Groupe de travail 4

QCD et collisions d'ions lourds

Synthèse

Carlos Muñoz Camacho, Cyrille Marquet, Michael Winn

Symposium de restitution, Jussieu (Paris), 20 janvier 2025

GT4 community

- **LHC heavy-ion programme**
  ALICE, LHCb collider & fixed-target, CMS
- **Theory community**
  large, diverse & leading/strong contributor in a number of areas
- **Hadron structure programme**
  Jefferson Lab & Electron-Ion Collider

In contrast to other countries:

- **Small community for lower beam energy hadron/heavy-ion collisions**
  not addressed here
- **Hadron spectroscopy not a main topic for any group**
  not addressed here

Strong CP problem and related experiments, in particular neutron electron dipole moment, in GT2

GT4 workshop & contribution summary

- **Large participation by QCD/heavy-ion community**
- **Interesting and lively discussions**
- **Document focused on heavy-ions submitted to arXiv & to French website**
- **8 GT4 contributions of various type submitted to national strategy**

  Expect additional submissions from the community to ESPPU directly

  No contradictions in view of scenarios among submitted documents

  Full list with links in back-up

https://indico.in2p3.fr/event/33460/

Strong interaction research: relation to neighboring fields

QCD-Lagrangian is known

BUT not able to derive the **emergent** properties of strongly interacting matter

Motivation not dependent on beyond-the-standard-model physics at accessible scales

Strong-interaction research is complementary in its way of thought with respect to particle physics in its hunt for new physics!

Strong interaction:

- dominating ordinary matter in the universe
- high-temperature matter in the early universe
- high-baryon density matter in astrophysical objects such as neutron stars

Driving physics questions

- **Momentum/spin/charge/mass** of hadrons/nuclei in terms of **partons**
- **The mass spectrum** of strongly interacting particles
- Strongly interacting **matter properties** at finite temperature & baryon density
- Gluon **saturation** at high energy
- **Thermalisation** of strongly interacting matter
- **Hadronisation** in vacuum & from finite temperature/density matter
- **Vacuum** polarisation

Besides accelerator-based research:

Lattice QCD, atomic physics & gravitational waves: complementary

GT4 executive summary

1. **Keep heavy-ion beam** until the end of the HL-LHC

2. **Engage on LHCb U2 & ALICE 3**

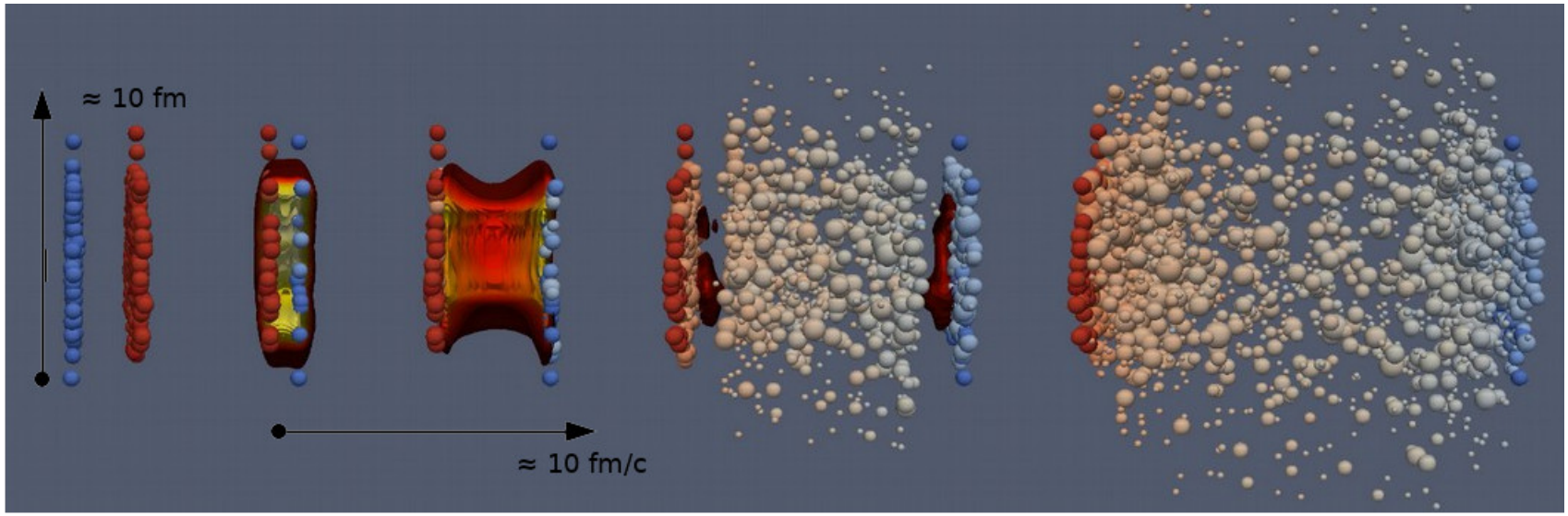
3. **FCC**-ee + FCC-hh as the first choice collider in Europe
   FCC-hh directly not viable, if no FCCee: prolongate LHC, lever LHC potential with LHeC, then FCC-hh

4. **Support** French & European teams on **Electron-Ion collider**
   physics and instrumentation synergy/interdependence with HL-LHC

5. **Support** French **theory** groups: keep leadership in key areas
   including areas relevant for precision Standard Model tests at low-Q^2

1) Heavy-ion beam until the end of HL-LHC: Motivation

Conventional Quark-Gluon Plasma (QGP) physics: convincing paradigm



Visualisation of a hydrodynamic simulation of a nucleus-nucleus collision by Madai project web page.

Time ordered ´standard model´ at colliders & in fixed-target LHC

- initial state
- preequilibrium phase ($\approx$ 0-1 fm/c)
- hydrodynamic phase ($\approx$ 1-10 fm/c)
- hadronisation

1) Heavy-ion beam until the end of HL-LHC: Motivation

Qualitative on key aspect

→ Understand **inner workings of the QGP and of its emergence**

- Microscopic picture of initial state
  Nuclear effects? Saturation?
- Onset of collectivity in small systems
  Where & what?
- Thermalisation from initial state to hydrodynamics
  How fast & how?
- Deconfinement: lattice QCD → cross-over!
  Where have all the *colours* gone? (P. Seeger adapted)
- Chiral restoration: lattice QCD → cross-over!
  Where have all the *partners* gone?
- Transition to hadrons: Hadronisation
  Statistical hadronization rules, but it didn't tell us the rules.

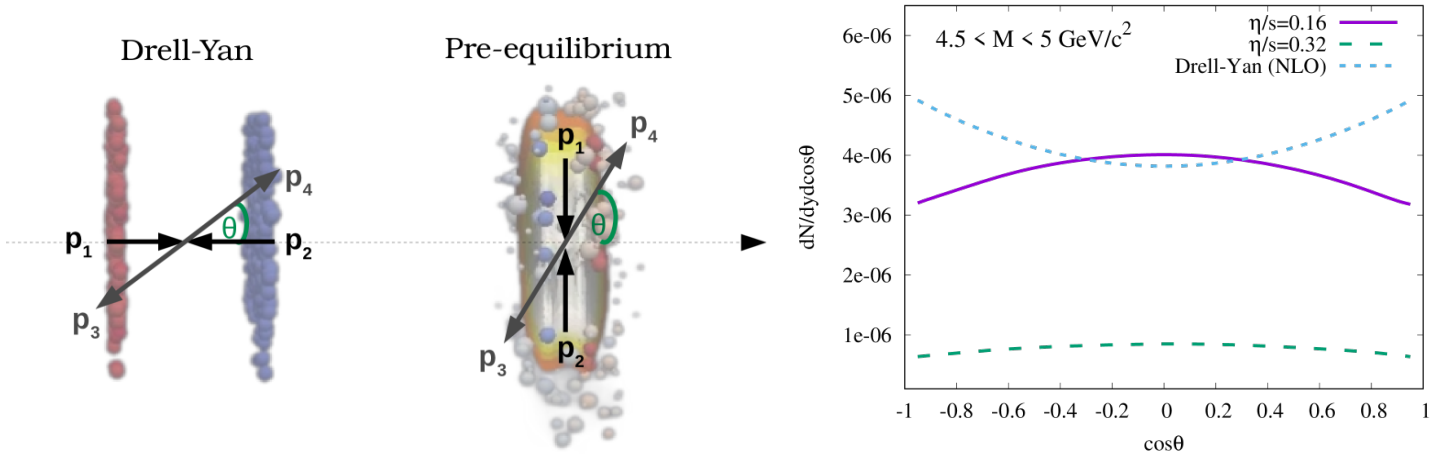
1) Heavy-ion beam until the end of HL-LHC: Observables

- Initial state
  → (semi)hard QCD in **hadron-γ/hadron@high lumi in parallel with EIC**
  p-nucleus/ultra-peripheral collisions, collider+fixed-target
- Onset of collectivity in small systems
  → **Light-ion collisions including p-nucleus vs. heavy-ion collisions**
- Thermalisation
  → **Light-ions**, **dileptons/γ from preequilibrium** , $D\bar{D}$ **(de)correlation**
- Deconfinement
  → **bound states with** > 2 **heavy quarks**: vary [acceptance, $\sqrt{s}$]→ crucial
- Chiral restoration
  → **line-shape** $\rho \to l^+l^-$,**net-baryon moments**: wide accept., $\sqrt{s} \to$ crucial
- Hadronisation
  → **heavy quarks**: vary [acceptance, $\sqrt{s}$] → crucial

Precision predictions for hard processes in multi-TeV ion collisions: 4 signing authors
Prospective report of the French QCD community to the ESPPU 2025 with respect to the program of the LHC Run 5 and beyond and future colliders at CERN 60 signing authors
French QCD community input to the ESPPU 2025 regarding the Electron-Ion Collider: 21 signing authors
QCD à haute énergie au HL-LHC et au futur collisionneur EIC: 6 signing authors

Intérêt français: particip. programme de physique & améliorations LHCb UII: 54 signing total, 25 'heavy-ion'

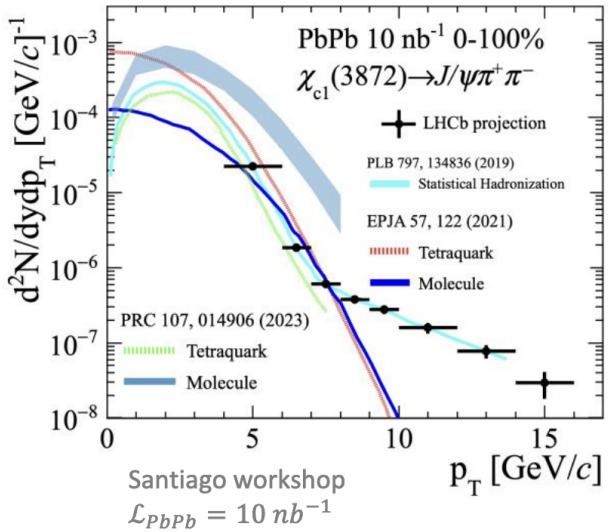
1) Example thermalisation: Dileptons

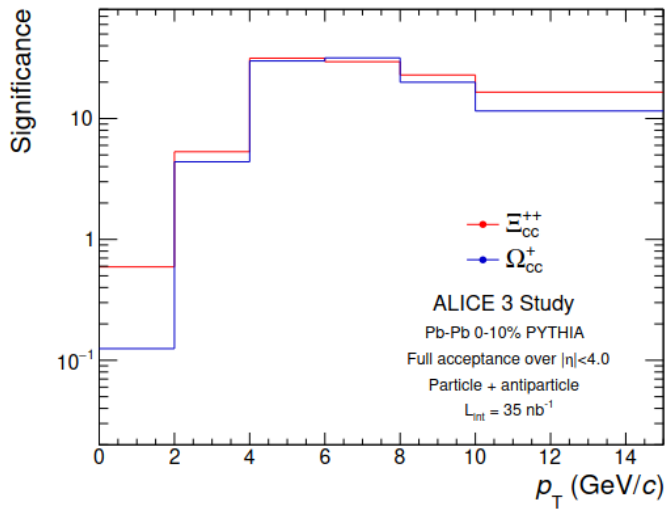


Collaboration between theorists & experimentalists in France & Germany in view of Run 5 PRL132, 232301 (2024)

- longitudinal expansion $\rightarrow$ initial pressure anisotropy, gluon domination $\rightarrow$ thermalisation pace to equilibrium badly constrained
- production yield dileptons: scenarios change production up to factor 10
  PLB 821 (2021) 136626
- polarisation dileptons: measure pressure anisotropy
  PRL132, 232301 (2024)
- excellent lepton ID at $p_T = 0.5 - 5$ GeV & heavy-flavour rejection
  LHCb U2 (muons) collider
  LHCb U2 (muons) fixed-target
  ALICE 3 collider (electrons)

1) Example deconfinement & hadronisation: Quarkonium, multi-heavy quark baryons & exotica





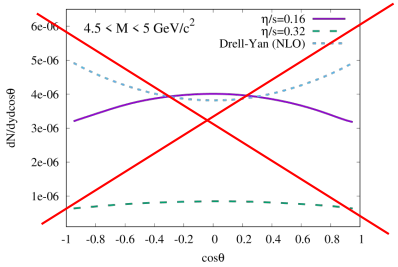
F. Fleuret (LHCb) [$c\bar{c}u\bar{u}$] & A. Maire (ALICE) [ucc, scc] @GT4 worksh.: LHCb U2 ions, ALICE3 LOI

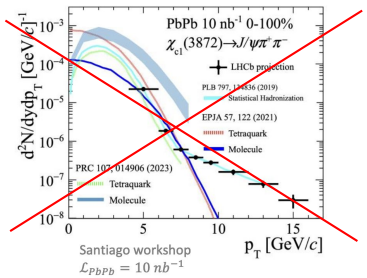
- deconfinement: defining QGP property
  → $c\bar{c}$ state regeneration: signature@LHC, but missing microscopics
  → fixed-target: assumed to reduce strongly regeneration
- hadronisation: limited microscopic understanding → major limitation
  → heavy quarks: additional constraints + variable size with exotica
- Run 5: multiple heavy-quark baryons, non-vector quarkonium states
  → vary rapidity, collision energy: T+heavy-quark density variation

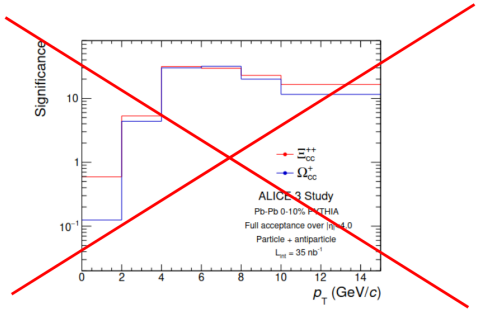
LHCb U2 collider & LHCb U2 fixed-target & ALICE 3 goals

2) Engage on LHCb U2 & ALICE 3

Programs not feasible without new instrumentation







- Complexity of heavy-ion collision physics
  → ≈ data-driven field

  → **advance** based on new instrumentation & new data: **non-linear**

  new full programs with advent of LHC, LHC proton-nucleus, RHIC-LHC non-round nuclei, precision angular correlations, flexible triggers in proton/nucleus-proton/nucleus and fixed-target collisions, see back-up
- **New fields** to take-off or from scratch with Run 5 instrumentation:
  → **femtoscopy**: heavy-quark state exotica spectroscopy pp to heavy-ions

  workshop GDR inF/QCD 2024 link

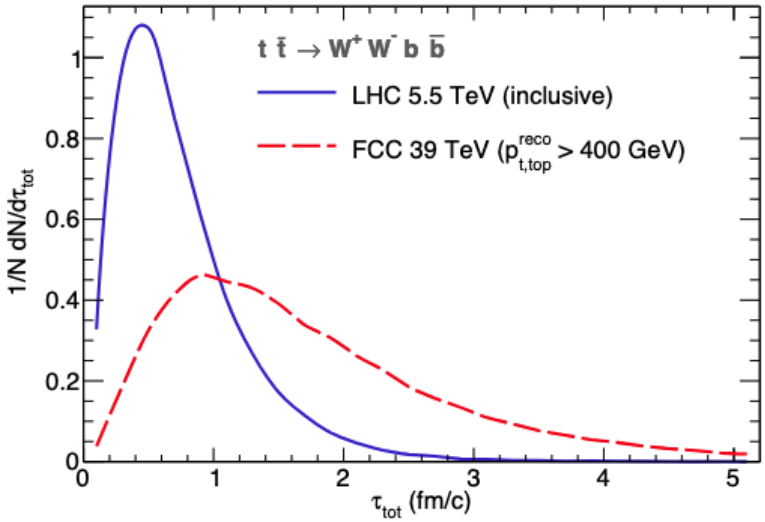
  → 10-300/*fb* for **high-multiplicity** *pp* **with soft physics**

  → **hydrodynamics for conserved charges**: not only energy-momentum
- instrumentation highly synergistic: LHCb U2 in common with GT2
  ALICE 3 vertexer/tracker precursor of FCCee

3) FCC-ee & FCC-hh as first choice collider in Europe

FCC-hh: QGP in a different regime and with new probes

- 500 charm quark pairs in central Pb-Pb collisions
- QGP state up to $\tau \approx 15\,\mathrm{fm}/c$
- collision energies and integrated luminosities:
  about 10× higher than the LHC each
- hard and heavy particles for tomography:
  $\rightarrow$ top quark, Higgs and other heavy objects also boosted in large numbers



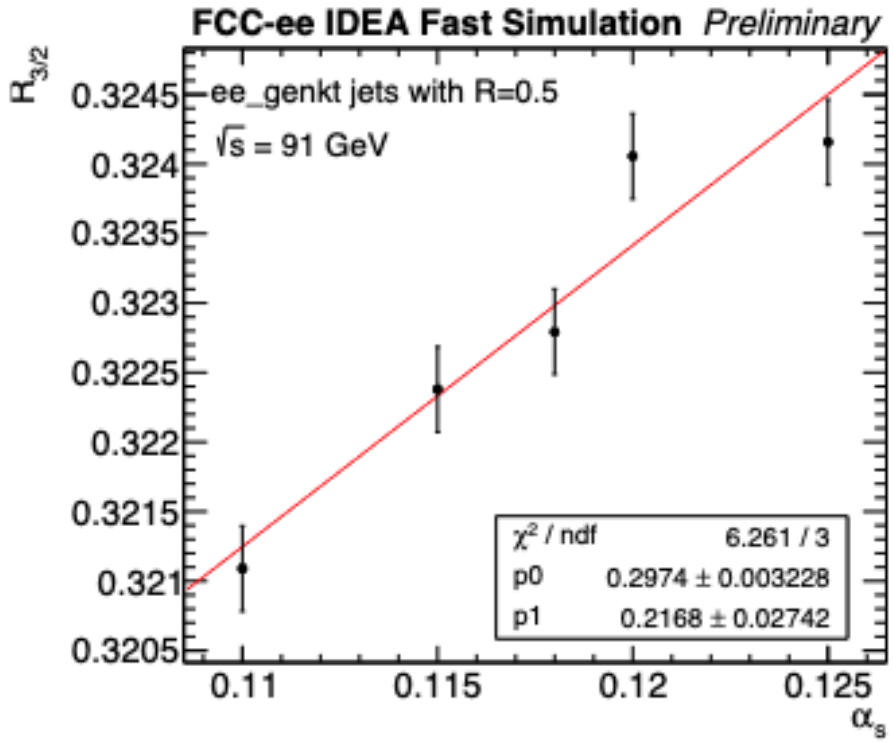
PRL 120 (2018) 23, 232301

Complementary new-physics-searches in $\gamma\gamma$-collisions with heavy ions
$(g-2)_\tau$, light-by-light scattering

Gluon saturation physics in γ-hadron: Bjorken-$x \leq 10^{-7}$

Prospective report of the French QCD community to the ESPPU 2025 with respect to the program of the LHC Run 5 & beyond and future colliders at CERN : 60 signing authors

3) FCC-ee & FCC-hh as first choice collider in Europe



Prospects of QCD and Lund Jet Plane studies at FCC-ee link

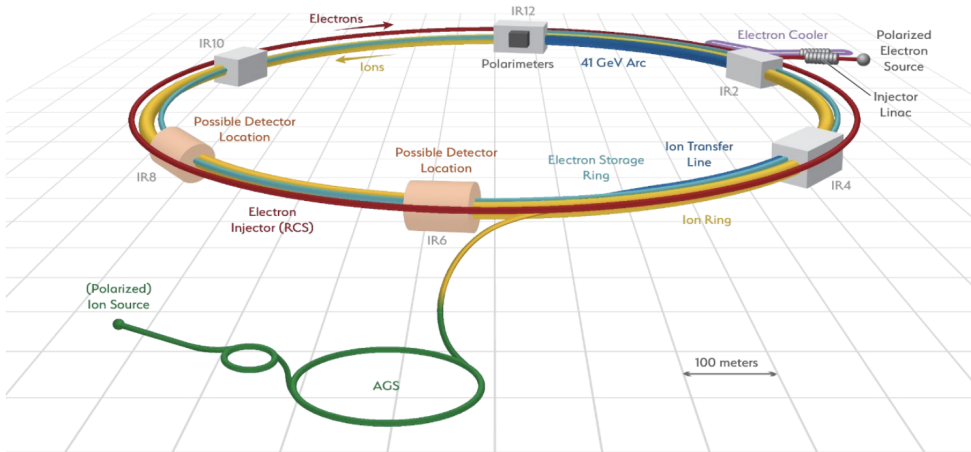
- Precision determination of α_s
- Precision studies of parton showers+non-perturbative phenomena with jets
- high-energy QCD in $\gamma^*\gamma^*$ collisions: small-x at lepton colliders
- Hadron spectroscopy

Prospective report of the French QCD community to the ESPPU 2025 with respect to the program of the LHC Run 5 & beyond and future colliders at CERN : 60 signing authors

Prospects of QCD and Lund Jet Plane studies at FCC-ee: 5 signing authors

4) Support Electron-Ion Collider

- Polarized beams: e, p, d/3He
- e beam 5-10 (18) GeV
- Luminosity $L_{ep} \sim 10^{33\text{-}34}$ $cm^{-2}sec^{-1}$ (100-1000 times HERA)
- 20-100 (140) GeV Variable CoM
- Nuclei from p to Uranium
- Two interaction regions
- One detector from day-0, strong wish for a second detector

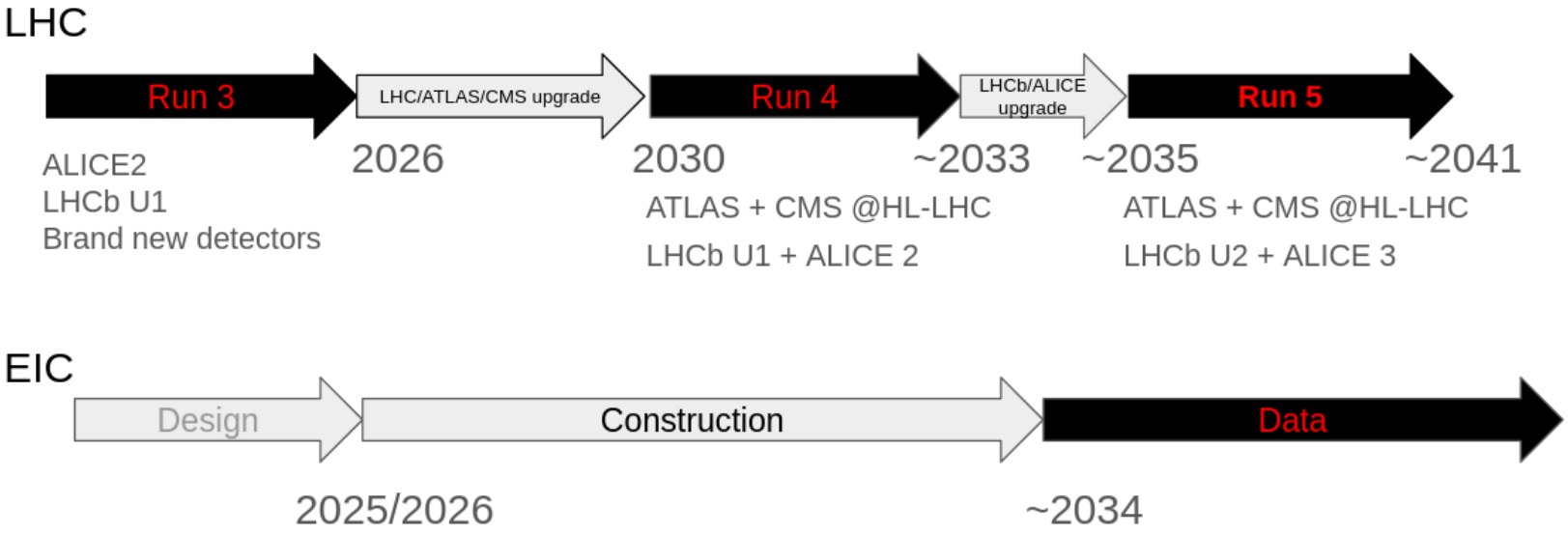


EIC in a nutshell from F. Bossu at GT4 workshop

- Electron-Ion Collider: GT4 supports strong French contribution

French QCD community input to the ESPPU 2025 regarding the Electron-Ion Collider: 21 signing authors
Prospective report of the French QCD community to the ESPPU 2025 with respect to the program of the LHC Run 5 & beyond and future colliders at CERN : 60 signing authors
QCD à haute énergie au HL-LHC et au futur collisionneur EIC: 6 signing authors

4) HL-LHC + Electron-Ion Collider timeline



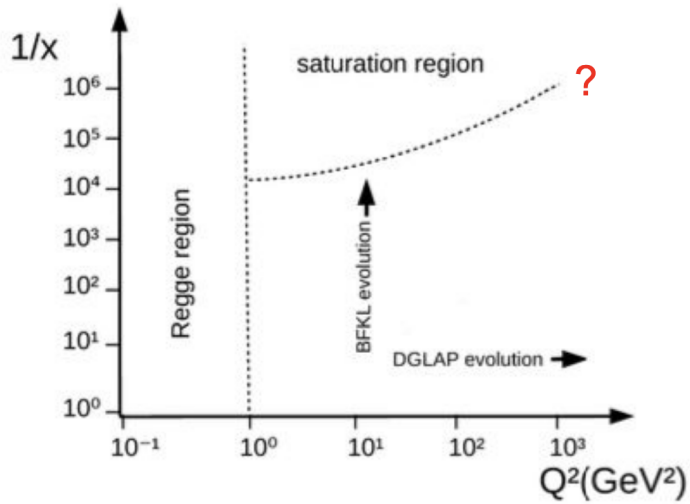
LHC and EIC will be running in parallel for 5-10 years

- Strongly beneficial for physics output during this period
- synergy & dependence of EIC instrumentation from ongoing LHC

  prominent technology example: CMOS pixel detectors for tracking

4) Example: synergy HL-LHC + EIC for gluon saturation

Major pillar of Electron-Ion Collider program



modified version of graphic in "QCD and collider physics", Ellis, Stirling, Webber

- French theory: key contributor
- Complementarity between LHC and EIC:

  $\rightarrow$ similar rates in photoproduction
  $\rightarrow$ Bjorken-x 10 times lower@LHC
  $\rightarrow$ better kinematic control & precision@EIC
- Support:

  - experimental programs at
  1) Electron-Ion Collider
  2) in photon-induced reactions at the LHC
  ultra-peripheral collisions
  - theory

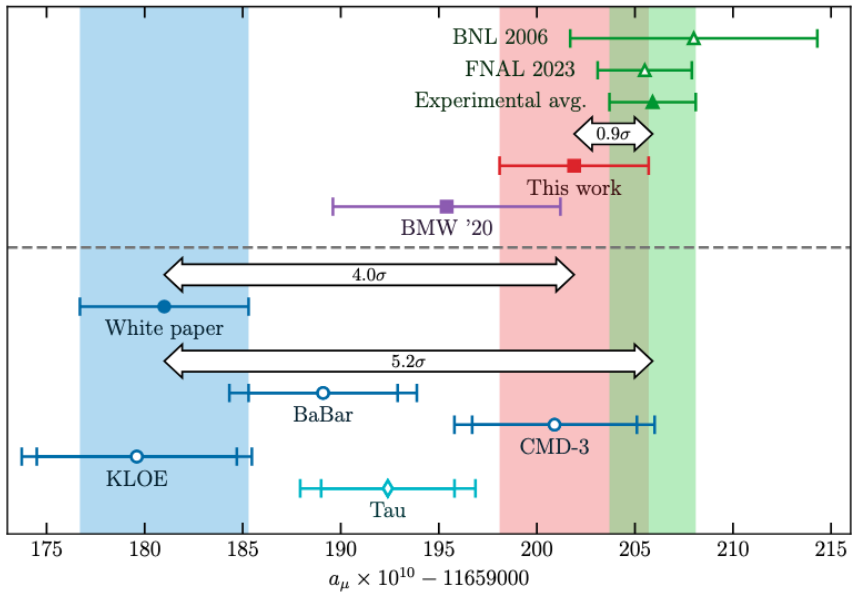
5) Support French theory groups: Overview

French community leader/strong contributor in a large number of domains

- Gluon saturation
- Quarkonium
- Hydrodynamics
- Heavy-quark and hadron transport
- Event generators and community software tools
- Jet physics and parton showers
- Generalised parton & transverse momentum dependent distributions
- Collinear proton and nuclear parton distribution functions
- Lattice QCD
- Higher order calculations
- Interfaces: nuclear & particle physics, cosmology, statistical mechanics, generic QFT

Precision predictions for hard processes in multi-TeV ion collisions: 4 signing authors, QCD sur réseau 8 signing authors, Prospects of future vacuum polarisation studies & applications: 14 signing authors, Prospective report of the French QCD community to the ESPPU 2025 with respect to the program of the LHC Run 5 & beyond and future colliders at CERN : 60 signing authors, French QCD community input to the ESPPU 2025 regarding the Electron-Ion Collider: 21 signing authors, QCD à haute énergie au HL-LHC et au futur collisionneur EIC: 6 signing authors

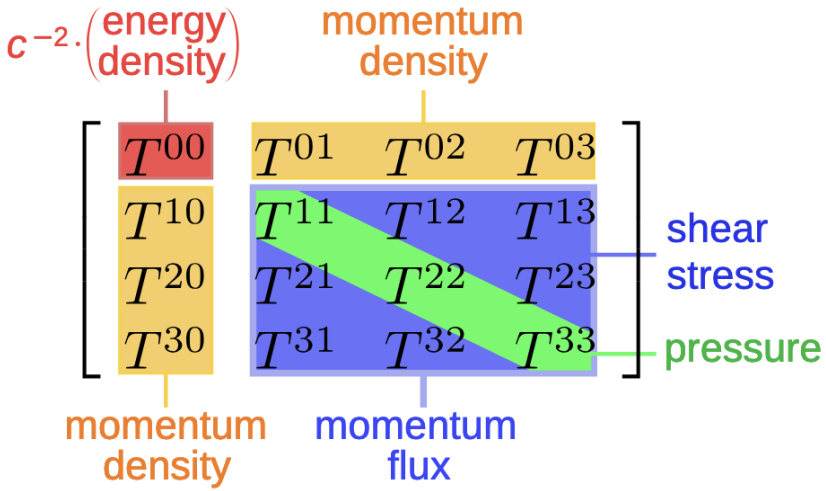
5) Example of QCD theory importance: precision Standard Model tests



arXiv:2407.10913: LQCD combined with dispersive approach for long-distance, French collaborators from both sides

- hadronic vacuum polarisation and hadronic light-by-light leading uncertainties in theory calculation of $(g-2)_\mu$
- Two competing approaches:
  1) data-driven dispersive framework using experimental data
  2) Lattice QCD
  $\rightarrow$ France key contributor on both sides
- Important part of particle physics ecosystem

5) Example of 'entanglement': experiment & theory in hadron structure



How energy, momentum, pressure are shared between quarks and gluons

Caveat: renormalization scheme and scale dependence

C. Lorcé *et al.*, PLB 776 (2018) 38-47,
M. Polyakov and P. Schweitzer,
IJMPA 33 (2018) 26, 1830025
C. Lorcé *et al.*, Eur.Phys.J.C 79 (2019) 1, 89

Taken from C. Mezrag at 1st French EIC Colloque 2024. link

- generalised parton distribution function:
  mass & spin decomposition, pressure in terms of partons
  → quantities-of-interest: difficult deconvolution problem
  → theory very involved in 'signal extraction'
- France key contributor:
  → concepts + software tools + perturbative calculus + new observables
  → develop use of lattice QCD on equal footing as experimental data
- strong theory important to fully exploit Electron-Ion Collider

Scientific responsibility: LHC data preservation

Large temporal gap between LHC & next hadron-hadron collider if built

Finite available resources & insight for full data exploitation during LHC lifetime

Need to enable further data analysis after LHC lifetime

- Extent knowledge about QCD
- Preserve knowledge for future hadron colliders if built

Not formalised in a GT4 contribution
$\rightarrow$ but lively debated at GT4 workshop

Discussed in S. Kraml's contribution:
Reinterpetation and preservation of data and analyses in HEP

Conclusion

QCD physics cases

compared to high-energy physics in the search of new physics

- **fundamentally different**
- **as fundamental** for our understanding of the universe

They embrace that the **world in its complexity cannot only be understood in a reductionist way** of thought that reduces a given system to the understanding of its constituents and their fundamental interactions.

'We must know, we will know.'
David Hilbert

Back-up

Submission summary

4 contributions with GT4 as primary group

- Prospective report of the French QCD community to the ESPPU 2025 with respect to the program of the LHC Run 5 and beyond and future colliders at CERN

  write-up from GT4 workshop, community report dominated by experimentalists focused on LHCb U2, ALICE 3, FCC, synergy with EIC

- French QCD community input to the ESPPU 2025 regarding the Electron-Ion Collider

  experimentalists dominated document in support of EIC; synergy in physics and instrumentation w.r.t. CERN-based projects

- QCD à haute énergie au HL-LHC et au futur collisionneur EIC

  saturation theory group in support of related theory and EIC and HL-LHC

- Precision predictions for hard processes in multi-TeV ion collisions

  group of perturbative QCD theorists, nuclear parton distribution functions from hard processes at HL-LHC

Submission summary

5 contributions with GT4 as secondary group

- Intérêt de la communauté française pour une participation au programme de physique et aux améliorations du détecteur LHCb pour la période 35–41 (LHCb Upgrade II)

  experimentalists interested in LHCb U2: flavour + QCD/heavy-ion

- QCD sur réseau

  theorist group, importance, support and challenges for lattice QCD

- Prospects of QCD and Lund Jet Plane studies at FCC-ee

  high-energy physics group support for precision QCD studies with jets with the Lund Jet plane for α_S determination and improvements in jet modeling, tagging and performance

- Prospects of future vacuum polarisation studies & applications

  diverse group: low/medium-Q^2 particle physics, atomic physics and lattice QCD for precision tests of the Standard Model partially limited by QCD knowledge

- Addendum: 'Contribution of the members of IRFU to ESPPU' on strong interaction

  IRFU DPhN physicists statement in view of future colliders

1) Example chiral transition: net-baryon fluctuations

- chiral restoration: defining property of QGP
- type of phase transition unknown: universality class
- net-baryon fluctuations on the lattice & in experiment via net-proton
- fluid dynamics not only with energy-momentum, but with conserved charges
  $\rightarrow$ large acceptance with hadron-ID down to low-p_T
- ALICE 3 goal

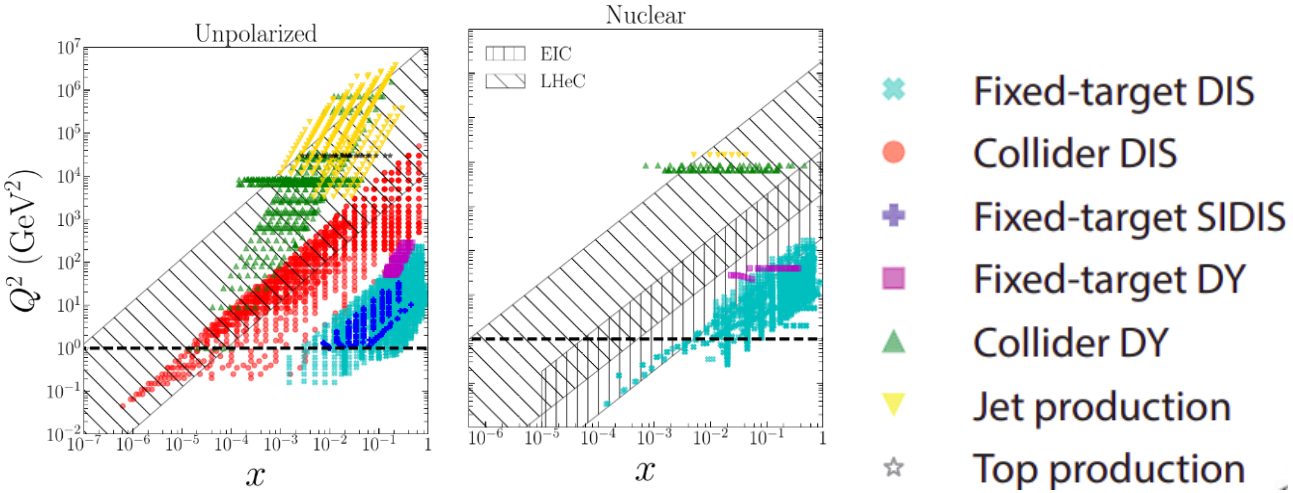
Prospective report of the French QCD community to the ESPPU 2025 with respect to the program of the LHC Run 5 & beyond and future colliders at CERN

Heavy-ion advances with new instrumentation and data

New subfields of heavy-ions at the LHC not existing before at RHIC
largely not anticipated prior to data, impact beyond QGP physics

- Collider nucleus-nucleus: vertexing and jet performance
  jet physics with substructure, heavy-flavour with baryons
- Collider proton-nucleus: precision at forward rapidity & high-rate recording or software triggering
  nuclear PDF, collectivity
- Collider proton-proton/nucleus: high-multiplicity triggering
  femtoscopy of baryon-baryon systems in particular hyperons for hadron-hadron interaction constraints
- Collider non-round nuclei: beam choice
  nuclear structure physics based on hydrodynamic paradigm
- Collider nucleus-nucleus: Angular precision correlations
  Bayesian fits matter properties
- collider proton/nucleus-nucleus: flexible triggers & forward instrument.
  γ-induced reactions for BSM & DIS physics
- Fixed-target: hadron-PID & heavy-quark
  cosmic ray reference for AMS
  hadronisation with heavy-quarks: valence quark impact

LHeC: genuine QCD motivation



ARNP Vol. 70, 2020 , for nuclear case without low-x by LHC charm/beauty production data.

- ep: electron beam > 50 GeV: $\sqrt{s} = 0.2 - 1.3$TeV ($\times$ 4 HERA), $L_{inst} = 10^{34}$ cm^{-2}s^{-1} ($\times$ 10^2-10^3 HERA) ≈ 100 fb^{-1}, ≈ 1 ab^{-1} total
- ePb: $\sqrt{s_{eN}} = 0.74$ TeV ($\times$ 10 EIC): $L_{inst,eN} = 0.7 \cdot 10^{33}$ cm^{-2}s^{-1} ($\approx$ EIC)
- LHeC: ultimate machine for saturation physics

  kinematic reach $\approx$ LHC but DIS + nuclear targets, French theory active on physic case
- precision collinear PDFs for hadronic collisions, α_s determination
- important to lever LHC (+FCC-hh) QCD+BSM, but limited number of experimentalists as first priority in past efforts (none in France)
- convert one interaction point from hh to eh focus at LHC
- HE-LHC partly discussed in community: since ´18 (WG5 Yellow Report), no further push

numbers for top energies: P. Newman at DIS 2024 link, The LHeC at the HL-LHC, JPGNPP 48 (2021), EIC CDR