Soft QCD and pA physics, with a focus on the ridge at LHCb

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on behalf of the LHCb collaboration

I. LHCb Experiment[1]

- Designed for study of b- and c-hadron decays
- Can be used for a much wider spectrum of physics analyses!
- Results **highly complementary** to other LHC experiments

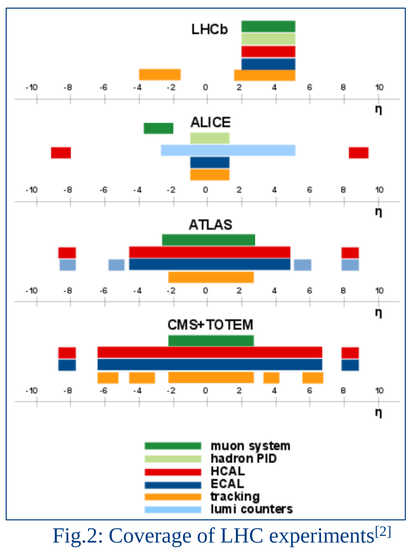

Fig.2: Coverage of LHC experiments[2]

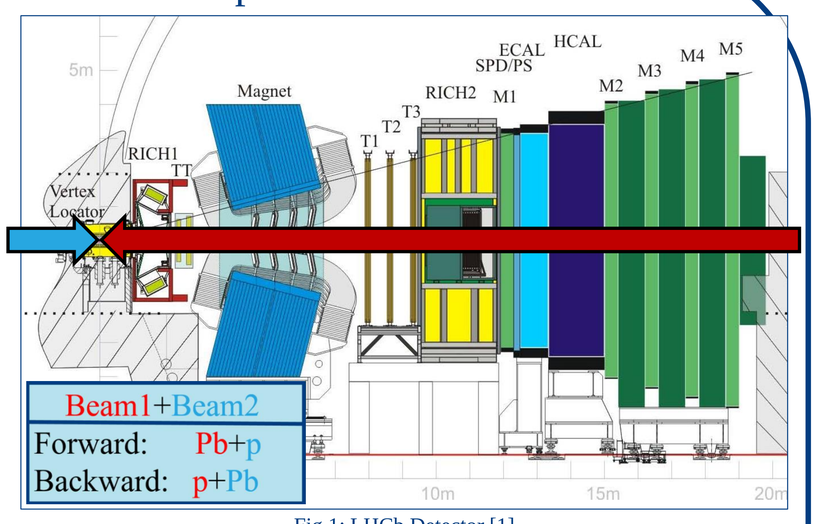

Fig.1: LHCb Detector [1]

Important notes:

- Fully instrumented in $2.0 < \eta < 4.5$
- IP resolution ~ 20 μm
- Decay time resolution ~ 45 fs
- Track momentum resolution $\frac{\Delta p}{p} = 0.4\%$ at low p (p ~ 5 GeV/c) to 1.0% at high p (p ~ 200 GeV/c)
- $\varepsilon_{K^{ID}} = 95\%$ (mis-ID$\varepsilon_{\pi\to K}$~ 5%)
- $\varepsilon_{\mu^{ID}} = 97\%$ (mis-ID$\varepsilon_{\pi\to\mu}$~ 1-3%)
- Beam configurations for pA run shown in Fig.1

II. Soft QCD at LHCb

- LHCb employs **low p_T** and **low mass triggers** for soft QCD analyses
- Kinematic coverage of LHCb is useful for studying **multi-parton interactions** (MPI)
- **Low pile-up environment** allows study of various **central-exclusive-production** (CEP)
- **Backwards coverage** of VELO used to identify diffractive events containing **large rapidity gaps** (LRG)

- Various analyses performed on Run-I data:
  - Measurement of the inelastic pp cross-section at centre-of-mass energy of $\sqrt{s}$=7 TeV **[arXiv:1412.2500]** (Fig.3)
  - Measurement of the forward energy flow in pp collisions at $\sqrt{s}$=7 TeV **[arXiv:1212.4755]**
  - Observation of charmonium pairs produced exclusively in pp collisions **[arXiv:1407.5973]** (CEP)
  - (and more)

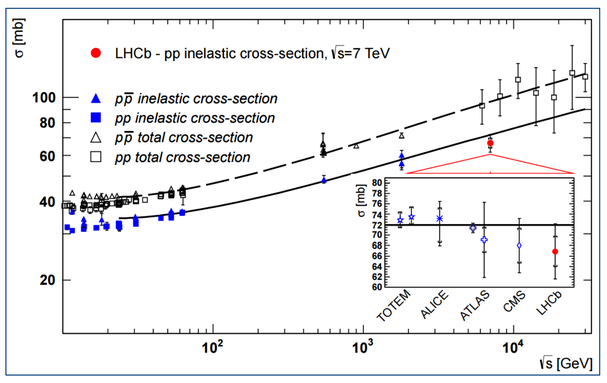

Fig.3: pp inelastic cross-section as a function to the centre-of-mass energy[3]

III. pA Physics at LHCb

- The proton-ion run at LHC in early 2013.
- LHC ran with **asymmetric beams**:
  - E_p = 4 TeV
  - E_{Pb} = 1.58 TeV
  - $\sqrt{s_{NN}}$ **= 5 TeV**
- Detector geometry permits exploration of two configurations (Fig.1).
- Rapidity coverage (in NN c.m.s. frame):
  - Forward: $1.5 < y < 4.5$
  - Backward: $-5.5 < y < -2.5$
- $\mathcal{L}$ **= 1.1 nb^{-1}** (forward) and **0.5 nb^{-1}** (backward)
- Used to study of **cold nuclear matter** (CNM) and **quark-gluon plasma** (QGP) effects.
- Production of promt J/ψ, J/ψ from b **[arXiv:1308.6729]** and prompt ψ(2S) and ψ(2S) from b **[LHCb-CONF-2015-005]** (and more) studied[4].
- Nuclear modification factor (Fig.4), R_{pA}, given as:

$$R_{pA} = \frac{1}{A}\frac{d\sigma_{pA}/dy}{d\sigma_{pp}/dy}$$

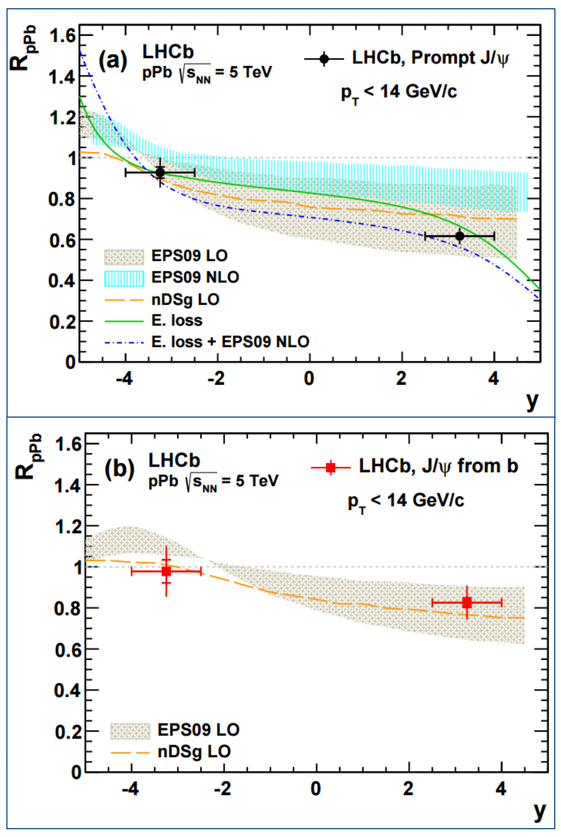

Fig.4:Nuclear modification factor for (a) prompt J/ψ mesons and (b) J/ψ from b[4]

- Ion program is complemented by the SMOG system (fixed target mode)
- Noble gasses (He, Ne, Ar) can be injected at interaction point 8 and targeted with proton or heavy-ion beam.

IV. 'Ridge Effect' at LHCb[5]

Measurement of two-particle angular correlations performed using:

$\mathcal{L}$ = **0.46 nb^{-1}** [p+Pb]

$\mathcal{L}$ = **0.30 nb^{-1}** [Pb+p]

Event Selection and Classes

- Five absolute activity classes split by hit multiplicity in VELO (Fig. 5)
- A **scaling factor** of $\mathbf{0.77 \pm 0.08}$ is applied to multiplicities in p+Pb configuration due to different absolute activities
- Each activity class analysed separately

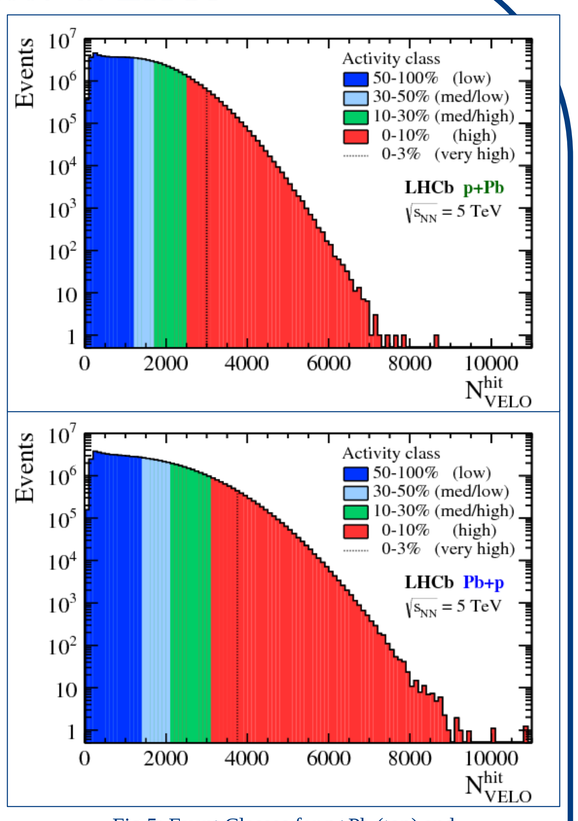

Fig.5: Event Classes for p+Pb (top) and Pb+p (bottom) configurations

- Combine trigger particles with each associated particle
- Reference sample based on event-mixing method
- The correlation function is given by:

$$\frac{1}{N_{trig}}\frac{d^2N_{pair}}{d\Delta\eta d\Delta\phi} = \frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)} \times B(0,0)$$

where $S(\Delta\eta,\Delta\phi) = \frac{1}{N_{trig}}\frac{d^2N_{same}}{d\Delta\eta d\Delta\phi}$ is the signal and $B(\Delta\eta,\Delta\phi) = \frac{d^2N_{mix}}{d\Delta\eta d\Delta\phi}$ is the background component.

Two-particle correlations are described as:

- **short-range** ($|\Delta\eta| \lesssim 2$)
- **long-range** ($|\Delta\eta| \gtrsim 2$)
- **near-side** ($|\Delta\phi| \approx 0$)
- **away-side** ($|\Delta\phi| \approx \pi$)

- Near-side short-range jet peak (truncated) in Fig.6 arises due to correlation of particles arising from the same jet.
- The away-side long-range structure balances the jet-peak and arises from conservation of momentum.
- Comparing the low activity events with high activity events a new elongated ridge-like structure can be observed on the near side.

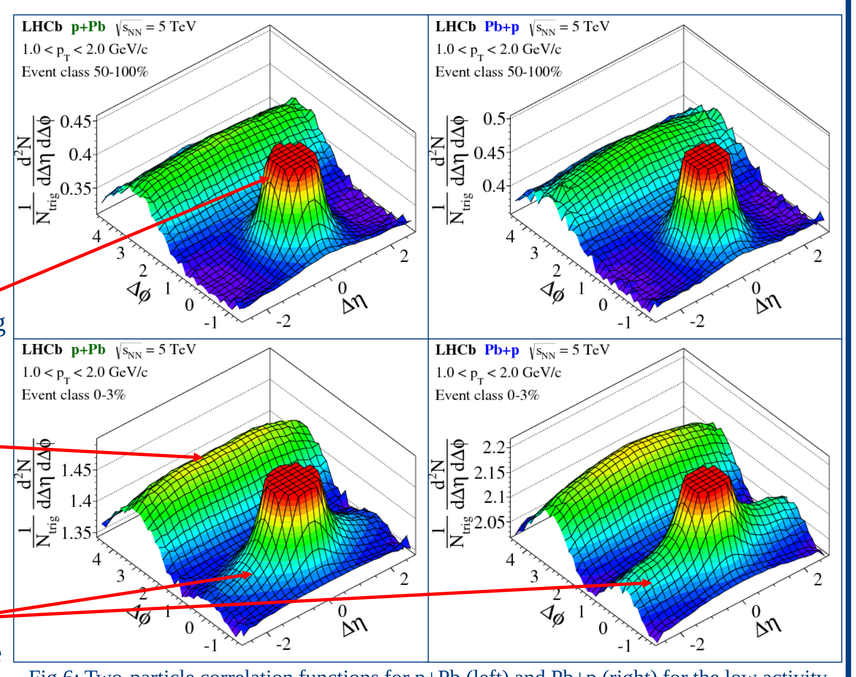

Fig.6: Two-particle correlation functions for p+Pb (left) and Pb+p (right) for the low activity (top) and high activity (bottom) class with for p_T between 1.0 and 2.0 GeV/c

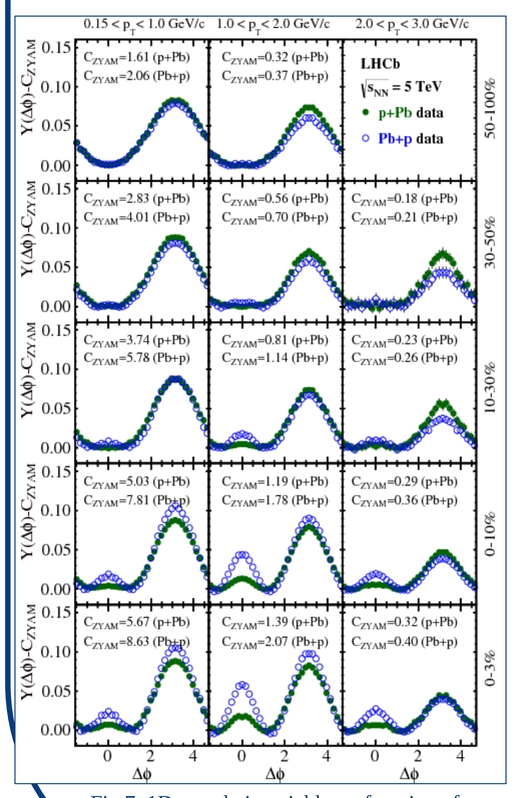

Fig.7: 1D correlation yield as a function of $\Delta\phi$ averaged over $2.0 < \Delta\eta < 2.9$.

- One dimensional projections of the correlation function on $\Delta\phi$ are calculated using:

$$Y(\Delta\phi) \equiv \frac{1}{N_{trig}}\frac{dN_{pair}}{d\Delta\phi} = \frac{1}{\Delta\eta_b - \Delta\eta_a}\int_{\Delta\eta_a}^{\Delta\eta_b}\frac{1}{N_{trig}}\frac{d^2N_{pair}}{d\Delta\eta d\Delta\phi}d\Delta\eta$$

and are shown in Fig.7.

- Done for $2.0 < |\Delta\eta| < 2.9$ to exclude the jet-peak
- Correlations extracted using zero-yield-at-minimum (ZYAM) method
- Ridge effect increases with the event activity
- Pb+p more prominent on near-side than p+Pb
- Away-side correlation decreases with increasing p_T

- This is further investigated by studying common bins of absolute activity, shown in Fig.8.

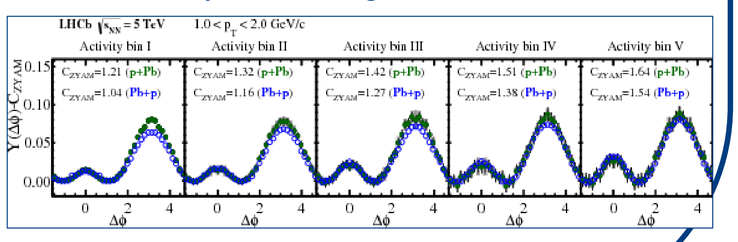

Fig.8: 1D correlation yield as a function of $\Delta\phi$ averaged over $2.0 < \Delta\eta < 2.9$ in common bins of absolute activity.

V. Summary

- Designed for the study of particles containing b and c quarks, LHCb has proven to be a multi-purpose detector.
- A number of soft QCD and CEP analyses have been carried out using the Run-I data collected by LHCb.
- LHCb participated in the pA run in 2013 yielding an array of proton-ion collision analyses.
- An interesting study of two-particle angular correlations were carried out, which showed the observation of the near-side long-range structure (ridge) in the pA collisions at large rapidities at LHCb

[1] The LHCb Detector at the LHC, LHCb Collaboration (A.Augusto Alves, Jr. (Rio de Janeiro, CBPF) *et al.*). 2008. 217 pp., JINST 3 (2008) S08005, DOI: 10.1088/1748-0221/3/08/S08005
[2] Messacrier, Laure Marie, LHCb results from proton-ion collisions, October 2015, https://cds.cern.ch/record/2061579
[3] Measurement of the inelastic pp cross-section at centre-of-mass energy of $\sqrt{s}$=7 TeV [arXiv:1412.2500], High Energy Phys. 02 (2015) 129, DOI: 10.1007/JHEP02(2015)129
[4] Study of J/ψ production and cold nuclear matter effects in pPb collisions at $\sqrt{s_{NN}}$=5TeV, Journal reference: JHEP 02 (2014) 072, DOI:10.1007/JHEP02(2014)072, arXiv:1308.6729
[5] Measurements of long-range near-side angular correlations in $\sqrt{s_{NN}}$ = 5 TeV proton-lead collisions in the forward region, LHCb Collaboration (Roel Aaij (CERN) *et al.*). Dec 1, 2015. 23 pp., LHCB-PAPER-2015-040, CERN-PH-EP-2015-308, arXiv:1512.00439

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