Parallel 2 summary: b and c-decays in heavy ions

The B_c meson: a promising incomer

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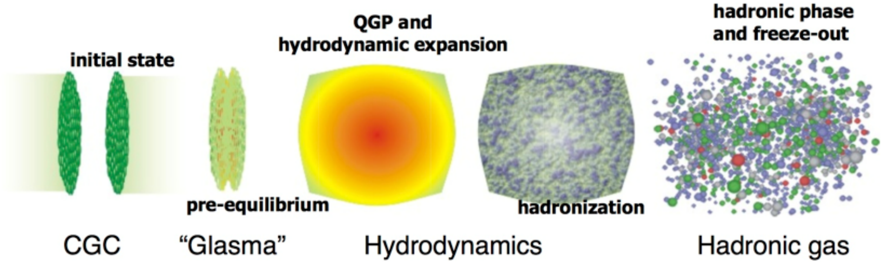
Results from CMS, LHCb and ALICE

GdR Intensity Frontier, Sommières
November 5th, 2019

The quark-gluon plasma **probed by heavy quarks**

- QCD at very high temperature ⟶ deconfinement
  ⟶ quarks and gluons move freely in a quark-gluon plasma (QGP)



- Standard Model QCD... Not fully understood yet!
- Heavy quarks produced on smaller time scales than QGP expansion
  ⟶ brings information on the **whole QGP history**

Our tool: heavy quarks modification

QGP effect? ⟶ compare to 'vacuum' pp:

$$R_{PbPb} = \frac{\text{PbPb XS, normalized to nucleon-nucleon collisions}}{\text{pp cross-section}}$$

Inclusive charm/beauty **VS** **Exclusive heavy decays**

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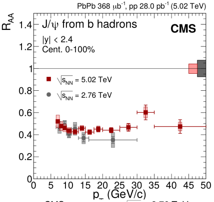
J/ψ from b decays

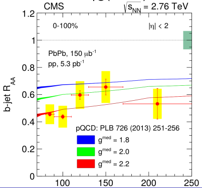
EPJC 78 (2018) 509



b-jets

PRL.113.132301

(2014)



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Inclusive charm/beauty **VS** **Exclusive heavy decays**

✓ High stats

✓ Total quark cross-sections

✗ No meson flavour discrimination

✗ Smeared kinematics

⟶ Global medium properties

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$$R_{PbPb} = \frac{\text{PbPb XS, normalized to nucleon-nucleon collisions}}{\text{pp cross-section}}$$

Inclusive charm/beauty **VS** **Exclusive heavy decays**

Inclusive charm/beauty:

- ✓ High stats
- ✓ Total quark cross-sections
- ✗ No meson flavour discrimination
- ✗ Smeared kinematics

⟶ Global medium properties

Exclusive heavy decays:

- ✗ Low stats
- ✓ Precise flavour content
- ✓ Clear decay kinematics
- ✓ Clean samples using resonances + PID (e.g. $J/\psi \to \mu\mu$ golden channel)

⟶ Detailed insight into medium dynamics

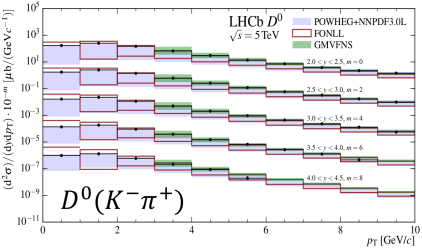
Effects of the initial state / of the QGP

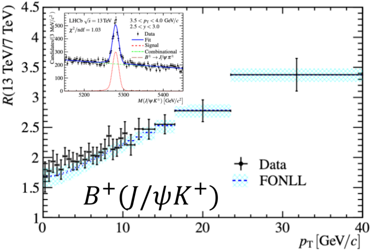
1. Not everything comes from the hot medium: initial state matters!
   ⟶ PDFs, nuclear PDFs, fragmentation, ...
2. Heavy quarks lose energy when traversing QGP
   ⟶ Mass hierarchy of energy loss?
3. Strangeness enhancement (thermal $s\bar{s}$ production from medium)
   ⟶ D_s/D and B_s/B ratios, to isolate effects on strangeness
4. Sequential suppression: dissociation of bound states depends on their size ⟶ Test exotic probes? χ_{c1}, $X(3872)$, Ξ_{cc}
5. Recombination with c quarks in the medium... Unambiguous proof?
   ⟶ First look at B_c mesons in PbPb collisions
6. Perspectives/conclusion

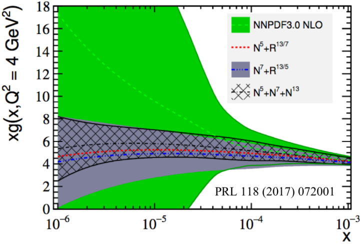
Open heavy flavor production

JHEP 06 (2017) 147
JHEP 12 (2017) 026

- Exclusive decays, very clean. Subjected to (very) small branching fraction





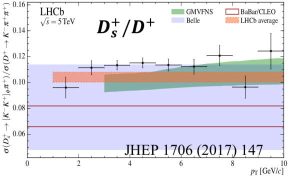


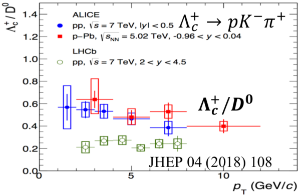
Cross-section and ratios at different energies good agreement with theory predictions in p_T, y intervals in all LHCb acceptance.

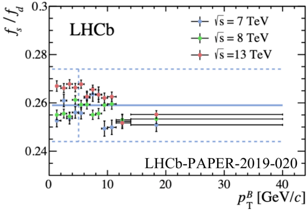
Strong constrains to gluon PDF at small-x.

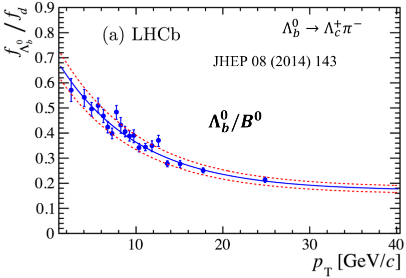
Reference for production in heavy-ion data.

Fragmentation









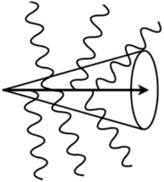
Fragmentation fraction depends on collision energy and kinematics

- ✓ $f_{\Lambda_b^0} \approx 8.9 \pm 1.2\%$ (PDG), $\approx 20\%$ (LHCb)
- ✓ Inconsistency for $f_{\Lambda_c^+}$ cross experiments

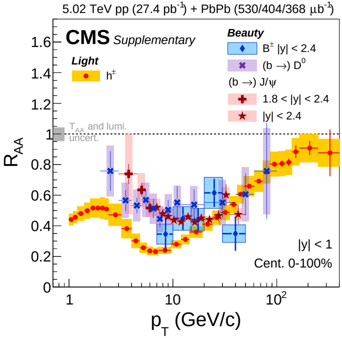
Measurements in *pp* collisions with the same condition is essential for heavy ion data.

Flavour dependence of energy loss

- Heavy quarks lose energy in the QGP (gluon radiation, elastic collisions), but:
  - Smaller color charge than gluons
  - Possible dead-cone effect



PLB 782 (2018)
EPJC 78 (2018)
JHEP 04 (2017)

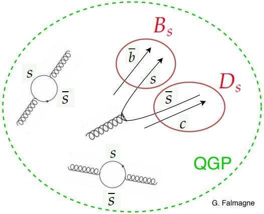


$\longrightarrow$ $1 > R_{AA}(B) > R_{AA}(D) > R_{AA}(h^{\pm})$...

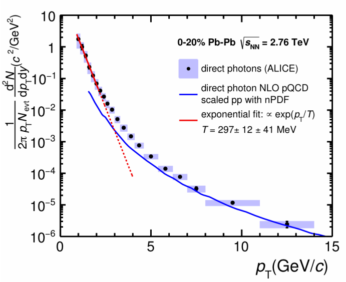
- **BUT** affects only low-p_T... Universal partonic energy loss at high-p_T? (jet quenching Arleo PRL 119, 062302)

Strangeness: a hot business

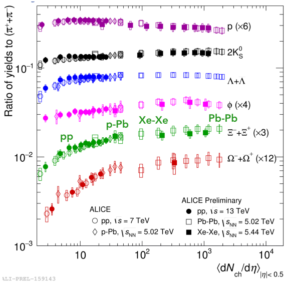
- $s\bar{s}$ mass is below QGP temperature
  $\longrightarrow$ many thermally produced virtual pairs
- If the pair interacts with other quarks in the medium $\longrightarrow$ more observed strange hadrons



Blackbody photon radiation



higher multiplicity = more strange hadrons



Strange + heavy mesons: D_s and B_s

Exclusive strange-heavy meson decays

⟶ Interplay with heavy quarks (NRQCD potentials)

⟶ Dynamics of strange hadronization

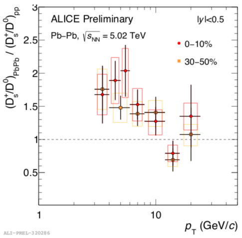
charm + strange?

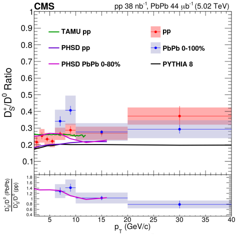
- Ratio D_s/D cancels the charm energy loss
- Double ratio PbPb/pp cancels the f_s/f_d fragmentation functions

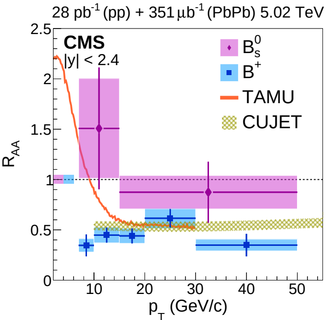
beauty + strange?

(First!) meas. of double ratio

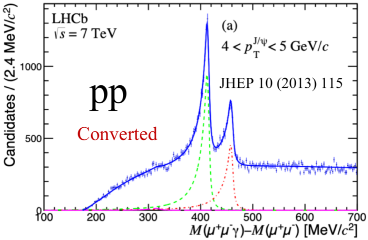
$$\frac{R_{\mathrm{PbPb}}(B_s^0)}{R_{\mathrm{PbPb}}(B^+)}$$

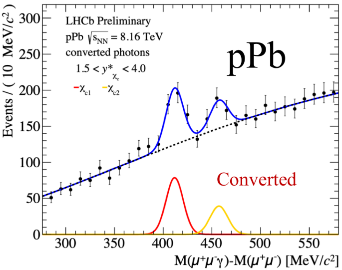


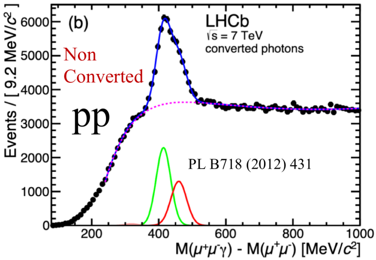




Non vector quarkonia



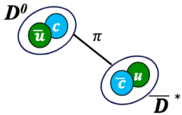




χ_{cJ} measured with both converted ($\gamma \to e^+e^-$) and non-converted photon in pp data. Reduced statistics but χ_{c1} and χ_{c2} peaks better resolved.

X(3872)

$$M_{\chi_{c1}(3872)} - (M_{D^0} + M_{\bar{D}^{*0}}) = 0.01 \pm 0.27 \text{ MeV}$$



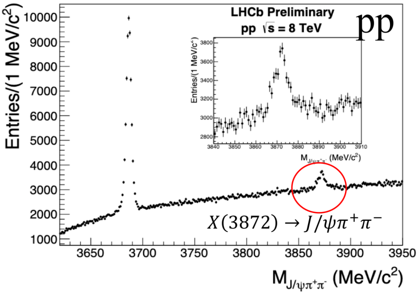
Hadronic molecular?

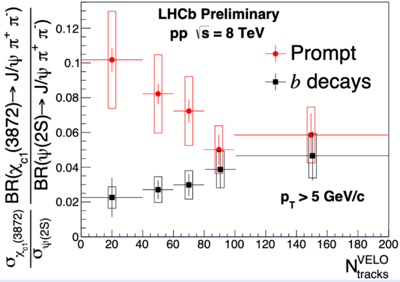
state	η_c	J/ψ	χ_{c0}	χ_{c1}	χ_{c2}	ψ'	X(3872) ($D\bar{D}^*$ Molecule)
mass [GeV]	2.98	3.10	3.42	3.51	3.56	3.69	3.872
ΔE [GeV]	0.75	0.64	0.32	0.22	0.18	0.05	0.00001±0.00027

Satz, J. Phys. G 32 (3) 2006

Another system to test sequential suppression/comover?

LHCb-CONF-2019-005

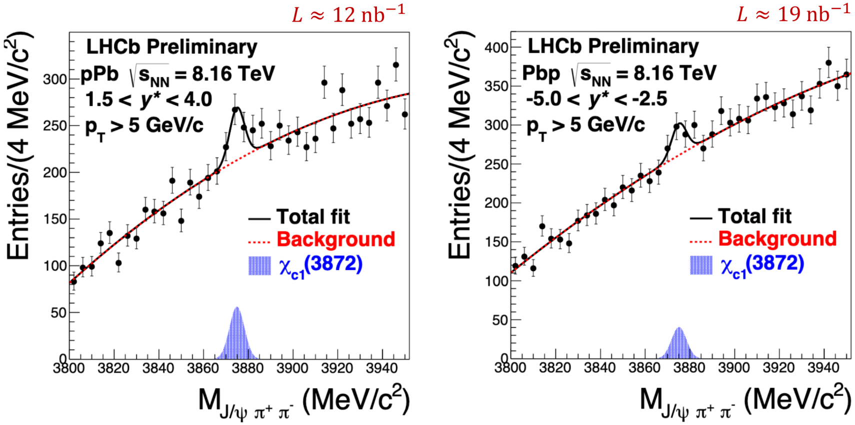




Production relative to $\psi(2S)$ decreases as event activity increases in pp data.

X(3872)

Accessible in proton-Pb collision, more suppressed in Pbp data?



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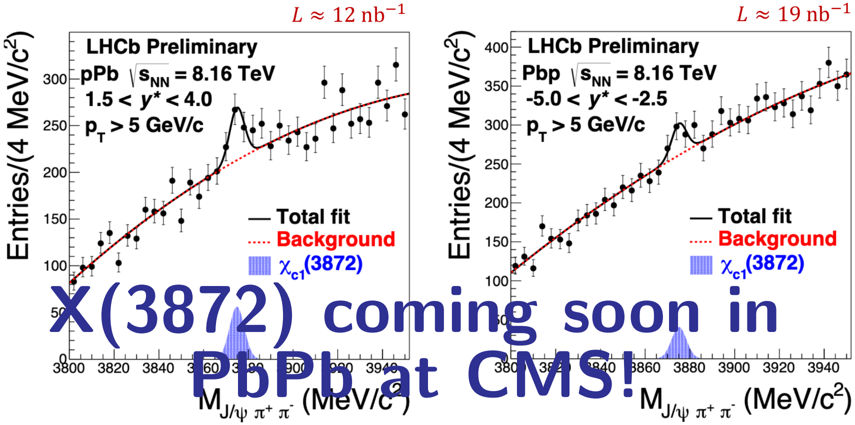

X(3872) coming soon in PbPb at CMS!

Ξ_{cc}^{++} production

- Difficult due to low production rate and small detection efficiency

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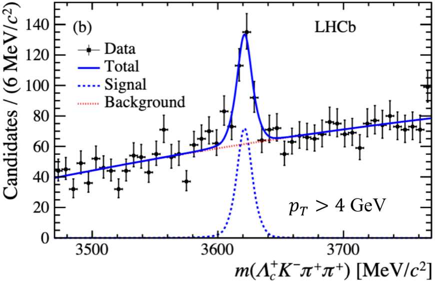


$\epsilon(\Xi_{cc}^{++}) \approx 1\%$ for $p_{\mathrm{T}} > 4$ GeV
$\sigma(\Xi_{cc}^{++} \to \Lambda_c^+ K^- 2\pi^+)/\sigma(\Lambda_c^+)$
$=(2.22 \pm 0.27 \pm 0.29)\times 10^{-4}$

- Production mechanism similar to J/ψ in PbPb collisions
  - Dissociation of primary production + medium recombination at low p_{T}
  - $E_b(ccq) = 1/2 E_b(c\bar{c})$, may be comparable rate of recombination as J/ψ
  - $N(\Xi_{cc}^{++}) \approx 0.02$/PbPb at mid y for 0-10% centrality, enhanced by $\times 10$ ($R_{AA} \gg 1$), however yield is strongly reduced at $p_{\mathrm{T}} > 4$ GeV

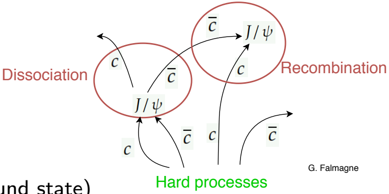
PR D97 (2018) 074003

Hope to reach low p_{T} in the future!

Recombination with charm?

- In LHC PbPb central collisions:
  up to 100-1000 charm quarks produced !
  ⟶ No enhancement of number of c quarks,
  but change of $\frac{\text{hidden charm}}{\text{open charm}}$?

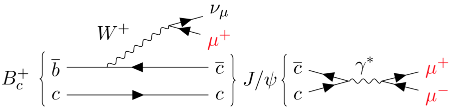
- How to discriminate among
  many recombination models for J/ψ?
  - Statistical hadronization
    (binding of uncorrelated deconfined c and $\bar{c}$)
  - Transport model
    (continuous dissocation/recombination of bound state)
  - ...



- B_c difficult to produce in 1 hard collision: need a $b\bar{b}$ and a $c\bar{c}$ pair.
  ⟶ If a b quark can recombine with charm in the medium ... dramatic augmentation! Up to $10^3 - 10^4$ in some papers (Rafelski et al. PRC62 (2000))
  ⟶ Could bring new insights/discriminate on recombination mechanisms!

B_c^+: a new and challenging QGP probe

- Possible dramatic recombination of B_c! But:
  - Mostly for $p_T \lesssim m_{B_c}$
  - Added to suppression mechanisms (b energy loss etc.)
- Two different heavy quarks bound
  $\longrightarrow$ original view of flavour dependence of energy loss
- Challenge of B_c exclusive decay measurement: low yields!
  - $p_T(B_c)$ peaks at 3 GeV $\longrightarrow$ try to lower p_T thresholds
  - CMS: use 2018 PbPb data, with lumi $4 \times \mathcal{L}_{2015}$!
    ALICE, LHCb: aim for Run3
  - Use (partially reconstructed) trimuon channel ($\mathcal{B}_{muonic} = 20 \times \mathcal{B}_{hadronic}$)



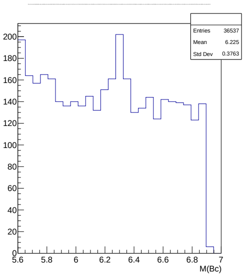
  - Small B_c displacement from primary vertex
    $\longrightarrow$ Optimize signal selection with BDT

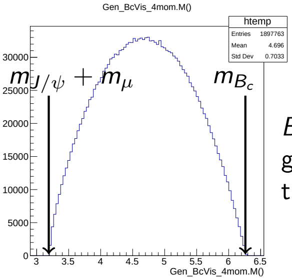
B_c^+: Hadronic or semi-leptonic channel?

Low cross section:

- Use (partially reconstructed) trimuon channel ($\mathcal{B}_{muonic} = 20 \times \mathcal{B}_{hadronic}$):
  - Hadronic channel observed in pp 2017 data, but $4\times$ less equivalent lumi in PbPb + potential suppression + higher track background $\longrightarrow$ hopeless in PbPb
  - Non-peaking signal $\longrightarrow$ have to master the backgrounds!
  - Smeared kinematics (possible p_T unfolding)

$B_c^+ \to J/\psi\ \pi^+$
reco+selected
pp data 5 TeV
$N_{B_c} \simeq 120$

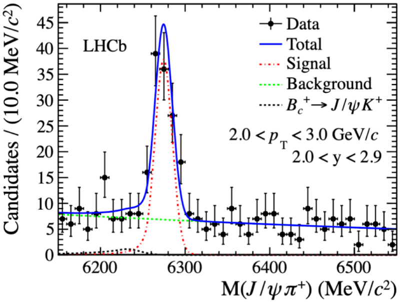




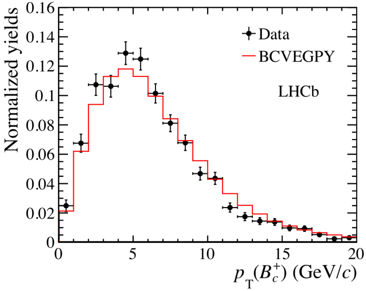
$B_c^+ \to \mu\mu\mu$
generated
trimuon mass

B_c^+ production

- Subjected to dissociation and recombination in medium
  - recombination dominate production in central collisions, enhanced by ~10
- LHCb measurement with $B_c^+ \to J/\psi\pi^+$ PR C62 (2000) 024905
  - 2 fb^{-1} pp data at 8 TeV



PRL 114(2015) 132001



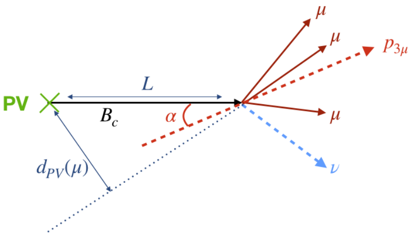
Reasonably clean signal, $N_{sig} \approx 3100$.

p_T distribution well modelled by BCVEGPY[hep-ph/0504017]

$$\frac{R(B_c^+ \to J/\psi\pi^+)}{R(B^+ \to J/\psi K^+)} = (0.68 \pm 0.02)\%$$

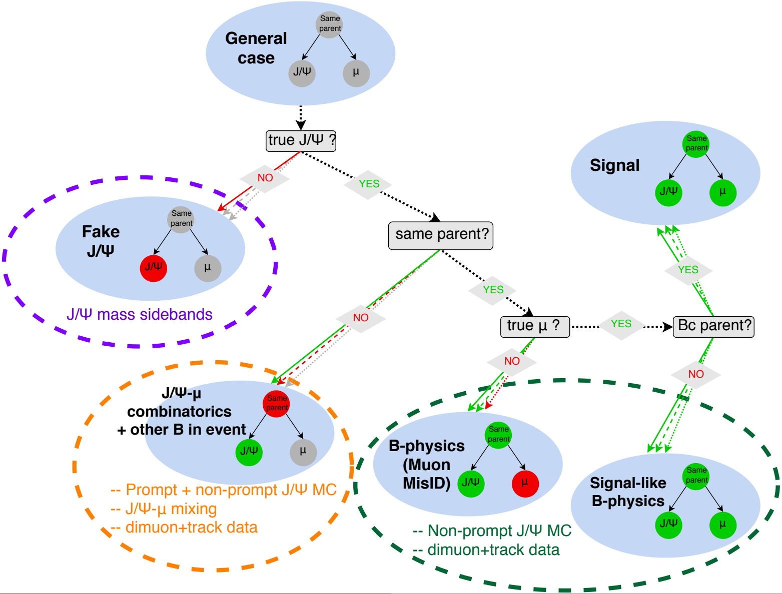
B_c: Analysis strategy (CMS)

- Preselection with standard selections for muons, dimuons, charged tracks
- Use discriminant variables to improve signal significance, via BDT
  - Lifetime significance
  - μ displacement from PV
  - angle $\overrightarrow{p_{3\mu}} - \overrightarrow{[PV, SV]}$
  - Vertex probability
  - $\sum_{i,j=1,2,3} |\Delta R(\mu_i, \mu_j)|$
  - $m_{corr}(\mu\mu\mu)$, corrected for $p_\perp(\nu)$
  - ...



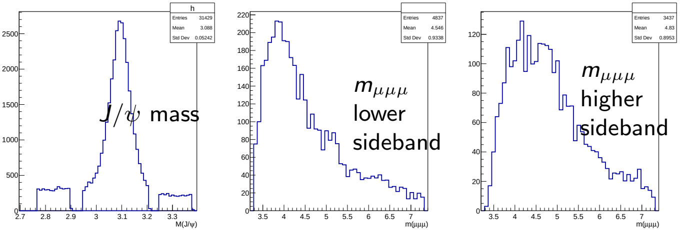
- Background studies: data-driven (sidebands, dimuon+track) + MC J/ψ
- Signal extraction from template fit of trimuon mass
  (but presented today: only pre-fit!)
- From signal yields + acceptance&efficiency corrections $\longrightarrow$ $R_{PbPb}(B_c)$

Mastering the backgrounds



Fake J/ψ

- charge ± 1 trimuon $\longrightarrow$ 2 opposite-sign dimuons $=$ 2 possible J/ψ
- Events with one dimuon in sidebands, and one in peak region: split between signal and background samples
  $\longrightarrow$ Obtain smooth trimuon mass distr. for lower and higher sidebands

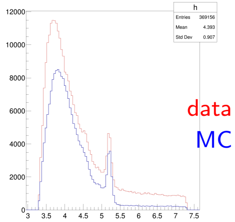


- Will fit both sidebands, and take the average shape as extrapolation under the peak

$B \to J/\psi\, X$ with muon misidentification

- $K \to \mu$ misID $= 0.3 - 0.5\%$ and $\pi \to \mu$ misID $\simeq 0.1\%$
  $\longrightarrow$ $B \to J/\psi\, X$ resonances (or partially reconstructed) give high background (e.g. $B^+ \to J/\psi\, K^+$)
- Obtained with non-prompt J/ψ MC
- This MC *should* also describe:
  displaced J/ψ + [other track from companion B or combinatorial]

Problem shows as well in dimuon+track data vs MC $\to$

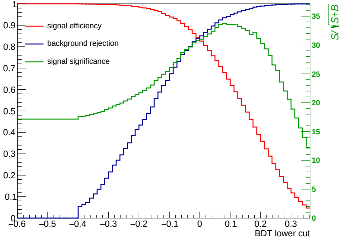


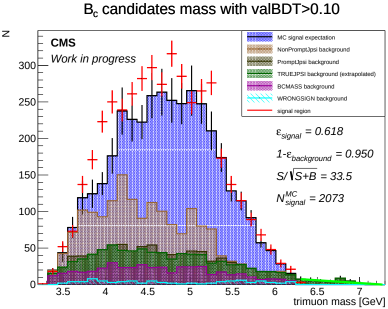
- Multiple data-driven methods tried now to find appropriate shape for this background

pp preliminary result

- Same sign $+++/---$ sample only shown for illustration
- More work needed on J/ψ-track combinatorics: here, ad-hoc shape extrapolated from high-mass control region
- J/ψ sidebands
- non-prompt J/ψ MC
- Signal MC B_c

Scan of BDT cut values





PbPb

- 4 times less nucleon-nucleon equivalent luminosity in PbPb than pp
- Possible suppression
- More track background than in pp
  $\longrightarrow$ Challenging to observe B_c signal!

... but promising first results, that could lead to the first $R_{PbPb}(B_c)$ measurement

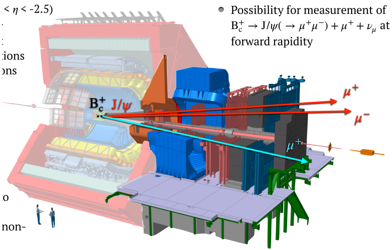
Possible in ALICE and LHCb too?

ALICE upgrades

Run 2: only the muon arm ($-4 < \eta < -2.5$) for $B_c \to \mu\mu\mu$ detection.
Upgrades for ALICE Run 3 could make it realistic to detect B_c in PbPb:

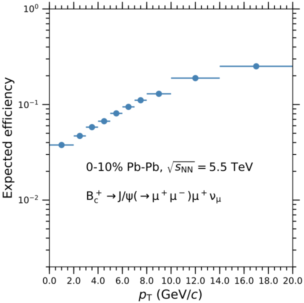
- new Muon Forward Tracker (MFT) to match muon tracks before and after the absorber
  → allow for prompt / non-prompt J/ψ separation

- new Inner Tracking System (ITS)
  → improvement in the impact parameter resolution by a factor 3 (5) in the transverse (longitudinal) direction



B_c feasibility in ALICE: trimuon channel

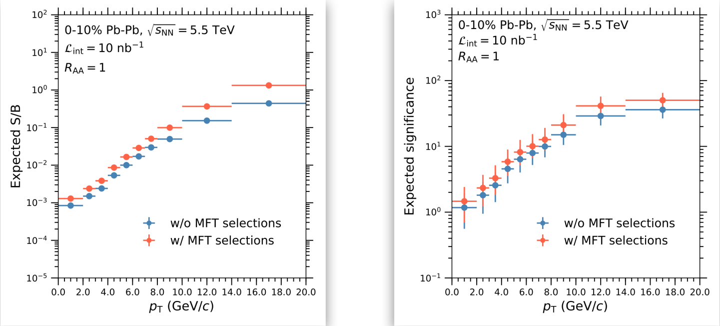
- Cross-sections from FONLL
- ratio of trimuon/hadronic branching fractions from LHCb
  PRD 90, 032009 (2014)
- Acc×Eff for J/ψ: from current PbPb measurements
- Third muon efficiency: considering efficiency of (MFT – muon arms) matching



B_c feasibility in ALICE: background estimation

- Combinatorial J/ψ background
- Various true/fake muon backgrounds
- Cut $M_{trimuon} > 5.5$ GeV to cut away correlated background

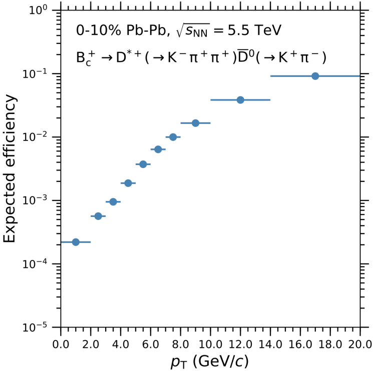
$B_c^+ \rightarrow J/\psi + \mu^+ + \nu_\mu$ - significance estimation

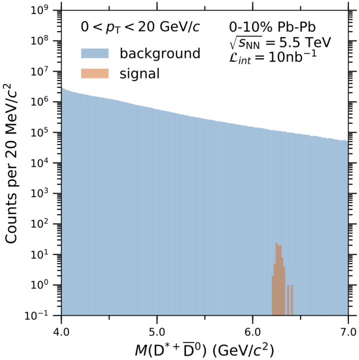


- With these assumptions significance expected to be larger than ~5 for $p_T > 4$ GeV/c
- Improvement with MFT (additional improvement could come from selection of displaced vertices)

$B_c \to D^{*+} + \bar{D}^0$ channel

- $B_c \to D(K\pi\pi)\,D(K\pi)$ channel also studied (with non-optimized selections), but quite hopeless due to much lower predicted (theoretical) branching fraction
- Would need 100× more luminosity than ALICE predicted Run 3





B_c^+ production with SL decays

- $B(B_c^+ \to J/\psi\mu^+\nu) = 1 - 8\%$, about $15\times B(B_c^+ \to J/\psi\pi^+)$
- LHCb measurement at 7 (1 fb^{-1}) and 13 TeV (1.7 fb^{-1})
  - $p_T(B_c^+) > 4$ GeV to reject background
  - Signal obtained from $m_{\rm cor} = \sqrt{m(J/\psi\mu^+)^2 + p_\perp^2} + p_\perp$ using templates
    - ✓ Signal, feed-down: simulated $B_c^+ \to J/\psi\mu^+\nu,\ \psi', \chi_c\, \mu^+\nu, J/\psi\tau^+\nu$ decay
    - ✓ Background: inclusive $b \to J/\psi$ decay from simulation

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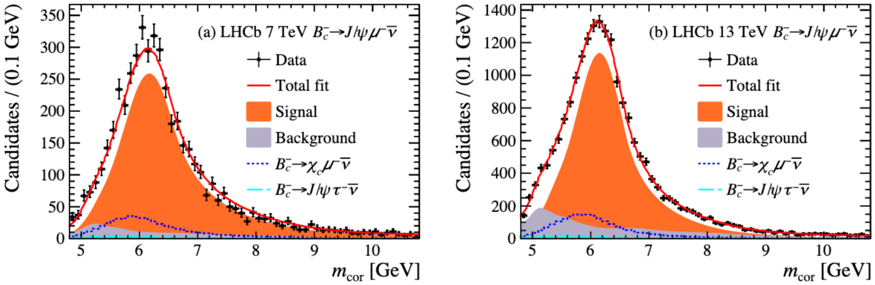
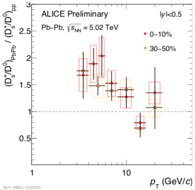
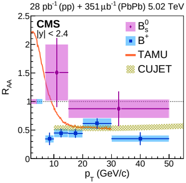


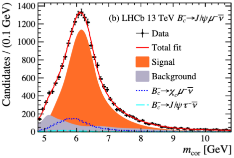
Almost background free. Total yields: 4K at 7 TeV and 15K at 13 TeV, about ×3 larger compared to $B_c^+ \to J/\psi\pi^+$. Losses due to p_T and other selection criteria.

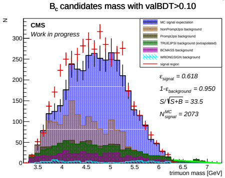
Conclusion and prospects

- Rich zoology of flavour studies in the QGP to be done at LHC!
  - Initial state + reference in pp: complete map of fragmentation?
  - All mentioned measurements: quantify c and b-quark energy loss
  - Exotic bound states dissociation in medium
  - B_s/B and D_s/D to isolate strangeness effects
    B_c/B to isolate charm recombination
    B_c/B_s to compare c recomb. and s enhancement? (more distant)









→ Could achieve a complete description of 'heavy' mesons in QGP
→ deeper understanding of QCD!

But: needs much more stats and manpower... Case for strong heavy ions program beyond Run 3, with our complementary experiments!

BACKUP

Introduction

- Unique probes of heavy-ion collisions
  - $m_Q \gg \Lambda_{QCD}$, production calculable with perturbative-QCD
  - $t_{\text{prod}} \sim 1/m_T$, information about initial and final state
- Information from heavy flavor
  - Initial state

    nPDF [PRL121(2018)052004, arXiv:1906.02512]

    saturation [Nucl.Phys.A735(2004)248…]

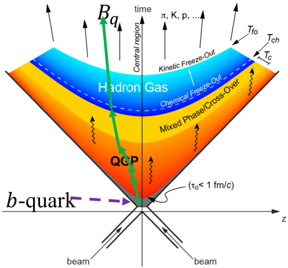
    …
  - Final state, medium properties

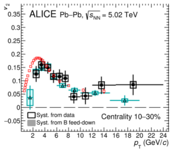
    Elliptic flow [Nucl.Phys.A735(2004)248…]

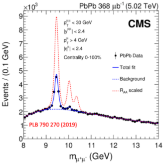
    Energy loss [Eur.Phys.J.A53(2017)5…]

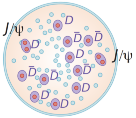
    Quarkonium dissociation/sequential suppression [Int.J.ofMod.Phys.A 28(2013)1340012…]

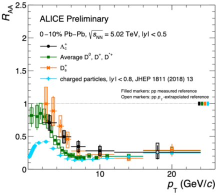
    Coalescence hadronization [PLB595(2004)202…]





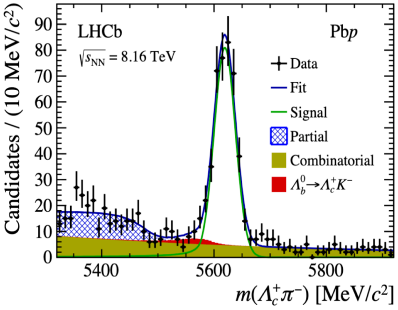


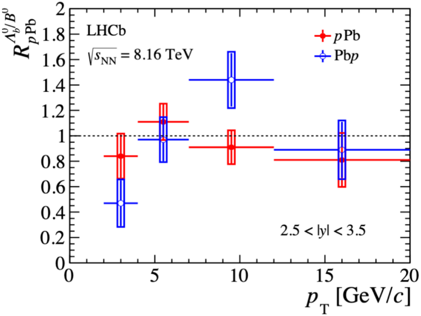




Semi-leptonic decays

PR D99 (2019) 052011





Decay	pPb	Pbp
$B^+ \to \overline{D}^0\pi^+$	1958 ± 54	1806 ± 55
$B^+ \to J/\psi K^+$	883 ± 32	907 ± 33
$B^0 \to D^-\pi^+$	1151 ± 38	889 ± 34
$\Lambda_b^0 \to \Lambda_c^+\pi^-$	484 ± 24	399 ± 23

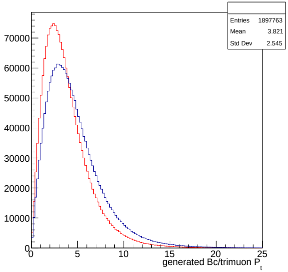
Yield will increase by ~10 using SL decays.
B_s^0 will also be possible (about 3% statistical uncertainty).
Alice studied non-prompt D^0, extended to B_s^0, Λ_b^0?
Towards precise fragmentation data in heavy ion collisions

Lowering p_T thresholds

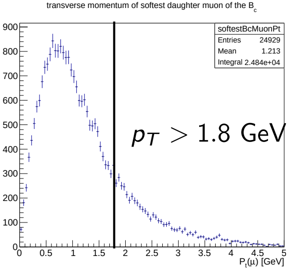
Low cross section:

- B_c production peaks at $p_T = 3$ GeV $\longrightarrow$ aim at lower p_T muons $\longrightarrow$ Push down muon kinematic acceptance cuts + allow a 3rd muon (not firing the *dimuon trigger*) in a looser acceptance

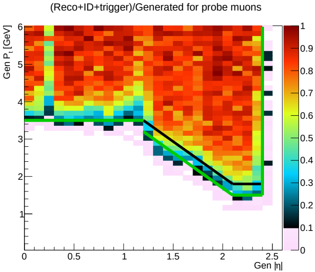
p_T of generated B_c
p_T of generated trimuon



p_T of softest muon (the other two μ are reconstructed)



New kinematic acceptance (for triggering muons)

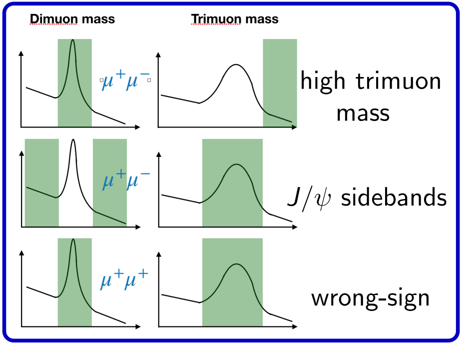


Used samples

- pp 2017 (300 pb^{-1}) and PbPb 2018 (1.5 nb^{-1}) at 5.02 TeV, with dimuon (J/ψ) trigger
- For B_c signal: use BCVEGPY2.2 specific generator, then: PYTHIA, EVTGEN, GEANT, ...

For background studies:

- Define samples w.r.t. trimuon sign (±1 or ±3) and J/ψ or trimuon mass sidebands
- MC for prompt J/ψ and non-prompt J/ψ (daughter of B^0, B^+, B_s)



- Dimuon+track data sample for track$\rightarrow\mu$ mis-identification

'Uncorrelated' J/ψ+track

Finding a shape for this background is enough

$\longrightarrow$ then, normalize with high trimuon mass control region

- Ad-hoc shape / shape parameters in the fit? $\longrightarrow$ too high systematics
- In (non)prompt J/ψ MC: $J/\psi + \mu$ not from same gen decay
  $\longrightarrow$ shape too wrong
- Dimuon+track data sample: better (and includes $B \to J/\psi\, X$ decays) but still imperfect shape
  $\longrightarrow$ would need $p/K/\pi$ PID (impossible at CMS) to get correct shape
- Best hope: consider all displaced J/ψ, flip the direction of their momentum and vertex displacement, and run trimuon analysis
- If problems with B event activity, try event mixing:
  put J/ψ in similar-looking event (but risks of fine-tuning)