Heavy Ion and Fixed-Target Physics at ATLAS, CMS and LHCb





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Heavy ions in ATLAS/CMS

- General purpose detectors (fully instrumented at mid-rapidities) can reconstruct heavy ion events, up to the most central PbPb collisions
- Exploiting the full potential of LHC luminosity



Large luminosities enabled first observations of rare processes.
 Noticeable examples: light-by-light scattering in PbPb (ATLAS), top production in pPb (CMS)

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Noticeable examples: light-by-light scattering in PbPb (ATLAS),
top production in pPb (CMS)

Tracking saturates for most central PbPb collisions ► LHCb more suited for smaller collision systems. Still, crucial environment to understand cold nuclear matter effects and collectivity in small systems

Unique forward coverage at LHC, with excellent performance for heavy flavours down to $0 \ p_{\rm T}$

-5mALICE 10m (2015) 1530022 ATLAS 10hadron PID Other Collision Systems 16 TeV pPbmuon system LHCb 110 GeV LHCh -10 10 lumi counters 10ATLAS/CMS HERA η HCAL CMS+TOTEM ALICE FCAL ALICE Muon 10^{5} tracking $\frac{Q^2}{GeV^2}$ -10 10 LHCb -10 10^{2} Sensitivity to small x (down to $\sim 10^{-5}$) 10^{1} ▶ gluon saturation Saturated region and to anti-shadowing region 10^{-2} 10^{-4} 10^{-3} 10^{-1} 10^{-} 10^{-5}

Heavy ions in LHCb

Magne

RICH1

Vertex Locator SPD/PS HCAL^{M2 M3} T3 RICH2 ECAL 2 M1



Fixed target collisions in LHCb



The System for Measuring Overlap with Gas (SMOG) allows to inject small amount of noble gas in the LHC vacuum **Turns LHCb into a fixed-target experiment!** Possible targets: **He, Ne, Ar**, and more in the future Typical pressure $\sim 2 \times 10^{-7}$ mbar \Rightarrow up to $\mathcal{L} \sim 10^{30} \text{cm}^{-2} \text{s}^{-1}$

 Collisions at √s_{NN} = 69-110 GeV (E_{beam} = 2.5 - 6.5 TeV) → relative unexplored energy scale between SPS and LHC experiments
 At √s_{NN} = 110 GeV, c.m. rapidity is -2.8 < y* < 0.2 → backward detector with access to large x value in target nucleon, sensitive to antishadowing/EMC region and intrinsic heavy quark content in nucleons





Samples acquired during Run 2, up to $\int \mathcal{L}dt \sim 100 \text{ nb}^{-1} \text{ (pNe)}$ and $\sim 100 \ \mu b^{-1} \text{ (PbNe)}$ LaThuile 2019

Outline

Heavy ion (and fixed target) submitted papers since last La Thuile conference:

ATLAS13 (+ 3 prelim.)CMS16 (+ 1 prelim.)LHCb5 (+ 1 prelim.)

A wide range of observables, with the main goals of

- characterising the properties of quark gluon plasma (QGP)
- understand collectivity in particle production across system size from pp to PbPb

A biased selection in this talk, focused on:

Heavy flavours

Sequential quarkonia suppression in PbPb and pPb Open heavy flavours in PbPb and pPb Flow of quarkonia in PbPb and pPb

Electroweak probes

W/Z boson production in PbPb and pPb γ -tagged jets Ultra-peripheral collisions (UPC)

Fixed target results

Charm production at large Bjorken-x"cosmic" collisions pHe \rightarrow antiprotons



Freezout – creation of particles seen in the detector

Reconstruction of Heavy Flavours

Rich heavy flavour samples collected by the three experiments, thanks to the large integrated luminosities and the excellent vertexing and particle id performance.

Prompt charm and charm-from-b components can be disentangled

 $\psi(') ext{ in PbPb EPJ C78 (2018) 762}$



Sequential quarkonia suppression in PbPb/pPb

- Suppression of quarkonia states from colour screening is the classical (predicted 1986) signature for QGP formation;
- important to distinguish prompt and non-prompt charmonia, as the latter are expected to be formed outside the QGP;
- charmonia regeneration is also expected to be important at LHC energies (not for bottomonia);
- parton energy loss in the medium can also affect the suppression pattern.



Observable is the nuclear modification factor
$$R_{AA} = \frac{\text{Yield}_{AA} / < N_{\text{coll}} >}{\text{Yield}_{pp}}$$

- Cold nuclear matter (CNM) effects need to be also taken into account: initial state effects (nPDF), coherent parton energy loss, interaction with comovers, p_T broadening...
- measurement in pPb as a reference for CNM effects

Charmonia suppression in PbPb

Measurement of $R_{\rm AA}$ for prompt and non-prompt J/ ψ and $\psi(2S)$

- Strong J/ψ suppression, decreasing at large p_T in similar way for prompt, non-prompt J/ψ and light charged particles. Hint for common parton energy loss mechanism?
- Double ratio $R_{AA}(\psi(2S))/R_{AA}(J/\psi)$ consistent with sequential suppression for prompt particles
- Increase of double ratio at large multiplicity could be due to relatively larger regeneration of $\psi(2S)$
- Some tension with the earlier CMS result. 2018 data should clarify the situation.









Bottomonia suppression in PbPb

PLB 790 (2019) 270



- Spectacular bottomonium sequential suppression observed by CMS
- Hydro model [Krouppa Strickland, Universe 2 (2016) 16], implementing color screening and tuned on charged-hadron measured spectra and flow, was able to predict data, but sizeable CNM effects are not excluded in other models

Same measurements in pPb



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R_{pPb} for open beauty

LHCb arXiv:1902.05599

Clean signals in four exclusive B decay modes:

Decay	$p \operatorname{Pb}$	$\operatorname{Pb} p$
${\rm B} \ ^+ \! \rightarrow \overline{D}{}^0 \pi^+$	1958 ± 54	1806 ± 55
$\mathrm{B}^{+} \to J/\psi K^{+}$	883 ± 32	907 ± 33
$B^{0} \rightarrow D^{-} \pi^{+}$	1151 ± 38	889 ± 34
$\Lambda_b^0 \to \Lambda_c^+ \pi^-$	484 ± 24	399 ± 23



- Suppression observed at forward rapidity and low $p_{\rm T}$, compatible with results from non-prompt J/ ψ
 - consistent with nPDF (shadowing)
- Similar pattern observed for hidden and open charm
- Rapidity dependence can also be explained by coherent parton energy loss Arleo and Peigné, JHEP 03 (2013) 122



J/ψ flow in PbPb



- **EPJ C78 (2018) 784**
- Azimuthal anisotropies are key observables to investigate interaction of the heavy flavour probes with the hot medium

$$\frac{dN}{d\phi} \propto 1 + \sum_{n=1}^{\infty} 2\boldsymbol{v_n} \cos[n(\phi - \psi_n)]$$

- Elliptic flow v_2 measured separately for prompt and non-prompt J/ψ
- Higher flow at low $p_{\rm T}$ for prompt J/ ψ , compatible with regeneration
- Hint for universal behaviour at high $p_{\rm T}$, like for $R_{\rm AA}$

 Similar measurements from ALICE and CMS, though at different energy and rapidity coverage, give consistent picture, suggesting sizeable collective behaviour of charm quarks in the QGP



J/ψ flow in pPb!!

PLB 791 (2019) 172 PRL121 (2018) 082301

- More surprising is the observation of such collective behaviour of heavy flavours in smaller collision systems: sizeable v₂ for prompt J/ψ and D⁰ in pPb measured by CMS in high-multiplicity events
- **QGP** in small systems?? Strong initial state momentum correlations?



Electroweak Probes: W/Z

• W/Z boson production provides information on the initial state, as decay products are not interacting strongly with the medium





- W production in the 8.16 TeV pPb data, based on 180k $W \rightarrow \mu\nu$ candidates
- Constraints on nPDF: good agreement with EPS09 and EPPS16, not compatible with DSSZ, nCTEQ15 and CT14 (nucleon)



- Precision W and Z production measurement in pp reference sample at 5.02 TeV
- Will serve as reference for measurements in PbPb and pPb at same energy

Photon-tagged jet energy loss



photon

jet (AA)

1.2 1.4 1.6 1.8

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- High- $p_{\rm T}$ photons, unmodified by the medium, can be used to tag the initial $p_{\rm T}$ of a recoiling jet
- Measure gamma-jet $p_{\rm T}$ asymmetry $x_{J\gamma} \equiv p_{\rm T}^{jet}/p_{\rm T}^{\gamma}$ after unfolding detector effects
- Peripheral PbPb collisions similar to pp : peak for balanced events
- Strong modification in central collisions; double-peak structure indicating strong event-by-event fluctuations

1.2 1.4 1.6 1.8

 $\boldsymbol{X}_{J\gamma}$

0.2 0.4 0.6 0.8



1.2 1.4 1.6 1.8

X_{Jγ}

1

0.2 0.4 0.6 0.8

(1/N^v)(dN/dx/_v)

(_v(xb/Nb)(_y)(_y)

0.2 0.4 0.6 0.8

Ultra-Peripheral Collisions

- UPC provide a flux of quasi-real photons probing the nuclear structure
- PbPb and pPb collisions exploit the large γ flux $\propto Z^2$
- For exclusive production of heavy flavour states, pQCD calculations are possible
- Sensitive to nPDF down to $x \sim 10^{-5}$ (for y up to 5)



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arXiv:1809.11080

- CMS observed first Υ signal in pPb UPC
- Sensitive to photon-proton energy $91 < W_{\gamma p} < 826$ GeV, filling the gap between HERA and LHCb (pp) measurements



$J\!/\psi\,$ in UPC PbPb

- LHCb observed a clean J/ ψ signal (and hint for $\psi(2S)$) in PbPb
- Coherent and incoherent J/ψ photoproduction can be distinguished from $p_{\rm T}$ shape
- Limited statistics, but precision of the measurement demonstrated
- Very good prospects with 2018 data





Result for coherent x-section, compared with phenomenological models

LHCb-CONF-2018-003

Dimuon photoproduction in non-UPC

• Dimuons photoproduced on top of hadronic collisions, identified through the acoplanarity α and $p_{\rm T}$ asymmetry A

$$\alpha \equiv 1 - \frac{|\phi^+ - \phi^-|}{\pi}; \quad A \equiv \frac{|p_{\rm T}^+ - p_{\rm T}^-|}{|p_{\rm T}^+ + p_{\rm T}^-|}$$

Significant broadening of the acoplanarity is observed in most central collision
 a novel clean probe of the QGP medium!



Light-by-light Scattering



- I4 events observed by CMS, with 11.1 ± 1.1 signal and 4.0±1.2 background events expected; confirms ATLAS's discovery
- Result is used to set a limit on contribution from axion-like particle (ALP)





Charm production in Fixed targets

arXiv:1809.01404, accepted by PRL

First charm samples from pHe@69 GeV ($7.6 \pm 0.5 \text{ nb}^{-1}$) and pAr@110 GeV (few nb⁻¹)

- First determination
 of cc cross-section
 at this energy scale
- No evidence for pHe sizeable intrinsic charm contribution
- More to come larger from sampAr ples on tape $100 \text{ nb}^{-1} \text{ pNe}$ $(\sim$ and \sim $100 \ \mu b^{-1}$ PbNe) G. Graziani slide 21

Cosmic Antiprotons

PRL 121 (2018), 222001

 Precision AMS-02 measurements of p/p ratio in cosmic rays at high energies, indirect search for Dark Matter

AMS02, PRL 117, 091103 (2016)

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Giesen et al., JCAP 1509, 023 (2015)
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- Prediction for p/p ratio from spallation of primary cosmic rays on intestellar medium (H and He) is presently limited by uncertainties on p production cross-sections
- First $\sigma(pHe \rightarrow \overline{p}X)$ measurement performed by LHCb with SMOG
- Accuracy below 10% in all kinematic bins, well below spread among models

Fixed target upgrade(s)

LHCb approved an upgraded gas target (SMOG2), consisting in a storage cell located in the proximity of the interaction point, to be be operational already in Run 3 (2021)

- allows larger gas density where needed increase luminosity by up to 2 orders of magnitudes with same gas flow
- more gas species possible: hydrogen and deuterium, heavier gas (Kr, Xe)
- precise control of gas density

Physics prospects summarized in LHCB-PUB-2018-015

More proposals for the future (see *Physics Beyond Colliders* forum):

- polarized gas target
- solid target coupled with bent crystal, to study electric and magnetic moments of charmed baryons
- solid microstrip target

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Heavy ions in future LHC Runs

Year	Systems, $\sqrt{s_{NN}}$	Time	L_{int}
2021	Pb–Pb 5.5 TeV	3 weeks	2.3 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2022	Pb–Pb 5.5 TeV	5 weeks	3.9 nb^{-1}
	О–О, р–О	1 week	$500 \ \mu b^{-1} \text{ and } 200 \ \mu b^{-1}$
2023	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2027	Pb–Pb 5.5 TeV	5 weeks	3.8 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2028	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2029	Pb-Pb 5.5 TeV	4 weeks	3 nb^{-1}
Run-5	Intermediate AA	11 weeks	e.g. Ar–Ar 3–9 pb^{-1} (optimal species to be defined)
	pp reference	1 week	

- Requirements and prospects for developing HI physics at the LHC have been summarised by the four LHC experiments within the HL-LHC workshop: report of WG5 in arXiv:1812.06772
- Proposed large increase in available luminosities, taking profit of upgrades of the experiments and of the HL-LHC

Conclusions

- ATLAS, CMS and LHCb are complementing ALICE in bringing breakthrough advances to the understanding of relativistic heavy ion collisions through a wealth of observables, exploting the complementarity of the detectors
- Much more results not covered here, notably on jet quenching and flow of light particles.

Summary of all HI results can be found at these web pages:

ATLAS: twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults CMS: cms-results.web.cern.ch/cms-results/public-results/publications/HIN/index.html LHCb: lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_IFT.html