Heavy-ion collision perspectives at high energies

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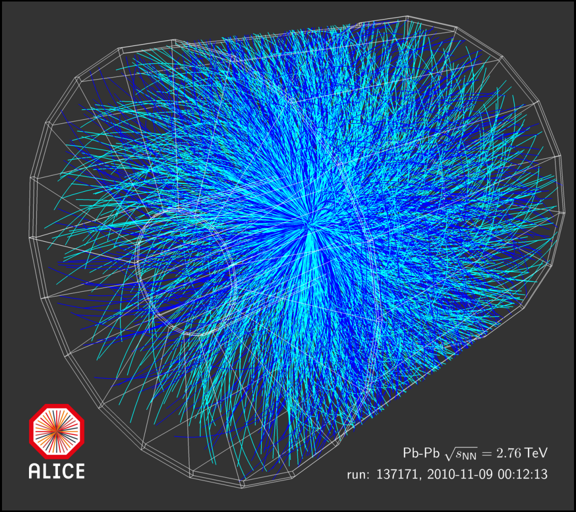
LLR retreat, 18th of September, 2019

Outline

1. Introduction to high-energy heavy-ion physics
2. Status at the LHC and open questions
3. Heavy-ions at the LHC in the 20ies
4. Ideas on heavy-ions at the LHC in the 30ies
5. Conclusions

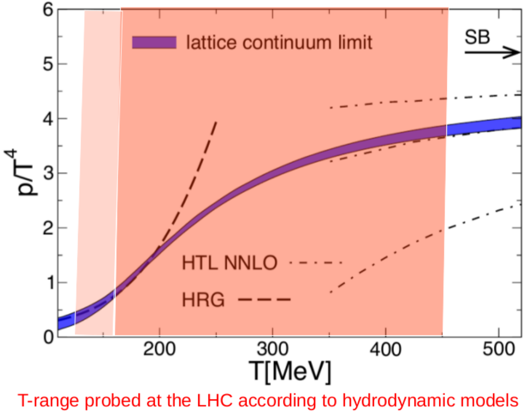
PbPb collisions at the LHC: a *macroscopic* system



nucleus–nucleus (PbPb) event display with ALICE TPC

average charged track multiplicity about 40 $\times$ average *pp* multiplicity
most central: about 2000 tracks per unit of rapidity   ALICE event displays

QCD & nucleus-nucleus collisions at high energies



p/T^4: pressure over temperature^4

HRG: Hadron Resonance Gas

HTL: Hard thermal loop

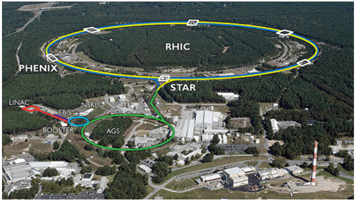
SB: Stefan-Boltzmann limit of non-interacting quarks and gluons

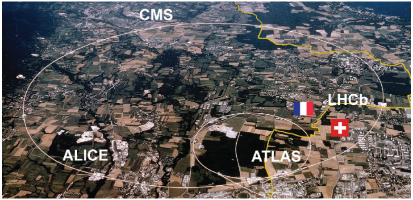
Figure taken from PLB 370 (2014), T-range from PRC 89, 044910 (2014)

The QCD many-body system in the lab: nucleus-nucleus (AA) collisions

- measure equilibrium properties
- understand non-equilibrium dynamics and relation to equilibrium

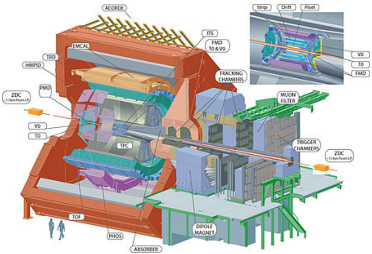
Facilities: RHIC and LHC

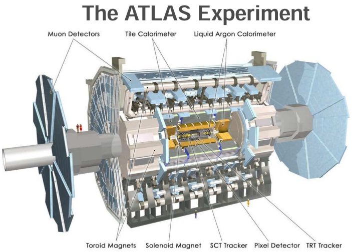


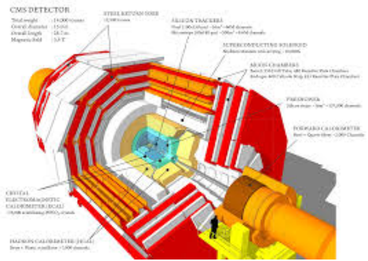


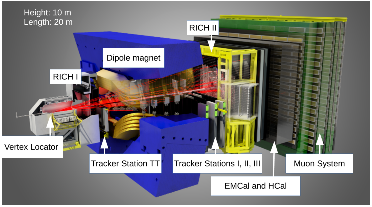
- Relativistic Heavy-Ion Collider (RHIC)
  $\sqrt{s_{NN}} = 7.7\text{-}\mathbf{200}$ GeV for AuAu, d-Au and many variations
  STAR and soon the new sPHENIX detector
- Large Hadron Collider (LHC)
  $\sqrt{s_{NN}} = \mathbf{2.76}$ **and** $\mathbf{5.0}$ TeV for PbPb, **5.0** and **8.2** TeV for *p*Pb
  ALICE, ATLAS, CMS, LHCb

LHC experiments







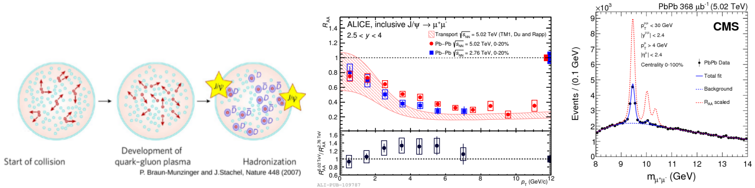


- the four LHC experiments take data in pPb and PbPb collisions

Achievements as contextualisation

- qualitative findings & features & overall picture
- not about uncertainty reduction w.r.t. previous measurements at RHIC
- *a selection*

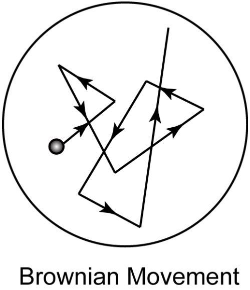
Highlights: J/ψ 'regeneration' and Υ suppression - deconfinement at play

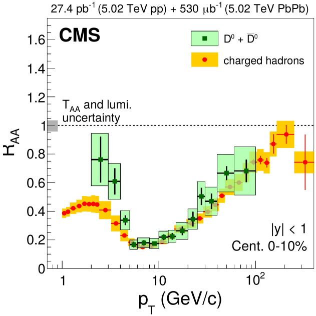


middle: PLB 766 (2017) 212, right: PLB790 (2019) 270.

- prediction: 'weaker' suppression or enhancement of J/ψ production compared to lower energies
- mechanism:
  deconfinement + large charm quark density + (partial) charm quark thermalisation
- observed!
- prominent example: the nuclear modification factor as function of p_T
  $R_{AA} = N^{PbPb}_{J/\psi}/(N_{coll} \cdot N^{pp}_{J/\psi})$
- first $\Upsilon(nS)$ precision measurements: Distinct suppression ordering!

Highlights: full reconstruction of charm/beauty hadrons - tracing colour charges

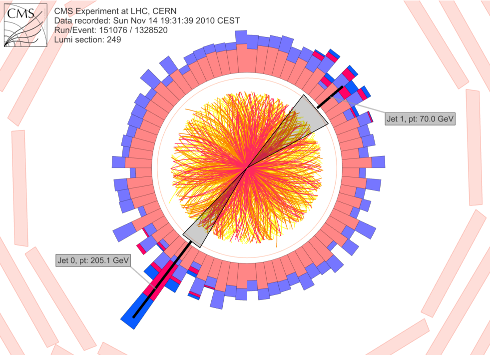




right: PLB 782 (2018) 474

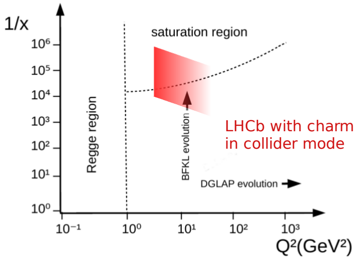
- heavy ($M_Q >> \Lambda_{QCD}, T$) quarks: produced early within short time, quantum numbers $\approx$ conserved
- LHC: first exclusive decay reconstructions in heay-ions thanks to higher rates, larger boosts and improved instrumentation
- charm/beauty: showing signs of thermalisation and strong energy loss
- modelled with Langevin/Fokker-Planck dynamics: data precision starting to constrain model space and parameters

Highlights: Parton energy loss with jets - stopping partons with QCD matter

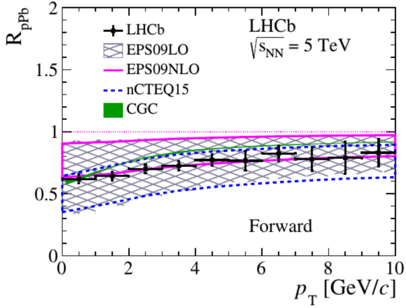


- jets abundantly produced and reconstructed
- spectacular manifestitation of highly energetic parton interaction with QCD matter
- opens up new opportunities using high-energy physics toolkit
- new subfield of heavy-ion research

Highlights: probe initial state at low-x probed with partons



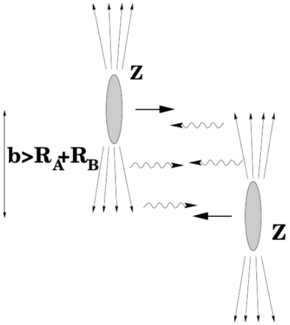
adapted from the 'pink book' QCD and collider physics

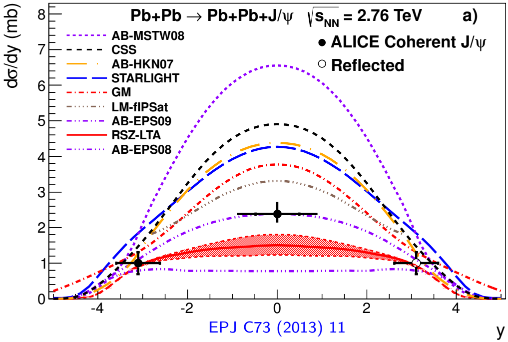


$R_{pPb} = \sigma_{pA}/(A^{Pb} \cdot \sigma_{pp})$ JHEP 1710 (2017) 090

- depletion of production: probing nucleus at low Bjorken-x, down to 10^{-6}
- either saturation or modification treateable within collinear factorisation
- alternative explanations via energy-loss not outruled
- saturation: connection to Electron-ion collider programme

Highlights: probe initial state at low-x probed with quasi-real photons

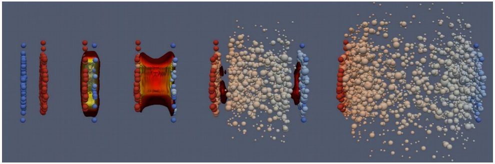


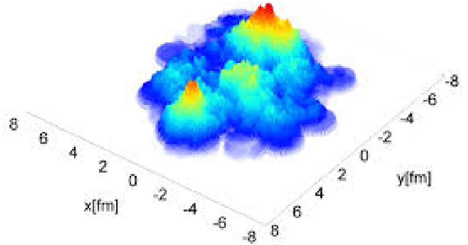


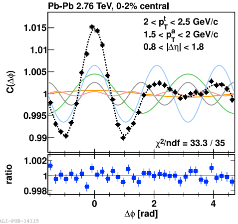
EPJ C73 (2013) 11

- depletion of production: Pb-nucleus probed at low Bjorken-x down 10^{-3}
- clean electromagnetic probe: no worries about energy loss
- probing GPD, not collinear PDF: knowledge transfer theoretically not trivial

Azimuthal correlations: collective motion under scrutiny



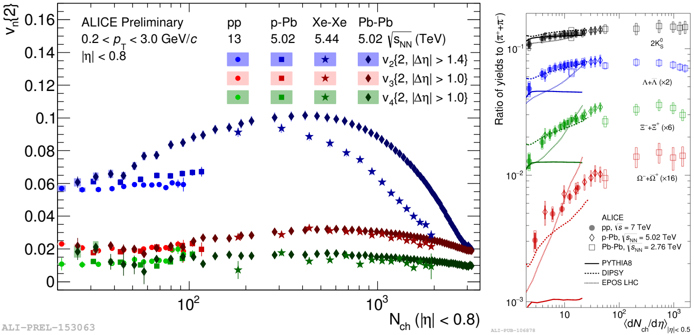




top: Madai visualisation of MUSIC hydro, right IP-Glasma initial $\epsilon(x, y)$, right: PLB 708 (2012) 249

- unprecedented precision: more particles per event and larger acceptances
- nearly ideal fluid - low dissipation: information on initial geometry fluctuations contained in data
- Fourier decomposition: directly related to initial state fluctuations
- Today: full probability distributions of 2nd and 3rd component measured!

Proton-proton and proton-lead collisions: surprises



left: preliminary submitted to PRL in next days; right: Nature Physics 13 (2017) 535

- $v_n\{2\} = \sqrt{< e^{in(\Delta\phi)} >_{pairs,events}}$ with $\Delta\phi$ between two tracks
- control variable N_{ch}: produced tracks $\propto$ 'freeze-out' volume
- PbPb: correlations $\rightarrow$ imprint of initial geometry; particle ratio $\rightarrow$ chemical equlibration
- partonic energy loss not (yet?) seen in pp/pPb

Résumé - status

Highlights with current data

- 'hydrogen atom of QCD', probing color force & deconfinement
  - quarkonium:
  qualitatively new behaviour as predicted

- 'perfect fluid' paradigm from RHIC confirmed in PbPb:
  even Bayesian inference of simulation parameters from data
  $\rightarrow$ *becoming quantitative* within Standard Model of heavy-ions

- perturbative QCD probes:
  Jet quenching with real jets and fully reconstructed
  heavy-flavour
  tracing colour charges and getting the tools to change the
  resolution scale of the 'microscope'

- pp and *p*Pb:
  sharing many aspects of ion-ion collisions: open outcome
  one of main points of community interests for the upcoming
  data takings

Résumé - open questions - a selection

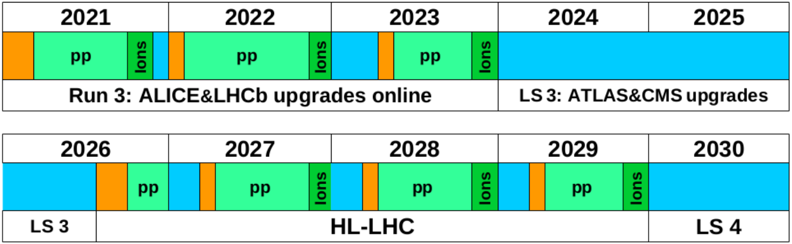
- material properties? E.g. viscosity as function of T?
- what about QGP in pp/pPb?
- what are the degrees of freedom at which T, Q^2 scale?
- what is the fate of heavy/light bound states at which T?
- how does thermalisation work?
- what is the initial state?
- which kind of chiral phase transition?

HL-LHC Yellow report: program to address these questions

High-luminosity (HL) & High-energy (HE) LHC: 1 of 5 chapters heavy-ions
Focus on Run 3-4 (2020ies): approved heavy-ion programme
- evaluate opportunities beyond

1. Characterising the **macroscopic long wavelength Quark-Gluon-Plasma properties** with unprecedented precision
2. Accessing the **microscopic parton dynamics** underlying QGP properties
3. Developing a **unified picture of particle production and QCD dynamics** from small (pp) to larger (pA and AA) systems
4. **Probing parton densities in nuclei** in a broad (x, Q^2) kinematic range and searching for the possible onset of parton saturation

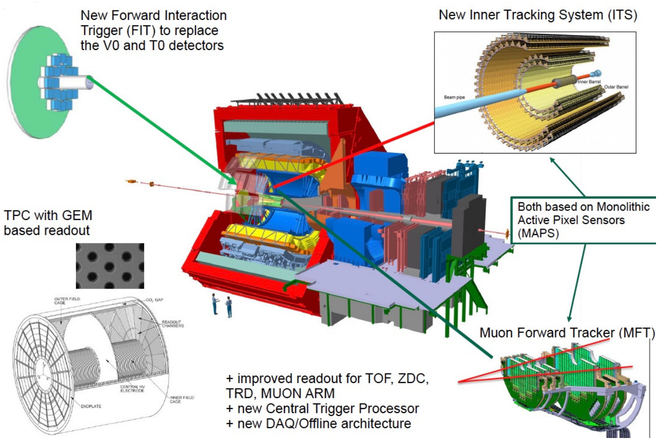
The future heavy-ion schedule



- Run 3&4 Pb-Pb:
  - 13 $\text{nb}^{-1} \approx 10 \times$ Run 1&2 luminosity
  - soft probes: $\approx 100 \times$ Run 1&2 thanks to ALICE continuous read-out
- Run 3&4 complements to Pb-Pb:
  - p-Pb: 1.2 pb^{-1} ATLAS/CMS, 0.6 pb^{-1} ALICE/LHCb & pp references
  - pp@14 TeV for high-multiplicity events: 0.2 fb^{-1} ALICE/ATLAS/CMS
  - short O-O and p-O runs in Run 3
- Run 5: proposal for lighter ions running for larger luminosities

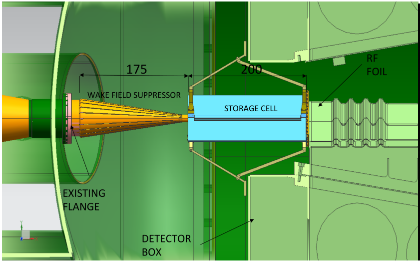
Detailed luminosities in HL/HE-LHC YR dense QCD, arXiv:1812.06772.

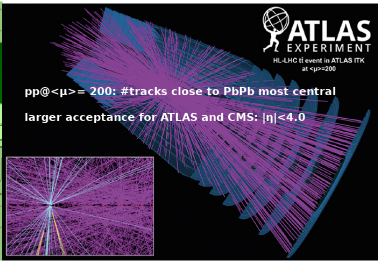
ALICE upgrade in a nutshell



- 50 kHz Pb-Pb continous read-out
  $\rightarrow$ integrated online-offline system O^2 with partial online calibration

ATLAS, CMS and LHCb upgrades in view of heavy-ions





- LHCb Run 3: fixed-target upgrade: 10-100 larger luminosity than Run 2
  $\rightarrow$ unique heavy-ion programme for heavy-flavour & soft physics
  LHCb-PUB-2018-015
- LHCb Run 3: tracking, trigger & read-out for 5$\times$ larger pp pile-up
  LHCb-TDR Velo, LHCb-TDR Tracker
  $\rightarrow$ better heavy-ion performance
- ATLAS/CMS Run 4: enlarged tracker performance & acceptance:
  $|\eta| < 2.5 \rightarrow |\eta| < 4.0$ CMS-TDR, ATLAS-TDR Pixel, ATLAS-TDR Strip
  $\rightarrow$ unprecedented correlation studies and more
- CMS Run 4: PID in $|\eta| < 3.0$ TDR
  $\rightarrow$ p/K/π separation with $0.7 < p_T < 3$ GeV/c

The physics of the future programme

1. Material properties of QCD matter & properties of the transition between phases?
   $\rightarrow$ Characterising the macroscopic long wavelength QGP properties

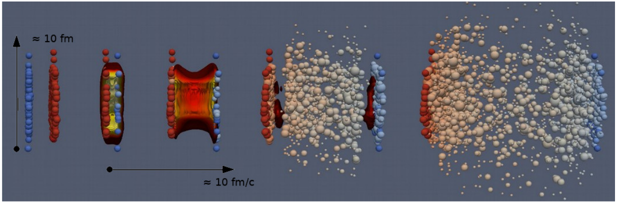
2. Degrees of freedom and their interactions?
   $\rightarrow$ Accessing the microscopic parton dynamics underlying QGP properties

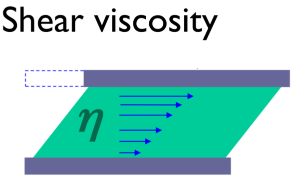
3. Where does the fluid description break down?
   $\rightarrow$ Developing a unified picture of particle production across collision systems

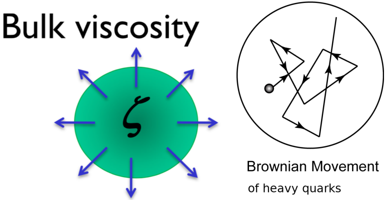
4. Characteristics of the initial stages?
   $\rightarrow$ Probing parton densities in nuclei in a broad (x, Q^2) range and searching for parton saturation

Beyond Standard Model physics and cosmic ray opportunities with heavy-ion beams in back-up.

Characterising the macroscopic properties







top: Madai visualisation of MUSIC hydrodynamics. left bottom: cartoon M. Attems.

Exploit the standard model of heavy-ion collisions to learn about QCD matter:

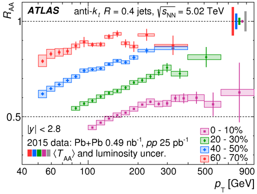
- shear and bulk viscosity, heavy-quark diffusion
- temperature and phase transition characteristics

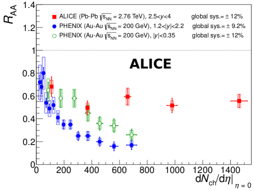
Access the microscopic dynamics underlying QGP properties

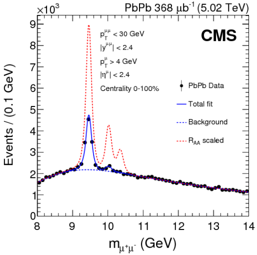
Use multi-scale objects as tools

- parton radiation in medium with jet observables arXiv:1808.03689

- QCD force via quarkonium arXiv:1506.03981

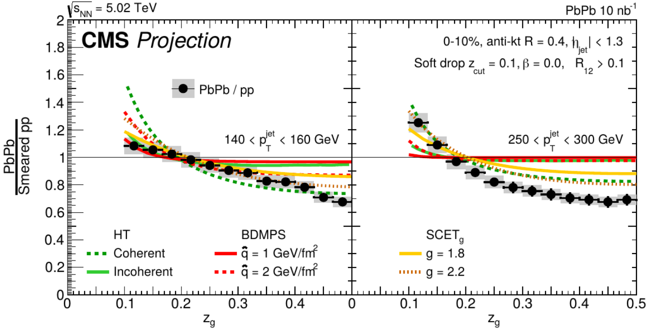






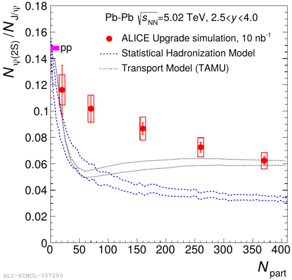
top to bottom: PLB 790 (2019) 108, PRL 109 (2012) 072301, PLB790 (2019) 270.

Microscopic parton dynamics



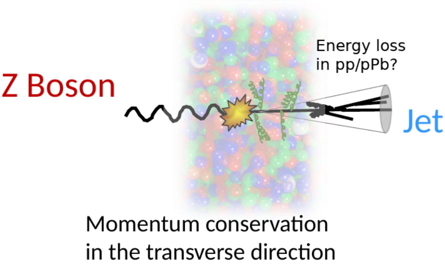
CMS-PAS-FTR-17-002.

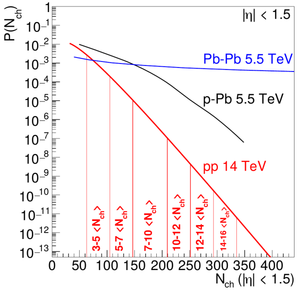
- jet structure measurements: constrain the in-medium radiation
- quarkonium production: constrain the in-medium force



ALICE-PUB-867.

Particle production and multi-body dynamics from small to larger collision systems

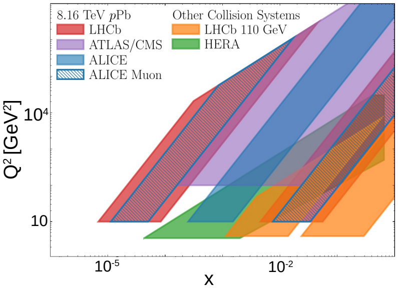


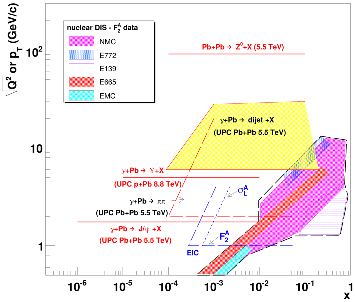


Unify our understanding of particle production from pp to Pb-Pb:

- search for energy loss and thermal radiation in small collision systems: p-Pb, pp and O-O
- explore pp and p-Pb collisions in Pb-Pb collision multiplicity regime

Partonic content of nuclei: initial conditions and the low-x limit

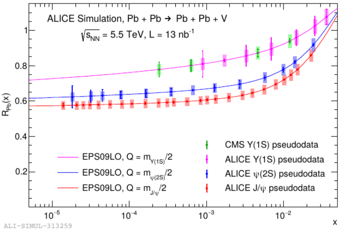


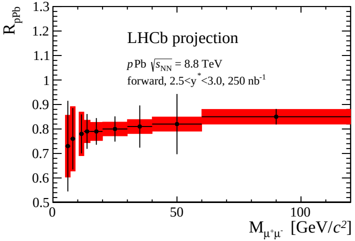


p-Pb collider kinematics of compared with HERA and fixed-target, nuclear DIS, UPC kinematics.

- nuclear parton distributions not strongly constrained as initial condition of heavy-ion collision
- extreme kinematics probing onset of non-linear effects

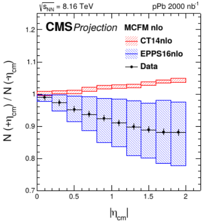
Probing a broad (x, Q^2) range and searching for the possible onset of saturation





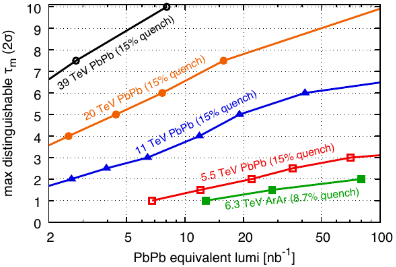
UPC Quarkonia ALICE-PUB-867/CMS-PAS-FTR-18-027, Drell-Yan LHCb-CONF-2018-005.

- probe nucleus with quasi-real photon in ultra-peripheral collisions (UPC)
- new observables in p-Pb with colour neutral final state at forward rapidity
- probe lowest available Bjorken-x & densest QCD systems
- precision data from ATLAS/CMS at intermediate/high-x



Beyond 2030: lighter ions for larger luminosity

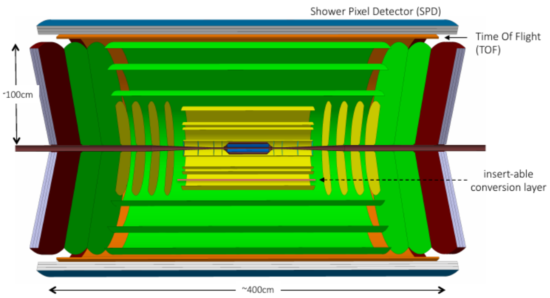
	$^{16}O^{8+}$	$^{40}Ar^{18+}$	$^{40}Ca^{20+}$	$^{78}Kr^{36+}$	$^{129}Xe^{54+}$	$^{208}Pb^{82+}$
γ	3760.	3390.	3760.	3470.	3150.	2960.
$\sqrt{s_{NN}}$/TeV	7.	6.3	7.	6.46	5.86	5.52
$\int_{month} L_{AA}\, dt/nb^{-1}$	5.89×10^4	3180.	2190.	218.	38.2	4.92
$\int_{month} L_{NN}\, dt/pb^{-1}$	1.51×10^4	5090.	3510.	1330.	636.	213.



Pb-Pb equivalent defined via nucleon-nucleon lumi., bottom: in Yellow Report based on: PRL120, 232301 (2018)

- lighter nuclei: larger nucleon-nucleon luminosities by more than factor 10
- make accessible new QGP probes
- example: time structure of jet-quenching with boosted top decays in ATLAS/CMS
- Argon - Argon collisions explored:
  final choice based on physics and accelerator considerations

New instrumentation beyond 2030



Magnetic Field
- B = 0.5 or 1 T

Spatial resolution
- Innermost 3 layers: σ ~ 1μm
- Outer layers: σ ~ 5μm

Vertex material thickness
- X/X0 ~ 0.05% / layer

Time Measurement
Outermost layer integrates high precision time measurement (σ_t ~ 20ps)

Concept from Adamova et al.: arXiv:1902.01211.

- concept for a next generation heavy-ion experiment:
  lightweight all-silicon, PID via timing and preshower, high rates, $|\eta| < 4.0$
- LHCb upgrade 2 LHCb-PUB-2018-009:
  upgrade to run in *pp* at pile-up ≈ 30
- together with higher luminosity with lighter nuclei
  $\rightarrow$ large potential for presently unaccessible observables
  ultra-hard probes, soft electro-magnetic electromagnetic radiation,
  multi-heavy-flavour and higher order fluctuations

Conclusions
The future of dense QCD studies at the LHC

A **broad programme in Run 3&4**

- based on the ALICE upgrade & ATLAS/CMS/LHCb upgrades
- 10 (hard) - 100 (soft) $\times$ larger data sets in Run 3&4

Scientific goals:

- **characterisation of QCD matter** in & out of equilibrium, hadronisation & the initial state of heavy-ion collisions
- construction of a **unified picture** from pp up to Pb-Pb

Opportunities beyond 2030:

- large statistics for hard scale physics, radiation, multi-heavy flavour and higher order fluctuations
  with collisions of **lighter ions**
- innovative **new instrumentation** for low/intermediate-p_T

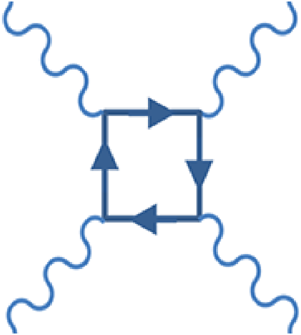
A few last words

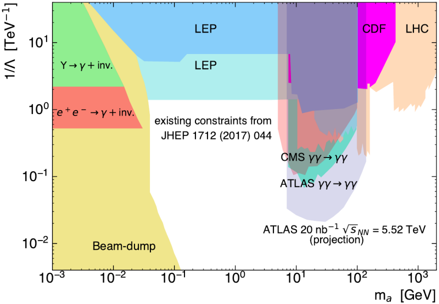
- heavy-ion programme at the LHC: a success story so far
  $\rightarrow$ strong achievements in the study of QCD many-body systems

  $\rightarrow$ both in establishing a standard model of heavy-ion collisions as well as in opening new exploratory roads
- good physics perspective for the next 10 years, beyond difficult to judge
- lower beam energies (but above $\sqrt{s_{NN}}$ =100 GeV) can be beneficial, but observable-by-observable question
  $\rightarrow$ exploit collision energy dependencies, e.g. interesting for quarkonium production

  $\rightarrow$ avoid large combinatorial background at highest energies
- both LLR projects, CMS and LHCb:
  $\rightarrow$ very well placed with different strenghts

Back-up: Further opportunities with heavy-ion beams



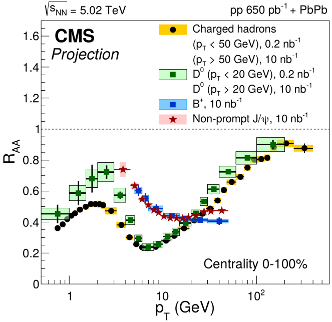


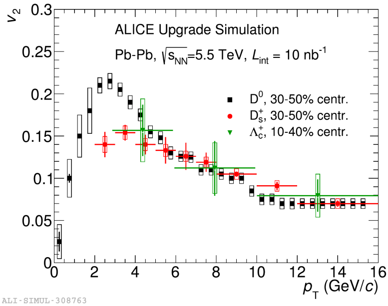
Right: ATL-PHYS-PUB-2018-018.

- larger statistics for light-by-light collision studies

  ATLAS and CMS with Run 2 data: evidence with 2015 data, Nature Physics 13 (2017) 852, ATLAS, arXiv:1810.04602, CMS, observation with 2018 data arXiv:1904.03536, ATLAS
- p-O collisions for cosmic ray related studies
- Further beyond Standard model searches explored in arXiv:1812.07688 exploiting low pile-up, strong e.m. fields and thermal production

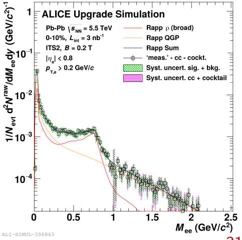
Characterising the macroscopic properties: unprecedented precision





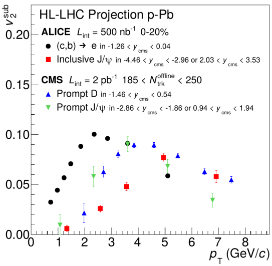
Nuclear modifications CMS CMS-PAS-FTR-17-002, v_2 with baryons ALICE ALICE-PUB-867.

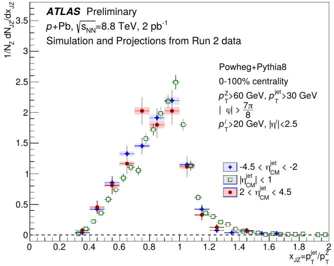
- heavy-flavour measurements: heavy-quark diffusion
- constrain hadronisation models: heavy-flavour baryons and exotic nuclei
- electro-magnetic radiation via dileptons: chiral restoration and temperature



ALICE-PUB-867.

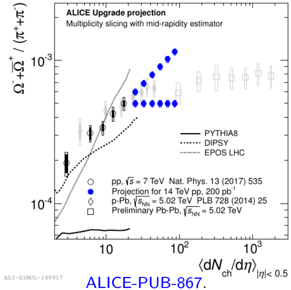
Developing a unified picture from small to larger systems





Left: CMS-PAS-FTR-18-026/ALICE-PUB-867, right: ATL-PHYS-PUB-2018-039.

- precision correlation studies with hard mass scale
- test energy loss with clean coincidence measurements not relying on normalisation
- probe hadron production with pp collisions in Pb-Pb multiplicity regime



ALICE-PUB-867.