Modification of B_u^+, B_s^0 and B_c^+ mesons in PbPb collisions with CMS detector

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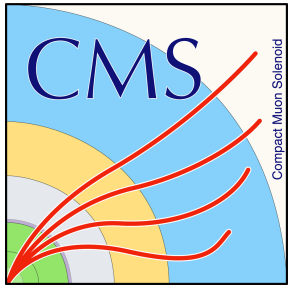
On behalf of the CMS collaboration

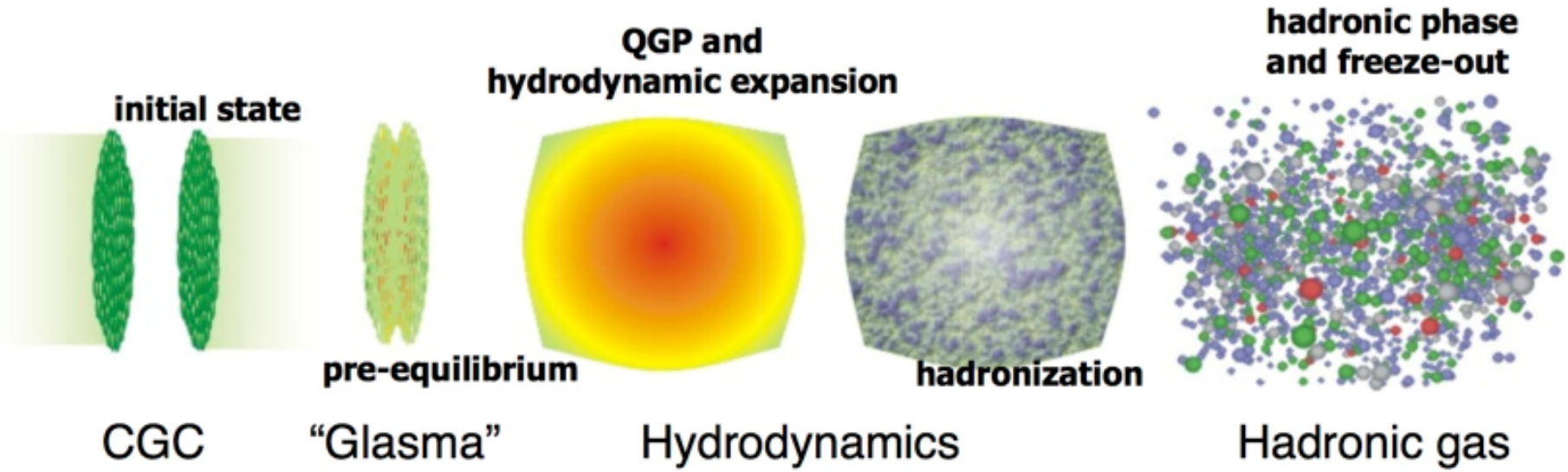


QGP France 2019

July 1st – 4th

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

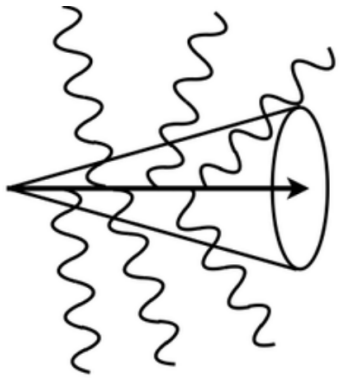
- QCD at very high temperature → deconfinement
  → quarks and gluons move freely in a quark-gluon plasma



- Heavy quarks produced on smaller time scales than QGP expansion
  → brings information on the **whole QGP history**
- This talk: **b quark**, bound with a u, s, or c quark.

Flavour dependence of 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)

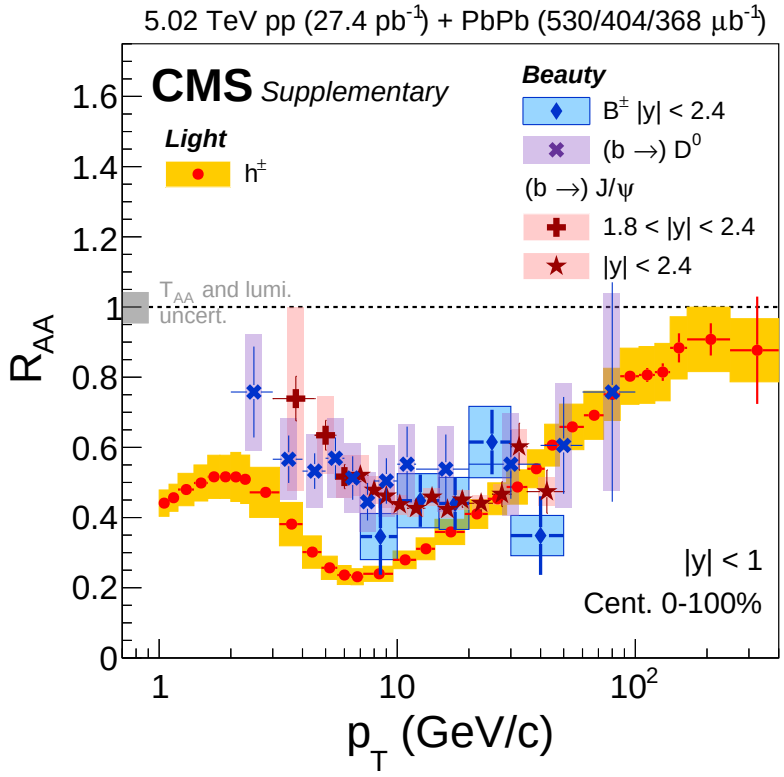


PLB 782 (2018)

EPJC 78 (2018)

JHEP 04 (2017)

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



Early interest in beauty at CMS: non-prompt J/ψ

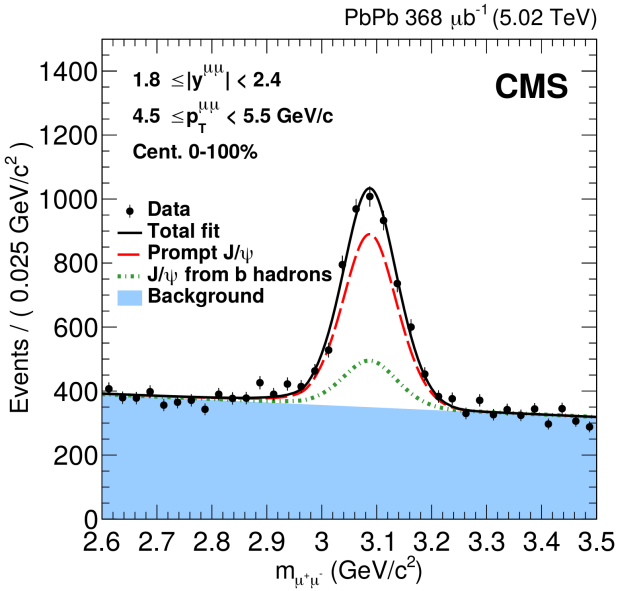
Run I (2.76 TeV): JHEP 05 (2012) 063
Run II (5.02 TeV): EPJC 78 (2018) 509

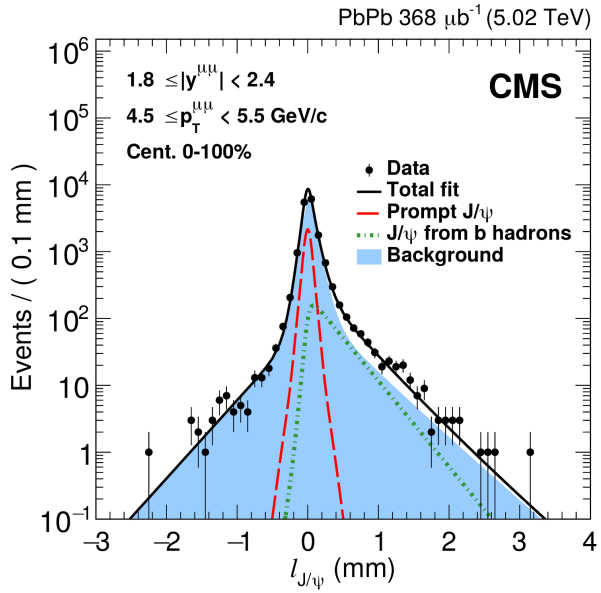
- J/ψ from b-hadron decays $\equiv$ measurable displacement from primary vertex
- Long B lifetime → J/ψ born outside of QGP → no colour screening
  → probes directly the b-quark energy loss
- Disentangles energy loss in open-beauty vs open-charm
  → insight into quark mass dependence of energy loss

2D fit of

- $m_{J/\psi}$
- Pseudo-proper length

$$L_{J/\psi} = L_{displacement} \frac{m_{J/\psi}}{|p_{\mu\mu}|}$$





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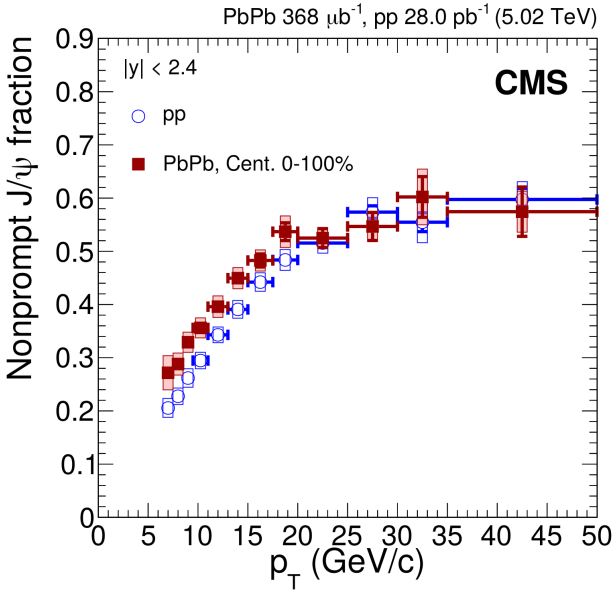
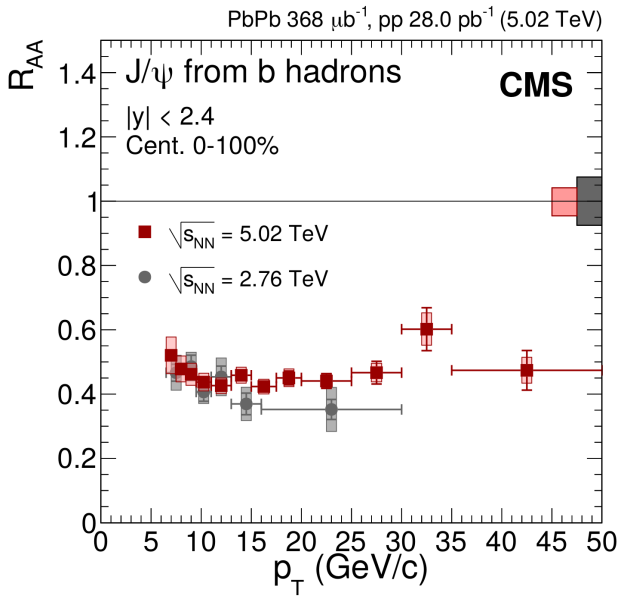
Run II (5.02 TeV): EPJC 78 (2018) 509

- Extract from 2D fit: $N_{J/\psi}$, $N_{\mu\mu\,bkg}$, and non-prompt fraction (all other parameters fixed from 1D data fits or MC fits)

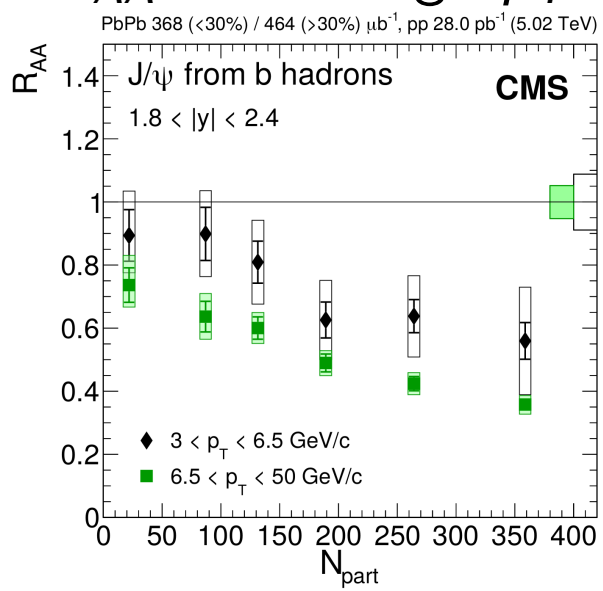
non-prompt fraction



$R_{AA}(p_T)$



R_{AA} low vs high p_T

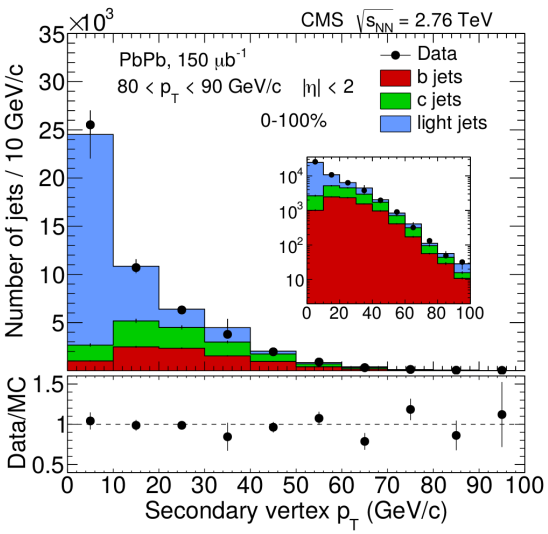


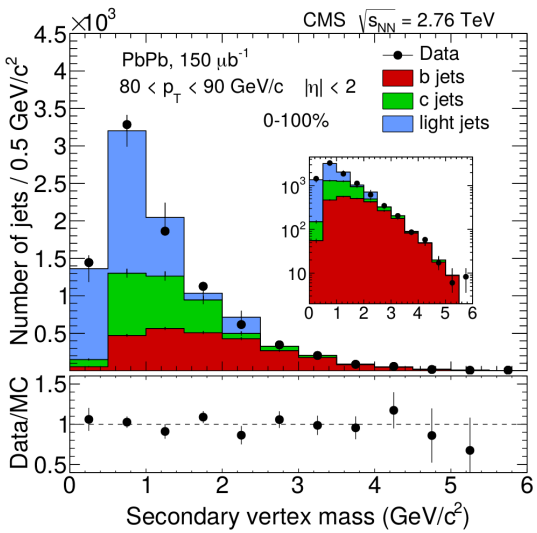
- R_{AA} at medium p_T: hierarchy with open charm and light hadrons R_{AA}?
- High p_T: radiative energy loss same than for light hadrons?
- Low p_T: less suppression than at high p_T

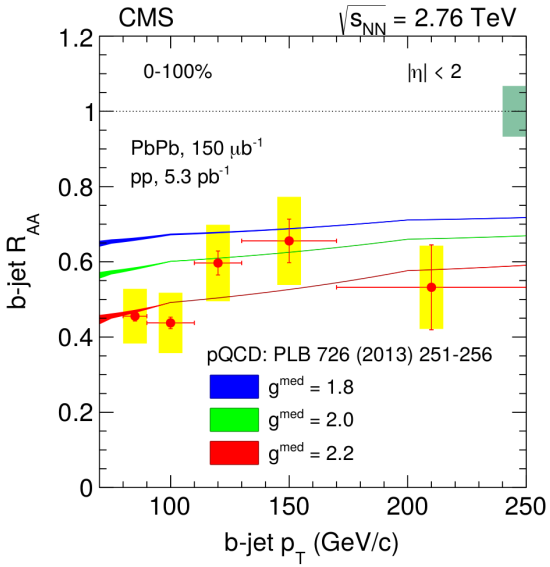
Early interest in beauty at CMS: b-jets

Run I: PhysRevLett.113.132301 (2014)

- b-jet $\equiv$ jet containing a displaced vertex, with mass constraints
- High p_T $\rightarrow$ suppression likely from radiative energy loss
- Caveat: part of b-jets come from gluon splitting (does not probe strictly b-quark energy loss)







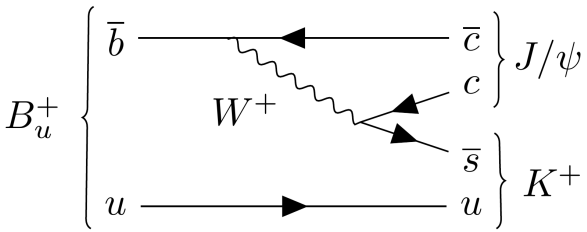
- Extracted jet-medium coupling consistent with that of inclusive jets
  $\rightarrow$ only mild mass dependence allowed at high p_T

Exclusive decays

- Inclusive: ✓ high stats but ✗ no flavour discrimination
  & large contamination from non-b partons & smeared kinematics
- Exclusive: ✗ low stats but ✓ clearer decay kinematics
  & exploits the golden $J/\psi \to \mu^+\mu^-$ channel

$B_u^+ \to J/\psi\ K^+$

PRL 119, 152301 (2017)

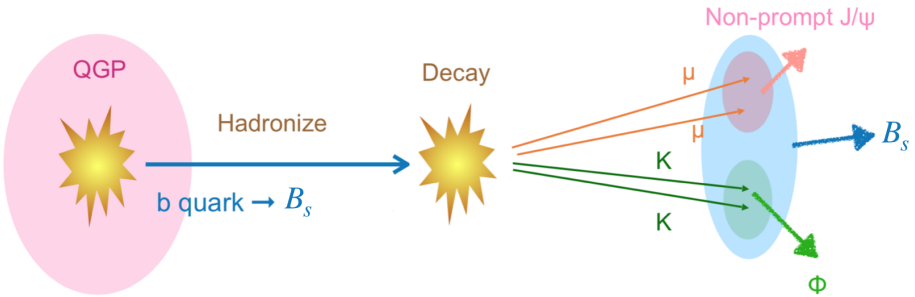


Exclusive b decay with highest stats

$B_s^0 \to J/\psi\ \phi$

$\phi \to K^+\ K^-$

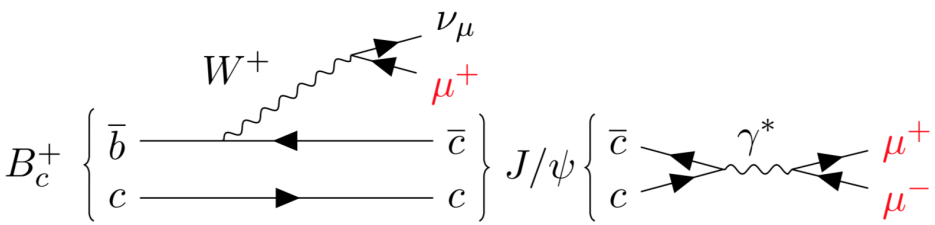
arXiv 1810.03022 (2018)



Compare suppression to that of B_u^+

$B_c^+ \to J/\psi\,\mu^+\,\nu$

Preliminary



Test recombination of b with c
use leptonic channel
→ 20× higher BF

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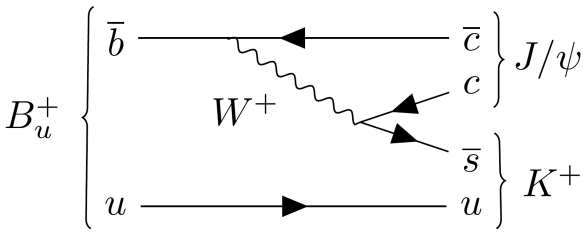

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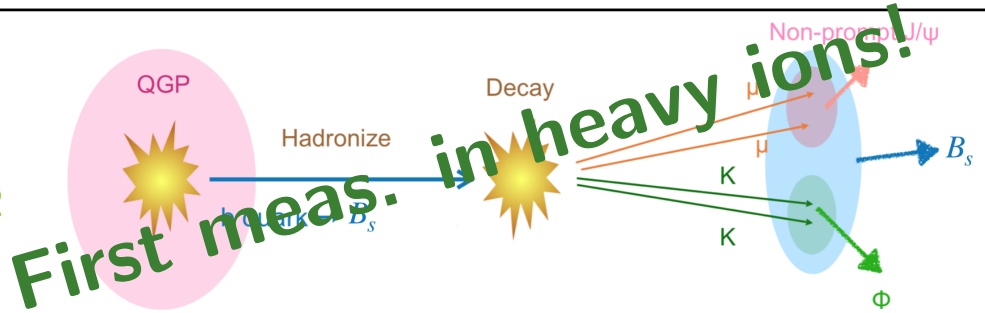

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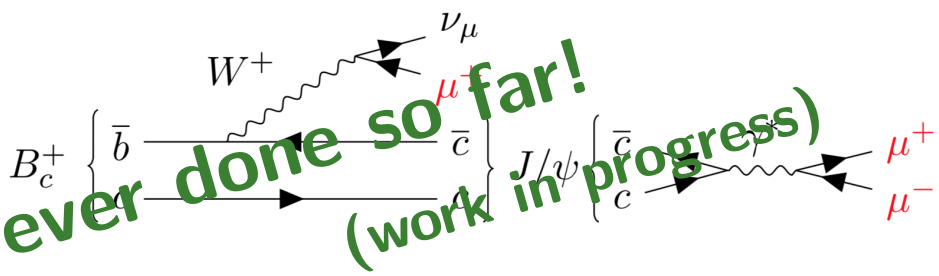

Test recombination of b with c
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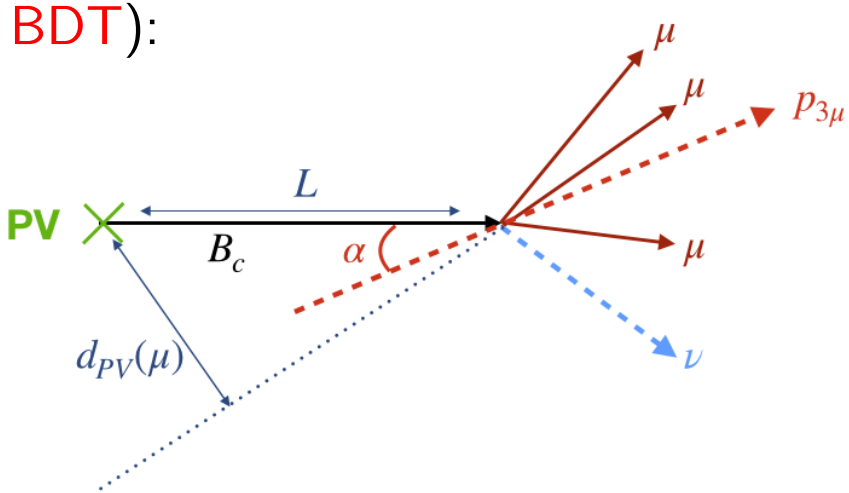
Common analysis strategy

- Measure $R_{\mathrm{PbPb}}(B_u^+,\ B_s^0,\ B_c^+)$ at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV with CMS Run II, and compare them
- Standard selections for muons, dimuons, charged tracks
- 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
  - $\sum_{i,j=1,2,3} |\Delta R(\mu_i, \mu_j)|$
  - ...

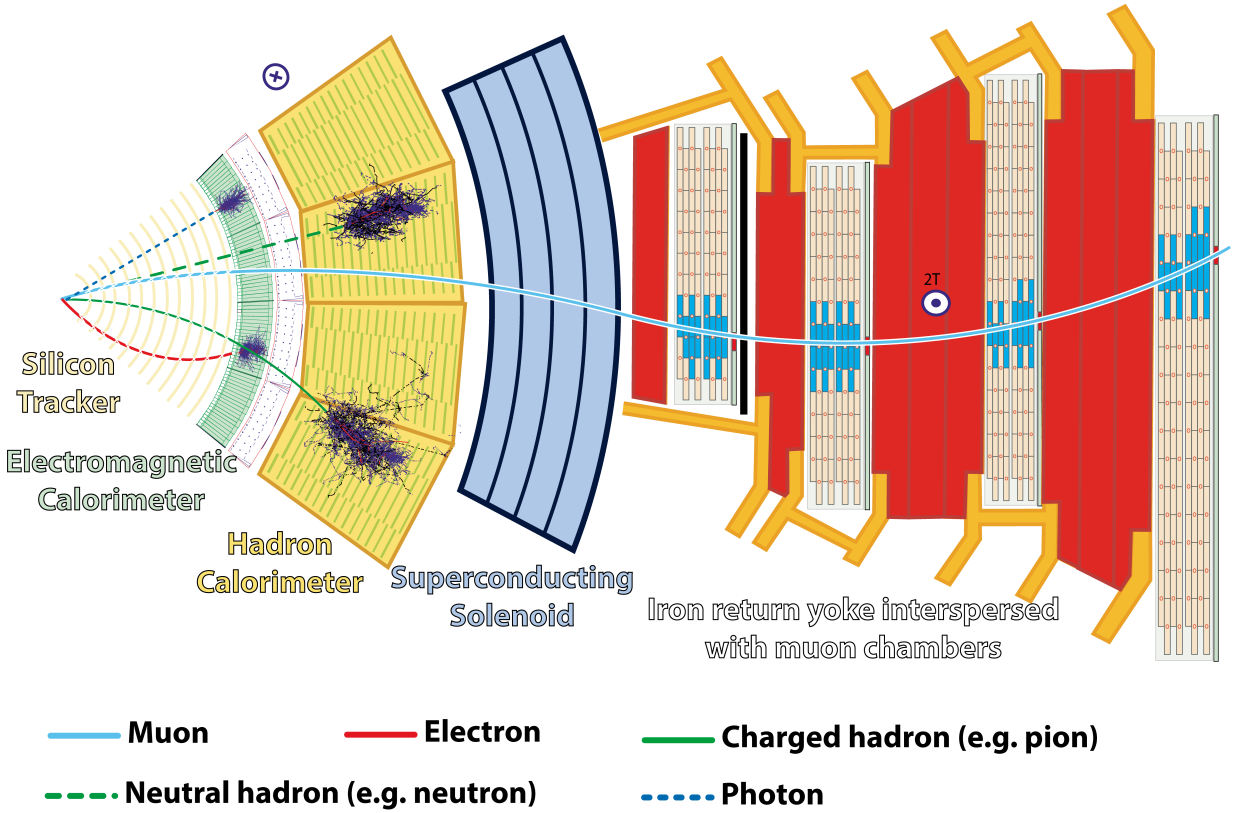


- Acceptance + efficiency + (partial) background studies with MC
- Part of background: data-driven studies
- Deeper background study necessary for B_c, because of partial reconstruction (non-resonant signal)

CMS data and MC samples

- Extensive use of CMS good displaced vertex reconstruction

- Kaons+Pions: tracker
- Muons: tracker + muon chambers



- data (B^+ and B_s): 2015 RunII at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, pp and PbPb
- data (B_c^+): High PbPb 2018 lumi ($4 \times \mathcal{L}_{2015}$) is key (and 2017 pp data)
- MC: PYTHIA8 + GEANT4 + EVTGEN + PHOTOS + HYDJET

Getting the cross sections and R_{PbPb}

$$\left.\frac{\mathrm{d}\sigma^{B}_{\mathrm{pp}}}{\mathrm{d}p_{\mathrm{T}}}\right|_{|y|<2.4} = \frac{1}{2}\frac{1}{\mathcal{B}\,\mathcal{L}}\,\frac{1}{\Delta p_{\mathrm{T}}}\,\left.\frac{N^{(B+\overline{B})}_{\mathrm{pp}}(p_{\mathrm{T}})}{\alpha_{\mathrm{pp}}(p_{\mathrm{T}})\varepsilon_{\mathrm{pp}}(p_{\mathrm{T}})}\right|_{|y|<2.4}$$

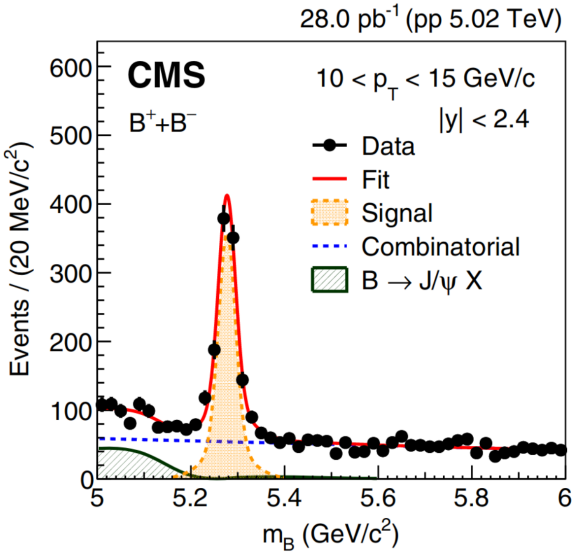
$$\left.\frac{1}{T_{\mathrm{AA}}}\frac{\mathrm{d}N^{B}_{\mathrm{PbPb}}}{\mathrm{d}p_{\mathrm{T}}}\right|_{|y|<2.4} = \frac{1}{2}\,\frac{1}{\mathcal{B}\,N_{\mathrm{MB}}\,T_{\mathrm{AA}}}\,\frac{1}{\Delta p_{\mathrm{T}}}\,\left.\frac{N^{(B+\overline{B})}_{\mathrm{PbPb}}(p_{\mathrm{T}})}{\alpha_{\mathrm{PbPb}}(p_{\mathrm{T}})\varepsilon_{\mathrm{PbPb}}(p_{\mathrm{T}})}\right|_{|y|<2.4}$$

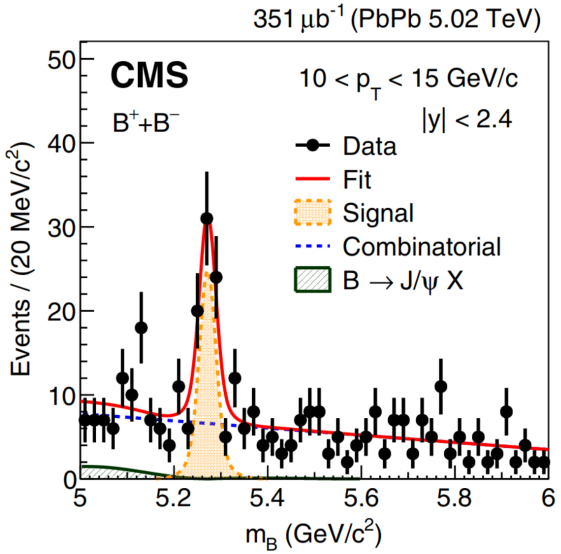
- $N_{\mathrm{pp,PbPb}}$ from the fits
- Branching fraction $\mathcal{B}$ from PDG
- Acceptance α and efficiency ε corrections calculated with MC
  - Comparison of MC and data distributions for discriminant variables
    → no bias for BDT

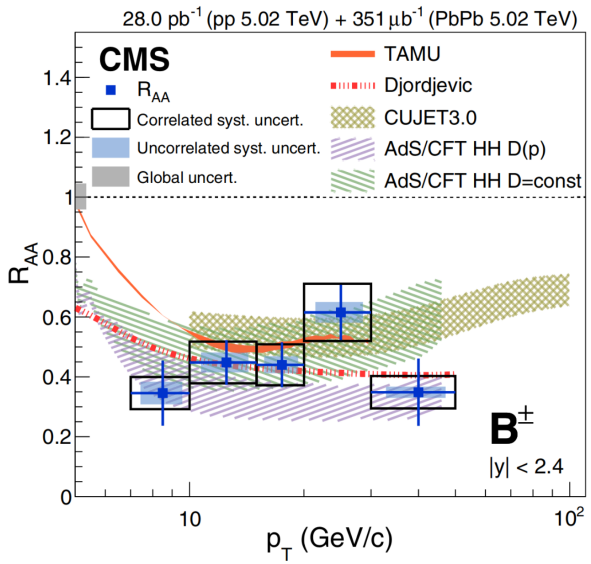
B_u^+ modification

- $B_u^+ \to J/\psi\ K^+$: combine $\mu + \mu +$ charged track with basic selection cuts
- $b \to J/\psi\ X$ background: shape from MC

- Standard systematics:
  fit shape, selection, MC distributions for acceptance×efficiency, ...







- Not enough stats to reject models yet, but incoming update with 2018 PbPb data!

A strange story for heavy mesons

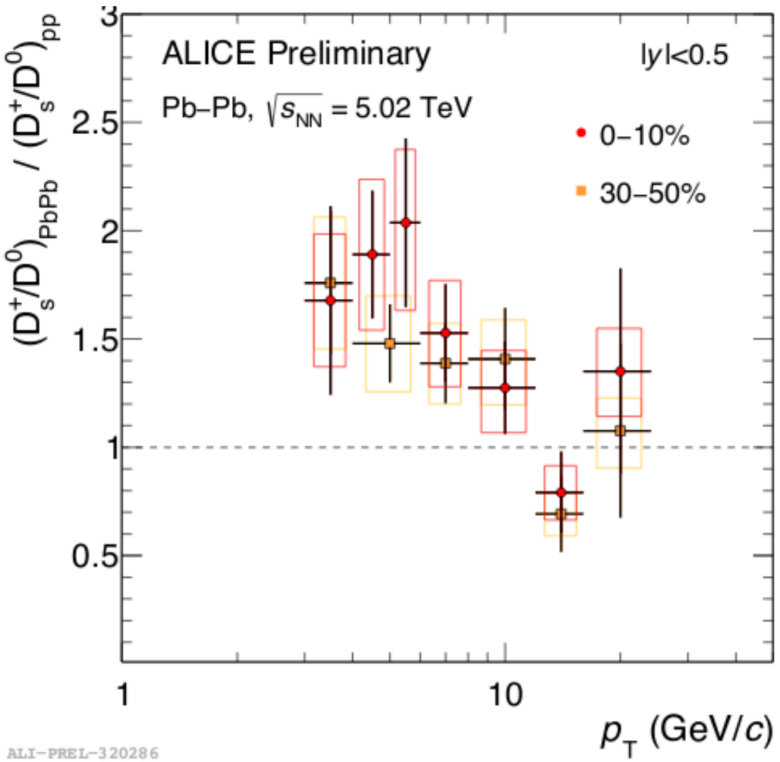
- **How strange** is the QGP?
  Known strangeness enhancement in the QGP
  → Enhancement of strange heavy mesons?
  Coalescence of heavy quark
  with a (thermal) s from the medium?

→ Compare B^+ and B_s^0 suppression,
to 'cancel' energy loss effects

Hint in ALICE: $R_{AA}(D_s^+) > R_{AA}(D)$

(JHEP 03 (2016) 082)

ALI-PREL-320286

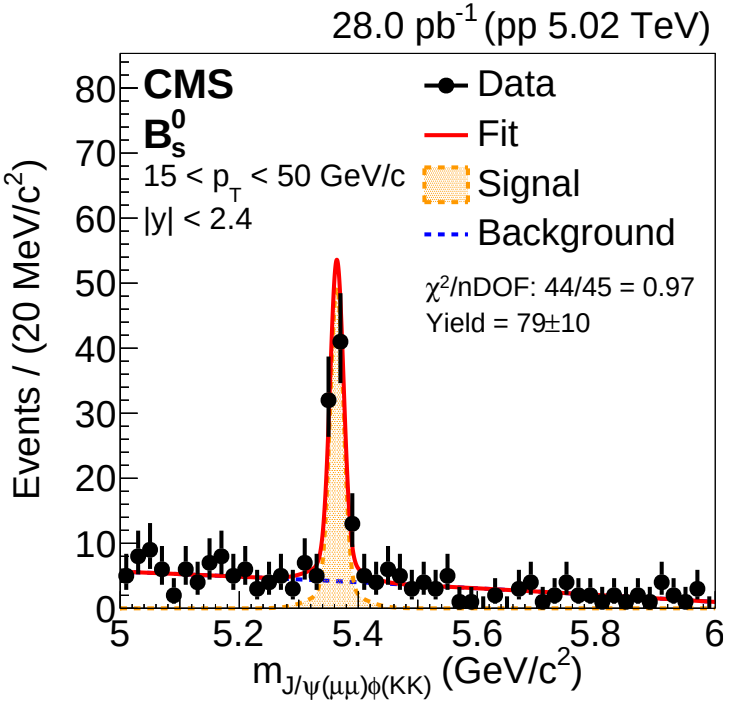


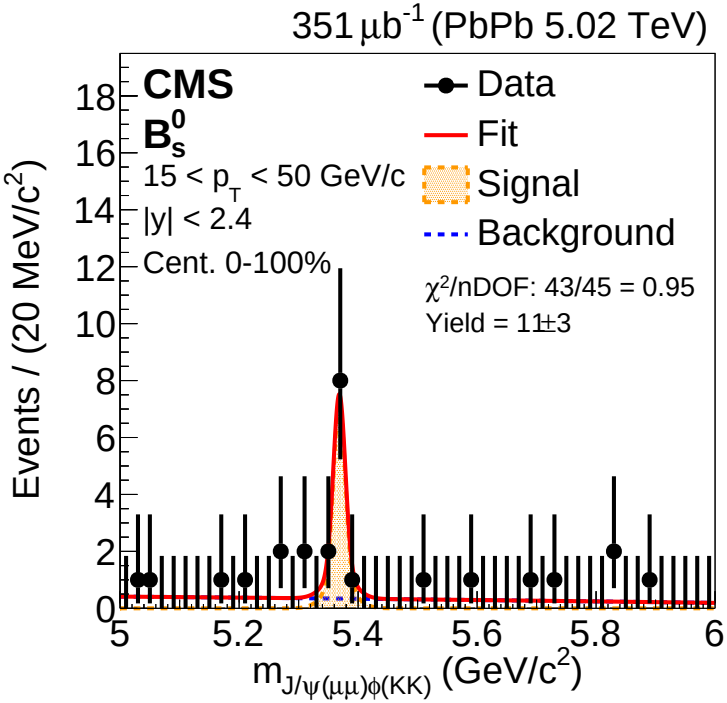
→ Measure double ratio $\frac{R_{PbPb}(B_s^0)}{R_{PbPb}(B^+)}$

B_s^0 reconstruction, selection, fitting

- $B_s^0 \to J/\psi\ \phi$ is reconstructed combining:
  - $J/\psi =$ dimuon with displaced vertex probability > 0.01
  - $\phi =$ displaced vertex fit of opposite-charge selected tracks
- Final selection done with BDT with discriminant variables
- $b \to J/\psi\ X$ background negligible thanks to tight ϕ mass cut

pp

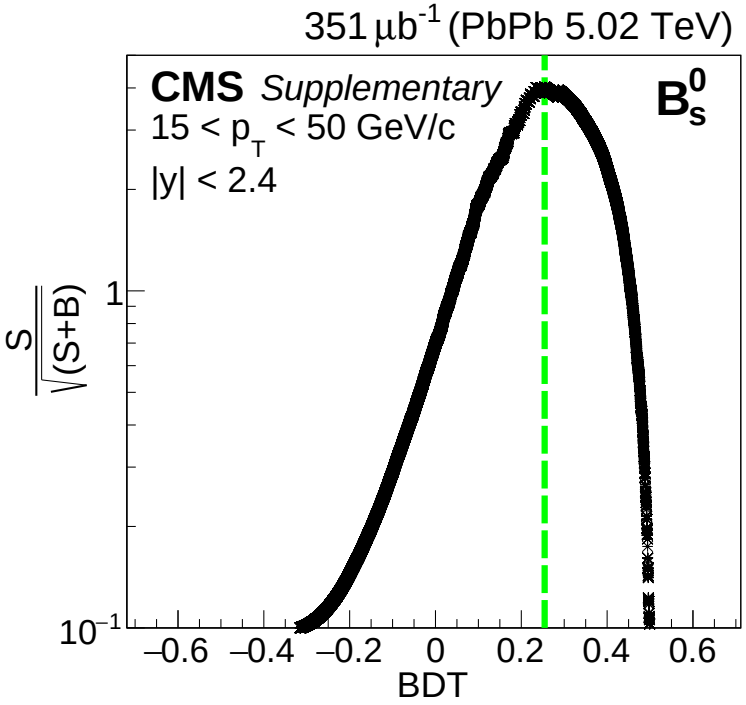




PbPb

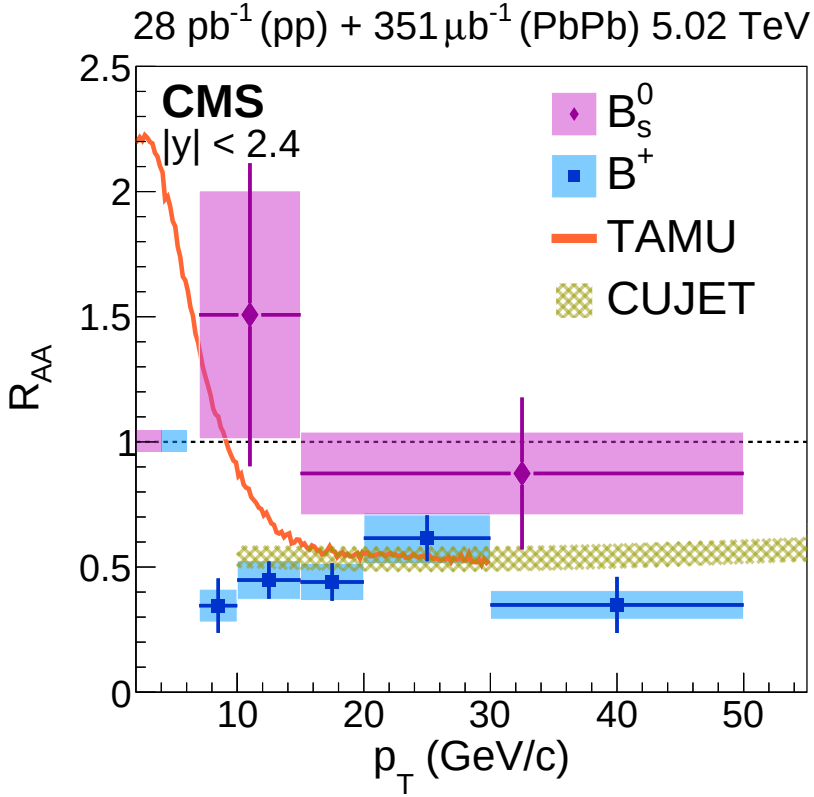
Focus on the Boosted Decision Tree

- Goal: maximize the statistical significance of B_s^0 signal
- Signal sample: B_s^0 MC (scaled to FONLL prediction)
  Background sample: B_s^0 mass sidebands in data
  (mostly random J/ψ and ϕ combinations)
- Input for BDT = variables with distinct signal and background shapes
- Gives BDT variable, which is cut to get the highest significance
- Checks with prompt J/ψ MC sample that background is not artificially peaking due to BDT



Results: B_s nuclear modification factor

$$R_{AA}(p_T) = \frac{1}{T_{AA}} \frac{dN^{B_s^0}_{PbPb}}{dp_T} \Big/ \frac{d\sigma^{B_s^0}_{pp}}{dp_T}$$



Comparison with:

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

→ $R_{AA}(B_s^0)$ consistent with 1,

but uncertainties leave room for possible enhancement or suppression

Results: ratio of B_s and B modification factors

Some uncertainties cancel in double ratio $R_{PbPb}(B_s^0)$ / $R_{PbPb}(B^+)$

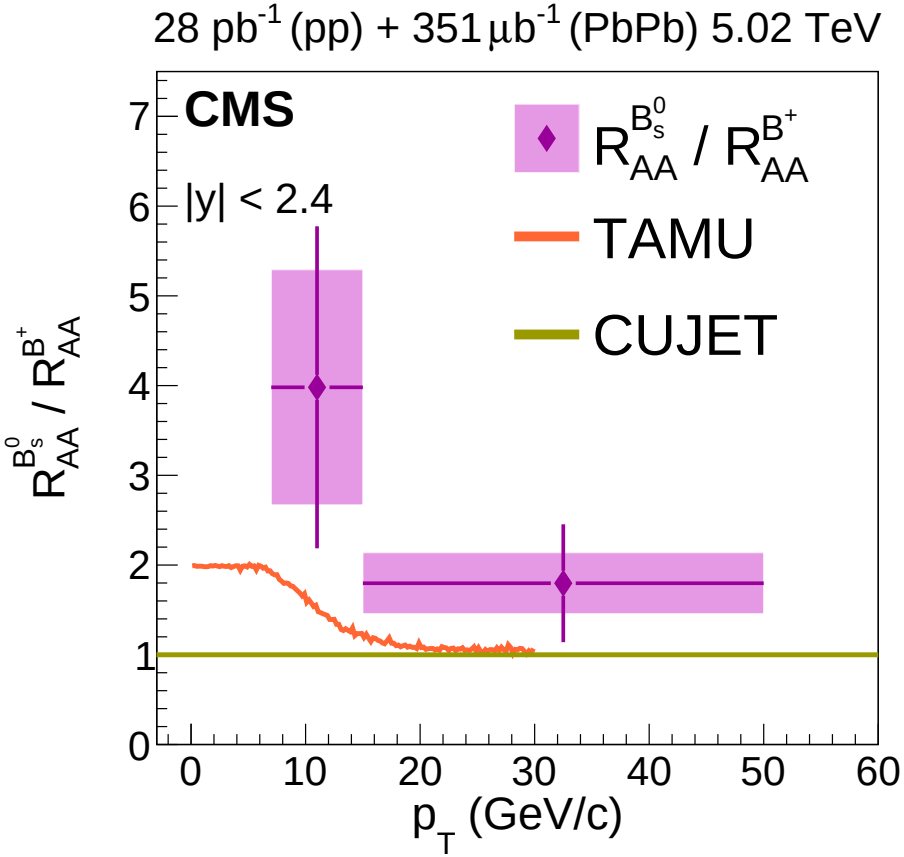
→ allows for quantifying how B_s^0 mesons are suppressed w.r.t. B^+

→ significant contribution of beauty recombination with strange quarks in heavy ion collisions ?

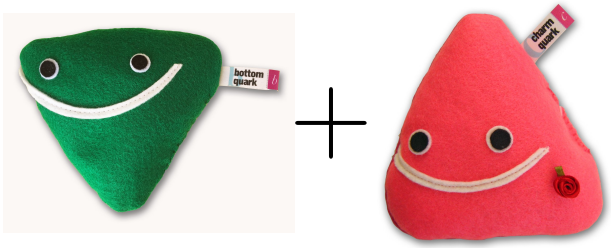
Indication of B_s^0/B^+ enhancement
(p-value 18% - 28%)

Not significant yet

→ need more statistics
(analysis in progress with 2018 data!)



Recombination with charm?



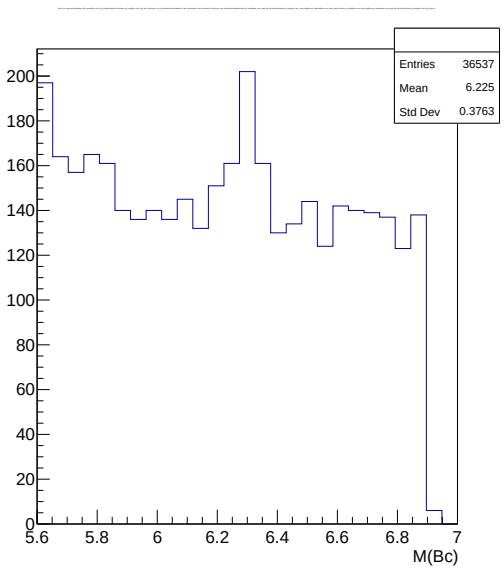
- At LHC energies, many charm quarks produced in the surrounding nuclear collision
- "Standard" recombination with J/ψ:
  - Binding of uncorrelated c and $\bar{c}$ (statistical hadronization)
  - continuous dissocation/recombination of bound state (transport model)
  - CGC, comovers, ...
- B_c difficult 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!
- Caveats: added to suppression mechanisms (b energy loss etc.), and happens at $p_T \lesssim m_{B_c}$
- Two different heavy quarks bound → original view of flavour dependence of energy loss

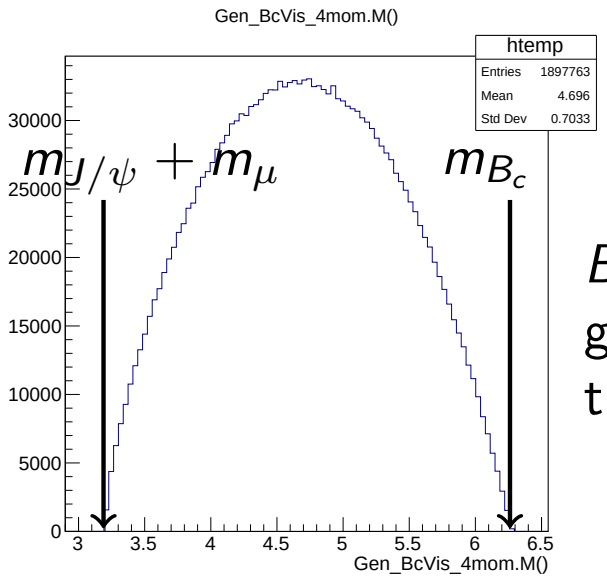
Additional challenges with B_c^+ trimuon analysis

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 (p_T unfolding to be planned)

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





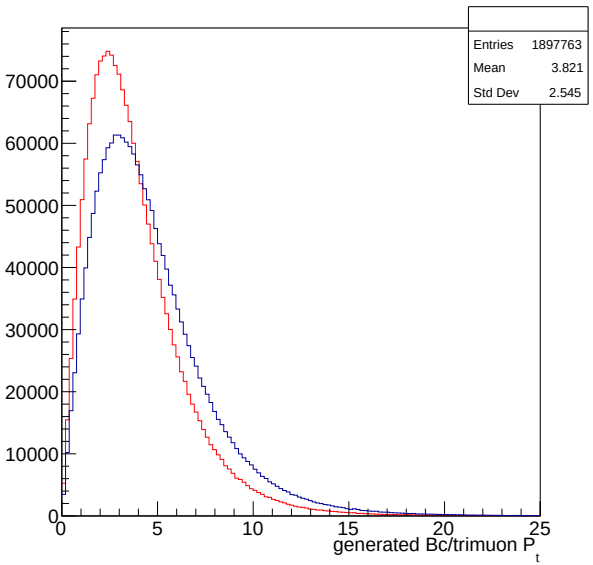
$B_c^+ \to \mu\mu\mu$
generated
trimuon mass

Additional challenges with B_c^+ trimuon analysis

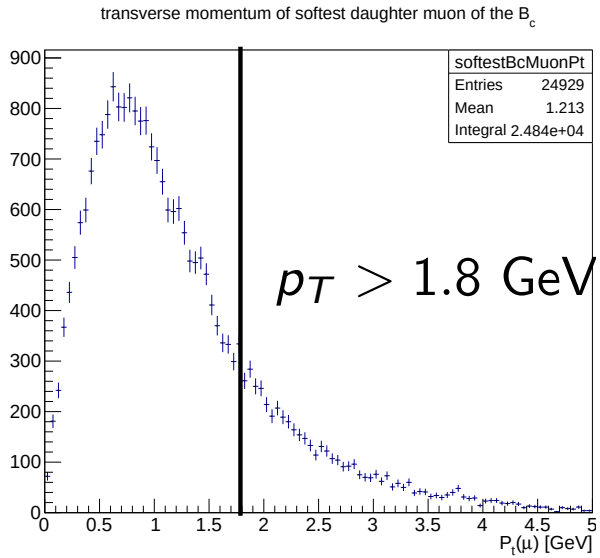
Low cross section:

- 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

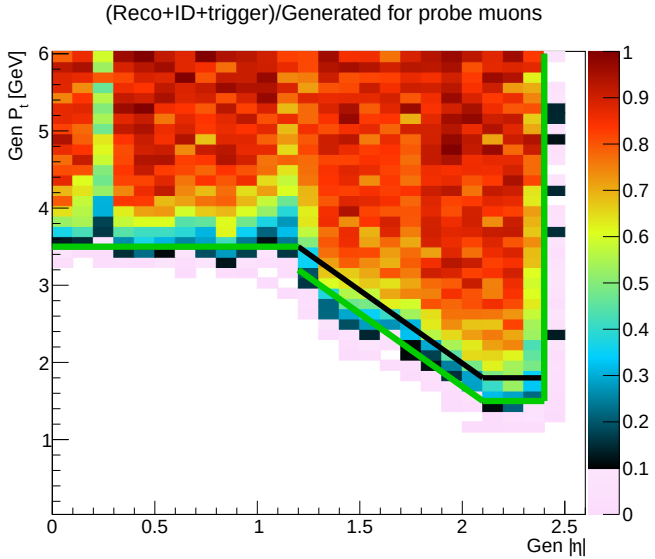
p_T of generated B_c
p_T of generated trimuon



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



New kinematic acceptance (for triggering muons)

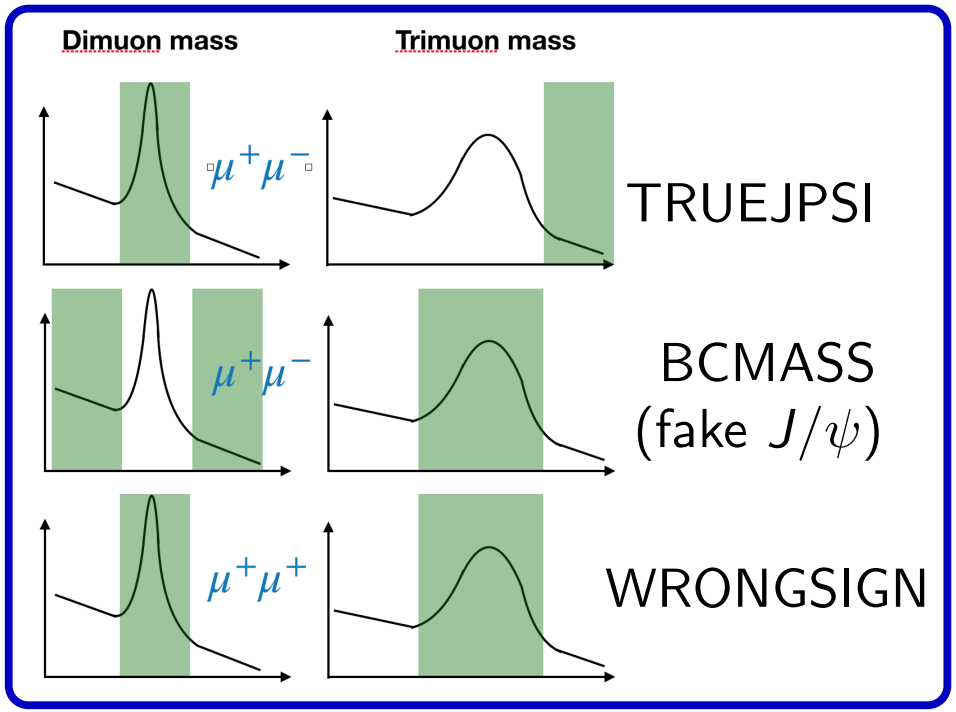


Used samples

- pp 2017 (300 pb^{-1}) and PbPb 2018 (1.5 nb^{-1}) at 5.02 TeV, with dimuon trigger
- For B_c signal: use BCVEGPY2.2 specific generator, then: PYTHIA, EVTGEN, GEANT, ...
- No embedded samples for PbPb yet (coming soon) → scale pp MC to PbPb luminosity

For background studies:

- MC for prompt J/ψ and non-prompt J/ψ (daughter of B^0, B^+, B_s)
- Define samples w.r.t. dimuon sign (0 or ± 2) and J/ψ or trimuon mass sidebands



Mastering the backgrounds

dimuon mass sidebands from data (BCMASS)

Extrapolate trimuon mass sideband (TRUEJPSI)

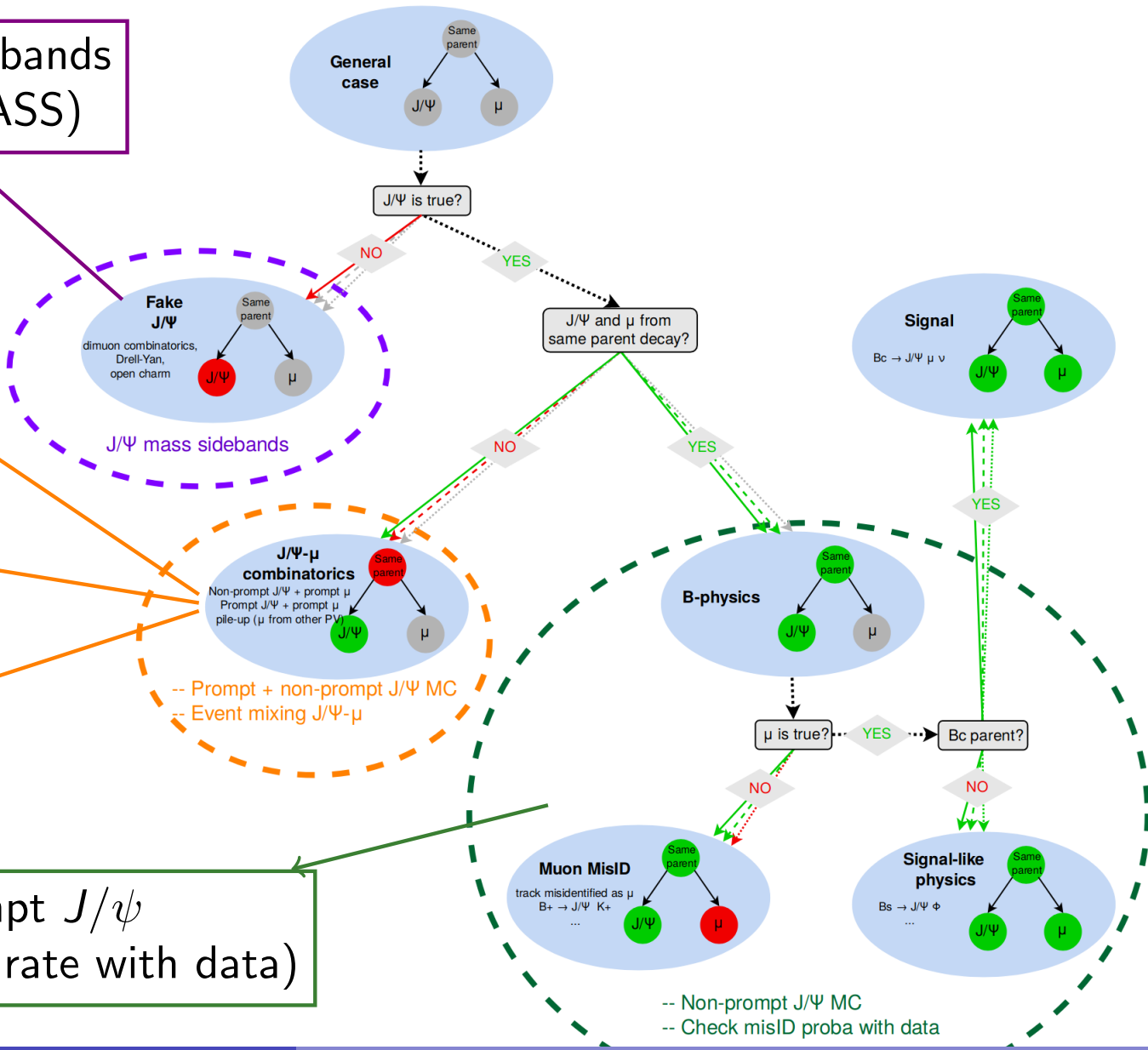
OR

MC (non-)prompt J/ψ combining with μ in underlying event

OR

mixing J/ψ and μ from $\neq$ data events

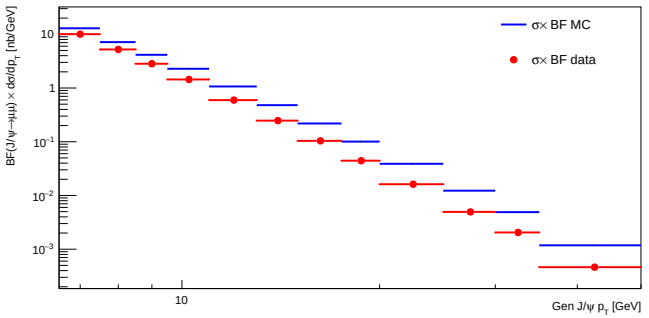
MC non-prompt J/ψ (check misID rate with data)

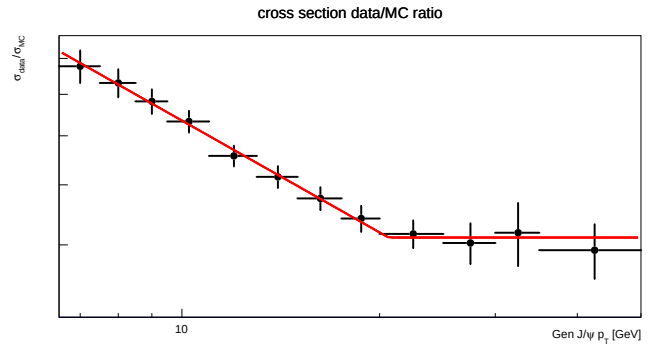


BDT & strategy for normalization

- Apply BDT after basic selection. Discriminant variables: same as $B_{(s)}$ + some topology, e.g. $\Delta R(J/\psi)/mean(\Delta R(\mu,\mu))$
- 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



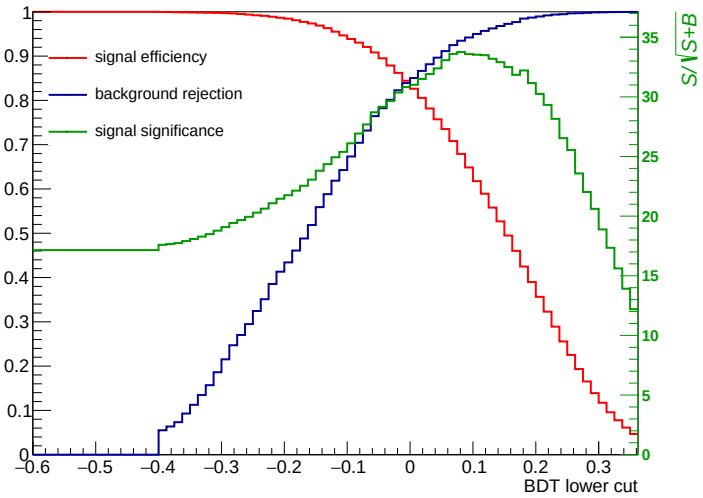


[1]: PRL.114.132001 (2015)
[2]: JHEP 2012,93(4)
[3]: CMS-PAS-BPH-13-002
[4]: EPJC 78 (2018) 509

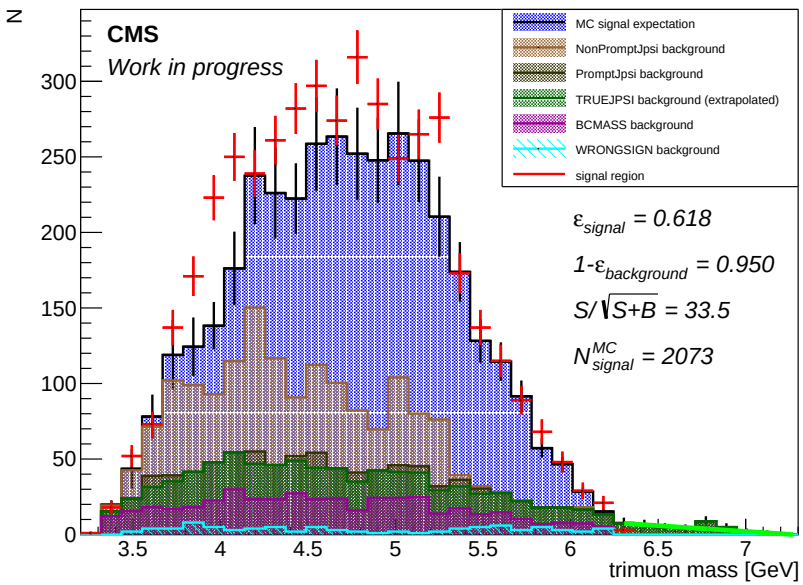
pp preliminary result

- Same sign $+++/---$ sample only shown for illustration
- More work needed on $J/\psi - \mu$ combinatorics: here, simplistic TRUEJPSI extrapolation
- data-MC agreement to be improved, but confidence in high $m_{\mu\mu\mu}$ region

Scan of BDT cut values



B_c candidates mass with valBDT>0.10

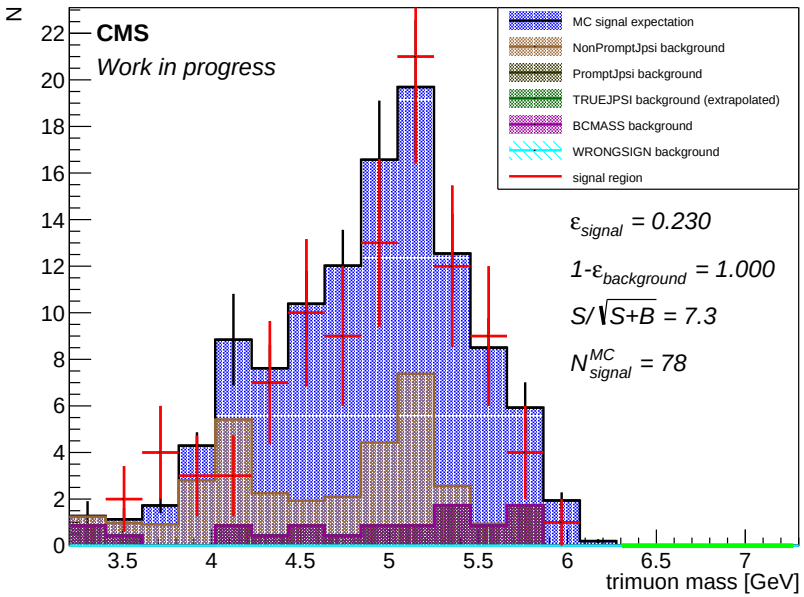


- To improve BDT performance, will run BDT separately in categories:
  p_T (2 bins),
  rapidity (2 bins) ($\neq m_{J/\psi}$ resolution), and
  $m_{\mu\mu\mu}$ (2-3 bins) (very $\neq$ backgrounds)
- Use control regions to check background description (e.g. invert BDT cut, or vertex probability cut for combinatorics)

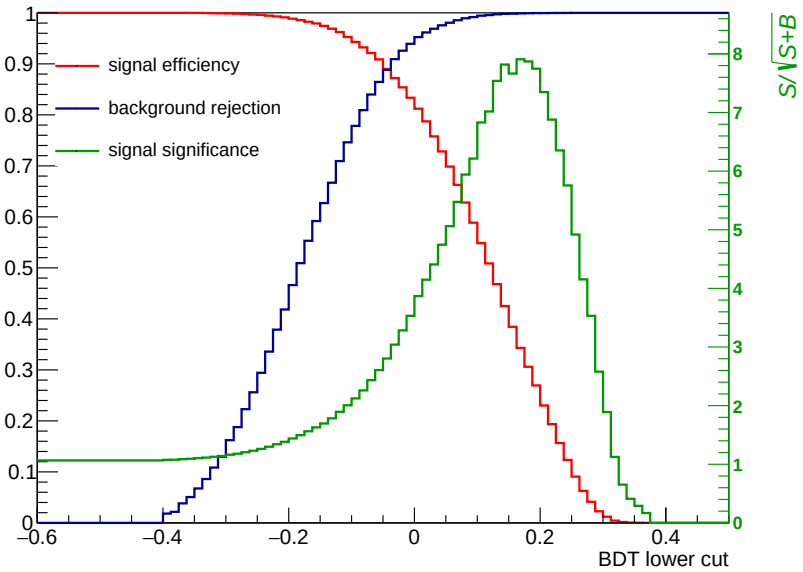
PbPb preliminary result

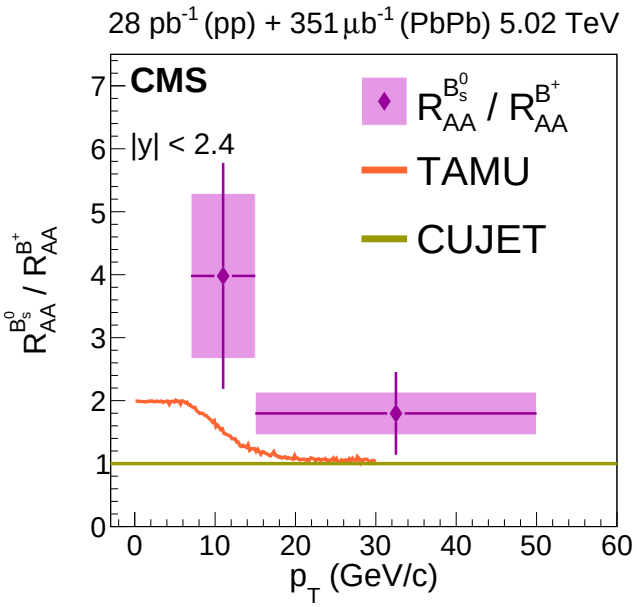
- Use pp MC for now (embedded MC not ready yet), assuming arbitrary R_{PbPb} for signal B_c, and using PbPb (non-)prompt J/ψ cross sections
- More work needed on backgrounds, but confidence in high $m_{\mu\mu\mu}$ region
- More MC stats to come → better BDT performance / less overtraining

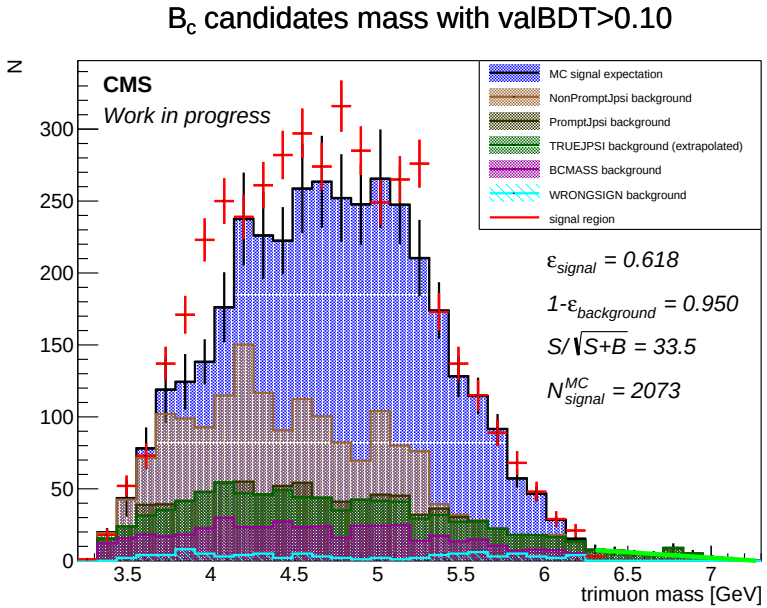
B_c candidates mass with valBDT>0.20



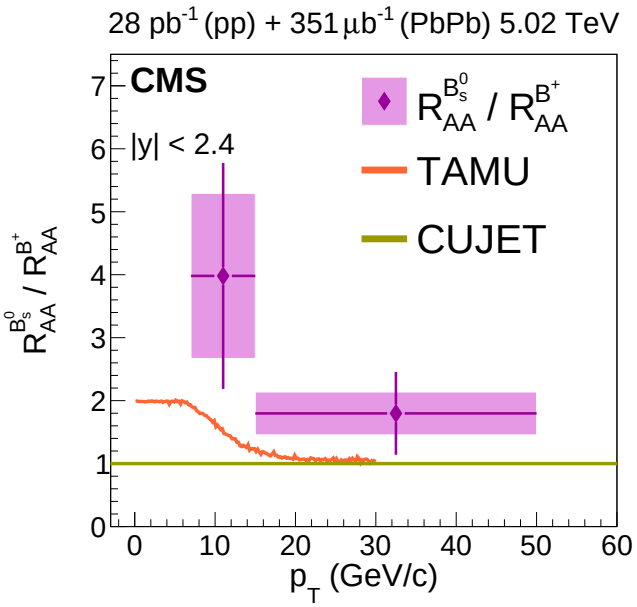
Scan of BDT cut values

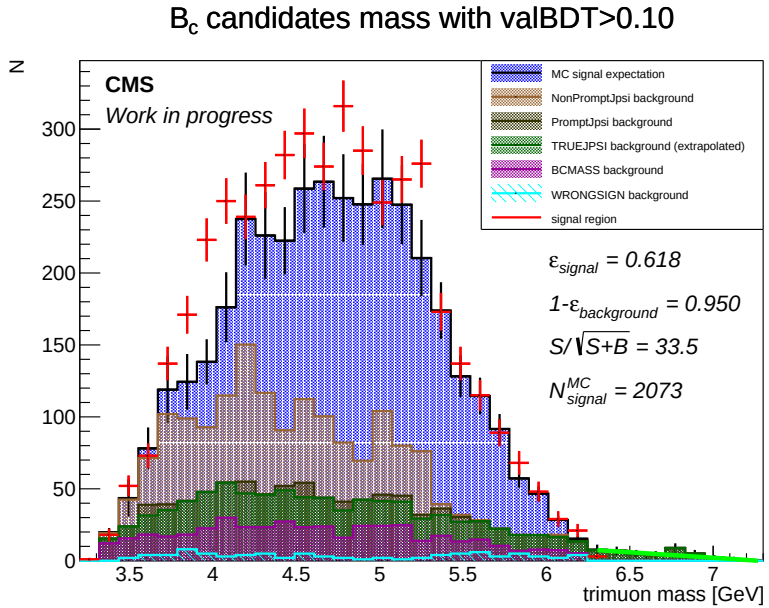






- Rich zoology of results on medium modifications of *b*-quark and *b*-mesons in PbPb with CMS
- First measurement of B_s^0 decays in heavy ions
- Work in progress: towards measurement of B_c^+ in heavy ions





- Rich zoology of results on medium modifications of *b*-quark and *b*-mesons in PbPb with CMS
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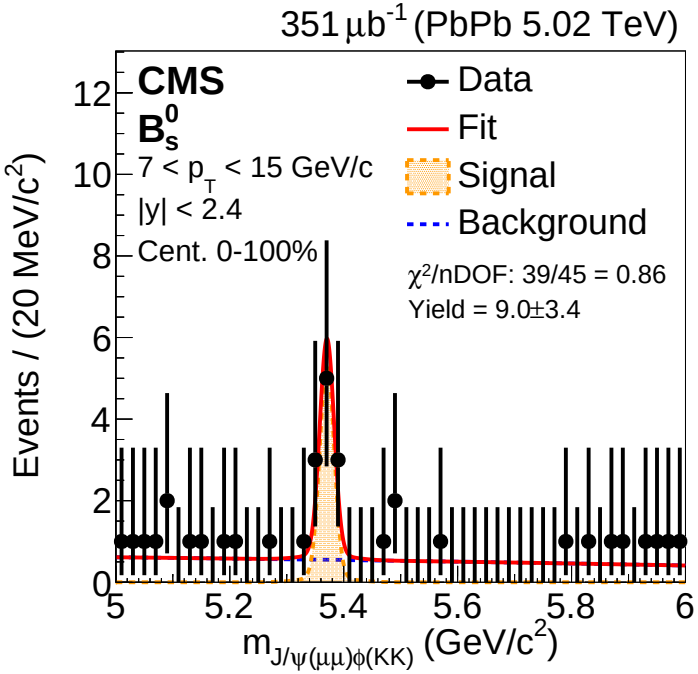
THANK YOU !

BACKUP

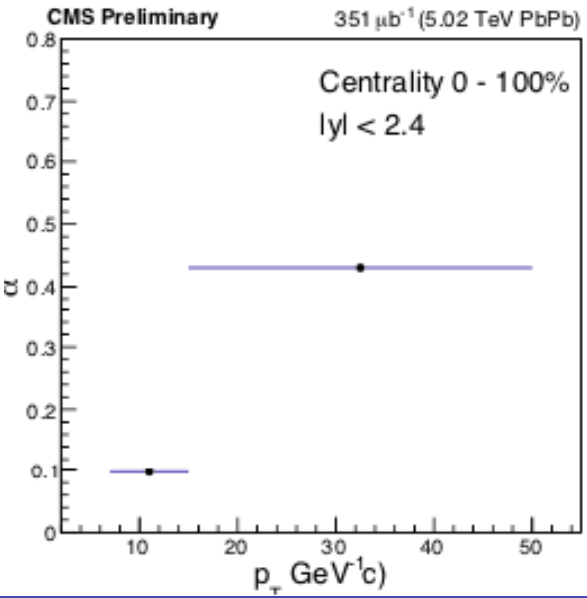
B_s Signal extraction: fit of raw yields

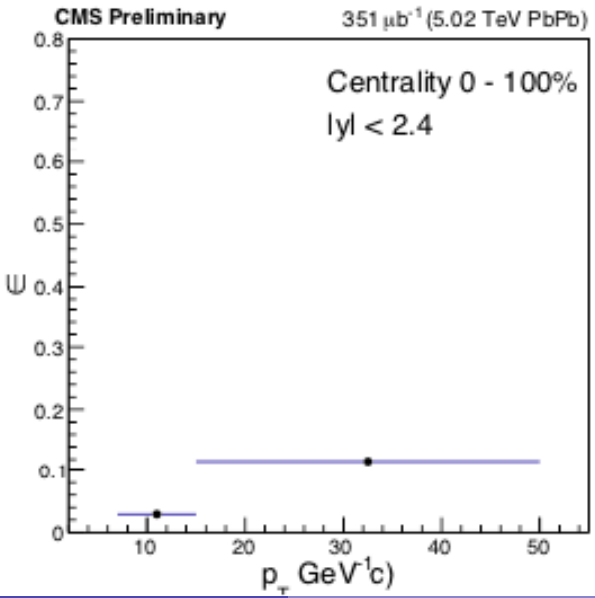
- Fit with unbinned extended maximum likelihood method B_s^0 mass
- Double gaussian (same means) for signal + linear function for combinatorial background
- Signal shapes from MC
- Non-prompt J/ψ background (from other B mesons) negligible thanks to tight ϕ mass cut

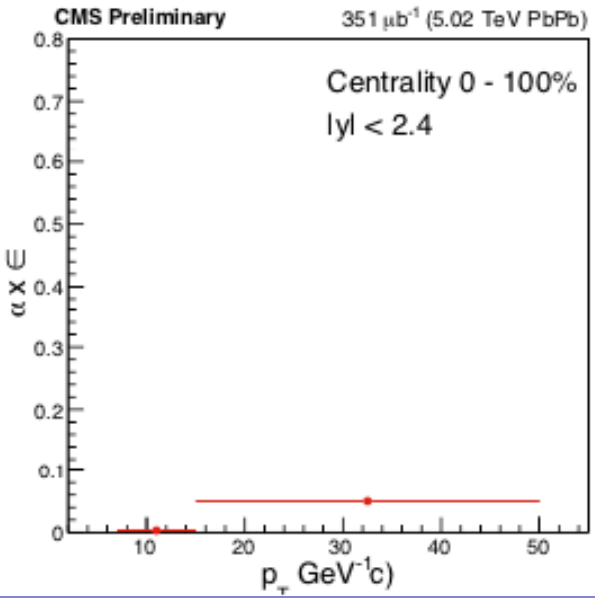


B_s acceptance and efficiency

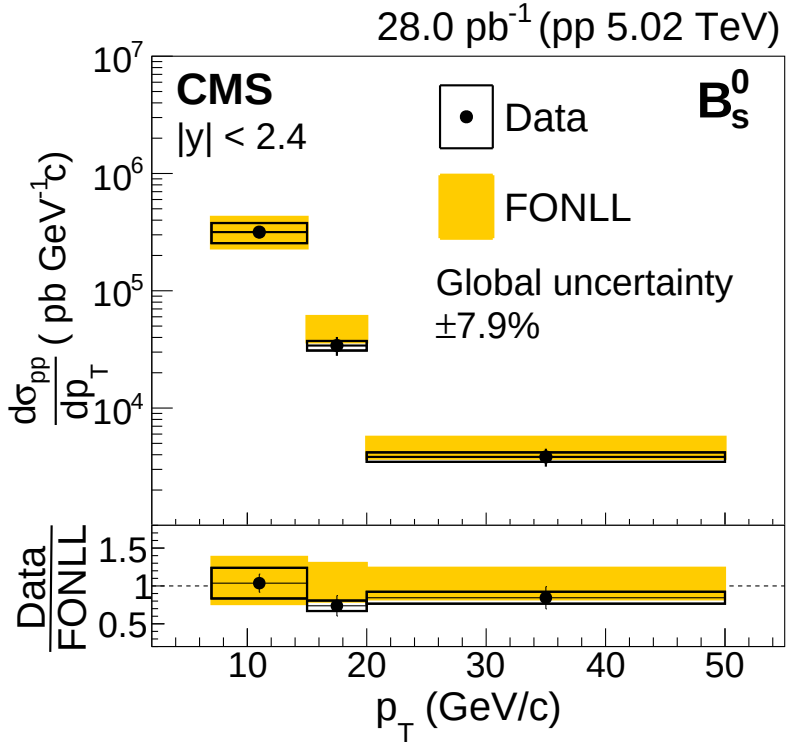
- α: Accepted B_s^0 = daughters pass basic detector acceptance cuts
- ε: Reconstructed B_s^0 = accepted + reconstructed daughters + pass selection cuts
- Measured on signal MC
- For BDT: check the similarity of MC and data distributions for discriminant variables







B_s proton-proton cross section: comparison to FONLL



- Spectrum calculated for all b-quark hadrons. Uncertainty from variation of m_b, m_c, μ_R, and μ_F.
- Apply (constant) production fraction of B_s: 10.3% from PDG (hypothesis checked with PYTHIA)

→ pp measurement consistent with FONLL prediction

Systematics on B_s pp and PbPb cross sections

Done separately for each p_T bin:

source	Rel. error on R_{PbPb}
luminosity / N_{MB} / T_{PbPb}	2-3%
branching fractions	8%
kaon tracking efficiency	8-12%
muon efficiency	3-5%
B_s^0 BDT selection efficiency	3-19%
Signal and background fit models	1-9%
Correction of B_s^0 p_T shape in MC	1-8%
B_s^0 acceptance difference in MC/data	1-2%

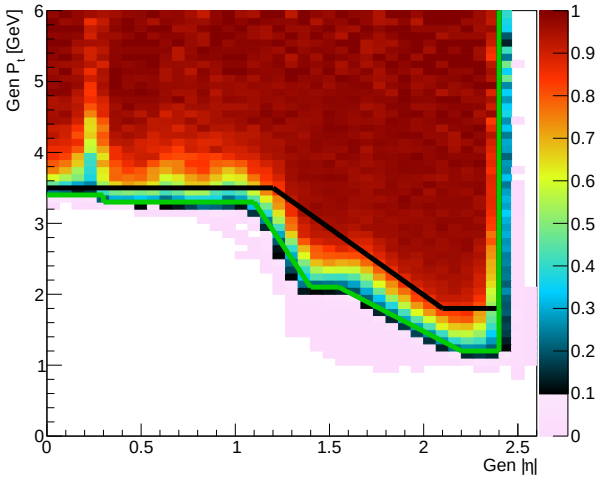
2017-2018 data: new single muon acceptance cuts

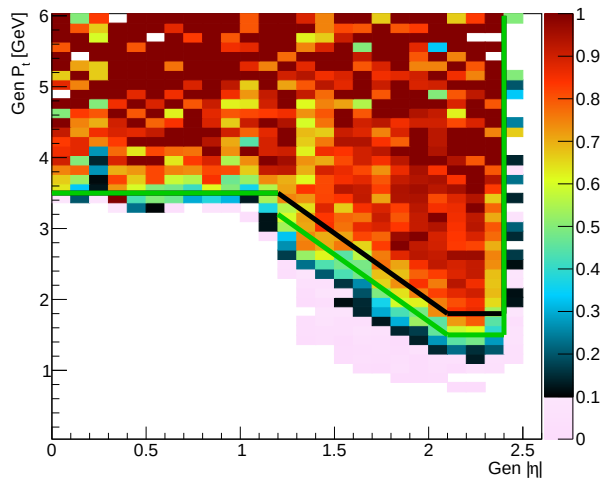
From single muon efficiency maps:

Reconstruction + ID

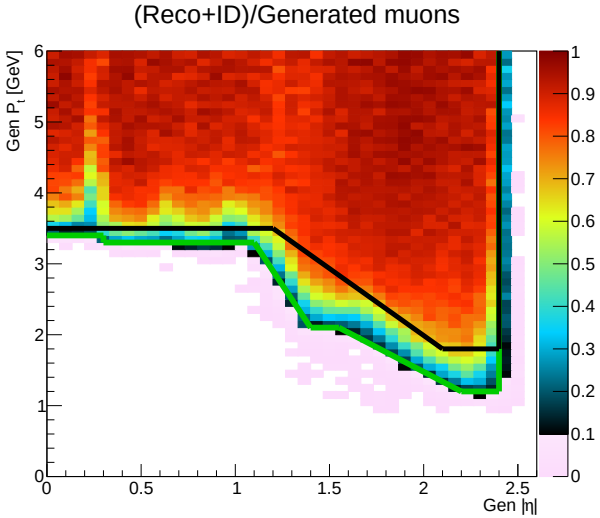
Reconstruction + ID + trigger

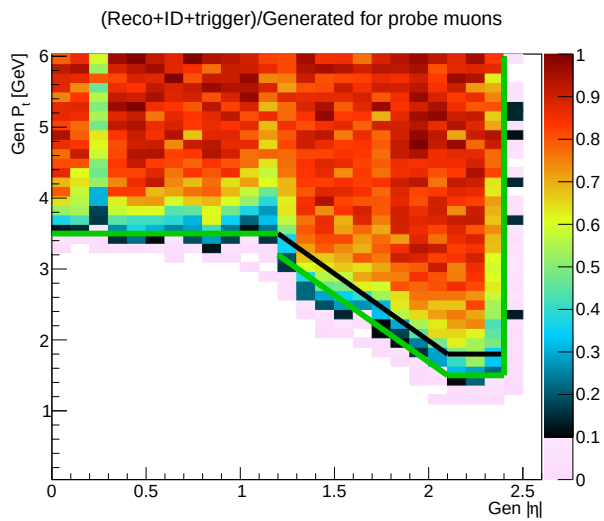
pp 2017





PbPb 2018





MC normalization for (non-)prompt J/ψ

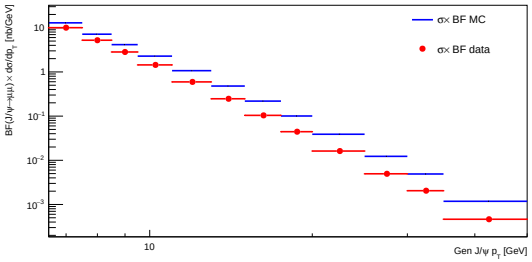
Scale to CMS data

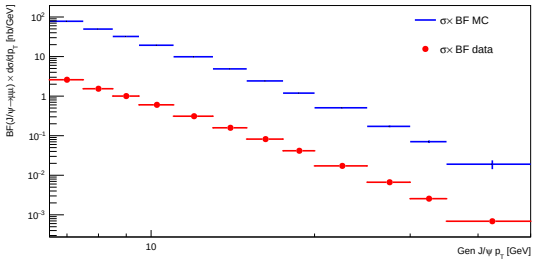
CMS-PAS-BPH-13-002

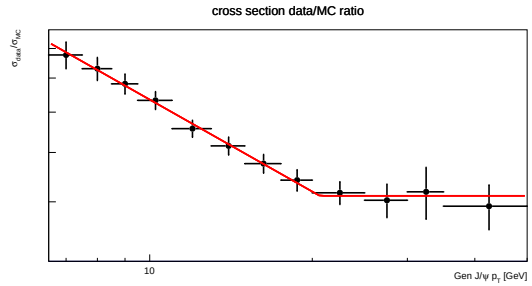
Prompt

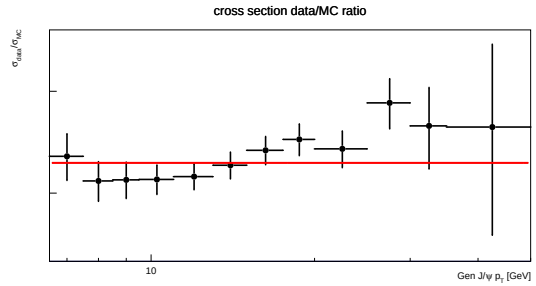
Non-prompt

pp

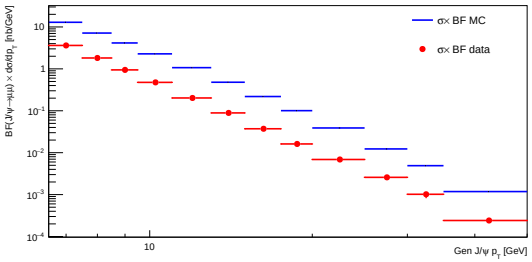


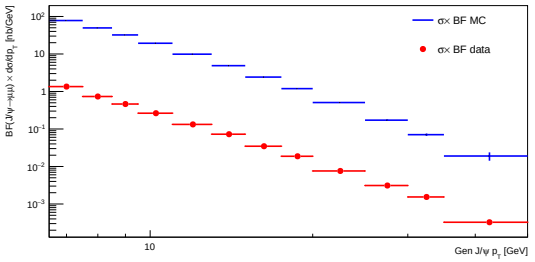


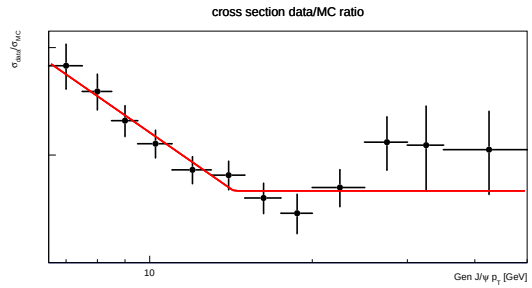


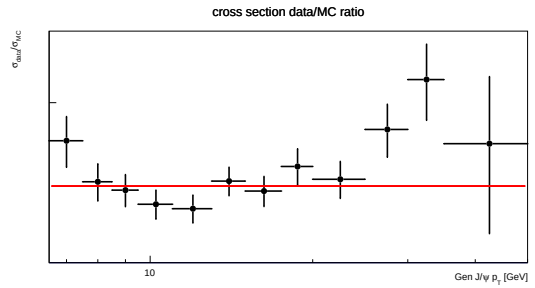


PbPb



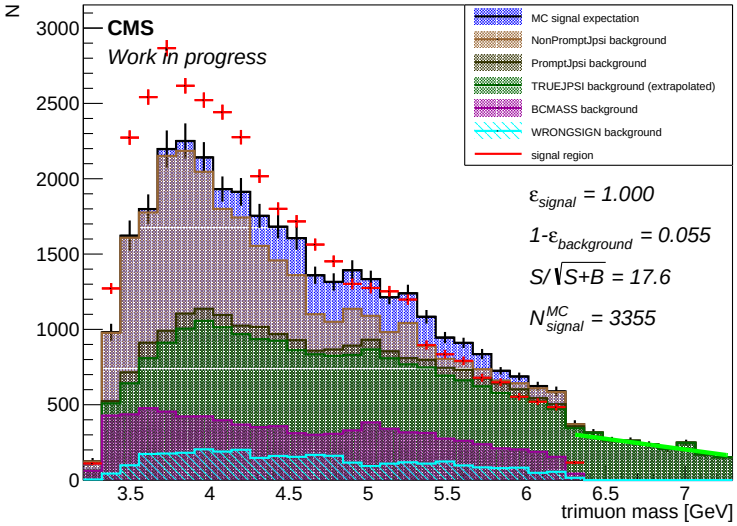




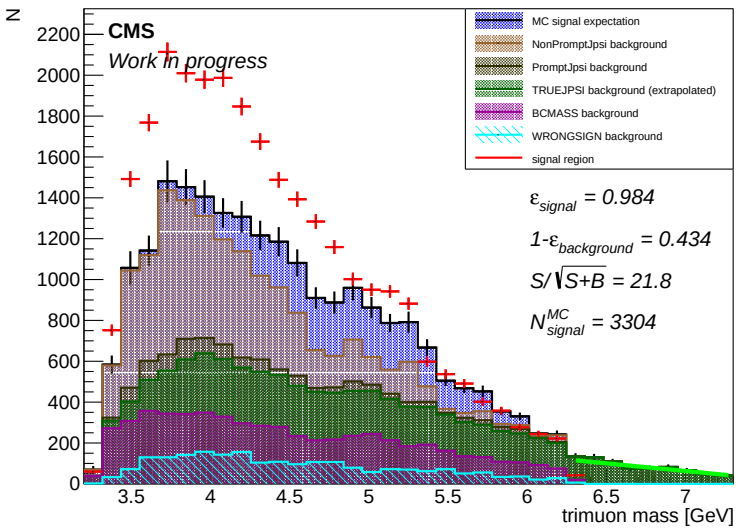


pp trimuon mass for various BDT cuts

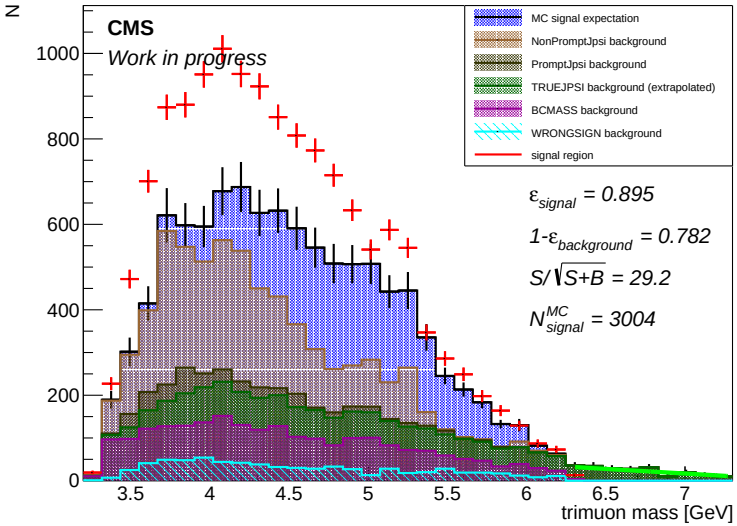
B_c candidates mass with valBDT>-0.40



B_c candidates mass with valBDT>-0.20



B_c candidates mass with valBDT>-0.05



B_c candidates mass with valBDT>0.25