Physics with the detector upgrades at the LHC

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Special thanks to:
Jan Fiete Grosse-Oetringhaus / Andrea Dainese / Alexander Kalweit (ALICE),
Zvi Citron (ATLAS), Yen-Jie Lee (CMS), Michael Winn (LHCb -> ALICE)
OUTLINE

• Heavy-ion collisions at the LHC and open questions
• The next ten years at the LHC
• Expected performance on a few key observables

Disclaimer: It is impossible to cover all Run 3/4 heavy ion physics topics in 20 mins, so this talk covers only a small selection.

**Heavy Ions at the LHC**

and open questions

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**Initial state**
- Nuclear parton distributions not strongly constrained
- Importance of initial state fluctuations
  - Characteristics of the initial state?
Heavy ions at the LHC

and open questions

Macroscopic properties (long wavelength characterisation)
- Description in terms of fluid- and thermodynamics
- Next level of precision and new observables (flow correlations, …)
  ➢ Properties of QCD matter and the transition between phases?

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HEAVY IONS AT THE LHC
and open questions

Microscopic dynamics (short wavelength characterisation)
• Strong energy loss for hard partons
• New jet substructure observables (splitting function, jet mass,…)
• Quarkonium suppression and regeneration
  ➢ Degrees of freedom at which stage and their interactions?

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Small systems
• Surprises in pp and p-Pb collisions (“flow”, “strangeness enhancement”)
  ➢ Is there a unified picture of QCD particle production from small (pp) to larger (p-A and A-A) systems?
13 nb⁻¹ Pb-Pb collisions
- ≈ 10 × combined Run 1/2 luminosity
- ≈ × 100 for soft probes (new ALICE read-out)

Complemented by (proposal of HL-LHC WG5)
- Larger p-Pb samples: 1.2 pb⁻¹ ATLAS/CMS, 0.6 pb⁻¹ ALICE/LHCb & pp references
- pp running for high-multiplicity events: 0.2 fb⁻¹
- Pilot-like O-O and p-O collisions run

Proposal for lighter ions, e.g. Ar–Ar (A = 40), running in Run 5 (2030+) to sample much larger luminosities

CERN-LPCC-2018-07
**Upgrades (LS 2):**

- 50 kHz Pb-Pb readout ($O^2$)
- New Inner Tracking System (ITS2)
- GEM readout for TPC
- Muon Forward Tracker
- Fast Interaction Trigger (FIT)

**Fixed-target upgrade** to sample 10-100 larger luminosity

- **New tracking detectors** and read-out for 5× pp pile-up
THE NEXT TEN YEARS

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- 50 kHz Pb-Pb readout (O²)
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- Fast Interaction Trigger (FIT)

Upgrades (LS 3):
- Upgrade of the ZDCs
- Larger tracking acceptance for ATLAS and CMS (|\eta| < 4) with better performance
- Better charged particle tracking in high-multiplicity events, improving b-tagging of jets, and more selective photon, electron, and muon triggers
- Extended PID capabilities

- Fixed-target upgrade to sample 10-100 larger luminosity
- New tracking detectors and read-out for 5× pp pile-up

References:
- ALICE-TDR-015 ALICE-TDR-016 ALICE-TDR-017
- ALICE-TDR-018 ALICE-TDR-019
- ALICE-PUBLIC-2018-013
- CMS-TDR-014 CMS-TDR-020
- ATLAS-TDR-025 ATLAS-TDR-030
- ALICE-TDR-017 ALICE-TDR-018 ALICE-TDR-015
### The Next Ten Years

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<thead>
<tr>
<th>Year</th>
<th>Event</th>
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<td>2030</td>
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#### Upgrades (LS 2):
- **50 kHz Pb-Pb readout** (O²)
- New Inner Tracking System (ITS2)
- GEM readout for TPC
- Muon Forward Tracker
- Fast Interaction Trigger (FIT) [ALICE-TDR-015, ALICE-TDR-016, ALICE-TDR-017, ALICE-TDR-018, ALICE-TDR-019]
- **Fixed-target upgrade** to sample 10-100 larger luminosity
- New tracking detectors and read-out for 5× pp pile-up [LHCb-PUB-2018-015, LHCb-TDR-013, LHCb-TDR-015]

#### Upgrades (LS 3):
- **Upgrade of the ZDCs**
- Larger tracking acceptance for ATLAS and CMS (|η| < 4) with better performance
- Better charged particle tracking in high-multiplicity events, improving b-tagging of jets, and more selective photon, electron, and muon triggers
- Extended PID capabilities

- LHCb Upgrade-II
- New heavy-ion detector at LHC point 2?

[arXiv:1902.01211 [physics.ins-det]]
### INITIAL STATE

- Nuclear PDFs not strongly constrained
- Probe lowest available Bjorken $x$
  - Onset of gluon saturation?

- High-luminosity p–Pb and Pb–Pb ($\gamma$–Pb) collisions
  - Highly-improved precision and kinematic coverage

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**Graphs:**
- **EPPS16**
  - $Q^2$ [GeV$^2$]
  - $x$

- **Ratio of nuclear modification factors**
  - $R^{Pb}_{S}(x, Q^2 = 10 GeV^2)$
  - $R^{Pb}_{g}(x, Q^2 = 10 GeV^2)$

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**Legend for Graphs:**
- fixed target DIS and DY
- LHC dijets
- LHC W & Z
- CHORUS neutrino data
- PHENIX $\pi^0$
**INITIAL STATE**

**ALICE-PUBLIC-2019-001**

ALICE Simulation, Pb + Pb → Pb + Pb + V

$\sqrt{s_{NN}} = 5.5$ TeV, $L = 13$ nb$^{-1}$

- **Pseudodata** projections for the nuclear suppression factor by ALICE and CMS measured with the photoproduction of three heavy vector mesons in Pb–Pb ultra-peripheral collisions are shown. The pseudodata points are derived from EPS09-based photoproduction cross section projections following the method described in Ref. [813].

Coherent J/$\psi$ photoproduction in UPCs was also studied in the $k_t$-factorization approach [823] in terms of the unintegrated nuclear gluon distribution, which determines the initial condition for the non-linear evolution equation. In the case of $\pi^+$ meson production, shadowing is a factor of $\sim 2$ stronger [824] than in the approach based on the Glauber model and the vector meson dominance model.

The higher LHC luminosity and experimental upgrades will allow us to collect vastly improved samples of UPC events. In particular, the planned ALICE continuous readout [825], will eliminate many of the trigger-based constraints that have limited UPC data collection, allowing for high-efficiency collection of large samples of photoproduced light mesons. The increases in sample sizes should be considerably larger than one would expect from merely scaling the luminosity.

In order to conclude this section on the opportunities with vector meson production, we want to give a list of not yet exploited measurements that provide further insight into photonuclear interactions with heavy, light and multiple vector meson production:

- Extend substantially the $x$ range for coherent J/$\psi$ photoproduction on nuclei using information on the impact parameter distribution in peripheral and ultra-peripheral collisions provided by forward neutron production [812]. The impact parameter distribution can be accessed in the context of UPCs by exploiting the properties of additional photon or hadronic interactions in addition to the photon that produces the vector meson. The rates for the combined processed can be found in [826] and the relationship between impact parameter and additional photon interactions is discussed [827]. The $x$-range can be also extended by using $p$–$A$ collisions to probe the nucleus. In the latter case, one would have to separate coherent J/$\psi$ production in $A$ and $p$ using a much more narrow $p_T$ distribution of $\pi^+$ produced in coherent $A$ scattering and very good $p_T$ resolution for the transverse momentum of the pair (LHCb).

- Measure with high enough statistics coherent $U(1S)$ production in $p$ and $A$ scattering to check the expectation of the 20% reduction of the coherent cross section, which would allow one to probe gluon shadowing at a factor of $\sim 10$ higher $Q^2$ than in J/$\psi$ production.

- Study coherent production of two pions with masses above 1 GeV/$c^2$ to study an interplay of soft and hard dynamics as a function of $M_{\pi\pi}$ and $p_T(\pi)$.

- Measure the production of heavier $2\pi$, $4\pi$ and other resonances on ion targets, and search for the photoproduction of the observed exotic mesons. By using data from both proton targets (at 134...
Nuclear PDFs:
- Probe with quasi-real photon in ultra-peripheral Pb-Pb collisions
- Probe with partons in initial state and colour neutral final state
**INITIAL STATE**

**Nuclear PDFs:**
- Probe with **quasi-real photon** in ultra-peripheral Pb-Pb collisions
- Probe with partons in initial state and **colour neutral neutral final state**

**Gluon saturation:**
- Nuclear modification of the gluon distribution
- Direct photon measurement in p–Pb collisions accessible in possible ALICE Forward Calorimeter

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- Probe with partons in initial state and **colour neutral neutral final state**

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MACROSCOPIC PROPERTIES

- Signatures of phase transitions at $\mu_B = 0$ (Lattice QCD)
- Hydrodynamic transport coefficients
- Temperature (evolution)
- Magnetic field
**Phase transition**

- Event-by-event net-proton number fluctuation as proxy for baryon susceptibility
- 6\textsuperscript{th} moment predicted to be sensitive to critical behaviour at chiral phase transition
**MACROSCOPIC PROPERTIES**

**Phase transition**
- Event-by-event net-proton number fluctuation as proxy for baryon susceptibility
- 6th moment predicted to be sensitive to critical behaviour at chiral phase transition

**Transport coefficients**
- Heavy quark diffusion coefficient by combining $R_{AA}$ and $v_2$ of heavy flavour particles

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**Diagram**
- ALICE Upgrade Simulation
  - Pb-Pb, $\sqrt{s_{NN}}=5.5$ TeV, $L_{int}=10$ nb$^{-1}$
  - $D^0$, 30-50% centr.
  - $D_s^+$, 30-50% centr.
  - $\Lambda^+$, 10-40% centr.

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**Figure**
- CERN-LPCC-2018-07
- ALICE-PUBLIC-2019-001

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**Text**
- ALI-SIMUL-308763
MACROSCOPIC PROPERTIES

Phase transition
- Event-by-event net-proton number fluctuation as proxy for baryon susceptibility
- 6th moment predicted to be sensitive to critical behaviour at chiral phase transition

Transport coefficients
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Temperature

- Measured with (virtual) photons
- Possible improvement with further ALICE upgrade (ITS3)
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- Measured with (virtual) photons
- Possible improvement with further ALICE upgrade (ITS3)

Strong electromagnetic fields
- Measurable in the charge dependent direct flow of charged particles
- A larger effect is predicted for heavy quarks
Effective constituents of QCD matter (characteristic length scales)?
Interaction with medium?
Use multi-differential jet measurements
Jet structure measurements

- Momentum sharing fraction $z_g$
- Constrain in-medium radiation
Jet structure measurements

- Momentum sharing fraction $z_g$
- Constrain in-medium radiation

Quasi particle structure

- Rutherford-type large angle jet–medium scattering
- Detection of recoil or of large angle deflections gives insight into the microscopic structure of the produced matter
• QCD potential and modification in color-deconfined medium
• Quarkonium melting and regeneration
Color screening and regeneration
• $R_{AA}$ of charmonia and bottomonia
**MICROSCOPIC DYNAMICS**

Color screening and regeneration
- $R_{AA}$ and $v_2$ of charmonia and bottomonia
- **Sensitive to details of heavy quark production**, e.g. thermalisation, time dependence of regeneration, energy loss, rescattering,…
Microscopic Dynamics

Color screening and regeneration
- $R_{AA}$ and $v_2$ of charmonia and bottomonia
- Sensitive to details of heavy quark production, e.g. thermalisation, time dependence of regeneration, energy loss, rescattering, …

Formation of hadrons and light nuclei
- Coalescence or by statistical hadronization?
- Precise measurements of nuclei and hyper-nuclei ($A=3,4$)
- Possible observation of exotic baryonic states
SMALL SYSTEMS

Hydrodynamic evolution \hspace{1cm} \text{Escape mechanism} \hspace{1cm} \text{Initial-momentum correlations}

Many scatterings \hspace{2cm} \text{Few scatterings} \hspace{2cm} \text{Initial conditions}

From JFGO (HL/HE-LHC Physics Workshop: Final Jamboree)
Small systems (pp, p-A) complement studies in A-A collisions

- Is there a unified picture of QCD particle production?
  - Initial state: gluon saturation, Color Glass Condensate
  - Macroscopic: fluid- and thermodynamics, thermal limit (grand canonical ensemble)
  - Microscopic: energy loss

- Extended and more precise measurements in different collision systems needed
Flow measurements in pp and p-Pb collisions
- Larger tracking acceptances for ATLAS and CMS available in Run 4.
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Strangeness production
- Bridge the present gap between pp and Pb–Pb collisions
- Sensitive to origin of enhancement
SMALL SYSTEMS

**Energy loss**
- Correlation of jets and photons
- A potential energy loss acting on the jet would directly alter the momentum fraction $x_{j\gamma}$ distribution

\[ x_{j\gamma} = \frac{p_{T}^{\text{jet}}}{p_{T}^{\gamma}} \]
Energy loss
- Correlation of jets and photons
- A potential energy loss acting on the jet would directly alter the momentum fraction $x_{jX}$ distribution

Thermal radiation
- Direct access to temperature of a potential emitting medium
  - 10% stat. uncertainty in Run 3 for predicted thermal yield
NEW OPPORTUNITIES

Lighter ions:
• Larger NN luminosities, e.g. x8-25 with Ar-Ar
  ➢ New probes of the QGP accessible, e.g. boosted top, onset of jet quenching in small systems
  ➢ With new heavy-ion detector: ultra-soft photons, multi-heavy-flavour hadrons,…
• Nuclei choice based on physics and accelerator considerations

And much more topics
• Light-by-light collision studies
• p-O collisions for cosmic ray related studies
• Further beyond SM physics (e.g. thermal production of magnetic monopoles)
• …

**SUMMARY**

**Microscopic dynamics**
Accessing the microscopic parton dynamics underlying QGP properties.

**Macroscopic properties**
Characterizing the macroscopic long-wavelength properties of the QGP with unprecedented precision.

**Initial state**
Probing nuclear PDFs in a broad range, onset of parton saturation.

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**LHCb projection**

- $p\bar{p} \sqrt{s_{NN}} = 8.8$ TeV
- $0.3 < p_T < 3.0$ GeV
- $0.3 < p_T < 3.0$ GeV

**ATLAS Preliminary**
Projection from Run-2

- $p\bar{p} \sqrt{s_{NN}} = 13$ TeV, 200 pb$^{-1}$
- $0.3 < p_T < 3.0$ GeV
- $0.3 < p_T < 3.0$ GeV

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Thank you

Citten, T (Ben Gurion U. of Negev); Dainese, A. (INFN, Padua); Grosse-Oetringhaus, J.F. (CERN); Jowett, J.M. (CERN); Lee, Y.-J. (MIT); Wiedemann, U.A. (CERN); Witten, M. (AIM, Saclay; Orsay, LAL); Andronic, A. (Munster U.); Bellini, F. (CERN); Bruna, E. (INFN, Turin); Chapon, E. (CERN); Dembinski, H. (Heidelberg, Max Planck Inst.); d’Entertia, D. (CERN); Grabowska-Bold, I. (AGH-UST, Cracow); Innocenti, G.M. (CERN; MIT); Loizides, C. (LBL, Berkeley); Mchapatra, S. (Columbia U.); Salgad, C.A. (Santiago de Compostela U., IGFAE); Verweij, M. (RIKEN BNL; Vanderbilt U.); Weber, M. (Stefan Meyer Inst. Subatomare Phys.); Aichelin, J. (SUBATECH, Nantes); Angerami, A. (LLNL, Livermore); Apollonio, L. (Lisbon, IST; LIP, Lisbon); Arleo, F. (Ecole Polytechnique); Arnesano, N. (Santiago de Compostela U., IGFAE); Arzalid, R.N. (INFN, Turin); Arslanbek, M. (U. Heidelberg (main)); Azzi, P. (INFN, Padua); Bailhache, R. (Frankfurt U.); Bass, S.A. (Duke U.); Bedda, C. (U. Heidelberg); Behera, N.K. (Inha U.); Bellwied, R. (Houston U.); Beraudo, A. (INFN, Turin); Bi, R. (MIT); Bierlich, C. (Lund U.; Bohr Inst.); Blum, K. (CERN; Weizmann Inst.); Borisov, A. (Munster U.); Braun-Munzinger, P. (Darmstadt, EMMI); Bruce, R. (CERN); Bruno, G.E. (Bari Polytechnic; INFN, Bari); Bufalino, S. (INFN, Turin); Castillo Castellanos, J. (IRFU, Saclay, DPHN); Chatterjee, R. (Calcutta, VECC); Chen, Y. (CERN); Chen, Z. (Rice U.); Cheshkov, C. (Lyon, IPN); Chiju, T. (Tsukuba U.); Conesa del Valle, Z. (Orsay, IPN); Contreras Nuno, J.G. (Prague, Tech. U.); Cunqueiro, R. (Heidelberg, MPA); Dahms, T. (Munich, Tech. U., University); Dang, N.P. (Louisville U.); De la Torre, H. (Michigan State U.); Dobrin, A.F. (CERN); Doenigsen, B. (Frankfurt U.); Van Doremalen, L. (U. Utrecht); Du, X. (Texas A-M); Dubla, A. (Darmstadt, EMMI); Dumancic, M. (Weizmann Inst.); Dyndal, M. (DESY); Fabbietti, L. (Munich, Tech. U.); Ferreiro, E.G. (Santiago de Compostela U., IGFAE); Fionda, F. (Bergen U.); Fleuret, F. (Ecole Polytechnique); Flochinger, S. (U. Heidelberg (main)); Giacalone, G. (IPhT, Saclay; GIammacono, A. (Louisiana U.); Gossiaux, P.B. (SUBATECH, Nantes); Graziani, G. (INFN, Florence); Greco, V. (Catania U.; INFN, LNS); Grelli, A. (U. Turin); Grosa, F. (INFN, Turin); Guibilbaud, M. (CERN); Gunji, T. (Tsukuba U., Graduate U. Adv. Studies); Guuzzy, V. (Helsinki Inst. of Phys.; St. Petersburg, INP; Jyvaskyla U.); Haidjidakis, C. (Osay, IPN); Hassan, S. (IRFU, Saclay, DPP); He, M. (Nanjing U. Sci. Tech.); Helenius, I. (Tbingen U.; Jyvaskyla U.); Hoo, P. (SUNY, Stony Brook); Jacobs, P.M. (LBL, Berkeley); Janus, P. (AGH–Krakow); Jebrambik, M.A. (CERN; Frankfurt U.); Jia, J. (Brookhaven Natl. Lab.; SUNY, Stony Brook); Joffe, A.P. (CERN); Kim, H. (Chonnam Natl. U.); Klasyk, P. (Munster U.); Klein, S.R. (LBL, Berkeley); Klusek-Gawenda, M. (Cracow, INP); Kremser, J. (AGH-UST, Cracow); Krintiras, G.K. (Louisiana U.); Kriizek, F. (Prague, Inst. Phys.); Kryshen, E. 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(Jyvaskyla U.); Pappalardo, L. (Ferrara U.; INFN, Ferrara); Park, J. (Korea U.); Faulkunnen, H. (Helsinki Inst. of Phys.; Jyvaskyla U.); Peng, C.C. (Purdue U.); Pereira Da Costa, H. (IRFU, Saclay, DPP); Perepelitsa, D. (Colorado U.); Peresunko, D. (Kurchatov Inst., Moscow); Peters, M. (MIT); Petterson, N.E. (Massachusetts U. Amherst); Piano, S. (INFN, Trieste); Pioro, T. (KIT, Karlsruhe); Pires, J. (Lisbon, CFTP; Lisbon, IST); Plosofko, M. (LBL, Berkeley); Plumari, S. (Catania U.; INFN, LNS); Prino, F. (INFN, Turin); Puccio, M. (INFN, Turin; Turin U.); Rapp, R. (Texas A-M); Redlich, K. (Darmstadt, EMMI; Wroclaw U.); Reygers, K. (U. Heidelberg (main)); Ristea, C. (Bucharest, Inst. Space Science); Robbe, P. (Orsay, LAL); Rossi, A. (INFN, Padua); Rustamov, A. (Darmstadt, EMMI; U. Heidelberg (main)); NNRC, Baku); Rybar, M. (Columbia U.); Schaumann, M. (CERN); Schenef, B. (Brookhaven Natl. Lab.); Schienbein, I. (LPSC, Grenoble); Schoeffel, L. (IRFU, Saclay, DPP); Selyuzhenkov, I. (Darmstadt, EMMI; Moscow Phys. Eng. Inst.); Sicksle, A.M. (Illinois U., Urbana); Sievert, M. (Rutgers U., Piscataway); Silva, P. (CERN); Song, T. (Giessen U.); Spousta, M. (Charles U.); Stachel, J. (U. Heidelberg (main)); Steinberg, P. (Brookhaven Natl. Lab.); Stocco, D. (SUBATECH, Nantes); Strickland, M. (Kent State U.); Strikman, M. (Penn State U.); Stupak, J. (Peking U., Beijing); Tapia Takaki, D. (Kansas U.); Tatar, K. (MIT); Terrevel, C. (Houston U.); Timmins, A. (Huston U.); Trogolo, S. (INFN, Turin; Turin U.); Trzcinski, B. (U. Utrecht); Trzupek, A. (Cracow, INP); Ulrich, R. (KIT, Karlsruhe); Uras, A. (Lyos, IPN); Venugopalan, R. (Brookhaven Natl. Lab.); Vitev, I. (Los Alamos); Vujanovic, G. (Ohio State U.; Wayne State U.); Wang, J. (MIT); Wang, T.W. (MIT); Xiao, R. (Purdue U.); Xu, Y. (Duke U.); Zampolli, C. (CERN; INFN, Bologna); Zanoli, H. (Sao Paulo U.); Zhou, M. (SUNY, Stony Brook); Zhou, Y. (Bohr Inst.)
## The next ten years

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<td>2021 (4 weeks)</td>
<td>Pb-Pb 5.5 TeV, 3 weeks pp 5.5 TeV, 1 week</td>
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<td>p-Pb: 0.6/pb ATLAS/CMS, 0.3/pb ALICE/LHCb</td>
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<td>pp 5.5: 300/pb ATLAS/CMS, 25/pb LHCb, 3/pb ALICE</td>
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<td>p-O + O-O 7 TeV, 1 week (after EYETS?) Pb-Pb 5.5 TeV, 5 weeks</td>
<td>pp 8.8: 100/pb ATLAS/CMS/LHCb, 1.5/pb ALICE</td>
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<td>pp 8.8 TeV, few days p-Pb 8.8 TeV, 3.x weeks</td>
<td>O-O: 500/\mu b</td>
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<td>p-O: 200/\mu b</td>
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<td><strong>LS3</strong></td>
<td>ATLAS/CMS upgrades, ALICE: ITS3? FoCal?</td>
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<tr>
<td><strong>RUN 4</strong></td>
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<td>2027 (4 weeks)</td>
<td>Pb-Pb 5.5 TeV, 3 weeks pp 5.5 TeV, 1 week</td>
<td>Pb-Pb: 6.8/nb, ALICE/ATLAS/CMS, 1/nb LHCb</td>
</tr>
<tr>
<td></td>
<td></td>
<td>p-Pb: 0.6/pb ATLAS/CMS, 0.3/pb ALICE/LHCb</td>
</tr>
<tr>
<td></td>
<td></td>
<td>pp 5.5: 300/pb ATLAS/CMS, 25/pb LHCb, 3/pb ALICE</td>
</tr>
<tr>
<td></td>
<td>Pb-Pb 5.5 TeV, 2 weeks p-Pb 8.8 TeV, 3.x weeks pp 8.8 TeV, few days</td>
<td>pp 8.8: 100/pb ATLAS/CMS/LHCb, 1.5/pb ALICE</td>
</tr>
<tr>
<td>2029 (4 weeks)</td>
<td>Pb-Pb 5.5 TeV, 4 weeks</td>
<td></td>
</tr>
</tbody>
</table>
MATERIAL

• Public notes:
  
  • ALICE-PUBLIC-2019-001 (ALICE Run 3/4)
  
  • LHCb-CONF-2018-005 (P-Pb)
  • LHCb-PUB-2018-015 (FIXED TARGET)
  
  • ATL-PHYS-PUB-2018-018 (UPC)
  • ATL-PHYS-PUB-2018-019 (JETS)
  • ATL-PHYS-PUB-2018-020 (BULK)
  • ATL-PHYS-PUB-2018-039 (NUCLEAR PARTON DISTRIBUTIONS)
  
  • CMS-PAS-FTR-17-002 (HEAVY IONS)
  • CMS-PAS-FTR-18-024 (HF)
  • CMS-PAS-FTR-18-025 (JETS)
  • CMS-PAS-FTR-18-026 (SMALL SYSTEMS)
  • CMS-PAS-FTR-18-027 (NUCLEAR PARTON DISTRIBUTIONS)
in nuclear parton distributions not strongly constrained as initial condition of heavy-ion collision

extreme kinematics probing onset of non-linear effects

\[ Q^2, p_T \text{ (GeV/c)} \]

\[ \frac{Q^2}{Q_{sat,Pb}(x)} \]

\[ x_A, y_{lab} = 0, \ldots, 6.6 \]

\[ \gamma + Pb \rightarrow dijet + X \] (UPC Pb+Pb 5.5 TeV)

\[ \gamma + Pb \rightarrow \gamma + X \] (UPC p+Pb 5.8 TeV)

\[ \gamma + Pb \rightarrow \pi X \] (UPC Pb+Pb 5.5 TeV)

\[ \gamma + Pb \rightarrow J/\psi + X \] (UPC Pb+Pb 5.5 TeV)

\[ \gamma + Pb \rightarrow Z^2 + X \] (5.5 TeV)

\[ \gamma + Pb \rightarrow \pi X \] (EIC)

\[ F_2^A \]

nuclear DIS - $F_2^A$ data

- NMC
- E772
- E139
- E665
- EMC

In Fig. 78, the kinematic regions covered by proton-nucleus collisions at the LHC and the FCC (the left panel, [400]) and UPCs at the LHC (right) are shown and compared with the regions where data currently used to constrain nPDFs lie. A huge enlargement is evident with respect to the presently existing data at the LHC. The HL-LHC offers new improved detectors and larger statistics for some observables like dijets or photon-jet correlations. The HE-LHC would enlarge the kinematic plane in a region intermediate between the LHC and the FCC. On the other hand, electron-nucleus collisions [793, 128]...
Jets in heavy-ion collisions

Well understood theoretically in

Hard scattered partons produce

Jet is a phenomenological object

back-to-back,

in elementary reactions

IpQCD

Microscopic Dynamics

- Effective constituents of QCD matter
- Characteristic length scales
- Use multi-differential jet measurements