First observation of B_c mesons in PbPb (and pp) collisions with CMS

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Heavy quarkonia in hot matter

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- Dissociation:
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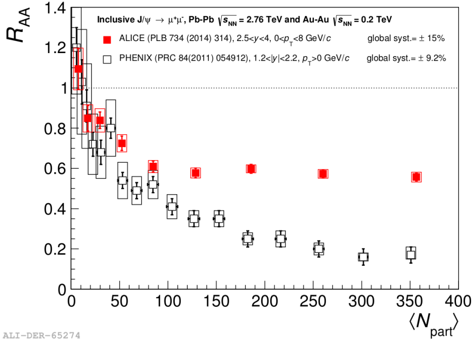

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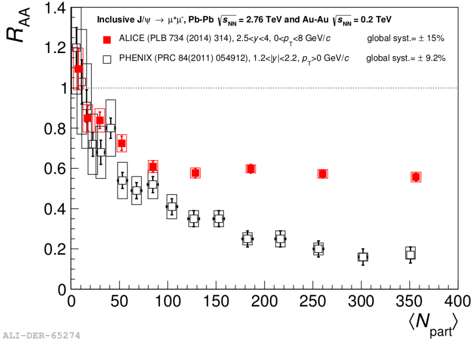

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- Energy loss on the precursor parton

Motivations to observe B_c in PbPb collisions

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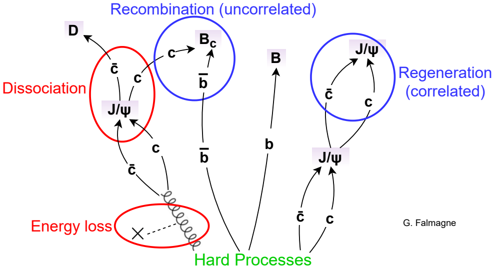

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- Recombination of b with uncorrelated c quark?
  small $\sigma_{\rm pp}^{B_c}$ ⟶ enhancement at $p_T \lesssim m_{B_c}$ could be dramatic !
  ($2 < R_{PbPb} < 18$ in PRC **87** (2013), 014910,
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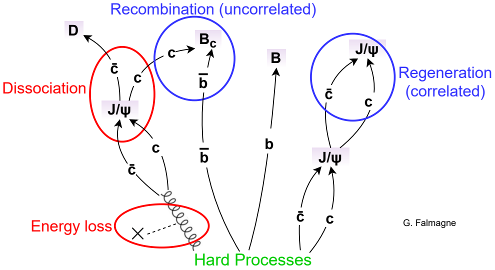

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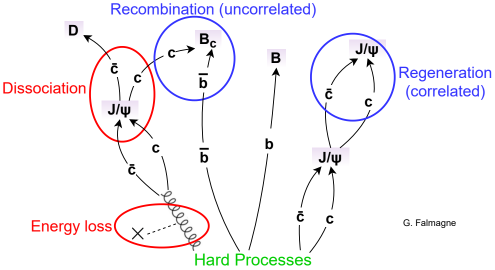
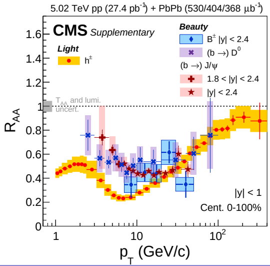
- Partonic energy loss:
  Mass and color-charge dependence?

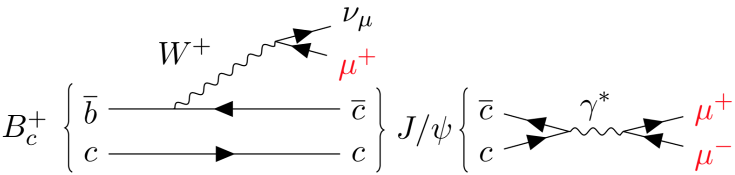
$\longrightarrow$ B_c = bridge between $c\bar{c}$ and $b\bar{b}$
and between open charm and open beauty

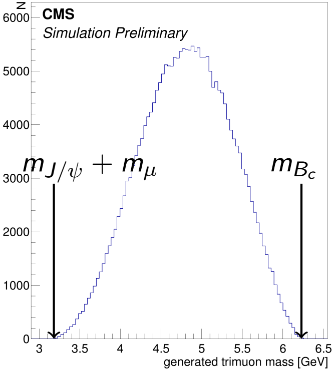




How to reach a first observation in heavy ions?

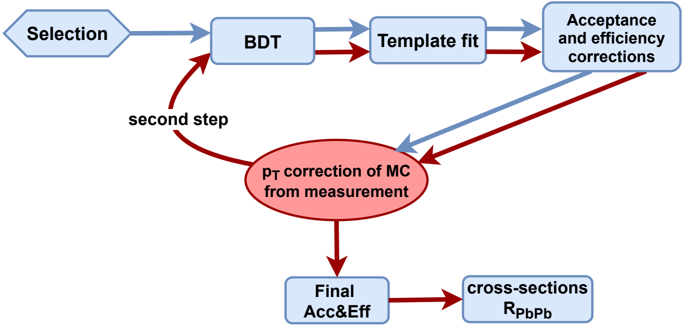
- Use leptonic channel $B_c^+ \to (J/\psi \to \mu\,\mu)\,\mu^+\nu_\mu$, because branching fraction = 20 times hadronic channel $B_c^+ \to J/\psi\,\pi^+$
  - Signal = displaced vertex of three muons
  - Trimuon mass $\in [3.2, 6.3]$ GeV
    → Need good understanding of backgrounds
  - Partially reconstructed
    → use visible (trimuon) kinematics





Analysis strategy

- Selection + BDT



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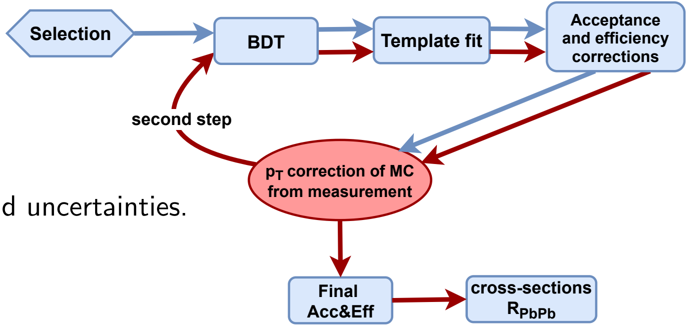

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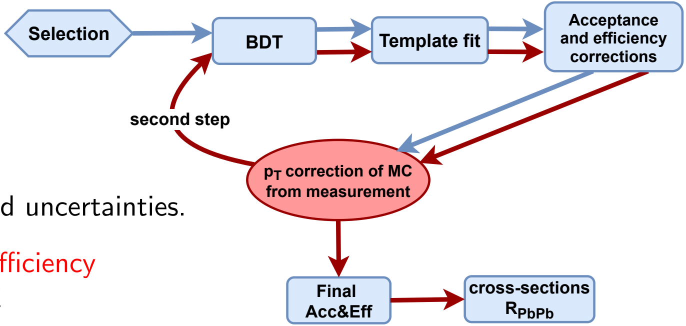

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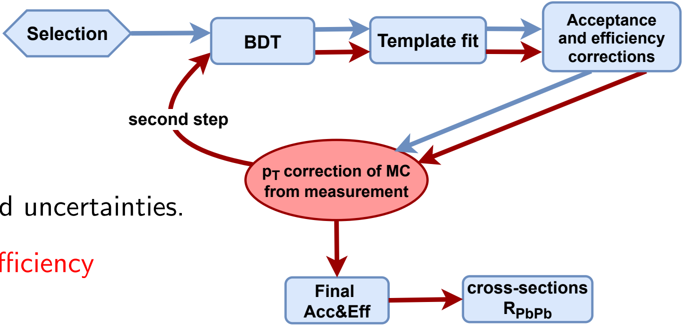
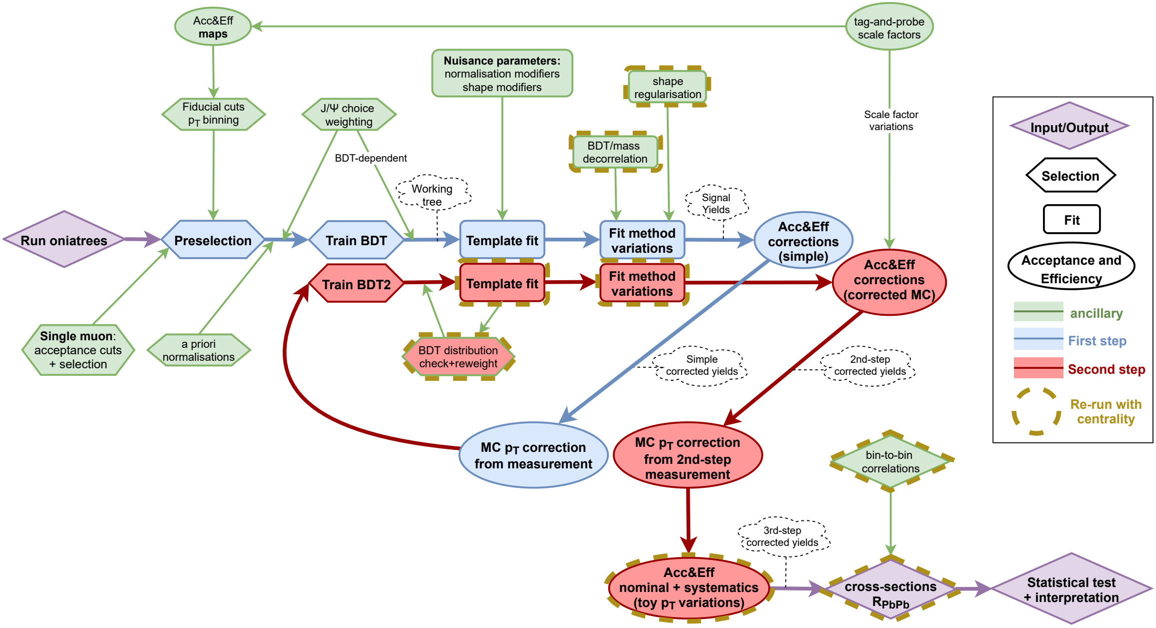


Note: We blinded 3/4 of PbPb data signal region until a late stage, to limit analyser bias.



Acc&Eff maps
tag-and-probe scale factors
Nuisance parameters: normalisation modifiers shape modifiers
shape regularisation
Fiducial cuts p_T binning
J/Ψ choice weighting
BDT-dependent
BDT/mass decorrelation
Scale factor variations
Working tree
Signal Yields
Run oniatrees
Preselection
Train BDT
Template fit
Fit method variations
Acc&Eff corrections (simple)
Train BDT2
Template fit
Fit method variations
Acc&Eff corrections (corrected MC)
Single muon: acceptance cuts + selection
a priori normalisations
BDT distribution check+reweight
Simple corrected yields
2nd-step corrected yields
MC p_T correction from measurement
MC p_T correction from 2nd-step measurement
bin-to-bin correlations
3rd-step corrected yields
Acc&Eff nominal + systematics (toy p_T variations)
cross-sections R_{PbPb}
Statistical test + interpretation
Input/Output
Selection
Fit
Acceptance and Efficiency
ancillary
First step
Second step
Re-run with centrality

CMS data, trigger, MC

- Signal signature =
  3 muons from a displaced vertex, with an opposite-sign pair in the J/ψ peak region

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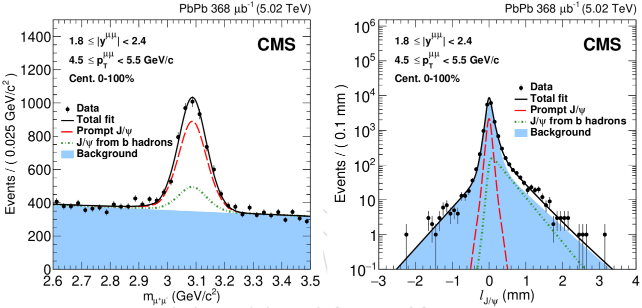
- Signal signature = 3 muons from a displaced vertex, with an opposite-sign pair in the J/ψ peak region
- CMS advantages:
  - excellent muon momentum and vertex resolutions
  - high luminosity
- 2017 pp and 2018 PbPb data ($\mathcal{L}_{\mathrm{PbPb}} = 1.61\ \mathrm{nb}^{-1}$, $\mathcal{L}_{\mathrm{pp}} = 302\ \mathrm{pb}^{-1}$) with dimuon trigger



- BCVEGPY specific generator for B_c MC. Standard PYTHIA8 for (non)prompt J/ψ MC. EVTGEN1.3 for decays. Normalisation from previous measurements (pp only for B_c).

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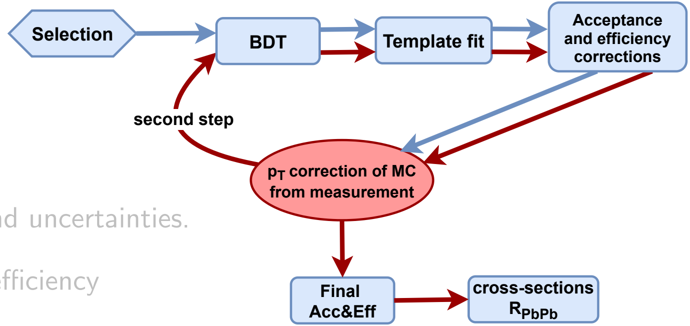
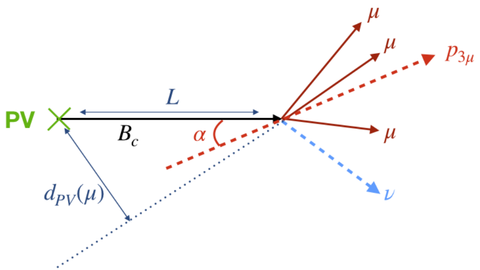


Selection

- Cut selection on these variables:
  - Trimuon and dimuon vertex probability
  - Lifetime significance $L/\sigma(L)$
  - $d_{z,PV}(\mu)$
  - angle $\overrightarrow{p_{3\mu}} - \overrightarrow{[PV, SV]}$
  - $\sum_{i,j=1,2,3} \Delta R(\mu_i, \mu_j)$
  - $m_{corr}(\mu\mu\mu)$, corrected for $p_{\perp}(\nu)$



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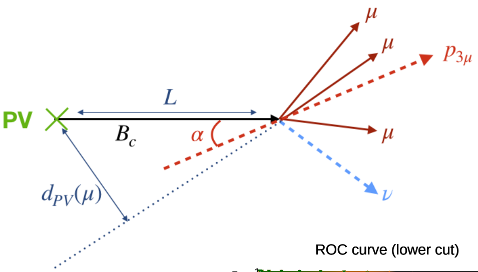
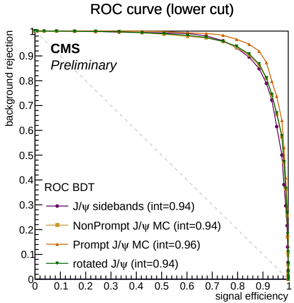
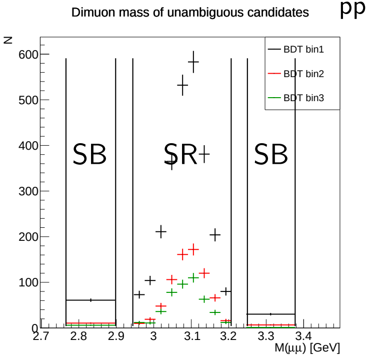


- Train BDT (TMVA), separately in 2 p_T bins and in two random halves.
  Checked data vs MC fitted distributions.
  Use 8 violet variables, including:
  - μ_W significance of displacement from PV
  - $\frac{\Delta R(J/\psi)}{\Delta R(\mu_W,\mu^-)+\Delta R(\mu_W,\mu^+)}$
  - Imbalance between $p_T(\mu_W)$ and $p_T(J/\psi)$



Who is the J/ψ?

- In a trimuon of charge ± 1, there are 2 opposite-sign (OS) dimuons
- Problematic if the 2 pairs are in the dimuon mass peak (SR) or sidebands (SB) region
- Dimuon mass criterium would bias fake J/ψ background



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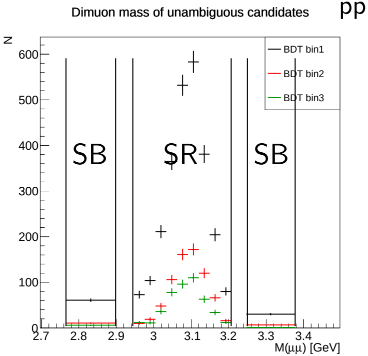

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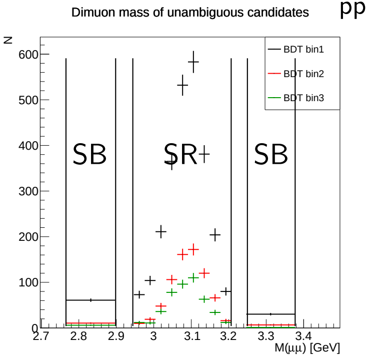
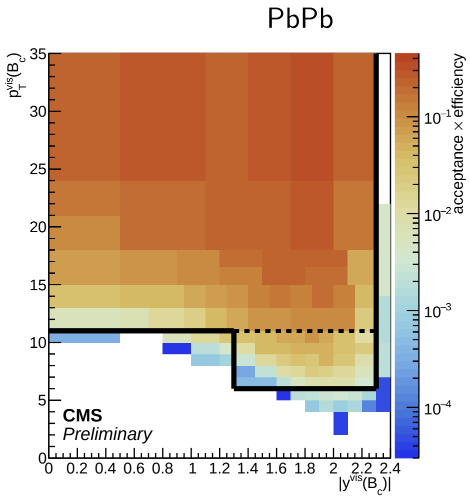
- Weights extracted from unambiguous trimuons in selected data
- Applied to trimuons having 2 OS pairs in SR or SB



Analysis bins (from acceptance and efficiency)

- Acceptance and efficiency from (p_T-corrected) signal MC + tag-and-probe single-muon corrections



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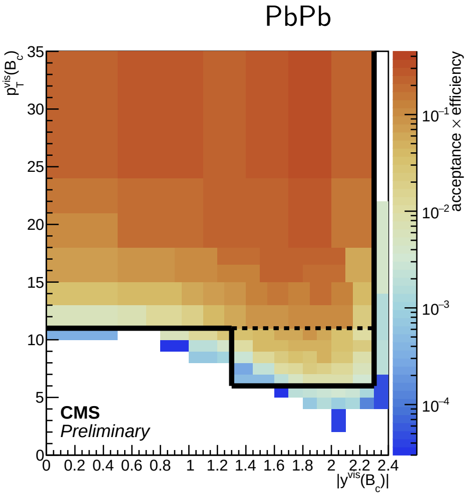
- Adapt binning to CMS shape (and need low p_T)

  → Choose two p_T bins with rapidity cuts:
  - $6 < p_T < 11$ GeV with $1.3 < |y| < 2.3$
  - $11 < p_T < 35$ GeV with $0 < |y| < 2.3$

- Also two centrality bins 0-20% and 20-90%, integrated over $(p_T, |y|)$ bins



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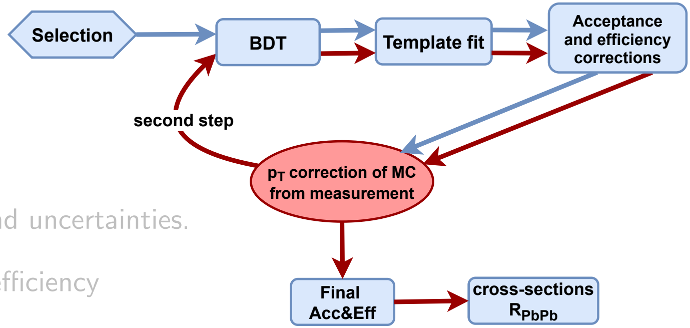

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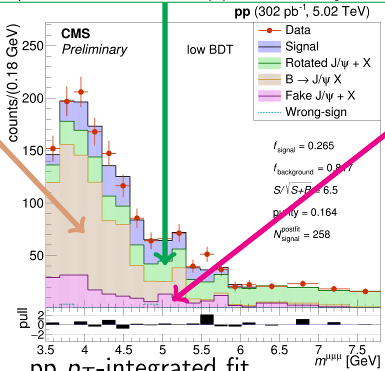
- Third muon is mostly a misidentified hadron
(3) Non-prompt J/ψ MC describes this $B \to J/\psi\, h^{\pm} X$ correctly

Background properties

- $J/\psi - \mu$ from $\neq$ vertices → use rotated J/ψ sample
- Rotate (around primary vertex) the flight direction and momentum of data J/ψ
- Data-derived normalisation in PbPb
- Leftover $J/\psi - \mu$ correlations in pp → vary rotation angles

- J/ψ and muon/hadron from same B decay: from MC
- Free normalisation in fit (misID rate)
- Cutoff at 5.3 GeV
- Very small in PbPb



pp p_T-integrated fit

- Fake J/ψ → dimuon mass sidebands
- Data-derived normalisation
- Allow variation between lower ($m_{\mu\mu} < m_{J/\psi}$) and upper sideband ($m_{\mu\mu} > m_{J/\psi}$)

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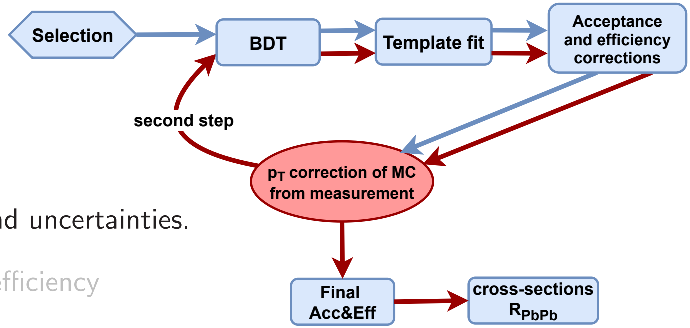

Template fit (pp)

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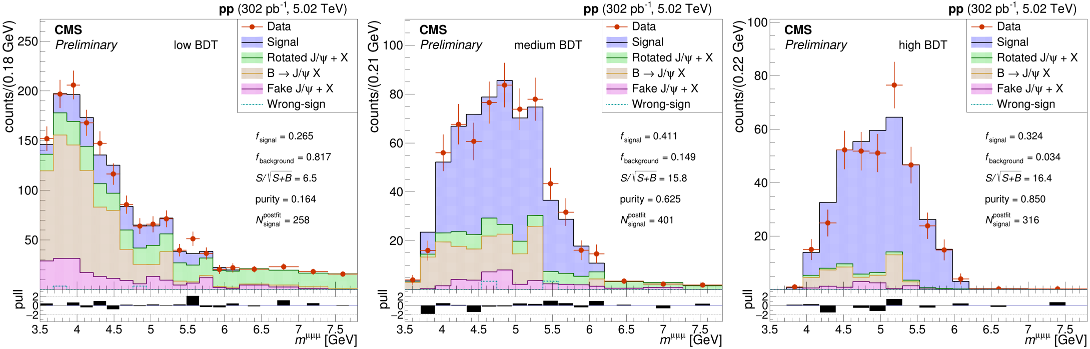

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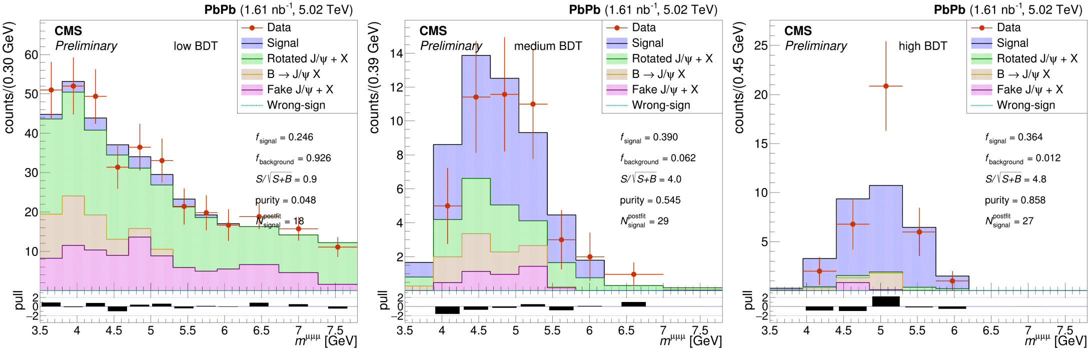

Template fit (PbPb, centrality)

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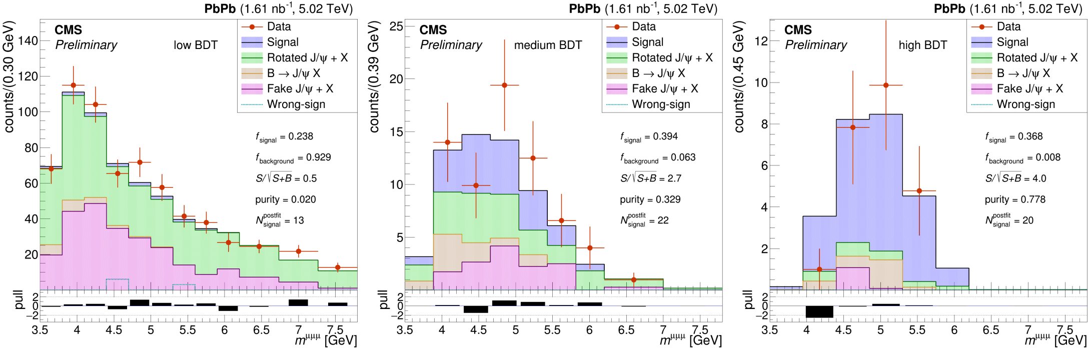
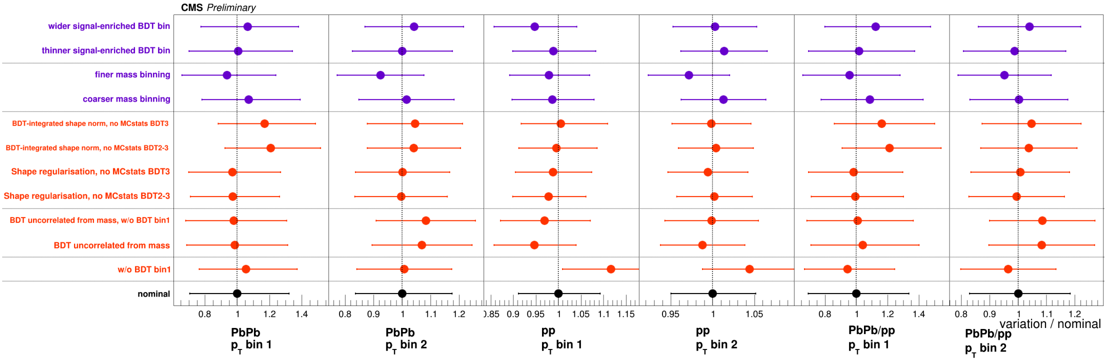
centrality 20 – 90% (p_T-integrated)



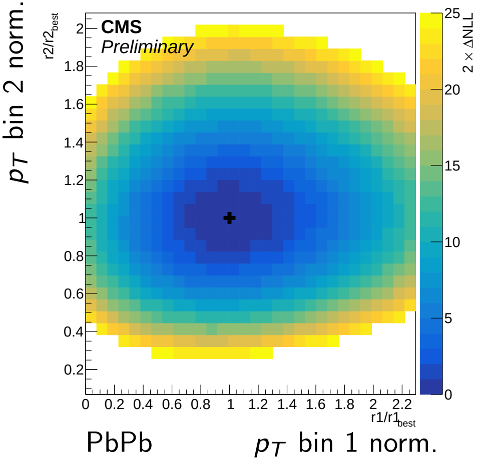
Fit method variations



- 11 variations of fit method: decorrelate BDT from mass, change mass or BDT binning, change treatment of stat. uncertainties on templates, ...
- Systematic uncertainty = RMS of the 3 orange categories of methods
- Violet: only checks (consistent with nominal)

Significance of observation in PbPb

- Coloured blob is 5σ significance, from the PbPb p_T-dependent-fit likelihood
- Include the fit method systematics
  $\longrightarrow$ Significance of observation of B_c in PbPb collisions is well above 5σ
- Other uncertainties are multiplicative:
  - Acceptance and efficiency
  - Tag-and-probe
  - Luminosity



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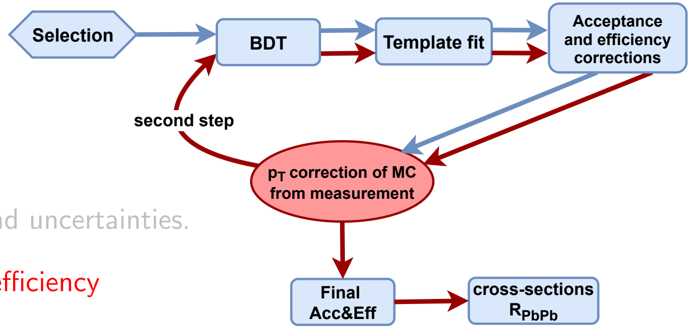

Acceptance and efficiency: iterative procedure

- Wide bins ⟶ $\alpha \times \varepsilon$ is very sensitive to the assumed p_T spectrum shape
- Need to correct *with our measurement* the p_T spectrum of MC, before recalculating $\alpha \times \varepsilon$
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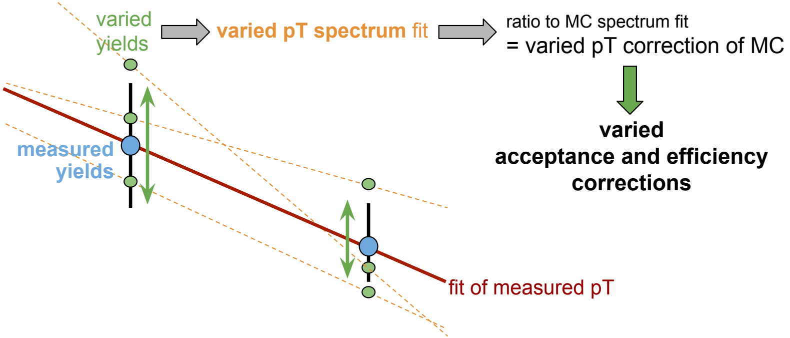
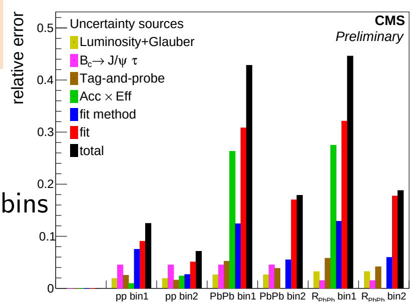


- For p_T-integrated bins: uncertainty $=$ RMS of varied $\alpha \times \varepsilon$ (⟶ dominant)
- For p_T bins: correlations between $\alpha \times \varepsilon$ and other uncertainties
  ⟶ Full uncertainty $=$ RMS of varied observed yield $\times$ varied $\alpha \times \varepsilon$ correction

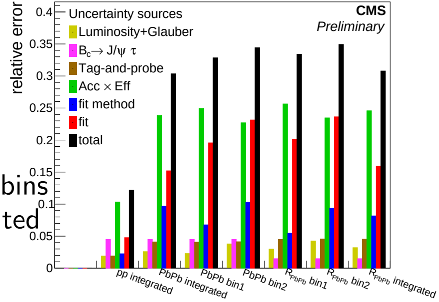
Summary of uncertainties

- Fit uncertainty (statistical+systematic) (dominates in p_T bins)
- Fit method variation
- Acceptance and efficiency ($dominates$ p_T-integrated bins)
- Tag-and-probe (scale factors on efficiency)
- Luminosity + Glauber model
- Contamination from other B_c decays:
  $B_c \to J/\psi\,(\tau \to \mu\,X)\,\nu_\tau$
  $B_c \to (c\bar{c} \to J/\psi\,X)\,\mu\,\nu_\mu$
  ⟶ estimated $\lesssim 4.5\%$
  and partially cancels in R_{PbPb}

p_T bins



centrality bins + integrated



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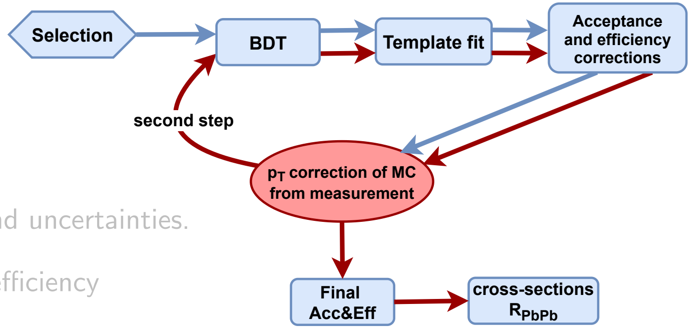
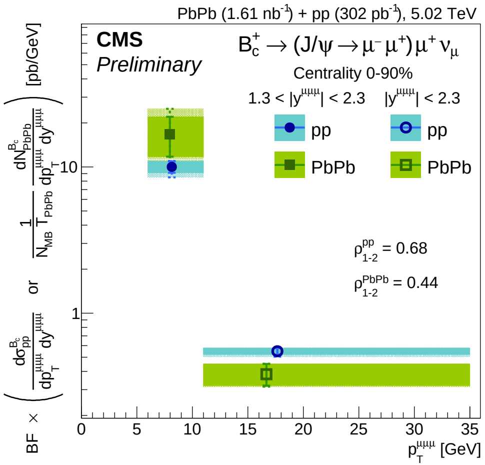
  → final acceptance and efficiency
- Result: $R_{PbPb}(B_c)$ in two p_T or centrality bins, with some rapidity cuts

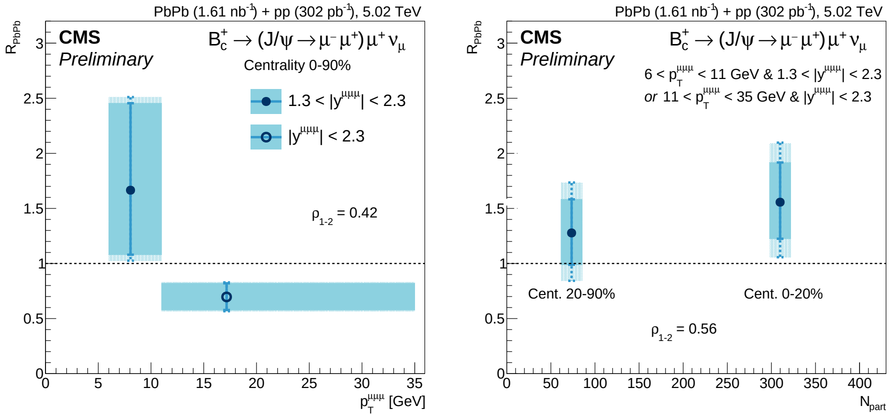


Cross sections



- Scale corrected yields by luminosity (pp) and $N_{\mathrm{MB}}\ T_{\mathrm{PbPb}}$ (PbPb)
- Correlation between bins fully calculated
- pp cross section integrated on p_T used for centrality bins

First $R_{PbPb}(B_c)$!

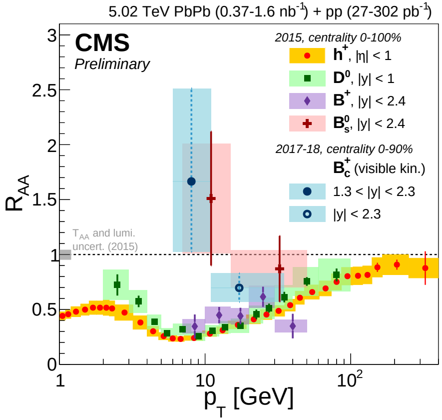


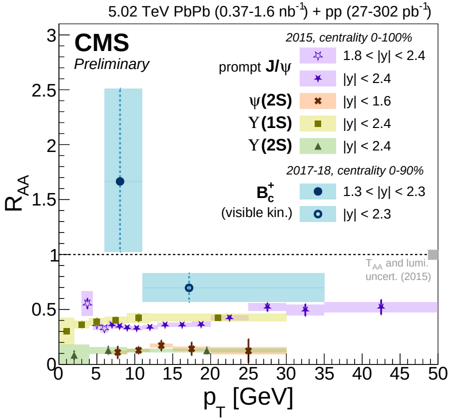
- Difference between two p_T bins: 1.6σ significance ⟶ Points at softening of p_T spectrum in PbPb collisions
- Uncertainties: bin-to-bin fully-uncorrelated VS total

Comparison with open and hidden heavy flavour at CMS

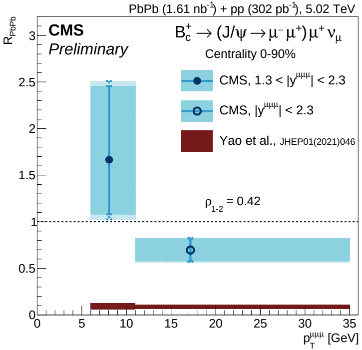
B_c and B_s modifications are similar, and less suppression than light hadrons + B and D

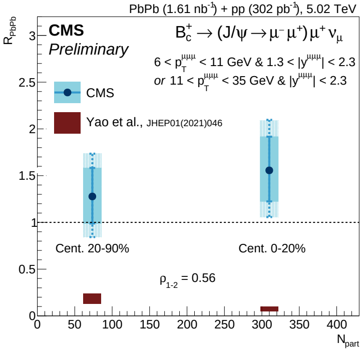
B_c much less suppressed than heavy quarkonia → different mechanisms at play than hidden heavy flavour?





Comparison with one theory prediction

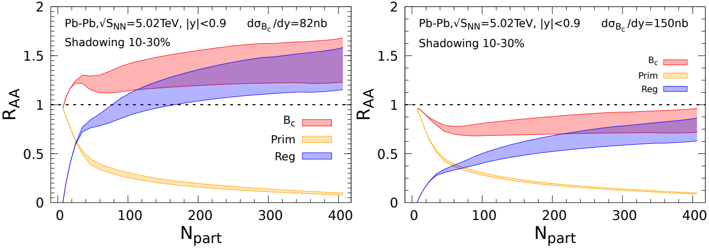




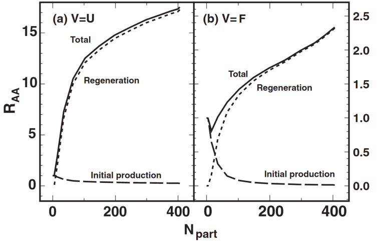
- Received one theory contribution yet, from Yao et al:
  - Transport model including correlated and uncorrelated recombination.
  - B_c (not trimuon) kinematics are used + no feed-down included
- Lower values than measurement. But no recombination of excited B_c states is included...
  ⟶ importance of recombination in B_c production (including cross-talk with excited states) ?

Other (phase-space-integrated) predictions

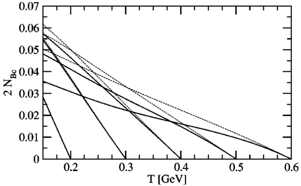
- TAMU transport model (B. Wu, Z. Tang and R. Rapp, in prep., based on PRC96(2017)054901 & Nucl.Phys.A 859 (2011) 114)
- CAVEAT: inclusive (p_T-integrated) (whereas $p_T > 6$ GeV ⟶ expected drop of recombination)



- Liu Greiner Kostyuk (PRC **87** (2013), 014910)
- p_T dependence seems doable

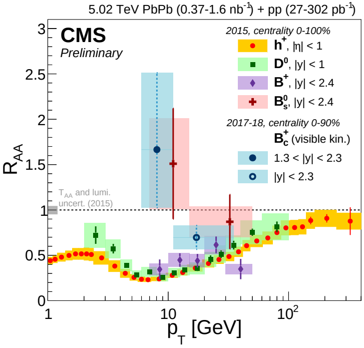


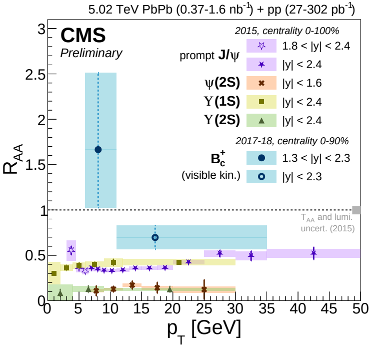
- Schroedter, Thews, Rafelski: $\sim \times 500$ enhancement in PRC **62** (2000), 024905 (without suppression effects)



Conclusion

- First observation of the B_c meson in PbPb collisions (well-above 5σ significance)
- Only one theory prediction yet, showing (much) more suppression than our result
- Results may point towards importance of recombination mechanism in B_c production + can help disentangle enhancement and suppression mechanisms in the QGP!

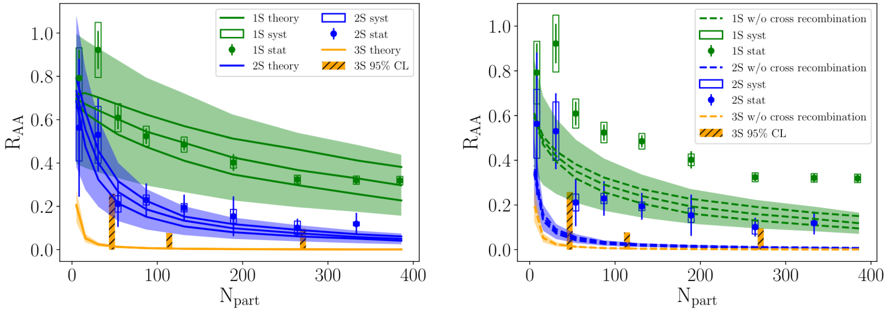




BACKUP

Yao et al. prediction, based on JHEP01(2021)046

- Recombination of excited states ('cross-talk' recombination) not included in present prediction
- Changes $R_{PbPb}(\Upsilon(nS))$ by a factor of ~ 2... But a factor of 5-10?



(a) With cross-talk recombination.

(b) Without cross-talk recombination.

Explicit cuts

- Fiducial B_c XS cuts:
  $0 < |y| < 1.3 \,\&\, 11 < p_T < 35$ GeV
  OR $1.3 < |y| < 2.3 \,\&\, 6 < p_T < 35$ GeV

- Loose HybridSoftID muon acceptance cut:
  $(p_T \geqslant 3.4) \,||\, (|\eta| \geqslant 0.3 \,\&\, |\eta| < 1.1 \,\&\, p_T \geqslant 3.3)$
  $||(|\eta| \geqslant 1.1 \,\&\, |\eta| < 1.4 \,\&\, p_T \geqslant 7.7 - 4.0 * |\eta|)$
  $||(|\eta| \geqslant 1.4 \,\&\, |\eta| < 1.55 \,\&\, p_T \geqslant 2.1)$
  $||(|\eta| \geqslant 1.55 \,\&\, |\eta| < 2.2 \,\&\, p_T \geqslant 4.25 - 1.39 * |\eta|)$
  $||(|\eta| \geqslant 2.2 \,\&\, |\eta| < 2.4 \,\&\, p_T \geqslant 1.2)$

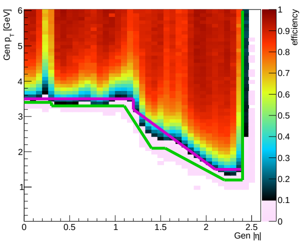
- Tight HybridSoftID+Trigger muon acceptance cut:
  $|\eta| < 2.4 \,\&$
  $((|\eta| < 1.2 \,\&\, p_T \geqslant 3.5)$
  $||(1.2 \leqslant |\eta| \,\&\, |\eta| < 2.1 \,\&\, p_T \geqslant 5.47 - 1.89 * |\eta|)$
  $||(2.1 \leqslant |\eta| \,\&\, p_T \geqslant 1.5))$

Single-muon acceptance + selection

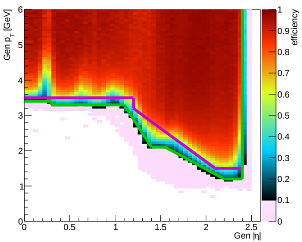
- Two muons must pass the J/ψ trigger, the third one only Hybrid-soft
- Hybrid-soft is:
  - Passes *global* and *tracker* muon ID
  - $d_{xy} < 0.3$ cm and $d_z < 20$ cm
  - tracker layers with measurement > 5
  - pixel layers with measurement > 0

PbPb single-muon efficiencies:

Hybrid-soft + trigger



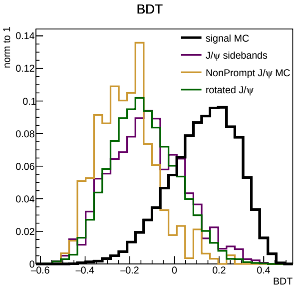
Hybrid-soft selection

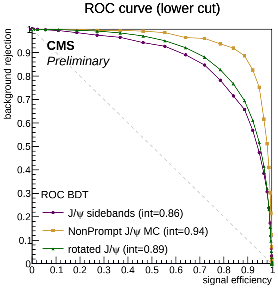


- Single-muon acceptance cuts from **efficiency $\gtrsim$10%**
- Looser acceptance cuts for the non-triggering muon

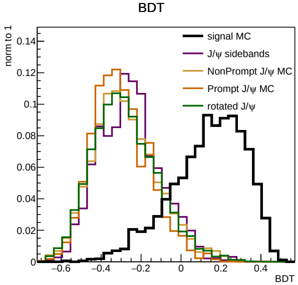
BDT variable

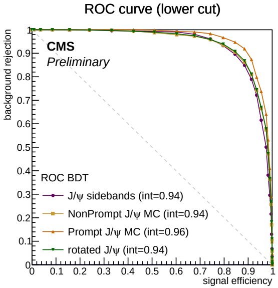
pp





PbPb

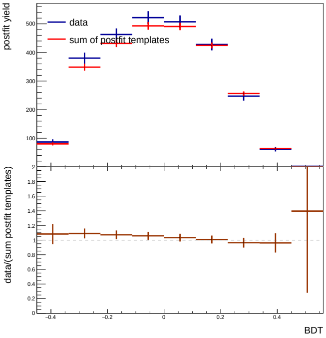




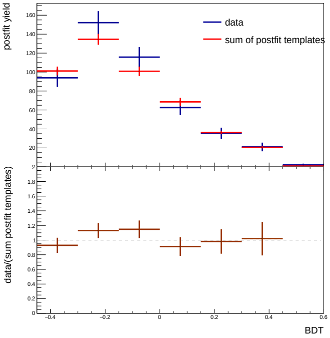
Check of BDT distributions

- After the second-step fit, we compare the BDT distribution in data VS the one of the sum of postfit templates
- Agreement within uncertainties in PbPb.
  In pp, use the ratio as weights applied to all templates before a final re-fit.

pp
2nd p_T bin
(after weighting)



PbPb
2nd p_T bin



Nuisance parameters

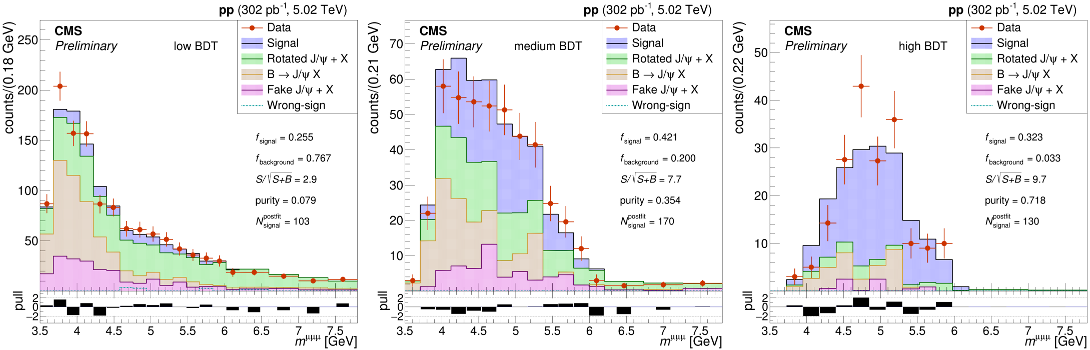
Profiling over nuisance parameters ⟶ systematic uncertainties reflected on signal normalisation fit uncertainty

- Fake J/ψ (1): morph *shape* to lower or upper sideband only ($\pm 2\sigma$)
- flipped J/ψ (2b):
  - pp: quasi-free normalisation, and 2 *shape* morphing parameters:
    - changing rotation angles
    - adding non-prompt or full combinatorial J/ψ MC (2a)
  - PbPb: self-normalised (fixed)
    + change shape to combinatorial J/ψ MC (2a)
- B decays (3): quasi-free normalisation
  + morph shape to include non-prompt combinatorial MC (pp only)
- One parameter per trimuon mass bin, to vary the templates within their statistical uncertainties

Template fit result (pp)

- r_1, r_2 close to 1 (pre-fit normalisation from previous measurements)
- signal normalisation uncertainty 5% (p_T bin 2) or 9% (p_T bin 1)
- Second-step fit is shown

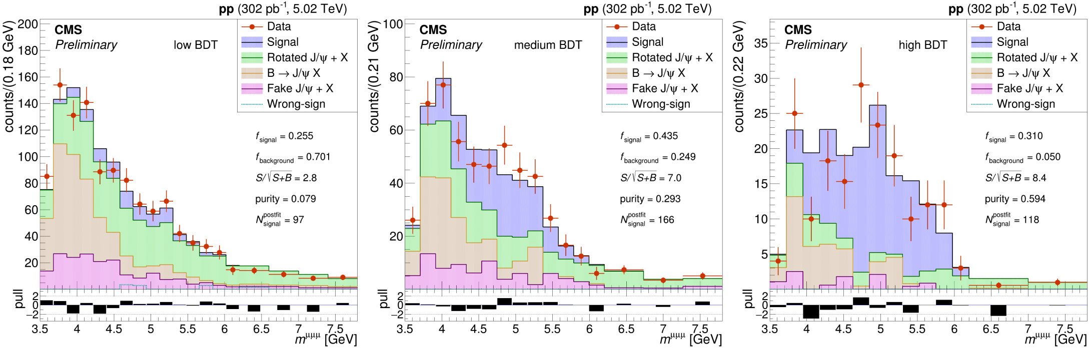
pp, $6 < p_T < 11$ GeV



Template fit result (pp) (BDT-mass decorrelated)

- As a fit method variation, decorrelate BDT from the trimuon mass

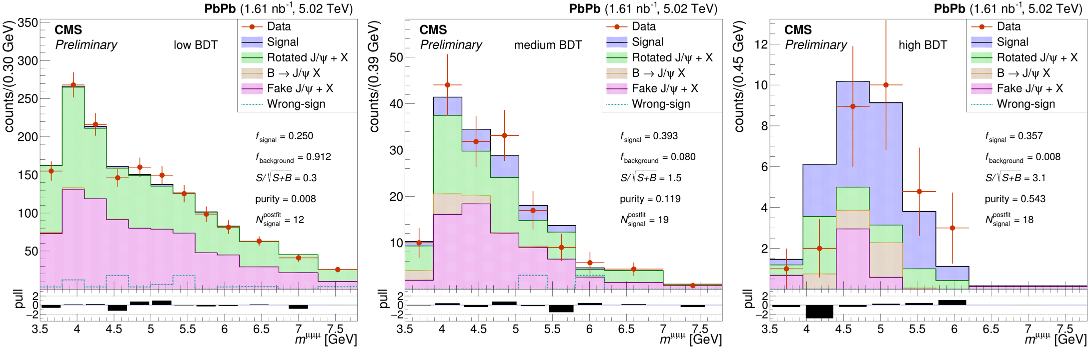
pp, $6 < p_T < 11$ GeV



Template fit result (PbPb)

- Signal normalisation uncertainty 17% (p_T bin 2) or 31% (p_T bin 1)
- Second-step fit is shown

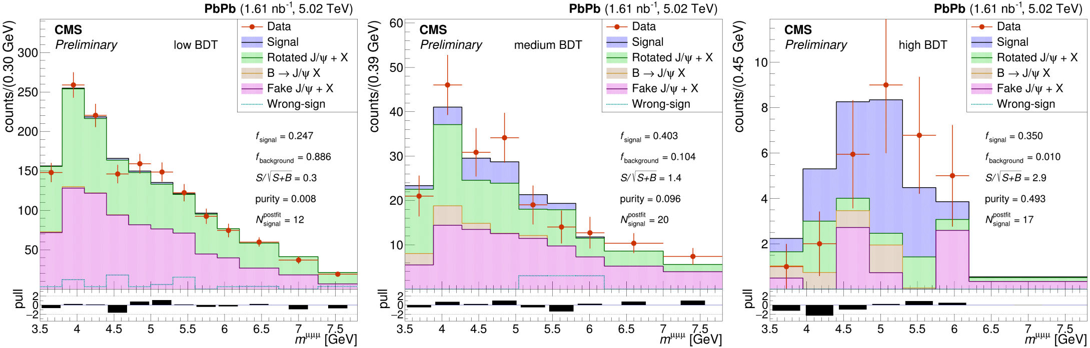
PbPb, $6 < p_T < 11$ GeV



Template fit result (PbPb) (BDT-mass decorrelated)

- As a fit method variation, decorrelate BDT from the trimuon mass

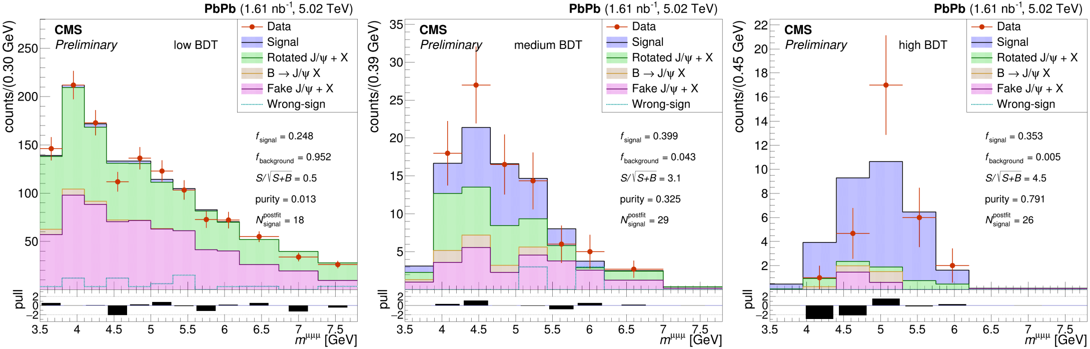
PbPb, $6 < p_T < 11$ GeV



Template fit result (PbPb, centrality)

- Signal normalisation uncertainty 20% (centrality bin 1) or 23% (centrality bin 2)

PbPb, centrality 0 – 20% (p_T-integrated)



Variations of fit method

11 variations of the fit method are run:

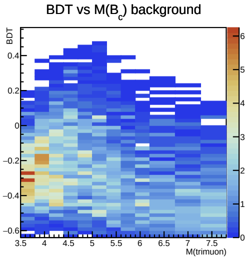
- Ignore BDT bin 1 in the fit (i.e. less constrained backgrounds)
- Fit with BDT decorrelated from mass (to leave discriminant power to the mass, see procedure in backup), with *or* without BDT bin 1
- Regularise the low-stats background shapes (3-bin floating average).
  In this case, need to ignore the nuisance parameters for bin-by-bin stat uncertainties, in BDT bin 3 *or* in BDT bin 2&3
- Normalise the shape variations to the nominal shape in each BDT bin (nominal: normalisation is integrated on BDT bins).
  In this case, need the low-stats regularisation as well (without bin-by-bin stat uncertainties, 2 cases)
- Change mass binning (finer *or* coarser), *or* BDT binning ($[20, 35, 45]\%$ or $[30, 45, 25]\%$ of signal in the 3 BDT bins)

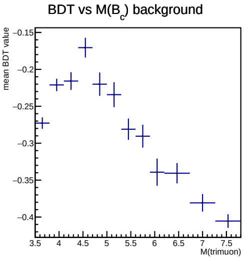
Uncorrelate BDT from trimuon mass

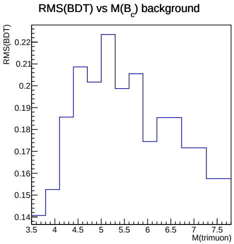
- The BDT, when optimising, realises that most signal is in [4.5,5.5] GeV...
  $\longrightarrow$ steals discriminative power from the template fit procedure
- Decorrelate BDT value from mass (in each p_T or centrality bin), and use alternative fit in the systematics
- Subtract the mean BDT mass (of total background) in each mass bin, and divide by the RMS of the BDT in each mass bin:

$$BDT_{new} = \frac{BDT_{old} - mean(BDT_{old})(M)}{rms(BDT_{old})(M)}$$

Example of PbPb 2nd p_T bin:

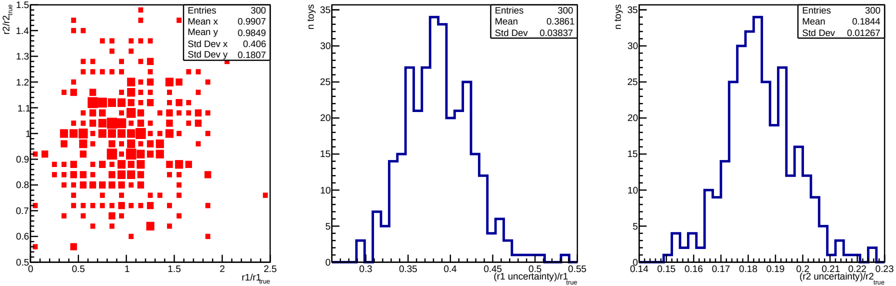






Toys for fit bias and uncertainty stability

- Run 300 toy PbPb datasets from the *post-fit* signal+background model
- Crosscheck the fit uncertainties (and $r_1 - r_2$ correlation) $\longrightarrow$ variability of about 10% of the uncertainty
- Negligible bias in the mean of POIs from toys
- Same check done in pp too



Two-steps strategy

- First step:
  - Calculate p_T-dependent corrected yields with one-binned strategy and original MC
  - Fit p_T spectrum ⟶ Correct p_T in signal MC
- Second step:
  - Re-run the analysis (new BDT training, check of BDT distribution, template fit, fit method systematics, $\alpha \times \varepsilon$ corrections)
  - Again: Fit p_T spectrum + correct signal MC
- Third step:
  - Nominal acceptance and efficiency correction from 2nd-step-corrected MC
  - Acceptance and efficiency uncertainty:
    - Vary second-step p_T-binned measurement within the uncertainties excluding $\alpha \times \varepsilon$ and global unc. (luminosity and $B_c \to J/\psi\,\tau$)
      ⟶ varied p_T spectrum of signal MC
      ⟶ varied $\alpha \times \varepsilon$ corrections