### Heavy Ion and Fixed Target Results at LHCb erc

Giulia Manca, erzo contro di sica con Universita` degli studi di Cagliari (IT) & I.N.F.N. oni Pesanti on behalf of the LHCb collaboration alle te Energia 2021 Outline The LHCb detector at the LHC Selected results in open/hidden heavy flavours Conclusions and outlook

IFIPAE Workshop 2021, Padova, 25-26.11.2021







## LHC and LHCb





pPb

2013

Pbp

PbPb

| 2015

pPb

2016

Pbp

10<sup>-2</sup> E

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| 2018

PbPb

рНе

pAr

pNe

2015

PbAr

pHe

| 2016

pHe

pNe

2017

pAr

pNe

PbNe

2018

### **Fixed Target Physics with LHCb**

### SMOG: System for Measuring the Overlap with Gas



### SMOG used for fixed target physics:

- precise vertexing allows to separate beam-beam and beam-gas contributions
- strong acceptance effects as a function of the z position
- energy densities are achieved which are between those probed at the SPS and RHIC
- => The gap between the SPS and LHC can be bridged by a single experiment

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### Phase Space Coverage and Running Modes

Kinematic acceptance & (existing/future) beam-target combinations



y\*: rapidity in nucleon-nucleon centre-ofmass system, with forward direction (positive values) in direction of the proton/beam

E <sub>beam</sub> (p)		рр		p-GAS		p-Pb/Pb-p		Pb-GAS	Pb-Pb	
150 GeV		0.90 TeV								
L.38 TeV		2.76 TeV								
2.5 TeV		5 TeV		69 GeV						
3.5 TeV		7 TeV								
I.0 TeV		8 TeV		87 GeV		5 TeV		54 GeV		
5.5 TeV		13 TeV		110 GeV		8.2 TeV		69 GeV	5.1 TeV	
	0 TeV	14 TeV		115 GeV		8.8 TeV		72 GeV	5.5 TeV	
p/Pb-GAS operation so far:										
	p/Pb-	GAS op	pei	ration	SC	o far:				
	p/Pb- Collision	GAS op 1s	oei √s	(GeV)	S(	o far: ength	# p	on target	Year	
	p/Pb- Collision pHe	GAS op ns	0 <b>€</b> √s 87	(GeV)	<b>S(</b> L) 8	o far: ength 4 h	<b># p</b> 4.6	on target x10 <sup>22</sup>	Year 2016	
	p/Pb- Collision pHe pHe	GAS or	0€1 √s 87 11	(GeV)	S( L) 8 1	D far: ength 4 h 8 h	# p 4.6 3x1	on target x10 <sup>22</sup> 0 <sup>21</sup>	Year 2016 2016	
	p/Pb- Collision pHe pHe pNe	GAS or	0 <b>e</b> I √s 87 11 11	(GeV) (GeV) .0	S ( 8 1 1	D far: ength 4 h 8 h 2 h	# p 4.62 3x1 1x1	on target x10 <sup>22</sup> 0 <sup>21</sup> 0 <sup>21</sup>	Year      2016      2016      2015	
	p/Pb- Collision pHe pHe pNe pHe	GAS or	0000 √s 87 11 11 11	(GeV) (GeV) .0 .0	S( L 8 1 1 8	D far: ength 4 h 8 h 2 h h	# p 4.62 3x1 1x1 2x1	on target x10 <sup>22</sup> 0 <sup>21</sup> 0 <sup>21</sup>	Year      2016      2016      2015	
	p/Pb- Collision pHe pHe pNe pHe pHe	GAS or	Oei √s 87 11 11 11	(GeV) (GeV) .0 .0 .0	S( L 8 1 1 8 1	D far: ength 4 h 8 h 2 h 2 h h 7 h	# p 4.62 3x1 1x1 2x1 4x1	on target x10 <sup>22</sup> 0 <sup>21</sup> 0 <sup>21</sup> 0 <sup>21</sup> 0 <sup>21</sup>	Year      2016      2015      2015      2015	
	p/Pb- Collision pHe pHe pNe pHe pHe pAr PbAr	GAS or	vs 877 111 111 111 69	(GeV) (GeV) .0 .0 .0 .0	SC L 8 1 1 8 1 1	D far: ength 4 h 8 h 2 h 2 h h 7 h 00 h	# p 4.62 3x1 1x1 2x1 4x1 2x1	on target x10 <sup>22</sup> 0 <sup>21</sup> 0 <sup>21</sup> 0 <sup>21</sup> 0 <sup>22</sup> 0 <sup>22</sup>	Year      2016      2015      2015      2015      2015      2015	
	p/Pb- Collision pHe pHe pNe pHe pAr PbAr pNe	GAS or	Vs 87 11 11 11 11 69 69	(GeV) (GeV) .0 .0 .0 .0	SC L 8 1 1 8 1 1 1	D far: ength 4 h 8 h 2 h 1 7 h 00 h 67 h	# p 4.62 3x1 1x1 2x1 4x1 2x1 4x1	on target x10 <sup>22</sup> 0 <sup>21</sup> 0 <sup>21</sup> 0 <sup>21</sup> 0 <sup>22</sup> 0 <sup>22</sup> 0 <sup>20</sup> 0 <sup>23</sup>	Year      2016      2015      2015      2015      2015      2015      2015      2015	

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Fixed target beyond 2022

### New project SMOG2 up and running !

Projection of ~1 year data taking in parallel mode						
Int. Lumi.			80 pb-1			
Sys.error o	of $J/\Psi$	xsection	~3%			
$J/\Psi$	yield		28 M			
$D^0$	yield		280 M			
$\Lambda_c$	yield		2.8 M			
$\Psi'$	yield		280 k			
$\Upsilon(1S)$	yield		24 k			
$DY \mu^+\mu^-$	yield		24 k			



- SMOG2 (TDR) is a standalone gas storage cell covering z ~-500—300 mm
- Up to x100 higher gas density with same gas flow of SMOG1
- Precise measurement of the gas pressure => luminosity
- Possibility to run in parallel with pp cllisions, and inject not only noble gases

# **Overview of LHCb Results**

### The LHCb Public results [here]

### Publications of the Ions and Fixed Target Working Group

[to restricted-access page]
ALL LHCB PUBLICATIONS
OTHER WORKING GROUPS
B DECAYS TO CHARMONIUM
B DECAYS TO OPEN CHARM
CHARMLESS <i>b</i> -HADRON DECAYS
b-HADRONS AND QUARKON
CHARM PHYSICS
FLAVOUR TAGGING
LUMINOSITY
QCD, ELECTROWEAK AND EXOTICA
RARE DECAYS
SEMILEPTONIC B DECAYS
DETECTOR PERFORMANCE

#### List of papers (Total of 18 papers and 938 citations)

TITLE	DOCUMENT NUMBER	JOURNAL	SUBMITTED ON	CITED
Measurement of the nuclear modification factor and prompt charged particle production in $p{\rm Pb}$ and $pp$ collisions at $\sqrt{s_{\rm NN}}=5{\rm TeV}$	PAPER-2021-015 arXiv:2108.13115 [PDF]	PLB	30 Aug 2021	1
Study of $J\!/\psi$ photo-production in lead-lead peripheral collisions at $\sqrt{s_{NN}}=5.02$ TeV	PAPER-2020-043 arXiv:2108.02681 [PDF]	PRL	05 Aug 2021	3
Study of coherent $J/\psi$ production in lead-lead collisions at $\sqrt{s_{NN}}=5~{\rm TeV}$	PAPER-2021-013 arXiv:2107.03223 [PDF]	JHEP	07 Jul 2021	1
Measurement of prompt-production cross-section ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ in <i>p</i> Pb collisions at $\sqrt{s_{NN}}$ = 8.16 TeV	PAPER-2020-048 arXiv:2103.07349 [PDF]	Phys. Rev. C103 (2021) 064905	12 Mar 2021	1
Observation of multiplicity-dependent prompt $\chi_{c1}(3872)$ and $\psi(2S)$ production in $pp$ collisions	PAPER-2020-023 arXiv:2009.06619 [PDF]	Phys. Rev. Lett. 126 (2021) 092001	14 Sep 2020	14
Observation of enhanced double parton scattering in proton-lead collisions at $\sqrt{s_{\rm NN}}=8.16~{\rm TeV}$	PAPER-2020-010 arXiv:2007.06945 [PDF]	Phys. Rev. Lett. 125 (2020) 212001	14 Jul 2020	5
Measurement of $B^+,B^0$ and $\Lambda^0_b$ production in $p{\rm Pb}$ collisions at $\sqrt{s_{NN}}=8.16~{\rm TeV}$	PAPER-2018-048 arXiv:1902.05599 [PDF]	Phys. Rev. D99 052011 (2019)	14 Feb 2019	37
First Measurement of Charm Production in its Fixed-Target Configuration at the LHC	PAPER-2018-023 arXiv:1810.07907 [PDF]	Phys. Rev. Lett. 122 (2019) 132002	18 Oct 2018	60
<u>Study of Y production in <i>p</i>Pb collisions at <math>\sqrt{s_{NN}} = 8.16</math> TeV</u>	PAPER-2018-035 arXiv:1810.07655 [PDF]	JHEP 11 (2018) 194	17 Oct 2018	42
Prompt $\Lambda_c^+$ production in $p{\rm Pb}$ collisions at $\sqrt{s_{NN}}=5.02~{\rm TeV}$	PAPER-2018-021 arXiv:1809.01404 [PDF]	JHEP 02 (2019) 102	05 Sep 2018	43
Measurement of antiproton production in $pHe$ collisions at $\sqrt{s_{NN}}=110~\text{GeV}$	PAPER-2018-031 arXiv:1808.06127 [PDF]	Phys. Rev. Lett. 121 (2018) 222001	18 Aug 2018	57
Study of prompt $D^0$ meson production in pPb collisions at $\sqrt{s}\text{=}\text{5}\text{ TeV}$	PAPER-2017-015 arXiv:1707.02750 [PDF]	JHEP 10 (2017) 090	10 Jul 2017	103
Prompt and nonprompt J/ $\psi$ production and nuclear modification in $p{\rm Pb}$ collisions at $\sqrt{s_{\rm NN}}=8.16~{\rm TeV}$	PAPER-2017-014 arXiv:1706.07122 [PDF]	Phys. Lett. B774 (2017) 159	21 Jun 2017	82
Study of $\psi(2S)$ production and cold nuclear matter effects in $p{\rm Pb}$ collisions at $\sqrt{s_{NN}}=5~{\rm TeV}$	PAPER-2015-058 arXiv:1601.07878 [PDF]	JHEP 03 (2016) 133	28 Jan 2016	59
Measurements of long-range near-side angular correlations in $\sqrt{s_{NN}}=5 \text{TeV}$ proton-lead collisions in the forward region	PAPER-2015-040 arXiv:1512.00439 [PDF]	Phys. Lett. B762 (2016) 473	01 Dec 2015	90
Observation of $Z$ production in proton-lead collisions at LHCb	PAPER-2014-022 arXiv:1406.2885 [PDF]	JHEP 09 (2014) 030	11 Jun 2014	61
Study of $\Upsilon$ production and cold nuclear matter effects in pPb collisions at $\sqrt{s_{NN}}=5TeV$	PAPER-2014-015 arXiv:1405.5152 [PDF]	JHEP 07 (2014) 094	20 May 2014	88
Study of $J/\psi$ production and cold nuclear matter effects in $p{\rm Pb}$ collisions at $\sqrt{s_{NN}}$ = 5 TeV	PAPER-2013-052 arXiv:1308.6729 [PDF]	JHEP 02 (2014) 72	30 Aug 2013	191



# **Proton-Lead**

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 $\chi_{c2}/\chi_{c1}$  production in pPb Hick

 $\chi_c$  P-wave charmonium state

Phys. Rev. C 103, 064905

erc

- Responsible for 30% feed-down to prompt  $J/\psi (\chi_{c->} J/\psi(->\mu\mu)\gamma)$ ;
- Difficult analysis for photon reconstruction
  - 2 approaches, using calorimeter and conversions



# $\frac{1}{2c^2/\chi_{c1}} \text{ production in pPb}$

### Phys. Rev. C 103, 064905

- First χ<sub>c</sub>-measurement in heavy-ion data at the LHC
- Measured the production ratio of the two states, consistent with one and with pp measurement
- Statistics not great
  Remember in pp...





### $J/\psi$ in *p*Pb collisions@8.16 TeV

LHCb-PAPER-2017-014 PLB 774 (2017) 159

- → First analysis of run2 pPb sample !
- $\rightarrow$  Double differential in y and  $p_T$
- $\rightarrow$  Prompt and non-prompt J/ $\psi$  separated through pseudoproper time distribution
- → Measured: differential cross sections & nuclear modification factors



## Double Ratios & open/hidden beauty JHEP11(2018)194





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## Baryon to meson ratio

### → Ratios $\Lambda_c/D^0$ in pPb collisions at 8.16 TeV



#### JHEP 02 (2019) 102

- Charm mesons and baryon measured in pPb/Pbp collisions at √s<sub>NN</sub> = 8 TeV.
- \* No strong dependance of the relative  $\Lambda_{c^+}/D^0$  ratio is observed versus  $p_T$  and rapidity.
  - Decreasing trend versus p<sub>T</sub> in pPb.
- Good description of the nuclear modification factors and forward-tobackward ratios with various nPDFs sets.
  - ➡ within large model uncertainties ...
- Tensions between models and data at higher p<sub>T</sub> in pPb collisions.
  - Data fluctuation ?
  - Additional effect ?

Double open charm in pPb

erc

- → Search for DPS in pPb collisions at 8,16 TeV, L~30nb<sup>-1</sup>, pPb & Pbp
- Measured the cross sections and kinematic correlations between different pairs of charm hadrons
- Confirmation of enhancement of DPS in pPb w.r.t. SPS

INFN



### Open charm in pPb at 8.16 TeV

### Analysis being refined for D<sup>0</sup>, being refined for other open charm states



- \* Preliminary results for D<sup>0</sup> cross-section in pPb/Pbp collisions at  $\sqrt{s_{NN}} = 8$  TeV up to  $p_T = 16$  GeV/c.
- \* Improved statistics by factor 20 compared to previous LHCb results.
- \* Tension between data and nPDFs predictions. Additional effects required.

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# **Fixed target**

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# Charm production in fixed-target

### arXiv:1810.07907





### Probing the intrinsic charm content of the nucleon



# Charm production in pAr & pHe



Yields agree reasonably with theory in shape and value

- Phenomenological parameterisation for J/ψ (JHEP 1303(2013) 122)
- HELAC-Onia model, calibrated on collisions data (STAR) (EPJC 77 (2017))



- Open-charm production in fixed-target LHCb acceptance : access to **anti-shadowing** and **intrinsic charm** content in the nucleons.
- \* **Precise**  $J/\psi$  and  $D^0$  measurements in pHe.
- Good agreement between data and theory with no strong intrinsic charm contribution observed.





Event 924938 Run 168926 Tue, 01 Dec 2015 19:34:07

. Swiftwarents

## Lead-Lead









- A proxy of the impact parameter b of the collisions can be given by "centrality" classes, defined as percentile of the inelastic PbPb/PbNe cross section as  $f(\sqrt{s})$
- We use the energy deposit in the Electromagnetic calorimeter to extract the centrality value through the Glauber model
- We use the MC Glauber model to derive N participants (<Npart>), N binary collisions (<Ncoll>), impact parameter (<b>), N

 $N_{\rm anc} = f \times N_{\rm part} + (1 - f) \times N_{\rm coll},$ 

### PbPb @ 5 TeV c.o.m. Energy



### PbNe @ 69 GeV c.o.m. Energy



ancestors

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# **Upgraded LHCb**

### LHCb detector : season 3 (2022)



(slide from B.Audurier at ECT\* workshop in Trento, Nov 2021)

# **Heavy-ion prospects**

### → In LHCb-CONF-2018-005

### HELAC-Onia + EPPS16 nPDF predictions



- \* Studies in this document :
  - D0-D0 correlations.
  - B+ meson productions.
  - Drell-Yan production
- Results obtained assuming similar systematics as in Run 2.
  - Dominated by tracking uncertainties and branching ratios in this scenario.
- Projections show valuable inputs for nPDF fit with limited data taking periods.

(slide from B.Audurier at ECT\* workshop in Trento, Nov 2021)



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# Summary and Outlook



- LHCb successfully participated in heavy ion data-taking in 2015,2016 & 2018
  - Collected good statistics  $\rightarrow$  could benefit from larger data samples
  - Many measurements performed; first ones with PbPb collisions ever!!
- Charmonium production in PbPb ultra peripheral collisions: refined analysis, good agreement with theory; 2018 results on the way!
- J/ψ studies in PbPb peripheral (hadronic!) collisions using centrality for the first time ! Results with 2018 dataset compared with theoretical predictions, discussion with theorists very lively
- More new results soon with these data
- Many results also studied in view of the new detector in Run3/4
  - Yellow report on the way LHCB-TDR-12 17; CERN-LHCC-2018-026; LHCB-TDR-019

