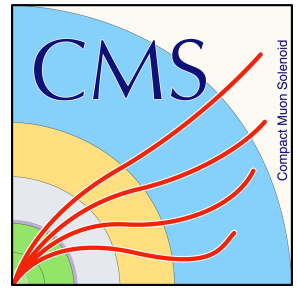
QGP studies with exclusive b and c-decays at CMS

The B_c meson: a promising incomer

Guillaume Falmagne

Laboratoire Leprince-Ringuet, Palaiseau (France)

On behalf of the CMS collaboration

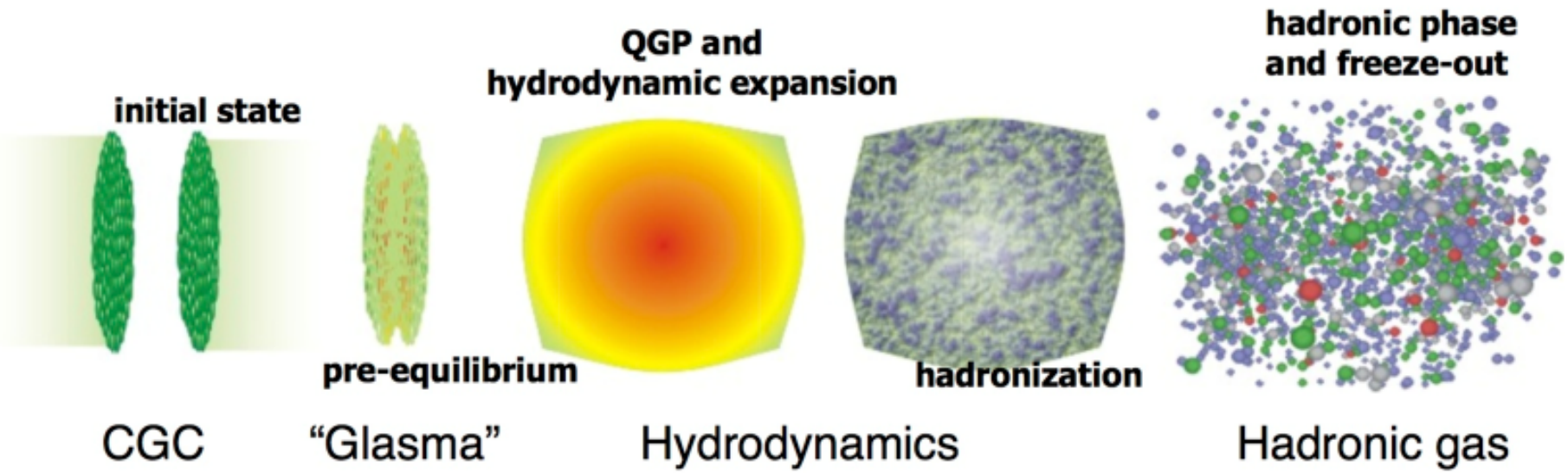


GdR Intensity Frontier, Sommières

November 4th, 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**

Our tool: heavy quarks modification

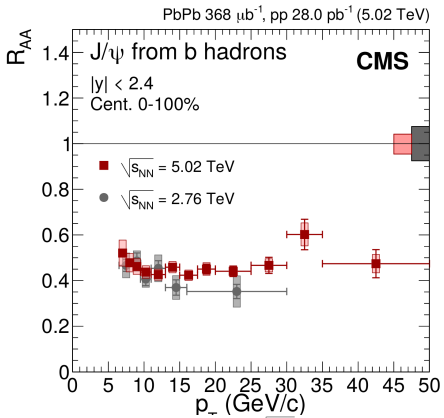
QGP effect? → compare to 'vacuum' pp:

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

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

J/ψ from b decays

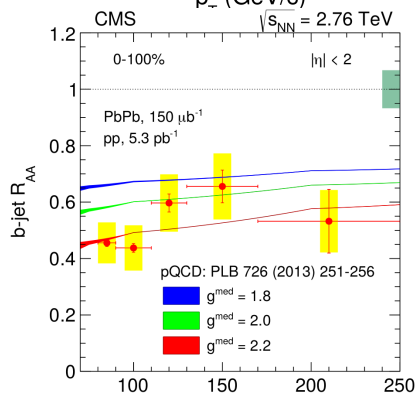
EPJC 78 (2018) 509



b-jets

PRL.113.132301

(2014)



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**

✓ High stats

✓ Total quark cross-sections

✗ No meson flavour discrimination

✗ Smeared kinematics

✗ Contamination from non-b partons

→ Global medium properties

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**

✓ High stats

✓ Total quark cross-sections

✗ No meson flavour discrimination

✗ Smeared kinematics

✗ Contamination from non-b partons

→ Global medium properties

✗ Low stats

✗ Depends on branching ratios and fragmentation

✓ 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 QGP

Quantify/discriminate effects → fundamental properties of the medium : thermodynamics/transport/impact on bound states/...

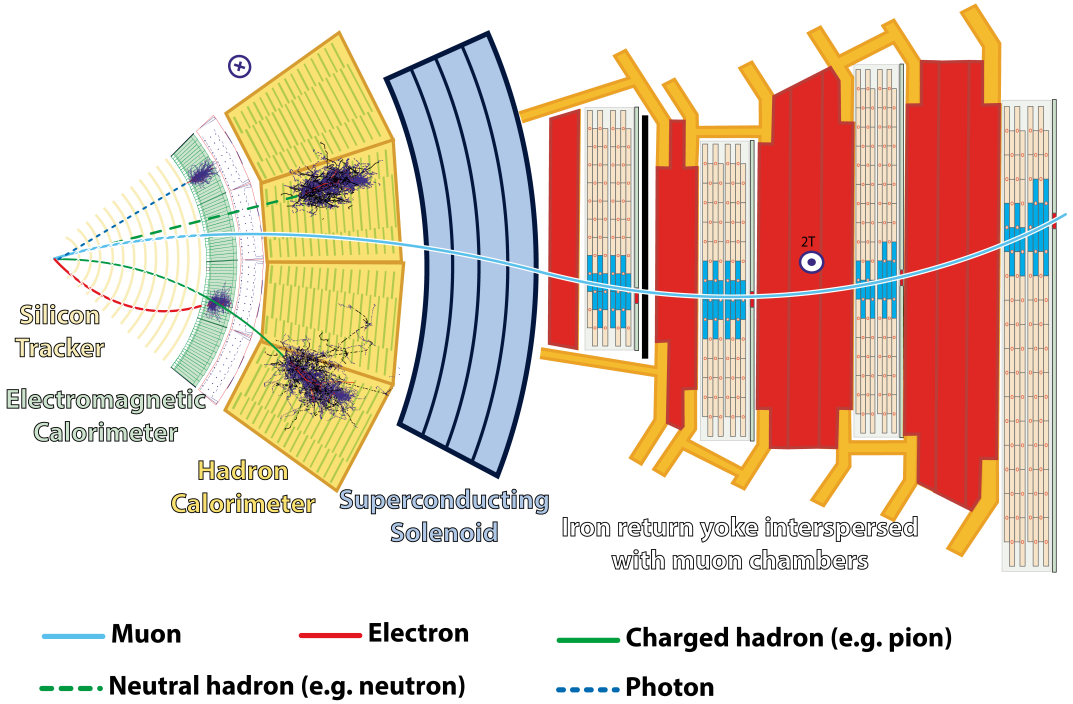
1. Heavy quarks lose energy when traversing QGP
   - 1.1 Mass hierarchy of energy loss?
     → Suppression of light hadrons vs D vs B

2. Strangeness enhancement (thermal $s\bar{s}$ production from medium)
   → Quantify it?
   - 2.1 Compare D_s and D mesons, to isolate effects on strangeness
   - 2.2 Compare B_s and B (idem)

3. Recombination with c quarks in the medium
   → Still debated... Unambiguous proof?
   - 3.1 First look at B_c mesons in PbPb collisions

4. Perspectives/conclusion

CMS detector



✓ 4π detector, specialized for muons

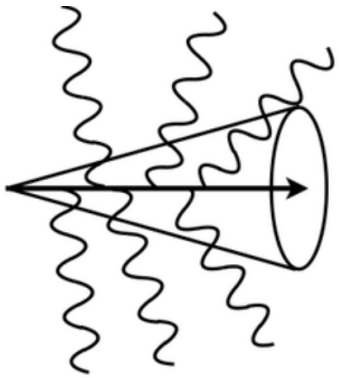
✓ Good displaced vertex reconstruction → B vertices

✓ High luminosity → exclusive decays until $p_T \lesssim 50$ GeV

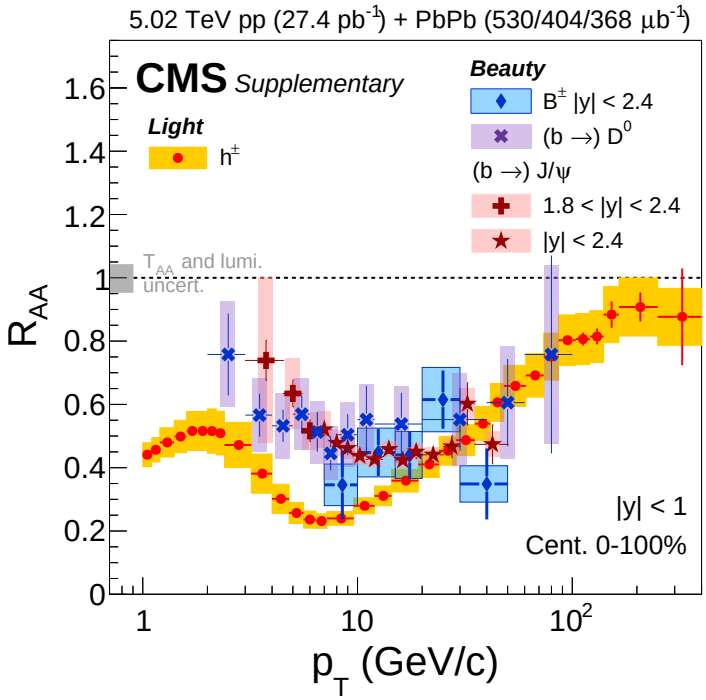
✗ Strong magnet → limited low-p_T acceptance for muons
→ Limits the reconstruction of low-p_T hadrons

Flavour dependence of energy loss

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



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

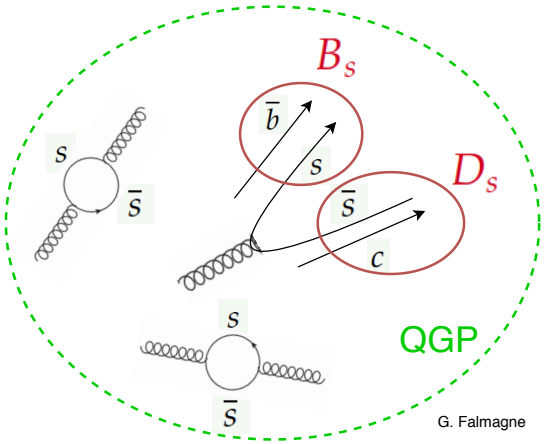


→ $1 > R_{AA}(B) > R_{AA}(D) > R_{AA}(h^{\pm})$...

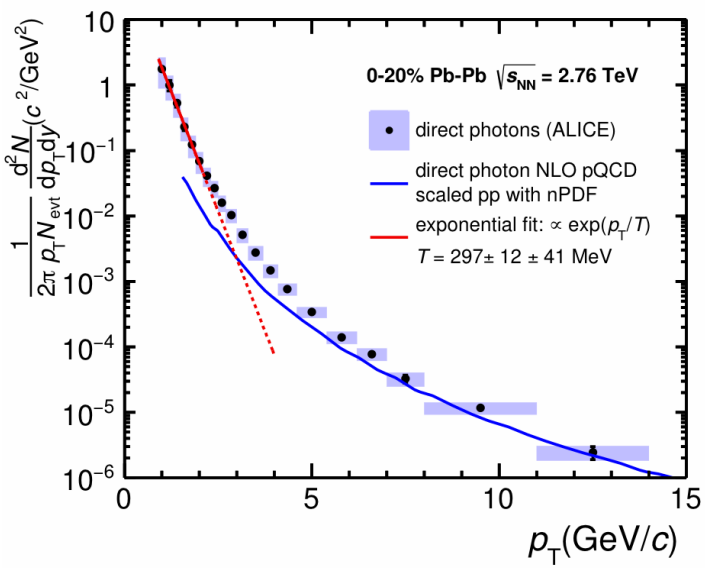
- **BUT** affects only low-p_T... Universal partonic energy loss at high-p_T? (jet quenching Arleo PRL 119, 062302)

Strangeness: a hot business

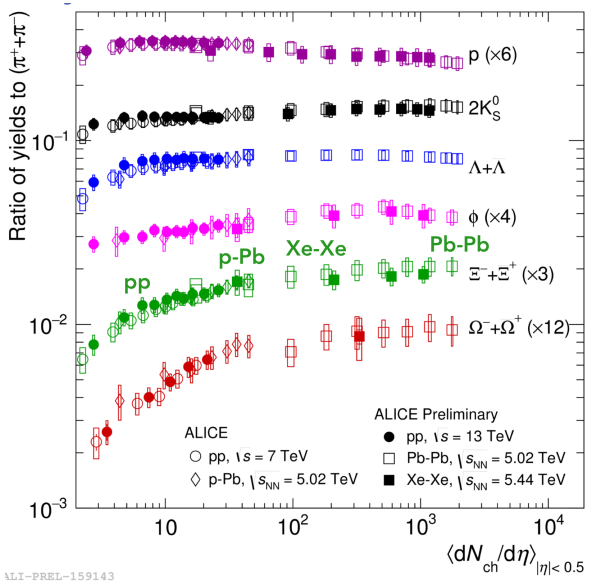
- $s\bar{s}$ mass is below QGP temperature
  → many thermally produced virtual pairs
- If the pair interacts with other quarks in the medium → more observed strange hadrons



Blackbody photon radiation



higher multiplicity = more strange hadrons



Strange + heavy mesons: D_s

Exclusive strange-heavy meson decays

→ Interplay with heavy quarks (NRQCD potentials)

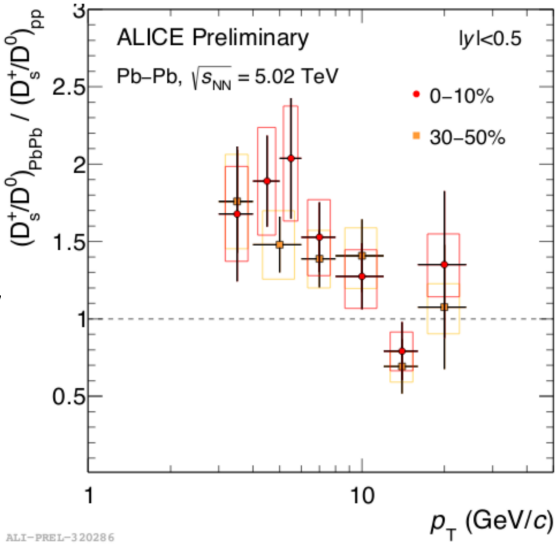
→ Dynamics of strange hadronization

charm + strange?

- Ratio D_s/D cancels the charm energy loss
  → isolates effect of strangeness
- Double ratio PbPb/pp → cancels the f_s/f_d fragmentation functions

ALICE

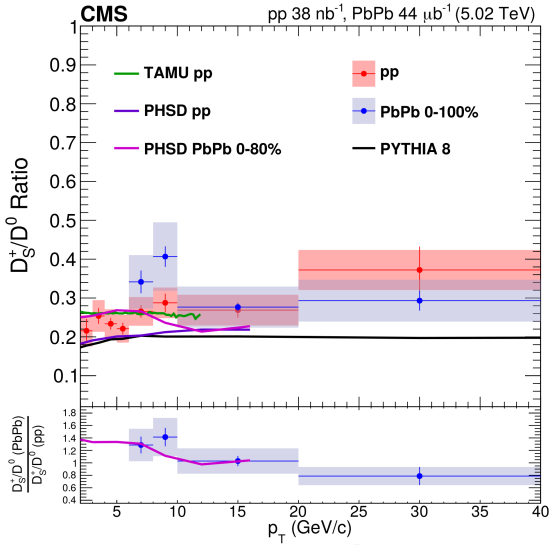
$p_T(D_s) > 3$ GeV



CMS

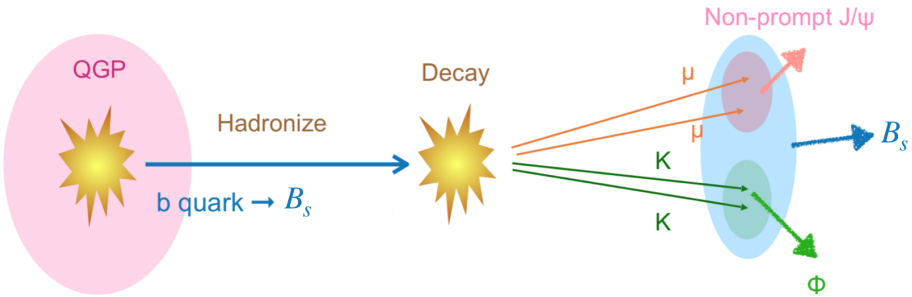
$p_T(D_s) > 6$ GeV

(2015 data)



Strange + heavy mesons: B_s

beauty + strange?



arXiv 1810.03022(2018)

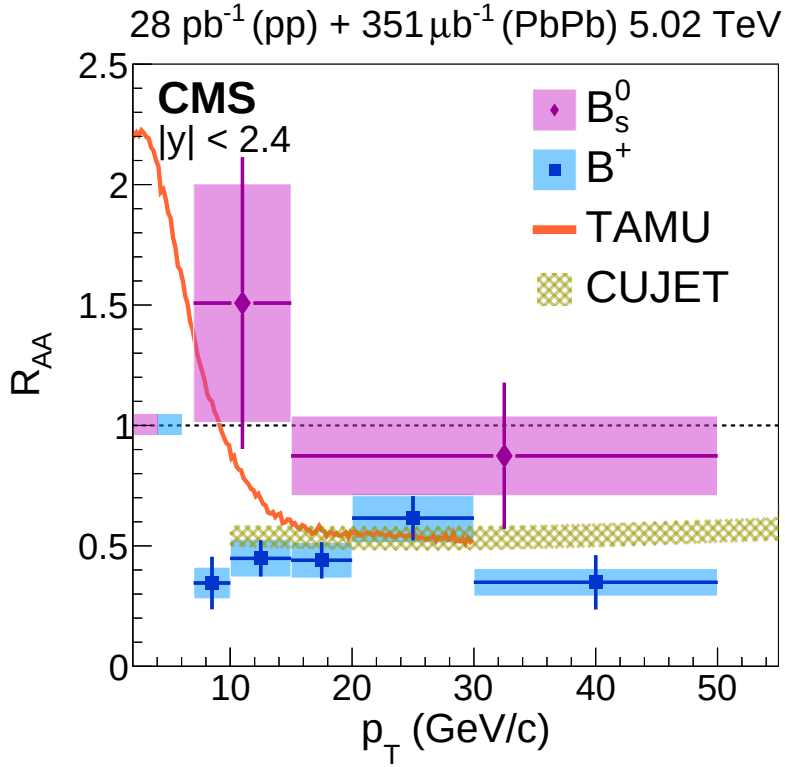
Coalescence of heavy quark with *s*-quark from the medium?

→ (First!) meas. of double ratio $\frac{R_{\mathrm{PbPb}}(B_s^0)}{R_{\mathrm{PbPb}}(B^+)}$

Comparison with:

- TAMU: Langevin transport model, with recombination
- CUJET: pQCD-based, without recombination

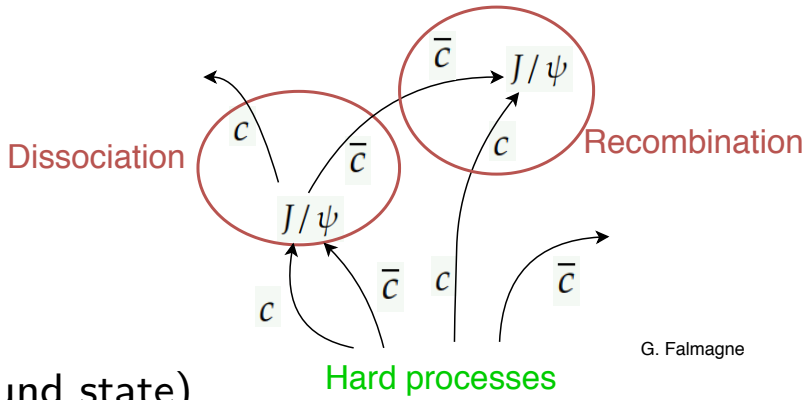
Incoming update on B_s/B with 2018 data!



Recombination with charm?

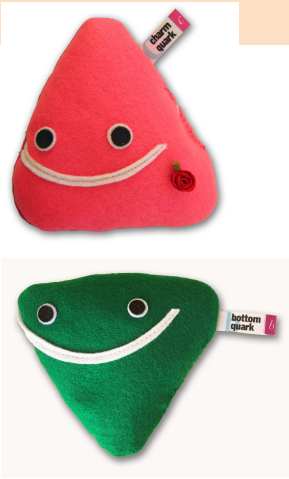
- In LHC PbPb central collisions:
  up to 100-1000 charm quarks produced !
  → No enhancement of number of c quarks,
  but change of $\frac{\text{hidden charm}}{\text{open charm}}$?

- 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)
  - ...

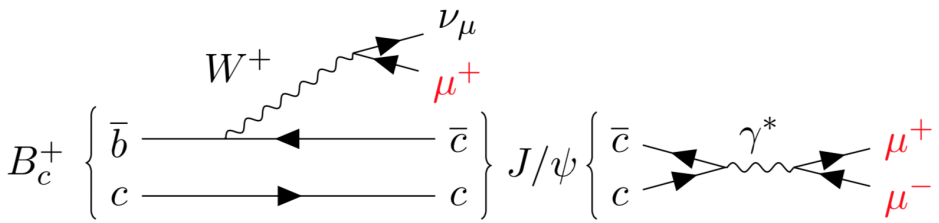


- B_c difficult to produce in 1 hard collision: need a $b\bar{b}$ and a $c\bar{c}$ pair.
  → If a b quark can recombine with charm in the medium ... dramatic augmentation! Up to $10^3 - 10^4$ in some papers (Rafelski et al. PRC62 (2000))
  → Could bring new insights/discriminate on recombination mechanisms!

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
  → 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 → try to lower p_T thresholds
  - Use 2018 PbPb data, with lumi $4 \times \mathcal{L}_{2015}$!
  - Use (partially reconstructed) trimuon channel ($\mathcal{B}_{muonic} = 20 \times \mathcal{B}_{hadronic}$)



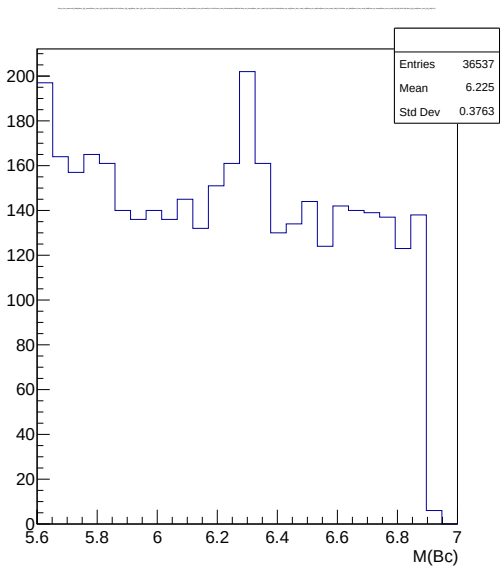
  - Small B_c displacement from primary vertex
    → Optimize signal selection with BDT

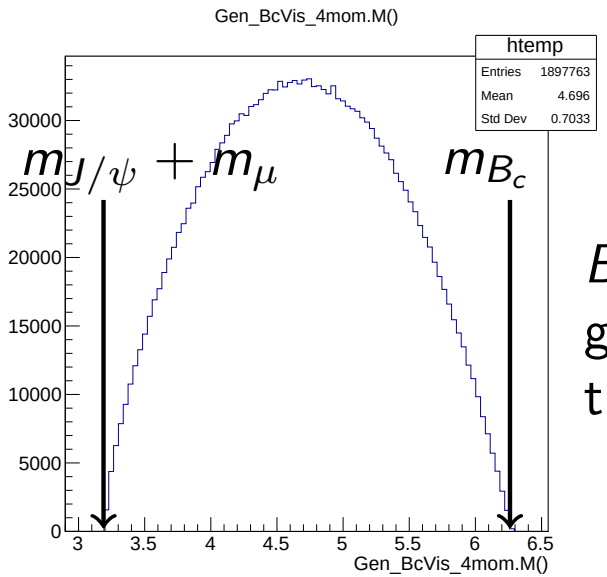
B_c^+: Hadronic or semi-leptonic channel?

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× less equivalent lumi in PbPb + potential suppression + higher track background → hopeless in PbPb
  - Non-peaking signal → have to master the backgrounds!
  - Smeared kinematics (possible p_T unfolding)

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





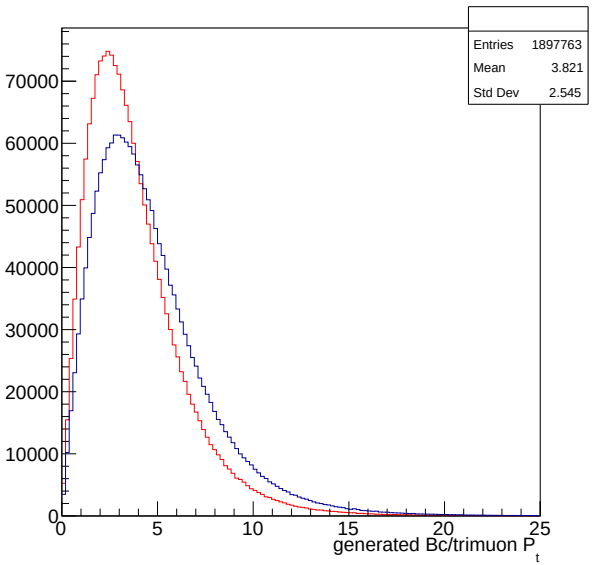
$B_c^+ \to \mu\mu\mu$
generated
trimuon mass

Lowering p_T thresholds

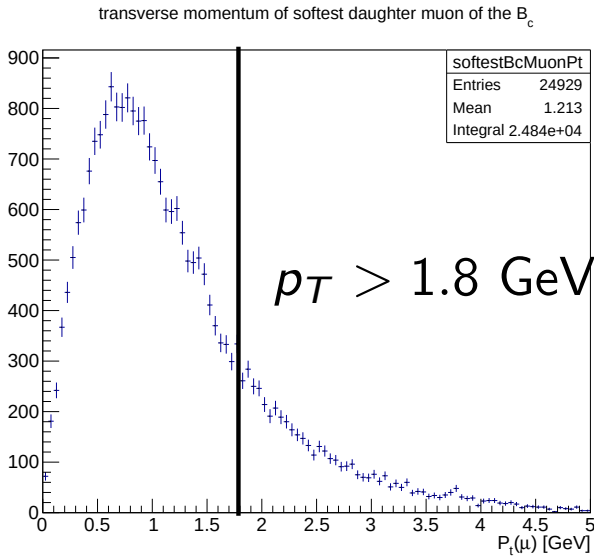
Low cross section:

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

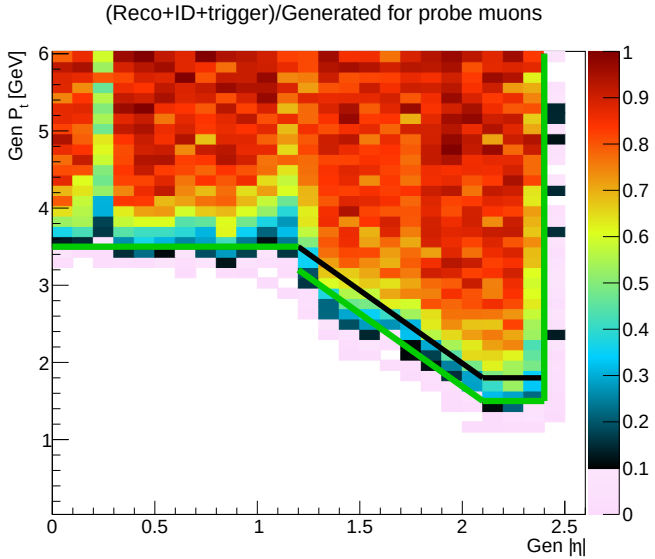
p_T of generated B_c
p_T of generated trimuon



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



New kinematic acceptance (for triggering muons)

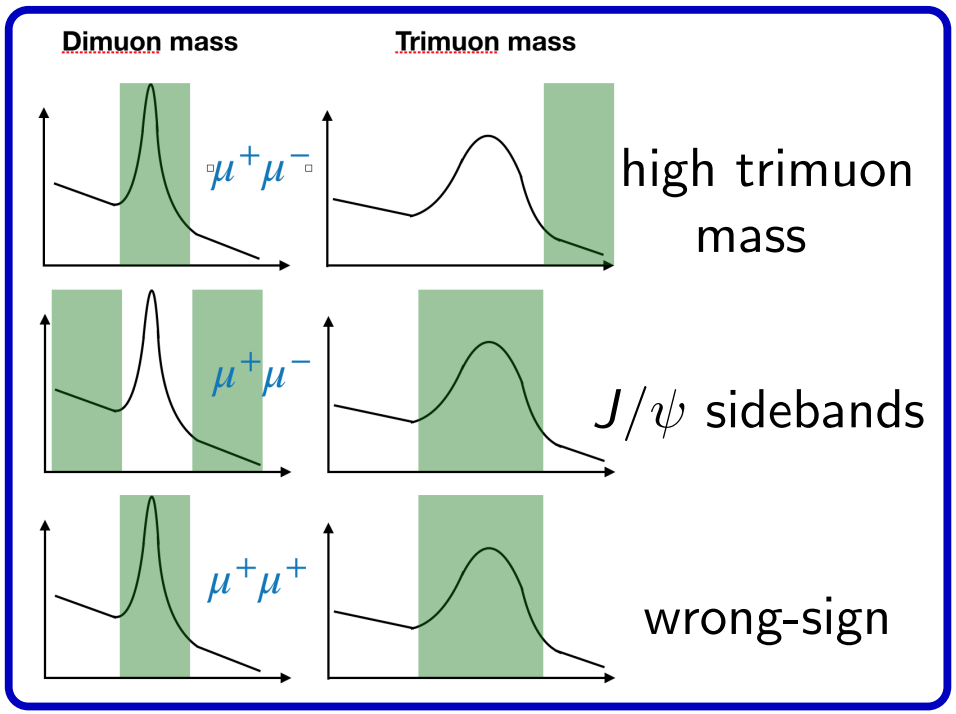


Used samples

- 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:

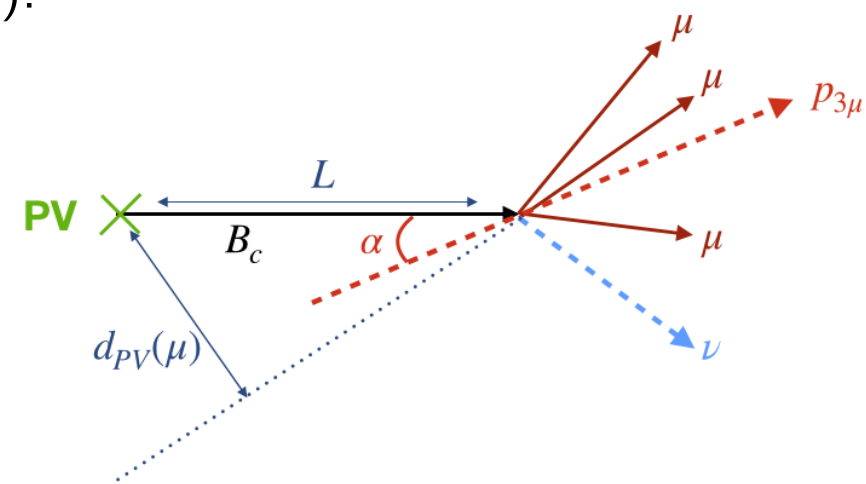
- Define samples w.r.t. trimuon sign (±1 or ±3) and J/ψ or trimuon mass sidebands
- MC for prompt J/ψ and non-prompt J/ψ (daughter of B^0, B^+, B_s)



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

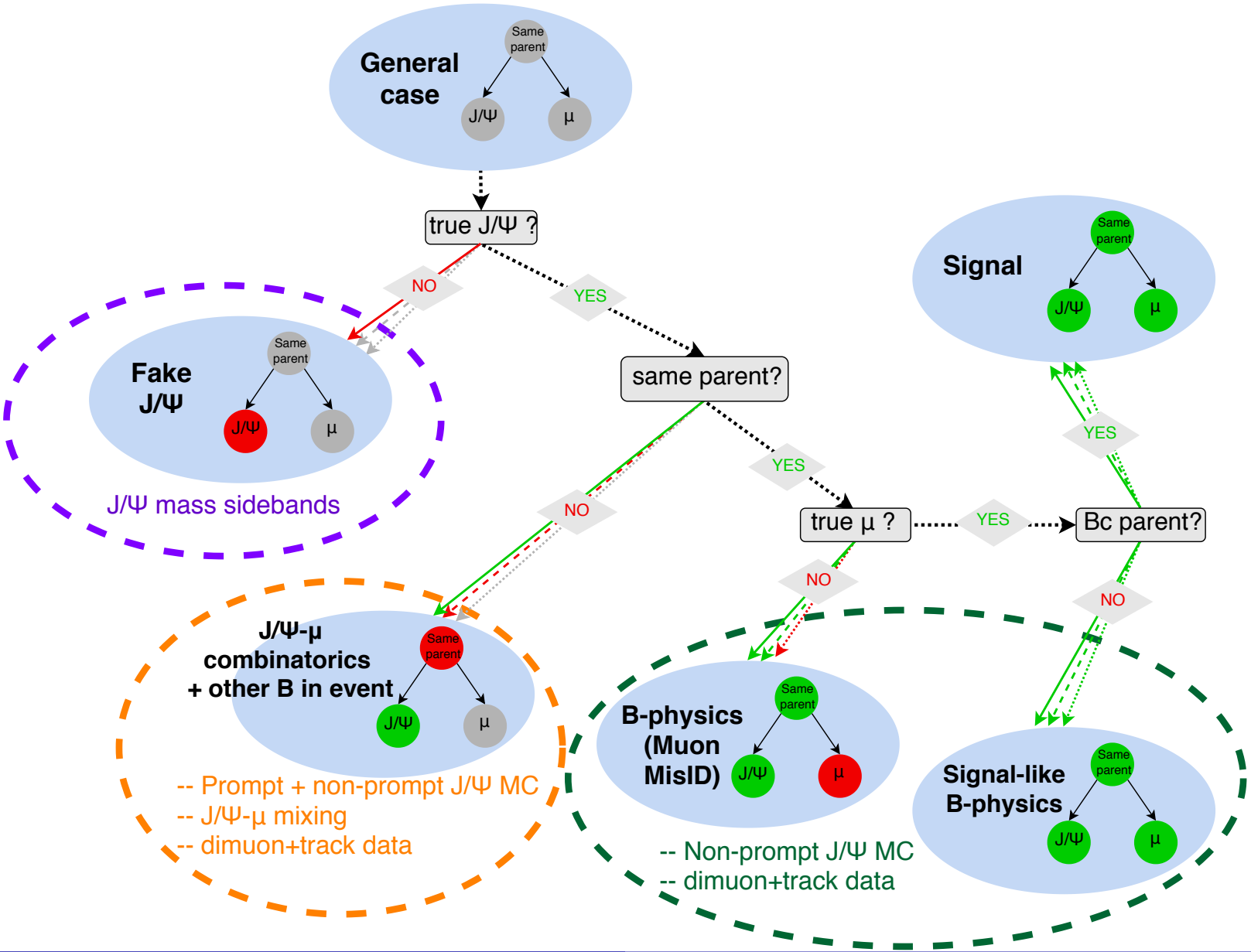
Analysis strategy

- Preselection with standard selections for muons, dimuons, charged tracks → B_c candidate = dimuon at J/ψ mass + μ pointing to same displaced vertex, total charge ± 1
- Use discriminant variables to improve signal significance, via MultiVariate Analysis (Boosted Decision Tree, 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 $p_\perp(\nu)$
  - ...



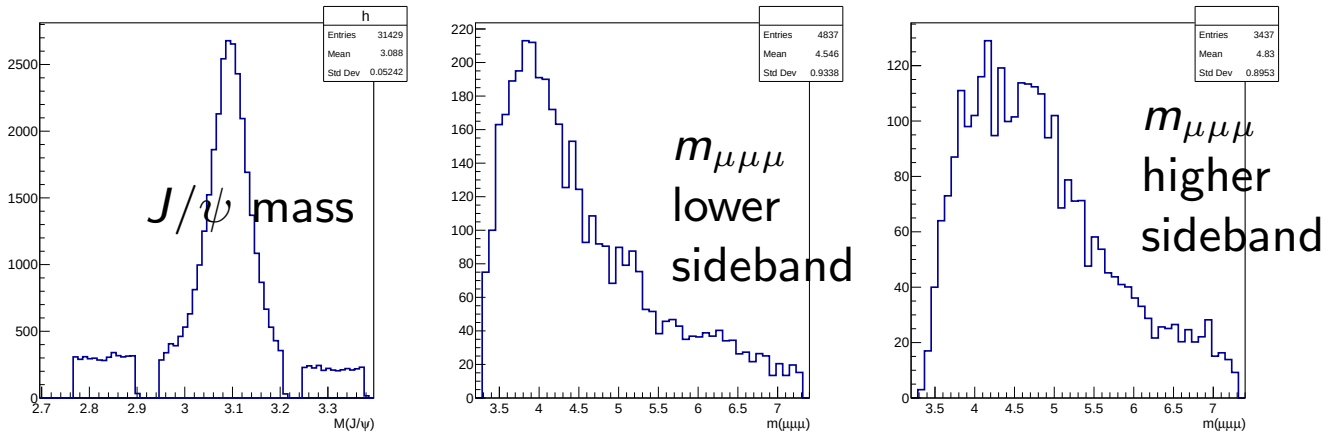
- Background studies: data-driven (sidebands, dimuon+track) + MC J/ψ
- Signal extraction from template fit of trimuon mass
  (but presented today: only pre-fit!)
- From signal yields + acceptance&efficiency corrections → $R_{PbPb}(B_c)$

Mastering the backgrounds



Fake J/ψ

- charge ± 1 trimuon → 2 opposite-sign dimuons = 2 possible J/ψ
- Cannot choose 'the closest to the J/ψ mass'
  (possible undersubstraction of fake J/ψ from under the J/ψ mass peak)
- Events with one dimuon in sidebands, and one in peak region: split between signal and background samples (w/ appropriate weights)
  → Obtain smooth trimuon mass distr. for lower and higher sidebands

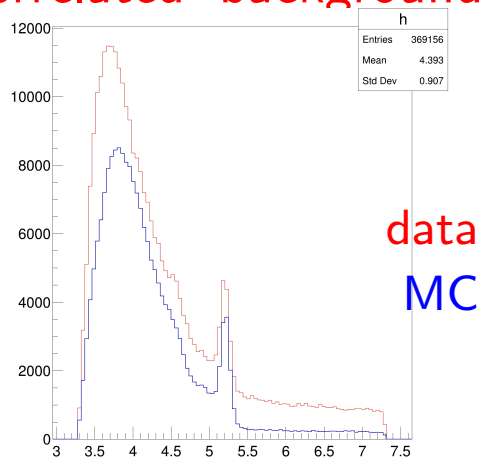


- Correct some variables for biased kinematics (incorrect dimuon mass)
- Will fit both sidebands, and take the average shape as extrapolation under the peak

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

- $K \to \mu$ misID $= 0.3 - 0.5\%$ and $\pi \to \mu$ misID $\simeq 0.1\%$
  $\rightarrow$ $B \to J/\psi X$ 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
  - Combinatorial J/ψ + (fake) muon
- BUT control region (high trimuon mass) shows underprediction of MC
  $\rightarrow$ Need data-driven methods for J/ψ+track 'uncorrelated' background

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



'Uncorrelated' J/ψ+track

Finding a shape for this background is enough

→ then, normalize with high trimuon mass control region

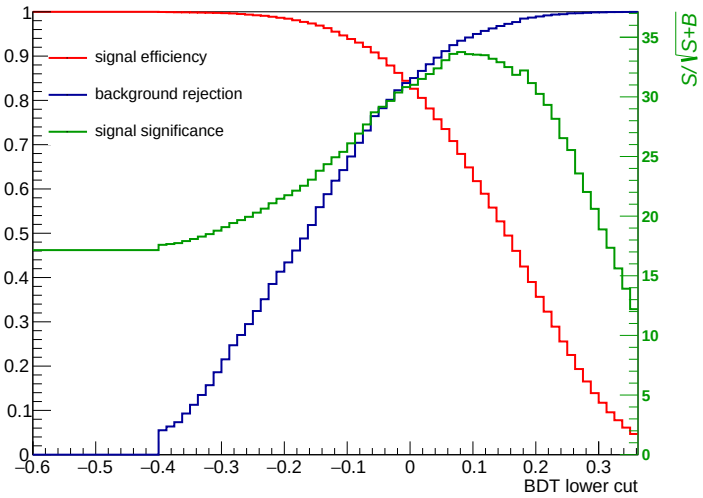
- Ad-hoc shape / shape parameters in the fit? → too high systematics
- In (non)prompt J/ψ MC: $J/\psi + \mu$ not from same gen decay
  → shape too wrong
- Dimuon+track data sample: better (and includes $B \to J/\psi X$ decays) but still imperfect shape
  → would need $p/K/\pi$ PID (impossible at CMS) 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)

pp preliminary result

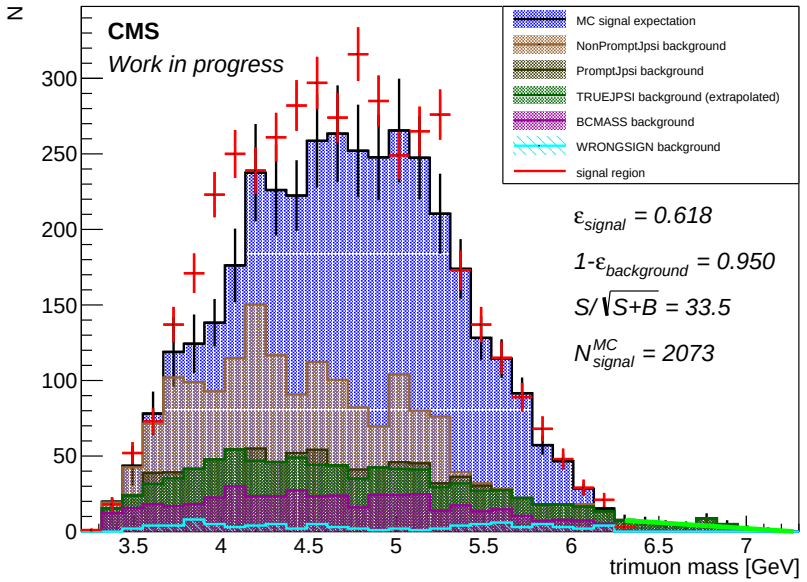
- Same sign $+++/---$ sample only shown for illustration
- More work needed on J/ψ-track combinatorics: here, ad-hoc shape extrapolated from high-mass control region
- J/ψ sidebands
- non-prompt J/ψ MC
- Signal MC B_c

- To improve BDT performance, will run BDT separately in categories: p_T (2 bins), rapidity (2 bins) ($\neq m_{J/\psi}$ resolution), and $m_{\mu\mu\mu}$ (2-3 bins) (very $\neq$ backgrounds)

Scan of BDT cut values



B_c candidates mass with valBDT>0.10



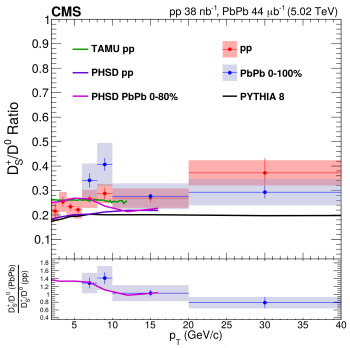
PbPb

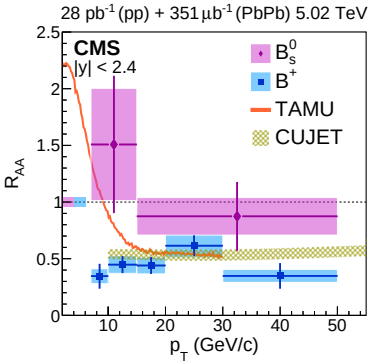
- 4 times less nucleon-nucleon equivalent luminosity in PbPb than pp
- Possible suppression
- More track background than in pp
  → Challenging to observe B_c signal!

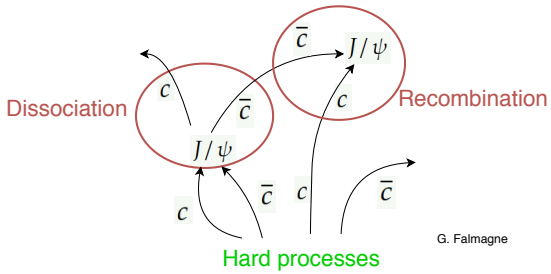
... but promising first results (too preliminary to be shown), that could lead to the first $R_{PbPb}(B_c)$ measurement

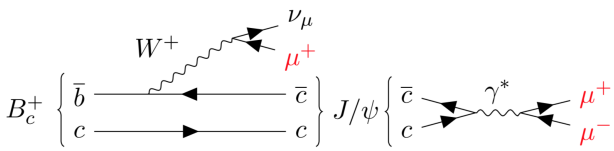
Conclusion and prospects

- Rich zoology of flavour studies in the QGP to be done at CMS!
  - All mentioned measurements: quantify *c* and *b*-quark energy loss
  - B_s/B and D_s/D: Strange hadronization/enhancement/nPDF
  - B_c/B: Isolate charm recombination? Discriminate recombin. models?
  - More distant goal: B_c/B_s to compare *c* recomb. and *s* enhancement?









→ Could achieve a complete description of 'heavy' mesons in QGP

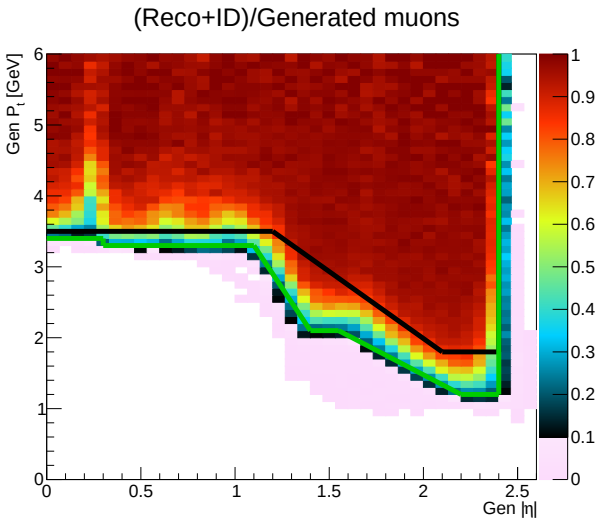
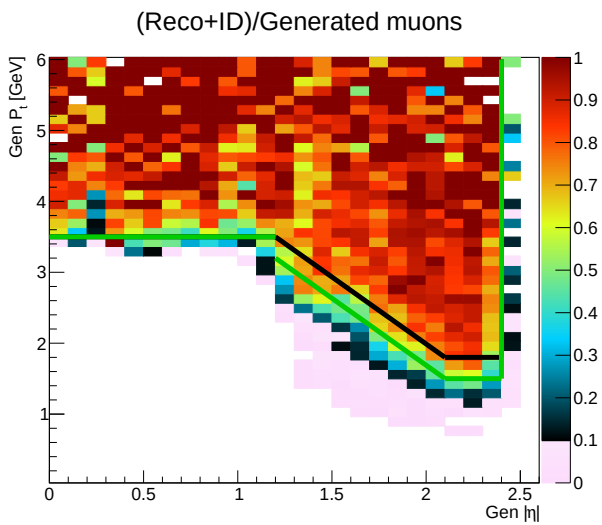
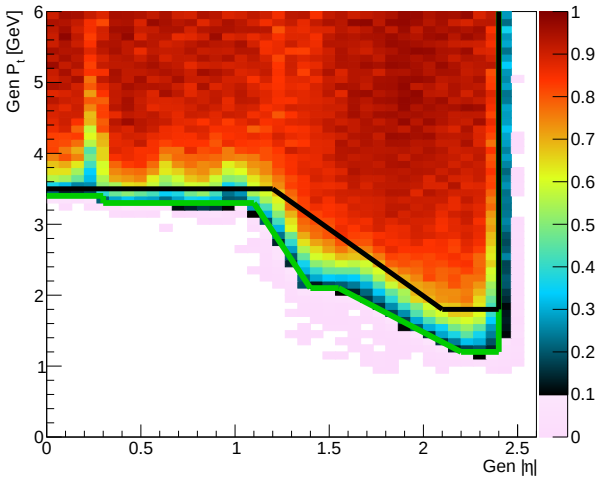
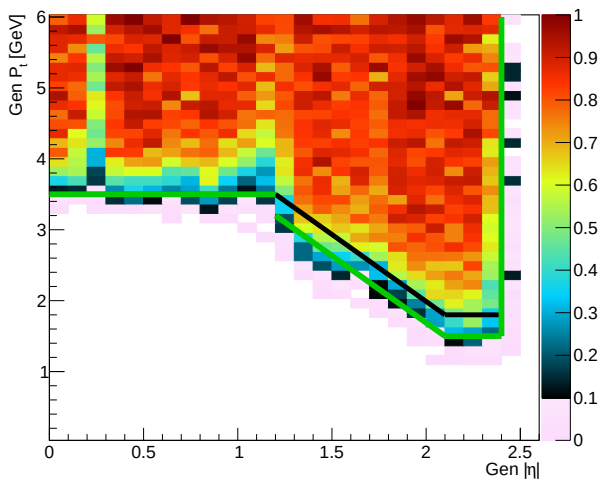
→ deeper understanding of QCD!

But: needs much more stats and manpower... Case for strong heavy ions program beyond Run 3!

BACKUP

2017-2018 data: new single muon acceptance cuts

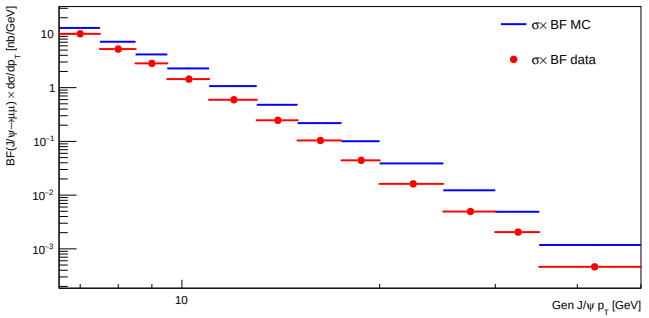
From single muon efficiency maps:

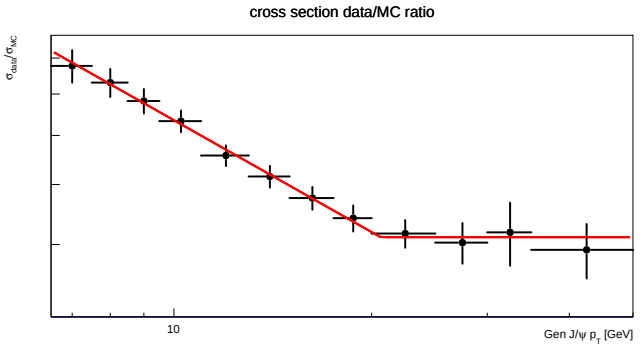
	Reconstruction + ID	Reconstruction + ID + trigger
pp 2017		
PbPb 2018		

BDT & strategy for normalization

- Apply BDT after basic selection
- BDT needs normalizations of signal & background samples
- As preliminary study, no fit of data is done: use a priori normalizations, even for signal MC, and compare with data
- Signal MC: scale to cross section from pp 7 TeV measurement (average from LHCb [1,2] and CMS [3]). Extrapolate to 5 TeV and to the whole phase space with BCVEGPY.
- (Non-)prompt J/ψ MC: use pp and PbPb cross sections from CMS meas. in same kinematic range, extrapolated for $p_T(J/\psi) < 6.5$ GeV [4]

pp, Prompt J/ψ





[1]: PRL.114.132001 (2015)
[2]: JHEP 2012,93(4)
[3]: CMS-PAS-BPH-13-002
[4]: EPJC 78 (2018) 509

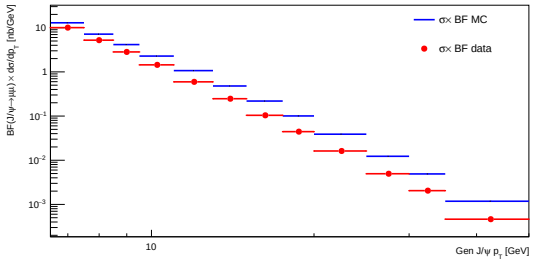
MC normalization for (non-)prompt J/ψ

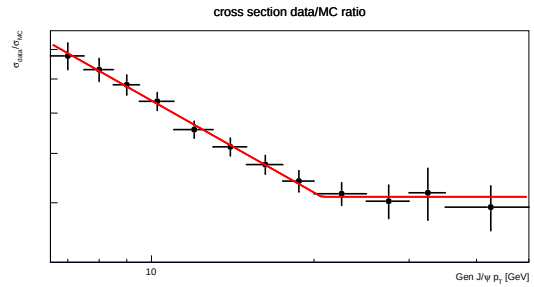
Scale to CMS data

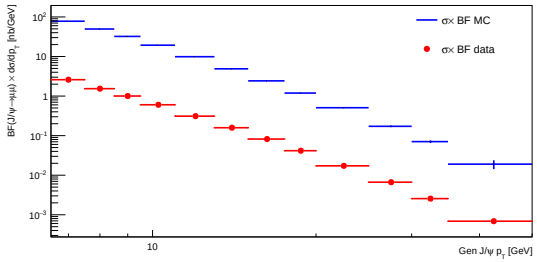
CMS-PAS-BPH-13-002

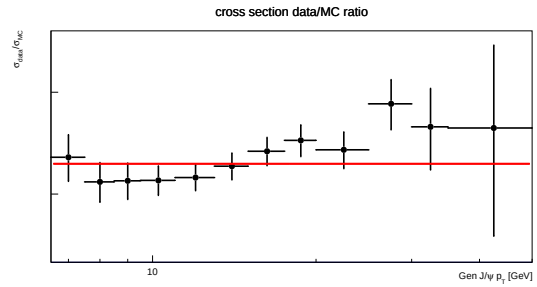
Prompt | **Non-prompt**

pp

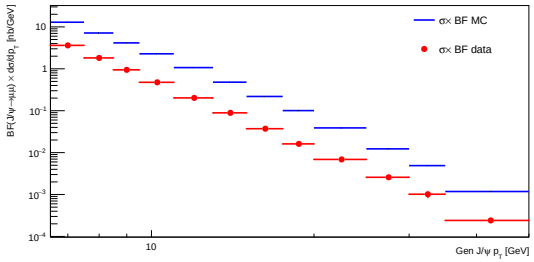


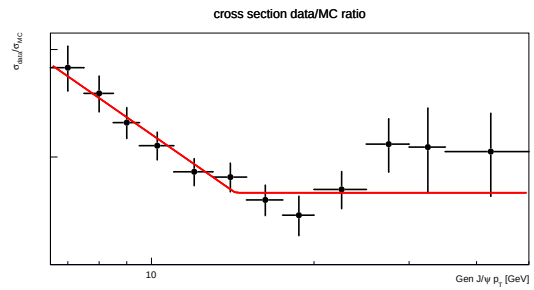


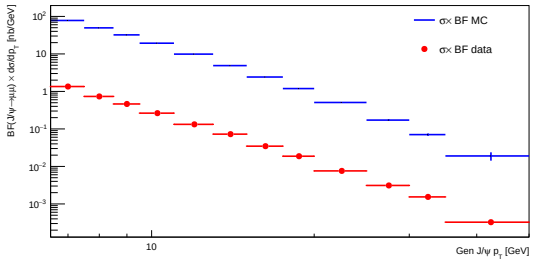


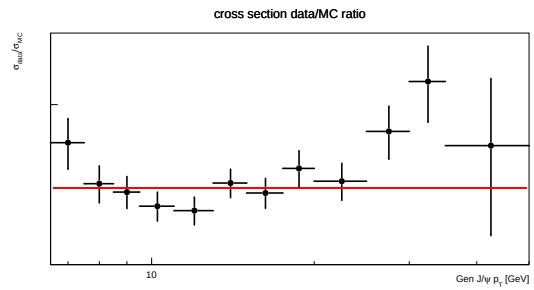


PbPb



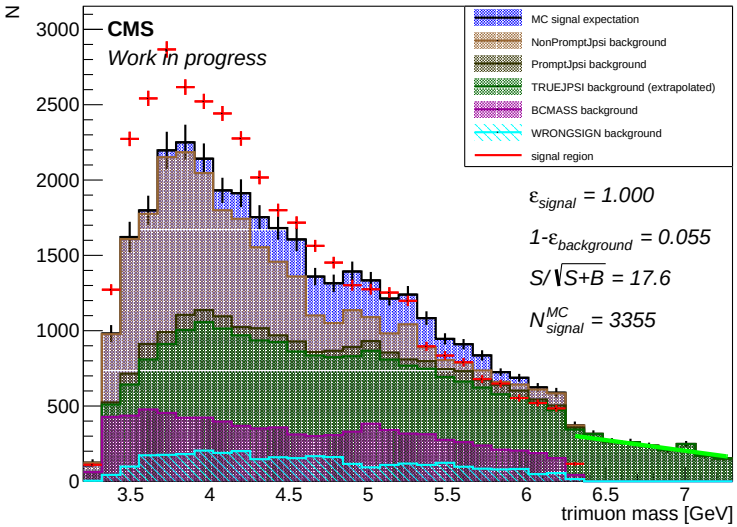




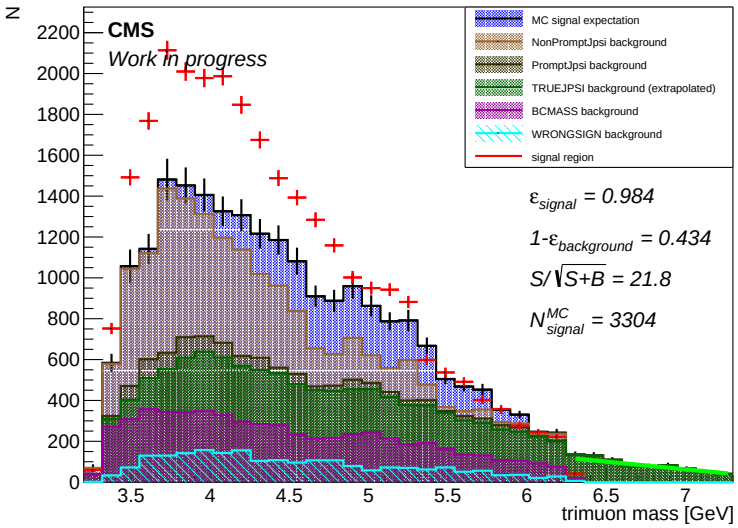


pp trimuon mass for various BDT cuts

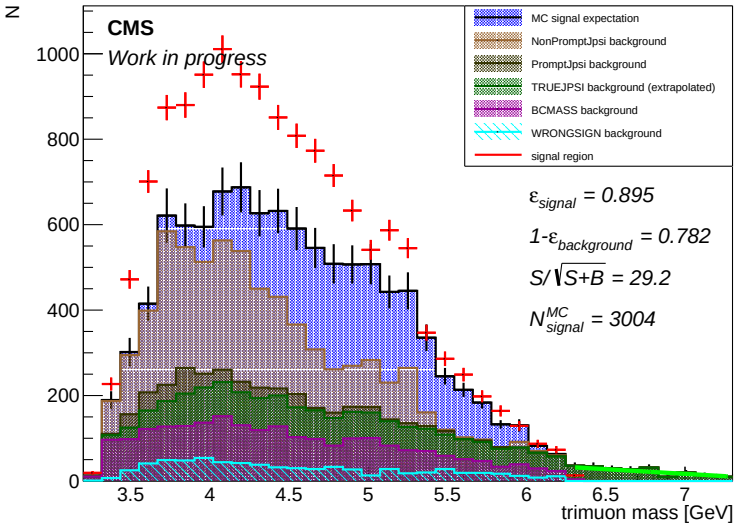
B_c candidates mass with valBDT>-0.40



B_c candidates mass with valBDT>-0.20



B_c candidates mass with valBDT>-0.05



B_c candidates mass with valBDT>0.25