An overview and remarks to the future of dense QCD studies at the LHC

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QGP France

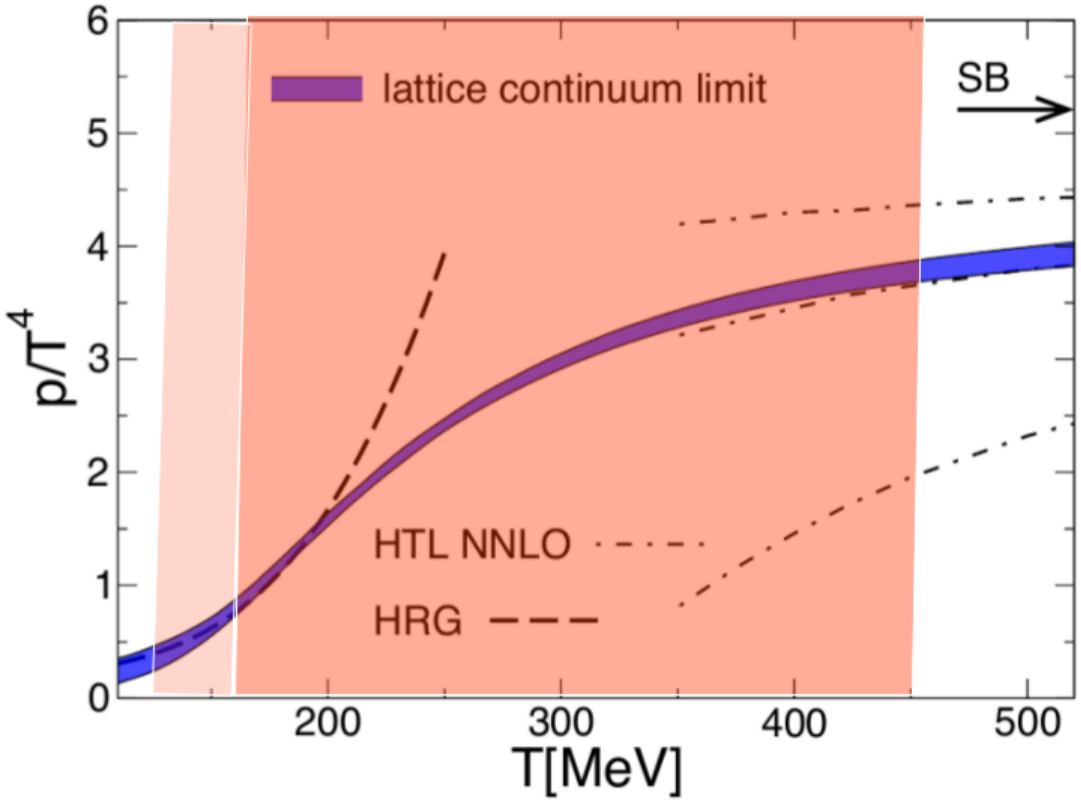
Based on LHCP material, but with additional comments

Thanks for discussions with my colleagues at DPhN, in France, at CERN, in Germany and elsewhere.

Outline

- introduction
- LHCP overview
- comments

QGP physics with nucleus-nucleus collisions at high energies



T-range probed at the LHC according to hydrodynamic models

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

Why **heavy-ion** collisions for QGP physics today and in the **future**?

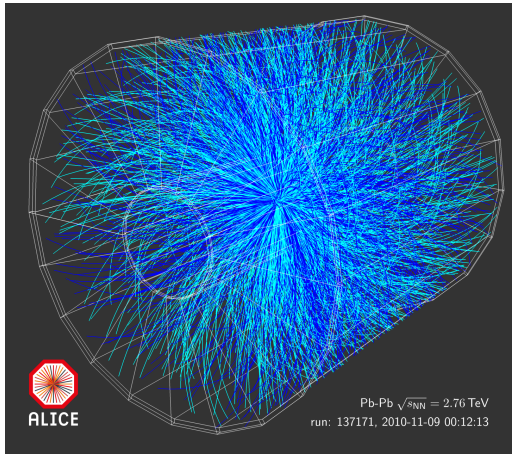
There are conceptual open questions!

- precondition:
  How does thermalisation work? Where does it work? Where fluid dynamics applicable?
- Phase transition properties w.r.t. deconfinement and chiral restoration?
- Underlying degrees of freedoms? pseudoparticles at which scale?
- Material properties and the interactions of d.o.f. at QCD at finite T?
- Initial wave function? Role of saturation?

Side products

- pushing relativistic hydrodynamics to the limits
- pushing perturbative and non-perturbative field theory calc. to the limits
- creating extreme electromagnetic fields in the laboratory
  to $\gamma\gamma/\gamma-$pomeron/odderon collider
- answer questions in astrophysics and spectroscopy
- hardware/software R&D

Why **high-energy** heavy-ion collisions?



- more particles, $\mu_B \to 0$: Lattice QCD, $\approx$ boost-invariant plateau over large range, perturbative probes
- time ordering of collision impact, parton production and system evolution
- if not critical point search or specific signature suffering at high-energy or energy dependence needed
  $\to$ high-energy advantageous
- large nucleus $\to$ more particles
- small nuclei instrumental to answer thermalisation questions and to challenge overall paradigm
  however for QGP properties, the largest system presumably easiest to connect to matter properties
- compromises: signal strength optimisation

Why high-energy heavy-ion collisions in the **future**?

- "standard model" based on prominent phenomena: flow & jet quenching
  → soft particle production described via hydrodynamic models
  → hard particle production "stopped/breaked" in dense QCD
  → synergy with HEP: techniques and observables
- solid ground to progress
- beyond this base paradigm: very model dependent statements
- Answering more ambitious questions:
  → more precise and new measurements
  → a leap to connect theory via phenomenology with data
- more than a smooth continuation:
  → requires self-critical revisions where needed
  → needs ambitious goals

even if this SM is still challenged (very healthy for our field!): see e.g. SQM Bierlich or Urs transport calc. or hydro of HF in pPb, PbPb QGP appears robust.

Yellow Report: The questions for future dense QCD studies

1. What are the material properties of QCD matter and the properties of the transition between phases?

2. What are the degrees of freedom and their interactions?

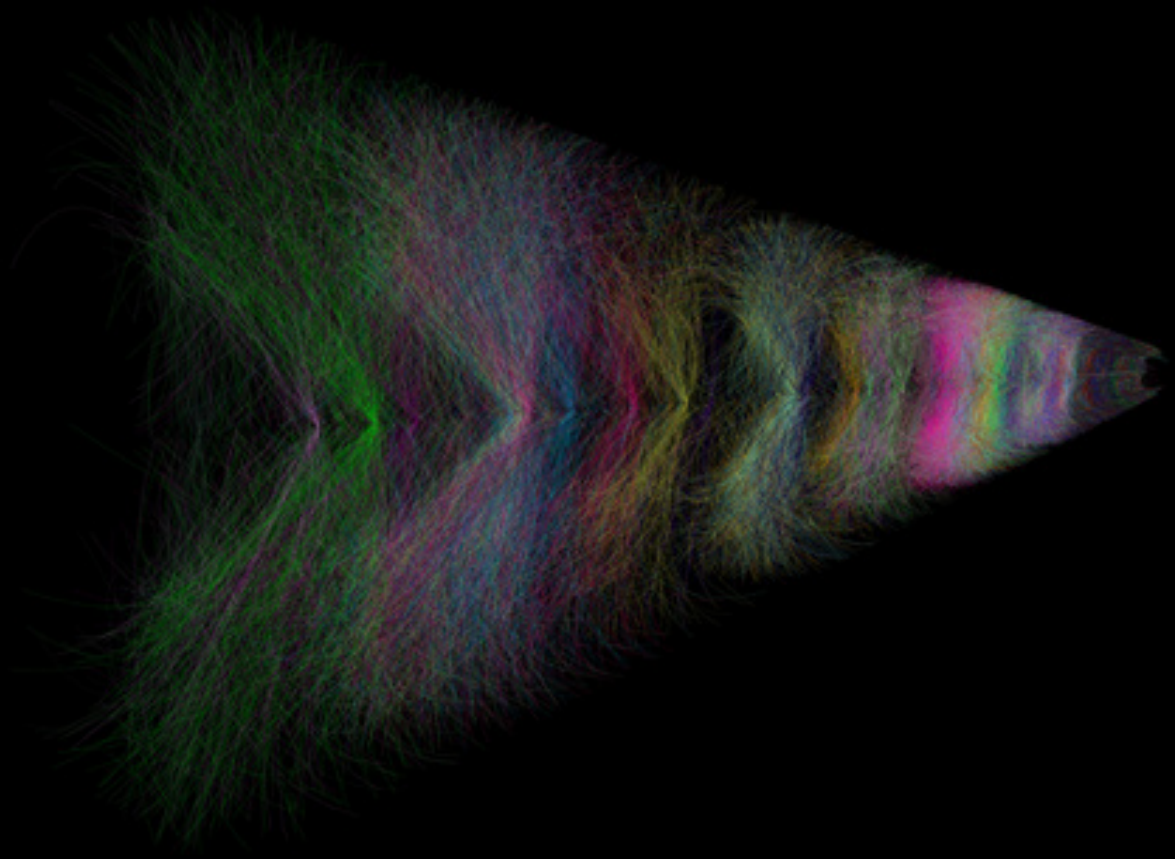
3. Where does the fluid description break down? Are there other concepts that we need to describe data with?

4. What are the characteristics of the initial stages?

$\rightarrow$ **future LHC programme**

in the following, material based on the HL-LHC Yellow Report, arXiv:1812.06772

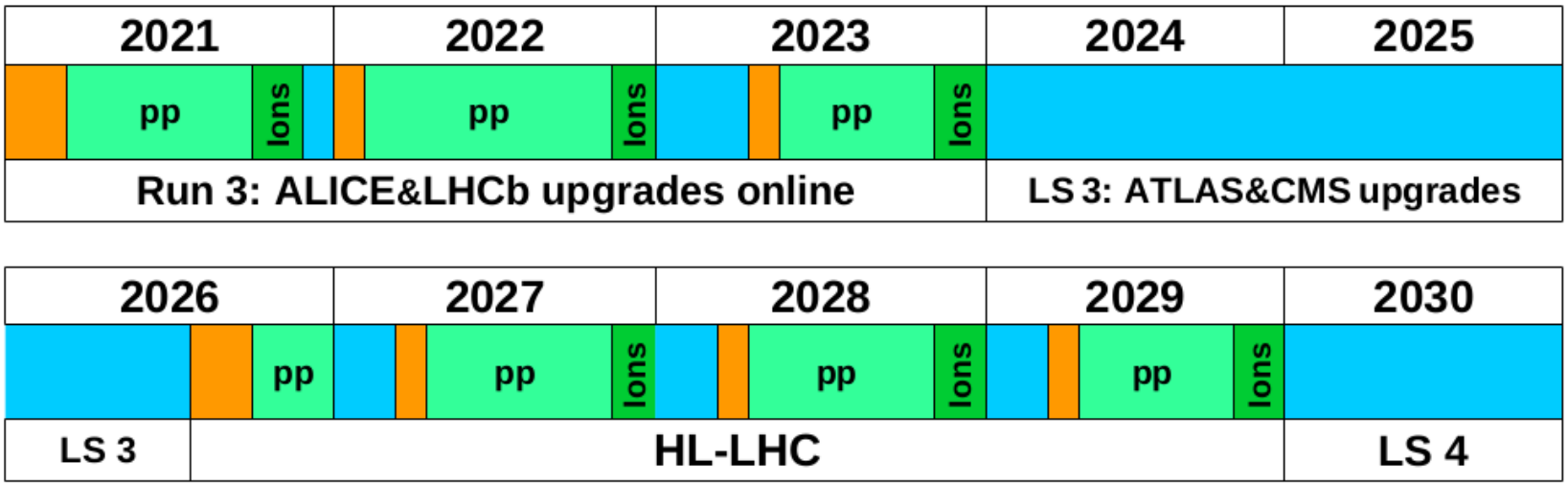
The upgrades for the future programme



50 kHz Pb-Pb with TPC, 2 ms, courtesy D. Rohr.

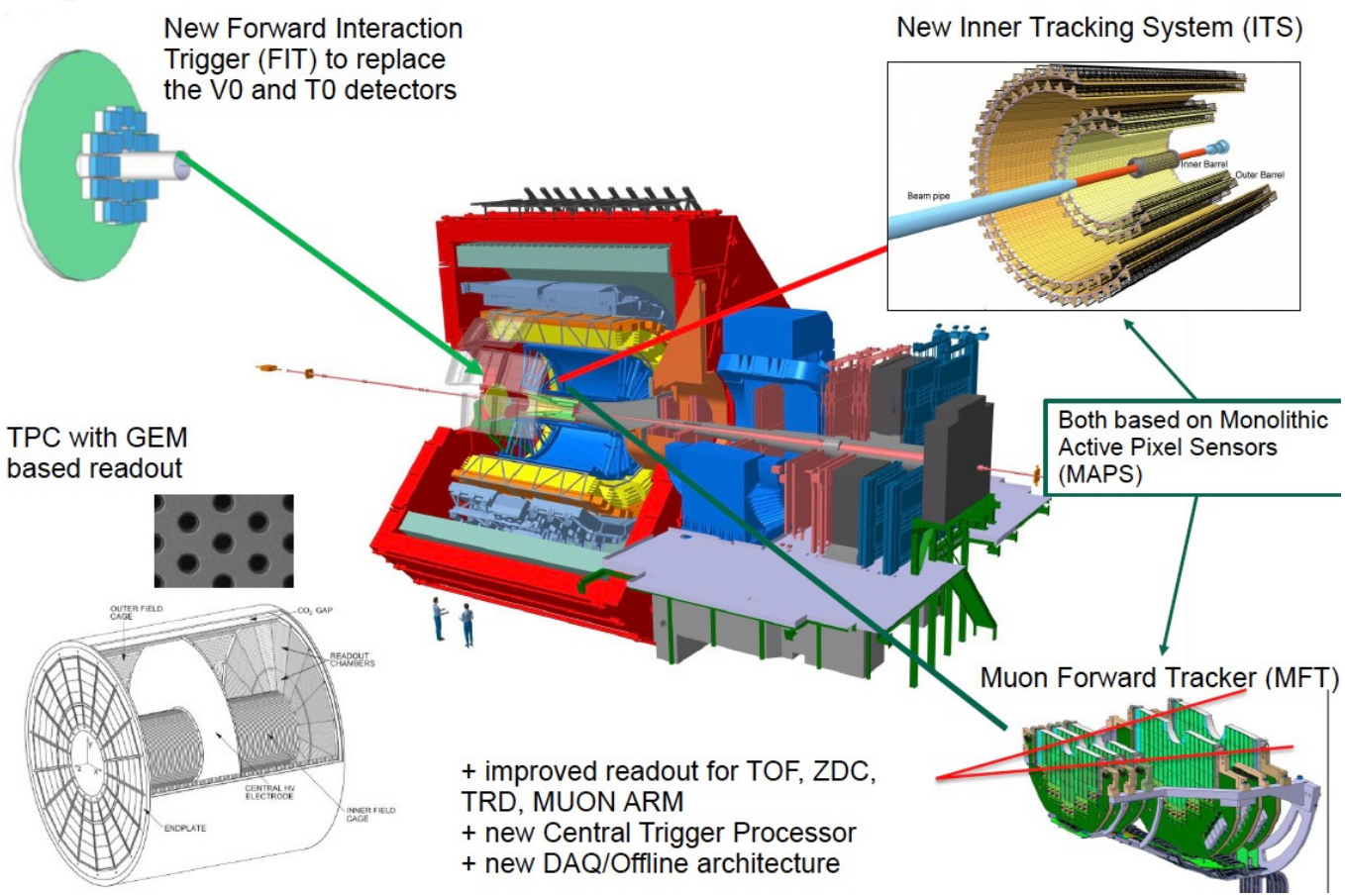
- a technological challenge for a broad physics programme

The future heavy-ion schedule: proposal from YR working group



- 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

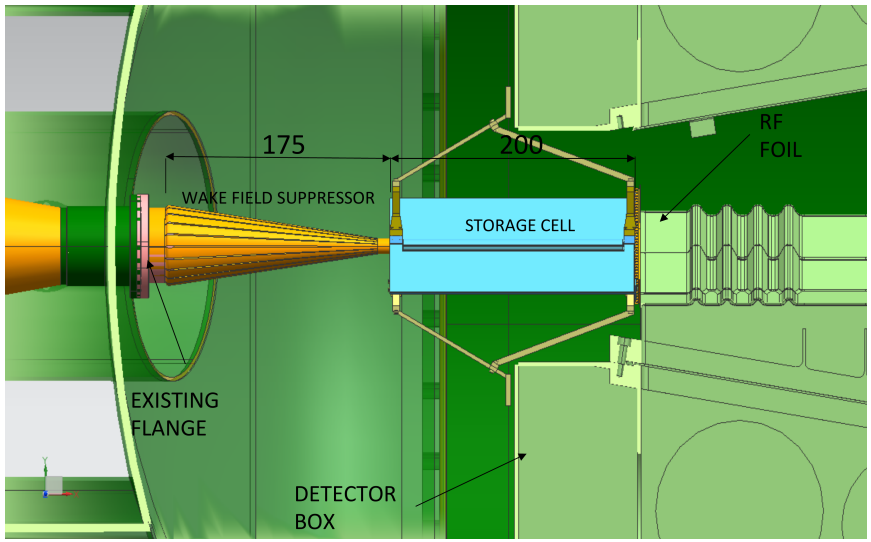
ALICE upgrade in a nutshell



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

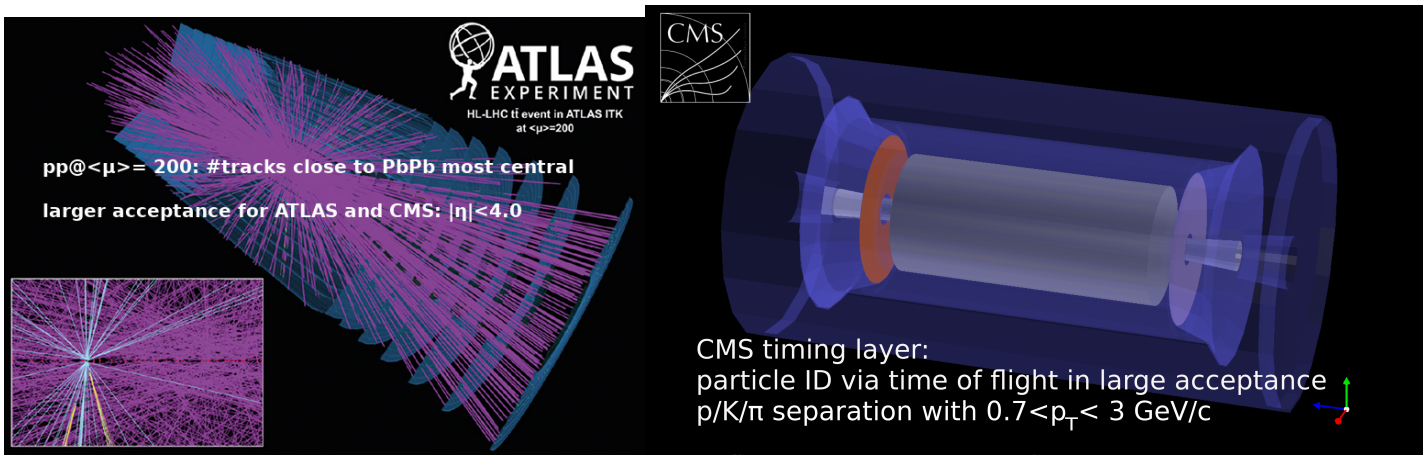
Run 3 upgrade overview: J. Norman parallel; FIT detector V. Grabski: poster.

LHCb upgrades for Run 3



- 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

CMS (ATLAS) upgrades for Run 4 in view of heavy-ions



- 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 from YR

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

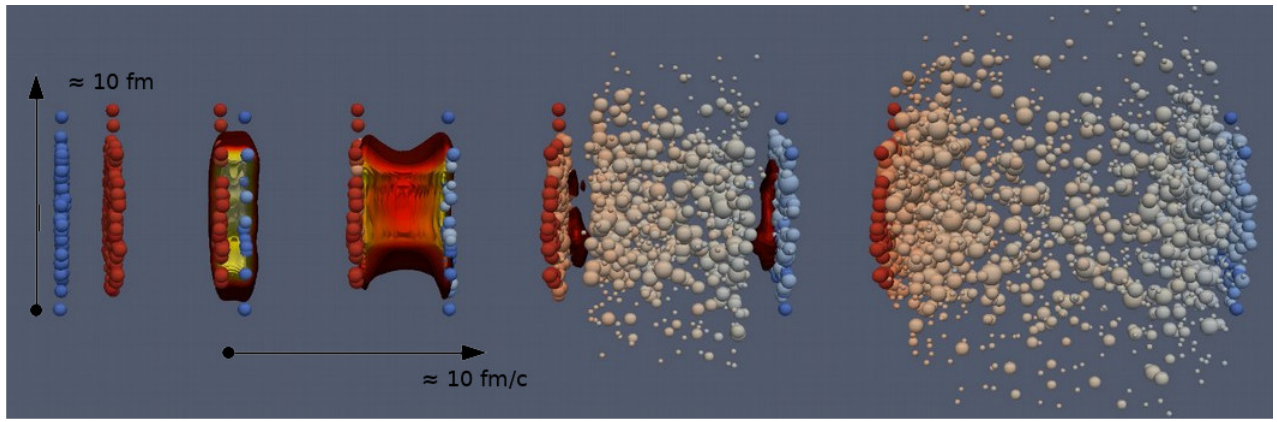
3. Where does the fluid description break down?
   $\rightarrow$ Developing a unified picture of particle production across collision systems

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

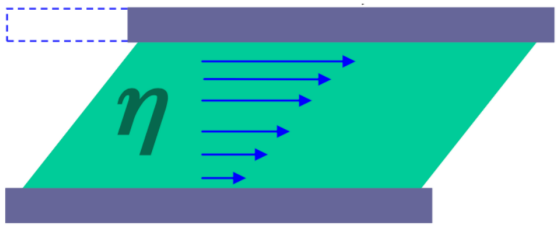
Beyond Standard Model physics and cosmic ray opportunities with heavy-ion beams in back-up.

Material available naturally reflects also current man-power in different projects and not "full" potential. Cutted

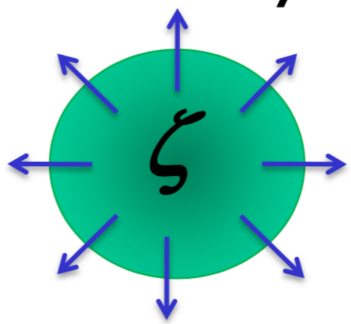
Characterising the macroscopic properties

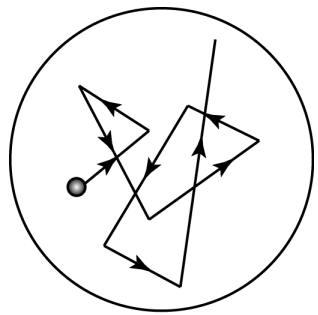


Shear viscosity



Bulk viscosity





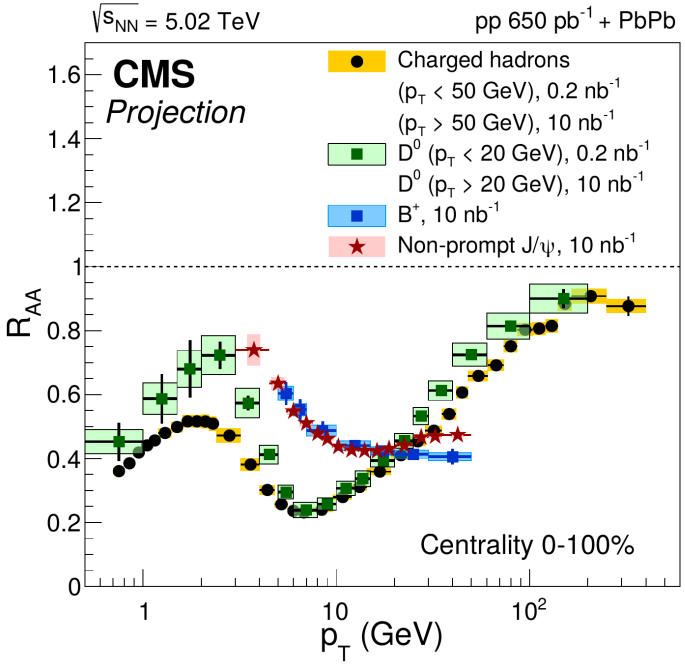
Brownian Movement
of heavy quarks

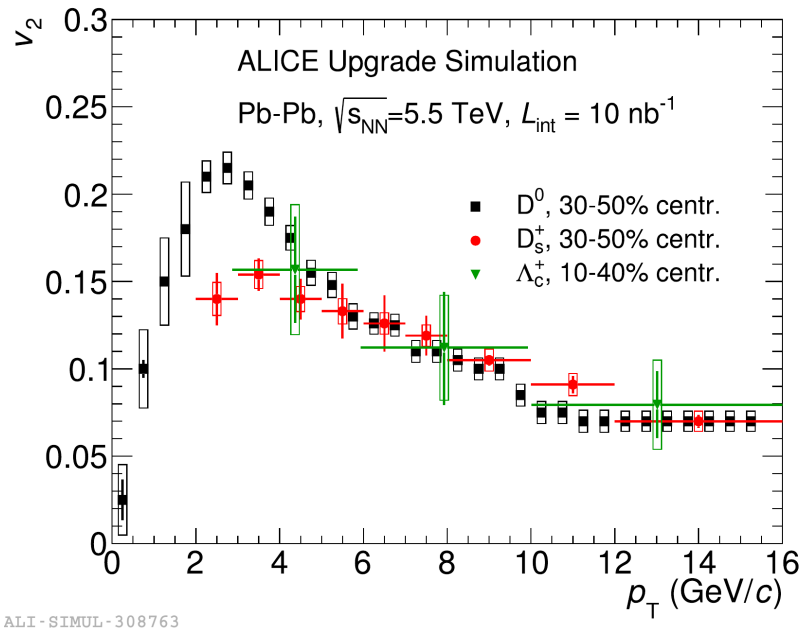
top: Madai visualisation of MUSIC hydrodynamics. left bottom: cartoon M. Attems.

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

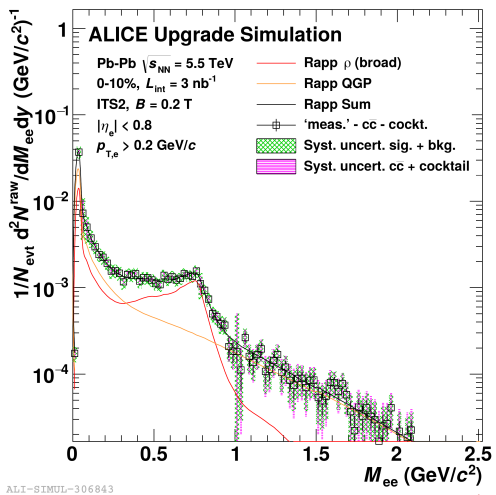
Characterising the macroscopic properties: unprecedented precision





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

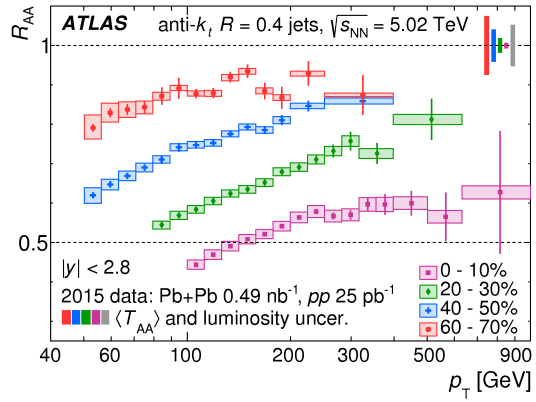


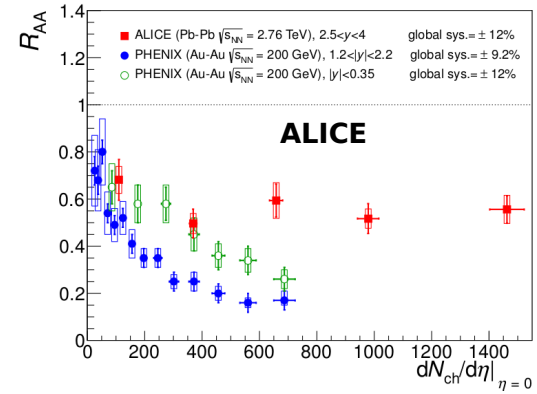
ALICE-PUB-867.

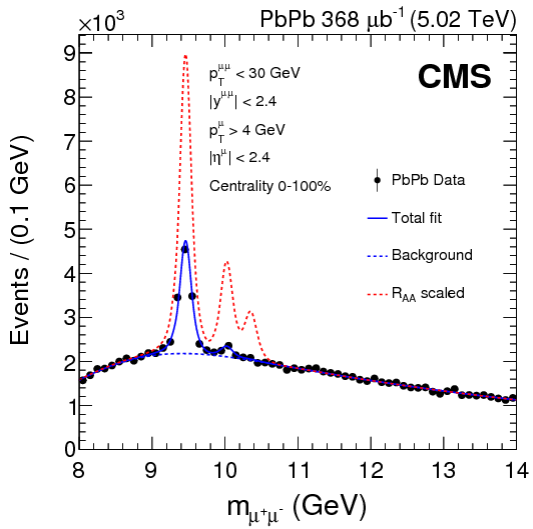
Access the microscopic dynamics underlying QGP properties

Use multi-scale objects as tools

- parton radiation in medium with jet observables arXiv:1808.03689
- QCD force via quarkonium arXiv:1506.03981

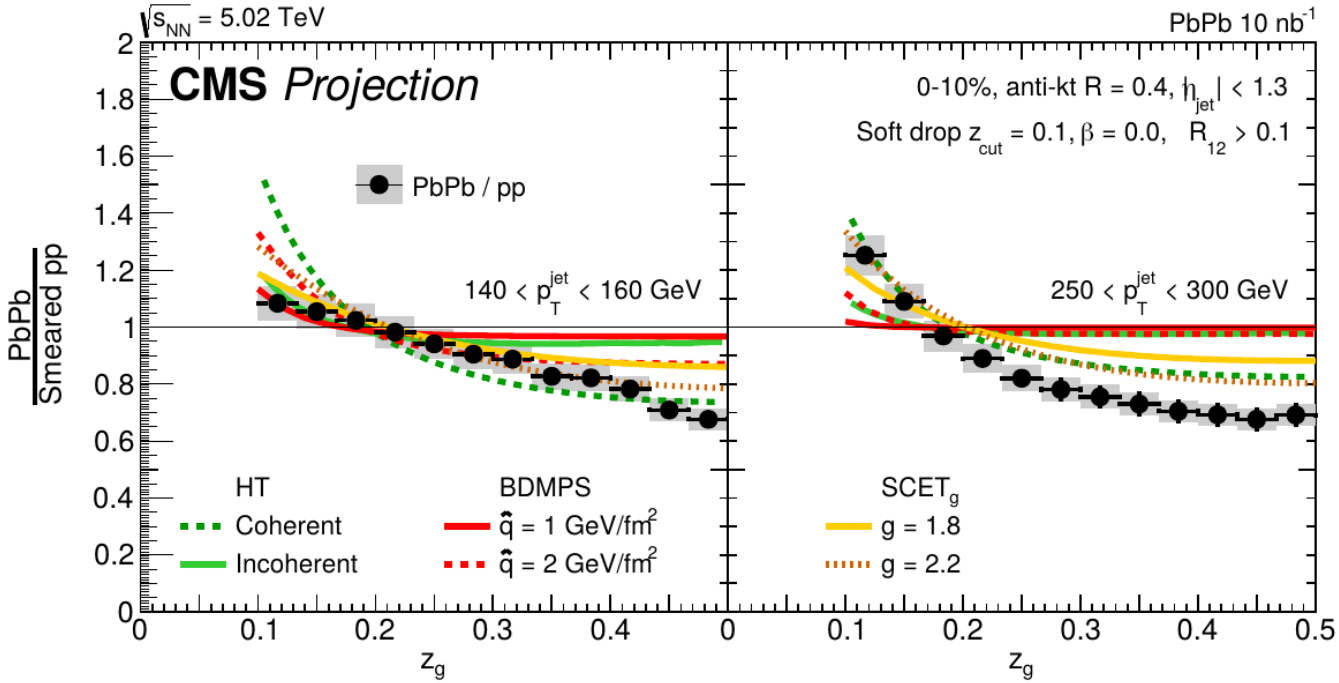






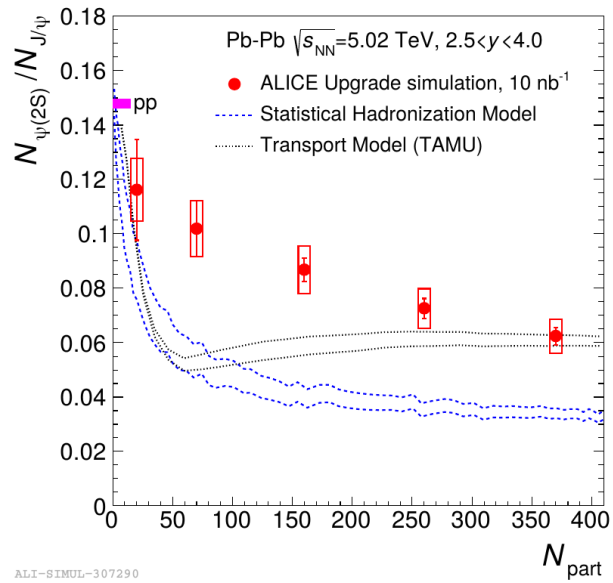
top to bottom: PLB 790 (2019) 108, PRL 109 (2012) 072301, PLB790 (2019) 270.

Microscopic parton dynamics



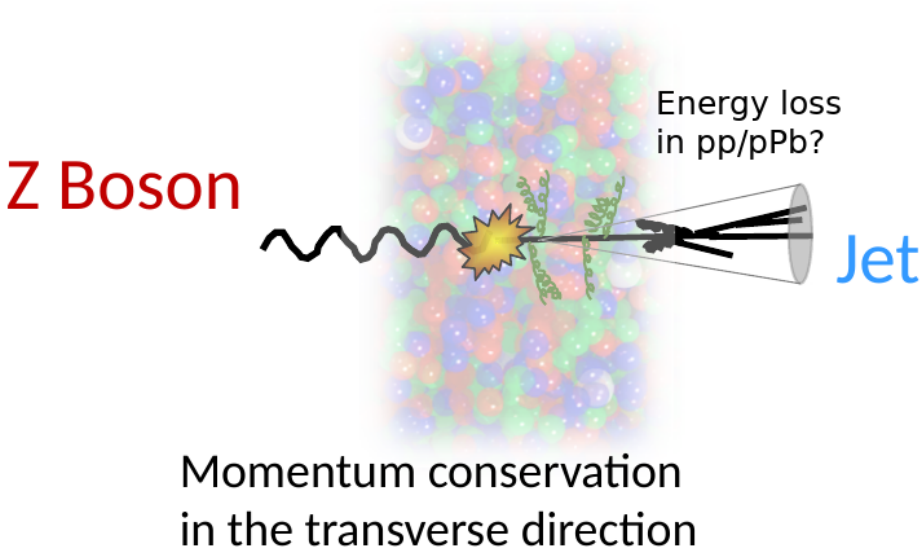
CMS-PAS-FTR-17-002.

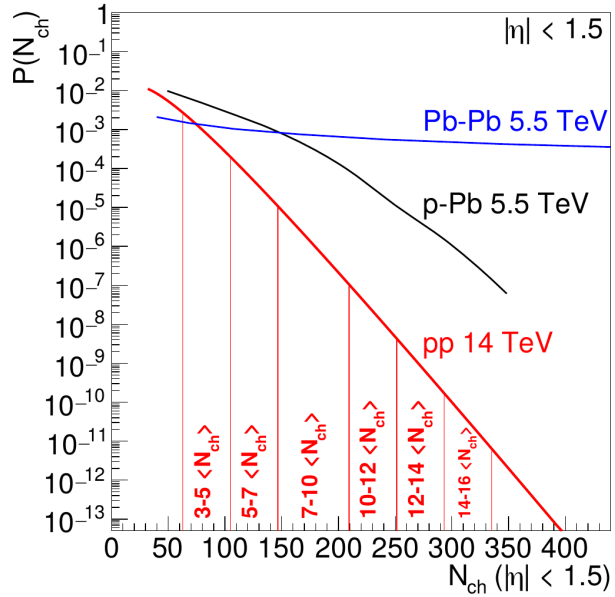
- jet structure measurements:
  constrain the in-medium radiation
- quarkonium production:
  constrain the in-medium force



ALICE-PUB-867.

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

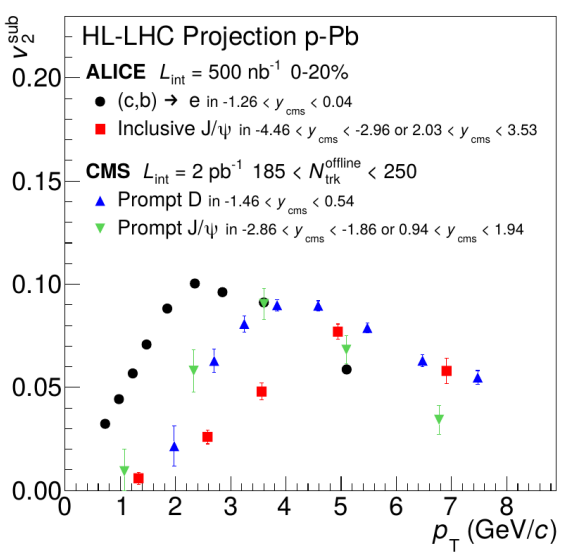


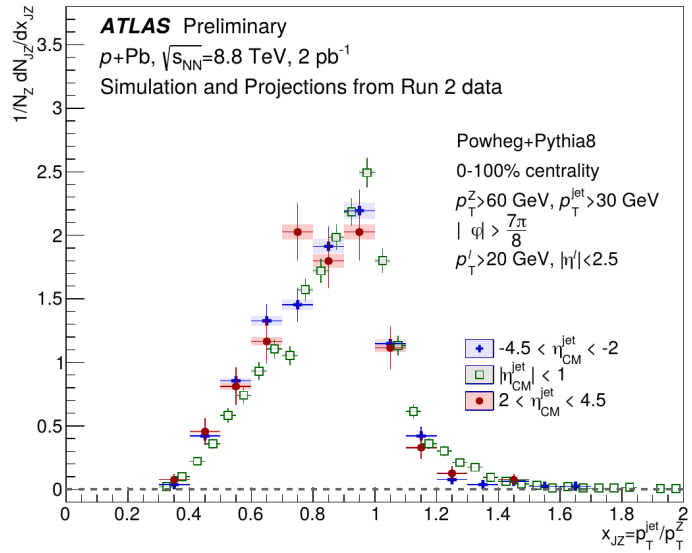


Unify our understanding of particle production from pp to Pb-Pb:

- 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

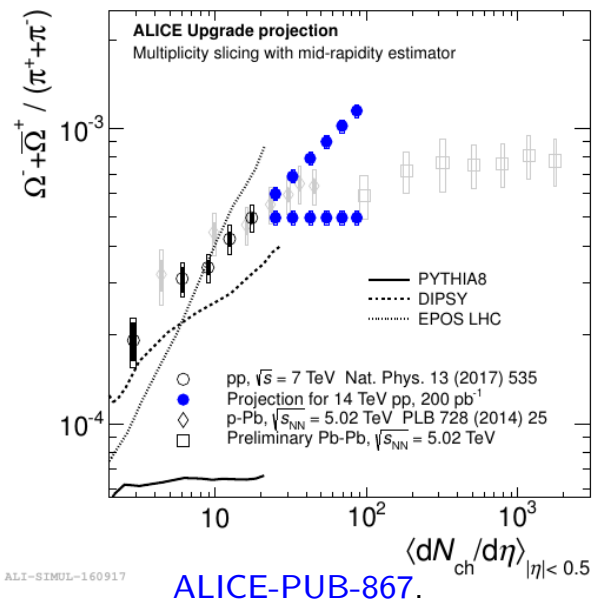
Developing a unified picture from small to larger systems





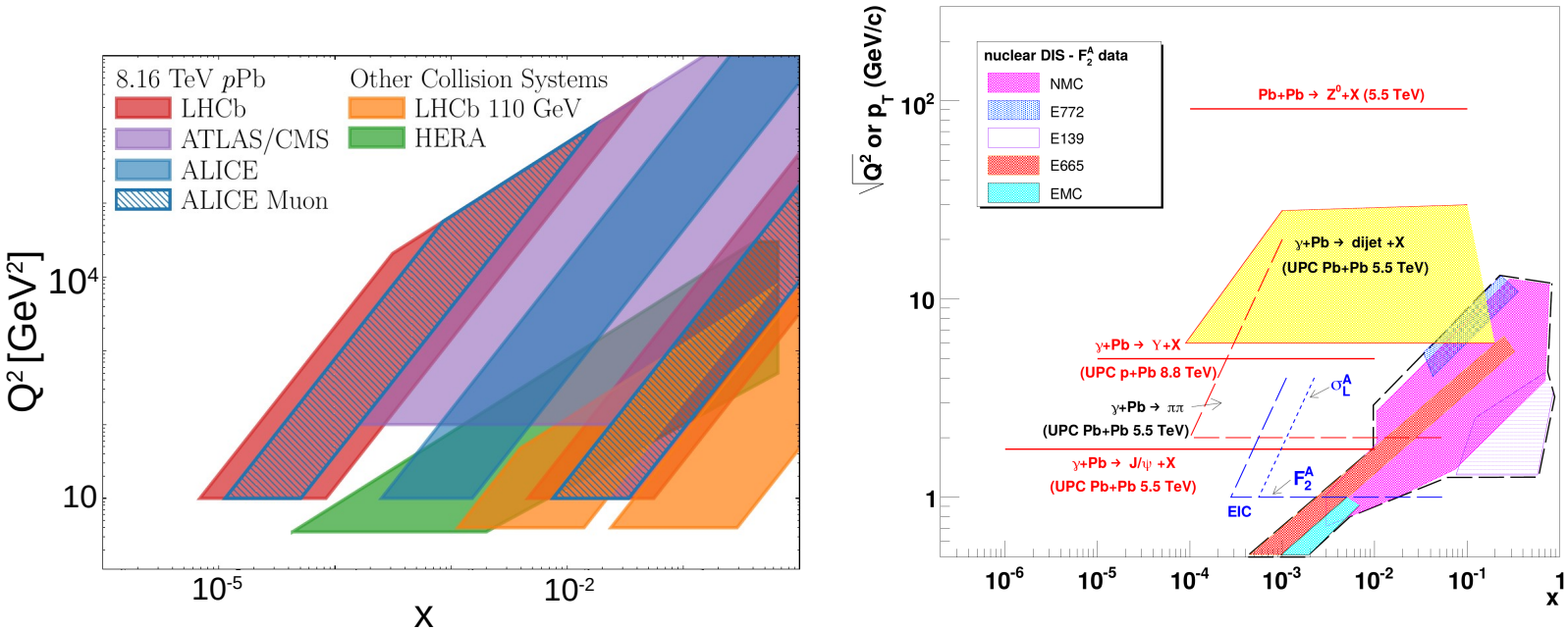
Left: CMS-PAS-FTR-18-026/ALICE-PUB-867, right: ATL-PHYS-PUB-2018-039.

- 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.

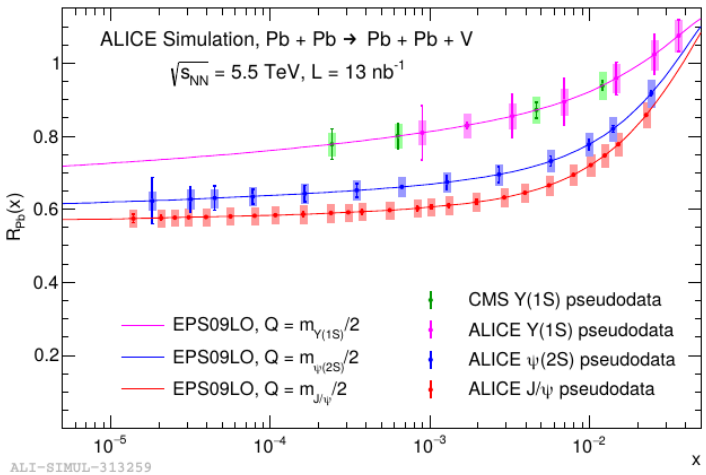
Partonic content of nuclei: initial conditions and the low-x limit

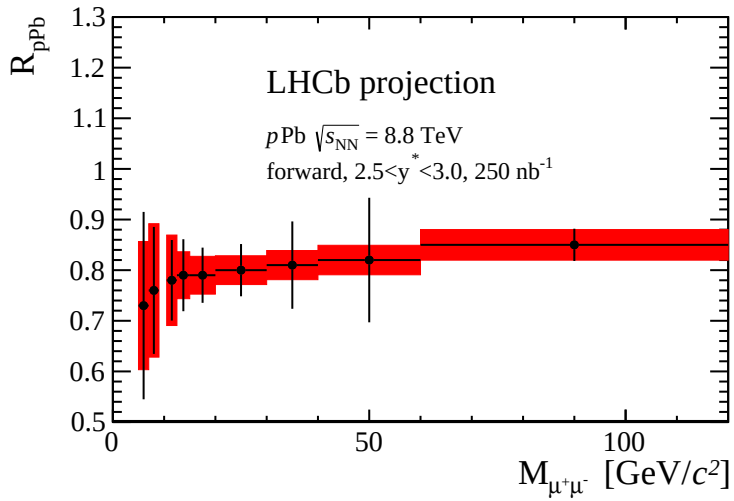


p-Pb collider kinematics of compared with HERA and fixed-target, nuclear DIS, UPC kinematics.

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

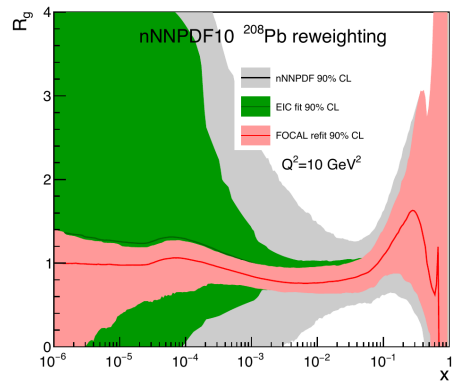
Probing a broad (x, Q^2) range and searching for the possible onset of saturation





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

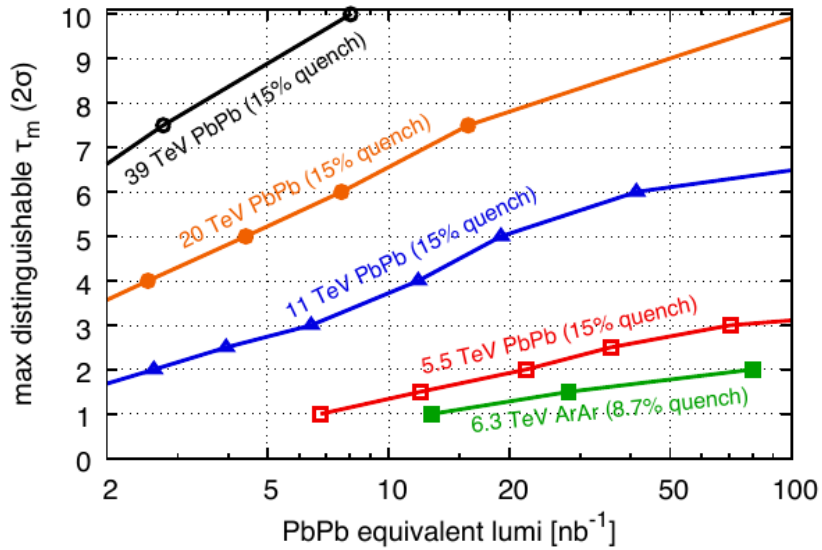
- probe nucleus with quasi-real photon in ultra-peripheral collisions (UPC)
- new observables in p-Pb with colour neutral final state at forward rapidity
- probe lowest available Bjorken-x & densest QCD systems
- forward calorimeter for Run 4 under consideration in ALICE, presentation by N. Novitzky link



Nuclear PDF constraint: isolated photons ALICE forward calorimeter.

Beyond 2030: lighter ions for larger luminosity

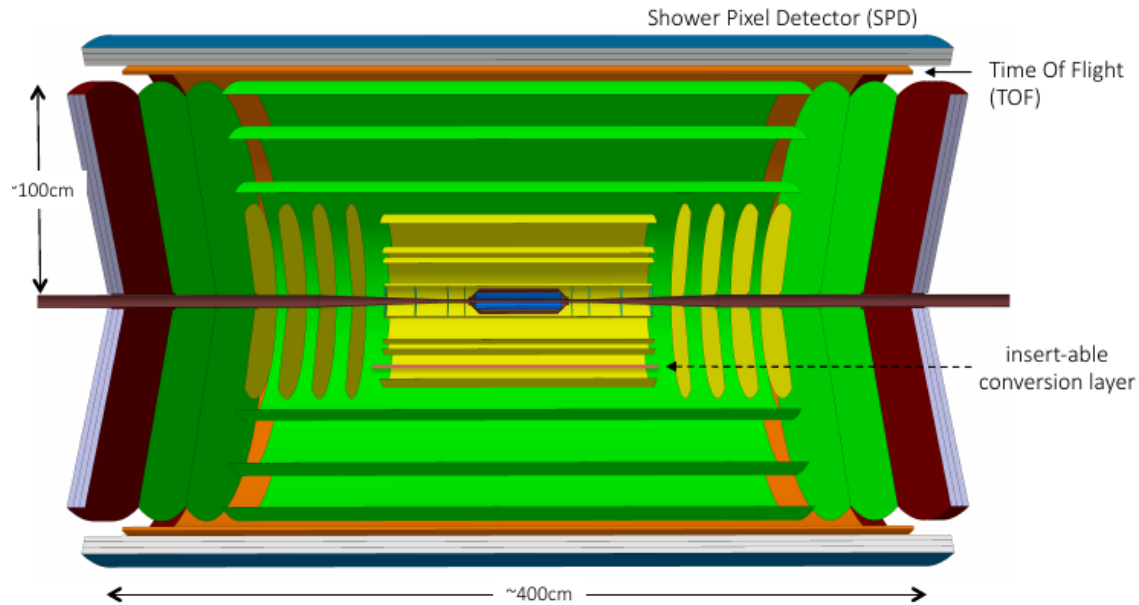
	$^{16}O^{8+}$	$^{40}Ar^{18+}$	$^{40}Ca^{20+}$	$^{78}Kr^{36+}$	$^{129}Xe^{54+}$	$^{208}Pb^{82+}$
γ	3760.	3390.	3760.	3470.	3150.	2960.
$\sqrt{s_{NN}}$/TeV	7.	6.3	7.	6.46	5.86	5.52
$\int_{month} L_{AA}$ dt/nb^{-1}	5.89×10^4	3180.	2190.	218.	38.2	4.92
$\int_{month} L_{NN}$ dt/pb^{-1}	1.51×10^4	5090.	3510.	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: $\sigma \sim 1\mu m$
- Outer layers: $\sigma \sim 5\mu m$

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

Time Measurement
Outermost layer integrates high precision time measurement ($\sigma_t \sim 20ps$)

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
- *with new detectors: intention to rerun in PbPb likely*

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

Thoughts on small systems in Run 3/4 and beyond

- a main focus of Run 3 as well as Run 4:
  conceptual questioning should be addressed throughoutly
  very important as a field as a whole
- RHIC will likely also contribut with OO runs or other system scans
- in my view: further future of a heavy-ion programme should not be centred around this question
  $\rightarrow$ "smaller" nuclei advantageous in terms of lumi or depending on findings of Run 3/4 as better lab
  $\rightarrow$ but not as a matter of study in itself

a comment on ALICE pp programme Run 3/4 in this context:
- identify where ATLAS/CMS/LHCb is not sufficient within much shorter running time
- exclusive or inclusive QCD measurements could be complements, where PID instrumentation and low material budgets beneficial:
double vector meson production for odderon search, DY-jet correlations at low scales for BFKL dynamics, glueball searches in KK-mass distribution etc.
$\rightarrow$ requires triggering on topologies!

Thoughts on long-term hard probes opportunities

- boosted objects and very high-p_T with precision
- use pp toolkit and beyond as well as weak interaction
  $\rightarrow$ interesting and synergistic with pp programme

Theory and phenomenology needs to be develop further in order to gauge its importance and the insight!

Thoughts on long-term soft probes opportunities

- electromagnetic radiation
- heavy-flavour/quarkonium
- net-charge transport, higher moments

In order to fully profit from precision improvements, need sustained theory effort!
$\rightarrow$ starting discussions: first at ALICE physics week in July
$\rightarrow$ first ideas to use a YR-like group to write-up the case after initial inputs including hard probes

Thoughts on relation to lepton-proton/ion opportunities

- lepton-ion machine helpful to resolve a number of modelling/theory uncertainties in particular in initial state
- potentially also contributions to conceptual questions: small systems correlations
  $\rightarrow$ in many cases, difficult to forecast how far the exchange will go
  $\rightarrow$ to fully exploit this opportunity: need to run in parallel EIC and a heavy-ion programme at high-energies

Participations in future projects

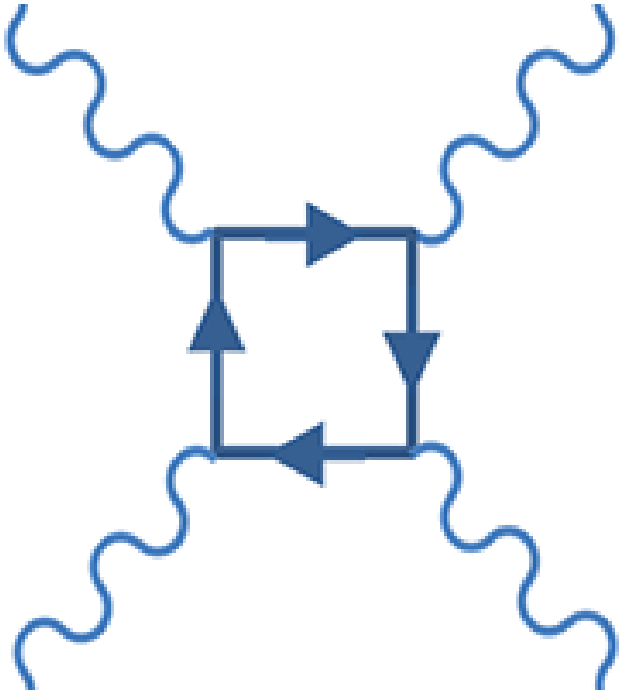
- good position: first-hand information from 3 experiments at the LHC
- future project(s) should have:
  - clear ambitious scientific goals: competitive
  - a spectrum of different observables: heavy-ions is dynamic
  - a critical mass
  - technically interesting aspects

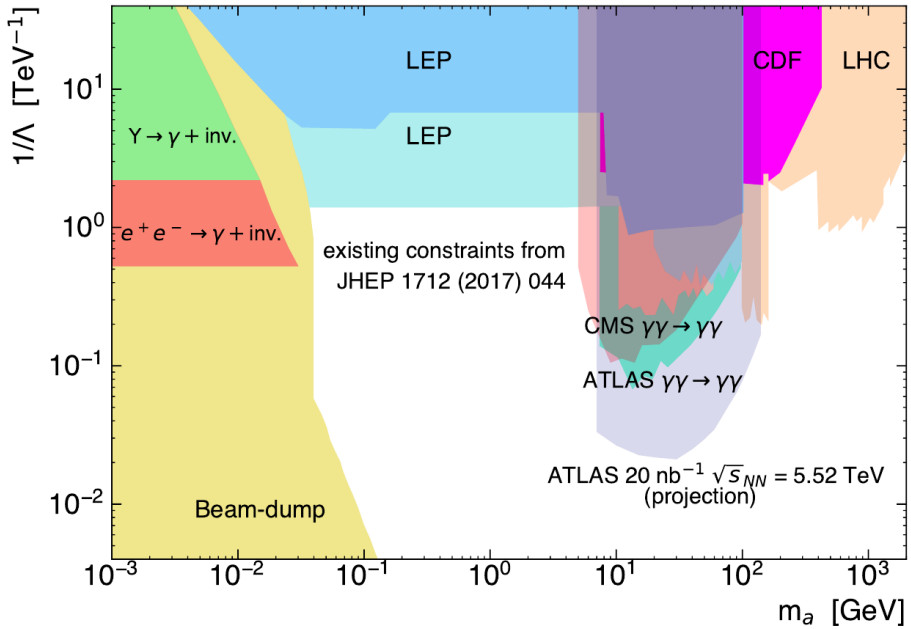
Examples:

- decipher geometry & time structure of QGP with electromagnetic and/or weak probes and "exclusive" probes:
  "take pictures of the QGP as function of time"
- measure qq-potential with different states
- measure phase transition universality class
- measure charge transport like energy transport ($\rightarrow$ flow not for energy, but for charge, baryon number etc.)
- something completely new
- more conceptual: "full event reconstruction"

Heavy-ion collisions has deep questions to answer and there are plenty opportunities

Back-up: Further opportunities with heavy-ion beams



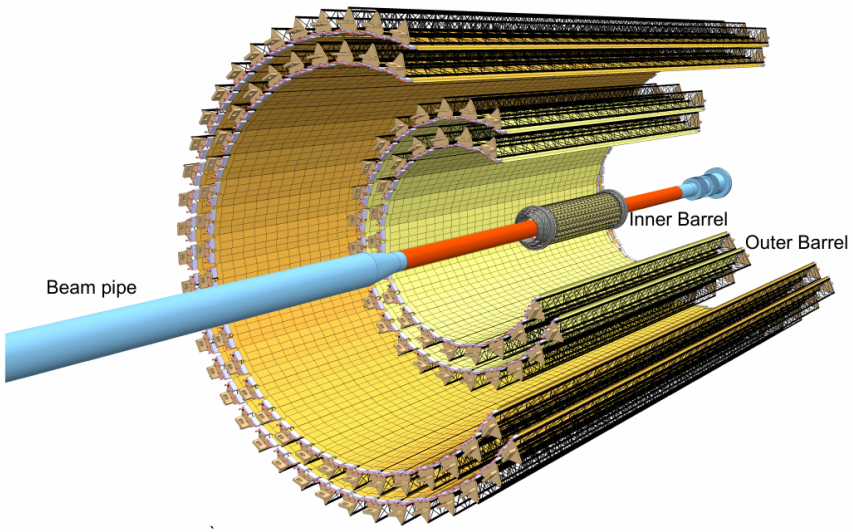


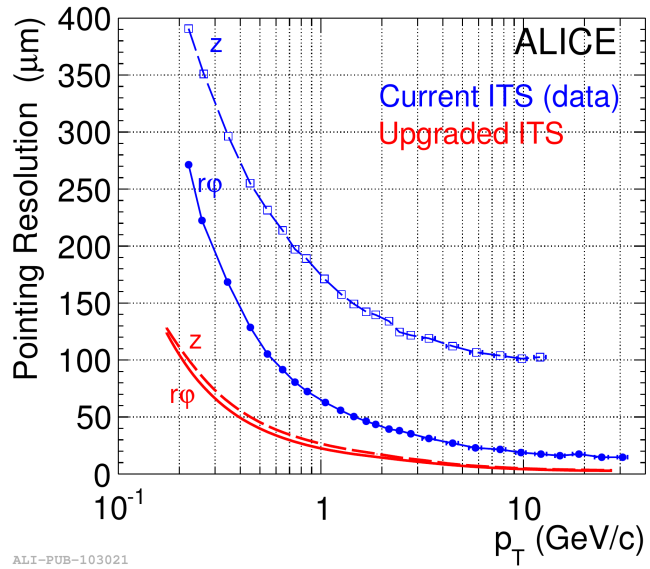
Right: ATL-PHYS-PUB-2018-018.

- 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

Inner Tracking System

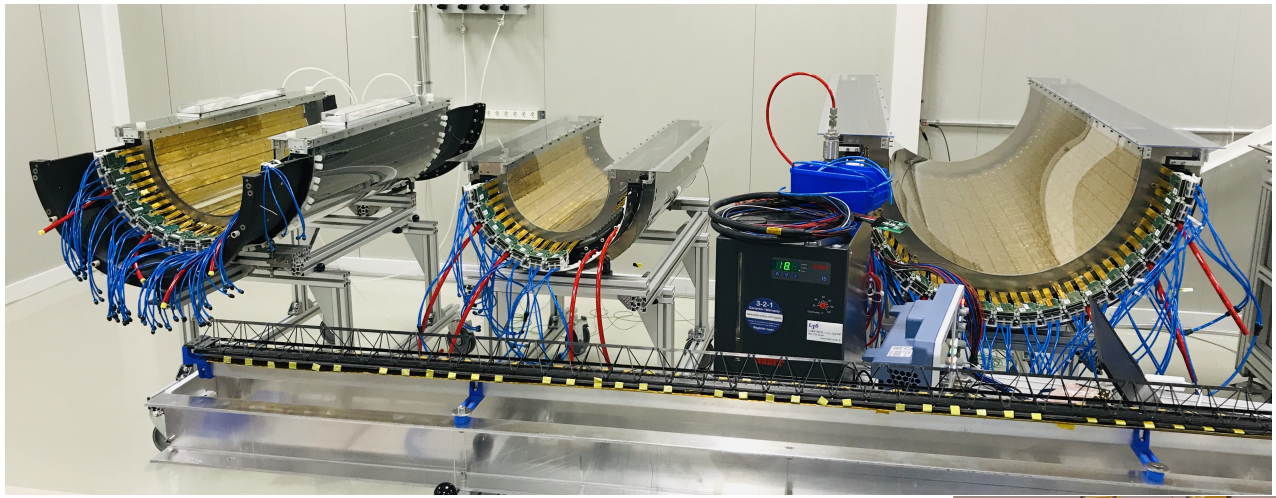




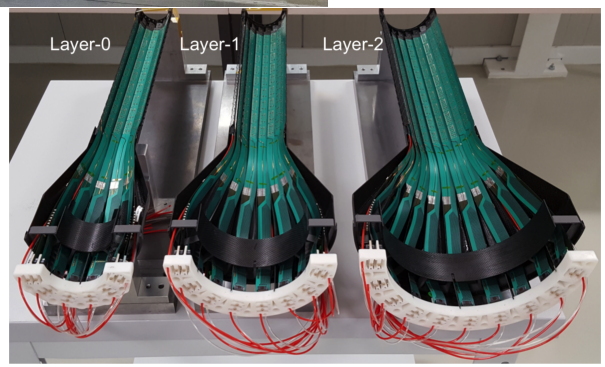
ALICE-TDR-017

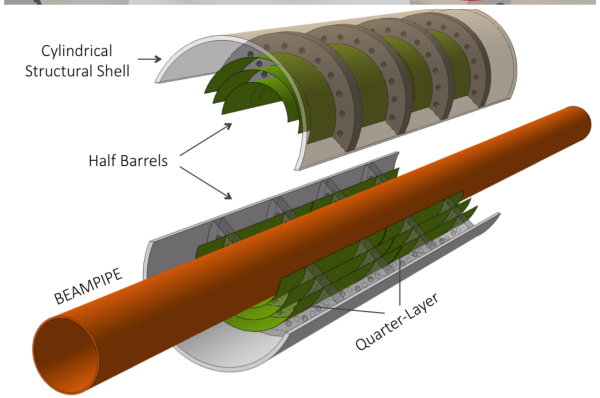
- ALice PIxel DEtector (ALPIDE):
  monolithic silicon pixel sensor with binary read-out
- 7 (3-2-2) layers
- innermost layer at 39 $\rightarrow$ 22 mm radius, 0.35% X_0 for inner layers
- 10 m^2, 12.5 billion pixels
- spatial resolution 5 μm

Inner Tracking System: assembly



Left: Halves of layers 4, 3, 5, right: inner barrel.

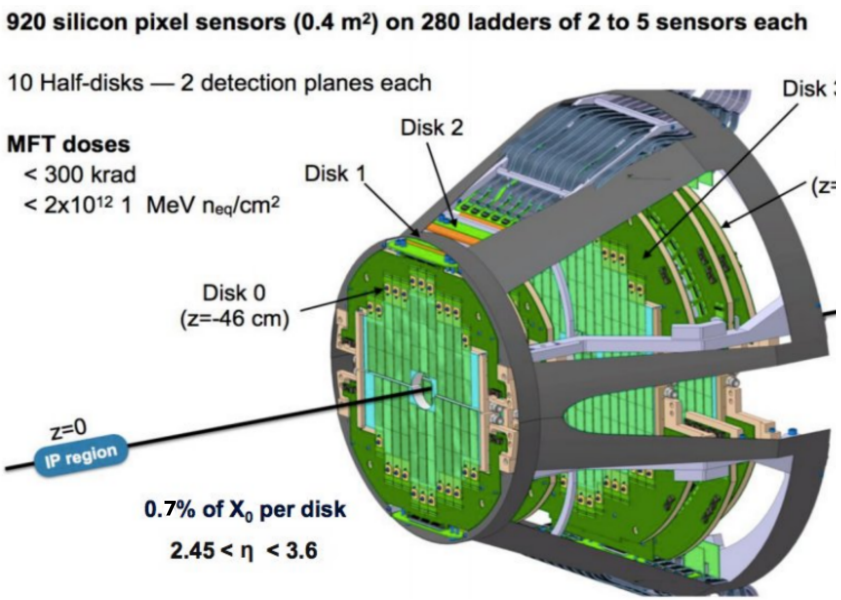


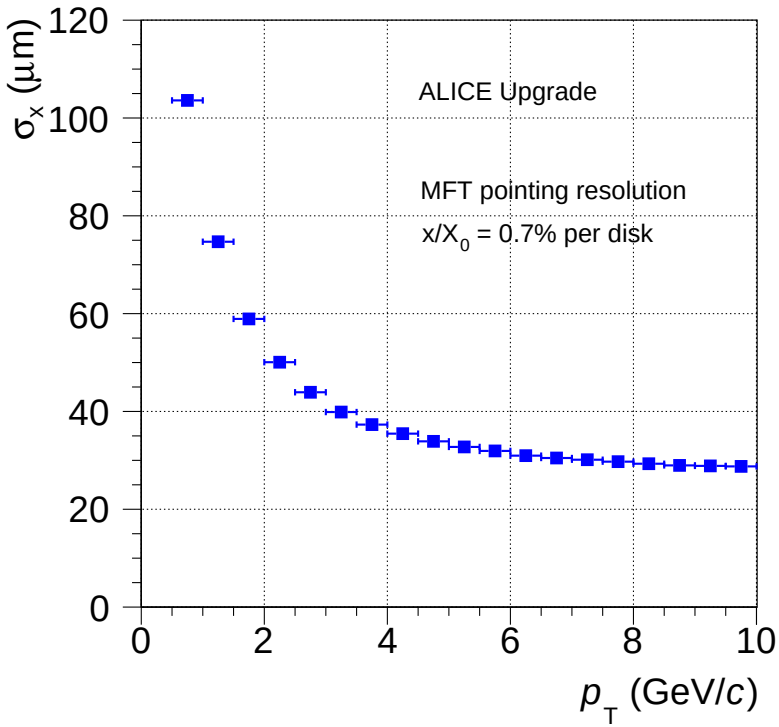


top: inner barrel, bottom: Run 4 proposal layout.

- assembly in full swing at CERN
- inner barrel and first half of middle and outer barrel completed
- ALICE Expression of Interest for a fully cylindrical Run 4 upgrade ALICE-PUBLIC-2018-013
  $\rightarrow$ see M. Keil's presentation link

Muon Forward Tracker

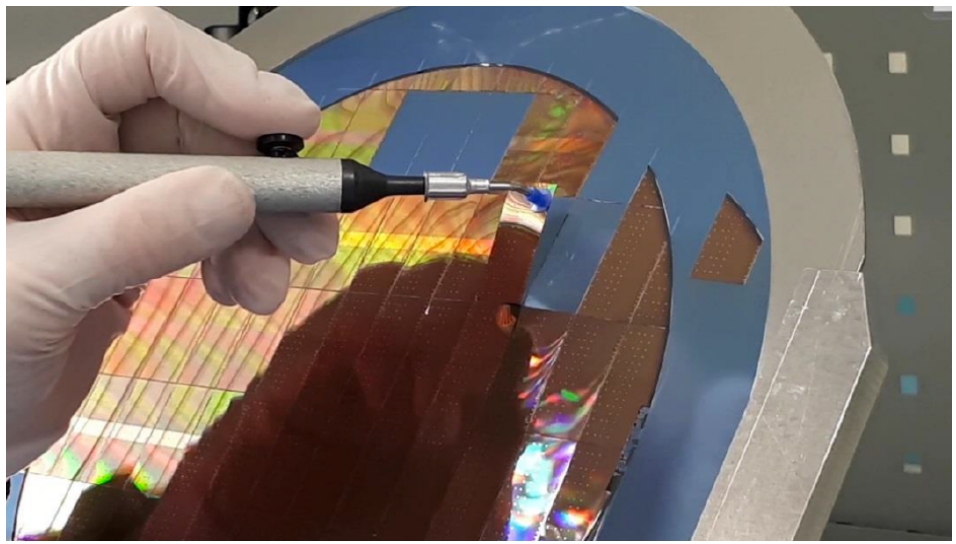




ALICE-TDR-018

- new silicon detector in front of muon absorber
- secondary vertexing for heavy-flavour and background reduction for low-p_T quarkonium and low-mass dileptons
- ALPIDE chip: 5 disks

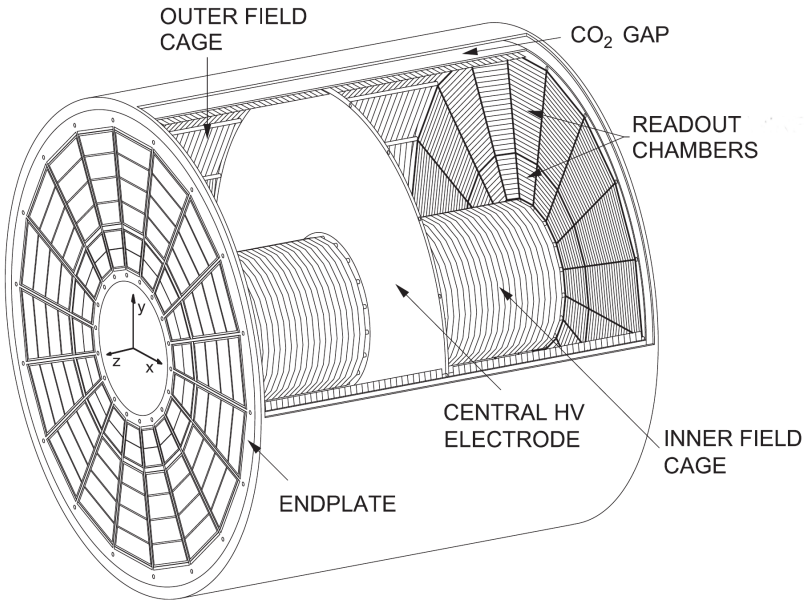
Muon Forward Tracker: final steps

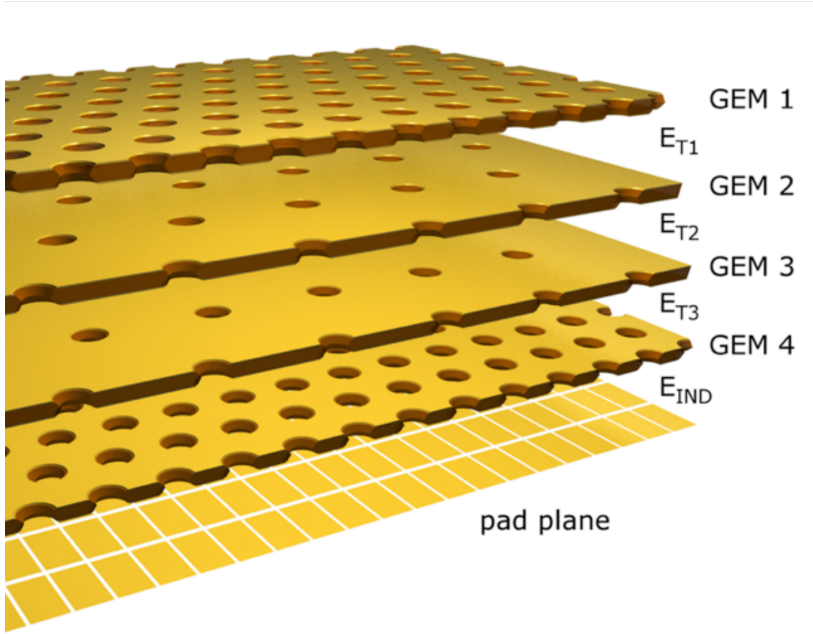



MFT Mechanical support structure (service barrel) and manual *pick and place* of waver.

- all components in their final steps
- final assembly this year at CERN
- more details in M. Marchisone's talk link

Time Projection Chamber

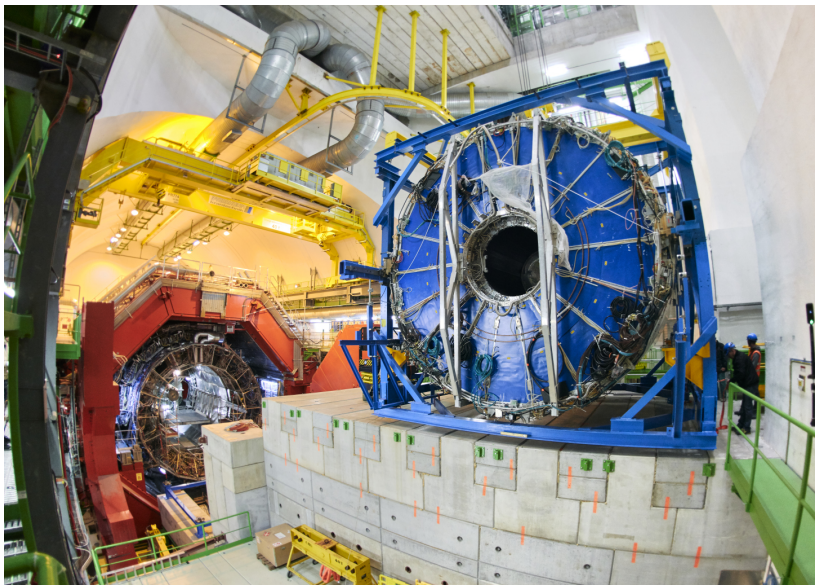




TPC layout, electrode overview ALICE-TDR-016

- 100 μs drift time, $\approx$ 90 m^3 gas volume
- replace gated multiwire-proportional chambers with quadruple GEM
- operational point:
  - ion-back flow in drift region $< 1\%$ for gain 2000 with Ne-CO_2-N_2 gas
  - local energy resolution $< 12\%$ with ^{55}Fe
- new electronics and partial online calibration
- Run 1/2 tracking and dE/dx performance with continuous read-out at 50 kHz Pb-Pb

Time Projection Chamber on its way to upgrade



Transport of TPC, last multi-wire proportional read-out chamber removed in May 2019.

- TPC on surface in clean room
- being equipped with quadruple GEMs
- details in E. Hellbär's talk link