Heavy-ion physics at LHCb: **Physics motivations and proposed measurements**

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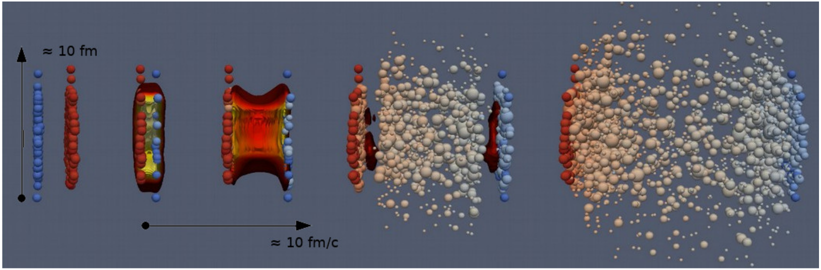
CSTD DPhN

Outline

- Context
- Dilepton observables
- Heavy-quark observables
- Conclusions
- Bonus: more on fixed-target, ultra-peripheral collisions, b-physics

Heavy-ion collisions at colliders in a nutshell



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

Time ordered ´standard model´ at colliders

- initial state: quarks and gluons in colliding hadrons
- preequilibrium phase ($\approx$ 0-1 fm/c): fast ´thermalisation´
- hydrodynamic phase ($\approx$ 1-10 fm/c): $\approx$ Quark-Gluon Plasma (QGP)
- hadronisation: transition from QGP to ordinary hadrons

Heavy-ion collisions at colliders: open questions

- **initial state**:
  saturation at highest collision energy?
  Novel access to nuclear and hadron geometry: What can we learn?
- **fast thermalisation**:
  Where, small system puzzle (hydro in proton-proton/ion), and how fast?
- **thermodynamics**:
  How we get precise equation of state & transport properties from data?
- **´inner workings´ of Quark-Gluon Plasma**:
  Which degrees of freedom at which temperature & resolution scale?
- **hadronisation**:
  Differences of hadronisation from QGP vs. vacuum?
  Unique hadron-hadron interaction from correlations: How far we can get?

A physics programme for the next 15 years

Heavy-ion at colliders:

- established ´standard-model´
- key open questions **to be addressed experimentally**

An experimental engagement should be:

- ambitious
- lasting $\rightarrow$ stand the tide of time
- diverse $\rightarrow$ field can change
- sustainable $\rightarrow$ physics all along the way
- realistic $\rightarrow$ well adapted to the human and budget ressources

Physics drivers of LQGP programme

- **Thermalisation**:
  Do heavy quarks fully thermalise? Under which conditions?
  Which time scale for kinetic & chemical equilibration towards hydro?

  need data from various colliding systems/energies
  photon/proton/heavy-nucleus + proton/heavy-nucleus/noble gases

- **Hadronisation**:
  progress on the microscopic picture with precision heavy-flavour data

  need data from various colliding systems/energies
  photon/proton/heavy-nucleus + proton/heavy-nucleus/noble gases

- **Saturation**:
  highest beam energy to test high-energy limit behaviour
  $\rightarrow$ so far elusive: need precision & different observables

Physics observables of LQGP programme & strategy

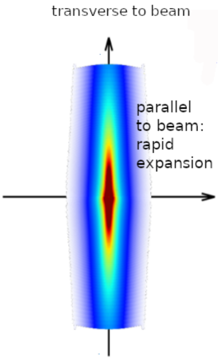
Two observable groups access thermalisation, saturation and hadronisation:

- **Continuum dileptons**
- **Open heavy-flavour + Quarkonium**

Ideal for this programme: **LHCb Upgrade 2**

- now & years to come:
  proton-proton, proton-lead, up to 30% lead-lead with LHCb Upgrade 1
  Complementary to ALICE LQGP activity in lead-lead collisions
- upgrade 2 starting in 2030ies:
  most central lead-lead collisions enabled by UT & other upgrades
  see Benjamin Audurier's talk
- further opportunities
  $\rightarrow$ Ultra-peripheral collisions: **saturation**/thermalisation/hadronisation
  $\rightarrow$ Fixed-target collisions: **thermalisation/hadronisation**

Why is the preequilibrium critical?



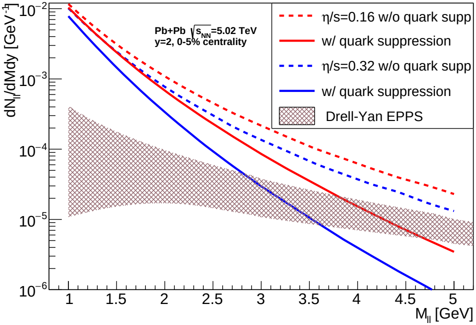
Longitudinal cooling at early times,

adapted from: Schlichting,

Teaney ARNPS 69 (2019)

- initially **far from equilibrium**
  rapid longitudinal expansion
  very few quarks initially
- **time scale not known** of hydro start:
  $\rightarrow$ very different Ansätze
  $\rightarrow$ **BUT:** universal scaling between Ansätze
- **no experimental access so far**:
  electromagnetic probe needed
- dileptons: mass ´dials in´ time

Dileptons: probe of the preequilibrium

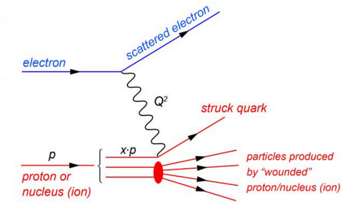


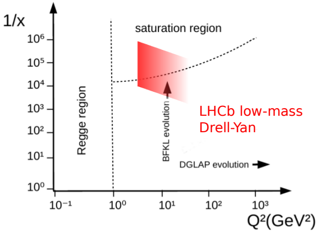
Coquet et al. PLB 821 (2021) 136626, m_T-scaling Nuclear Physics A 1030 (2023) 122579

- immediate equilibration & quark suppression from state-of-the-art
- equilibration time scale $\propto \eta/s$: **one order of magnitude variation at high mass**
- **polarisation: access to QGP anisotropy** Coquet et al. PRL 132, 232301 (2024)

Theory collaboration: DPhN-IPhT(Saclay theory)-Uni Bielefeld

Dileptons and saturation

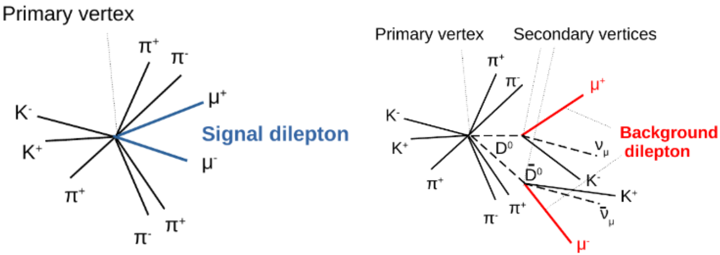




- standard picture of initial state: non-interacting partons, quarks & gluons
- theory: break-down at large collision energy (small x)
  $\rightarrow$ growing gluon densities don´t fit into hadrons: gluon saturation

- Drell-Yan: theoretically cleanest at hadron collider
- no competition with deep-inelastic scattering (DIS), but
  low-mass LHCb Drell-Yan beyond reach of past & future DIS

Dileptons: background challenge



- charm & beauty cross sections large at hadron colliders: many gluons
  → charm/beauty hadrons decay semileptonically: about 10% probability
  → Drell-Yan 1-2 orders of magnitude smaller
- no publication: missing central piece of LHC physics

Dileptons: Why LHCb?

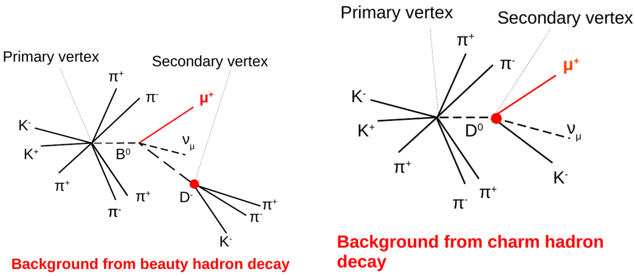
Instrumentation and acceptance

- best vertexing: best resolution, longitudinal boost
- good muon performance
  →provided ideal PID: muons better than electrons
  Less hadron decays ending up with muons than with electrons (π^0/η)
- forward rapidity for saturation
- complementary to ALICE

Beyond heavy-ion physics

- hadron structure: complementary to Electron-Ion Collider
- collaboration interest in Dark Photon searches with same final state

Dileptons: new methods



Beauty and charm background.

- **Rejection so far**: based on lepton and lepton pair kinematics
- **Proposal**: tagging secondary vertices related to muons
  $\rightarrow$ if tagged: 1 order of magnitude better S/B
  $\rightarrow$ game changer enabled by longitudinal boost at forward rapidity
  $\rightarrow$ first exploratory study Phys.Lett.B 821 (2021) 136626

Dileptons: status and plans

Status

- Funding from French ANR and Physics graduate school
- 2 postdocs: Imanol Correira (2024-2027), Carolina Arata (2024-2026), PhD student Alisha Lightbody (2024-2027)
- Trigger preparation: lower momentum threshold 2024 implemented $\rightarrow$ allow first measurement, discussion ongoing with collaborators

Short-term goals

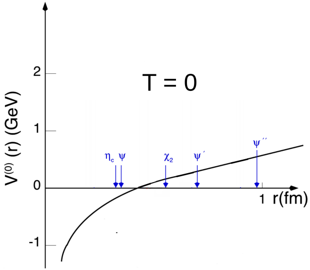
- heavy-flavour vertex tagging to improve S/B
- proton-proton Drell-Yan down to mass $\approx$ 3.0 GeV with 2024/2025 data
  about 100 x more lumi than LHCb-preliminary LHCb-CONF-2012-013
- feasibility study in heavy-ion collisions in Run 3 and in Upgrade 2
- optional: pPb measurement

Theory support

- PhD Mika Spier (2023-2026) with Bielefeld:
  NLO preequilibrium, event generator for dileptons & extension to charm
- PDF/TMD expertise in house (V. Bertone) for best-practice for fits

Quark-Gluon Plasma: heavy quarkonium as a tool

- Key measurements in heavy-ion collisions:
  signatures of deconfinement
- **Heavy quarkonia:**
  bound states of $c\bar{c}/b\bar{b}$—quark pairs
  model systems for interaction of color charges at T=0 and finite T

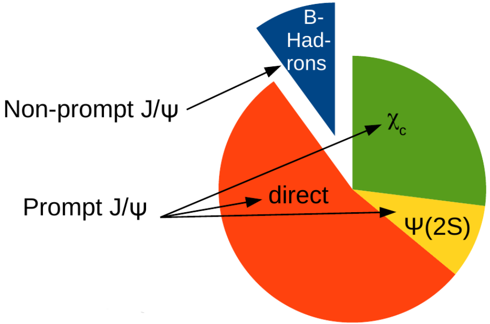


Adapted from EPJC 71:1534 (2011).

- Color screening and medium-induced dissociation influencing bound states
  suppression first as sign of deconfinement in heavy-ion collisions by Matsui & Satz PLB 178 (1986)
- Theory effort towards quantitative understanding
  theory review by A. Rothkopf Phys.Rept. 858 (2020)

Detection in heavy-ion collisions

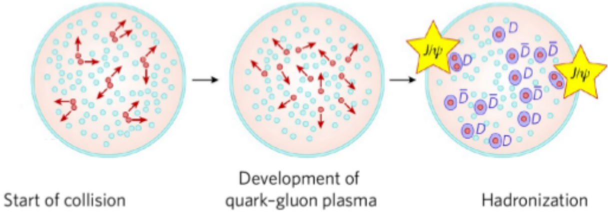
- Charmonium ($c\bar{c}$) bound vector states **J/ψ and ψ(2S)**
  BR(J/ψ $\rightarrow$ $e^+e^-/\mu^+\mu^-$) $\approx$ 6 %
  BR(ψ(2S)$\rightarrow$ $e^+e^-/\mu^+\mu^-$) $\approx$ 0.8 %
  $\rightarrow$ **accessible in nucleus-nucleus collisions**
- final states with hadrons or photon at low p_T: huge combinatorial background ($\pi^{\pm}$,$K^{\pm}$,p, $\bar{p}$ $\pi^0 \rightarrow \gamma\gamma$/event$>>$1)
  $\rightarrow$ no measurements in nucleus-nucleus collisions: **so far!**
- **Inclusive** J/ψ production in hadronic collisions:



- approx. production fractions integrated over p_T in pp collisions at TeV-scale collision energies.
- most commonly measured J/ψ includes significant χ_c contribution
  $\rightarrow$ need to be modelled!

Charmonium in heavy-ion collisions at the LHC

- Large initial charm quark densities & charm conserved: new recombination mechanism beyond ´melting´ $\rightarrow$ late stage production or **non-primordial production: sign of deconfinement**



P. Braun-Munzinger and J.Stachel, Nature 448 (2007)

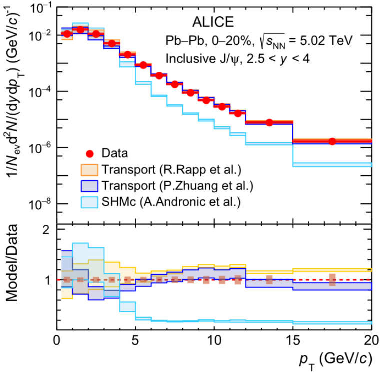
2 type of scenarios in this spirit:
statistical hadronisation & transport models

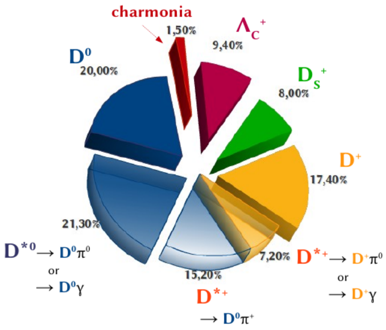
statistical hadronisation (SHMc): PLB797 (2019) 134836, transport (Rapp) NPA 943, (2015). transport (Zhuang): PRC89, 5(2014)

Confirmed experimentally with ALICE, leading contribution from Saclay

e.g. PRL 109 (2012) 072301, PLB 734 (2014), JHEP 05 (2016) 179, PLB 849 (2024) 138451

Charmonium: deconfinement & the initial state

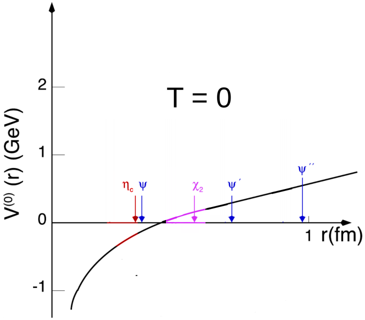


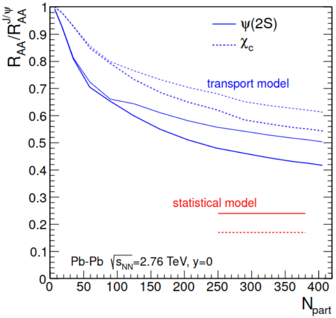


Left: PLB 849 (2024) 138451; Right: total charm in e^+e^- link; different in pp JHEP 12 (2023) 086.

- common uncertainty: total charm production in nucleus-nucleus collisions
  → in transport model nearly 2× larger than in statistical hadronisation
- **Total charm production is an observable!**
  → goal LHCb U1 & U2 forward: complementary w.r.t. ALICE/CMS

Charmonium: deconfinement beyond vector states

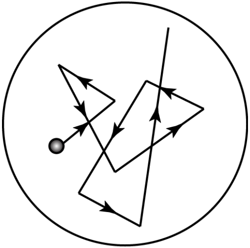


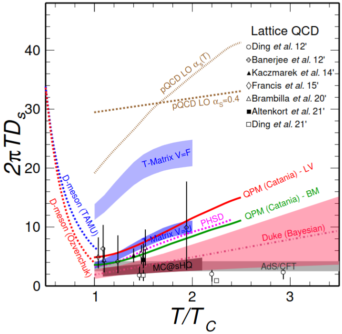


Right: link, $R_{AA} = Y^{AA}/(< T_{AA} > \cdot \sigma_{pp})$, i.e. deviation from AA as nucleon-nucleon superposition.

- Only S-wave $q\bar{q}$-states in nucleus-nucleus so far
  $\rightarrow$ precision ALICE/CMS/LHCb: 20ies with J/ψ & ψ(2S)
- goal LHCb: χ_c, η_c fixed-target + collider
  $\rightarrow$ confirmation of J/ψ & ψ(2S)
  $\rightarrow$ beyond established qualitative picture: time-scales & quantum aspects

Heavy quarks: Brownian motion & hadronisation





Right: charm-quark spatial diffusion D_s Apolinario, Lee, Winn. Prog.Part.Nucl.Phys. 127 (2022) 103990

- Heavy quarks: massive colour charge carrier diffusion in QGP
  → large theory/experimental uncertainties: better precision needed
- 20ies:
  → ALICE, CMS, LHCb (up to 30% centr.) tracking precision limitation
  → statistically limited for hadronisation (baryons) & beauty
- LHCb Upgrade 2: constrain hadronisation, transport precision with beauty
  → conserved charm/bottom, exotic states: Tetraquark et al.

Heavy quarks: Why LHCb?

Instrumentation and acceptance

- best vertexing: best resolution, longitudinal boost
- good muon and hadron-particle identification performance
- most interesting rapidity range: change of charm/beauty density
- complementary acceptance to ALICE and CMS

Beyond heavy-ion physics at collider

- hadron structure: complementary to Electron-Ion Collider
- high-luminosity charm/beauty physics in pp
  flavour physics
  high-multiplicity pp programme
- fixed-target lever arm in energy: unique at LHC

Heavy quarks: key methods

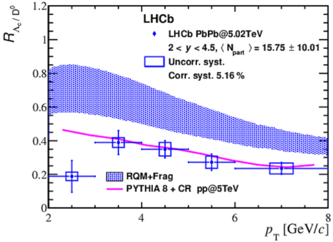
Tracking

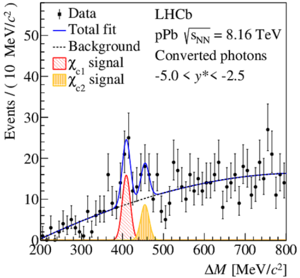
- heavy-ion collisions
  $\rightarrow$ profit already now from Upgrade 2 studies to improve running Run 3/4
- leading expertise

Secondary vertexing

- synergy with dilepton measurements to push to low-p_T and to $c\bar{c}$ correlations

First steps: baryons in peripheral collisions & χ_c in pPb





Left PbPb Λ_c: JHEP 06 (2023) 132, Right pPb χ_c: PRL 132 (2024) 102302

- χ_c in pPb showing feasibility in semi-peripheral collisions
- 1st charm baryons by LHCb in PbPb (2018 data): challenge for models in conjunction with ALICE/CMS
- next with 2023/2024 data: azimuthal anisotropy v_n
- next with 2023/2024 data: more central collisions limitation from 70% (2018) to 30% (2023), see Benjamin talk for details

Heavy quarks: status and plans

Status

- PhD student Carlos Barbero Pretel (2023-2026) with Santiago de Compostella on lead-lead χ_c analysis
- Benjamin Audurier involved in first Λ_C/D^0 measurement in 2023 data with CERN-master student

Short-term and midterm goals

- first χ_c measurement in heavy-ion collisions at the LHC
- first flow measurements of open charm forward at the LHC

- enlarge programme to fixed-target collisions in next years
  $\rightarrow$ co-supervision Gabriel Ricart with LLR (PhD, 2022-25) pNe, D^+/D_s^+
  $\rightarrow$ Andry Rakotozafindrabe involved in physics studies at the origin of LHCb fixed-target (AFTER)

Luminosity: pp, heavy-ion programme now & upgrade 2

Accelerator limited, data-rates/radiation PbPb $<<$ pp

- Now modest requirements for Drell-Yan pp: a few 1/fb
- Now modest requirements for first χ_c in PbPb: 2024 plan sufficient

- Drivers Upgrade 2: beauty, $c\bar{c}$ correlations, dileptons, χ_c in central charm programme + less differential dilepton studies: lower luminosities

$\rightarrow$ **ask for as much as possible**

- Goals pPb (HL-LHC Yellow Report): 1 month run 500/nb total
  baseline for Run 3/4 projections link
- Tentative goals PbPb for upgrade 2 if PbPb: 2.8 /nb per month
  factor 2 below ALICE/ATLAS/CMS, see ALICE link
  worst case: factor 5 below (plan 2023-2025)
- Lower than ALICE:
  1): $L \propto 1/\beta^*$, β^*_{ALICE} =0.5 m, best LHCb so-far (pPb): β^*_{LHCb} =1.5m, investigation: 0.8-1.0 m
  2): PbPb: bunch structure & filling scheme, difficult to collide in LHCb+ALICE: compromise to be found
  3) ultimate limit collimation: $Z-1$-ion production, secondary beam
- Lower mass ions: larger luminosities

Results now: LHCb stronger player at the table

Risks: heavy-ions at LHCb in Upgrade 2 at Saclay

No/little LHCb Upgrade 2

e.g. because of early FCCee

- pp, pA, UPC programme not affected; fixed-target ion-ion partially
- still a full programme
- nucleus-nucleus: light enough ions for LHCb, but still with QGP
  WG5 HL-LHC Yellow Report & ALICE 3 LOI: higher luminosities
  link Table 1 for newest numbers, e.g. Kr-Kr or Ar-Ar

Strong group committments ALICE+LHCb

- exploitation ALICE + LHCb in the years to come:
  next staff recruitment on LHCb with hardware affinity
  technical associate for ALICE for maintenance in long shutdown
- until Upgrade 2: involvement on current LHCb hardware modest (piquet...)
  $\rightarrow$ reconstruction implication to be reevaluated after initial phase
- constant personnel on LQGP topic at DPhN required to keep promises
  currently 8 staff members: two departures before 2030
  $\rightarrow$ to be replaced

Conclusions

Now: unique dileptons and heavy quark programme in collider mode

- Drell-Yan in proton-proton & heavy-flavour in nucleus-nucleus collisions
- fixed-target data analysis as complement, UPC if capacity

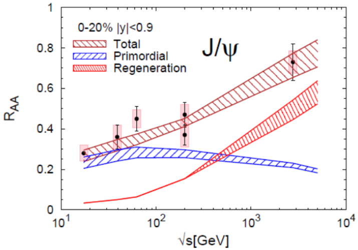
Long-term: a diverse programme to explore

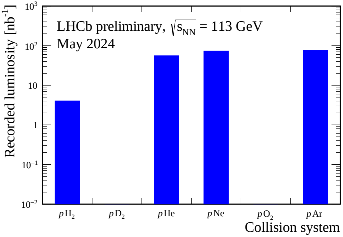
- **Thermalisation, hadronisation and saturation with LHCb U2**
  → **dileptons** from preequilibrium
  → non-vector state **heavy quarkonium**
  → **total charm and beauty** including baryons
  → $c\bar{c}$ **correlations**
  → high-multiplicity pp programme including **heavy-quark exotica**

LQGP: unique **value chain from detector & reconstruction over analysis to theory**

successful exploitation: need constant FTE for LQGP in years to come

Other opportunities: fixed-target





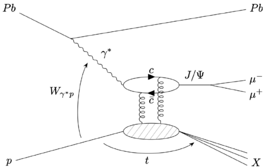
Left R. Rapp at QM 2017, Right: Lumi 2024 at 1-10 h of running per species.

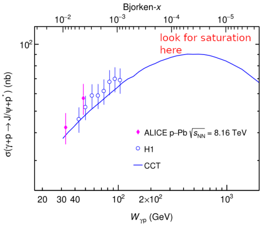
- LHCb: only LHC experiment with fixed-target programme
  $\rightarrow$ fast exchange of target, run parallel to collider all the time
- QGP studies at different initial energy density and heavy-quark density
- interesting for hadron structure: Drell-Yan
- lead by LLR: co-supervision Gabriel Ricart (PhD, 2022-2025) pNe, D^+/D_s
- intention to extent in this direction in coming years
  $\rightarrow$ polarised target also being developped: enlarge observables for hadron structure

Other opportunities: ultra-peripheral collisions inclusive

- photon-hadron interactions: the closest to DIS at hadron collider
  $\rightarrow$ difference: $Q^2 \approx 0$, need hard object produced for perturbative QCD, backgrounds
- past: exclusive quarkonium measurements $\rightarrow$ extension possible!
  $\rightarrow$ inclusive photoproduction studies@Orsay link: feasible for quarkonium in pPb (γp), but better with Zero-Degree-Calorimeter, PbPb: to be studied, need ZDC to decide photon-emitter, depends on final state advantage w.r.t. EIC: much lower x
  $\rightarrow$ exclusive continuum dileptons: Time-like Compton scattering
- synergy with GPD Theory@DPhN: see Dutrieux, Winn, Bertone PRD 107 (2023) 11
- not only saturation: hadronisation + correlations
- intention to extent if sufficient time/new woman/manpower
  $\rightarrow$ driver for Run 4 pPb high-luminosity run planned 2029

Other opportunities: ultra-peripheral collisions dissociative/exclusive





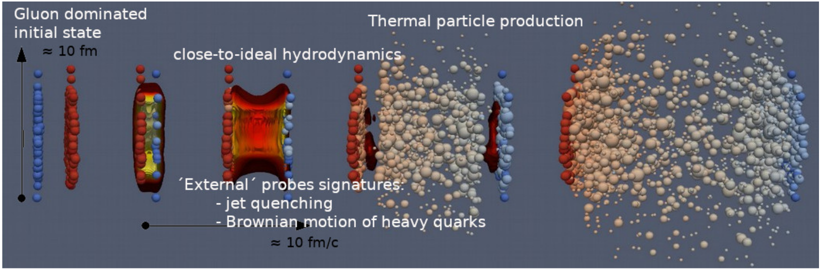
One example observable, where DPhN played lead-role in ALICE, first dissociative measurement PRD (2023) 11, 112004

- photon-hadron interactions: the closest to DIS at hadron collider
  $\to$ difference: $Q^2 \approx 0$, need hard object produced for perturbative QCD, backgrounds
- past: exclusive quarkonium measurements $\to$ extension possible!
  $\to$ dissociative pioneered at DPhN in ALICE: feasible, also in LHCb (advantage: forward, best resolution for t)
- synergy with GPD Theory@DPhN: see Dutrieux, Winn, Bertone PRD 107 (2023) 11
- intention to extent if sufficient time/new woman/manpower
  $\to$ driver for Run 4 pPb high-luminosity run planned 2029

Other opportunities: b-physics

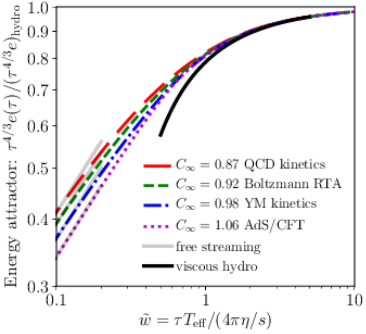
- possible option for particle physics department
- complementary to ATLAS/CMS focused on Higgs and direct searches
  ATLAS/CMS b-physics limited w.r.t. LHCb/Belle2
- a document has been written in the context of the HCERES evaluation to see the options
- no concrete plans yet
- potentially interesting in view of FCC-ee programme:
  strong component of b-physics at Z-pole

Heavy-ion collisions at colliders: key observations



- ´ideal liquid´: nearly ideal hydrodynamics for energy-momentum flow
  review: Gale, Jeon, Schenke; Int.J.Mod.Phys.A 28 (2013), 1340011
- ´jet quenching´: energy loss of energetic partons in matter
  review: Apolinário, Lee, Winn; Prog.Part.Nucl.Phys. 127 (2022) 103990
- ´Brownian motion´ & tests of deconfinement with heavy quarks
  review: Apolinário, Lee, Winn; Prog.Part.Nucl.Phys. 127 (2022) 103990
- ´thermal matter´: chemical equilibrium at hadronisation
  review: Andronic, Braun-Munzinger, Redlich, Stachel; Nature 561 (2018) 7723, 321
- ´small systems´: continuities proton-proton/nucleus to nucleus-nucleus
  review: Nagle, Zajc; Ann.Rev.Nucl.Part.Sci. 68 (2018) 211

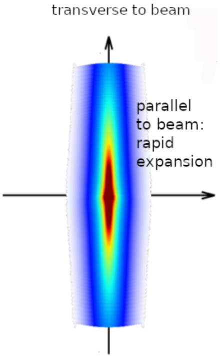
Theory of preequilibrium: progress



Giacalone, Mazeliauskas, Schlichting PRL, 123(26) (2019).

- despite very different scenarios: $\rightarrow$ universal scaling observed as function of $\tilde{w} \propto 1/(\textit{equilibration time})$
- equilibration time itself within modeling
  $\rightarrow$ kinetic equilibration
  $\rightarrow$ chemical equilibration
- no experimental access so far
- crucial for limits of hydrodynamics in proton-proton/proton-nucleus

Why is the preequilibrium critical?

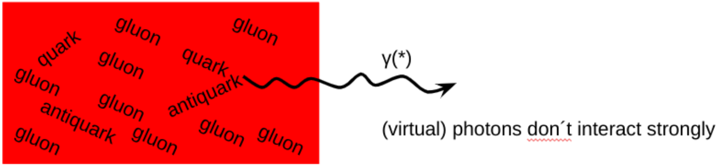


Adapted from "The first fm/c of Heavy-ion Collisions"

Schlichting, Teaney ARNPS 69 (2019)

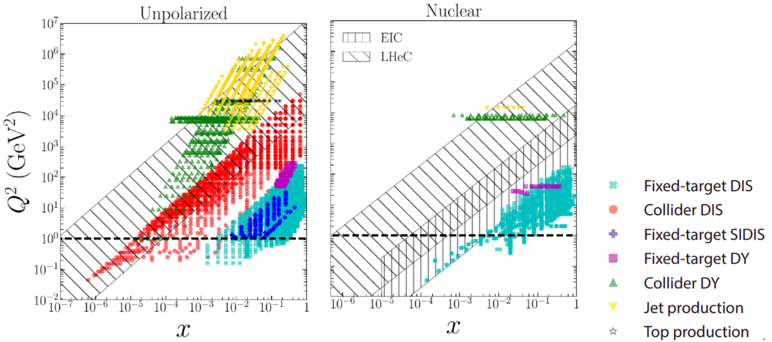
- initially **far from equilibrium**
  $\rightarrow$ kinetically:
  rapid longitudinal expansion
  $\rightarrow$ chemically:
  very few quarks initially
- **time scale not known** of hydro start:
  $\rightarrow$ very different model assumptions
  $\rightarrow$ nonetheless: universal scaling
  1-parameter for kinetic isotropisation η/s
  chemical equilibration: same coupling
- no experimental access so far
- crucial for limits of hydrodynamics in proton-proton/proton-nucleus
- only dileptons a clean observable:
  $\rightarrow$ only mass ´dials in´ time
- early time emission
  $\rightarrow$ high mass emission

Dileptons: probe of the preequilibrium



- wanted: decoupling earlier than hadrons & sensitive to GeV-energy scale
  $\rightarrow$ real photons and electron-positron or muon-antimuon pairs (dileptons)
- only dileptons a clean observable:
  $\rightarrow$ only mass ´dials in´ time
- early time emission
  $\rightarrow$ high mass emission

Dileptons and saturation

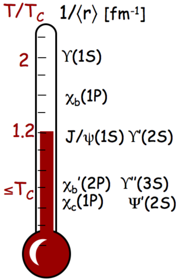


Kinematic coverage in terms of x and Q^2 (corresponding to the mass or transverse mass scale in case of Drell-Yan production) of c ommonly used data for global parton distribution fits for the proton (left) and for nuclei (right) and of future DIS facilities (EIC and LHeC).

- Drell-Yan: theoretically cleanest for hadron structure at hadron collider
- no competition in precision with deep-inelastic scattering (DIS)
- But Drell-Yan in LHCb down to about 3 GeV: beyond low-x reach of past & future DIS

Charmonium in heavy-ion collisions: ´melting´ as initial idea

- **Suppression of J/ψ production** via color screening as a probe of deconfinement in heavy-ion collisions since 1986
  Matsui & Satz PLB 178 (1986)
- **Sequential Suppression** of quarkonia as a function of temperature:
  $\rightarrow$ quarkonia as thermometer
  F. Karsch, H. Satz F.Karsch, H. Satz, Z.Phys. C51 (1991)



adapted from A. Mócsy EPJC 61, 705 (2009), T_c: pseudocritial temperature separating hadrons from QGP.

- Underlying picture:
  charmonia produced before QGP formation
  $\rightarrow$ subsequent ´melting´ in fireball

1st scenario: destruction & regeneration of bound-states in the QGP

Transport model

$$\frac{\mathrm{d}N_\Psi(\tau)}{\mathrm{d}\tau} = -\Gamma_\Psi(T(\tau))\left[N_\Psi(\tau) - N_\Psi^{\mathrm{eq}}(T(\tau))\right]$$

Dynamic modelling as function of time τ with reaction rate Γ_Ψ

- J/ψ production and destruction during lifetime of deconfined phase from initially uncorrelated and from same hard scattering $c\bar{c}$ pairs
first in: R. L. Thews, M. Schroeder, J. Rafelski PRC, 63 (2001),
- different type of models for quarkonium-medium interaction used
comover model with gain term (Ferreiro): Phys. Lett. B731 (2014) 57, TAMU model (Rapp et al.): Nucl.Phys.A 943 (2015) 147, most recent update: arXiv:2111.13528, Tsinghua model (Pengfei et al.), e.g.: Phys.Rev.C89,054911(2014)

2nd scenario: generation at hadronization

Statistical Hadronization

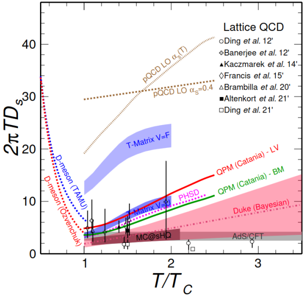
$$N_{c\bar{c}} = \frac{1}{2} g_c V \left(\sum_i n^{\text{th}}_{D_i} + n^{\text{th}}_{\Lambda_i} + \cdots \right) + g_c^2 V \left(\sum_i n^{\text{th}}_{\psi_i} + n^{\text{th}}_{\chi_i} + \cdots \right) + \cdots$$

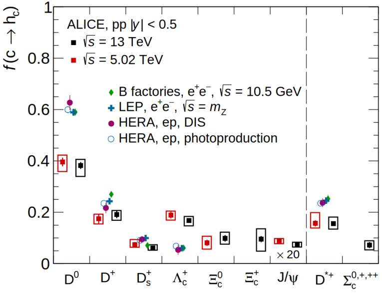
Input production of charm, Volume V, thermal densities n: fixes fugacity g_c

- **The statistical hadronization model**
  charmonium production exclusively at phase boundary
  first in: P. Braun-Munzinger and J. Stachel PLB, 490 (2000),

  most recent account in literature discussing all charmed states JHEP 07 (2021) 03
- extreme case scenario with few parameters

Heavy quarks: Brownian motion & hadronisation





charm-quark spatial diffusion $2D_s$ compilation Prog.Part.Nucl.Phys. 127 (2022) 103990, hadronisation measurement ALICE JHEP 12 (2023) 086

- Heavy-quark: massive colour charge carrier, test diffusion in QGP
  $\rightarrow$ large theory and experimental modeling uncertainties
  $\rightarrow$ need better precision in experiment and theory
  improved in Run 3/4 with ALICE, CMS and LHCb (up to 30% centrality), but precision tracking a challenge for all three
- statistically limited: hadronisation (baryons) & beauty quarks
  $\rightarrow$ heavy-quarks also a chance: opportunity to constrain hadronisation
  $\rightarrow$ additional conserved charge, exotic states (Tetraquark et al.)

Referee questions: Eric Dumonteil

Q1: differences/common points UPC and DIS
UPC Q^2 close to zero (need hard probe for pQCD), backgrounds from hadronic interactions, however, larger kinematics
Q2: diffusion coefficient uncertainty reduction with Run 3/4
strong reduction expected; however conceptual limitations from hadronisation (measurement input will remain statistically limited), beauty measurements (easier treatment in effective field theory and pQCD) statistically limited; tracking precision limited in ALICE (TPC space charge!), LHCb (ghost rate), CMS/ATLAS (low-p_T performance)
Q3: tracking responsibilities in LHCb
by now only indirectly via upgrade activities tracking
certainly interest, however need to avoid overcommittment, will depend on group development

Referee questions: Eric Dumonteil

Q4: b-physics and other opportunities beyond LQGP
particle physics department: principle interest, exchanges ongoing, at the moment not planned
polarised target, hadron structure: principle interest, exchanging ongoing, at the moment not planned Q5: SPARC vs. HV-CMOS, see talk by Benjamin
Q6: absence/little upgrade 2 impact on programme
full programme remaining; need to push for small-mass nucleus-nucleus collisions Q7: next hiring profile, affialiation LHCb or ALICE?
LHCb, help for technical implication in ALICE

Referee questions: Anton Andronic

Q1: hardware responsibilities until LS4
only related to Upgrade 2 and smaller contributions for operations (piquet)
Q2: UT 3-layers, see Benjamin
off table
Q3: time resolution UT, see Benjamin
bunch crossing separation needed, not more
Q4: committments regarding FTEs for U2 realistic?
planning based on constant FTE of LQGP requires hirings for departures

Referee questions: Gaëlle Boudoul

Q1a: target luminosities LHC and LHCb for heavy-ions Run 4
see slide on luminosity, minimal target factor 5 below ALICE/CMS/ATLAS
Q1c: target luminosities LHC and LHCb for heavy-ion Run 5
see slide on luminosity, tentative target factor 2 below ALICE/CMS/ATLAS
LHC numbers in ALICE 3 LOI
may evolve depending on β^* and ion species (filling scheme, collimation)
Q1b: target luminosities LHC and LHCb fixed-target
fixed-target: limited by accelerator, pile-up negligible for possible gas pressures

Referee questions: Gaëlle Boudoul

Q2: Velo incident impact on physics presented
No impact, since data 2024 alone already sufficient
Q3: FTEs presented: profile and hiring process
Most of FTE CDI:
Physicists hiring via job opening at DPhN
Technical stuff associated with DEDIP: shared among different activities
→ planning in close collaboration with DEDIP
Project postdocs already selected via selection committee