Soft and hard QCD processes in LHCb

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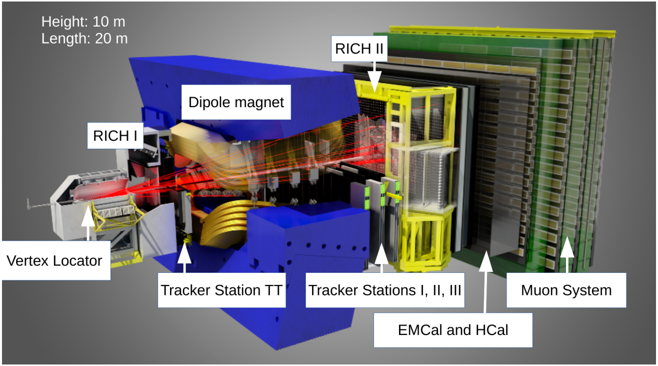
Bad Honnef, 29.09.2017

Outline

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

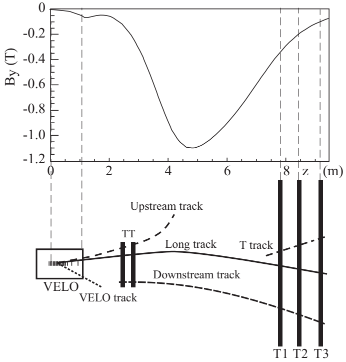


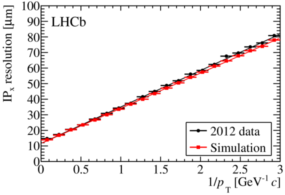
JINST 3 (2008) S08005.

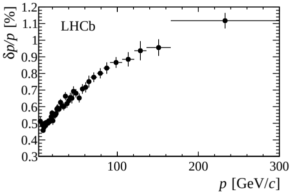
- collect large number of B-hadrons in small angular acceptance: about 27% of b-quarks within acceptance in pp collisions

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

LHCb Tracking



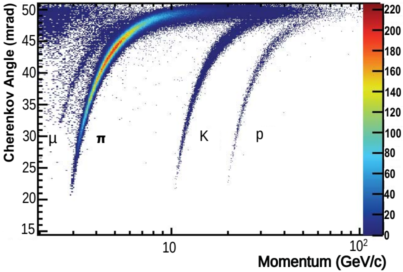


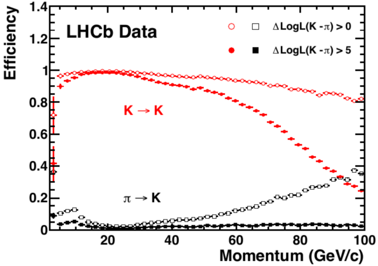


Int. J. Mod. Phys. A 30 1530022.

- VELO: silicon strip telescope down to radial distance to beam $r = 0.8$ 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

LHCb particle identification

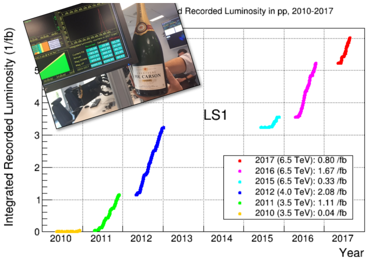


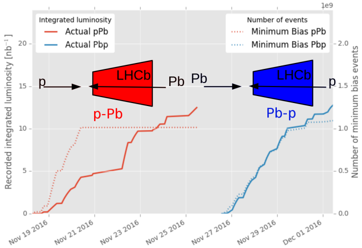


JINST 3 (2008) S08005

- 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

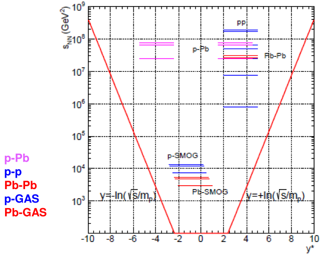
Collision systems and running conditions in collider mode

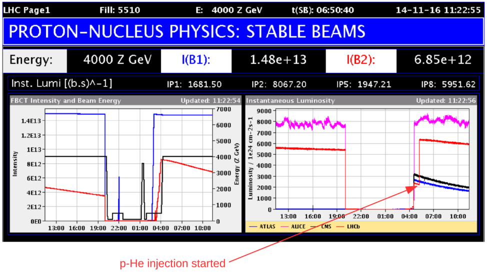




- luminosity levelling with ≈ 1 visible collisions per beam-beam encounter every 25 ns in pp: $L \approx 4 \times 10^{32}$ cm^{-2} s^{-1}
- $6 fb^{-1}$ from 2010-now at $\sqrt{s}$ =0.9,2.76,5,**7,8,13** TeV
- pPb/Pbp 2016: running at $\lesssim$ 200 kHz interaction rate with $\lesssim$ 0.1 visible collisions 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

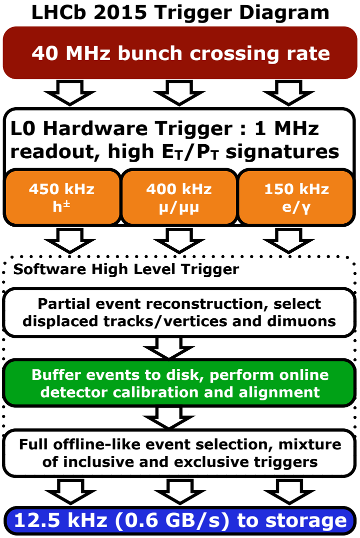
Collision systems and running conditions in fixed-target collisions





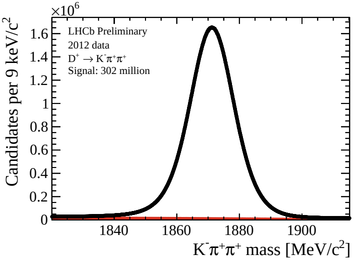
- noble gas injected in interaction region:
  improve luminosity measurement by beam imaging J. Instrum. 9 (2014) P12005
- residual gas pressure in beam pipe increased by 2 orders of magnitude: $O(10^{-7})$ mbar
- used for fixed target with proton and Pb beams: LHCb $\approx$ midrapidity rapidity coverage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

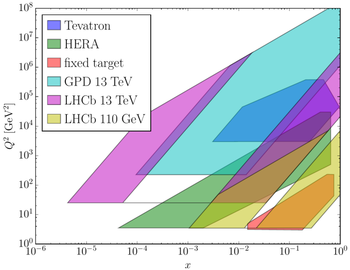
LHCb trigger system, data acquisition and calibration



- 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?

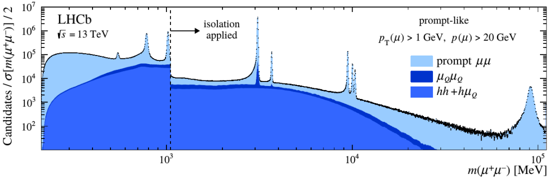


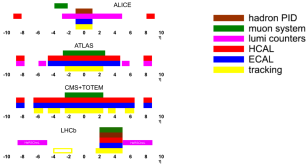


Left: LHCb-CONF-2016-005.

- 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

Why QCD studies with LHCb?



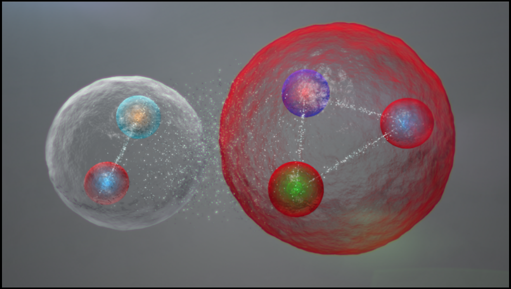


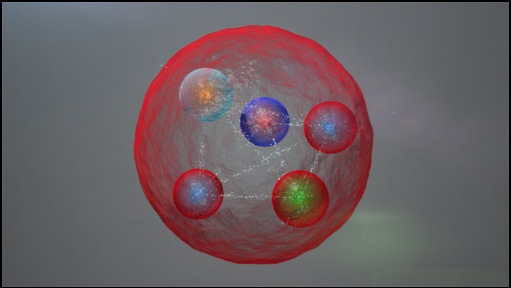
dimuon mass spectrum for dark photon search trigger line with 1.6fb^{-1}(2016 statistics, arXiv:1709.XXX).

- 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

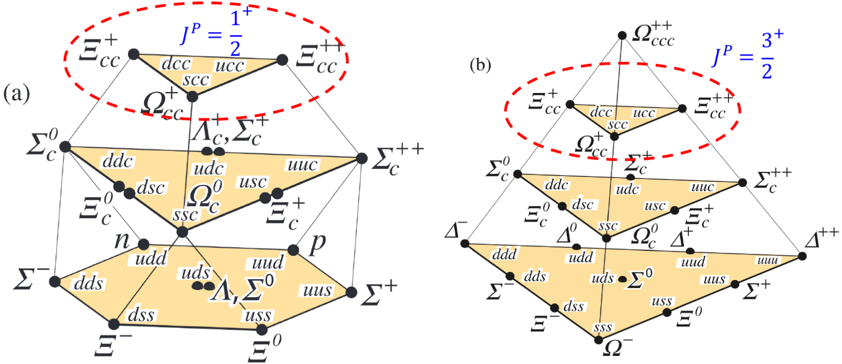
Not possible to cover all QCD@LHCb results:
$\rightarrow$ *examples to illustrate the different possibilities.*

Spectroscopy: looking for (un)conventional bound states and their properties



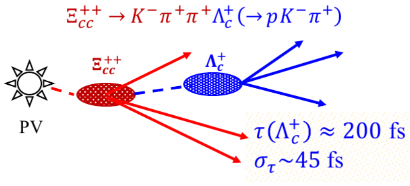


Search for double charm baryons

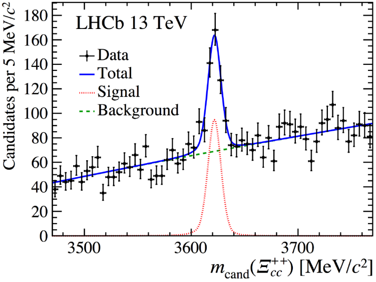


- A $J^P \frac{1}{2}^+$ and a $J^P = \frac{3}{2}$ flavour SU(3)-triplet with two charm quarks: $\Xi_{cc}^+(ccd), \Xi_{cc}^+(ccu), \Omega_{cc}^+(ccs)$
- $\frac{1}{2}^+$-states weakly decaying

A new conventional state: Ξ_{cc}^{++}



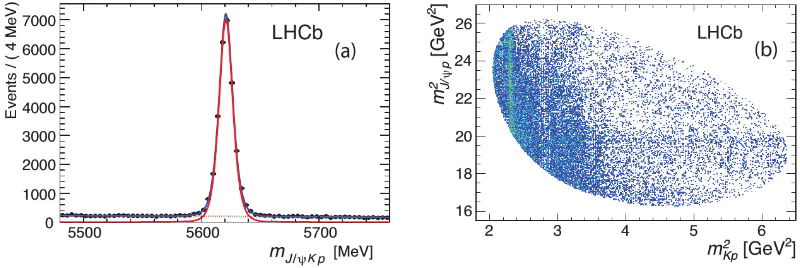
60 M fully reconstructed
$\Lambda_c^+ \to pK^-\pi^+$ signal decays



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

- 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 $t/\sigma_t > 5$

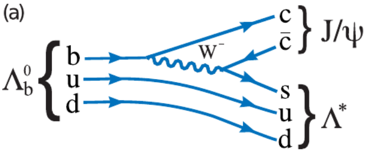
Unconventional bound states of QCD

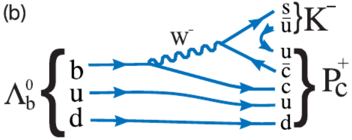


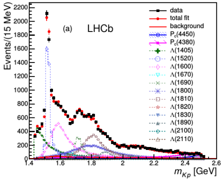
Phys. Rev. Lett. 115, 072001 (2015)

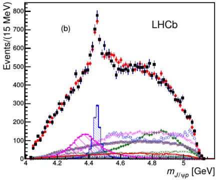
- $q\bar{q}$ mesons and qqq baryons in accordance with quark-model keep being discovered
- no reason not having exotic strongly interacting bound states
- pentaquark ($qqq\bar{q}q$) often discovered and always refuted until 2015
- Interesting features in $\Lambda_b \to J/\psi Kp$: need full partial-wave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

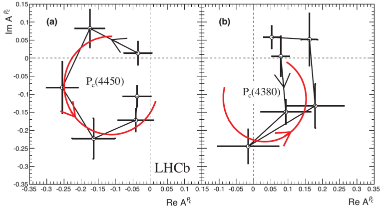
Spectroscopy: Pentaquark discovery







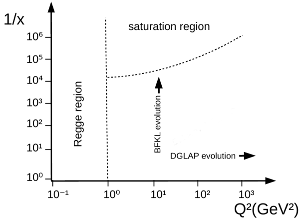


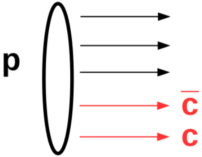


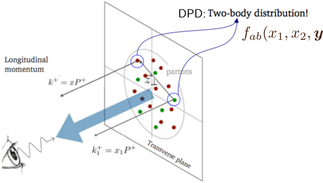
Phys. Rev. Lett. 115, 072001 (2015)

- partial wave analysis with 14 considered Λ^* resonances with 4 angles and the pK-mass
- pattern not explanable 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 $(3/2^+, 5/2^-)$ $(5/2^+,3/2^-)$
- confirmed with model-indepedent analysis Phys. Rev. Lett. 117, 082002 (2016), evidence seen in Cabibbo-surpressed analogue decay $\Lambda_b \to J/\psi \pi p$ Phys. Rev. Lett. 117, 082003 (2016)

The partons inside hadrons



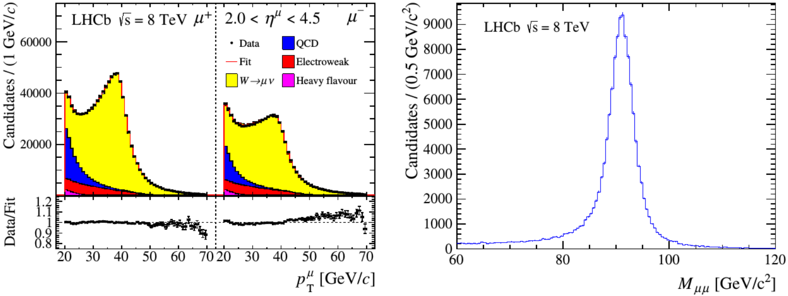




left: adapted from R. Ellis, W. Stirling, and B. Webber. QCD and collider physics. Camb. Monogr. Part. Phys. Nucl. Phys. Cosmol., 8:1–435, 1996; right: from Matteo Rinaldi@MPI 2015

- 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 $\rightarrow$ towards more exclusive observables and their understanding

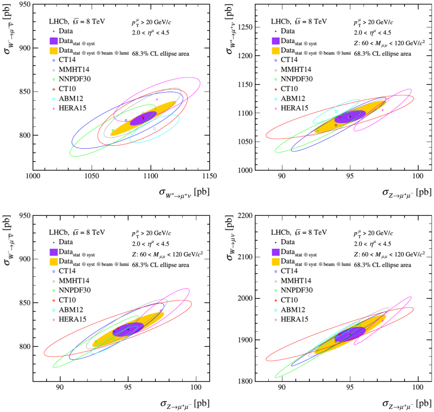
W and Z measurements in pp collisions

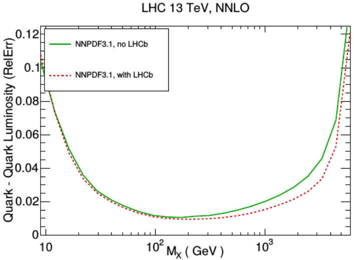


JHEP 01 (2016) 155.

- precision meausurement 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

W and Z measurements in pp collisions

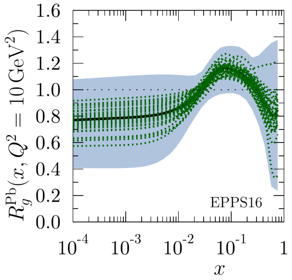


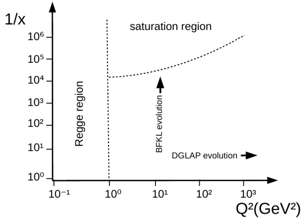


Left: JHEP 01 (2016) 155; right: taken from arXiv:1795.04468; new measurements at 13 TeV with both $Z \to e^+e^-$ and $Z \to \mu^+\mu^-$ JHEP 09 (2016) 136 also available, see back-up.

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

Charm production in p*Pb* collisions: limits of collinear factorisation



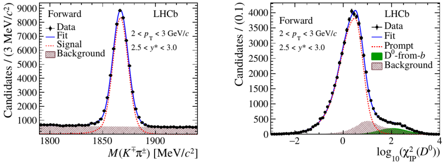


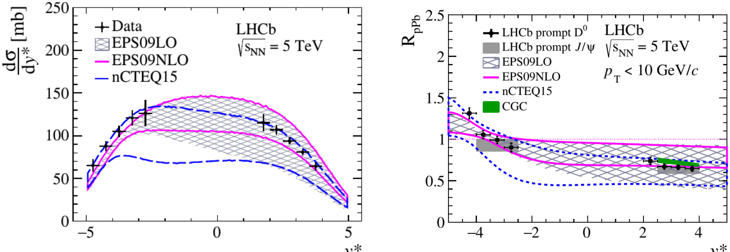
Right: modified version of graphic in "QCD and collider physics", Ellis, Stirling, Webber; Left: Eur.Phys.J. C77 (2017) no.3, 163.

- **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 $Q_s^2 \propto A_{nucleus}^{1/3} \rightarrow$ 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 ?

D^0 in pPb

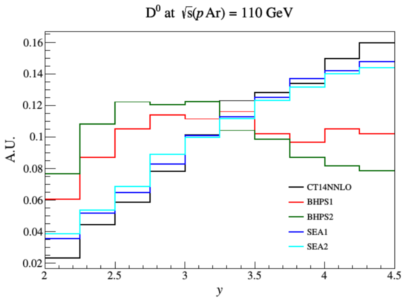


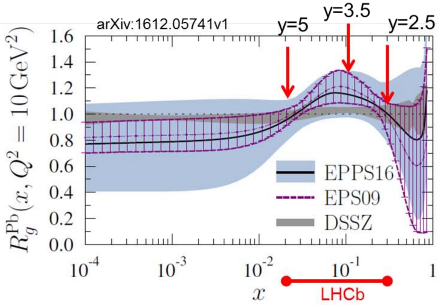


arXiv:1707.02750, accepted by JHEP, $R_{pA} = \sigma_{pA}/(A_{Pb}(= 208) \cdot \sigma_{pp})$, y^* rapidity in nucleon-nucleon collision frame, $y^* = y_{lab} - (+)0.465$ for forward (backward) configuration.

- 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



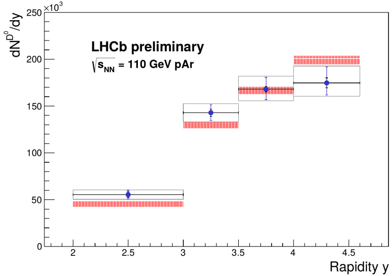


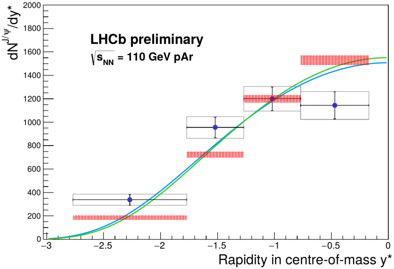
Left: Figure by Philip Ilten link, considered pdfs models based on CT14 from: Phys. Rev. D 93, 074008, Right: Figure from talk by Emilie Maurice at QM 2017

- sensitive to nuclear modification of parton distribution function & intrinsic charm

Charm production in fixed target collisions: first results

Rapidity in cms: $y^* = y - 4.77$

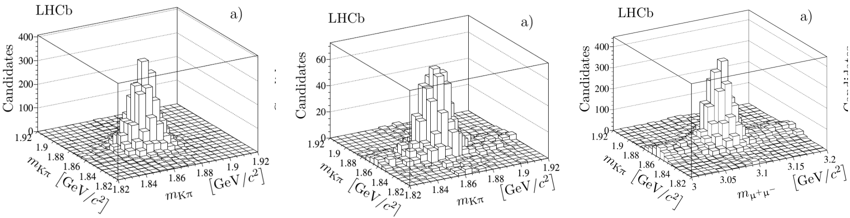




LHCb-CONF-2017-001

- 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



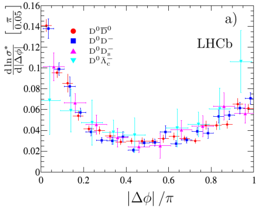
355 pb^{-1} with $2 < y_{D,J/psi} < 4$ and $3 < p_{T,D} < 12$ GeV/c $p_{T,J/\psi} < 12$ GeV/c JHEP 1206 (2012) 141.

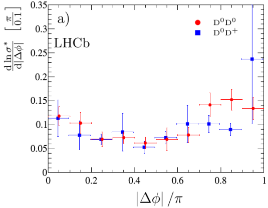
- detection of $c + c$ or $J/\psi(c\bar{c}) + c$-events sensitive to multiple parton scattering
- Q^2 small: large cross sections, also relative to single parton scattering

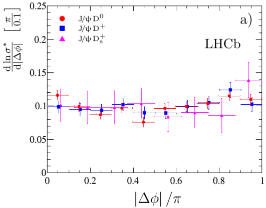
Double charm production involving open charm

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



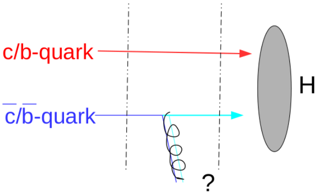




JHEP 1206 (2012) 141

- 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 analysis using B-hadrons decaying to J/ψ addressing beauty production: arXiv:1708.05994

Factorisation and effective field theory in quarkonium production



Measurement of the $\eta_c(1S)$ production cross-section in proton-proton collisions via the decay $\eta_c(1S) \rightarrow p\overline{p}$

by LHCb and the theory rebound:

η_c production at the LHC challenges nonrelativistic-QCD factorization

Mathias Butenschoen, Zhi-Guo He, Bernd A. Kniehl (Hamburg U., Inst. Theor. Phys. II)

Nov 19, 2014 - 5 pages

Phys.Rev.Lett. 114 (2015) no.9, 092004
(2015-03-06)
DOI: 10.1103/PhysRevLett.114.092004
DESY-14-219
e-Print: arXiv:1411.5287 [hep-ph] | PDF

η_c production at LHC and indications on the understanding of J/ψ production

Hao Han (Peking U. & Peking U., SKLNPT) , Yan-Qing Ma (Maryland U. & Peking U., CHEP) , Ce Meng (Peking U. & Peking U., SKLNPT) , Hua-Sheng Shao (CERN & Peking U. & Peking U., SKLNPT) , Kuang-Ta Chao (Unlisted, CN & Peking U., CHEP & Peking U., SKLNPT)

Nov 26, 2014 - 5 pages

Phys.Rev.Lett. 114 (2015) no.9, 092005
(2015-03-06)
DOI: 10.1103/PhysRevLett.114.092005
e-Print: arXiv:1411.7350 [hep-ph] | PDF

Impact of η_c hadroproduction data on charmonium production and polarization within NRQCD framework

Hong-Fei Zhang (Third Military Med. U., Chongqing) , Zhan Sun (Chongqing U.) , Wen-Long Sang (SWU, Chongqing & Beijing, Inst. Theor. Phys.) , Rong Li (Xian Jiaotong U.)

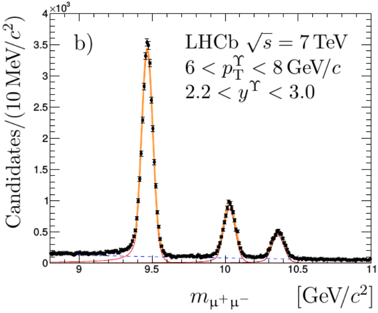
Dec 1, 2014 - 5 pages

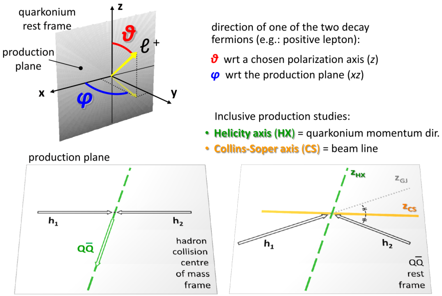
Phys.Rev.Lett. 114 (2015) no.9, 092006
(2015-03-06)
DOI: 10.1103/PhysRevLett.114.092006
e-Print: arXiv:1412.0508 [hep-ph] | PDF

Right: title of Eur.Phys.J. C75 (2015) no.7, 311 and theory reactions.

- hadro-quarkonium production endeavour started ’93: 1st silicon vertex detector at hadron collider $\rightarrow$ 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 $\approx$ ok for ψ/Υ production rates: **but** complete picture of all observables **not fully understood** within one framework
- LHCb: see for example talk by Andrii about unique η_c-measurements, unique measurement of J/ψ in Jets Phys. Rev. Lett. 118, 192001, details in back-up

Tests of factorisation approaches: Υ-polarisation in *pp* collisions

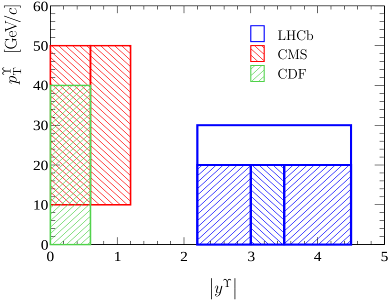


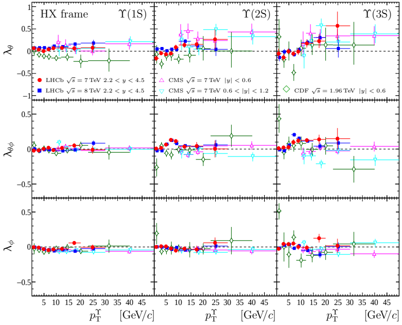


Left: signal peaks from arXiv:1709.01301; Right: from Pietro Faccioli 2010 CERN seminar

- precision measurement of Υ 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

ϒ-polarisation in pp collisions

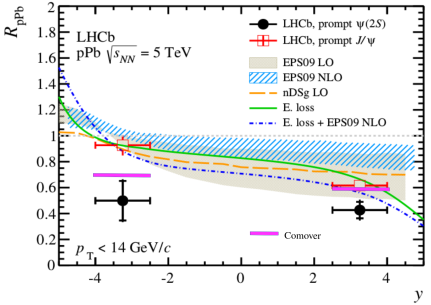


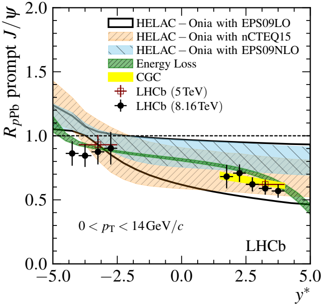


acceptance and example comparison for helicity frame from arXiv:1709.01301

- 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

Break-down of factorisation in nuclear collisions

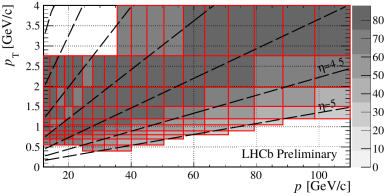


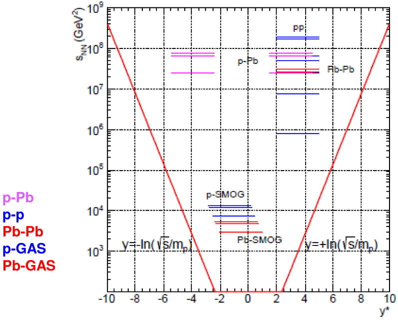


5 TeV: JHEP 02 (2014) 072, JHEP 1603 (2016) 133; 8.16 TeV arxiv:1706.07122, accepted by PLB.

- J/ψ result compatible with nuclear PDFs, coherent energy loss model, recent Color Glass Condensate calculations
- additional suppression for ψ(2S) not explained by nuclear PDFs nor by coherent energy loss
- 'comover' model with no precisely specified secondary interaction Phys.Lett. B749 (2015) 98-103: additional suppression also with Hadron Resonance Gas + QGP ansatz by Du & Rapp Nucl.Phys. A 943 (2015)
- 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

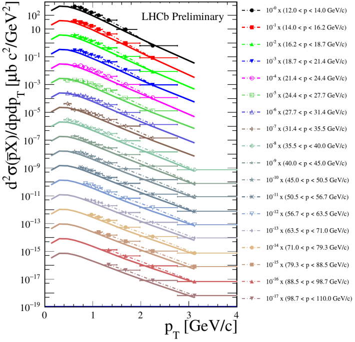




Left kinematic bins of $\bar{p}$-cross section measurement in pHe LHCb-CONF-2017-002

- 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

$\bar{p}$-production in pHe collisions

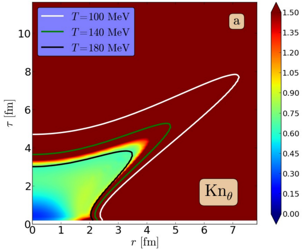


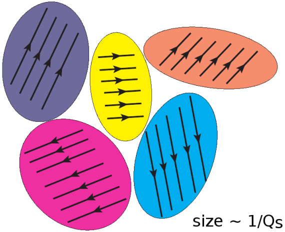
Statistical:	
Yields in data and PID calibration	0.7 – 10.8% (< 3% for most bins)
Normalization	2.5%
Correlated Systematic:	
Normalization	6.0%
Event and PV requirements	0.3%
PV reco	0.8%
Tracking	2.2%
Nonprompt background	0.3 – 0.7%
Residual vacuum background	0.1%
Uncorrelated Systematic:	
Tracking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

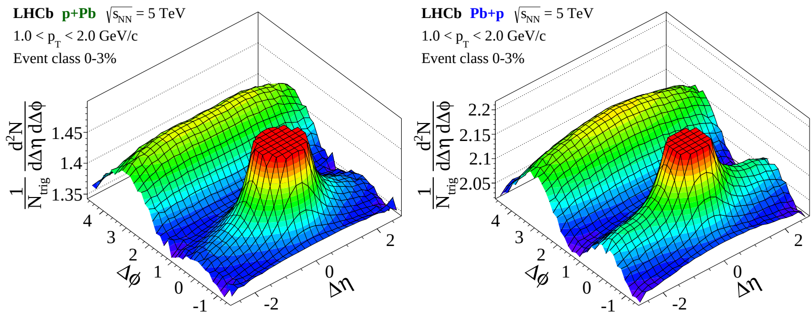




Left: taken from arXiv:1404.7327 $Kn = L_{micro}/L_{macro}$, already dN/dη=270! Right: taken from arXiv:1611.00329.

- correlations & bulk production@low-p_T & large multiplicity: **'same' patterns as in PbPb**, where sign for locally thermalised system
- **hydro** in large multiplicity pPb: set-up as in PbPb **describing data** despite **precondition doubts** arXiv:1705.03177
- color class condensate & color reconnections explanations not ruled out arXiv:1607.02496, arXiv:1705.00745
- recently explanation via interference of multi-parton scatterings arXiv:1708.08241

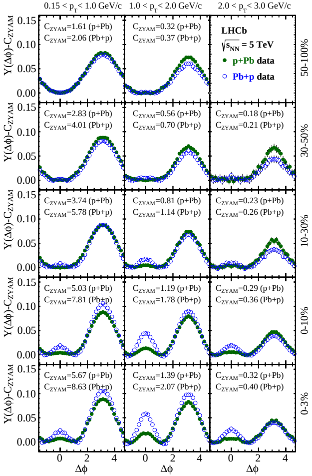
LHCb di-hadron correlations in *p*Pb collisions

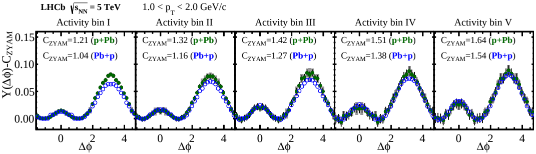


Phys. Lett. B 762 (2016) 473-483.

- 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 $2.0 < \eta < 4.9$

LHCb di-hadron correlations in pPb collisions

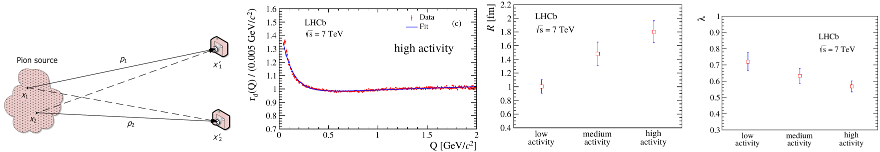




Phys. Lett. B 762 (2016) 473-483.

- 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

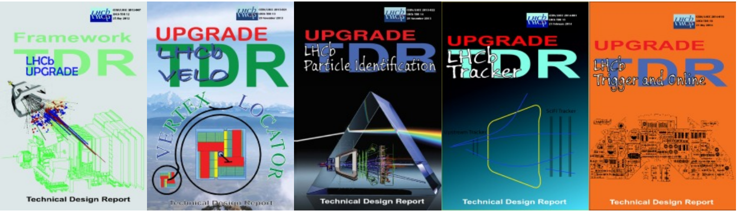
Bose-Einstein correlations: probing the particle emission source



arXiv:1709.01769, R: source size parameter from an exponential fit; λ chaoticity/correlation strength parameter.

- correlating particles with 4-momenta q_1, q_2 with small $Q = \sqrt{-(q_1 - q_2)^2}$: information on coordinate space via Fourier transformation
  $\rightarrow$ for same-charged pions: interference following Bose-Einstein-statistics used to extract particle emission source information
  method first developped for photons in astrophysics, well established in heavy-ion physics review
- complementary to large scale ϕ, η-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

The LHCb upgrade



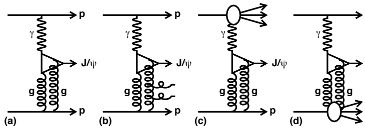
Framework TDR,Velo TDR, PID TDR,Tracker TDR,Trigger & Online TDR

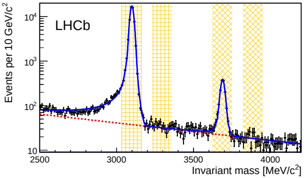
- LHCb detector upgrade in 2019/2020
- run at $L_{inst} = 2 \times 10^{33}$ cm^{-2} s^{-1}:
  on average 5.2 visible pp collisions per bunch crossing
- process full pp input rate in HLT without hardware trigger
- tracker fully replaced: increased granularity
- silicon vertex locator from strip to pixel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

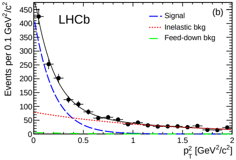
Conclusions

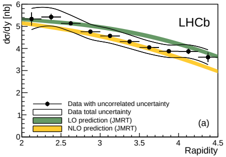
- LHCb: fully instrumented spectrometer with unique kinematics with flexible trigger system in collider and fixed-target mode
- important QCD results in several areas:
  - conventional and unconventional QCD bound states and their properties
  - unique constraints on parton densities at large x and low 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

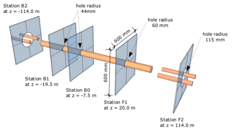
Central exclusive production with LHCb: J/ψ and $\psi(2S)$ production at $\sqrt{s} = 7$ TeV







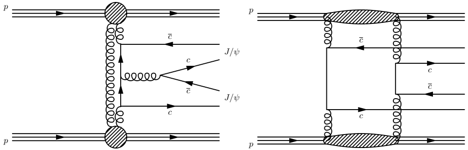


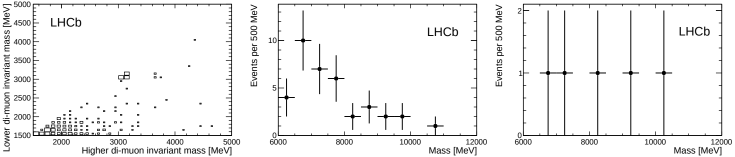


J. Phys. G: Nucl. Part. Phys. 41 (2014) 055002

- average collision numbers of about 1: central exclusive studies with high statistics
- vector meson production via γ-$\mathbb{P}$
- forward acceptance: low-x leverage
- purity improvements: Herschel scintillators since 2015

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

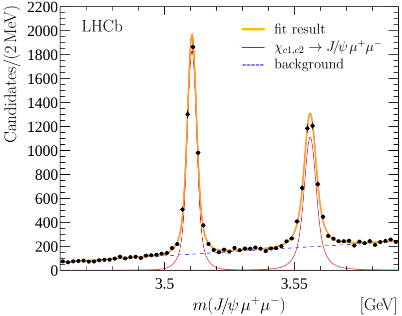


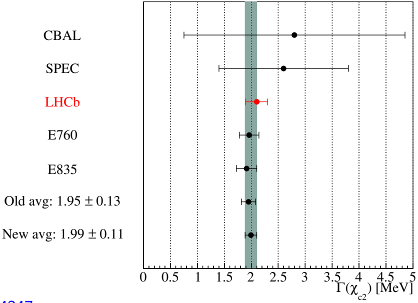


J. Phys. G: Nucl. Part. Phys. 41 (2014) 11500; middle (right): double-J/ψ (J/ψ-ψ(2S)) masses.

- 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/ψ production:
  $58 \pm 10(stat) \pm 6(syst)$ pb within $2.0 < y < 4.5$
- cross section for exclusive J/ψ-ψ(2S) production:
  $63^{+27}_{-18}(stat) \pm 10(syst)$ pb within $y < 2.0 < 4.5$
- upper limits on double ψ(2S) and double χ_c-production

Precision χ_c spectroscopy with new decay channel





arXiv:1709.04247

- first observation of muonic dalitz decay
  $\chi_{c1,c2} \to J/\psi(\to \mu^+\mu^-)\gamma^*(\to \mu^+\mu^-)$
  $\to$ demanding pure μ-PID down to p =3 GeV/c
- among the most precise single experiment determinations of χ_{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