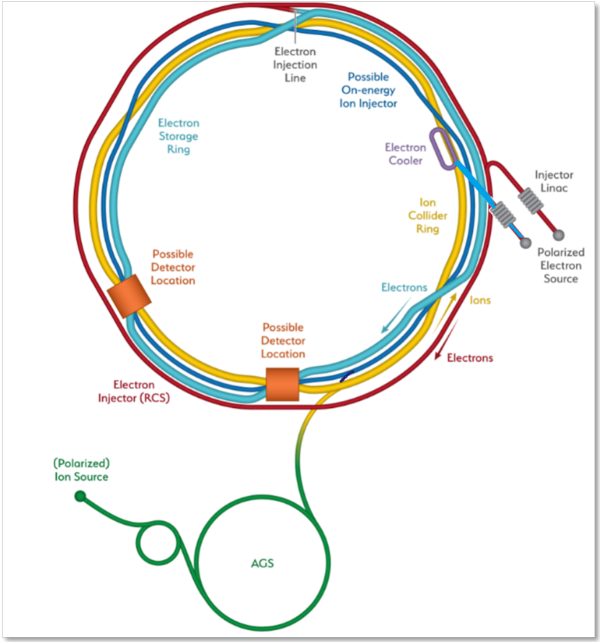
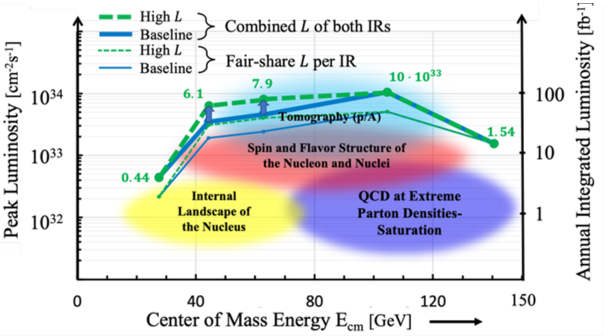
# The EIC mission – Challenges for theory and experiment

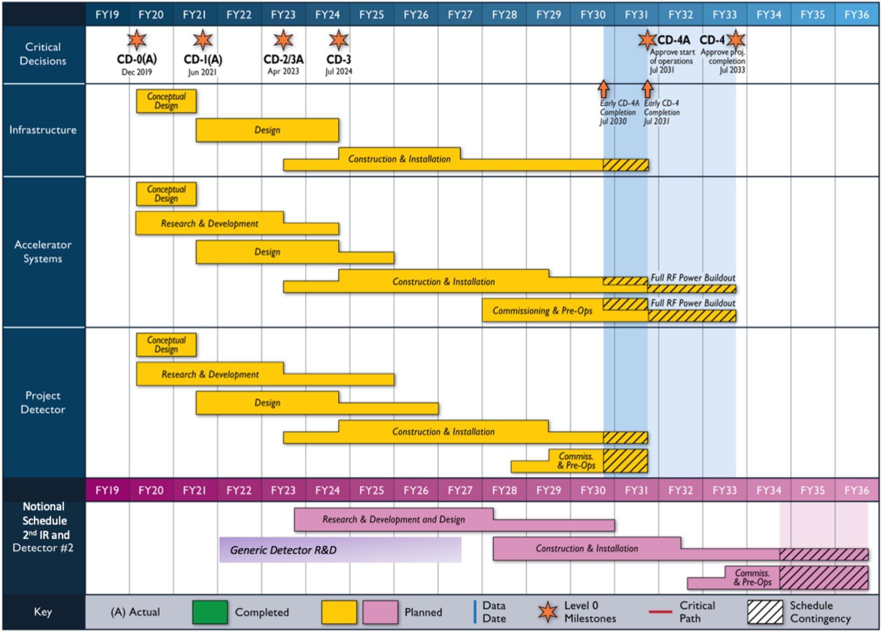
Andreas Schäfer (many thanks to E. Aschenauer, F. Maas, ...)

- The EIC project is advancing fast, driven by broad international support, including massive commitments
- Why? – The physics case of the EIC
- A few opportunities for Germany:
  - Technological competence: PANDA DIRC technology, ALICE Si detector technology, streaming DAQ, ...
  - Theory: Lattice QCD for joint fits, ...


Electron
Injection
Line
Possible
On-energy
Ion Injector
Electron
Storage
Ring
Electron
Cooler
Injector
Linac
Ion
Collider
Ring
Polarized
Electron
Source
Possible
Detector
Location
Electrons
Ions
Possible
Detector
Location
Electrons
Electron
Injector (RCS)
(Polarized)
Ion Source
AGS

| Double Ring Design Based on Existing RHIC Facilities | |
|---|---|
| **Hadron Storage Ring: 40 - 275 GeV** | **Electron Storage Ring: 5 - 18 GeV** |
| RHIC Ring and Injector Complex: p to Pb | Many Bunches, Large Beam Current - 2.5 A |
| 1160 bunces @ 1A Beam Current<br>9 ns bunch spacing | 9 MW Synchrotron Radiation |
| Light ion beams (p, d, $^3$He) polarized (L,T) | Polarized electron beams |
| Nuclear beams: d to U | **Electron Rapid Cycling Synchrotron** |
| Requires Strong Cooling: new concept → CEC | Spin Transparent Due to High Periodicity |
| **High Luminosity Interaction Region(s)** | |
| 25 mrad Crossing Angle with Crab Cavities | |

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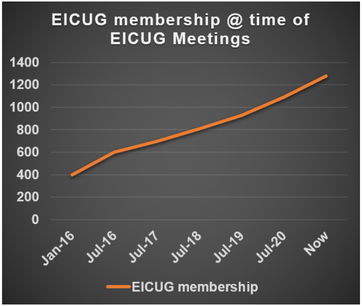
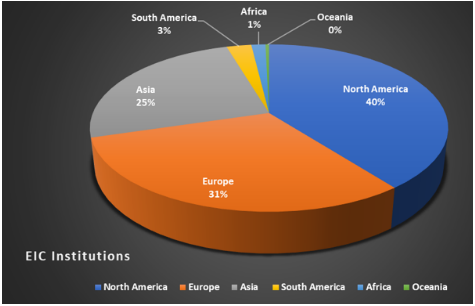
Critical Decisions
CD-0(A) Dec 2019
CD-1(A) Jun 2021
CD-2/3A Apr 2023
CD-3 Jul 2024
CD-4A Approve start of operations Jul 2031
CD-4 Approve proj. completion Jul 2033
Infrastructure
Early CD-4A Completion Jul 2030
Early CD-4 Completion Jul 2031
Conceptual Design
Design
Construction & Installation
Accelerator Systems
Conceptual Design
Research & Development
Design
Construction & Installation
Full RF Power Buildout
Commissioning & Pre-Ops
Full RF Power Buildout
Project Detector
Conceptual Design
Research & Development
Design
Construction & Installation
Commiss. & Pre-Ops
Notional Schedule 2nd IR and Detector #2
Research & Development and Design
Generic Detector R&D
Construction & Installation
Commiss. & Pre-Ops
Key
(A) Actual
Completed
Planned
Data Date
Level 0 Milestones
Critical Path
Schedule Contingency

| BNL and TJNAF Jointly Leading Process to Select Project Detector | | |
|---|---|---|
| 2020 | Call for Expressions of Interest (EOI)<br>https://www.bnl.gov/eic/EOI.php | May 2020 |
| | EOI Responses Submitted | November 2020 |
| | Assessment of EOI Responses | On-going |
| 2021 | Call for Collaboration Proposals for Detectors<br>https://www.bnl.gov/eic/CFC.php | March 2021 |
| | BNL/TJNAF Proposal Evaluation Committee | Spring 2021 |
| | Collaboration Proposals for Detectors Submitted | December 2021 |
| ✓ | Decision on Project Detector | March 2022 |

# The EIC User Group




The EIC is a truly international effort. Note the strong European engagement (CERN, Nov. 24).

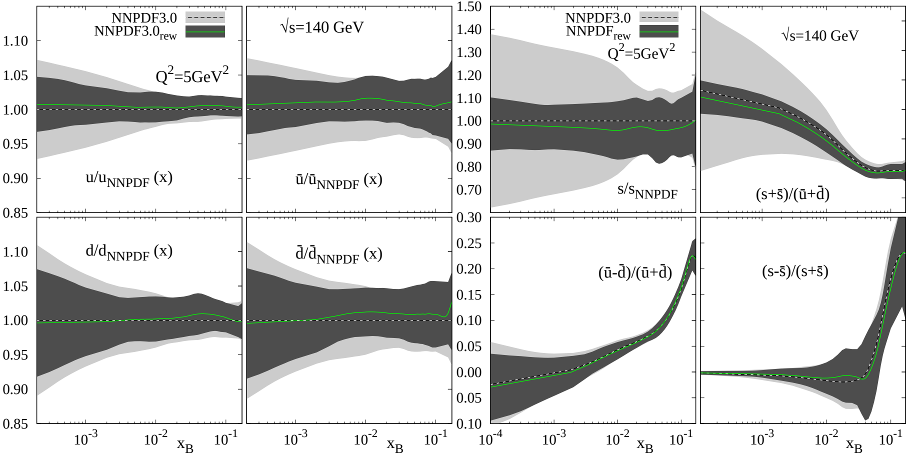
# Physics case (Yellow Report 2103.05419)

QCD is the phenomenologically richest sector of the standard model, encompassing many different highly active subfields.

- In energy these range from low, e.g. nuclear structure physics, to the highest available, e.g. Heavy-Ion physics.
- In complexity these range from hard reactions of few partons, to manifold interference effects linked to the multi-particle wave function of a hadron.
- In theoretical tools these range from hydrodynamics to pQCD and Lattice QCD
- EIC has polarized beams!

Combining input from different sources holds a huge discovery potential. In addition to p+p and A+A one needs e+p and e+A with broad kinematic range: JLab@12GeV and EIC.

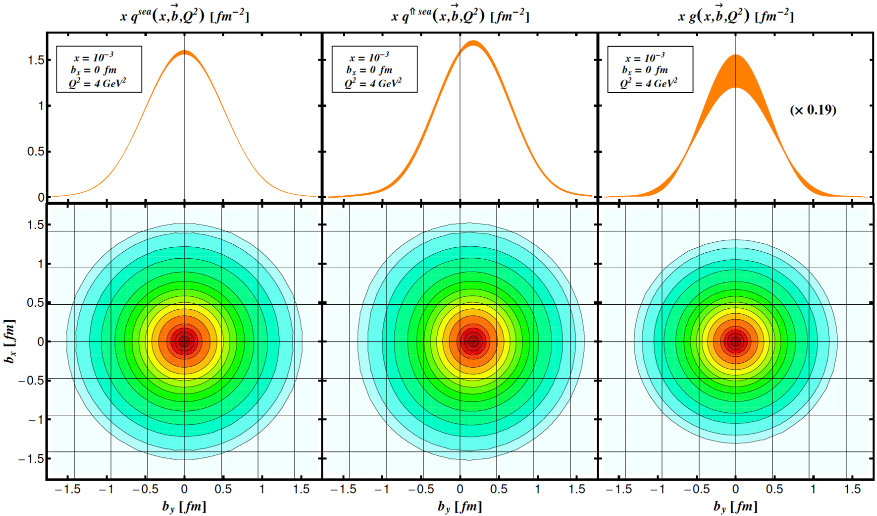
# Impact plots from the Yellow Report I: PDFs and FFs



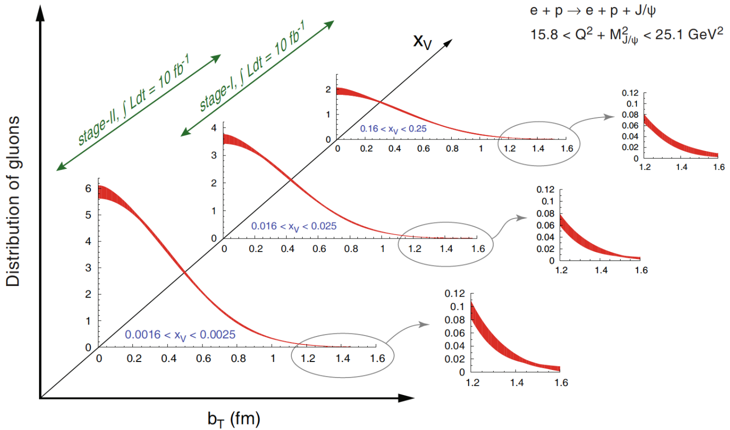

## Results of a combined fit of PDFs and FFs for EIC pseudo data

Aschenauer, Borsa, Sassot, Van Hulsen, 1902.10663 by NNPDF

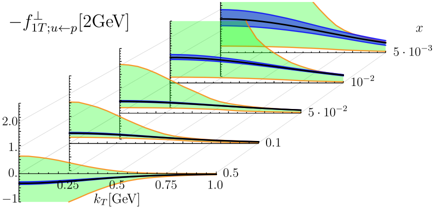
# Impact plots from the Yellow Report II: quark GPDs

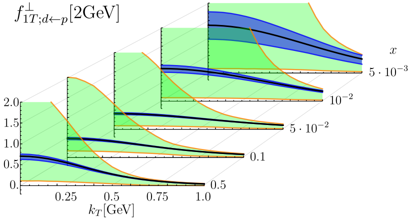


# Impact plots from the Yellow Report III: Gluon GPDs



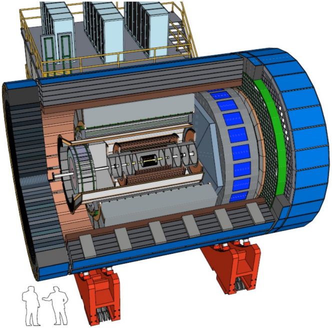
## Impact plots from the Yellow Report IV: quark Sivers distributions

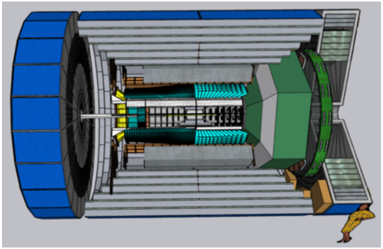


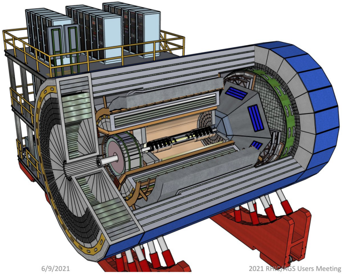



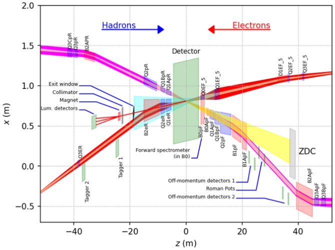

The big question: Can the systematic uncertainties (theory and experiment) match this precision? The combination of global expertise is needed. An opportunity for German groups ?!

# Experiment: The detector proposals ATHENA, CORE or ECCE







ATHENE: https://sites.temple.edu/eicatip6/

- spokesperson: S. Dalla Torre (INFN Trieste) deputy: B. Surrow, Temple Univ.
- ~ 100 collaborating institutions
- YR reference detector

CORE: https://eic.jlab.org/core/

- contacts: CH. Hyde (ODU) and P. Nadel-Turonski (JLab)
- ~ 20-30 collaborators

ECCE: https://www.ecce-eic.org

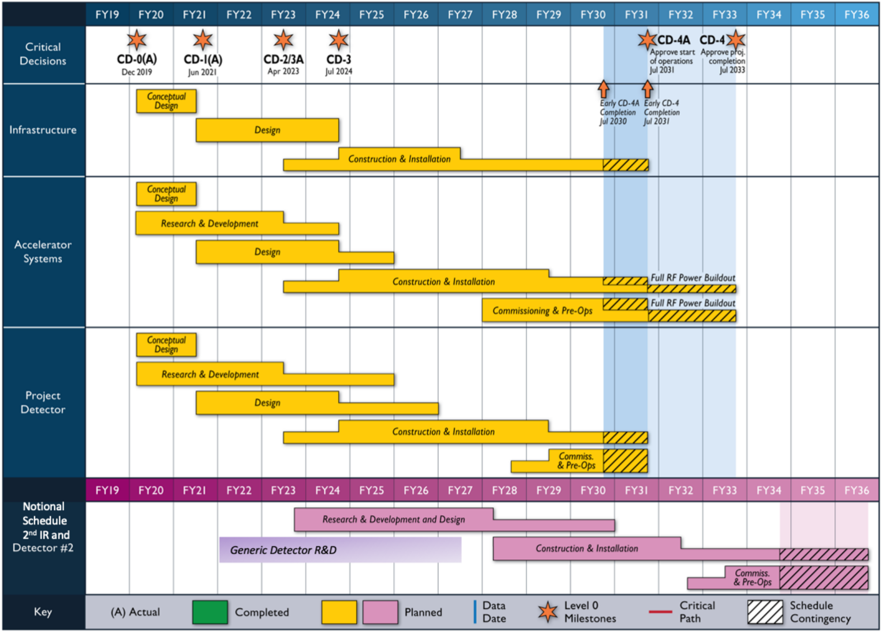
- leadership team: O. Hen (MIT), T. Horn (CUA), J. Lajoie (Iowa State)
- ~ 80 collaborating institutions

## Advantages of second detector

- The EIC has a very broad physics spectrum and aims at very high precision $\Rightarrow$ Two somewhat complementary detectors using different technologies are highly advantageous. For example: Optimized for different energy ranges, e+p versus e+A etc.
- Need for double-checks
- The option of having two differently optimized IRs.

DOE does not plan to finance the second detector (?!)

The second detector will come later.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Early CD-4 Completion Jul 2031
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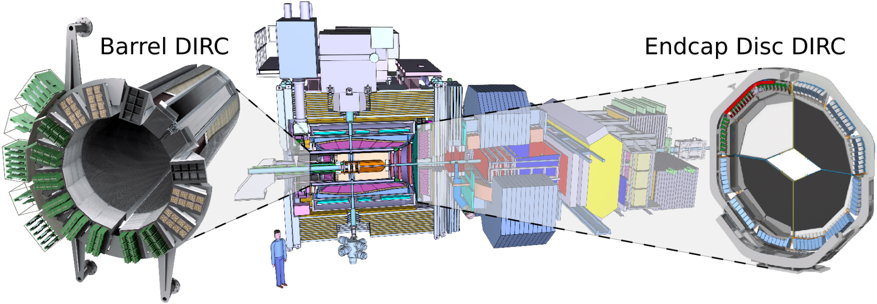
Conceptual Design
Research & Development
Design
Construction & Installation
Full RF Power Buildout
Commissioning & Pre-Ops
Full RF Power Buildout
Project Detector
Conceptual Design
Research & Development
Design
Construction & Installation
Commiss. & Pre-Ops
Notional Schedule 2nd IR and Detector #2
Research & Development and Design
Generic Detector R&D
Construction & Installation
Commiss. & Pre-Ops
Key
(A) Actual
Completed
Planned
Data Date
Level 0 Milestones
Critical Path
Schedule Contingency

# Concrete examples. 1. PANDA hpDIRC



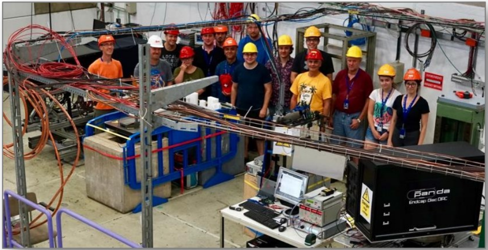

hpDIRC R&D Achievements:

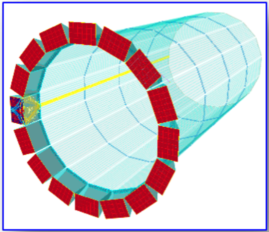
Developed of EIC PID detector with momentum coverage reaching 6 GeV/c for $\pi/K$;

Integrated in all EIC detector designs.

Validated performance in detailed Geant4 simulation

Developed innovative 3-layer lens, built and validated radiation hard prototype



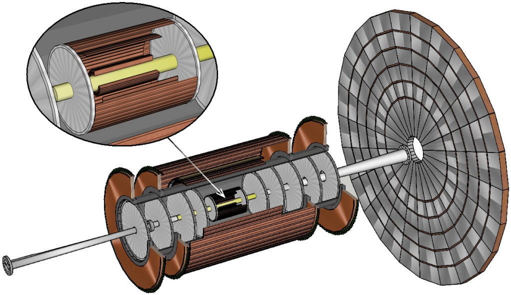



EIC-PANDA crew 2018 at CERN

GEANT simulation

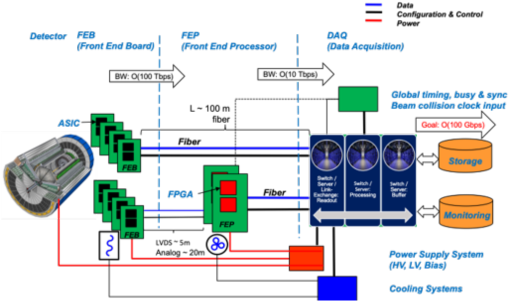
# Concrete examples. 2. Monolithic Active Pixel Sensors

- ongoing R&D collaboration with CERN/ALICE ITS-3 (innermost tracking layer) development
- new development: low mass EIC ITS-3 based forward disks

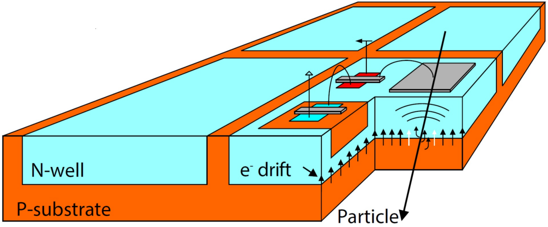


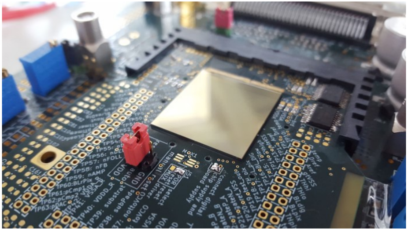
# Concrete examples. 3. Streaming readout

- baseline DAQ for EIC (and most future experiments)
- Large synergies, i.e. with GSI and LHC-b
- fully cognizant detectors, AI/ML integrated as close as possible to hardware.



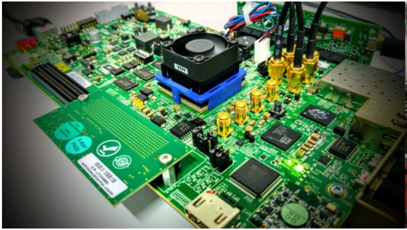
## Just one example: PANDA

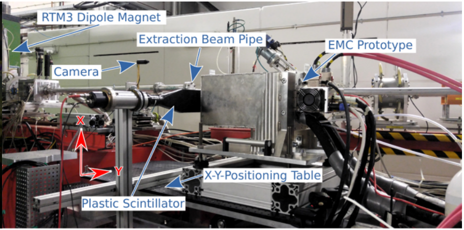


- DMAPS “Depleted Monolithic Active Pixel Sensors”
- codeveloped by Bochum, Heidelberg, Karlsruhe, Mainz

## The full streaming chain






- no trigger, very fast on-chip digital processing
- measuring differnt decay modes simultaneously
- Extensive tests at MAMI

**4.) Theory:** With novel lattice approaches formulated in recent years, lattice calculations can play a much more important role.

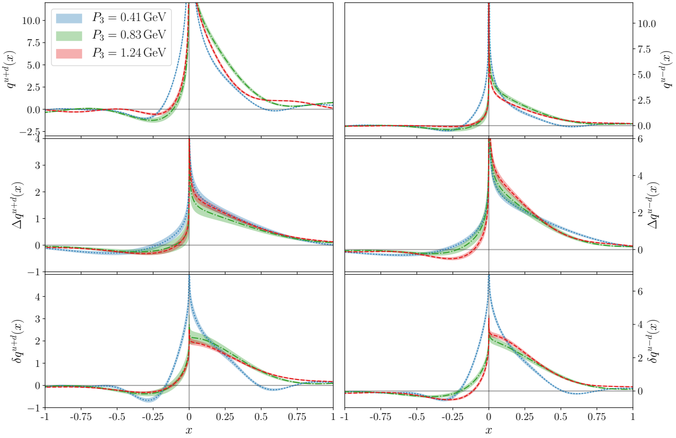
- X. Ji, PRL 110 (2013) 262002; arXiv:1305.1539
  quasi-PDFs etc.
- Y.Q. Ma and J.W. Qiu PRD 98 (2018) 074021;
  arXiv:1404.6860 lattice cross sections
- A. Radyushkin, PRD96 (2017) 034025; arXiv:1705.01488
  pseudo-PDFs etc.
- U. Aglietti et al. Phys.Lett. B441 (1998) 371;
  hep-ph/9806277
- V. Braun and D. Müller, EPJ C55 (2008) 349;
  arXiv:0709.1348
- A.J. Chambers et al., PRL 118 (2017) 242001;
  arXiv:1703.01153
- ...

I am a member of LPC (Y.B. Yang, X. Ji)

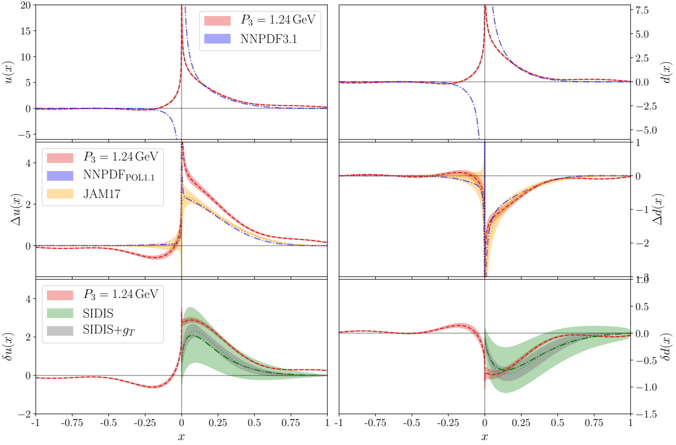
## The idea in a nutshell

- What is needed are correlators along the lightcone $t \pm z$. These cannot be calculated on the lattice because of analytic continuation to Euclidean time $t \to -ix_4$ resulting in $e^{iS} \to e^{-S_E}$
- Old method: Mellin moments. $\int_0^1 dx\, x^{n-1}\, q(x)$ given by local correlators (Operator Product Expansion)
- Problem: Operator mixing
- New method: Calculate quasi-PDFs, quasi-TMDs, quasi- ... nonlocal in space and relate quasi-PDfs etc. to PDFs. etc. by continuum perturbation theory.
- The limit $P_z \to \infty$ is problematic but the method seems to work better than expected.

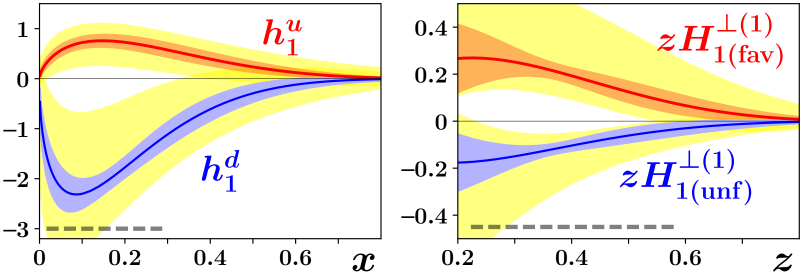
# Some results of ETMC 2106.16065




light quark PDFs, quasi-PDFs




the light quark PDFs

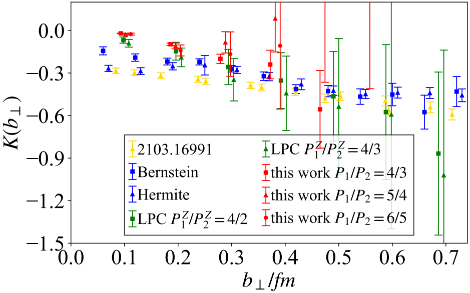


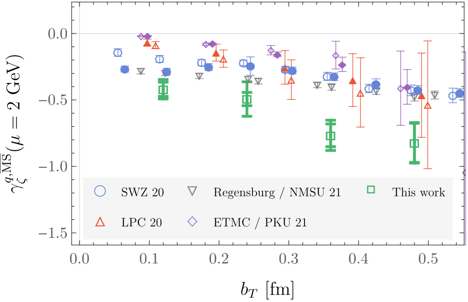

Lattice augmented transversity fits from JAM
Lin et al. arXiv:1710.09858

Transversity PDFs $h_1^{u,d}$ and favored $zH_{1(fav)}^{\perp(1)}$ and un-favored $zH_{1(unfav)}^{\perp(1)}$ Collins FFs

## A crucial theory input for the physics of TMDs: the Collins-Soper kernel

## The newest result from Beijing/ETMC 2106.13027 and MIT/ANL/BNL/FNL 2107.11930



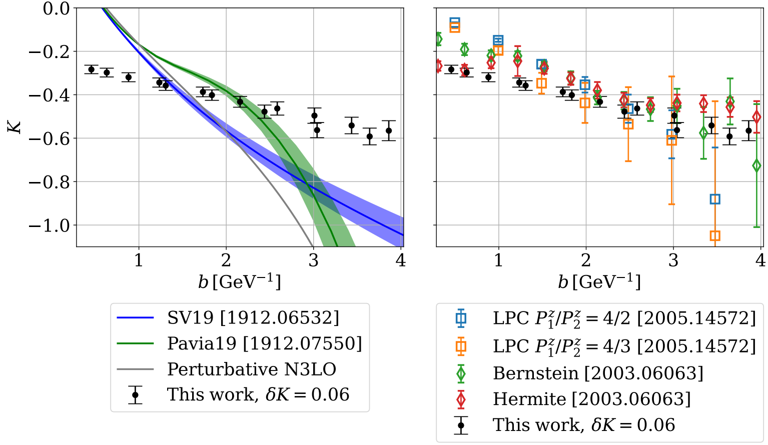




Five groups using three different lattice approaches get compatible results (most reliable way to estimate systematic uncertainties)

# Conclusions

- EIC, LHC, FAIR, ... are highly complementary. High-energy hadron physics has a bright future
- The EIC will explore many aspects of the many-particle wave functions of hadrons which are presently only poorly known or even unknown.
- EIC is moving forward very fast. Many commitments have already been made. There are three detector proposals: ATHENA, CORE, and ECCE. The plans are very ambitious and additional expert knowledge is still in high demand.
- Concrete examples for collaboration were given. Windows of opportunity for others will close in the not so distant future.
- Lattice QCD will be a complementary discovery tool.

# A crucial theory input for the physics of TMDs: the Collins-Soper kernel arXiv:2103.16991




Estimated higher twist uncertainty $\delta K = 0.06$