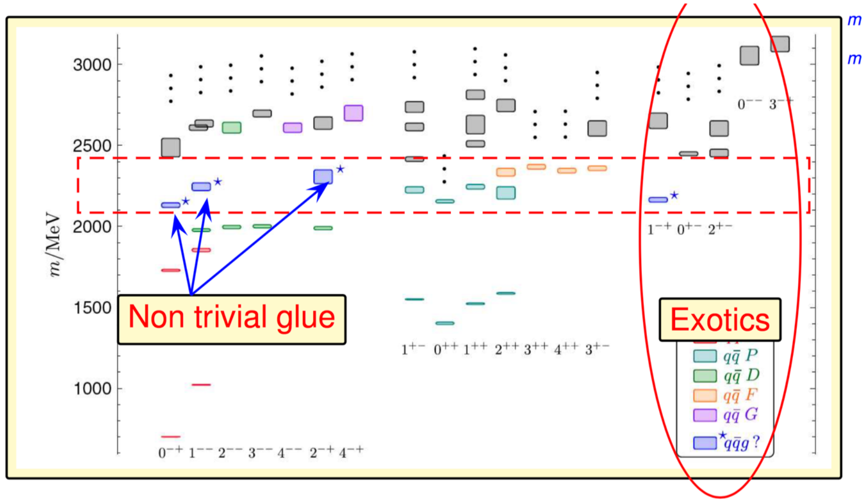
example 3D imaging of quarks and gluons



high statistics in five or more dimensions and multiple particles

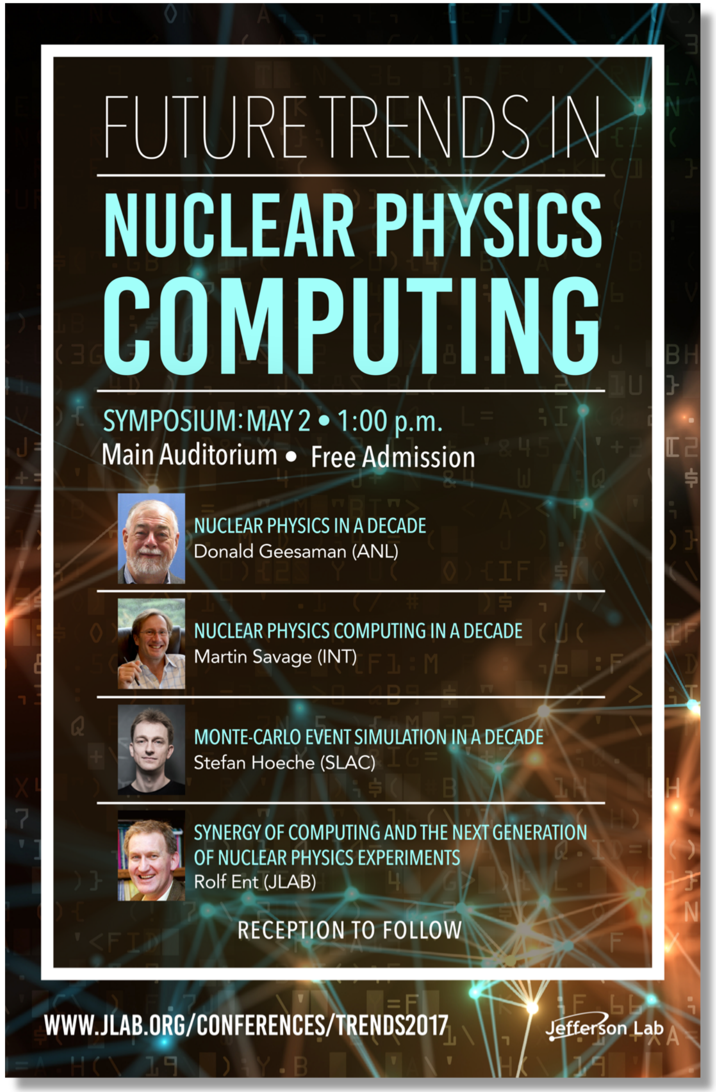
multiple channel challenges

example discovery search of gluon-based exotic particles (PWA, 1000s of waves)



strongly iterative analysis for reliable, model-independent analysis

Future Trends in Nuclear Physics Computing



Donald Geesaman (ANL, former NSAC Chair) "*It will be **joint progress of theory and experiment** that moves us forward, not in one side alone"*

Martin Savage (INT) *"The next decade will be looked back upon as a **truly astonishing period in NP** and in our understanding of fundamental aspects of nature. This will be **made possible by advances in scientific computing** and in how the NP community organizes and collaborates, and how DOE and NSF supports this, to take full advantage of these advances."*

Towards the next generation research model in NP

NP research model not changed for over 30 years
Science & Industry remarkable advances in computing & microelectronics

goal evolve & develop **NP research model** based on these advances

rethink **how measurements are compared to theory**

- examine capabilities of event level analysis taking the multi-dimensional challenges of NP fully into account

What are our requirements? What do theoreticians wish from experiments? What do experimentalists wish from theoreticians? What technical and sociological challenges do we face?

Selected analysis requirements

High-precision analysis tools:
- high-precision MCEG
- radiative correction library
- multi-dimensional analysis

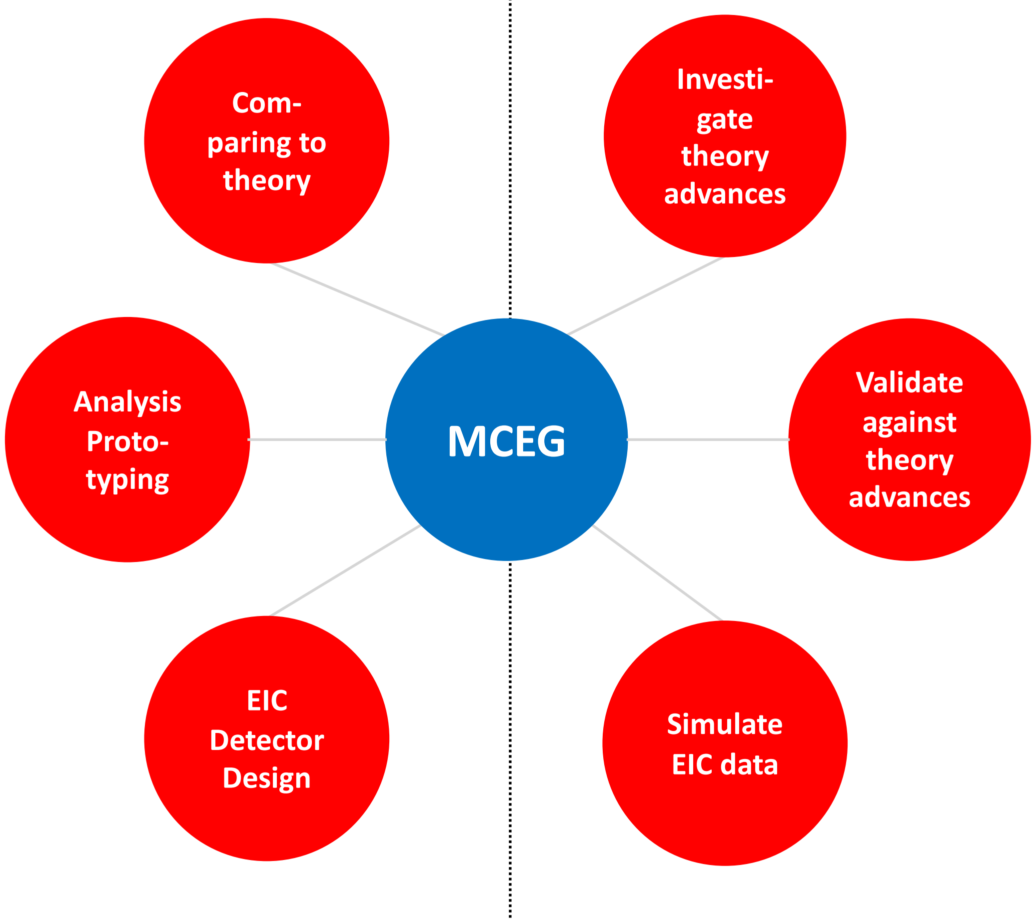
Long-lived data repositories

- COMPASS, HERMES, JLab, RHIC
- document analysis publicly for analysis and theory development (RIVET)
- combined *global* analysis (e.g., HERA fit), possibly on event level

MCEG in Experiment and Theory

Experiment

Theory



TMD MCEG

gmc_trans
- single-hadron inclusive DIS

TMDGen
- two-hadron inclusive DIS

CASCADE
- CCFM evolution,parton branching unintegrated PDFs

Pythia
- General purpose MCEG

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

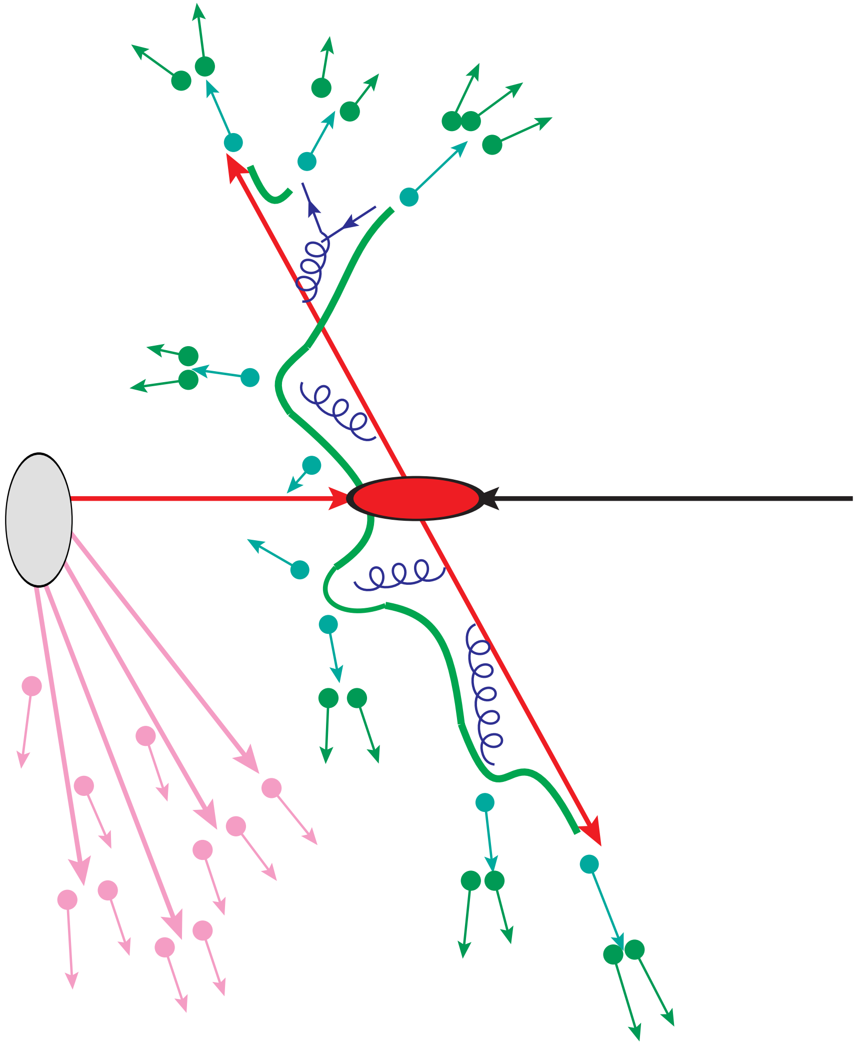
Monte Carlo Event Generator

MCEG

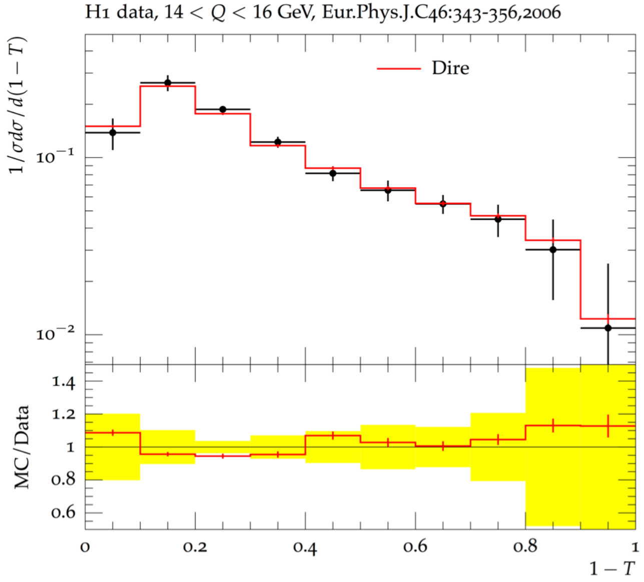
- faithful representation of QCD dynamics
- based on QCD factorization and evolution equations

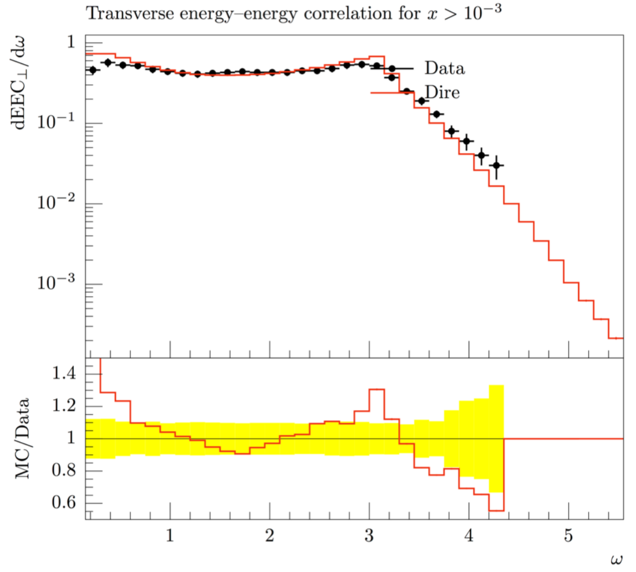
Algorithm of general-purpose MCEG

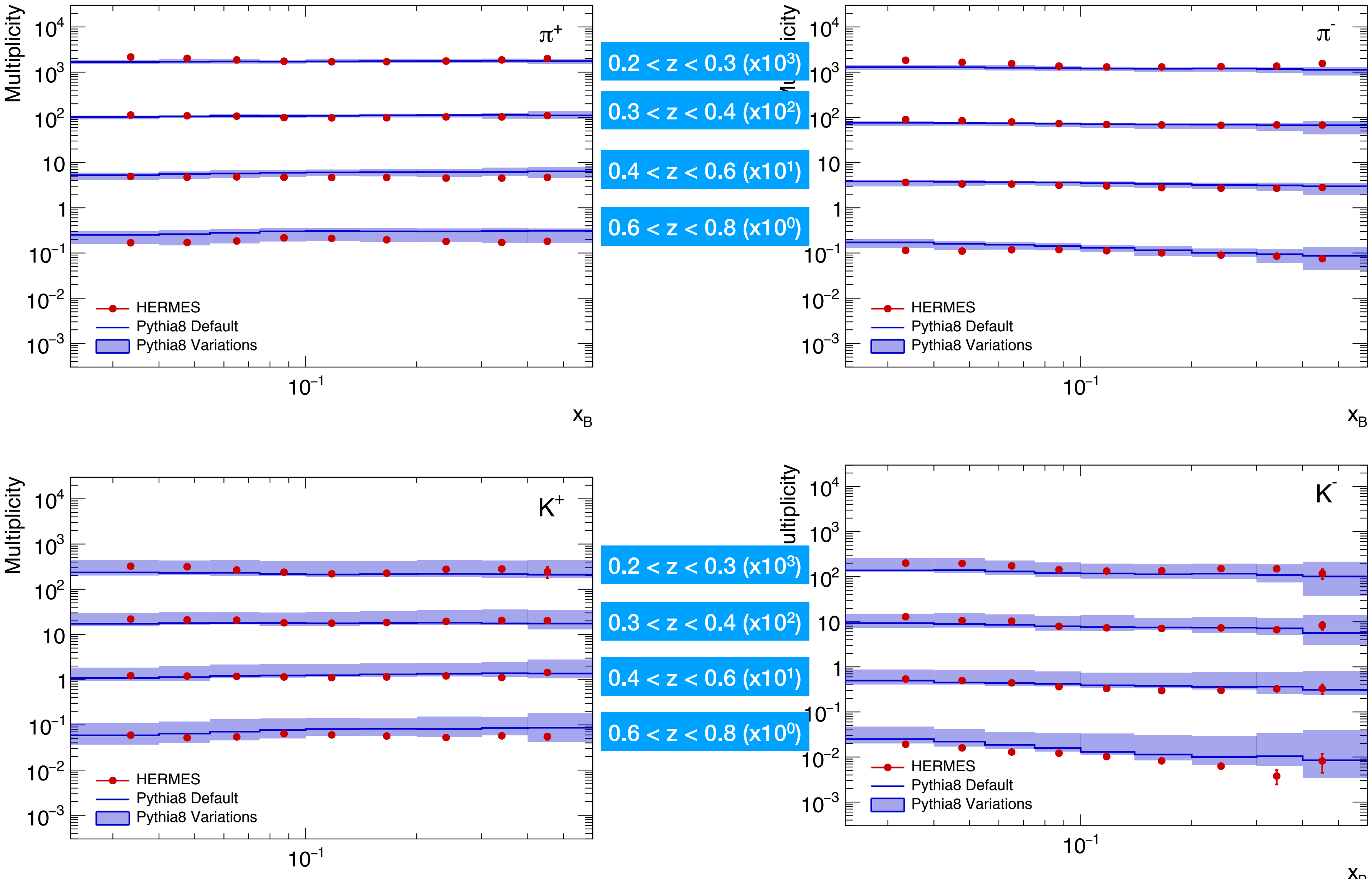
1. Generate kinematics according to fixed-order matrix elements and a PDF.
2. QCD Evolution via parton shower model (resummation of soft gluons and parton-parton scatterings).
3. Hadronize all outgoing partons including the remnants according to a model.
4. Decay unstable hadrons.



Pythia8: Simulating DIS results







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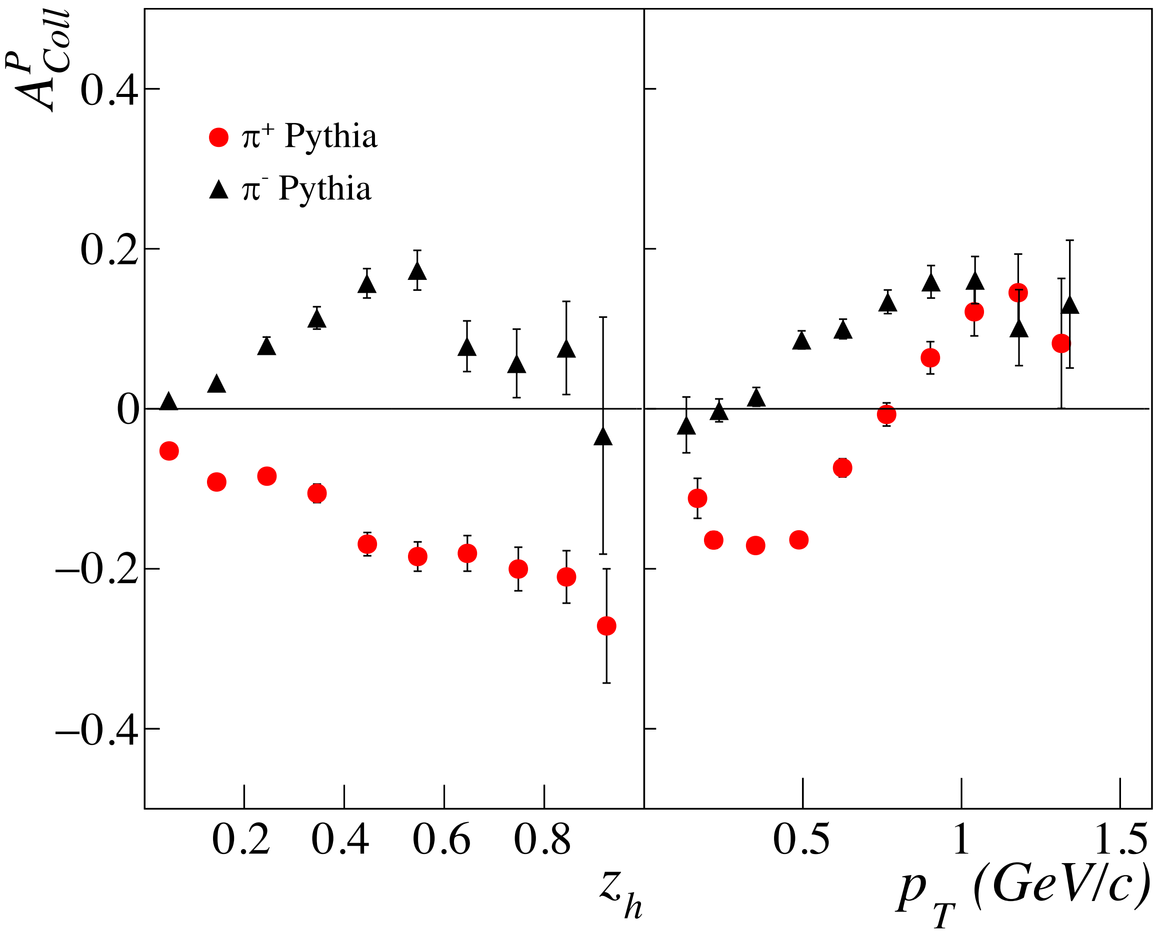
Pythia8 with SPIN

Albi Kerbizi, Leif Lönnblad



Project Jefferson Lab community, LUND, INFN Trieste

First attempt

COMPASS kinematics

u quarks polarized along **y**

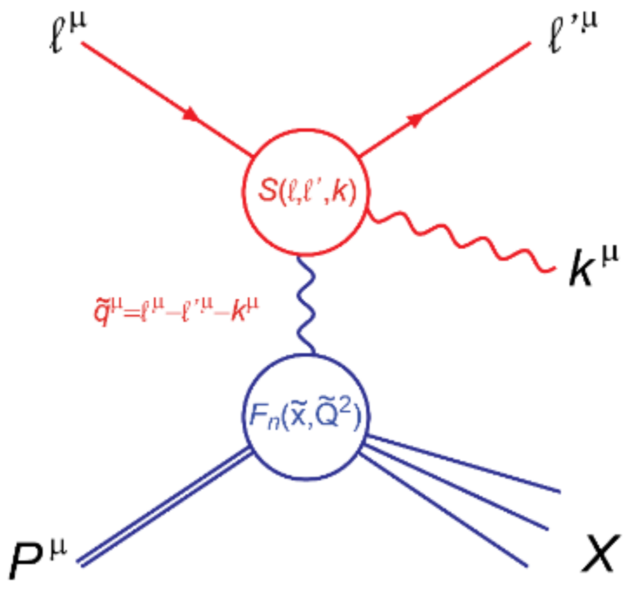
d quarks polarized along **–y**

all other quarks unpolarized

no transversity PDF

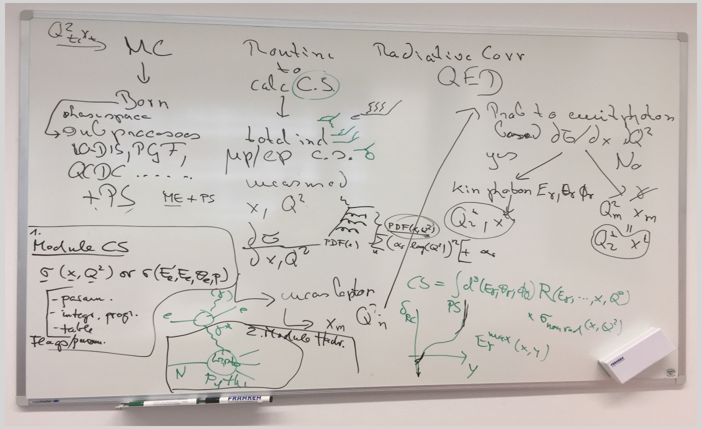
Radiative effects

- change kinematics on an event by event basis:
  - smearing of kinematic distributions
- change of virtual-photon direction:
  - false asymmetries in the azimuthal distribution of hadrons
- correction:
  - unfolding procedure, requires MCEG including radiative corrections / effects



ESC: Radiative effects library

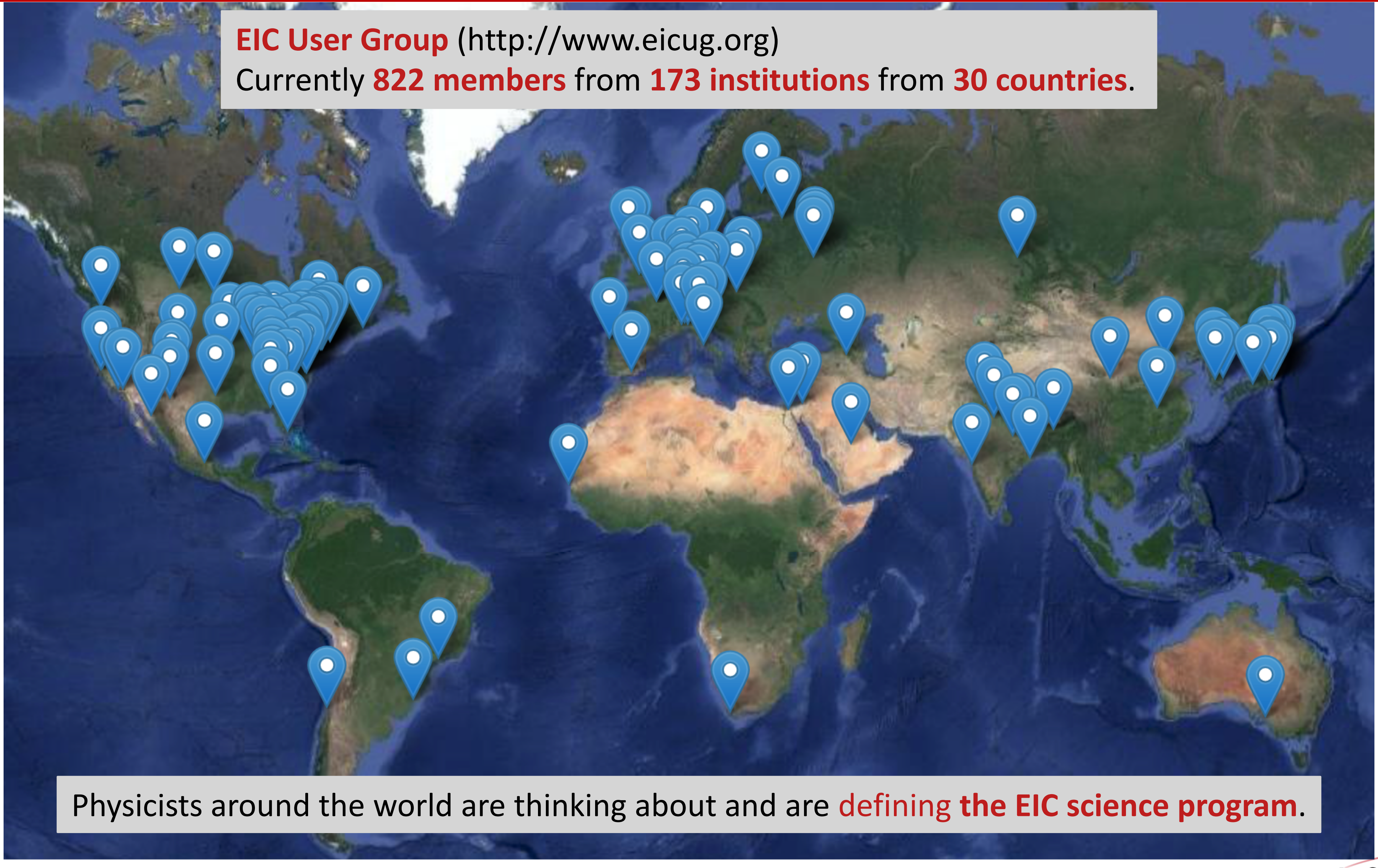
- Elke-Caroline Aschenauer, Andrea Bressan
- essential for high-precision measurements at the EIC
- collaboration with Hubert Spiesberger:
  - start back from HERACLES part of Djangoh
  - work on interface to PYTHIA6/8



Organization

EIC User Group

EIC User Group



EICUG Software Working Group

Charge

The EICUG Software working group's initial focus will be on **simulations of physics processes and detector response** to enable quantitative assessment of measurement capabilities and their physics impact. This will be pursued in a manner that is **accessible, consistent, and reproducible to the EICUG as a whole**. It will embody simulations of all processes that make up the EIC science case as articulated in the White-paper. The Software working group is to engage with new major initiatives that aim to further develop the EIC science case, including for example the upcoming INT program(s), and is anticipated to play key roles also in the preparations for the EIC project(s) and its critical decisions. The working group will build on the considerable progress made within the EIC Software Consortium (ESC) and other efforts. The evaluation or development of experiment-specific technologies, e.g. mass storage, clusters or other, are outside the initial scope of this working group until the actual experiment collaborations are formed. The working group will be open to all members of the EICUG to work on EICUG related software tasks. It will communicate via a new mailing list, eswg@eicug.org, and organize regular online and in-person meetings that enable broad and active participation from within the EICUG as a whole.

Conveners

David Blyth (ANL), Markus Diefenthaler (JLAB)

Engage with theory community and learn about theory tools and requirements.

Markus Diefenthaler
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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?

- **Requirements** theory, accelerator, detector, computing