Soft and hard QCD processes in LHCb

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Bad Honnef, 29.09.2017
1. LHCb: detector capabilities
2. Spectroscopy: new (un)conventional bound states of QCD
3. The partons in the proton and ions: insights at low and high $x$
4. Tests of factorisation and effective field theory
5. Soft and collective particle production: precise measurements and (un)expected features
6. Outlook and Conclusions
LHCb designed as heavy-flavour precision experiment

- collect large number of B-hadrons in small angular acceptance: about 27% of b-quarks within acceptance in pp collisions

Example: first observation of rare $B_S \rightarrow \mu^+ \mu^-$ decay together with CMS Nature 522 (2015) 68, most precise single experiment measurement of the $\gamma$ angle in the CKM matrix JHEP 12 (2016) 087
LHCb Tracking

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

- **VELO**: silicon strip telescope down to radial distance to beam $r = 0.8 \text{ cm}$
- **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

$\begin{align*}
\text{LHCb} \\
\text{IP, resolution [\mu m]} \\
\text{2012 data} & \quad \text{Simulation} \\
0 & \quad 100 \\
1 & \quad 90 \\
2 & \quad 80 \\
3 & \quad 70 \\
4 & \quad 60 \\
5 & \quad 50 \\
6 & \quad 40 \\
7 & \quad 30 \\
8 & \quad 20 \\
9 & \quad 10 \\
10 & \quad 0 \\
\end{align*}$

$\begin{align*}
\text{LHCb} \\
\text{\delta p/p [\%]} \\
0.3 & \quad 0.4 \\
0.5 & \quad 0.6 \\
0.7 & \quad 0.8 \\
0.9 & \quad 1.0 \\
1.1 & \quad 1.2 \\
\end{align*}$

$\begin{align*}
\text{LHCb} \\
\text{1/p_T [GeV^{-1}c]} \\
0 & \quad 0.5 \\
1 & \quad 1.5 \\
2 & \quad 2.5 \\
3 & \quad 3 \\
\end{align*}$

$\begin{align*}
\text{p [GeV/c]} \\
100 & \quad 200 \\
300 & \quad 400 \\
500 & \quad 600 \\
600 & \quad 700 \\
\end{align*}$
2 RICH systems with 2 radiators for charged track PID

- muon-ID behind calorimetry: $\varepsilon_{\mu \rightarrow \mu} \approx 97\%$ for $\varepsilon_{\pi \rightarrow \mu} \approx 1-3\%$ Mis-ID
- photon measurement & electron/photon-ID with calorimetry and preshower
  $\Delta m(\mu^+ \mu^-, \mu^+ \mu^- \gamma)$-resolution: $5 \text{ MeV}/c^2$ from $\chi_{c1,2} \rightarrow J/\psi + \gamma$-decay with calorimeter
Collision systems and running conditions in collider mode

- Luminosity levelling with $\approx 1$ visible collisions per beam-beam encounter every 25 ns in $pp$: $L \approx 4 \times 10^{32}$ cm$^{-2}$ s$^{-1}$
- $6fb^{-1}$ 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  
  \[ J. \text{Instrum.} \ 9 \ (2014) \ P12005 \]
- 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
- \( p\text{He}, \ p\text{Ar}, \ p\text{Ne}, \ Pb\text{Ne} \) and \( Pb\text{Ar} \) data samples available
- \( p\text{Ar} \) and \( p\text{He} \) \( O(\text{nb}^{-1}) \) integrated luminosities
LHCb trigger system, data acquisition and calibration

- Offline quality at the software trigger level since 2015
- Analysis directly with trigger reconstruction output
- Used for e.g. charm cross section measurement at 13 TeV [JHEP 10 (2015) 172, JHEP 03 (2016) 159]
- \( pPb/Pbp \) conditions: able to process all events in HLT
- \( PbPb \) conditions: recorded all events on tape; tracking up to \( \approx 50 \% \) centrality
- \( p-Ar,p-He \) fixed target: able to process all events in HLT
Why QCD studies with LHCb?

- largest recorded $c, b$-hadron yields – hard quark mass scale as opportunity for QCD studies:
  - effective field theory for bound state properties
  - test diagrammatic approaches & factorisation schemes as low as possible in $Q^2$
- forward acceptance at the LHC: unique kinematics in $Q^2 - x$-plane
- the only fixed-target programme at the LHC: unique kinematics

Left: LHCb-CONF-2016-005.
Why QCD studies with LHCb?

- highest software trigger rate at the LHC: flexible high-rate selections down to low $p_T$
- only detector at the LHC with charged hadron-id, muon-id and calorimeters in same acceptance
- about 1 collision per bunch crossing in $pp$: clean events also for low-$Q^2$ & possibility of exclusive production studies
- "overdesigned" trigger for heavy-ion beam rates

Not possible to cover all QCD@LHCb results: examples to illustrate the different possibilities.
Spectroscopy: looking for (un)conventional bound states and their properties
Search for double charm baryons

- A $J^P = \frac{1}{2}^+$ and a $J^P = \frac{3}{2}^+$ flavour SU(3)-triplet with two charm quarks: $\Xi^+_cc(ccd), \Xi^+_cc(ccu), \Omega^+_cc(ccs)$
- $\frac{1}{2}^+$-states weakly decaying
A new conventional state: $\Xi_{cc}^{++}$

$\Xi_{cc}^{++} \rightarrow K^- \pi^+ \pi^+ \Lambda_c^+ (\rightarrow pK^- \pi^+)$

- rare process with 6 tracks in final state
- first unambiguous discovery of a double charm baryon
- signal yield: 313 ± 13
- resolution 6.6 ±0.8 MeV/$c^2$
- local significance $> 14\sigma$
- it is a weak decay: signal remains prominent with cut $t/\sigma_t > 5$

PRL 119 (2017) 112001, see also CERN seminar by Yanxi Zhang.
Unconventional bound states of QCD

- $q\bar{q}$ mesons and $qqq$ baryons in accordance with quark-model keep being discovered
- no reason not having exotic strongly interacting bound states
- pentaquark ($qqq\bar{q}q$) often discovered and always refuted until 2015
- Interesting features in $\Lambda_b \to J/\psi Kp$: need full partial-wave analysis to dissect

Spectroscopy: Pentaquark discovery

- Partial wave analysis with 14 considered $\Lambda^*$ resonances with 4 angles and the $pK$-mass
- Pattern not explainable without additional structure in $J/\psi p$ system
- 2 Breit-Wigners with statistical significances of 8 and 12, best fit with $J^P (3/2^-, 5/2^-)$, acceptable also $(3/2^+, 5/2^+) (5/2^+, 3/2^-)$
The partons inside hadrons

- **H1 and ZEUS at HERA**: high-precision benchmark of perturbative DGLAP evolution in deep inelastic scattering
- **LHCb at LHC**: unique opportunity to dive deep at low-\(x\) checking the limits and at high-\(x\) looking for "exotic" compounds
- "Counting more than one": multi-parton scattering at moderate/low-\(Q^2\) with charm and beauty → towards more exclusive observables and their understanding
$W$ and $Z$ measurements in $pp$ collisions

- precision measurement with uncoloured final state with high mass scale down to $x = 10^{-4}$ and up to high $x$ in $pp$ collisions
- constraining parton distribution functions including flavour separation via $W$ in phase space not accessible to other experiments

JHEP 01 (2016) 155.
$W$ and $Z$ measurements in $pp$ collisions

Left: JHEP 01 (2016) 155; right: taken from arXiv:1795.04468; new measurements at 13 TeV with both $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$ JHEP 09 (2016) 136 also available, see back-up.

- precision measurement with impact
- relevant for high-mass object production

QCD physics school  Michael Winn, LHCb Collaboration
Charm production in pPb collisions: limits of collinear factorisation


- **no HERA equivalent for lepton-nuclei**: parton flux **unconstrained** for LHC heavy-ion low-\(p_T\) heavy-quark production. Total charm, beauty production in \(p\)-nucleus vital input for AA.

- **saturation** scale \(Q_s^2 \propto A_{\text{nucleus}}^{1/3}\) → linear parton evolution break-down?

- Which framework if collinear factorisation no longer valid? color glass condensate Ann.Rev.Nucl.Part.Sci. 60?

- Are there further effects like energy loss by enhanced small-angle gluon radiation JHEP 1303 (2013) 122?
D⁰ in pPb

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 \( x = 10^{-6} \)
- consistency between Color Glass Condensate and nuclear PDF predictions: to be investigated
- more precise than present nPDF-based calculations: looking forward for global fit and consistency tests with prompt and non-prompt J/ψ-data from LHCb arXiv:1706.07122, accepted by PLB
Charm production in fixed-target collisions: unique constraints

- sensitive to nuclear modification of parton distribution function & intrinsic charm
Charm production in fixed target collisions: first results

- normalised distributions compared with *pythia* 8 with CT09MCS and with parameterisation of world-data by Arleo et al. for charmonium
- final analysis together with p-He result soon
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 \cite{JHEP1206141}.

- 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
Double charm production involving open charm

- about $\sigma_{cc}$ 10% of $\sigma_{c\bar{c}}$ in LHCb acceptance
- assuming only double parton scattering contribution for $J/\psi + c$: similar $\sigma_{eff} = \sigma_1 \cdot \sigma_2 / \sigma_{12}$ as in extractions at ATLAS/CMS/CDF at higher $Q^2$
- production ratios & correlations: information about process contributions
- $b\bar{b}$-correlation analysis using B-hadrons decaying to $J/\psi$ addressing beauty production: arXiv:1708.05994
Factorisation and effective field theory in quarkonium production

- hadro-quarkonium production endeavour started '93:
  1st silicon vertex detector at hadron collider → unexpected large prompt production of $J/\psi/\psi(2S)$
- non-relativistic QCD (NRQCD) applied: effective field theory separating the production scale with the scale of the quarkonium structure, long-distance elements universal
- NLO NRQCD & "NNLO*" Color Singlet Model today ≈ ok for $\psi/\Upsilon$ production rates: but complete picture of all observables not fully understood within one framework
- LHCb: see for example talk by Andrii about unique $\eta_c$-measurements, unique measurement of $J/\psi$ in Jets Phys. Rev. Lett. 118, 192001, details in back-up
Tests of factorisation approaches: $\Upsilon$-polarisation in $pp$ collisions

- precision measurement of $\Upsilon$ polarisation down to 0 $p_T$
- valuable input for tests of NRQCD and Color-Singlet Model
- important measurement also to eliminate dominating uncertainty of rate measurements

Left: signal peaks from arXiv:1709.01301; Right: from Pietro Faccioli 2010 CERN seminar
**Γ-polarisation in pp collisions**

- measurement in complementary phase space compared to previous measurements
- in 3 different reference frames
- only statistically limited & different frames consistent w.r.t. each other
- agreement with CMS results at midrapidity
- another input to progress in the understanding of quarkonium hadroproduction

Comparison with results obtained by the CDF and CMS collaborations are shown in Figs. ... visibility. The error bars indicate the sum of the statistical and systematic uncertainties added in quadrature.

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QCD physics school  Michael Winn, LHCb Collaboration
Break-down of factorisation in nuclear collisions

5 TeV: JHEP 02 (2014) 072, JHEP 1603 (2016) 133; 8.16 TeV arxiv:1706.07122, accepted by PLB.

- $J/\psi$ result compatible with nuclear PDFs, coherent energy loss model, recent Color Glass Condensate calculations
- additional suppression for $\psi(2S)$ not explained by nuclear PDFs nor by coherent energy loss
- calculation from gluon-kicks estimated with Color Glass Condensate approach and Colour Evaporation model can explain the data arXiv:1707.07299
Soft and collective particle production

forward spectrometer geometry allows low $p_T$ measurements at moderate track momenta

in fixed-target mode: production studies close to midrapidity well suited for cosmic-ray physics references

Left kinematic bins of $\bar{p}$-cross section measurement in $p$He

LHCb-CONF-2017-002
\( \bar{p} \)-production in \( pHe \) collisions

![Graph showing \( \frac{d\sigma(\bar{p}X)}{dp_T} \) vs. \( p_T \)]

- **Statistical:**
  - Yields in data and PID calibration: 0.7 – 10.8% (< 3% for most bins)
  - Normalization: 2.5%
- **Correlated Systematic:**
  - Normalization: 6.0%
  - Event and PV requirements: 0.3%
  - PV reco: 0.8%
  - Tracking: 2.2%
  - Nonprompt background: 0.3 – 0.7%
  - Residual vacuum background: 0.1%
- **Uncorrelated Systematic:**
  - Tracking: 3.2%
  - IP cut efficiency: 1.0%
  - PID: 2.0 – 28% (< 10% for most bins)
  - Simulated sample size: 0.8 – 15% (< 4% for \( p_T < 2 \text{ GeV/c} \))

- LHCb-CONF-2017-002, EPOS in solid lines.
- Precise measurement demonstrates the feasibility of primary particle spectra measurements in fixed-target events
- Luminosity determined via elastic e-proton scattering
- EPOS-LHC underestimates the cross sections by about 50%
- Starting point for comparative studies for other particle species and collision systems: crucial input for MC-modelling with relevance for heavy-ion and cosmic-ray physics
$p$-nucleus/$pp$ high multiplicity events: interesting questions


▶ correlations & bulk production@low-$p_T$ & large multiplicity: 
'same' patterns as in PbPb, where sign for locally thermalised system

▶ hydro in large multiplicity $p$Pb: set-up as in PbPb describing data 

despite precondition doubts arXiv:1705.03177

▶ color class condensate & color reconnections explanations not ruled out 


▶ recently explanation via interference of multi-parton scatterings

arXiv:1708.08241
LHCb di-hadron correlations in \( pPb \) collisions

\[ \text{LHCb } p+Pb \quad \sqrt{s_{NN}} = 5 \text{ TeV} \]

- \( 1.0 < p_T < 2.0 \text{ GeV/c} \)
- Event class 0-3%

\[ \text{LHCb } Pb+p \quad \sqrt{s_{NN}} = 5 \text{ TeV} \]

- \( 1.0 < p_T < 2.0 \text{ GeV/c} \)
- Event class 0-3%

- 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 \( 2.0 < \eta < 4.9 \)

LHCb di-hadron correlations in $pPb$ collisions

- increase of near-side correlation towards larger multiplicities and lower $p_T$ after pedestal subtraction
- results at forward and backward rapidity at same estimated absolute multiplicity in acceptance: similar results of correlation strength after pedestal subtraction
- looking forward to phenomenological models: kinematics should be favourable for better control in CGC calculations

Bose-Einstein correlations: probing the particle emission source

\[ Q = \sqrt{-(q_1 - q_2)^2} \]: information on coordinate space via Fourier transformation

- correlating particles with 4-momenta \( q_1, q_2 \) with small
- for same-charged pions: interference following Bose-Einstein-statistics used to extract particle emission source information

- method first developed for photons in astrophysics, well established in heavy-ion physics

- complementary to large scale \( \phi, \eta \)-correlations

- first measurement by LHCb in \( pp \): starting point for measurements at forward rapidity

- increase of source size and decrease of correlation strength as function of charged particle multiplicity: qualitatively in agreement with ALICE/ATLAS/CMS at midrapidity

\text{arXiv:1709.01769, } R: \text{ source size parameter from an exponential fit; } \lambda: \text{ chaoticity/correlation strength parameter.}
The LHCb upgrade

- LHCb detector upgrade in 2019/2020
- run at $L_{\text{inst}} = 2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$: on average 5.2 visible pp collisions per bunch crossing
- process full pp input rate in HLT without hardware trigger
- tracker fully replaced: increased granularity
- silicon vertex locator from strip to pixel detector
Conclusions

- LHCb: fully instrumented spectrometer with unique kinematics with flexible trigger system in collider and fixed-target mode
- important QCD results in several areas:
  - conventional and unconventional QCD bound states and their properties
  - unique constraints on parton densities at large $x$ and low $x$ in the proton and nuclei
  - tests of effective field theory and factorisation
  - soft & correlation studies in unique phase-space
- ambitious upgrade programme for higher luminosity and processing of all events in software trigger
Central exclusive production with LHCb: J/ψ and ψ(2S) production at \( \sqrt{s} = 7 \text{ TeV} \)

- average collision numbers of about 1: central exclusive studies with high statistics
- vector meson production via \( \gamma-p \)
- forward acceptance: low-\( x \) leverage
- purity improvements: Herschel scintillators since 2015

Double $J/\psi$ production in central exclusive events at $\sqrt{s} = 7$ and 8 TeV

- first observation of this experimental signature from both energies
- veto of tracks in $\eta \in (-3.5,-1.5)$ and $\eta \in (1.5,5.0)$
- cross section for exclusive double $J/\psi$ production:
  $58 \pm 10\,(\text{stat}) \pm 6\,(\text{syst})$ pb within $2.0 < y < 4.5$
- cross section for exclusive $J/\psi-\psi(2S)$ production:
  $63^{+27}_{-18}\,(\text{stat}) \pm 10\,(\text{syst})$ pb within $y < 2.0 < 4.5$
- upper limits on double $\psi(2S)$ and double $\chi_c$-production
first observation of muonic dalitz decay
\[ \chi_{c1,c2} \rightarrow J/\psi (\rightarrow \mu^+ \mu^-) \gamma^* (\rightarrow \mu^+ \mu^-) \]
→ demanding pure \( \mu^-\) -PID down to \( p = 3 \text{ GeV}/c \)

among the most precise single experiment determinations of \( \chi_{c2} \)-width and masses with different systematic uncertainties

past experiments beam energy scans with \( p\bar{p} \)

starting point for more studies with this precision resolution channel