Heavy-ion beams at the LHC: status & future opportunities in EIC-connected topics

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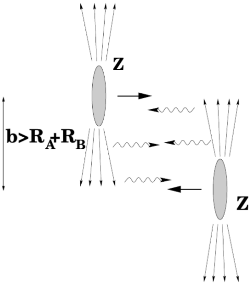
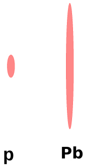
Trento, Spectroscopy at EIC, 19.12.2018

Outline

- Introduction to UPC and pPb collisions at the LHC
- Highlights in Run 1 and 2
- Future data taking: luminosities and detectors
- A selection of measurements in future
- Conclusions

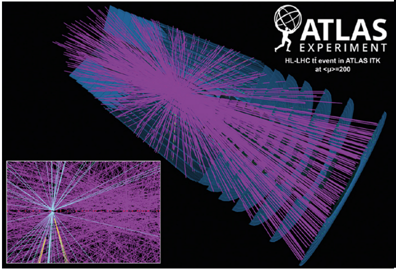
Ultra-peripheral collisions and *p*Pb collisions

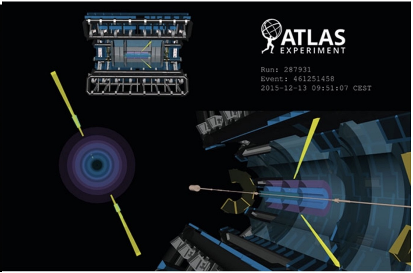




- large quasi-real photon flux: Z^{82}-lead nuclei in *p*Pb and PbPb:
  - gain in signal/background compared to *pp* collisions
  - allows photoproduction at low-x and spectroscopy in γ-induced reactions
  - in *p*Pb: Pb preferentially γ-emitter $\rightarrow$ resolve *pp* ambiguity
- *p*Pb collisions – dense-dilute prototype – + *pp* reference at same $\sqrt{s} \approx 8$ TeV:
  - large kinematic range to explore partonic content
  - basis for PbPb understanding

PbPb and *p*Pb collisions in comparison to *pp*

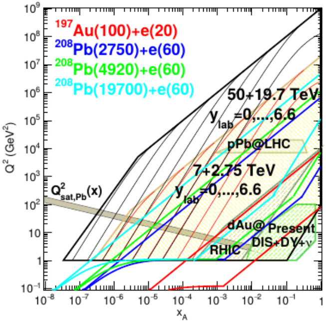


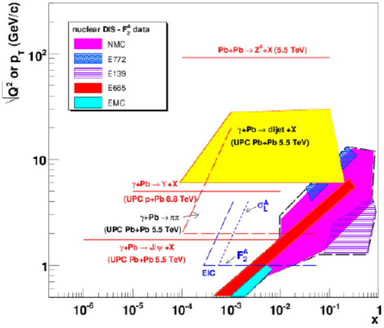


- average number of visible collisions per bunch crossing in standard *pp*: ATLAS/CMS: 30-40, LHCb: ≈ 1.0, ALICE $O(1\%)$
- average number of visible collisions per bunch crossing in *pp* (2027): ATLAS/CMS: up to 200, LHCb: ≈ 5.0, ALICE $O(1\%)$
- in *p*Pb and PbPb: average number of visible collisions in all experiments < 1.0 now and in future
- heavy-ion collisions often advantageous for exclusive and soft production

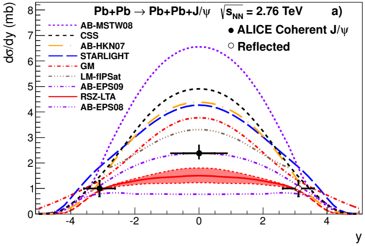
UPC/pPb collisions in comparison to DIS

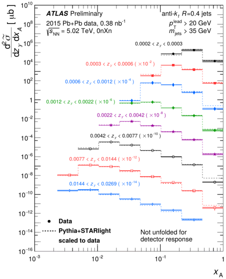
- complementary to electron-ion collider:
  - large kinematic reach, large rates, lowest Bjorken-x available
  - mostly no complete final state or restricted to photo ($Q^2 \approx 0$)-case

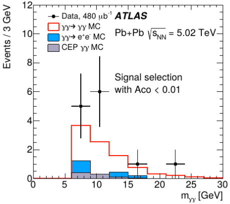


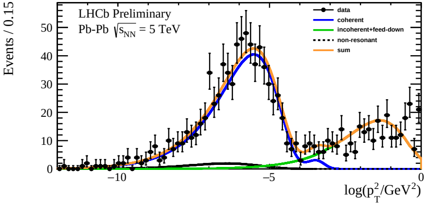


UPC in Run 1 and 2



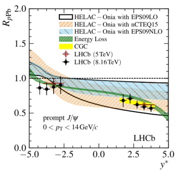


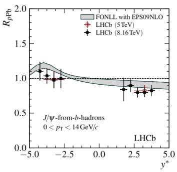


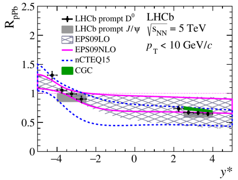


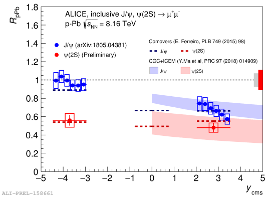
- nuclear shadowing with coherent J/ψ photoproduction
- indication of Light-by-Light scattering (ATLAS/CMS)
- first inclusive photo-production measurement: dijets by ATLAS
- LHCb resolution & forward acceptance → low p_T/mass

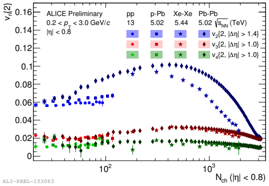
pPb in Run 1 and 2

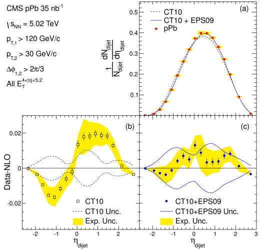












- charm/beauty + quarkonia nuclear modification: energy loss vs. very low-x nPDF/saturation
- correlated particle emission – collectivity: pPb interpreted in view of initial state as well hydrodynamic response
- non-expected suppression of excited quarkonia states
- nPDF constraints at high-Q^2: dijets and gauge bosons (W,Z, now also γ)

Future data taking in the 20ies

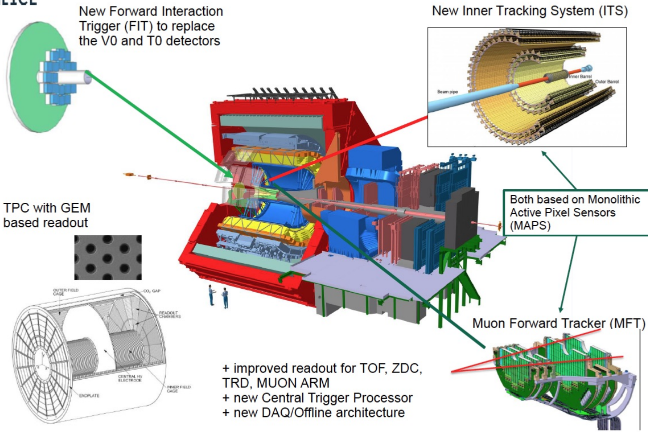
- heavy-ion running foreseen about every year, larger luminosities: O(5-10) more lumi for *p*Pb and PbPb
- major upgrades ALICE/LHCb for 2021
- major upgrades ATLAS/CMS for 2026:
  larger tracker acceptance $|\eta| < 4.0$, possibly time of flight (PID)
- details in yellow report WG5, on arXiv since yesterday:
  https://arxiv.org/abs/1812.06772

The proposed ion-schedule

- larger *p*Pb luminosity & pO/OO runs added w.r.t. 2012 planning
- ion working group:
  ion running longer by 4 weeks in 6 running years Run3/4
- N.B.: ALICE asked for 0.2 fb^{-1} *pp* running for high-multiplicity studies
  $\rightarrow$ to be investigated for light-flavour spectroscopy with PID in ALICE

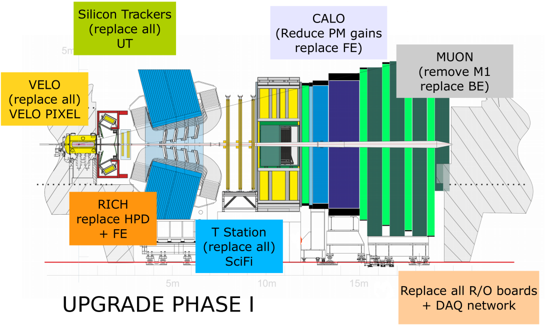
Year	Systems, $\sqrt{s_{\mathrm{NN}}}$	Time	L_{int}
2021	Pb–Pb 5.5 TeV	3 weeks	2.3 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2022	Pb–Pb 5.5 TeV	5 weeks	3.9 nb^{-1}
	O–O, p–O	1 week	500 $\mu\mathrm{b}^{-1}$ and 200 $\mu\mathrm{b}^{-1}$
2023	p–Pb 8.8 TeV	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	

ALICE detector upgrade



- Run 1&2: central barrel read-out limited to O(0.2-1) kHz
  overall rate limited to 8 kHz PbPb, about 200 kHz in pp/Pbp
- Run 3&4: continuous read-out with 50 kHz PbPb and 1 MHz pp/pPb

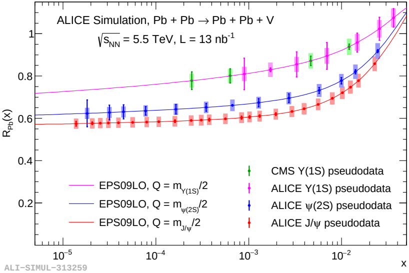
Detector upgrades: LHCb



- *pp* from 1 MHz $\rightarrow$ 30 MHz software trigger input rate, i.e. only software!
- *pp* pile-up 1 to pile-up $\approx$ 5
- replace all tracking detectors, new read-out
- "overdesigned" for heavy-ion rates: high flexibility

UPC in Run 3/4: photo-production of vector mesons

- precise vector mesons: ρ, J/ψ, ψ(2S) and Υ(nS)
- associated processes as $\rho + J/\psi$ come into reach
- high-t exclusive processes available, background control to be seen
- γPb in pPb to reach lower-x: good resolution needed

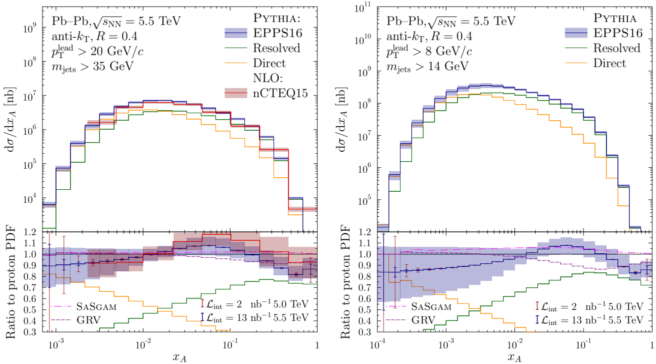


	PbPb					
Meson	σ	All Total	Central 1 Total	Central 2 Total	Forward 1 Total	Forward 2 Total
$\rho \to \pi^+\pi^-$	5.2b	68 B	5.5 B	21B	4.9 B	13 B
$\rho' \to \pi^+\pi^-\pi^+\pi^-$	730 mb	9.5 B	210 M	2.5 B	190 M	1.2 B
$\phi \to$ K$^+$K$^-$	0.22b	2.9 B	82 M	490 M	15 M	330 M
J/$\psi \to \mu^+\mu^-$	1.0 mb	14 M	1.1 M	5.7 M	600 K	1.6 M
ψ(2S) $\to \mu^+\mu^-$	30μb	400 K	35 K	180 K	19 K	47 K
Y(1S) $\to \mu^+\mu^-$	2.0 μb	26 K	2.8 K	14 K	880	2.0 K

S. Klein, V. Guzey, M. Strikman, E. Kryshen, D. Takaki, G. E. Contreras Nuno et al.

Ultra-peripheral collisions in Run 3/4: photo-production of dijets

- inclusive photoproduction of dijets pioneered by ATLAS: large potential
- extension to $c\bar{c}/b\bar{b}$: using clear signature to reach lower $Q^2 \rightarrow$ lower x at same rapidity
- top should become just in reach



A. Angerami, I. Helenius, V. Guzey, M. Klasen S. Klein et al.

$\gamma\gamma \to p\bar{p}$ with PbPb UPC

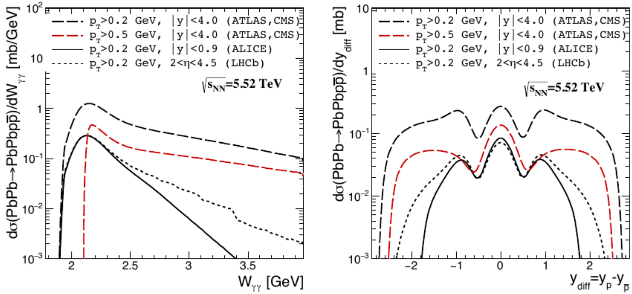
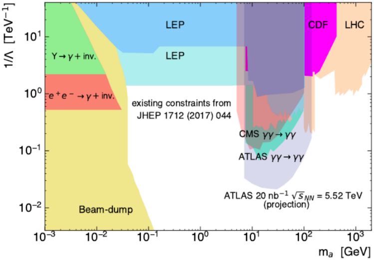


Fig. 99: Differential cross sections as a function of $p\bar{p}$ invariant mass (left) and rapidity distance between proton and anti-proton (right) in Pb–Pb collisions at $\sqrt{s_{NN}}$=5.52 TeV for four experimental acceptance requirements. For ATLAS and CMS experiments two requirements for proton $p_T > 0.2$ GeV or $p_T > 0.5$ GeV are considered.

- process studied in e^+e^--collisions: LEP, Belle and others
- UPCs provide large $\sqrt{s}$ and sizeable rates
- testing ground for hadron exchange (proton or 2^{++} meson) $q\bar{q}$ production
- details in https://arxiv.org/pdf/1708.09836.pdf M. Klusek-Gawenda et al.

$\gamma\gamma \to \gamma\gamma$ with PbPb UPC

- from O(10) events in 0.4 nb^{-1} (ATLAS example 2015) to O(700) events in 10 nb^{-1} with slightly looser p_T selection
- competitive limits with bump search for Axion-like particles via ($\gamma\gamma \to a \to \gamma\gamma$)
- lower masses to be explored by ALICE and LHCb



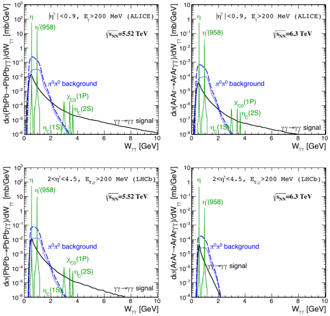
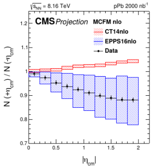


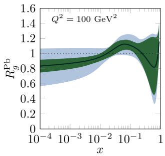
Fig. 101: Di-photon invariant mass distributions for Pb–Pb collisions at $\sqrt{s_{NN}}$=5.52 TeV (left) and Ar–Ar collisions at $\sqrt{s_{NN}}$=6.3 TeV (right) for ALICE at mid-rapidity (top) and LHCb at forward pseudorapidity (bottom). The $\pi^0\pi^0$ background is shown with the acoplanarity requirement of 0.01 (dotted line) and also without it (dashed line).

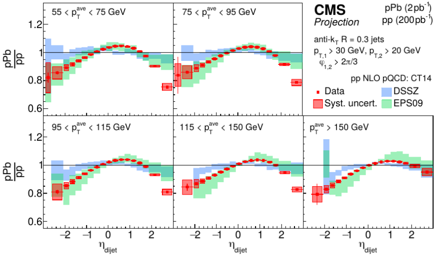
I. Grabowska-Bold et al.

pPb collisions: precision high-Q^2

- first W,Z.Dijet measurements in inelastic collisions
- used in global NLO nuclear PDF fits
- can reach very good precision based on pp experience with higher statistics as in Run 3/4



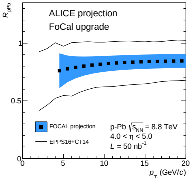


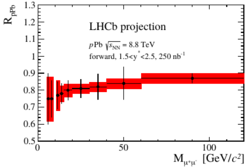


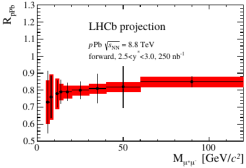
E. Chapon, Z. Citron et al.

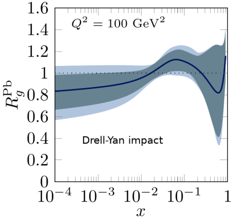
pPb collisions: new low/moderate-Q^2 probes

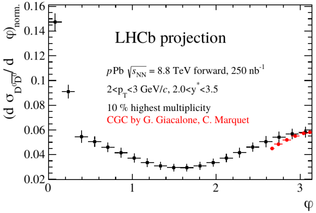
- cleaner photon and Drell-Yan measurements will become available at forward rapidity
- high luminosity will allow for precision W/Z/Dijet measurements for nPDF constraints
- $c\bar{c}$ correlations as an example of a precise not yet measured saturation scale sensitive observable



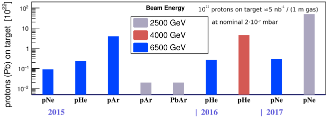


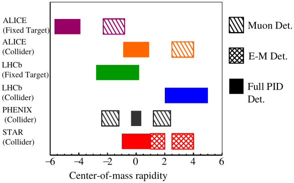






Fixed-target collisions at the LHC





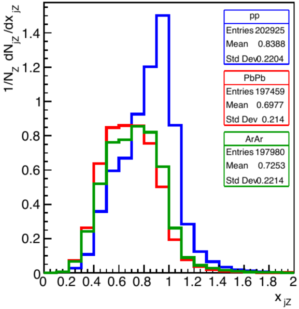
	SMOG largest sample p–Ne@68 GeV	SMOG2 example p–Ar@115 GeV
Integrated luminosity	$\sim$ 100 nb^{-1}	100 pb^{-1}
syst. error on J/ψ x-sec.	6–7%	2–3 %
J/ψ yield	15k	35M
D^0 yield	100k	350M
Λ_c yield	1k	3.5M
$\psi(2S)$ yield	150	400k
$\Upsilon(1S)$ yield	4	15k
Low-mass ($5 < M_{\mu\mu} < 9$ GeV/c^2) Drell-Yan yield	5	20k

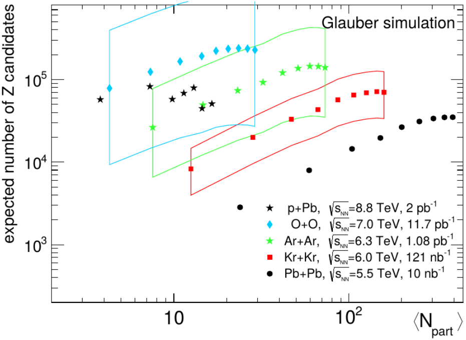
G. Graziani, P. di Nezza, F. Fleuret, J. Lansberg C. Hadjidakis et al.

- LHCb: fixed target physics with gas injection in interaction region:
  $\bar{p}$-production in pHe PRL 121, 222001 (2018), charm in pAr/pHe arXiv:1810.07907, submitted to PRL
- LHCb fixed-target upgrade for data taking in 2021: larger lumi by factor 10-100, interaction point displaced
- options for ALICE being investigated: possible start $\approx$ 2026
- many ideas collected within AFTER and in PBC workshop, one example for exclusive production:
  - η_c for oderon search, radiative background from J/ψ to be studied

Lighter ions: beyond current luminosities for inclusive studies

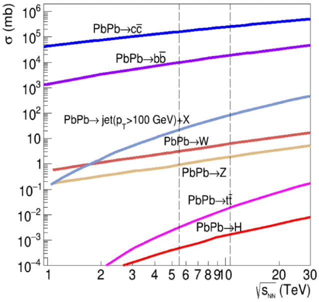
- high-p_T and/or mass observables not possible or strongly limited in PbPb/pPb in inclusive collisions
- lighter ions as an avenue to overcome luminosity limitations
- equivalent γ-luminosities typically slightly larger than in PbPb

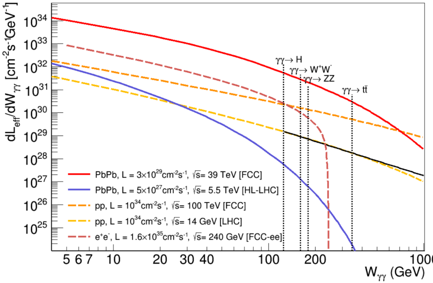




A few words on HE-LHC

- FCC-hh 16 T magnets in LHC tunnel
- factor 2 higher energy, factor ≈ 2 luminosity estimated for PbPb
- $\gamma - \gamma$ collisions: higgs into reach





Conclusions

A rich pPb and UPC collisions:
many corners in current data not yet fully exploited

- 20ies:
  - new observables and better precision in UPC/pPb
  - profit from increase luminosities and detector upgrades
- interesting possibilities for EIC physics in very different environment

10 High energy QCD with proton-nucleus collisions and ultra-peripheral collisions

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11 Other opportunities with ion and proton beams at the LHC

11.1 Physics motivation for collisions of light ions

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11.2 Physics of $\gamma\gamma$ interactions in heavy-ion collisions

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Authors of the WG5 yellow report chapters

Dijets in UPC

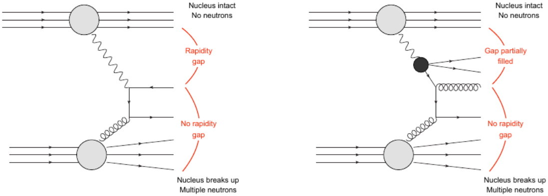

Figure 1: Diagrams representing different types of leading-order contributions to dijet production in high-energy photo-nuclear collisions. The left diagram represents the direct contribution in which the photon itself participates in the hard scattering. The right diagram represents the "resolved" contribution in which virtual excitations of the photon, into a state involving at least a $q\bar{q}$ pair and possibly multiple gluons, participates in the hard scattering in the target nucleus.

$$H_{\mathrm{T}} \equiv \sum_i p_{\mathrm{T}\,i}, \quad m_{\mathrm{jets}} \equiv \left[\left(\sum_i E_i\right)^2 - \left|\sum_i \vec{p}_i\right|^2\right]^{1/2}, \quad y_{\mathrm{jets}} \equiv \frac{1}{2}\ln\left(\frac{\sum_i E_i + \sum_i p_{z\,i}}{\sum_i E_i - \sum_i p_{z\,i}}\right), \qquad z_\gamma \equiv \frac{m_{\mathrm{jets}}}{\sqrt{s}} e^{+y_{\mathrm{jets}}}, \quad x_{\mathrm{A}} \equiv \frac{m_{\mathrm{jets}}}{\sqrt{s}} e^{-y_{\mathrm{jets}}}$$