ALP searches prospects with heavy ions at LHCb

Murilo Rangel
on behalf of the LHCb Collaboration

Heavy Ions and New Physics

20-21 May 2021
ECT* - European Center for Theoretical Studies in Nuclear Physics and Related Areas
Europe/Zurich timezone

Outline

--- Opportunities for ALP searches at LHCb

--- LHCb experiment overview

--- Prospects for ALP searches in heavy ion collisions at LHCb based on Refs [1,2]

[1] Production of axionlike particles in PbPb collisions at the LHC, HE–LHC and FCC: A phenomenological analysis, R.O. Coelho, V.P. Goncalves, D.E. Martins, M.S. Rangel, e-Print: 2002.06027 [hep-ph], Published in: Phys.Lett.B 806 (2020), 135512

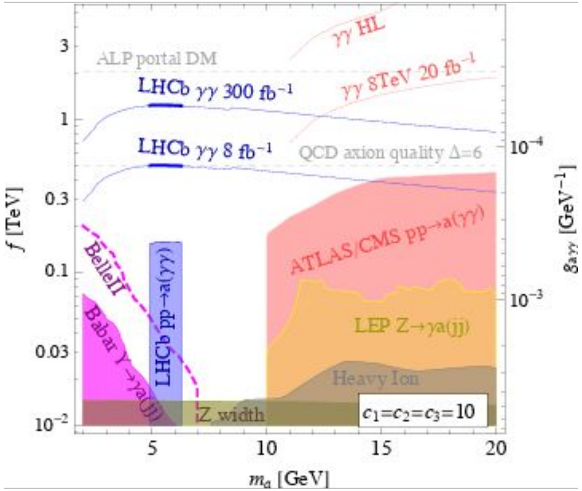
[2] Searching for axionlike particles with low masses in pPb and PbPb collisions, V.P. Goncalves, D.E. Martins, M.S. Rangel, e-Print: 2103.01862 [hep-ph]

Opportunity at LHCb for ALPs in pp collisions (not in this talk)

New Axion Searches at Flavor Factories

Xabier Cid Vidal (Santiago de Compostela U., IGFAE), Alberto Mariotti (Brussels U., IIHE), Diego Redigolo (Tel Aviv U. and Princeton, Inst. Advanced Study and Weizmann Inst.), Filippo Sala (DESY), Kohsaku Tobioka (Florida State U. and KEK, Tsukuba), e-Print: 1810.09452 [hep-ph], Published in: JHEP 01 (2019), 113, JHEP 06 (2020), 141 (erratum)

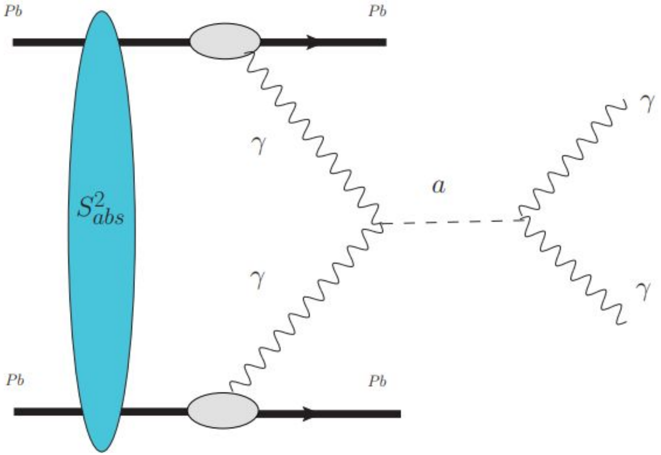
$$\mathcal{L}_{\rm eff} = \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 + \frac{a}{f}\sum_{i=1}^{3} c_i \frac{\alpha_i}{4\pi} F_{i,\mu\nu}\tilde{F}_i^{\mu\nu}$$



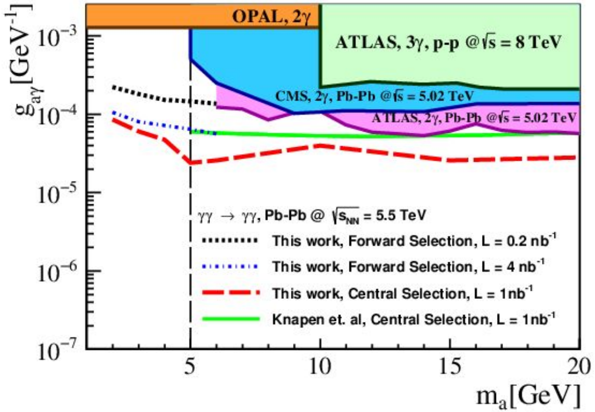
Opportunity at LHCb for ALPs in heavy ion collisions (this talk)

Production of axionlike particles in PbPb collisions at the LHC, HE–LHC and FCC: A phenomenological analysis, R.O. Coelho, V.P. Goncalves, D.E. Martins, M.S. Rangel, e-Print: 2002.06027 [hep-ph], Published in: Phys.Lett.B 806 (2020), 135512

Searching for axionlike particles with low masses in pPb and PbPb collisions, V.P. Goncalves, D.E. Martins, M.S. Rangel, e-Print: 2103.01862 [hep-ph]



$$\mathcal{L} = \frac{1}{2}\partial^\mu a \partial_\mu a - \frac{1}{2} m_a^2 a^2 - \frac{1}{4} g_a a F^{\mu\nu} \tilde{F}_{\mu\nu}$$



++ If ALPs couple only to photons, they will be observed in PbPb collisions

++ CMS and ATLAS have ~10 more data than LHCb in 2018 PbPb

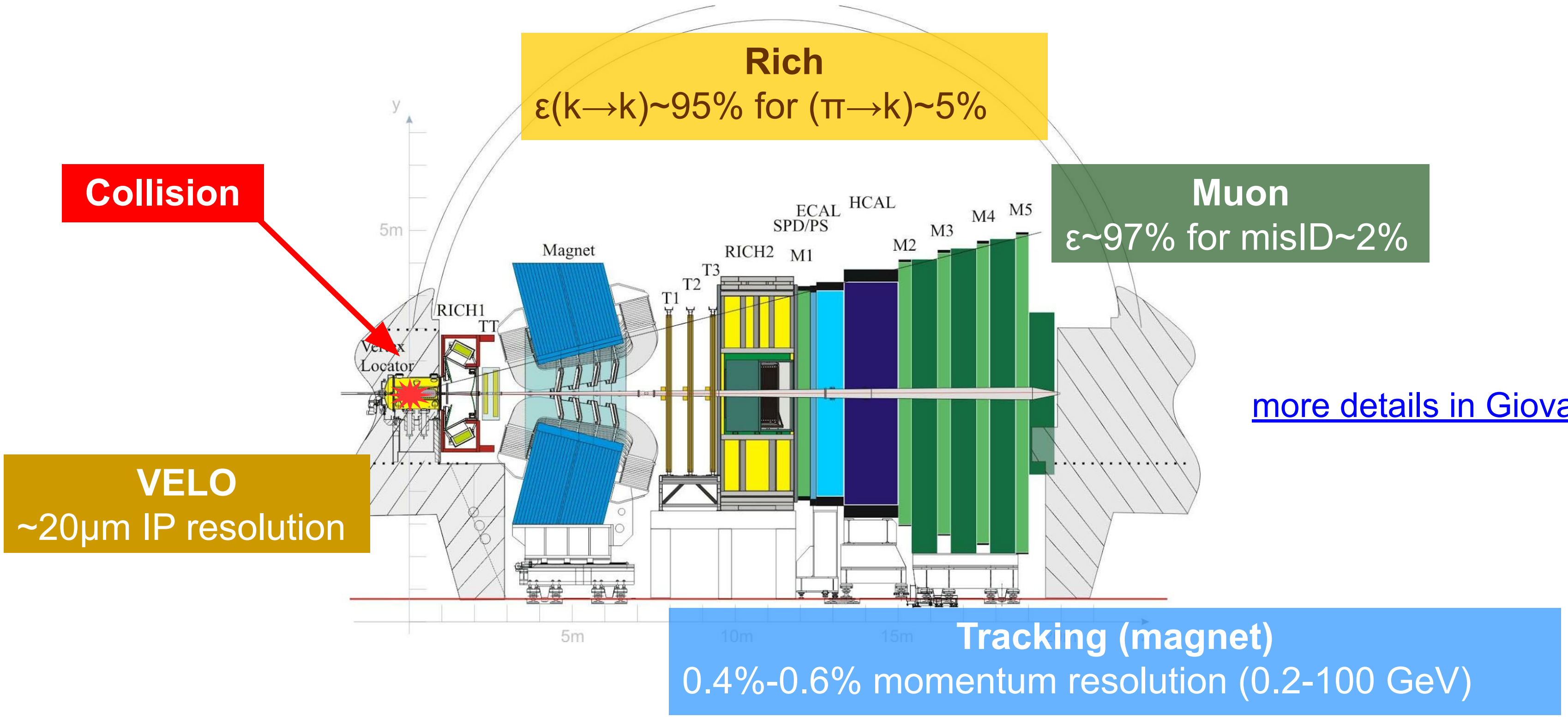
++ CMS (ATLAS) can reach masses down to **5 GeV (6 GeV)**
CMS Collaboration, Phys.Lett.B 797 (2019), 134826
ATLAS Collaboration, JHEP 03 (2021), 243

LHCb can provide complementary search for masses below **5 GeV**.

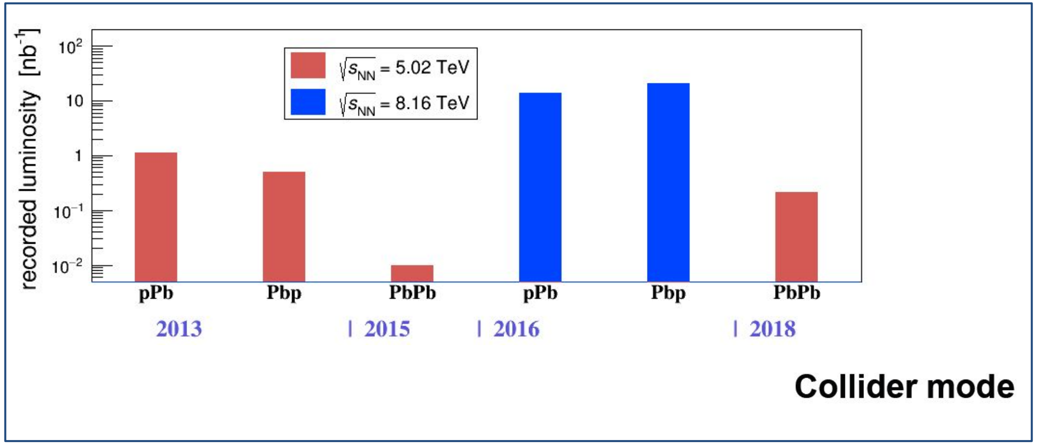
LHCb is a single arm spectrometer fully instrumented in the forward region (2.0<η<5.0)

Designed for heavy flavour physics and also exploited for general purpose physics

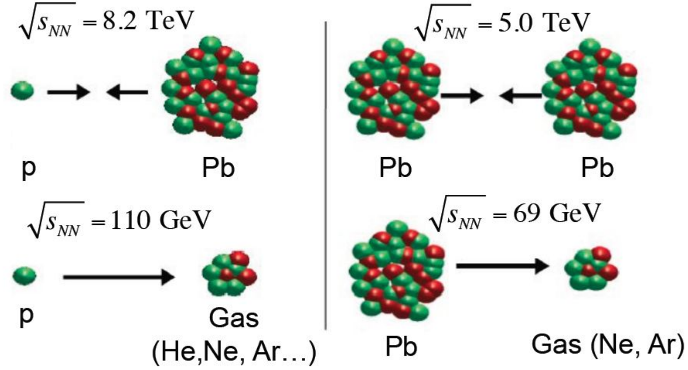
[Int. J. Mod. Phys. A 30, 1530022 (2015)]



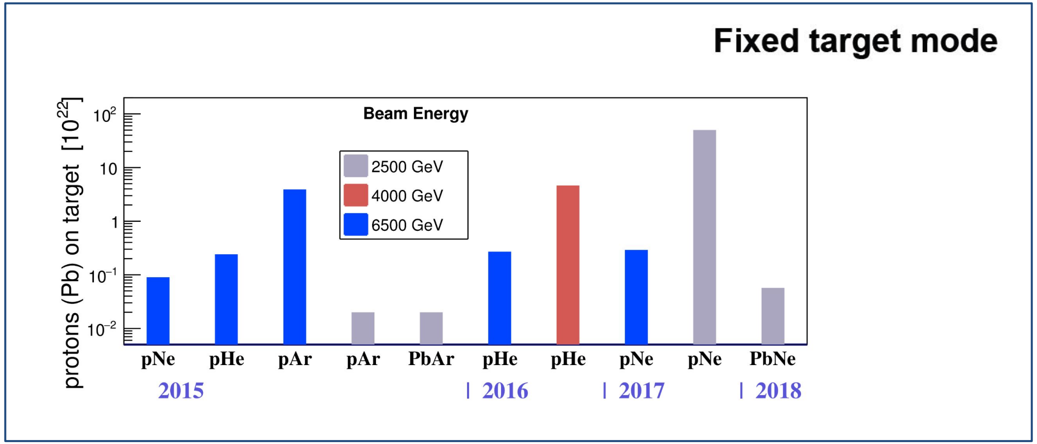
more details in Giovanni's talk



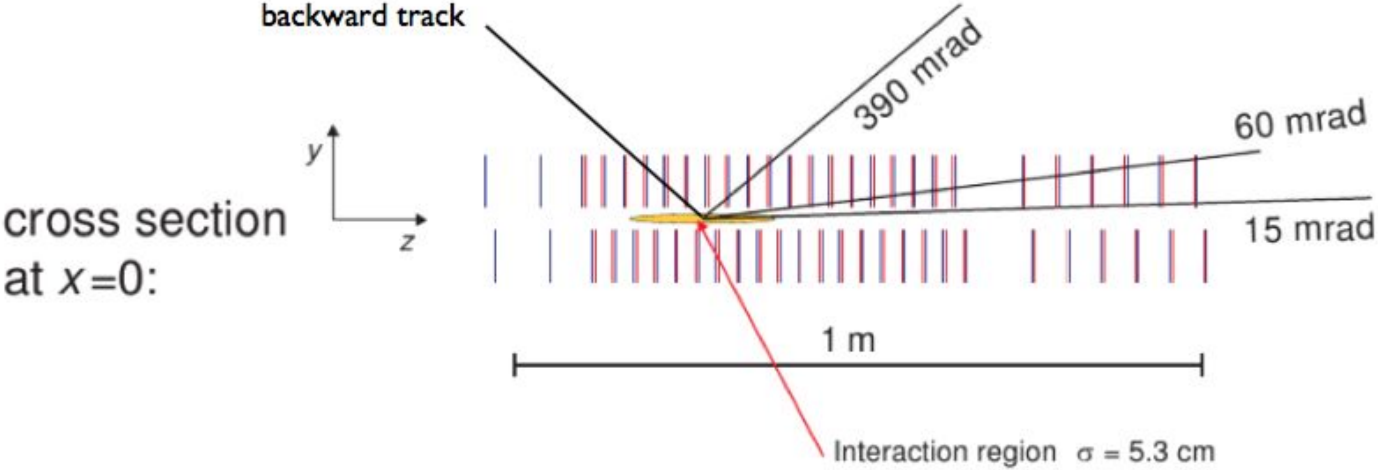
recorded luminosity [nb^{-1}]
10^2
10
1
10^{-1}
10^{-2}
$\sqrt{s_{NN}}$ = 5.02 TeV
$\sqrt{s_{NN}}$ = 8.16 TeV
pPb
Pbp
PbPb
pPb
Pbp
PbPb
2013
2015
2016
2018
Collider mode



$\sqrt{s_{NN}} = 8.2$ TeV
p
Pb
$\sqrt{s_{NN}} = 5.0$ TeV
Pb
Pb
$\sqrt{s_{NN}} = 110$ GeV
p
Gas
(He,Ne, Ar…)
$\sqrt{s_{NN}} = 69$ GeV
Pb
Gas (Ne, Ar)



Fixed target mode
protons (Pb) on target [10^{22}]
10^2
10
1
10^{-1}
10^{-2}
Beam Energy
2500 GeV
4000 GeV
6500 GeV
pNe
pHe
pAr
pAr
PbAr
pHe
pHe
pNe
pNe
PbNe
2015
2016
2017
2018

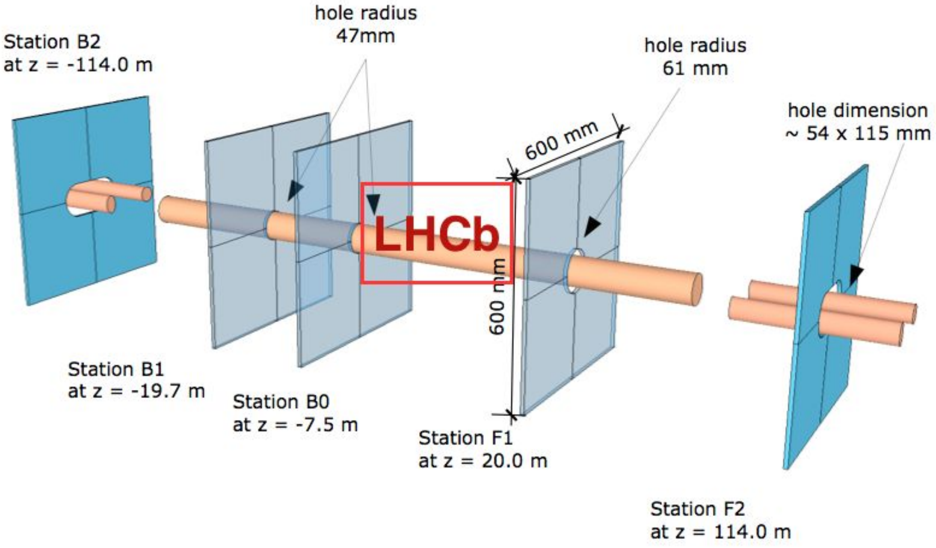


VELO (Vertex Locator)

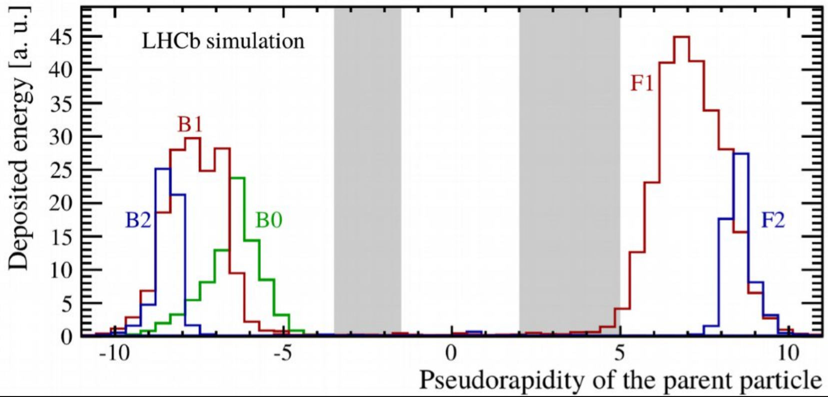
- → surrounds the interaction point
- → no magnetic field
- → reconstructs backward tracks $(-3.5<\eta<-1.5)$

High **R**apidity **S**hower **C**ounters for **L**HCb – HERSCHEL

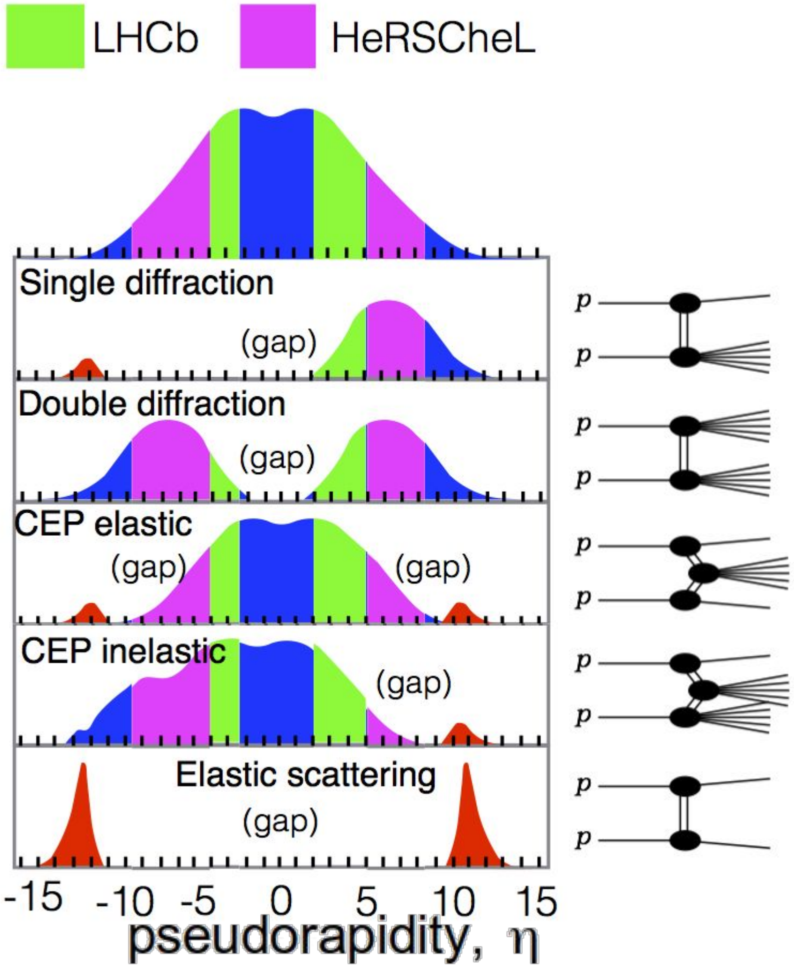
- installed at the end of 2014 → increase pseudorapidity coverage
- 5 stations with 4 scintillators with PMT
- able to detect forward particle showers and veto events with these



JINST 13 (2018) no.04, P04017



Typical acceptance for pp collisions



Run I ---- 2011-2012 / pp at 7-8 TeV

1) Measurement of the exclusive Υ production cross-section at 7 TeV and 8 TeV
JHEP 1509 (2015) 084.

2) Observation of charmonium pairs produced exclusively in pp collisions
J.Phys. G41 (2014) no.11, 115002.

3) Updated measurements of exclusive J/ψ and ψ(2S) production cross-sections in pp at 7 TeV
J.Phys. G41 (2014) 055002.

4) Exclusive dimuon measurements: non-resonant and χc
LHCb-CONF-2011-022

Run II --- pp (PbPb) at 13 (5) TeV

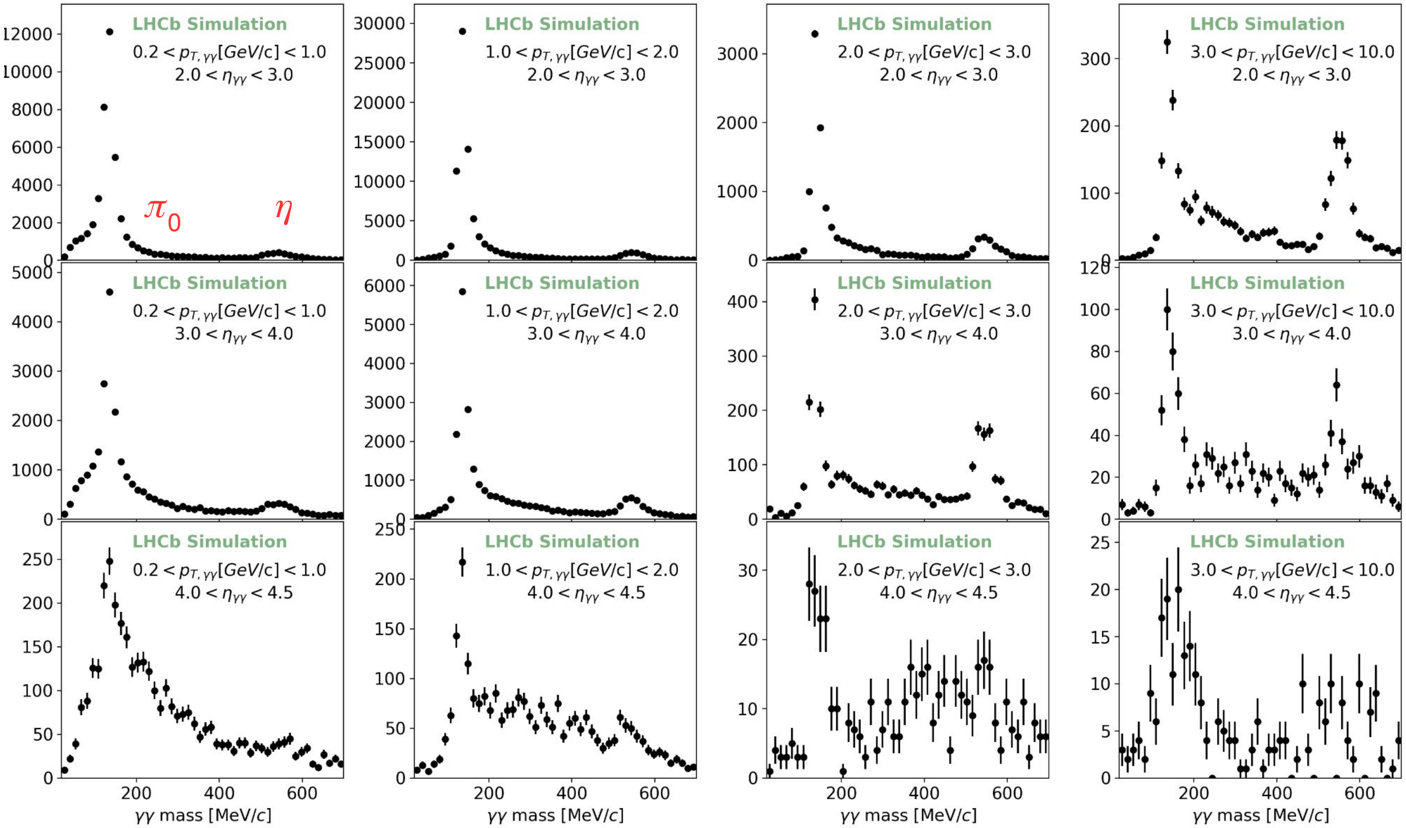
1) Study of coherent J/ψ production in lead-lead collisions at 5 TeV
LHCb-CONF-2018-003

2) Central exclusive production of J/ψ and ψ(2S) mesons in pp collisions at 13 TeV
JHEP 10 (2018) 167

Photons in heavy ions

Using photons obtained from LHCb simulation for pPb collisions.

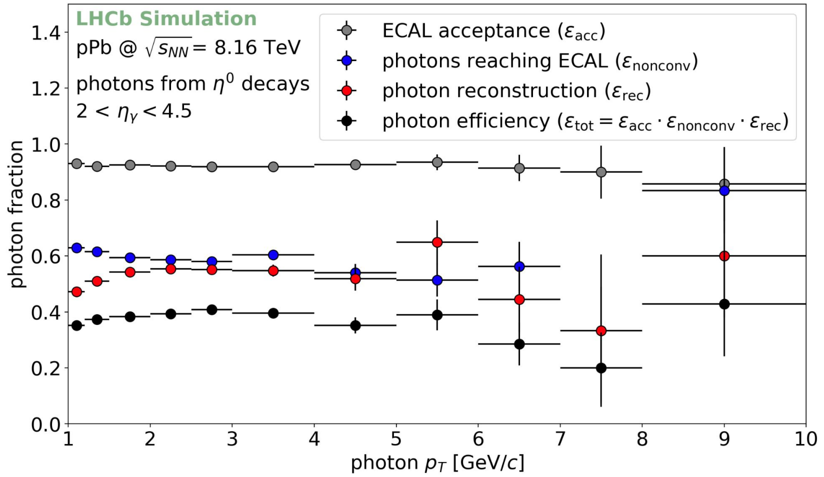
LHCb-FIGURE-2020-006



Photons in heavy ions

Using photons obtained from LHCb simulation for pPb collisions.

LHCb-FIGURE-2020-006



$$\varepsilon_{\rm acc} = \frac{\text{photons in ECAL acceptance}}{\text{photons in } 2 < \eta_\gamma < 4.5}$$

$$\varepsilon_{\rm nonconv} = \frac{\text{photons reaching ECAL}}{\text{photons in ECAL acceptance}}$$

$$\varepsilon_{\rm rec} = \frac{\text{photons measured by ECAL}}{\text{photons in ECAL acceptance and reaching ECAL}}$$

--- The efficiency is affected by surrounding activity in the ECAL (this is a lower limit for ALP searches)

--- Low multiplicity events were collected with single photon trigger (E_T > 1 GeV) for heavy ion collisions

In a first study, the event generators Superchic3 and FPMC (modified to include PbPb) were used.
For LHCb acceptance (including herschel veto), LbL is the most important non-reducible background.

Double Diffractive Production (DDP) is suppressed by the Herschel veto and the acoplanarity

QCD induced (Durham) has low cross-section.

$PbPb$ at $\sqrt{s_{NN}} = 5.5$ TeV	LbL	Durham	DDP	$m_a = 3$ GeV
Total Cross section [nb]	18000.0	167.0	17.7	13000.0
$m_X > 1\,\text{GeV}, p_T(\gamma,\gamma) > 0.2\,\text{GeV}$	13559.0	142.0	17.6	12873.0
$1 - (\Delta\phi/\pi) < 0.01$	8834.0	51.0	0.2	11033.0
$p_T(\gamma\gamma) < 0.1$ GeV	8826.0	47.0	0.0	11019.0
$2.0 < \eta(\gamma,\gamma) < 4.5$	616.0	3.7	0.0	974.0
$2 < m(\gamma\gamma) < 4$	83.7	3.2	0.0	974.0
$5 < m(\gamma\gamma) < 7$	32.0	1.0	0.0	-
$13 < m(\gamma\gamma) < 17$	0.0	0.0	0.0	-
$38 < m(\gamma\gamma) < 42$	0.0	0.0	0.0	-

Phys.Lett.B 806 (2020) 135512

In a second result, using Superchic4 event generator
considering the di-electron as background
assuming 0.5% for $e\rightarrow\gamma$ mis-identification probability
The current limits are expected to be improved with an ALP search at the LHCb experiment.

$Pb-Pb$ @ $\sqrt{s_{NN}}$ = 5.5 TeV	LbL	$e^+e^-(\gamma\gamma)$	ALP							
			$m_a = 2$ GeV		$m_a = 3$ GeV		$m_a = 4$ GeV		$m_a = 5$ GeV	
Coupling $(g_{a\gamma})[\text{GeV}^{-1}]$	-	-	$1\cdot10^{-3}$	$8\cdot10^{-4}$	$1\cdot10^{-3}$	$8\cdot10^{-4}$	$1\cdot10^{-3}$	$8\cdot10^{-4}$	$1\cdot10^{-3}$	$8\cdot10^{-4}$
Generation level										
Total Cross section [nb]	18000.0	13000.0	17640.0	11288.0	13000.0	8369.0	11000.0	6914.0	8944.0	5725.0
Exclusivity cuts										
$m_{\gamma\gamma} > 1$ GeV, $p_T(\gamma,\gamma) > 0.2$ GeV	13559.0	2500.0	17245.0	11035.0	12873.0	8289.0	10928.0	6869.0	8916.0	5707.0
$1-(\Delta\phi/\pi) < 0.01$	8834.0	1550.0	13217.3	8458.0	11033.0	7102.0	9846.0	6189.0	8389.5	5370.1
$p_T(\gamma\gamma) < 0.1$ GeV	8826.0	1550.0	13206.0	8450.5	11019.0	7092.0	9827.0	6177.0	8369.0	5357.0
Forward selection										
$2.0 < \eta(\gamma,\gamma) < 4.5$	616.0	87.5	1282.2	820.5	974.0	614.0	784.0	493.0	580.3	371.4
$1.5 < m(\gamma\gamma) < 2.5$	166.0	23.5	1282.2	820.5	-	-	-	-	-	-
$2.5 < m(\gamma\gamma) < 3.5$	33.0	5.0	-	-	974.0	614.0	-	-	-	-
$3.5 < m(\gamma\gamma) < 4.5$	11.3	1.8	-	-	-	-	784.0	493.0	-	-
$4.5 < m(\gamma\gamma) < 5.5$	5.9	0.8	-	-	-	-	-	-	580.3	371.4

e-Print: 2103.01862 [hep-ph]

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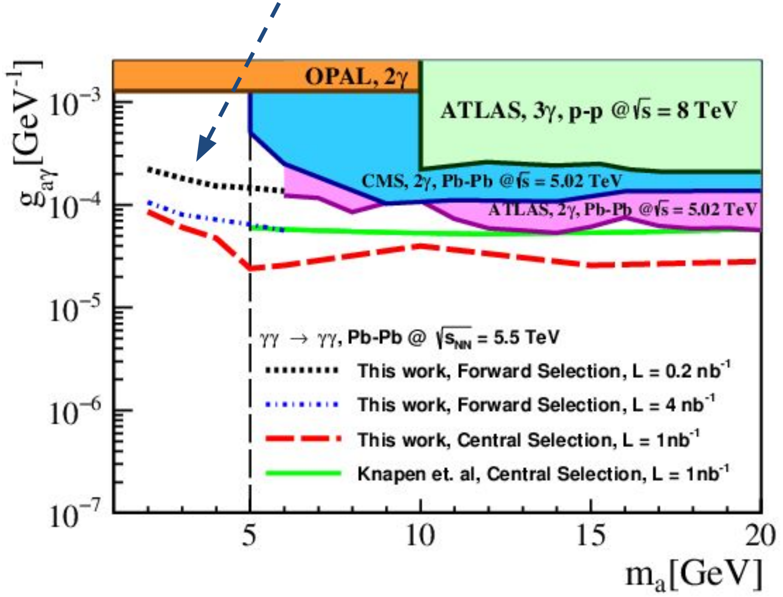
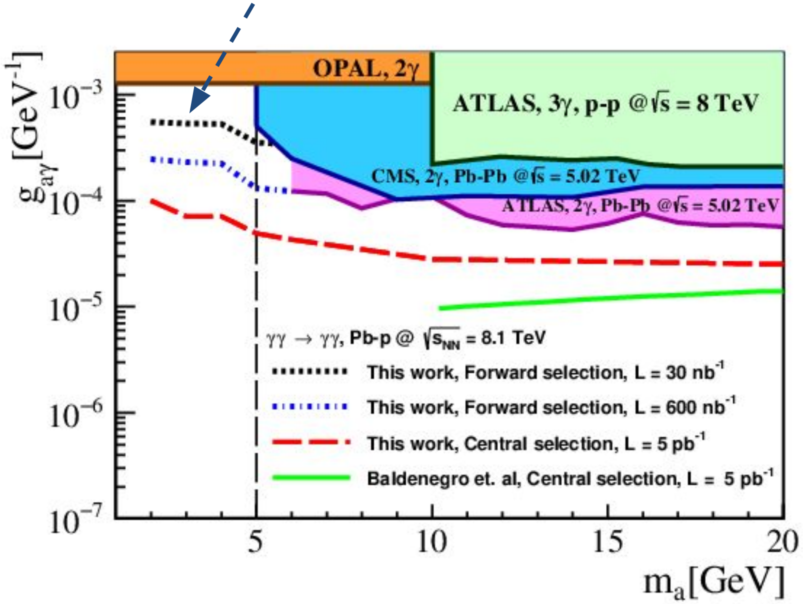




e-Print: 2103.01862 [hep-ph]

Conclusions

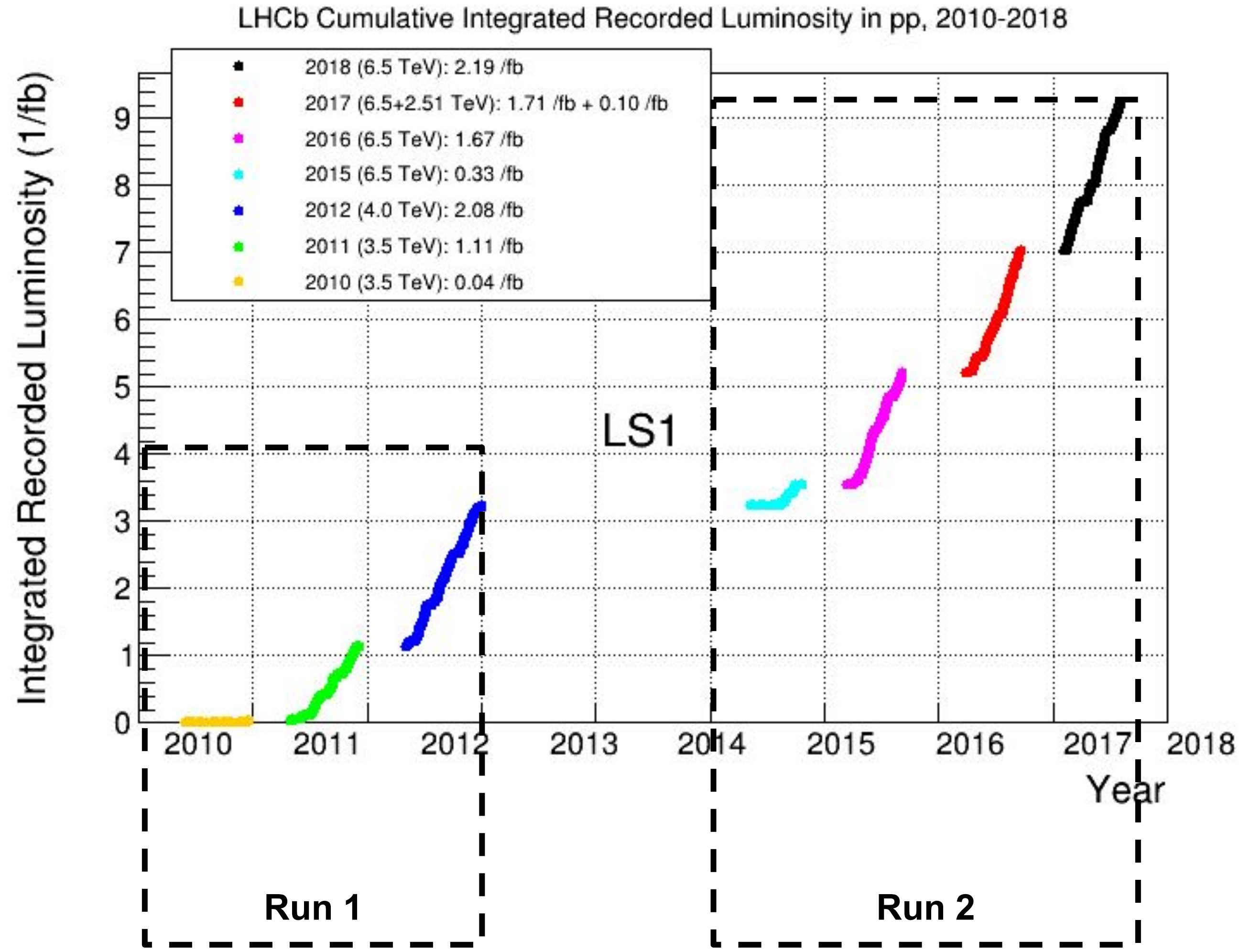
--- LHCb experiment collected data in heavy ion collisions with low multiplicity trigger lines

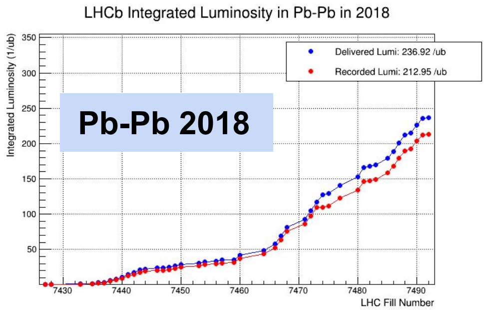
--- Photon reconstruction can reach lower E_T then CMS/ATLAS

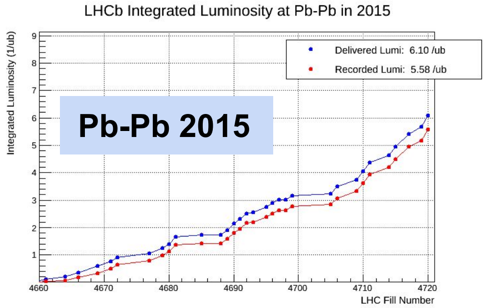
--- Current limits can be improved for masses below 5 GeV using PbPb/pPb dataset

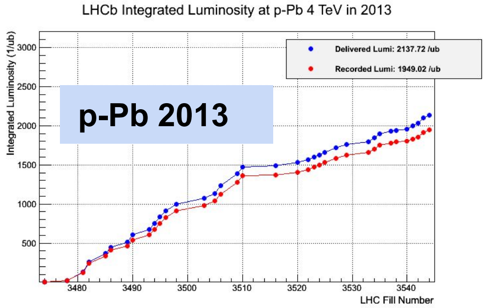
Thank you

BACKUP


LHCb Cumulative Integrated Recorded Luminosity in pp, 2010-2018
2018 (6.5 TeV): 2.19 /fb
2017 (6.5+2.51 TeV): 1.71 /fb + 0.10 /fb
2016 (6.5 TeV): 1.67 /fb
2015 (6.5 TeV): 0.33 /fb
2012 (4.0 TeV): 2.08 /fb
2011 (3.5 TeV): 1.11 /fb
2010 (3.5 TeV): 0.04 /fb
Integrated Recorded Luminosity (1/fb)
Year
LS1
Run 1
Run 2


LHCb Integrated Luminosity in Pb-Pb in 2018
Delivered Lumi: 236.92 /ub
Recorded Lumi: 212.95 /ub
Pb-Pb 2018
Integrated Luminosity (1/ub)
LHC Fill Number


LHCb Integrated Luminosity at Pb-Pb in 2015
Delivered Lumi: 6.10 /ub
Recorded Lumi: 5.58 /ub
Pb-Pb 2015
Integrated Luminosity (1/ub)
LHC Fill Number


LHCb Integrated Luminosity at p-Pb 4 TeV in 2013
Delivered Lumi: 2137.72 /ub
Recorded Lumi: 1949.02 /ub
p-Pb 2013
Integrated Luminosity (1/ub)
LHC Fill Number

https://www.sciencedirect.com/science/article/pii/S0370269319305404?via%3Dihub

2015 data

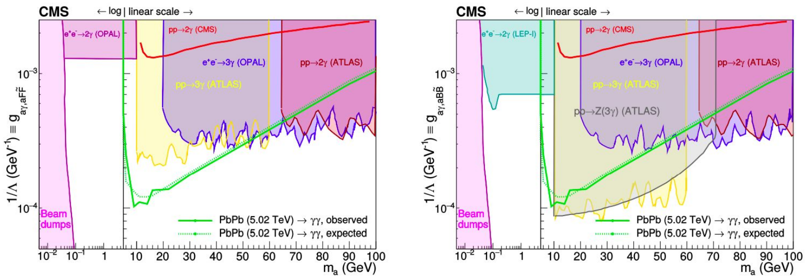


Figure 7: Exclusion limits at 95% CL in the ALP-photon coupling $g_{a\gamma}$ versus ALP mass m_a plane, for the operators $aF\widetilde{F}/4\Lambda$ (left, assuming ALP coupling to photons only) and $aB\widetilde{B}/(4\Lambda\cos^2\theta_W)$ (right, including also the hypercharge coupling, thus processes involving the Z boson) derived in Refs. [30, 56] from measurements at beam dumps [60], in e^+e^- collisions at LEP-I [56] and LEP-II [57], and in p p collisions at the LHC [13, 58, 59], and compared to the present PbPb limits.

https://cds.cern.ch/record/2719516

2018 data

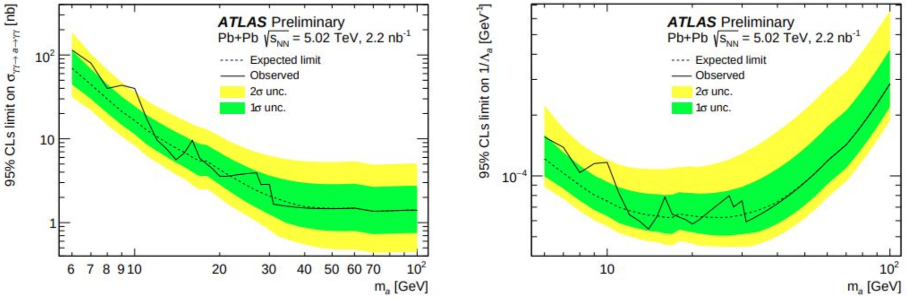


Figure 9: The 95% CL upper limit on the ALP cross section $\sigma_{\gamma\gamma\to a\to\gamma\gamma}$ (left) and ALP coupling $1/\Lambda_a$ (right) for the $\gamma\gamma \to a \to \gamma\gamma$ process as a function of ALP mass m_a. The observed upper limit is shown as a solid black line and the expected upper limit is shown by the dashed black line, with a green $\pm1\sigma$ and a yellow $\pm2\sigma$ band.

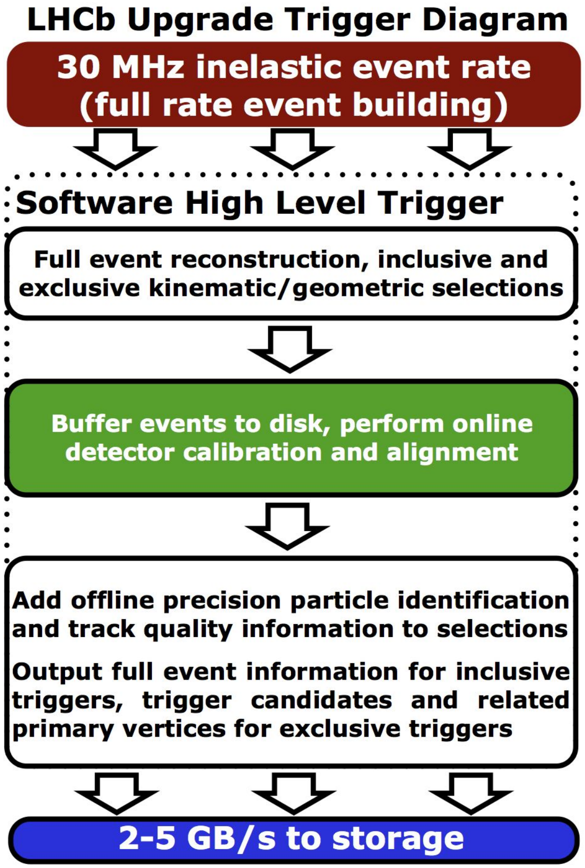
LHCb Upgrade I

❈ Increase instantaneous luminosity:
$4 \times 10^{32} \rightarrow 2 \times 10^{33}$ cm^{-2} s^{-1}

❈ Replacement of tracking detectors
♯ finer granularity to cope with higher particle density
♯ new front-end electronics compatible with 30 MHz readout

❈ Remove hardware trigger stage and operate software trigger at 30 MHz input rate with 5 x more pileup than Run 2.

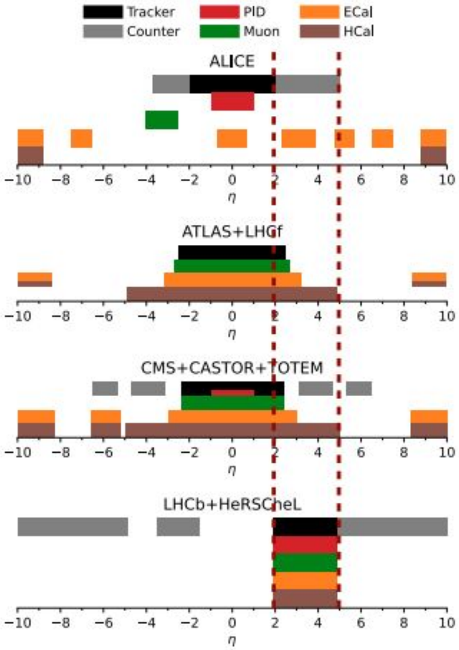
❈ HLT1 output: from 100 kHz to 1 MHz
Disk buffer contingency: from weeks to days
HLT2 output: from 0.6 GB/s to 10 GB/s



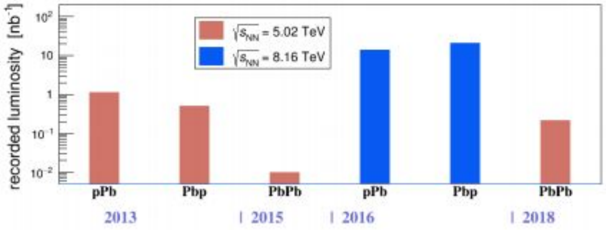
LHCB-PUB-2014-027

Heavy ion collisions at LHCb

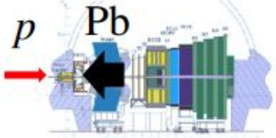
- Only detector at LHC fully equipped in forward region



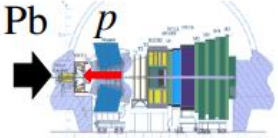
- Full run 1+2 dataset from HI collisions:



- Two configurations in pPb collisions:



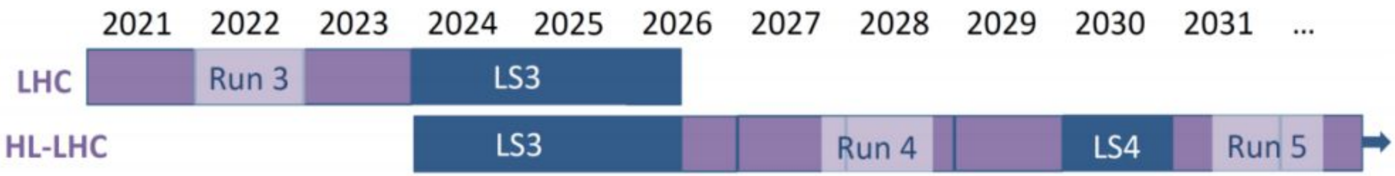
Forward $\eta > 0$



Backward $\eta < 0$

Boost of nucleon-nucleon cms system: $\eta = \eta_{lab} - 0.465$

Future samples (possible schedule)



LS2 – LHCb upgrade 1a →

LS3 – LHCb upgrade 1b →

LS4 – LHCb upgrade 2 →

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}
	O–O, p–O	1 week	500 μb^{-1} and 200 μb^{-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	

arXiv:1812.06772 - CERN-LPCC-2018-07