Soft-hard correlations workshop

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Outline

- Motivation
- LHCb set-up
- LHCb measurements
- Conclusions

Motivations for soft-hard correlations

- **any** hard scale measurement for QGP physics adresses

  implicitly - already pp vs. pPb vs. PbPb inclusive - or

  explicitly - centrality in PbPb -

  a **soft-hard** correlation:
  medium (bulk) driven by comparatively soft/semi-hard scales up to O(1 GeV) in m/p_T
- in AA to us heavy-ion physicists "natural":
  - empirically confirmed arguments like centrality-multiplicity corr., large v_2 in semi-central
  - however precision of ingredients not well controlled
- non-inclusive as multiplicity-differential observables can bring complications at the definition level, but even more at the interpretation level
  $\rightarrow$ goes as deep as basic concepts: centrality in AA - see ALICE bias study at Quark Matter for peripheral collisions

Motivations for soft-hard correlations

- possible strategies:
  1) idealisation: focus on corners, where we think to understand things
  e.g. broad centrality bins in most central AA, inclusive *pp*
  $\rightarrow$ fear: "otherwise lost in uncontrolled details without any outcome"
  2) see different collision systems as limiting cases of each other
  $\rightarrow$ "question two paradigms at once" (small systems punch line)

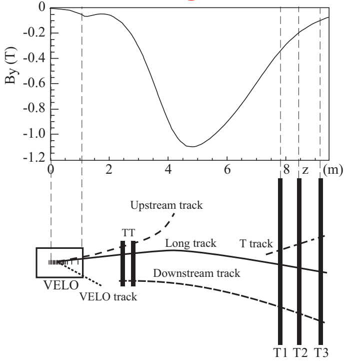
Not black-white: both approaches can profit from their respective insights

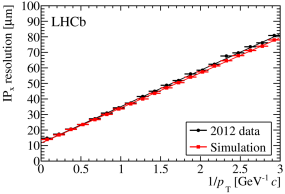
Motivations for soft-hard correlations

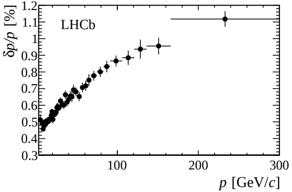
- attempt to resolve different sources of correlations in any collision system:
  - "pQCD" physics: higher Fock states of proton wave function, partonic structure nuclear modifications, correlations in momentum space - role of "final state interaction"
  - role of geometry motivating notion "centrality"
  - level of thermalisation
- notoriously difficult the smaller the system, the softer the scale:
  - should not include non-clear physics in observable definitions
- demand an overall consistent picture from ourselves

LHCb could contribute decisively in several areas.

LHCb tracking



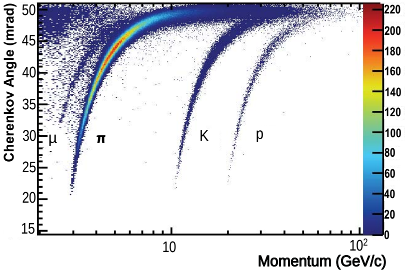


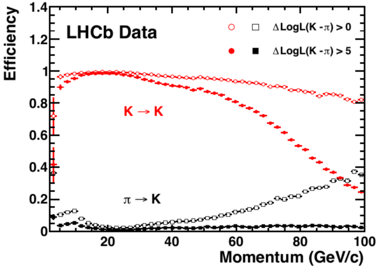


Int. J. Mod. Phys. A 30 1530022.

- VELO: silicon strip telescope down to radial distance to beam $r = 0.8$ cm
- VELO+RICH1+silicon strip+ 4Tm dipole + straw tubes/silicon strips
- tracker with $\approx 30\%$ X_0
- momentum resolution below 1% in wide range
- topological ID of charm and beauty hadrons down to 0 p_T: longitudinal boost
- backward tracks without PID/p_T: $\Delta\eta$ up to 8-9

LHCb particle identification

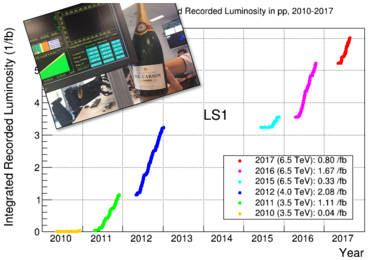


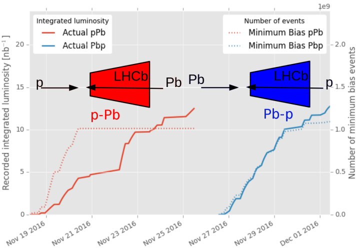


JINST 3 (2008) S08005

- 2 RICH systems with 2 radiators for charged track PID
- muon-ID behind calorimetry: $\varepsilon_{\mu\to\mu} \approx 97\%$ for $\varepsilon_{\pi\to\mu} \approx$ 1-3 % Mis-ID
- photon measurement & electron/photon-ID with calorimetry and preshower
  $\Delta m(\mu^+\mu^-, \mu^+\mu^-\gamma)$-resolution: 5 MeV/$c^2$ from $\chi_{c1,c2} \to J/\psi + \gamma$-decay with calorimeter

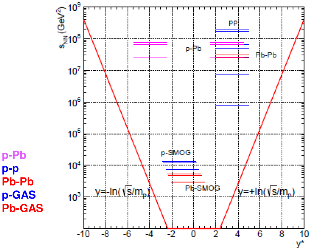
Collision systems and running conditions in collider mode

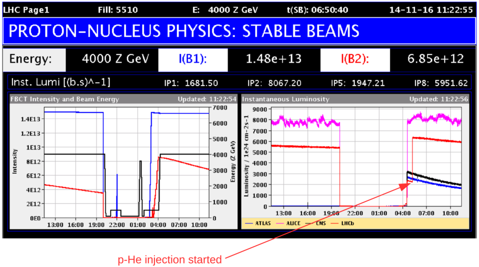




- luminosity levelling with ≈ 1 visible collisions per beam-beam encounter every 25 ns in pp: $L \approx 4 \times 10^{32}$ cm^{-2} s^{-1}
- 6 fb^{-1} from 2010-now at $\sqrt{s}$ =0.9,2.76,5,**7,8,13** TeV
- pPb/Pbp 2016: running at $\lesssim$ 200 kHz interaction rate with $\lesssim$ 0.1 visible collisions per beam-beam encounter: 34.4 nb^{-1} in two beam configurations at $\sqrt{s_{NN}}$ =8.16 TeV, 0.5 nb^{-1} at $\sqrt{s_{NN}} = 5$ TeV in one configuration
- 1.6 nb^{-1} at $\sqrt{s_{NN}} = 5$ TeV in both beam configurations accumulated in 2013
- in PbPb 2015: luminosity equivalent to about 50 million hadronic minimum bias collisions

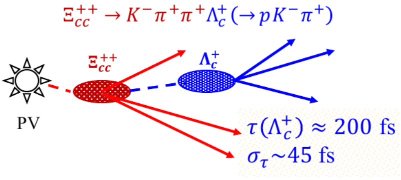
Collision systems and running conditions in fixed-target collisions



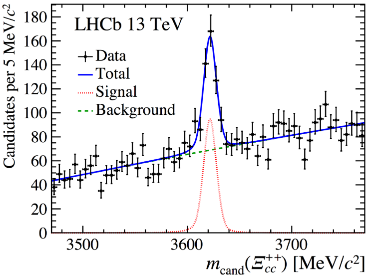


- noble gas injected in interaction region:
  improve luminosity measurement by beam imaging J. Instrum. 9 (2014) P12005
- residual gas pressure in beam pipe increased by 2 orders of magnitude: $O(10^{-7})$ mbar
- used for fixed target with proton and Pb beams: LHCb $\approx$ midrapidity rapidity coverage at lower collision energies
- *p***He,** *p***Ar**, *p***Ne**, *Pb*Ne and *Pb***Ar** data samples available
- *p*Ar and *p*He 7.6 nb^{-1}, integrated lumi, *p*Ne about a factor 10 more protons on target than *p*He

Measurements in *pp*: Ξ_{cc}^{++} as an example



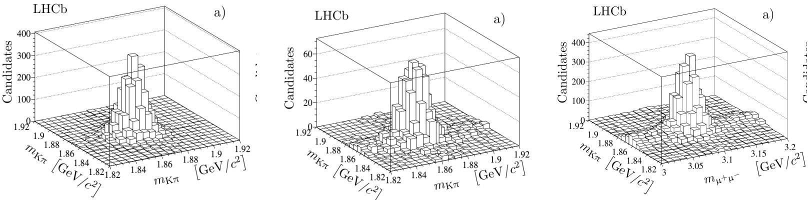
60 M fully reconstructed
$\Lambda_c^+ \to pK^-\pi^+$ signal decays



PRL 119 (2017) 112001, see also CERN seminar by Yanxi Zhang.

- an example with 6 tracks in the final state
- there is plenty useable statistics: trigger configuration suitability depends heavily on data sample and on trigger configuration, different final-state by final-state
- ion-physics interested man-power focussing at the moment on pPb and SMOG

Measurements in pp: Double charm production involving open charm



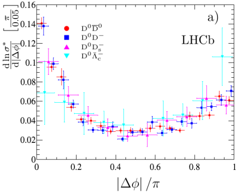
355 pb^{-1} with $2 < y_{D,J/psi} < 4$ and $3 < p_{T,D} < 12$ GeV/c $p_{T,J/\psi} < 12$ GeV/c JHEP 1206 (2012) 141.

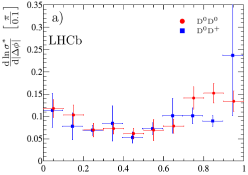
- detection of $c + c$ or $J/\psi(c\bar{c}) + c$-events sensitive to multiple parton scattering
- Q^2 small: large cross sections, also relative to single parton scattering
- early measurement with comparatively little luminosity

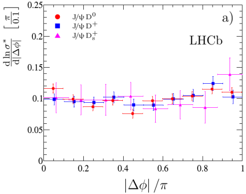
Double charm pp

Mode	σ [nb]	$\sigma_{CC}/\sigma_{C\overline{C}}$ [%]	$\sigma_{C_1}\sigma_{C_2}/\sigma_{C_1C_2}$ [mb]
D^0D^0	$690 \pm 40 \pm 70$	10.9 ± 0.8	$2 \times (42 \pm 3 \pm 4)$
$D^0\overline{D}^0$	$6230 \pm 120 \pm 630$		$2 \times (4.7 \pm 0.1 \pm 0.4)$
D^0D^+	$520 \pm 80 \pm 70$	12.8 ± 2.1	$47 \pm 7 \pm 4$
D^0D^-	$3990 \pm 90 \pm 500$		$6.0 \pm 0.2 \pm 0.5$
$D^0D_s^+$	$270 \pm 50 \pm 40$	15.7 ± 3.4	$36 \pm 8 \pm 4$
$D^0D_s^-$	$1680 \pm 110 \pm 240$		$5.6 \pm 0.5 \pm 0.6$
$D^0\bar{\Lambda}_c^-$	$2010 \pm 280 \pm 600$	—	$9 \pm 2 \pm 1$
D^+D^+	$80 \pm 10 \pm 10$	9.6 ± 1.6	$2 \times (66 \pm 11 \pm 7)$
D^+D^-	$780 \pm 40 \pm 130$		$2 \times (6.4 \pm 0.4 \pm 0.7)$
$D^+D_s^+$	$70 \pm 15 \pm 10$	12.1 ± 3.3	$59 \pm 15 \pm 6$
$D^+D_s^-$	$550 \pm 60 \pm 90$		$7 \pm 1 \pm 1$
$D^+\Lambda_c^+$	$60 \pm 30 \pm 20$	10.7 ± 5.9	$140 \pm 70 \pm 20$
$D^+\bar{\Lambda}_c^-$	$530 \pm 130 \pm 170$		$15 \pm 4 \pm 2$

Mode	$\sigma_{J/\psi C}/\sigma_{J/\psi}$ $[10^{-3}]$	$\sigma_{J/\psi C}/\sigma_C$ $[10^{-4}]$	$\sigma_{J/\psi}\sigma_C/\sigma_{J/\psi C}$ [mb]
$J/\psi D^0$	$16.2 \pm 0.4 \pm 1.3^{+3.4}_{-2.5}$	$6.7 \pm 0.2 \pm 0.5$	$14.9 \pm 0.4 \pm 1.1^{+2.3}_{-3.1}$
$J/\psi D^+$	$5.7 \pm 0.2 \pm 0.6^{+1.2}_{-0.9}$	$5.7 \pm 0.2 \pm 0.4$	$17.6 \pm 0.6 \pm 1.3^{+2.8}_{-3.7}$
$J/\psi D_s^+$	$3.1 \pm 0.3 \pm 0.4^{+0.6}_{-0.5}$	$7.8 \pm 0.8 \pm 0.6$	$12.8 \pm 1.3 \pm 1.1^{+2.0}_{-2.7}$
$J/\psi \Lambda_c^+$	$4.3 \pm 0.7 \pm 1.2^{+0.9}_{-0.7}$	$5.5 \pm 1.0 \pm 0.6$	$18.0 \pm 3.3 \pm 2.1^{+2.8}_{-3.8}$



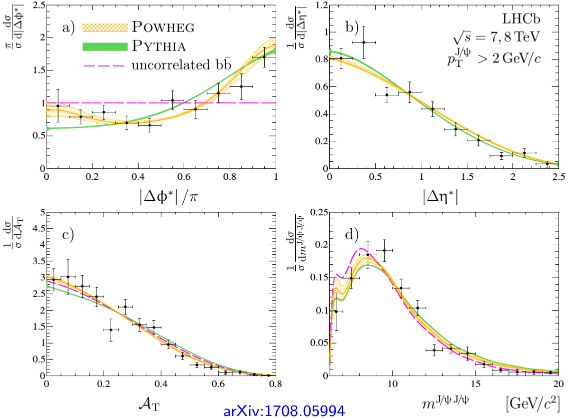




JHEP 1206 (2012) 141

- about σ_{cc} 10% of $\sigma_{c\bar{c}}$ in LHCb acceptance
- assuming only double parton scattering contribution for $J/\psi + c$: similar $\sigma_{eff} = \frac{\sigma_1 \cdot \sigma_2}{\sigma_{12}}$ as in extractions at ATLAS/CMS/CDF at higher Q^2
- production ratios & correlations: information about process contributions

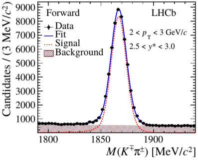
$b\bar{b}$-correlation via non-prompt J/ψ

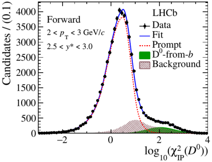


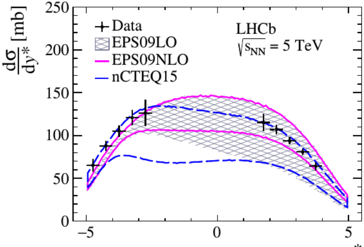
arXiv:1708.05994

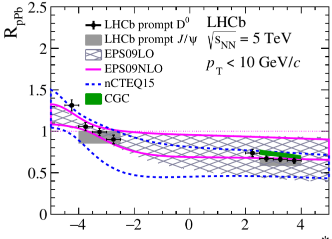
- correlation decribed by Pythia (LO) and POWHEG (NLO)
- no large contribution from gluon splitting in contrast to $c\bar{c}$ measurement by LHCb J. High Energy Phys., 06 (2012) 141: no prominent peak at $\Delta\phi = 0$
- measurement based on 3 fb^{-1} at 7 and 8 TeV: future measurements for better discrimination power

Charm measu





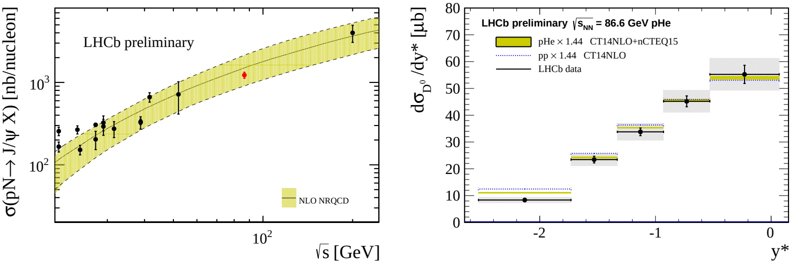




arXiv:1707.02750, accepted by JHEP, $R_{pA} = \sigma_{pA}/(A_{Pb}(=208) \cdot \sigma_{pp})$, y^* rapidity in nucleon-nucleon collision frame, $y^* = y_{lab} - (+)0.465$ for forward (backward) configuration.

- sensitive to gluons down to $x = 10^{-5}$
- consistent with CGC and nuclear PDFs, coh. e-loss to be calculated
- more precise than present nPDF uncertainty: looking forward for global fit and consistency tests with prompt and non-prompt J/ψ-data from LHCb arXiv:1706.07122, accepted by PLB
- only 5 TeV with Λ_C and D^0: about 20 times larger lumi 2016 at 8.16 TeV!

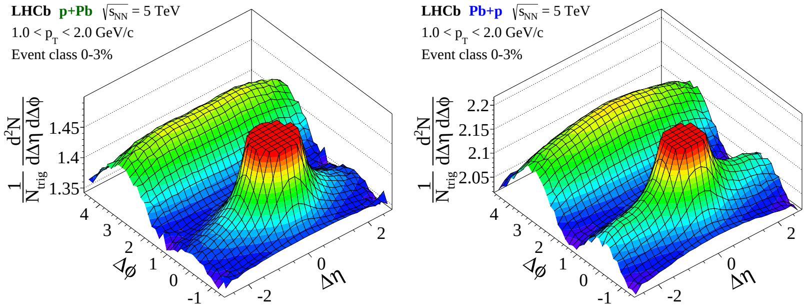
D^0 and J/ψ production in pHe fixed target



LHCb-PAPER-2018-022, in preparation.

- production meausurements in pHe and in pAr
- roughly 10 times larger pNe data set to be analysed
- starting point for future ion-ion collisions:
  open charm & charmonium down to 0 $p_{\rm T}$ at $\sqrt{s_{NN}} = 69$ GeV
- in particular in pNe differential studies as function of multiplicity could be envisaged

Non-inclusive measurements example: LHCb di-hadron correlations in pPb collisions



Phys. Lett. B 762 (2016) 473-483.

- unique forward acceptance with full tracking
- qualitative agreement with mid-rapidity findings by ALICE, ATLAS and CMS in high multiplicity events
- significant difference between lead and proton fragmentation side, when comparing same fraction of events based on multiplicity in experimental acceptance $2.0 < \eta < 4.9$
- so far measurements this and the HBT *pp* measurement only multiplicity differential results: natural since main dependence to be investigated

Current logic and line of thought

- focus is "completion" of inclusive measurements: accessible quarkonium states also apart from vector states, b-hadrons and c-hadrons including baryons, $c + \bar{c}$-correlations, photons, Drell-Yan, charged particles $\rightarrow$ clear observable definition, unique acceptance and often unique performance
- second step: define observables that make use of heavy-flavour and charged tracks in same acceptance: multiplicity dependence of yields, production characteristics, isolation variables

Conclusions

- soft-hard correlations in core of QGP physics even implicitly in inclusive measurements
  $\rightarrow$ intrinsic motivation from QGP physics side to understand all ingredients, otherwise: quantitative QCD matter property extraction remains very difficult $\rightarrow$ need to develop a dialogue to find ways how to falsify and converge on a common precise picture for all description ingredients that are testable
- LHCb has a large potential, in particular in heavy-flavour sector in pp (largest yields recorded by any experiment, scanning full delivered luminosity at low pile-up), pPb, Pbp (unique combination of full recorded luminosity and low-p_T and precision) and SMOG (unique)
- these measurements should be done:
  if we as field are interested pushing the understanding the basics with precision
- these measurements will not grow on trees