3DPartons:
Recent achievements and prospects

Valerio Bertone
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June 17, 2024, Present and future perspectives in hadron Physics, Frascati

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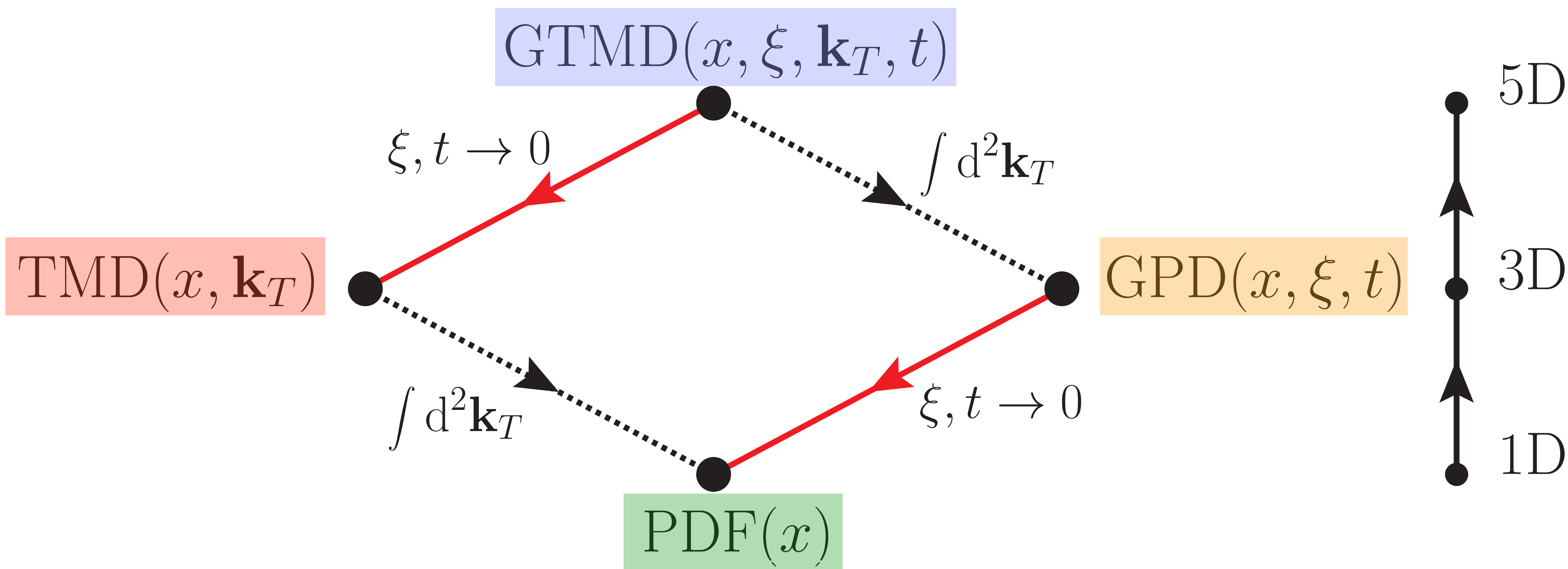
Introduction

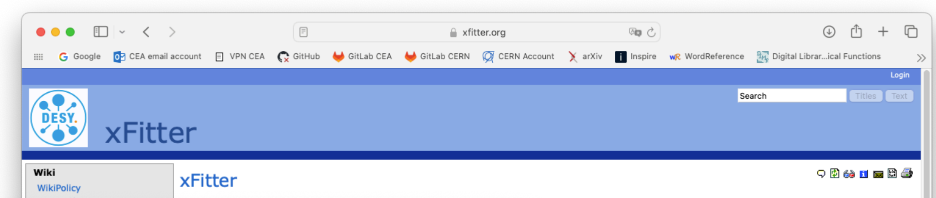
- **3DPartons** is one of the two **virtual-access** (VA) packages of **STRONG2020**:
  - it gives access to **open-source code** necessary for phenomenology in the field of **3D hadron structure**.

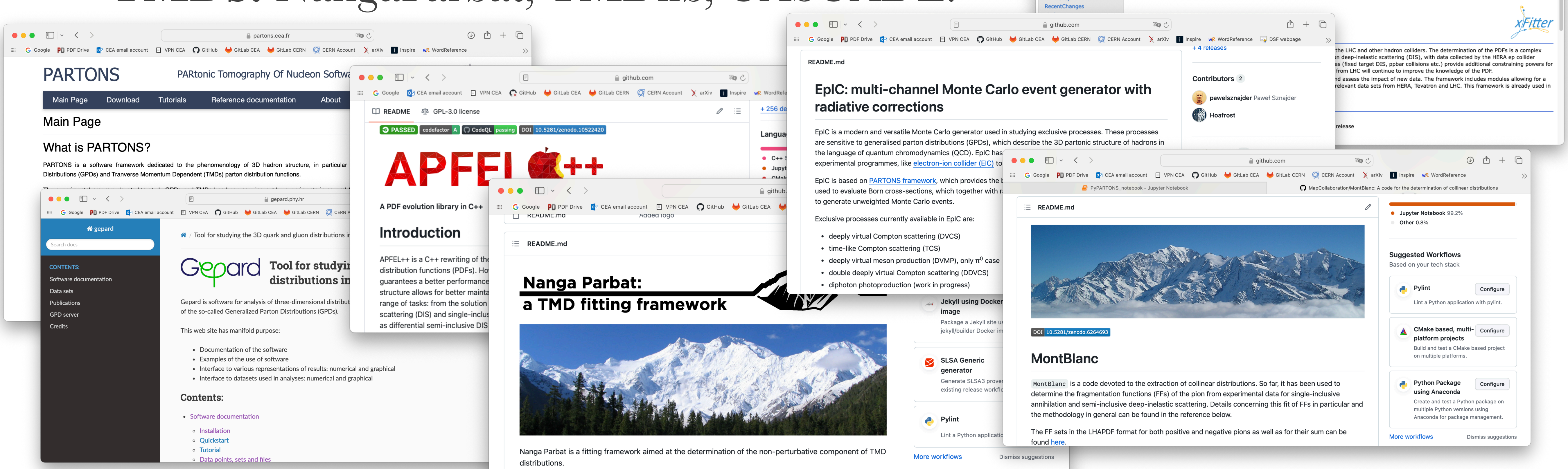


- **3DPartons** has given a contribution to better understand *all* of the four categories of distributions above.

Introduction

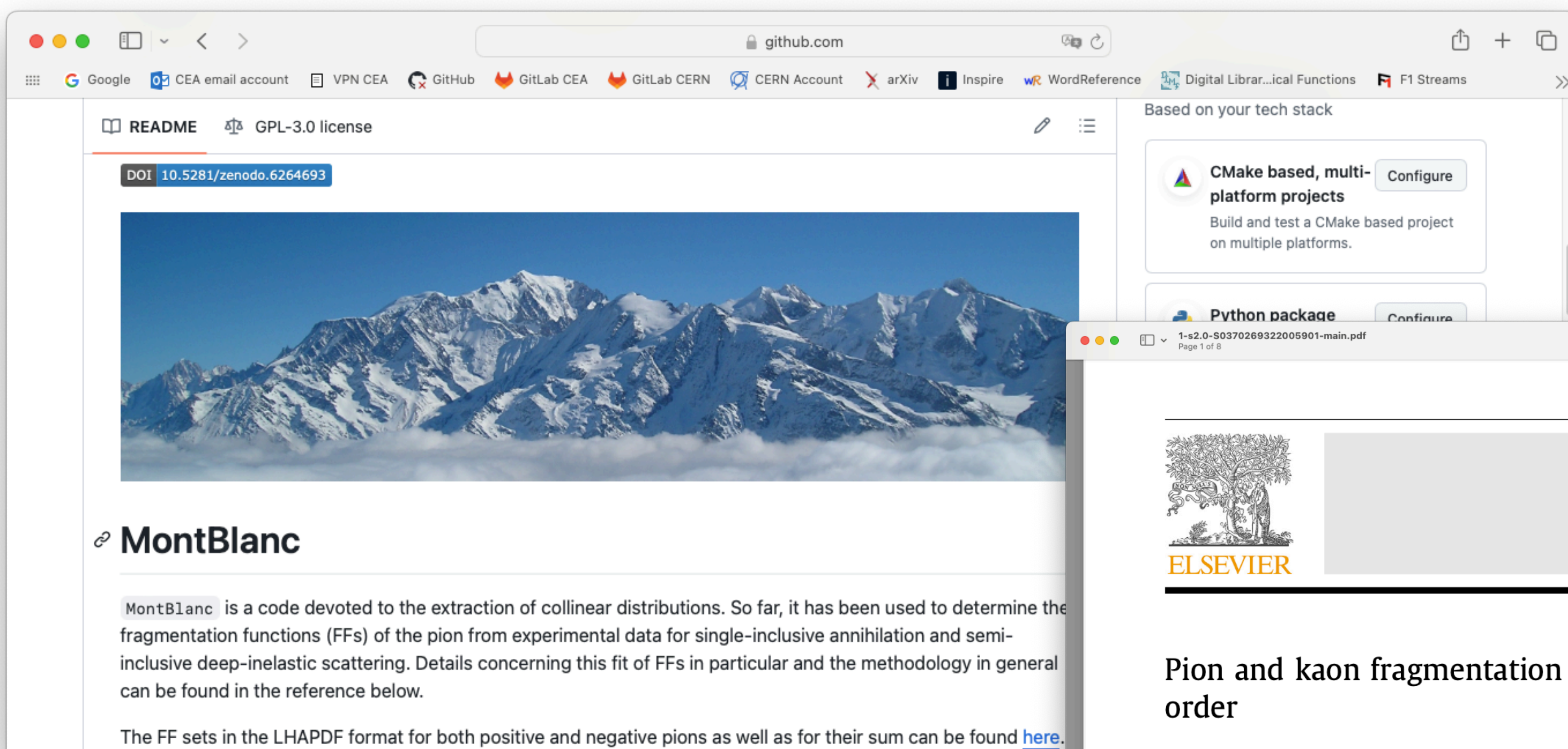
- 3DPartons consists of **several libraries organised in a modular way:**
  - continuous improvements and addition of new models, channels, and theoretical refinements.
- As of today, **3DPartons** is based on parts of, or offers interfaces to, various existing codes:
  - **PDFs/FFs:** LHAPDF, APFEL/APFEL++, xFitter, MontBlanc, Denali,
  - **GPDs:** PARTONS, EpIC, GeParD,
  - **TMDs:** NangaParbat, TMDlib, CASCADE.



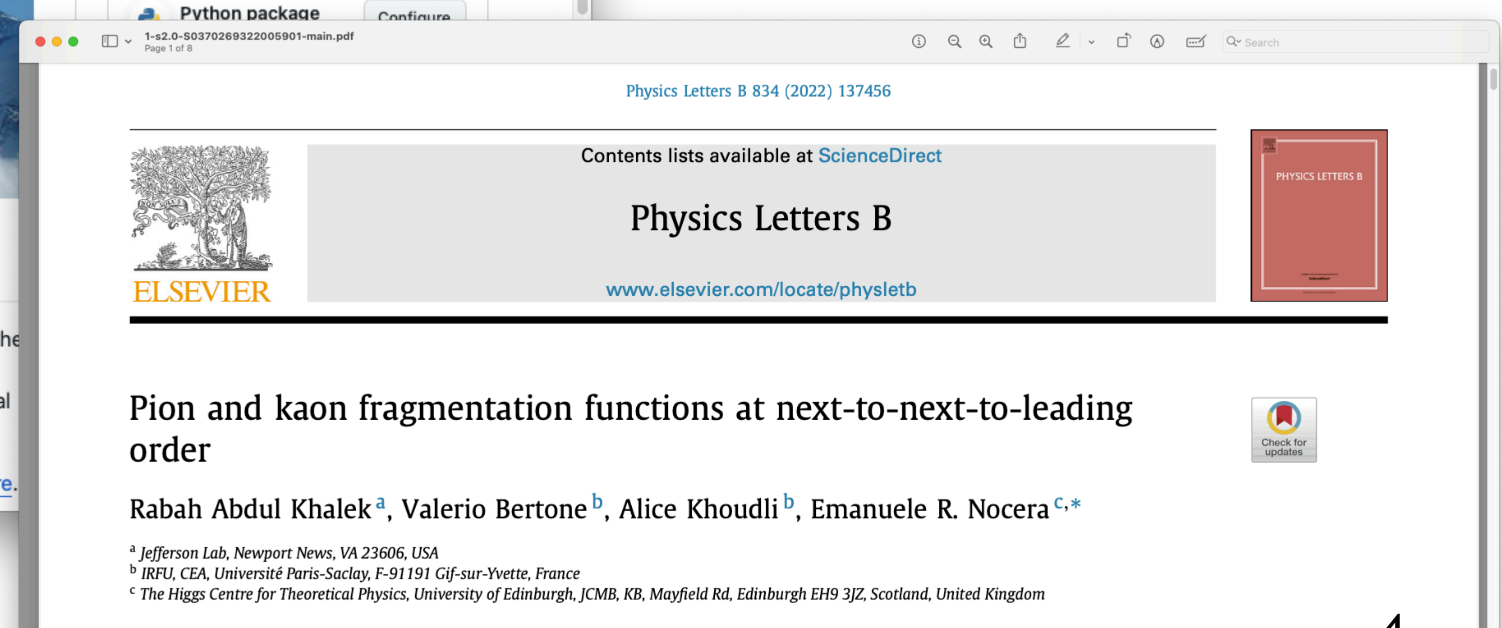


Highlights: pion and kaon FFs

- Extraction of collinear FFs of charged **pions** and **kaons** at **NNLO** accuracy:
  - based on data for inclusive production of hadrons in e^+e^- annihilation (SIA) and *ep* collisions (DIS).
  - FFs parameterised by means of a **Neural Network** with **Monte Carlo** representation of the uncertainties.
  - Code (**MontBlanc**) publicly available.

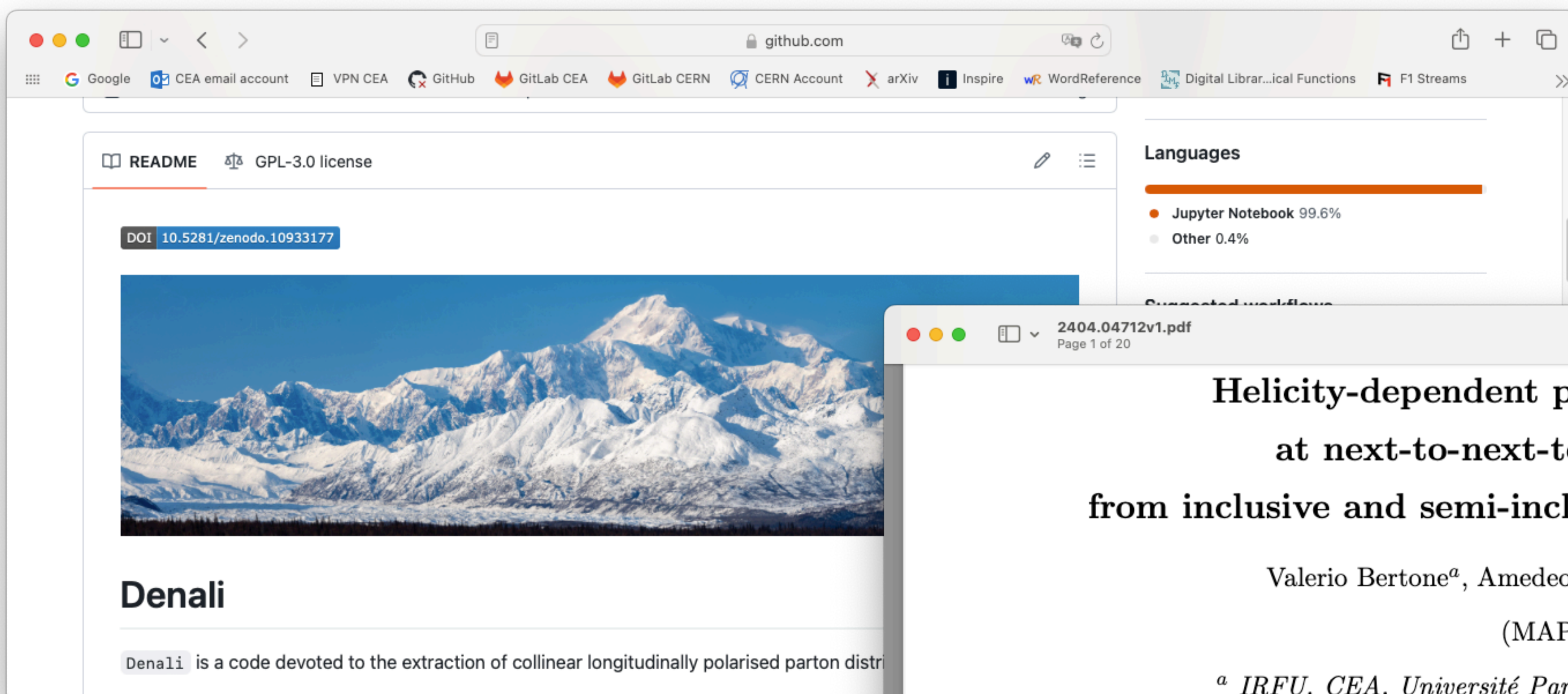


[Phys.Lett.B 834 (2022) 137456]

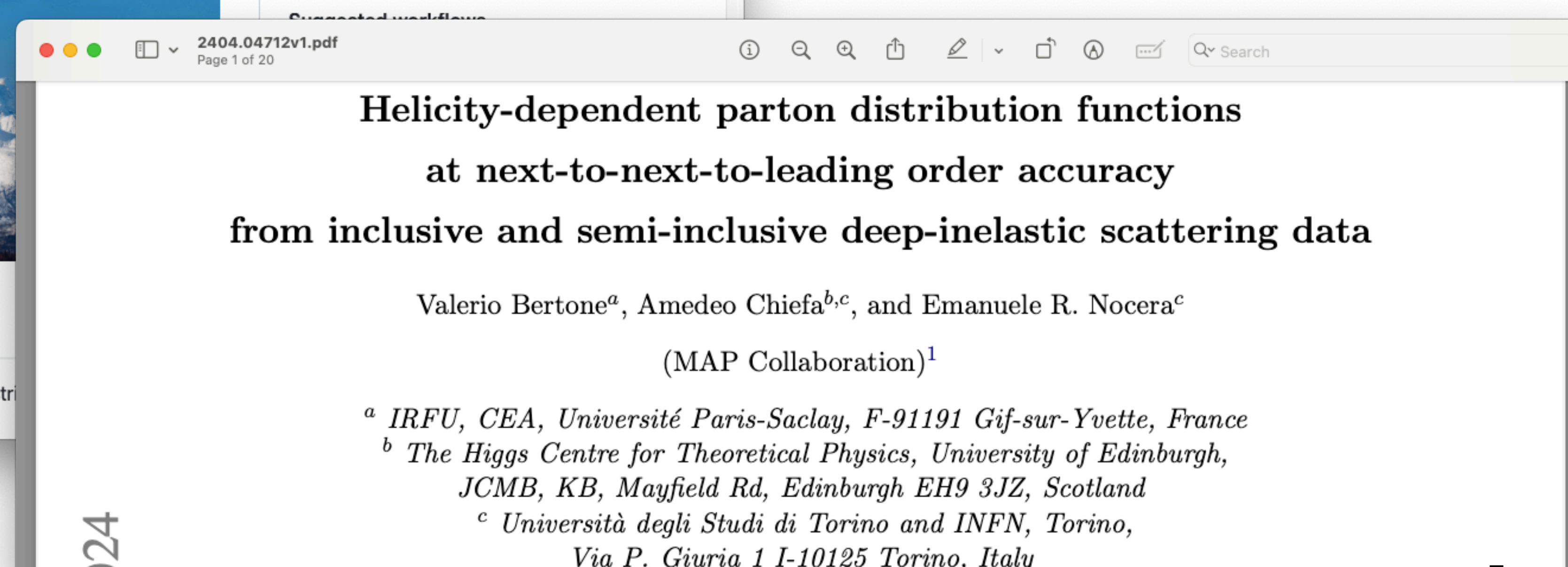


Highlights: helicity PDFs

- First ever extraction of collinear helicity PDFs of the proton at **NNLO** accuracy:
  - based of experimental data for fully-inclusive and semi-inclusive *ep* (DIS) collisions.
  - PDFs parameterised by means of a **Neural Network** with **Monte Carlo** representation of the uncertainties.
  - Code (**Denali**) publicly available.



[e-Print: 2404.04712]
Paper under review



Helicity-dependent parton distribution functions
at next-to-next-to-leading order accuracy
from inclusive and semi-inclusive deep-inelastic scattering data

Valerio Bertone[a], Amedeo Chiefa[b,c], and Emanuele R. Nocera[c]

(MAP Collaboration)[1]

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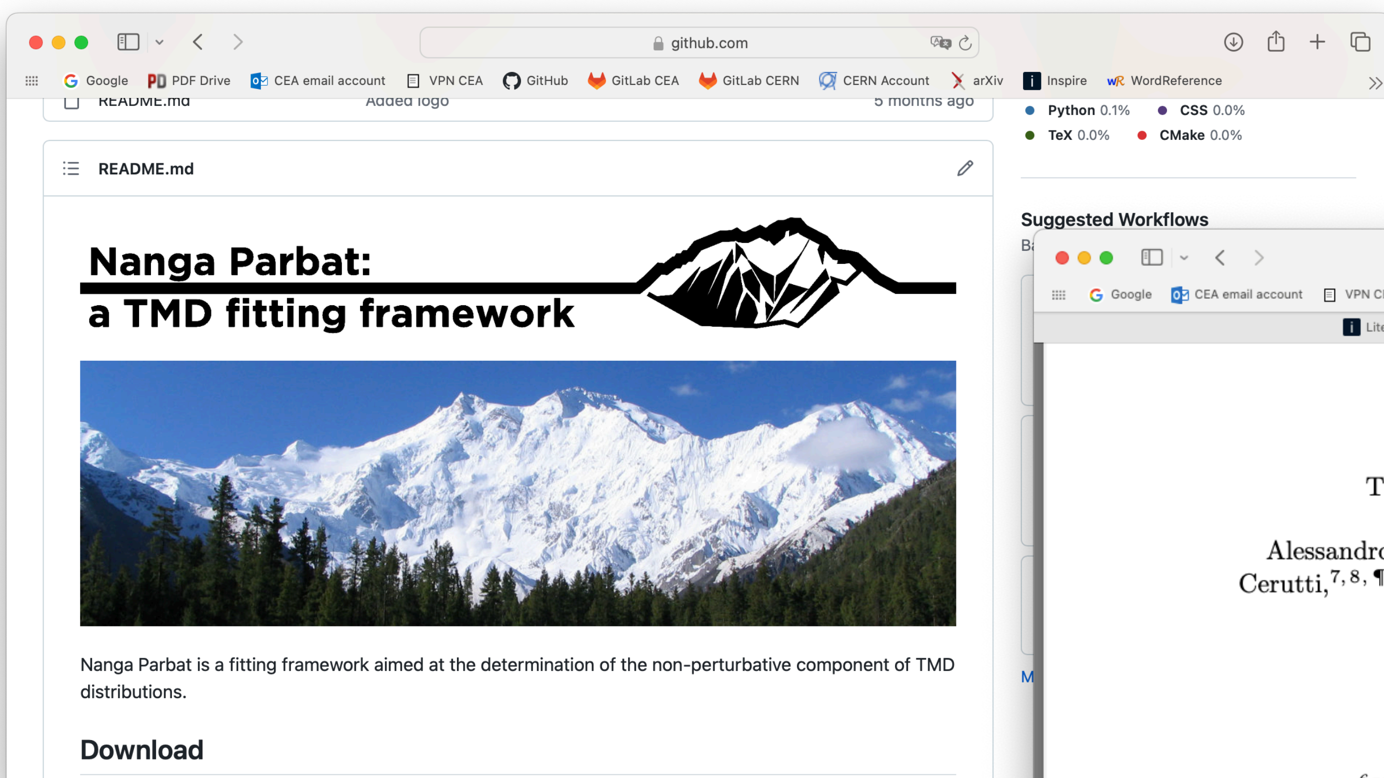
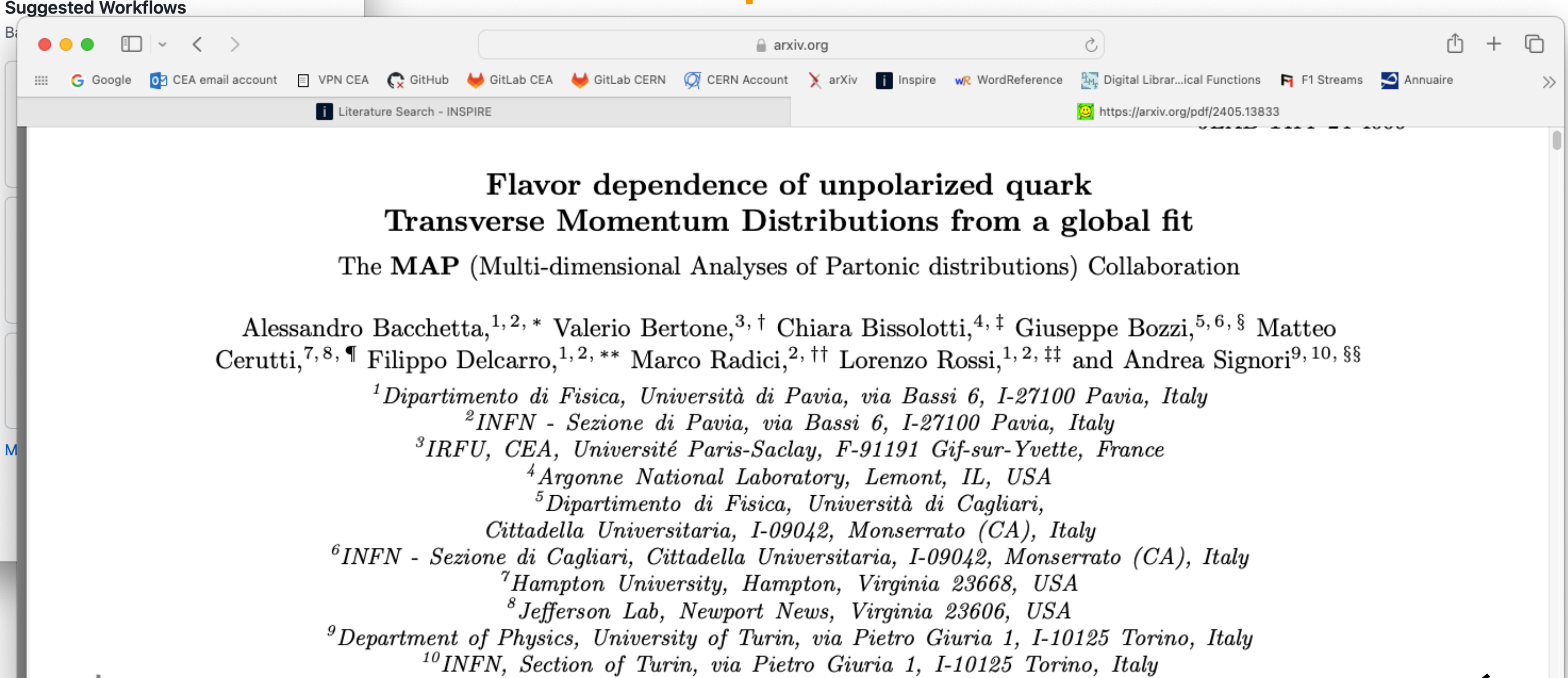
[b] The Higgs Centre for Theoretical Physics, University of Edinburgh, JCMB, KB, Mayfield Rd, Edinburgh EH9 3JZ, Scotland
[c] Università degli Studi di Torino and INFN, Torino, Via P. Giuria 1 I-10125 Torino, Italy

Highlights: TMDs

- Simultaneous extraction of TMD PDFs of the proton and TMD FFs of light hadrons (pions and kaons):
  - based of experimental data for semi-inclusive hadron production in *ep* (**SIDIS**) collisions and **Drell-Yan** production in *pp* collisions.
  - State-of-the art **N^{3}LL** accuracy.
  - First **flavour-dependent** extraction from a global analysis.
  - Code (**NangaParbat**) publicly available.



[e-Print: 2405.13833]
Paper under review



Flavor dependence of unpolarized quark Transverse Momentum Distributions from a global fit

The **MAP** (Multi-dimensional Analyses of Partonic distributions) Collaboration

Alessandro Bacchetta,[1,2,*] Valerio Bertone,[3,†] Chiara Bissolotti,[4,‡] Giuseppe Bozzi,[5,6,§] Matteo Cerutti,[7,8,¶] Filippo Delcarro,[1,2,**] Marco Radici,[2,††] Lorenzo Rossi,[1,2,‡‡] and Andrea Signori[9,10,§§]

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[3] *IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France*
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[5] *Dipartimento di Fisica, Università di Cagliari, Cittadella Universitaria, I-09042, Monserrato (CA), Italy*
[6] *INFN - Sezione di Cagliari, Cittadella Universitaria, I-09042, Monserrato (CA), Italy*
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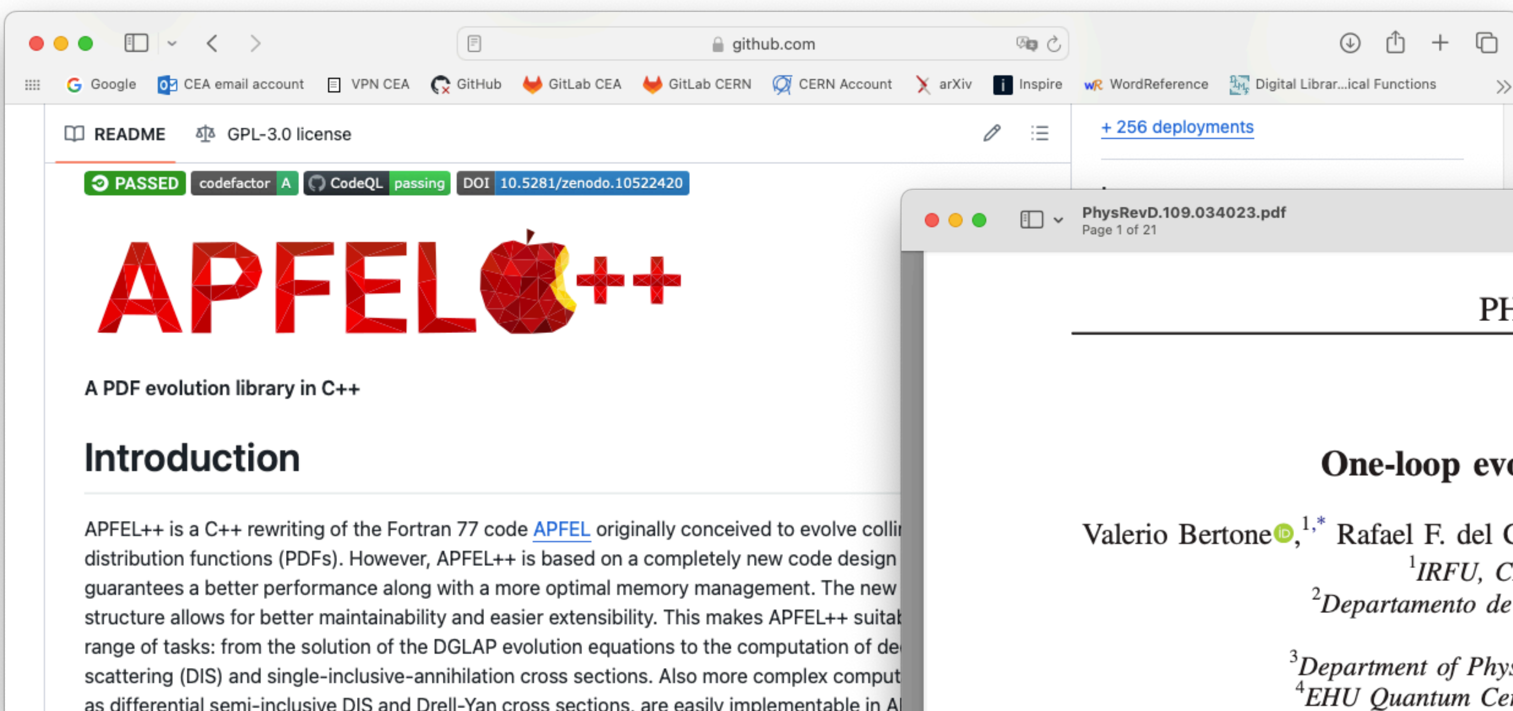
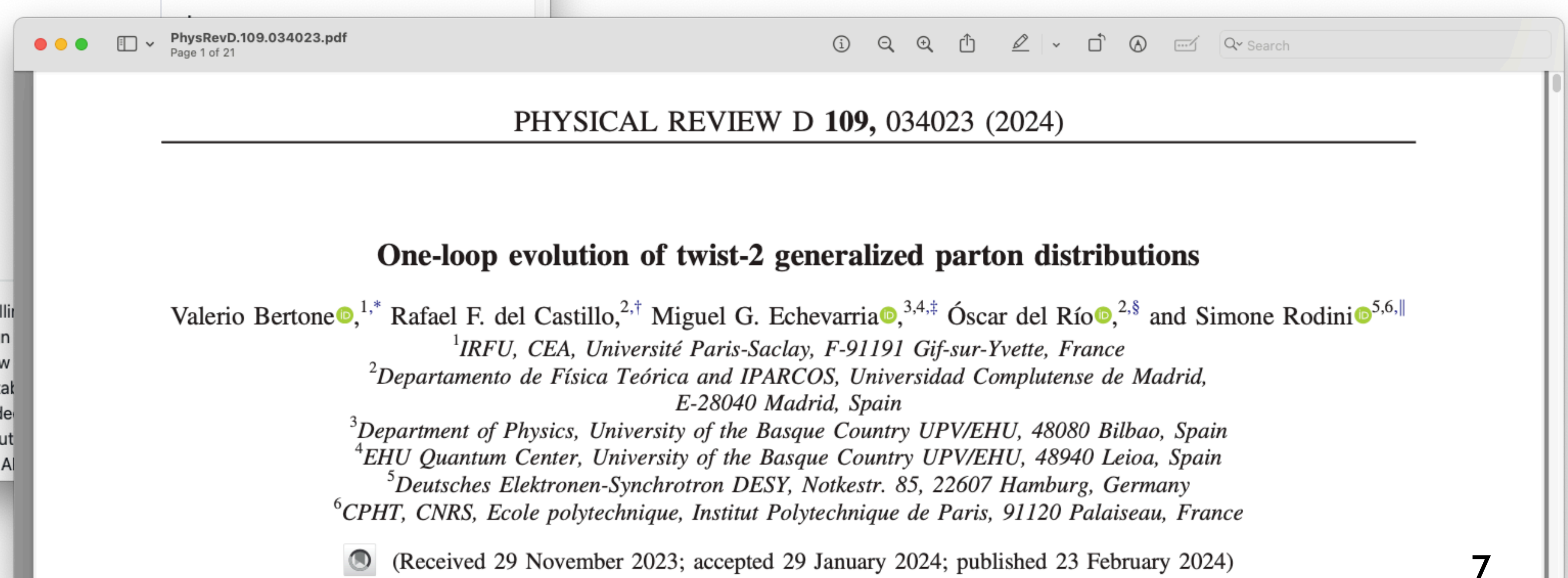
[9] *Department of Physics, University of Turin, via Pietro Giuria 1, I-10125 Torino, Italy*
[10] *INFN, Section of Turin, via Pietro Giuria 1, I-10125 Torino, Italy*

Highlights: GPDs

- Recomputation *and* implementation of **one-loop evolution** for GPDs for *all* of the **twist-2 quark and gluon** distributions:
  - diagrammatic computation in **light-cone** gauge.
  - Fast and accurate implementation that ranges between **DGLAP** ($\xi = 0$) and **ERBL** ($\xi = 1$) limits.
  - Possibility to evolve any GPD model (*e.g.* those present in PARTONS) in the **variable-flavour number scheme**.
  - Code (**APFEL++/PARTONS**) publicly available.



[*Phys.Rev.D* 109 (2024) 3, 034023]


PhysRevD.109.034023.pdf
Page 1 of 21

PHYSICAL REVIEW D **109,** 034023 (2024)

One-loop evolution of twist-2 generalized parton distributions

Valerio Bertone,[1,*] Rafael F. del Castillo,[2,†] Miguel G. Echevarria,[3,4,‡] Óscar del Río,[2,§] and Simone Rodini[5,6,∥]

[1]*IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France*
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[5]*Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany*
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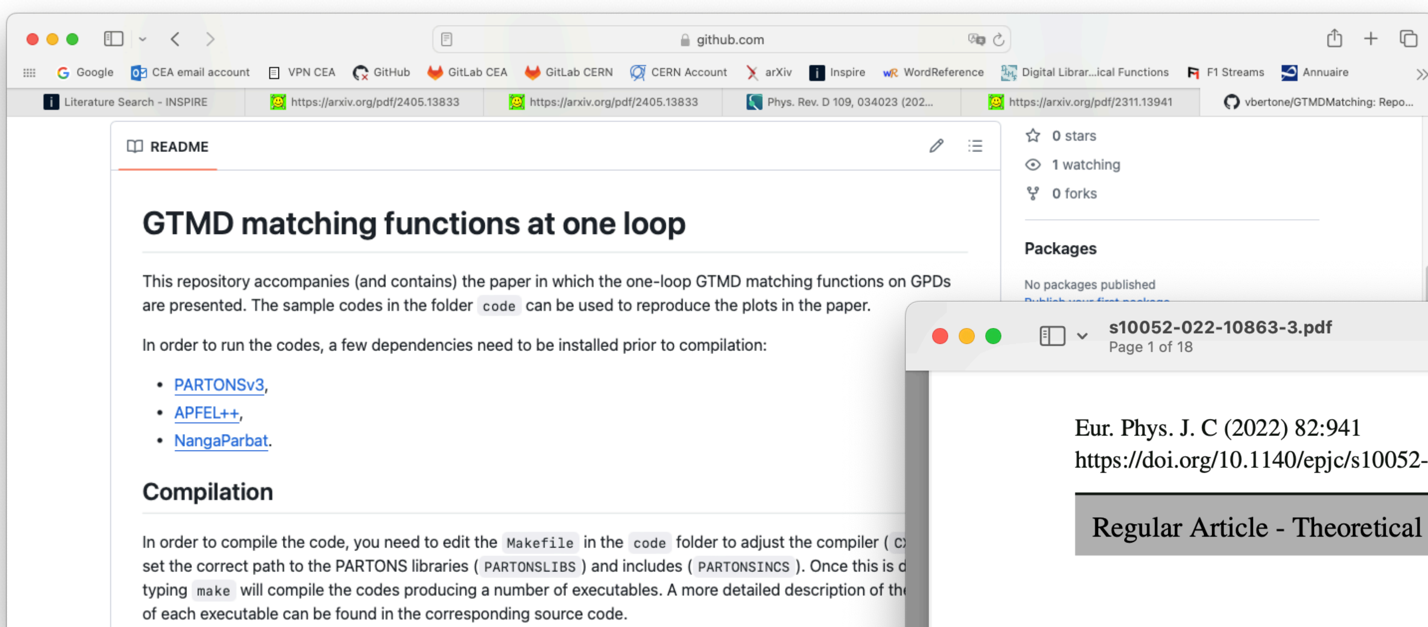
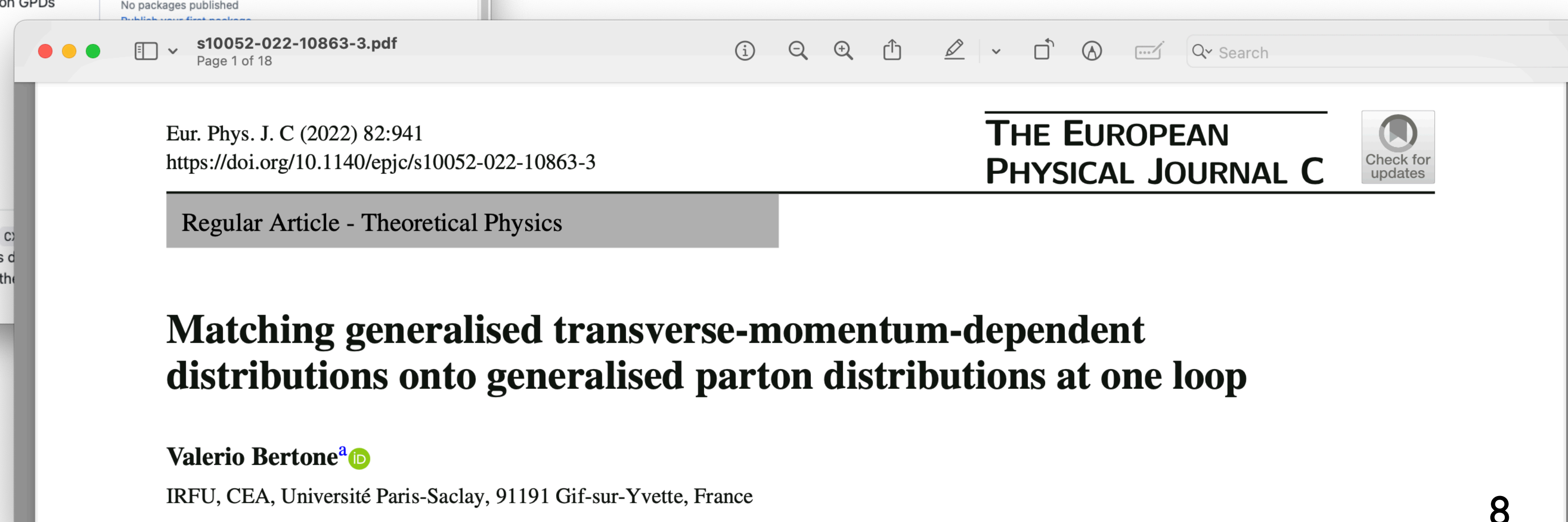
Highlights: GTMDs

- First complete computation of the GTMD **matching functions** at **one-loop** accuracy:
  - they allow to **reconstruct GTMDs in terms of GPDs**.
  - computation valid in both **DGLAP** ($\xi < x$) and **ERBL** ($\xi > x$) regions.
  - Perfect example of **interoperability** (APFEL+PARTONS+NangaParbat).
  - Calculation valid in the **unpolarised** case:
    - extension to all other twist-2 polarisations on the way.

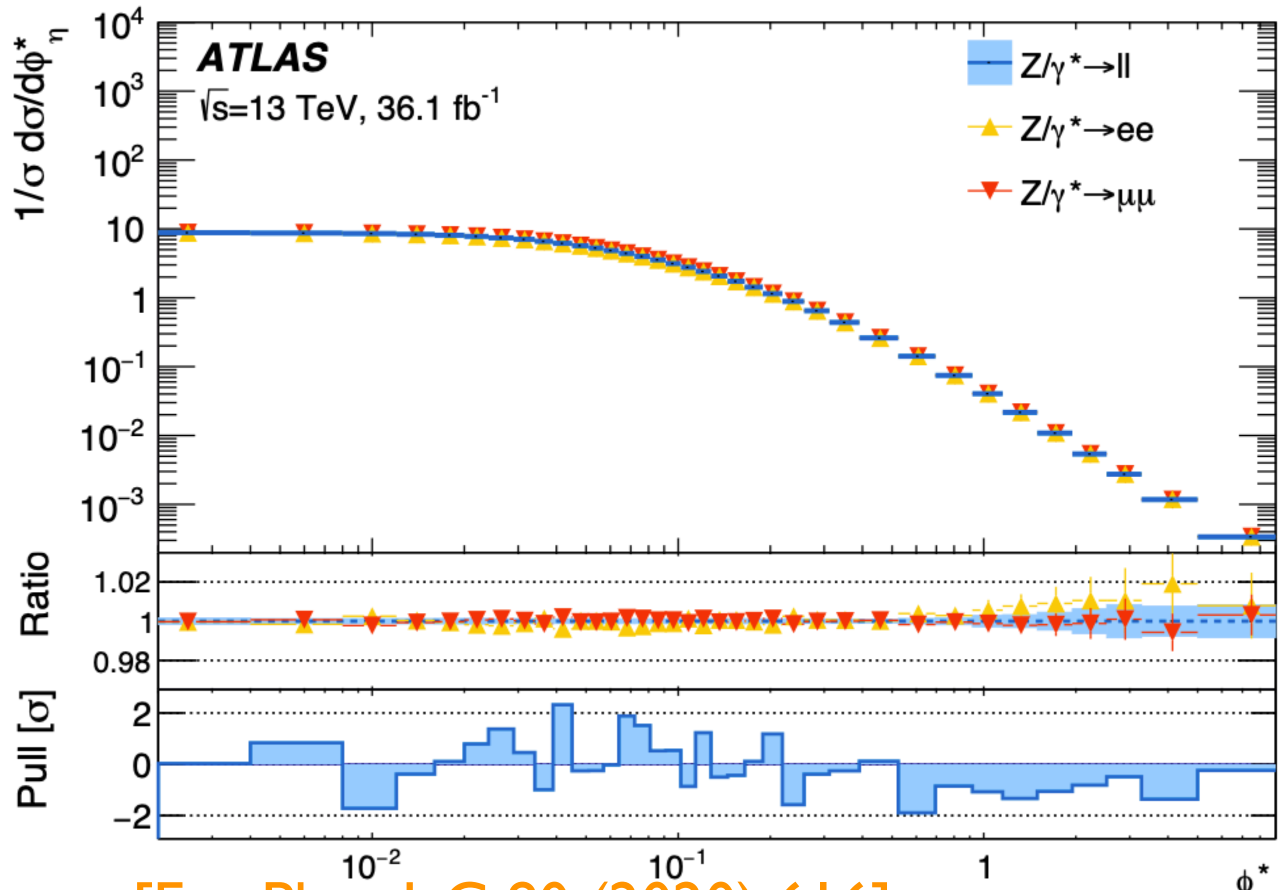


[Eur.Phys.J.C 82 (2022) 10, 941]

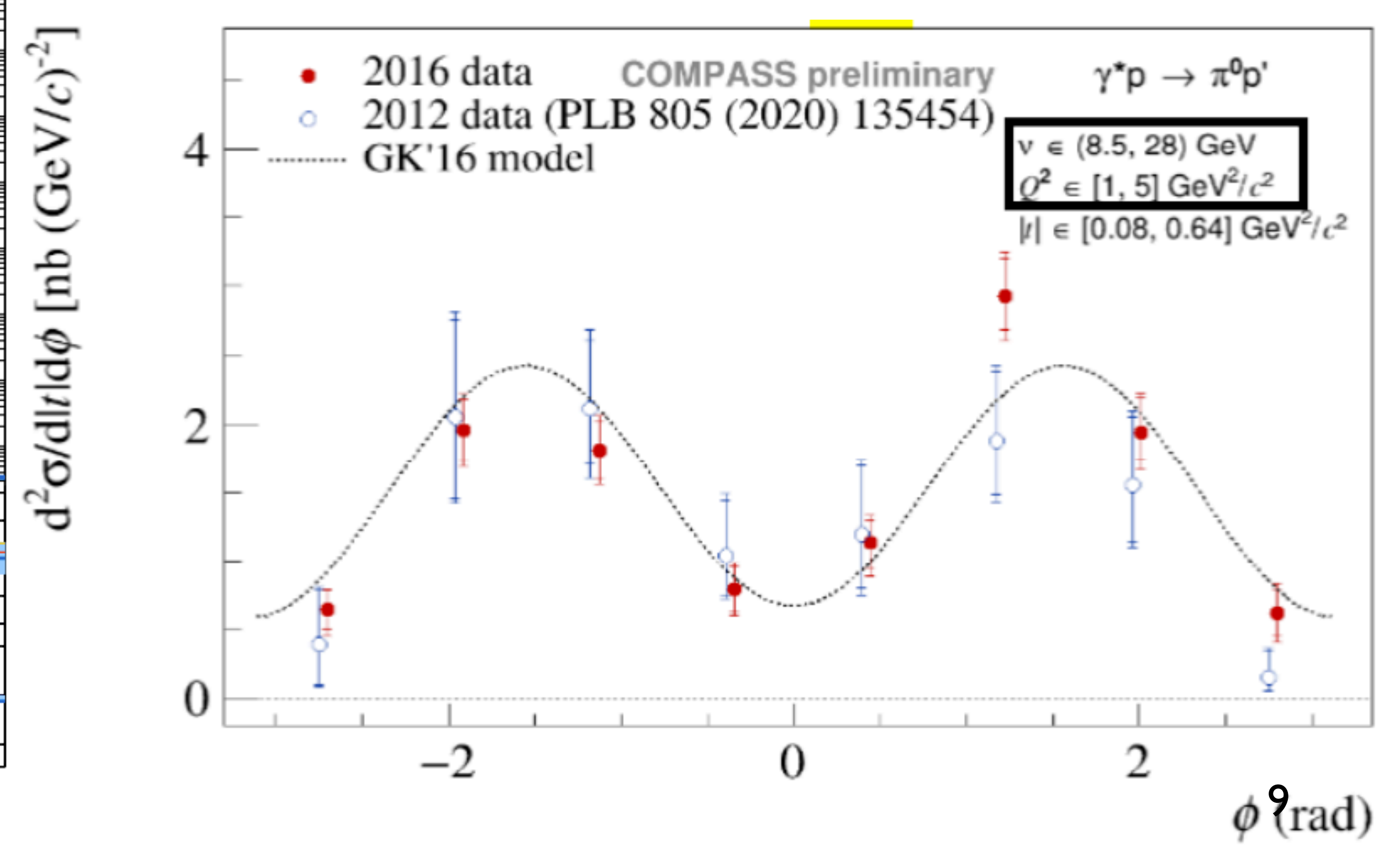


Experimental opportunities

- Presently, many facilities around the world are delivering high-precision data that could be **exploited** to achieve a better understanding of the hadron structure:
  - CERN (LHC, COMPASS/AMBER, LHCSpin/SMOG2)
  - JLab (Hall A, B (CLAS12), C)
  - BNL (STAR, (s)PHENIX)
  - B-factories (BELLE, BABAR, BES III)



[Eur. Phys. J. C 80 (2020) 616]



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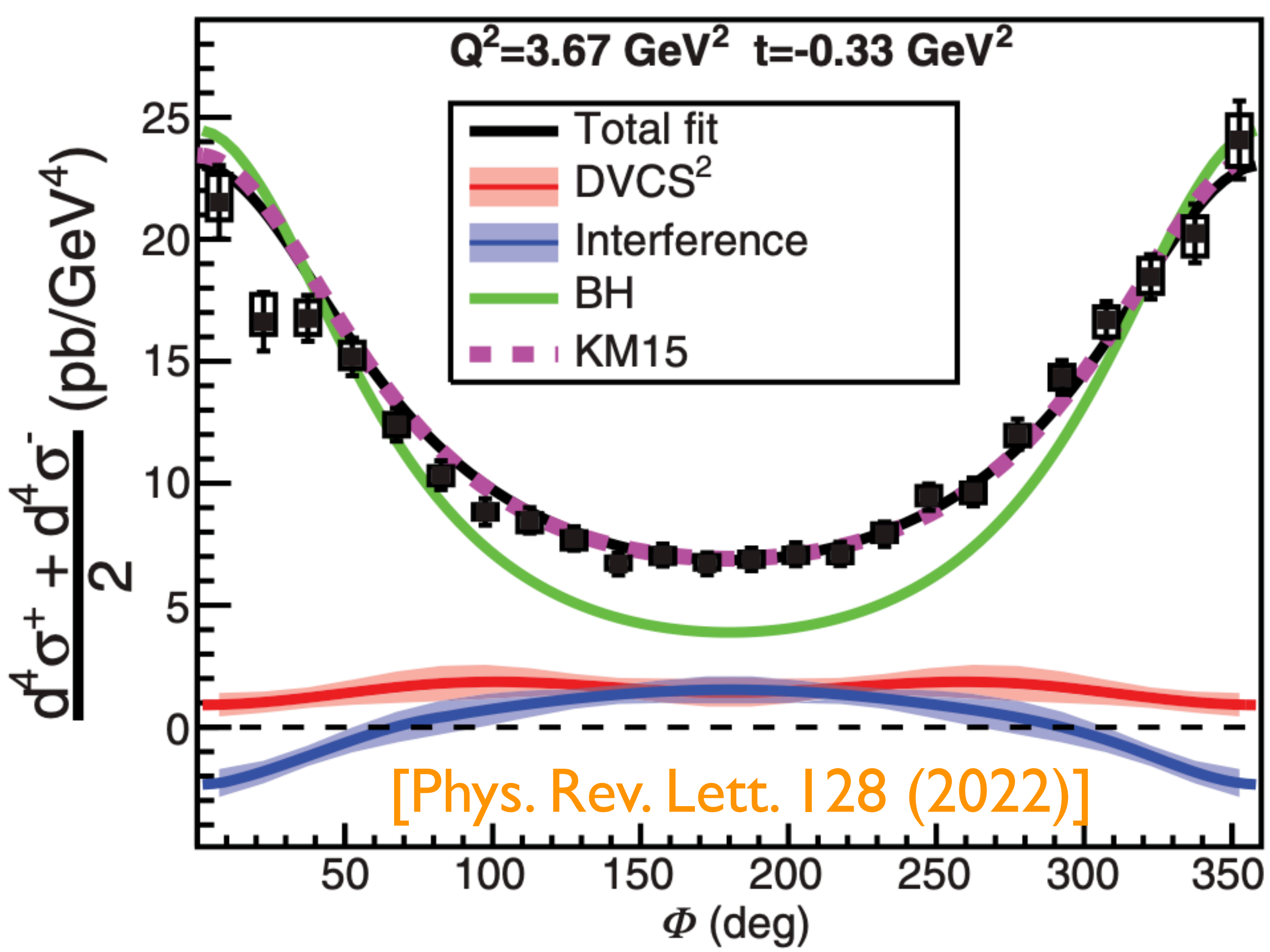
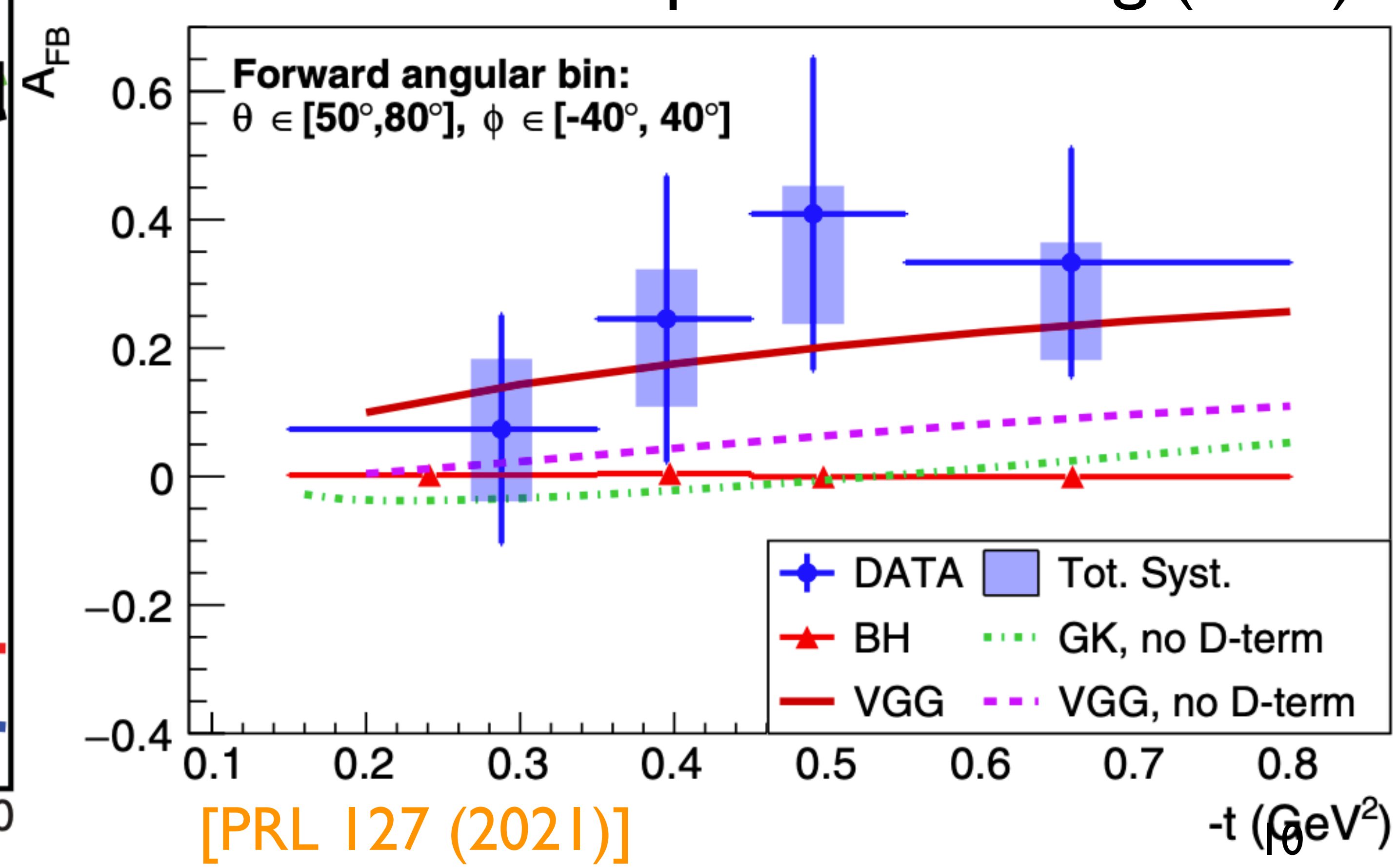


Timelike Compton Scattering (TCS)



[PRL 127 (2021)]

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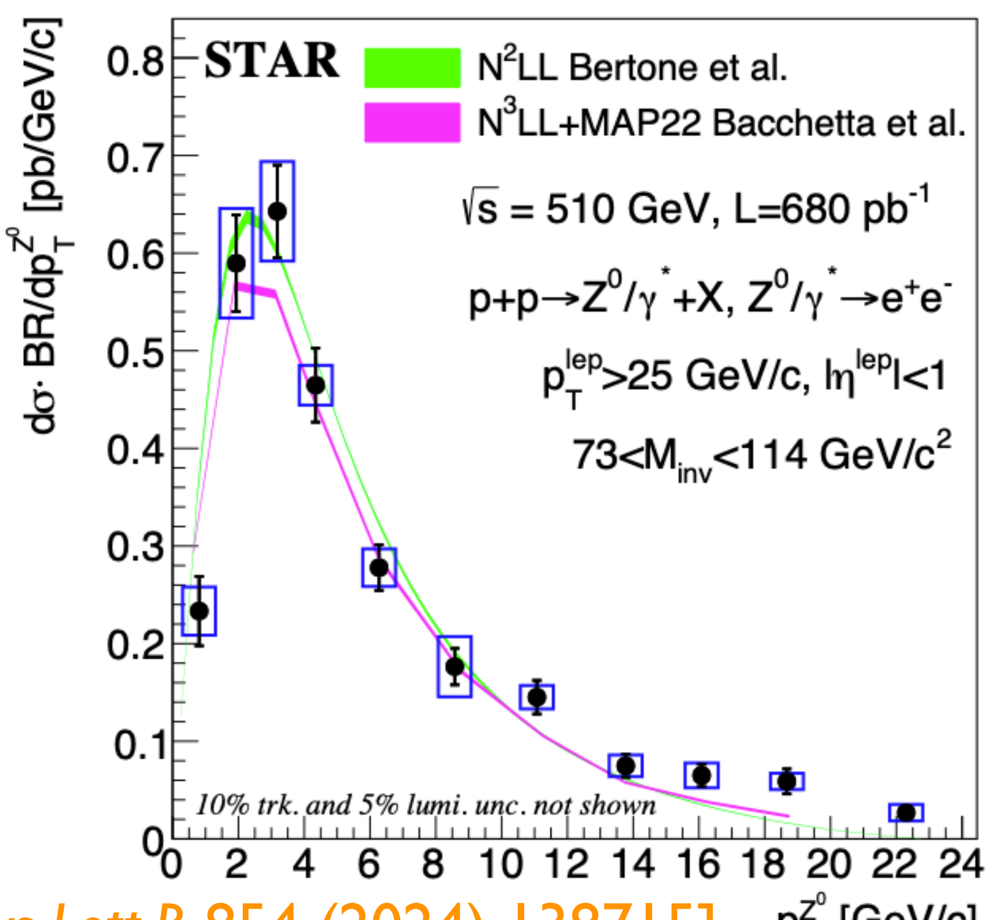
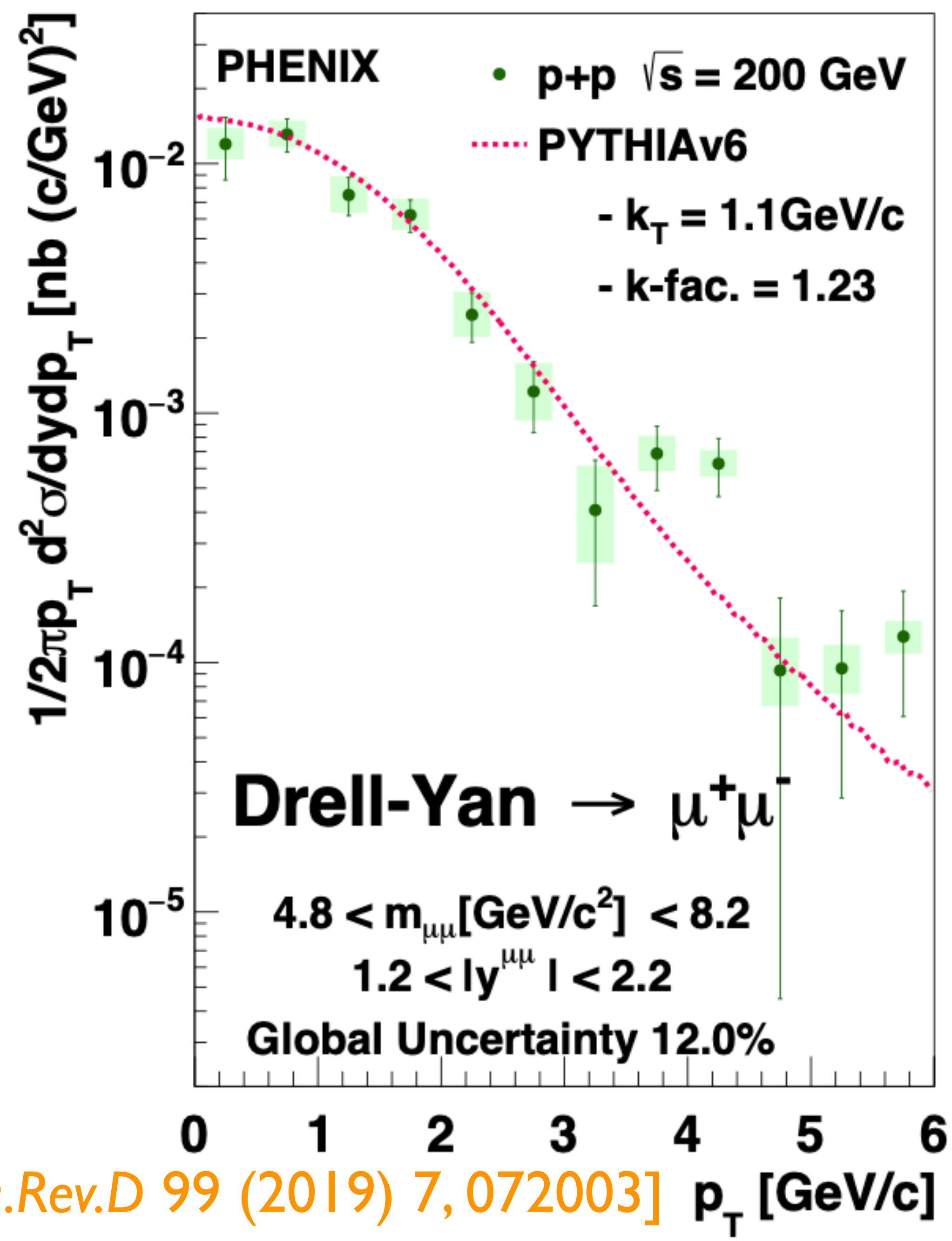


[*Phys.Lett.B* 854 (2024) 138715]



[*Phys.Rev.D* 99 (2019) 7, 072003]

Experimental opportunities

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  - CERN (LHC, COMPASS/AMBER, LHC
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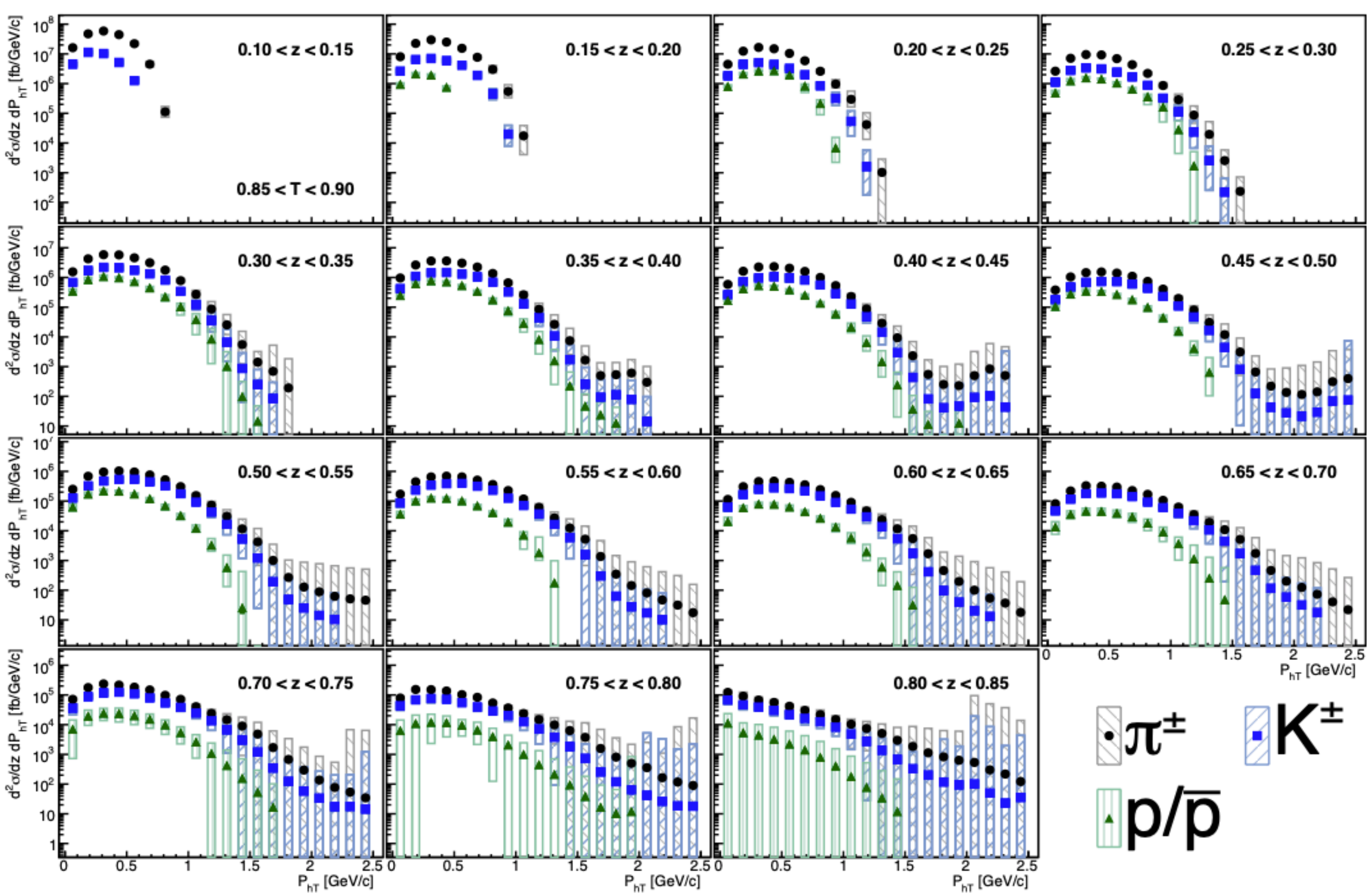
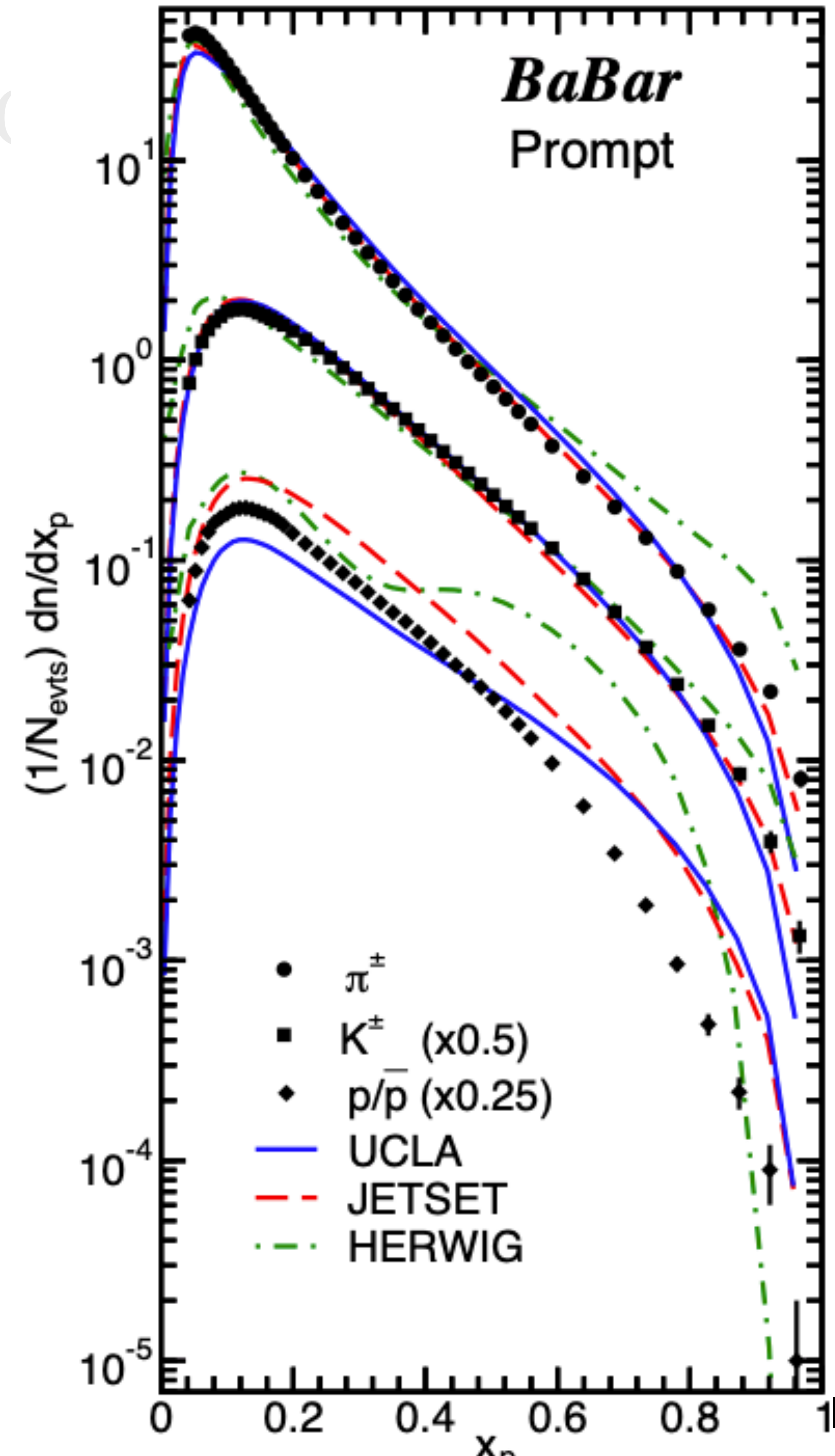


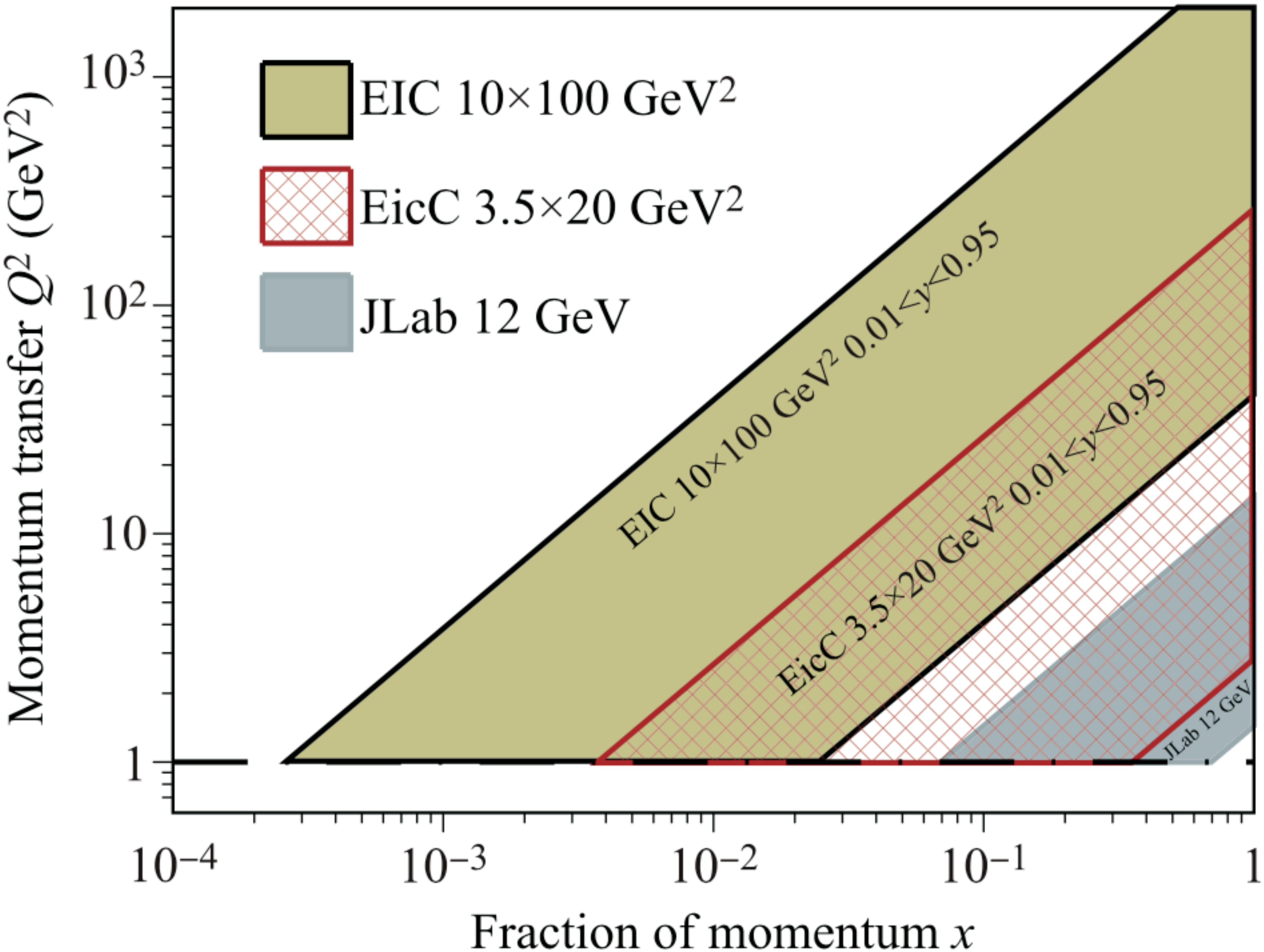
[*Phys.Rev.D* 99 (2019) 11, 112006]



[*Phys.Rev.D* 88 (2013) 032011]

Experimental opportunities

- The future **EIC** (US) and **EicC** (China) are unique to broaden our knowledge of the internal structure of hadrons.



[Front.Phys.(Beijing) 16 (2021) 6, 64701]

Experimental opportunities

- The future **EIC** (US) and **EicC** (China) are unique opportunities to broaden our knowledge of the internal structure of hadrons.

EIC Science Highlights

SPIN is one of the fundamental properties of matter. All elementary particles, but the Higgs carry spin. Spin cannot be explained by a static picture of the proton It is the interplay between the intrinsic properties and interactions of quarks and gluons

The EIC will unravel the different contribution from the quarks, gluons and orbital angular momentum.

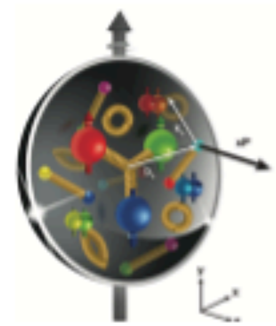
Does the mass of visible matter emerge from quark-gluon interactions?

Atom: Binding/Mass = 0.00000001

Nucleus: Binding/Mass = 0.01

Proton: Binding/Mass = 100

For the proton the EIC will determine an important term contributing to the proton mass, the so-called "QCD trace anomaly

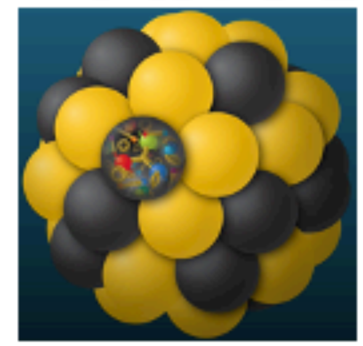


How are the quarks and gluon distributed in space and momentum inside the nucleon & nuclei?

How do the nucleon properties emerge from them and their interactions?

How can we understand their dynamical origin in QCD?

What is the relation to Confinement

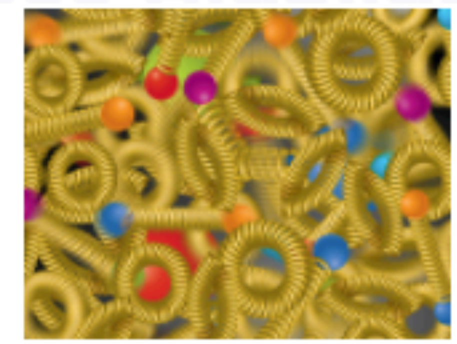


Is the structure of a free and bound nucleon the same?

How do quarks and gluons, interact with a nuclear medium?

How do the confined hadronic states emerge from these quarks and gluons?

How do the quark-gluon interactions create nuclear binding?



How many gluons can fit in a proton?

How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

What happens to the gluon density in nuclei? Does it saturate at high energy?

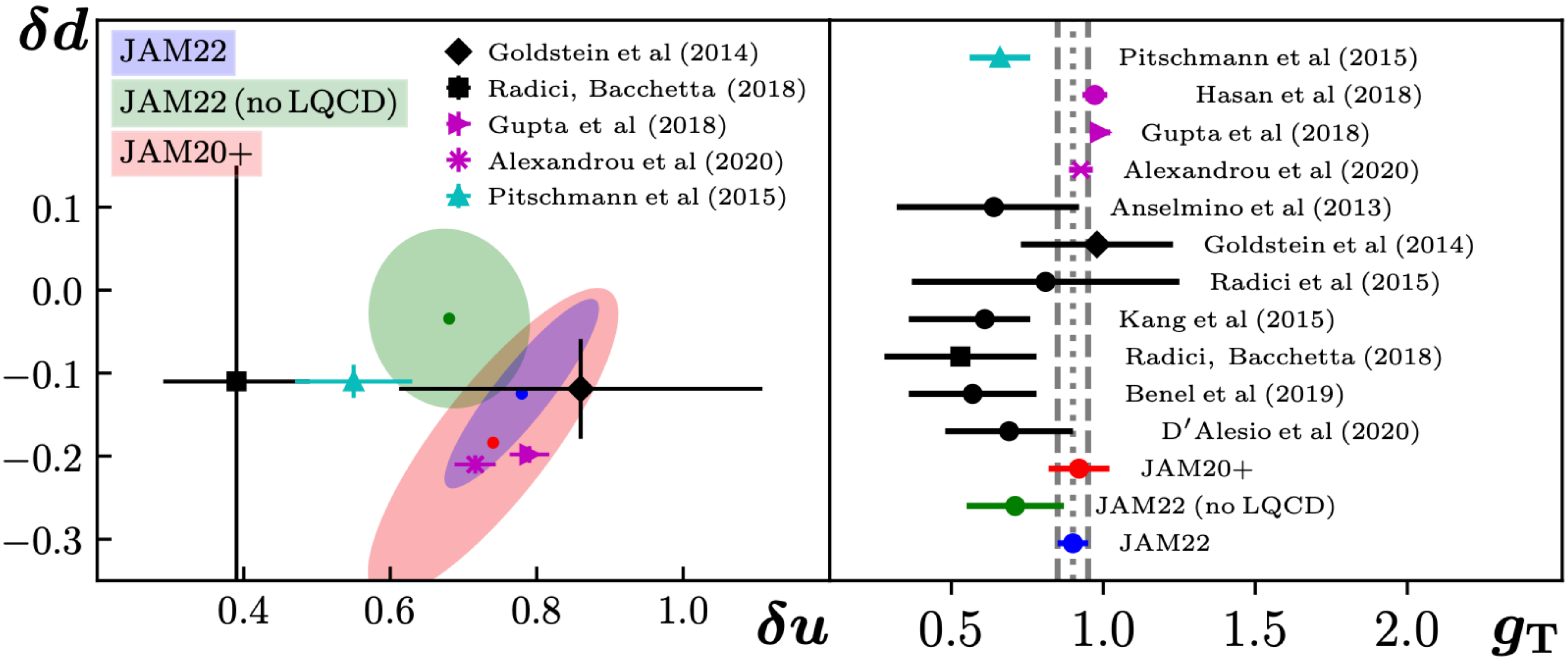
gluon splitting

gluon recombination

[Credit: E.C. Aschenauer @ Transversity 2024]

Theory opportunities

- Prominent new techniques in **Lattice QCD** (LQCD) have recently open new avenues to compute parton distributions:
  - **quasi-** and **pseudo-distributions**.
- LQCD started playing an important role in hadron structure:

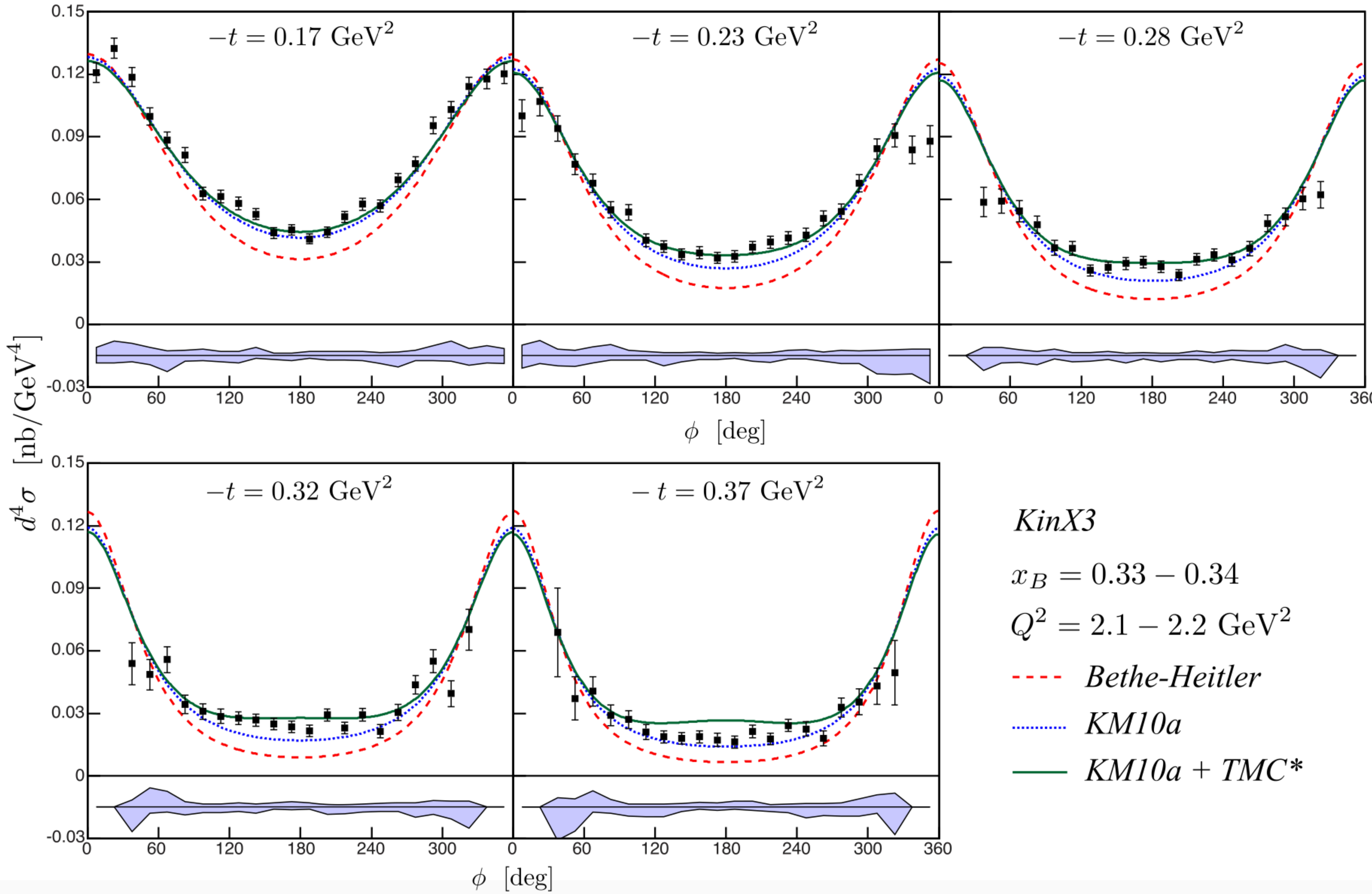


[Phys. Rev. D **106**, 034014 (2022)]

- LQCD is likely to become an indispensable tool.

Theory opportunities

- **Higher-twists** (HT) corrections, especially in the typical kinematic coverage of *exclusive* processes are typically **sizeable**:



[Phys.Rev.C92,055202(2015)]

- Important to account for HT effects.

Theory opportunities

- **Resummation** is a crucial ingredient for phenomenology at high-energies:
  - collinear resummation (DGLAP),
  - high-energy resummation (BFKL/BK/JIMWLK),
  - threshold resummation,
  - transverse-momentum resummation (CSS/CdFG),
  - resummation of power corrections,
  - …
- It is of the utmost importance to **incorporate** these effects in existing numerical frameworks:
  - make them easily **accessible** to the community (public codes),
  - determine parton distributions (PDFs/TMDs/GPDs) accounting for them.

Technological opportunities

- We are in the **high-performance-computing** (HPC) era:
  - hadron-structure community at the forefront to exploit this resourc.
- **Artificial intelligence** (AI) and **machine learning** (ML):
  - these technologies have already been very fruitful in the field of hadronic structure,
  - 3DPartons has already made massive use of them,
  - therefore, we are in a advantageous position to keep exploiting these technologies at best.
- **Quantum Computing** is now gaining momentum:
  - fast development of new devices and algorithms,
  - applications to physics in an exploratory phase,
  - prominent synergy with ML (QML).
- The NuPECC LRP provides a snapshot of the current status.

Conclusions

- **3DPartons** delivered **impactful results** in many areas of **hadronic structure**.
- It is built upon a solid **code infrastructure** that consistently incorporates the resulting developments making them **publicly available**.
- This puts 3DPartons in a unique position to exploit **present and future opportunities**:
  - current and future experimental facilities,
  - theoretical developments,
  - technological advances.