Studying the quark-gluon plasma with CMS detector:

The B_c meson production in heavy ion collisions

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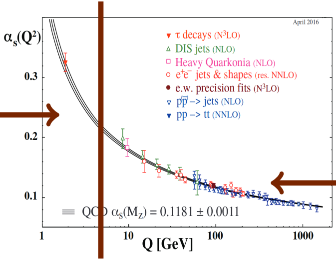
QCD and color confinement (the racist theory)

- Quantum Chromodynamics (QCD) governs the strong interaction, bounding nuclei together

We are slaves of hadrons!
Please save us!

- Stability of nuclei ↔ quarks are bound together ↔ all observed objects carry no colour charge ('white') = confinement

- Confinement
- large distances
- low energy
- quarks/gluons (= partons) are strongly interacting

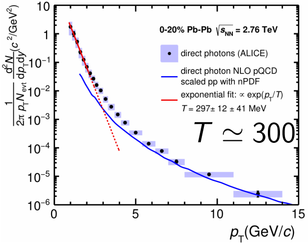


- Deconfinement
- Sub-nucleon distances
- high energy/temperature
- partons are 'free'? → quark-gluon plasma (QGP)?

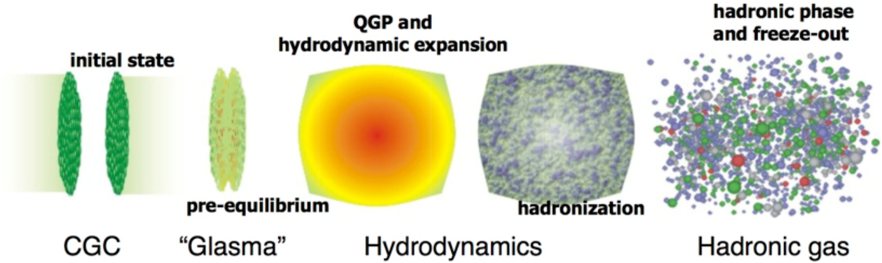
The quark-gluon plasma

- QCD at very high temperature
  ⟶ color deconfinement
  ⟶ quarks and gluons move freely
  in a quark-gluon plasma (QGP)
- Present in neutrons stars
  and first μs after Big Bang
- Reproducible in **heavy ion collisions**!

Blackbody photon radiation



$T \simeq 300$ MeV



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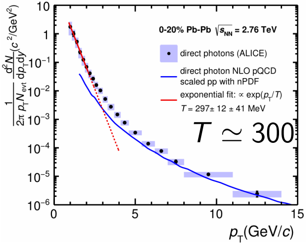

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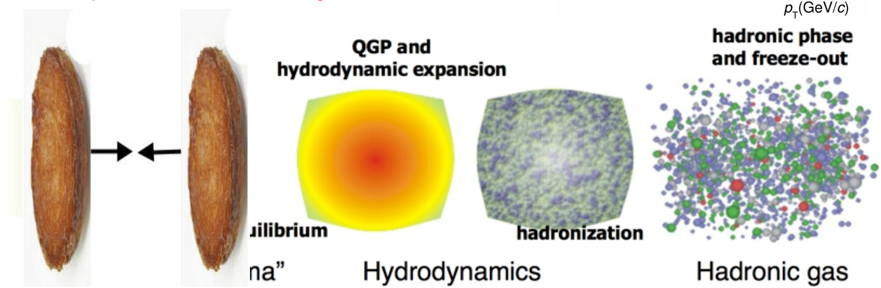

Heavy quarks to probe the QGP

- Standard Model QCD... Not fully understood yet!
  How to probe this new state of matter?
- Heavy quarks (b and c) are excellent probes:
  - Produced in hard collisions = before QGP expands
    & lifetime before decay $\gg$ QGP lifetime
    ⟶ brings information on the **whole QGP history**
  - Mass $\gg$ (QGP temperature $\simeq \Lambda_{QCD}$)
    ⟶ Separation of scales
    ⟶ easier (perturbative) calculations/observables
- Quantify/discriminate effects of the medium on these probes
  ⟶ fundamental properties of the medium :
  thermodynamics/transport/bound states...

The 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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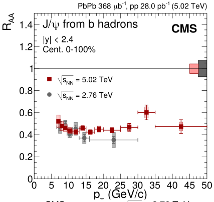
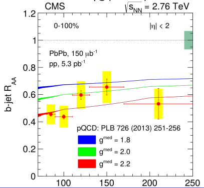
J/ψ from b decays

EPJC 78 (2018) 509

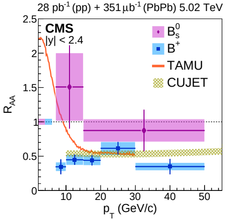


b-jets

PRL.113.132301 (2014)



B_s^0 and B^+ exclusive decays



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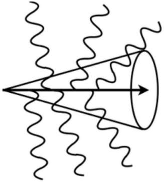
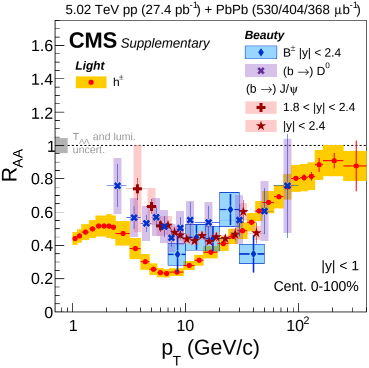
$$R_{PbPb} = \frac{\text{PbPb XS, normalized to nucleon-nucleon collisions}}{\text{pp cross-section}}$$

Inclusive charm/beauty	**VS**	**Exclusive heavy decays**
✓ High stats		✗ Low stats
✓ Total quark cross-sections		✓ Precise flavour content
✗ No meson flavour discrimination		✓ Clear decay kinematics
✗ Smeared kinematics		✓ Clean samples (resonances + PID)
⟶ Global medium properties		⟶ Detailed insight into medium dynamics

An effect of QGP: parton energy loss

- Heavy quarks lose energy in the QGP (gluon radiation, elastic collisions). However:
  - Smaller energy loss than gluons, due to smaller color charge
  - Smaller energy loss than light quarks, due to possible dead-cone effect (relevant at low p_T)



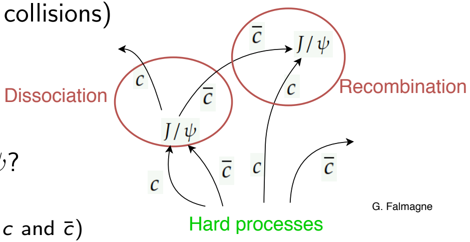


$\rightarrow$ $1 > R_{AA}(B) > R_{AA}(D) > R_{AA}(h^{\pm})$...

Where does the B_c fit in this picture?

Recombination with charm?

- In LHC PbPb central collisions:
  up to 100-1000 charm quarks produced !
  (from uncorrelated nucleon-nucleon collisions)



- 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)
  - ...

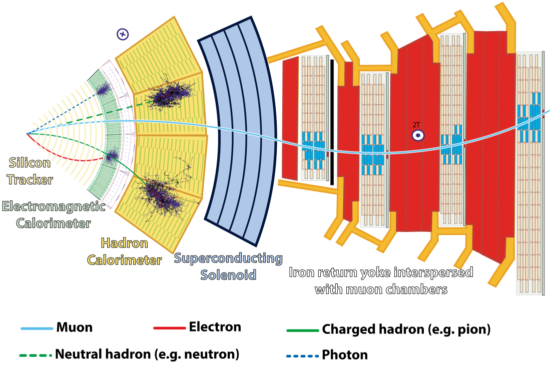
- B_c difficult to produce in 1 hard collision: need a $b\bar{b}$ and a $c\bar{c}$ pair.
  ⟶ If a b quark can recombine with charm in the medium ...
  dramatic augmentation!
  ⟶ Could bring new insights/discriminate on recombination mechanisms!

Compact Muon Solenoid

✓ Excellent muon detection

✓ Excellent secondary vertex reconstruction

✗ Strong longitudinal magnetic field
→ Limited low $p_{\perp}$ muon acceptance



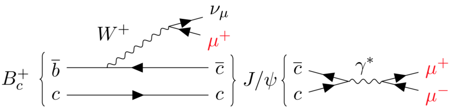
- data: RunII at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, pp 2017 (300 pb^{-1}) and PbPb 2018 (1.5 nb^{-1})
- MC: PYTHIA8 + GEANT4 + EVTGEN
- B_c signal MC: use specific generator BCVEGPY before PYTHIA

B_c^+: a new and challenging QGP probe

- Possible large recombination of B_c! Caveats:
  - Mostly for $p_T \lesssim m_{B_c}$ (hard with CMS)
  - Added to suppression mechanisms

- Two different heavy quarks bound
  ⟶ original view of energy loss VS flavour

- Challenge of B_c exclusive decay measurement: low yields!
  - $p_T(B_c)$ peaks at 3 GeV ⟶ try to lower p_T thresholds
  - Use partially reconstructed tri-muon channel ($\mathcal{B}_{muonic} = 20 \times \mathcal{B}_{hadronic}$)



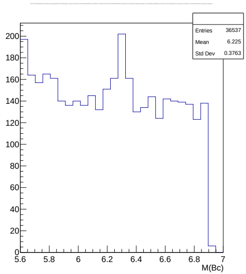
  - Small B_c displacement from primary vertex
    ⟶ Optimize signal selection with BDT (Boosted Decision Tree)

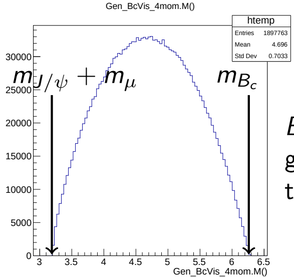
B_c^+: Hadronic or semi-leptonic channel?

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 + higher background + potential suppression... ⟶ hopeless in PbPb
  - Non-peaking signal ⟶ have to master the backgrounds!

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





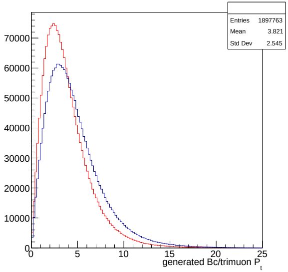
$B_c^+ \to \mu\mu\mu$
generated
trimuon mass

Preliminary: lowering p_T thresholds

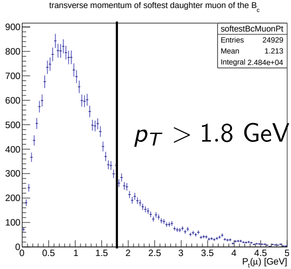
Low cross section:

- 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

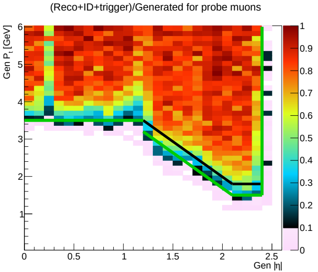
p_T of generated B_c
p_T of generated trimuon



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



New kinematic acceptance (for triggering muons)

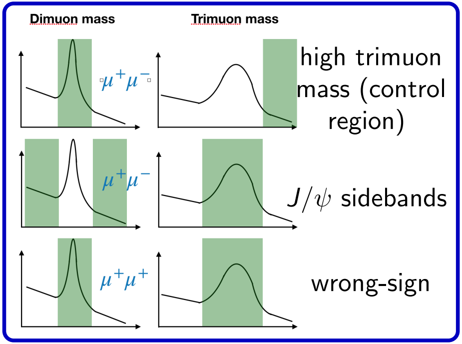


Used samples

- pp and PbPb at 5.02 TeV, with dimuon (J/ψ) trigger
- B_c signal MC: from BCVEGPY2.2 specific generator

For background studies:

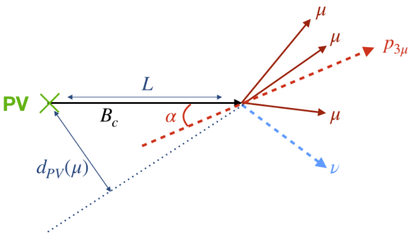
- Define samples w.r.t. trimuon sign (±1 or ±3) and J/ψ or trimuon mass sidebands



- For track$\rightarrow\mu$ mis-identification:
  - MC for prompt J/ψ and non-prompt J/ψ (daughter of B^0, B^+, B_s) for correlated background
  - dimuon+track data (with $\simeq$ muon selection for the track)
  - flipped-J/ψ data (where J/ψ is rotated in same event) for uncorrelated background

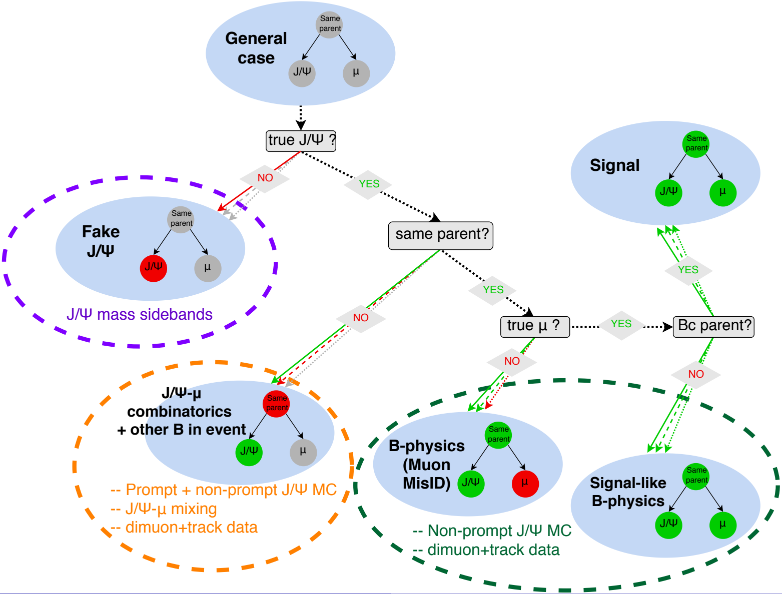
Analysis strategy

- Preselection: standard (loose) for muons and dimuons
  ⟶ 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 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 $p_\perp(\nu)$
  - ...



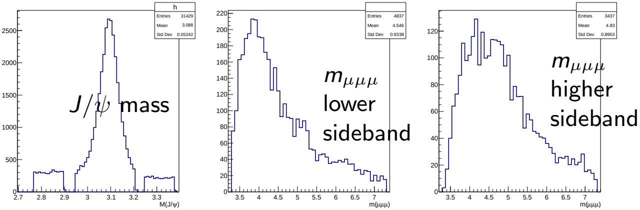
- Background studies: data-driven (sidebands, dimuon+track) + MC J/ψ
- Signal extraction: determine shapes for the different backgrounds
  ⟶ template fit of trimuon mass (where only normalizations are free)
  (but presented today: only pre-fit!)
- From signal yields + acceptance&efficiency corrections ⟶ $R_{PbPb}(B_c)$

Mastering the backgrounds



Fake J/ψ

- charge ± 1 trimuon $\longrightarrow$ 2 opposite-sign dimuons = 2 possible J/ψ
- Cannot choose 'the closest to the J/ψ mass', or biases $M(\mu\mu)$ shape (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 (with appropriate weights)
- Correct some variables for biased kinematics (from incorrect dimuon mass)



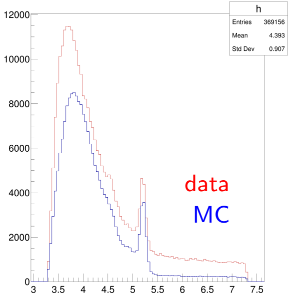
- Will fit both sidebands (with error function + decreasing exponential), and take the average shape as extrapolation under the peak

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

- *track* $\to \mu$ misID is of order $= 0.1 - 0.5\%$
  ⟶ $B \to J/\psi\, X$ decays give high background (e.g. $B^+ \to J/\psi\, K^+$)
- Obtained with non-prompt J/ψ MC
- This MC *should* also describe:
  - J/ψ + track from other displaced vertex ($\bar{b}$ from the $b\bar{b}$ pair)
  - Combinatorial: J/ψ + random track
- BUT control region (high trimuon mass) shows underprediction of MC!

  ⟶ Need data-driven methods for J/ψ+track 'uncorrelated' background

Problem shows as well in dimuon+track data vs MC →



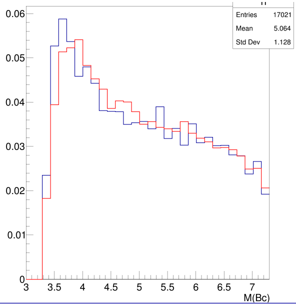
'Uncorrelated' J/ψ+track

Goal: find a shape for this background
(then, normalize with high trimuon mass control region)

- From (non)prompt J/ψ MC: shape too wrong
- Dimuon+track data: still imperfect shape (and includes correlated $B \rightarrow J/\psi X$)
  ⟶ would need to extract misID probabilities from data
  + probability to be K or π (impossible at CMS)
- Current method: consider all displaced J/ψ, flip the direction of their momentum and vertex displacement, and run trimuon analyzer

J/ψ direction flipping

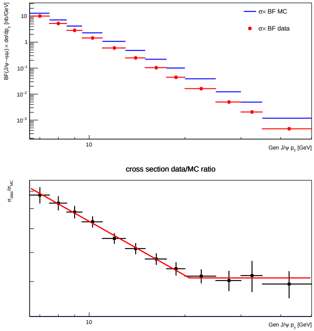
- To describe combinatorial J/ψ+track background, can rotate by some angle:
  - The dimuon momentum direction
  - The dimuon flight distance (PV–secondary vertex segment)
- Then: look for a displaced trimuon (usual business)
- Does the rotation angle change the resulting shape? Or describe different (correlated) backgrounds?
- Example: compare the shapes from same side η and opposite side η flipping
  ⟶ Get different normalizations, but similar trimuon mass shapes



BDT & strategy for normalization

- Apply BDT after loose pre-selection
- BDT needs normalizations of signal & background samples
  → use a priori normalizations

pp, Prompt J/ψ

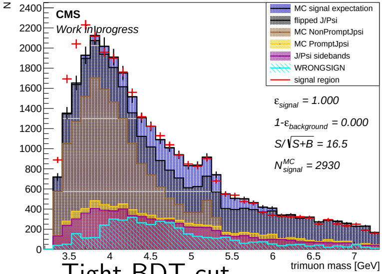


- Signal MC: scale to cross section from pp 7 TeV measurements (average from LHCb and CMS) extrapolated to 5 TeV
- (Non-)prompt J/ψ MC: use pp and PbPb cross sections from CMS measurement (extrapolated to low p_T)

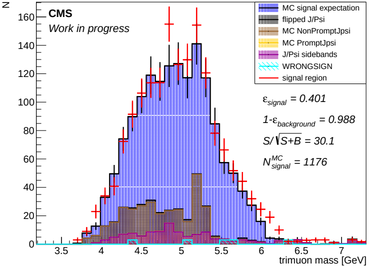
pp preliminary result

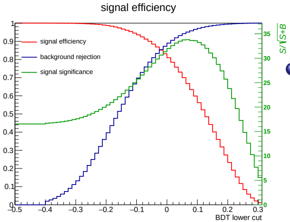
- Same sign $+++/---$ sample only shown for illustration
- More work needed on J/ψ-muon combinatorics: here, J/ψ flipping
- J/ψ sidebands
- non-prompt J/ψ MC ($\times 2$ for wrong misID in MC)
- Signal MC B_c

No BDT cut



Tight BDT cut





- To improve BDT performance, will run it separately in categories

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 observation of B_c in PbPb

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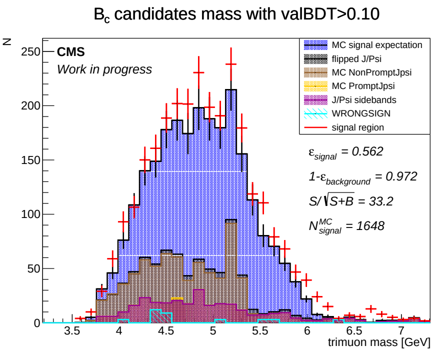
Conclusion

- pp analysis well advanced
- PbPb analysis first results seem promising
- Could lead to first measurement of $R_{PbPb}(B_c)$!

Will give an original view on:

- heavy quark energy loss
- charm recombination in the QGP



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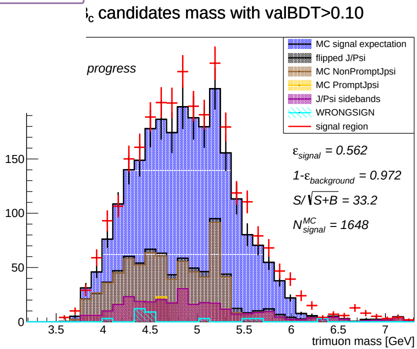
THANK YOU !



Will give an original view on:

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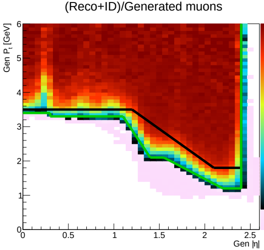
BACKUP

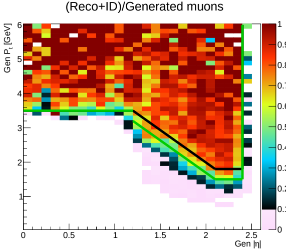
2017-2018 data: new single muon acceptance cuts

From single muon efficiency maps:

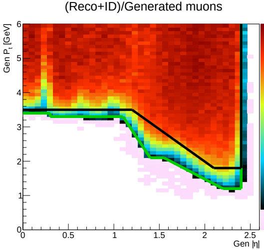
Reconstruction + ID | **Reconstruction + ID + trigger**

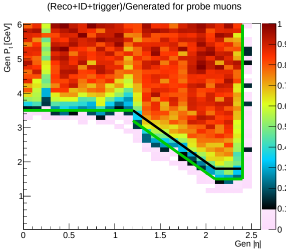
pp 2017





PbPb 2018





MC normalization for (non-)prompt J/ψ

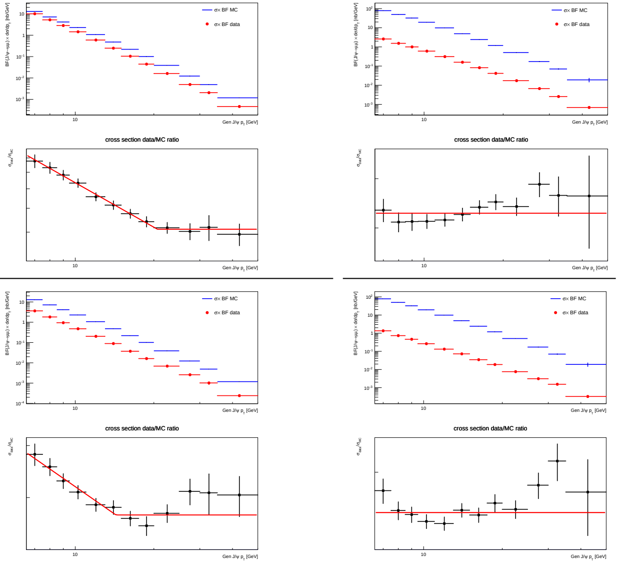
Scale to CMS data

CMS-PAS-BPH-13-002

Prompt **Non-prompt**

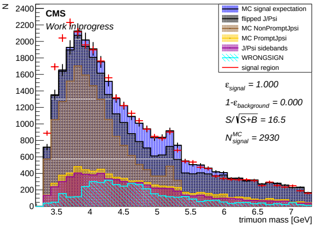
pp

PbPb

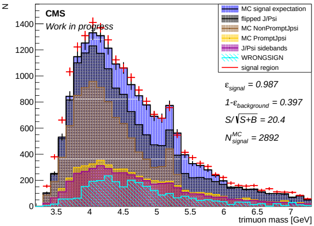


pp: trimuon mass for increasing BDT cuts

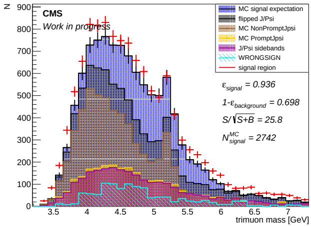
B_c candidates mass with valBDT>-0.50



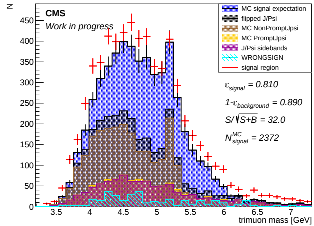
B_c candidates mass with valBDT>-0.20



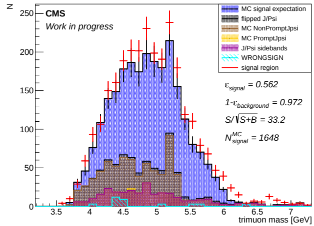
B_c candidates mass with valBDT>-0.10



B_c candidates mass with valBDT>0.00



B_c candidates mass with valBDT>0.10



B_c candidates mass with valBDT>0.25